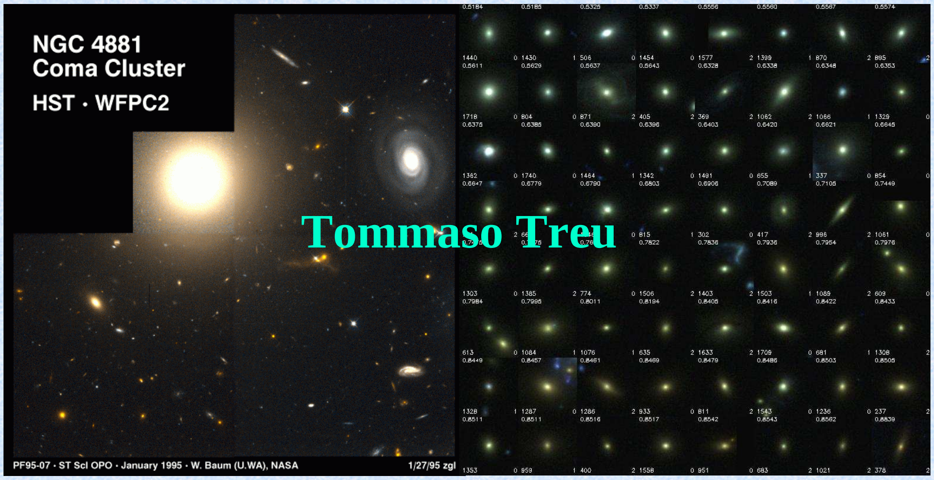
Cosmic Evolution of Spheroids: Dark Halos, Stellar Mass, and Supermassive Black-Holes

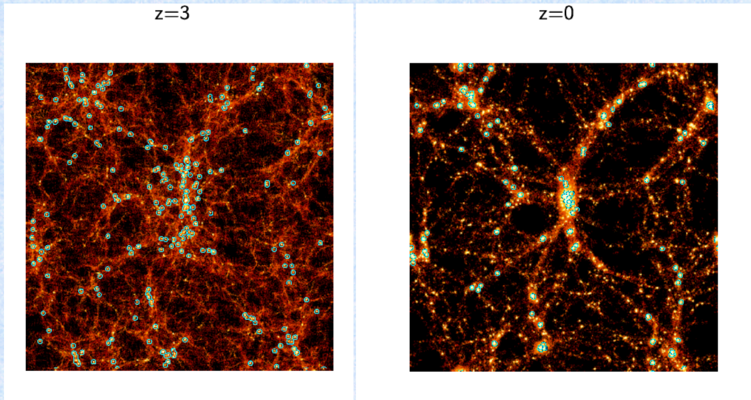


Tommaso Treu

Outline

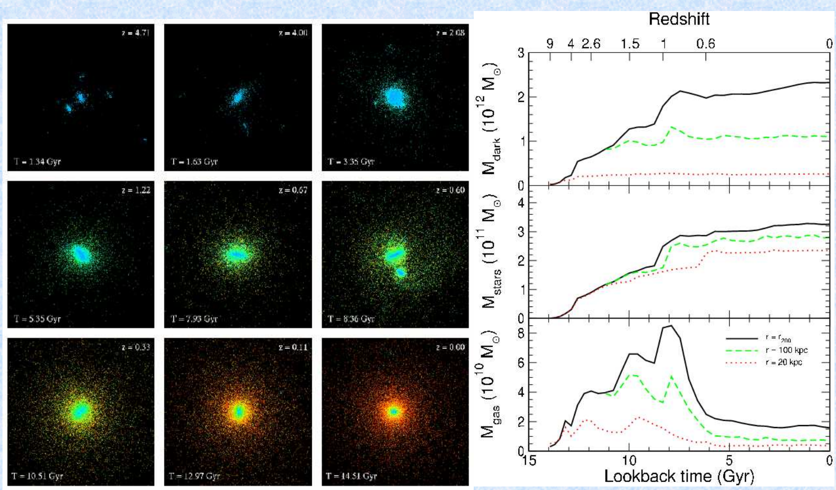
- Introduction: modeling galaxy formation
- Three key observational goals at high-z:
  1. Do high-z E+S0s live in dark matter halos? What can we learn about them?
  2. What is the relationship between luminous and dark matter? When is stellar mass formed?
  3. When and how do super-massive black holes and spheroids (E+S0+bulges) form and evolve
- Conclusions

Hierarchical models



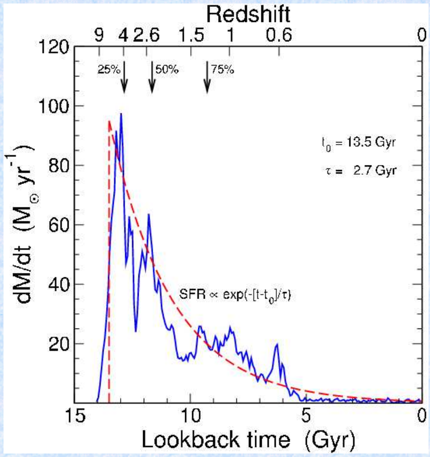
- Galaxy form in dark matter halos.
- Galaxy and star formation in clusters in anticipated.
- E/S0 are “younger” in the field than in clusters (Kauffmann 1996; Diaferio et al. 2001).

