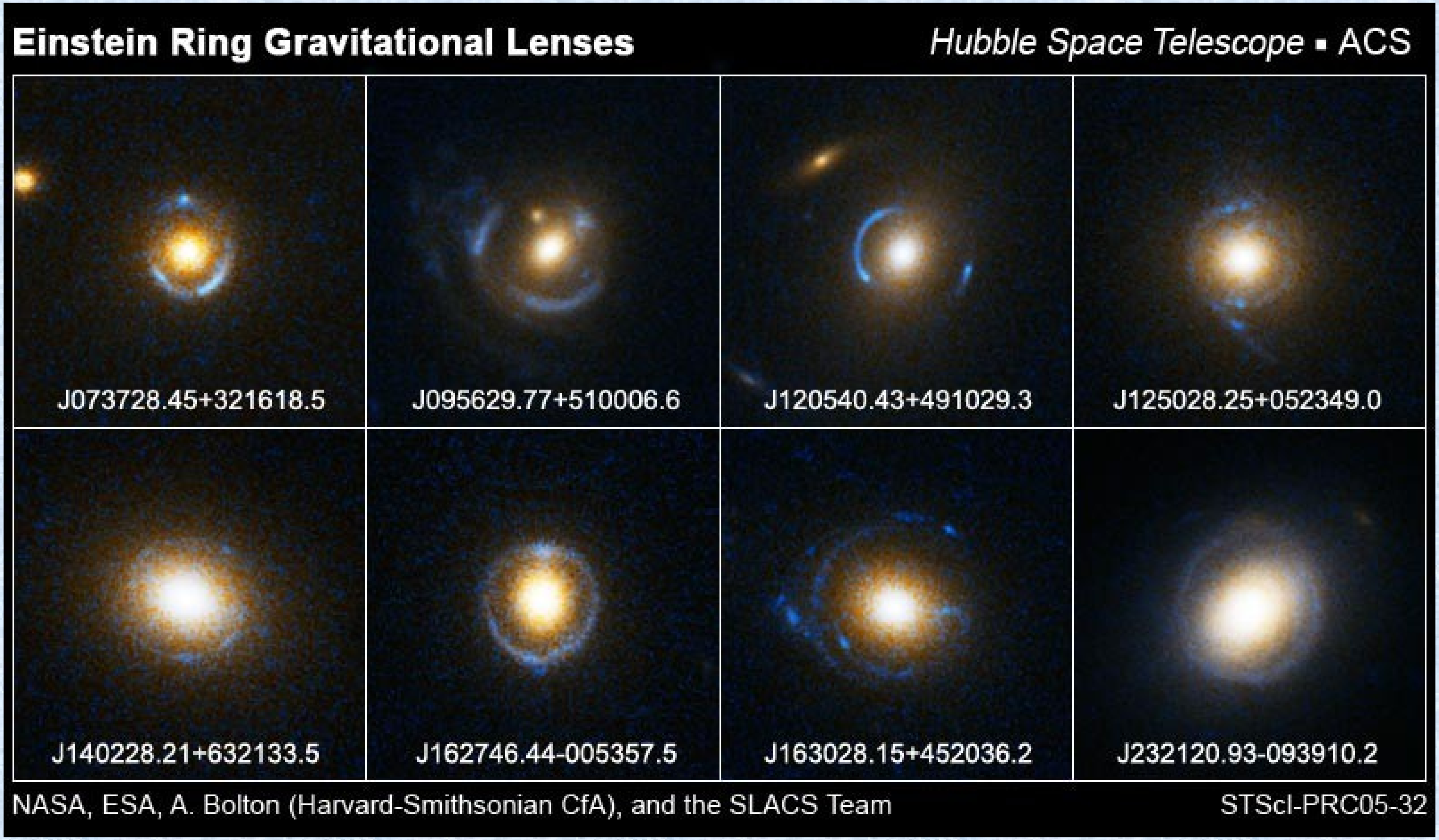
Dark Matter and Black holes over cosmic time



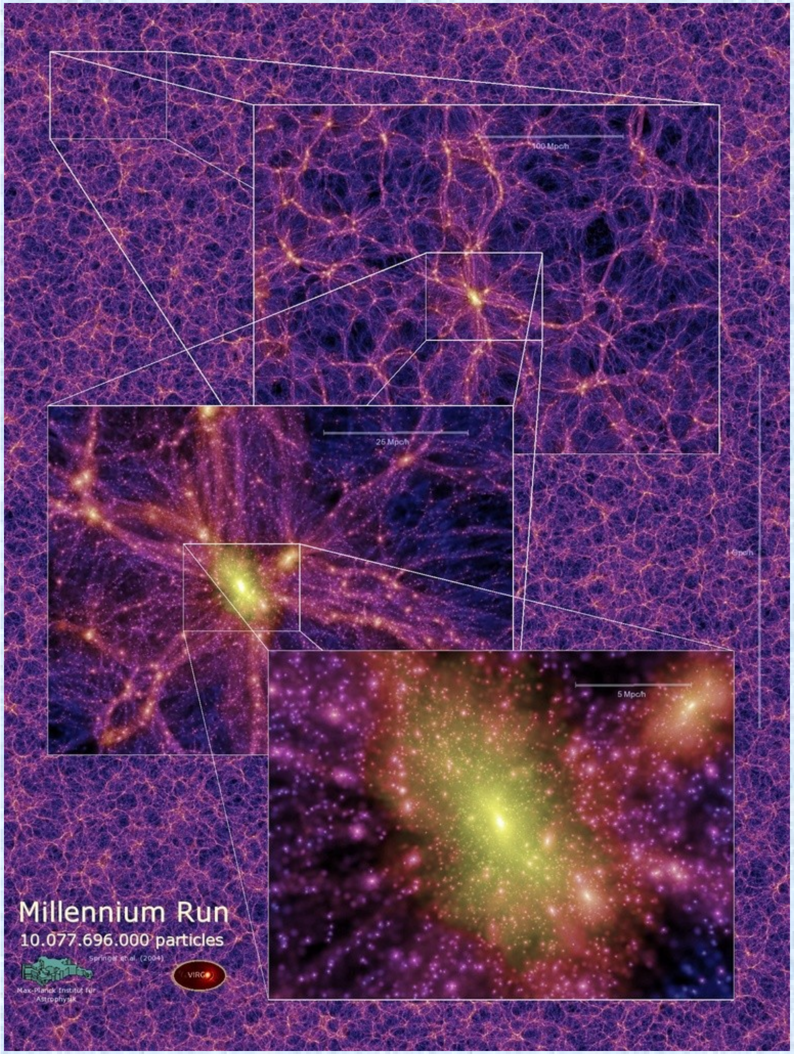
Tommaso Treu (UCSB)

Outline

- Introduction: modeling (early-type) galaxy formation
- Two observational goals at high-z:

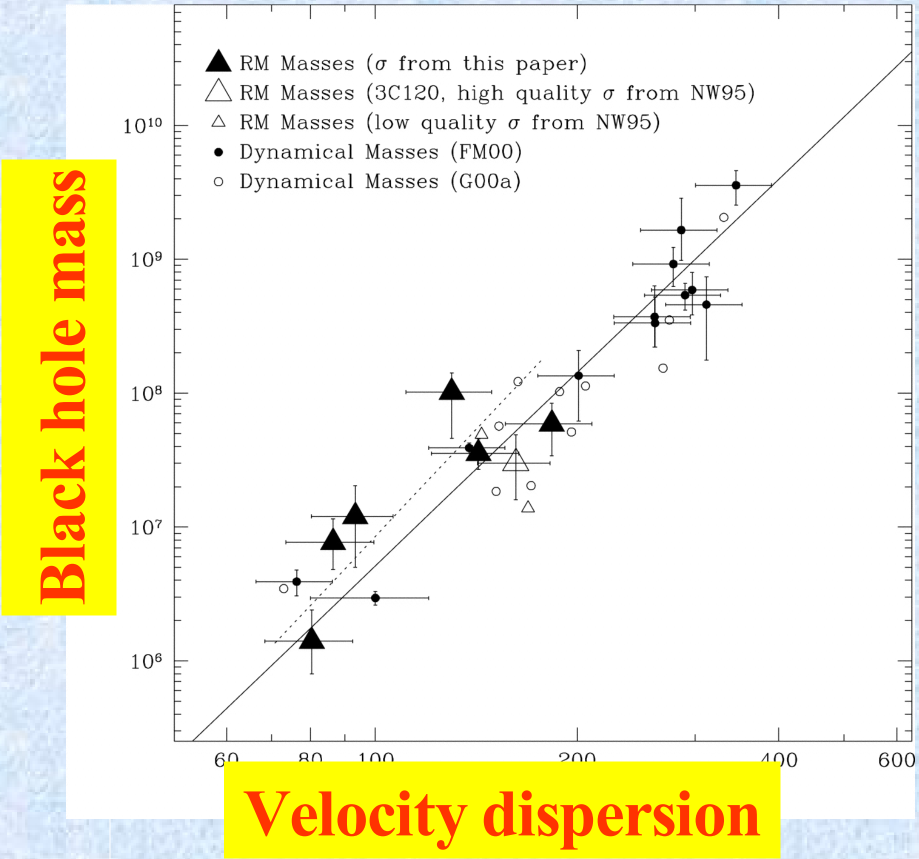
1. Do high-z E+S0s live in dark matter halos? What can we learn about them? What is the relationship between luminous and dark matter?
2. When and how do super-massive black holes and spheroids form and evolve?

Hierarchical formation

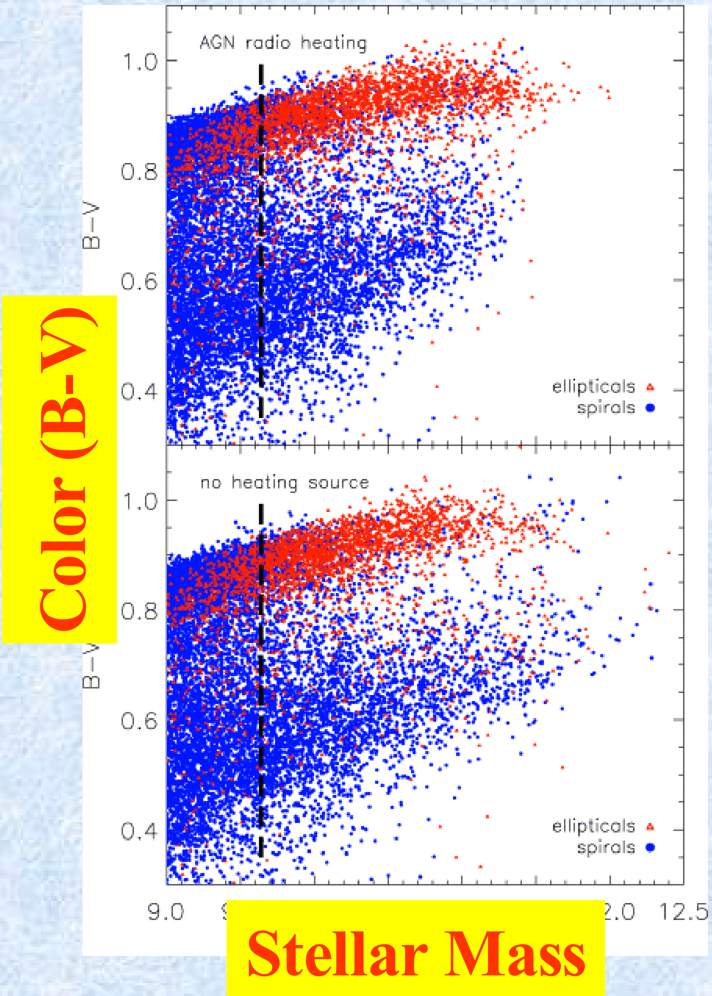


- Disks form in dark matter halos
- Spheroids form by mergers of disks
- Halos (and the galaxies inside) grow hierarchically over time

The black hole connection



Ferrarese & Merritt 2001



Granato et al. 2004; Croton et al. 2006

Clues from the local universe ("Fossil evidence")

- Dark matter halos detected
- Most stars are old
- Most spheroids (possibly all) host a supermassive black hole
- Tight correlations between various properties, velocity dispersion, size, luminosity, black hole mass…

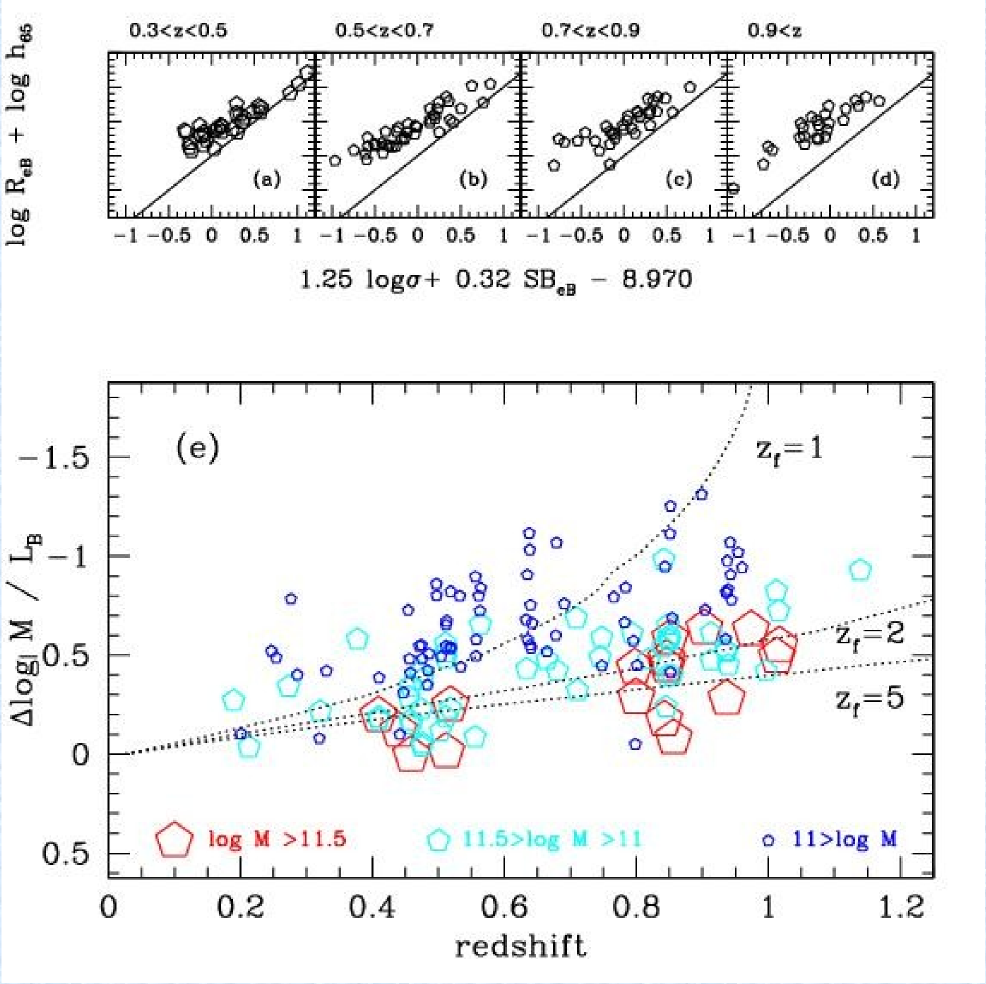
By going to high redshift (back in time) we can observe spheroids while they are forming

Stellar populations: current state of affairs

- Stars in massive early-type galaxies are old
- Stars in smaller galaxies are younger
- Is this “downsizing” compatible with hierarchical models?
  - Perhaps, if massive galaxies are assembled without forming new stars (AGN feedback?)
  - But can other properties be reproduced as well?

An example from high redshift studies..

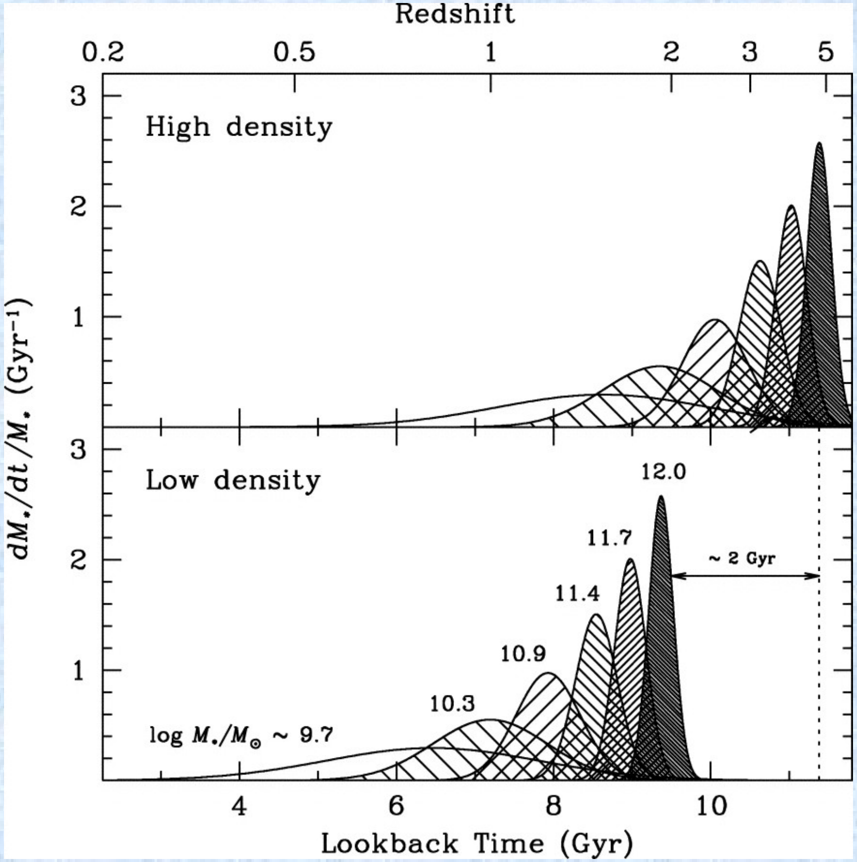
- Evolution of mass to light ratio is a function of dynamical mass
- More massive galaxies evolve slower than less massive ones, i.e. older stars (“downsizing”)



Treu et al. 2005a

… and an example from the local universe

- Age of the stellar populations is a function of mass (downsizing)
- And to second order environment ("double downsizing")

