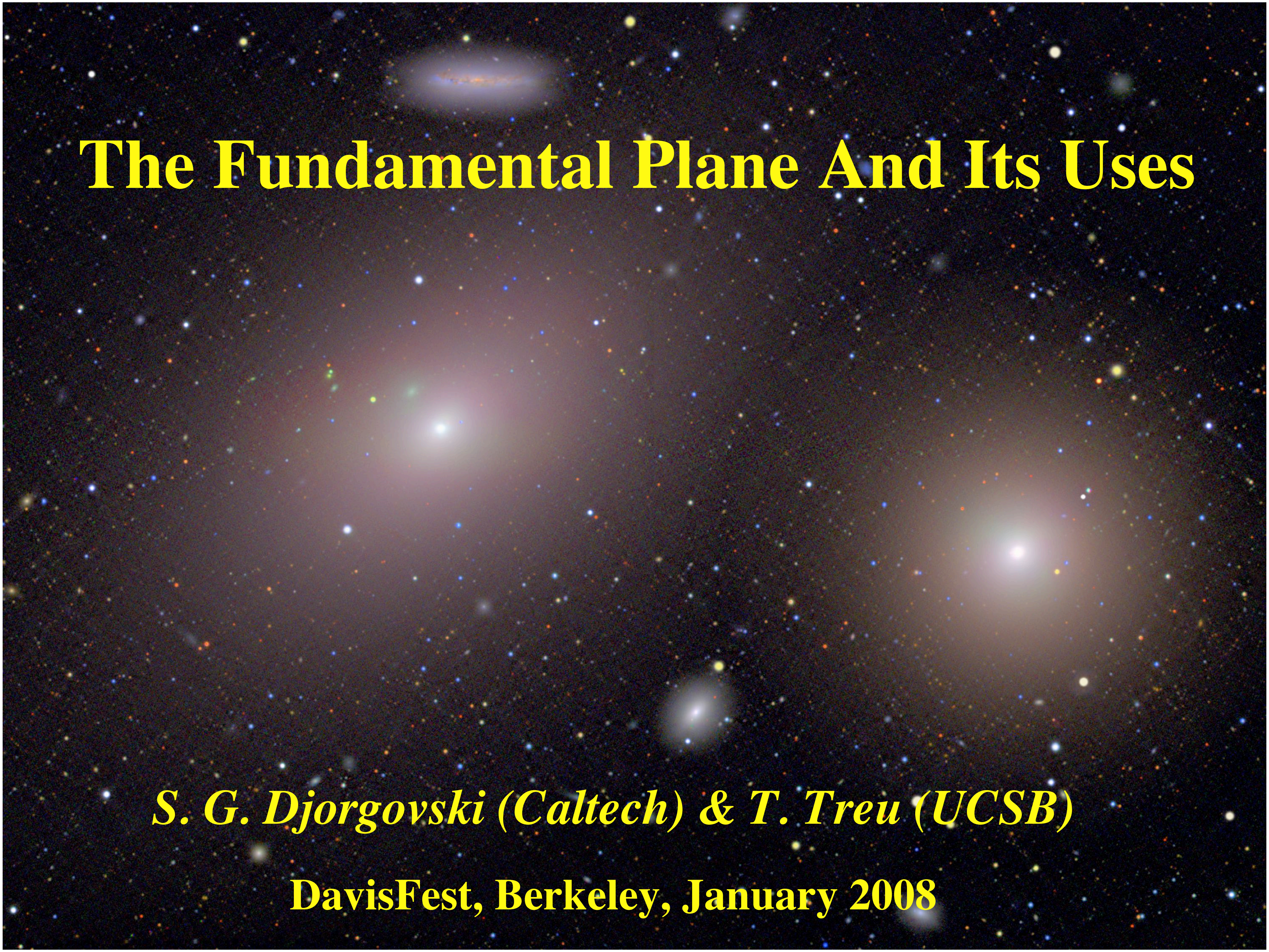


The Fundamental Plane And Its Uses

S. G. Djorgovski (Caltech) & T. Treu (UCSB)

DavisFest, Berkeley, January 2008

An Overview

- Some history, and Marc's role in the discovery of the FP
- The uses of the FP:

  1. **Relative distance and peculiar velocity indicator**

     … not covered in this talk …

  2. **Constraints on the structure and formation of ellipticals**
     - The origins and the derivation of the FP
     - The slope: the breakdown of the homology
     - The scatter: a major and outstanding mystery

  3. **A probe of evolution of early-type galaxies**
     - Clusters out to $z \sim 1.5$
     - Field vs. clusters, "downsizing"
     - The Tolman test

- Concluding comments

NB: This is a *huge* subject, and we cannot review it properly in the short time available here. Our apologies if we neglect to mention your fine work…

Towards the Discovery of the FP

There were two motivational streams:

1. ***How many statistically significant properties describe elliptical galaxies, and how are they related?*** Or: what is the "manifold of elliptical galaxies"?
   - The pioneering work by Brosche (1973), Brosche & Lentes (1982)
2. ***What is the "2nd parameter" in the F-J relation, so that it can be improved as a distance indicator for early-type galaxies?***
   - The Davis-Djorgovski-Kent mini-survey (1982/3) [6 parameters?]
   - The Fall & Efstathiou paper (1984) [L-σ-Mg plane]
   - Lauer's study of E-galaxy cores (1986) [almost!]

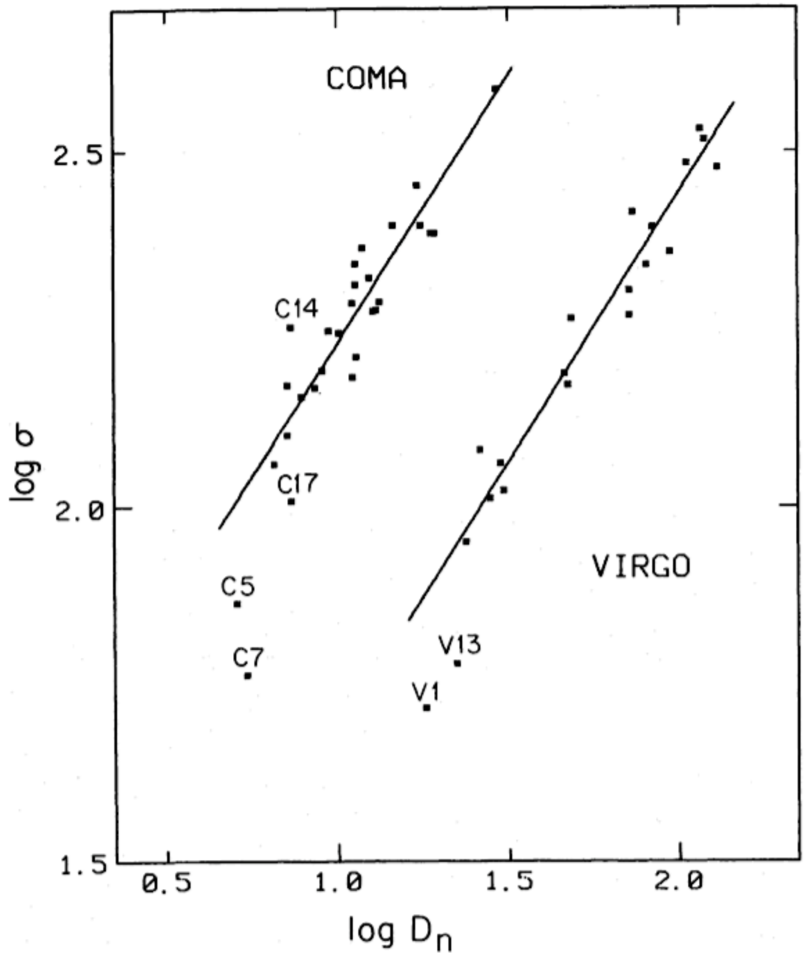
The actual discovery/realization:

Dressler et al. (1987) [the "7 Samurai"]: the D_n-σ relation

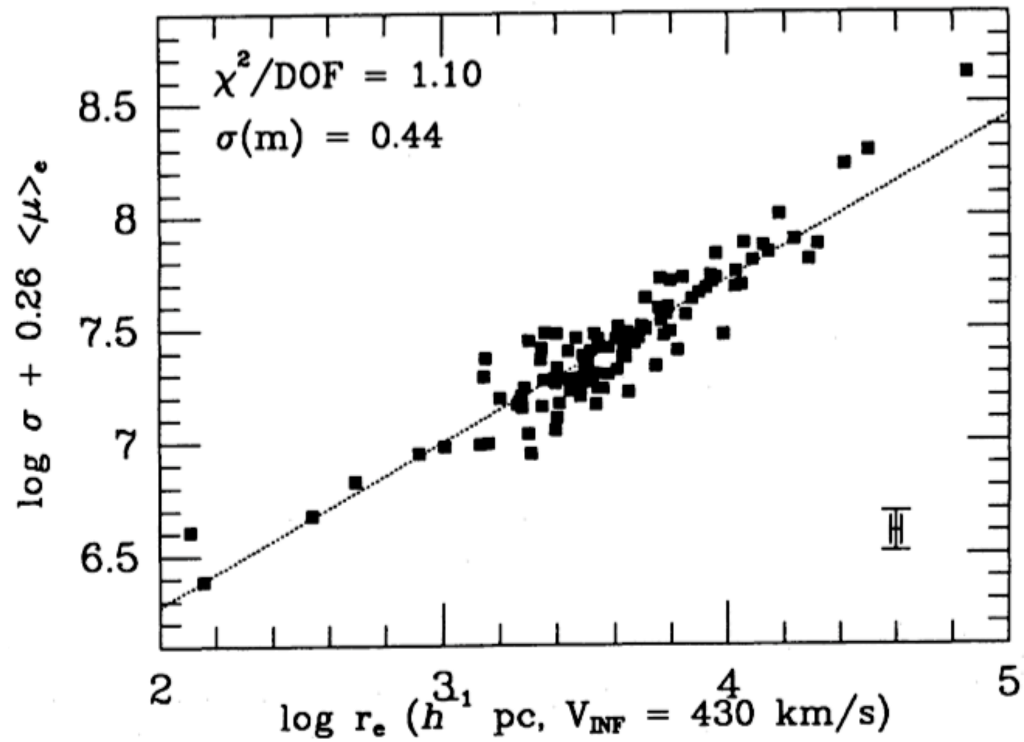
Djorgovski & Davis (1987): a plane in the L-R-σ-μ space

The Initial Renderings

D_n-σ, Dressler et al. 1997



R-σ-μ, Djorgovski & Davis (1987)



The "canonical form": $R \sim \sigma^A I^B$

R = non-isophotal radius (r_e, r_η, …)

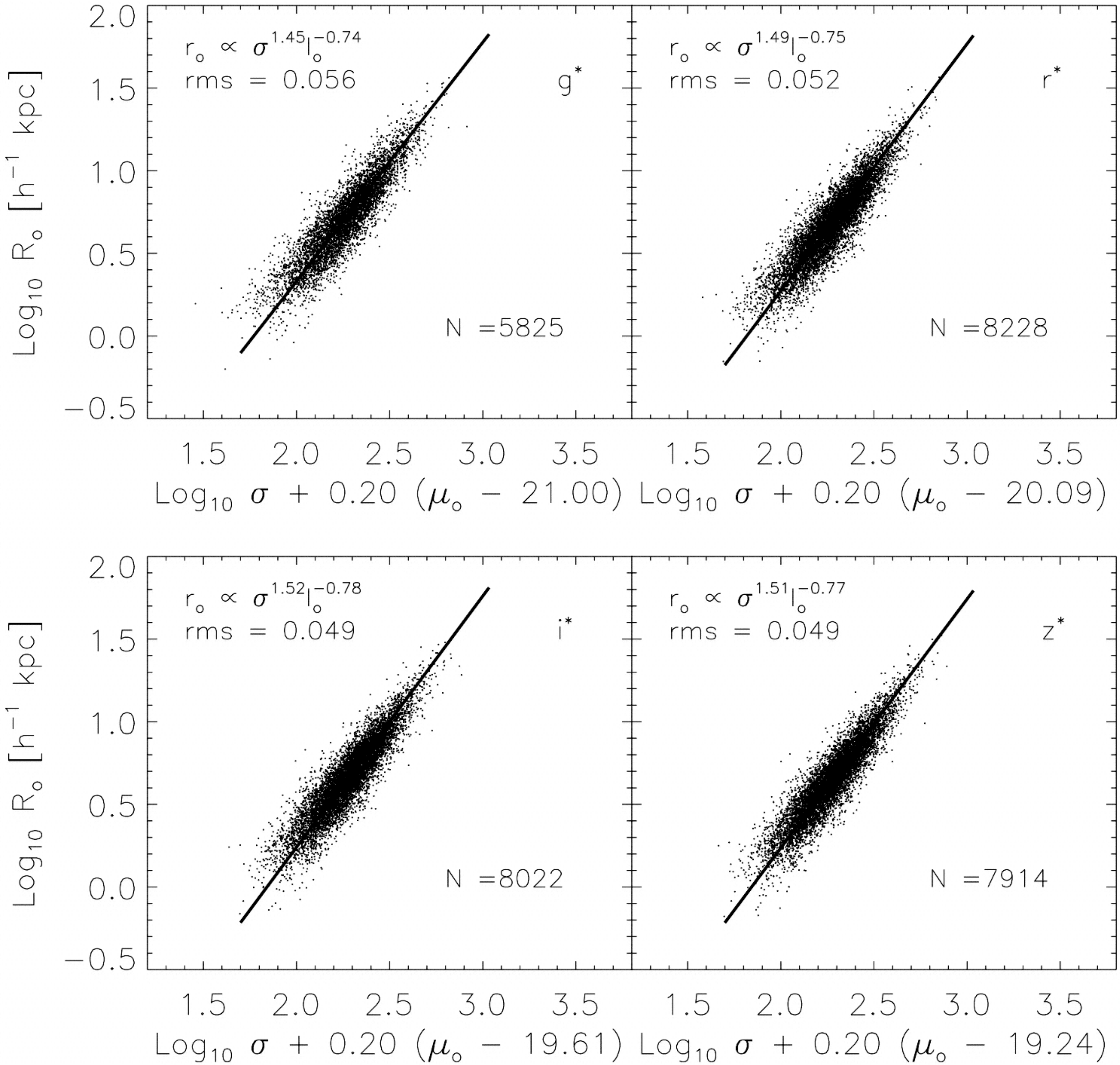
σ = central proj. velocity disp.

