Studying Invisible Giants: Measuring SMBH masses using Schwarzschild modelling

-Anirban Roy Chowdhury

What is a Black Hole?

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- Point of infinite density (“singularity”) surrounded by a surface of no return (“event horizon”)
- More importantly, it is a highly compact object that does not emit light
- Two types: stellar mass BH - born from collapsing stars, relatively well understood
- Supermassive BH- much bigger, relatively poorly understood

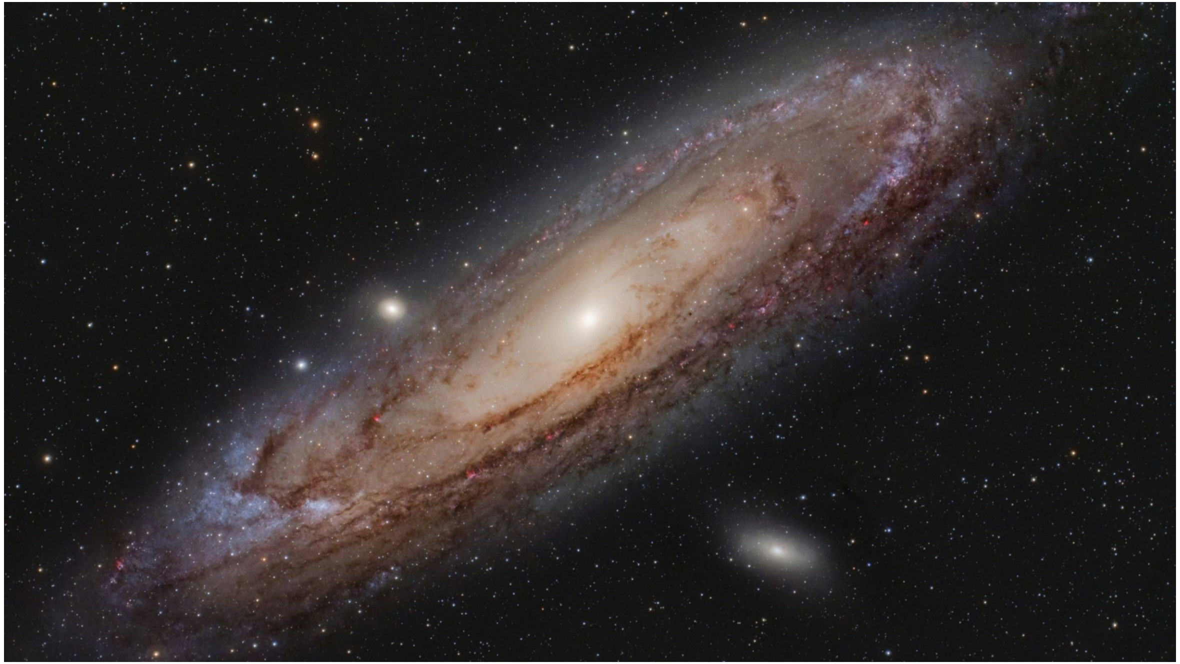
“Super”-Massive?

- Why is there such a stark difference between the mass range of stellar mass black holes and SMBHs?
- Did ancient stellar mass BHs merge to form SMBHs we see today? Was there a heavier seed?
- Do intermediate mass black holes exist?

Galaxies

- Two major types: Elliptical and Spiral galaxies (with some variations in between)
- Detailed classification-can be done by Morphological type, color, formation history etc.
- We shall focus on ellipticals and lenticular galaxies for this talk.

