Dynamics of High Redshift Galaxies

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Lecture plan:

1. **Introduction. Galaxy kinematics at high redshift.**

2. **Dynamics of elliptical galaxies at high redshift and evolution of the Fundamental Plane.**

3. **Evolution of the black hole mass vs galaxy mass relation. Dynamics without kinematics.**

4. **Future developments in the study of the dynamics of high redshift galaxies.**

Early-Type vs Ellipticals

- Historical difference rather than real.
- Early-type galaxies include lenticulars (S0), ellipticals (E and gE) and cD (= gE with extended luminous halo). cD galaxies are often the brightest cluster members (BCG).
- Small ellipticals are fast rotators and have disks.
- Some bulges share the properties of ellipticals with the same mass.
- At high-z one cannot tell the difference between ellipticals and lenticulars.

Why do we study ellipticals?

Baum and NASA

Understanding the formation of ellipticals is essential to understand the formation of galaxies.

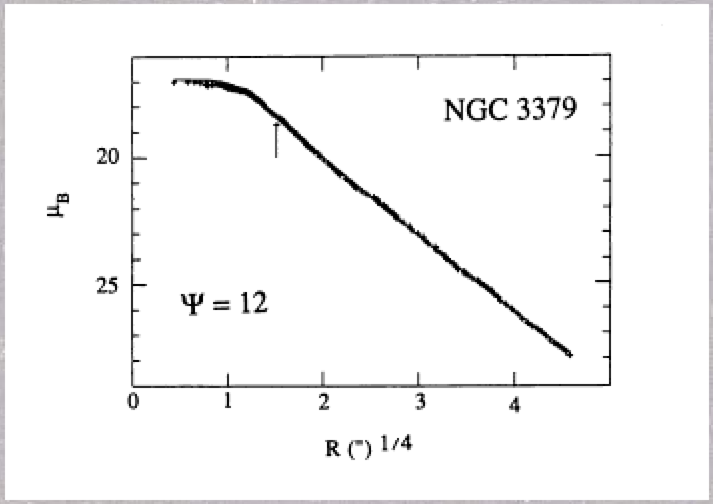
Why do we study ellipticals?

- Old stellar populations
  - Little/no HI
  - No HII regions
  - Regular morphology
  - Red colors

Baum and NASA

Why do we study ellipticals?

- Old stellar populations
- Universal light profile



de Vaucouleurs & Capaccioli 1979

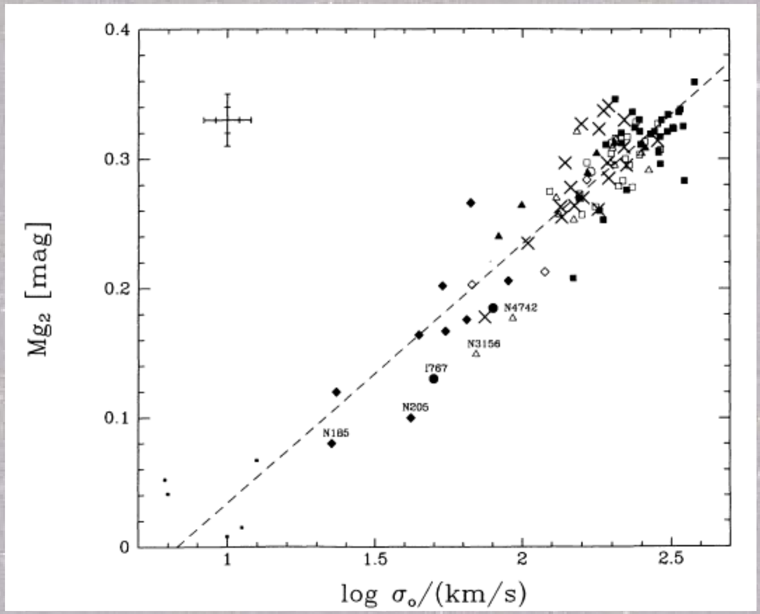
Baum and NASA

Why do we study ellipticals?

- Old stellar populations
- Universal light profile
- M-Z relation

Baum and NASA

The metal content, e.g. measured with Mg_2 or other more sophisticated indicators, correlates with the mass (and the velocity dispersion).



