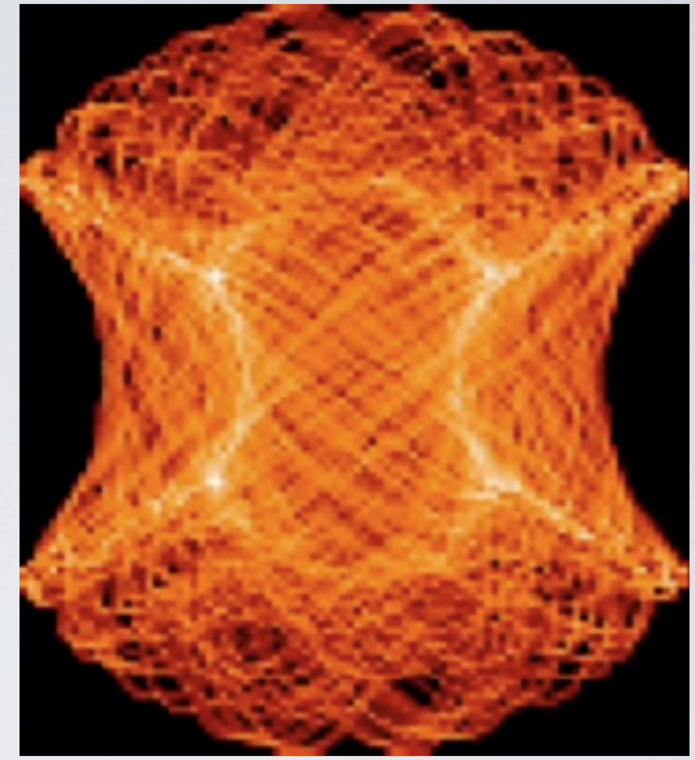
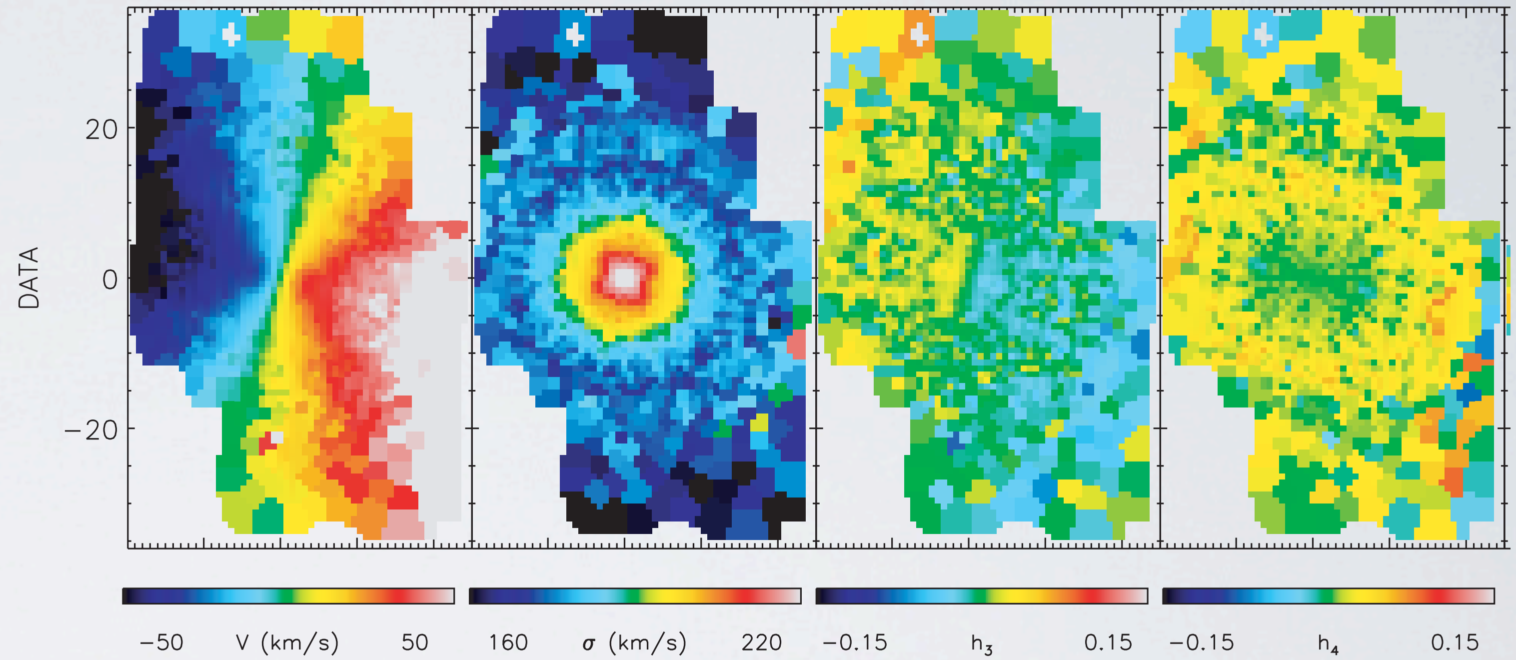


METHODS OF MEASURING SMBH MASSES: STELLAR DYNAMICAL MEASUREMENTS

Remco van den Bosch MPIA

STELLAR DYNAMICS



- All galaxies contain stars
- Gravity is well well understood
- Stars are well suited to measure the mass distributions including the SMBH mass, but also stellar and dark matter component
- As a result, most direct BH mass measurement come from stellar dynamics

STELLAR DYNAMICS

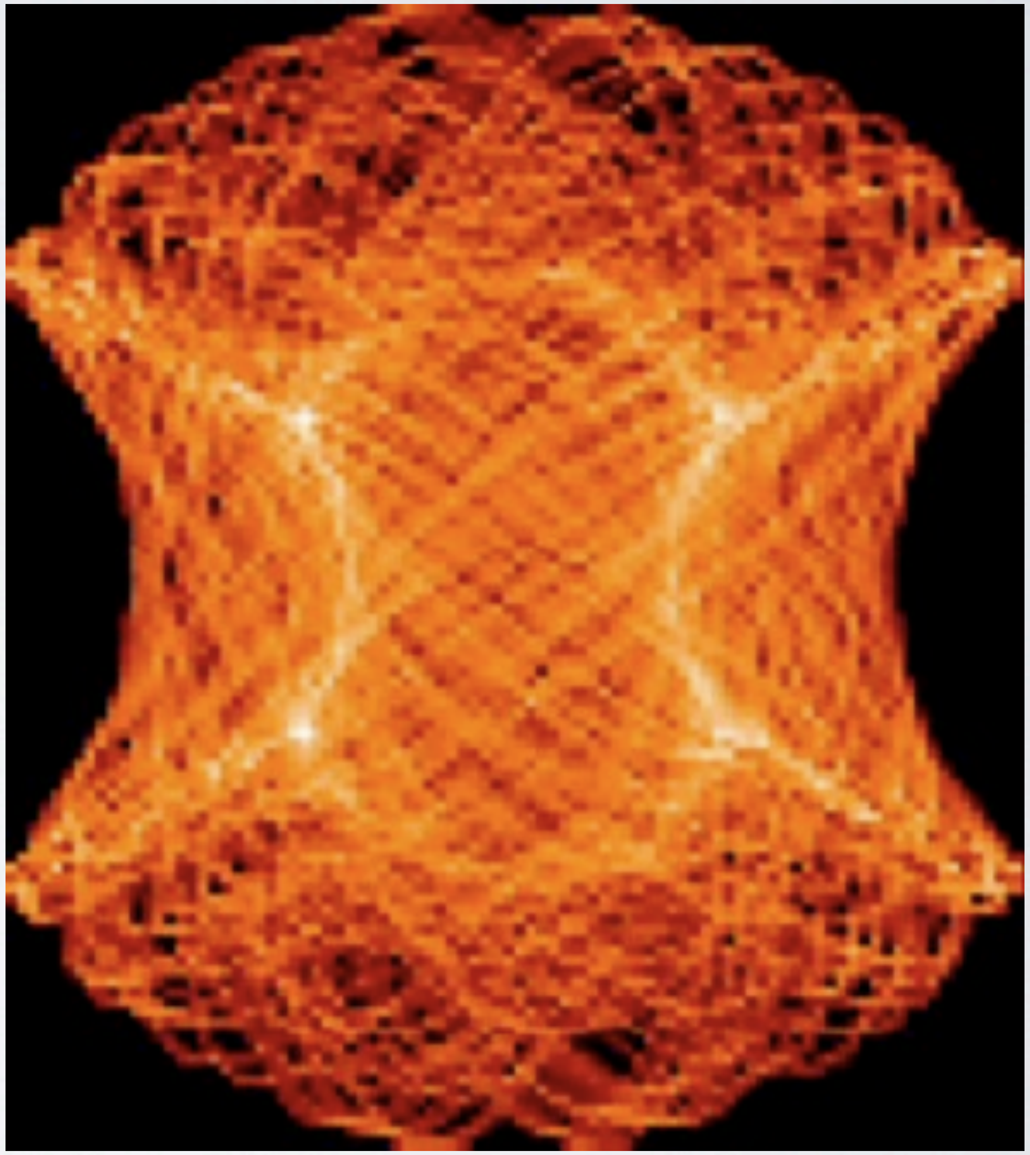
- Virial theorem $$M = \frac{\sigma_{rms}^2 R_g}{G}$$
  - Applies to intrinsic 3D properties, but generally we can only observe (part of) a projection.
- Thus dynamical models are needed to `de-project' the galaxies
- All analytical solutions, including Jeans, require strong assumptions (on the anisotropy)
- Jeans models only constrain the second moment: $\sqrt{V^2 + \sigma^2}$
  - Mass-anisotropy degeneracy
- N-body models are not practical for SMBH masses, due to dynamic range

ORBIT-BASED MODELS

- Orbit-based models do not place any assumptions on the anisotropy (orbit configuration) and can use all kinematic information (higher moments)
- Still imposes some assumptions: equilibrium, geometry
- Contain many parts/steps and numerical integrals, but are all well understood.
- Several implementations exist: Spherical (Magorrian), axisymmetric (NUKERS, van der Marel, Valluri), Triaxial (van den Bosch)

ORBIT-BASED MODELS

(1) Integrate orbit in the potential and store all the observables, including kinematics



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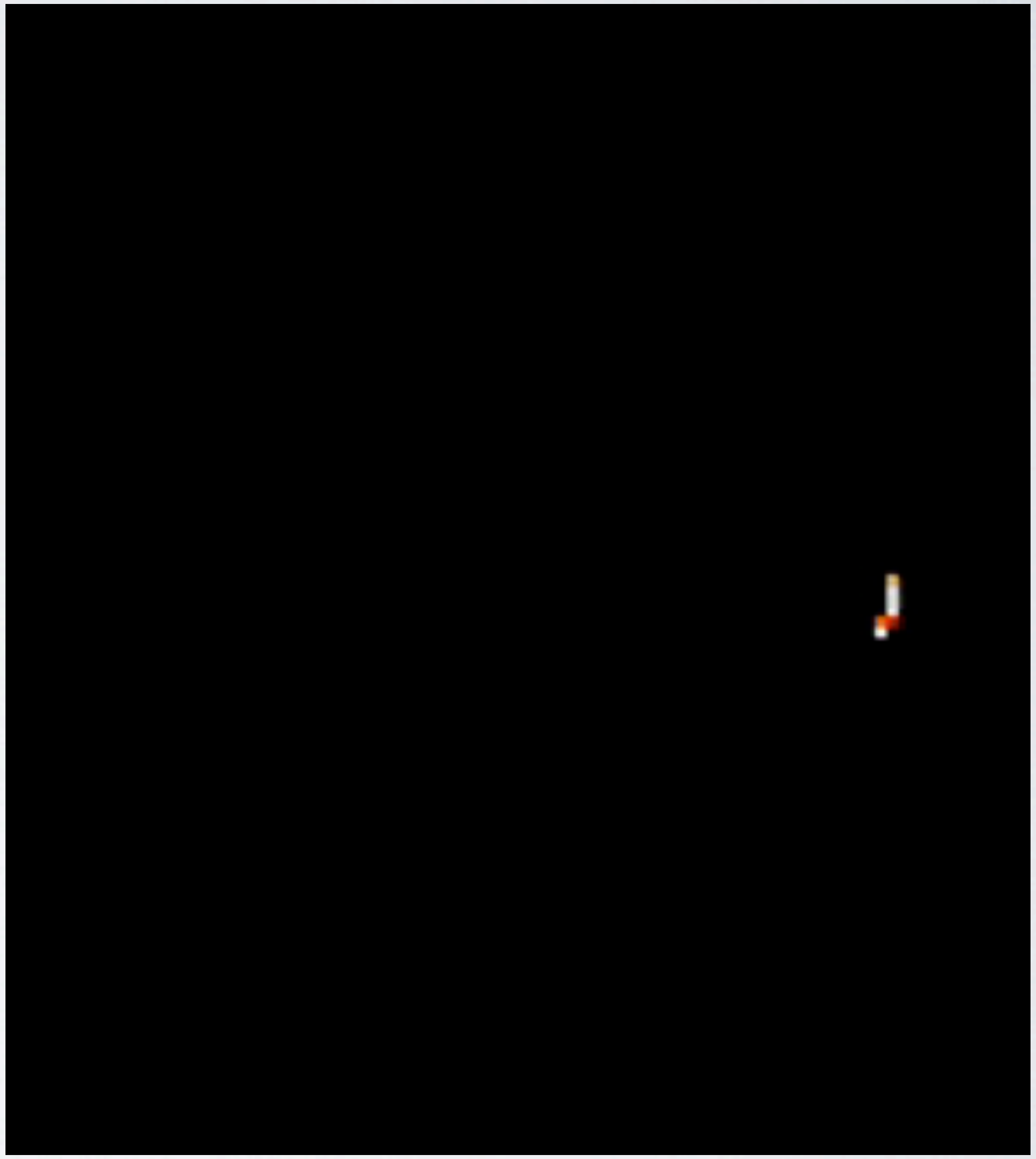
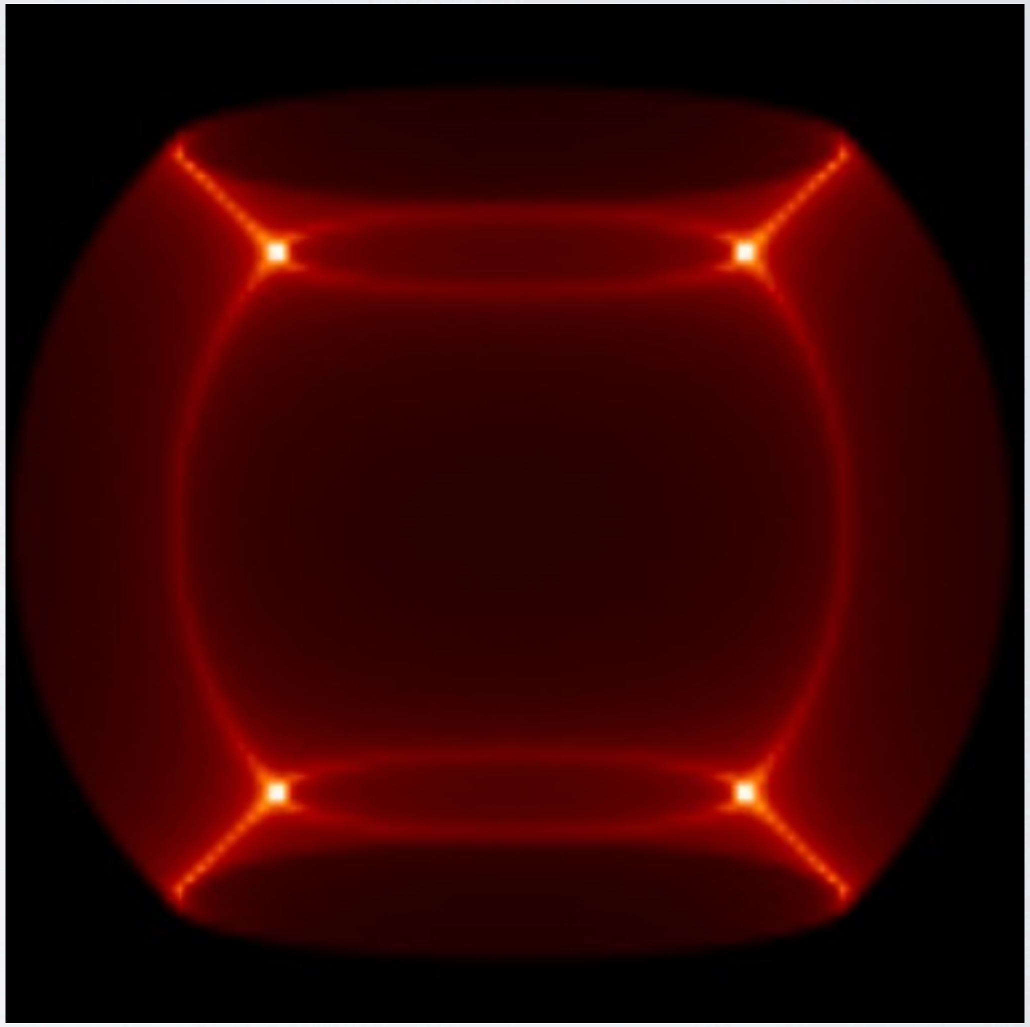


