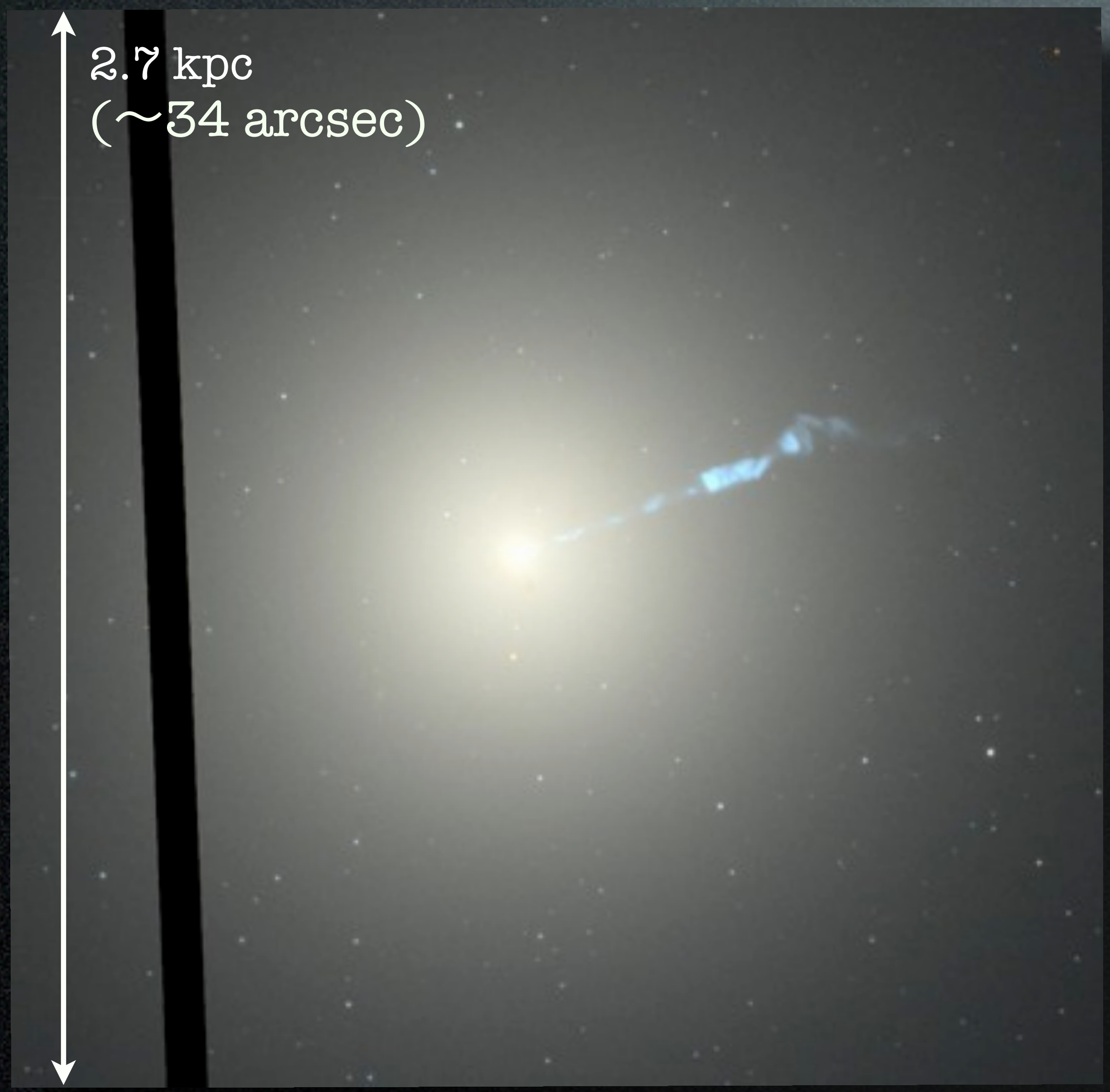
Supermassive Black Holes

Laura Ferrarese
Herzberg Institute of Astrophysics,
National Research Council of Canada

Science with the Hubble Space Telescope — III: Two Decades and Counting
Venezia, 11 Ottobre 2010

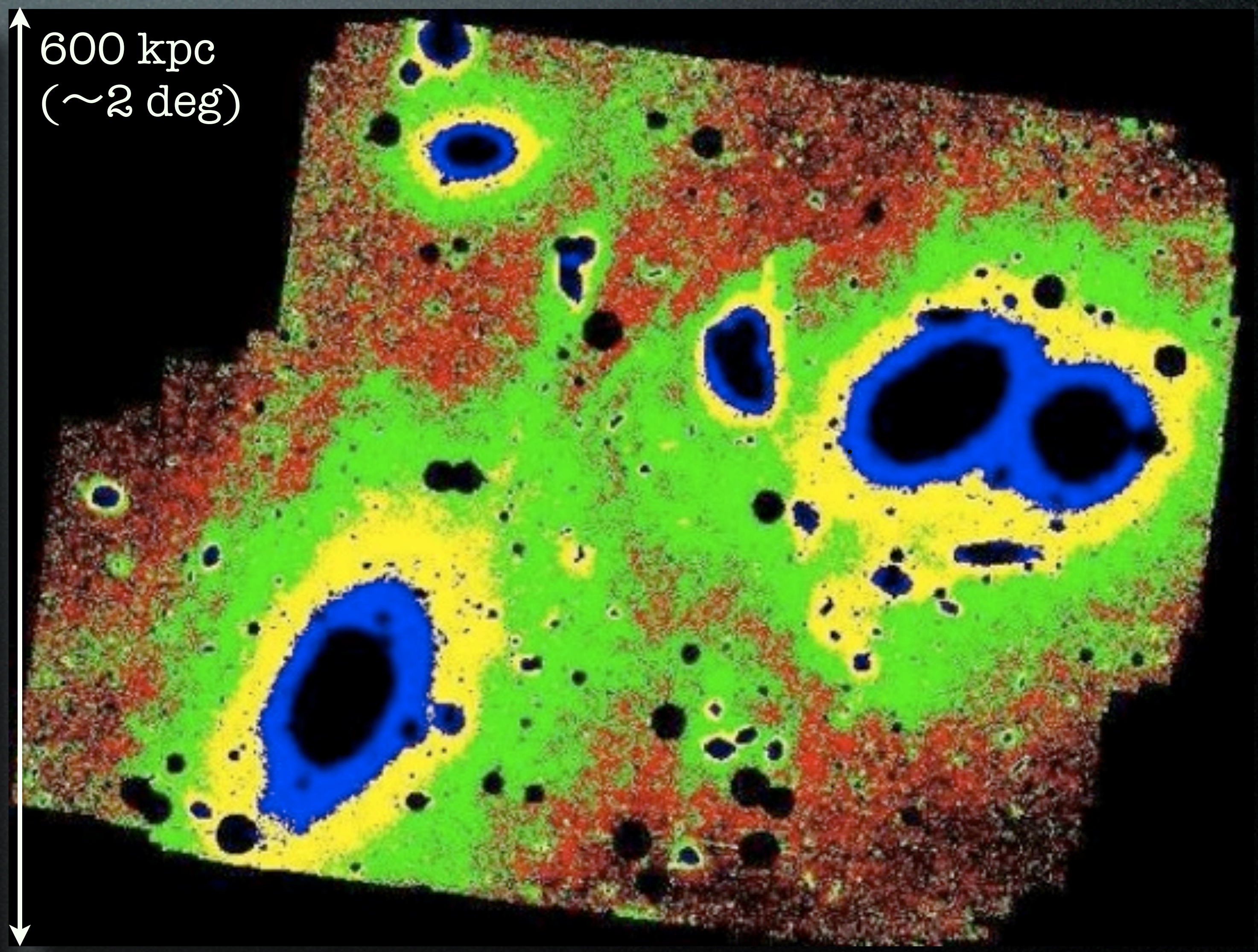
From Nuclear to Global Scales: Unifying the Picture

Ferrarese et al (2006)



HST/ACS/WFC

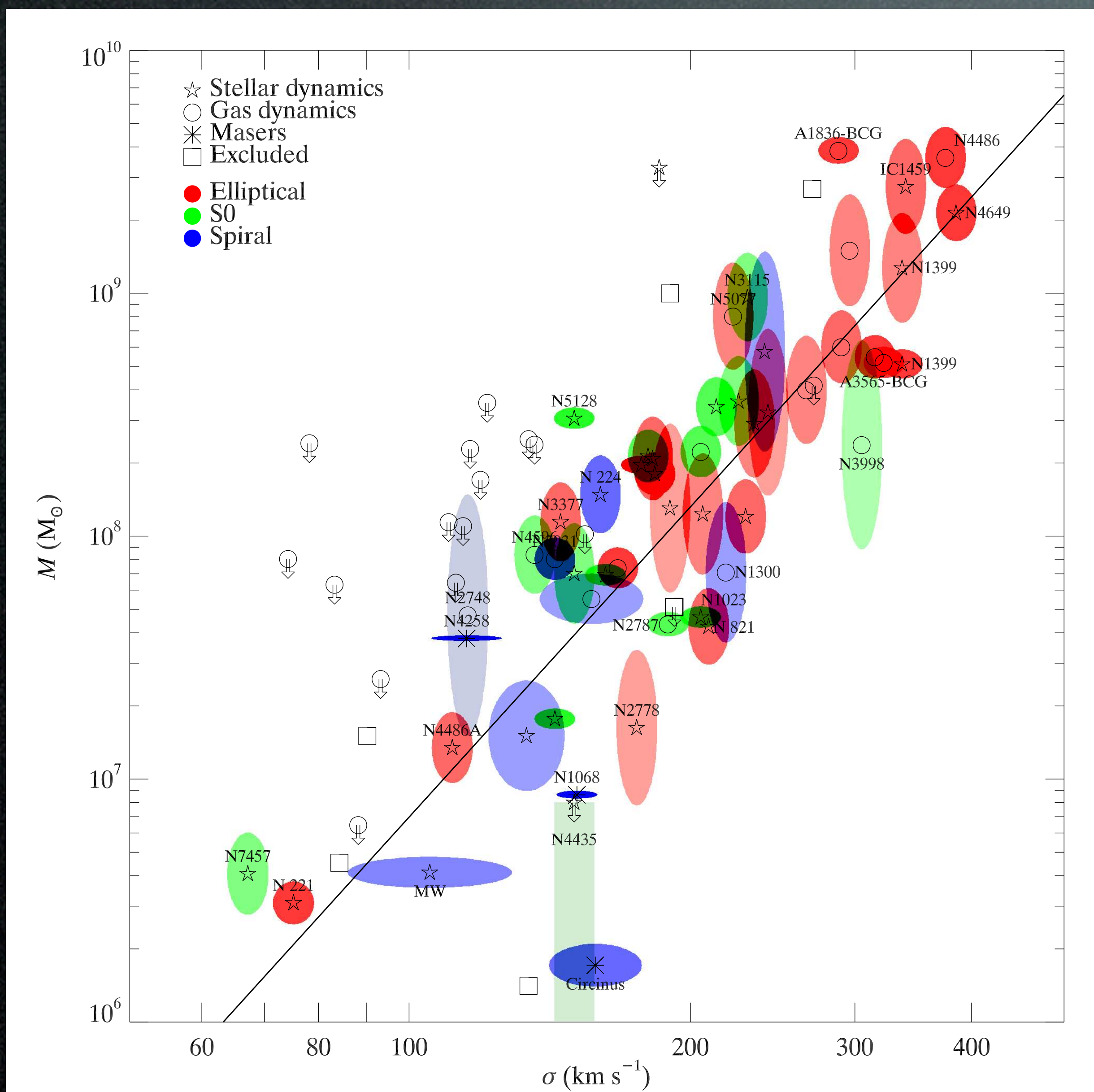
Mihos et al (2005)



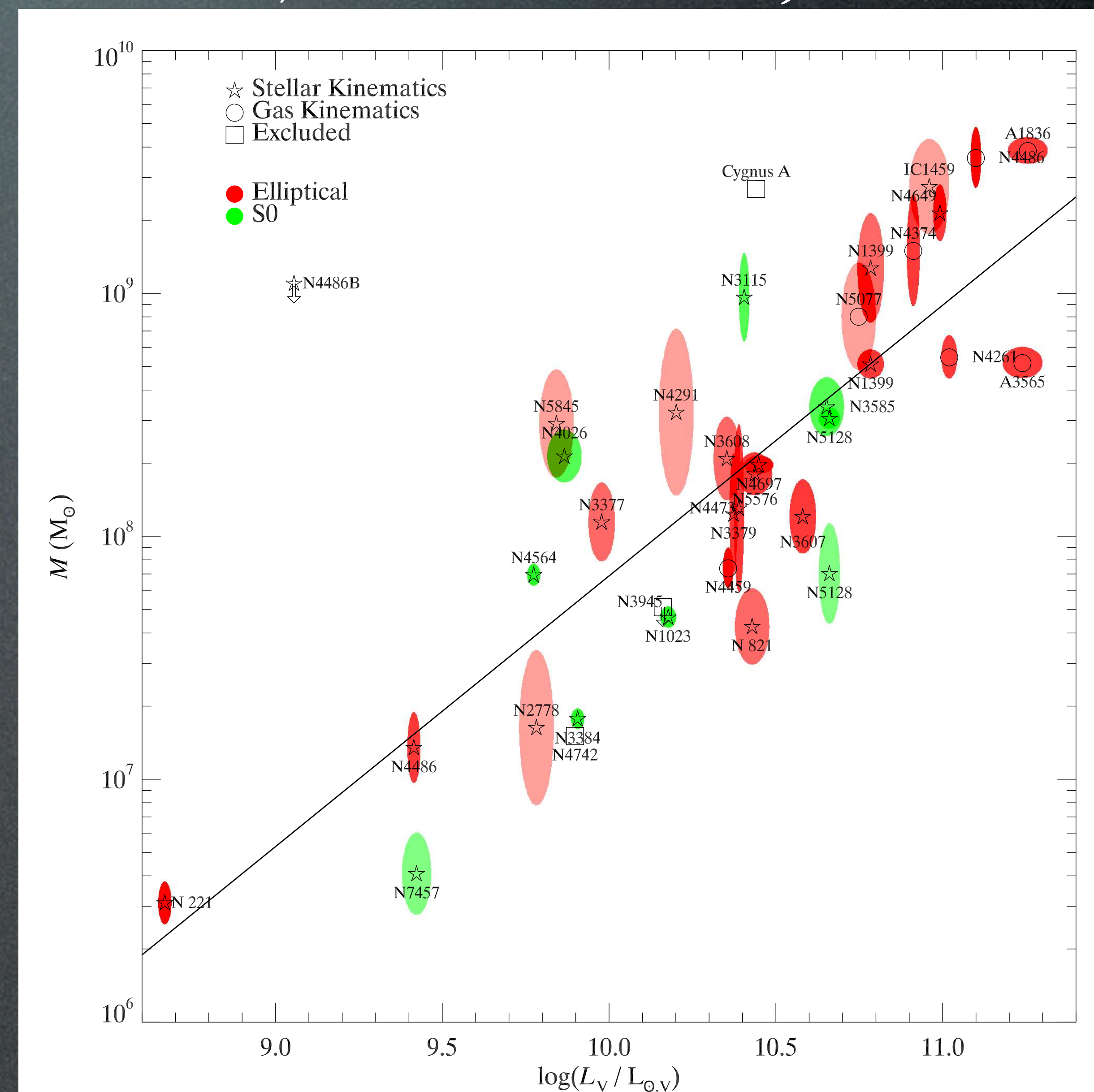
0.6m Burrell Schmidt Telescope

The Black Hole — Galaxy Connection

M_{BH} -σ (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Ferrarese & Ford 2005; Gultekin et al. 2009)



M_{BH}-L (Kormendy & Richstone 1995; Magorrian et al. 1998; McLure & Dunlop 2001; Marconi & Hunt 2003; Ferrarese & Ford 2005; Gultekin et al. 2009)



Gultekin et al. (2009)

Intrinsinc scatter 0.44±0.06
(0.31±0.06 for Early-Type galaxies)

Intrinsinc scatter 0.38± 0.09

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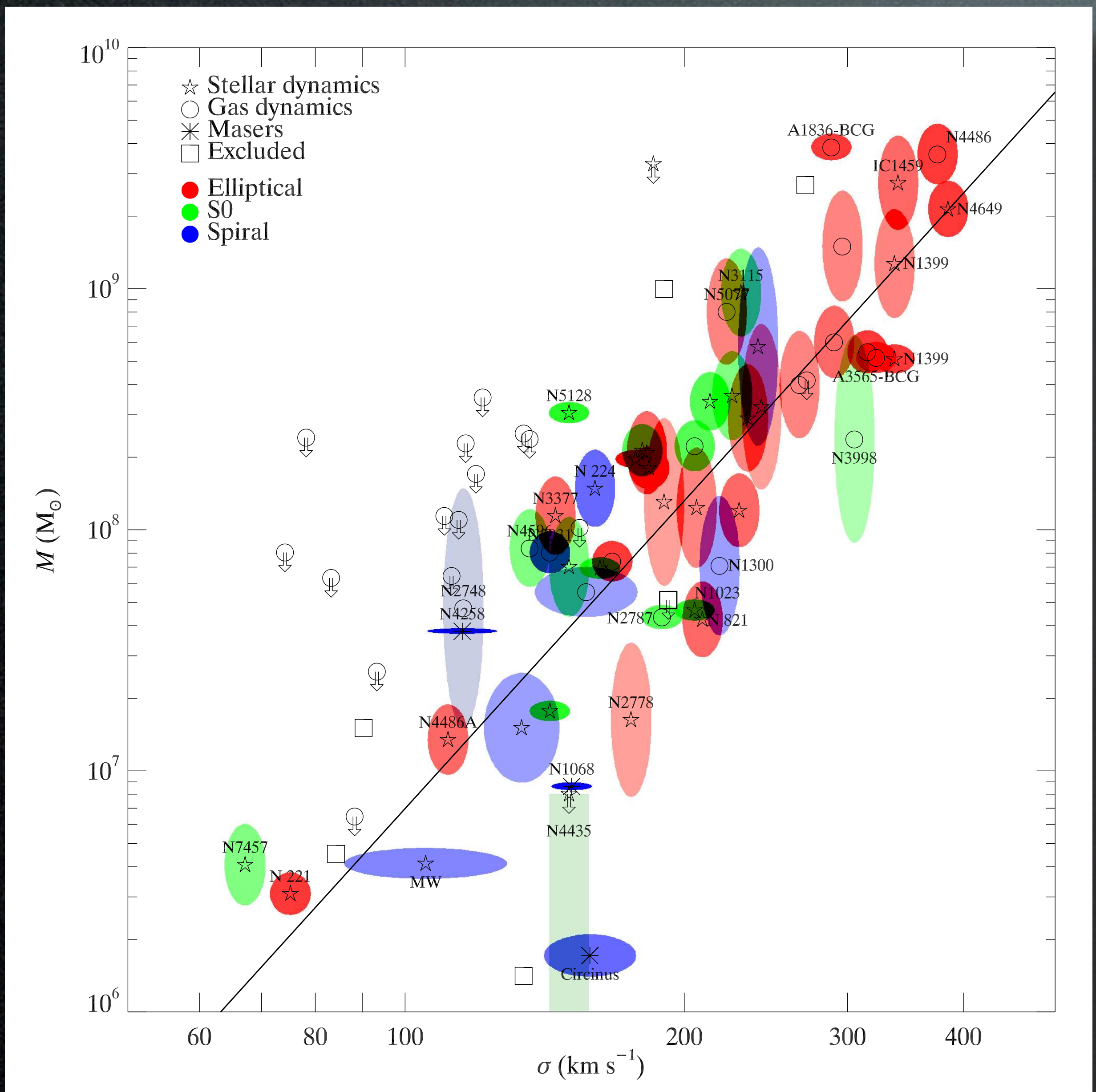

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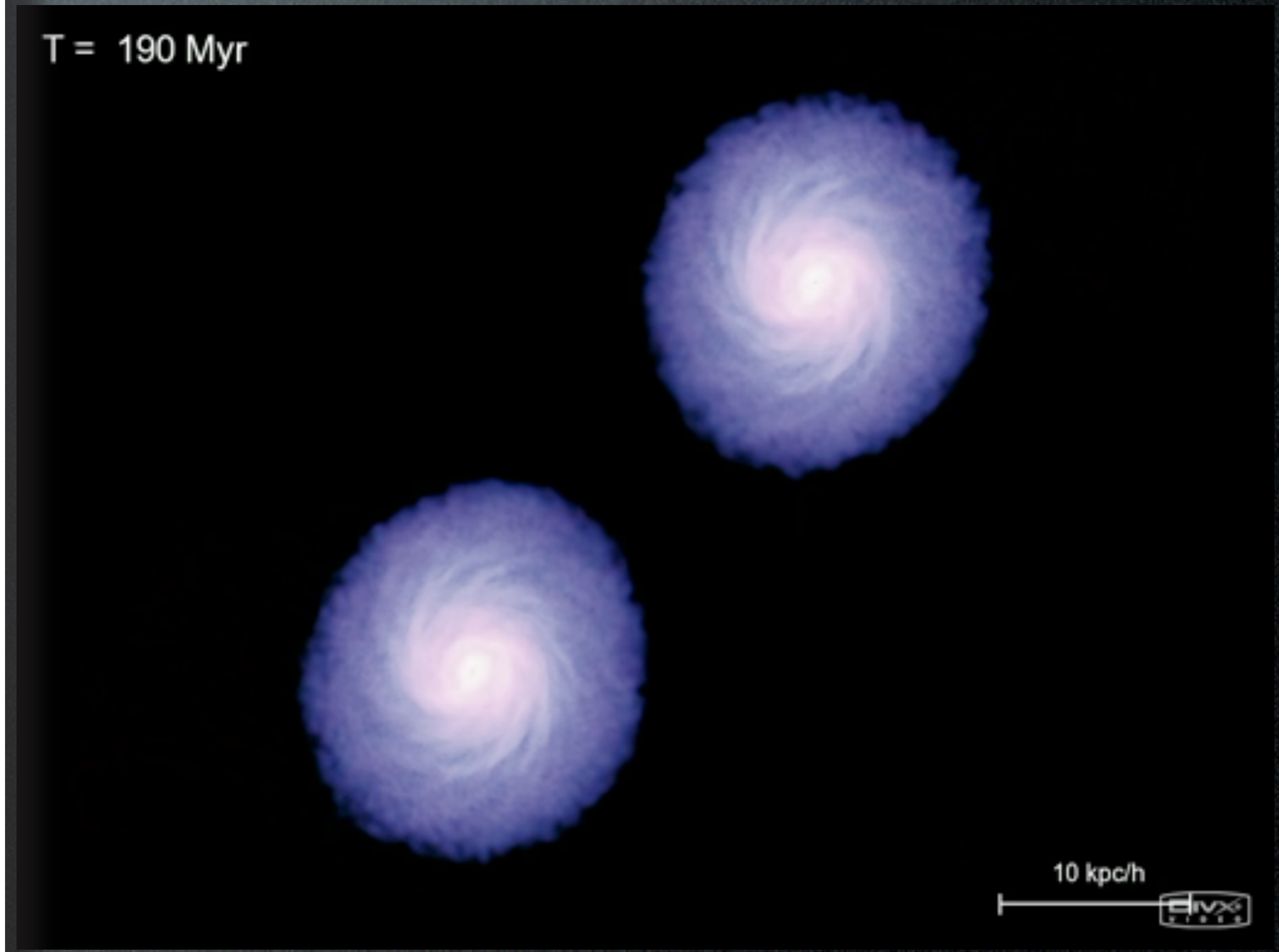

Springel et al. (2005);
Di Matteo et al (2005, 2008)