Bender, Burstein & Faber 1993

Origin of the M-Z relation

- Let's imagine a simple model of formation with star formation continuing until interrupted by a galactic wind powered by supernovae. The energy released by supernovae is: $E_{SN} \sim \eta \, Z \, c^2$, i.e. it's proportional to the final gas metallicity, *Z*.
- The gravitational binding energy per unit mass is :

$$W \sim GM/R$$

- The galactic winds occurs when $W = E_{SN}$. This establishes a mass-metallicity relation:

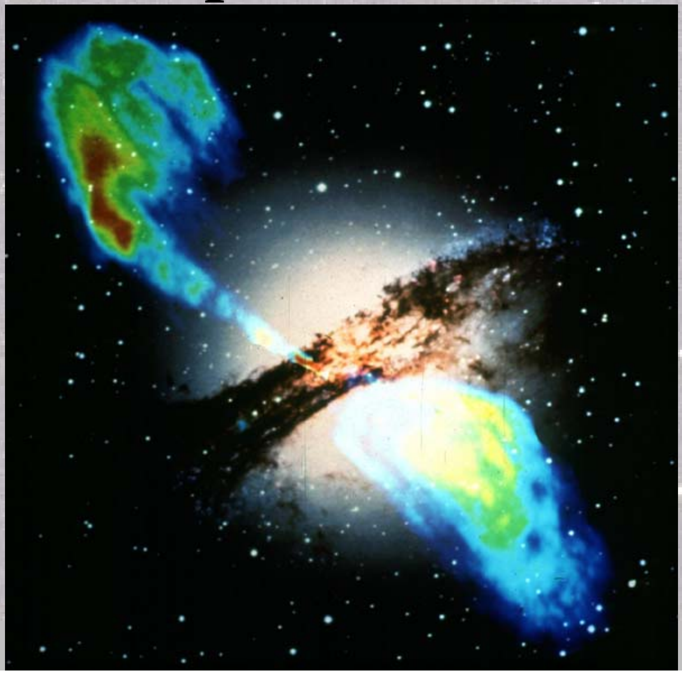
$$Z \sim M$$

(see Stiavelli & Matteucci 1991 for a numerical model)

Why do we study ellipticals?

- Old stellar populations
- Universal light profile
- M-Z relation
- Supermassive BH and most powerful RG

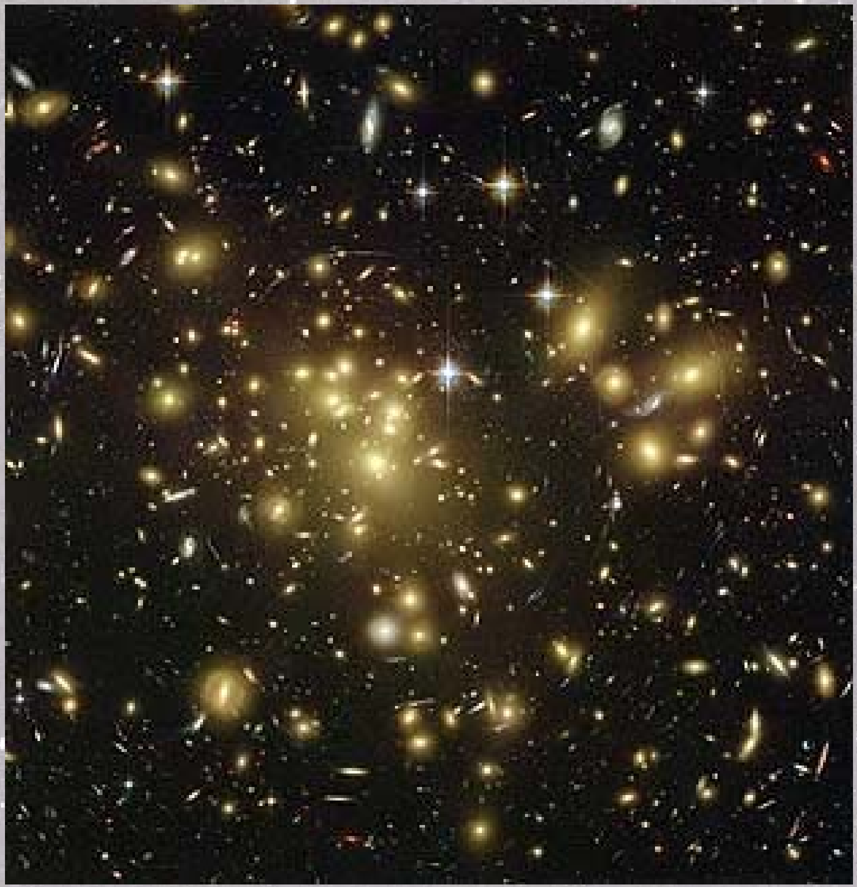
Baum and NASA



Burns and Clarke (1988)

Why do we study ellipticals?