ORBIT-BASED MODELS

(1) Integrate orbit in the potential and store all the observables, including kinematics

(2) Generate a library of orbits



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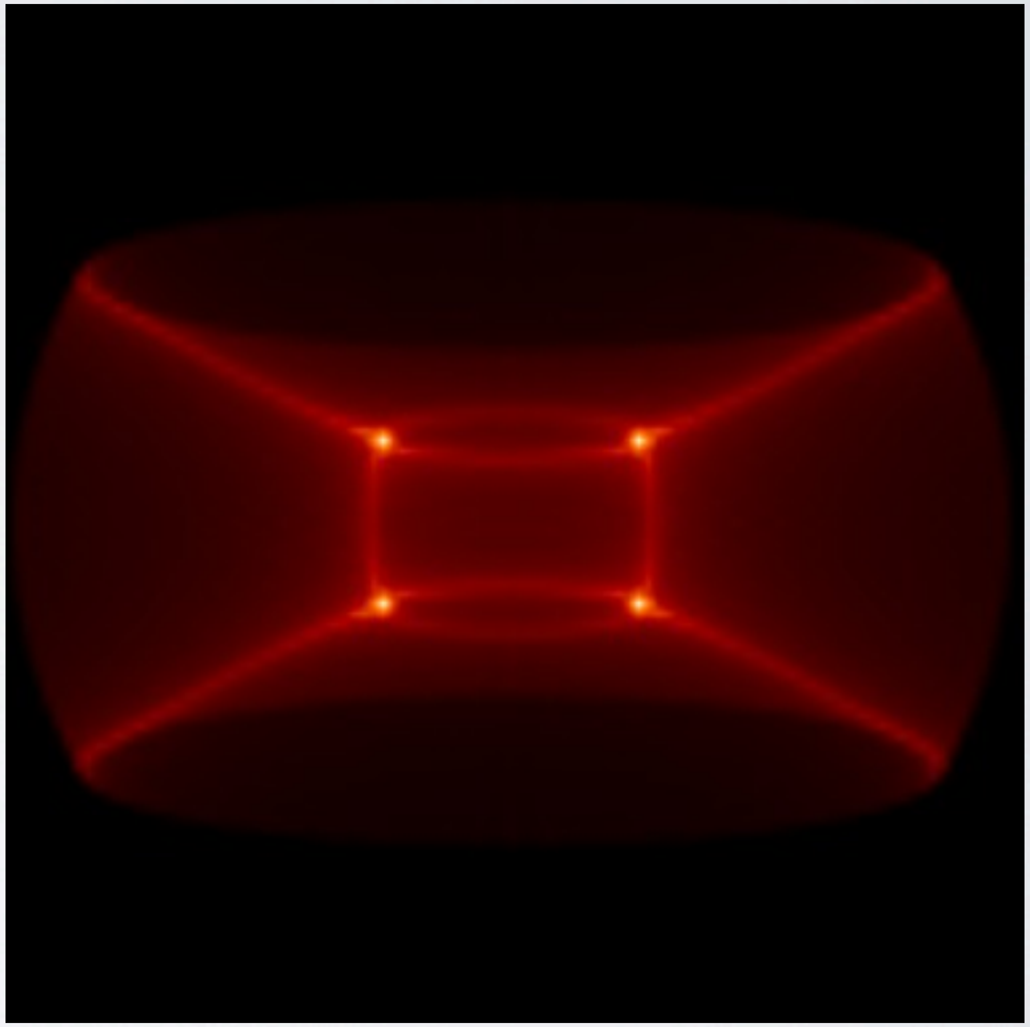

ORBIT-BASED MODELS

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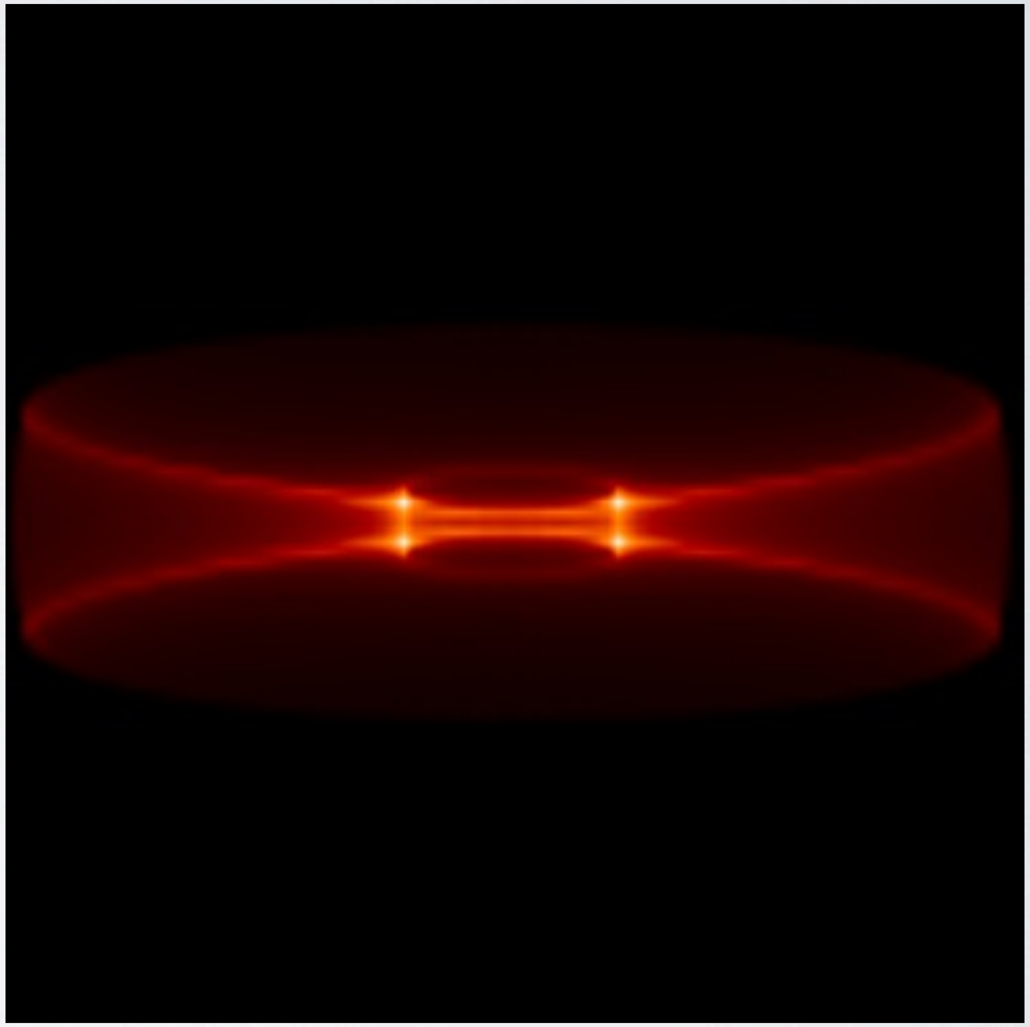


ORBIT-BASED MODELS

(1) Integrate orbit in the potential and store all the observables, including kinematics

(2) Generate a library of orbits

(3) Construct a superposition using least squares

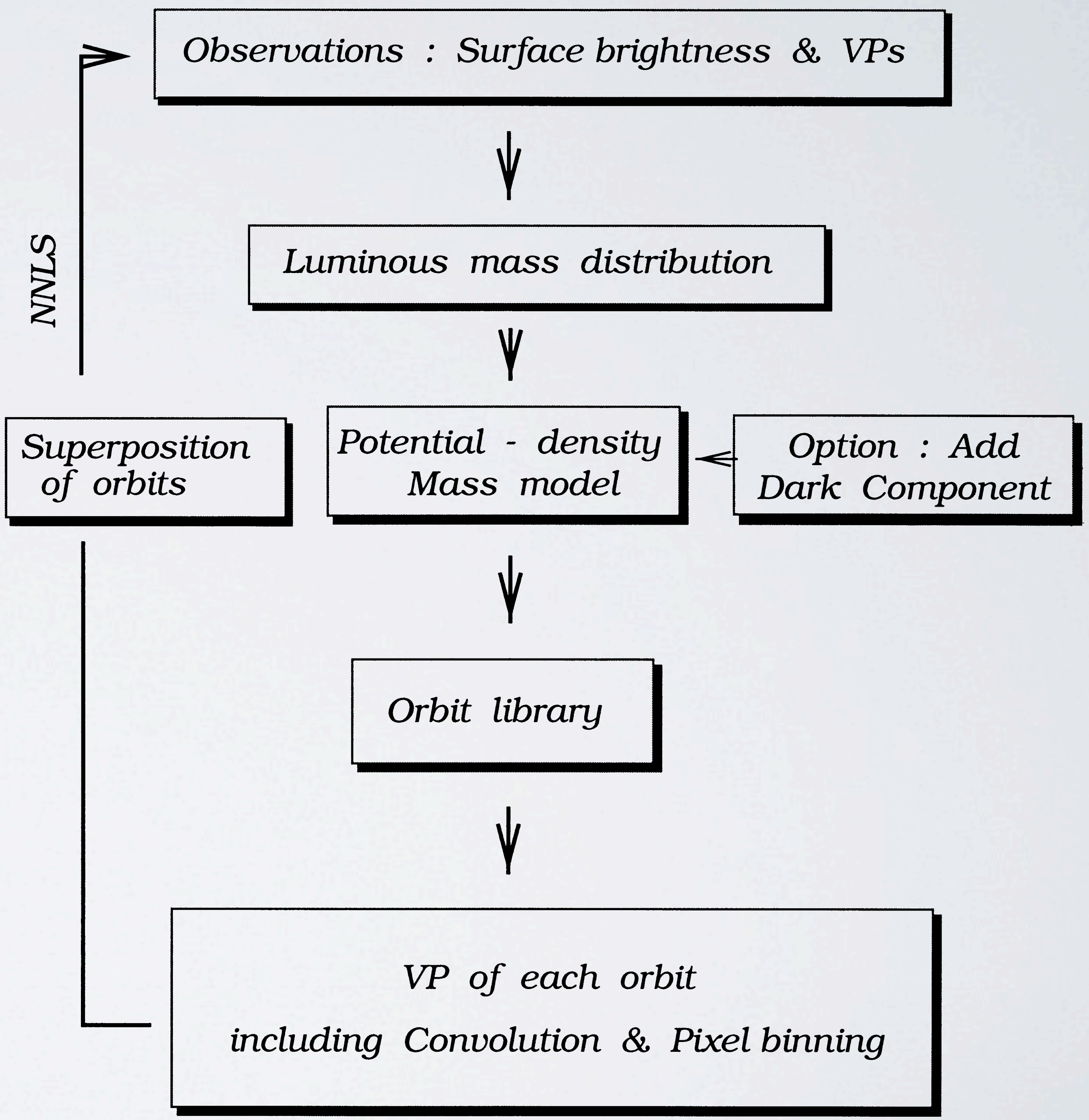
ORBIT-BASED MODELS

Loop over all possible mass distributions:

SMBH, viewing angles, stellar mass-to-light ratio and dark matter

Marginalize over all to get to the SMBH mass measurement

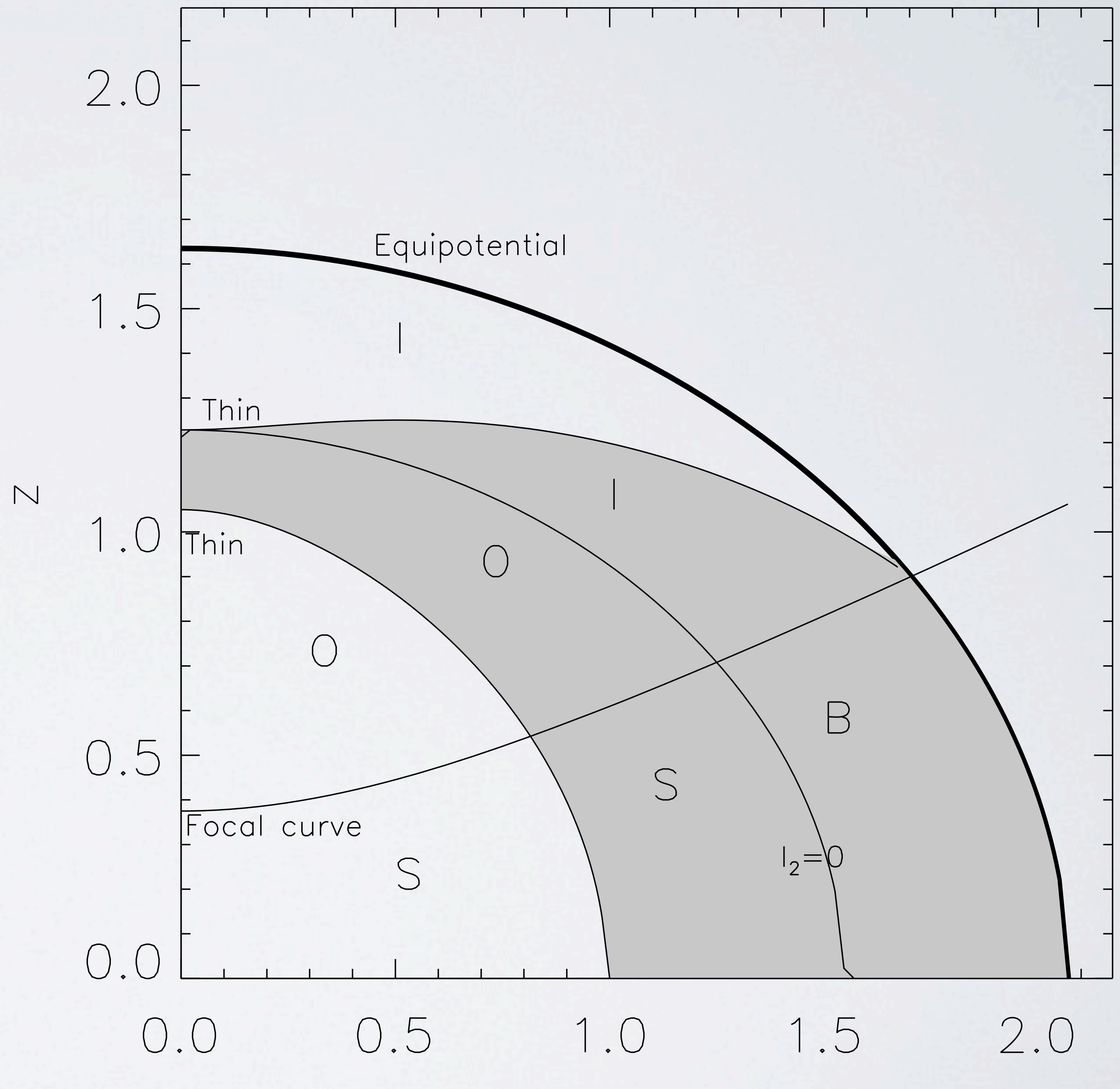
Computationally challenging, but not impossible



Cretton et al. 1998

THE SIZE OF AN ORBIT LIBRARY

- How do you know the orbit library is complete?
- Three conserved quantities: Integrals motions (Energy, Angular momentum and I3)
- In (non-rotating) potentials all orbits pass orthogonally through the x-z plane
- Sampling orbits is thus trivial



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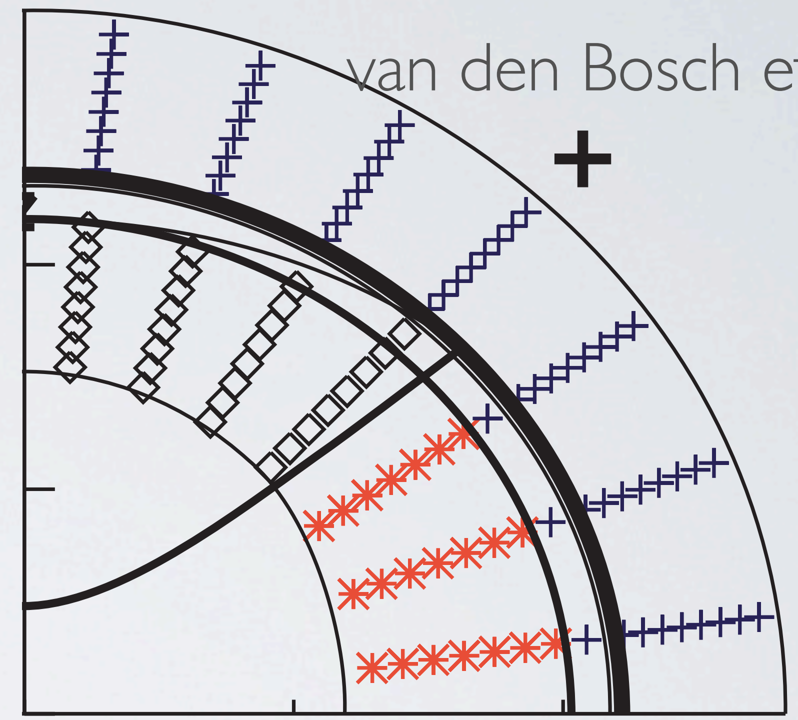
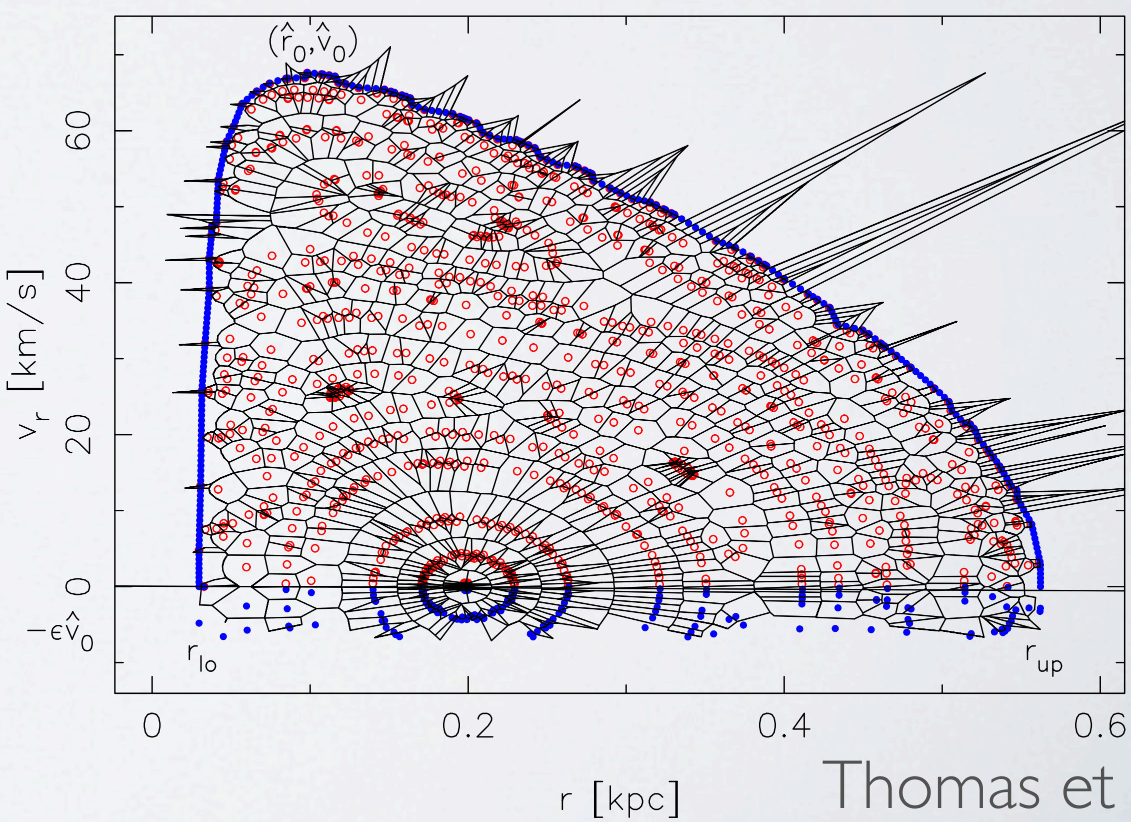
- In (non-rotating) potentials all orbits pass orthogonally through the x-z plane
- Sampling orbits is thus trivial
- Sampling schemes differ, but it is easy to show convergence is reached.



