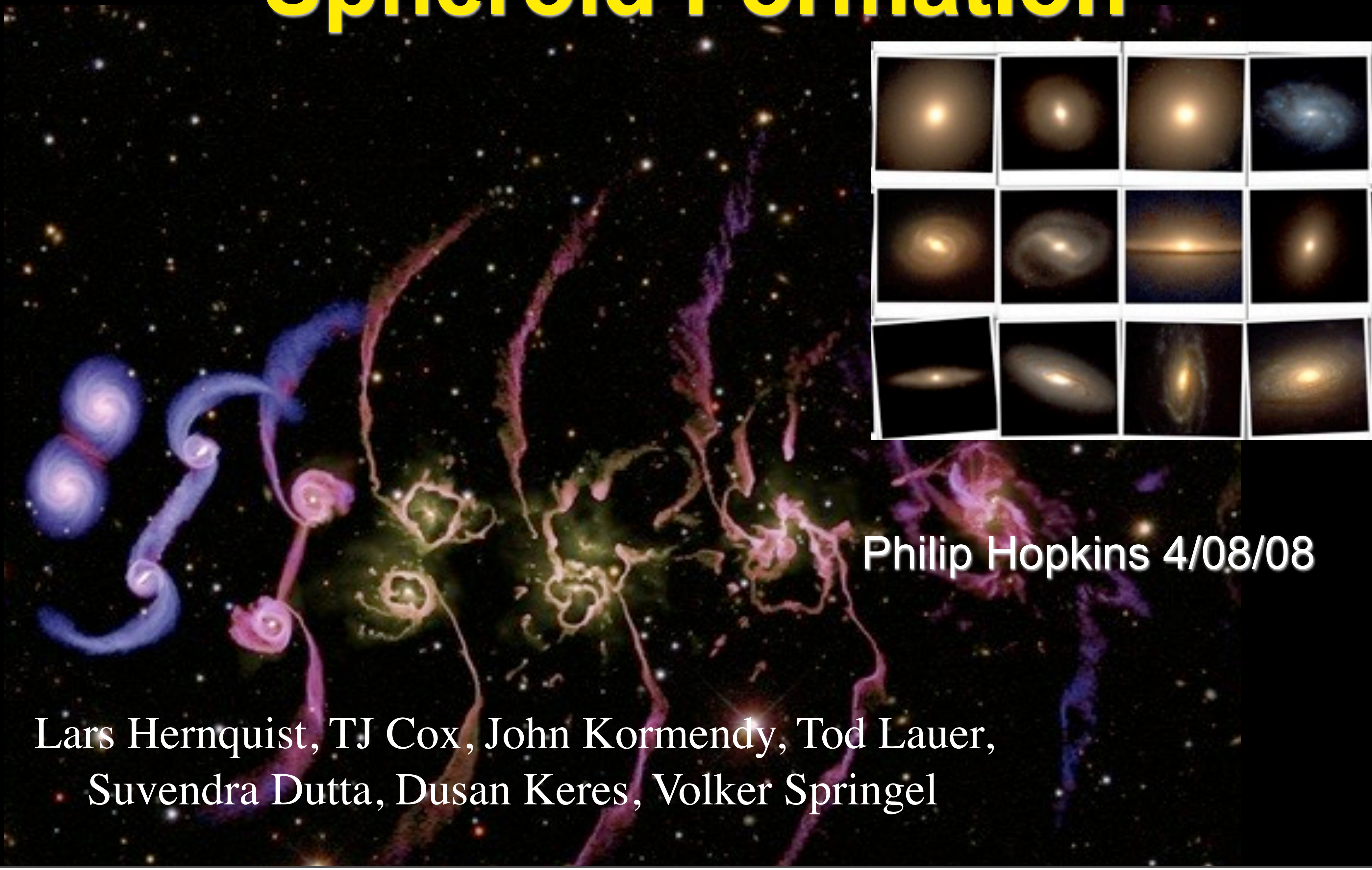
The Role of Dissipation in Spheroid Formation



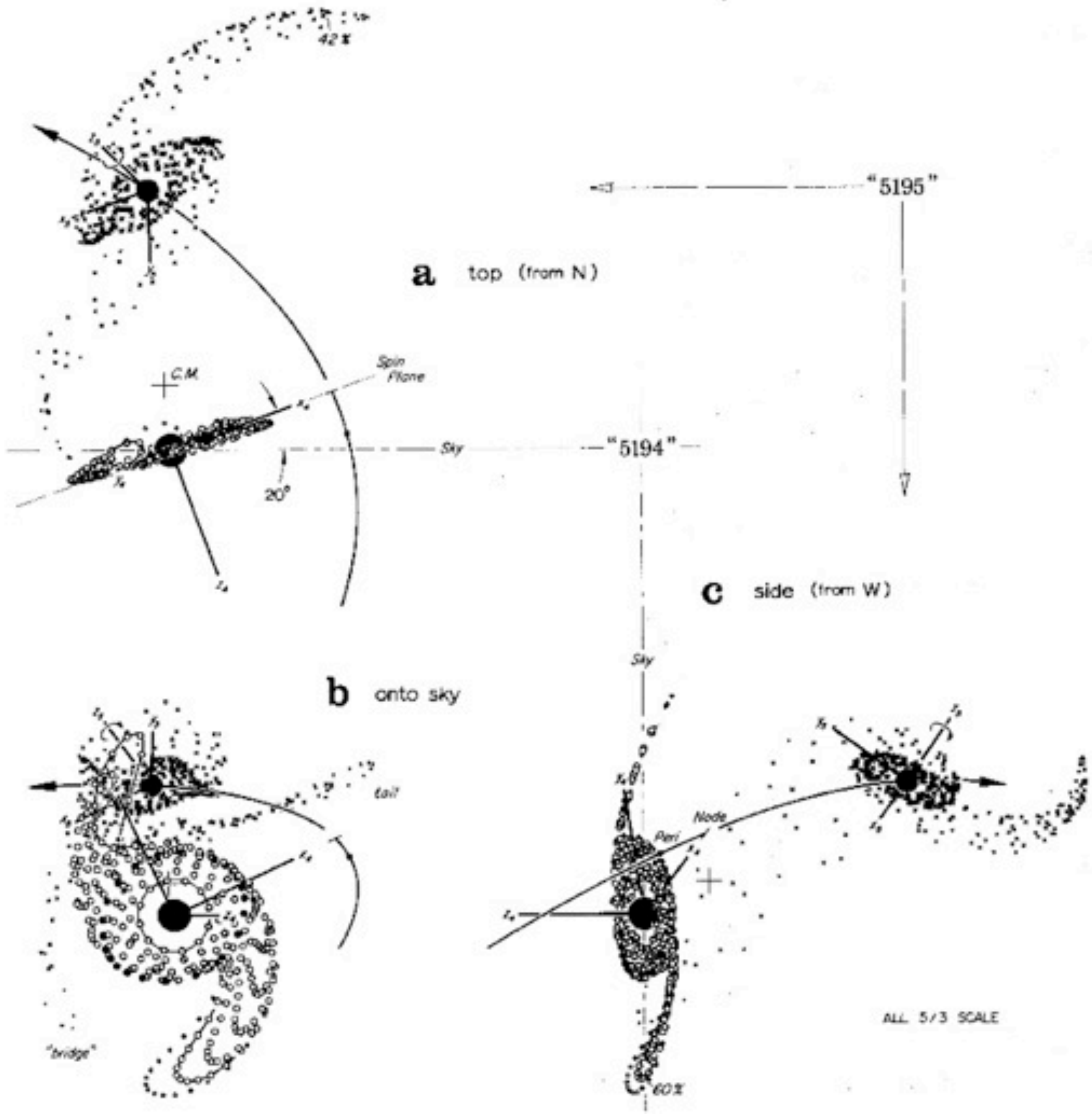
Philip Hopkins 4/08/08

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

Ellipticals & Bulges: Formation in Mergers?

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

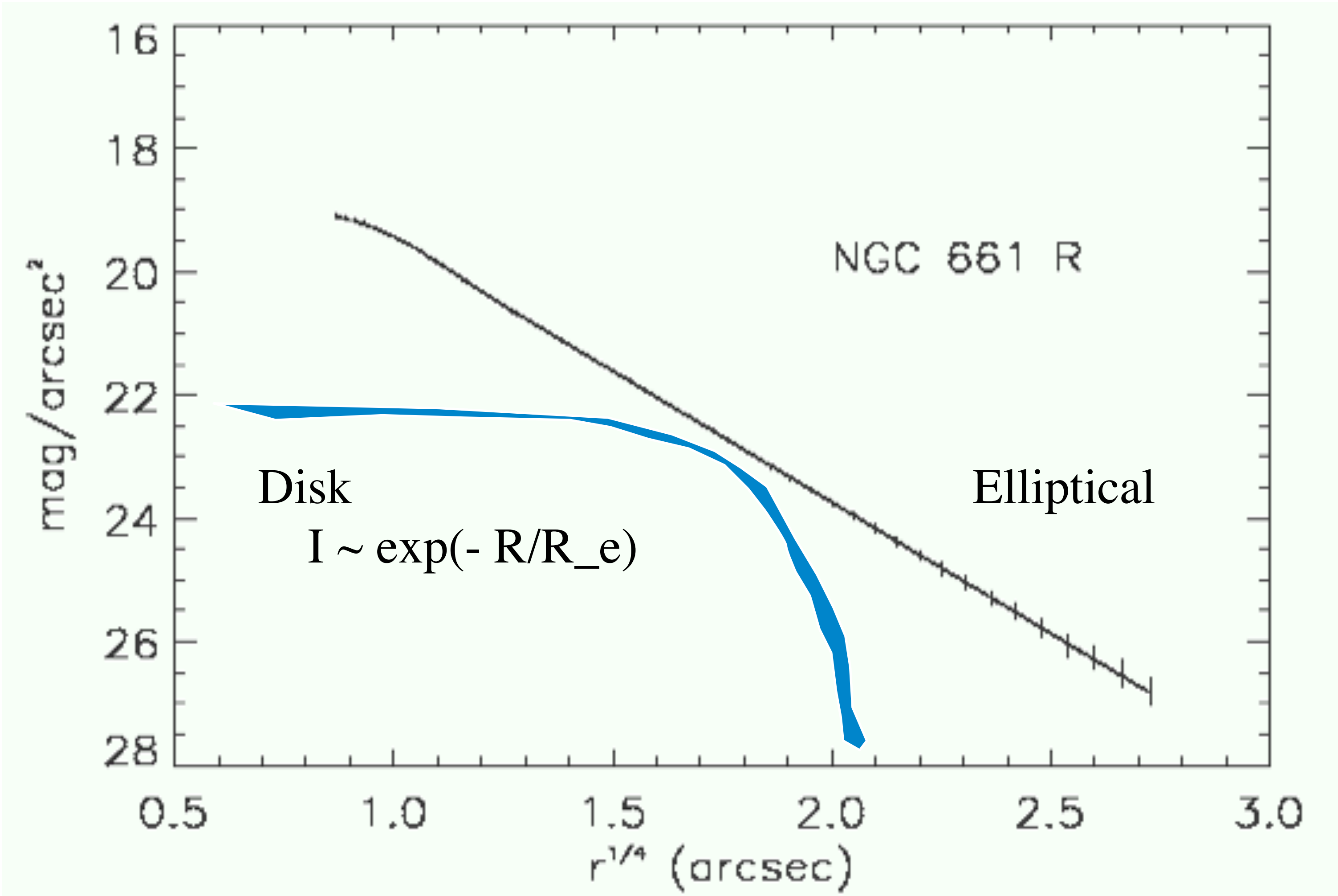
ellipticals are made by the collision and merger of spirals



Ellipticals & Bulges: Formation in Mergers?

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

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



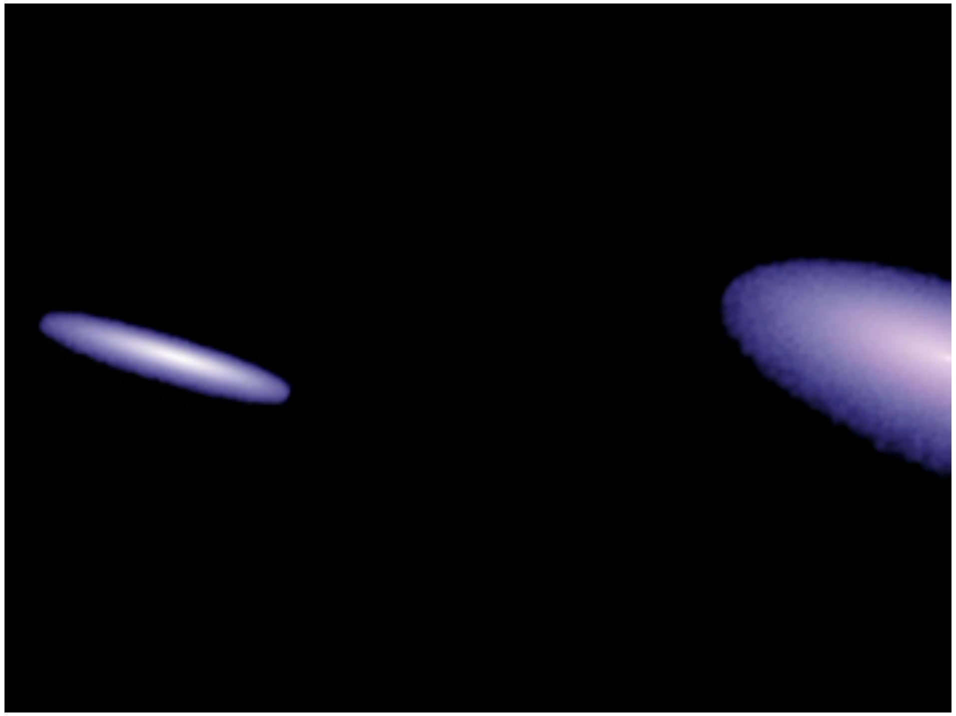
- Lynden-Bell: violent relaxation: rapidly changing potential: stars scatter off the changing potential, mixing their orbits and energies

Ellipticals & Bulges: Formation in Mergers?

There was, however, some controversy about the idea....

Ellipticals & Bulges: Formation in Mergers?

- Modern-day simulations have advanced a lot....



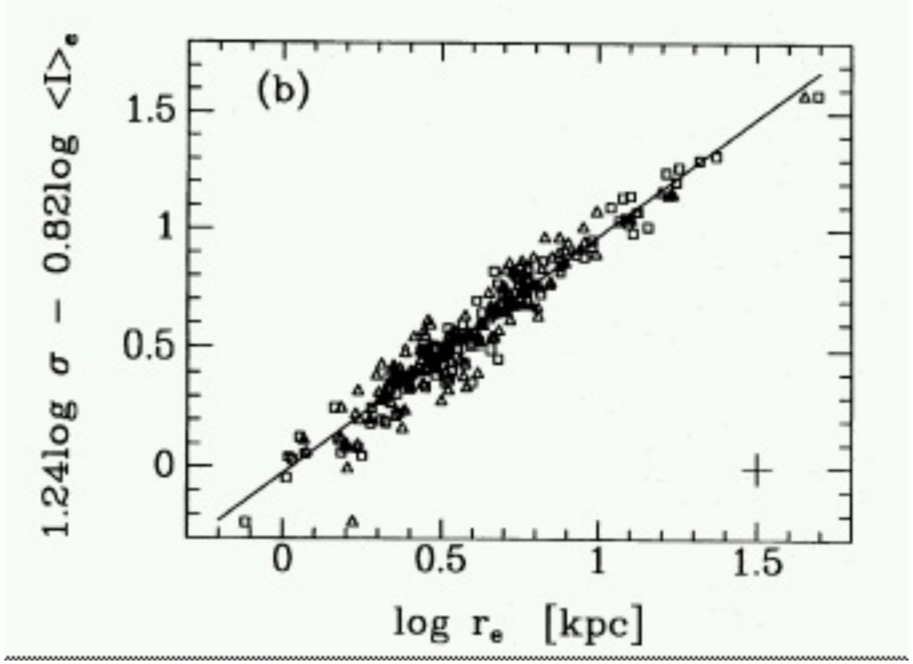
- But are we making "real" ellipticals?

The Problem:

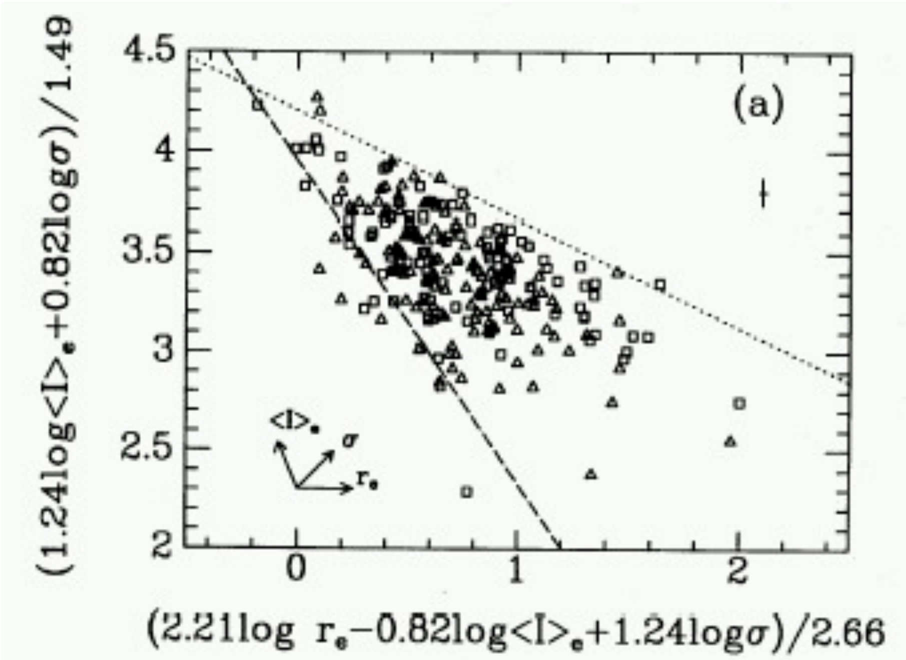
The Fundamental Plane correlates R_e, surface brightness, and σ for elliptical galaxies.

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



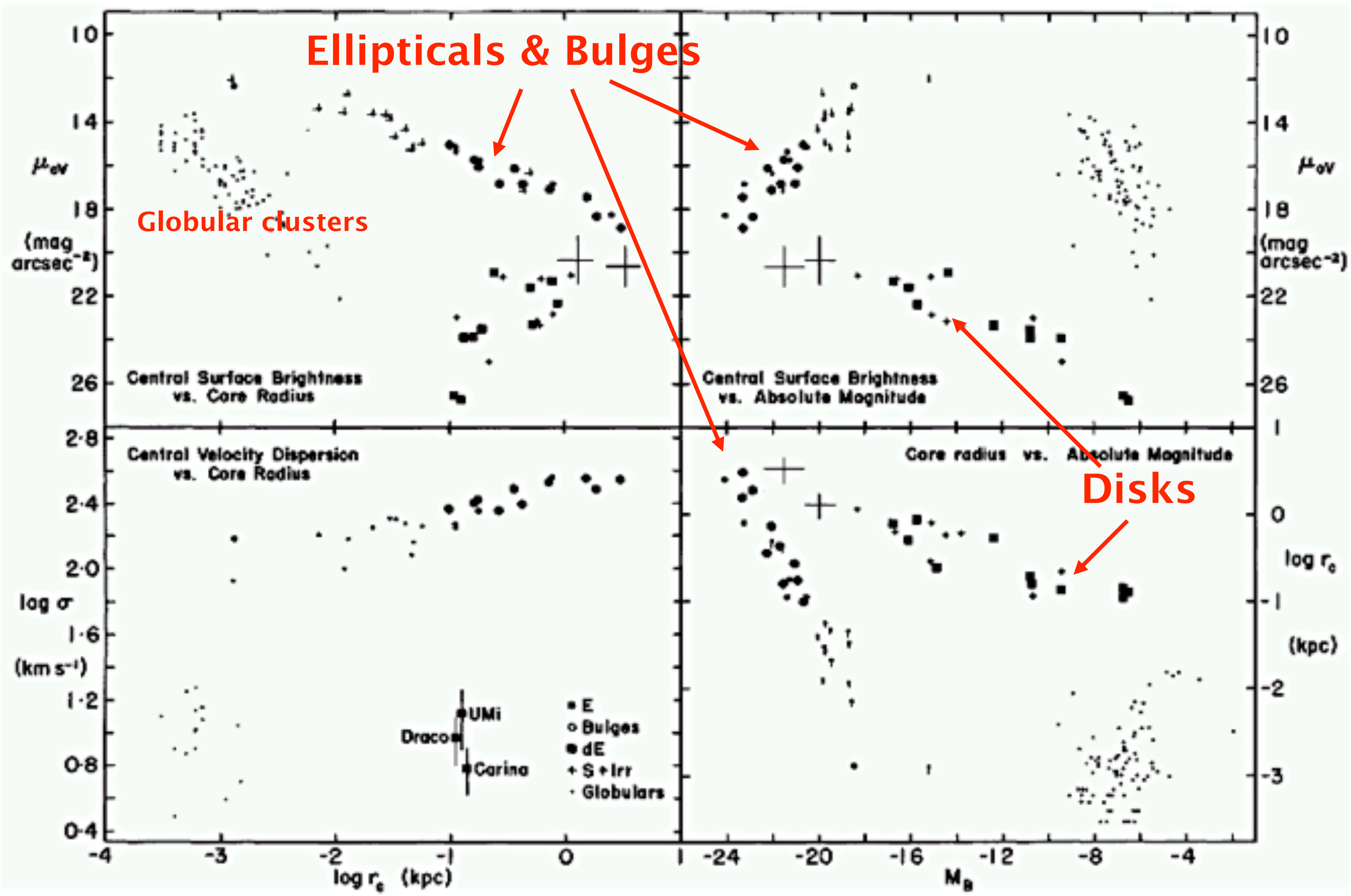
Fundamental Plane face on

Jorgensen 1996

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

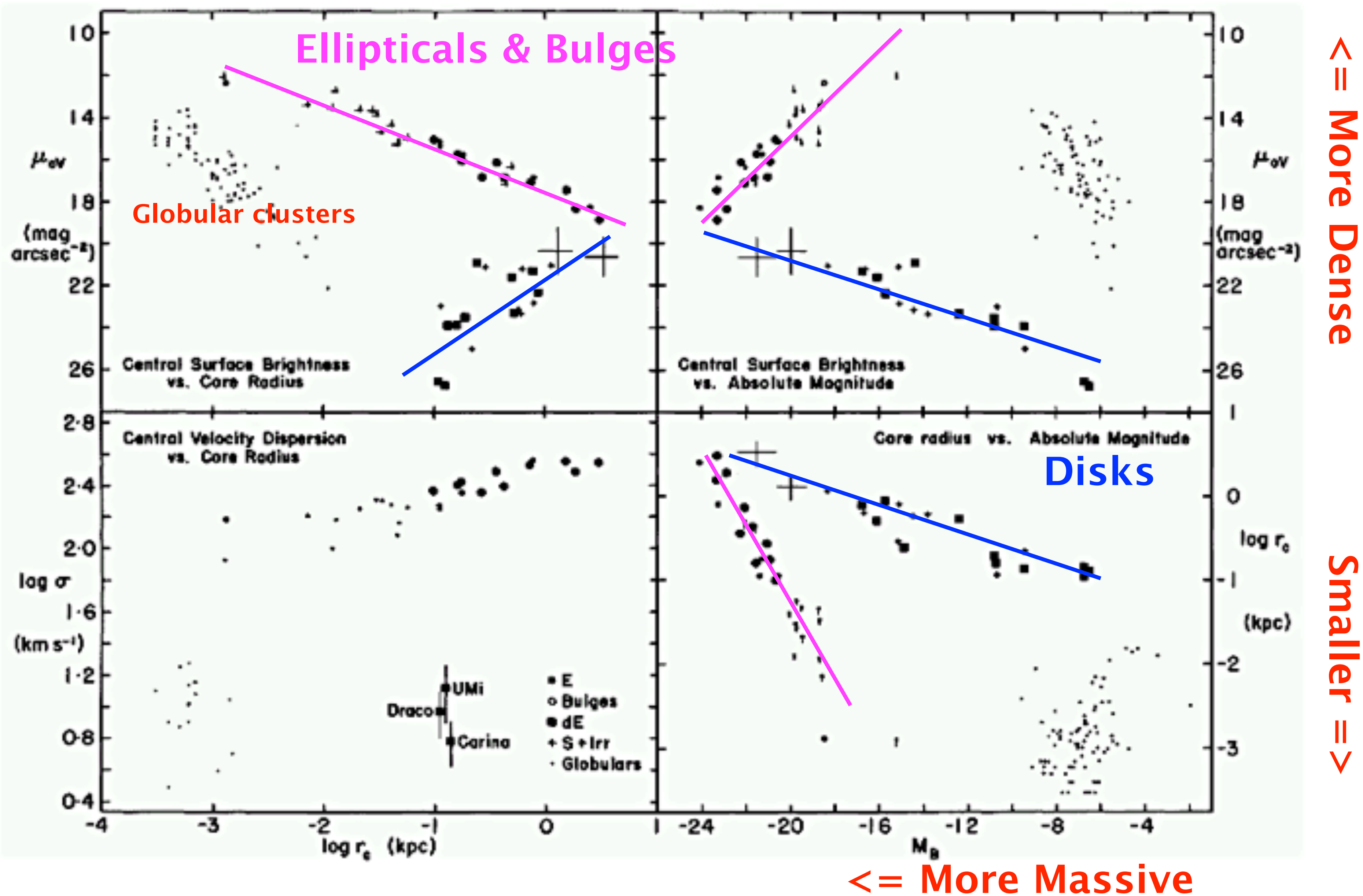
Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

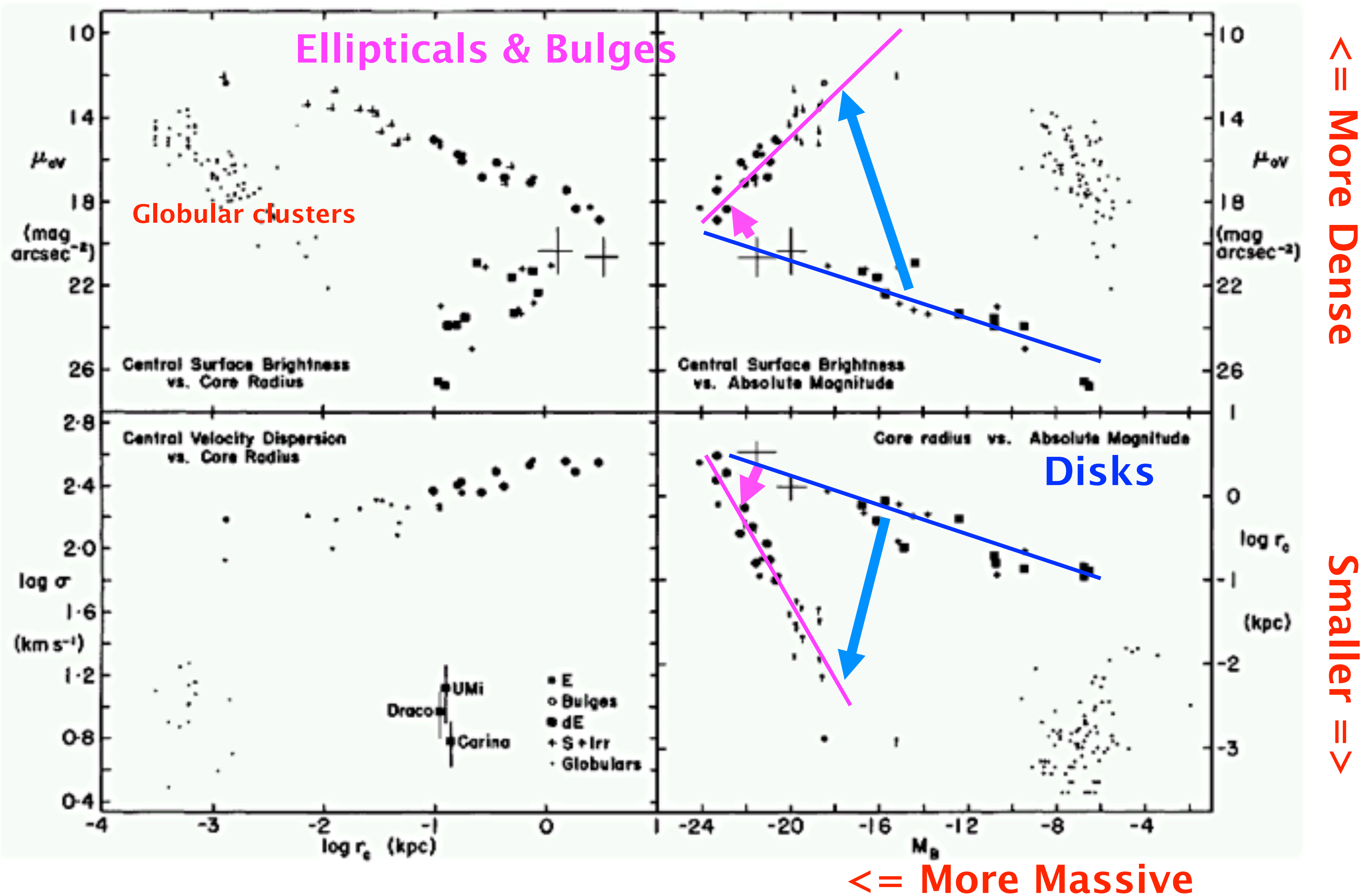
Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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...

(1) many low-mass ellipticals formed at $z<1$

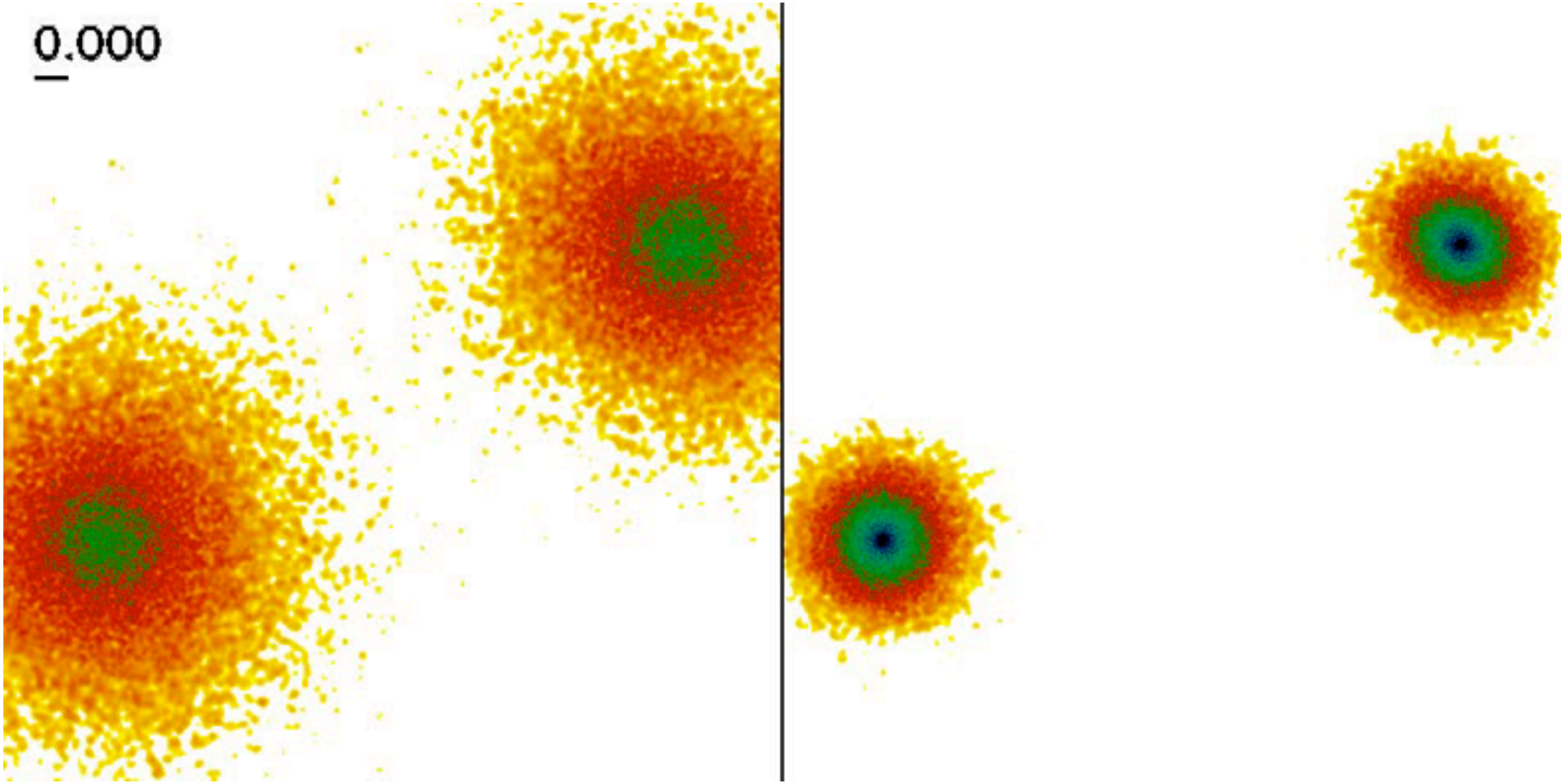
(2) observed evolution is weak

Solution 2: Gas dissipation

The Problem

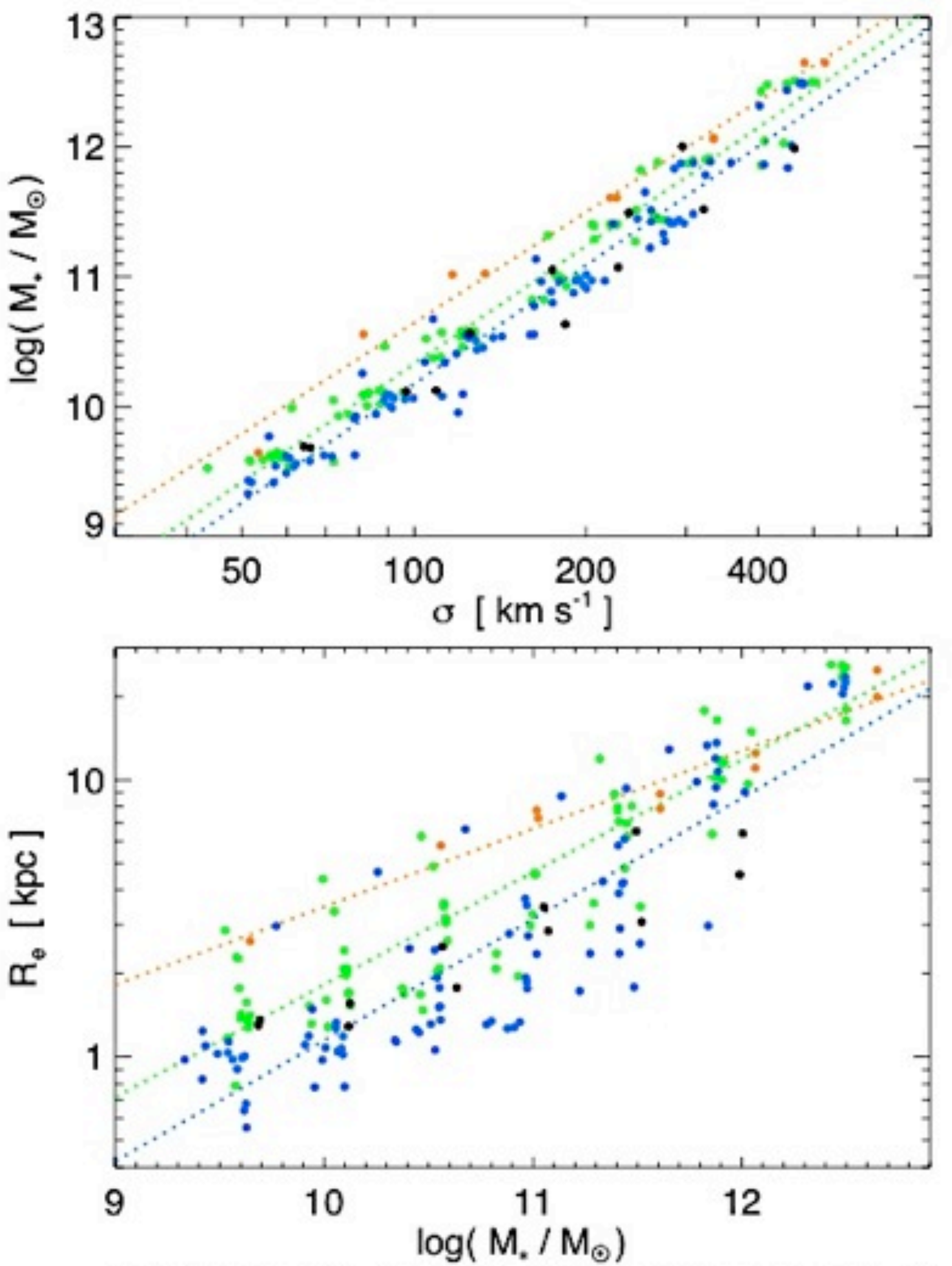
FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- 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

fgas = 0.1

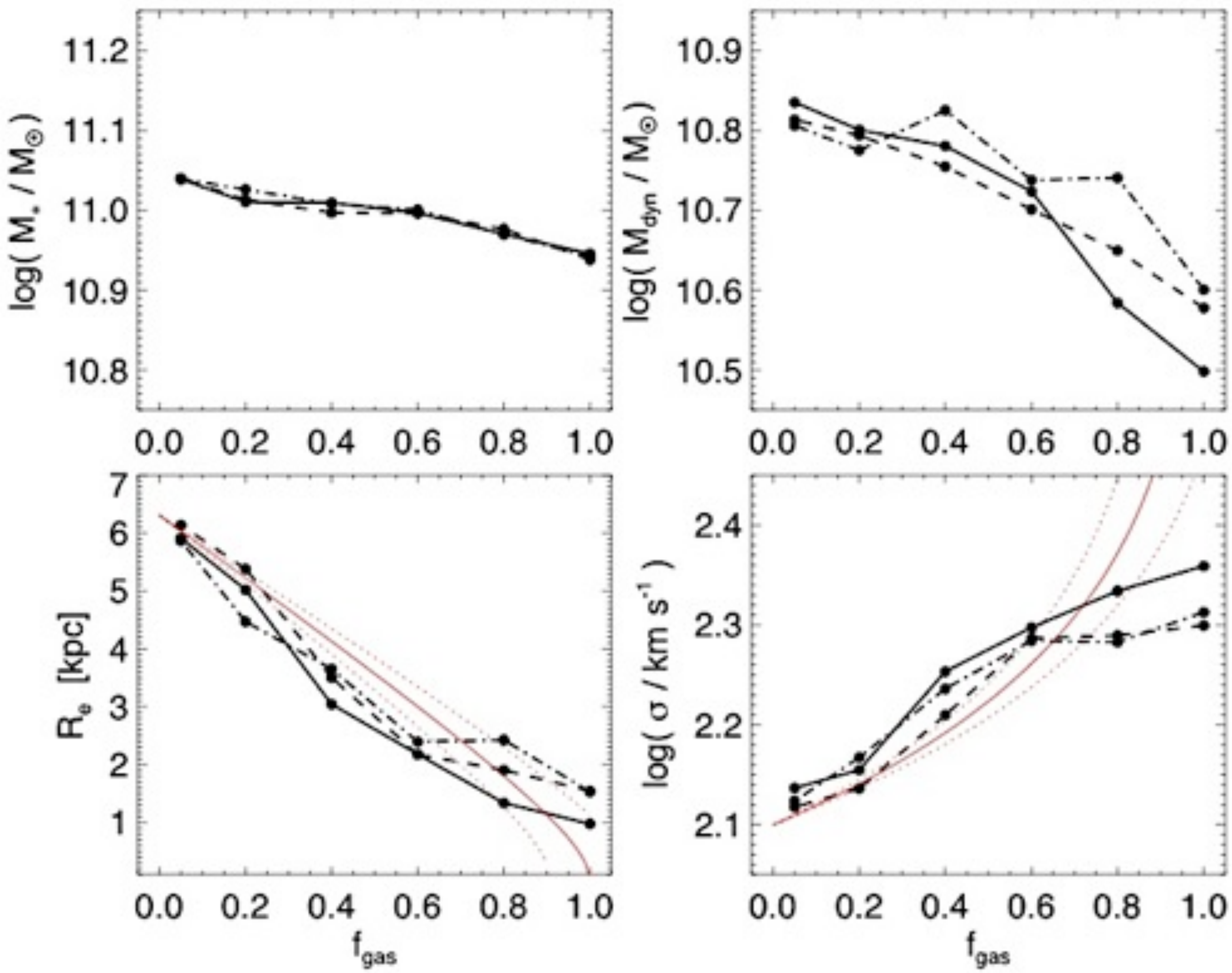
fgas = 0.4

fgas = 0.8

PFH, Hernquist, Cox et al., 2007

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

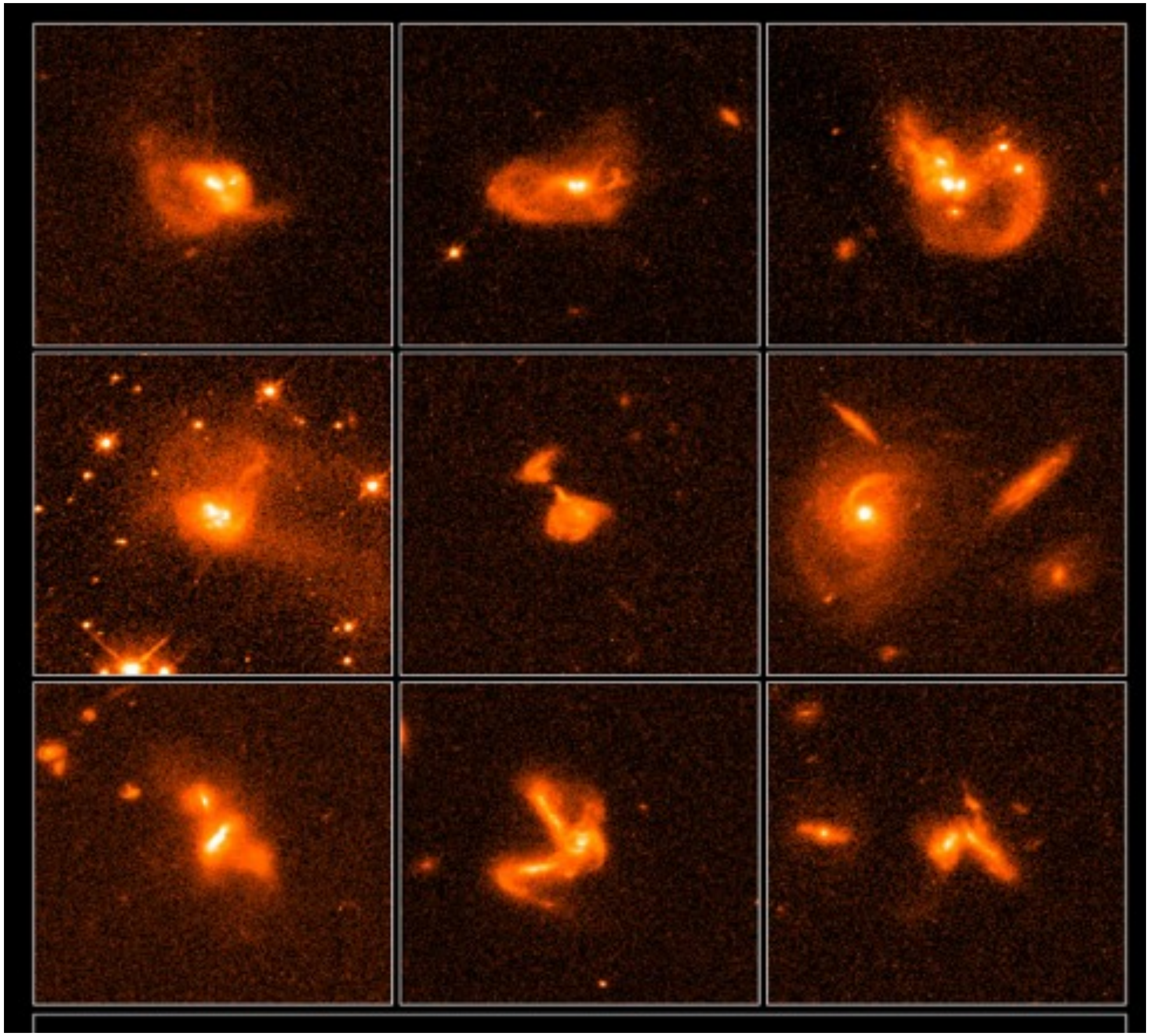
PFH, Hernquist, Cox et al., 2007

The Solution: Gas Dissipation?

