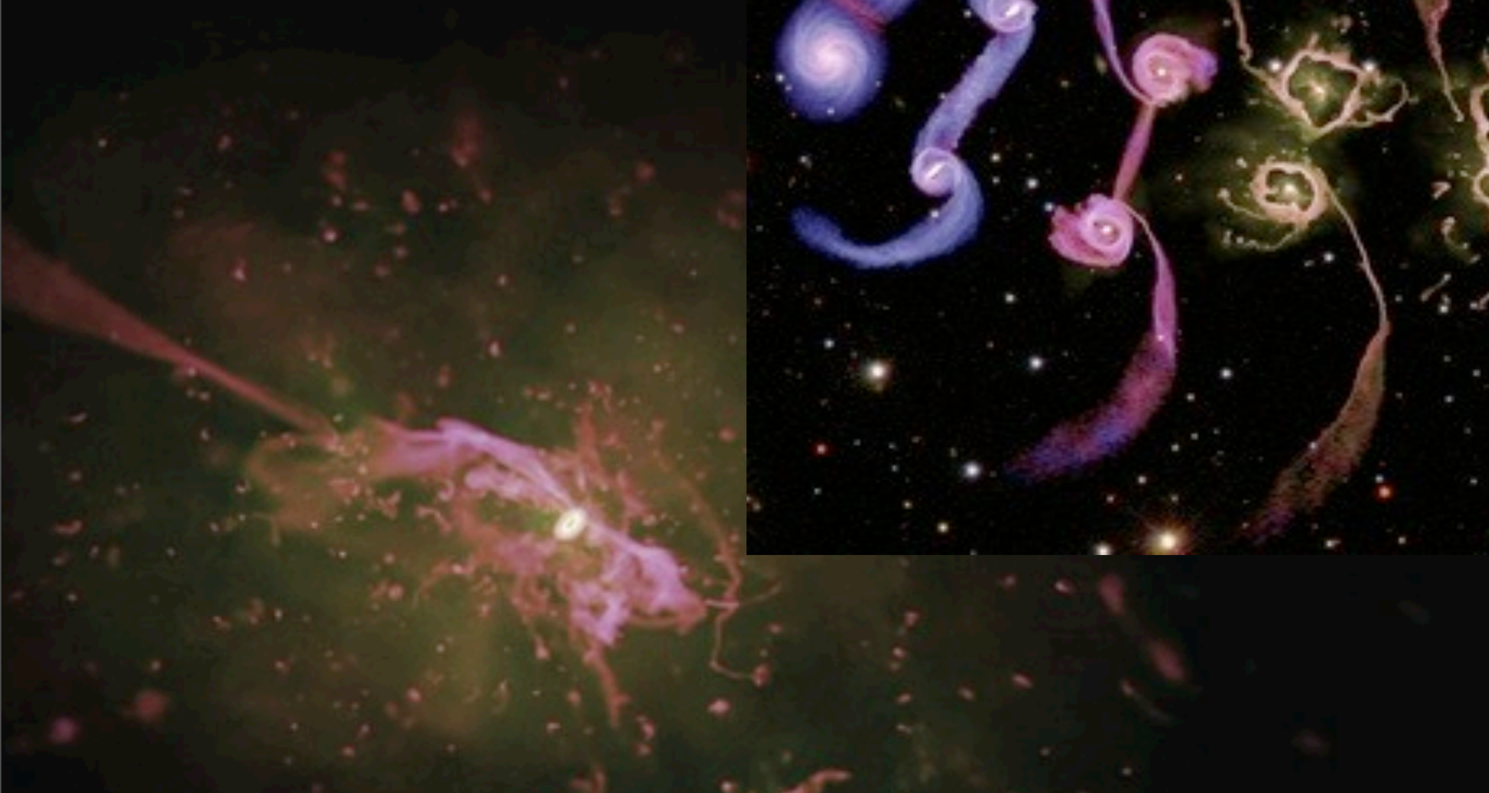
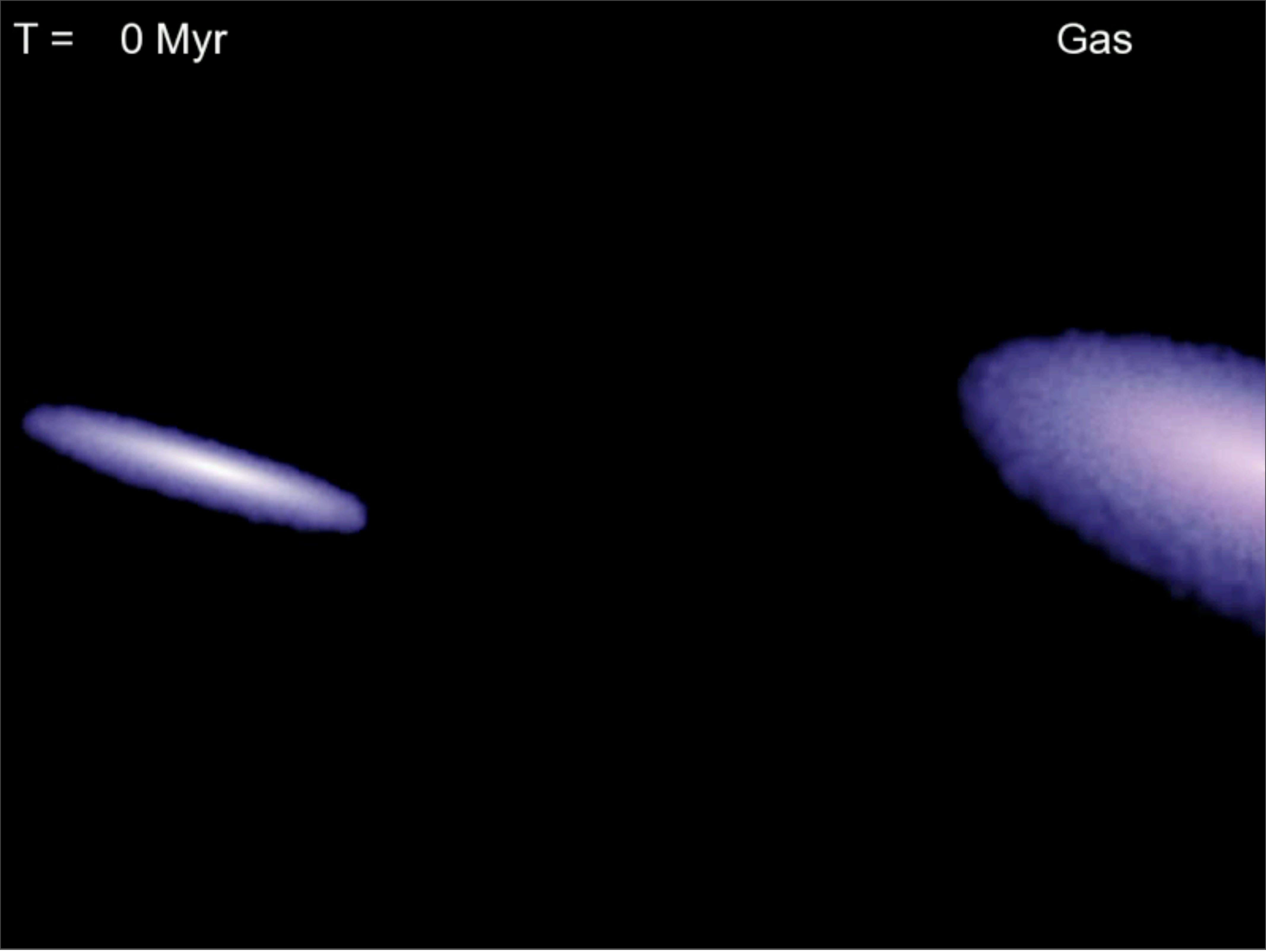
Gas in Galaxy Mergers: More Important than You Think

Philip Hopkins

11/13/08

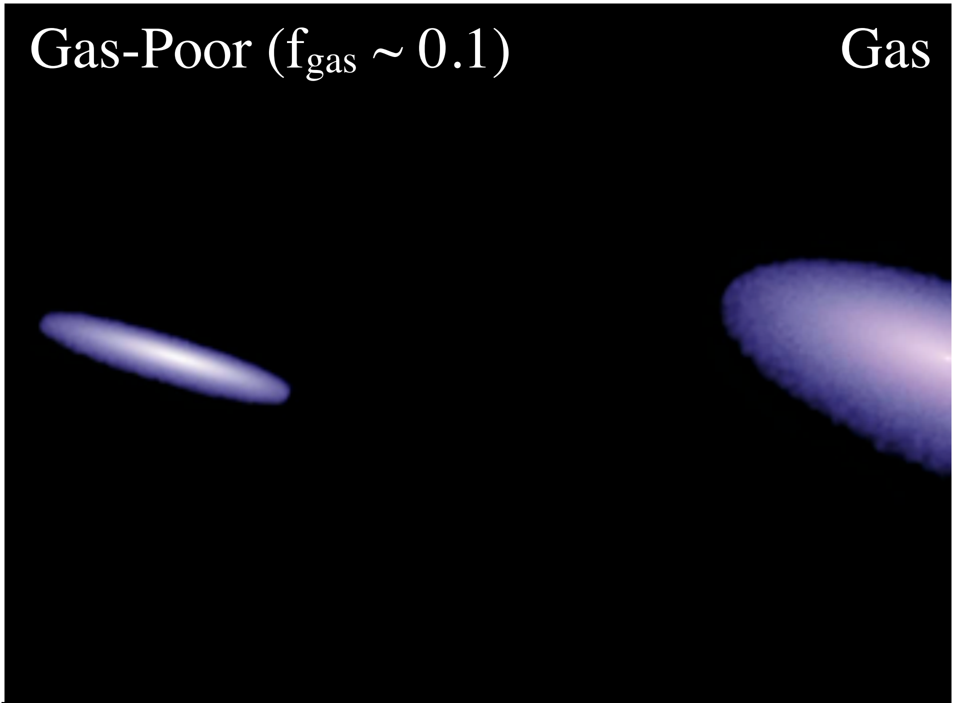


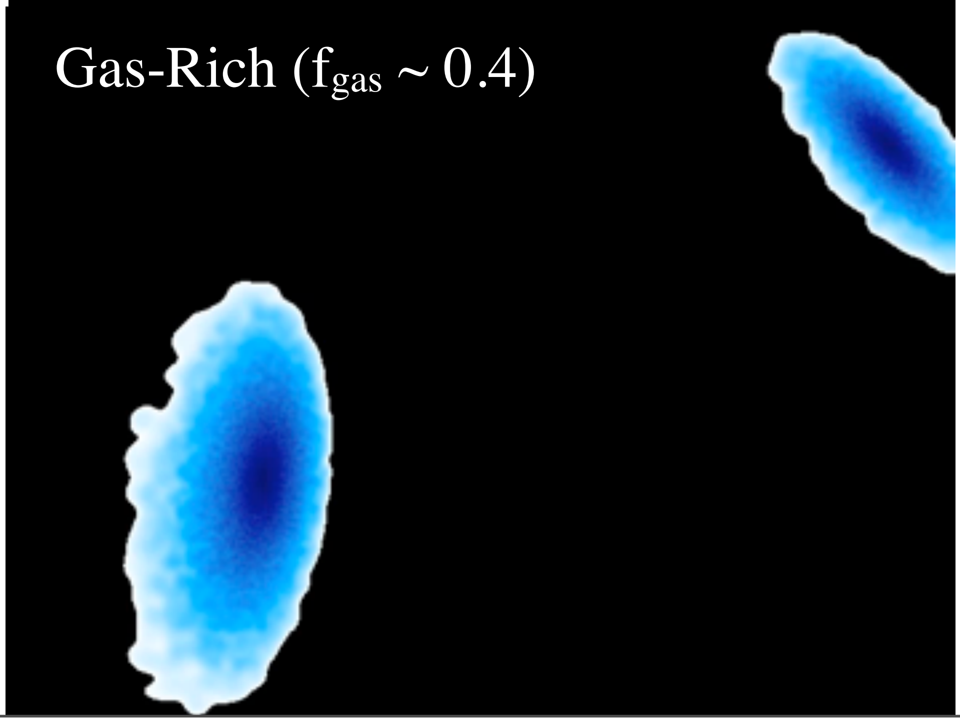
Lars Hernquist, T. J. Cox, Josh Younger, John Kormendy, Barry Rothberg, Tod Lauer, Eliot Quataert, Chung-Pei Ma, Dusan Keres, Volker Springel

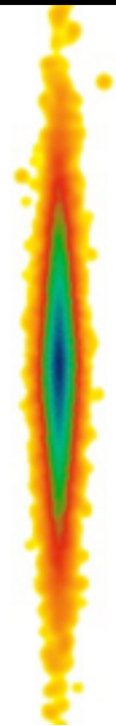

T = 0 Myr
Gas

Galaxy Mergers

HOW GOOD IS OUR CONVENTIONAL WISDOM?

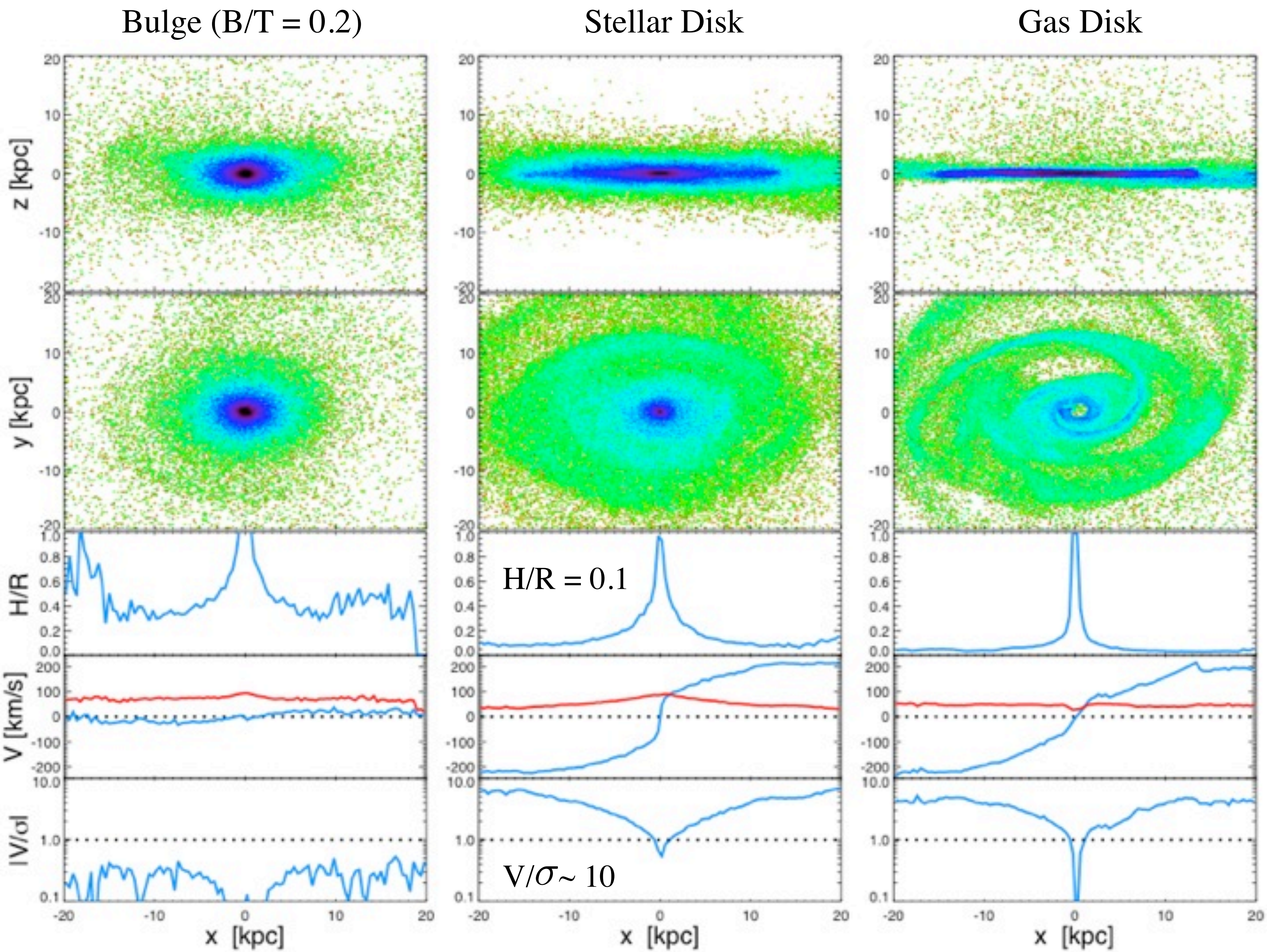






Major Merger Remnants

DO MERGERS DESTROY DISKS?



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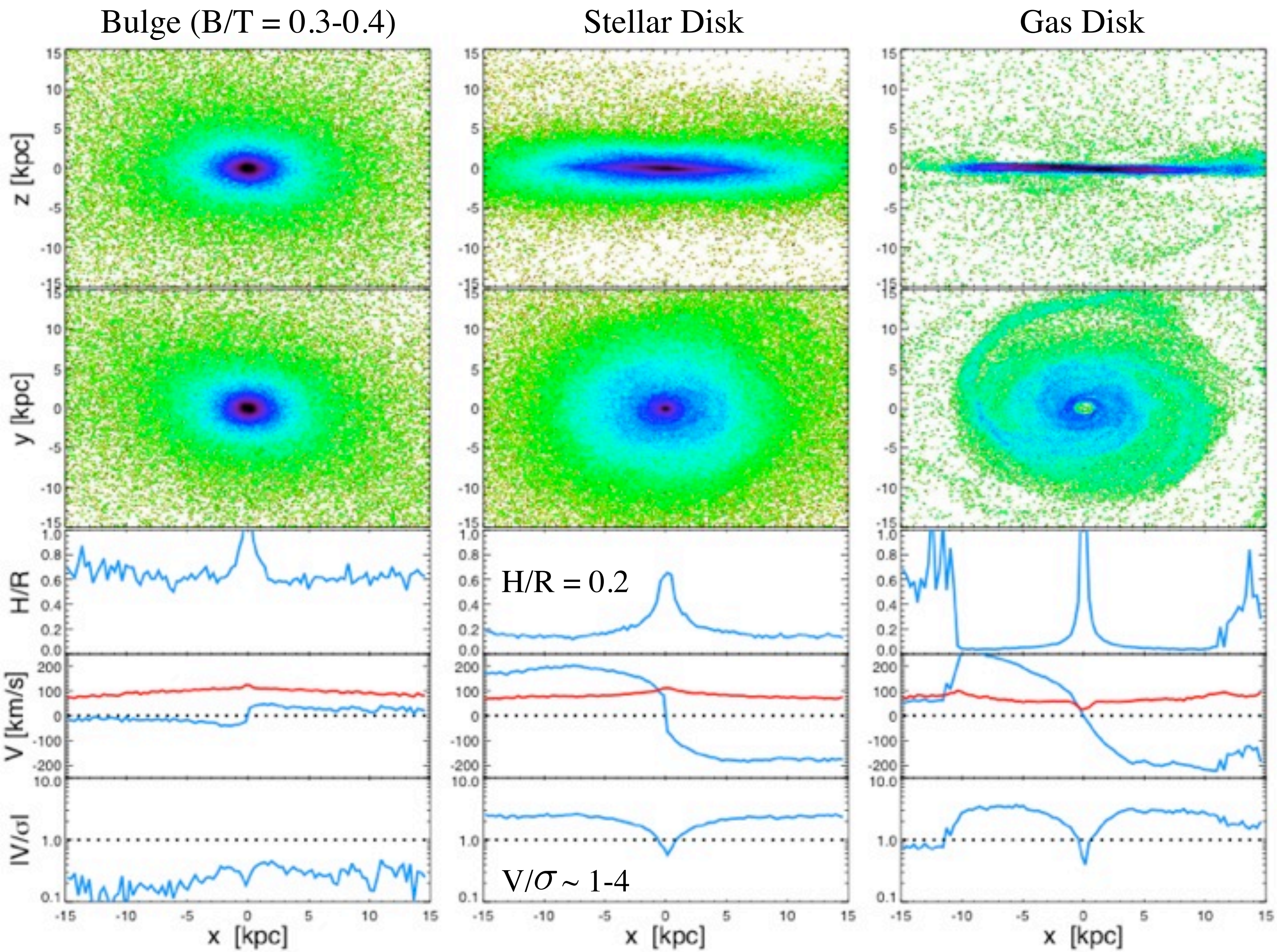

The Unsolved Questions

HOW CAN A DISK SURVIVE?

- Stellar disks are collisionless: they violently relax when they collide

+

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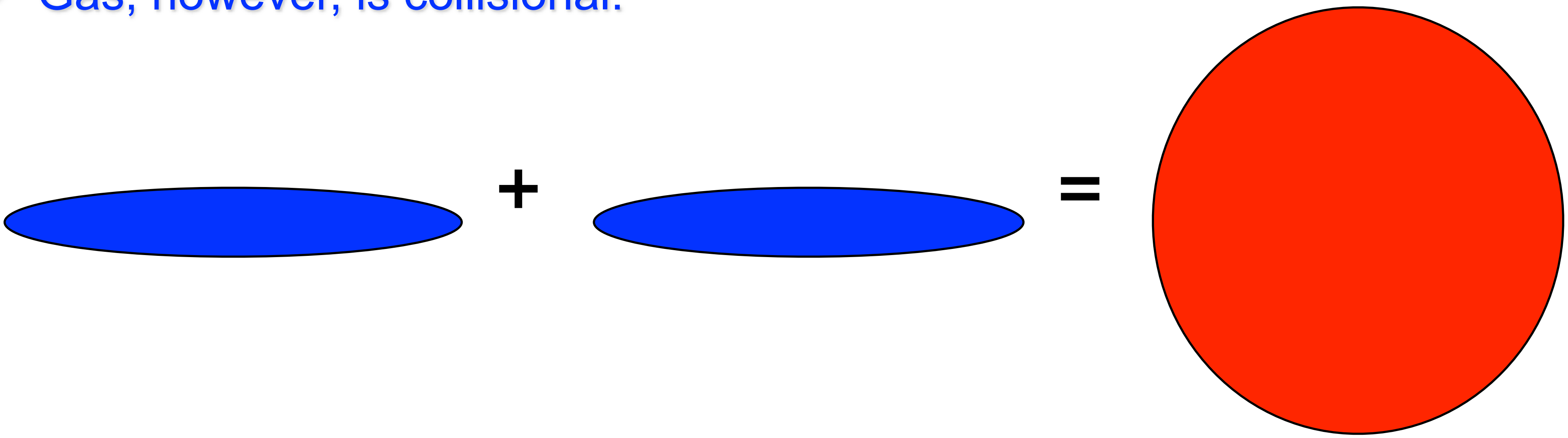
- Can't "cool" into a new disk

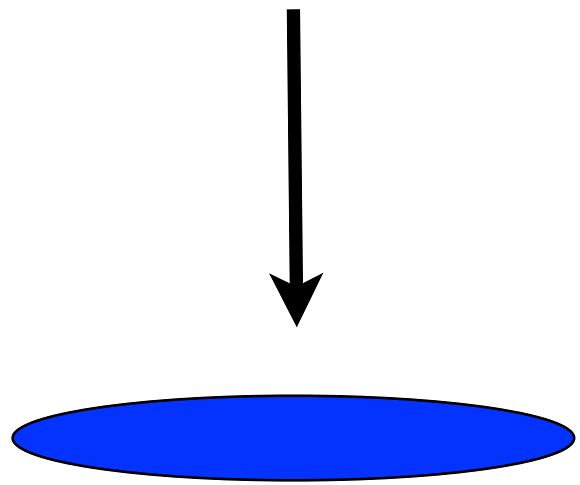
The Unsolved Questions

HOW CAN A DISK SURVIVE?

