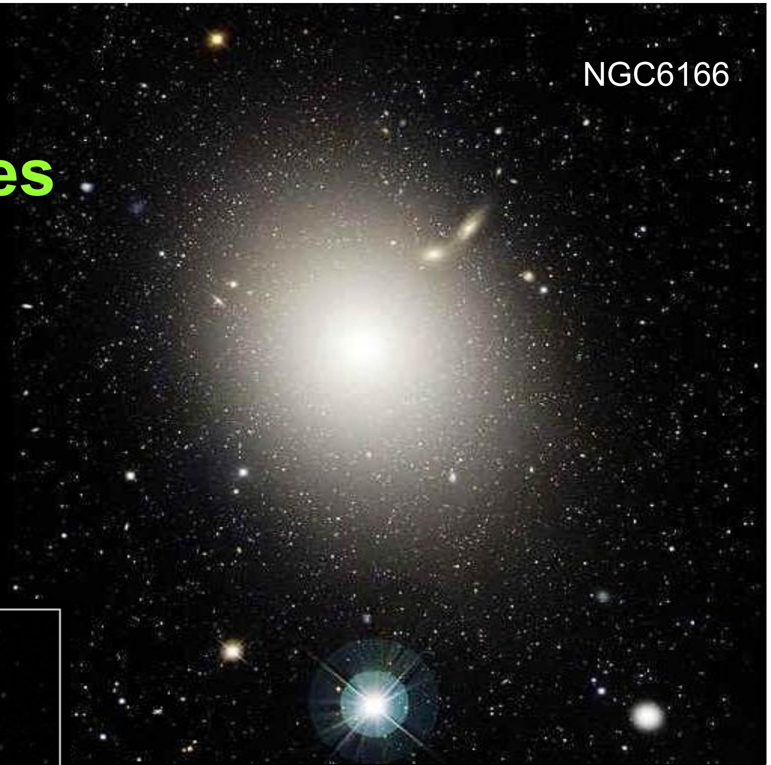
Accuracy in Black Hole Mass Measures

Karl Gebhardt (University of Texas)



Old School Results:

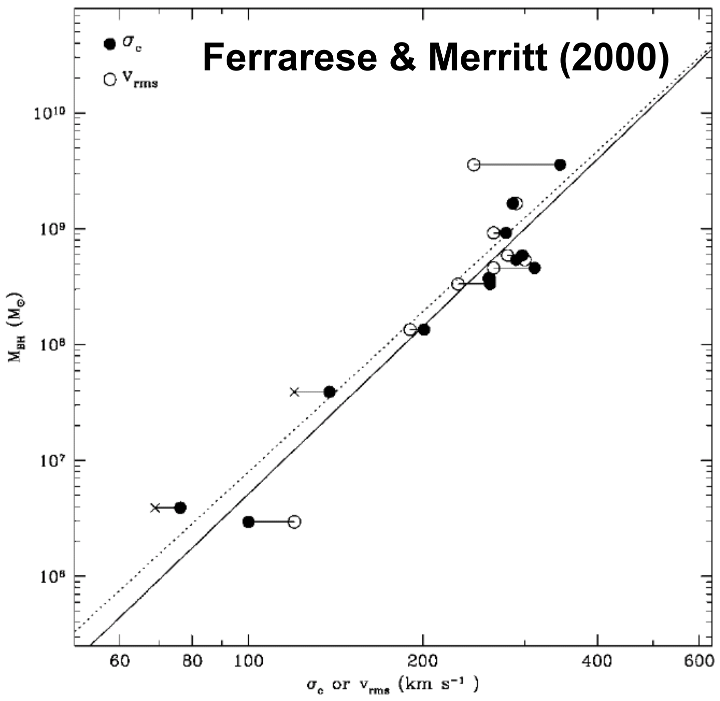
The original papers on the BH correlations suggest that the intrinsic scatter is consistent with zero.

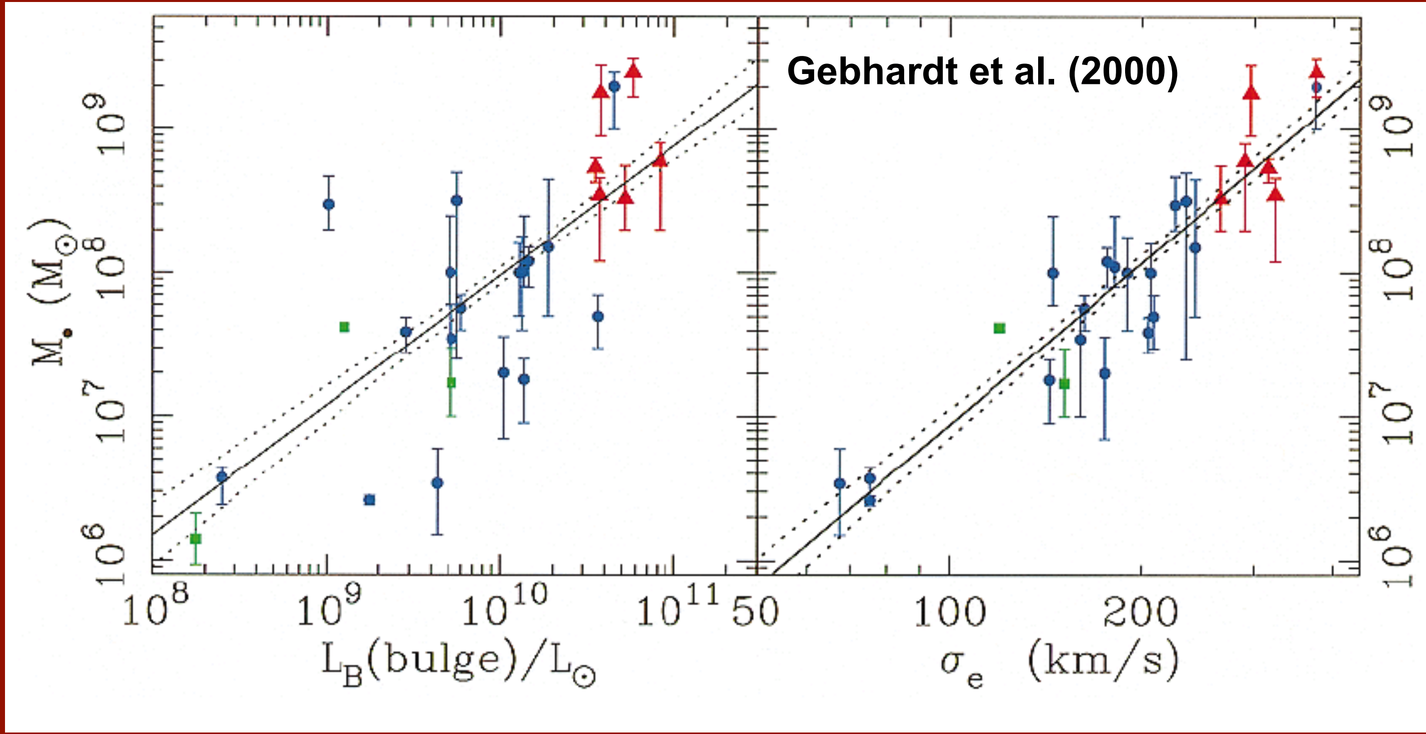
→ **There are many reported BH correlations**

→ **Suffer from inhomogeneous measures**

→ **Concern at the upper end**

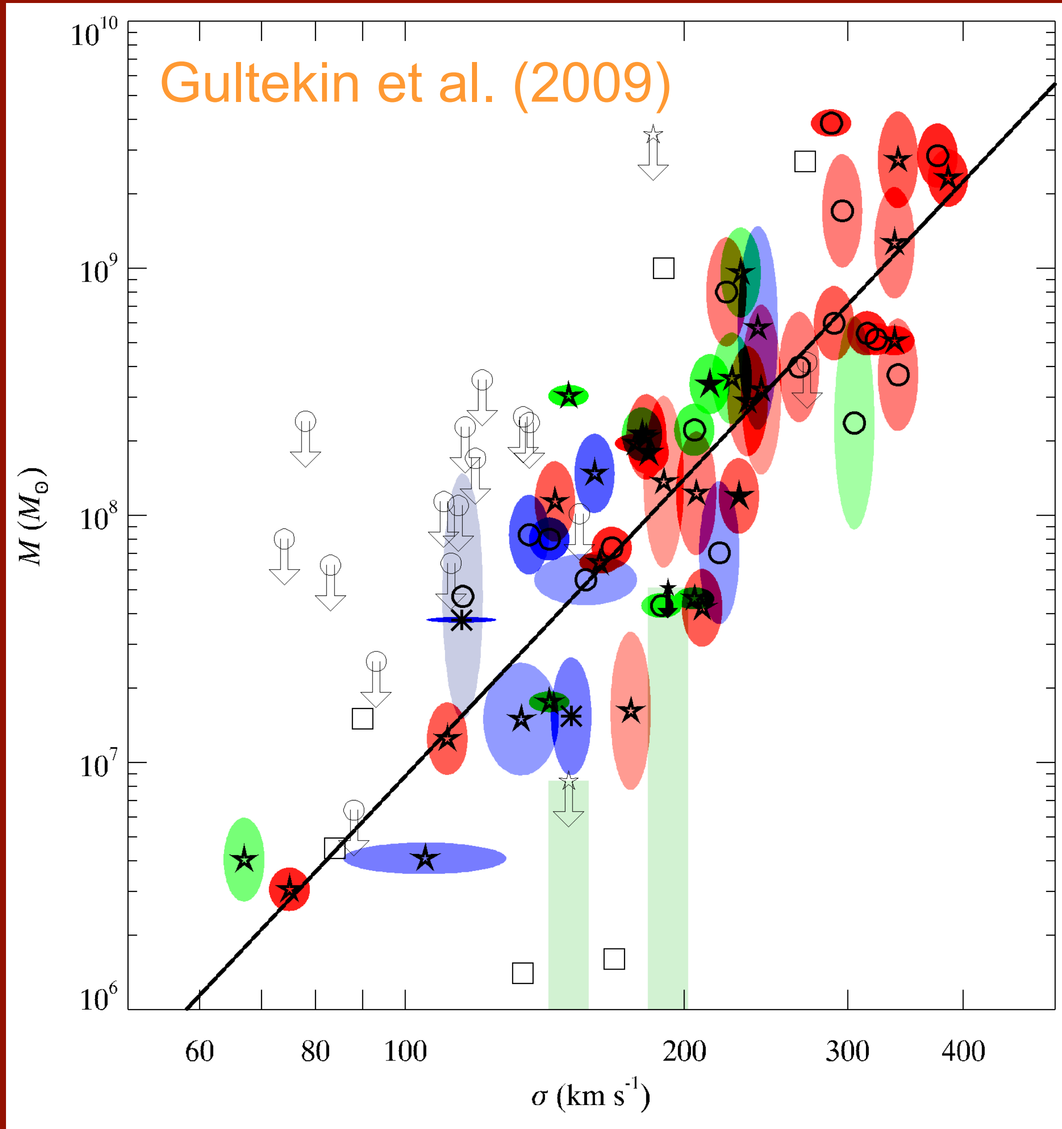
→ **How low do the correlations extend**





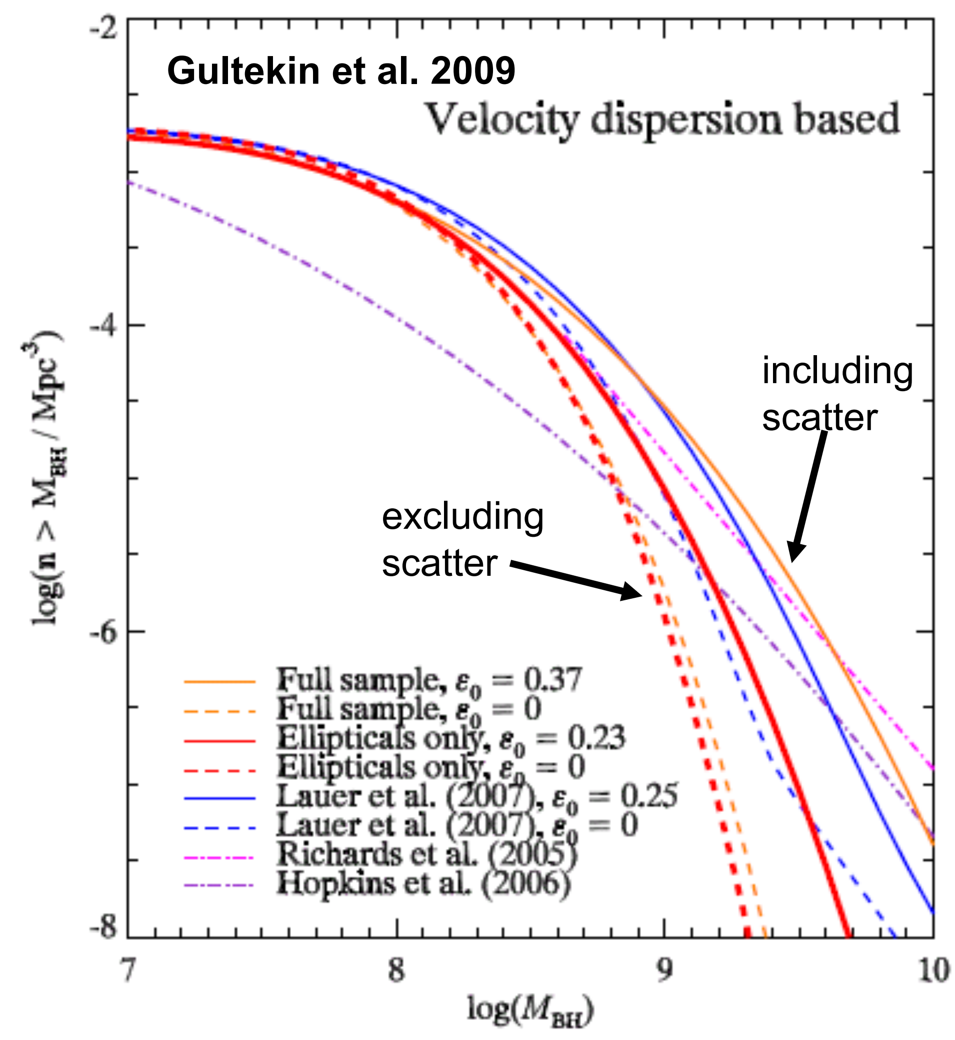
New School Results:

- Power law slope of 4 (+-0.3)
- Intrinsic scatter of 0.39 dex
- Scatter for ellipticals is 0.25
- Distribution is Gaussian in logM
- Evolution of BH correlations are biased by the scatter
- Not clear what determines the scatter, but the scatter with sigma contains important information (e.g. Volonteri et al.)

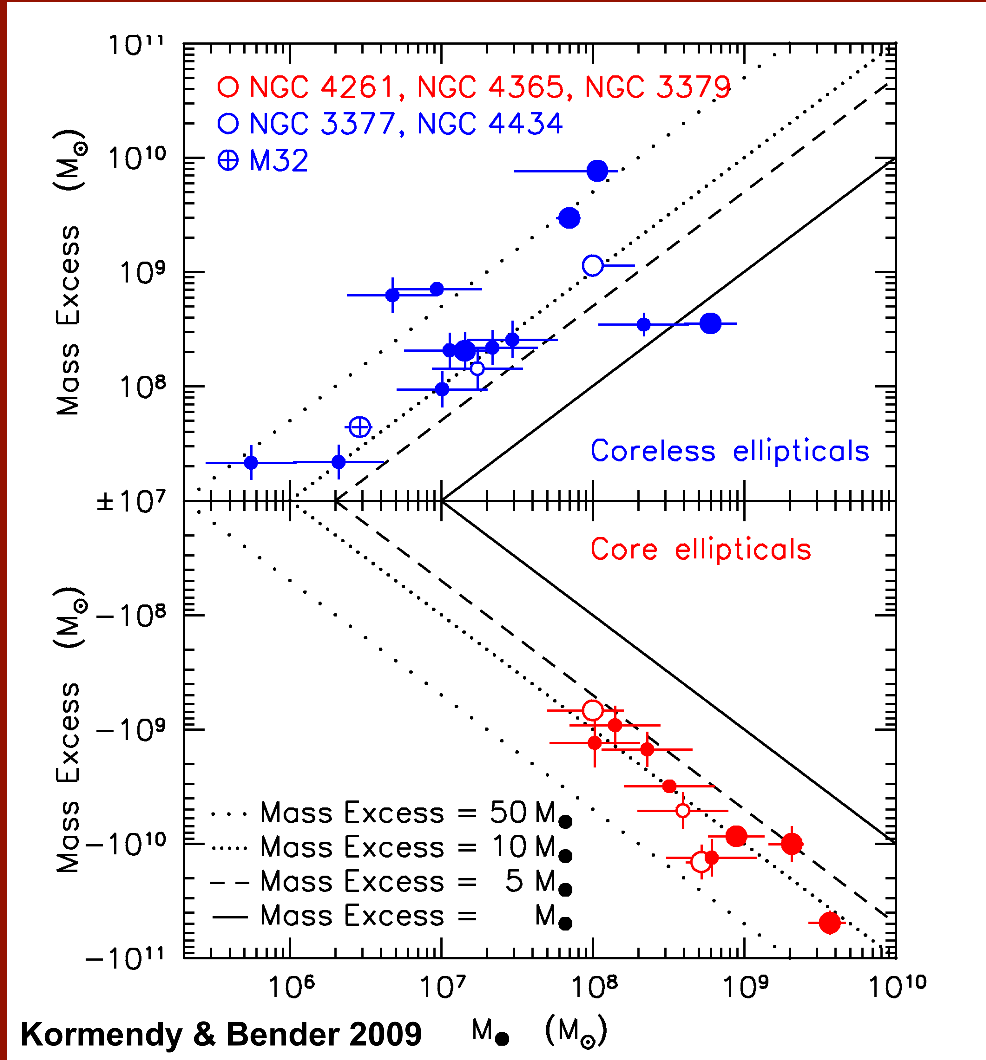


How good is good enough for the BH mass and its uncertainty and How good can we do realistically?

