

The Role of Dissipation in Spheroid Formation



Philip Hopkins 12/03/07

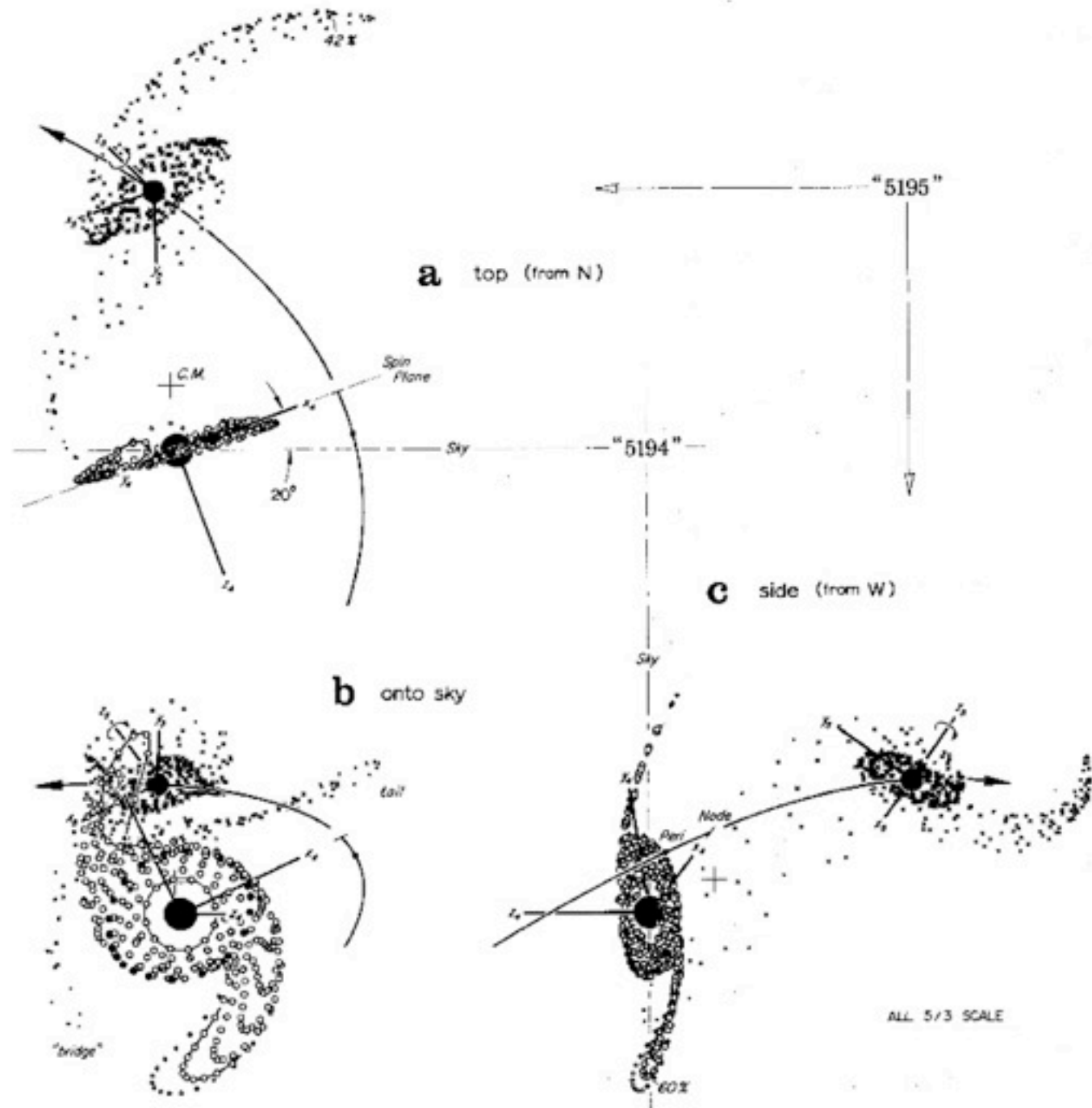
Lars Hernquist, TJ Cox, Dusan Keres, Volker Springel,
Suvendra Dutta, John Kormendy, Tod Lauer

Rachel Somerville (MPIA), Gordon Richards (JHU), Kevin Bundy (Caltech),
Alison Coil (Arizona), Adam Lidz (CfA), Adam Myers (Illinois), Yuexing Li (CfA),
Paul Martini (OSU), Ramesh Narayan (CfA), Elisabeth Krause (Bonn)

Ellipticals & Bulges: Formation in Mergers?

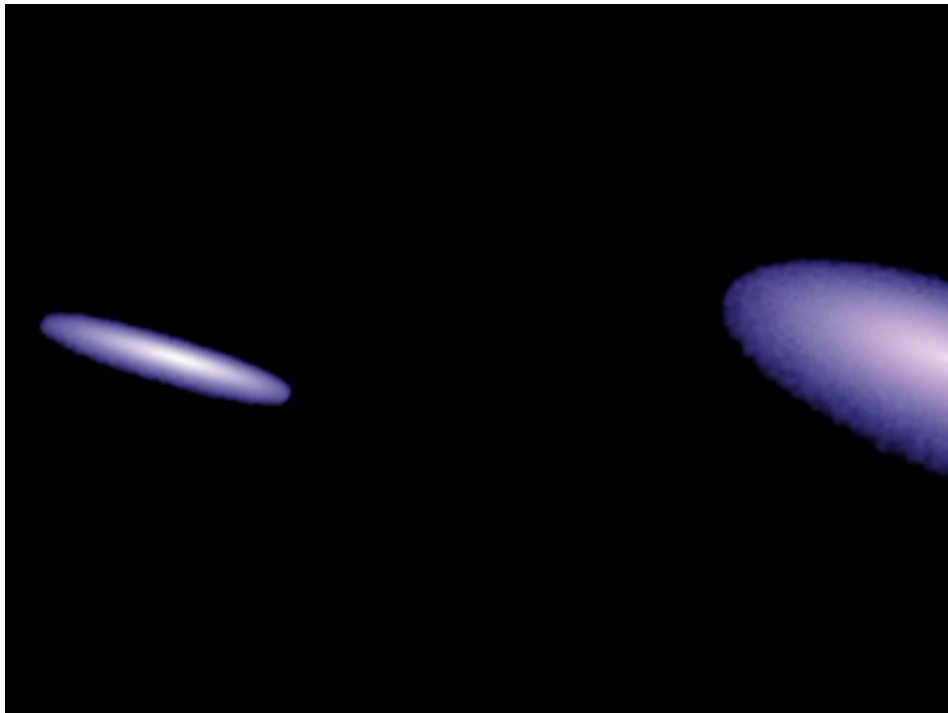
Toomre & Toomre (1972) ::
the “merger hypothesis”

ellipticals are made by the
collision and merger of
spirals



Fundamental Plane Tilt

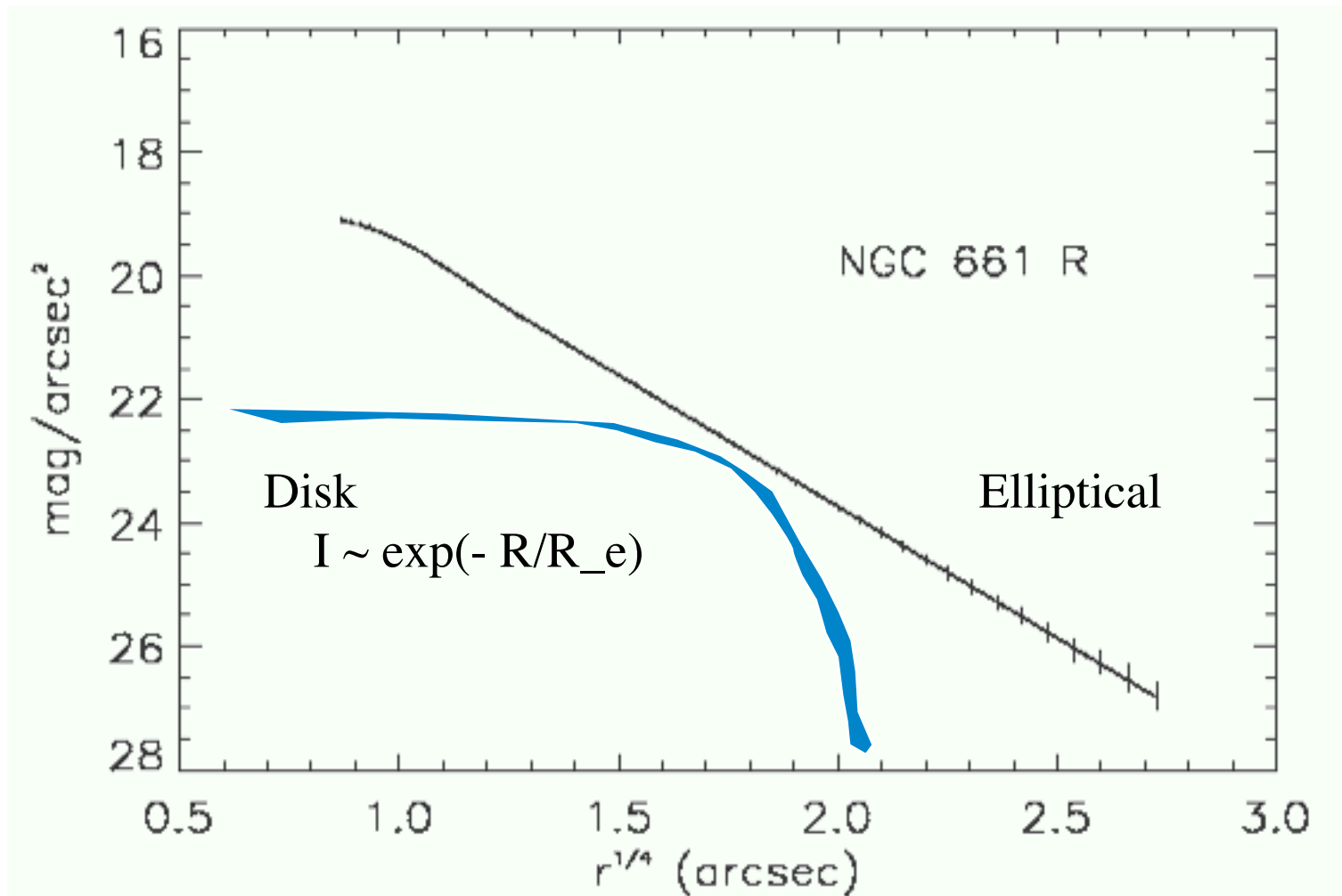
STRUCTURAL NON-HOMOLOGY



Ellipticals & Bulges: Formation in Mergers?

De Vaucouleurs (1948): Spheroids follow an $r^{1/4}$ (ish) law

$$I(R) = I_0 \exp(-b [R/R_e]^{1/4})$$



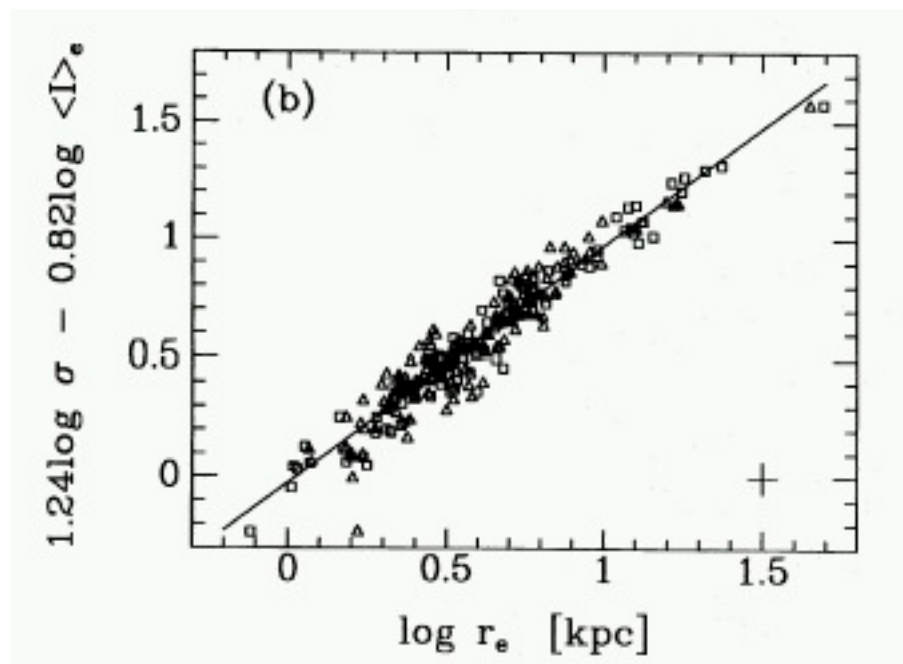
- Lynden-Bell: violent relaxation: rapidly changing potential: stars scatter off the changing potential, mixing their orbits and energies

The Problem:

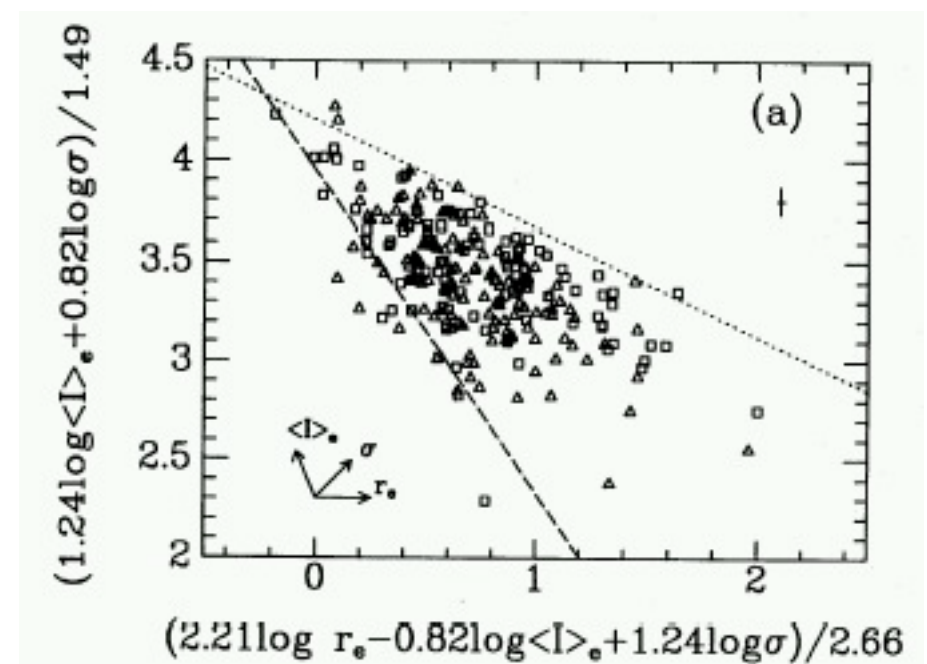
The Fundamental Plane correlates R_e , surface brightness, and σ for elliptical galaxies.

Faber–Jackson & Kormendy relations link size or dispersion to luminosity or stellar mass:

Ellipticals are much more dense than spirals of the same mass!



Fundamental Plane edge on



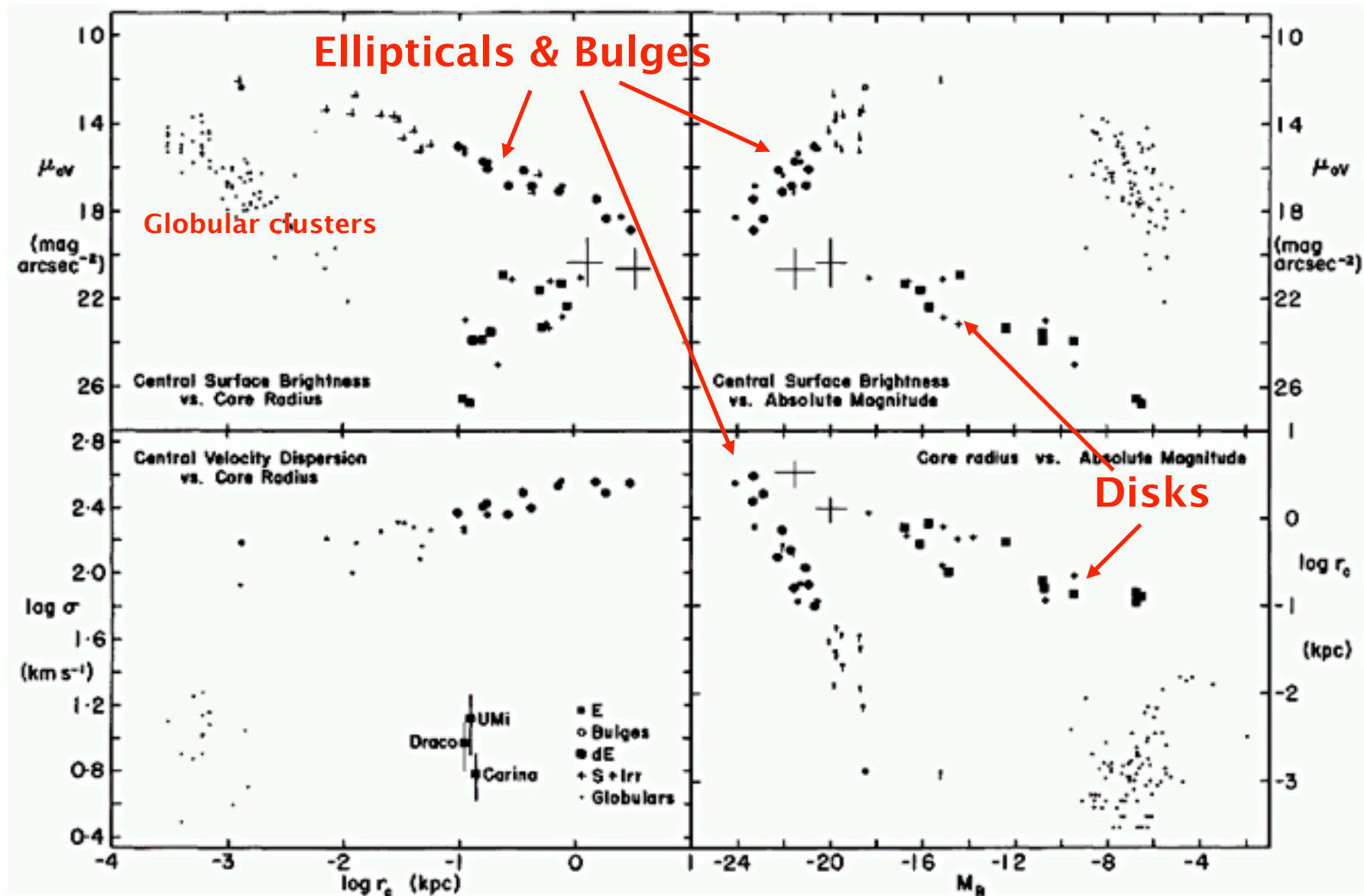
Fundamental Plane face on

Jorgensen 1996

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

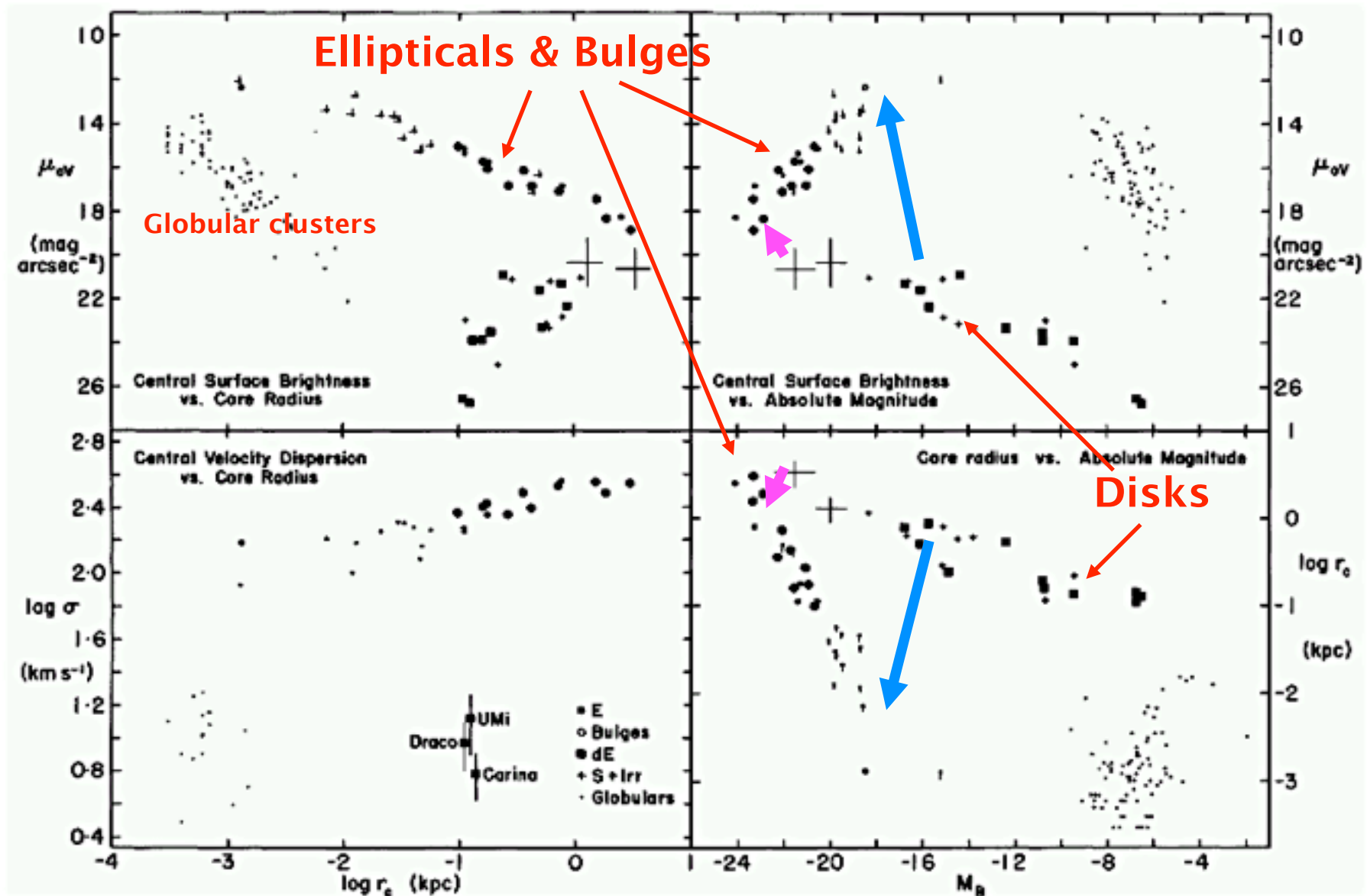
Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

Louisville's Theorem: cannot increase phase space density
in collisionless mergers

Solution 1: High- z mergers from more compact disks
but...

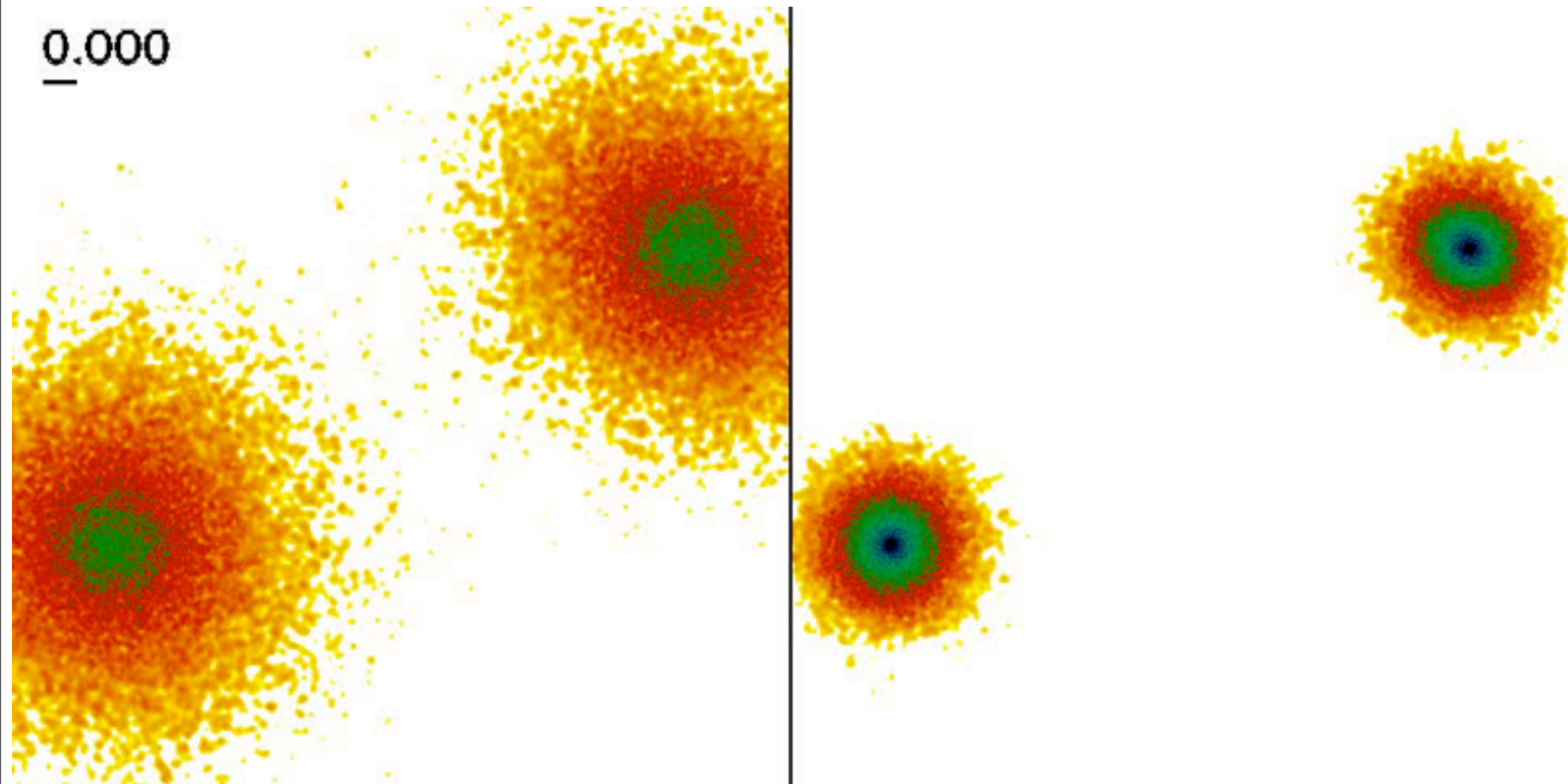
many low-mass ellipticals formed at $z < 1$
observed evolution is relatively weak

Solution 2: Gas dissipation

The Problem

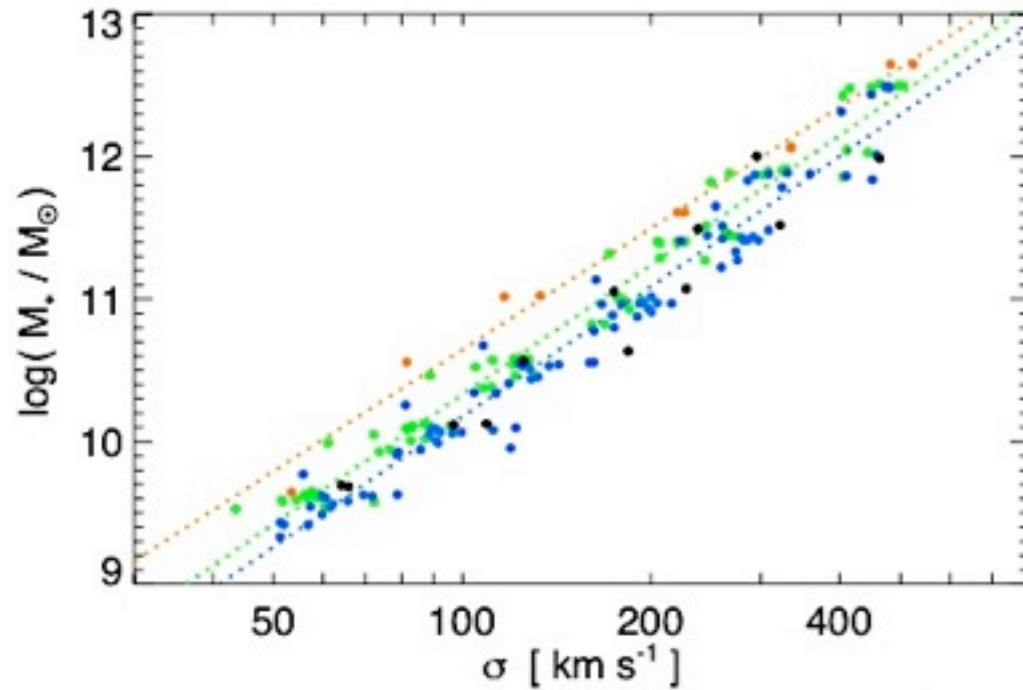
FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- Why are ellipticals so much smaller than disks?
Gas dissipation allows them to collapse to small scales!