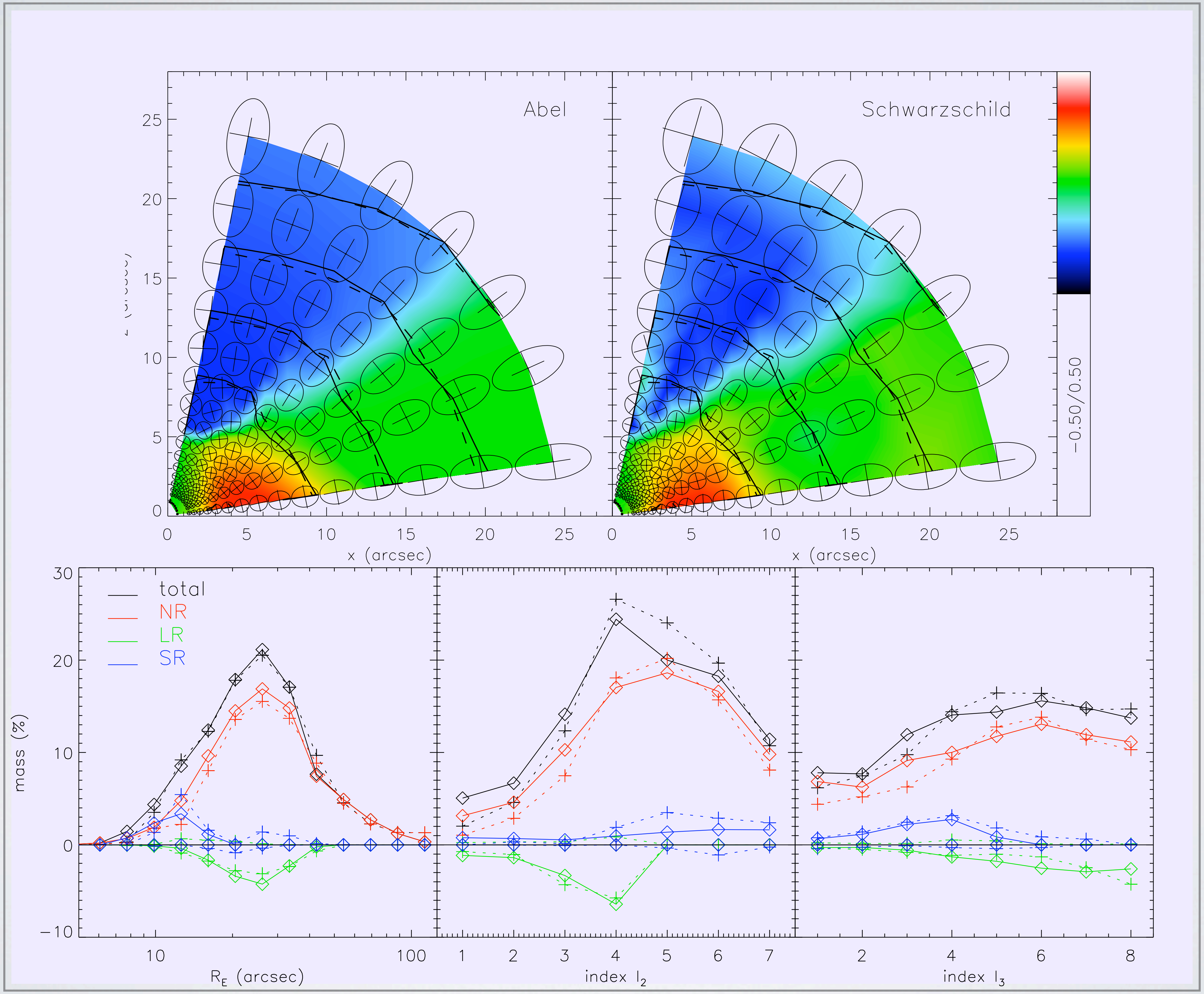
van den Bosch et al. 2008



Thomas et al 2004

van de Ven, de Zeeuw & van den Bosch, 2008

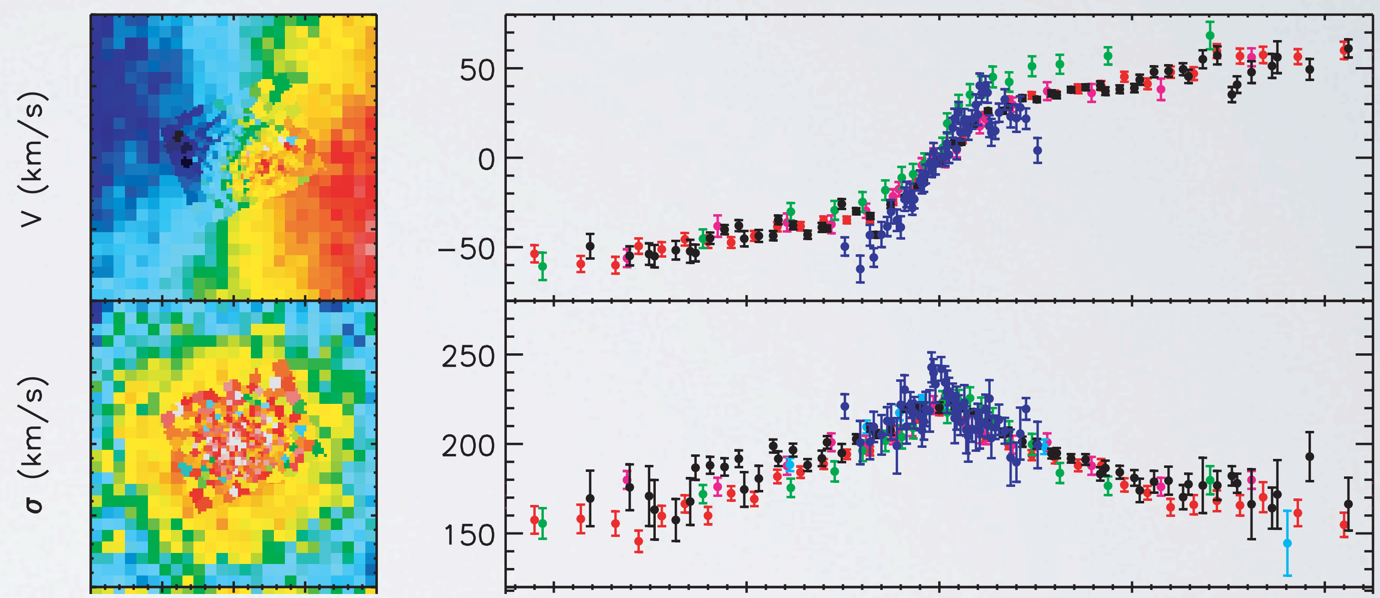
TESTING THE MODELS

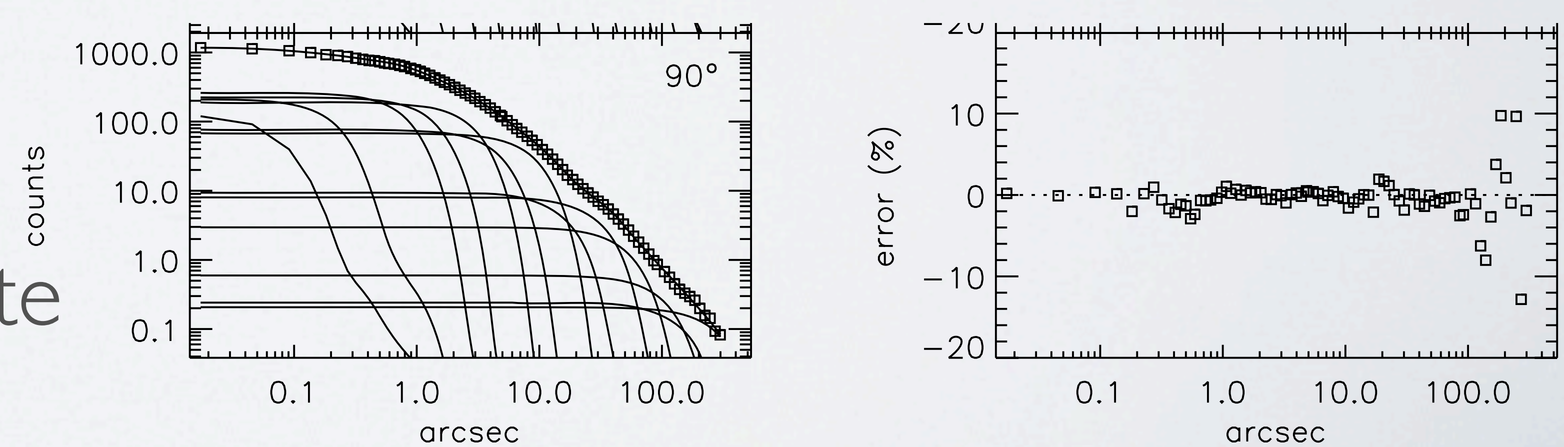


Shapiro et al. 2006

NGC3379

- Combination of 4 data sets
- OASIS kinematics near the BH
- SAURON kinematics for the stars
- HST WFPC2 imaging and MDM ground based
- Assumed no DM and oblate axisymmetric

