Low-Mass Black Holes and Nuclear Star Clusters in Nearby Galaxies

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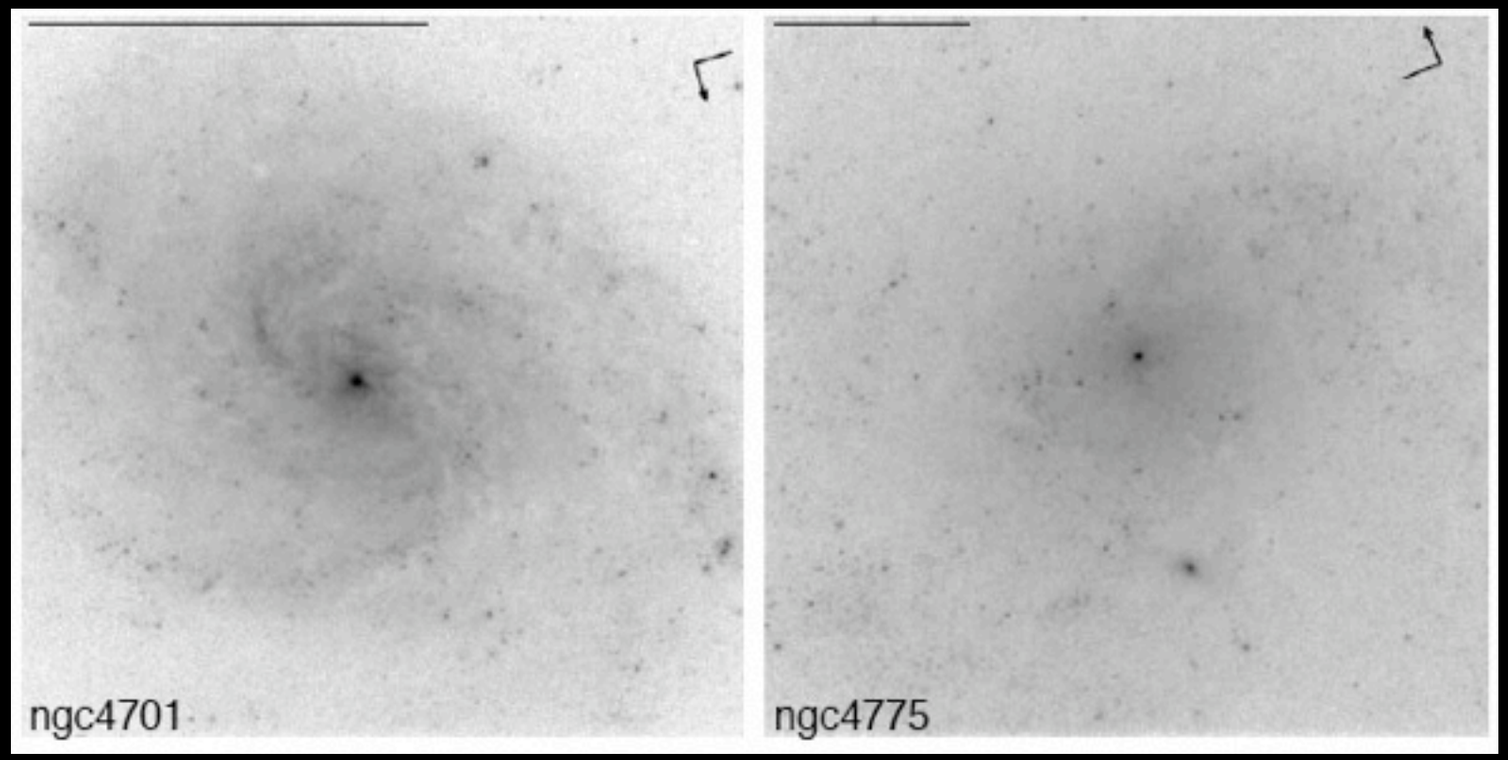
Hubble Space Telescope image of NGC 3621

SDSS Image

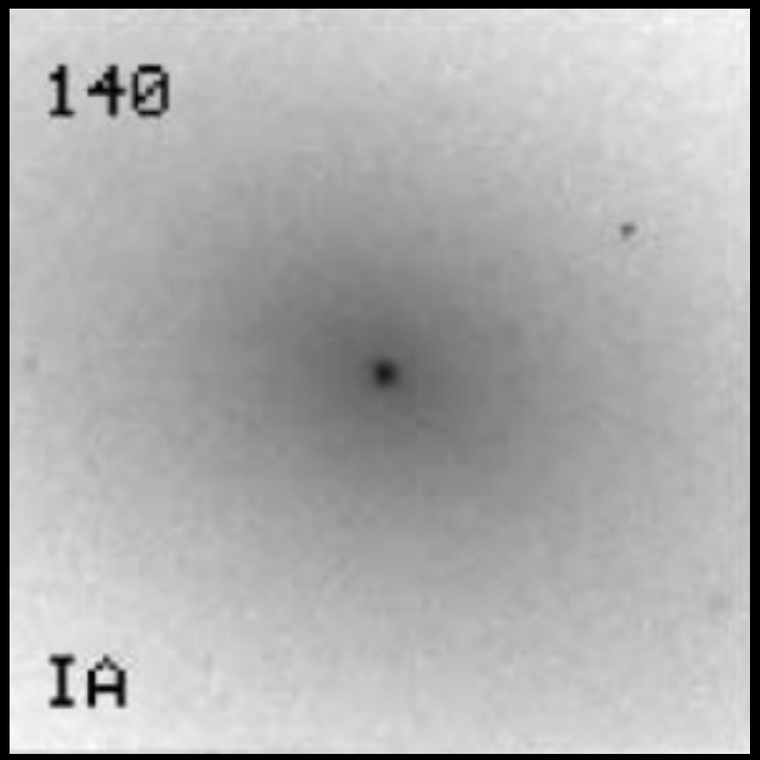
NGC 4244

Nuclear Star Clusters are:

- **Distinct from underlying galaxy profile**
- **Very Compact** (radius ~5 pc)
- **Massive** (~10^7 $M_\odot$) (Walcher+ 2005)
- **Dense** (~10^5 $M_\odot/pc^2$)



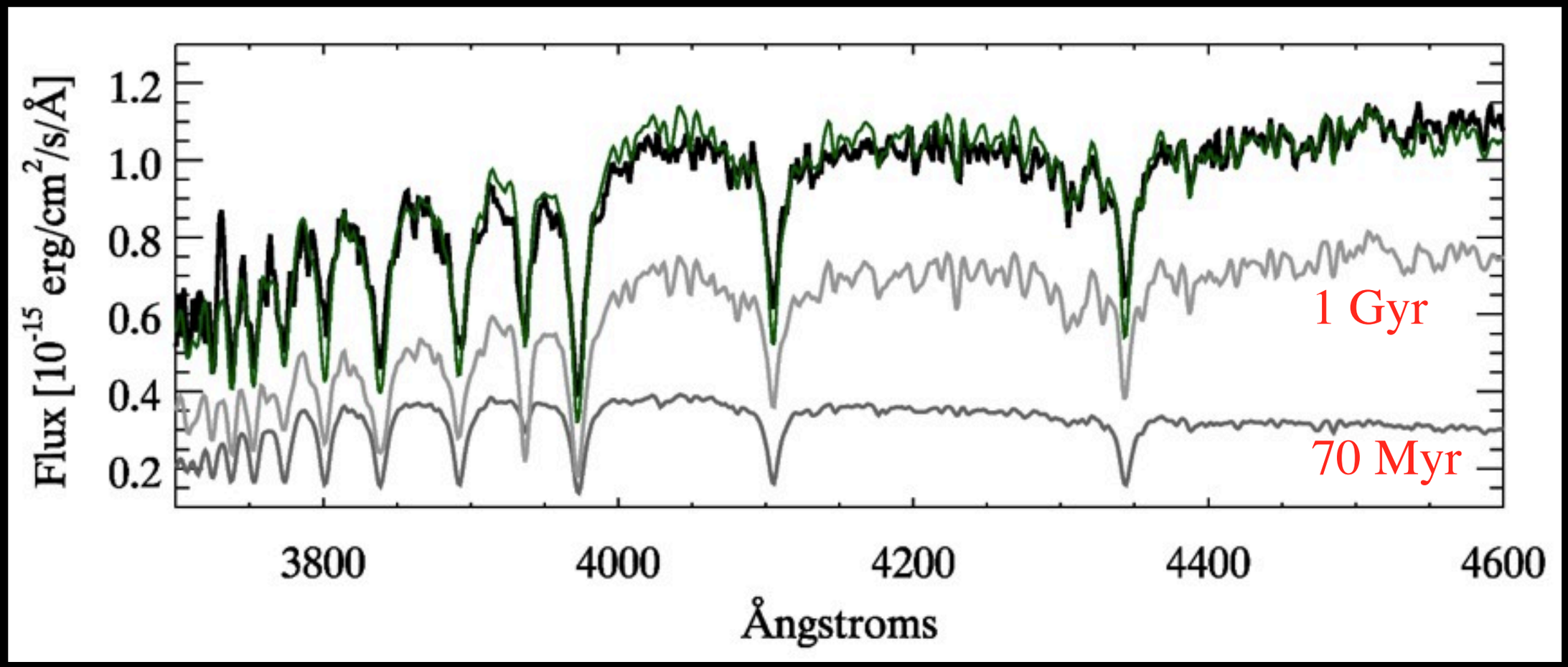
Böker+, 2002



Côté+, 2006

Nuclear Star Clusters (NSCs) have:

- Multiple stellar populations.
- Young stars & ongoing star formation are common.

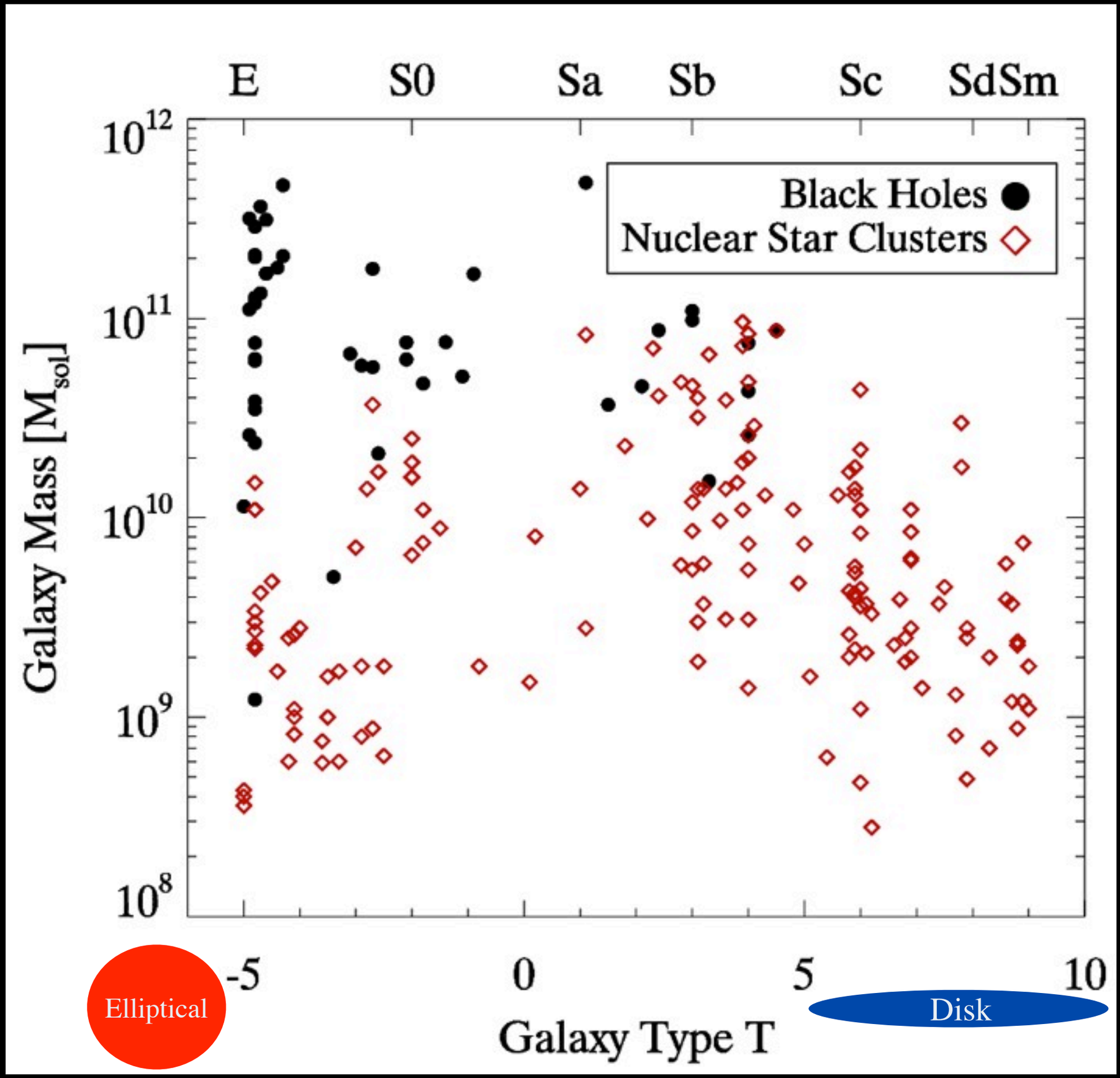


Seth+ 2006 (also Walcher+ 2006, Rossa+ 2006)

All galaxies have black holes!

75% of galaxies have nuclear star clusters.

Black holes are hard to find!