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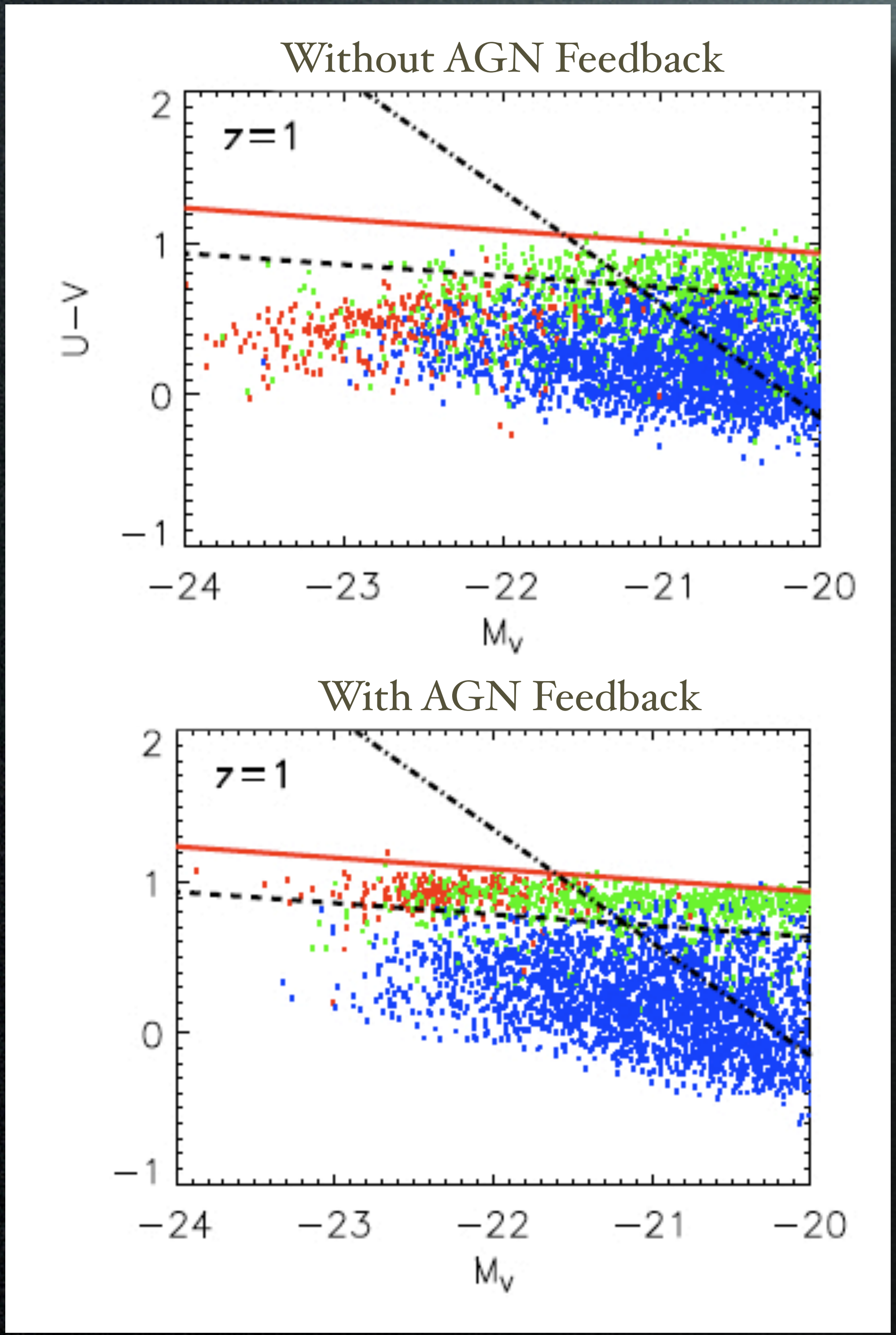
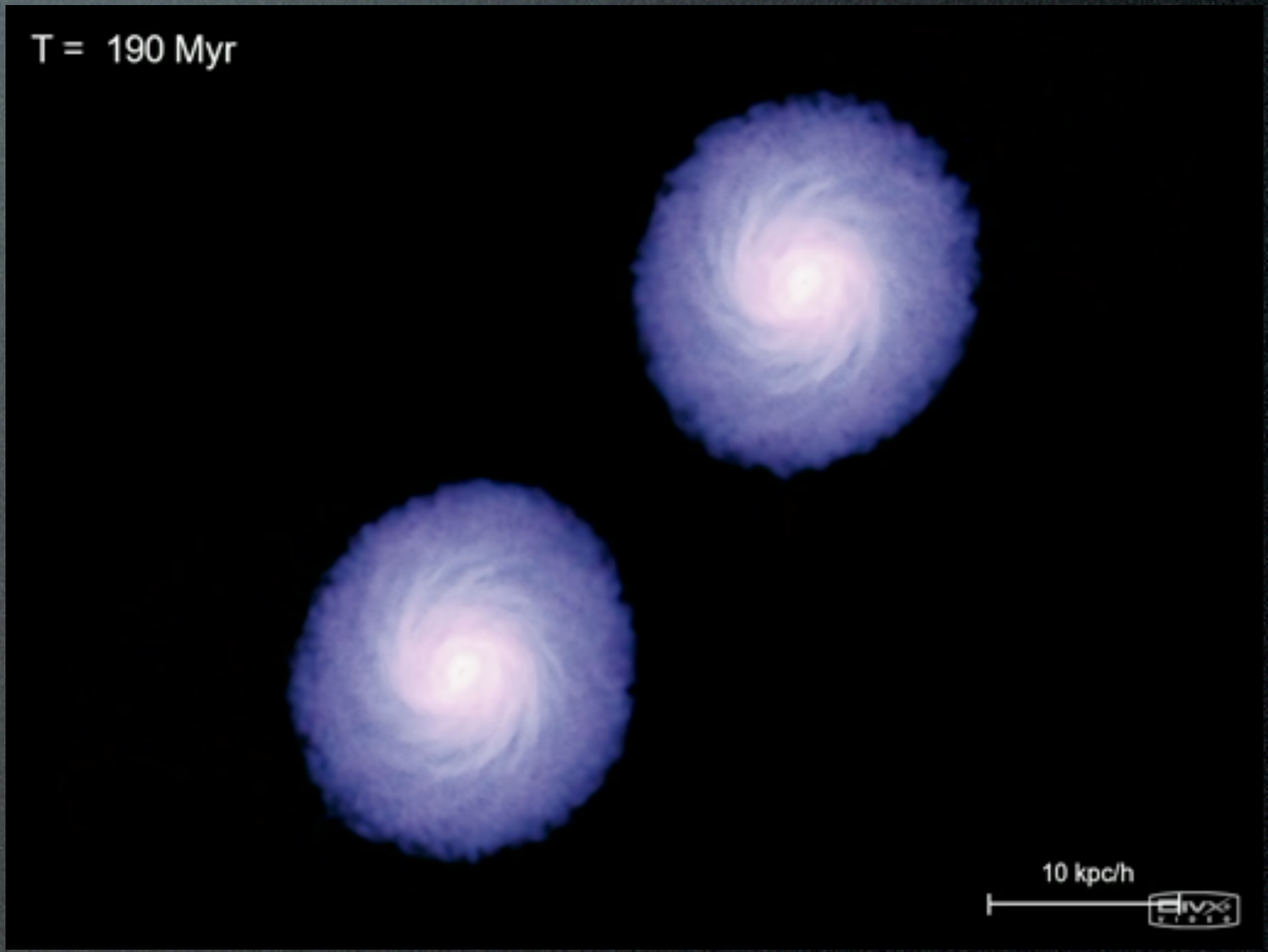


Cattaneo et al. (2006)



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Dynamical Detections of Supermassive Black Holes

METHOD	DISTANCE PROBED	No. of DETECTIONS	MASS RANGE ($\mathcal{M}_\odot$)	TYPICAL DENSITY ($\mathcal{M}_\odot$ pc^{-3})
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e.g.: Cappellari et al. 2002; Verolme et al. 2002; Bender et al. 2005; Gebhardt et al. 2003; Bower et al. 2001; Gebhardt et al. 2007; Houghton et al. 2006; Emsellem et al. 1999; Barth et al. 2001; Gebhardt et al. 2000; Gultekin et al. 2009; Cretton & van den Bosch 1999; Nowak et al. 2007; Silge et al. 2005; Cappellari et al. 2009.

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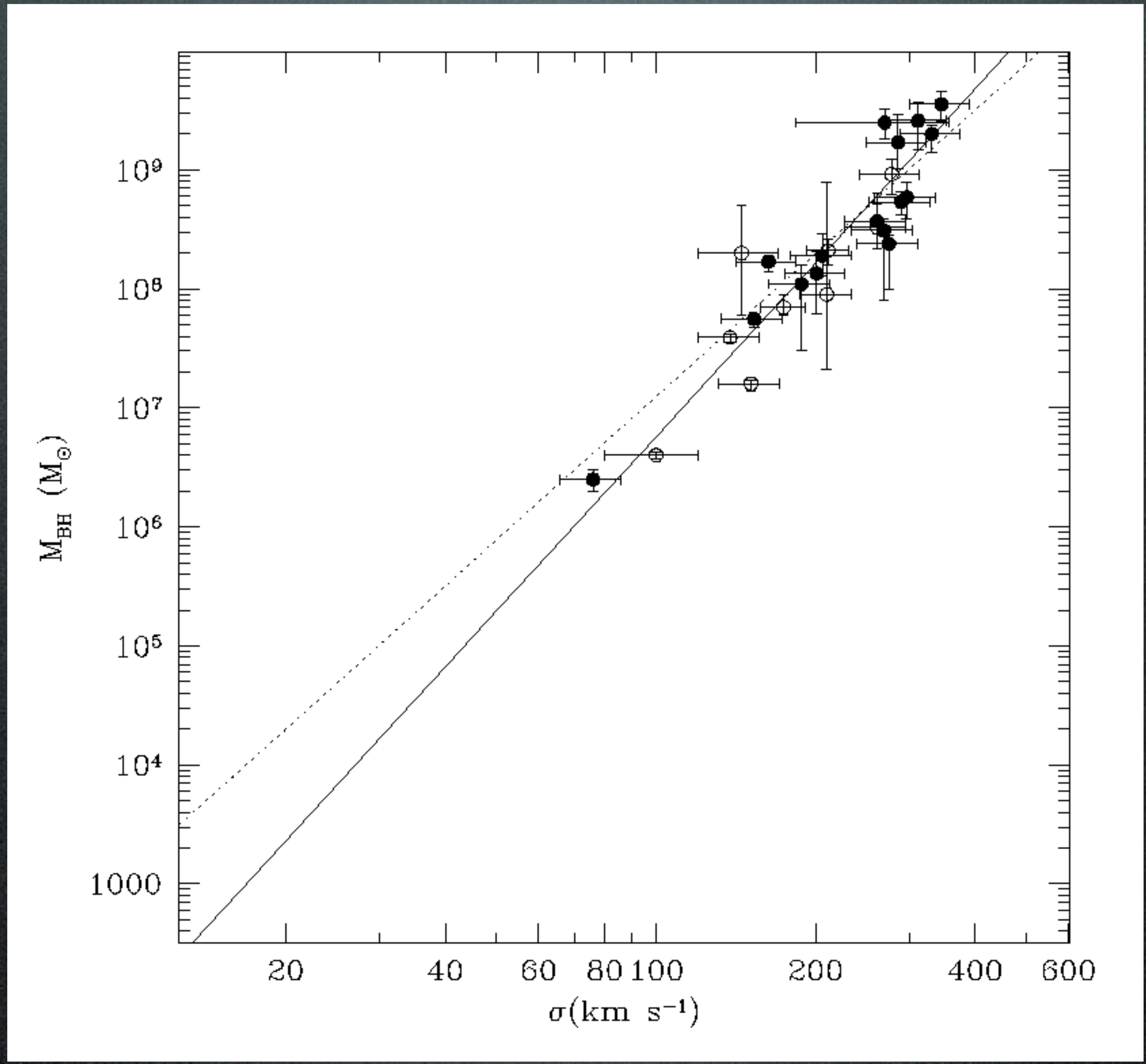
HST's Contribution no. 1: Spatial Resolution



$$R_{\rm infl} \sim 11 \frac{M_{\rm BH}/10^8\,M_\odot}{(\sigma/200\ {\rm km\ s^{-1}})^2}\ {\rm parsec}$$

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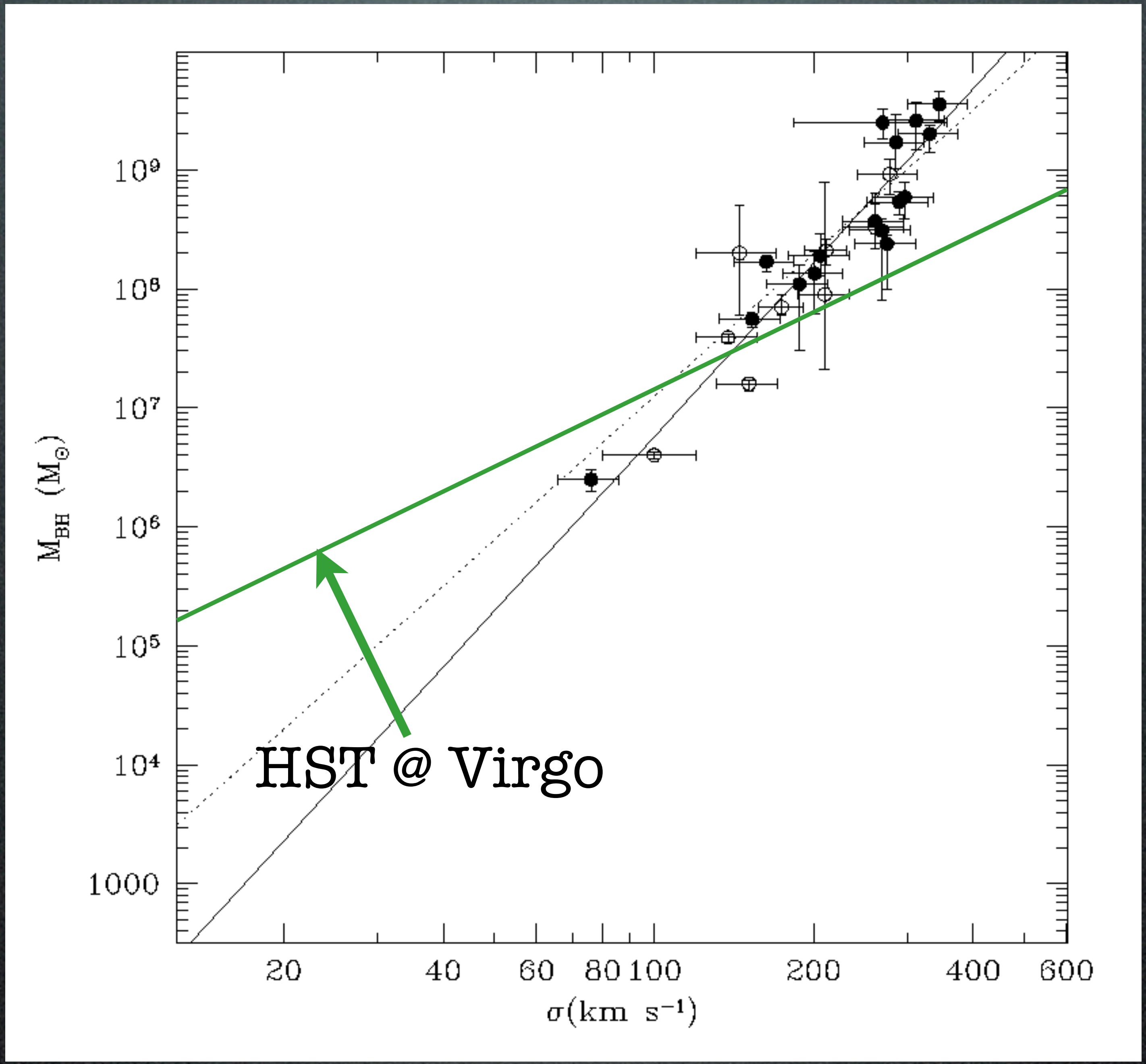

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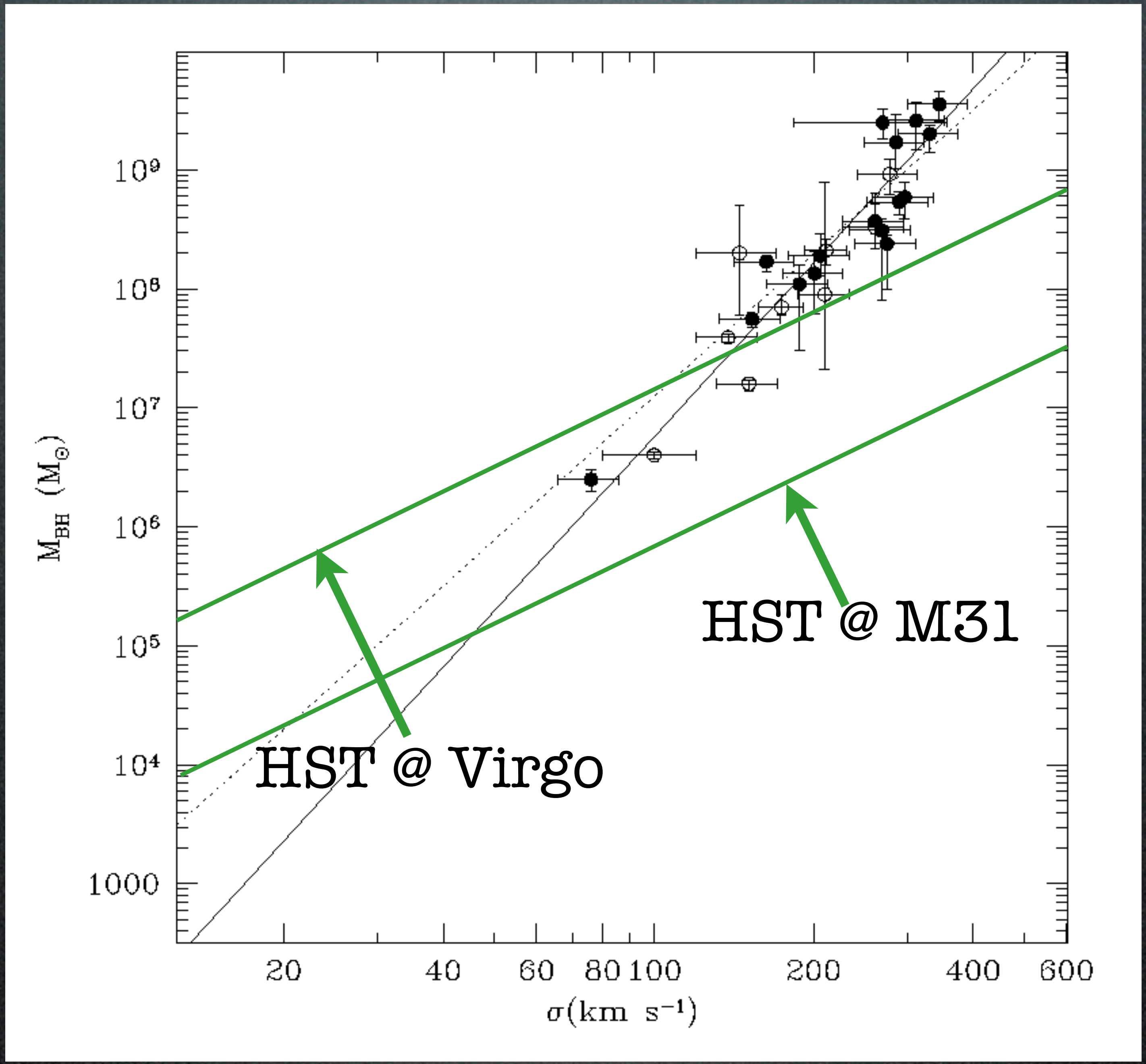

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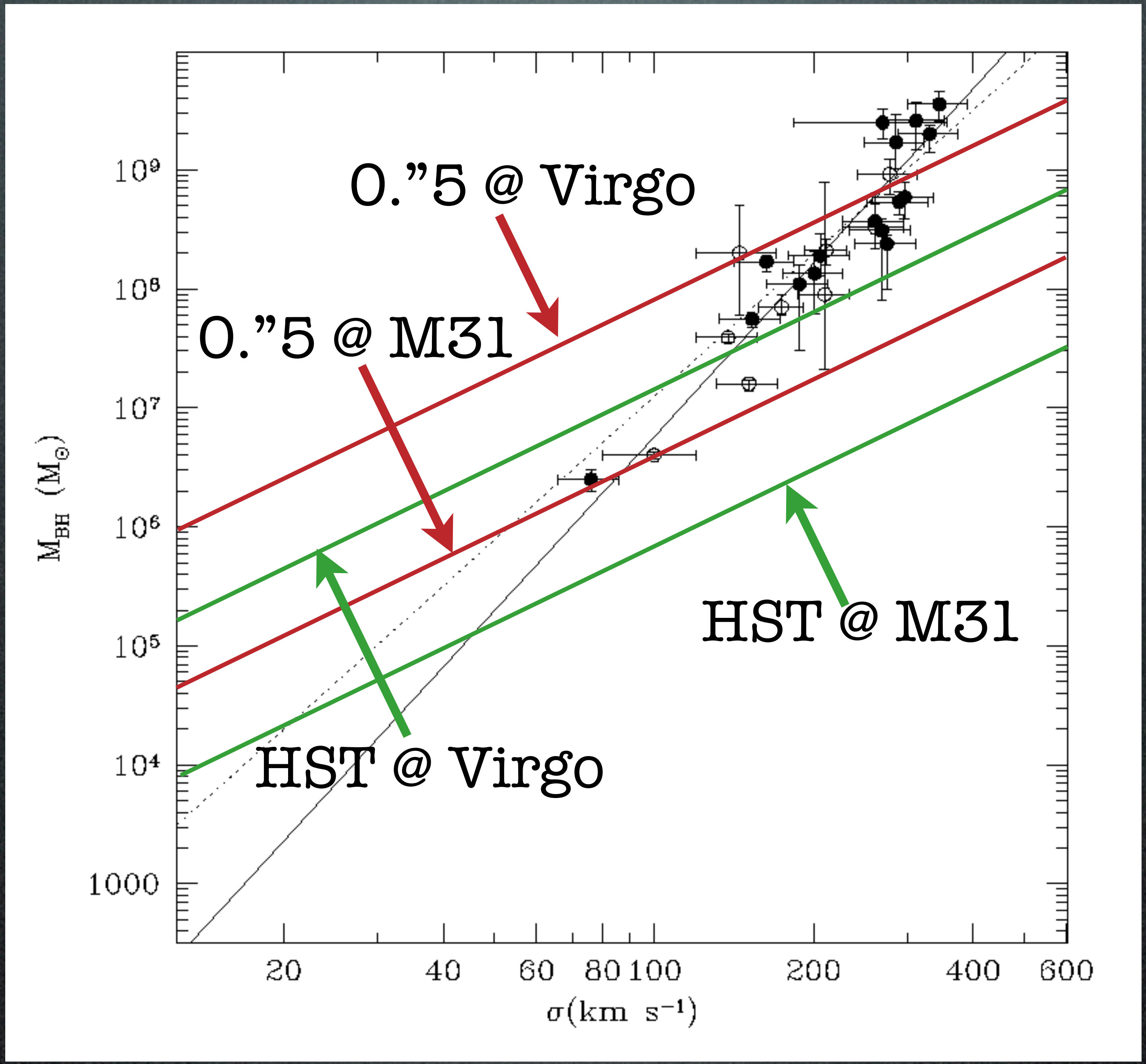

