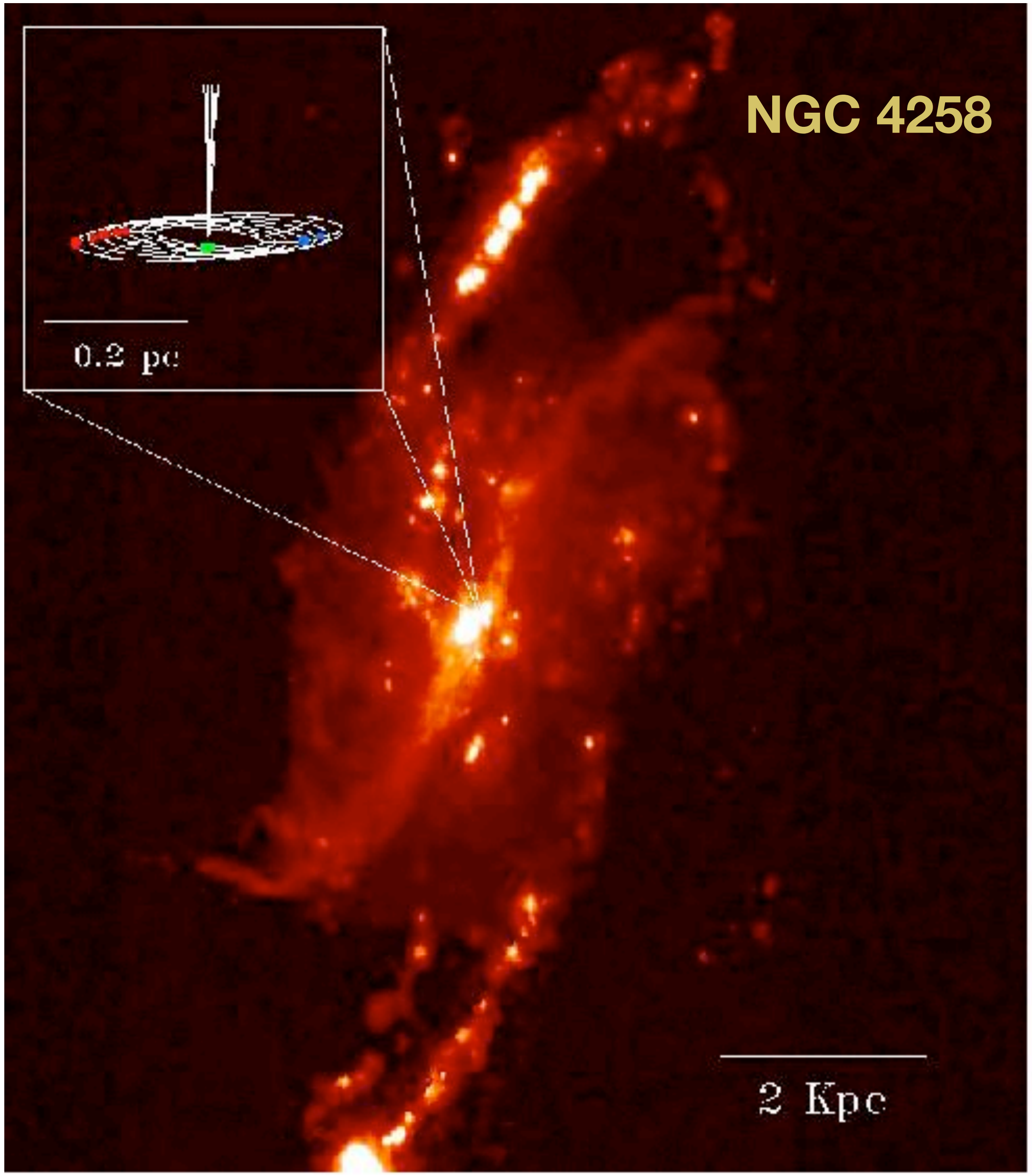
Local Black Hole Demographics

Jenny Greene (Princeton)

A Sense of Scale

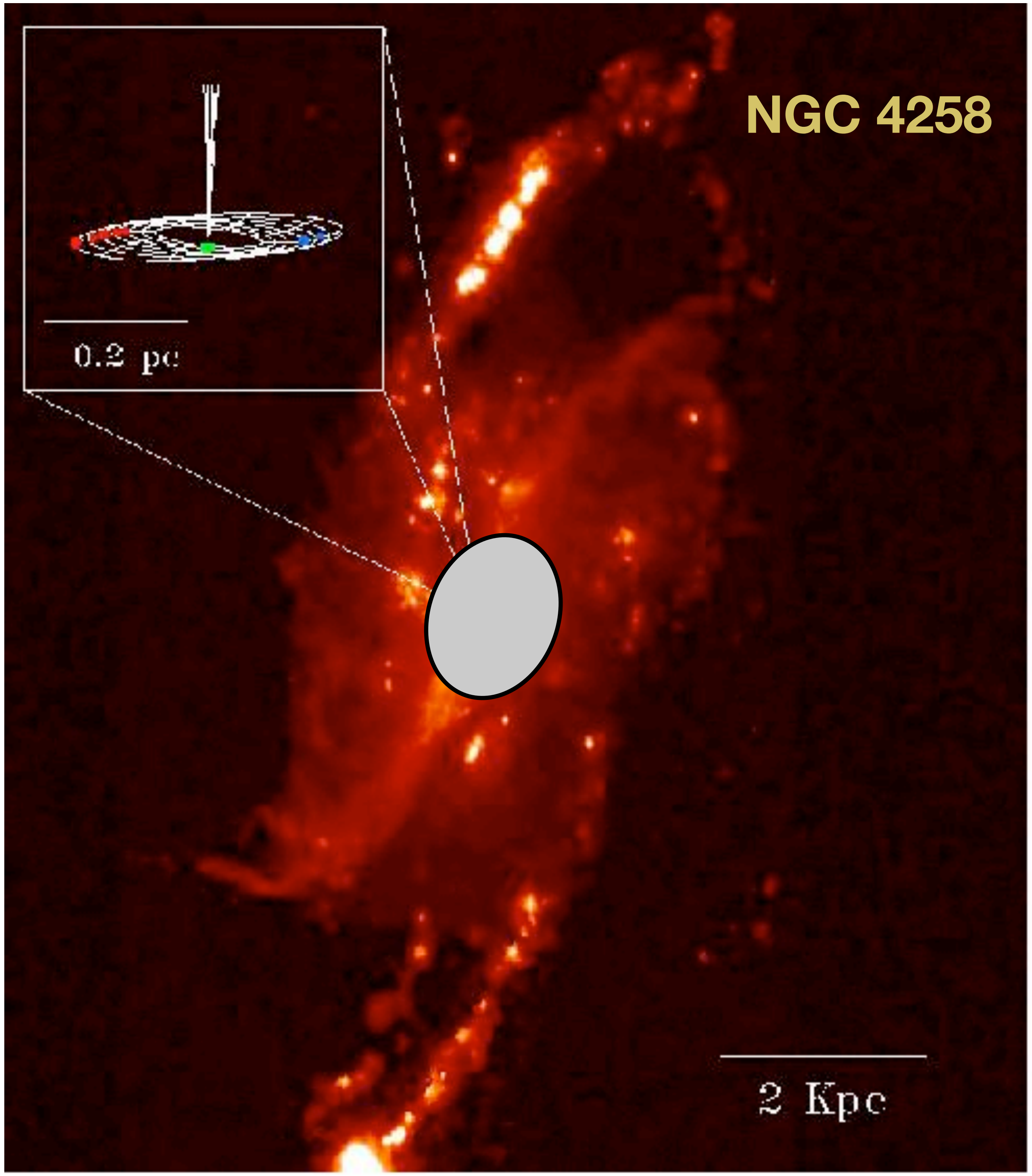
Subpc molecular disks



A Sense of Scale

Subpc molecular disks

narrow-line regions
~100pc scales



A Sense of Scale

Subpc molecular disks

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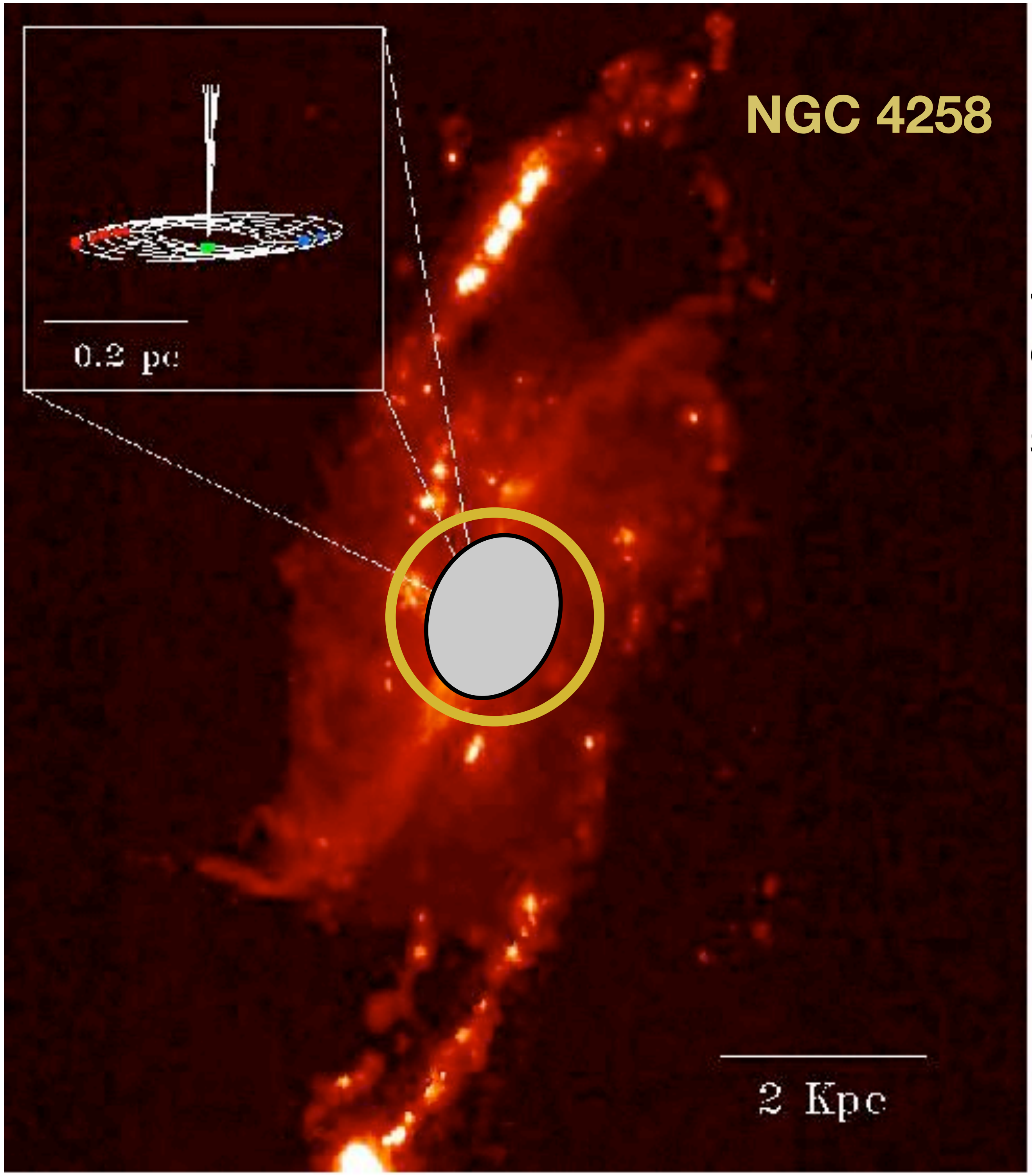


Stellar velocity dispersions ($\sigma_\star$) on kpc scales (R_e)

Outline

Using nuclear activity to study BHs

Using dynamics to study BHs

Scaling relations

Outstanding questions

Outline

Using nuclear activity to study BHs

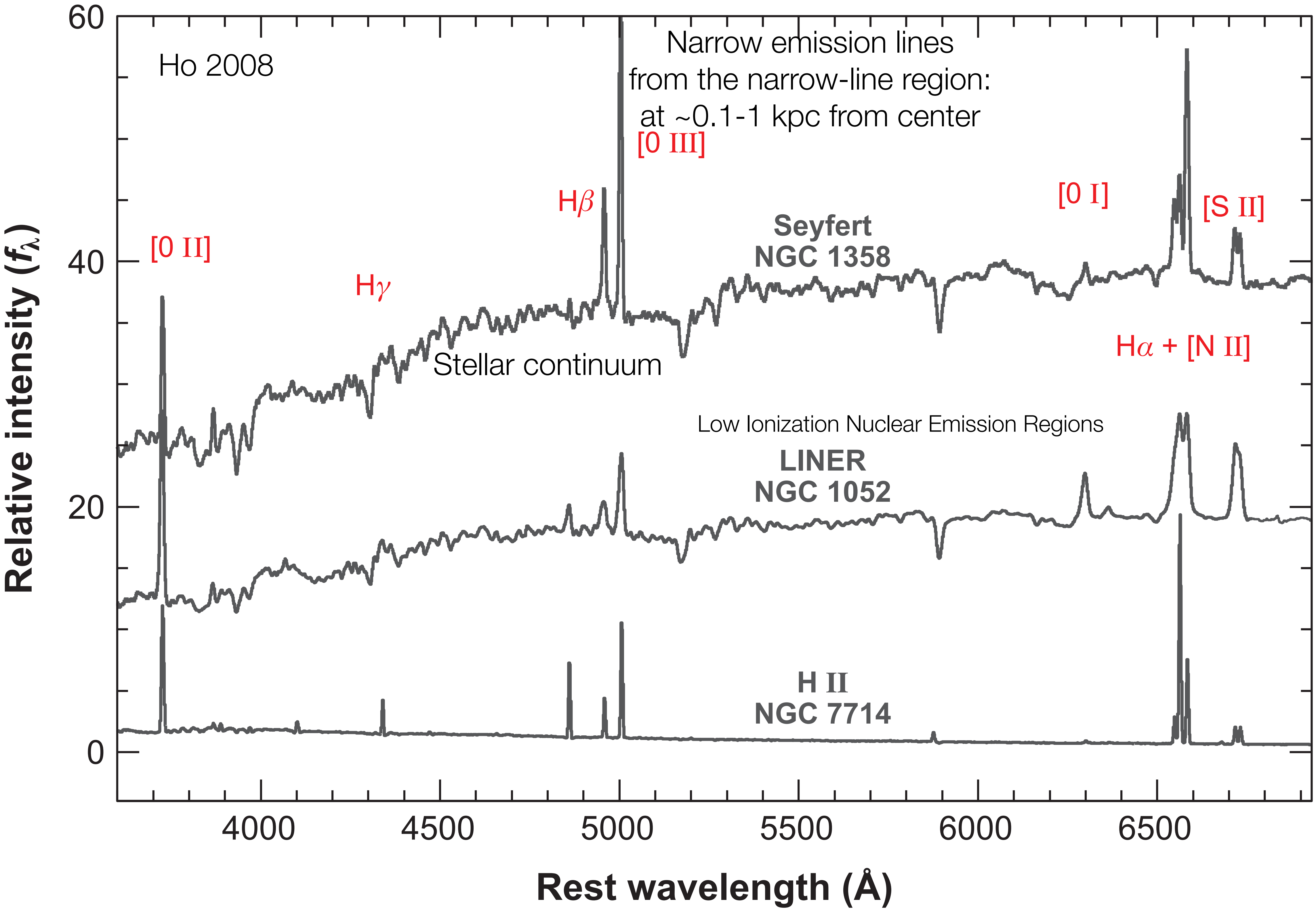
Using dynamics to study BHs

} BHs are ubiquitous at the centers of massive galaxies

Scaling relations

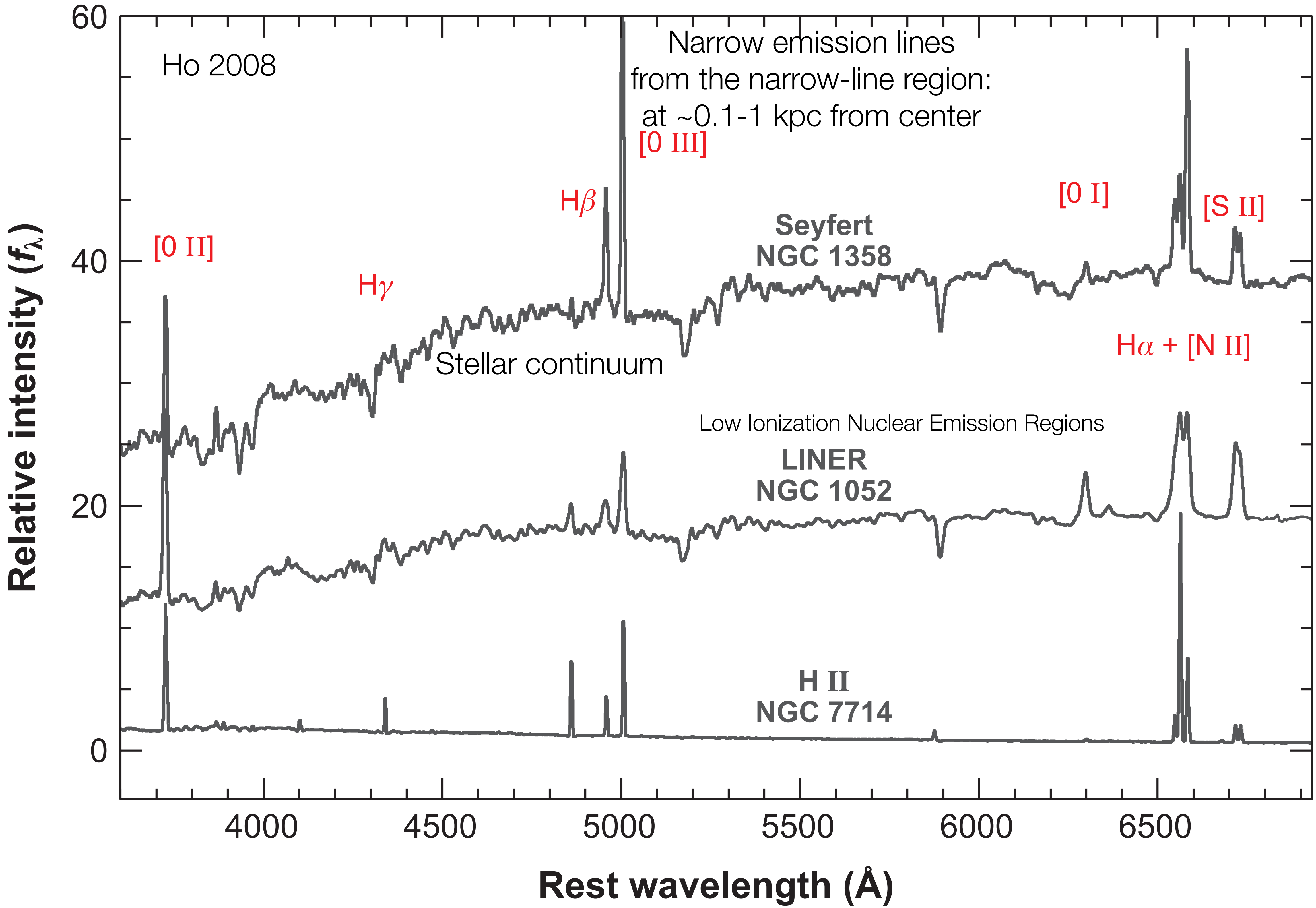
Outstanding questions

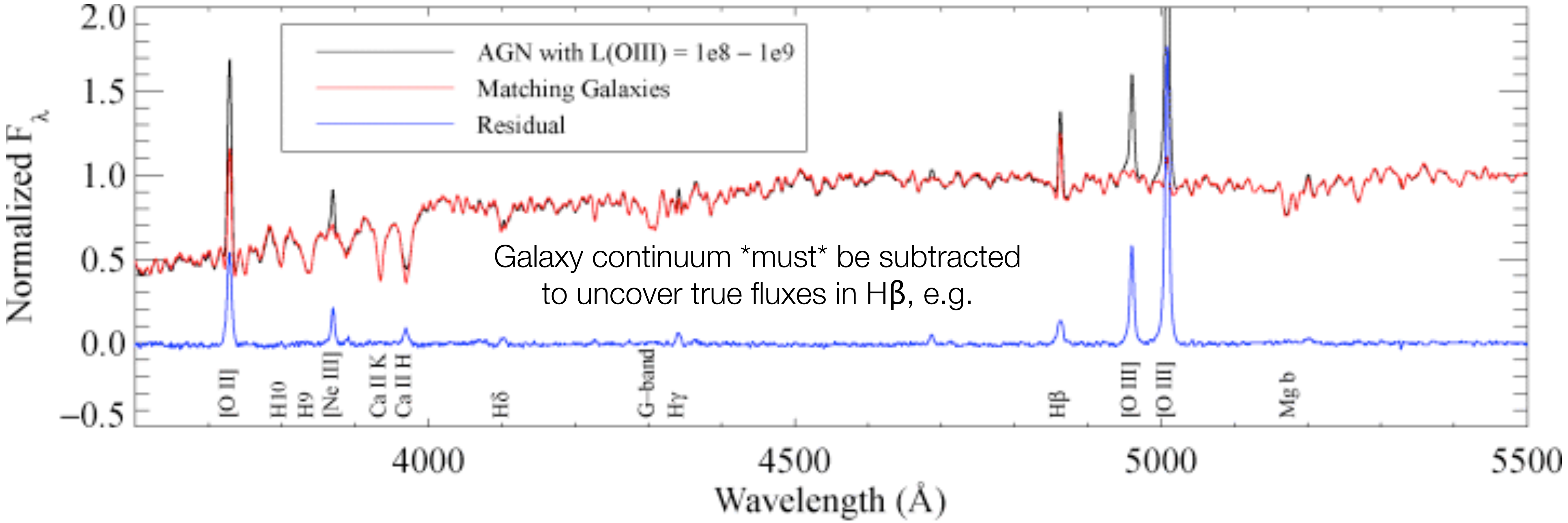
Nuclear Activity (I): Optical Spectra



Nuclear Activity (I): Optical Spectra

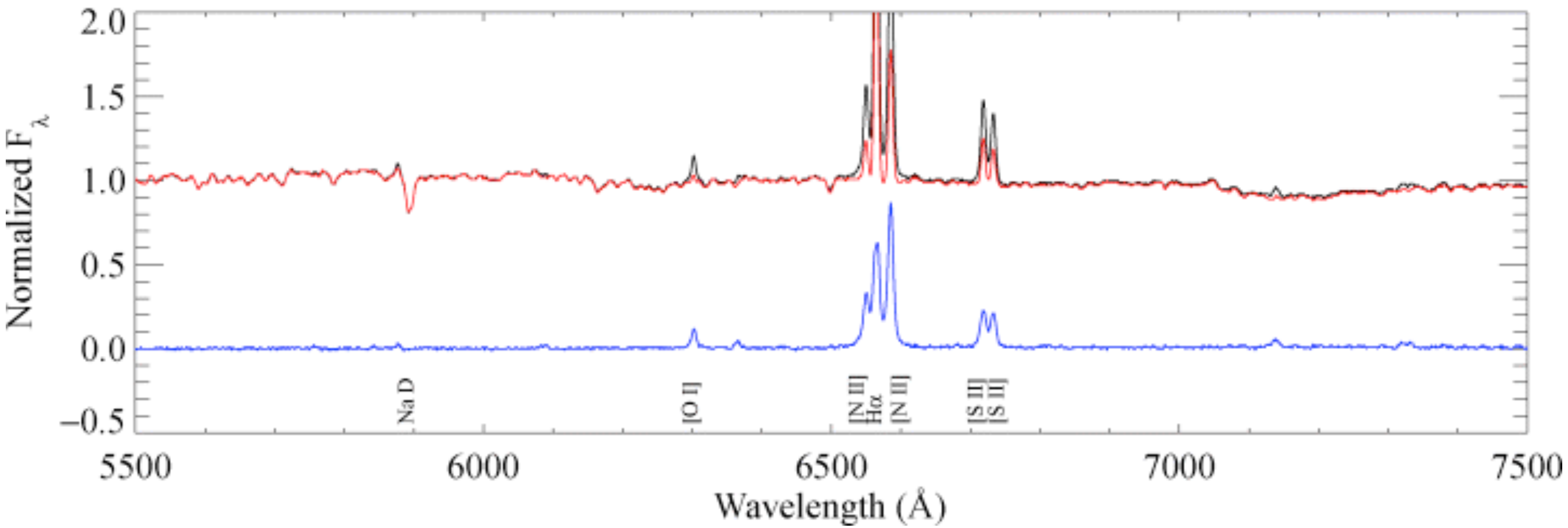
Note the major difference between AGN and HII galaxies is the strength of the low ionization lines





Galaxy continuum *must* be subtracted to uncover true fluxes in Hβ, e.g.

Kauffmann et al. 2003



We use the so-called "BPT" diagram

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 93 February 1981 No. 551

CLASSIFICATION PARAMETERS FOR THE EMISSION-LINE SPECTRA OF EXTRAGALACTIC OBJECTS

J. A. BALDWIN AND M. M. PHILLIPS

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AND

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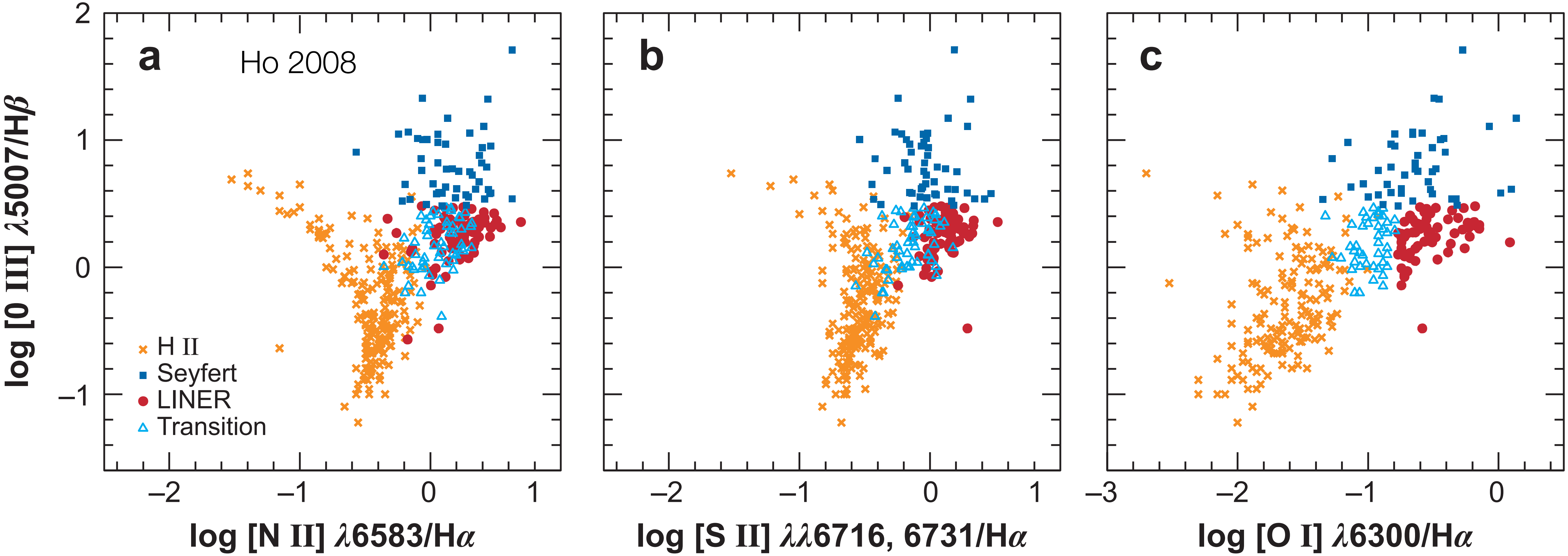
Received 1980 August 21

An investigation is made of the merits of various emission-line intensity ratios for classifying the spectra of extragalactic objects. It is shown empirically that several combinations of easily-measured lines can be used to separate objects into one of four categories according to the principal excitation mechanism: normal H II regions, planetary nebulae, objects photoionized by a power-law continuum, and objects excited by shock-wave heating. A two-dimensional quantitative classification scheme is suggested.

What is the excitation mechanism?

- Photoionization by O stars (HII galaxies, star-forming galaxies, etc)
- Photoionization by a power-law continuum -- typified by a wide range of ionization states
- PNe -- photoionization by evolved star
- Shock heating

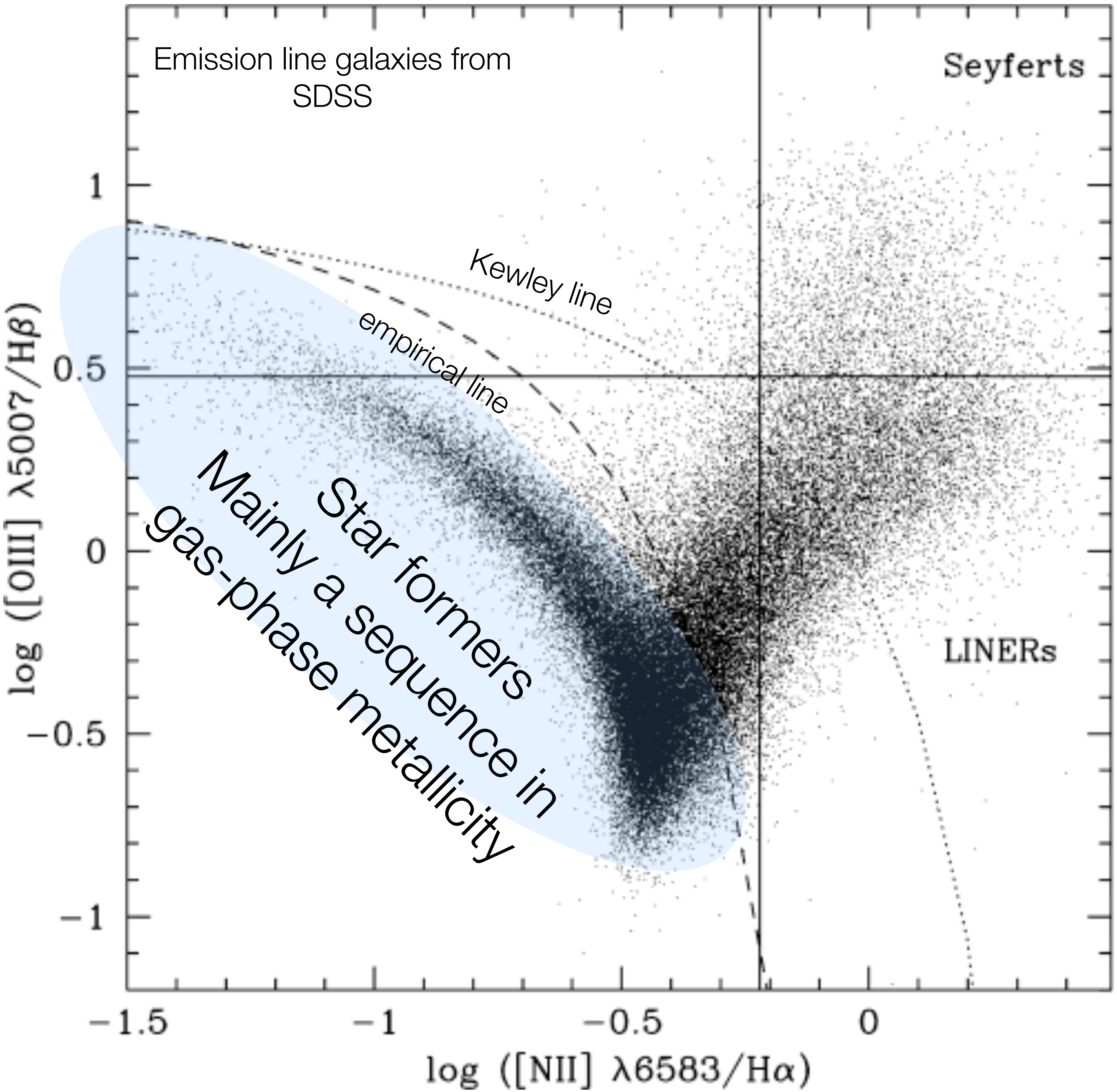


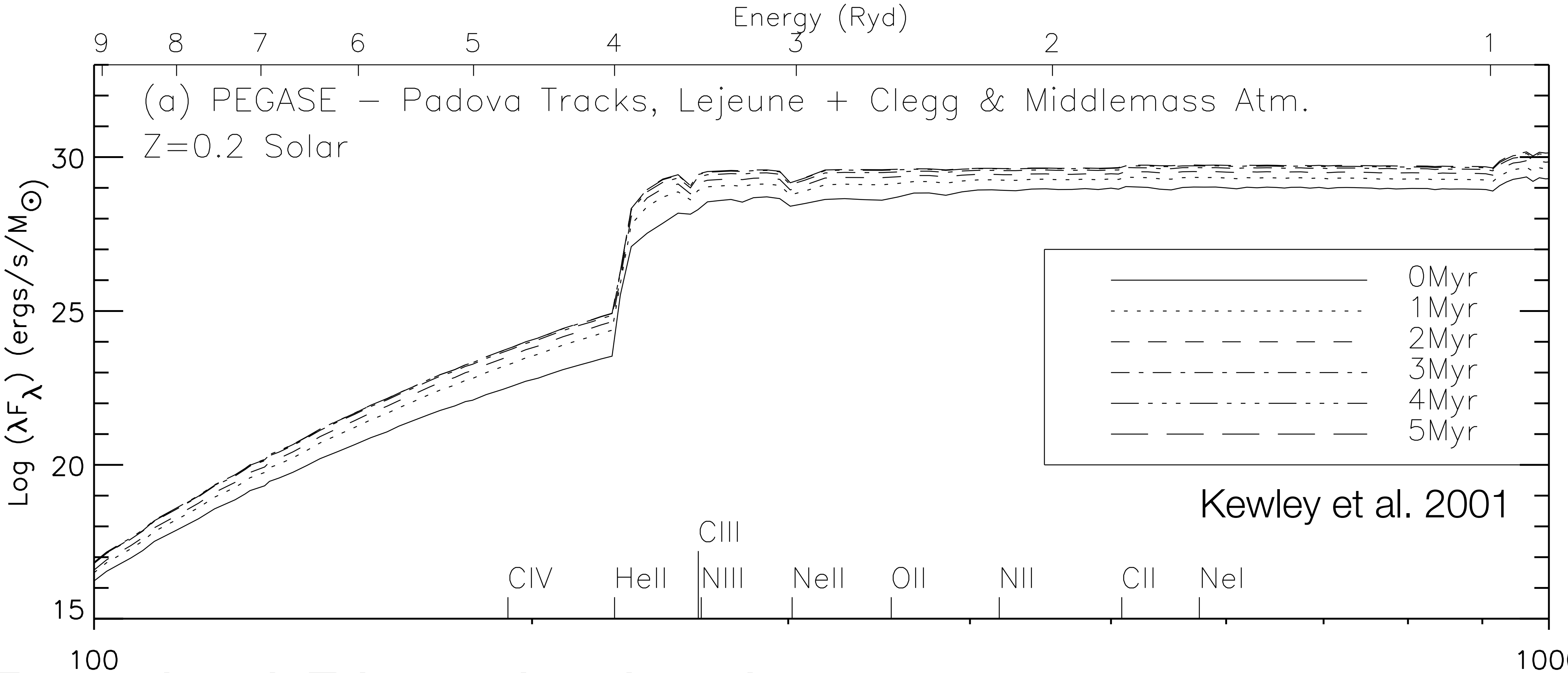
- Use strong, ubiquitous lines ([OIII] 4363/[OIII] 5007 is sensitive to temp...but impossible to measure): Veilleux & Osterbrock 1987