- Gas, however, is collisional:

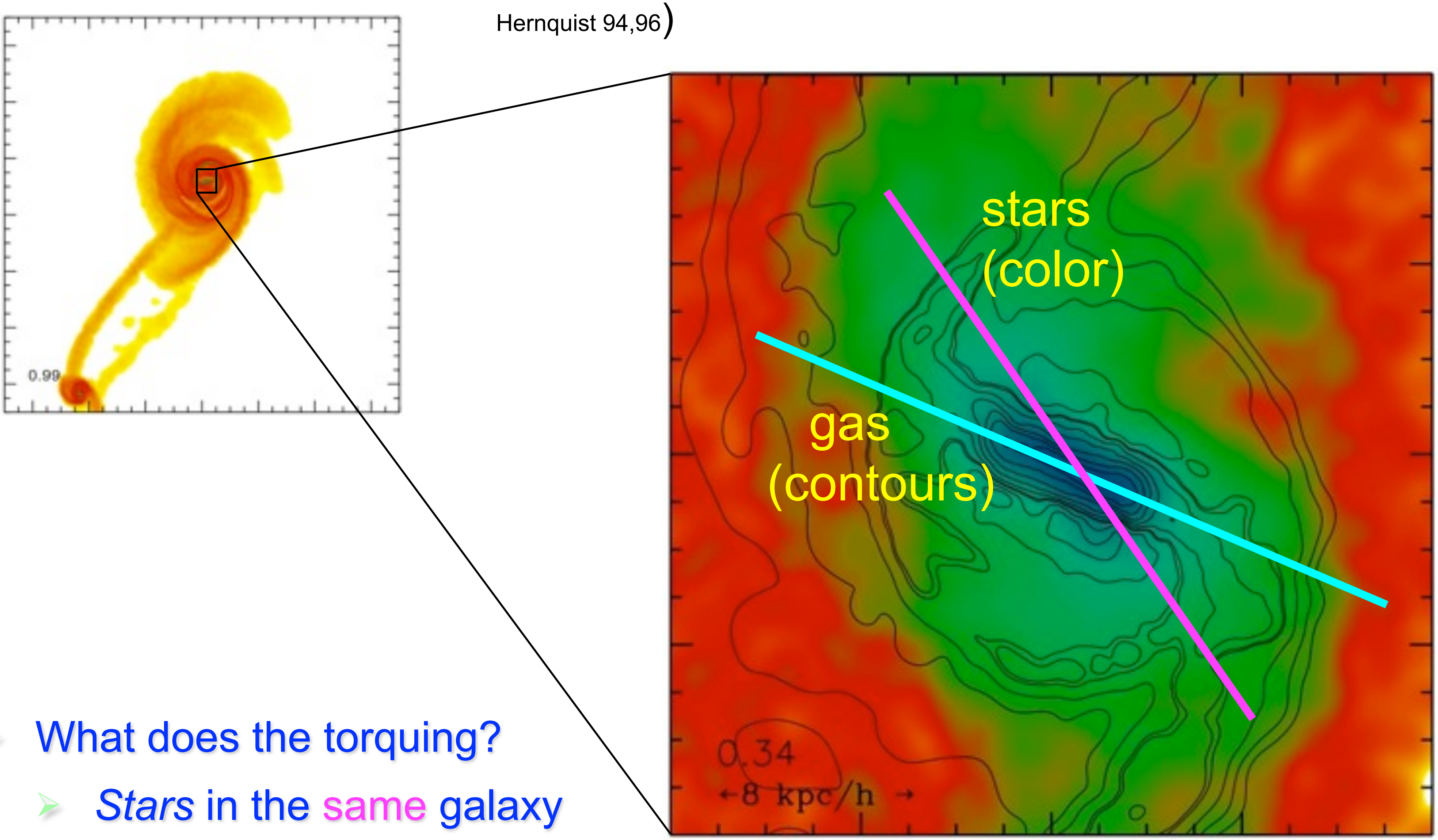


- Will cool into a new disk:
  only goes to center and
  bursts if angular momentum
  is removed



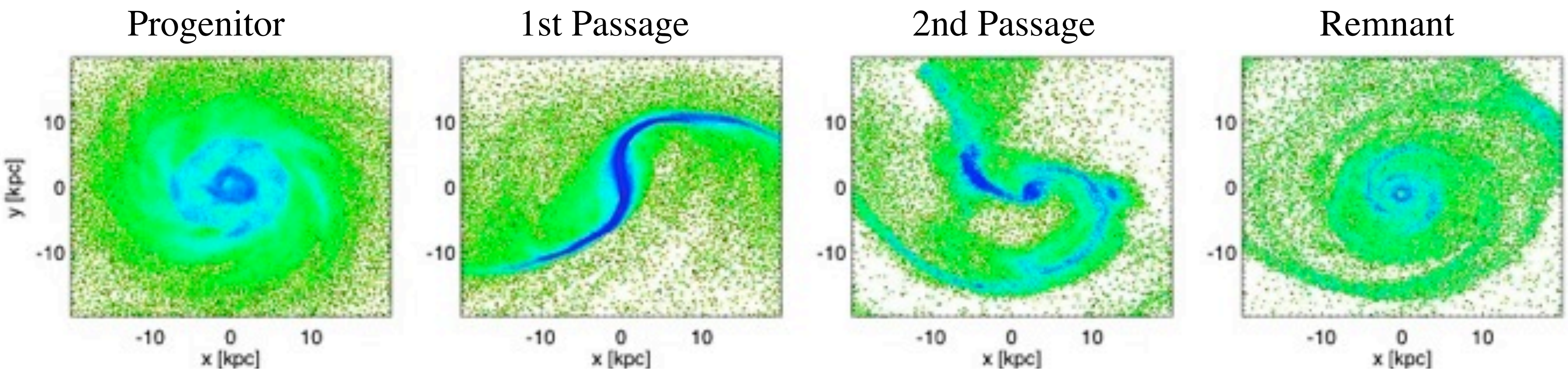
How Do Disks Survive Mergers?

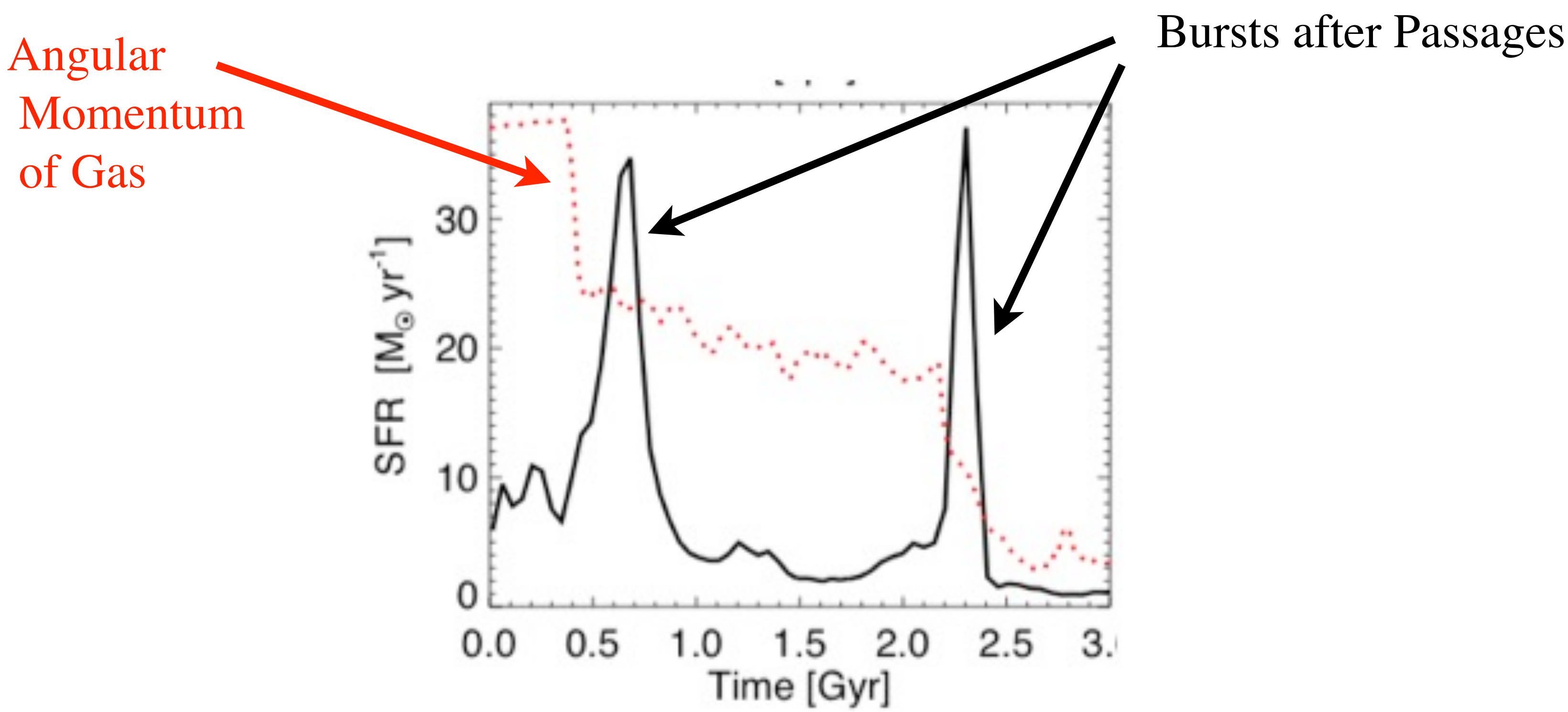
companions -- bars -- gas/star offset -- torques -- gas inflow (see, e.g., Barnes 92, Barnes & Hernquist 96, Mihos & Hernquist 94,96)



- What does the torquing?
  - *Stars* in the same galaxy

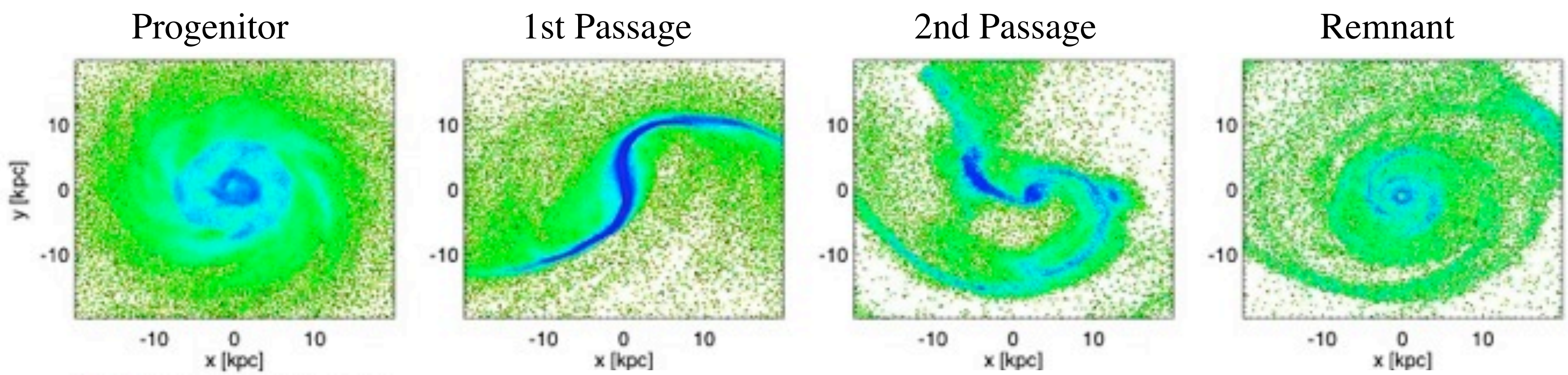
How Do Disks Survive Mergers?

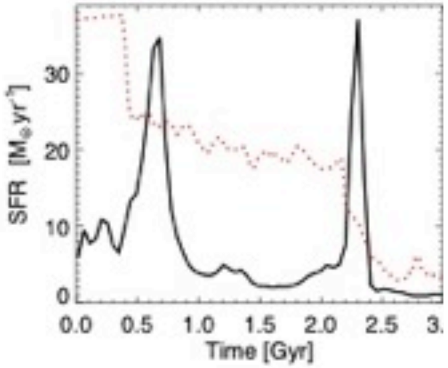


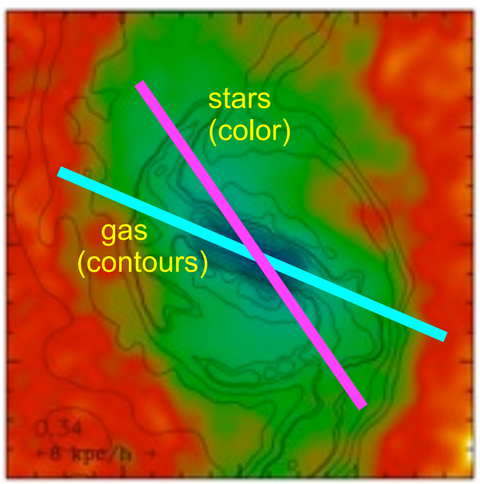


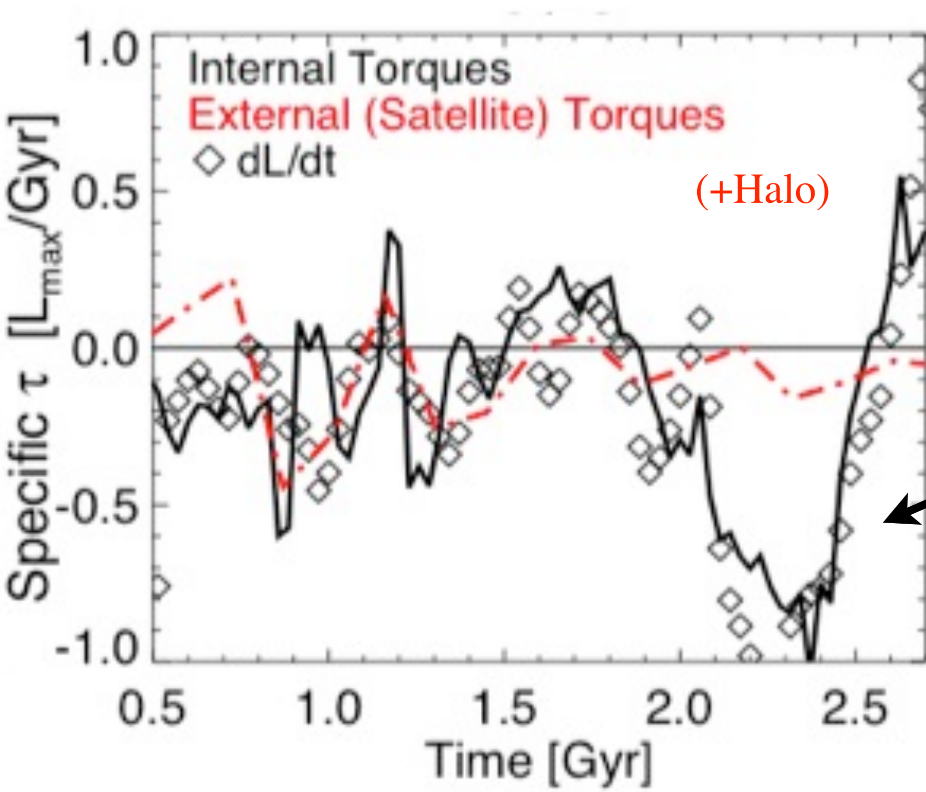
PFH et al. '08

How Do Disks Survive Mergers?





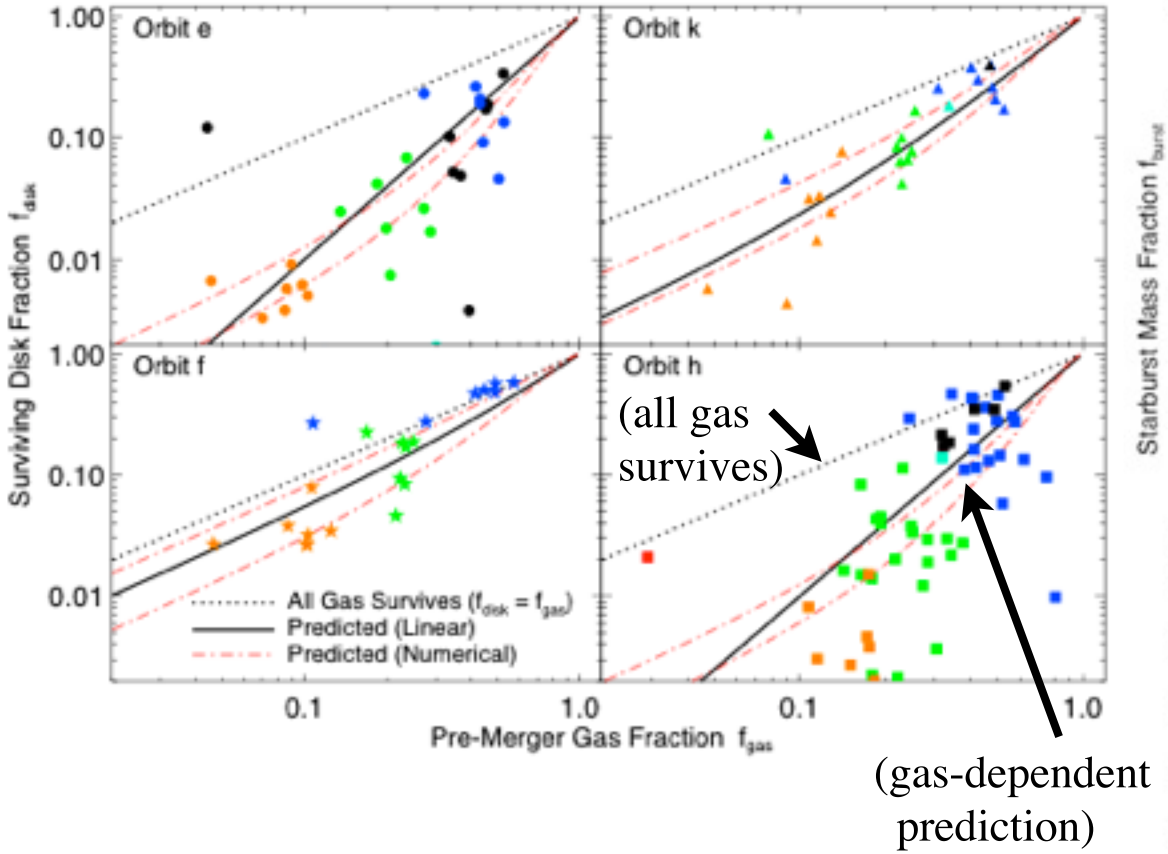




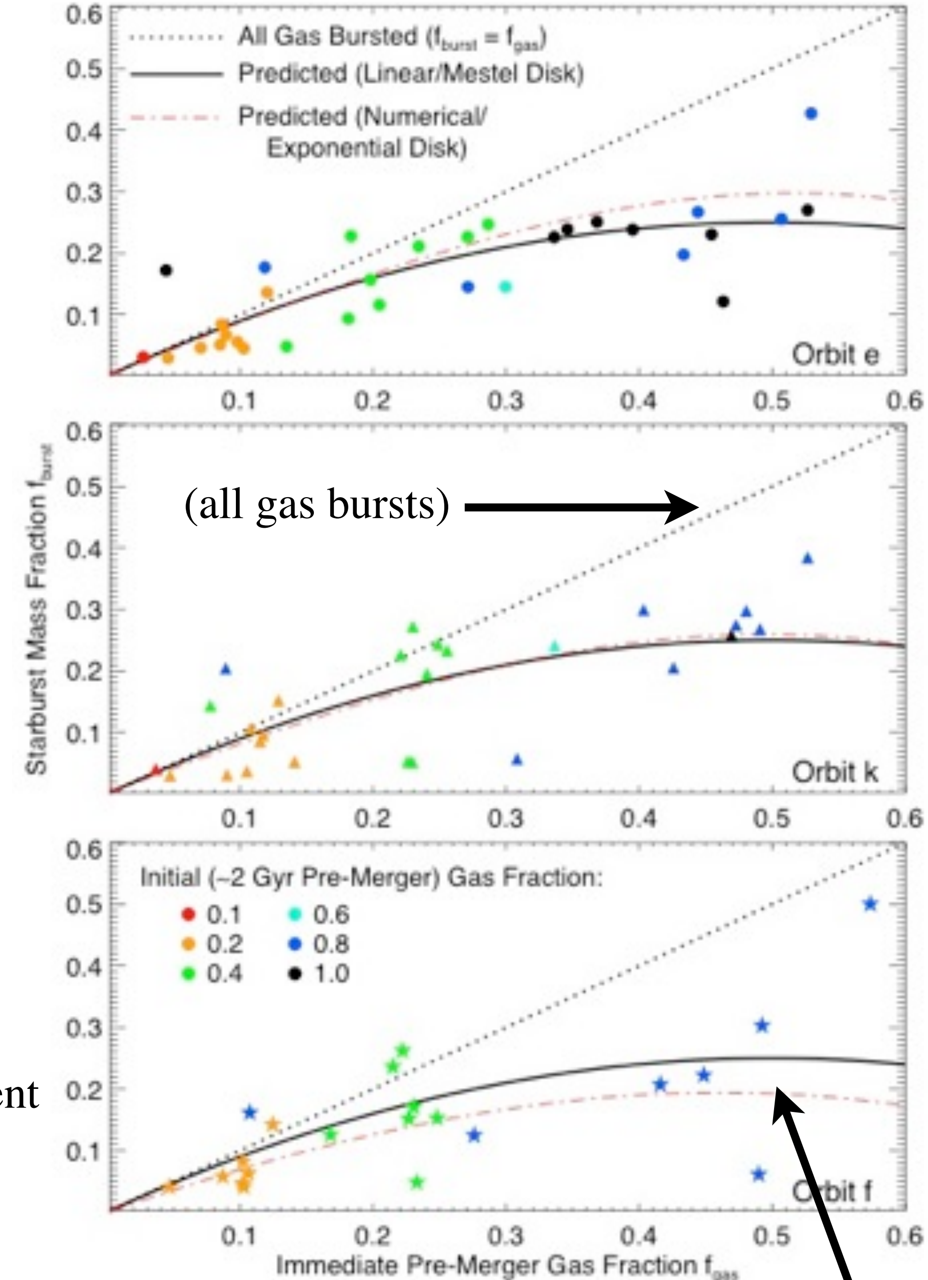
J_{gas} loss dominated by *stars* in the *same* disk

How Do Disks Survive Mergers?

Surviving Gas Disk Mass vs. f_{gas}



Burst mass vs. f_{gas}



(gas-dependent prediction)

Torque on gas:

$t \sim G\, M_{\text{stellar bar}} / dr$

for the same merger/perturbation,

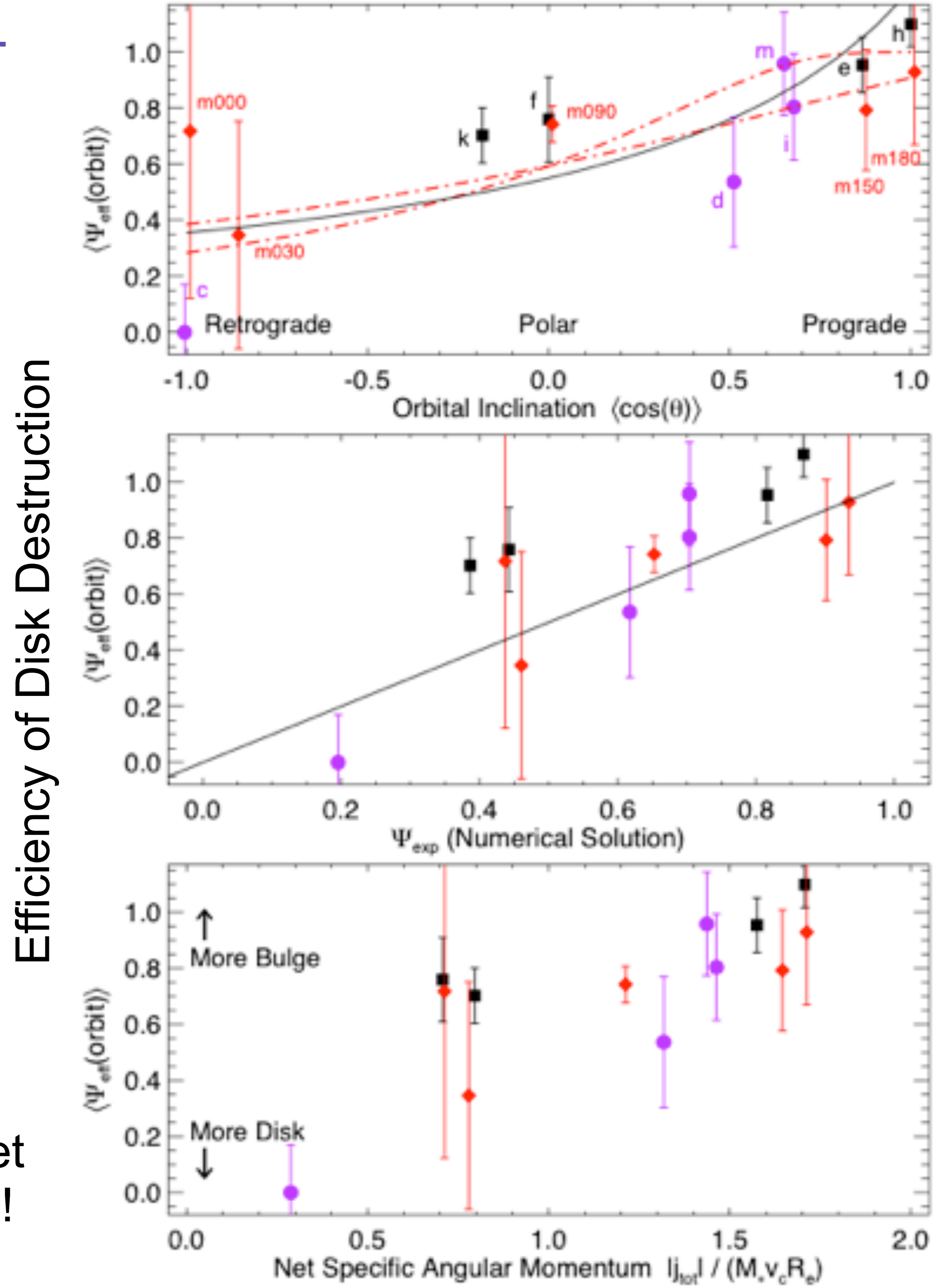
$M_{\text{stellar bar}} \propto M_{\text{stellar}} \propto (1 - f_{gas})$

How Do Disks Survive Mergers?