I = mean surf. br. in linear units

FP from SDSS:

Bernardi et al. (2003)

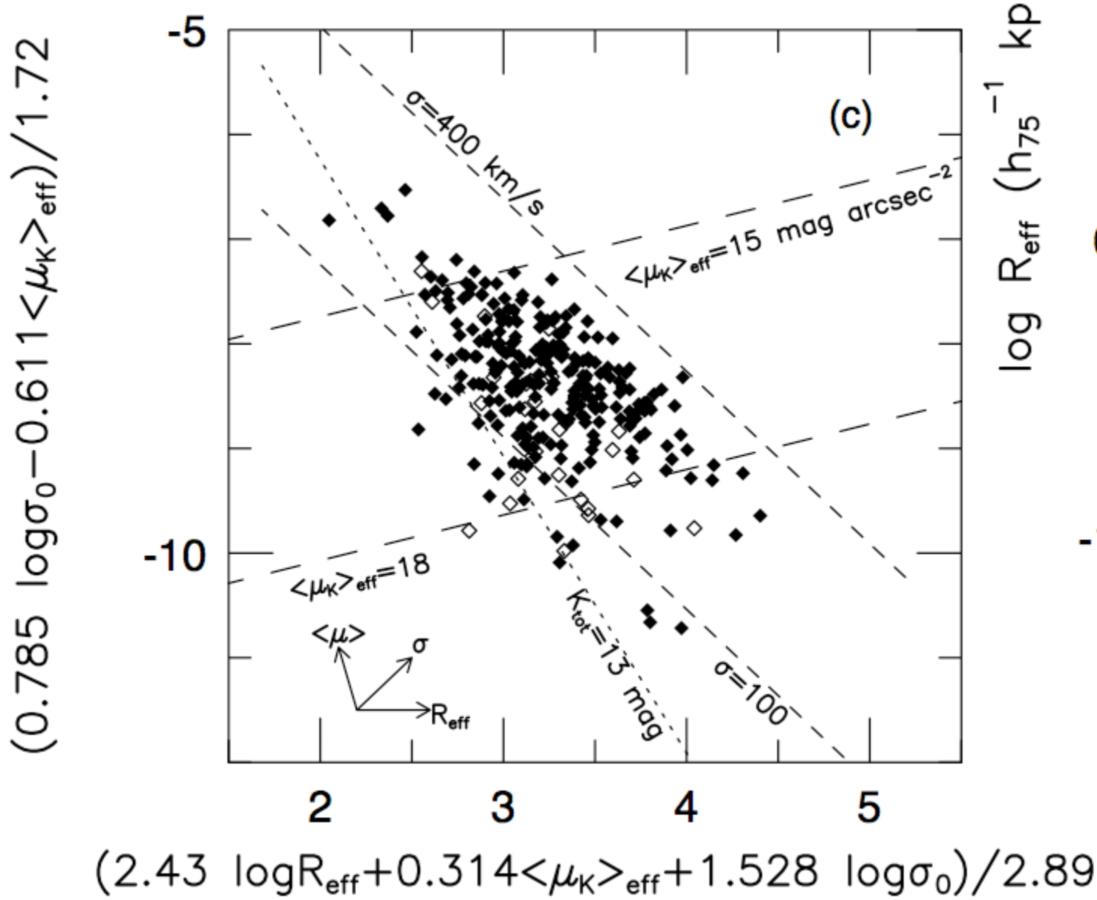
Nearly 9000 galaxies



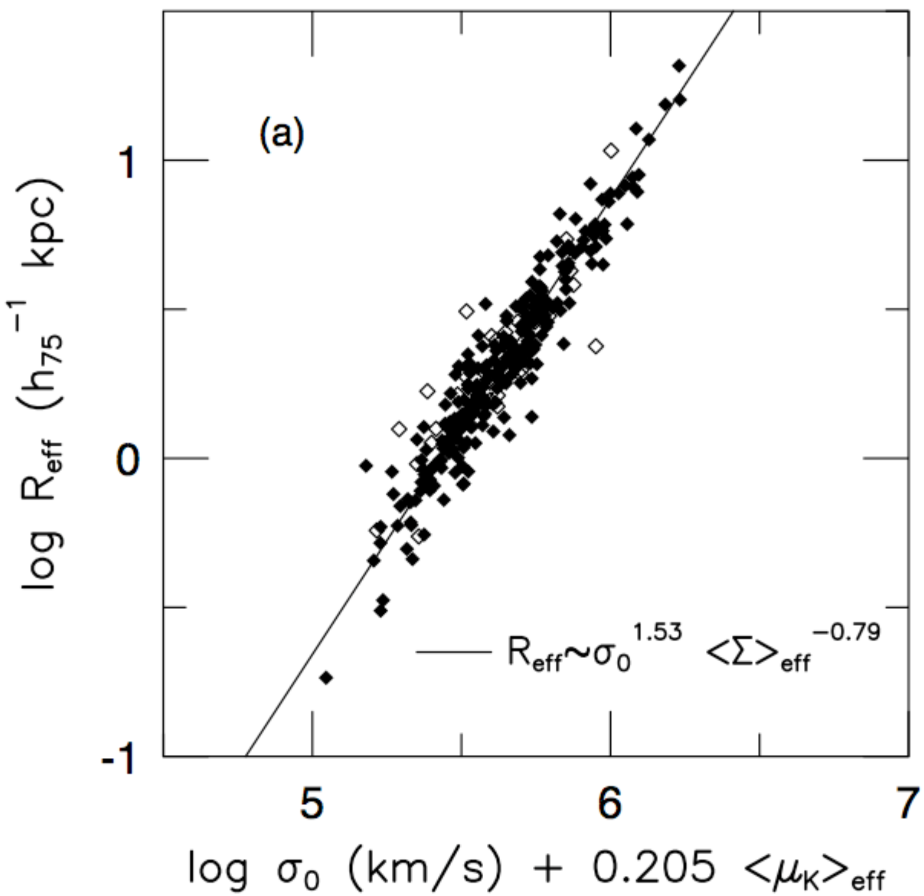
FP in the K-Band (~ nearly bolometric)

(Pahre et al. 1988)

Face-on

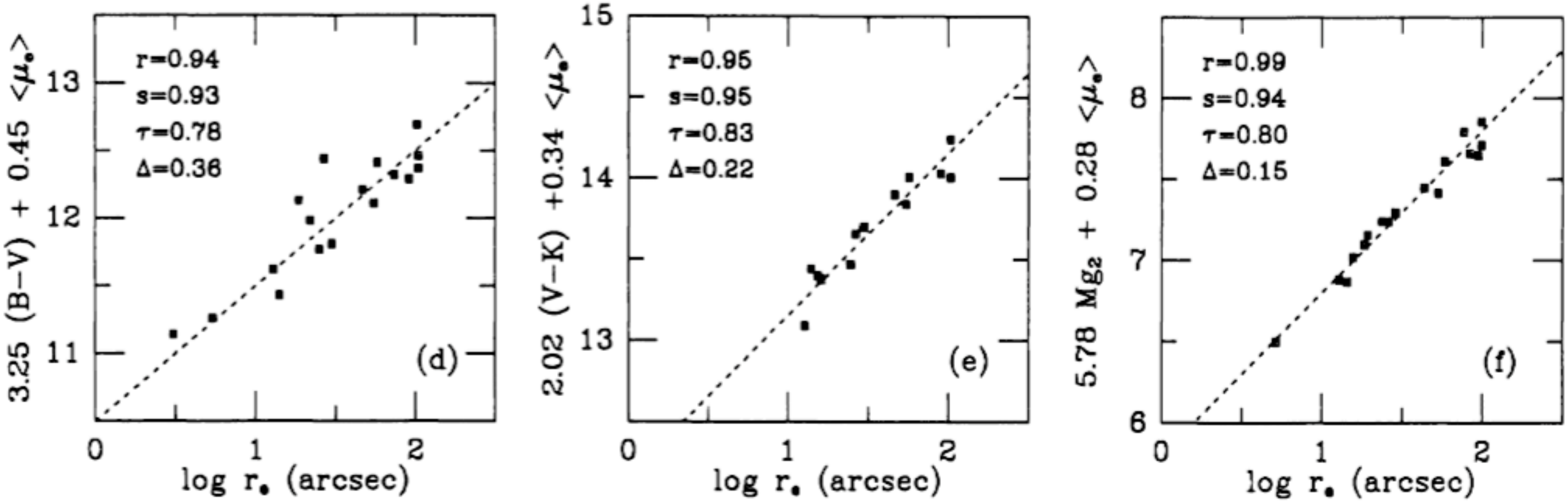


Edge-on



Stellar Population Variables Also Participate in the FP (de Carvalho & Djorgovski 1989)

Metallicity and age dependent colors   Line strengths



This implies that the chemical enrichment (and star formation?) histories of ellipticals are regulated by their global dynamical and structural parameters

… And so are their central SMBHs (many authors…)

Deriving the Scaling Relations

Start with the Virial Theorem: $$\frac{GM}{\langle R \rangle} = k_E \frac{\langle V^2 \rangle}{2}$$

Now relate the observable values of ***R, V*** (or σ), ***L***, etc., to their "true" mean 3-dim. values by simple scalings:

$$R = k_R \langle R \rangle \qquad V^2 = k_V \langle V^2 \rangle \qquad L = k_L I R^2$$

One can then derive the "virial" versions of the FP and the TFR:

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1}$$

$$L = K_{SL} V^4 I^{-1} (M/L)^{-2}$$

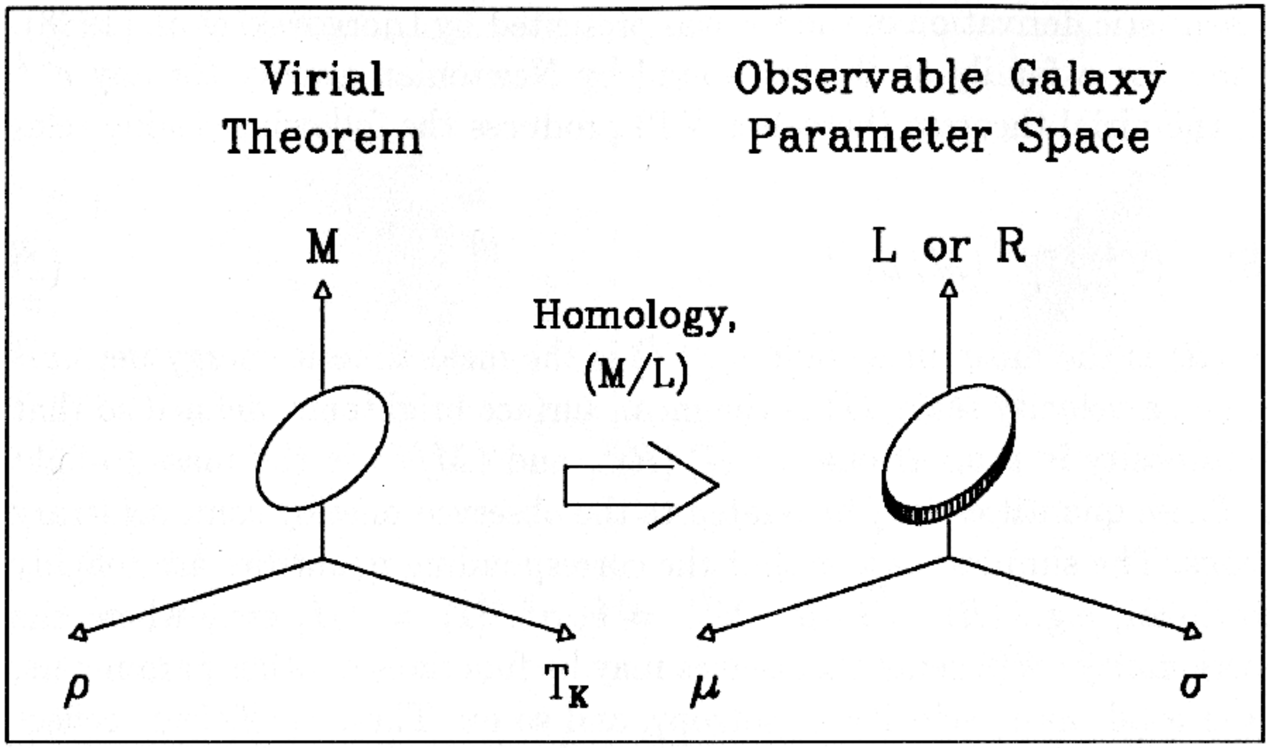
Where the "structure" coefficients are:

$$K_{SR} = \frac{k_E}{2G k_R k_L k_V}$$

$$K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_V^2}$$

Deviations of the observed relations from these scalings must indicate that either some ***k'***s and/or the ***(M/L)*** are changing