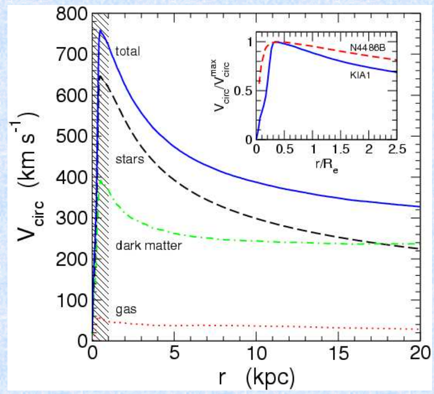
Detailed cosmological simulations. I



Meza, Navarro, Steinmetz, Eke 2003

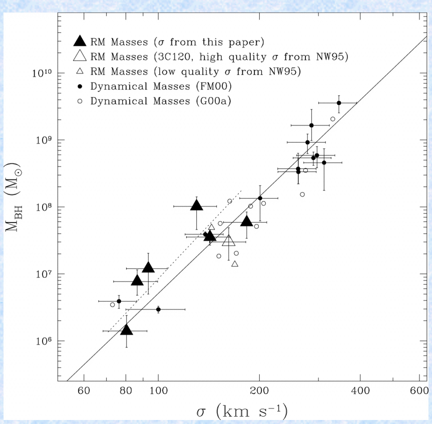
Detailed cosmological simulations. II

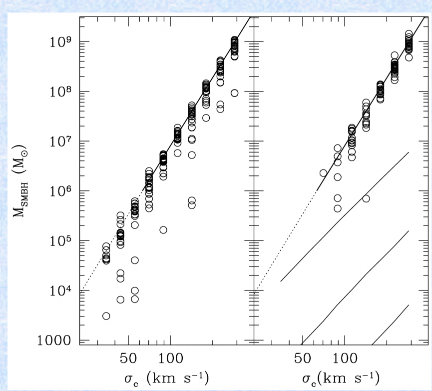




Meza, Navarro, Steinmetz, Eke 2003

The black hole connection





Ferrarese & Merritt 2001

Volonteri Haardt & Madau 2003

Clues from the local Universe (“Fossil Evidence”)

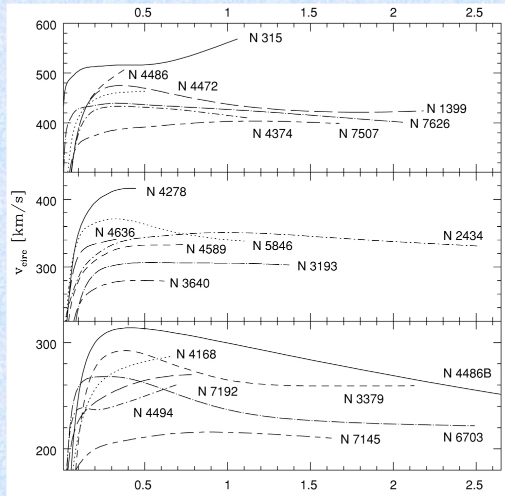
- Most stars are “old”
- Color, M/L, Mg, black hole mass… correlate with velocity dispersion (and mass?)
- At any given mass, very little scatter in luminosity, color, metallicity
- No significant difference in scaling laws for cluster and field E/S0

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

1: Dark Halos

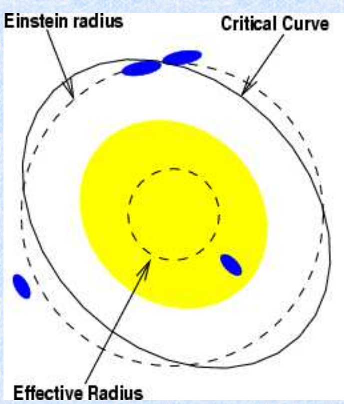
The mass distribution of E/S0. z=0

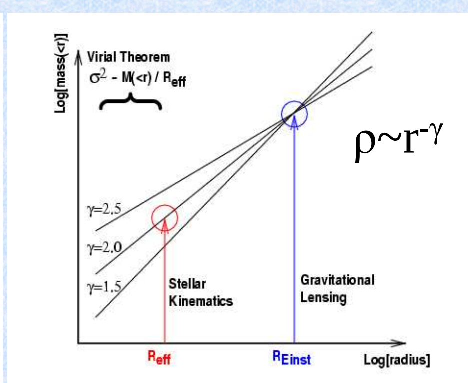
- Evidence for dark matter from dynamics and X-ray. Dark matter distribution poorly constrained, because of paucity of dynamical tracers at large radii.
- "Traditional" dynamical tracers at large radii (PN, Globular clusters) inapplicable at z>0.



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

Z>0: lensing + dynamics





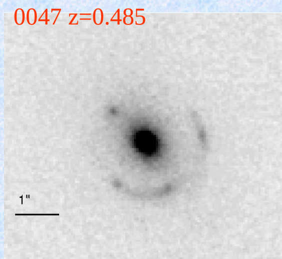
The Lensing Structure and Dynamics (LSD) Survey:

- Sample: 11 E/S0 that are gravitational lenses, i.e. all known suitable systems
- Aim: measure extended kinematic profiles along major (and minor) axis or central velocity dispersion.
- Status: COMPLETED DECEMBER 2002!
  In 8 nights of ESI at the Keck-II we have obtained extended kinematic profiles for 10 lenses and 1 central velocity dispersion (MG2016+112 z=1.004).
  Typical integration time 6 hrs in excellent conditions.