Galaxies



Galaxies

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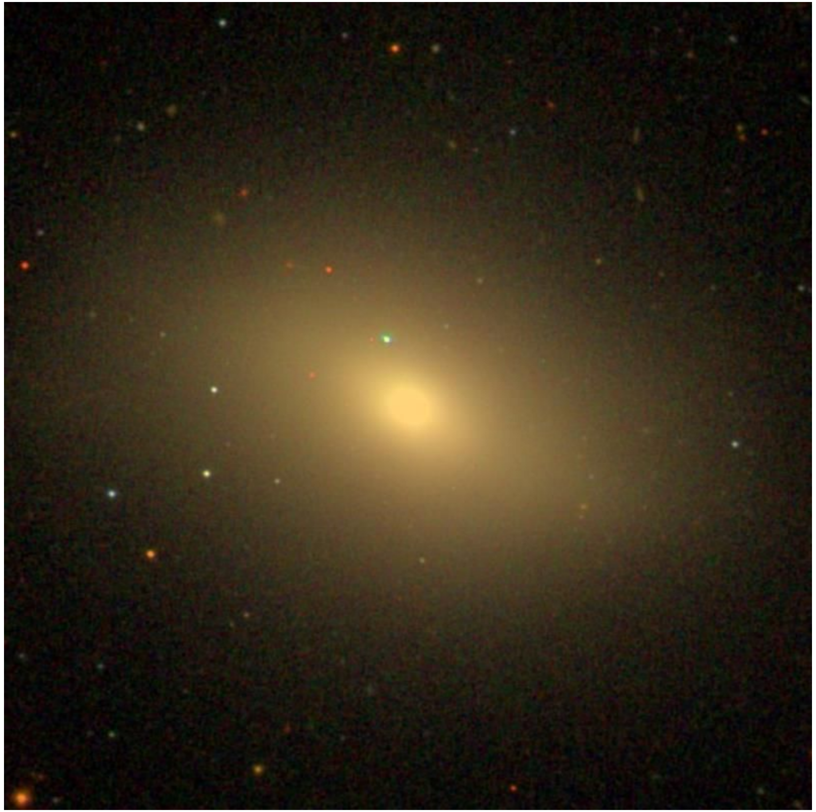
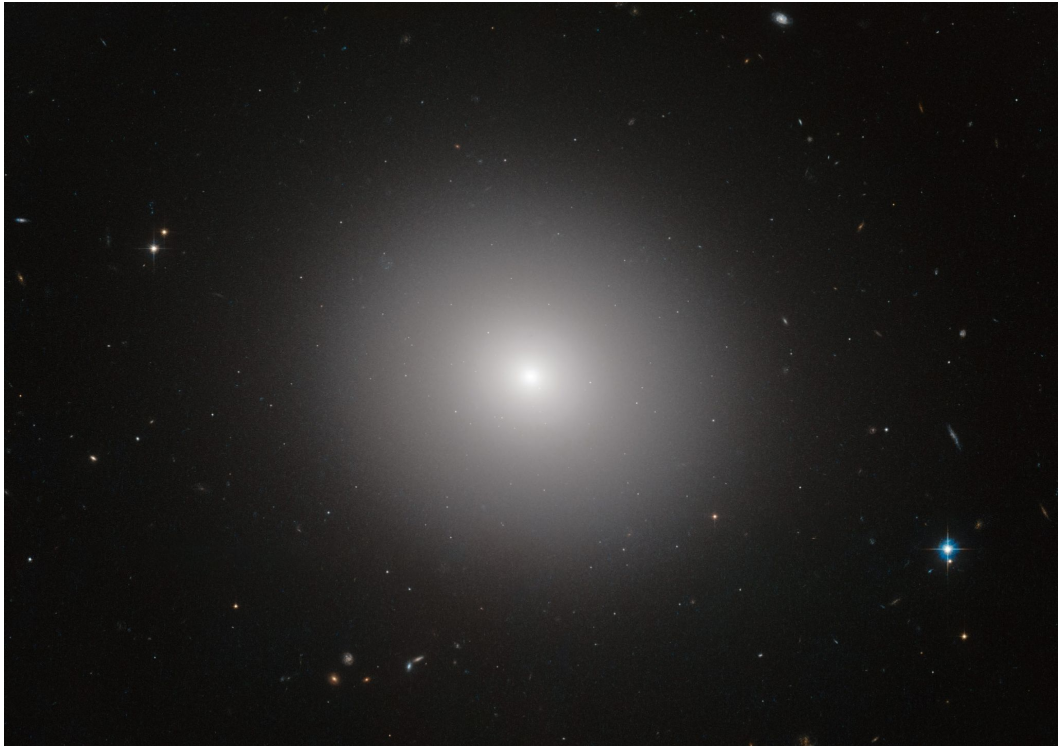
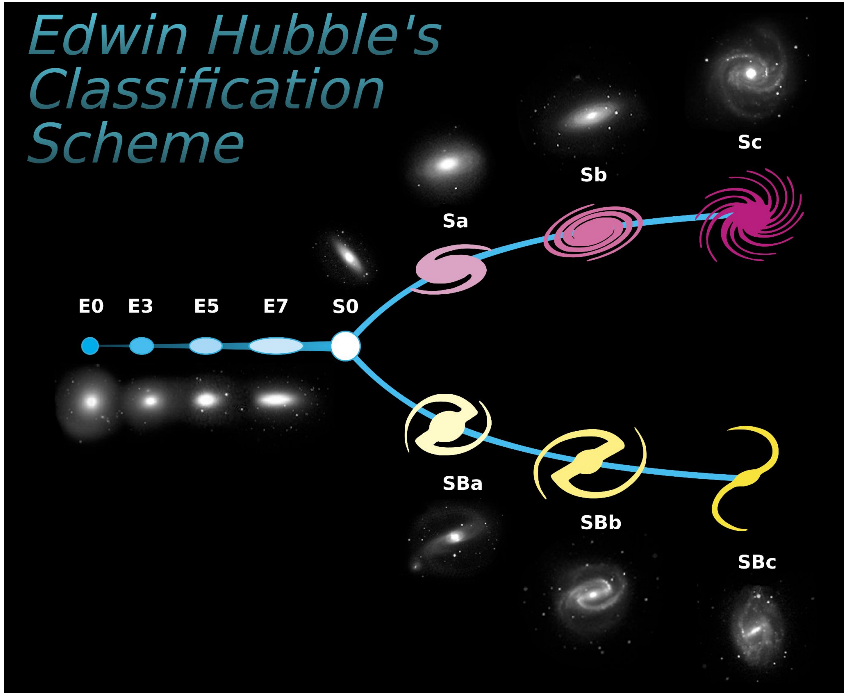