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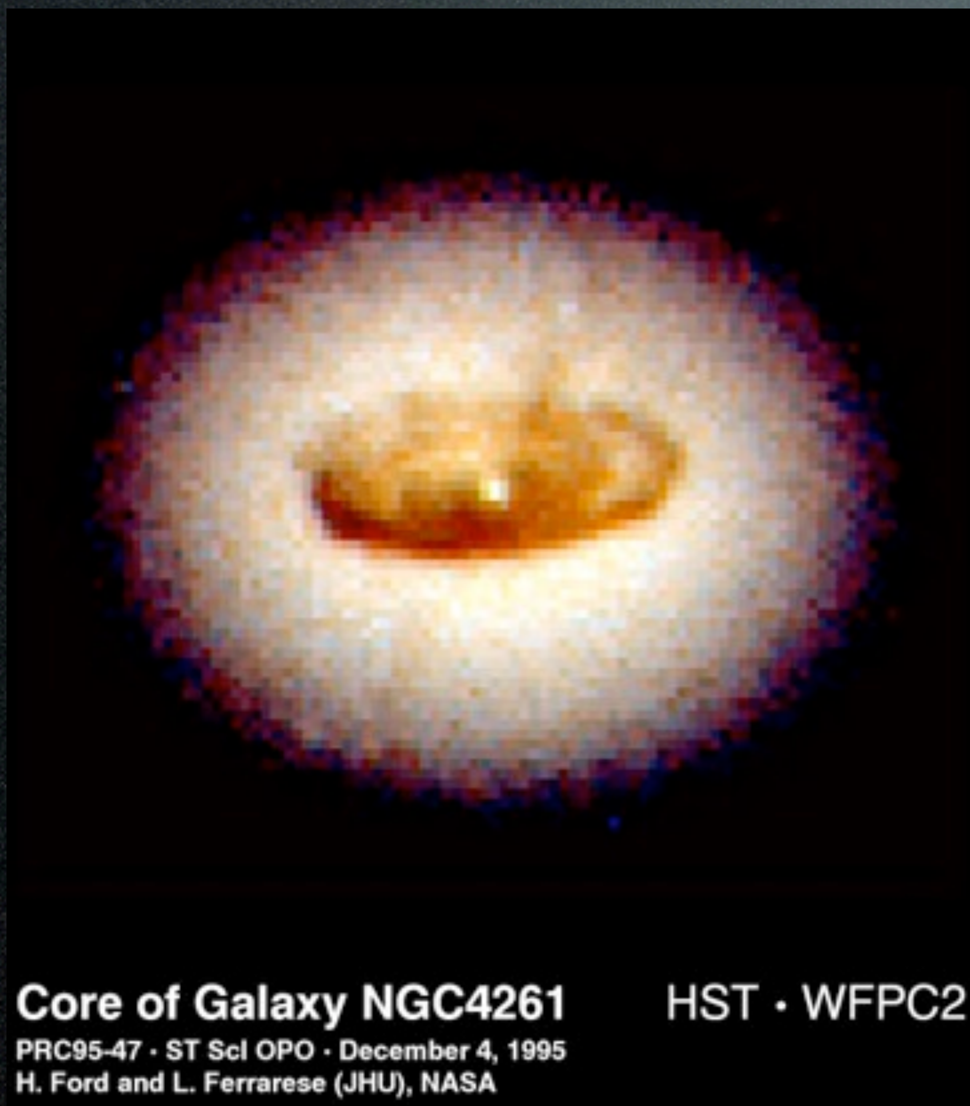
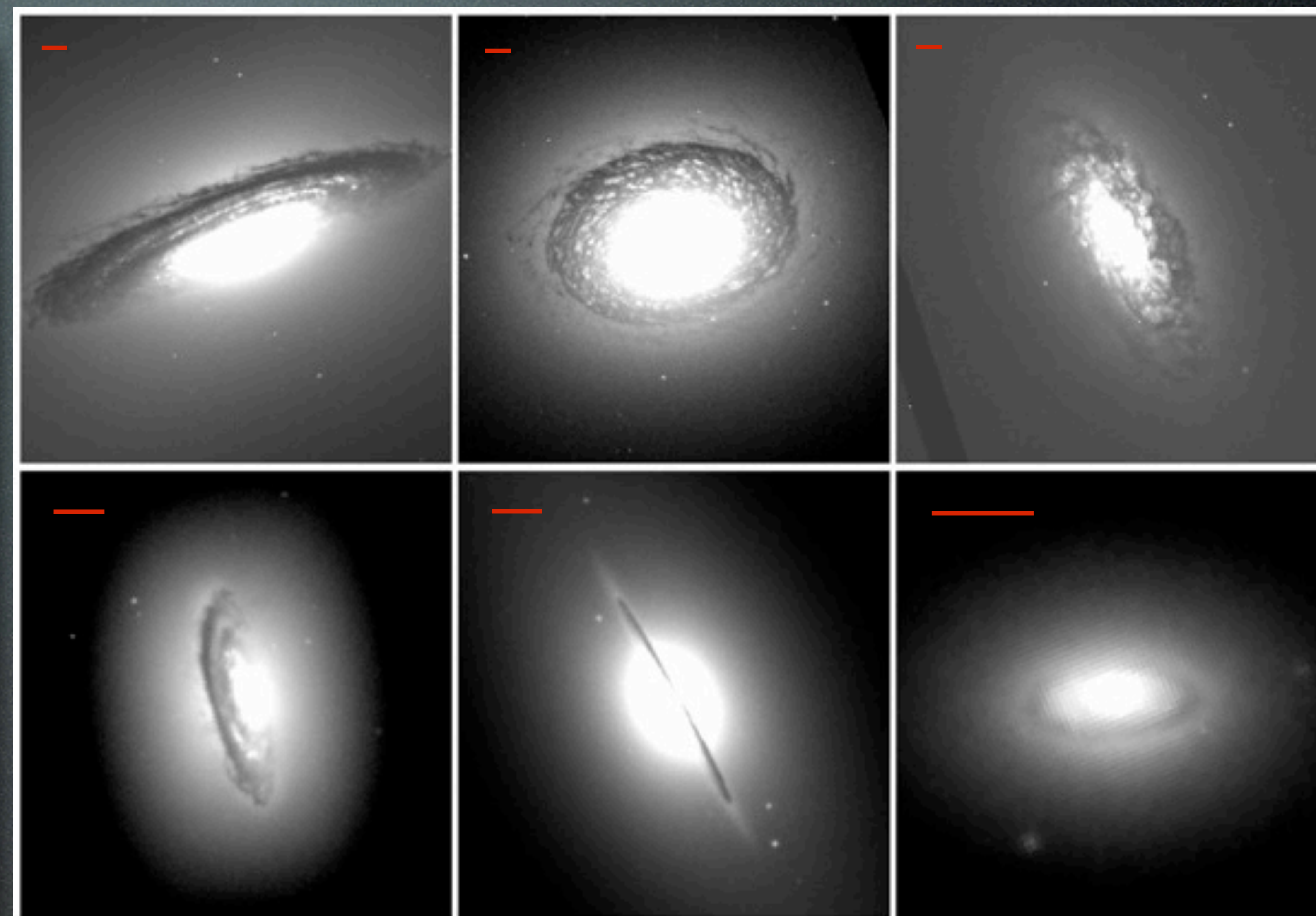
HST's Contribution no. 2: Nuclear Gas Disks



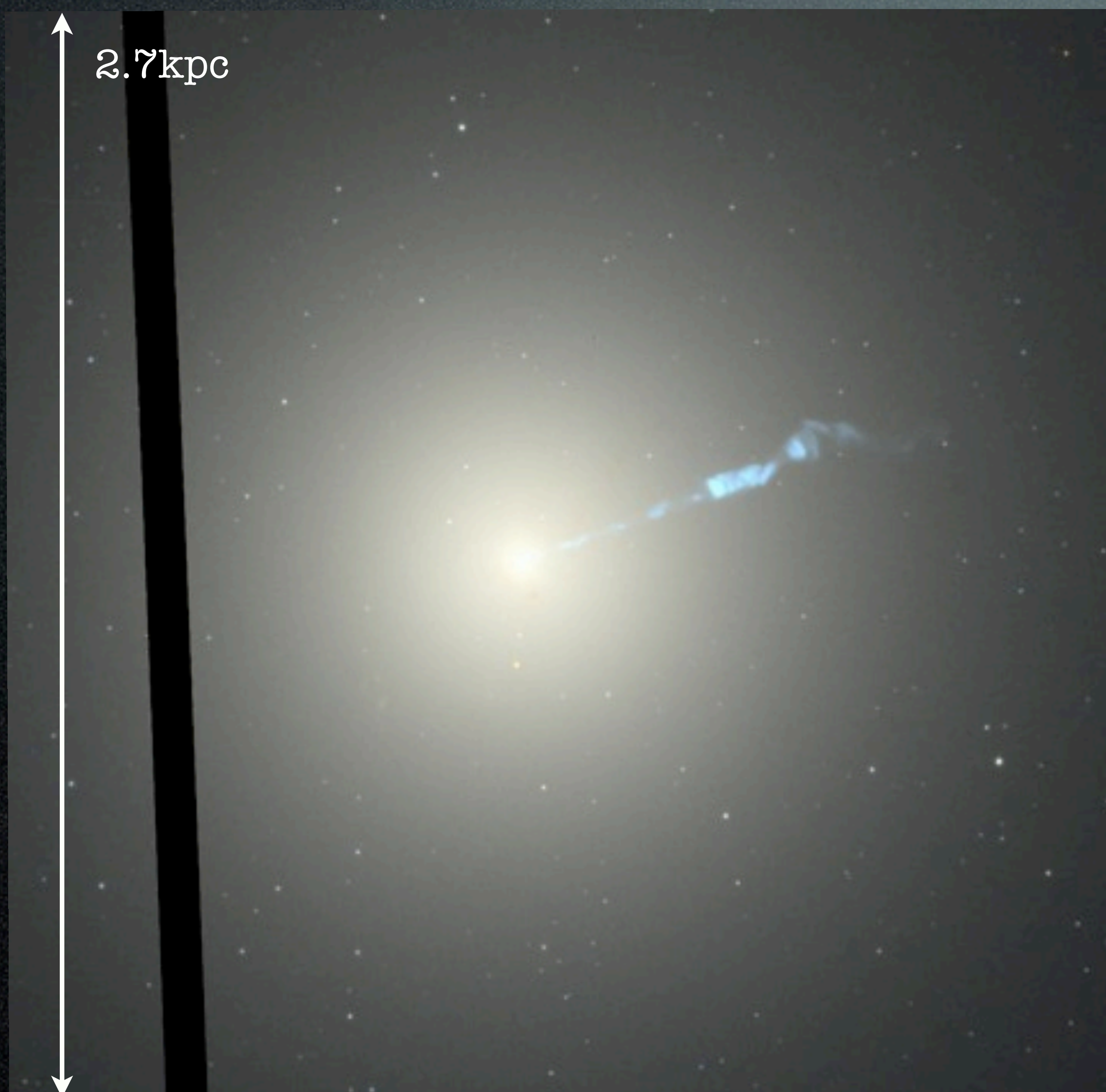


Ferrarese et al. (2006)

- Nuclear dust/gas disks are present in ~20% of Early-Type galaxies (Tran et al. 2001; Ferrarese et al. 2004)

- Regular geometry is promise of simple kinematics (Atkinson et al. 2005; Sarzi et al. 2001; Devereux et al. 2003; Barth et al. 2001; de Francesco et al. 2006; Ferrarese et al. 1996; Bower et al. 1998; Macchetto et al. 1997; de Francesco et al. 2008; Ferrarese & Ford 1999; van der Marel & van den Bosch 1998; Wold et al. 2006; Dalla Bonta' et al. 2009)

Evolution of a Black Hole (1978 - 2009): M87



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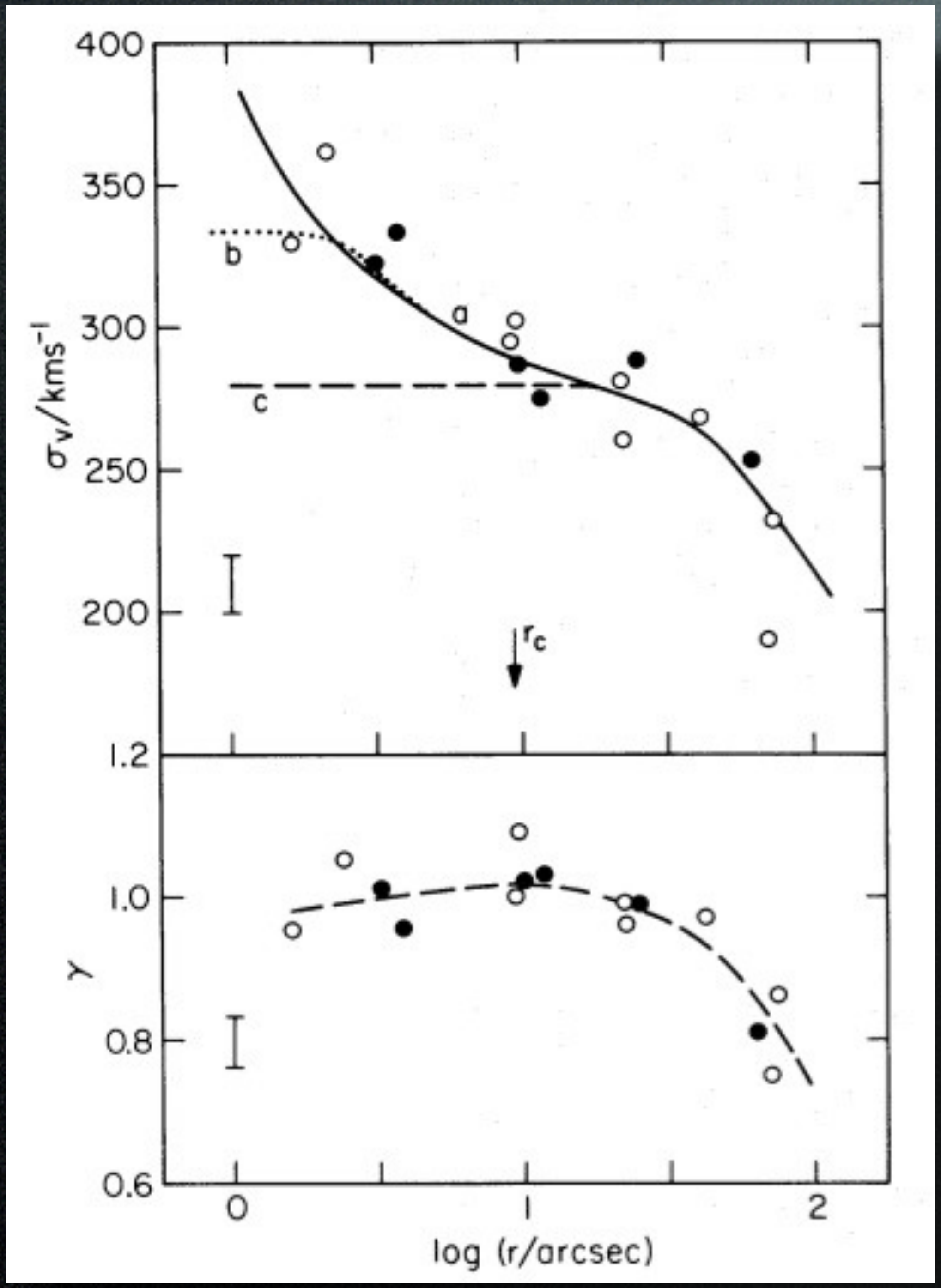

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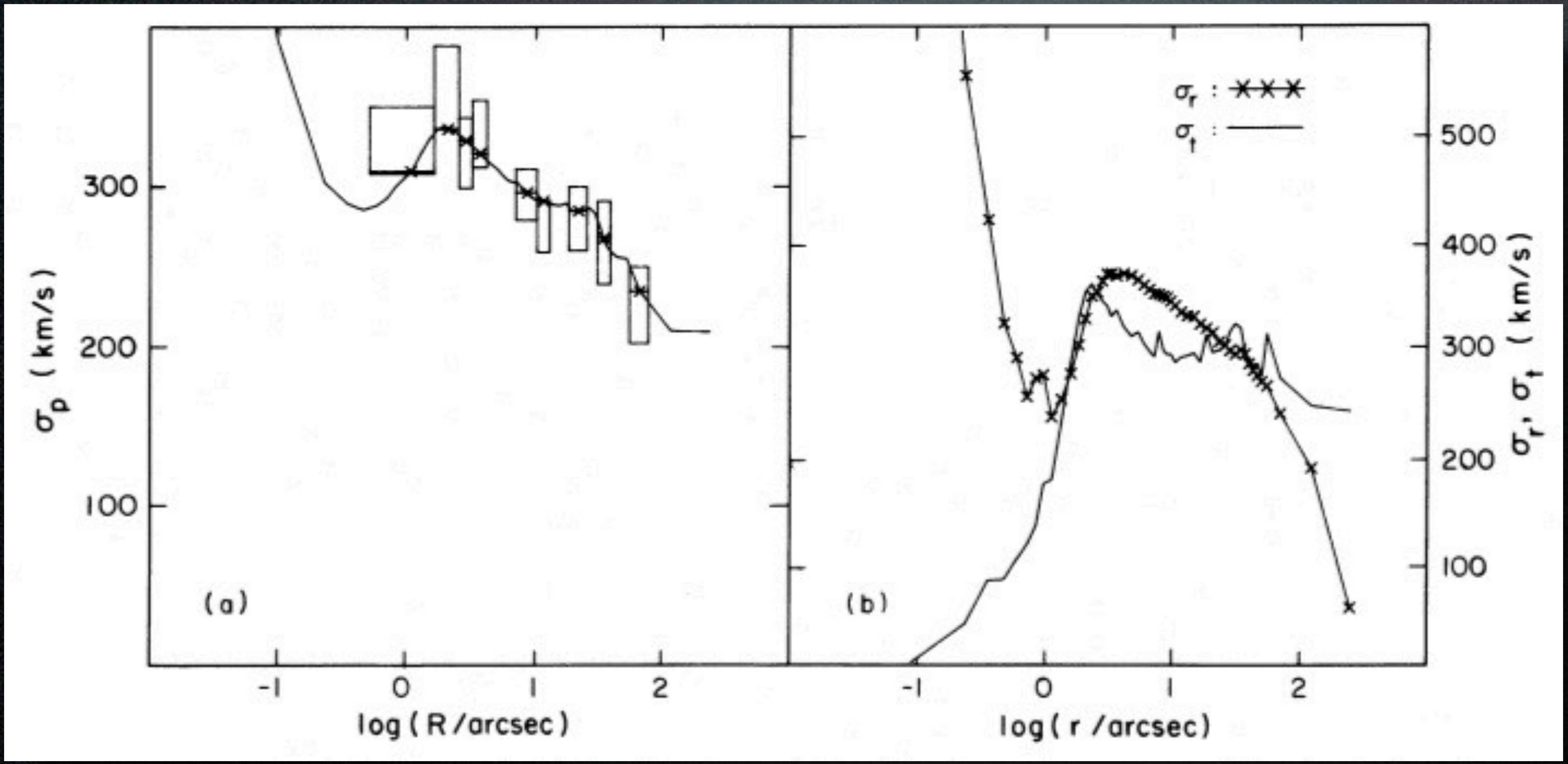

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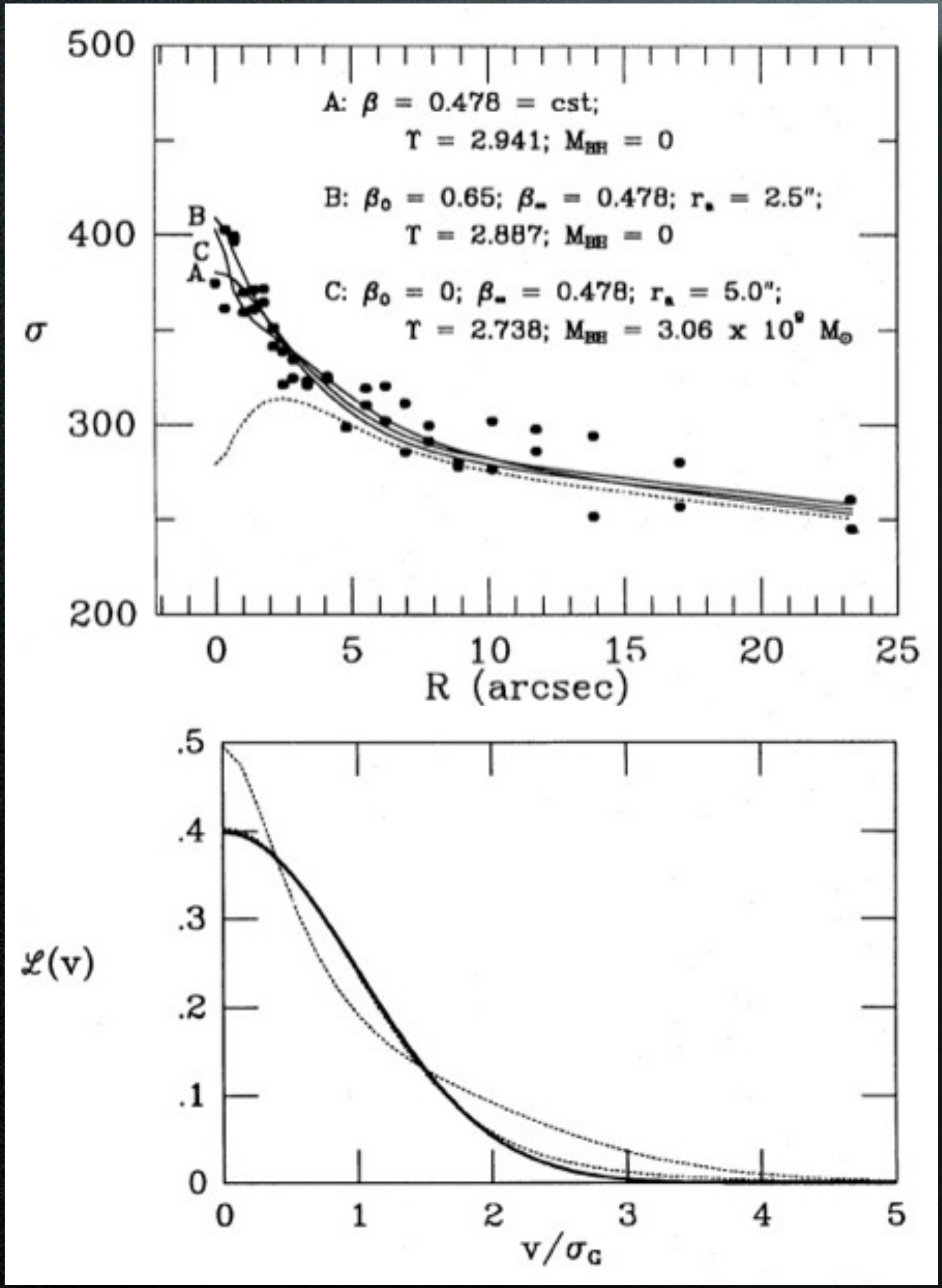

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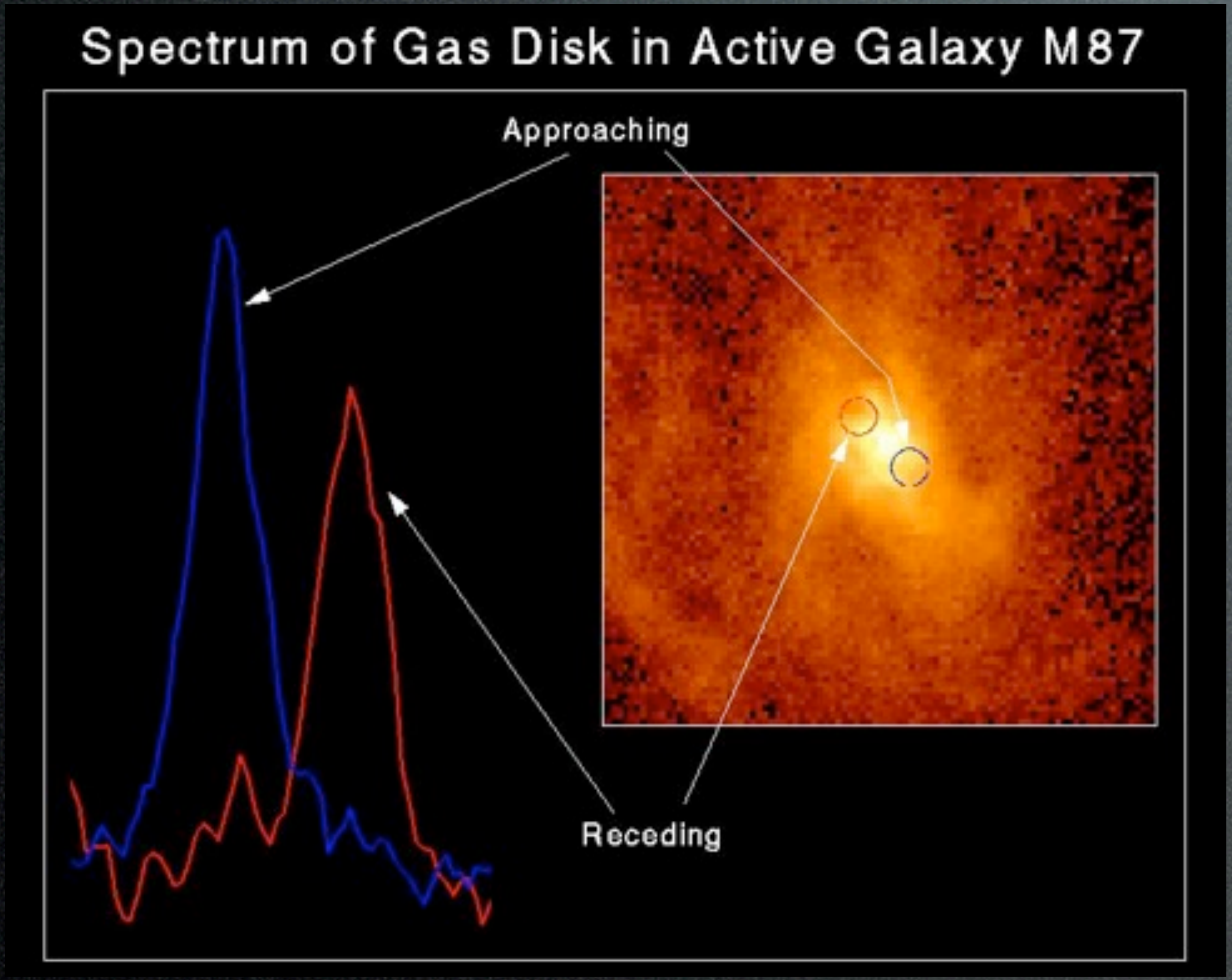