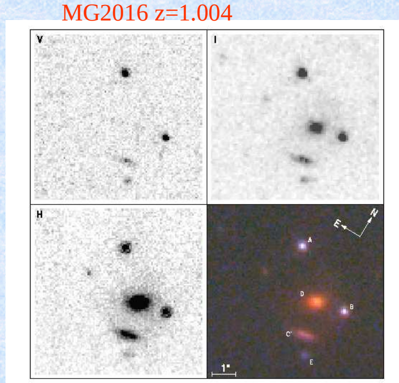
Treu & Koopmans 2002a, 2003,2004; Koopmans & Treu 2002, 2003

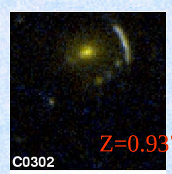
High redshift sample

0047 z=0.485

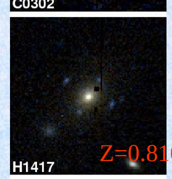


MG2016 z=1.004

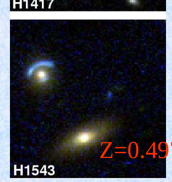




Z=0.937



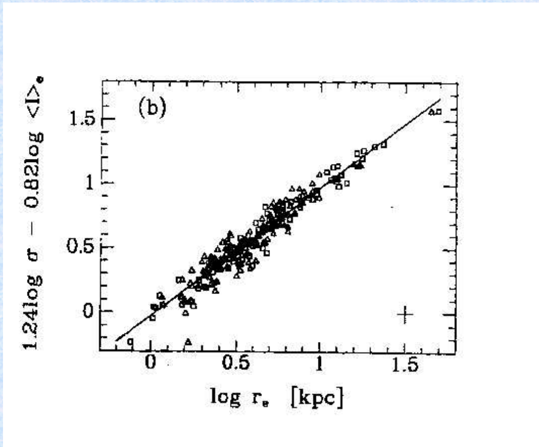
Z=0.810



Z=0.497

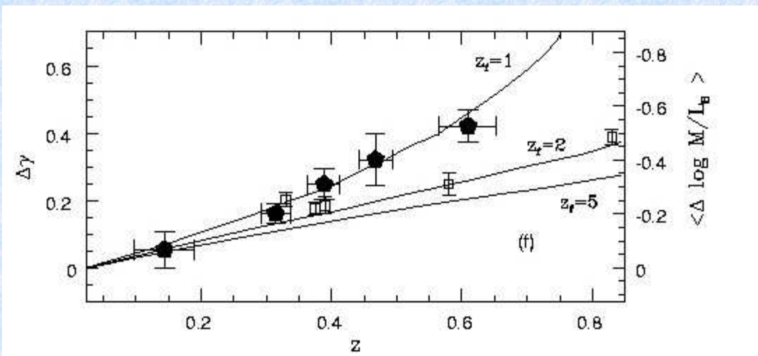
The Fundamental Plane: an additional constraint to M/L

- Empirical correlation between size, luminosity and velocity dispersion
- Gives "effective M/L" at "effective mass"



Dressler et al. 1987; Djorgovski & Davis 1987;
Bender Burstein & Faber 1992; Jorgensen et al. 1996

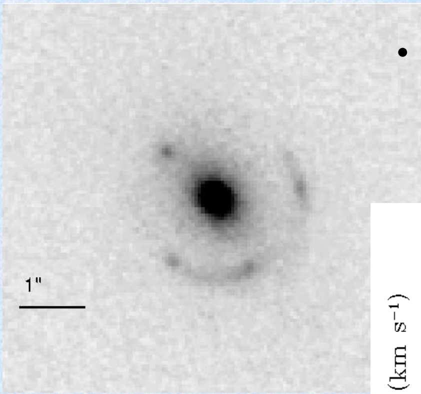
The FP as an additional constraint



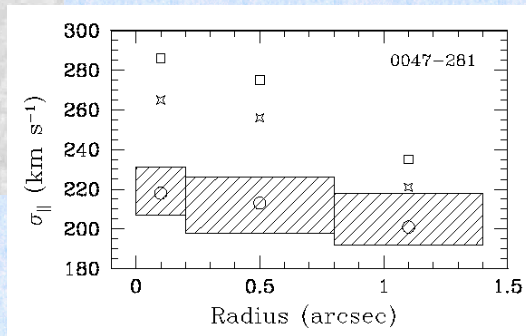
Treu et al. 1999,2001,2002; see also van Dokkum et al. 2001, Gebhardt et al. 2003; van Dokkum & Ellis 2003

Assuming constant slopes and no structural evolution, the offset to the local FP measures the evolution of M/L, hence combined with local measurements, yields M/L at any given z.

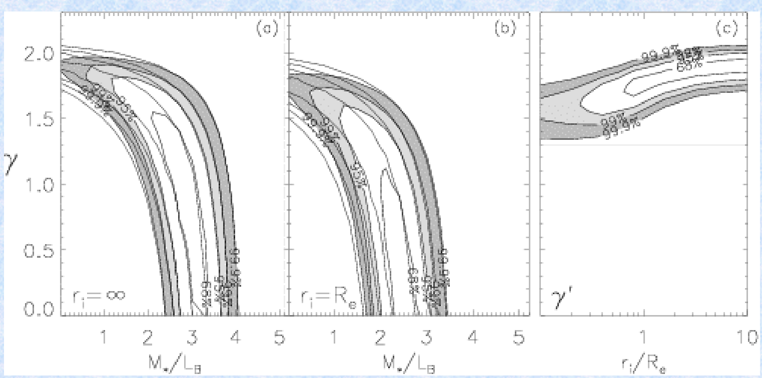
Example of the data: 0047 at z=0.485



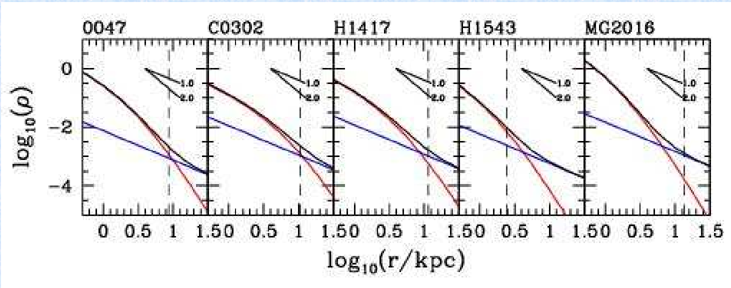
- 5.75 hrs integration yielded velocity dispersion profile to ~5 % accuracy



