5-6-2019

The Supermassive Black Hole Mass of NGC 4151 from Stellar Dynamical Modeling

Caroline Roberts

Follow this and additional works at: https://scholarworks.gsu.edu/phy_astr_diss

Recommended Citation
https://scholarworks.gsu.edu/phy_astr_diss/113

This Dissertation is brought to you for free and open access by the Department of Physics and Astronomy at ScholarWorks @ Georgia State University. It has been accepted for inclusion in Physics and Astronomy Dissertations by an authorized administrator of ScholarWorks @ Georgia State University. For more information, please contact scholarworks@gsu.edu.
THE SUPERMASSIVE BLACK HOLE MASS OF NGC 4151 FROM STELLAR DYNAMICAL MODELING

by

CAROLINE ANNA ROBERTS

Under the Direction of Misty C. Bentz, PhD

ABSTRACT

The mass of a supermassive black hole ($M_{\text{BH}}$) is a fundamental property that can be obtained through observational methods. Constraining $M_{\text{BH}}$ through multiple methods for an individual galaxy is important for verifying the accuracy of different techniques, and for investigating the assumptions inherent in each method. However, there exist only a few galaxies where multiple $M_{\text{BH}}$ determination techniques can be applied. NGC 4151 is one of these rare galaxies for which multiple methods can be used, stellar and gas dynamical modeling because of its proximity and reverberation mapping because of its active accretion. In this work, we reduced the integral field unit spectroscopy of the nucleus of NGC 4151 from Onken et al., observed in the $H$ band with Gemini North NIFS, improving the process itself as well as the analysis of the spatially-resolved spectra. We also improved on
the methods for constraining the line of sight velocity distribution as a function of position within the nucleus. Stellar dynamical modeling was then performed over a range of choices of $M_{BH}$ and mass-to-light ratio $\Upsilon$, as well as the de-projected luminosity density for various inclinations. The best reproduction of the observed kinematics and luminosity density was found with $M_{BH} = 2.44 \pm 0.16 \times 10^7 M_\odot$ and $\Upsilon_H = 0.318 \pm 0.003 M_\odot/L_\odot$ and an inclination of $45^\circ$. This measurement falls within the range of values in the literature; it is below the reverberation mapping mass of Bentz et al. ($3.59^{+0.45}_{-0.37} \times 10^7 M_\odot$) and above the reverberation mapping mass of De Rosa et al. ($1.97 \pm 0.04 \times 10^7 M_\odot$), and within the uncertainties on both the gas dynamical modeling mass of Hicks & Malkan ($3.0^{+0.8}_{-2.2} \times 10^7 M_\odot$) and the stellar dynamical modeling mass of Onken et al. ($3.60 \pm 1.10 \times 10^7 M_\odot$). This work also represents a preparatory step in the application of a new bar-optimized stellar dynamical modeling code.

INDEX WORDS: Observational astronomy, Galaxy evolution, Active galactic nuclei, Seyfert galaxies, Supermassive black holes, Stellar dynamical modeling
THE SUPERMASSIVE BLACK HOLE MASS OF NGC 4151 FROM STELLAR
DYNAMICAL MODELING

by

CAROLINE ANNA ROBERTS

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy
in the College of Arts and Sciences
Georgia State University
2019
THE SUPERMASSIVE BLACK HOLE MASS OF NGC 4151 FROM STELLAR DYNAMICAL MODELING

by

CAROLINE ANNA ROBERTS

Committee Chair: Misty C. Bentz
Committee: D. Michael Crenshaw
Mukesh Dhamala
Monica Valluri

Electronic Version Approved:

Office of Graduate Studies
College of Arts and Sciences
Georgia State University
May 2019
DEDICATION

THE FIRST CHAPTER

To my parents, Tracy and Peter Roberts. Thank you for giving me life, my education, and your love. “In the beginning, God created the Heaven and the Earth.” - Genesis 1:1

CHAPTER 2

To my grandmother Wilma, uncle Kris, and brothers Andrew and William. Thank you for your love. “I’m glad the stars are over me, and not beneath my feet. Where we should trample on them, like cobbles on the street. I think it is a happy thing, that they are set so far. It’s best to have to look up high, when you would see a star.” - Unknown Author

CHAPTER 3

To Dr. Kenneth Rumstay. Thank you for believing in me. “My heart trembles like a poor leaf. The planets whirl in my dreams. The stars press against my window. I rotate in my sleep. My bed is a warm planet.” - Marvin Mercer

CHAPTER 4

To Frances. Thank you for being the best Physics lab partner, and my good friend. “...I have loved the stars too fondly to be fearful of the night.” - Sarah Williams

THE LAST CHAPTER

To Chantal. Thank you for your love. Thank you for sharing your life with me, for letting me share mine with you. “Sometimes the night wakes in the middle of me. And I can do nothing but become the Moon.” - Nayyirah Waheed
ACKNOWLEDGMENTS

Above all, I would like to thank and acknowledge my research advisor, Dr. Misty Bentz. She has given me so much of her knowledge, time, effort, and guidance, and I am forever grateful.

I would like to acknowledge the additional members of my dissertation committee, Dr. Monica Valluri, Dr. Mike Crenshaw, and Dr. Mukesh Dhamala. In particular I want to acknowledge Dr. Monica Valluri for all of her help and advice, especially regarding the use of her MASMOD code. I want to acknowledge Dr. Eugene Vasiliev for his great discussion and suggestions. I want to acknowledge Dr. Merida Batiste for her tremendous help learning NIFS data reduction. I want to acknowledge Dr. Chris Onken for his help regarding the NGC 4151 NIFS data, Dr. Eric Emsellem for his help with the SAURON data, and Dr. Michael Fausnaugh for his help with his mapspec software.

I want to acknowledge and thank the Georgia State University Physics & Astronomy Department faculty, staff, and students. In particular, I want to acknowledge all of my professors who taught me classes and all of the astronomy graduate students, past and present, including but not limited to: Bentz Group research siblings: Rachael Merritt, Justin Robinson, and Katie Reyes. Incoming Fall 2014 classmates: Katie Lester, Mitchell Revalski, Sushant Mahajan, Wes Peters, Karen Garcia, and Daniel Horenstein. AstroPALs: Crystal Gnilka, Aparna Venkataramanasarmastry, and Eliot Vrijmoet. Roommates and neighbors: Dr. Dicy Saylor, Katie Lester, Neda Hejazi, and Beena Meena.
TABLE OF CONTENTS

ACKNOWLEDGMENTS ................................................................. v

LIST OF TABLES ........................................................................ viii

LIST OF FIGURES ......................................................................... ix

1 Introduction .............................................................................. 1

1.1 Active Galactic Nuclei ......................................................... 1

1.2 Direct Measurements of $M_{BH}$ ............................................ 5

1.2.1 Reverberation Mapping .................................................. 7

1.2.2 Stellar Dynamical Modeling ............................................. 10

1.3 Scaling Relationships and Complications .............................. 12

1.4 Difficulty Determining $M_{BH}$ When a Bar is Present .......... 16

1.5 The Importance of NGC 4151 ................................................ 18

2 Observations and Reduction .................................................... 20

2.1 Integral Field Spectroscopy ................................................... 20

2.2 Observations ....................................................................... 22

2.3 Reduction ............................................................................ 25

2.3.1 Telluric Templates .......................................................... 27

2.3.2 NGC 4151 Data and Velocity Templates ........................... 28

2.3.3 Variance Information ....................................................... 32

2.4 SAURON Wide-Field IFS ....................................................... 33

3 Stellar Kinematics Analysis ..................................................... 34

3.1 Preparation with Voronoi Binning ........................................ 34

3.2 Gemini NIFS Stellar Kinematics ........................................... 38

3.2.1 Use of pPXF and its Parameters .................................... 39

3.2.2 Final Kinematic Maps and Additional Considerations ...... 51
3.3 SAURON Stellar Kinematics .............................................. 55

4 Stellar Dynamical Modeling .................................................. 59
  4.1 Required Code Information ............................................... 61
    4.1.1 Multi-Gaussian Expansion Decomposition ......................... 61
    4.1.2 Inclination Angles .................................................. 63
    4.1.3 Mass-to-Light Ratio ............................................... 63
    4.1.4 apang ............................................................... 64
    4.1.5 Point-Spread Function ............................................. 65
    4.1.6 Distance to NGC 4151 .............................................. 68
  4.2 Orbit Library ............................................................. 69
  4.3 Non-Negative Least Squares Optimization Algorithm ................. 71
  4.4 Best-fit Model Results .................................................. 71

5 Conclusion ............................................................................ 75
  5.1 Discussion ....................................................................... 75
  5.2 Future Work .................................................................... 84
  5.3 Summary ......................................................................... 87

REFERENCES .............................................................................

APPENDICES .............................................................................
  A NIFS Kinematic Observations ..............................................
  B SAURON Kinematic Observations .......................................
# LIST OF TABLES

Table 1.1 Measurements of $\langle f \rangle$ ..................................................... 13

Table 2.1 NGC 4151 Gemini NIFS Observations ........................................... 24

Table 3.1 Inputs for pPXF ................................................................. 51

Table 4.1 Inputs for Sosa/Solpa ........................................................... 61

Table 4.2 MGE Results for NGC 4151 ..................................................... 62

Table 4.3 3-Component PSF for NIFS Data ............................................. 68

Table 4.4 1-Component PSF for SAURON Data ....................................... 68

Table 5.1 MASMOD Results .............................................................. 76

Table 5.2 Measurements of $M_{BH}$ for NGC 4151 .................................... 83
LIST OF FIGURES

Figure 1.1  The optical spectrum of the Seyfert 1 AGN NGC 5548 from Peterson (2001). The bottom panel shows the same spectrum as the top panel; the y-axis has only been zoomed in for ease of viewing. Note the strong permitted and forbidden narrow emission lines and permitted broad emission lines characteristic of Seyfert 1s. In a Seyfert 2, Hβ emission at 4861 Å would appear narrow like the [OIII] emission doublet at λ4959, 5007 Å. .................. 3

Figure 1.2  A simplified model of an AGN from Urry & Padovani (1995). The supermassive black hole (black, center) is surrounded by a thin accretion disk (pink) and a dusty torus (orange). Matter from the accretion disk loses angular momentum and upon infall to the supermassive black hole may be ejected as jets (yellow/white) or as outflow winds (not shown). Surrounding the accretion disk at large distances are the narrow line region clouds and at close distances are the broad line region clouds (gray), the latter employed for reverberation mapping along with the accretion disk. Note the spacing of the parts of the diagram are relative and not to scale. .................. 4

Figure 1.3  The Seyfert 1 galaxy NGC 4151 (Hubble Space Telescope, Judy Schmidt). Displayed here is a Wide-Field Camera 3/UVIS optical image with F350LP, F814W, and F555W filters. North is 30° counter-clockwise from up. ............ 5

Figure 1.4  Figure taken from Peterson (2001), where light curves of the continuum (top two panels) and different broad emission lines (bottom five panels) are shown. On the left are the observed data. By eye, a lag can be seen between the continuum light curves and the light curves from the lines of the responding BLR clouds, but the cross-correlation coefficient panels on the right show the delay of each line with more clarity, including an autocorrelation function for the 1350 Å continuum in the top right. .................. 9

Figure 1.5  Figure from Riffel (2010) where the dotted line is a standard Gaussian. In the top panels, $h_3$ is varied, in the center panels, $h_4$ is varied, and in the bottom panels, both Gauss-Hermite terms are varied. .................. 11

Figure 1.6  Figure from Batiste et al. (2017b), the $M_{BH} - \sigma_*$ relationship. The best-fit relationship for the quiescent sample is the gray dotted line (with slope of 4.76), while the best-fit relationship for the AGN sample is the blue dashed line (with slope of 3.90). The average virial scaling factor used, $\langle f \rangle$, is 4.82±1.67. The position of NGC 4151 is labeled. .................. 14
Figure 1.7 Figure 12 of Brown et al. (2013), showing differences between measured $V, \sigma, h_3, h_4,$ and surface mass density as determined from galaxy models with and without a bar. The top row shows the differences between a barred disk galaxy and a disk galaxy, and the bottom row shows the differences between a barred disk+bulge galaxy and disk+bulge galaxy. In these difference maps, green colors represent areas where the measurements are very similar in both terms of the subtraction and there is no influence of a bar. The presence of a bar inflates both the measured central $\sigma$ and surface mass density (shown by red and yellow residuals in these central regions).

Figure 2.1 Layout of an image-slicer IFU. The left side shows the optical path while the right side shows cartoon examples of the light or instrumentation at the location along the path. Before the start of the orange arrows, light enters the telescope and travels through its optics. Along the path of the arrows, the light comes into contact with the image-slicing mirror, which divides the field-of-view (FOV) into a number of slices of the image. These slices continue through additional optics before entering slits that lead to the spectrograph. At the spectrograph, all slices of the FOV hit the grating and create a spatially-resolved spectrum that falls onto the CCD (Gemini Observatory; Robert Content, Durham).

Figure 2.2 The progression of the data through the reduction process. 2.2a shows the FOV of the data when it is observed, while 2.2b shows a typical raw CCD image of the data. The bright vertical lines are sky lines that were later removed. Figure 2.2c shows a nightly observation in cube form ($x \times y \times \lambda$), while 2.2d shows a nightly observation once the cube has been drizzled. 2.2e shows the final data cube once all nightly cubes have been aligned and combined. Blue boxes mark out one of the 29 slices; white boxes mark out individual spaxels. In figures other than 2.2b, north is $15^\circ$ clockwise of up and east is counterclockwise of north.

Figure 2.3 From the xtellcor program, the bottom panel shows the expected atmospheric response in yellow while xtellcor's initial guess at a telluric spectrum is shown in white with green marking the locations of stellar Hydrogen features. The user adjusts the scaling of the model Hydrogen lines in the top panel to remove them from the telluric spectrum.

Figure 2.4 Both a part of nftelluric, 2.4a shows an extracted central spectrum of the science data before telluric correction and 2.4b shows finding the shift and scaling needed to remove the telluric features. In 2.4b the bottom panel is the telluric spectrum and the top panels are resultant telluric corrected data. Note the features removed at $\sim 15750$ and $16100\,\text{Å},$ as well as the large number of telluric lines removed redward of $17000\,\text{Å}.$
Figure 3.1  Bins for one-half the data cube with a constant S/N within each bin. The scheme was reflected across the center to produce point-symmetric bins.

Figure 3.2  A representative spectrum from the data, this bin at \( \sim [0.25'' , 0.25'' ] \).

Figure 3.3  The top panel shows spectral fits for the bin at \( \sim [0.25'' , 0.25'' ] \) from the AGN, where black is the observation and red is the template fit. The center panel shows the residuals between the observation and the template in green, while the purple dots show the GOODPIXELS. The bottom panel shows the error spectrum for the bin.

Figure 3.4  Same as Figure 3.3 but for the bin at \( \sim [0.75'' , 0.75'' ] \) from the AGN.

Figure 3.5  The red line shows the initial input values of \( h_3 \) and \( h_4 \), while the black points show the output values of the same as a function of increasing \( \sigma \). Figures 3.5a-3.5e are for BIAS values of 0, 0.2, 0.4, 0.6, and 0.8, respectively.

Figure 3.6  Kinematic results for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. Shown here are the results when the BIAS value is set to 0 (top), 0.2, 0.4, 0.6, and 0.8 (bottom), respectively. The numbers displayed at the top indicate the range of the color scheme, with black and dark blue corresponding to the lowest values and red and white corresponding to the highest values. The innermost bins have poor results due to the spectra being dominated by the AGN. Note how \( h_3 \), \( h_4 \), \( h_5 \), and \( h_6 \) become increasingly biased toward 0 (yellow, green) as the penalty term increases.

Figure 3.7  An example of point symmetry (red) and bi-symmetry (blue). The black \( x \) denotes the center. In point symmetry, points are symmetric across the center. In bi-symmetry, points are symmetric across the center as well as being mirrored across the axes.

Figure 3.8  The left panel shows the smoothed, bi-symmetrized data. The right panel shows the smoothed, non-symmetrized data, with the kinematic position angle overlaid in white. The small black dots indicate the bin centers, and the colors indicate the velocity measurements, with high values denoted by red and low values denoted by blue. This process also constrains the systemic velocity.

Figure 3.9  Legendre polynomials of orders 0-4. These polynomials are used to improve the fit to the AGN continuum and can be multiplicative or additive.

Figure 3.10  Kinematic results and errors for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. North is 15\(^{\circ}\) counterclockwise of the y-axis. The numbers displayed at the top indicate the range of the color scheme, with black and dark blue corresponding to the lowest values and red and white corresponding to the highest values.
Figure 3.11 For the $V$ and $\sigma$ terms, examples of the results of first binning the inner spaxels (3.11a contrasted with 3.11b) and then examining symmetric spaxels and replacing with the best pPXF fit (3.11a contrasted with 3.11c) are shown.

Figure 3.12 Kinematic results for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. North is $15^\circ$ counterclockwise of the y-axis. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low. The missing bins were masked and excluded from the analysis going forward.

Figure 3.13 Kinematic results and errors for NGC 4151 as observed with SAURON for two Gauss-Hermite terms. North is up, east is left. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 3.14 Figure 3.14a displays the masked kinematic results NGC 4151 as observed with SAURON for six Gauss-Hermite terms. North is up, east is left. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low. The missing bins are masked and excluded going forward. In Figure 3.14b, the left panel shows the smoothed, bi-symmetrized data. The right panel shows the smoothed, non-symmetrized data, with the kinematic position angle overlaid in white. The small black dots indicate the bin centers.

Figure 4.1 In 4.1a, the orientation of the data on the sky is shown with north up and east left, with $3.6^\circ$ between the kinematic position angles of the major axis. As the error bars are large, in 4.1b we let the kinematic PAs align, but make the arbitrary location of the angle be in between the two measured locations, $19.8^\circ$ east of north.

Figure 4.2 For inclusion of SAURON kinematic data less than 14.5 (all data), 12, 10, 8, and 6$^\prime$ in radius, plots show the smoothed, non-symmetrized data with the kinematic position angle overlaid in white determined from the smoothed, bi-symmetrized (axisymmetric) data (not shown). The small black dots indicate the bin centers. Note that the center bins are masked due to AGN contamination; the code interpolates the kinematics at these small radii.

Figure 4.3 Figure 4.3a shows the NIFS only \textsc{masmod} $\chi^2$ contour map for $i=45^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 4.3b-4.3c show the observed kinematics and the best-fit model kinematics, respectively. North is $15^\circ$ counterclockwise of the y-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 4.4 $\chi^2$ for the best-fit $\Upsilon$ (marginalized over $M_{BH}$) and $M_{BH}$ (marginalized over $\Upsilon$). We adopt the 3$\sigma$ cutoffs as the uncertainties for the measurements.
Figure 5.1  Figure 5.1a shows the NIFS only \textit{M}AS\textit{M}OD $\chi^2$ contour map for $i=30^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.1b-5.1c show the observed kinematics and the best-fit model kinematics, respectively. North is 15$^\circ$ counterclockwise of the y-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.2  Figure 5.2a shows the NIFS only \textit{M}AS\textit{M}OD $\chi^2$ contour map for $i=75^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.2b-5.2c show the observed kinematics and the best-fit model kinematics, respectively. North is 15$^\circ$ counterclockwise of the y-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.3  Figure 5.3a shows the NIFS + SAURON \textit{M}AS\textit{M}OD $\chi^2$ contour map for $i=30^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.3b-5.3c show the observed NIFS kinematics and the best-fit model kinematics for NIFS, respectively. North is 15$^\circ$ counterclockwise of the y-axis for NIFS. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.4  5.4a displays the observed SAURON kinematics and 5.4b displays the best-fit model kinematics for SAURON. North is up. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.5  Figure 5.5a shows the NIFS + SAURON \textit{M}AS\textit{M}OD $\chi^2$ contour map for $i=45^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.5c-5.5a show the observed NIFS kinematics and the best-fit model kinematics for NIFS, respectively. North is 15$^\circ$ counterclockwise of the y-axis for NIFS. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.6  5.6a displays the observed SAURON kinematics and 5.6b displays the best-fit model kinematics for SAURON. North is up. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.

Figure 5.7  A comparison of the measured $M_{\text{BH}}$ values for NGC 4151. Here the y-axis, order on the y-axis, and colors of the points are only present for contrast.
Figure 5.8 The $M_{BH} - \sigma_*$ relationship from Hartmann et al. (2014), where lines of best fit are show for classical bulges, barred classical bulges, and barred pseudo bulges (less compact bulges not formed through mergers) in black (gray), red, and blue, respectively. A slope of 3.78 is used in all cases. Note how on average the barred objects fall below the relationship. The position of NGC 4151 from Onken et al. (2014) is noted with the large red box, and from this work the new position is marked with the large blue box.
1.1 Active Galactic Nuclei

In 1908, E. A. Fath and V. M. Slipher observed the first spectrum of an active galactic nucleus (AGN), a non-stellar, luminous point source at the center of a galaxy. Their observations of the nearby $z = 0.0038$ spiral galaxy NGC 1068 showed strong, resolved emission lines with sizeable widths on the order of 100s km s$^{-1}$. Seyfert (1943) showed these AGN to be a distinct class of objects and observed spiral galaxy targets with lines having even larger widths on the order of 1000s km s$^{-1}$ as well as high-excitation emission.

Study of similar point sources intensified, in part with a number of radio surveys. The spectra consistently appeared star-like in appearance or similar to what would be expected from quasi-stellar objects, which led to these targets being referred to as quasars (which was the name reserved for these observations in the radio) and QSOs (usually used for the optical), though these terms are used interchangeably in the present day. One of the key breakthroughs that allowed these mysterious objects to be understood was the discovery by Schmidt (1963) that some of these objects had high redshifts, indicating that quasars were in fact at cosmological distances.

This was unexpected, as the high luminosities implied by such large distances ($L_{bol} > 10^{43}$ ergs s$^{-1}$; comparable to or exceeding the luminosity of the host galaxies) had in part led to the general assumption that the sources must be within the Milky Way. Variability on short timescales (<10 days), implying very small source sizes, was also discovered (Matthews & Sandage 1963; Smith & Hoffleit 1963), and the mystery intensified. The output energy
necessary was not only scaled considerably, but the flux needed to originate from a region only light days in radius. It was unknown what type of object could exhibit these properties.

Regardless of the identity of the sources, Burbidge et al. (1963) proposed that these unique objects would lend themselves handily to study of cosmic evolution and galaxy formation. If these objects were at the distance of extragalactic ‘nebulae’, perhaps they could probe the Universe beyond our own galaxy and offer insights into its early stages. Independently, Salpeter (1964), Zel’dovich & Novikov (1964), and Lynden-Bell (1969) demonstrated that accretion onto extragalactic black holes was the only possible source of such large luminosities emanating from such distant and small regions. From their energy output, these objects had to be some of the most massive compact objects in the Universe (Hoyle & Fowler 1963a,b).

High-redshift quasars and low-redshift AGN in spiral galaxies (or Seyferts) were found to be analogs of one another. Khachikian & Weedman (1974) additionally divided Seyferts into two main classifications. Seyfert 1s had both narrow permitted and forbidden emission lines as well as broad permitted lines in their spectra (all indicative of high-velocity material), while Seyfert 2s only had narrow permitted and forbidden lines. This distinction is displayed in Figure 1.1. Several lines of evidence indicate that this presence and absence of broad emission lines is likely due to an orientation effect, where Seyfert 1s and 2s are a continuation of the same type of object where the observed properties are a product of the viewing angle (Antonucci & Miller 1985). Our current understanding of the structure of AGN is illustrated with the cartoon diagram shown in Figure 1.2 where the same object would be observed as a Seyfert 1 from a low inclination (close to face-on) and as a Seyfert 2 from a high inclination (close to edge on, with the obscuring torus blocking the broad line region from view).

There is now consensus that at the center of every massive galaxy is a supermassive
Figure 1.1 The optical spectrum of the Seyfert 1 AGN NGC 5548 from Peterson (2001). The bottom panel shows the same spectrum as the top panel; the y-axis has only been zoomed in for ease of viewing. Note the strong permitted and forbidden narrow emission lines and permitted broad emission lines characteristic of Seyfert 1s. In a Seyfert 2, Hβ emission at 4861 Å would appear narrow like the [OIII] emission doublet at λλ 4959, 5007 Å.