Look at late-stage merger remnants

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

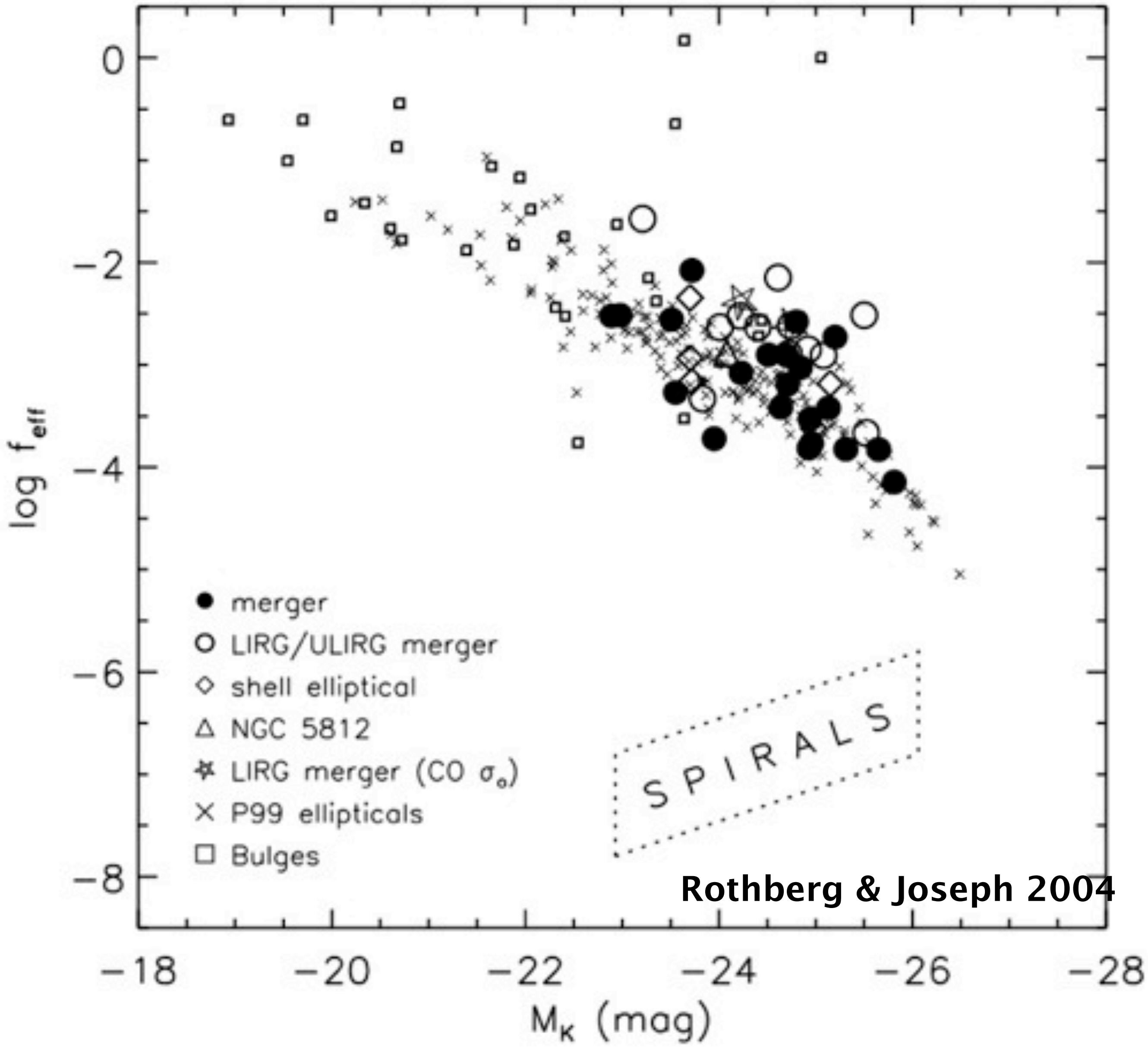
Extremely compact (<kpc scales)



Borne et al., 2000

The Solution: Gas Dissipation?

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

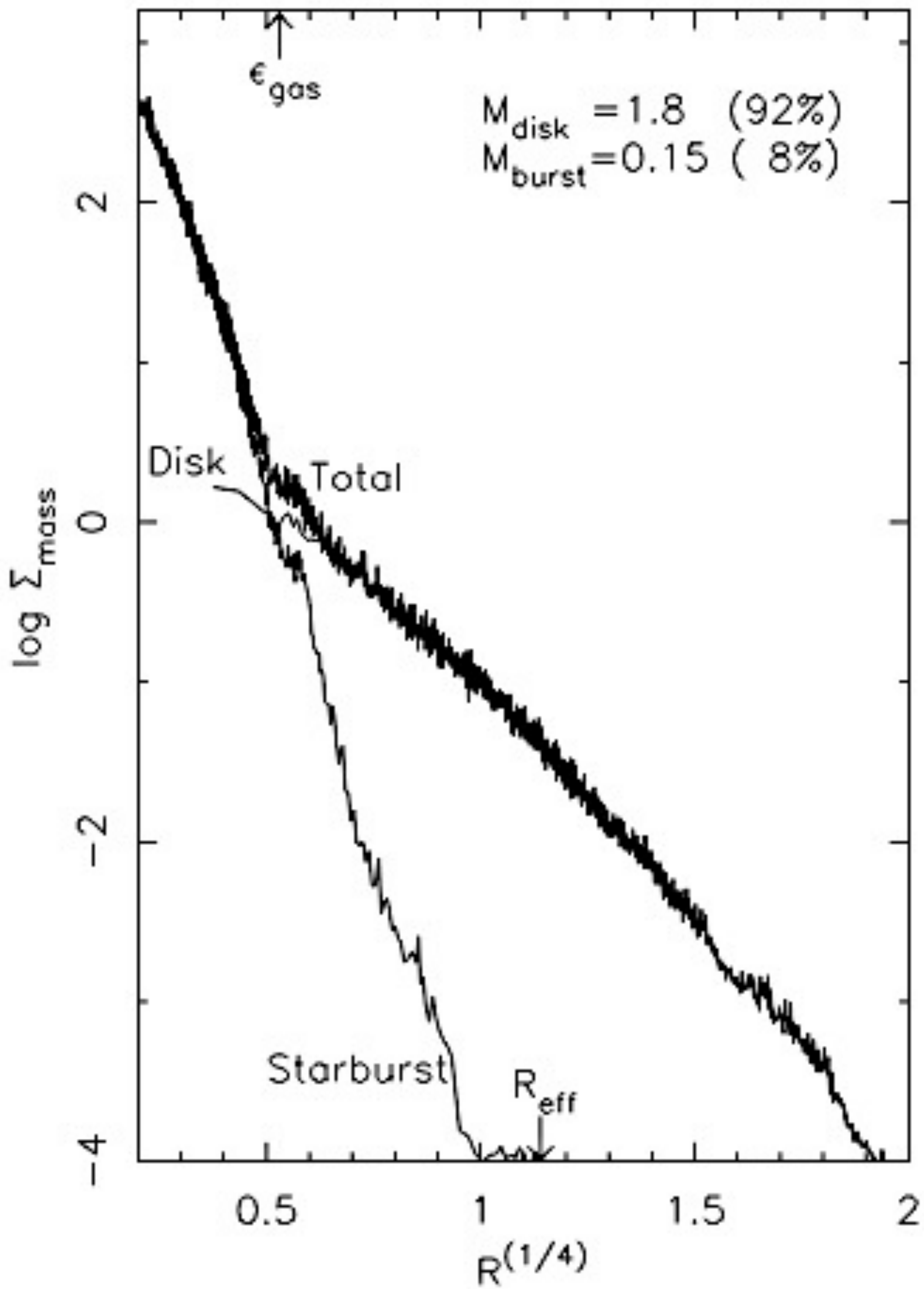


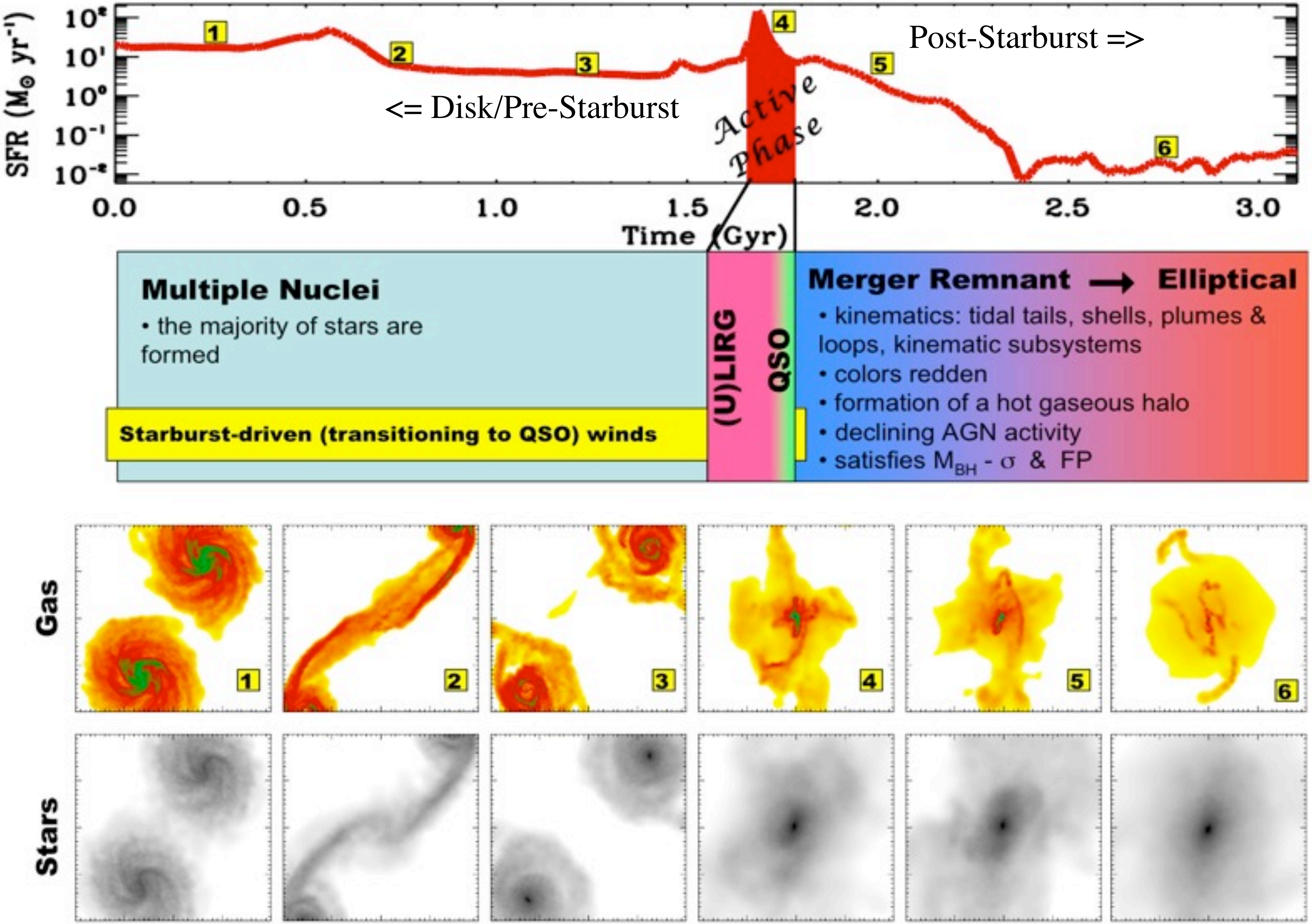
Starburst Stars in Simulations Leave an "Imprint" on the Profile

Mihos & Hernquist 1994

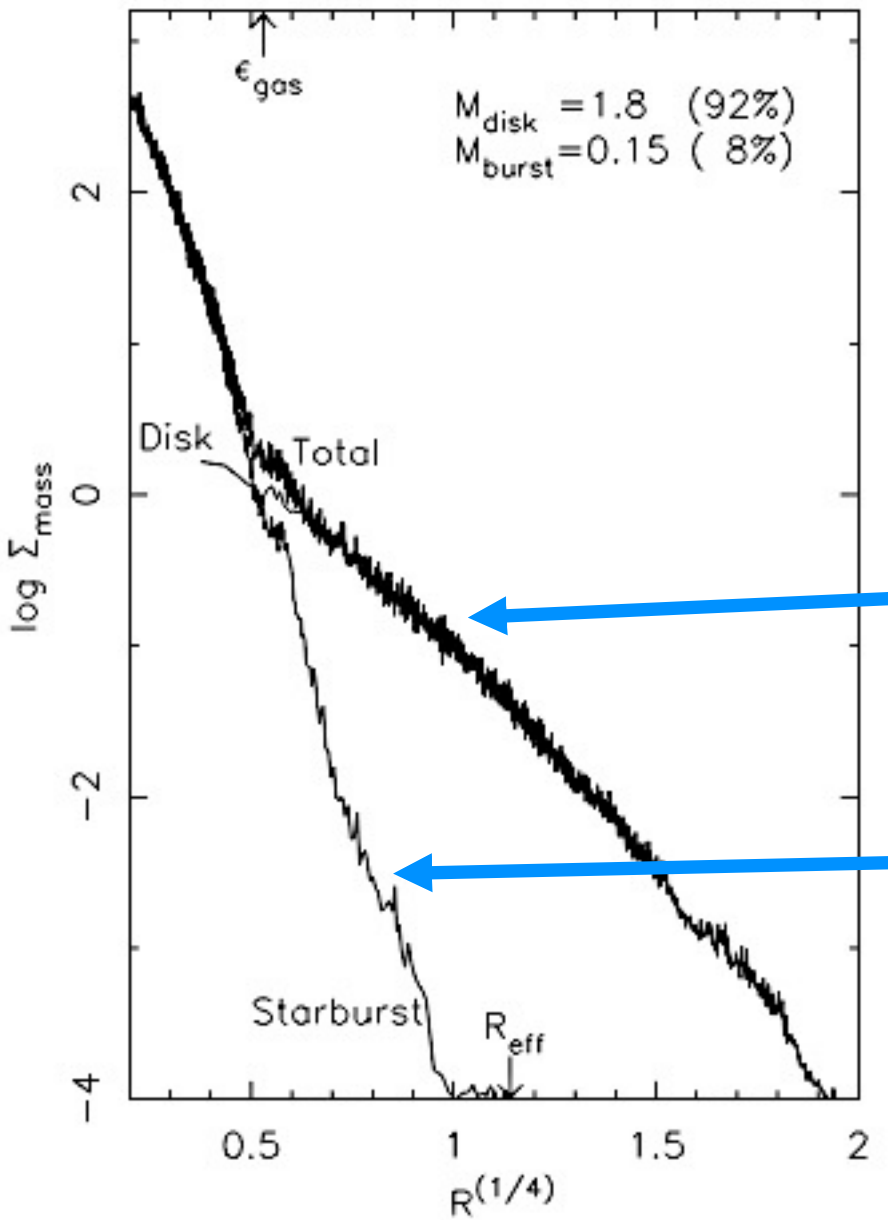
Separate stars into 3 populations:

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




SFR ($M_\odot$ yr^{-1})
10^2
10^1
10^0
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
1
2
3
4
5
6
<= Disk/Pre-Starburst
Post-Starburst =>
Active Phase
Multiple Nuclei
• the majority of stars are formed
Starburst-driven (transitioning to QSO) winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

Starburst Stars in Simulations Leave an "Imprint" on the Profile



Mihos & Hernquist 1994:

Merger remnant elliptical profiles should be fundamentally two-component:

Pre-starburst/Disk (dissipationless, violently relaxed)

Starburst (dissipational, no strong violent relaxation)

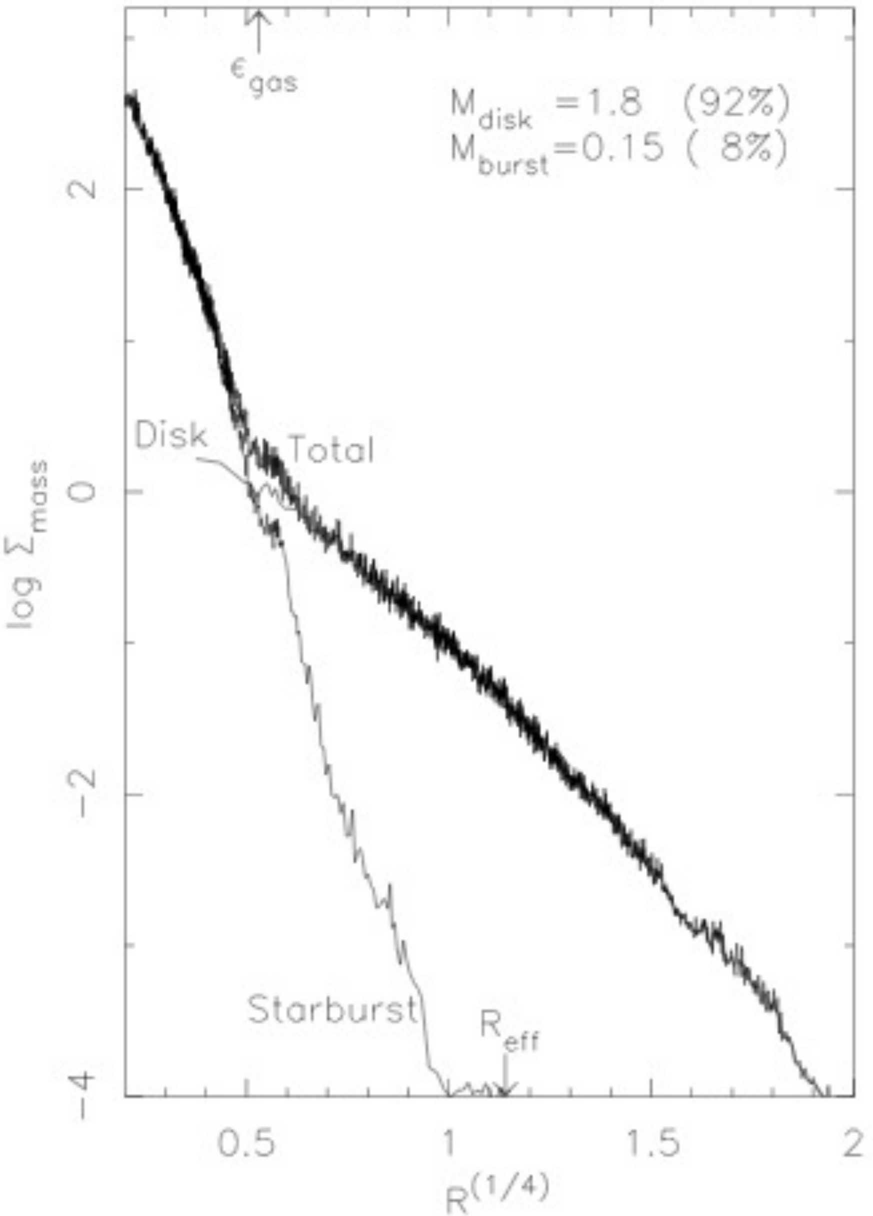
Not observed at the time:

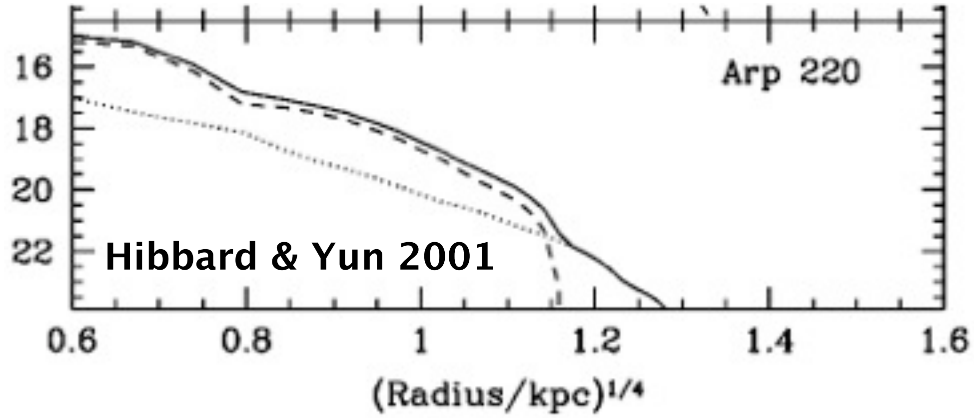
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

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

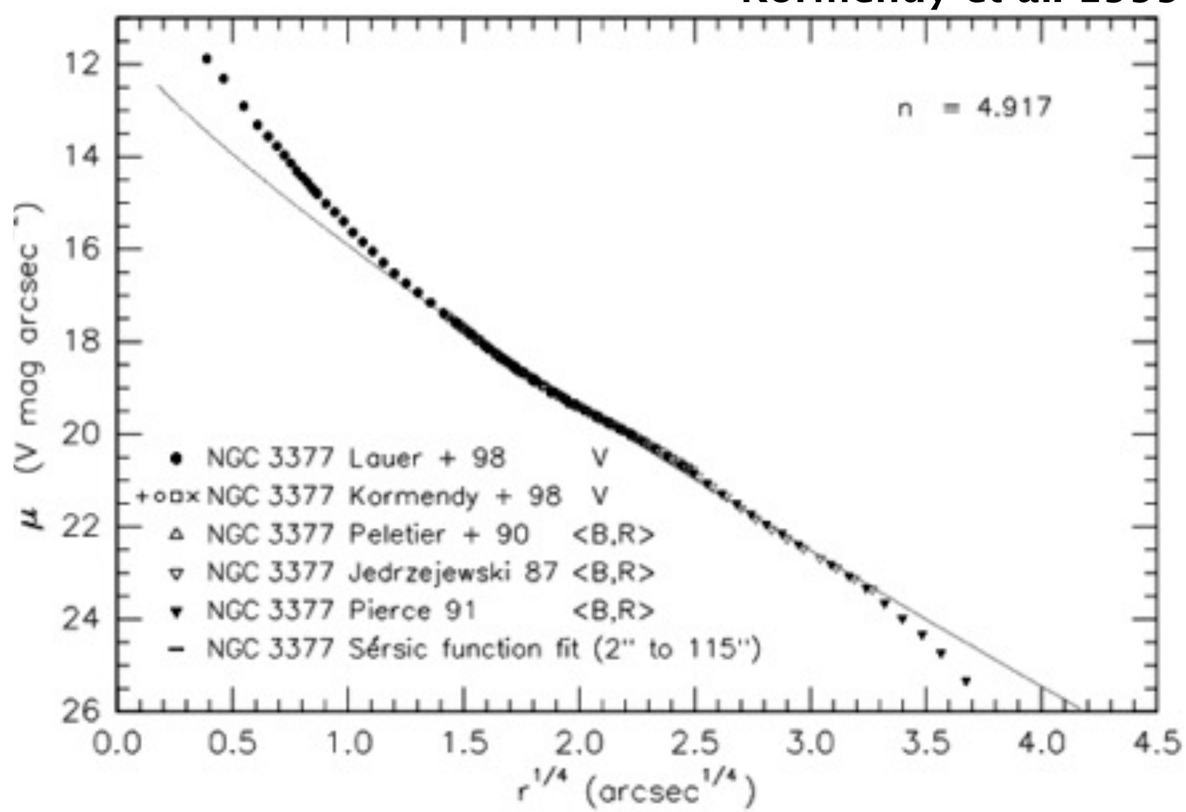
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...





Kormendy et al. 1999

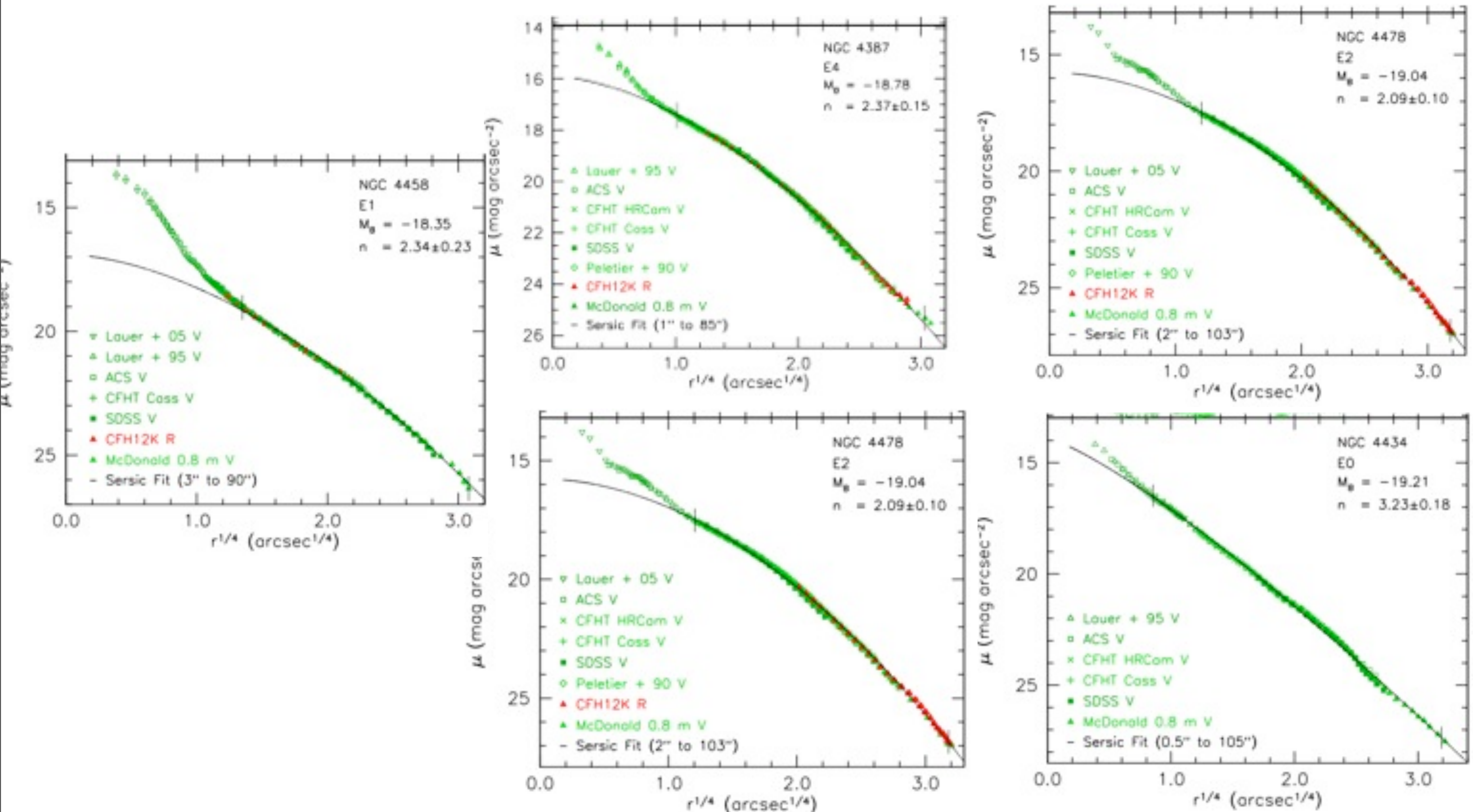


Starburst Stars in Simulations Leave an "Imprint" on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

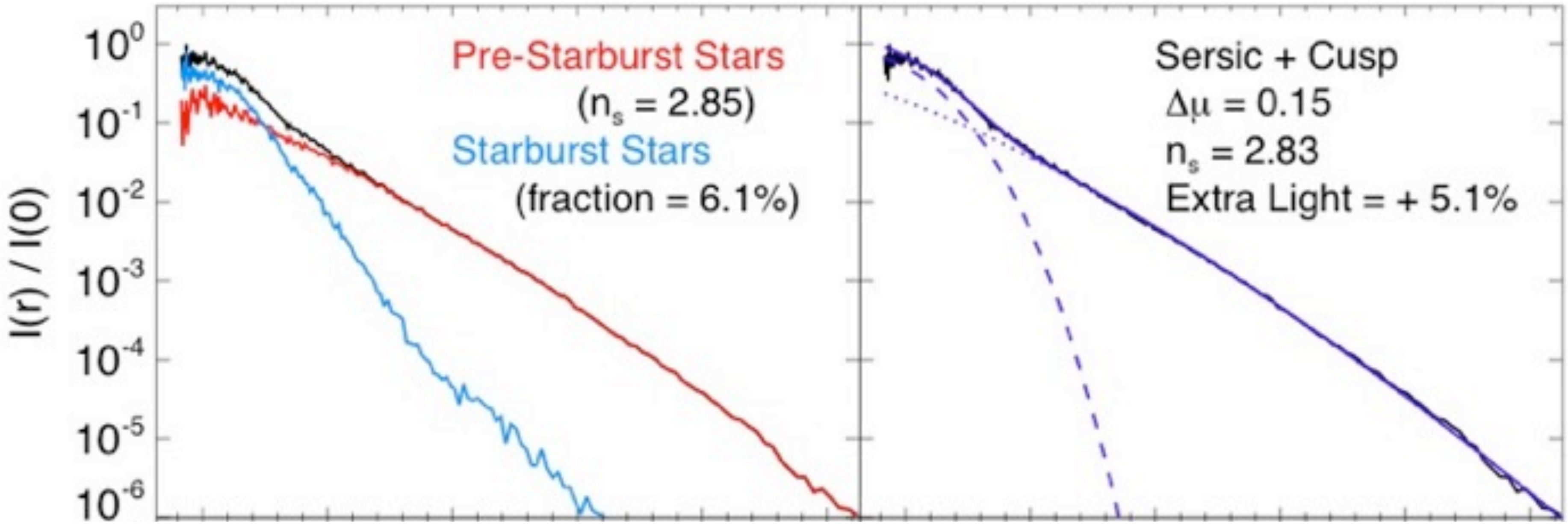
- Since then...

Kormendy et al. 2008(?)



"Normal and low-luminosity ellipticals... in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles."

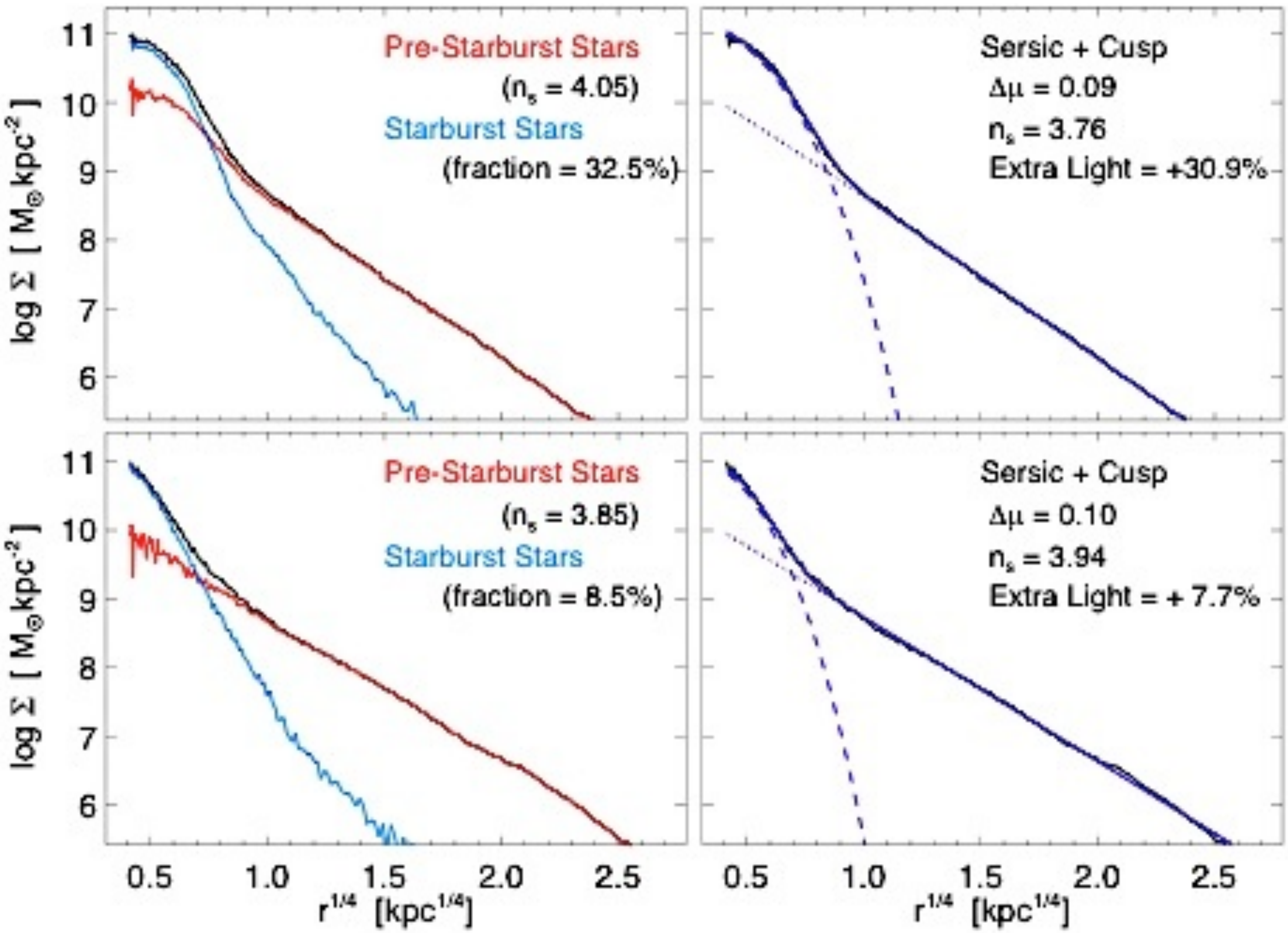
Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



PFH et al. 2008

Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

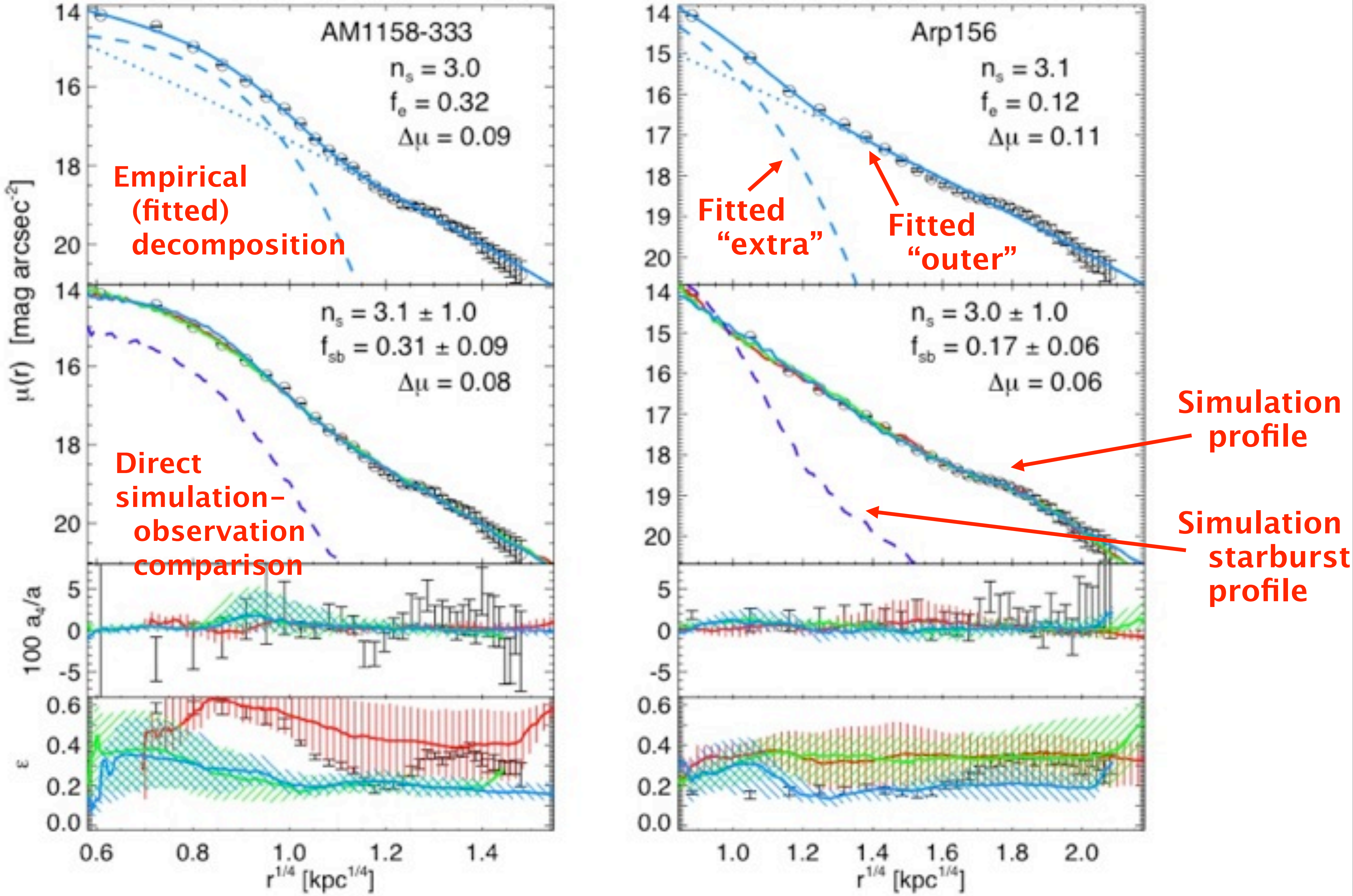


Application: Merger Remnants

RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

- Apply this to a well-studied sample of local merger remnants:

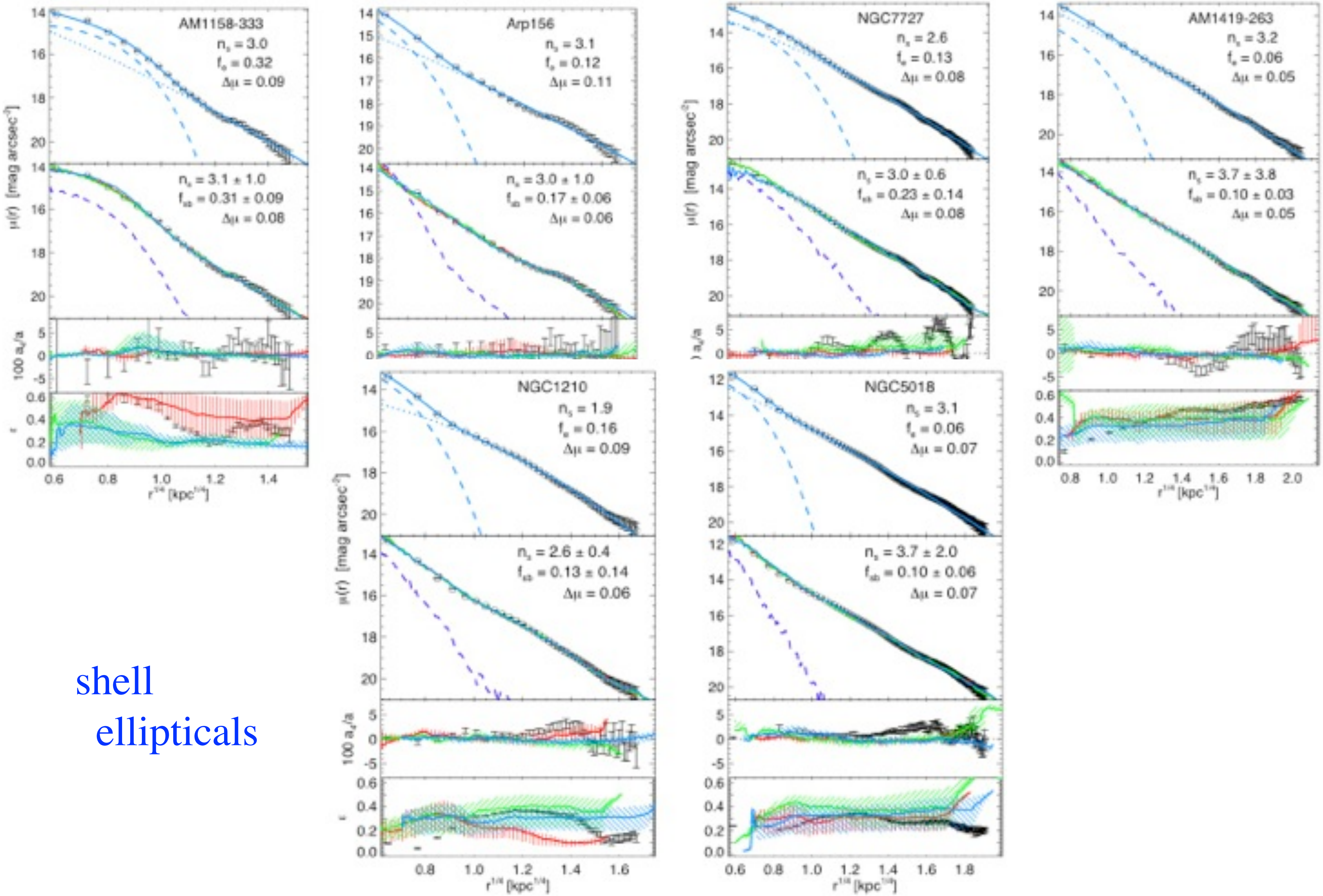


Application: Merger Remnants

RECOVERING THE ROLE OF GAS

bright, young mergers

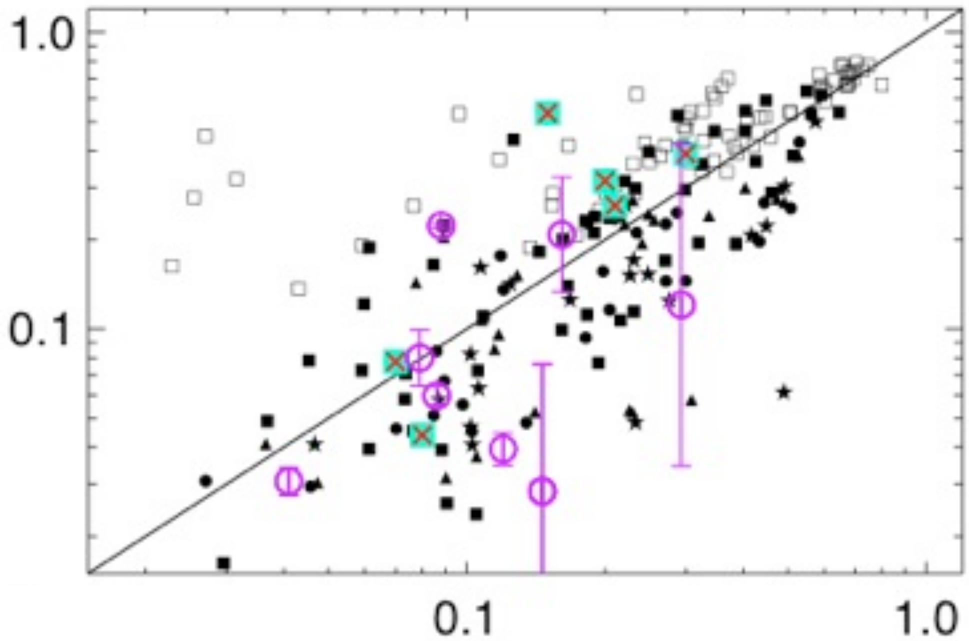
low-luminosity, relaxed mergers



shell
ellipticals

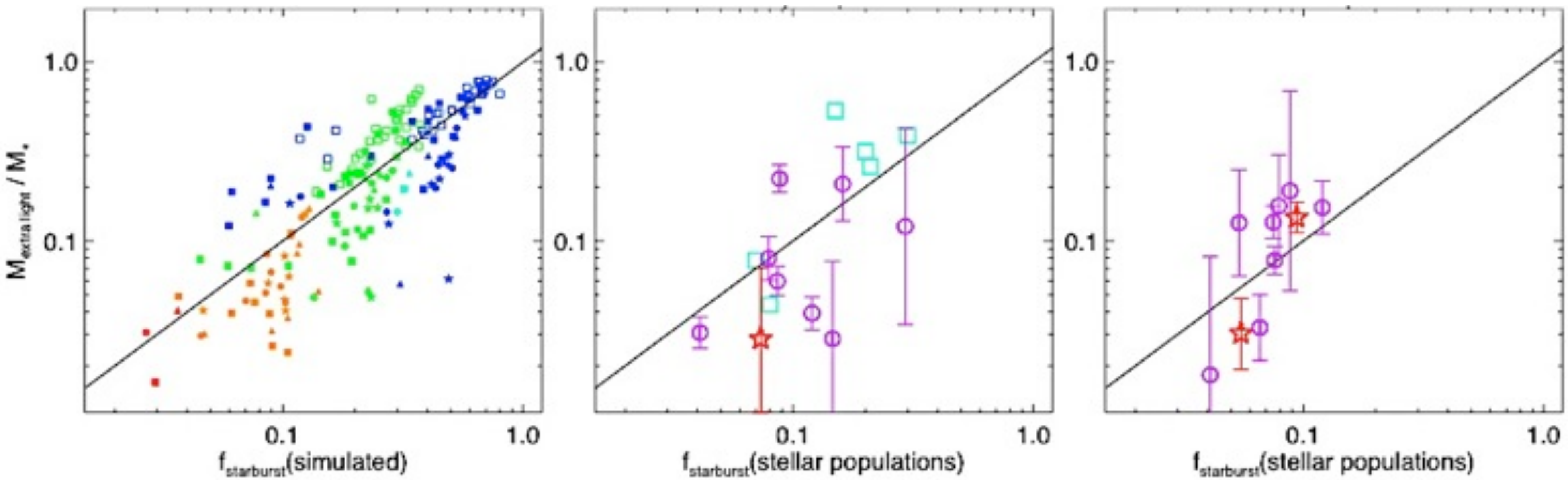
Application: Merger Remnants

RECOVERING THE ROLE OF GAS



f(starburst)

Compare:
- Parametric fitting
- Direct simulation fitting
- Stellar population models