Redshift Evolution

SIZE-MASS RELATIONS

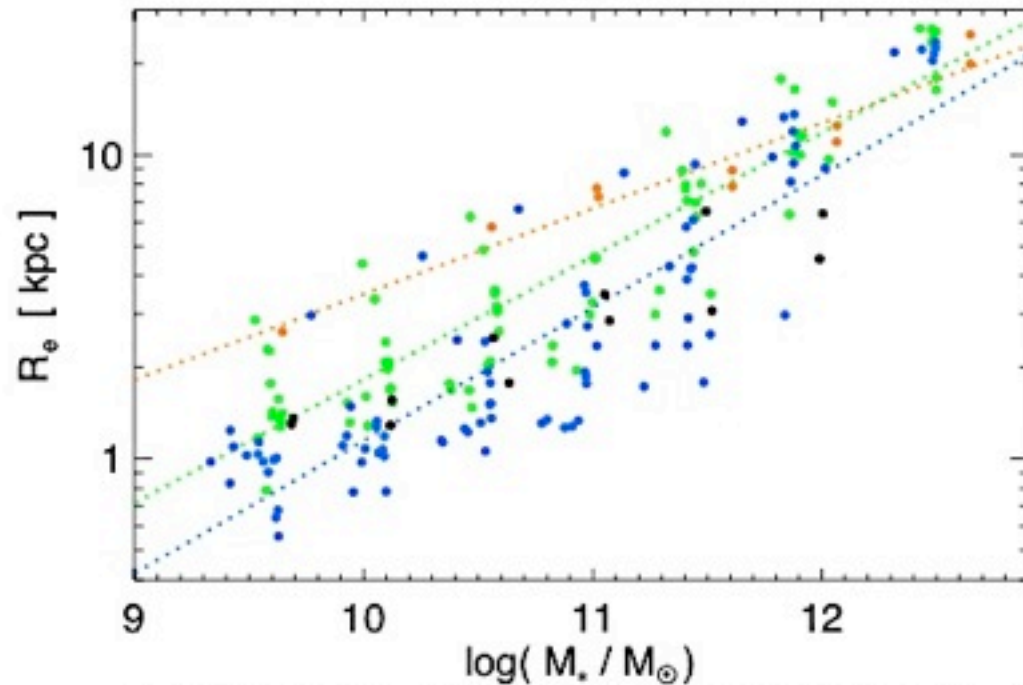


➤ Faber-Jackson & size-mass vs. disk gas content

$f_{\text{gas}} = 0.1$

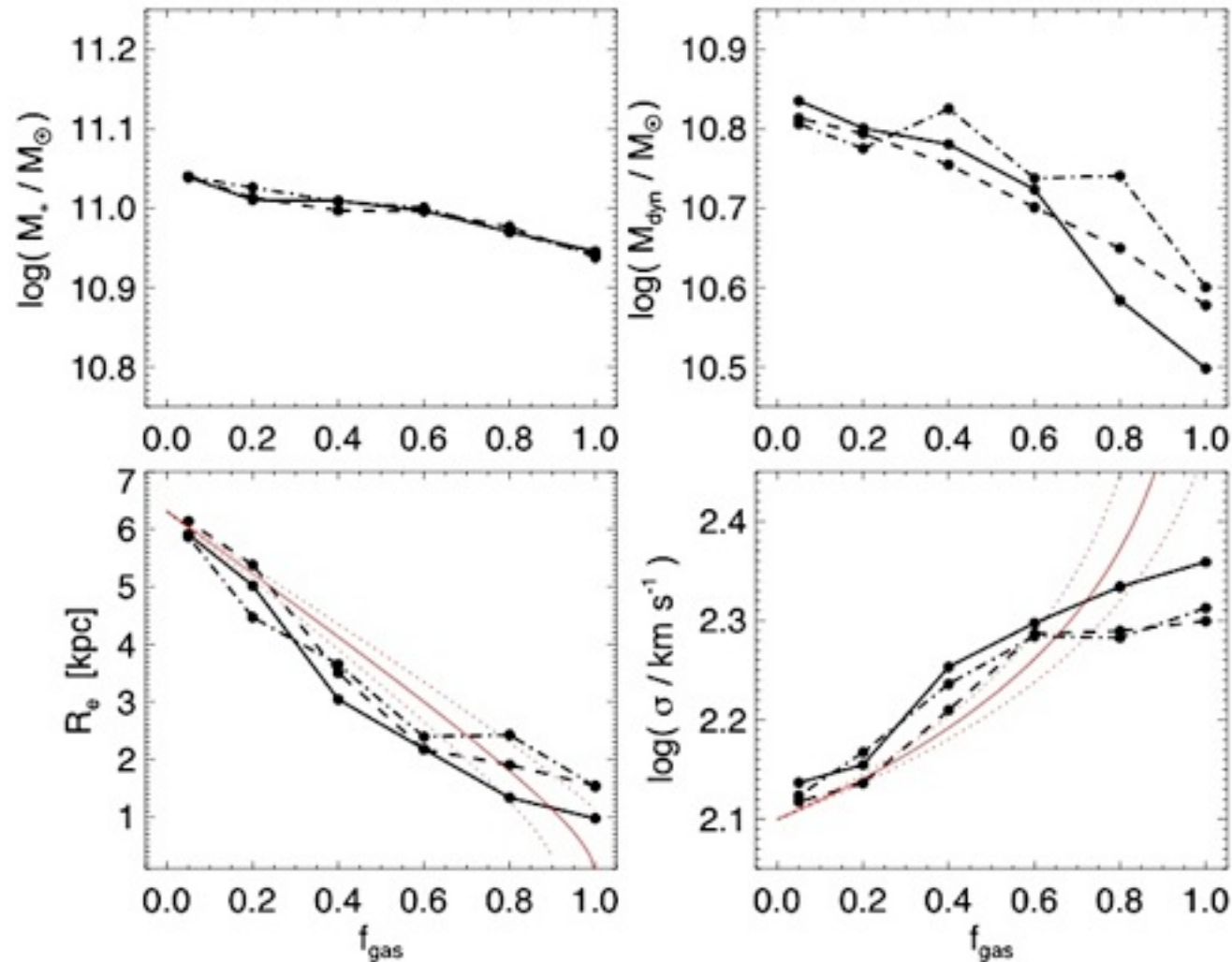
$f_{\text{gas}} = 0.4$

$f_{\text{gas}} = 0.8$



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS



- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential

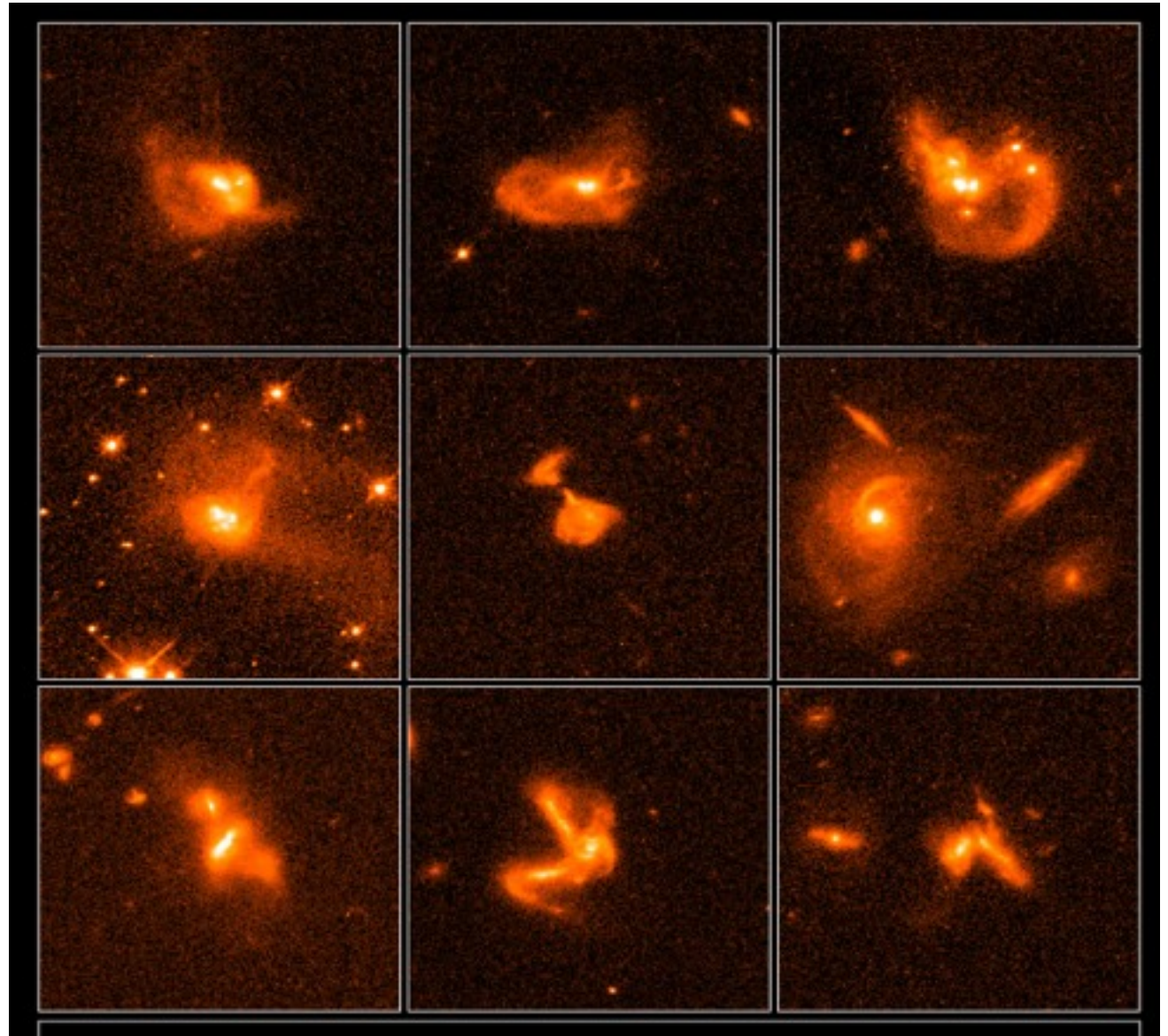
The Solution: Gas Dissipation?

Look at late-stage merger remnants

Bright ULIRGs make stars at a rate of $>100 M_{\odot}/\text{yr}$.

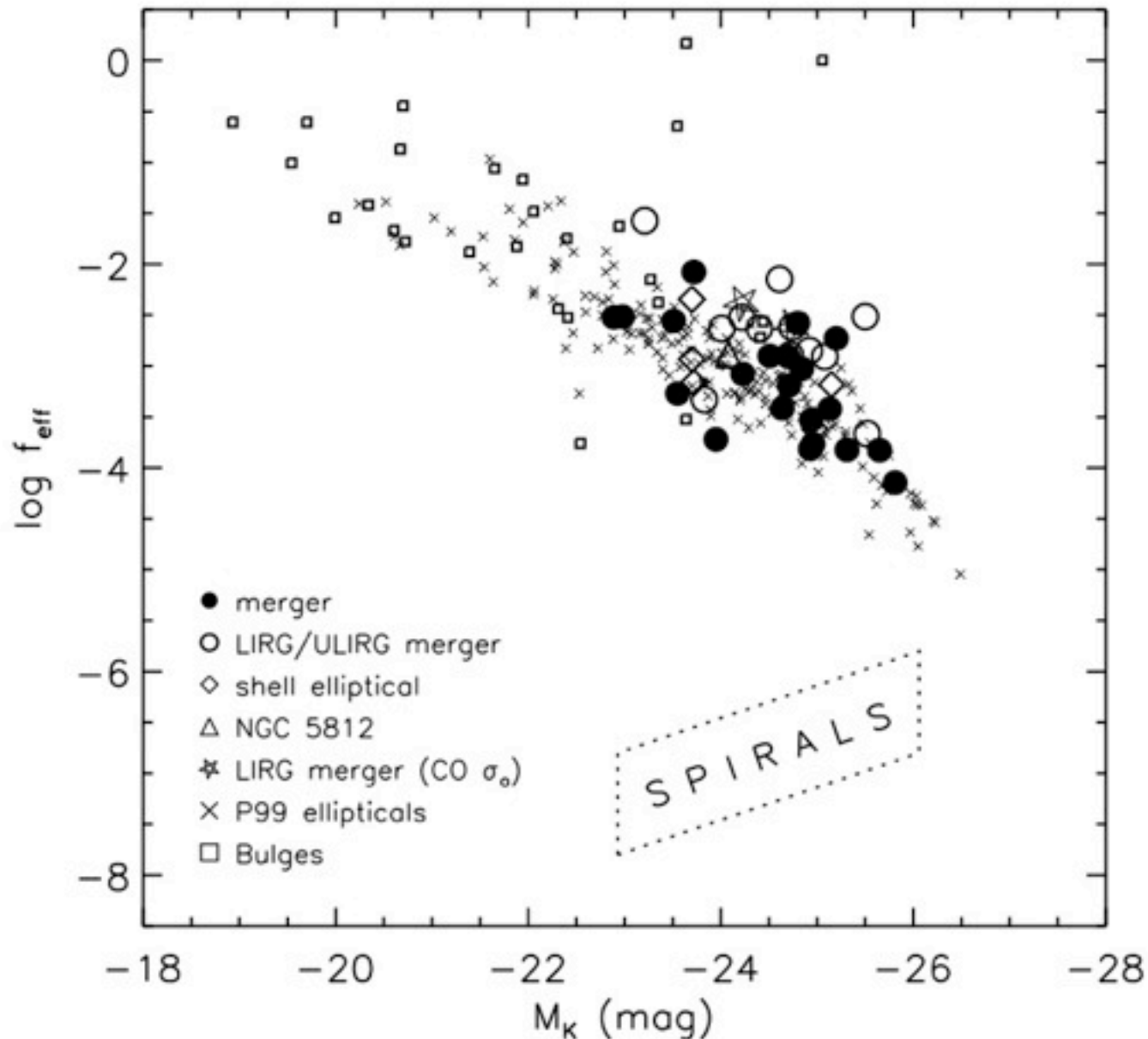
Extremely compact ($< \text{kpc}$ scales)

Borne et al., 2000



The Solution: Gas Dissipation?

- Mergers **have** solved this problem: we just need to understand it

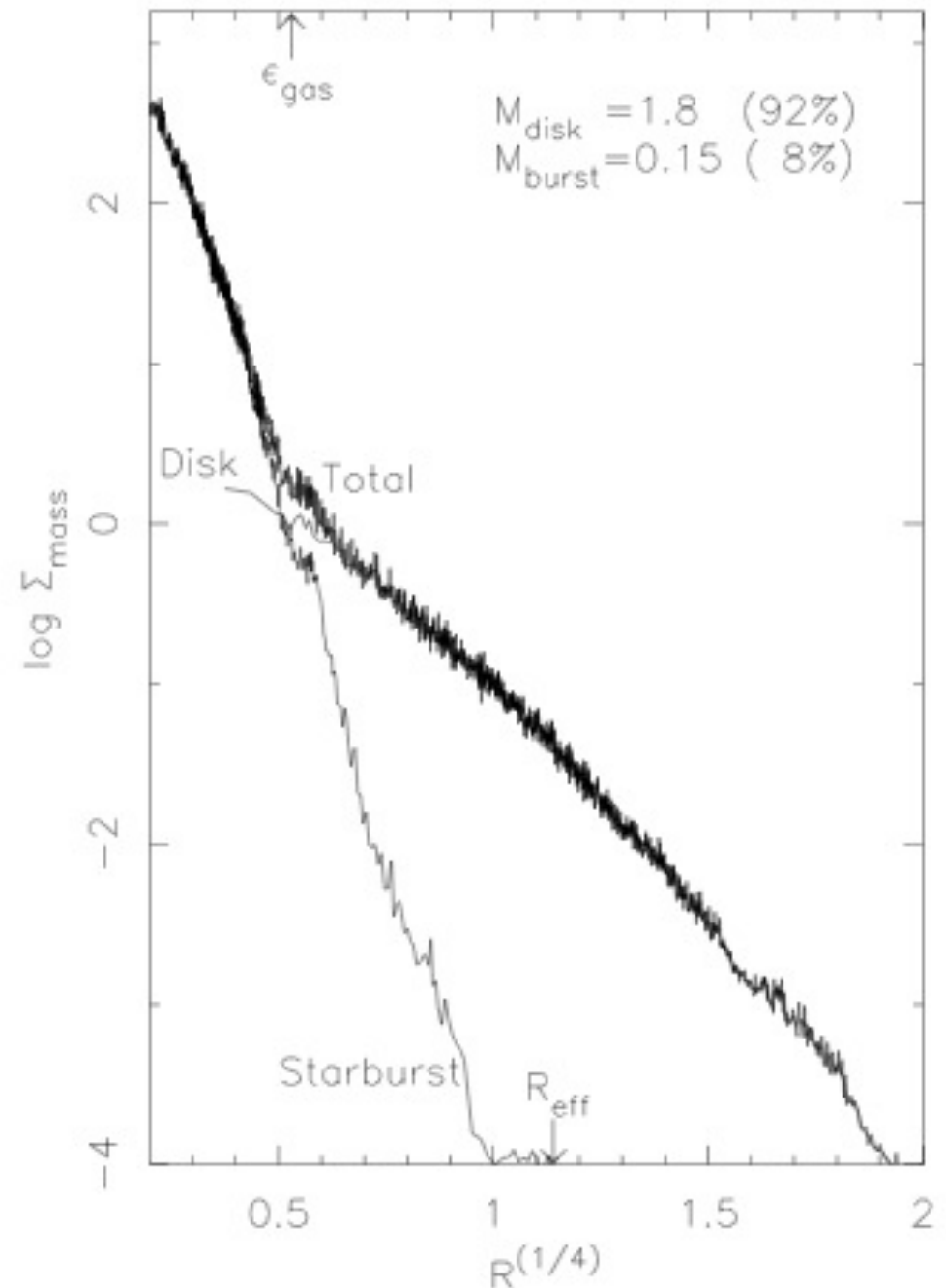


Starburst Stars in Simulations Leave an “Imprint” on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

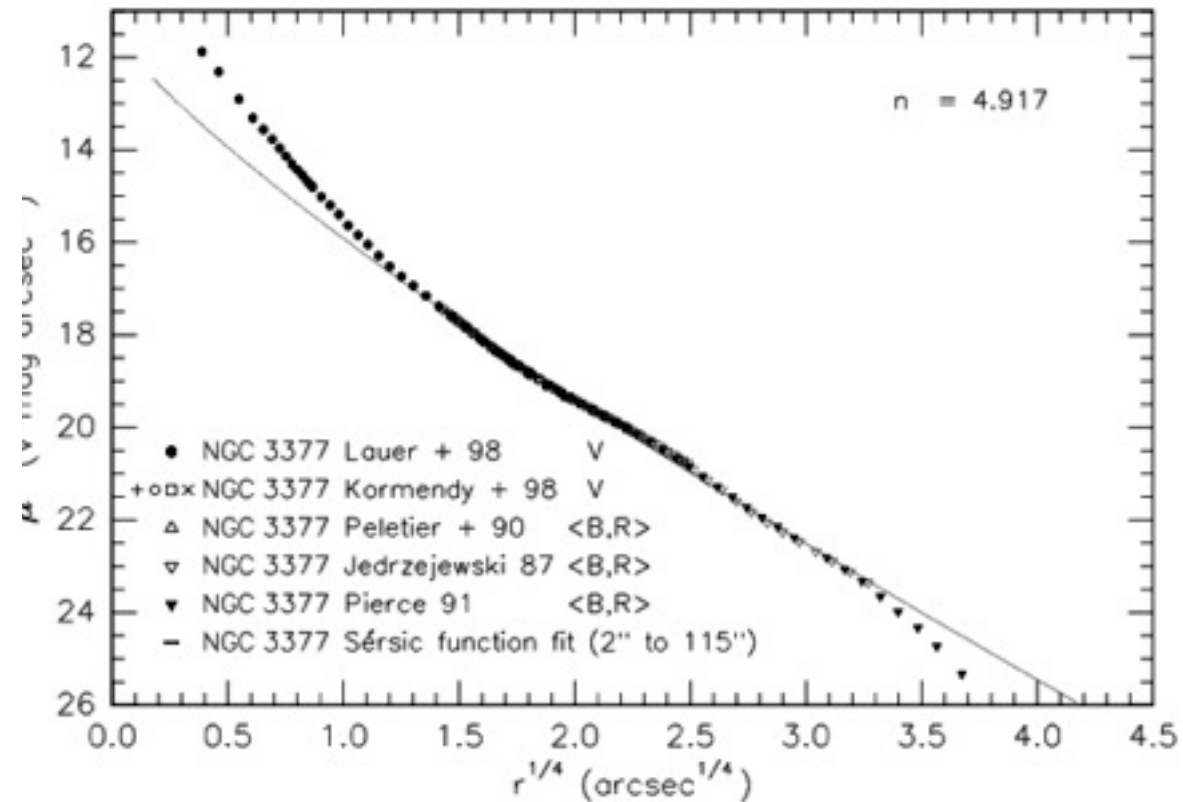
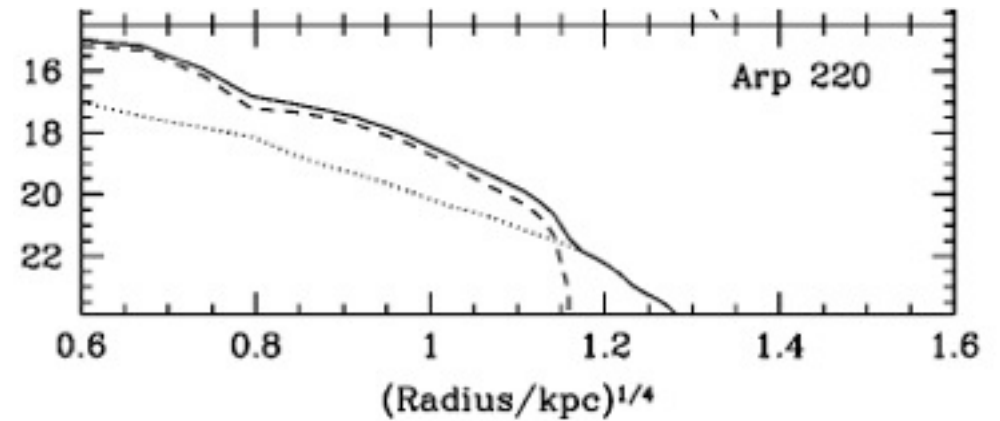
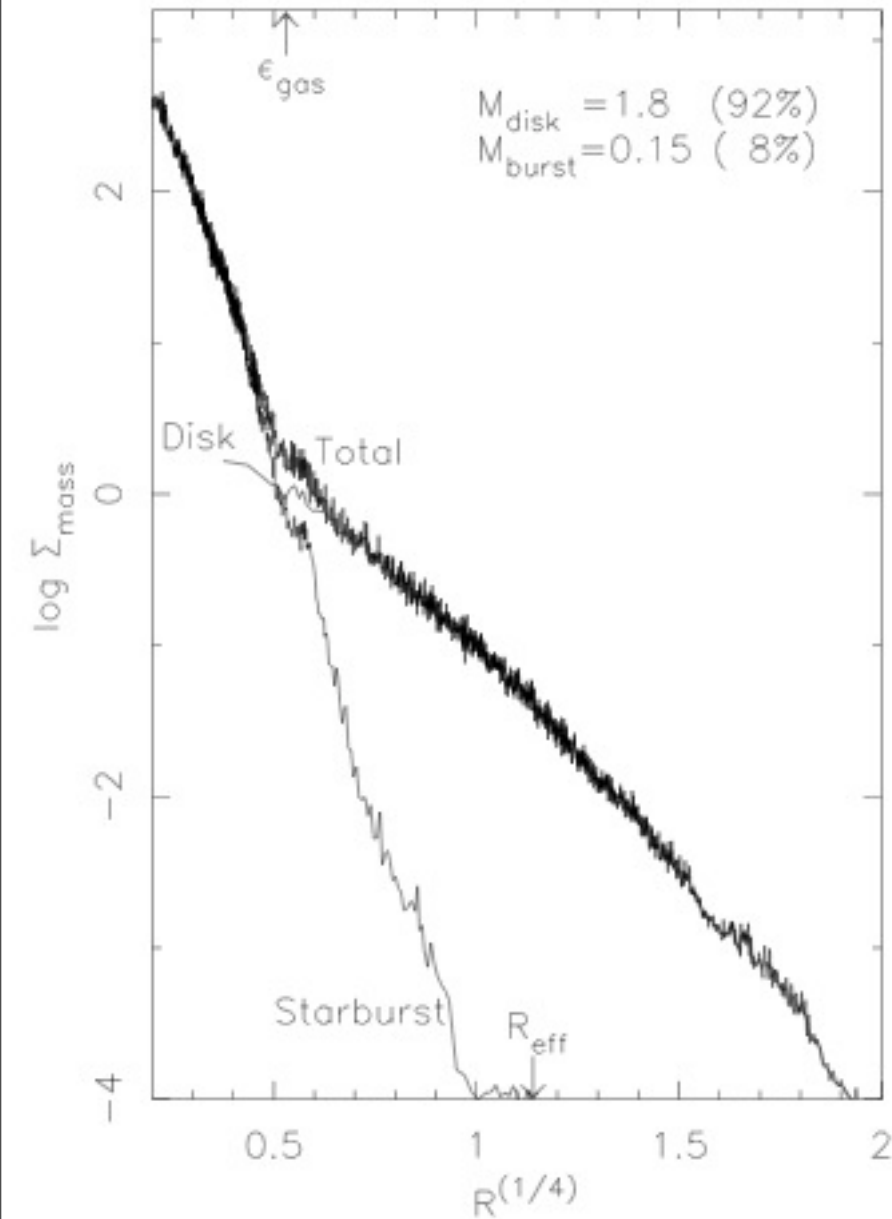
Separate stars into 3 populations:

1. Disk/pre-starburst
2. Starburst
3. Post-starburst
(embedded kinematic subsystems)



Starburst Stars in Simulations Leave an “Imprint” on the Profile

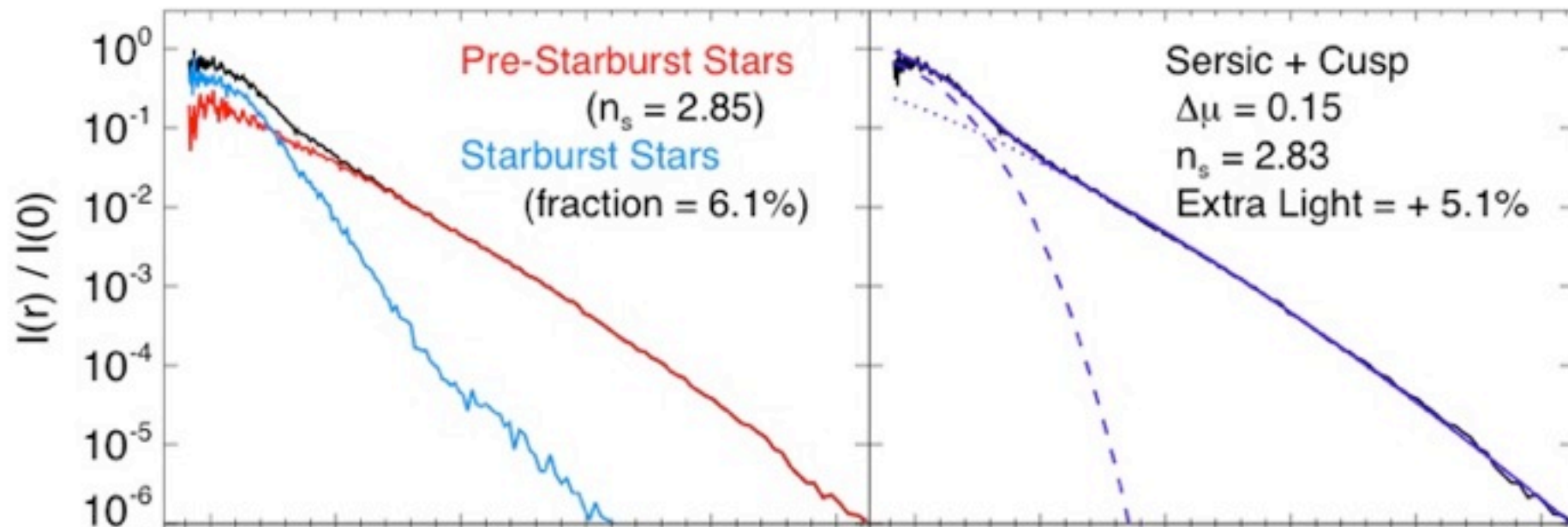
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