- For BH correlations: based on scatter from most reliable masses and from simple theoretical considerations, need <50% accuracy
- For internal orbit structure: need <30% accuracy otherwise little information on internal velocity moments
- Systematic uncertainty appear to be large (50%), but these can be understood better
- Getting any BH mass to better than 20% is difficult, but hopefully this is good enough. What counts now is the accuracy of the uncertainty.



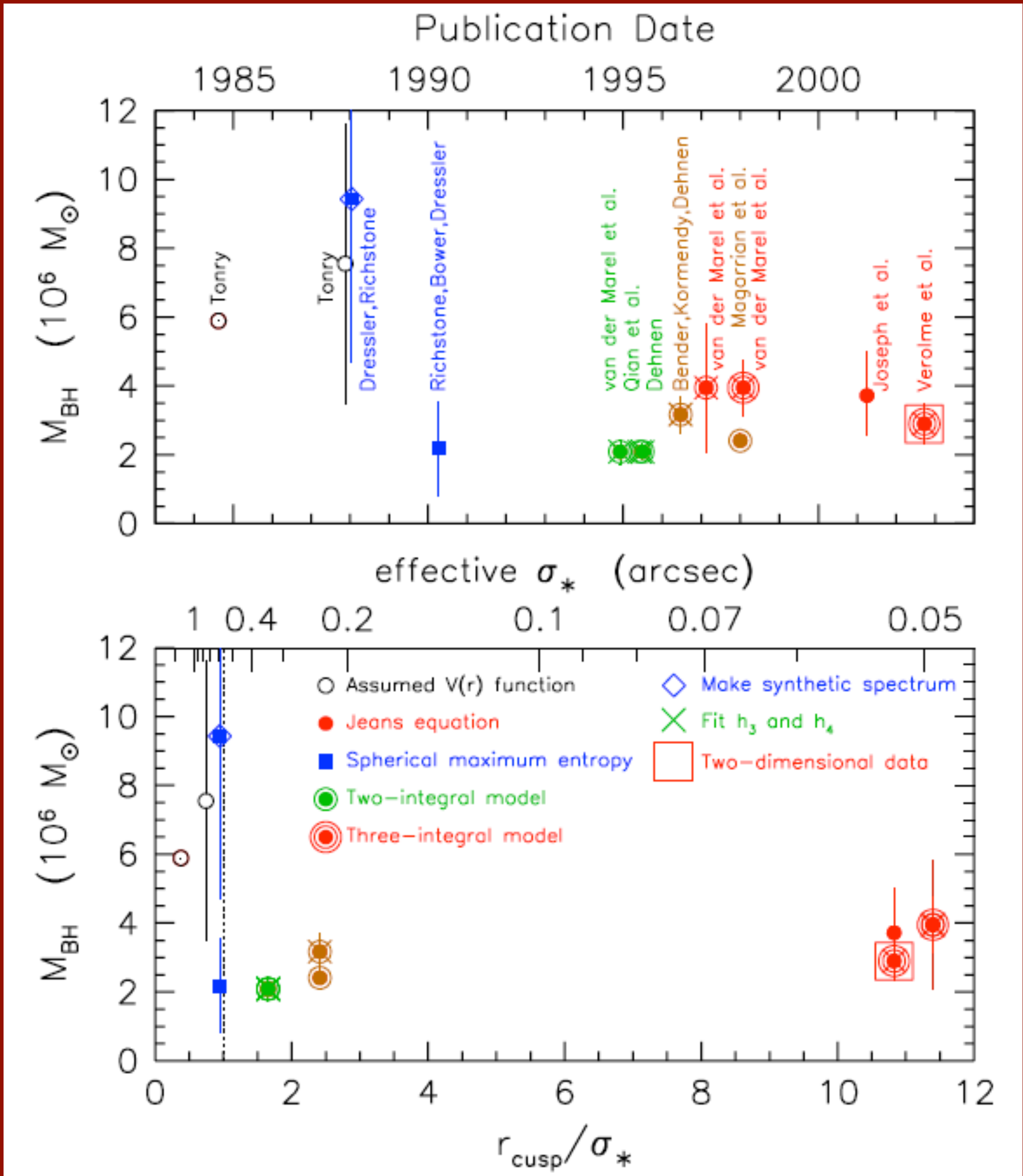
Number density of black holes depends critically on understanding the intrinsic scatter (Lauer et al 07).



Lauer et al. 2007, Faber et al. 1997, Ebizusaki et al. 1991 suggest the galaxy core is due to BH merging.

Evidence for BH scouring is also seen in kinematics, with tangential orbits.

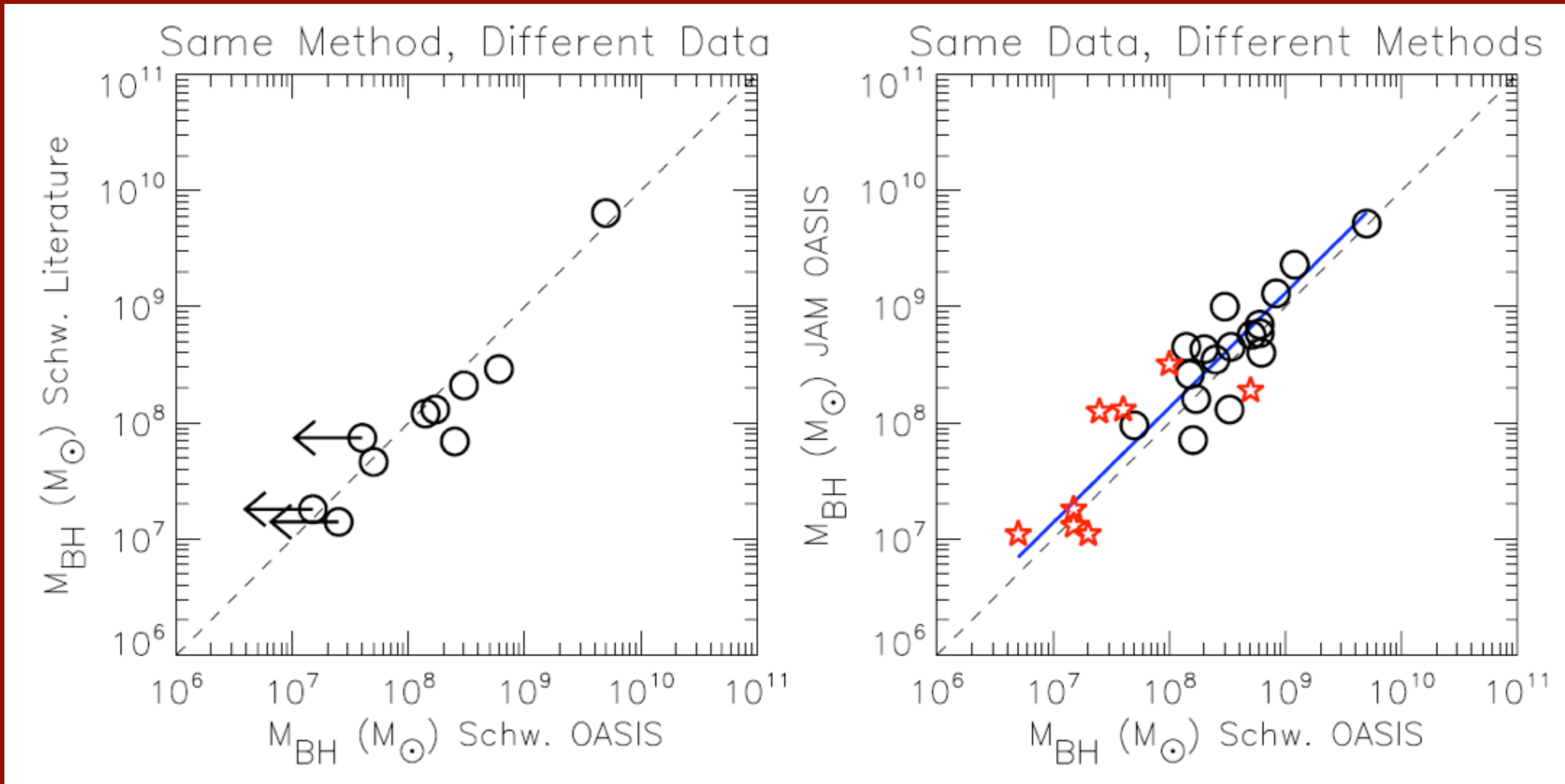
History of M32's BH mass estimate (Kormendy 2004)



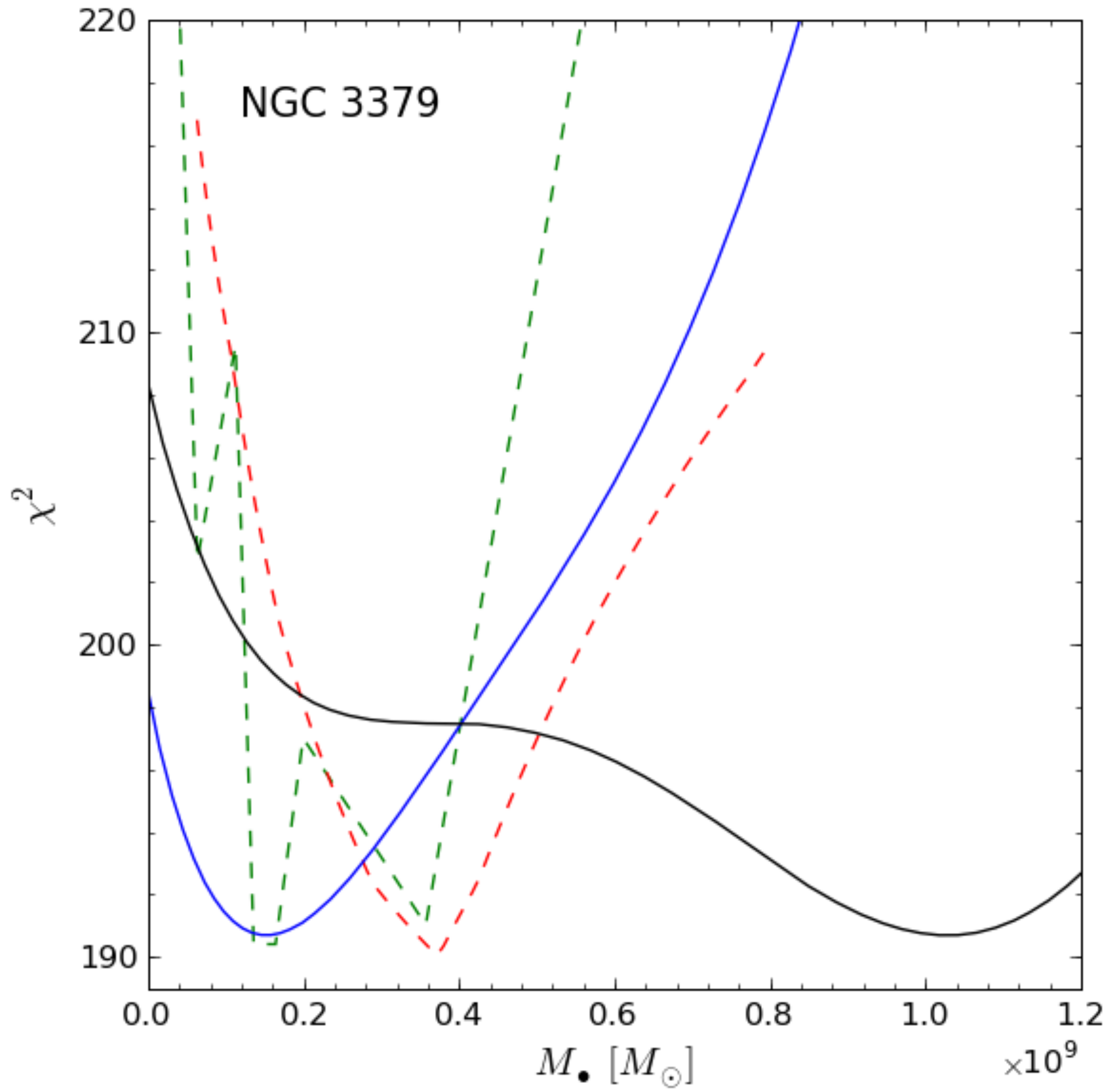
van den Bosch & de Zeeuw 2010

M32's BH mass has been impressively consistent over spatial resolution and model complexity.

Cappellari et al (2010) show consistent results between data and models



How Bad Can it Get (for the BH)



BH models for N3379 :

- ➢ no dark matter (blue)
- ➢ maximum DM (black)
- ➢ Shapiro et al. (green)
- ➢ Triaxial model from van den Bosch (red)

- ➢ All of these use the same dataset!

The lesson is if you want to push to galaxies where the BH kinematic influence is poorly resolved, you need a very good M/L profile.

But, we have a problem. For galaxies with recently measured masses:

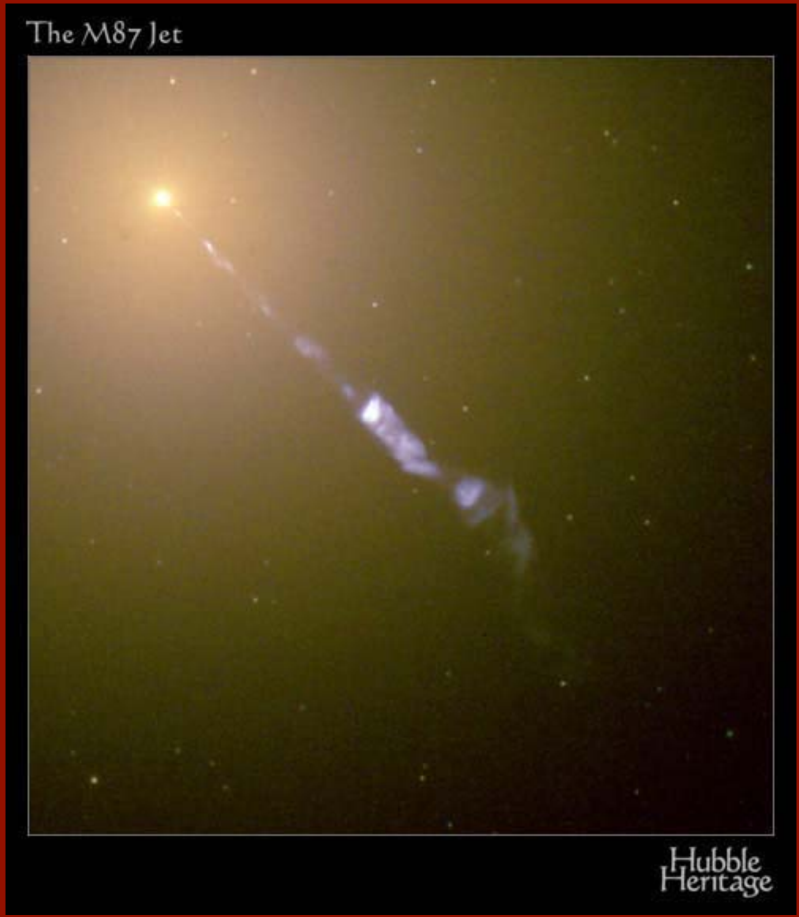
Galaxy	BH mass	Change	Reason
M87	7e9	2-3x	Dark halo included in models (kg & Thomas 09)
N4649	4.5e9	2x	Better phase space? (Shen & kg 10)
N3379	4e8	2x	Triaxial models (van den Bosch et al 09)
N6086	5e9	10x	Dark halo inc. (McConnell et al. 10)
N4594	5e8	0.5x	Orbit-based models (Jardel et al. 10)
N4697	2.5e8	1.4x	Dark halo inc. (Forestell et al. 09)

In order to understand what is going on, we need:

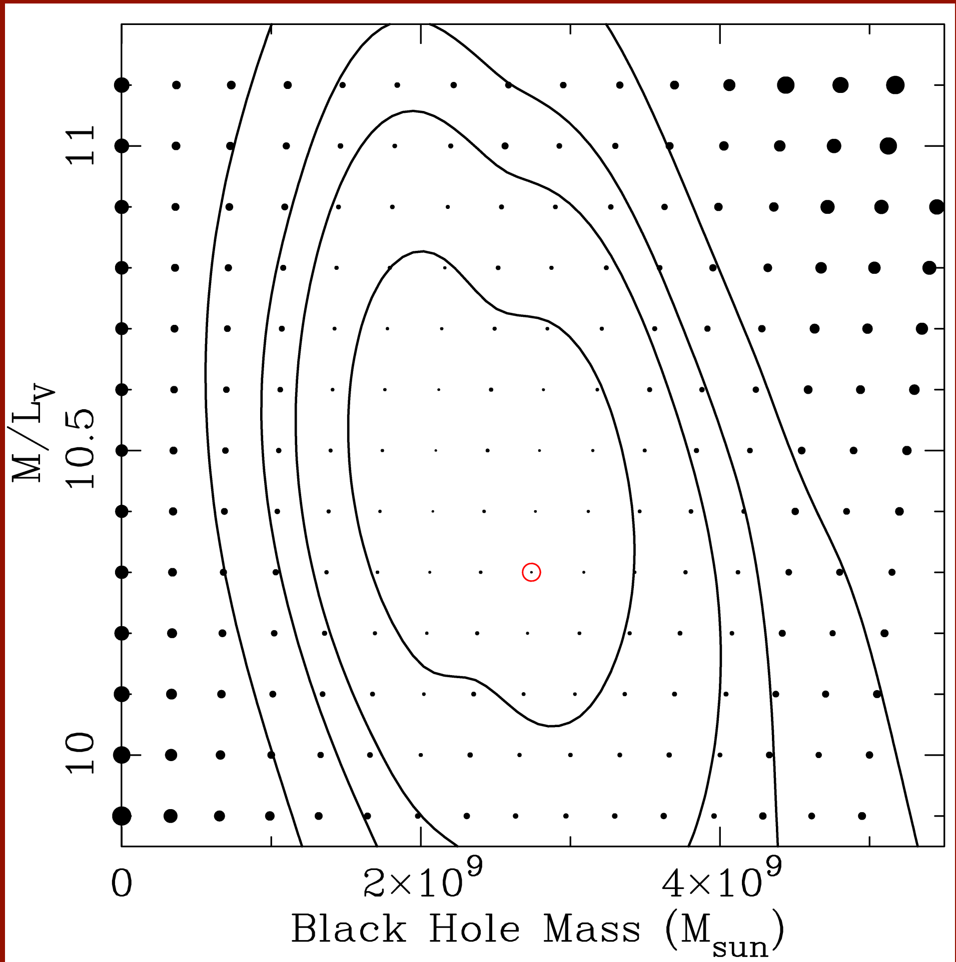
- Adaptive optics on large telescope: after some initial growing pains, AO systems are delivering
- Dynamical models: the models are now nearly as general as possible, with triaxial models and made-to-measure techniques (N-body+Schwarzschild)
- Multiple techniques: galaxies studied with multiple observing techniques is growing, by combining stellar and gaseous data (including X-rays).

M87 re-analysis, with dark matter

- Kinematics from Sauron and long-slit in the central regions (van der Marel 94)
- Globular cluster velocities to 8 Re
- X-ray data out to similar radii
- Need to include both BH and DM, especially due to M87's large core
- Requires a new mode to run the library of orbits
- Want 10 BHs, 10 M/Ls, 10 DM scale radii, 10 DM circ velocity, and each model takes a few hours
- This would not be possible without the TACC (Texas Advanced Computing Center) and the 5800 and 60,000 node systems



M87 results without a dark halo



→ Best-fitted BH mass is 2.5 e9 using stellar data only

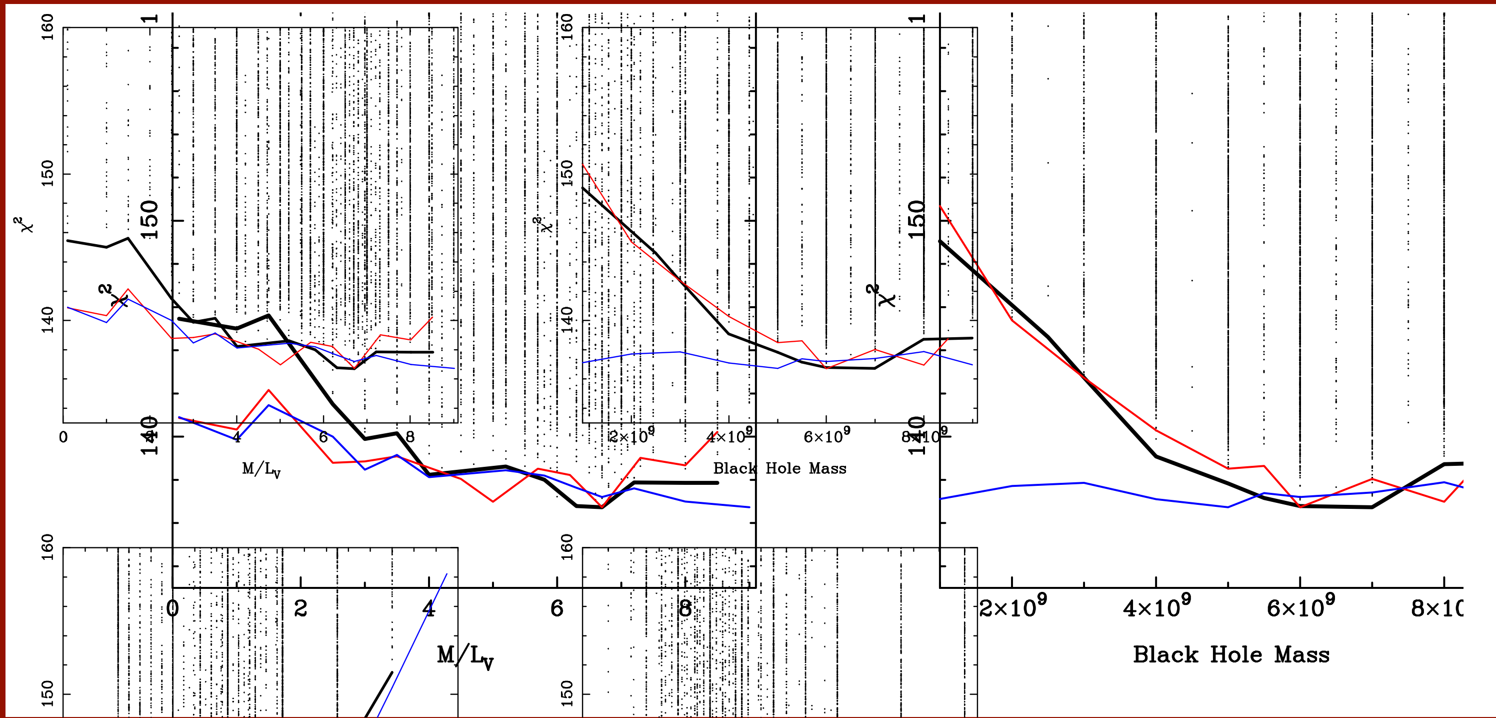
→ HST gas mass is 3.5(+-1)e9

→ Previous stellar dynamical masses are around 1-3e9

→ Everything is consistent

But…..

M87 BH models with a dark halo
(kg and Thomas 09)



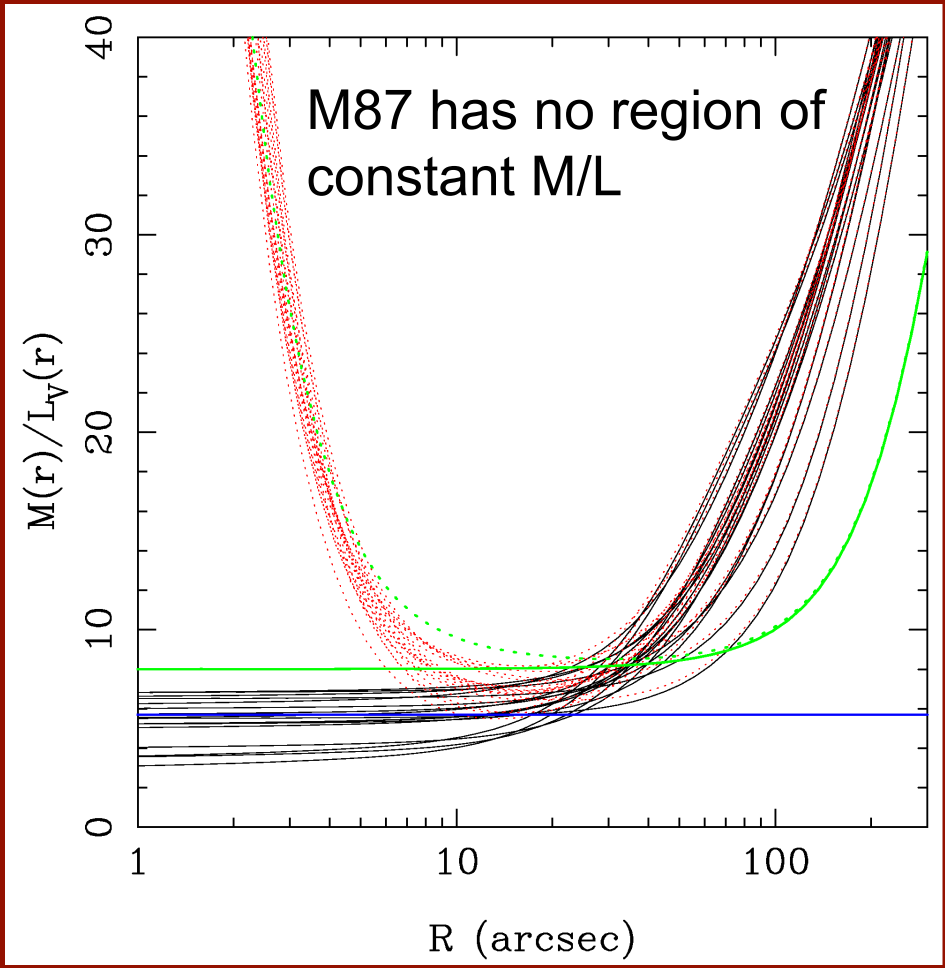
After 70,000 hours on the TACC computers:

1. Best-fitted BH mass is 6.4(+-0.5)e9
2. M/L went from 10.5 (no DM) to 6 (with DM); the M/L derived from stellar population work is 6
3. DM profile is more massive than the X-ray profile

BH changed since:

1. M/L decreased
2. Significant contribution to central kinematics from large radii in projection
3. Orbit structure changed due to DM inclusion

- → BH masses at the upper end need to be re-evaluated
- → Larger BH masses have a significant consequence on understanding space density of BHs
- → For example, if M87 has a 6.4e9 BH, it will help problem of the large inferred BH mass from QSO
- → Could have a significant effect on the measured BH correlations, which feed back into galaxy evolution models
- → Next logical extension is to include triaxial models (R. van den Bosch)



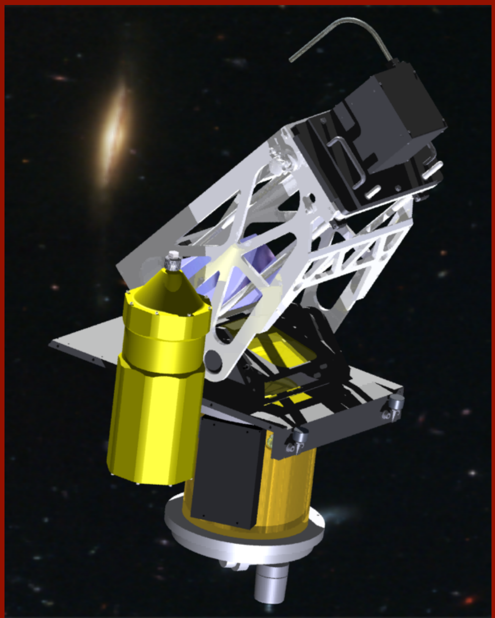
All of the work with understanding the BH correlations need to include systematic effects

Gemini/NIFS laser AO data for M87

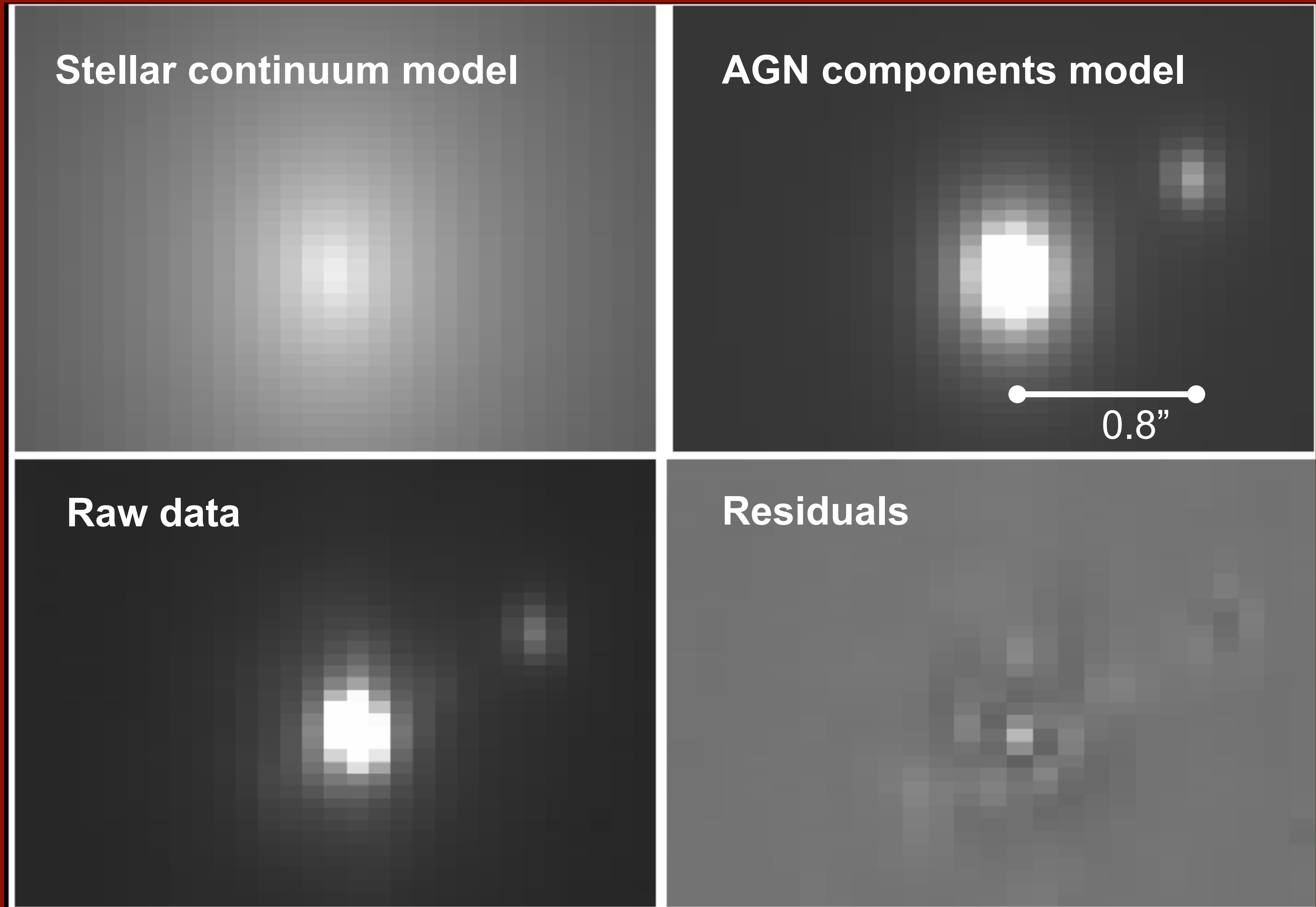
Adams, kg, Richstone, Lauer, Tremaine, Gultekin