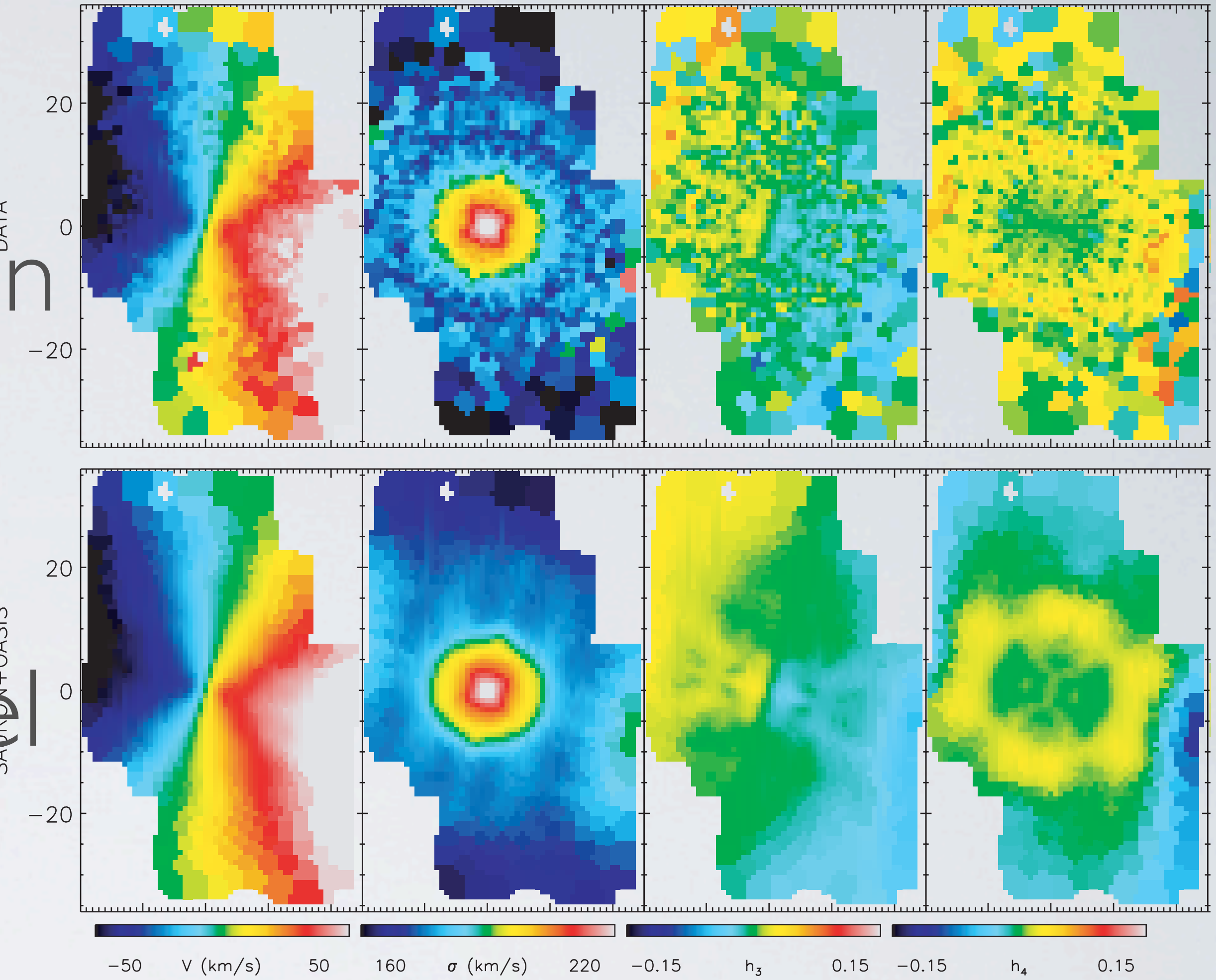


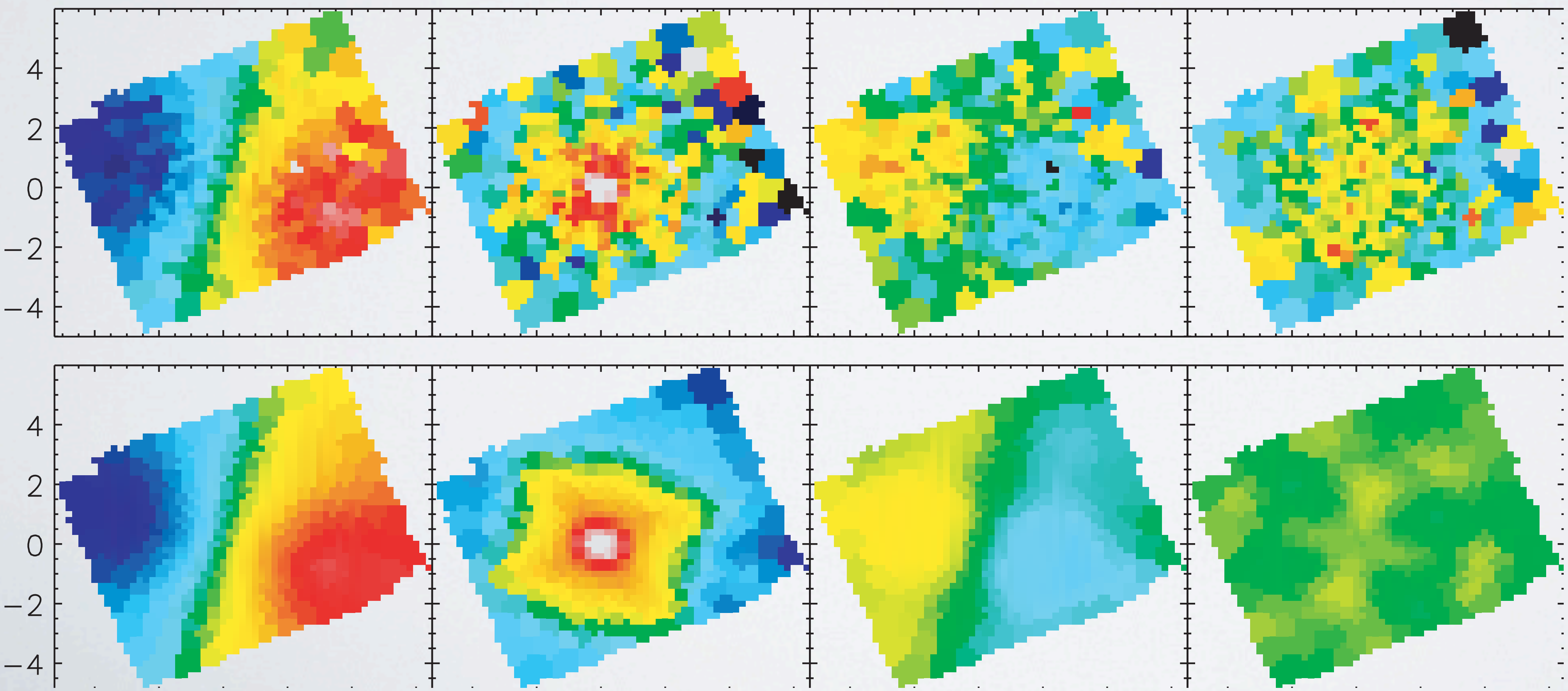


BEST-FIT MODEL REPRODUCES THE KINEMATICS

Sauron

Model





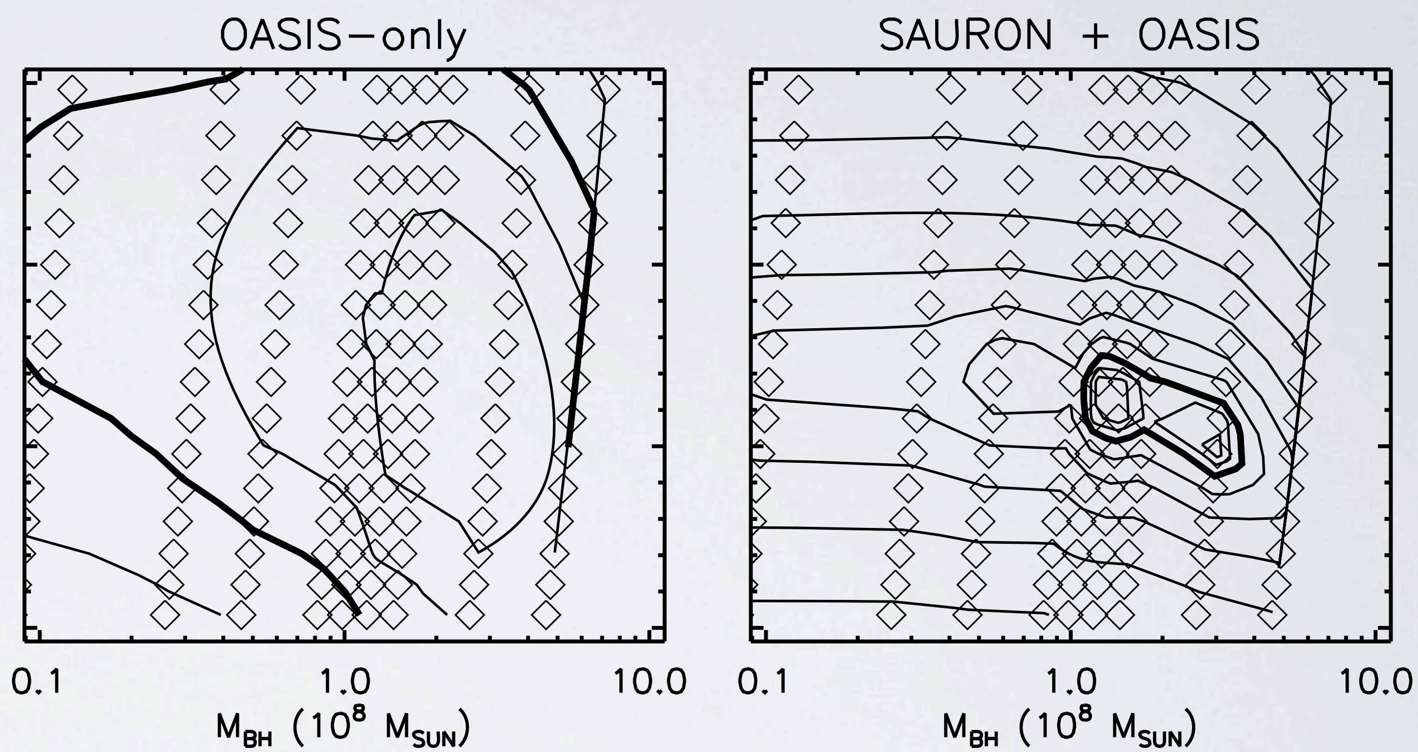
Oasis

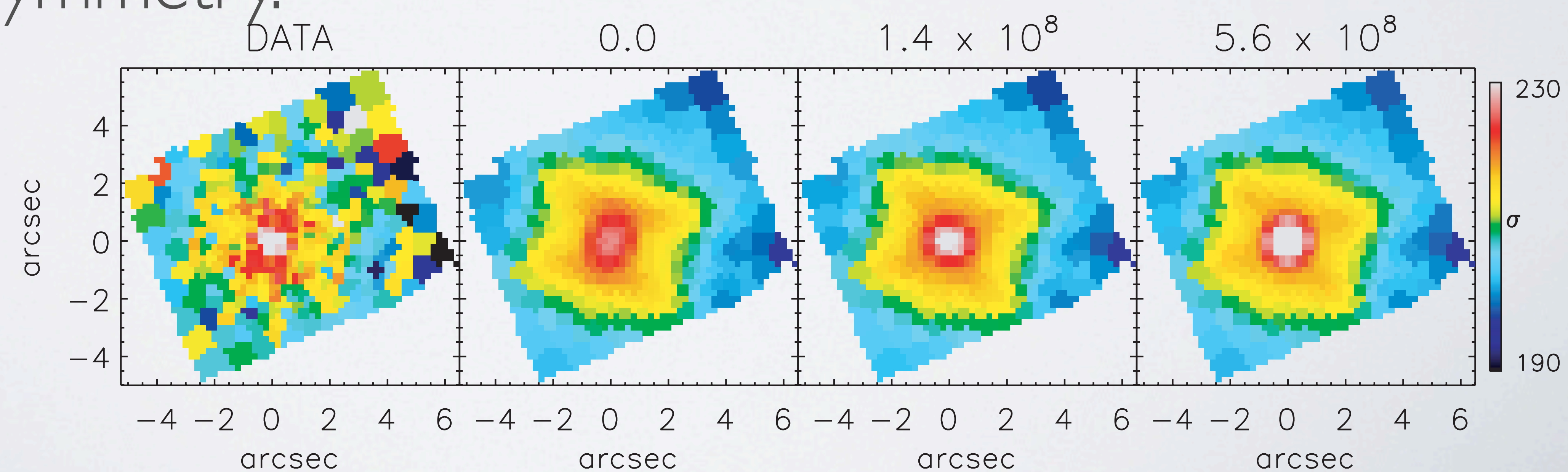
Model

Shapiro et al. 2006

NGC3379

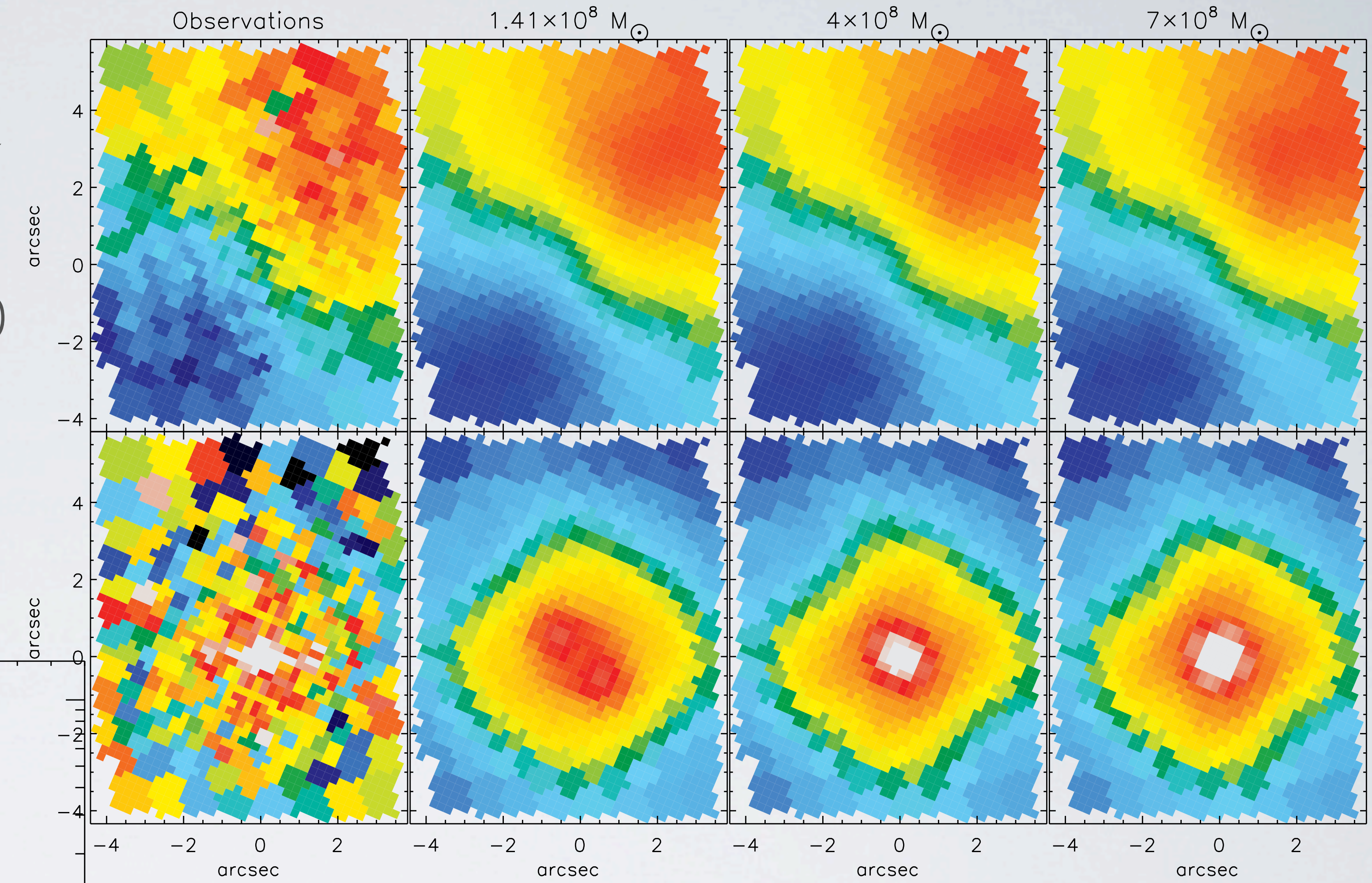
- Black hole mass is 1.4e8
- Large scale kinematics needed to break degeneracy.
- Assumed axisymmetry.

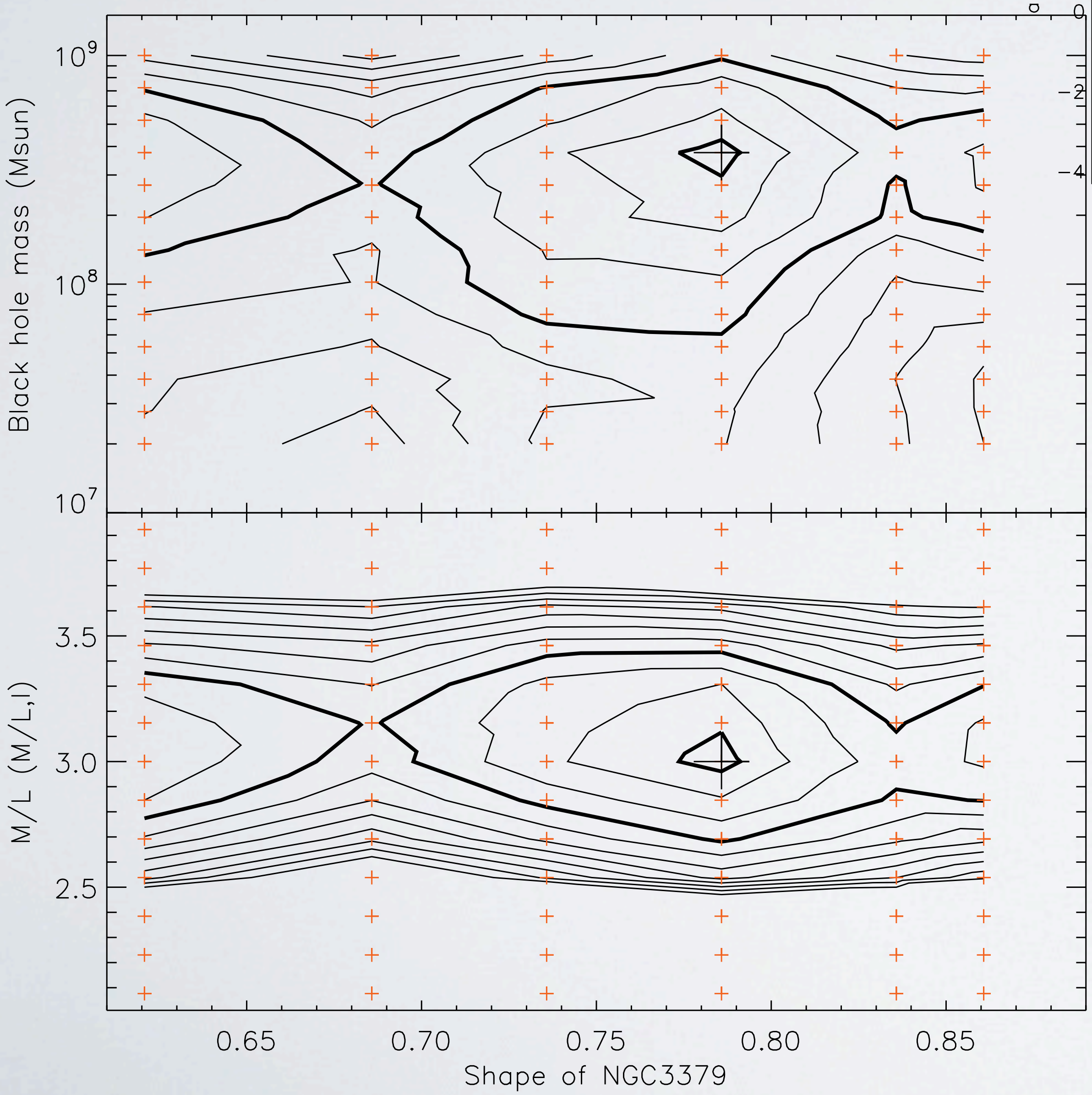




TRIAXALITY

van den Bosch et al. 2010





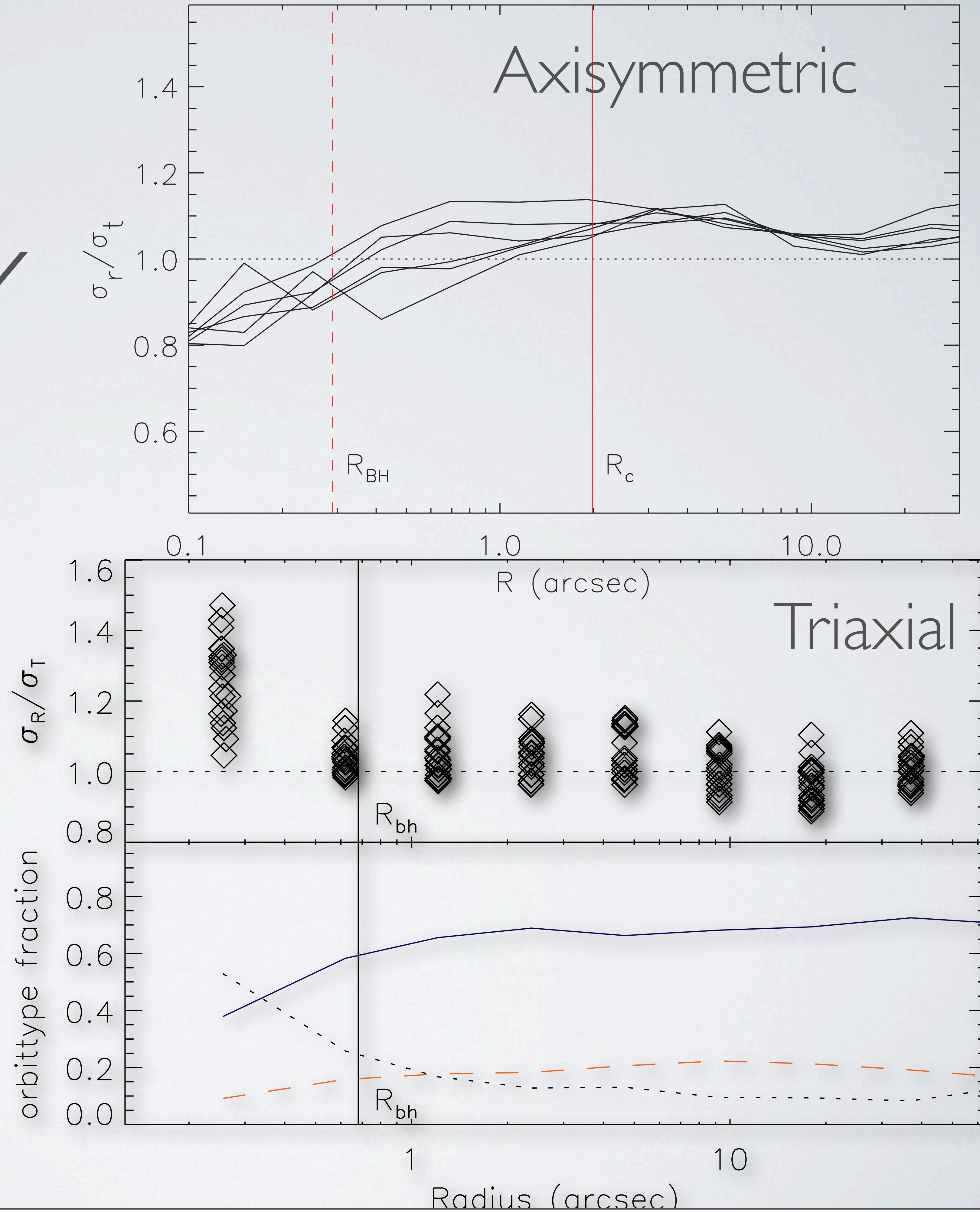
- We first tested the axisymmetric case and found the same Mbh and M/L.
- Then we tried triaxial geometries and found a black hole mass that is 3 times bigger, mostly due to a more face-on viewing angle

NGC3379 PREVIOUS ESTIMATES

- 2.5-4.5 e8 Long-slit 2I Magorrian et al (1998)
- 1-2 e8 FOS stars 3I Gebhardt et al 2000
- 1-3 e8 OASIS axisymmetric Shapiro et al 2006
- 3-5 e8 OASIS triaxial van den Bosch & de Zeeuw 2010
- Changes mostly due to improved (aux.) data.