Galaxies



Galaxies-Morphological type



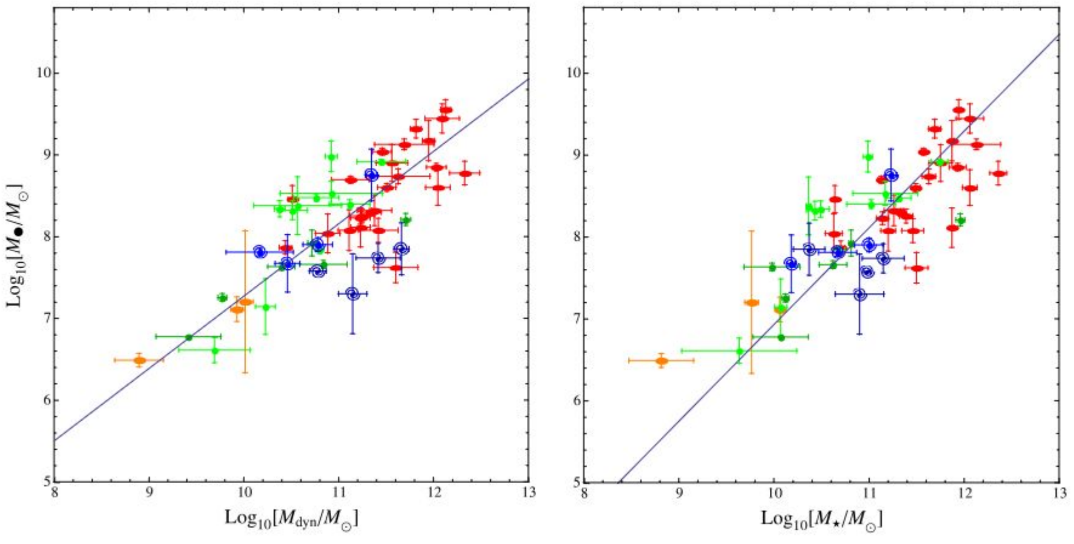
So What?

Why do we care about SMBH mass? How does it help us?