- 24 10-minute exposures
- laser AO using AGN as TT

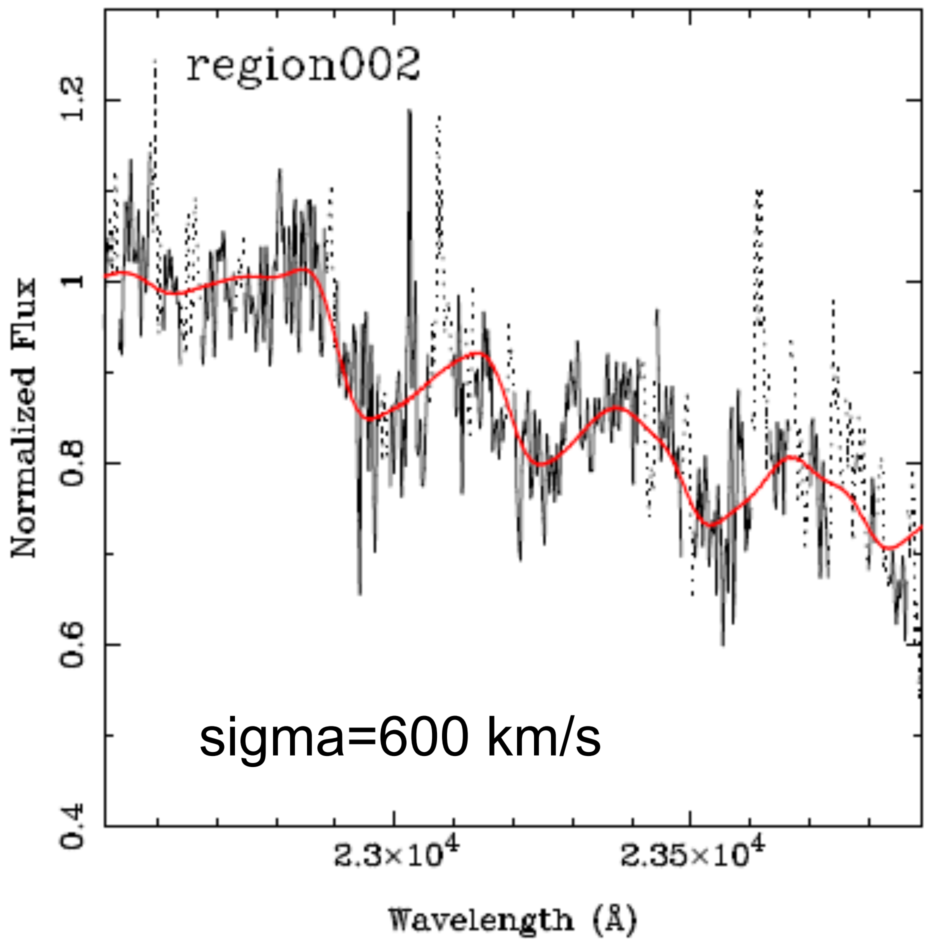
Outer Radii data from SAURON (to 30”) and VIRUS-P (to 250”, Murphy & kg 09)

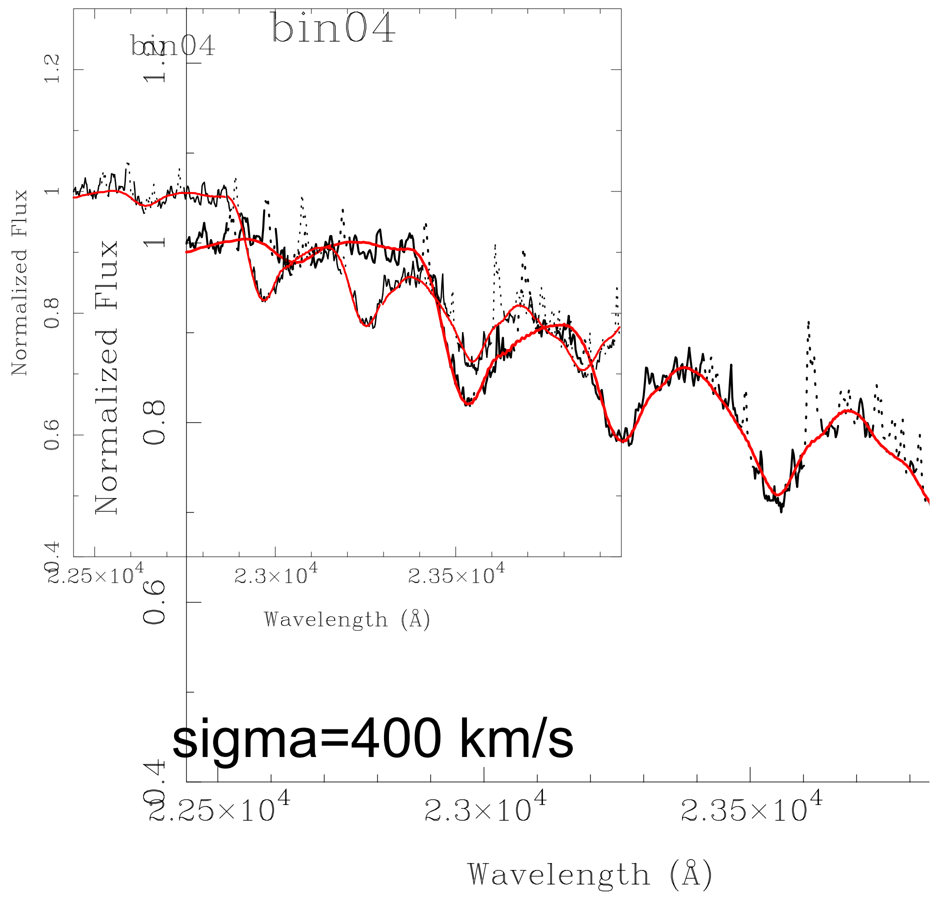


M87 central region reconstructed from NIFS AO data



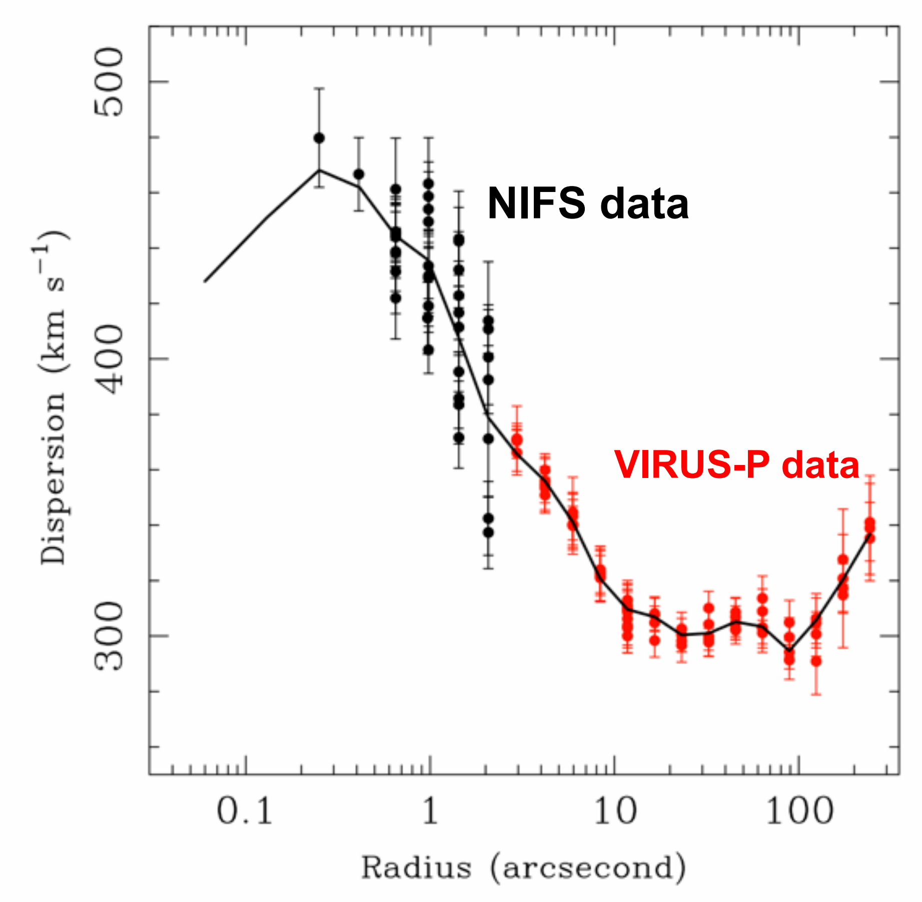
Gemini/NIFS Spectra in Center and Outer Regions

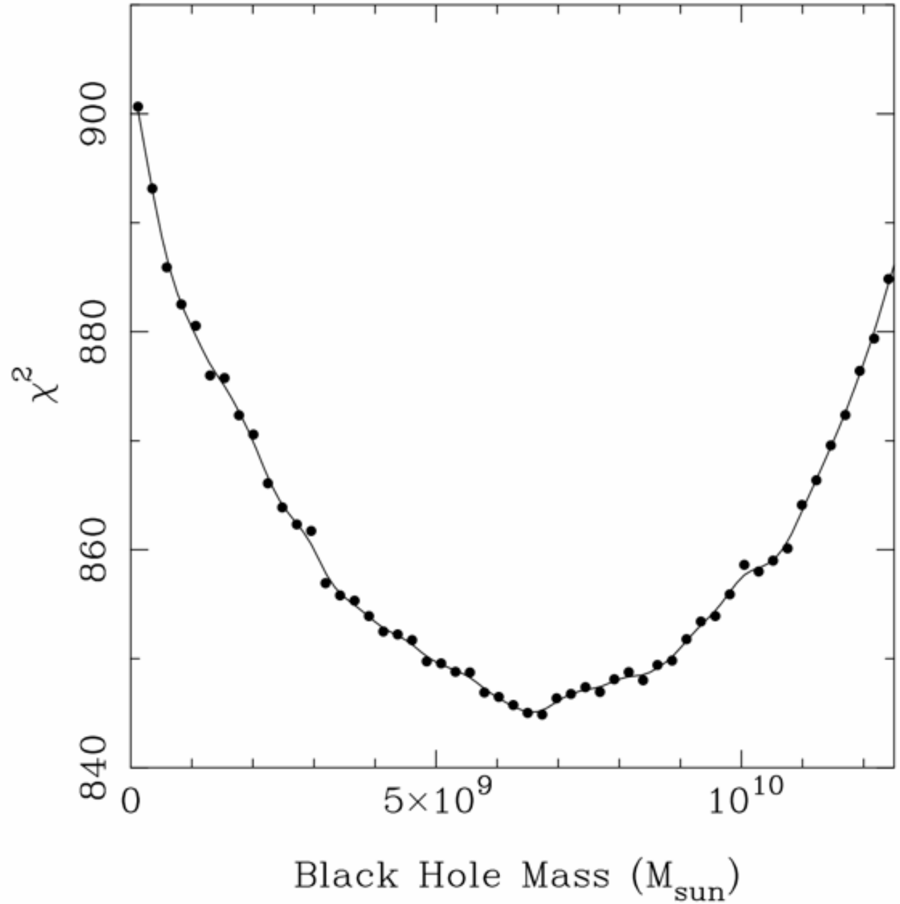




Once dispersions get this fat, it is hard to measure them robustly.

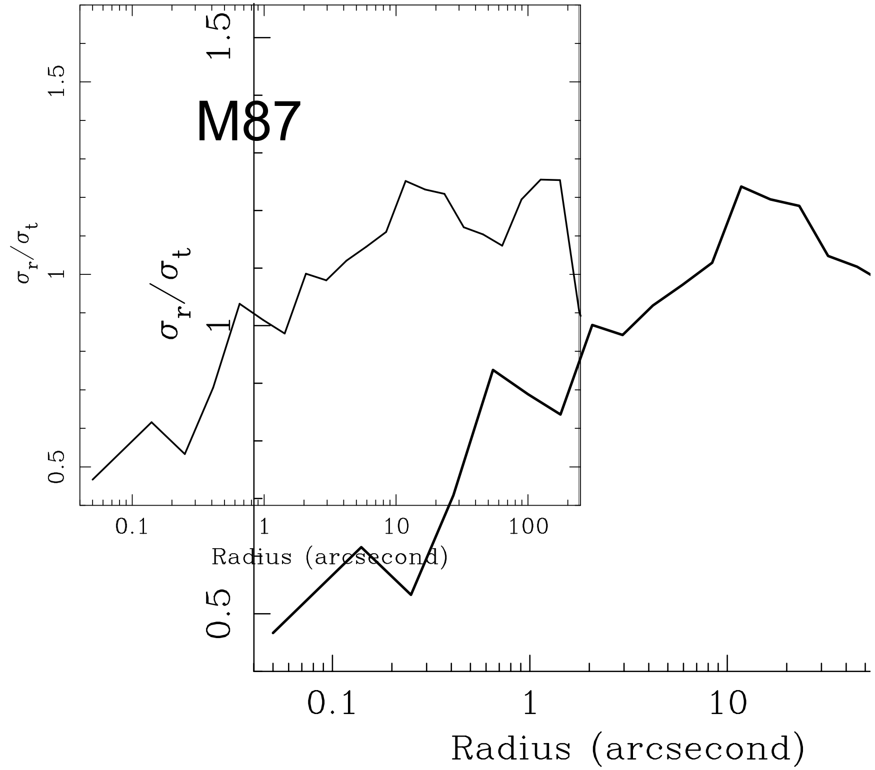
Data and models for M87

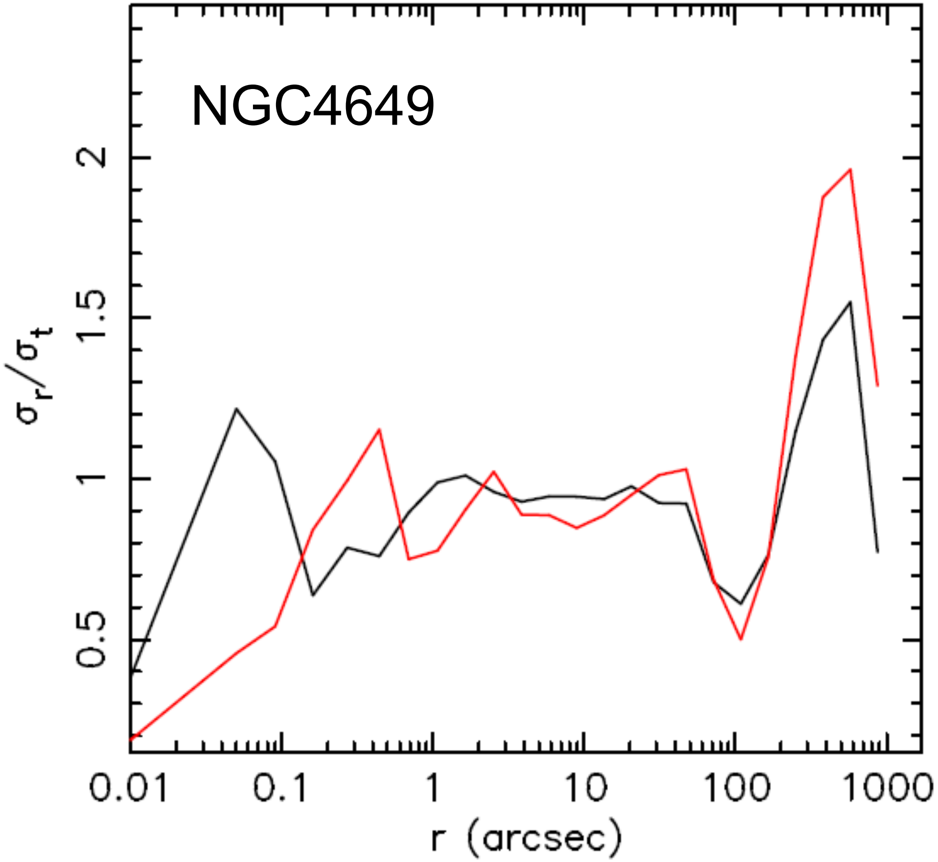




- BH mass from NIFS+VIRUS-P data is 6.6e9, with almost no dependence on dark halo.
- BH mass from published and SAURON data is 6.4e9, with strong dependence on dark halo.
- Sargent et al. (1978) reported 6e9!
- Gas mass (Macchetto et al.) can be made consistent with a small inclination change of disk.

Ratio of radial to tangential Internal velocity dispersion for best-fitted models



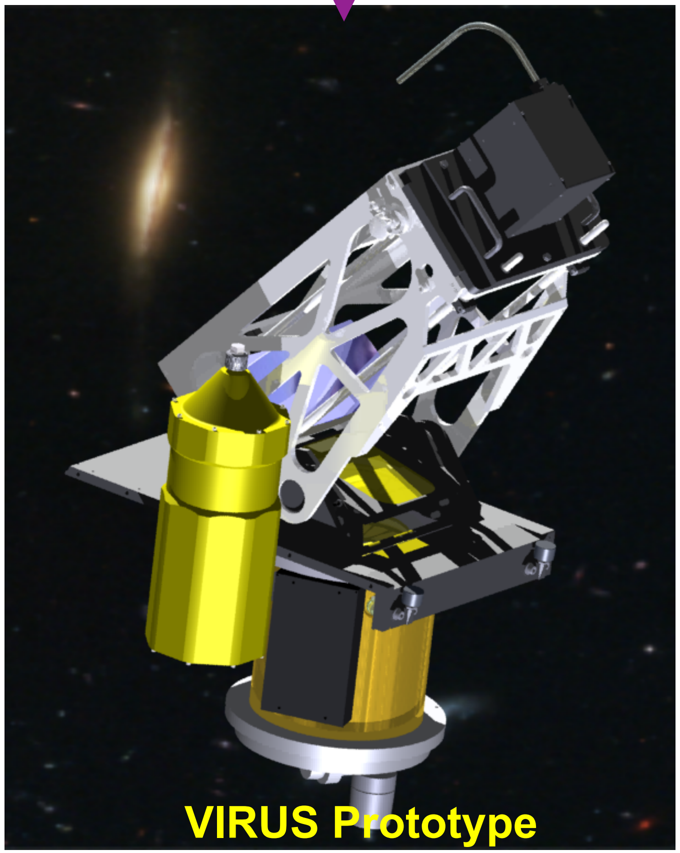


Strong tangential bias in the central region (seen in other galaxies) suggest black hole growth from stellar accretion – consistent with black hole scouring models.