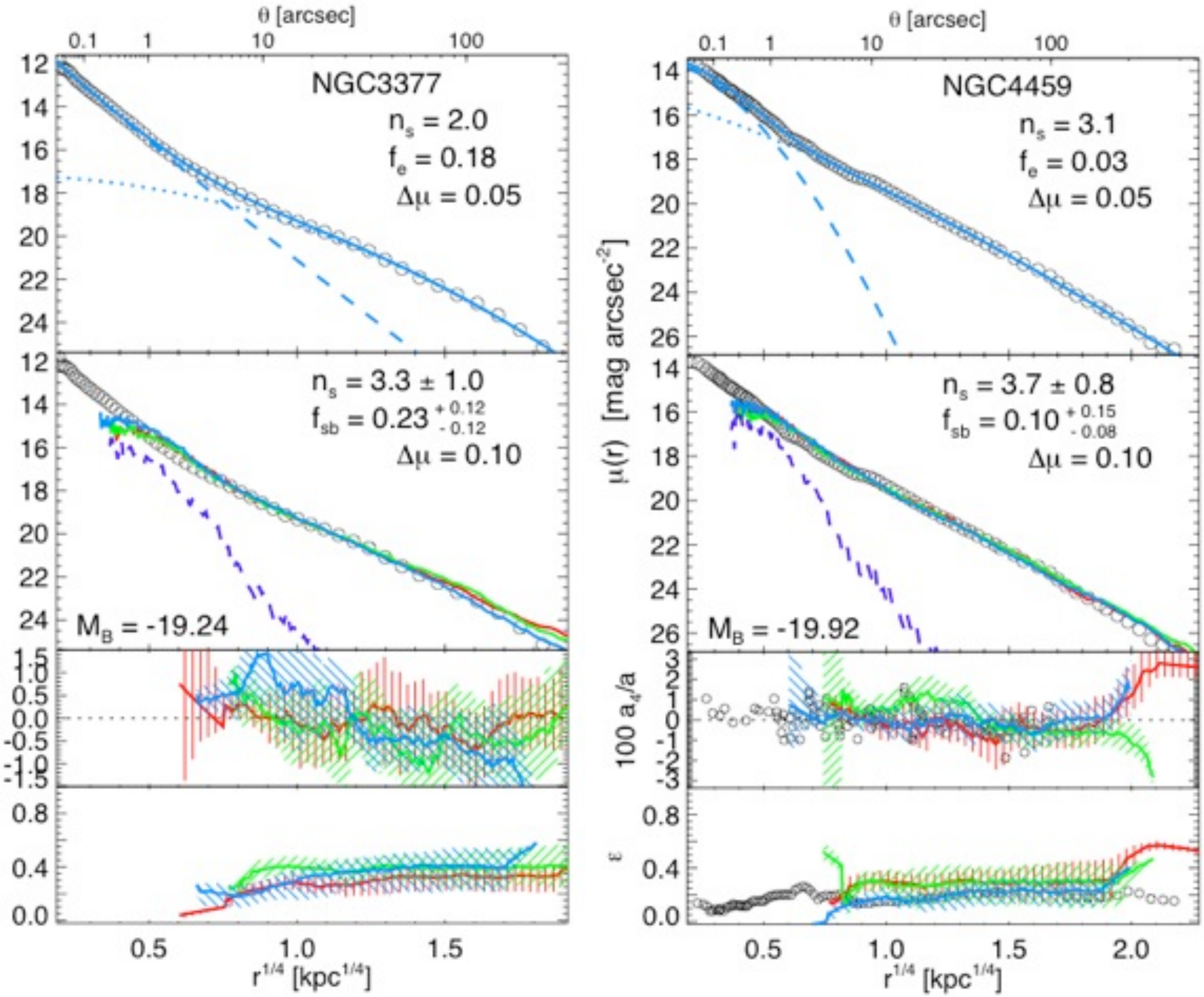


Application: "Cusp" Ellipticals

RECOVERING THE ROLE OF GAS

PFH & Kormendy et al. 2008

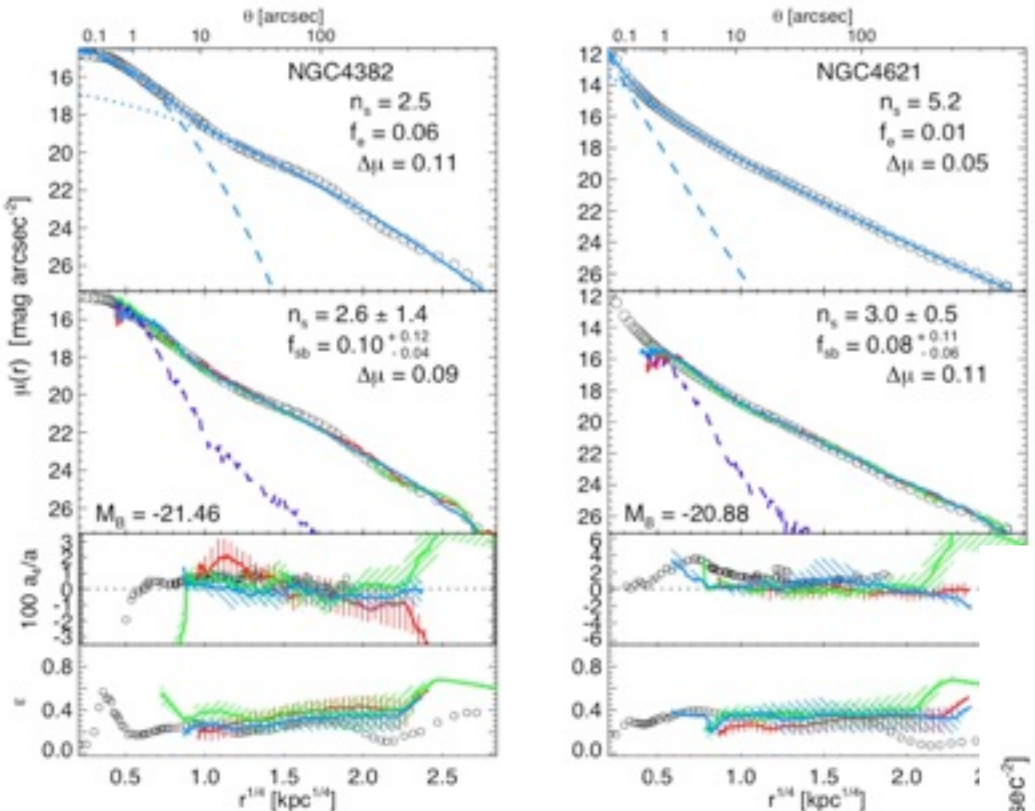
- Extend this to "cusp" ellipticals:



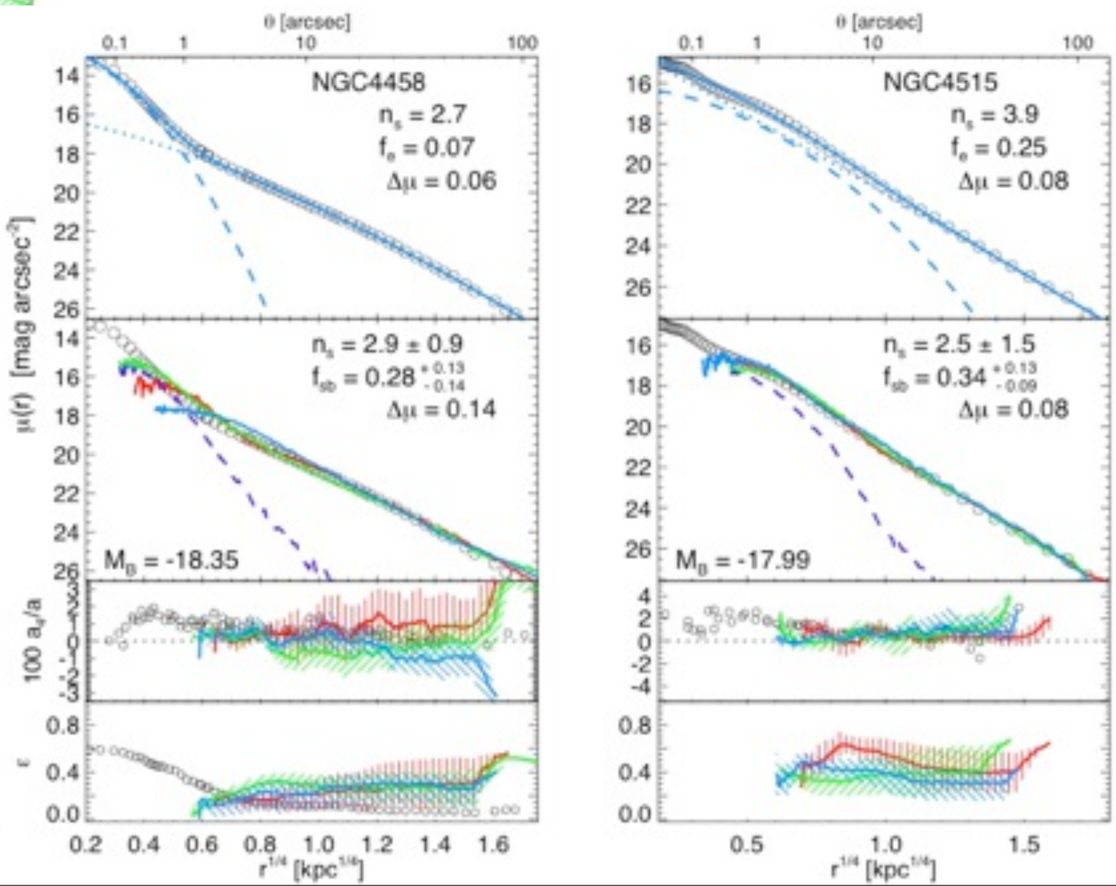
- Made possible by incredibly accuracy & dynamic range of data from KFCB 2008

Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS



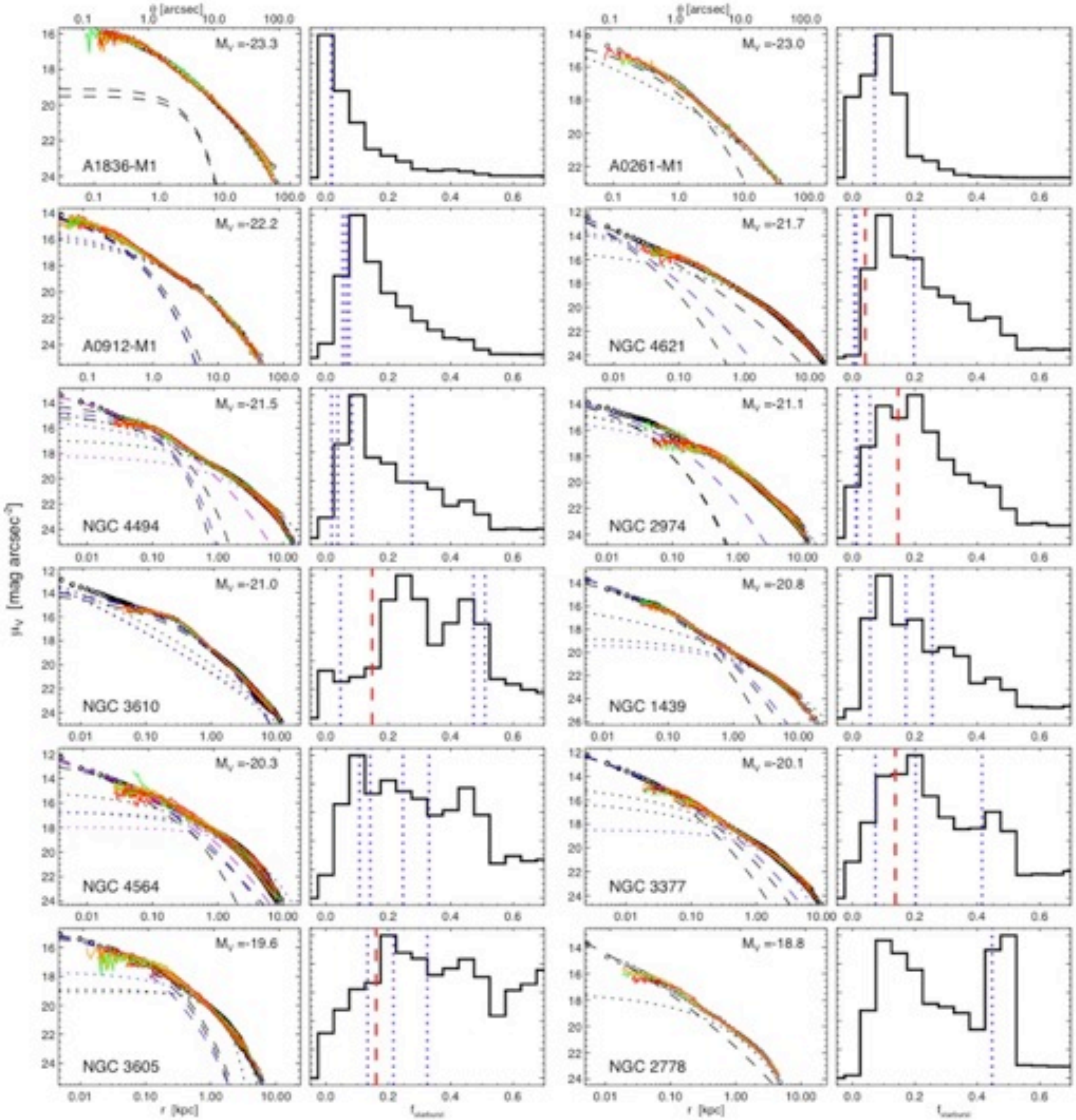
L > L* ellipticals



L < 0.1 L* ellipticals

Application

RECOVERING THE ROLE OF GAS



Compare:

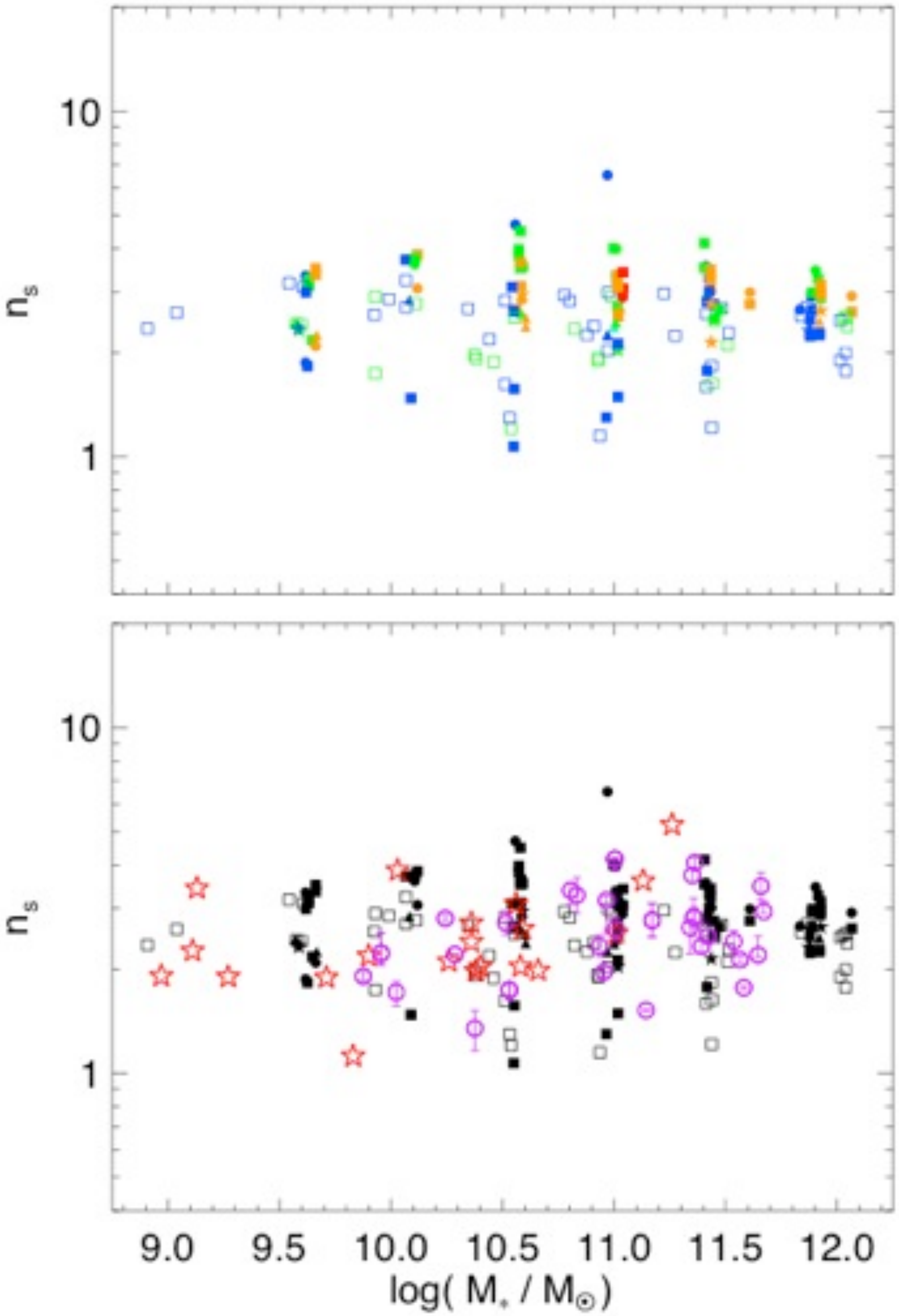
- Parametric fitting
- Direct simulation fitting
- Stellar population models

Data from Lauer et al. & others

Application: "Cusp" Ellipticals

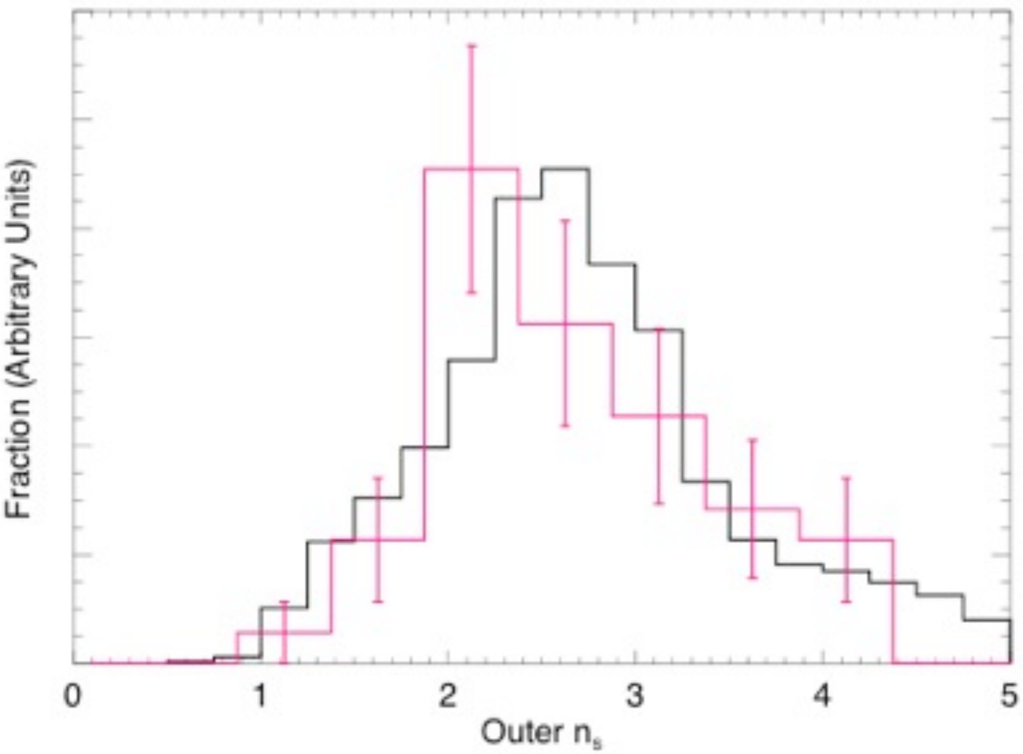
RECOVERING THE ROLE OF GAS

PFH & Kormendy et al. 2008



Inner component = extra light

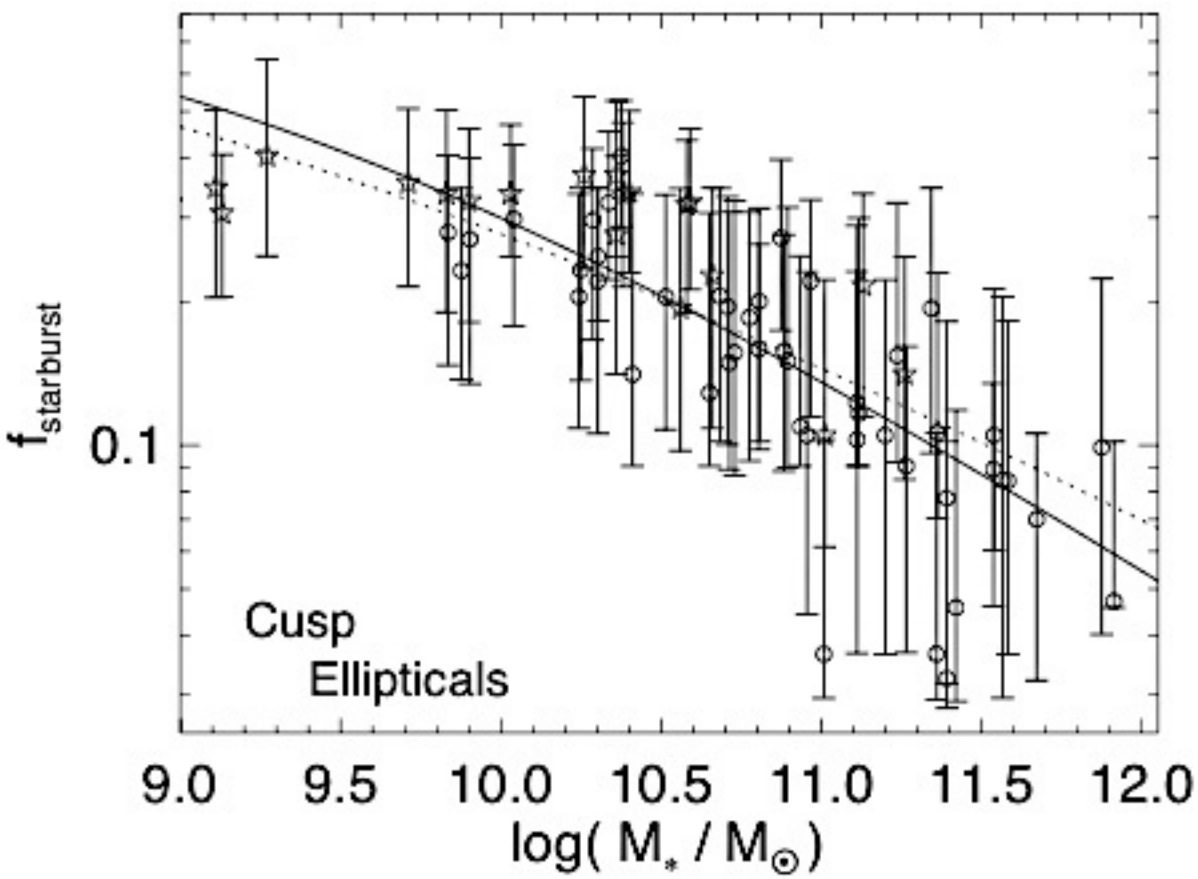
OUTER component is Sersic-like:
sersic index is independent of
mass, radius, etc.
--- similar formation histories:
small # mergers



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

PFH & Kormendy et al. 2008



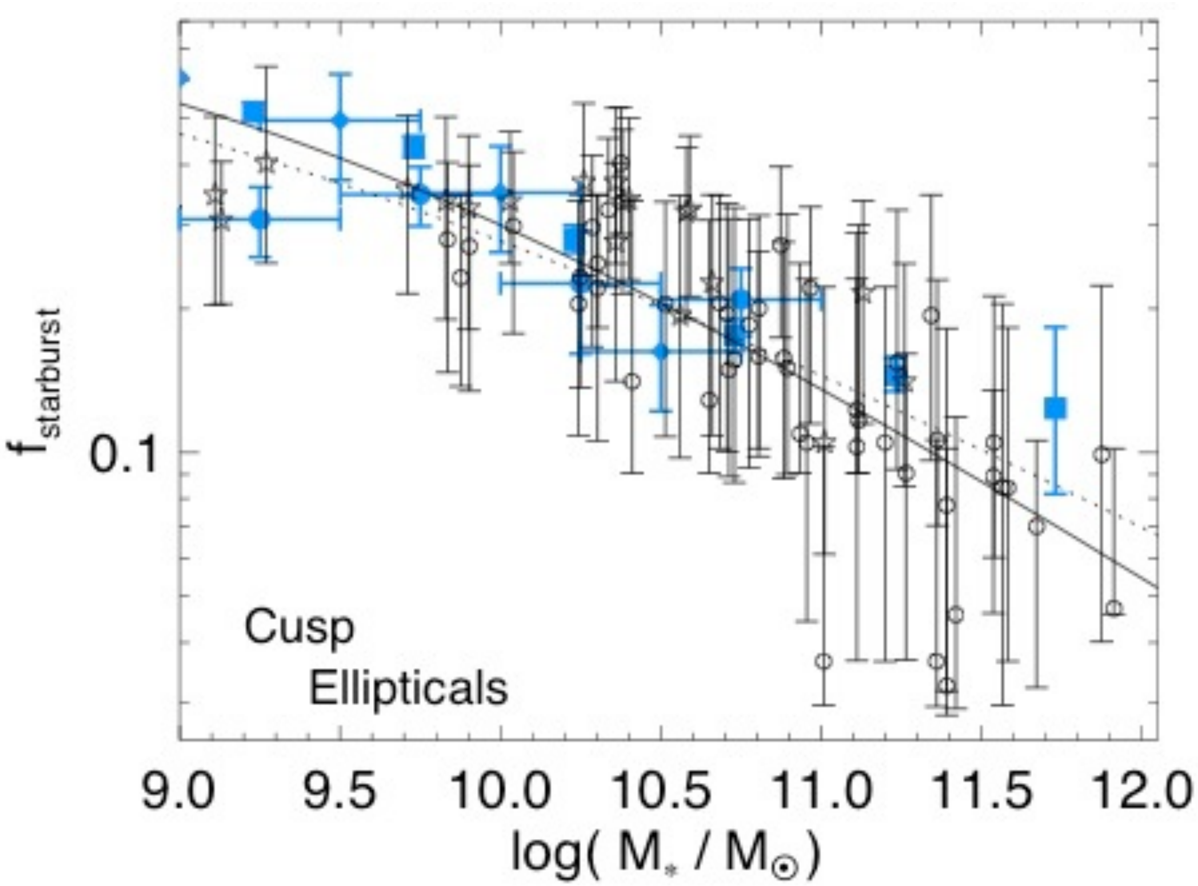
- Can match all (cusp) ellipticals with simple gas-rich merger remnants
- NEED systematically higher gas content in the progenitors at lower masses to explain the observed profile shapes

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

PFH & Kormendy et al. 2008

- 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 n



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

- Can match all (cusp) ellipticals with simple gas-rich merger remnants
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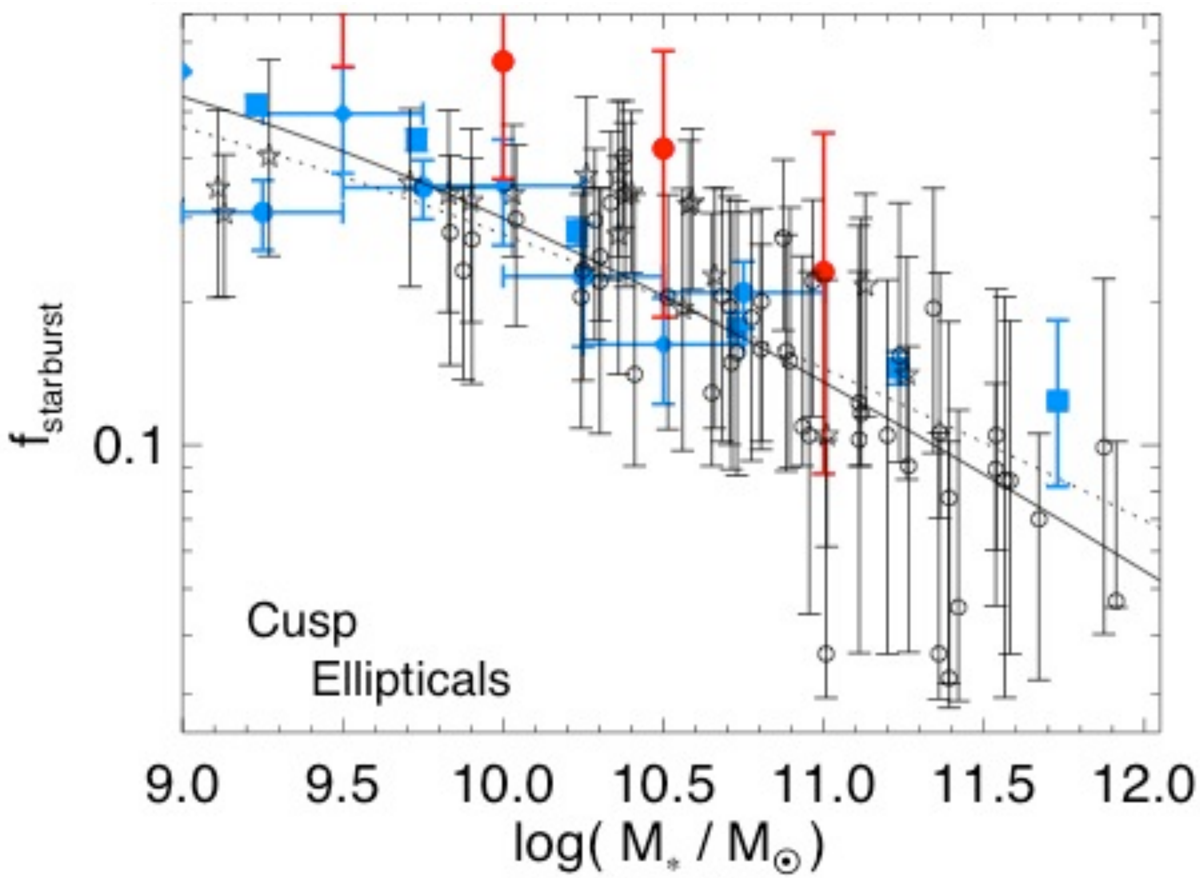
PFH & Kormendy et al. 2008

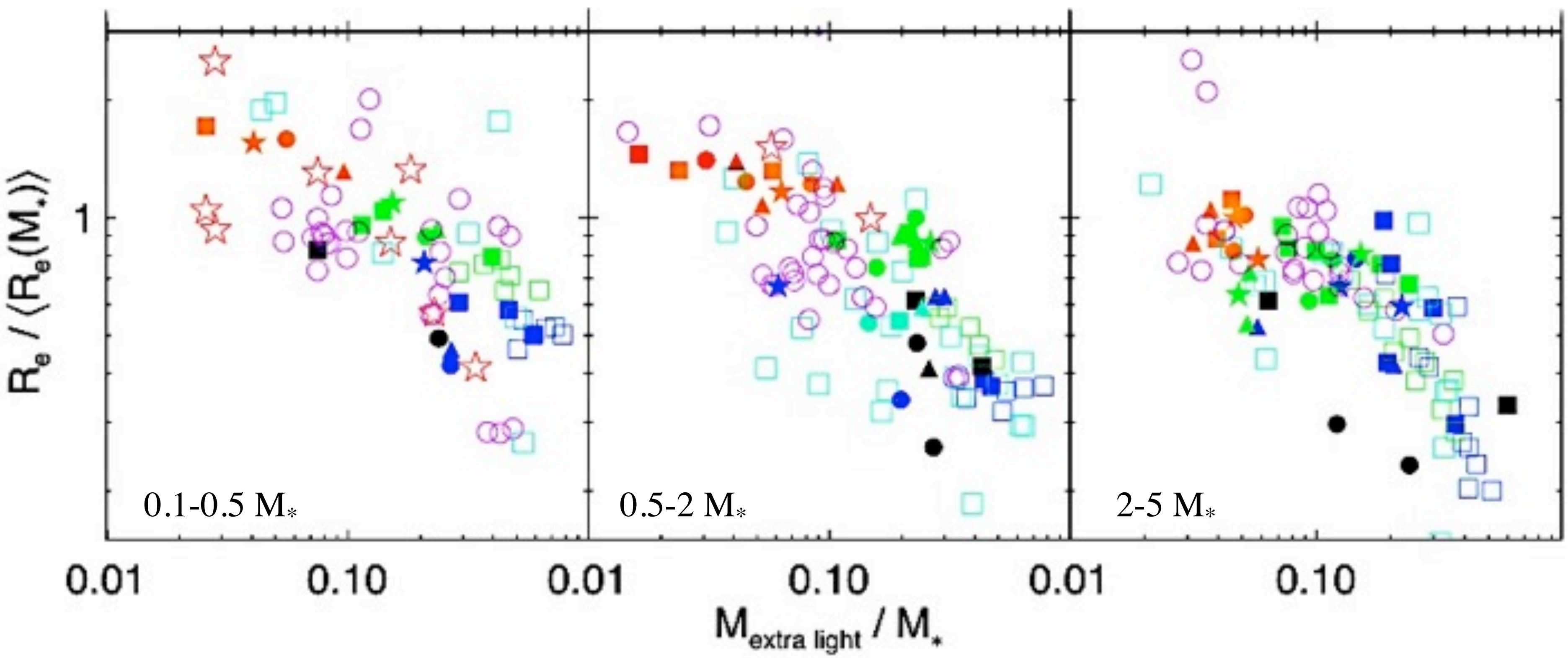


Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

- Systems with more "extra light" are smaller

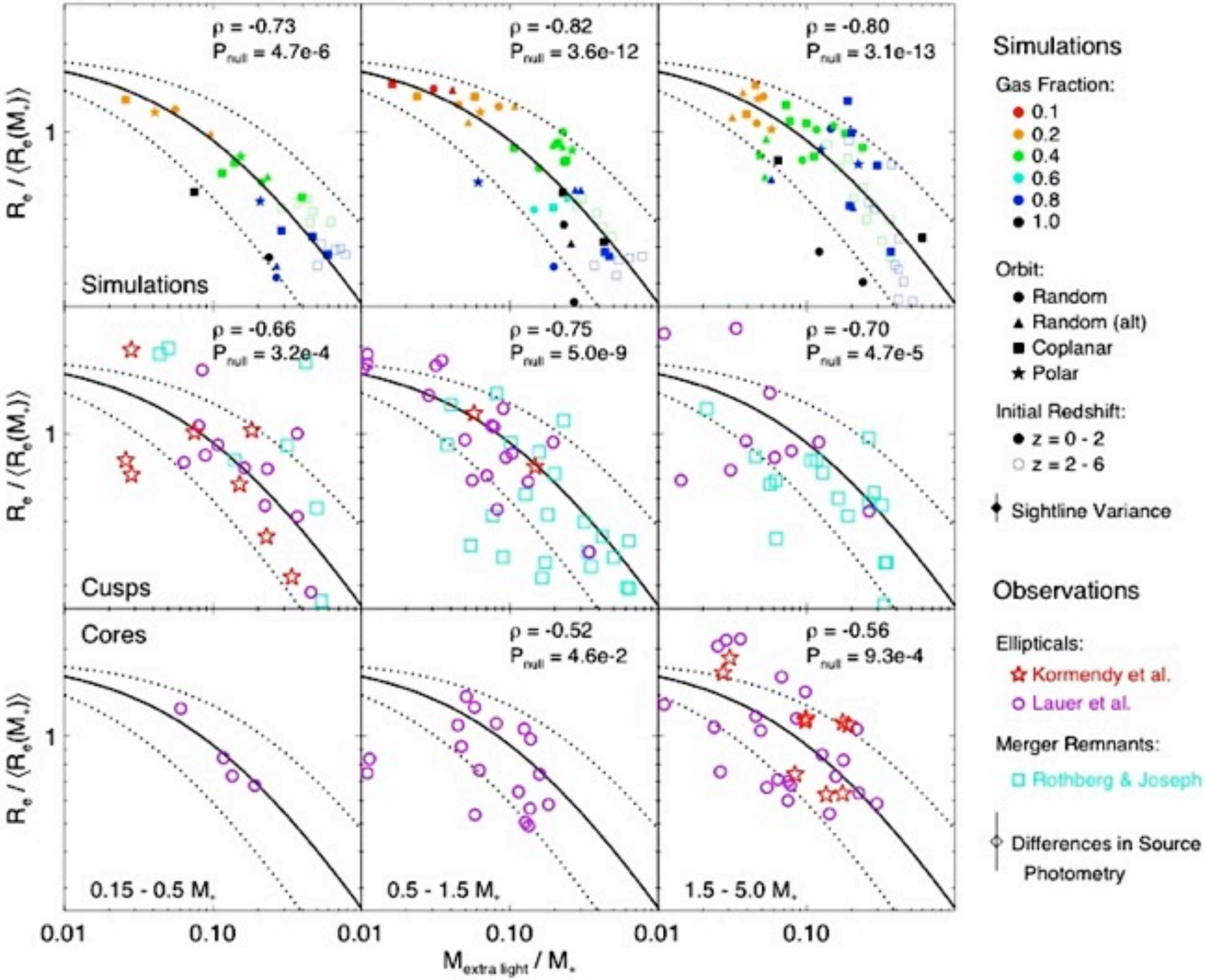
- Put more mass into a central dissipational component:
  moves R_e inward
  more of the mass inside R_e is this (totally baryon-dominated)
  central cusp



Structure in Elliptical Light Profiles

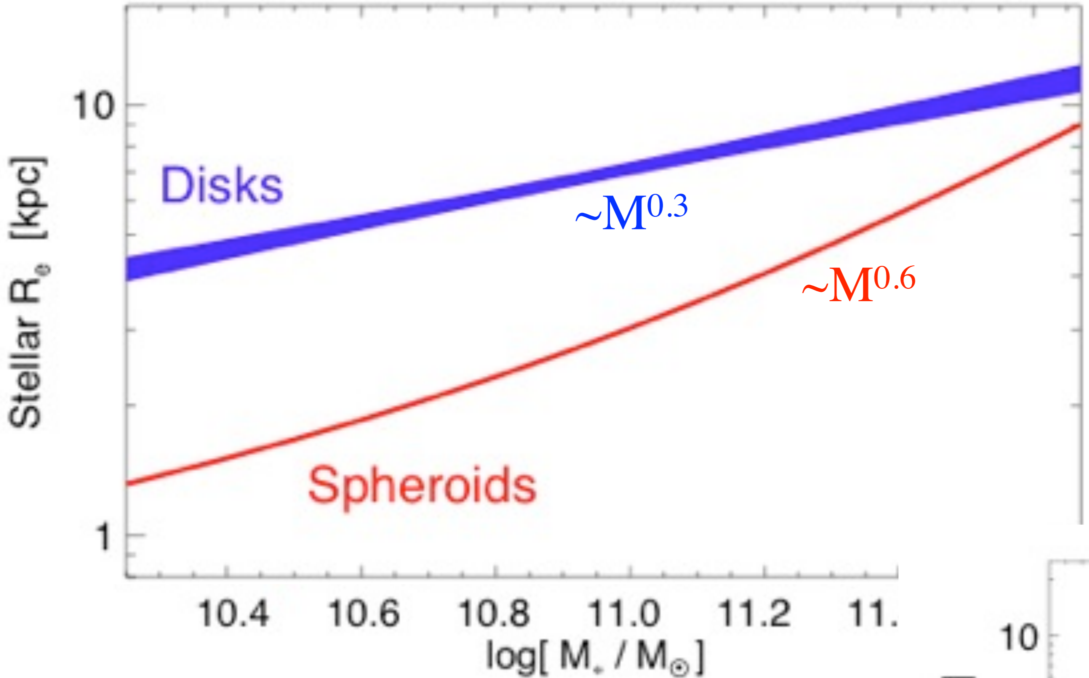
RECOVERING THE ROLE OF GAS

PFH & Kormendy et al. 2008

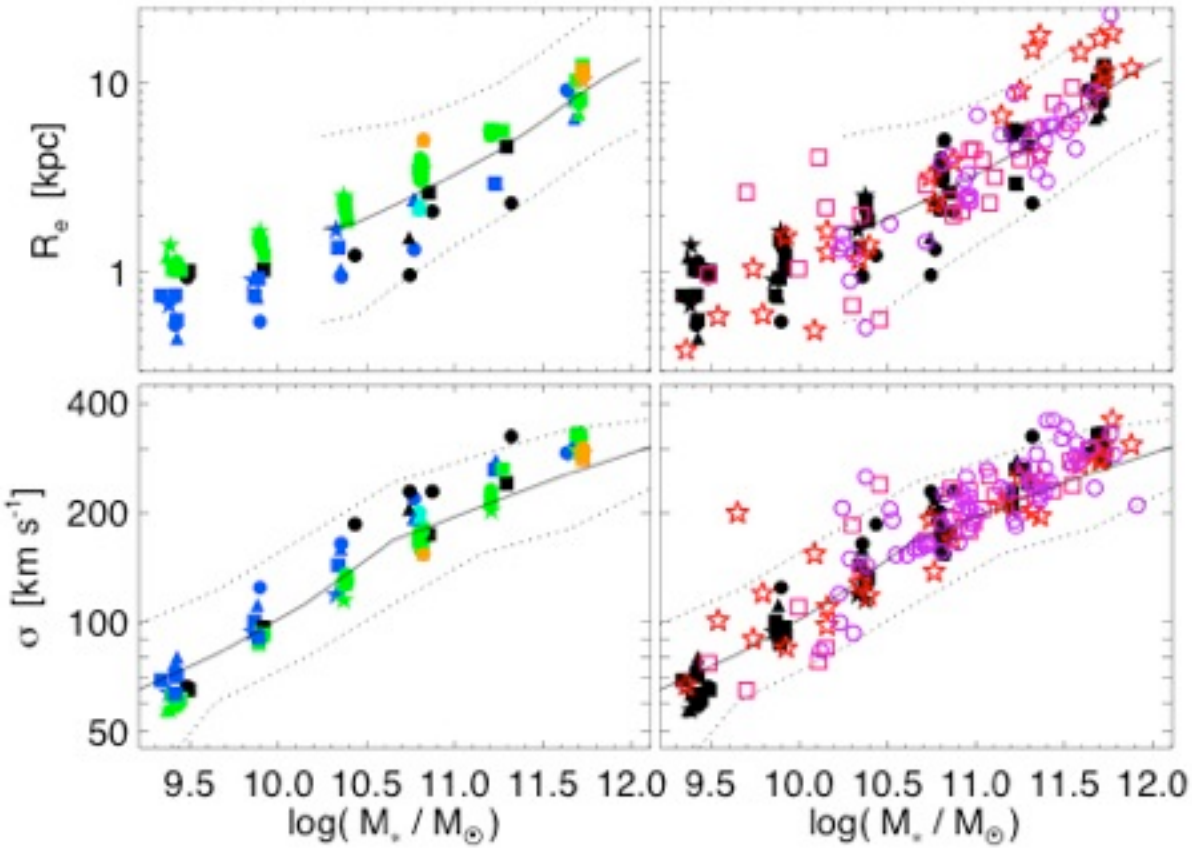


Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



- Recall, low-M ellipticals are more compact than disks of similar mass

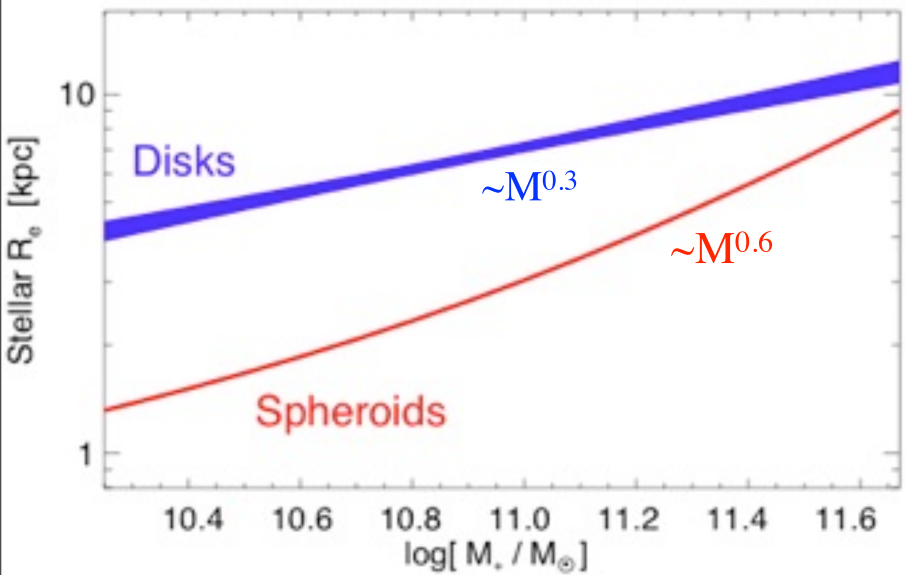


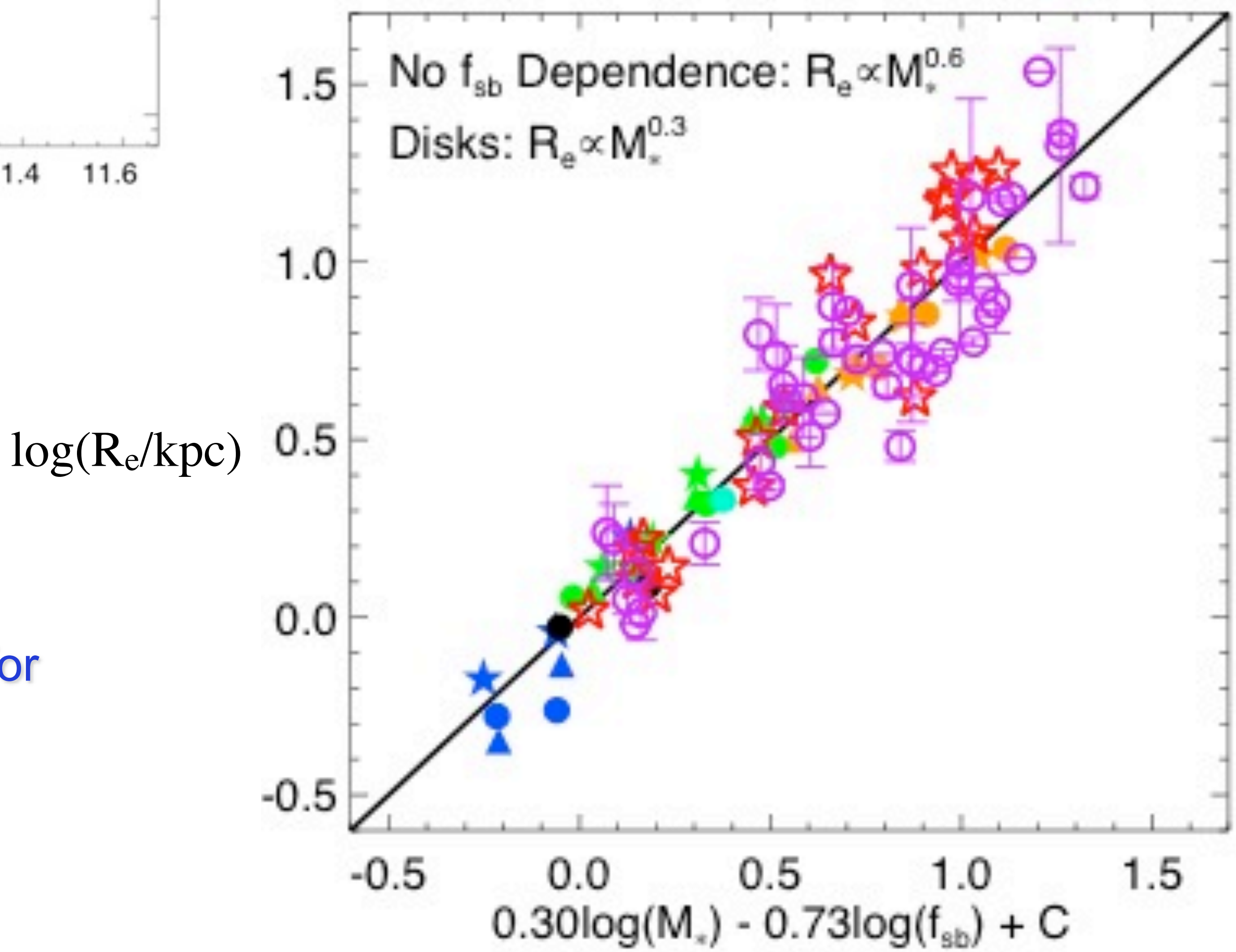
- Instead of <R>(M), fit R(M, $f_{dissipational}$)?

