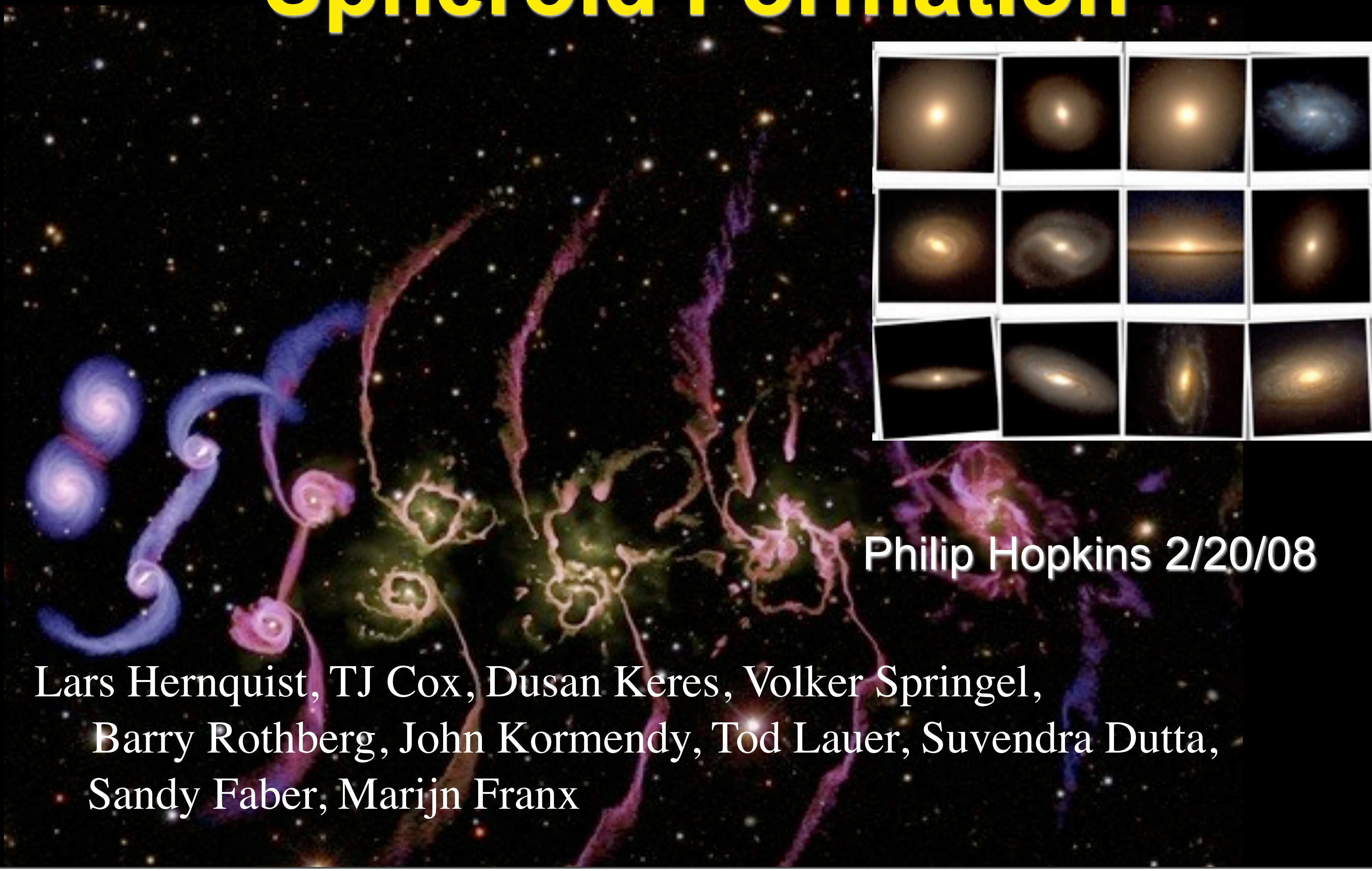
The Role of Dissipation in Spheroid Formation



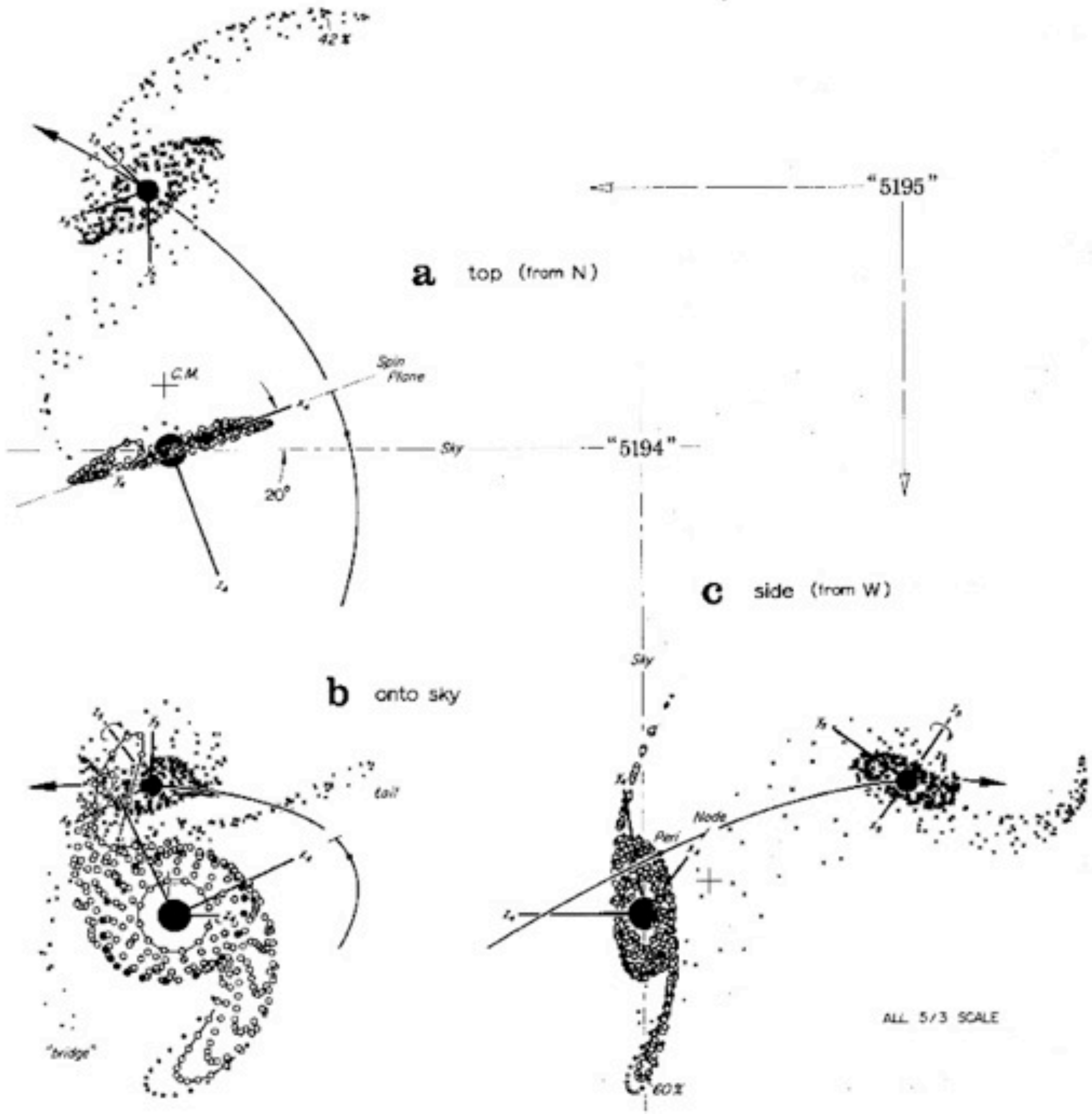
Philip Hopkins 2/20/08

Lars Hernquist, TJ Cox, Dusan Keres, Volker Springel,
Barry Rothberg, John Kormendy, Tod Lauer, Suvendra Dutta,
Sandy Faber, Marijn Franx

Ellipticals & Bulges: Formation in Mergers?

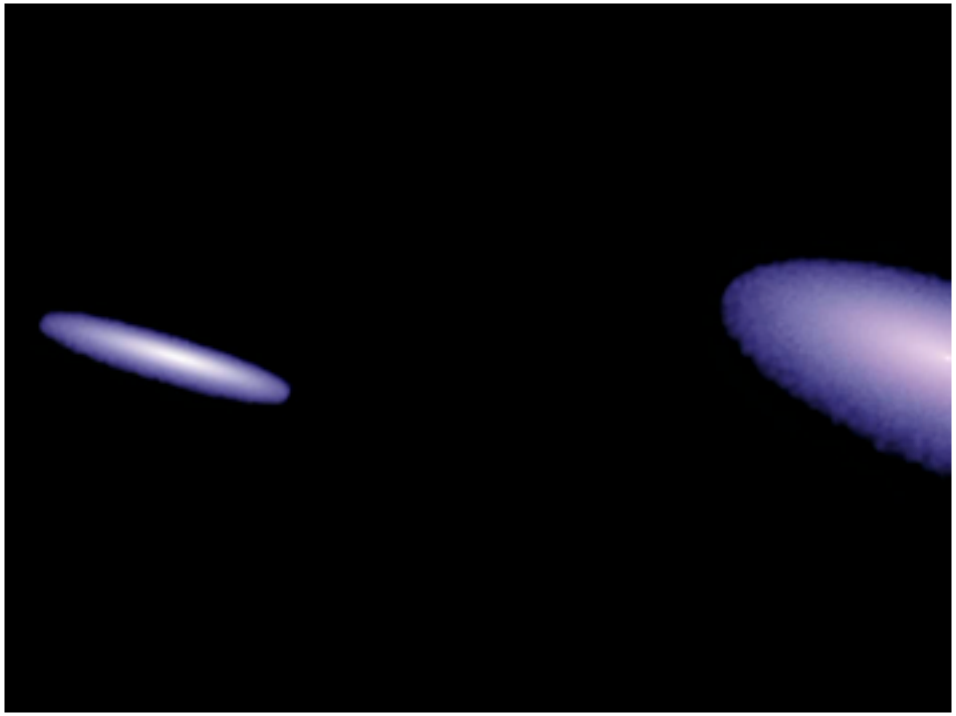
Toomre & Toomre (1972) ::
the “merger hypothesis”

ellipticals are made by the collision and merger of spirals



Fundamental Plane Tilt

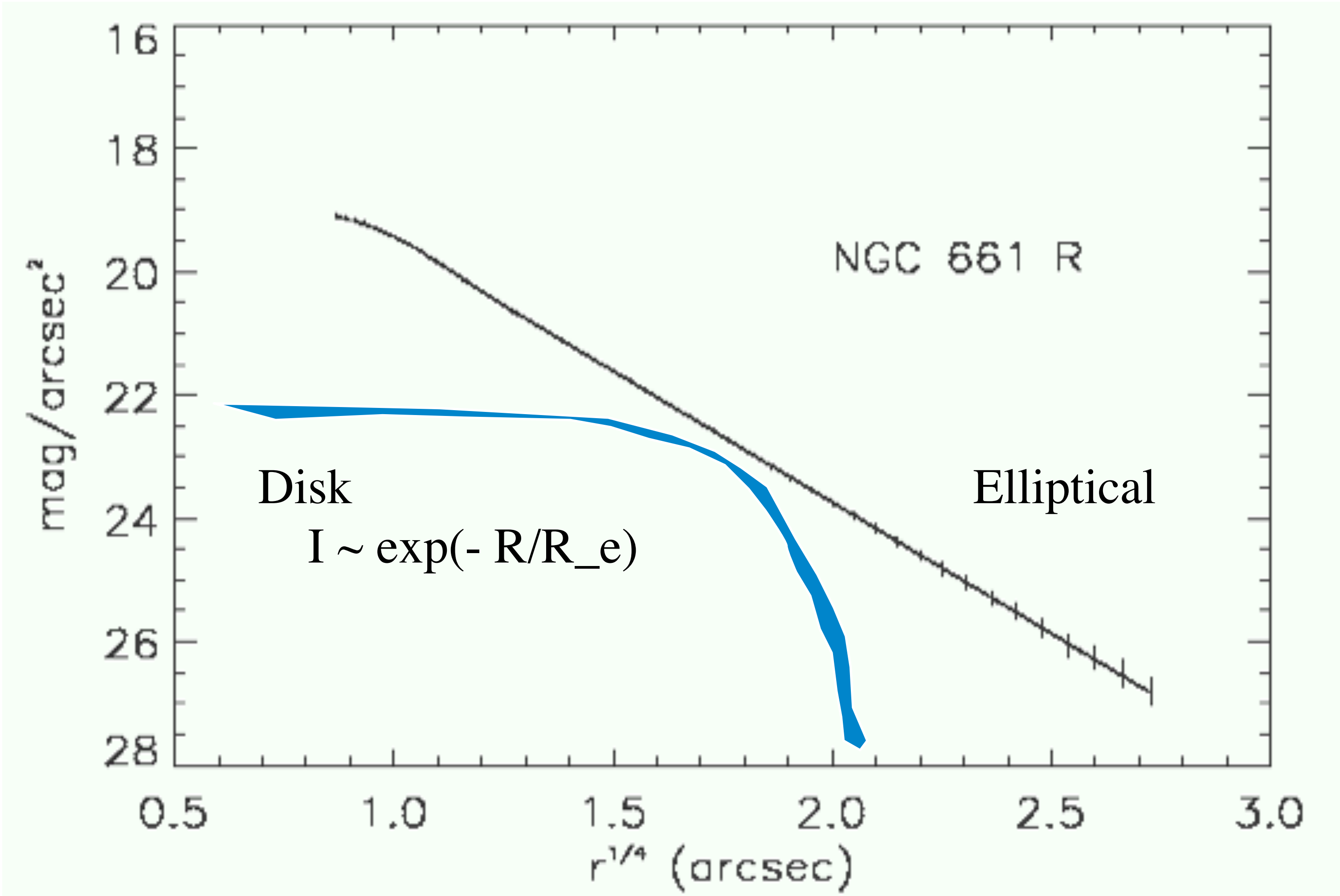
STRUCTURAL NON-HOMOLOGY



Ellipticals & Bulges: Formation in Mergers?

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

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



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

Ellipticals & Bulges: Formation in Mergers?

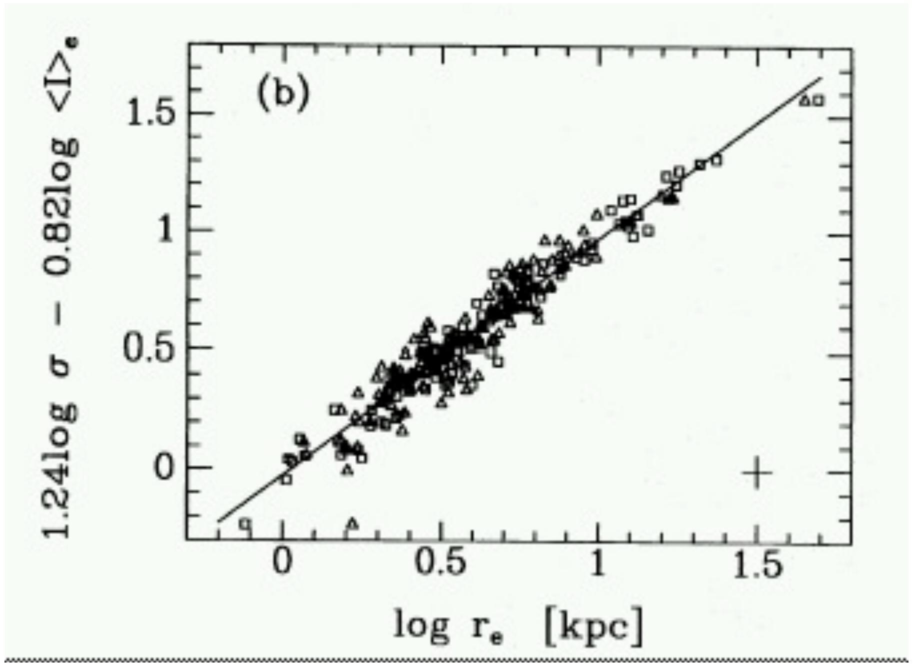
There was, however, some controversy about the idea....

The Problem:

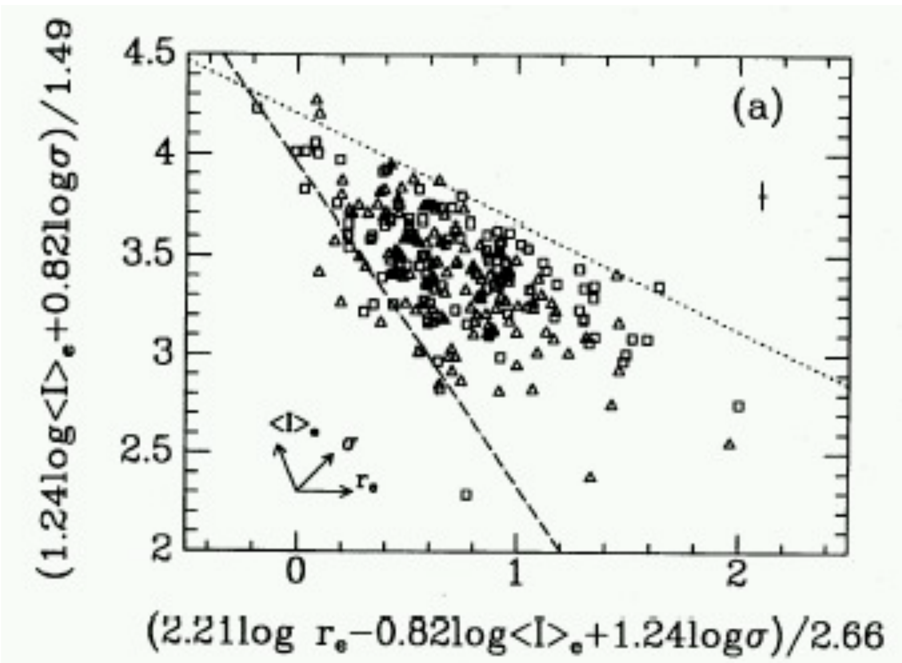
The Fundamental Plane correlates R_e, surface brightness, and σ for elliptical galaxies.

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

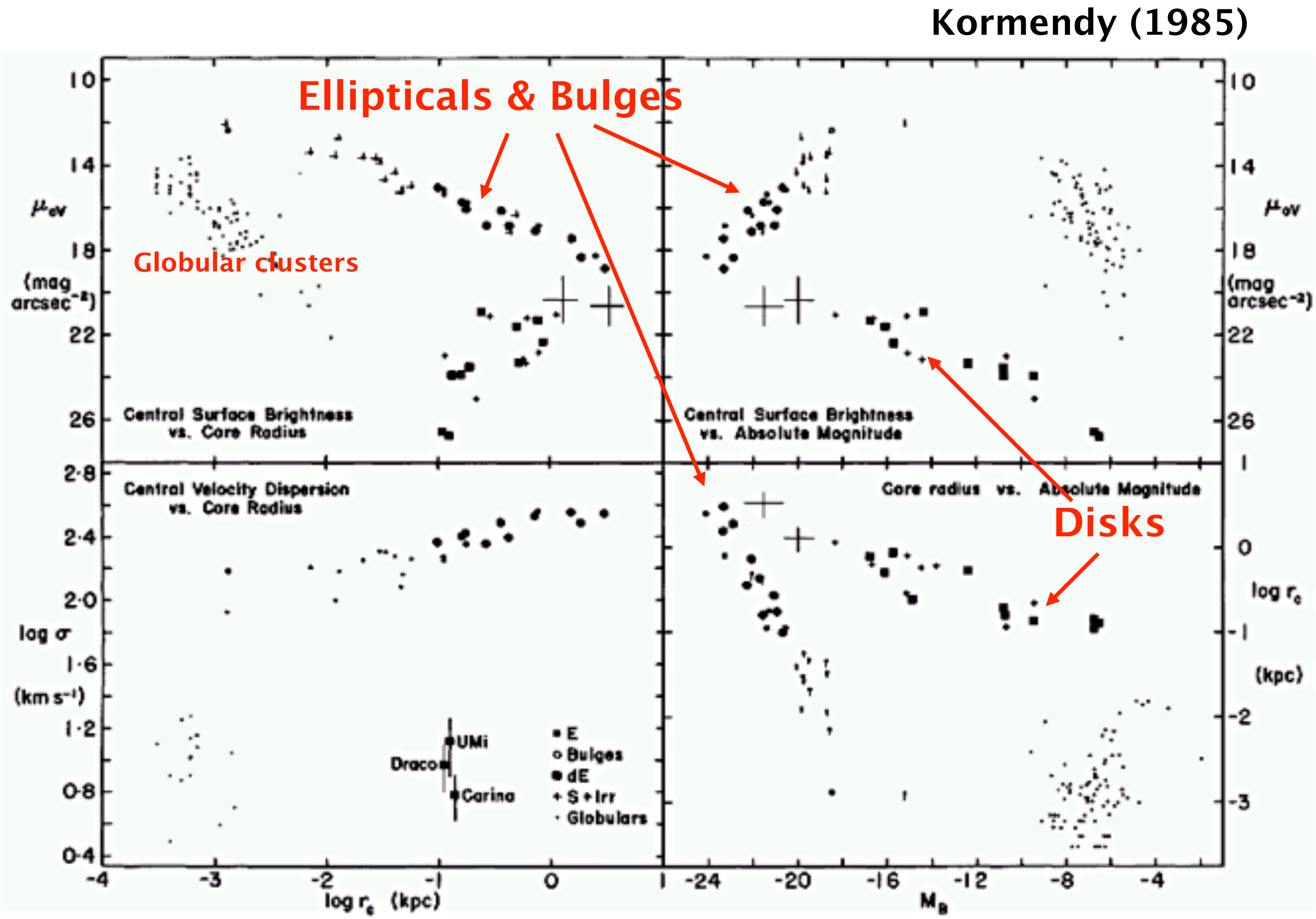


Fundamental Plane face on

Jorgensen 1996

The Problem

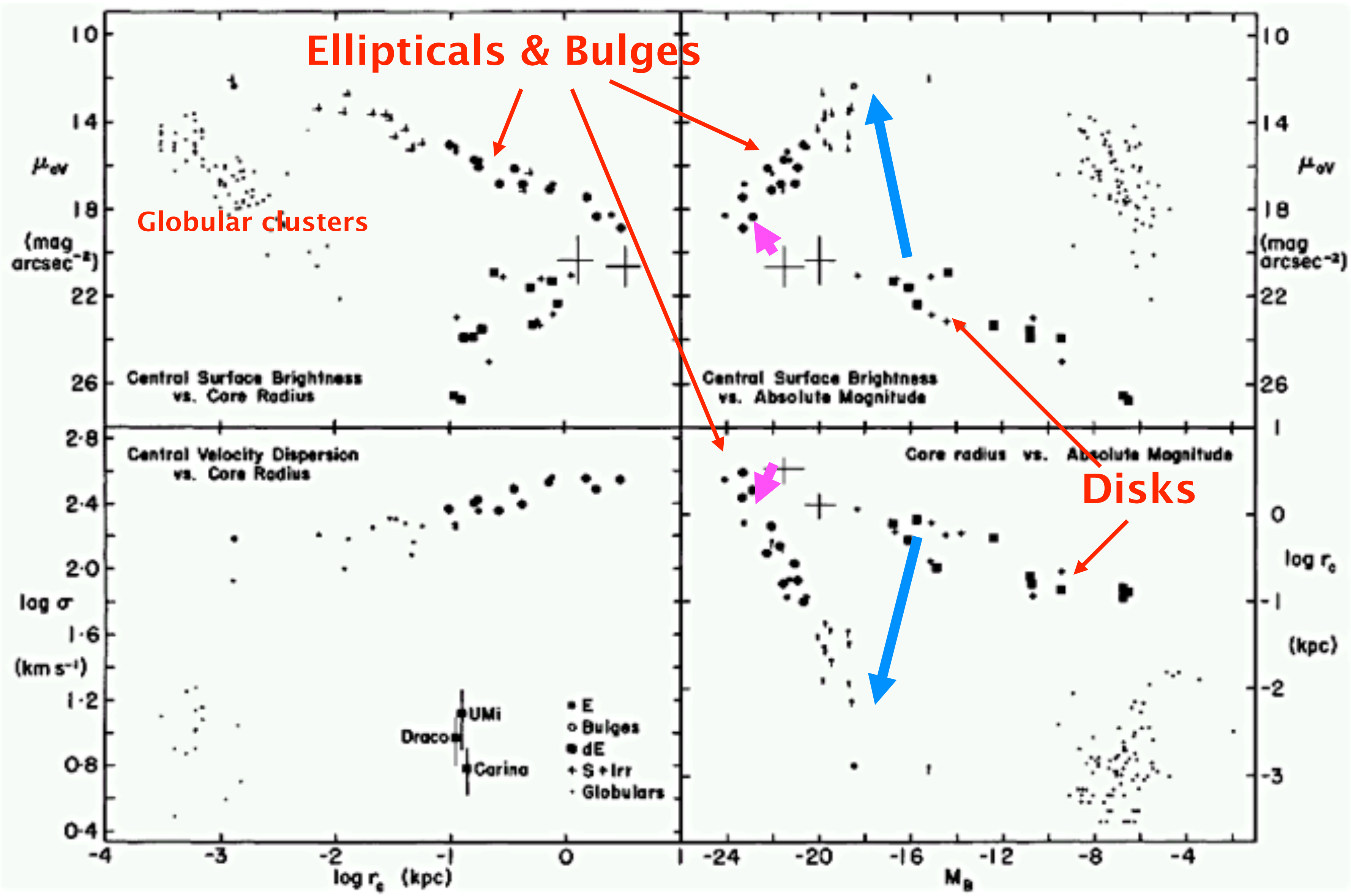
FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS



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...

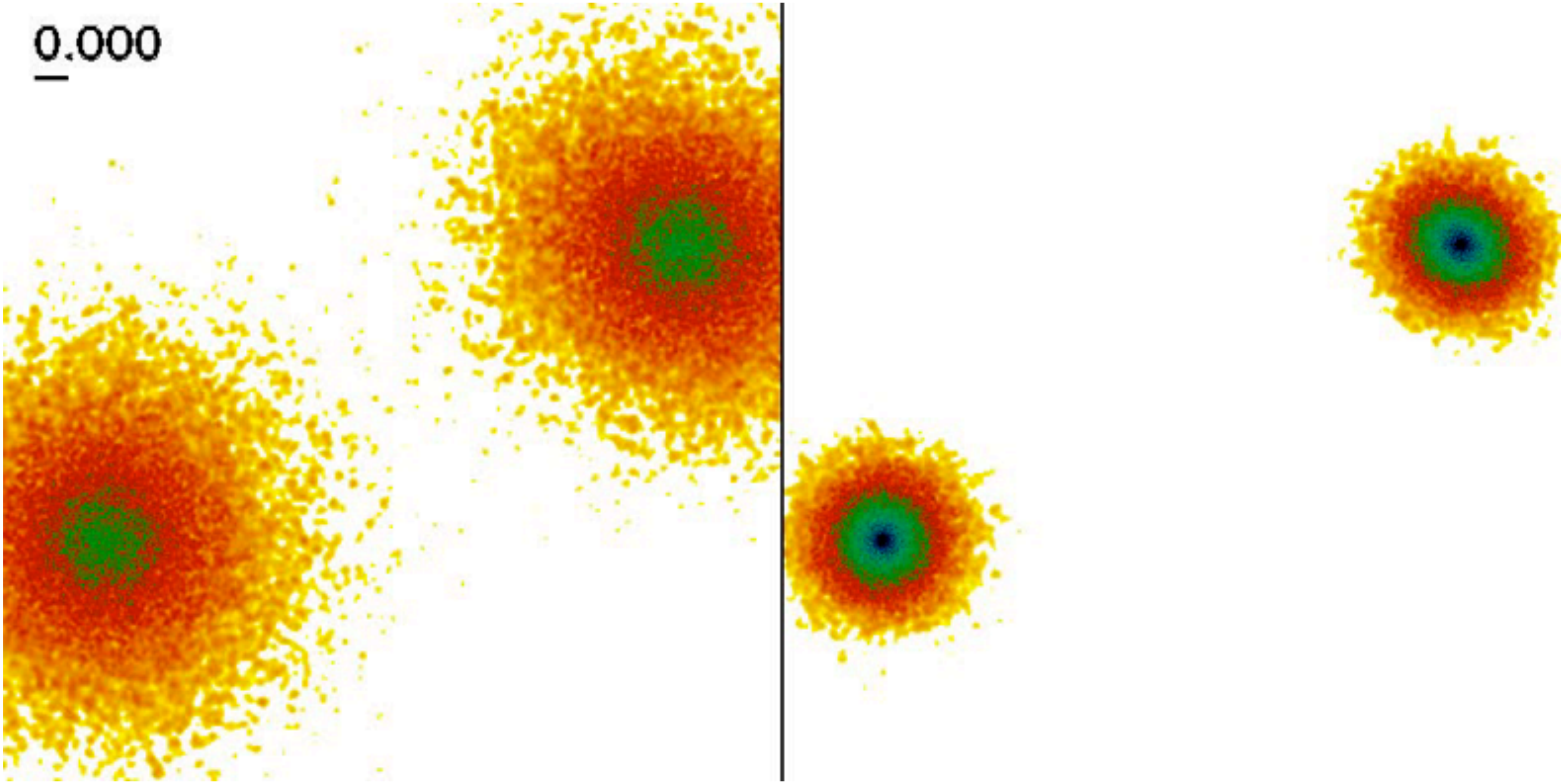
- many low-mass ellipticals formed at $z<1$
- observed evolution is relatively weak

Solution 2: Gas dissipation

The Problem

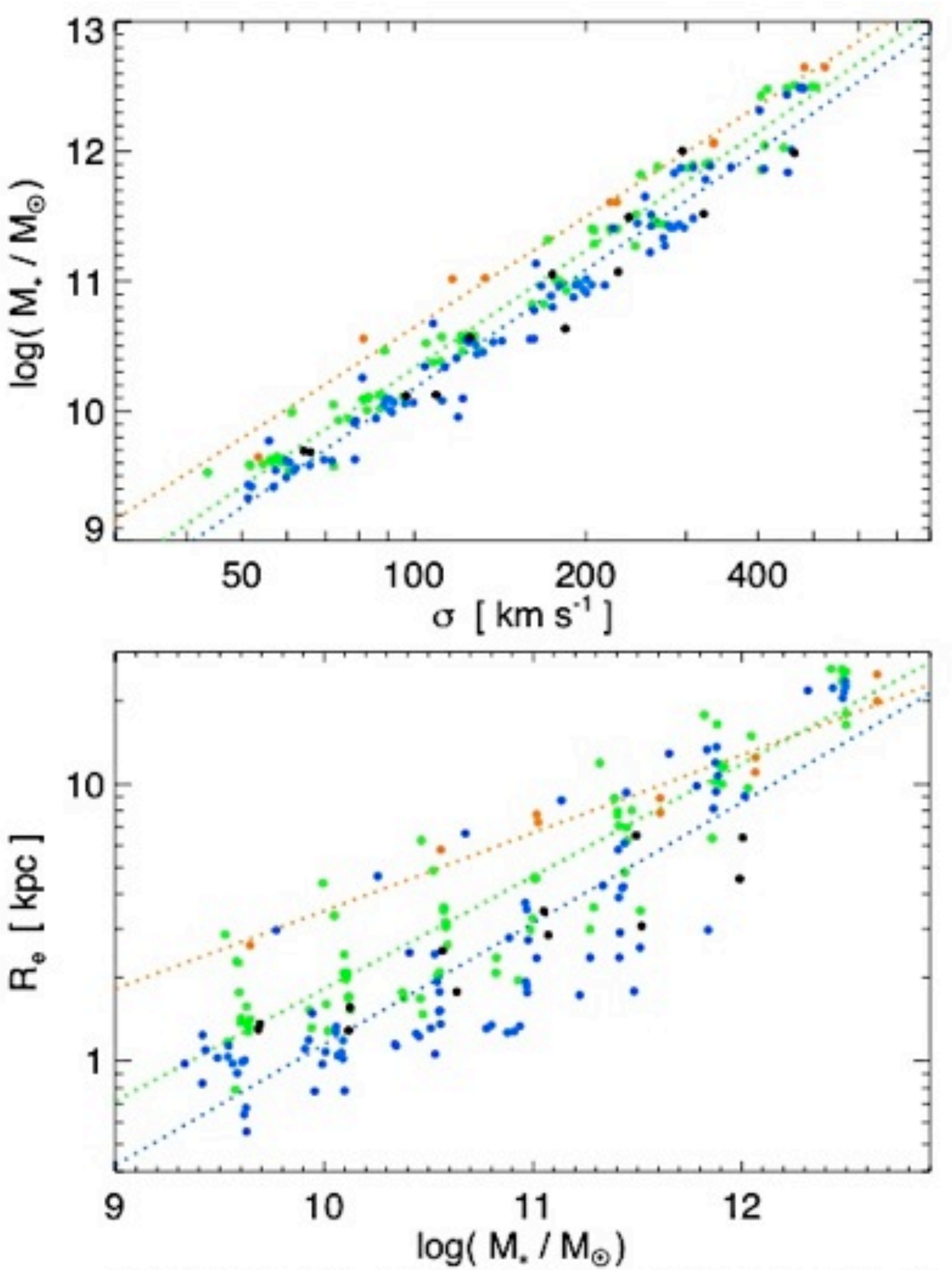
FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- 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

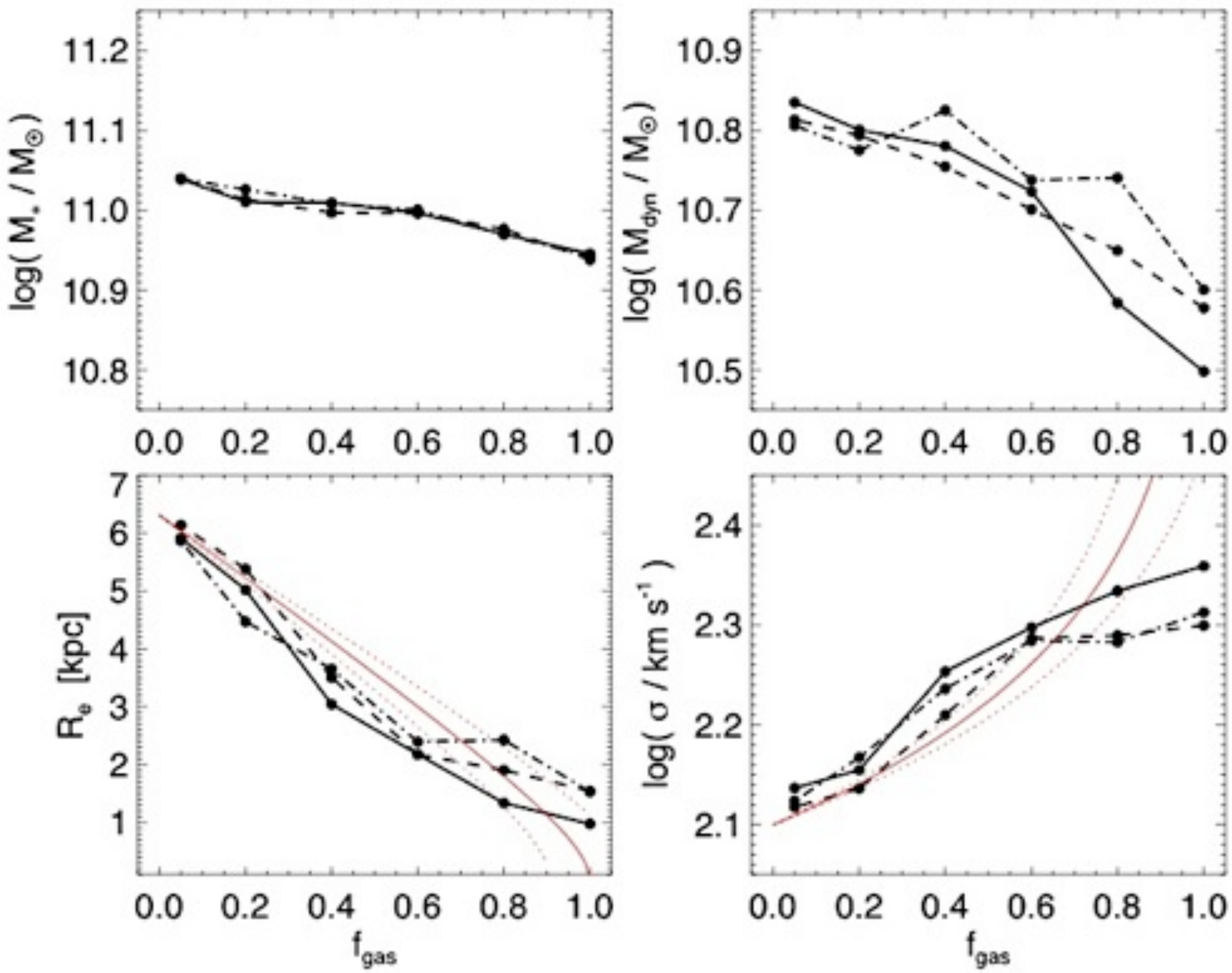
fgas = 0.1

fgas = 0.4

fgas = 0.8

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS



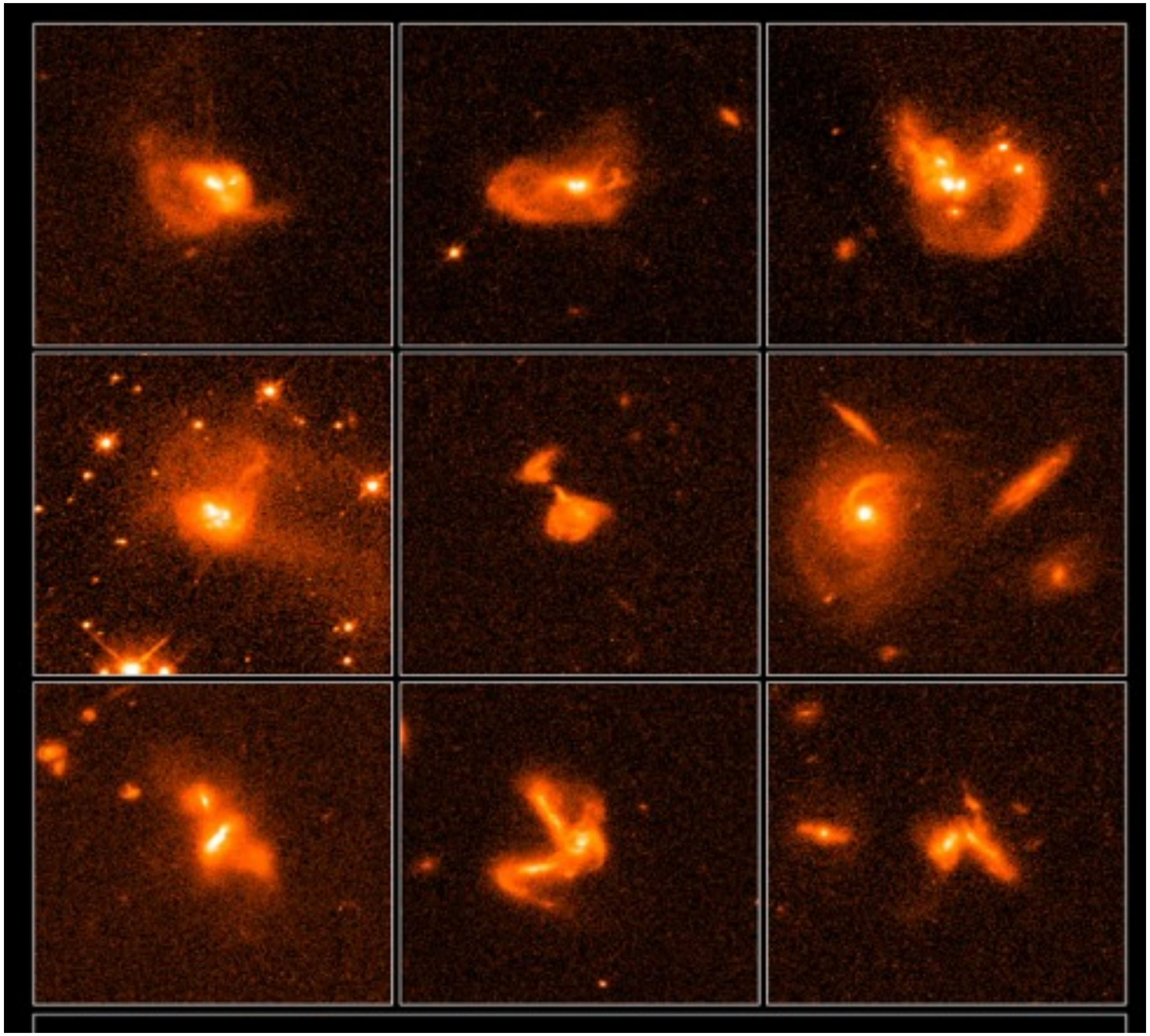
- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential

The Solution: Gas Dissipation?

Look at late-stage merger remnants

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

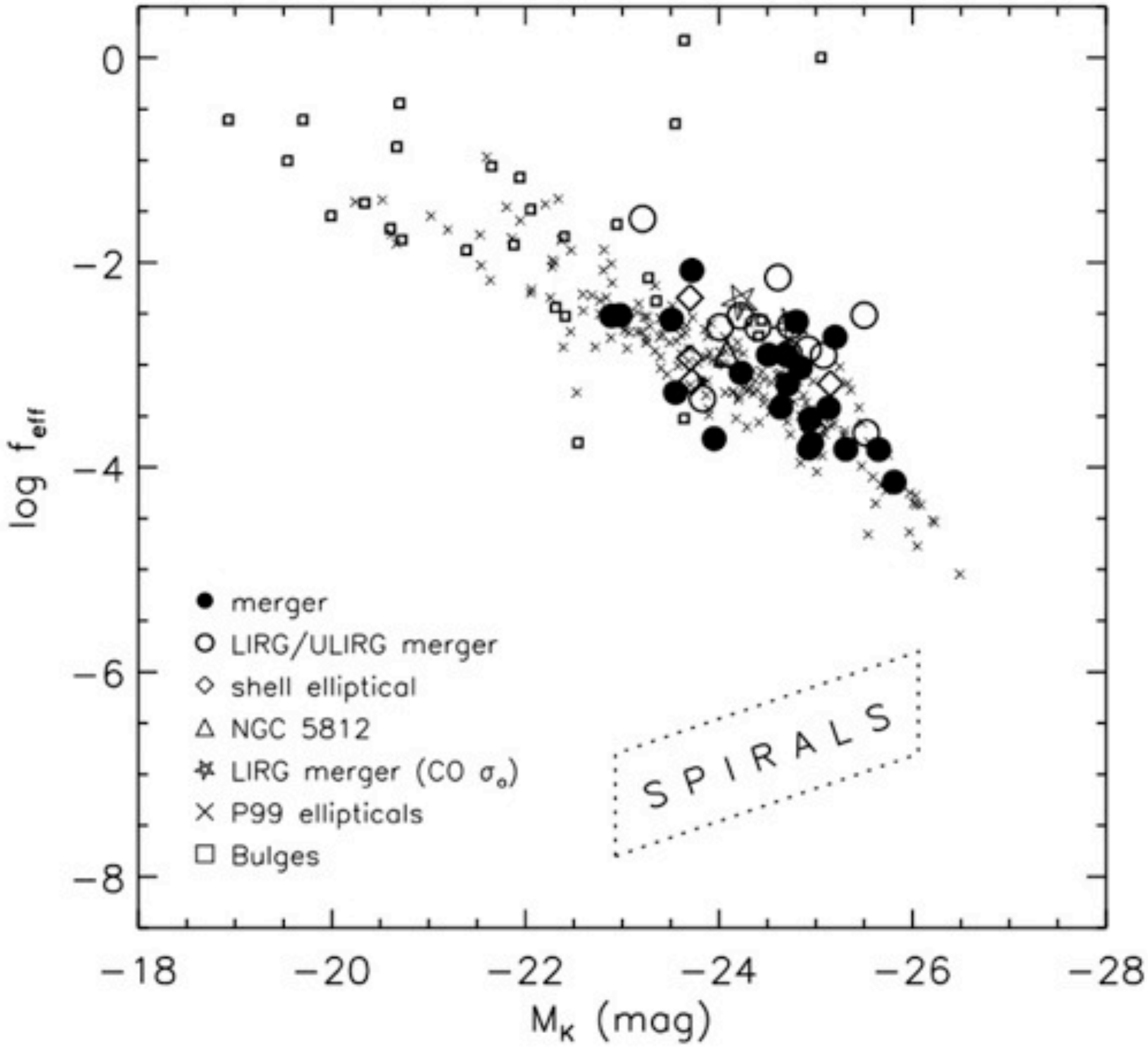
Extremely compact (<kpc scales)



Borne et al., 2000

The Solution: Gas Dissipation?