Can similarly calculate
dependence on orbital parameters

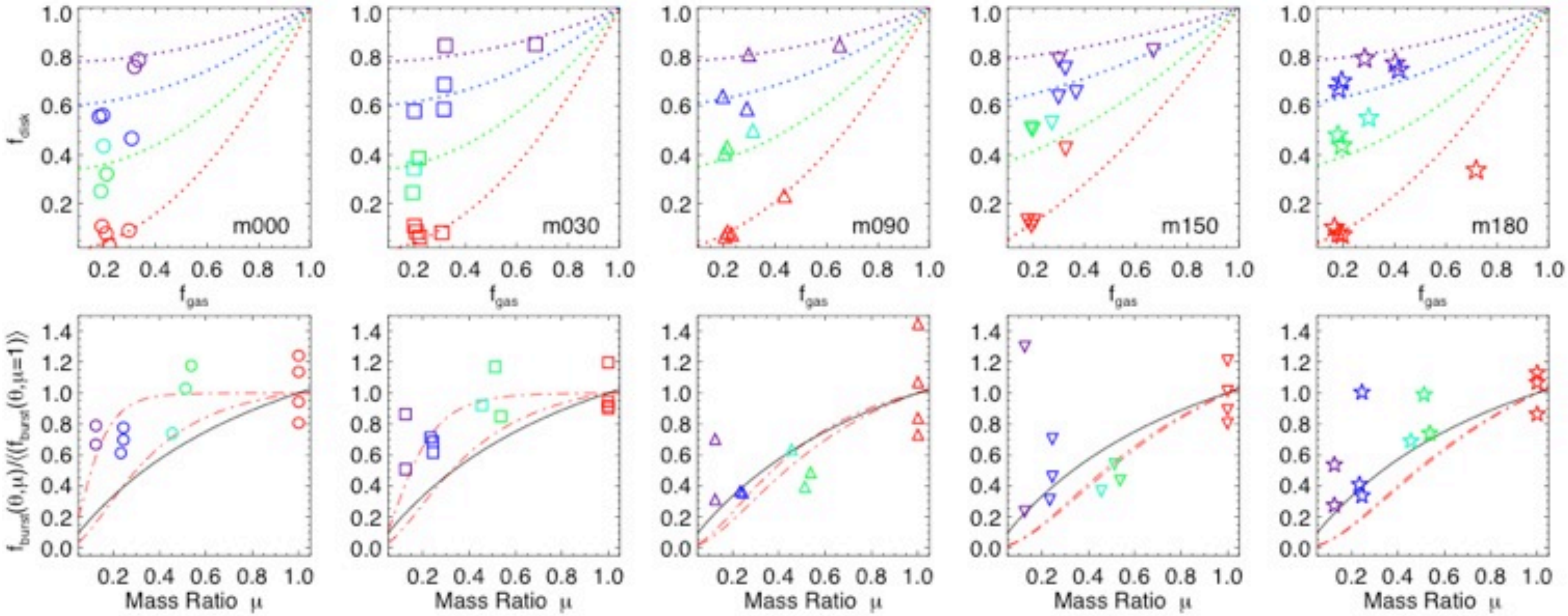
- A *driven* distortion:
  much simpler than secular

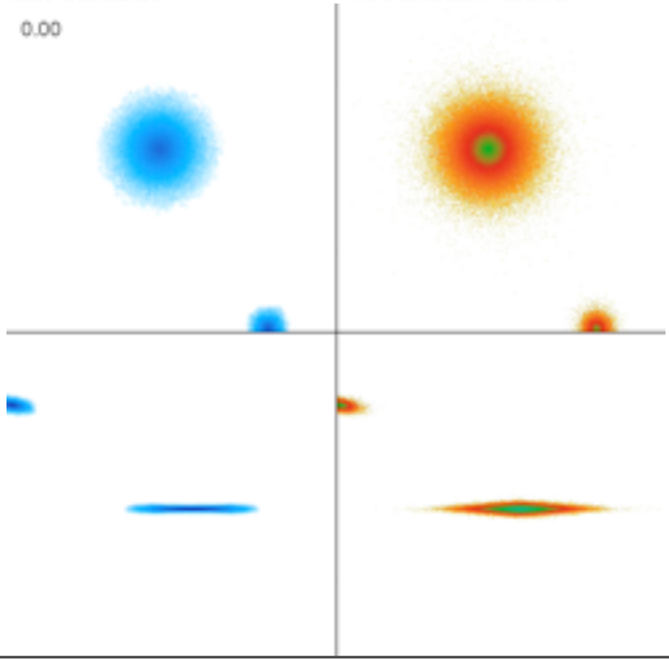
- Timescales are short:
  halo/secular exchange
  can be completely ignored



Nothing to do with net
angular momentum!

How Do Disks Survive Mergers?





Likewise, versus mass ratio μ

- To lowest order, magnitude of everything (fraction of disk destroyed) $\propto \mu$

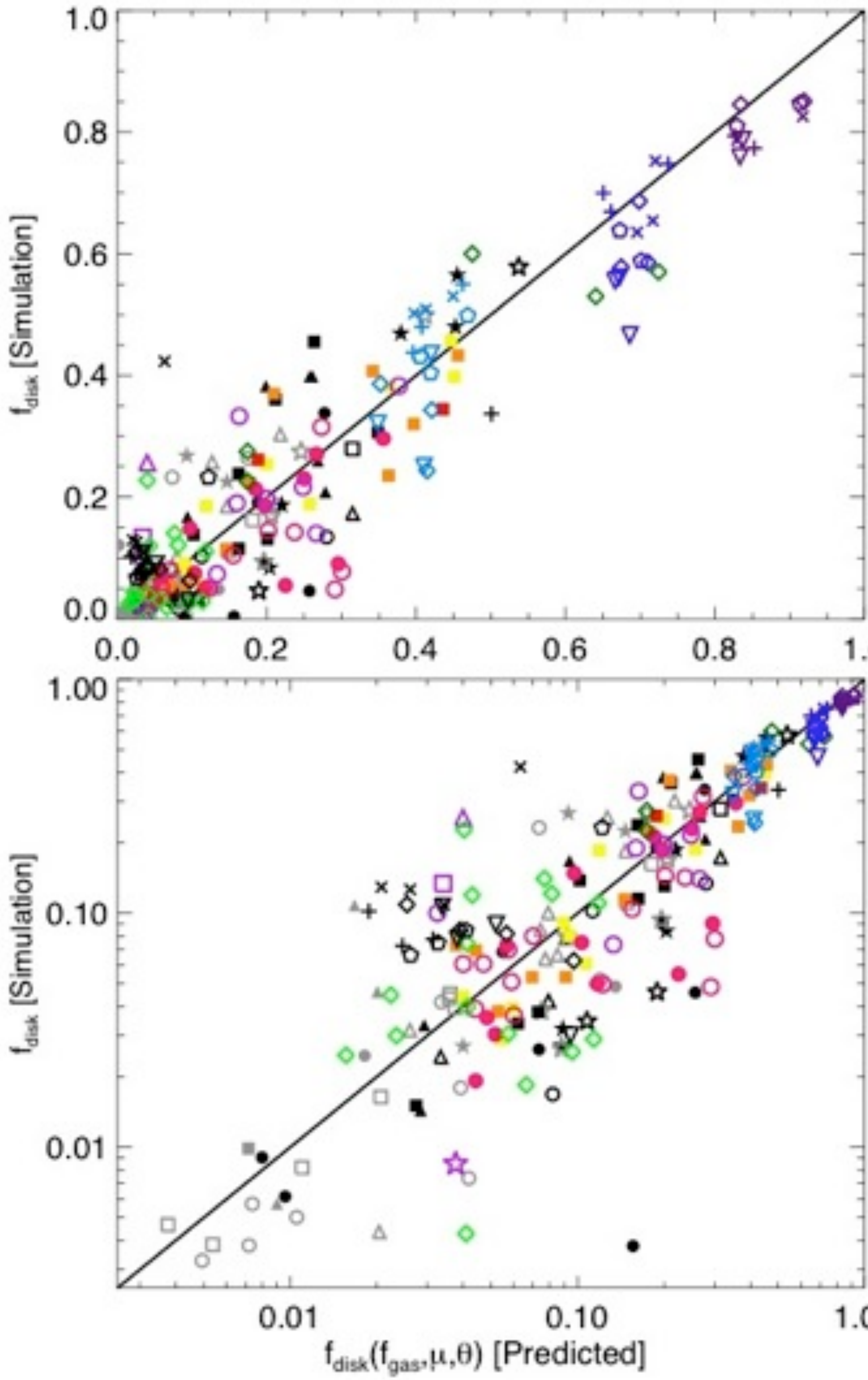
How Do Disks Survive Mergers?

THE PUNCHLINE

Derive:

Gas angular momentum loss/starburst mass
Surviving gas disk fraction
Violently relaxed fraction of stellar disk

$$= F(f_{gas},\ \mu,\ \theta_{orbit})$$



Works varying:
- Baryonic/halo mass
- Redshift
- BH properties (presence, mass, feedback)
- Galaxy concentrations/initial B-T/sizes
- Mass ratio, orbital parameters, gas fraction
- Stellar feedback

Purely gravitational process:

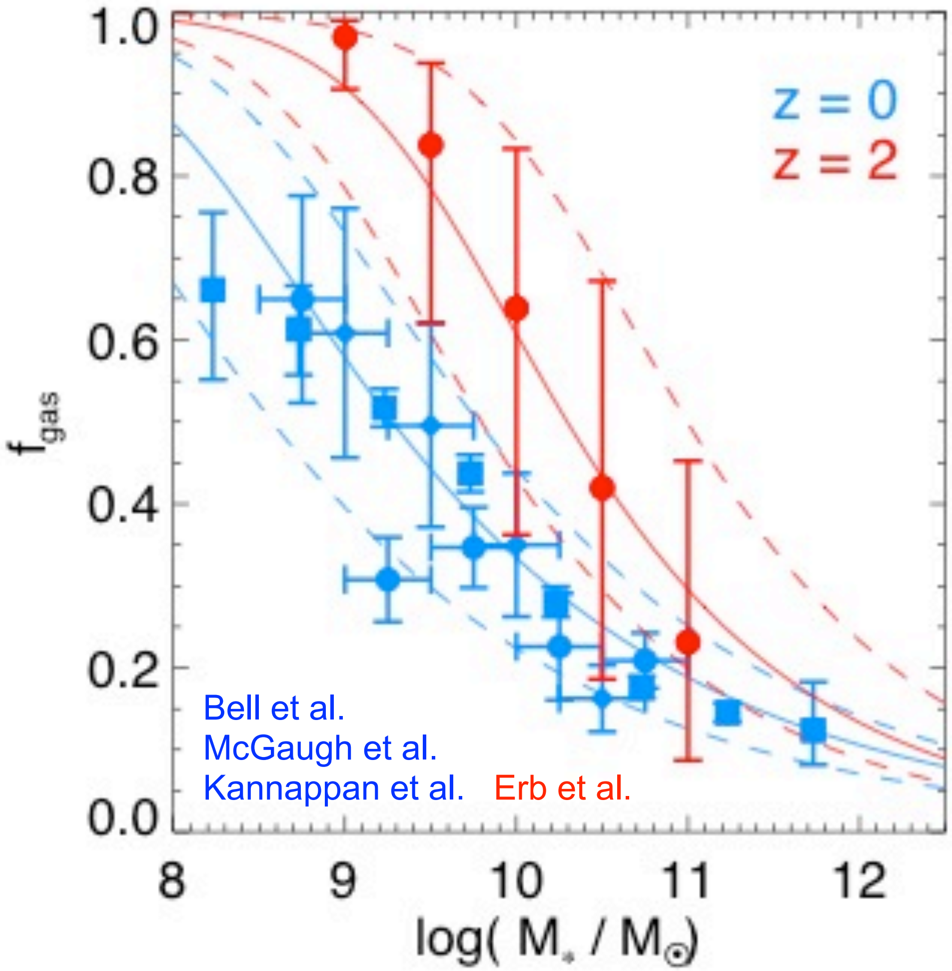
Independent of feedback

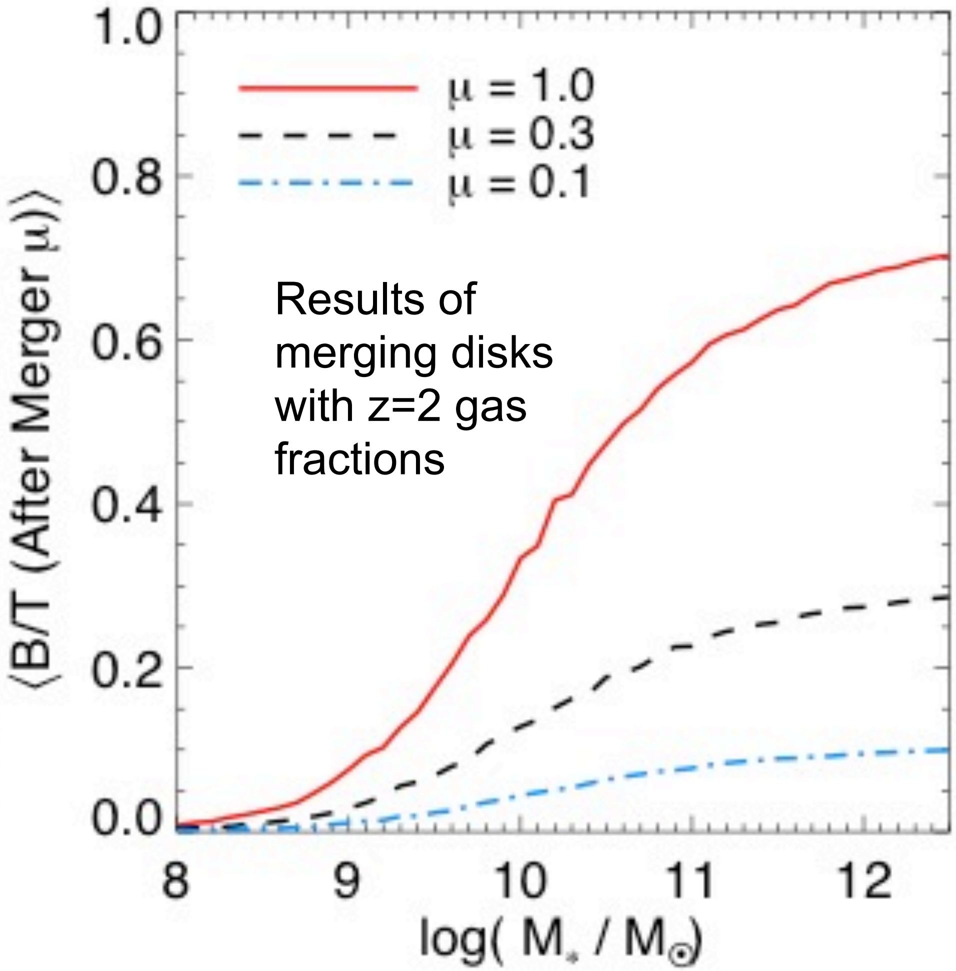
Must happen

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

- Fold this into a cosmological model: why do we care?





- Low-mass galaxies have high gas fractions: less B/T for the same mergers

Why Do We Care?

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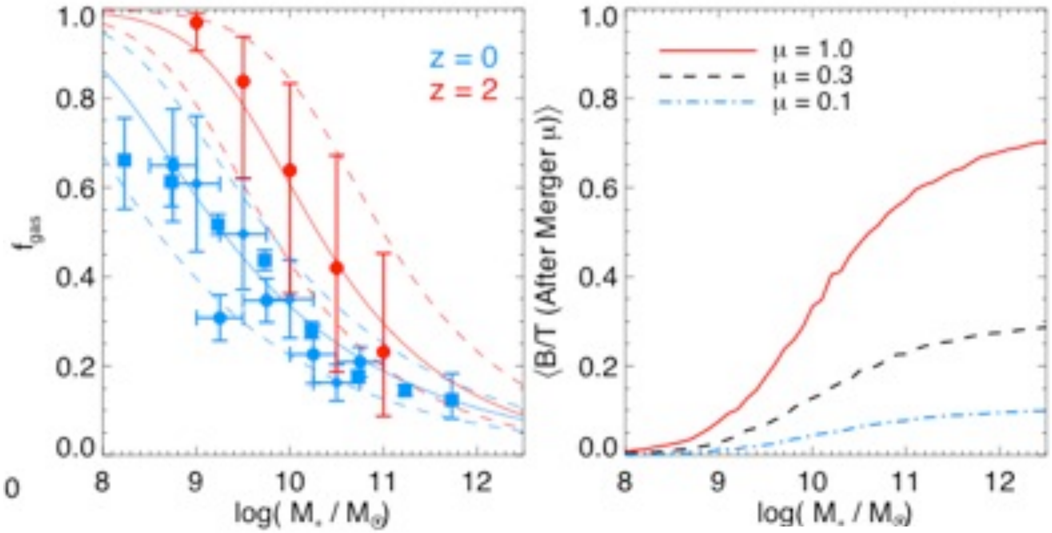

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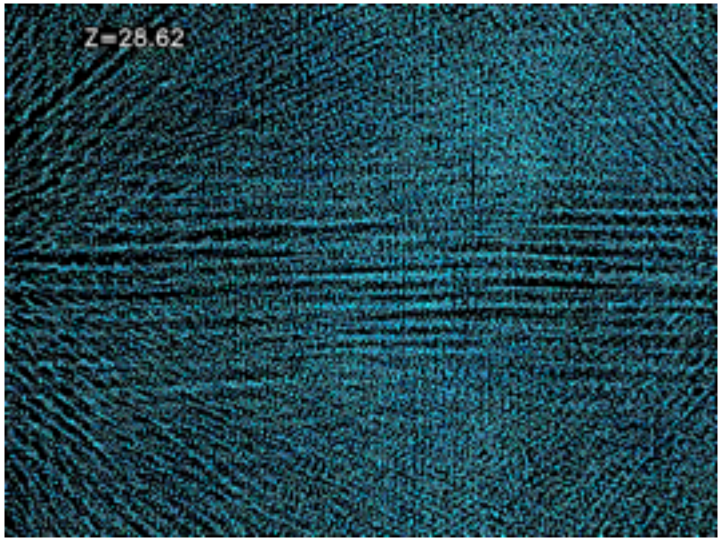

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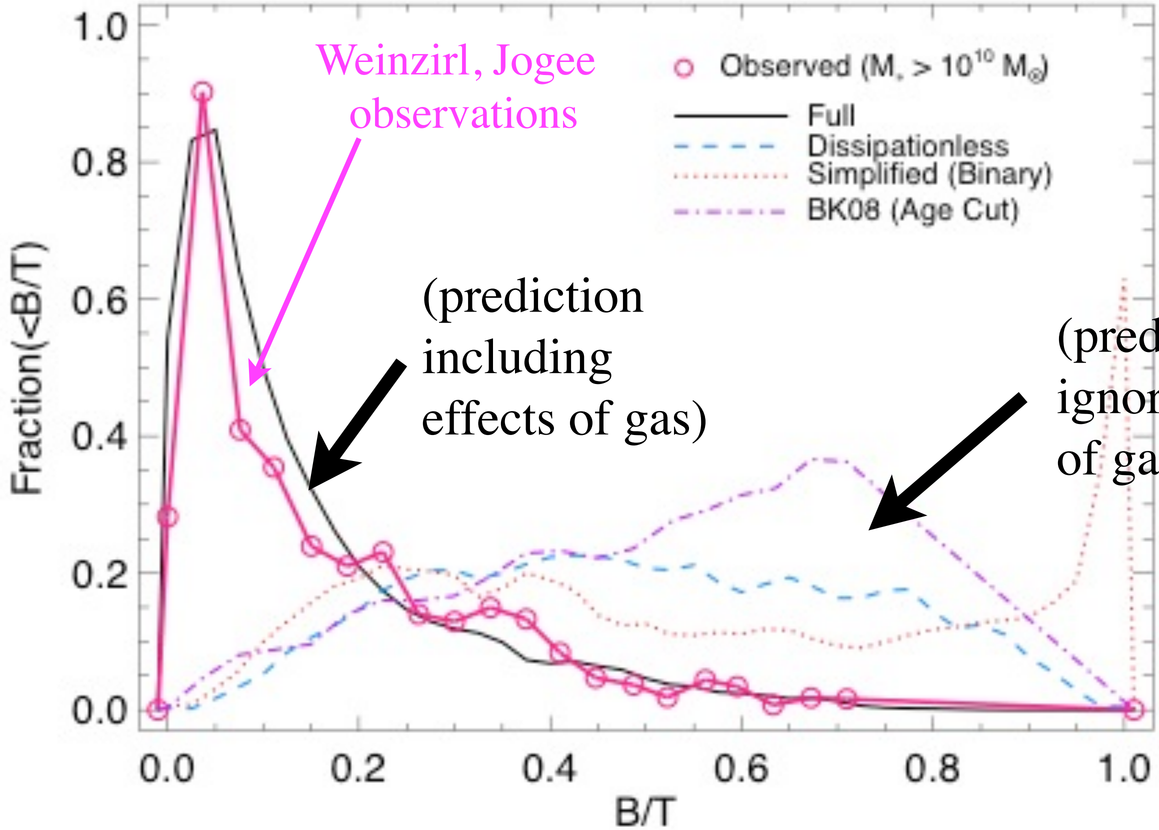