PFH et al. 2008b

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



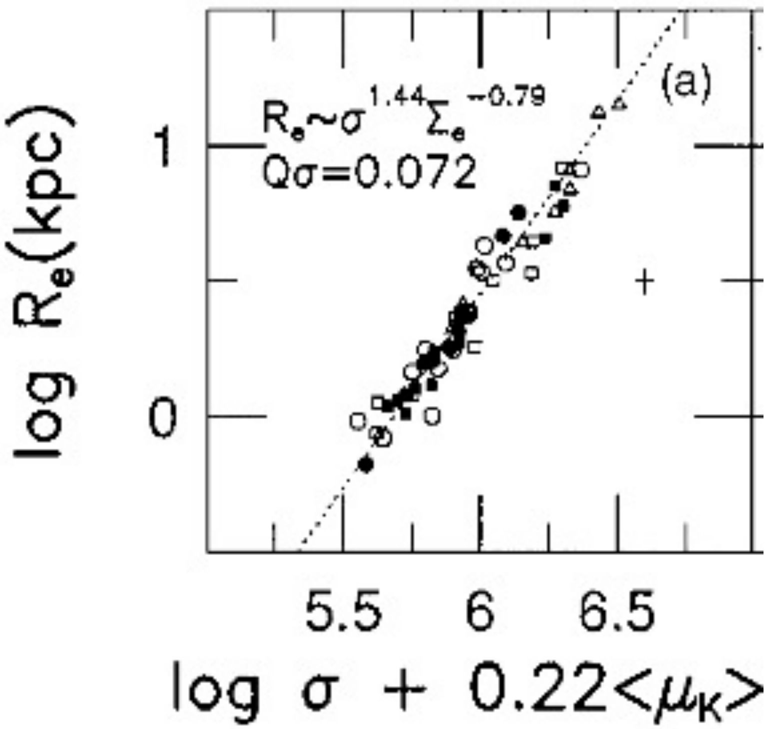


- Dissipation accounts for the difference

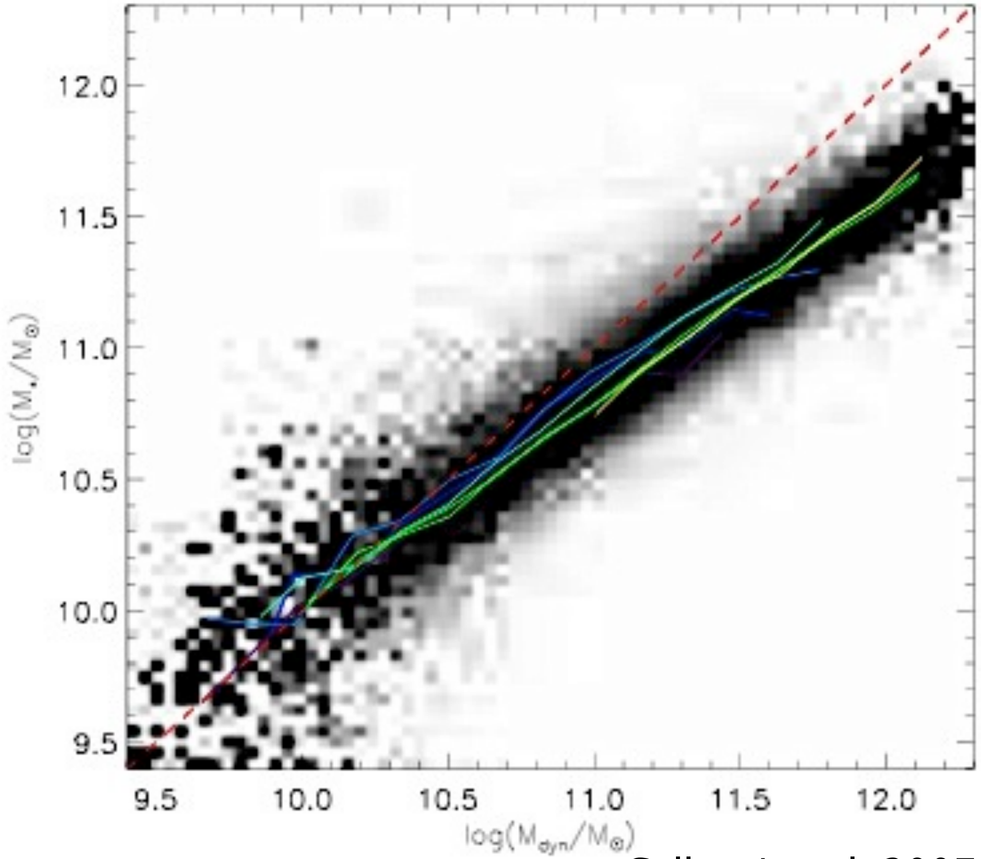
PFH et al. 2008b

Fundamental Plane Tilt

WHERE DOES IT COME FROM?



Pahre et al. 1998



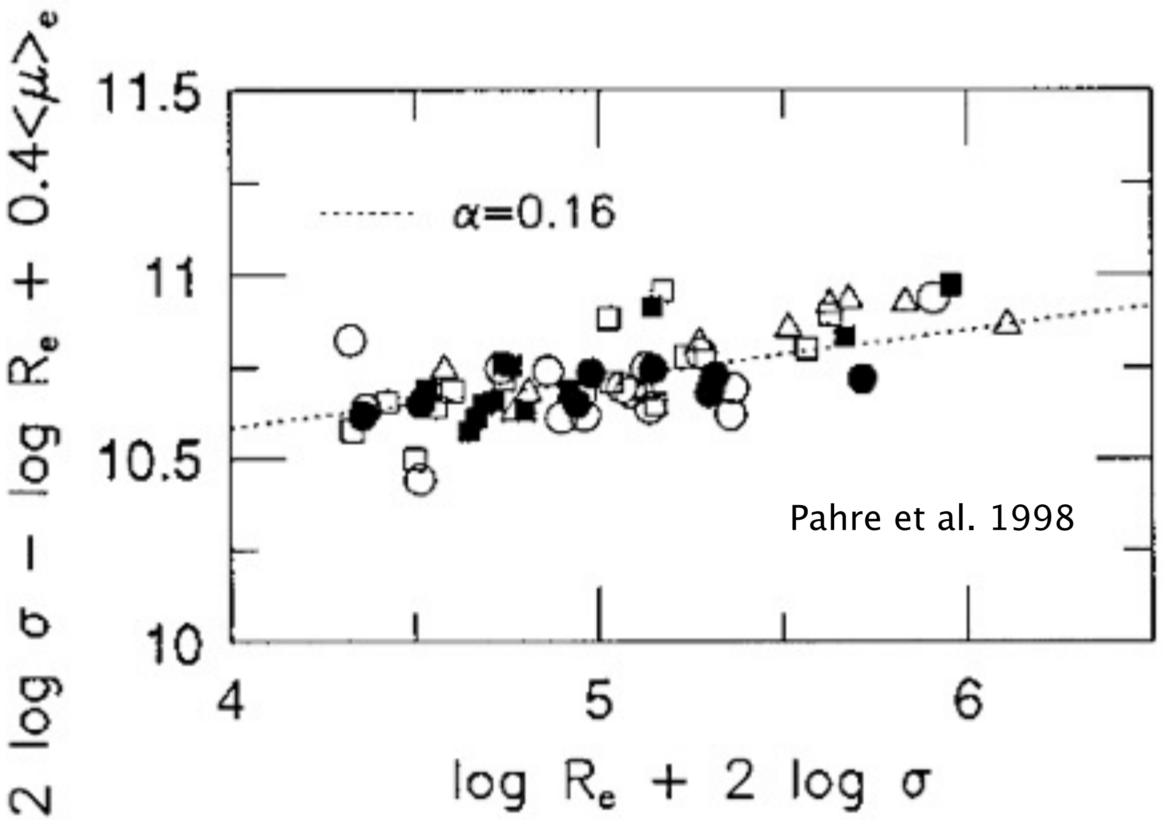
Gallazzi et al. 2007

- Correlation relating $I_e(\sim M_{stellar}/R^2)$, R_e, and s
- Expect (virial theorem) $M_{stellar} \sim M_{dyn} \sim s^2 R_e / G$
- Get: $M_{dyn} \sim M_{stellar}^{(1+a)}$

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- M_dyn / M_stellar is an increasing function of M ("tilt")

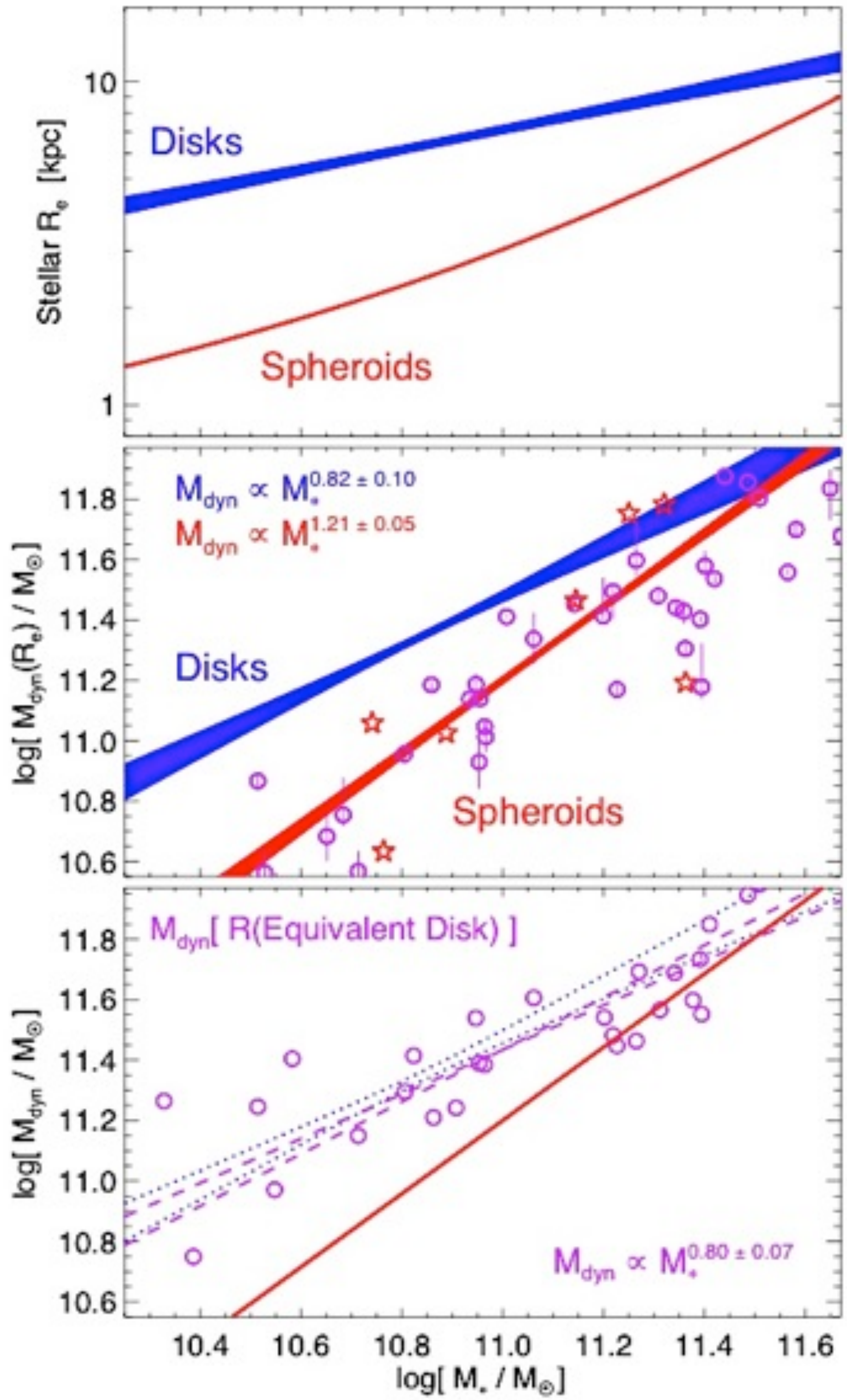


- Various observations (Bolton et al., Cappellari et al.) with masses from kinematic modeling, lensing, gas all agree:
    - Low-mass ellipticals are more baryon-dominated (have fractionally less DM) inside their stellar R_{eff}

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- This is opposite the trend in disks/naively expected of baryons in halos
- Akin to comparison of sizes/compactness



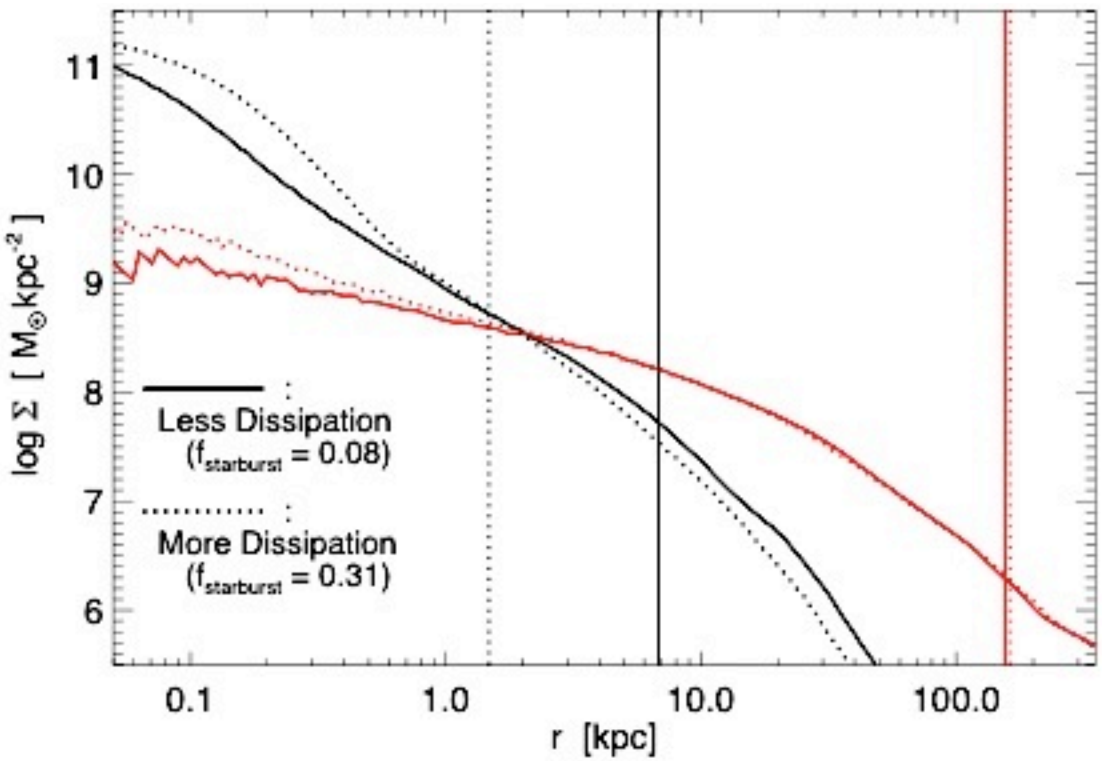
PFH et al. 2008b

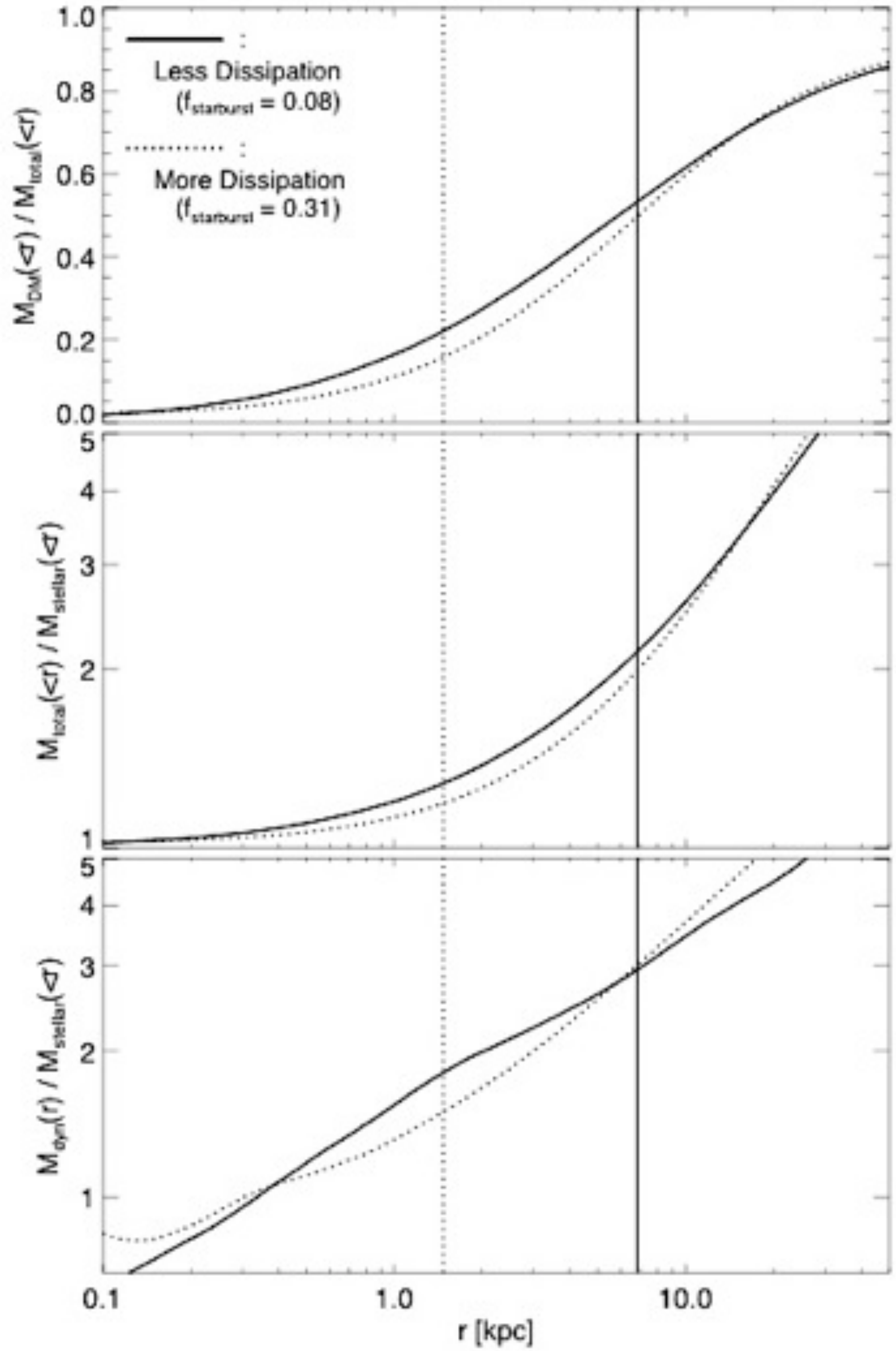
Fundamental Plane Tilt

WHERE DOES IT COME FROM?

PFH et al. 2008b

- Dissipation has been invoked to explain this (Robertson et al. 2006)





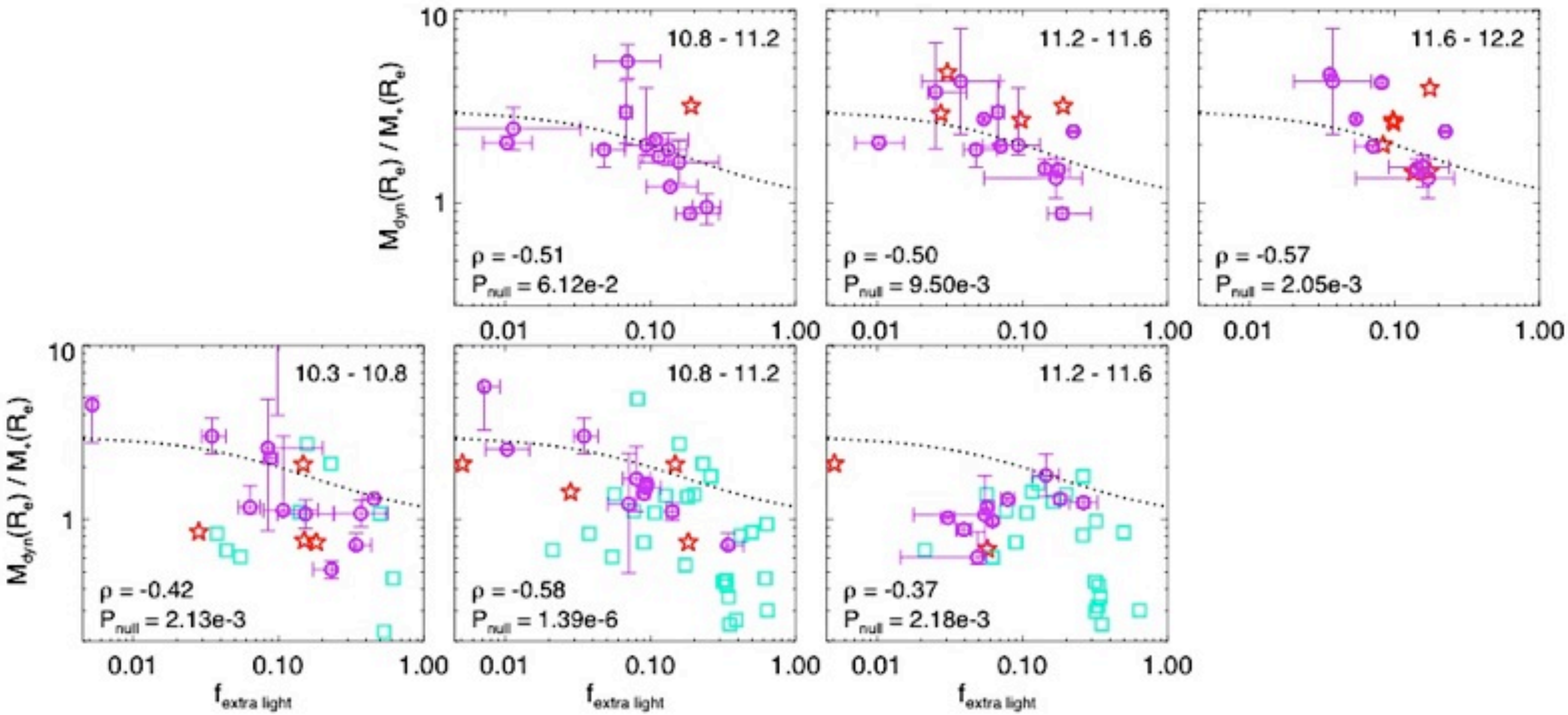
- If dissipational fraction scales w. mass, simulations can match FP

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Does it work?

PFH et al. 2008b



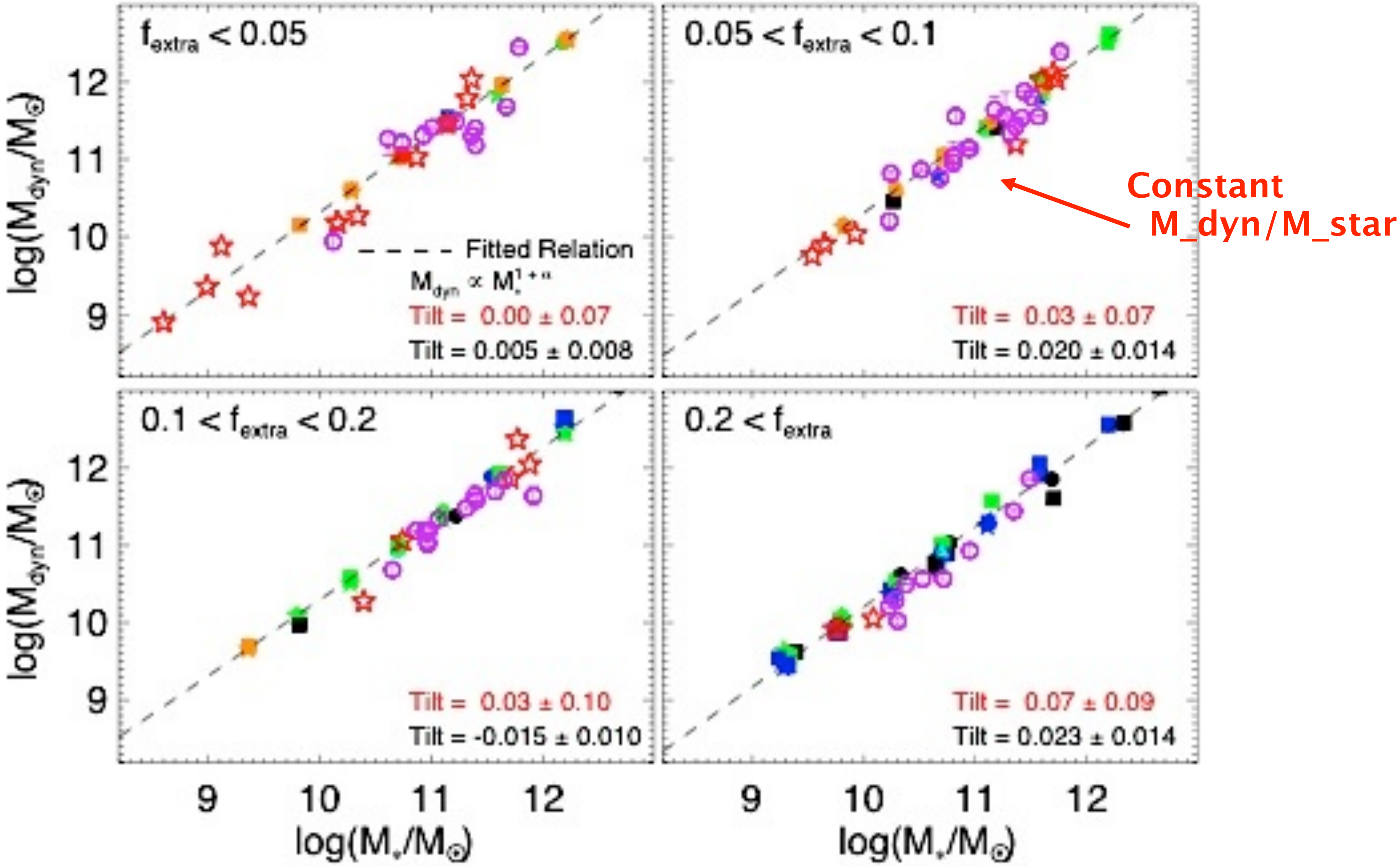
- $M_{dyn}/M_{stellar}$ depends on $f_{dissipational}$ at all M

Fundamental Plane Tilt

PFH et al. 2008b

WHERE DOES IT COME FROM?

- Does it work?

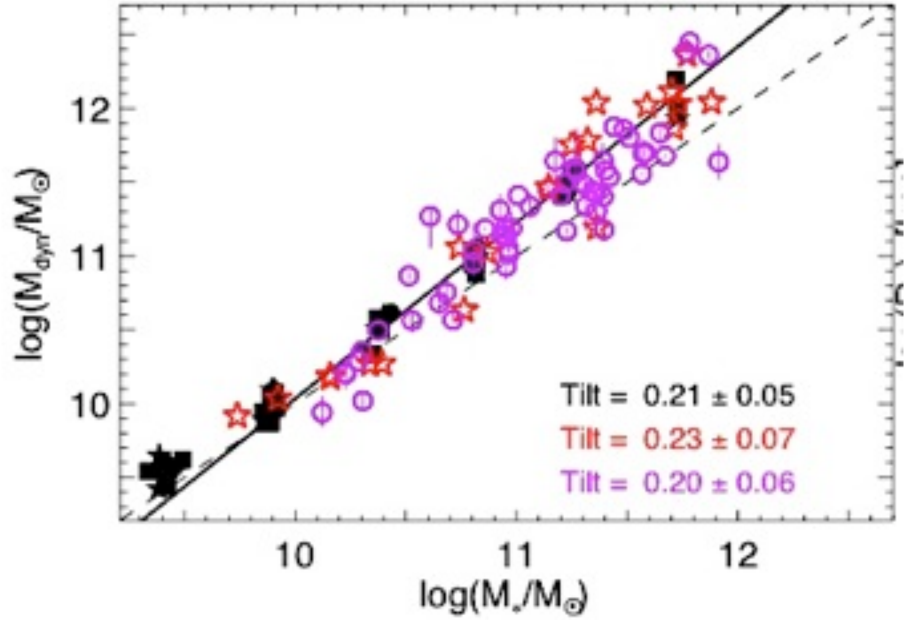


- At FIXED $f_{dissipational}$, there is NO TILT

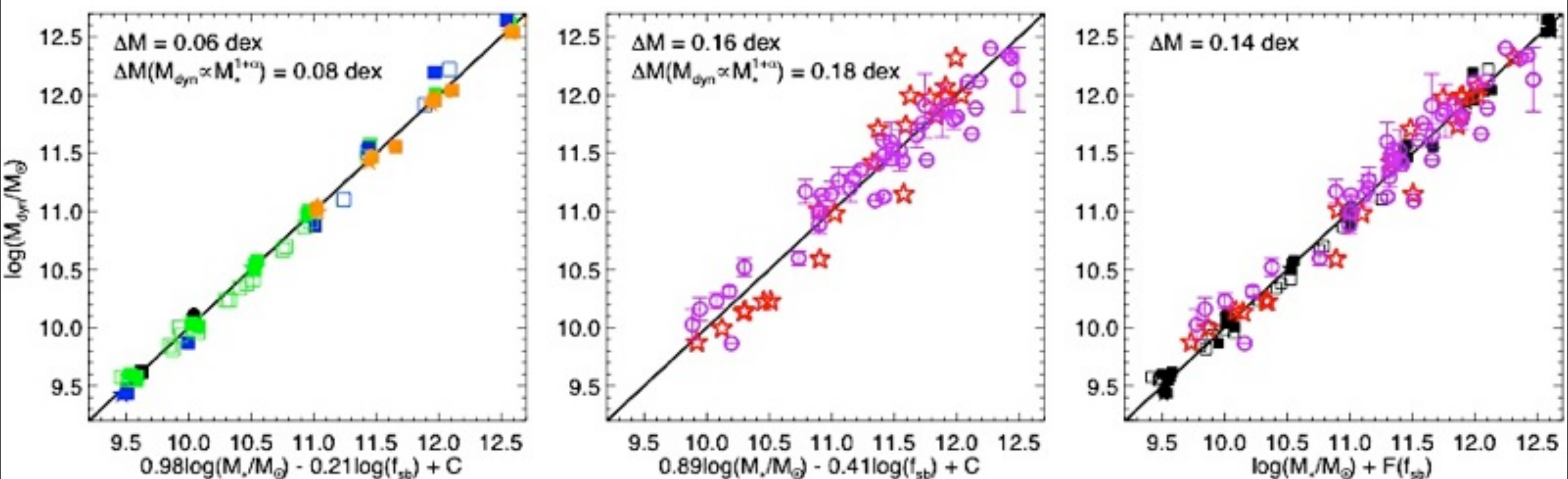
Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Instead of thinking of the FP as
  $M_{dyn} \sim M_{stellar}^{(1+a)}$



- We should think of it in terms of
  $M_{dyn} \sim M_{stellar} \times F(f_{dissipational})$

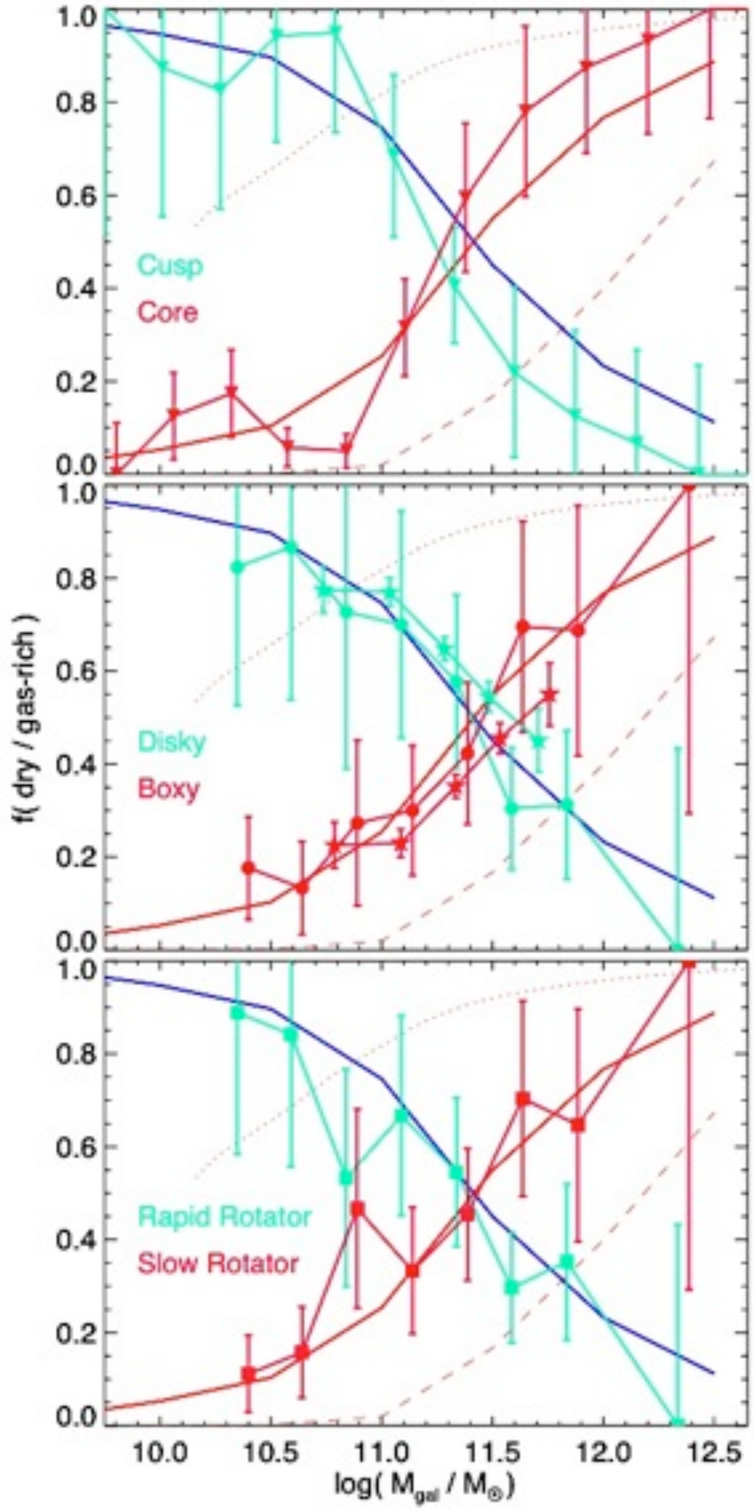


What about the "Cores"?

CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?

- Massive ellipticals tend to have "cores" or flattening in their centers (central ~10-30pc)
  - 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 ~a few % of their light (~10-50x M_bh) out to ~100-500 pc
  - What happened to all that "extra light"?

Data: Lauer et al., Bender et al.

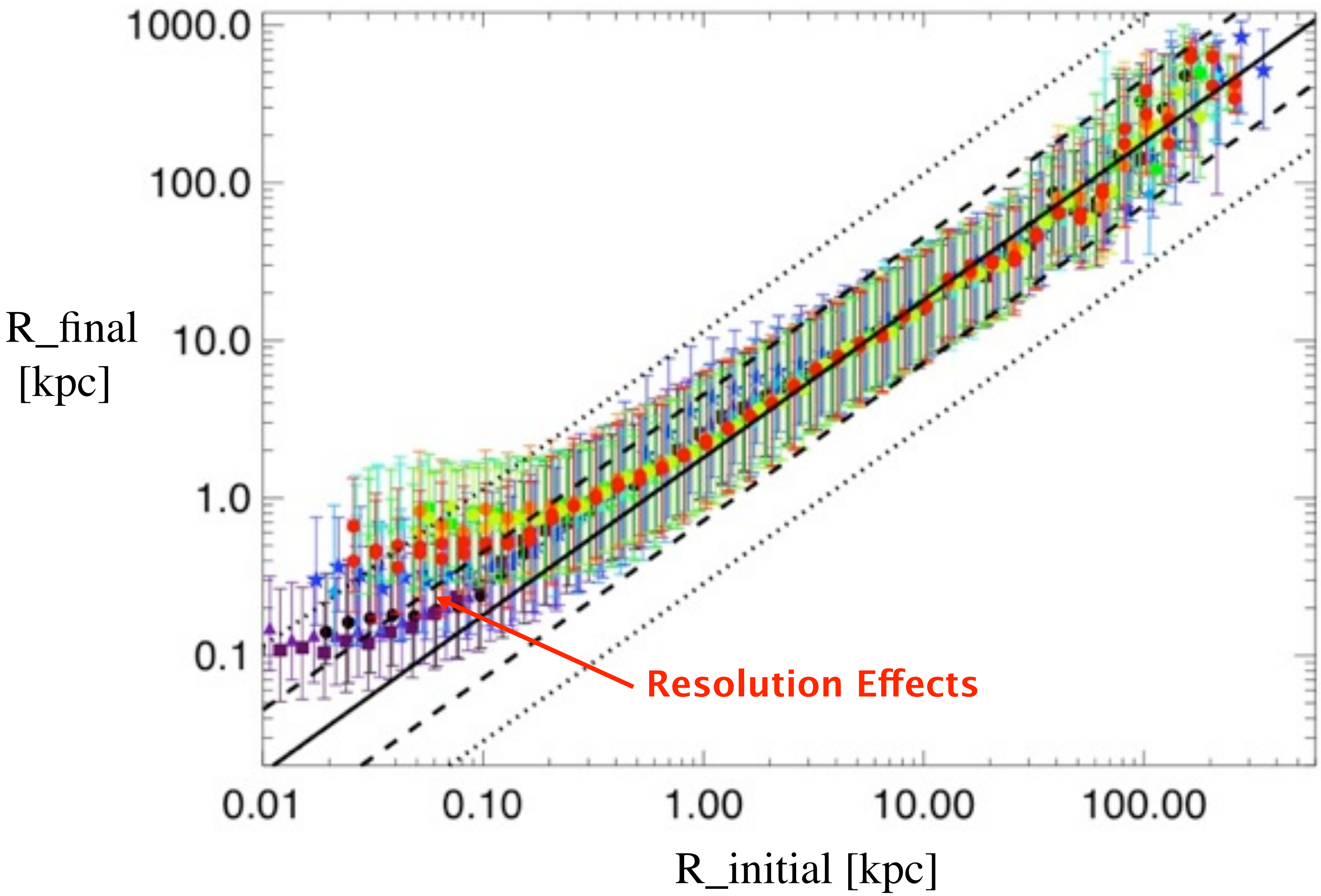


PFH et al. 2005

Application: “Core” Ellipticals

PFH et al. 2008c

WHAT HAPPENS TO THE “EXTRA LIGHT”?

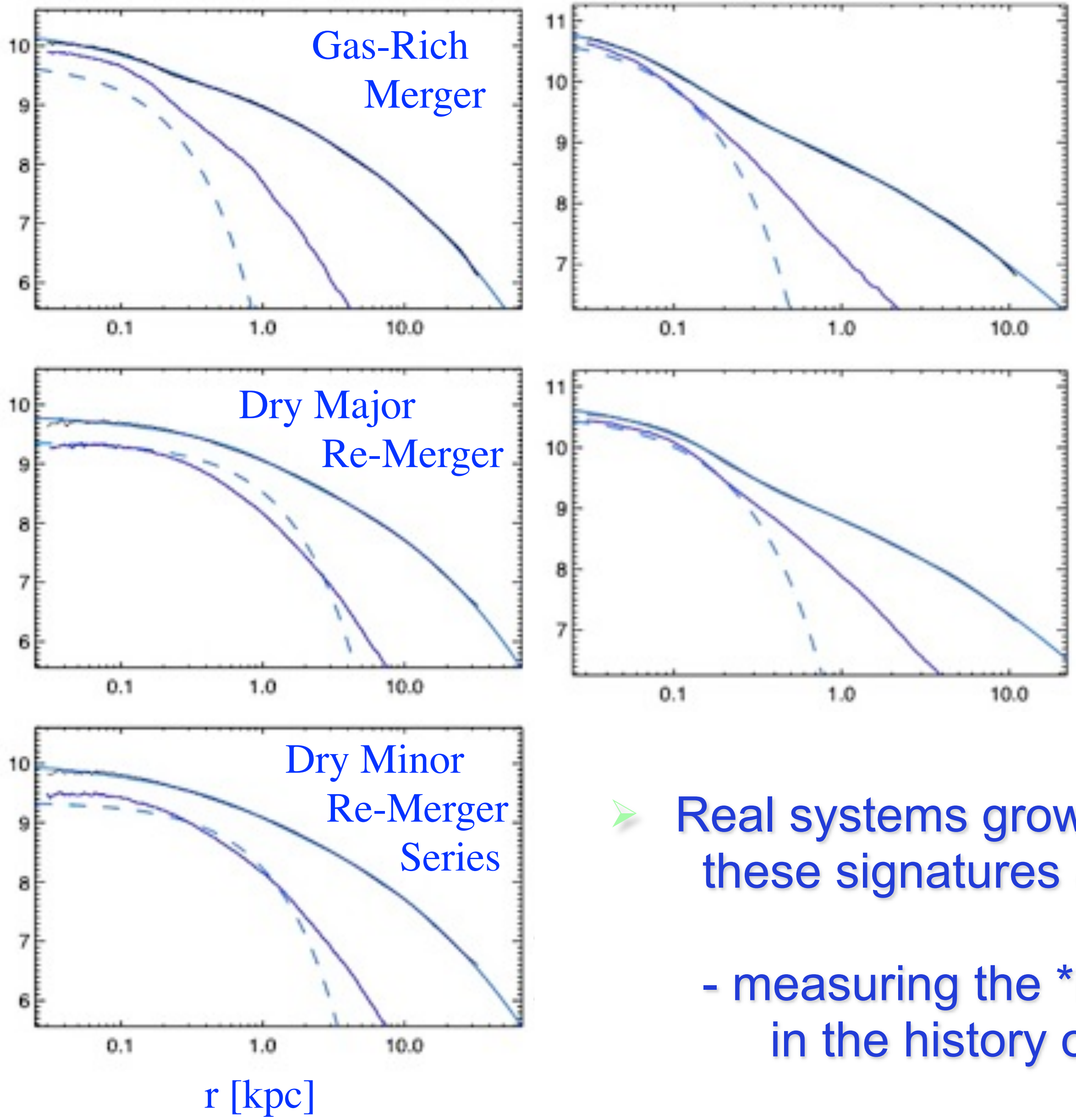


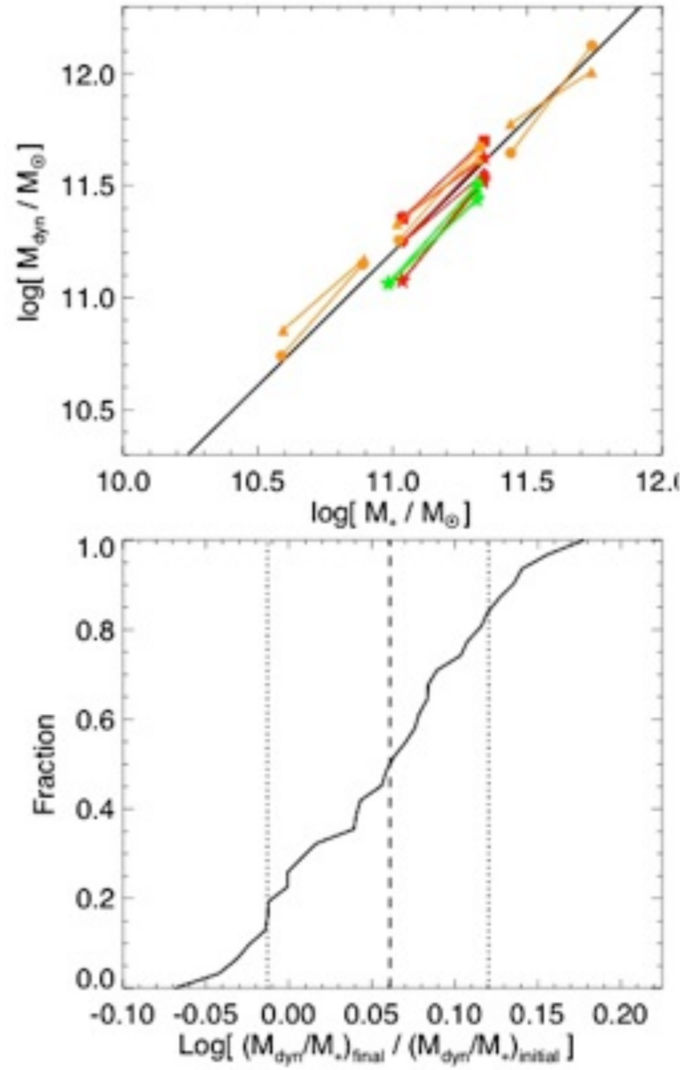
- Stars are puffed out, but preserve rank-ordering in radius (or binding energy)
  - Extra light is *NOT* destroyed in “dry mergers”

- However, there is significant (~0.4 dex) scattering :: the transition is “smoothed”

Caveats

SOME GENERAL CONSIDERATIONS



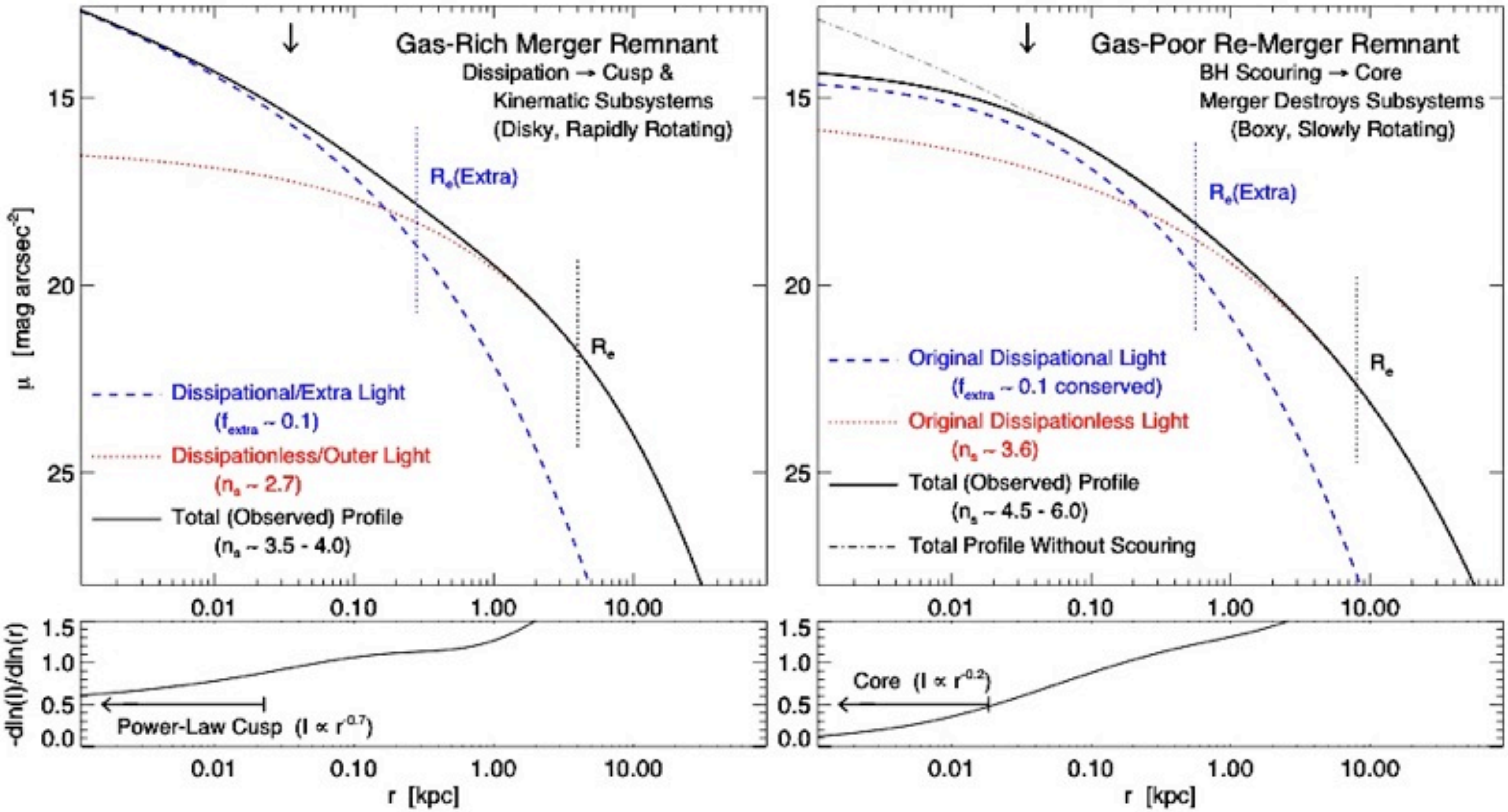


- Real systems grow in a series of mergers: fortunately, these signatures & the FP are conserved:

  - measuring the *integral* amount of dissipation in the history of the elliptical formation -

Application: “Core” Ellipticals

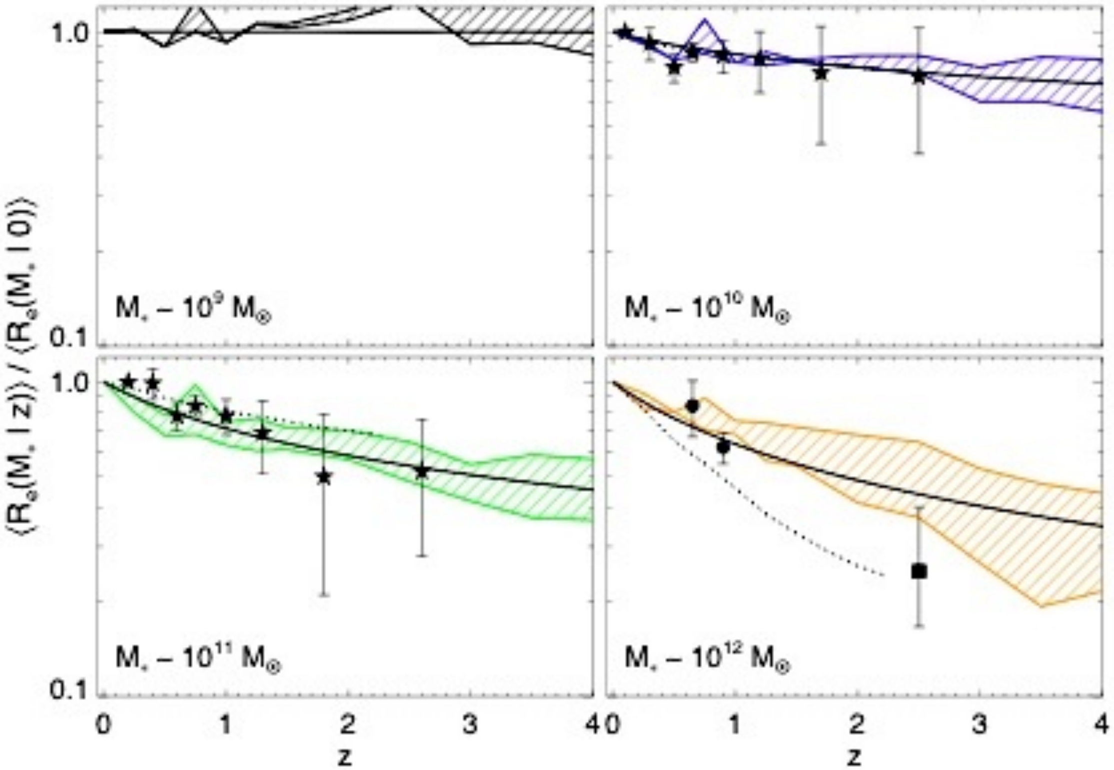
WHAT HAPPENS TO THE “EXTRA LIGHT”?