- Uses rest-frame optical lines: perfect for low-z demographics

- Lines are close together = importance of reddening minimized

Kauffmann et al. 2003

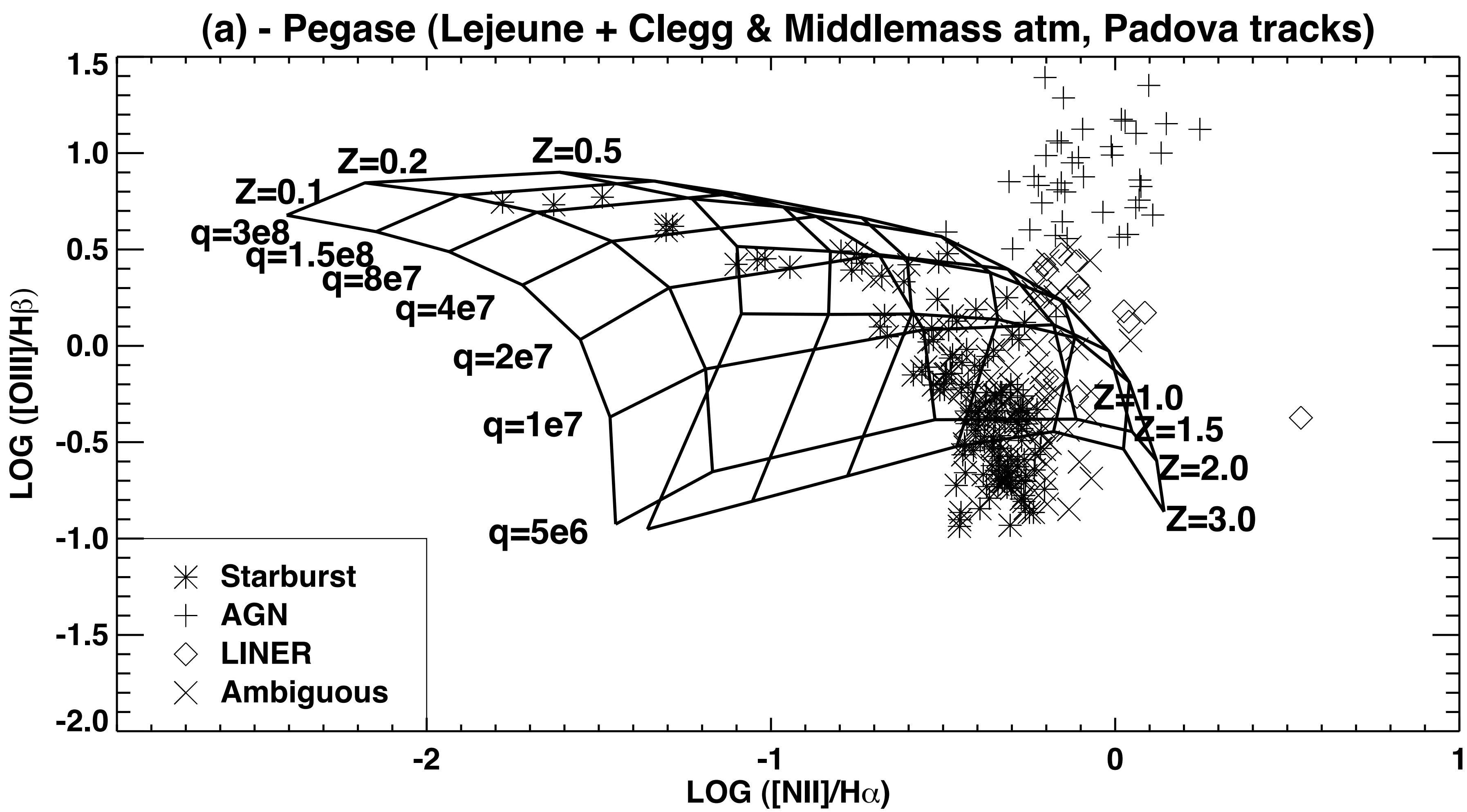


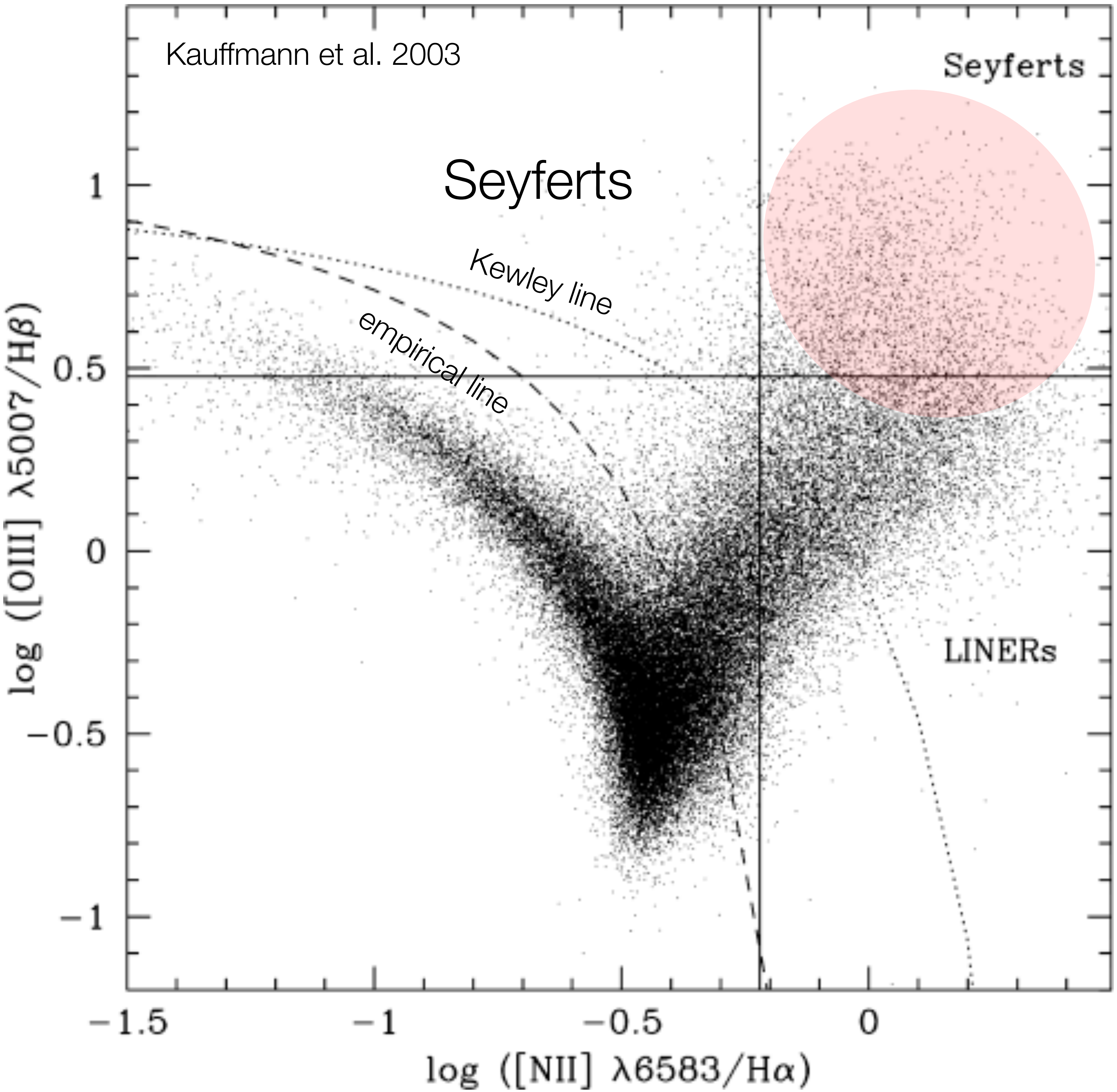


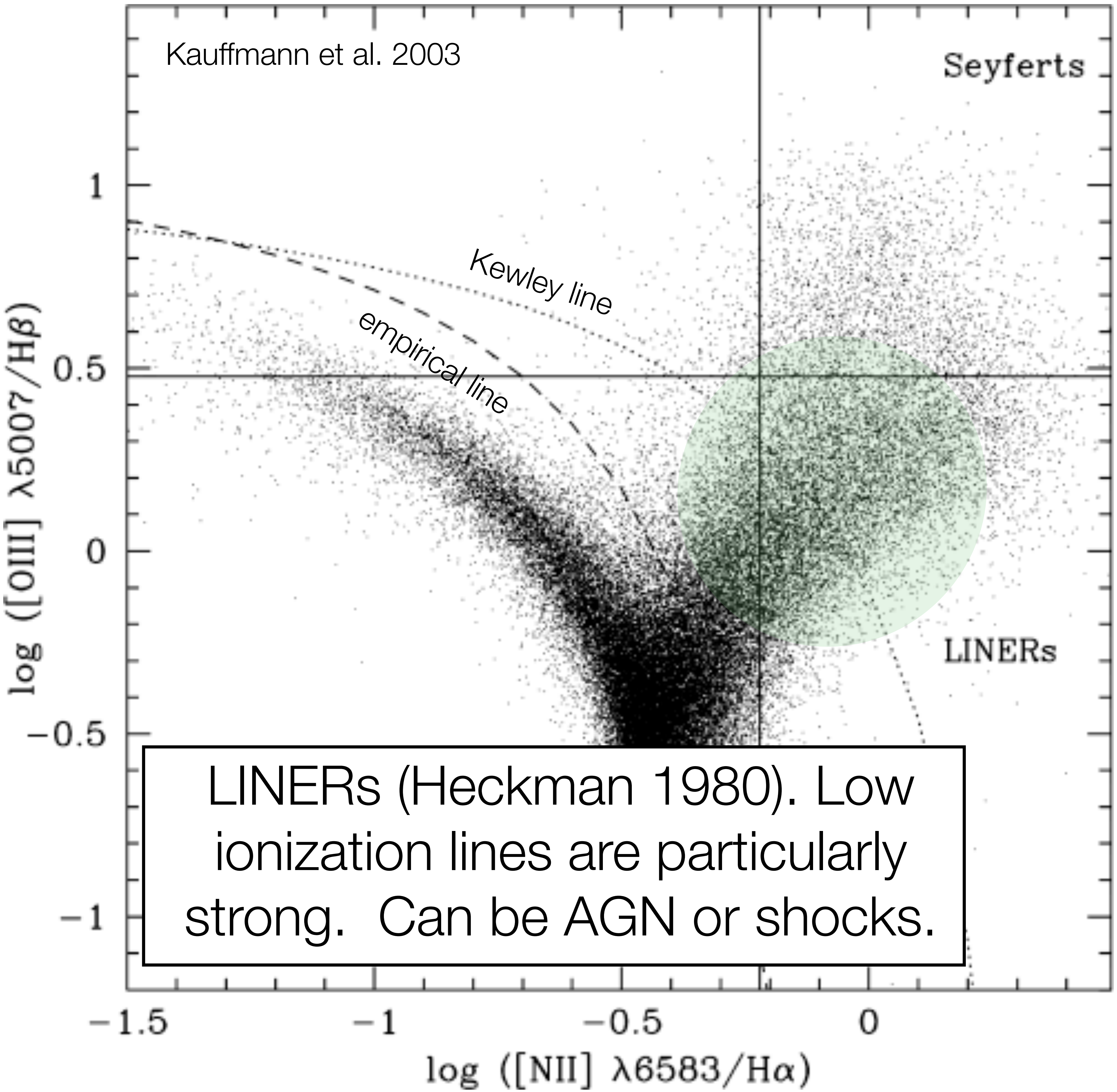
Range of assumptions for the shape of the ionizing continuum

Detailed Photoionization Models

Range of assumptions for the metallicity and density of the gas

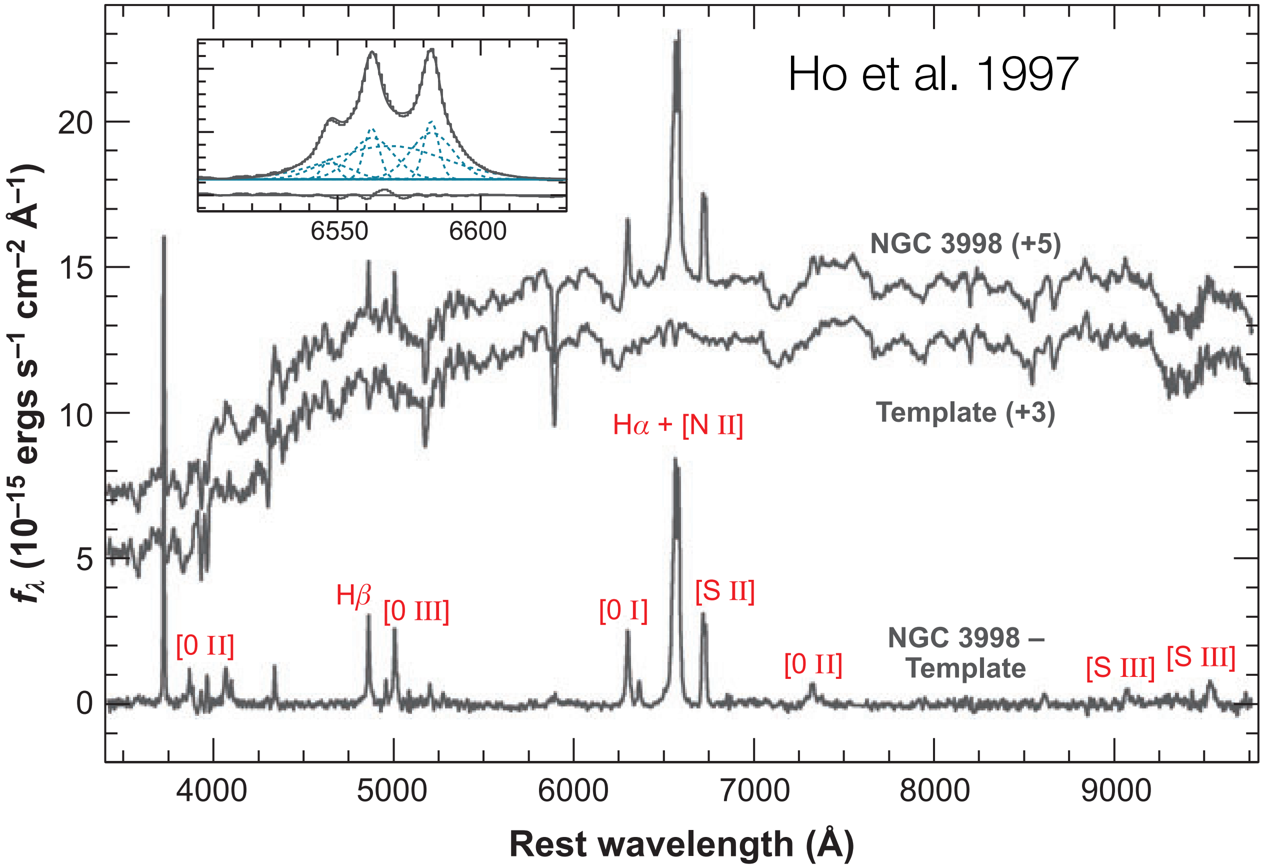



Kauffmann et al. 2003
Seyferts
Seyferts
Kewley line
empirical line
LINERs
log ([OIII] λ5007/Hβ)
log ([NII] λ6583/Hα)
1
0.5
0
−0.5
−1
−1.5
−1
−0.5
0

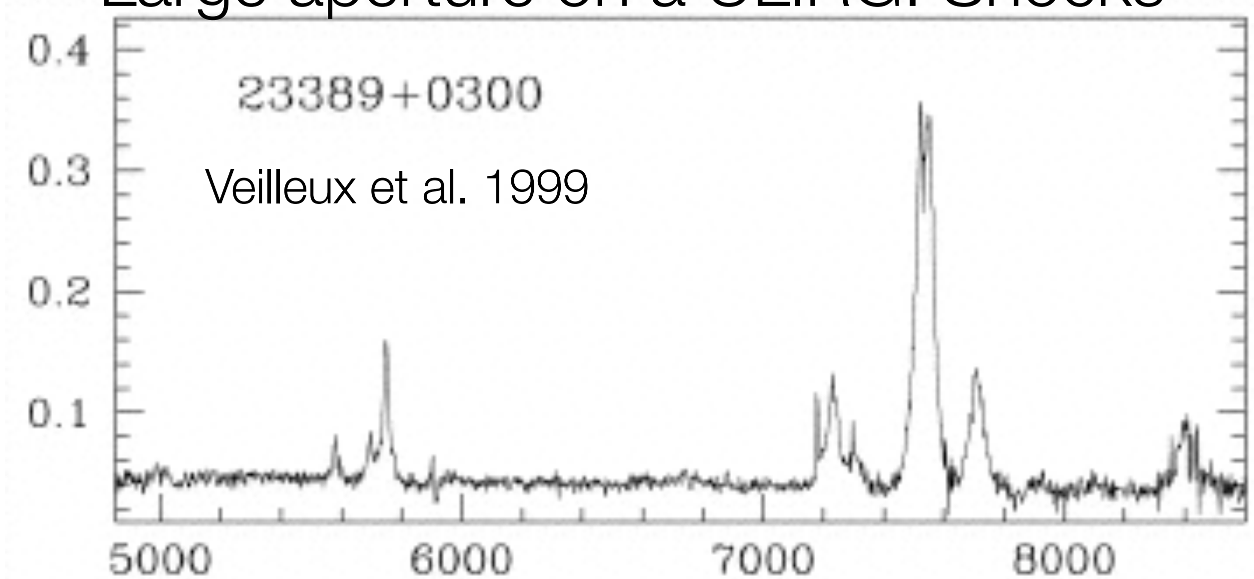


LINERs (Heckman 1980). Low ionization lines are particularly strong. Can be AGN or shocks.

Digression: What powers LINERs?

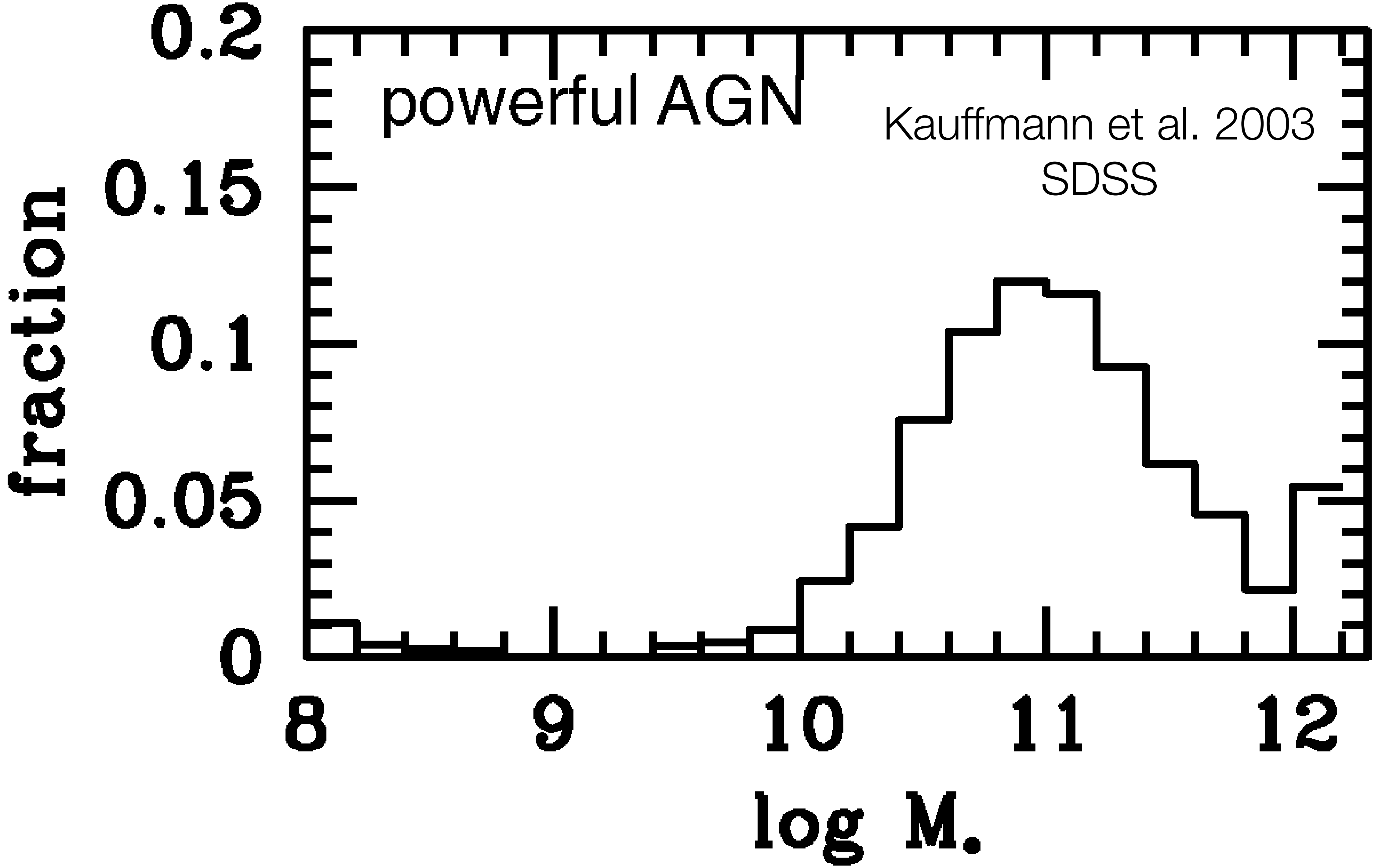


Large aperture on a ULIRG: Shocks

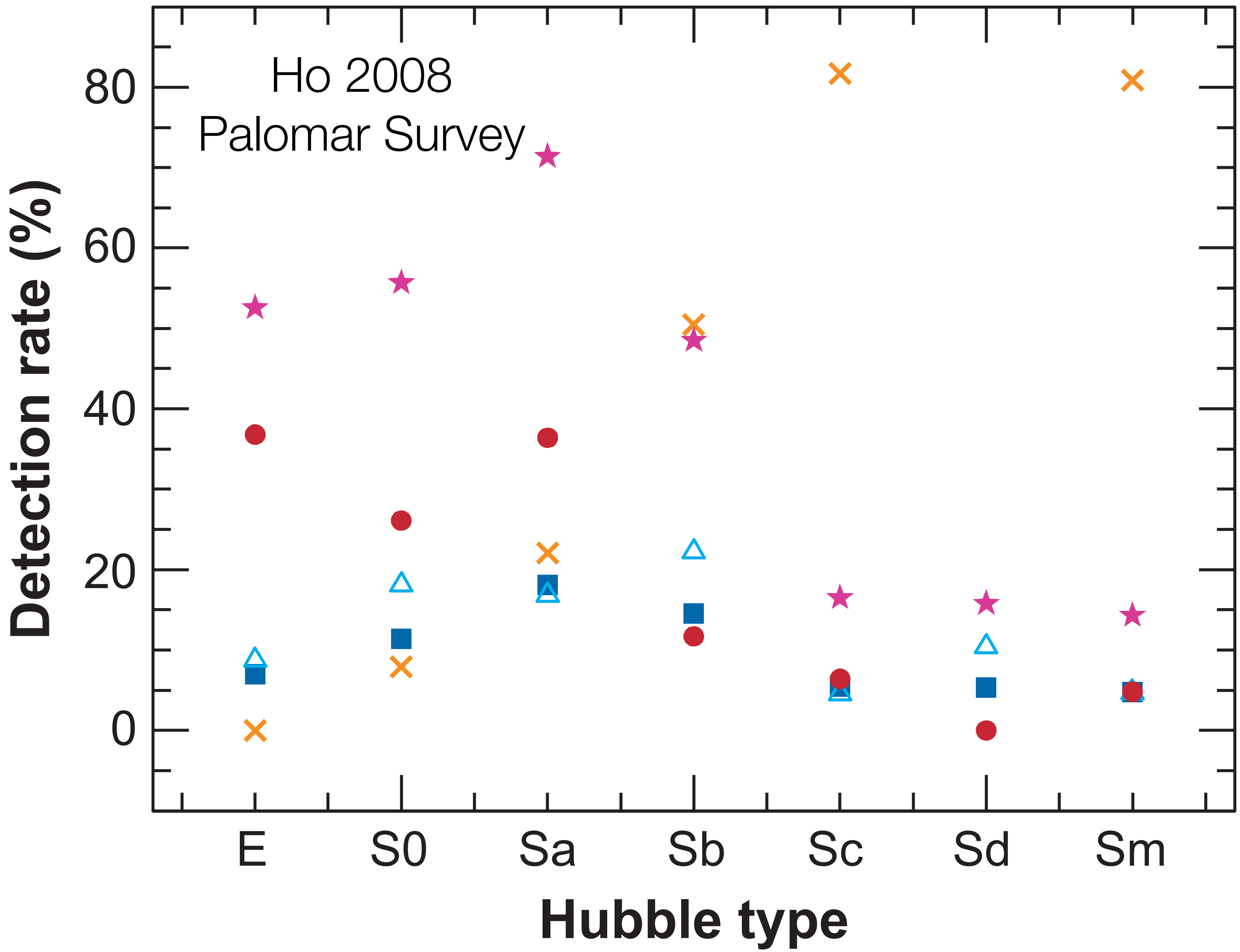


Answer: It depends. But there is no doubt that LINER emission from the very center of nearby massive ellipticals is powered by BHs. See Eracleous et al. 2010 for detailed analysis of power source of LINERs.

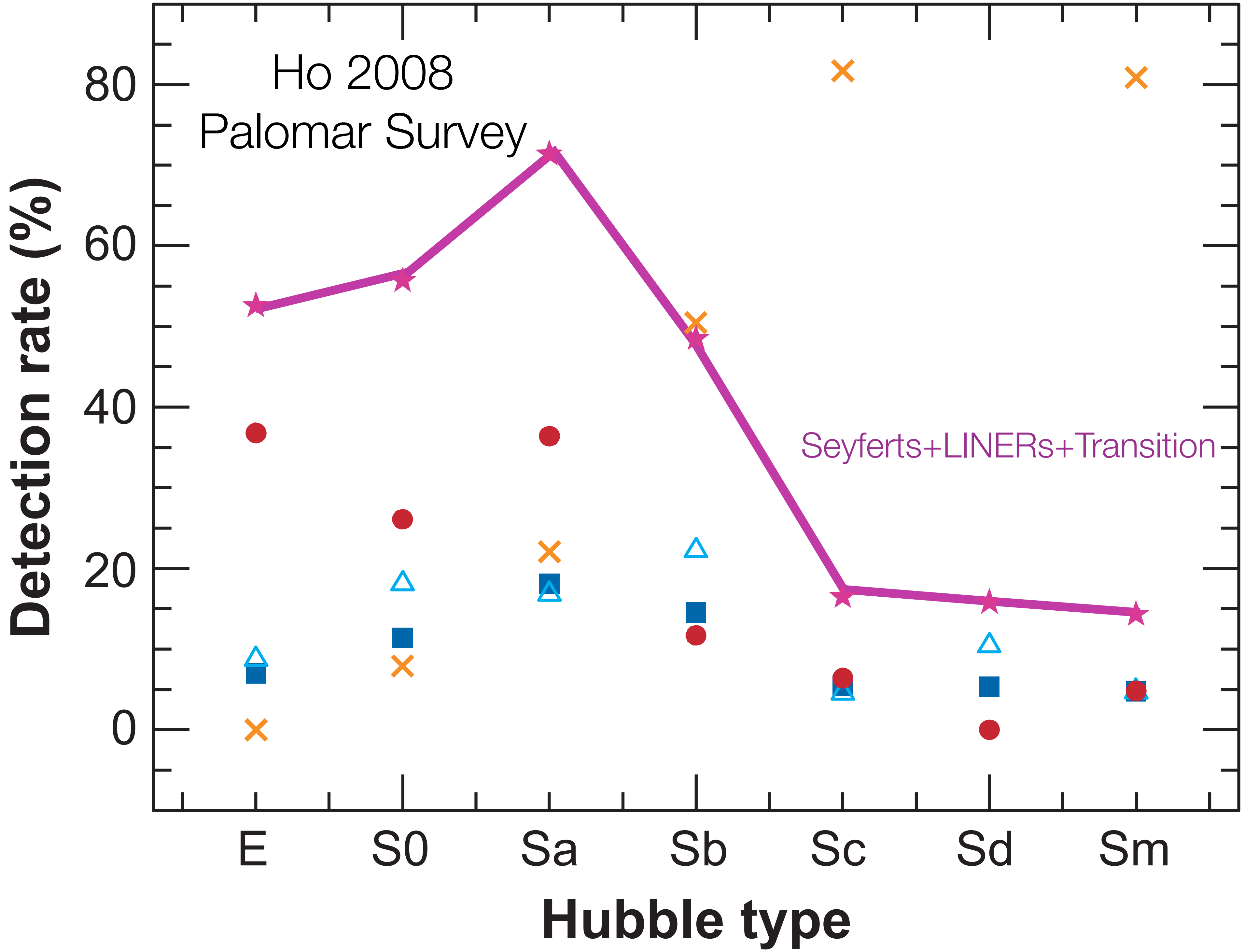
Black Hole Demographics



Point 1: Accreting black holes are found in massive, bulge-dominated galaxies



Point 2: If you look hard enough you find that virtually ALL massive, bulge-dominated galaxies contain (very weakly) accreting supermassive black holes



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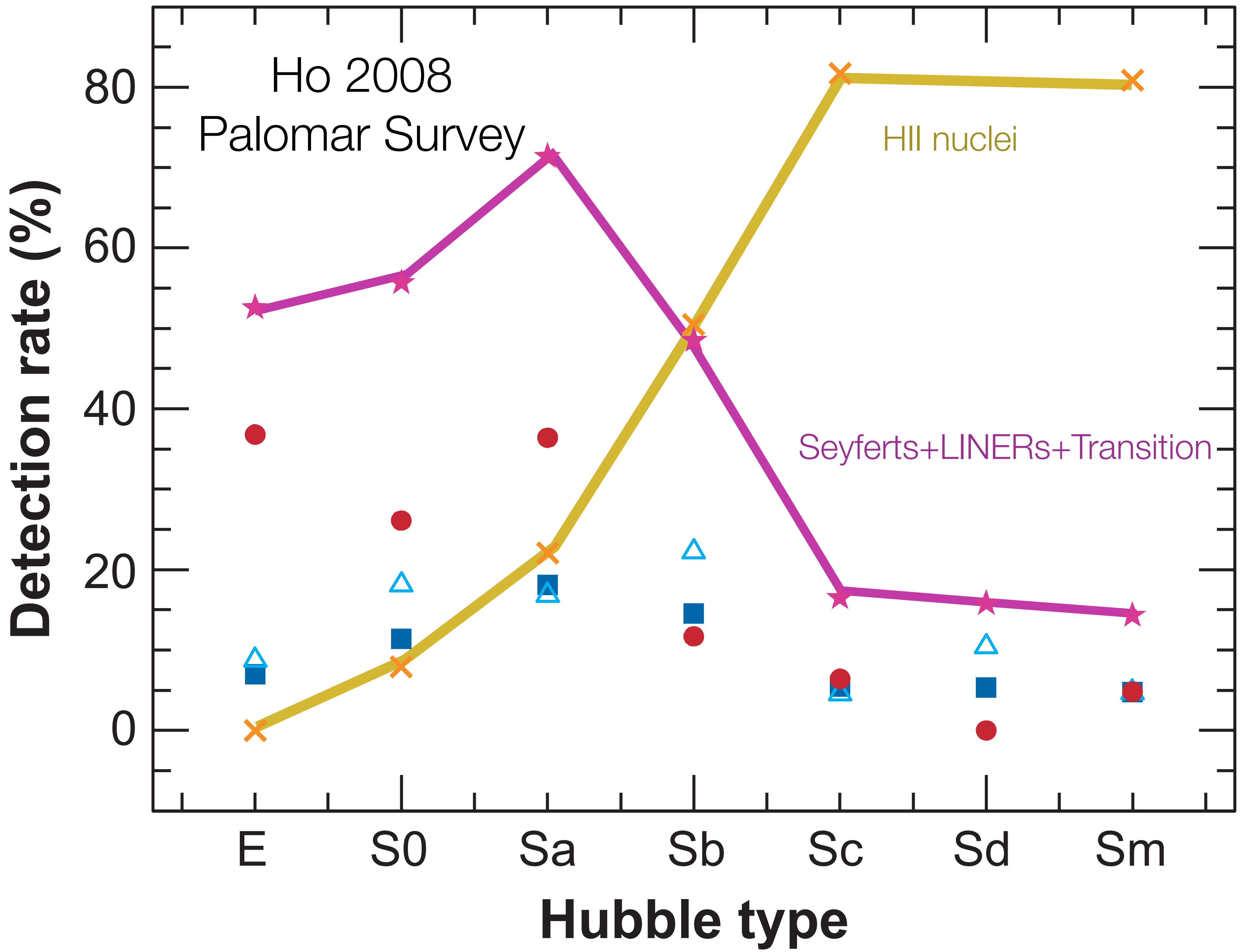