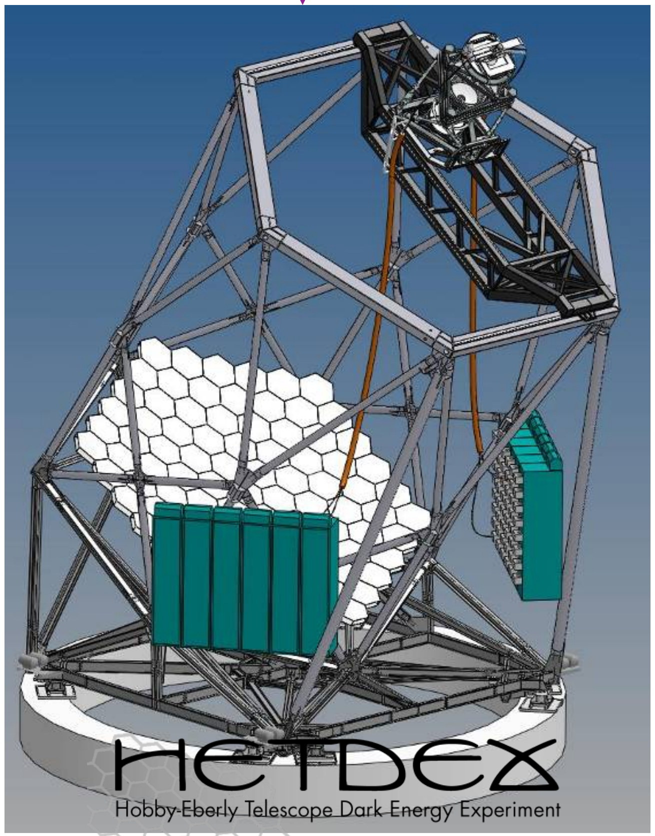
There is a need to include a dark halo in the models

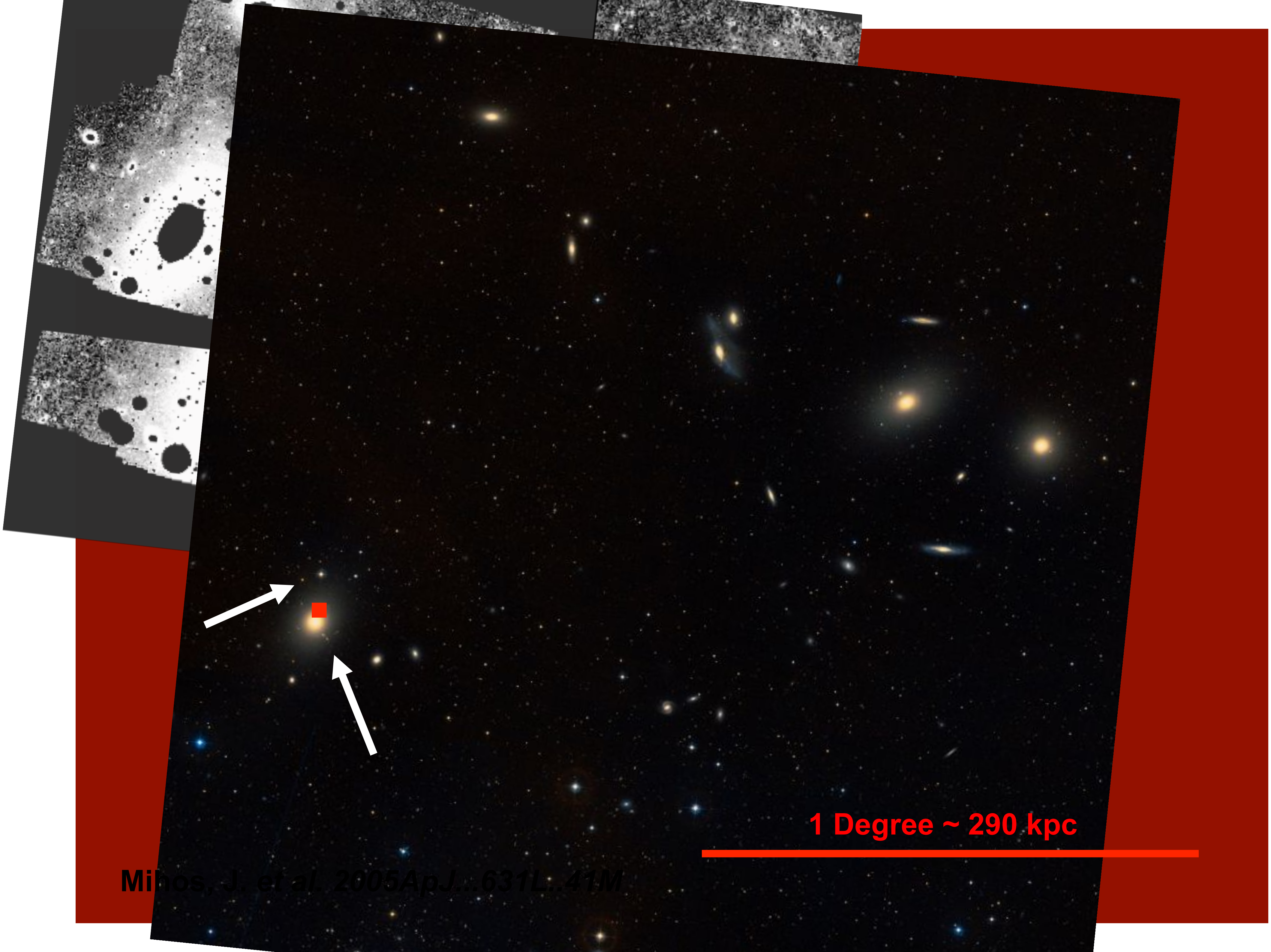
- Stellar light is faint, GCs too rare, PNs and GCs difficult to model
- Gravitational lensing works ok for average profiles
- For stellar work, need spectral coverage over large area:

VIRUS-P, the first unit spectrograph for HETDEX



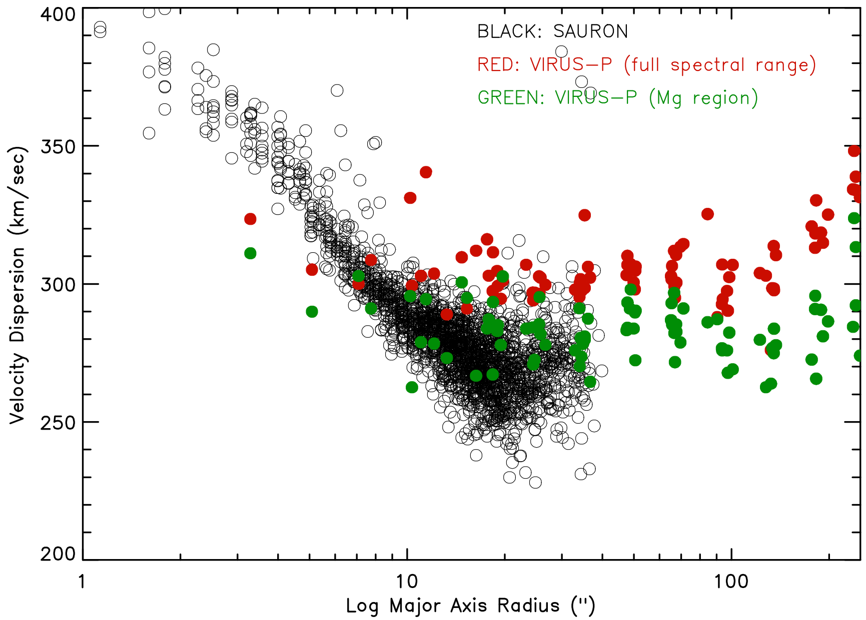
- **1.8'x1.8' FOV on McDonald 2.7m**
- **245 fibers of 4.2" diameter**
- **350-580 nm**
- **R=900**
- **Science coming from V-P is similar in scope to SAURON (Emsellem et al. 04) but larger and longer wavelength coverage.**



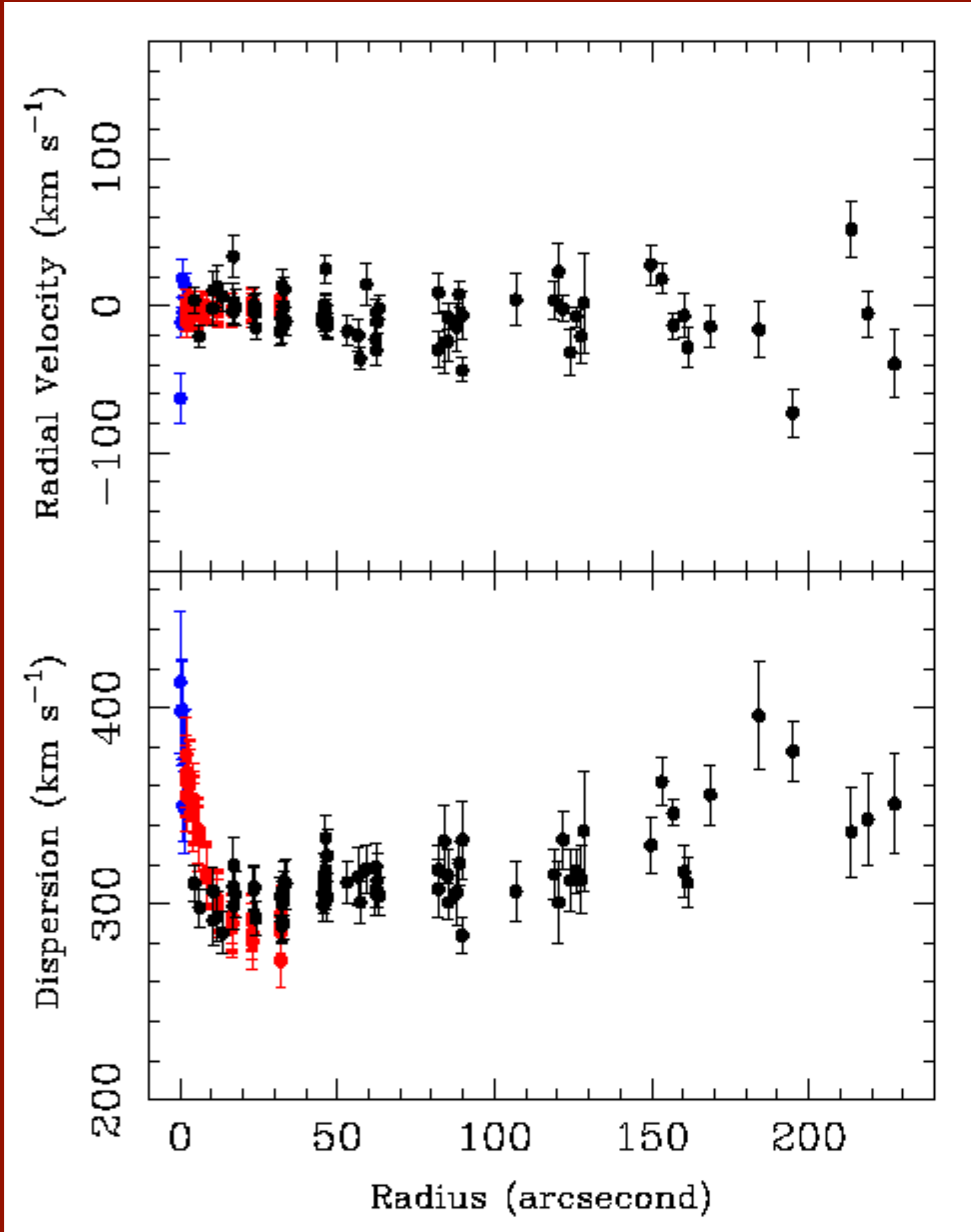


Mihos, J. et al. 2005ApJ...631L..41M

One major systematic issue is template mismatch (below are different dispersion estimates for M87)

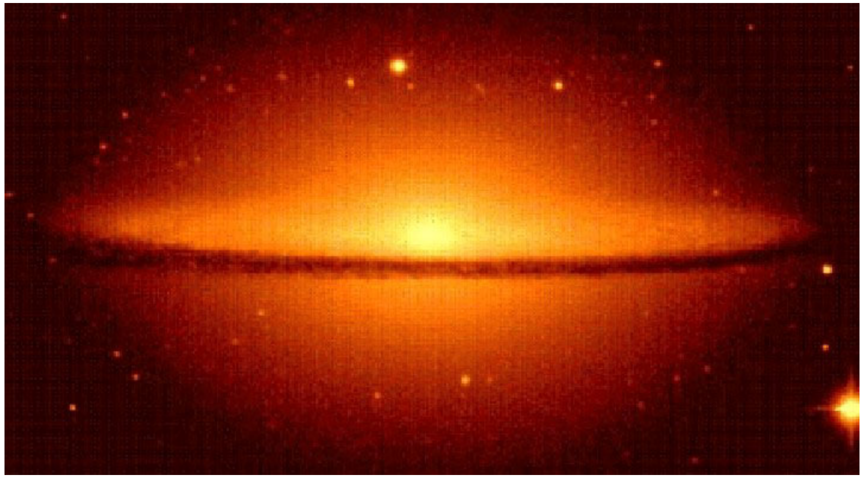


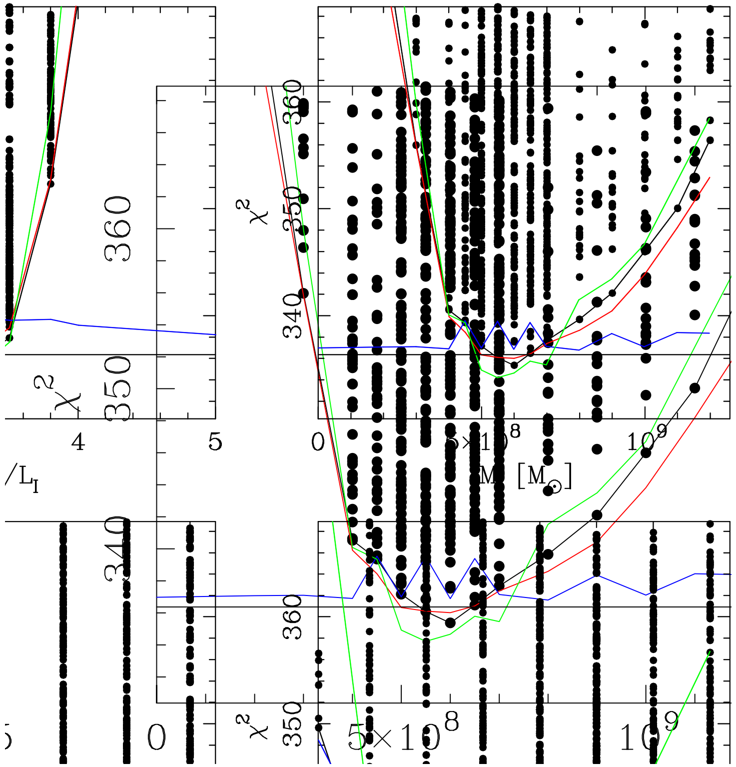
Extraction of kinematics from spectra is limited to around 1 or 2% of the velocity dispersion; due to continuum placement, template, parameterization (Gauss-Hermites are unphysical)



M87 large radial kinematics

Black: VIRUS-P (Murphy & kg)
Red: SAURON
Blue: van der Marel





N4594, Sombrero results (Jardel, kg et al. 09): Gemini GNIRS long-slit, and GC kinematics out to a few Re

We are in the process of re-modelling everything we can find (Schulze, Jardel, Shen kg et al.).

All of kg etal 03 BHs have been remeasured, including dark halos and newest models. We find an average increase in BH masses of around 30%; slight trend for more massive BHs to increase more.

The orbital structure changes quite a bit (more tangential anisotropy).

