A JWST View of the Central Stellar Kinematics in M87

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Abstract

The supermassive black hole (BH) in the giant elliptical galaxy M87 is one of the most well-studied black holes in the local universe, with black hole mass (M_{BH}) measurements from both stellar and gas dynamics. However, different measurement methods yield varying results. To obtain the most robust stellar dynamical measurement for this key anchor to the upper end of the M_{BH} and host galaxy relations, we acquired high angular resolution and high signal-to-noise (S/N) spectra from the James Webb Space Telescope (JWST). Here we present the observations from the central 3x3" of M87 using the NIRSpec integral field unit (IFU) covering a wavelength region of 1.66-3.17 μm. We show preliminary results for the measured stellar kinematics in this region.

Introduction

BHs are believed to play a significant role in galaxy growth and evolution. This fact has been established based on several relations between the black hole mass (M_{BH}) and other large-scale properties of the host galaxy like bulge luminosity and stellar velocity dispersion [1]. However, the low ($M_{BH} \lesssim 10^6$ $M_\odot$) and high ($M_{BH} \gtrsim 10^9$ $M_\odot$) mass are not well understood and the scaling relations even make diverging predictions for the BHs in galaxies with very high luminosity and velocity dispersion [2]. The giant elliptical galaxy, M87, at a distance of 16.8 Mpc is an excellent object for constraining the upper end of the M_{BH} and host galaxy relations. However, different methods of obtaining M_{BH} find varying results for the BH in M87.

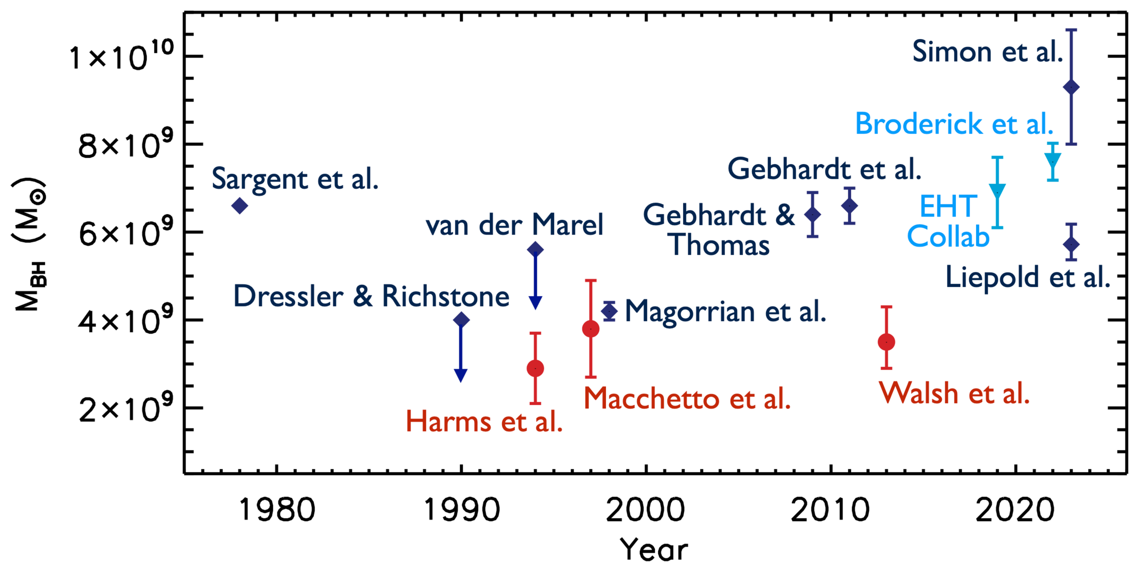

Figure 1: History of M87 BH measurements M_{BH} from stellar **(blue diamond)** and gas **(red circle)** kinematics, along with the EHT determination **(light blue triangle)**.

Data

We obtain JWST NIRSpec IFU data of the central 3x3″ region of M87 on 31 May 2023. With the G235H grating and F170LP filter, the spectra span a wavelength range of 1.66-3.17 μm at R~2700. We use the NRSIRS2 readout mode and integrate for a total of ~6.6 hours on-source using 20 groups, 1 integration, and 16 exposures dithered using the small (0.25″ extent) cycle pattern to improve sampling of the point spread function. We also obtained a LeakCal exposure at the first science dither position.