- Old stellar populations
- Universal light profile
- M-Z relation
- Supermassive BH and most powerful RG
- Found in clusters of galaxies



Benitez and the ACS team

The Fundamental Plane of Elliptical Galaxies

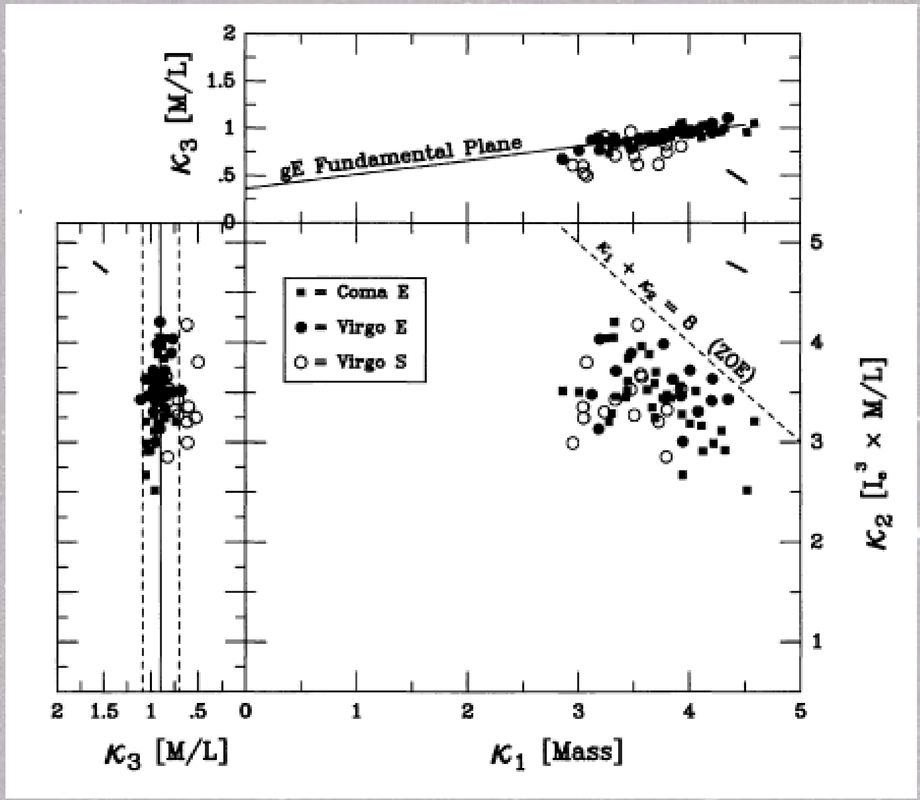
Ellipticals display various correlations. The most important is the Fundamental Plane :

$$\text{Log } r_e = \alpha \text{ Log } I_e + \beta \text{ Log } \sigma + \gamma$$

r_e is the half light radius, I_e is the mean surface brightness within r_e, and σ is the stellar velocity dispersion.

The fundamental plane is a correlation **between mass** ($=\sigma^2 r_e/G$) and **mass-to-light ratio** ($= \sigma^2/I_e r_e G$).

The history of star formation is hidden in this correlation.



Bender, Burstein & Faber 1993

The Fundamental Plane of Elliptical Galaxies

It is easy to understand the origin of the FP :

virial theorem $M = \xi \sigma^2 r_e / G$

star formation $L = \eta M^{\mu}$

definition of I_e $L = 2 I_e \pi r_e^2$

After some algebra one finds:

$$\mathrm{Log}\, r_e = \alpha\, \mathrm{Log}\, I_e + \beta\, \mathrm{Log}\, \sigma + \gamma$$