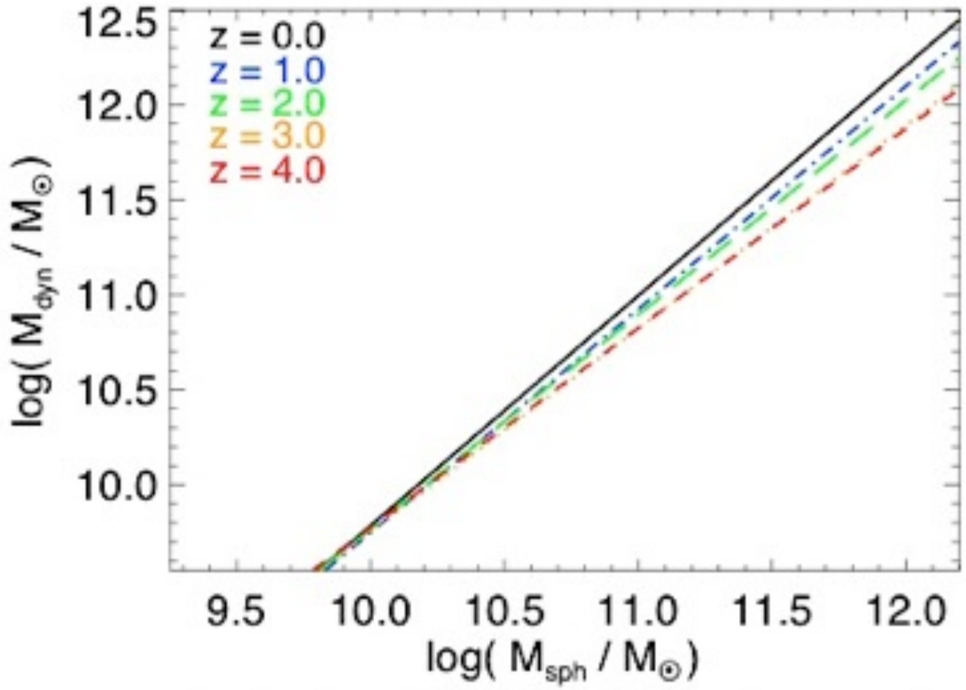
Dissipation versus Redshift

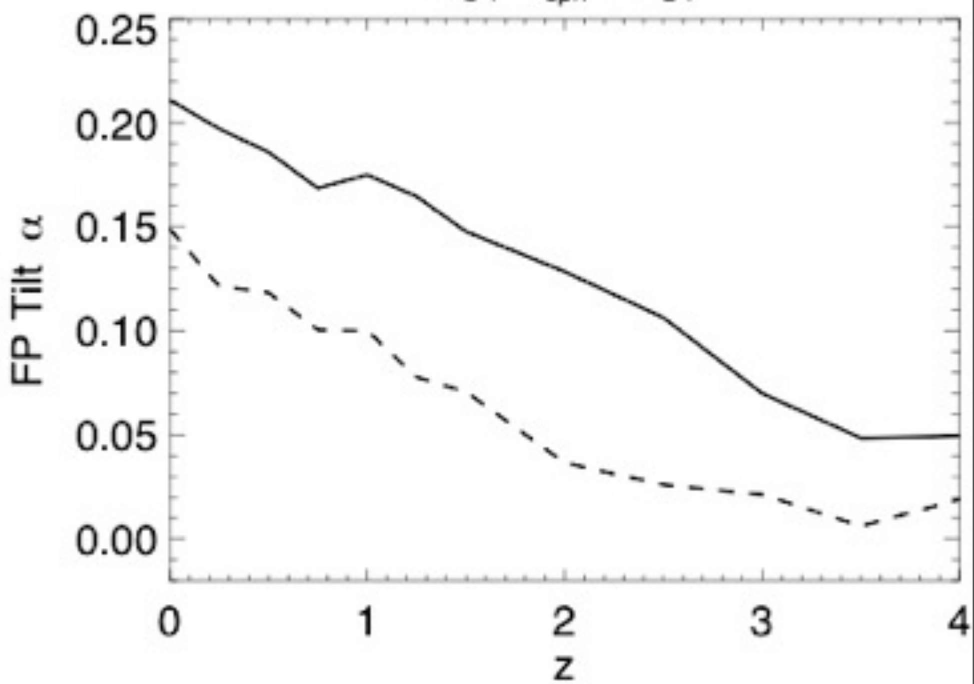
HIGH-Z DISKS ARE MORE GAS RICH...

- So get more compact ellipticals



Observed elliptical size evolution (points): Trujillo et al., McIntosh et al., Zirm et al. (z~3)





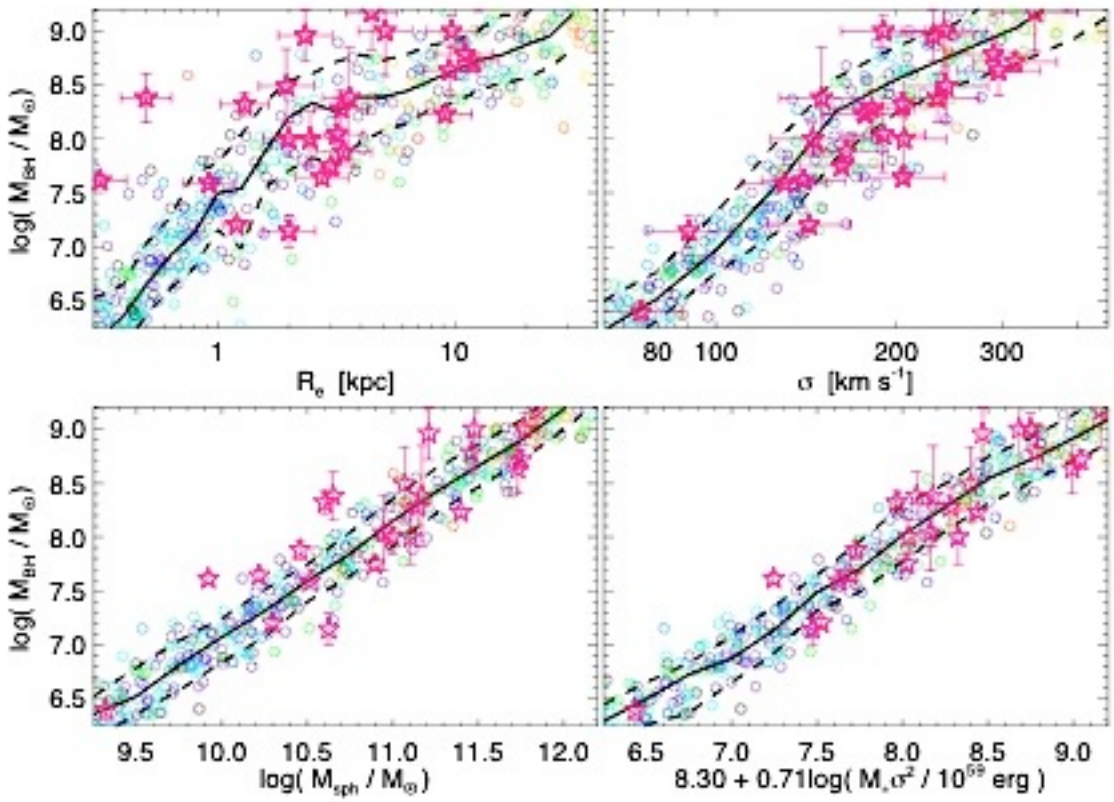
PFH et al. 2008(d?)

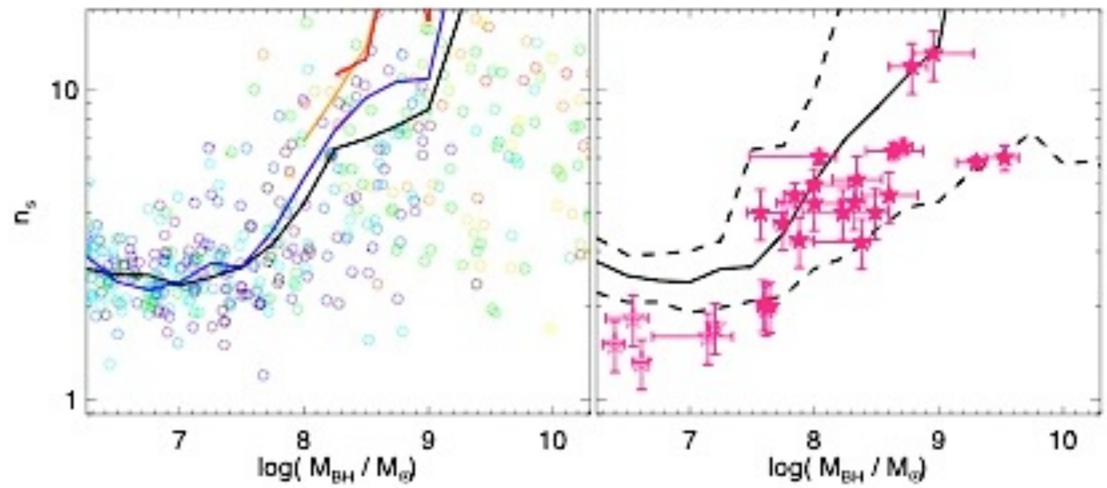
Summary

- 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", many properties of these systems should still reflect how much dissipation was involved in their original formation
  - Care is needed: the appearance of two components may vanish with successive dry mergers
- This has important implications for redshift evolution of elliptical (and BH) scaling relations
  - High-z progenitors more gas rich >> more dissipation >> more compact ellipticals

Implications for BH-Host Correlations

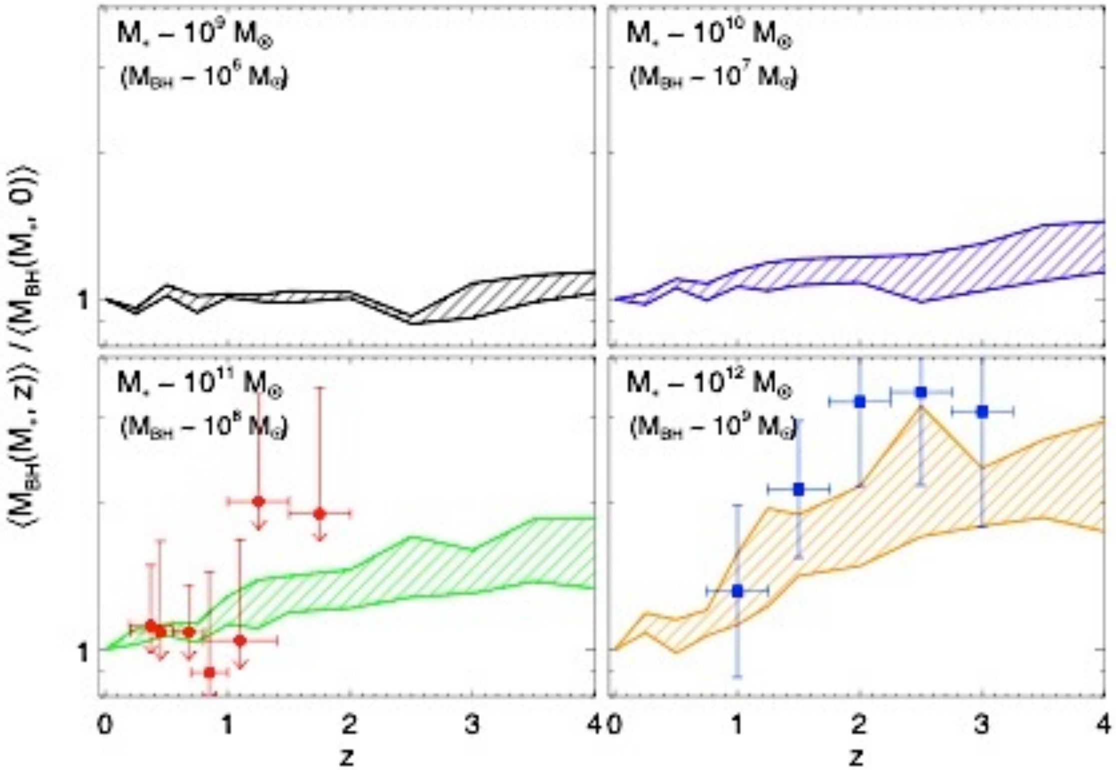
AT Z=0

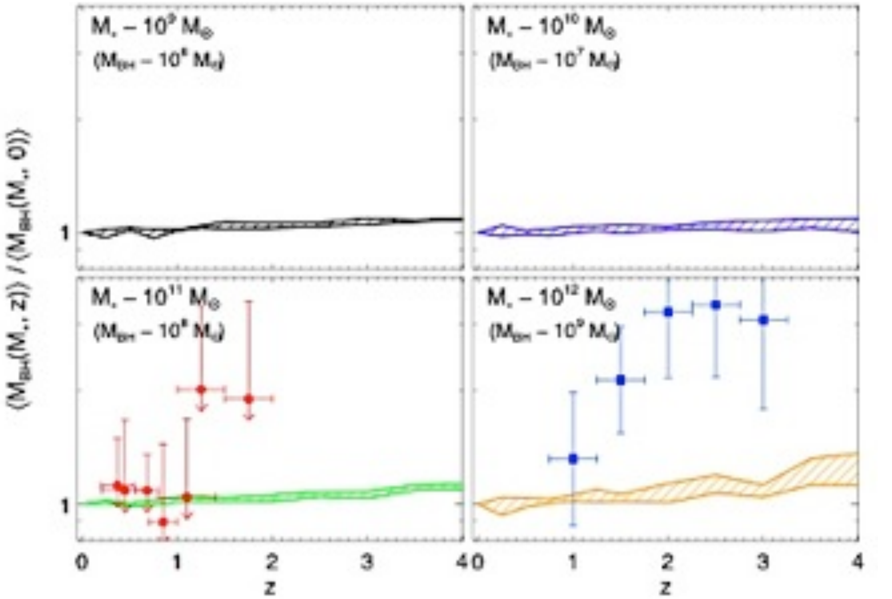




Implications for BH-Host Correlations

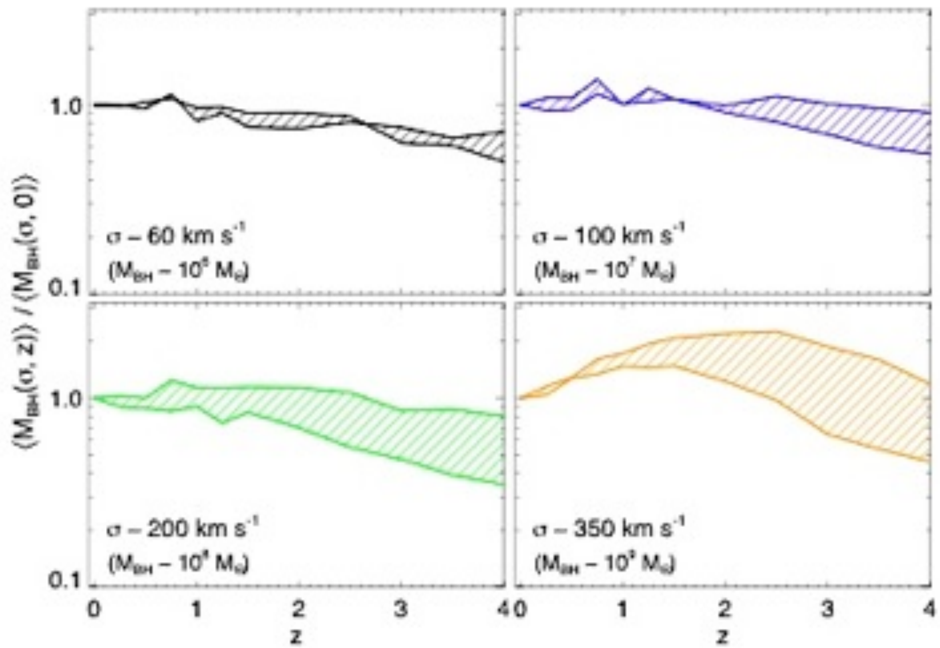
EVOLUTION WITH REDSHIFT





- (without dissipation=no evolution)

- Deeper potential wells at fixed M



- (Weaker in sigma)

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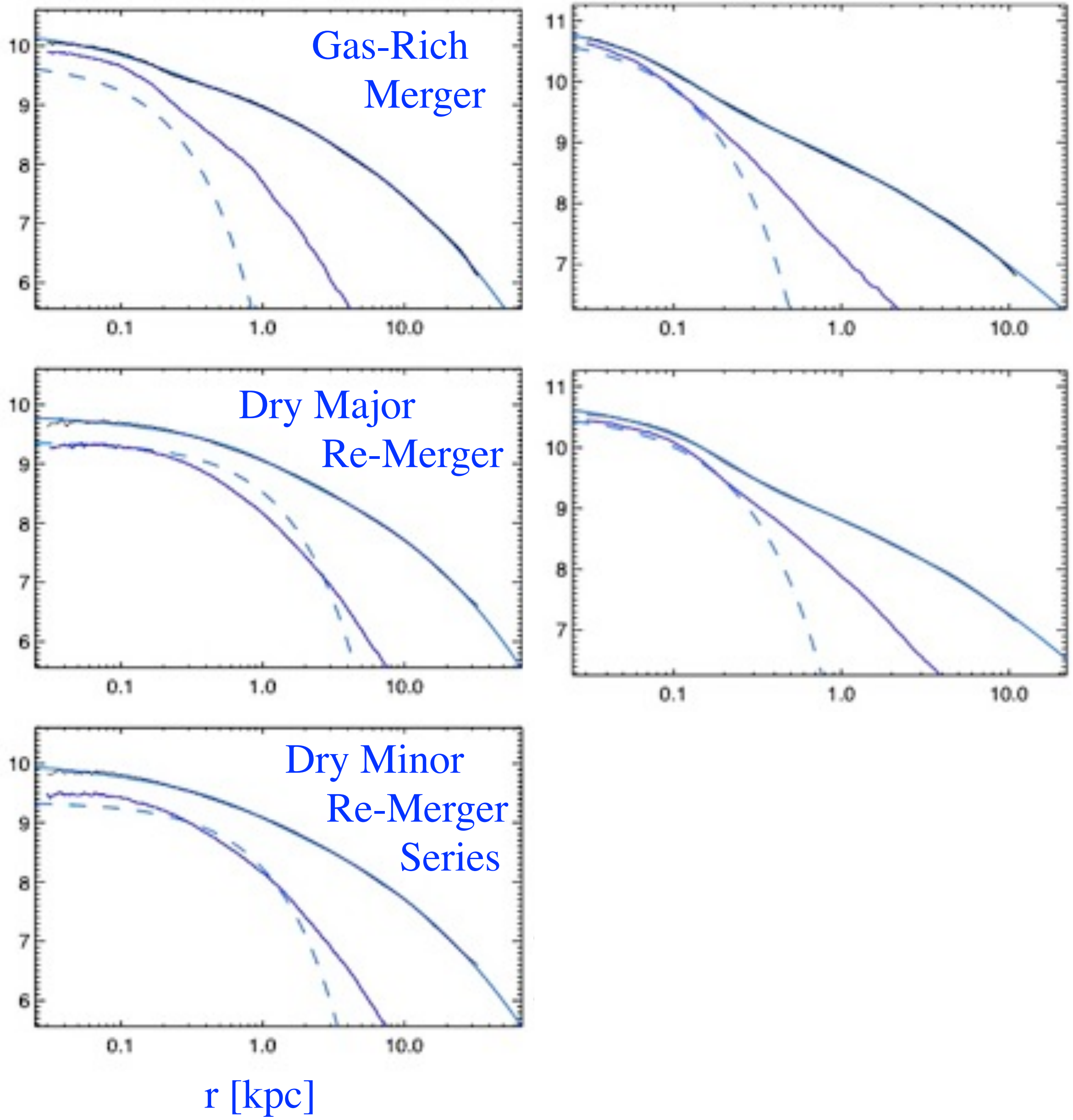
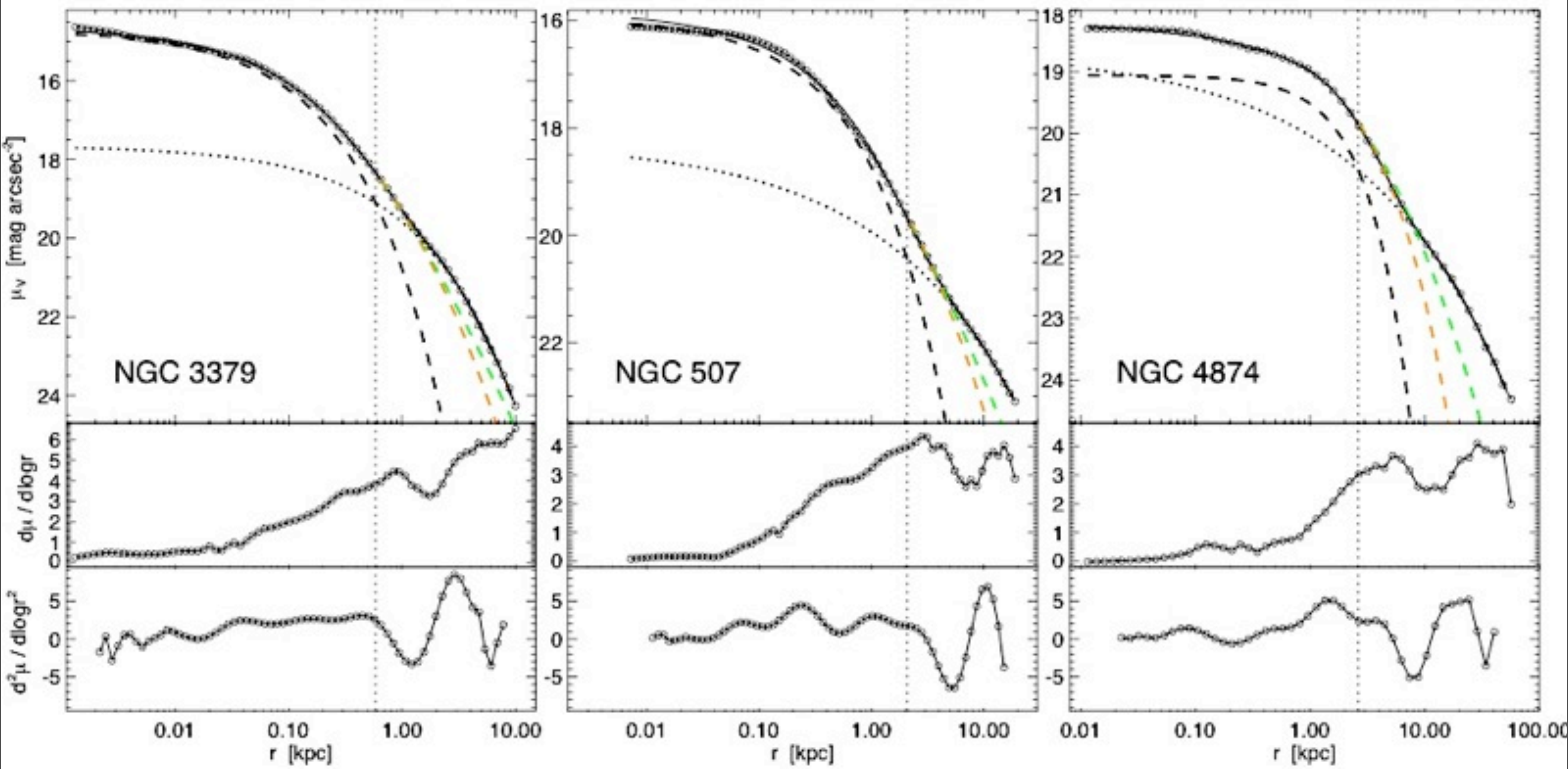


- Re-mergers in simulations preserve the extra light: applying our decomposition reliably extracts the "original" starburst stars

Application: “Core” Ellipticals

WHAT HAPPENS TO THE “EXTRA LIGHT”?



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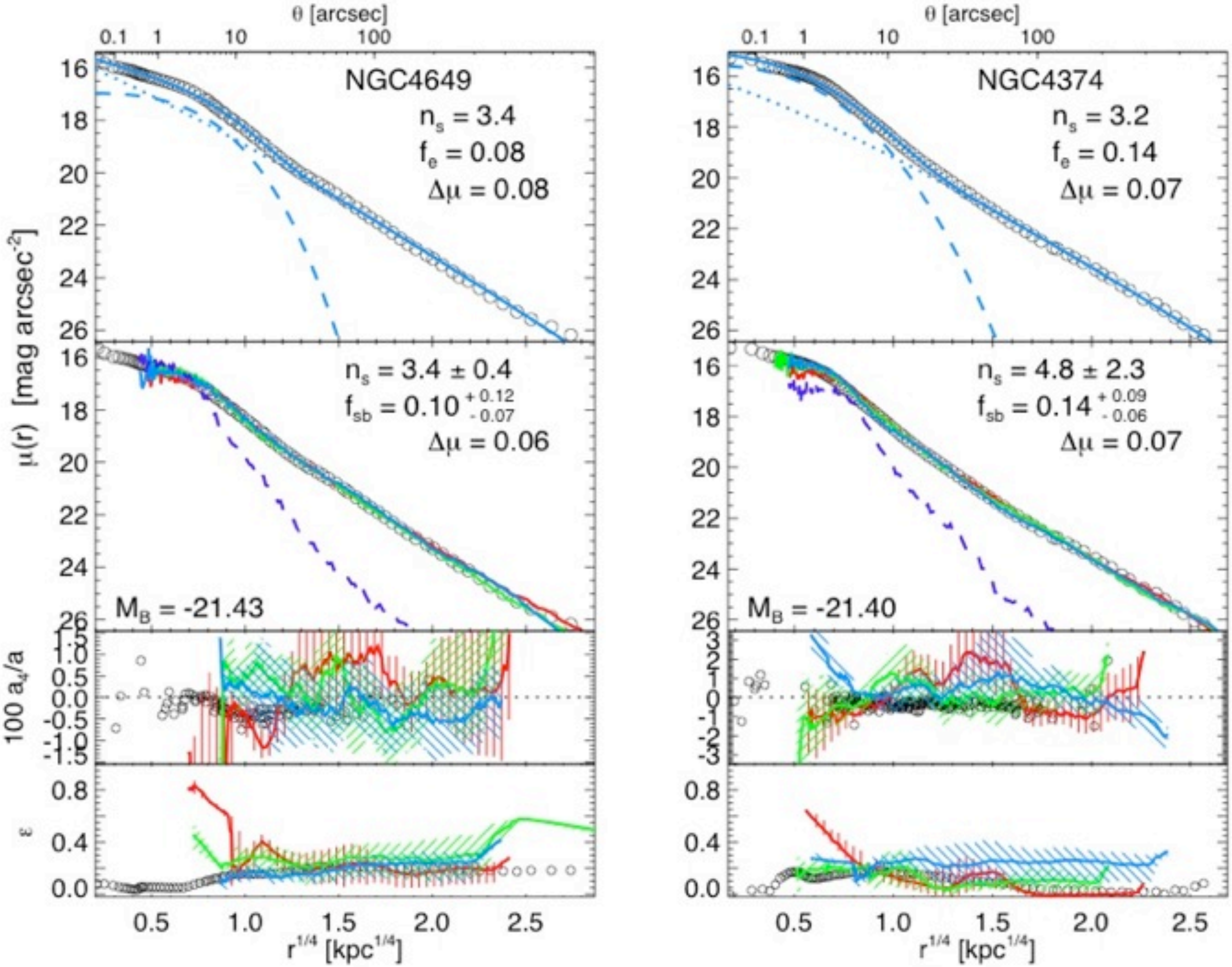

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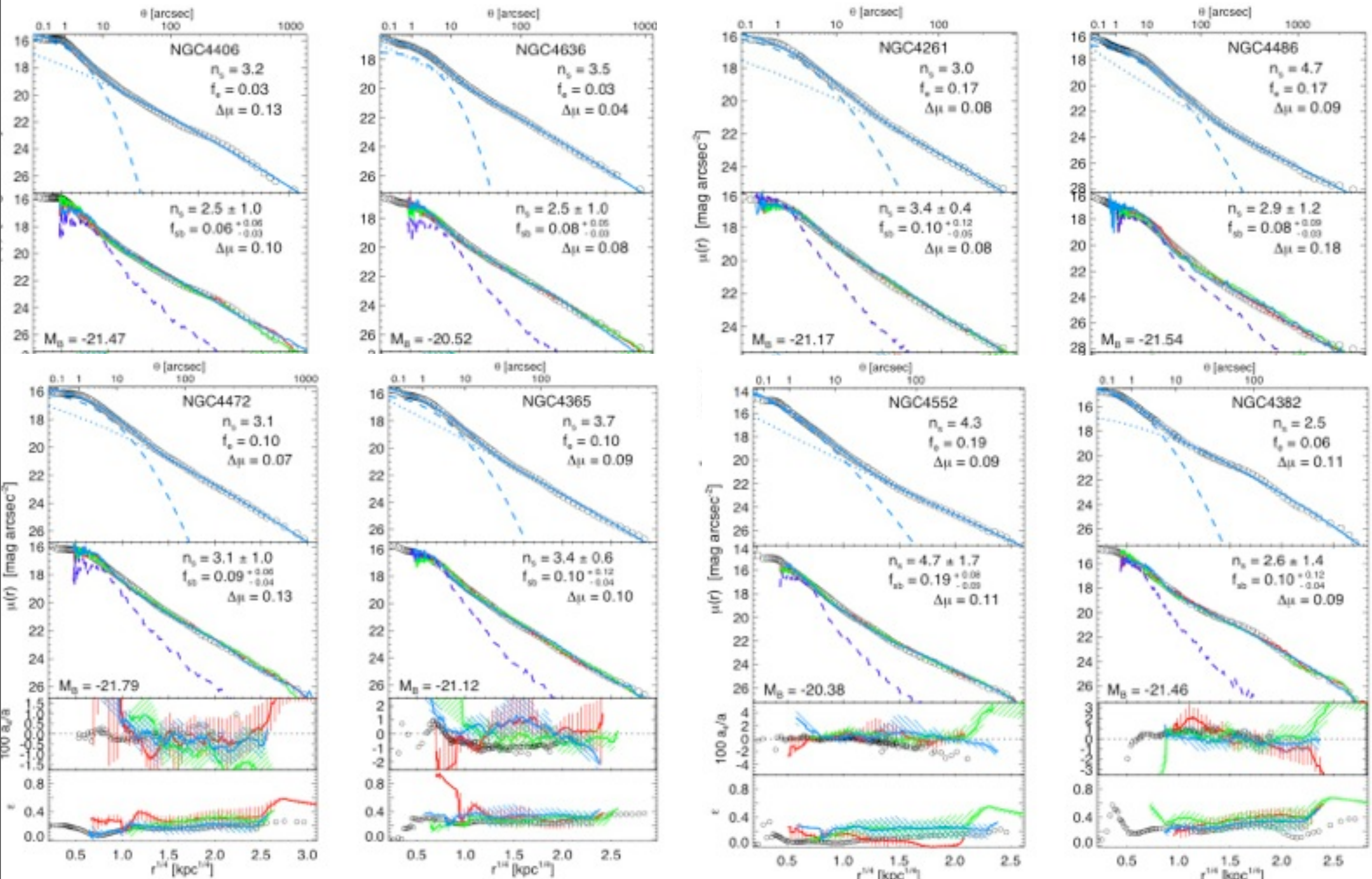

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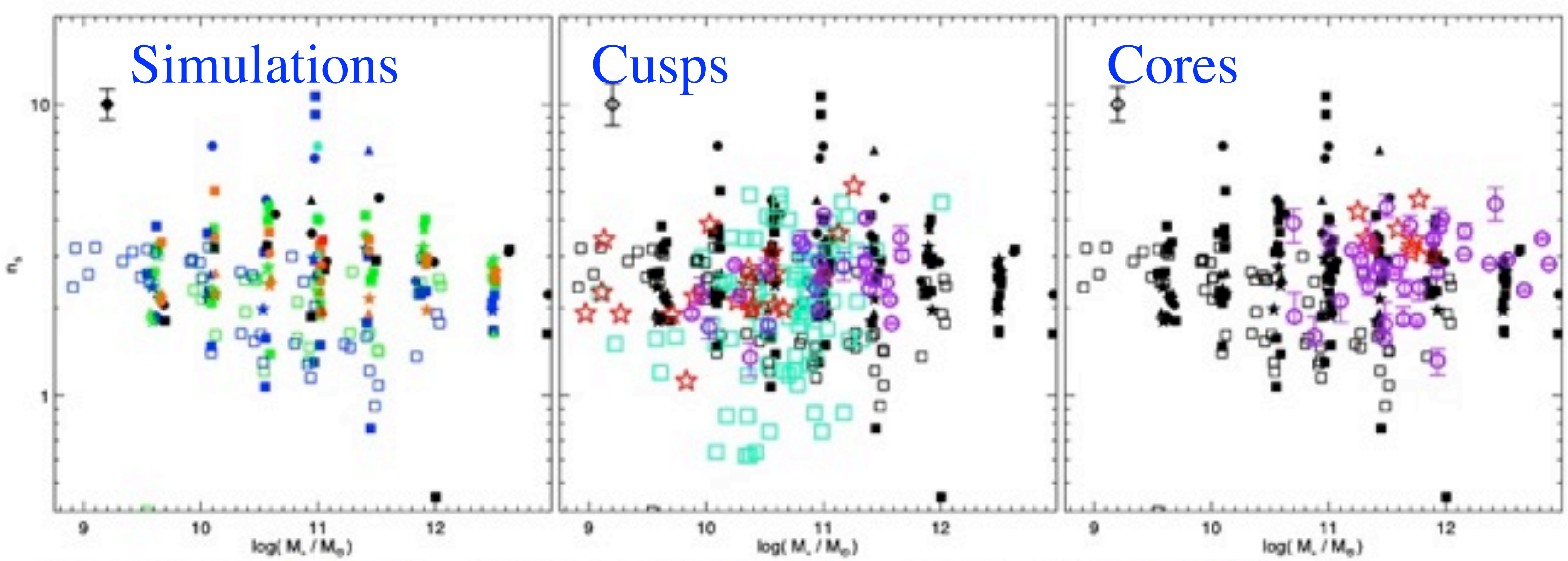
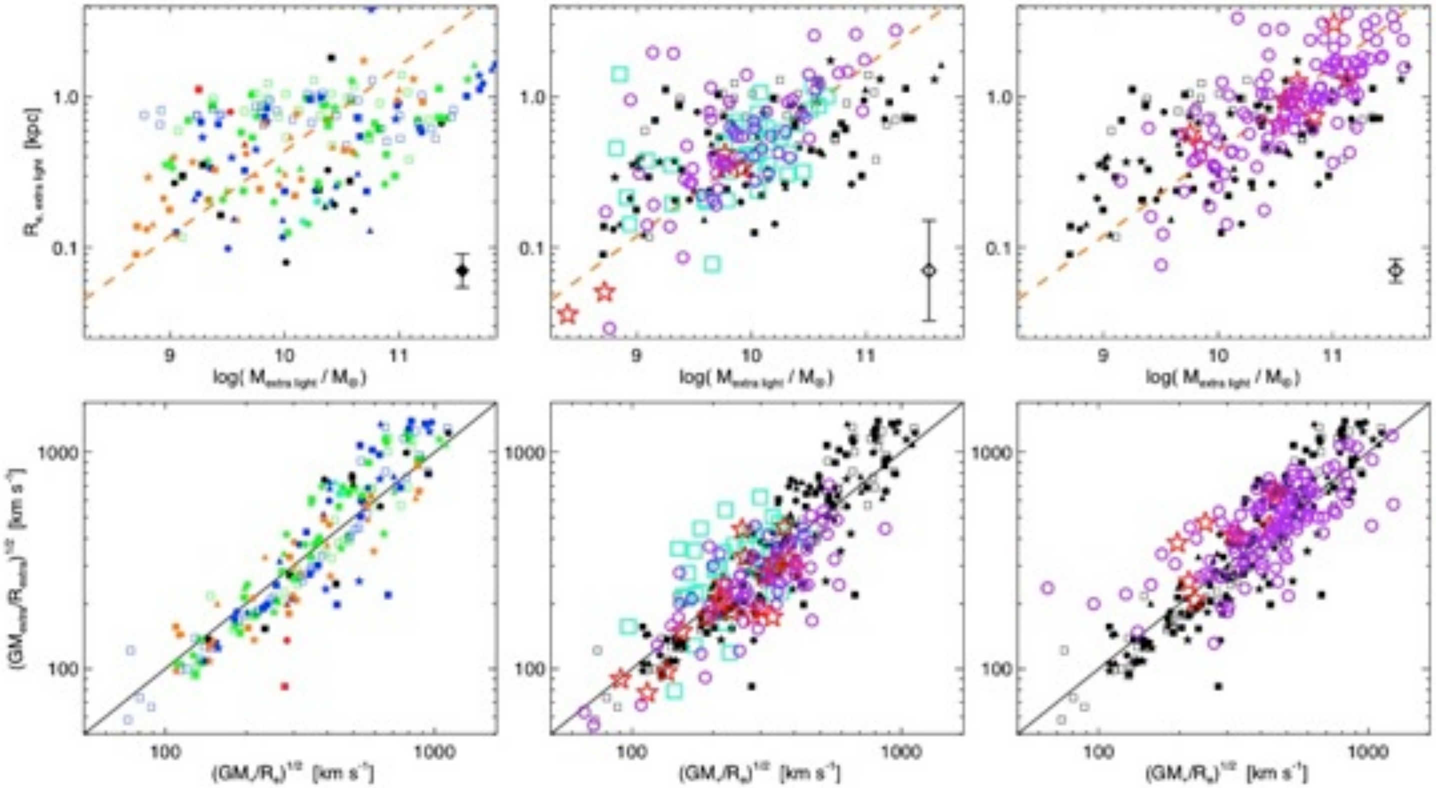


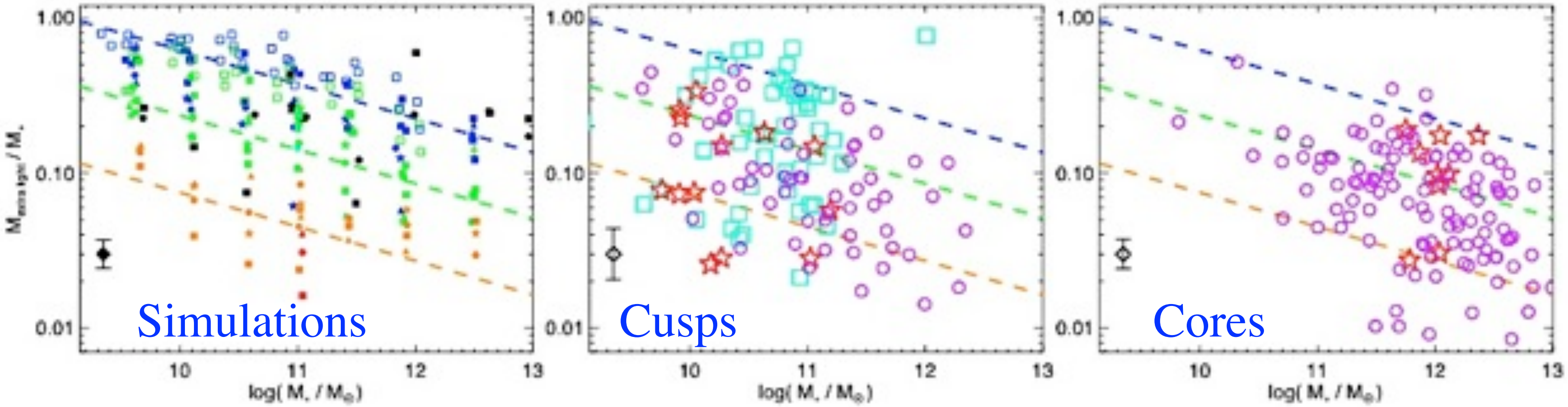
Outer Sersic index



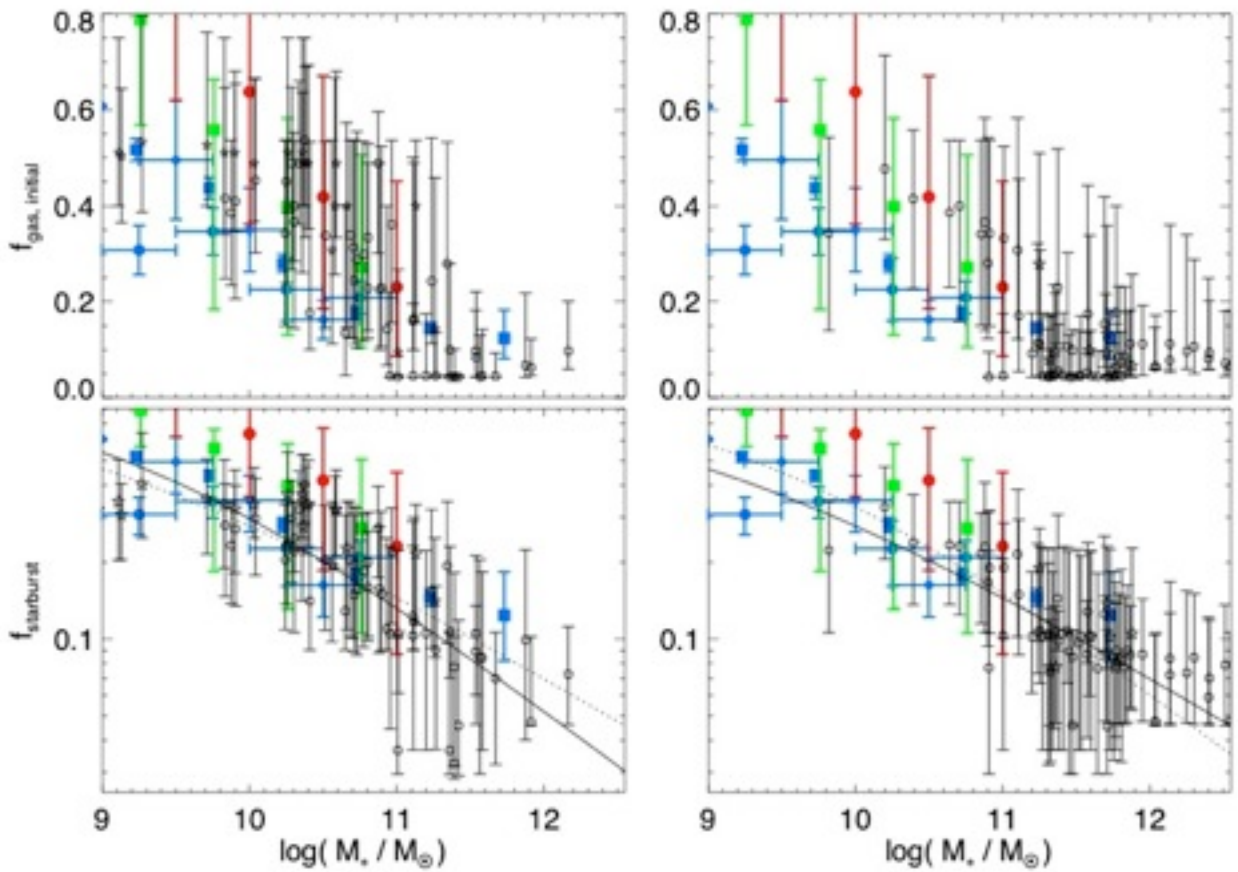
Extra light sizes/ velocity dispersions

Application: "Core" Ellipticals

WHAT HAPPENS TO THE "EXTRA LIGHT"?