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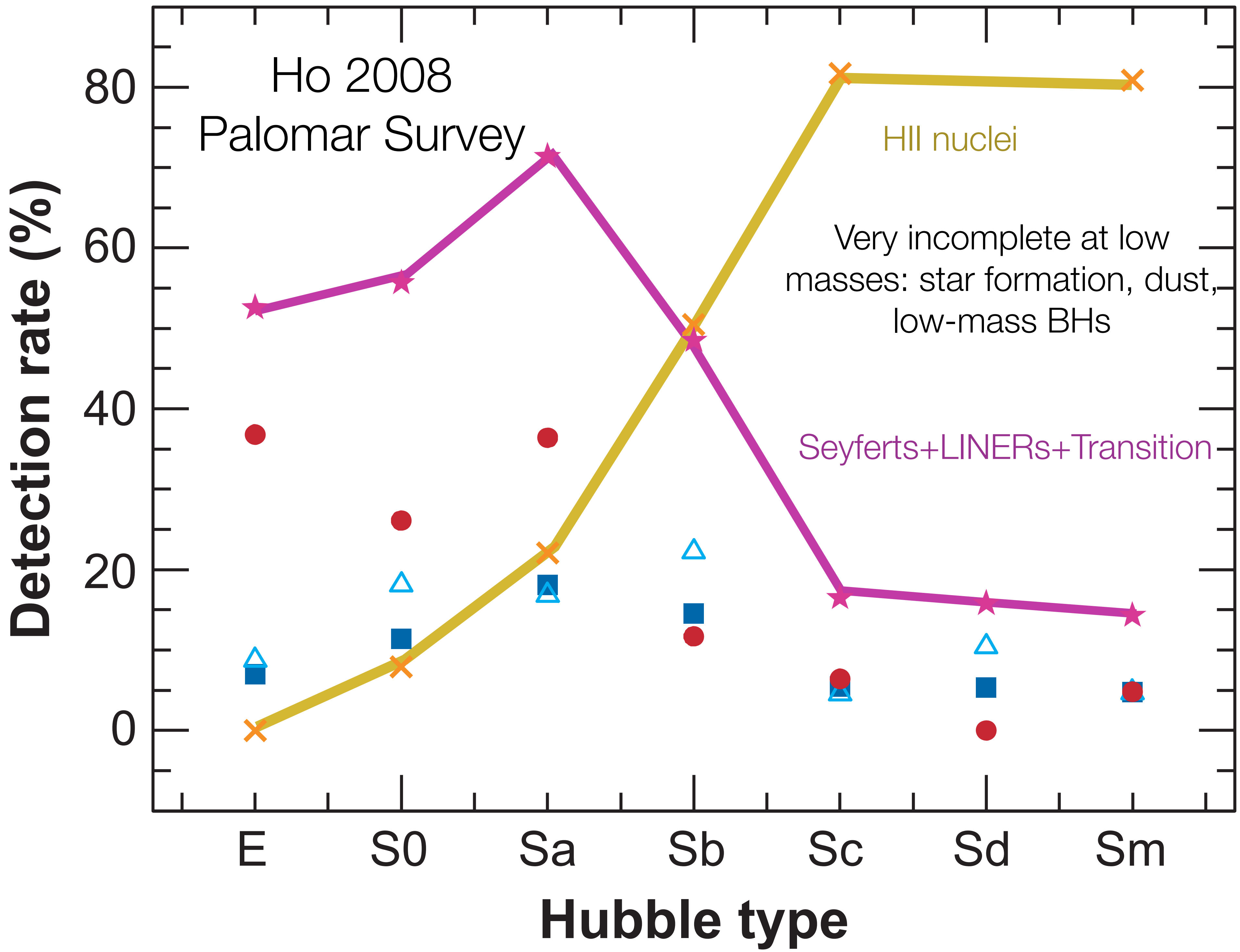

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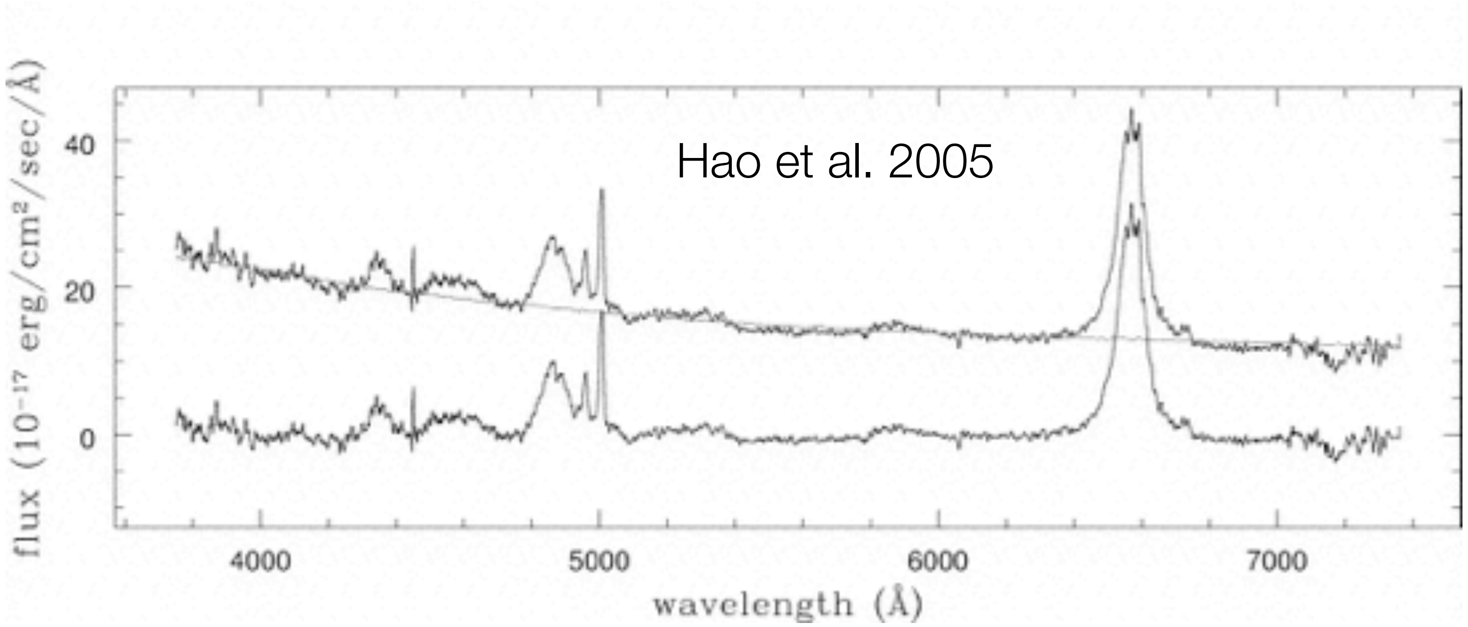
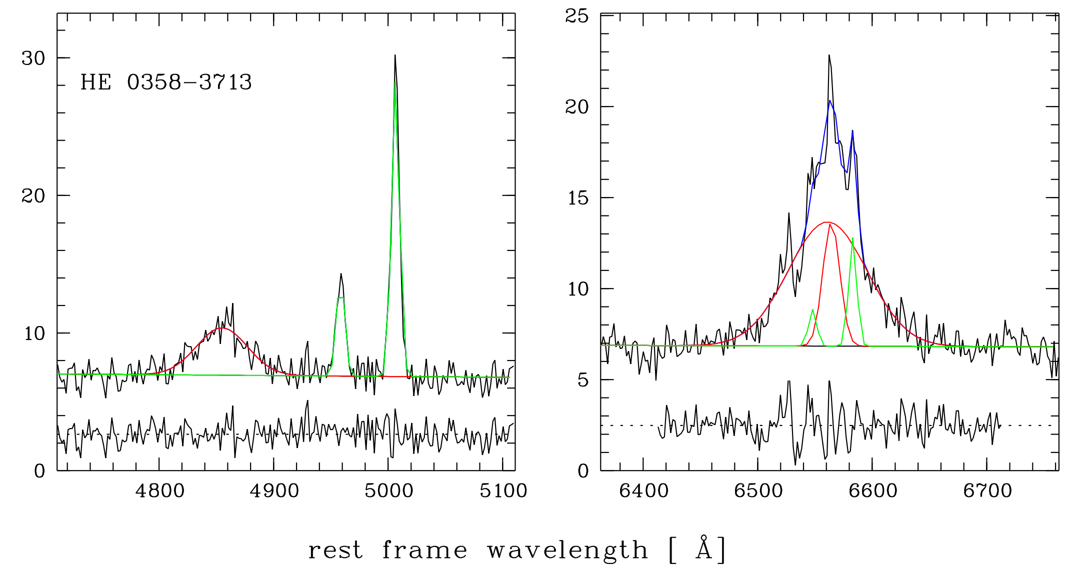
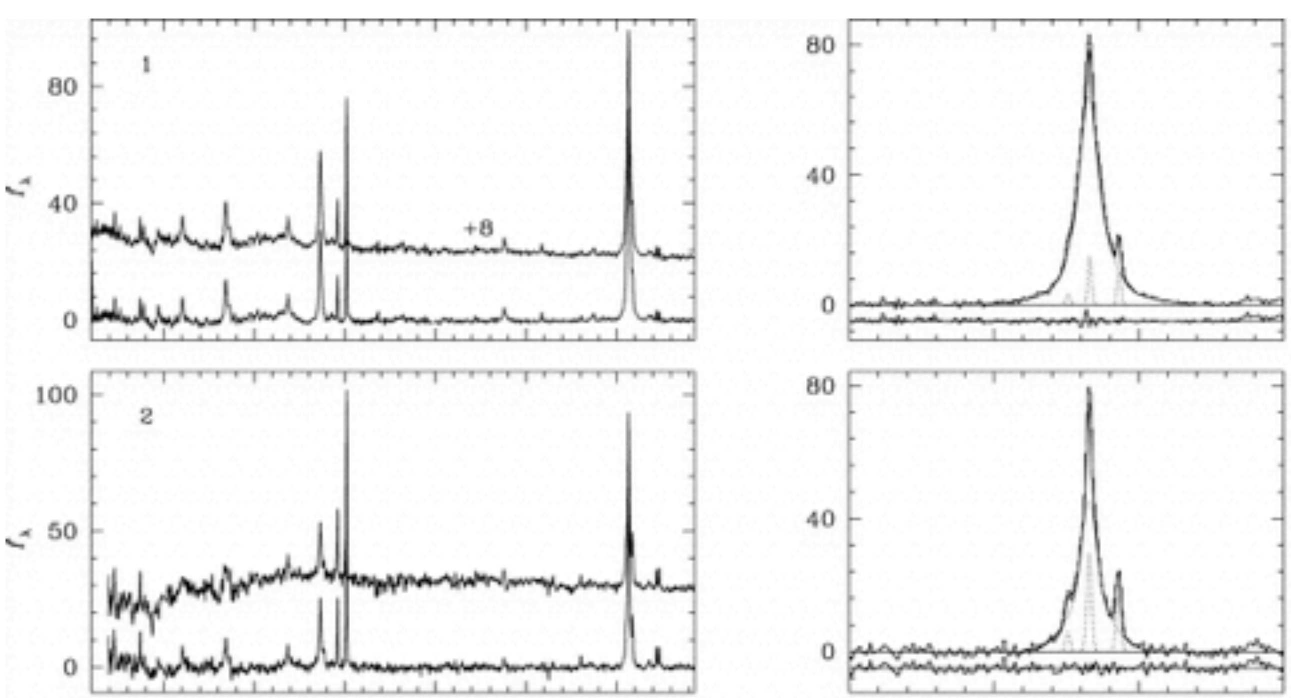
Also Broad Emission Lines

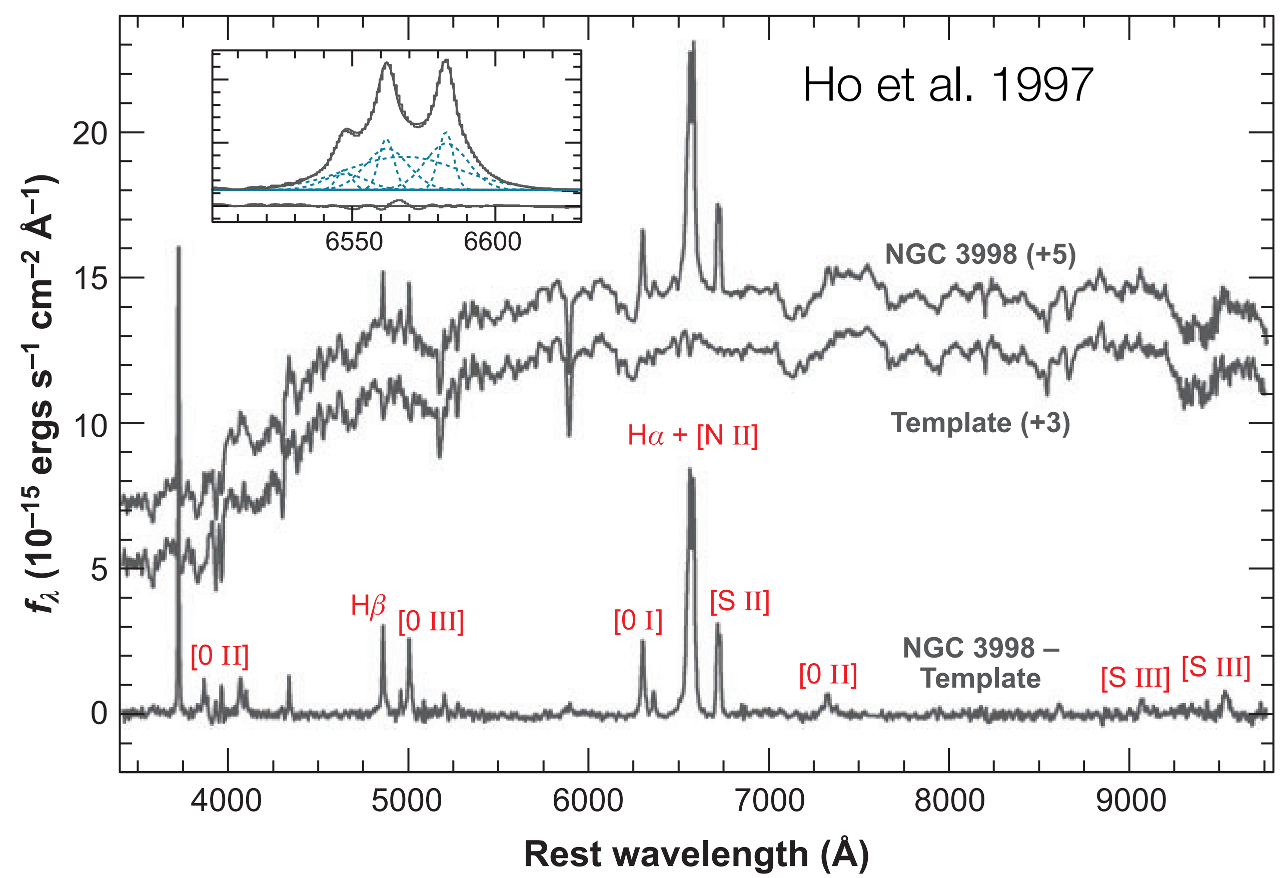


Schulze & Wiszotski 2009

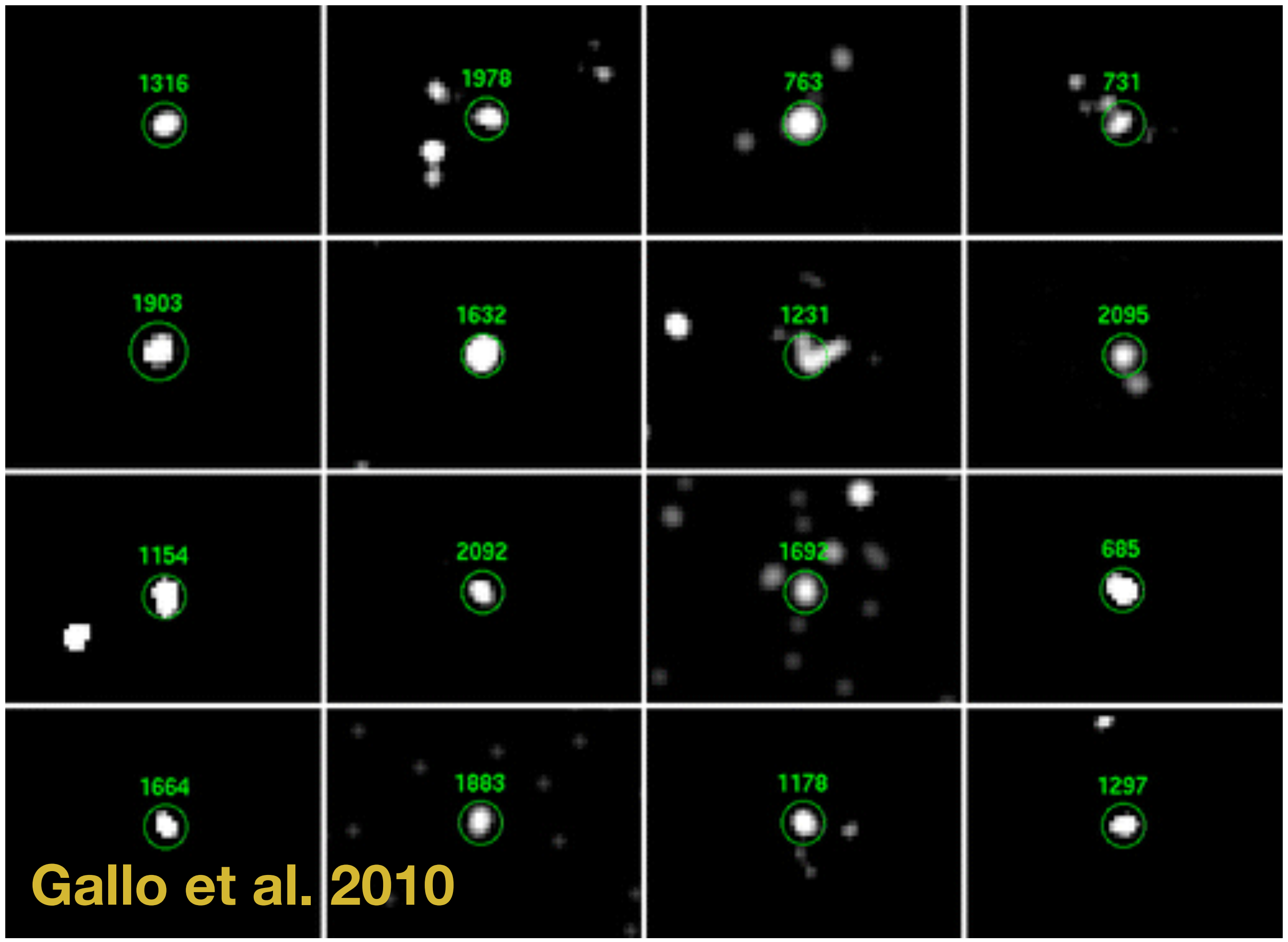


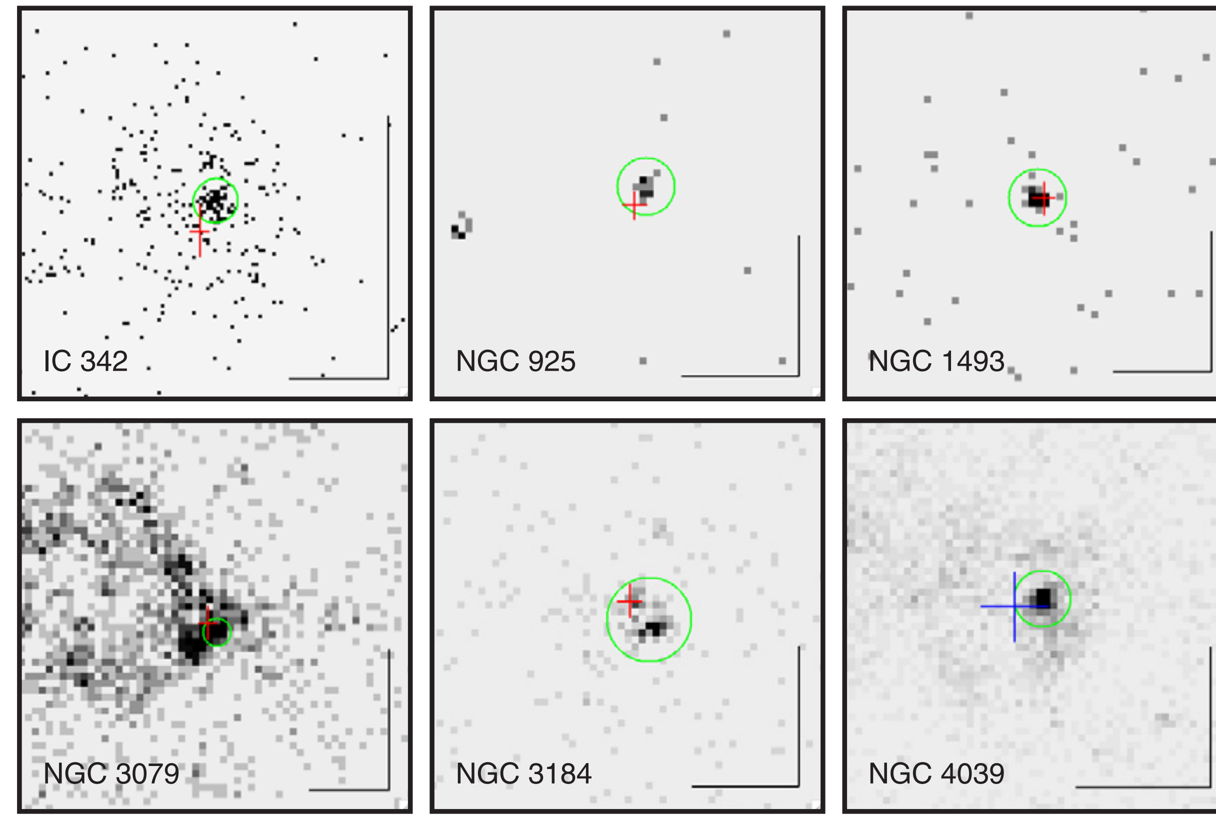
Greene & Ho 2004





Nuclear Acitivity (II): X-ray/Radio Emission



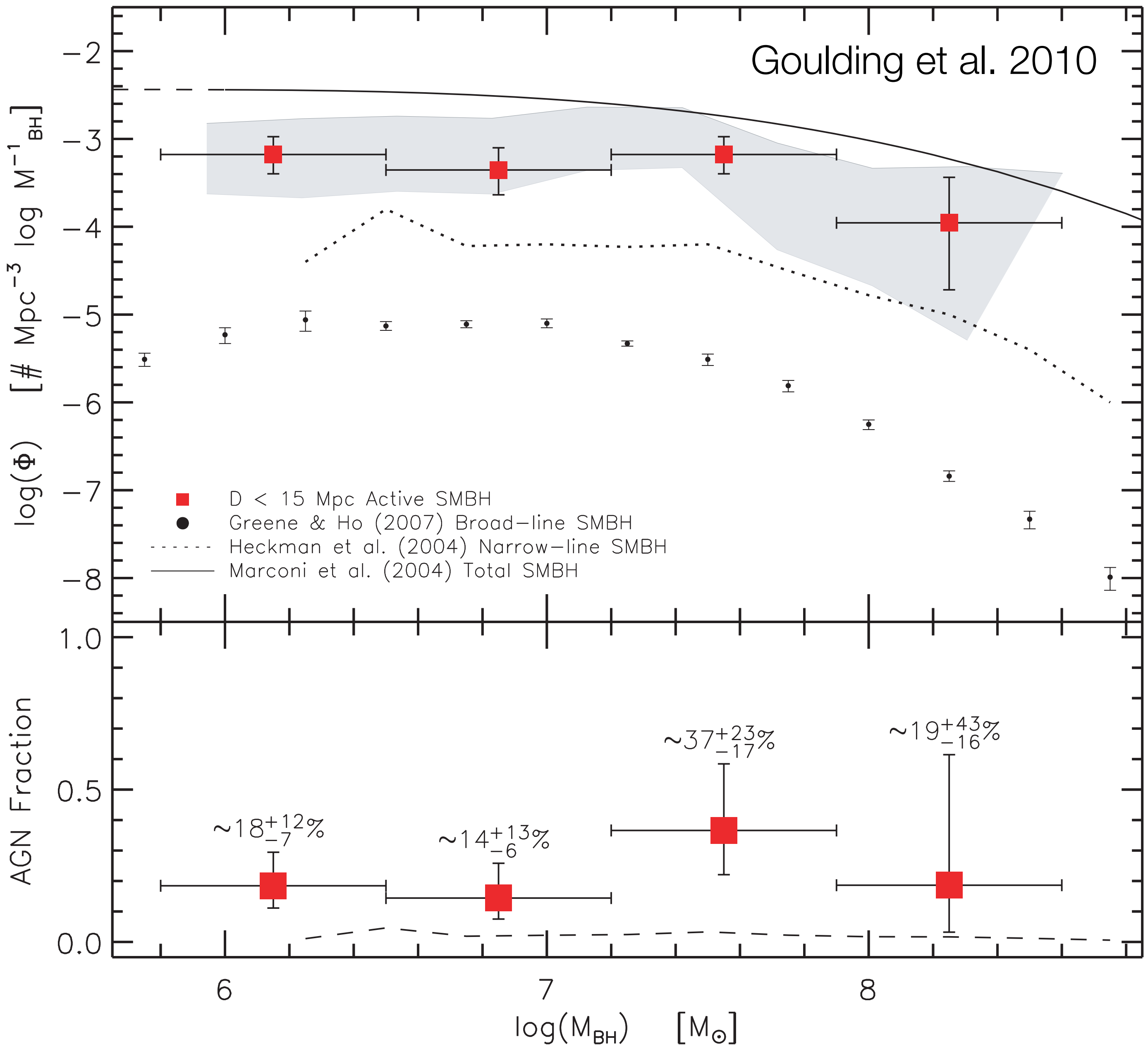


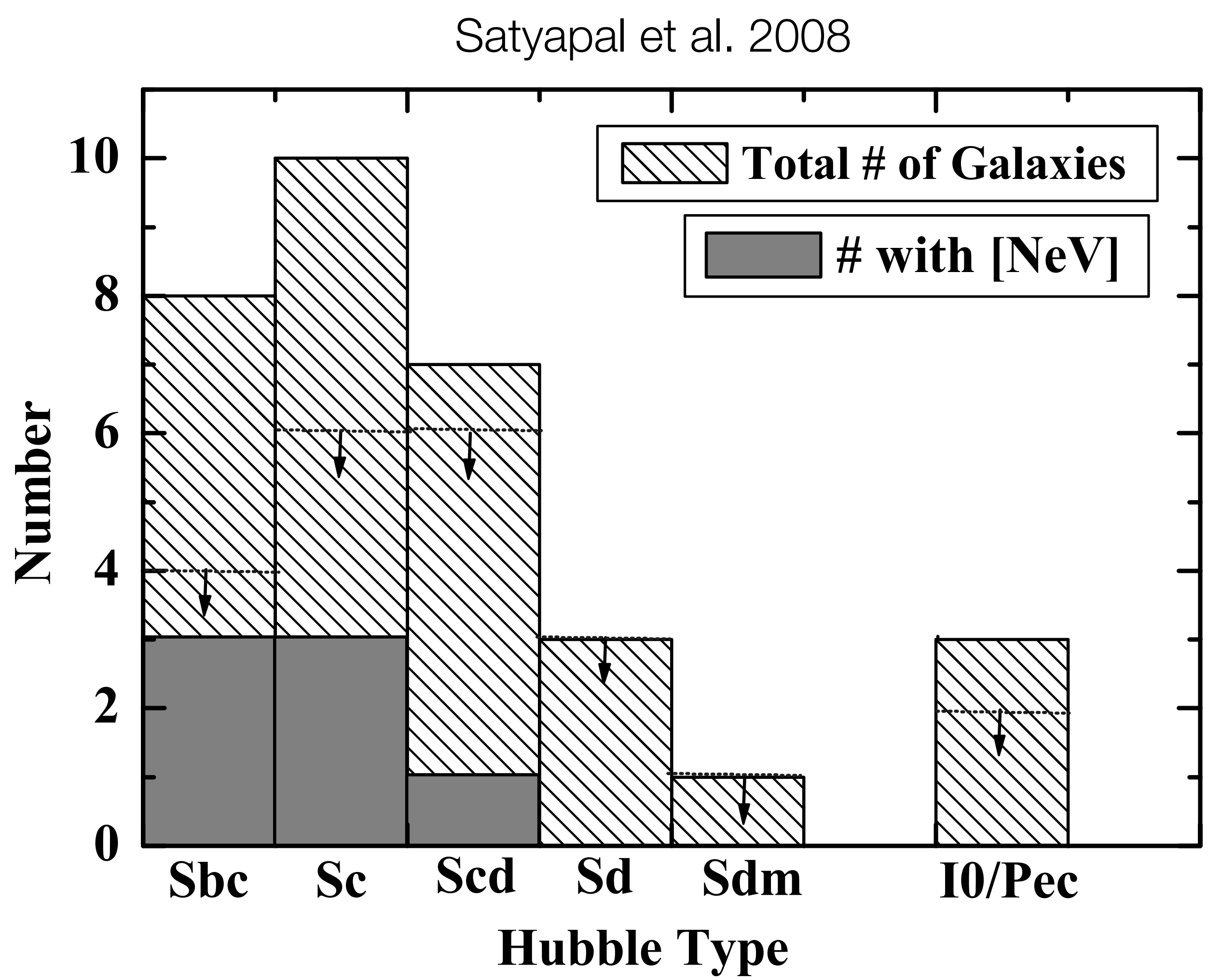
Desroches & Ho 2009

Very important to: (a) Confirm the targets identified in the optical, particularly the LINERs, (b) Search in targets with high star formation rates, high dust obscuration, weak BHs (see Gallo talk)

Lots of work with Swift/BAT survey that I will not cover.

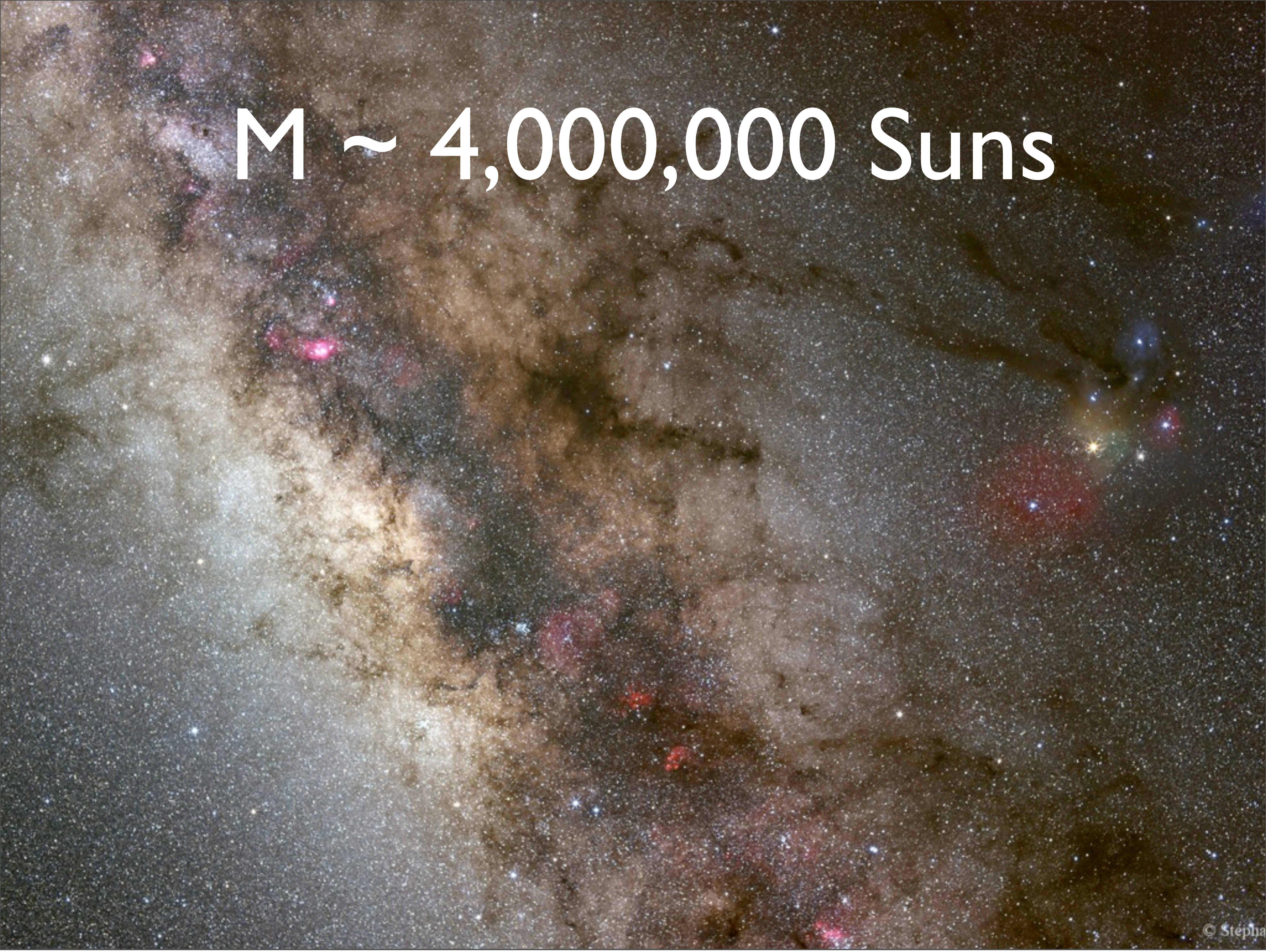
Nuclear Activity (III): MIR





Using [NeV]λ14.3, 15.1 μm lines as indicator of an AGN. Stay tuned for results from Hershel and WISE...