Structure in Elliptical Light Profiles

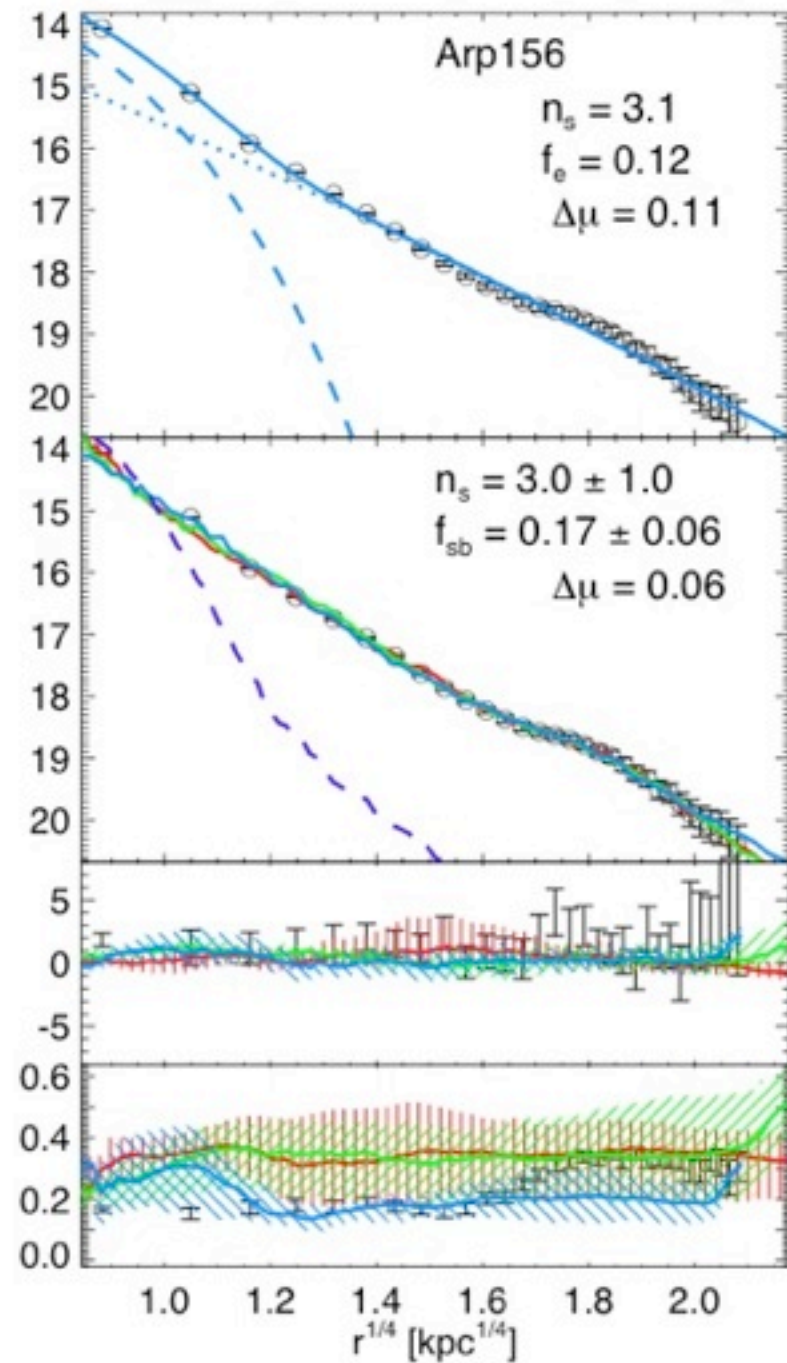
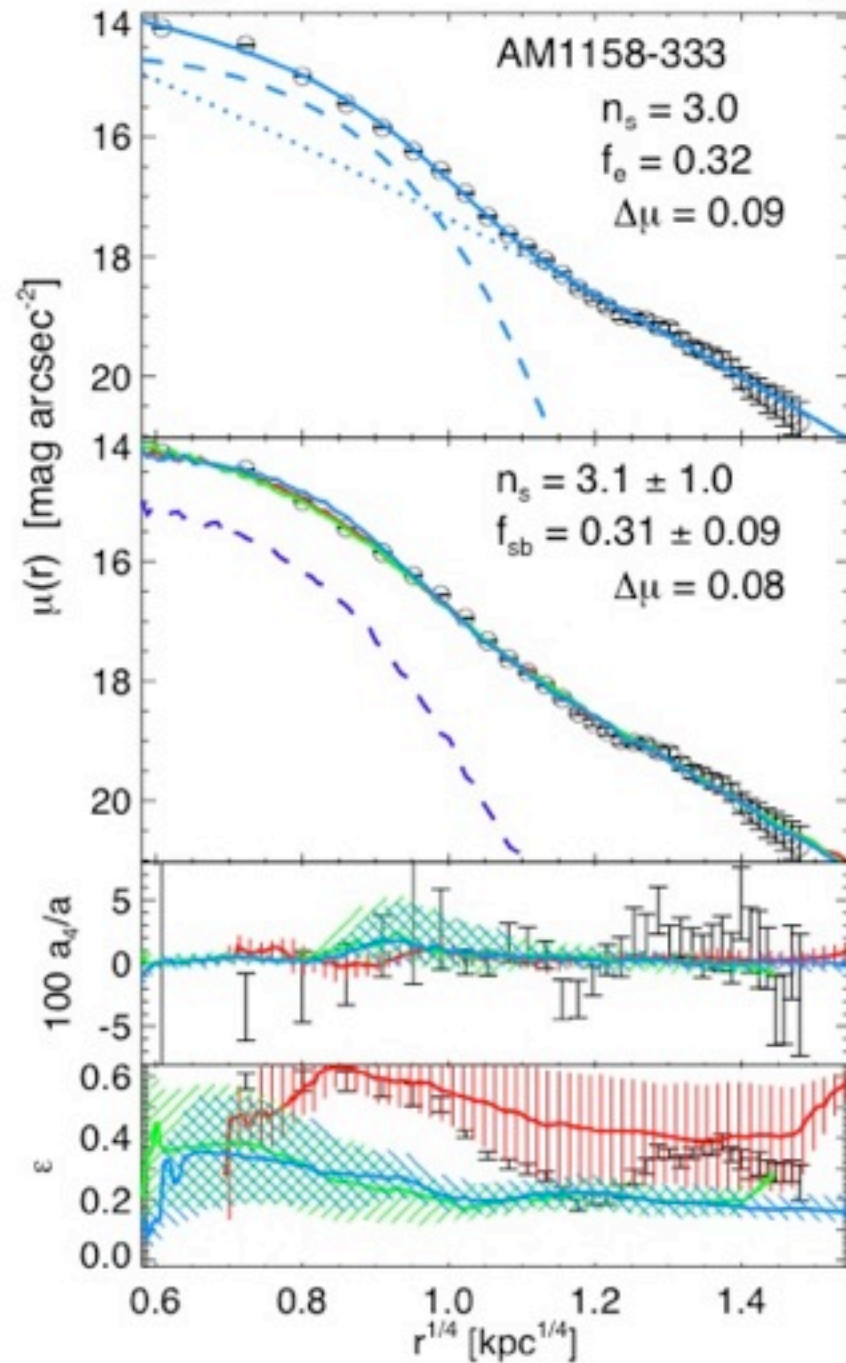
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



Application: Merger Remnants

RECOVERING THE ROLE OF GAS

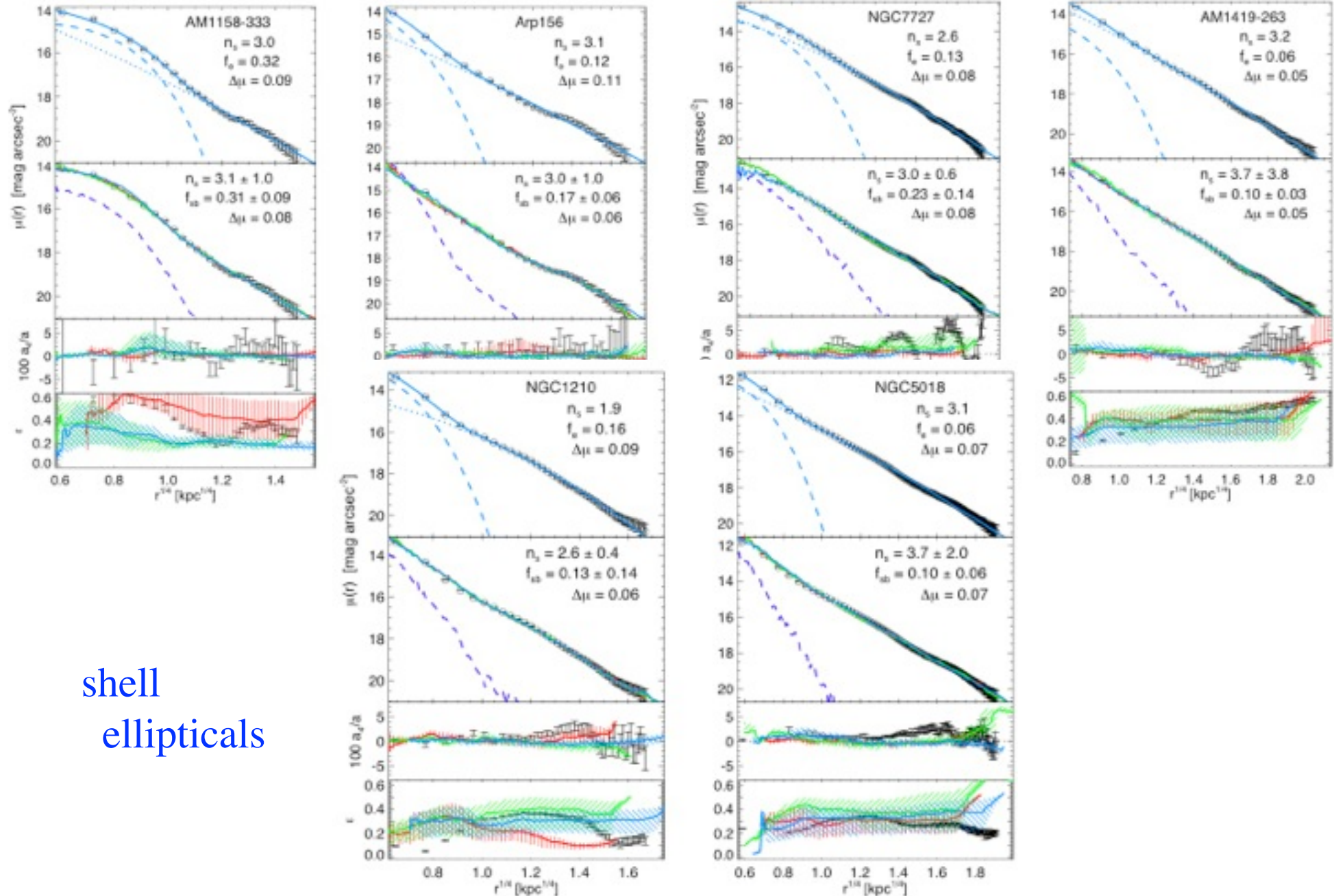


Application: Merger Remnants

RECOVERING THE ROLE OF GAS

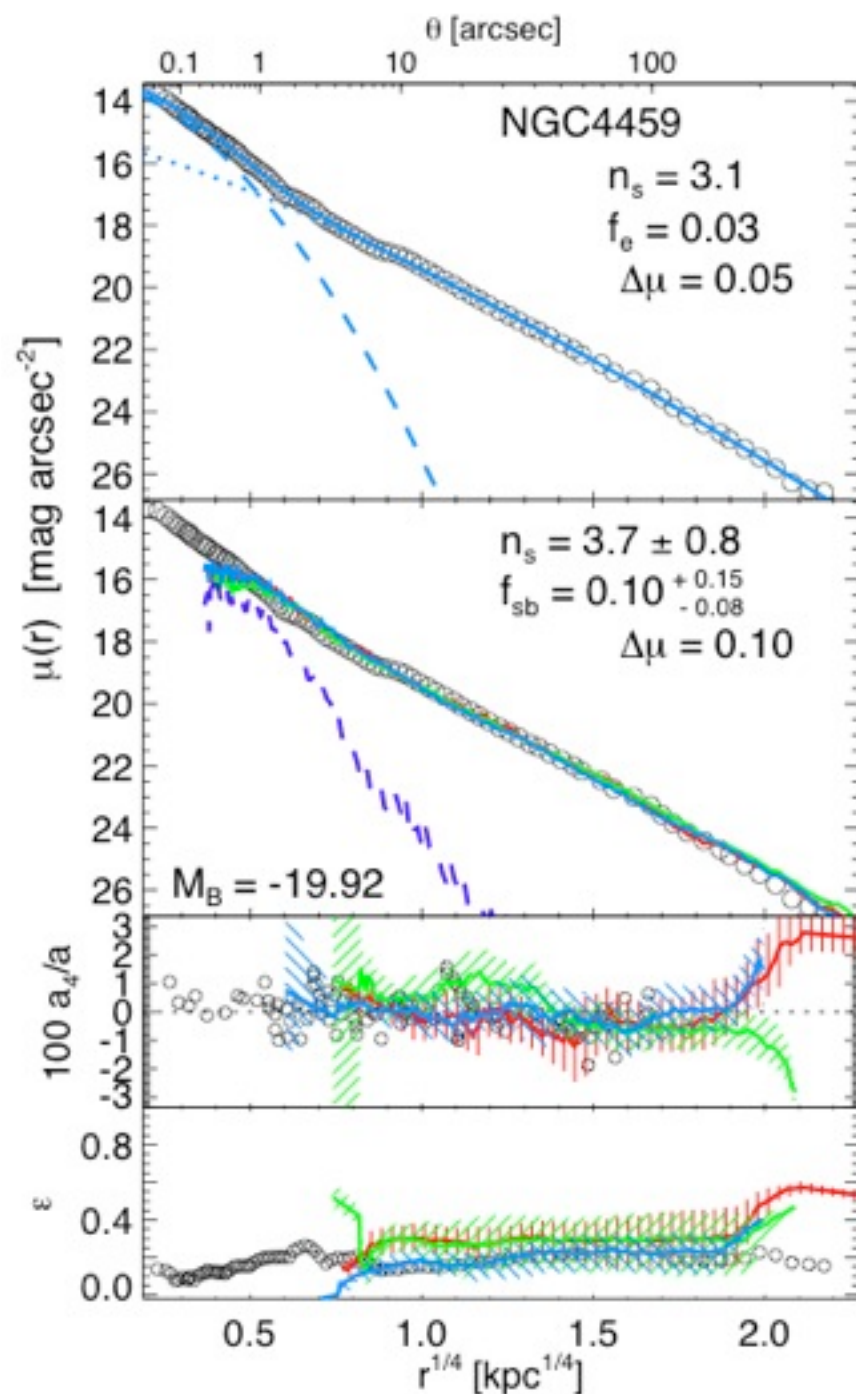
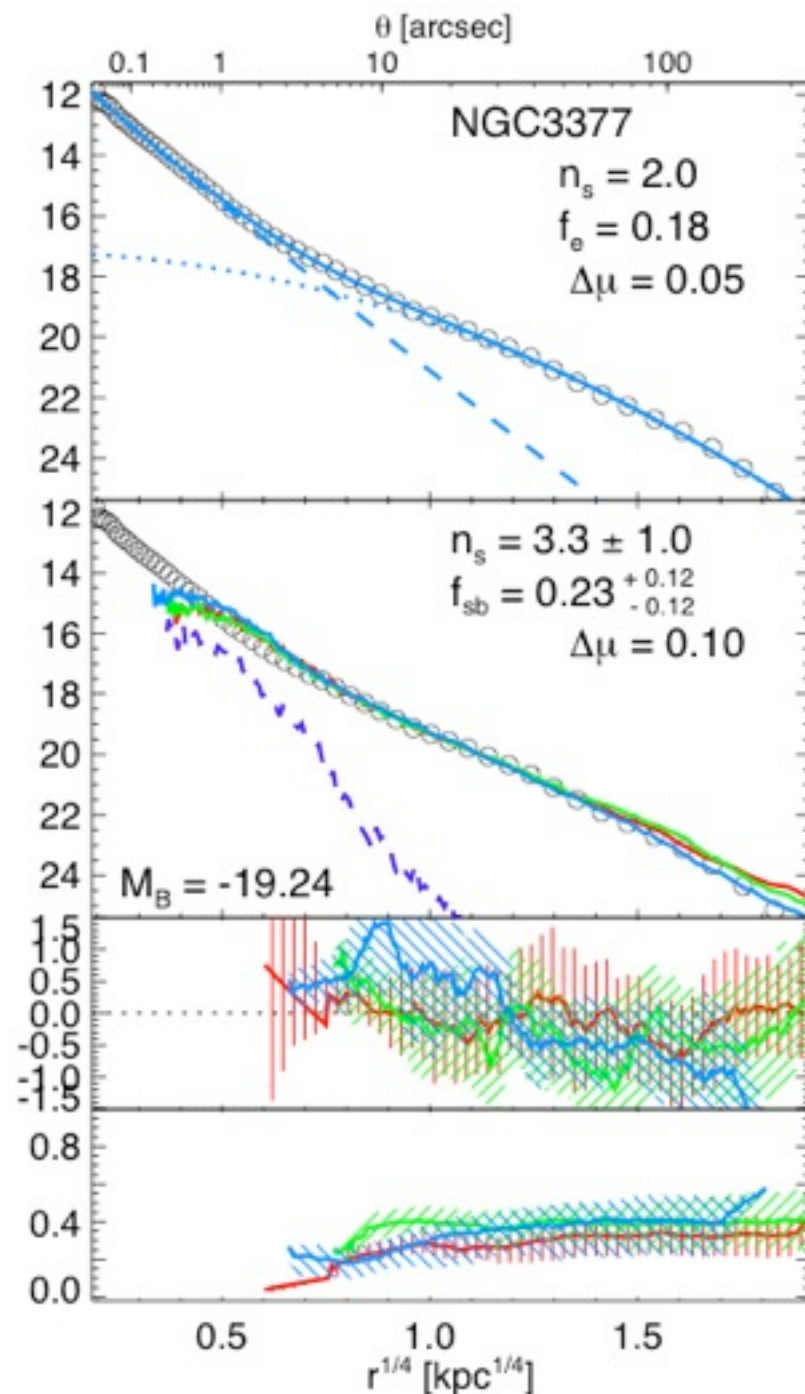
bright, young mergers

low-luminosity, relaxed mergers



Application: "Cusp" Ellipticals

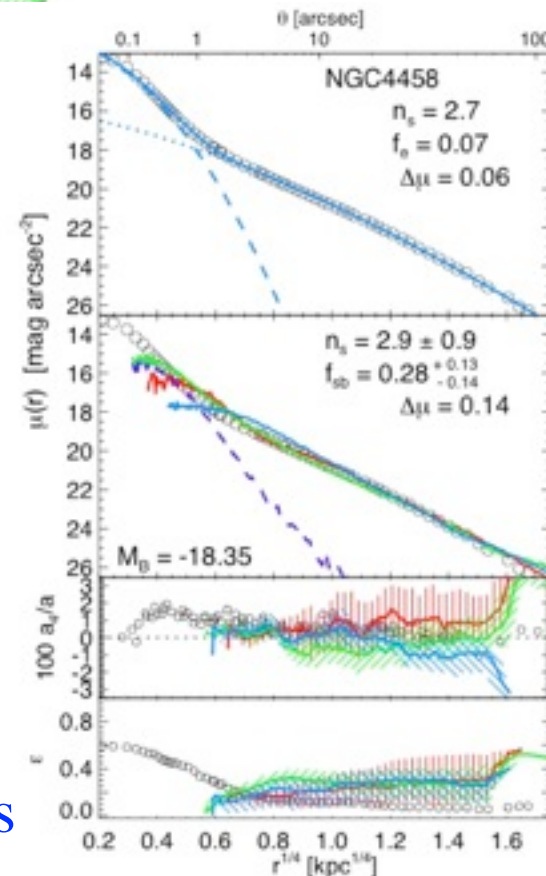
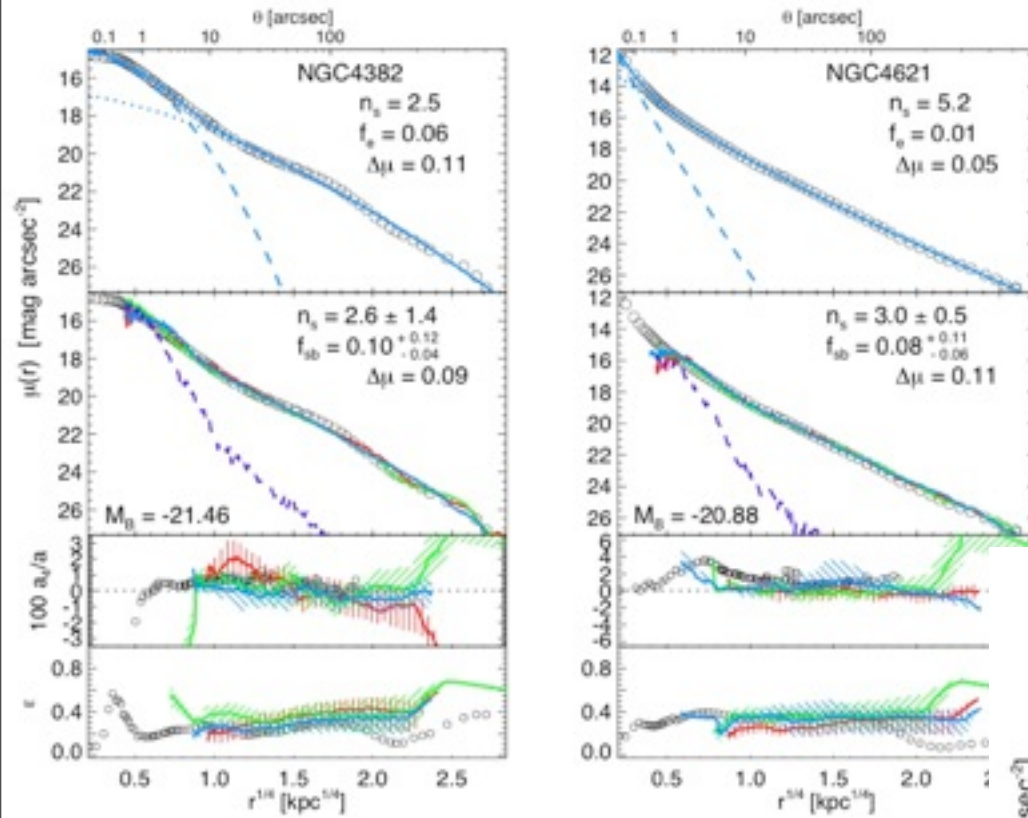
RECOVERING THE ROLE OF GAS



Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS

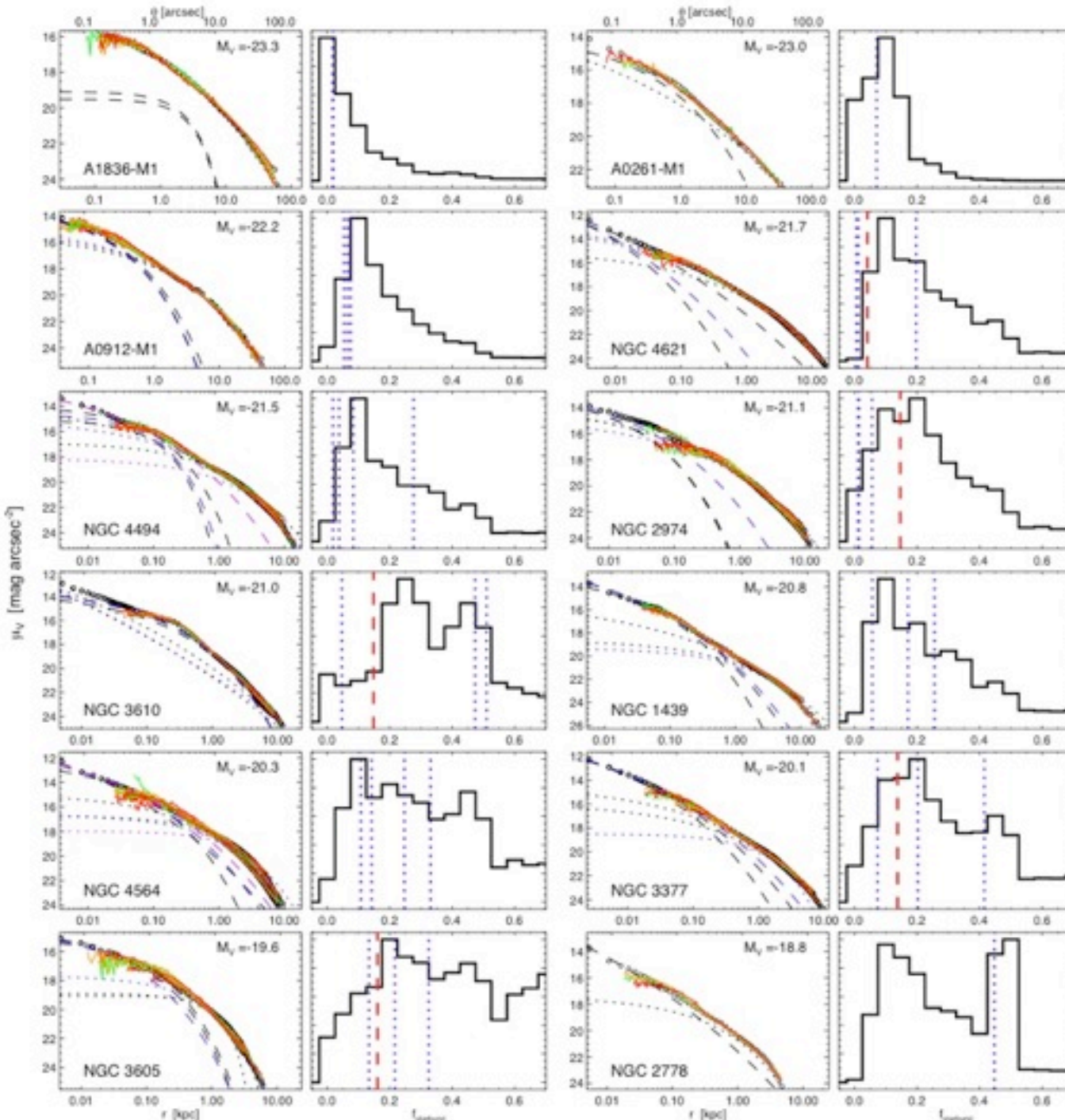
$L > L^*$ ellipticals



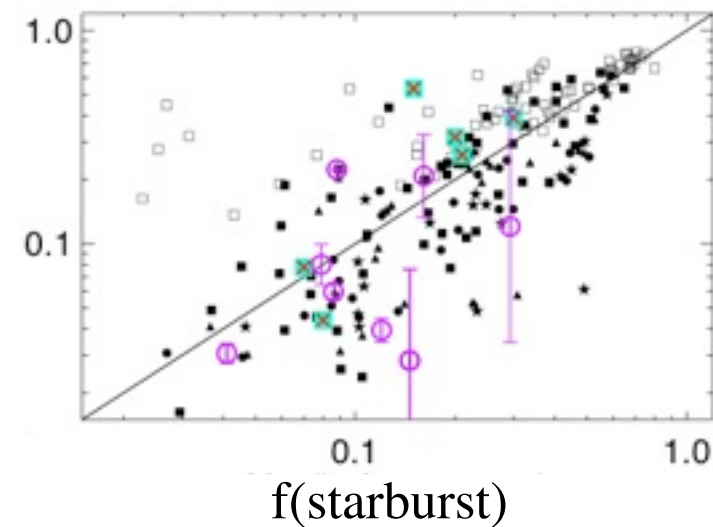
$L < 0.1 L^*$ ellipticals

Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS

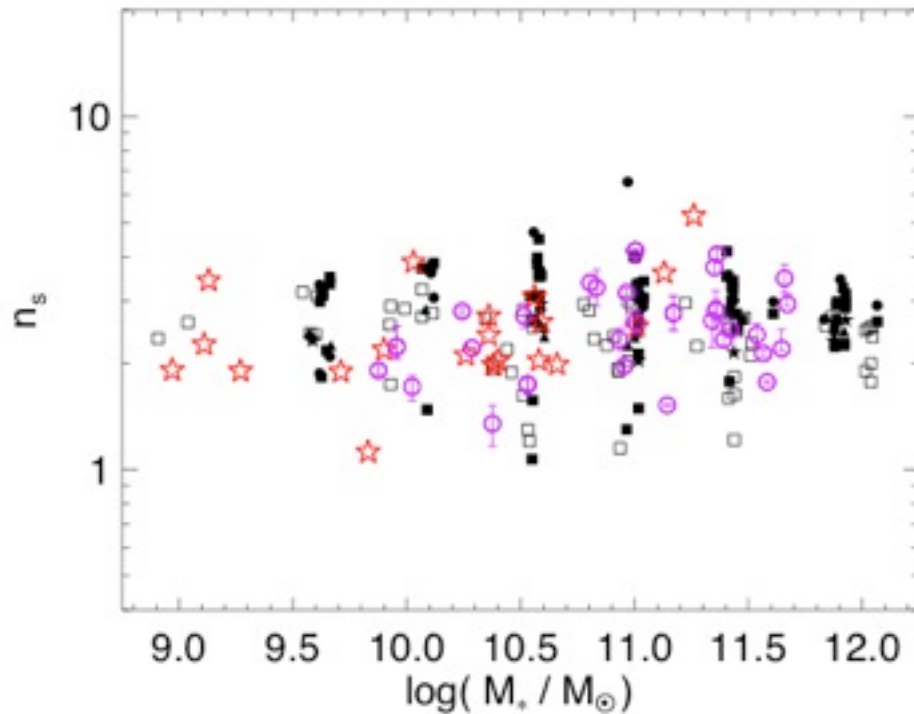
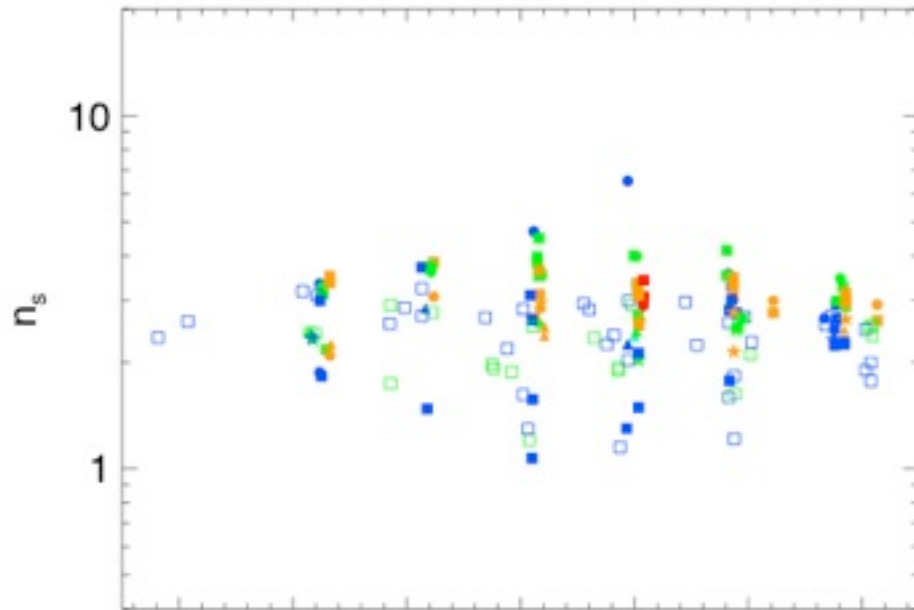


Compare:
Parametric fitting
Direct simulation fitting
Stellar population models

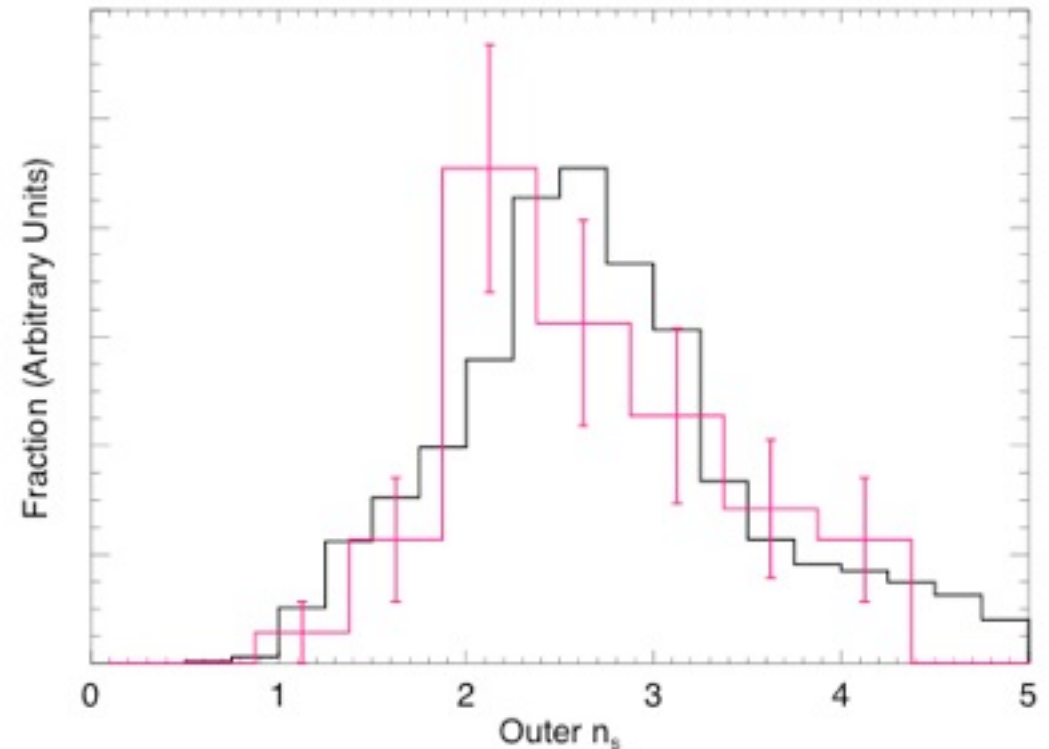


Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS

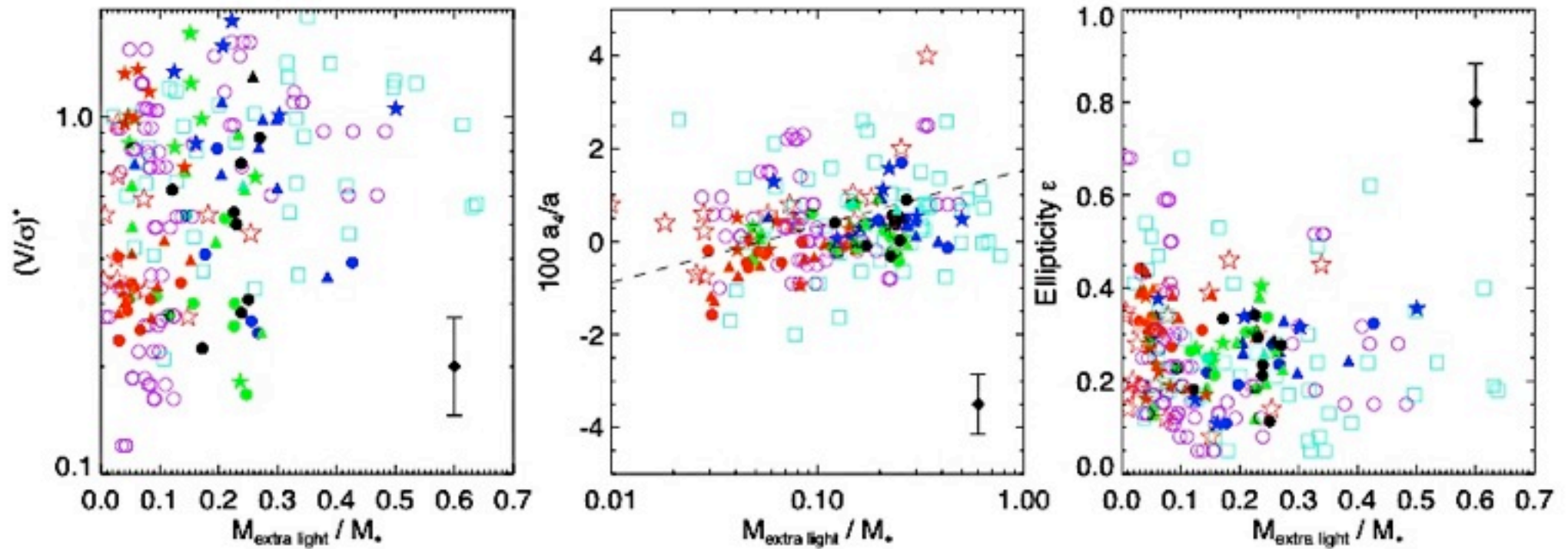


OUTER Sersic index is independent of mass, radius, etc.
--- gravity is self-similar



Structure in Elliptical Light Profiles

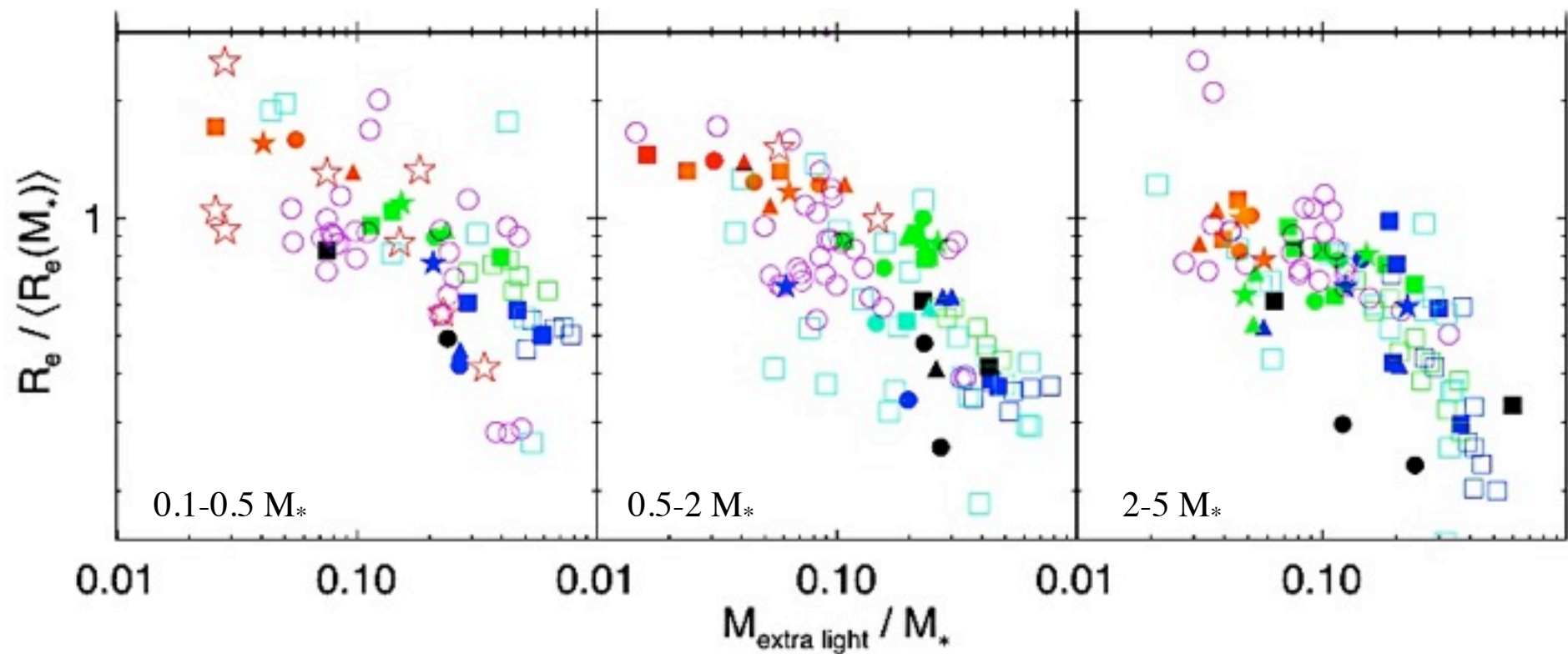
RECOVERING THE ROLE OF GAS



Structure in Elliptical Light Profiles

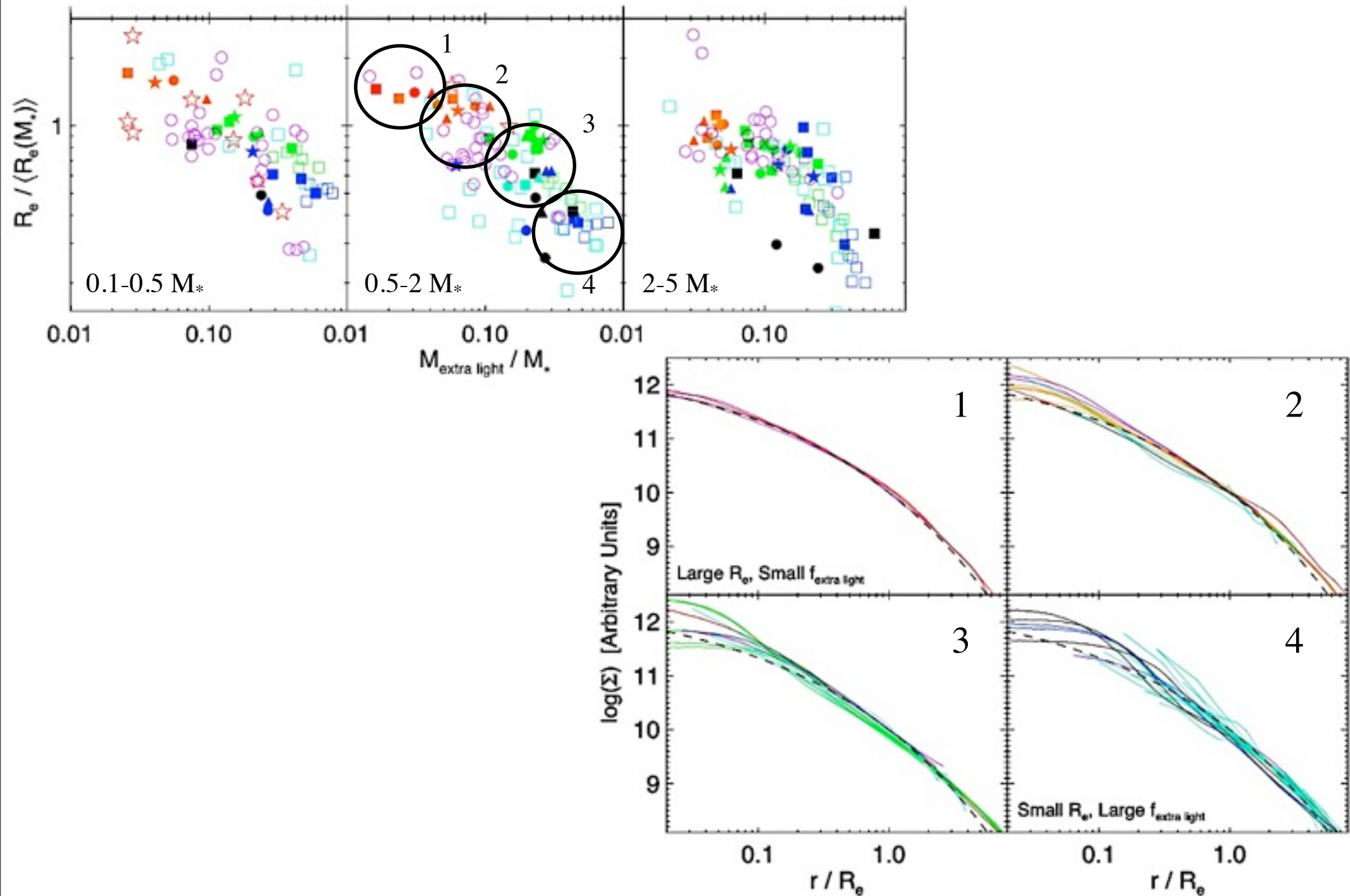
RECOVERING THE ROLE OF GAS

- Systems with more “extra light” are smaller
- Put more mass into a central dissipational component:
moves R_e inward
more of the mass inside R_e is this (totally baryon-dominated)
central cusp



Structure in Elliptical Light Profiles

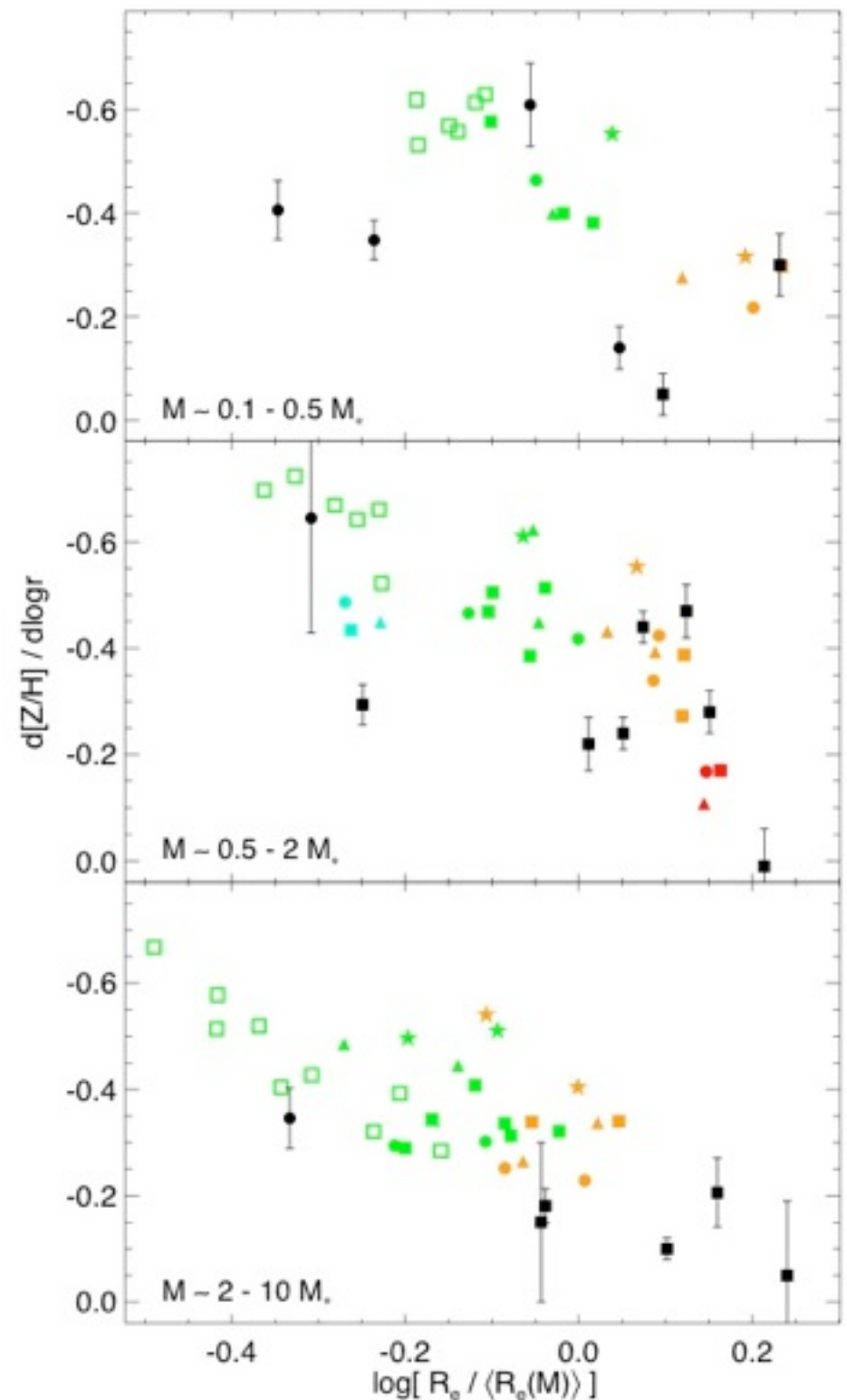
RECOVERING THE ROLE OF GAS



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

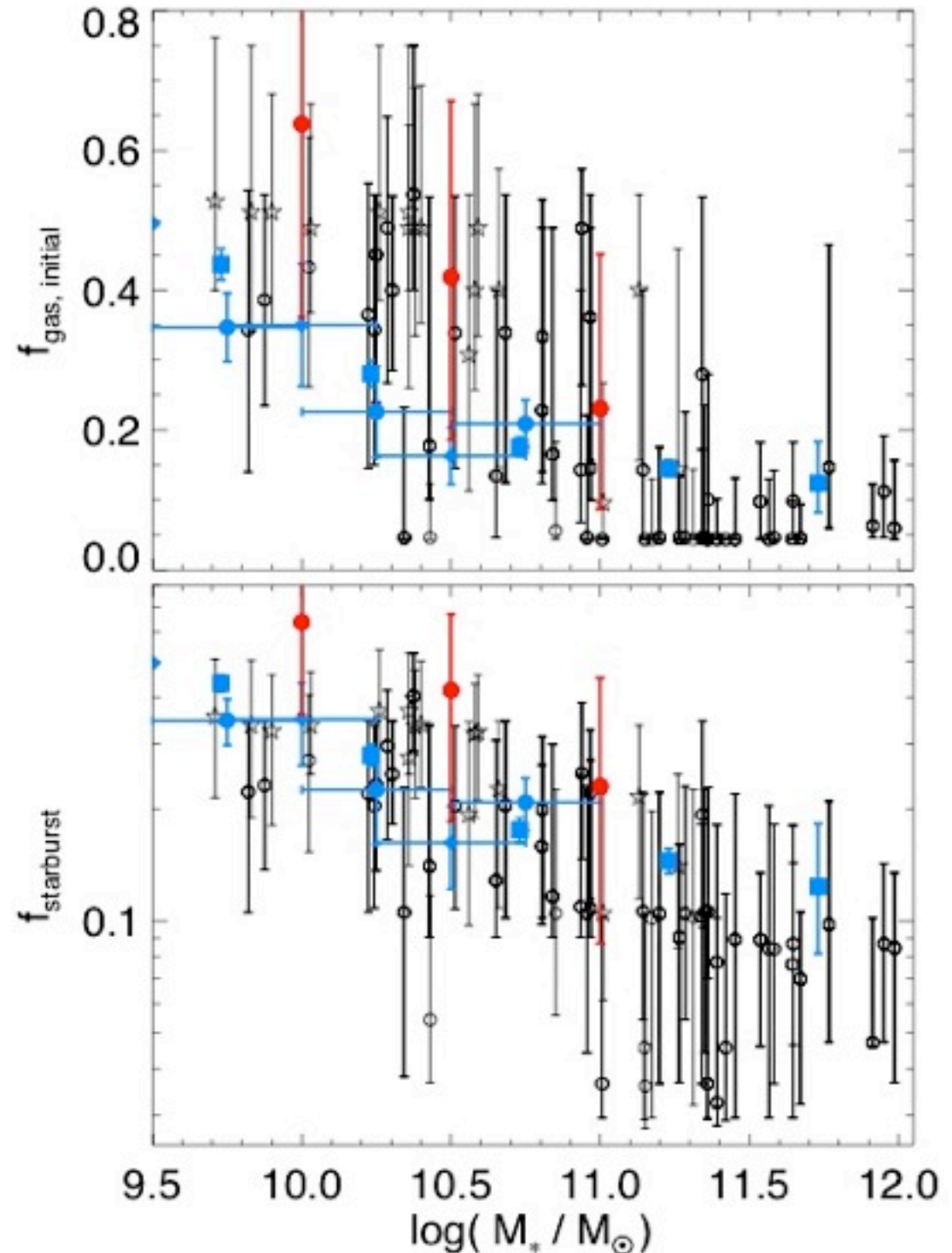
- Get accompanying predictions for how stellar populations & their gradients should scale with size, luminosity, etc.



Structure in Elliptical Light Profiles

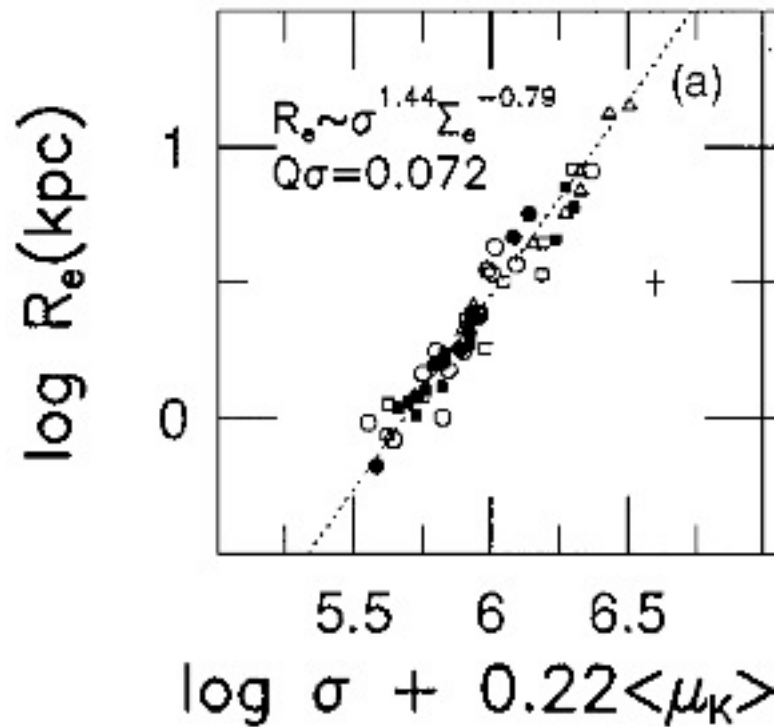
RECOVERING THE ROLE OF GAS

- Can match all (cusp) ellipticals with simple gas-rich merger remnants
- NEED systematically higher gas content in the progenitors at lower masses to explain the observed profile shapes
- Recover the *observed* dependence of f_{gas} on disk mass

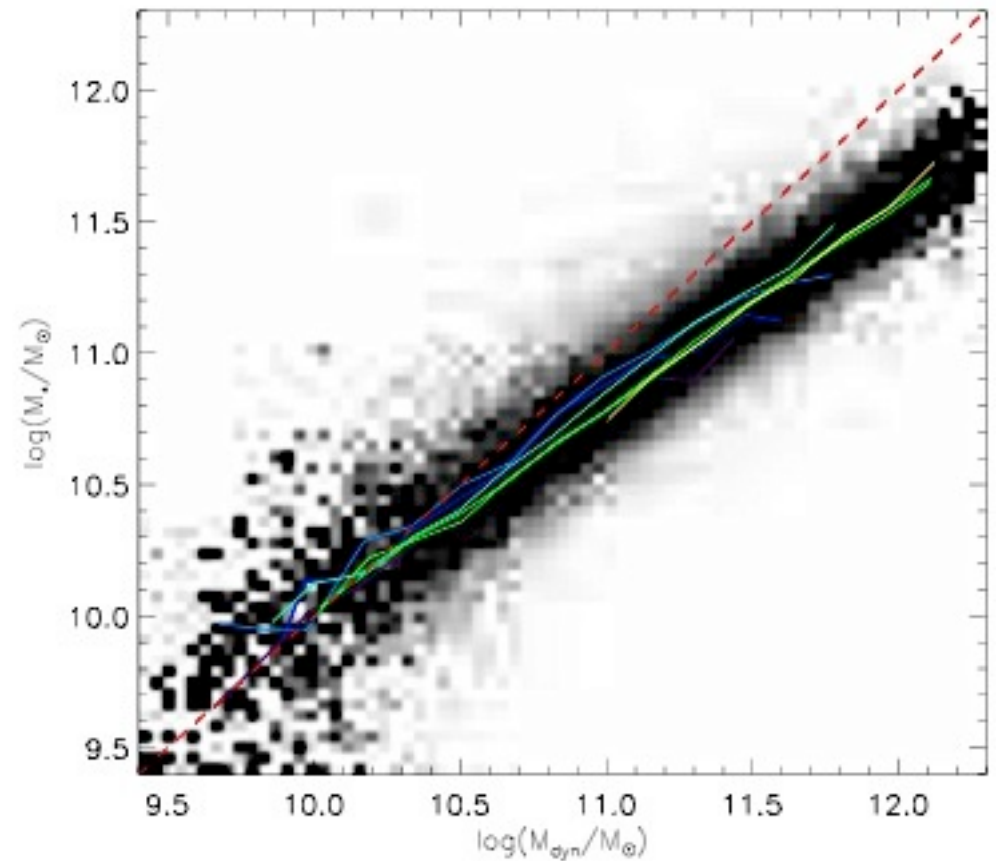


Fundamental Plane Tilt

WHERE DOES IT COME FROM?