Data from: Böker+ 2002, Côté+ 2006, Carollo+ 1998-2002 Seth+ 2006, 2008a, Gültekin 2009

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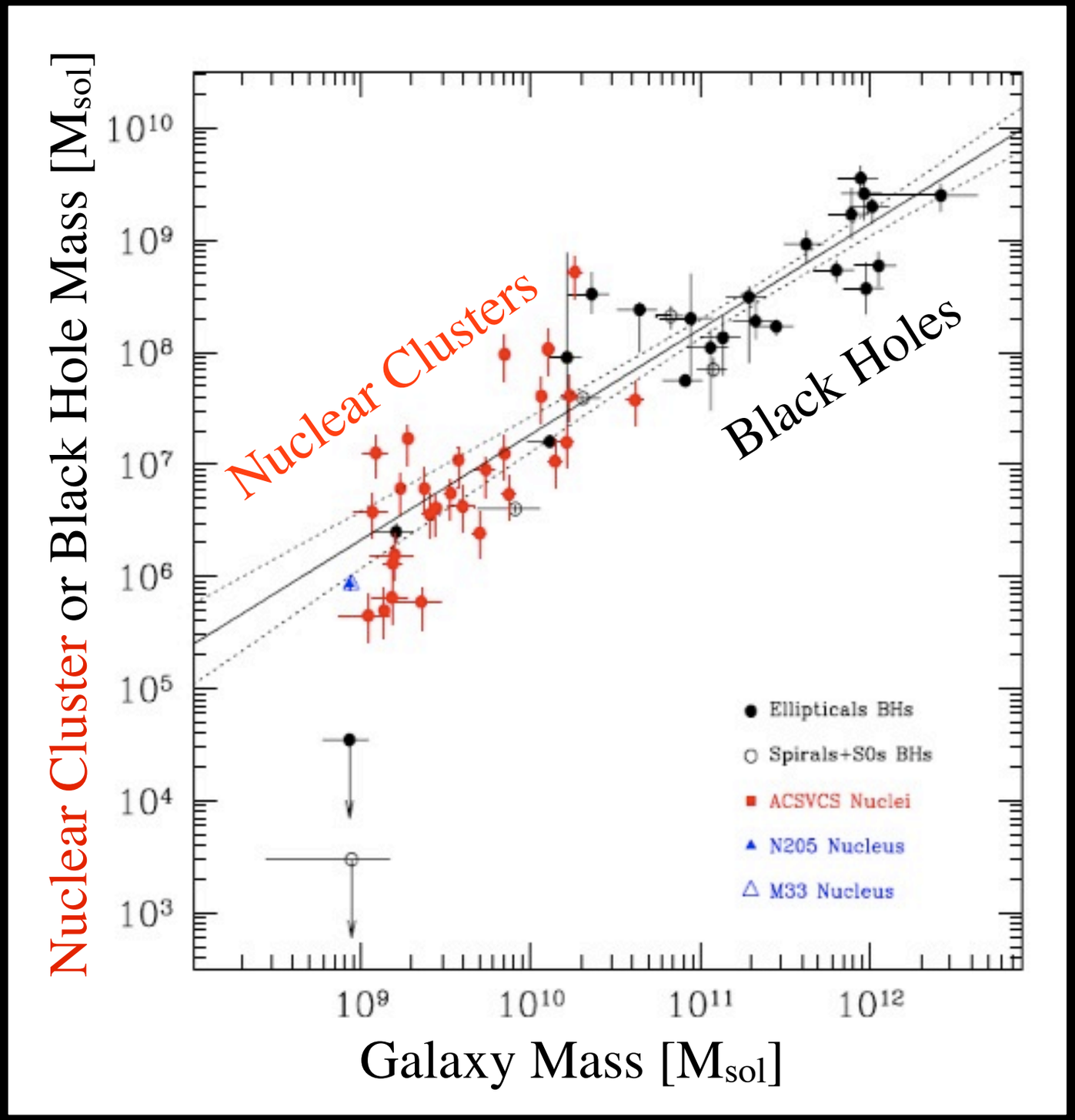
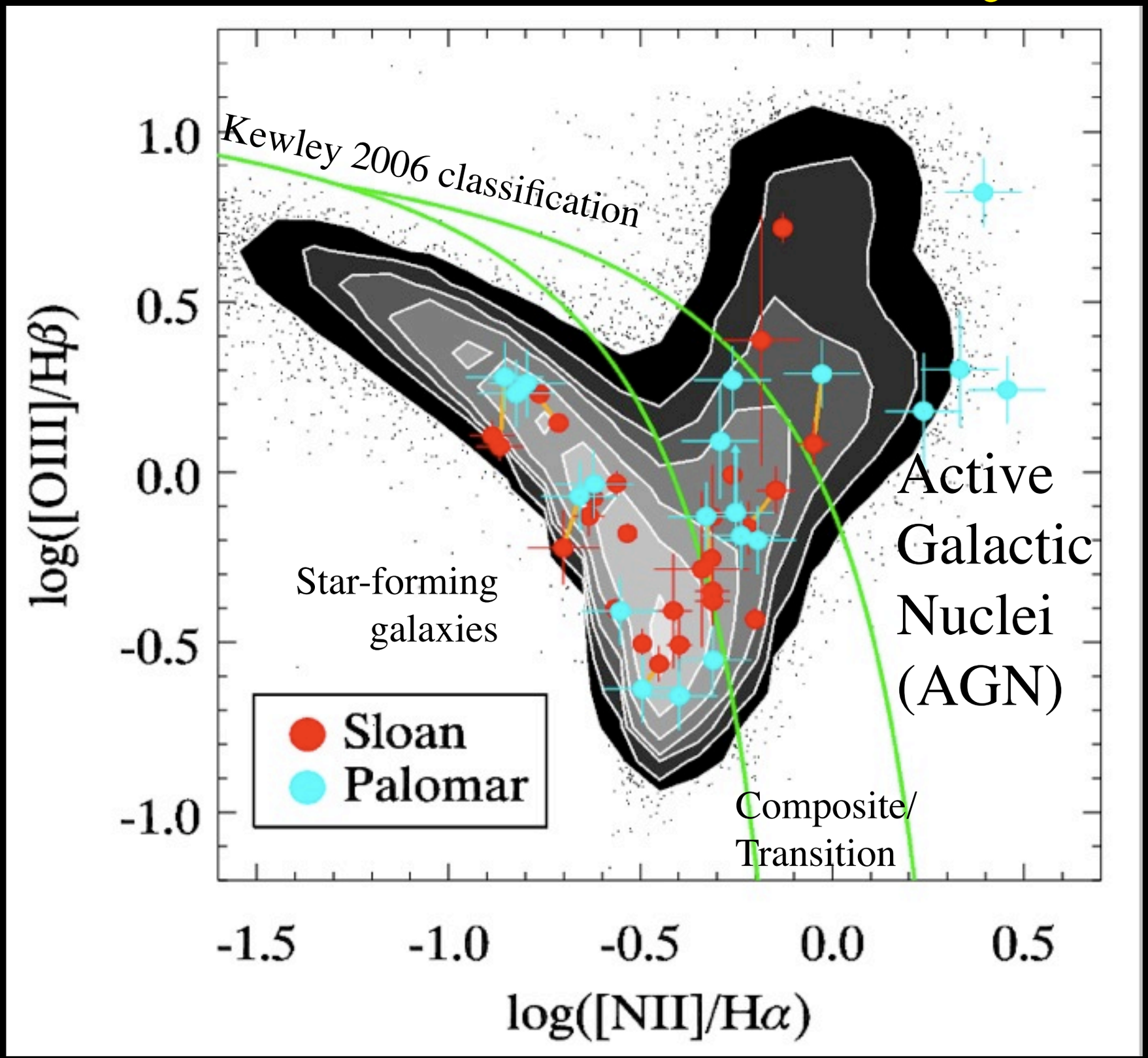
A surprisingly simple relationship



Ferrarese + 2006 (for Elliptical Galaxies)

- NSC and black hole masses correlated with galaxy masses and bulge velocity dispersions. (Wehner & Harris 2006, Rossa+ 2006, Ferrarese+ 2006, Graham & Driver, 2007 Erwin & Gadotti 2010)
- Suggests links between galaxies, nuclear star clusters and black holes

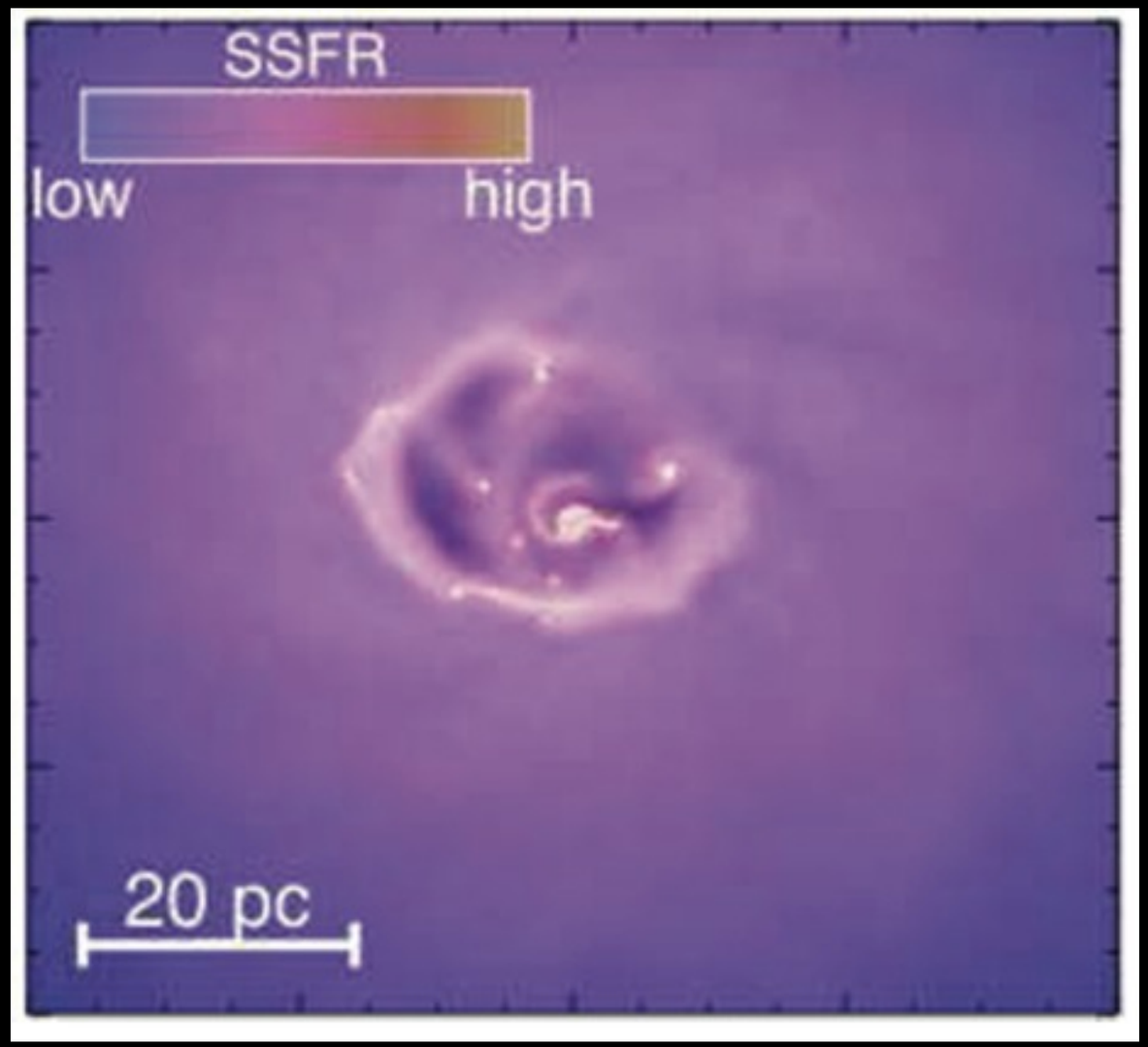
NSCs & BHs commonly coexist



Seth+ 2008a

>10% of NSCs have AGN-type spectra suggesting black hole accretion

The BH - NSC connection

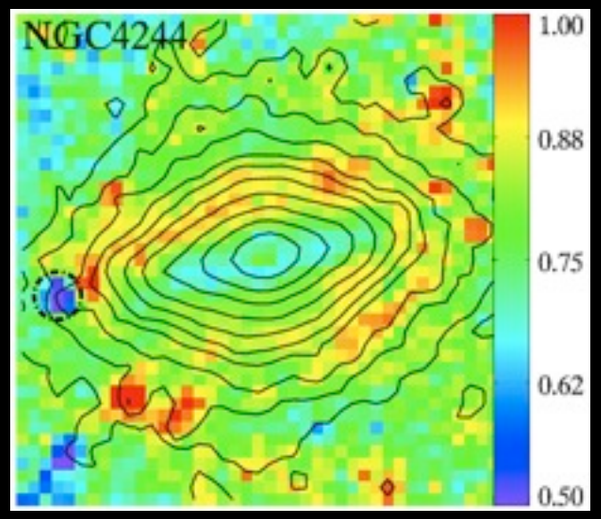


- Both are fed from the same events?
  (e.g. Hopkins & Quataert 2010a,b)
- NSC formation results in BH formation?
  (e.g. Portegies Zwart 2004, Vespirini 2010)

Need to study systems with nuclear star clusters and black holes

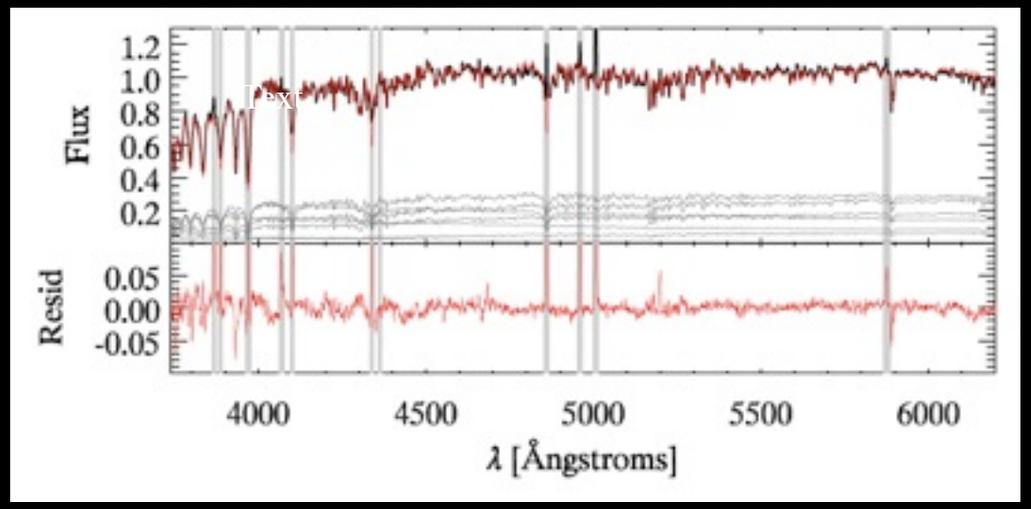
Resolving Nearby Nuclear Star Clusters

1) Morphology



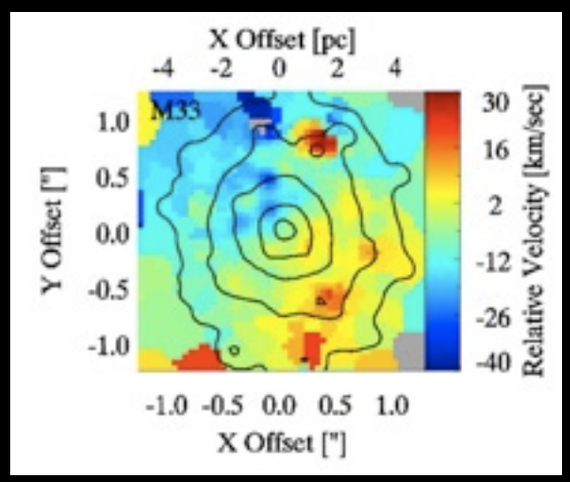
Hubble Space Telescope Imaging

2) Stellar Ages



Optical Spectra (Magellan, MMT, VLT)

3) Kinematics



Adaptive optics infrared spectra (Gemini, VLT)