Example of the results: 0047



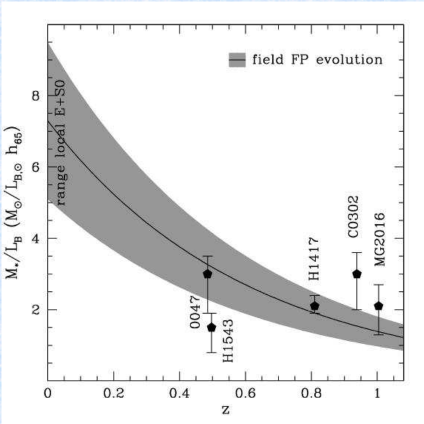
Results. I: luminous and dark matter in high-z E/S0s



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

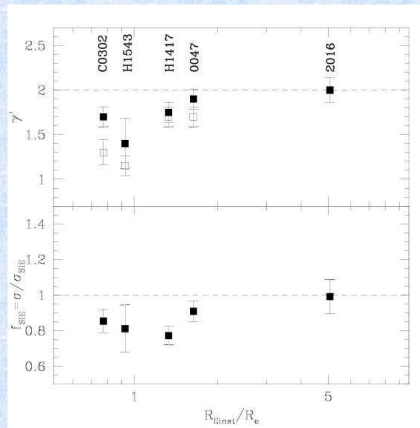
Results. II: stellar populations vs dynamical evolution

- 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



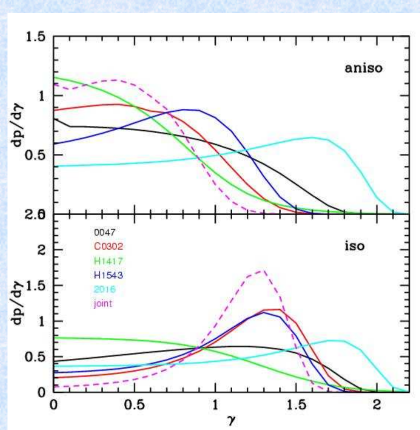
Results. III: the homogeneity of lens galaxies

- The total mass distribution of lens galaxies is close to isothermal, i.e. logarithmic slope ~-2 within 0.3, suggestive of dark-luminous matter conspiracy
- Isothermal approximation not accurate enough for precision measurements, like the Hubble Constant



Results. IV: the inner slopes of dark matter halos

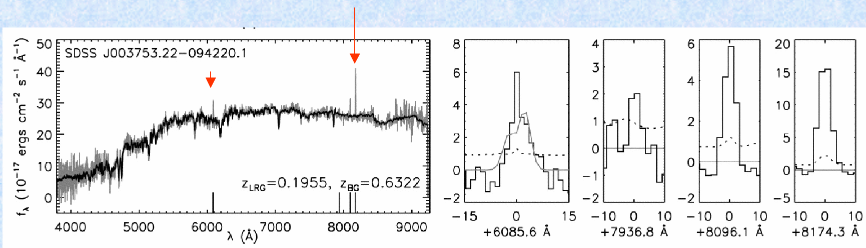
- CDM predicts inner slopes of 1-1.5
- Consistent with the observed data only if
  - Baryonic collapse does not steepen the potential
  - Pressure tensor is not strongly radial



LSD so far..

- Mass distribution of E/S0 galaxies can be measured 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?
- Inner slope of dark matter halos shallower than 1-1.5, consistent with NFW only for no steepening during baryonic collapse and isotropic orbits. CDM ~ok

Building a larger sample: SLACS

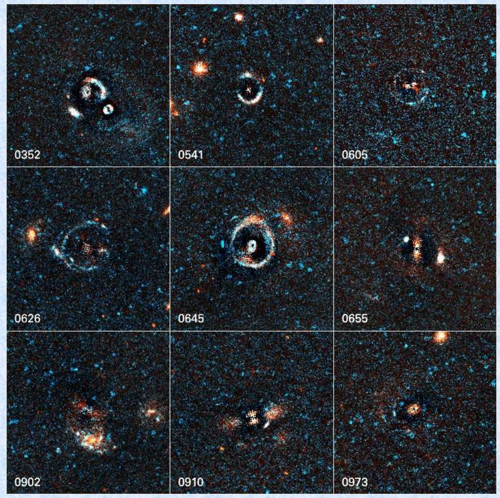


- Candidate lenses selected from SDSS as red galaxies with “spurious” emission lines
- 49 candidates from SDSS-DR1