Pahre et al. 1998

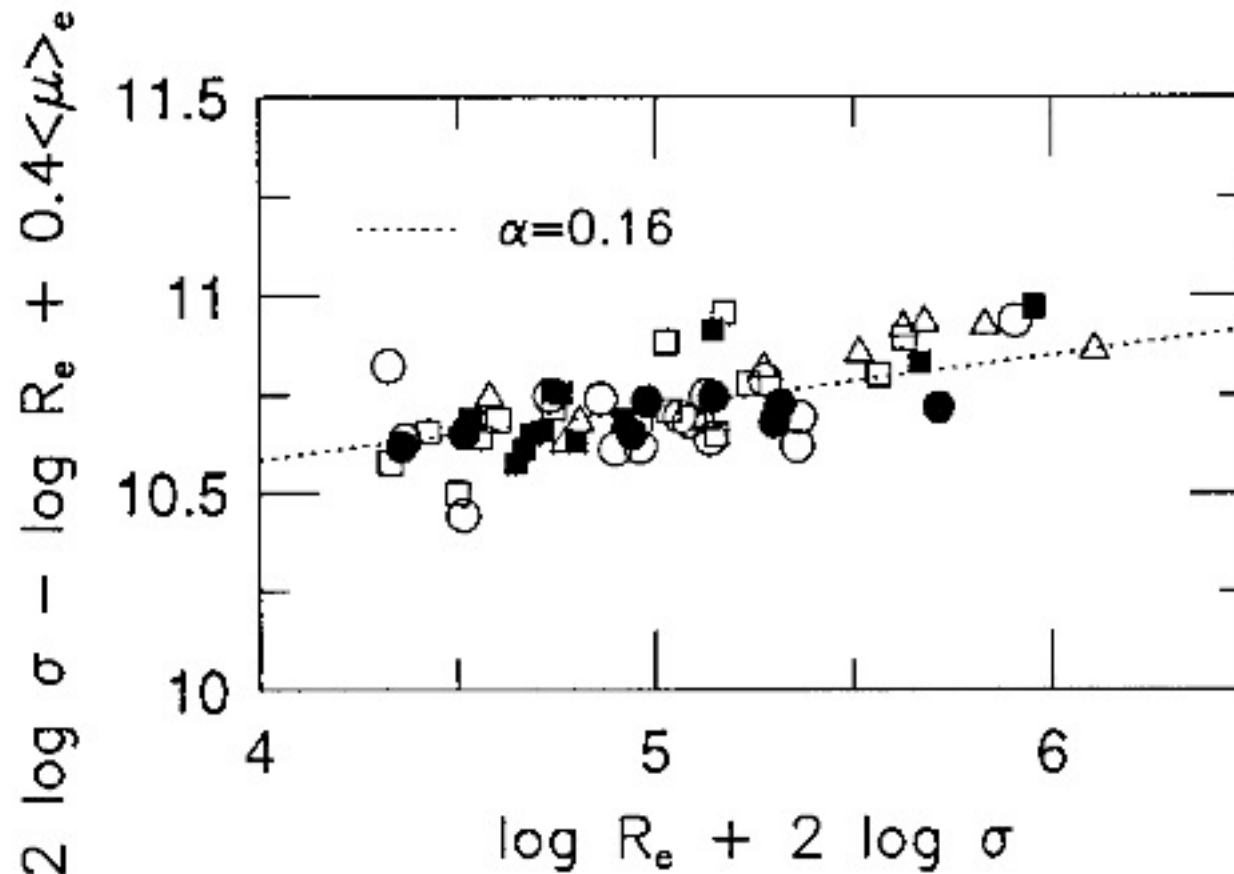


Gallazzi et al. 2007

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- $M_{\text{dyn}} / M_{\text{stellar}}$ is an increasing function of either M



- SOME non-homology in ellipticals

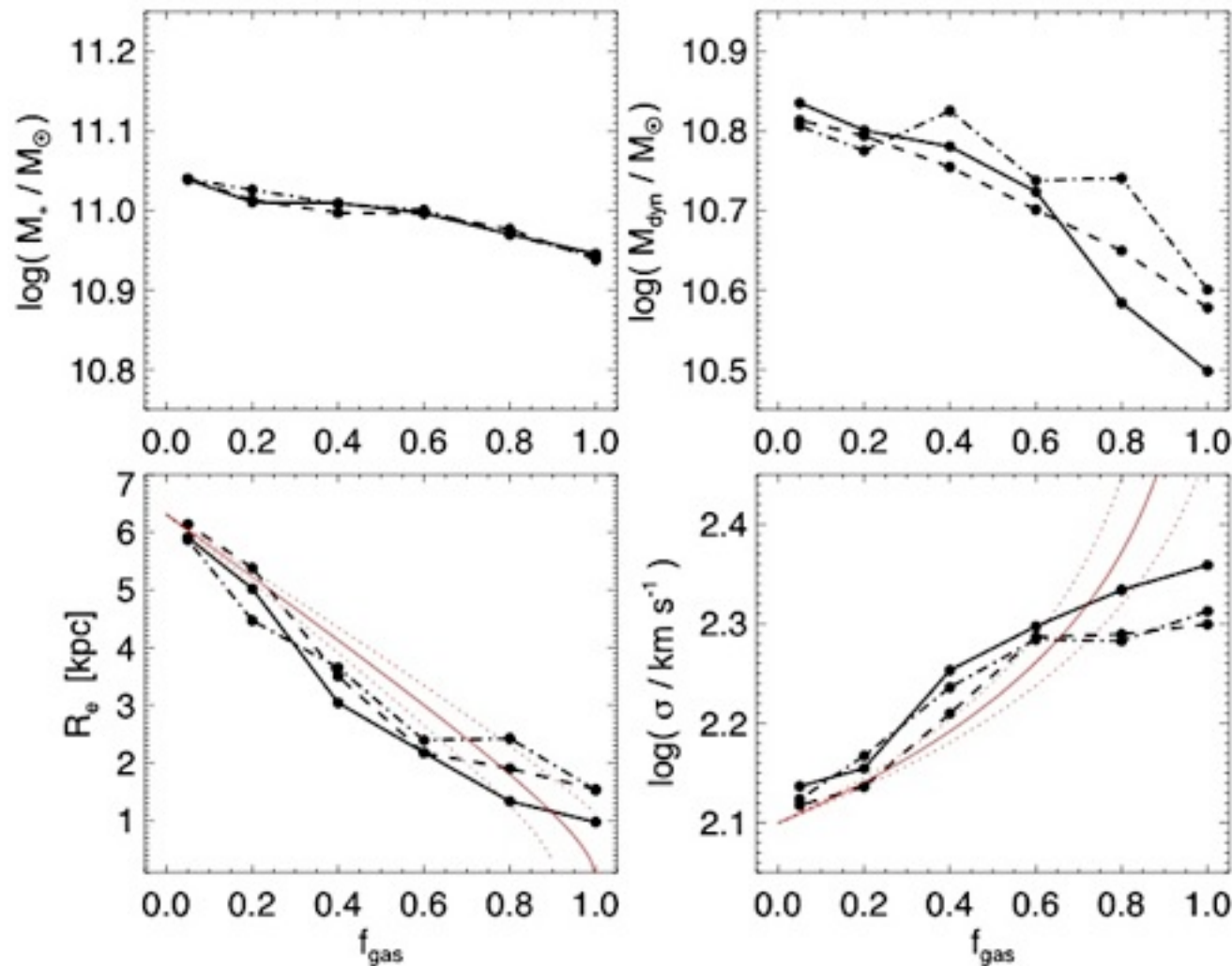
Pahre et al. 1998

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Recall: more dissipation moves R_e in, to where the system is more baryon-dominated:

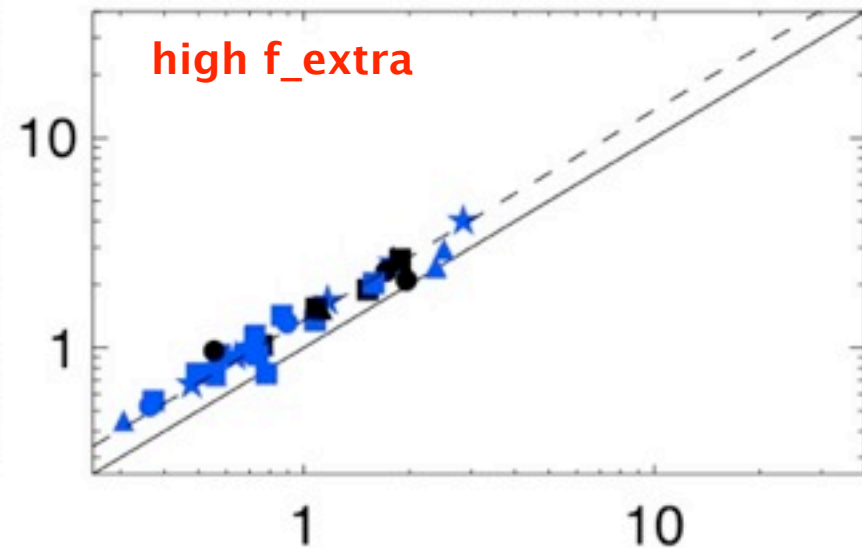
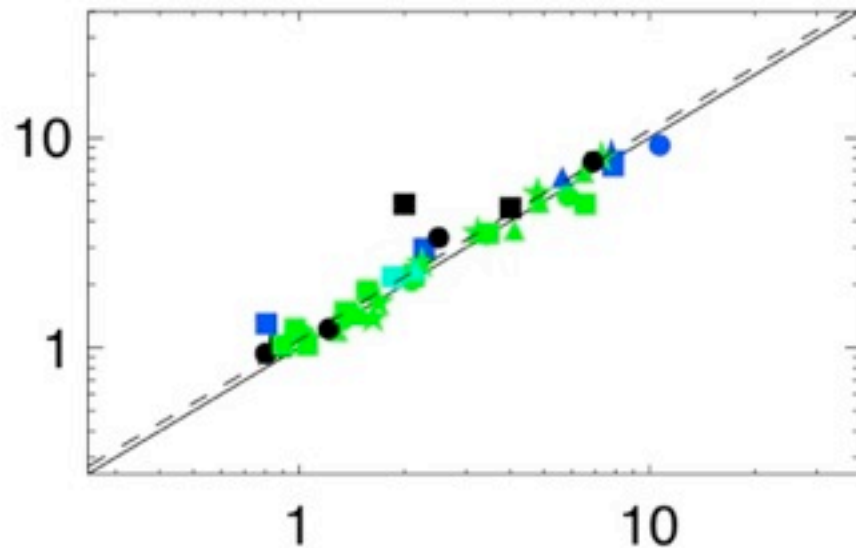
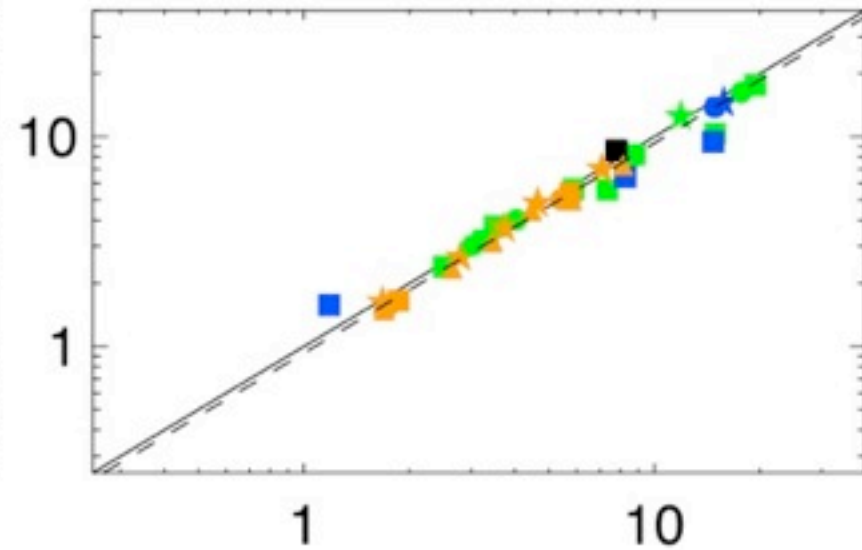
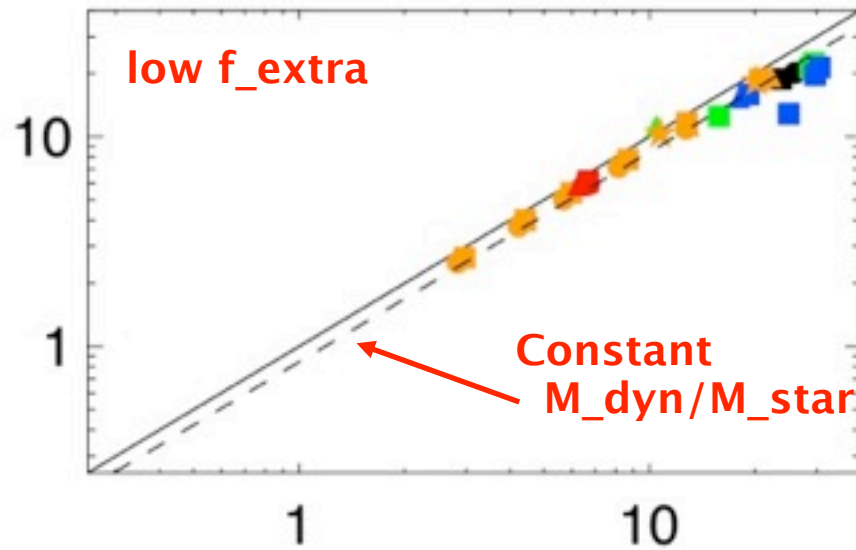
lowers $M_{\text{dyn}} / M_{\text{stellar}}$



Fundamental Plane Tilt

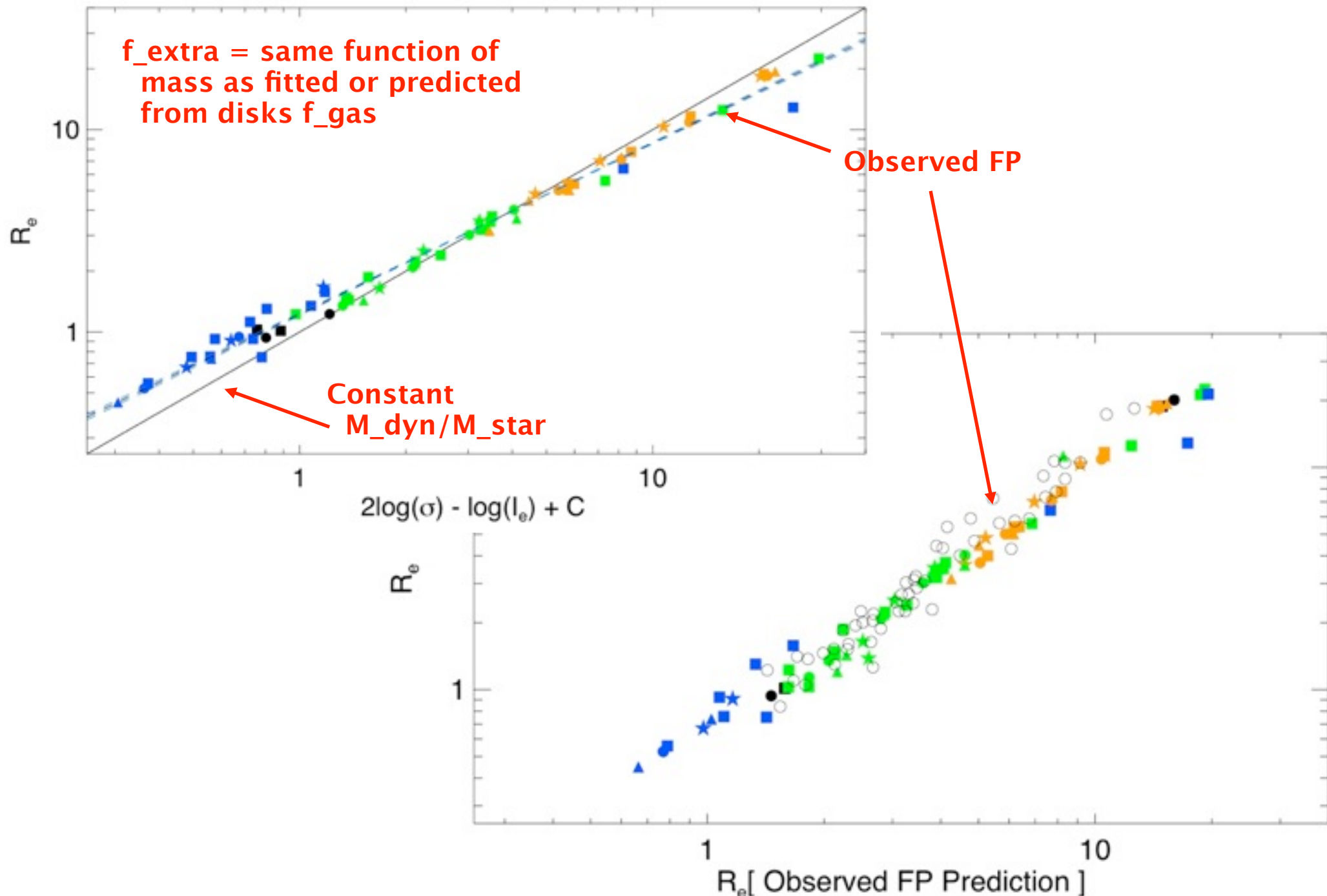
WHERE DOES IT COME FROM?

- Look at systems with the *same* extra light mass::



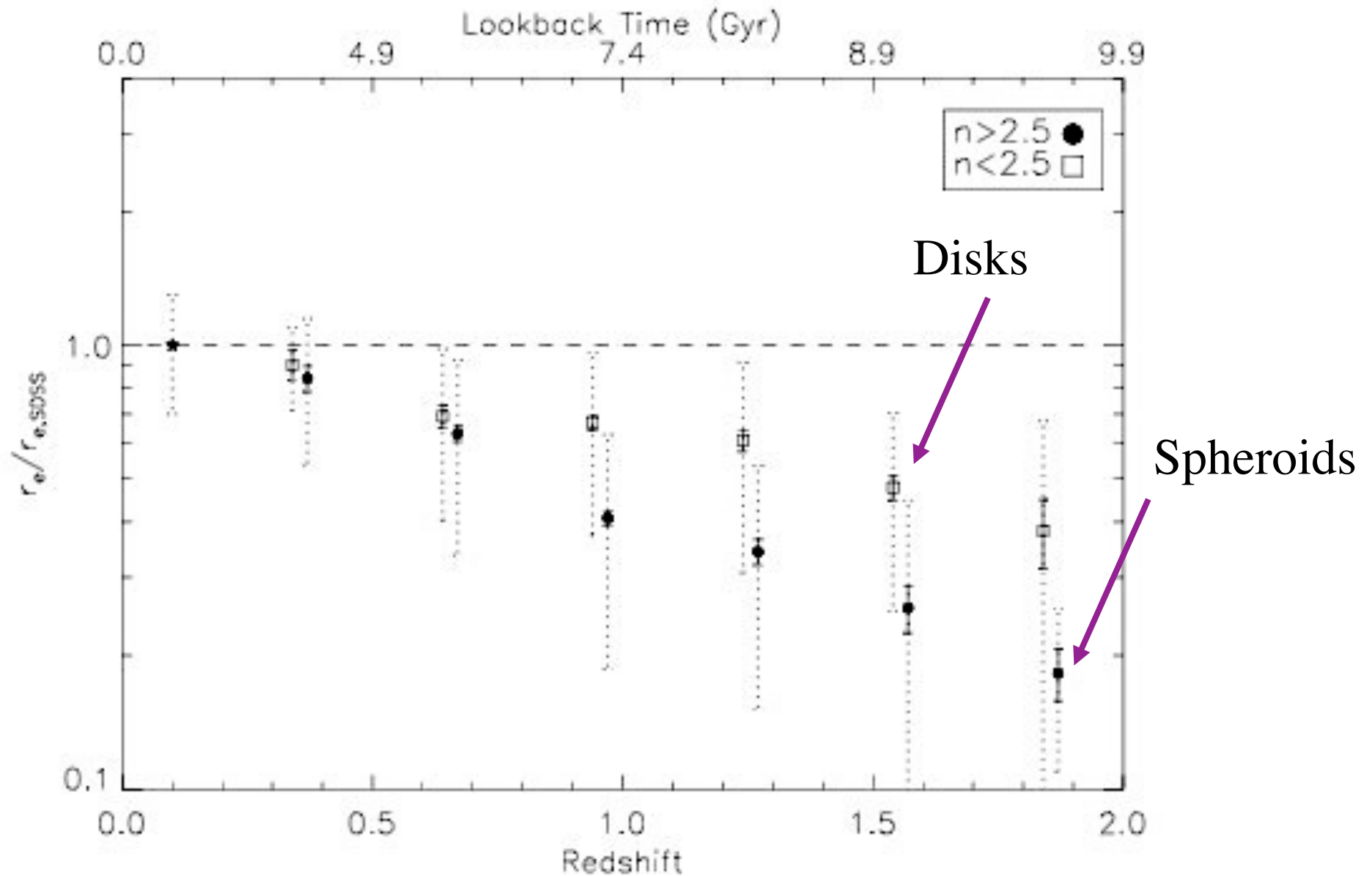
Fundamental Plane Tilt

WHERE DOES IT COME FROM?



SIZE-MASS RELATIONS

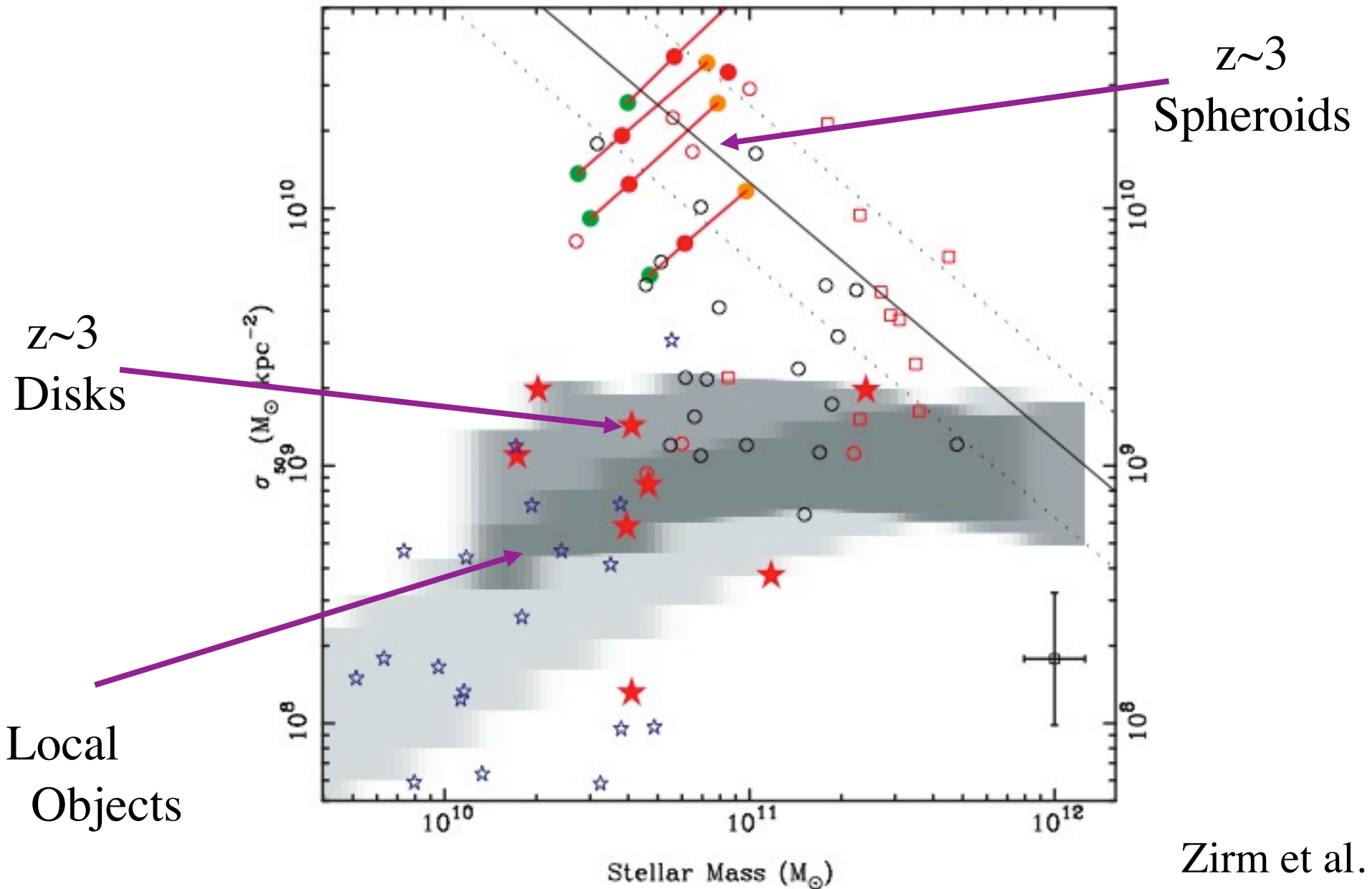
- Spheroids are getting smaller >2x as quickly as disks!