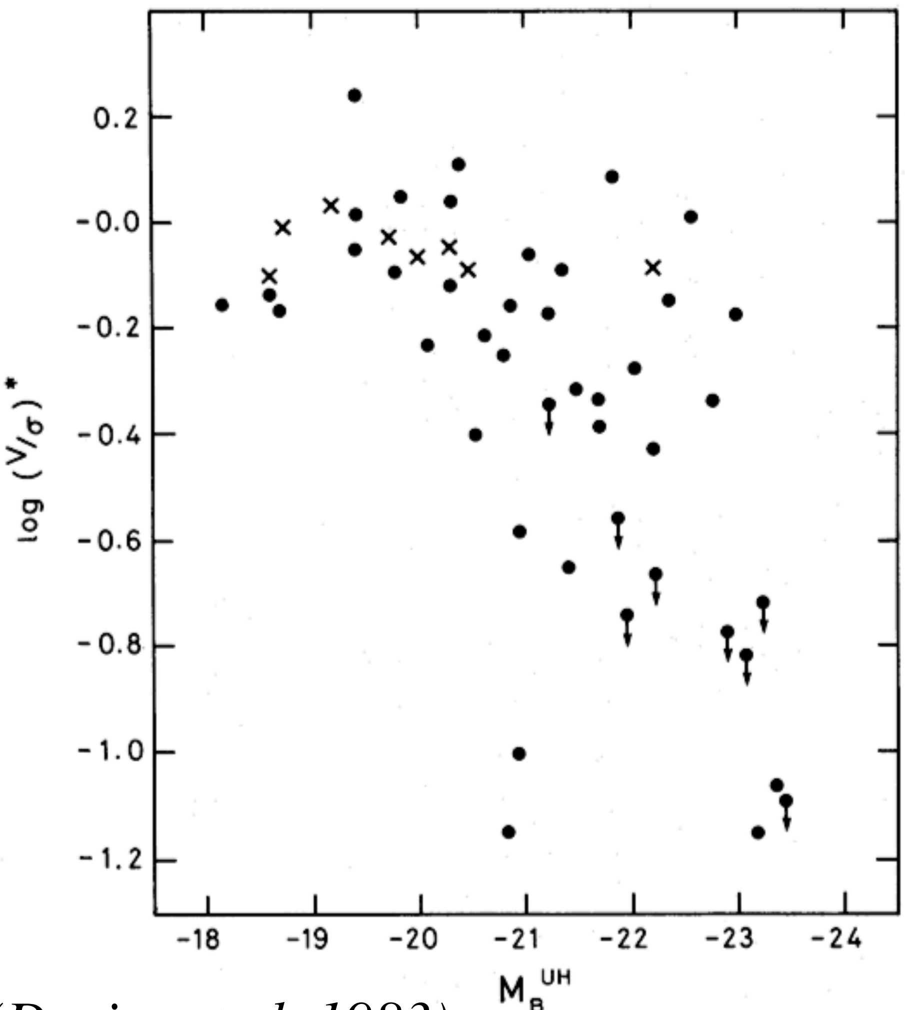
From Virial Theorem to FP



- Galaxies must be on a "Virial Theorem Plane" in the space of mass, mean density, and kinetic temperature
- ***If*** galaxies represent a homologous family of structures ***and*** had (M/L) = const., then they should follow the VTP: $R \sim \sigma^2 I^{-1}$
- Since they don't, and the observed FP scaling is: $R \sim \sigma^{1.4} I^{-0.8}$, either one or both of these assumptions must be broken

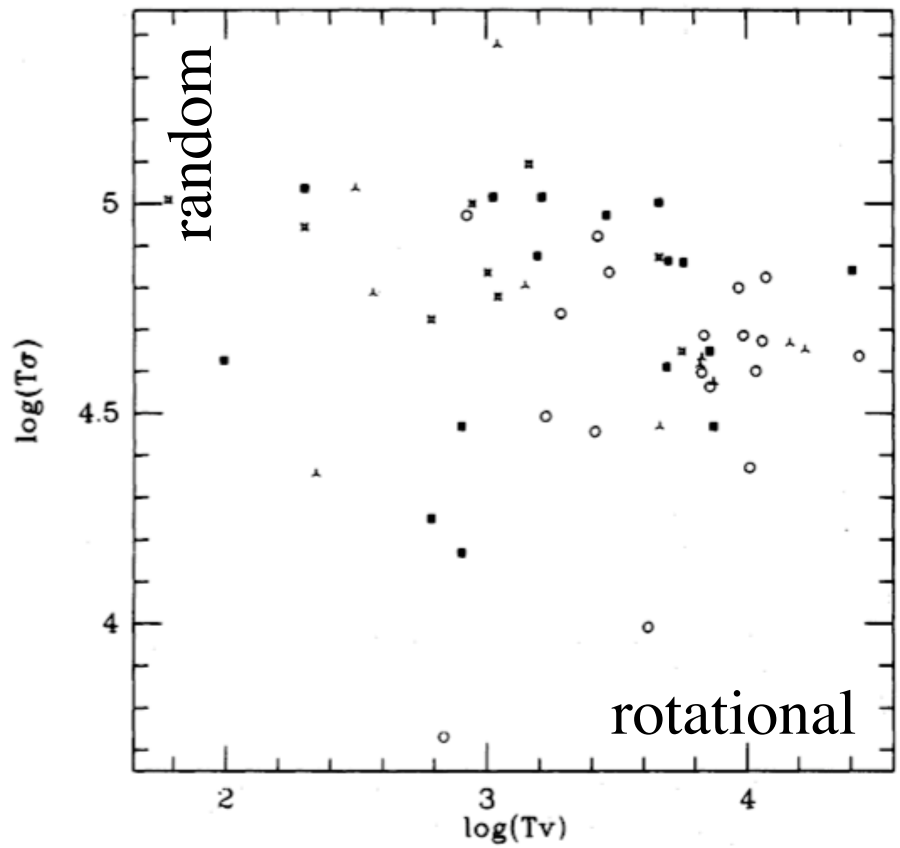
Breaking the Homology: Dynamics

More luminous/larger ellipticals are more radially anisotropic:



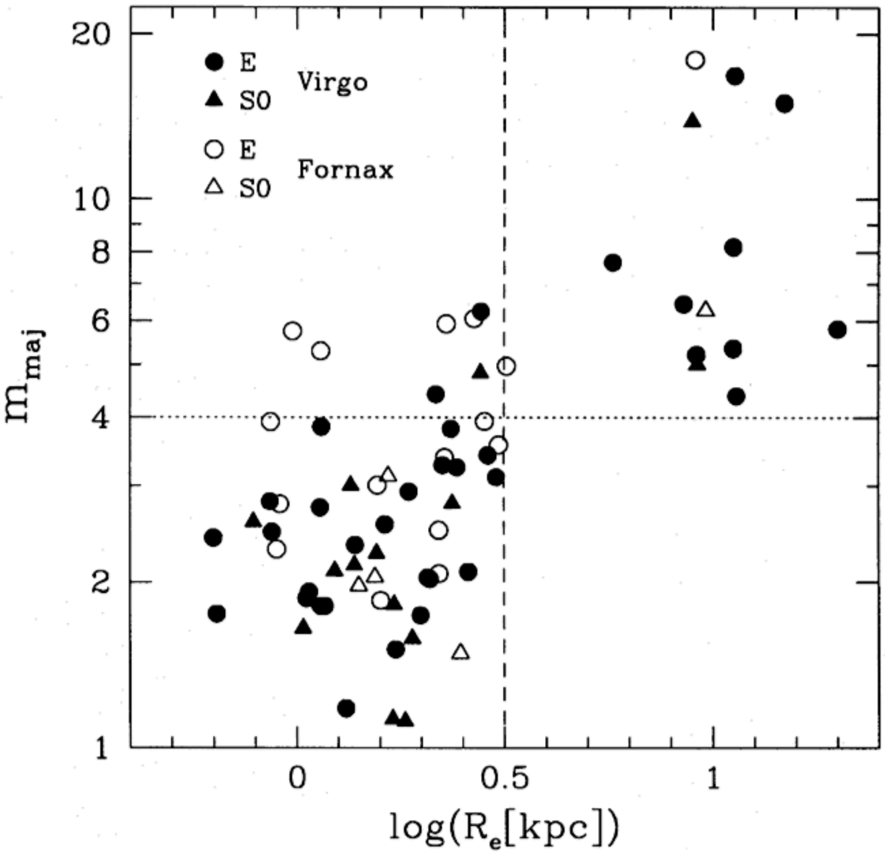
(Davies et al. 1983)

There is a wide spread in rotational contributions to the total kinetic energy:



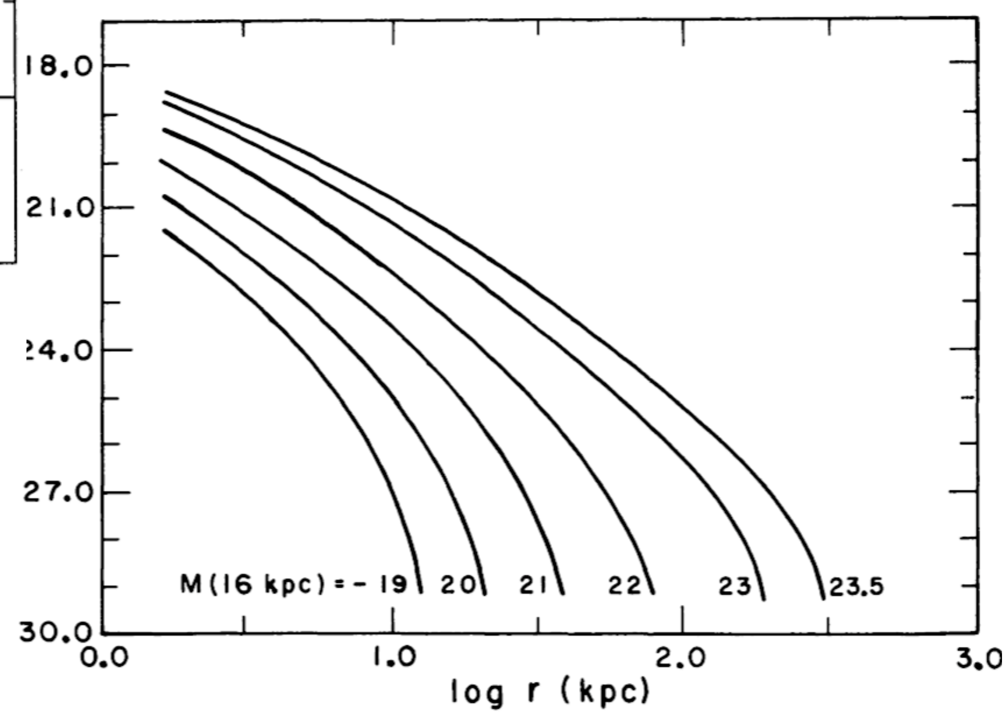
(Busarello et al. 1992)

Breaking the Homology: Density Profiles



← Sersic profile index ($r^{1/n}$) correlates with the galaxy size *(D'Onofrio et al. 1994)*