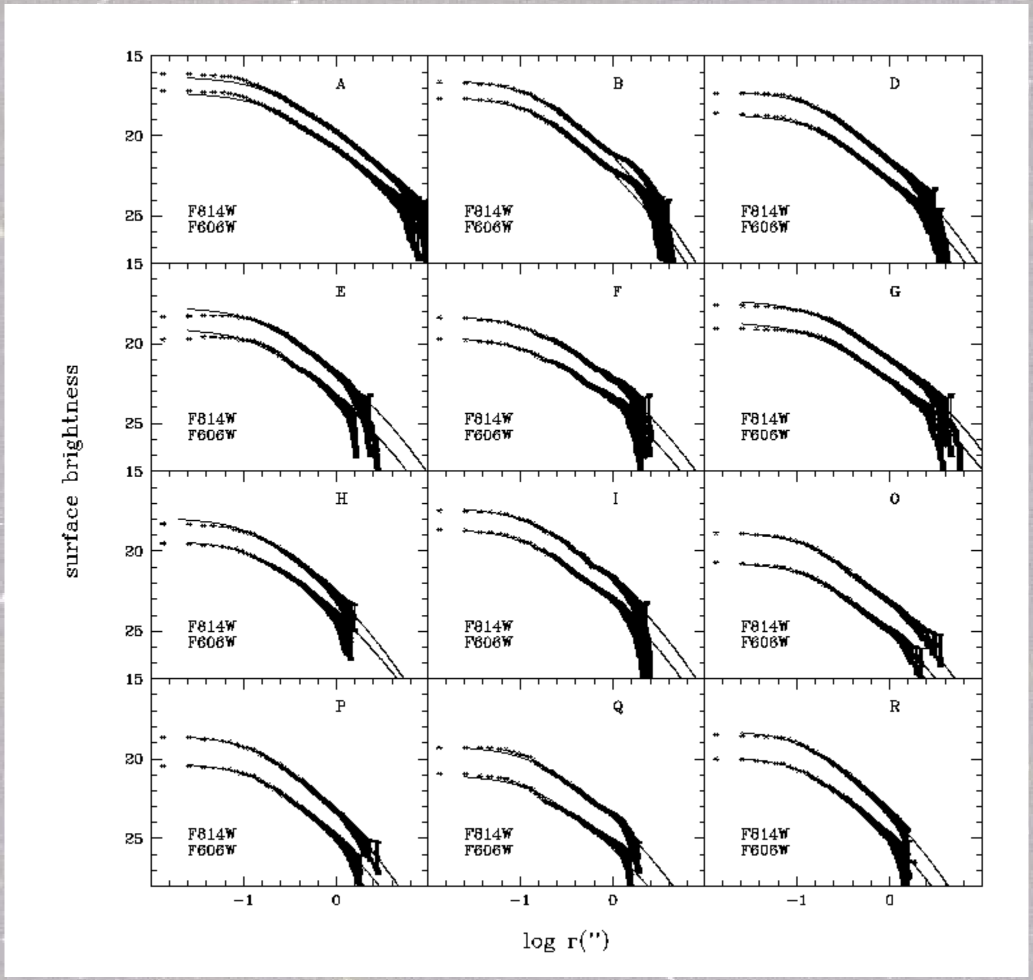
This relation predicts a relation between α e β.

The observed values of α e β satisfy the relation if $\mu \approx 0.8$ (i.e. M/L aumenta con M).

The zero point γ depends on the dynamical parameter ξ and on the M/L parameters η e μ

Evolution of the Fundamental Plane

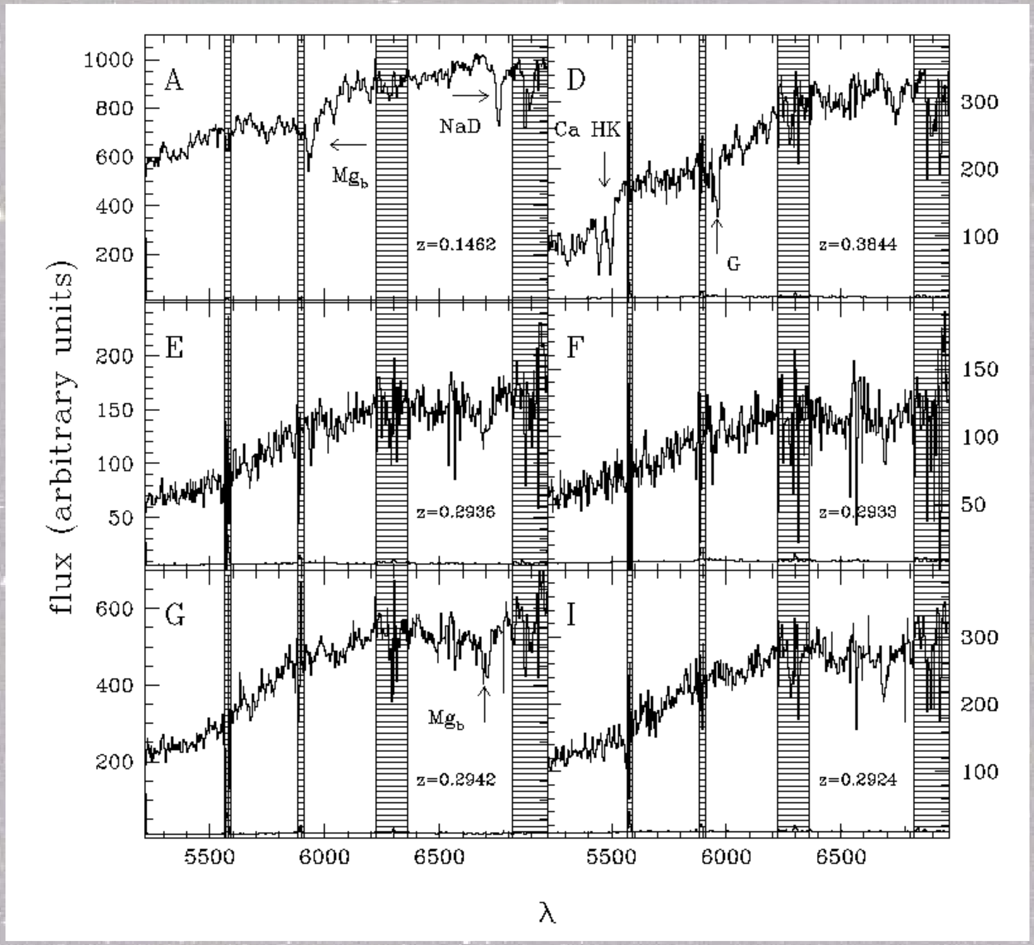
- The FP requires high precision measurements (was discovered in 1986).
- Generally one needs HST to measure r_e and I_e