NGC3379 ANISTROPY

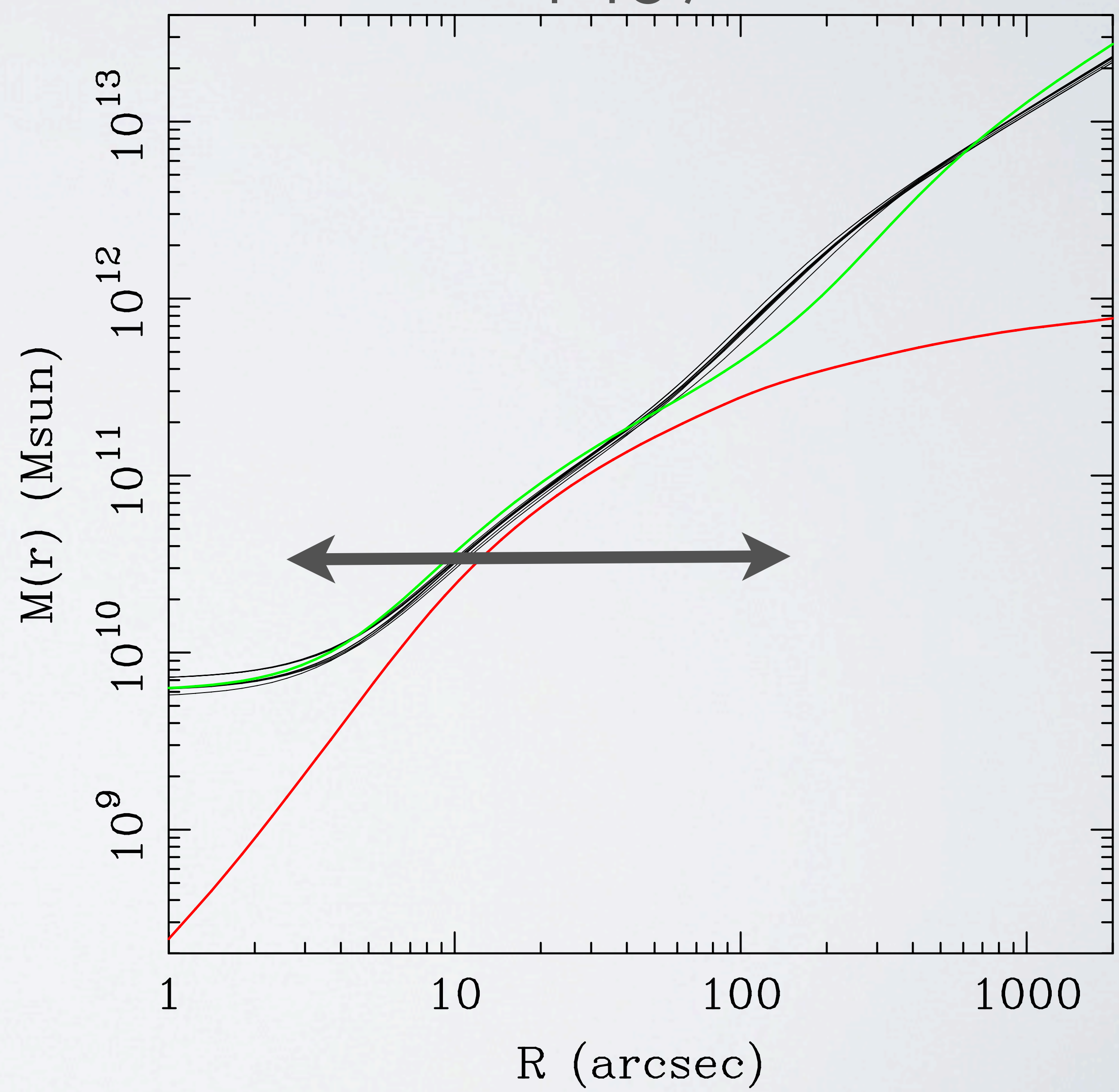
- Orbit distribution is very different, due to box orbits in the center



THE ROLE OF DARK MATTER

- Models measure the enclosed mass, but only where the is information from kinematic data.
- The stellar M/L is over estimated of the DM is not included, which can lower the black hole mass
- Schulze & Gebhardt 2010 showed that the DM only matter when the SOI is not well resolved.

M87



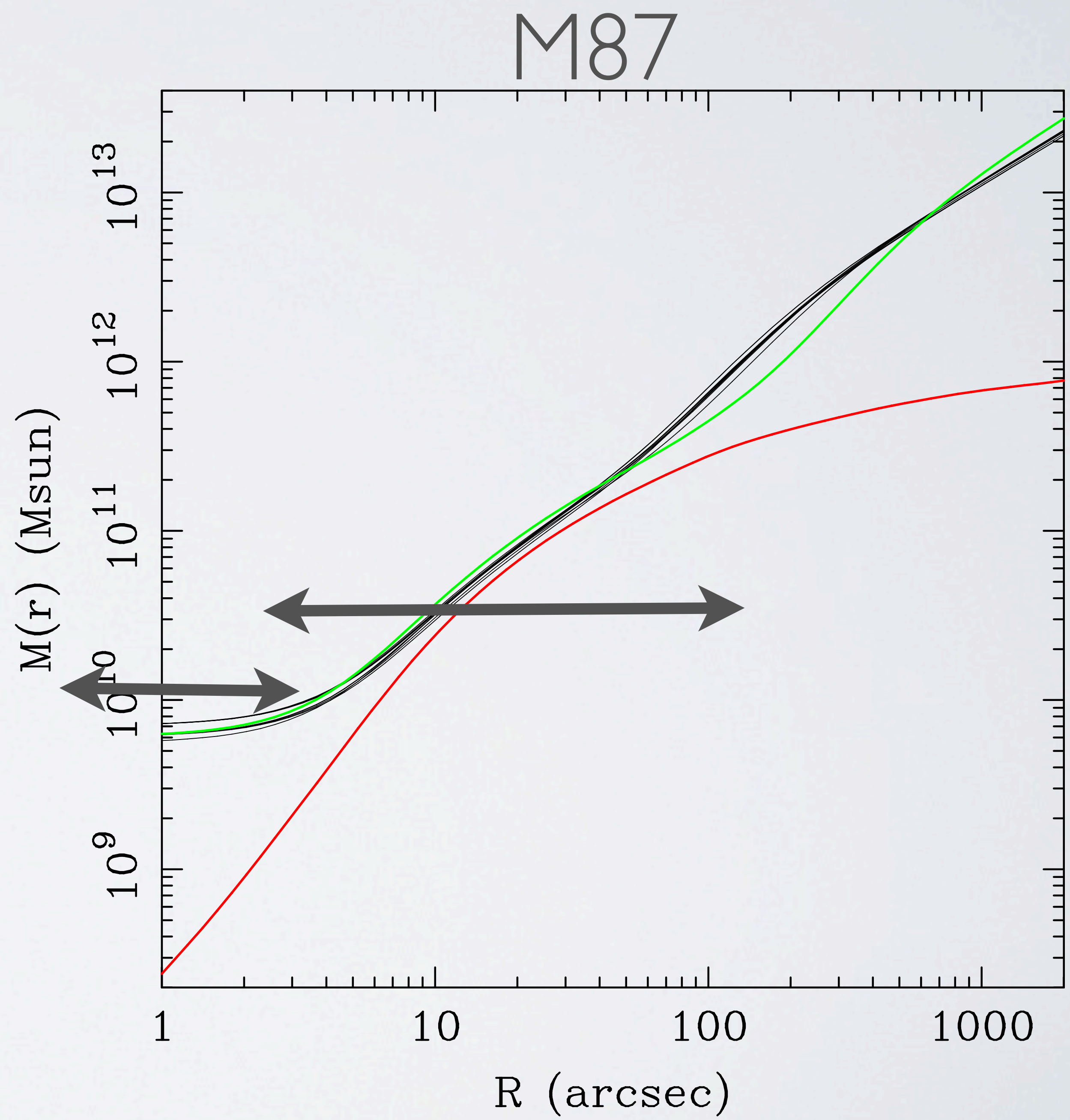
Gebhardt & Thomas 2007

Monday, August 22, 11

DYNAMICAL MODEL MEASURE ENCLOSED MASS

- Models measure the enclosed mass, but only where the is information from kinematic data.

- M87 black hole mass changed: Gebhardt & Thomas 2007 and Gebhardt et al. 2010 due to inclusion of central AO data.



Gebhardt & Thomas 2007

MEASUREMENT TECHNIQUES

Milky Way	Individual Keplerian Orbits	1
MegaMaser	VLBI of H2O Maser Discs	8
Gas Disc	Spectroscopy + warped thin disc	15
Stars	Spectroscopy + dynamical Model	40
AGN	Reverberation mapping/single Epoch	40+

- Different methods work on different galaxies
- Only a couple of cross calibrations exist
- And within the stellar dyn. the assumptions and uncertainties are measured in different ways by different groups (e.g. LOSVDs vs. GH)

WHY ARE THERE FEW BLACK HOLE MASS MEASUREMENTS?

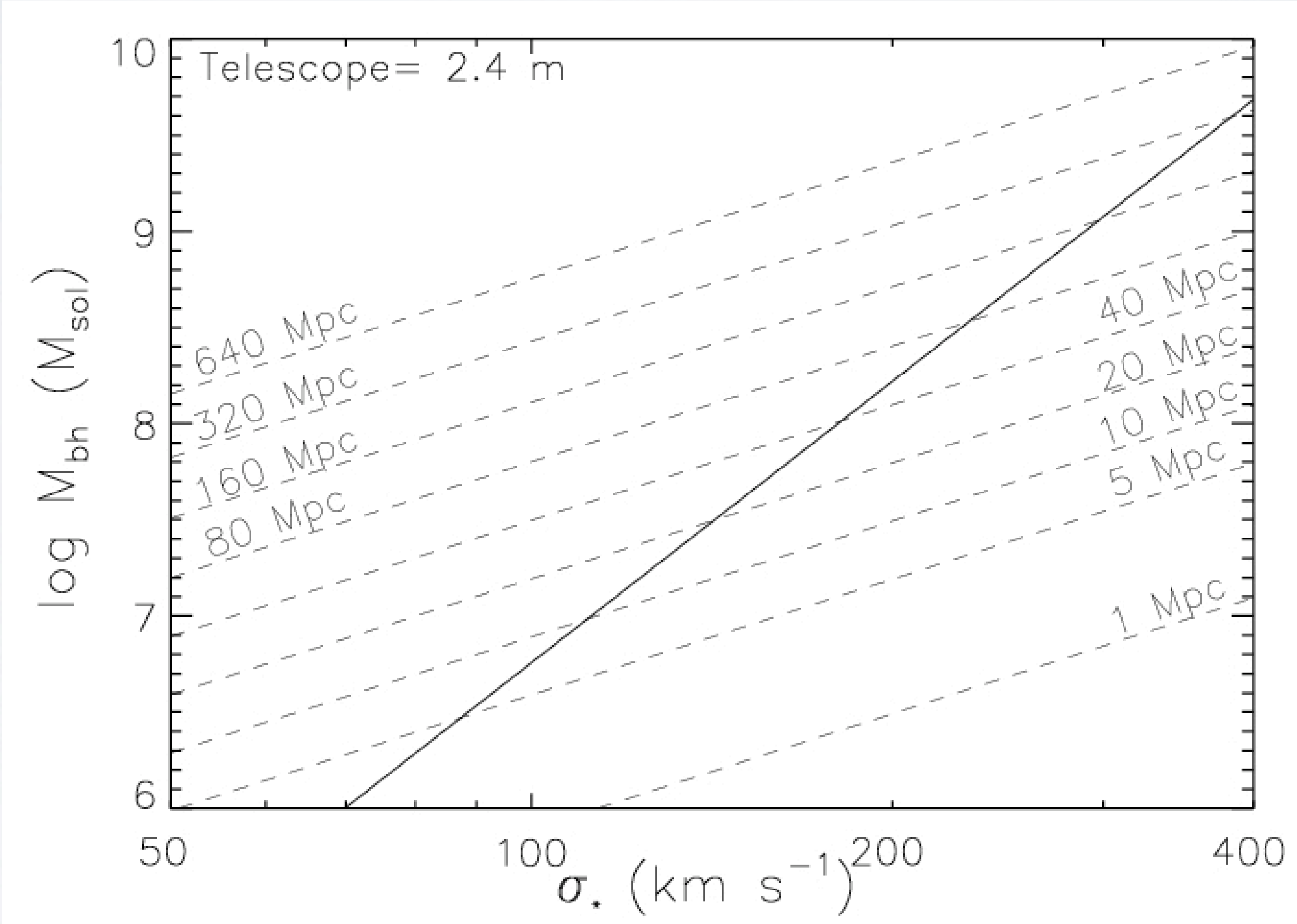
- **MANY REQUIREMENTS FOR DYNAMICAL ESTIMATES:**

- Resolve the Sphere-of-influence

$$R_{soi} = \frac{GM_\bullet}{D\sigma^2} \propto \frac{\sigma^{2.2}}{D}$$

Thus HST/STIS or AO. And few available targets

- Plus large scale kinematics and high resolution photometry and large scale photometry for stellar mass model



Batcheldor

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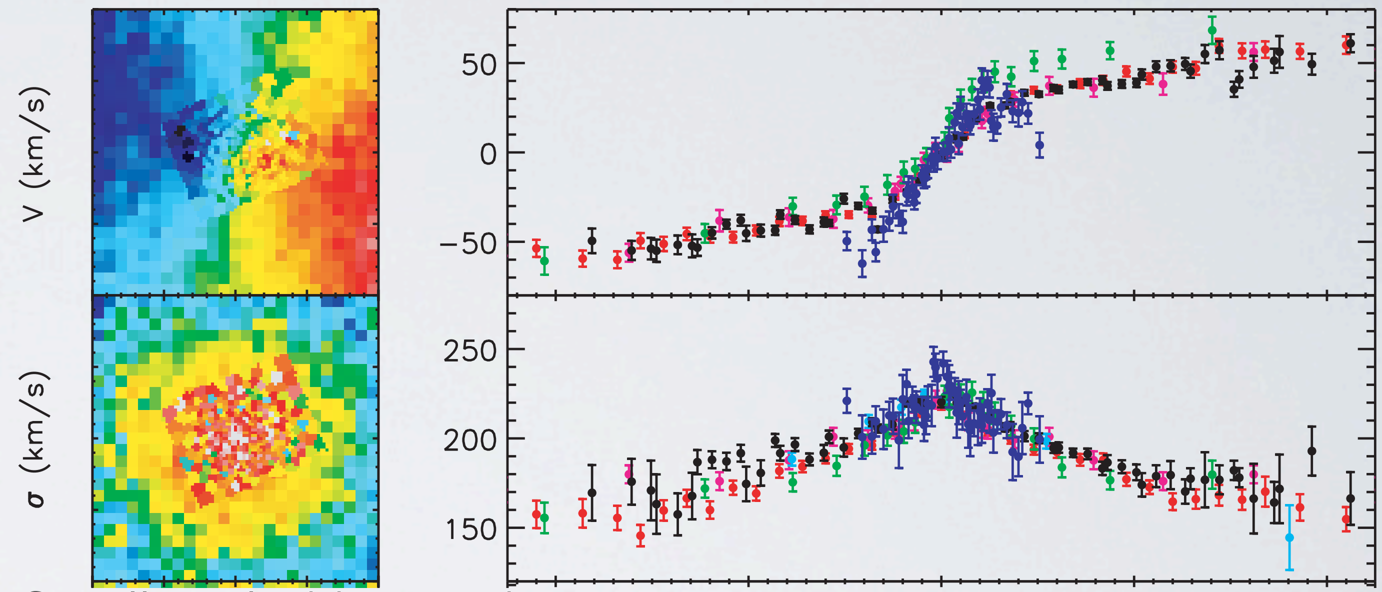
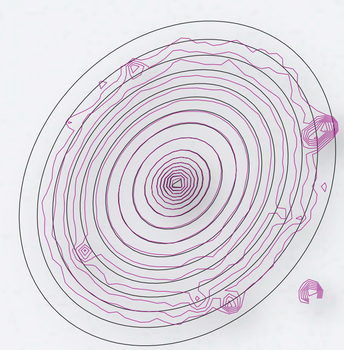
Large scale