Demographics from Dynamics


M ~ 4,000,000 Suns
© Stepha

M ~ 4,000,000 Suns

Dynamics

Def of gravitational sphere of influence

$$r_{\rm G} = 0.11 \left(\frac{M_{\bullet}}{10^8 M_{\odot}} \right) \left(\frac{200 \text{ km s}^{-1}}{\sigma_{\star}} \right)^2 \left(\frac{20 \text{ Mpc}}{D} \right) \text{ arcsec.}$$

Required HST to achieve (although now we can also achieve with IFU+AO)

In addition to stellar dynamical modeling, it is also possible to model gas disks (when they exist)

Finally, in special cases we can use very compact masing disks

THE ASTROPHYSICAL JOURNAL, **221**:721–730, 1978 May 1

EVIDENCE FOR A SUPERMASSIVE OBJECT IN THE NUCLEUS OF THE GALAXY M87 FROM SIT AND CCD AREA PHOTOMETRY

PETER J YOUNG, JAMES A. WESTPHAL, JEROME KRISTIAN, AND CHRISTOPHER P. WILSON
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington

AND

FREDERICK P. LANDAUER
Space Photography Section, Jet Propulsion Laboratory
Received 1977 June 10; accepted 1977 October 7

ABSTRACT

Two-dimensional SIT and CCD detectors have been used to measure the surface brightness of the peculiar elliptical radio galaxy M87. Measurements were made in three broad-band colors (B, V, and R) to a distance of 80″ from the nucleus, with 1″ spatial resolution and photometric accuracy of the order of 1%.

The data are given in some detail and are compared with earlier photographic results. The most obvious feature of the data is a bright, barely resolved central luminosity spike, which is not seen in similar data on other nearby normal ellipticals. Also, attempts to fit isothermal or King models away from the nuclear spike show additional excess luminosity in the central regions of the galaxy ($r < 10''$), which cannot be fitted by such a model.

A model-independent dynamical analysis, using the photometric data combined with spectrographic results by Sargent *et al.*, shows that the nucleus of M87 contains a compact mass of low luminosity, with $M = 5 \times 10^9\ M_\odot$, $r < 100$ pc, and $M/\mathscr{L} > 60$. All of the existing data is well fitted by a King model containing a central black hole of mass $M = 3 \times 10^9\ M_\odot$ and a point luminosity source. While such a model is not uniquely required by the data, it is perhaps the most plausible of several possible models considered. At present, M87 is probably the best case for a hypothetical massive black hole in a galaxy nucleus.

AL, 221:

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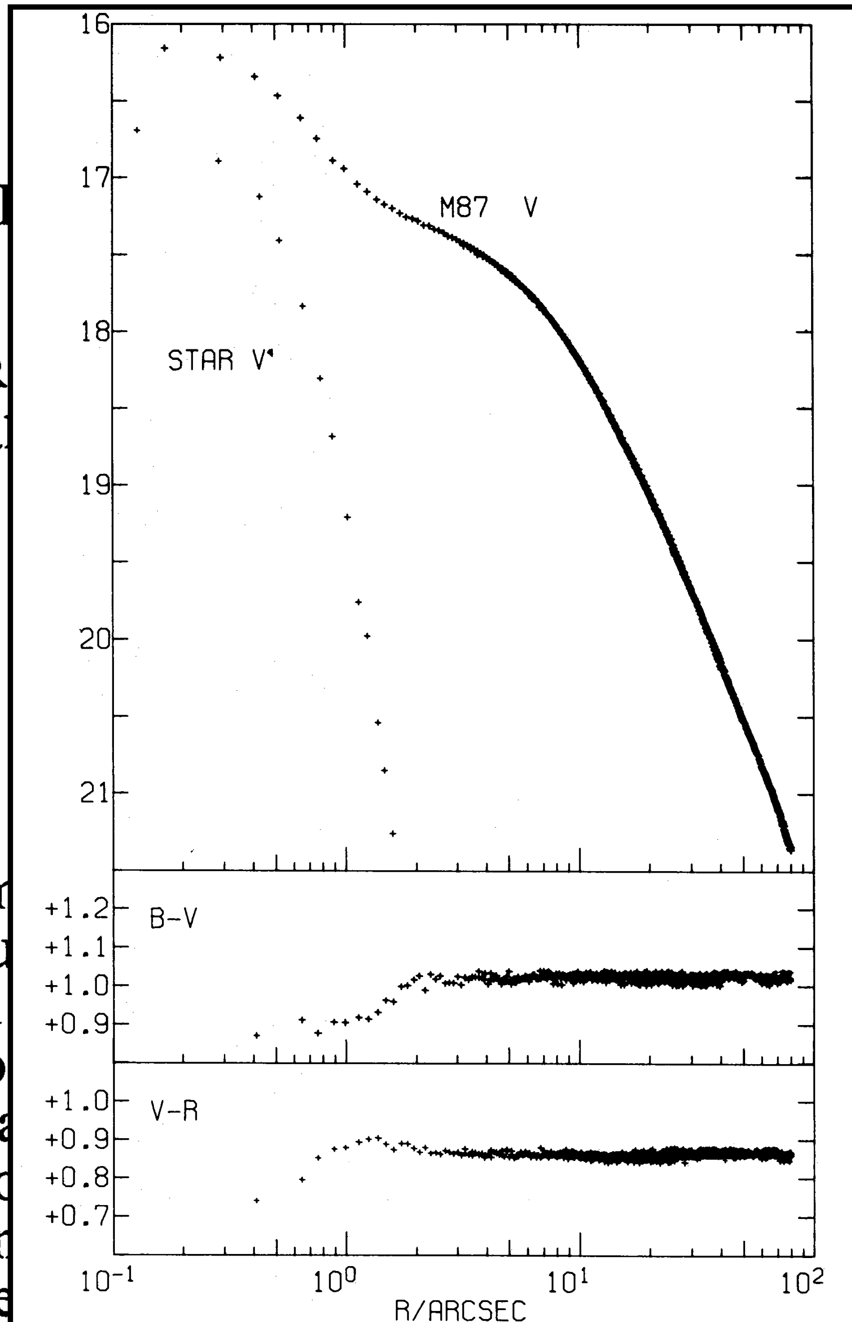

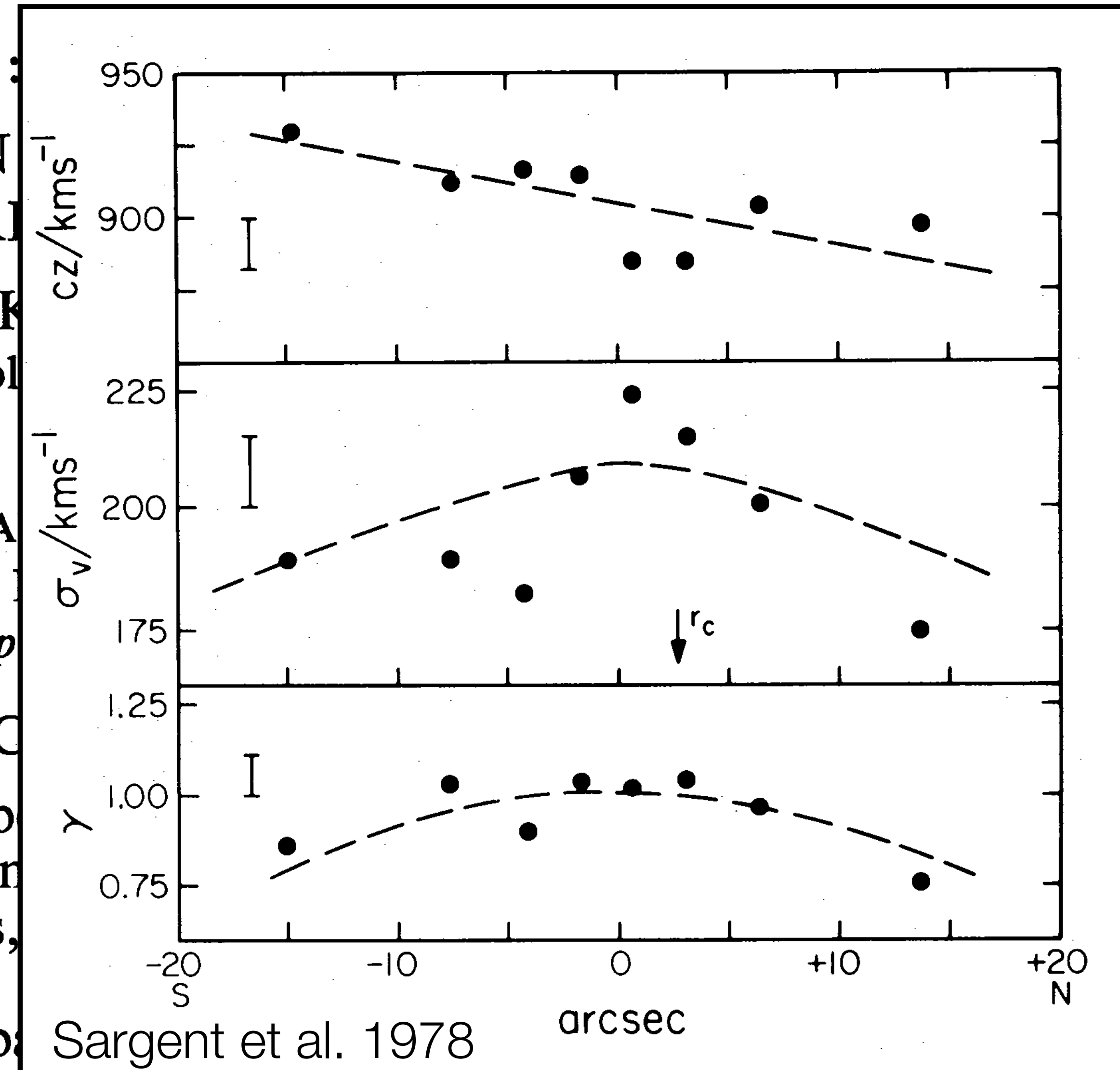

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The data… compa… most obvio… barely resolved central luminosity spike, which is not seen in… rmal ellipticals. Also, attempts to fit isothermal or King mode… w additional excess luminosity in the central regions of the galaxy ($r < 10''$), which cannot be fitted by such a model.

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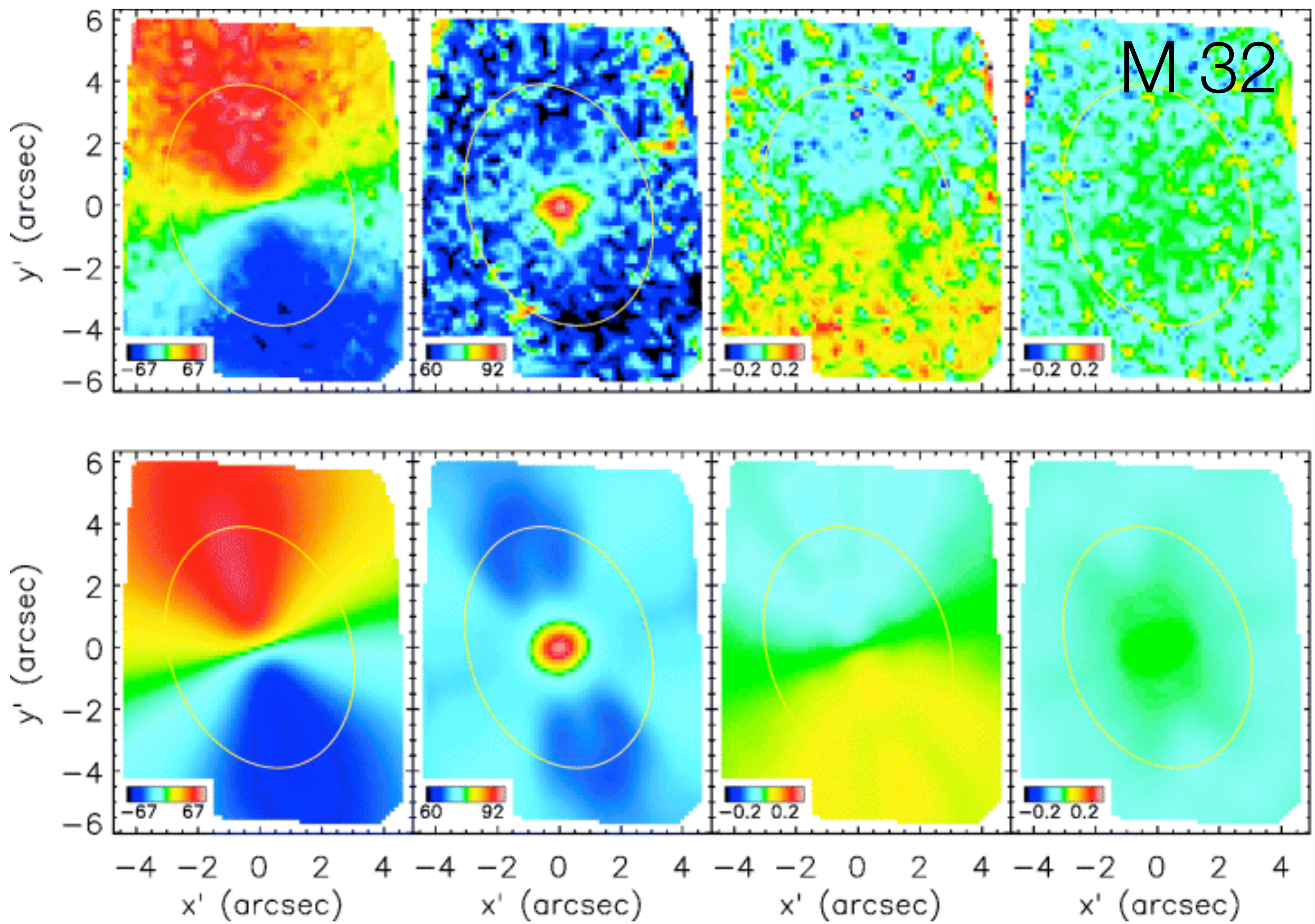
Observed Kinematics
V, σ, h3, h4 -- this from SAURON



Stellar dynamical model
Based on a library of orbits

Verolme et al. 2002

Observed Kinematics
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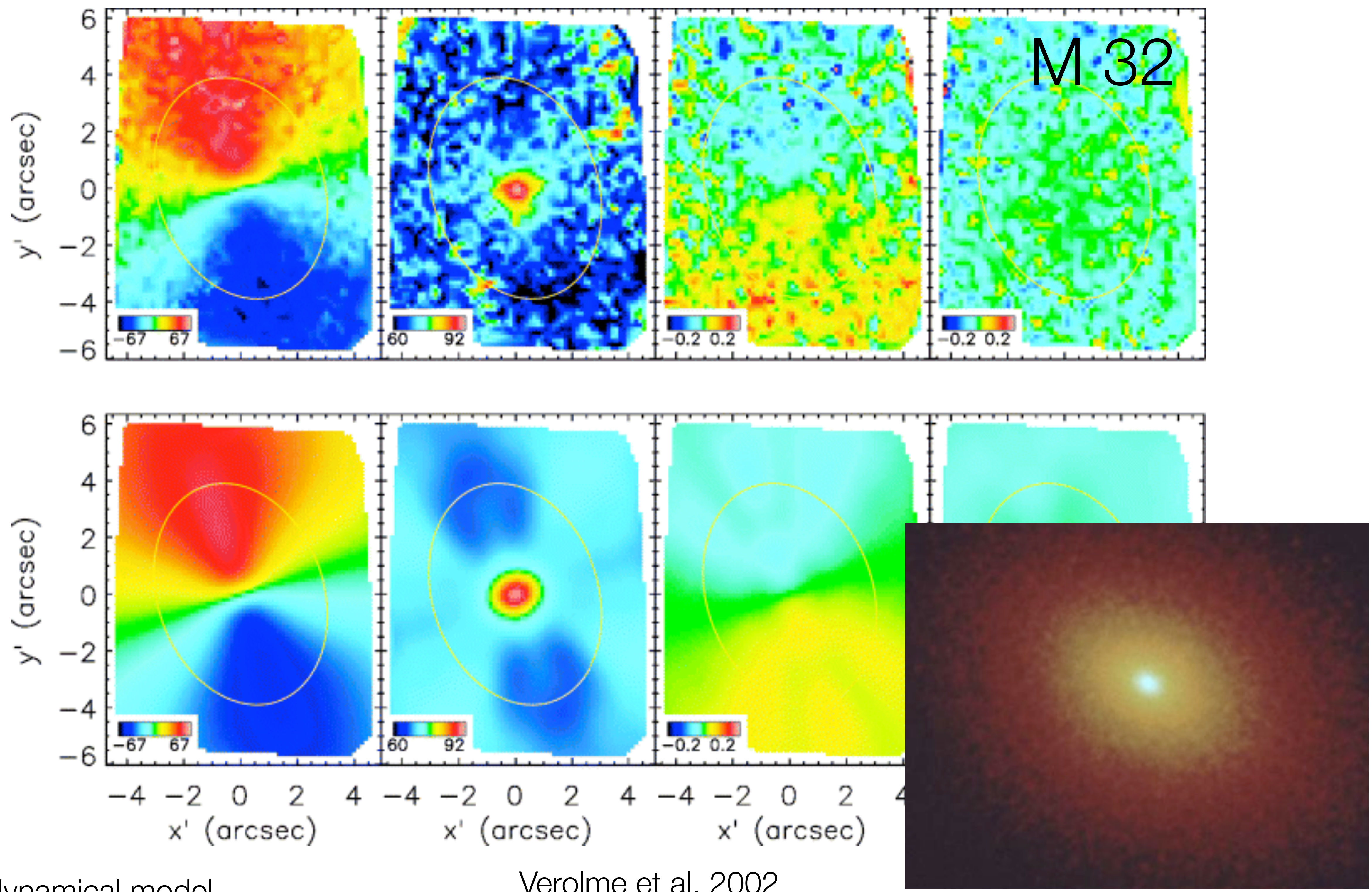
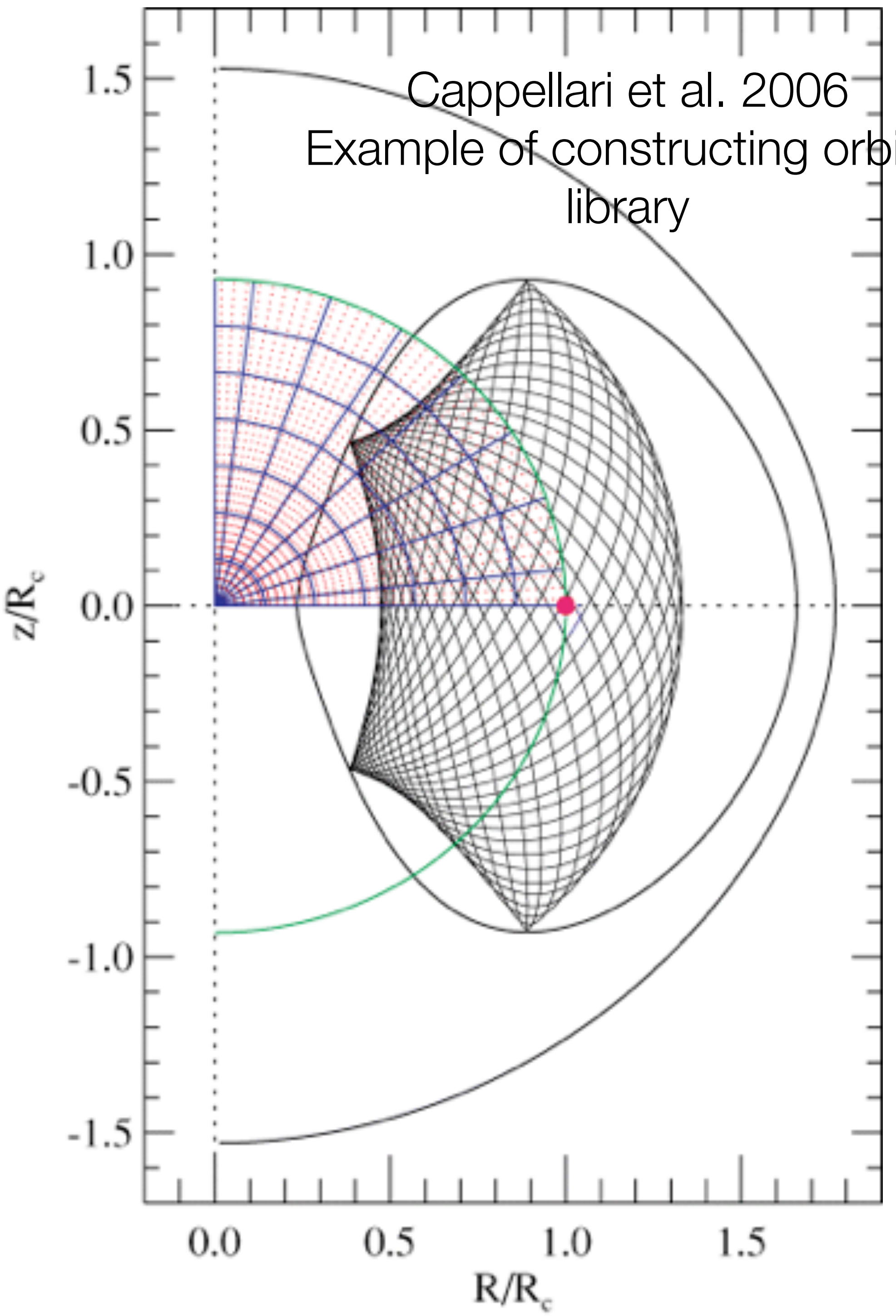


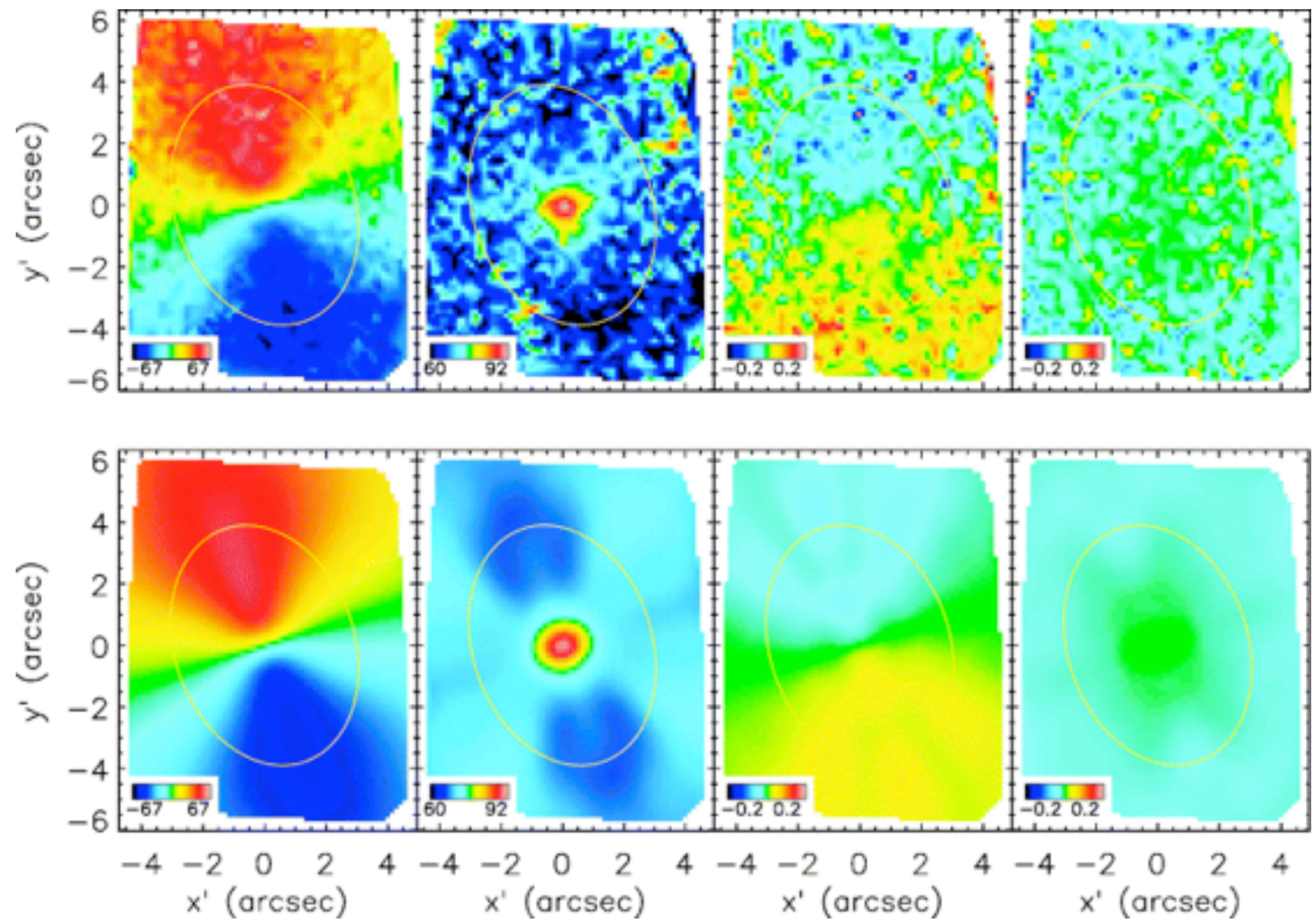
Stellar dynamical model
Based on a library of orbits

Verolme et al. 2002

HST+ground-based
imaging (+deprojection)
gives mass distribution

Cappellari et al. 2006
Example of constructing orbital library





From the collisionless Boltzmann Equation we have:

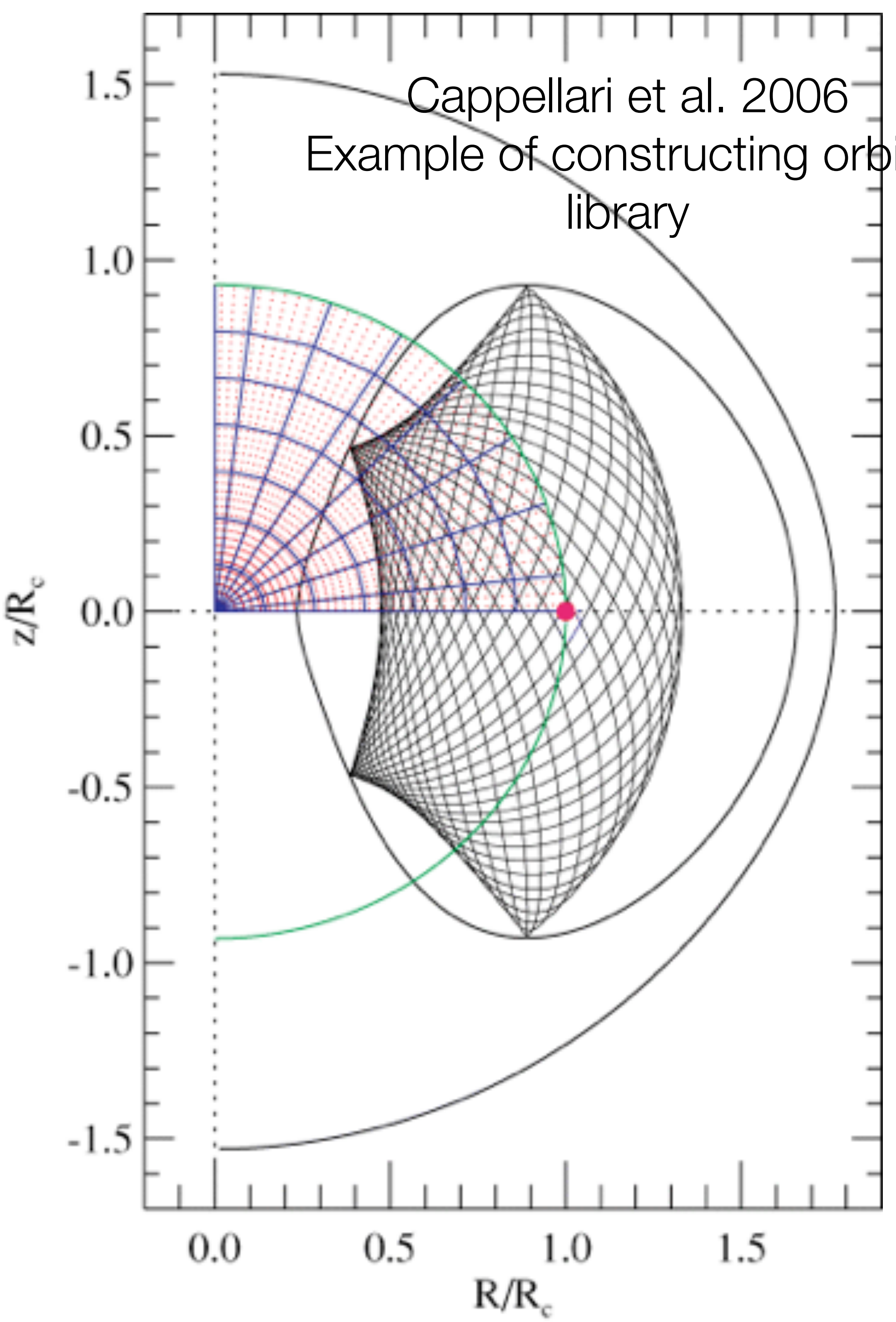
$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d \ln \nu}{d \ln r} - \frac{d \ln \sigma_r^2}{d \ln r} - \left(1 - \frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1 - \frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

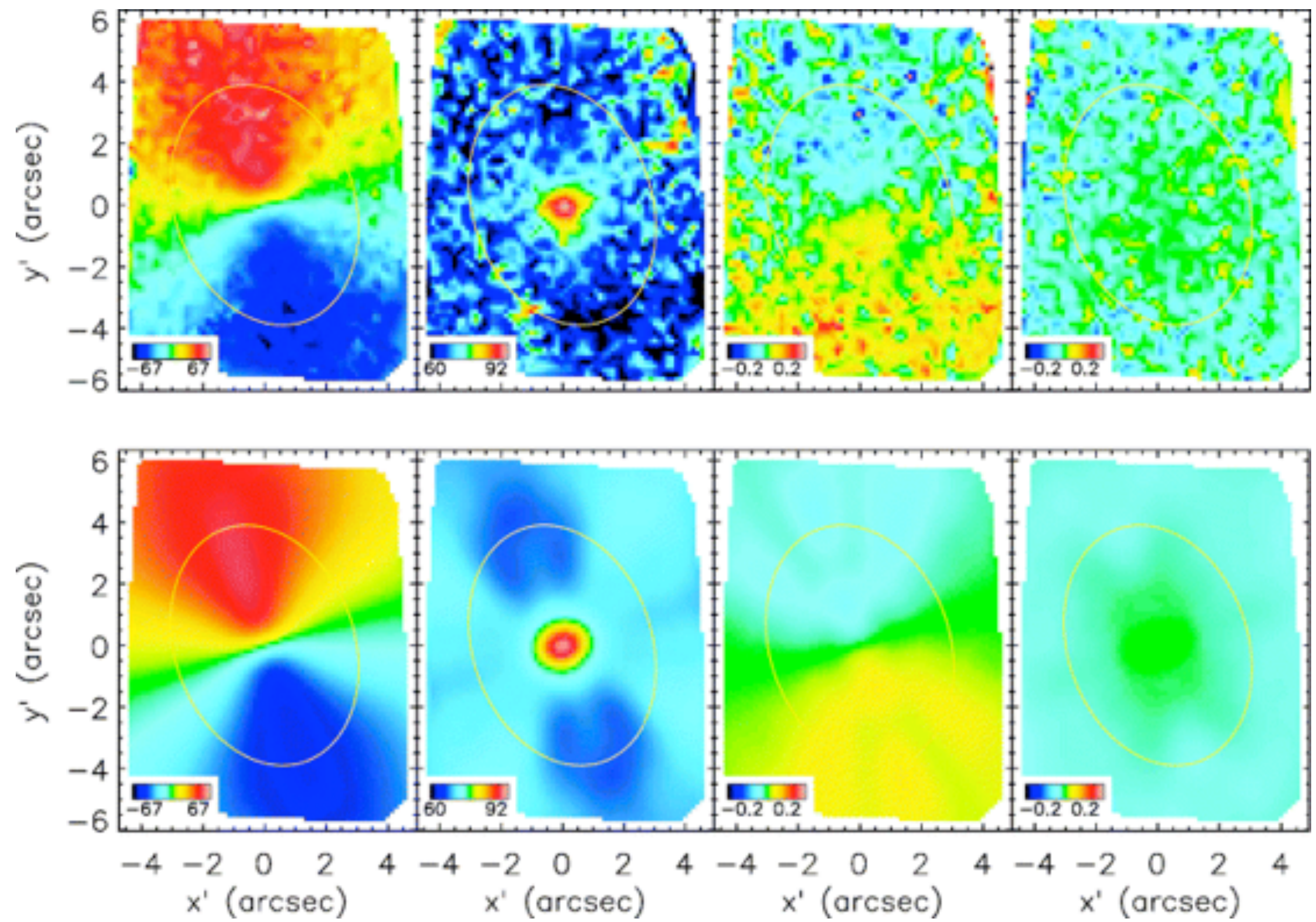
density of the tracer population

anisotropy

Outstanding uncertainties: triaxiality? DM halo?