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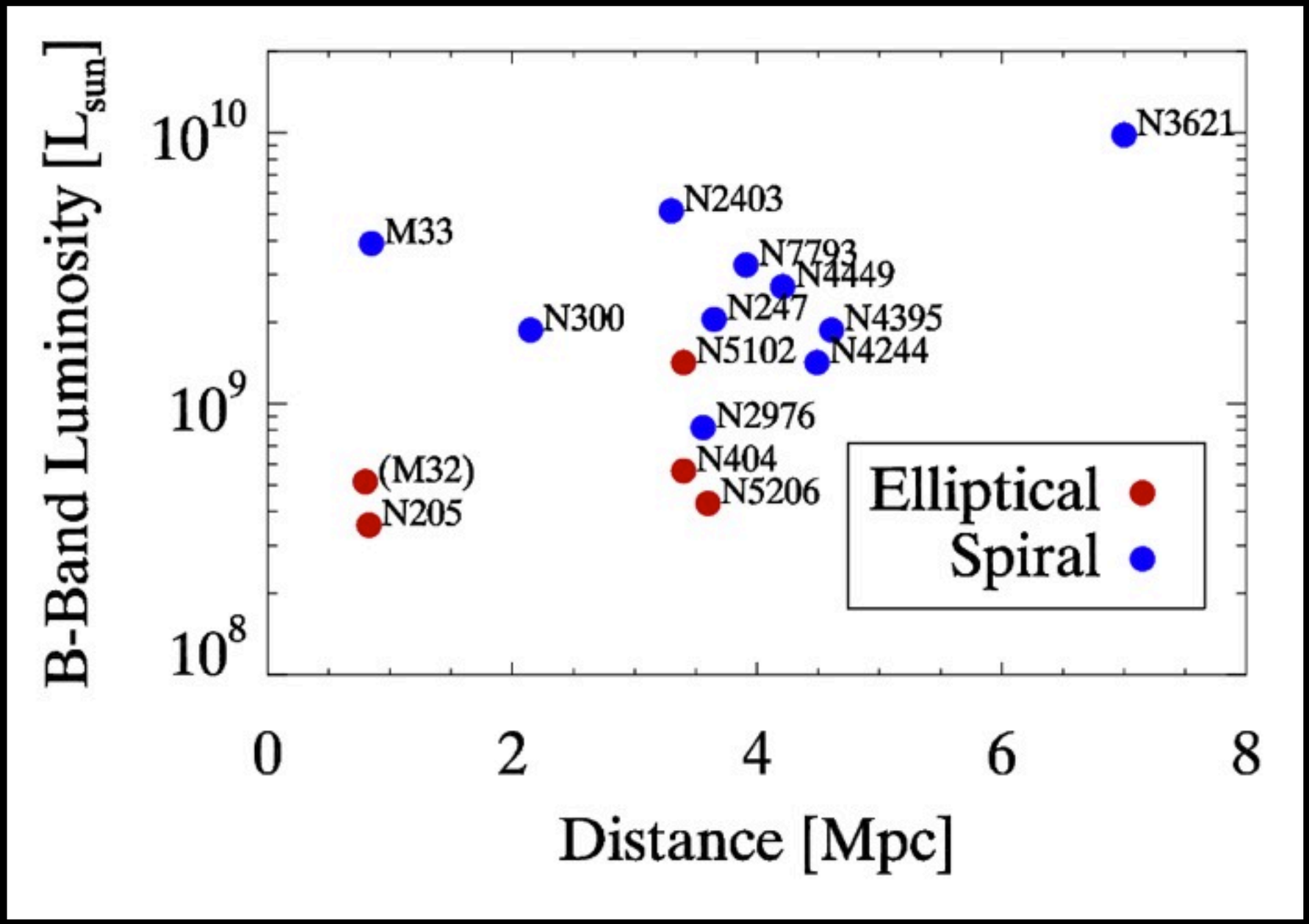
Nearby Nuclear Star Cluster Survey



Seth+ 2008b, Seth+ 2010, Seth 2010, Neumayer+ *in prep*

Primary Collaborators:

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Michele Cappellari
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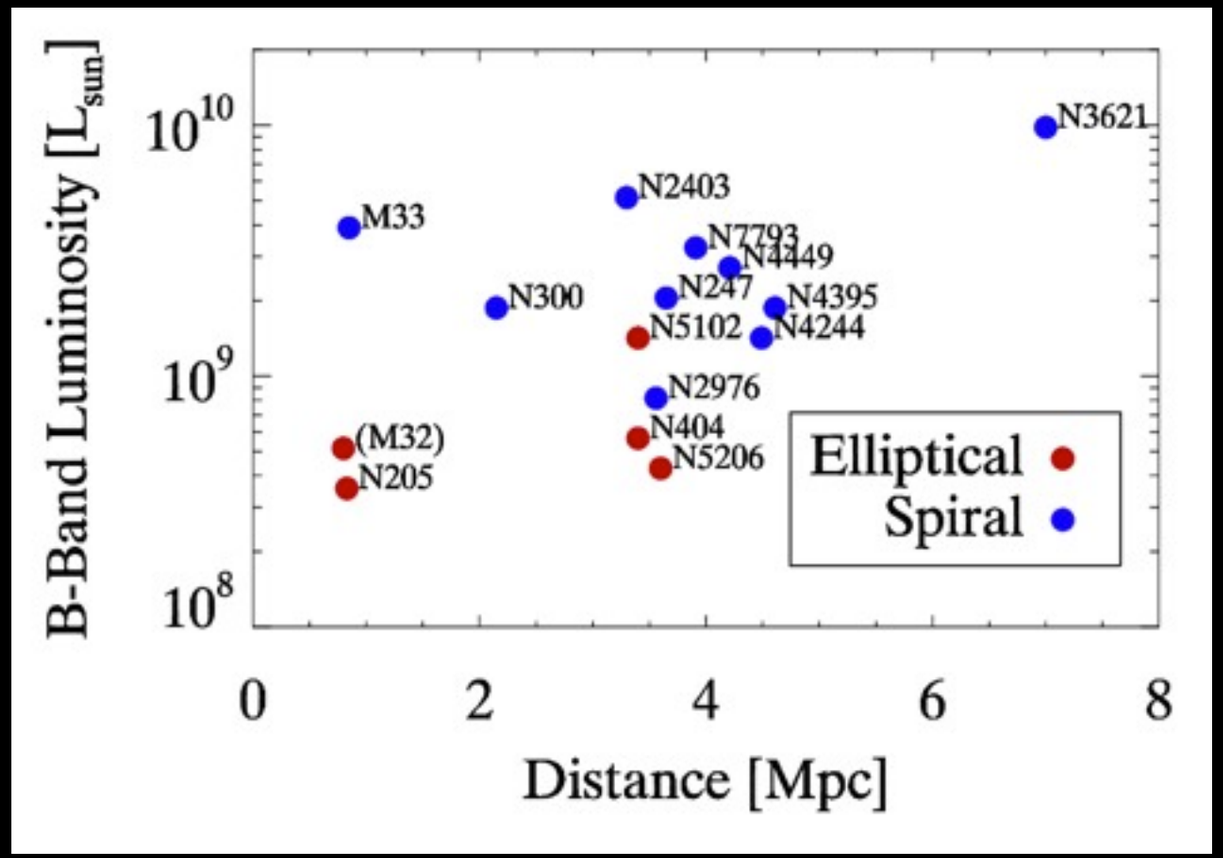
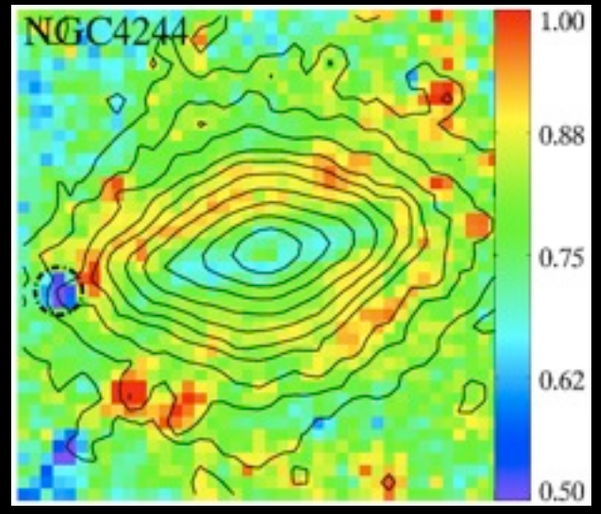
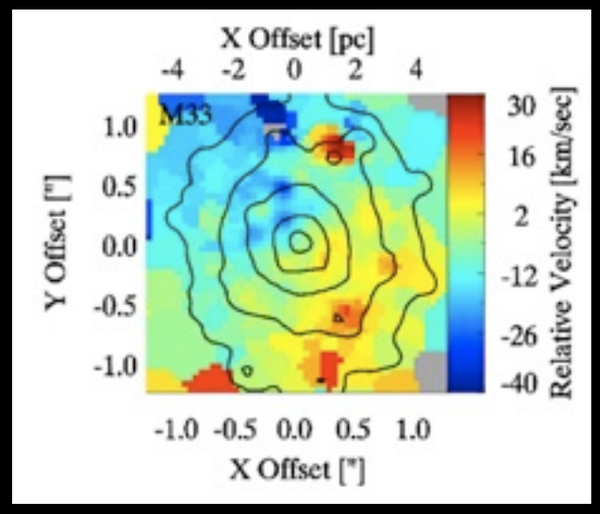
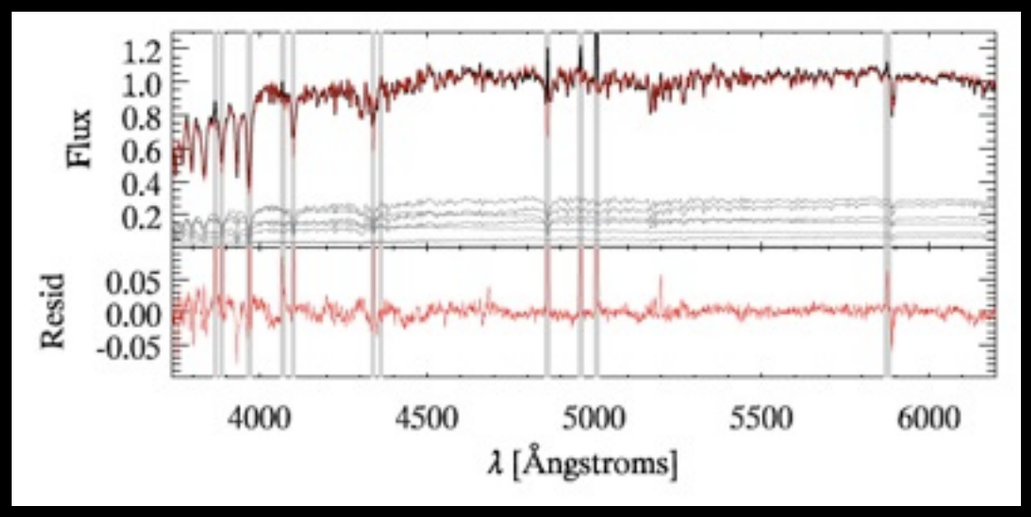


Survey Goals

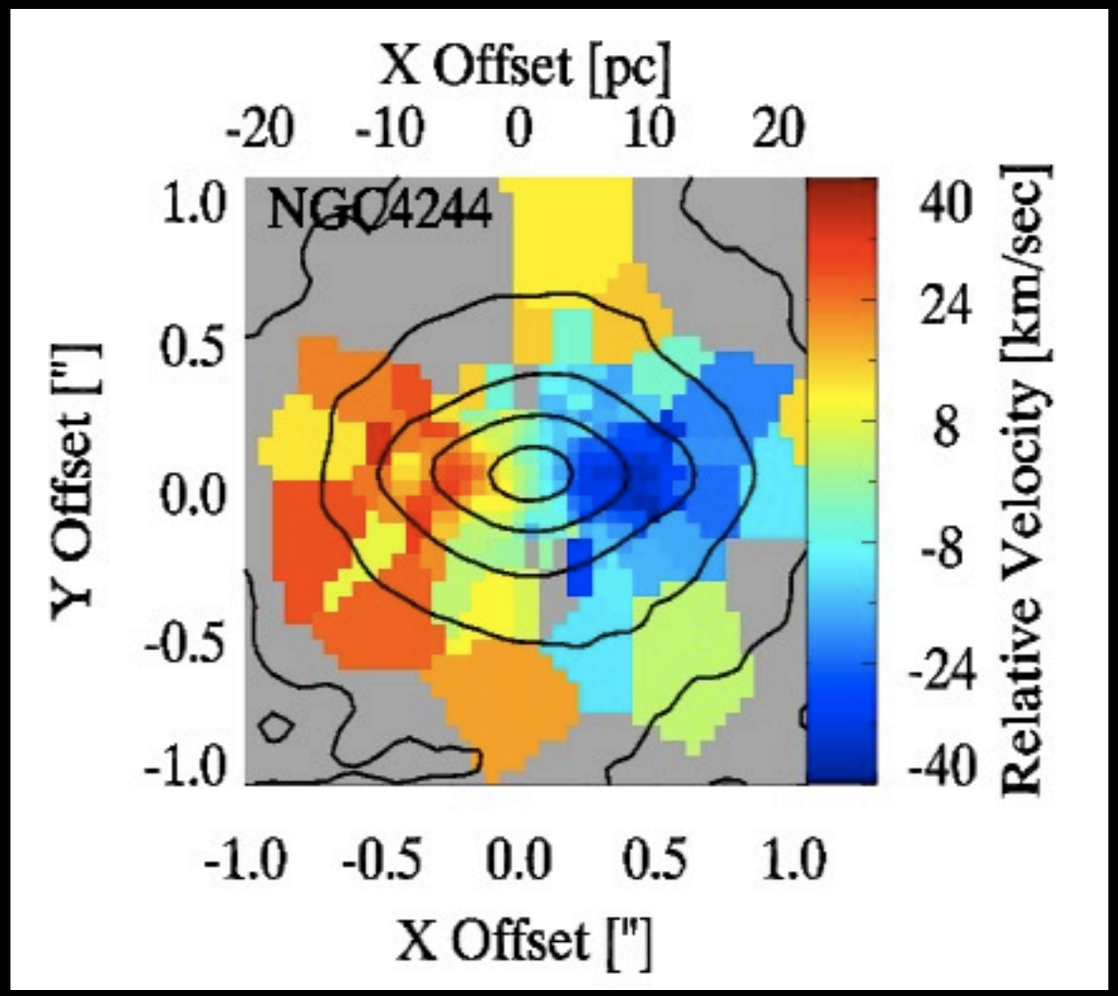
- Understand the formation of nuclear star clusters