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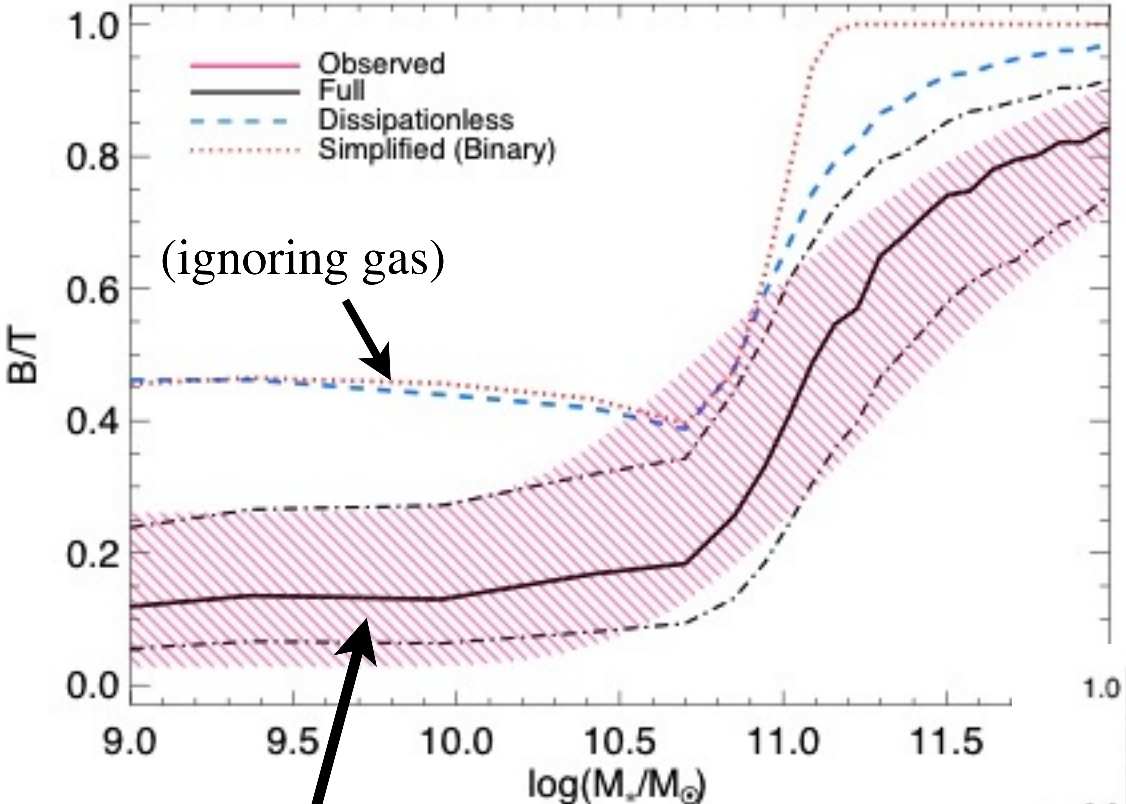
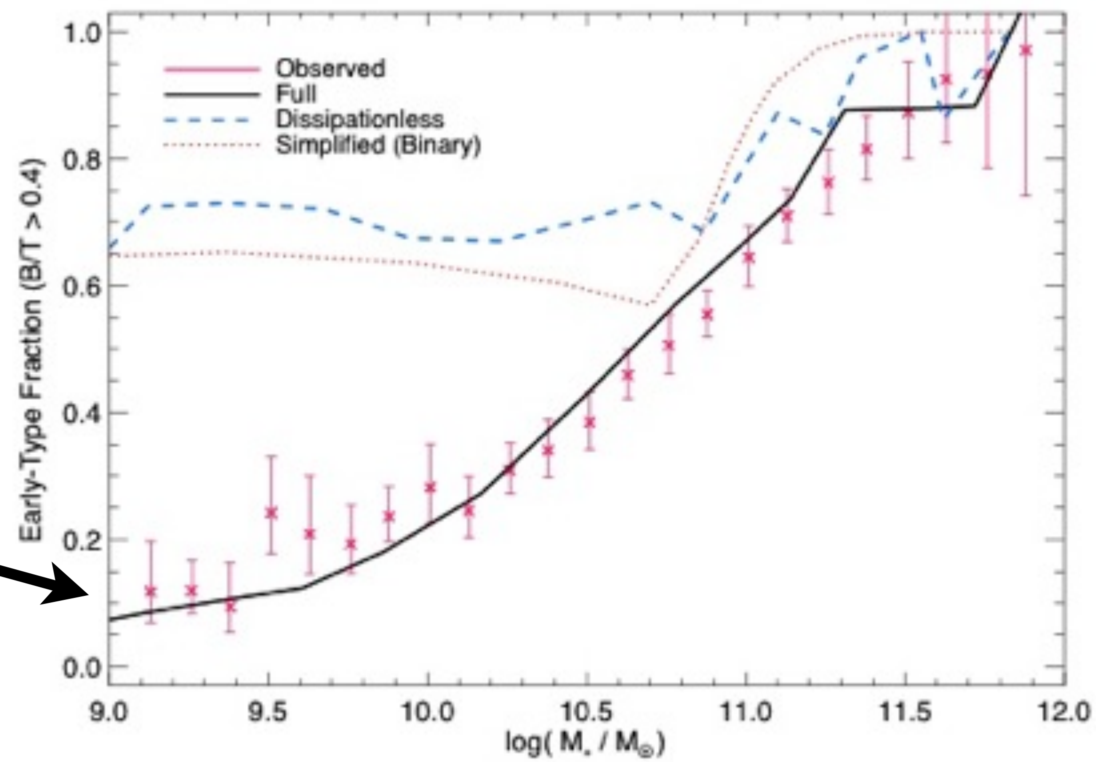


(ignoring gas)

(including effects of gas)



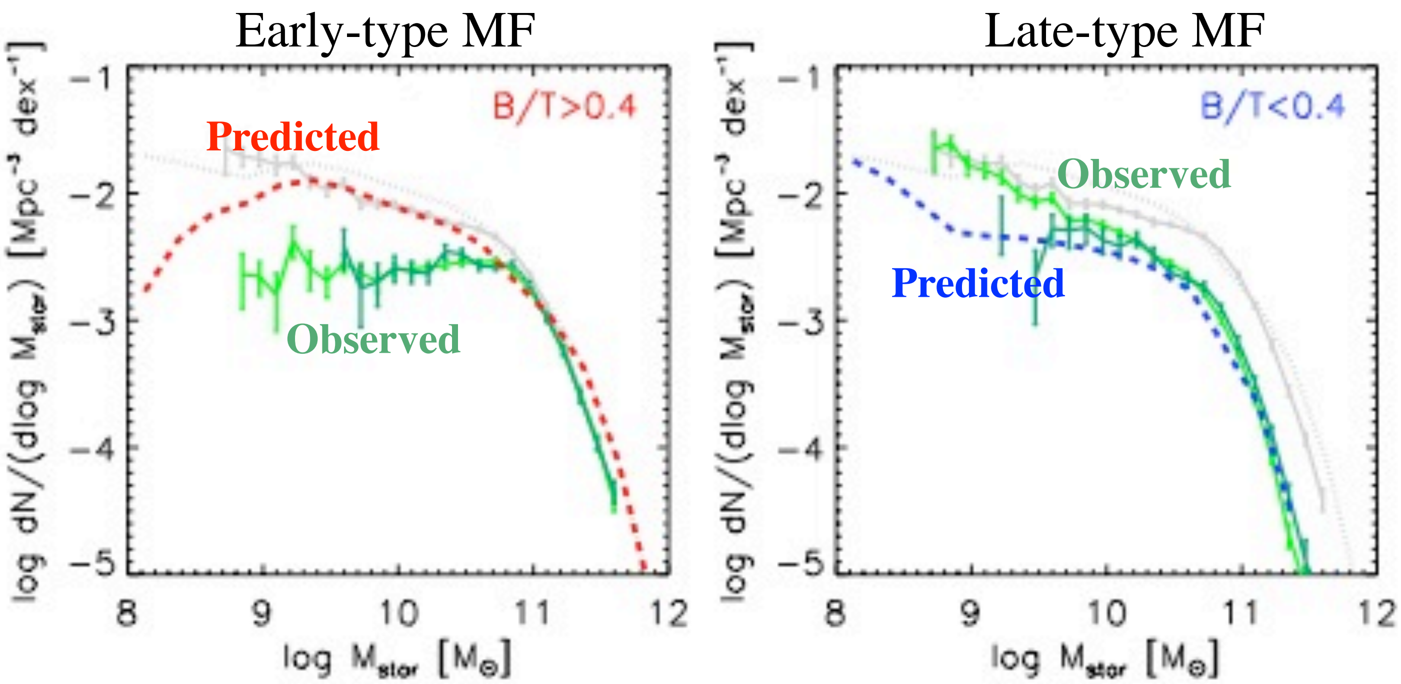
- Morphology-mass relation:
  - NOT possible to obtain with just dependence of merger history on mass/environment
    - (Stewart, Khochfar talks)
  - Natural consequence of f_{gas}-mass

(Discrepancy between gas-blind models and observations grows at z=1, as merger rates rise)

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

Gas-blind models:



Somerville, Croton, Bower+ SAMs; alternative HOD models:

Hundreds/thousands of model runs with ~10-20 free parameters each: always overproduce low-mass bulge-dominated population

Why Do We Care?

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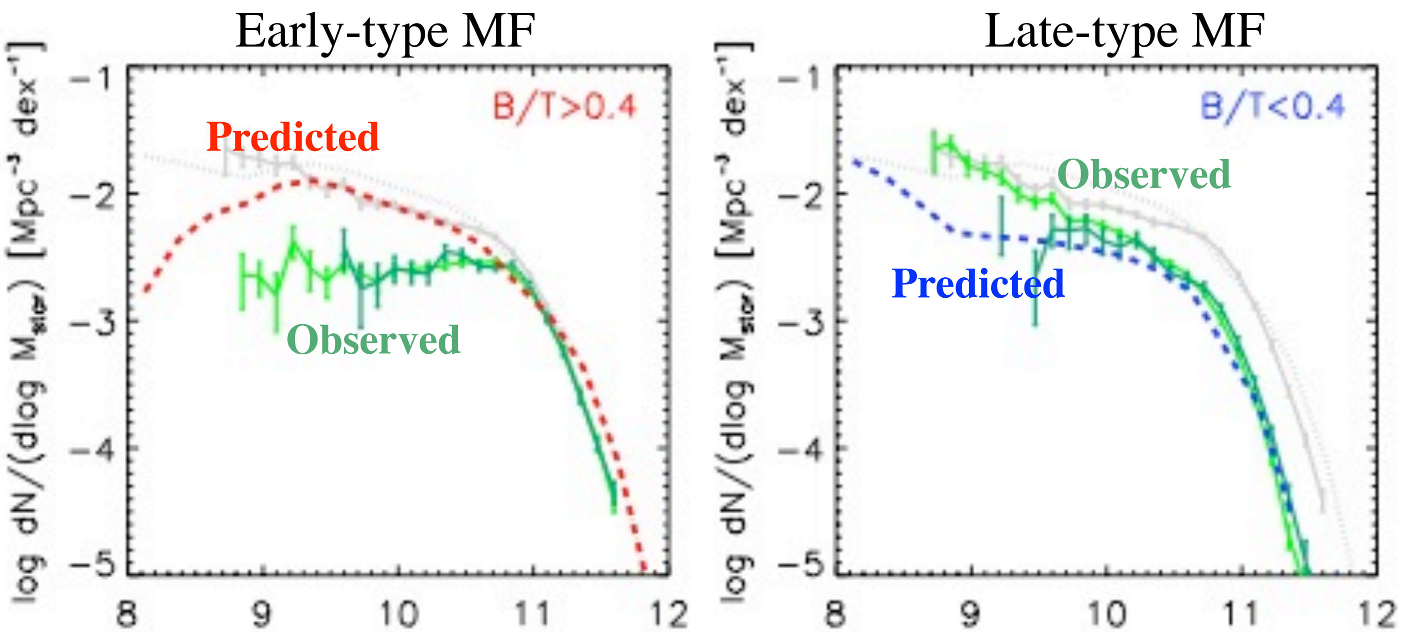
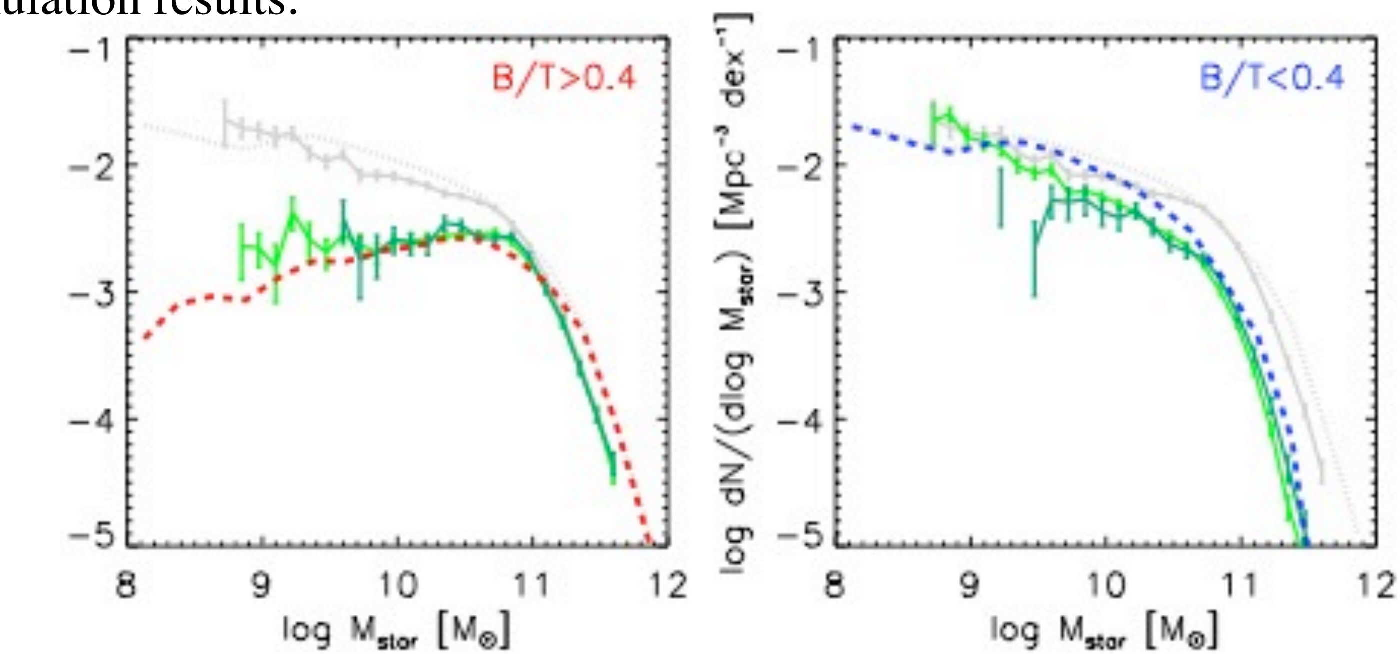
Gas-blind models:



Exact same model, adding f_{gas}-dependent simulation results:



Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

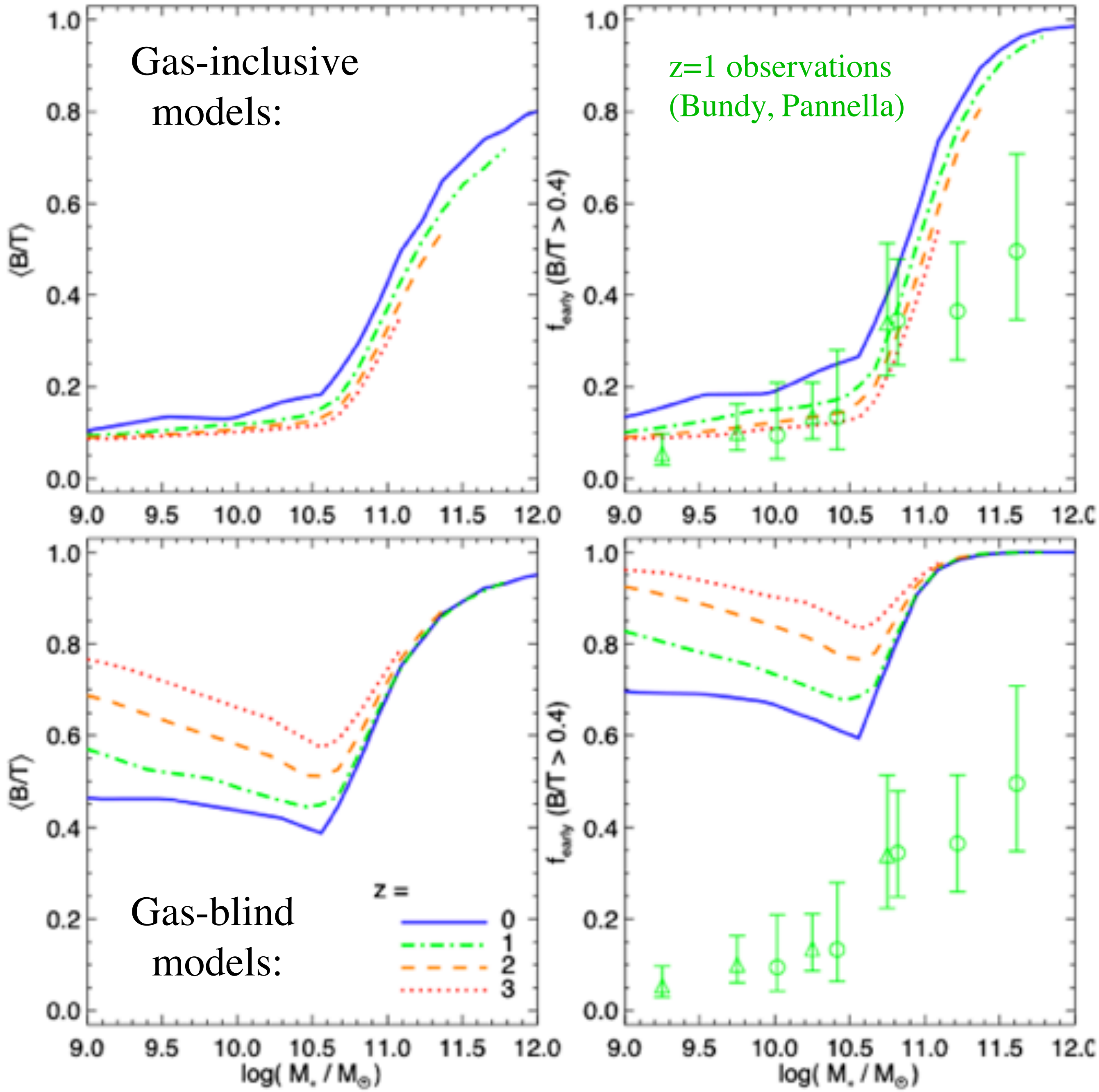
Weak evolution:

Makes existence of high-z disks much easier

Disks could form (at least some mass) earlier than z=1

May be seeing this at high redshift:

- Hammer talk
- Robertson & Bullock ’08
- Shapiro talk (turbulent, low V/σ disks)



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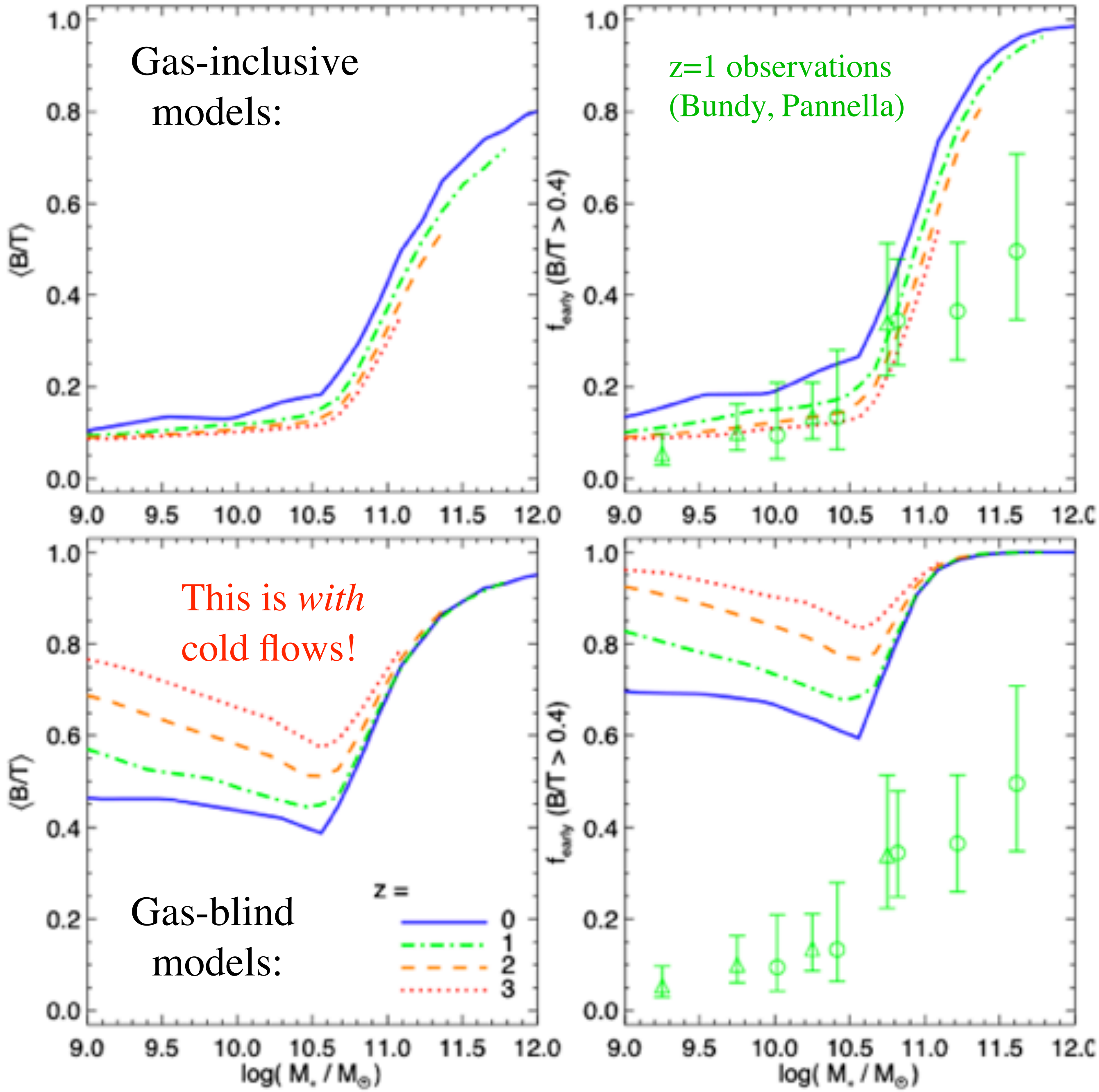

Disk Survival In Mergers

HOW CAN A DISK SURVIVE?

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    - And stars are collisionless

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      - This *will* happen

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- If gas fractions are anything close to what observers tell us...

Disk Survival In Mergers

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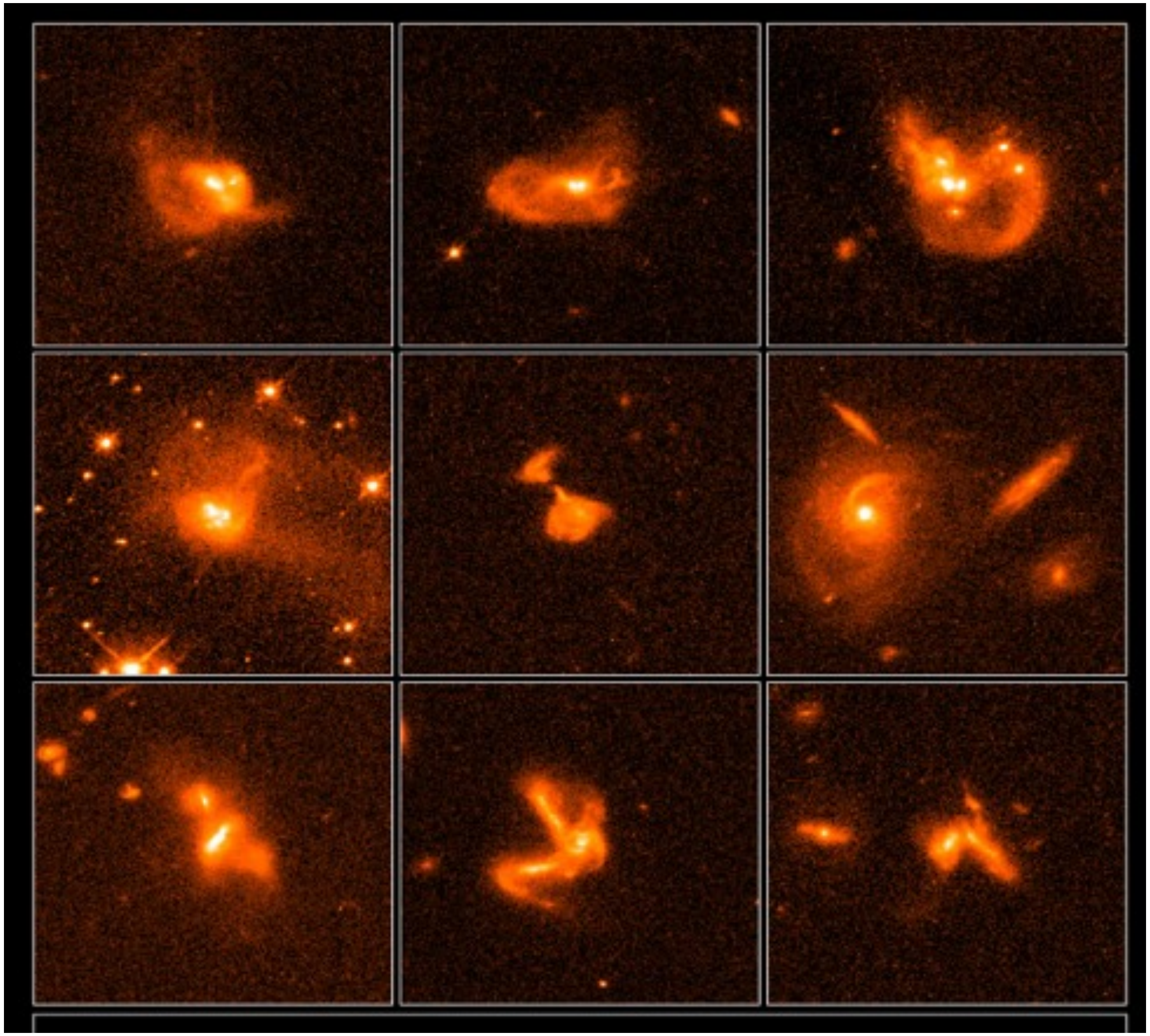
- The efficiency of disk destruction/bulge formation scales inversely with gas content
  - This is a purely gravitational process:
    - If gas is collisional
    - And stars are collisionless
    - And we understand gravity
      - This *will* happen
- If gas fractions are anything close to what observers tell us...
  - This *is* very important for bulge formation

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

Borne et al., 2000



Funneled to the center
-> massive starbursts

Look at late-stage
merger remnants

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

Compact (<kpc scales)

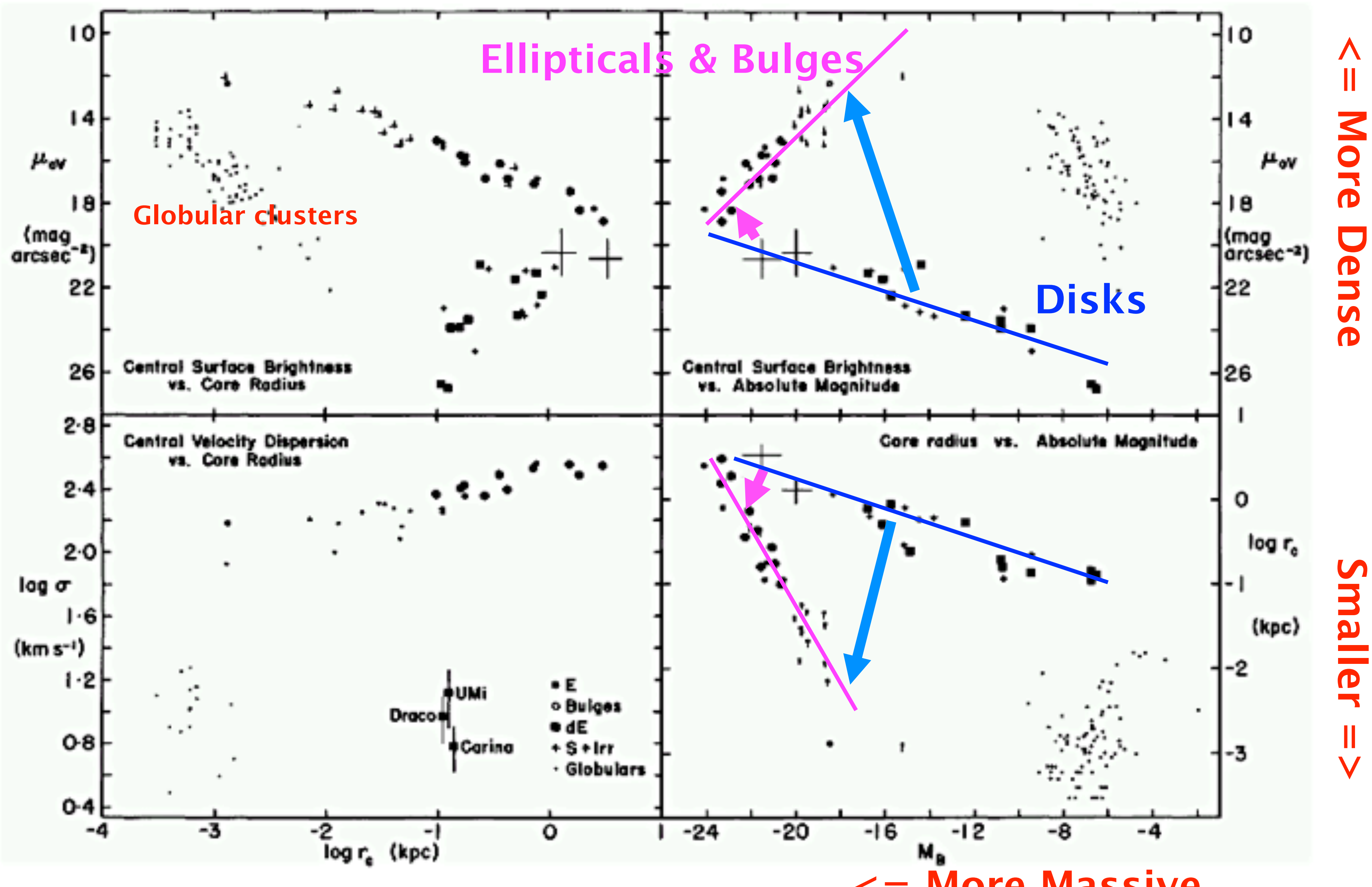
Most luminous starbursts in the Universe:
are they the progenitors of ellipticals?