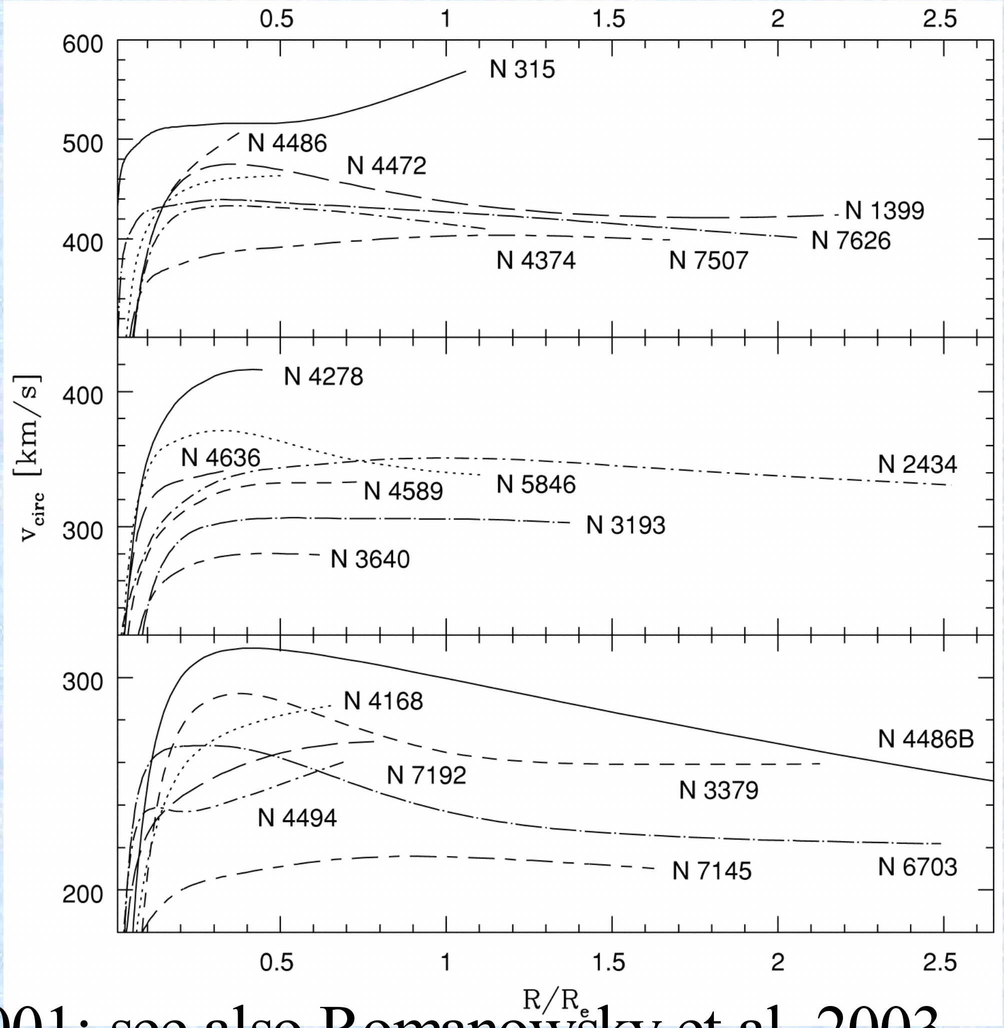


Thomas et al. 2005

Dark Matter

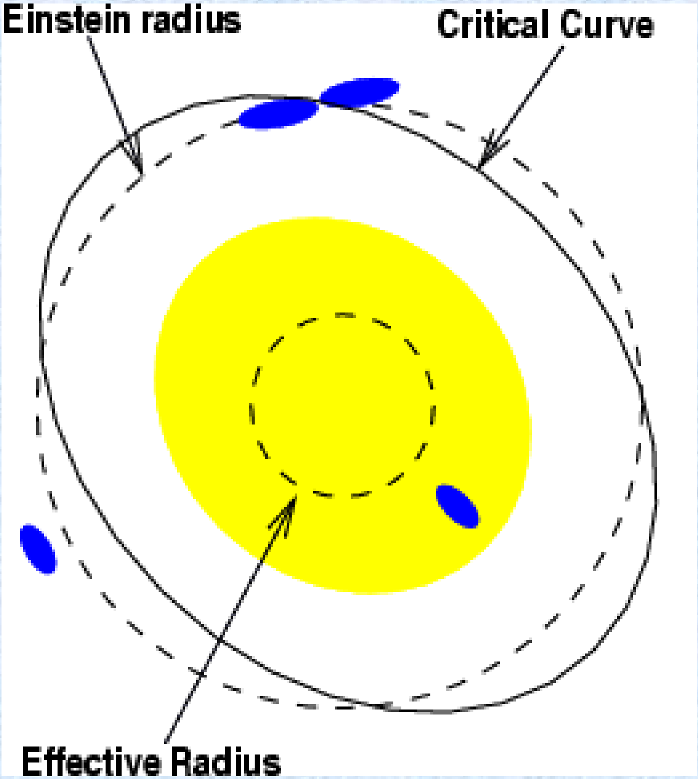
The mass distribution of E/S0. z=0

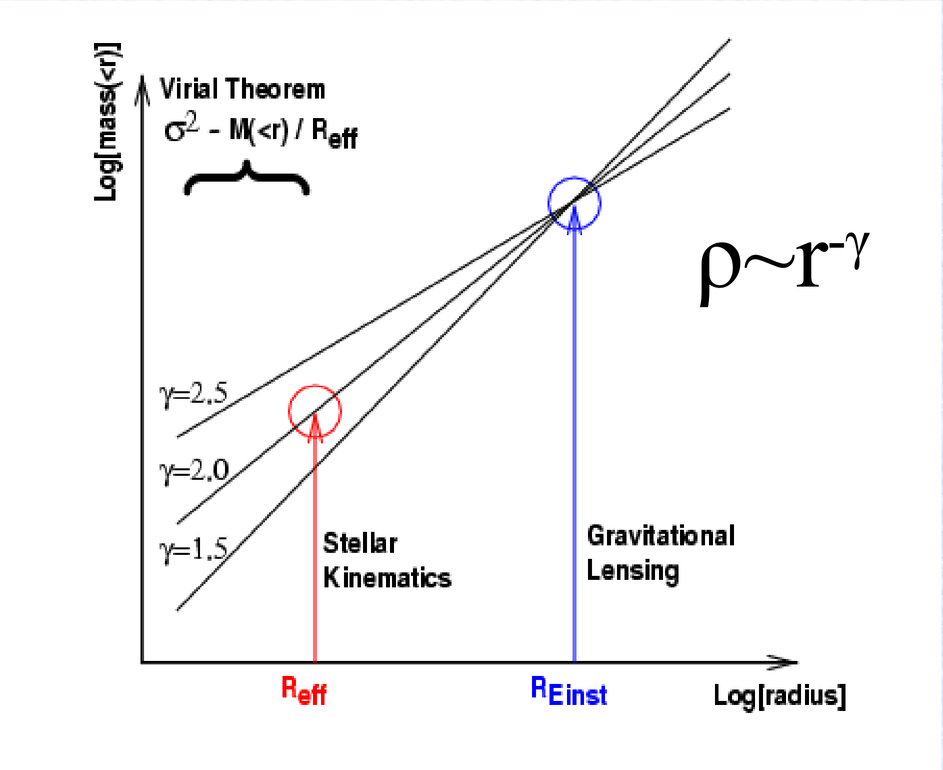
- Evidence for dark matter from dynamics and X-ray. Dark matter distribution poorly constrained, because of paucity of dynamical tracers at large radii.
- “Traditional” dynamical tracers at large radii (PN, Globular clusters) inapplicable at z>0.



Gerhard et al. 2001; see also Romanowsky et al. 2003

Z>0: lensing + dynamics



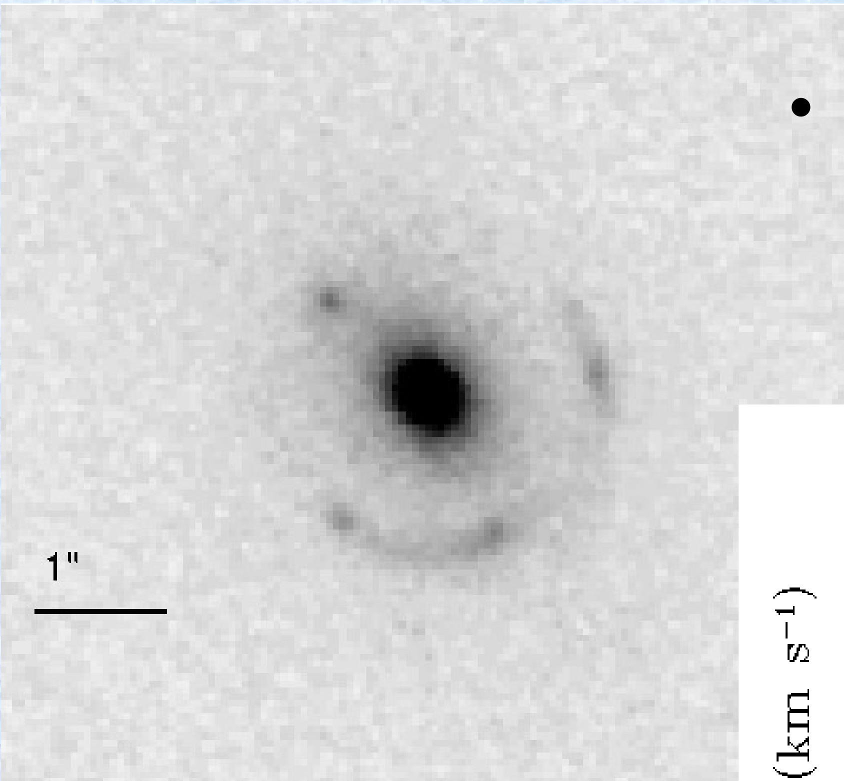


The Lensing Structure and Dynamics (LSD) Survey:

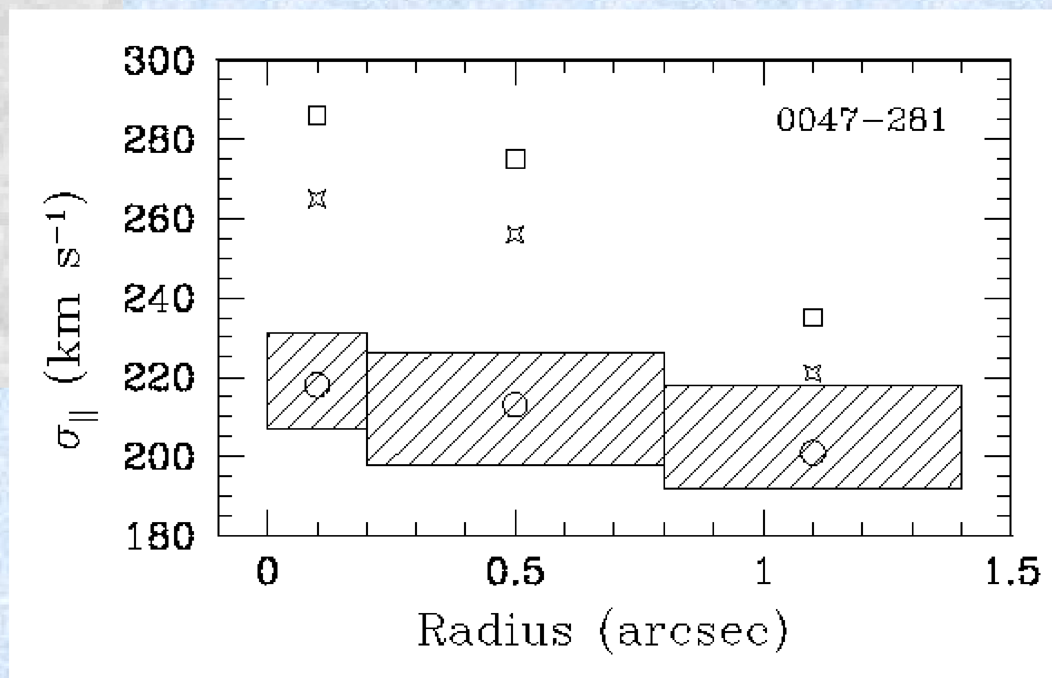
- Sample: all 11 suitable gravitational lenses known at the time
- Aim: Spatially resolved kinematics profiles
- Status: COMPLETED DECEMBER 2002
  - 8 nights on ESI/Keck-II
  - extended kinematic profiles for 10 lenses and 1 central velocity dispersion out to z=1

Treu & Koopmans 2002a, 2003,2004; Koopmans & Treu 2002, 2003

Example of data: 0047 at z=0.485



- 5.75 hrs integration; velocity dispersion profile to ~5 %



Method: dynamical model

Two spherical components

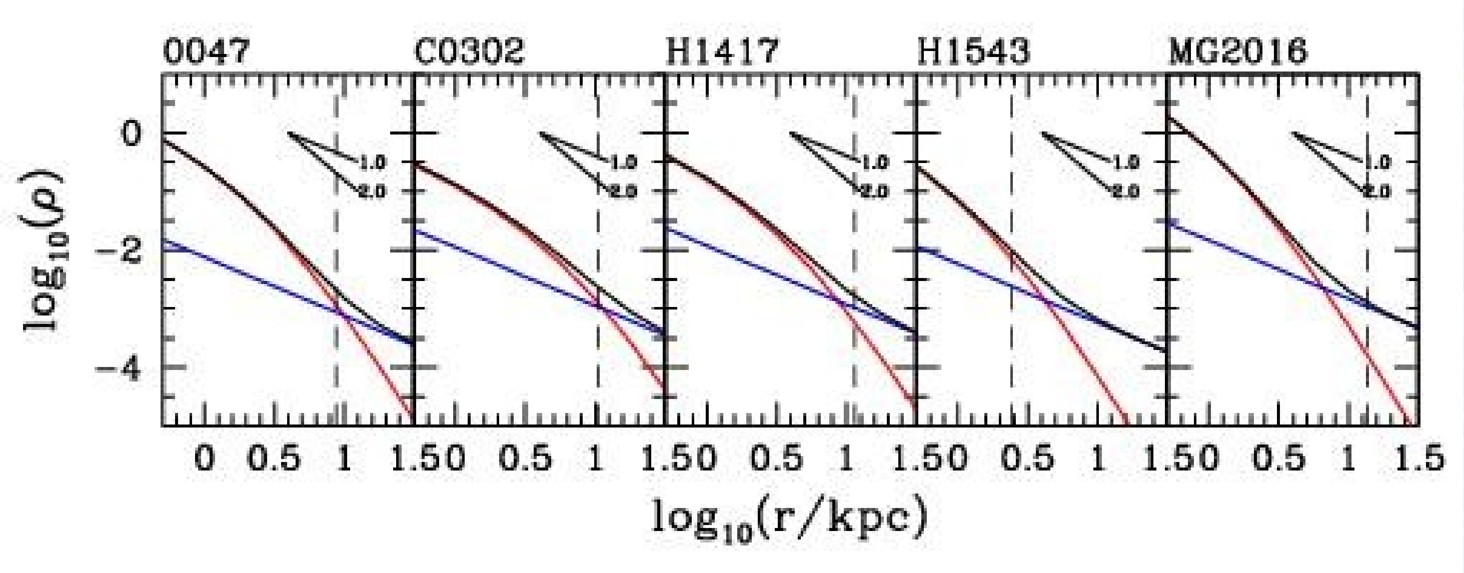
- **Luminous component: Hernquist/Jaffe mass distribution**
- **Dark matter profile: generalized NFW profile, with inner slope -γ, outer slope -3, break radius R_b**
- **Osipkov-Merritt parametrization of the anisotropy, or constant anisotropy.**

Spherical Jeans equation

$$\frac{d\rho_*(r)\sigma_r^2(r)}{dr} + \frac{2\beta(r)\rho_*(r)\sigma_r^2(r)}{r} = -\frac{GM(r)\rho_*(r)}{r^2}$$

$$\beta(r) = \begin{cases} 1 - \frac{\sigma_\theta^2}{\sigma_r^2} = \frac{r^2}{r^2+r_i^2} & r_i^2 \geq 0 \\ b_{iso} \in [-1,+1] \end{cases}$$

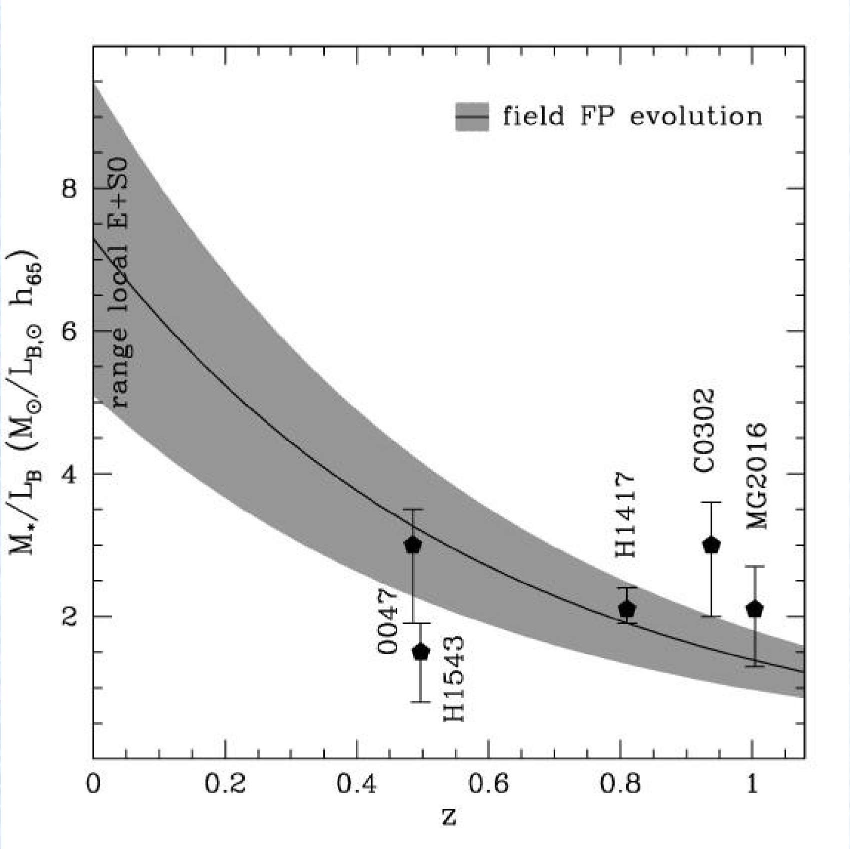
Results. I: luminous and dark matter in high-z E/S0s



- Constant M/L ruled out; dark matter halos detected!!
- Isotropic or mildly radial orbits
- Approximately flat rotation curve
- Result of (incomplete) violent relaxation?