Redshift Evolution

SIZE-MASS RELATIONS

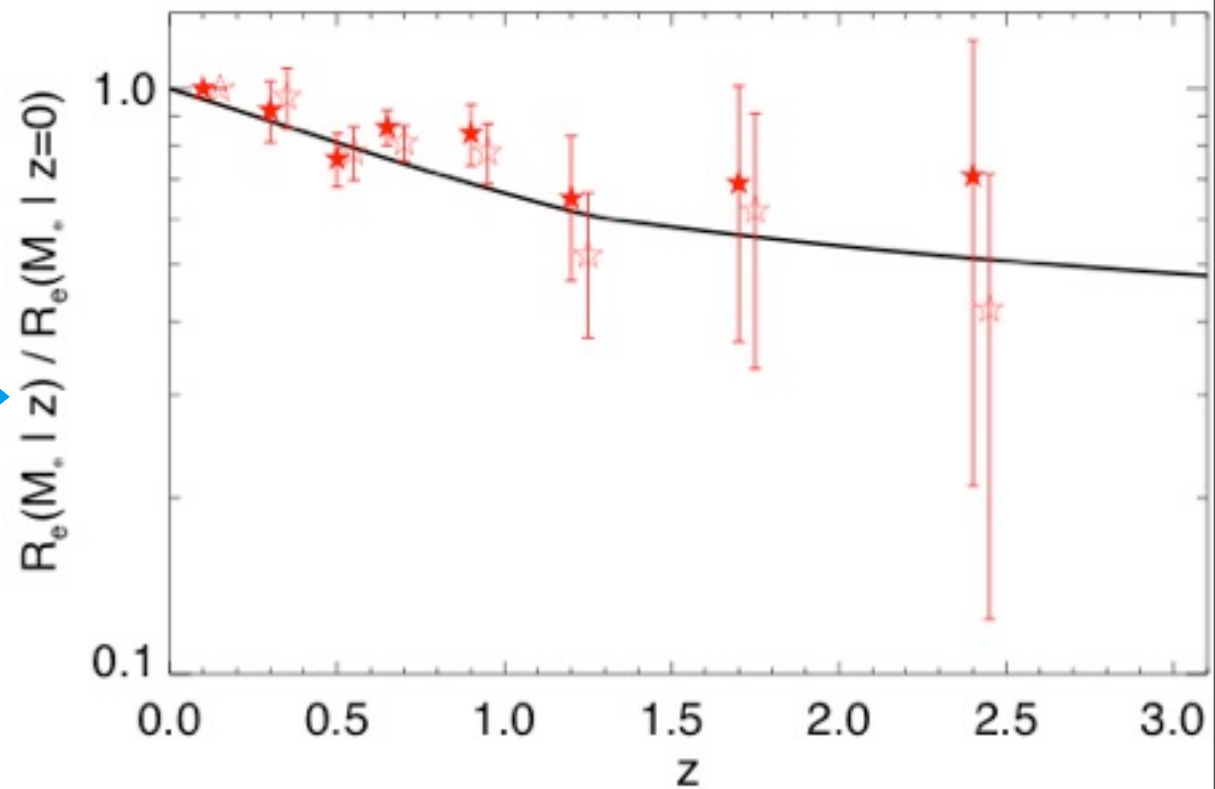
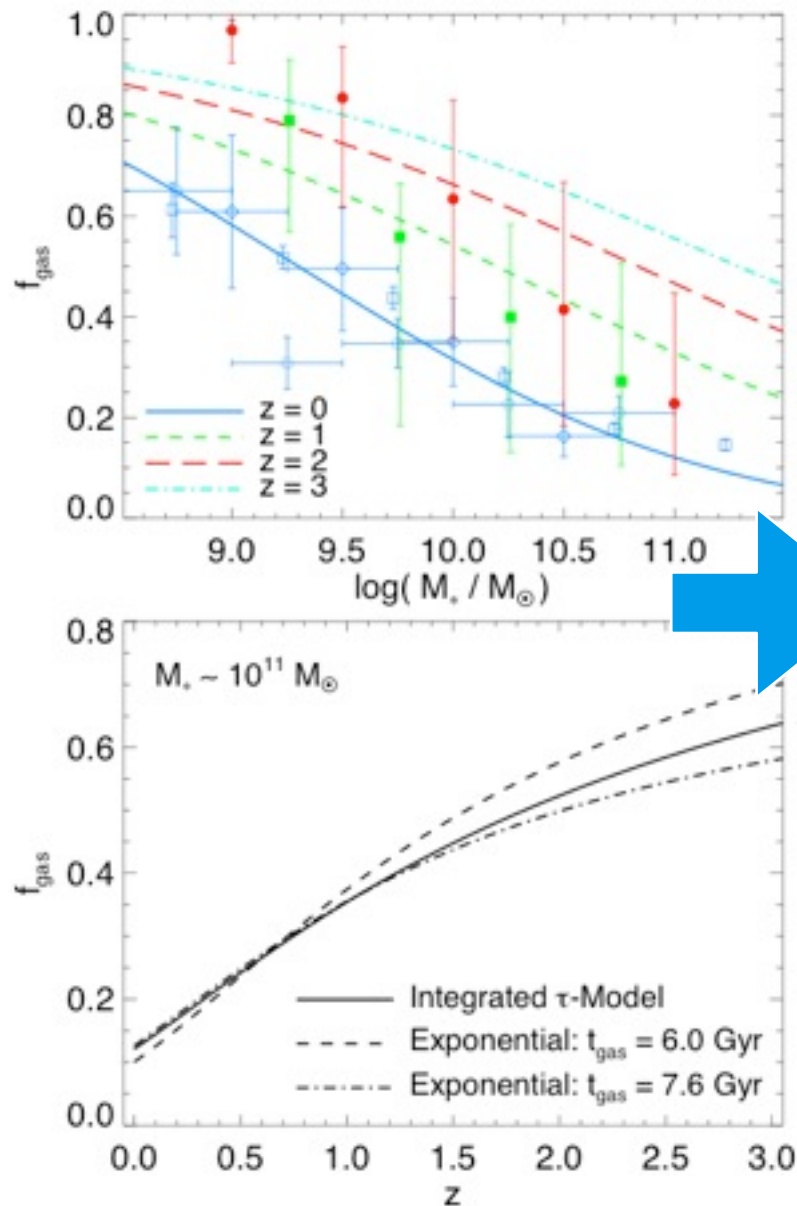
- By $z \sim 3$, massive ellipticals are little bigger than a starburst ($\sim \text{kpc}$)



Redshift Evolution

SIZE-MASS RELATIONS

- High- z galaxies are more gas-rich:
 - Expect more compact remnants (see also Khochfar & Silk)



Redshift Evolution

SIZE-MASS RELATIONS

- Where are they now?

- Dry (spheroid-spheroid) merger:

Typical orbits weakly bound -- $E_{\text{final}} = E_{\text{initial}} = 2 (M_i \sigma_i^2)$

$M_f = 2 M_i$ -- so $\sigma_f = \sigma_i$

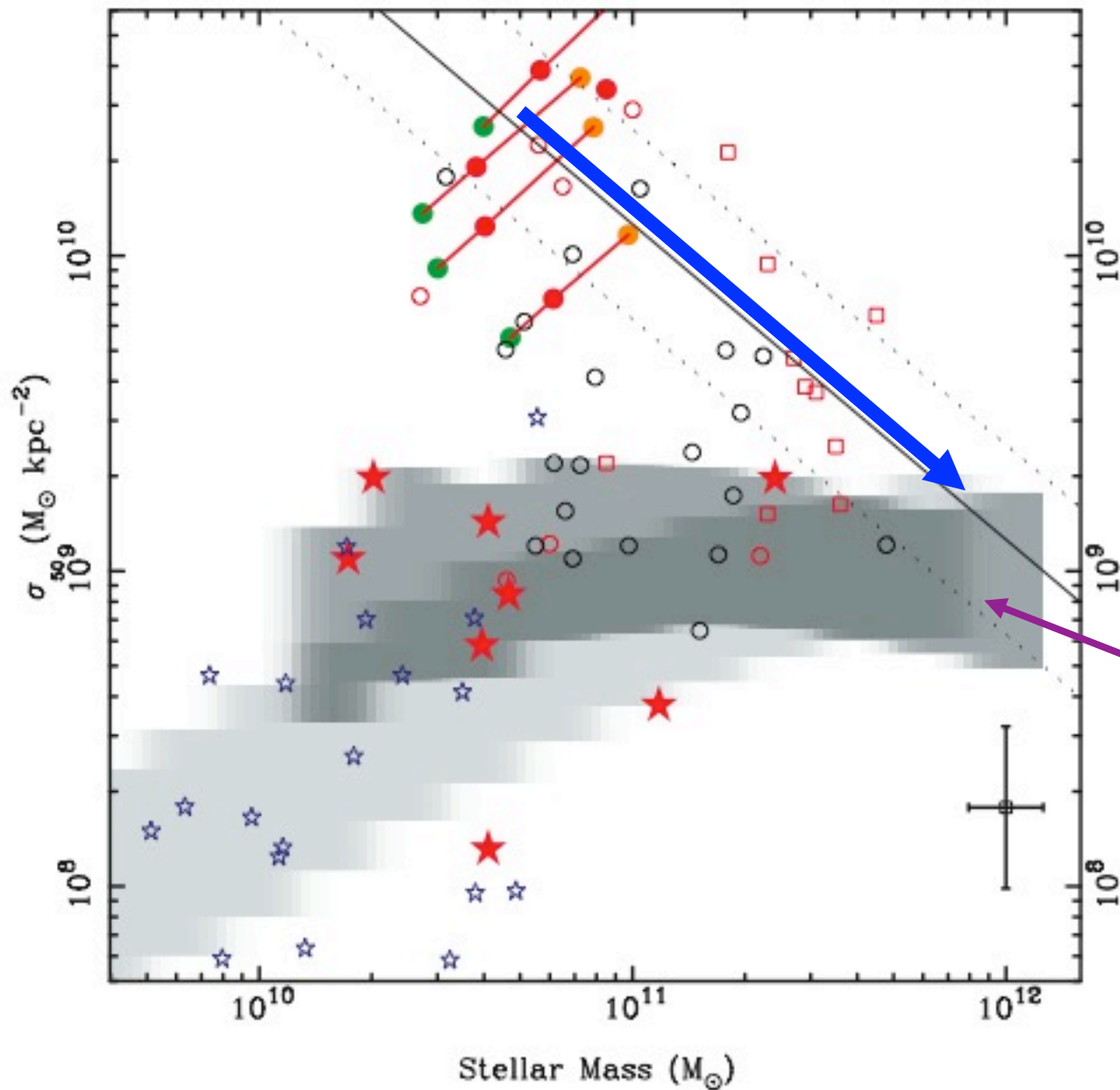
virial theorem -- $R_f = 2 * R_i$

- Relative to the slope of the size mass relation ($R \sim M^{1/2}$), you're rapidly moving up (increasing R)
- High-z early mergers are **exactly** the systems expected to have more dry mergers

Redshift Evolution

SIZE-MASS RELATIONS

Direction dry mergers
move you

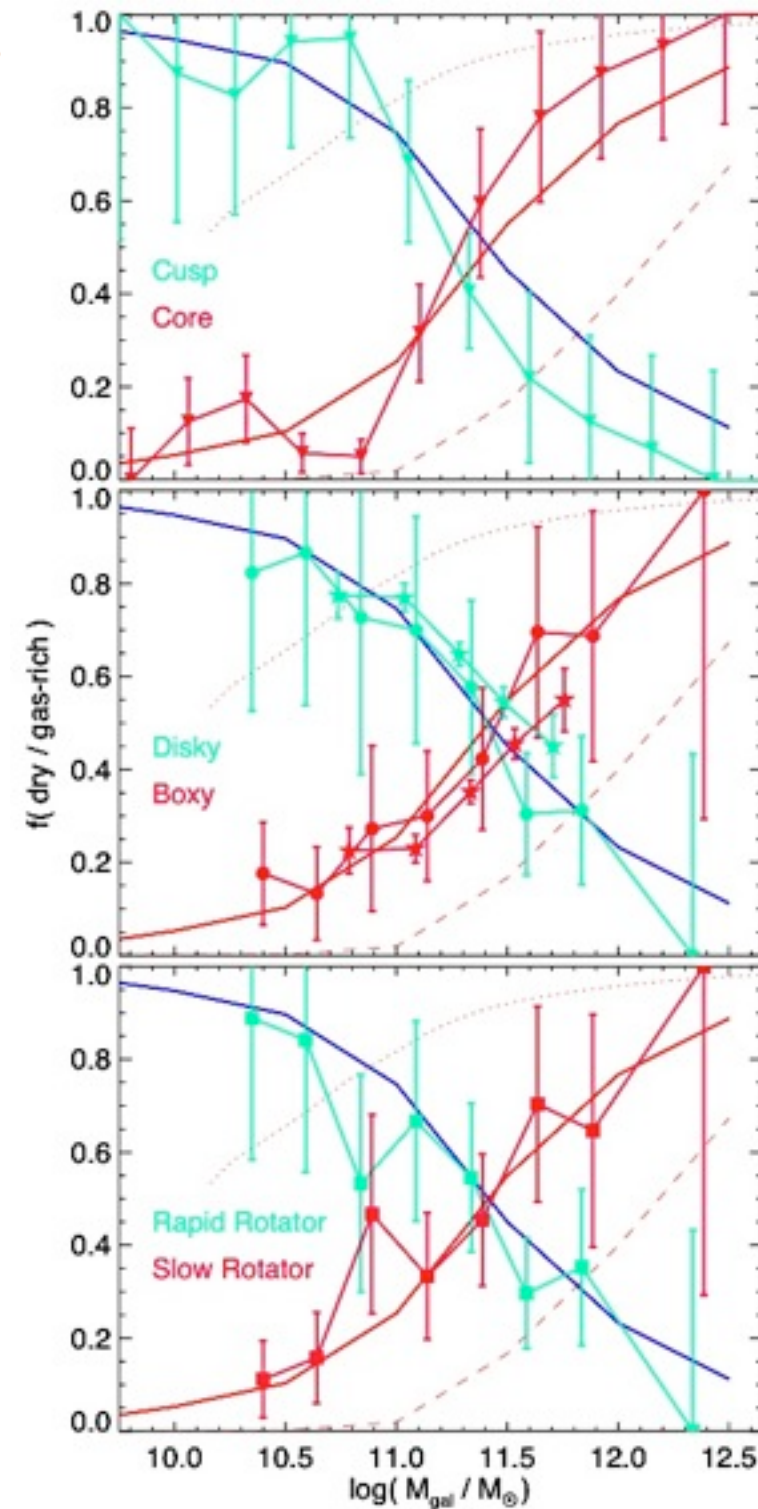


these $z \sim 3$
galaxies
are the
most
massive
galaxies
today

What about the “Cores”?

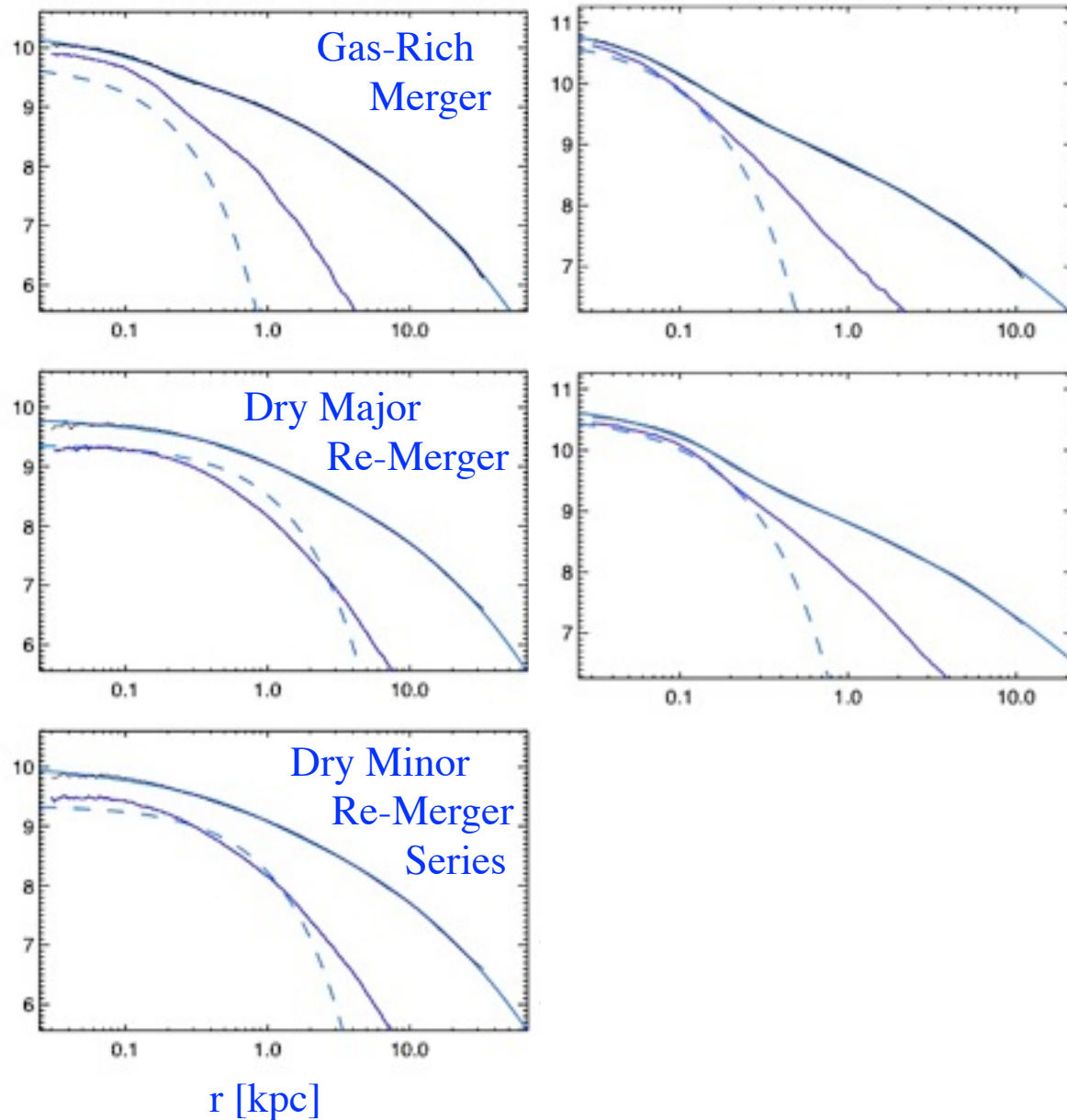
CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?

- Massive ellipticals tend to have “cores” or flattening in their centers (central $\sim 10\text{-}30\text{pc}$)
- Typically associated with BH “scouring” in subsequent gas-poor re-mergers (“dry mergers”)
- But now it is typically claimed that they are “missing” up to $\sim$ a few % of their light ($\sim 10\text{-}50\times M_{\text{bh}}$) out to $\sim 100\text{-}500\text{ pc}$
- What happened to all that “extra light”?



What about the “Cores”?

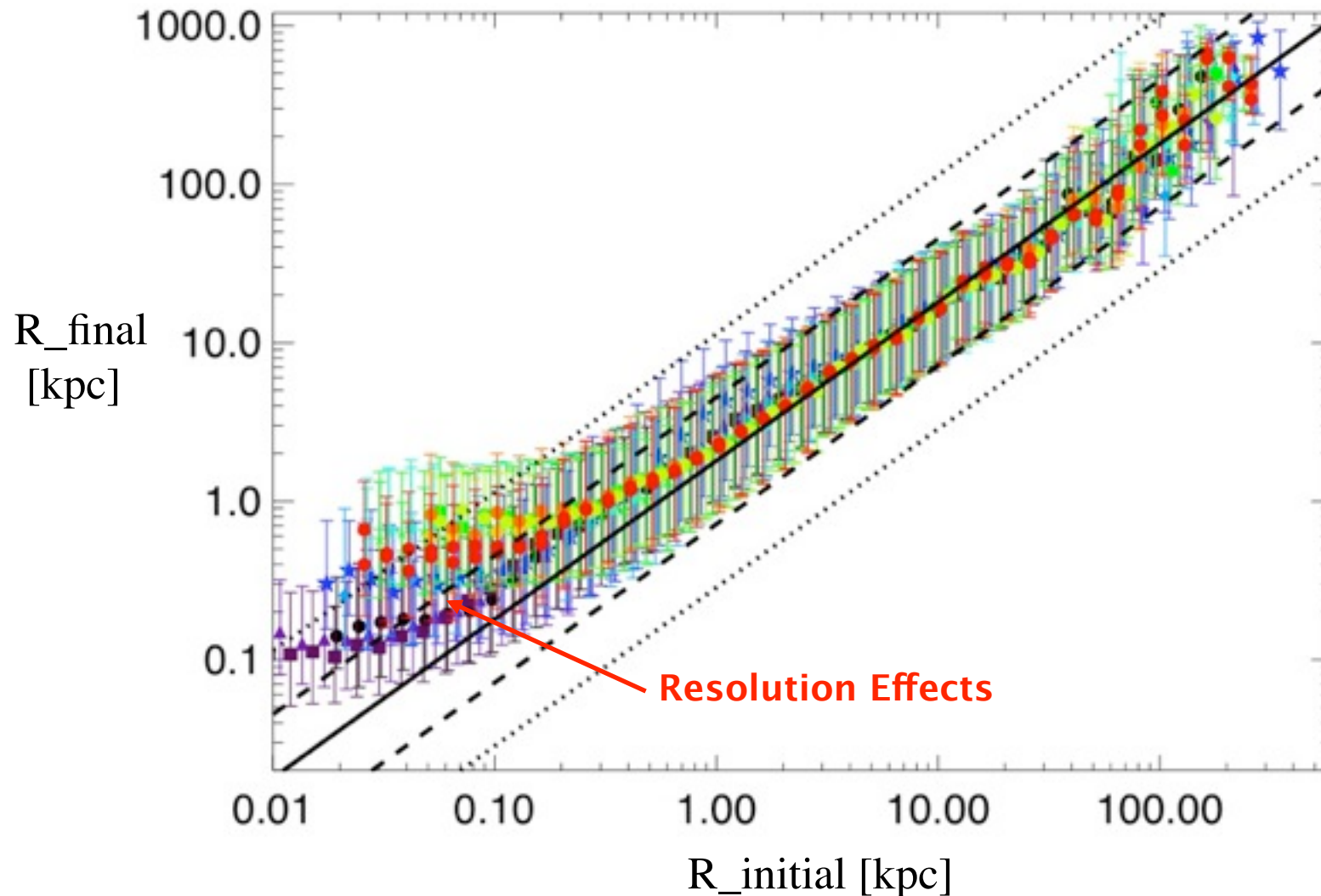
CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?



➤ Re-mergers in simulations preserve the extra light: applying our decomposition reliably extracts the “original” starburst stars

Application: “Core” Ellipticals

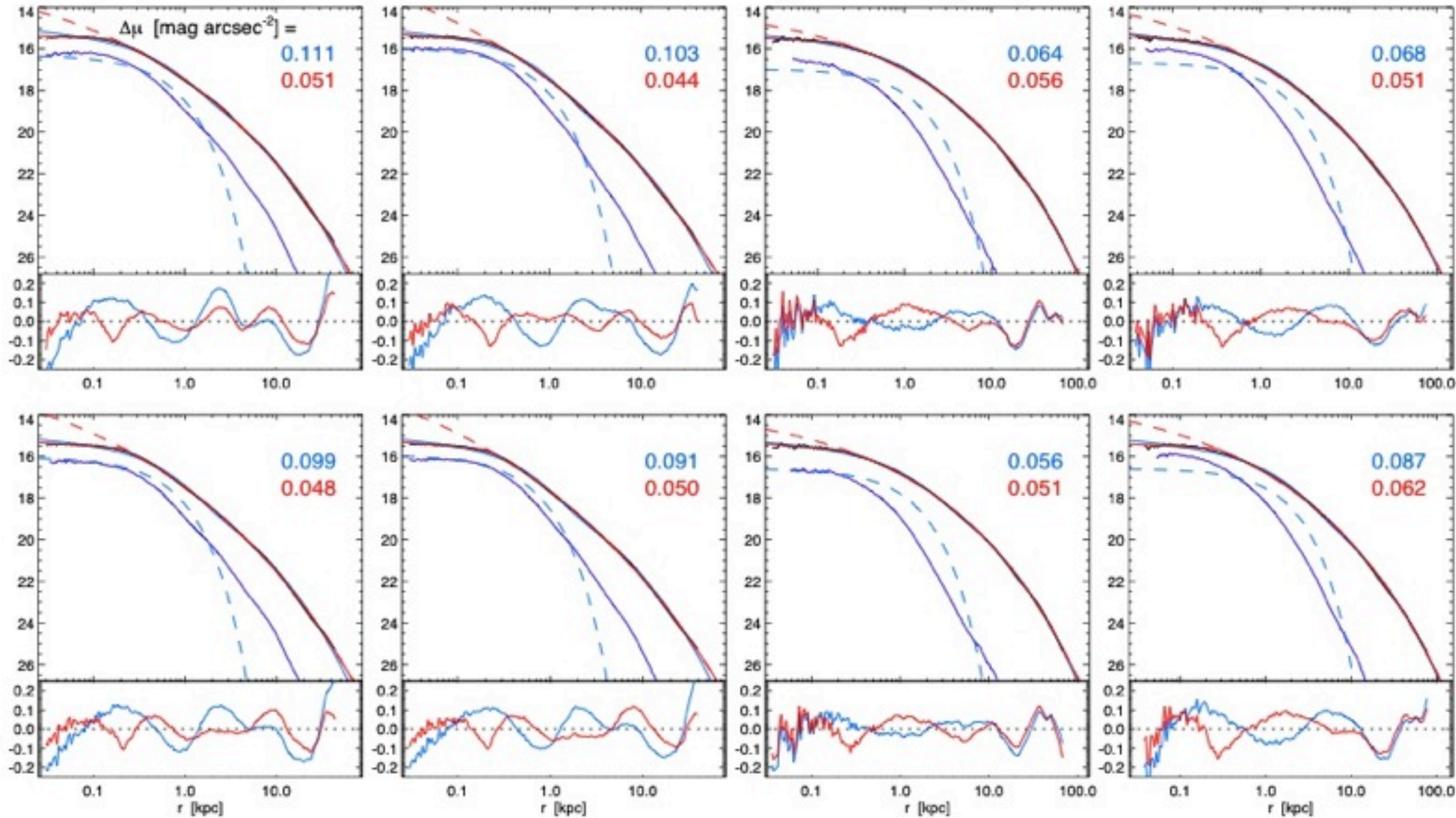
WHAT HAPPENS TO THE “EXTRA LIGHT”?



- Stars are puffed out, but preserve rank-ordering in radius (or binding energy)
 - Extra light is **NOT** destroyed in “dry mergers”
- However, there is significant (~ 0.4 dex) scattering $\therefore$ the transition is “smoothed”

Application: “Core” Ellipticals

WHAT HAPPENS TO THE “EXTRA LIGHT”?

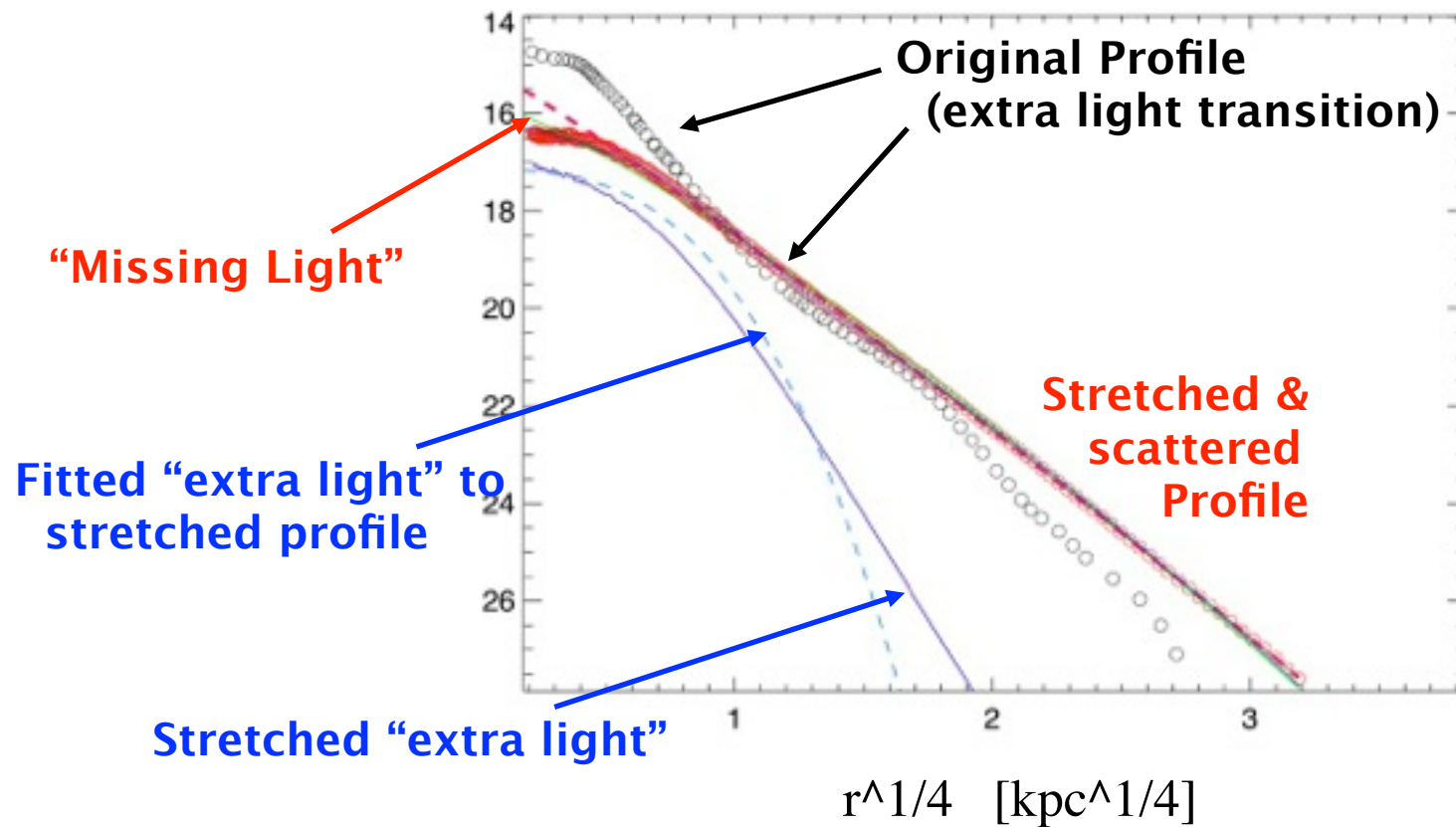


- Systems are now often better fit (technically) by a “core-Sersic” law with MISSING light in the center!