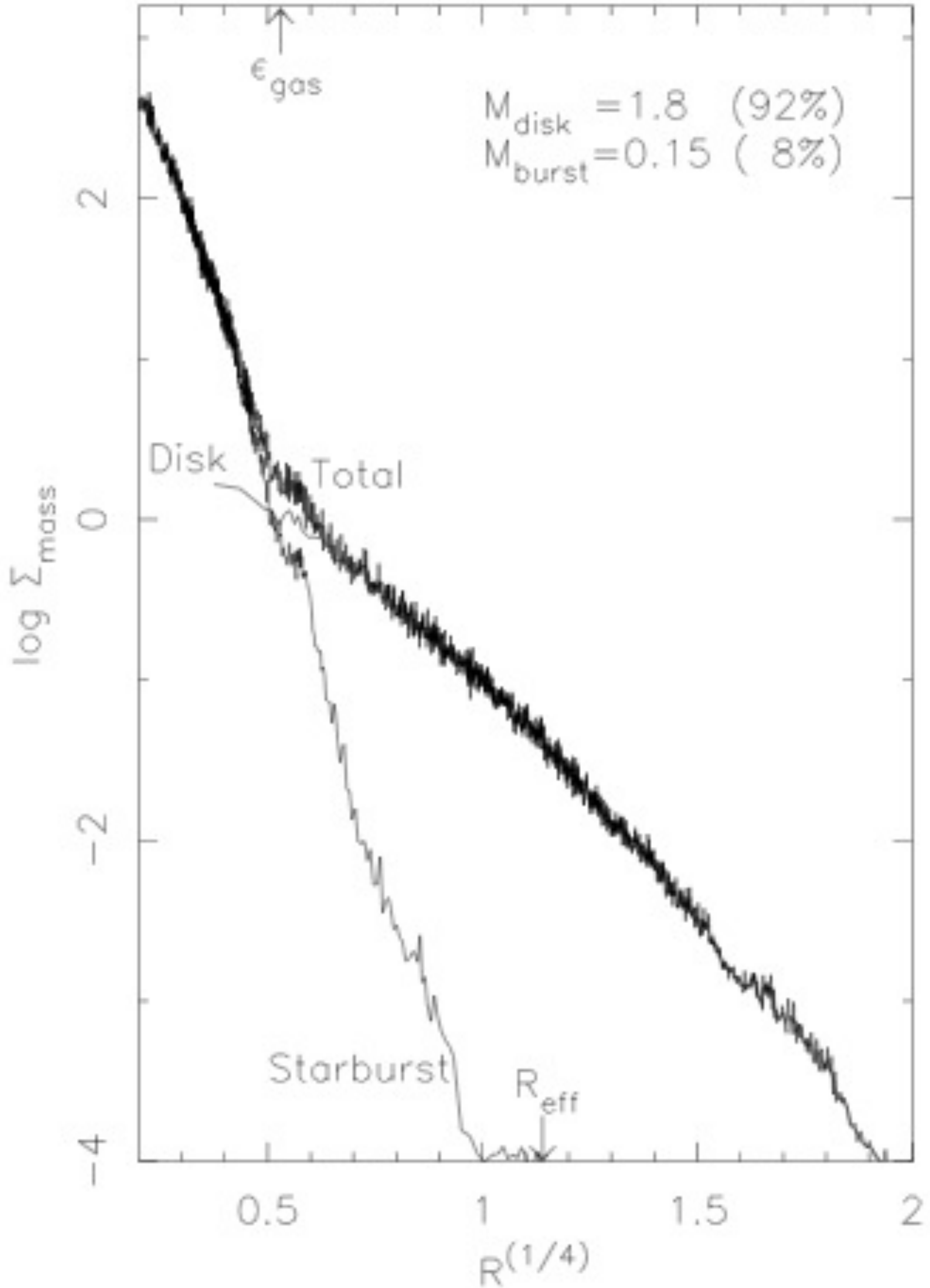
- Mergers *have* solved this problem: we just need to understand it



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

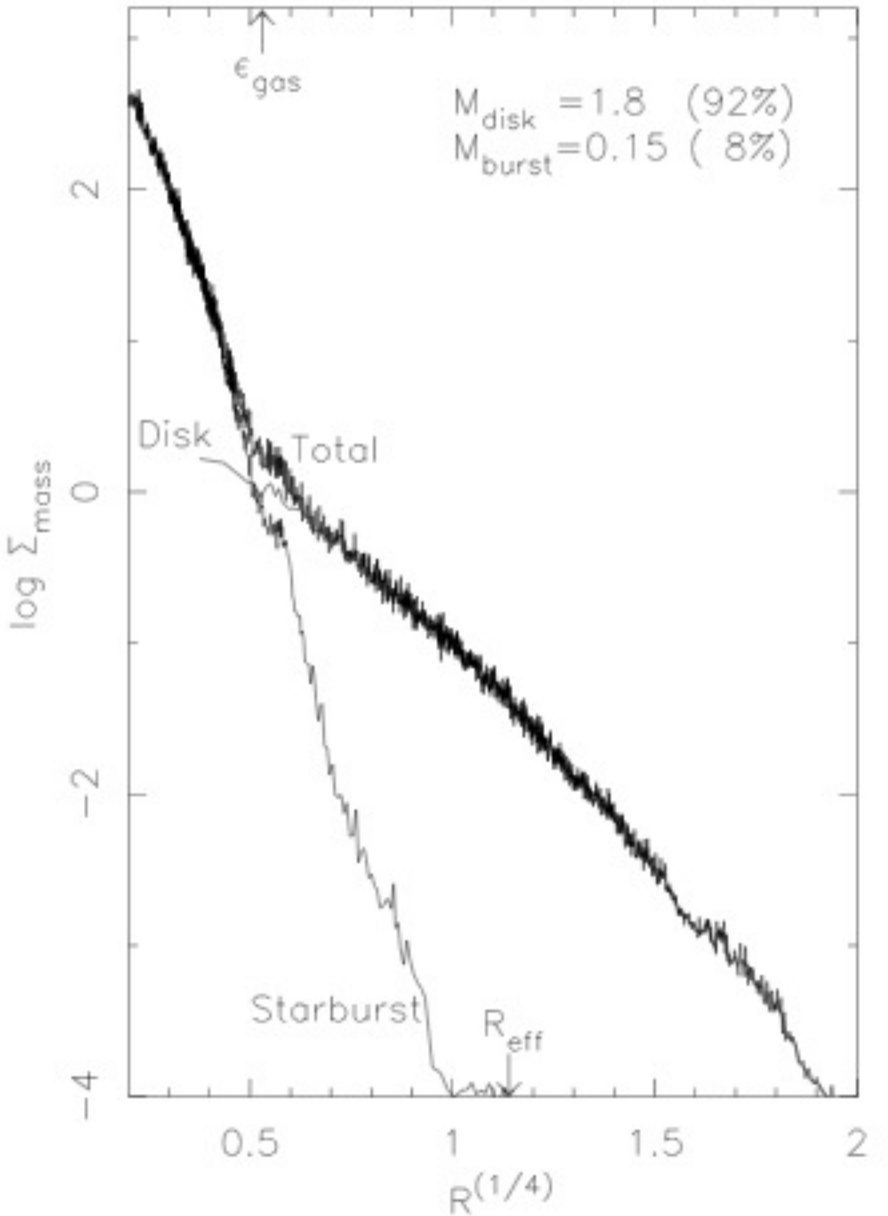
Separate stars into 3 populations:

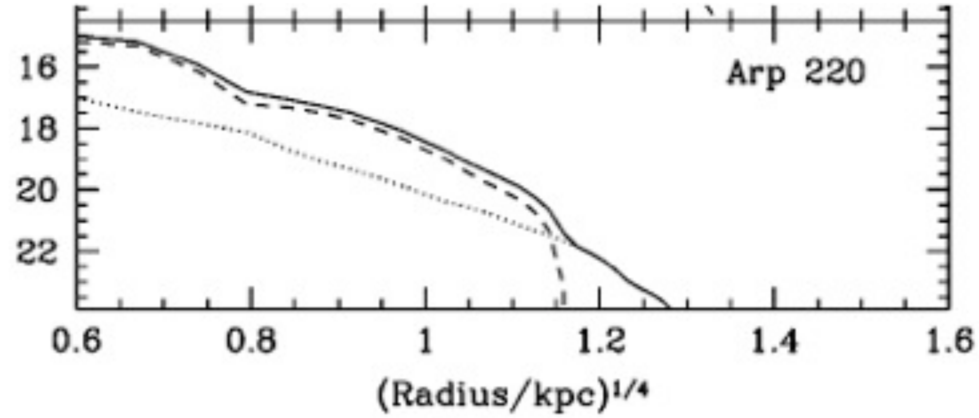
1. Disk/pre-starburst
2. Starburst
3. Post-starburst
   (embedded kinematic subsystems)

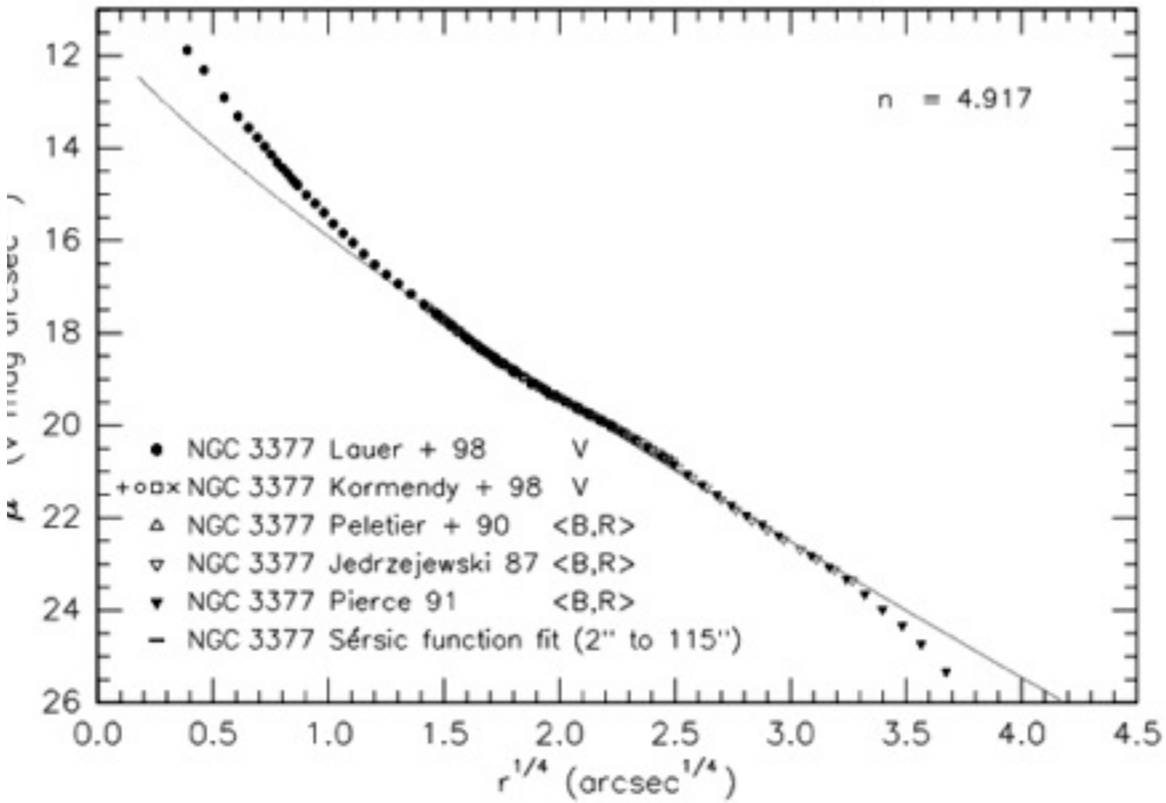


Starburst Stars in Simulations Leave an “Imprint” on the Profile

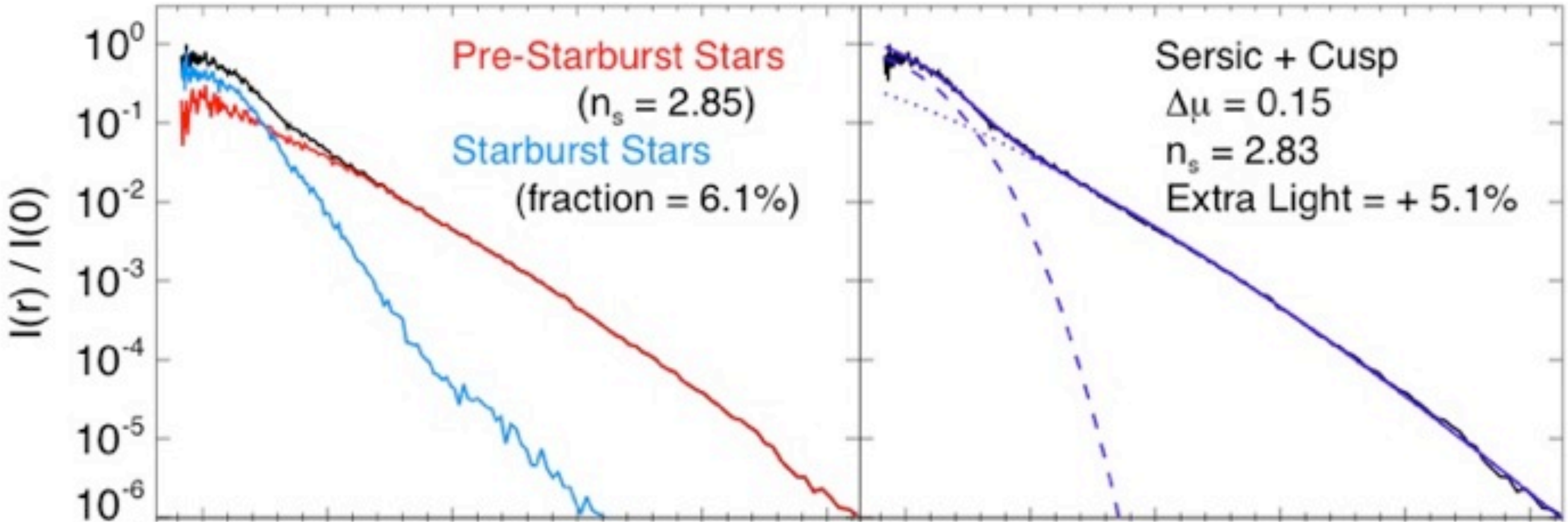
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS





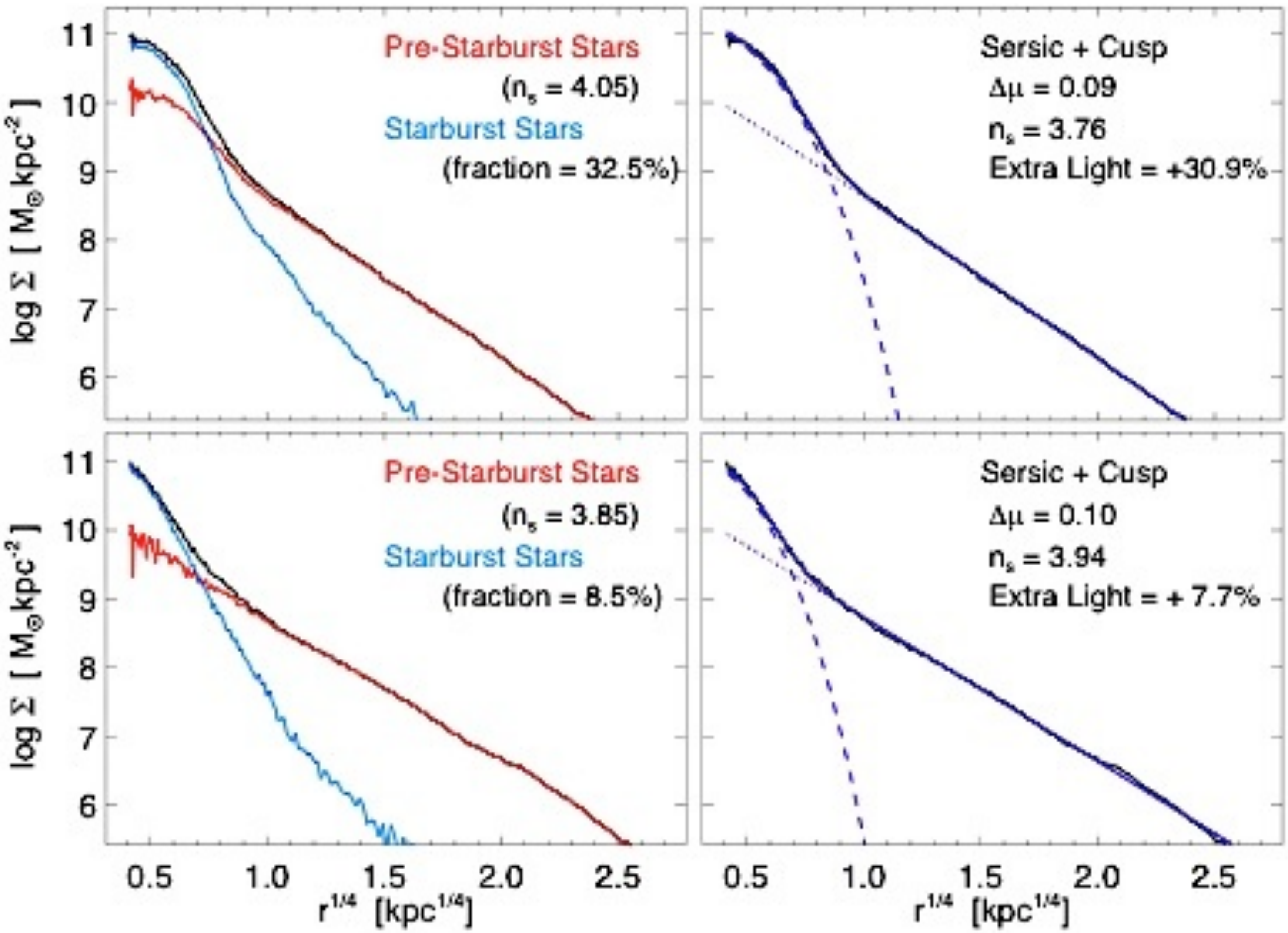


Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



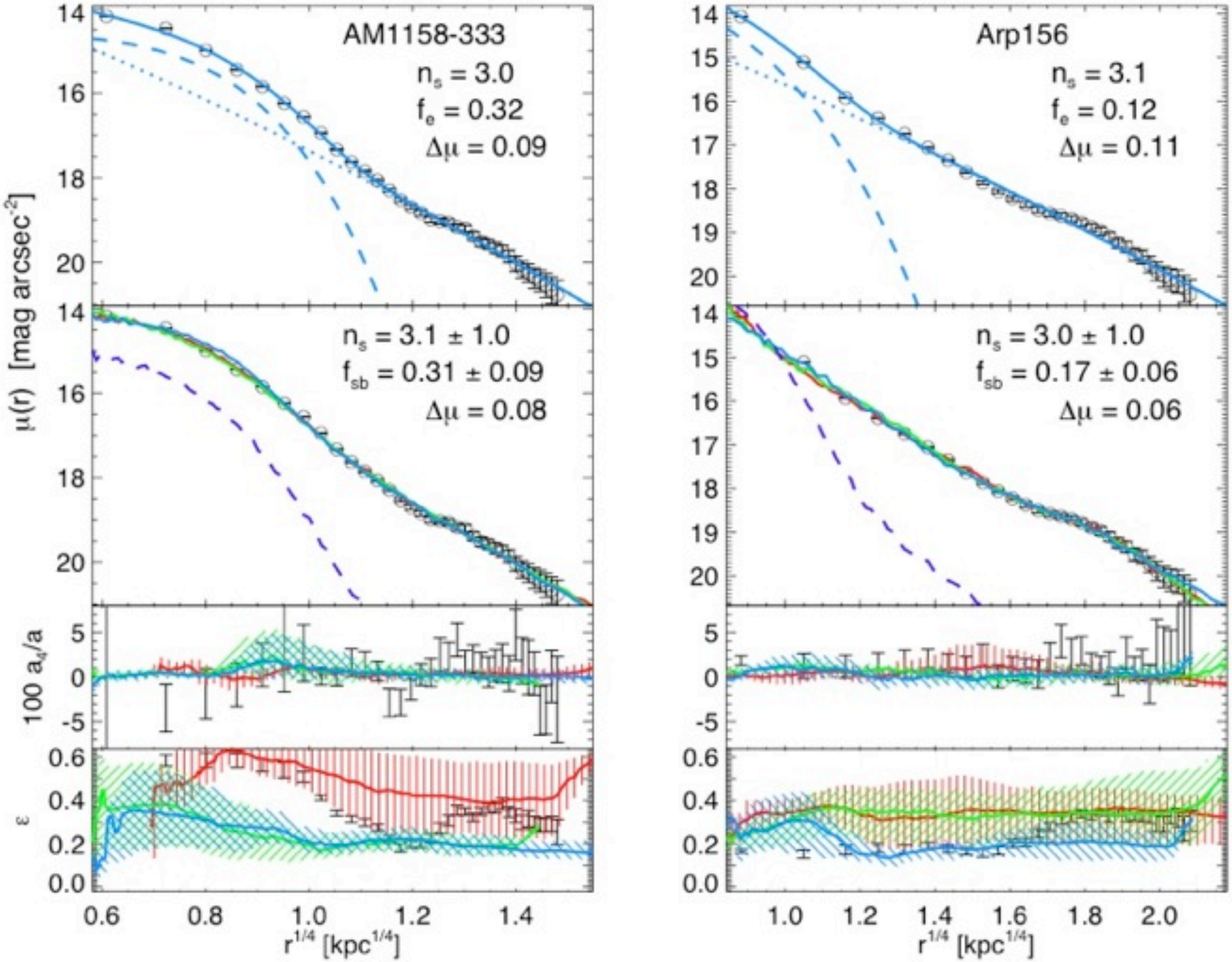
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



Application: Merger Remnants

RECOVERING THE ROLE OF GAS

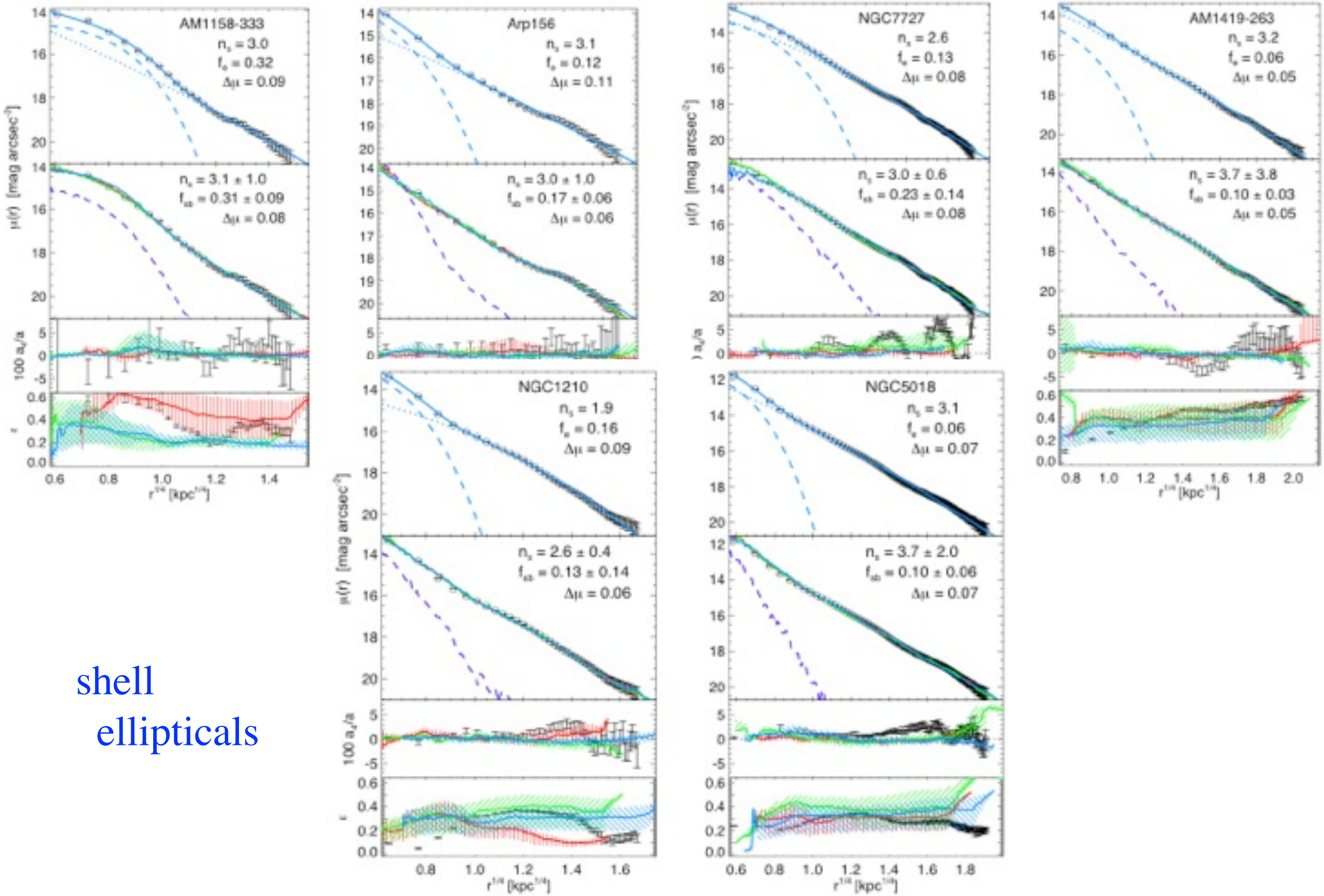


Application: Merger Remnants

RECOVERING THE ROLE OF GAS

bright, young mergers

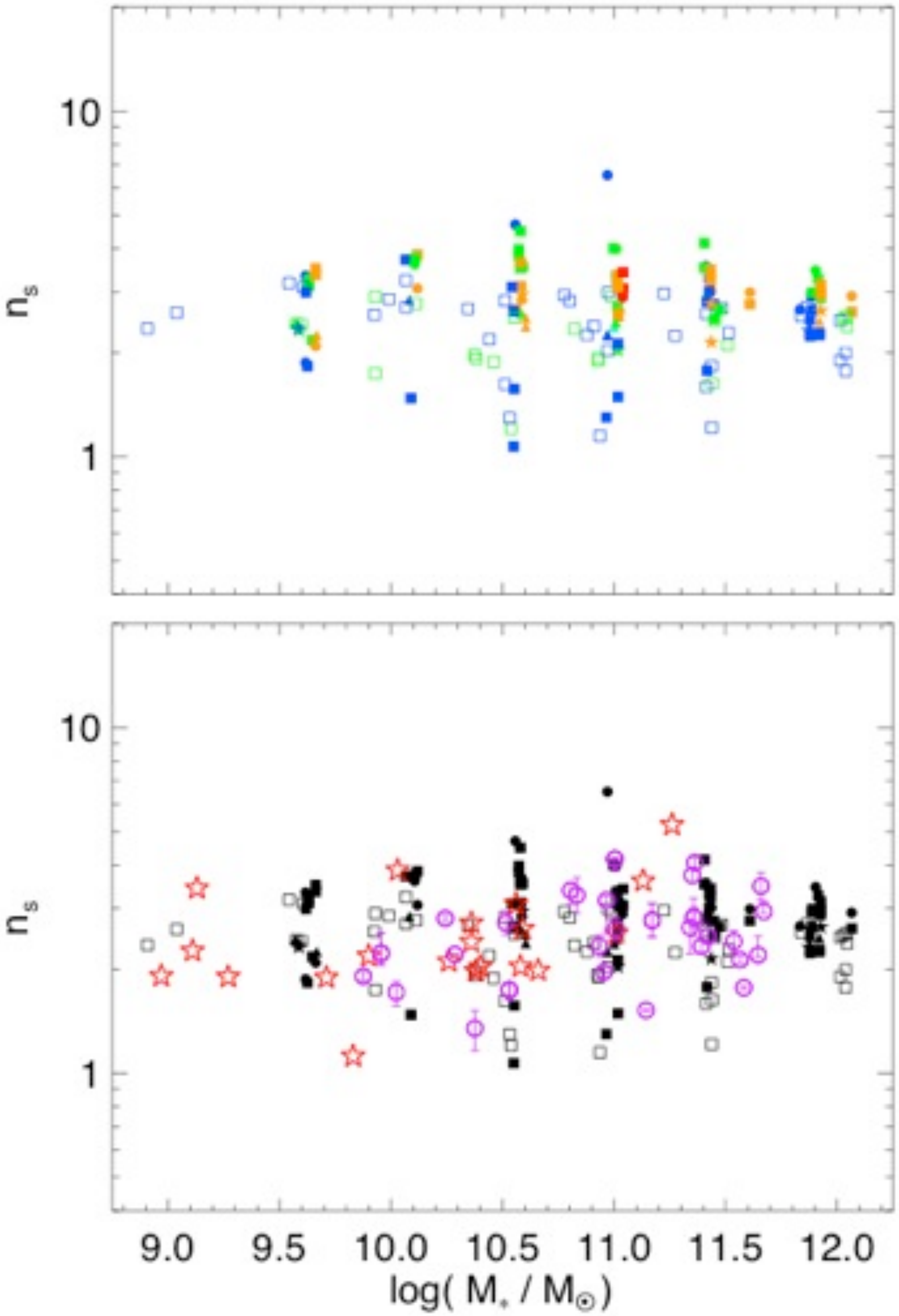
low-luminosity, relaxed mergers



shell
ellipticals

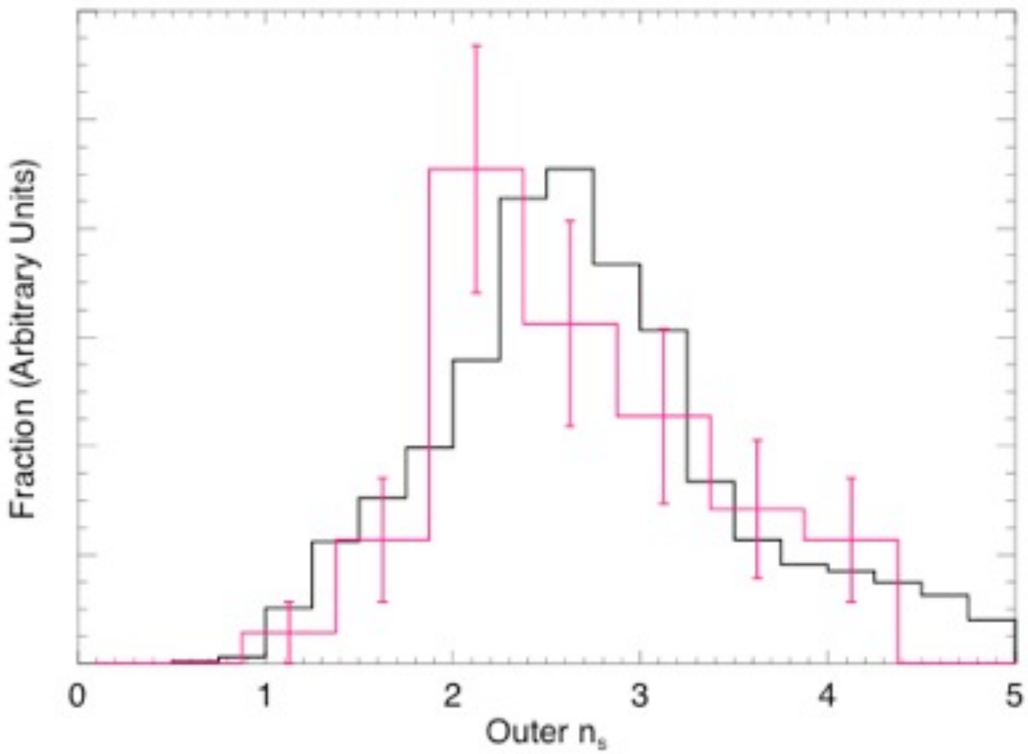
Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS



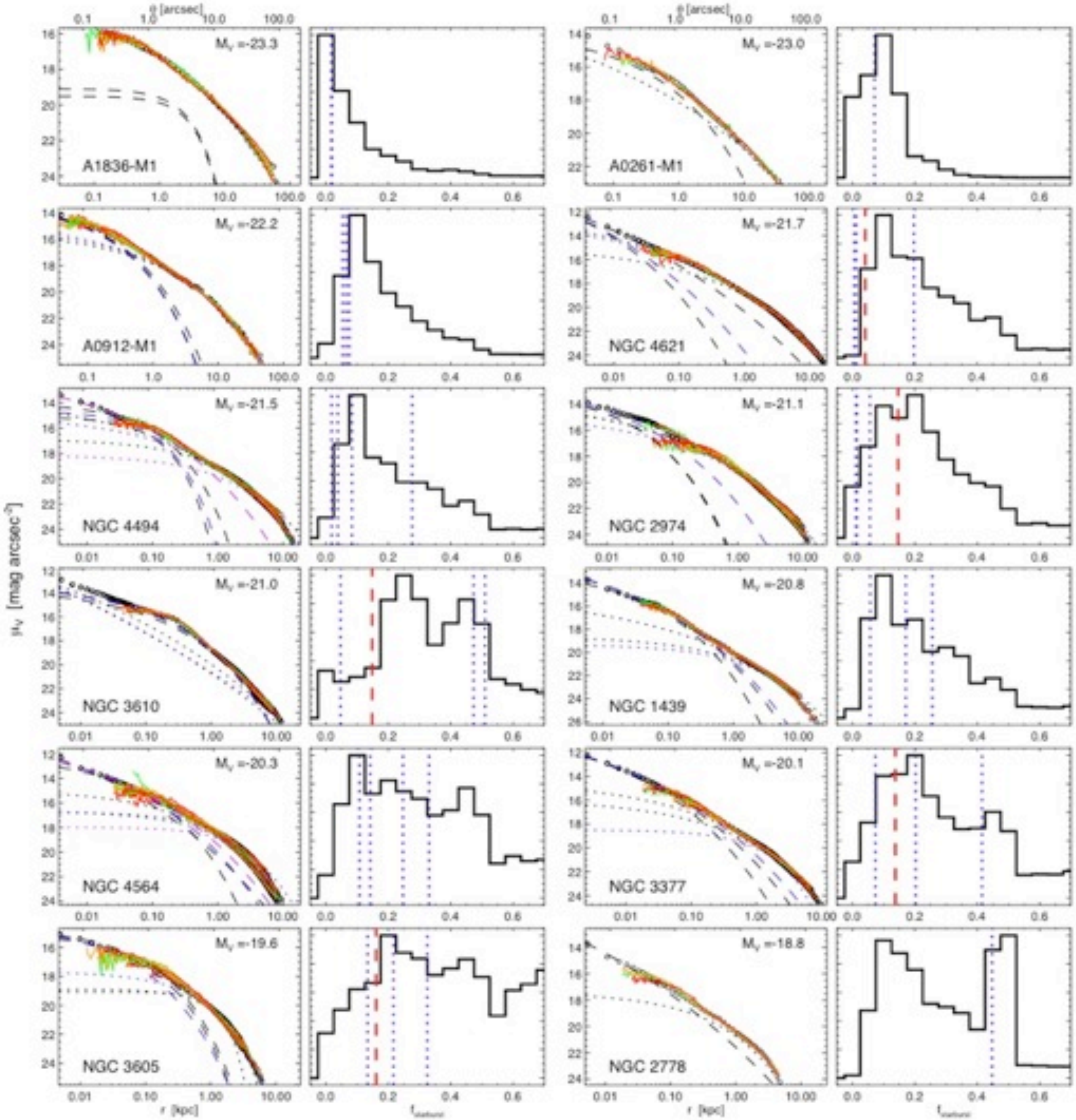
OUTER Sersic index is independent of mass, radius, etc.

--- gravity is self-similar



Application

RECOVERING THE ROLE OF GAS

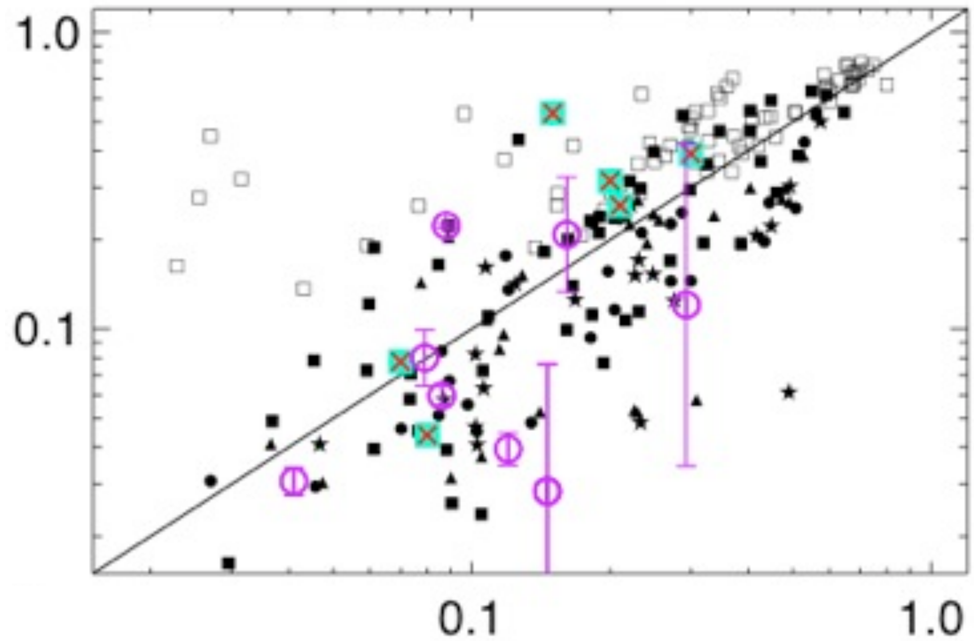


Compare:

- Parametric fitting
- Direct simulation fitting
- Stellar population models

Application: Merger Remnants

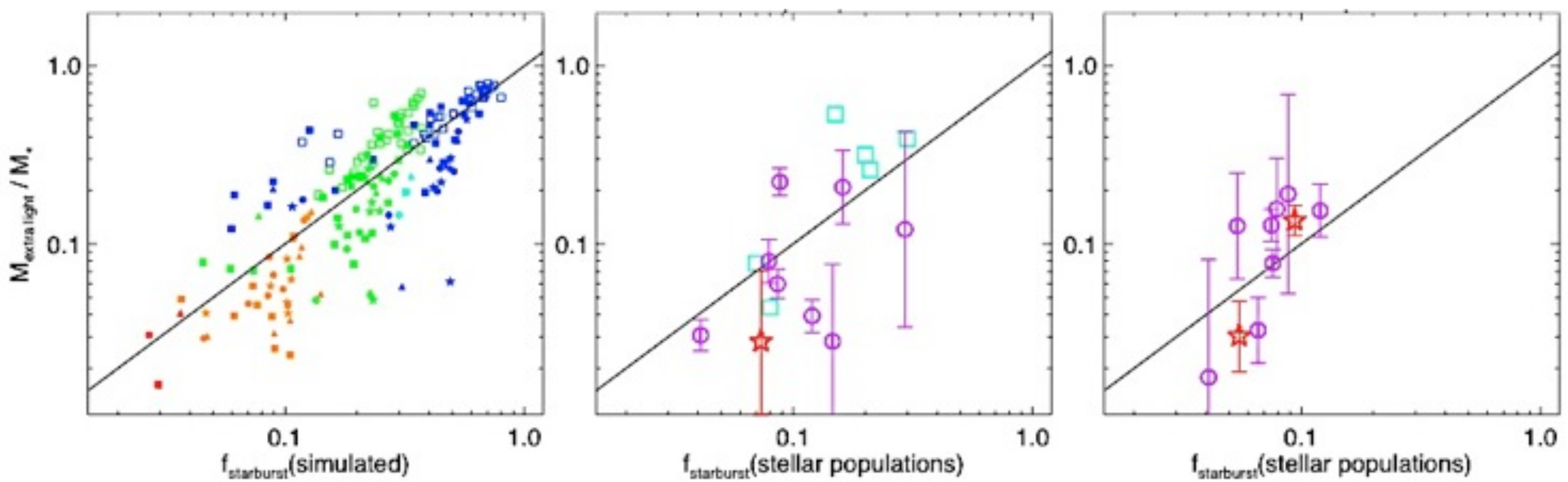
RECOVERING THE ROLE OF GAS



f(starburst)

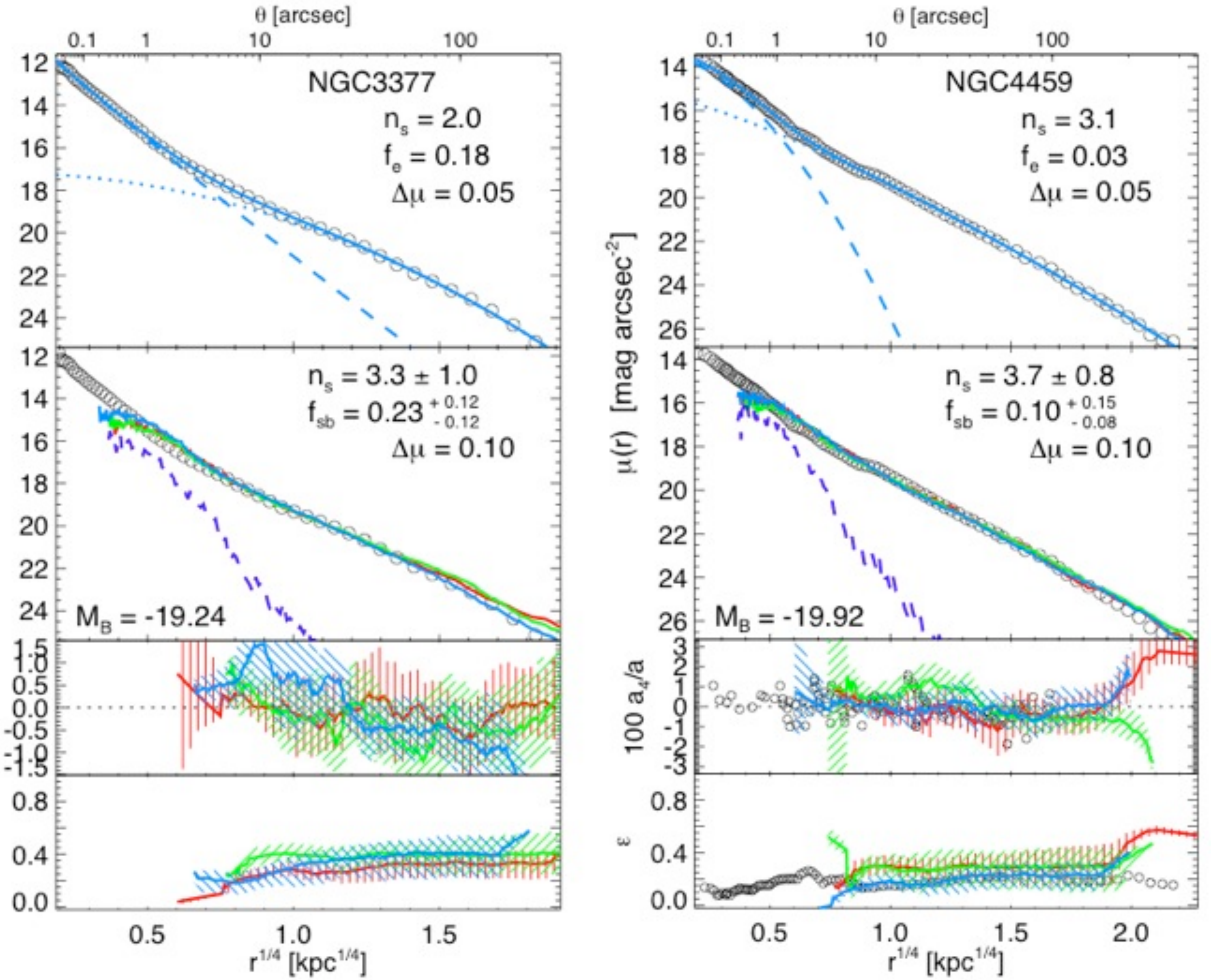
Compare:

- Parametric fitting
- Direct simulation fitting
- Stellar population models



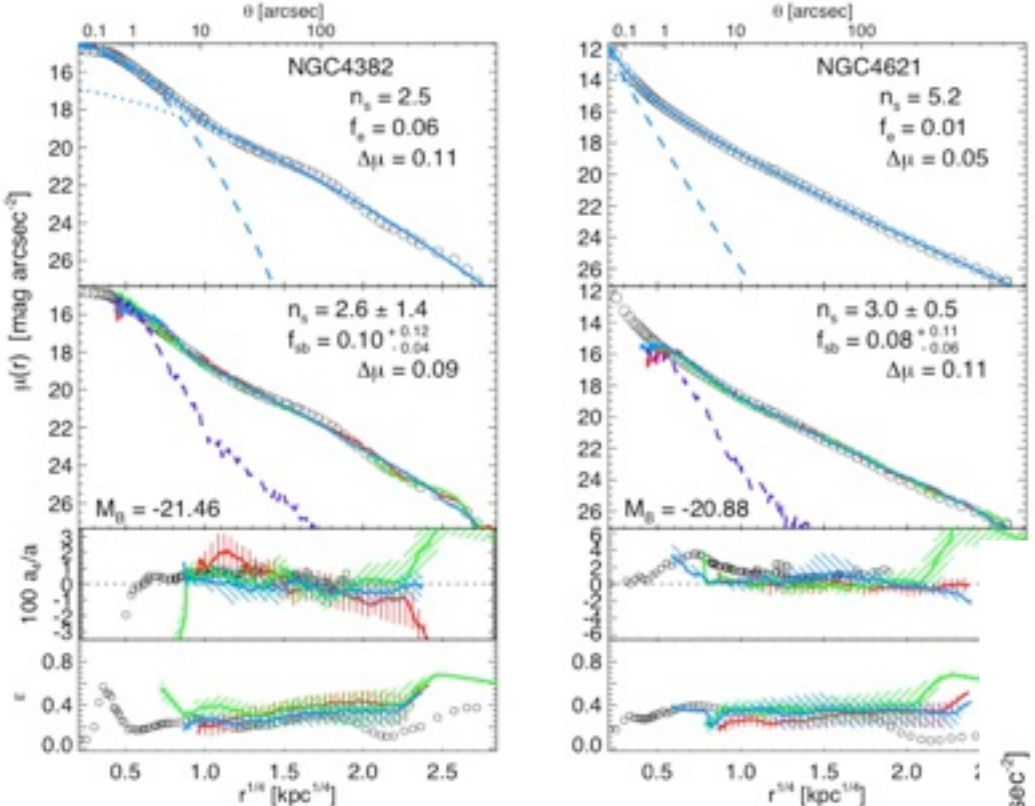
Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS

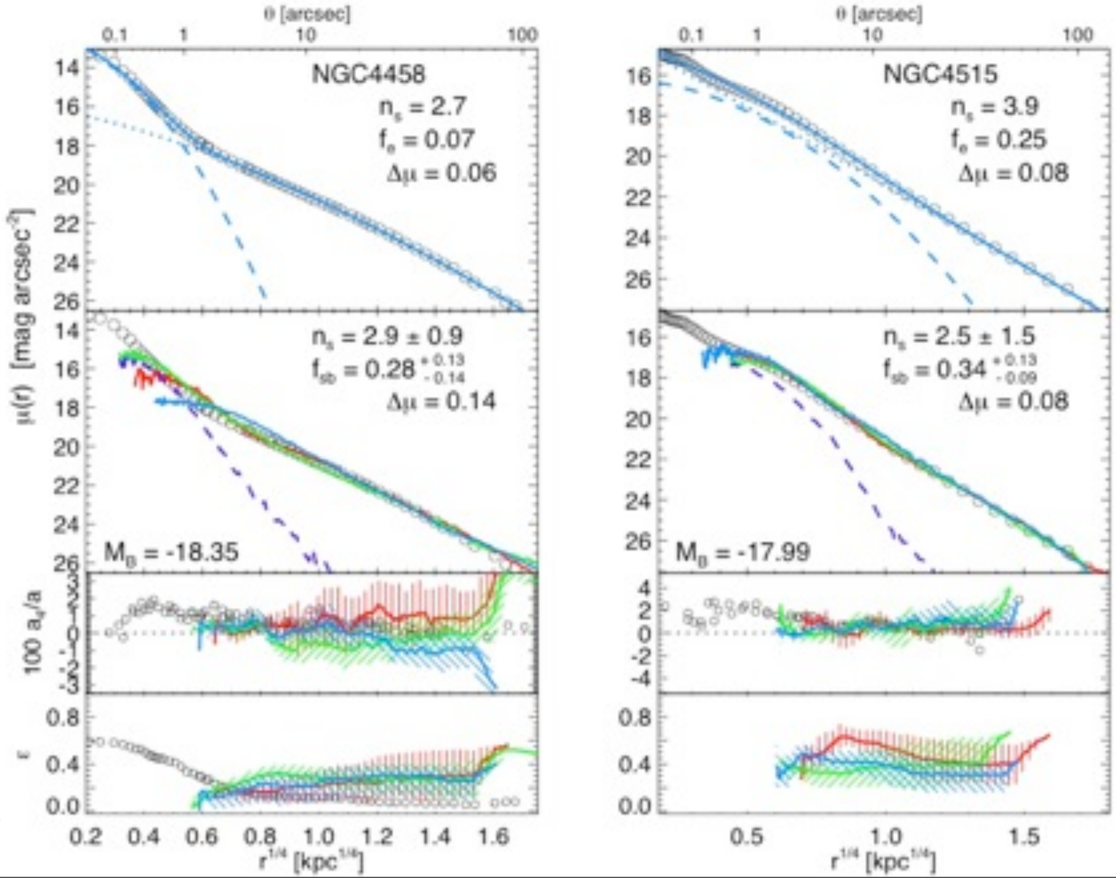


Application: “Cusp” Ellipticals

RECOVERING THE ROLE OF GAS



L > L* ellipticals

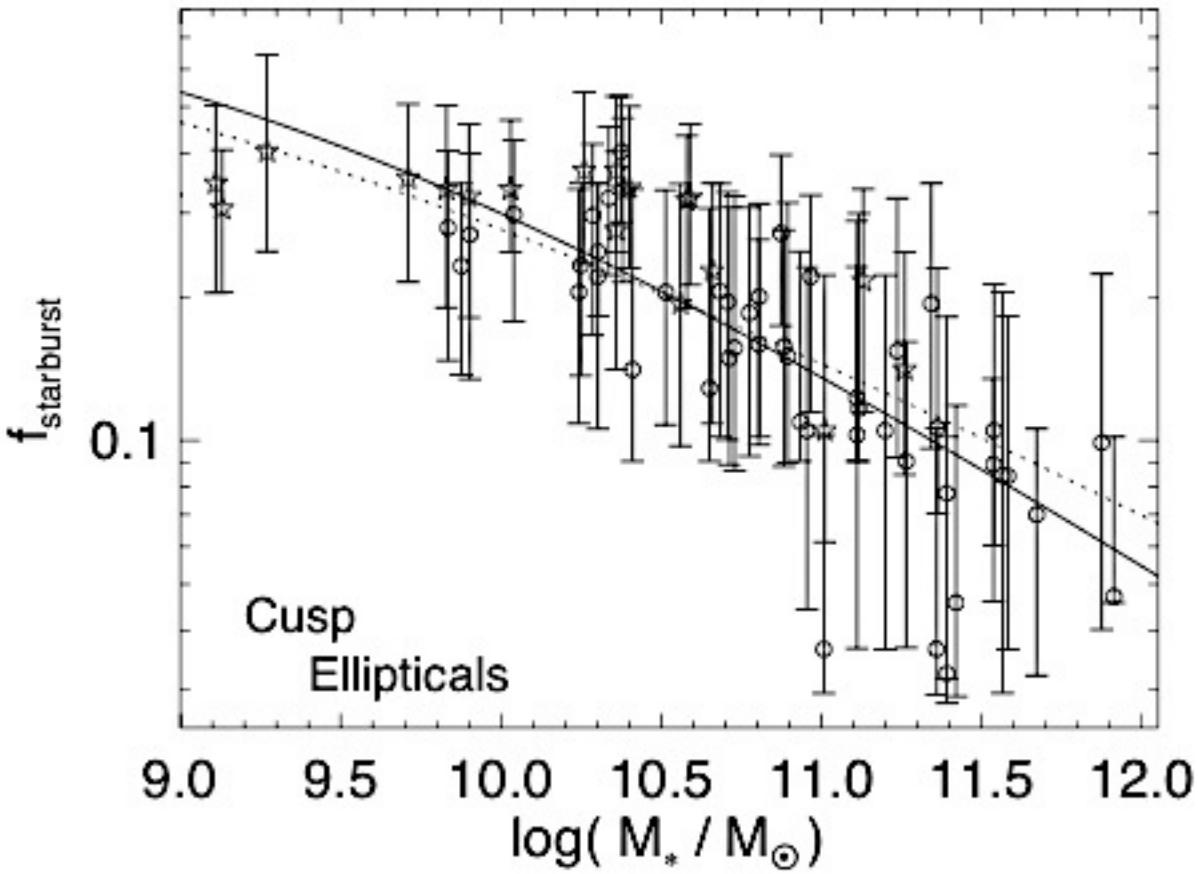


L < 0.1 L* ellipticals

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

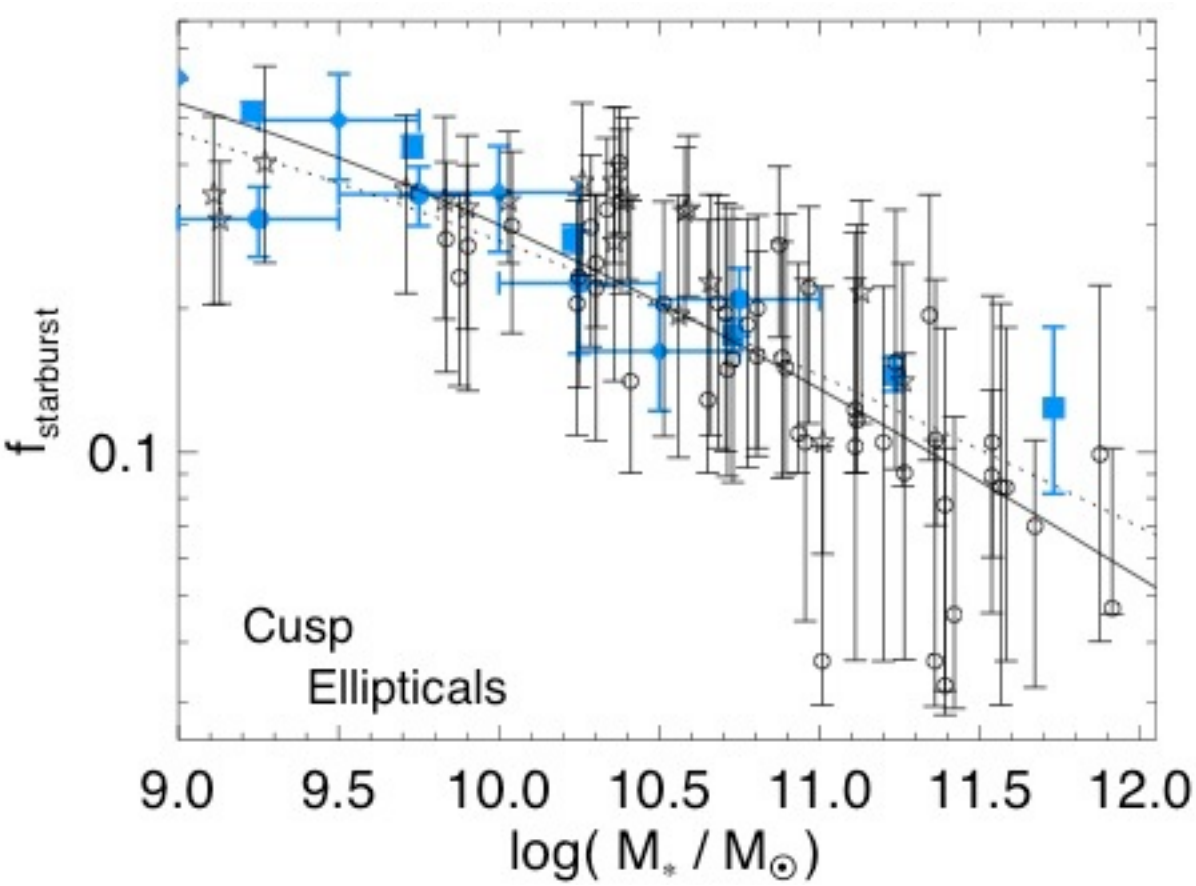
- Can match all (cusp) ellipticals with simple gas-rich merger remnants
- NEED systematically higher gas content in the progenitors at lower masses to explain the observed profile shapes



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 n



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

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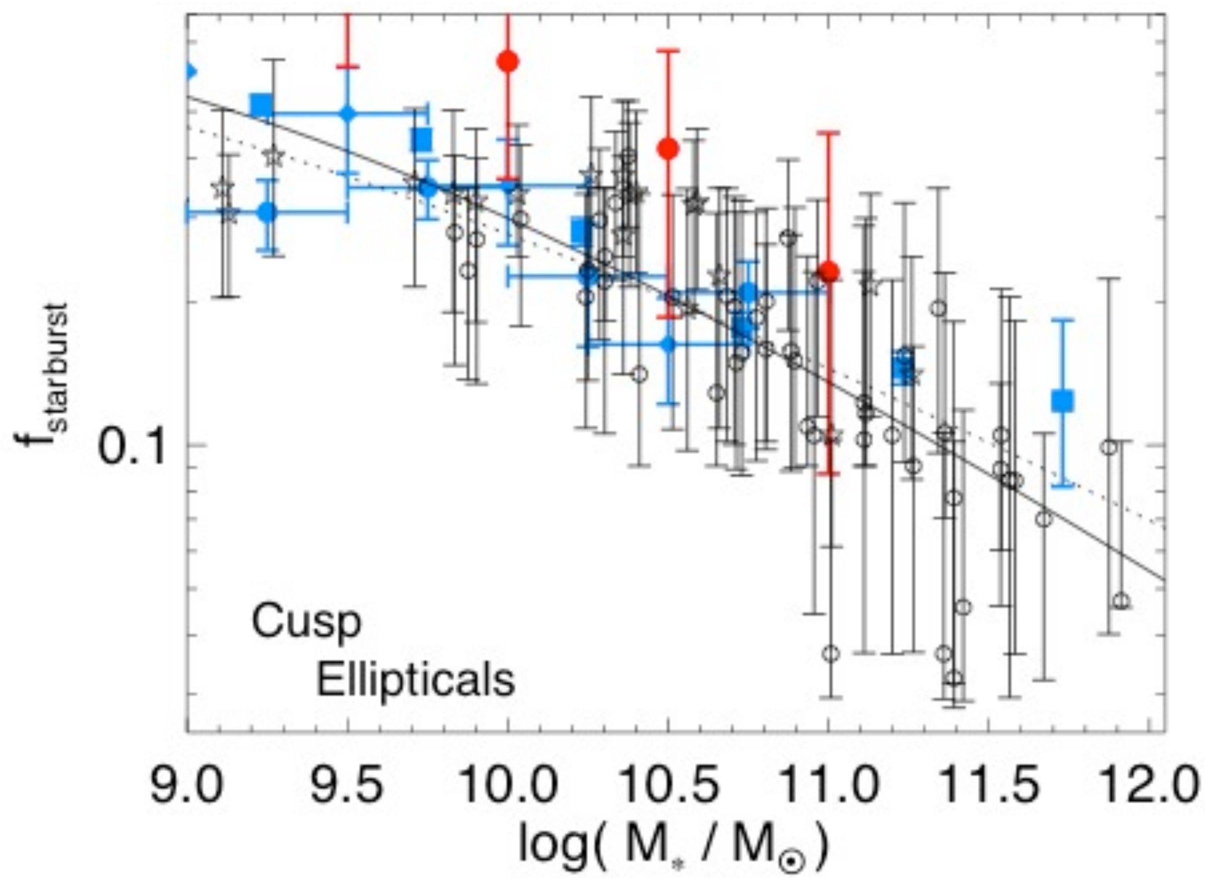
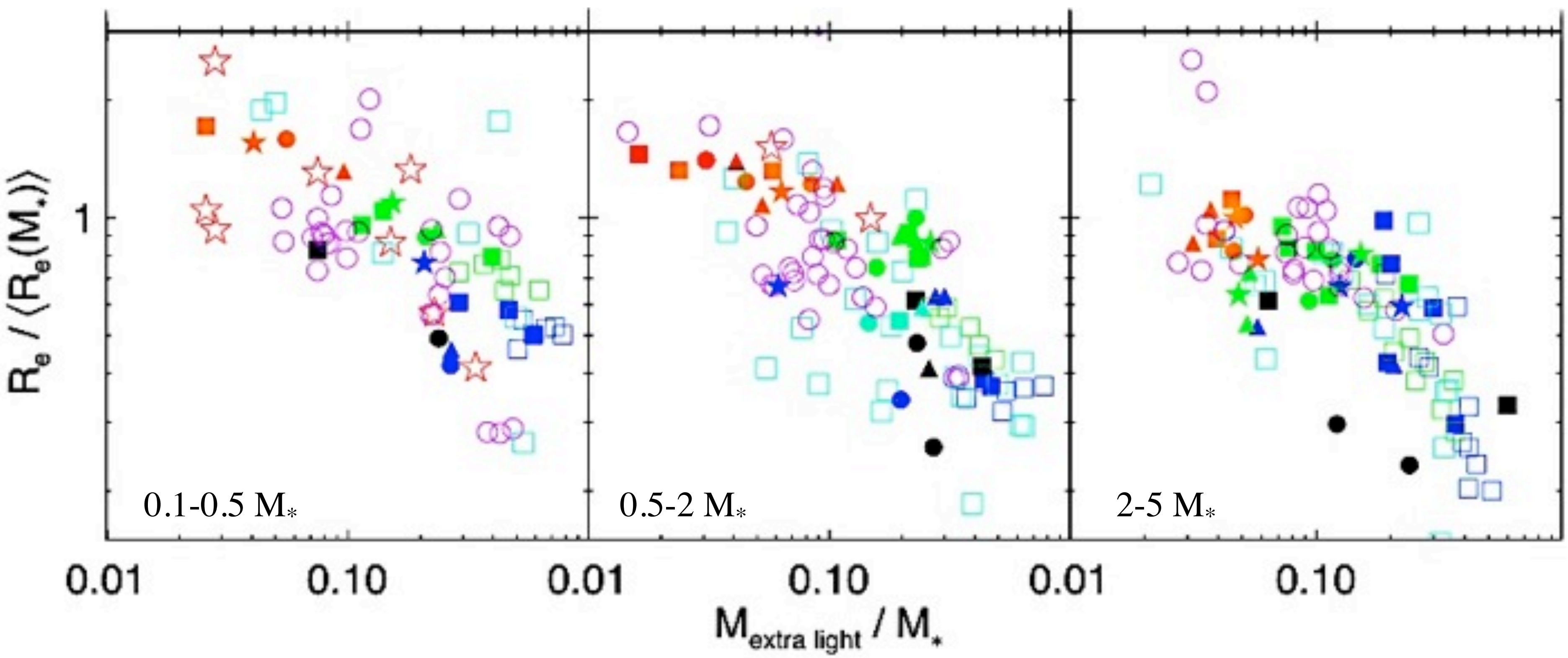


Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

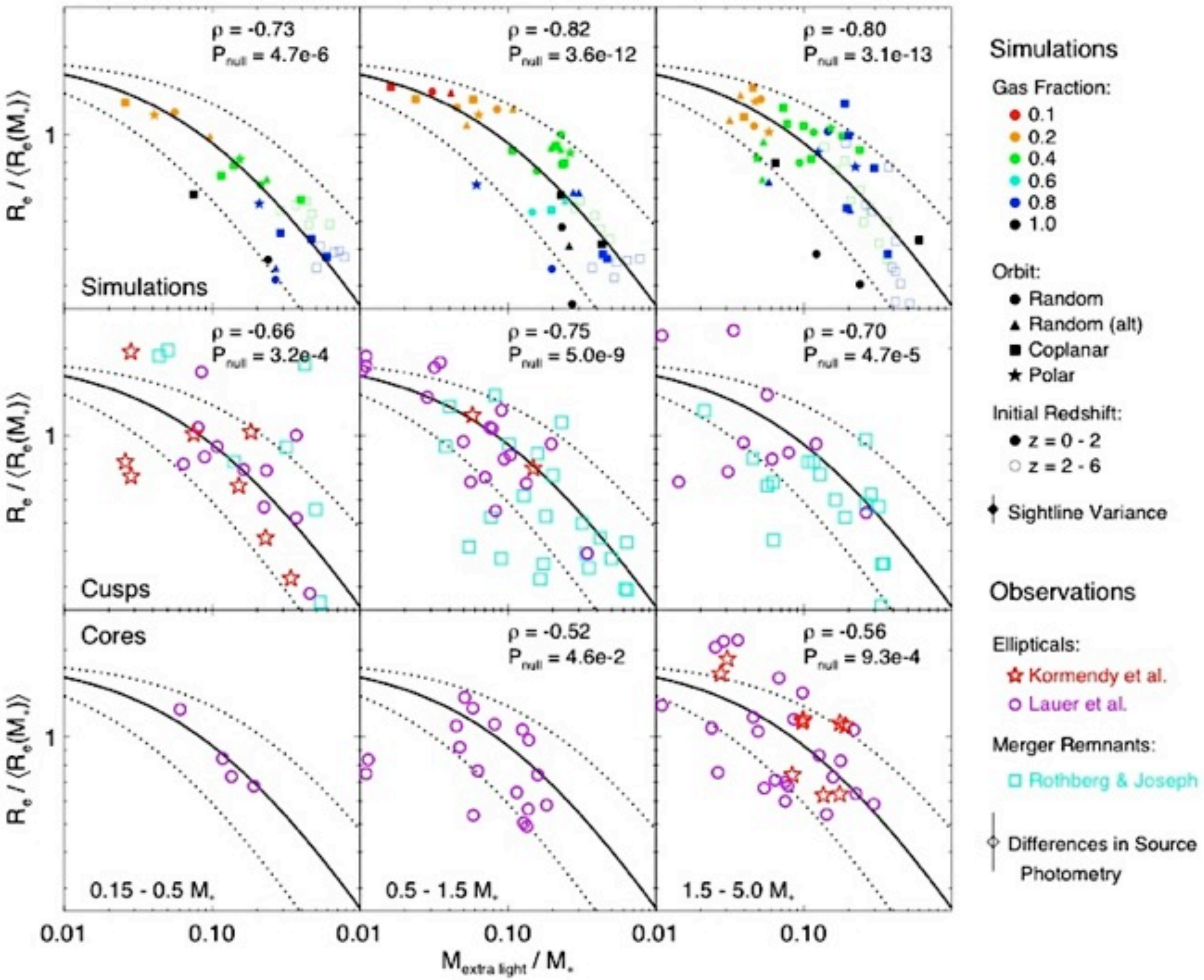
- Systems with more "extra light" are smaller

- 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



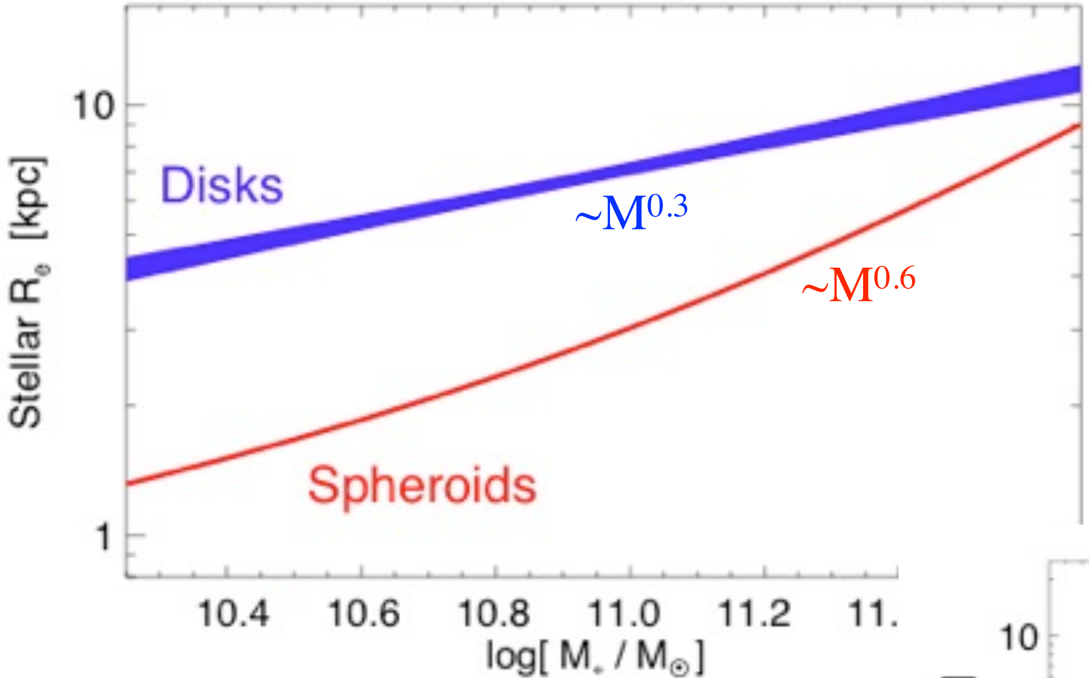
Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

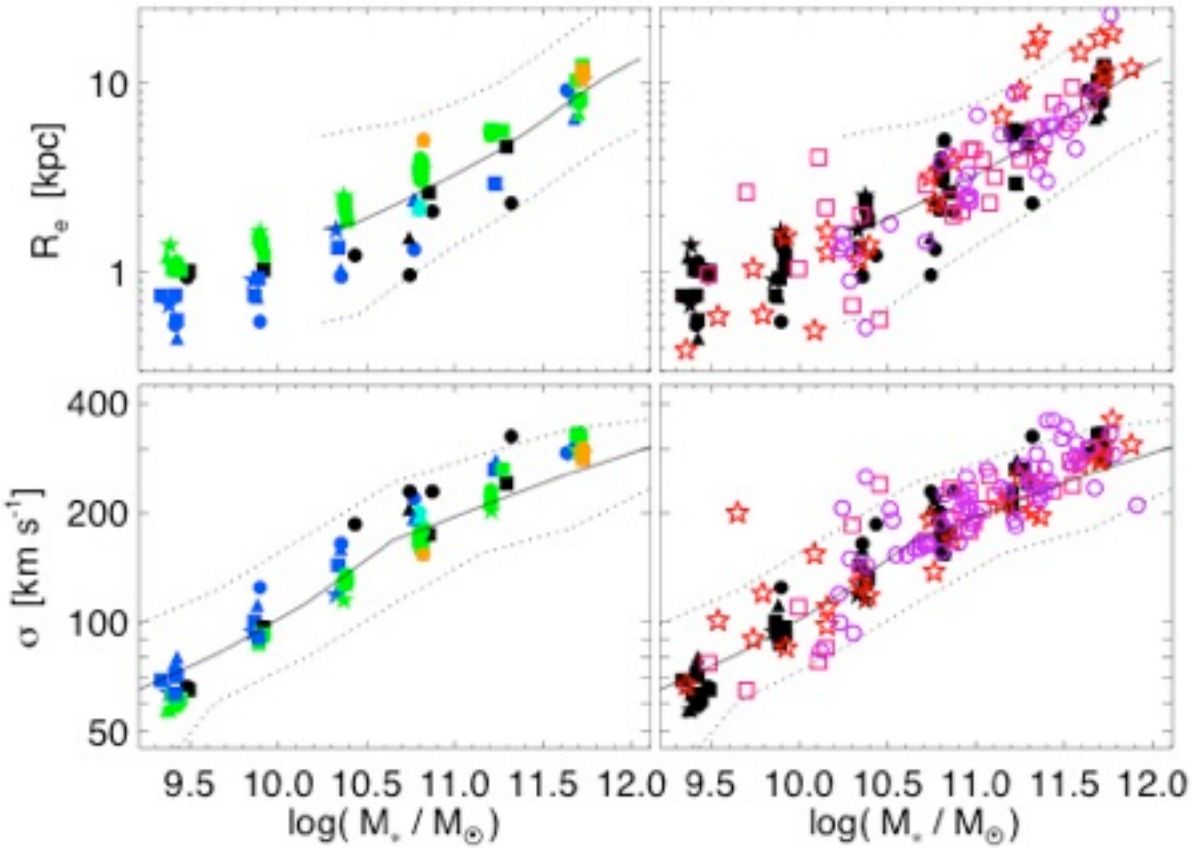


Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



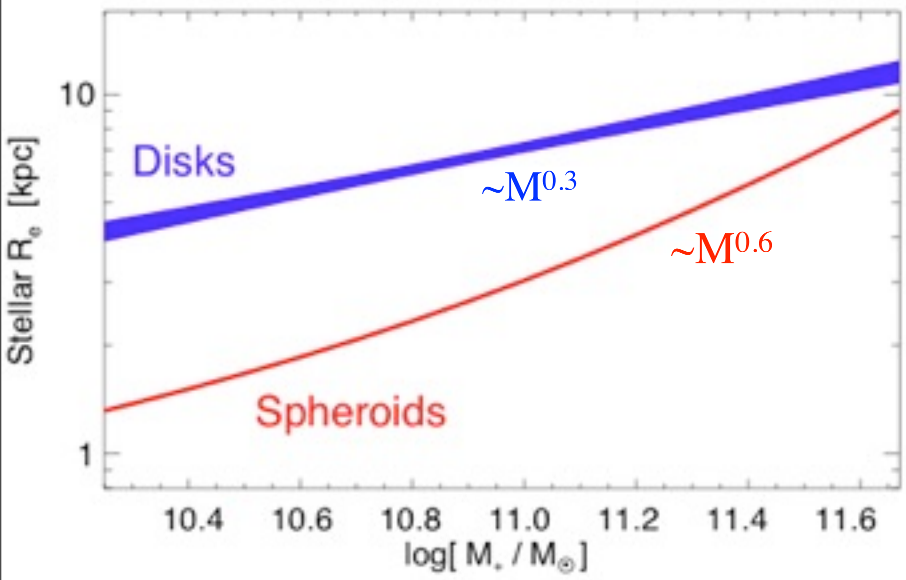
- Recall, low-M ellipticals are more compact than disks of similar mass

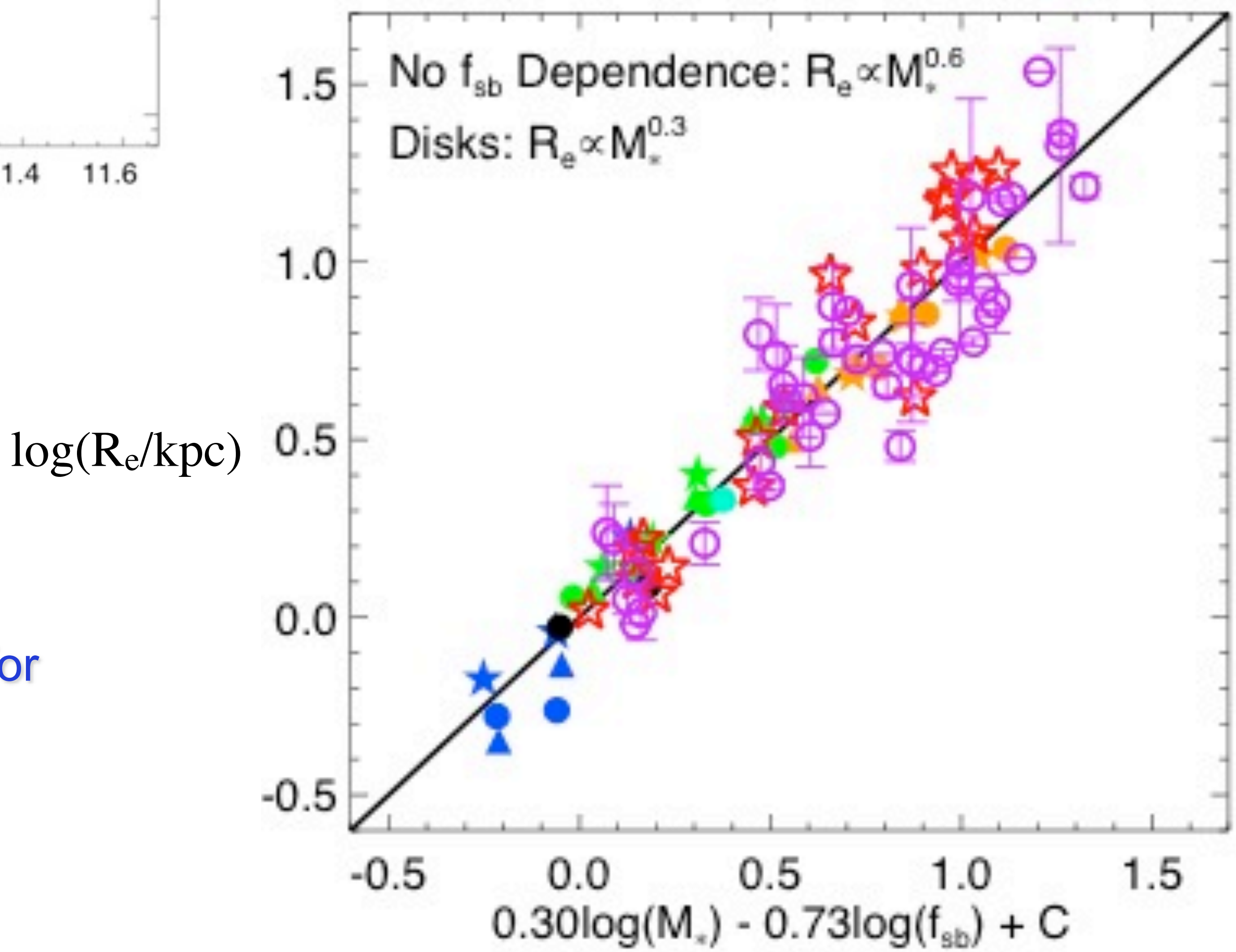


- Instead of <R>(M), fit R(M, $f_{dissipational}$)?

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

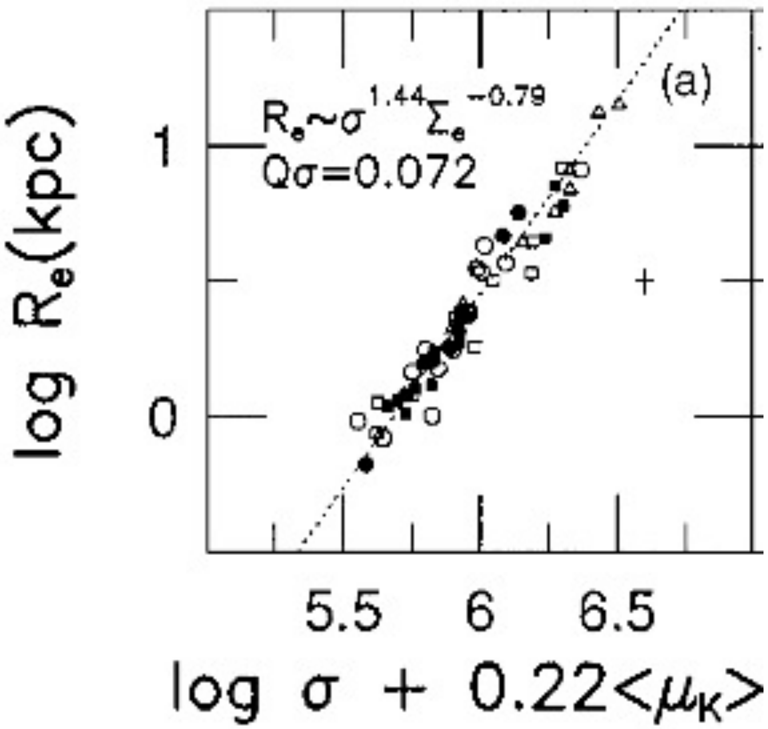




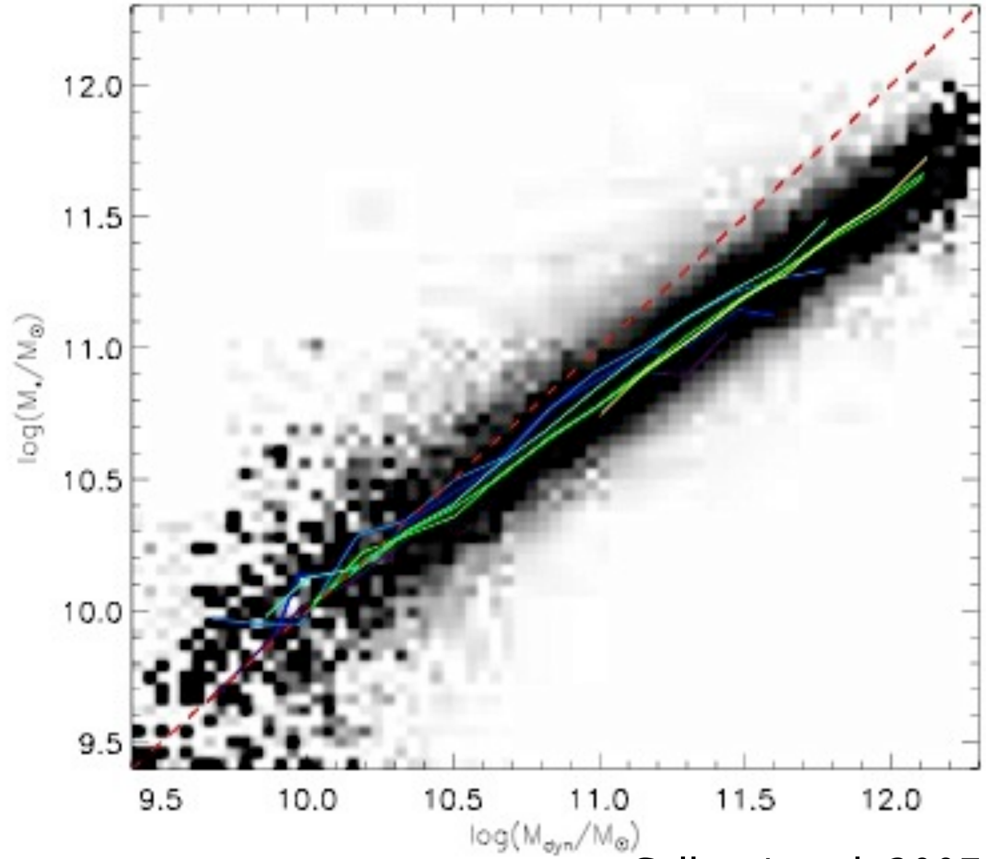
- Dissipation accounts for the difference

Fundamental Plane Tilt

WHERE DOES IT COME FROM?