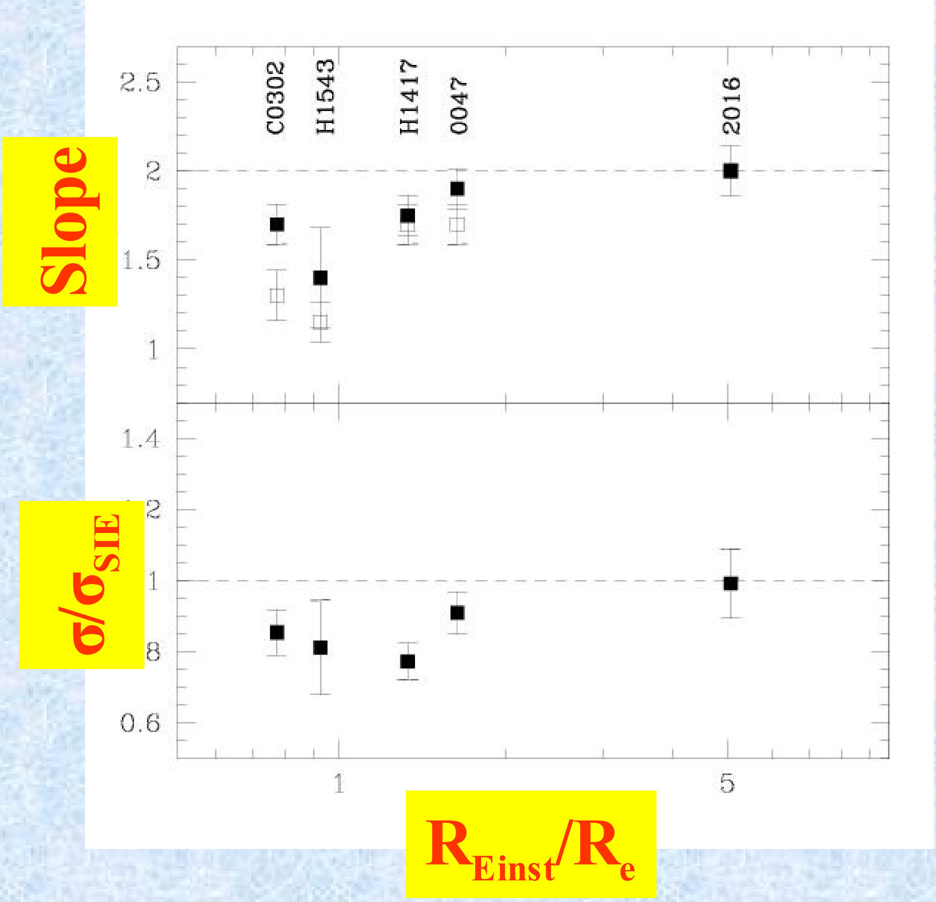
Results. II: stellar populations vs dynamical evolution

- Evolution of dynamically determined stellar M/L is consistent with the one derived from the FP
- Consistent with no structural evolution between z~1 and today



Results. III: homogeneity of lens galaxies

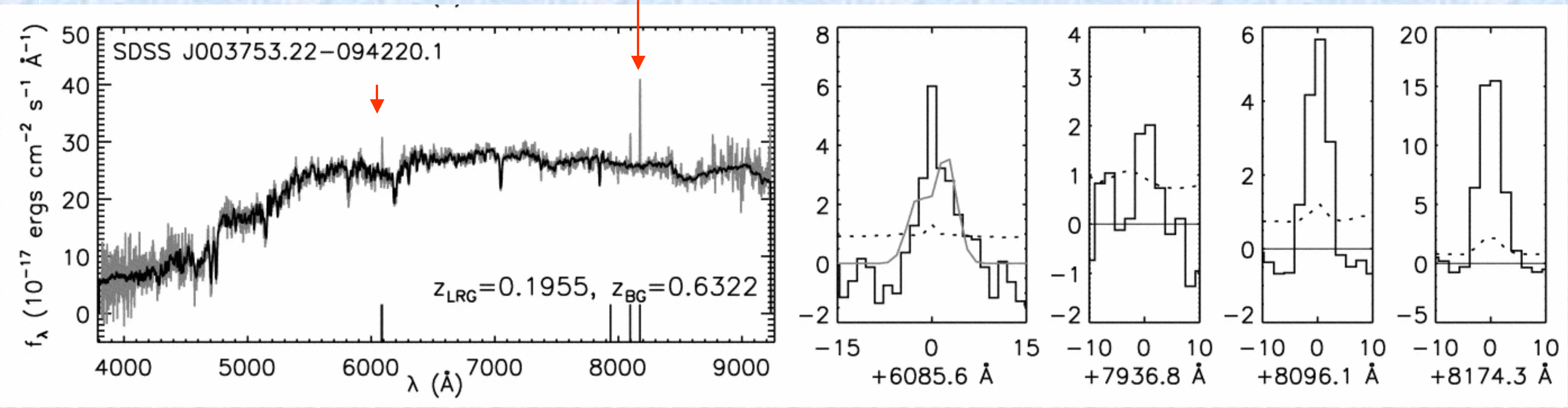
- The total mass distribution of lens galaxies is close to isothermal, i.e. logarithmic slope ~-2 within 0.3.
- Dark luminous matter conspiracy (bulge-halo conspiracy)



LSD so far…

- Mass distribution of E/S0 galaxies measured out to z=1.
- Dark matter halos detected. CDM ok
- Total mass profile is approximately (~15 %) “isothermal” within the Einstein radius. CDM?
- Spatially resolved data inconsistent with strong tangential or radial anisotropy. CDM?

SLACS: the strong lens factory (www.slacs.org)

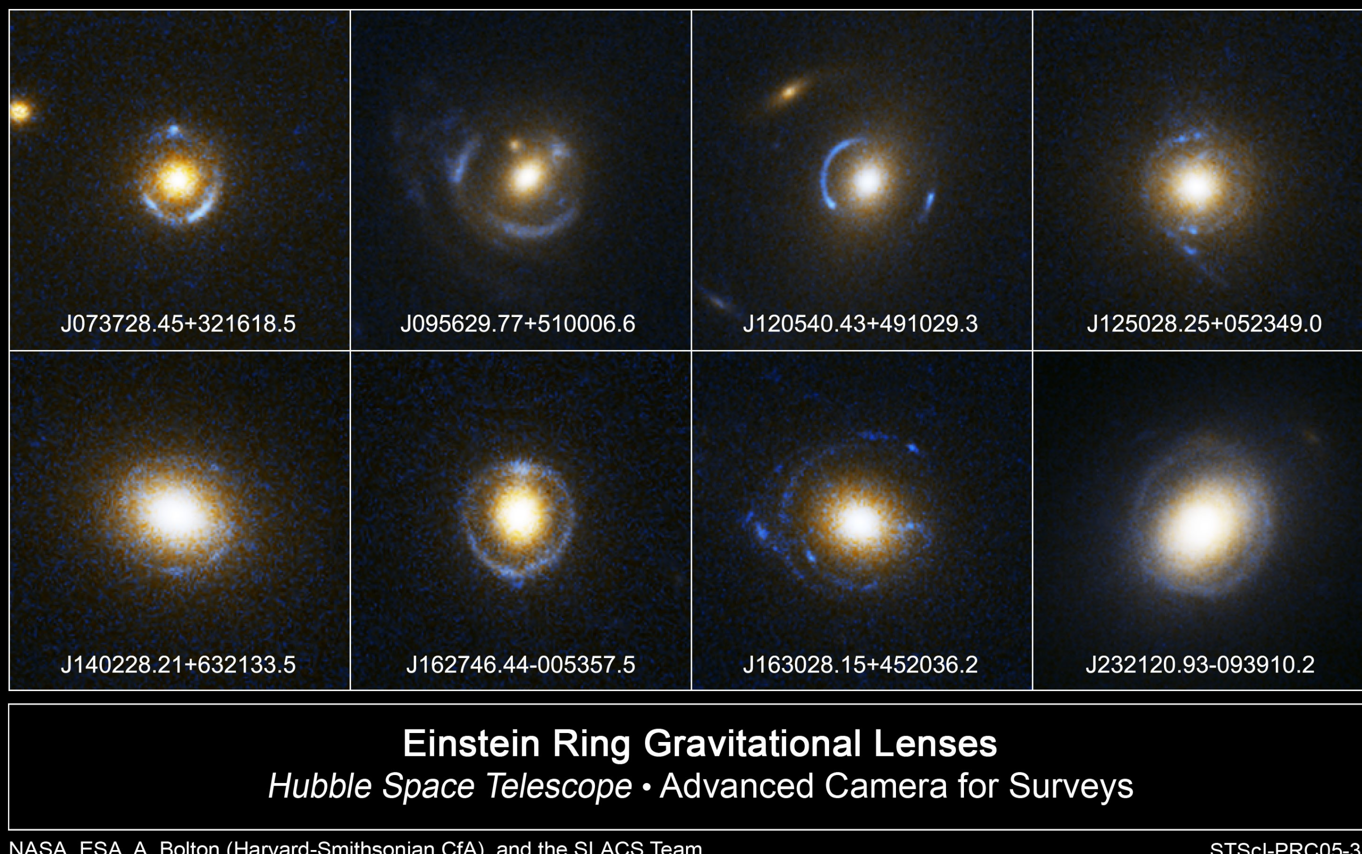


- Candidate lenses selected from SDSS as red galaxies with "spurious" emission lines (Bolton et al. 2004,2005,2006,2007)
- 167 snapshot targets approved for HST imaging in Cycles 13-14
- 155 GO orbits approved in Cycle 14-15
- **SDSS velocity dispersion can be used to pre-select masses and estimate success rate**

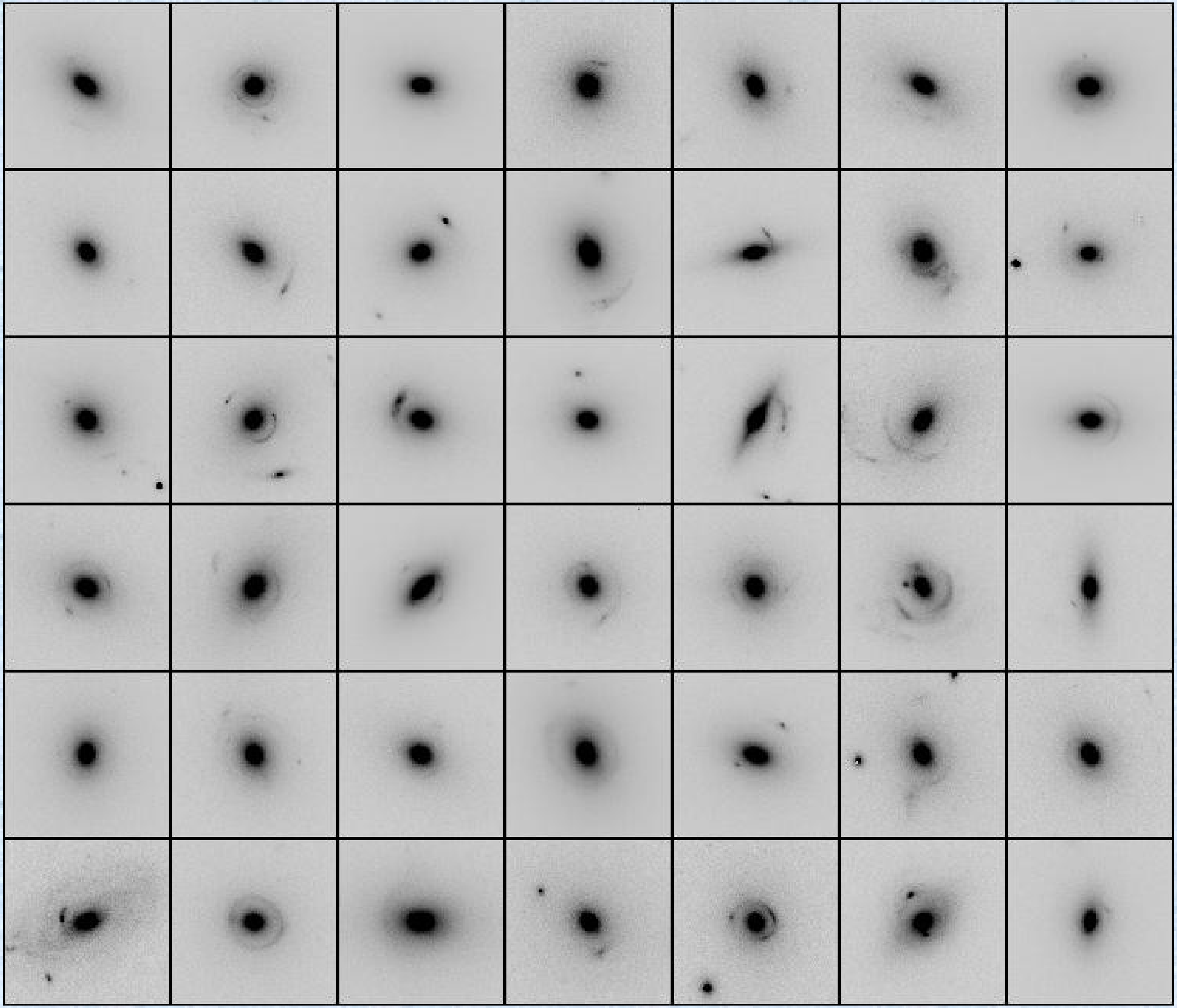
Treu + Koopmans, Bolton, Burles & Moustakas

SLACS: the largest search for lenses..

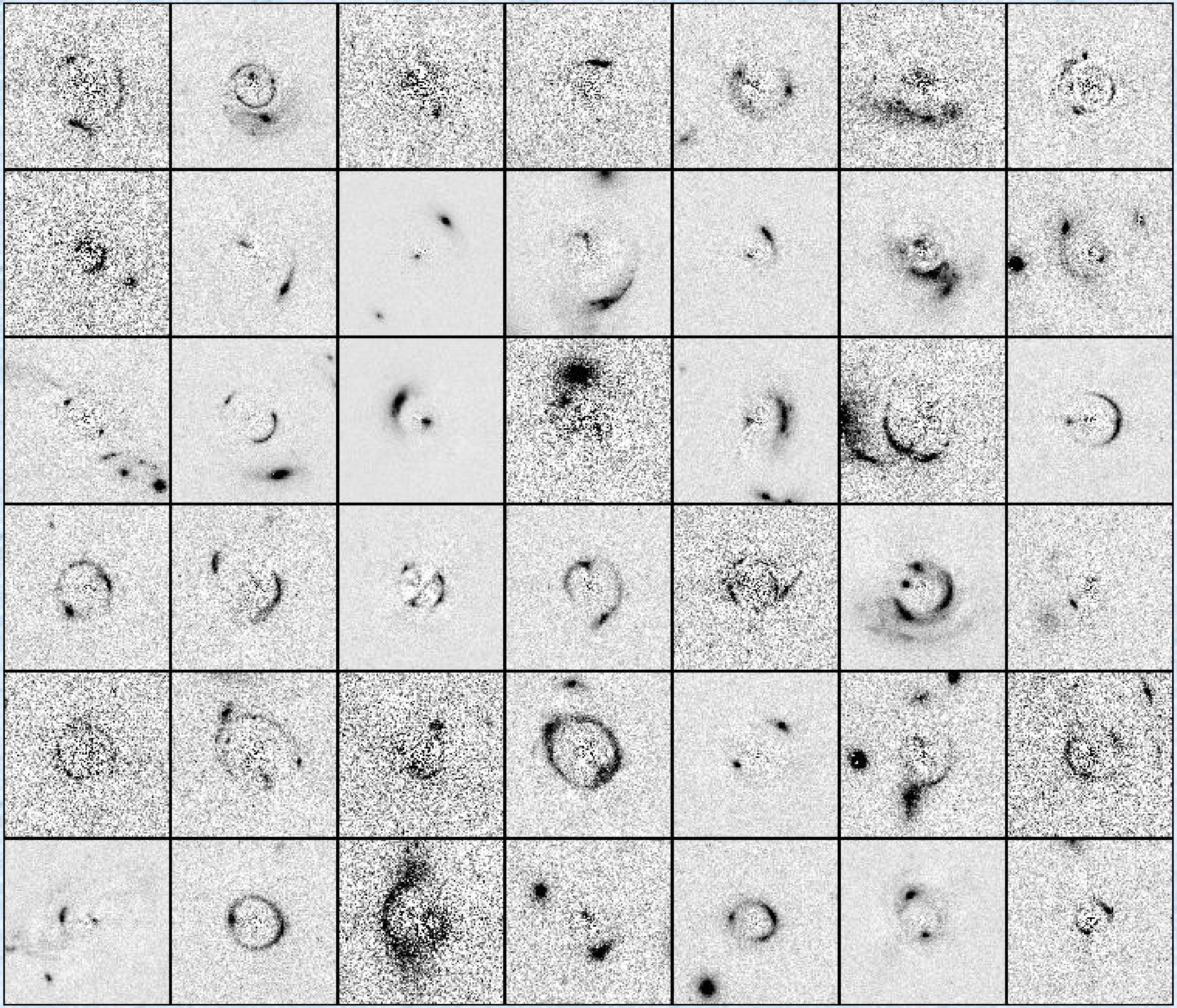
See www.slacs.org and Bolton et al. 2006, 2007



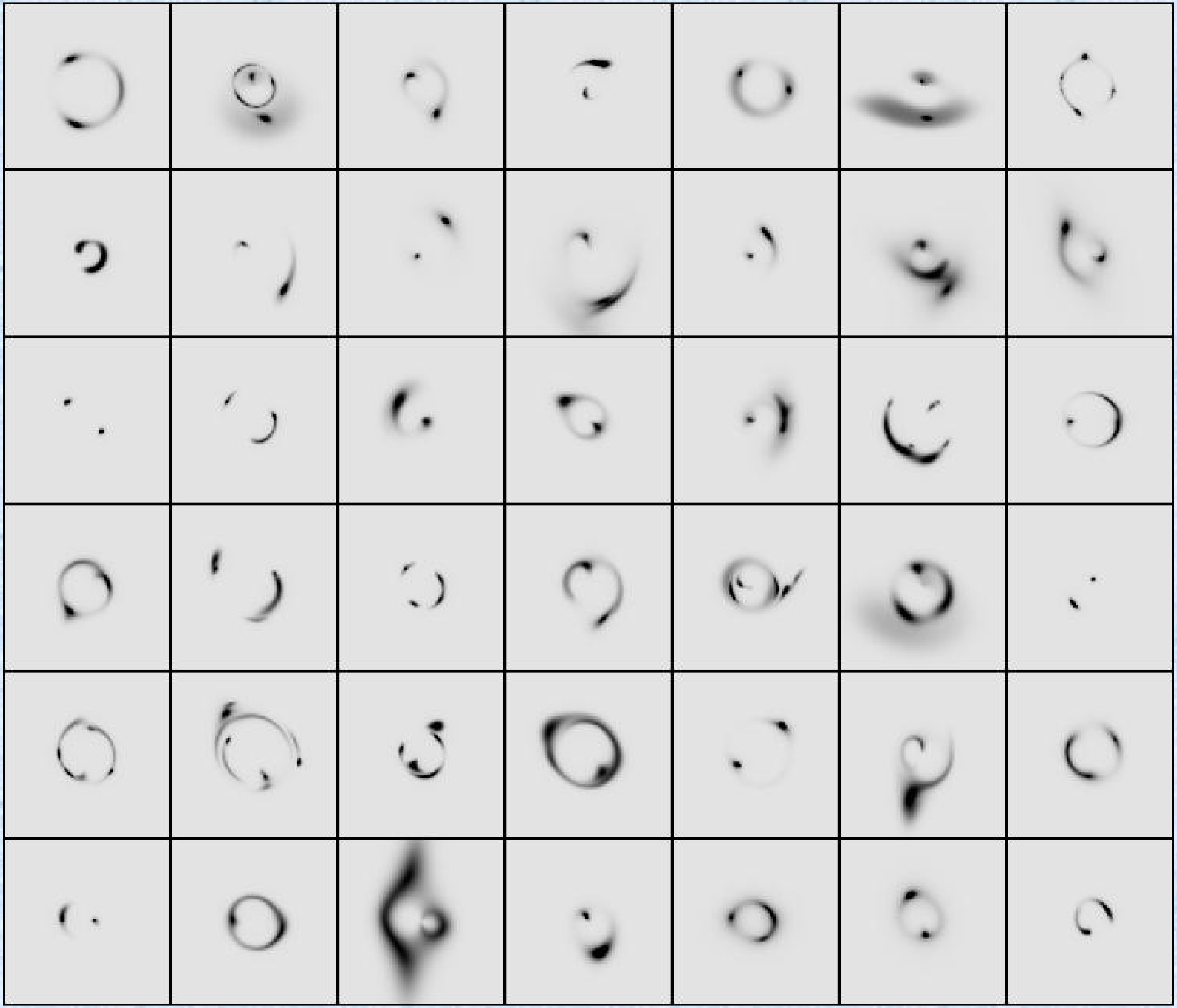
58 confirmed as of 11/2006 ..! Goal is 100 lenses with cycle 15