Bolton, Burles, Koopmans, **TT**, Moustakas

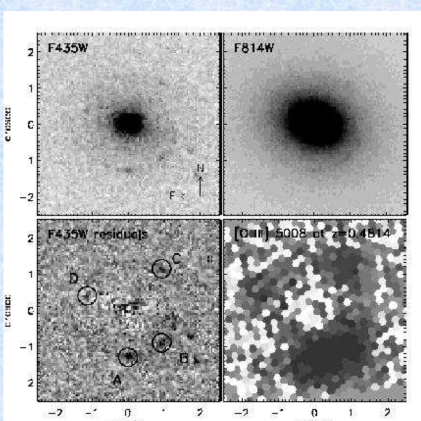
Building a larger sample: SLACS

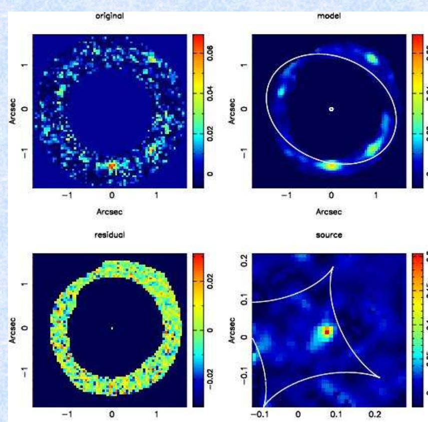
- Lenses confirmed with HST-ACS “snapshot” imaging (7 minutes per filter B and I)
- >10/17 confirmed so far