Pahre et al. 1998



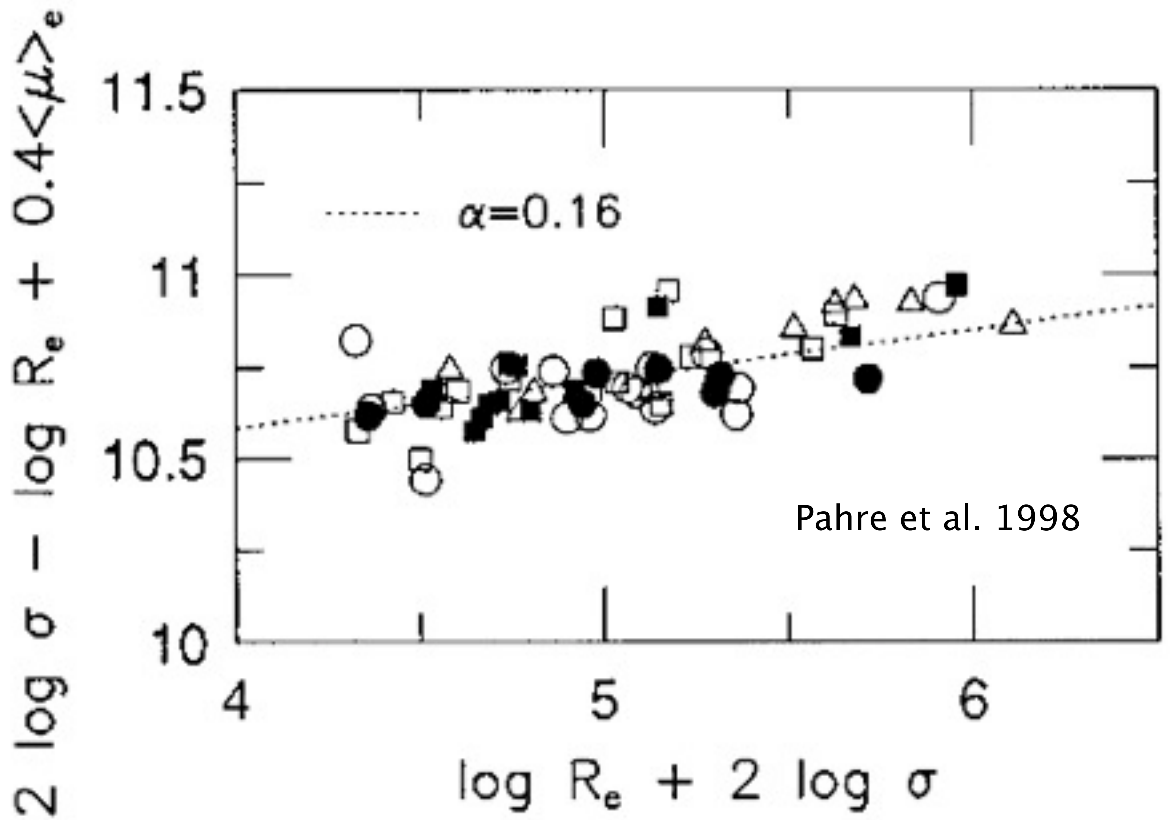
Gallazzi et al. 2007

- Correlation relating Ie(~$M_{stellar}/R^2$), 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")

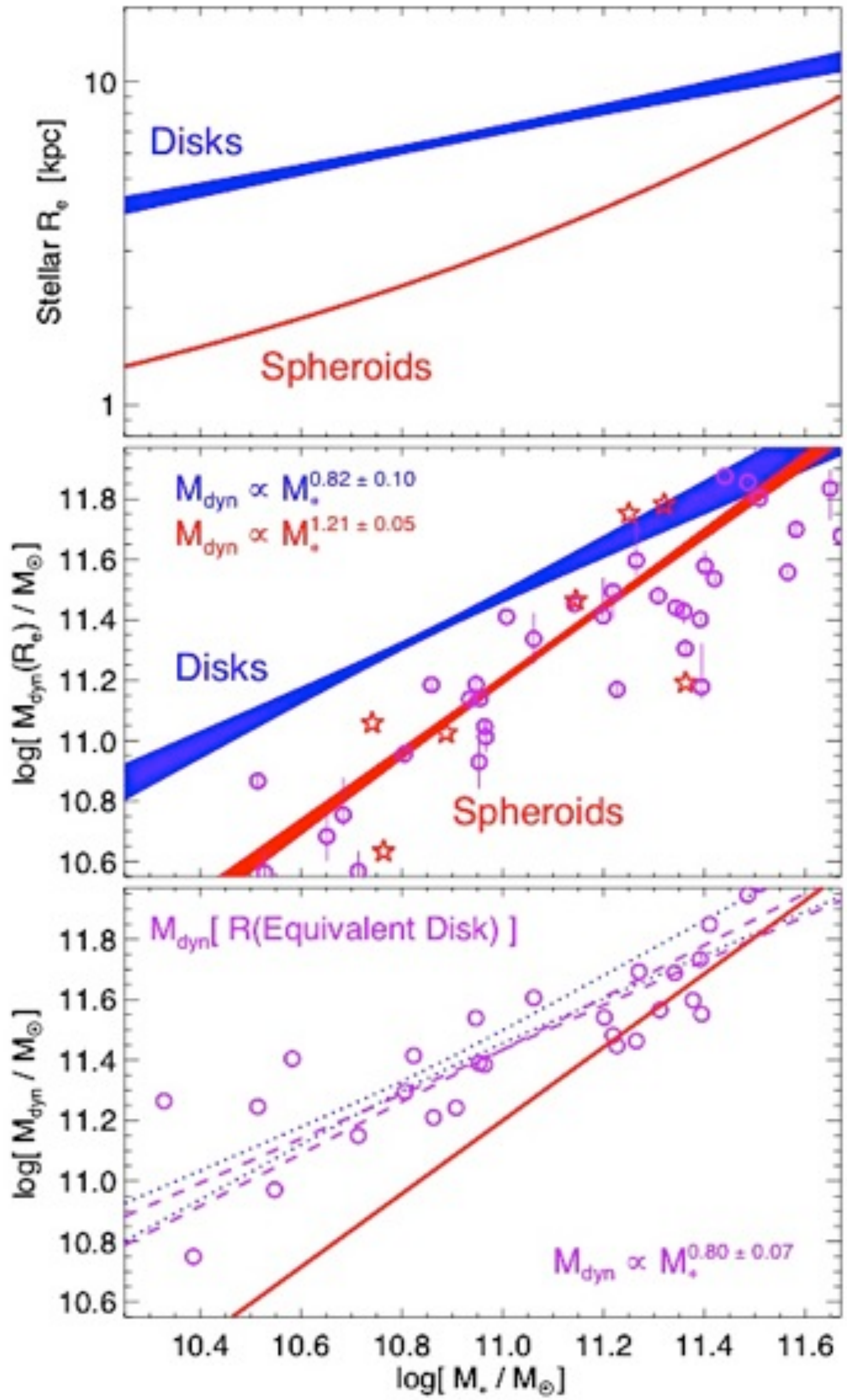


- Various observations (Bolton et al., Cappellari et al.) with masses from kinematic modeling, lensing, gas all agree:
  - Low-mass ellipticals are more baryon-dominated (have fractionally less DM) inside their stellar R_{eff}

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

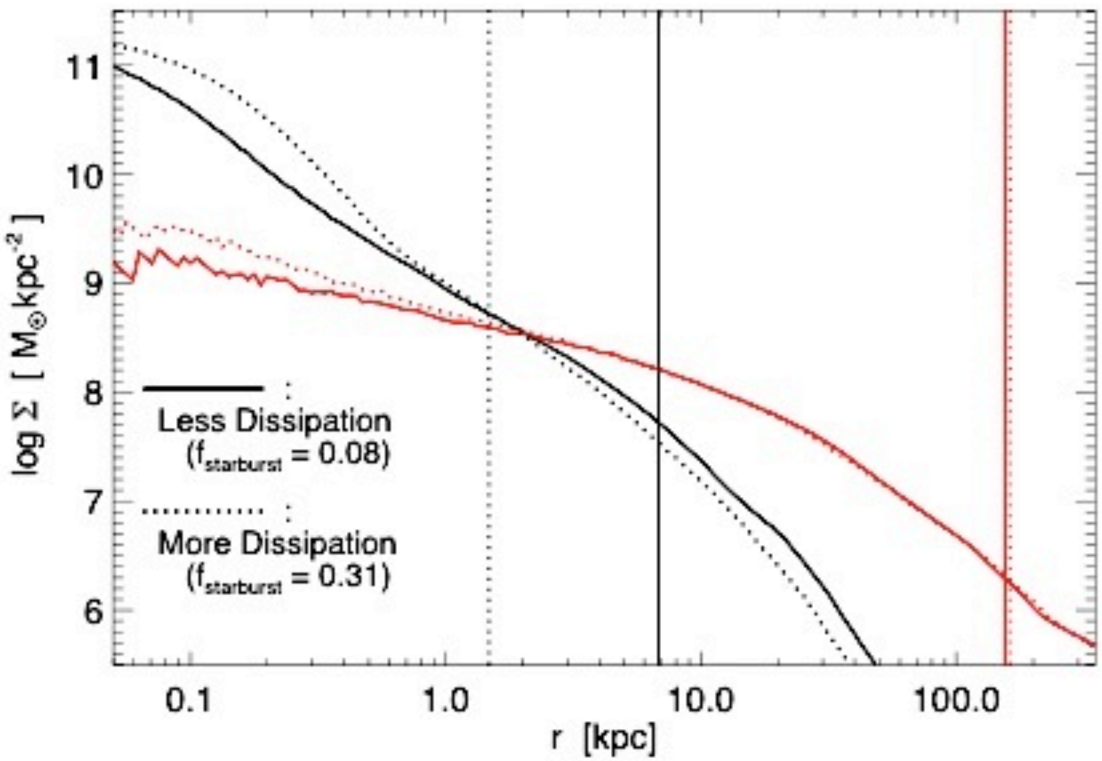
- This is opposite the trend in disks/naively expected of baryons in halos
- Akin to comparison of sizes/compactness

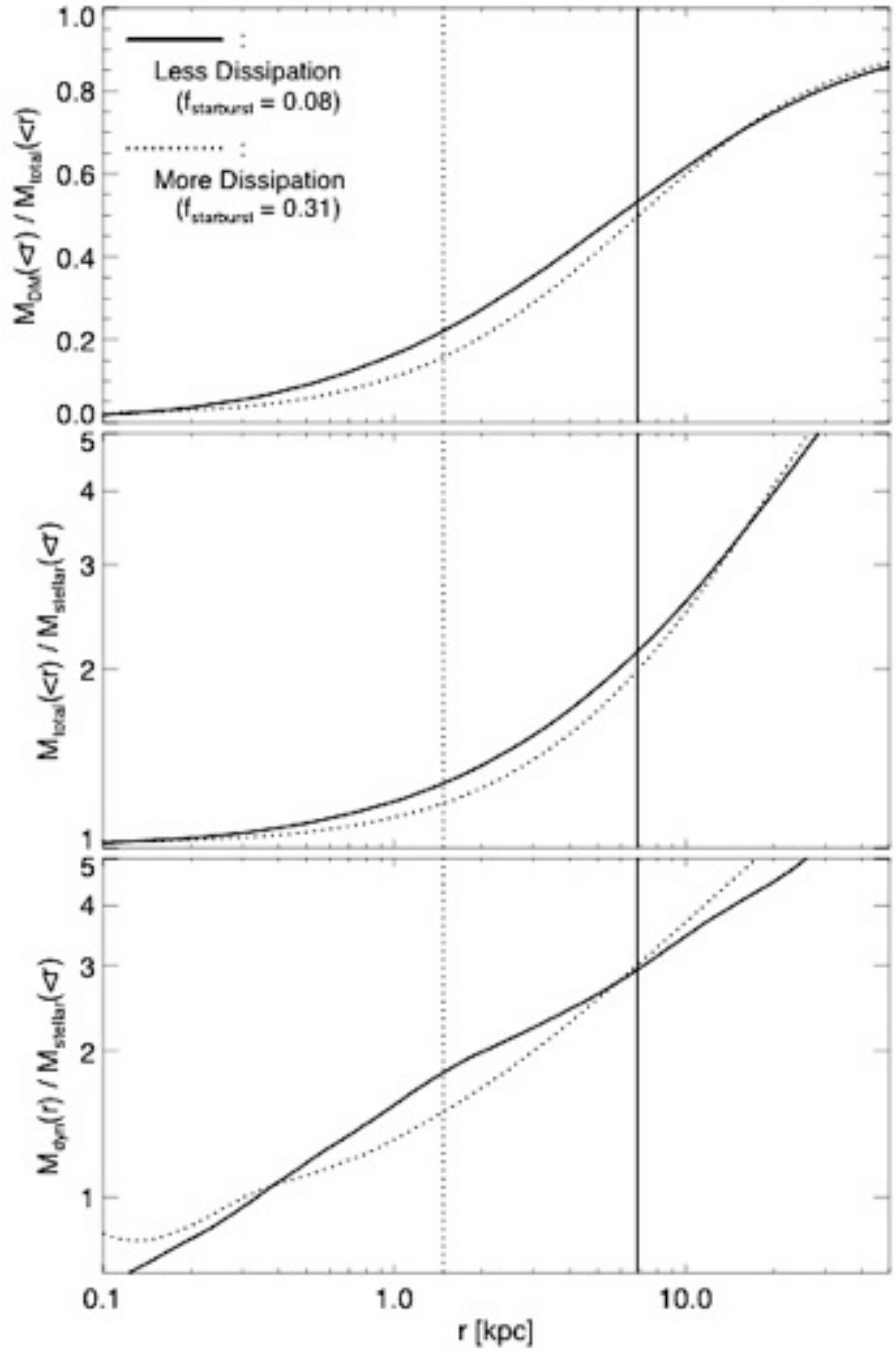


Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Dissipation has been invoked to explain this



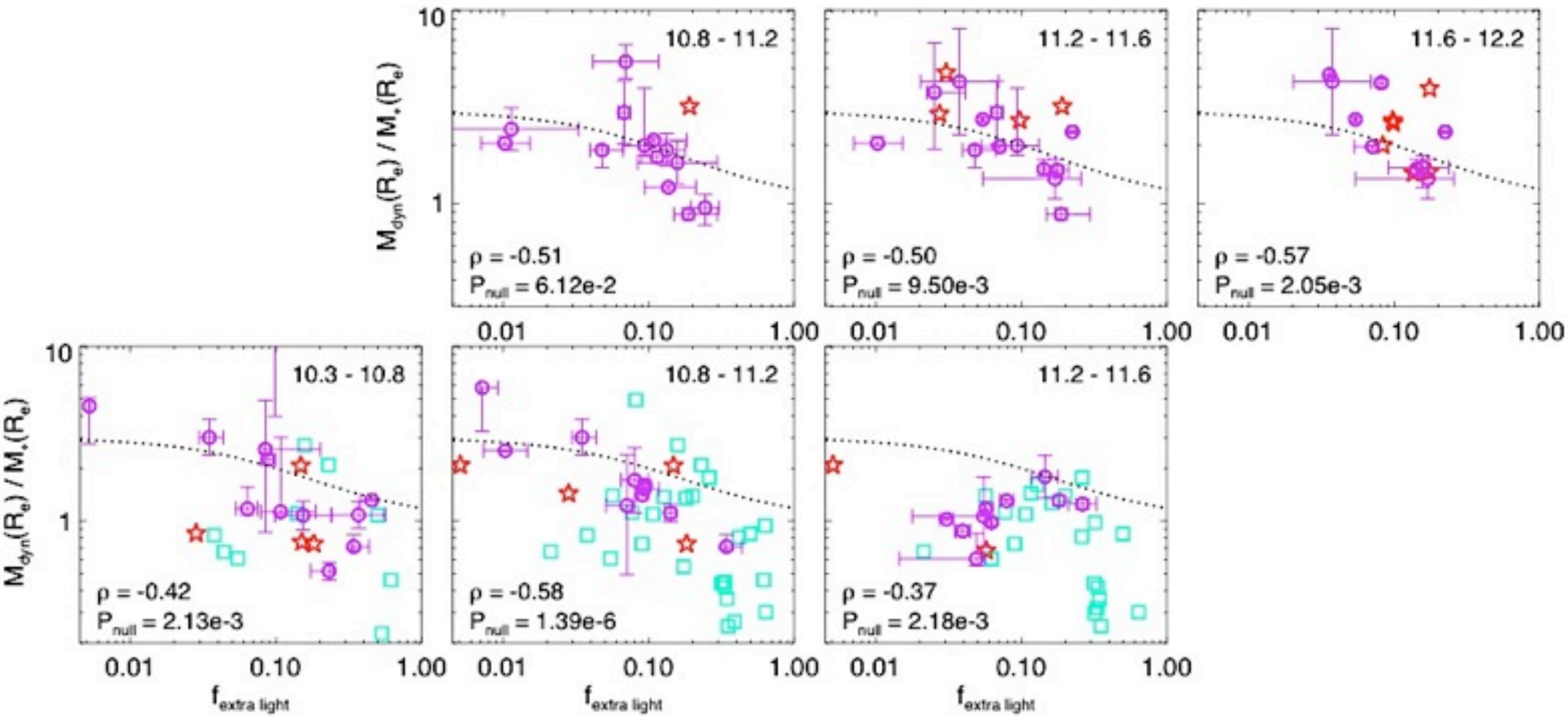


- If dissipational fraction scales w. mass, simulations can match FP

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Does it work?

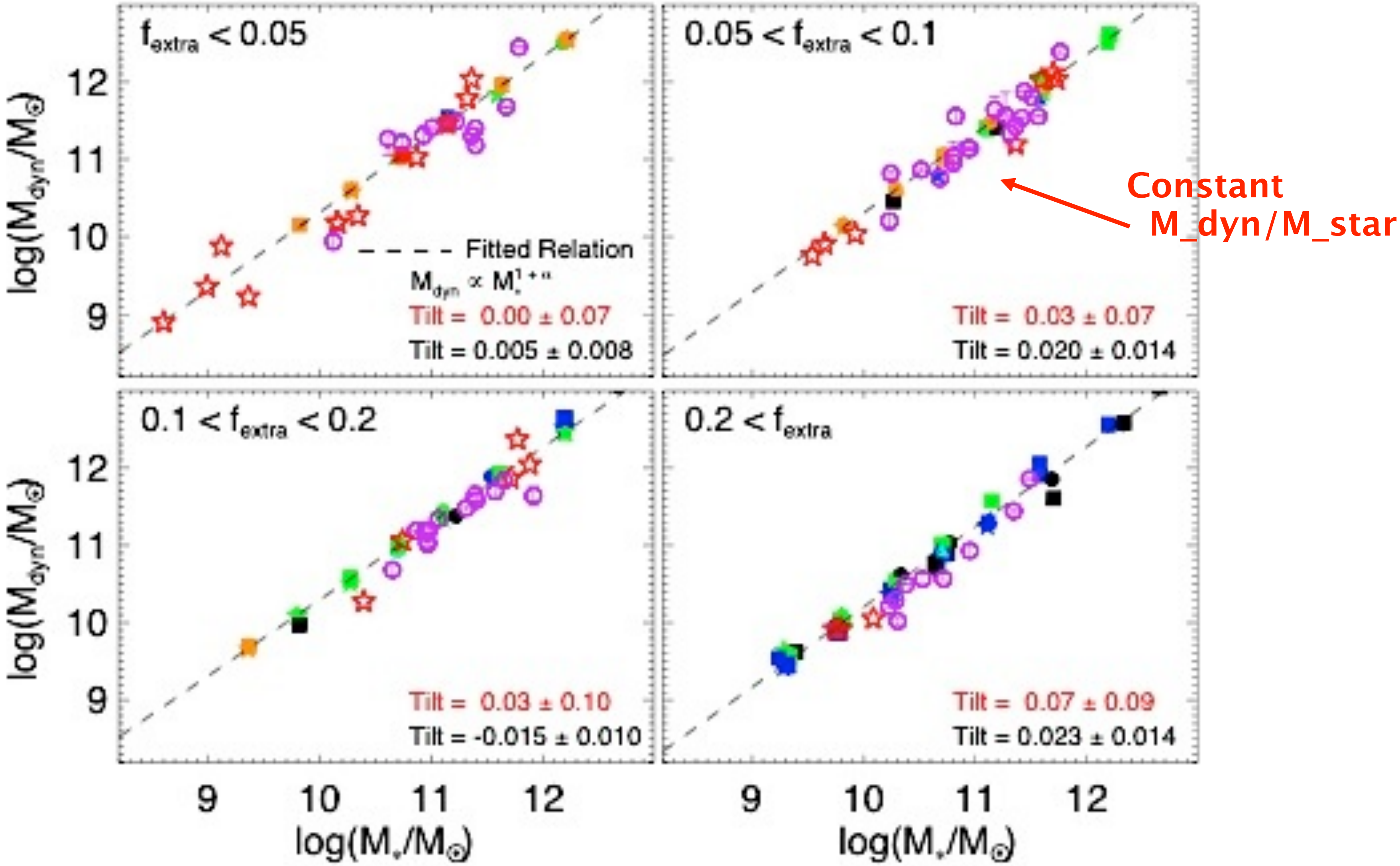


- $M_{dyn}/M_{stellar}$ depends on $f_{dissipational}$ at all M

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

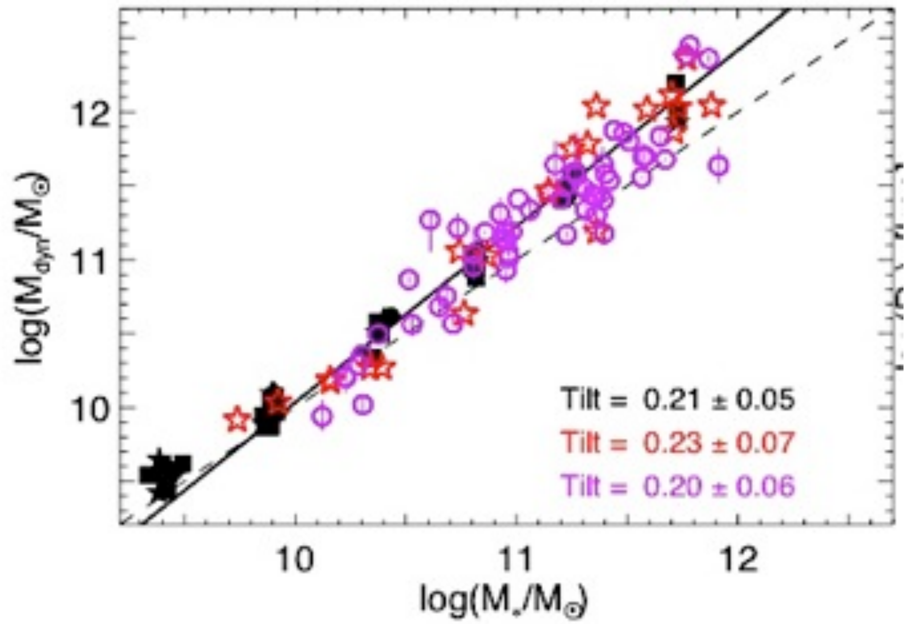
- Does it work?



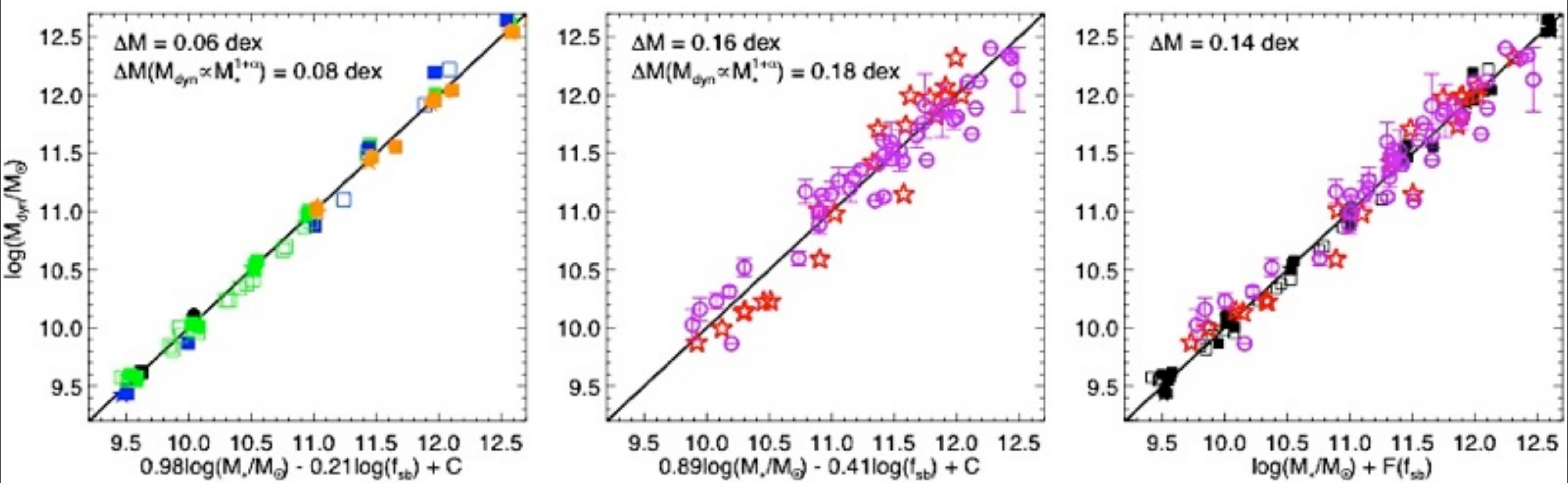
- At FIXED $f_{dissipational}$, there is NO TILT

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

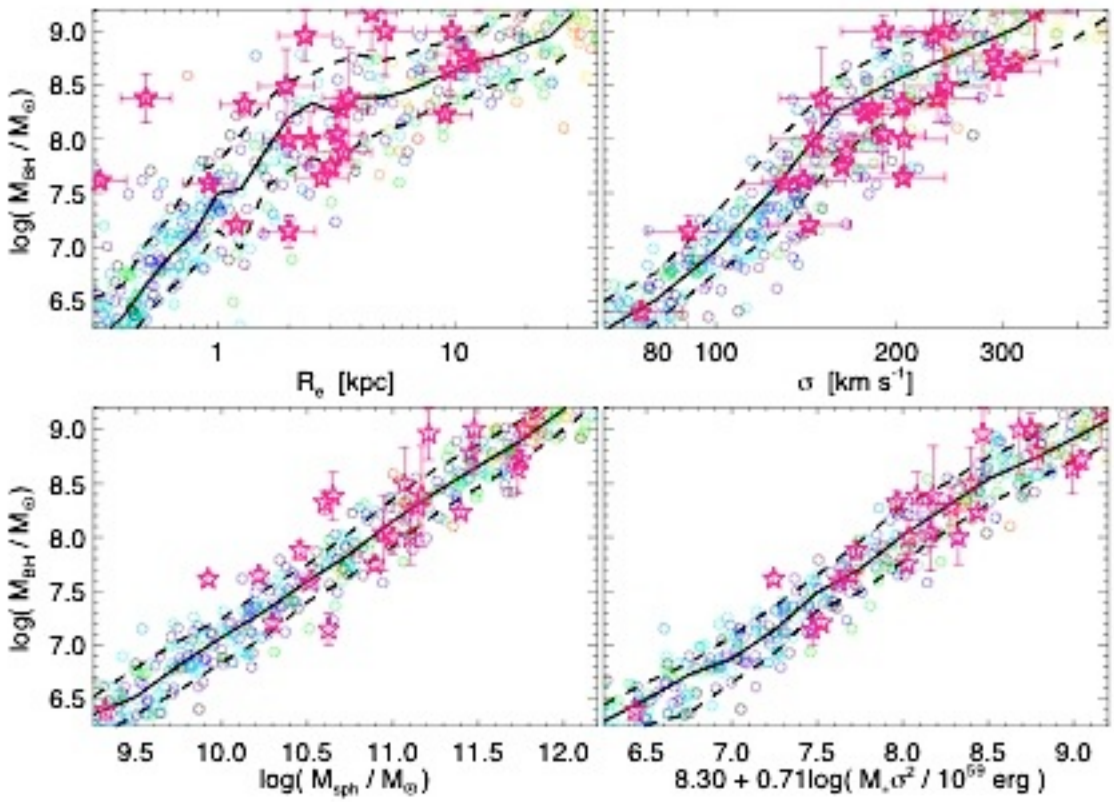


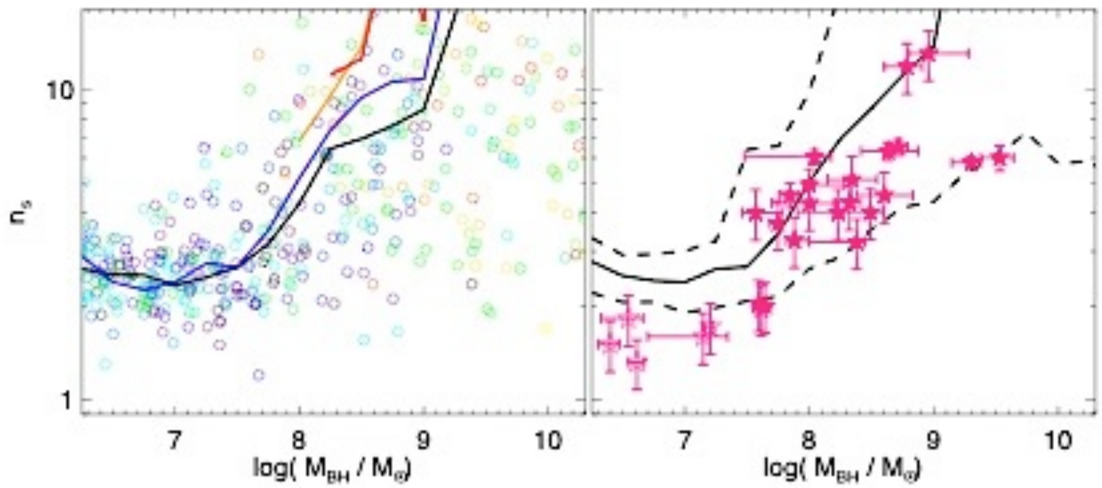
- Instead of thinking of the FP as $M_{dyn} \sim M_{stellar}^{(1+a)}$
- We should think of it in terms of $M_{dyn} \sim M_{stellar} \times F(f_{dissipational})$



Implications for BH-Host Correlations

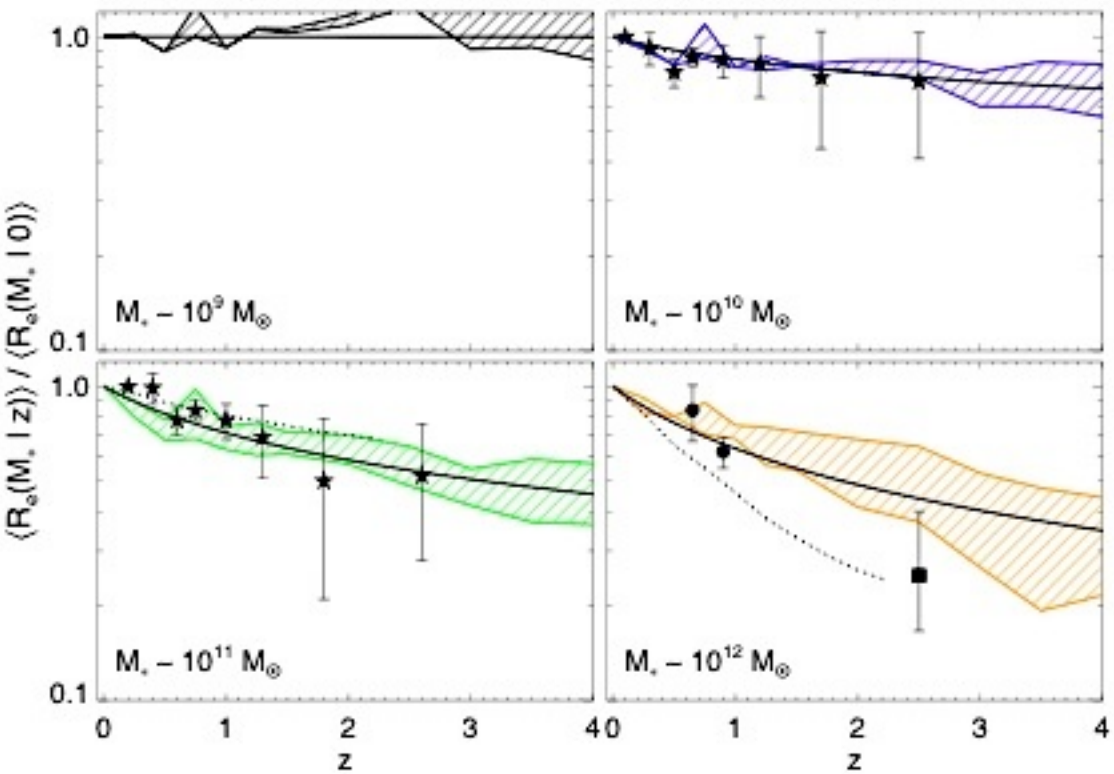
AT Z=0

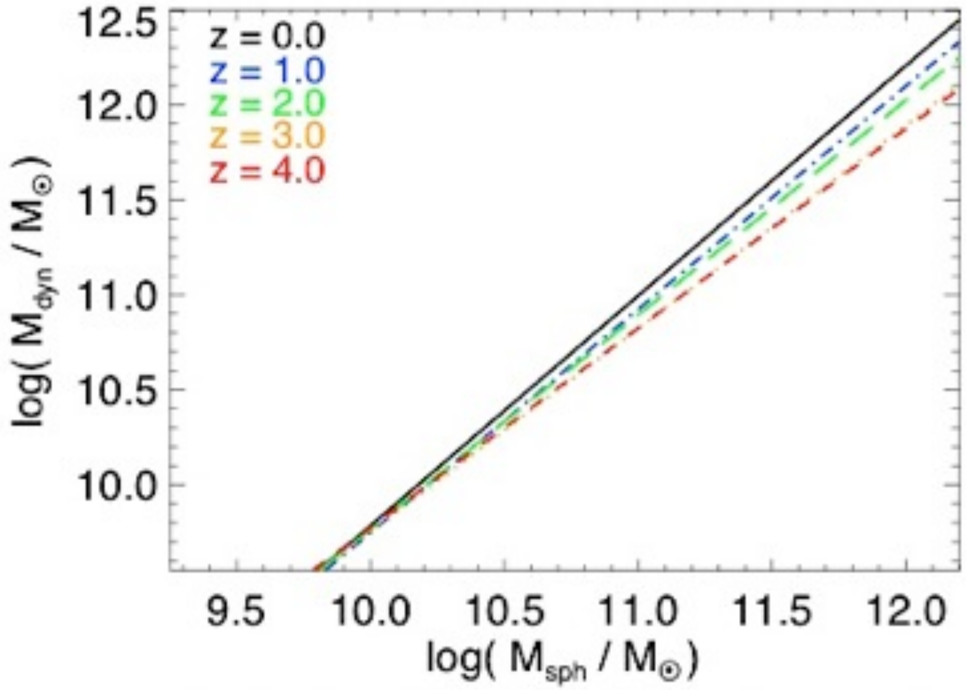


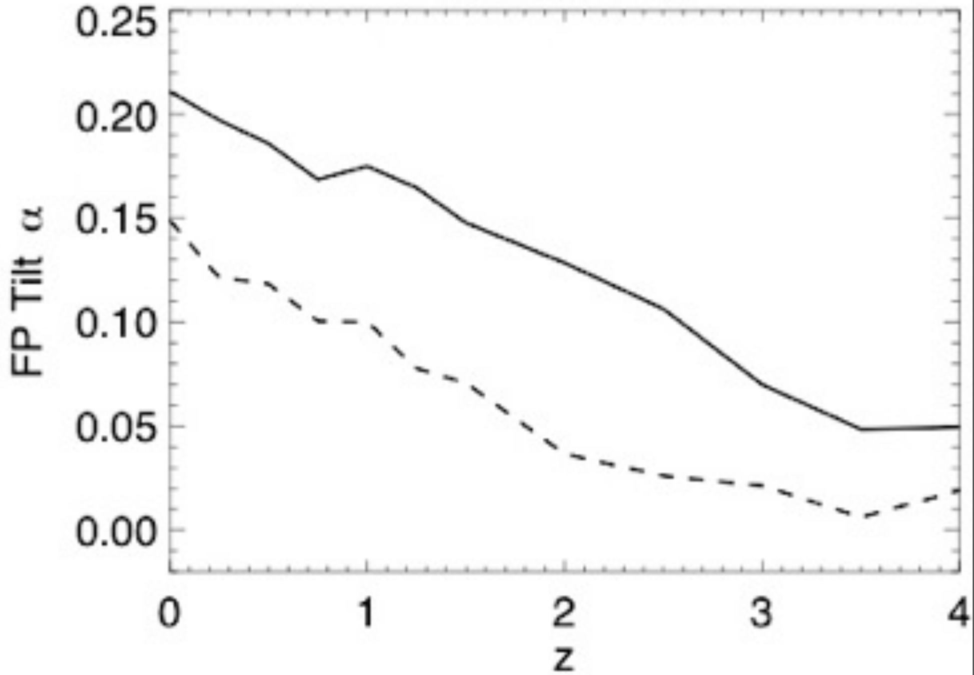


Dissipation versus Redshift

HIGH-Z DISKS ARE MORE GAS RICH...



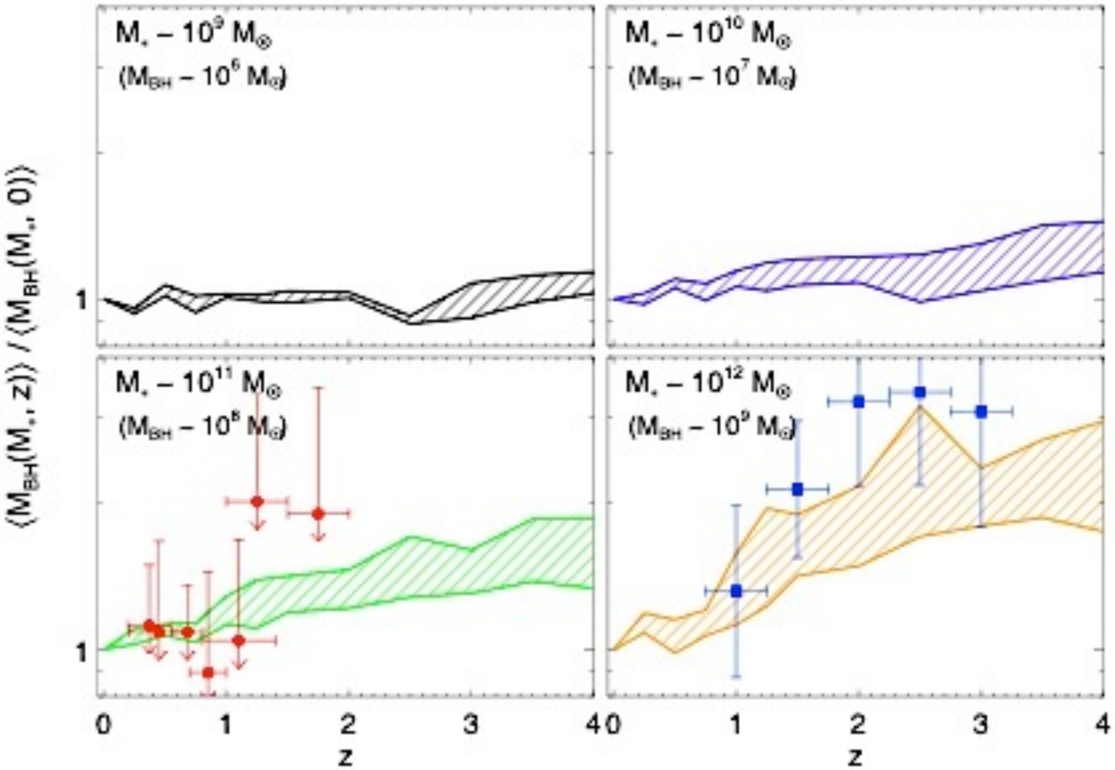


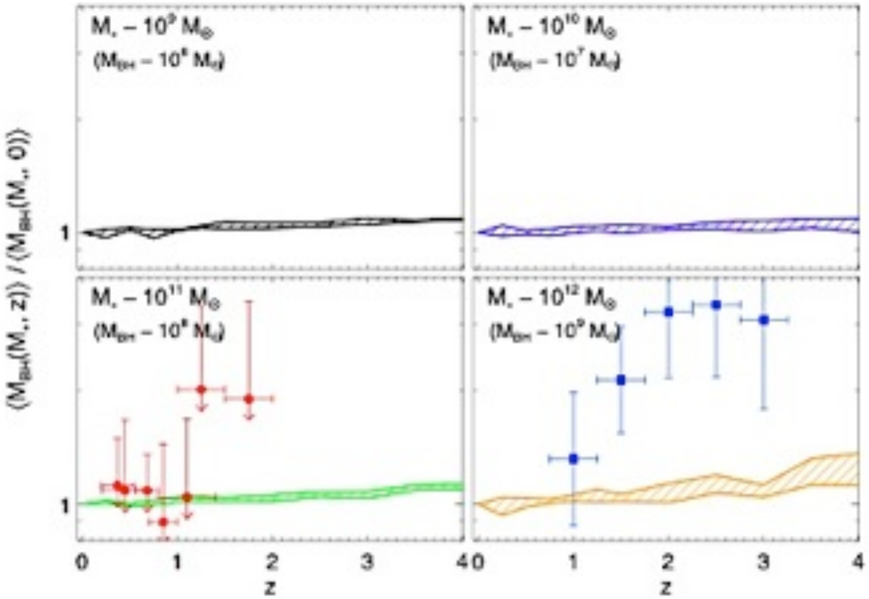


- So get more compact ellipticals

Implications for BH-Host Correlations

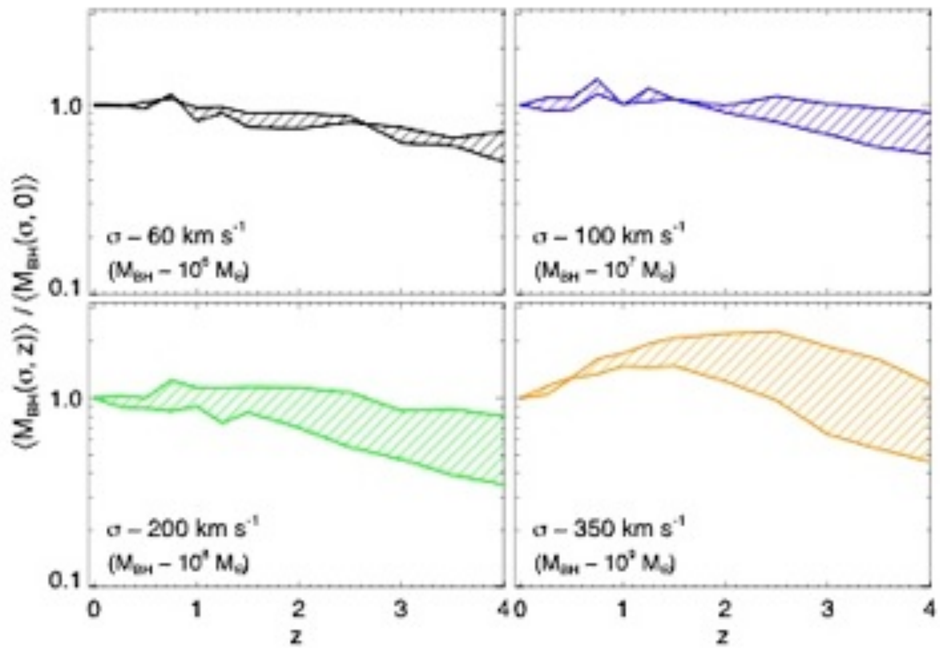
EVOLUTION WITH REDSHIFT





- (without dissipation=no evolution)

- Deeper potential wells at fixed M

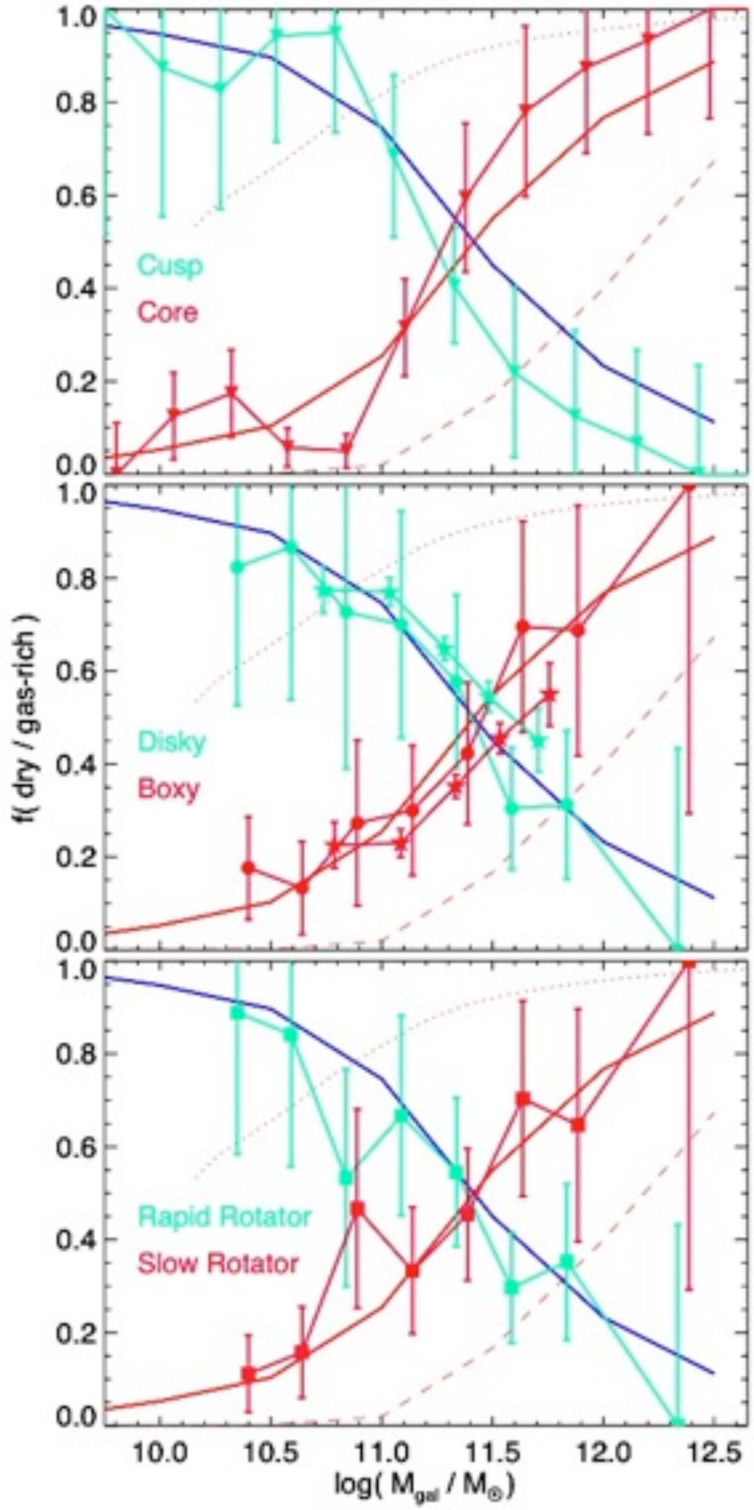


- (Weaker in sigma)

What about the "Cores"?