Treu et al. 1997

Evolution of the Fundamental Plane

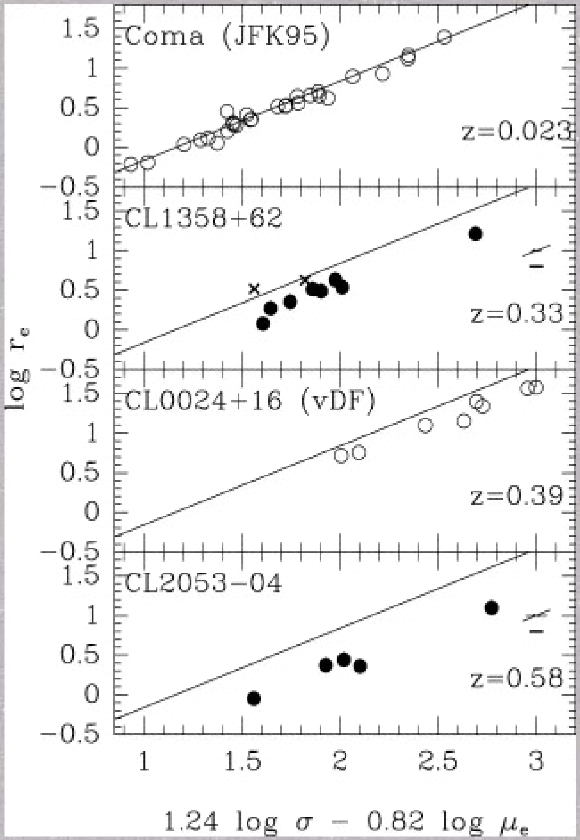
- The stellar velocity dispersion can be measured using 4m telescopes up to z~=0.4 but requires 8-10m telescopes for z~=0.6 and beyond.
- Selection effects, K-correction, and template mismatch need to be under control.



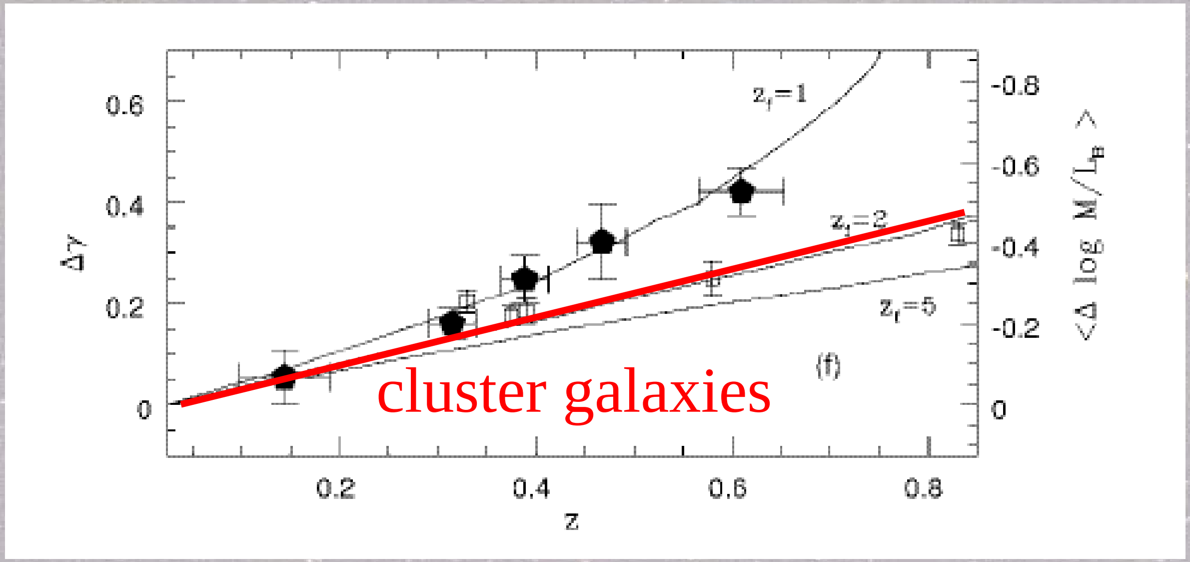
Treu et al. 1997

Evolution of the Fundamental Plane

- The FP in clusters of galaxies it's easier to measure and shows evolution →
- **In the absence of Λ ellipticals would be "older than the Universe"**