More luminous ellipticals have shallower profiles → *(Schombert 1986)*

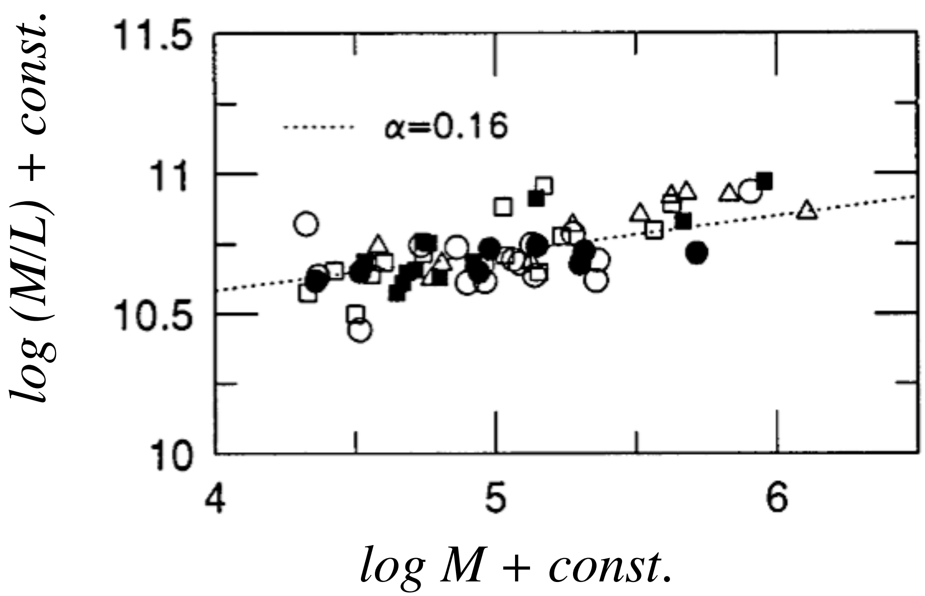


Fundamental Plane and M/L Ratios

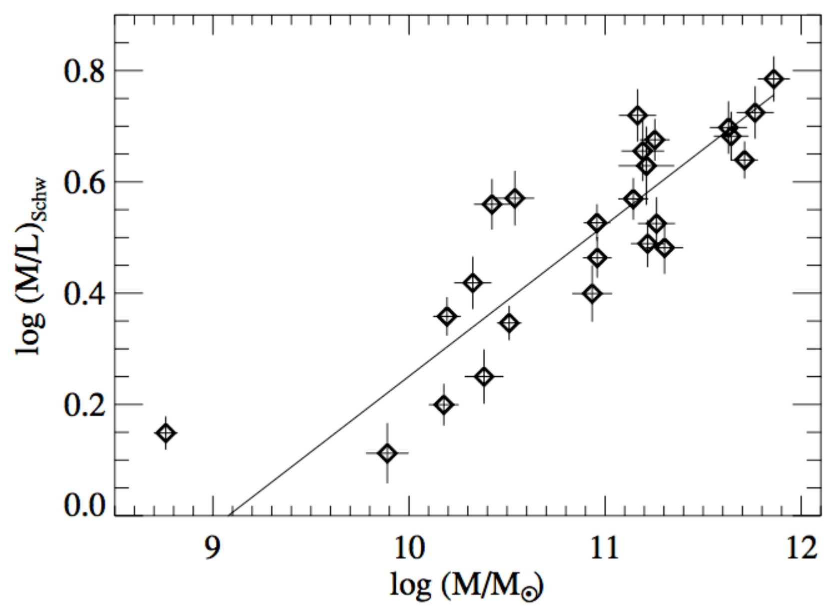
If we *assume* homology and attribute all of the FP tilt to the changes in ***(M/L)*** , $(M/L) \sim L^{\alpha}$, $\alpha \sim 0.2$ (vis) or ~ 0.1 (IR)

Possible causes: systematic changes in $M_{visible}/M_{dark}$, or in their relative concentrations; or in the stellar IMF

Pahre et al. 1995: K-band FP



Cappellaro et al. 2006: SAURON dynamical modeling

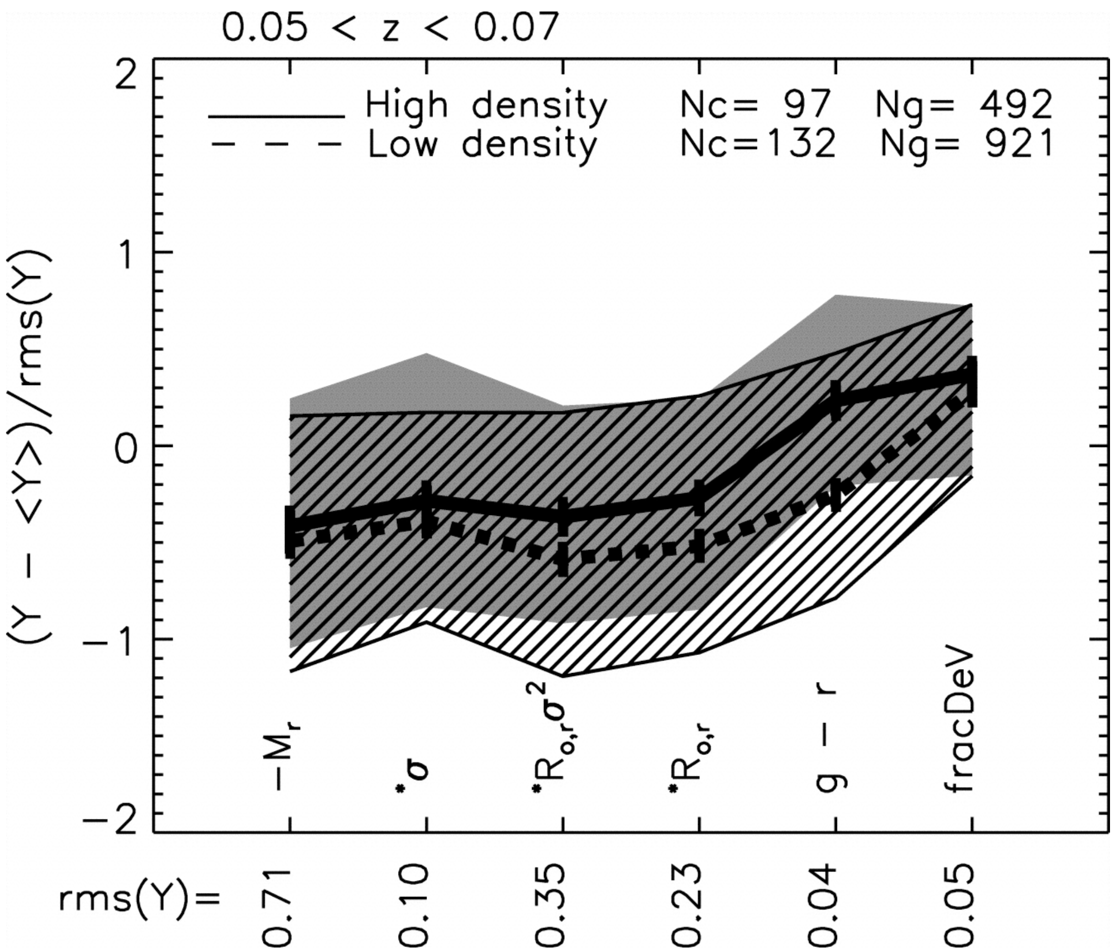


Environmental Dependence (?)

- FP intercepts (zero-points) are operationally interchangeable with peculiar velocities; zero-point variations would cause spurious V_{pec}'s
  - A highly controversial subject…
- Numerous spectroscopic studies find systematic differences between E's in different density environments
- However, ***no convincing evidence*** for cluster-to-cluster variations has been found by a number of studies
- Even if we assume that *all* FP-based V_{pec}'s are entirely spurious, due to environmental variations, that would imply the zero-point differences of at most ~ 10%; and clearly that is an overestimate
- ***Thus, we conclude that for the present-day (cluster) E's, the intercepts of the FP are universal to better than 10% (and could be 0%)***

Environmental Dependence

Numerous spectroscopic studies indicate that *E's in denser environments are systematically redder, older, more metal-rich, dimmer* - but it is not clear if coeval E-galaxy populations would have different FP zero points



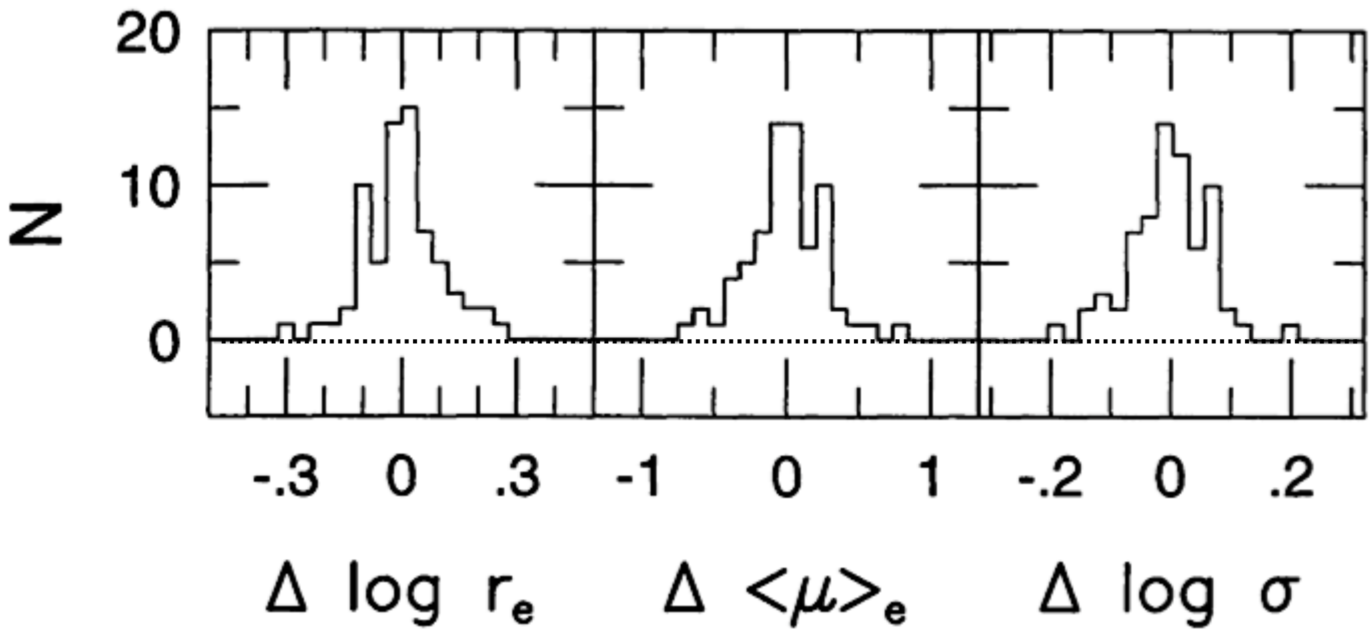
Probably the best study to date: Bernardi et al. (2006), from SDSS:

Implies ~ 0.075 mag difference between FPs for E's in low and high density environments

The Remarkably Small Scatter of the FP

Residuals from the FP fit in each of the 3 observable quantities

(Djorgovski et al. 1995, and consistent with other studies)



	Δ log r_e	Δ $<\mu>_e$	Δ log σ
Total r.m.s.	0.085	0.23	0.054
Est. intrinsic	< 0.055	< 0.15	< 0.035

Thus, the intrinsic thickness of the FP is at most a few % (and could be zero) - despite the observed broad variety of kinematical and density profiles, projection effects, etc. etc.

For any elliptical galaxy today, big or small,

Just Two Numbers

determine *to within a few percent or less*:

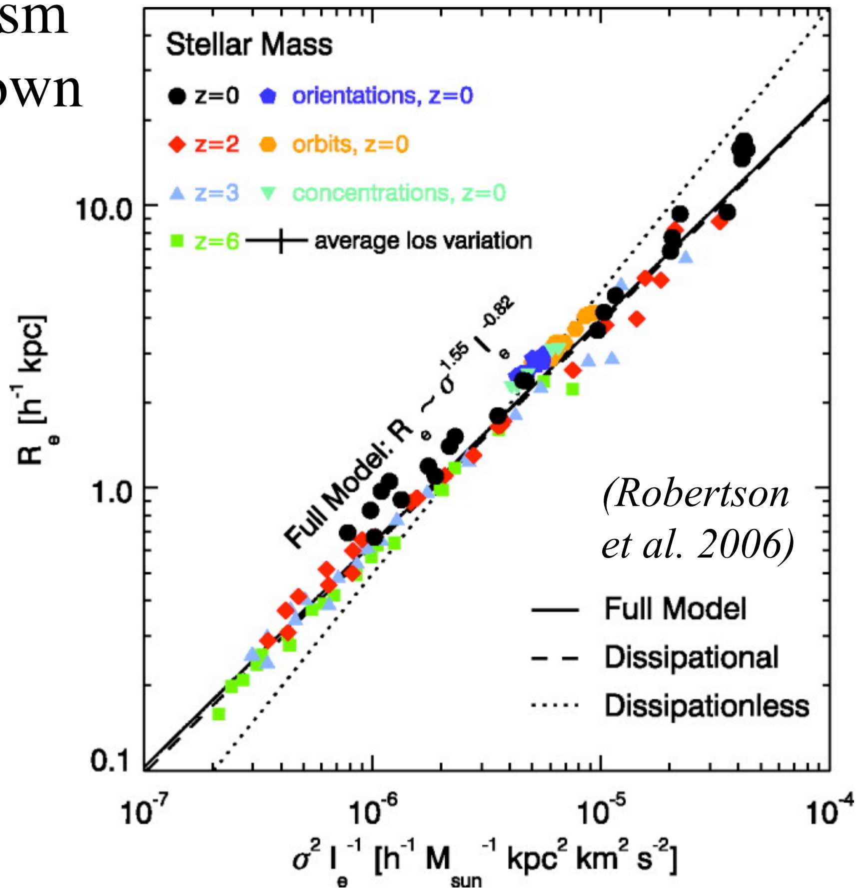
- Mass, luminosity (in any OIR band),
- Any consistently defined radius
- Surface brightness or projected mass density
- Derived 3-d luminosity, mass, or phase-space density
- Central projected radial velocity dispersion
- OIR colors, line strengths, and metallicity
- Mass of the central black hole
- … and maybe other things as well

And they do so regardless of the:

- Star formation and merging formative/evolutionary history
- Large-scale environment
- Details of the internal structure and dynamics (including S0's)
- Projection effects (direction we are looking from)