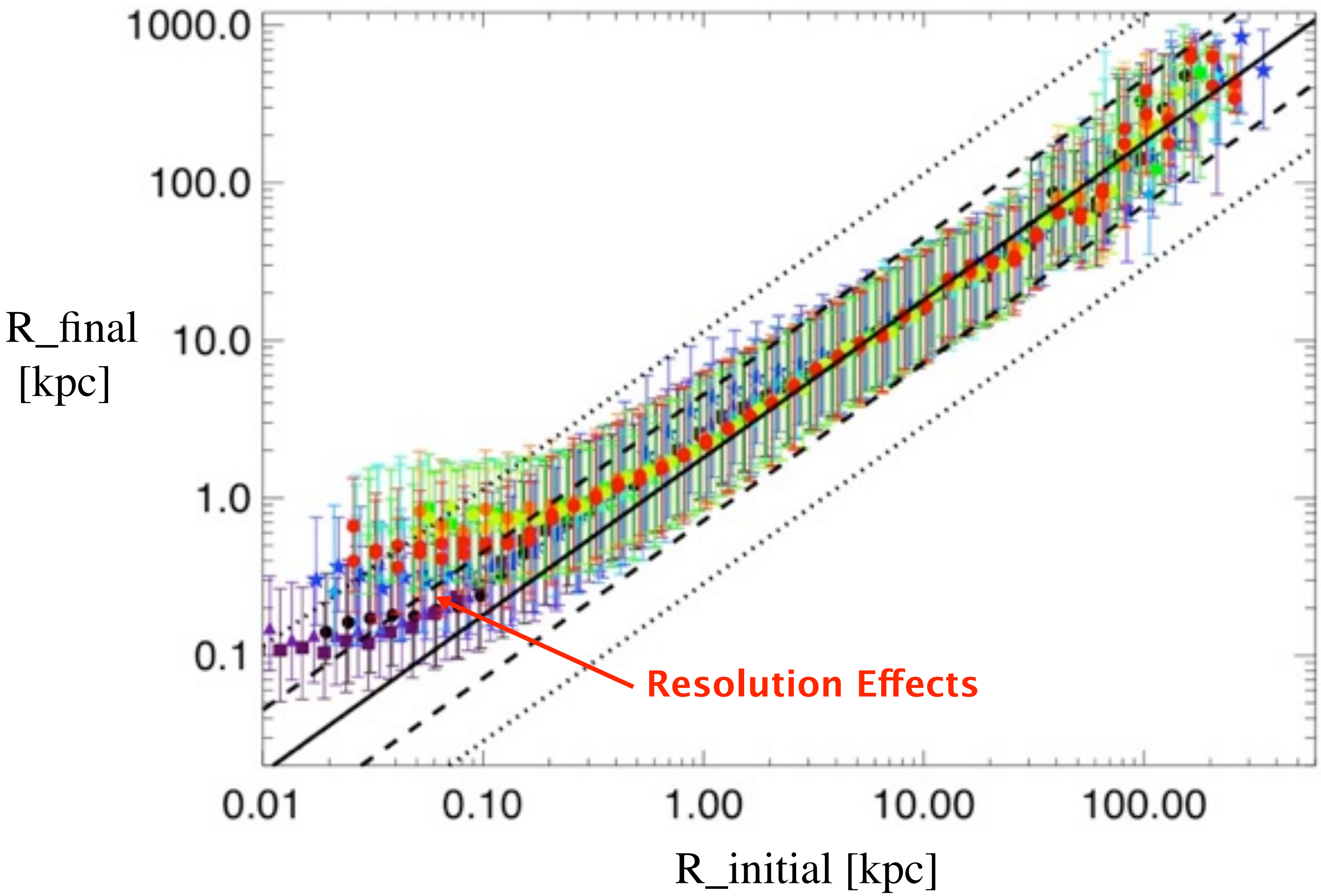
CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?

- 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"?



Application: “Core” Ellipticals

WHAT HAPPENS TO THE “EXTRA LIGHT”?



- Stars are puffed out, but preserve rank-ordering in radius (or binding energy)
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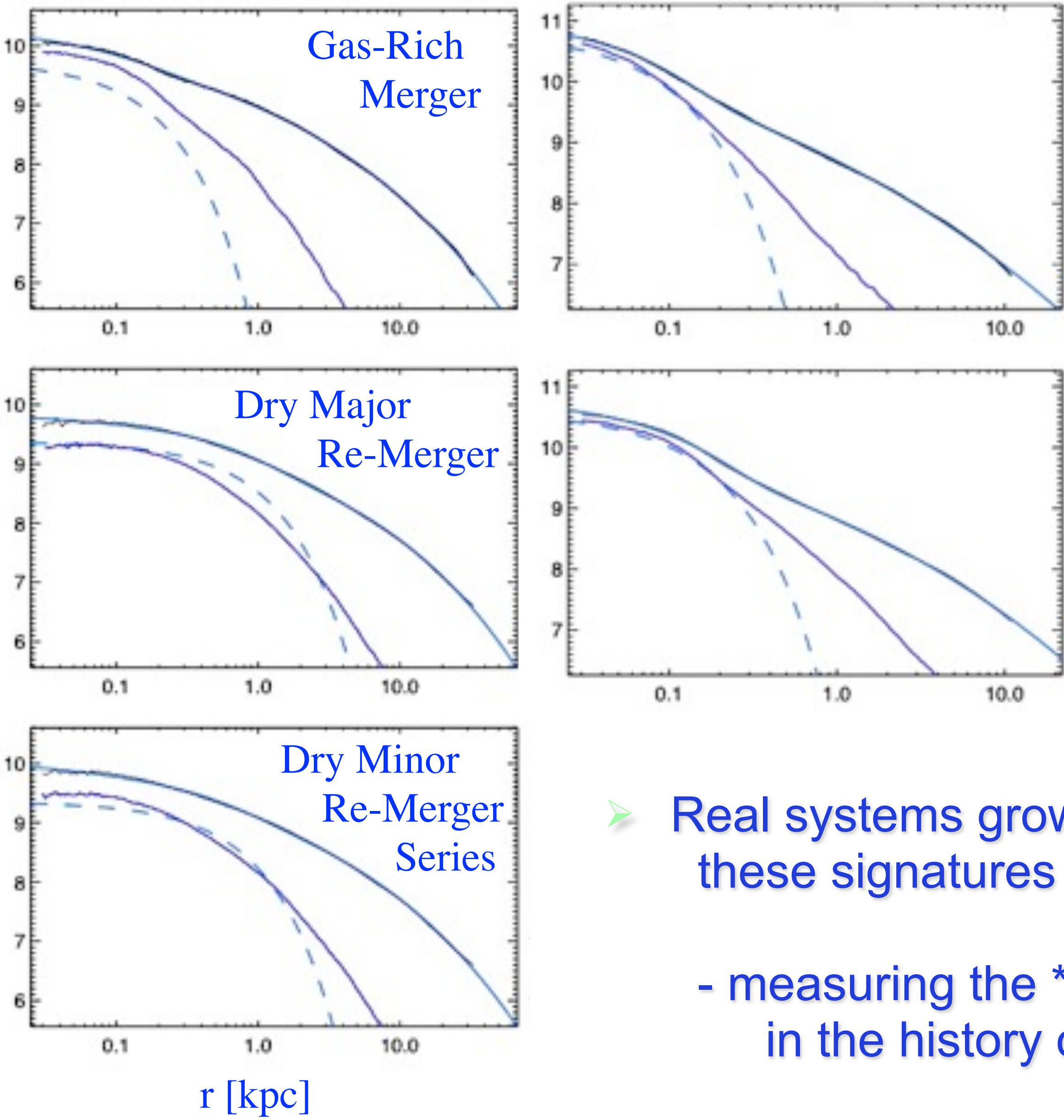
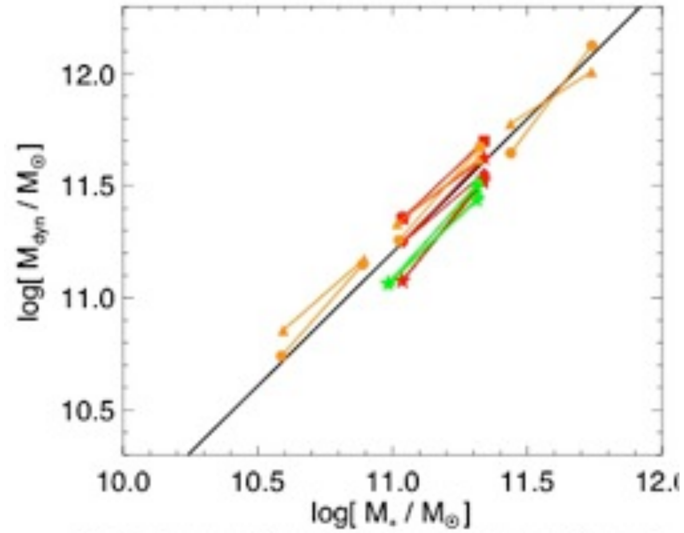
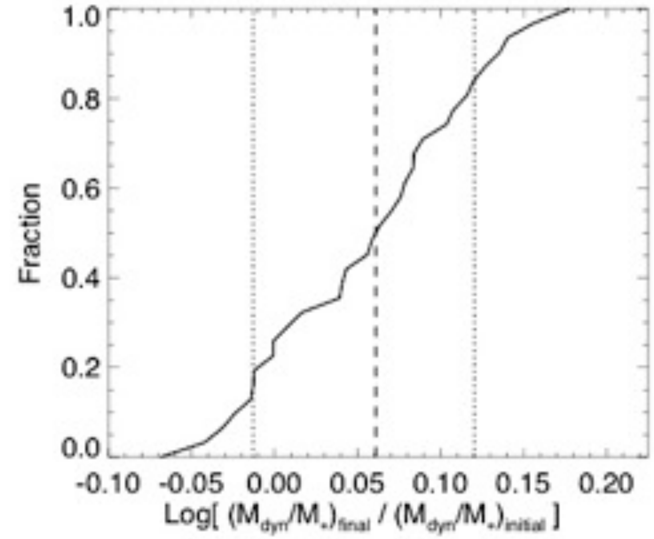
Caveats

SOME GENERAL CONSIDERATIONS





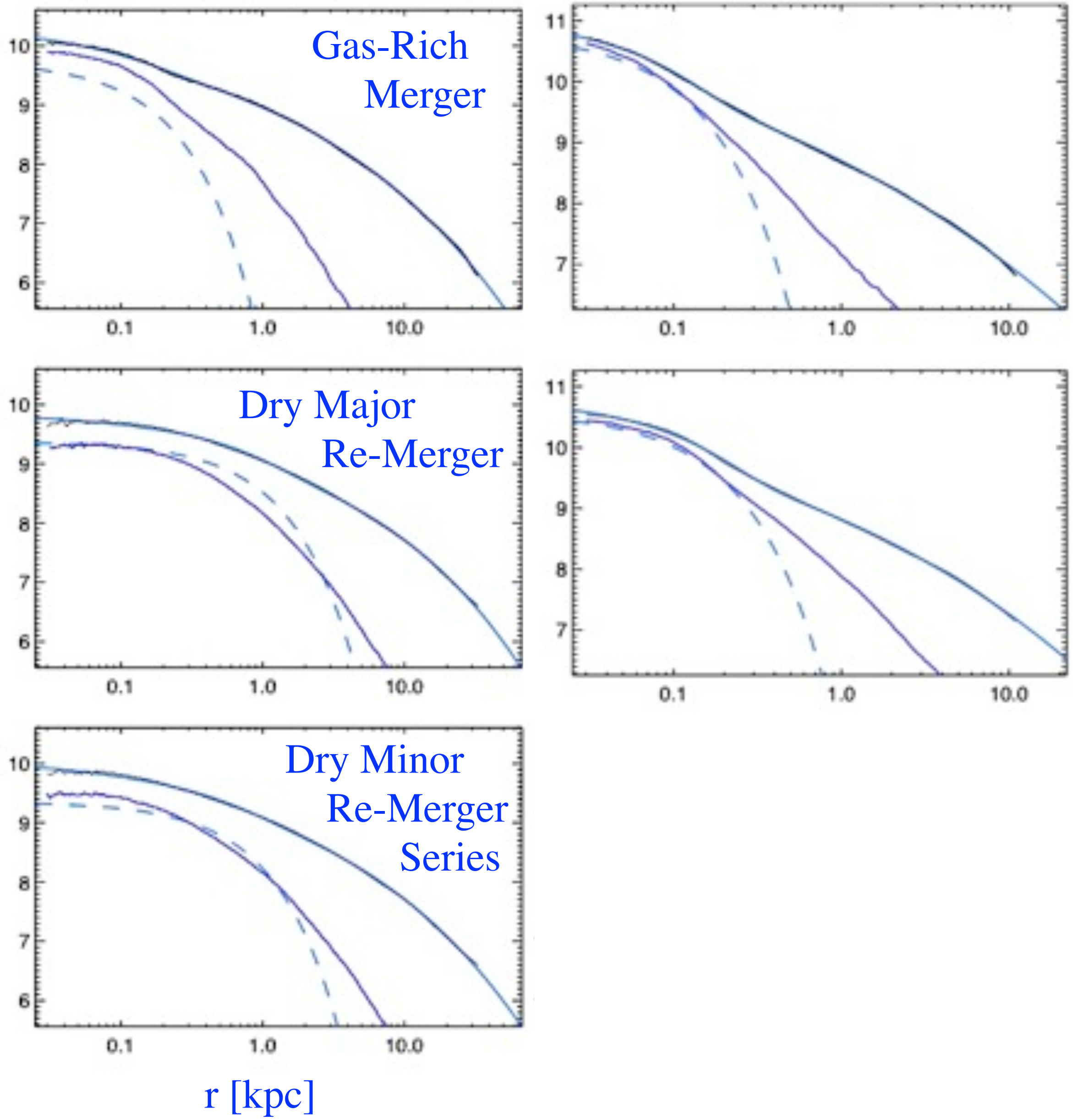


- Real systems grow in a series of mergers: fortunately, these signatures & the FP are conserved:

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

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

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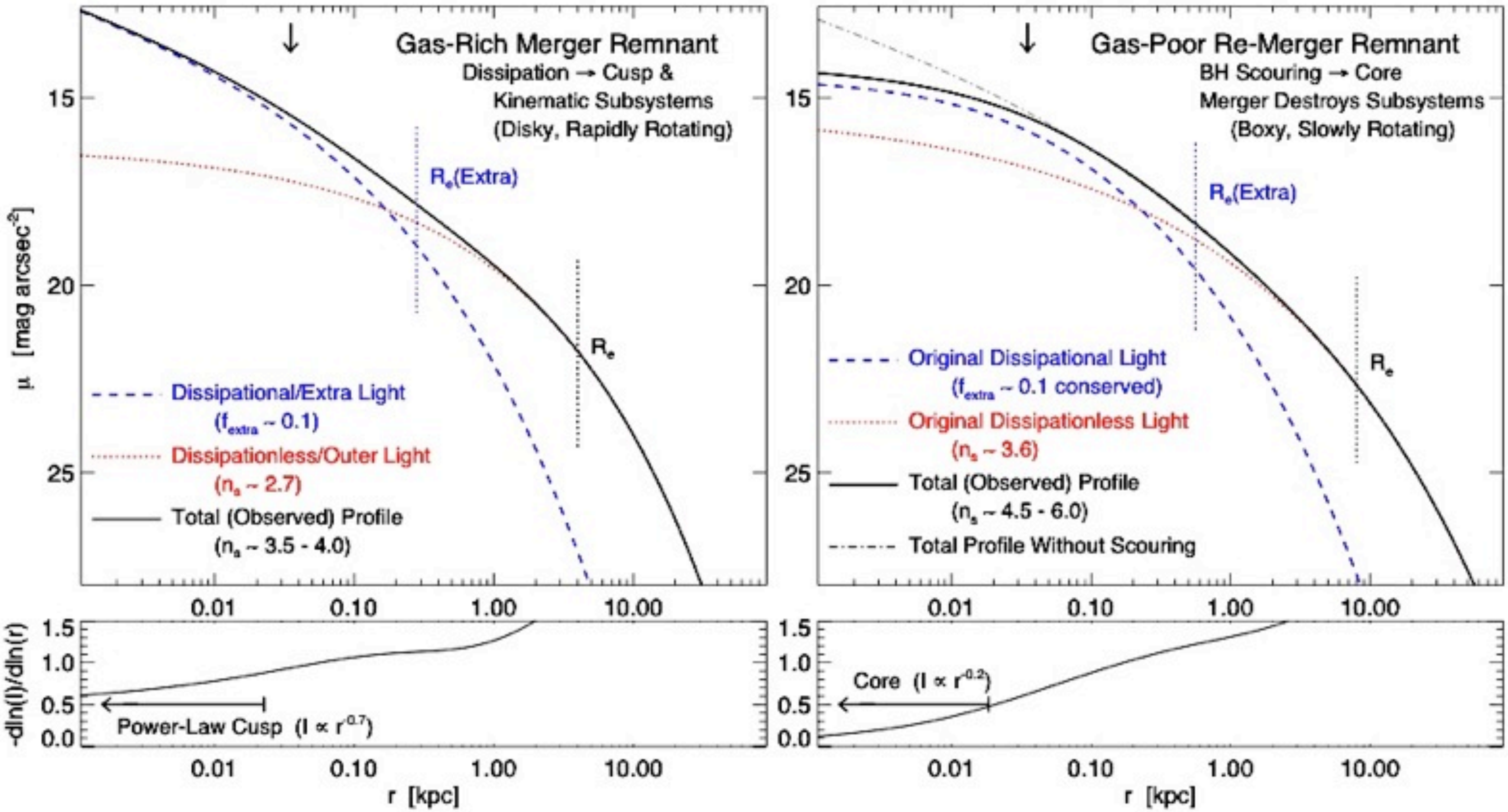

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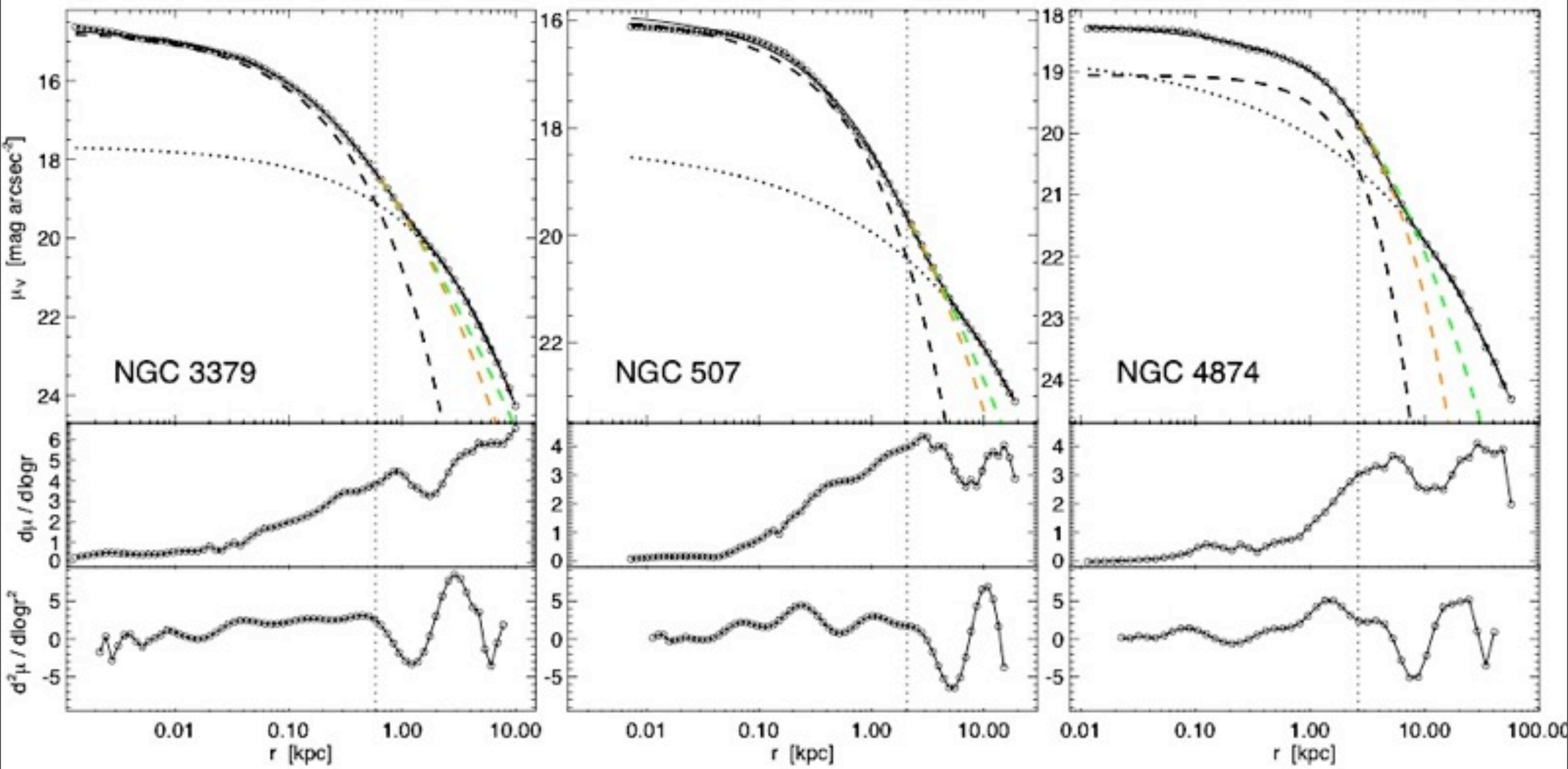

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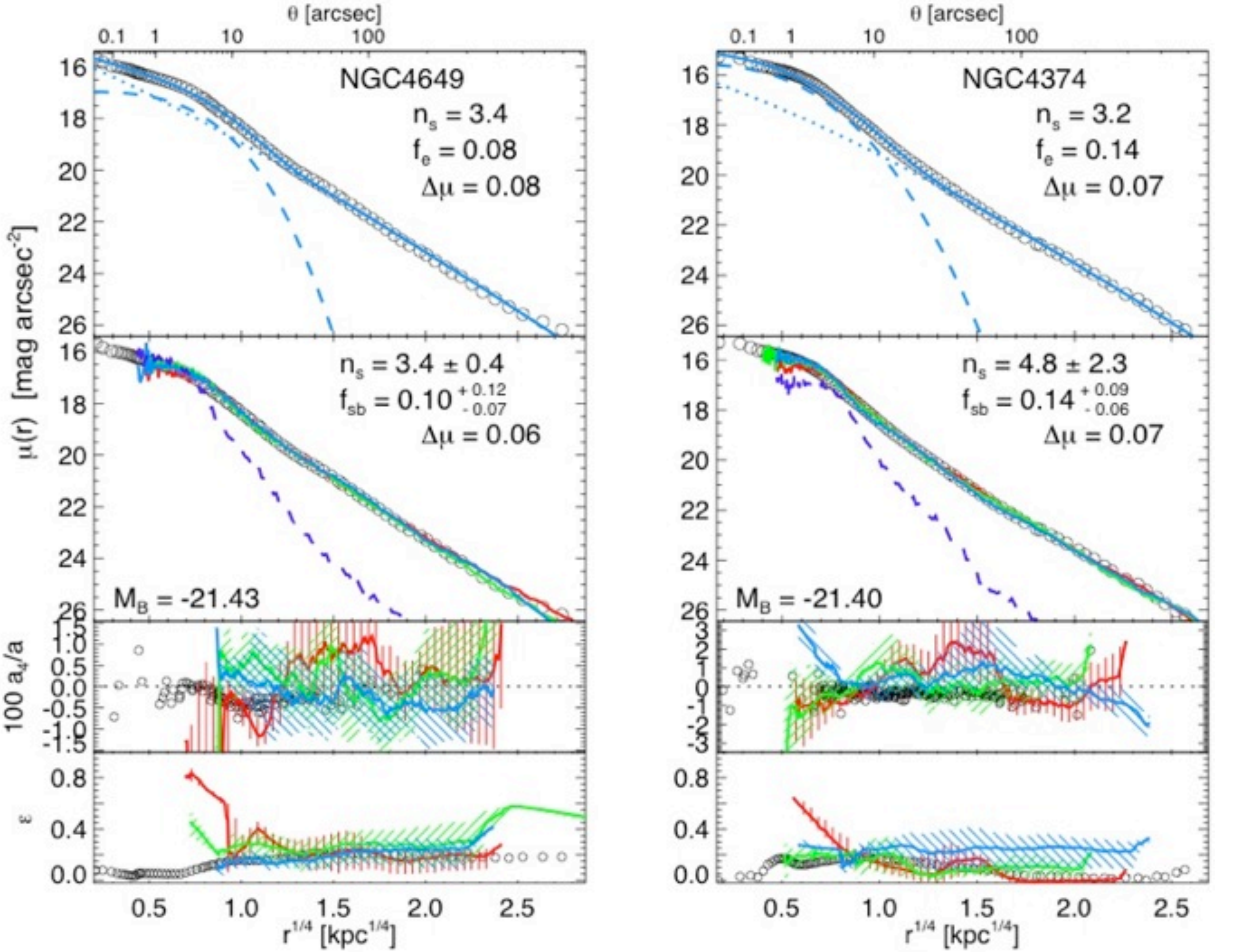

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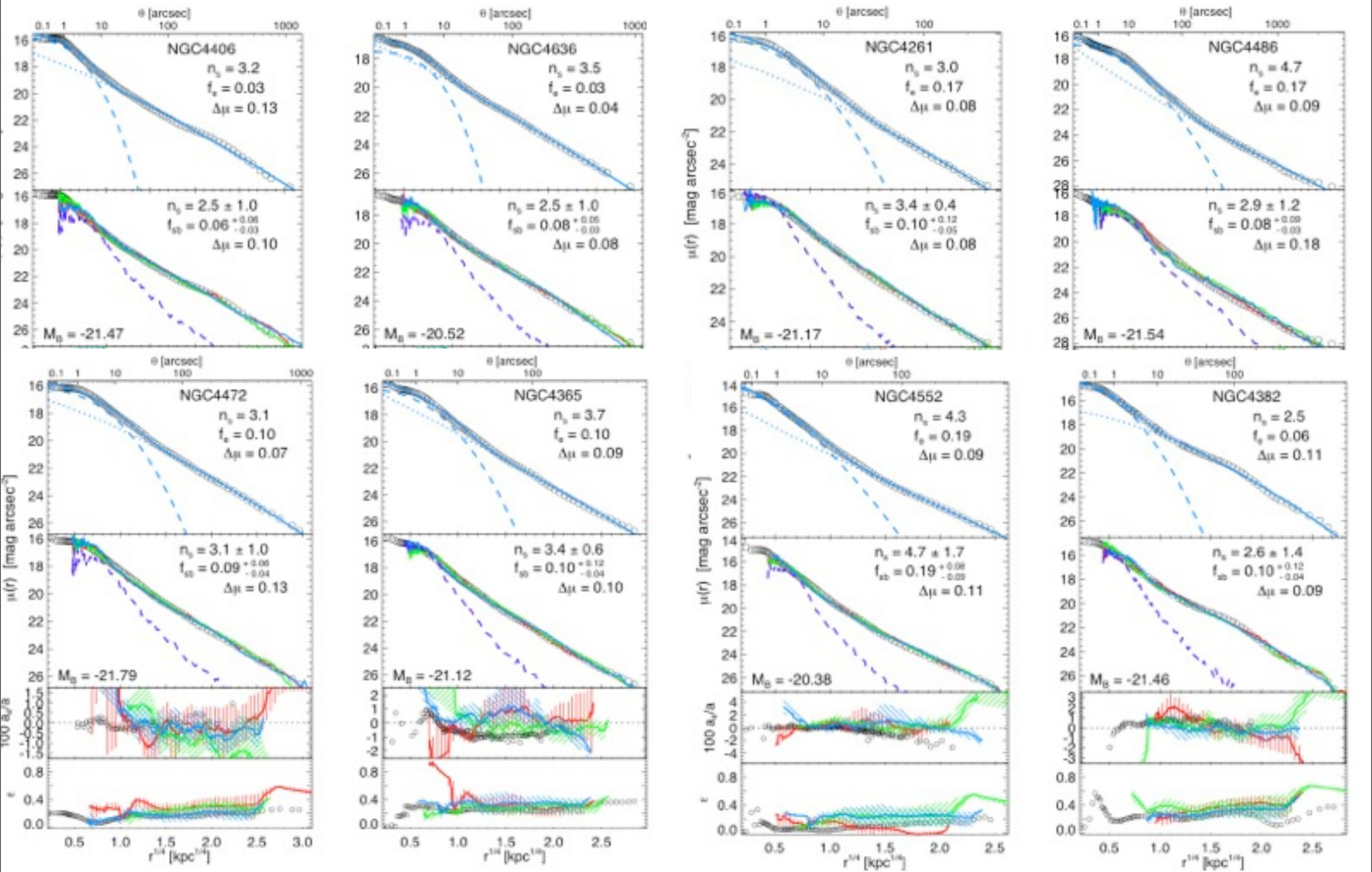

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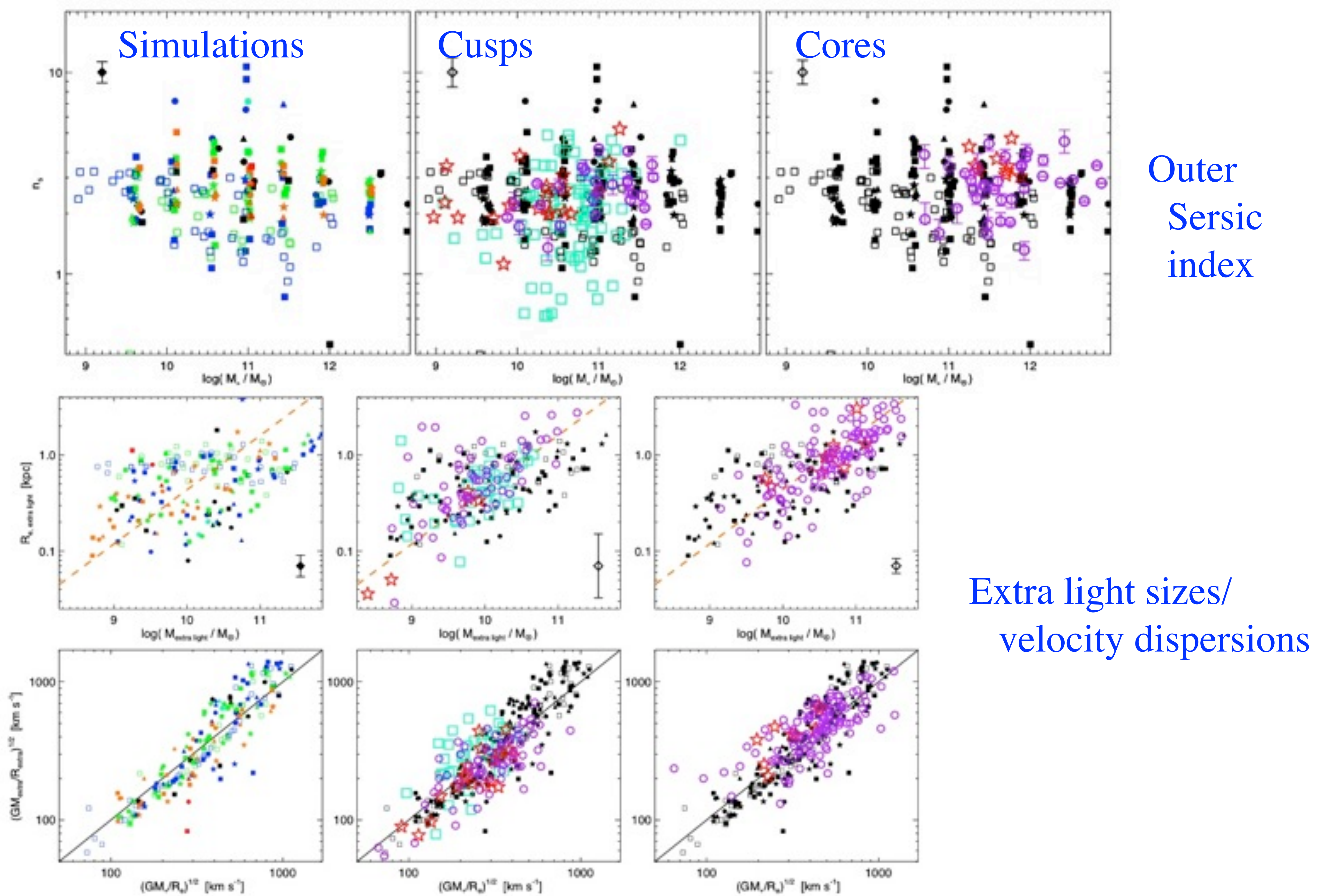

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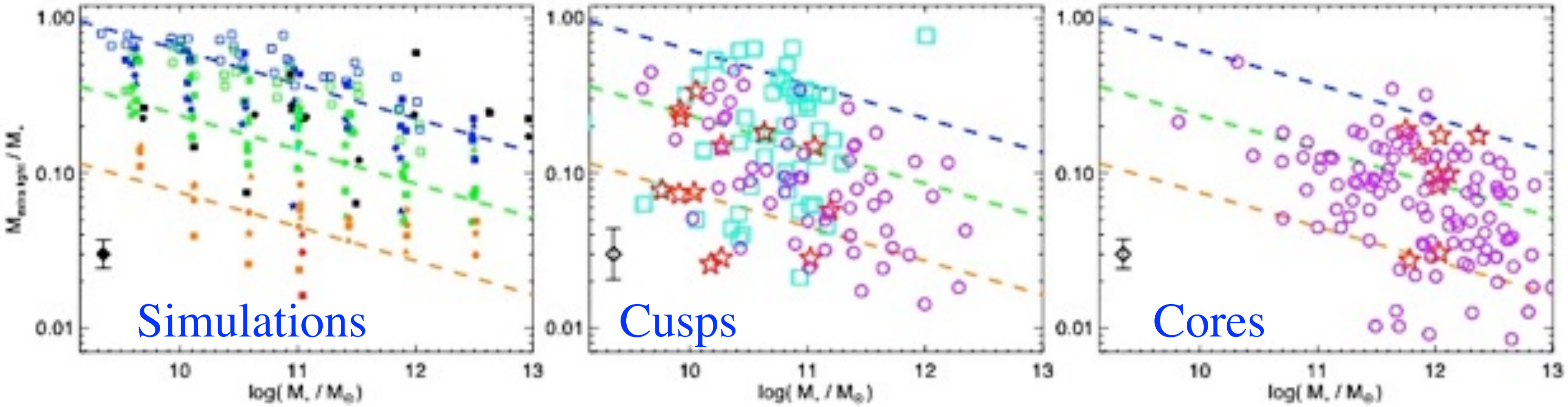
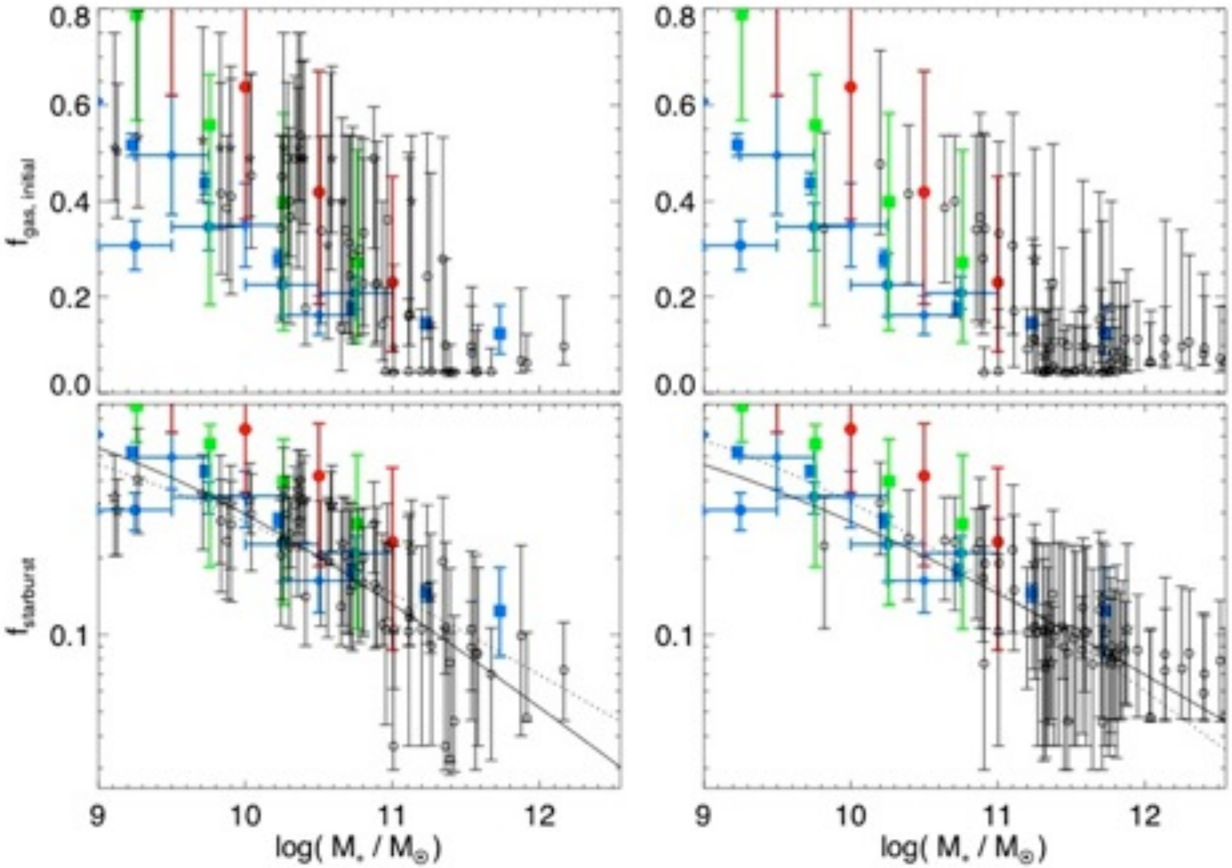
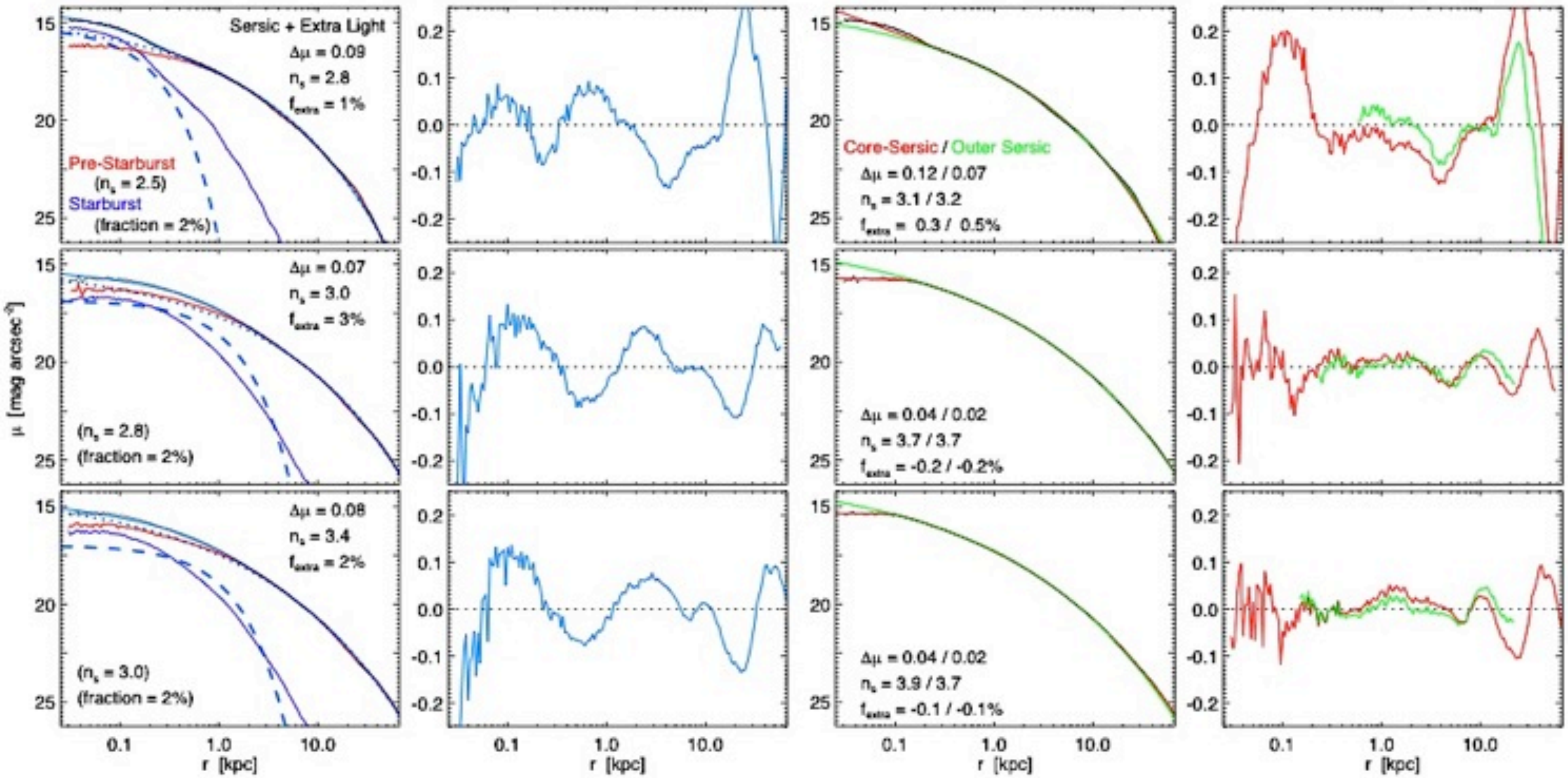


Extra
light
mass
fraction



Application: “Core” Ellipticals

HOW MUCH IS “MISSING LIGHT”?