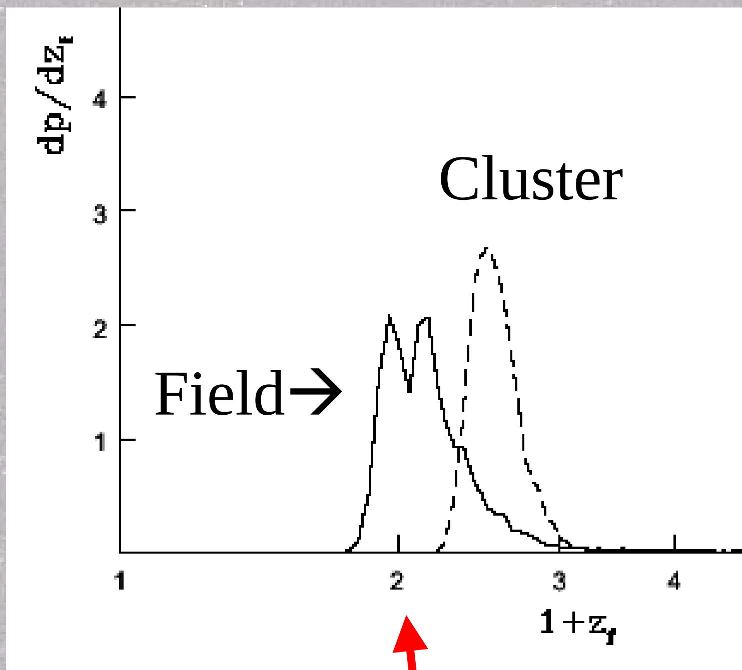
Kelson et al. 1997



Treu et al. 2002

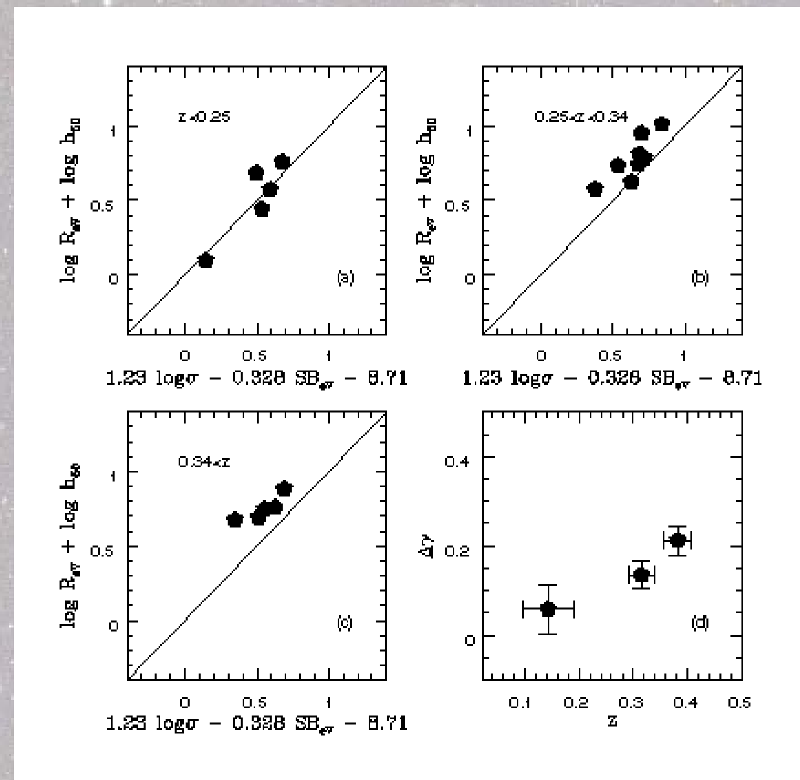
Evolution of the Fundamental Plane

- **The evolution in the field is different from that in clusters.**



Treu et al. 2002

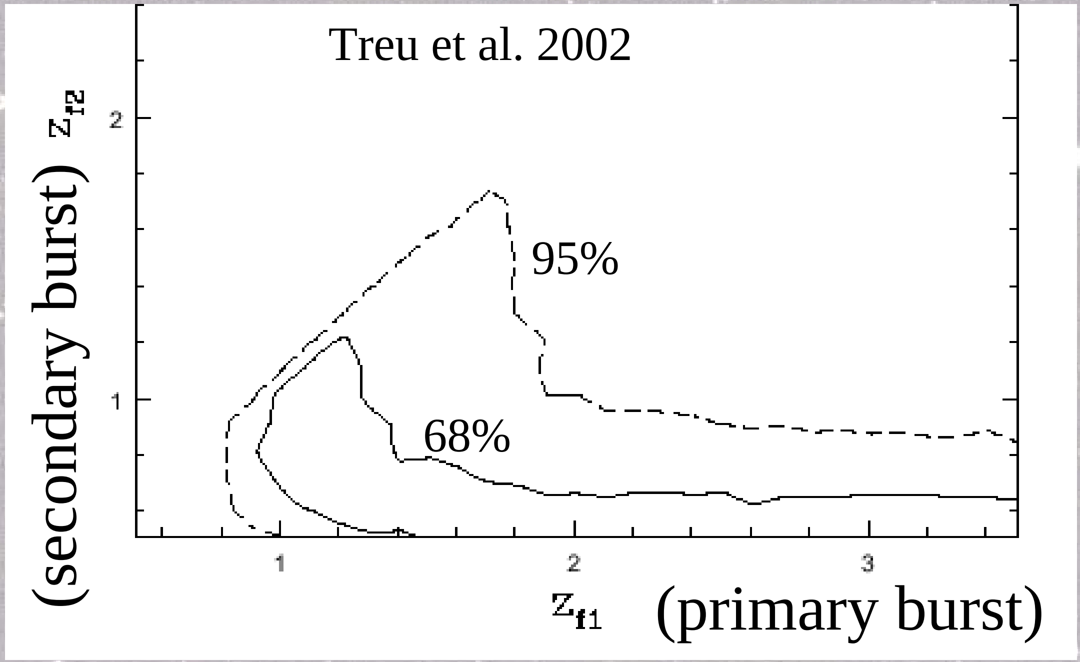
z=1



← Stellar populations are younger in the field

Evolution of the Fundamental Plane

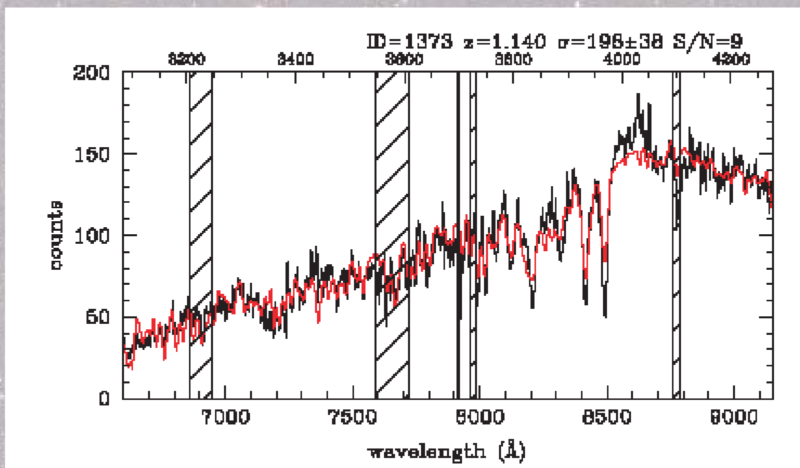
- The FP evolution appears to confirm model predictions of a faster evolution in clusters.