Bolton et al. 2007

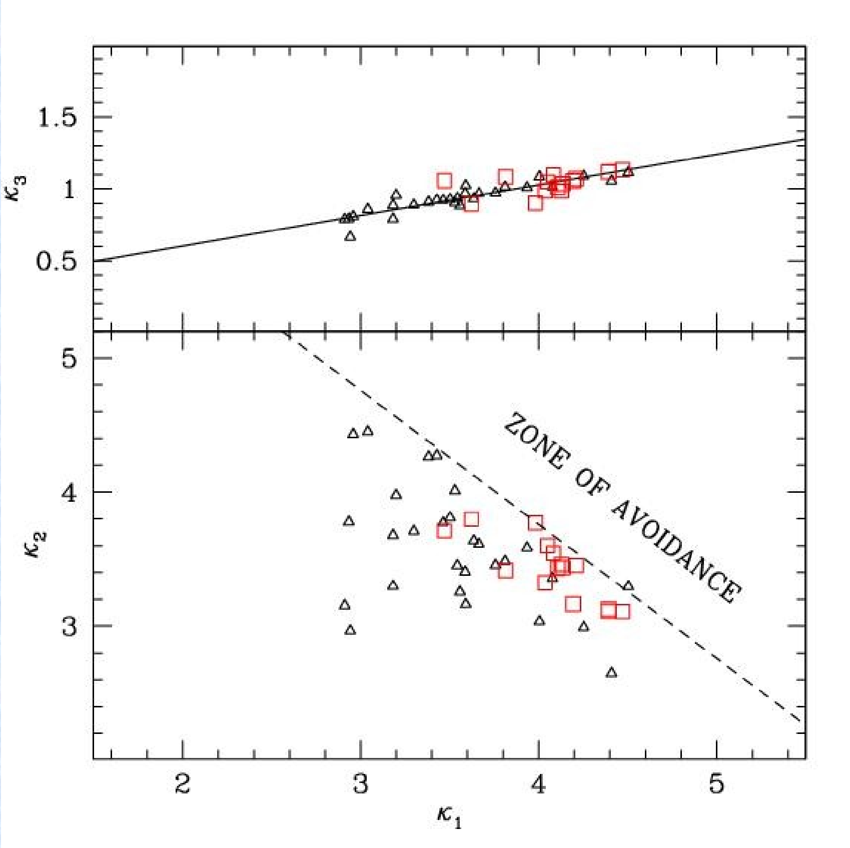


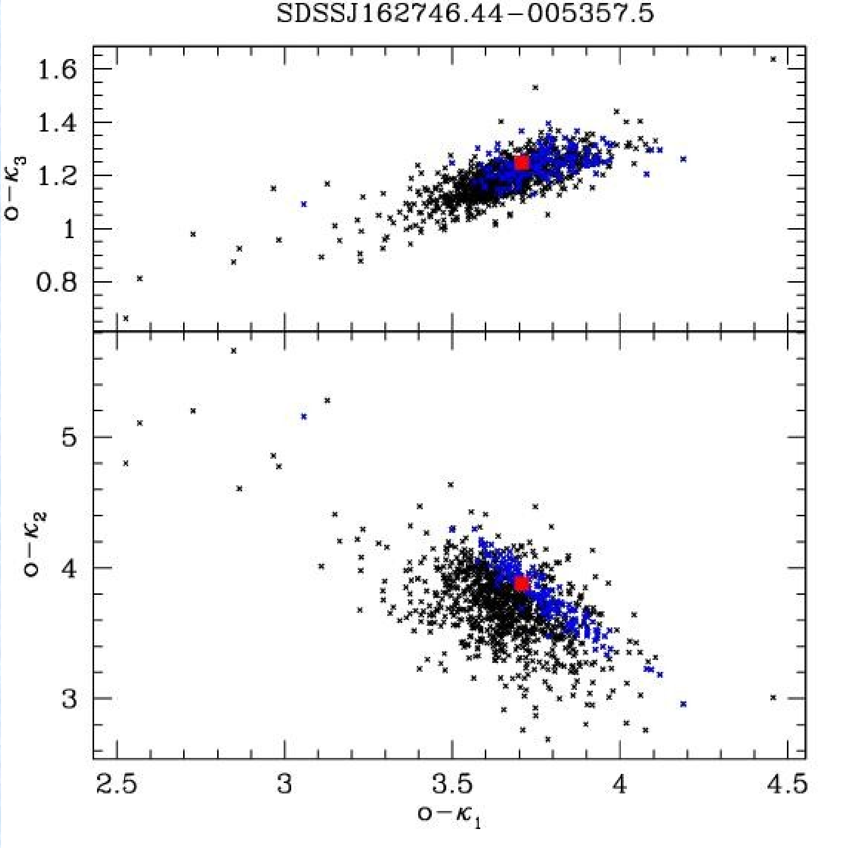
Bolton et al. 2007



Bolton et al. 2007

Results: lenses are "normal" spheroids

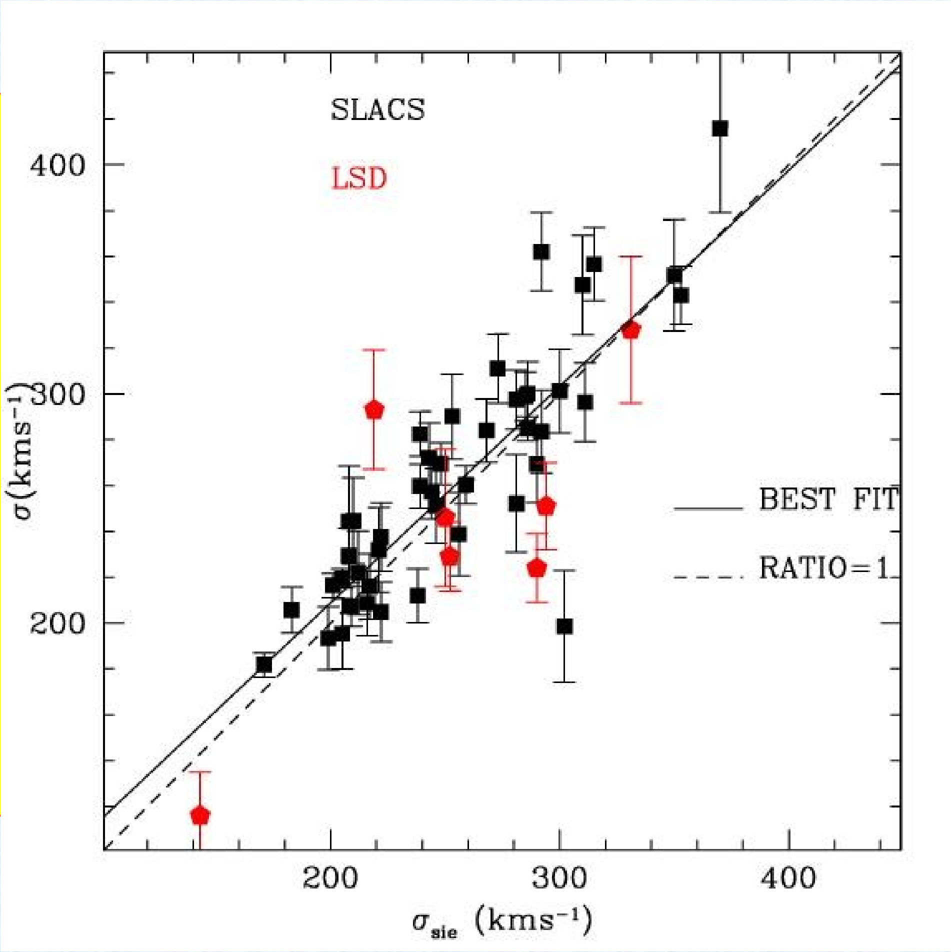




Lenses live in the same FP as normal spheroids, once selection in σ is taken into account (Treu et al. 2006)

Results: a scaling law measuring mass profiles!

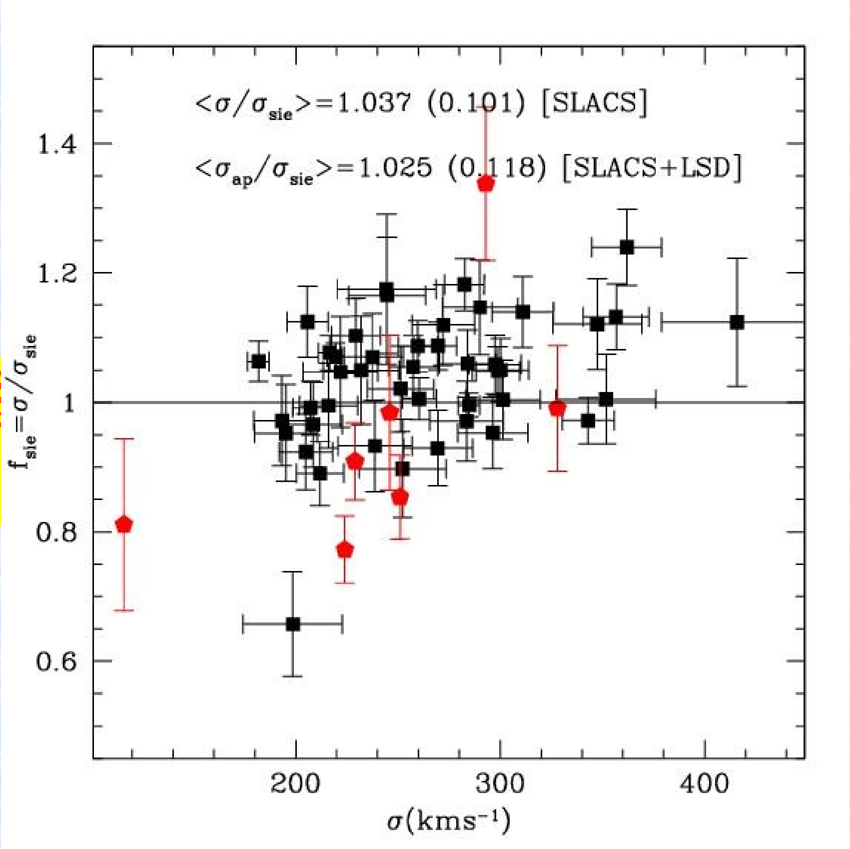
Stellar velocity dispersion



"Lensing" velocity dispersion

Or in terms of ratio…

- The ratio of the stellar velocity dispersion to that of the best fitting lens model is very close to unity
- **The mass profile is close to isothermal: $\rho \sim r^{-2}$.**
- How do the stars and dark matter know "where to go"?
- **Dark-luminous mass "conspiracy"**

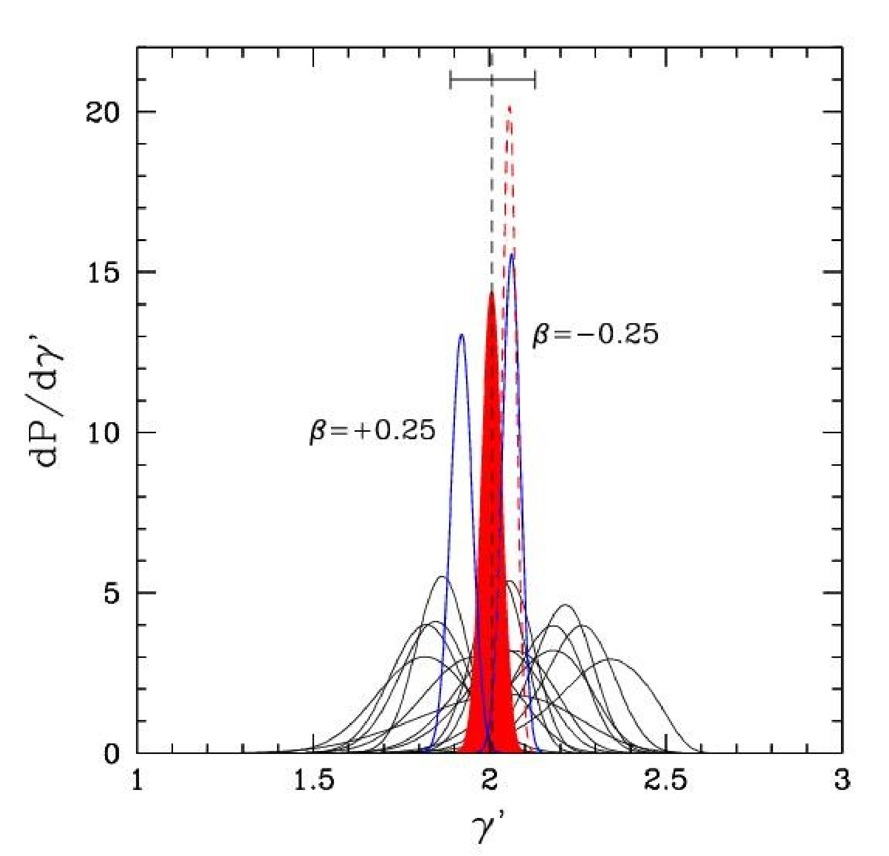


σ/σ_{SIE}

σ

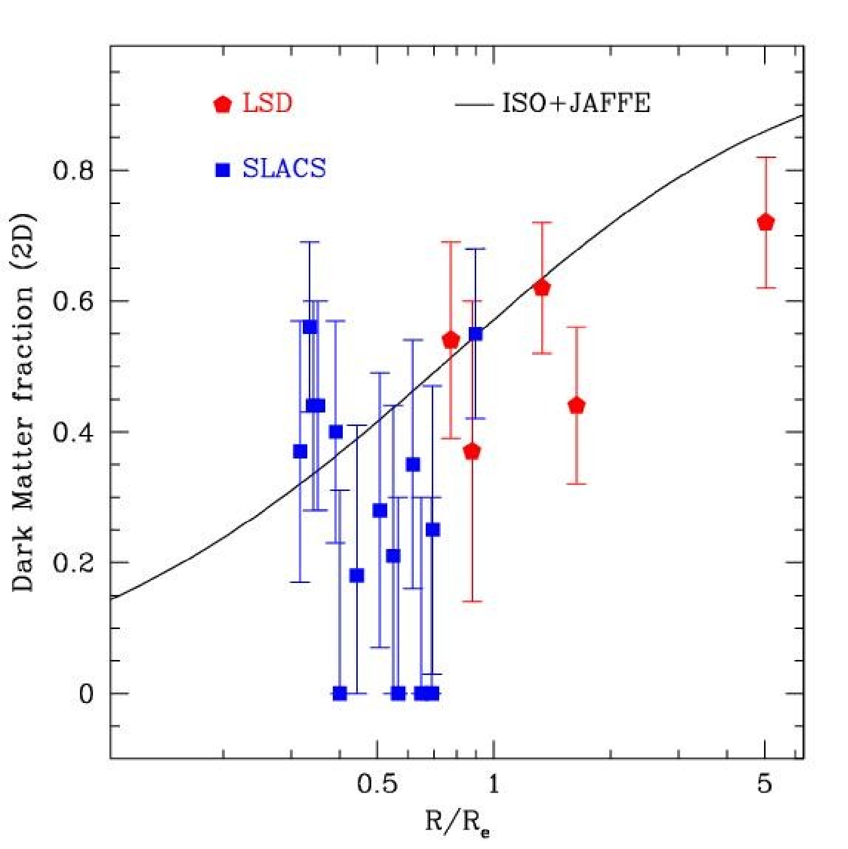
In terms of mass density profile

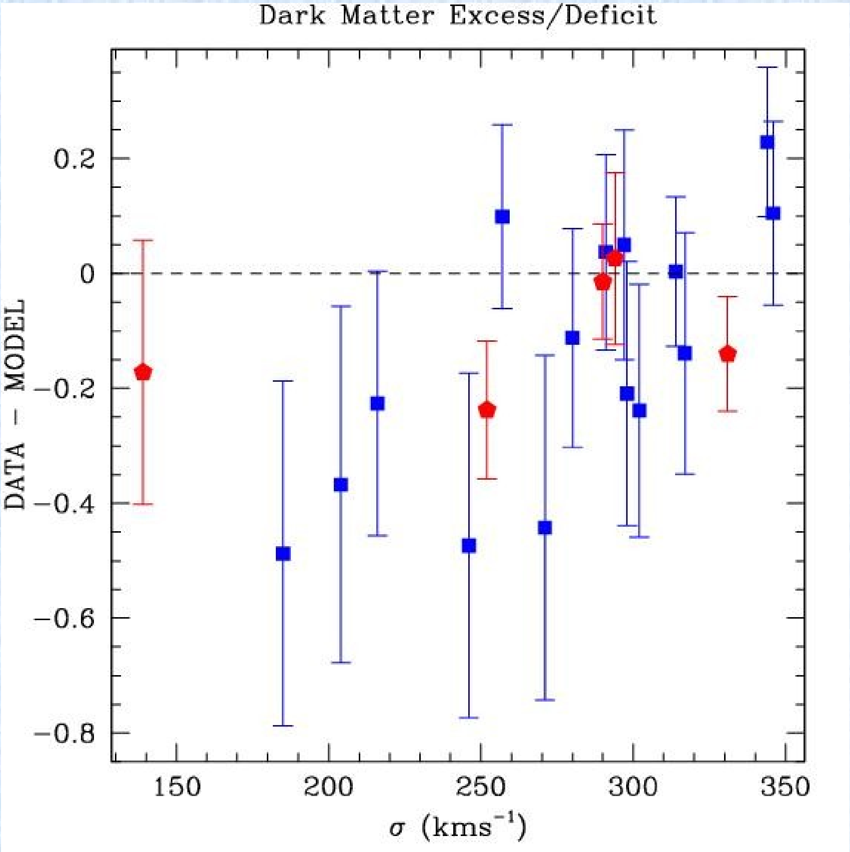
- The logarithmic slope is -2 with very little scatter
- No cosmic evolution (+LSD)
- If assembly with dry mergers, progenitor must have been isothermal
- Isothermal nature is established at early-times



Koopmans, Treu et al. 2006

Are E/S0 exactly isothermal? 1. Velocity dispersion trends





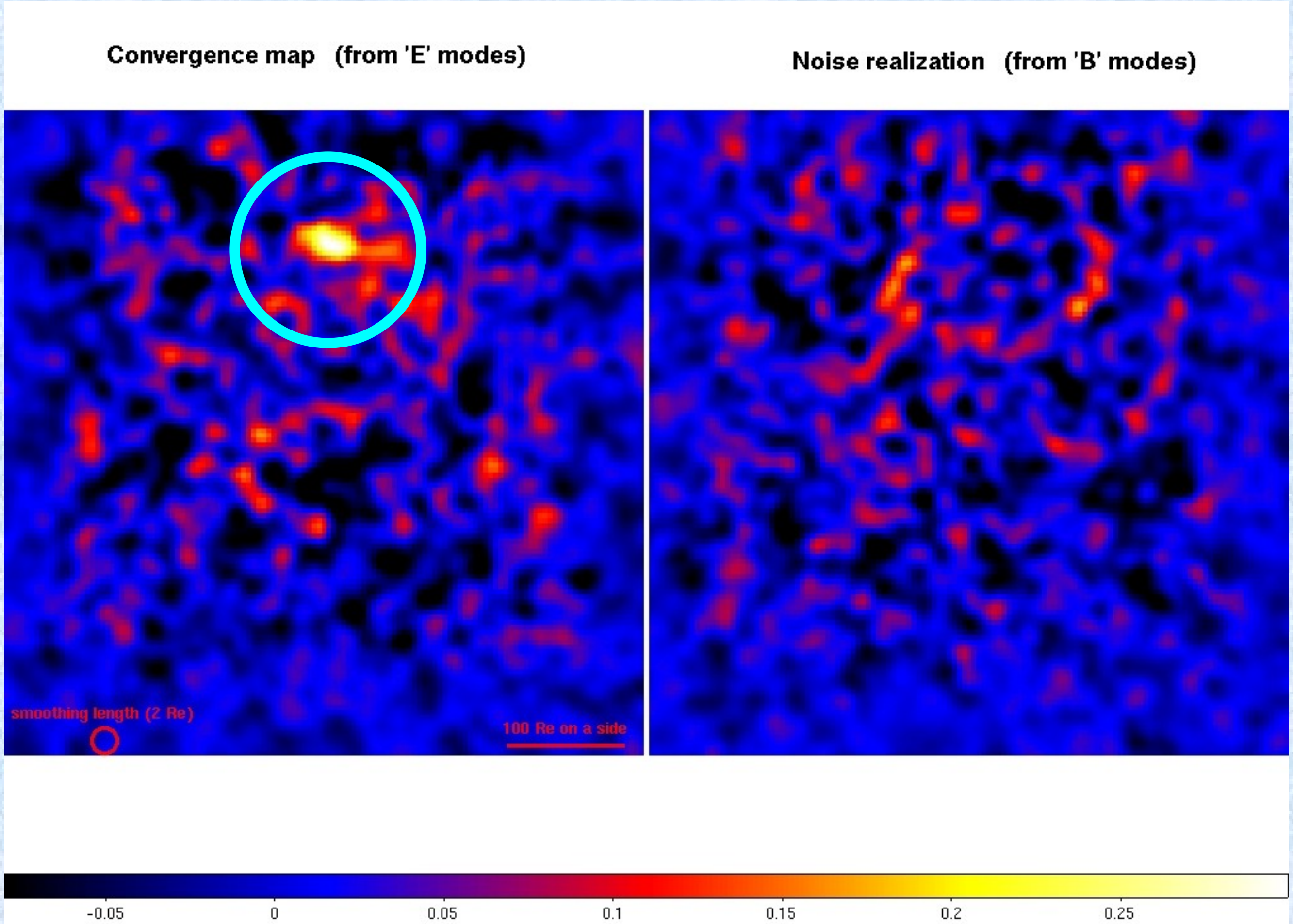
Do more massive galaxies have more dark matter?
Wait for the next SLACS papers….