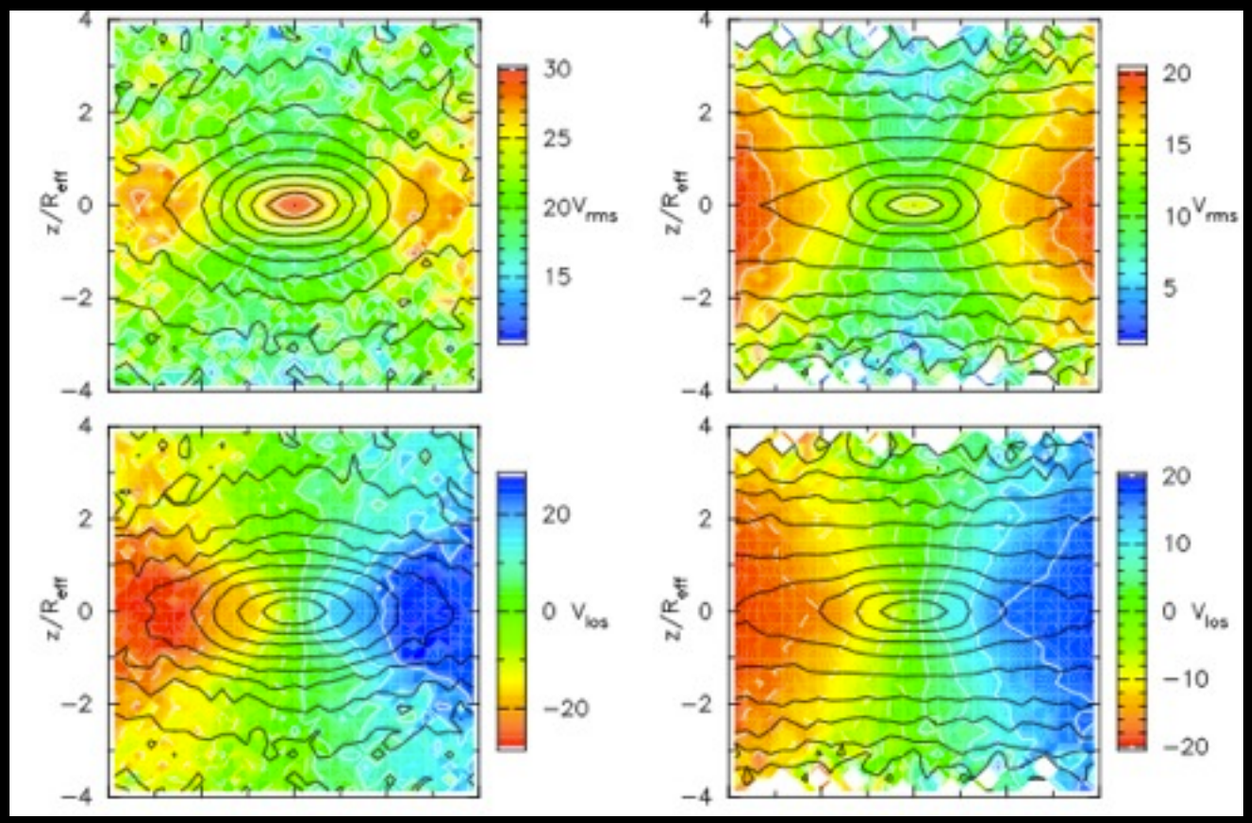






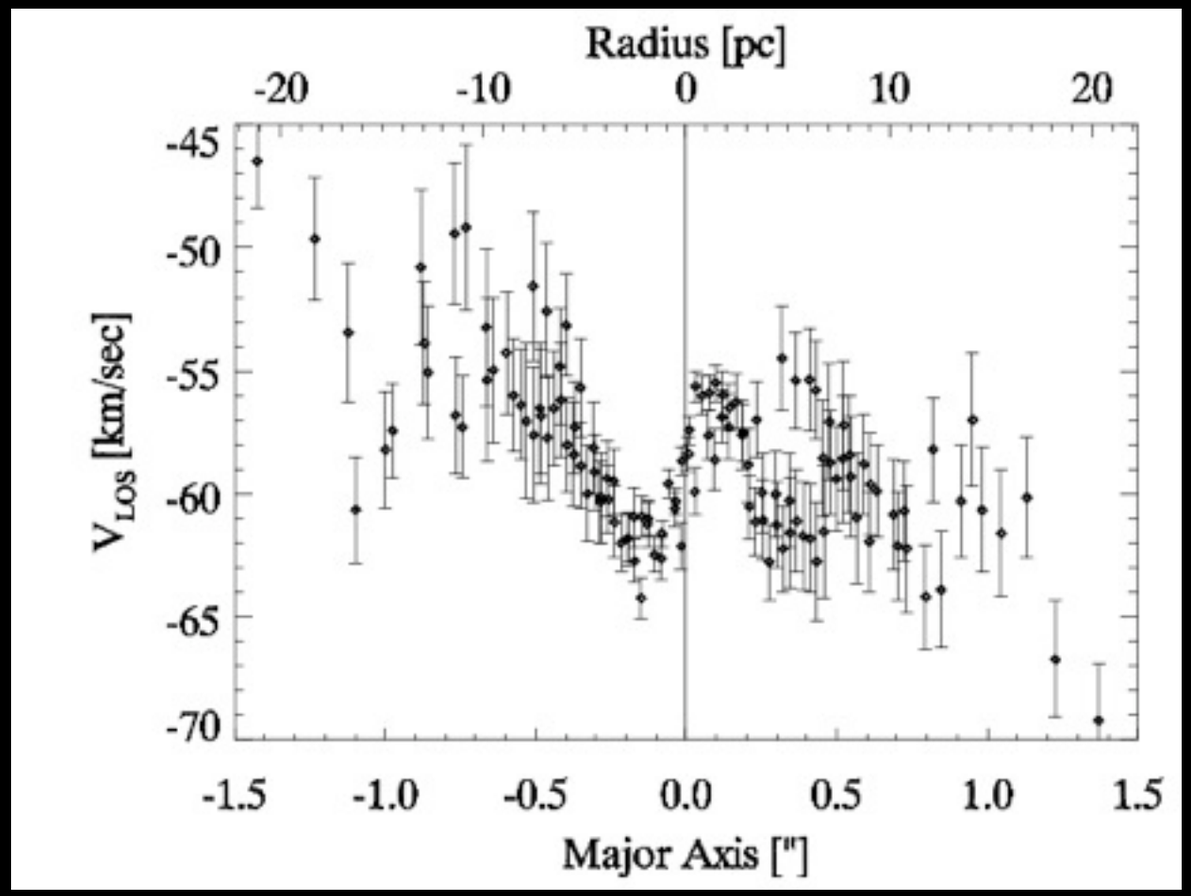
- Find and measure the mass of the smallest central black holes





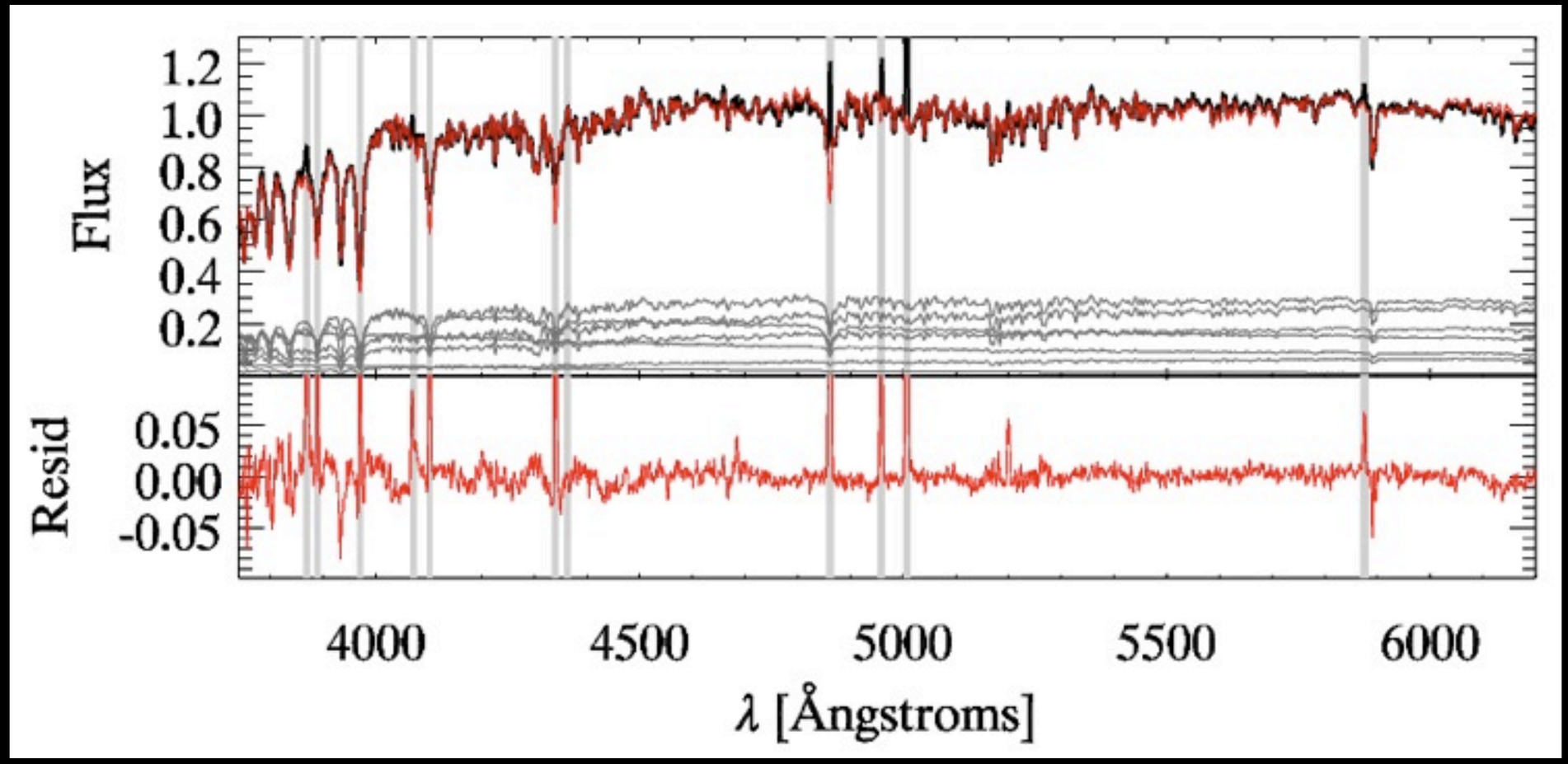
Formation of Nuclear Star Clusters

- Rotation is common
  (Seth+ 2008b, Seth+ *in prep)*
- Episodic gas and star cluster accretion are required (Agarwal & Milosavljevic 2011, Hartmann+ 2011)



Evidence for merger accretion in nearby S0 galaxy, NGC 404

(Seth+ 2010)



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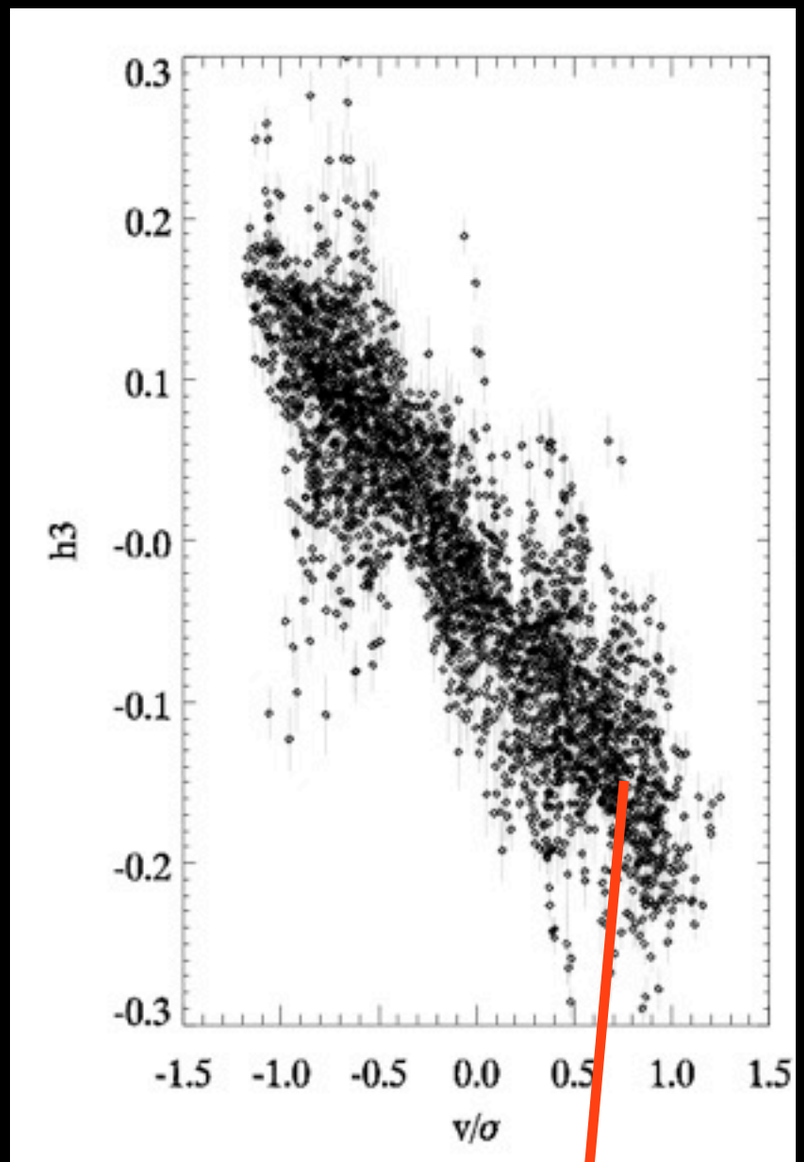
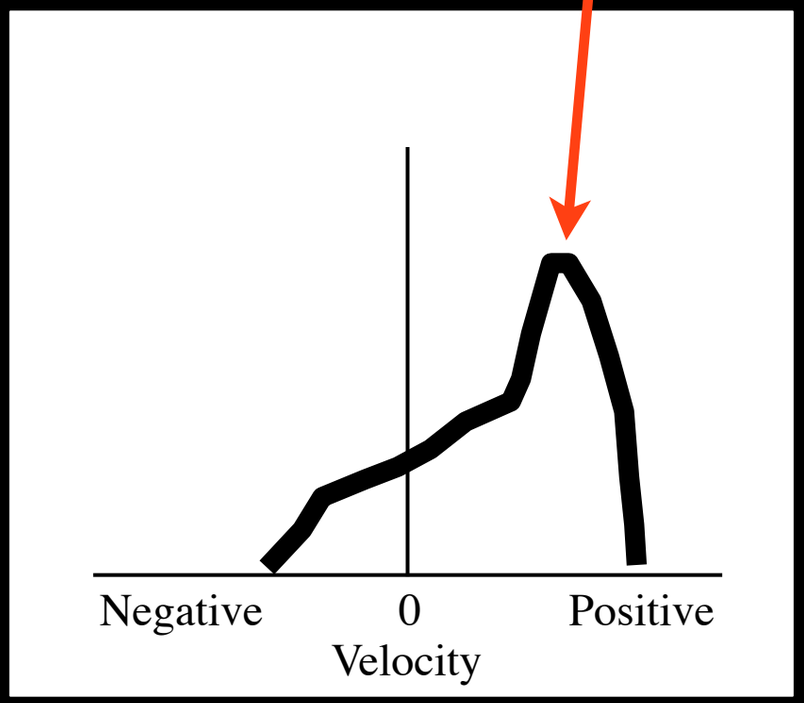