Stellar Clusters with good central stellar kinematics:

- G1 : most massive cluster in local group
- omega Cen: maybe not a GC

- M54: central cluster in Sag dwarf, maybe a nucleus of an accreted galaxy
- 47Tuc: traditional GC
- M15: very painful history

- M80: lots of un-analyzed data
- G280: shows no evidence for central concentration
- M33 nucleus: no evidence for central concentration

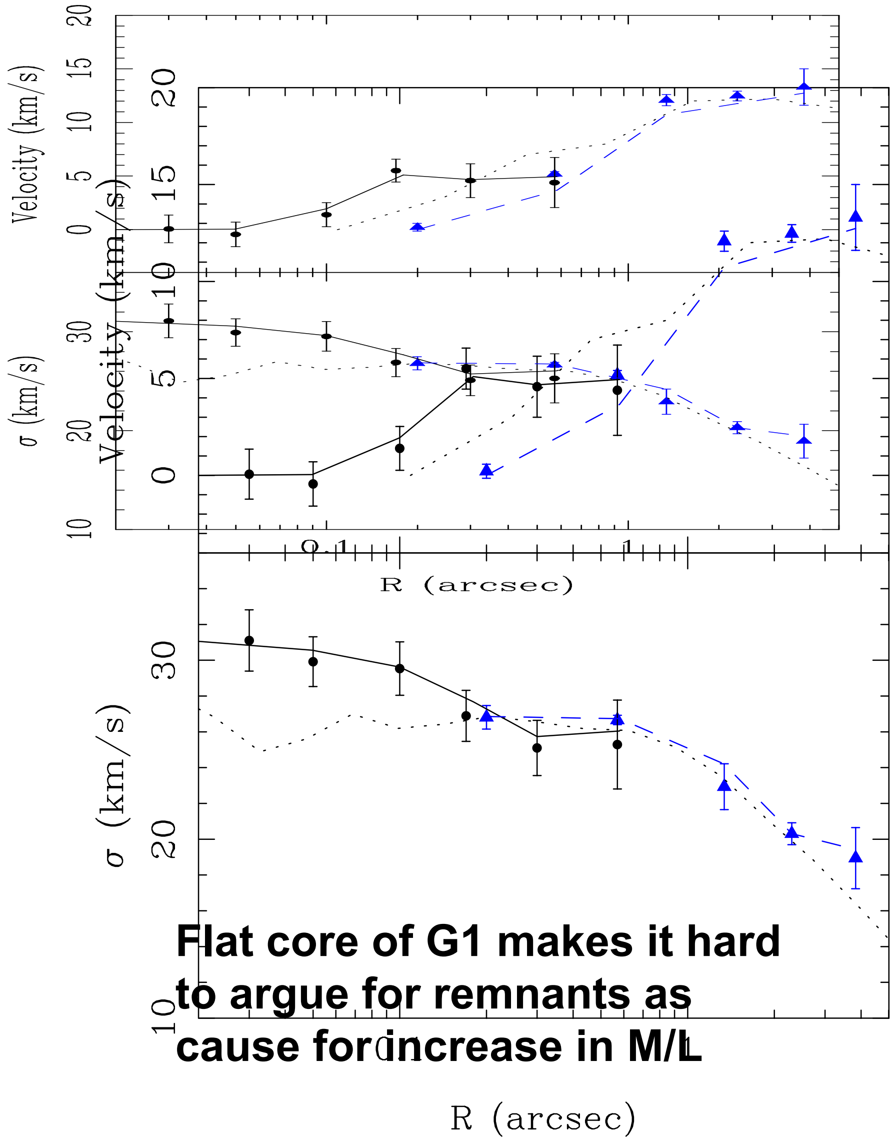
Constraints on BHs in clusters can come from:

PHOTOMETRY: Surface brightness profiles plus evolutionary models; e.g. Baumgardt et al., Miocchi, Lanzoni et al., Trenti; Noyola & Gebhardt provide central SB profiles.

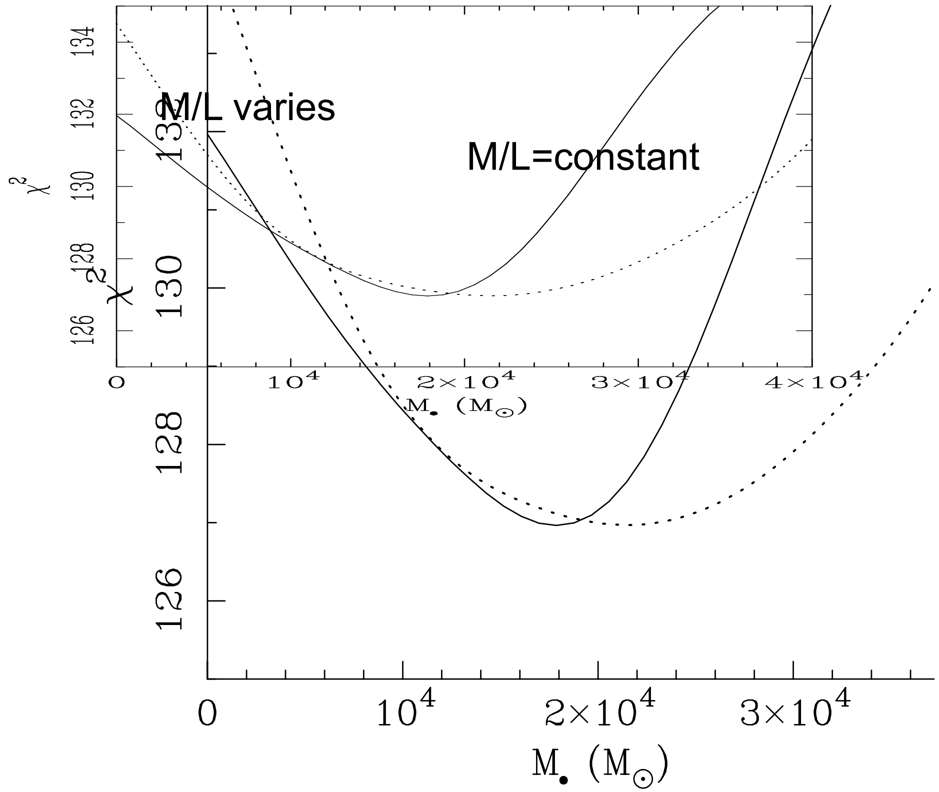
KINEMATICS: Radial velocities and proper motions (stars and pulsars) are the best way we have to measure the mass. Requirement should be around 20% based on what we learned in galaxies.

NON-THERMAL EMISSION: Radio and X-rays provide the compelling signature for a black hole (Ulvestad et al., Maccarone et al.). Cannot measure mass accurately enough. And there needs to be gas.

Data and Models for G1

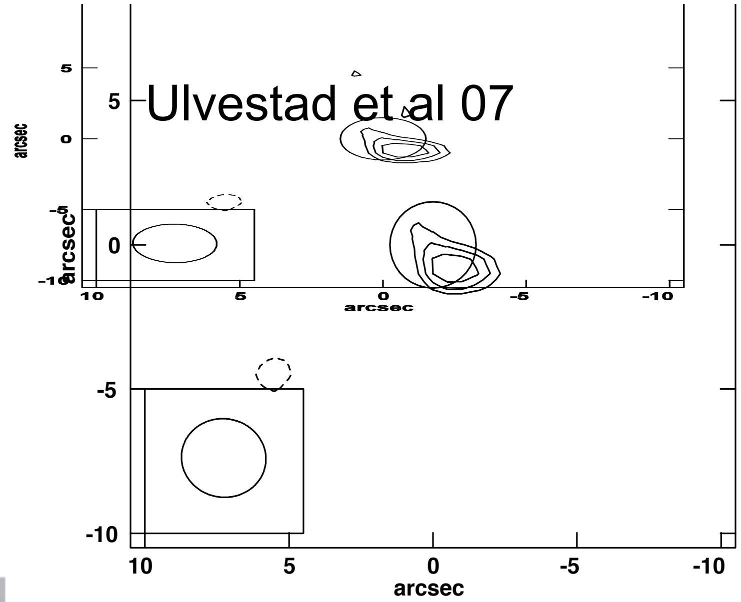


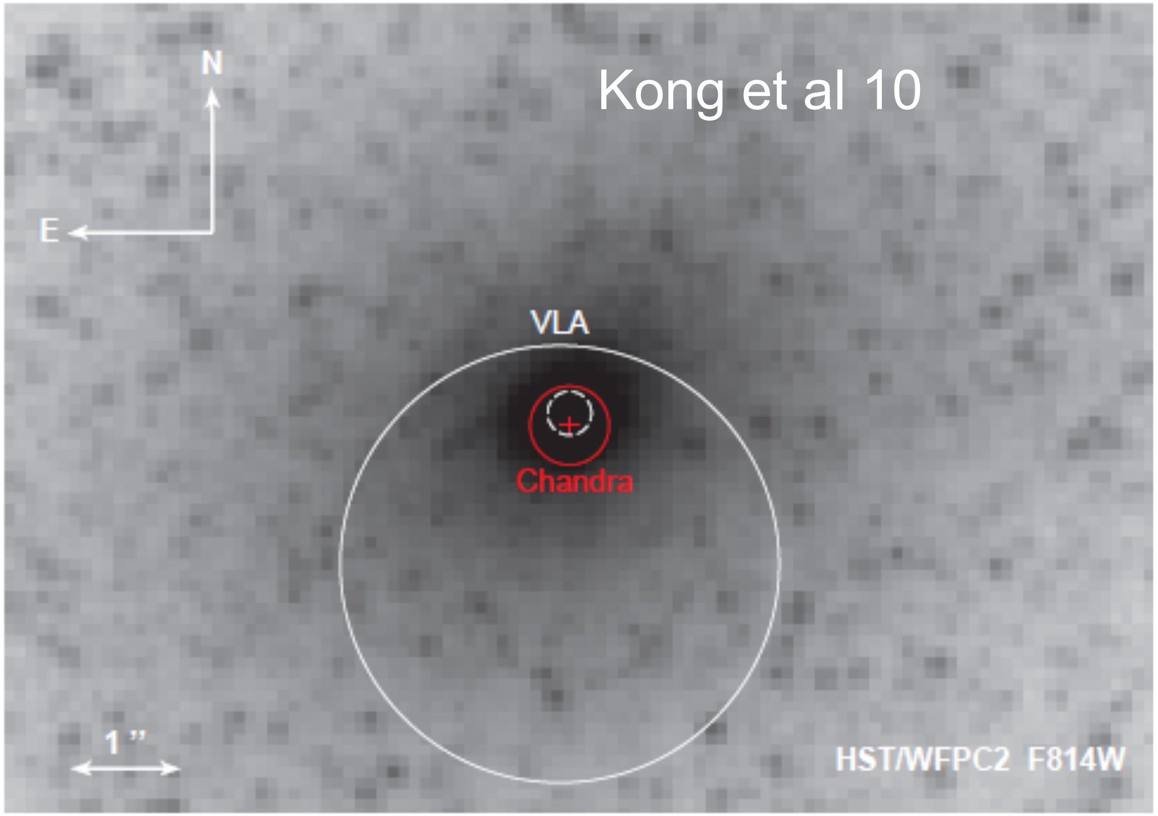
Flat core of G1 makes it hard to argue for remnants as cause for increase in M/L



from kg, Rich and Ho (02,05)

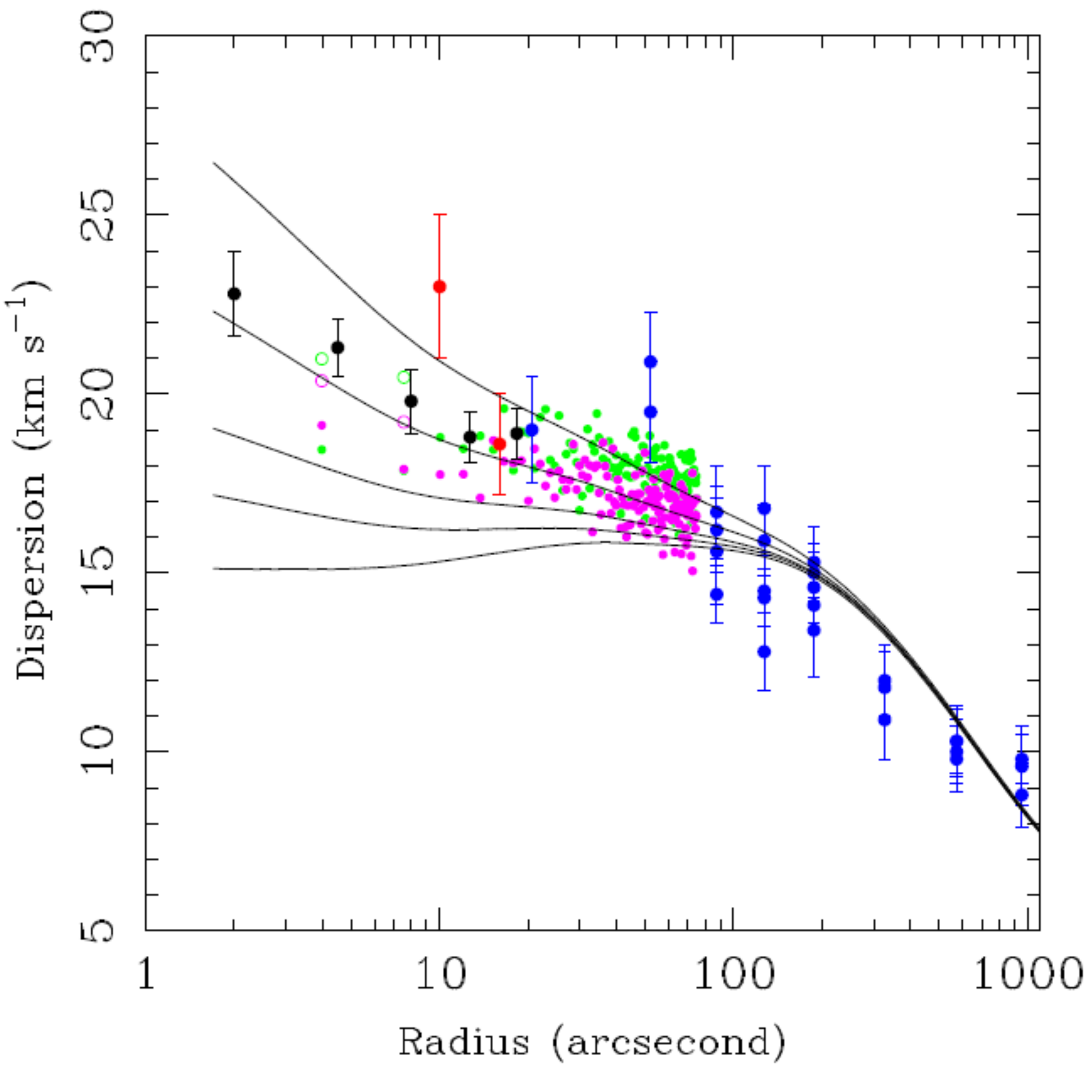
Gas (radio and X-ray) in G1



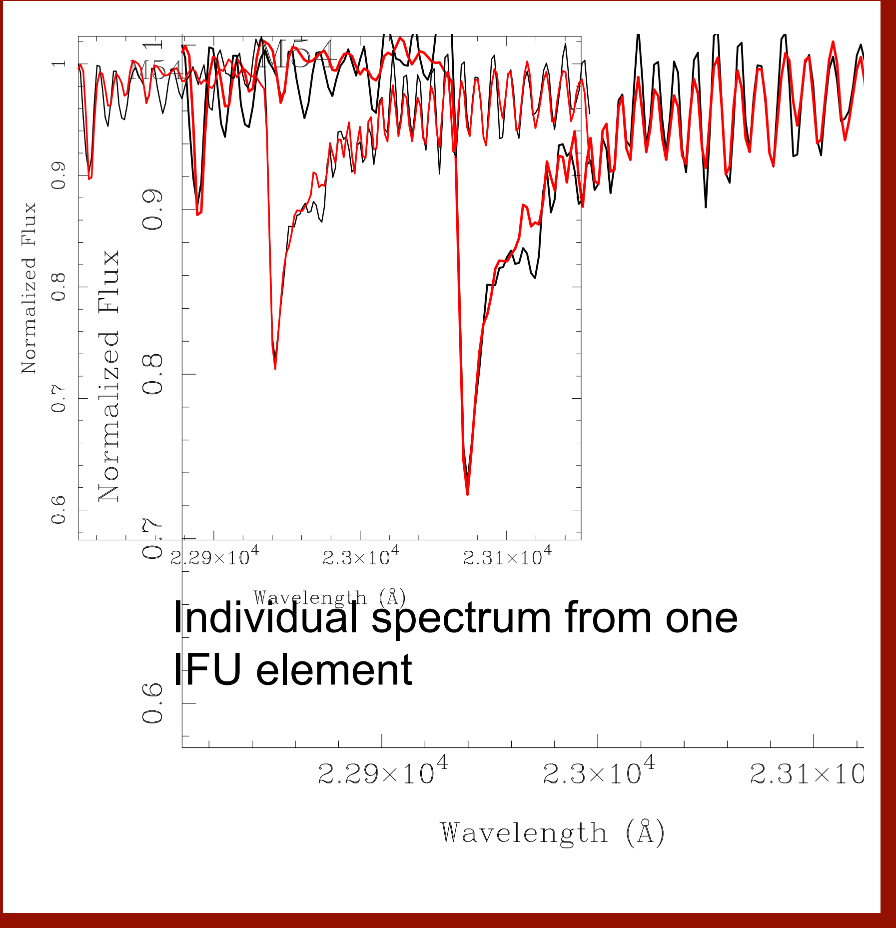


- Ulvestad, Greene & Ho detect radio emission from G1 at 4.5 sigma
- Trudolyubov & Priedhorsky detect X-rays from Chandra
- Kong et al. 10 show that the X-rays are coming from within G1's core
- Combined with the kinematic measure, the case for a BH is compelling

Dispersion measures from VLT/FLAMES (black) and from proper motions (green and magenta); thus, both rv and pm appear consistent