Cappellari et al. 2006
Example of constructing orbital library





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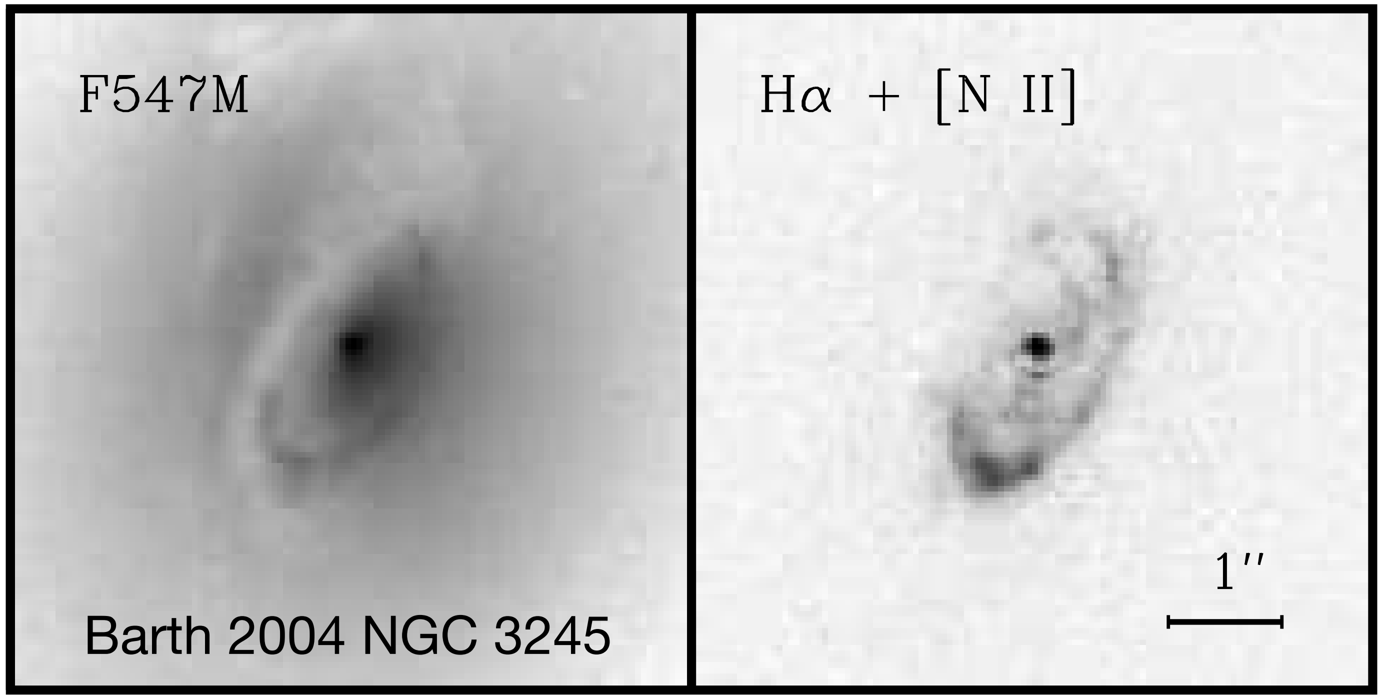
density of the tracer population

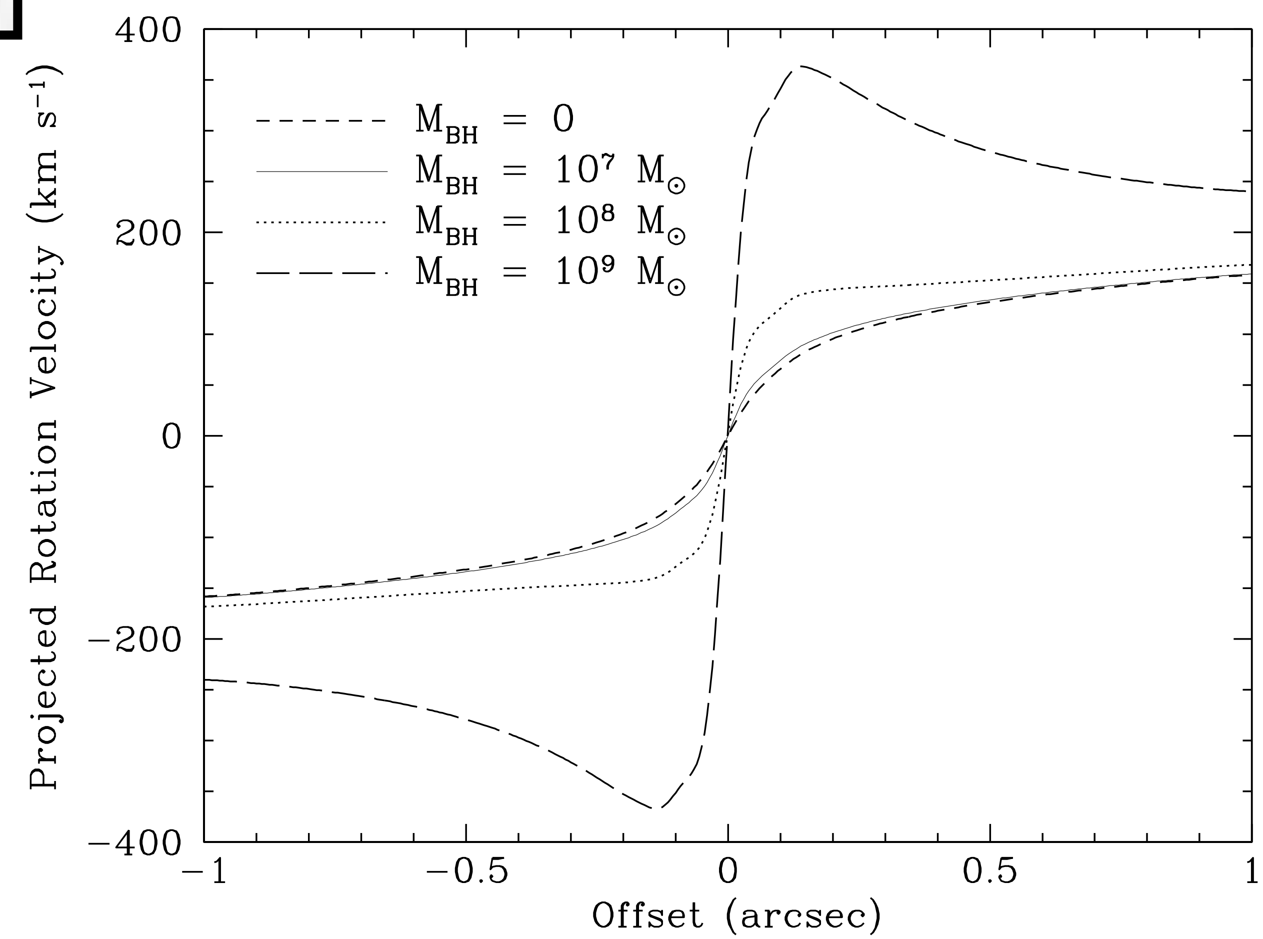
anisotropy

Gas-dynamical Measurements

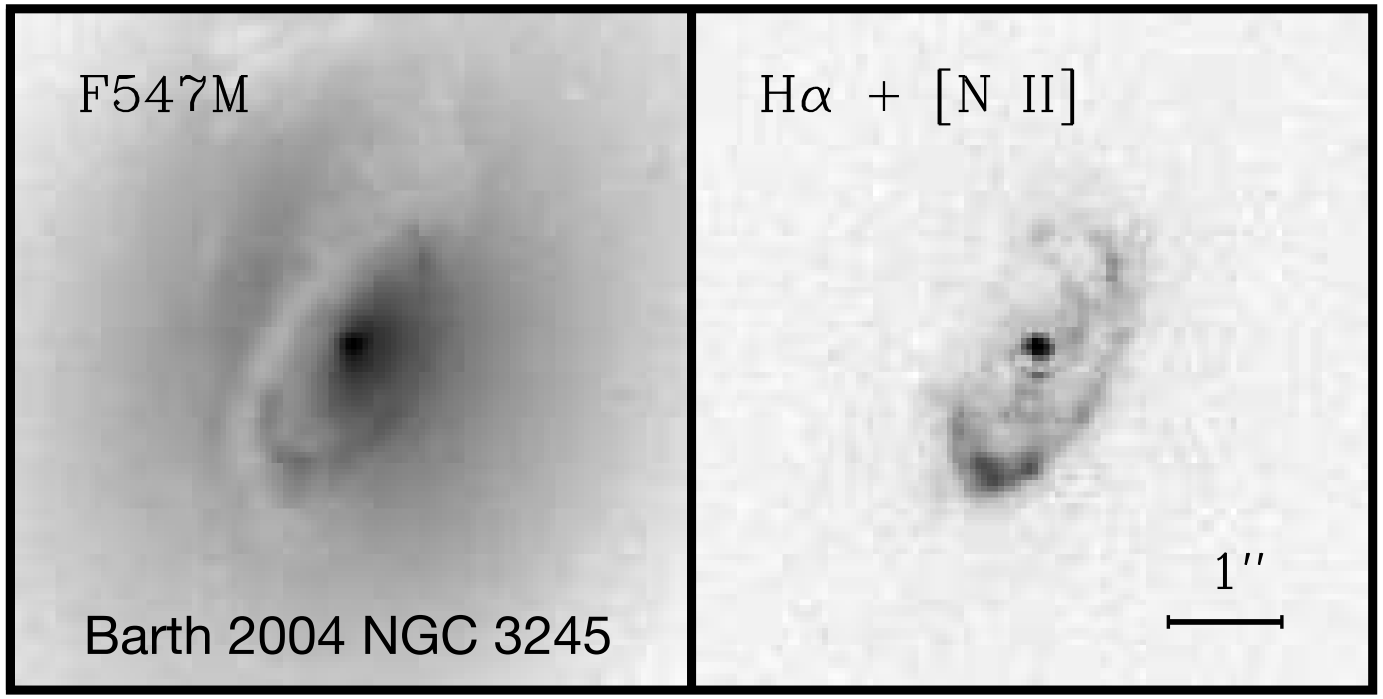


Example ionized gas disk. HST finds ~20% of ellipticals contain well-organized ionized gas disks at their center

Rotation curves for different enclosed masses. Like the stellar-dynamical case, a luminosity profile is needed to derive the potential



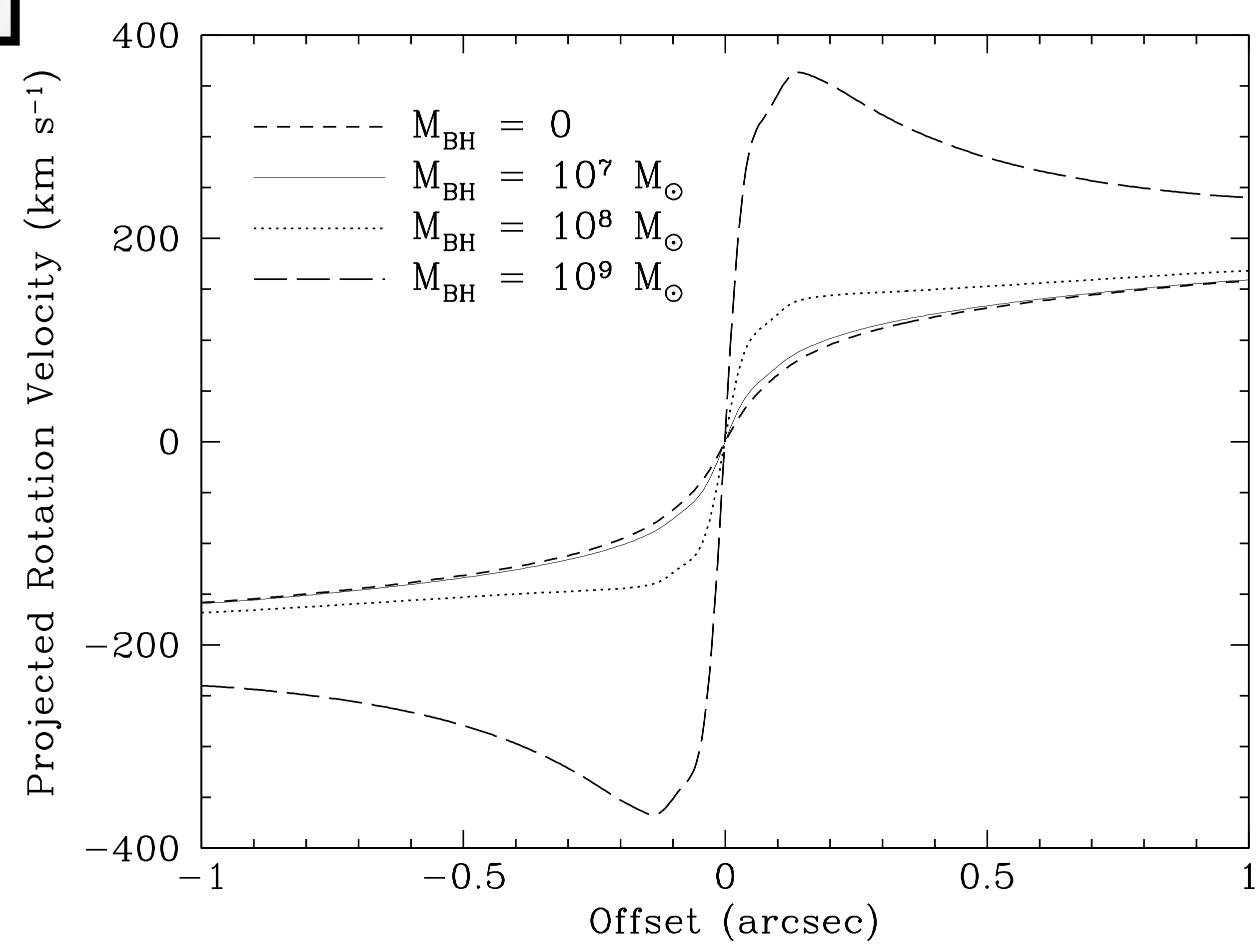
Gas-dynamical Measurements



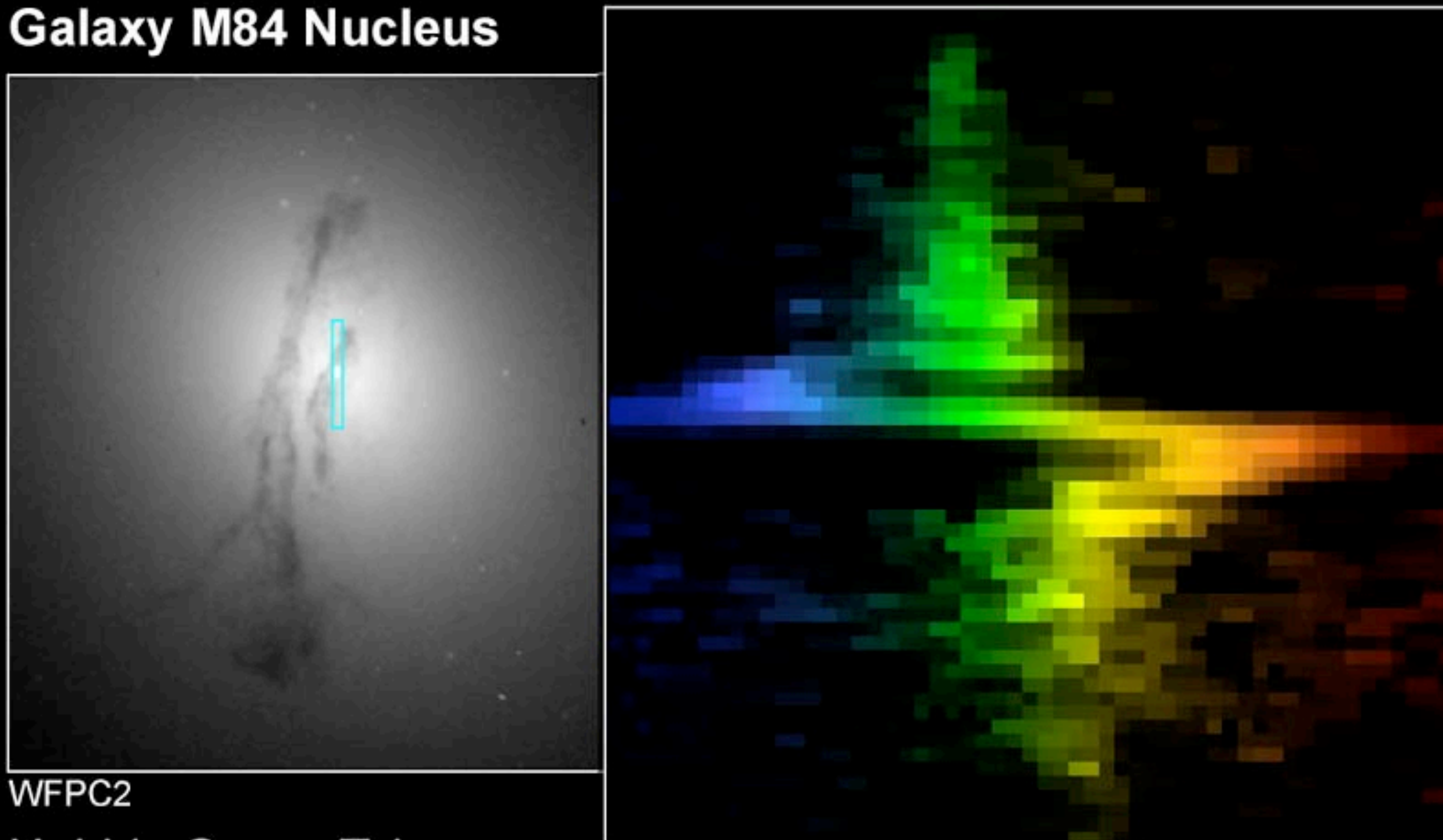
Example ionized gas disk. HST finds ~20% of ellipticals contain well-organized ionized gas disks at their center

Outstanding uncertainties: inclination? turbulence?

Rotation curves for different enclosed masses. Like the stellar-dynamical case, a luminosity profile is needed to derive the potential



Galaxy M84 Nucleus



WFPC2

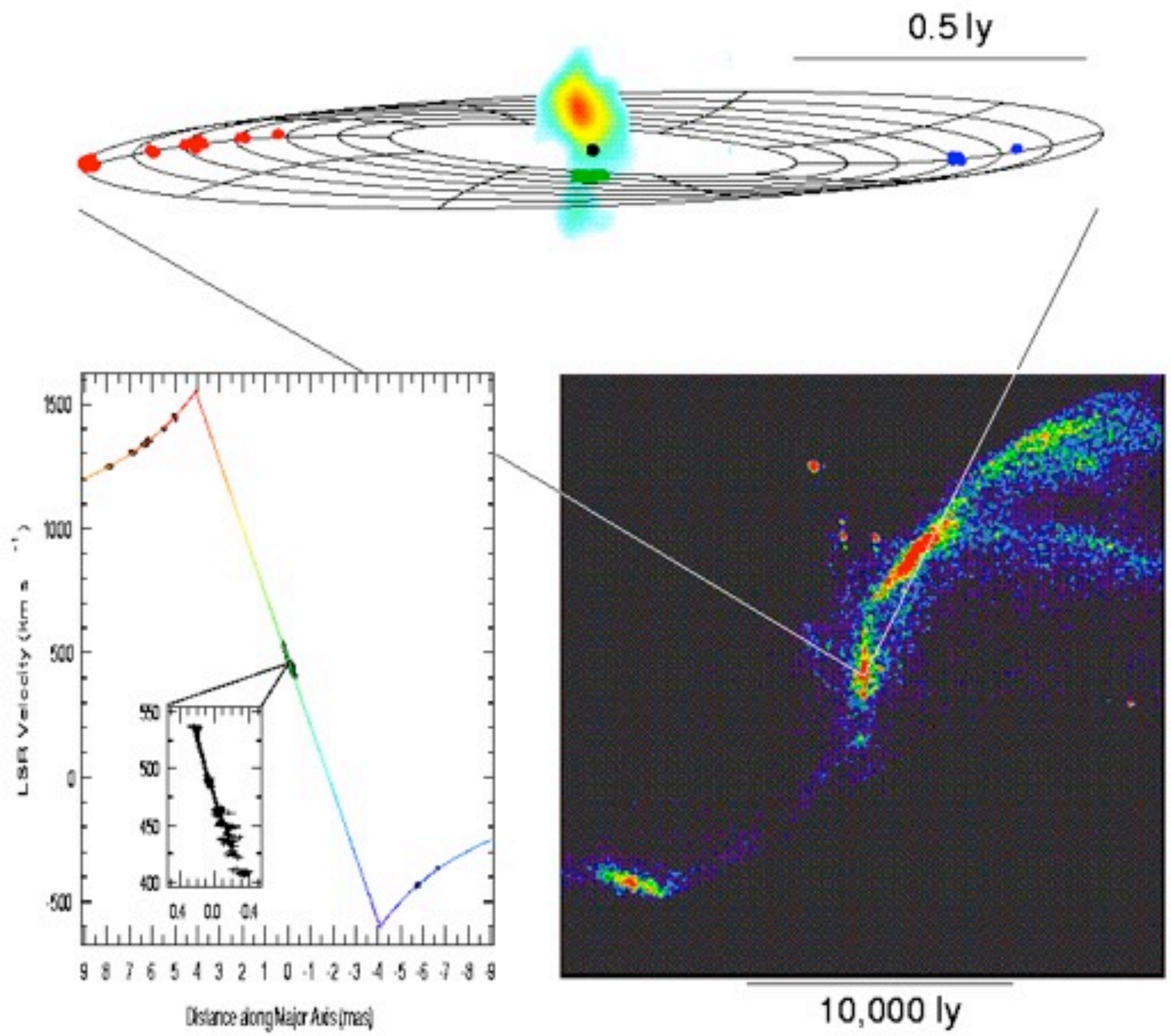
STIS

Hubble Space Telescope

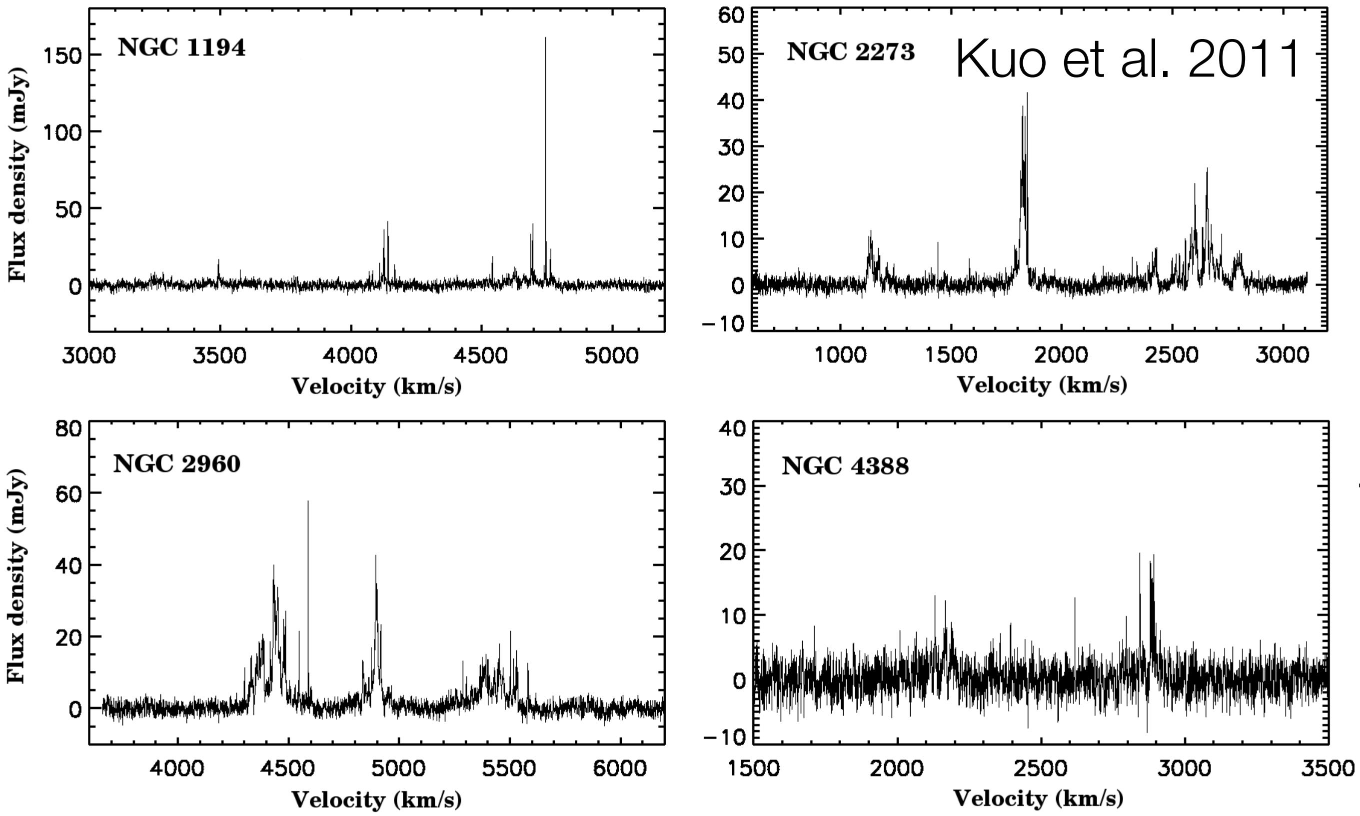
PRC97-12 • ST ScI OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

Megamasers: NGC 4258

- H_2O megamasers (microwave amplification by stimulated emission; 10^2-10^4 $L_\odot$) as dynamical tracers
- Very precise BH mass ($3.9 \pm 0.1 \times 10^7$ $M_\odot$), relatively free of systematic bias
- With accelerations, also measure an angular-diameter distance
- Along with MW, best case to rule out astrophysical alternatives to SMBH (e.g., Maoz et al. 1995, 1998)

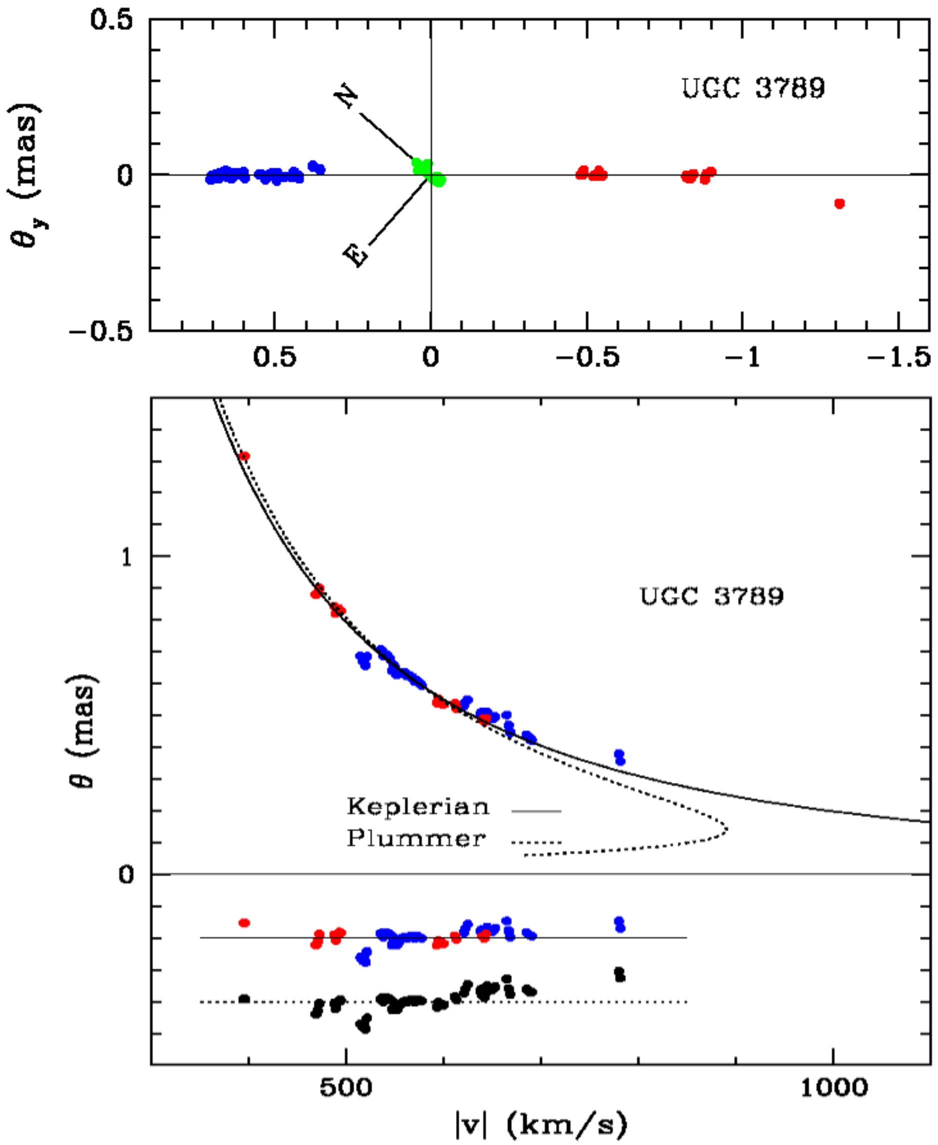


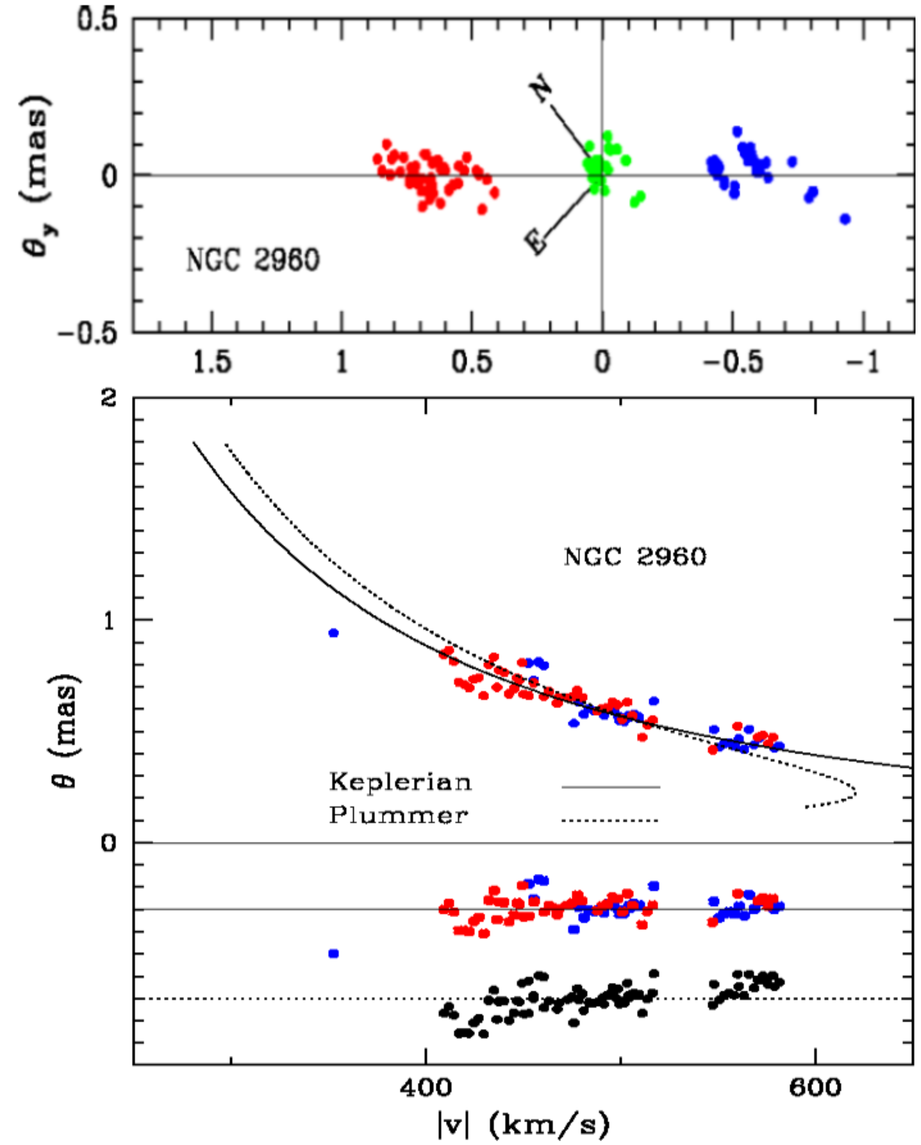
Miyoshi et al., Herrnstein et al., Greenhill, Humphreys, Moran
galaxy is ~7 Mpc away



8 new megamaser disks with beautiful Keplerian rotation curves. Yield BH masses with <10% precision (!). Hoping for 10 more soon.

Important to cross-calibrate stellar-dynamical masses with maser masses.

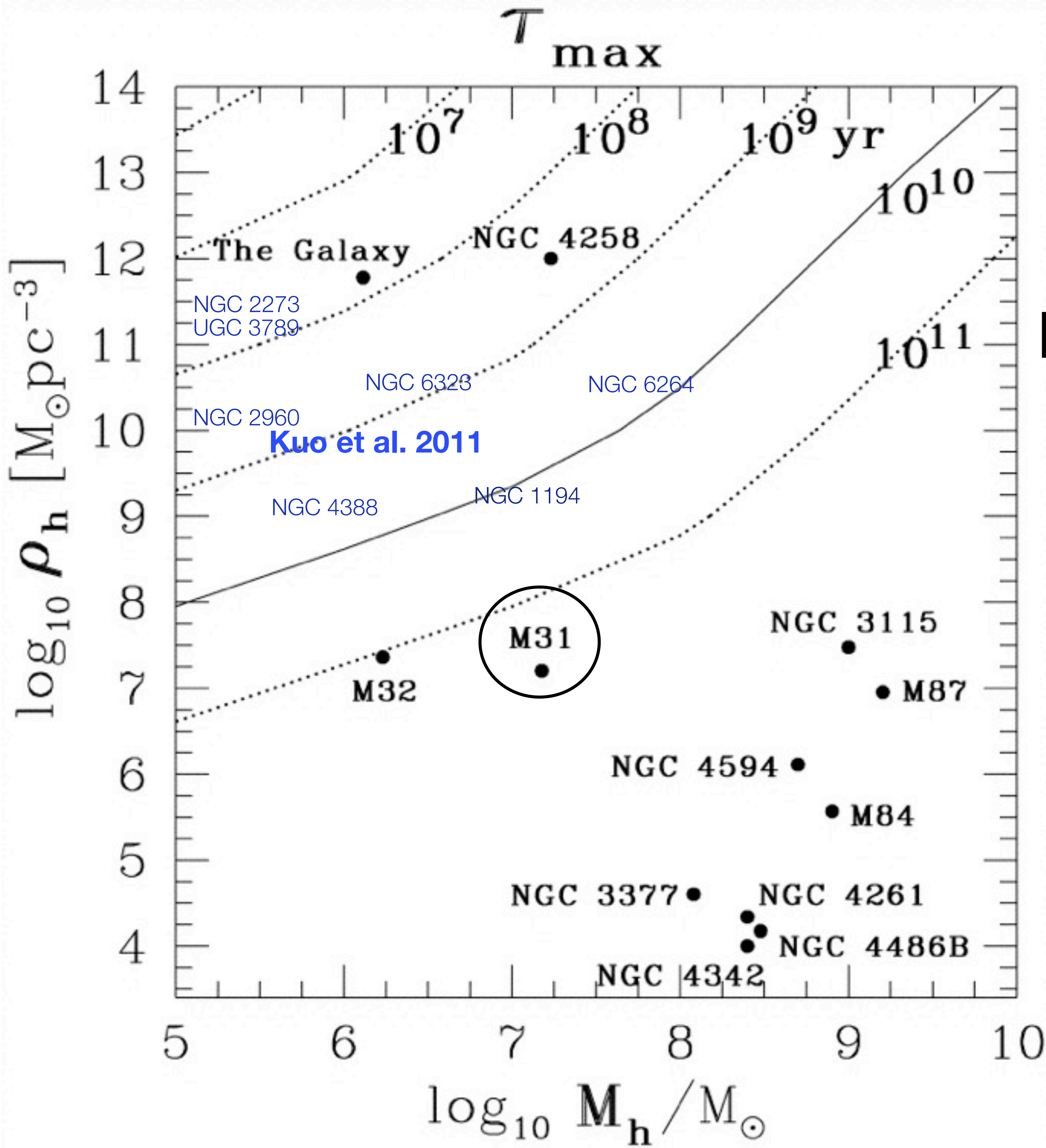




All Massive Galaxies Harbor Massive Black Holes

The first, and most basic, conclusion of the dynamical studies is that all bulge-dominated galaxies contain BHs. This is identical to the result from the active galaxies.