We process the data using the JWST data reduction pipeline (version 1.11.4) . Where Stage 1 of the pipeline performs detector level corrections to produce count rate images of the uncalibrated ramps. Here we opt to turn snowball flagging on to correct for large cosmic ray impacts. Next, stage 2 applies physical corrections and calibrations to each exposure to produce calibrated (unrectified) exposures. We also subtract the LeakCal exposure from each M87 exposure. Finally, stage 3 identifies additional outliers that were not flagged in stage 1, then the default pipeline generates a combined data cube of all the exposures. However, we further manually flag bad pixels and artifacts that remain after the outlier detection step of stage 3 by adjusting the data quality array and then calling the cube building step. We generate a data cube with 0.05″ square spaxels. In the extracted spectrum the K-band CO bandheads are very clear and we use these absorption features to measure the stellar kinematics (Figure 2, right). We also find emission lines, which previously have gone undetected in the near-infrared [3]. We will measure gas kinematics from the warm molecular H_2 lines and the hydrogen recombination lines and compare to published ionized gas kinematics at the center of M87 [4], [5].

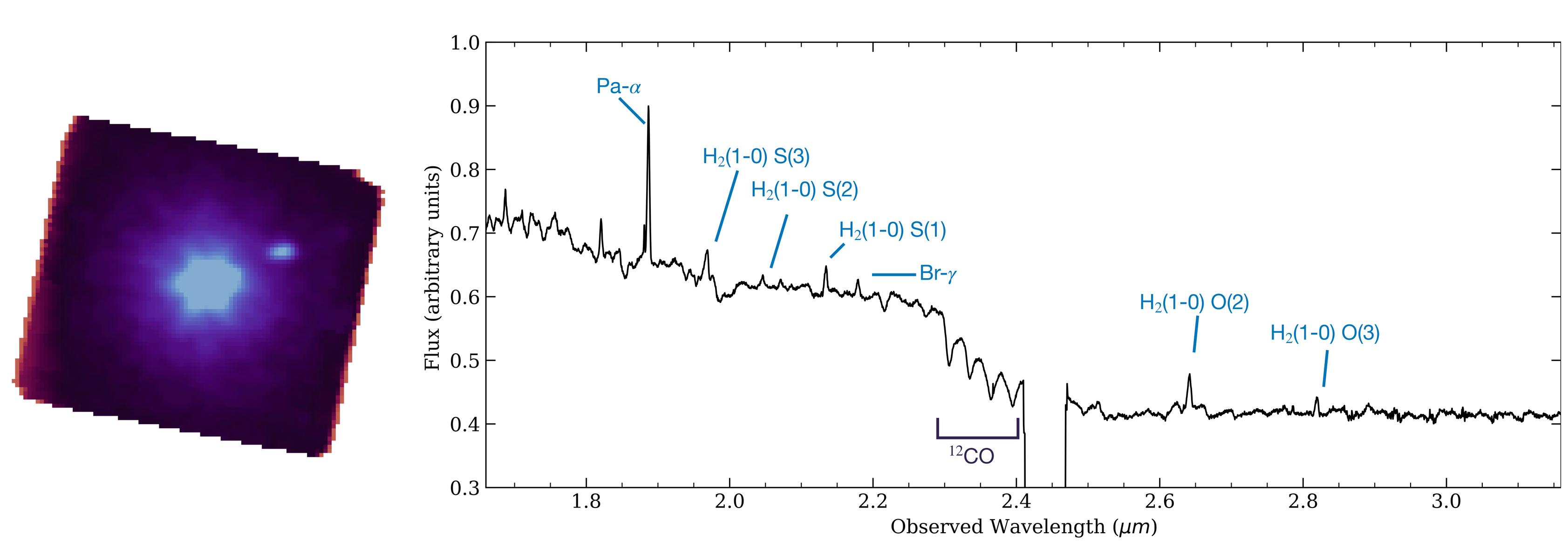

Figure 2: (left) Final data cube collapsed along the wavelength axis. North is up and east is to the left. The field spans a ~3x3" region, where 1" corresponds to 81 pc. (Right) full spectrum extracted from a 0.3x0.3" bin at x = -0.4", y = 0.3" from the center with labeled spectral features. The missing portion of the spectrum at ~2.45μm is due to the physical gap between the two NIRSpec detectors

Kinematic Measurements & Results

Prior to measuring the stellar kinematics, typically spectra are binned to achieve the necessary high S/N to reliably measure the detailed shape of the line-of-sight velocity distribution (LOSVD) as a function of spatial location. In the best cases, this process yields ~100 bins with a minimum S/N ~40-60 over a few arcsecond by few arcsecond field of view [6]. In contrast, the JWST/NIRSpec data of M87 are spectacular and a majority of individual spaxels have S/N $\gtrsim$150, as shown in Figure 3. We employ a small amount of binning in the outermost regions using the Voronoi binning method [7] and mask the central 0.6x0.6″ region due to unphysical wiggles in the spectrum caused by resampling noise [8]. We also mask the jet knot to the upper right of the nucleus. In total, there are 3959 spatial bins, 3659 of which are composed of a single 0.05x0.05″ spaxel.