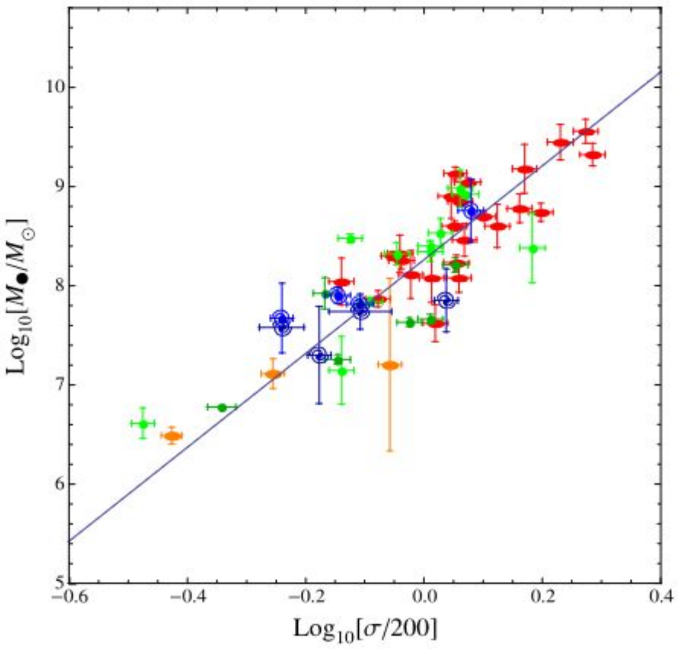
Motivation-Scaling Relations

- Astronomers over the years have calculated a number of ‘global’ galaxy properties.
- Let’s compare them against the SMBH mass.

Scaling Relations



Scaling Relations



Scaling Relations

- Why does this happen? We don’t know. Scaling relations persist across morphological type and redshift.

- Some discrepancies exist, especially in the very low and high mass regimes.

- This most likely points to co-formation and co-evolution of the SMBH and the galaxy.

- Still, in order to better understand the physical process behind these relations, we need to make more (and more accurate!) SMBH mass measurements.

Dynamical Modelling-Principle

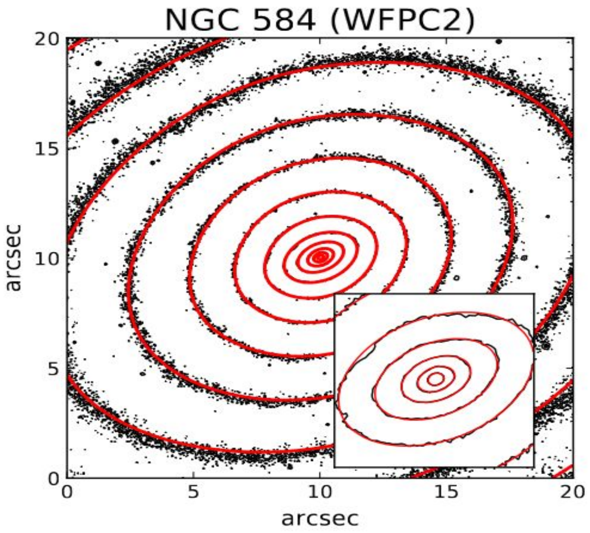
- The total gravitational potential of a galaxy is given as follows:

$$V_{tot} = V_{BH} + V_{stars} + V_{DM}$$

- If we can find what V_{BH} is, mass can be calculated with a simple algebraic relation.

Stellar potential-MGE

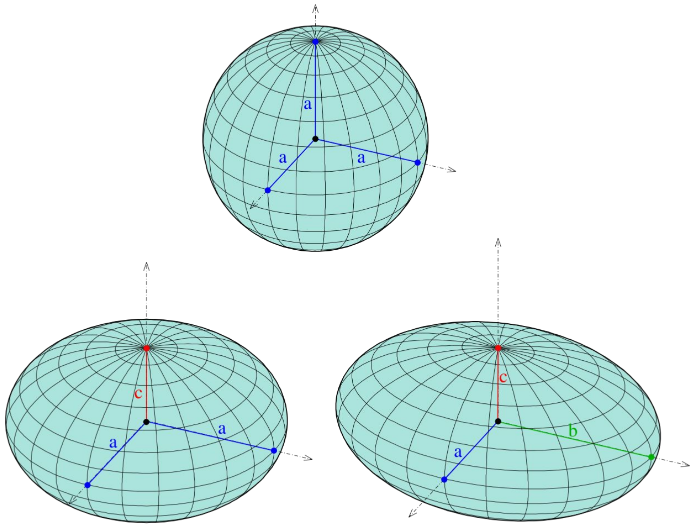
- In order to find the potential contribution of the stars, we must have a 3-dimensional distribution of them for our galaxy.
- We parametrize the 2D surface brightness as a Multi Gaussian Expansion (MGE). The brightness profile is fit to a sum of concentric 2D Gaussians.
- The MGE is then 'deprojected' to obtain a 3D distribution of stars in terms of their luminosity. This can be multiplied by a mass-to-light ratio (M/L) to get the mass distribution.