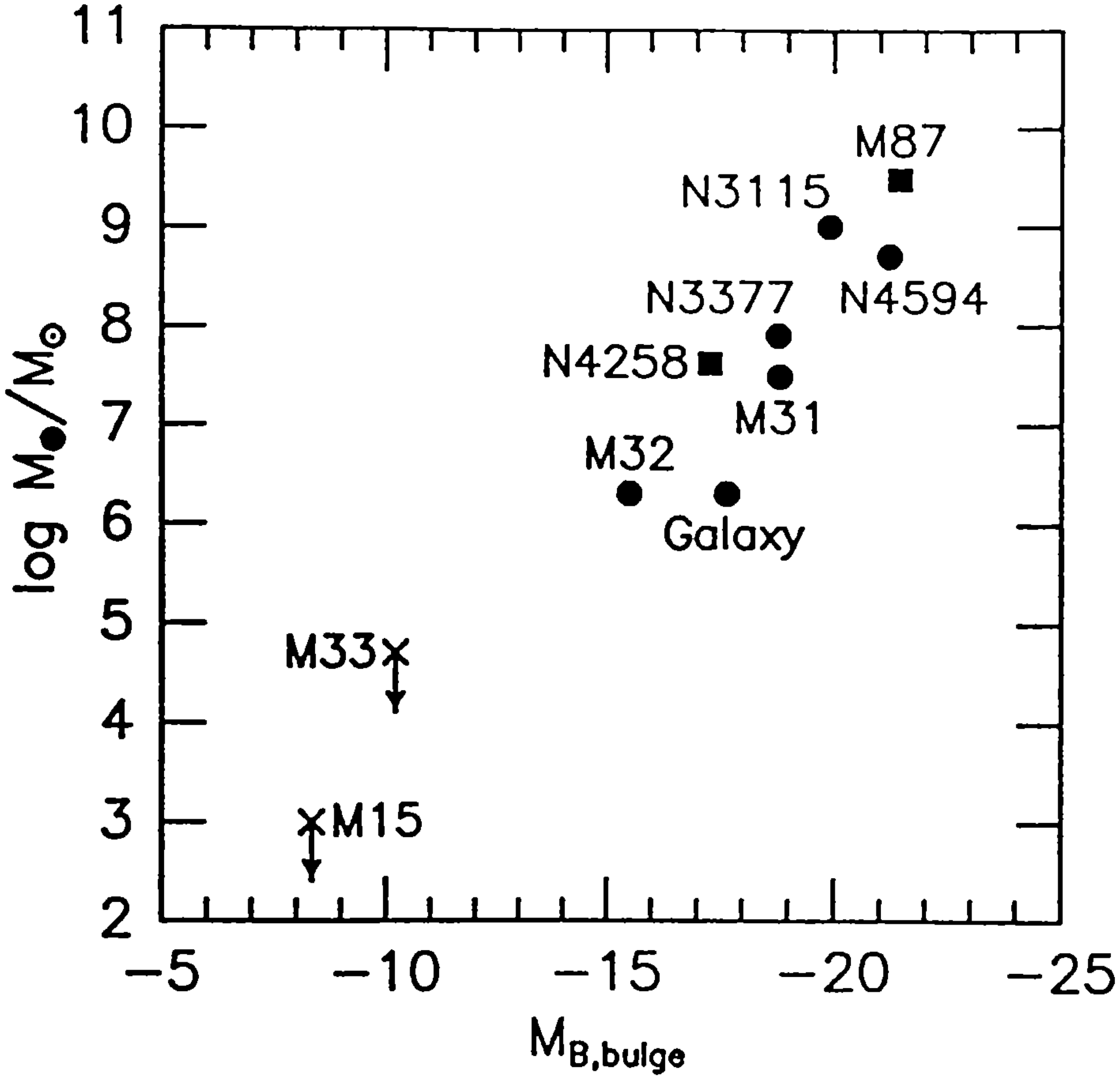
Maoz 1998

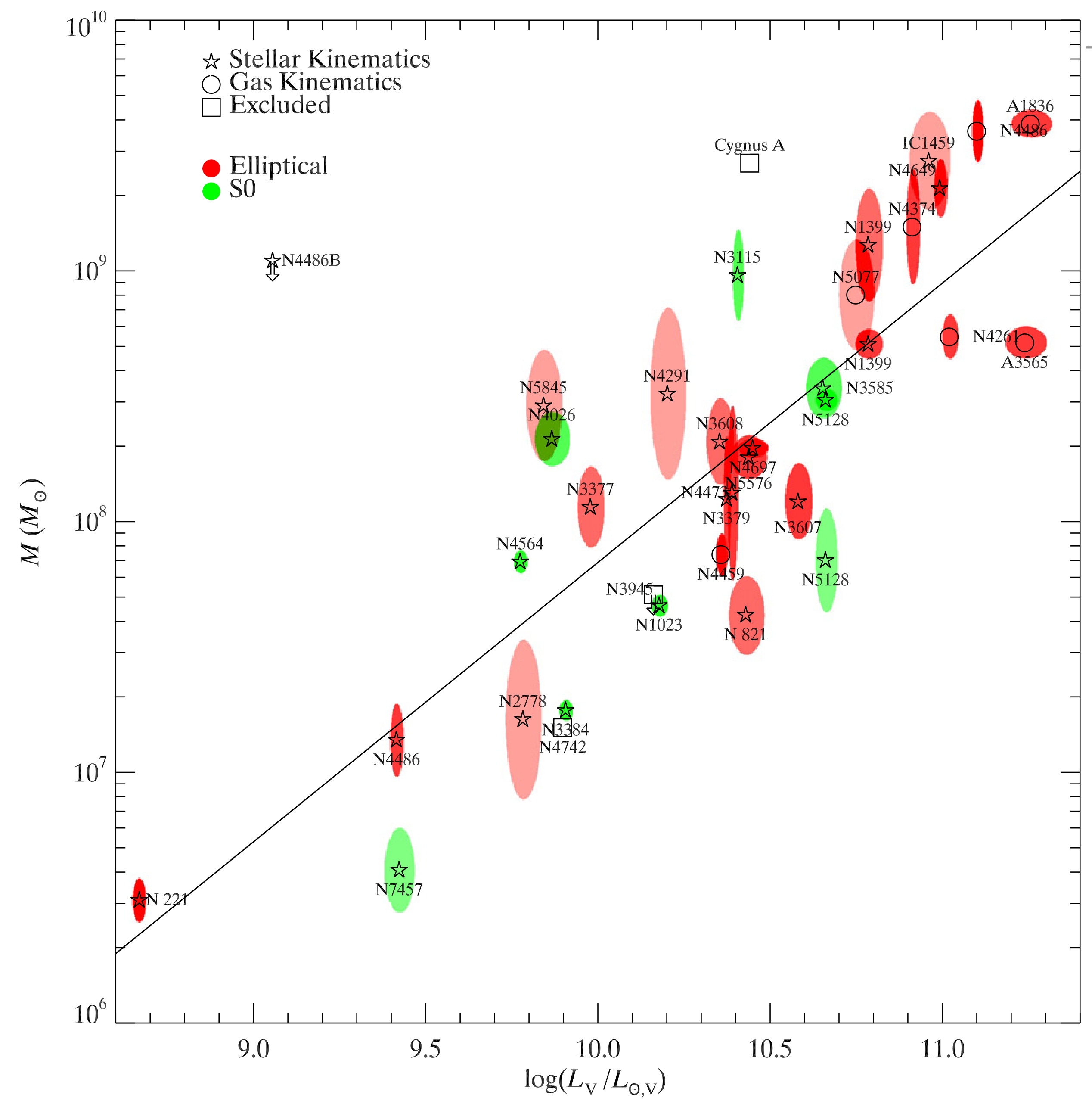


Real BHs!

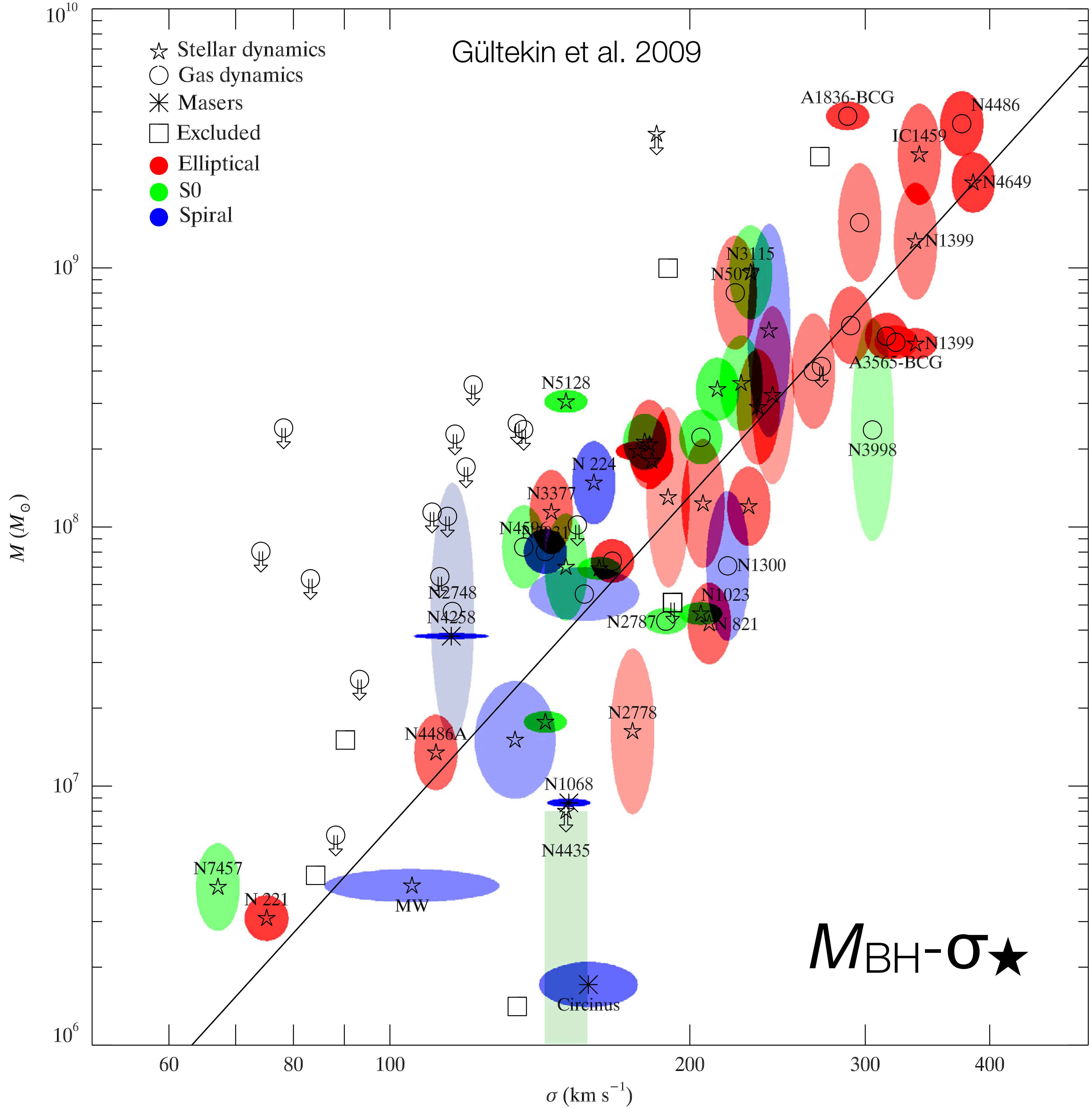
Scaling Relations -- First Luminosity

Kormendy & Richstone 1995





Gültekin et al. 2009

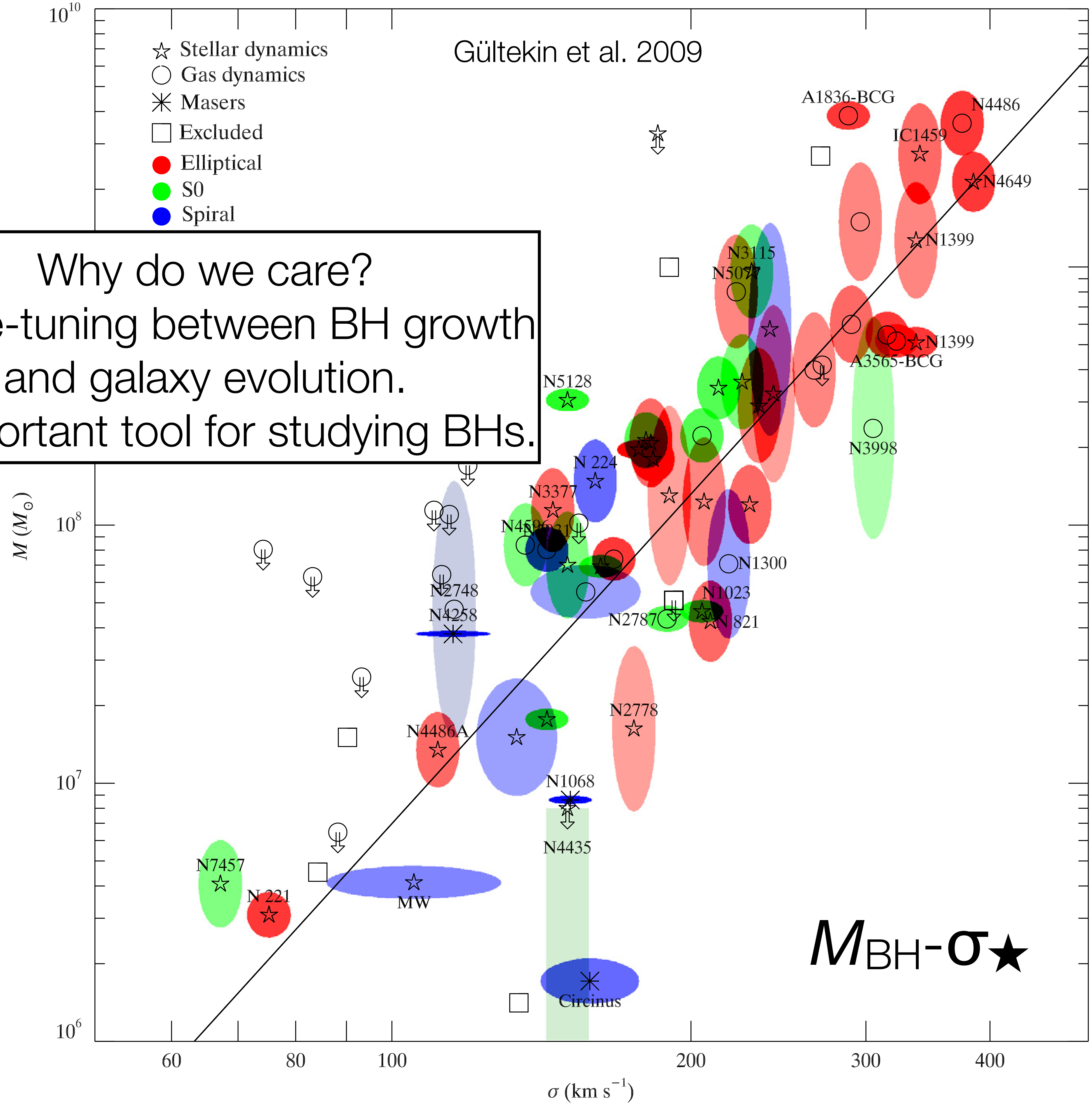


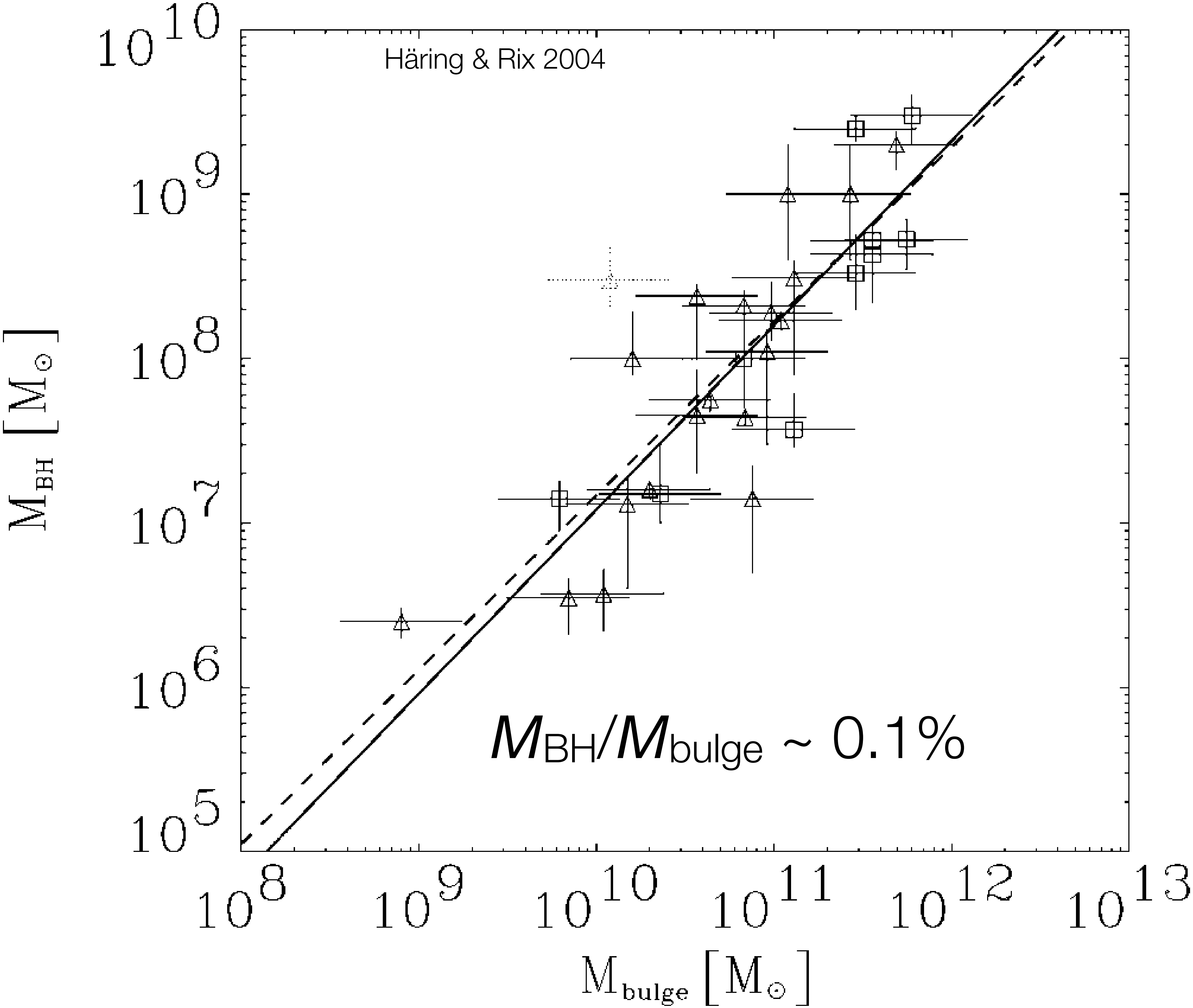
Friday, July 22, 2011

Why do we care?

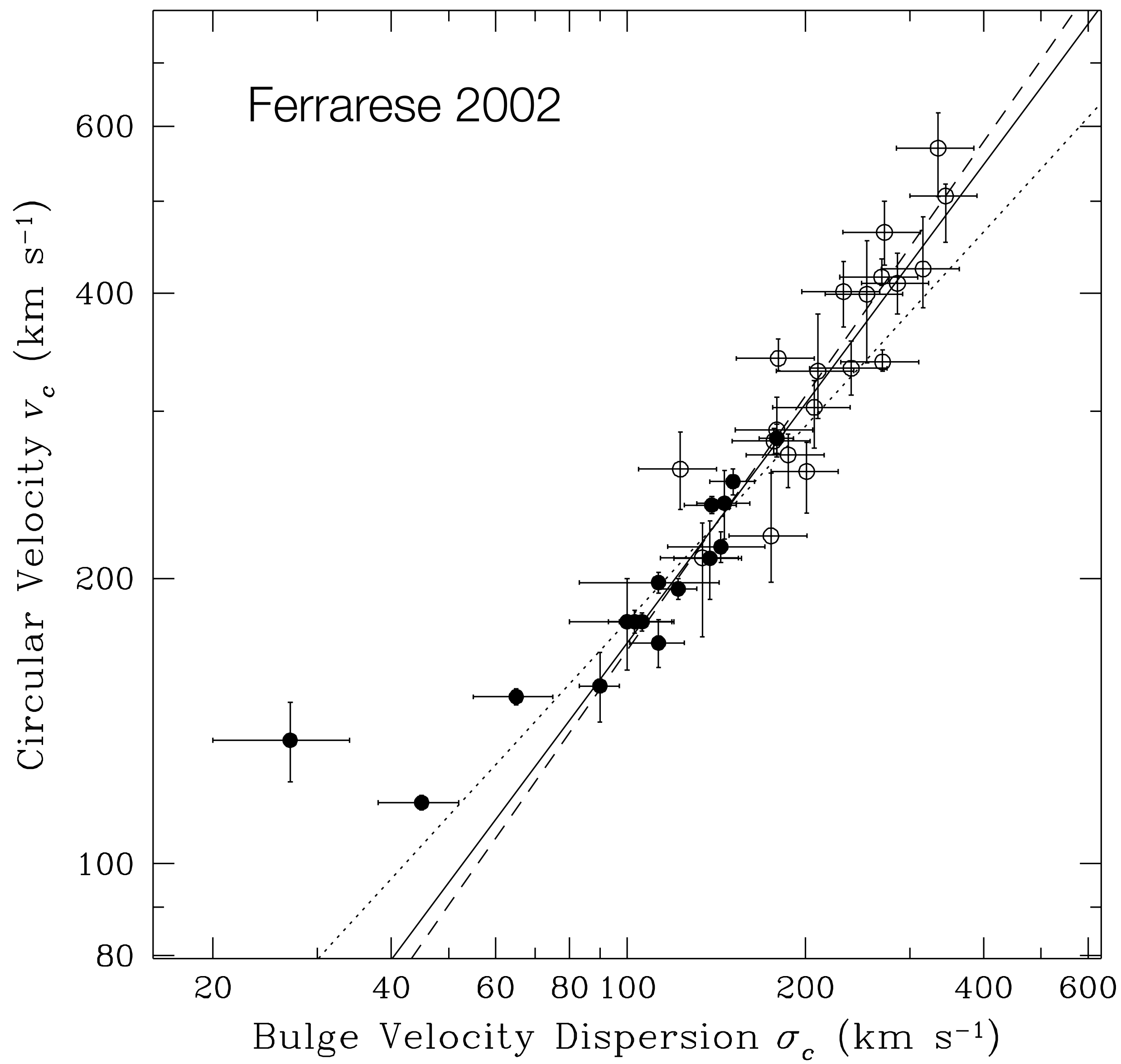
1. Fine-tuning between BH growth and galaxy evolution.

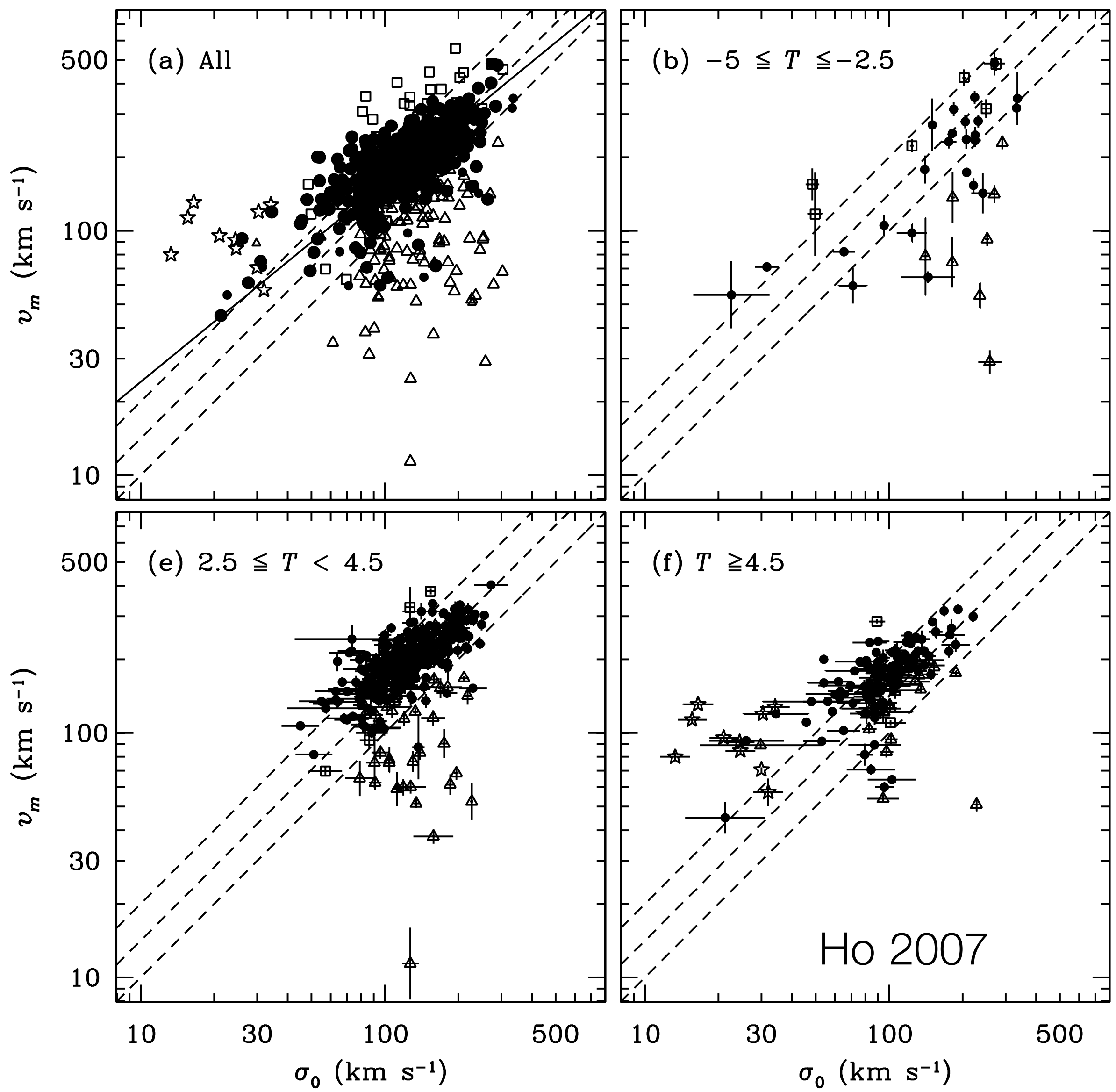
2. Important tool for studying BHs.



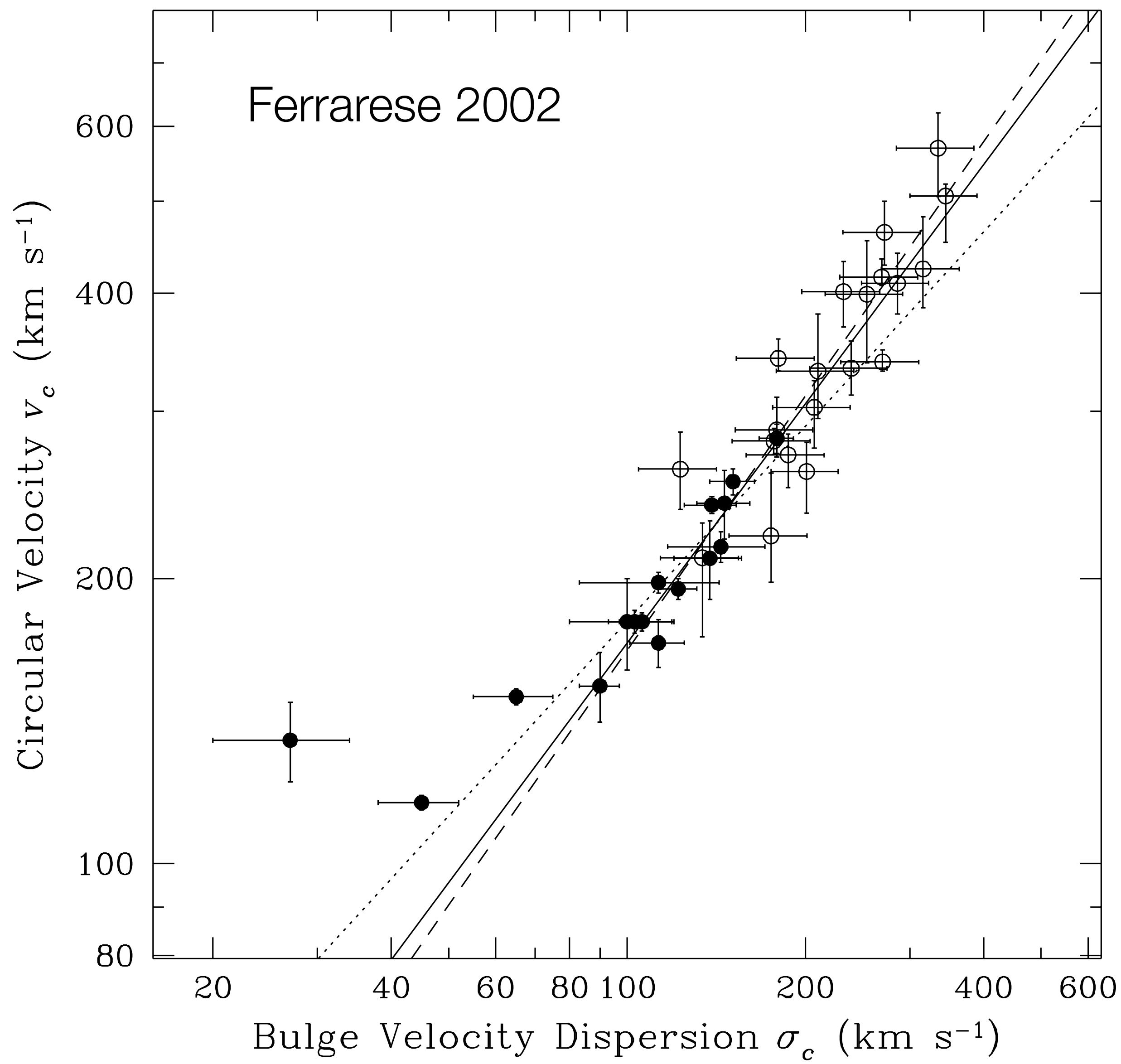

Häring & Rix 2004
M_{BH}/M_{bulge} ~ 0.1%
M_{BH} [$M_\odot$]
M_{bulge} [$M_\odot$]
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}

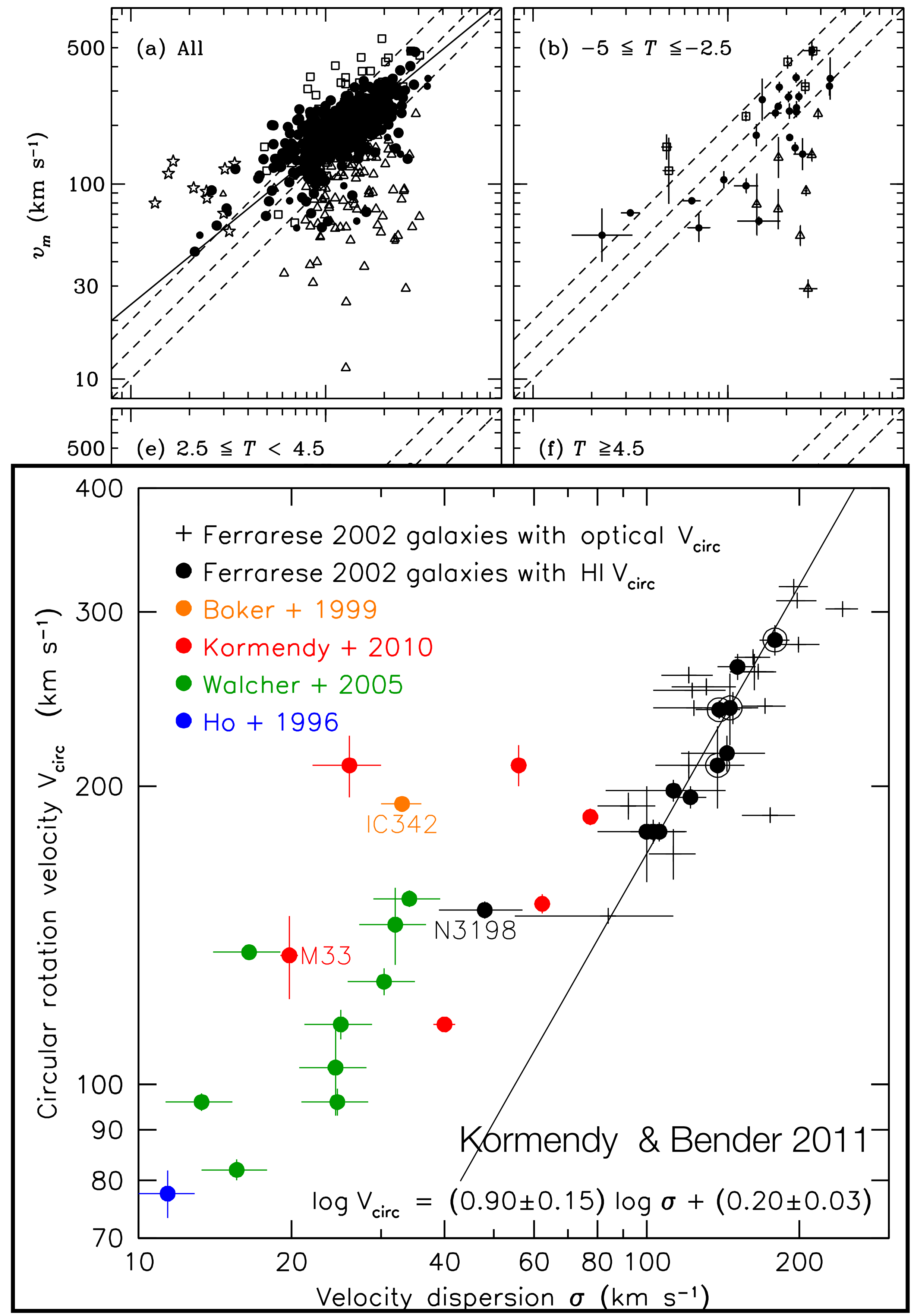
Dark Halo Mass?