$\left(10^6M_\odot - 10^{10}M_\odot\right)$ black hole (SMBH; Magorrian et al. 1998; Kormendy 2004). AGN are a subclass of these objects where accretion onto the SMBH produces high luminosities, high Doppler velocities, and a wide range of variability timescales and wavelengths of emission. Spectral energy distributions of AGN range from the radio to gamma rays (e.g., Elvis et al. 1994), with the infrared and X-ray emission originating from the torus and corona, respectively, and the accretion disk emitting light in the infrared, optical, ultraviolet (the location of the peak of the emission), and soft X-ray (originating from the inner disk). NGC 4151, the subject of this research, is one such AGN and is a Seyfert 1.5 (Véron-Cetty & Véron 2006;
Figure 1.2 A simplified model of an AGN from Urry & Padovani (1995). The supermassive black hole (black, center) is surrounded by a thin accretion disk (pink) and a dusty torus (orange). Matter from the accretion disk loses angular momentum and upon infall to the supermassive black hole may be ejected as jets (yellow/white) or as outflow winds (not shown). Surrounding the accretion disk at large distances are the narrow line region clouds and at close distances are the broad line region clouds (gray), the latter employed for reverberation mapping along with the accretion disk. Note the spacing of the parts of the diagram are relative and not to scale.

having strong broad permitted lines with noticeable narrow components) and is the brightest Seyfert 1 in the northern hemisphere (Figure 1.3; Section 1.5). The galaxy NGC 4151 has a de Vaucouleurs et al. (1964) classification\(^1\) of (R?)SAB(rs)ab, having a possible outer ring (R?), a weak bar (SAB), an inner ring and inner spiral structure (rs), and a moderately large bulge and tightly wound spiral arms (ab). It likely has a pseudo bulge, bulges formed from secular processes and not from mergers that are less compact (see Section 1.3). It is located at RA=12h 10m 32.6s and Dec=+39° 24′ 21″ in the constellation Canes Venatici

\(^1\)NASA/IPAC Extragalactic Database; https://ned.ipac.caltech.edu/
Figure 1.3 The Seyfert 1 galaxy NGC 4151 (Hubble Space Telescope, Judy Schmidt). Displayed here is a Wide-Field Camera 3/UVIS optical image with F350LP, F814W, and F555W filters. North is 30° counter-clockwise from up.

and has a redshift of 0.003319. As we find AGN similar to NGC 4151 in every direction we observe at both low and high redshift, we realize the power of these objects to inform our understanding of how SMBHs and their growth influence galaxy evolution and vice-versa, as Burbidge et al. (1963) predicted.

1.2 Direct Measurements of $M_{\text{BH}}$

The most convincing piece of evidence for the existence of supermassive black holes is also a unique method for $M_{\text{BH}}$ determination; this is the study of the Milky Way center, Sagittarius
A*. A supermassive black hole with $M_{\text{BH}} = 4 \times 10^6 M_\odot$ is the only explanation for the fast speeds indicated by the proper motions of several individual stars in the Galactic Center resolved by Ghez et al. (1998); Genzel et al. (1997); Schödel et al. (2002). Observing the proper motions of individual stars in the centers of other galaxies is not possible due to the distances involved. Thus, another direct method for constraining $M_{\text{BH}}$ is the use of edge-on water maser disk emission in the radio (Miyoshi et al. 1995; Herrnstein et al. 2005; Greene et al. 2016). The maser emission in the disk traces out the Keplerian rotation curve of the gas, constraining the enclosed mass. Constraining $M_{\text{BH}}$ through the use of water maser emission is beneficial because the technique is able to determine masses for objects that are usually difficult to study because of viewing angle and obscuration. But maser emission in galaxy nuclei is also quite rare, so there are only a few galaxies where this technique may be used.

For larger samples of black hole masses, dynamical modeling is often used. Gas dynamical (GD) modeling looks at spatially-resolved gas motions in galaxy nuclei and infers the geometry and inclination of the gas as well as the enclosed mass, $M_{\text{BH}}$ (Macchetto et al. 1997; den Brok et al. 2015), though the gas may be affected by outflows of the narrow line region that disrupt the gas. Stellar dynamical (SD) modeling is similar, but uses the bulk motions of stars instead. And reverberation mapping (RM) uses light echoes in AGN emission to constrain the orbits of gas on spatially unresolvable scales. Both stellar dynamical modeling and reverberation mapping are prolific measurement techniques, each having been used to determine masses of $\sim 100$ supermassive black holes. Tens of thousands of indirect measurements that are based on the information gleaned from these samples of direct $M_{\text{BH}}$ measurements have also been made by large surveys. Though the opportunities to use direct methods are costly in resource, their implementation is essential for determining and im-
proving the indirect $M_{\text{BH}}$ scaling relationships that allow large samples to be explored across cosmic history.

### 1.2.1 Reverberation Mapping

Reverberation mapping (RM; Blandford & McKee 1982; Peterson 1993) is the technique by which broad line region (BLR) radii and supermassive black hole masses can be measured through comparison of accretion disk continuum and broad line emission variability. RM is an independent, direct technique used for $M_{\text{BH}}$ determination. To our current understanding, in an AGN, continuum emission streams out from the centermost region, traveling away from the center at the speed of light. The size of the accretion disk is assumed to be much smaller than the distance from the accretion disk to the BLR. This light photoionizes BLR gas, and the flux is reprocessed and re-emitted as spectral lines. The continuum flux varies most likely due to disturbances and instabilities in the disk and/or variable accretion, and the BLR clouds respond. If both the the continuum radiation and the broad spectral lines are monitored, the light curves will show variations with a time delay between them, as demonstrated in Figure 1.4. This time delay can be combined with measurements of the Doppler-shifted broad-line cloud emission to obtain $M_{\text{BH}}$ from the virial theorem:

$$M_{\text{BH}} = f \frac{c \tau \sigma_{\text{line}}^2}{G},$$

(1.1) where $f$ is replaced with $\langle f \rangle$, the average scaling factor, an order-unity scaling factor that depends on the geometry and other details (see Section 1.3), $c$ is the speed of light, $\tau$ is the delay from the light curves, $\sigma_{\text{line}}$ is the line dispersion of the RMS of the broad line spectra (for each wavelength of the spectra obtained, the square root of the mean of the squared
flux values of all collected spectra is calculated), and $G$ is the gravitational constant. As recombination timescales of the BLR are negligible, $c\tau$ is the light-crossing time for the BLR, or $R_{BLR}$, the radius of the broad line region. RM is a secondary direct method of finding $M_{BH}$, as its spectral information and high temporal resolution light curves only produce a scaled virial product (VP) that, in most cases, must be multiplied by a scaling factor to obtain $M_{BH}$. The $M_{BH}$ measurement will depend on the choice of the scaling factor that is used.

Reverberation mapping may be applied to many regions within the AGN structure in addition to the BLR. The time delay between the optical/UV continuum variations and the near-IR broad-band response can set the size scale for the edge of the dust sublimation zone (or the inner wall of the putative torus, e.g., Minezaki et al. 2004). Time delays between different continuum bands in the UV and optical can set the size of the accretion disk itself (e.g., Mudd et al. 2018; Edelson et al. 2019).

The BLR is stratified in ionization as high ionization lines return smaller radii for the BLR than low ionization lines. These small radii are accompanied by high velocities, suggesting a virialized BLR. Examining the validity of the assumption of gravity domination in the BLR is important as supermassive black hole mass calculations assume a viralized BLR. This is supported by the $\tau$-$\sigma_{\text{line}}$ correlation, which shows that as the time delay increases, the velocity dispersion of the BLR decreases as $\tau^{-0.5}$, expected for a virial relationship (e.g., Bentz et al. 2010).

RM campaigns require certain assumptions and conditions. We assume the geometry of the BLR is of a symmetric shape. Sufficient signal-to-noise is needed for a successful campaign, as are sufficient temporal sampling, variability of the AGN continuum, and an
Figure 1.4 Figure taken from Peterson (2001), where light curves of the continuum (top two panels) and different broad emission lines (bottom five panels) are shown. On the left are the observed data. By eye, a lag can be seen between the continuum light curves and the light curves from the lines of the responding BLR clouds, but the cross-correlation coefficient panels on the right show the delay of each line with more clarity, including an autocorrelation function for the 1350 Å continuum in the top right.

observation campaign free of excessive interruptions from weather, etc. As discussed, because the geometry of the BLR is unknown, RM produces only a VP that must be multiplied by \( \langle f \rangle \), to obtain the true \( M_{BH} \). Velocity-resolved RM (Pancoast et al. 2014; Grier et al. 2017) constrains the likely geometry of the BLR to obtain this value for specific AGN.
1.2.2 Stellar Dynamical Modeling

Stellar dynamical (SD) modeling is a primary method that constrains $M_{BH}$ from spatially resolved spectroscopy and comparison of the bulk kinematics of stars to mock observations of a simulated galaxy from a computer code. A large number of stellar orbit libraries representing a galaxy with known $M_{BH}$, mass-to-light ratio $\Upsilon$, and inclination $i$ are constructed, and the model that best reproduces the observations of the real galaxy is found. SD modeling is built on the Schwarzschild (1979, 1993) orbit superposition method and depends on the ability to spatially resolve, or nearly so, the SMBH sphere of influence, or the region where the gravity of the SMBH dominates over the gravity of the stars. Some authors argue that resolving the sphere of influence is not strictly necessary (e.g., see Davies et al. 2006). This method of $M_{BH}$ determination depends on distance.

SD modeling has been applied to $\sim$100 objects (McConnell & Ma 2013). The goal of the method is to constrain the line of sight velocity distribution (LOSVDs) at several spatial positions and the surface brightness distribution of the stellar population in the observed system. The LOSVDs can then be compared to mock observations of model galaxies to determine the most likely combination of $M_{BH}$, $\Upsilon$, and inclination to the observer’s line of sight. The LOSVDs are derived from spatially-resolved spectroscopy of the center of a galaxy. Spectral templates are then convolved with Gauss-Hermite polynomials, providing information on velocity $V$, velocity dispersion $\sigma$ (the width of the line), $h_3$ (similar to skewness), $h_4$ (similar to kurtosis), $h_5$, and $h_6$ as a function of position within the galaxy, as demonstrated in Figure 1.5.

Stellar dynamical modeling codes are limited by a number of factors (Kormendy & Ho
Figure 1.5 Figure from Riffel (2010) where the dotted line is a standard Gaussian. In the top panels, $h_3$ is varied, in the center panels, $h_4$ is varied, and in the bottom panels, both Gauss-Hermite terms are varied.

2013). First, most codes only use axisymmetric density profiles, unable to deal with triaxial systems. Some codes (e.g., Gebhardt & Thomas 2009) account for halo dark matter, but not all do. And no current code is capable of dealing with the dynamics of barred disk galaxies. There is great need for creation of a bar-orbit superposition code that can account for bars (see Sections 1.4 and 1.5). Additionally, inclination $i$ is not closely coupled with $M_{\text{BH}}$ and $\Upsilon$ and can be difficult to constrain. $\Upsilon$ is also often difficult to constrain, leading to coupling between $M_{\text{BH}}$ and $\Upsilon$, though this issue has been somewhat mitigated by the more frequent use of spatially resolved spectroscopy. Additionally, as Valluri et al. (2004)
describe, if sufficiently large numbers of orbits are not used for the models, the errors on the best-fit $M_{\text{BH}}$ in stellar dynamical modeling become very small, biasing the best-fit values.

### 1.3 Scaling Relationships and Complications

The masses of supermassive black holes ($M_{\text{BH}}$) are correlated with properties of the host galaxy in which the supermassive black hole resides, such as the stellar velocity dispersion of the host spheroid ($\sigma_*$; e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000b; Tremaine et al. 2002; Hu 2008; Gültekin et al. 2009; Schulze & Gebhardt 2011; Graham et al. 2011; Beifiori et al. 2012), the mass of the host spheroid (e.g., Marconi & Hunt 2003; Haring & Rix 2004; Magorrian et al. 1998; Sani et al. 2011), and the luminosity of the host spheroid (e.g., Kormendy & Gebhardt 2001; Kormendy et al. 2011; Beifiori et al. 2012). The host spheroid is, for an elliptical galaxy, the galaxy in its entirety, while the host spheroid of a disk galaxy is only the central stellar bulge. These scaling relationships are quite remarkable, as the SMBH is almost negligible in mass relative to the rest of the galaxy, and on average only a ten-thousanth of the radius in size. These relationships hold true especially for elliptical hosts and galaxies with classical bulges (formed by galaxy mergers, unlike pseudo bulges). Reverberation mapping (RM) stellar dynamical (SD) modeling, and gas dynamical (GD) modeling are the direct methods of $M_{\text{BH}}$ determination by which $M_{\text{BH}} - \sigma_*$ and other relationships are anchored.

The scaling factor for RM is found by determining the multiplicative factor necessary to bring the $M_{\text{BH}} - \sigma_*$ relationship for AGN into coincidence with the $M_{\text{BH}} - \sigma_*$ relationship for quiescent galaxies (e.g., Onken et al. 2004). Each galaxy has its own value of $f$, but it can only be found directly in a few instances (discussed further in Section 1.5), and so
a population average is generally adopted. The population average value is generally in the range of 4-5 depending on the particulars of the analysis, as can be seen in Table 1.1. For determining $\langle f \rangle$, each reference in the table uses measurements of the VP that were calculated using $\sigma_{\text{line}}$ rather than the FWHM of the broad emission line under study.

The $M_{\text{BH}} - \sigma_*$ relationship for active and inactive galaxies is seen in Figure 1.6. The barred and unbarred AGN have $M_{\text{BH}}$ masses obtained through RM (Bentz & Katz 2015), while the quiescent galaxies have $M_{\text{BH}}$ obtained through SD modeling (Kormendy & Ho 2013). The AGN data points are shifted into agreement with the quiescent data points by multiplying each RM VP by $\langle f \rangle$. Encoded in this factor is information about the average kinematics, geometries, and inclinations of the systems. Large surveys such as Shen et al. (2011) rely on additional well-calibrated relationships such as $R_{\text{BLR}}-L$ to perform their single-epoch surveys of the local universe to increase knowledge of galactic properties across redshifts and better construct galaxy accretion and feedback computing codes. Therefore, rigorous work must go into careful RM $\langle f \rangle$ determination.

<table>
<thead>
<tr>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.82 ± 1.67</td>
<td>Batiste et al. (2017b)</td>
</tr>
<tr>
<td>4.3 ± 1.1</td>
<td>Grier et al. (2013)</td>
</tr>
<tr>
<td>5.1 ± 1.3</td>
<td>Park et al. (2012)</td>
</tr>
<tr>
<td>2.8 ± 0.6</td>
<td>Graham et al. (2011)</td>
</tr>
<tr>
<td>5.2 ± 1.2</td>
<td>Woo et al. (2010)</td>
</tr>
<tr>
<td>5.5 ± 1.8</td>
<td>Onken et al. (2004)</td>
</tr>
</tbody>
</table>

The $M_{\text{BH}}-\sigma_*$ dependence still possesses much uncertainty; $\sigma_*$ and VPs include biases and limitations we must consider. As an example, the definition of the radius at which $\sigma_*$ is measured is not uniform (Batiste et al. 2017a). The measured value of $\sigma_*$ for barred galaxies
Figure 1.6 Figure from Batiste et al. (2017b), the $M_{BH} - \sigma_\star$ relationship. The best-fit relationship for the quiescent sample is the gray dotted line (with slope of 4.76), while the best-fit relationship for the AGN sample is the blue dashed line (with slope of 3.90). The average virial scaling factor used, $\langle f \rangle$, is 4.82±1.67. The position of NGC 4151 is labeled.

will be affected by the angle chosen for a spectroscopic slit measuring the value. For many galaxies, $\sigma_\star$ has only been obtained using data from longslit spectrographs, which only give a few or even just one data point for determining $\sigma_\star$. Additionally, different radii have been chosen at different times as the standard for measuring $\sigma_\star$. This quantity should describe the property of velocity dispersion for all galaxies in a comparable manner, but there is historical variation in the way this value has been defined and calculated.

In addition, using $M_{BH}$-$\sigma_\star$ as a tool to determine the population average $\langle f \rangle$ relies on the
assumption that quiescent galaxies and AGN follow the same $M_{BH} - \sigma_*$ relationship (Onken et al. 2004; Woo et al. 2010), but there is evidence quiescent galaxies may have a separate slope for the relationship than AGN (Wandel 2002; McConnell & Ma 2013). Different $M_{BH} - \sigma_*$ relationships with distinct slopes may hold for galaxies of different morphologies. Graham (2008), Hu (2008), and Gültekin et al. (2009) found spiral galaxies with bars and pseudobulges to be offset from the early-type galaxy $M_{BH} - \sigma_*$ relationship. In general, barred objects fell below the main relationship. Hartmann et al. (2014) found strong bars increase scatter in $\sigma$, the line-of-sight velocity dispersion, by 10%. Inclined disk galaxies have $\sigma$ increased by 10-25% because disk light contaminates the measured observations of the bulge (Debattista et al. 2013; Hartmann et al. 2014; Brown et al. 2013). Rotational broadening from the disk also increases $\sigma$ (Graham et al. 2011; Bellovary et al. 2014; Woo et al. 2010). $H_2O$ maser $M_{BH}$ determinations on the $M_{BH} - \sigma_*$ relationship (Miyoshi et al. 1995; Herrnstein et al. 2005; Greene et al. 2016), with edge-on disks by definition, are sensitive to this issue. All of these issues affect spiral galaxies whether they host active or inactive black holes, which are prevalent in the local universe.

The study of SMBHs and their host galaxies and properties, and how they evolve together and migrate onto the scaling relationships is an area of great research in extragalactic astronomy (see the reviews by Kormendy & Ho 2013; Heckman & Best 2014; Fabian 2012). There seems to be co-evolution between SMBHs and their host galaxies, promoted mainly by feedback from the AGN in the form of outflows and winds. As matter in the accretion disk around an AGN loses angular momentum and infalls, much of the accreted matter is either ejected from the AGN along magnetic field lines of the jet (if one is present), or by way of outflows into the host galaxy. Feedback, when present, works to quench both star for-
mation and additional AGN feeding, implying that AGN and non-active, quiescent galaxies are related objects in different stages of their lives and evolution.

1.4 Difficulty Determining $M_{\text{BH}}$ When a Bar is Present

Brown et al. (2013) demonstrate that in barred systems, $M_{\text{BH}}$ can be overestimated by axisymmetric stellar dynamical modeling codes. This is credited as a result of two factors; one is a bias that arises from axisymmetric modeling and one is a real property of these galaxies. Observationally, there are orientation effects from the disk inclination relative to the line of sight and the angle of the bar to the line of nodes, and the anisotropic stellar orbits in a barred system project kinematics that increase the measured stellar velocity dispersion $\sigma$. Second, $\sigma$ is also physically larger in barred systems: the growth of $M_{\text{BH}}$ in a barred system alters the bar potential, transporting angular momentum outward and resulting in increased central $\sigma$.

Using time-evolving n-body simulations, Brown et al. (2013) examined how the growth of a SMBH affected $\sigma$ when a bar was present and when it was absent, with the presence of a bar introducing at most a $\sim$10-15% increase in $\sigma$, as demonstrated in Figure 1.7. Conversely, Hartmann et al. (2014) looked at how the formation of a bar affected $\sigma$ when a SMBH was already present and, depending on the strength of the bar, inclination of the bar, and bar position angle, found up to a 40% increase in $\sigma$ as compared to the initial axisymmetric system. This positive offset in $\sigma$ aligns with the observation of spiral galaxies with bars falling below the $M_{\text{BH}} - \sigma_*$ relationship, as mentioned in Section 1.3.

Additionally, stellar orbits traveling along a bar produce negative $h_4$ values, which translates into a direct inflation of the recovered $M_{\text{BH}}$ in axisymmetric SD modeling codes. The
Figure 1.7 Figure 12 of Brown et al. (2013), showing differences between measured $V$, $\sigma$, $h_3$, $h_4$, and surface mass density as determined from galaxy models with and without a bar. The top row shows the differences between a barred disk galaxy and a disk galaxy, and the bottom row shows the differences between a barred disk+bulge galaxy and disk+bulge galaxy. In these difference maps, green colors represent areas where the measurements are very similar in both terms of the subtraction and there is no influence of a bar. The presence of a bar inflates both the measured central $\sigma$ and surface mass density (shown by red and yellow residuals in these central regions).

An axisymmetric orbit code tries to replicate this negative $h_4$ map by including many stars on tangential orbits. This does very little to contribute to the high $\sigma$, and therefore axisymmetric modeling codes will require larger enclosed masses, overestimating $M_{\text{BH}}$.

The mass of the SMBH of the system is likely over-estimated by a factor of $\sim 2$ if a bar is present and an axisymmetric SD modeling code is used, Brown et al. (2013) argued. In general, if $M_{\text{BH}}$ in barred systems is routinely overestimated, the $M_{\text{BH}} - \sigma_*$ relationship followed by barred galaxies may be even more drastically offset from the $M_{\text{BH}} - \sigma_*$ relationship for unbarred galaxies than we now see with potentially more correlation than is actually present. Two-thirds of local spiral galaxies are barred, a further motivation for a bar-optimized code.
1.5 The Importance of NGC 4151

For the case of barred galaxies like NGC 4151, it is important to model the kinematics with superposition codes that account for the unique stellar orbits that are found in a bar. A bar orbit superposition code is currently under development by Vasiliev & Valluri (2019, in prep). In this work, we present the results of a complete reanalysis of the Gemini NIFS data of Onken et al. (2014) with several improvements to the data treatment to prepare for application of the bar-optimized code.

NGC 4151 has been studied by SD modeling (Onken et al. 2007, 2014), GD modeling (using H$_2$; Hicks & Malkan 2008), and RM (Bentz et al. 2006; De Rosa et al. 2018). Onken et al. (2014) assumed the distance to NGC 4151 to be 13.9 Mpc, while Hicks & Malkan (2008) assumed a distance of 13.4 Mpc, based on the redshift and assuming $H_0 = 75 km/s/Mpc$.

As mentioned, velocity-resolved RM recovers the geometry of the BLR to obtain $f$ for specific AGN. If $M_{\text{BH}}$ of an object can be found through both SD modeling and RM, an independent method for obtaining $f$ is produced. This comparison of two different techniques for a single object can only be performed on a small sample of galaxies. The target must be able to be studied by RM (only Seyfert 1 AGN) and also be near enough to resolve the black hole sphere of influence for SD modeling under current observational constraints. There are only a handful of objects that fit these criteria and can be studied with multiple methods of $M_{\text{BH}}$ determination. For SD modeling and RM comparison, to date, comparison has only been done for NGC 4151 (Onken et al. 2014; Bentz et al. 2006) and NGC 3227 (Davies et al. 2006; Denney et al. 2010).

Onken et al. (2014) resolved the sphere of influence of the supermassive black hole of
NGC 4151 and obtained values for $M_{BH} = 3.76 \pm 1.15 \times 10^7 M_\odot$ and $\Upsilon = 0.34 \pm 0.03 M_\odot/L_\odot$.

But as shown in their paper by S-shaped isovelocity contours and low values of $h_4$, NGC 4151 is a weakly-barred galaxy. The simulations of Brown et al. (2013) and Hartmann et al. (2014) show how $\sigma$ is increased in barred systems by up to 40\% their true values, and again, Brown et al. (2013) argue that $M_{BH}$ is likely over-estimated by a factor of $\sim 2$ when modeled with axisymmetric SD modeling codes.

The bar-orbit superposition code in development, while not the first non-axisymmetric SD modeling code (van den Bosch et al. 2008), will be the first able to work with barred disk galaxies with the unique orbits found in a galaxy bar. In this work devoted to NGC 4151, we analyzed Gemini Observatory infrared spectroscopy to study the stellar kinematics of the galaxy at small radii, improving the $M_{BH}$ measurement. In Chapter 2, the observations and data reduction are described. In Chapter 3 we describe the spectral analysis and kinematic measurements. In Chapter 4, the stellar dynamical modeling procedure is described and results are presented, and in Chapter 5, we discuss and present future work.
CHAPTER 2
Observations and Reduction

2.1 Integral Field Spectroscopy

The long-slit spectrographs used throughout the majority of the 20th century primarily give wavelength information of one spatial dimension only. But more information can be obtained when extended sources such as galaxies are studied with spectroscopy taken from two spatial dimensions. The advent of integral field spectroscopy (IFS) in the 1990s allowed astronomers the ability to study spatially-resolved spectral information in a novel way, improving the understanding of the IFS targets.

Placing three-dimensional data (two spatial dimensions and wavelength) on a two-dimensional CCD is one of the challenges of IFS. There are a number of ways of dealing with this complication in the internal optics of the integral field unit (IFU). Fibers or lenslets (an array of small lenses) can set the spatial sampling on the sky. An additional option is an image-slicer IFU, an example of which is displayed in Figure 2.1. In this setup, an image-slicing mirror with angled stages intercepts the light from the target, breaking it up into slices displaced relative to one another that can then be passed through the rest of the optical path. The light from each slice is dispersed by a grating, and the optics line up each dispersed slice onto the CCD. Image slicer IFUs are one of the most compact options for IFS, though manufacture of the slicing mirror is difficult, increasing the cost.