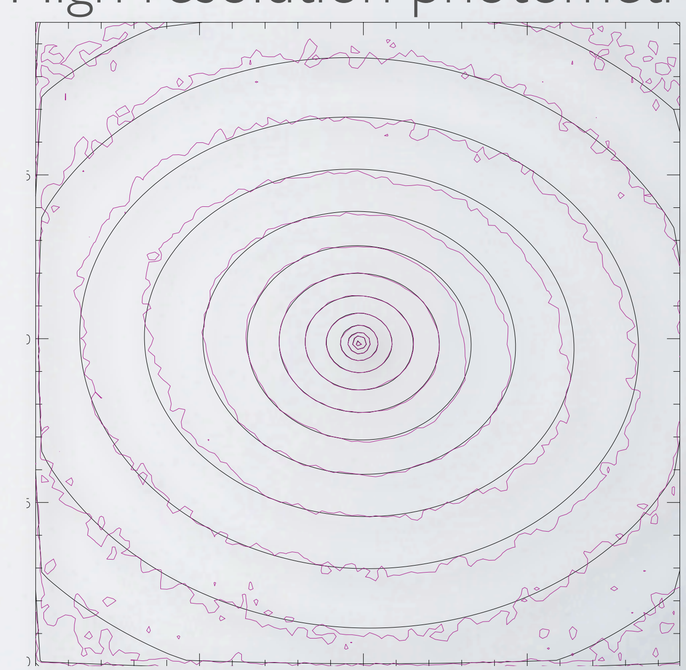


Small scale kinematics

Large scale photometry



High resolution photometry



HET OBSERVATIONS

- Long slit spectra with the Marcario Low Resolution Spectrograph
- 4200-7400 AA, 180km/s resolution, 2''x2.5' slit
- 367 galaxies observed
- Distances are 40~140 Mpc
- Effectively probing the most massive nearby galaxies
- ~100 more queued

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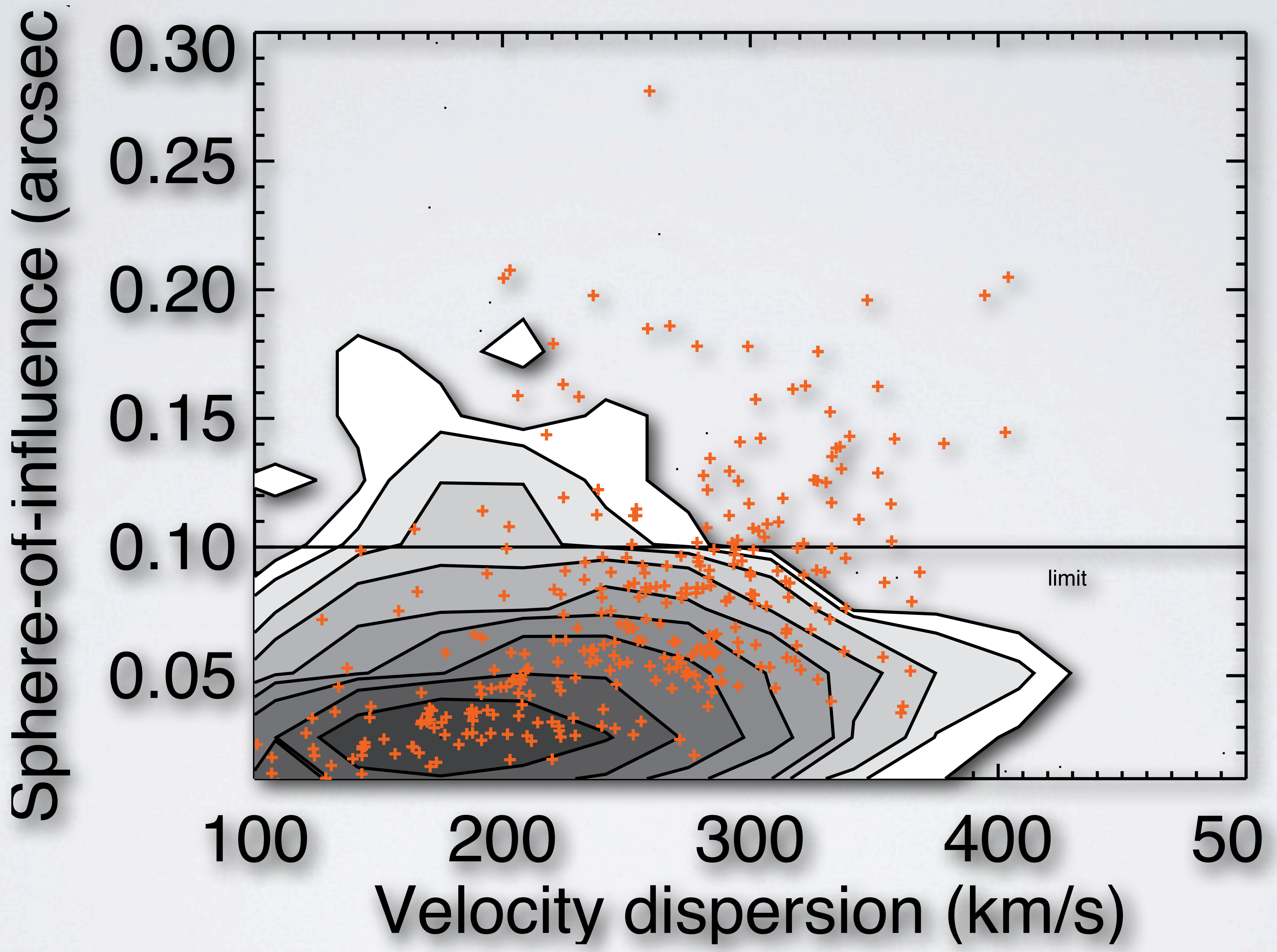
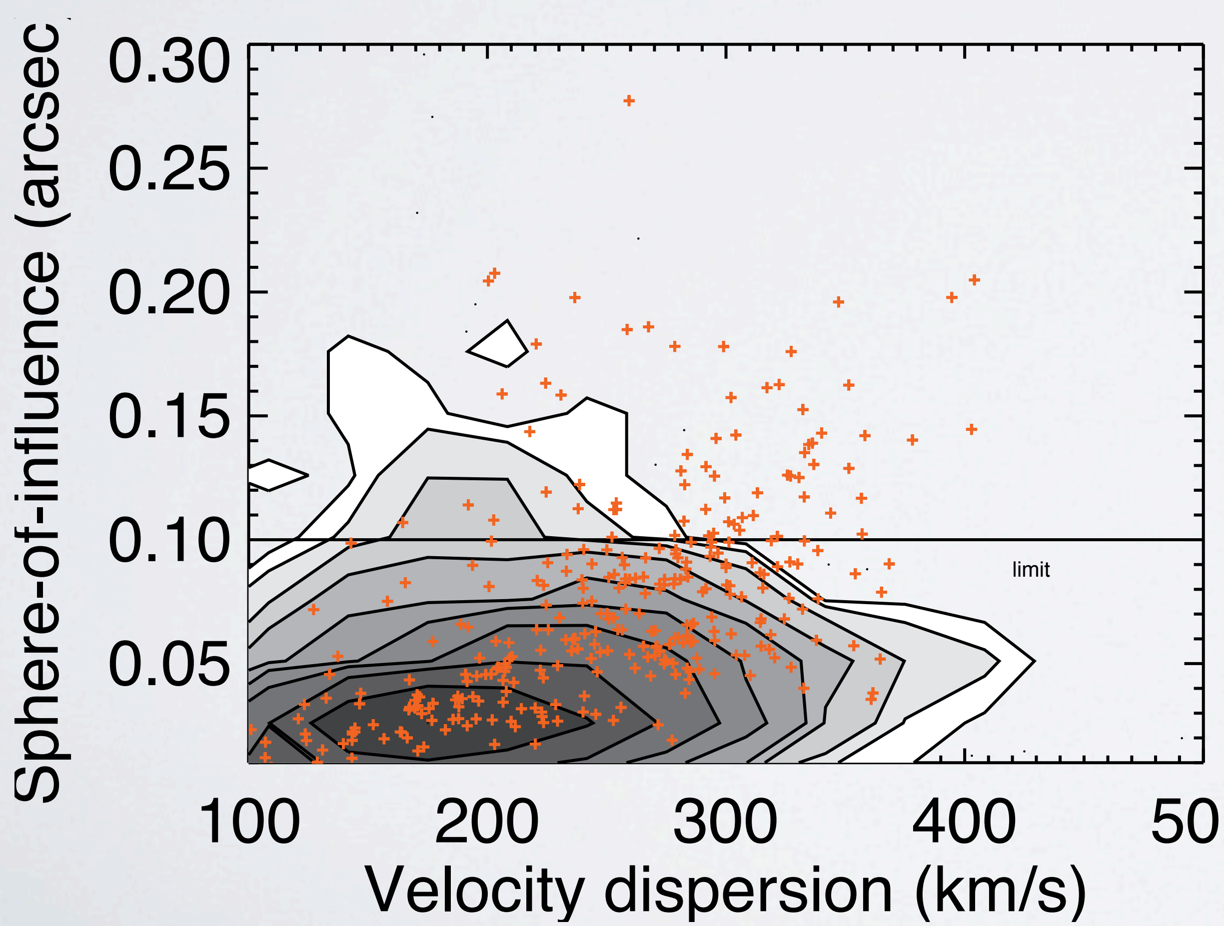
GATEWAY TO MORE BLACK HOLE MASSES

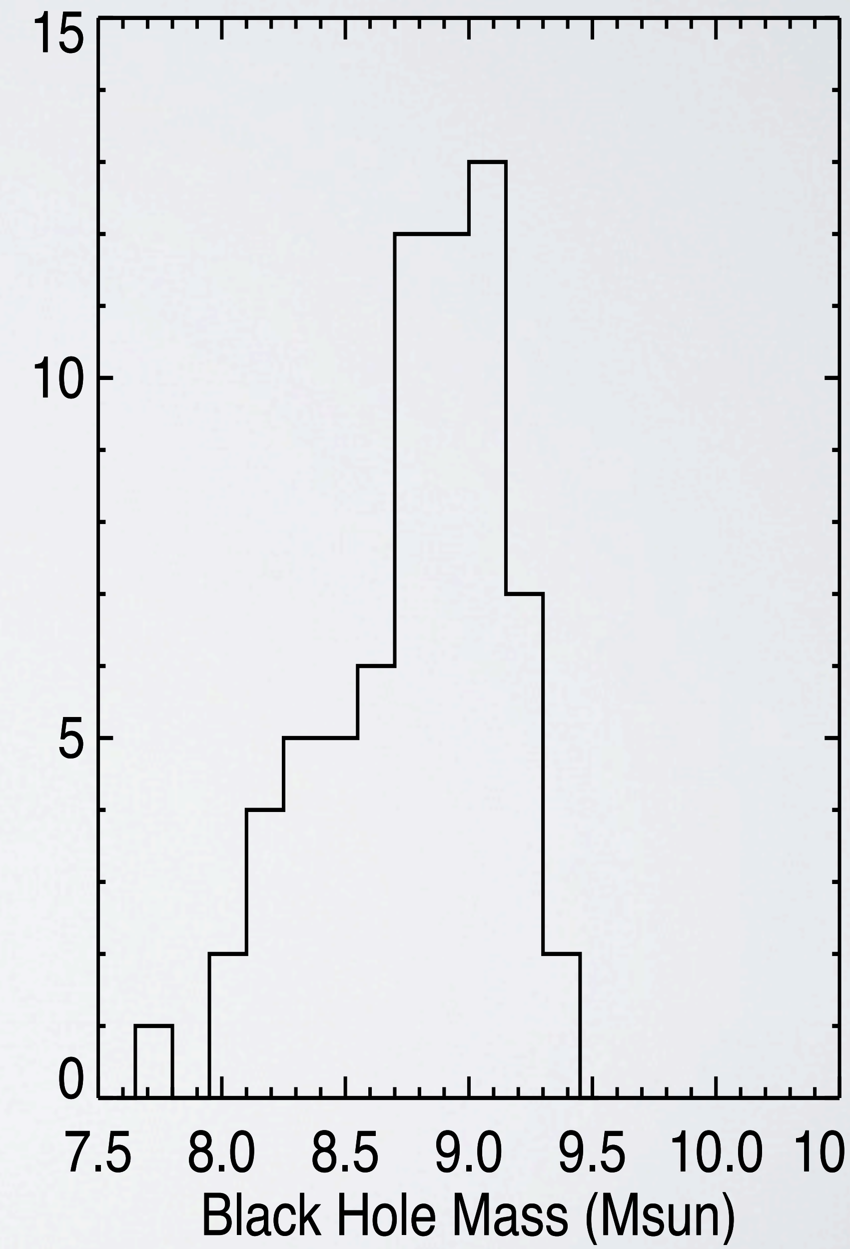


- Survey has probed nearly all likely candidates.