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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

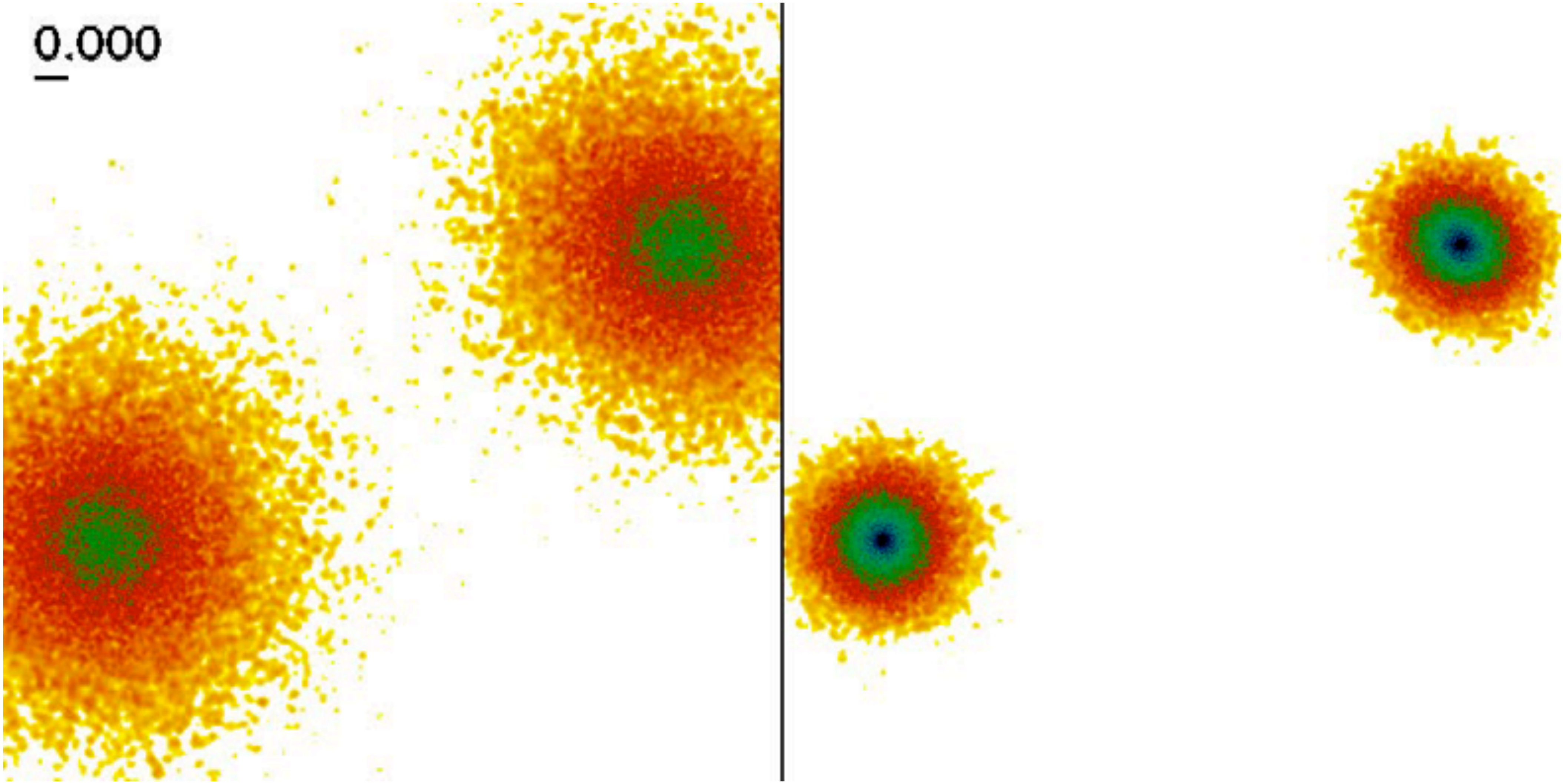
Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

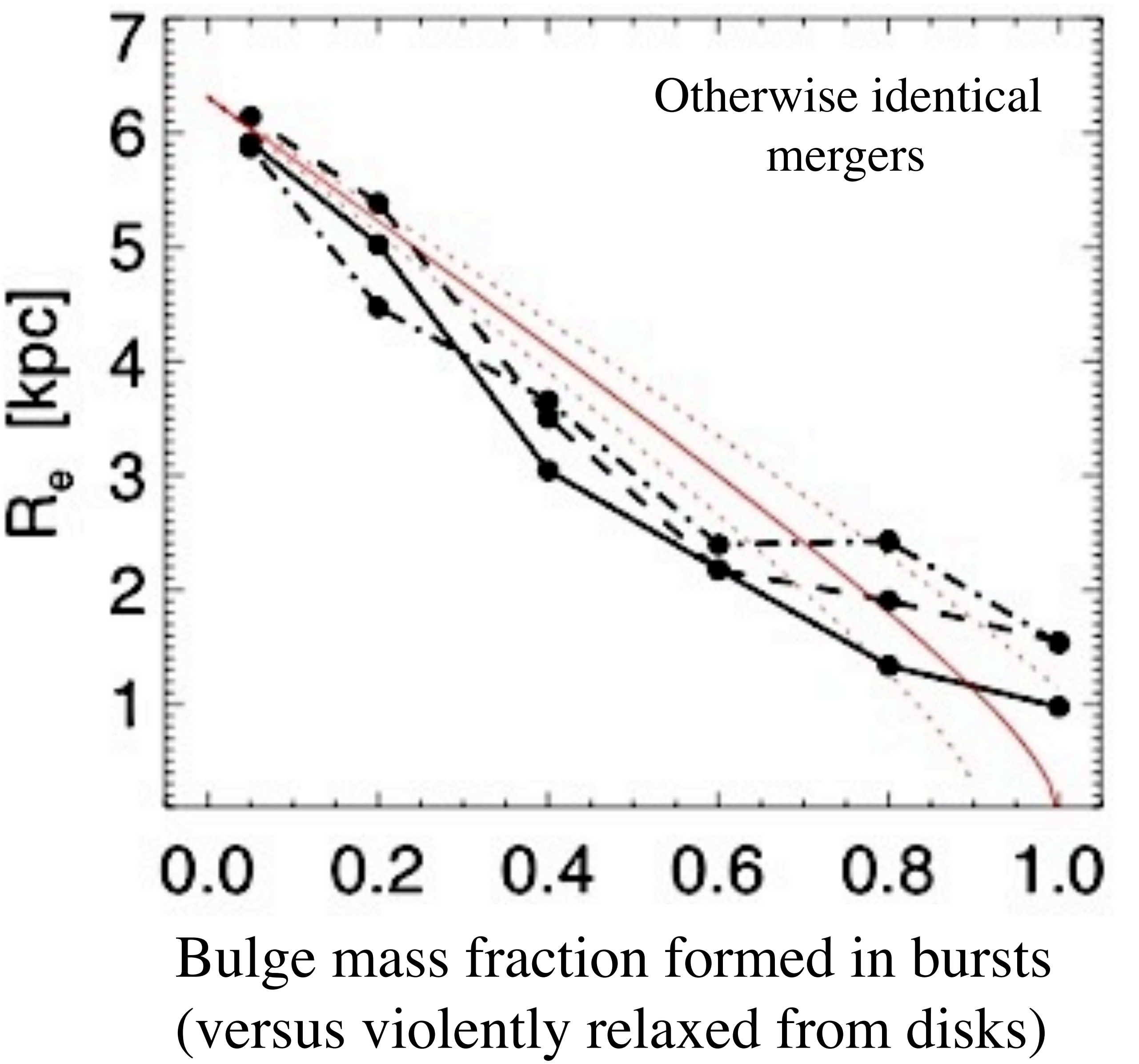
- Why are ellipticals so much smaller than disks?
  Gas dissipation allows them to collapse to small scales!



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

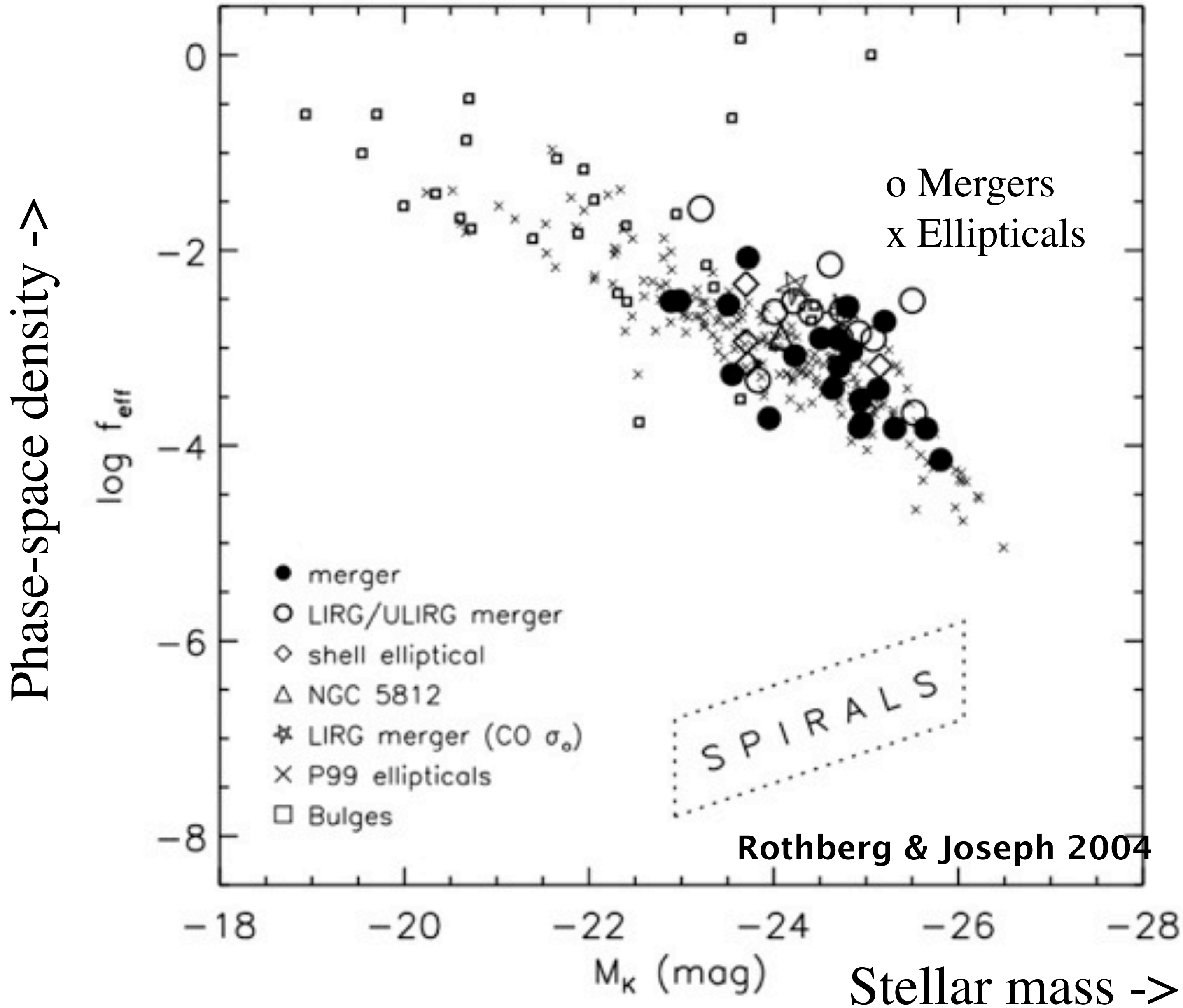
- Increased dissipation→smaller, more compact remnants (Cox; Robertson; Khochfar; Naab)



The Solution: Gas Dissipation?

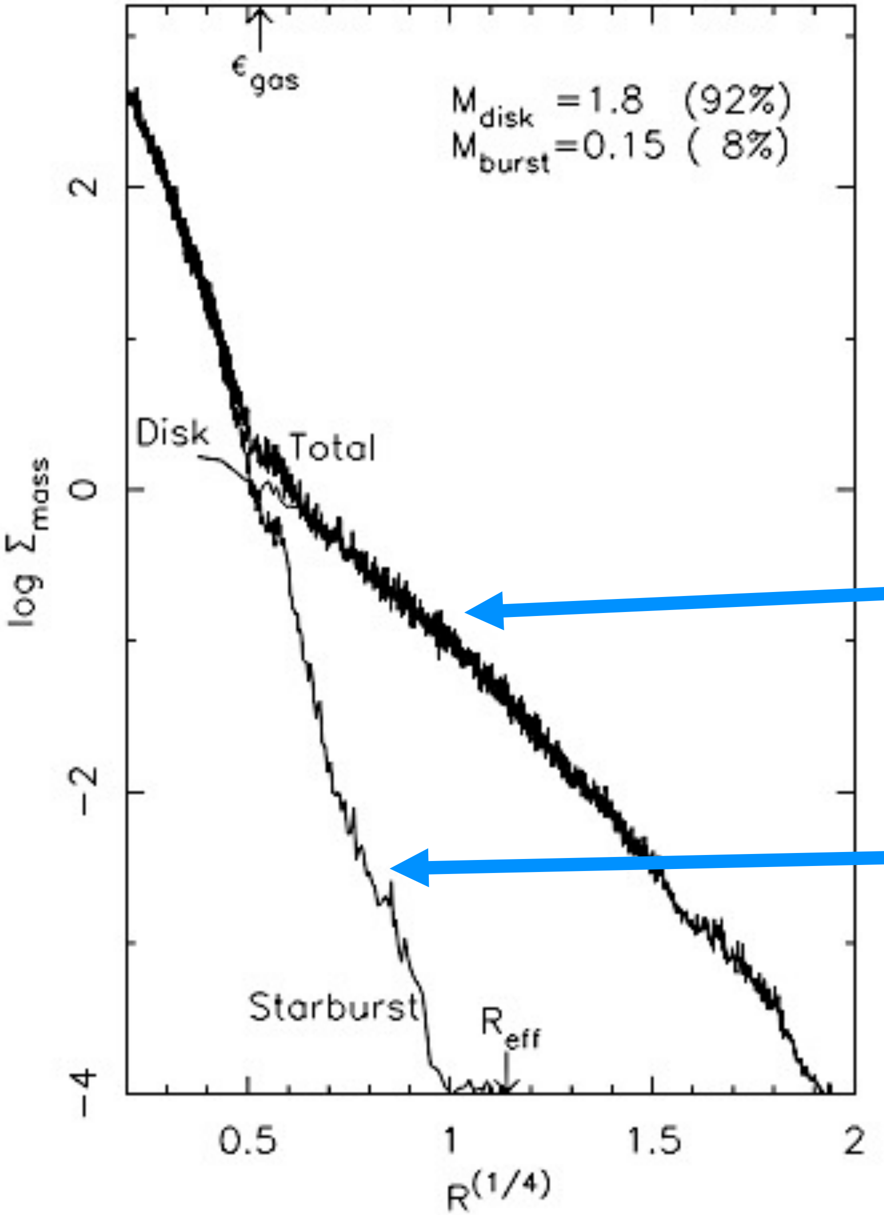
COMPARE WITH OBSERVED RECENT GAS-RICH MERGER REMNANTS

- 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



Mihos & Hernquist 1994:

Merger remnant elliptical profiles should be fundamentally two-component:

Pre-starburst/Disk (dissipationless, violently relaxed)

Starburst (dissipational, no strong violent relaxation)

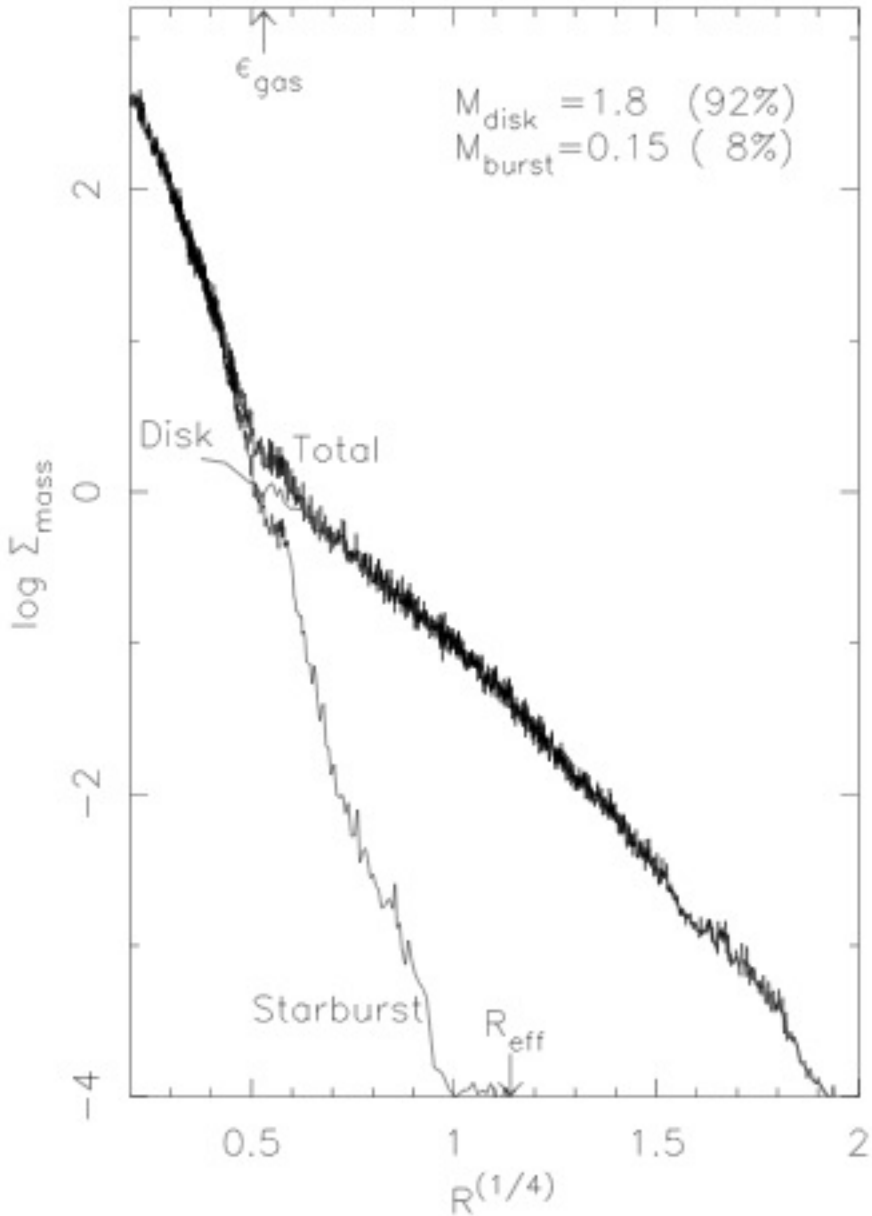
Not observed at the time:

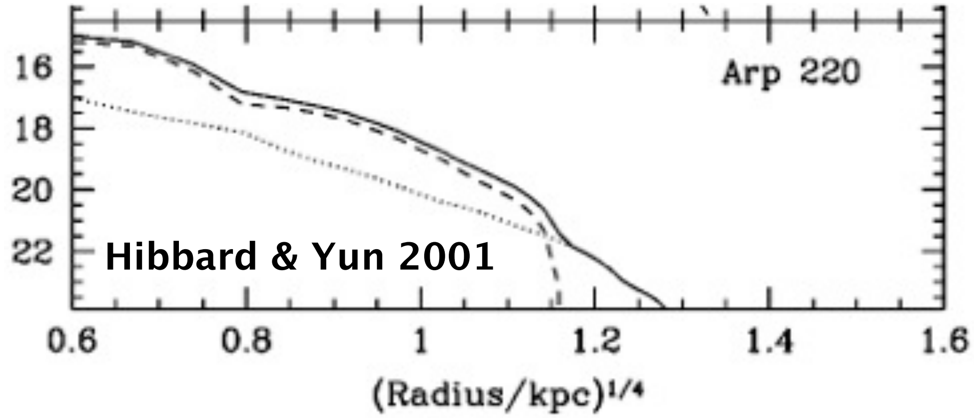
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

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

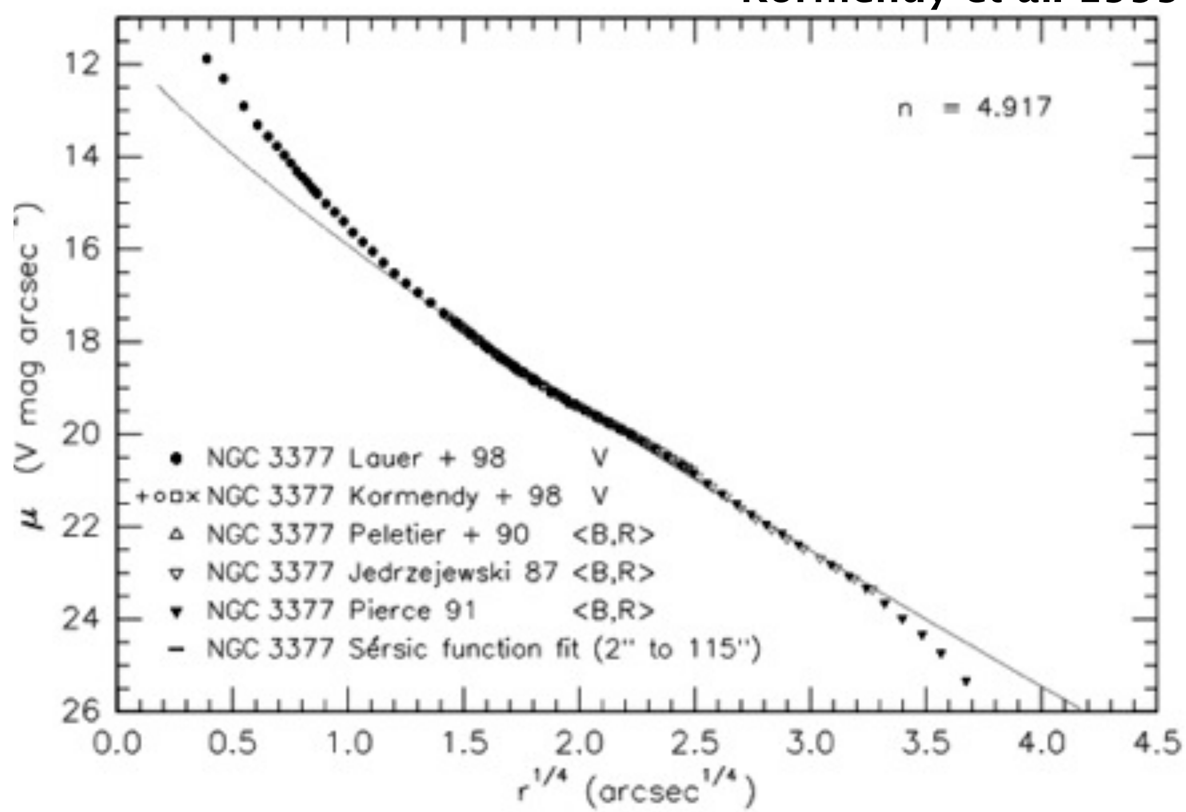
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...