Bolton, Burles, Koopmans, **TT**, Moustakas

SLACS: the first target

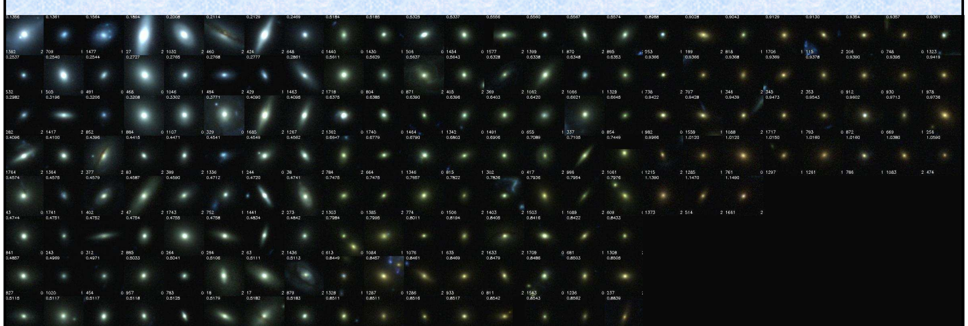




Bolton, Burles, Koopmans, **TT**, Moustakas, 2004, ApJL

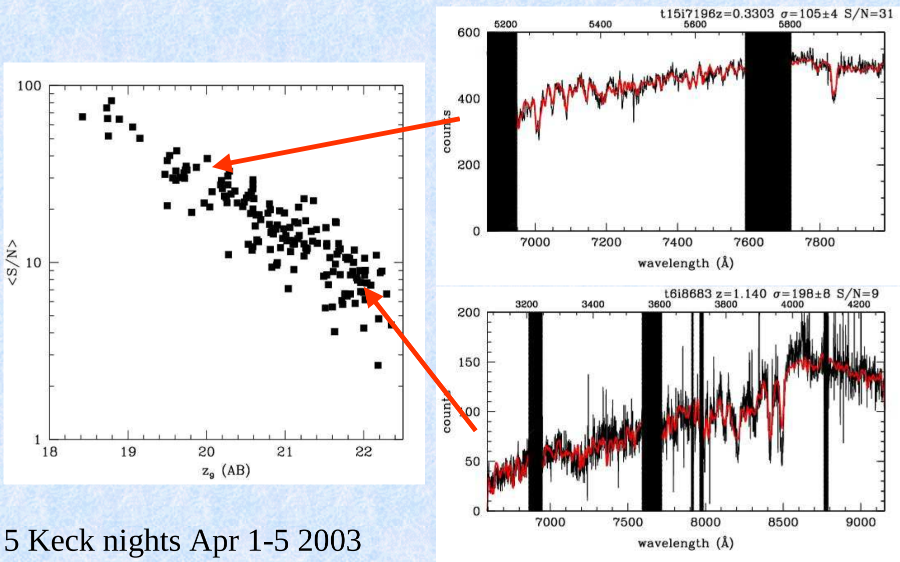
2: Stellar Mass

Star formation history of E+S0s



Treu, Ellis, Liao, van Dokkum + DEEP2 Collaboration

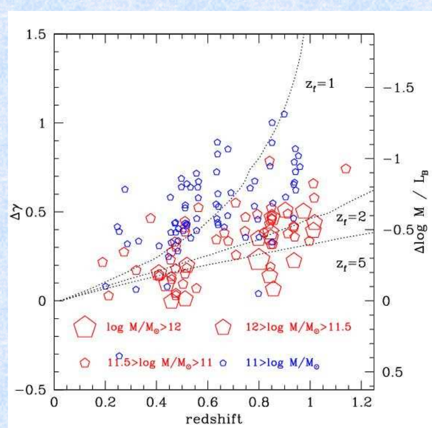
High Quality Spectra



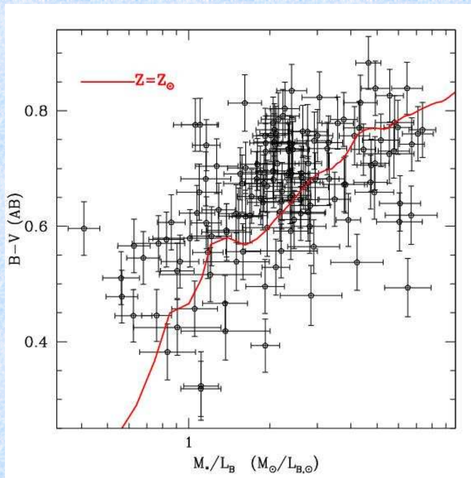
5 Keck nights Apr 1-5 2003

Dynamical Mass to Light ratios

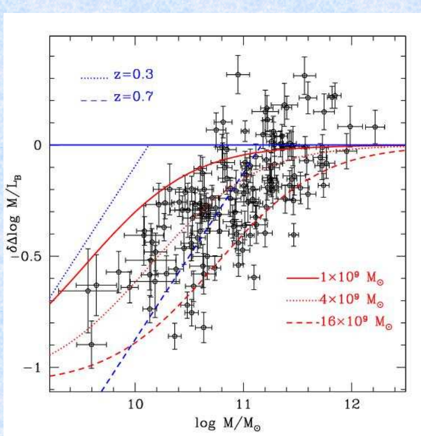
- Evolution of mass to light ratio is a function of dynamical mass
- More massive galaxies evolve slower than less massive ones, i.e. their stars are older