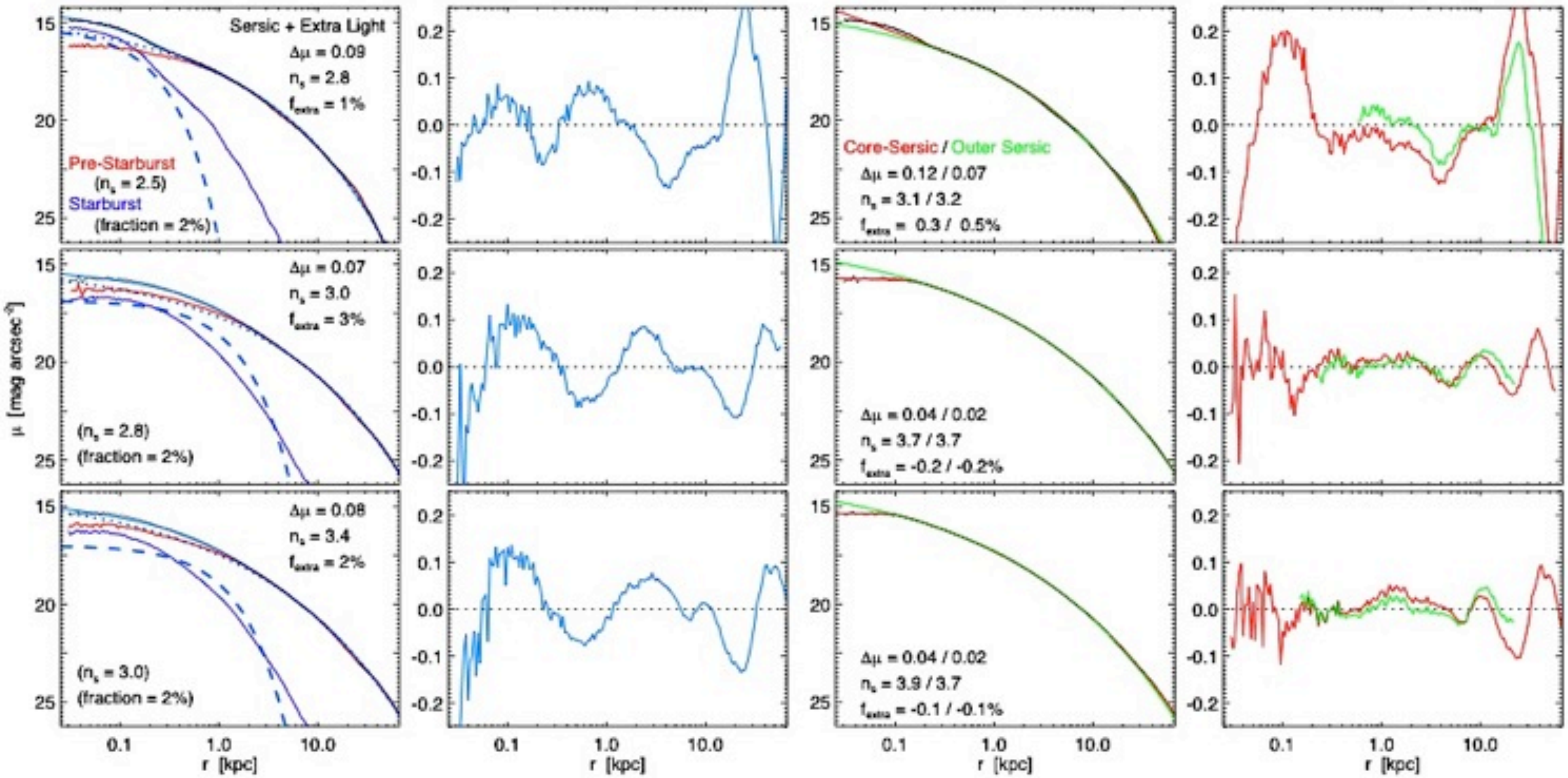


Extra light mass fraction



Application: "Core" Ellipticals

HOW MUCH IS "MISSING LIGHT"?



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

Application: “Core” Ellipticals

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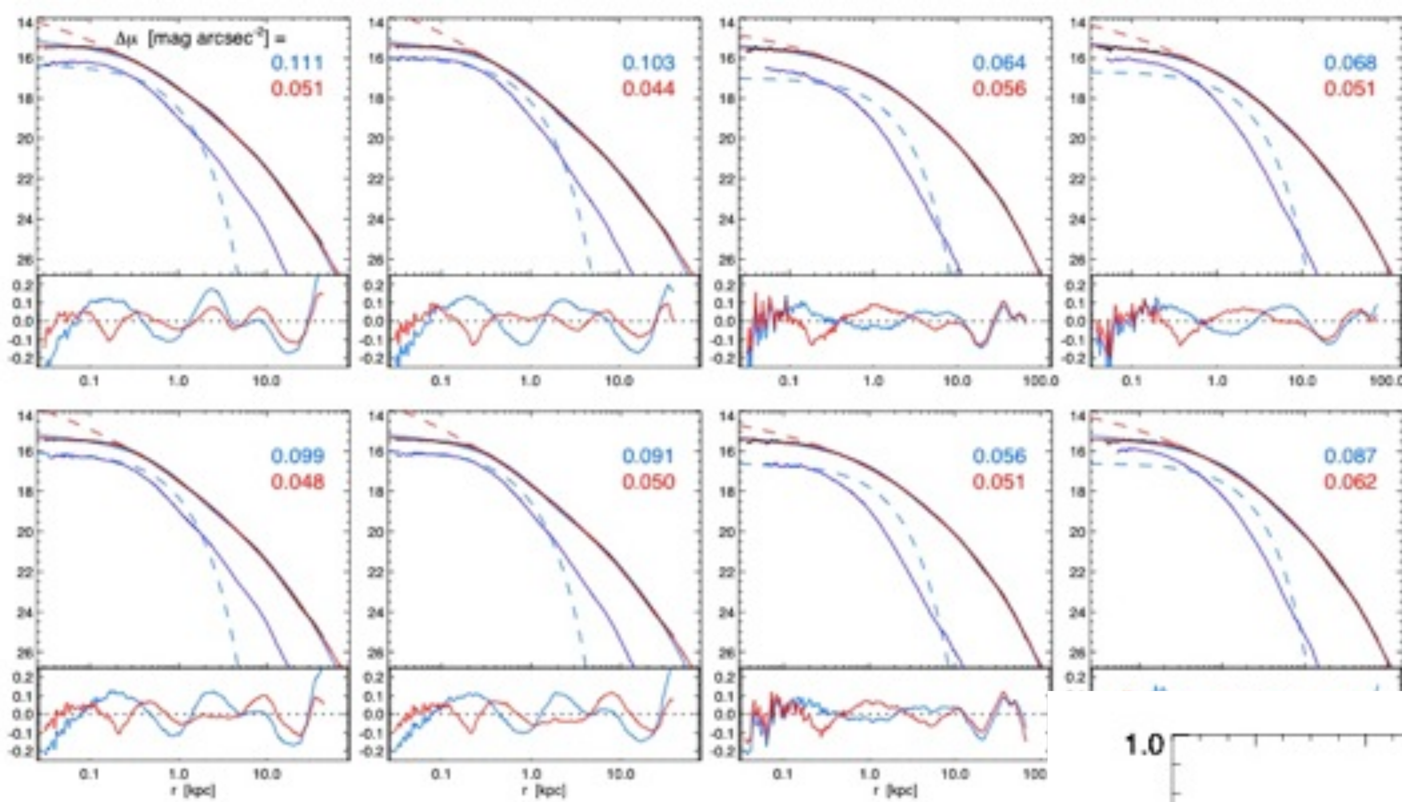

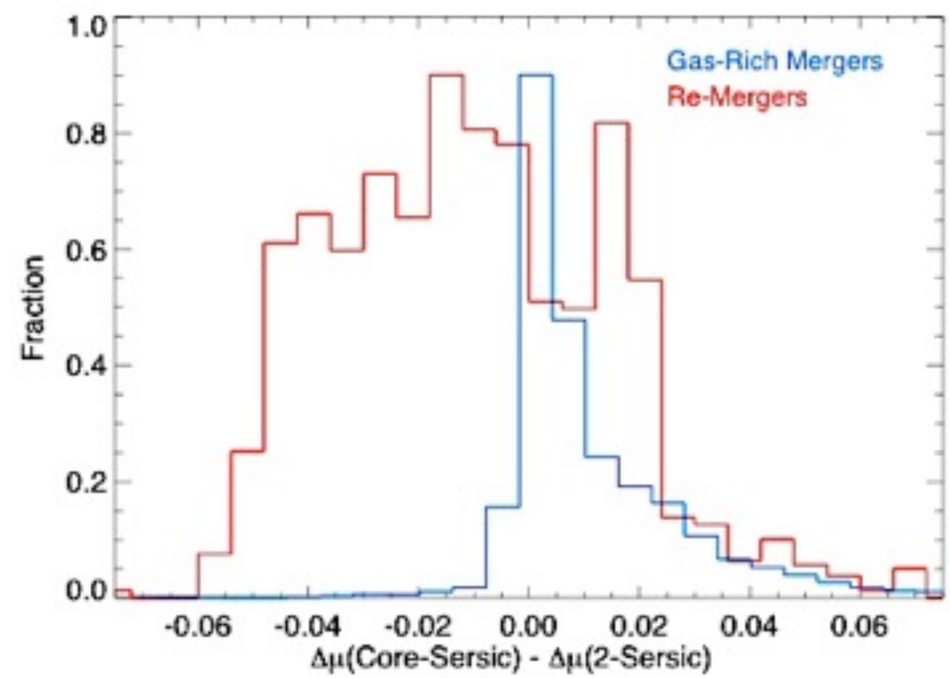

Application: “Core” Ellipticals

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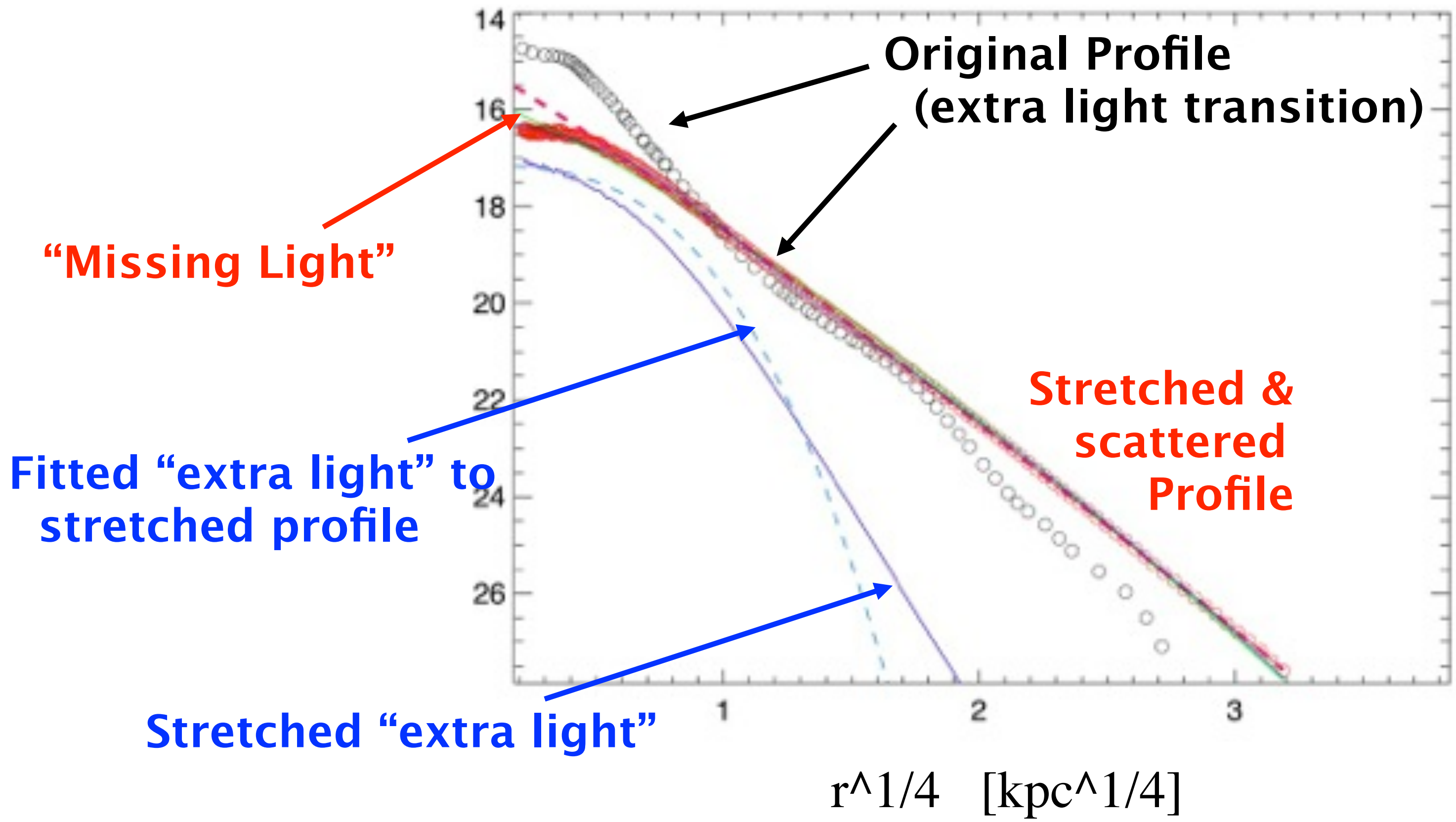

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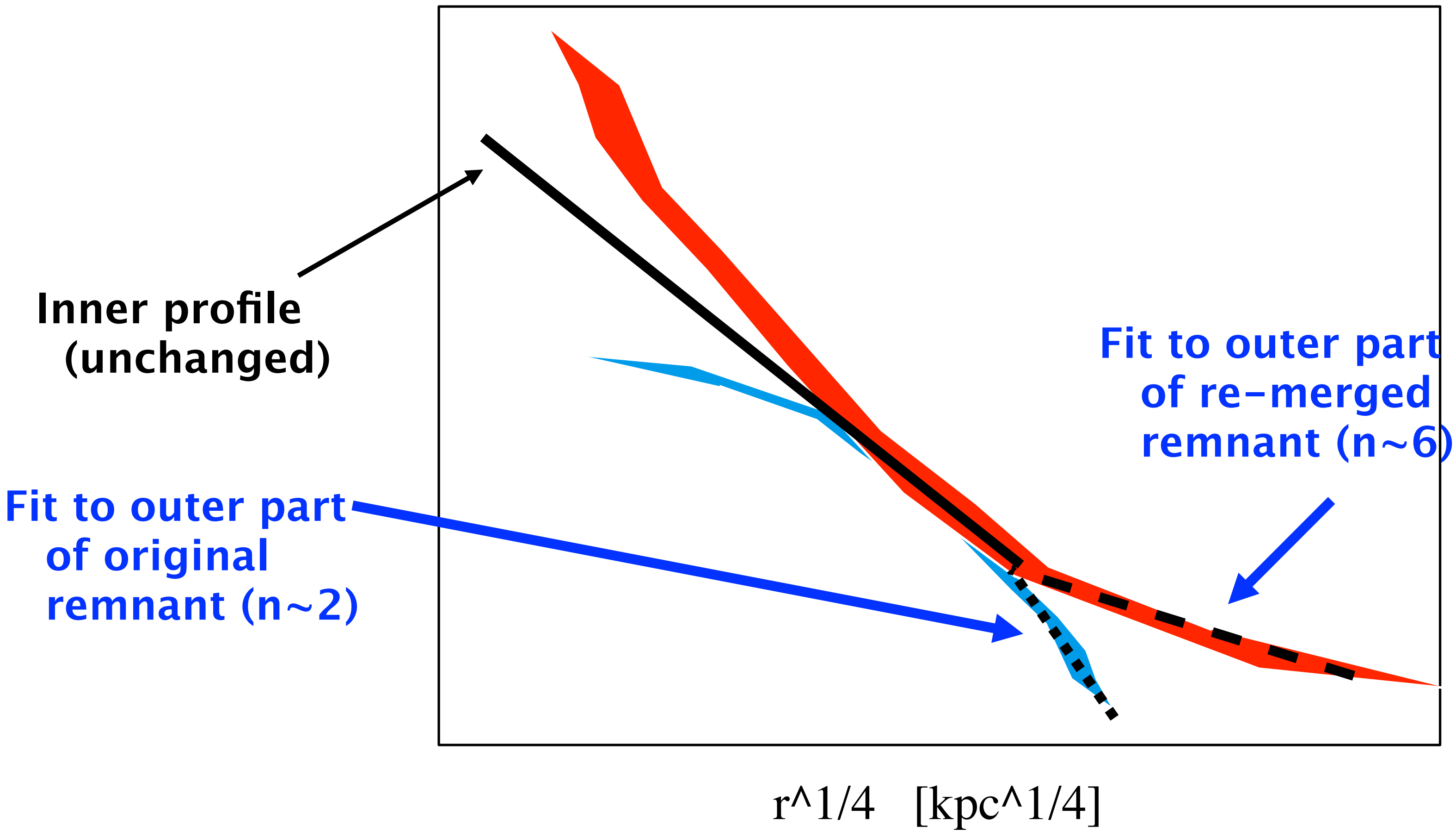

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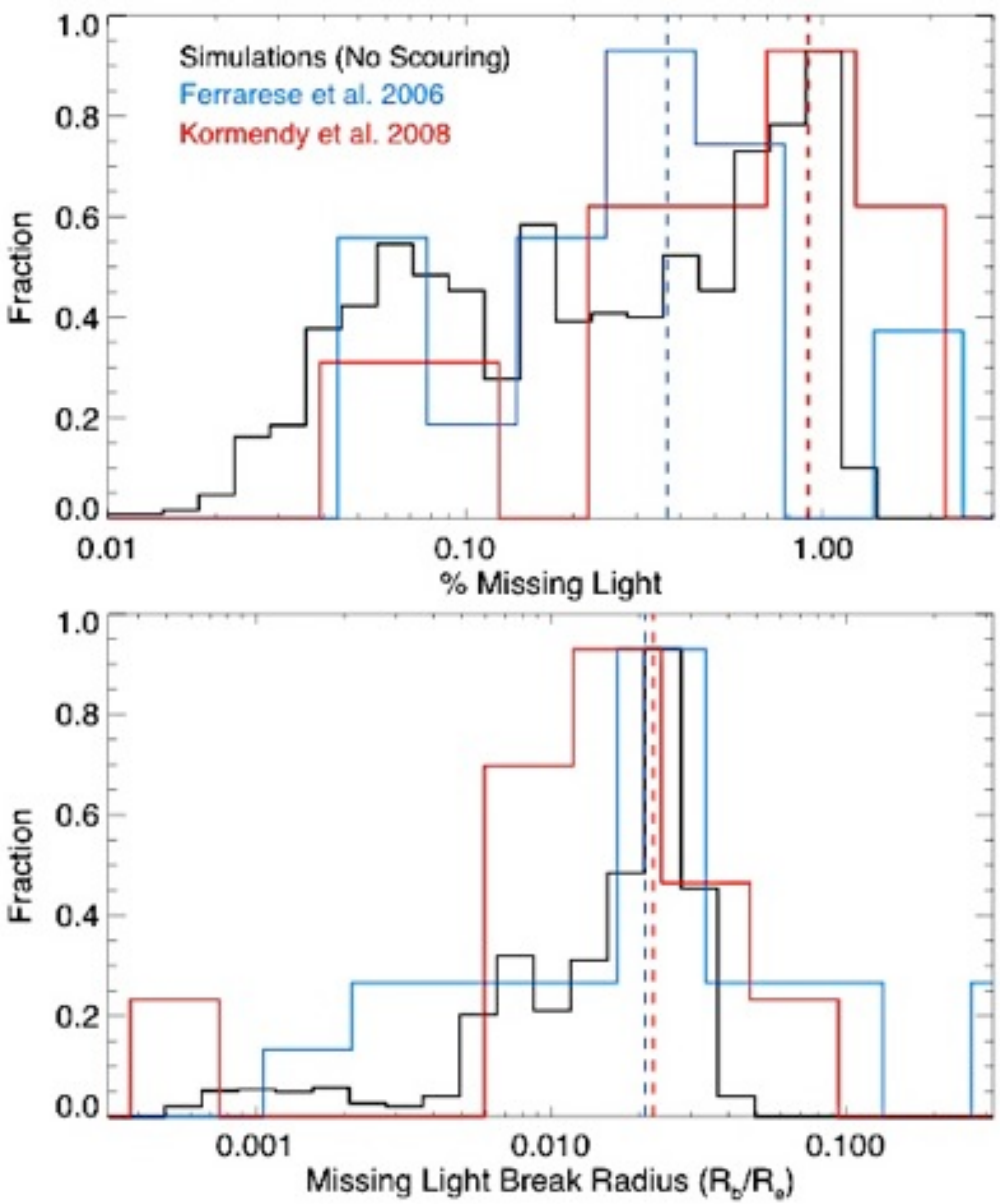
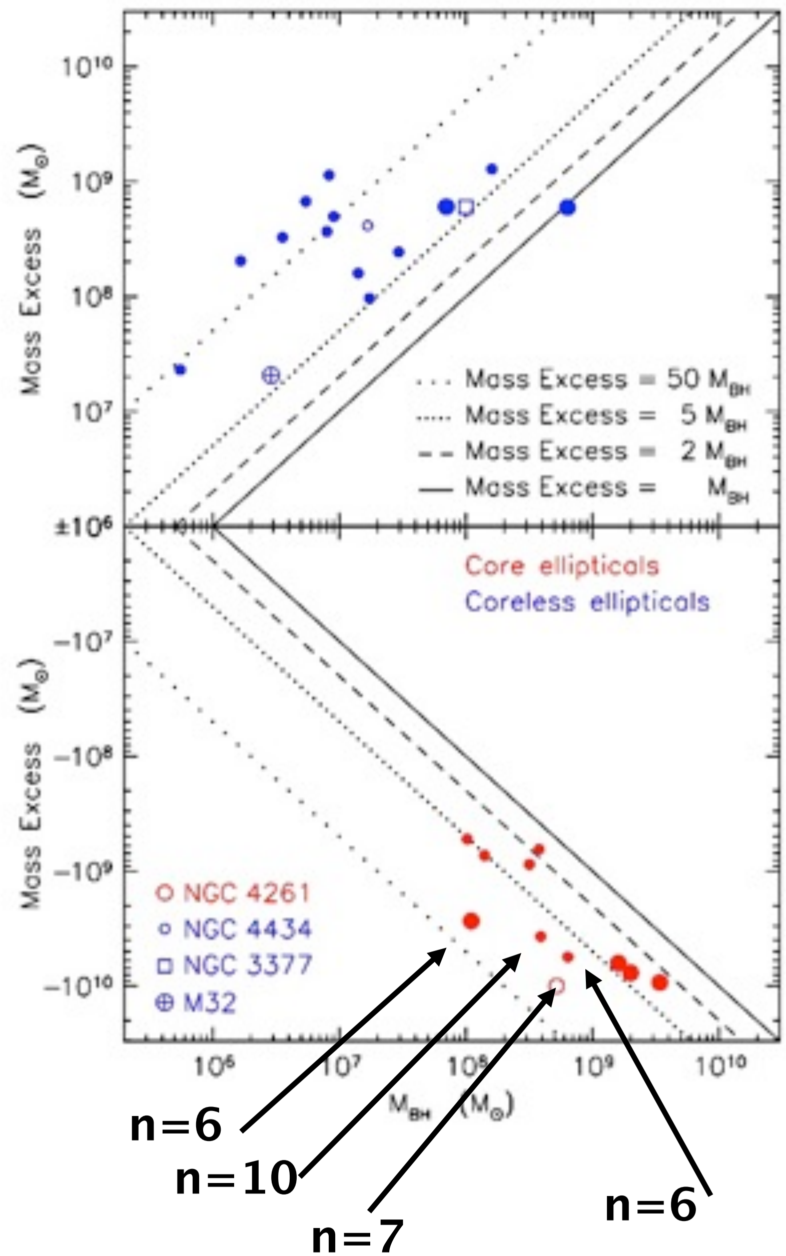
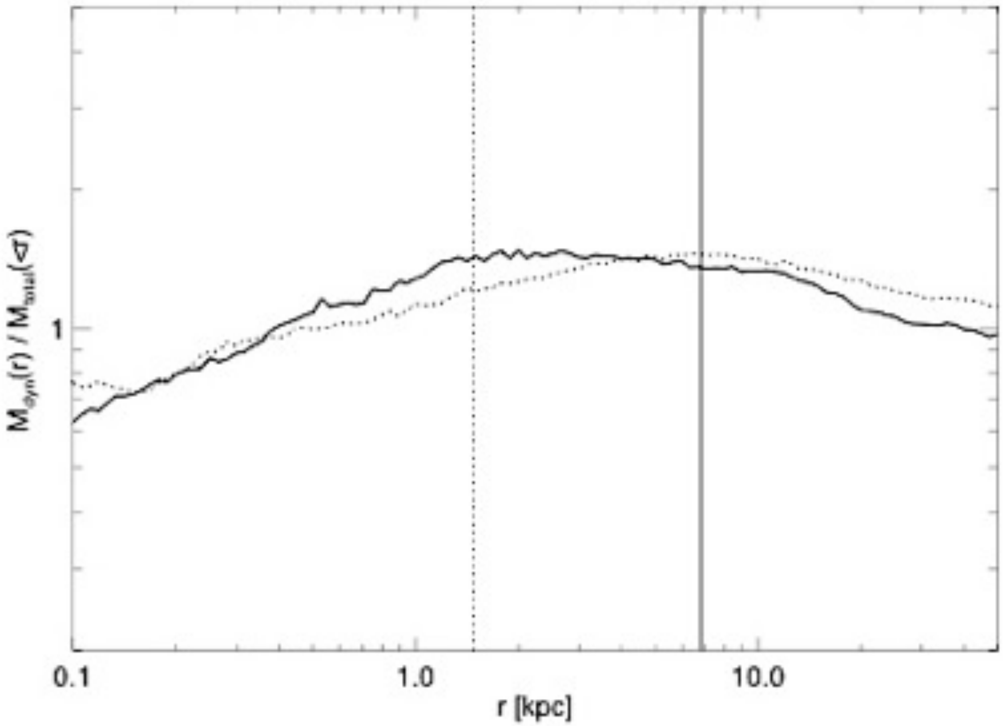
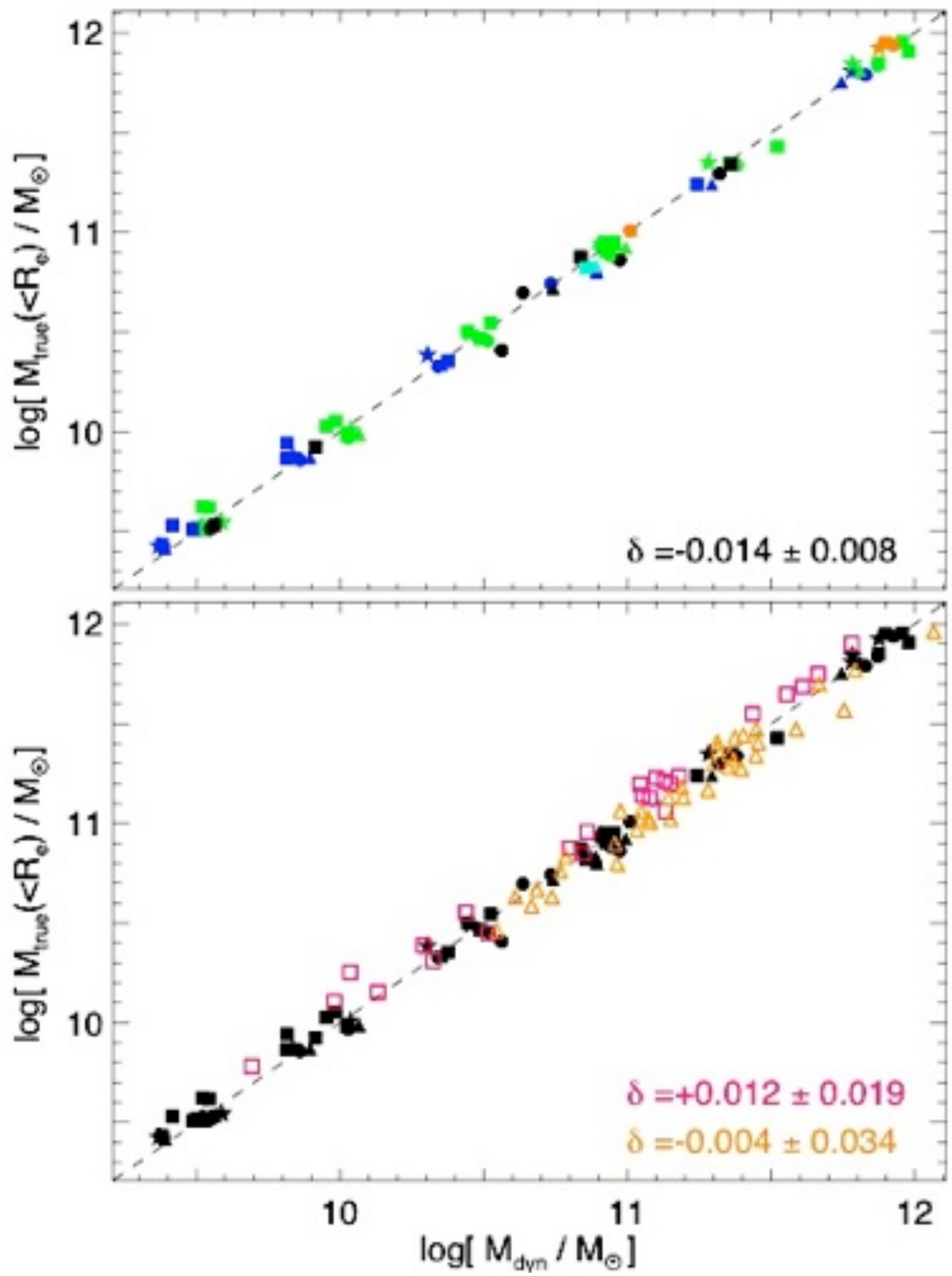




Fundamental Plane Tilt

HOMOLOGY VS. NON-HOMOLOGY



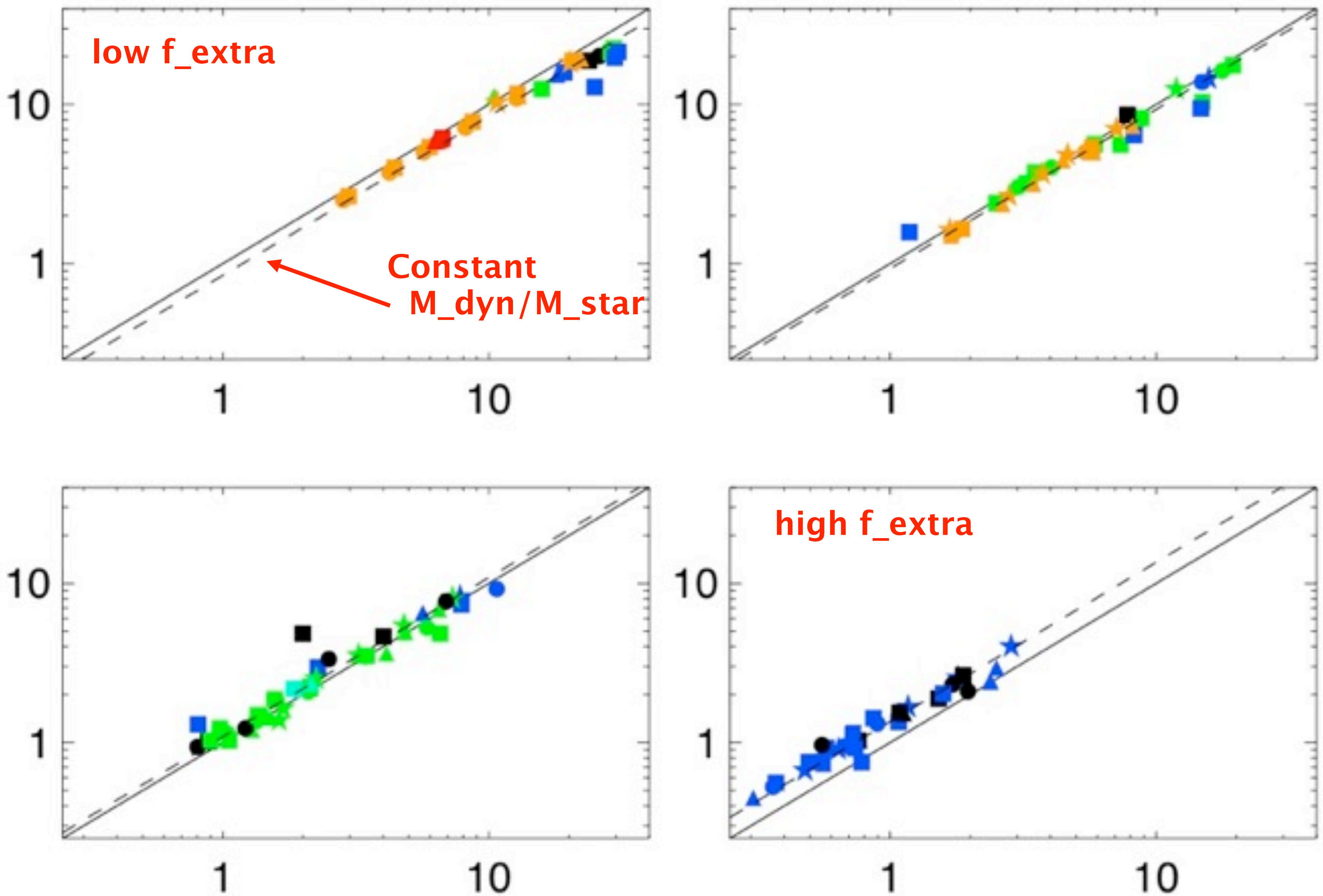


Tuesday, December 25, 12

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

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



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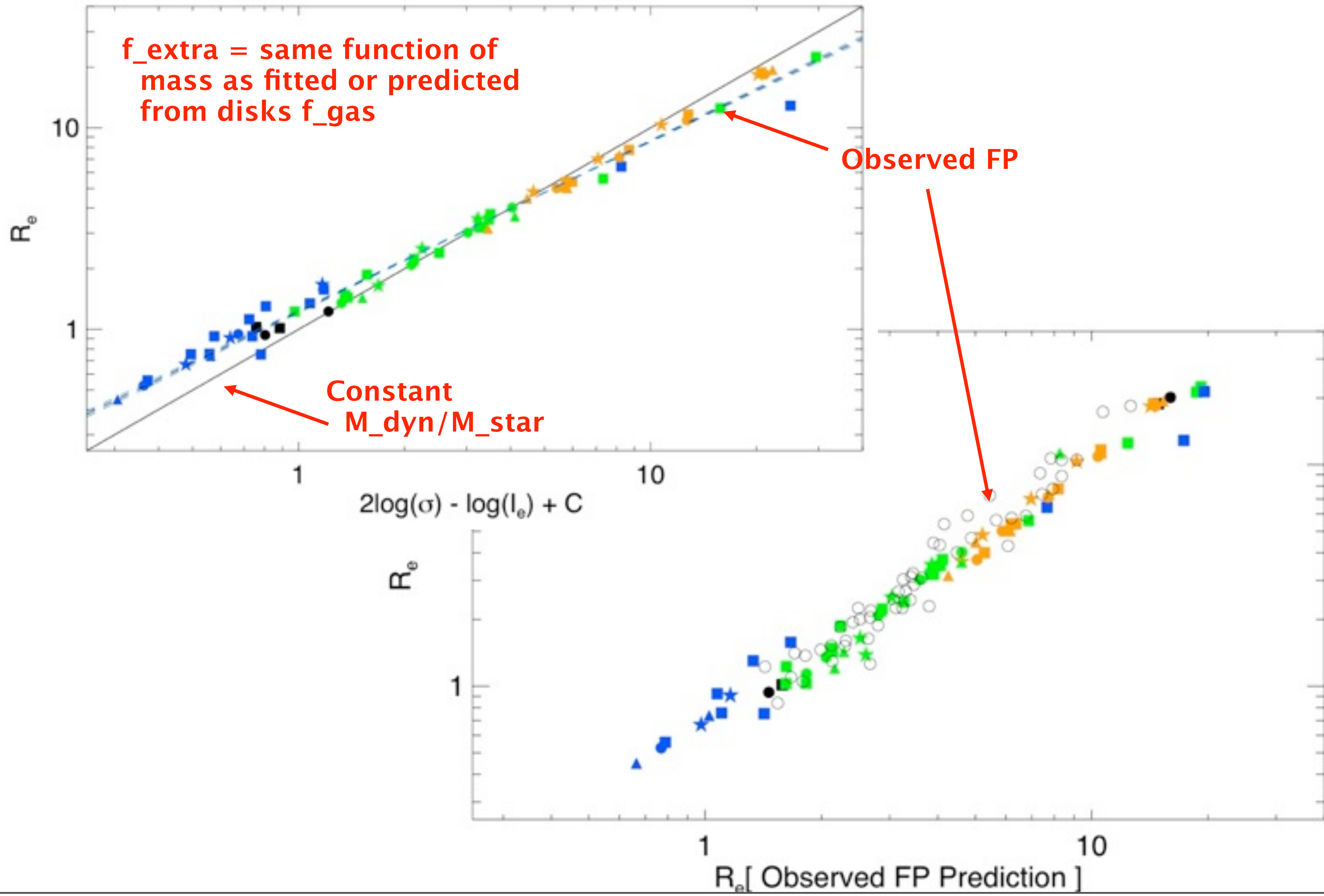
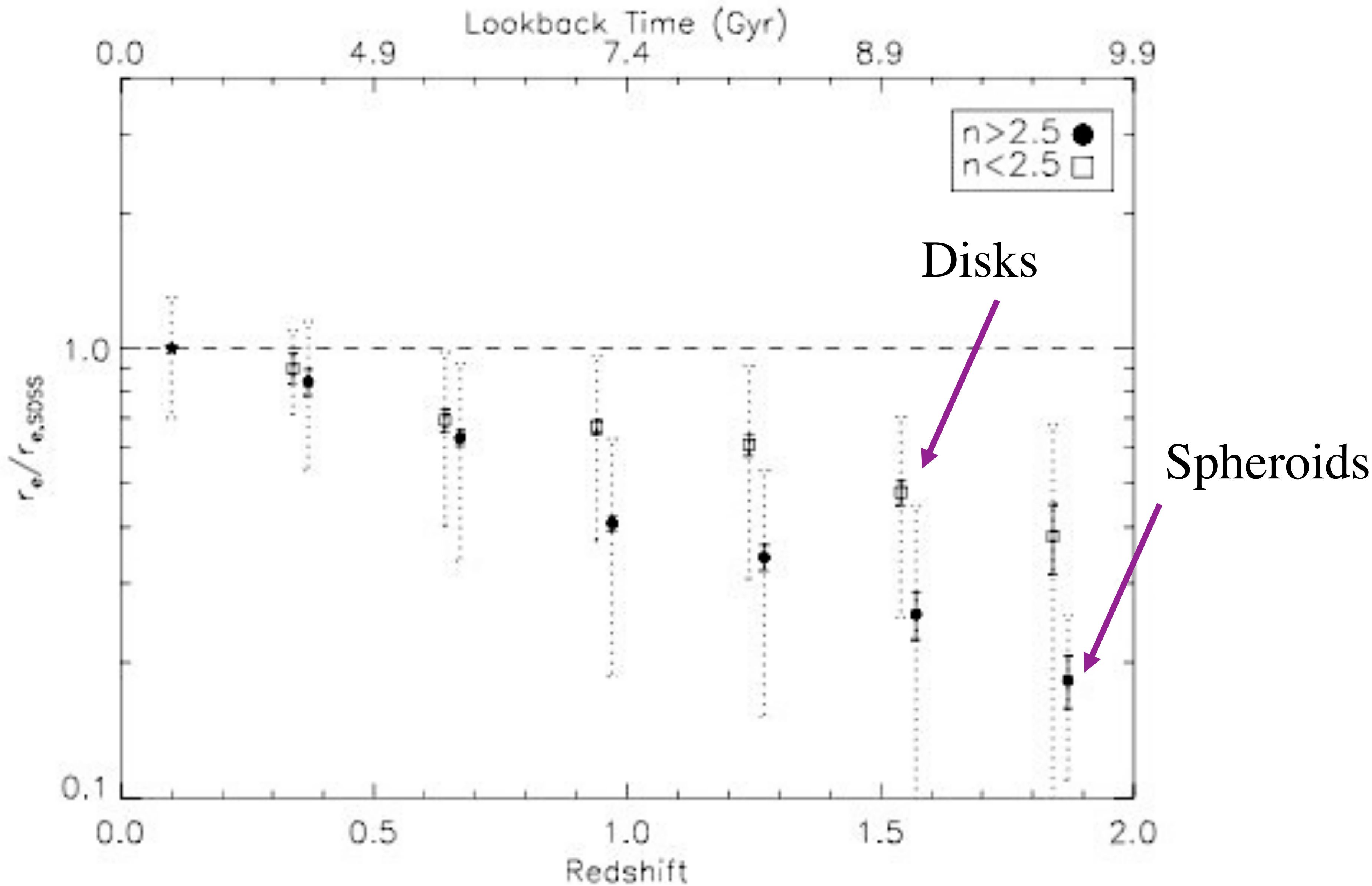


Redshift Evolution

SIZE-MASS RELATIONS

Trujillo et al. 2007

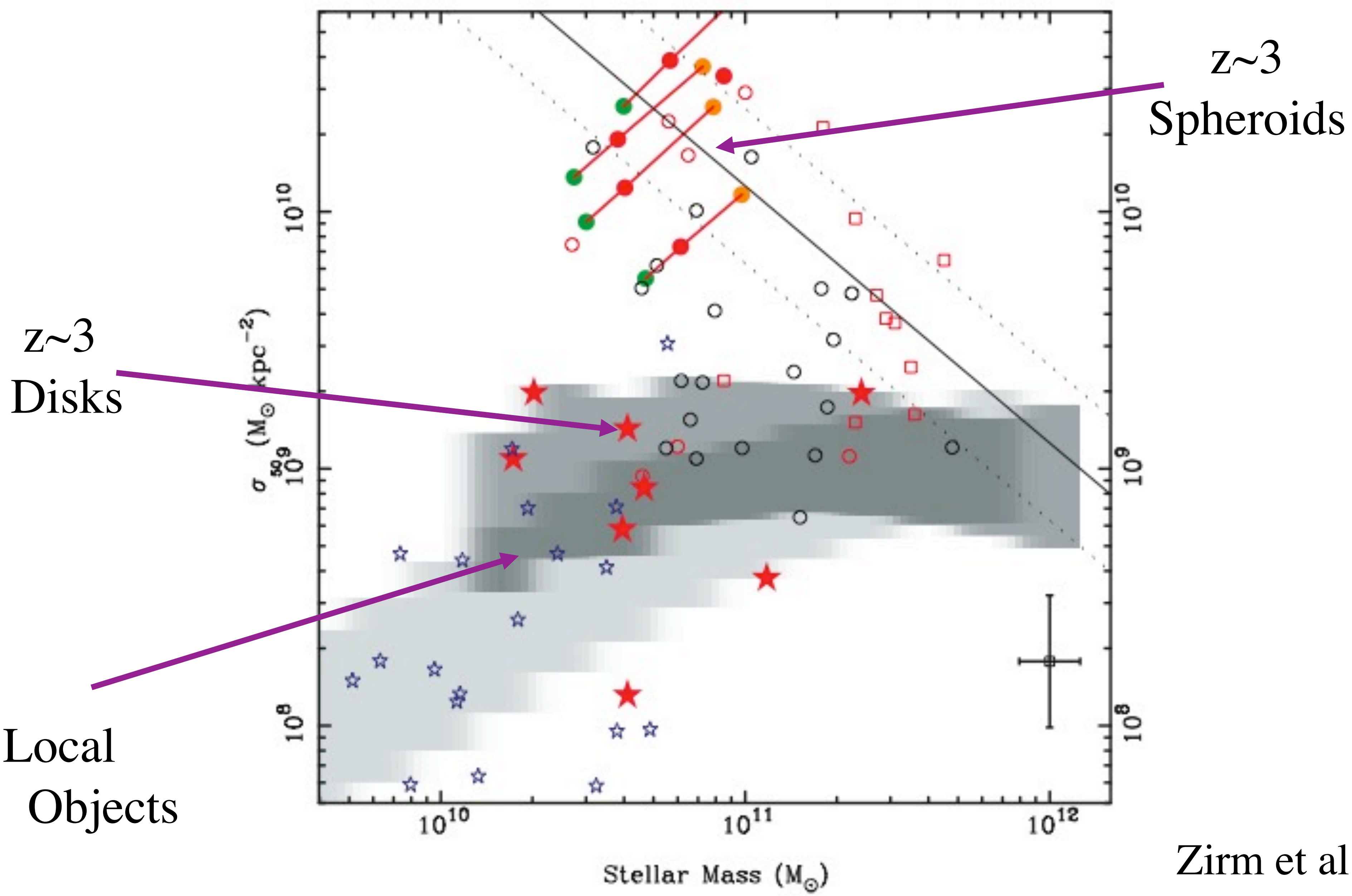
- Spheroids are getting smaller >2x as quickly as disks!