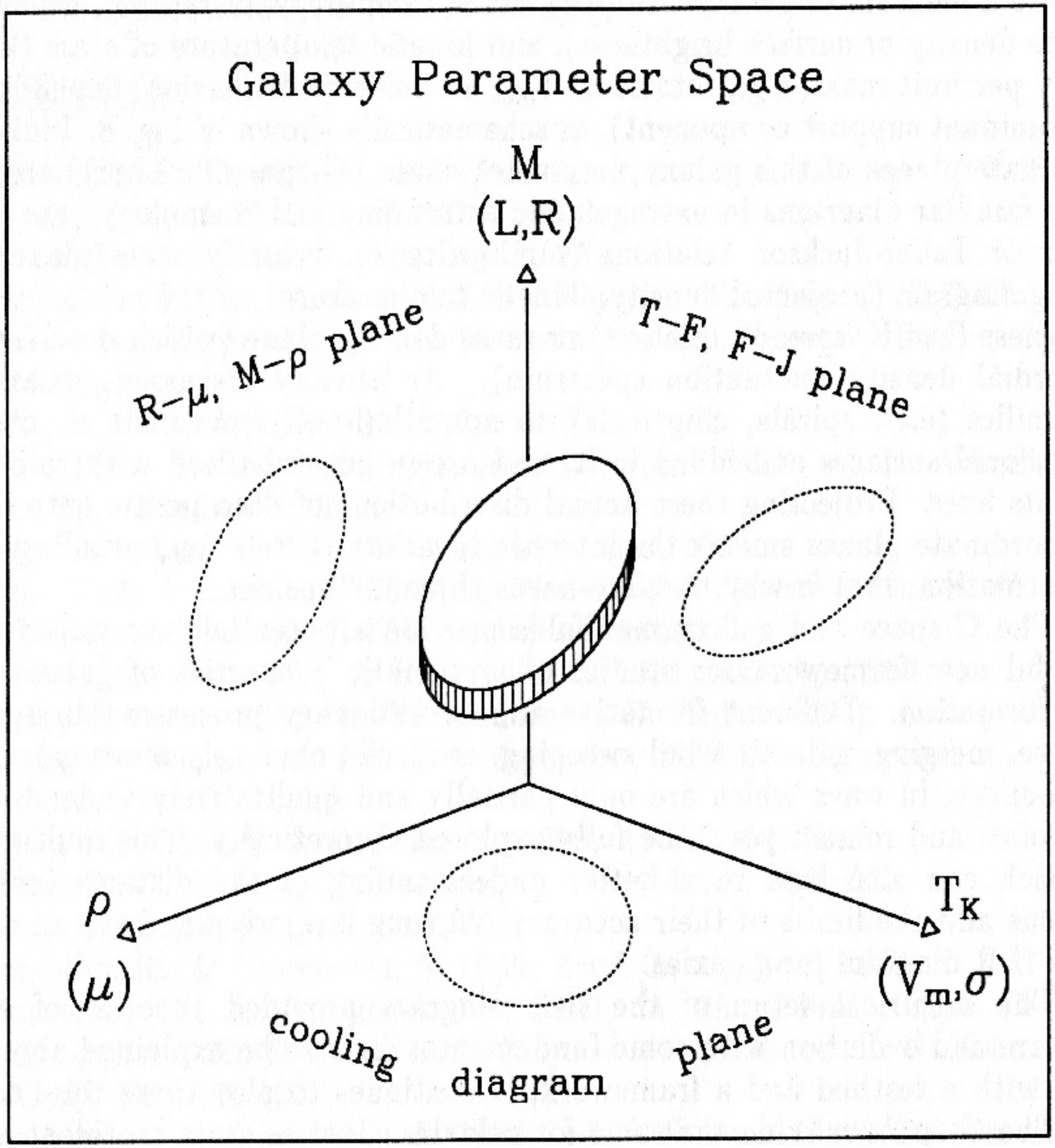
How Can This Be?

- The implication is that elliptical galaxies occupy only a small, naturally selected, subset of all dynamical structures which are in principle open to them
  - Maximum entropy states? But gravothermal entropy is notoriously difficult to define, and the mechanism to achieve this is completely unknown
- Numerical sim's can *reproduce* the observed structures of E's, and the FP, but they *do not explain* them
- Understanding of the origin of the small scatter of the FP (or, equivalently, the narrow range of their dynamical structures) is ***an outstanding problem***



(Robertson et al. 2006)

The Galaxy Parameter Space



A more general picture

Galaxies of different families form 2-dim. sequences in a 3+ dimensional parameter space of physical properties, much like stars form 1-dim. sequences in a 2-dim. parameter space of {L,T} - this is an equivalent of the H-R diagram, but for galaxies

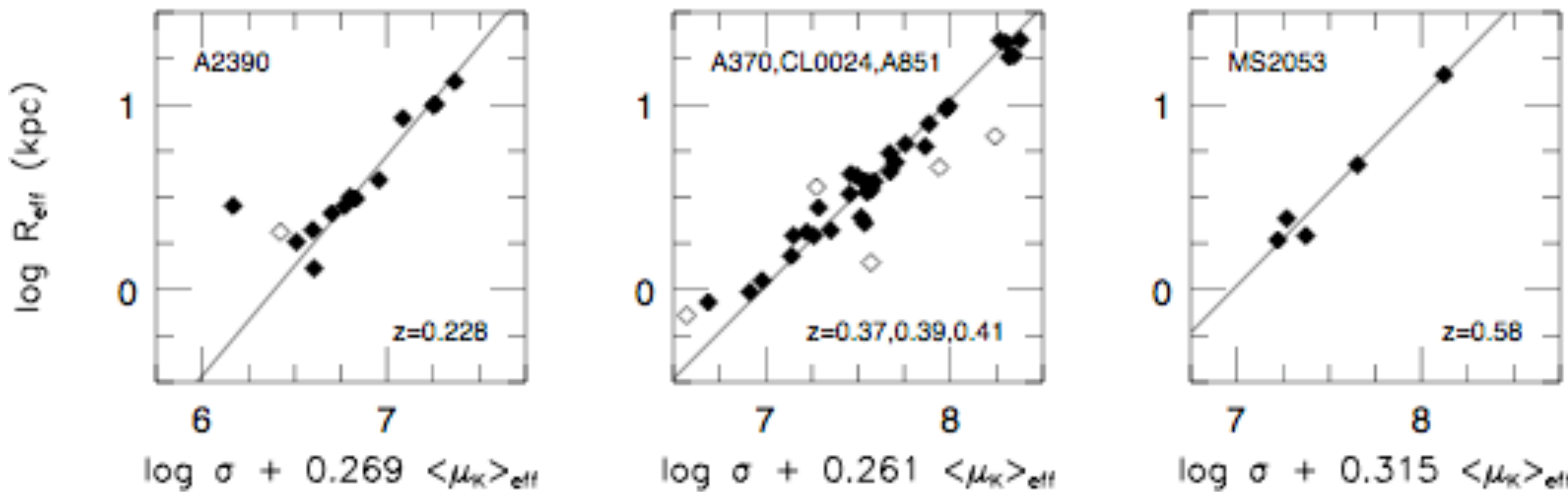
(Djorgovski 1992)

Scaling Relations as Evolution Probes

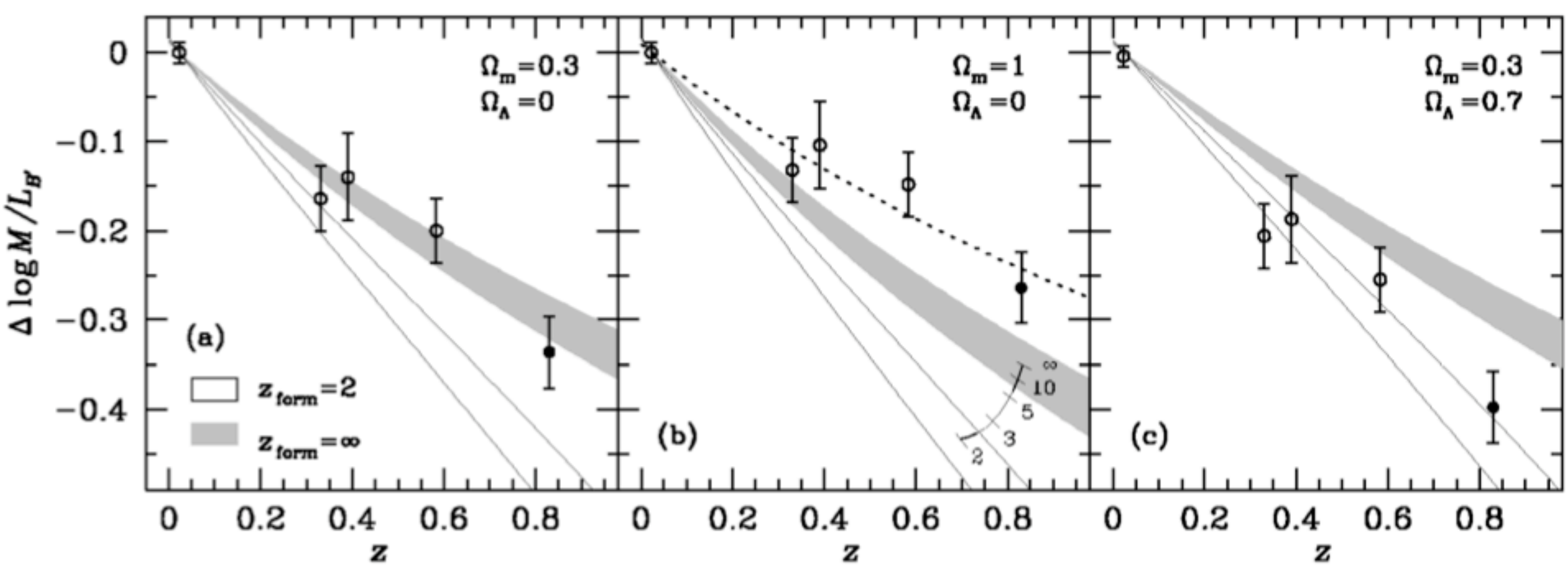
- Empirical ways of characterizing any population, in order of increasing power:
  - Characteristic values (e.g., mean luminosity, “typical” SFR…)
  - Distribution functions (e.g., luminosity function)
  - Correlations (e.g., the FP, TF relations)
- The FP family of correlations encapsulates many (most?) of the fundamental properties of ellipticals, in a statistically optimal way; and it is a product of their formative and evolutionary histories
- Thus it is potentially a powerful way to study the evolution of ellipticals, now out to $z \sim 1.5$ (lbt ~ 9 Gyr)
  - Enabled by the spectroscopy with 8-10-m class telescopes (Keck, then VLT), and HST imaging

Early Work: FP Evolution in Clusters

Pahre et al. 1998: FP evolution out to $z \sim 0.6$



van Dokkum et al. 1998: (M/L) evolution out to $z \sim 0.8$

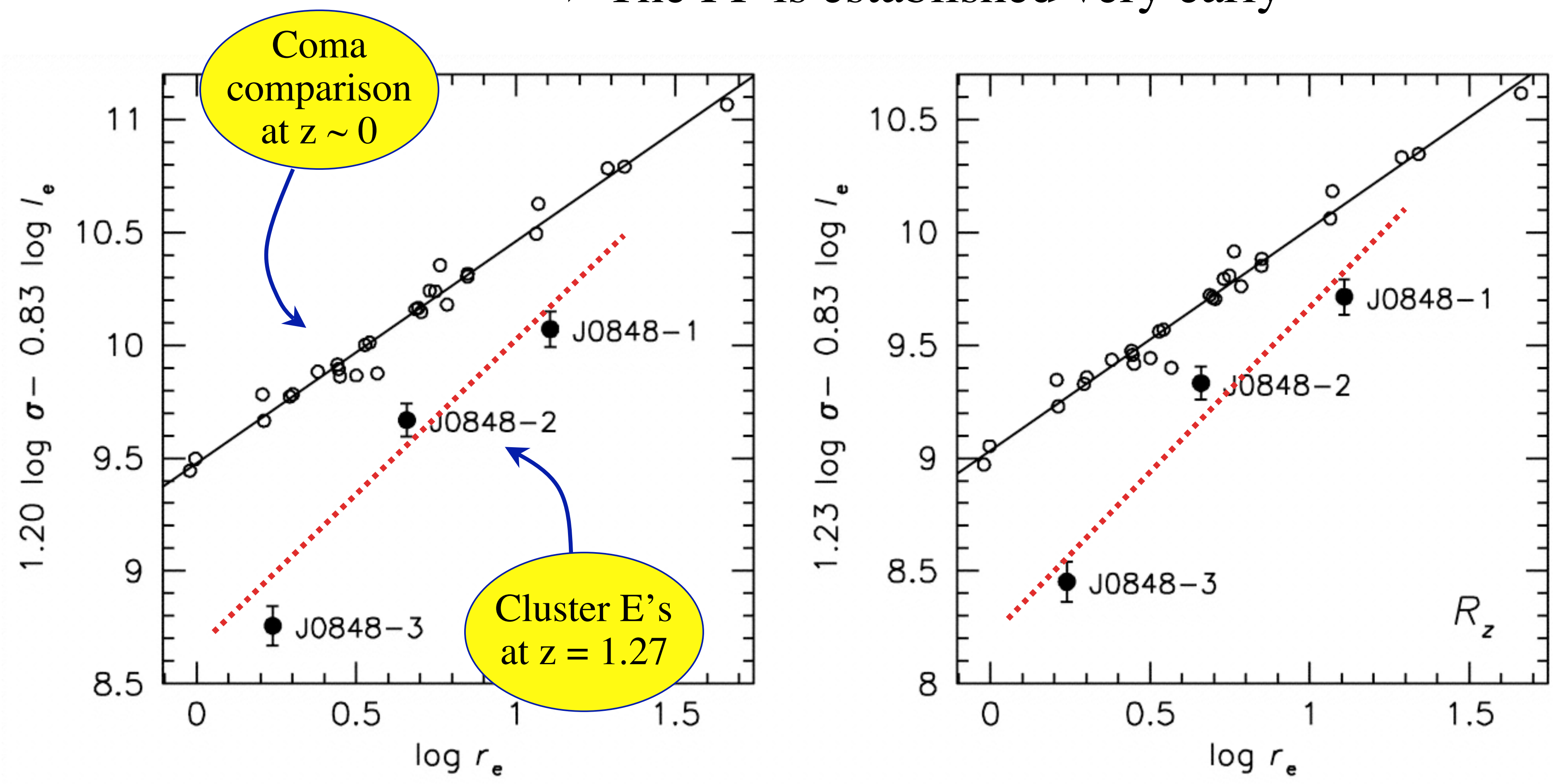


The Most Distant FP Measured So Far

Cluster at z =1.27

(van Dokkum & Stanford 2003)