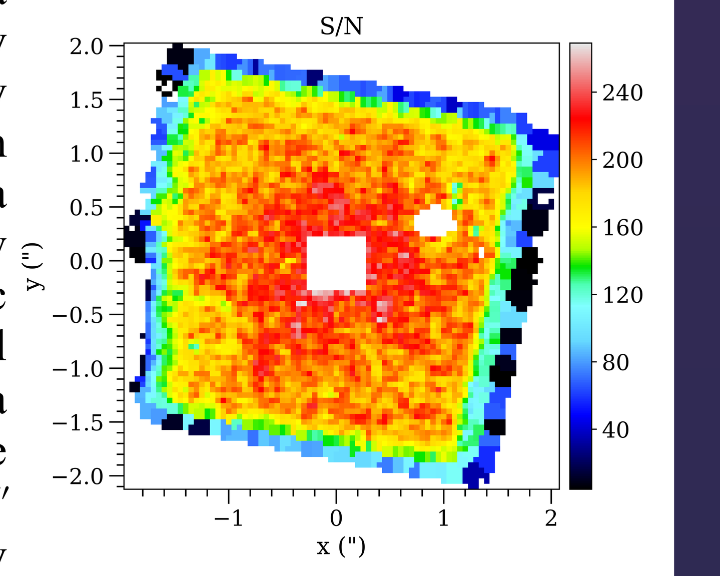

Figure 3: S/N map of the JWST/ NIRSpec data of M87

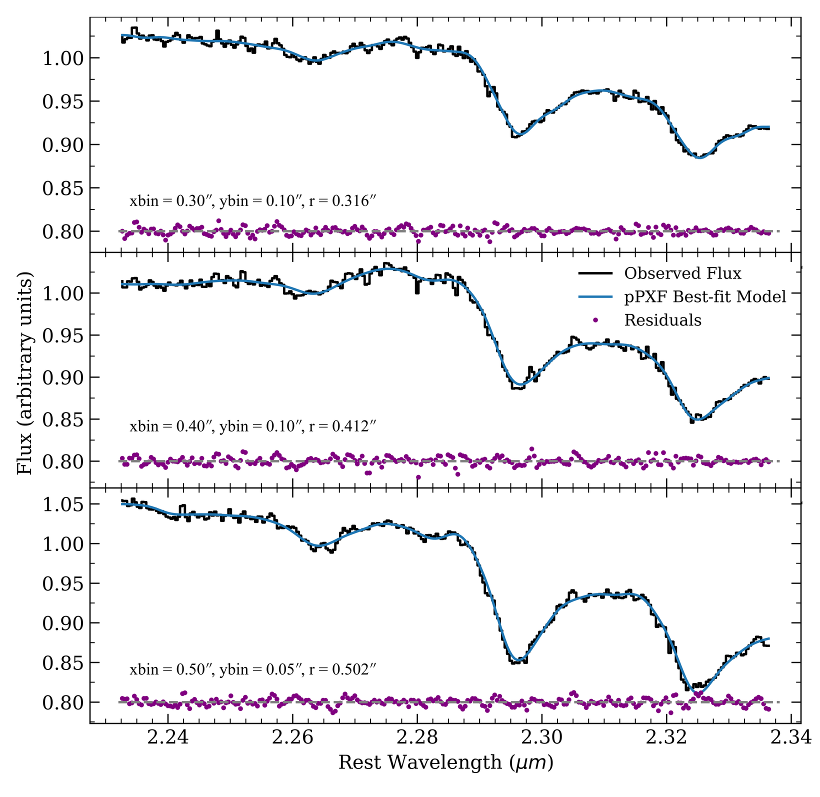

Figure 4: The trimmed M87 spectrum (black) with the pPXF best-fit model (blue) for a several bins are shown. The residuals are also plotted at an offset in arbitrary flux units (purple dots).

We use the penalized pixel fitting method (pPXF; [9]) to compare template stars, convolved with an LOSVD, to the M87 spectra. We parameterize the LOSVD in terms of a Gauss-Hermite (GH) series and measure the velocity, V, the velocity dispersion, σ, and higher order moments ($h_3 - h_8$) to quantify the distribution's asymmetric and symmetric deviations from a Gaussian. During the measurement, we use the PHOENIX stellar template library, and include an additive degree 0 and a multiplicative degree 4 Legendre polynomial to adjust the continuum shape, matching the M87 observations. The spectra were fit over a trimmed wavelength range, which focuses on the first two CO bandheads. Some of the pPXF best-fits are shown in Figure 4 and the kinematic maps are shown in Figure 5.