The Near-infrared Integral Field Spectrometer (NIFS; McGregor et al. 2003) is an image-slicer IFU at the Gemini North Observatory on Mauna Kea in Hawaii. NIFS has a $2.99'' \times 2.97''$ field of view, and employs a 29-stage image-slicing mirror, cutting the field-of-view (FOV)
Figure 2.1 Layout of an image-slicer IFU. The left side shows the optical path while the right side shows cartoon examples of the light or instrumentation at the location along the path. Before the start of the orange arrows, light enters the telescope and travels through its optics. Along the path of the arrows, the light comes into contact with the image-slicing mirror, which divides the field-of-view (FOV) into a number of slices of the image. These slices continue through additional optics before entering slits that lead to the spectrograph. At the spectrograph, all slices of the FOV hit the grating and create a spatially-resolved spectrum that falls onto the CCD (Gemini Observatory; Robert Content, Durham).
along the y-axis. These 29 two-dimensional pseudo-longslit spectra fall onto the HAWAII-2RG detector horizontally stacked on top of each other, with wavelength in the x-direction. The detector has 2048×2048 pixels, but the outer four rings of pixels are not used, leaving 2040×2040 pixels to collect the light. In the x-direction on the sky, as 2.99" is divided into 29 slices, there is a spatial resolution of 0.103"pix⁻¹. In the y-direction on the sky, each slice has a spatial width of 2.97" and this is placed on the 2040×2040 CCD with the 29 slices horizontally stacked on top of another, thus giving each slice 69 pixels in the y-direction (with a small number of empty pixels separating each slice), or 0.043"pix⁻¹. See Figure 2.2a-2.2b for further clarification.

2.2 Observations

The web-based Gemini Archive holds data from the Gemini North and South 8.2-m telescopes. We retrieved previously-collected NIFS IFU observations of NGC 4151 from the Gemini Archive for reduction and analysis (Program ID GN-2008A-Q-41; science PI, Christopher Onken). NGC 4151 was observed with the Gemini North NIFS instrument on February 16-17 and 19-24, 2008 (see Table 2.1).

The NGC 4151 NIFS IFU data were taken in the H-band with the JH_G0602 filter while using the H_G5604 grating (spectral range ~14900-18000 Å) with R~5290 and a dispersion of 1.6 Åpix⁻¹. The instrumental resolution was measured to be 3.2 Åpix⁻¹. The data were acquired at a position angle (PA) of –15° east of north (see Figure 2.2). For the observations, the Altair AO system was used (Herriot et al. 1998) with the AGN serving as the guide star.

Each exposure of NGC 4151 had a length of 120s, and 252 individual exposures were obtained during the 8 nights of observations. The data quality and weather conditions
Figure 2.2 The progression of the data through the reduction process. 2.2a shows the FOV of the data when it is observed, while 2.2b shows a typical raw CCD image of the data. The bright vertical lines are sky lines that were later removed. Figure 2.2c shows a nightly observation in cube form \((x \times y \times \lambda)\), while 2.2d shows a nightly observation once the cube has been drizzled. 2.2e shows the final data cube once all nightly cubes have been aligned and combined. Blue boxes mark out one of the 29 slices; white boxes mark out individual spaxels. In figures other than 2.2b, north is 15° clockwise of up and east is counterclockwise of north.
were good; only 3% of the data did not meet the expectations in quality checks such as cloud cover, water vapor/transparency, and background counts indicated by the PI prior to the observations. At all times the data were marked as usable by the Gemini staff’s quality assessment. The airmass was rarely above 1.5 (only 5% of the time), and the average airmass was 1.2.

Table 2.1: NGC 4151 Gemini NIFS Observations

<table>
<thead>
<tr>
<th>Date (Feb. 2008)</th>
<th>Target</th>
<th>Type</th>
<th>Exp. Time (s)</th>
<th># Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>19</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>20</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>21</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>22</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>HIP 60145</td>
<td>Template (M0)</td>
<td>5.3</td>
<td>4</td>
</tr>
<tr>
<td>24</td>
<td>NGC 4151</td>
<td>Science</td>
<td>120</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>HD 98152</td>
<td>Telluric (A0)</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 116405</td>
<td>Telluric (A0)</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 35833</td>
<td>Template (G0)</td>
<td>5.3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HD 40280</td>
<td>Template (K0III)</td>
<td>5.3</td>
<td>4</td>
</tr>
</tbody>
</table>

Observations of stars in the Milky Way were also collected to produce telluric spectra to
quantify the excess absorption of light from molecules in Earth’s atmosphere (most notably water vapor; Section 2.3.1). The two A0V telluric stars observed were HD 98152 and HD 116405, with exposure lengths of 40 s and 30 s, respectively. They were observed throughout each of the eight nights of the observations interspersed between the science observations in order to monitor the varying telluric feature strengths due to changing airmass and weather conditions.

Three giant stars were also observed to serve as velocity templates for assistance in the interpretation of the NGC 4151 spectra. For each of the three stars, HD 35833 (G0), HD 40280 (K0III), and HIP 60145 (M0), four 5.3 s exposures were obtained in a single night. G, K, and M giant stars were chosen as the templates as low-mass stars dominate the stellar emission in the near-infrared, and the high luminosities of these giant stars are responsible for the bulk of the emission from the galaxy at these wavelengths.

Observations of NGC 4151 and the telluric and velocity template stars were typically obtained in an object-sky-object-object-sky-object dithering pattern to allow for sky subtraction. The telescope was moved ~200″ to the side of the FOV for the NGC 4151 data (~5″ for telluric and velocity template stars) before re-centering on the target for the next exposure. The AO was turned on for the science data and the telluric stars, but not for the velocity templates.

2.3 Reduction

The reduction of the IFU data followed the NIFS reduction pipeline created by Tracy Beck and Richard McDermid in 2012 for the National Optical Astronomy Observatory’s Image
Reduction and Analysis Facility (IRAF)\(^1\). We modified these scripts and their processes as necessary to fit our individual needs and improved on them where desirable as described in Sections 2.3.1 and 2.3.3. Many of the reduction procedures are the same as those employed in the original study of these data by Onken et al. (2014), but we highlight the improvements we have made to the reductions below.

To begin the reduction of each night of data, we first produced the calibration files. We began by making the flat field by combining individual 8 s flats. Flat field correction divides out differences in the responsivity of each pixel in the CCD due to the electronics of the CCD and differences in the reflectivity of the mirror. We next created the bad pixel mask, which removes the signatures of dead or ‘hot’ pixels along with photoelectric counts associated with incident cosmic rays. We produced the wavelength calibration file by combining 10 s arclamp exposures and dividing by the flat field. The wavelength solution was then found, an interactive process where the observed emission is cross-checked with a known argon line list, identifying lines by their relative features in the spectra in the 29 slices of the IFU. This wavelength calibration accounts for the flexure of the telescope and its instrument as it moves throughout the observation session. Individual 8 s Ronchi flats were next combined and divided by the flat field. The Ronchi flats were produced by illuminating a Ronchi grating, which is a screen having thin, sharp rulings held against a substrate that allows for measurement of the spatial distortions induced by the optics of the system. This too was an interactive process where 10 intensity peaks per slice were identified with their relative positions on the detector quantifying the spatial curvature and distortion. This information

\(^1\)IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
is important for calibrating the spatial dimension of the data and producing a proper spatial rectification of the data cubes.

Once we had produced our calibration files themselves, we reduced all the science data comprised of the NGC 4151 data, the telluric stars, and the velocity template stars. In all cases we used the off exposures to subtract night sky emission lines, which come from both man-made and natural sources such as street lamps and atmospheric airglow. We flat fielded the data, masked bad pixels, and found and applied the spectral and spatial and transformations to transform the two-dimensional CCD image into a three-dimensional data cube with two spatial axes and one wavelength axis (see Figure 2.2). For NIFS data, there is no application of a bias charge and the dark current is low \(0.01 \text{e}^{-\text{s}^{-1}\text{pix}^{-1}}\) and so these corrections are not applied in the NIFS reduction pipeline.

### 2.3.1 Telluric Templates

Next, we produced the telluric templates. For each of the eight nights, a combination of the two stars, HD 98152 and HD 116405, were observed 2-4 times, with four exposures per observation. After the basic data reduction steps described above, we extracted a one-dimensional spectrum from each individual observation of a telluric star. This was accomplished by summing all spectra within a default 0.5\(^{\prime}\) radius aperture in the center of the FOV, a size that represented the the spatial extent of the seeing-limited telluric star observations. All the spectra of telluric stars that were collected at one time during a night were median combined with no rejection.

We then made telluric calibration spectra from these telluric star observations using the software \texttt{xtellcor} (Vacca et al. 2003). The telluric star spectra consist of stellar continuum
and stellar absorption with telluric features superimposed on top. To create the telluric templates, we needed to isolate the telluric features. \texttt{xtellcor} uses a high-resolution, synthetic spectrum of Vega to model the spectra of A0V stars and isolate telluric features. Each median-combined telluric star spectrum was fed to \texttt{xtellcor} along with the B and V magnitudes of the telluric standard star (8.98 and 8.93 for HD 98152, 8.27 and 8.34 for HD 116405). In the software, the telluric star spectrum was displayed along with the expected atmospheric transmission for the wavelength range. Our telluric standard stars, while being the same spectral type as Vega, had different absorption line widths in their spectra than that of Vega, and so \texttt{xtellcor} scaled and blurred the model of Vega to better match the intrinsic stellar absorption features as displayed in Figure 2.3. The best-fit model was then subtracted from the observed spectrum of the telluric standard, leaving only the telluric absorption spectrum. With multiple telluric templates spanning the time during which the observations were taken each night, we were then able to correct for the telluric features in the science data. For telluric correction, Onken et al. (2014) employed the ‘nffixa0’ script written by Peter McGregor (who was behind the instrumentation of NIFS) to remove stellar features from the spectra.

\subsection*{2.3.2 NGC 4151 Data and Velocity Templates}

Each individual NGC 4151 observation was telluric corrected using the telluric template spectrum obtained closest in time. This was performed with the task \texttt{nftelluric} by extracting the central spaxel of the datacube as demonstrated in Figure 2.4a and then interactively finding the shifts and scales to the telluric spectrum required to correct for the atmospheric telluric absorption as shown in Figure 2.4b. In finding the fit, we ignored
Figure 2.3 From the xtellcor program, the bottom panel shows the expected atmospheric response in yellow while xtellcor’s initial guess at a telluric spectrum is shown in white with green marking the locations of stellar Hydrogen features. The user adjusts the scaling of the model Hydrogen lines in the top panel to remove them from the telluric spectrum.

the edges of the spectrum, which were often dominated by noise. The best-fit correction is spatially independent, and so the solution found for the central spaxel was applied to all spectra collected during a single exposure.

After telluric correction, all 252 individual exposures were then reformatted into three-dimensional data cubes, drizzling and rectifying each exposure’s 29 two-dimensional spectral slices of 2040 spectral channels by 69 pixels into a 60×62 spaxel (spatial pixel) data cube with a spatial sampling of 0.05”×0.05”, or a spatial resolution of ~0.1”×0.1” from Nyquist
Figure 2.4 Both a part of nftelluric, 2.4a shows an extracted central spectrum of the science data before telluric correction and 2.4b shows finding the shift and scaling needed to remove the telluric features. In 2.4b the bottom panel is the telluric spectrum and the top panels are resultant telluric corrected data. Note the features removed at \( \sim 15750 \) and \( 16100 \) Å, as well as the large number of telluric lines removed redward of 17000 Å.
sampling. The sphere of influence of NGC 4151 is estimated to be ∼15 parsecs, or ∼0.2″, and so this region is resolved with these data. We ensured the wavelength axis was consistent among all the cubes by adopting a fixed dispersion of 1.6 Å pix$^{-1}$ and identical starting wavelengths for each cube. Then, to align and combine the cubes, we first implemented a point-spread function (PSF) seeing cut at a natural break of 0.25″ when viewing a slice of each cube centered on the wavelength of the Brackett 10 emission line (Br10; λ17424.5 Å), an emission line intrinsic to the unresolved AGN. A total of 21 individual observations were determined to fail this cut, the majority being observed in the last two nights of observations, February 23 and 24. This left 231 individual cubes to be aligned and combined into a final data cube. The AGN was not always in the center of the FOV and so integer pixel alignment shifts were determined by examining the centroid location of Br10 for each of the cubes. We performed a median combine with $2/3$ of the cubes kept in the final product. We also clipped the extremities of each dimension of the cube to remove edge effects.

For the velocity template star reduction, telluric corrections were found and applied. A one-dimensional spectrum was extracted from the $x \times y \times \lambda$-format cube by summing all spectra within an aperture in the center of the FOV with a larger extraction radius than that which was used for extracting the telluric spectra, as AO was not turned on for these observations. As the four spectra for each of the G, K, and M templates were separately combined, a median scaling was used to account for slight differences in the flux level as flux calibration was not performed, a region that excluded edge effects was chosen for statistics calculations, and no rejection was allowed because of the low number of observations.
2.3.3 Variance Information

Variance information for the data was recorded at the time of observation, but the current version of the NIFS reduction pipeline does not carry this information through to the end of the process. Thus, we developed a method for quantifying the adjustments to the variance at each remaining step in the pipeline and producing a final noise cube to match the final data cube. The inclusion of the propagated errors for the dataset is an improvement on the method of Onken et al. (2014), where a constant error of 2% was assumed.

The first challenge was to determine, by hand, the error propagation for the $\texttt{xtellcor}$ and $\texttt{nftelluric}$ steps, and then create scripts to carry the variance frames through these operations. We then combined the nightly variance cubes with the same PSF cut, integer offsets, and clipping as the data cube by summing the variances and then taking the square root and dividing by the number of input cubes. Due to the rejection scheme adopted when combining our science cubes, we were left with the complication when combining our variance cubes of not having a record of each spaxel in each cube that passed the rejection threshold and for which we should keep the variance information. Instead, we experimented with different rejection schemes until we found a combination that produced an error cube with spectra that approximated the night sky emission features. Night sky emission is the main source of noise for ground-based near-infrared observations, and we expected its features to dominate our noise spectra. This required a rejection of 4% of cubes and was our final noise cube for the analysis and for a few additional steps. However, we also created a $1/3$ rejection cube (up to $1/3$ of the pixels could be rejected during the final median-combining of the data cubes), planning to use this only for determining our data binning.
2.4 SAURON Wide-Field IFS

An additional data cube with wider-field IFU observations of NGC 4151 was provided by Eric Emsellem. The observations were collected as part of the study by Dumas et al. (2007), where IFS from the SAURON IFU was used to examine the kinematics of the stellar and gaseous components of a sample of galaxies including NGC 4151. Three 30 min exposures were collected on the 4.2-m William Herschel Telescope (WHT) in La Palma, Spain in March 2004. SAURON is a lenslet system rather than an image-slicer, and the IFU has a field-of-view of $33'' \times 41''$ with a spatial resolution of 0.94$''$ per lens, resulting in $\sim1500$ spectra per pointing. Use of data from this instrument with its large FOV allows for anchoring of the NIFS data by constraining the $\Upsilon$ value at large radii. The spectral range is in the optical, covering 4825-5380 Å, and the instrument has a spectral resolution of 4.2 Å pix$^{-1}$.

The SAURON data were reduced with the XSAURON software and SAURON pipeline (Bacon et al. 2001; de Zeeuw et al. 2002). In this process, a bias and dark subtraction was performed, followed by wavelength calibration, flat-fielding, cosmic ray correction, sky subtraction, and flux calibration. The three individual cubes were then aligned and drizzled onto a $0.8'' \times 0.8''$ square grid. The final data cube had a FWHM of the PSF of $2.0'' \pm 0.3''$. For further information on the data, we refer the reader to Dumas et al. (2007).
Having produced the data cube, noise cube, and velocity template spectra, we began the analysis to characterize the stellar kinematics as a function of position within the galaxy nucleus. We used a spectral fitting method to shift and blur the spectra of our template stars to match the spatially-resolved spectra of NGC 4151. The templates were used to find the parameters that characterized the line-of-sight velocity distribution within each spatial bin that was sampled.

3.1 Preparation with Voronoi Binning

Beginning with our x-, y-, and λ-clipped data cube with a spatial sampling of 0.05” x 0.05” spaxels with a dispersion of 1.6 Å pix$^{-1}$, we employed the adaptive binning method of CapPELLARI & Copin (2003). This binning procedure is based on Voronoi tessellations (Voronoi 1908) and assigns adjacent spaxels into a scheme that produces constant signal-to-noise (S/N) spectra across the FOV. The code prioritizes bins that approximate the shape of the spaxels, i.e. not overly irregularly shaped, even at the expense of some irregularity in the S/N. This Voronoi binning method preserves the high spatial resolution bins at the center of the galaxy where the S/N is highest while adaptively binning the spaxels at the edges of the field to increase their collective S/N.

To begin, the data and noise cubes were first centered and cropped, noting that the center of the FOV is defined by the centroid of the AGN position. Here we assumed the supermassive black hole is in the center of the galaxy, which appears to be a valid assumption based on our final kinematic measurements in Section 3.2.2. Due to the required alignment,
we had created 74×76 spaxel data and noise cubes from nightly cubes of 60×62 spaxels, and as a result, some of the spaxels at the edges were a median combine of very few spectra. We only determined the binning for the inner 49×49 spaxels, clipping the rest. Our data and noise cubes needed to have an odd number of spaxels on each side because the spaxel containing the AGN was centered.

We first determined the S/N choice for our bins and the general binning pattern of our data cube with the Voronoi binning code. Both the cube itself and the final noise cube (where 4% of cubes were rejected) were needed in this first step of the process. To characterize the S/N of each spaxel we produced both a slice of the data cube (the signal) and a slice of the noise cube that well-represented the cubes as a whole. We focused on the region between the 16200 Å CO (6-3) bandhead and the strong [FeII] emission line at 16440 Å. For the data slice, we median combined ∼10 adjacent slices from the continuum, and for the noise slice, we median combined ∼100 slices. The noise characteristics vary sharply as a function of wavelength because of the many night sky features present in the H band. Thus we averaged together ∼100 slices for a better representation of the average noise per spaxel. From these slices we had a signal and noise value for each spaxel.

The Voronoi binning program uses the signal and noise slices to assign the bins. An ideal Voronoi binning pattern will be characterized by small bins at the center that preserve the spatial information and large bins at the edges that improve the S/N. The choice of these bins is an iterative process that depends on the desired spatial resolution and S/N. As the former is optimized for, we obtain a larger number of assigned bins but lose the capacity to measure the details of the absorption line profiles, and as the latter is optimized for, we obtain a smaller number of assigned bins but lose spatial information.
Within the Voronoi binning program, we iterated our choice of S/N for the bins until we found a pattern that produced optimal bins. Even with averaging out a large amount of the noise features, there were still irregularities in the locations of the small Voronoi bins; they were not always at the center. However, the general desired pattern for the bins could be seen. We determined our target S/N for the bins to be ∼90.

This first Voronoi binning implementation with the final noise cube with 4% rejection was only performed to obtain the S/N for each bin and approximate the size and shapes of our final Voronoi bins. Next, both the cube itself and the 1/3 rejection cube we made during the reduction process were needed in a second step of the process. We median combined adjacent slices from the region in between 16200 and 16440 Å again, with ∼10 slices for both the data and noise cubes as this time we only needed to average out a few spurious noise spikes. We compared a few different choices for the continuum regions in order to find which region produced the most smooth signal and noise slices.

We identified the Voronoi bin pattern for only one-half of the FOV because as discussed in Section 3.2.1.3, we needed to ensure that each bin had a symmetric analog on the other half of the FOV. The central column containing the spaxel with the AGN cannot be easily reflected if its bins are assigned with Voronoi binning. So instead, we binned half the FOV minus the central row. We then optimized the Voronoi binning program for our data with a similar number of small bins in the center and large bins at the edges as that which was found before; as stated we were using 1/3 rejection cube so there would be no irregularities in the locations of the small Voronoi bins. Once we determined our optimal bins, we reflected the bin pattern across the center, and for creating the bins for the the center row, we assigned the central spaxels in the bottom half of the field to one side, and the central spaxels in the
Figure 3.1 Bins for one-half the data cube with a constant S/N within each bin. The scheme was reflected across the center to produce point-symmetric bins.

top half of the field to the other side. This half-plane binning scheme ensured that symmetry across the center was retained, giving each bin a symmetric partner bin on the other half of the FOV. Our final Voronoi binning spaxel assignments for one-half the FOV can be seen in Figure 3.1. Our total number of bins for the cube found in this process was 173.

Once the Voronoi bin assignments were determined, the spaxels that were assigned to
each particular bin were combined for both the data cube and the final 4% rejection noise cube. For all the spaxels that went into a particular bin, the spectra from the data cube were co-added, channel by channel, and the spectra from the noise cube were added in quadrature. About 21% of the binned noise cube had 0 flux (the step of the reduction process that determined the spatial and spectral transformation introduced some negative counts in the variance information that were assigned 0 flux when the square root was taken to create the cube). We replaced counts in the noise cube with 2% of the median of the binned data cube, relocating the baseline of the error spectra from 0 to a small positive number. 2% of the mean of the data spectrum was chosen because this was used as the noise in Onken et al. (2014) and is close to our average noise. Voronoi binning the spectra is an improvement of the data treatment over that of Onken et al. (2014) where there was less spatial resolution as the data were binned into 0.2"×0.2" bins.

3.2 Gemini NIFS Stellar Kinematics

In the near infrared, observations of the host spheroid of a supermassive black hole will be dominated by the summation of spectra of late-spectral-type, luminous giant stars. Stellar absorption profiles in these spectra give information about the bulk kinematics of the unresolved population of stars along the line of sight at each spatial position. In addition to a central wavelength shift indicating typical velocity \( V \), the detailed shapes of the absorption profiles can be approximated with higher-order Gauss-Hermite terms, including velocity dispersion \( \sigma \) (the width of the line), \( h_3, h_4, h_5, \) and \( h_6 \). Data with S/N>30 is necessary for making sure that the higher order moments of the Gauss-Hermite polynomials can be constrained. The S/N of each of our bins was set at 90 during the Voronoi binning, which
permitted us to break degeneracies in the dynamical modeling going forward. The Penalized Pixel-Fitting method pPXF of Cappellari & Emsellem (2004); Cappellari (2017) constrains the Gauss-Hermite approximation to absorption line profiles through determination of the shifting and blurring required to match a stellar absorption template to an observed galaxy spectrum. The line-of-sight velocity distribution within the galaxy is thus constrained by the detailed Gauss-Hermite that, when convolved with the template spectrum, minimizes the differences with respect to the galaxy spectrum. In this way, the unknown stellar kinematics can be recovered and mapped across the FOV.

### 3.2.1 Use of pPXF and its Parameters

The basis of pPXF entails taking stellar templates and fitting them to each galaxy spectrum from each bin of the observation, recovering the kinematic information at each position. However, as with any modeling process, there are many choices of parameters to consider carefully when running the program.

#### 3.2.1.1 GOODPIXELS

Our data covered the wavelength range between \(\sim15100-17700\ \text{Å}\), as is evident in Figure 3.2. Notable features within the wavelength range included forbidden iron (Fe) emission on the blue side, including the strongest line at 16440 Å, and hydrogen Brackett 11 and 10 lines on the red side at 16811 and 17367 Å, respectively. We focused our stellar absorption pPXF fit on the wavelength range \(\sim15200-16400\ \text{Å}\), which included the \(\sim16200\ \text{Å}\) CO (6-3) bandhead and blueward absorption.

The GOODPIXELS keyword allows the pPXF user to specify the wavelength ranges of the
spectra that will be included in the analysis. If a channel is listed in the GOODPIXELS range, the fit of the templates to the spectrum for that channel will be part of the calculation for determination of the best-fit spectrum. We fit GOODPIXELS to the ranges $\sim$15150-15330, 15450-15500, 15530-16000, 16060-16130, and 16180-16350 Å, the same as Onken et al. (2014). These ranges satisfactorily masked the strong emission lines in the region while focusing the analysis on the strongest expected stellar absorption features. We also examined including the red wavelengths and other variations of the GOODPIXELS values, but found the best kinematic maps from the ranges listed. Shown in Figures 3.3 and 3.4 are spectra from bins at $\sim$[0.25", 0.25"] and $\sim$[0.75", 0.75"] ($\sim \frac{1}{3}$ and $\sim \frac{2}{3}$ of the field from the center), where the choices of GOODPIXELS can be seen in the center panel.

3.2.1.2 BIASES

As absorption and emission profiles can be described by Gaussians, when the noise of spectra is high or the data are undersampled with too low a velocity resolution, the proper use of pPXF is to bias or penalize higher order terms toward zero, defaulting them to more Gaussian in shape. The correct amount of penalty for a set of observations is found from running a
Figure 3.3 The top panel shows spectral fits for the bin at \( \sim [0.25'' , 0.25'' ] \) from the AGN, where black is the observation and red is the template fit. The center panel shows the residuals between the observation and the template in green, while the purple dots show the GOODPIXELS. The bottom panel shows the error spectrum for the bin.