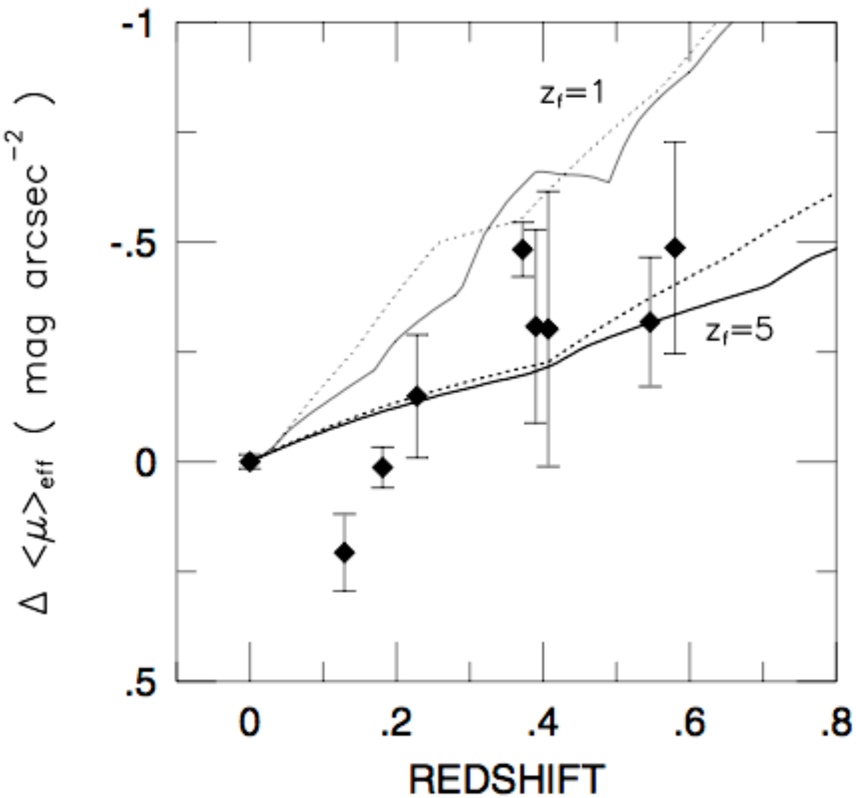
➡ The FP is established very early



FP Evolution in Clusters Out to z ~ 0.6

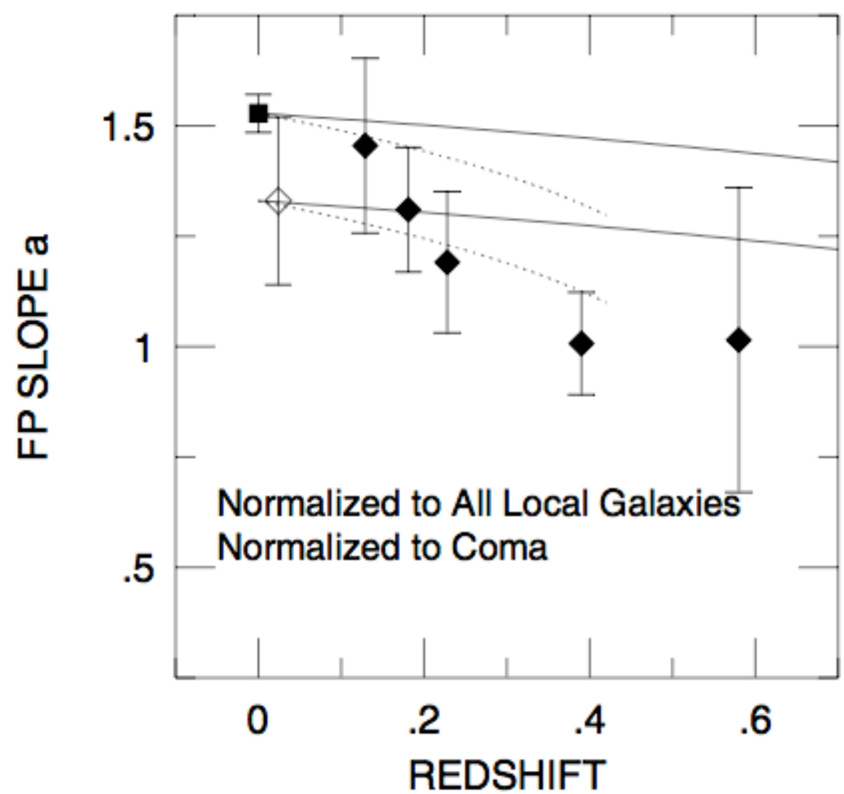
(Pahre et al. 1998, 2001)

Evolution of the s.b. intercept



Implies formation at high *z*'s, and passive evolution (or dry merging) thereafter

Evolution of the σ slope

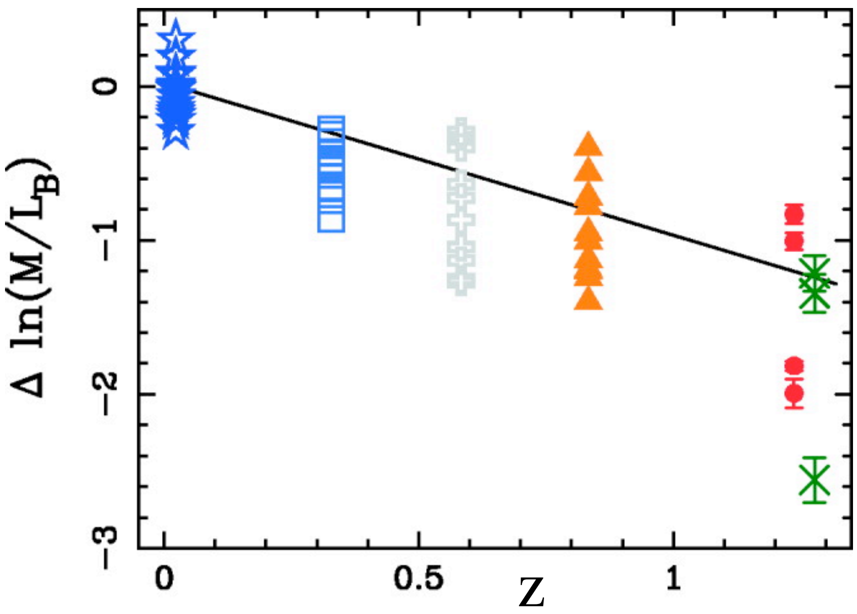


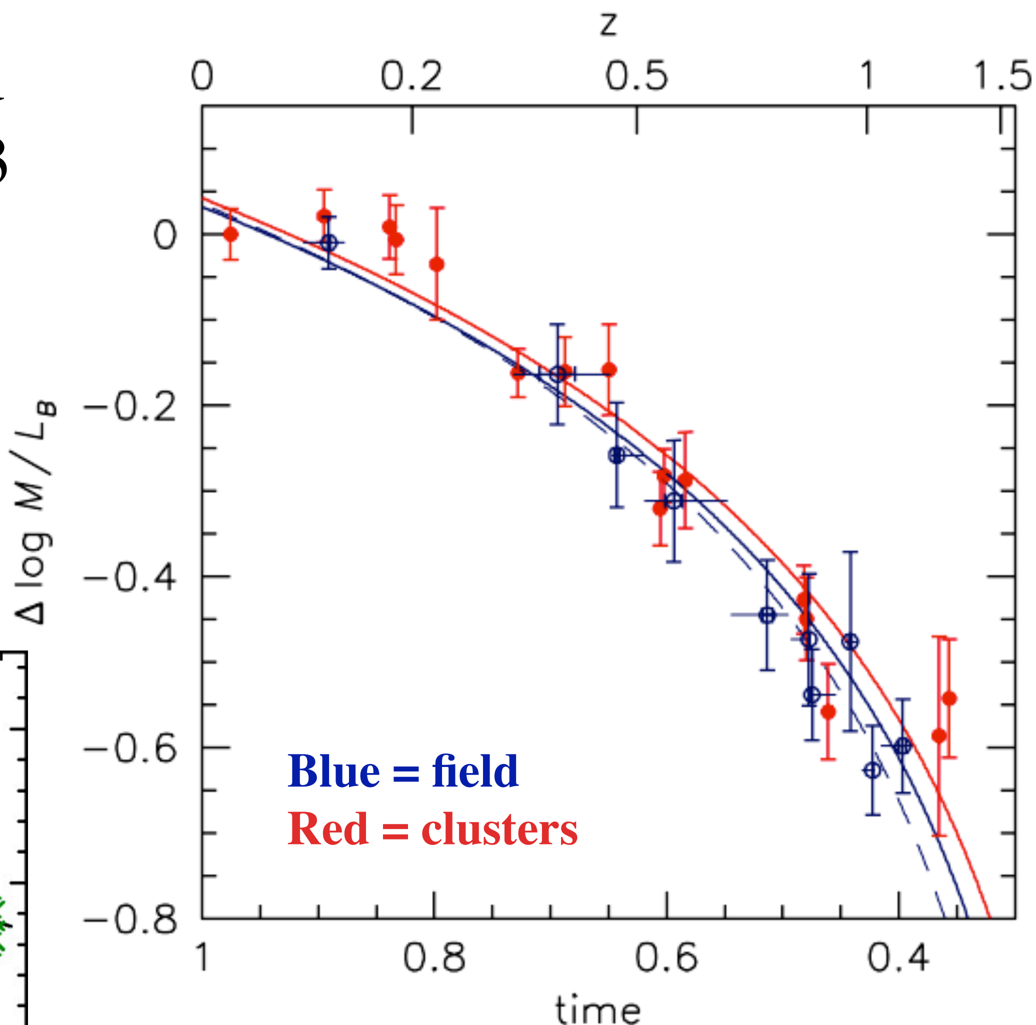
FP rotation: implies a mass dependent evolution (aka downsizing)

Evolution of the (M/L) Ratios

A clear and systematic trend out to z ~ 1.5, or the past 2/3 of the age of the universe

(NB: these plots restricted to the more massive galaxies, e.g., $M > 10^{11}\ M_{\odot}$)





↑ *van Dokkum & van der Marel 2007*

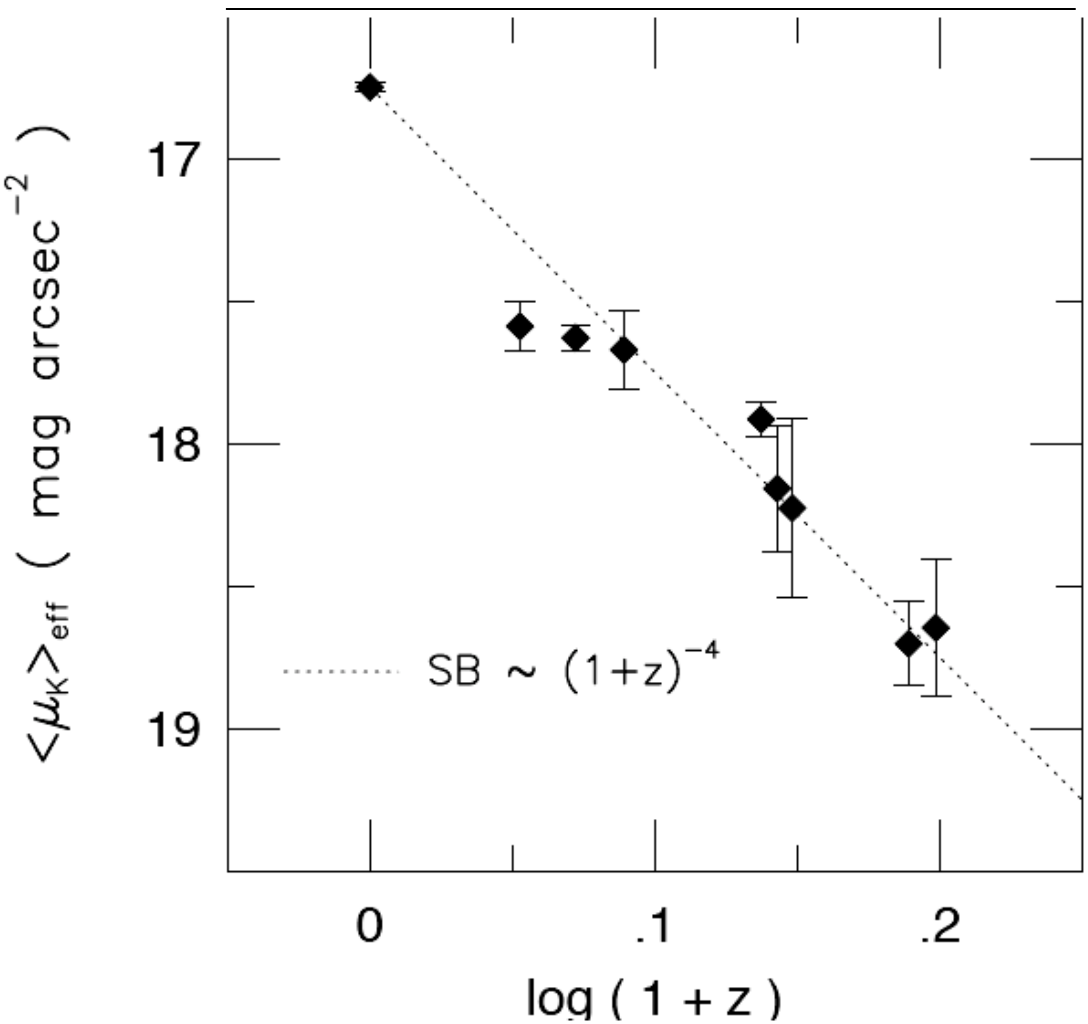
← *Holden et al. 2005*

The Tolman Test

- Use the surface brightness intercept of the FP in clusters at different *z*'s as the "standard fuzz" in the classical Tolman test for the expansion of the universe
- However, one has to account for the stellar luminosity evolution
- Assuming a simple, passive evolution model with galaxy formation at z ~ 5, produces the expected Tolman signal:

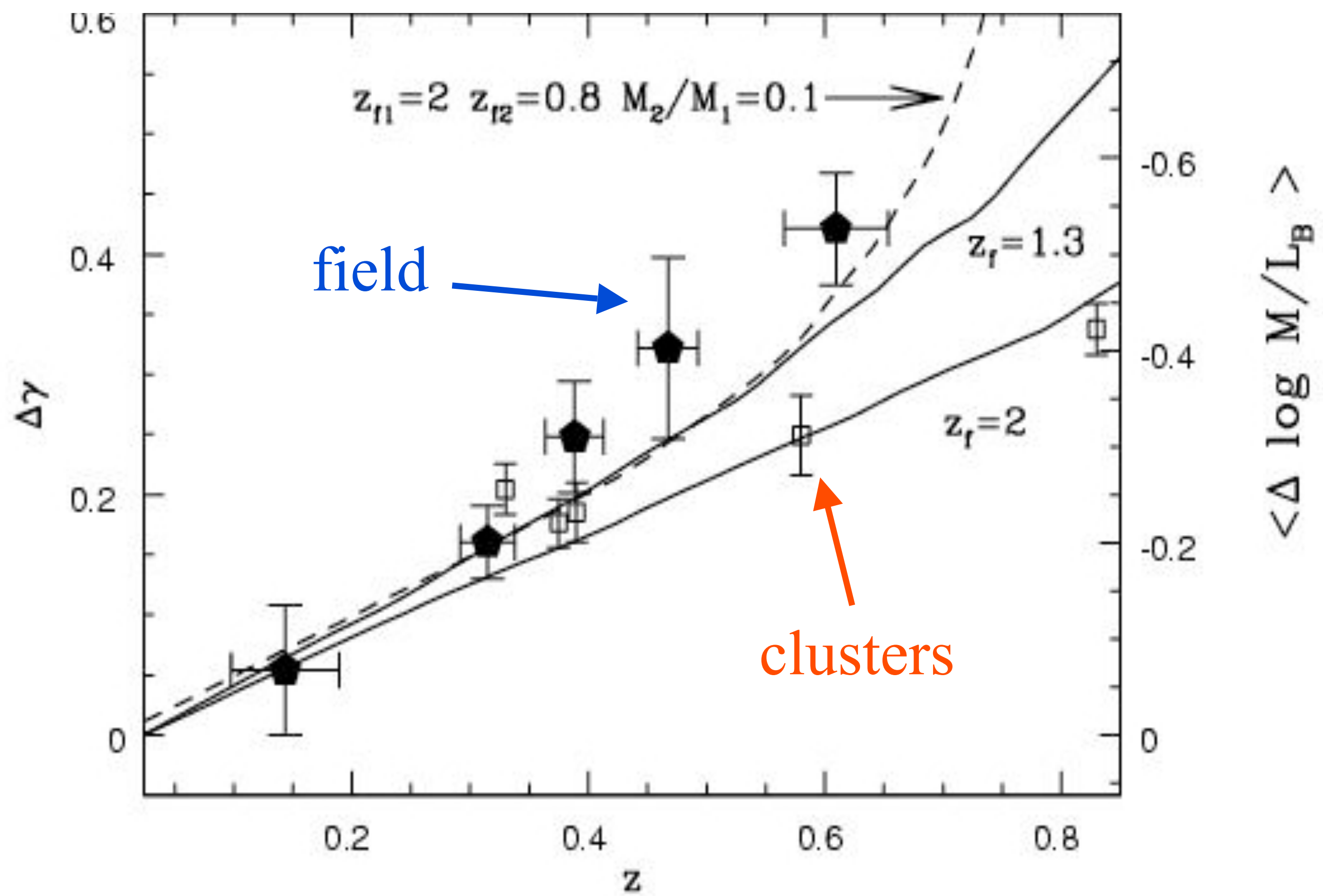
$$\boldsymbol{SB \sim (1+z)^{-4}}$$

(Pahre et al. 1996, 2001)



Clusters vs. Field

Initially, it appeared that the field E's are evolving more rapidly than the cluster samples *(Treu et al. 1999, 2001, 2002; Gebhard et al. 2003)*



But it turns out that this can be mostly explained in terms of mass dependent evolution, and the rarity of massive E's in the field

Mass-Dependent Evolution

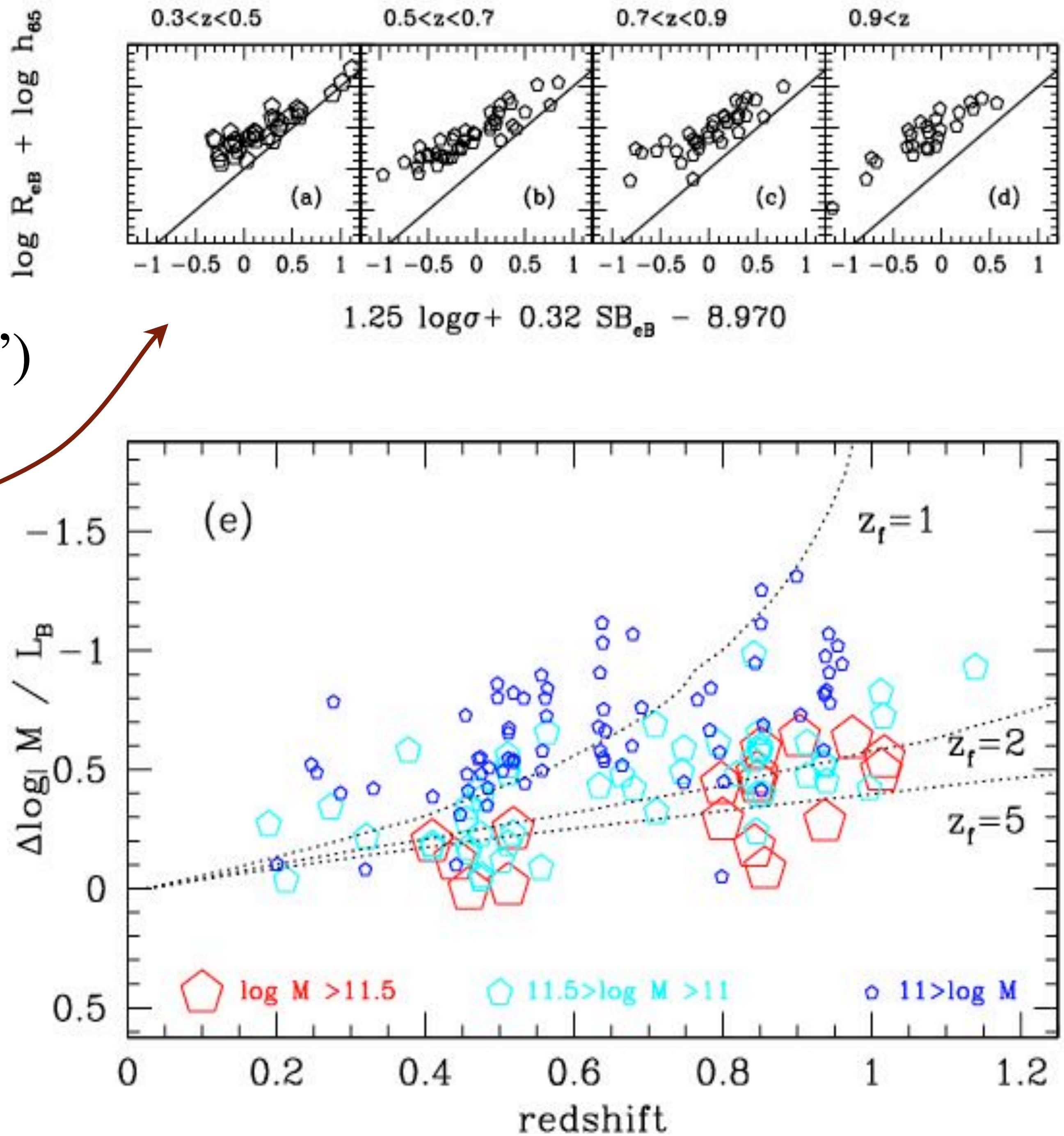
(aka "downsizing")

FP shift and rotation

Mass-dependent (M/L) evolution:

(Treu et al. 2005)