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Application: “Core” Ellipticals

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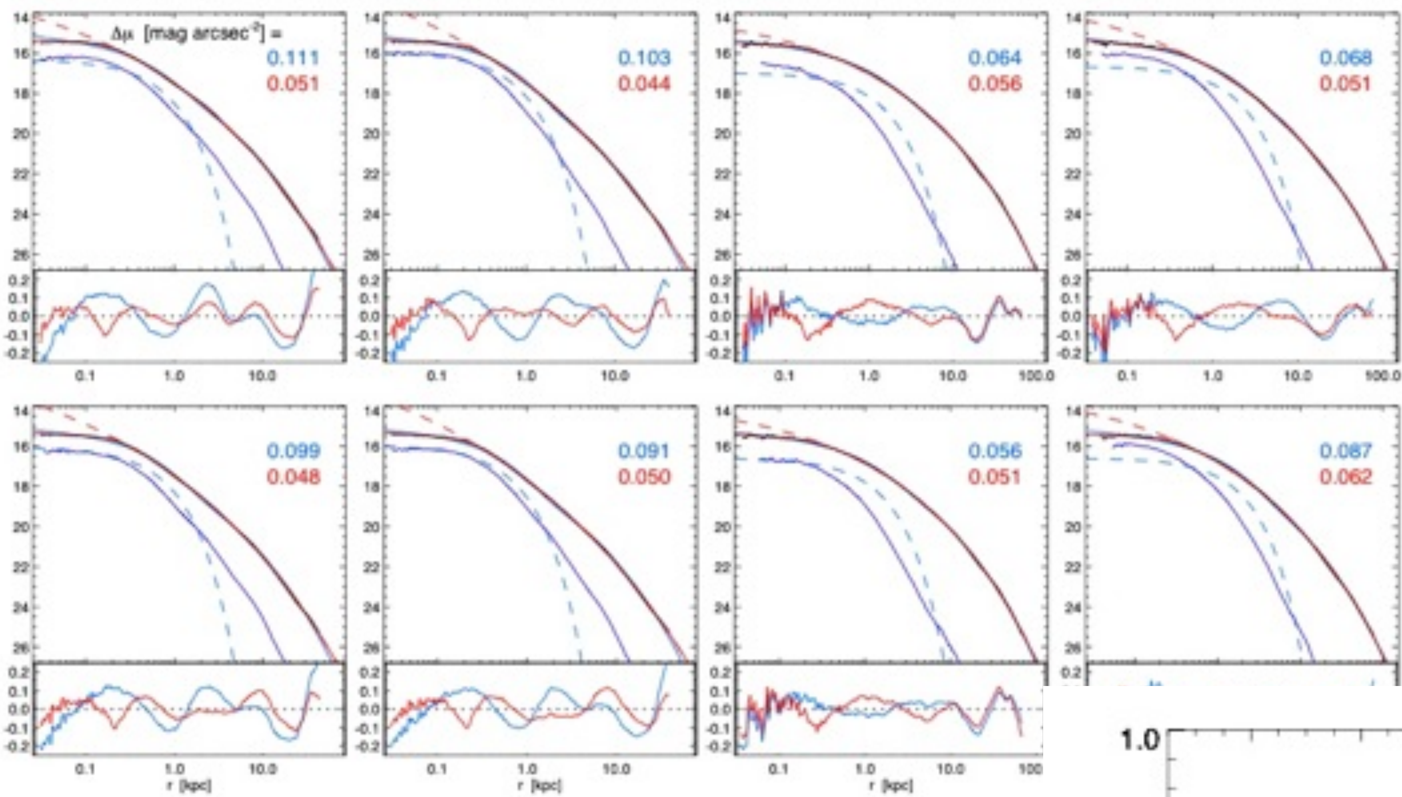
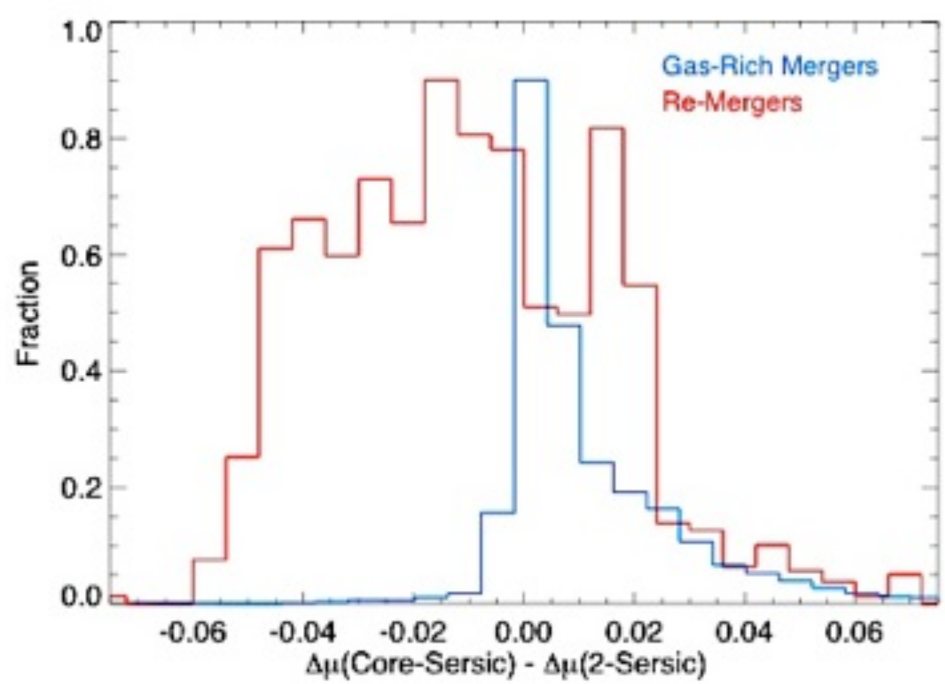
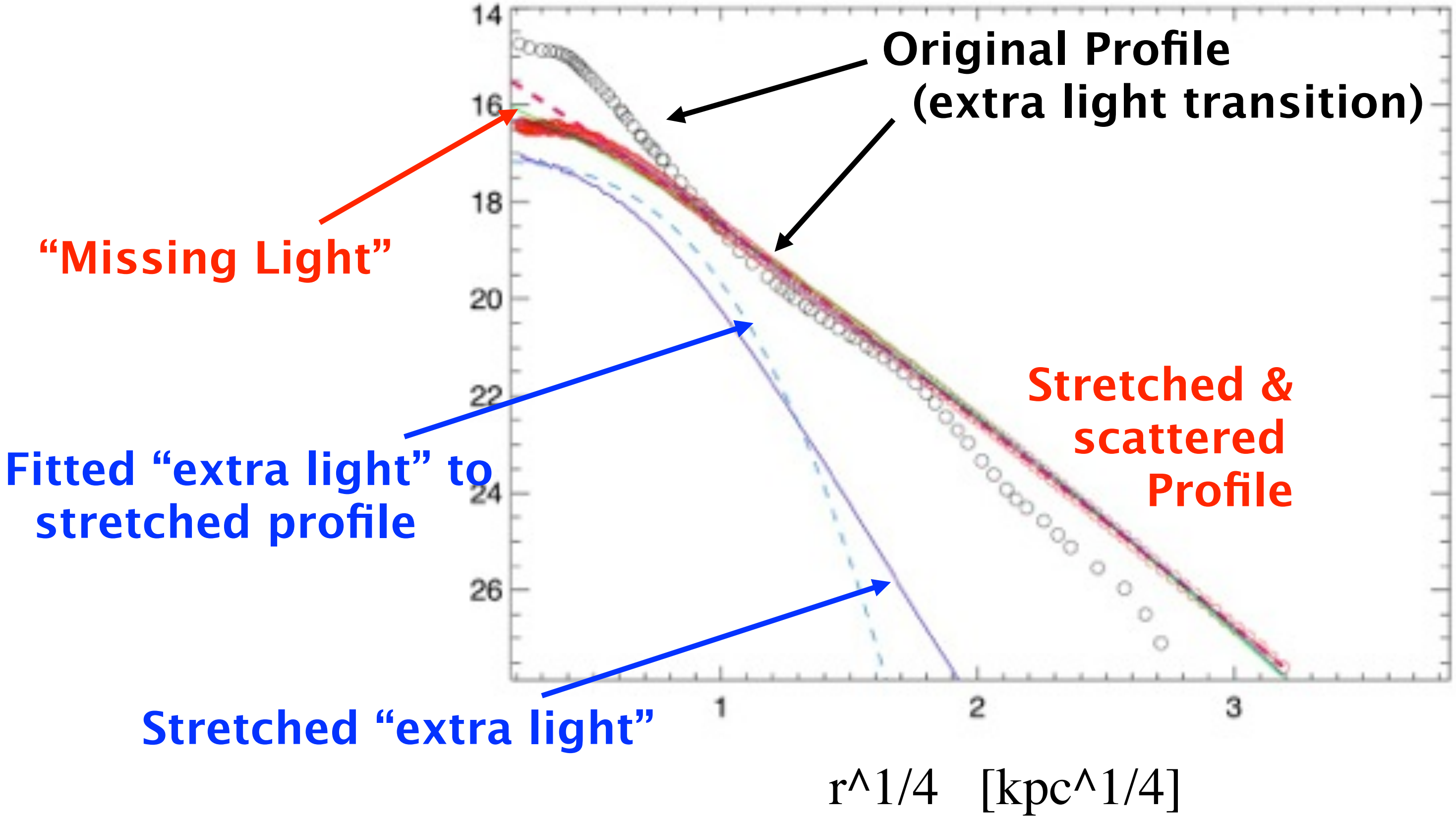




Application: "Core" Ellipticals

WHAT HAPPENS TO THE "EXTRA LIGHT"?

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



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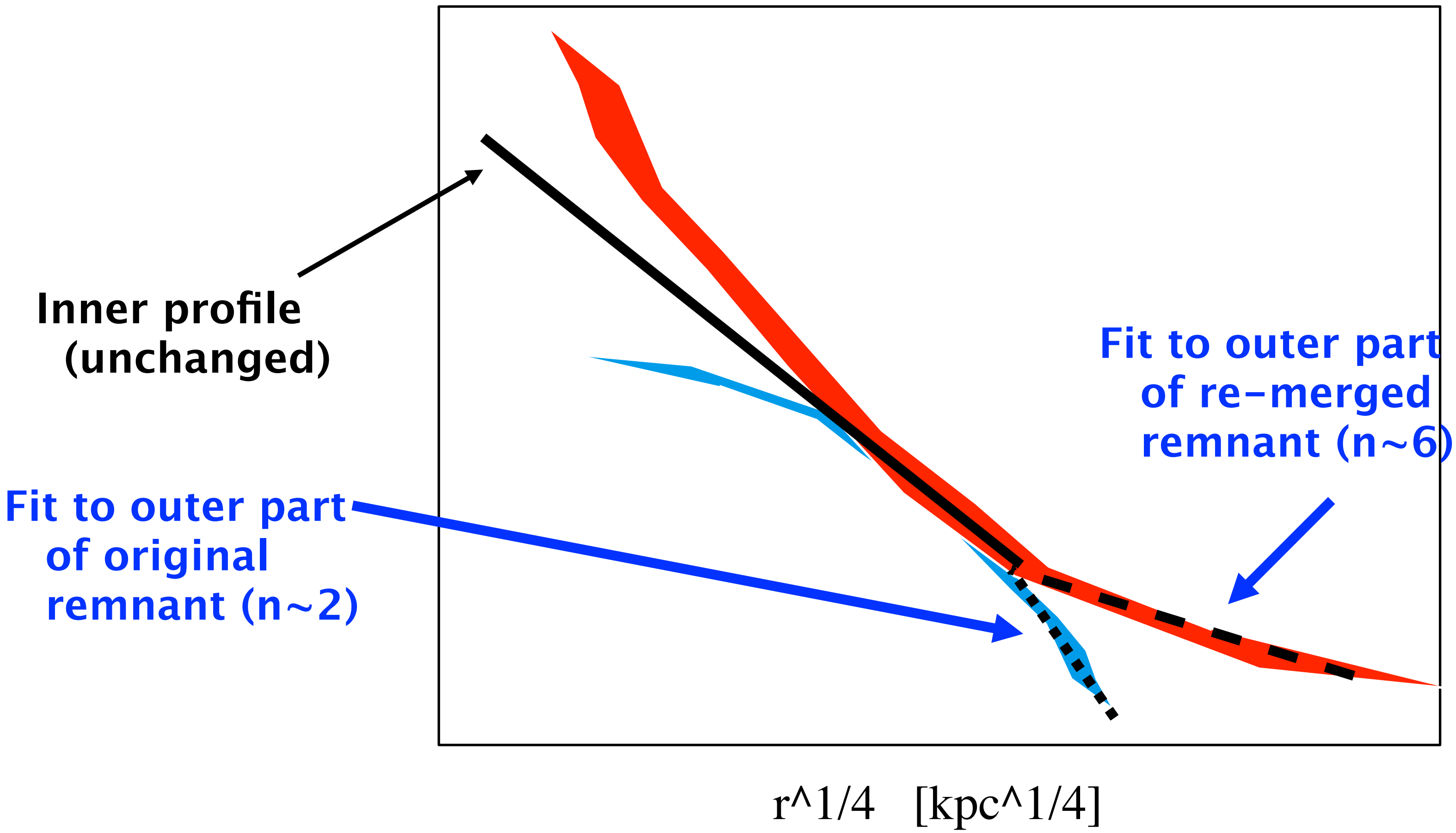

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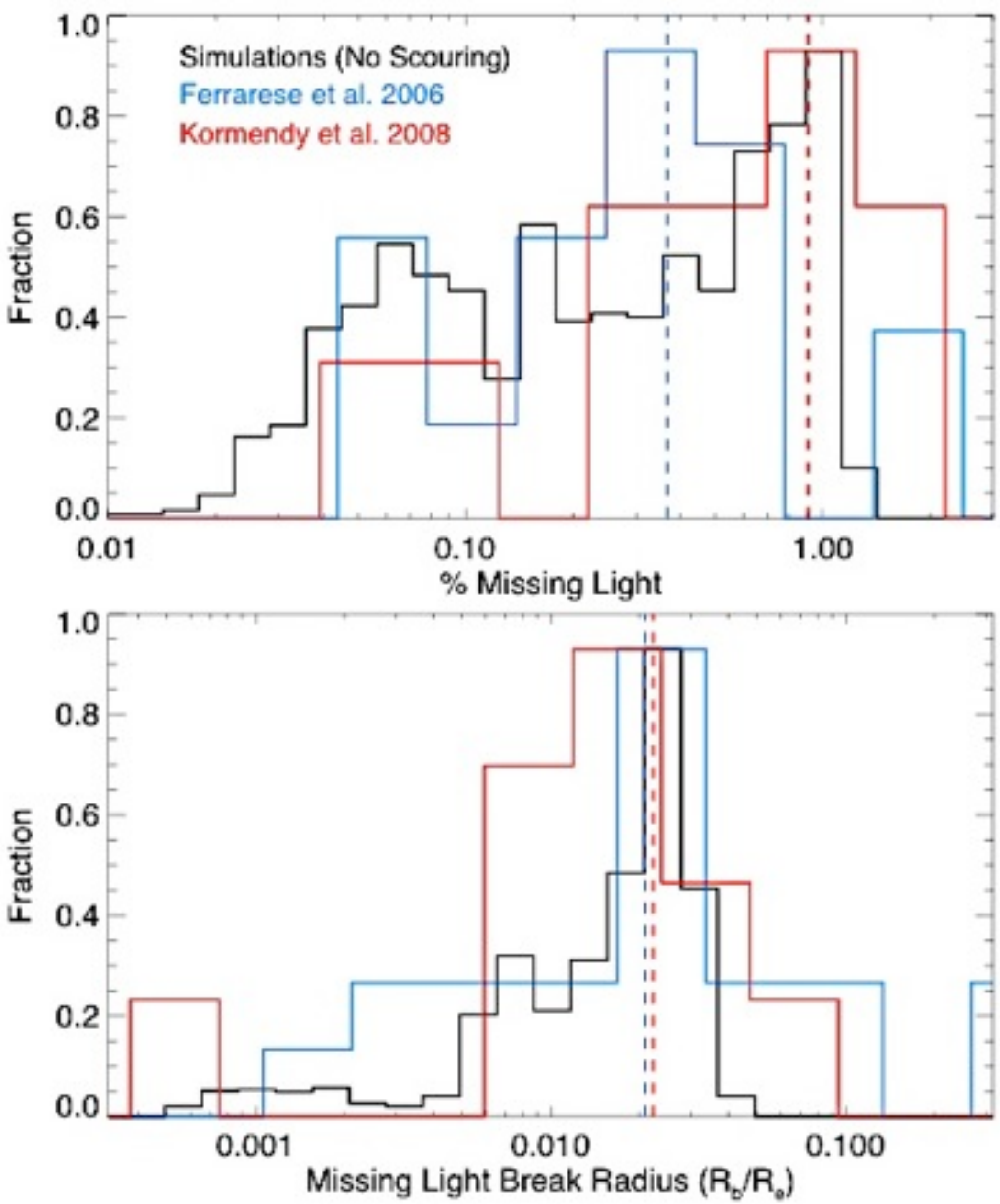
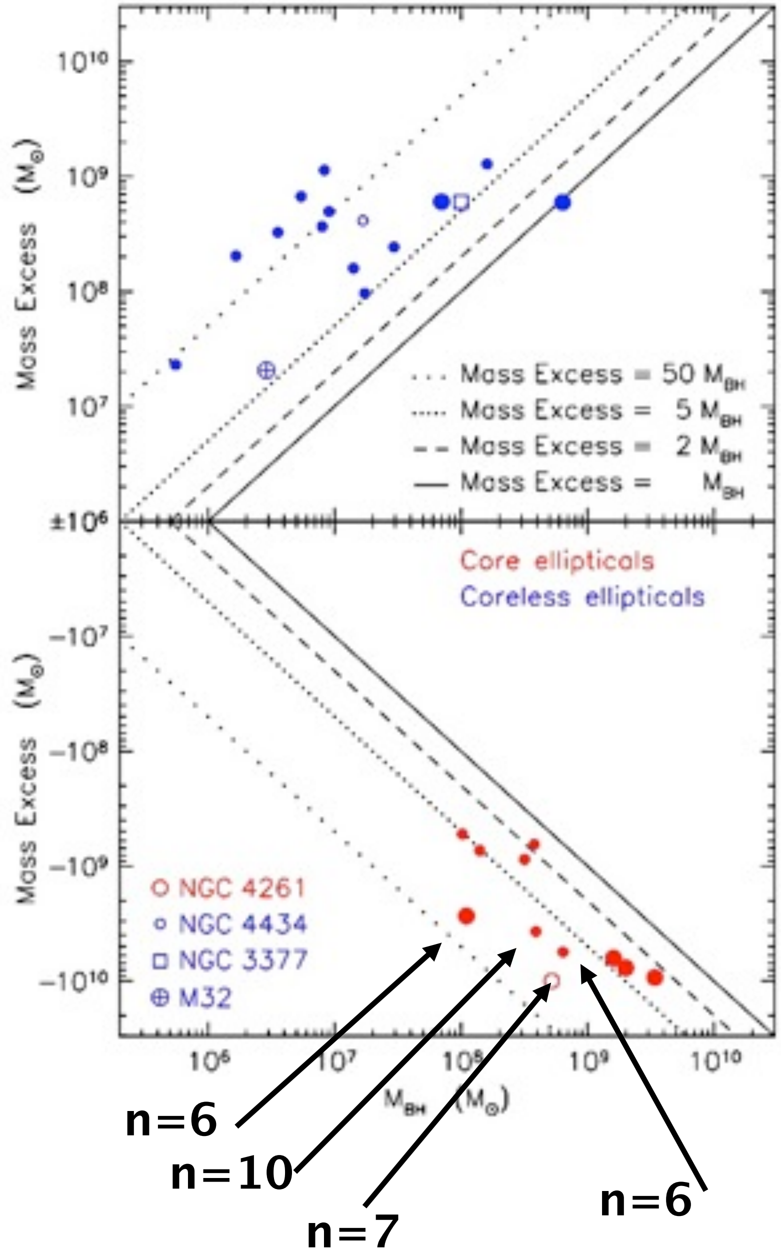


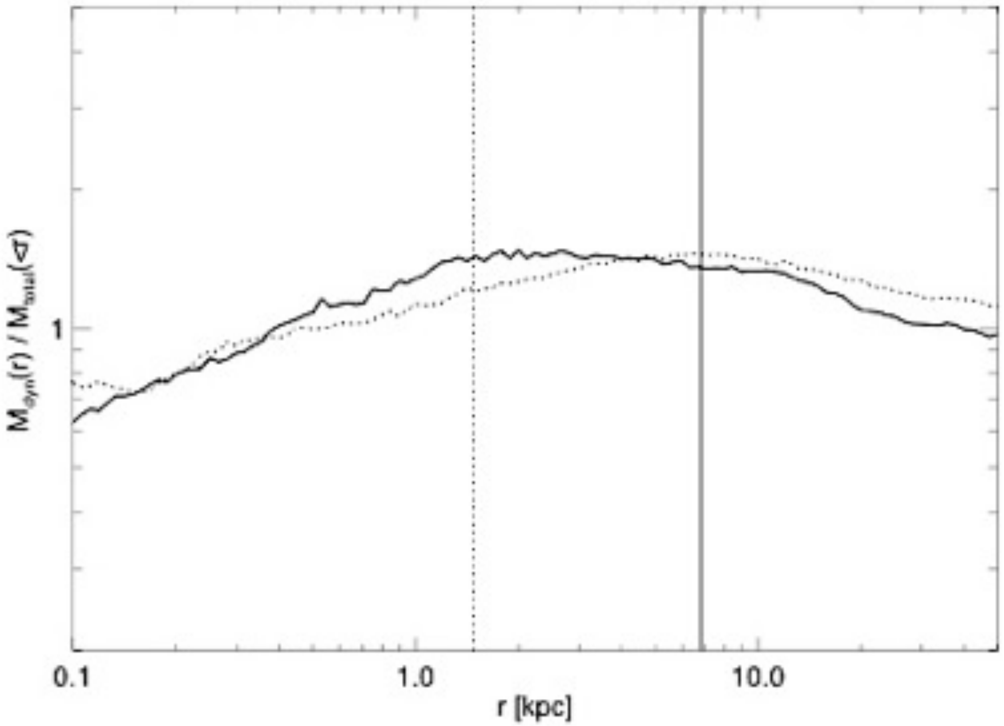


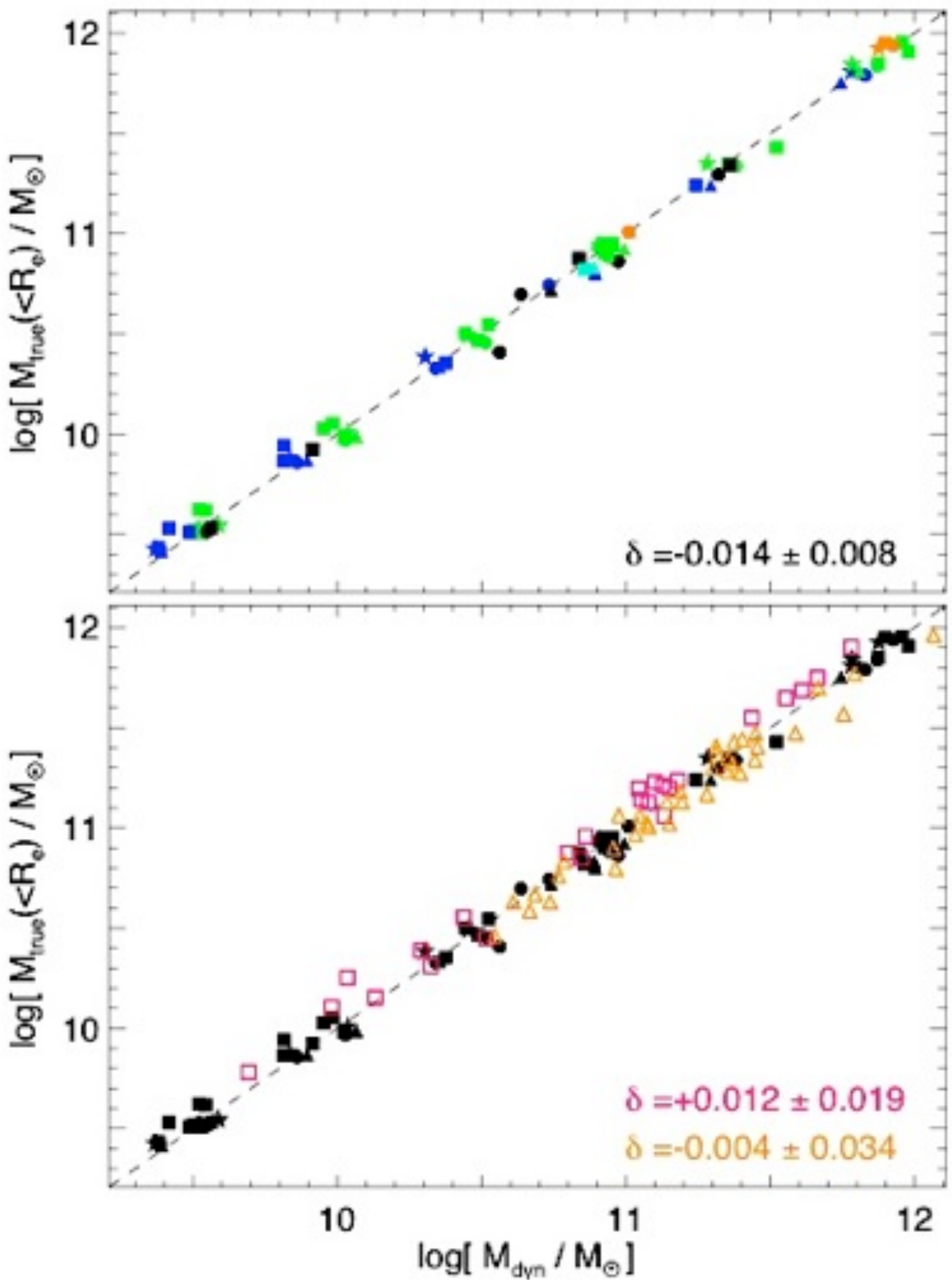
Summary

- 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

Fundamental Plane Tilt

HOMOLOGY VS. NON-HOMOLOGY

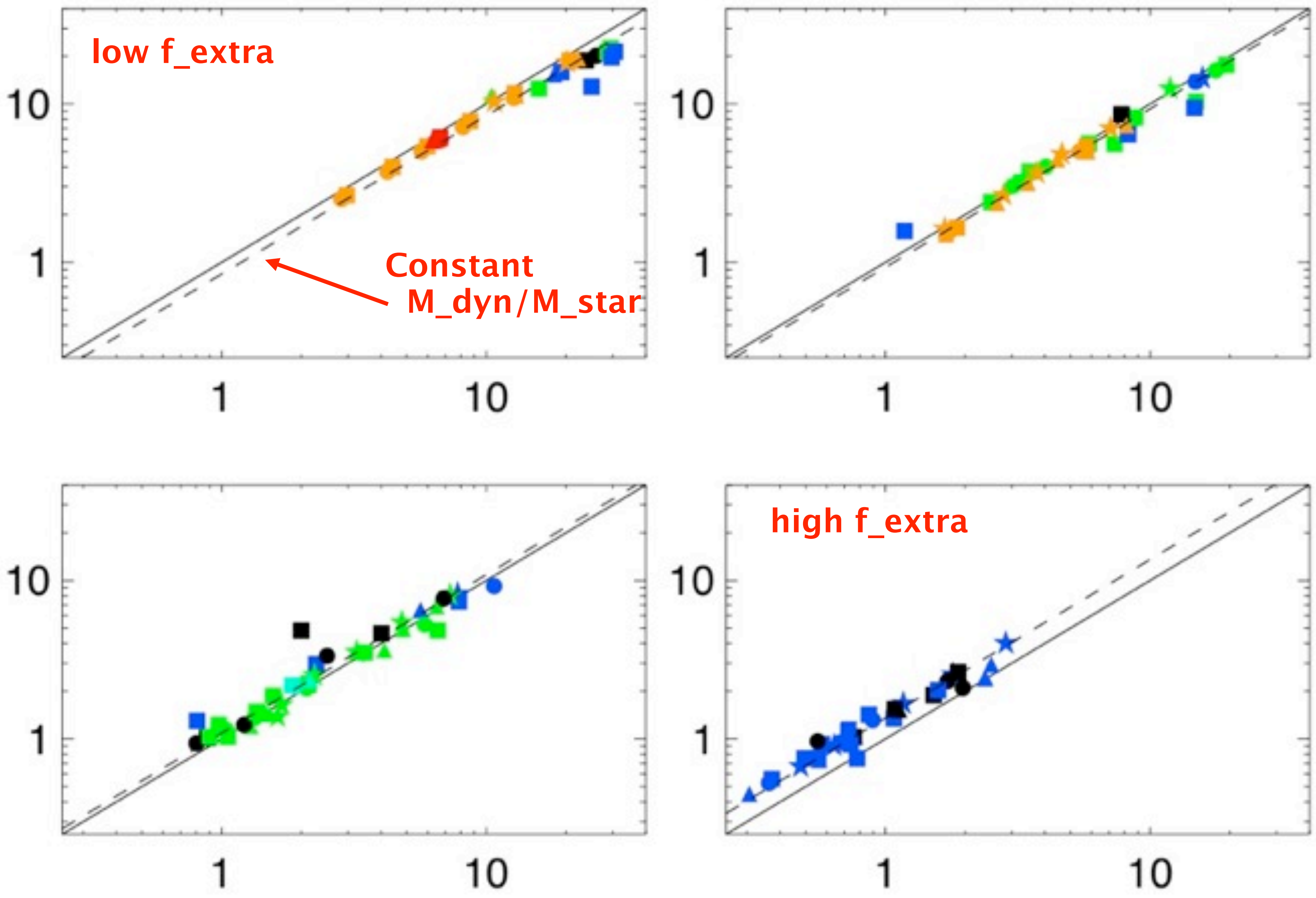




Fundamental Plane Tilt

WHERE DOES IT COME FROM?

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



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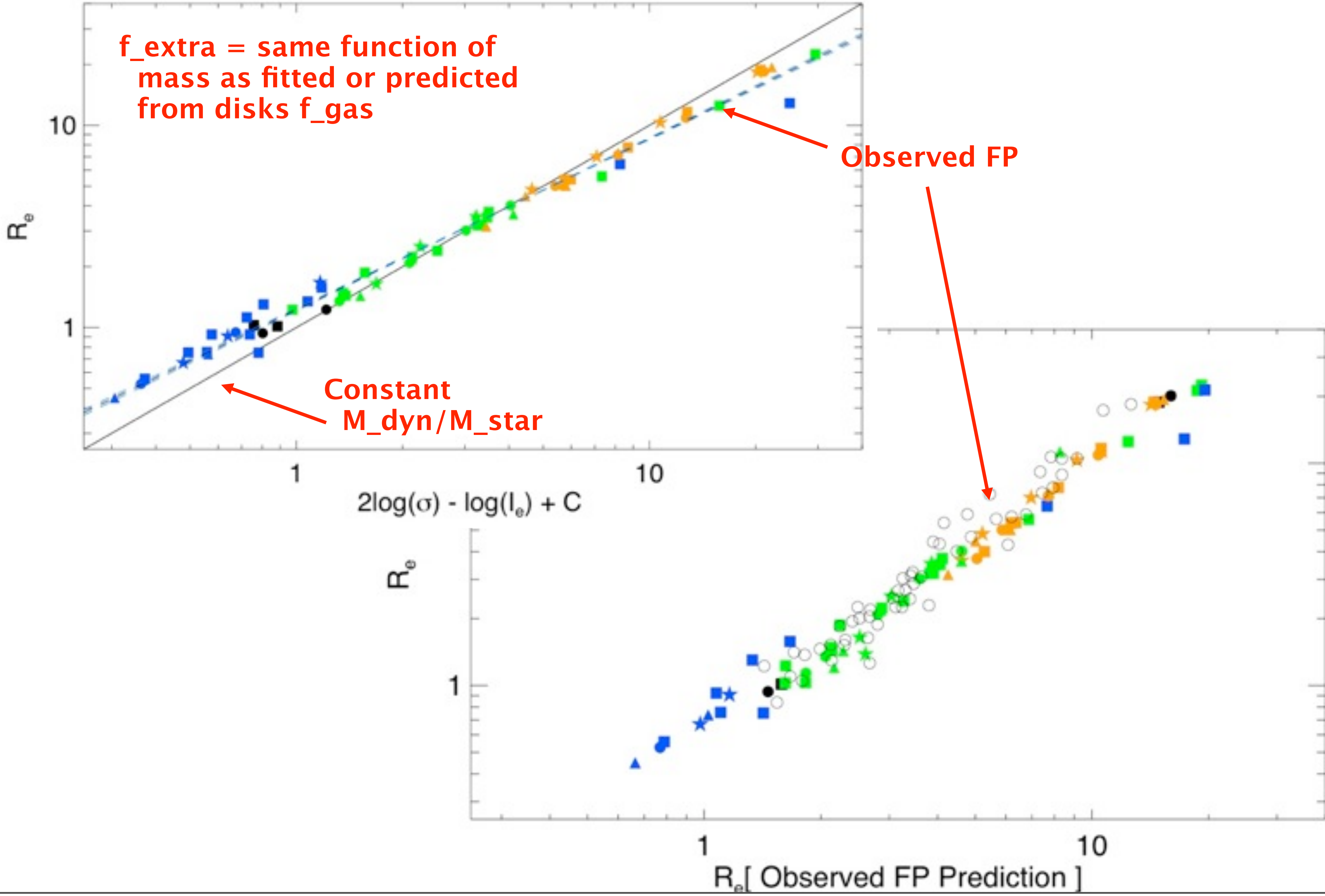
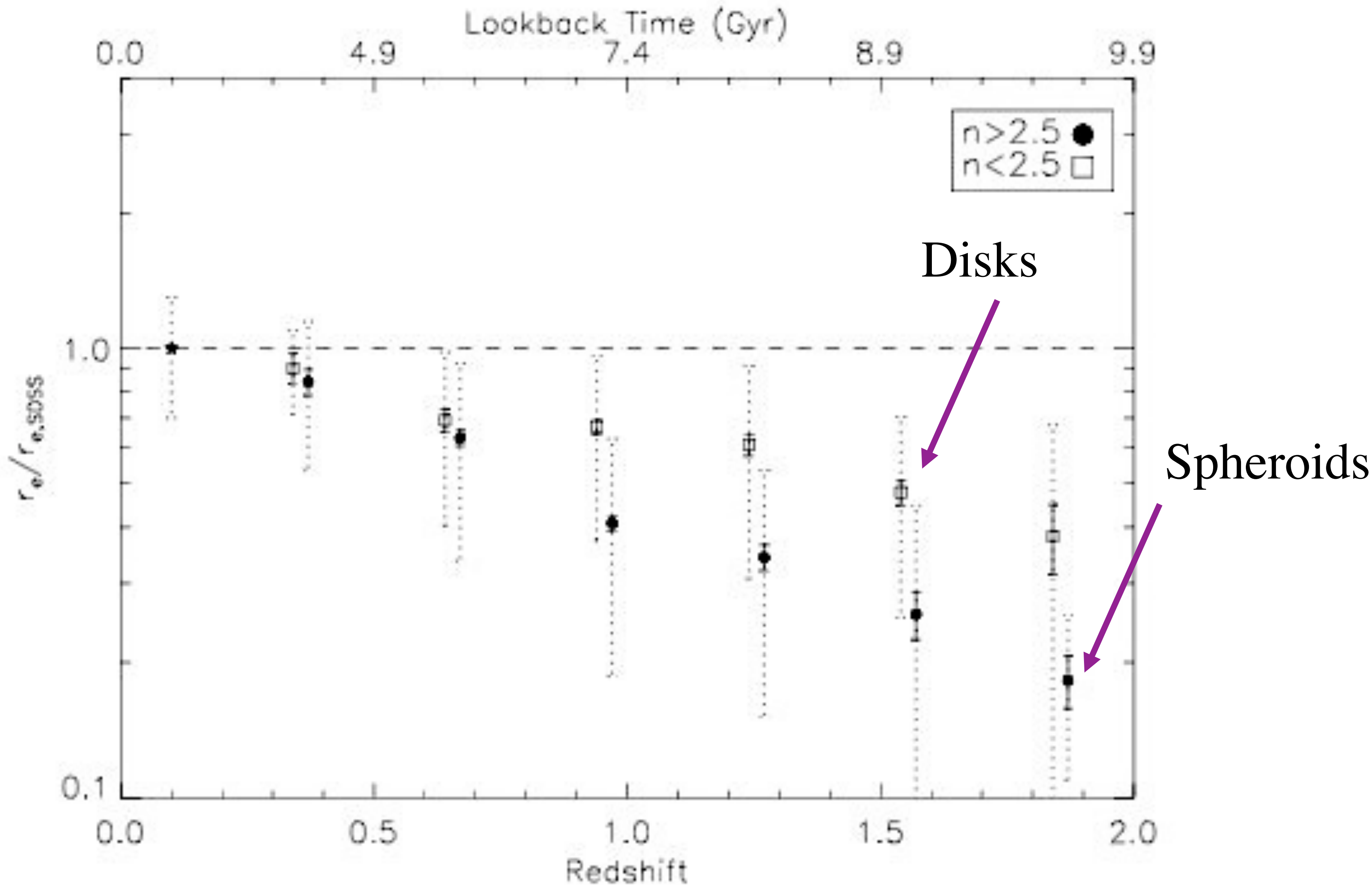


Redshift Evolution

SIZE-MASS RELATIONS

Trujillo et al. 2007

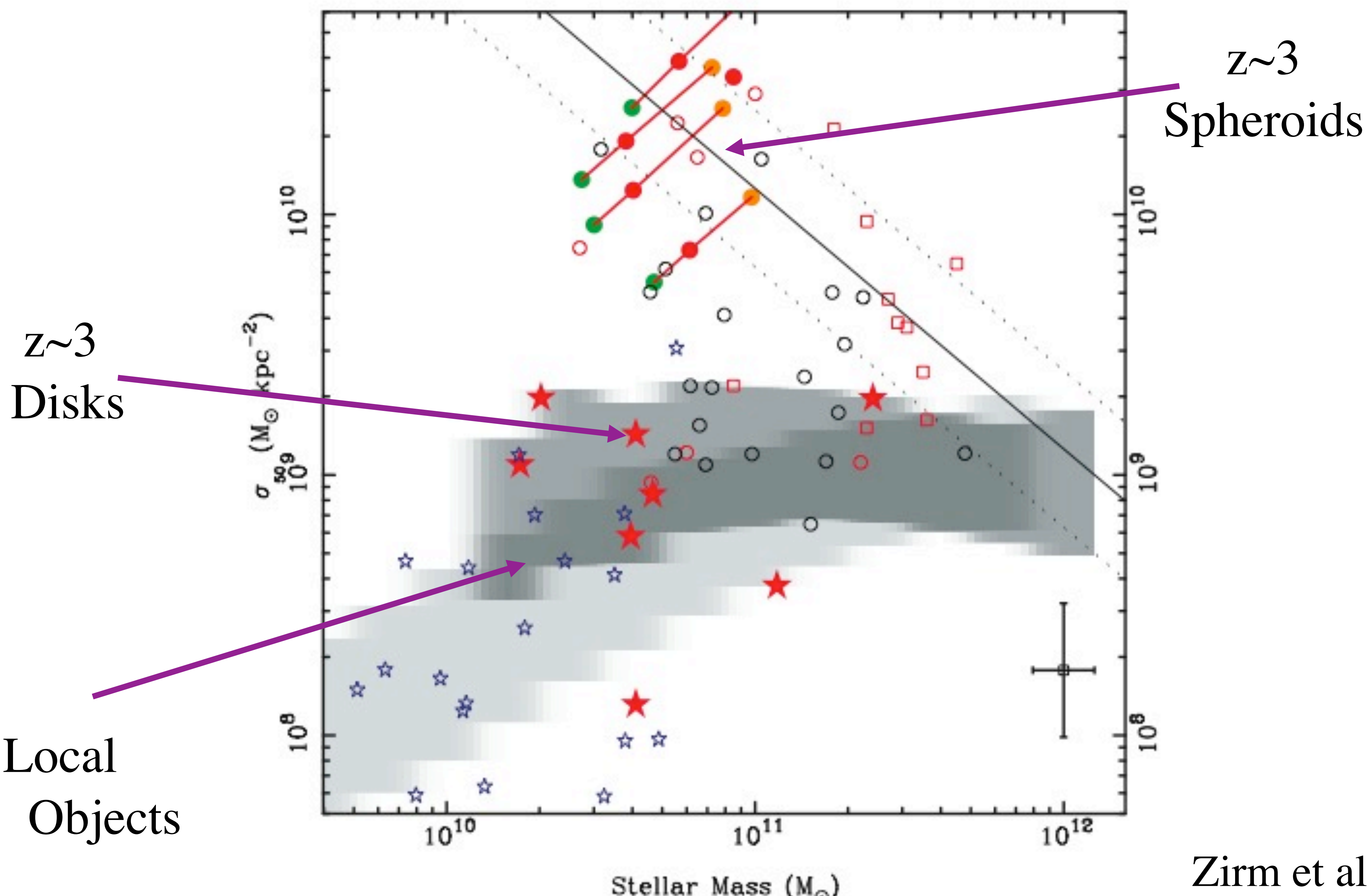
- Spheroids are getting smaller >2x as quickly as disks!



Redshift Evolution

SIZE-MASS RELATIONS

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

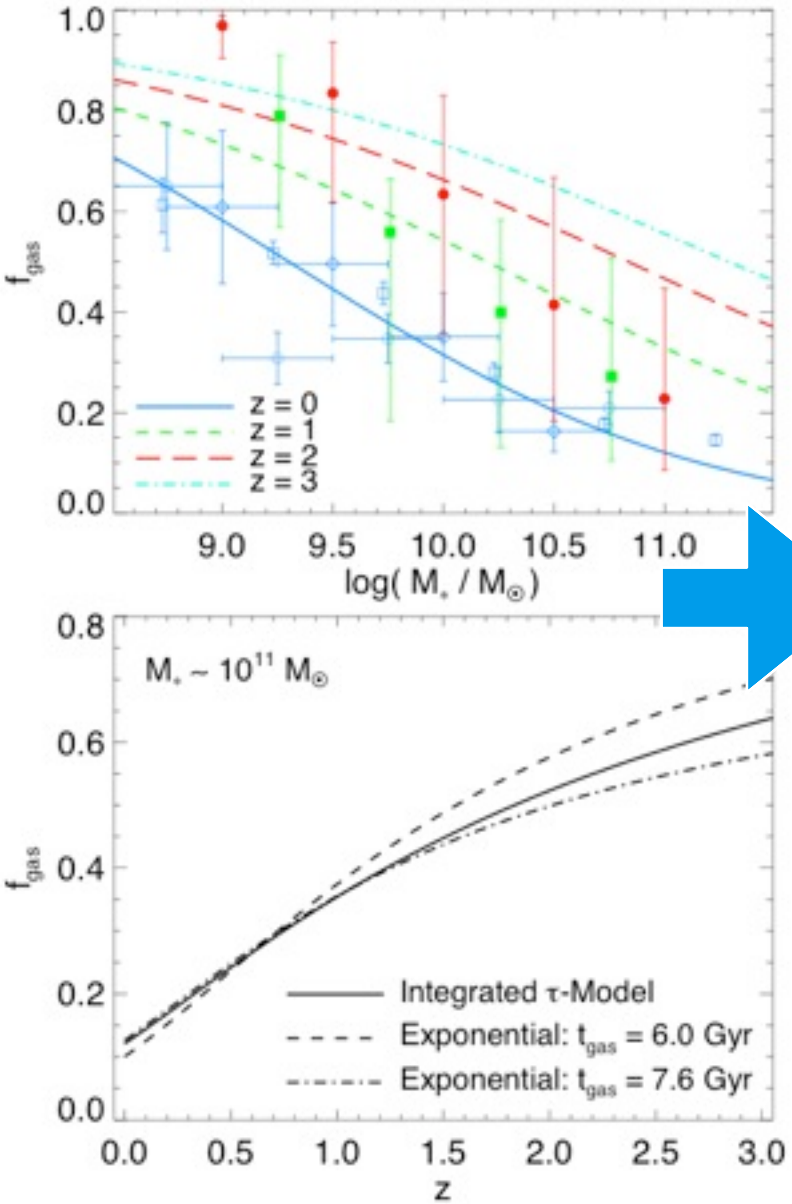


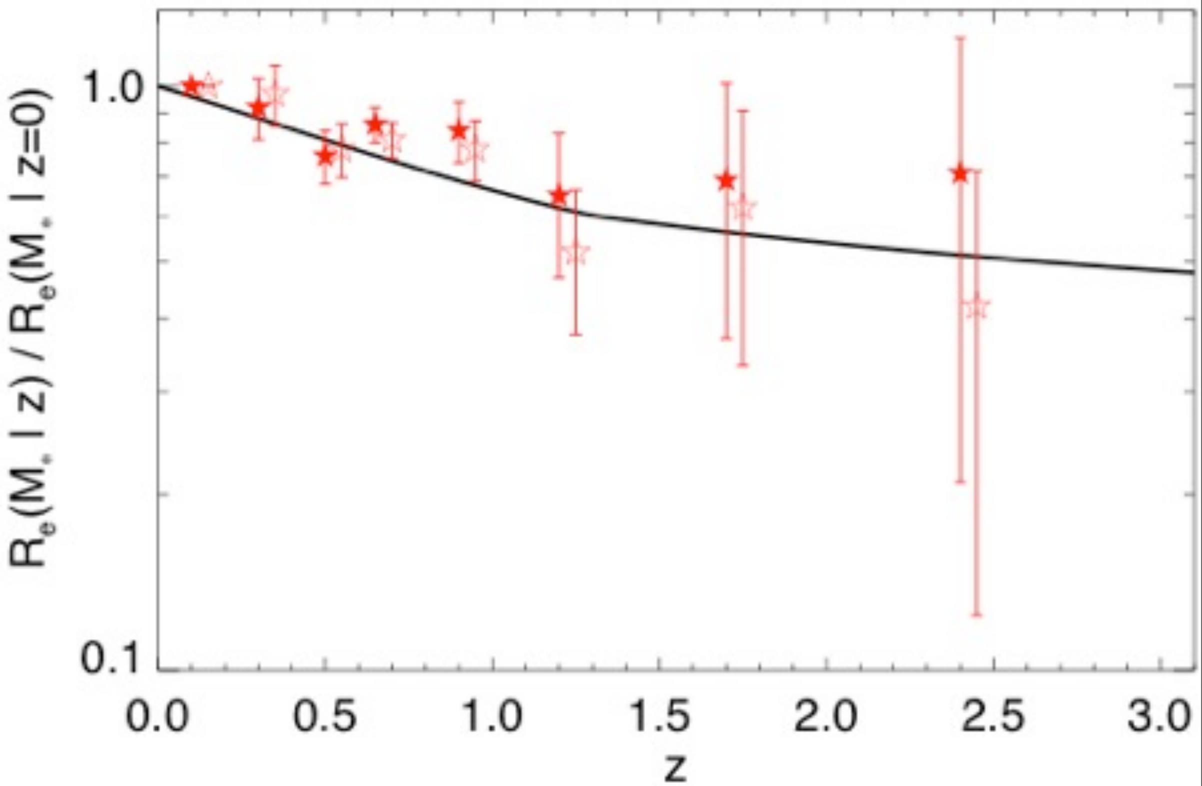
Zirm et al.