Monte Carlo simulation of the spectra within the pPXF program. With the S/N and the typical values of the \( V, h_3, \) and \( h_4 \), simulated spectra are generated, given the S/N and resolution of the data.

By forcing the solutions to be simply Gaussian profiles, the purpose of the method is to remove noise from the higher order kinematic maps that arises when S/N is low or the velocity resolution is low. However, this BIAS term that is chosen should not be too low; if kinematics can be recovered, the non-zero terms should be kept. A balance is required between noise in the kinematic maps and the ability to resolve the high-order Gaussian terms.
Figure 3.4 Same as Figure 3.3 but for the bin at $\sim [0.75'', 0.75'']$ from the AGN.

In the simulation, the output $h_3$, and $h_4$ higher-order terms from pPXF are plotted as a function of $\sigma$ for the Monte-Carlo iteration. The BIAS is found by examining the difference between the average output $h_3$ or $h_4$ and the observed $h_3$ or $h_4$ at a $\sigma$ value a few times that of the velocity resolution. The BIAS value is decided on when this difference is still much less than the scatter in the output terms themselves as portrayed in Figure 3.5. Note how as the velocity dispersion approaches zero in an individual BIAS panel, the spectra become undersampled and the higher-order terms cannot be recovered, as well as note the how increasing the BIAS reduces the noise in the output $h_3$ and $h_4$ terms.

Figure 3.5 demonstrates how as the BIAS is increased, even though the scatter in the output $h_3$ and $h_4$ decreases, it becomes harder to recover the correct values for the higher-order terms because the flexibility of the Gaussian is lost. We adopt a BIAS of 0.6 because
Figure 3.5 The red line shows the initial input values of $h_3$ and $h_4$, while the black points show the output values of the same as a function of increasing $\sigma$. Figures 3.5a-3.5e are for BIAS values of 0, 0.2, 0.4, 0.6, and 0.8, respectively.
further increasing the penalty beyond this point brought the difference between the average output $h_3$ or $h_4$ and the observed $h_3$ or $h_4$ to a value close to the scatter in the output terms themselves. This value reduced the most scatter while still keeping the most ability to fit the absorption profiles. Figure 3.6 gives kinematic plots of the data when a BIAS corresponding to the value in each panel of 3.5 is adopted. Examining the largest changes when the BIAS is set to both the correct value and BIAS=0 can give information about which bins are unreliable and might need to be masked.

3.2.1.3 VSYST

Point symmetry (mirror symmetry) will be assumed in the bar orbit superposition code when used with barred galaxies. In axisymmetric stellar dynamical modeling codes, further symmetry is assumed, with bi-symmetry or four-point symmetry a requirement for the data to be fully compatible with the model. In a point-symmetric system, a point and its pair (flipped directly over the center point) have equal value. In a bi-symmetric system, a point has three values equal to it, including the point symmetric pair and the mirrors of each point across the axes, making a rectangle, as demonstrated in Figure 3.7. Because point symmetry is assumed inherent to our system, we ran point-symmetric two-sided pPXF fitting on our spectra. Two identically-shaped bins symmetric across the center are fed to pPXF simultaneously. However, we noticed that the order in which each bin is fed to pPXF changes the output kinematic fit slightly. For the final Gauss-Hermite term values for each pair of bins, we therefore average the two outputs that come from each bin leading the input to pPXF. This symmetric fitting is another improvement of the treatment data over that of Onken et al. (2014). In that study, the bins were fit independently and then the output
Figure 3.6 Kinematic results for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. Shown here are the results when the BIAS value is set to 0 (top), 0.2, 0.4, 0.6, and 0.8 (bottom), respectively. The numbers displayed at the top indicate the range of the color scheme, with black and dark blue corresponding to the lowest values and red and white corresponding to the highest values. The innermost bins have poor results due to the spectra being dominated by the AGN. Note how $h_3$, $h_4$, $h_5$, and $h_6$ become increasingly biased toward 0 (yellow, green) as the penalty term increases.
measurements were symmetrized instead.

For point-symmetric implementation of pPXF, the systemic velocity is an important term because the velocities on opposite sides of the galaxy center will be defined as positive and negative velocities with respect to systemic, the velocity of the galaxy due solely to its motion through space. We used the method of Krajnović et al. (2006) to find this value. The program uses the kinematic measurements derived from a prior pPXF run, smooths them, bi-symmetrizes them, and outputs the best-fit systemic velocity along with the kinematic position angle of the system as measured from the y-axis. This angle represents the line of maximum galaxy rotation, perpendicular to the axis of rotation, and for our kinematics is
Figure 3.8 The left panel shows the smoothed, bi-symmetrized data. The right panel shows the smoothed, non-symmetrized data, with the kinematic position angle overlaid in white. The small black dots indicate the bin centers, and the colors indicate the velocity measurements, with high values denoted by red and low values denoted by blue. This process also constrains the systemic velocity.

37.2° clockwise from the y-axis. The best-fit results are illustrated in Figure 3.8. We found the systemic velocity of NGC 4151 to be 1013.1 km s$^{-1}$. We input this value to the pPXF code as the parameter $V_{Syst}$.

3.2.1.4 TEMPLATES

As described in Chapter 2, the observations of NGC 4151 also included observations of G, K, and M giant stars to be used as the velocity templates. Their reduced spectra were input as our TEMPLATES. One or more of these spectra may make the main contributions to the kinematics, however, and so we determined the best templates to use for our fit.

If stellar templates are not observed when the data is collected for the galaxy, spectra may be fit with templates taken from an observed stellar library (Leitherer et al. 1999;
Bruzual & Charlot 2003; Maraston 2005; Conroy & Gunn 2010; Conroy 2013; Vazdekis et al. 2010). Additionally, the fits to the kinematics can be made with synthetic templates, but this relies on the uncertainties of the models, which may not always incorporate the necessary physics to construct spectra accurately. Synthetic templates, or model stellar atmosphere spectra, are created from simulated application of astrophysical processes such as atomic transitions, opacity, line-blanketing, hydrostatic equilibrium, mixing-length theory, and radiative transfer. As synthetic templates are model-dependent, their use is not as reliable as that of observed templates for fitting unresolved stellar populations, but the application can provide otherwise unobtained wavelength coverage. Both types of templates must be degraded to that of the instrument of the kinematic observations, and performing these resolution corrections to the spectra may introduce errors into the fit.

3.2.1.5 WEIGHTS

Among the parameters that are returned by pPXF is the parameter WEIGHTS, which contains the number each velocity template star spectrum was multiplied by to contribute to the fit to the galaxy spectrum in a particular bin. A small number is a lower contribution and a large number is a higher contribution, with WEIGHTS=0 indicating that a template did not contribute to that particular fit. If one or more templates are not contributing very frequently, or if they contribute frequently but have a very small weight and so still have a low contribution overall, we want to exclude that template in the final fit. In our fitting, we found that the G star was only used in 20% of the best-fit spectra and so we omitted it as a tempate. The M star contributed 97% of the time and the K star contributed 94% of the time, and so we included both templates in our final fit. This is a slight difference from the
Figure 3.9 Legendre polynomials of orders 0-4. These polynomials are used to improve the fit to the AGN continuum and can be multiplicative or additive.

method of Onken et al. (2014), who only used the M star template.

3.2.1.6 DEGREE, MDEGREE, POLYWEIGHTS

In the process of convolving the velocity template spectra to match the observations, pPXF provides the option to include Legendre polynomials (Whittaker & Watson 1920; Figure 3.9) to improve the fit to the AGN continuum contribution. The additive polynomials (DEGREE) can mediate some of the effects of template mismatch (where poor fits of kinematics are obtained due to templates that incompletely represent the observations) and imperfect sky subtraction in the data reduction, while the multiplicative polynomials (MDEGREE) can aid with slight imperfections in the flux calibration and reduce or remove the need for reddening correction.
In order to choose the correct orders of the DEGREE and MDEGREE parameters, we first examined how the weights of the Legendre polynomials change as we include higher orders with the POLYWEIGHTS keyword. Similar to the weights of the templates, we did not include polynomials that had 0 or low contribution. The output POLYWEIGHTS were slightly different for each of the input point-symmetric spectra pairs, but the trends were similar across the field. Additionally, we considered the goodness of the fits by investigating the $\chi^2$ per degree of freedom ($\chi^2$/dof) values (related to the GOODPIXELS) that came with the output solution for each bin. We also examined the actual fits to the spectra themselves when the fits are plotted, such as those seen in the top panels of Figures 3.3 and 3.4. We found a good balance between polynomial weights and goodness of fits when adopting 2nd order additive and 2nd order multiplicative Legendre polynomials, identical to what was found by Onken et al. (2014). These low-order polynomials improved the overall shape of the best fits to the spectra without introducing localized fluctuations that might have inhibited our ability to constrain the kinematics.

3.2.1.7 /CLEAN

In Figures 3.3 and 3.4, the GOODPIXELS fit are not always identical. This is because we turned on the /CLEAN parameter in pPXF for our final fits for almost all of our bins. The /CLEAN option allows pPXF to iteratively identify spikes and high noise channels within the spectrum as it carries out the template fitting. This setting only performs well if the user has a reliable estimate of the noise, which we have for our spectra.
3.2.2 Final Kinematic Maps and Additional Considerations

We have improved the result of Onken et al. (2014) in the ways that follow: To produce our telluric spectra for use in the telluric correction, we used a portion of the telluric correction method of Vacca et al. (2003) which allowed us to more completely remove telluric features from the spectra. We included noise information from the observations in our analysis rather than assuming a constant noise of 2%. We increased the central spatial resolution by binning the spectra by S/N rather than by 0.2” × 0.2” as done before, noting that the halo of the PSF need not set the resolution limit. This binning (Cappellari & Copin 2003) also increased the signal to noise at the edges of the field. We included a penalty for higher-order LOSVD terms in the kinematics for SD modeling, fit the template star spectra to galaxy spectra by fitting symmetric bins across the center at the same time, and considered wide-field kinematic constraints (Section 3.3). With all of the adopted parameters for pPXF (see Table 3.1), we determined the final stellar kinematics based on the observations of the nucleus of NGC 4151. Our initial results are shown in Figure 3.10a.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Onken et al. (2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOODPIXELS</td>
<td>Wavelengths fit</td>
<td>~15150-15330, 15450-15500, 15530-16000,</td>
<td>SAME</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16060-16130, &amp; 16180-16350 Å</td>
<td></td>
</tr>
<tr>
<td>BIAS</td>
<td>Higher-order term penalty</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>VSYST</td>
<td>Systemic velocity</td>
<td>1013.1 km s(^{-1})</td>
<td>N/A</td>
</tr>
<tr>
<td>Point-symmetric mode</td>
<td>pPXF fits symmetric spectra</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>TEMPLATES</td>
<td>Velocity templates</td>
<td>M, K</td>
<td>M</td>
</tr>
<tr>
<td>DEGREE</td>
<td>Additive continuum fit</td>
<td>2</td>
<td>SAME</td>
</tr>
<tr>
<td>MDEGREE</td>
<td>Multiplicative continuum fit</td>
<td>2</td>
<td>SAME</td>
</tr>
<tr>
<td>/CLEAN</td>
<td>Masking of spurious pixels</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>
Figure 3.10 Kinematic results and errors for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. North is 15° counterclockwise of the y-axis. The numbers displayed at the top indicate the range of the color scheme, with black and dark blue corresponding to the lowest values and red and white corresponding to the highest values.

3.2.2.1 Errors

Deriving the uncertainties on the observed galaxy spectra began with carrying the noise spectra through the data reduction process. There are uncertainties included with the best-fit kinematic measurements from pPXF, and the documentation notes that the final uncertainties for each fit can be found by multiplying the pPXF output uncertainties by the square root of the $\chi^2/DOF$ value for the bin. However, this approximation is only valid in the case where $\chi^2/DOF$ is close to 1, otherwise the uncertainties may be severely underestimated or the measurements may be affected by template mismatch. Also, when $\chi^2/DOF$ is not close to 1, this indicates a poor estimate on the noise spectrum and it is not safe to use the /CLEAN parameter. We did not find this to be the case; our $\chi^2/DOF$ values were low and close to 1, indicating it was safe to proceed both with our errors and using /CLEAN. As mentioned, we used both the M and K star templates in our fits to the data, however, we believed our errors
were underestimated, and not sufficiently conservative. To obtain our final uncertainties for each kinematic term as seen in Figure 3.10b, we ran both contributing templates through pPXF separately. Then, we found the weighted standard deviation between the template results. This increased our errors by \( \sim 5 \text{ km s}^{-1} \) in \( V \) and \( \sim 15 \text{ km s}^{-1} \) in \( \sigma \).

3.2.2.2 Inner Binning, Symmetric Fits

In the inner spaxels, the stellar absorption profiles are difficult to detect due to the strong AGN continuum emission, and thus the spectral fits were very poor at the center. We attempted to improve the constraints on the kinematics at the center of the field by first looking at performing binning of the spectra at the inner regions. The inner bins are single spaxels, but, for example, adding four spaxels into one bin may be beneficial. This change did not significantly improve the fit, and an example of this method can be seen between Figures 3.11a and 3.11b.

Next, we examined the point-symmetric inner spaxels. Rather than adding these spaxels together into larger bins, we re-ran pPXF on each inner bin individually and then examined the plots of the spectral fits to each of the bins in the pair. When one fit appeared better than the other with lower residuals, we adopted the resulting Gauss-Hermite terms for that side of the fit and assigned it to both bins in the point-symmetric pair. An example of this change can be seen between Figures 3.11a and 3.11c. Additionally, when inner binning is performed, the plots of the fits of the symmetric spectra of these bins can be examined, performing both methods in conjunction. Like the former approach, the latter slight adjustments also did not significantly improve our resultant kinematic maps; for this reason we did not adopt the techniques for our final kinematics.
Figure 3.11 For the $V$ and $\sigma$ terms, examples of the results of first binning the inner spaxels (3.11a contrasted with 3.11b) and then examining symmetric spaxels and replacing with the best pPXF fit (3.11a contrasted with 3.11c) are shown.
Figure 3.12 Kinematic results for NGC 4151 as observed with NIFS for six Gauss-Hermite terms. North is 15° counterclockwise of the y-axis. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low. The missing bins were masked and excluded from the analysis going forward.

3.2.2.3 Masking

We were not able to reliably recover the stellar kinematic signature at the center of the FOV, so for the NIFS data we omit these bins by masking radii less than \( \sim 0.15'' \). We also exclude some individual bins in the fit as determined by the BIAS parameter in Section 3.2.1.2. Once the best value of the BIAS is set, if a change in the BIAS greatly reduces or increases the value of any bins, their fit is unreliable and is omitted. This left 86 bins, and our final masked kinematics are displayed in Figure 3.12.

3.3 SAURON Stellar Kinematics

We also reanalyzed the Dumas et al. (2007) SAURON data of NGC 4151 previously discussed in Chapter 2; we planned to include this data cube so that we could investigate whether the wide-field SAURON data aided in constraining the $\Upsilon$ value at large radii. The data was already Voronoi binned (Cappellari & Copin 2003) to a S/N of 60, with 482 total bins. We ran pPXF using the synthetic stellar templates of Vazdekis (1999); Vazdekis et al. (2010). Of the 19 templates, we found two templates contributed most significantly and used these for the final kinematics.
We adopted the entire spectral region of 4825-5380 Å as our GOODPIXELS range for pPXF except for regions with strong AGN emission lines ([OIII] λ4959, 5007 Å). /CLEAN was not used as it was not found to improve the fit. We determined a BIAS parameter of 0.4. We determined DEGREE and MDEGREE values of 4 and 0 to be the best polynomial fits to the continuum. The final kinematics are displayed in Figure 3.13a. Because the data cube was already binned with irregular bins, we were unable to carry out the kinematic measurements using the point-symmetrization option, so each bin was fit individually.

For characterizing the uncertainties on the measured kinematics as displayed in Figure 3.13b, we adopted the standard deviation results given by each of the the five templates with the highest contribution to the fit. To prevent certain bins from imposing overly stringent constraints, we imposed a lower limit on the uncertainties of $V$ and $\sigma$ in the SAURON data, with the error set to be at least 2 km s$^{-1}$. Then, to improve the fit to the data from the SD modeling code, we included $h_3$-$h_6$ but imposed constraints on these higher-order Gauss-Hermite coefficients, requiring them to be zero with uncertainty set to 0.02. We then masked central, AGN-contaminated spaxels, choosing a cutoff of radius of $\sim$3″. We also exclude radii greater than 14.5″ to avoid the predominance of emission from the disk, rather than the bulge, of the galaxy. This left 377 bins, and this masking is displayed in Figure 3.14a. We fit for the kinematic position angle to use in the modeling, and find a value of 18.6° east (counterclockwise) of north (up), as demonstrated in Figure 3.14b.
Figure 3.13 Kinematic results and errors for NGC 4151 as observed with SAURON for two Gauss-Hermite terms. North is up, east is left. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 3.14 Figure 3.14a displays the masked kinematic results NGC 4151 as observed with SAURON for six Gauss-Hermite terms. North is up, east is left. The numbers displayed at the top indicate the range of the color scheme, with red/white being high and blue/black being low. The missing bins are masked and excluded going forward. In Figure 3.14b, the left panel shows the smoothed, bi-symmetrized data. The right panel shows the smoothed, non-symmetrized data, with the kinematic position angle overlaid in white. The small black dots indicate the bin centers.
Applications of the three-integral axisymmetric Schwarzschild orbit superposition method (Schwarzschild 1979, 1993) can recover $M_{\text{BH}}$ from stellar kinematics. In codes used for the process, a grid of $M_{\text{BH}}$ and mass-to-light ratio ($\Upsilon$) estimates is first set up. Then, for each combination of $M_{\text{BH}}$ and $\Upsilon$ in the grid, a model density distribution is constructed, with $\Upsilon$ being used to convert from the de-projected galaxy light distribution to a mass distribution of stars. Into this density distribution all possible stellar orbits are placed. These orbits are integrated sufficiently to provide a time-averaged measurement of the contribution to each location for the mass, velocity $V$, velocity dispersion $\sigma$, and higher order terms. Projection, PSF convolution, and pixel binning are next accounted for, and the observable quantities for each orbit are then linearly co-added with weights for each orbit chosen by a non-negative least squares algorithm. This results in a model for each value of $M_{\text{BH}}$-$\Upsilon$ that gives the best fit to the observed data for those parameters. The differences between the mock observations and the actual galaxy data are calculated for each model in the grid. For our observations of NGC 4151, within the limits of the errors on the observed kinematics, the best-fit values of $M_{\text{BH}}$, $\Upsilon$, and inclination ($i$) of the system can be recovered by varying the values of these three unknowns and determining the combination that best matches the observations.

The MASMOD code (Valluri et al. 2004, 2005) is one of the major Schwarzschild orbit superposition codes in use. Additional modeling machines are in use, including the Nuker code (Gebhardt et al. 2003, 2000a; Richstone et al. 2004; Thomas et al. 2004; Thomas 2010; Siopis et al. 2009) and the Leiden code (van der Marel et al. 1998; Cretton et al. 1999; Cappellari 2002; Cappellari et al. 2006; Verolme & de Zeeuw 2002; van den Bosch et al. 2008). Since
its original implementation, several additions and improvements have been adopted. MASMOD was updated to allow for multiple IFU datasets rather than just longslit spectroscopy, and the binning scheme was improved so all bins at a particular radius have roughly the same mass. Additionally, the code was modified to obtain the surface brightness information from a multi-Gaussian expansion (MGE) deprojection method (Emsellem et al. 1994; Cappellari 2002). The MGE method is a means of parameterizing galaxy surface brightness as multiple nested two-dimensional Gaussian functions that are then easily deprojected into three-dimensional brightness profiles.

From the user’s perspective, the process of implementing MASMOD is largely divided into two steps. A first portion of the code, SOSA (Schwarzschild Orbit Superposition Algorithm), creates an orbit library for various desired values of $M_{BH}$ at a primary $\Upsilon$ and chosen inclination angle $i$. The next step, SOLPA (Schwarzschild Orbit (Non-Negative Least Squares Optimization; formerly Linear Programming) Algorithm) then scales the libraries for different $\Upsilon$ values and computes a weighted superposition of orbits in the library that best fits all the observed data, generating the LOSVDs for each orbit in each aperture on the IFUs and storing these LOSVDs in the library. With orbit libraries for various $M_{BH}$ and $\Upsilon$ values, SOLPA then calculates mock observations of model kinematics through the apertures of the observational data. Using non-negative least squares optimization, a preferred combination of $M_{BH}$, $\Upsilon$, and $i$ is found by computing the $\chi^2$ of the fit of each model to the data, where the minimum in the $\chi^2$ is the best-fit model. In total, we examined 100 combinations of $M_{BH}$ and $\Upsilon$ for each plausible galaxy inclination, angles which were derived from the axis ratios of the large scale disk as well as the ability of the Schwarzchild models to fit the galaxy rotation curves.
4.1 Required Code Information

MASMOD relies on a number of carefully-considered input values and files of pre-determined information. We describe the processes for our choices here, and summarize these variables that are obtained as input to the code in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination Angles</td>
<td>15° - 75°</td>
<td>15°</td>
</tr>
<tr>
<td>$M_{BH}$</td>
<td>$1.5 \times 10^7 - 10.5 \times 10^7 M_\odot$</td>
<td>$1 \times 10^7 M_\odot$</td>
</tr>
<tr>
<td>$\Upsilon_H$</td>
<td>$0.2 - 0.5 M_\odot/L_\odot$</td>
<td>$0.33 M_\odot/L_\odot$</td>
</tr>
<tr>
<td>$\text{apang}_{NIFS}$</td>
<td>124.8°</td>
<td>-</td>
</tr>
<tr>
<td>$\text{apang}_{SAURON}$</td>
<td>109.8°</td>
<td>-</td>
</tr>
<tr>
<td>Distance</td>
<td>13.3 Mpc</td>
<td>-</td>
</tr>
</tbody>
</table>

4.1.1 Multi-Gaussian Expansion Decomposition

For obtaining surface brightness information for NGC 4151, Misty Bentz utilized WFC3 $H$-band imaging of NGC 4151 from the Hubble Space Telescope (HST). She first employed the two-dimensional surface brightness fitting algorithm GALFIT (Peng et al. 2002, 2010) to create a model of the surface brightness components of the galaxy. GALFIT models the target using 2-D analytic functions such as Sérsic/de Vaucouleurs, Nuker, Gaussian, Moffat, etc. The components included in the model were the exponential disk, the bulge, the weak bar, the central unresolved AGN, and the background sky. In the adopted model, the central positions of all the components were tied together, as were the position angles of the central galaxy components (not including the disk), which was set to correspond to the kinematic position angle of the kinematic data. With final GALFIT models, each surface brightness component of the image can be separated. The models of the AGN and background sky
were subtracted from the image, leaving behind only the light from the galaxy.

The surface brightness of a galaxy can be approximated as Gaussians using the Multi-Gaussian Expansion (MGE) program of Emsellem et al. (1994) and Cappellari (2002). In MGE decomposition, the center is found and the field is binned in angle and radius. Photometry in counts is found for each point on the grid, and then two-dimensional Gaussian intensity distributions with variable axis ratios and central intensities are fit to this two-dimensional intensity map. The Gaussian parameters of intensity in counts and width in pixels ($\sigma$) are then converted to surface brightness and $\sigma$ in arcsec, giving the final characteristics of the stellar surface brightness.

Table 4.2 shows the final MGE results, where the first column is the surface density, the second column is the standard deviation of the Gaussian $\sigma$, and the third column is the axis ratio or the minor axis divided by the major axis $q (\frac{b}{a})$. We excluded the disk components in our fit as we only aimed to characterize the luminosity distribution of the galaxy where the bulge dominates because the MGE code recreates the three-dimensional luminosity distribution of bulge-like components with quasi-spherical shapes. We required that any PAs of elongation of the Gaussians aligned with the kinematic PA. \textsc{masmod} will then also align any Gaussian elongation with this angle.