Gemini/GNIRS data for M54

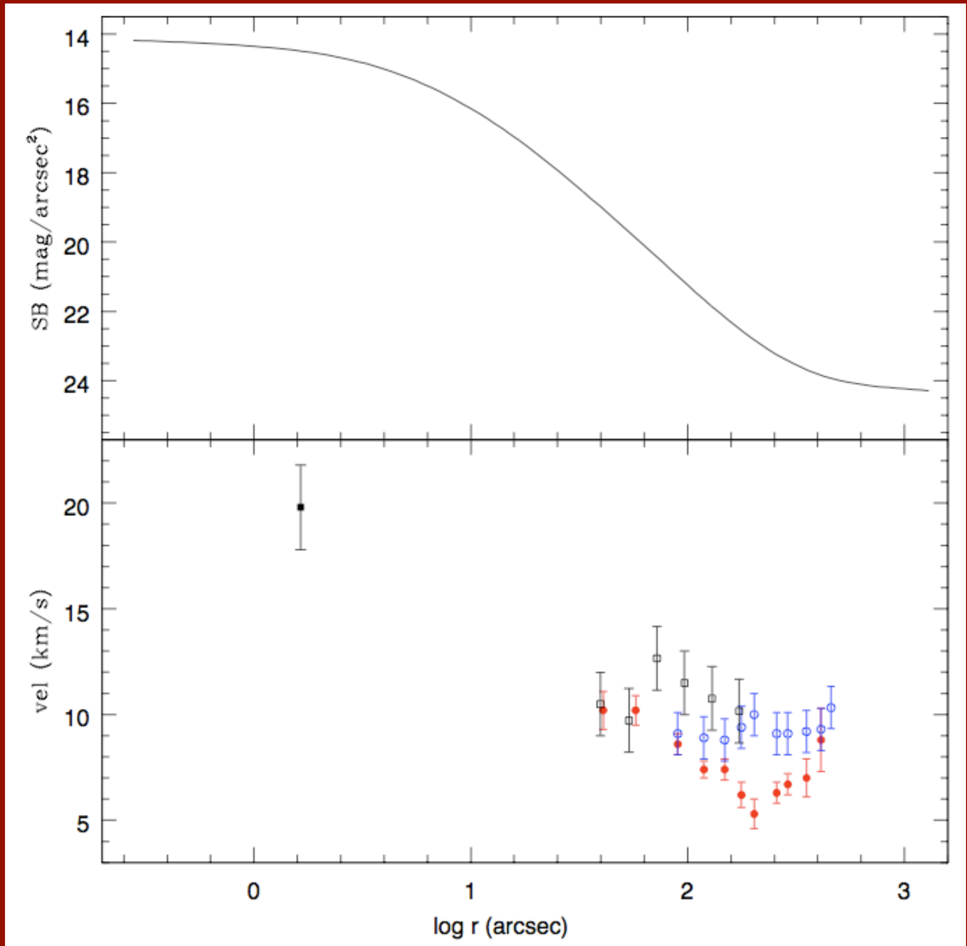


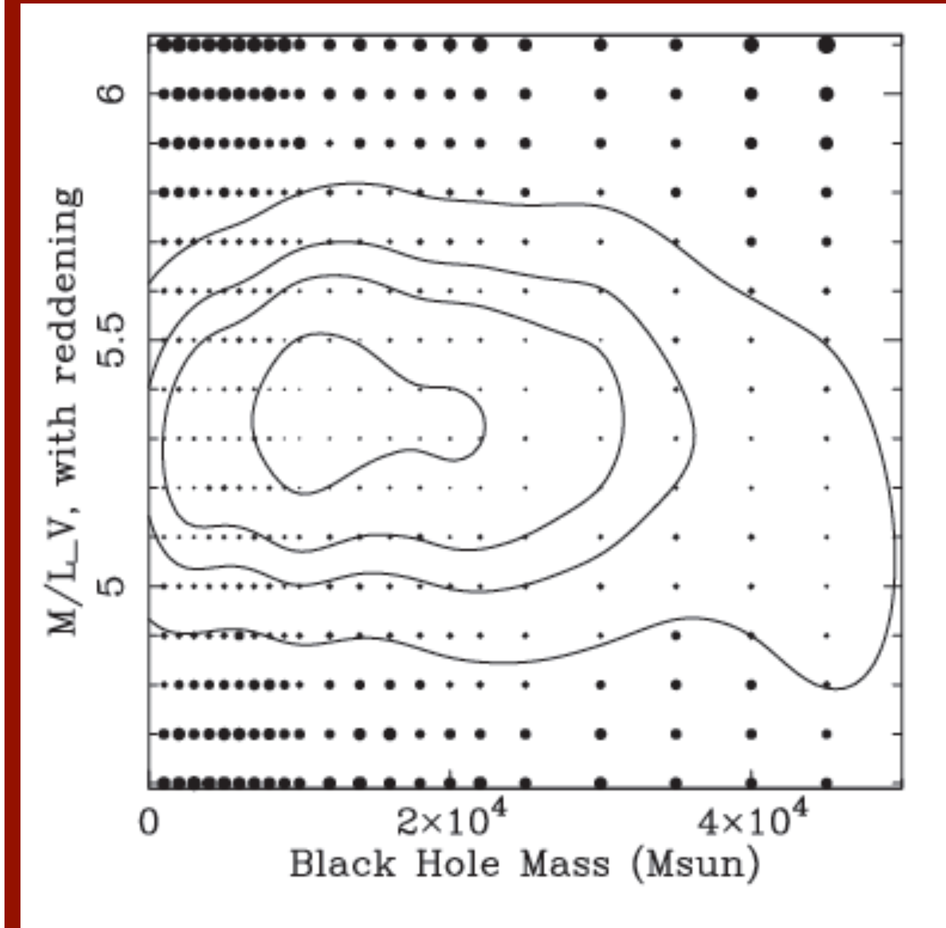
Individual spectrum from one IFU element

Reconstructed IFU map with velocity map overlaid.

- Rotation has an amplitude of 13 km/s, with a dispersion of 15 km/s

Surface Brightness and kinematic profiles, and dynamical models for M54





GMOS data at small radii and large radii velocities from Bellazzini et al.

BH Correlations and Dark Matter Studies, AND their Relationship

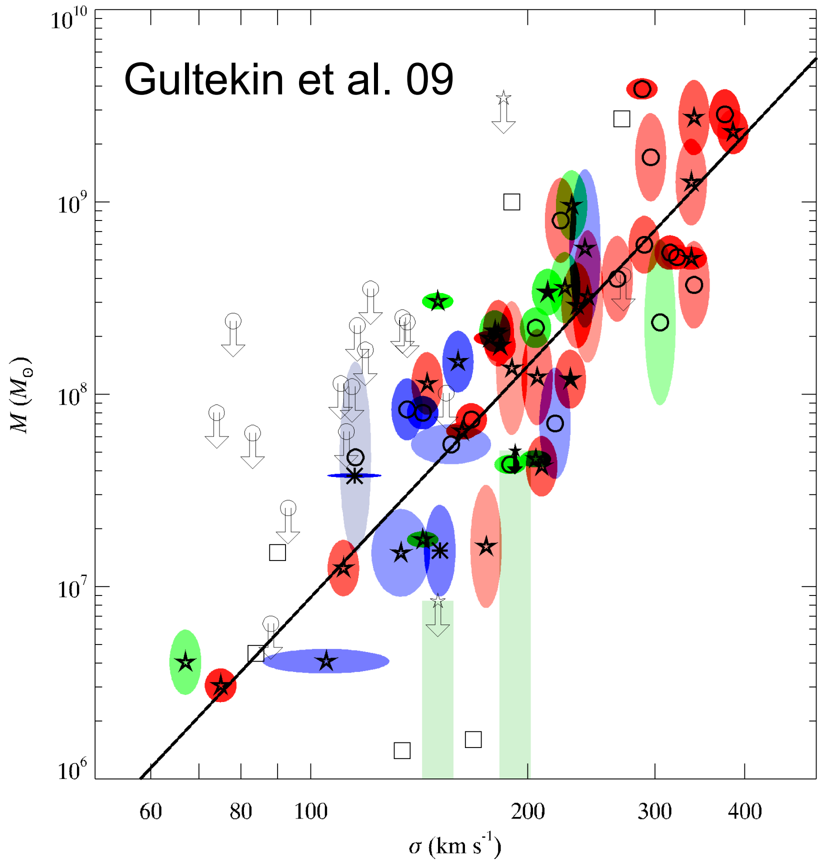
Black Hole Results

1. High BH masses may be biased (M>1e9)
   - → M87 mass of 6.6e9 Msun
   - → Need to include DM profile in model
2. Mid-range BH masses (1e6-1e9) show tight BH/sigma correlation, but difficult to quantify due to systematics
3. BH correlation with sigma show little evidence for 2^{nd} parameter
4. Low-range BHs (1e5) appear to exist
5. Smaller BHs (1e2-5e4) in globular clusters:
   - → G1 and omega Cen are best cases
   - → ULXs remain interesting
   - → No significant upper limit for BH in any GC

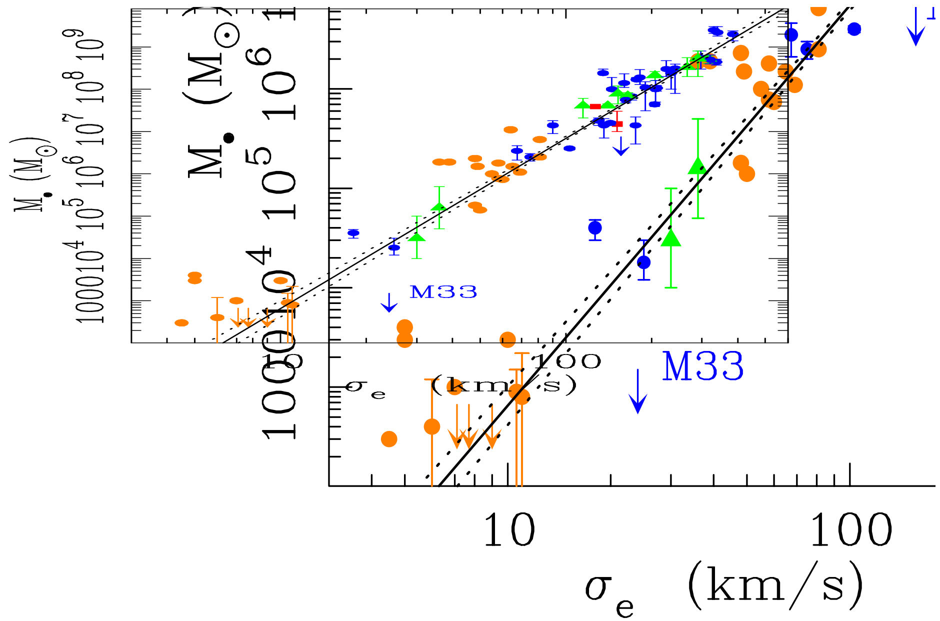
Dark Matter Results

1. Dynamical analysis of stars, GCs, PNe and distortions around ellipticals require dark matter. Results not consistent yet.
2. Best-fitted dark matter profiles are flatter and more extended than NFW
3. Stellar kinematics easily obtained out to >3 effective radii on McDonald 2.7m with VIRUS-P
4. Combining DM and BH studies is important for unbiased results

BH correlation for galaxies…



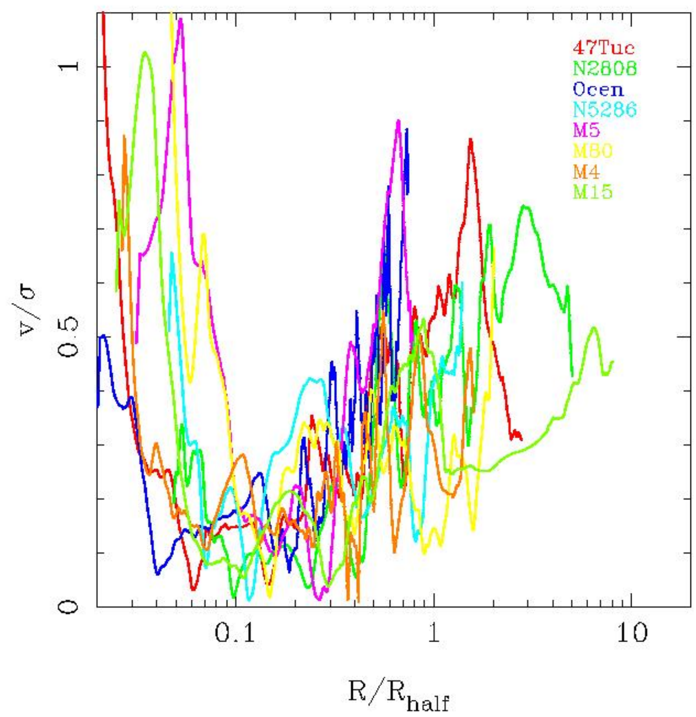
including clusters



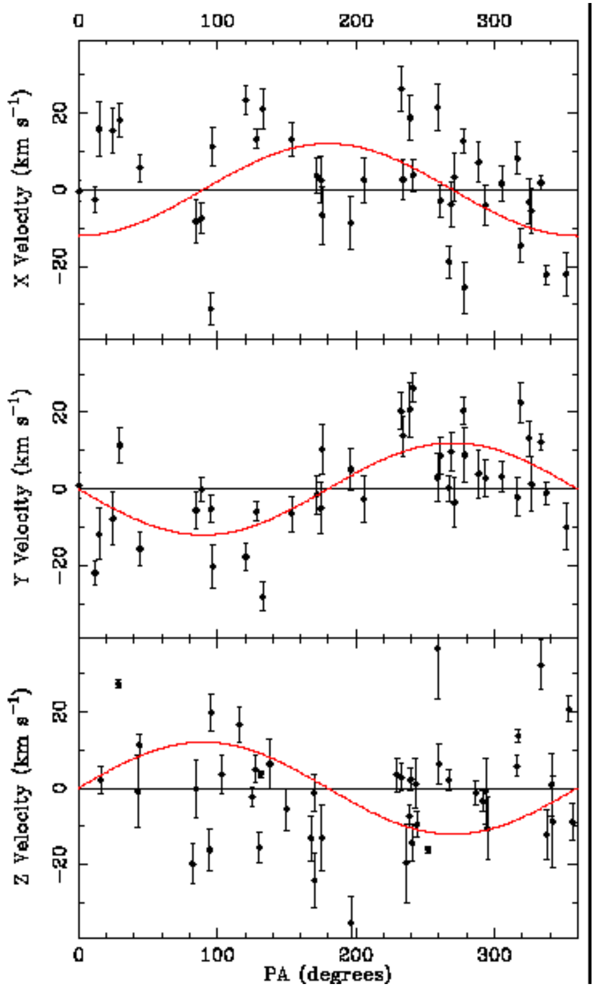
- BHs in the range 100-1e5 Msun are very important to understand to SMBH growth
- One major issue is understanding the seed for SMBH
- A central BH in a GC will have very important consequences for its evolution

Rotation in Globular Clusters

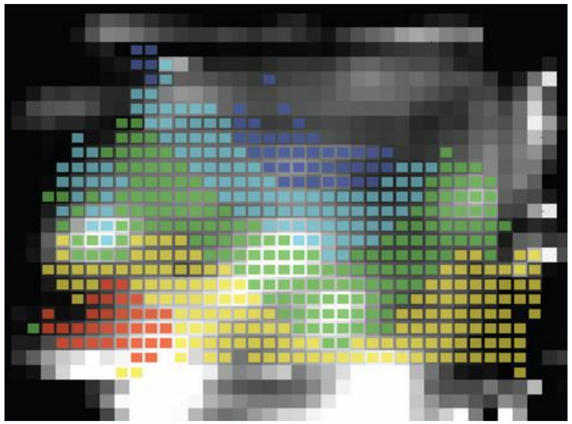
Clusters with more than 500 radial velocities



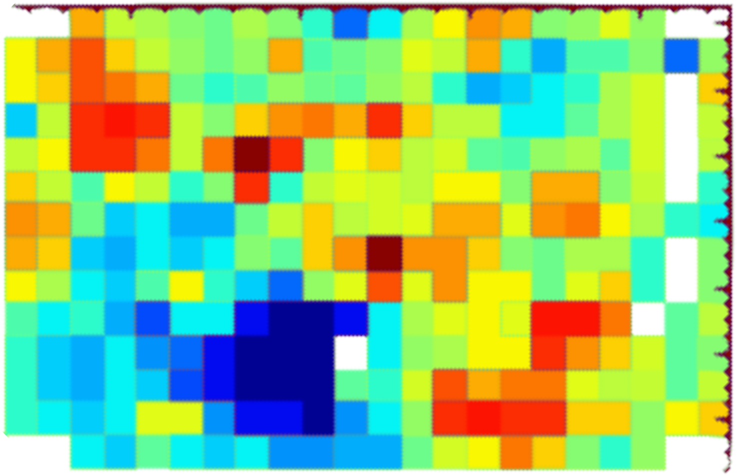
M15 rotation seen in rv and pm (van den Bosch et al. 06)