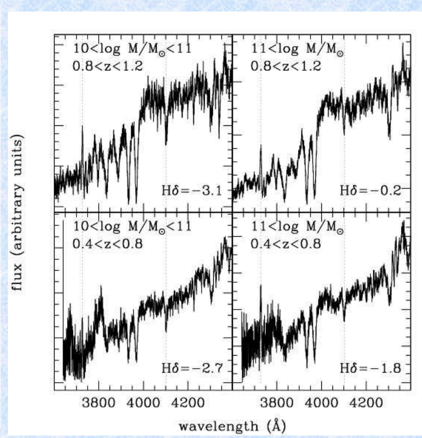


M/L traces stellar ages



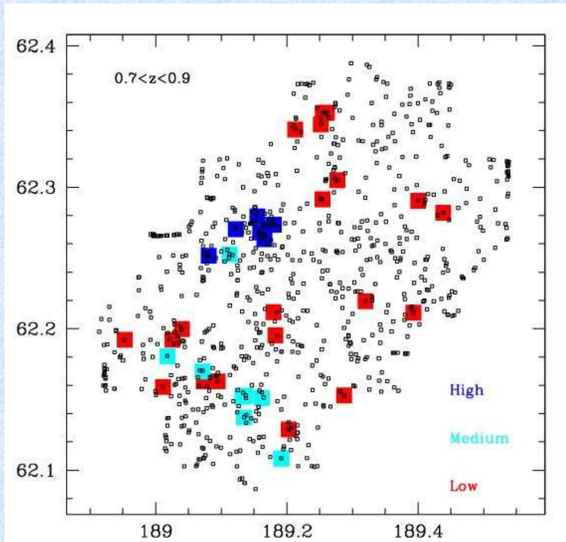
Average Stellar Age Increases with Mass





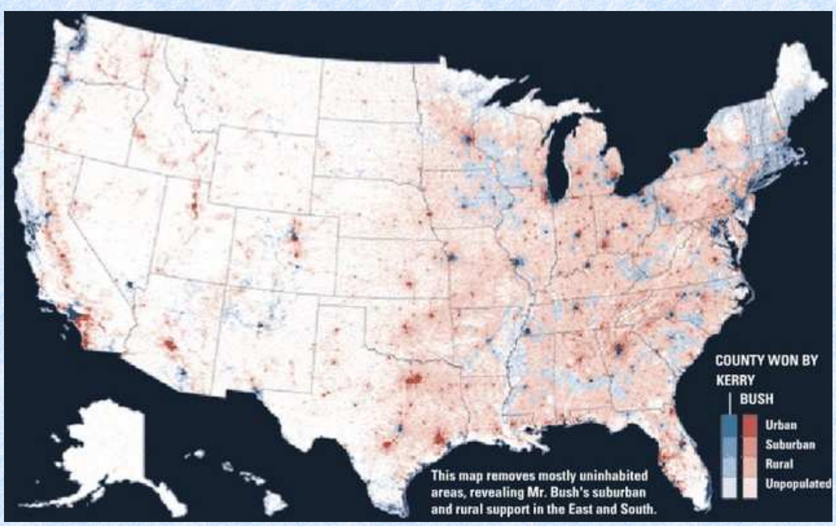
Treu et al. 2004

The importance of environment



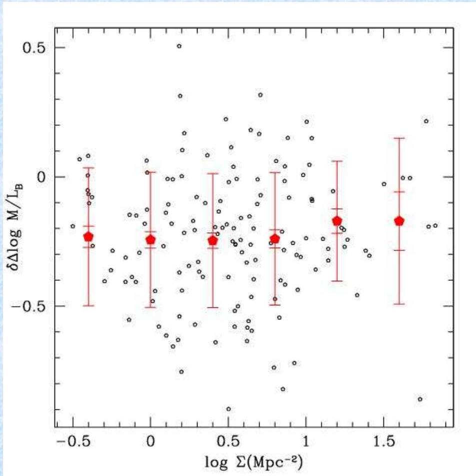
Treu et al. 2004

The importance of environment



New York Times 2004

No trend with environment is found

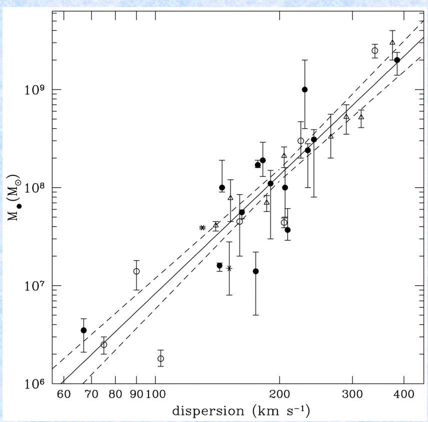


Stellar mass assembly

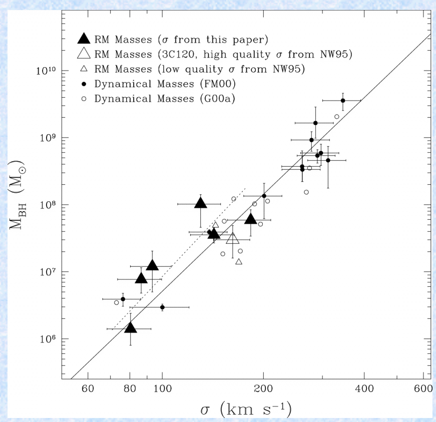
- Mass not environment is the key variable to determine stellar ages, at variance with "standard' CDM predictions (Kauffmann 1996; Diaferio et al. 2001)
- Massive early-type galaxies form their stars at very high redshift
  - If mergers, they must be "dry"
  - Feedback or other mechanism to suppress star formation in massive galaxies
- Smaller mass early-type galaxies form a significant fraction of their stars at relatively low redshift, by eating satellites or via gas rich mergers
- Is this "downsizing" compatible with hierarchical models?

3: Supermassive Black Holes

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 M_sun /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 BHMS relation so tight? (scatter consistent with measurement errors)
- When was it formed? Did a correlation between black hole mass and velocity dispersion always exist?
- What is the cosmic evolution of the BHMS relation?
  – What does its evolution tell us about unified models of black-holes and spheroids formation?

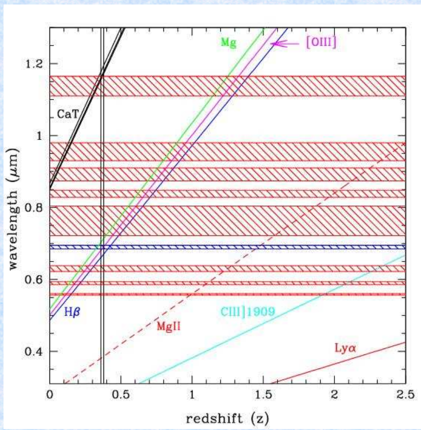
The distant universe: two problems

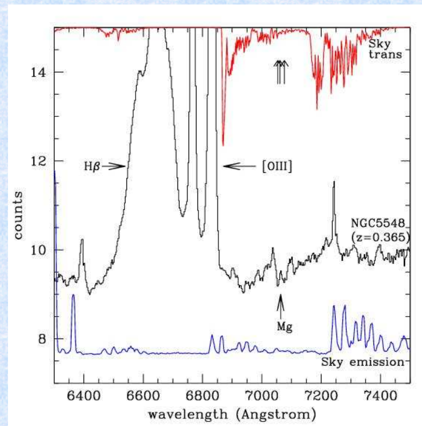
- **Black hole mass**: 1” at z=1 corresponds approximately to 8kpc, so we CANNOT resolve the sphere of influence. We need to use active galaxies.
- **Velocity dispersion**: distant objects are faint and not resolved. If the galaxy is active we CANNOT avoid AGN contamination

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

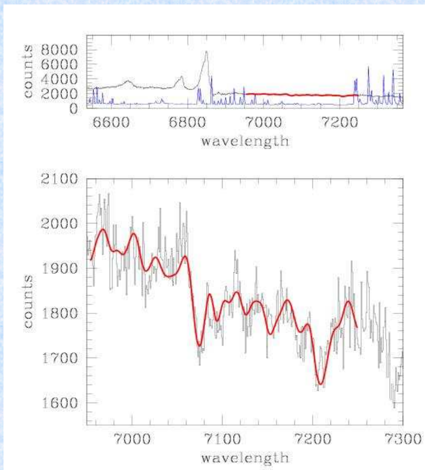


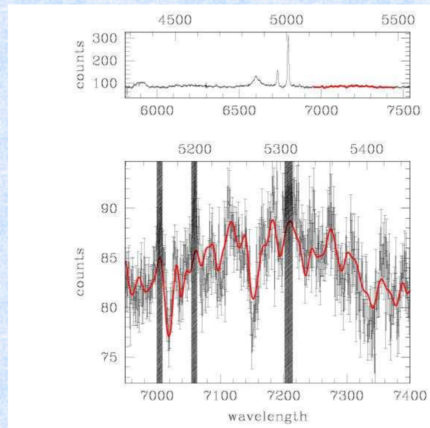


Galaxies Far Away (4 Gyrs).. Selected From SDSS

- Galaxies selected from SDSS based on redshift, width of Hb
  - Rejection of objects with strongest Fe bumps
- 15 objects observed so far (13 in 2003, 2 in 2004) in the few hours when weather gave us a break..
- 13 fully analyzed and described here. 7 objects yielded reliable sigma and black hole mass.

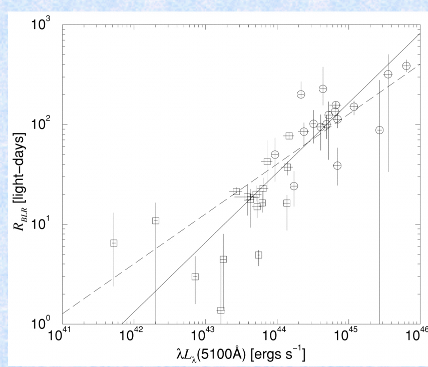
Measuring velocity dispersion.