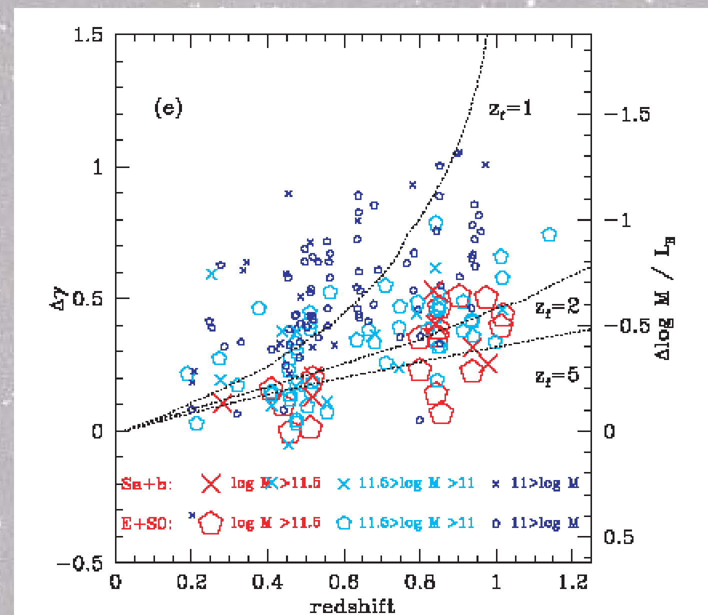
How robust is this? We know that adding a 10% in younger stars to an old galaxy can make it appear much younger even if it formed the bulk of its stars at z>2.

Evolution of the Fundamental Plane

GOODS-N photometry and Keck spectroscopy for a sample of 165 ellipticals and 61 bulges (Treu et al. 2005, 633, 174).



Spectrum of an elliptical (black) and of a stellar template convolved to the velocity dispersion of the galaxy (red).