<table>
<thead>
<tr>
<th>$I_H$ ($L_\odot$, $H$/pc$^2$)</th>
<th>$\sigma$ (arcsec)</th>
<th>$q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.434 \times 10^4$</td>
<td>0.91</td>
<td>0.887</td>
</tr>
<tr>
<td>$1.140 \times 10^4$</td>
<td>2.12</td>
<td>0.995</td>
</tr>
<tr>
<td>$2.832 \times 10^3$</td>
<td>6.51</td>
<td>0.913</td>
</tr>
<tr>
<td>$8.269 \times 10^2$</td>
<td>10.24</td>
<td>1.000</td>
</tr>
</tbody>
</table>

This MGE decomposition is similar to previous results. For their surface brightness data,
Onken et al. (2014) used a composite of information: the \(H\)-band Gemini/NIFS data itself, optical HST/Advanced Camera for Surveys (ACS) data, and \(H\)-band Ohio State University Bright Spiral Galaxy Survey (OSUBSGS) data. Additionally, Misty Bentz examined MGE results she produced with \(H\)-band imaging from Kitt Peak’s WIYN High-Resolution Infrared Camera (WHIRC); this also had a similar result.

### 4.1.2 Inclination Angles

The bulge of NGC 4151 appears close to circular in projection, which suggests a spherical shape. This component could then be being viewed from any orientation. The disk components of our MGE results, which were not included in the final deprojected luminosity distribution, had \(q\) values of 1.0. From Bentz et al. (2009), \(q\) for the disk component of NGC 4151 is 0.69, giving an inclination of 46.4\(^\circ\). Also examining the ratio of the minor to major axis of HI distribution, Simkin (1975) found the inclination to be 21 \(\pm\) 5\(^\circ\). This study used photographic plates taken with H\(\alpha\) and \(U\) (UG2 + CuSO\(_4\)) filters and in the UV/blue (Wr2C filter, IIIa-J emulsion, 3950-5450 \(\AA\)). From the information we have, we focused our search around an inclination of 45\(^\circ\), but also considered inclinations of 15, 30, 60, and 75\(^\circ\), as stellar dynamical modeling is only able to constrain the inclination to within \(\sim\)30\(^\circ\).

### 4.1.3 Mass-to-Light Ratio

Determination of how mass in the center of a galaxy traces the emitted light is integral to understanding the gravitational potential of the galaxy for modeling. Onken et al. (2014) found starting estimates of mass-to-light ratio \(\Upsilon\) for the modeling using the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS) \(H\)-band imaging along with SDSS \(g\)-
and $i$-band imaging to produce color-color maps. The maps resulted in average colors for
the bulge of $(g-i) = 1.1 \pm 0.1$ mag and $(i-H) = 2.4 \pm 0.2$ mag. When combined with the
models of Zibetti et al. (2009), these colors predict $\Upsilon_H \simeq 0.4 \pm 0.2 M_\odot/L_\odot$. Our models
explore a range of values from $0.2 - 0.5 M_\odot/L_\odot$. Another option for finding $\Upsilon$ is to use the
spectral observations themselves with stellar population synthesis models. In this method
(), the spectroscopy is used to construct SEDs which are fit by those derived from stellar
models where metallically, reddening, etc. are varied. As we additionally examined wide-field
spectroscopy, we worked to examine $\Upsilon$ at larger radii. With HST $V$- and $H$-band images,
Misty Bentz determined the color across the whole field of view, finding it to be similar at
large and small radii.

\subsection{apang}

Another input is the aperture angle, $\text{apang}$. This is the angle the x-axis of either IFU must
be rotated counterclockwise to align with the kinematic major axis derived from the velocity
field of that data, and again comes from the method of Krajnović et al. (2006) that was
described and performed earlier for the NIFS and SAURON data, where kinematic position
angle and systemic velocity are returned. The y-axis of the NIFS IFU is offset by $15^\circ$ west or
clockwise from north. The kinematic position angle is $37.2 \pm 6.2^\circ$ counterclockwise from the
y-axis ($22.2^\circ$ east of north). The SAURON IFU is aligned with north up, and the kinematic
position angle is $18.6 \pm 3.1^\circ$ east of north, as displayed in Figure 4.1a. The uncertainty on
the kinematic PA of the NIFS data is twice as large as the uncertainty on the SAURON
kinematic PA, so we settle on a final kinematic PA for the galaxy of $19.8^\circ$ east of north, giving
$\text{apang}=124.8^\circ$ for NIFS and $\text{apang}=109.8^\circ$ for SAURON. These points are illustrated in
As previously described, we only plan to fit the SAURON data out to 14.5\arcsec, excluding any kinematics that we believe may be contaminated by the bar. The \texttt{MASMOD} code also includes the option to fit only the kinematic data within a certain radius, allowing us to probe inward for possible additional bar contamination. However, in Figure 4.2 in all cases the same kinematic PA is returned, regardless of the radii of data that is fit.

### 4.1.5 Point-Spread Function

The point-spread function (PSF) is the two-dimensional distribution of a point source (such as an AGN) when it is imaged due to telescope optics, the atmosphere, etc. To characterize the PSF of NIFS for \texttt{MASMOD} for convolving the mock data, we took a slice of the datacube at a wavelength corresponding to AGN emission and subtracted off a slice of the datacube at a wavelength corresponding to the stellar and AGN continuum. This final image left only the AGN point source, allowing us to determine the PSF. We examined a few combinations of emission wavelengths and continuum wavelengths, including the Hydrogen Brackett 10 broad line (Br10) in order to isolate which combination would produce the best PSF image.

Once the PSF image was created, Misty Bentz characterized the PSF by fitting with Gaussian components, each having different widths ($\sigma$) and contributions. The final three-component model with circular Gaussian components is shown in Table 4.3. This three-component common-center model fills the wings of the function and is a good fit to the PSF. If only two components were used, the fit was not as good but the values agreed more closely with what was found in Onken et al. (2014) for these data. The fit improved further when the Gaussians were allowed to deviate from circular, but \texttt{MASMOD} expects circular Gaussian
Figure 4.1 In 4.1a, the orientation of the data on the sky is shown with north up and east left, with 3.6° between the kinematic position angles of the major axis. As the error bars are large, in 4.1b we let the kinematic PAs align, but make the arbitrary location of the angle be in between the two measured locations, 19.8° east of north.
Figure 4.2 For inclusion of SAURON kinematic data less than 14.5 (all data), 12, 10, 8, and 6'' in radius, plots show the smoothed, non-symmetrized data with the kinematic position angle overlaid in white determined from the smoothed, bi-symmetrized (axisymmetric) data (not shown). The small black dots indicate the bin centers. Note that the center bins are masked due to AGN contamination; the code interpolates the kinematics at these small radii.
components for modeling the PSF. For SAURON, our PSF was taken from Dumas et al. (2007) and can be seen in Table 4.4.

<table>
<thead>
<tr>
<th>Component #</th>
<th>Weight</th>
<th>$\sigma$ (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.339</td>
<td>0.045</td>
</tr>
<tr>
<td>2</td>
<td>0.306</td>
<td>0.082</td>
</tr>
<tr>
<td>3</td>
<td>0.356</td>
<td>0.409</td>
</tr>
</tbody>
</table>

Table 4.4: 1-Component PSF for SAURON Data

<table>
<thead>
<tr>
<th>Component #</th>
<th>Weight</th>
<th>$\sigma$ (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

4.1.6 Distance to NGC 4151

When performing SD modeling, the distance is a large source of uncertainty in determining $M_{\text{BH}}$. The scale or radii of the galactic features being probed are directly related to the distance and $M_{\text{BH}}$. Multiple methods have been used to determine the distance, including the Tully-Fisher method (see Tully et al. 2009), which relies on studying the rotation of a galaxy. But as discussed in Onken et al. (2014), the particular set of observations were unreliable. Hönig et al. (2014) found a dust-parallax distance of 19 Mpc to the supermassive black hole in NGC 4151. Using the inner radius of the putative dusty torus from RM and the angular size of the torus from infrared photometry the small angle formula give a distance. However, this method depends on the inclination angle of the system, which is difficult to determine, as seen in Section 4.1.2. Onken et al. (2014) relied on a recessional velocity distance measurement of 13.9 Mpc from Pedlar et al. (1992), though recessional velocity is a poor predictor of distance for any galaxy closer than 100 Mpc because of peculiar velocities.
A Cepheid distance to NGC 4151 is currently being obtained by Michael Fausnaugh, with Bradley Peterson as PI of the HST program (Program 13765). The Cepheid distance technique uses the period of pulsating Cepheid variable stars within a galaxy to obtain the absolute and apparent magnitudes. Based on preliminary results, the Cepheid-based distance is $13.3 \pm 1.3$ Mpc, which we adopted for our modeling.

4.2 Orbit Library

We began the SD modeling with the first portion of the MASMOD, SOSA, which constructs the orbit libraries for each $M_{\text{BH}}$ at a value of $\Upsilon$ which we chose to be $0.3 \, M_\odot/L_\odot$ (Section 4.1.3). The initial mass density and gravitational potential are then obtained from the de-projected luminosity density using this primary value of $\Upsilon$. We assumed $\Upsilon$ was constant as Misty Bentz found the $V-H$ color of the galaxy (determined from HST images) to be relatively constant across the region that was examined, but the software can vary $\Upsilon$ radially. The gravitational potential is given as

$$\Phi(\varpi, z) = \Phi_*(\varpi, z) - \frac{G M_{\text{BH}}}{\sqrt{\varpi^2 + z^2 + \epsilon^2}},$$

(4.1)

where $\varpi$ is the orbital position radial dimension in cylindrical coordinates, $z = 0$ gives the equatorial plane, $\Phi_*$ is the stellar component of the potential, $G$ is the gravitational constant, and $\epsilon$ is the softening used to avoid numerical divergence of the gravitational force ($1 \times 10^{-5}$, in program units). $\Phi$ is found from multipole expansion of the three-dimensional MGE stellar luminosity density distribution for the assumed $\Upsilon$ (Binney & Tremaine 2008). The $M_{\text{BH}}$ term in the equation is one of our unknowns along with $\Upsilon$, which is contained in $\Phi_*(\varpi, z)$, and so many different initial potentials are created, each one having a unique
combination of $M_{\text{BH}}$ and $\Upsilon$ values. The mass grid is polar on the meridional plane $(R, z)$ with 20 logarithmically spaced radial bins and 16 polar bins spaced at equal intervals in $\theta$, where $\theta$ is the standard polar angle. For each orbit library, the stellar orbits are integrated with a Runge-Kutta integrator and their information is stored at equal time intervals at each point on a $(R, \theta)$ cylindrical-coordinate, logarithmically-spaced grid. The integrated stellar orbits are then treated to mimic observations from the assumed viewing angle. They are first convolved with the PSF model described in 4.3 using a fast Fourier transform, and then converted to Cartesian coordinates that mimic the apertures, or spaxel bins, of the observations. SOSA generates the LOSVDs for each orbit in each aperture on the IFUs and these LOSVDs are stored in the library. The spatial grid had spatial dimension sizes of $\sim 5.5 \times 5.5$ and $\sim 72 \times 72$, for the NIFS and SAURON data respectively, and pixel sizes for the model of $0.03''$ and $0.4''$ for the same. The velocity grid is computed by setting high and low values, here $\pm 207$, and a number of grid points, here 152, giving a velocity grid resolution of $\sim 2 \text{ km s}^{-1}$, $\sim 15 \times$ finer than the velocity resolution of the observed spectra. We base our $M_{\text{BH}}$ range ($1.5 \times 10^7 M_\odot - 10.5 \times 10^7 M_\odot$) on the previously-discussed mass estimates for NGC 4151 from stellar dynamical modeling and reverberation mapping. Our $M_{\text{BH}}$ grid increments by $1 \times 10^7 M_\odot$, allowing 10 points at this specific $\Upsilon$.

The $\Phi_*$ mass contribution to the potential is created with orbit libraries with large numbers of stars ($\sim 17,000$). The orbits within the library are described with three integrals of motion: one of energy $E$, one of angular momentum $L_z$, and a third integral, $I_3$, or $\eta$ (in standard notation, e.g., Cretton et al. 1999) which defines the angle above the $z=0$ place at which an orbit is launched, allowing the orbits full permeation of three-dimensional phase space. The orbits are created for one sense of orbit rotation and their counterparts for
opposite orientation are found from a sign change. Each model has a total of 16940 orbits.

4.3 Non-Negative Least Squares Optimization Algorithm

In the SOLPA step of MASMOD, the stellar orbit libraries in their potential for each $M_{BH}$ are scaled for a grid of possible values of $\Upsilon$, given that mass $m \sim V^2$ (van der Marel et al. 1998; Cretton et al. 1999). We examine a grid of $\Upsilon$ values ranging from $0.2M_\odot/L_\odot$ to $0.5M_\odot/L_\odot$ in increments of $0.033M_\odot/L_\odot$, allowing for 10 grid points in the $\Upsilon$ direction. The LOSVDs generated by Soba are rescaled for each $\Upsilon$ by rescaling the velocity grid $[V_{\text{min}}, V_{\text{max}}]$ to $\sqrt{\Upsilon/\Upsilon_{\text{primary}}} \times [V_{\text{min}}, V_{\text{max}}]$. SOLPA then parametrizes each orbital LOSVD by a GH series using the observed velocities $V_0$ and $\sigma_0$ as the central velocity and dispersion and computes $V$, $\sigma$, and $h_3 - h_6$. The model LOSVD in each aperture that results from the weighted superposition is then reparametrized in terms of $V$, $\sigma$, and $h_3 - h_6$ and these model values are compared with observed values of the parameters ($V_0$, $\sigma_0$, and $h_3o - h_6o$) in each aperture to determine the $\chi^2$. As previously discussed, after masking certain bins, we were left with 86 NIFS bins and 377 SAURON bins. The combination of $M_{BH}$ and $\Upsilon$ that leads to the lowest $\chi^2$ for all the apertures is the best-fit model.

4.4 Best-fit Model Results

The contour plotting routine of MASMOD possesses multiple options for computing the $\chi^2$ for the $M_{BH}$-$\Upsilon$ grid to find the minimum or best-fit model. Two methods are as follows: in one, the $\chi^2$ is directly obtained from the sum of the deviations between the Gauss-Hermite terms derived from the observations at each aperture and the Gauss-Hermite terms of the LOSVD of the model at each aperture, with $V$, $\sigma$, $h_3$, and $h_4$ contributing to the $\chi^2$ results, while
$h_5$ and $h_6$, which are quite noisy, are ignored. Another option is to take the Gauss-Hermite terms derived from the observations at each aperture and compute LOSVDs, then computing the $\chi^2$ from the net of the deviations between the LOSVDs of each aperture (again with only $V+\sigma+h_3+h_4$ contributing). These values give a better result for larger orbit libraries, and are on average larger than those from the previous method, with a wider minimum in the contour plot $\chi^2$ valley. We use the second method. While the $\chi^2$ is limited to $V+\sigma+h_3+h_4$ in its calculation, the optimization algorithm itself always fits all terms as well as the aperture mass.

We find our best-fit $M_{\text{BH}}=2.44 \pm 0.16 \times 10^7 M_\odot$ and the best-fit $\Upsilon_H=0.318 \pm 0.003 M_\odot/L_\odot$ (3$\sigma$ errors), assuming a galaxy inclination of 45° from the analysis of the disk component from Bentz et al. (2009) and including only the NIFS kinematics (which are the only kinematics with the spatial resolution necessary to constrain to the MBH value). The contour plots showing the $\chi^2$ surface as a function of $M_{\text{BH}}$ and $\Upsilon$ are displayed in Figure 4.3a, Figure 4.3b shows the observed NIFS kinematic maps with the best-fit model kinematics displayed in Figure 4.3c. The ridge of high $\sigma$ values in the model kinematics are not a good match to the observed kinematics, but otherwise the model is in good agreement with the observations. Figure 4.4a (4.4b) shows the $\chi^2$ for the best-fit marginalized over $\Upsilon$ ($M_{\text{BH}}$).
Figure 4.3a shows the NIFS only \textit{MASMOD} $\chi^2$ contour map for $i=45^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 4.3b-4.3c show the observed kinematics and the best-fit model kinematics, respectively. North is 15$^\circ$ counterclockwise of the $y$-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 4.4 $\chi^2$ for the best-fit $\Upsilon$ (marginalized over $M_{\text{BH}}$) and $M_{\text{BH}}$ (marginalized over $\Upsilon$). We adopt the 3$\sigma$ cutoffs as the uncertainties for the measurements.
5.1 Discussion

Our best estimate of the galaxy inclination to our line of sight is about $45^\circ$, and the models of the NIFS kinematics were able to constrain a best-fit $M_{BH}$ and $\Upsilon$ for this inclination. But as we previously discussed, we also examined galaxy inclinations of 15, 30, 60, and $75^\circ$. The models were also able to find best-fit $M_{BH}$ and $\Upsilon$ values for inclinations of $30^\circ$ and $75^\circ$. These results are summarized in Table 5.1.

Furthermore, we also examined models for all of these inclinations using the NIFS and the wider-field SAURON kinematics. The models were able to find best-fit values of $M_{BH}$ and $\Upsilon$ for inclinations of $30^\circ$ and $45^\circ$ in this case as well. These results are also included in Table 5.1.

The $\chi^2$ contour maps and best-fit model kinematics compared to the observed kinematics are displayed in Figures 5.1 and 5.2 for the NIFS models at $i=30^\circ$ and $i=75^\circ$, respectively. Figures 5.3 and 5.4 show the $\chi^2$ contour maps and model NIFS and SAURON kinematics compared to the observed kinematics for $i=30^\circ$. Figure 5.5 and 5.6 show the same for $i=45^\circ$.

It is clear from Figures 5.3-5.6 that including the wider-field SAURON kinematics produces a poorer match to the kinematics. Onken et al. (2014) also examined wider-field kinematics in addition to those derived from the NIFS observations and concluded that the wider-field kinematics may be affected by the weak bar in the galaxy, which cannot be properly modeled with the axisymmetric code employed here. Our results also support this conclusion, and so we focus instead on the modeling results derived only from the NIFS data.
Comparing the results from the NIFS-only models, we see that the best-fit kinematics predicted by the $i=45^\circ$ and $i=75^\circ$ models are fairly similar to each other and to the observations. In both cases, however, the model kinematics in the $\sigma$ term are not a good fit to the observed kinematics, overpredicting $\sigma$. They also find similar best-fit $M_{\text{BH}}$ and $\Upsilon$ values. The $i=75^\circ$ model seems to be the best fit to the $V$ field; as projection of $V$ gives indication of system inclination, we acknowledge $i=75^\circ$ as an estimation of the galaxy inclination with reliability similar to that of our $i=45^\circ$ estimate. The models using $i=30^\circ$, however, underpredict $\sigma$ and overpredict $h_4$ compared to the observations, and they in turn find a somewhat larger $M_{\text{BH}}$ and smaller $\Upsilon$.

**Table 5.1: MASMOD Results**

<table>
<thead>
<tr>
<th>Included Kinematics</th>
<th>Inclination (°)</th>
<th>$M_{\text{BH}}$ ($\times 10^7 M_\odot$)</th>
<th>$\Upsilon$ ($M_\odot/L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIFS 30</td>
<td>30</td>
<td>$4.50 \pm 0.16$</td>
<td>$0.242 \pm 0.003$</td>
</tr>
<tr>
<td>NIFS 45</td>
<td>45</td>
<td>$2.44 \pm 0.16$</td>
<td>$0.318 \pm 0.003$</td>
</tr>
<tr>
<td>NIFS 75</td>
<td>75</td>
<td>$2.11 \pm 0.16$</td>
<td>$0.305 \pm 0.003$</td>
</tr>
<tr>
<td>NIFS+SAURON 30</td>
<td>30</td>
<td>$1.44 \pm 0.16$</td>
<td>$0.402 \pm 0.003$</td>
</tr>
<tr>
<td>NIFS+SAURON 45</td>
<td>45</td>
<td>$4.81 \pm 0.16$</td>
<td>$0.488 \pm 0.003$</td>
</tr>
</tbody>
</table>

Additionally, we can also compare our best-fit $M_{\text{BH}}$ and $\Upsilon$ to those found by Onken et al. (2014). We note our $\Upsilon_H$ value of $0.318 \pm 0.003 M_\odot/L_\odot$ is within the uncertainty on the $\Upsilon_H$ value found by Onken et al. (2014), $0.34 \pm 0.03 M_\odot/L_\odot$, and within the range of $\Upsilon_H$ predicted for the dataset using the $\Upsilon$ color relations of Zibetti et al. (2009). Our best-fit $M_{\text{BH}}$ value of $2.44 \pm 0.16 \times 10^7 M_\odot$ is somewhat smaller than that found by Onken et al. (2014) ($M_{\text{BH}} = 3.60 \pm 1.10 \times 10^7 M_\odot$), within the uncertainties. This slight difference in best-fit mass is perhaps not surprising given the many improvements we have implemented in the data reduction and analysis process. We also list in Table 5.2 all other $M_{\text{BH}}$ determinations for
Figure 5.1 Figure 5.1a shows the NIFS only MASMOD $\chi^2$ contour map for $i=30^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.1b-5.1c show the observed kinematics and the best-fit model kinematics, respectively. North is $15^\circ$ counterclockwise of the y-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.2 Figure 5.2a shows the NIFS only MASMOD $\chi^2$ contour map for $i=75^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.2b-5.2c show the observed kinematics and the best-fit model kinematics, respectively. North is $15^\circ$ counterclockwise of the y-axis. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.3 Figure 5.3a shows the NIFS + SAURON MASMOD $\chi^2$ contour map for $i=30^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.3b-5.3c show the observed NIFS kinematics and the best-fit model kinematics for NIFS, respectively. North is 15$^\circ$ counterclockwise of the y-axis for NIFS. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.4 5.4a displays the observed SAURON kinematics and 5.4b displays the best-fit model kinematics for SAURON. North is up. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.5a shows the NIFS + SAURON MASMOD $\chi^2$ contour map for $i=45^\circ$. The first six contours surrounding the star indicating the minimum are contours of 1-6$\sigma$. Figures 5.5c-5.5a show the observed NIFS kinematics and the best-fit model kinematics for NIFS, respectively. North is 15$^\circ$ counterclockwise of the y-axis for NIFS. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.6 5.6a displays the observed SAURON kinematics and 5.6b displays the best-fit model kinematics for SAURON. North is up. The numbers displayed at the top of the kinematic maps indicate the range of the color scheme, with red/white being high and blue/black being low.
Figure 5.7 A comparison of the measured $M_{\text{BH}}$ values for NGC 4151. Here the y-axis, order on the y-axis, and colors of the points are only present for contrast.

NGC 4151 from other direct methods, as well as display them in Figure 5.7. It is important to keep in mind that the SD and GD modeling masses depend on the value adopted for the distance, and the RM measurements on the choice of $\langle f \rangle$. We adjust the Onken et al. (2014) and Hicks & Malkan (2008) measurements accordingly. Our measurement is between the two RM masses from Bentz et al. (2006) and De Rosa et al. (2018), and slightly lower than the $\text{H}_2$ GD modeling mass of Hicks & Malkan (2008), but within the uncertainties.

### Table 5.2: Measurements of $M_{\text{BH}}$ for NGC 4151

<table>
<thead>
<tr>
<th>Method</th>
<th>Mass ($\times 10^7 M_\odot$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD Modeling</td>
<td>3.60 ± 1.10</td>
<td>Onken et al. (2014)</td>
</tr>
<tr>
<td>SD Modeling</td>
<td>2.44 ± 0.16</td>
<td>This work</td>
</tr>
<tr>
<td>RM ($\langle f \rangle = 4.3$, Grier et al. (2013))</td>
<td>$3.59^{+0.45}_{-0.37}$</td>
<td>Bentz et al. (2006)</td>
</tr>
<tr>
<td>RM ($\langle f \rangle = 4.3$, Grier et al. (2013))</td>
<td>1.97 ± 0.04</td>
<td>De Rosa et al. (2018)</td>
</tr>
<tr>
<td>GD Modeling</td>
<td>$3.0^{+0.8}_{-2.2}$</td>
<td>Hicks &amp; Malkan (2008)</td>
</tr>
</tbody>
</table>

The $\langle f \rangle$ factor applied to the RM masses in this case is a population average value found using a large sample of AGN, each of which would have their own individual $f$ factor based on the details of their BLR geometry, kinematics, and inclination to our line of sight.
The individual $f$-factor can be obtained with velocity-resolved reverberation mapping or through study of a single galaxy with both RM and another $M_{\text{BH}}$ measurement technique. The RM measurements of NGC 4151 (Bentz et al. 2006; De Rosa et al. 2018), $3.59^{+0.45}_{-0.37} \times 10^7 M_\odot$ and $1.97 \pm 0.04 \times 10^7 M_\odot$, respectively, were computed with $\langle f \rangle = 4.3$, and so their virial products are $8.35$ and $4.58 \times 10^6 M_\odot$. If we use our best-fit black hole mass of $M_{\text{BH}} = 2.44 \pm 0.16 \times 10^7 M_\odot$, a tentative range for the $f$-factor of NGC 4151 is 3.1-5.6. This range agrees well with the population average value, and with the individual $f$ factors that have been derived for a handful of other AGN through velocity-resolved RM (Pancoast et al. 2014; Grier et al. 2017).