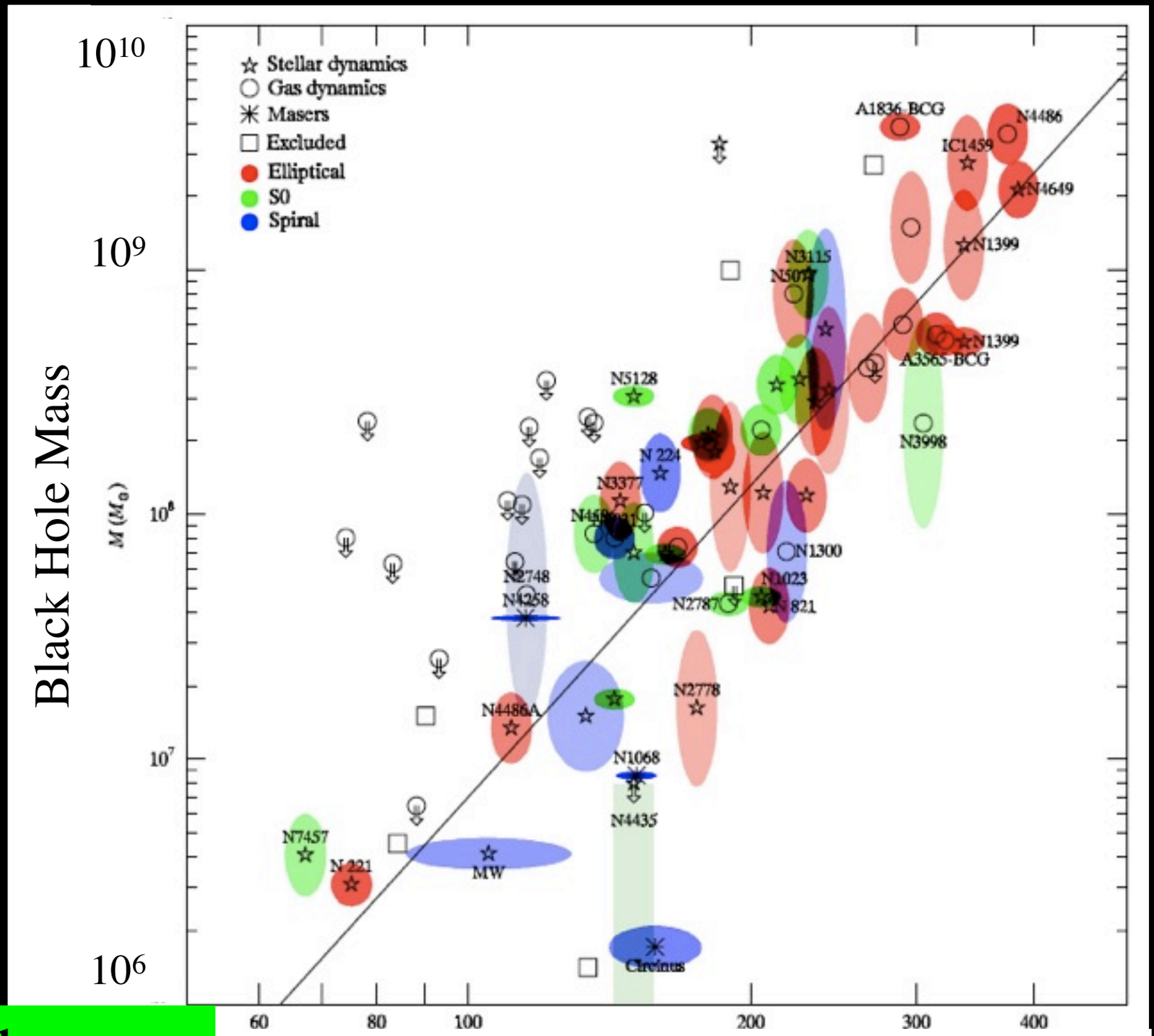


Multiple components in the central 3” of M32

(Seth 2010b)

- Stellar population and abundance gradients suggest disk formed from stellar winds of galaxy

(e.g. Bailey 1980)



Nearby Nuclear Star Cluster Sample

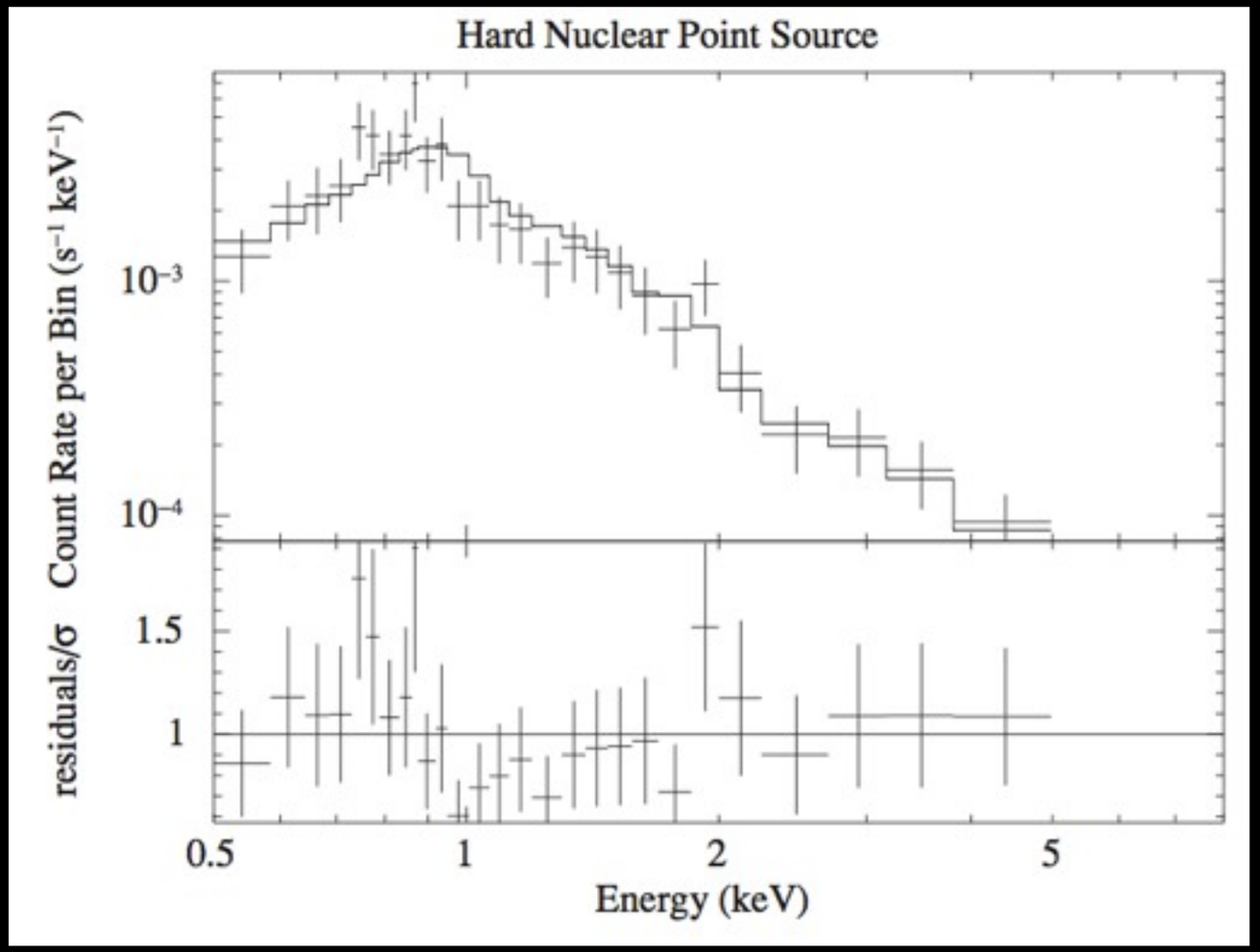
Gultekin+ 2009

NGC404:

(D~3 Mpc, σ=35 km/s)

- Nearest S0-type galaxy
- $M_{stellar}$ ~10^9 $M_\odot$
- Galaxy disk and bulge is old (90% of stars >10 Gyr) (Williams, AS+ 2010)
- HI & SF in outskirts (del Rio+ 2004, Thilker+ 2010)
- LINER (Ho+ 1997)
- 10^7 $M_\odot$ NSC with ~1 Gyr old population (Seth+ 2010)

GALEX UV Image of NGC 404

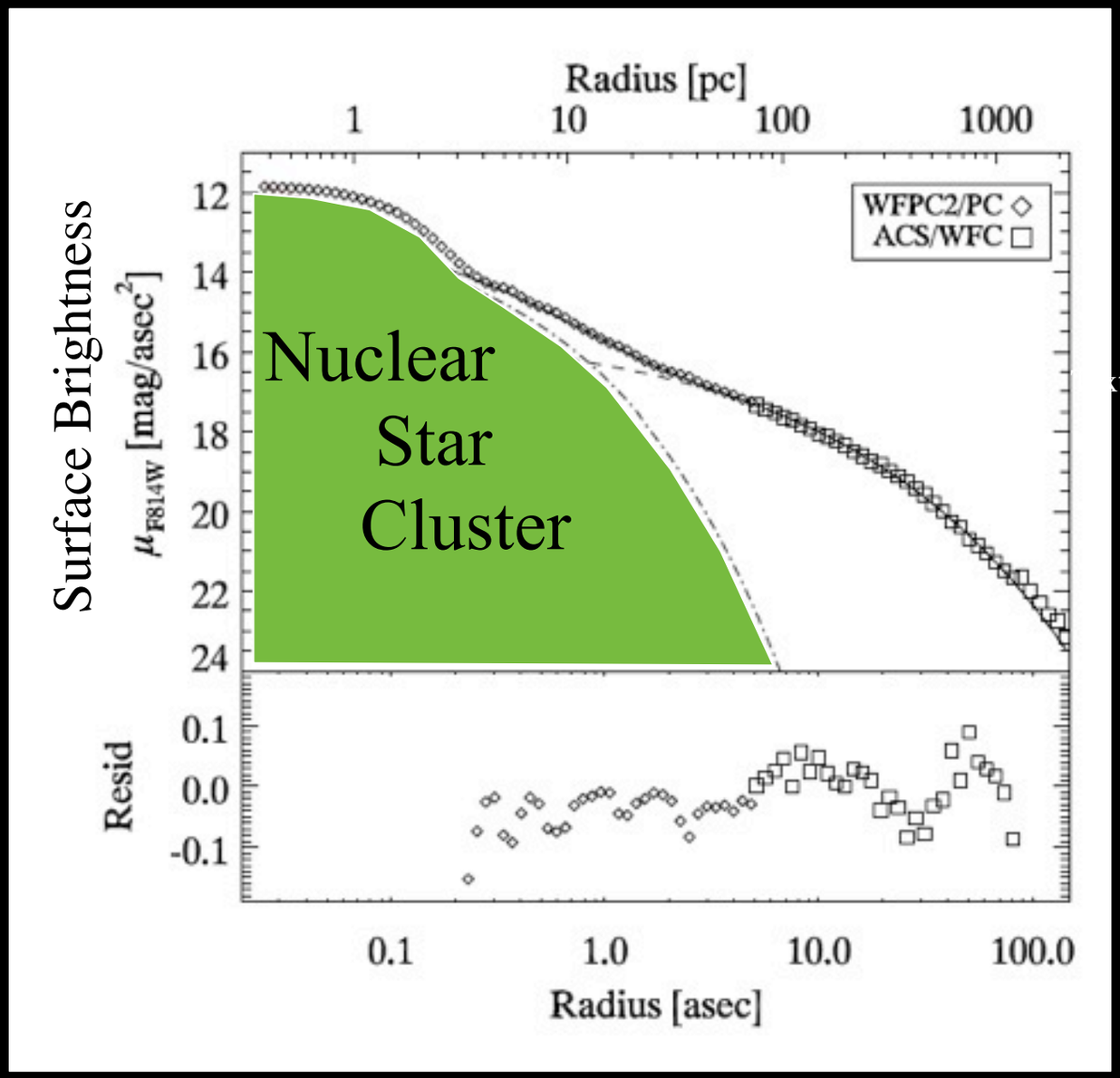


- Strong evidence for black hole accretion: variable UV emission, compact dust & hard X-ray emission

(Maoz+ 2005, Seth+ 2010, Binder+ 2011)

GALEX UV Image of NGC 404

Dynamical detection of black holes (NGC404)