Are E/S0 exactly isothermal? 2. Enter weak lensing…

- Deeper ACS data (1 orbit F814W) available for 22 SLACS lenses (85 expected by the end of cycle 15).
- Background galaxy density ~80/ square arcmin
- Stacked weak-lensing analysis yields a significant detection of the shear
- Analysis exploits the most advanced corrections for ACS-PSF systematics (breathing, CTE…) developed for cosmic shear analysis (Rhodes et al. 2006)

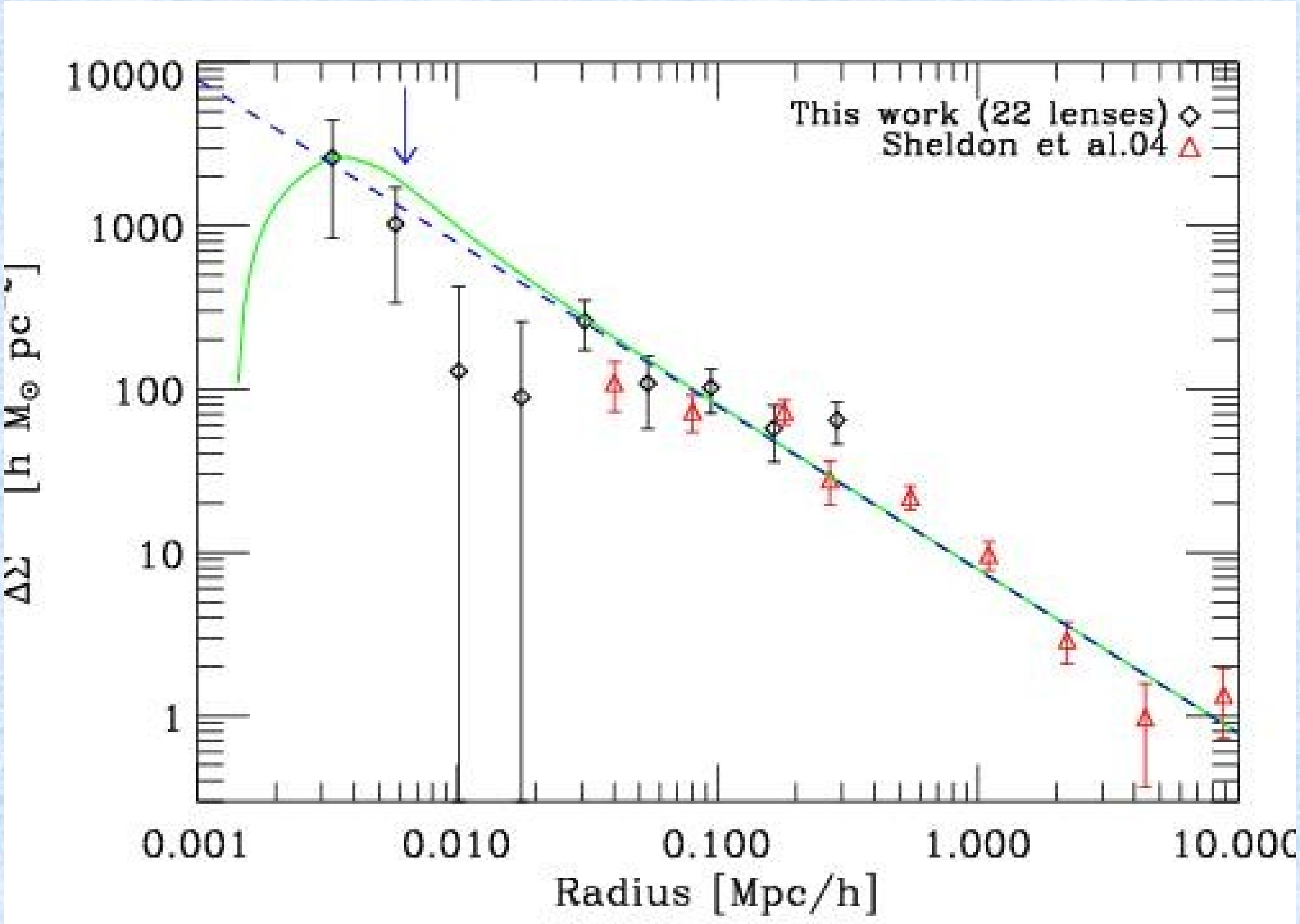
Gavazzi, TT et al. 2006

Are E/S0 exactly isothermal? 2. Voila'!



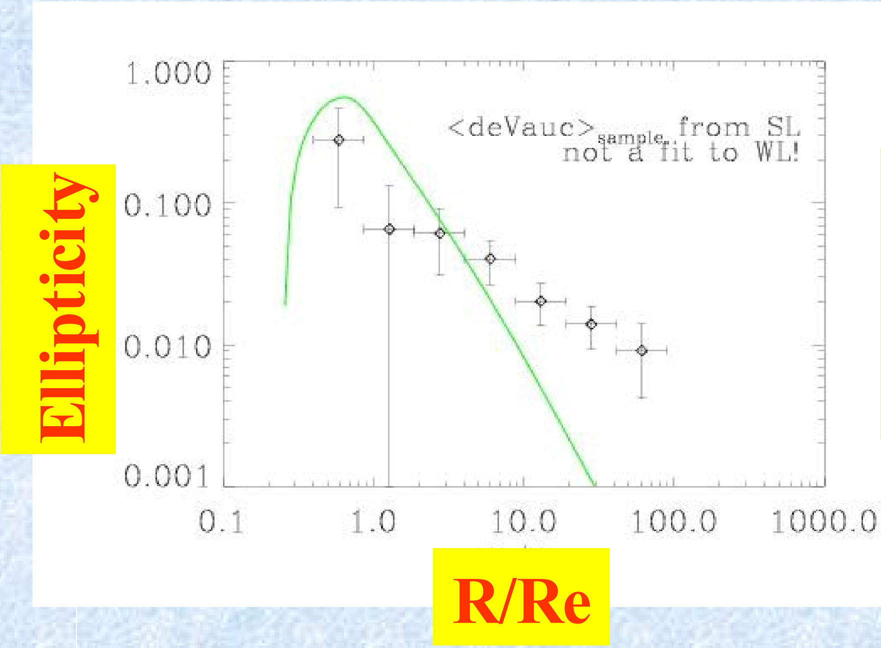
Gavazzi, TT et al. 2006

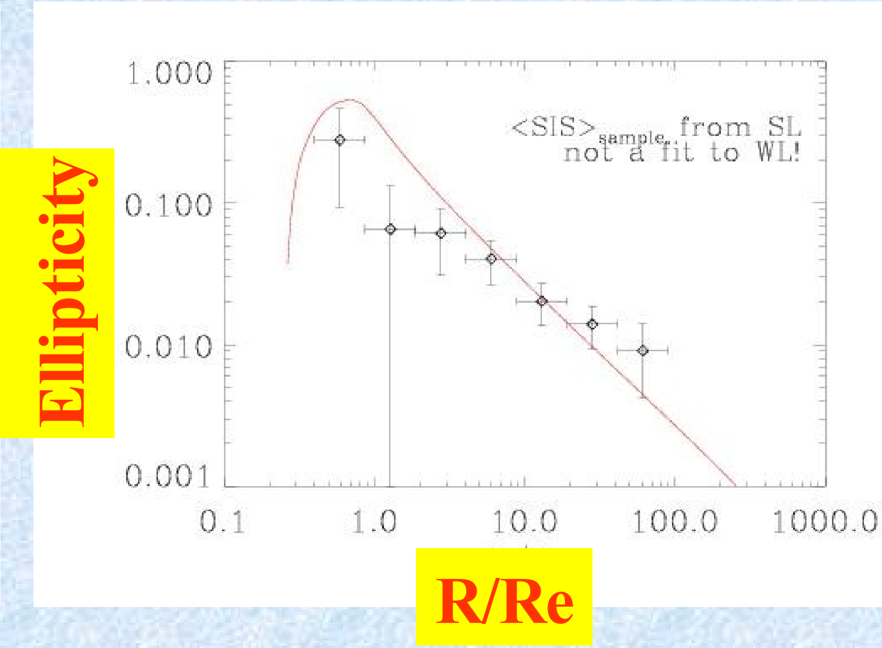
Shear profile



Gavazzi, TT et al. 2006

Are E/S0 exactly isothermal? 2. Behavior at large radii



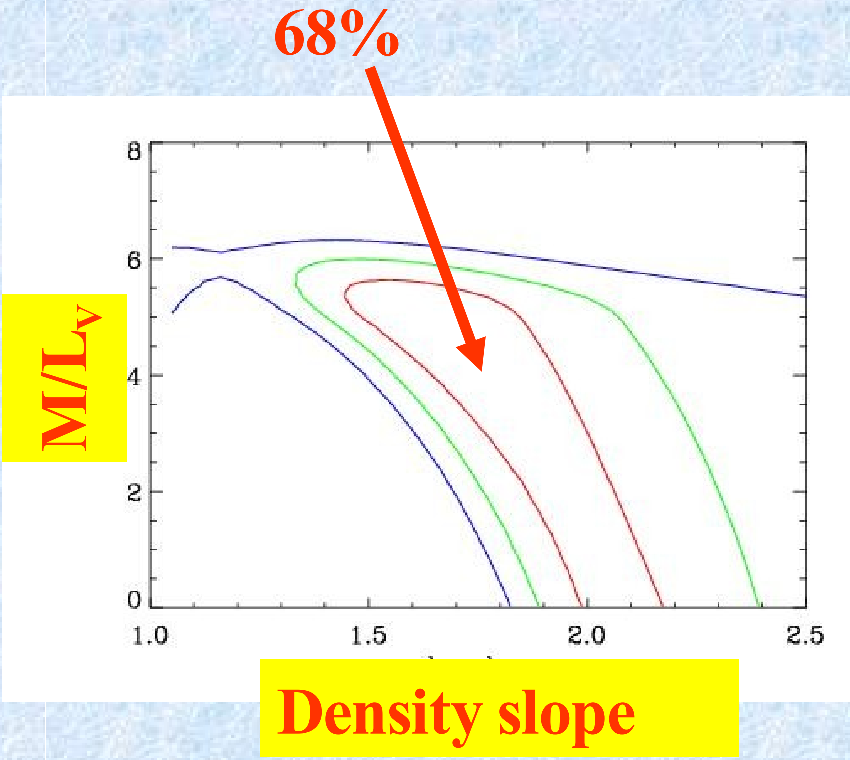


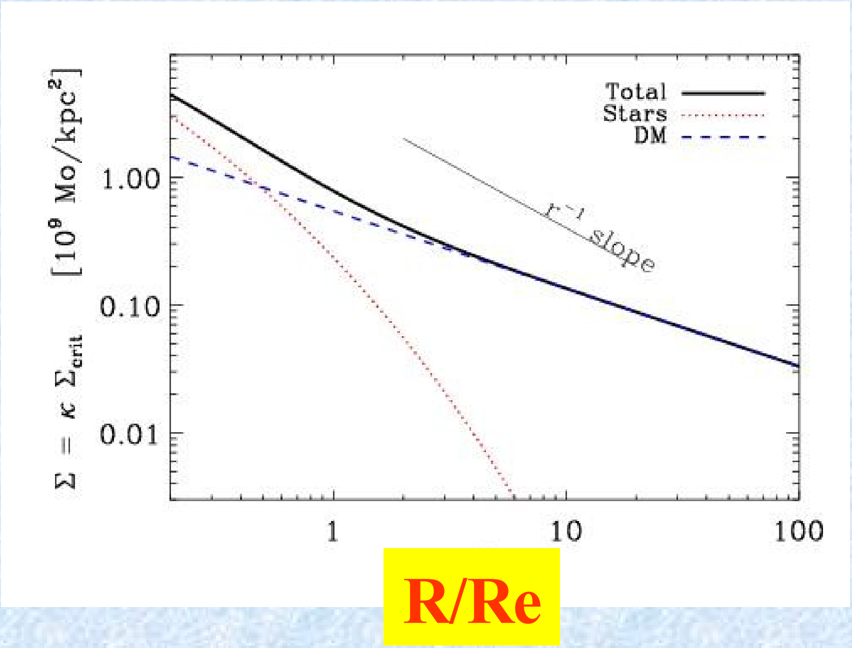
Constant M/L ratio doesn't work

Isothermal works well

Gavazzi, TT et al. 2006

Are E/S0 exactly isothermal? 2. Behavior at large radii

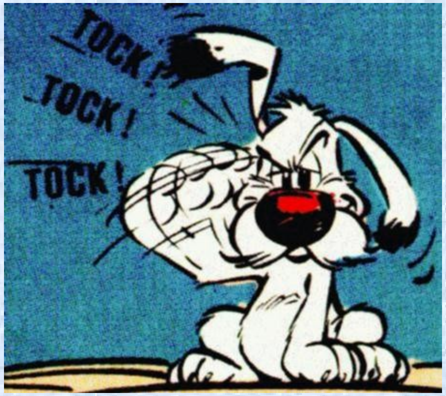


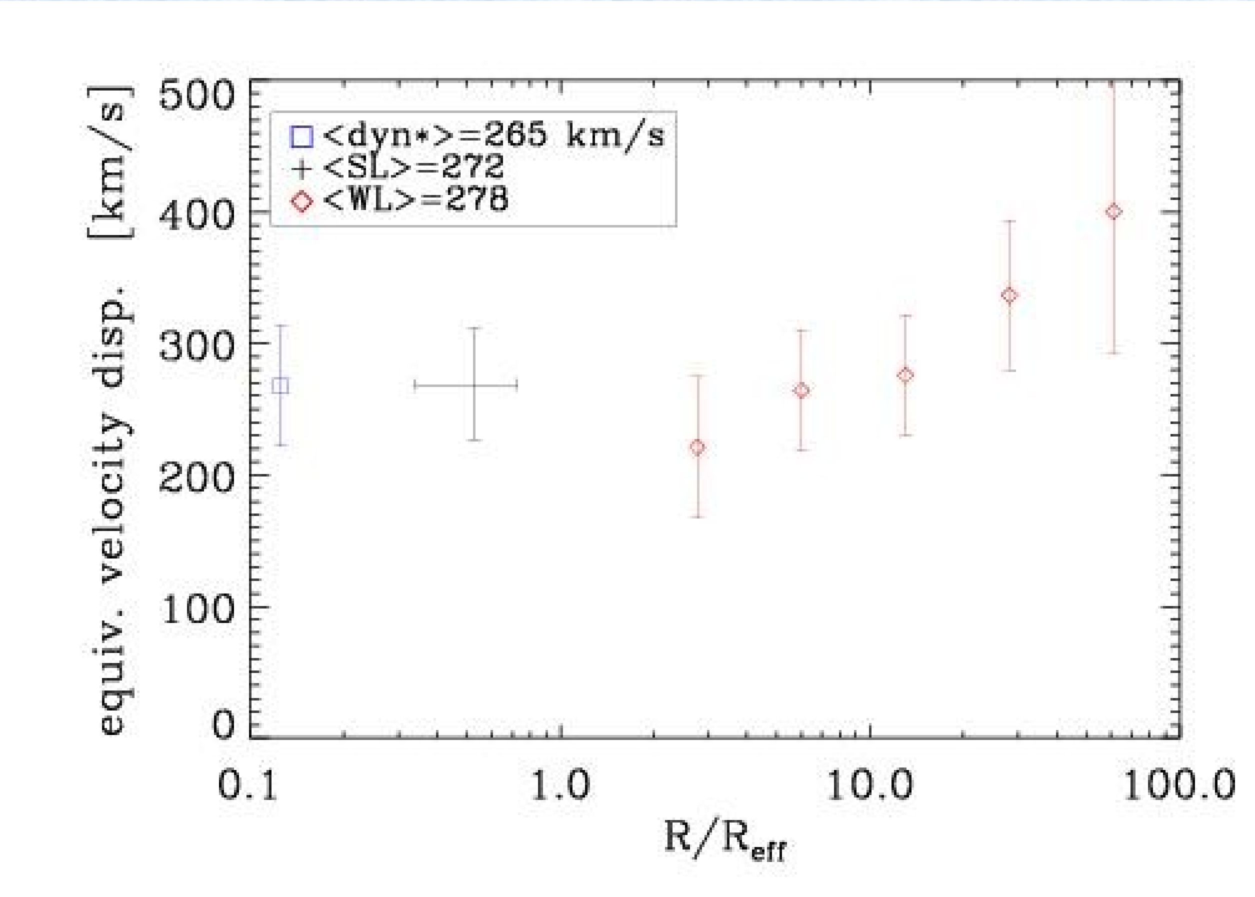


Two component fit. Best slope with M/L=0 is 2.08+-0.08

Gavazzi, TT et al. 2006

Are E/S0 exactly isothermal? 3. "Velocity dispersion" profile





Gavazzi, TT et al. 2006

Conclusions

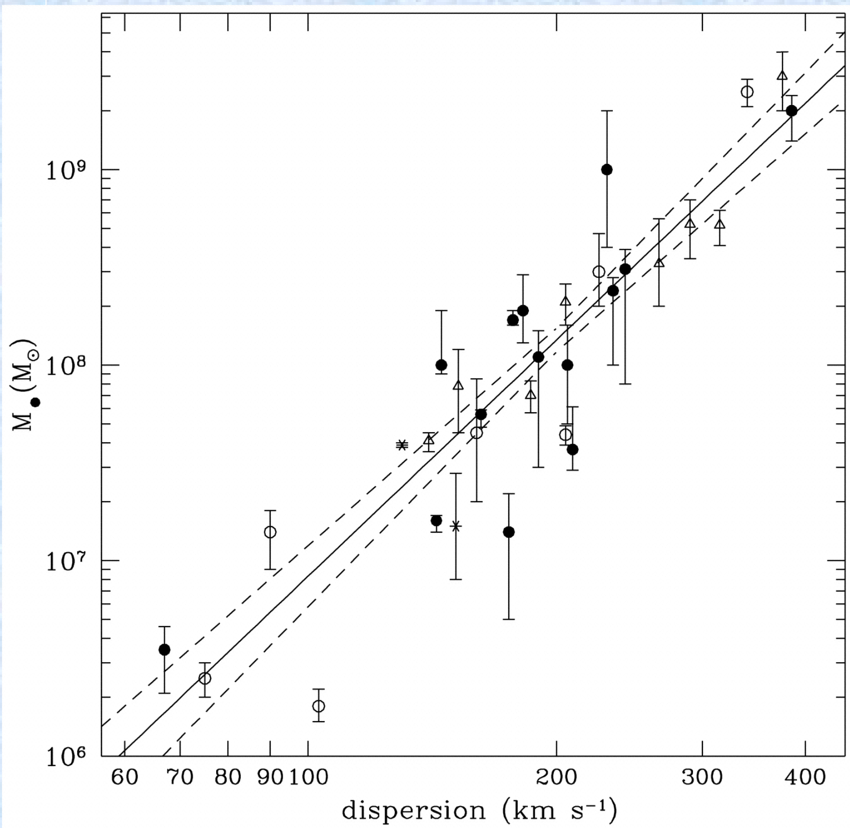
- The mass density profile of E/S0s can be measured to z~1 by combining lensing and stellar dynamics
- Massive E/S0 lens galaxies are well reproduced by singular isothermal ellipsoids out to z=1:
  - Bulge/Halo conspiracy
  - Jury still out whether the trend extends to smaller masses
- Dark halos can be detected out to ~100 effective radii combining weak-lensing.
  - The total mass profile appears to be close to isothermal all the way out. The plot thickens…