GATEWAY TO MORE BLACK HOLE MASSES

- Survey has probed nearly all likely candidates.
- 69 new targets of which 22 with black holes bigger than 10^9 Msun





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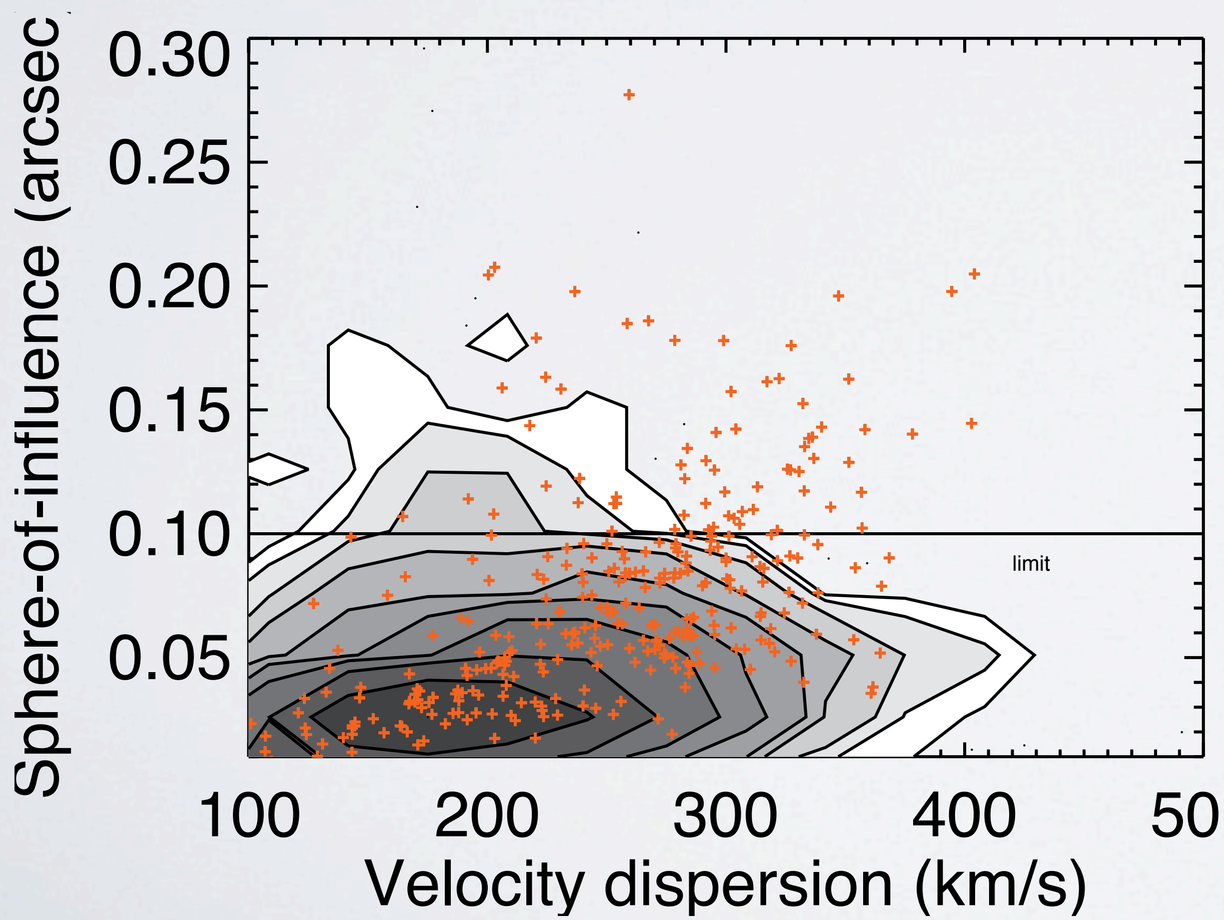
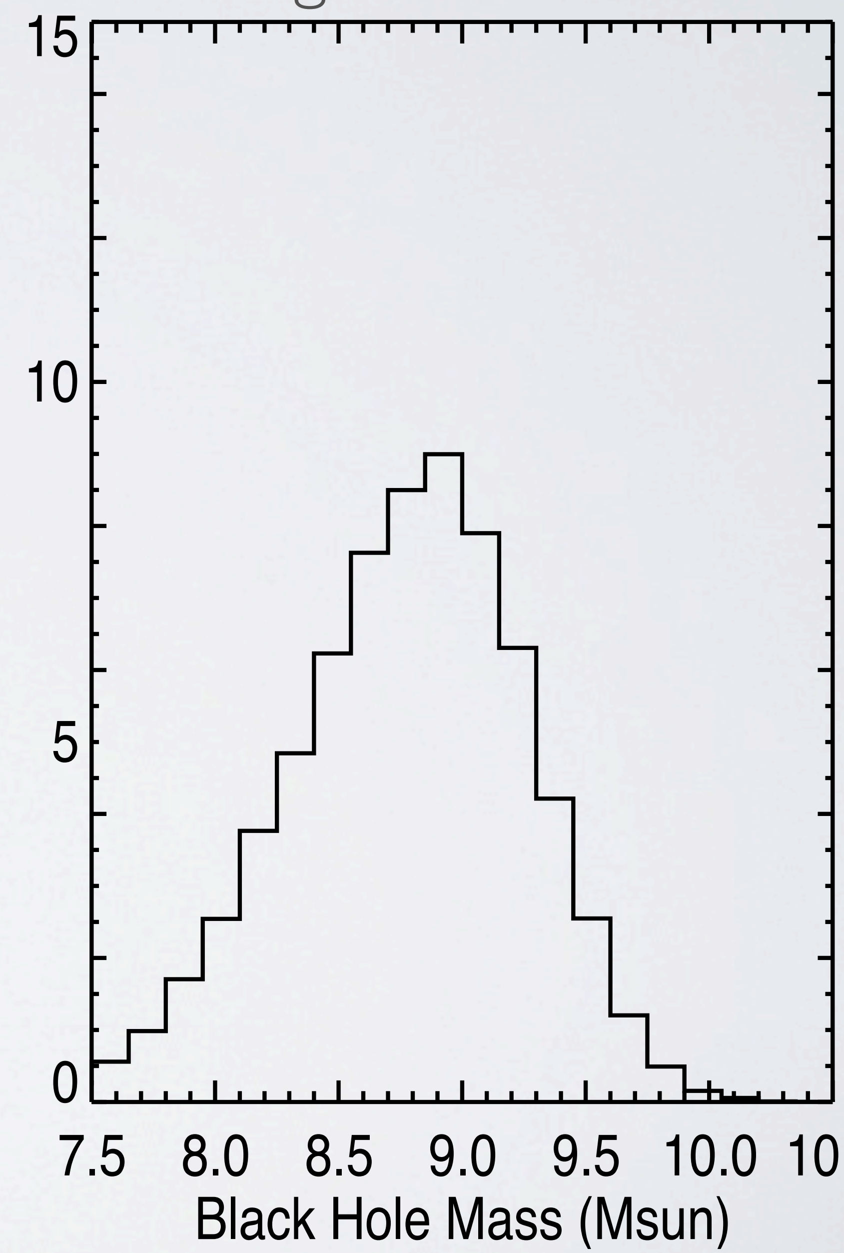


Including intrinsic scatter

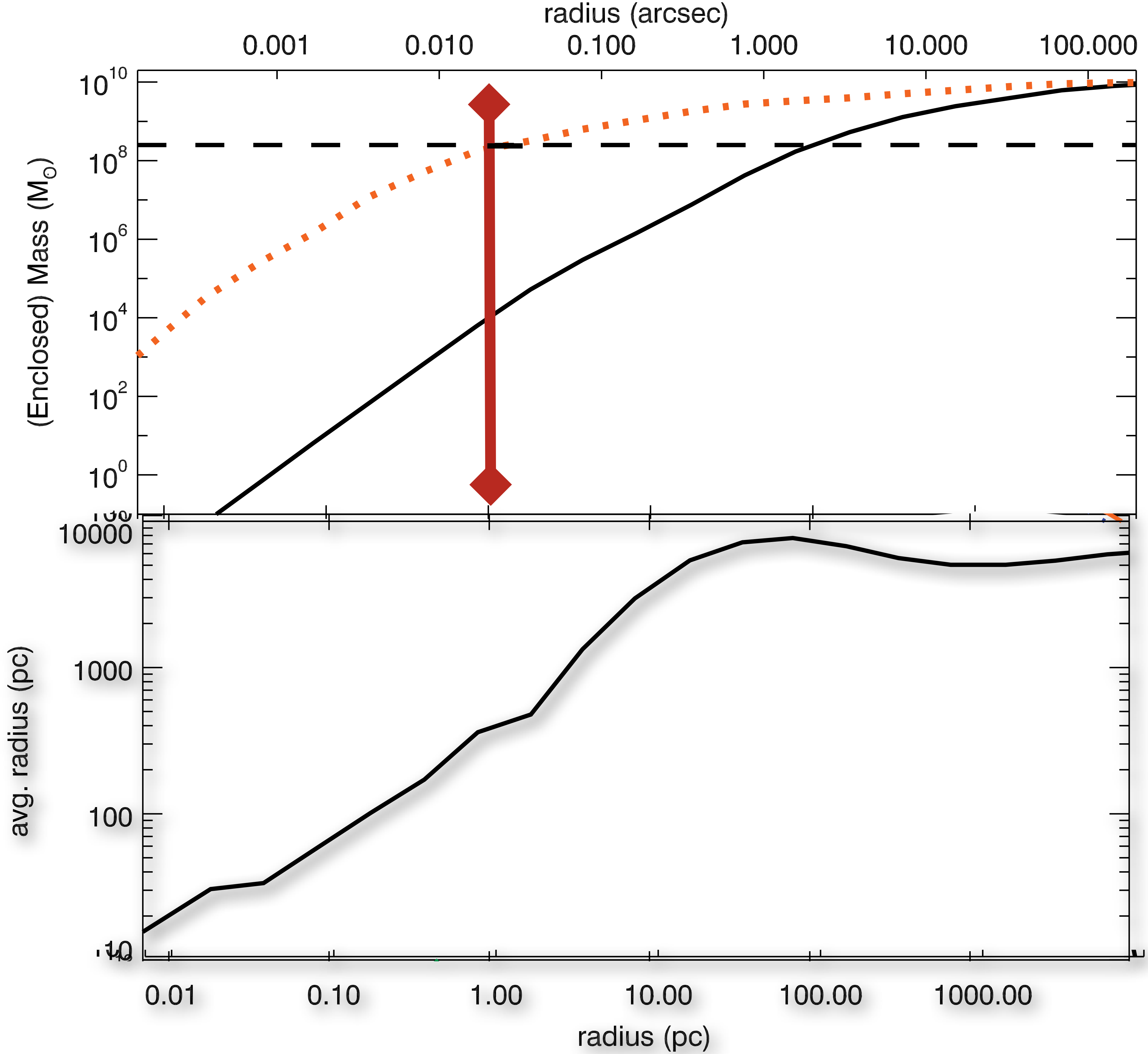


CONCLUSIONS & QUESTIONS

- Dynamical models are a good way to measure masses of black hole, but also measure other properties of a galaxy, like M/L
- But they require combining several datasets per galaxy
- SMBH masses have changed, but this is mostly due to improvement of data.
- long slit kinematics of nearly all good candidates now exists

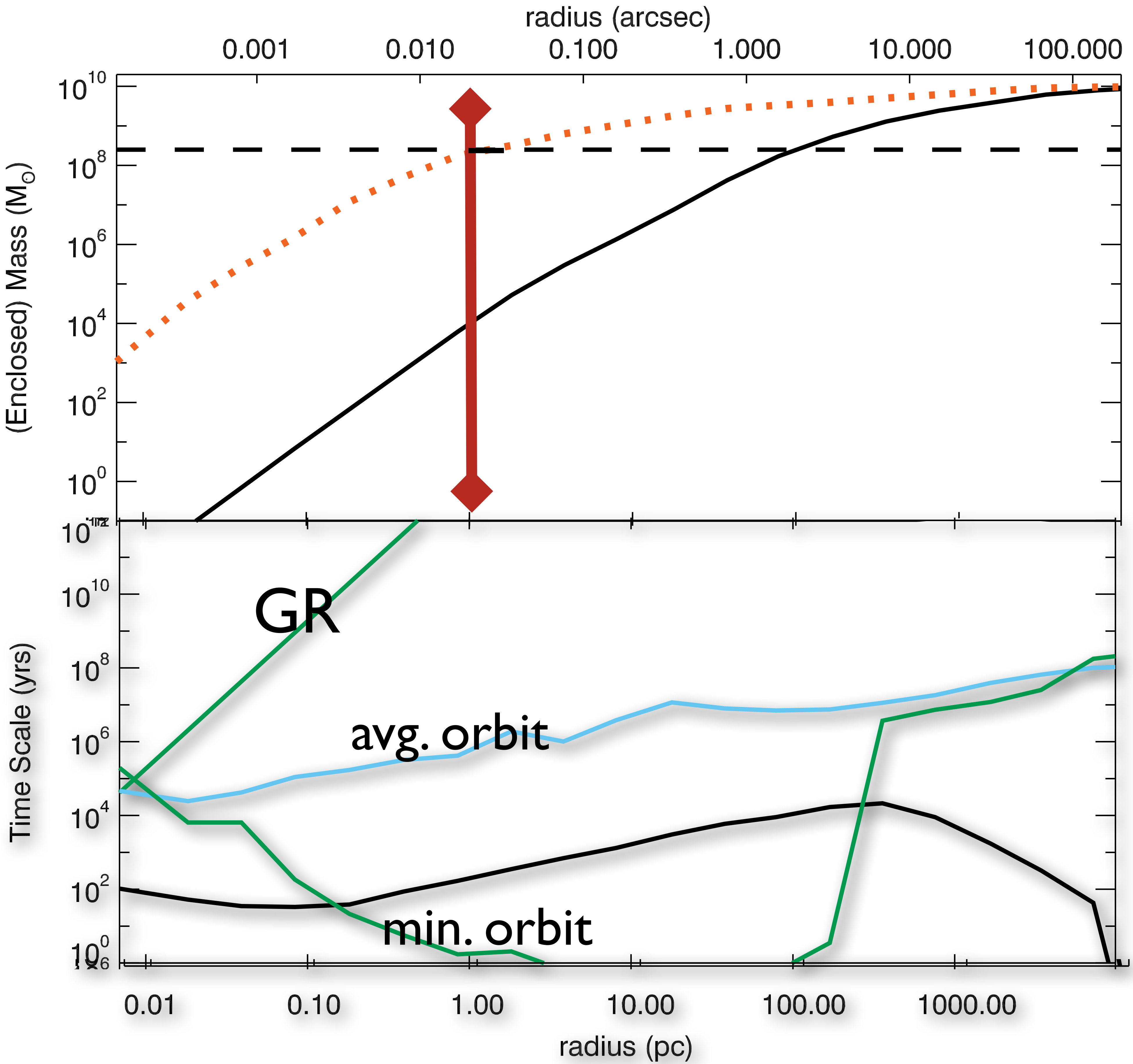
- Going forward with the dynamical SMBH mass measurements is it more important to a) do galaxies with extreme properties b) add more consistency c) do comparisons with other methods
- What is the physical interpretation of empirical quantities in the scaling relations (sigma_e)
- Do black holes with a mass of more than 10^10 Msun exist? And if yes, in what nearby galaxy might we expect to find one?

NGC 3379



radius (arcsec)
0.001
0.010
0.100
1.000
10.000
100.000
(Enclosed) Mass ($M_\odot$)
10^{10}
10^8
10^6
10^4
10^2
10^0
avg. radius (pc)
10000
1000
100
10
0.01
0.10
1.00
10.00
100.00
1000.00
radius (pc)

NGC 3379


radius (arcsec)
0.001
0.010
0.100
1.000
10.000
100.000
(Enclosed) Mass ($M_\odot$)
10^{10}
10^8
10^6
10^4
10^2
10^0
Time Scale (yrs)
10^{10}
10^8
10^6
10^4
10^2
10^0
GR
avg. orbit
min. orbit
0.01
0.10
1.00
10.00
100.00
1000.00
radius (pc)