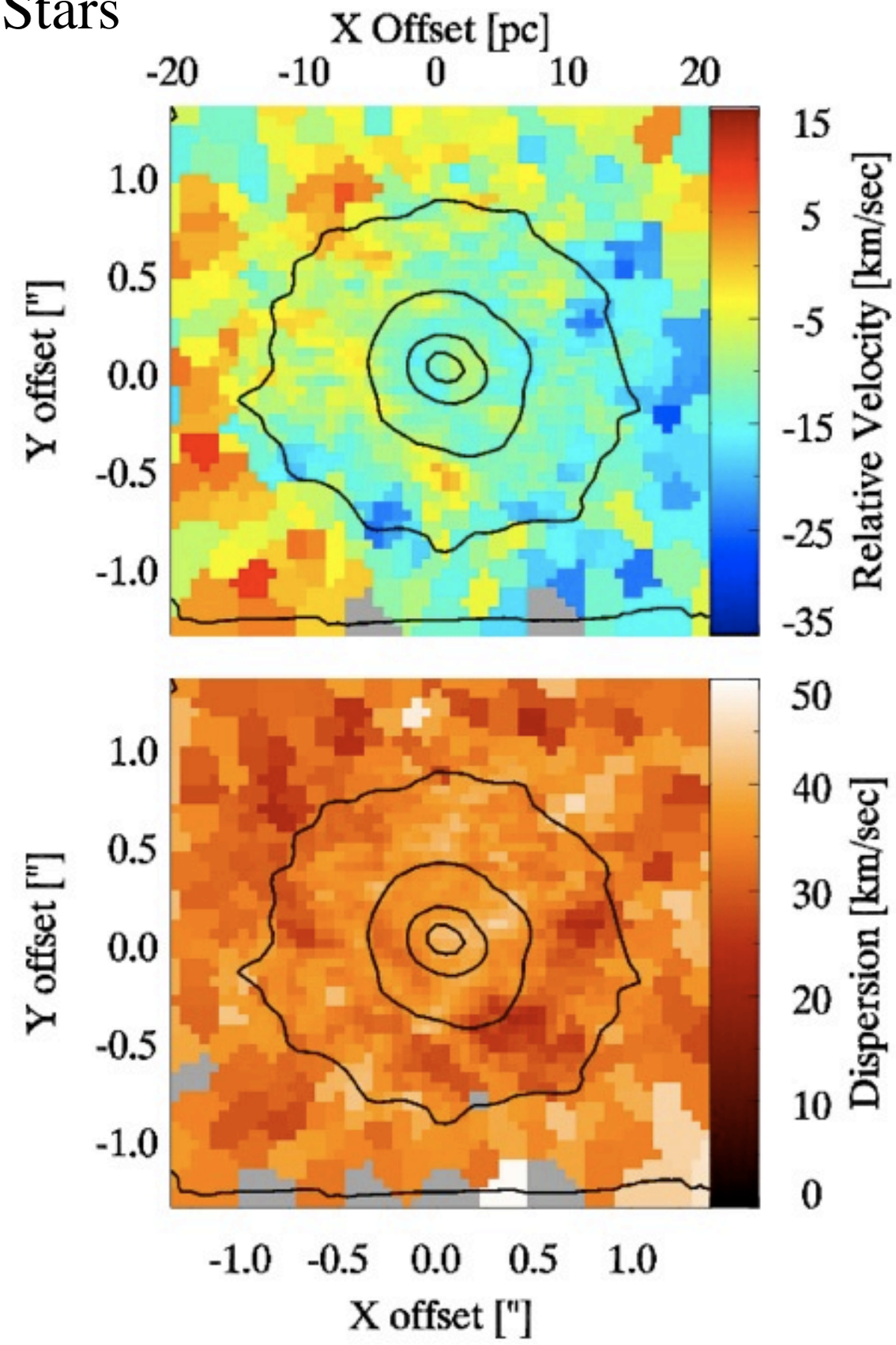
Seth+ 2010

Ingredients:

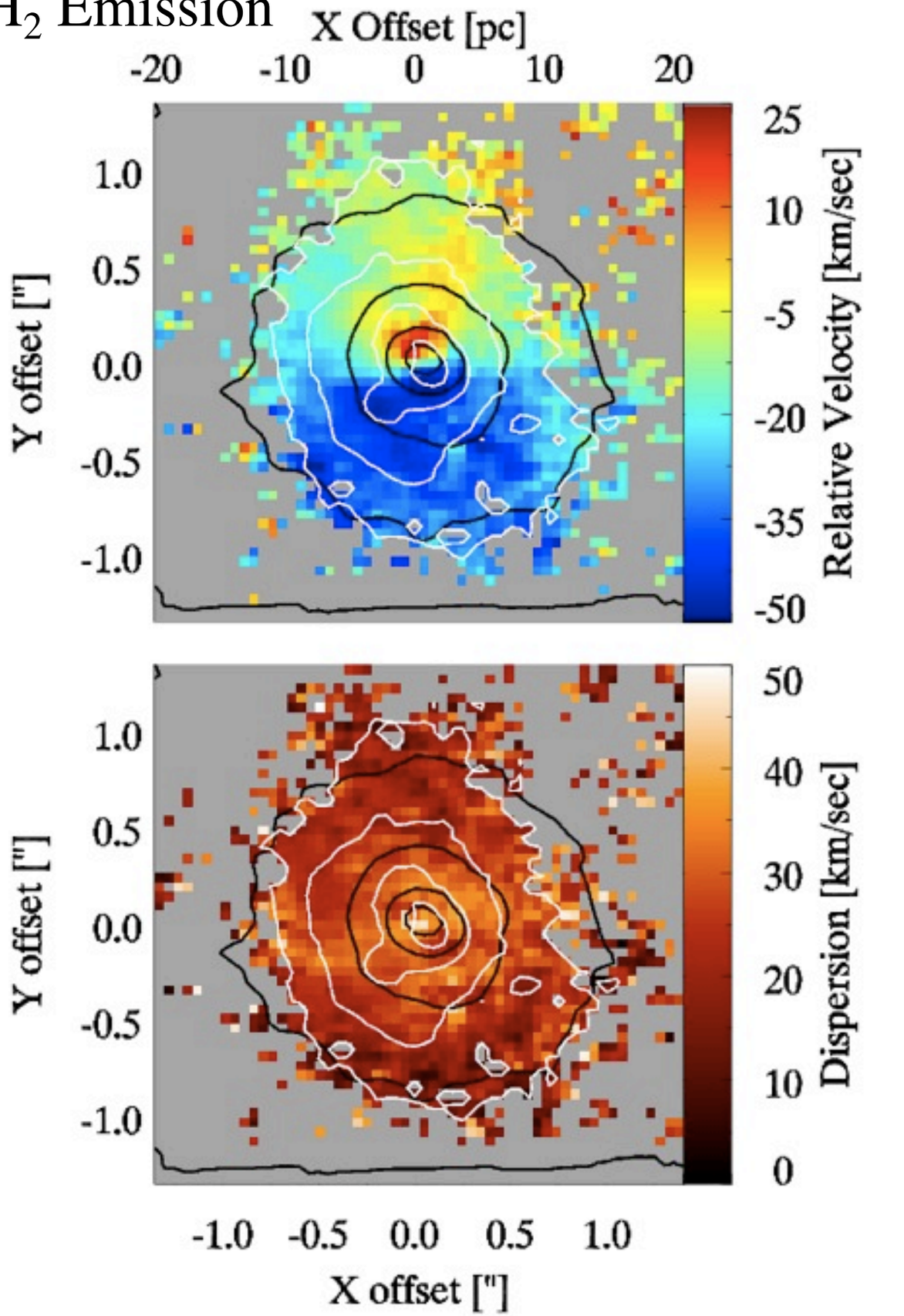
1) Stellar Mass Profile
   - Luminosity Profile
   - fit a Mass-to-Light ratio for stellar light

2) Dynamical Tracer

Stars



H_2 Emission



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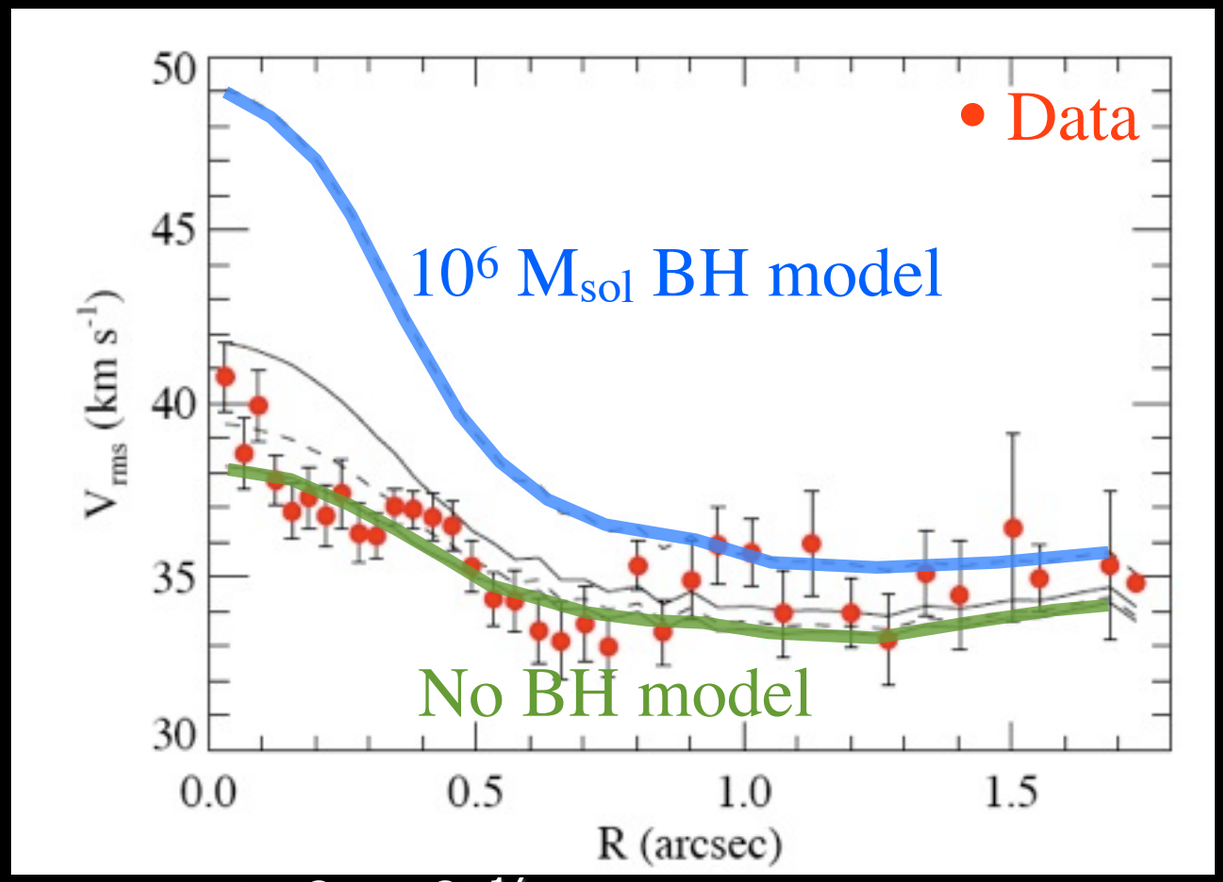
Limits on the BH mass: Stars

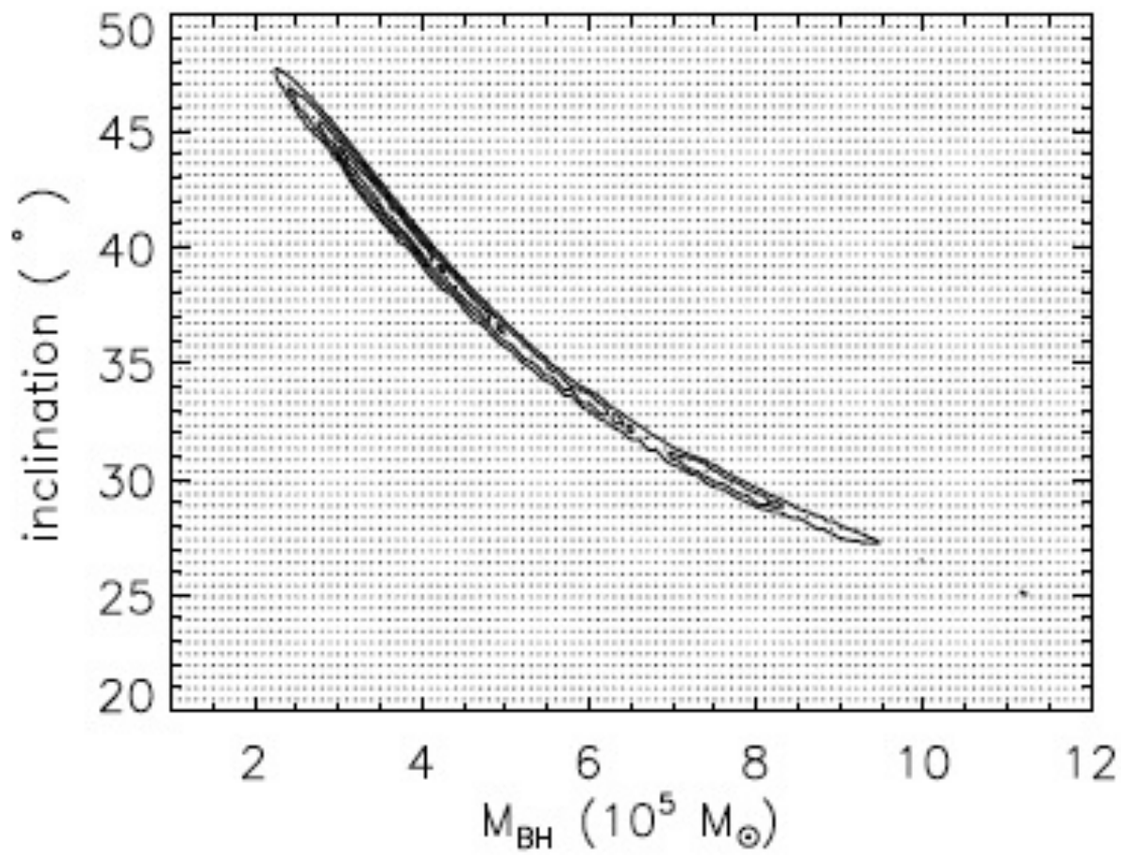
- Model using JAM code (Cappellari 2008)
- Fit M_{BH}, anistropy & mass-to-light ratio
- $M_{BH} < 1x10^5\ M_\odot$ at 3σ ($\sim 0.5x10^5\ M_\odot$)

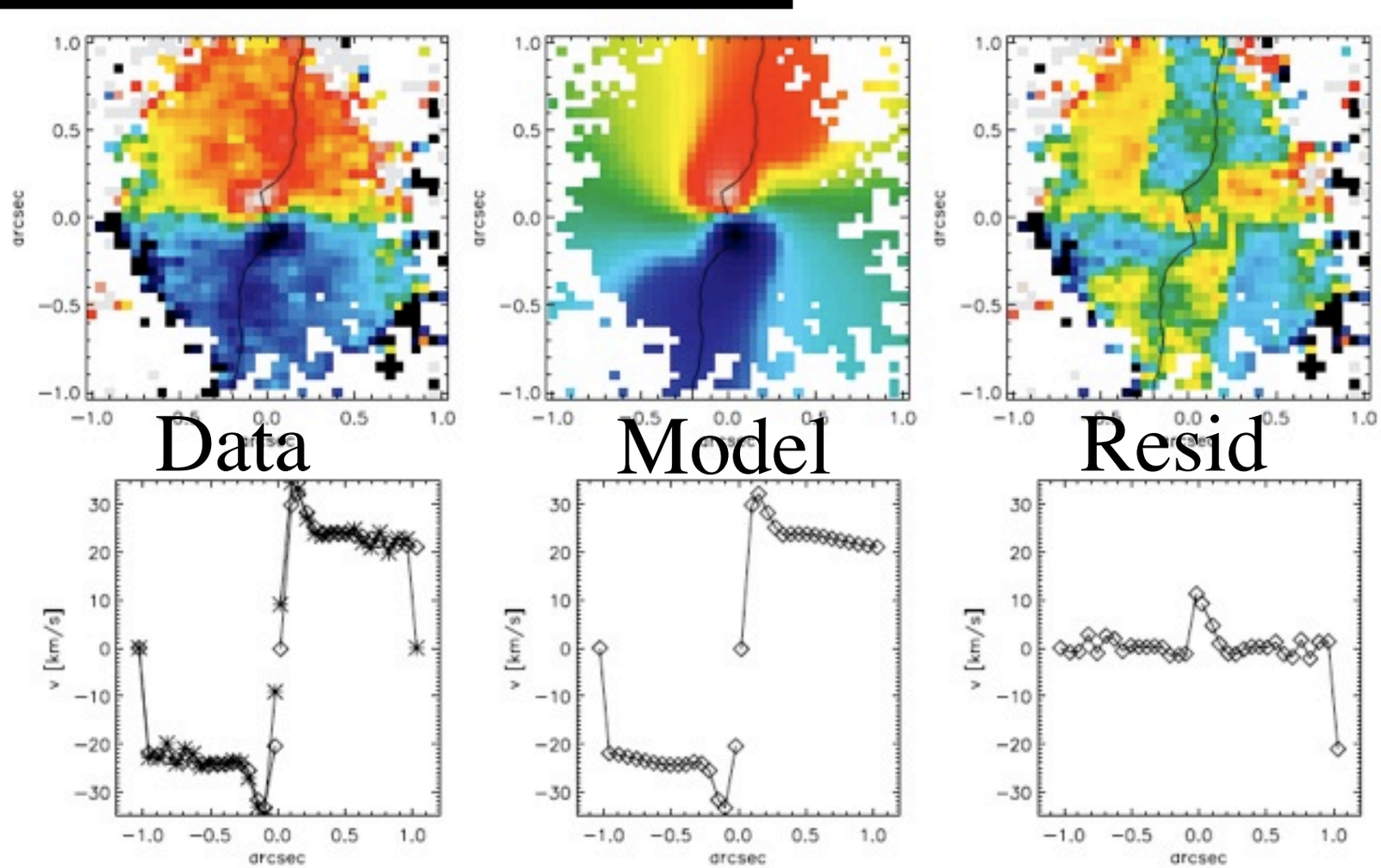


$V_{rms}=(V^2+\sigma^2)^{1/2}$

Limits on the BH mass: H_2 Gas

- Data require two thin disks
- Fit inner inclination, and M_{BH}
- Best fit $4.5 \pm 3 \times 10^5\ M_\odot$ (3σ)