Dark Halo Mass?





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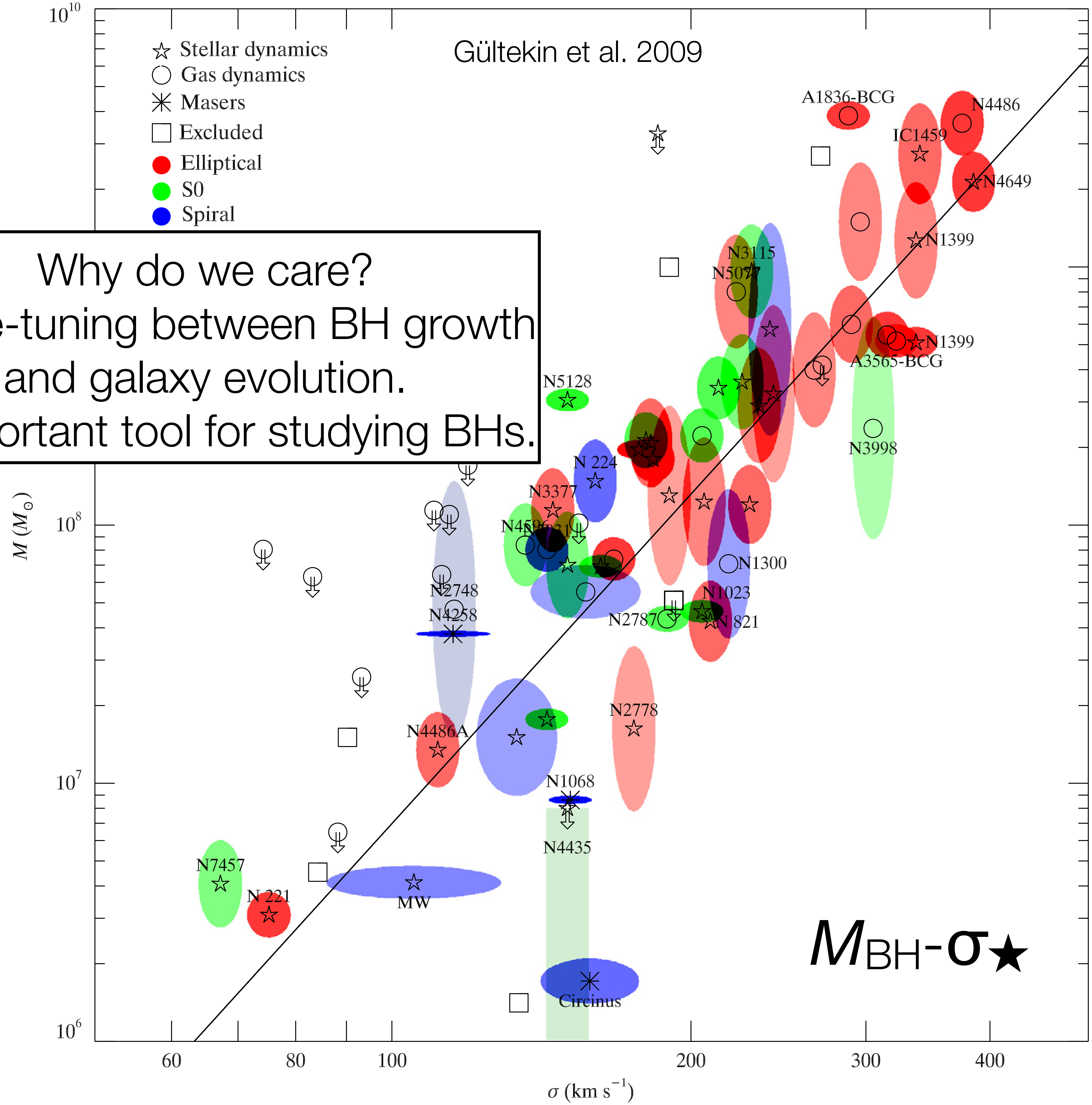
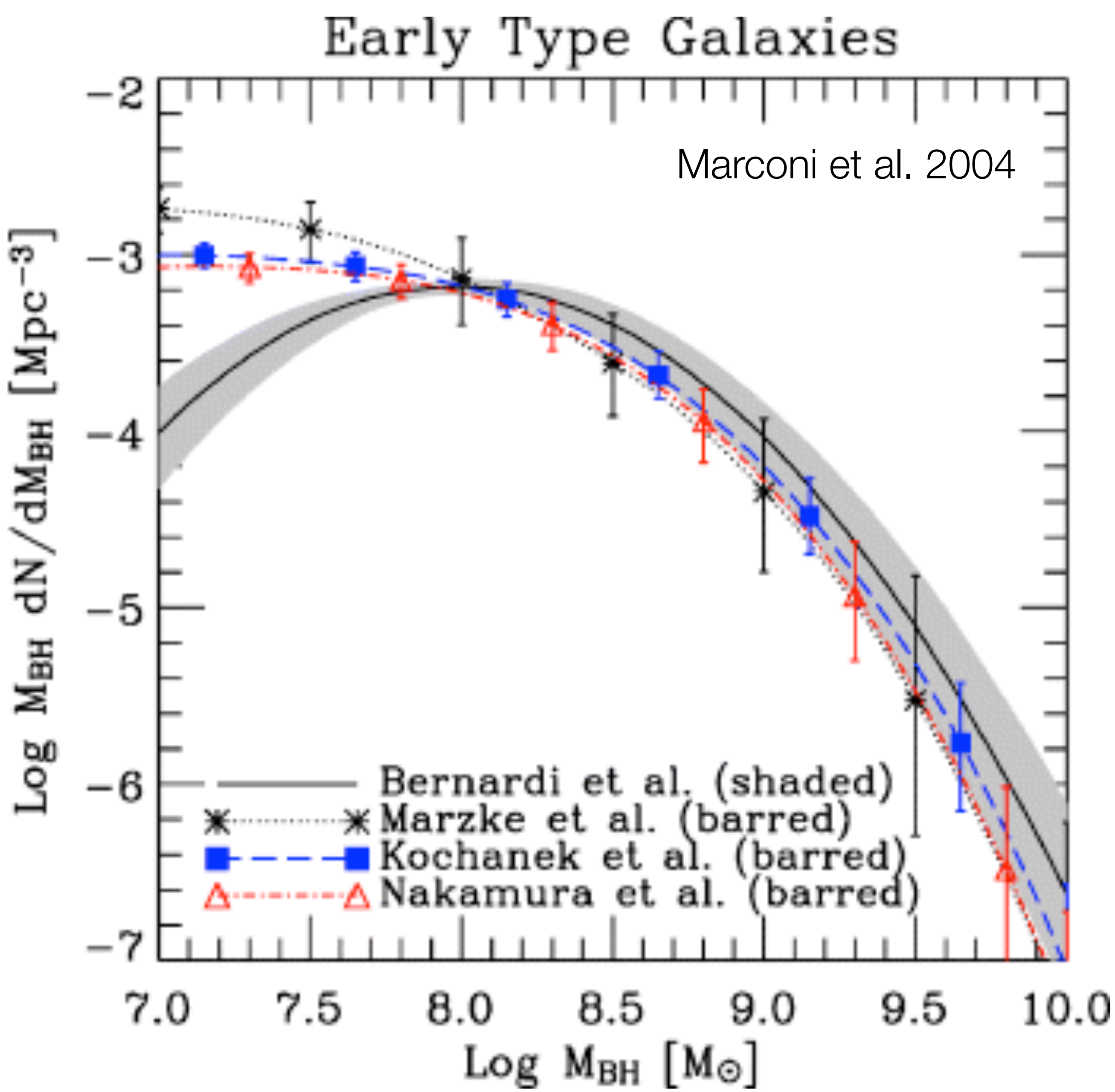


BH Mass Density

Use BH-bulge scaling relations + observed galaxy population to infer BH mass function and BH mass density today.

Then compare with integrated luminosity in quasars over cosmic time (the Sołtan argument; see Yu & Tremaine 2002) -- BHs mostly grew in Eddington-limited, optically bright phases

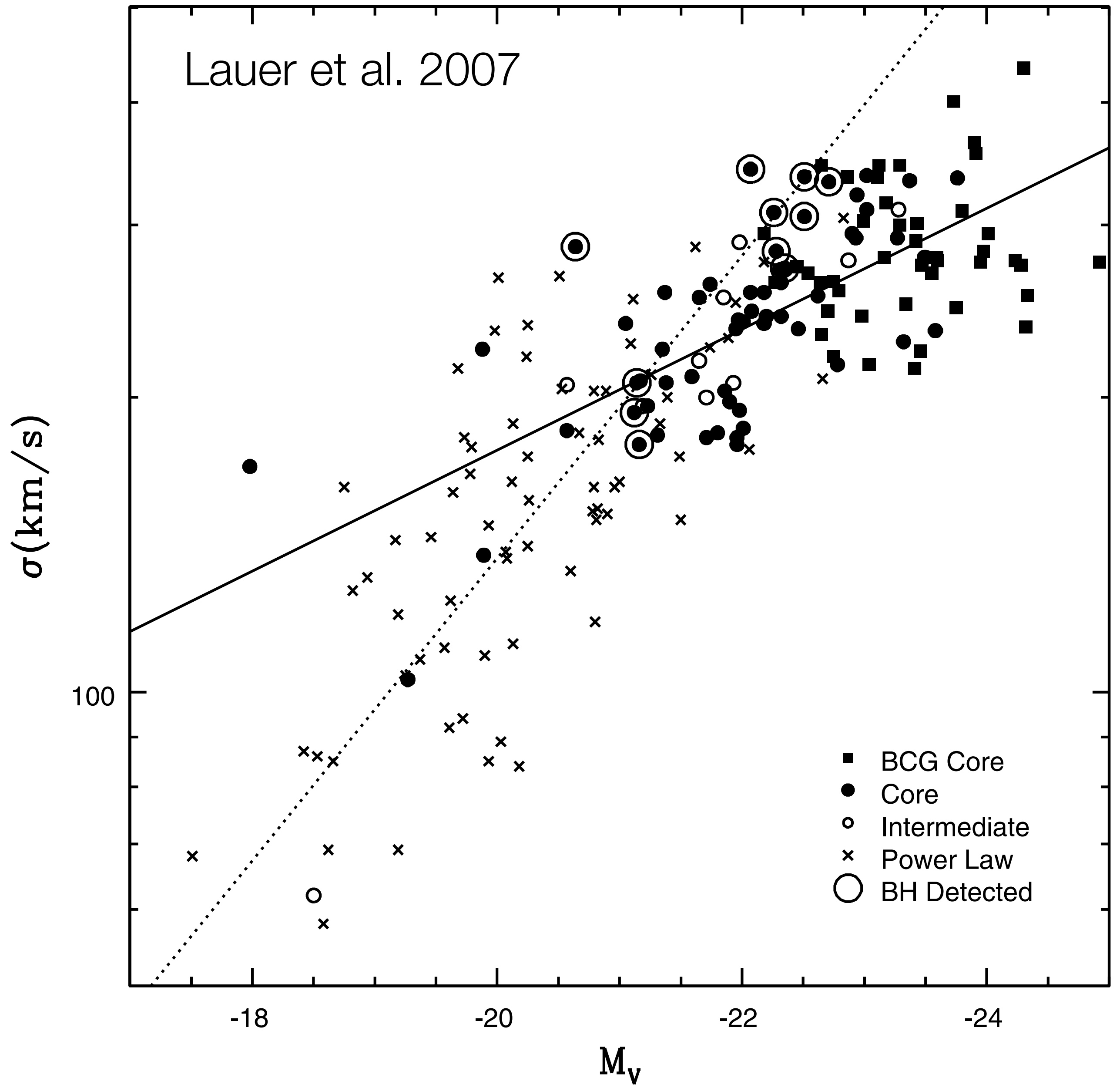


Need to know *intrinsic* scatter

Also, space density of most massive BHs...

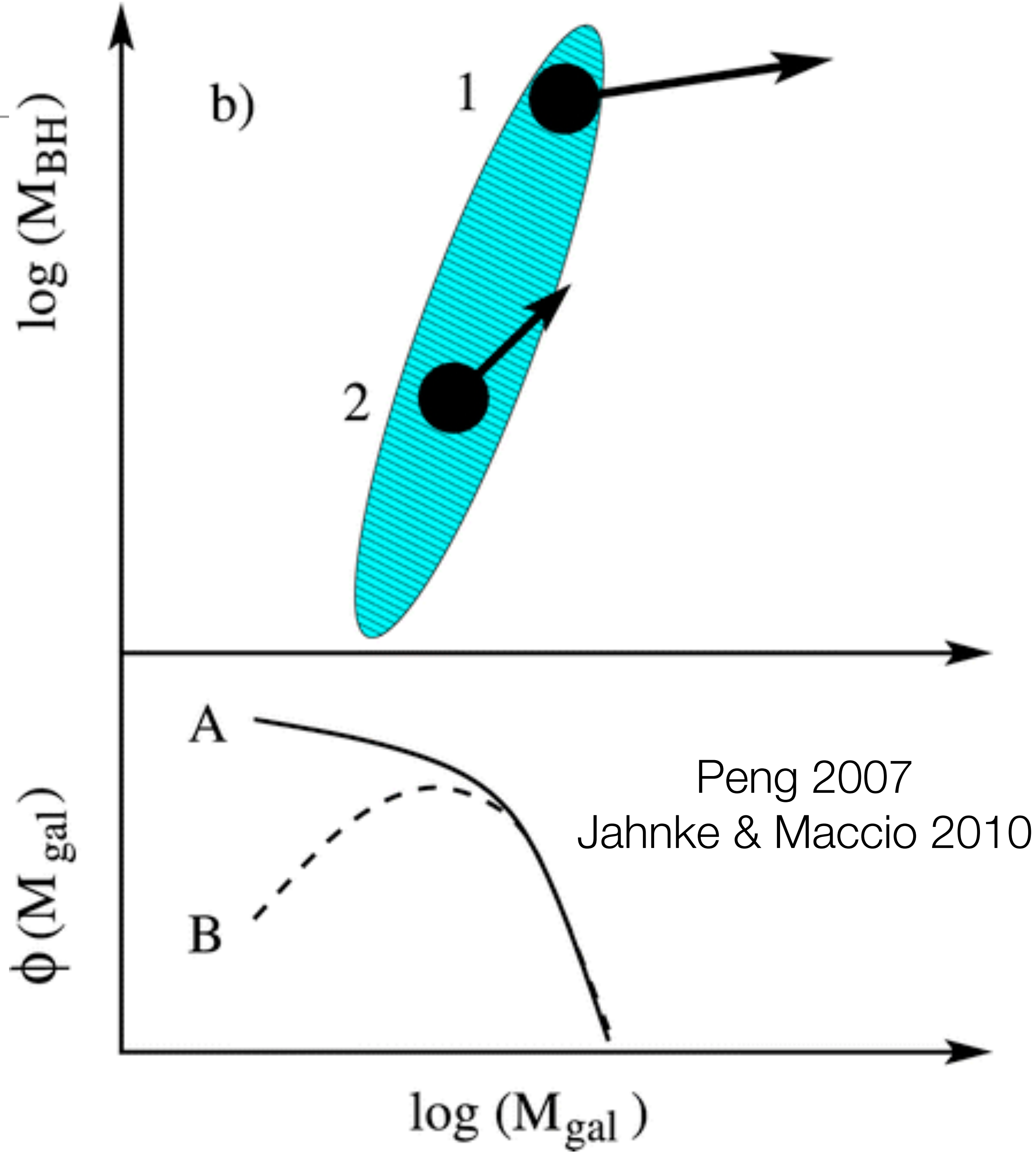
What is the shape of the mass function at the most massive end? M_{BH}-$\sigma_\star$ relation and M_{BH}-L_{bulge} relations don't predict the same mass function.

We need to know what the primary correlation is.



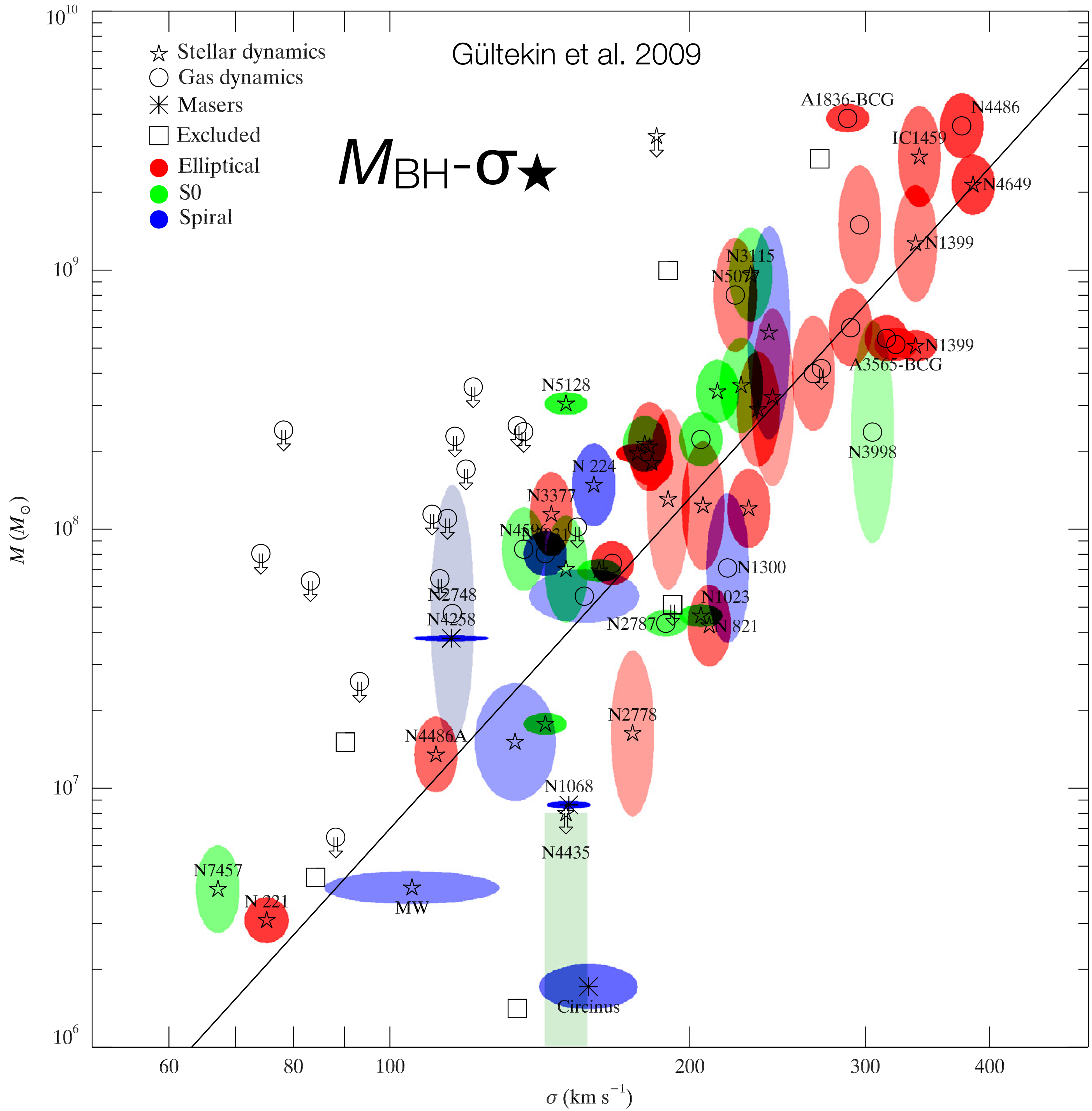
Origin of Scaling Relations?

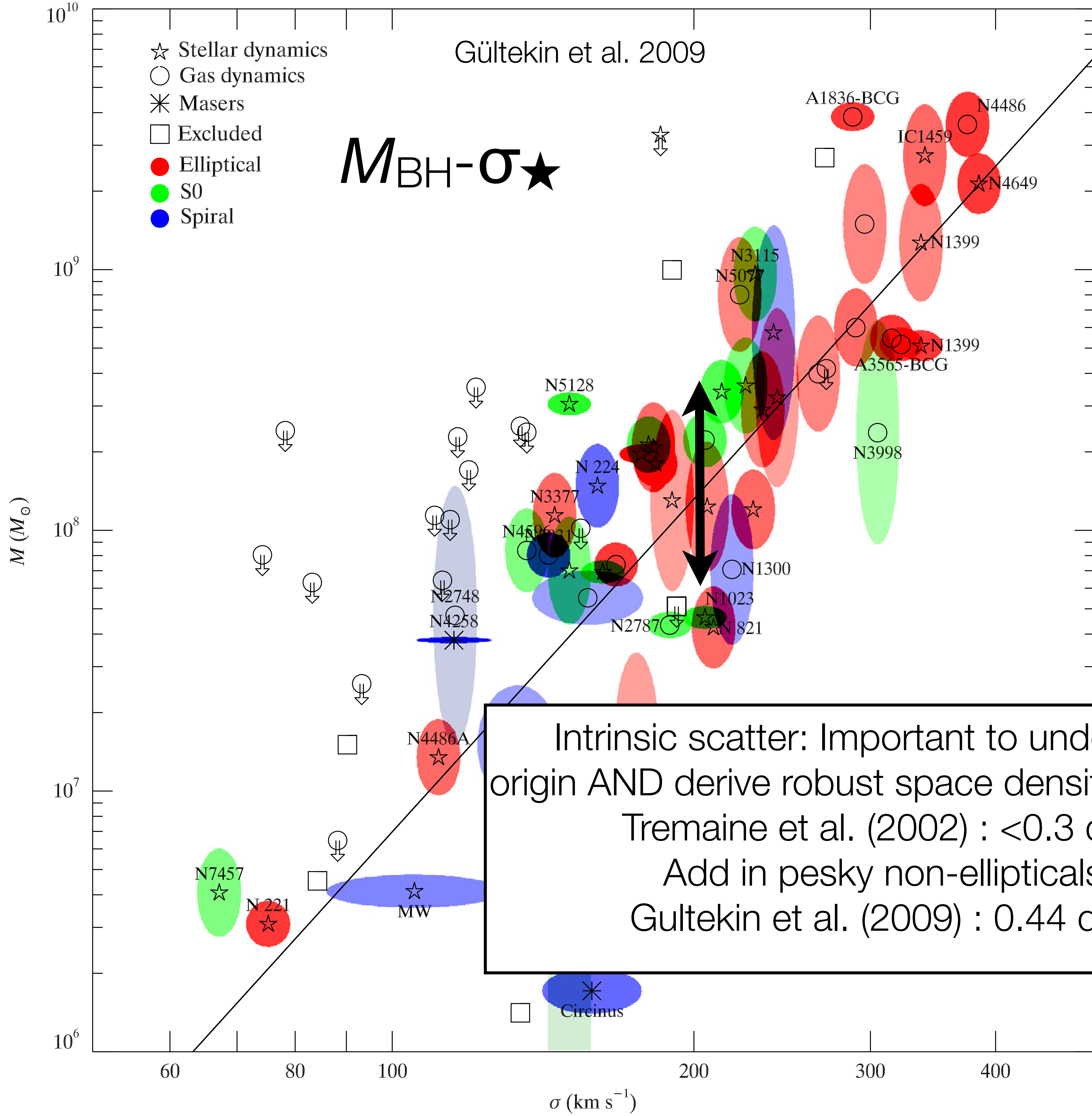
Feedback (ala Hopkins/Springel/Hernquist)?



Or just hierarchical merging?

Need to know how BH-bulge scaling relations and scatter depend on galaxy morphology and mass.


Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
Gültekin et al. 2009
M_{BH}-$\sigma_\star$
M ($M_\odot$)
σ (km s^{-1})
A1836-BCG
N4486
IC1459
N4649
N1399
N3115
N5077
N1399
A3565-BCG
N3998
N5128
N 224
N3377
N1300
N1023
N2787
N 821
N2748
N4258
N2778
N4486A
N1068
N4435
N7457
N 221
MW
Circinus

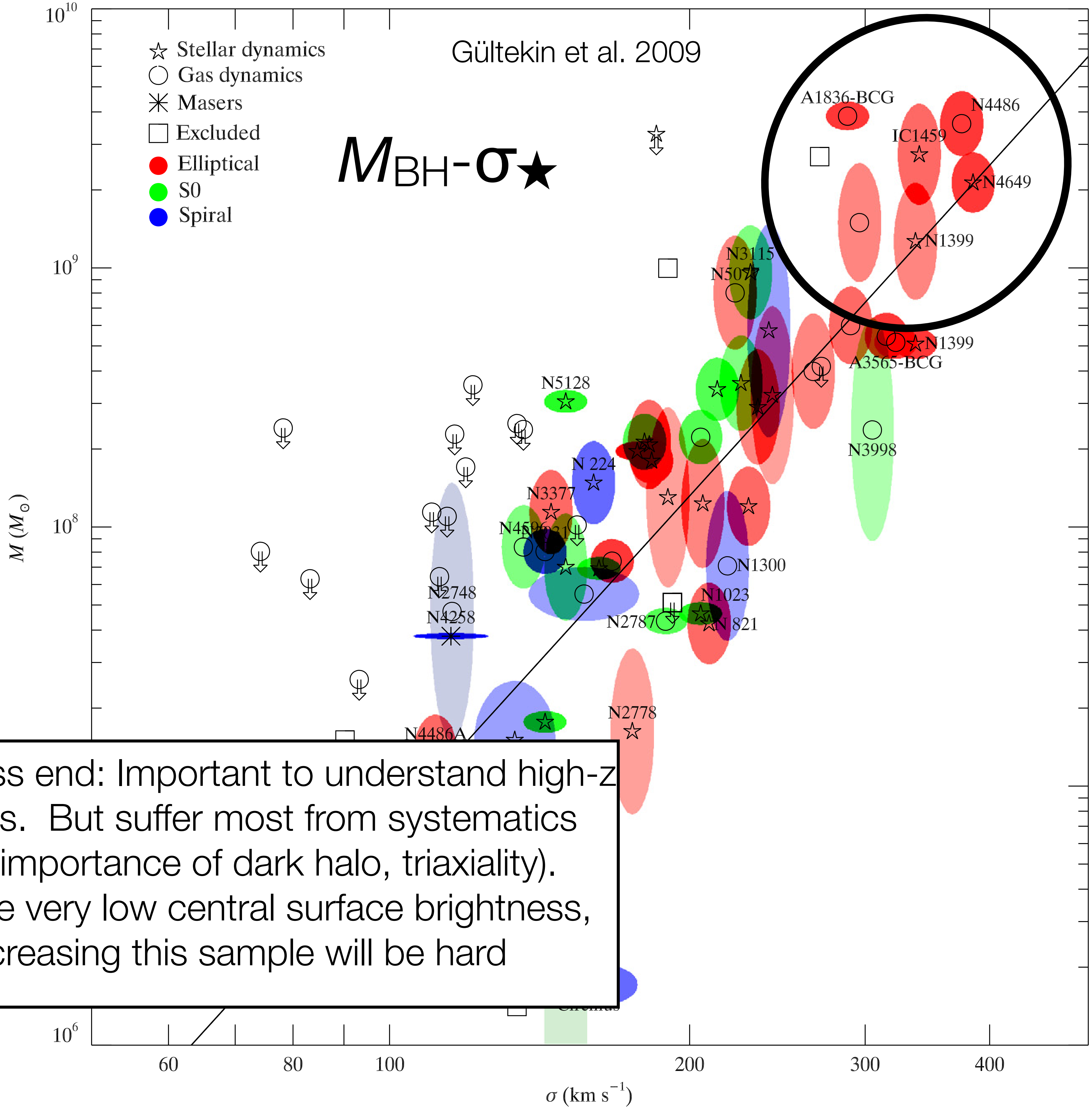


Intrinsic scatter: Important to understand origin AND derive robust space densities of BHs.