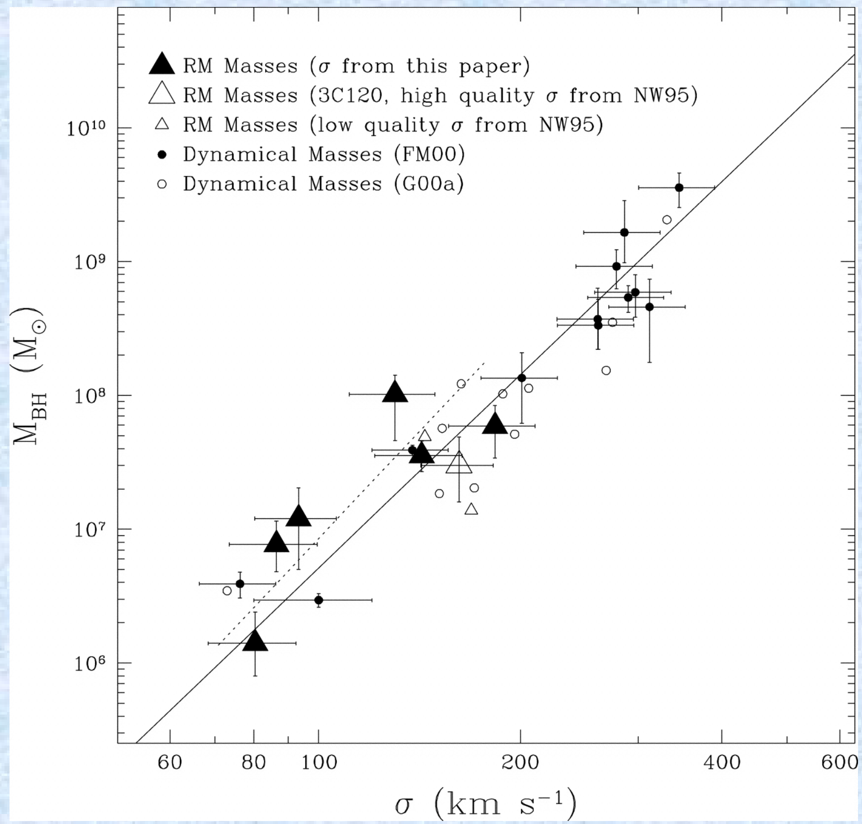
Black Holes

"The last I heard, Medwick was working on a model black hole in his lab."

With Jonghak Woo (UCSB), Matt Malkan (UCLA) and Roger Blandford (Stanford)

The local Universe





Gebhardt et al. 2001; Tremaine et al. 2002

Ferrarese & Merritt 2001

How do black-holes and spheroids know about each other?

- The size of the dynamical sphere of influence of a BH is $R \sim M_{BH7} / (\sigma_{200})^2$pc ~0.1-10 pc
- The size of the spheroid is of order kpc
- Typical accretion rates are of order 0.01 solar mass per yr for a 10^7 M_sun black hole. Masses of black holes could change over a Gyr timescale.
- If spheroids evolve by mergers, what makes the BH and spheroids stay on the same correlation?

Open questions

- Why is the M-sigma relation so tight?
- When was it formed?
- What does its evolution tell us about unified models of black-holes and spheroids formation?

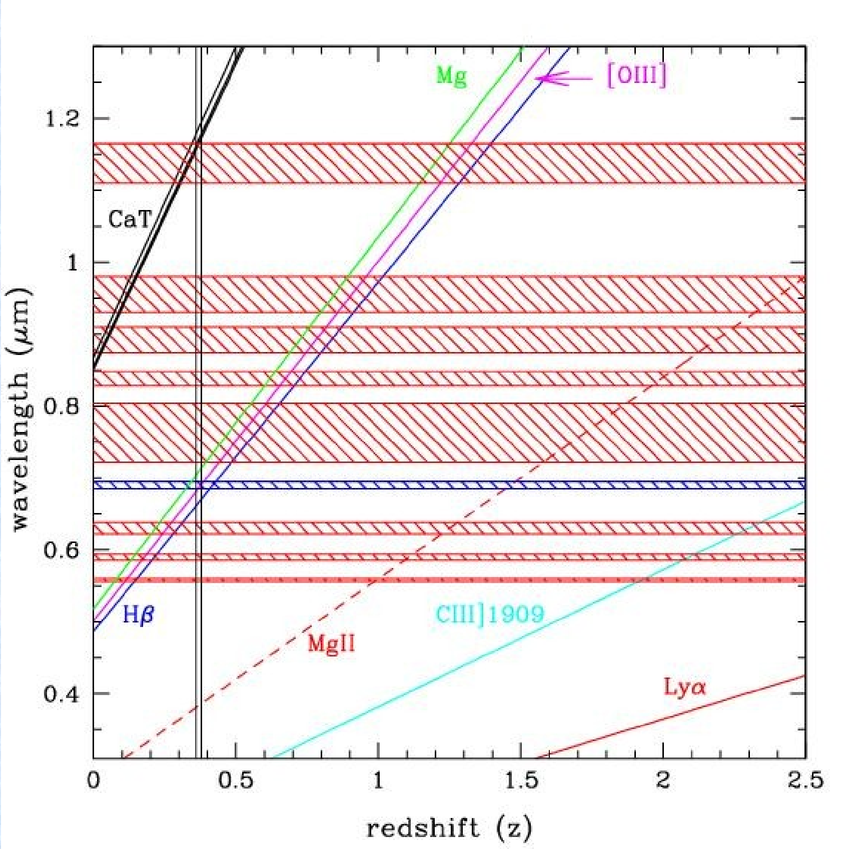
The distant universe: two problems

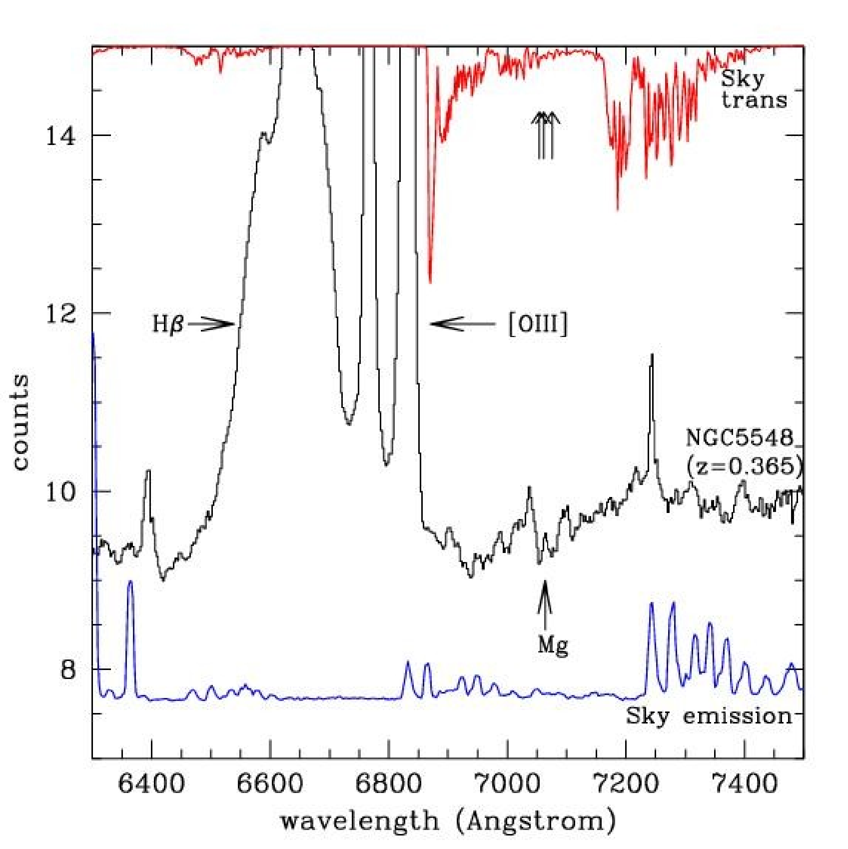
- **Black hole mass**: 1" at z=1 is ~8kpc. We CANNOT resolve the sphere of influence, active galaxies are the only option
- **Velocity dispersion**: distant objects are faint and not resolved. If the galaxy is active we CANNOT avoid AGN contamination

The distant universe: a solution, focus on Seyfert 1s

- **Black hole mass:**
  - Reverberation mapping (Blandford & McKee 1982) does not need spatial resolution.
  - Empirically calibrated photo-ionization (ECPI: Wandel, Peterson & Malkan 1999) based on reverberation masses
- **Velocity dispersion:**
  - integrated spectra have enough starlight that with good spectra it is possible to measure the width of stellar absorption features on the "featureless AGN continuum".

Black Hole Mass vs Sigma. Feasibility at high redshift



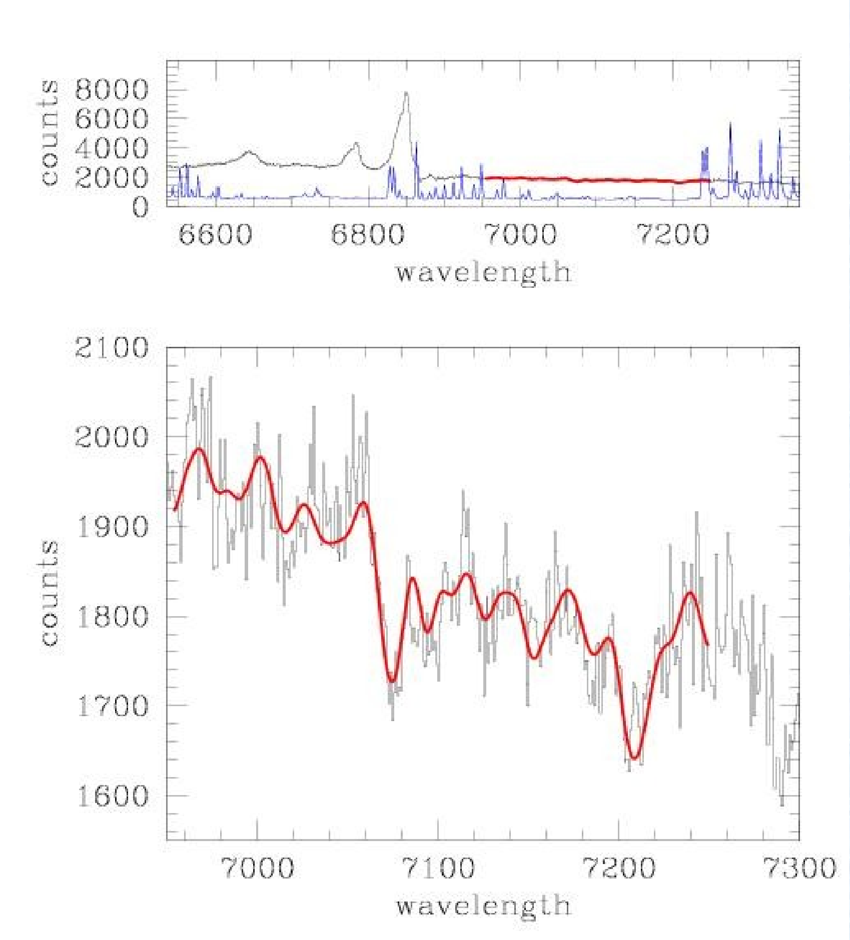


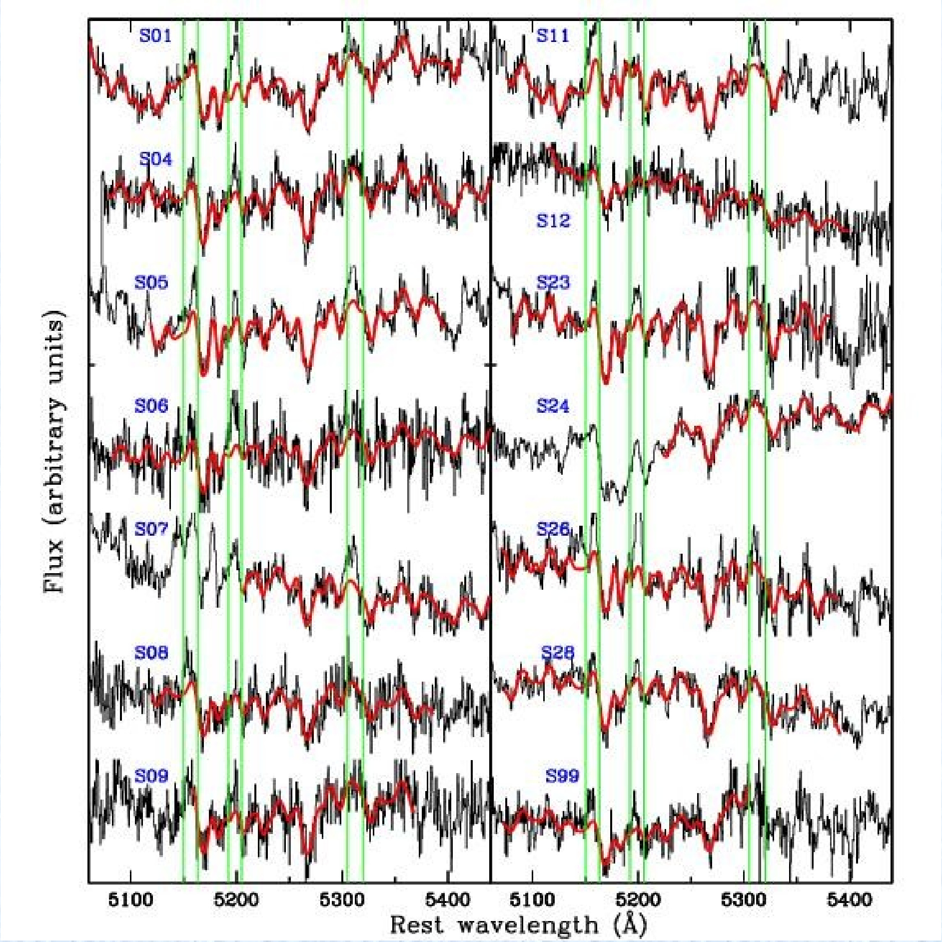
Galaxies Far Away (4 Gyrs)…

- Selected from SDSS based on redshift ($z=0.365\pm0.010$) and broad Hβ
- 20 objects observed over the past 3 yrs in the few hours when weather gave us a break.. (3/9 Keck nights)
- 14 objects so far yielded reliable sigma and black hole mass

Treu, Malkan & Blandford 2004; Woo, Treu, Malkan & Blandford 2006

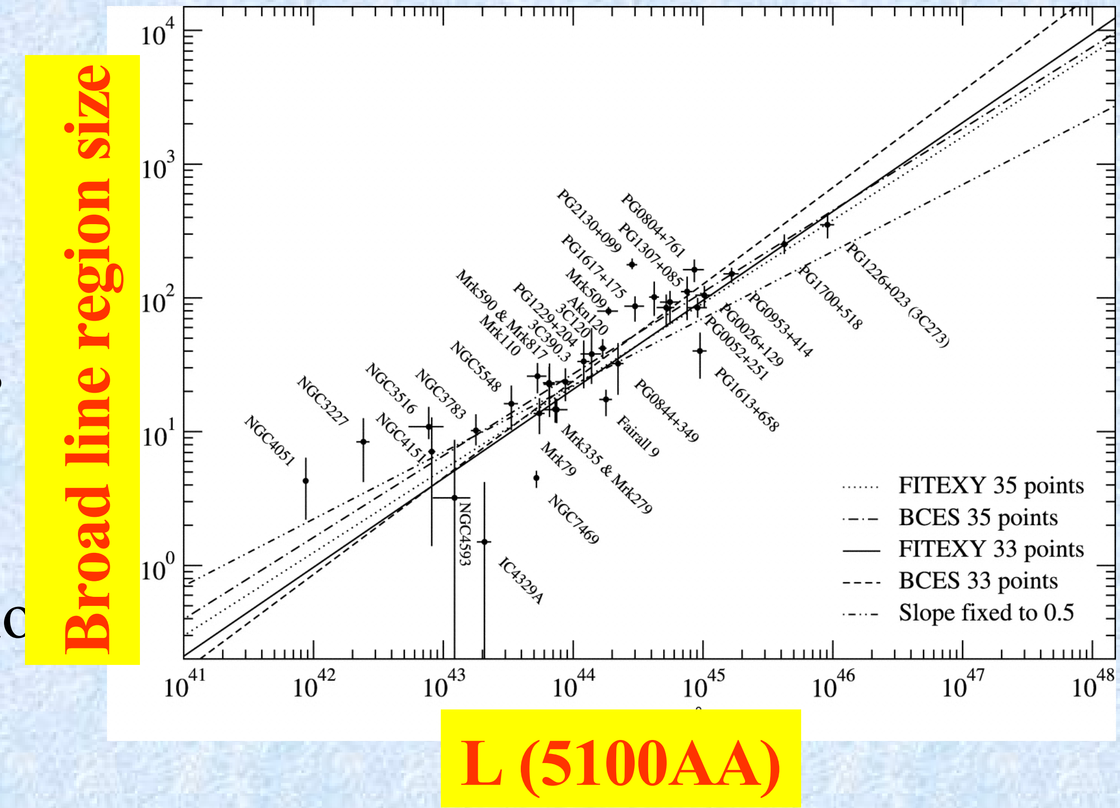
Measuring velocity dispersion.