Our best-fit $M_{\text{BH}}$ measurement predicts that NGC 4151 will end up lower on the $M_{\text{BH}} - \sigma_*$ relationship, as is displayed in Figure 5.8. However, while we excluded the larger-field kinematics that are more likely to be affected by the weak bar in this galaxy, it is possible that our best-fit $M_{\text{BH}}$ is still too high given our use of an axisymmetric code.

5.2 Future Work

While we have improved on the results of Onken et al. (2014), there are still additional concerns to be investigated. First, an axisymmetric stellar dynamical modeling code will assume bi-symmetrized kinematics, but we have only point-symmetrized our kinematics measurements in preparation for use with the bar-orbit superposition code in the near future. Second, there is a new version of MASMOD available. The major update to the modeling code is that the mass grid now contains polar bins spaced at equal intervals in $\cos \theta$ rather than just $\theta$. This allows the mass contributions to each bin to be equivalent, and improves the mass fit. In the coming months, MASMOD is also scheduled to receive a further update, with
Figure 5.8 The $M_{BH} - \sigma_*$ relationship from Hartmann et al. (2014), where lines of best fit are show for classical bulges, barred classical bulges, and barred pseudo bulges (less compact bulges not formed through mergers) in black (gray), red, and blue, respectively. A slope of 3.78 is used in all cases. Note how on average the barred objects fall below the relationship. The position of NGC 4151 from Onken et al. (2014) is noted with the large red box, and from this work the new position is marked with the large blue box.
the Non-Negative Least Squares Optimization Algorithm being replaced by a program that will improve the treatment of the mass further. Both of the updates to the modeling code are likely to impact our best-fit $M_{\text{BH}}$ and $\Upsilon$ determinations and will require further investigation.

In the process of fitting the spectra and constraining the observed LOSVDs, we used a G0, a K0III, and an M0 star template for our analysis. Template mismatch occurs when the stellar templates used in fitting the kinematics influence the resultant measurements. Ideally, to avoid template mismatch, dozens of templates are used and individual templates are scaled by their best contributing weight to compose the best-fit spectrum. We have only three templates that were observed with the same instrumental configuration, and so our future work will need to consider the use of additional template libraries. There are few spectral libraries available in the H band, but we are considering the use of the IGRINS library (Park et al. 2018). Additionally, though they are less reliable than observational data as they are model-dependent, we may consider the use of synthetic spectral templates in the infrared such as the POLLUX database (Palacios et al. 2010).

All dynamical masses rely on an accurate distance to the galaxy. For our modeling, we assumed the Cepheid distance for NGC 4151 obtained by Michael Fausnaugh using HST Program 13765 observations (PI Bradley Peterson), but this is a preliminary result. The analysis is still awaiting a closer look at H-band observations; at this time only optical imaging has been used. The final Cepheid-based distance will be similar to what we have assumed here, but the new measurement will improve the accuracy of our MBH constraint.

Finally, when our NIFS kinematic maps are viewed (e.g., Figures 5.1b, 5.2b, 5.3b, or 5.5b), we clearly see characteristics indicative of a barred system. The $V$ panel (far left) has twisted isovelocitity contours, and the $h_4$ panel (right center) has negative values. NGC
NGC 4151 is a weakly barred system that requires a bar-optimized stellar dynamical modeling code. The bar-orbit superposition code of Vasiliev & Valluri (2019, in prep) is based on the action-based galaxy modelling library (AGAMA) of Vasiliev (2019). It will be the first Schwarzschild orbit superposition code capable of deriving $M_{\text{BH}}$ in rotating triaxial barred galaxies while also accounting for the presence of the disk. Throughout this work, our data and analysis has been performed in preparation for use with the bar-optimized code, and we expect the mass constraints derived from it to be the most accurate dynamical mass for NGC 4151 to date.

5.3 Summary

The supermassive black hole in NGC 4151, being both in a nearby galaxy ($z=0.0033$) and an active galactic nucleus, is one of the few that may be studied using multiple $M_{\text{BH}}$ determination techniques, including stellar dynamical modeling and reverberation mapping. We rely on comparisons of these methods to serve as cross-checks of inherent assumptions in the techniques. In this work, using the spectral fitting method of Cappellari & Emsellem (2004); Cappellari (2017) and the MASMOD stellar dynamical modeling code of Valluri et al. (2004, 2005), we performed a complete reanalysis of Gemini NIFS IFU data of NGC 4151, improving the reduction and analysis approach in several ways. We found best-fit values of $M_{\text{BH}}=2.44\pm0.16\times10^7 M_\odot$ and $\Upsilon_H=0.318\pm0.001 M_\odot/L_\odot$ with an assumed galaxy inclination of 45°. In our reanalysis, we took steps to ensure that the kinematic measurements were easily compatible with the format of the bar-orbit superposition code of Vasiliev & Valluri (2019, in prep). In future work, the bar-optimized code will be applied to these data, and at that time, the results obtained from that work will provide the best comparison of stellar...
dynamical modeling and reverberation mapping to date.
REFERENCES


de Vaucouleurs, G. H., de Vaucouleurs, A., & Shapley, H. 1964, University of Texas Monographs in Astronomy, Austin: University of Texas Press, —c1964
Fabian, A. C. 2012, ARA&A, 50, 455
Kormendy, J. 2004, Coevolution of Black Holes and Galaxies, 1
Kormendy, J., & Gebhardt, K. 2001, 20th Texas Symposium on relativistic astrophysics, 586, 363
Kormendy, J., Bender, R., & Cornell, M. E. 2011, Nature, 469, 374
Peterson, B. M. 2001, Advanced Lectures on the Starburst-AGN, 3
Schmidt, M. 1963, Nature, 197, 1040

Thomas, J. 2010, Reviews in Modern Astronomy, 22, 143


Voronoï, G. F. 1908, Journal fr die reine und angewandte Mathematik, 134, 198-287


Zel’dovich, Y. B., & Novikov, I. D. 1964, Soviet Physics Doklady, 9, 246
APPENDICES
A NIFS Kinematic Observations

NIFS Kinematics for 86 Bins

<table>
<thead>
<tr>
<th>x (&quot;)</th>
<th>y (&quot;)</th>
<th>V (km/s)</th>
<th>σ (km/s)</th>
<th>h3</th>
<th>h4</th>
<th>h5</th>
<th>h6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>-0.10</td>
<td>-32.2 ± 0.1</td>
<td>122.2 ± 53.1</td>
<td>-0.055 ± 0.065</td>
<td>-0.013 ± 0.002</td>
<td>0.067 ± 0.125</td>
<td>-0.032 ± 0.060</td>
</tr>
<tr>
<td>0.17</td>
<td>0.10</td>
<td>12.3 ± 6.3</td>
<td>99.2 ± 25.7</td>
<td>0.071 ± 0.010</td>
<td>0.032 ± 0.004</td>
<td>0.010 ± 0.083</td>
<td>0.010 ± 0.010</td>
</tr>
<tr>
<td>-0.32</td>
<td>-0.07</td>
<td>12.5 ± 9.6</td>
<td>94.6 ± 18.7</td>
<td>0.030 ± 0.055</td>
<td>-0.051 ± 0.010</td>
<td>-0.072 ± 0.022</td>
<td>0.062 ± 0.025</td>
</tr>
<tr>
<td>-0.23</td>
<td>0.13</td>
<td>4.2 ± 9.6</td>
<td>99.2 ± 19.1</td>
<td>0.052 ± 0.011</td>
<td>-0.004 ± 0.046</td>
<td>-0.107 ± 0.015</td>
<td>0.003 ± 0.096</td>
</tr>
<tr>
<td>-0.44</td>
<td>0.04</td>
<td>19.6 ± 12.0</td>
<td>110.6 ± 30.9</td>
<td>-0.119 ± 0.036</td>
<td>-0.095 ± 0.047</td>
<td>0.035 ± 0.023</td>
<td>-0.040 ± 0.036</td>
</tr>
<tr>
<td>-0.44</td>
<td>-0.21</td>
<td>7.6 ± 6.3</td>
<td>103.7 ± 19.6</td>
<td>0.026 ± 0.039</td>
<td>0.069 ± 0.006</td>
<td>0.011 ± 0.024</td>
<td>-0.060 ± 0.100</td>
</tr>
<tr>
<td>-0.19</td>
<td>-0.35</td>
<td>-8.2 ± 2.9</td>
<td>100.9 ± 27.3</td>
<td>-0.089 ± 0.005</td>
<td>-0.004 ± 0.058</td>
<td>-0.016 ± 0.054</td>
<td>0.068 ± 0.032</td>
</tr>
<tr>
<td>-0.54</td>
<td>-0.10</td>
<td>20.6 ± 0.3</td>
<td>98.3 ± 26.8</td>
<td>-0.072 ± 0.095</td>
<td>0.052 ± 0.122</td>
<td>0.040 ± 0.036</td>
<td>0.006 ± 0.001</td>
</tr>
<tr>
<td>-0.46</td>
<td>-0.37</td>
<td>6.4 ± 12.6</td>
<td>79.4 ± 31.2</td>
<td>-0.022 ± 0.036</td>
<td>-0.054 ± 0.024</td>
<td>-0.036 ± 0.029</td>
<td>0.058 ± 0.029</td>
</tr>
<tr>
<td>-0.63</td>
<td>-0.27</td>
<td>1.2 ± 9.0</td>
<td>102.1 ± 36.0</td>
<td>-0.034 ± 0.021</td>
<td>0.029 ± 0.026</td>
<td>0.060 ± 0.018</td>
<td>-0.032 ± 0.033</td>
</tr>
<tr>
<td>-0.27</td>
<td>-0.45</td>
<td>-4.5 ± 3.4</td>
<td>98.7 ± 33.6</td>
<td>0.008 ± 0.076</td>
<td>0.056 ± 0.092</td>
<td>-0.011 ± 0.042</td>
<td>-0.044 ± 0.075</td>
</tr>
<tr>
<td>-0.06</td>
<td>-0.47</td>
<td>-17.3 ± 1.1</td>
<td>116.5 ± 26.8</td>
<td>0.022 ± 0.033</td>
<td>0.011 ± 0.107</td>
<td>-0.006 ± 0.087</td>
<td>-0.100 ± 0.074</td>
</tr>
<tr>
<td>-0.42</td>
<td>-0.59</td>
<td>-7.7 ± 11.2</td>
<td>103.5 ± 13.9</td>
<td>0.061 ± 0.031</td>
<td>0.003 ± 0.034</td>
<td>-0.042 ± 0.035</td>
<td>0.048 ± 0.016</td>
</tr>
<tr>
<td>-0.68</td>
<td>-0.49</td>
<td>17.2 ± 9.0</td>
<td>97.2 ± 31.6</td>
<td>-0.019 ± 0.002</td>
<td>-0.026 ± 0.034</td>
<td>-0.008 ± 0.033</td>
<td>0.036 ± 0.010</td>
</tr>
<tr>
<td>-0.74</td>
<td>-0.08</td>
<td>16.4 ± 4.8</td>
<td>87.4 ± 29.9</td>
<td>-0.051 ± 0.061</td>
<td>0.073 ± 0.114</td>
<td>0.004 ± 0.035</td>
<td>0.062 ± 0.030</td>
</tr>
<tr>
<td>-0.95</td>
<td>-0.29</td>
<td>10.0 ± 7.4</td>
<td>104.3 ± 31.4</td>
<td>0.009 ± 0.062</td>
<td>0.033 ± 0.019</td>
<td>0.006 ± 0.009</td>
<td>0.044 ± 0.015</td>
</tr>
<tr>
<td>-0.13</td>
<td>-0.64</td>
<td>-22.5 ± 2.0</td>
<td>92.9 ± 25.4</td>
<td>0.038 ± 0.085</td>
<td>0.076 ± 0.107</td>
<td>-0.046 ± 0.032</td>
<td>-0.010 ± 0.083</td>
</tr>
<tr>
<td>-0.68</td>
<td>-0.76</td>
<td>-2.2 ± 1.0</td>
<td>96.4 ± 37.9</td>
<td>0.027 ± 0.055</td>
<td>0.039 ± 0.102</td>
<td>0.014 ± 0.034</td>
<td>-0.002 ± 0.048</td>
</tr>
<tr>
<td>-0.36</td>
<td>-0.83</td>
<td>-15.2 ± 3.9</td>
<td>100.3 ± 19.0</td>
<td>0.074 ± 0.037</td>
<td>0.049 ± 0.085</td>
<td>-0.025 ± 0.002</td>
<td>-0.044 ± 0.057</td>
</tr>
<tr>
<td>-1.00</td>
<td>-0.03</td>
<td>24.8 ± 10.0</td>
<td>108.8 ± 26.2</td>
<td>-0.060 ± 0.048</td>
<td>0.059 ± 0.068</td>
<td>0.047 ± 0.015</td>
<td>-0.023 ± 0.088</td>
</tr>
<tr>
<td>-0.79</td>
<td>0.15</td>
<td>20.2 ± 4.0</td>
<td>90.3 ± 33.8</td>
<td>-0.050 ± 0.045</td>
<td>0.088 ± 0.007</td>
<td>0.065 ± 0.026</td>
<td>0.057 ± 0.059</td>
</tr>
<tr>
<td>-0.44</td>
<td>0.20</td>
<td>15.9 ± 3.2</td>
<td>108.8 ± 19.6</td>
<td>0.003 ± 0.065</td>
<td>-0.016 ± 0.022</td>
<td>-0.008 ± 0.038</td>
<td>-0.044 ± 0.072</td>
</tr>
<tr>
<td>-0.95</td>
<td>-0.98</td>
<td>-10.3 ± 4.1</td>
<td>100.4 ± 15.5</td>
<td>-0.008 ± 0.030</td>
<td>-0.031 ± 0.010</td>
<td>0.022 ± 0.026</td>
<td>0.076 ± 0.007</td>
</tr>
<tr>
<td>-0.57</td>
<td>-1.07</td>
<td>-17.7 ± 1.8</td>
<td>98.8 ± 28.9</td>
<td>0.021 ± 0.022</td>
<td>0.063 ± 0.074</td>
<td>-0.013 ± 0.005</td>
<td>-0.015 ± 0.023</td>
</tr>
<tr>
<td>-0.09</td>
<td>-0.84</td>
<td>-25.7 ± 1.8</td>
<td>116.9 ± 25.2</td>
<td>-0.003 ± 0.037</td>
<td>-0.026 ± 0.066</td>
<td>0.046 ± 0.014</td>
<td>-0.050 ± 0.115</td>
</tr>
<tr>
<td>-0.04</td>
<td>-0.31</td>
<td>-1.9 ± 6.2</td>
<td>112.8 ± 16.2</td>
<td>0.017 ± 0.014</td>
<td>-0.055 ± 0.047</td>
<td>0.044 ± 0.039</td>
<td>-0.036 ± 0.067</td>
</tr>
</tbody>
</table>
### NIFS Kinematics for 86 Bins

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.17</td>
<td>-1.09</td>
<td>-20.4 ± 10.7</td>
<td>100.2 ± 16.7</td>
<td>0.036 ± 0.046</td>
<td>-0.041 ± 0.038</td>
<td>0.015 ± 0.015</td>
<td>0.070 ± 0.019</td>
<td></td>
</tr>
<tr>
<td>-1.05</td>
<td>0.23</td>
<td>12.8 ± 2.3</td>
<td>99.2 ± 28.9</td>
<td>-0.126 ± 0.131</td>
<td>0.069 ± 0.061</td>
<td>0.095 ± 0.009</td>
<td>-0.011 ± 0.063</td>
<td></td>
</tr>
<tr>
<td>-0.49</td>
<td>0.35</td>
<td>14.8 ± 9.7</td>
<td>96.3 ± 22.6</td>
<td>-0.021 ± 0.019</td>
<td>0.038 ± 0.055</td>
<td>-0.007 ± 0.005</td>
<td>-0.016 ± 0.064</td>
<td></td>
</tr>
<tr>
<td>-0.95</td>
<td>0.45</td>
<td>25.9 ± 2.1</td>
<td>99.2 ± 23.3</td>
<td>-0.036 ± 0.032</td>
<td>0.063 ± 0.148</td>
<td>0.022 ± 0.003</td>
<td>-0.017 ± 0.054</td>
<td></td>
</tr>
<tr>
<td>-0.33</td>
<td>0.29</td>
<td>10.8 ± 11.9</td>
<td>108.5 ± 17.8</td>
<td>0.087 ± 0.075</td>
<td>-0.047 ± 0.059</td>
<td>-0.026 ± 0.010</td>
<td>-0.106 ± 0.098</td>
<td></td>
</tr>
<tr>
<td>-0.36</td>
<td>0.40</td>
<td>13.1 ± 7.3</td>
<td>105.7 ± 24.9</td>
<td>-0.012 ± 0.038</td>
<td>-0.025 ± 0.028</td>
<td>-0.100 ± 0.097</td>
<td>0.037 ± 0.034</td>
<td></td>
</tr>
<tr>
<td>-0.23</td>
<td>0.35</td>
<td>8.5 ± 2.5</td>
<td>107.2 ± 28.4</td>
<td>0.033 ± 0.032</td>
<td>0.034 ± 0.064</td>
<td>0.023 ± 0.006</td>
<td>-0.036 ± 0.036</td>
<td></td>
</tr>
<tr>
<td>-0.08</td>
<td>0.28</td>
<td>23.1 ± 2.2</td>
<td>108.2 ± 25.1</td>
<td>0.016 ± 0.029</td>
<td>-0.068 ± 0.071</td>
<td>-0.038 ± 0.075</td>
<td>-0.026 ± 0.031</td>
<td></td>
</tr>
<tr>
<td>-0.13</td>
<td>0.36</td>
<td>22.2 ± 6.4</td>
<td>107.5 ± 13.1</td>
<td>-0.059 ± 0.010</td>
<td>0.004 ± 0.028</td>
<td>0.023 ± 0.005</td>
<td>-0.062 ± 0.051</td>
<td></td>
</tr>
<tr>
<td>-0.38</td>
<td>0.56</td>
<td>15.6 ± 0.8</td>
<td>110.6 ± 15.3</td>
<td>-0.020 ± 0.011</td>
<td>-0.081 ± 0.012</td>
<td>0.064 ± 0.048</td>
<td>0.004 ± 0.054</td>
<td></td>
</tr>
<tr>
<td>-0.21</td>
<td>0.48</td>
<td>14.1 ± 14.1</td>
<td>96.8 ± 16.8</td>
<td>-0.030 ± 0.019</td>
<td>0.039 ± 0.024</td>
<td>-0.014 ± 0.011</td>
<td>-0.095 ± 0.041</td>
<td></td>
</tr>
<tr>
<td>-0.07</td>
<td>0.40</td>
<td>6.3 ± 13.6</td>
<td>111.9 ± 8.0</td>
<td>-0.015 ± 0.038</td>
<td>-0.034 ± 0.122</td>
<td>-0.067 ± 0.057</td>
<td>-0.112 ± 0.102</td>
<td></td>
</tr>
<tr>
<td>-0.23</td>
<td>0.66</td>
<td>8.4 ± 13.1</td>
<td>104.2 ± 19.4</td>
<td>-0.006 ± 0.094</td>
<td>0.011 ± 0.023</td>
<td>0.025 ± 0.022</td>
<td>0.022 ± 0.013</td>
<td></td>
</tr>
<tr>
<td>-0.31</td>
<td>0.86</td>
<td>15.9 ± 3.2</td>
<td>102.3 ± 33.6</td>
<td>-0.046 ± 0.017</td>
<td>-0.020 ± 0.057</td>
<td>0.040 ± 0.076</td>
<td>0.030 ± 0.066</td>
<td></td>
</tr>
<tr>
<td>-0.10</td>
<td>0.79</td>
<td>14.6 ± 0.8</td>
<td>101.4 ± 15.1</td>
<td>-0.077 ± 0.079</td>
<td>-0.019 ± 0.036</td>
<td>0.013 ± 0.079</td>
<td>0.081 ± 0.026</td>
<td></td>
</tr>
<tr>
<td>-0.52</td>
<td>1.05</td>
<td>24.2 ± 11.9</td>
<td>112.0 ± 18.3</td>
<td>0.006 ± 0.039</td>
<td>-0.027 ± 0.004</td>
<td>0.029 ± 0.027</td>
<td>0.062 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>-0.15</td>
<td>1.05</td>
<td>13.7 ± 15.5</td>
<td>98.8 ± 25.3</td>
<td>0.026 ± 0.020</td>
<td>0.022 ± 0.062</td>
<td>0.007 ± 0.030</td>
<td>0.061 ± 0.019</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>-1.05</td>
<td>24.2 ± 11.9</td>
<td>112.0 ± 18.3</td>
<td>-0.006 ± 0.039</td>
<td>-0.027 ± 0.004</td>
<td>-0.029 ± 0.027</td>
<td>0.062 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>0.52</td>
<td>-1.05</td>
<td>-24.2 ± 11.9</td>
<td>112.0 ± 18.3</td>
<td>-0.006 ± 0.039</td>
<td>-0.027 ± 0.004</td>
<td>-0.029 ± 0.027</td>
<td>0.062 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>-0.79</td>
<td>-14.6 ± 0.8</td>
<td>101.4 ± 15.1</td>
<td>0.077 ± 0.079</td>
<td>-0.019 ± 0.036</td>
<td>-0.013 ± 0.079</td>
<td>0.081 ± 0.026</td>
<td></td>
</tr>
<tr>
<td>0.31</td>
<td>-0.86</td>
<td>-15.9 ± 3.2</td>
<td>102.3 ± 33.6</td>
<td>0.046 ± 0.017</td>
<td>-0.020 ± 0.057</td>
<td>-0.040 ± 0.076</td>
<td>0.030 ± 0.066</td>
<td></td>
</tr>
<tr>
<td>0.23</td>
<td>-0.66</td>
<td>-8.4 ± 13.1</td>
<td>104.2 ± 19.4</td>
<td>0.006 ± 0.094</td>
<td>0.011 ± 0.023</td>
<td>-0.025 ± 0.022</td>
<td>0.022 ± 0.013</td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>-0.40</td>
<td>-6.3 ± 13.6</td>
<td>111.9 ± 8.0</td>
<td>0.015 ± 0.038</td>
<td>-0.034 ± 0.122</td>
<td>0.067 ± 0.057</td>
<td>-0.112 ± 0.102</td>
<td></td>
</tr>
<tr>
<td>0.21</td>
<td>-0.48</td>
<td>-14.1 ± 14.1</td>
<td>96.8 ± 16.8</td>
<td>0.030 ± 0.019</td>
<td>0.039 ± 0.024</td>
<td>0.014 ± 0.011</td>
<td>-0.095 ± 0.041</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>-0.56</td>
<td>-15.6 ± 0.8</td>
<td>110.6 ± 15.3</td>
<td>0.020 ± 0.011</td>
<td>-0.081 ± 0.012</td>
<td>-0.064 ± 0.048</td>
<td>0.004 ± 0.054</td>
<td></td>
</tr>
<tr>
<td>0.13</td>
<td>-0.36</td>
<td>-22.2 ± 6.4</td>
<td>107.5 ± 13.1</td>
<td>0.059 ± 0.010</td>
<td>0.004 ± 0.028</td>
<td>-0.023 ± 0.005</td>
<td>-0.062 ± 0.051</td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>-0.28</td>
<td>-23.1 ± 2.2</td>
<td>108.2 ± 25.1</td>
<td>-0.016 ± 0.029</td>
<td>-0.068 ± 0.071</td>
<td>0.038 ± 0.075</td>
<td>-0.026 ± 0.031</td>
<td></td>
</tr>
<tr>
<td>0.23</td>
<td>-0.35</td>
<td>-8.5 ± 2.5</td>
<td>107.2 ± 28.4</td>
<td>-0.033 ± 0.032</td>
<td>0.034 ± 0.064</td>
<td>-0.023 ± 0.006</td>
<td>-0.036 ± 0.036</td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>-0.40</td>
<td>-13.1 ± 7.3</td>
<td>105.7 ± 24.9</td>
<td>0.012 ± 0.038</td>
<td>-0.025 ± 0.028</td>
<td>0.100 ± 0.097</td>
<td>0.037 ± 0.034</td>
<td></td>
</tr>
<tr>
<td>0.33</td>
<td>-0.29</td>
<td>-10.8 ± 11.9</td>
<td>108.5 ± 17.8</td>
<td>-0.087 ± 0.075</td>
<td>-0.047 ± 0.059</td>
<td>0.026 ± 0.010</td>
<td>-0.106 ± 0.098</td>
<td></td>
</tr>
<tr>
<td>Bin</td>
<td>NIFS Kinematics for 86 Bins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>----------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td>-0.45</td>
<td>-25.9 ± 2.1</td>
<td>99.2 ± 23.3</td>
<td>0.036 ± 0.032</td>
<td>0.063 ± 0.148</td>
<td>-0.022 ± 0.003</td>
<td>-0.017 ± 0.054</td>
<td></td>
</tr>
<tr>
<td>0.49</td>
<td>-0.35</td>
<td>-14.8 ± 9.7</td>
<td>96.3 ± 22.6</td>
<td>0.021 ± 0.019</td>
<td>0.038 ± 0.055</td>
<td>0.007 ± 0.005</td>
<td>-0.016 ± 0.064</td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>-0.23</td>
<td>-12.8 ± 2.3</td>
<td>99.2 ± 28.9</td>
<td>0.126 ± 0.131</td>
<td>0.069 ± 0.061</td>
<td>-0.095 ± 0.009</td>
<td>-0.011 ± 0.063</td>
<td></td>
</tr>
<tr>
<td>0.17</td>
<td>1.09</td>
<td>20.4 ± 10.7</td>
<td>100.2 ± 16.7</td>
<td>-0.036 ± 0.046</td>
<td>-0.041 ± 0.038</td>
<td>-0.015 ± 0.015</td>
<td>0.070 ± 0.019</td>
<td></td>
</tr>
<tr>
<td>0.04</td>
<td>0.31</td>
<td>1.9 ± 6.2</td>
<td>112.8 ± 16.2</td>
<td>-0.017 ± 0.014</td>
<td>-0.055 ± 0.047</td>
<td>-0.044 ± 0.039</td>
<td>-0.036 ± 0.067</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>0.84</td>
<td>25.7 ± 1.8</td>
<td>116.9 ± 25.2</td>
<td>0.003 ± 0.037</td>
<td>-0.026 ± 0.066</td>
<td>-0.046 ± 0.014</td>
<td>-0.050 ± 0.115</td>
<td></td>
</tr>
<tr>
<td>0.57</td>
<td>1.07</td>
<td>17.7 ± 1.8</td>
<td>98.8 ± 28.9</td>
<td>-0.021 ± 0.022</td>
<td>0.063 ± 0.074</td>
<td>0.013 ± 0.005</td>
<td>-0.015 ± 0.023</td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td>0.98</td>
<td>10.3 ± 4.1</td>
<td>100.4 ± 15.5</td>
<td>0.008 ± 0.030</td>
<td>-0.031 ± 0.010</td>
<td>-0.022 ± 0.026</td>
<td>0.076 ± 0.007</td>
<td></td>
</tr>
<tr>
<td>0.44</td>
<td>-0.20</td>
<td>-15.9 ± 3.2</td>
<td>108.8 ± 19.6</td>
<td>-0.003 ± 0.065</td>
<td>-0.016 ± 0.022</td>
<td>0.008 ± 0.038</td>
<td>-0.044 ± 0.072</td>
<td></td>
</tr>
<tr>
<td>0.79</td>
<td>-0.15</td>
<td>-20.2 ± 4.0</td>
<td>90.3 ± 33.8</td>
<td>0.050 ± 0.045</td>
<td>0.088 ± 0.007</td>
<td>-0.065 ± 0.026</td>
<td>0.057 ± 0.059</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>0.03</td>
<td>-24.8 ± 10.0</td>
<td>108.8 ± 26.2</td>
<td>0.060 ± 0.048</td>
<td>0.059 ± 0.068</td>
<td>-0.047 ± 0.015</td>
<td>-0.023 ± 0.088</td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>0.83</td>
<td>15.2 ± 3.9</td>
<td>100.3 ± 19.0</td>
<td>-0.074 ± 0.037</td>
<td>0.049 ± 0.085</td>
<td>0.025 ± 0.002</td>
<td>-0.044 ± 0.057</td>
<td></td>
</tr>
<tr>
<td>0.68</td>
<td>0.76</td>
<td>2.2 ± 1.0</td>
<td>96.4 ± 37.9</td>
<td>-0.027 ± 0.055</td>
<td>0.039 ± 0.102</td>
<td>-0.014 ± 0.034</td>
<td>-0.002 ± 0.048</td>
<td></td>
</tr>
<tr>
<td>0.13</td>
<td>0.64</td>
<td>22.5 ± 2.0</td>
<td>92.9 ± 25.4</td>
<td>-0.038 ± 0.085</td>
<td>0.076 ± 0.107</td>
<td>0.046 ± 0.032</td>
<td>-0.010 ± 0.083</td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td>0.29</td>
<td>-10.0 ± 7.4</td>
<td>104.3 ± 31.4</td>
<td>-0.009 ± 0.062</td>
<td>0.033 ± 0.019</td>
<td>-0.006 ± 0.009</td>
<td>0.044 ± 0.015</td>
<td></td>
</tr>
<tr>
<td>0.74</td>
<td>0.08</td>
<td>-16.4 ± 4.8</td>
<td>87.4 ± 29.9</td>
<td>0.051 ± 0.061</td>
<td>0.073 ± 0.114</td>
<td>-0.004 ± 0.035</td>
<td>0.062 ± 0.030</td>
<td></td>
</tr>
<tr>
<td>0.68</td>
<td>0.49</td>
<td>-17.2 ± 9.0</td>
<td>97.2 ± 31.6</td>
<td>0.019 ± 0.002</td>
<td>-0.026 ± 0.034</td>
<td>0.008 ± 0.033</td>
<td>0.036 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>0.42</td>
<td>0.59</td>
<td>7.7 ± 11.2</td>
<td>103.5 ± 13.9</td>
<td>-0.061 ± 0.031</td>
<td>0.003 ± 0.034</td>
<td>0.042 ± 0.035</td>
<td>0.048 ± 0.016</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>0.47</td>
<td>17.3 ± 1.1</td>
<td>116.5 ± 26.8</td>
<td>-0.022 ± 0.033</td>
<td>0.011 ± 0.107</td>
<td>0.006 ± 0.087</td>
<td>-0.100 ± 0.074</td>
<td></td>
</tr>
<tr>
<td>0.27</td>
<td>0.45</td>
<td>4.5 ± 3.4</td>
<td>98.7 ± 33.6</td>
<td>-0.008 ± 0.076</td>
<td>0.056 ± 0.092</td>
<td>0.011 ± 0.042</td>
<td>-0.044 ± 0.075</td>
<td></td>
</tr>
<tr>
<td>0.63</td>
<td>0.27</td>
<td>-1.2 ± 9.0</td>
<td>102.1 ± 36.0</td>
<td>0.034 ± 0.021</td>
<td>0.029 ± 0.026</td>
<td>-0.060 ± 0.018</td>
<td>-0.023 ± 0.033</td>
<td></td>
</tr>
<tr>
<td>0.46</td>
<td>0.37</td>
<td>-6.4 ± 12.6</td>
<td>79.4 ± 31.2</td>
<td>0.022 ± 0.036</td>
<td>-0.054 ± 0.024</td>
<td>0.036 ± 0.029</td>
<td>0.058 ± 0.029</td>
<td></td>
</tr>
<tr>
<td>0.54</td>
<td>0.10</td>
<td>-20.6 ± 0.3</td>
<td>98.3 ± 26.8</td>
<td>0.072 ± 0.095</td>
<td>0.052 ± 0.122</td>
<td>-0.040 ± 0.036</td>
<td>0.006 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>0.19</td>
<td>0.35</td>
<td>8.2 ± 2.9</td>
<td>100.9 ± 27.3</td>
<td>0.089 ± 0.005</td>
<td>-0.004 ± 0.058</td>
<td>0.016 ± 0.054</td>
<td>0.068 ± 0.032</td>
<td></td>
</tr>
<tr>
<td>0.44</td>
<td>0.21</td>
<td>-7.6 ± 6.3</td>
<td>103.7 ± 19.6</td>
<td>-0.026 ± 0.039</td>
<td>0.069 ± 0.006</td>
<td>-0.011 ± 0.024</td>
<td>-0.060 ± 0.100</td>
<td></td>
</tr>
<tr>
<td>0.44</td>
<td>-0.04</td>
<td>-19.6 ± 12.0</td>
<td>110.6 ± 30.9</td>
<td>0.119 ± 0.036</td>
<td>-0.005 ± 0.047</td>
<td>-0.035 ± 0.023</td>
<td>-0.040 ± 0.036</td>
<td></td>
</tr>
<tr>
<td>0.23</td>
<td>-0.13</td>
<td>-4.2 ± 9.6</td>
<td>99.2 ± 19.1</td>
<td>-0.052 ± 0.011</td>
<td>-0.004 ± 0.046</td>
<td>0.107 ± 0.015</td>
<td>0.003 ± 0.096</td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>0.07</td>
<td>-12.5 ± 9.6</td>
<td>94.6 ± 18.7</td>
<td>-0.030 ± 0.055</td>
<td>-0.051 ± 0.010</td>
<td>0.072 ± 0.022</td>
<td>0.062 ± 0.025</td>
<td></td>
</tr>
<tr>
<td>0.17</td>
<td>-0.10</td>
<td>-12.3 ± 6.3</td>
<td>99.2 ± 25.7</td>
<td>-0.071 ± 0.010</td>
<td>0.032 ± 0.004</td>
<td>-0.010 ± 0.083</td>
<td>0.010 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>0.17</td>
<td>0.10</td>
<td>32.2 ± 0.1</td>
<td>122.2 ± 53.1</td>
<td>0.055 ± 0.065</td>
<td>-0.013 ± 0.002</td>
<td>-0.067 ± 0.125</td>
<td>-0.032 ± 0.060</td>
<td></td>
</tr>
</tbody>
</table>
## SAURON Kinematic Observations