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 $\sigma_f = \sigma_i$

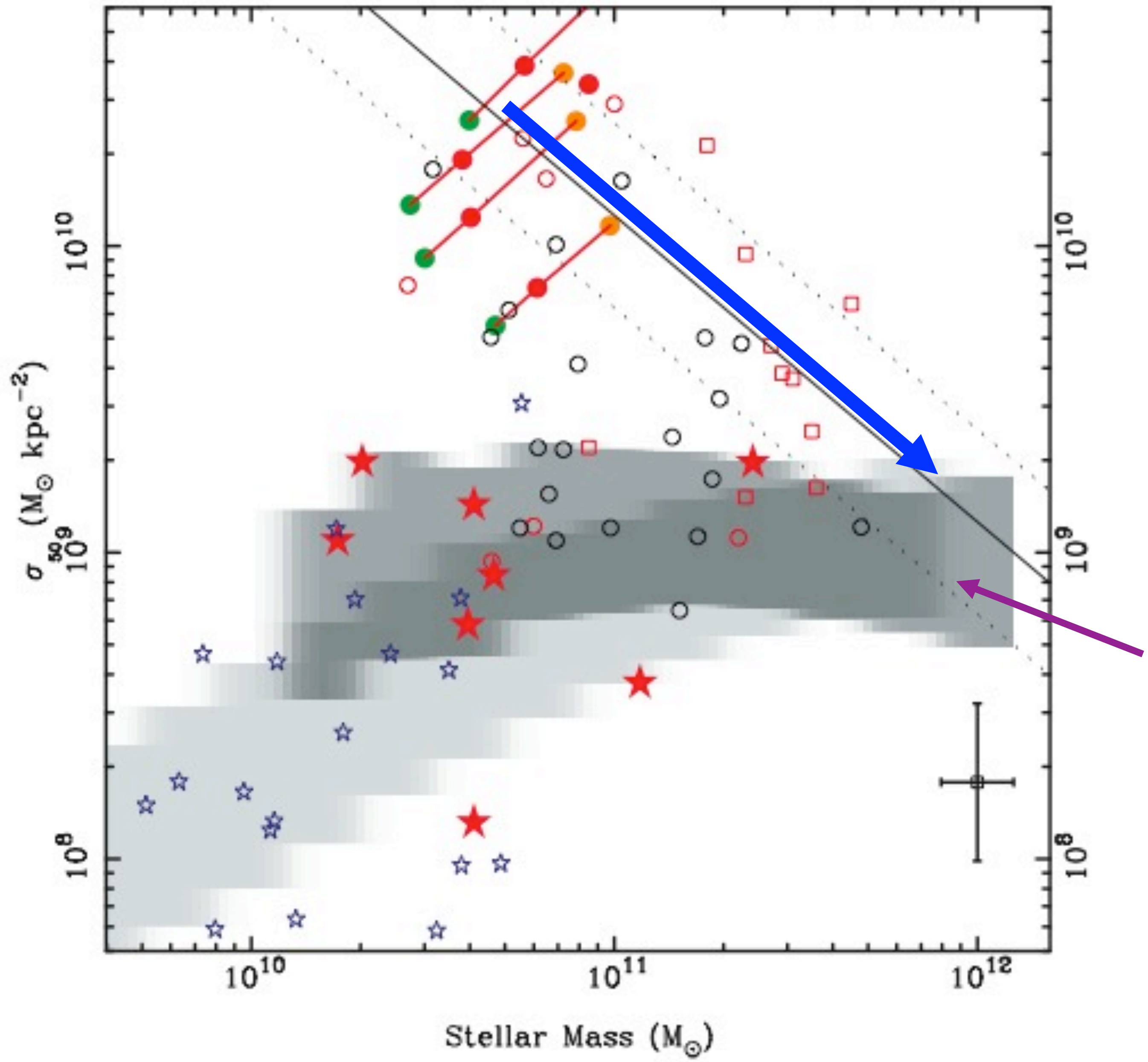
  virial theorem -- $R_f = 2 * R_i$

- Relative to the slope of the size mass relation ($R \sim M^{1/2}$), 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~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 ~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
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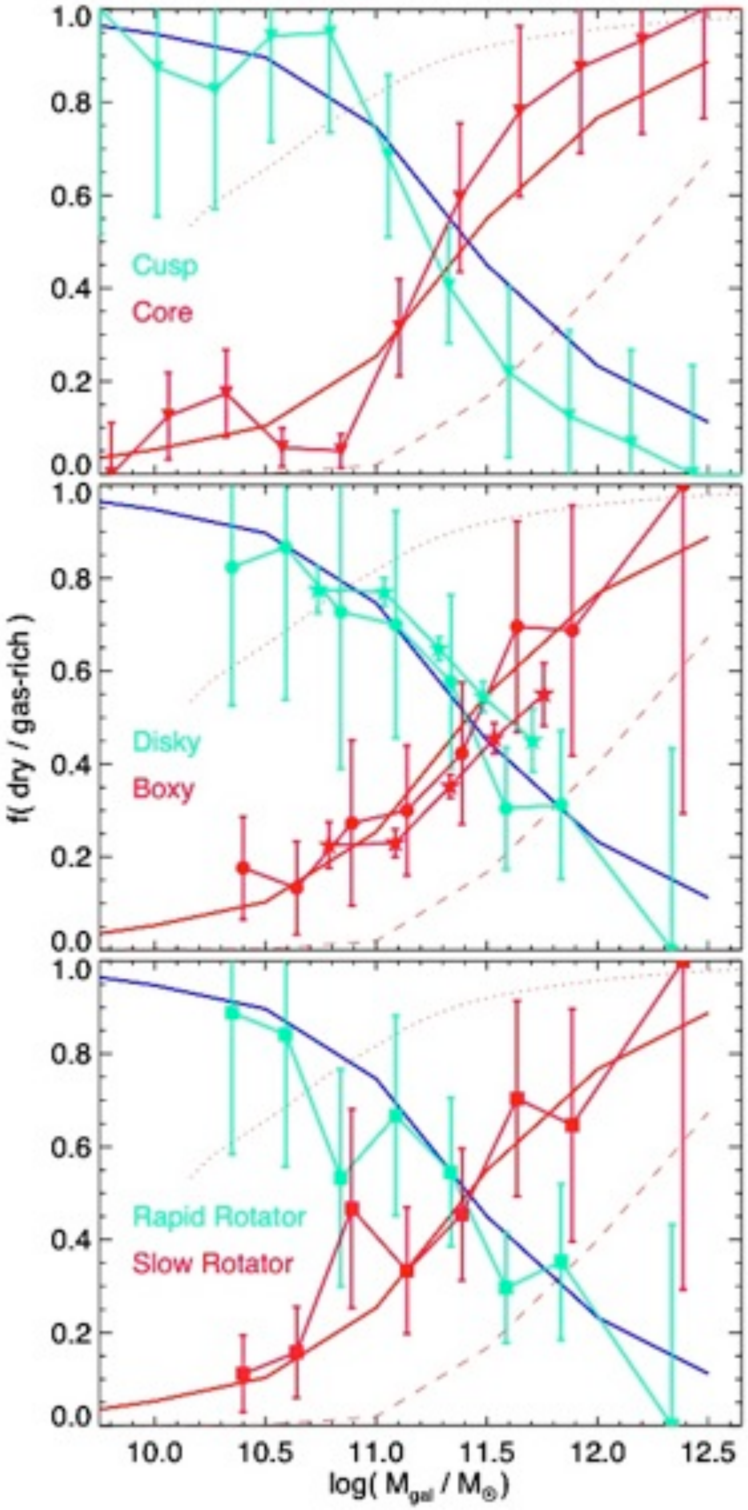

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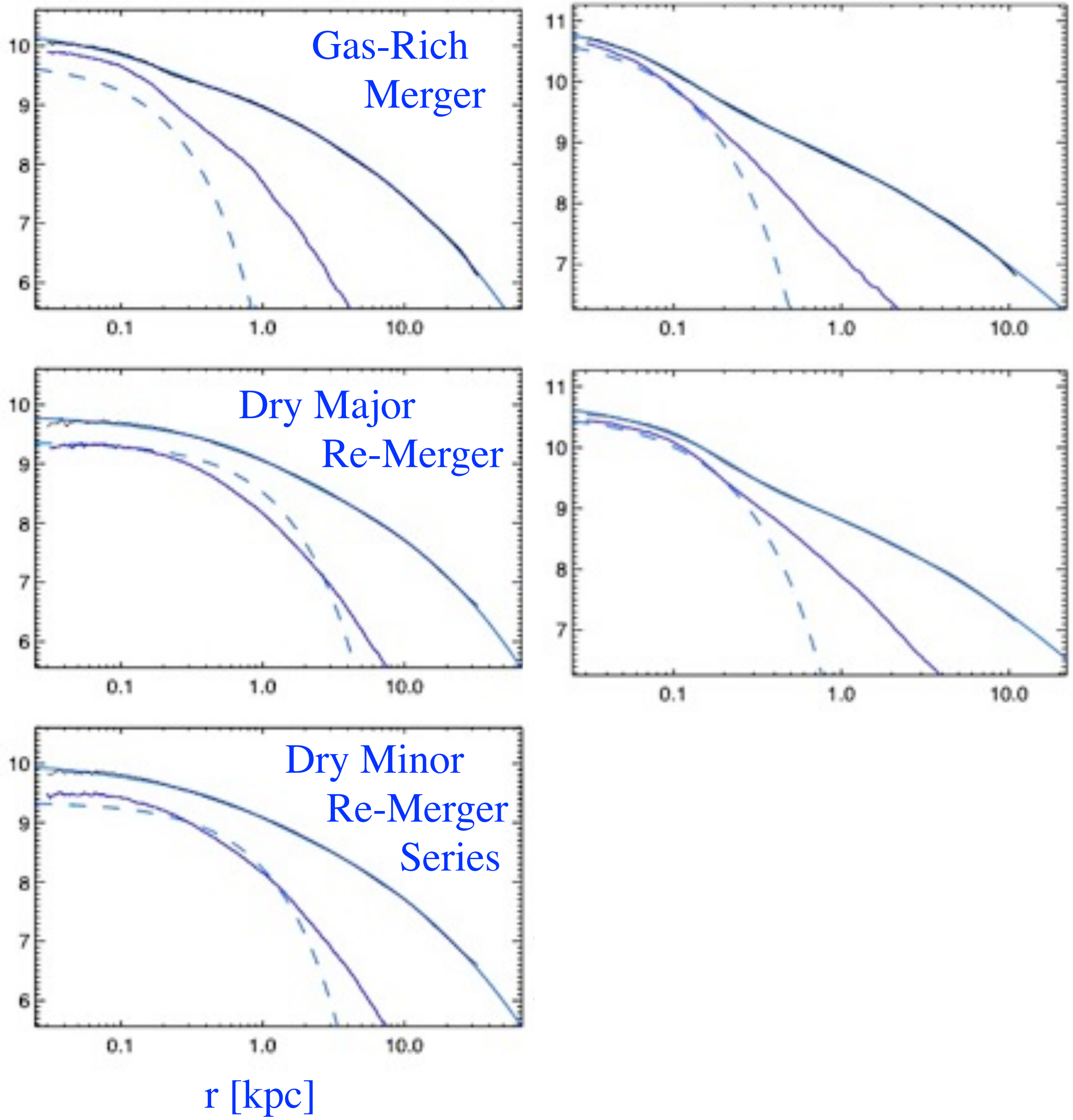

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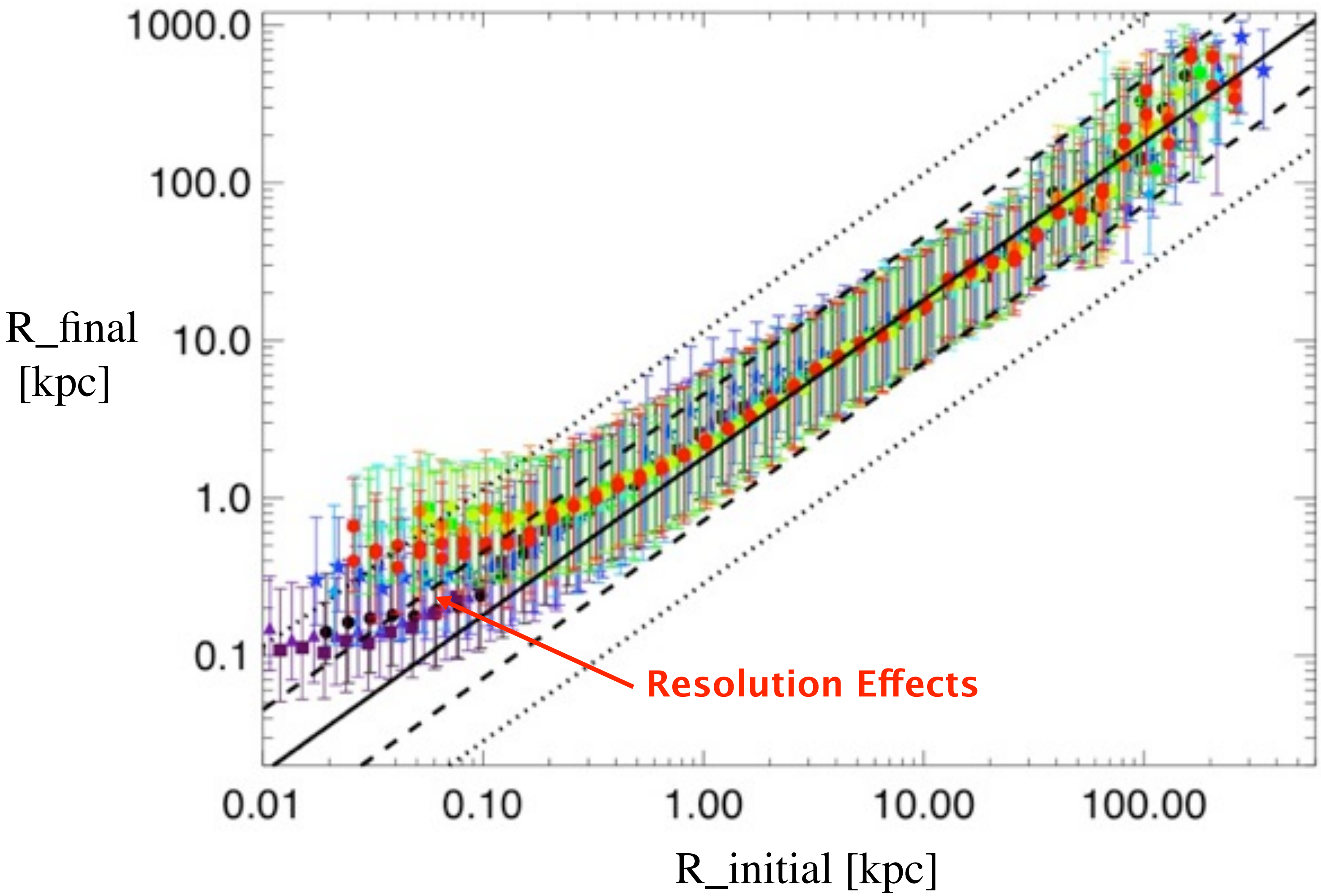

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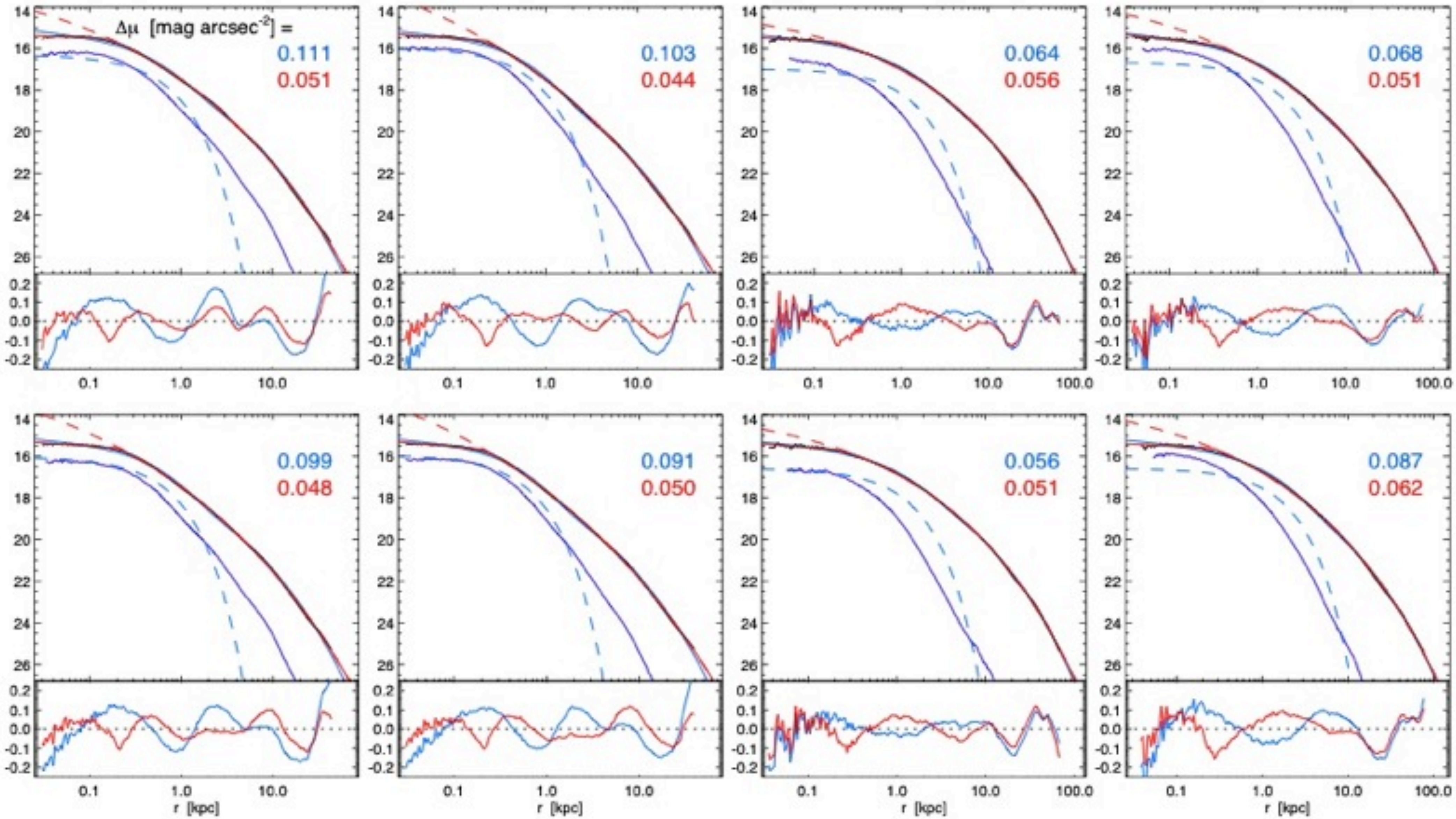

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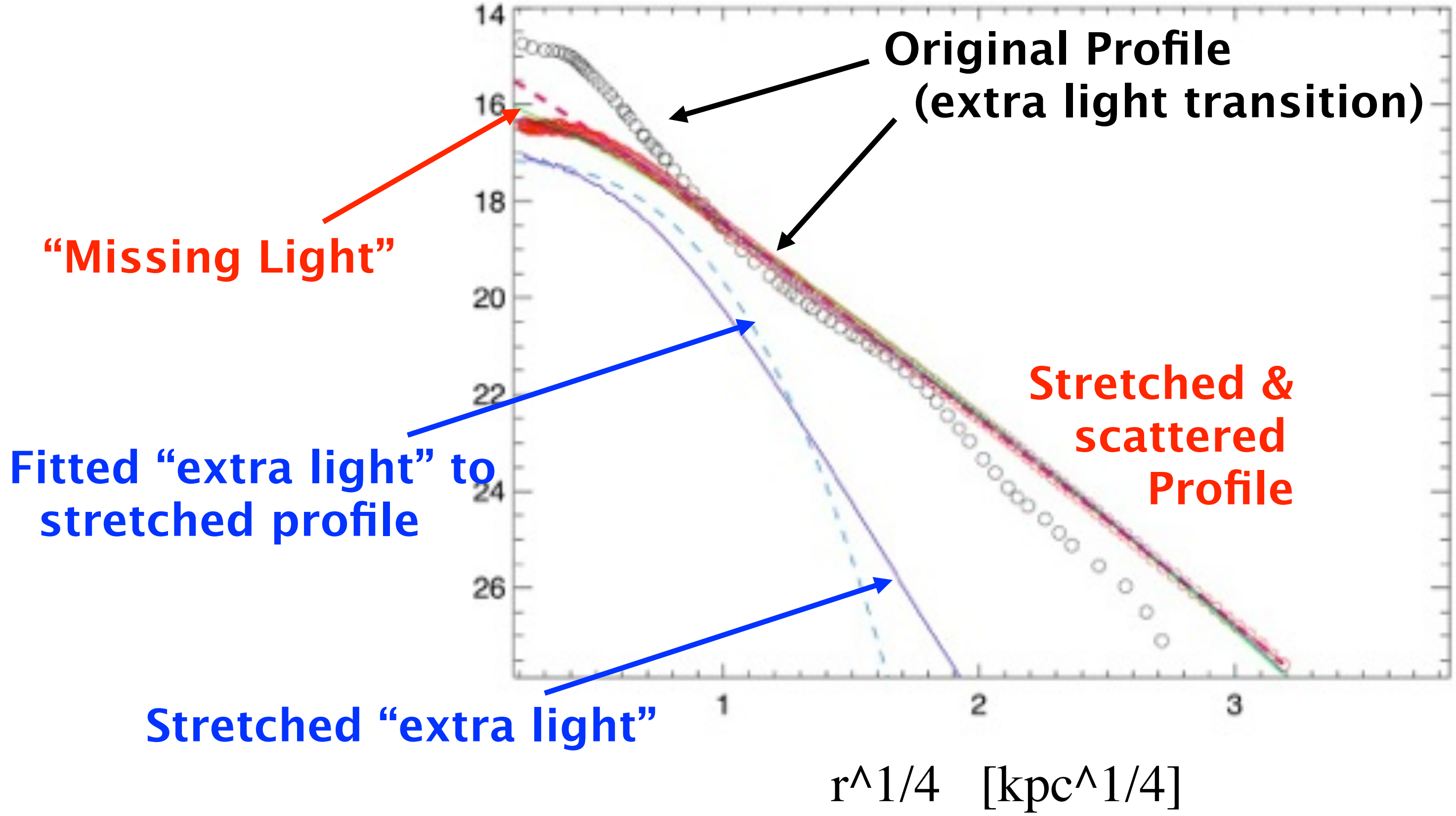

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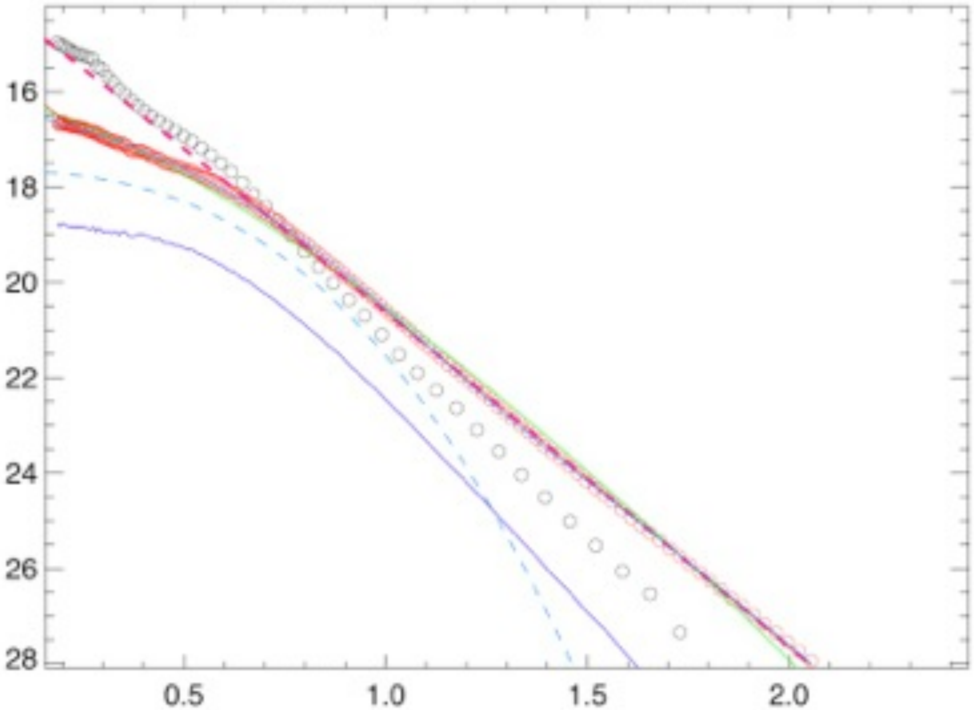
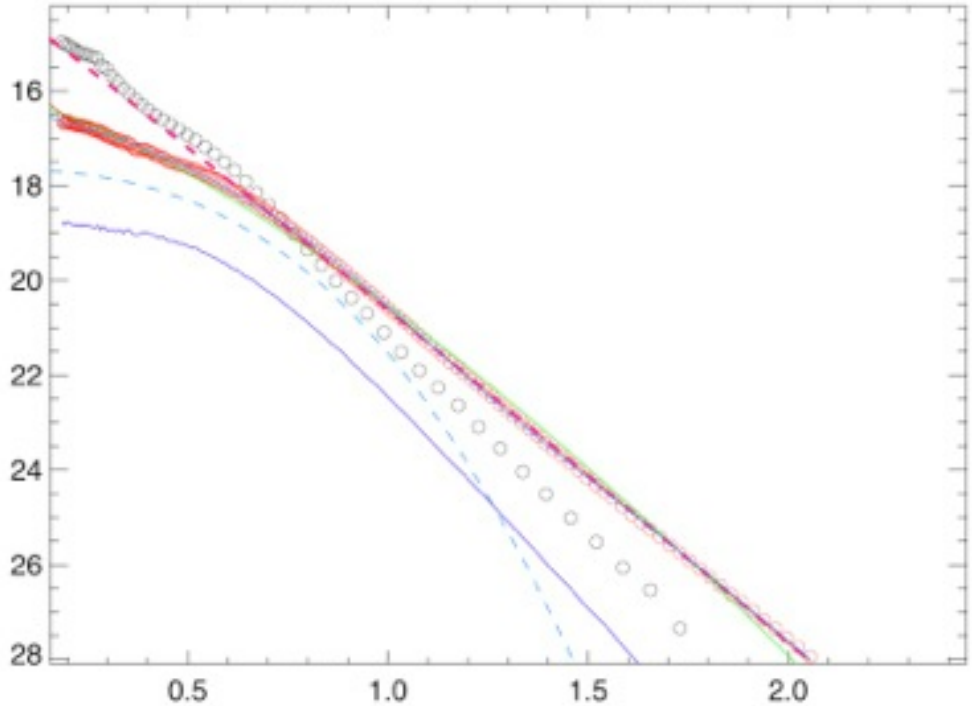


r^1/4 [kpc^1/4]



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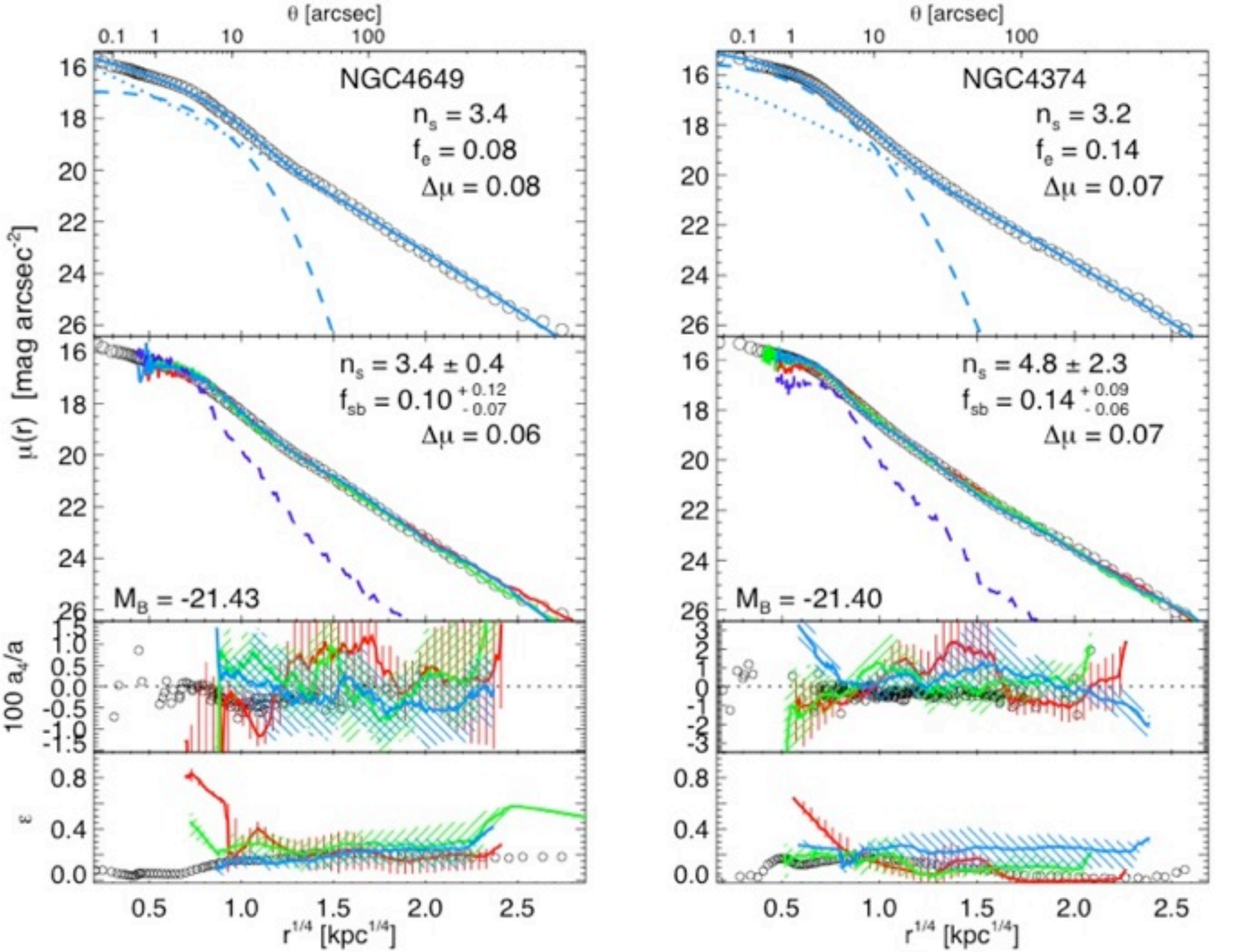

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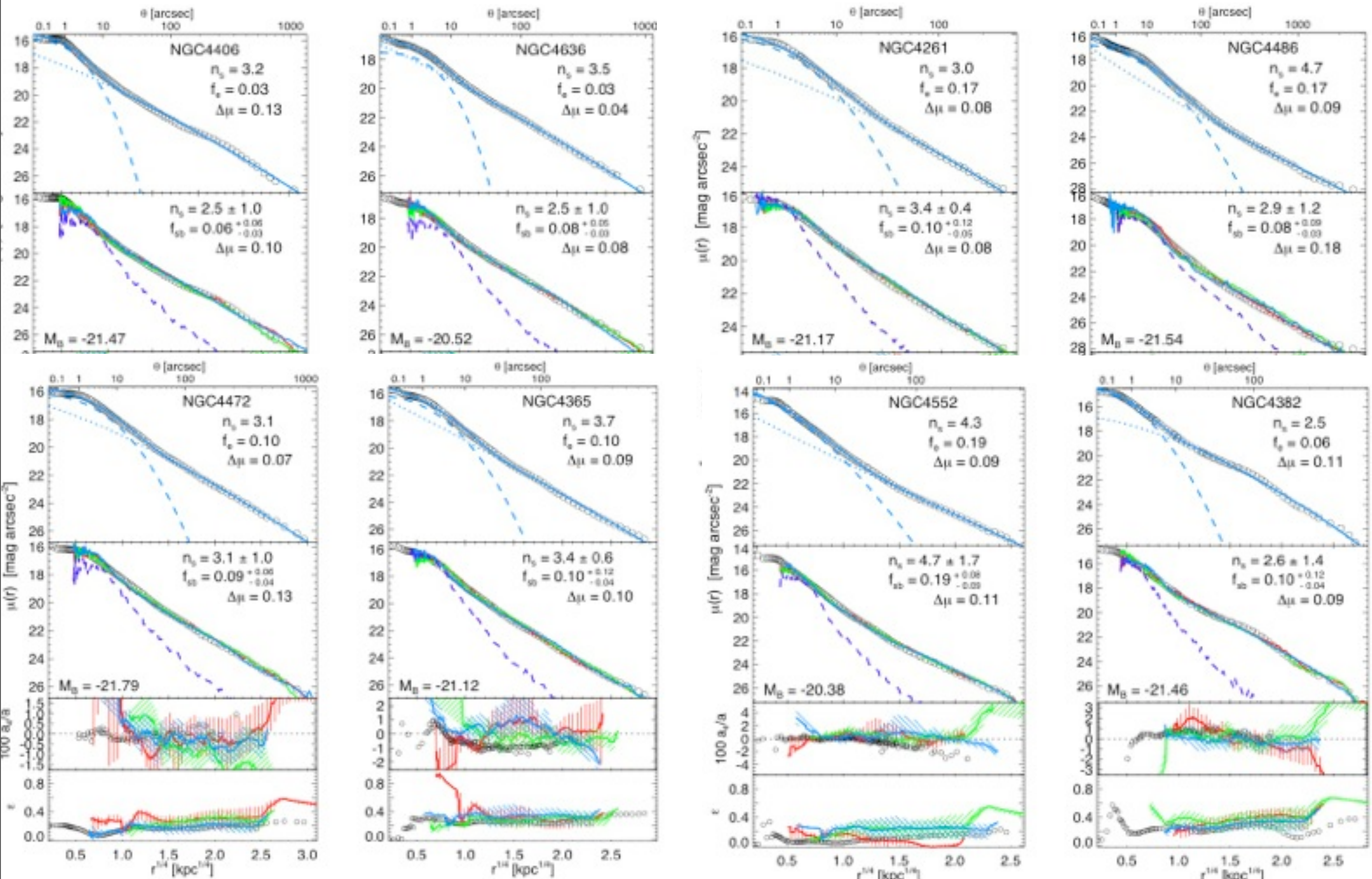

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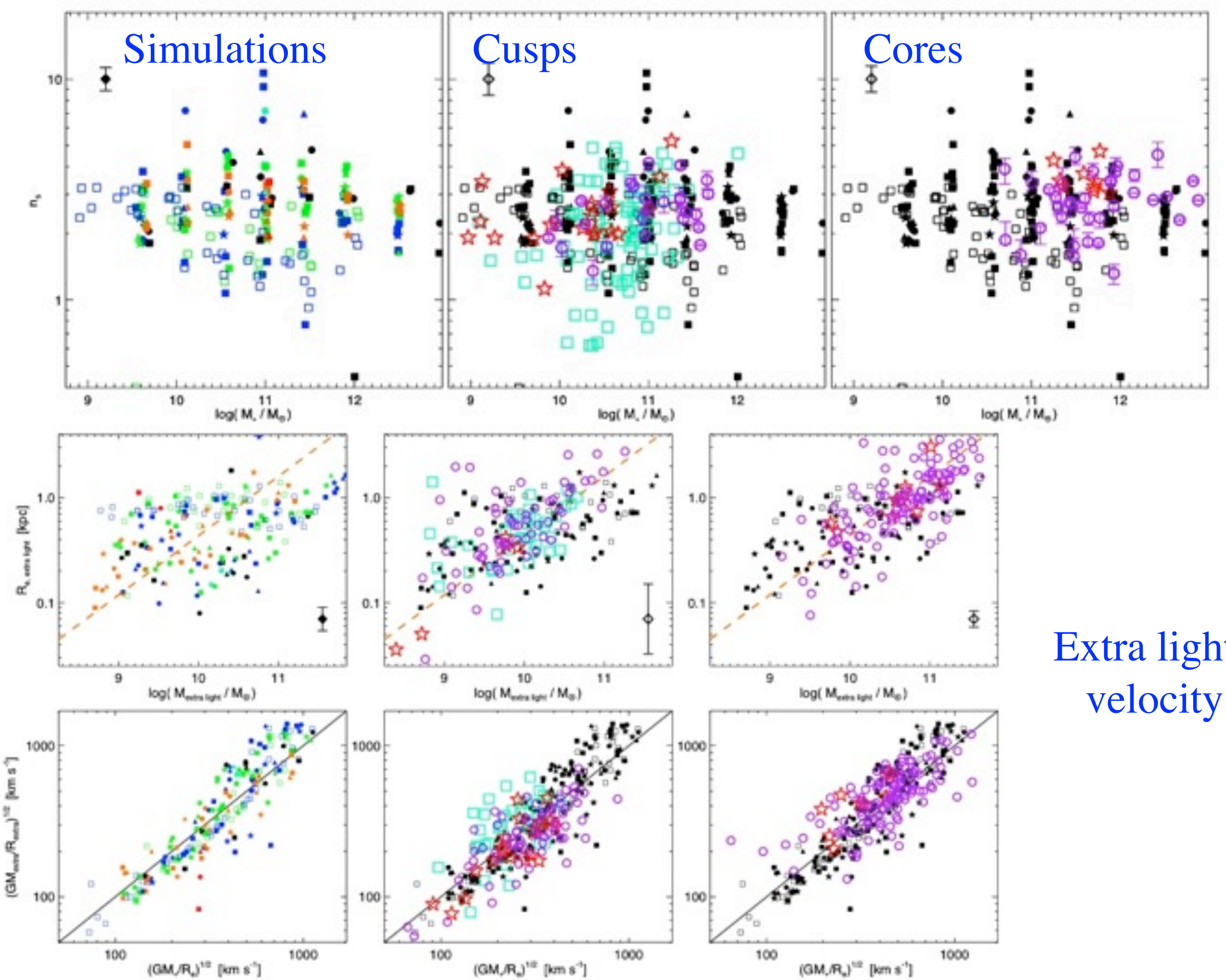

Outer Sersic index

Extra light sizes/ velocity dispersions

Application: “Core” Ellipticals

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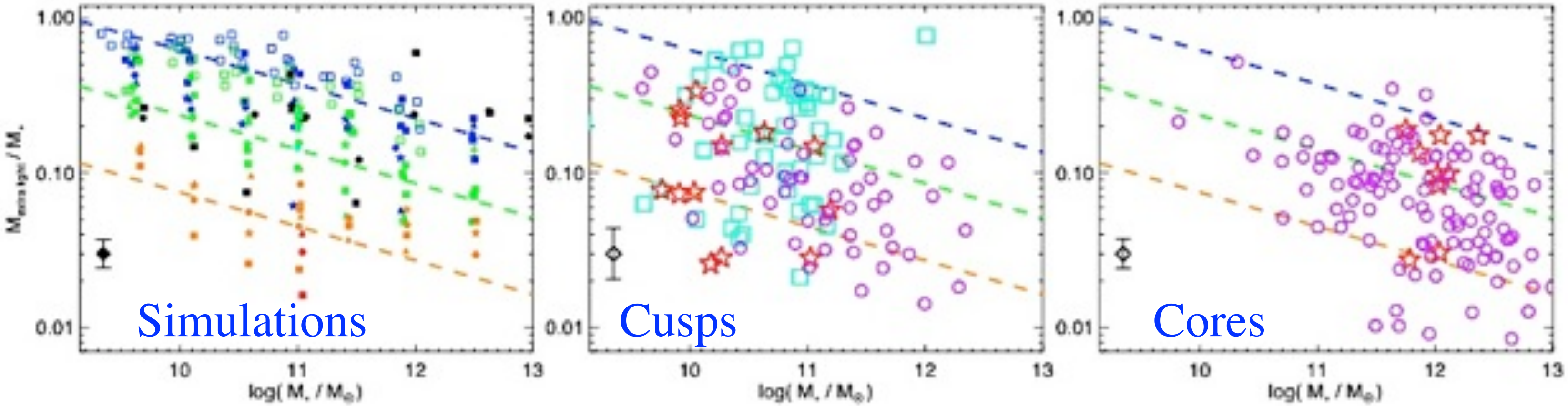
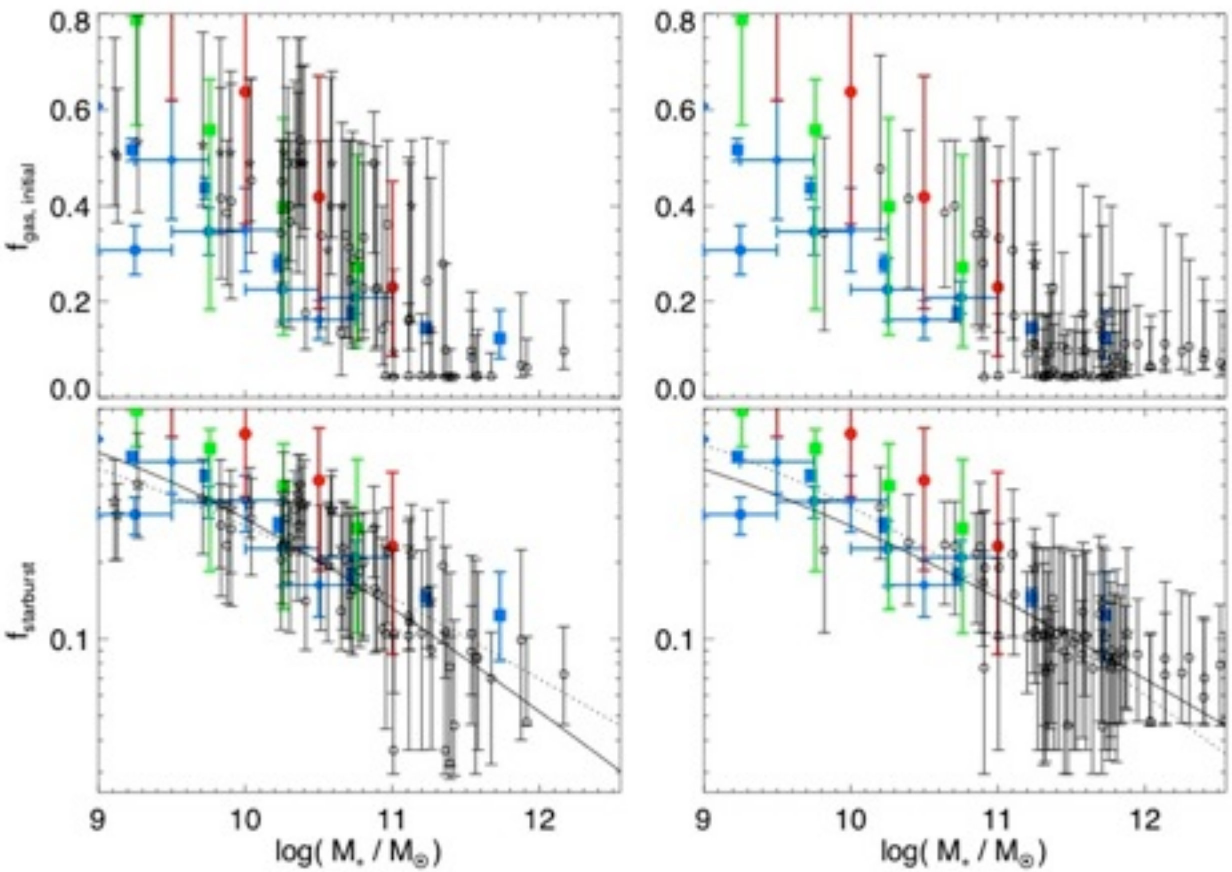