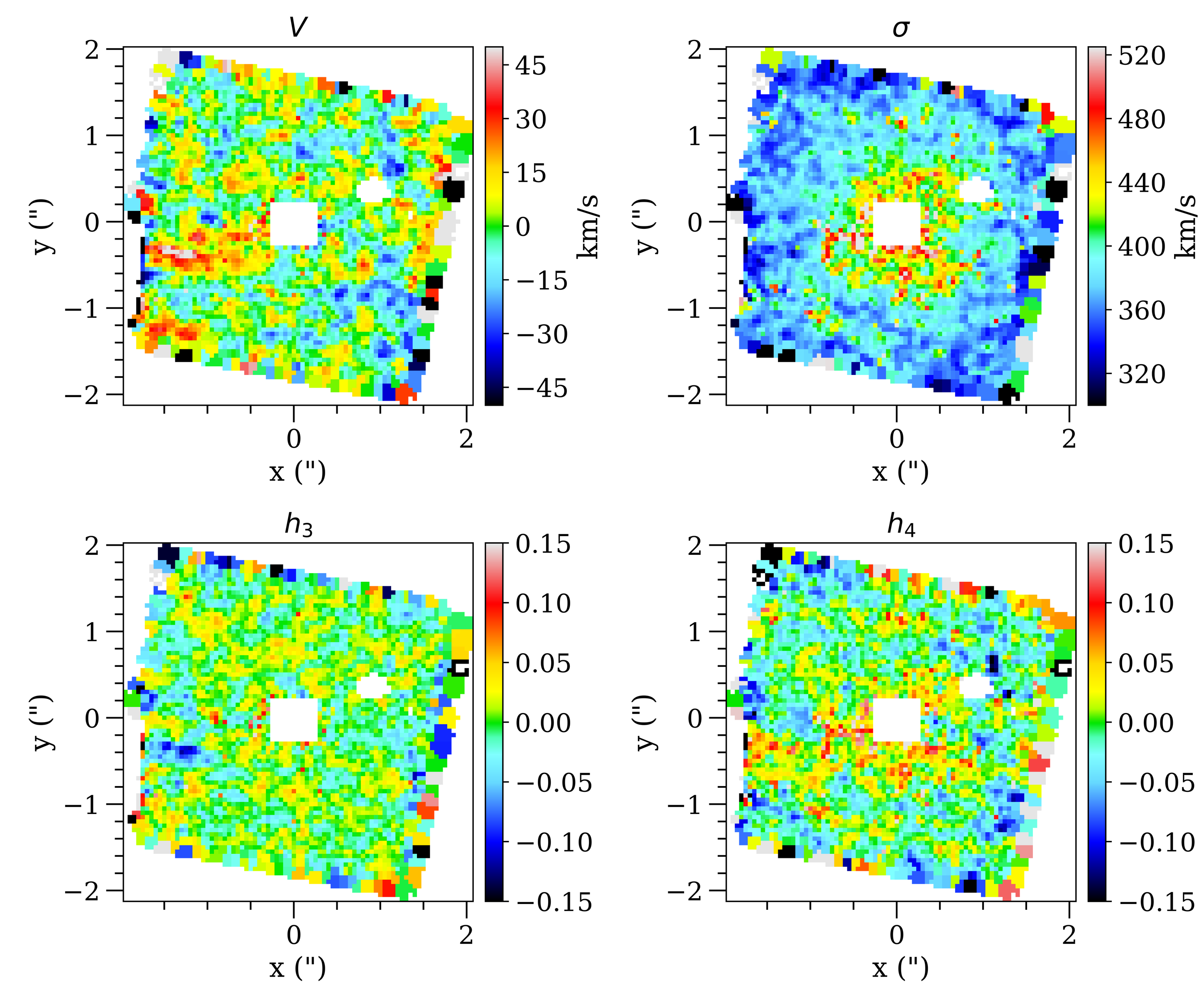

Figure 6: Stellar kinematic maps for the central region of M87. Here we show the first four out of the eight measured GH moments.

Conclusions & Future Work

JWST offers the most detailed kinematic view of the center of the famous giant elliptical galaxy, M87, which harbors one of the most massive BHs known. With future work, we will explore the cube building step and the resampling issues currently affecting the innermost spaxels. Next, we will more carefully extract the stellar kinematics, making use of a wider wavelength range, and we will conduct tests to assess the robustness of the kinematics. The NIRSpec stellar kinematics will be combined with existing large-scale kinematics from Keck/KCWI [10] and we will construct triaxial, orbit-based dynamical models (e.g., [11]) in order to obtain the most robust stellar-dynamical BH mass for M87 to date.

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