### SAURON Kinematics for 377 Bins

<table>
<thead>
<tr>
<th>$x$ ($''$)</th>
<th>$y$ ($''$)</th>
<th>$V$ (km s$^{-1}$)</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>$h_3-h_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.80</td>
<td>-1.60</td>
<td>2.1 ± 5.4</td>
<td>109.3 ± 3.1</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.80</td>
<td>-0.80</td>
<td>11.3 ± 6.5</td>
<td>105.4 ± 2.2</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.80</td>
<td>0.00</td>
<td>14.8 ± 7.2</td>
<td>104.5 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.80</td>
<td>0.80</td>
<td>19.4 ± 8.3</td>
<td>104.1 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.80</td>
<td>1.60</td>
<td>21.8 ± 10.4</td>
<td>101.0 ± 2.2</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.80</td>
<td>2.40</td>
<td>29.9 ± 9.6</td>
<td>96.8 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>-3.20</td>
<td>-19.5 ± 3.9</td>
<td>97.4 ± 4.3</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>-2.40</td>
<td>-11.8 ± 4.5</td>
<td>101.7 ± 2.4</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>-1.60</td>
<td>-4.3 ± 6.5</td>
<td>107.3 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>-0.80</td>
<td>9.4 ± 5.3</td>
<td>108.9 ± 3.6</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>0.80</td>
<td>16.1 ± 9.0</td>
<td>100.3 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>1.60</td>
<td>15.3 ± 2.0</td>
<td>96.7 ± 13.6</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>2.40</td>
<td>12.7 ± 2.0</td>
<td>102.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-4.00</td>
<td>3.20</td>
<td>24.0 ± 7.9</td>
<td>101.7 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>-4.00</td>
<td>-20.8 ± 3.9</td>
<td>94.3 ± 3.8</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>-3.20</td>
<td>-16.3 ± 3.9</td>
<td>99.0 ± 3.9</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>-2.40</td>
<td>-2.8 ± 5.2</td>
<td>105.6 ± 2.7</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>-1.60</td>
<td>-5.5 ± 4.7</td>
<td>107.6 ± 2.1</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>-0.80</td>
<td>-3.3 ± 5.3</td>
<td>108.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>0.00</td>
<td>8.0 ± 5.6</td>
<td>105.0 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>3.20</td>
<td>14.5 ± 2.0</td>
<td>98.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-3.20</td>
<td>4.00</td>
<td>30.4 ± 8.6</td>
<td>96.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>-4.80</td>
<td>-23.2 ± 4.4</td>
<td>95.8 ± 3.9</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>-4.00</td>
<td>-26.4 ± 3.2</td>
<td>93.5 ± 4.4</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>-3.20</td>
<td>-15.3 ± 4.1</td>
<td>107.1 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>-2.40</td>
<td>-6.9 ± 5.0</td>
<td>108.5 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>-1.60</td>
<td>-13.0 ± 5.0</td>
<td>111.0 ± 5.1</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-2.40</td>
<td>4.00</td>
<td>32.6 ± 9.7</td>
<td>94.4 ± 2.6</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>-4.80</td>
<td>-30.7 ± 4.0</td>
<td>90.7 ± 4.7</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>-4.00</td>
<td>-22.1 ± 3.7</td>
<td>98.0 ± 2.4</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>-3.20</td>
<td>-15.2 ± 3.2</td>
<td>110.3 ± 2.0</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>-2.40</td>
<td>-14.5 ± 4.4</td>
<td>108.2 ± 14.5</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>4.00</td>
<td>30.5 ± 10.4</td>
<td>96.6 ± 3.3</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-1.60</td>
<td>4.80</td>
<td>28.0 ± 10.2</td>
<td>100.3 ± 2.9</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-0.80</td>
<td>-4.80</td>
<td>-29.8 ± 5.1</td>
<td>89.1 ± 3.9</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-0.80</td>
<td>-4.00</td>
<td>-23.2 ± 3.7</td>
<td>97.4 ± 2.7</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-0.80</td>
<td>-3.20</td>
<td>-11.7 ± 7.9</td>
<td>88.0 ± 13.4</td>
<td>0.000 ± 0.020</td>
</tr>
<tr>
<td>-0.80</td>
<td>4.00</td>
<td>26.7 ± 6.7</td>
<td>104.0 ± 2.9</td>
<td>0.000 ± 0.020</td>
</tr>
</tbody>
</table>
### SAURON Kinematics for 377 Bins

<table>
<thead>
<tr>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
<th>Value 6</th>
<th>Value 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.80</td>
<td>4.80</td>
<td>29.1 ± 8.9</td>
<td>101.2 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>-4.80</td>
<td>-27.8 ± 3.2</td>
<td>101.9 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>3.20</td>
<td>18.4 ± 2.9</td>
<td>104.0 ± 17.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>4.00</td>
<td>19.3 ± 4.7</td>
<td>109.7 ± 3.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>4.80</td>
<td>25.0 ± 7.4</td>
<td>103.9 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>-4.80</td>
<td>-31.4 ± 4.3</td>
<td>92.8 ± 3.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>4.00</td>
<td>20.4 ± 4.1</td>
<td>115.7 ± 4.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>4.80</td>
<td>25.0 ± 6.7</td>
<td>110.7 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>-4.80</td>
<td>-28.3 ± 5.5</td>
<td>78.3 ± 3.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>3.20</td>
<td>17.6 ± 2.0</td>
<td>119.6 ± 5.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>4.00</td>
<td>22.3 ± 4.2</td>
<td>116.2 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>4.80</td>
<td>18.5 ± 6.4</td>
<td>107.0 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>3.20</td>
<td>15.9 ± 3.0</td>
<td>117.4 ± 5.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>4.00</td>
<td>17.0 ± 4.8</td>
<td>109.5 ± 3.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>-4.80</td>
<td>-33.0 ± 4.0</td>
<td>69.8 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>-4.00</td>
<td>-23.5 ± 4.6</td>
<td>61.3 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>1.60</td>
<td>-0.2 ± 7.4</td>
<td>118.9 ± 8.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>2.40</td>
<td>8.4 ± 2.9</td>
<td>117.1 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>3.20</td>
<td>10.6 ± 4.0</td>
<td>114.3 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>4.00</td>
<td>12.0 ± 4.6</td>
<td>109.2 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>-4.80</td>
<td>-42.7 ± 3.4</td>
<td>84.2 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>-4.00</td>
<td>-26.1 ± 2.6</td>
<td>56.8 ± 7.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>-3.20</td>
<td>-17.9 ± 5.7</td>
<td>70.9 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>0.80</td>
<td>-2.7 ± 4.5</td>
<td>117.7 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>1.60</td>
<td>1.6 ± 4.4</td>
<td>118.5 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>2.40</td>
<td>10.2 ± 4.0</td>
<td>114.6 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>3.20</td>
<td>7.2 ± 4.3</td>
<td>109.7 ± 2.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-4.00</td>
<td>-32.3 ± 3.0</td>
<td>91.1 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-3.20</td>
<td>-18.8 ± 2.0</td>
<td>100.1 ± 3.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-2.40</td>
<td>-11.7 ± 3.1</td>
<td>100.0 ± 3.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-1.60</td>
<td>-5.8 ± 4.5</td>
<td>114.0 ± 3.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>0.00</td>
<td>-4.9 ± 3.3</td>
<td>110.1 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>0.80</td>
<td>-9.6 ± 3.6</td>
<td>110.3 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>1.60</td>
<td>-10.6 ± 3.6</td>
<td>110.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-2.40</td>
<td>-11.0 ± 4.7</td>
<td>103.4 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>2.40</td>
<td>1.3 ± 3.9</td>
<td>109.8 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>4.80</td>
<td>20.7 ± 5.8</td>
<td>109.7 ± 3.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>4.80</td>
<td>36.9 ± 10.9</td>
<td>94.2 ± 2.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>-5.60</td>
<td>-31.4 ± 2.6</td>
<td>99.9 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>0.00</td>
<td>-16.8 ± 3.0</td>
<td>100.7 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>0.00</td>
<td>20.3 ± 7.3</td>
<td>102.4 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
<td>vx</td>
<td>vy</td>
<td>vz</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>5.60</td>
<td>27.5 ± 6.2</td>
<td>106.1 ± 4.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>-5.60</td>
<td>-43.4 ± 3.1</td>
<td>90.8 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.80</td>
<td>-5.60</td>
<td>-40.6 ± 4.2</td>
<td>88.8 ± 5.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-0.80</td>
<td>-12.8 ± 3.2</td>
<td>104.2 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>0.80</td>
<td>-9.3 ± 4.2</td>
<td>104.2 ± 3.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>-4.00</td>
<td>-18.2 ± 4.4</td>
<td>96.7 ± 5.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>4.00</td>
<td>10.4 ± 5.1</td>
<td>108.8 ± 3.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>-0.80</td>
<td>7.9 ± 7.7</td>
<td>95.9 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>0.80</td>
<td>25.7 ± 8.0</td>
<td>101.2 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>5.60</td>
<td>32.5 ± 7.1</td>
<td>111.7 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.80</td>
<td>5.60</td>
<td>28.9 ± 8.7</td>
<td>96.2 ± 3.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>4.00</td>
<td>35.1 ± 10.7</td>
<td>97.5 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.20</td>
<td>-4.80</td>
<td>-20.9 ± 4.4</td>
<td>88.1 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.80</td>
<td>-3.20</td>
<td>-12.3 ± 4.1</td>
<td>98.7 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>-5.60</td>
<td>-40.6 ± 2.8</td>
<td>89.8 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.60</td>
<td>-5.60</td>
<td>-43.6 ± 2.9</td>
<td>88.0 ± 5.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>3.20</td>
<td>5.3 ± 4.6</td>
<td>105.2 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-1.60</td>
<td>-22.9 ± 3.3</td>
<td>99.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>4.80</td>
<td>21.4 ± 5.8</td>
<td>105.6 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>1.60</td>
<td>-0.6 ± 4.1</td>
<td>106.3 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.80</td>
<td>3.20</td>
<td>32.7 ± 10.8</td>
<td>101.7 ± 2.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.20</td>
<td>4.80</td>
<td>38.0 ± 11.2</td>
<td>94.6 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>-1.60</td>
<td>3.6 ± 8.1</td>
<td>96.9 ± 5.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>1.60</td>
<td>32.9 ± 9.3</td>
<td>104.2 ± 2.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>5.60</td>
<td>27.7 ± 12.2</td>
<td>103.1 ± 8.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.60</td>
<td>5.60</td>
<td>33.6 ± 9.1</td>
<td>98.0 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>-5.60</td>
<td>-36.1 ± 3.7</td>
<td>86.7 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-2.40</td>
<td>-27.6 ± 3.2</td>
<td>91.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.40</td>
<td>-5.60</td>
<td>-31.6 ± 4.6</td>
<td>92.1 ± 4.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>2.40</td>
<td>3.2 ± 3.8</td>
<td>104.7 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>-2.40</td>
<td>-10.1 ± 5.9</td>
<td>94.9 ± 3.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>5.60</td>
<td>27.6 ± 6.6</td>
<td>100.2 ± 7.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>2.40</td>
<td>32.4 ± 8.7</td>
<td>100.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.40</td>
<td>5.60</td>
<td>45.2 ± 10.1</td>
<td>98.2 ± 7.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>-4.80</td>
<td>-17.9 ± 5.3</td>
<td>93.7 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.80</td>
<td>-4.00</td>
<td>-19.3 ± 4.7</td>
<td>95.7 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>4.00</td>
<td>9.2 ± 5.2</td>
<td>109.2 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>4.80</td>
<td>17.5 ± 6.0</td>
<td>96.3 ± 7.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.80</td>
<td>4.00</td>
<td>36.1 ± 11.3</td>
<td>99.2 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>4.80</td>
<td>40.3 ± 11.7</td>
<td>97.9 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>-6.40</td>
<td>-37.8 ± 3.9</td>
<td>90.0 ± 4.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>0.00</td>
<td>-19.5 ± 3.7</td>
<td>100.5 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
<td>Value 4</td>
<td>Value 5</td>
<td>Value 6</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>-5.60</td>
<td>-36.7 ± 3.1</td>
<td>82.2 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-3.20</td>
<td>-20.9 ± 2.2</td>
<td>96.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>-6.40</td>
<td>-48.1 ± 3.8</td>
<td>84.3 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.80</td>
<td>-6.40</td>
<td>-45.9 ± 3.3</td>
<td>88.7 ± 4.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>-0.80</td>
<td>-15.1 ± 3.8</td>
<td>99.6 ± 2.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.72</td>
<td>0.80</td>
<td>-20.5 ± 4.5</td>
<td>99.4 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.20</td>
<td>-5.60</td>
<td>-27.0 ± 5.7</td>
<td>88.4 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>3.20</td>
<td>1.6 ± 4.5</td>
<td>100.3 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>-3.56</td>
<td>45.4 ± 7.7</td>
<td>105.1 ± 8.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.71</td>
<td>-0.80</td>
<td>3.7 ± 5.9</td>
<td>84.7 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.71</td>
<td>0.80</td>
<td>22.5 ± 8.4</td>
<td>95.0 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.60</td>
<td>3.20</td>
<td>36.9 ± 12.7</td>
<td>93.9 ± 7.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.56</td>
<td>5.60</td>
<td>24.7 ± 5.2</td>
<td>106.2 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>6.72</td>
<td>42.3 ± 7.3</td>
<td>97.7 ± 9.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.80</td>
<td>6.72</td>
<td>45.4 ± 8.0</td>
<td>109.5 ± 10.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.55</td>
<td>5.60</td>
<td>56.6 ± 13.8</td>
<td>91.7 ± 13.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>-6.40</td>
<td>-49.3 ± 3.7</td>
<td>84.1 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.60</td>
<td>-6.74</td>
<td>-35.8 ± 4.5</td>
<td>88.5 ± 5.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>-1.60</td>
<td>-24.2 ± 3.7</td>
<td>98.8 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.72</td>
<td>1.60</td>
<td>-10.1 ± 4.3</td>
<td>102.6 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.72</td>
<td>-1.60</td>
<td>13.8 ± 8.1</td>
<td>93.2 ± 5.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.70</td>
<td>1.60</td>
<td>33.9 ± 9.4</td>
<td>96.5 ± 5.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>6.71</td>
<td>43.4 ± 7.2</td>
<td>95.6 ± 9.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.60</td>
<td>6.72</td>
<td>38.4 ± 7.2</td>
<td>104.1 ± 9.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-4.80</td>
<td>-38.1 ± 2.3</td>
<td>88.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.13</td>
<td>-4.80</td>
<td>-16.0 ± 4.7</td>
<td>96.0 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.13</td>
<td>4.80</td>
<td>40.0 ± 10.3</td>
<td>101.5 ± 3.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>5.14</td>
<td>11.7 ± 4.6</td>
<td>98.1 ± 7.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.40</td>
<td>-6.74</td>
<td>-29.3 ± 6.3</td>
<td>82.6 ± 7.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>-6.40</td>
<td>-46.3 ± 4.2</td>
<td>78.7 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.72</td>
<td>-2.40</td>
<td>2.4 ± 5.1</td>
<td>108.1 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.72</td>
<td>2.40</td>
<td>33.1 ± 10.5</td>
<td>93.2 ± 3.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2.40</td>
<td>6.72</td>
<td>49.8 ± 8.1</td>
<td>101.9 ± 9.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.35</td>
<td>-5.60</td>
<td>-21.5 ± 5.1</td>
<td>89.4 ± 6.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>-2.40</td>
<td>-27.0 ± 3.7</td>
<td>96.6 ± 2.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>6.73</td>
<td>36.5 ± 7.2</td>
<td>101.0 ± 6.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.73</td>
<td>2.40</td>
<td>-2.1 ± 4.1</td>
<td>96.1 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.92</td>
<td>4.00</td>
<td>43.2 ± 9.8</td>
<td>104.9 ± 10.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>-5.60</td>
<td>-27.4 ± 2.5</td>
<td>76.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-4.00</td>
<td>-29.4 ± 3.1</td>
<td>93.4 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>4.35</td>
<td>7.3 ± 4.9</td>
<td>104.1 ± 5.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.20</td>
<td>-6.74</td>
<td>-27.7 ± 6.0</td>
<td>80.2 ± 7.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.73</td>
<td>-3.20</td>
<td>-10.1 ± 4.6</td>
<td>96.4 ± 8.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>-6.72</td>
<td>-46.7 ± 3.4</td>
<td>79.5 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.72</td>
<td>-3.20</td>
<td>-37.5 ± 2.9</td>
<td>87.9 ± 3.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.39</td>
<td>-7.20</td>
<td>-45.3 ± 3.1</td>
<td>87.4 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.73</td>
<td>3.20</td>
<td>34.7 ± 9.7</td>
<td>99.0 ± 5.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.73</td>
<td>3.20</td>
<td>1.8 ± 5.0</td>
<td>96.4 ± 6.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3.20</td>
<td>6.72</td>
<td>55.5 ± 11.3</td>
<td>91.6 ± 13.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.20</td>
<td>6.74</td>
<td>30.6 ± 7.4</td>
<td>105.2 ± 6.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.20</td>
<td>-0.40</td>
<td>-24.7 ± 4.0</td>
<td>95.5 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.19</td>
<td>-7.20</td>
<td>-55.4 ± 3.7</td>
<td>76.8 ± 8.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-5.60</td>
<td>-28.5 ± 2.2</td>
<td>82.6 ± 3.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-4.80</td>
<td>-40.0 ± 3.6</td>
<td>85.6 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.20</td>
<td>-2.00</td>
<td>-29.9 ± 2.7</td>
<td>91.7 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.15</td>
<td>5.60</td>
<td>46.4 ± 8.0</td>
<td>103.5 ± 8.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>-6.72</td>
<td>-32.7 ± 3.0</td>
<td>88.5 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.70</td>
<td>-4.00</td>
<td>-40.3 ± 3.3</td>
<td>88.0 ± 3.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>-7.54</td>
<td>-57.9 ± 2.1</td>
<td>78.6 ± 5.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>-6.74</td>
<td>-31.3 ± 6.3</td>
<td>85.9 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.74</td>
<td>-4.00</td>
<td>-15.1 ± 5.1</td>
<td>87.2 ± 7.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.74</td>
<td>4.00</td>
<td>10.5 ± 6.0</td>
<td>98.0 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>6.73</td>
<td>30.2 ± 5.5</td>
<td>102.1 ± 9.5</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4.00</td>
<td>6.73</td>
<td>60.6 ± 12.4</td>
<td>83.3 ± 9.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-5.92</td>
<td>-25.2 ± 2.2</td>
<td>93.0 ± 2.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.94</td>
<td>-5.60</td>
<td>-11.3 ± 3.7</td>
<td>99.3 ± 7.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>-6.73</td>
<td>-21.9 ± 2.0</td>
<td>93.0 ± 3.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>-5.14</td>
<td>-36.3 ± 3.9</td>
<td>86.9 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.40</td>
<td>-8.00</td>
<td>-37.7 ± 5.0</td>
<td>89.5 ± 6.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.19</td>
<td>-8.00</td>
<td>-49.8 ± 5.1</td>
<td>80.5 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>-0.40</td>
<td>-17.8 ± 5.4</td>
<td>98.1 ± 4.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.13</td>
<td>-6.40</td>
<td>-18.4 ± 6.2</td>
<td>87.4 ± 8.6</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>5.95</td>
<td>21.0 ± 6.0</td>
<td>96.5 ± 6.1</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>1.20</td>
<td>-10.2 ± 6.4</td>
<td>97.8 ± 5.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.74</td>
<td>-4.80</td>
<td>-11.1 ± 5.8</td>
<td>91.9 ± 7.4</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>5.15</td>
<td>16.3 ± 5.7</td>
<td>98.6 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.80</td>
<td>6.75</td>
<td>26.3 ± 6.1</td>
<td>86.2 ± 12.0</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>-1.99</td>
<td>-31.6 ± 3.5</td>
<td>88.3 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.98</td>
<td>-8.00</td>
<td>-30.4 ± 6.1</td>
<td>84.9 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-8.00</td>
<td>-0.39</td>
<td>13.7 ± 8.4</td>
<td>91.8 ± 7.9</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.40</td>
<td>8.00</td>
<td>48.8 ± 9.5</td>
<td>102.8 ± 7.2</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.73</td>
<td>4.80</td>
<td>36.0 ± 6.5</td>
<td>99.4 ± 8.7</td>
<td>0.000 ± 0.020</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SAURON Kinematics for 377 Bins