Black-Hole Mass. Empirically Calibrated Photo-Ionization Method

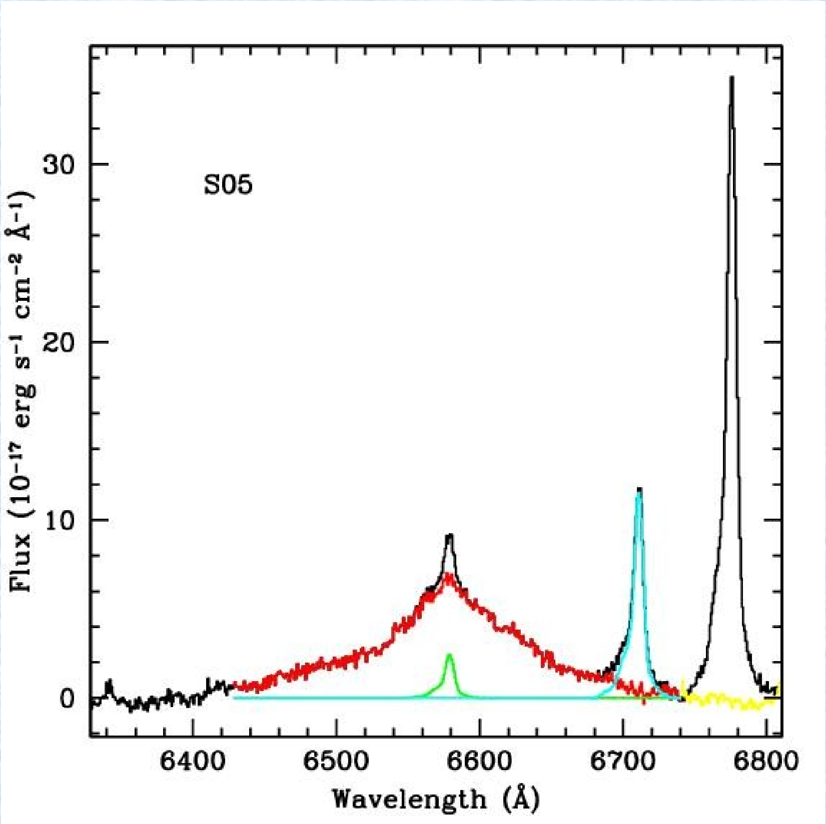
- The flux needed to ionize the broad line region scales as L(ion)/r^2. Coefficients too hard to compute theoretically
- An empirical correlatio is found, calibrated using reverberation mapping



Wandel Peterson & Malkan 1999; Kaspi et al. 2000
Kaspi et al. 2005

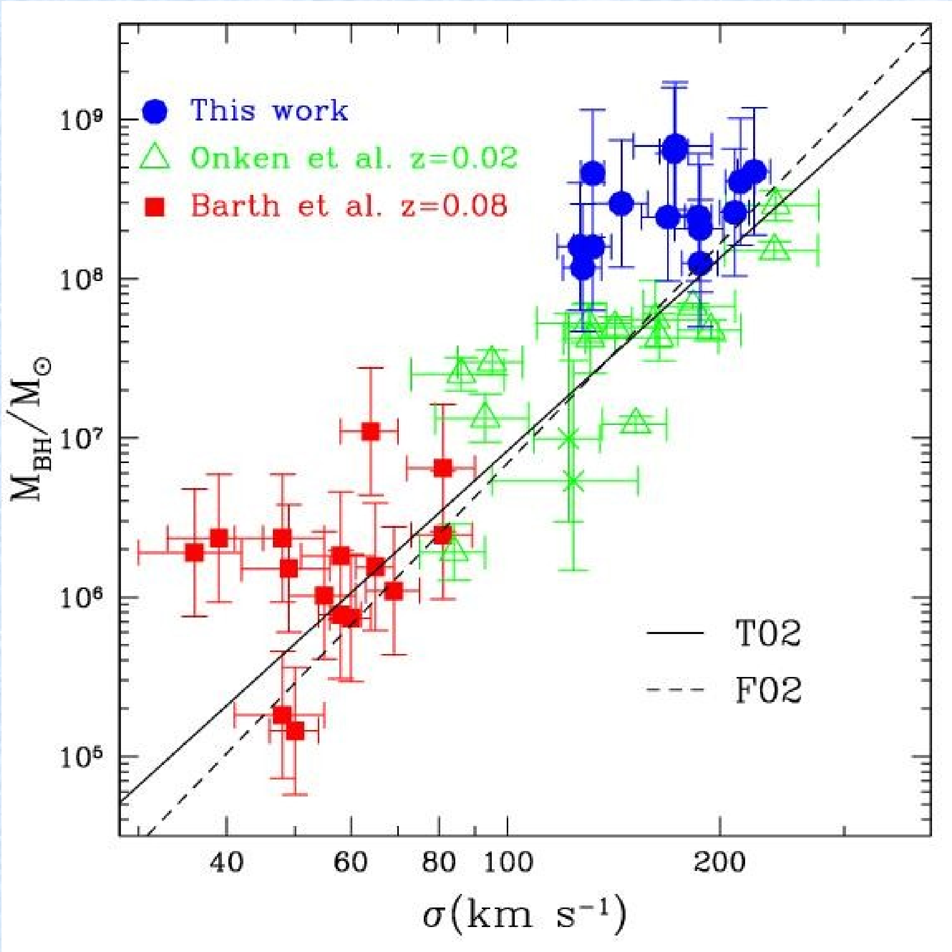
Black-Hole Mass.
Hb width determination

- Hb width from single epoch spectra provides a good estimate of the kinematics of the broad line region if constant narrow component is removed. (Vestergaard & Peterson 2006)
- **Overall uncertainty on BH mass ~0.4 dex**

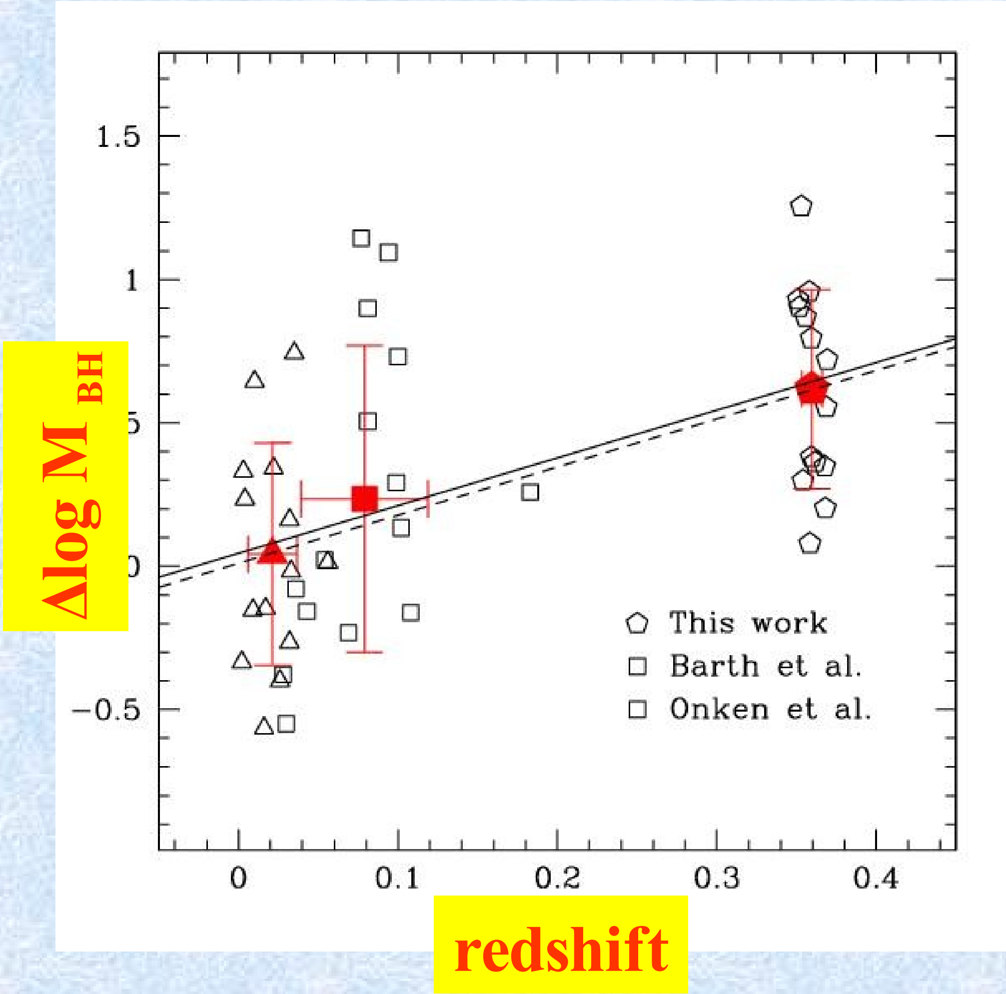


$$M_{\rm BH} = 2.15 \times 10^8 M_\odot \times \left(\frac{\sigma_{H\beta}}{3000 {\rm km s^{-1}}}\right)^2 \left(\frac{\lambda L_{5100}}{10^{44} {\rm erg s^{-1}}}\right)^{0.69}$$

The Black-Hole Mass vs Sigma relation at z=0.36



The Black-Hole Mass vs Sigma relation at z=0.36; cosmic evolution?



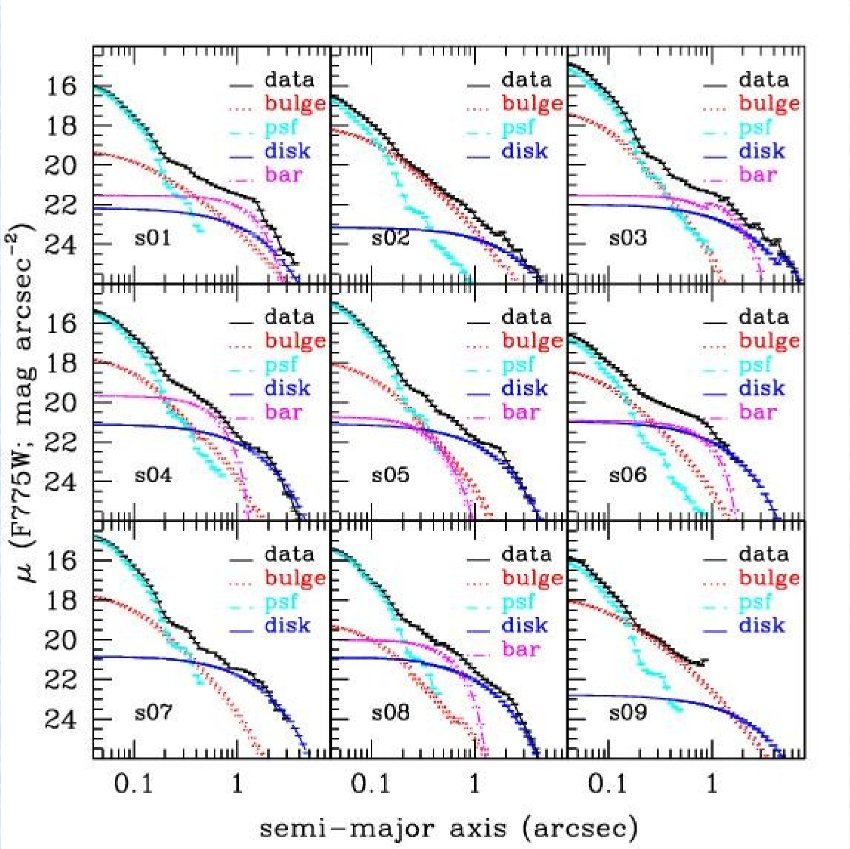
$\Delta \log M_{BH} = 0.62 \pm 0.10 \pm 0.25$ dex

Conclusions.

- Bulges at z=0.36 smaller than their black-hole masses suggest. Three possibilities:
  1. Selection effects
  2. Problem with the ECPI method
  3. Evolution

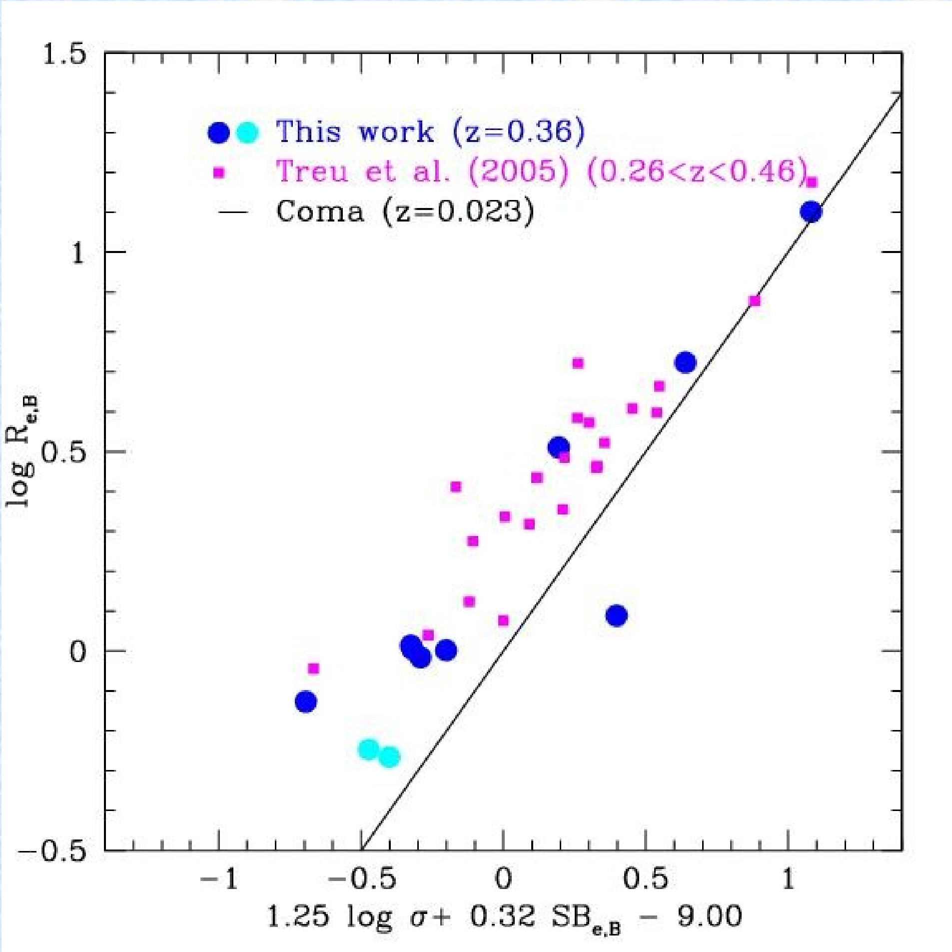
Is evolution real? An independent check with other scaling relations

- Black holes and spheroids follow other scaling relations, such as M_{BH}-L_B, and the Fundamental Plane
- With available HST-ACS images we can explore those other scaling relations to improve our understanding
- HST photometry gives nuclear luminosity and improves MBH.



First do surface photometry; GALFIT, etc…

The FP of active (and inactive) bulges/spheroids at z~0.4

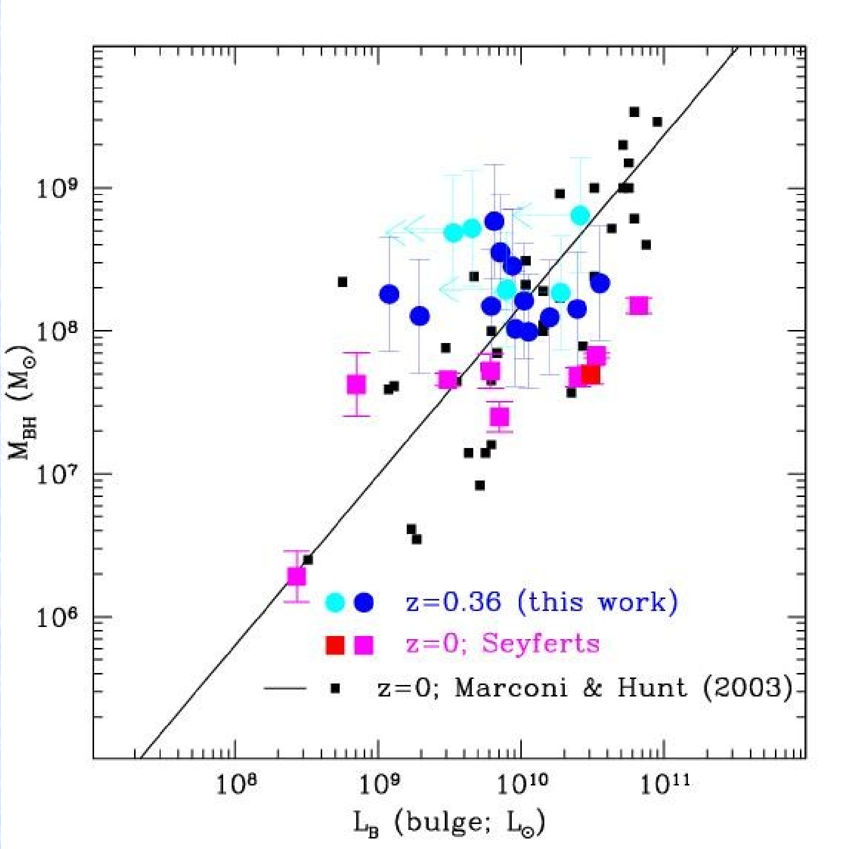


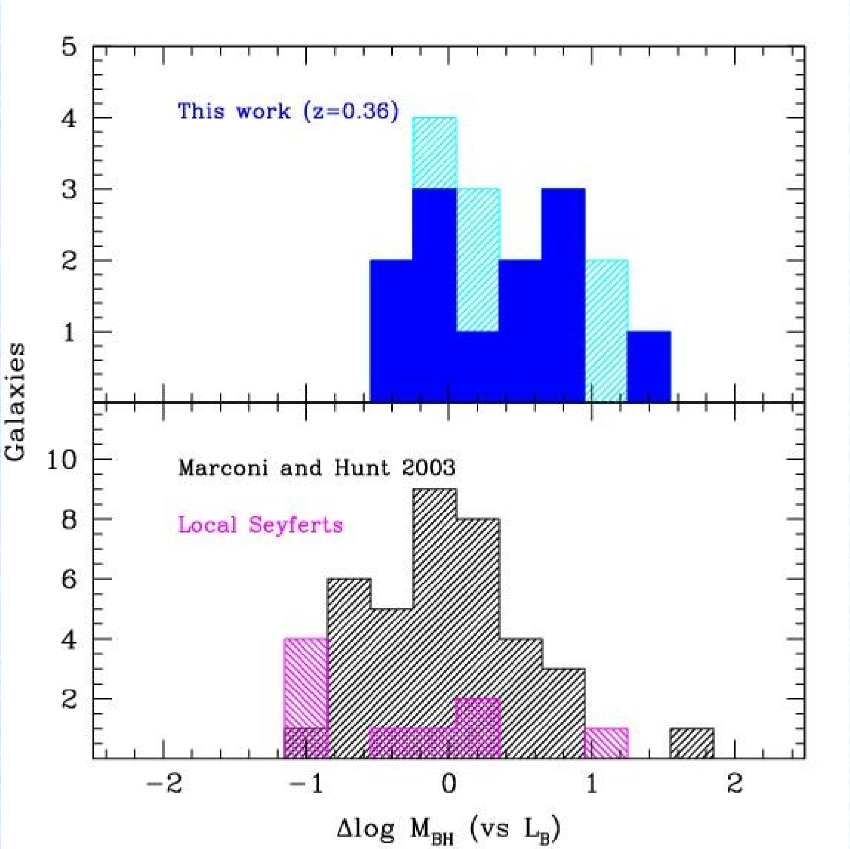
Spheroids are overluminous for their mass

Generally interpreted as passive evolution

Treu et al. 2006b

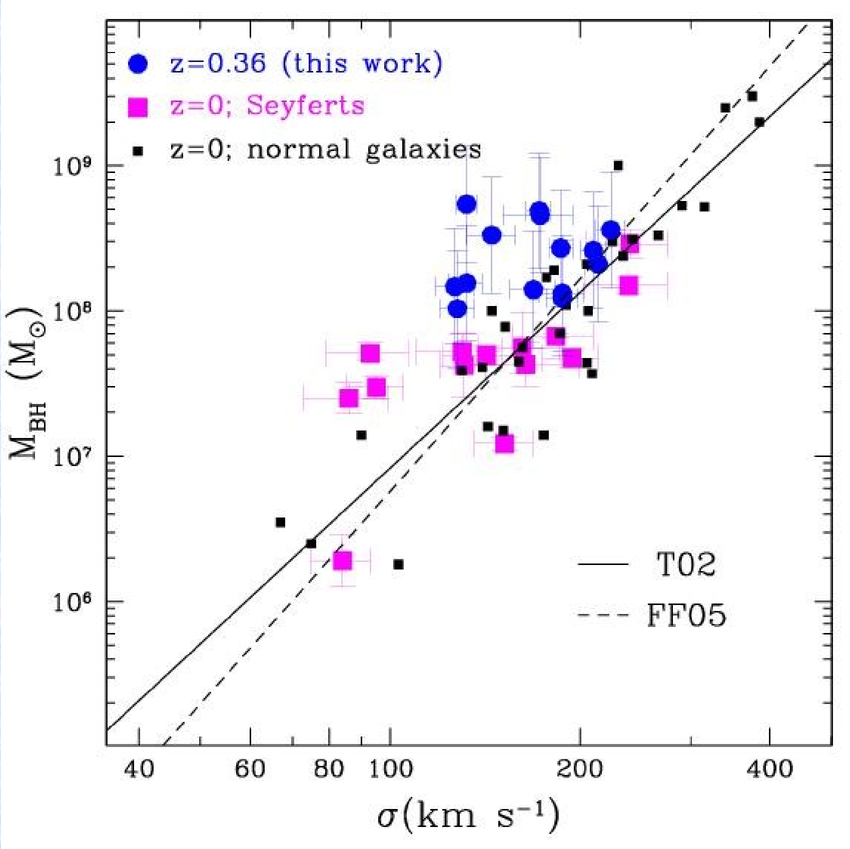
The black hole mass bulge luminosity relation