Black-Hole Mass. Empirically Calibrated Photo-Ionization Method

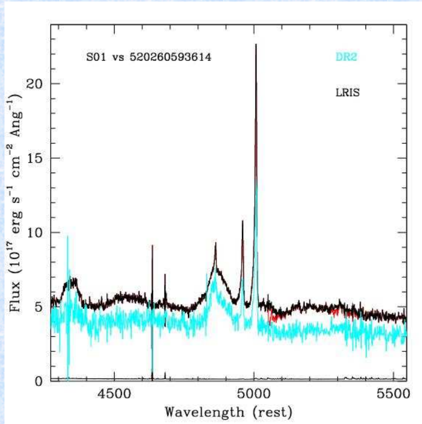
- The amount of photons needed to ionize the broad line region is proportional to L(ion)/r^2. Coefficients too hard to compute theoretically
- An empirical correlation is found, which can be calibrated using reverberation mapping



Wandel Peterson & Malkan 1999; Kaspi et al. 2000

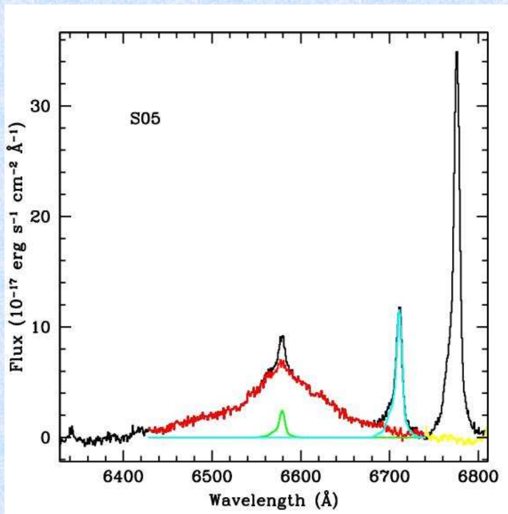
Black-Hole Mass. L5100 determination

- Calibration of spectrophotometry on SDSS-DR2 photometry
- Correction for AGN light fraction using line strength and slit correction.



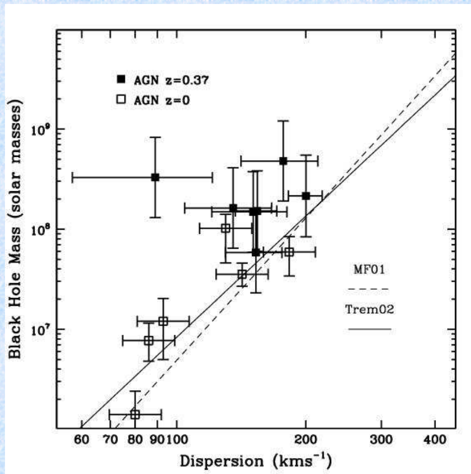
Black-Hole Mass. Hb width determination

- The Hb width should be measured on the rms spectrum (i.e. the variable component)
- Single epoch spectra provide a good approximation if constant narrow component is removed (Vestergaard 2002).



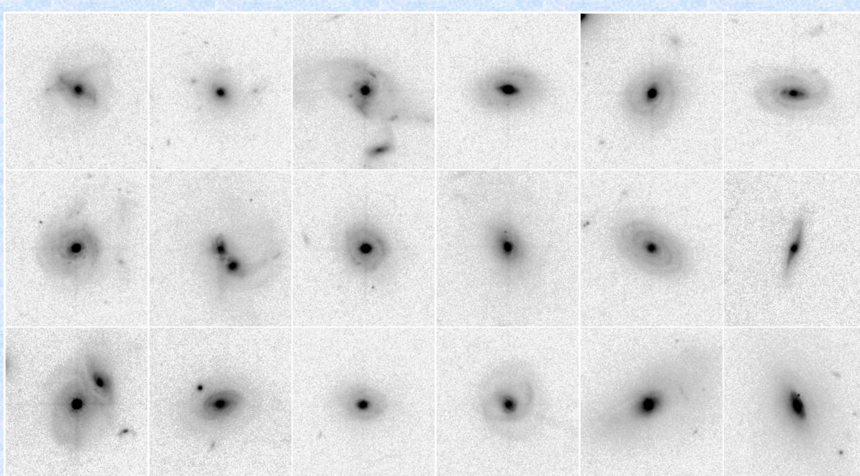
Treu, Malkan & Blandford 2004

The Black-Hole Mass vs Sigma relation at z~~0.37



Treu, Malkan & Blandford 2004

Recent evolution of (active) bulges?



HST-ACS images of the first 18/20 objects (GO-10216; PI Treu)

Conclusions

- **It is possible to measure black-hole mass and sigma at z>0.**
- **For our sample of Seyferts at z~0.4 (i.e. 4 Gyrs ago) at fixed black hole mass corresponds a smaller spheroid mass.**
- **Bulges of active spirals appear to have undergone significant evolution in the past 4 Gyrs, consistent with the high interaction rate observed in the HST images.**

Coming up..

- Reverberation mapping campaign ended at Lick on Nov 3 2004 (20 nights allocated)
- Complete the sample of 20 objects and increase success rate at Keck (proposal submitted to UC-TAC for 2005A)
- HST imaging of 20 galaxies to be completed in 2004/2005
- Higher z.. >2005

The end