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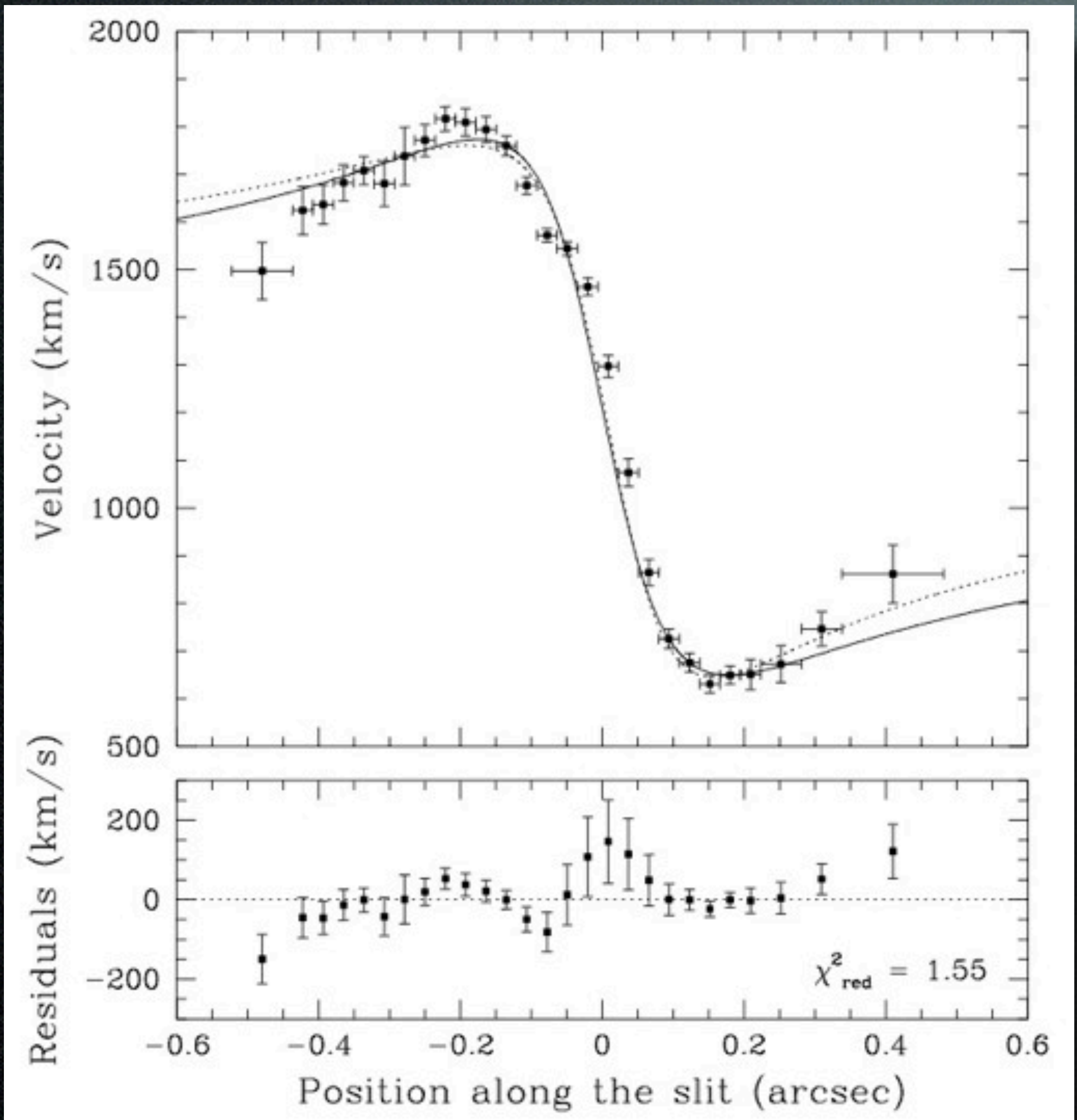

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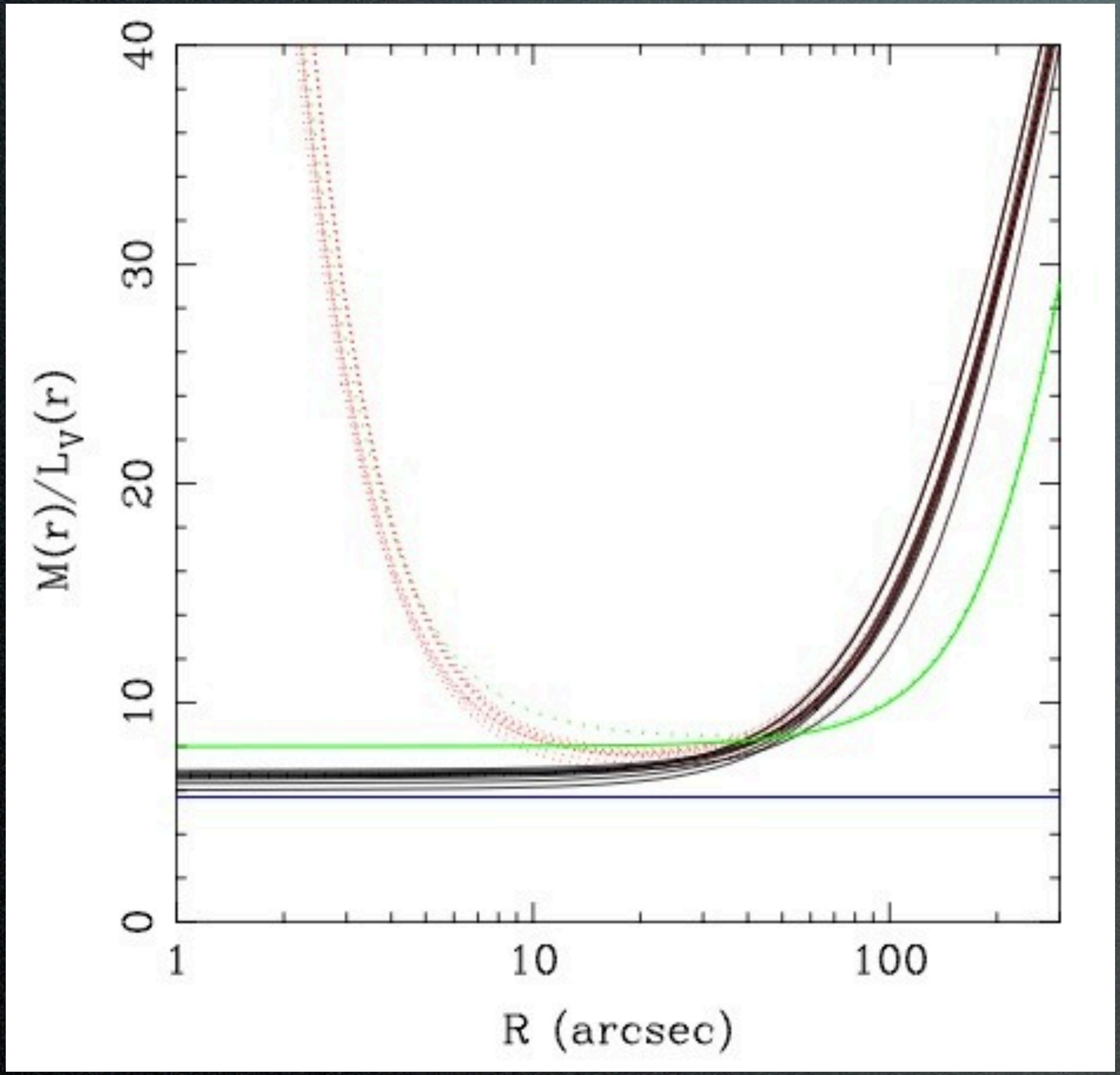

Gebhardt & Thomas (2009)

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Gebhardt & Thomas 2009,
stars (ground)+GCs+X-ray

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Going beyond HST's spatial coverage is necessary to move into a phase of precision BH demographics. 2d kinematics and large scale tracers are necessary to:

- constrain inclination (e.g. Verolme et al. 2002)
- simultaneously constrain DM halo and BH (Gebhardt & Thomas 2009; Gebhardt et al. 2010)
- constrain the galaxy shape (van den Bosch & de Zeeuw 2009)

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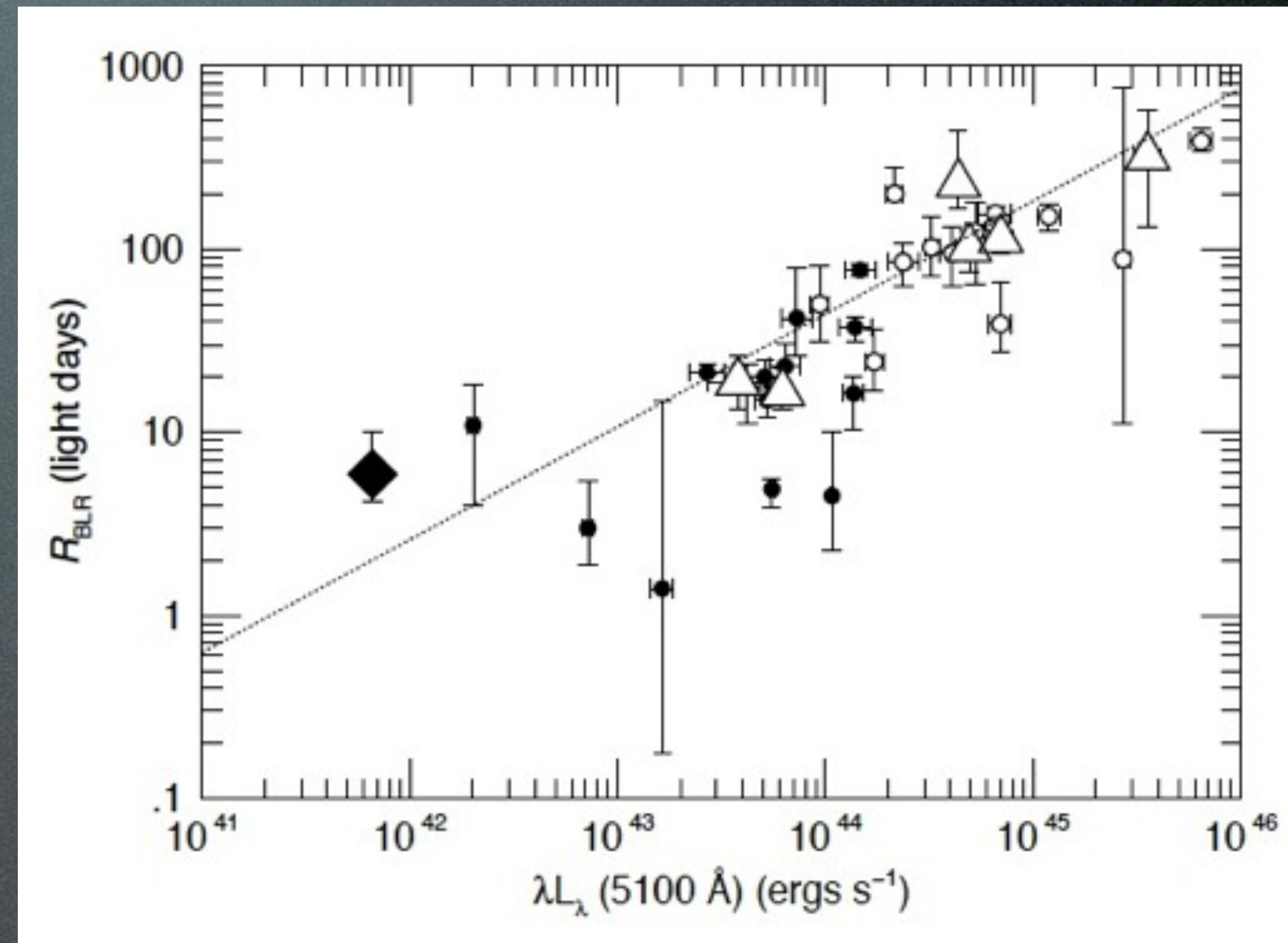
The BLR radius luminosity correlation:

- basis for all secondary techniques used to estimate black hole masses in AGNs (e.g., Laor 1998; Wandel et al. 1999; McLure & Jarvis 2002; Vestergaard & Peterson 2006)

- probe cosmological evolution of the MBH-σ relationship (e.g., Peng et al. 2006; Woo et al. 2008).



Peterson (2001)

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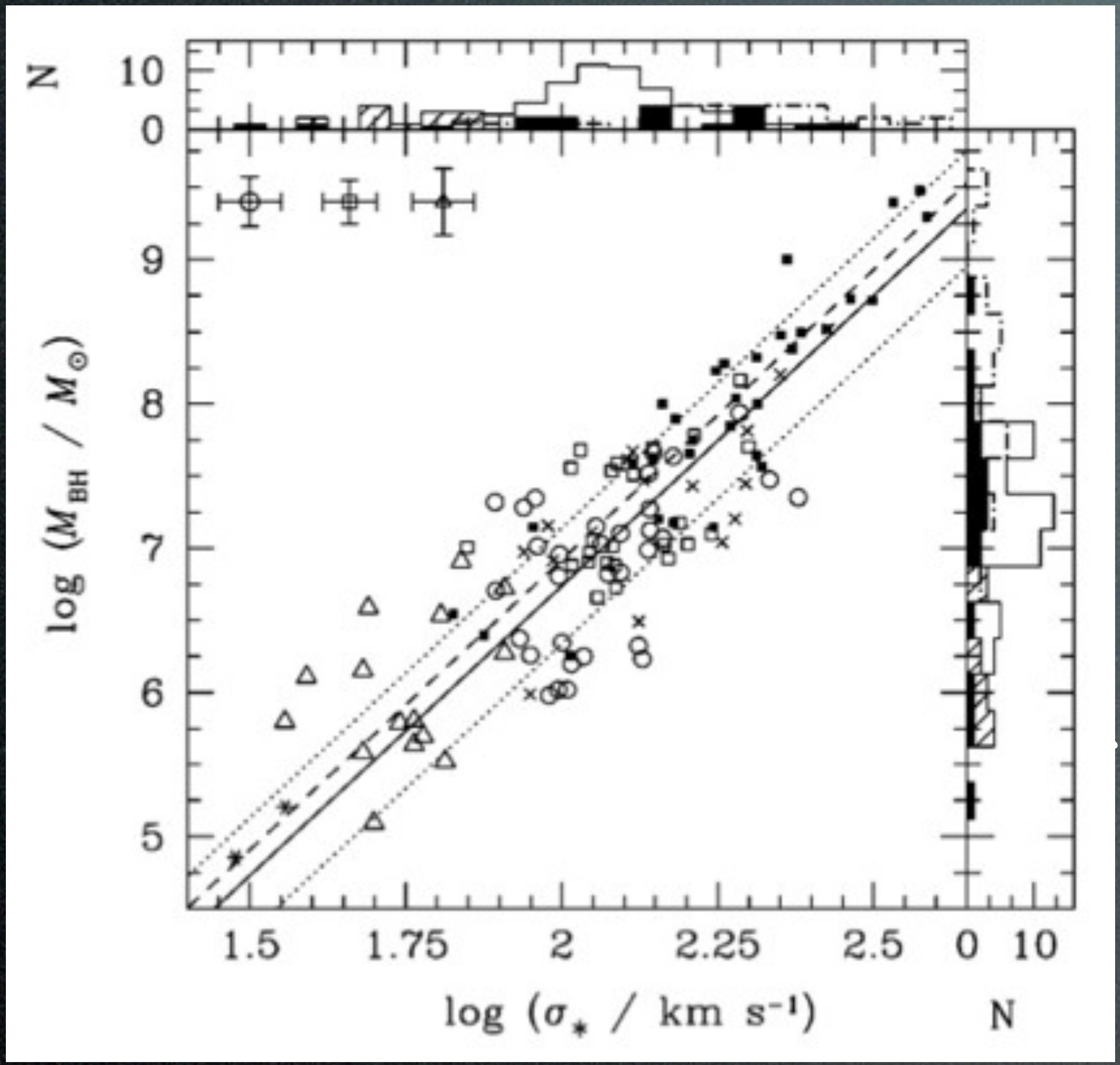
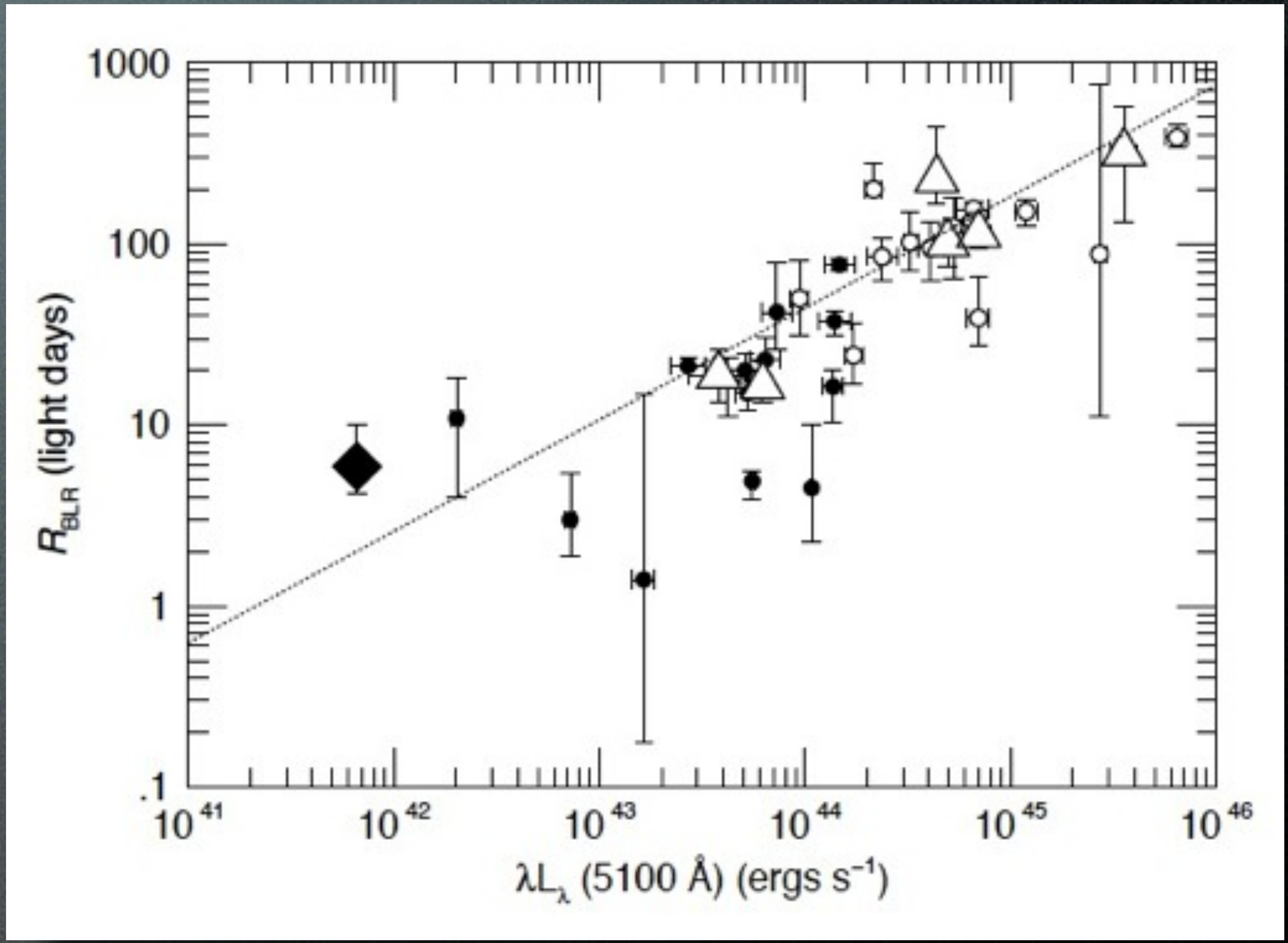


Greene & Ho (2007)



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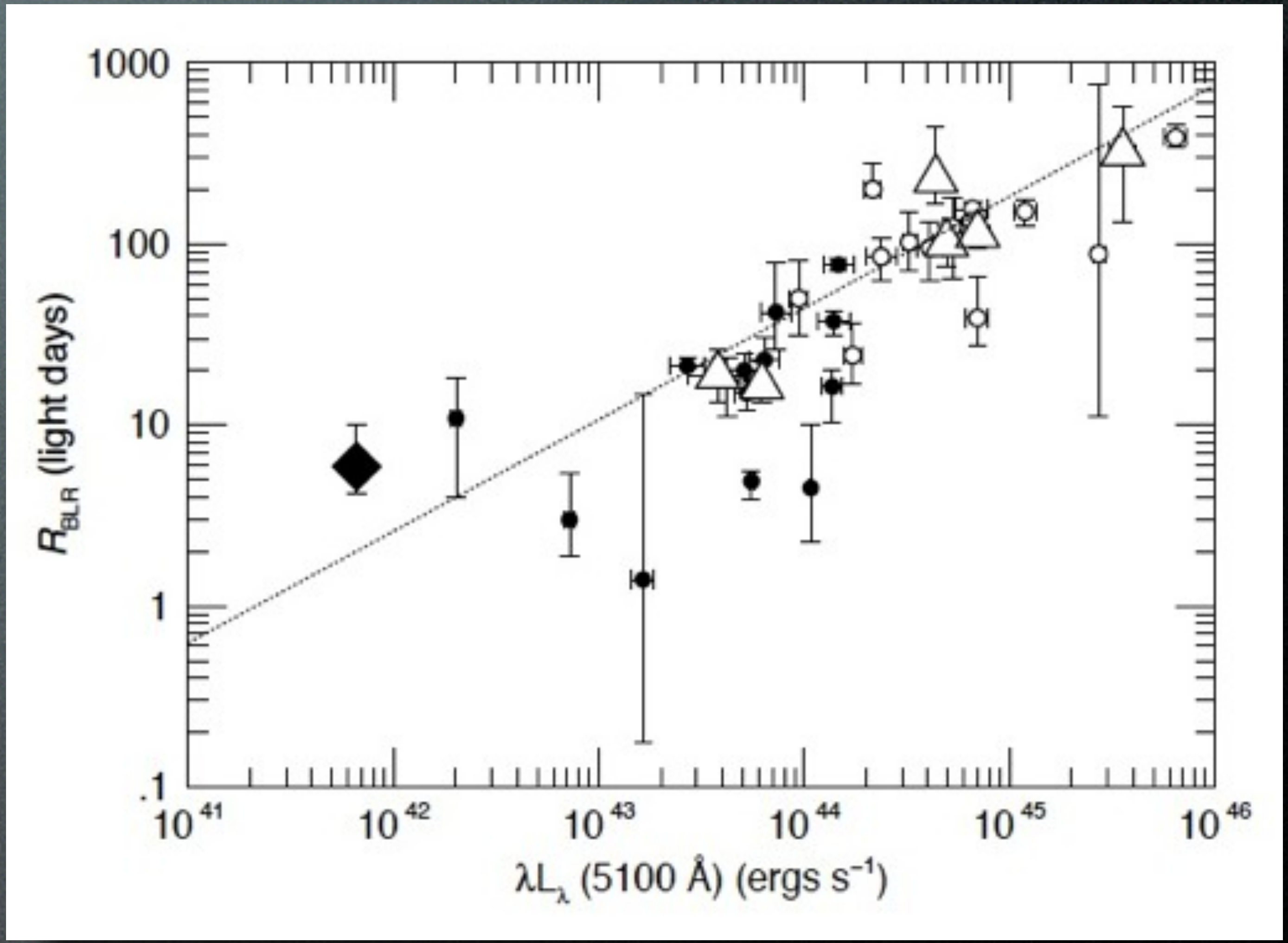

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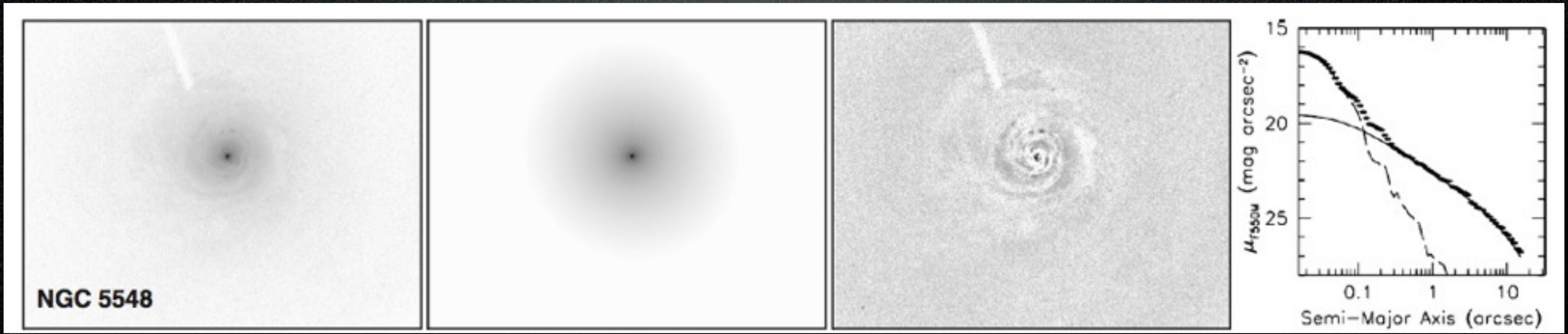