MGE deprojection

- Only possible for a certain range of angles of inclination.
- Deprojection is going from a 2-D image to a 3-D distribution, so it is non-unique in general.
- Certain assumptions of the galaxy's shape also need to be made. In general, elliptical and lenticular galaxies have a triaxial shape.

MGE deprojection



Black Hole potential

- The SMBH is parametrized as a Plummer Black Hole with the potential given by:

$$\phi_{BH} = \frac{GM_{BH}}{\sqrt{x^2+y^2+z^2+a^2}}$$

- a is the softening length, introduced to avoid infinities.

Dark Matter potential

- Dark matter- parameterized as a spherical NFW halo with 2 parameters, mass of dark matter inside R_{200} (f) and concentration of dark matter (c).

$$\rho_0 = \frac{200}{3} \frac{c^3}{\ln(1+c) - c/(1+c)} \times \rho_{\rm crit},$$

$$\Phi_{\rm DM}(r) = -\frac{4\pi G \rho_0 R_s^3}{r} \ln(1 + \frac{r}{R_s}).$$

$$R_s = \left[\frac{3}{800\pi} \frac{M_* f}{\rho_{\rm crit} c^3}\right]^{1/3}.$$

Total potential-stellar kinematics

- The motion of stars is dictated by the total gravitational potential. So hypothetically if we knew the 3-dimensional motion of every star in the galaxy, we could find the total potential perfectly.
- Unfortunately, we don't. Spatial resolution of our telescopes is too low to resolve individual stars in other galaxies.
- To add to this, there is no way to calculate the proper motion of these stars as well.
- The best we can do is the 1-dimensional motion (along the line-of-sight) for a multitude of stars in a single spaxel.