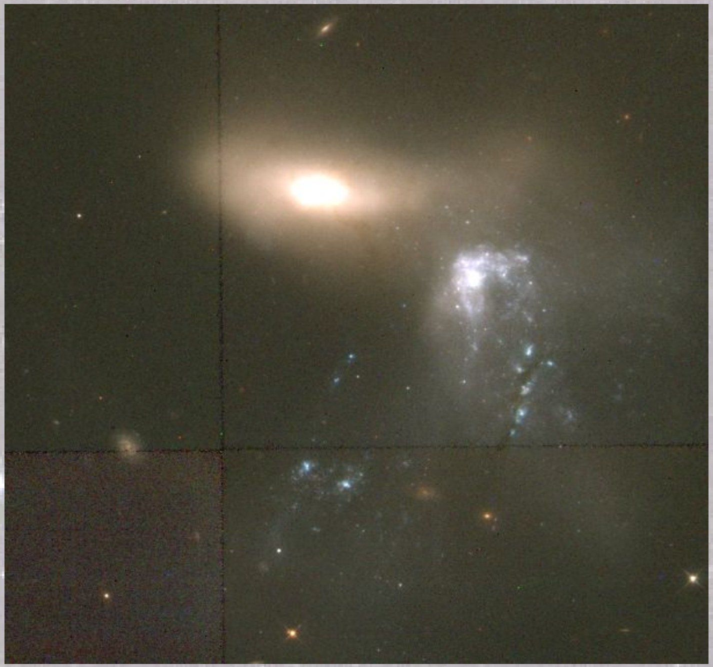


The most massive objects formed first.

Treu et al. 2005, ApJ, 633, 174

Evolution of the Fundamental Plane

- In the local Universe we see interactions.
- Star formation in ellipticals is more common at high-z, e.g., the number of objects with [OII] increases with redshift (Treu et al., Warren et al.)



Stiavelli et al. 1998

NGC 454 : una futura E+A ?

Evolution of the Fundamental Plane

Areas of concern:

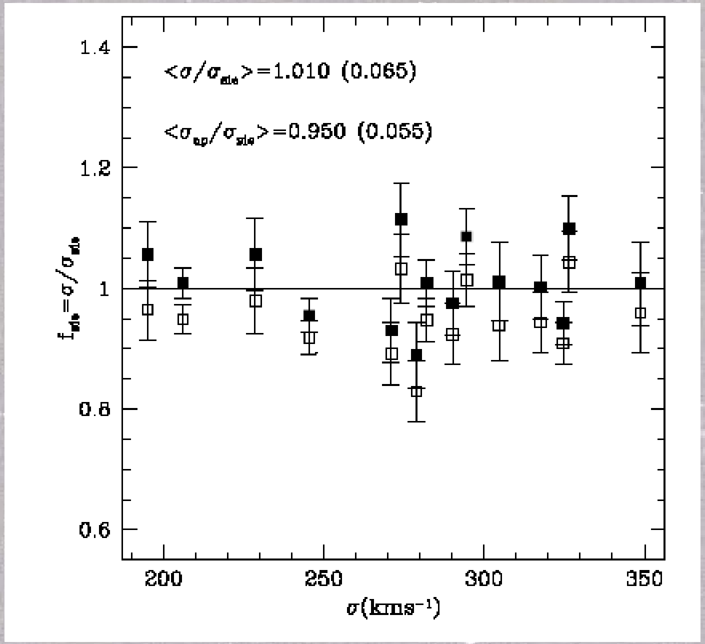
- Sample choice – morphology? Red colors?
  (see discussion in van Dokkum and Franx 2001)
- Knowing when the stars formed doesn't tell us when the galaxy was assembled.
- An evolving M/L could be caused by structural evolution rather than stellar population effects.

  This could be tested.

Kinematical mass vs lensing mass

For ellipticals acting as strong lenses (ie producing gravitational arcs) it's possible to derive directly the gravitational mass and compared it to the dynamical mass. A comparison of the two fundamental planes allows us to verify whether there are structural variations.

This idea has been implemented by Treu, Koopmans and collaborators (Treu et al. 2006, ApJ, 640, 662). They have derived gravitational masses and velocity dispersions for 15 strong lenses at redshift up to 1.0. The figure shows the ratio of the measured velocity dispersion to the velocity dispersion of the isothermal sphere providing the best fit to the lens. (open SDSS measured, filled corrected to central value).The agreement is very good!



Summary

- FP of ellipticals is an interesting probe for evolution.
- Large telescopes for sigmas and HST for imaging
- Cluster ellipticals are older than field ellipticals.
- Massive ellipticals are older than lower mass ones.
- The M/L evolution is not a consequence of structural evolution but tells us about the stellar populations.