Redshift Evolution

SIZE-MASS RELATIONS

- By z~3, massive ellipticals are little bigger than a starburst (~kpc)

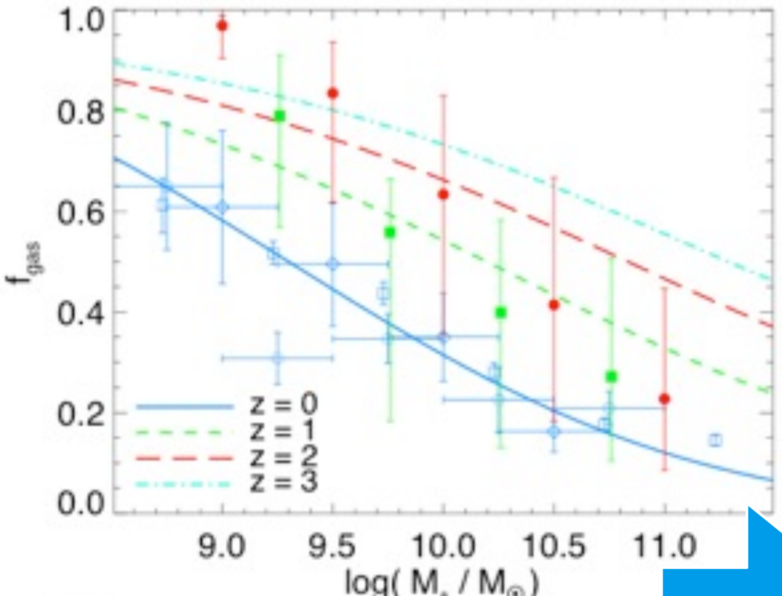


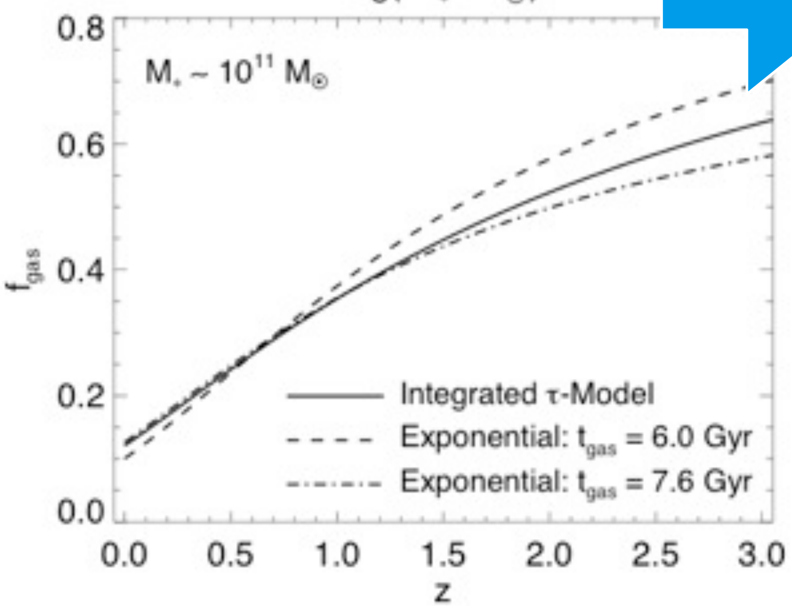
Zirm et al.

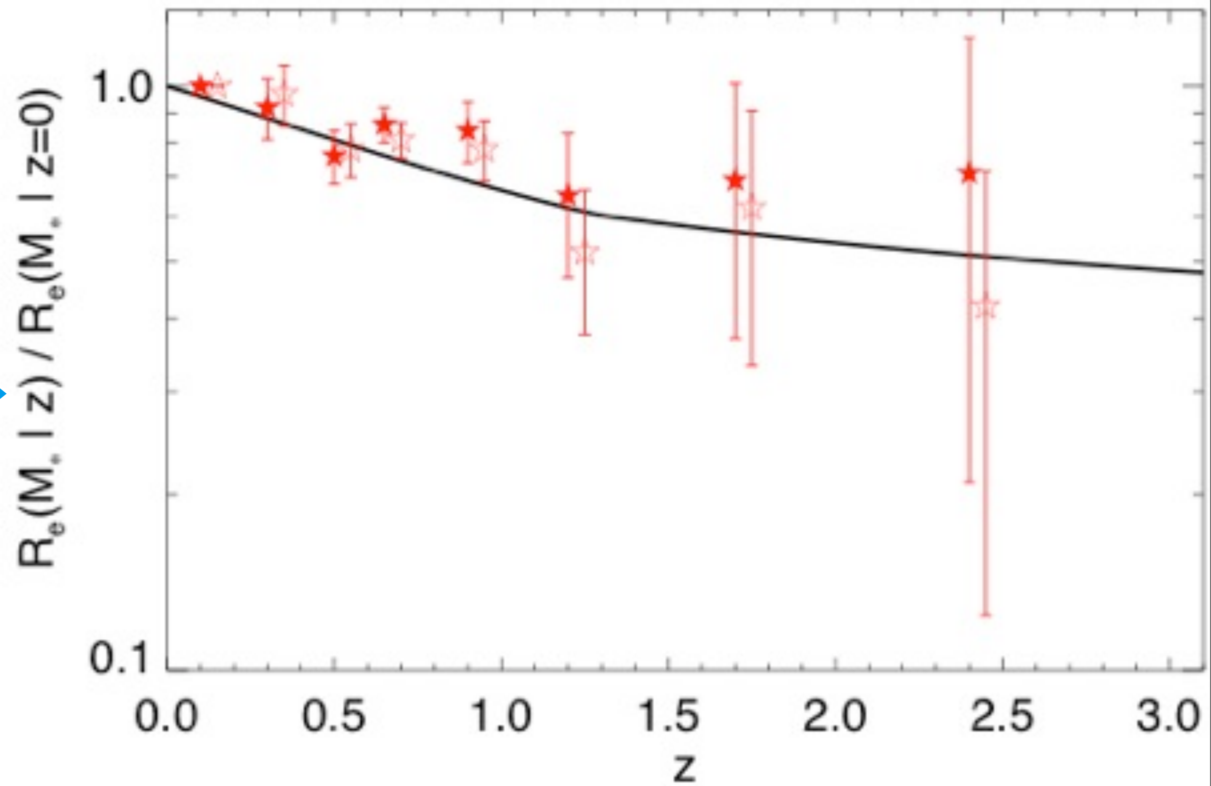
Redshift Evolution

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_final = E_initial = 2 (M_i * sigma_i^2)

  M_f = 2 M_i -- so sigma_f = sigma_i

  virial theorem -- R_f = 2 * R_i

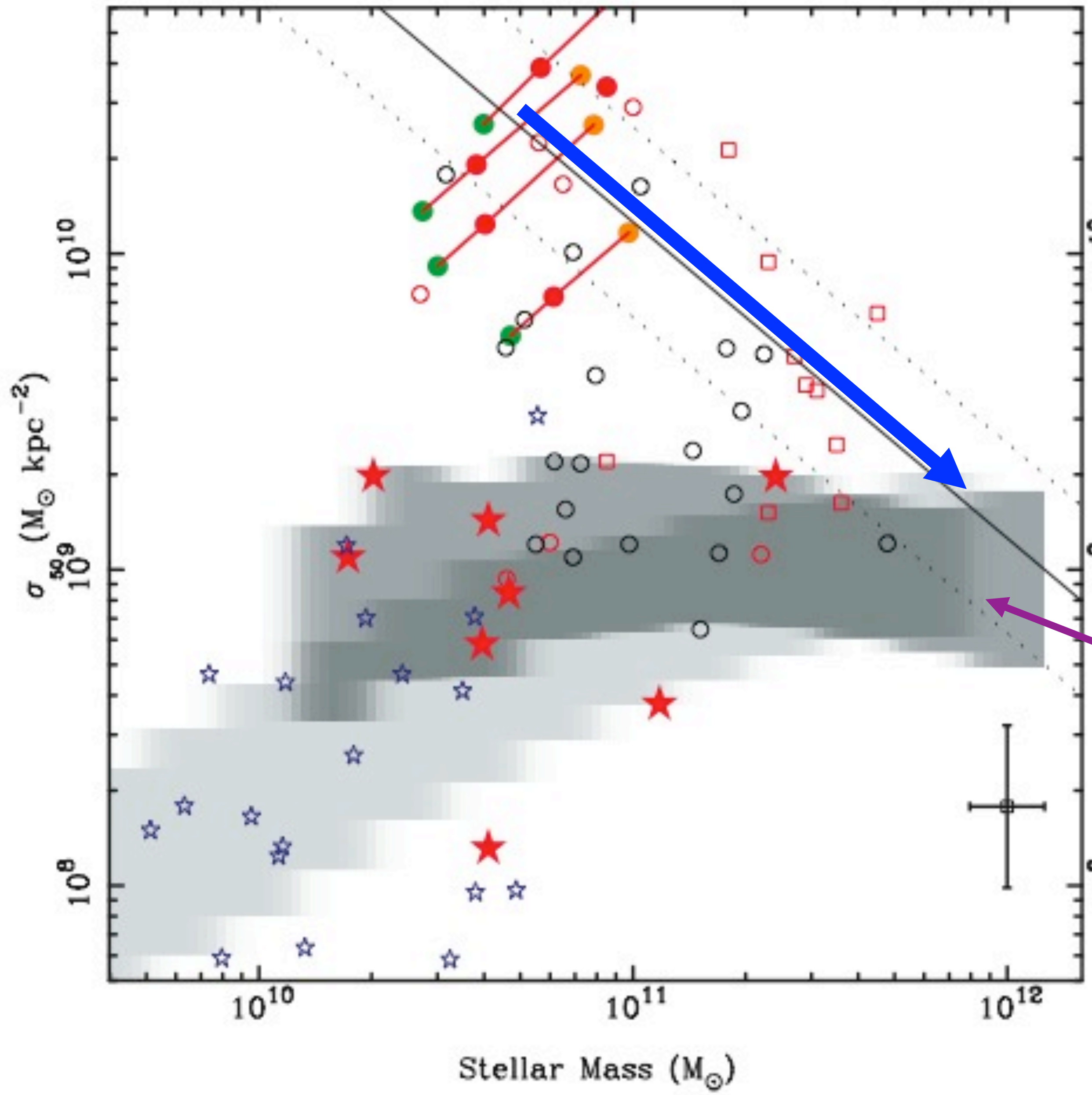
- Relative to the slope of the size mass relation (R ~ M^1/2), you're rapidly moving up (increasing R)

- 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~3 galaxies are the most massive galaxies today

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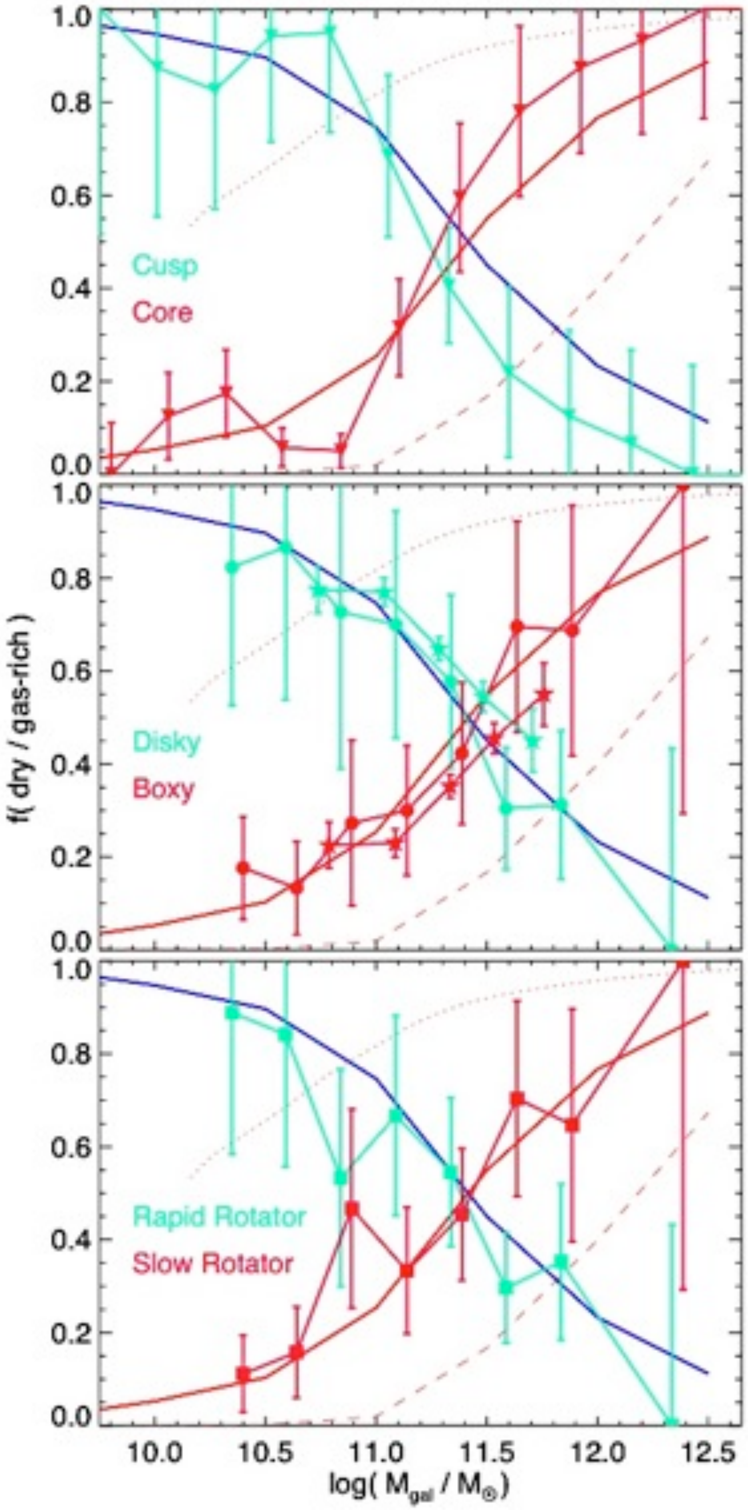

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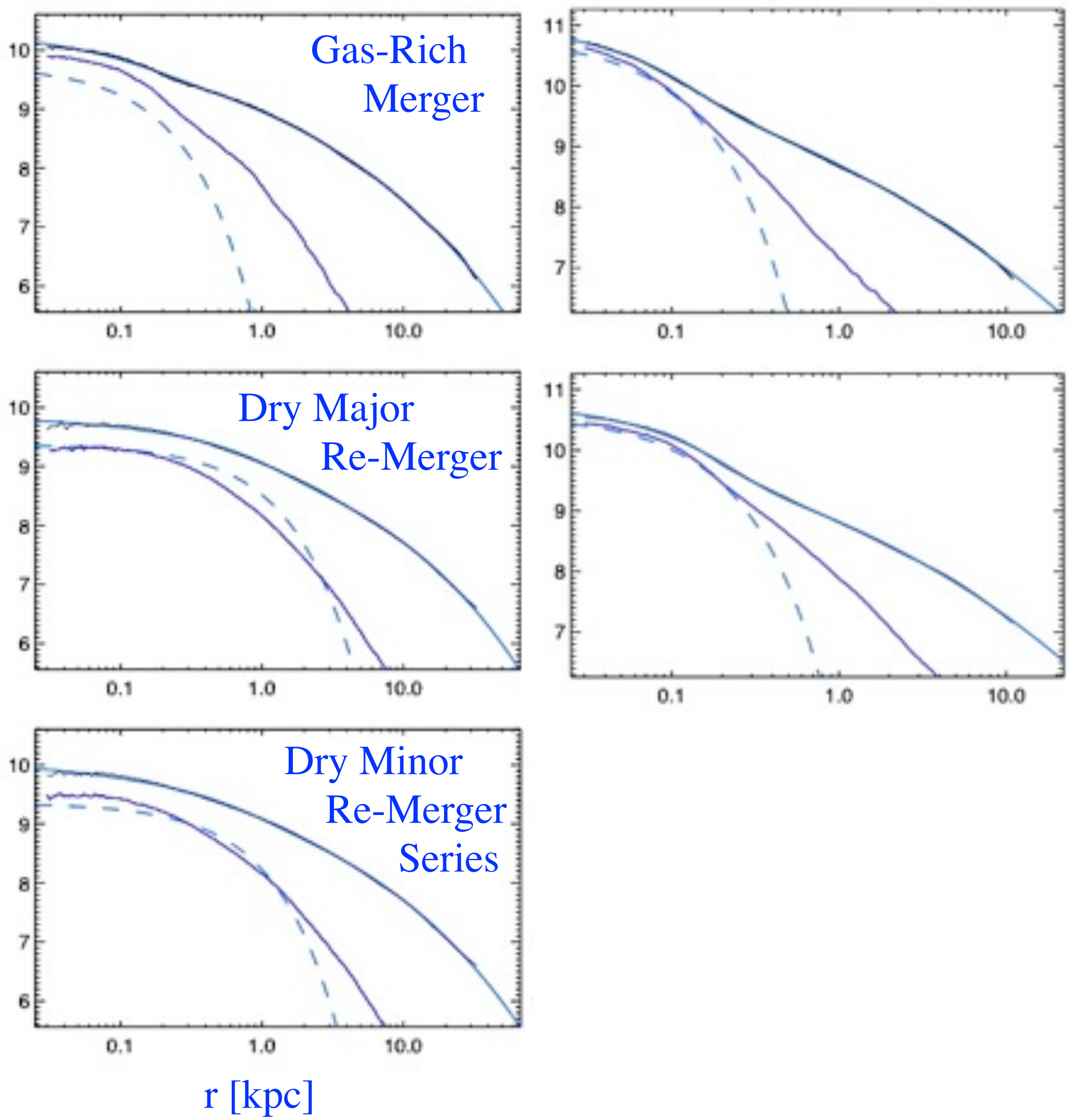

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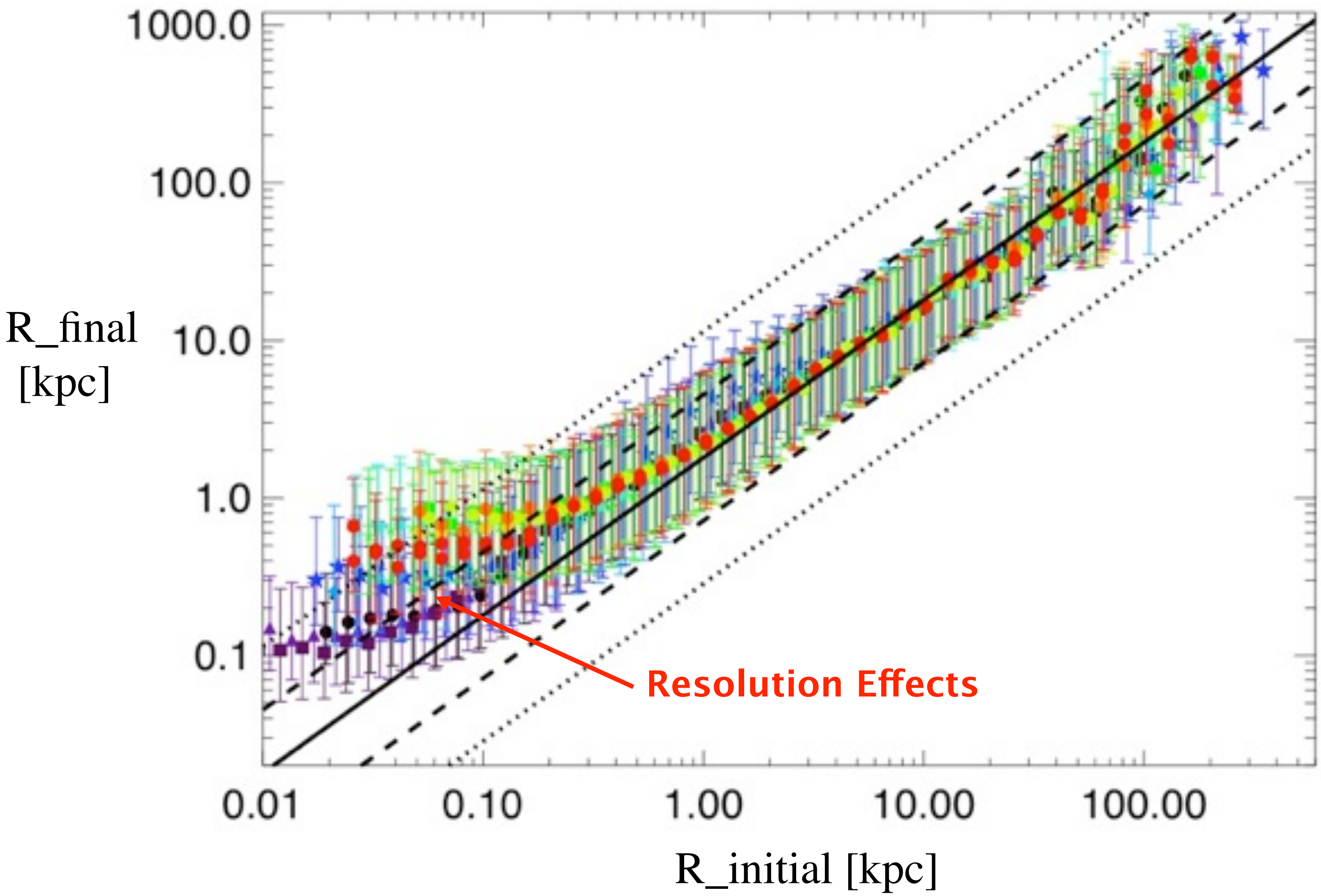

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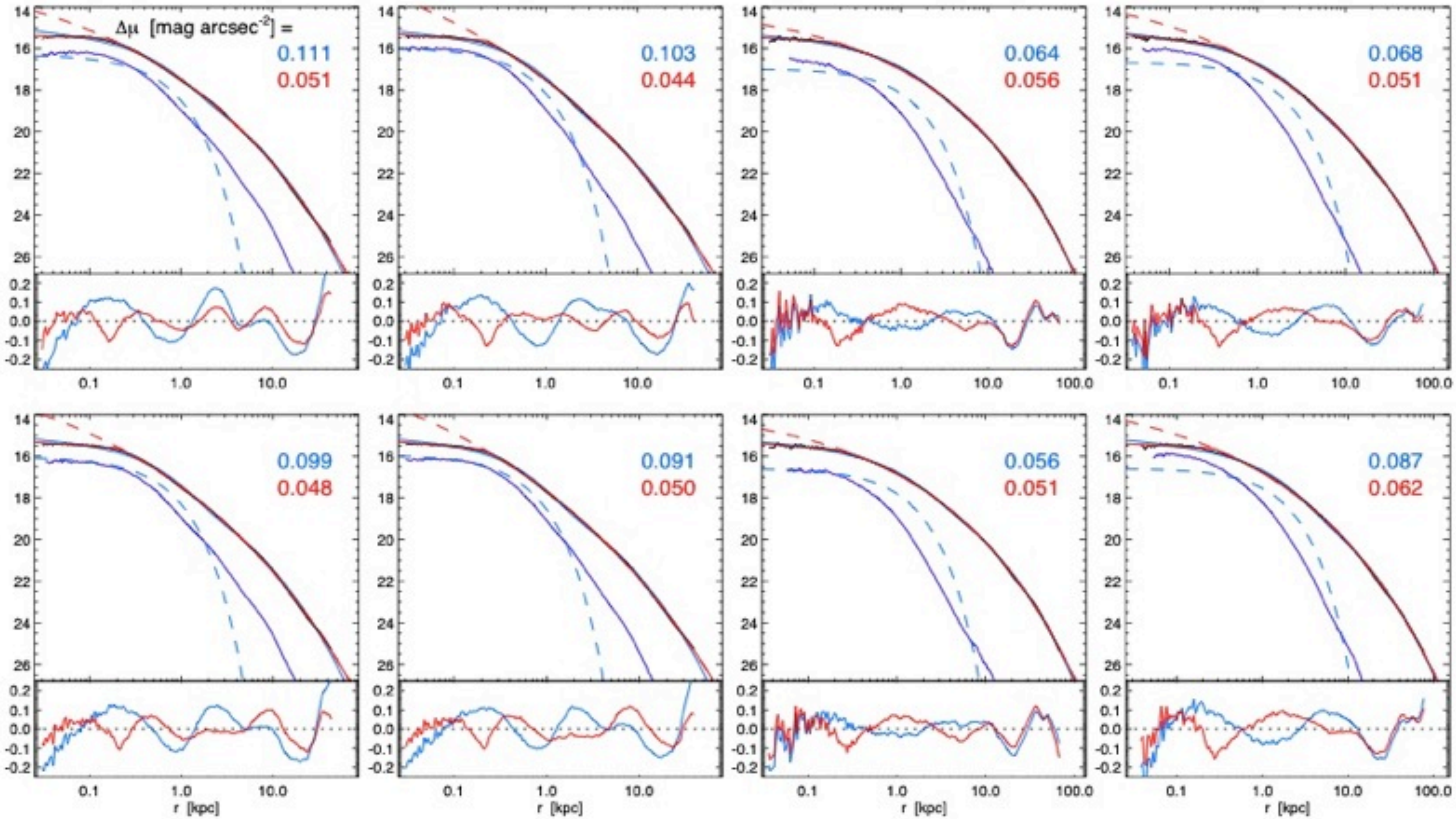

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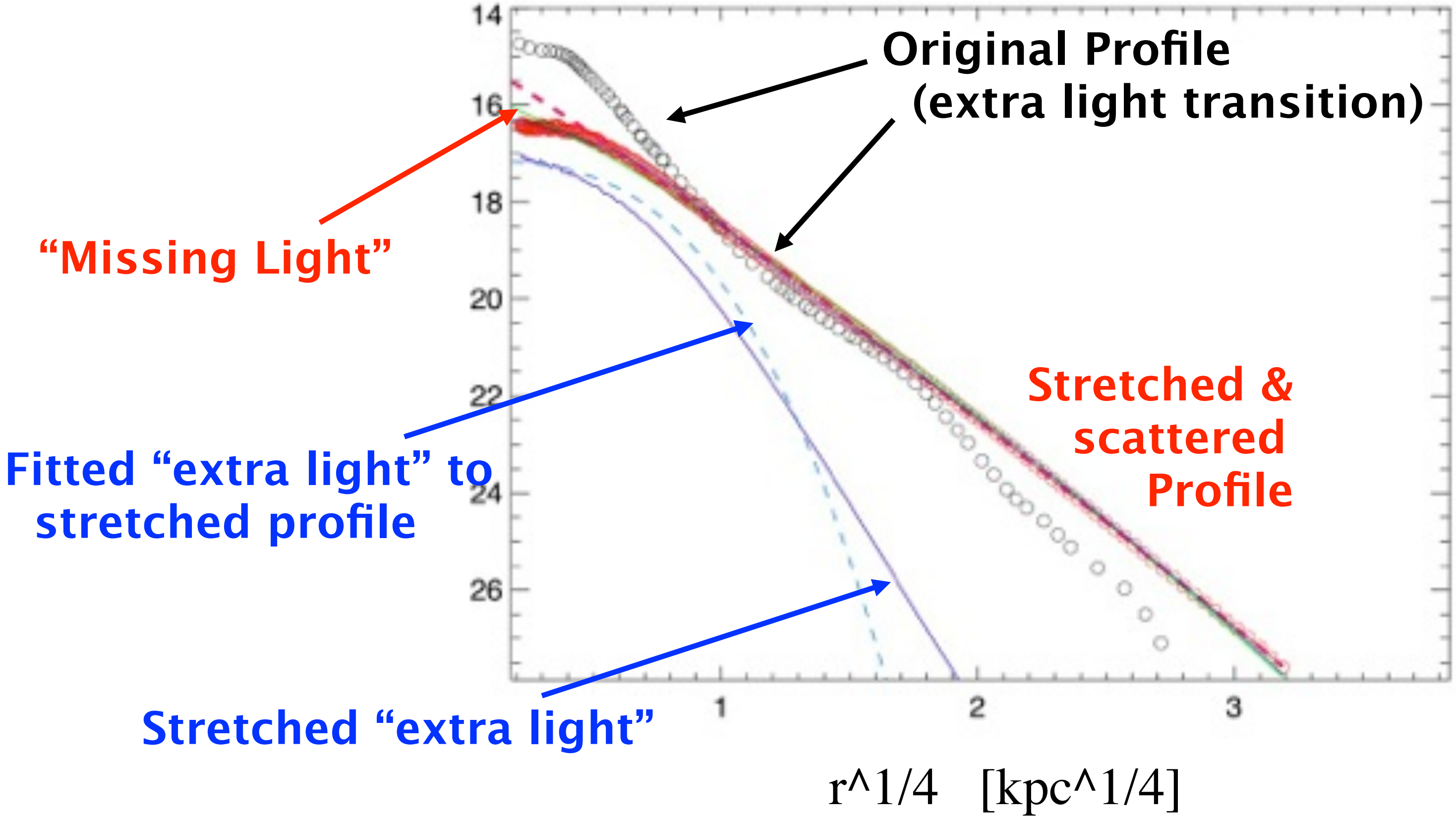

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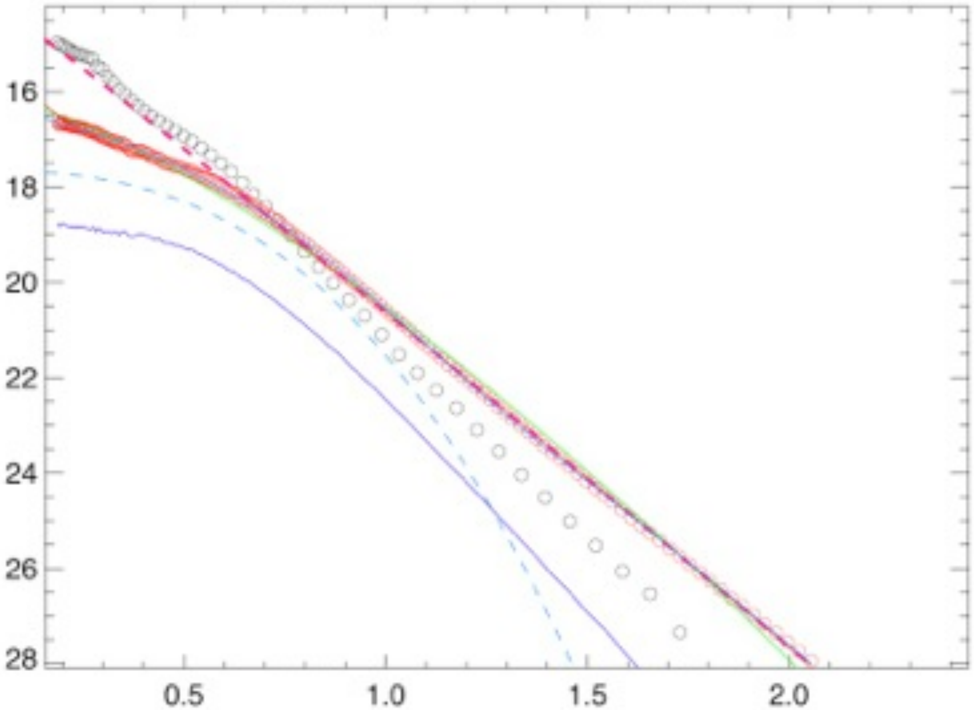
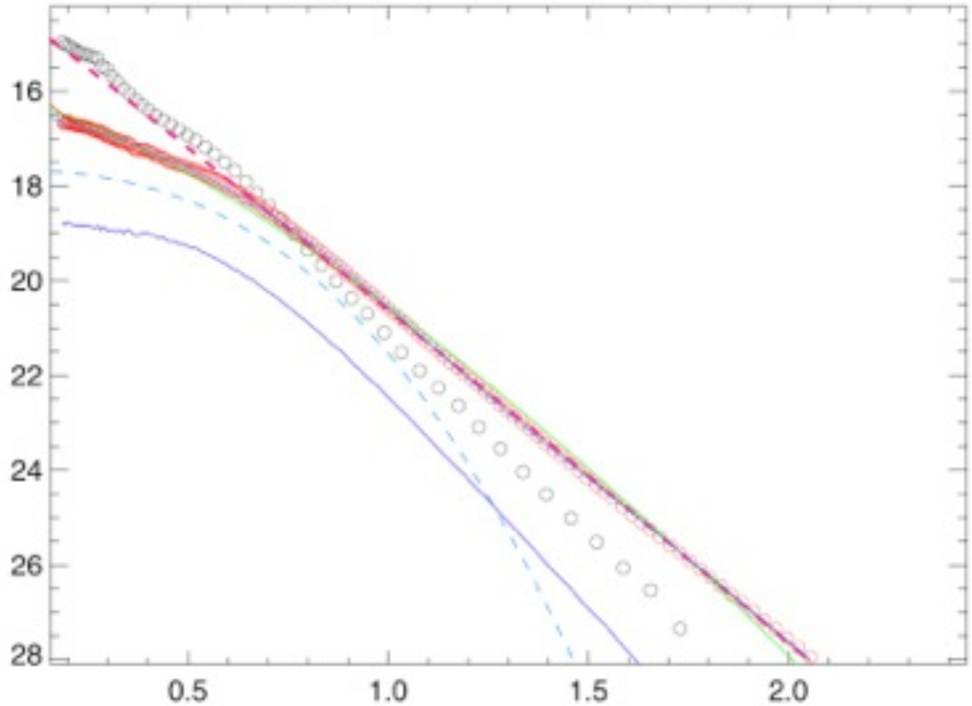


r^1/4 [kpc^1/4]



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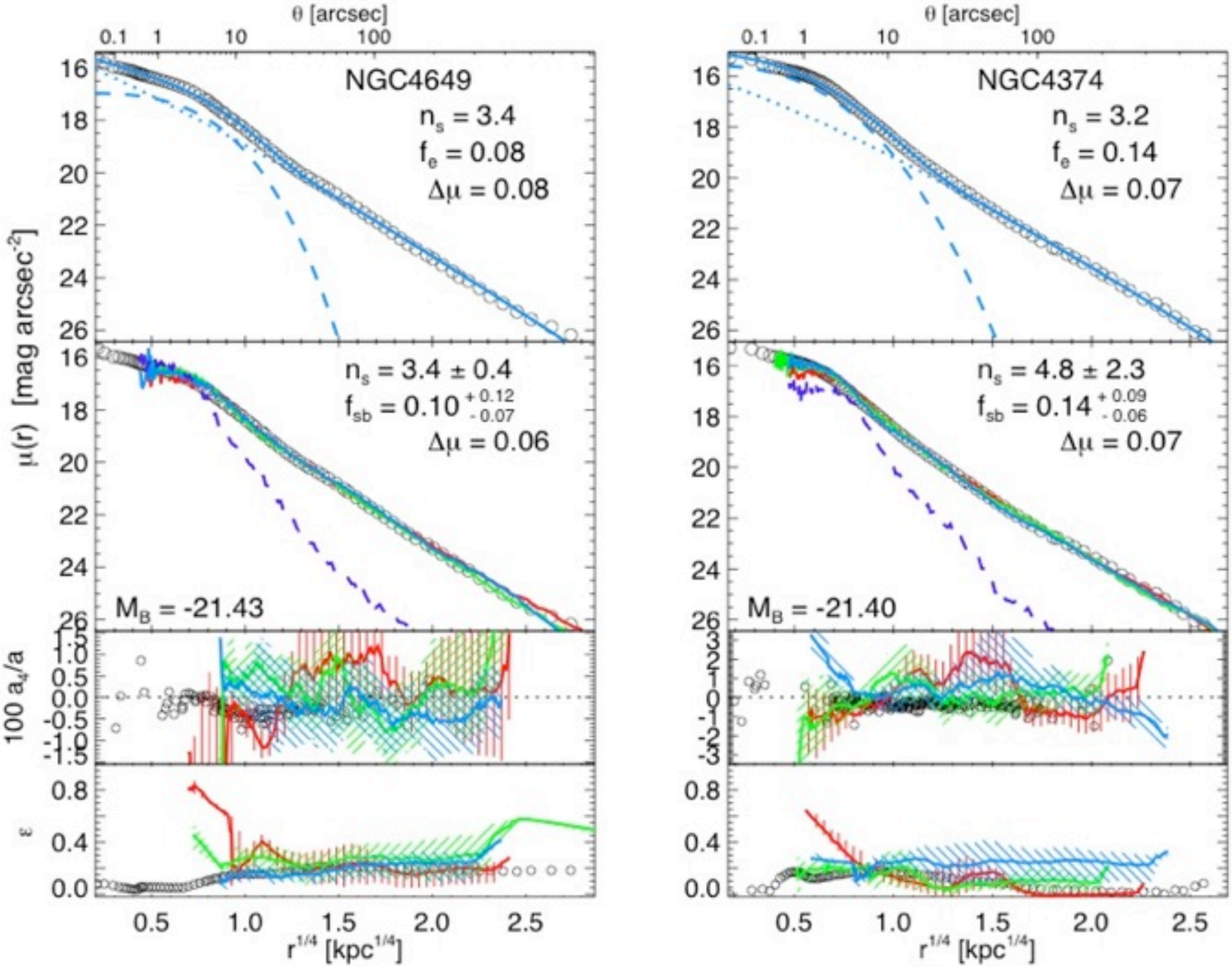

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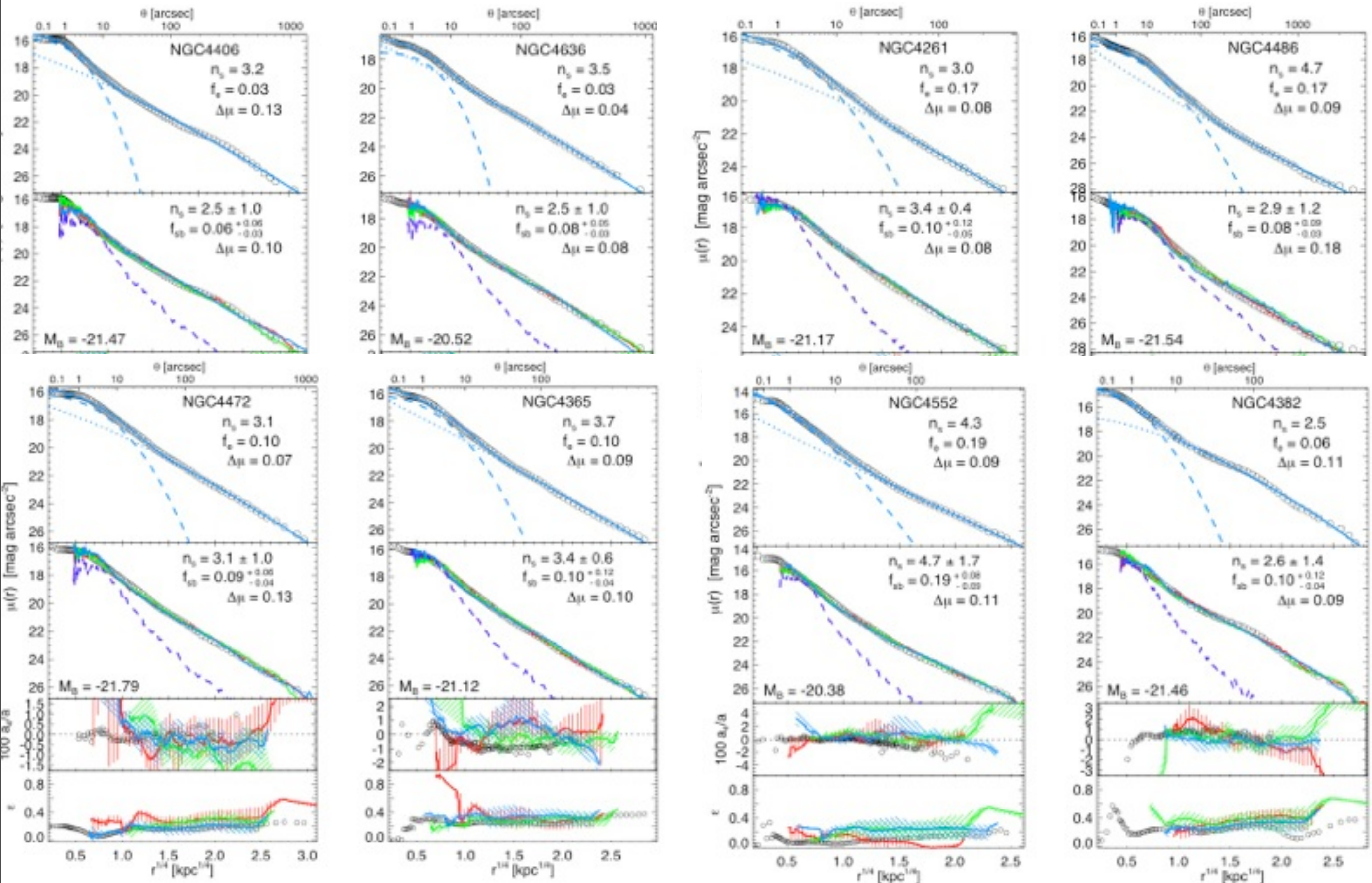

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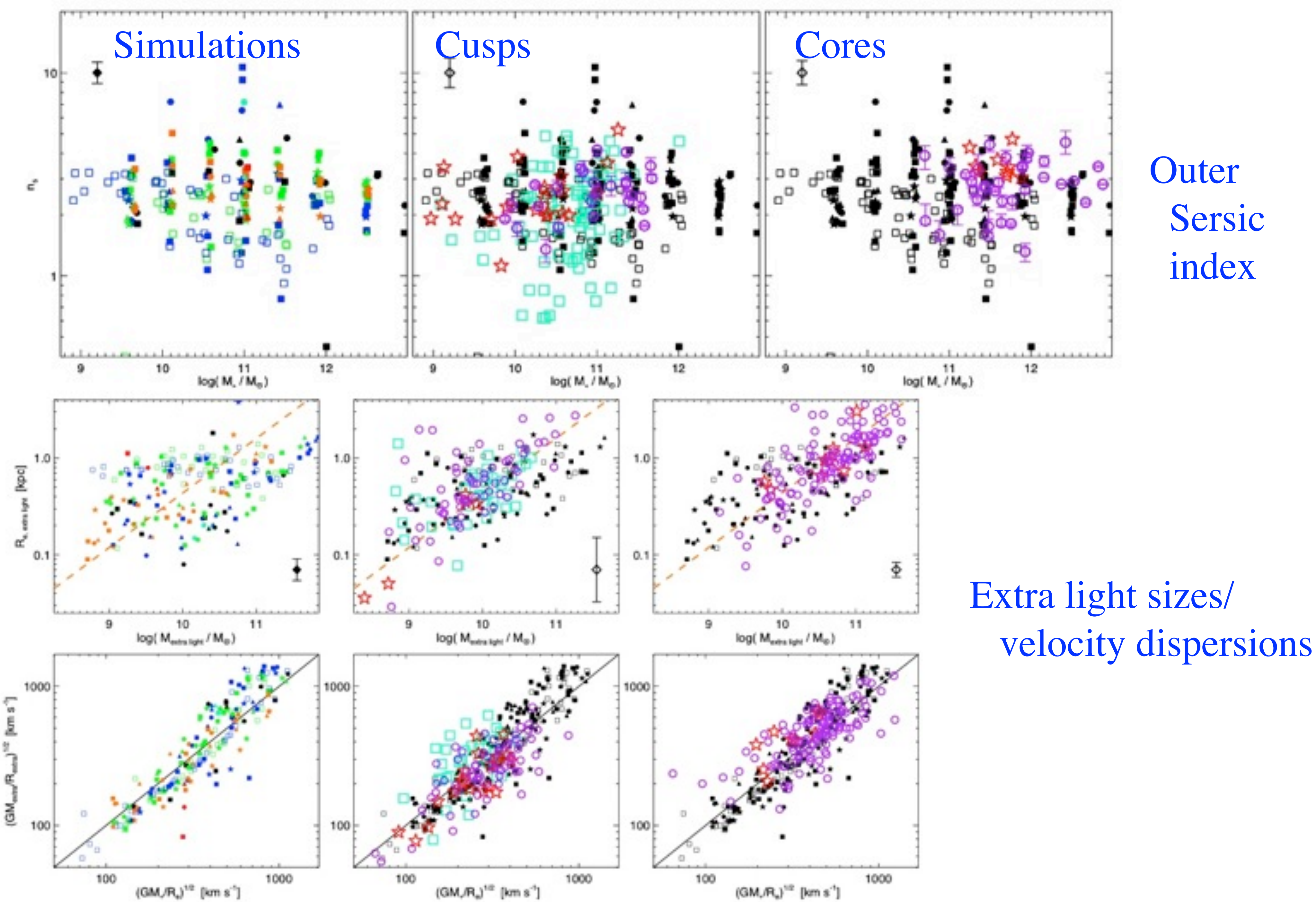