Kormendy et al. 1999



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RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

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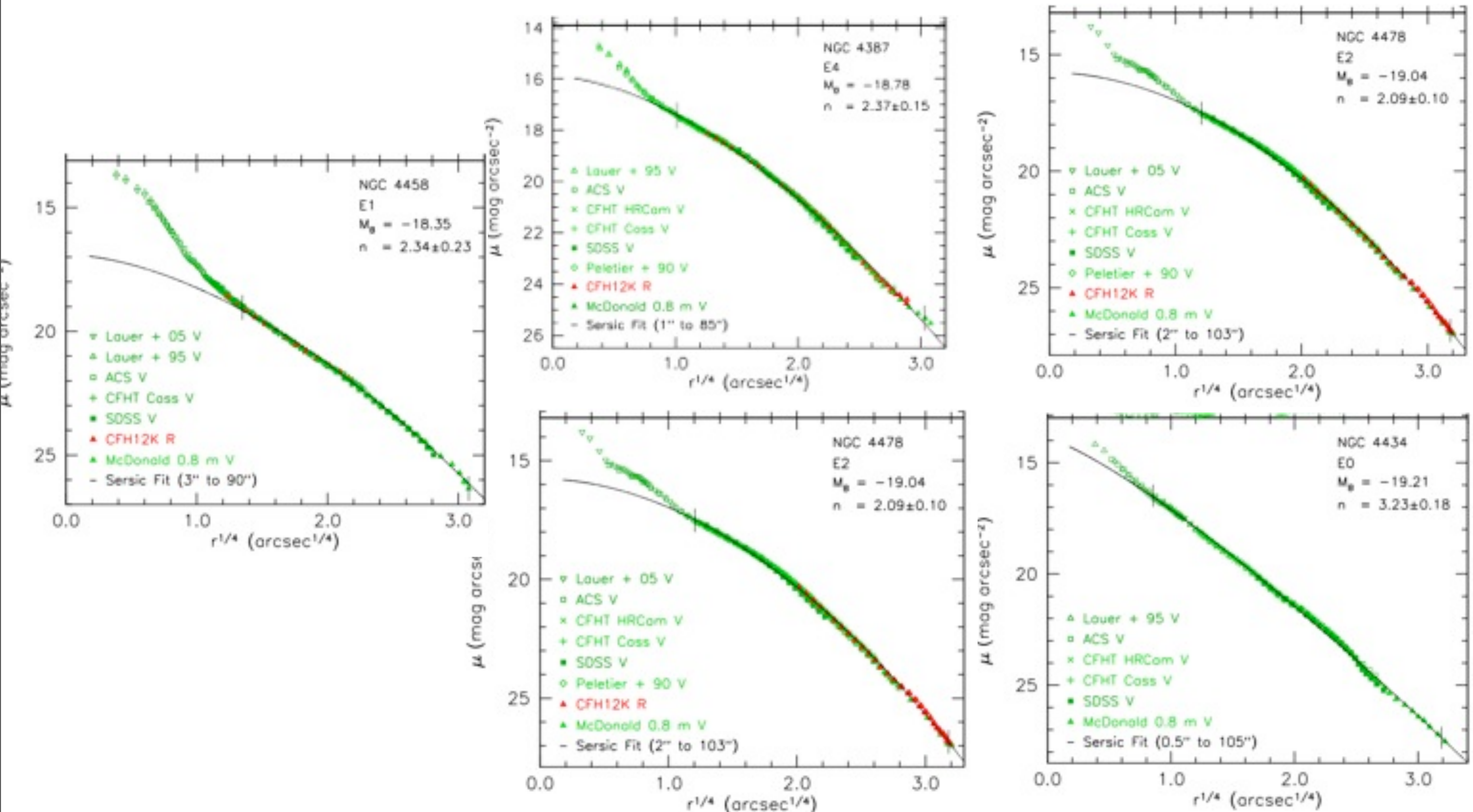
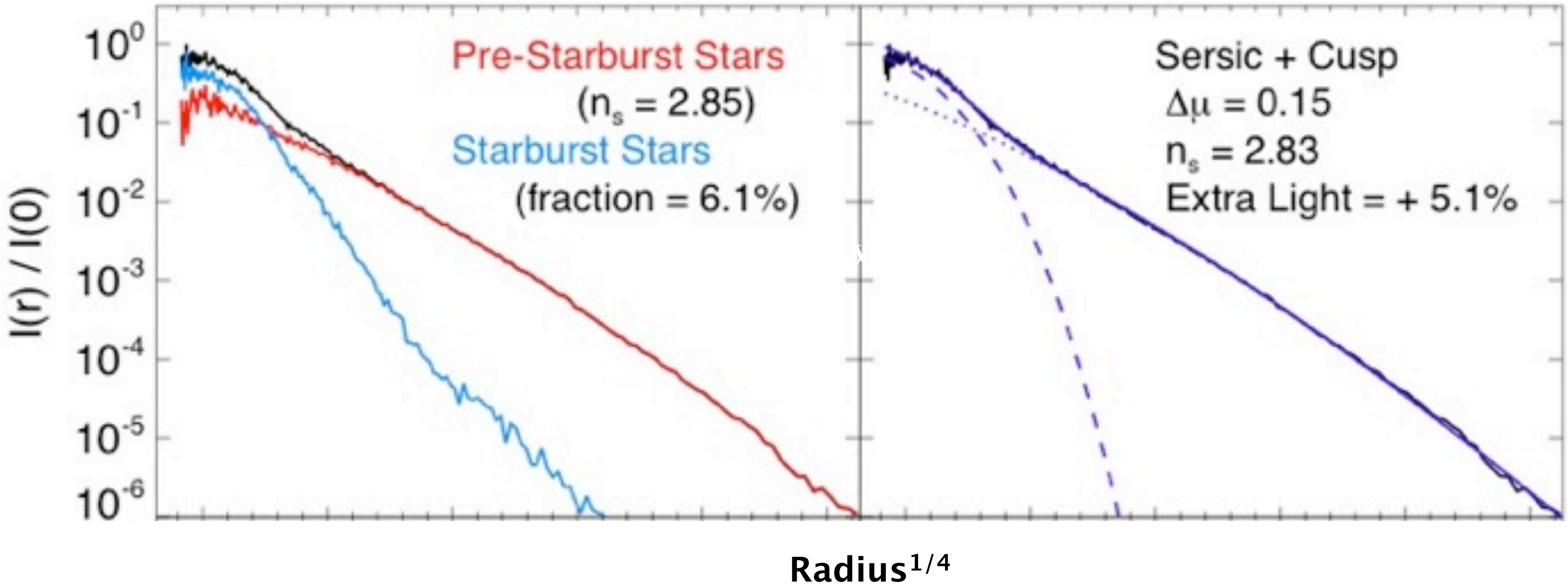
Kormendy et al. 2008



“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?



Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

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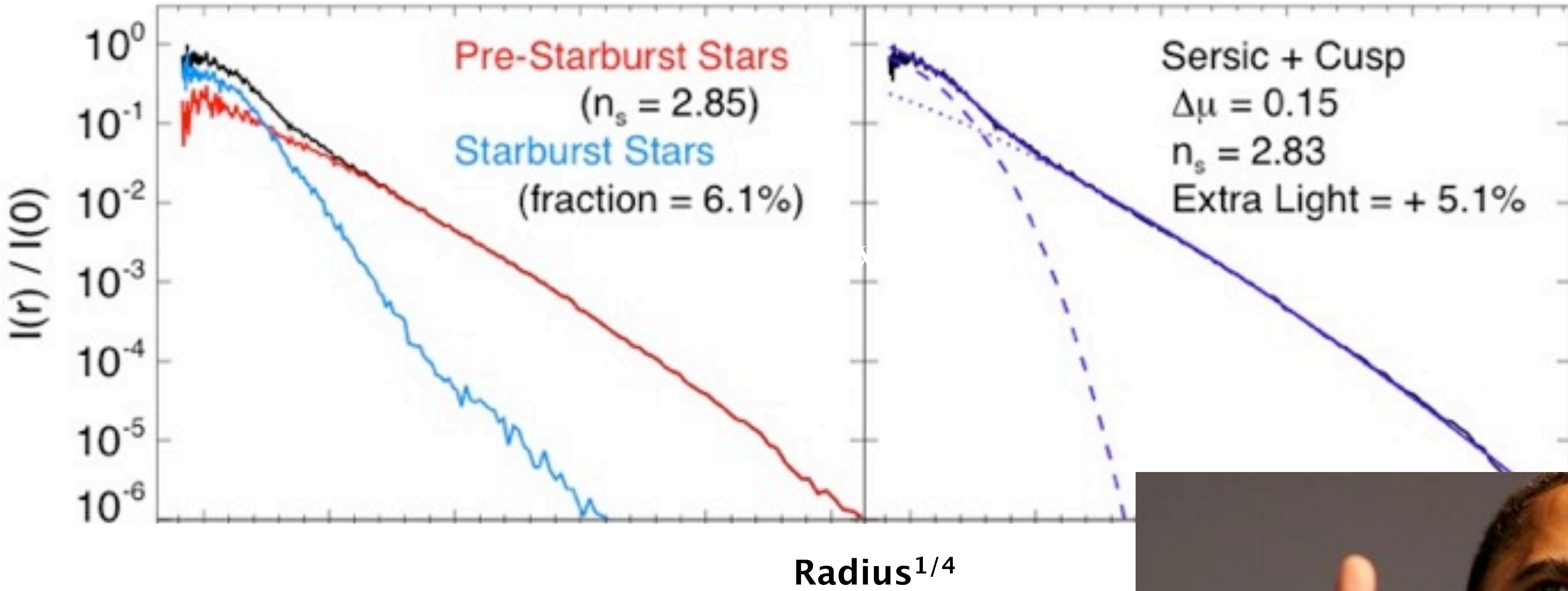
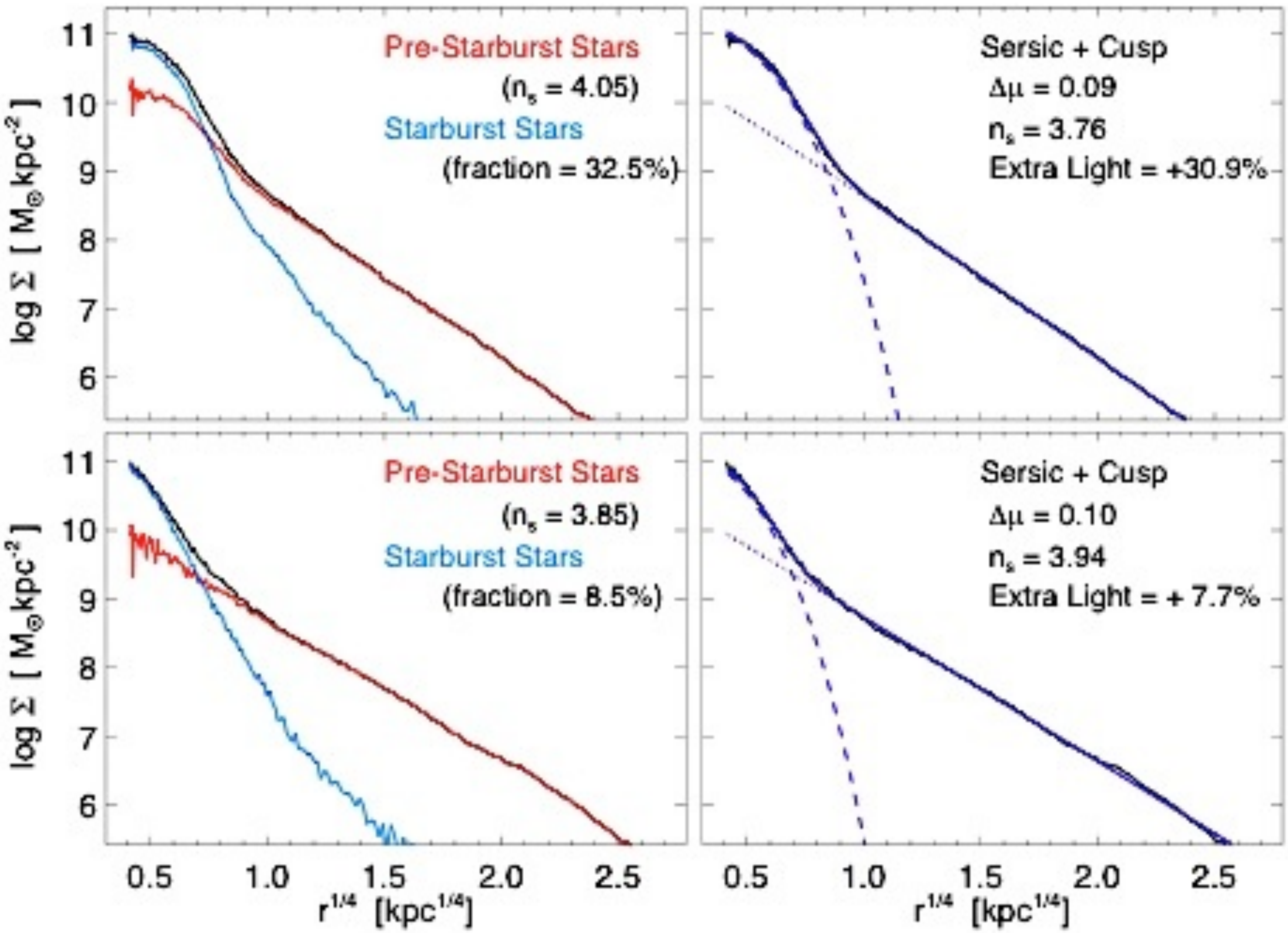


A: Yes we can

(Kormendy talk; Balcells talk)

Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



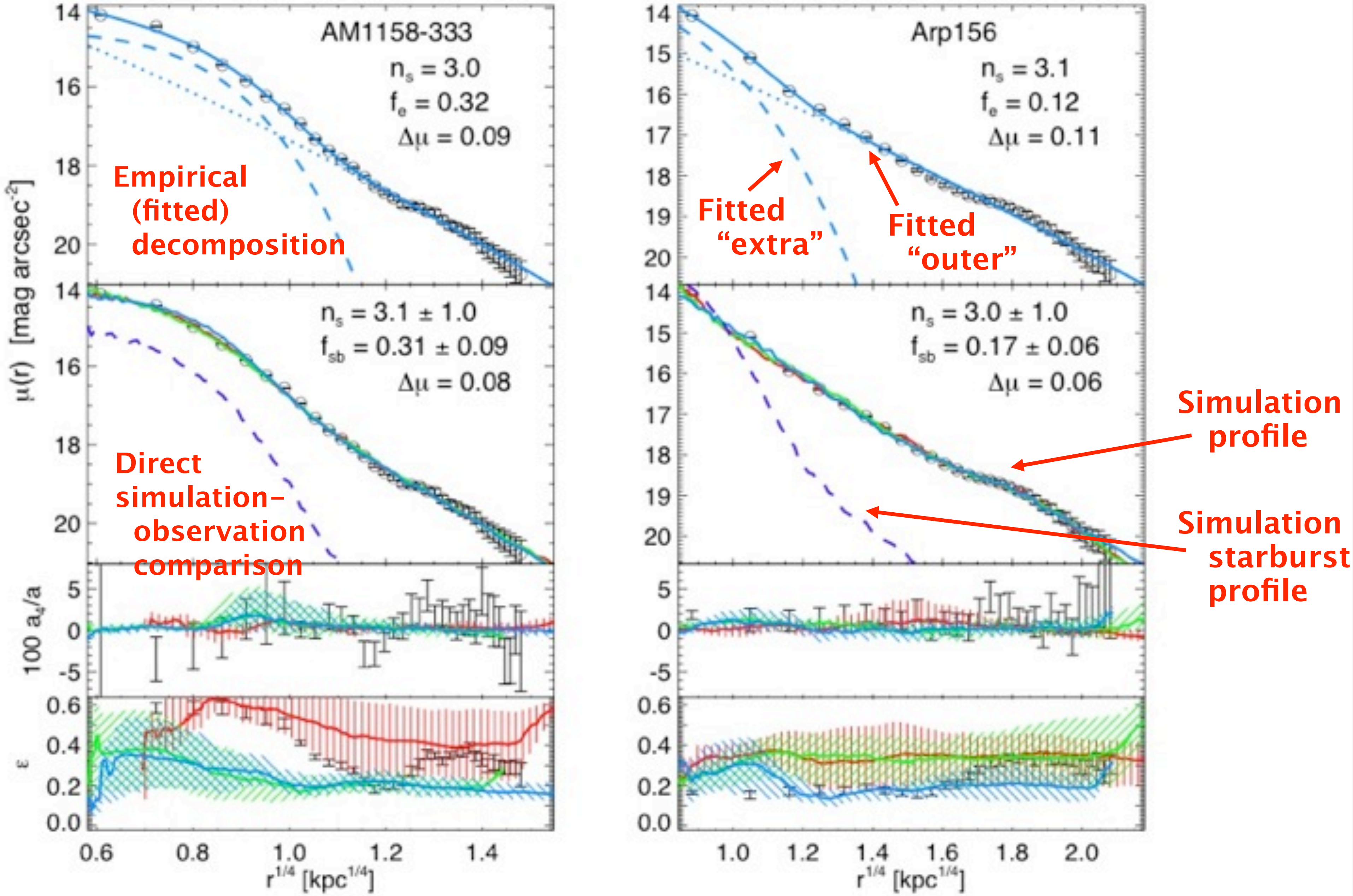
Application: Merger Remnants

RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

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



Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

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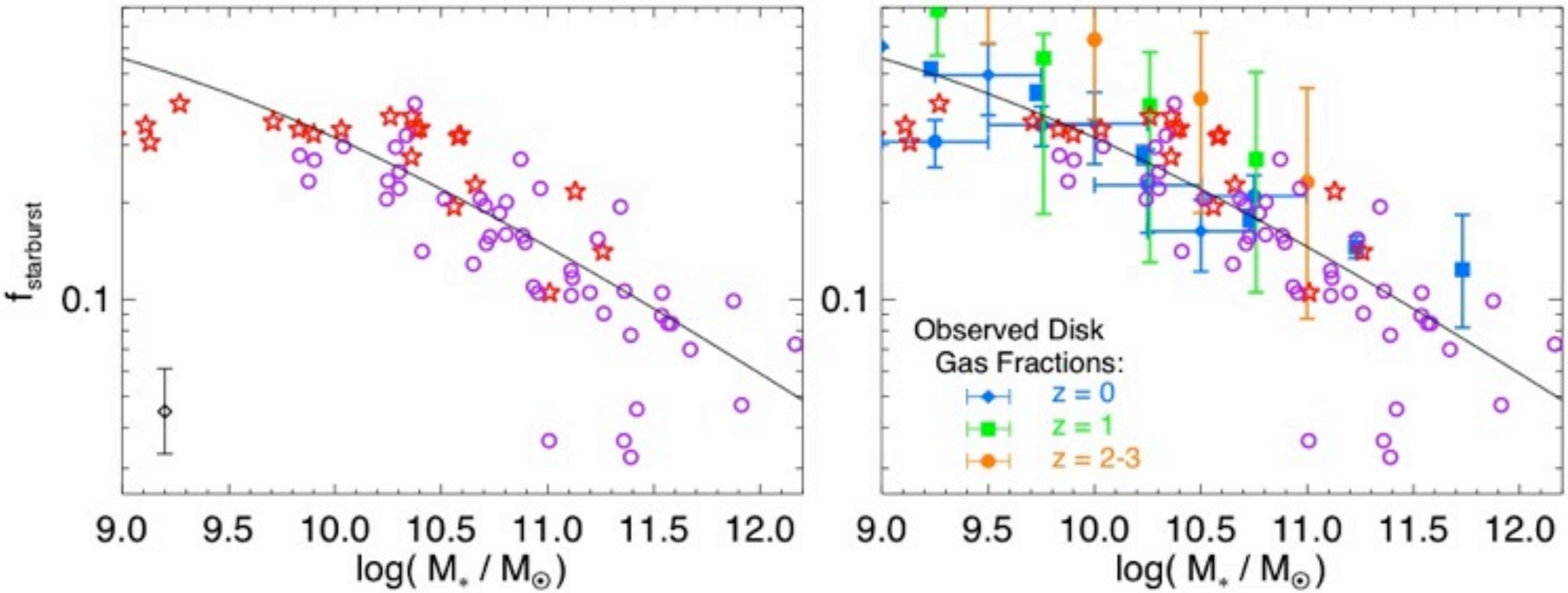
Starburst gas mass needed to match observed profile (or fitted to profile shape):

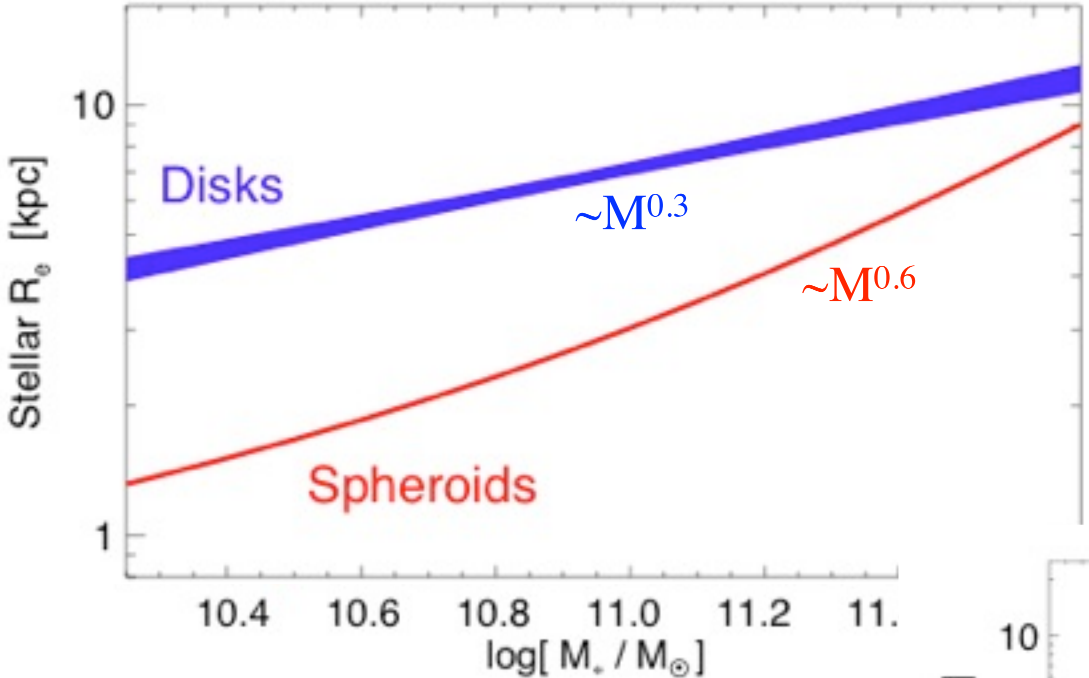


- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns (e.g. Graves talk)