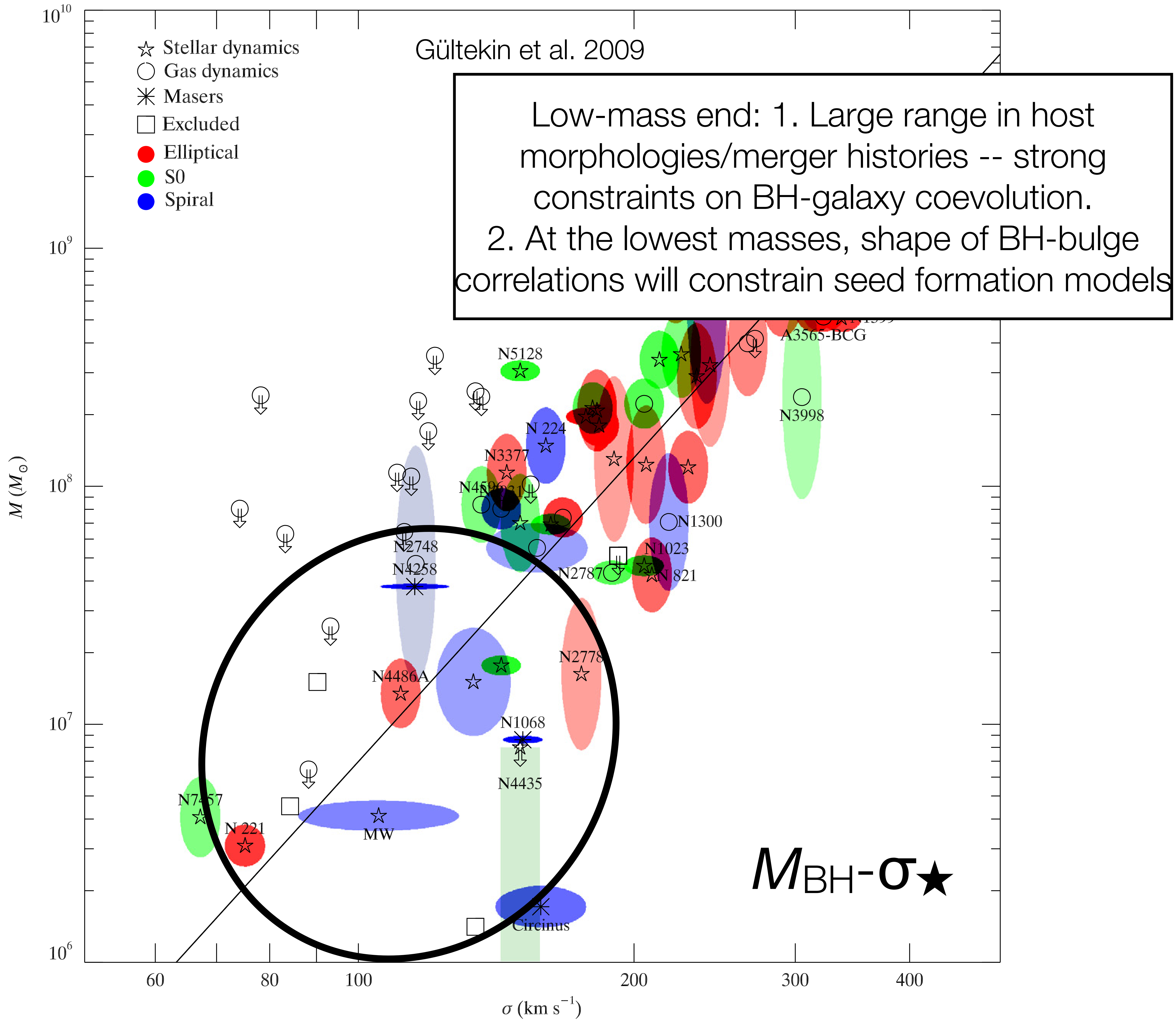
Tremaine et al. (2002) : <0.3 dex

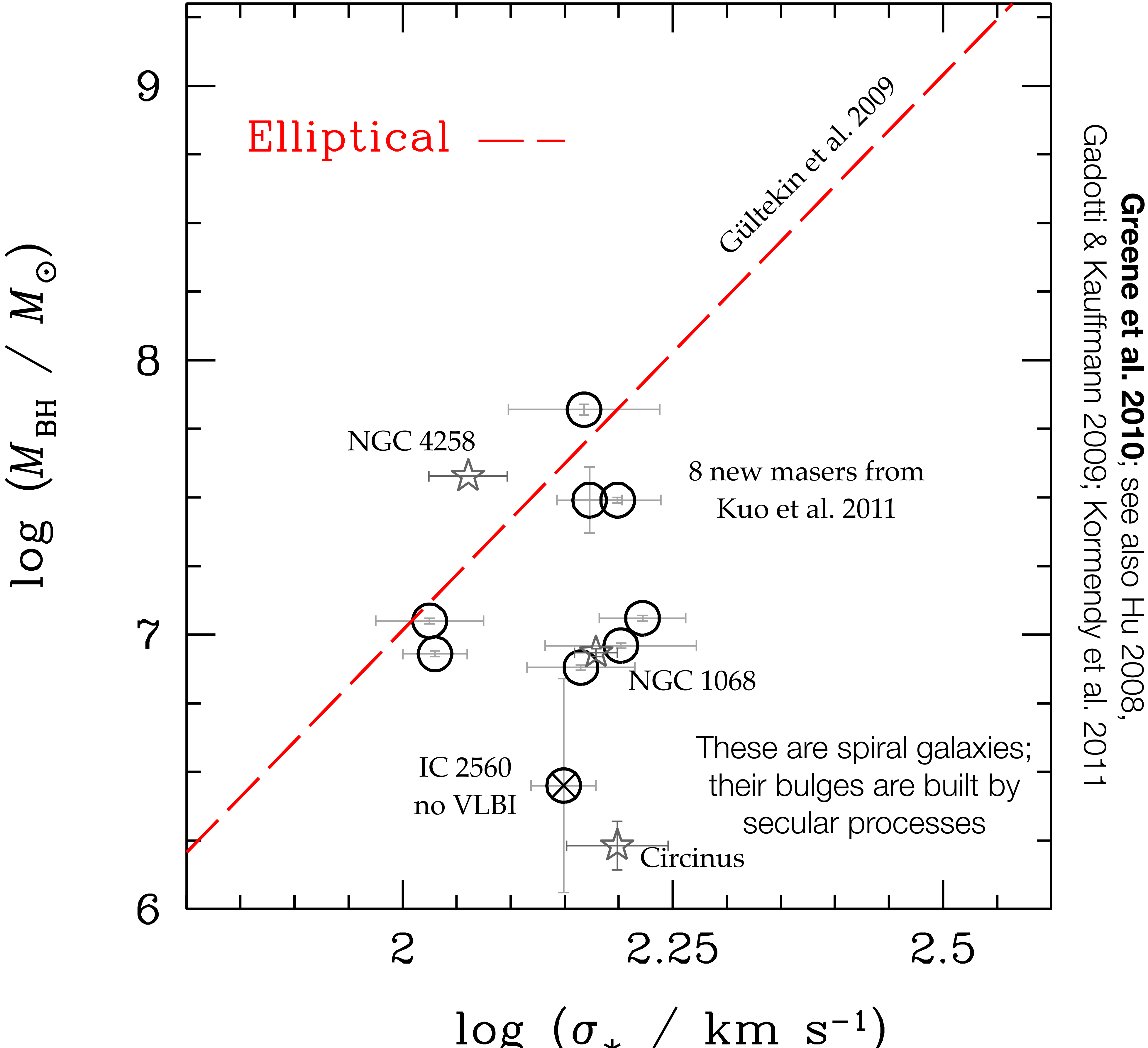
Add in pesky non-ellipticals

Gultekin et al. (2009) : 0.44 dex



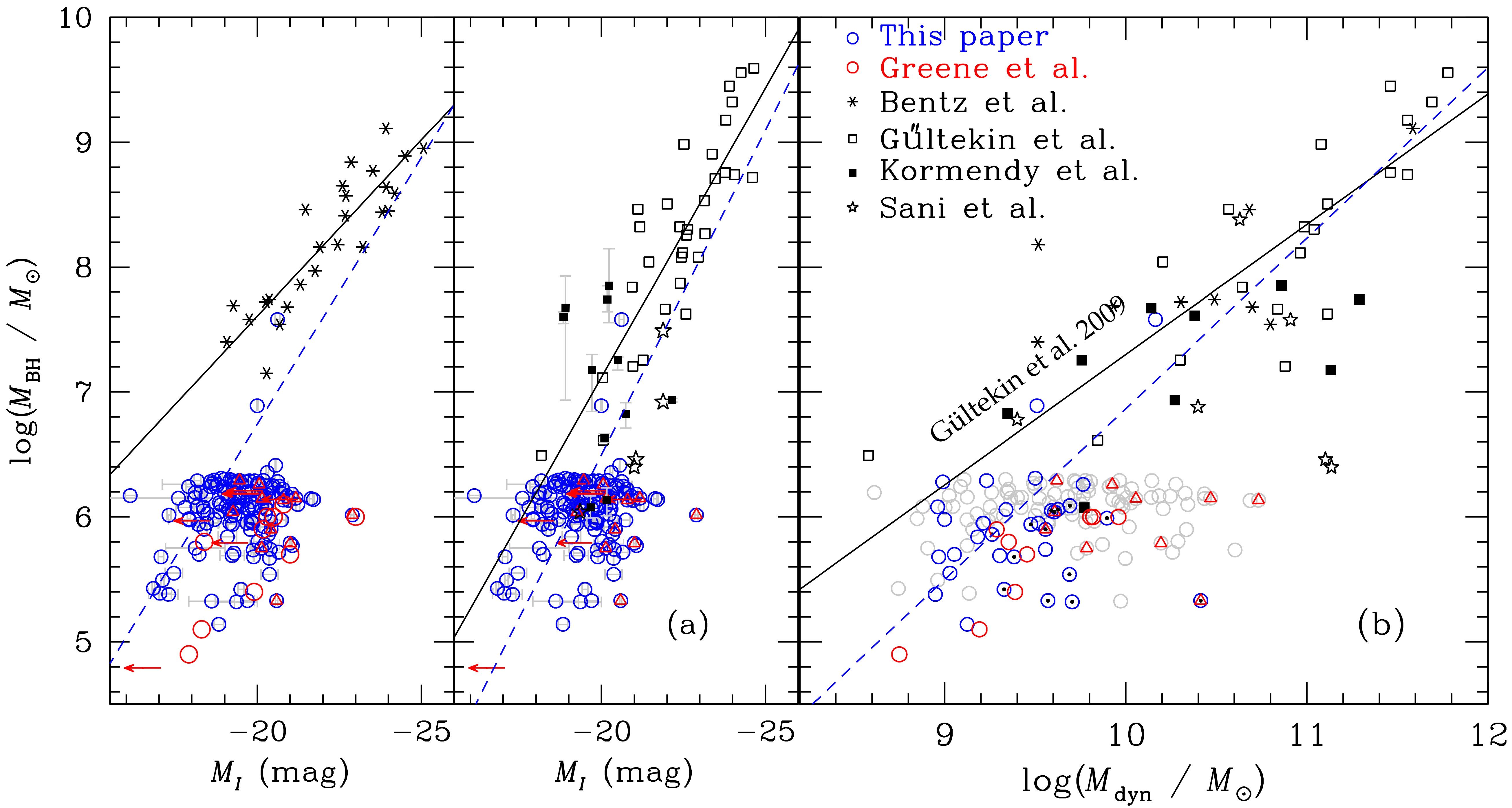
High-mass end: Important to understand high-z quasars. But suffer most from systematics (e.g., importance of dark halo, triaxiality). Because very low central surface brightness, increasing this sample will be hard


Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
Gültekin et al. 2009
Low-mass end: 1. Large range in host morphologies/merger histories -- strong constraints on BH-galaxy coevolution.
2. At the lowest masses, shape of BH-bulge correlations will constrain seed formation models
A3565-BCG
N5128
N3998
N 224
N3377
N1300
N2748
N4258
N1023
N2787
N 821
N2778
N4486A
N1068
N4435
N7457
N 221
MW
Circinus
M_{BH}-$\sigma_\star$
M ($M_\odot$)
σ (km s^{-1})
10^{10}
10^9
10^8
10^7
10^6
60
80
100
200
300
400



The M_{BH}-$\sigma_\star$ relation is *not* universal

Jiang, Greene, & Ho 2011, accepted (astroph/1107.4103)

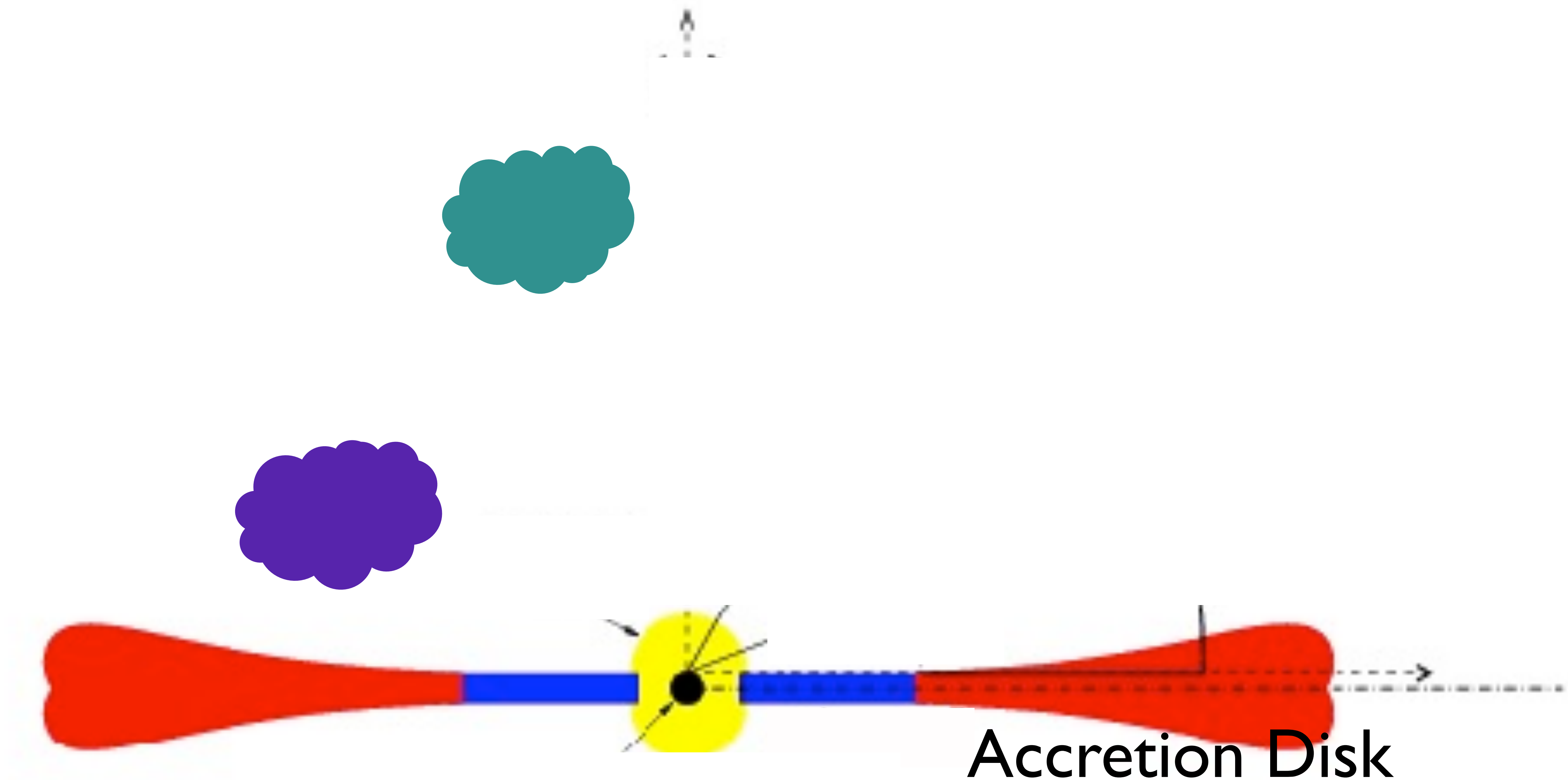


HST observations of SDSS broad-line AGNs with $M_{BH} < 10^6\ M_\odot$.

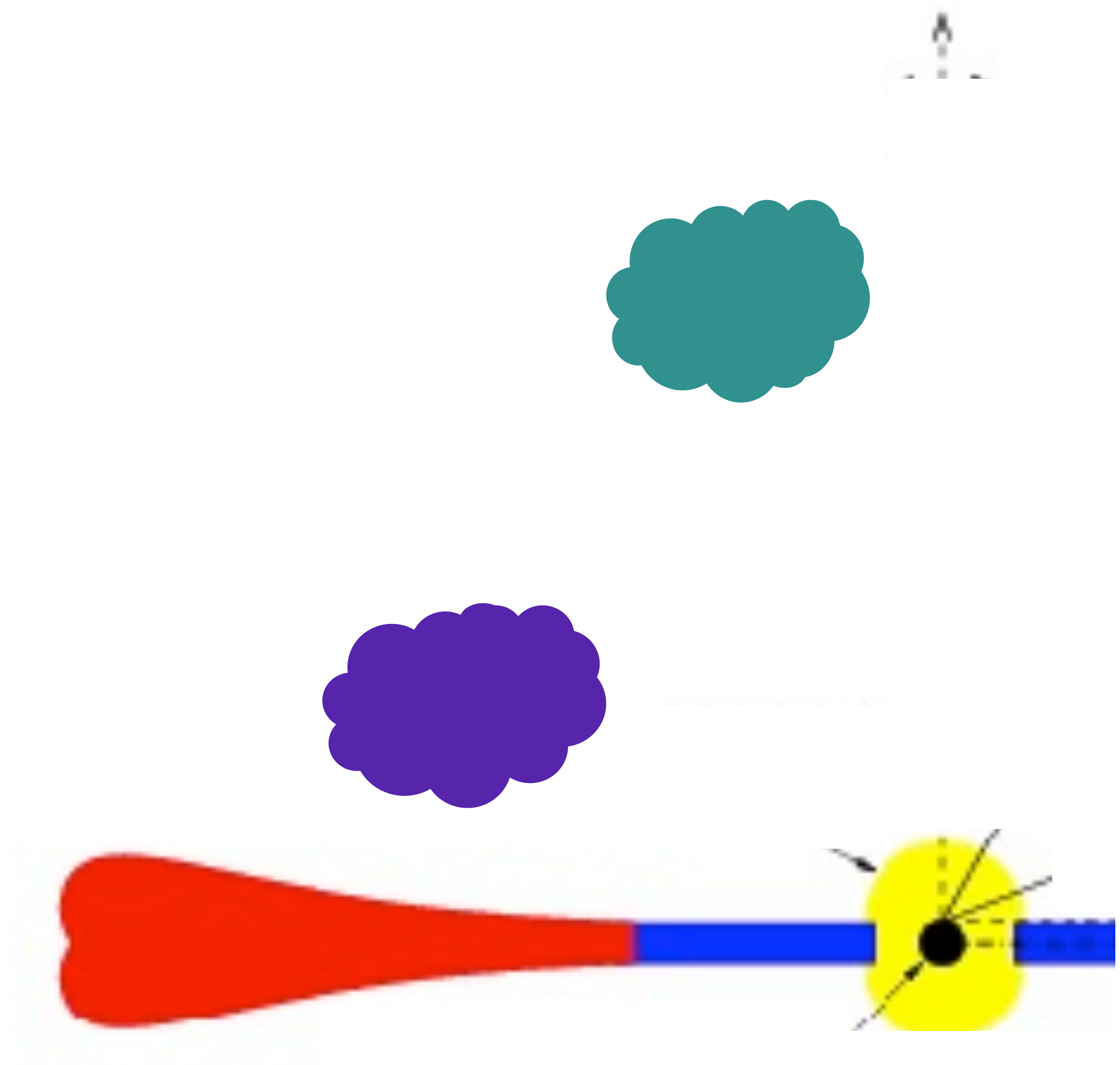
BH masses from scaling relations based on reverberation mapping.

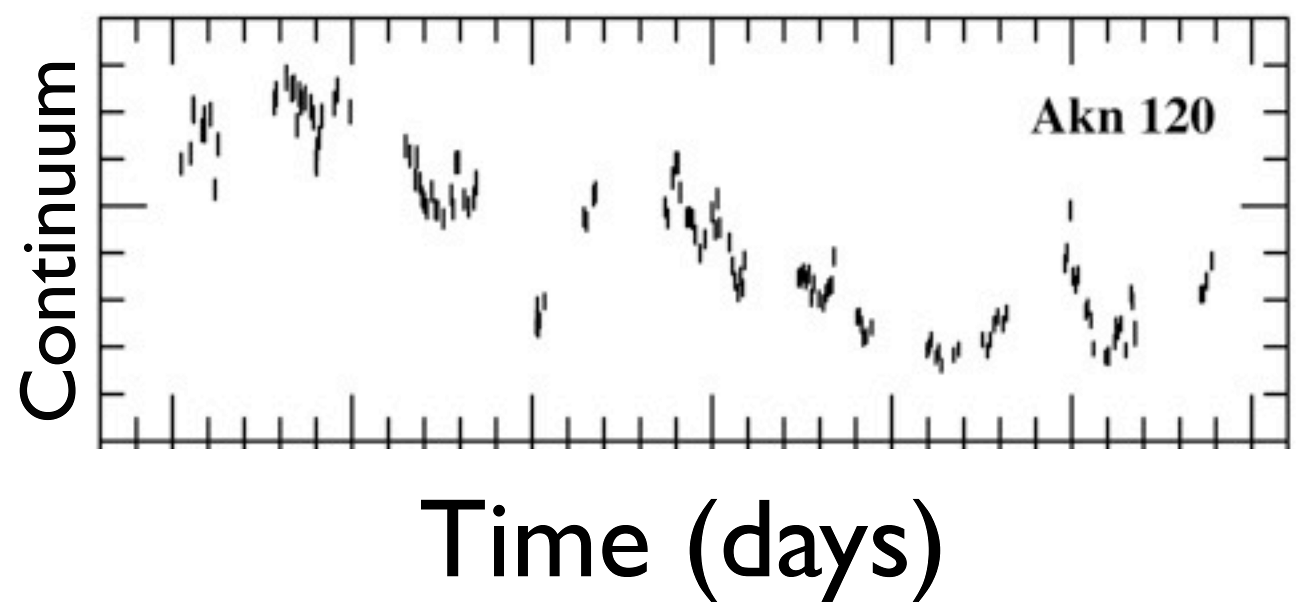
We see flattening as expected in models with massive seed BHs.

Reverberation Mapping

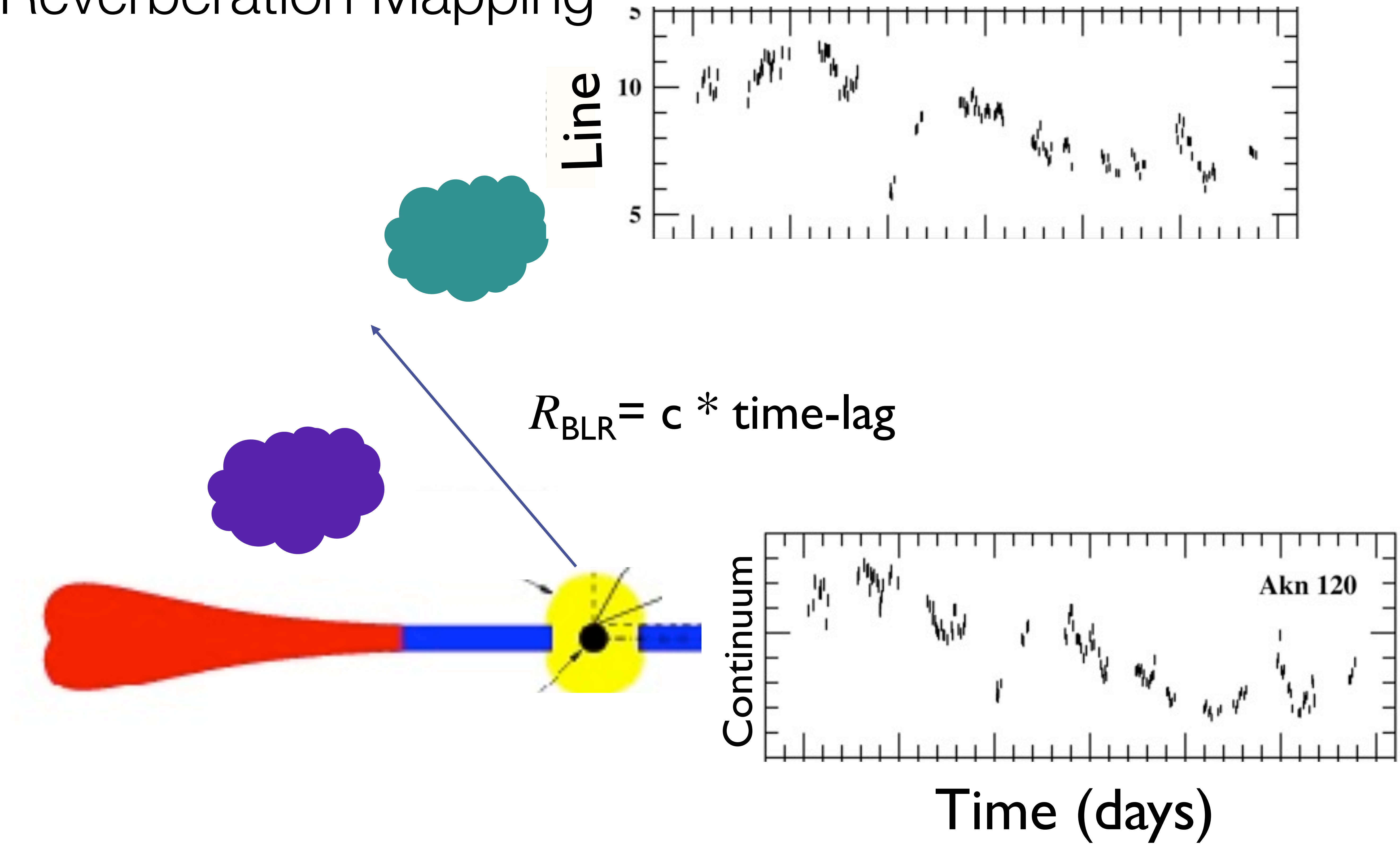


Reverberation Mapping



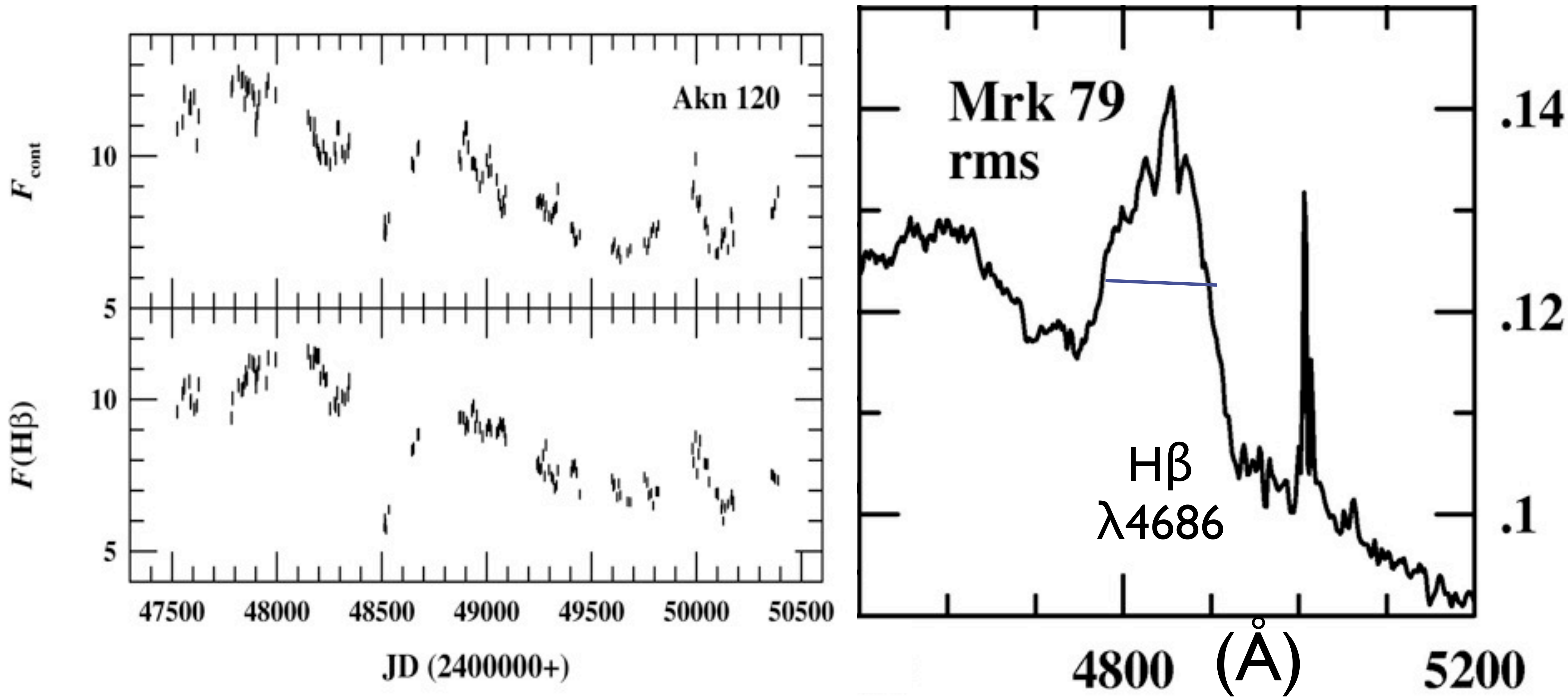


Reverberation Mapping



Lag (τ) between line and continuum variations

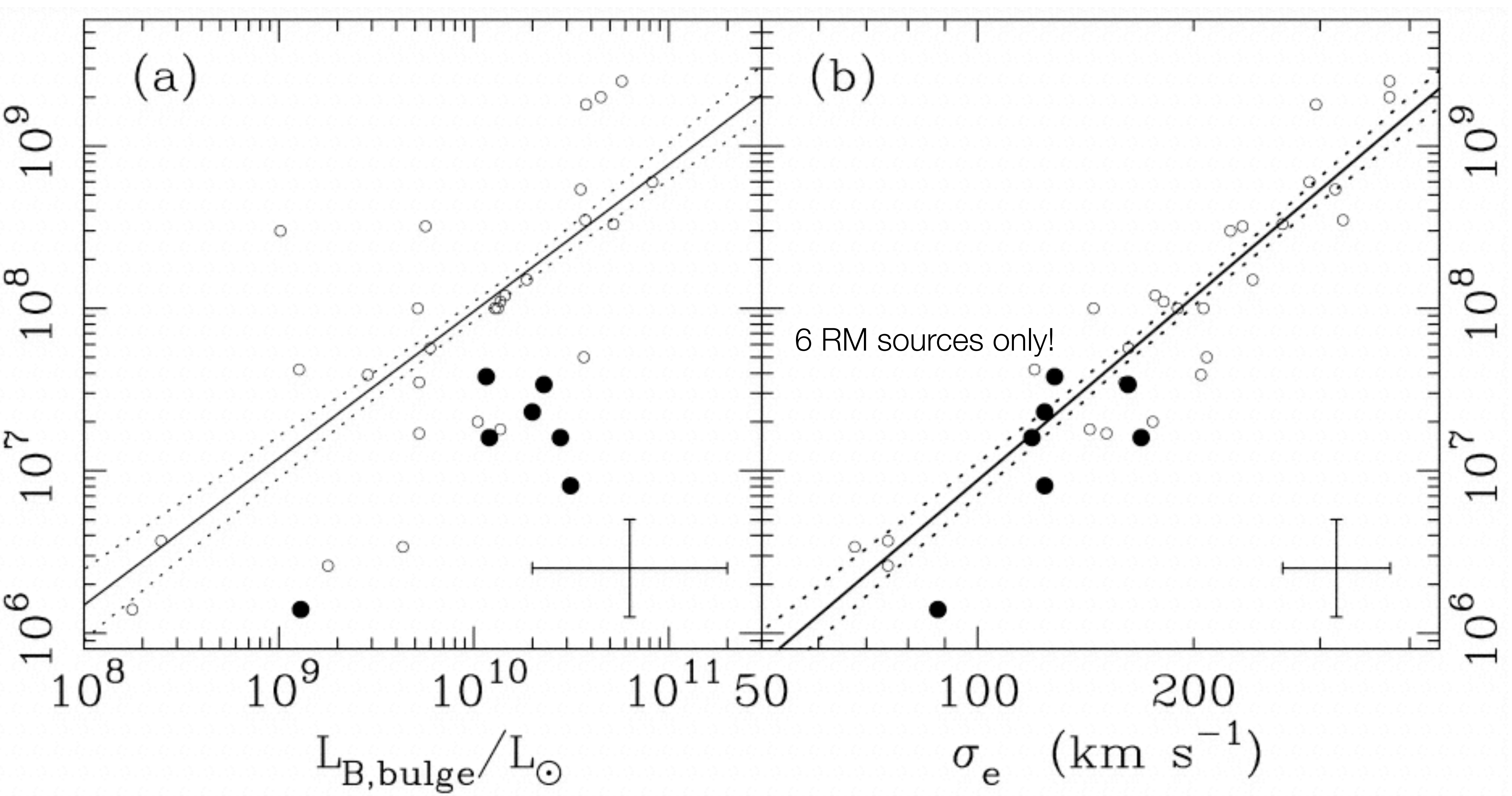
$R_{BLR} \sim c\ \tau$

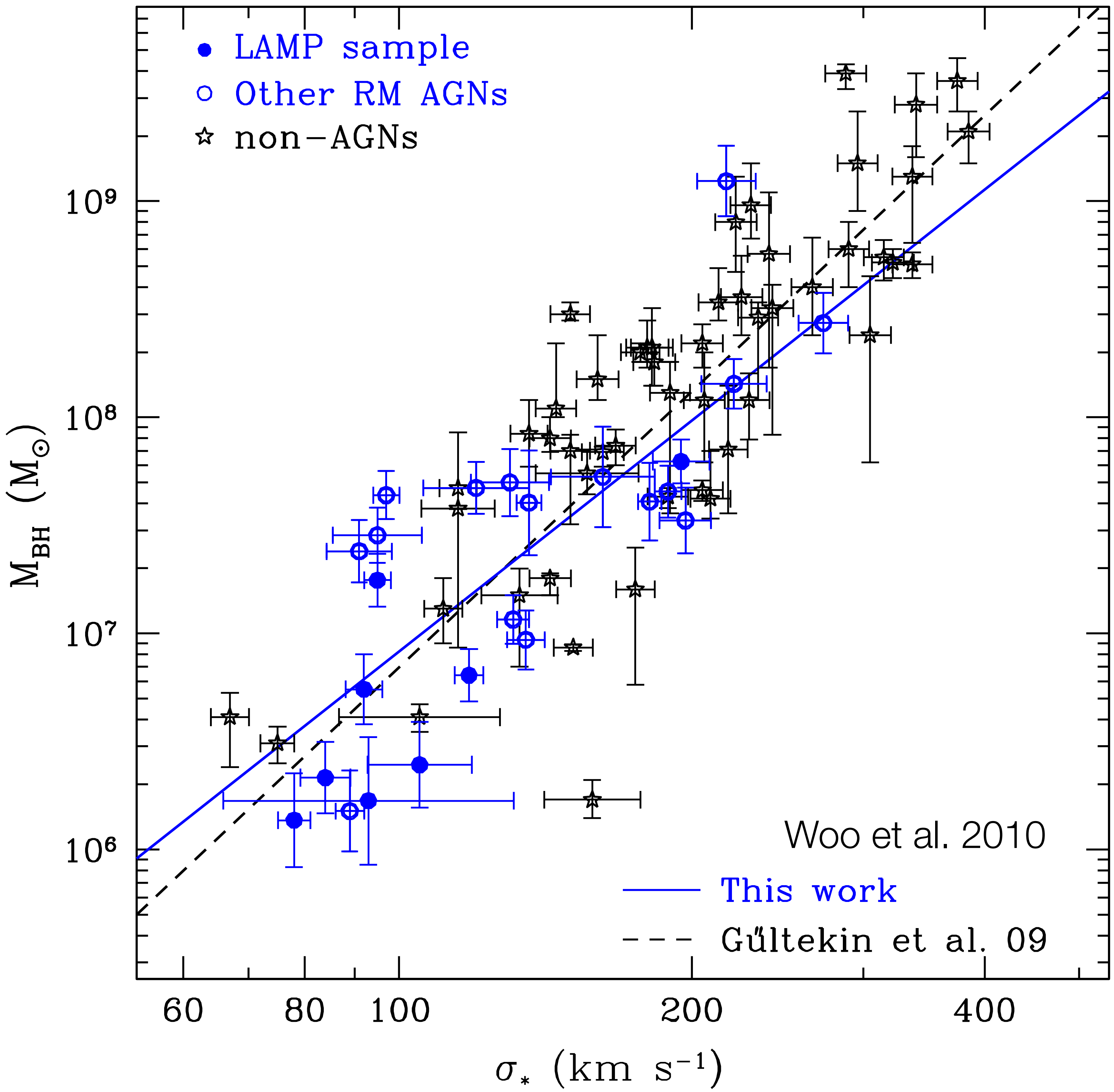


$$M_{BH} = f\ R_{BLR}\ \upsilon^2\ /\ G$$

Can we believe them?

Gebhardt et al. 2000





Lick AGN Monitoring Project (PI Barth). We reproduce the M_{BH}-$\sigma_\star$ relation with the RM sources...Dynamical masses are hard (Hicks et al., Davies et al., Onken et al.)

Summary

Massive galaxies always make a central supermassive black hole. The situation remains unclear for lower-mass systems that sometimes but not always, host black holes.

We are building a strong case that these central massive dark objects are real black holes.

There are tight correlations between black hole mass and bulge properties.

But how tight are they? And how do the scaling relations depend on mass? What is the most massive black hole? What is the importance of galaxy morphology?

Gebhardt 2004

Dimension of Velocity Ellipsoid

parametric
nonparametric

Dimension of Potential

	1D Isotropic	2D r, θ	3D r, θ, ϕ
1D Spherical	King models Plummer many, many others *Gebhardt & Fischer (95)*	King (66), Michie (63) Merritt (85), Osipkov (79) *Binney & Mamon (82)* *Merritt & Gebhardt (94)* *Rix et al. (97)*	*Richstone & Tremaine (84)*
2D Axisymmetric	Isotropic rotators	Toomre (82), scale−free Richstone (84), scale−free Binney et al. (90) van der Marel (91) Magorrian et al. (98) *Merritt et al. (97), edge−on*	Kuzmin & Kutuzov (62) Dejonghe & de Zeeuw (88) Levison & Richstone (87) *Gebhardt, Richstone (03)* *van der Marel et al. (98)* *Cretton et al. (99)* *Verolme et al. (02)*
3D Triaxial	Stackel Potential de Zeeuw (85), Statler (87) *Zhao (96)* *Verolme et al. (03)*		