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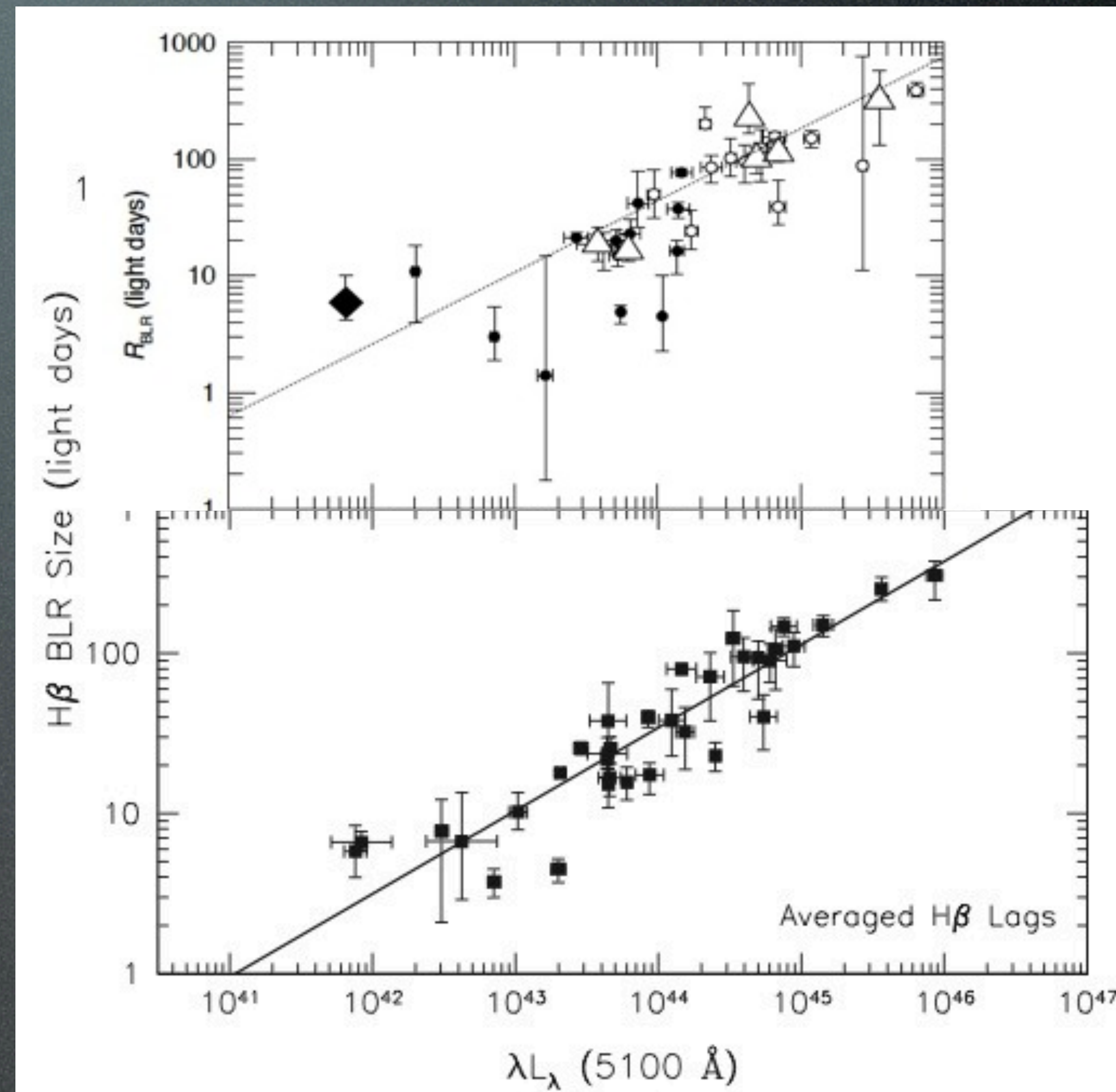
Slope: from 0.67±0.08 to 0.53±0.05

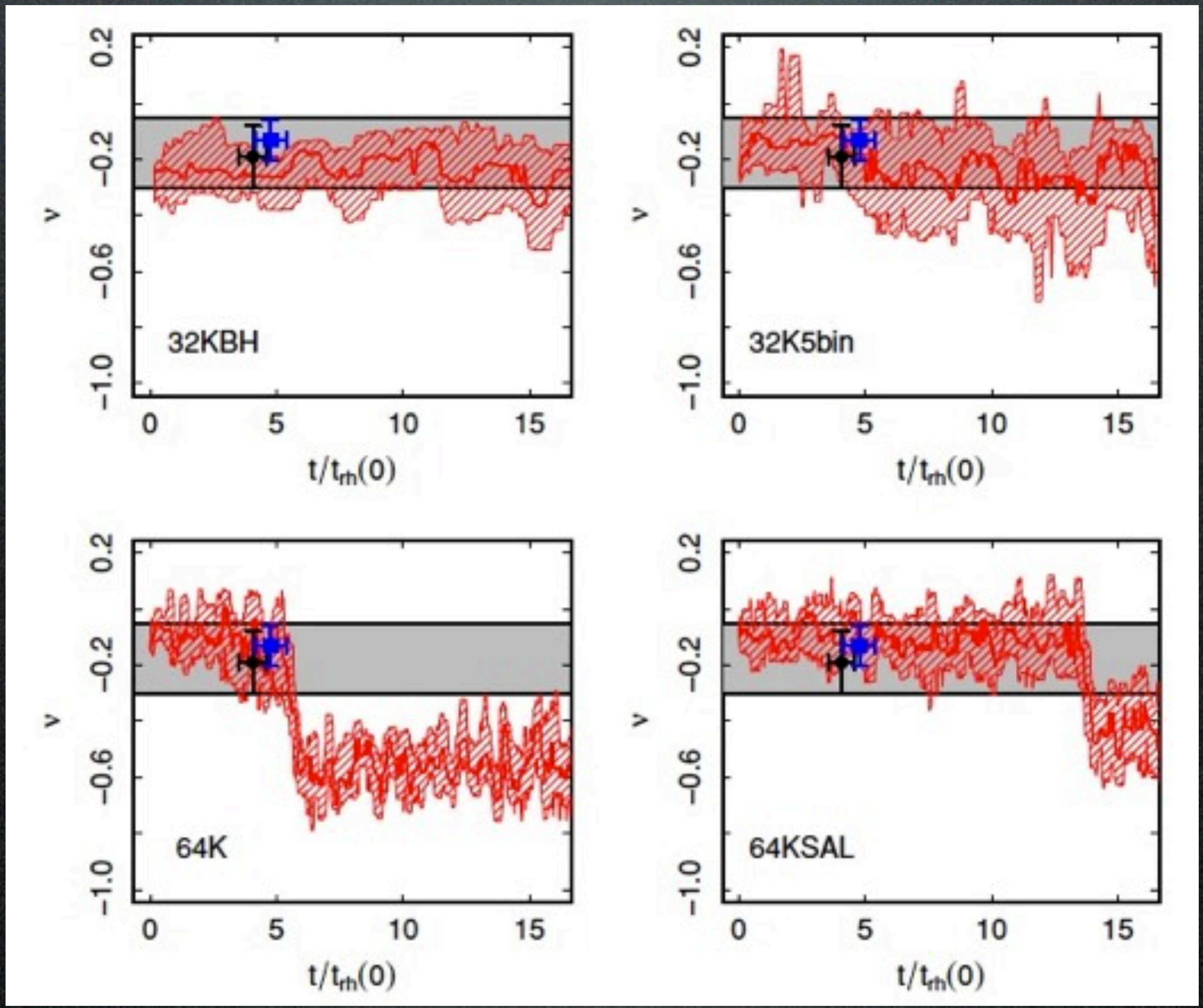
Scatter: decreased by 25%.



Bentz et al. (2009)

Intermediate Mass Black Holes in GCs?

- Shallow density cusps. BH induces the formation of a Bahcall-Walf shallow density cusp ($\mu \sim R^{\nu}$, with ν =–0.3 to –0.05) and inhibits mass segregation (Baumgardt et al. 2005; Trenti et al. 2007a; Miocchi 2007; Umbreit et al. 2009, Gilli et al. 2008, Pasquato et al. 2010). Shallow cusps observed with HST/ACS in several galactic GCs (Noyola & Bebhardt 2006). However this is not a unique signature (Vesperini & Trenti 2010)



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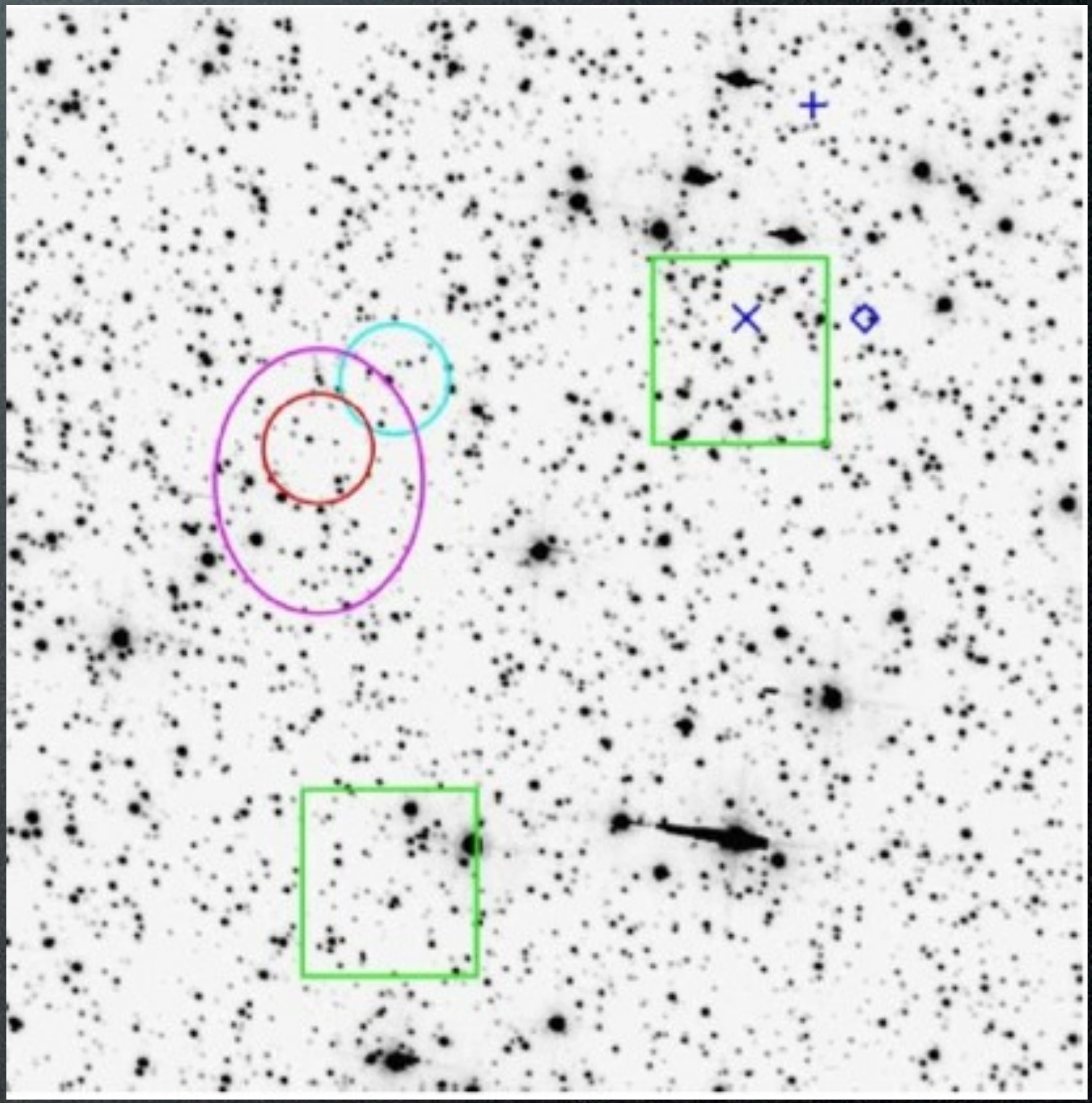
- Increase in line of sight velocity dispersion:

  - M15 $\mathcal{M}$ =1700 to 3200 $\mathcal{M}_{\odot}$ (HST/STIS; Gerssen et al. 2002, 2003) dark mass could also be attributed to segregation of dark remnants towards the center (e.g., Baumgardt et l. 2003)

  - G1 (M31, 770 kpc). $\mathcal{M}$ =(1.8±0.5)×10^{4} $\mathcal{M}_{\odot}$ (Keck kinematics + HST photometry; Gebhardt et al. 2002, 2005) futher supported by radio and X-ray data. Low statistical significance (Baumgardt et l. 2003)

Intermediate Mass Black Holes in GCs?

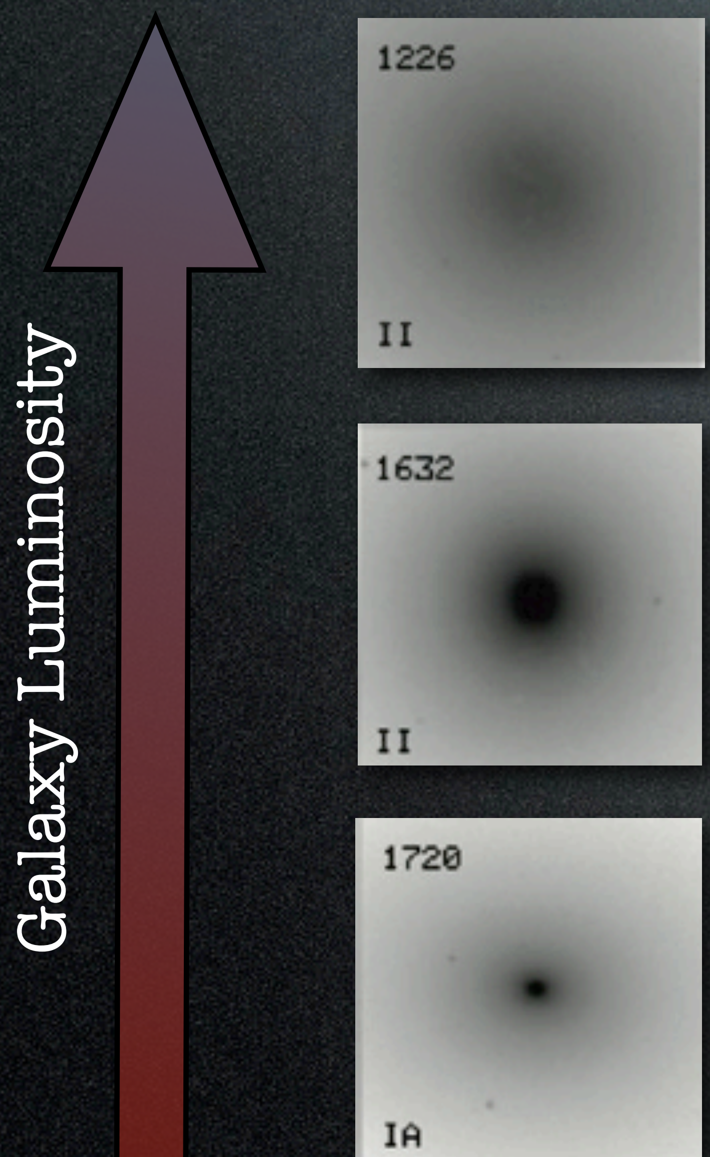
- Proper motion
  - M15 $\mathcal{M} < 500\ \mathcal{M}_\odot$ (HST/WFPC2, McNamara et al. 2003; van den Bosch et al. 2006);
  - 47 Tuc (HST/WFPC2/ACS, $\mathcal{M} < 1000\ \mathcal{M}_\odot$ McLaughlin et 2006)
  - Omega Cen.
    - $\mathcal{M} \sim 4.0\times10^4\ \mathcal{M}_\odot$ based on Gemini/ GMOS integrated light spectroscopy + HST photometry (Noyola et al. 2008)
    - $\mathcal{M} < 1.8\times10^4$ BH based on HST/ACS proper-motion–velocity-dispersion data for ~50,000 stars within 2” (van del Marel & Anderson 2010; Anderson & van der Marel 2010)
    - $\mathcal{M} \sim 3.0$ to $5.2\times10^4\ \mathcal{M}_\odot$ (VLT/ FLAMES) (Noyola et al. 2010)

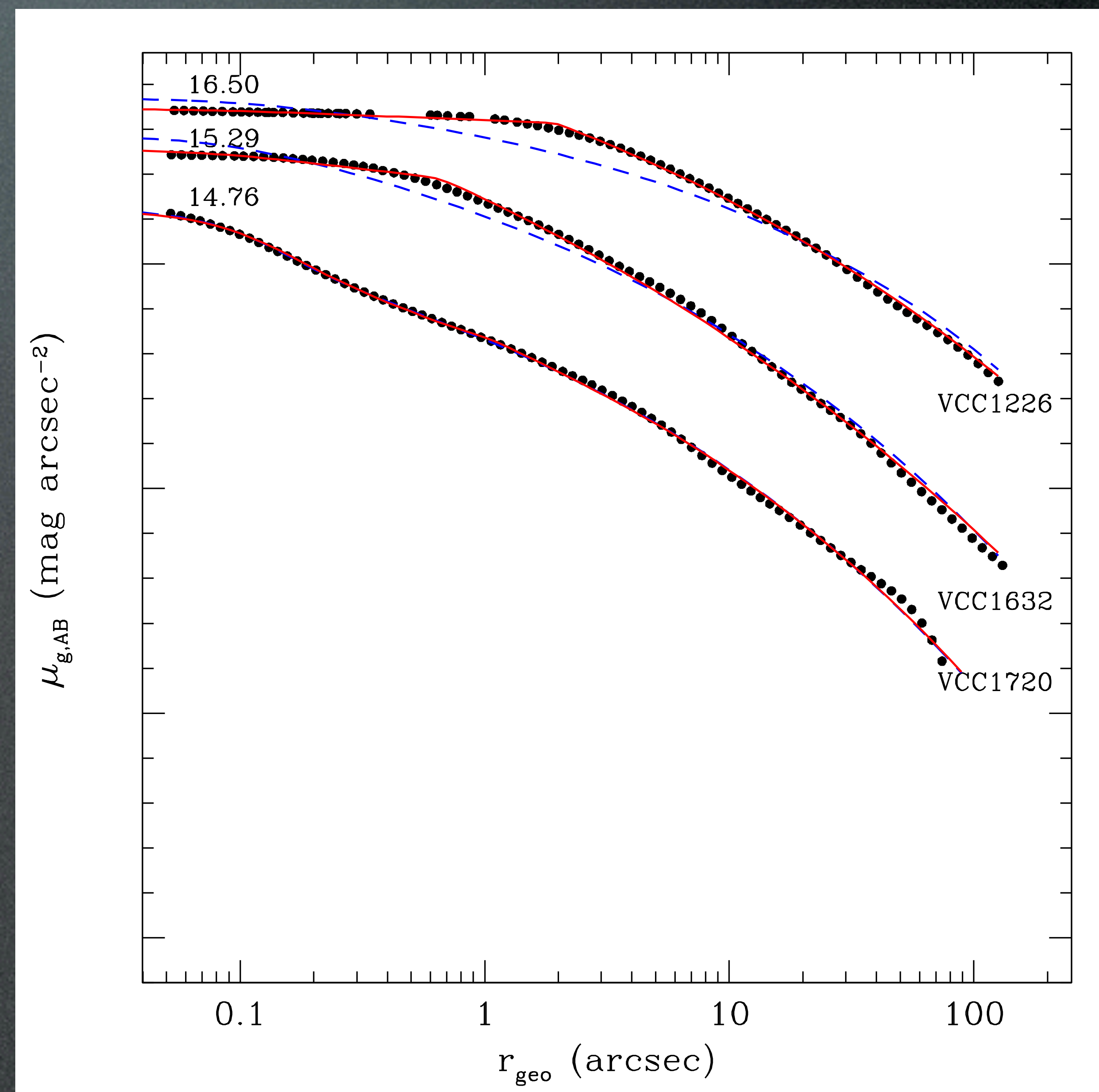


Omega Cen, 30X30 arcsec
(Andersen & van der Marel 2010)

Beyond the Sphere of Influence: BH Host Galaxies

- HST made it possible to study the central structural parameters of nearby galaxies in unprecedented detail (e.g., Crane et al. 1993; Ferrarese et al. 1994; Lauer et al. 1995, 2005; Phillips et al. 1996; Carollo et al. 1997, 1998; Matthews et al. 1999; Rest et al. 2001; Ravindranath et al. 2001; Ferrarese et al. 2006ab; Cote et al. 2006, 2007).





Ferrarese et al. 2006

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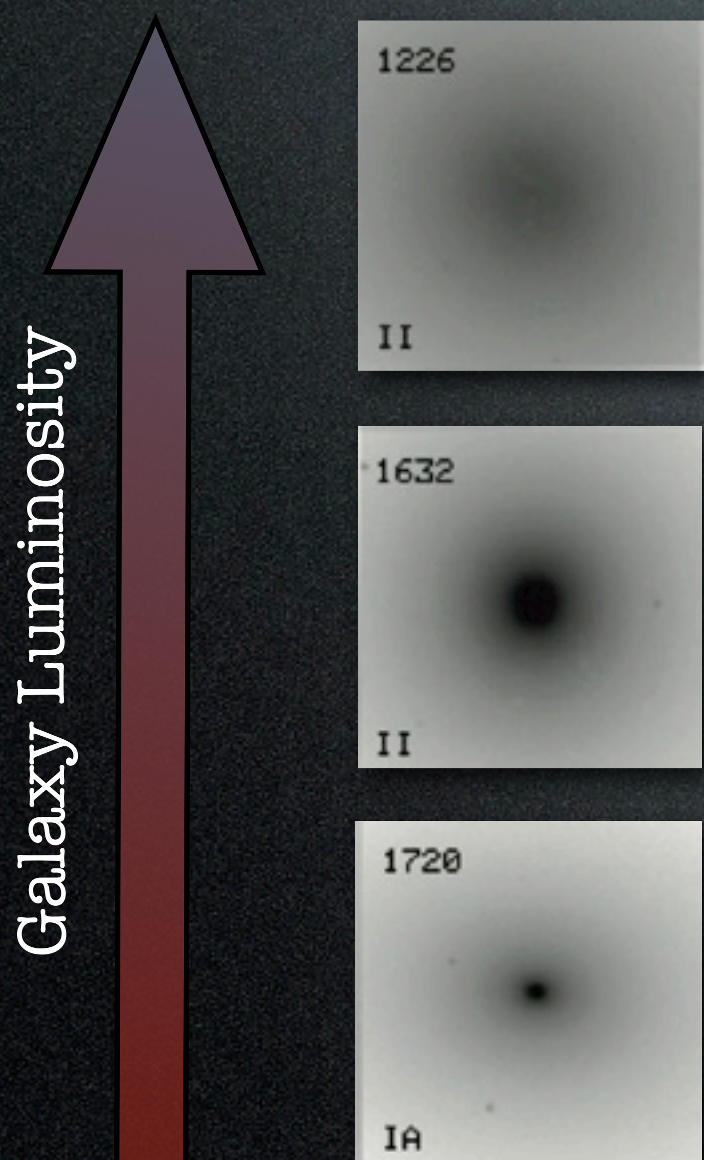
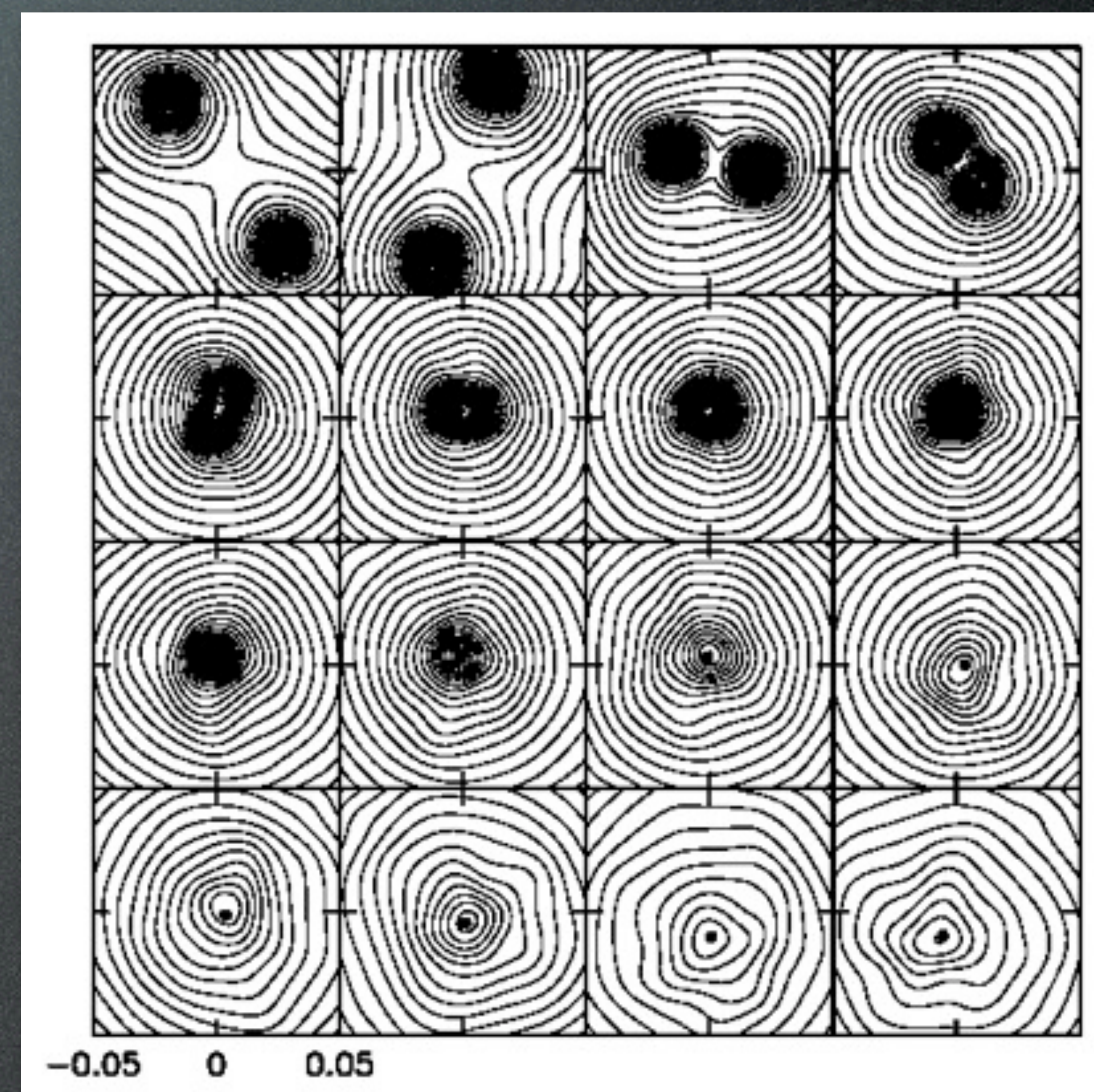