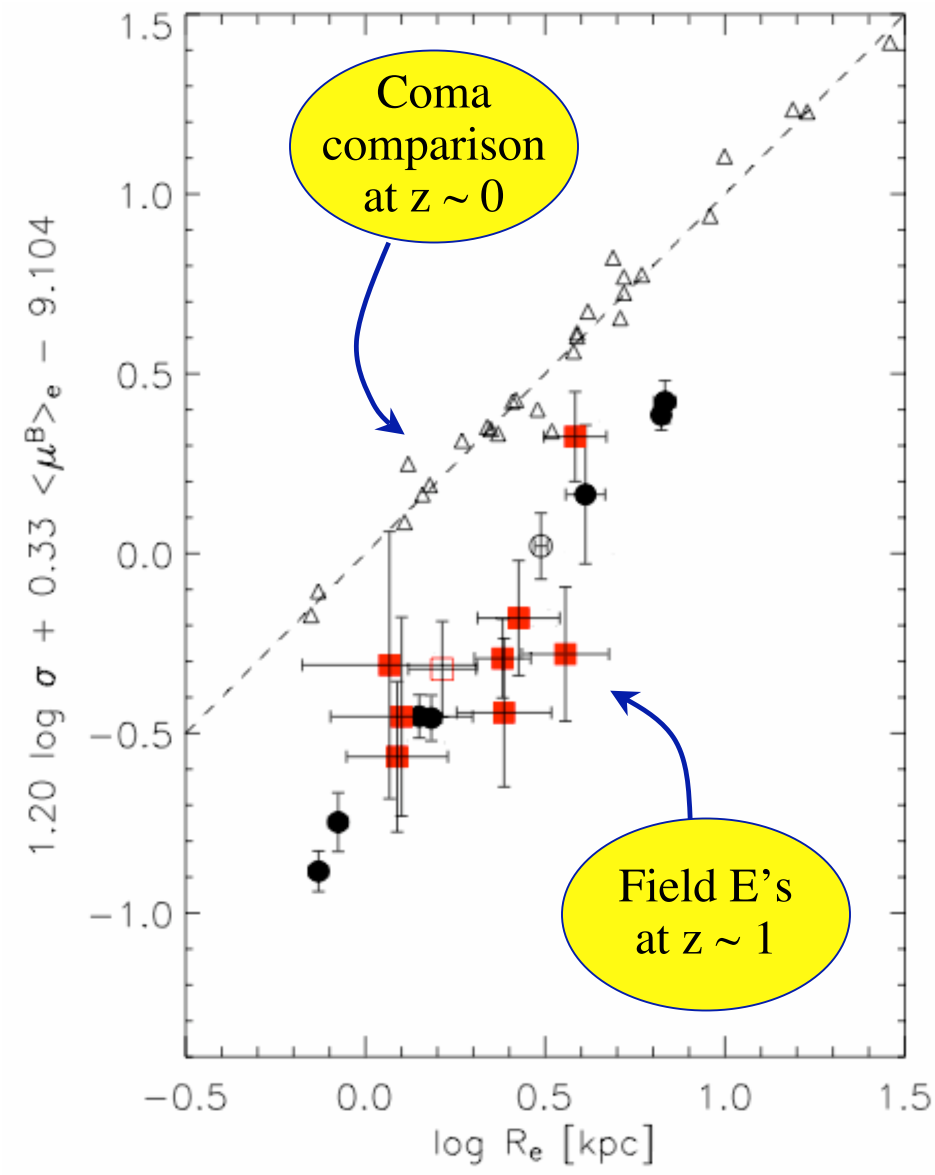
Marc

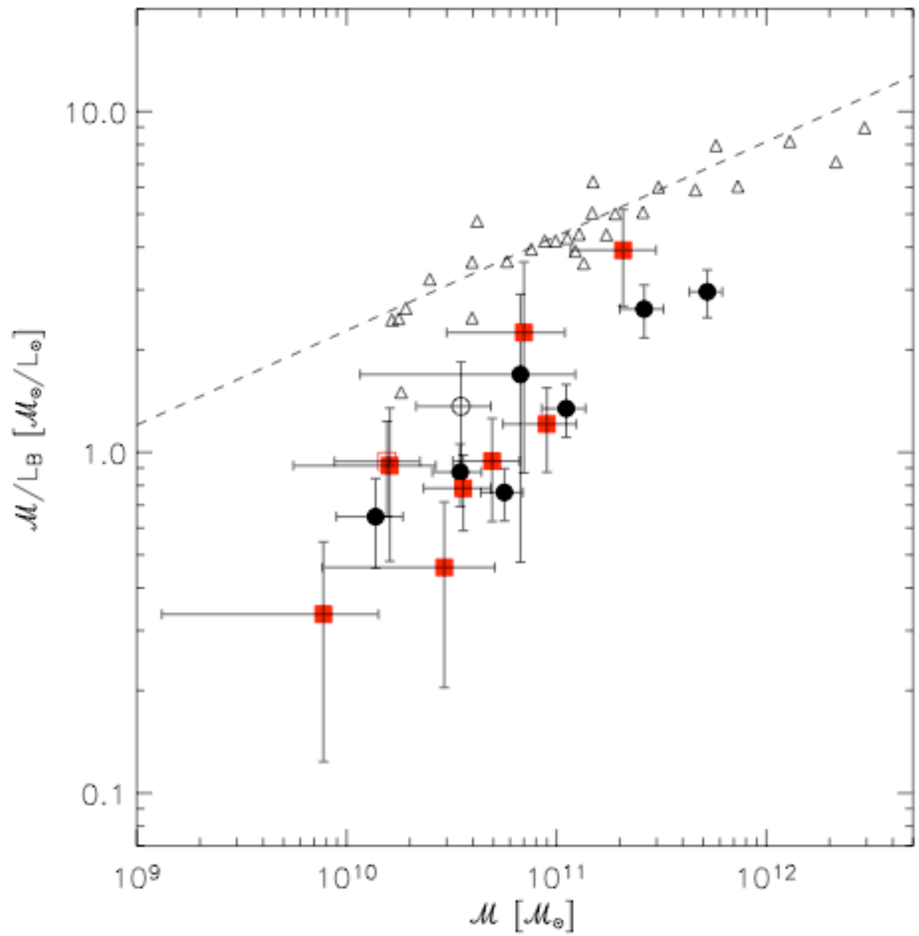


Mass-Dependent Evolution

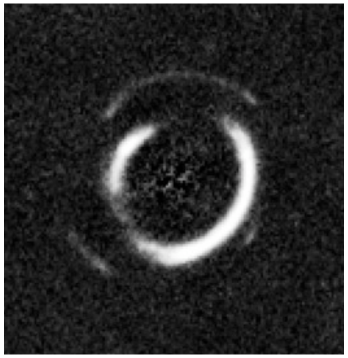
This is now seen in essentially all deep FP samples, e.g., field E's at $z \sim 0.9$ - 1.3, in the K band

(di Serego Alighieri et al. 2005)

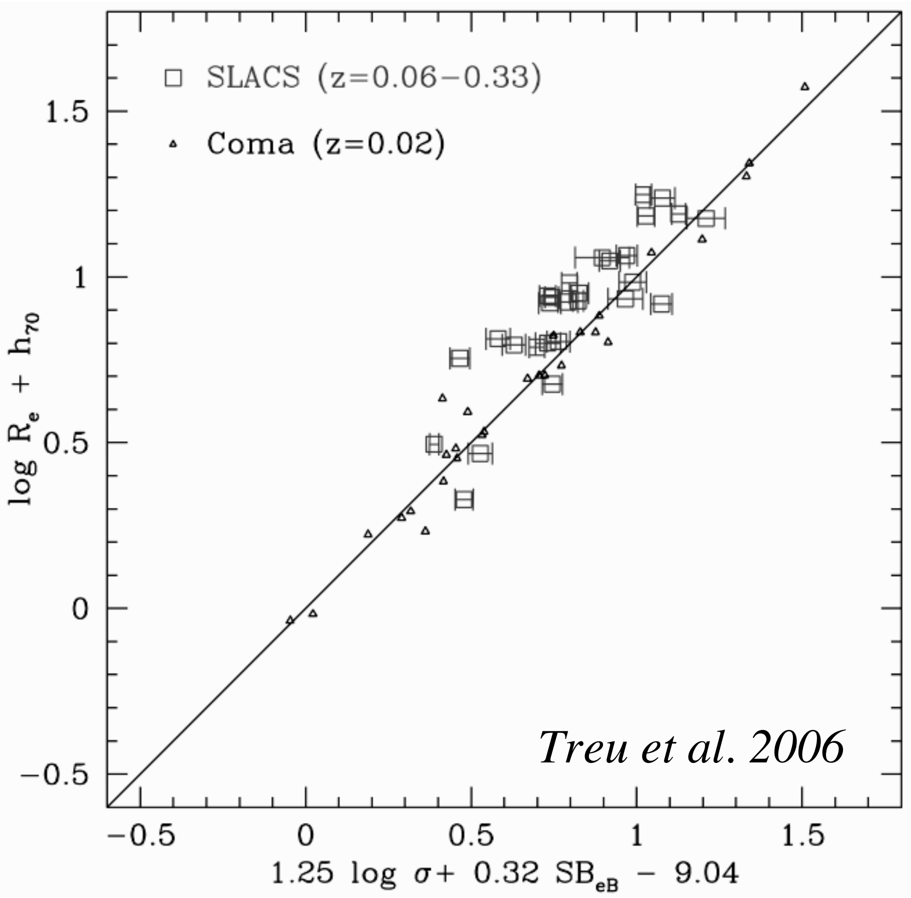


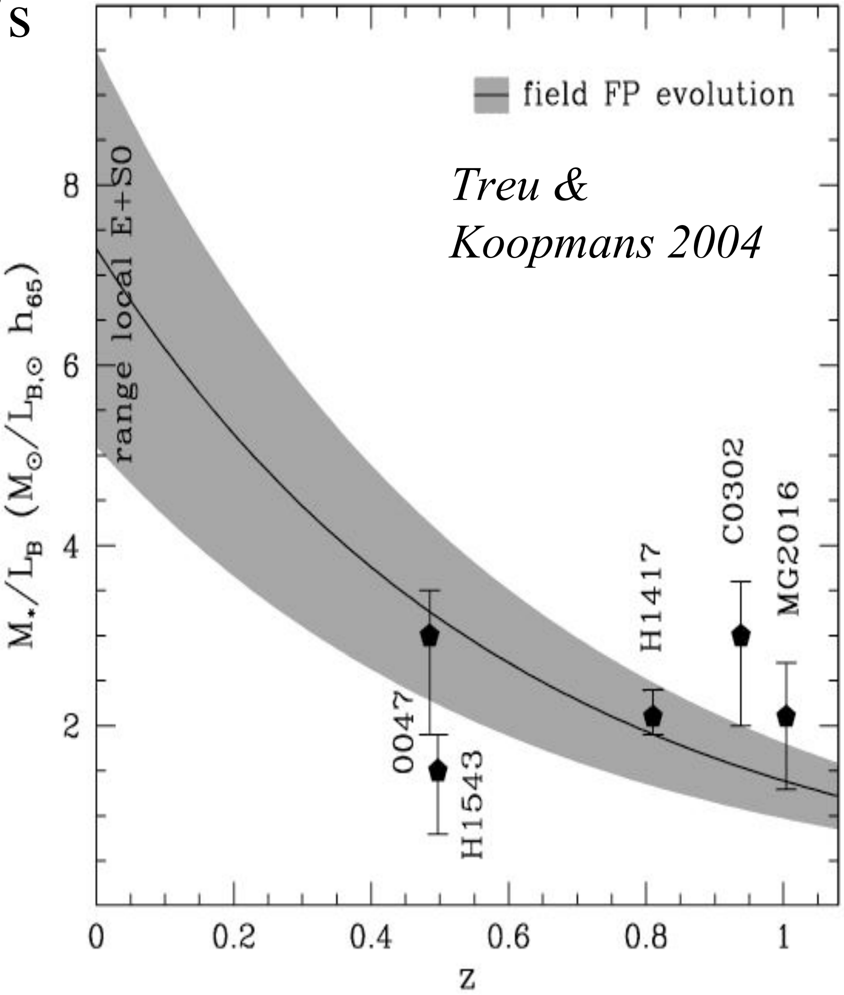


FP of Lensing Galaxies



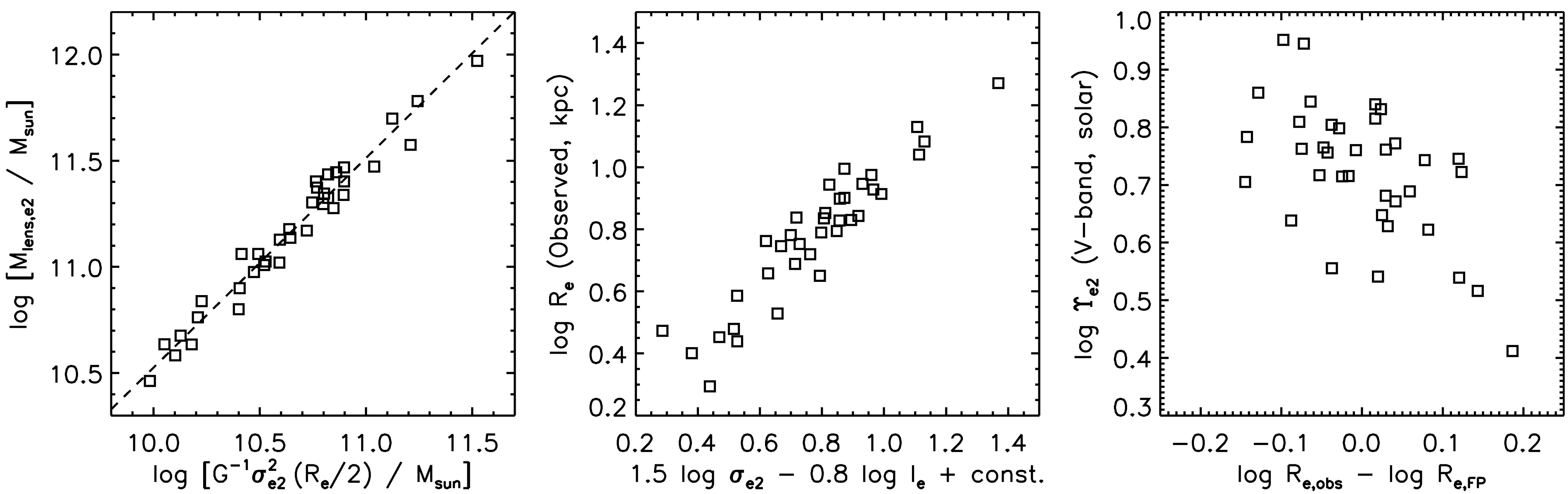
Treu, Koopmans, and collaborators have been using galaxy lenses (HST imaging + Keck spectroscopy) to derive their dynamical structure and parameters: They follow the same FP as the field E's





Mass-Based Fundamental Plane

The use of lensing galaxies allows for the determination of their ***mass-based*** structural parameters *(Bolton et al. 2007)*



Traditional FP fit gives $\boldsymbol{R \sim \sigma^{1.4} I^{-0.8}}$, consistent with other work. *Replacing* the surface brightness $\boldsymbol{I}$ with the *projected mass density* $\boldsymbol{\Sigma}$ gives a "mass plane" scaling: $\boldsymbol{R \sim \sigma^{1.8 \pm 0.2} \Sigma^{-1 \pm 0.2}}$, consistent with the Virial Theorem, and with a smaller scatter!

This implies *a homology of mass* (if not light) structures of E's

FP Evolution Studies at High Z's: A Consensus Circa 2007

- FP is already established in clusters at $z \sim 1.5$, maybe beyond
- There is a clear detection of the stellar evolution fading signal; most massive E's formed most of their stars at $z > 2$ or 3
  - Observed as an evolution of FP intercepts or (M/L)
- There is a mass-dependent evolution difference in that less massive galaxies form larger fractions of their stars at lower redshifts (aka "downsizing")
  - This manifests as the rotation of the FP
- After accounting for this mass dependence, there is little (if any) difference between the field and cluster populations
- Lensing galaxies belong to the same population as the field E's, and allow studies of mass-based FP correlations

Summary

- The FP correlations provide unique observational constraints on the structure, formation, and evolution of early-type galaxies
- Their formative processes tightly couple the dynamical structure, chemical enrichment (star formation) history, and growth of their central black holes, in a remarkably robust manner, with just two parameters accounting for many fundamental properties
- The small scatter of the FP implies that ellipticals cover only a very limited, standardized range of dynamical structures; the mechanism of this natural selection is not yet understood
- FP correlations are the sharpest tool in our observational arsenal to study the evolution of early-type galaxies: it appears to be the same in all environments, and mass dependent ("downsizing")
- FP studies of lensing galaxies open important new avenues to explore these questions