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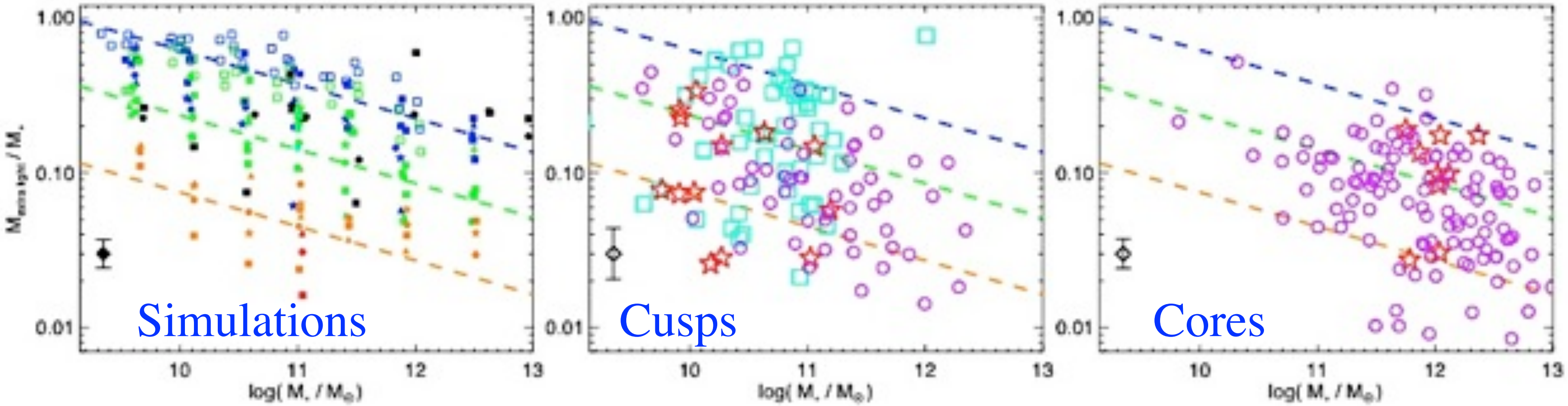
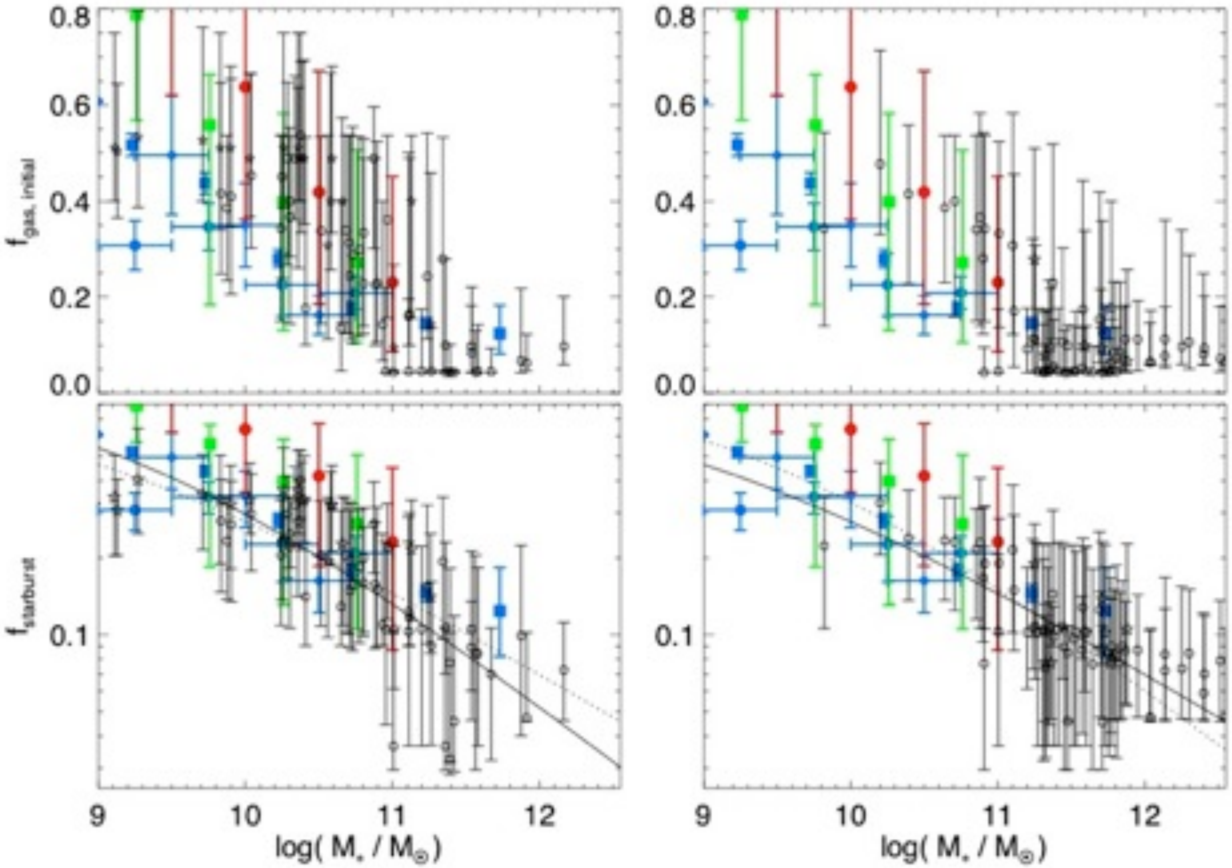


Extra light mass fraction



Structure of Spheroids

UNDERSTANDING THE FUNDAMENTAL PLANE

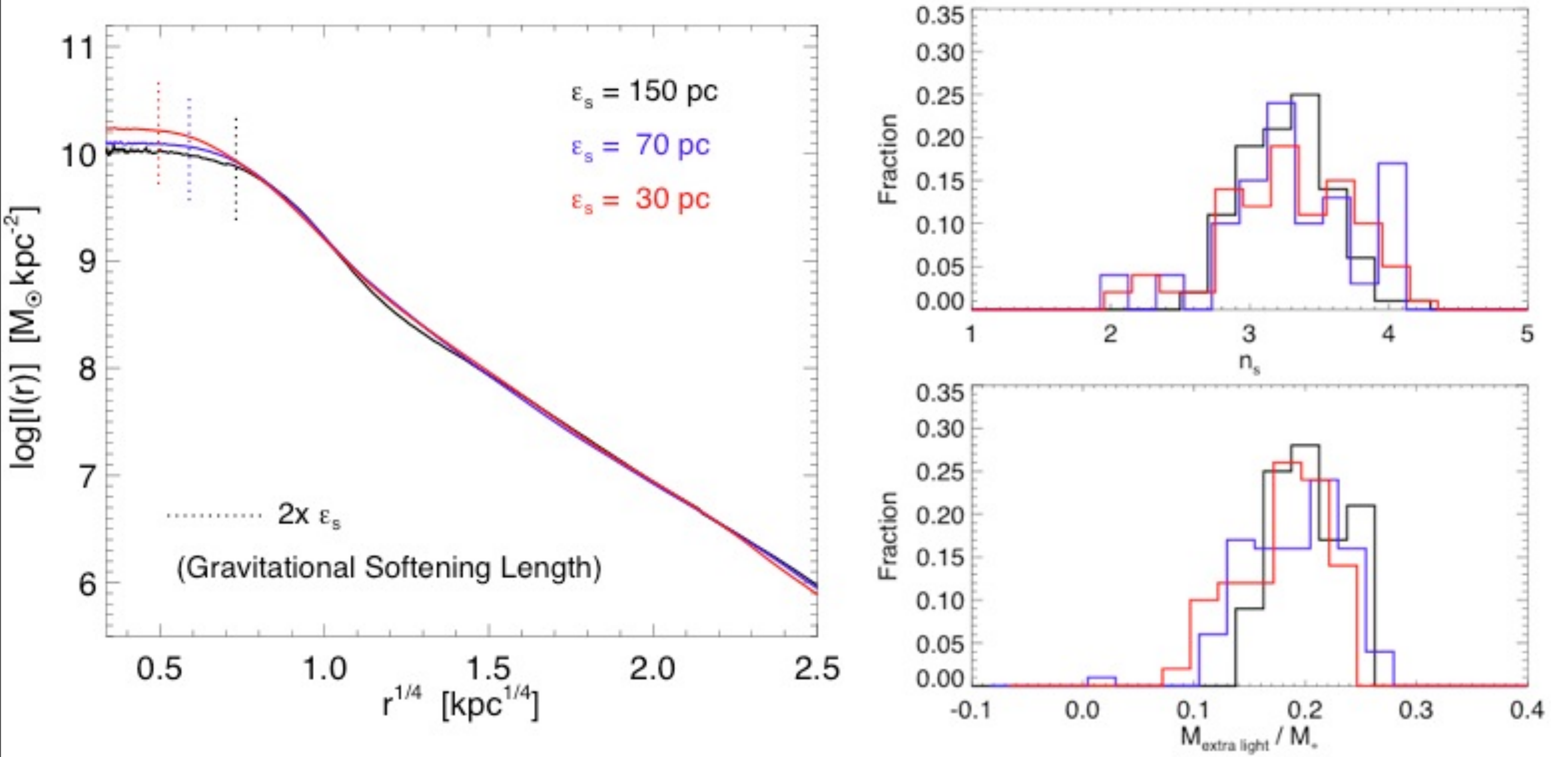
- Instead, the FP is “tilted”:
  - (L / M_dyn) ~ M^{0.1-0.3, depending on the band}
  - three possible explanations:
  - stellar population variation:

    M_dyn ~ M_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)

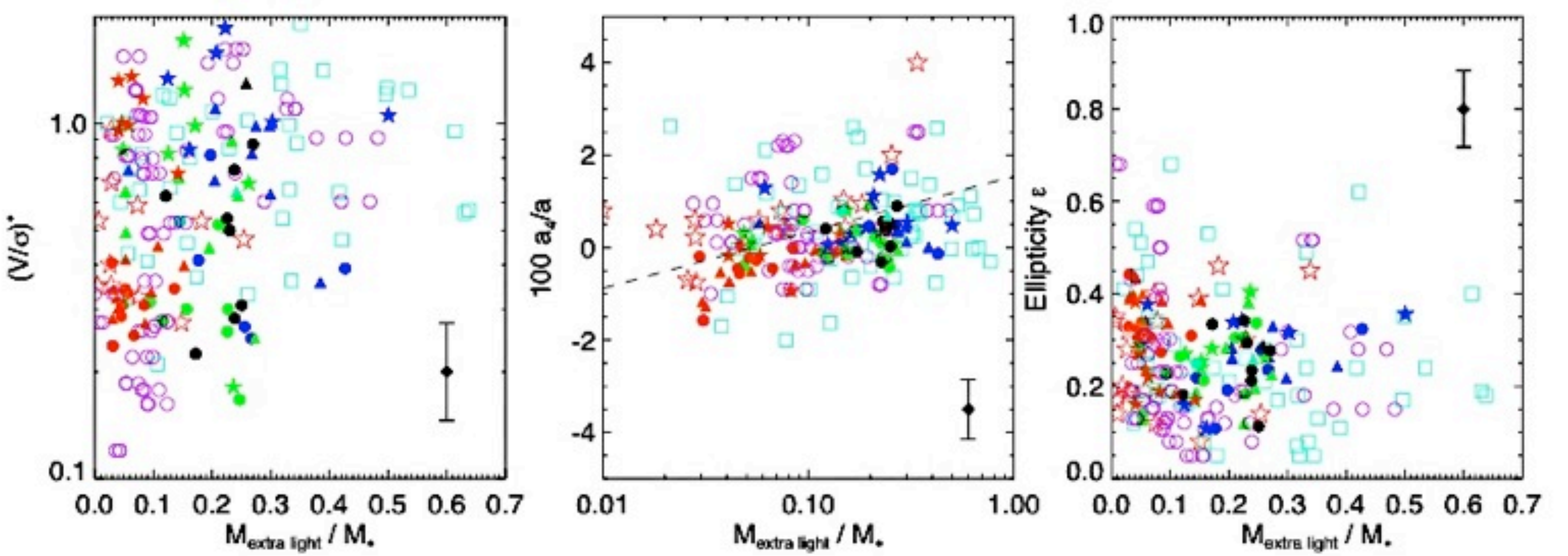
Resolution Studies

RECOVERING THE ROLE OF GAS



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



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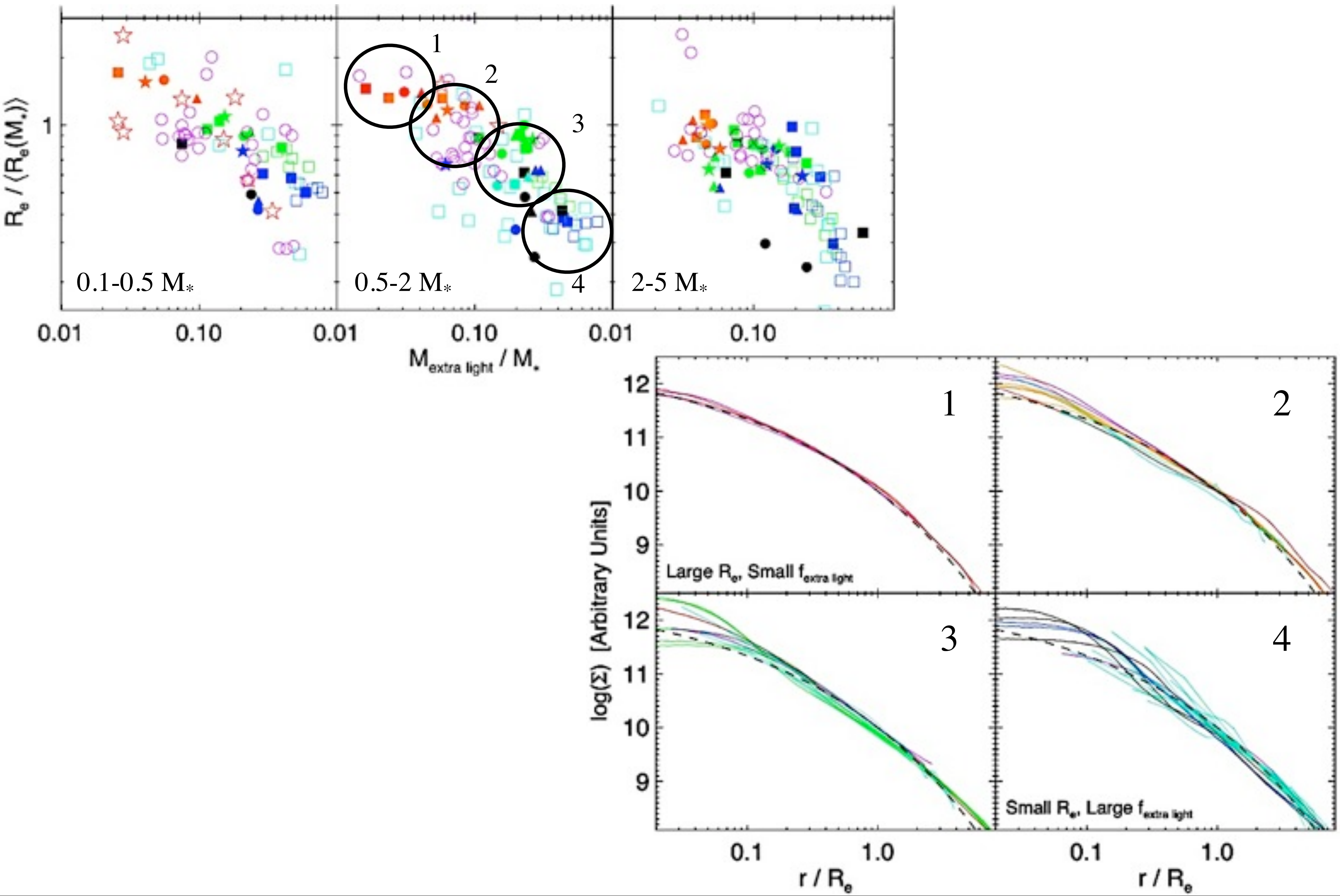
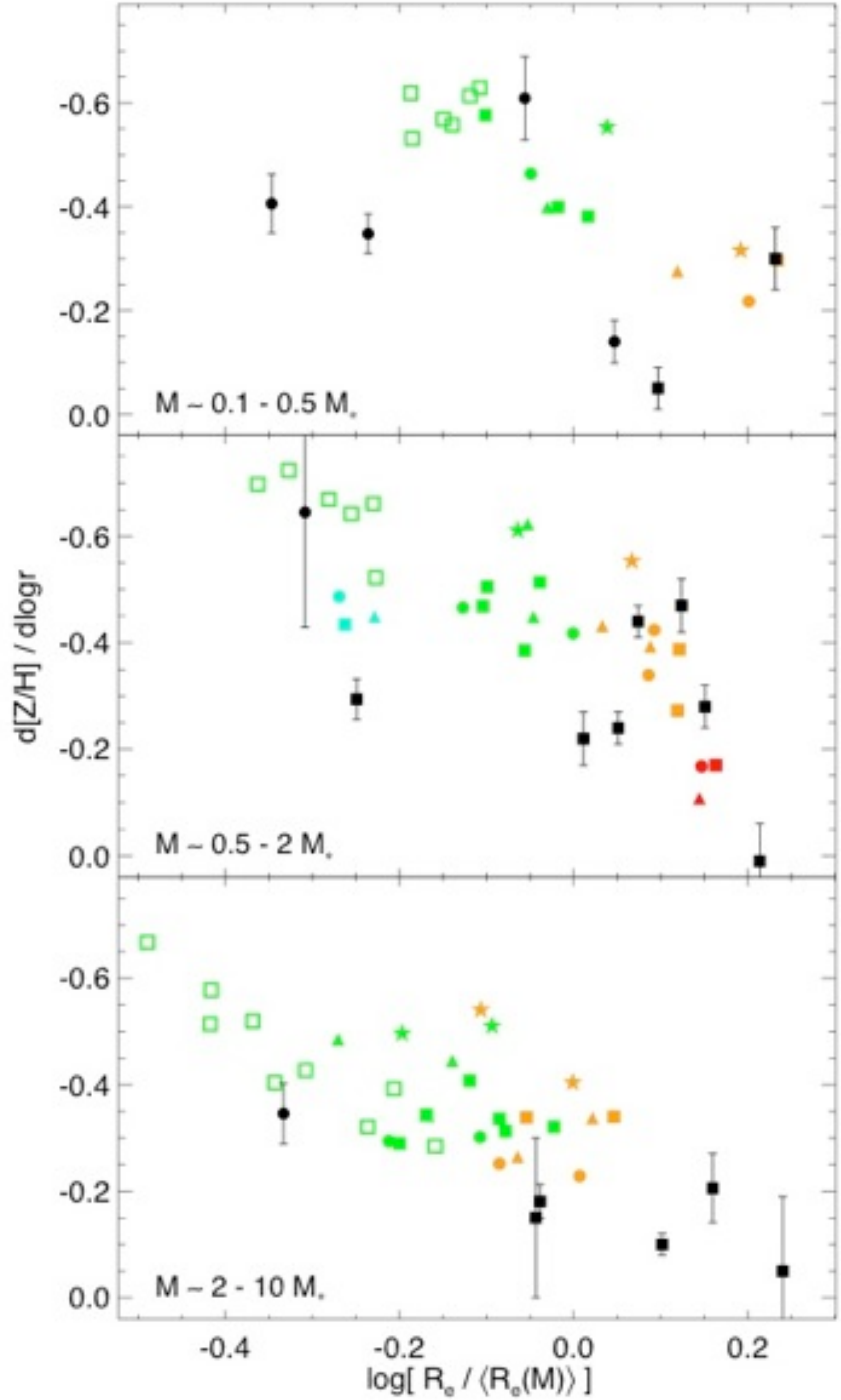


Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

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



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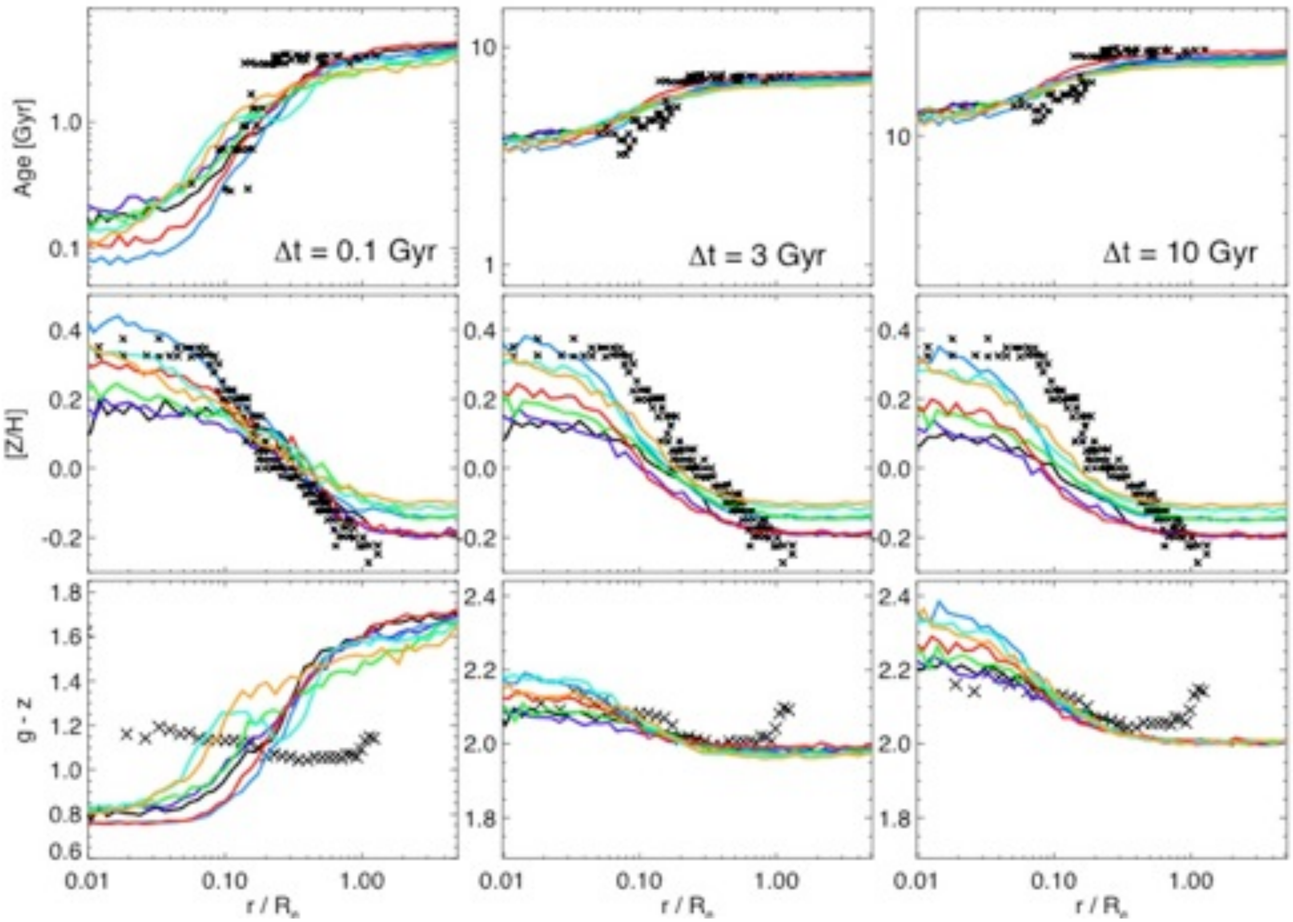
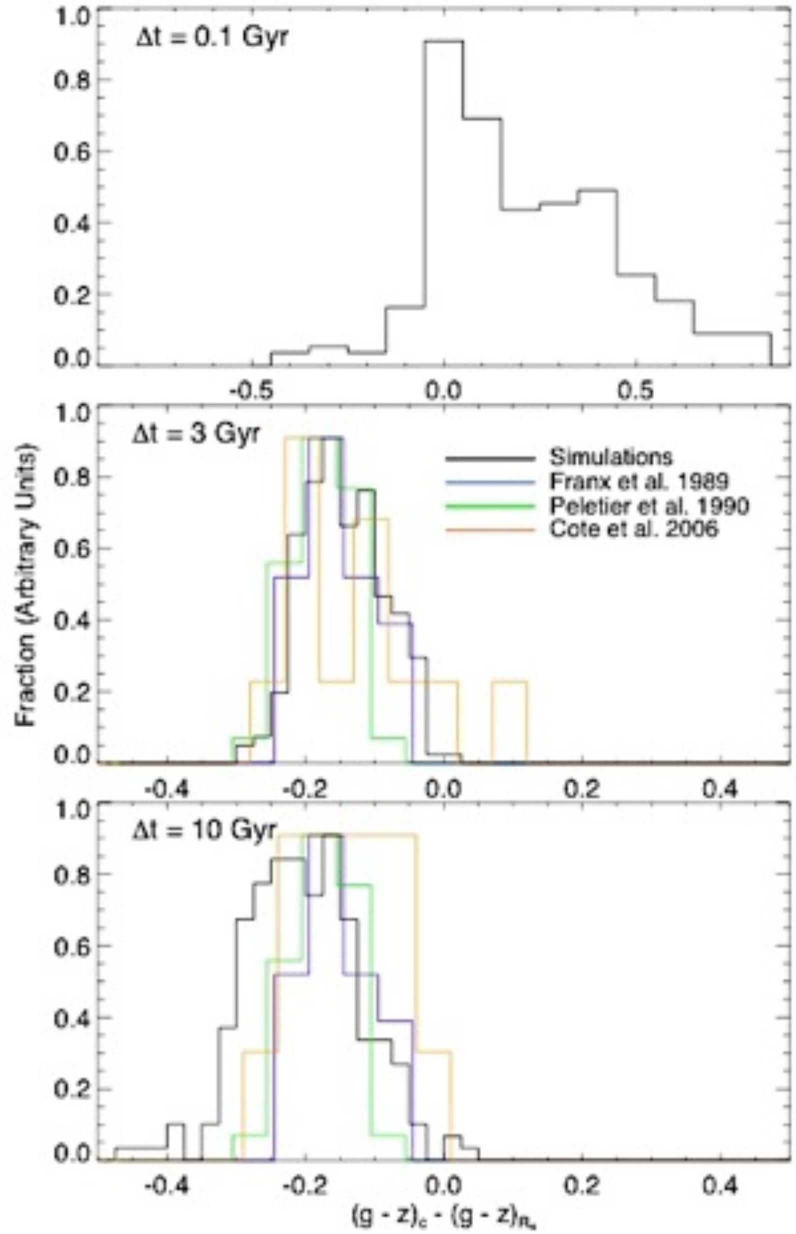
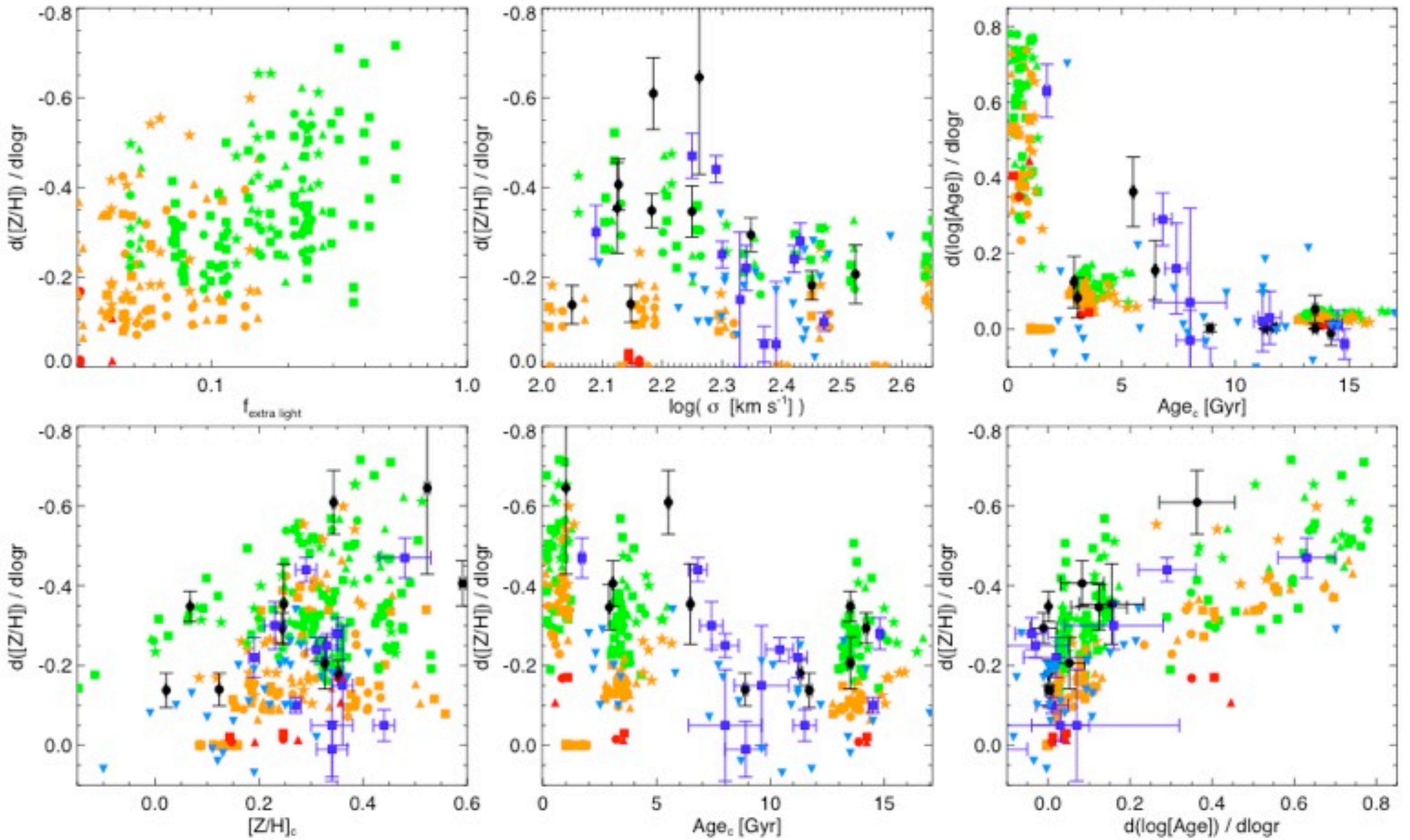


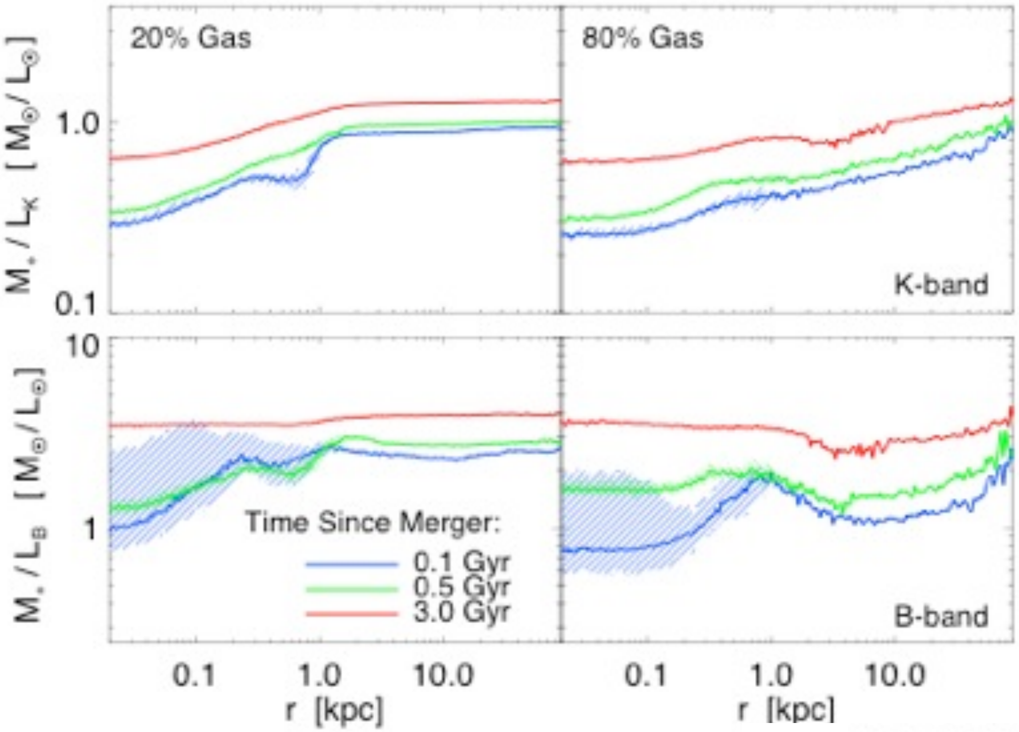


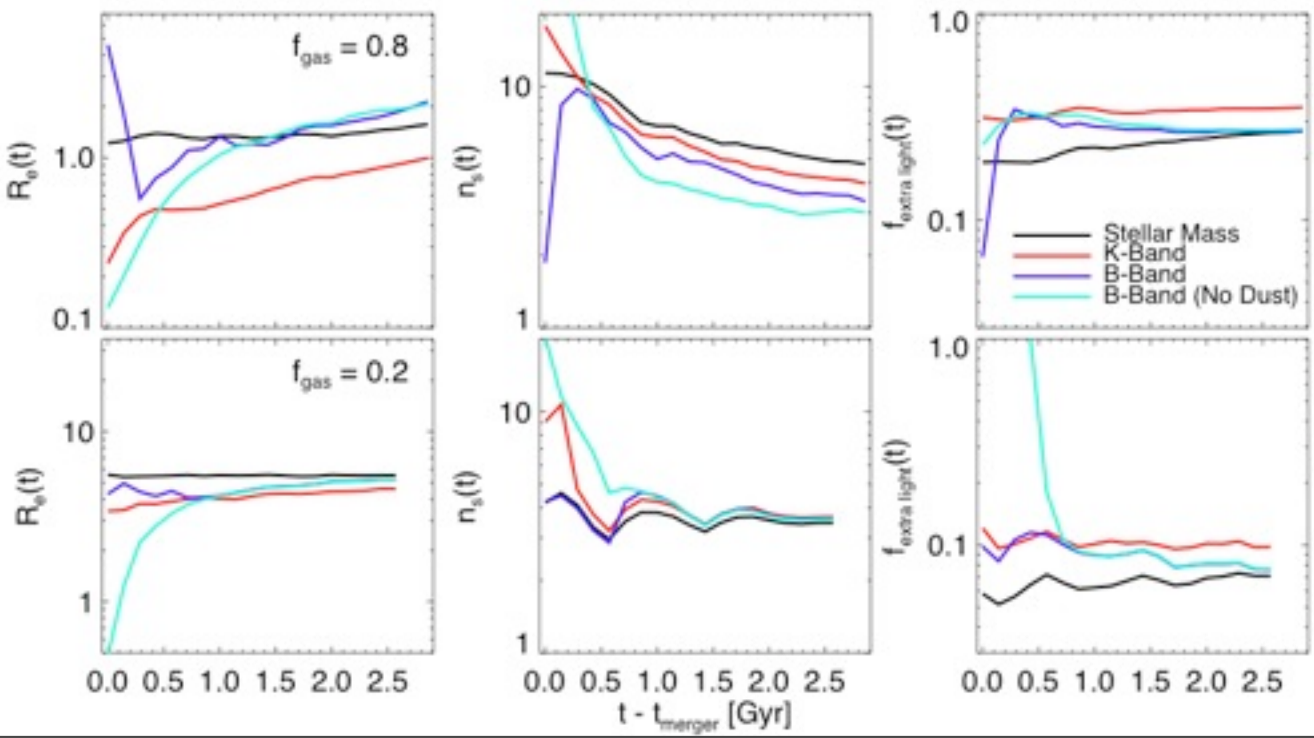
Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



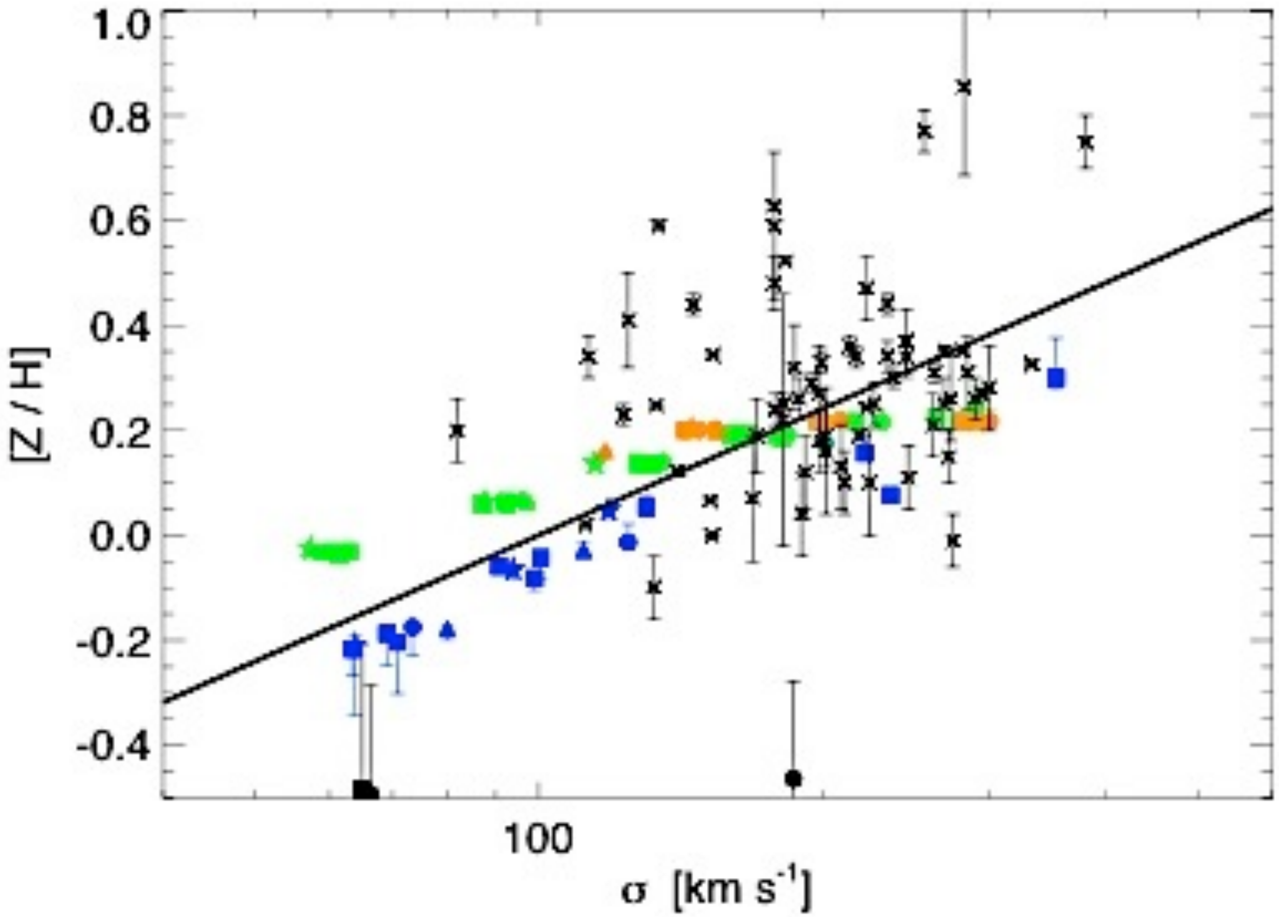
Stellar Population Effects





Fundamental Plane Tilt

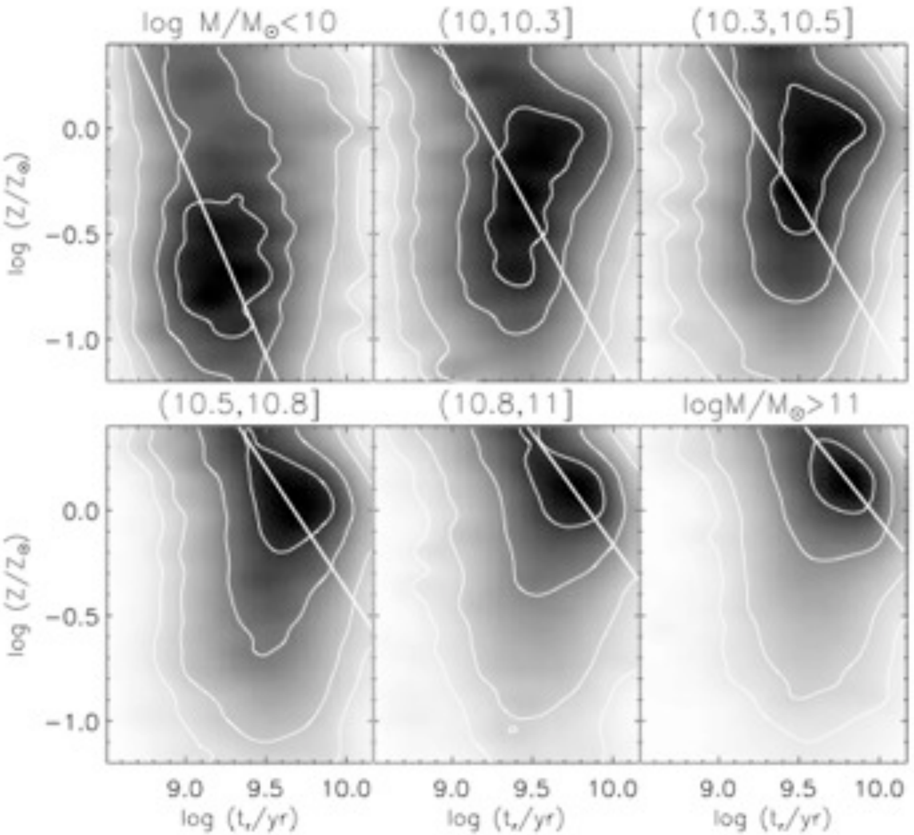
STELLAR POPULATION VARIATION

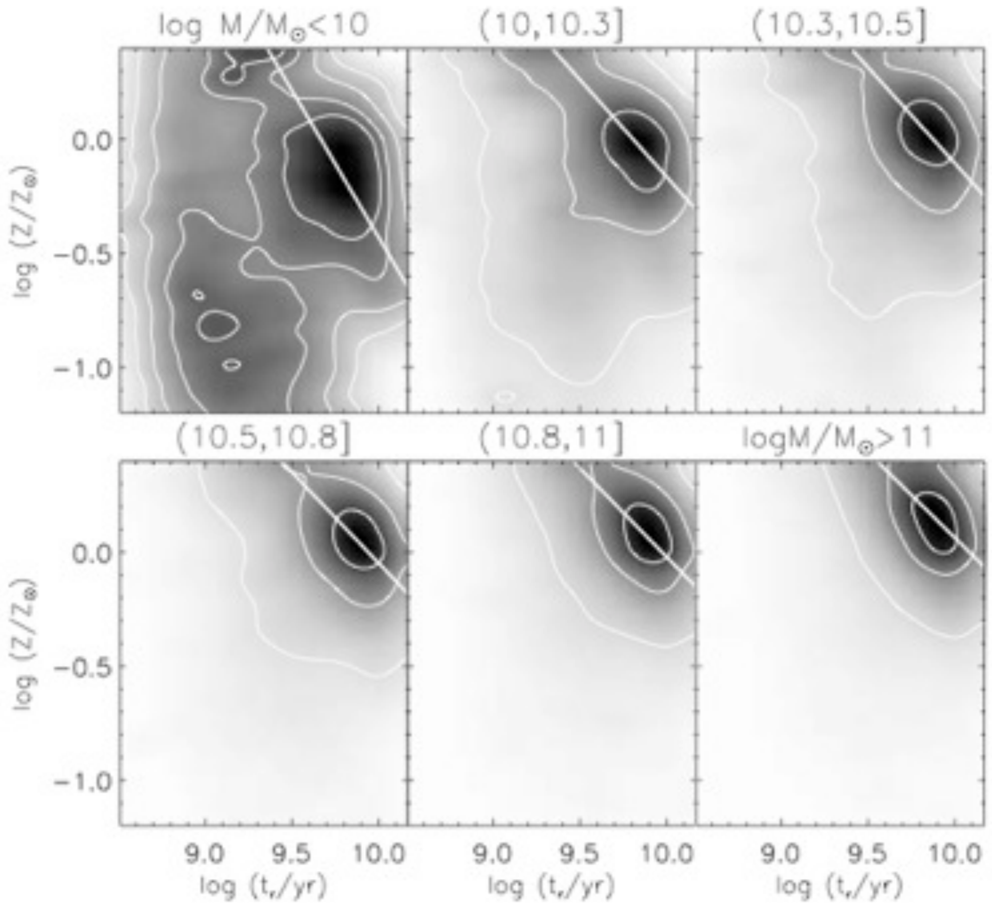


Fundamental Plane Tilt

STELLAR POPULATION VARIATION

- Where do these come from?

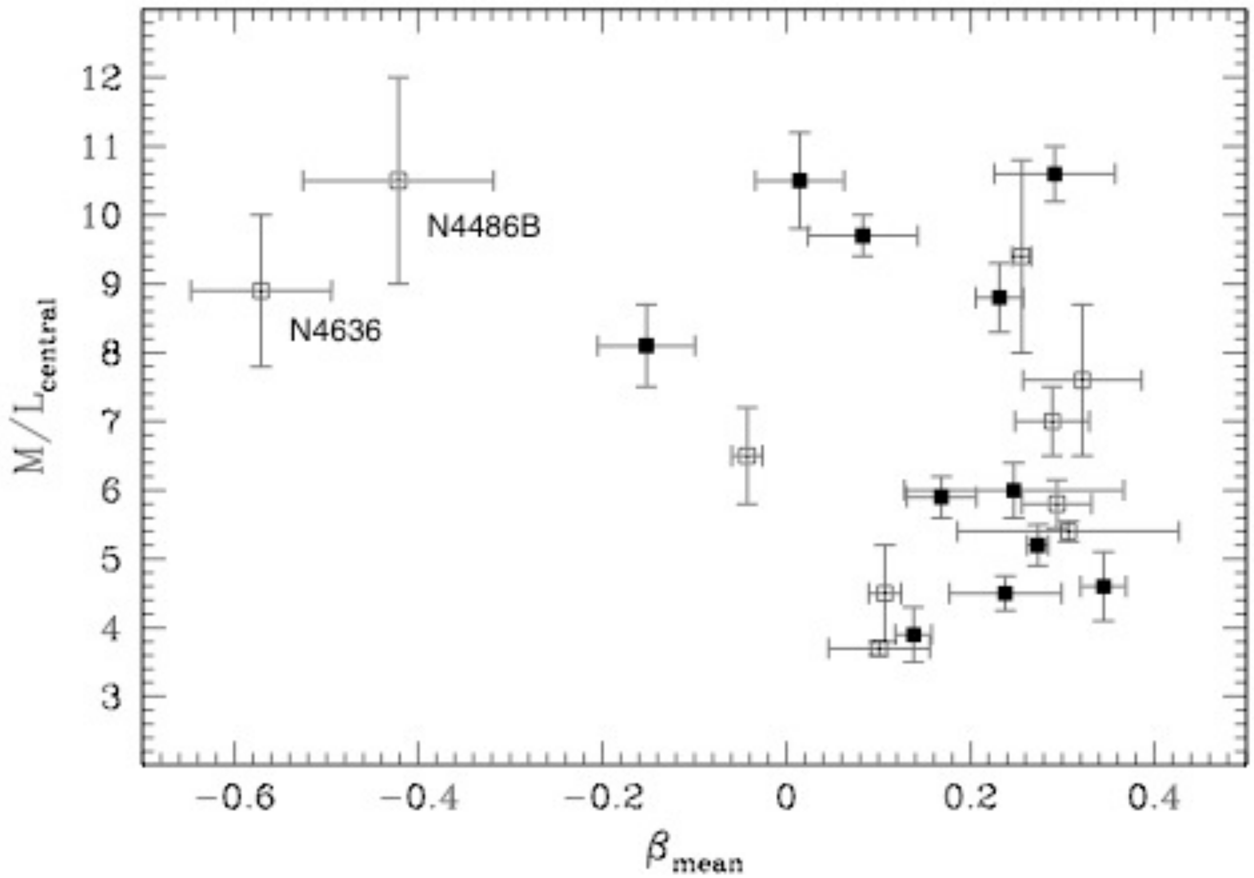




Fundamental Plane Tilt

KINEMATIC NON-HOMOLOGY

- Is sigma_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