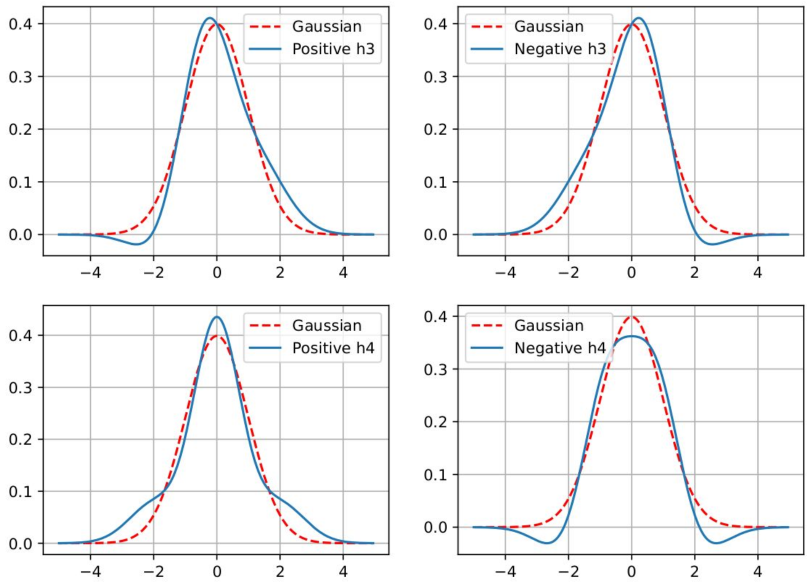
LOSVDs-Calculation

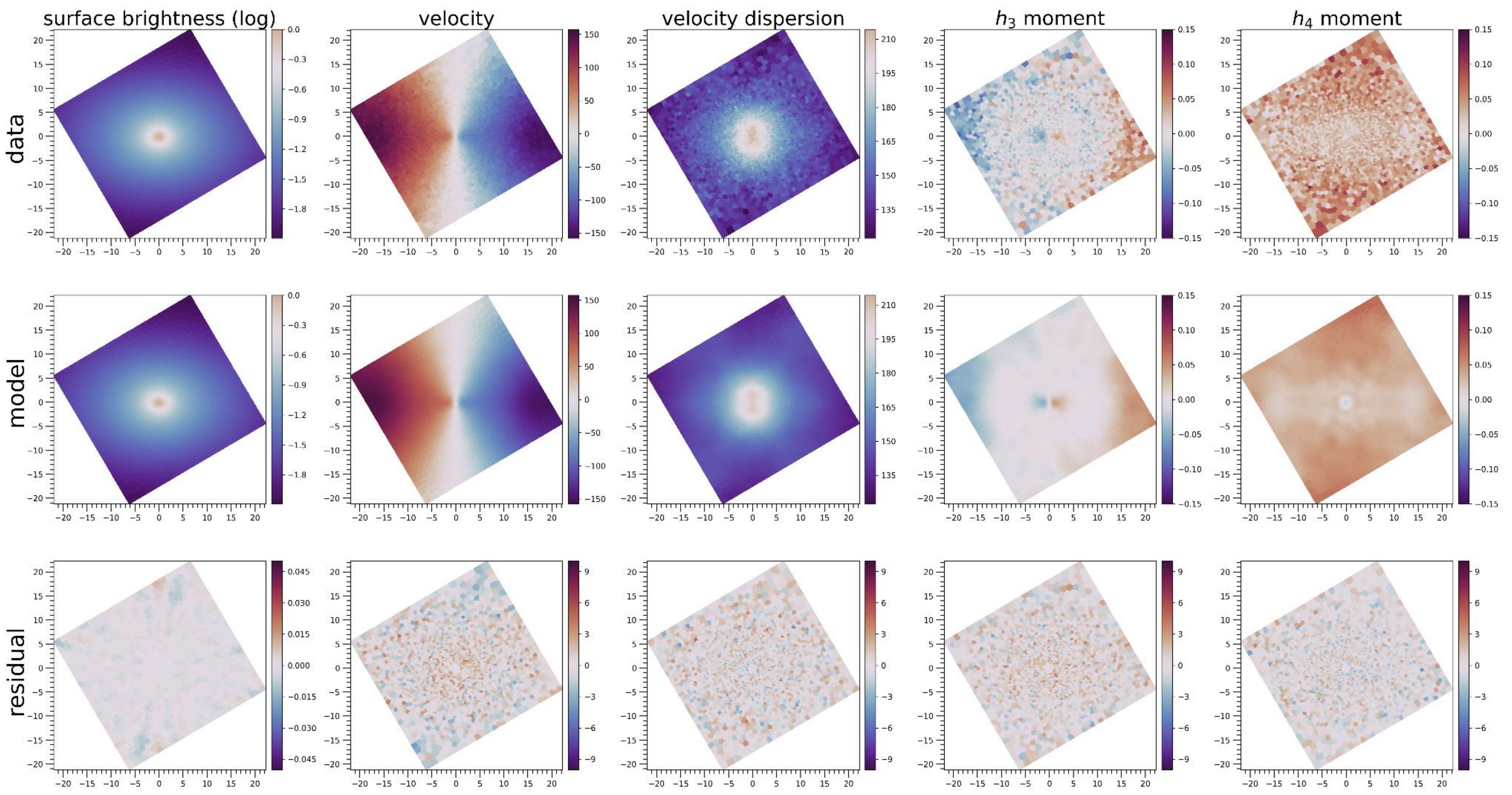
- We use the observed spectrum from each pixel and compare it to a known stellar spectra. Using the Doppler effect will give us the Line of Sight Velocity Distribution (LOSVD) for each pixel.

- For example, shift in a spectral line will give us the mean velocity (V) along the line of sight. The thickness of the spectral line will give us the velocity dispersion along the line of sight.

- For our purposes, we calculate the first 4 moments of the LOSVD (V, sigma, h3 (related to skew) and h4 (related to kurtosis)).

Gauss-Hermite polynomials





surface brightness (log)
velocity
velocity dispersion
h_3 moment
h_4 moment
data
model
residual

Bringing it all together

- We now have our kinematic maps, but this is not sufficient information to derive the potential.
- Given the number of free parameters (unknowns), we must instead ‘guess’ parameter values for the potential and see if this guess accurately reproduces our kinematic maps.
- Realistically, a random guess isn’t going to work, so we must iterate over many possible values and find the ‘best-fit’ model.

Schwarzschild modelling

- In essence, we pick a point in our allowed parameter space, construct the potential based on that, and calculate the trajectories of a large amount of orbits.
- We then reproduce the kinematic maps from this and compare it to our observed kinematics, assigning a chi-square value for the deviation of our model kinematics to the observed kinematics.
- We iterate over our parameter space and find the model with the lowest chi-square. This is our best-fit model.

Problems and Limitations

- Very computationally intensive
- Requires high resolution IFU data, enough to resolve the sphere of Influence of the SMBH.
- Poorly constrains Dark Matter parameters.
- Struggles to model spiral galaxies well.

THANK YOU