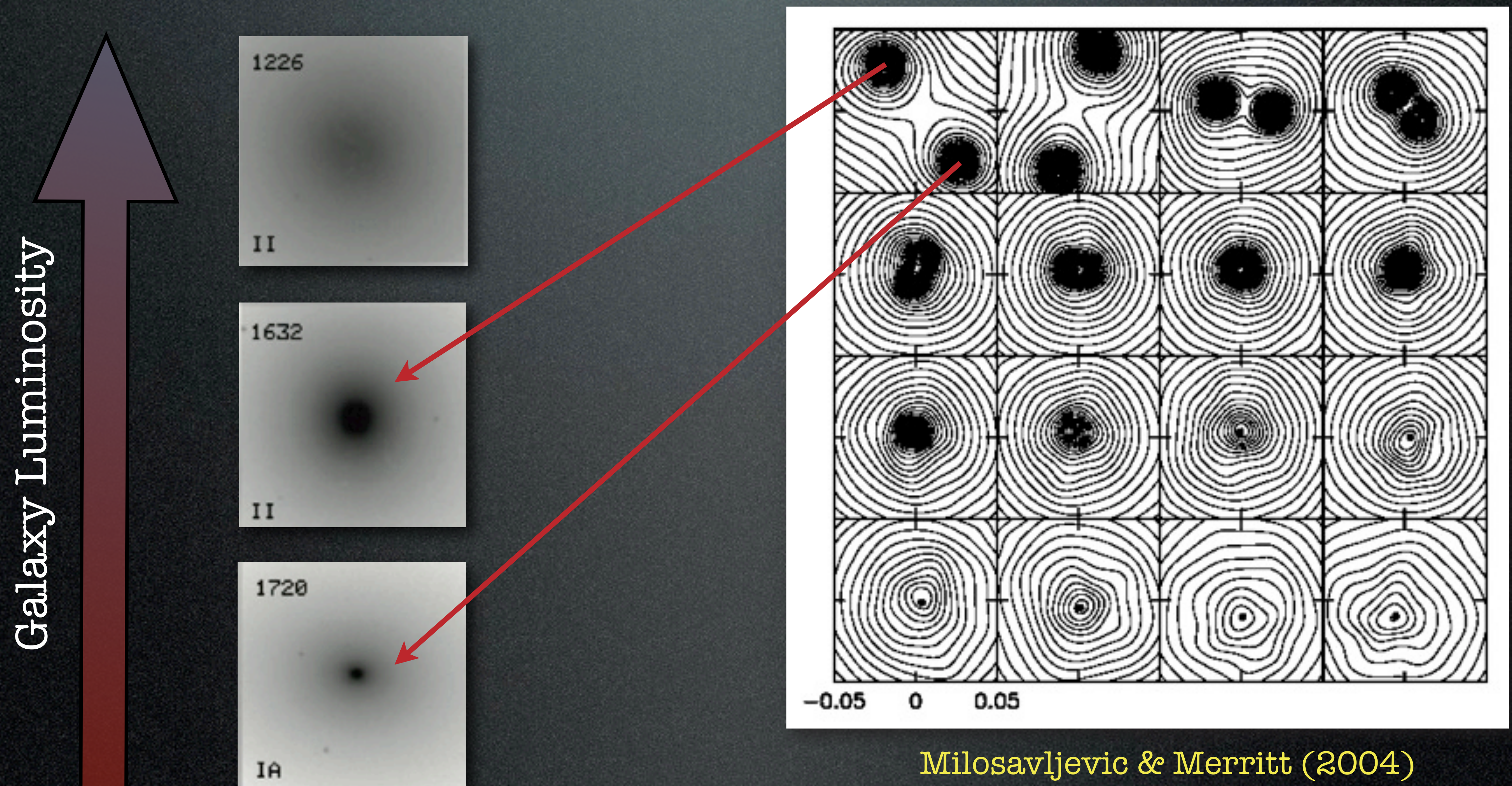
Ferrarese et al. 2006



Milosavljevic & Merritt (2004)

Beyond the Sphere of Influence: BH Host Galaxies

- HST made it possible to study the central structural parameters of nearby galaxies in unprecedented detail (e.g., Crane et al. 1993; Ferrarese et al. 1994; Lauer et al. 1995, 2005; Phillips et al. 1996; Carollo et al. 1997, 1998; Matthews et al. 1999; Rest et al. 2001; Ravindranath et al. 2001; Ferrarese et al. 2006ab; Cote et al. 2006, 2007).



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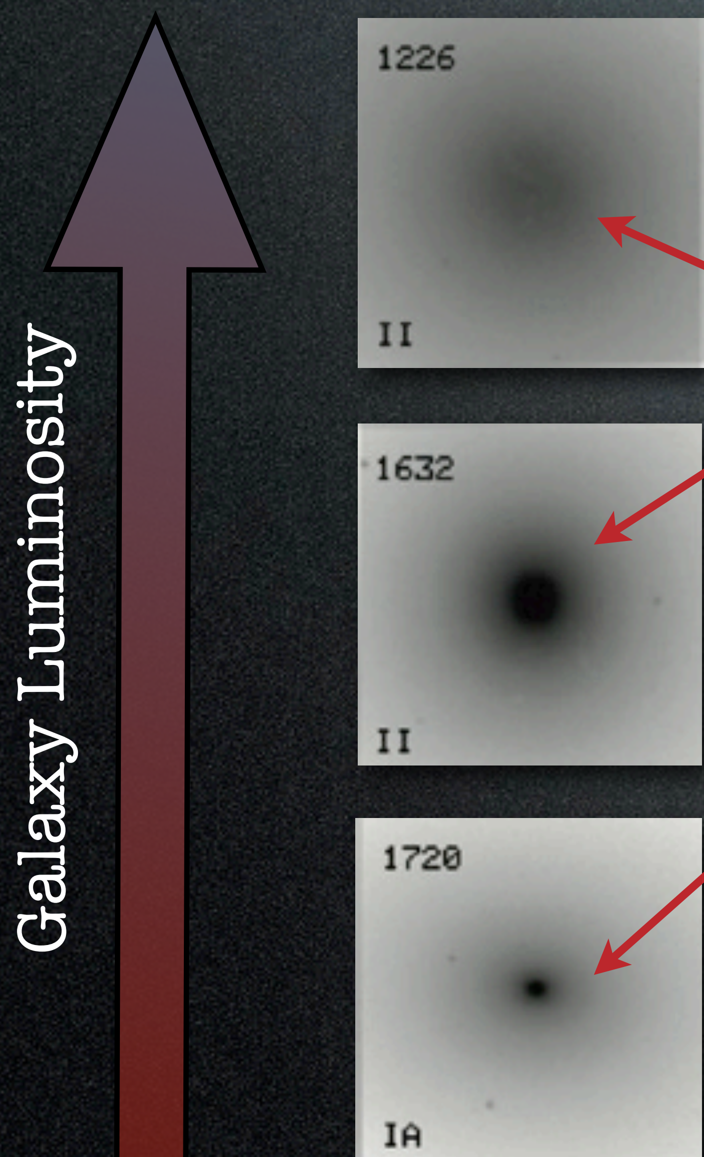

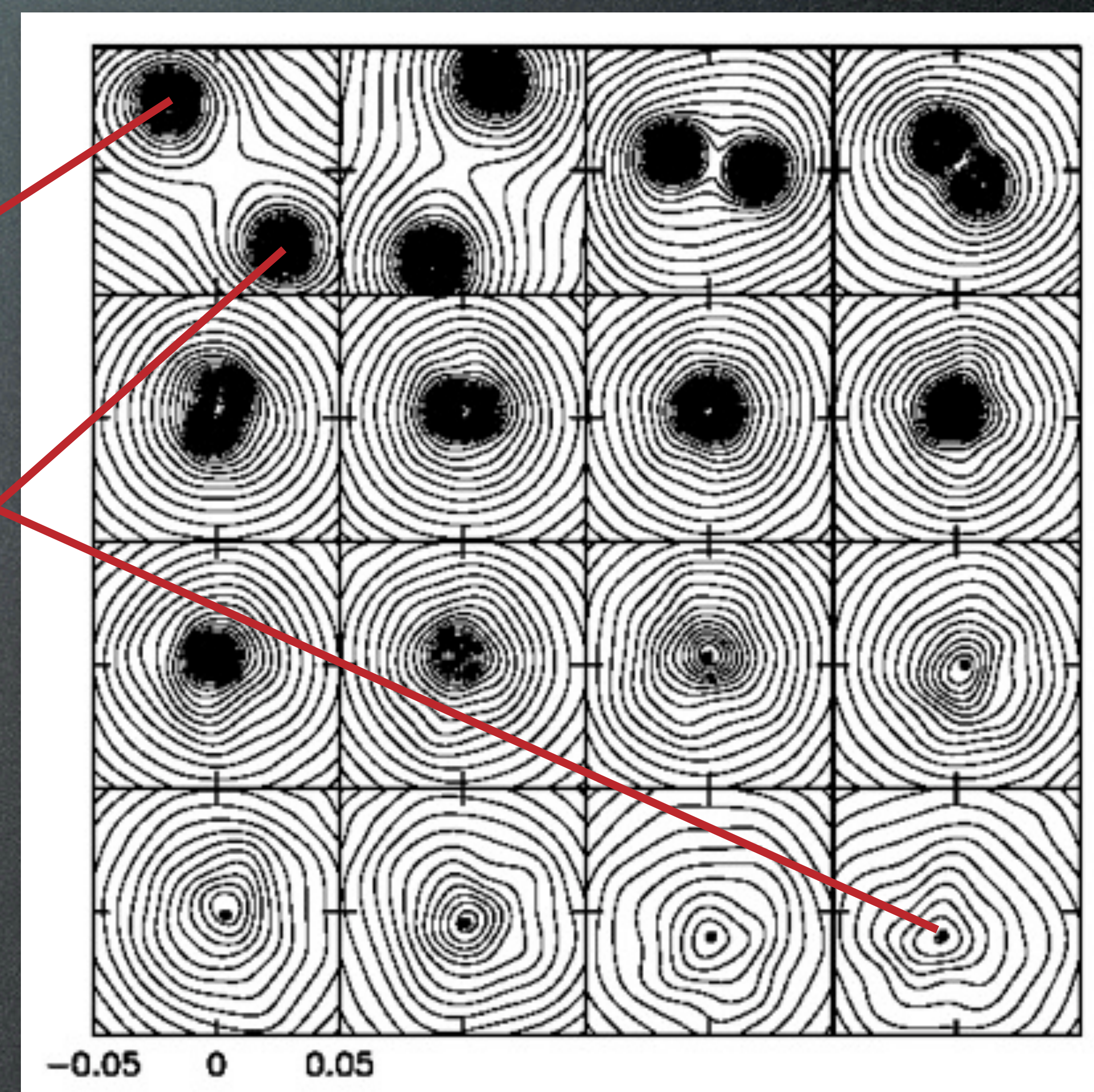

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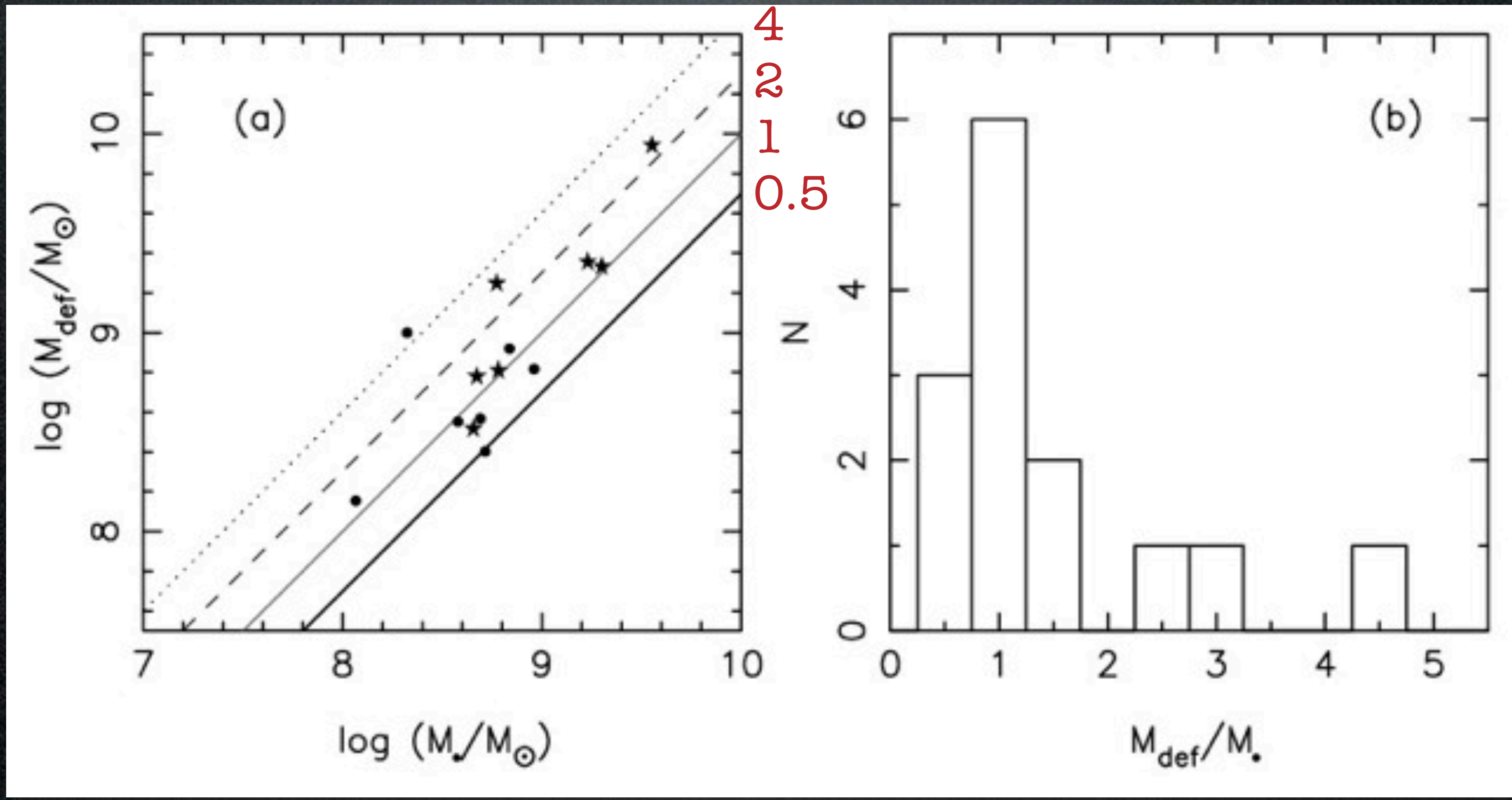
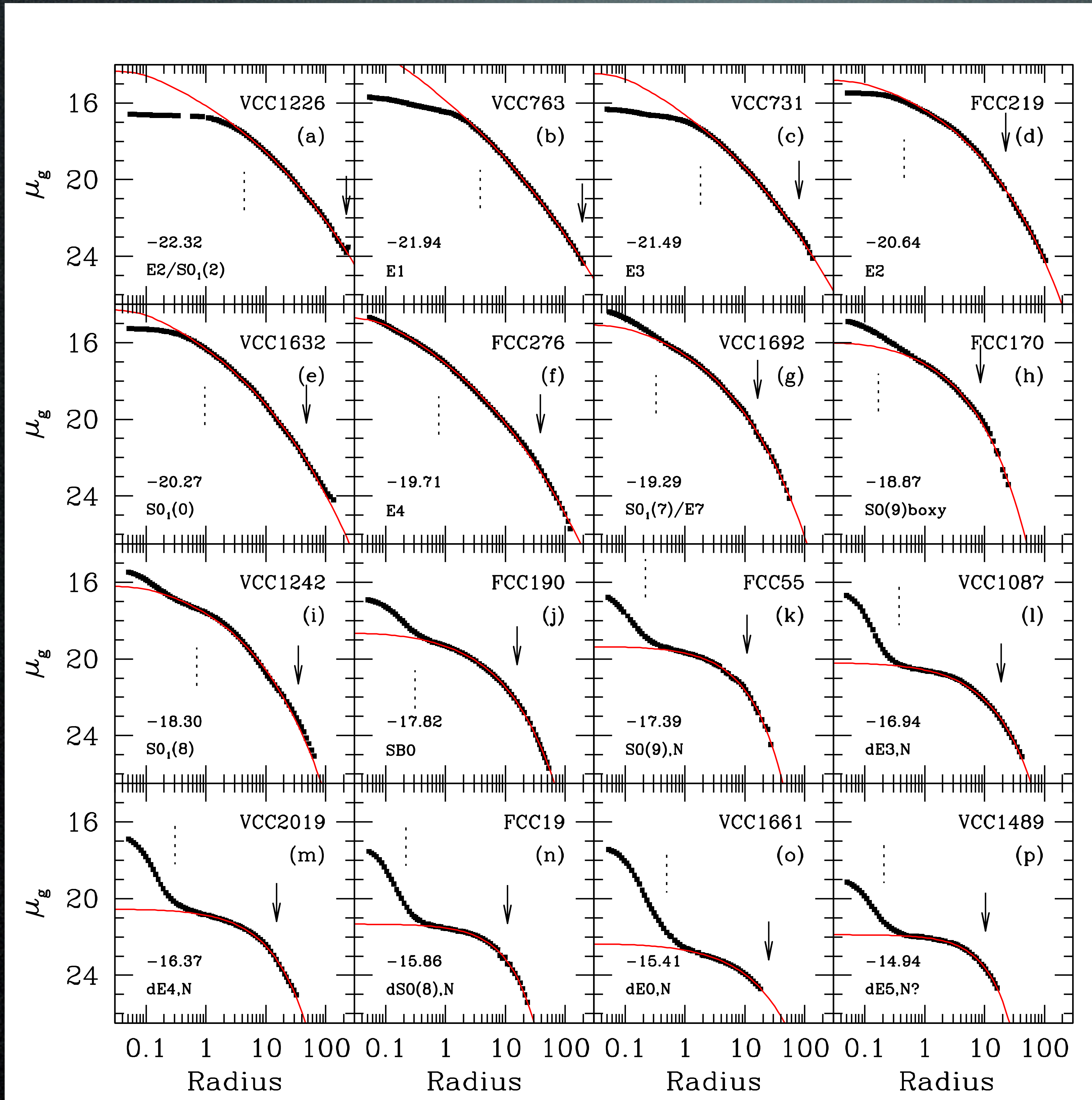
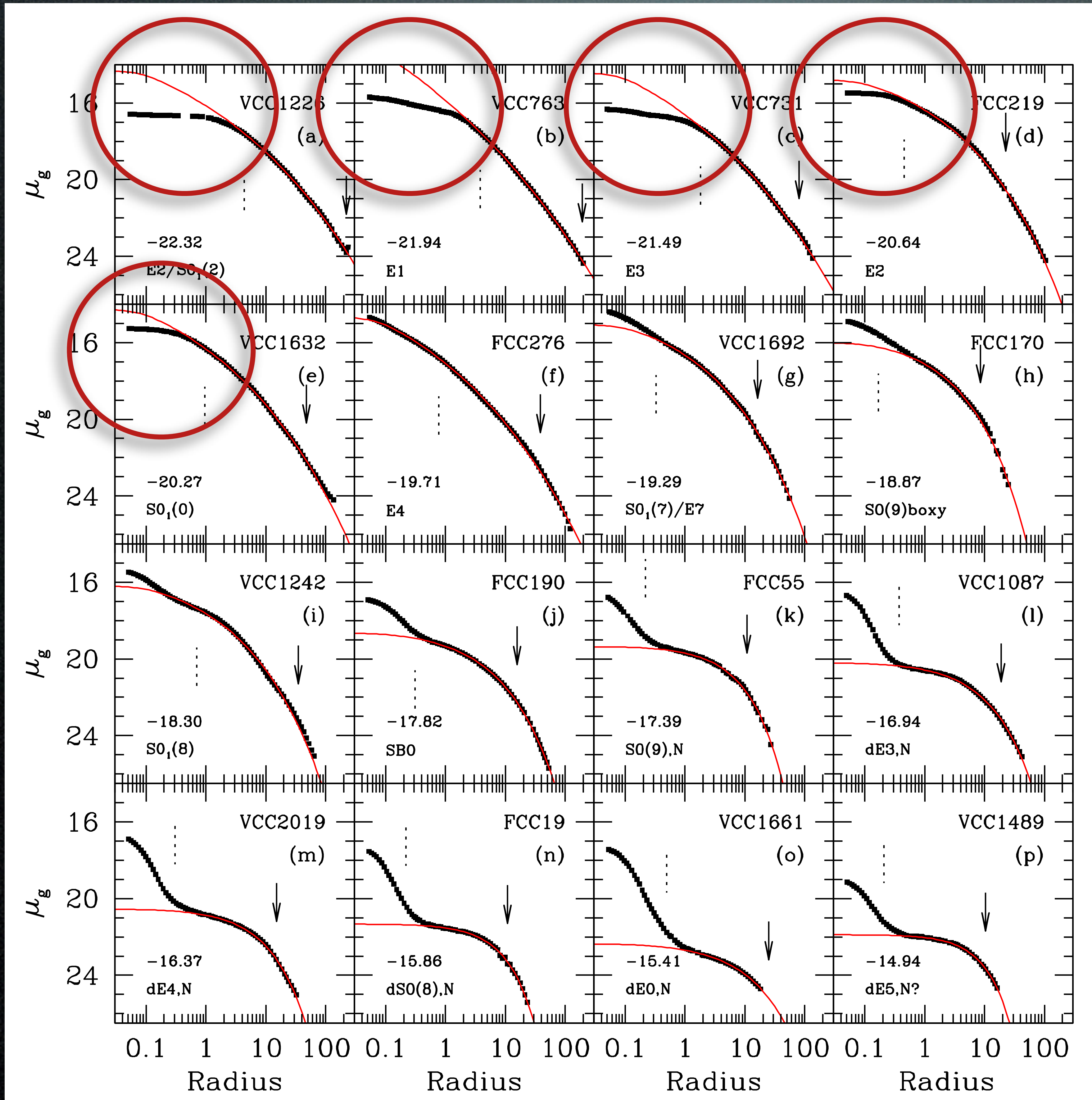
- Magnitude of the deficit is related to the galaxy merger history (e.g.: Milosavljevic et al. 2002; Graham 2004; Ferrarese et al. 2006; Merritt 2006; Kormendy & Bender 2009; Hopkins & Hernquist 2010)
- $\mathscr{M}$(deficit) ~ 0.5 $\mathscr{M}$(BH binary) (Merritt 2006)





Ferrarese et al. (2006a,b); Côté et al. (2006,2007) [confirmed by Kormendy et al. 2009]