Application: “Core” Ellipticals

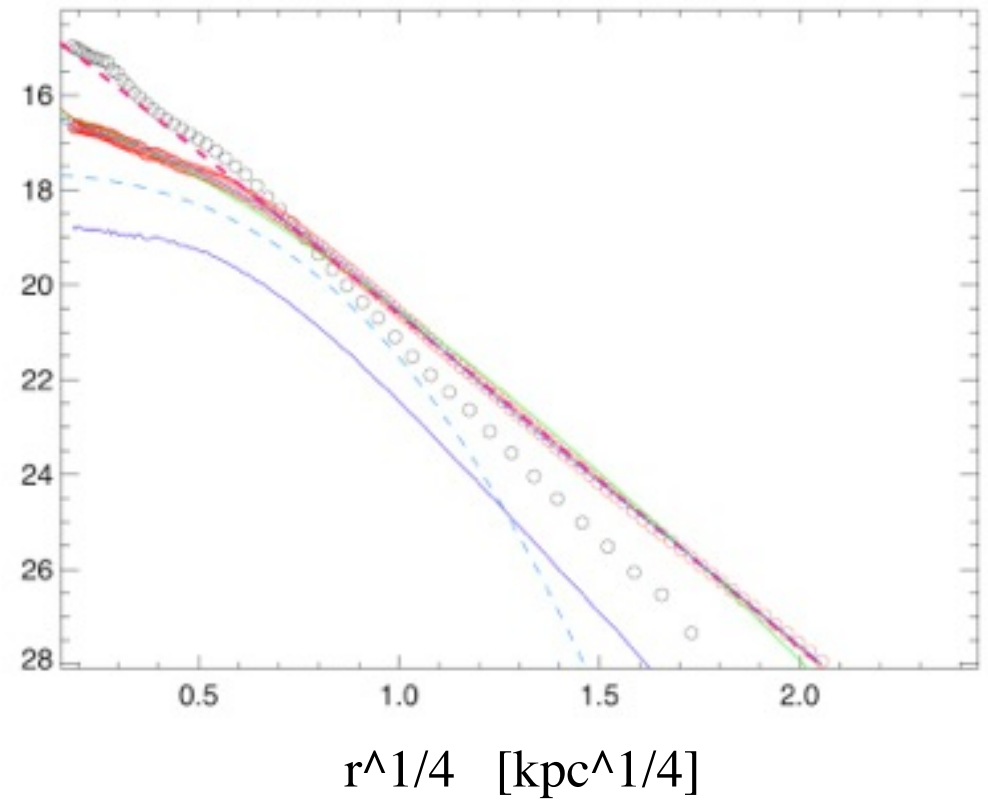
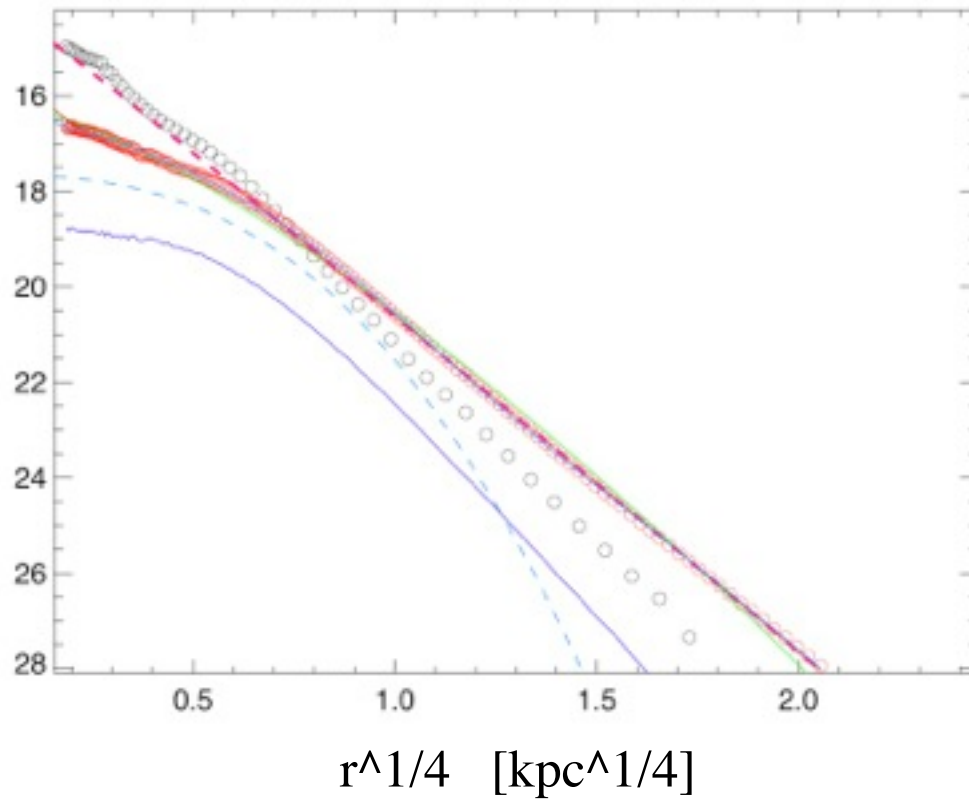
WHAT HAPPENS TO THE “EXTRA LIGHT”?

- Play the same game with the observed systems: stretch & scatter their stars



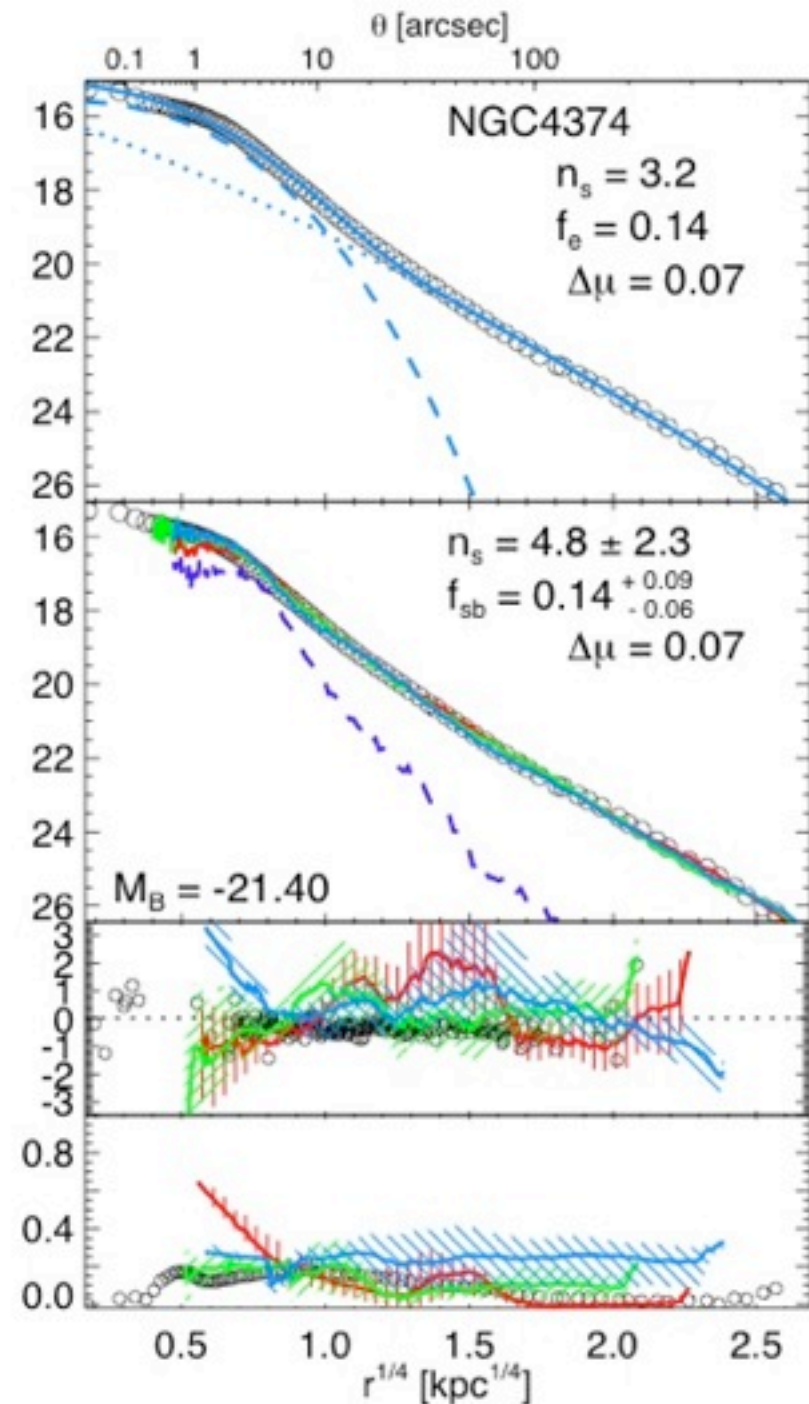
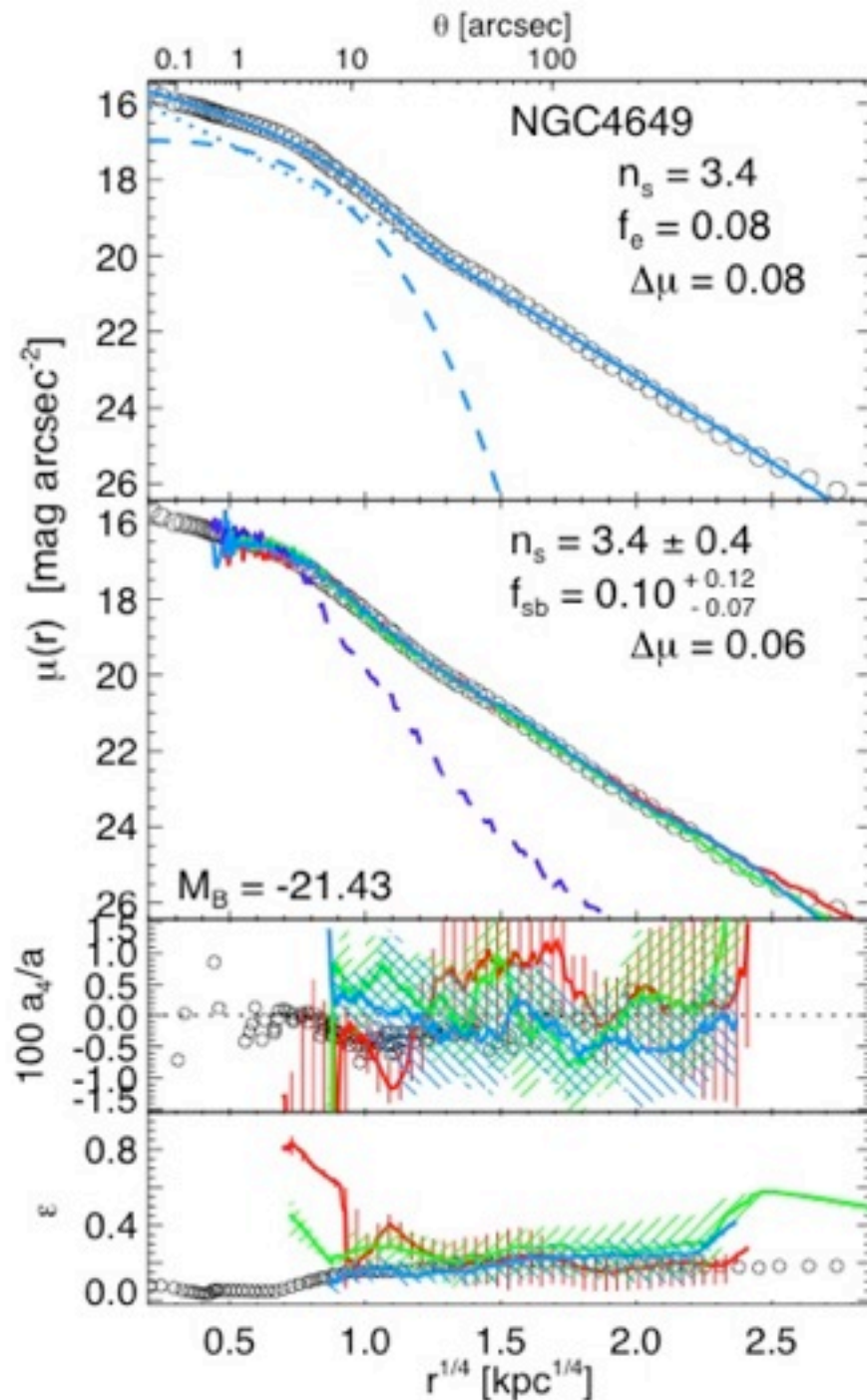
Application: “Core” Ellipticals

WHAT HAPPENS TO THE “EXTRA LIGHT”?



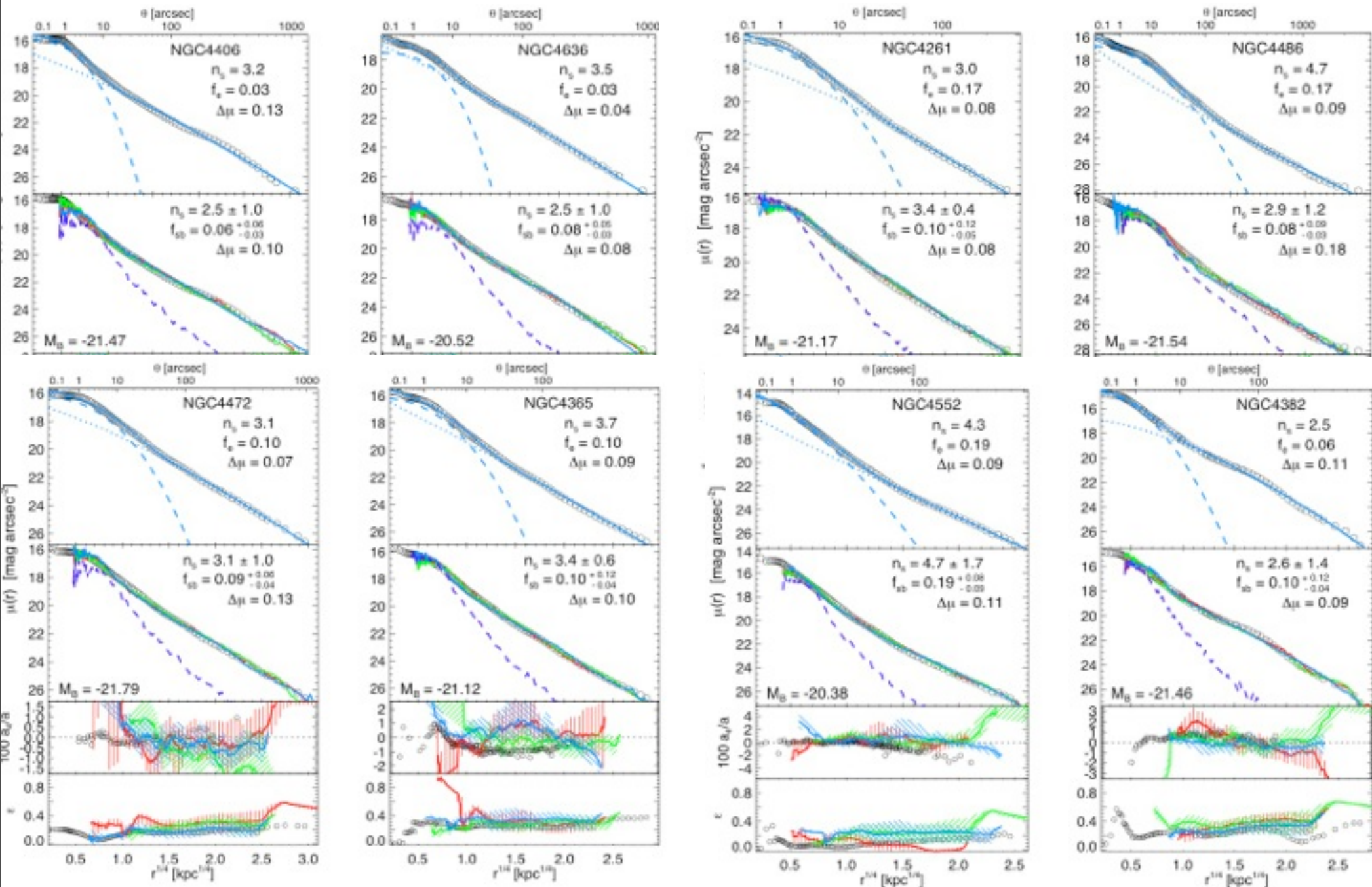
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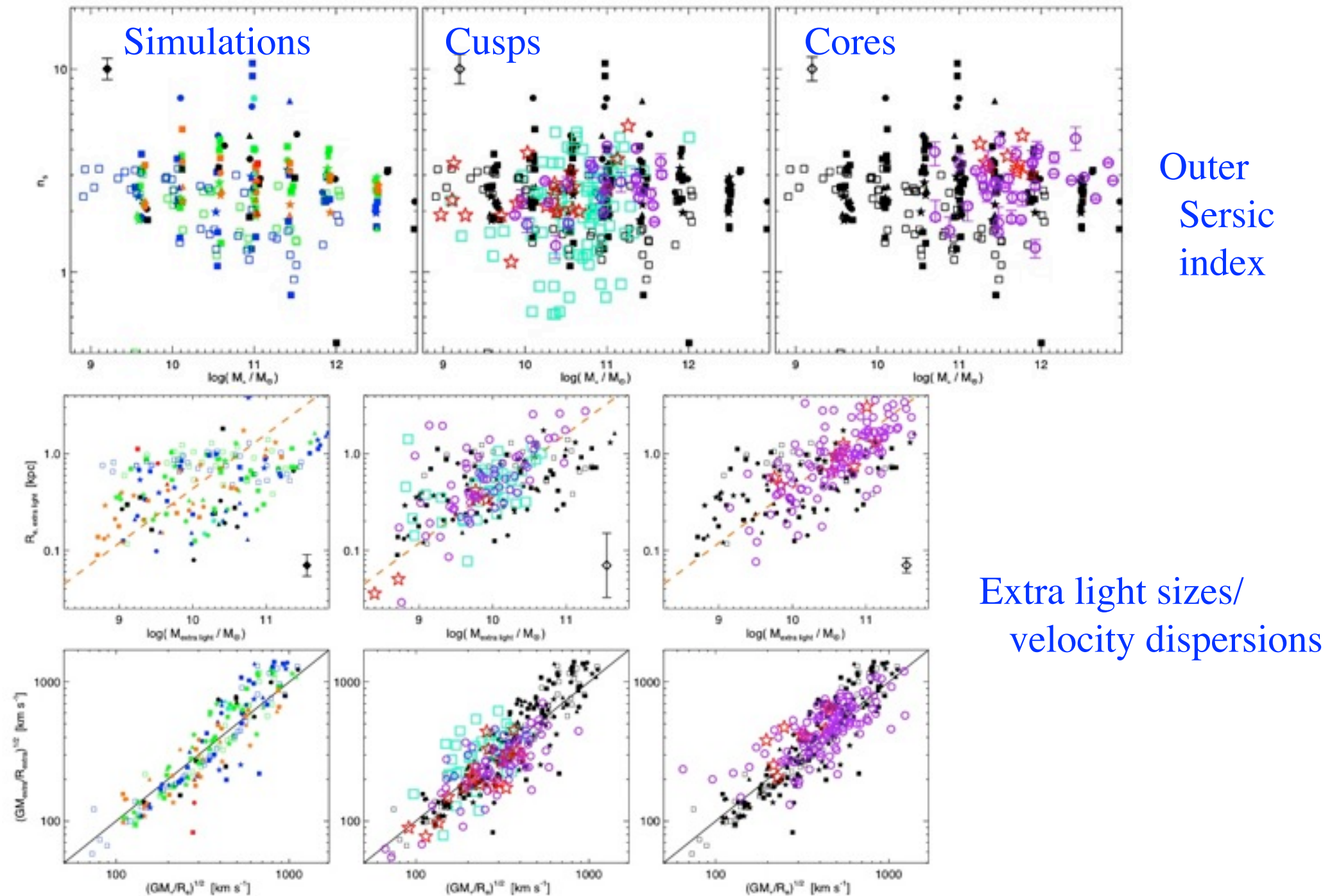
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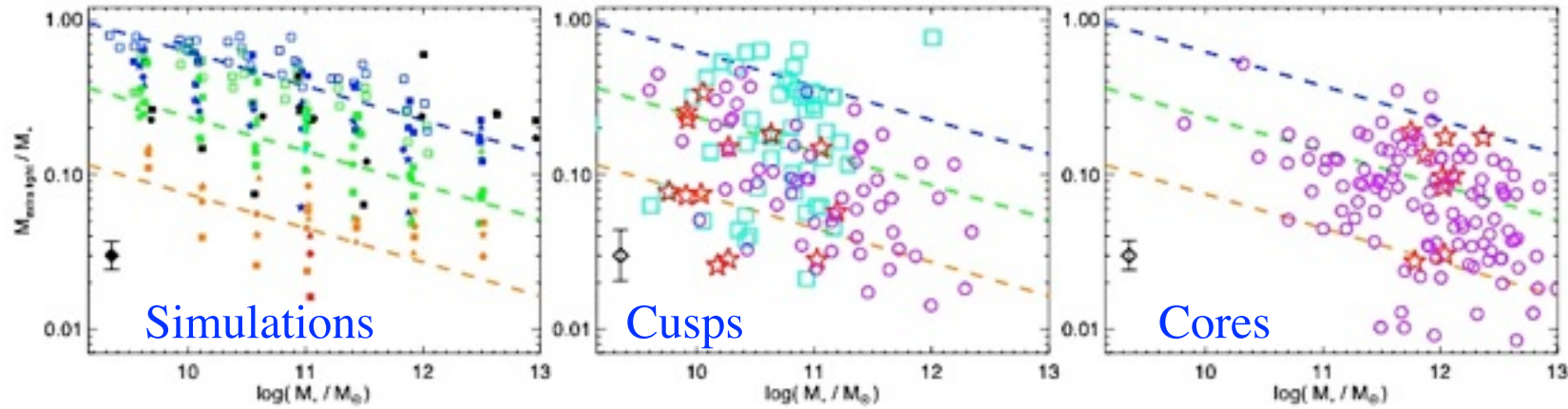
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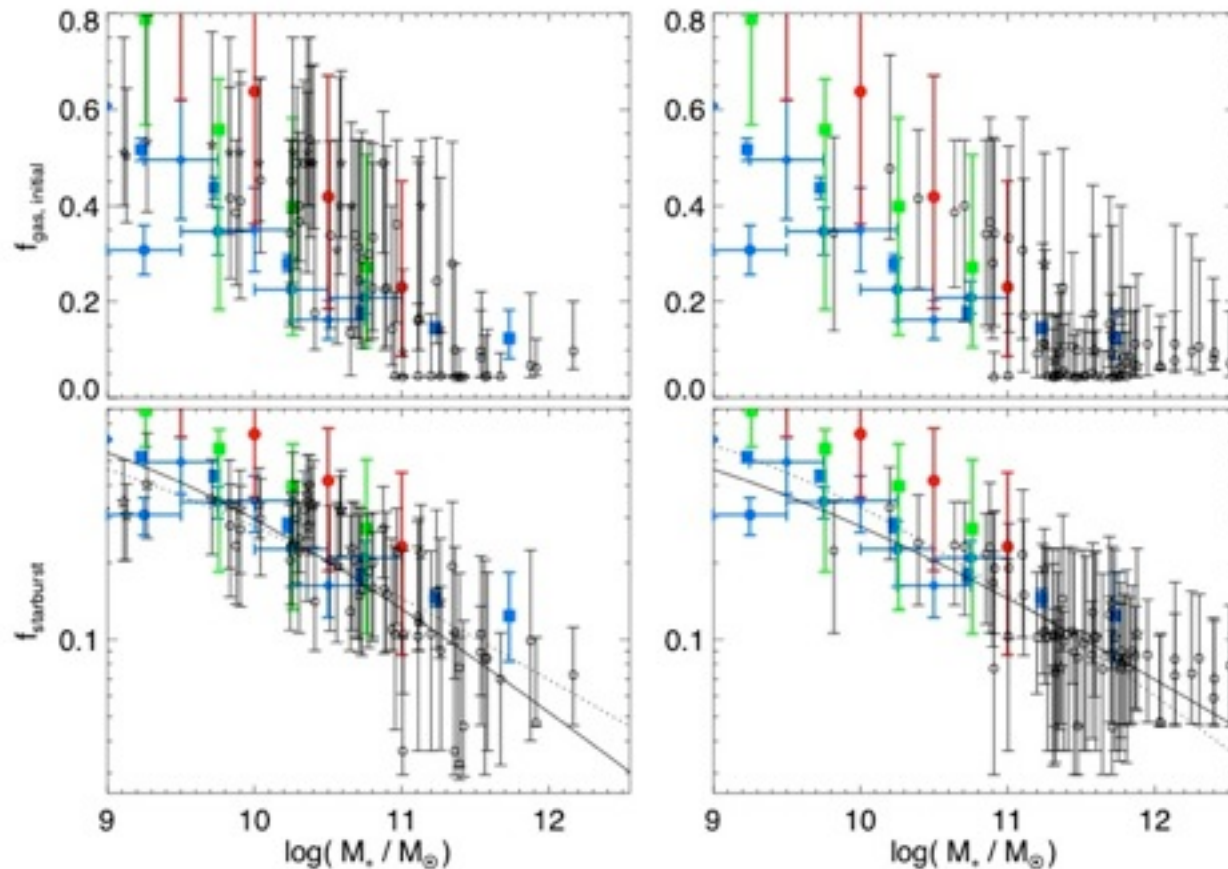


Application: “Core” Ellipticals

WHAT HAPPENS TO THE “EXTRA LIGHT”?