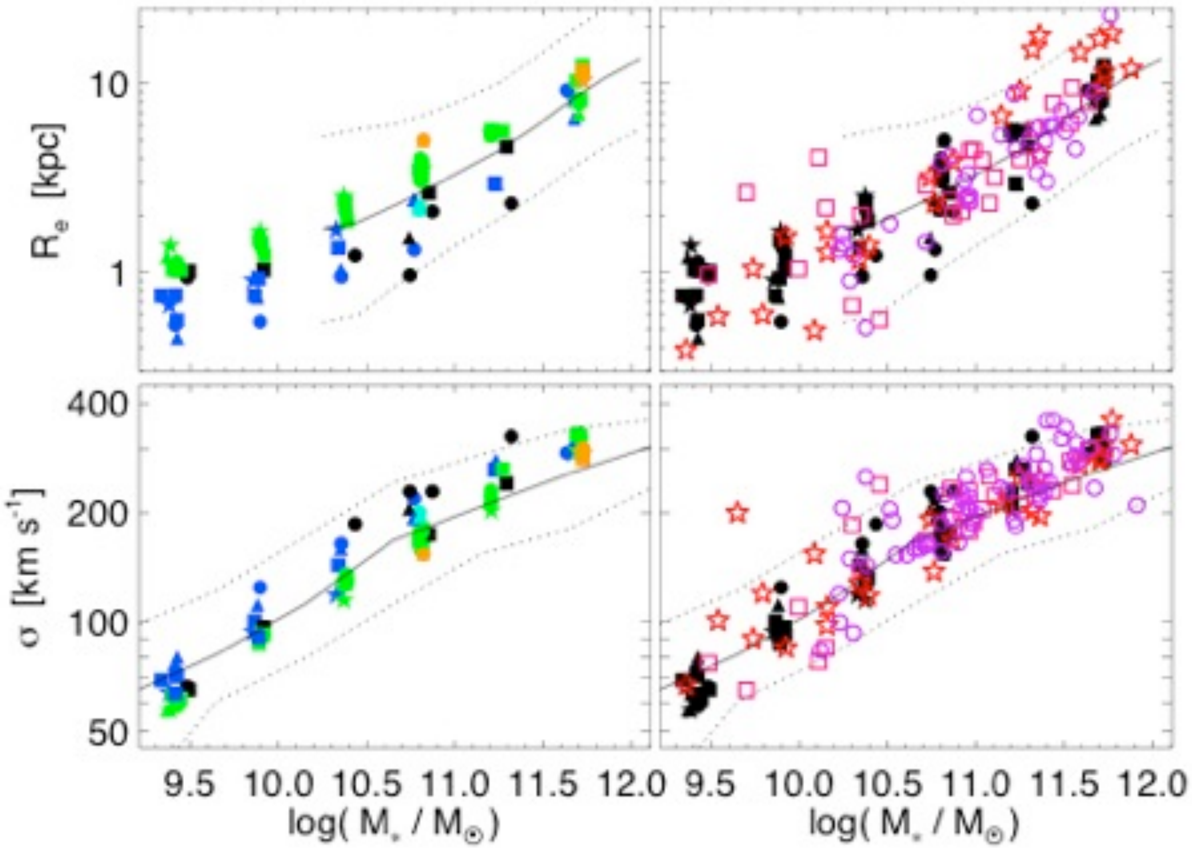
Structure in Elliptical Light Profiles

PFH, Cox, & Hernquist 2008

THE ROLE OF GAS IN THE SIZE-MASS RELATION



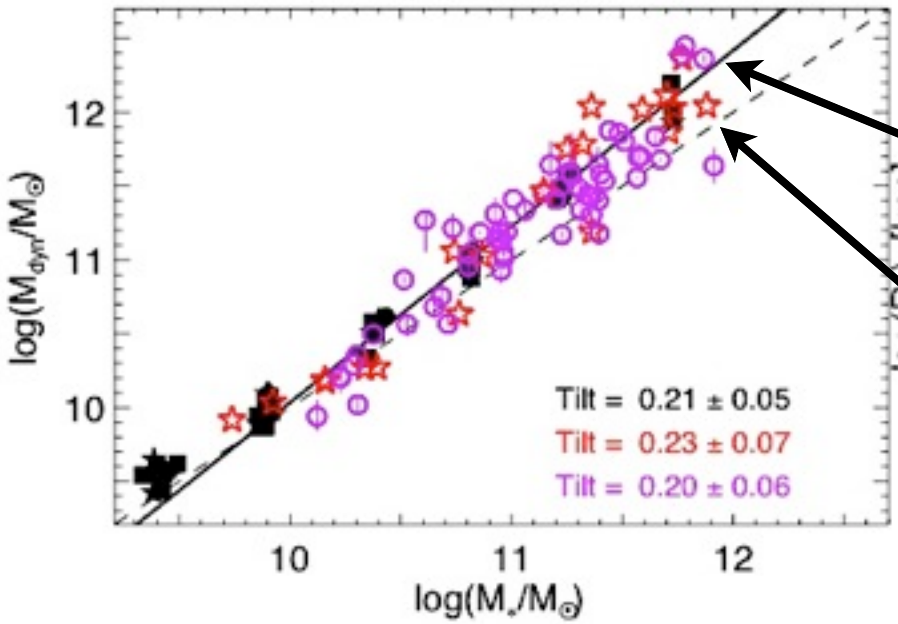
- Recall, low-M ellipticals are more compact than disks of similar mass



- Include effects of gas: reproduce fundamental plane, sizes, etc. of ellipticals

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

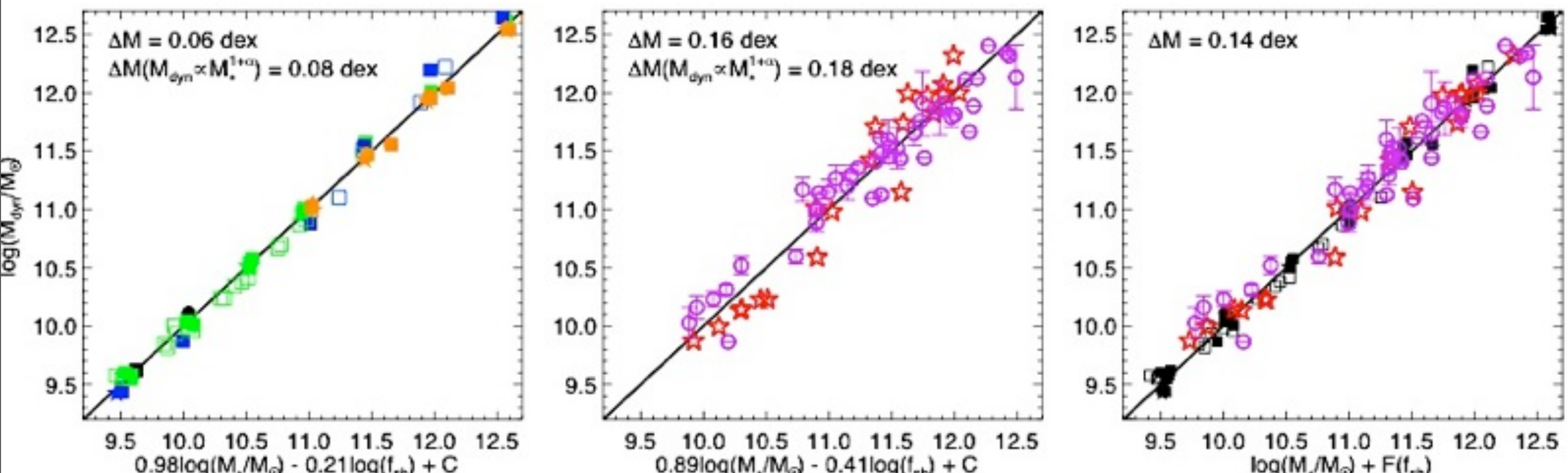


- Simulate just galaxies on observed f_{gas}-$M_{stellar}$ relation:
  - Observed FP!

Observed FP:
$M_{dyn} / M_{stellar} \sim M^{0.2}$

Relation without gas:
$M_{dyn} / M_{stellar} = \text{constant}$

- Having some f_starburst for each observed system, can we factor it out?
  Yes: FP can be physically restated as $M_{dyn} \sim M_{stellar} \times F(f_{dissipational})$



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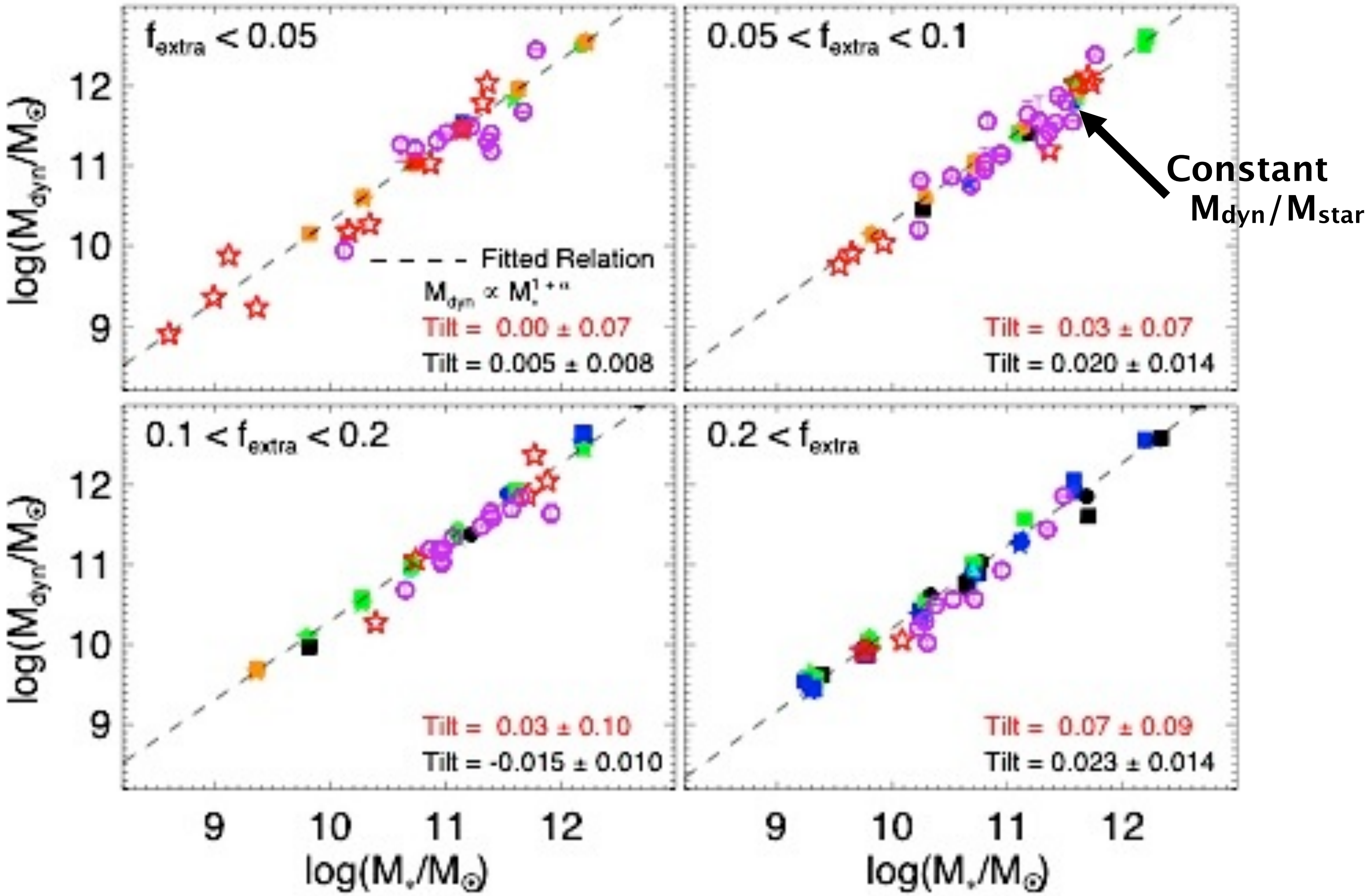
- Go further: is there any FP ‘tilt’ left if we just consider systems with the same amount of dissipation?

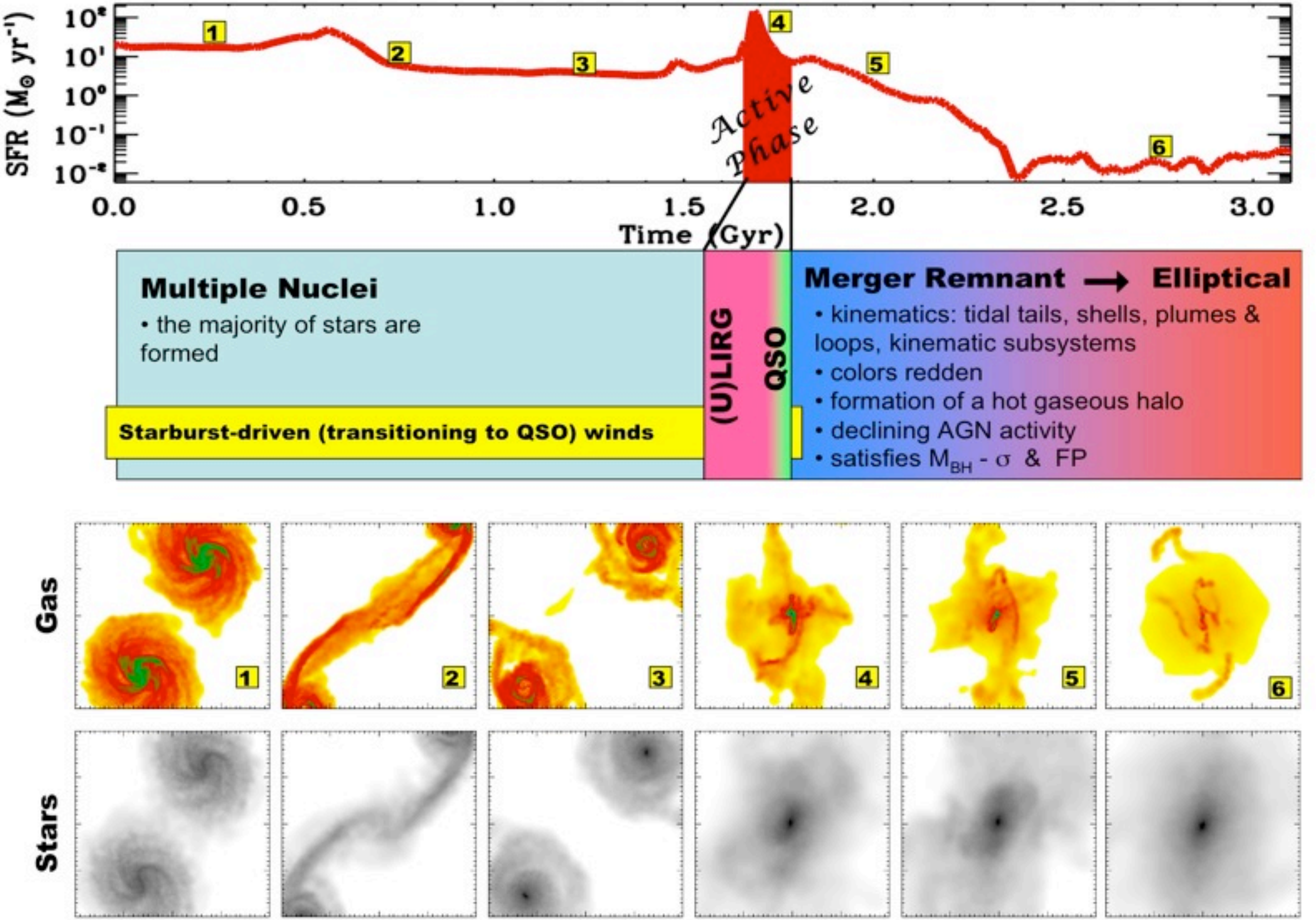


- At FIXED $f_{dissipational}$, there is NO TILT
  - Same for size-mass and other bulge correlations: without dissipation, follow disks

Summary

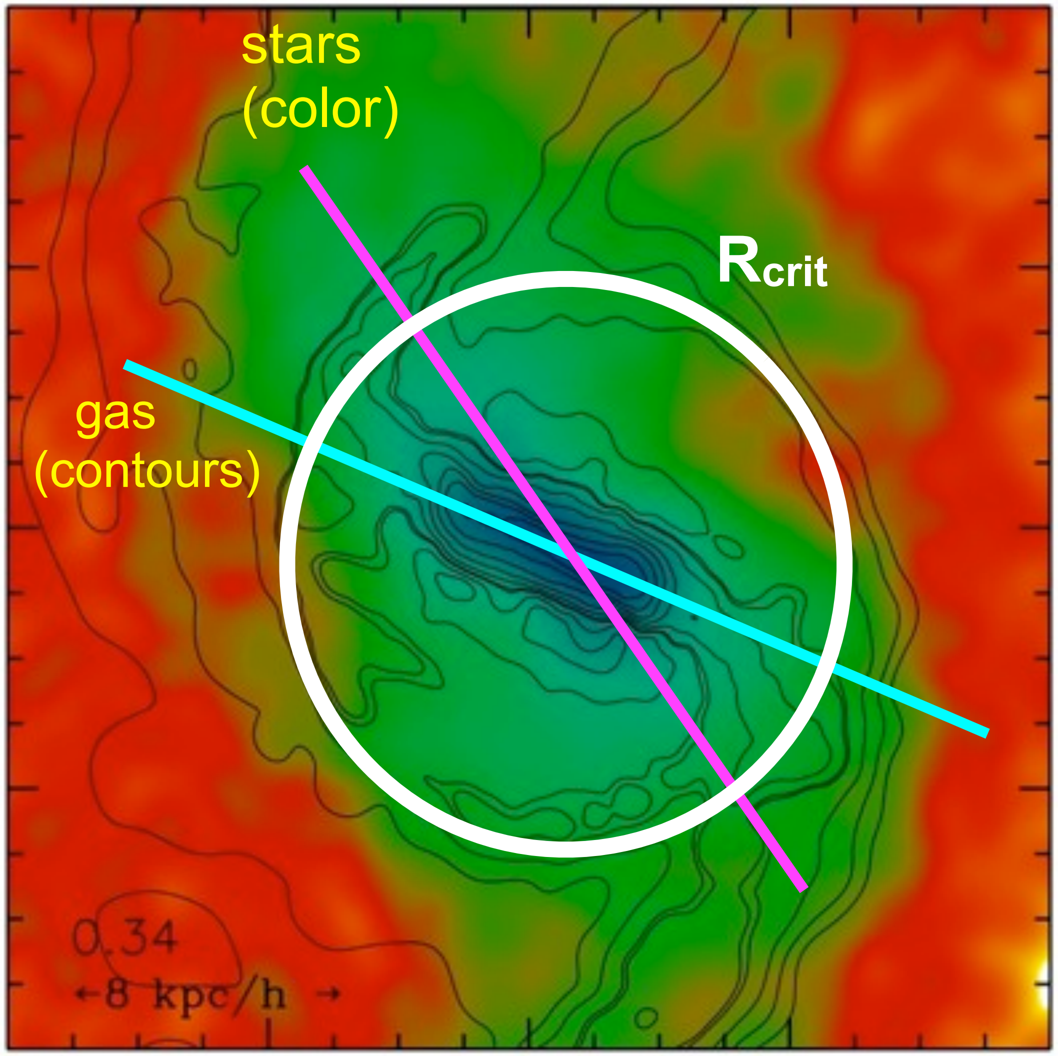
- How do disks *survive* mergers?
  - Being very gas rich (f_{gas} >~ 0.3-0.5): fewer stars = less angular momentum loss
    - *Independent* of feedback.... in an instantaneous sense:
      - Feedback is *hugely* important for the initial conditions: determining how much gas is available and where it is (relative to the stars)
        (Governato, Navarro talks)
      - Rapid accretion/cold flows make life easier: don't need to entirely save massive disks from high-z to z=0; just need to suppress the efficiency of high-z bulge formation

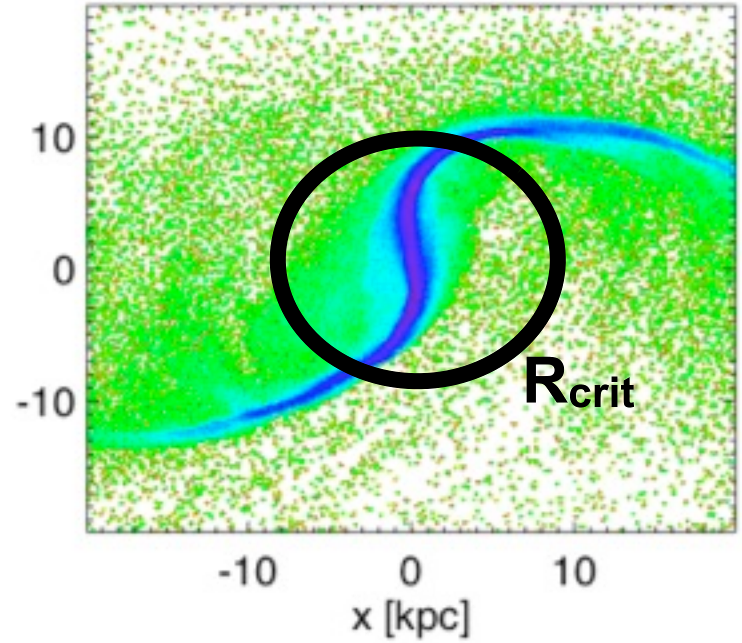
- How do we make a *real* elliptical?
  - Gas again! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed (f_{gas} ~ 0.1 - 0.5)
    - A given elliptical can only be made by mergers with a narrow range of f_{gas}
    - We're finally making "realistic" ellipticals: direct 1-to-1 SB profiles, kinematics, stellar populations, isophotal shape, enrichment,
      - Observed scaling of f_{gas} with disk mass explains difference between global bulge and disk scaling laws: FP, size-mass, Faber-Jackson, stellar populations+FP residuals, phase-space densities, etc.


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)
Active Phase
1
2
3
4
5
6
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

How Do Disks Survive Mergers?

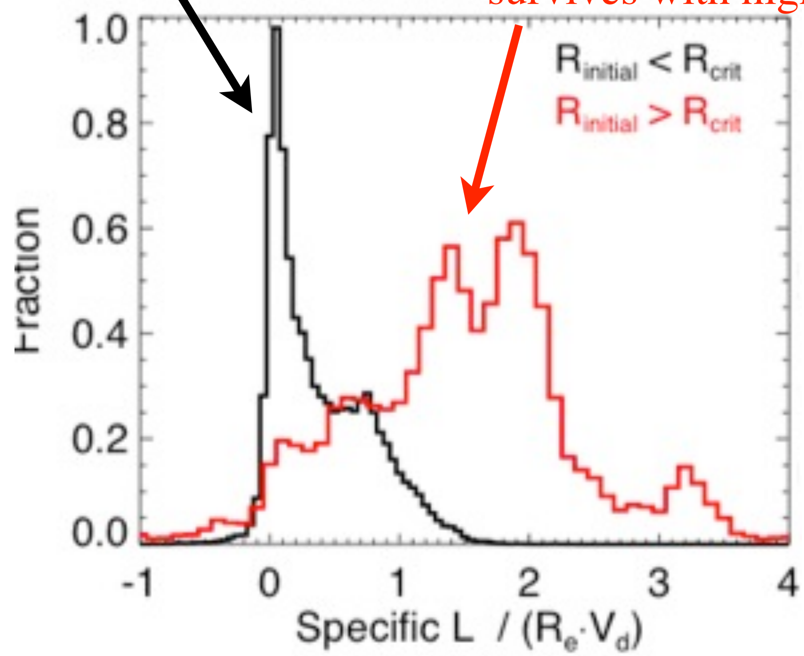
Corrollary: J_{gas} loss inside R_{crit} where torques/stellar distortion are strong (torque*dynamical time >> J)





Gas inside R_{crit} falls to center and bursts

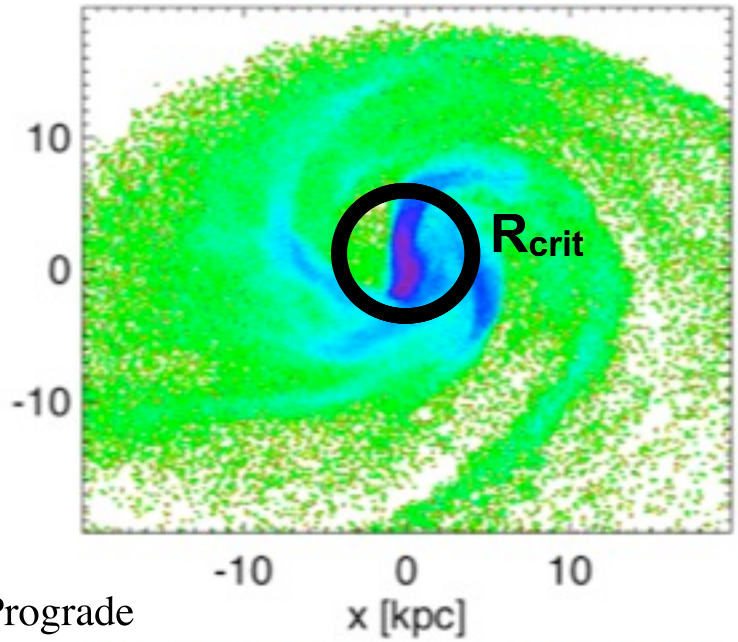
Gas outside R_{crit} survives with high J



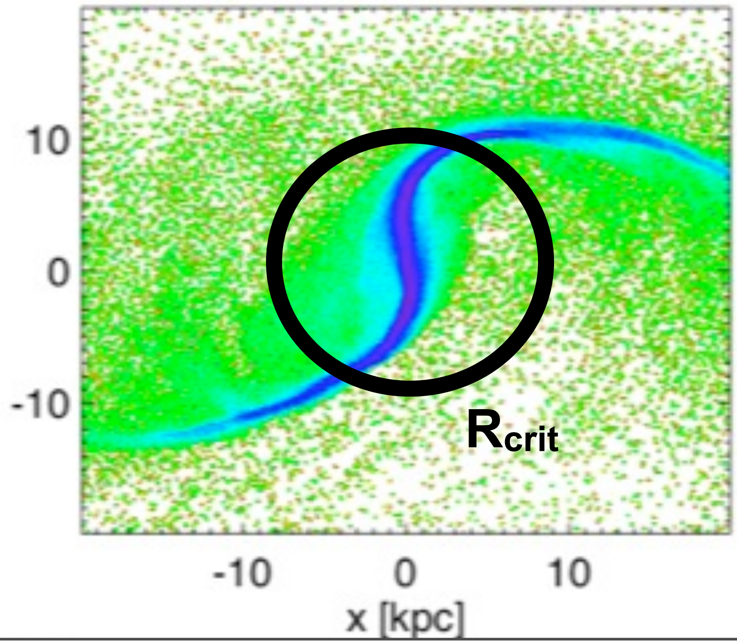
(Final angular momentum)

How Do Disks Survive Mergers?