Extra light mass fraction



Structure of Spheroids

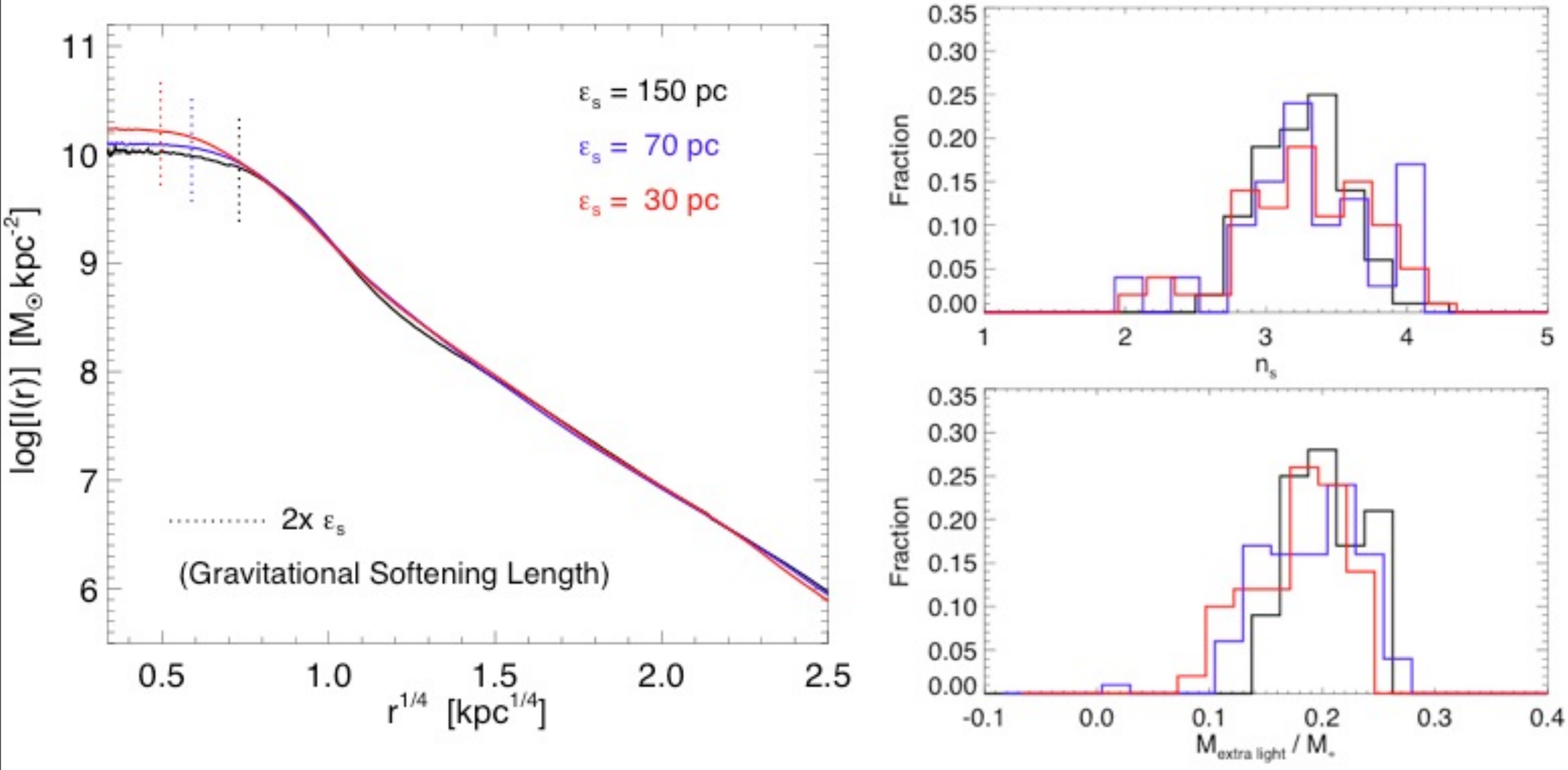
UNDERSTANDING THE FUNDAMENTAL PLANE

- 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

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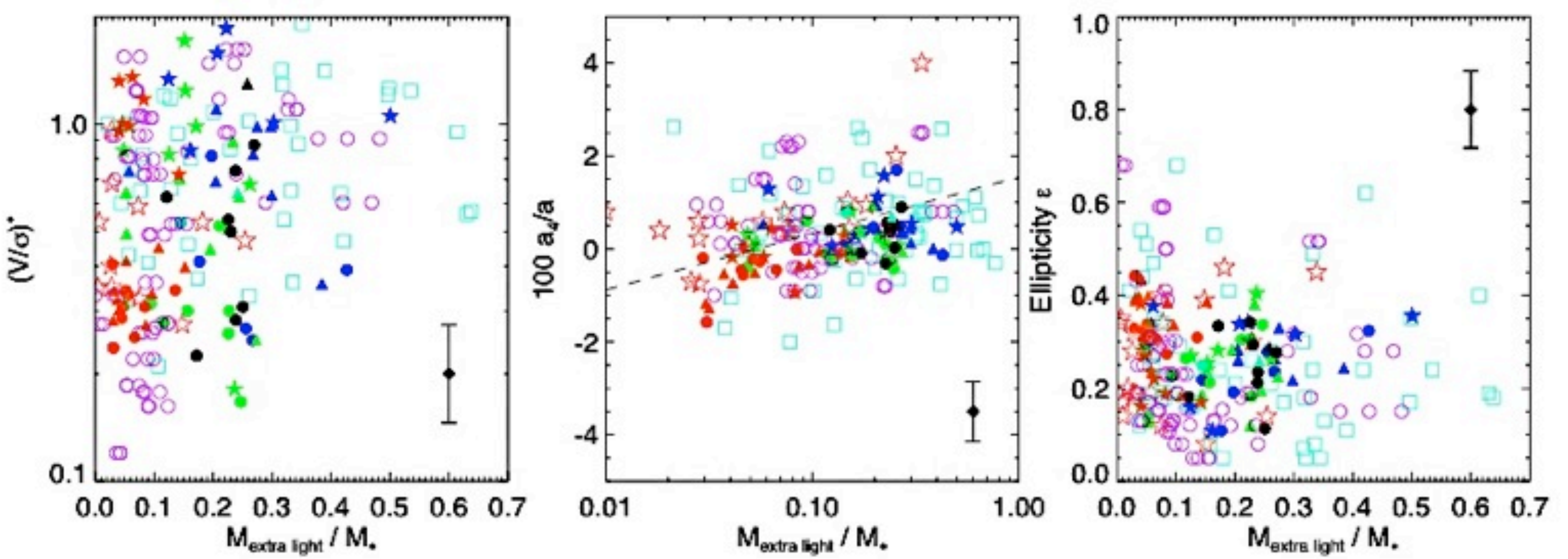

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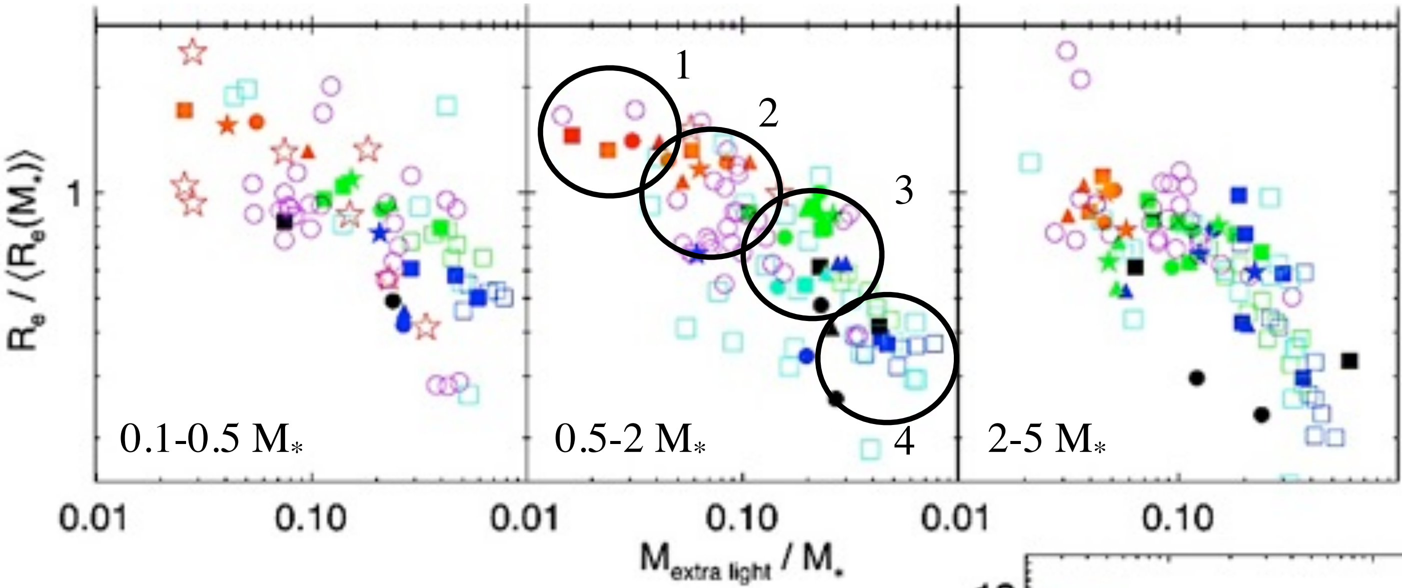
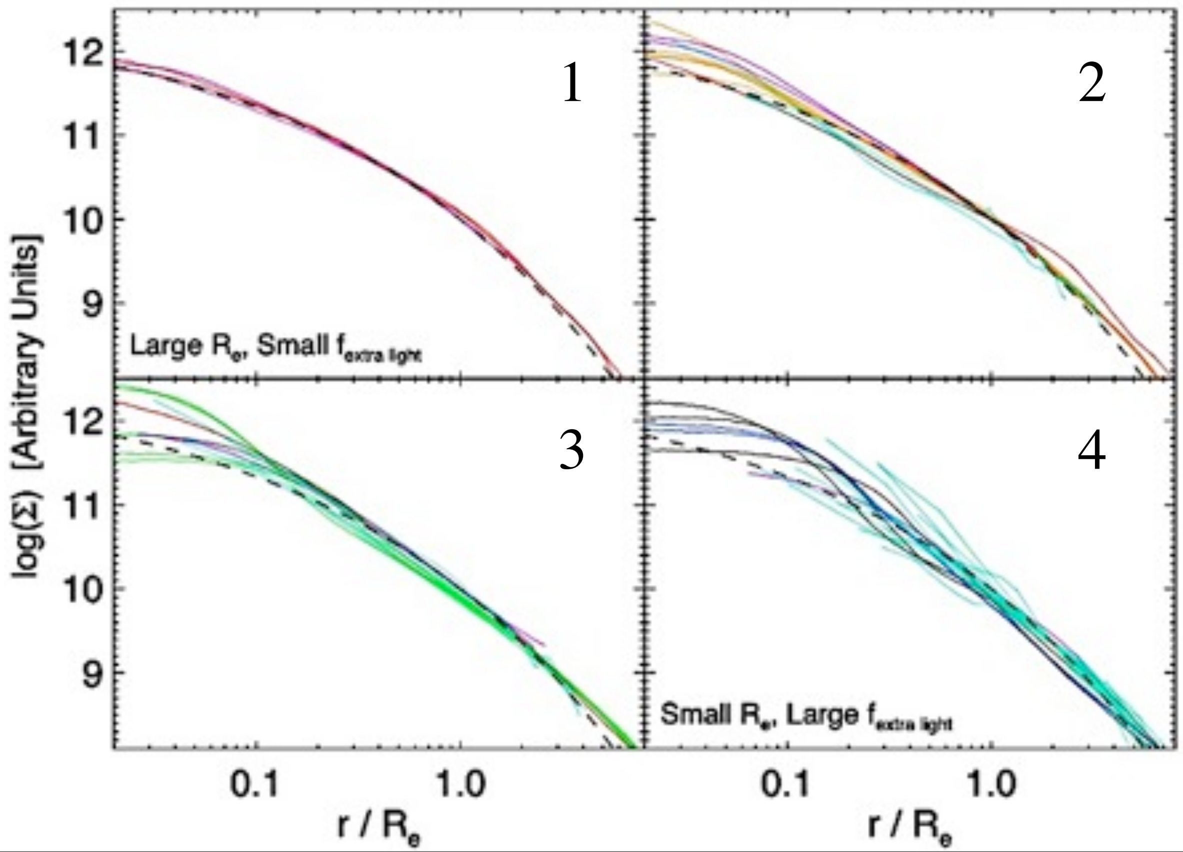
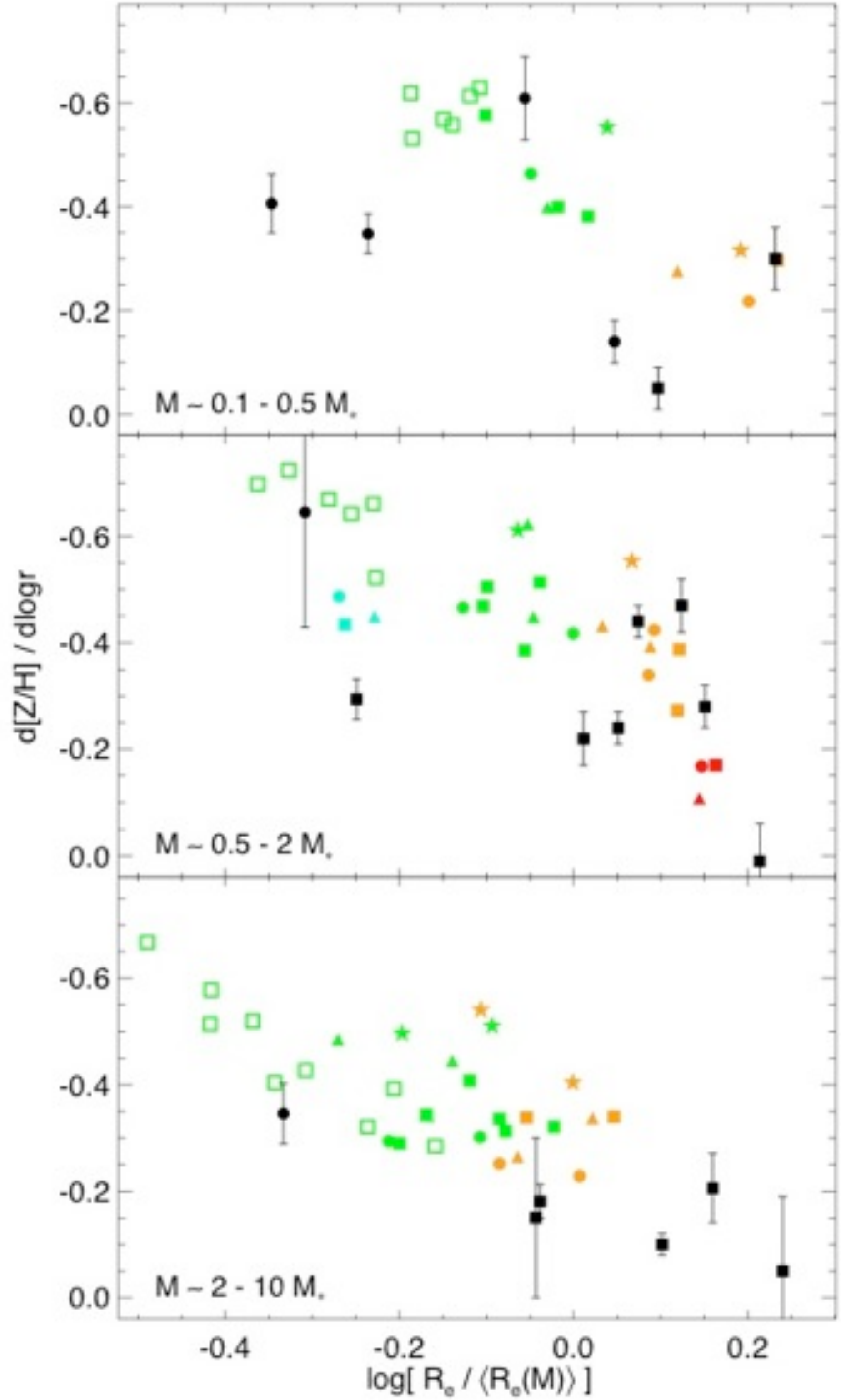




Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

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



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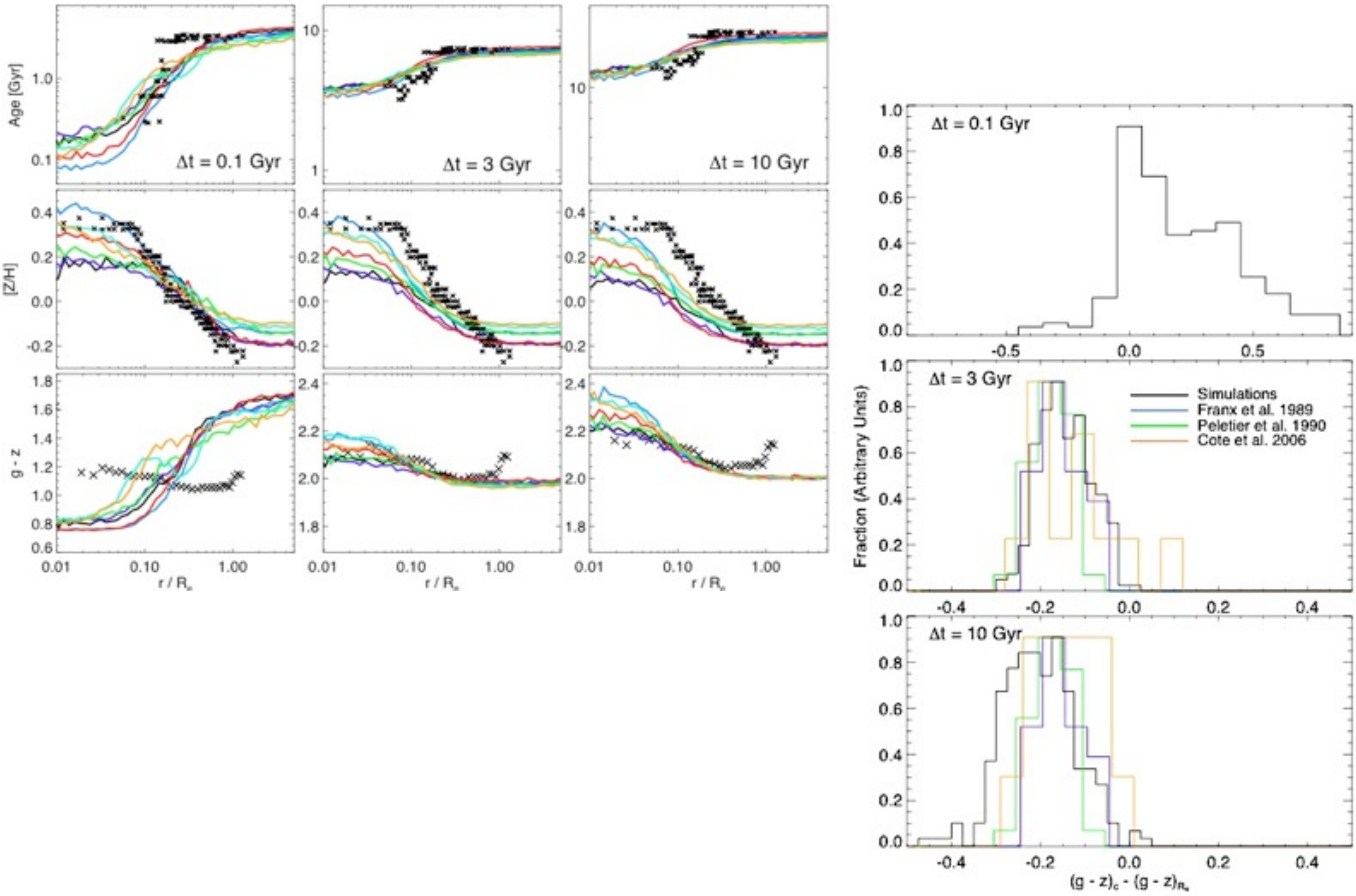

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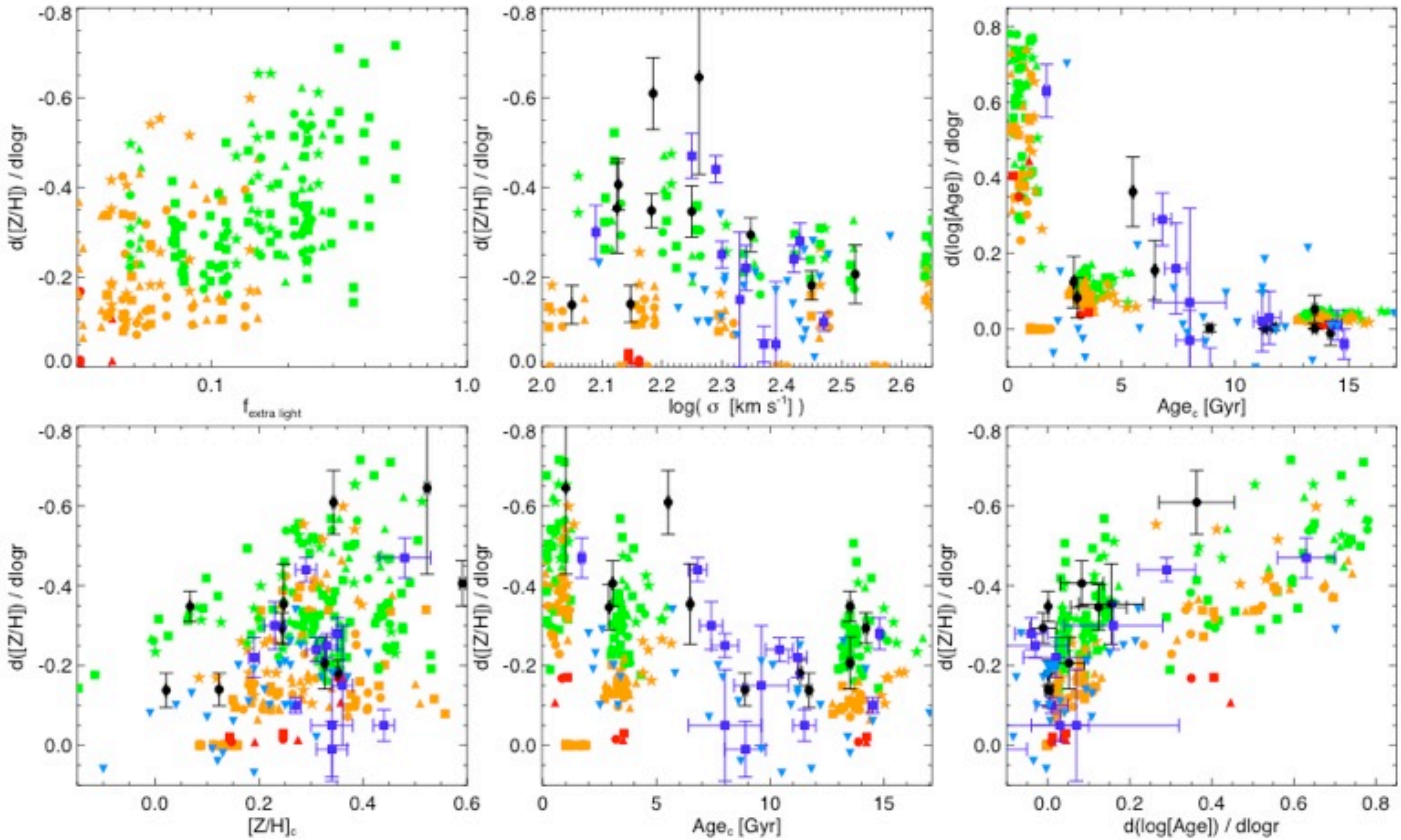
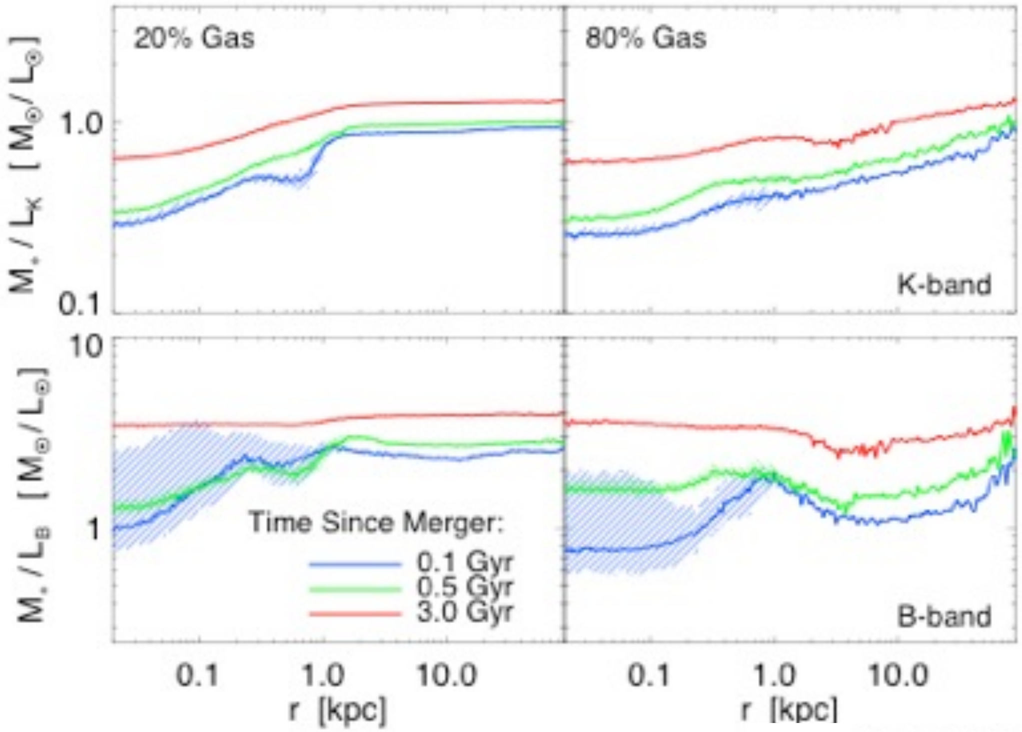
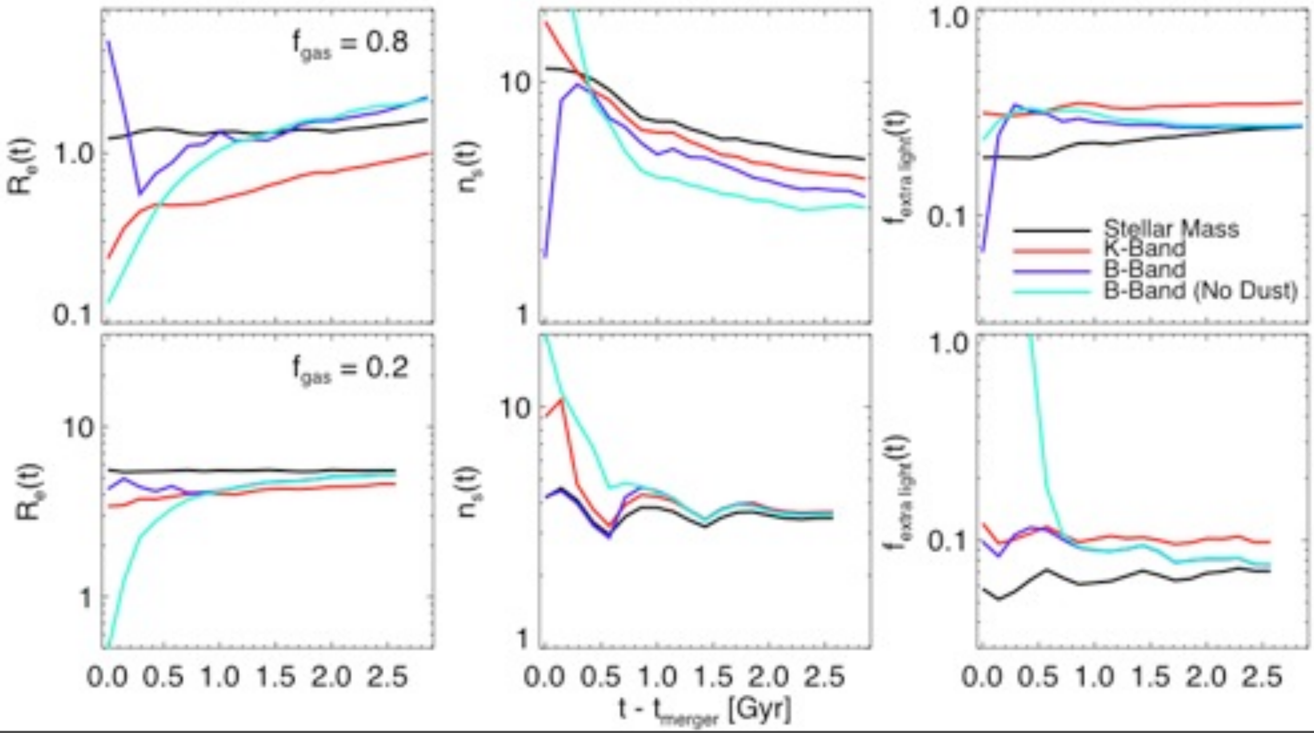


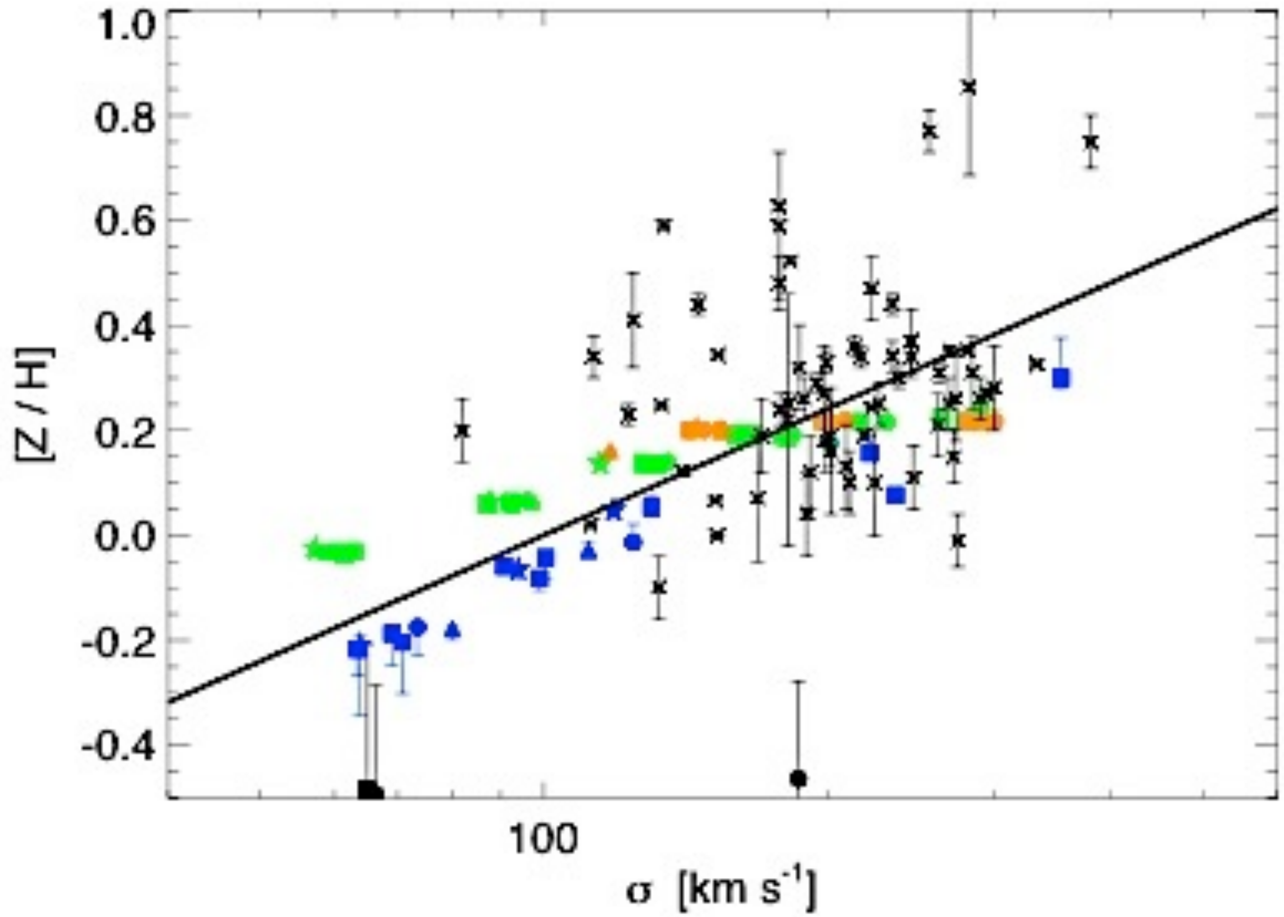
Stellar Population Effects





Fundamental Plane Tilt

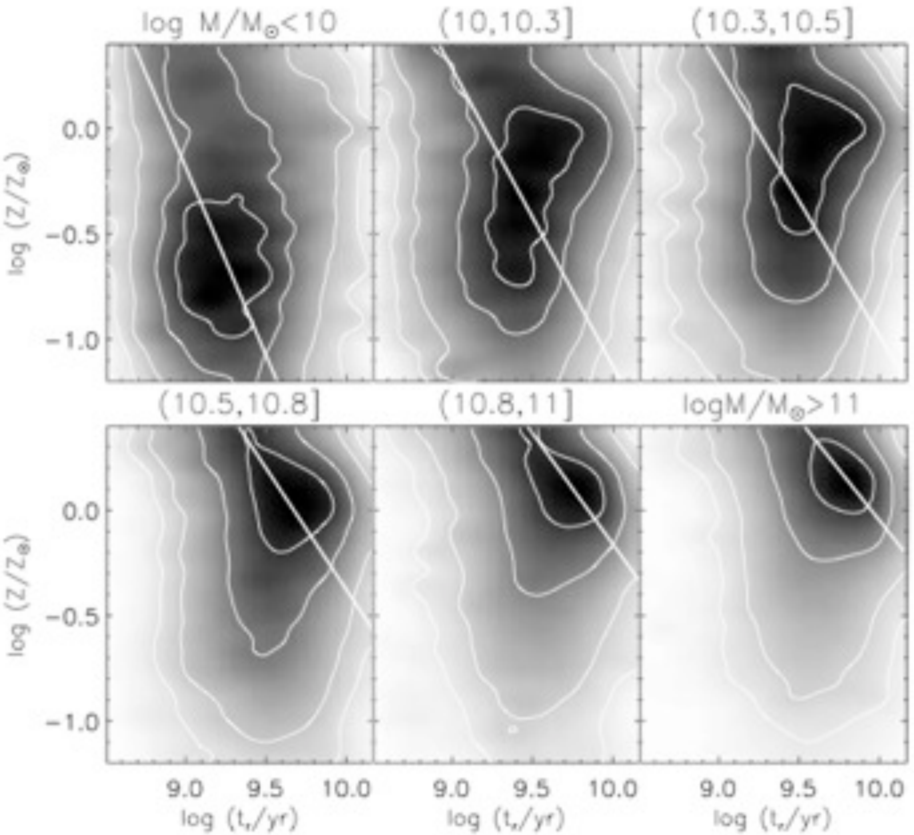
STELLAR POPULATION VARIATION

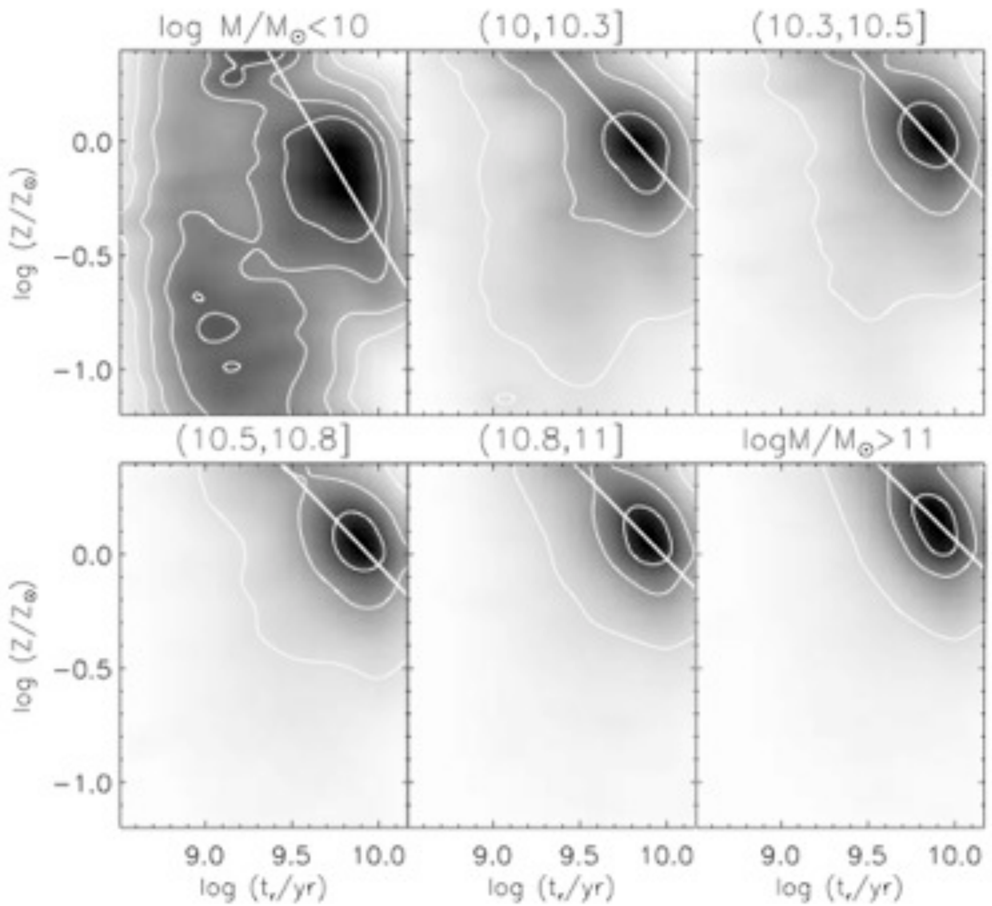


Fundamental Plane Tilt

STELLAR POPULATION VARIATION

- Where do these come from?

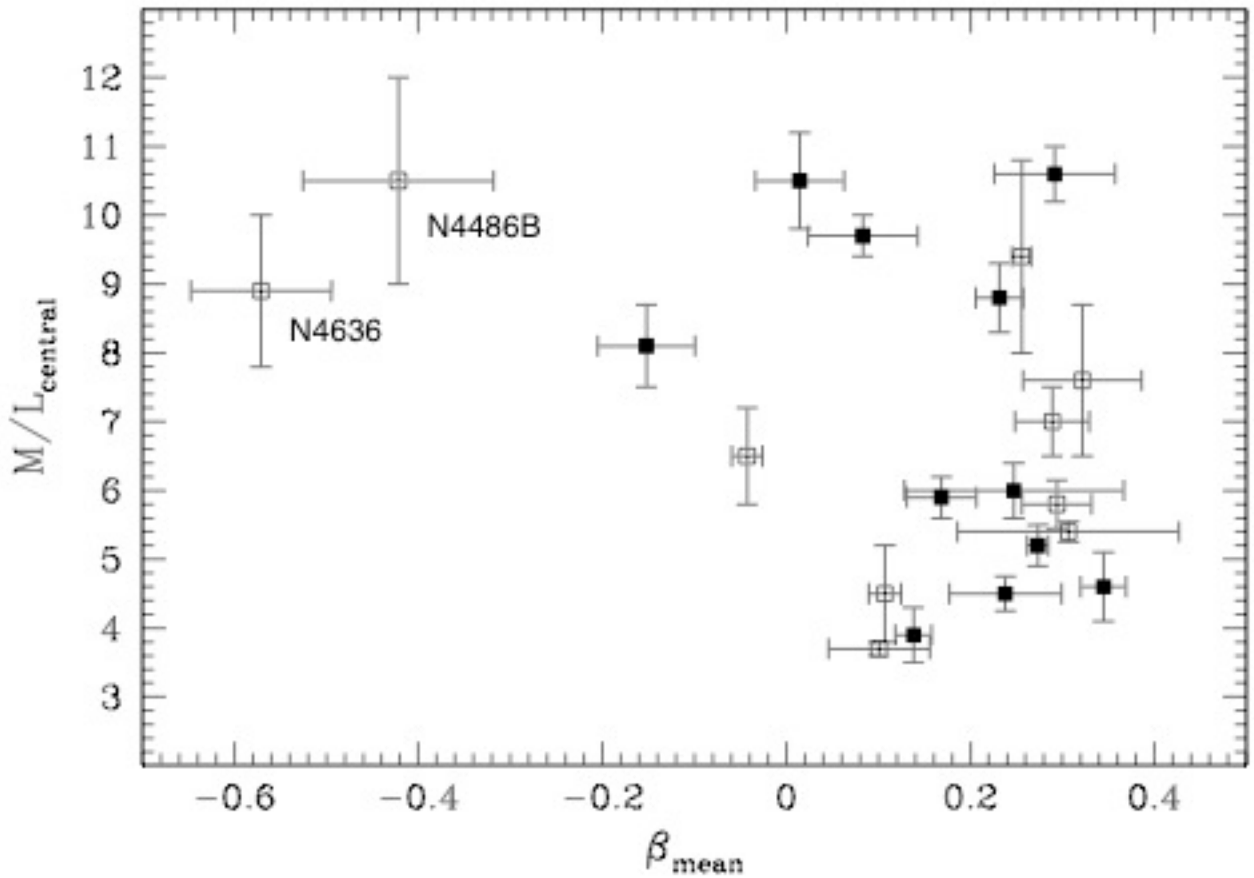




Fundamental Plane Tilt

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