Extra
light
mass
fraction



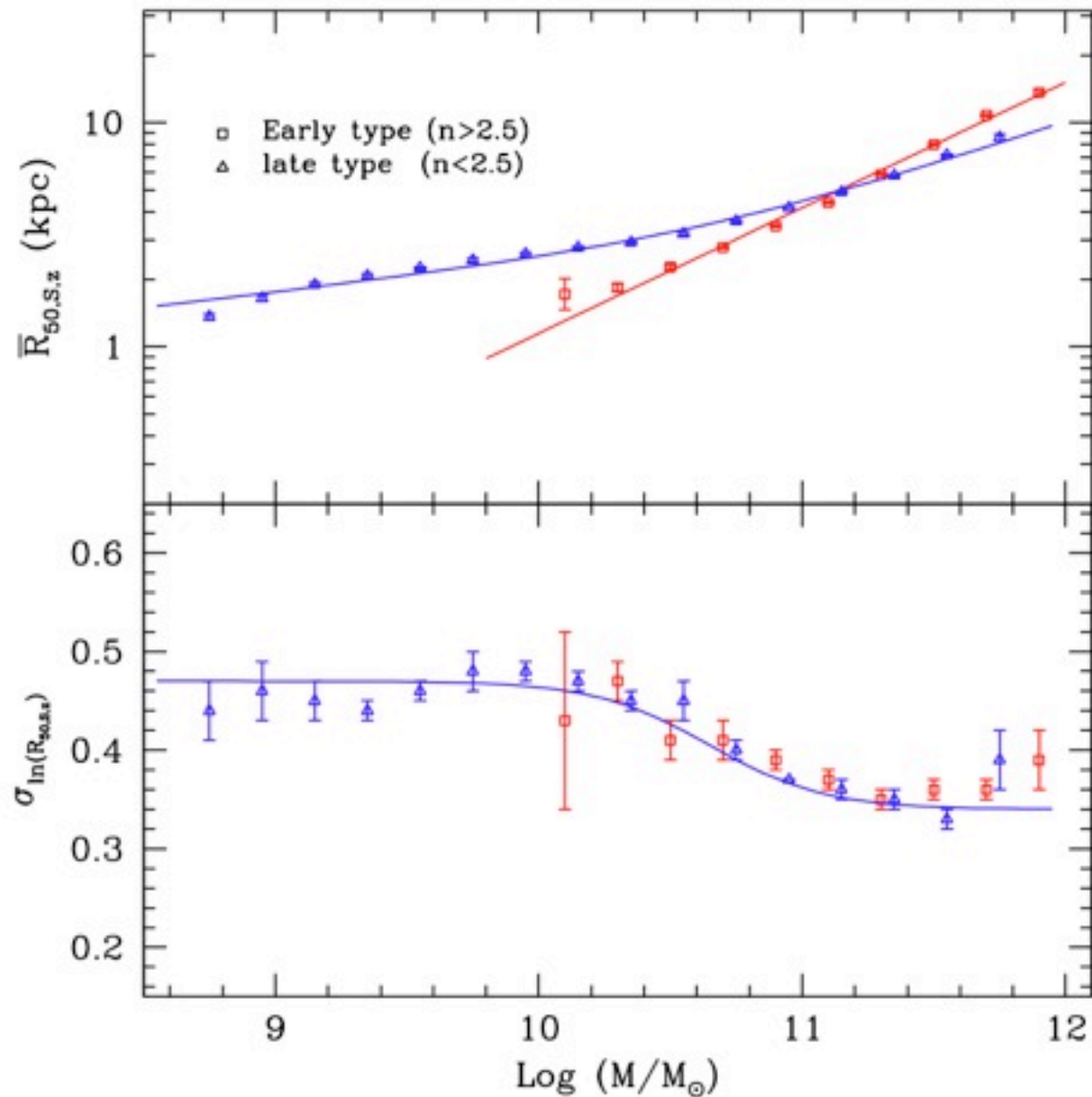
Summary

- All ellipticals have “extra light,” the remnants of the dissipational starburst from their formation event
 - Detailed observations can be separated into starburst light & violently relaxed populations
 - Extra light scales with mass: lower-mass systems had more dissipation
- This drives galaxies along the fundamental plane: more dissipation yields more compact remnants
 - This provides the first means to directly observationally test the idea that different degrees of dissipation produce the tilt in the FP
- While scouring may create “cores”, “missing light” is often an illusion caused by a particular choice of parametric fitting functions
 - Core ellipticals and cusp ellipticals have the same extra/starburst components: they both were formed *originally* in dissipational events

Structure in Elliptical Light Profiles

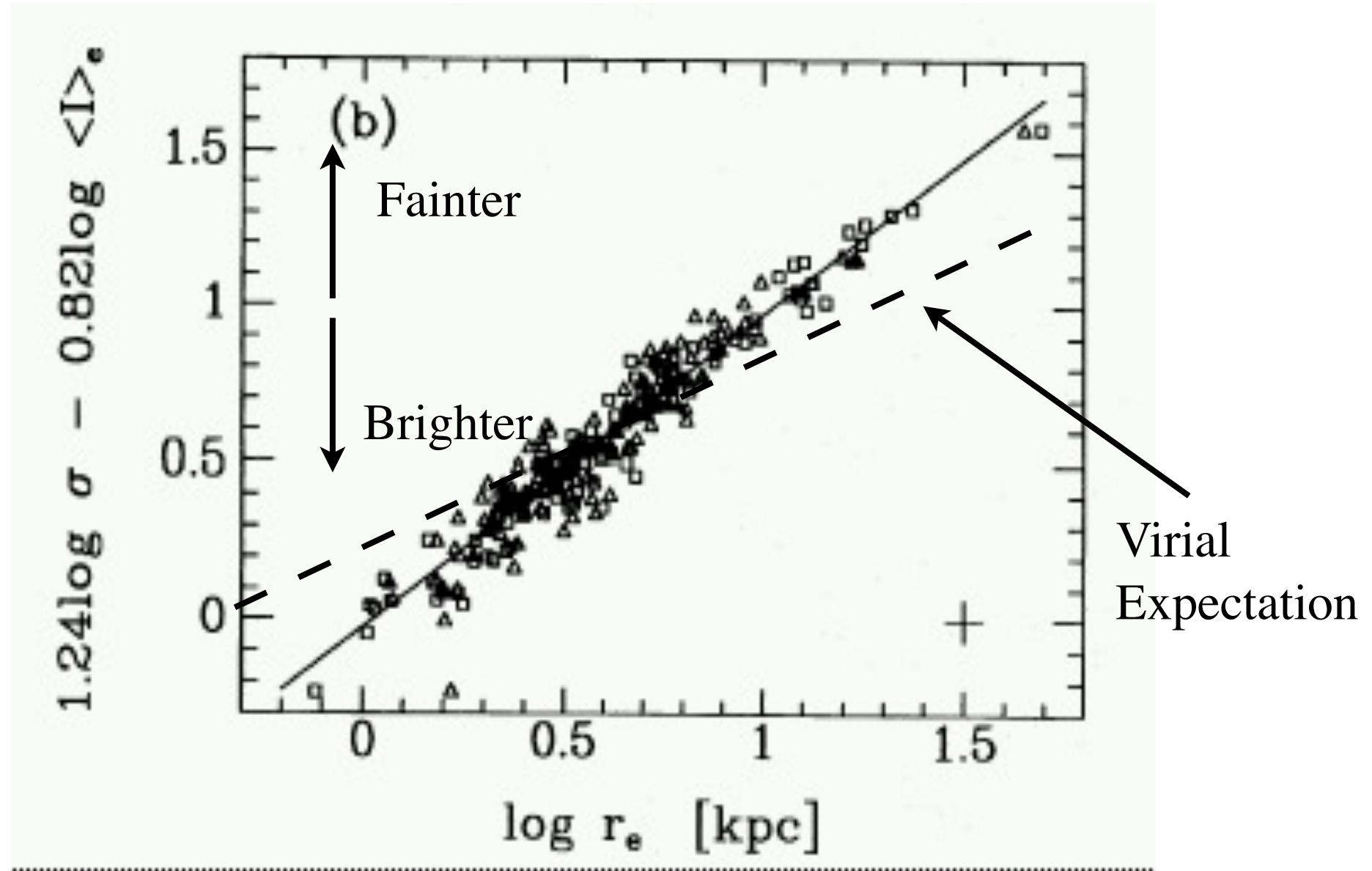
THEIR SCALING LAWS

- Size-Mass Relation: $R \sim M^{0.56}$ (Shen et al. 2003)



Fundamental Plane Tilt

STELLAR POPULATION VARIATION



- (L/M) decreases with mass: older, more metal rich?

Structure of Spheroids

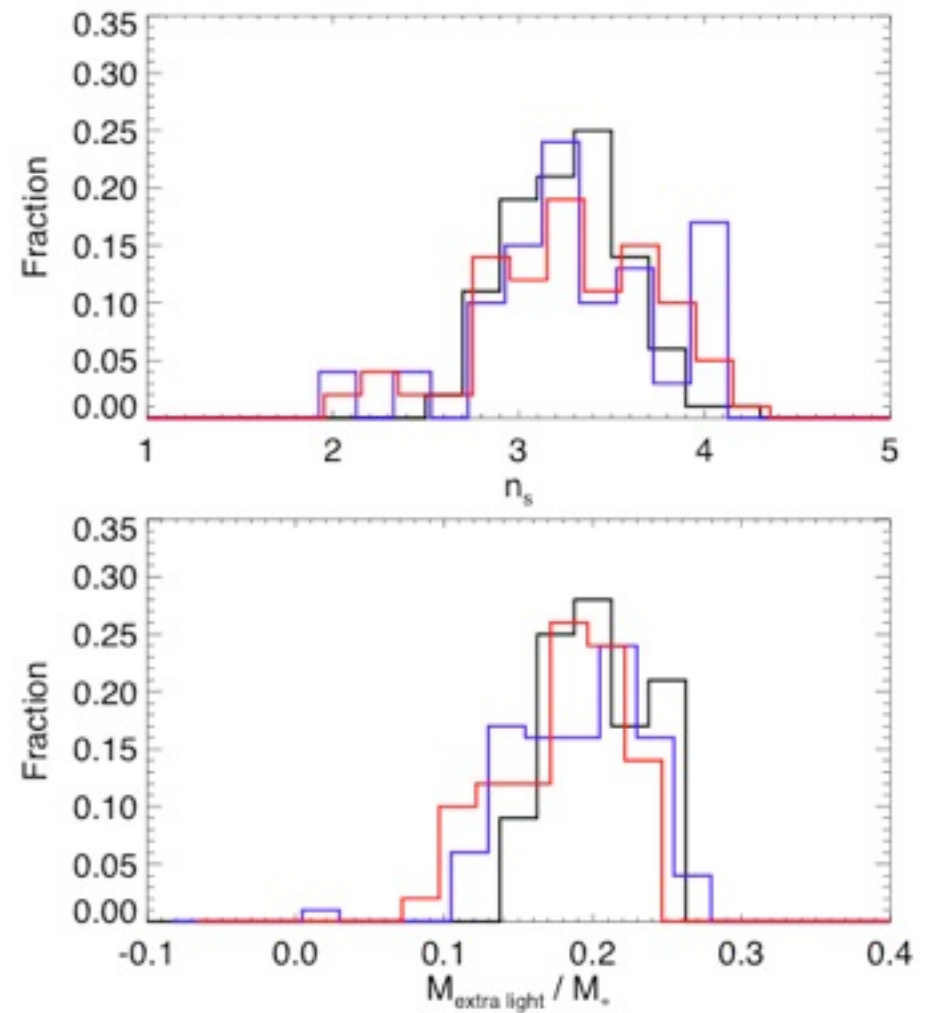
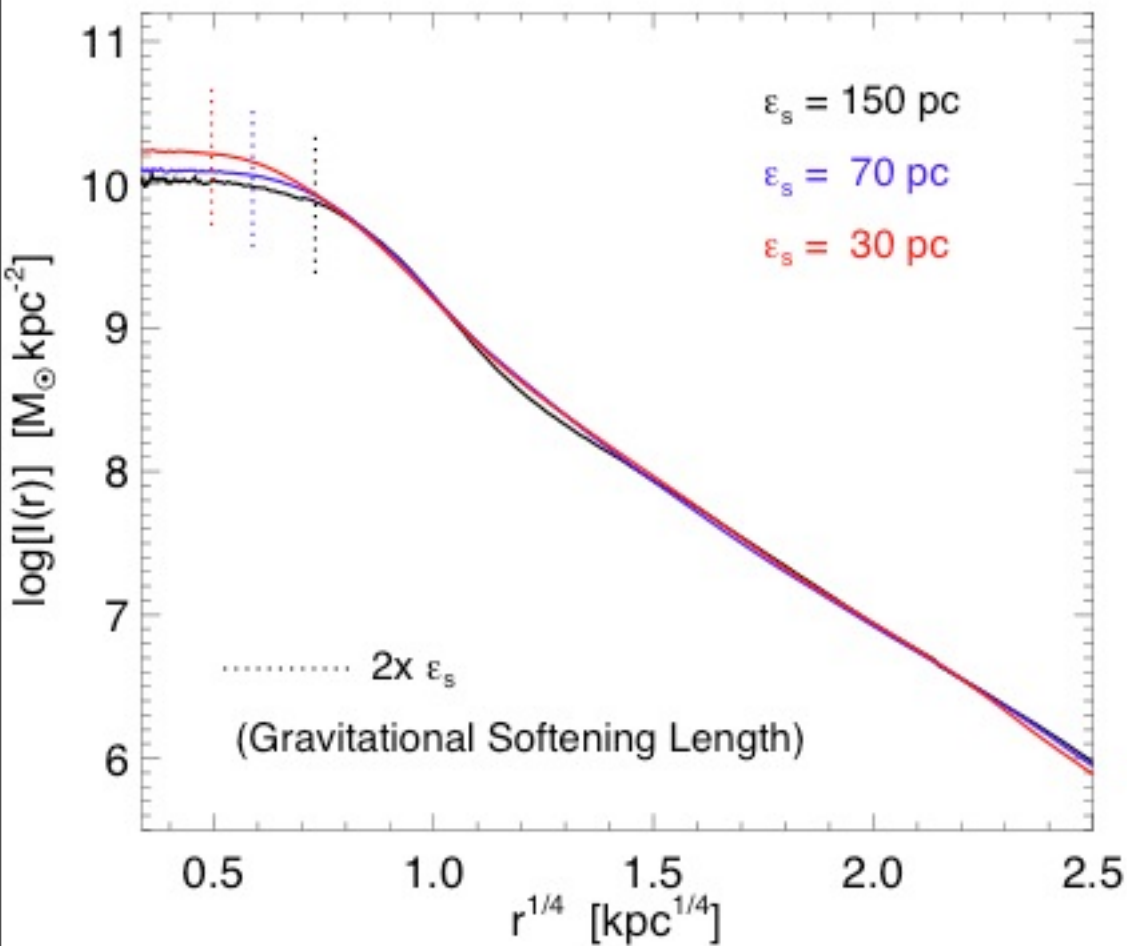
UNDERSTANDING THE FUNDAMENTAL PLANE

- Instead, the FP is “tilted”:
 - $(L / M_{\text{dyn}}) \sim M^{\{0.1-0.3, \text{ depending on the band}\}}$
 - three possible explanations:
 - stellar population variation:

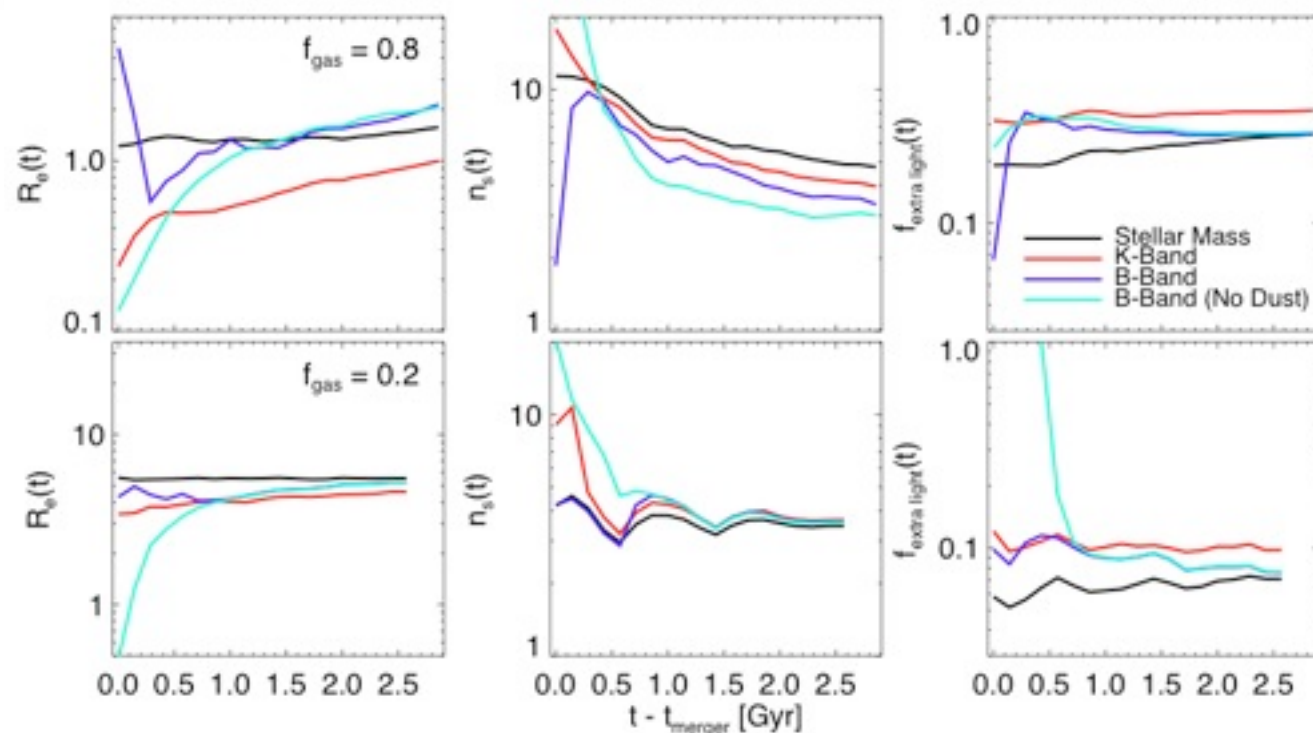
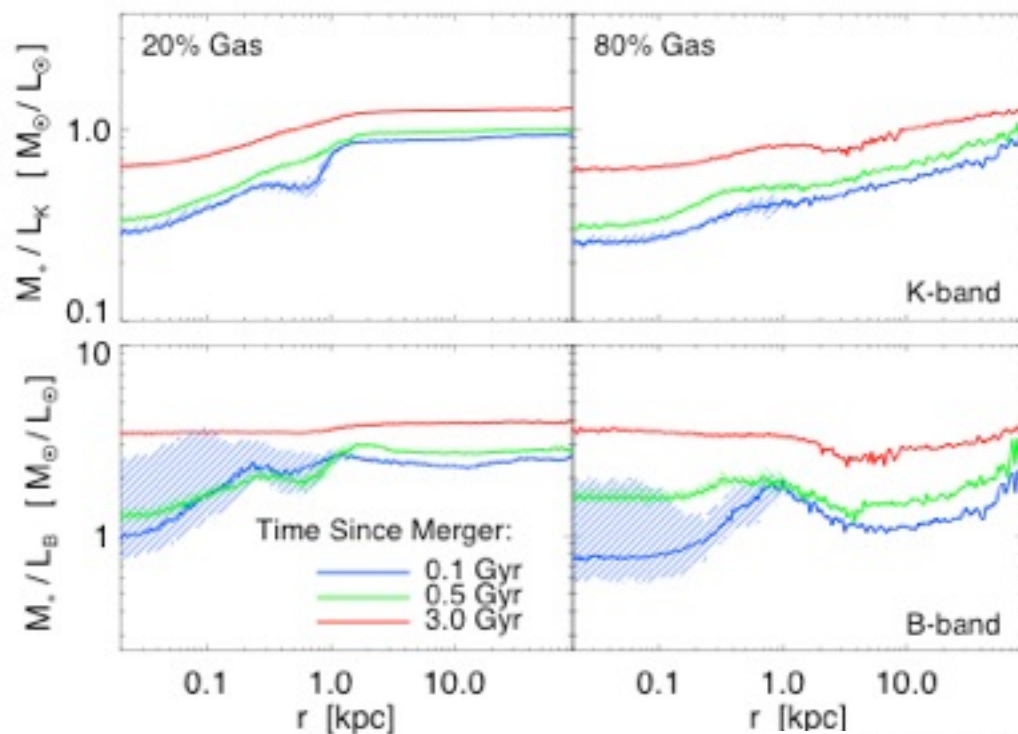
$M_{\text{dyn}} \sim M_{\text{stellar}}$ holds, but (L/M_{stellar}) varies with L
 - kinematic non-homology:
 - velocity fields change
 - structural non-homology:
 - profile shape changes with mass
 - stellar-to-dark-matter mass ratio changes (can be the same as the above, or different)

Resolution Studies

RECOVERING THE ROLE OF GAS



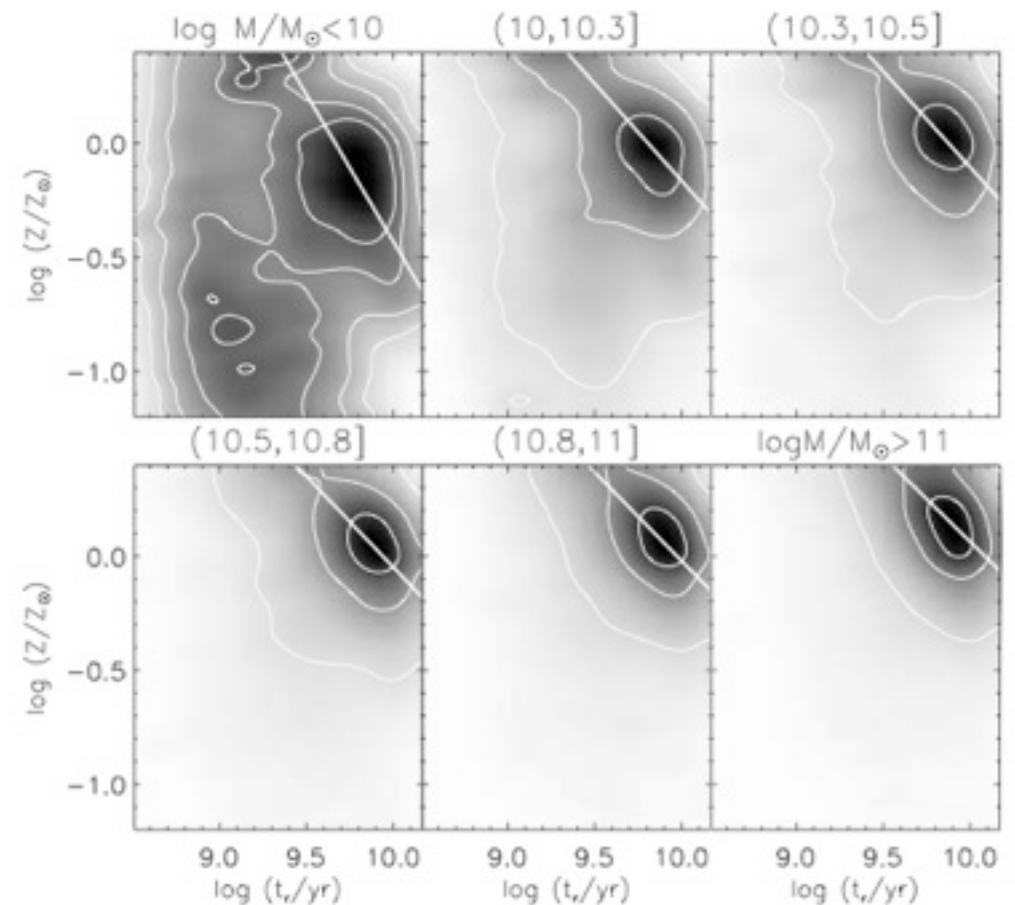
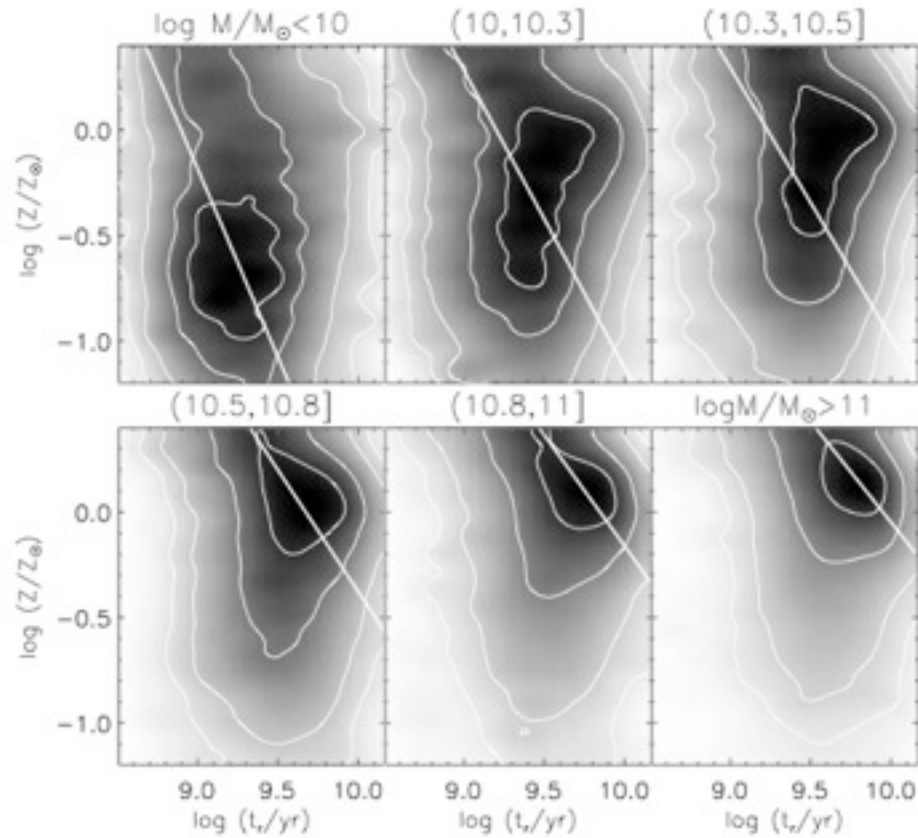
Stellar Population Effects



Fundamental Plane Tilt

STELLAR POPULATION VARIATION

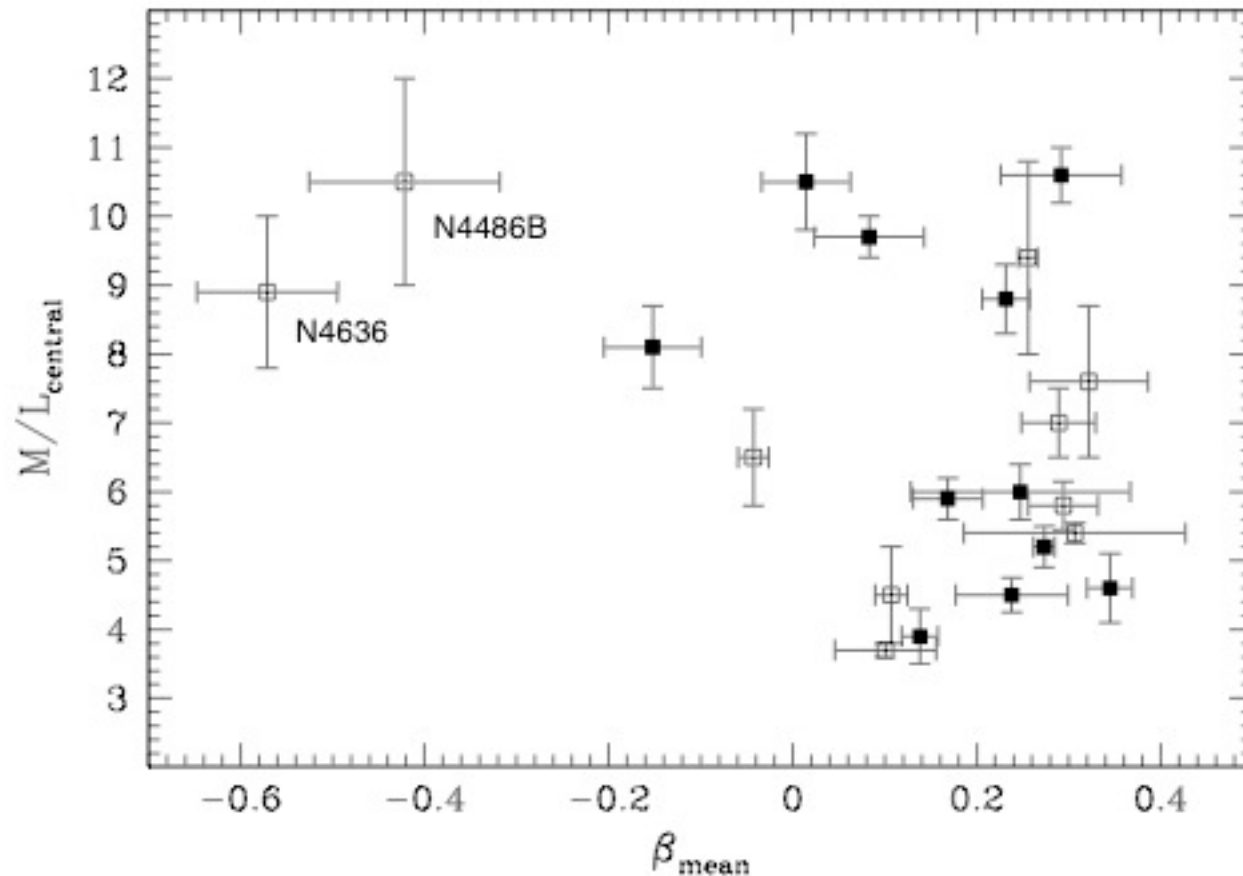
➤ Where do these come from?



Fundamental Plane Tilt

KINEMATIC NON-HOMOLOGY

- Is σ_{obs} systematically higher than it “should” be in high-mass systems?



- Inclusion of circular velocity in low-mass ellipticals should actually bias you the *opposite* way