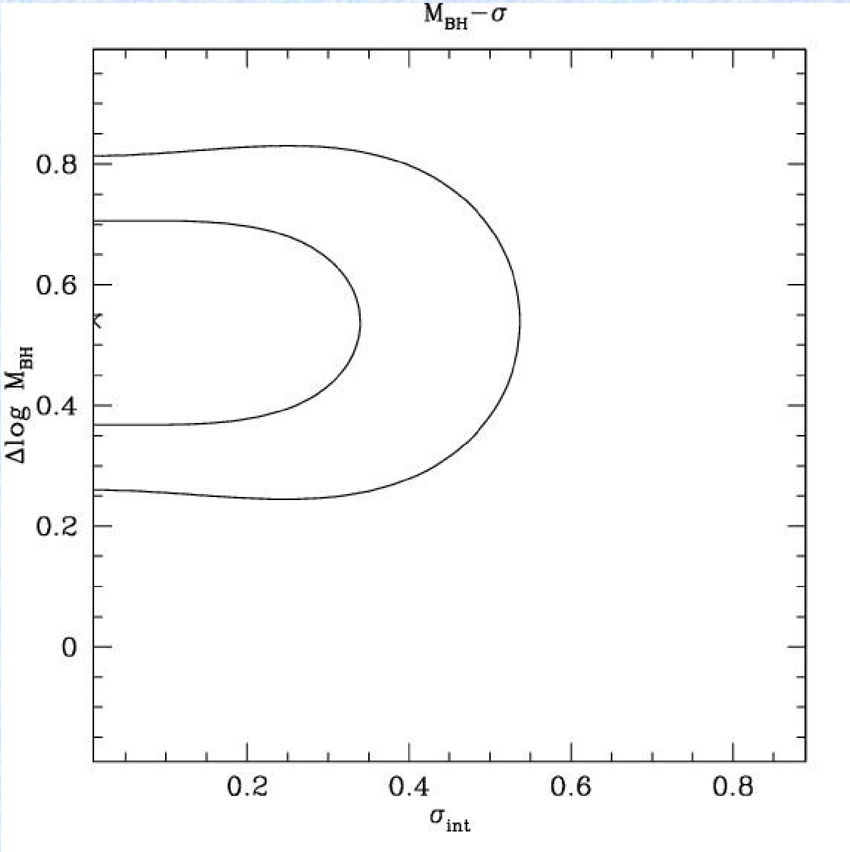




$\Delta \log M_{BH} > 0.42 \pm 0.14 \pm 0.07$ dex

The black hole mass velocity dispersion relation, updated





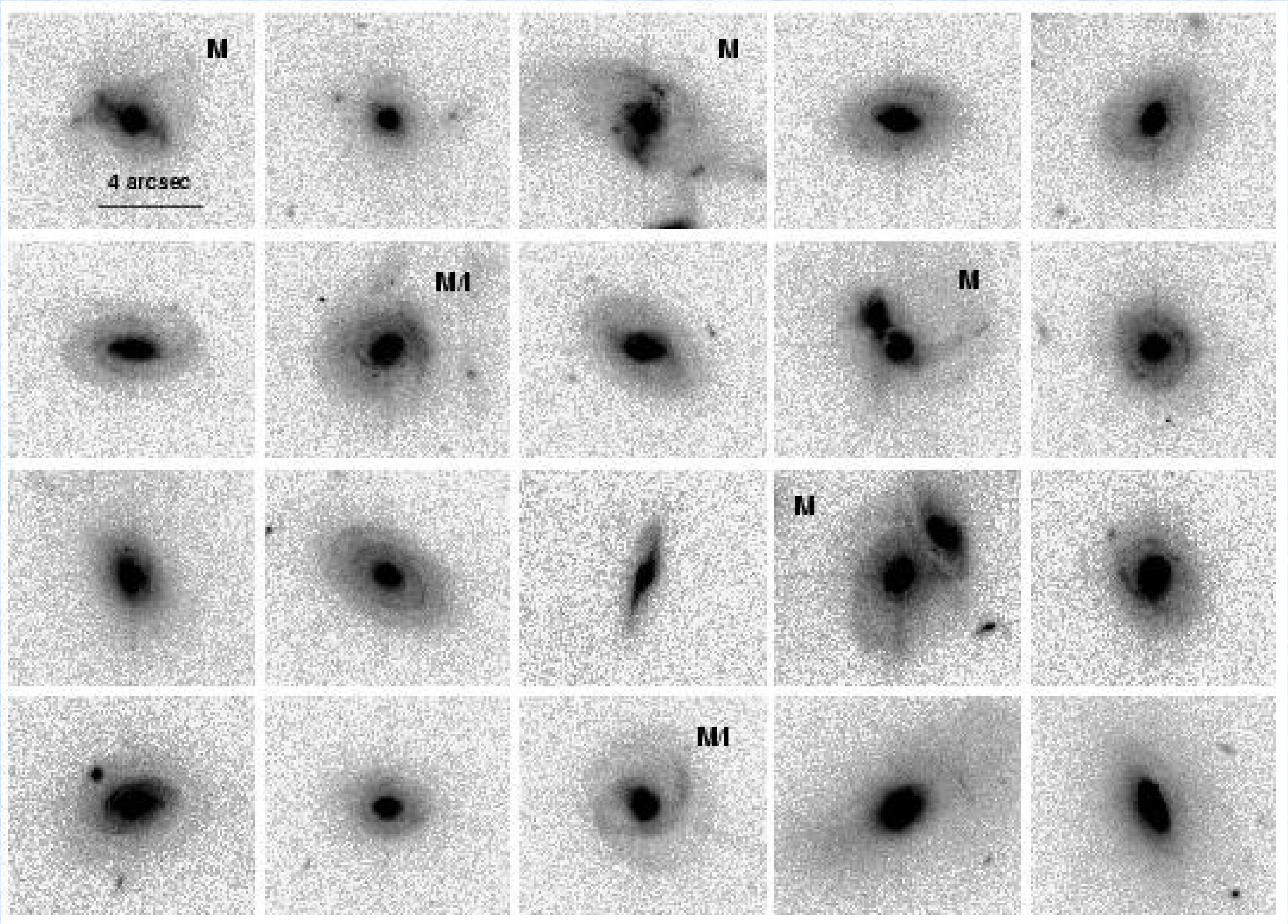
$\Delta\log M_{BH} = 0.54\pm0.12\pm0.21$ dex

Conclusions.

- **Analysis of HST images confirms what is found via spectroscopy**
- **Bulges at z=0.36 are less luminous/massive than their black-hole masses suggest. Three possibilities:**

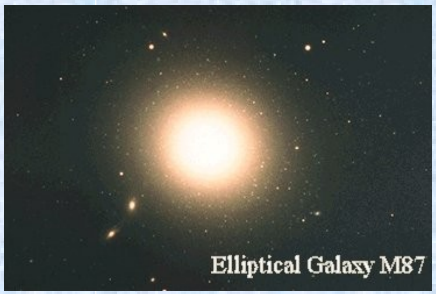
1. **Selection effects**
2. **Problem with the ECPI method (masses overestimated?)**
3. **Evolution**

Recent evolution of (active) bulges?



Treu et al. 2006b

What happens during mergers? I



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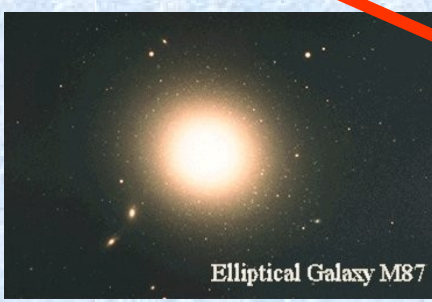
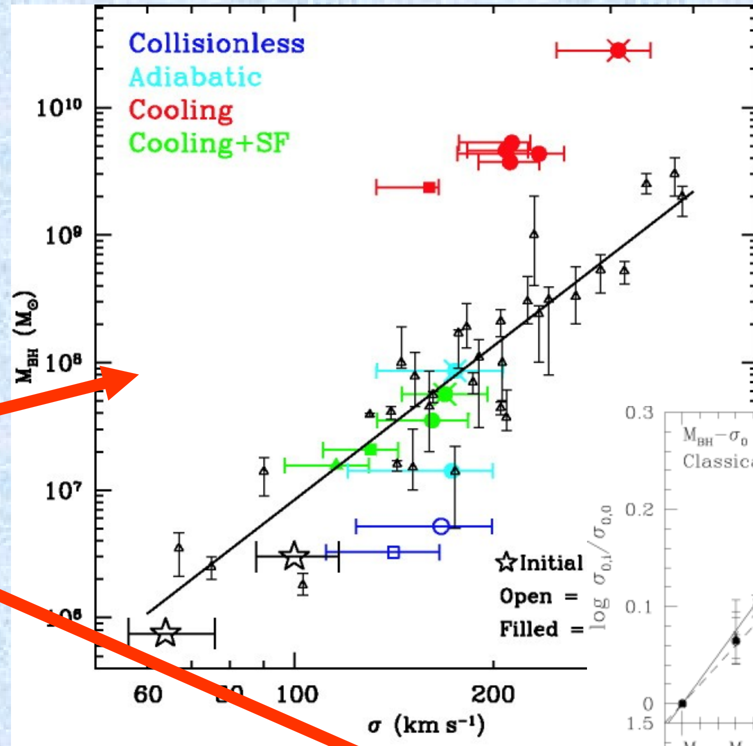
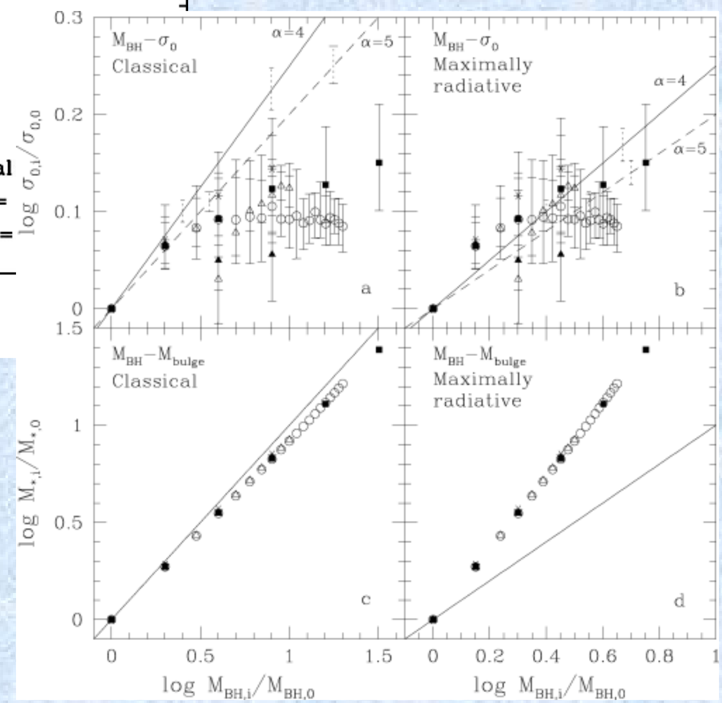


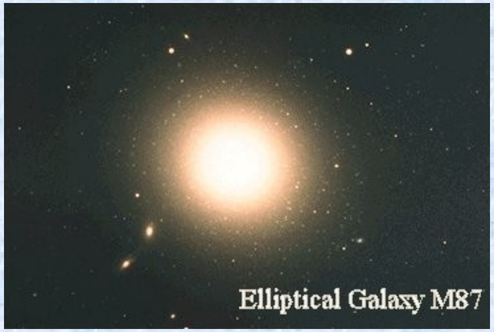


Kazantzidis et al. 2005



Nipoti, Londrillo & Ciotti 2003
Also Boylan-Kolchin et al. 2006

What happens during mergers? II



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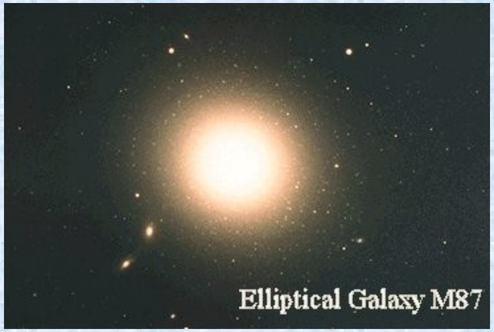

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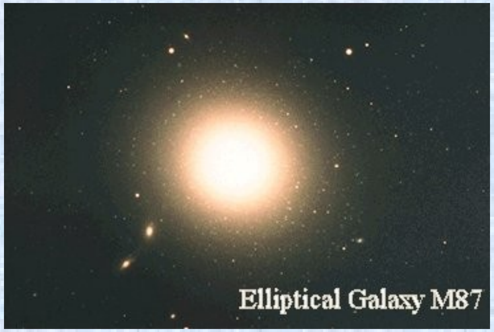
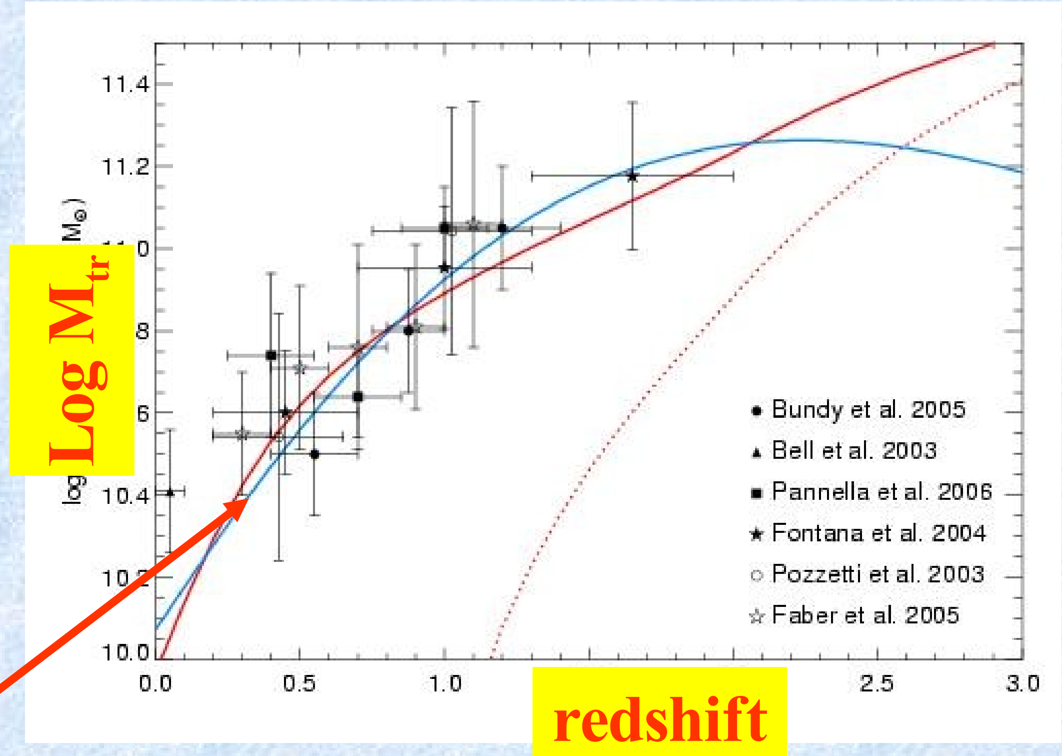


What happens during mergers? III

- Velocity dispersion can stay the same (collisionless mergers with no orbital energy) or increase (especially in collisional mergers)
- Two+ Black-holes can merge, with or without losses for gravitational radiation, or not.. (one or more of the black holes can be expelled)
- One (or two) black holes can increase their mass by accretion
- Luminosity of the bulge should increase in any case.. (even without star formation)

Closing remarks: conjectures and predictions…

- Galaxies form initially as blue disks
- Major mergers 1) trigger AGN activity, 2) quench star formation, 3) increase the bulge size
- The characteristic mass scale decreases with time ('downsizing'), consistent with **that of our galaxies at *z*=0.36**

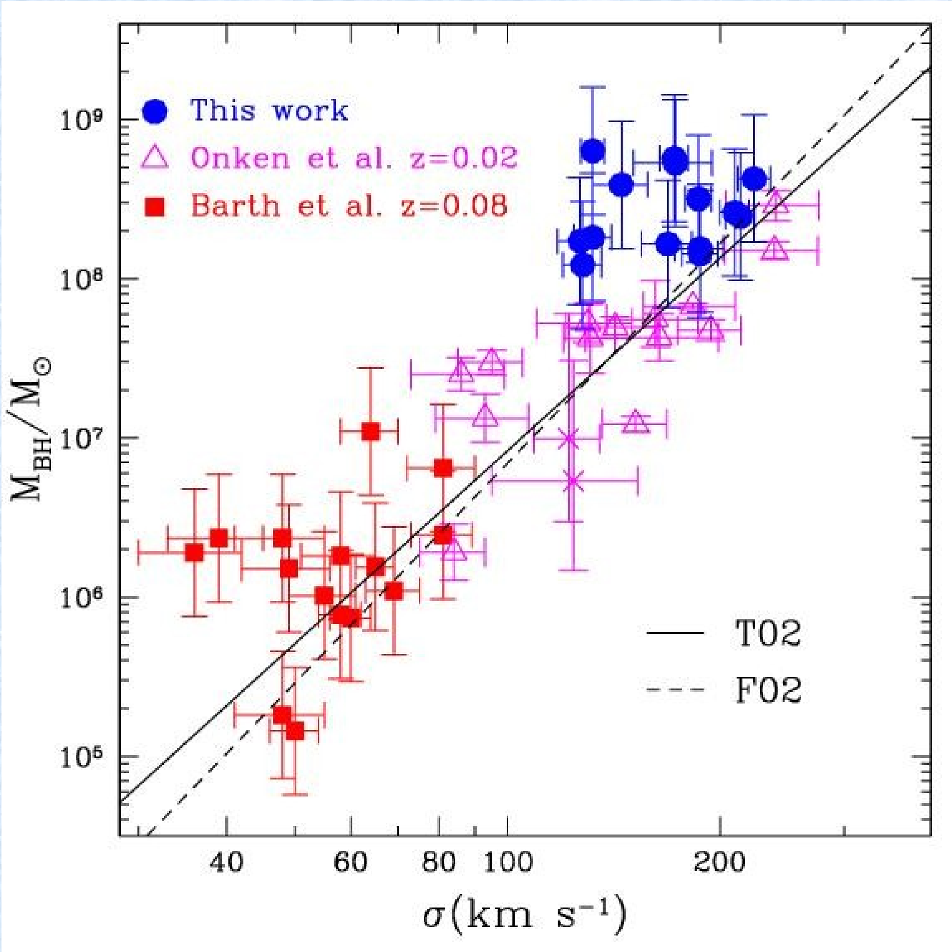


Hopkins et al. 2006

The M-sigma relation should be already in place for larger masses!

The end

The Black-Hole Mass vs Sigma relation at z=0.36



Redone with recent recalibration by Bentz et al. 2006, no change!