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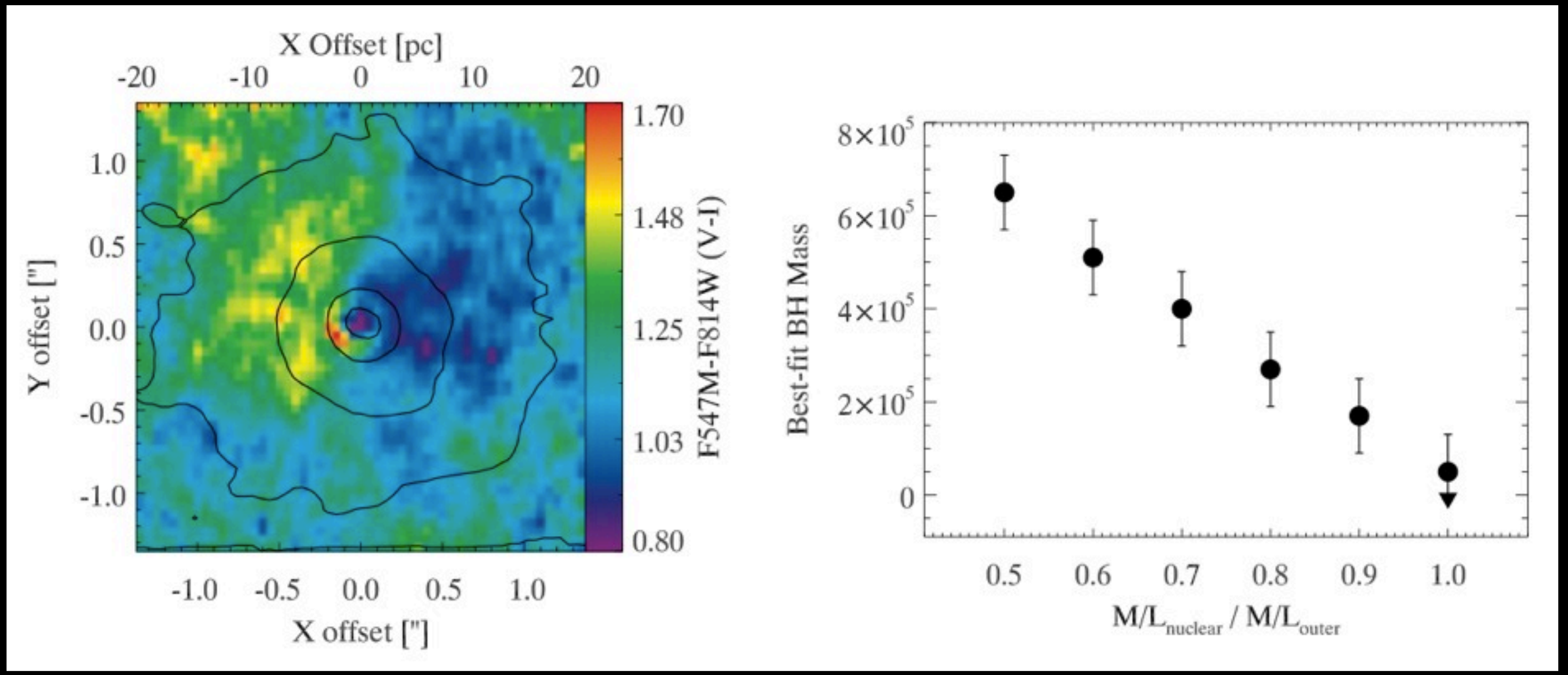
Improving the BH mass estimate



- Color map suggests possible M/L variations
- Use STIS to model M/L variations

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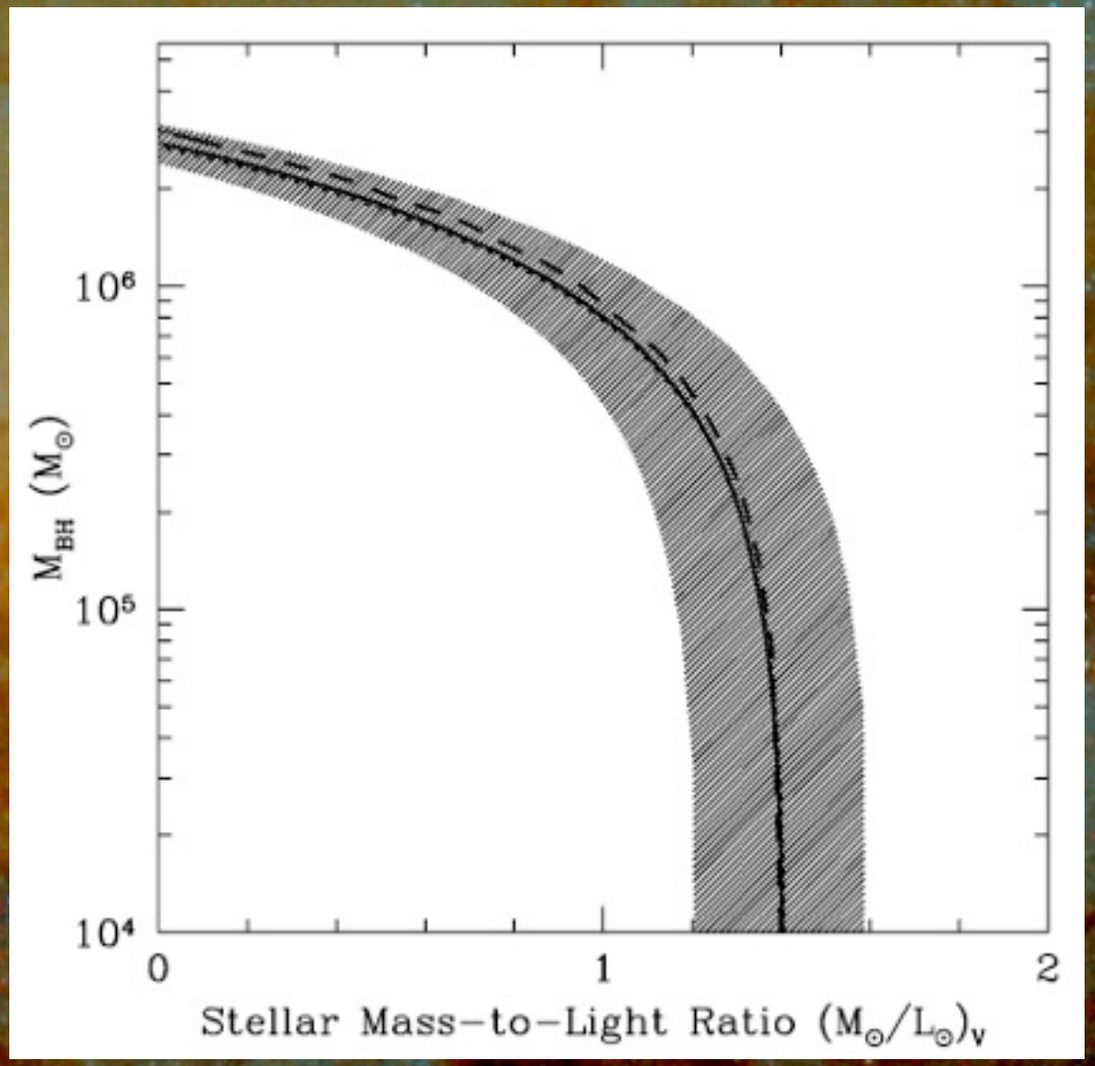
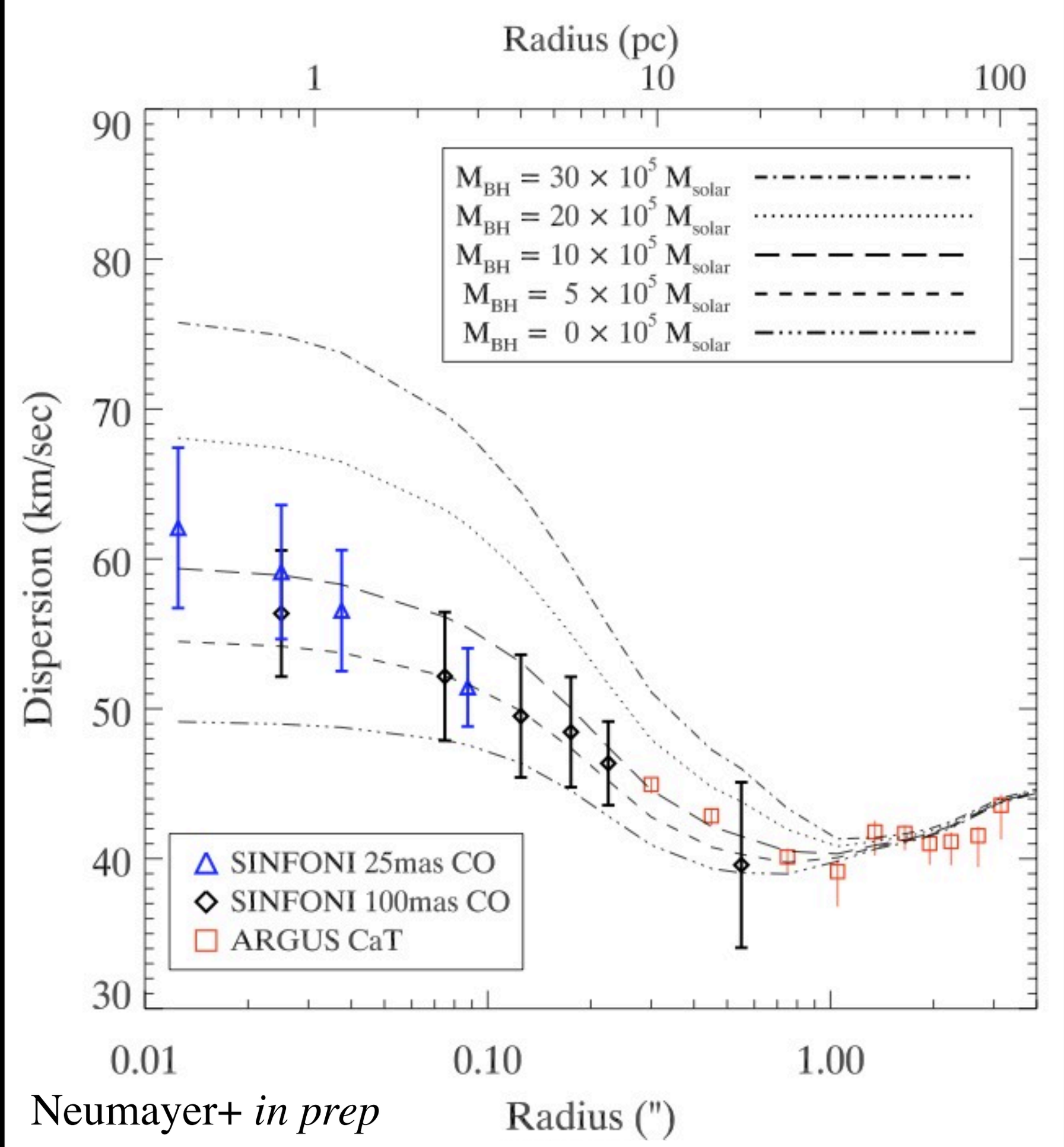
NGC 3621, Sd galaxy



- [NeV] lines detected (Satyapal+ 2007)
- Integrated dispersion of 43 km/sec, $M_{BH} < 3x10^6\ M_\odot$ (Barth+ 2009)
- X-ray source suggests $M_{BH} > 10^3\ M_\odot$ (Gliozzi+ 2009)