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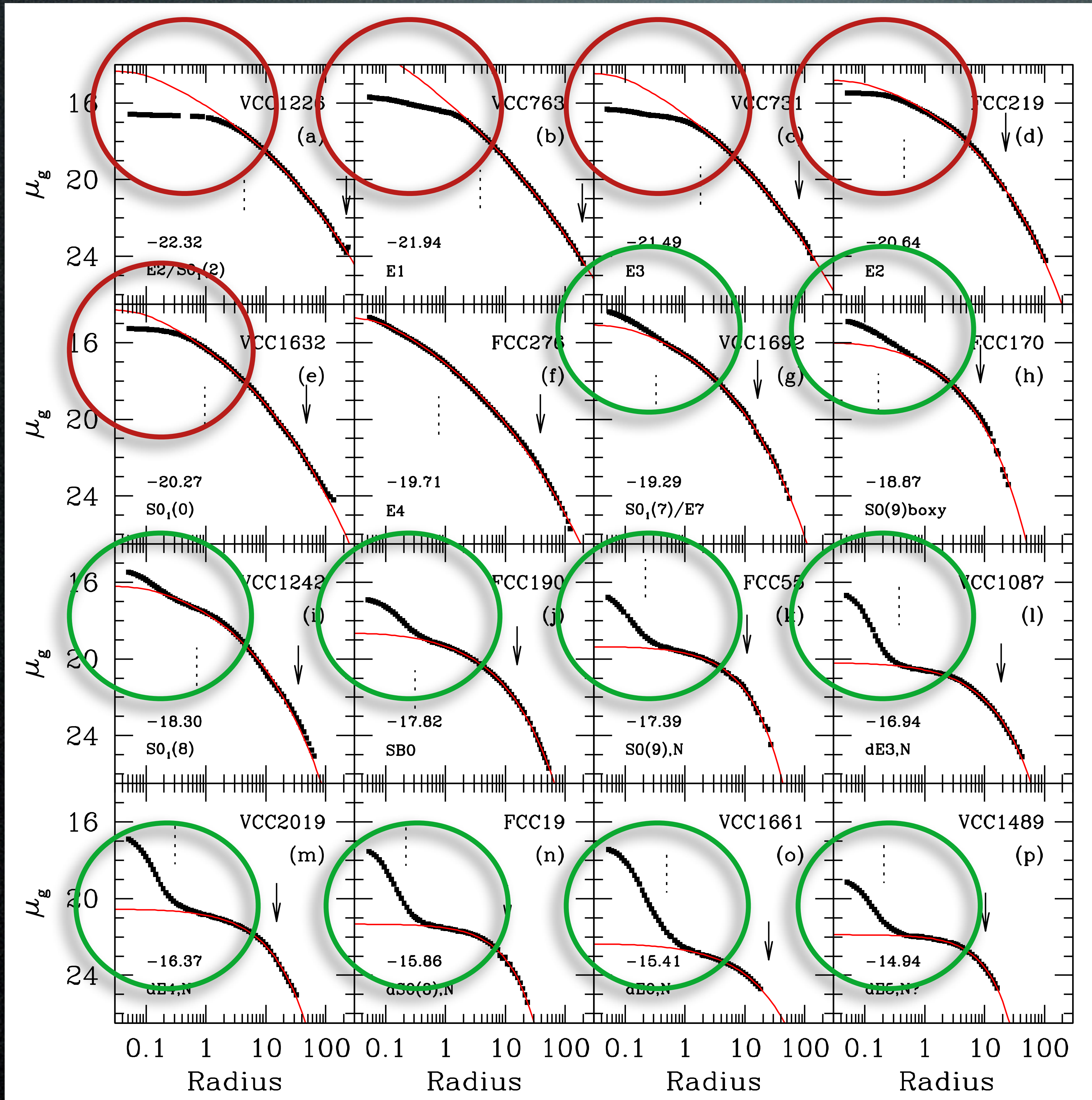

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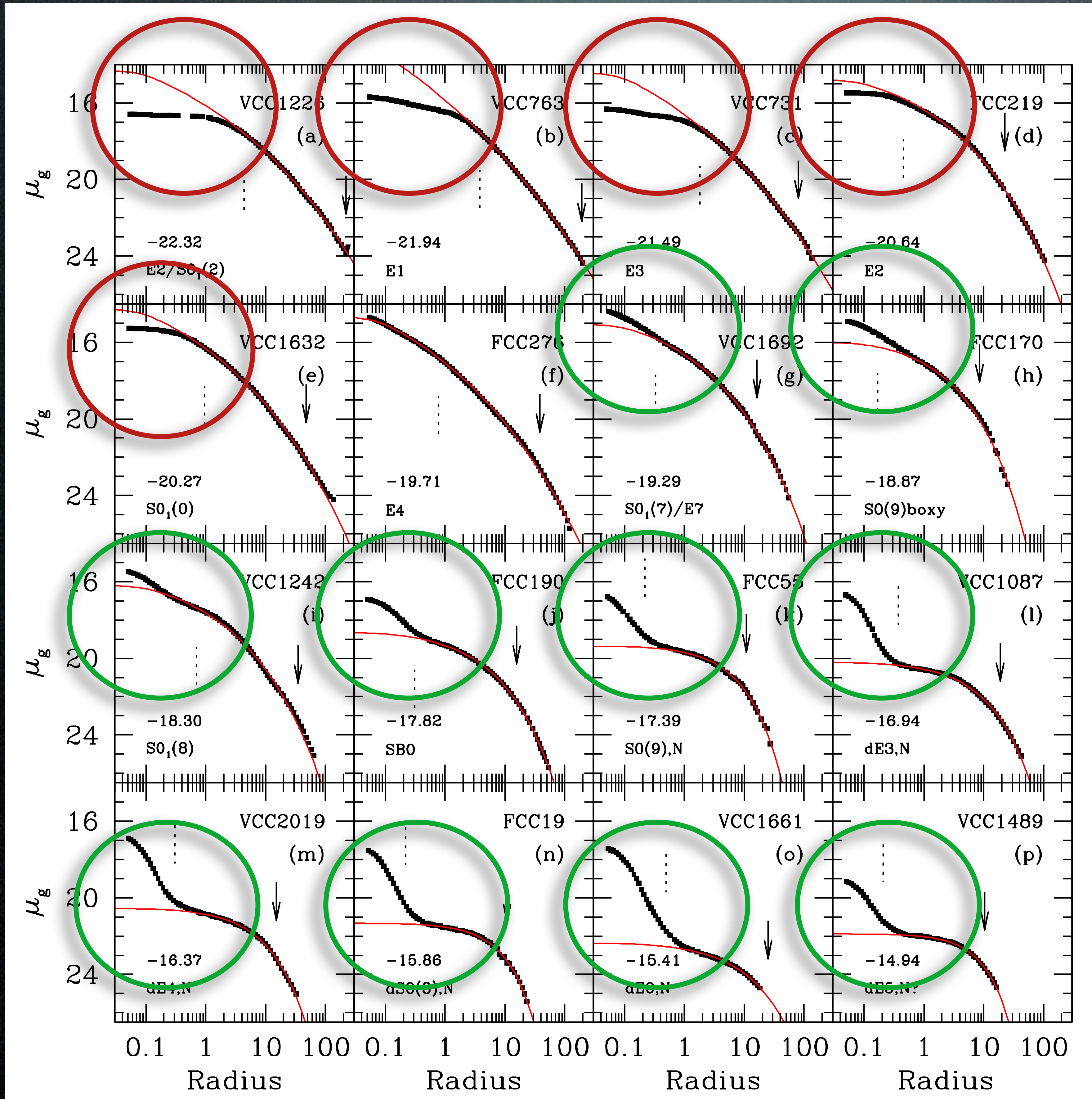
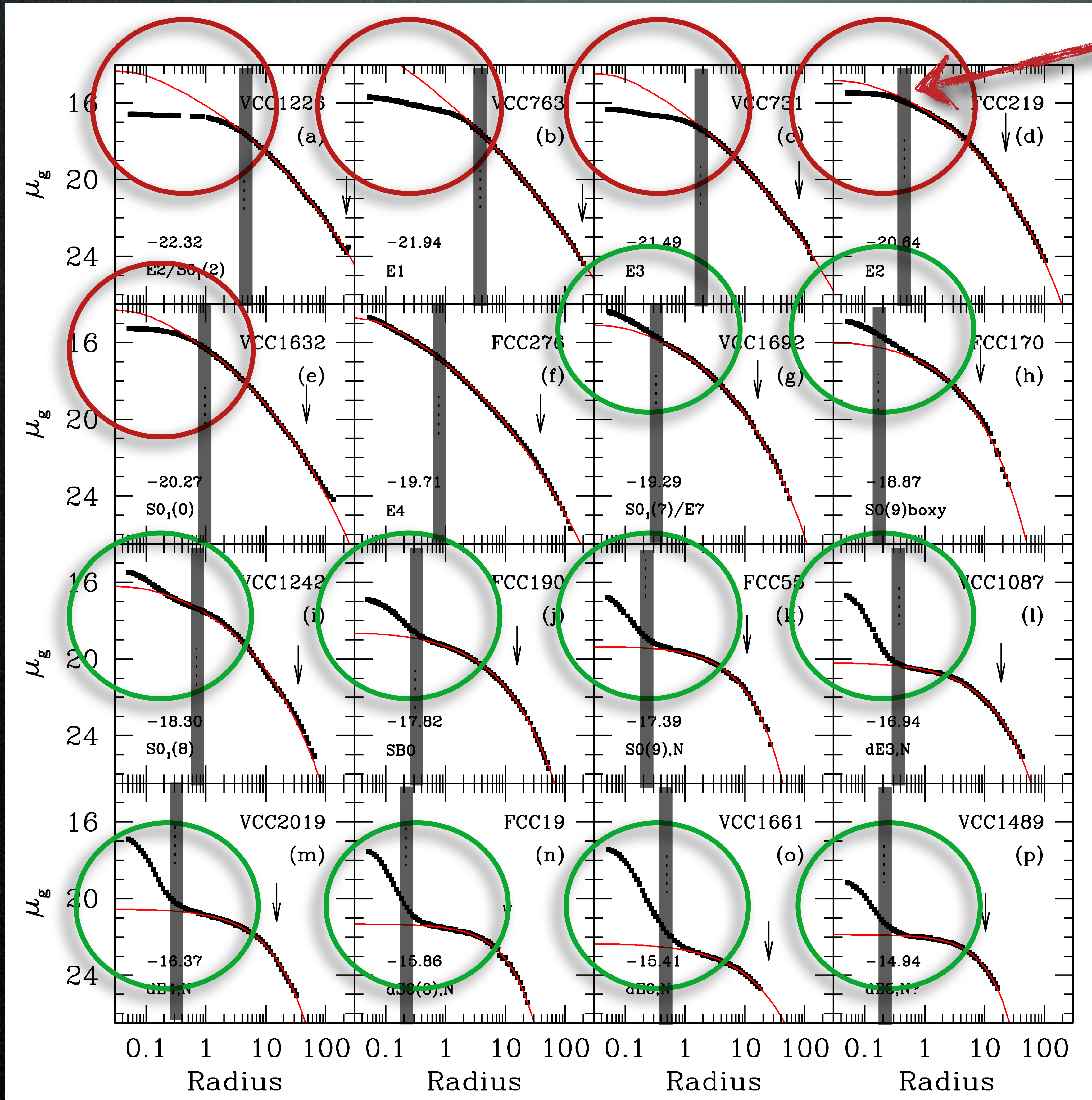


Luminosity "Deficit"

Transition from Central **Luminosity Deficit** to **Excess:** M(B) ≈ -20 mag

Luminosity "Excess" (aka Nucleus)

Ferrarese et al. (2006a,b); Côté et al. (2006,2007) [confirmed by Kormendy et al. 2009]



2%Re

Luminosity "Deficit"

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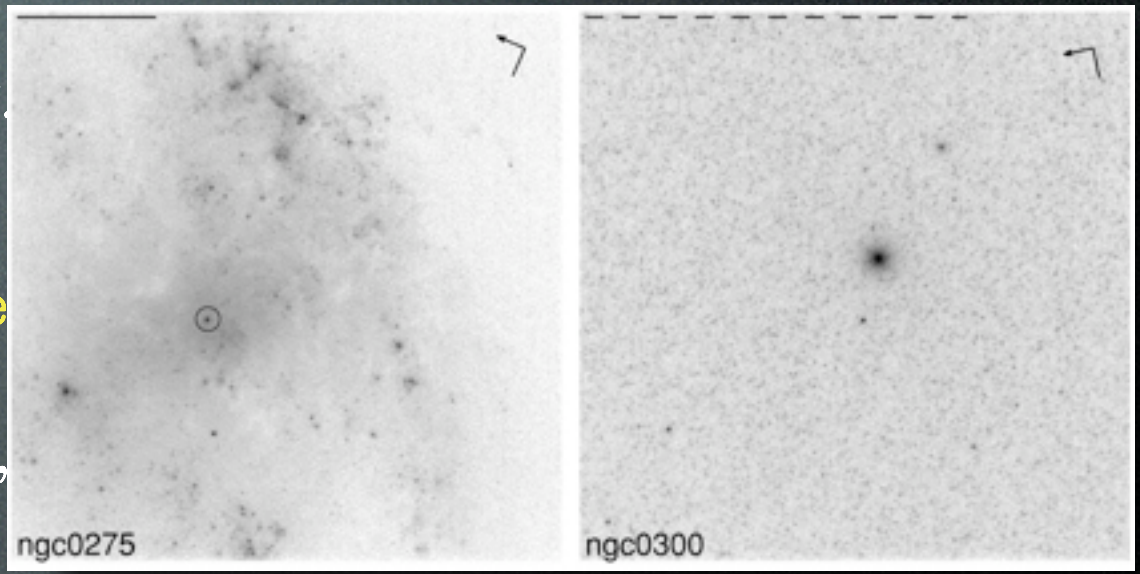
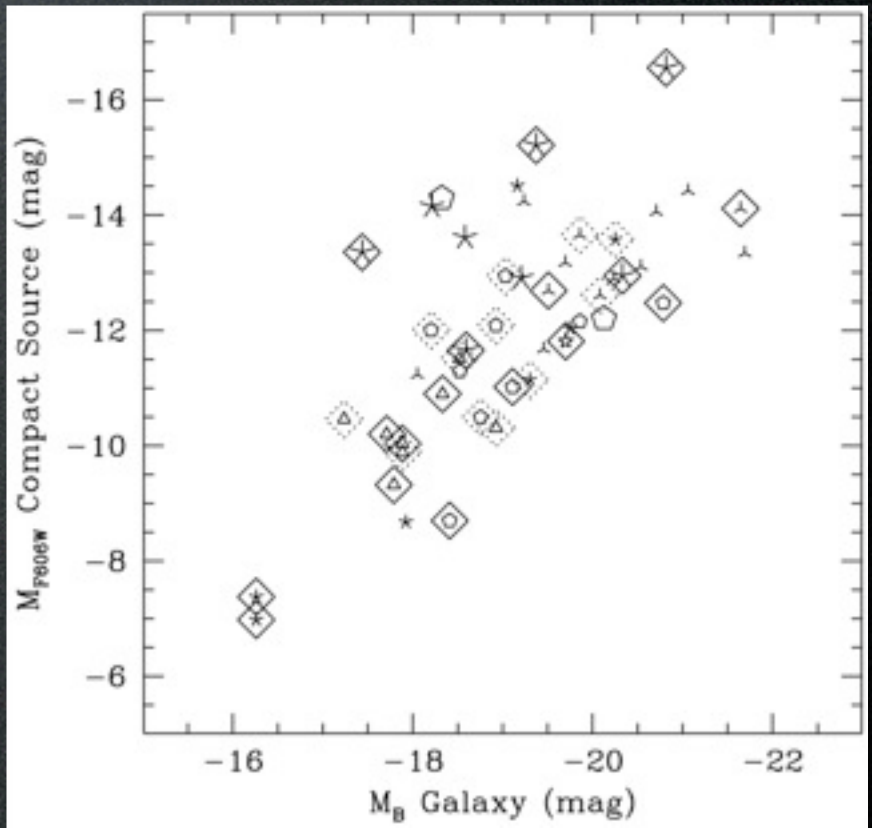
Ferrarese et al. (2006a,b); Côté et al. (2006,2007) [confirmed by Kormendy et al. 2009]

Luminosity Excesses: Compact Stellar Nuclei

- Detected in galaxies ranging from E to Sm.
- Overall frequency of nucleation: 50-80%, with (possibly) a weak dependence on Hubble type (e.g. Phillips et al. 1996; Carollo et al. 1997, 1998; Matthews et al. 1999; Cote, LF et al. 2006; Seth et al. 2006, 2010; Baarth et al. 2009; Munoz-Marin e al. 2010)
- $-14 \leq M_I \leq -10$ mag. ; more luminous then “typical globular clusters.
- Typical sizes: R_e ~ 2–5 pc, with apparently no strong dependence on Hubble Type. Marginally resolved with HST.
- Luminosity and sizes of nuclei found to correlate with host luminosity (in both late- and early-types).
- Spectroscopy (HST/STIS, VLT) in late type galaxies indicates masses of ~ 10^6–10^7 solar masses (well above the mean mass of globular clusters, ~$10^{5.4}$ solar masses) and multiple episodes of star formation with mean ages showing a weak correlation with Hubble type (Sarzi et al. 2005, Seth et al. 2006, Rossa et al. 2006)

Böker et al. (2002)





Carollo et al. (1998)

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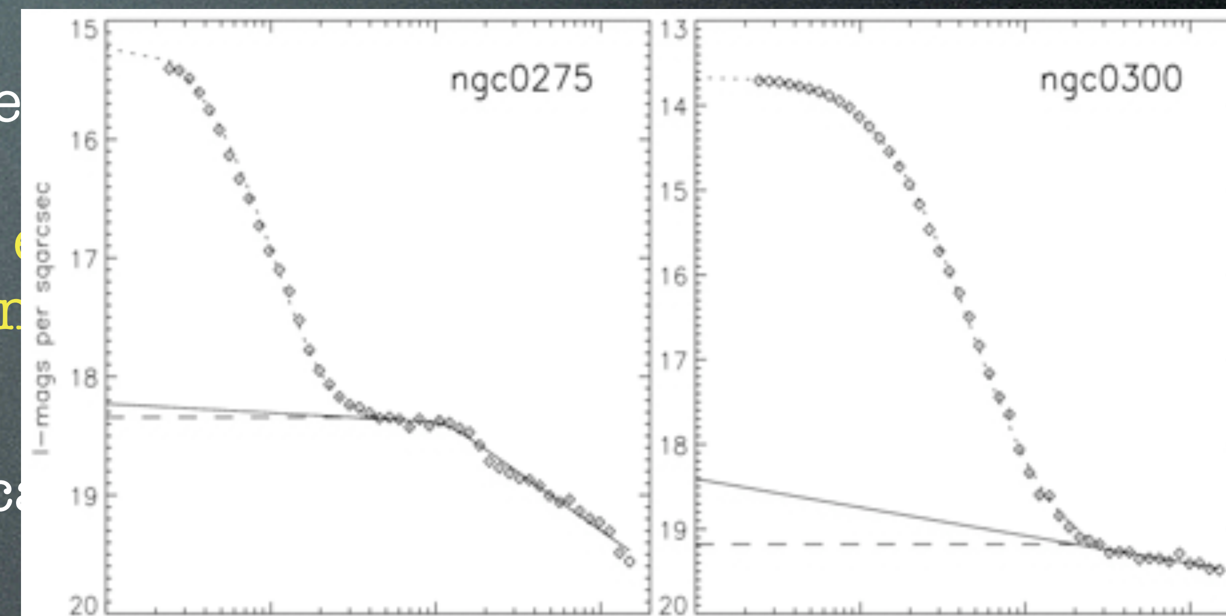
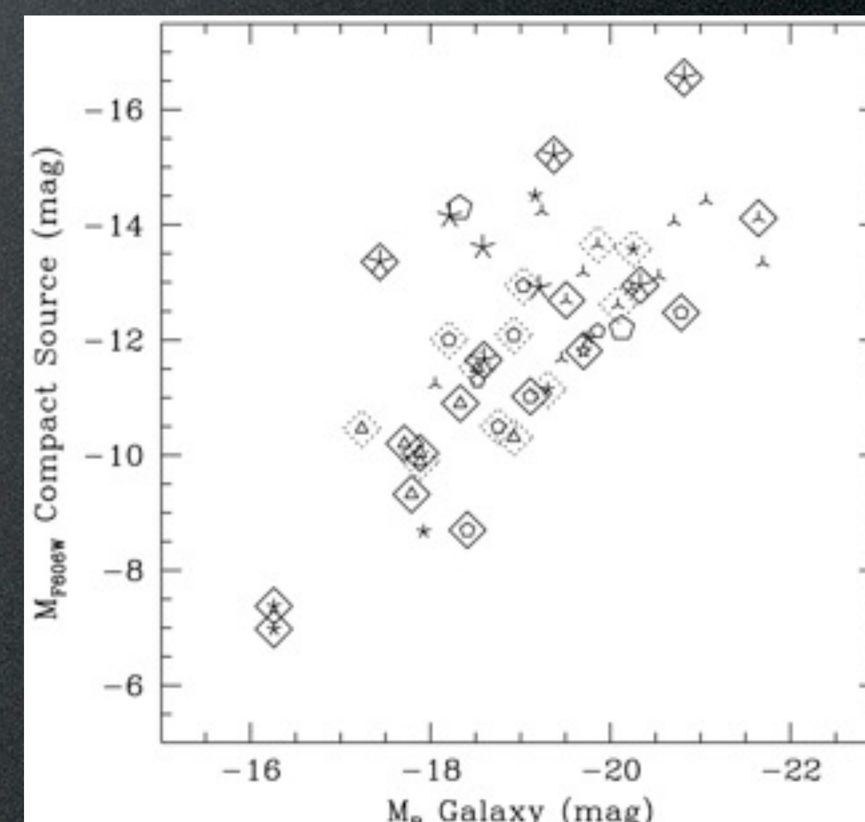




Carollo et al. (1998)

From Mass Deficit to Excess

Ferrarese et al. 2006b

M60

M(B) = -21.4

Deficit $\simeq 2.2 \times 10^9 \mathcal{M}_\odot$

$\mathcal{M}(\mathrm{SBH}) = (2 \pm 0.5) 10^9 \mathcal{M}_\odot$

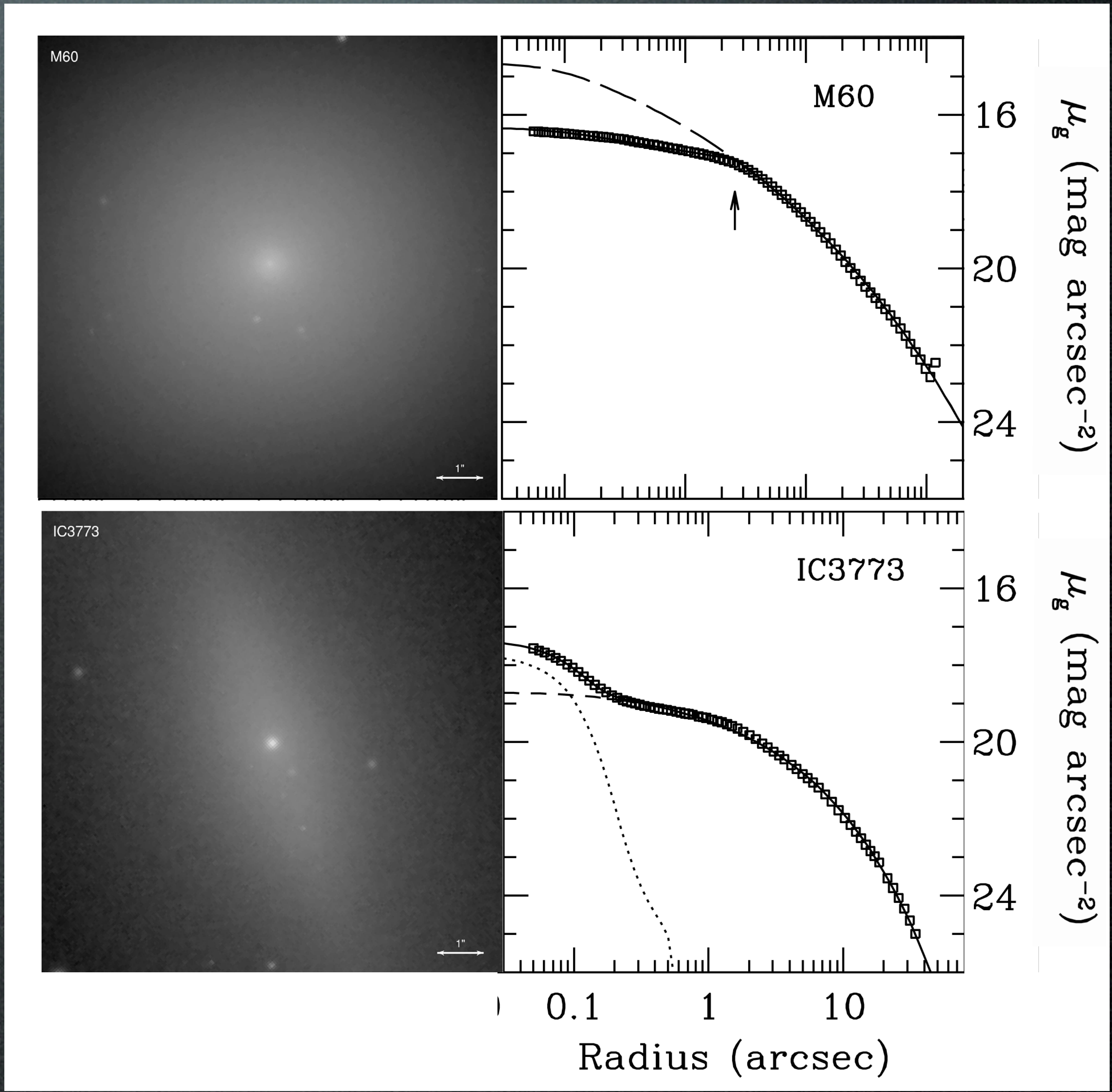
(Gebhardt et al. 2003)