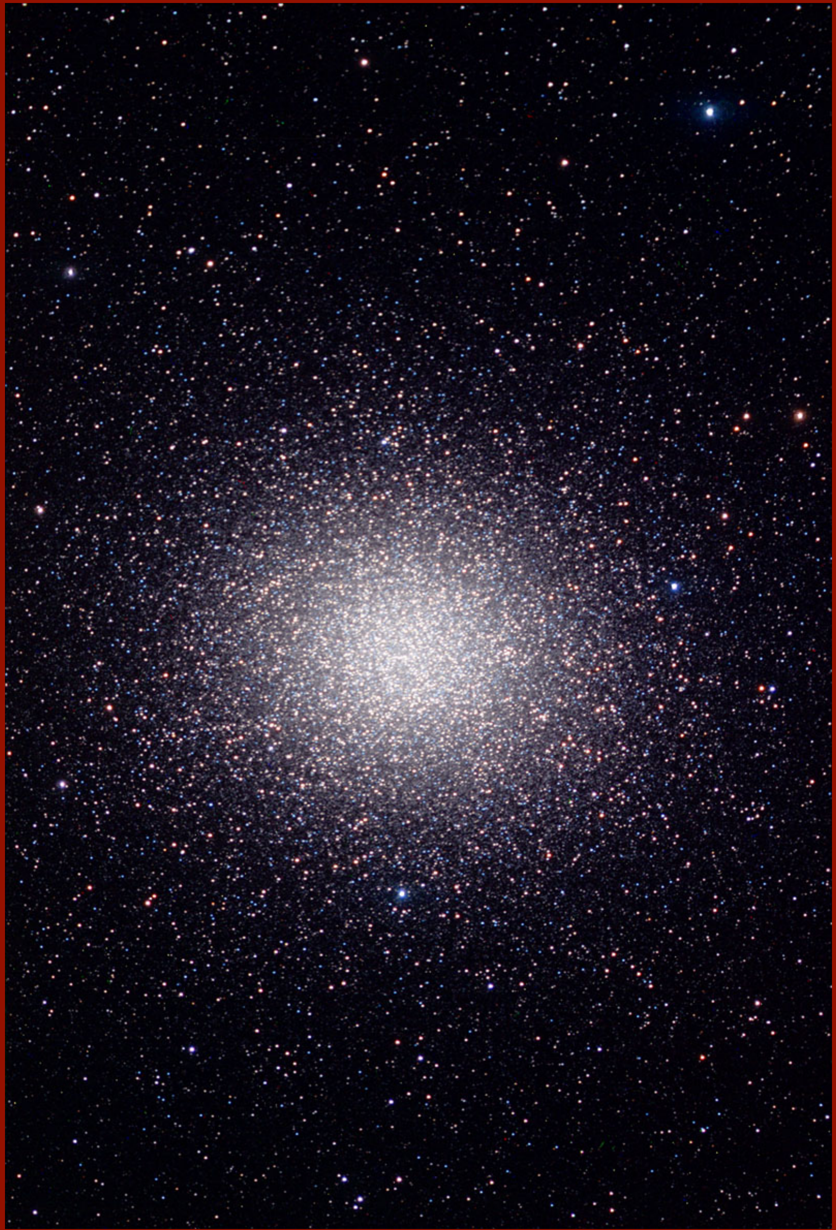
M54 with v/sig=0.8



N6266 from FLAMES, 15km/s amplitude



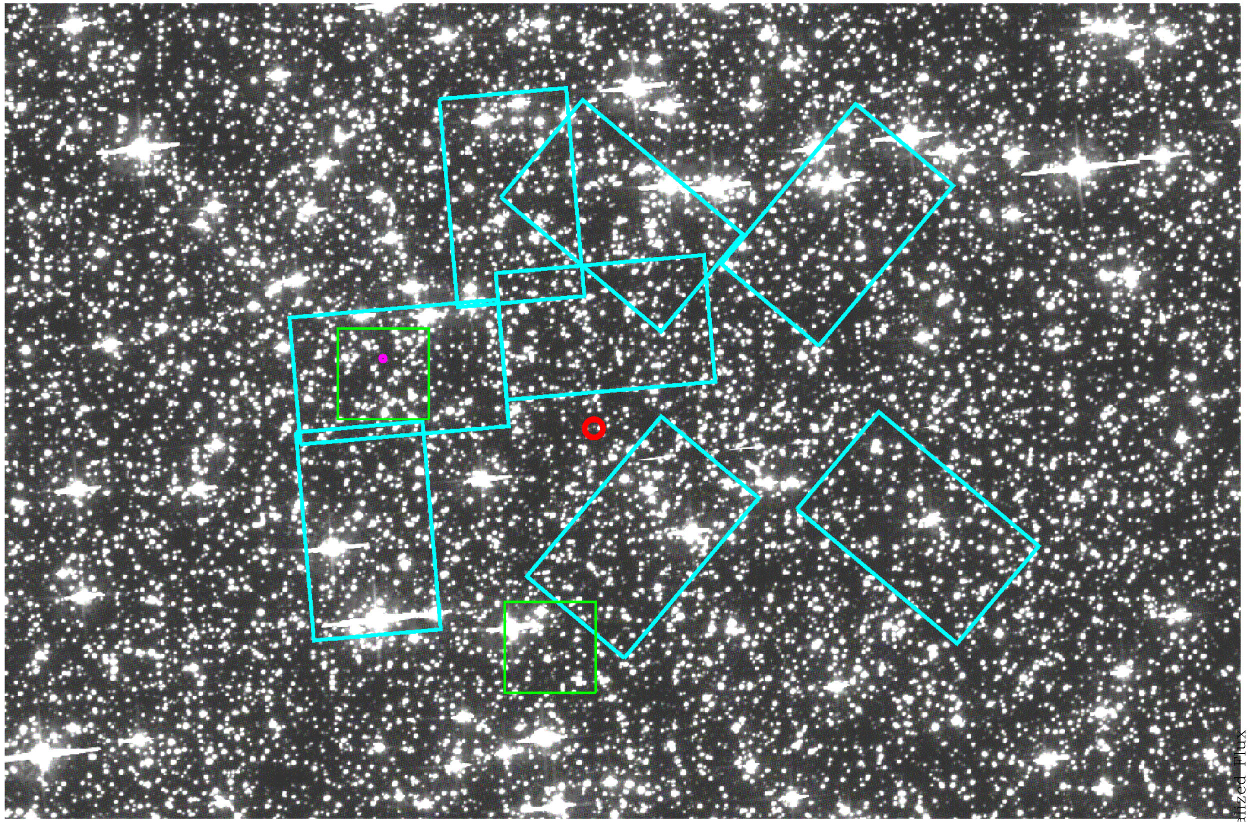
So What is Going on in omega Cen?



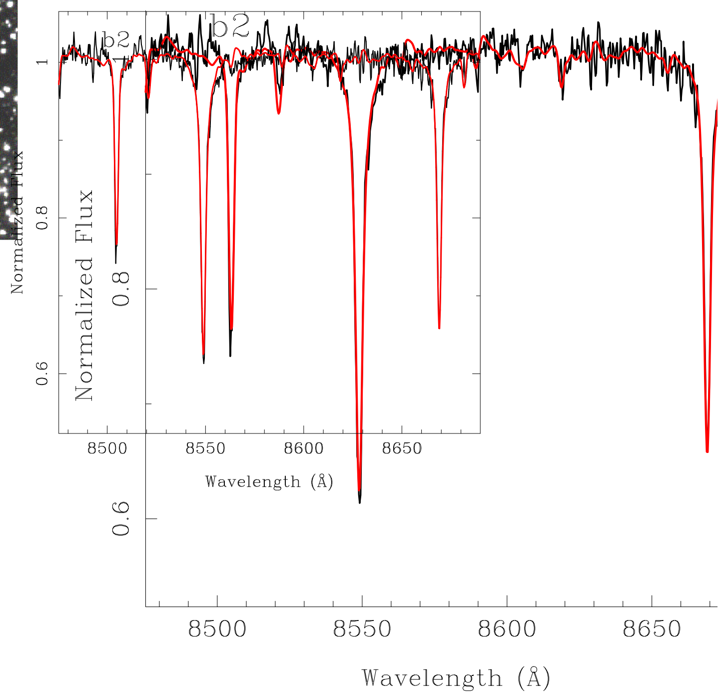
- omega Cen is the most massive of the MW star clusters; suggested to be the stripped core of an accreted galaxy
- van de Ven 06 have detailed dynamical model at large radii
- Noyola et al 08 argue for a central SB cusp; Anderson & van der Marel argue for a core (due to center difference)
- Kinematics from radial velocities: Noyola et al. using Gemini and VLT of integrated light, kg et al. from VLT with individual stars
- Kinematics from proper motions: Anderson & vdM and vdM & Anderson use HST pm for 80000 stars
- NGB argue for a BH, vdM&A argue the data are inconclusive

VLT/FLAMES IFU observations of omega Cen

(Noyola, kg, Jalali, Lutzgendorf, Kissler-Patig, Baumgardt, de Zeeuw)



FLAMES is an amazing instrument, the perfect one for this project. We have excellent data on oCen, N2808, N5286, N6266, and N6388.



There are 4700 spectra at R=10000; to the right is a combination in one of the 5 radial bins. Each IFU is 11.5x7.3".

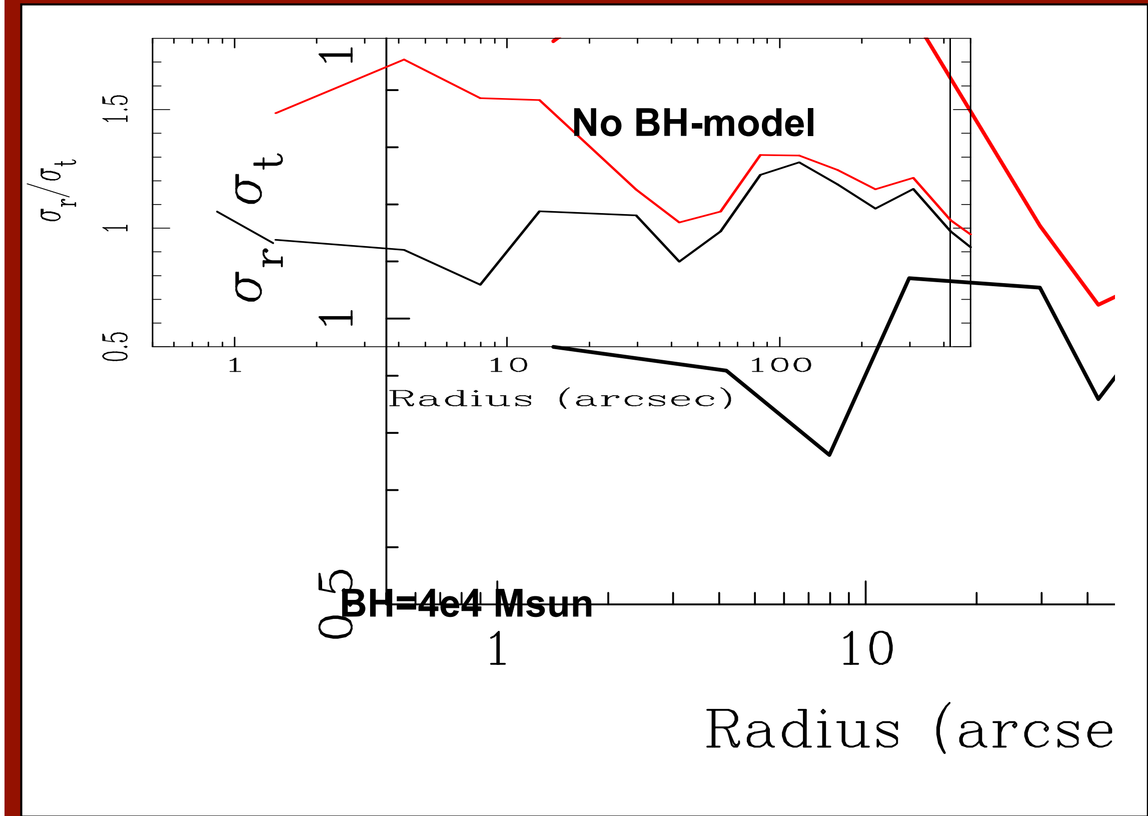
The two main interpretation issues for a BH in oCen are:

Anisotropy

• axisymmetric orbit-based models (G1 and oCen) show better fit to BH models and strongly radial orbits for no-BH models

• hard to have strong radial anisotropy (not seen in simulations)

• van de Ven et al (06) find isotropy at large radii



Remnants

• central density is 5e7 Msun/pc^3 (4e4 Msun inside 0.058 pc)

• core mass (R<60") = 4e4 Msun

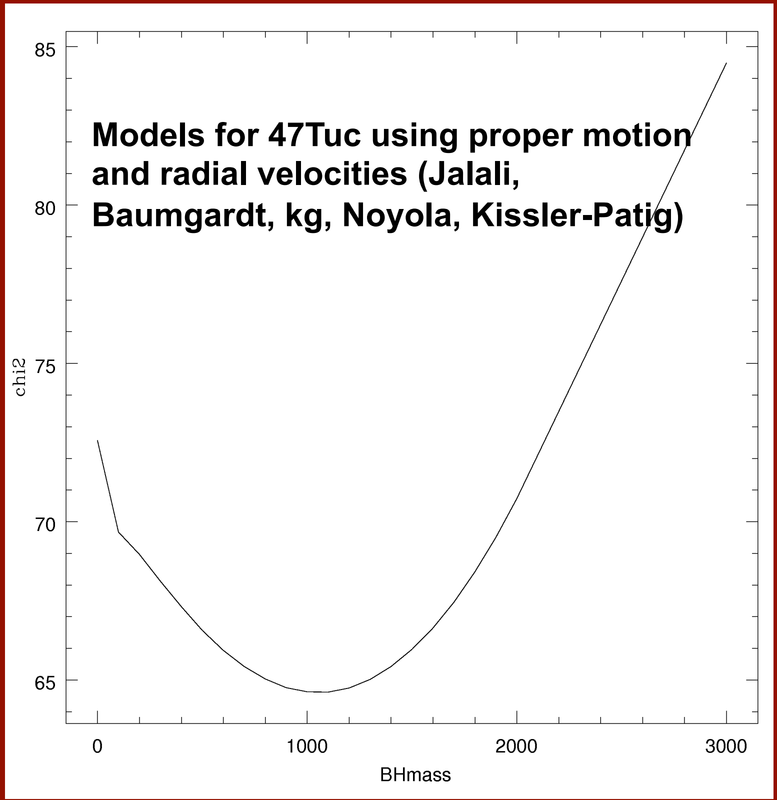
• if all remnants, then size of cluster would be less than 10"

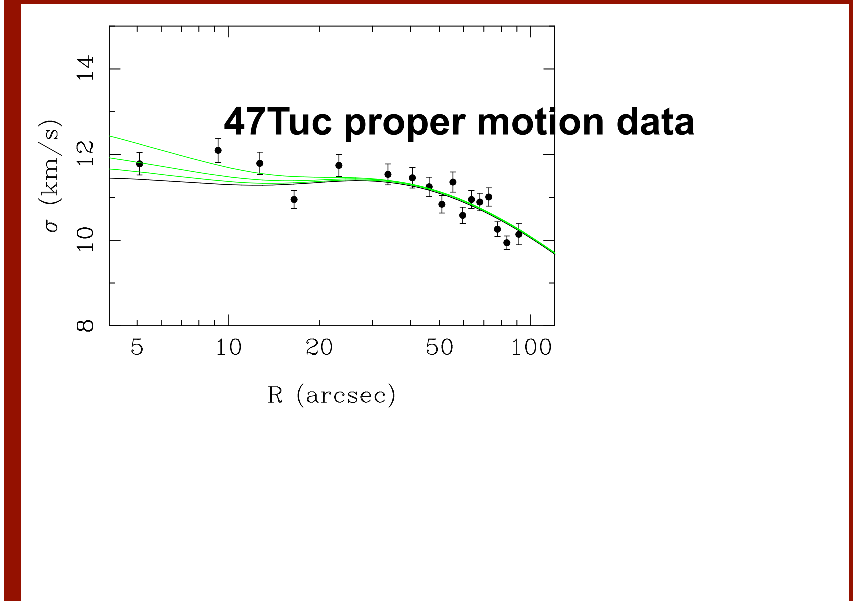
• a cluster of ns or heavy wd would evaporate on a short timescale

• if all remnants implies a very top-heavy IMF

• clearly calls for a simulation

• lack of blue stragglers in core (Ferraro et al 06) can be explained by interaction with IMBH





Current BH in GC results

→ oCen: 4+-0.8 x10^4, rho0=5e7

→ G1: 1.5+-0.3 x10^4, rho0=1e7

→ M54: 1+-0.5 x10^4

→ 47Tuc: 1000+-300

→ M15: 900+-900, rho0=7e6

→ high central rotation

→ weak cusp in brightness profile

➢ Focus now is on both improved kinematics (mainly from VLT) and evolutionary models.