Neumayer+ *in prep*

NGC 3621

best fit BH mass is $6.5 \times 10^5 M_\odot$

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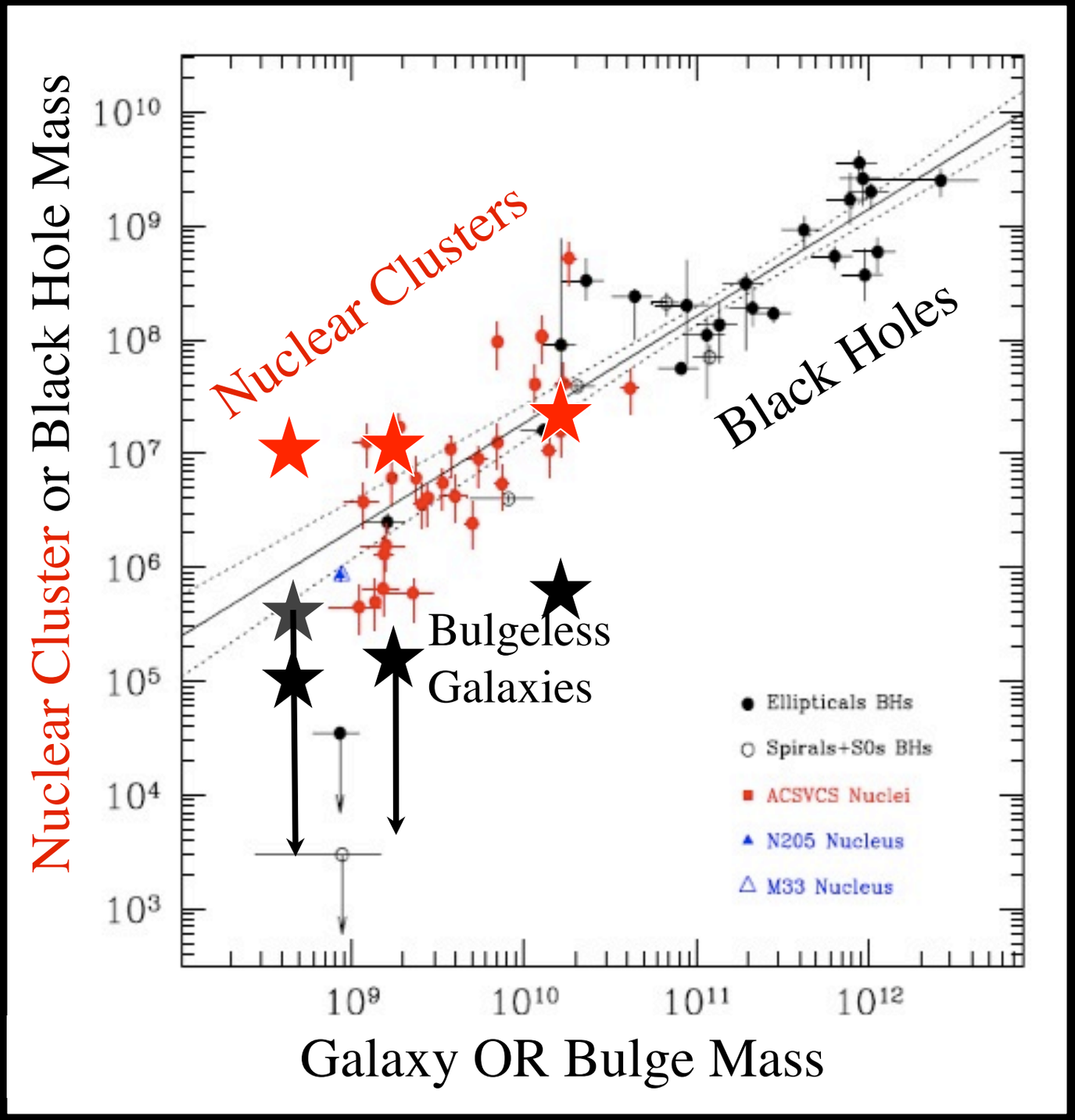
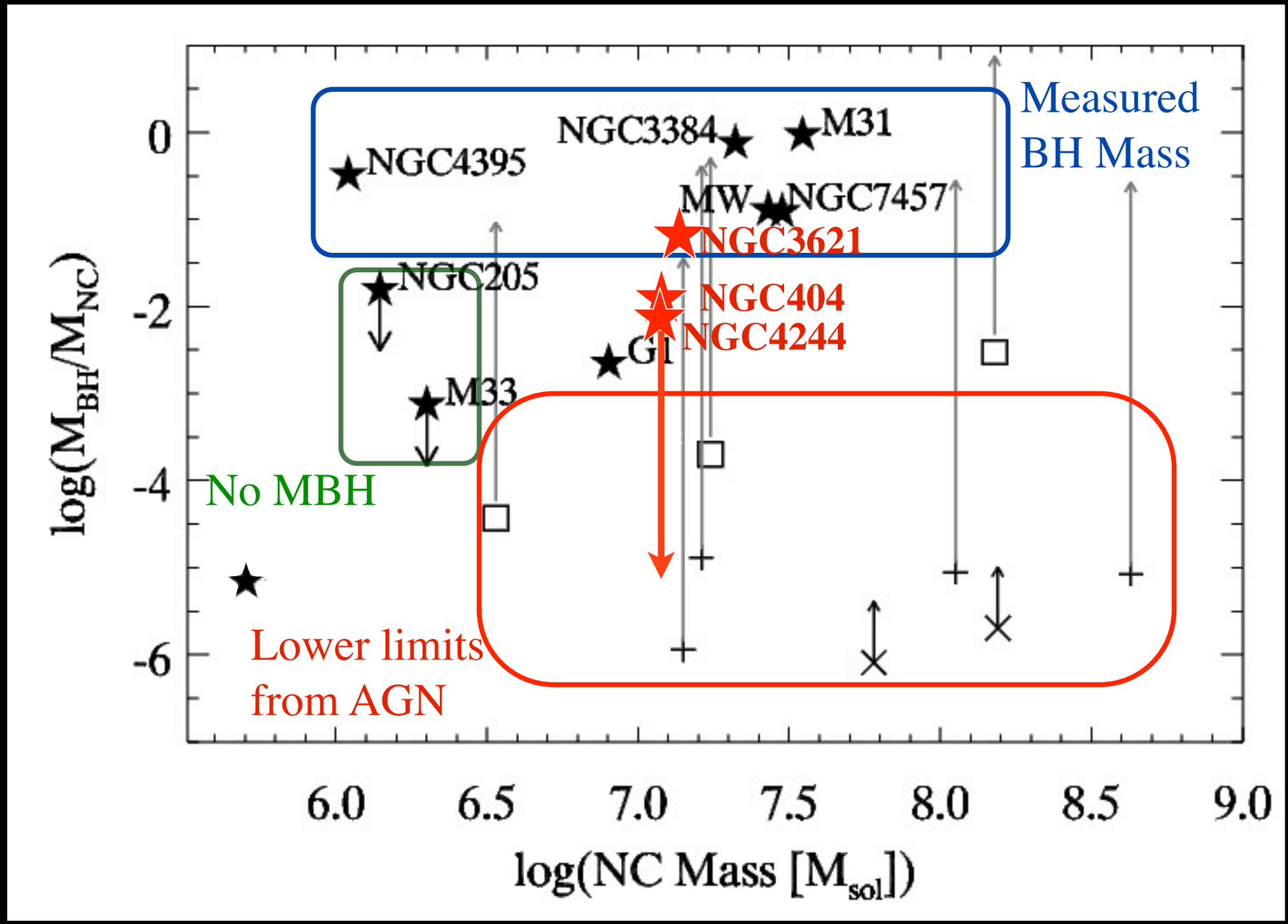
Scaling Relations



Ferrarese+ 2006

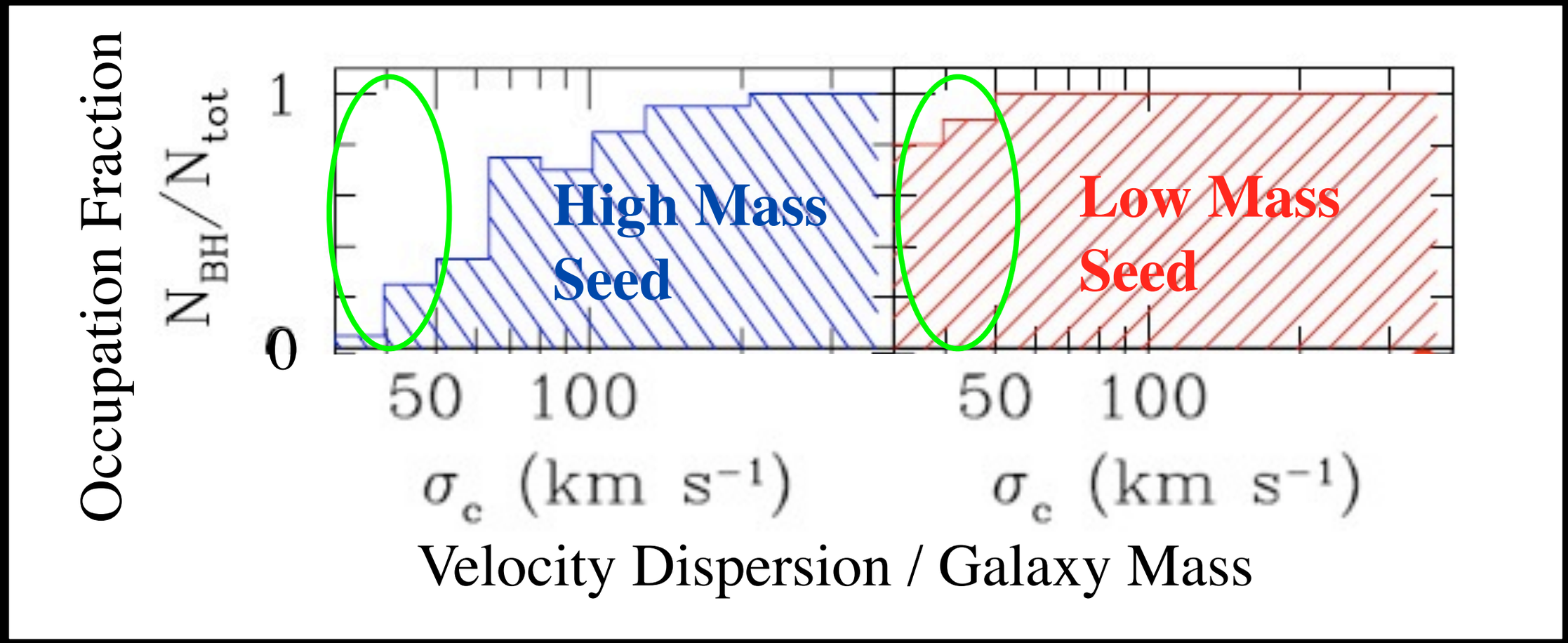
- Probing below the mass of previously detected black holes.
- Dynamical NSC masses
- What galaxy components are correlated?
- More to come!

Relative Mass of NSCs and BHs



Square=Seyferts, +=LINERS, ×=X-ray

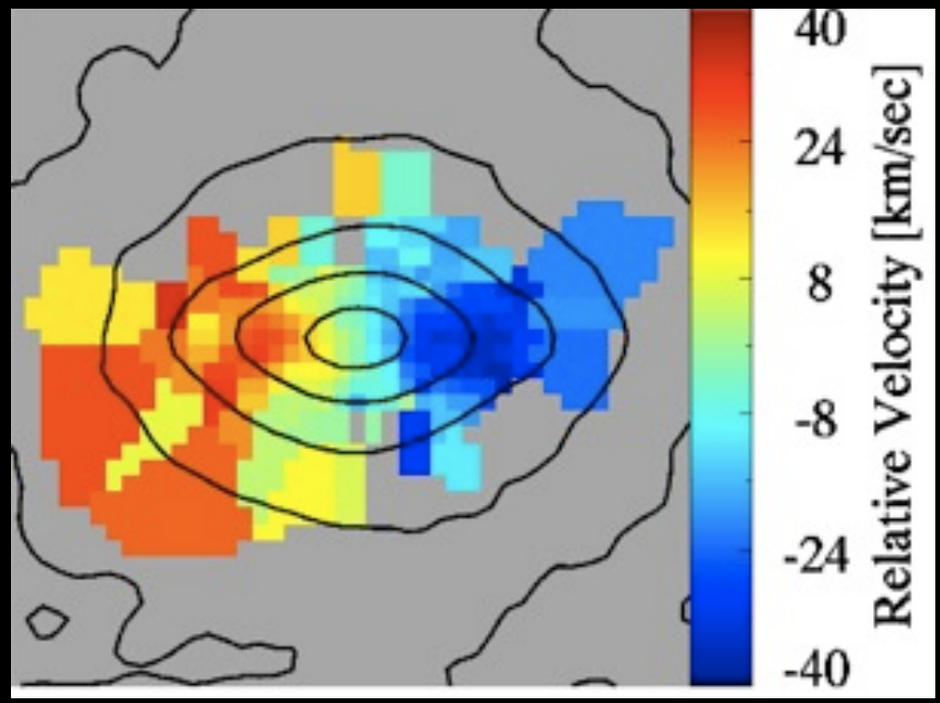
Seth+ 2008a



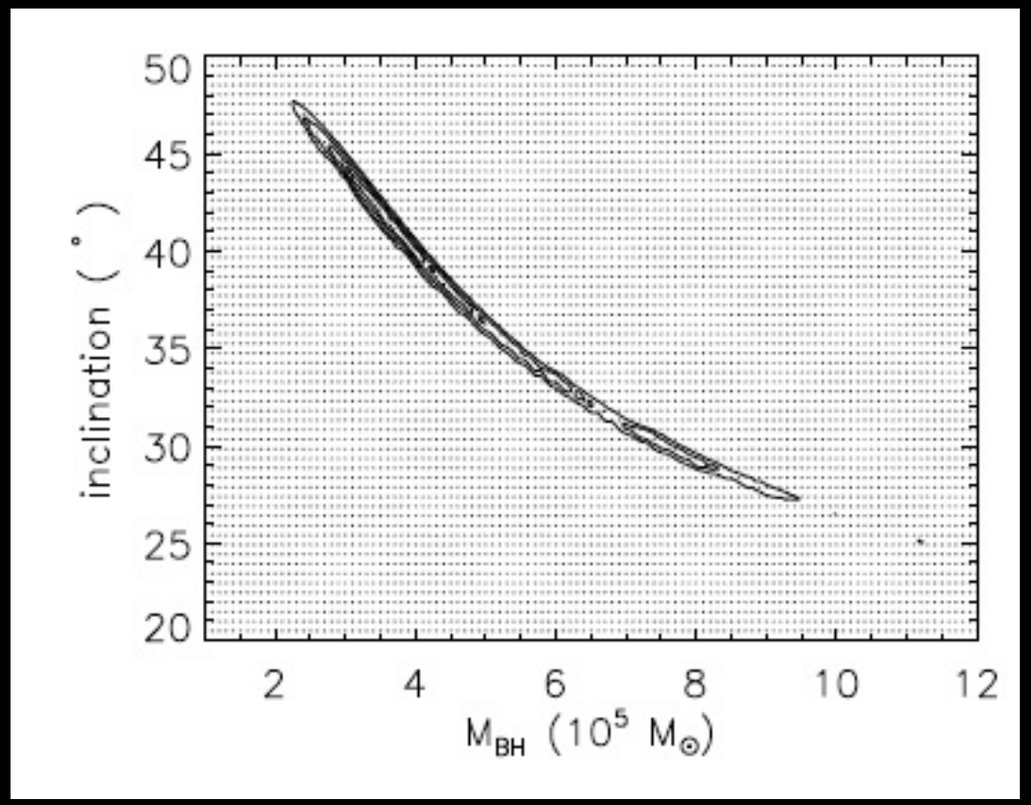
Volonteri+ 2008

Conclusions

- Multiple pathways to nuclear star cluster formation.



- Best place to probe the low end of the BH mass function.



Open Questions

- What is the relation between the formation of BHs and NSCs?
  - Can BHs form without NSCs?
- Are there differences in NSC scaling relations between galaxy types? Do these parallel differences in BH scaling relations?
- Accretion vs. Dynamical Detection: which is the best for constraining the presence of low-mass BHs?