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.00</td>
<td>1.19</td>
<td>33.2 ± 8.8</td>
<td>86.4 ± 8.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.05</td>
<td>6.63</td>
<td>48.2 ± 8.7</td>
<td>99.3 ± 8.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.18</td>
<td>8.00</td>
<td>37.2 ± 7.9</td>
<td>97.8 ± 9.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.00</td>
<td>-1.98</td>
<td>1.3 ± 5.1</td>
<td>101.0 ± 5.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.97</td>
<td>8.00</td>
<td>50.8 ± 6.9</td>
<td>99.2 ± 7.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.69</td>
<td>3.73</td>
<td>39.2 ± 7.0</td>
<td>100.3 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>2.78</td>
<td>-0.5 ± 5.4</td>
<td>100.1 ± 6.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.79</td>
<td>8.00</td>
<td>32.3 ± 6.3</td>
<td>104.6 ± 7.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.43</td>
<td>2.61</td>
<td>40.1 ± 7.3</td>
<td>96.7 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>3.58</td>
<td>-8.00</td>
<td>-46.7 ± 2.6</td>
<td>80.6 ± 7.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>-3.58</td>
<td>-30.8 ± 5.0</td>
<td>92.3 ± 2.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.20</td>
<td>-5.17</td>
<td>-42.3 ± 4.0</td>
<td>86.8 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-3.57</td>
<td>-8.00</td>
<td>-34.7 ± 5.8</td>
<td>97.4 ± 4.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-6.64</td>
<td>5.85</td>
<td>44.3 ± 6.4</td>
<td>106.4 ± 5.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.14</td>
<td>-7.20</td>
<td>-19.2 ± 7.2</td>
<td>98.8 ± 6.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.20</td>
<td>-3.49</td>
<td>-6.4 ± 3.8</td>
<td>76.9 ± 13.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.20</td>
<td>5.16</td>
<td>14.7 ± 3.3</td>
<td>102.0 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-3.46</td>
<td>8.23</td>
<td>52.1 ± 6.3</td>
<td>84.1 ± 11.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-0.41</td>
<td>-8.80</td>
<td>-44.1 ± 4.1</td>
<td>84.2 ± 9.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.19</td>
<td>-8.80</td>
<td>-47.9 ± 4.5</td>
<td>72.0 ± 9.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.80</td>
<td>-0.41</td>
<td>-25.0 ± 5.0</td>
<td>87.7 ± 9.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.80</td>
<td>1.19</td>
<td>-16.7 ± 6.2</td>
<td>82.3 ± 10.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.01</td>
<td>-0.29</td>
<td>19.2 ± 8.4</td>
<td>94.5 ± 9.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.97</td>
<td>-8.80</td>
<td>-46.2 ± 3.4</td>
<td>89.8 ± 9.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.02</td>
<td>-1.88</td>
<td>-23.5 ± 5.0</td>
<td>78.0 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.01</td>
<td>1.08</td>
<td>23.3 ± 6.6</td>
<td>93.9 ± 6.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-0.30</td>
<td>9.01</td>
<td>49.7 ± 7.5</td>
<td>86.8 ± 15.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.09</td>
<td>9.00</td>
<td>48.2 ± 6.9</td>
<td>97.5 ± 11.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.23</td>
<td>4.26</td>
<td>9.5 ± 6.1</td>
<td>100.3 ± 11.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>-6.75</td>
<td>-26.2 ± 2.0</td>
<td>86.0 ± 4.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>4.27</td>
<td>8.23</td>
<td>35.3 ± 5.7</td>
<td>111.8 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.02</td>
<td>-1.87</td>
<td>6.7 ± 5.5</td>
<td>97.5 ± 7.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.87</td>
<td>9.02</td>
<td>48.0 ± 6.4</td>
<td>101.5 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.60</td>
<td>-7.55</td>
<td>-36.2 ± 2.0</td>
<td>87.5 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.79</td>
<td>-8.80</td>
<td>-58.2 ± 2.5</td>
<td>83.9 ± 7.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-6.65</td>
<td>-6.65</td>
<td>-14.3 ± 5.6</td>
<td>92.2 ± 9.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>6.64</td>
<td>6.64</td>
<td>14.3 ± 5.1</td>
<td>87.0 ± 11.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.03</td>
<td>2.68</td>
<td>-4.2 ± 5.3</td>
<td>87.9 ± 14.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.80</td>
<td>7.66</td>
<td>28.5 ± 5.8</td>
<td>94.3 ± 9.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.70</td>
<td>-5.33</td>
<td>-10.6 ± 5.9</td>
<td>97.9 ± 8.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.68</td>
<td>9.02</td>
<td>37.3 ± 8.6</td>
<td>109.8 ± 8.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.85</td>
<td>7.44</td>
<td>53.7 ± 7.2</td>
<td>88.8 ± 14.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>8.00</td>
<td>-5.18</td>
<td>-37.8 ± 2.5</td>
<td>80.5 ± 4.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.01</td>
<td>-8.45</td>
<td>-42.4 ± 3.2</td>
<td>83.1 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.01</td>
<td>-3.71</td>
<td>-39.4 ± 4.4</td>
<td>80.1 ± 6.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.15</td>
<td>-8.34</td>
<td>-23.6 ± 6.9</td>
<td>87.0 ± 6.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-3.47</td>
<td>-9.02</td>
<td>-47.5 ± 3.1</td>
<td>88.4 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.32</td>
<td>5.16</td>
<td>45.4 ± 5.1</td>
<td>102.3 ± 8.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-4.53</td>
<td>8.50</td>
<td>62.9 ± 9.6</td>
<td>85.9 ± 11.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-0.28</td>
<td>-9.82</td>
<td>-49.0 ± 2.9</td>
<td>87.1 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.20</td>
<td>-6.76</td>
<td>-26.1 ± 2.0</td>
<td>90.6 ± 4.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.82</td>
<td>-0.29</td>
<td>-20.7 ± 8.3</td>
<td>81.0 ± 15.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.08</td>
<td>-9.82</td>
<td>-48.3 ± 3.6</td>
<td>84.9 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>3.74</td>
<td>-9.28</td>
<td>-46.7 ± 4.7</td>
<td>74.7 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.82</td>
<td>1.07</td>
<td>-9.1 ± 6.5</td>
<td>94.4 ± 10.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.86</td>
<td>-9.83</td>
<td>-40.6 ± 3.4</td>
<td>87.8 ± 9.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.12</td>
<td>-4.38</td>
<td>5.1 ± 6.7</td>
<td>98.4 ± 8.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-10.14</td>
<td>-0.79</td>
<td>13.2 ± 5.6</td>
<td>96.1 ± 6.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.63</td>
<td>-10.08</td>
<td>-50.6 ± 5.1</td>
<td>76.1 ± 10.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.82</td>
<td>-2.69</td>
<td>-30.6 ± 2.5</td>
<td>74.7 ± 10.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.24</td>
<td>5.86</td>
<td>18.3 ± 5.5</td>
<td>94.8 ± 8.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-0.80</td>
<td>10.14</td>
<td>55.9 ± 7.8</td>
<td>88.2 ± 11.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.52</td>
<td>6.75</td>
<td>49.0 ± 10.0</td>
<td>95.0 ± 11.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.34</td>
<td>3.93</td>
<td>39.9 ± 6.8</td>
<td>101.7 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.93</td>
<td>1.98</td>
<td>25.7 ± 4.5</td>
<td>98.6 ± 8.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.59</td>
<td>10.14</td>
<td>56.7 ± 7.4</td>
<td>96.5 ± 8.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.02</td>
<td>-5.08</td>
<td>-43.2 ± 2.9</td>
<td>79.7 ± 6.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.93</td>
<td>-2.78</td>
<td>-0.5 ± 4.6</td>
<td>83.7 ± 12.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.30</td>
<td>4.53</td>
<td>5.3 ± 4.9</td>
<td>92.0 ± 5.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-2.78</td>
<td>9.93</td>
<td>53.1 ± 4.8</td>
<td>95.2 ± 8.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.16</td>
<td>9.12</td>
<td>34.5 ± 7.6</td>
<td>100.5 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.07</td>
<td>3.42</td>
<td>1.7 ± 5.0</td>
<td>98.2 ± 9.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.24</td>
<td>-6.65</td>
<td>-31.8 ± 3.9</td>
<td>74.8 ± 5.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>6.66</td>
<td>-8.24</td>
<td>-32.8 ± 2.5</td>
<td>95.6 ± 3.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.56</td>
<td>7.55</td>
<td>14.8 ± 6.8</td>
<td>78.0 ± 10.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>3.58</td>
<td>9.91</td>
<td>44.0 ± 7.9</td>
<td>89.2 ± 11.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.55</td>
<td>-7.55</td>
<td>-16.5 ± 5.3</td>
<td>84.9 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-6.61</td>
<td>-8.47</td>
<td>-33.7 ± 4.7</td>
<td>100.5 ± 5.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.54</td>
<td>-6.31</td>
<td>-5.9 ± 5.6</td>
<td>106.2 ± 6.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.73</td>
<td>-1.19</td>
<td>-27.2 ± 5.2</td>
<td>77.9 ± 7.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.01</td>
<td>-10.85</td>
<td>-52.6 ± 4.1</td>
<td>87.1 ± 8.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-4.37</td>
<td>-9.92</td>
<td>-41.9 ± 3.9</td>
<td>102.3 ± 4.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>-10.87</td>
<td>-52.2 ± 2.3</td>
<td>70.5 ± 13.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-6.79</td>
<td>8.49</td>
<td>54.6 ± 8.3</td>
<td>76.3 ± 17.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.74</td>
<td>1.99</td>
<td>2.2 ± 7.7</td>
<td>101.4 ± 8.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-----------</td>
<td>-------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>-11.07</td>
<td>0.78</td>
<td>29.4 ± 6.5</td>
<td>84.2 ± 11.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-4.37</td>
<td>9.93</td>
<td>48.2 ± 7.0</td>
<td>104.1 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-2.75</td>
<td>-10.72</td>
<td>-35.4 ± 6.4</td>
<td>105.1 ± 12.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.07</td>
<td>-9.82</td>
<td>-45.3 ± 3.9</td>
<td>82.2 ± 4.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.83</td>
<td>9.57</td>
<td>51.4 ± 6.4</td>
<td>101.0 ± 8.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.73</td>
<td>-3.59</td>
<td>-27.8 ± 4.7</td>
<td>88.0 ± 6.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.15</td>
<td>6.76</td>
<td>19.5 ± 9.6</td>
<td>82.6 ± 17.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>6.77</td>
<td>9.15</td>
<td>33.9 ± 6.8</td>
<td>86.6 ± 14.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.92</td>
<td>-5.99</td>
<td>-39.9 ± 3.4</td>
<td>83.2 ± 5.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>3.96</td>
<td>-10.95</td>
<td>-49.0 ± 3.8</td>
<td>88.3 ± 3.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-10.94</td>
<td>3.40</td>
<td>45.2 ± 7.2</td>
<td>103.6 ± 5.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.37</td>
<td>6.48</td>
<td>43.6 ± 4.9</td>
<td>112.0 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.98</td>
<td>-9.97</td>
<td>-34.8 ± 5.4</td>
<td>99.6 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>-11.73</td>
<td>-52.3 ± 3.0</td>
<td>74.9 ± 12.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.53</td>
<td>0.40</td>
<td>-9.6 ± 7.5</td>
<td>95.8 ± 9.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.16</td>
<td>5.54</td>
<td>3.3 ± 5.7</td>
<td>92.5 ± 6.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.36</td>
<td>-8.34</td>
<td>-35.5 ± 2.9</td>
<td>93.6 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-10.04</td>
<td>-5.71</td>
<td>-8.8 ± 6.9</td>
<td>99.5 ± 9.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.12</td>
<td>-9.35</td>
<td>-36.7 ± 4.0</td>
<td>90.0 ± 3.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.46</td>
<td>-7.37</td>
<td>-31.4 ± 3.4</td>
<td>73.6 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.09</td>
<td>-3.97</td>
<td>6.5 ± 6.3</td>
<td>94.4 ± 12.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.36</td>
<td>-11.72</td>
<td>-52.3 ± 3.0</td>
<td>101.5 ± 7.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.17</td>
<td>-5.06</td>
<td>-23.8 ± 4.0</td>
<td>88.8 ± 6.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.88</td>
<td>-2.40</td>
<td>-15.9 ± 5.5</td>
<td>101.0 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.46</td>
<td>-1.45</td>
<td>23.2 ± 5.3</td>
<td>112.5 ± 7.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-0.79</td>
<td>11.50</td>
<td>45.3 ± 7.3</td>
<td>93.0 ± 12.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>1.46</td>
<td>11.44</td>
<td>49.3 ± 7.2</td>
<td>105.9 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.44</td>
<td>8.66</td>
<td>48.9 ± 7.4</td>
<td>103.7 ± 8.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.56</td>
<td>10.75</td>
<td>39.9 ± 8.7</td>
<td>89.8 ± 12.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.54</td>
<td>3.59</td>
<td>-5.3 ± 6.4</td>
<td>102.1 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>5.97</td>
<td>-10.73</td>
<td>-49.4 ± 4.3</td>
<td>84.8 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-3.21</td>
<td>11.67</td>
<td>47.3 ± 8.8</td>
<td>87.9 ± 10.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.10</td>
<td>5.36</td>
<td>37.1 ± 5.8</td>
<td>104.6 ± 4.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>3.26</td>
<td>11.87</td>
<td>40.2 ± 5.2</td>
<td>102.8 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-4.66</td>
<td>-11.47</td>
<td>-30.8 ± 4.0</td>
<td>90.6 ± 6.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>12.69</td>
<td>-0.78</td>
<td>-23.6 ± 2.8</td>
<td>96.0 ± 4.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.89</td>
<td>8.46</td>
<td>22.4 ± 6.3</td>
<td>101.3 ± 8.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-8.08</td>
<td>-9.29</td>
<td>-17.9 ± 5.7</td>
<td>102.1 ± 5.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.72</td>
<td>-7.96</td>
<td>-4.9 ± 5.7</td>
<td>106.4 ± 5.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-2.35</td>
<td>-12.31</td>
<td>-46.0 ± 3.8</td>
<td>84.9 ± 9.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>12.42</td>
<td>1.78</td>
<td>-18.7 ± 3.9</td>
<td>96.8 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
</tbody>
</table>
### SAURON Kinematics for 377 Bins

<table>
<thead>
<tr>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
<th>Value 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.52</td>
<td>-6.79</td>
<td>-36.2 ± 3.4</td>
<td>78.9 ± 4.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.64</td>
<td>5.32</td>
<td>5.1 ± 5.3</td>
<td>96.2 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-12.84</td>
<td>-0.01</td>
<td>36.2 ± 6.6</td>
<td>97.6 ± 8.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.32</td>
<td>11.03</td>
<td>47.1 ± 7.2</td>
<td>107.9 ± 10.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-1.56</td>
<td>13.49</td>
<td>50.7 ± 7.3</td>
<td>83.5 ± 11.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-12.52</td>
<td>2.30</td>
<td>32.9 ± 9.7</td>
<td>92.6 ± 6.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-12.64</td>
<td>-2.60</td>
<td>9.5 ± 4.7</td>
<td>98.0 ± 6.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-5.35</td>
<td>11.91</td>
<td>58.4 ± 7.8</td>
<td>78.1 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.79</td>
<td>-10.67</td>
<td>-37.4 ± 4.8</td>
<td>73.3 ± 4.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>4.73</td>
<td>-12.31</td>
<td>-53.1 ± 2.0</td>
<td>90.0 ± 12.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>12.81</td>
<td>-3.88</td>
<td>-25.8 ± 3.5</td>
<td>105.4 ± 6.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>8.20</td>
<td>10.35</td>
<td>25.0 ± 4.8</td>
<td>85.4 ± 10.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.88</td>
<td>-5.79</td>
<td>-1.2 ± 3.7</td>
<td>99.8 ± 6.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.42</td>
<td>-11.11</td>
<td>-19.5 ± 3.7</td>
<td>95.9 ± 7.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.88</td>
<td>7.91</td>
<td>3.4 ± 4.8</td>
<td>106.6 ± 3.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>-13.39</td>
<td>-41.4 ± 5.2</td>
<td>79.9 ± 8.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-10.83</td>
<td>8.01</td>
<td>43.3 ± 6.4</td>
<td>93.0 ± 7.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>2.36</td>
<td>-13.37</td>
<td>-48.2 ± 3.6</td>
<td>90.8 ± 9.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.53</td>
<td>-9.51</td>
<td>-20.8 ± 2.3</td>
<td>100.5 ± 2.9</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-13.51</td>
<td>4.43</td>
<td>36.1 ± 5.3</td>
<td>96.7 ± 7.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.01</td>
<td>-8.36</td>
<td>-20.6 ± 2.7</td>
<td>83.7 ± 4.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>0.85</td>
<td>13.44</td>
<td>55.9 ± 8.9</td>
<td>98.6 ± 13.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>6.82</td>
<td>12.15</td>
<td>41.3 ± 5.2</td>
<td>102.0 ± 7.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>4.81</td>
<td>13.04</td>
<td>7.4 ± 4.1</td>
<td>97.0 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>13.44</td>
<td>3.39</td>
<td>3.9 ± 5.9</td>
<td>109.4 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-4.22</td>
<td>-13.43</td>
<td>-40.5 ± 4.7</td>
<td>99.8 ± 4.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-6.08</td>
<td>-12.56</td>
<td>-29.7 ± 4.2</td>
<td>91.6 ± 5.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.88</td>
<td>-8.11</td>
<td>-10.6 ± 5.4</td>
<td>101.1 ± 5.7</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>7.07</td>
<td>-12.51</td>
<td>-39.4 ± 3.9</td>
<td>92.7 ± 5.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>12.69</td>
<td>6.58</td>
<td>2.8 ± 4.3</td>
<td>92.4 ± 6.1</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>10.20</td>
<td>10.15</td>
<td>9.9 ± 7.1</td>
<td>99.3 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-13.65</td>
<td>-4.53</td>
<td>11.4 ± 6.5</td>
<td>100.6 ± 4.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.58</td>
<td>-10.31</td>
<td>-18.4 ± 4.4</td>
<td>91.6 ± 6.8</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>13.55</td>
<td>-5.68</td>
<td>-42.3 ± 4.7</td>
<td>97.1 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-9.60</td>
<td>10.56</td>
<td>44.0 ± 6.5</td>
<td>93.2 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-13.54</td>
<td>7.41</td>
<td>41.2 ± 6.4</td>
<td>103.0 ± 5.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>9.47</td>
<td>-11.82</td>
<td>-26.2 ± 2.4</td>
<td>94.0 ± 2.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>12.96</td>
<td>8.61</td>
<td>0.7 ± 4.8</td>
<td>110.7 ± 6.3</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>13.52</td>
<td>-7.99</td>
<td>-32.5 ± 6.2</td>
<td>102.9 ± 4.6</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.46</td>
<td>-10.23</td>
<td>-21.8 ± 2.4</td>
<td>94.4 ± 3.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-7.66</td>
<td>13.74</td>
<td>40.8 ± 10.4</td>
<td>91.8 ± 10.2</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>-11.42</td>
<td>12.09</td>
<td>27.2 ± 3.2</td>
<td>125.7 ± 2.0</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>Angle</td>
<td>Some Value</td>
<td>Another Value</td>
<td>Yet Another Value</td>
<td>Fourth Value</td>
<td>Fifth Value</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>13.91</td>
<td>-10.62</td>
<td>-40.3 ± 2.9</td>
<td>81.2 ± 3.4</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
<tr>
<td>11.58</td>
<td>-12.90</td>
<td>-37.0 ± 2.0</td>
<td>103.9 ± 2.5</td>
<td>0.000 ± 0.020</td>
<td></td>
</tr>
</tbody>
</table>