IC3773

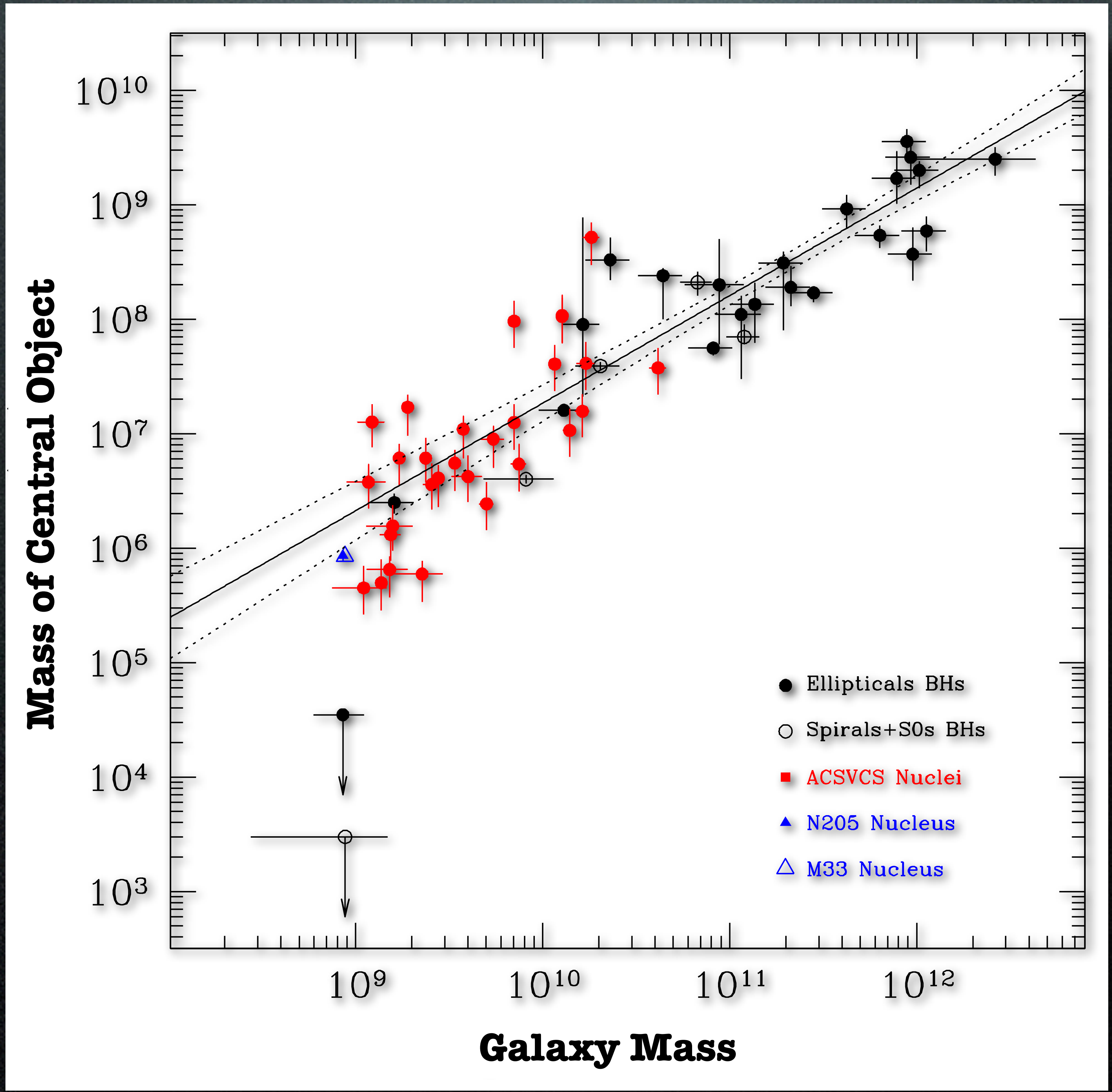
M(B) = -17.3

$\mathcal{M}(\mathrm{nuc}) \simeq (1.3 \pm 0.5) 10^6 \mathcal{M}_\odot$

(Côté et al. 2006)



$\mathscr{M}_{\text{CMO}}/\mathscr{M}_{\text{Galaxy}} = 0.17\%\ (0.06\% - 0.50\%)$



Early-type galaxies; Ferrarese et al. 2006b

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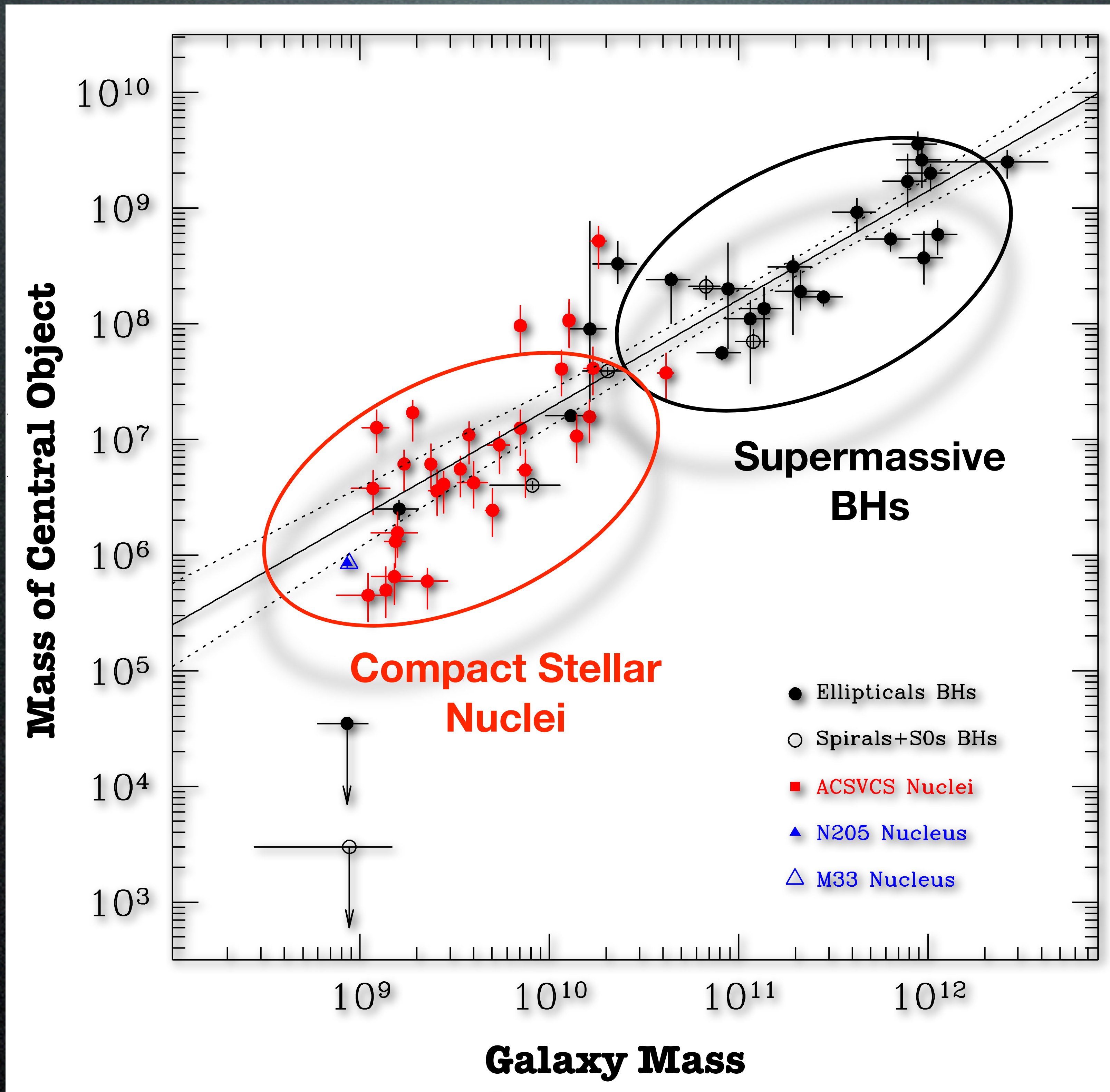

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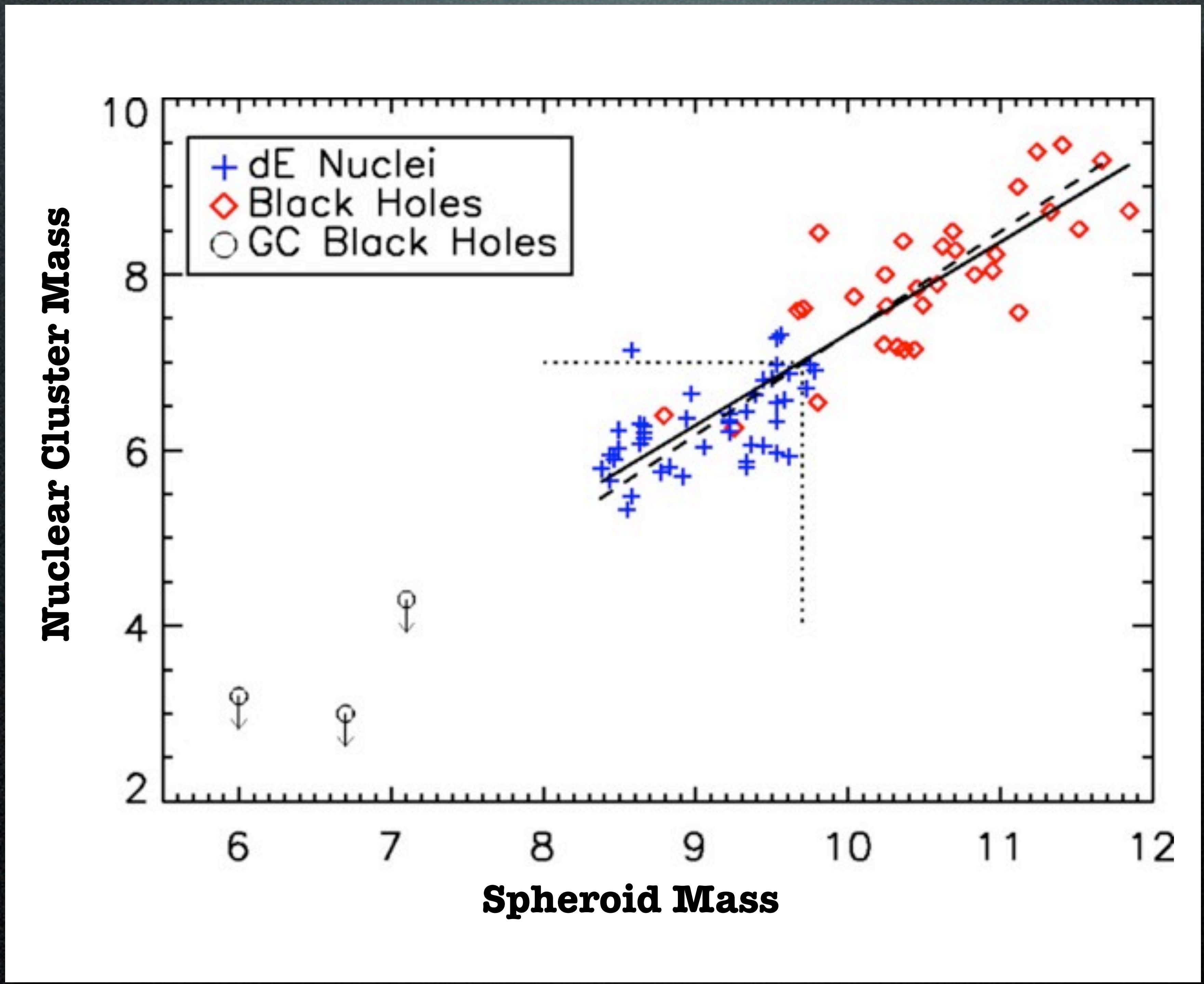
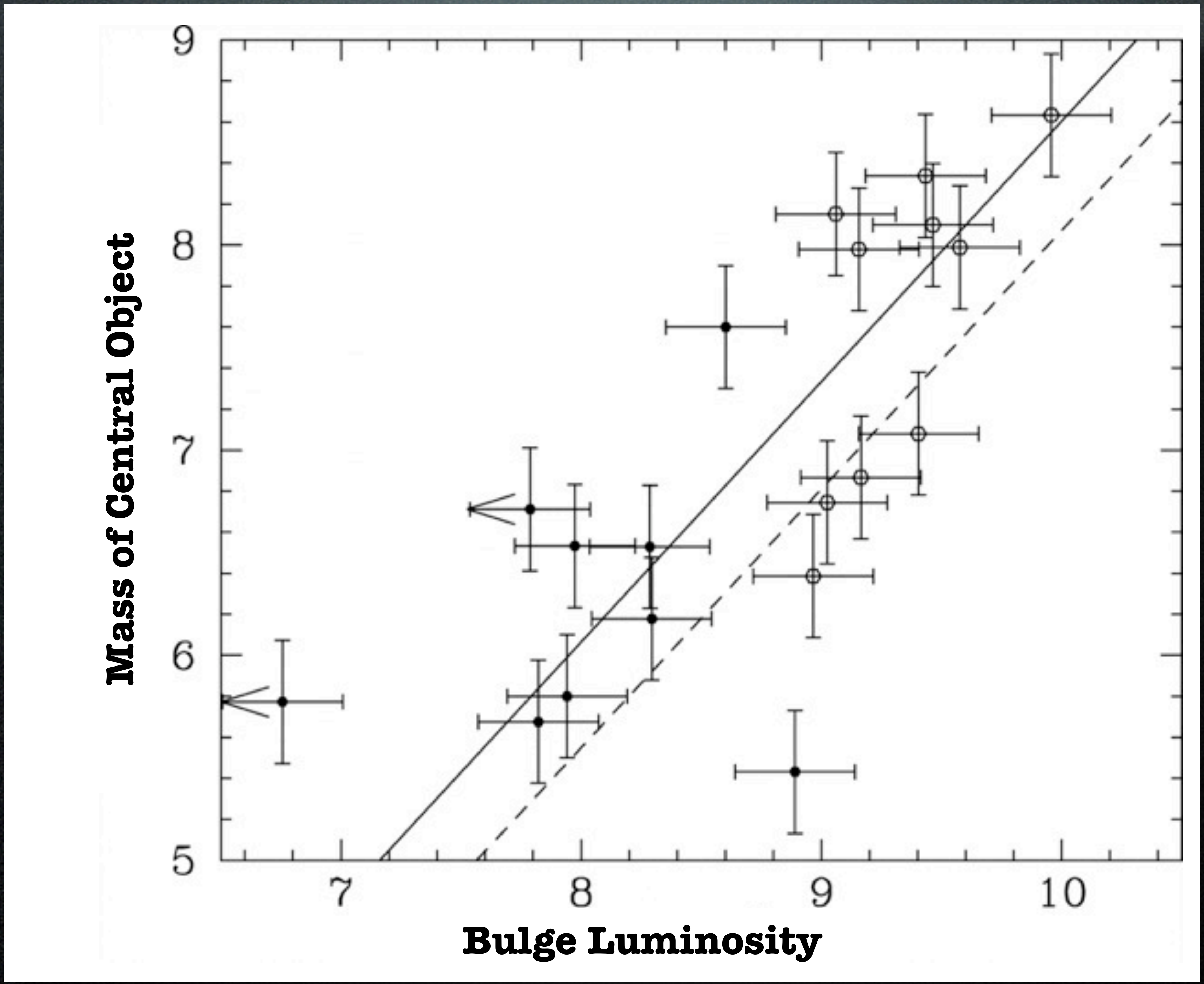


Early-Type Dwarfs (Wehner & Harris 2006)

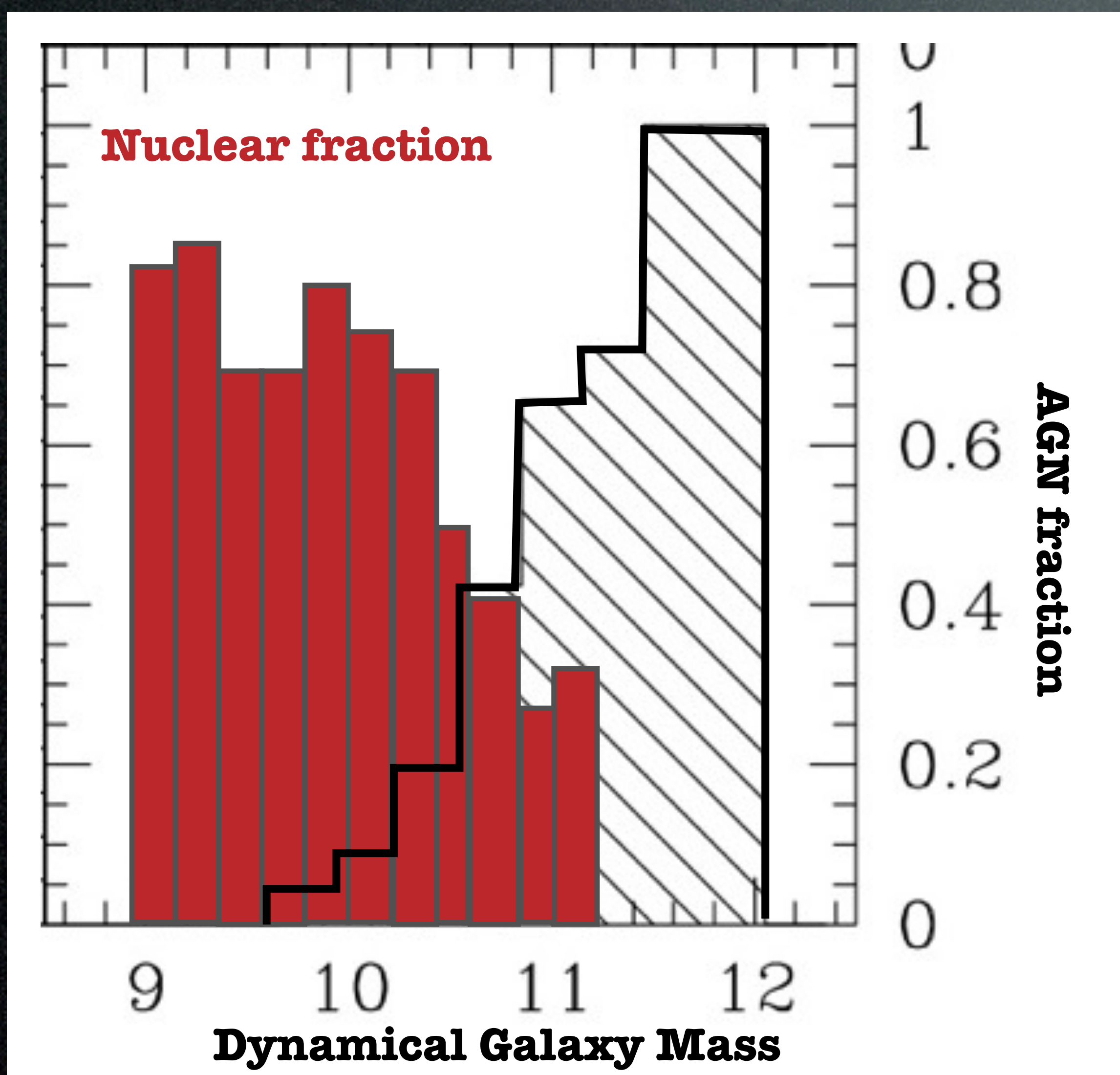
$\mathscr{M}_{\text{CMO}} / \mathscr{M}_{\text{Galaxy}} = 0.17\% \ (0.06\% - 0.50\%)$



Late Type Spirals (Rossa et al. 2006)

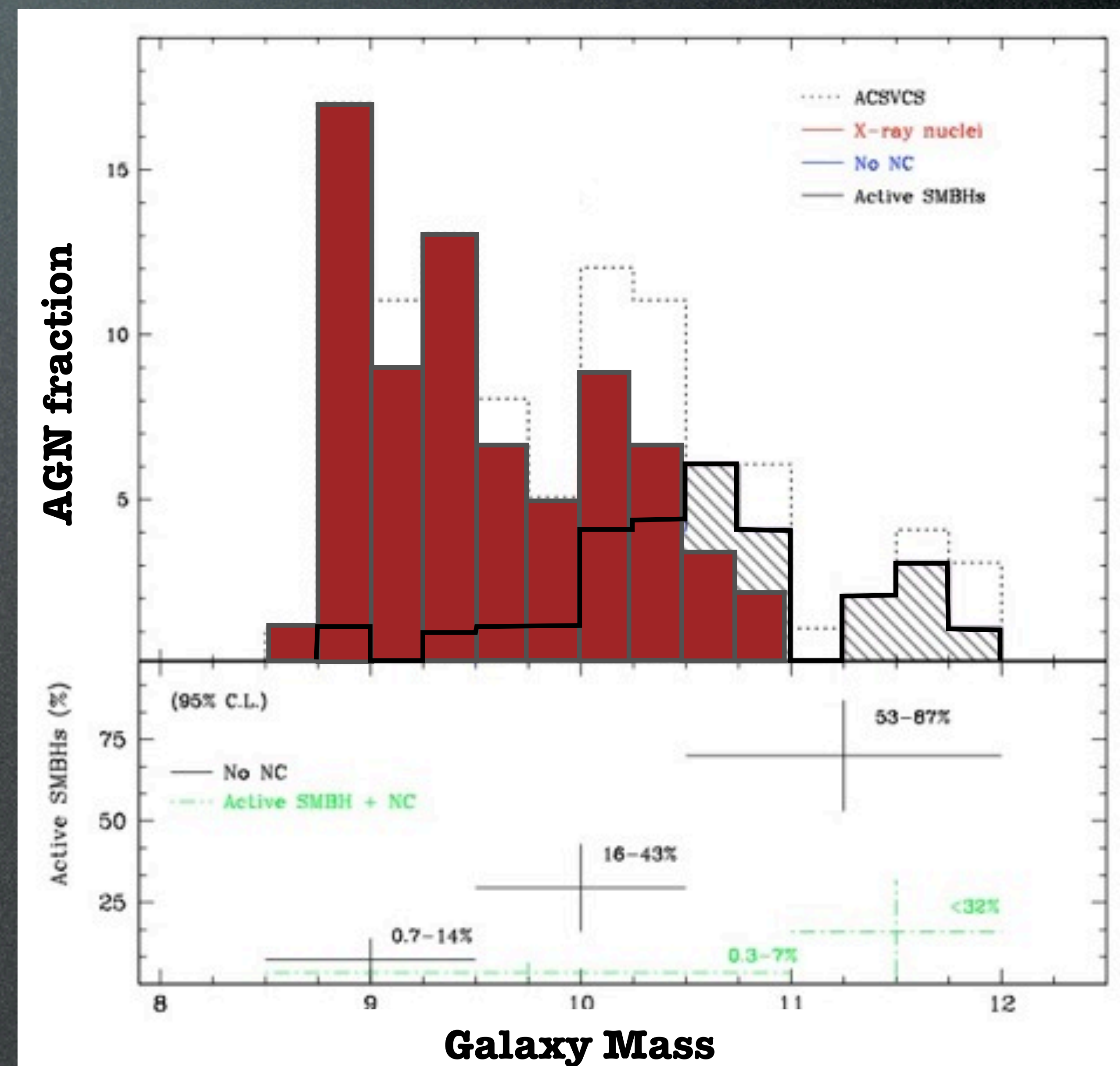
Nuclei **and** Supermassive Black Holes?

- Spectroscopic census of a nearly complete sample of 213 Virgo late-type galaxies with $M > 10^{8.5}\ M_{\odot}$.
- "It is found that AGNs are hosted exclusively in massive galaxies: i.e. $M_{dyn} \gtrsim 10^{10}\ M_{\odot}$."



Decarli et al. (2007)

- AMUSE-Virgo: Chandra observations of 100 ACSVCS Virgo early-type galaxies, to search for low-level SBHs ($L_X \gtrsim 4\times10^{38}$ erg s^{-1}).



Gallo et al. (2008, 2009)

SBHs and HST: What's Next?

- SBHs detections:
  - HST's resolution and light gathering ability have been exploited to their fullest; dwarf galaxies, brightest cluster galaxies, low surface brightness galaxies, late type spirals are still largely unexplored and beyond HST's capabilities. This will likely be the domain of the next generation of 30m AO-assisted ground-based telescopes.
  - Where HST can still help:
    - Proper motion studies in Galactic GCs (but are we running out of time?)
    - Dynamical studies targeting specific interesting galaxies (for instance to test different methods).
- Accretion history of SBHs:
  - HST still essential to study high-z host-galaxy morphology, nuclear/total/spheroid luminosity (van Dokkum & Brammer 2010; Bennert et al. 2010, merloni et al. 2010, Zheng et al. 2010; Jahanke et al. 2010; Georgakakis et al. 2010, Treu et al. 2007, Peng et al. 2006; Fiore et al. 2009)
- The Nuclear and Global Structure of Galaxies:
  - stellar nuclei are mostly unresolved from the ground; HST is needed to study stellar populations (at least in the brightest cases).