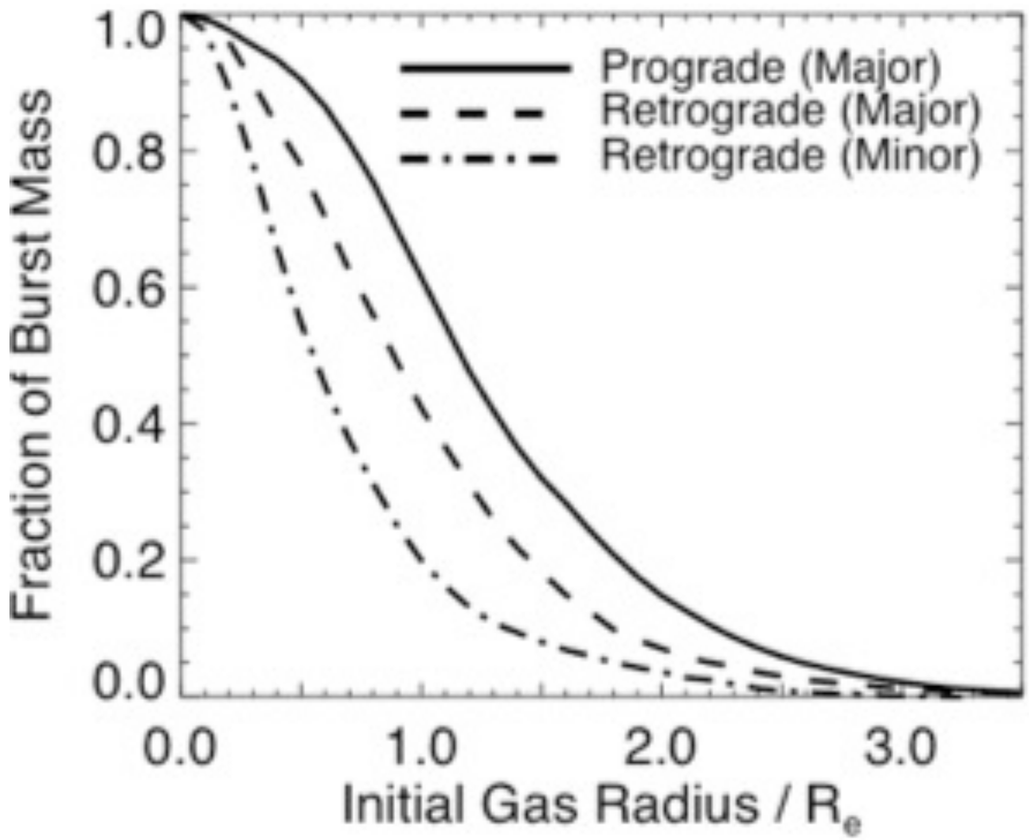
Retrograde



Prograde



More violent/resonant mergers -- remove angular momentum further out in the disk



PFH et al. '08

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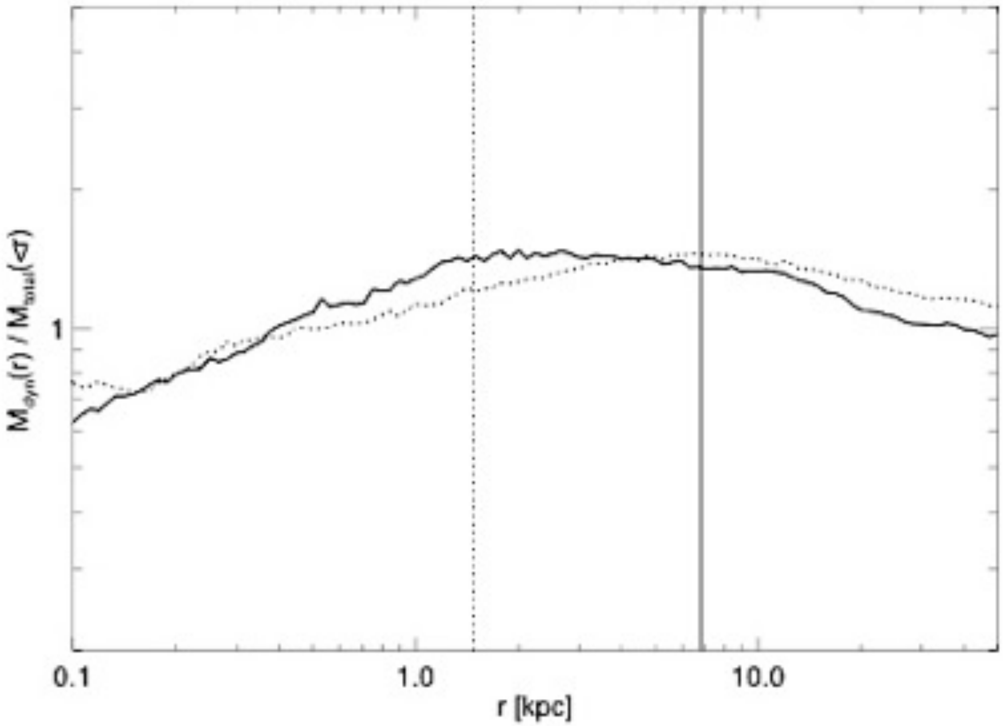
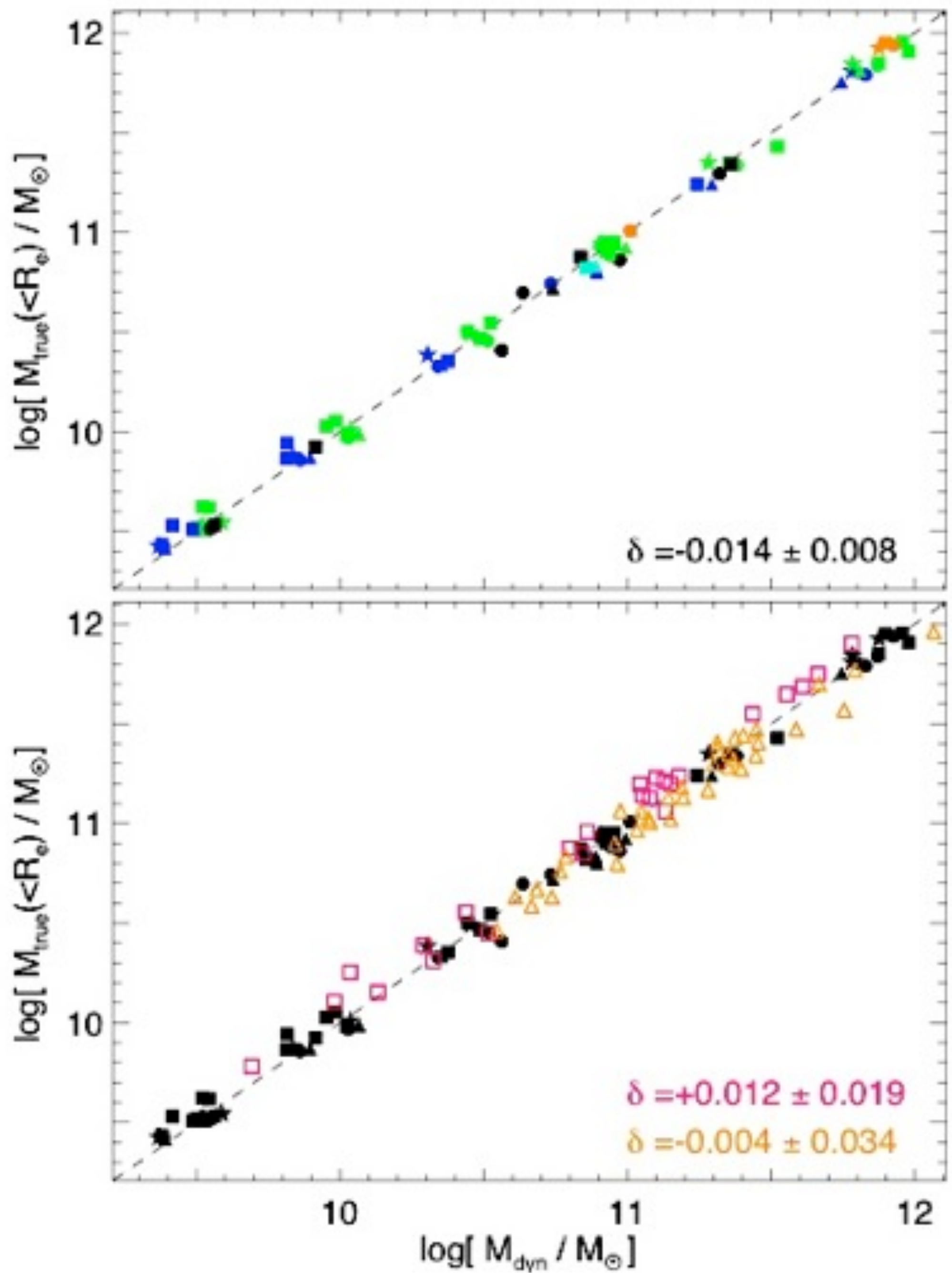
HOMOLOGY VS. NON-HOMOLOGY





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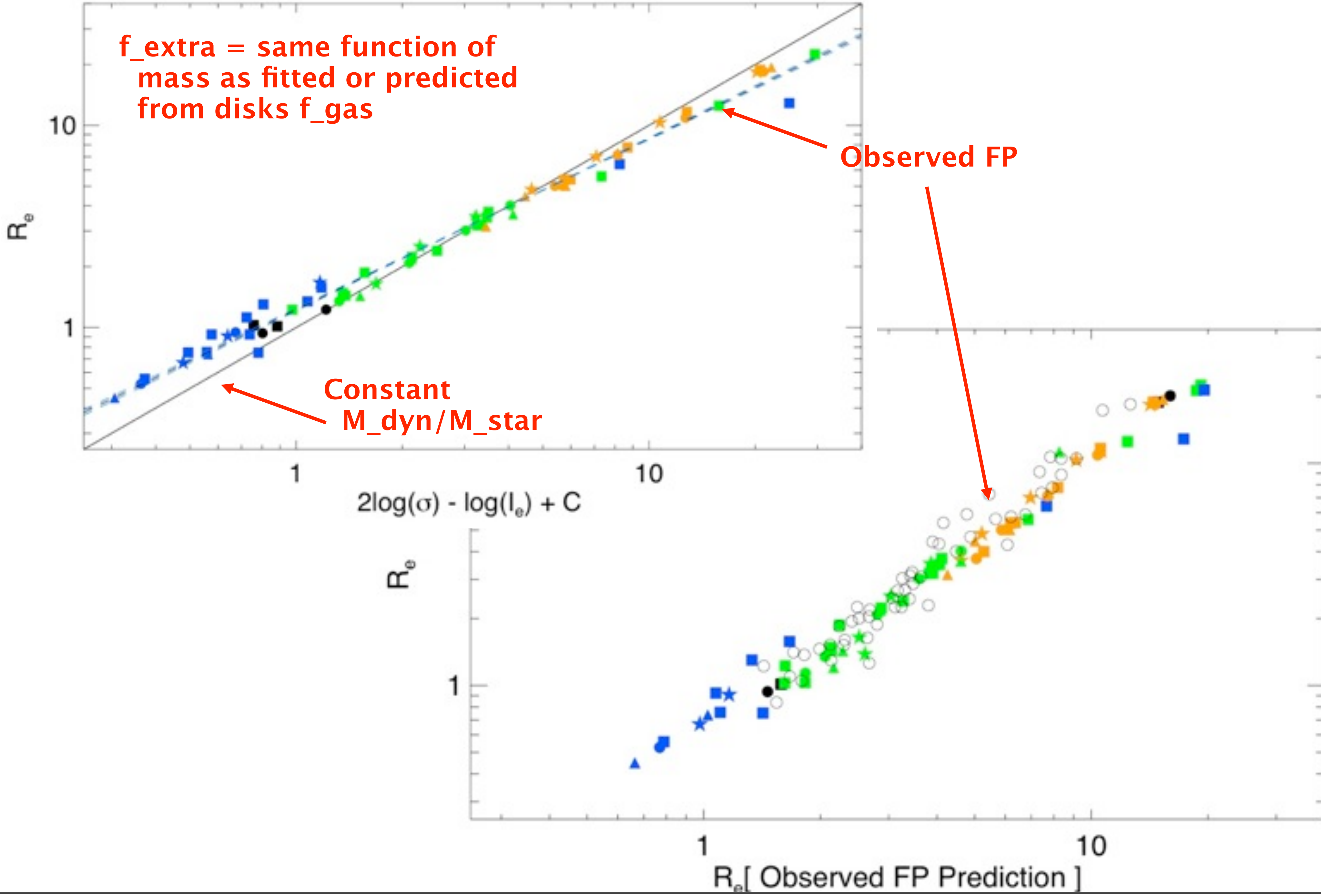
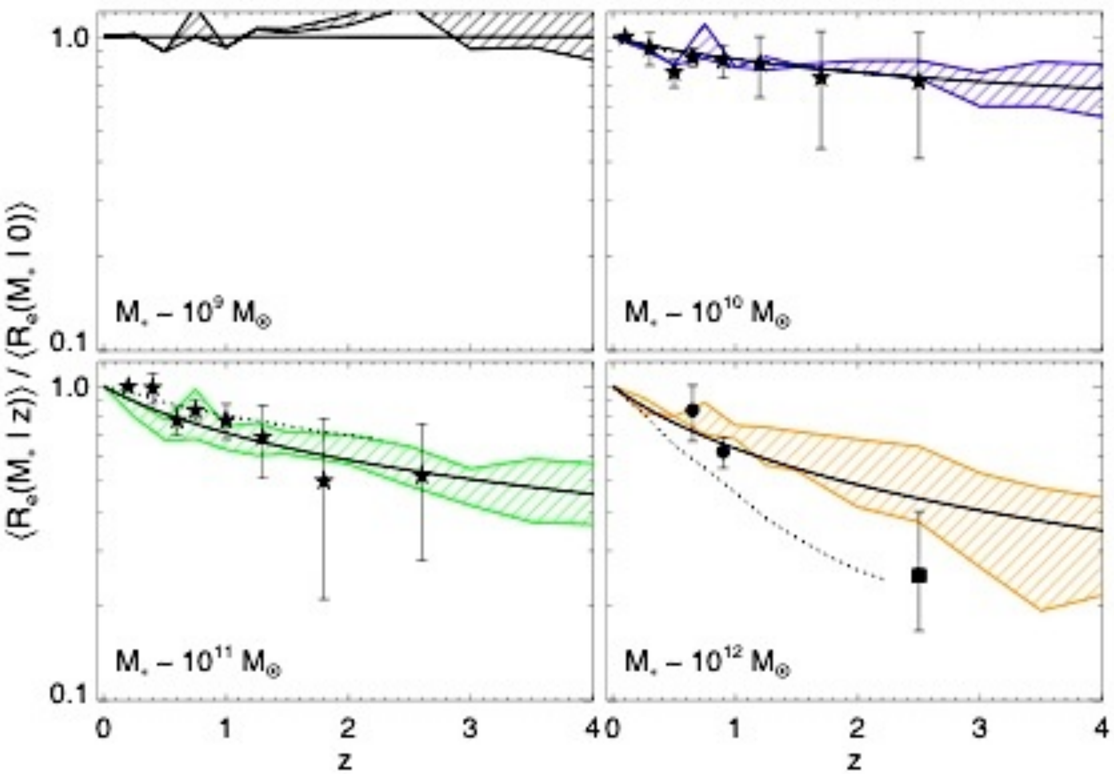
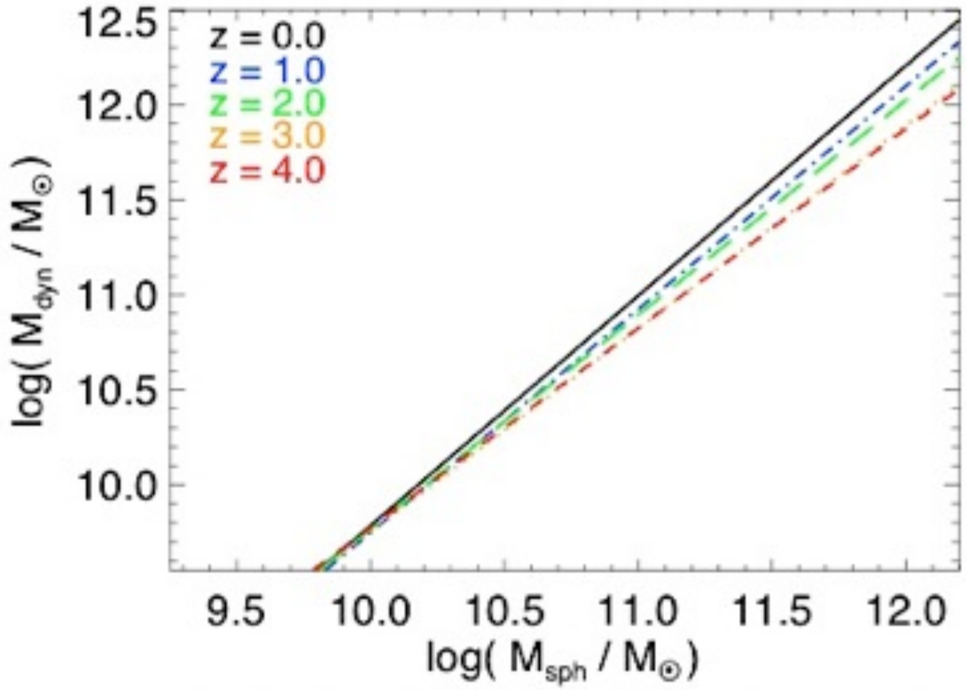
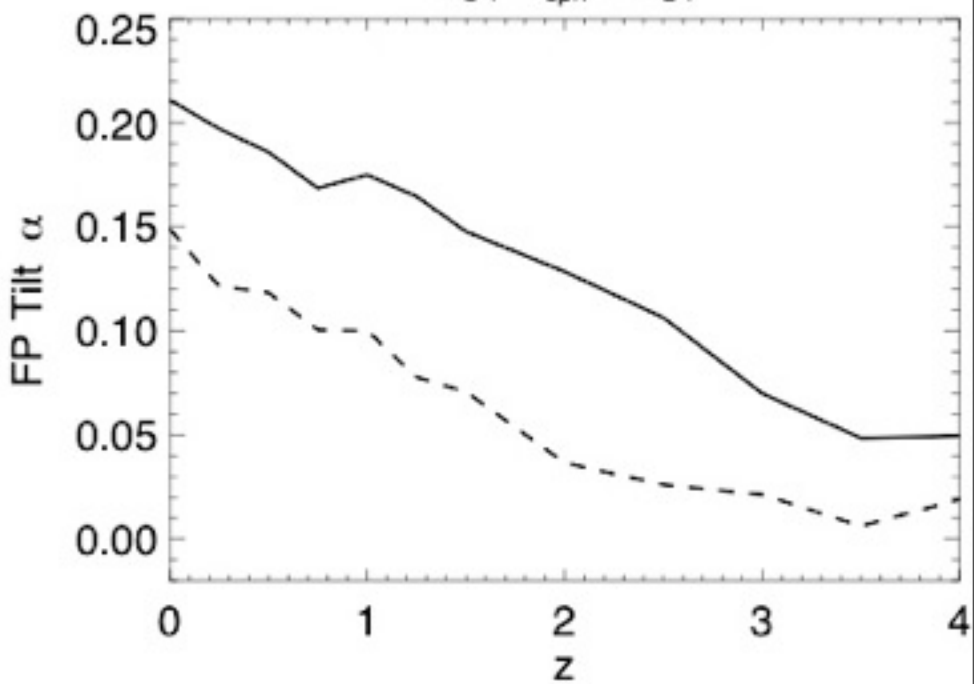


Dissipation versus Redshift

HIGH-Z DISKS ARE MORE GAS RICH...



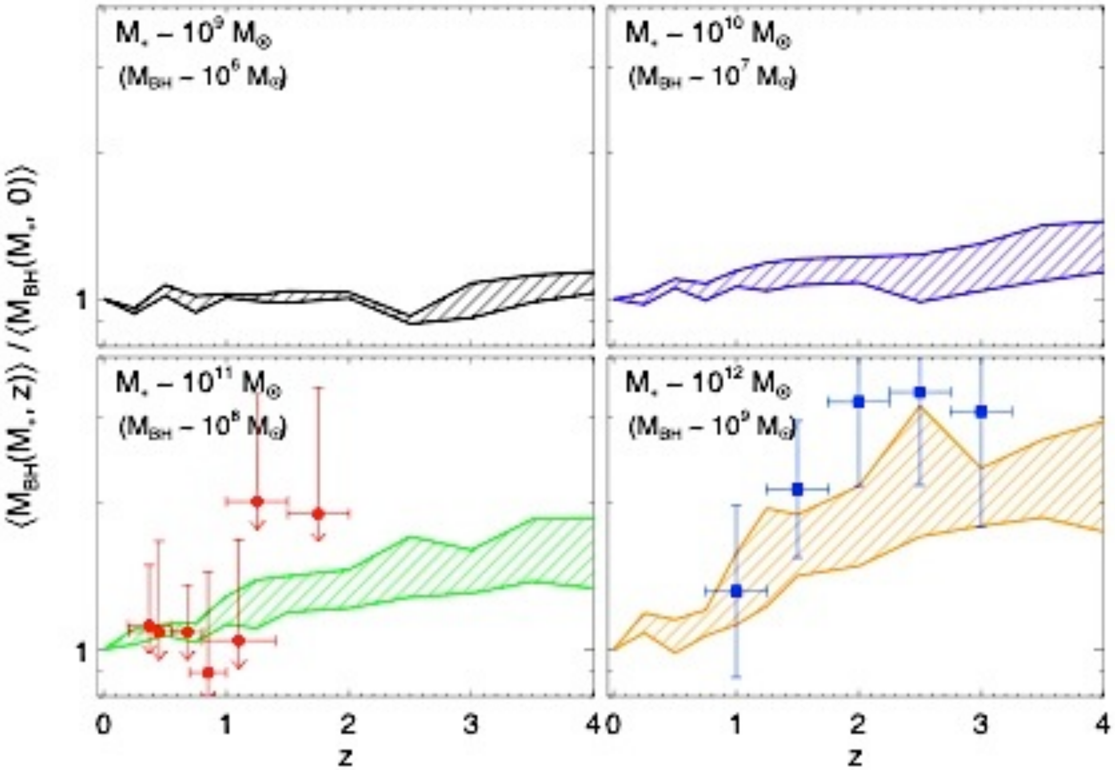


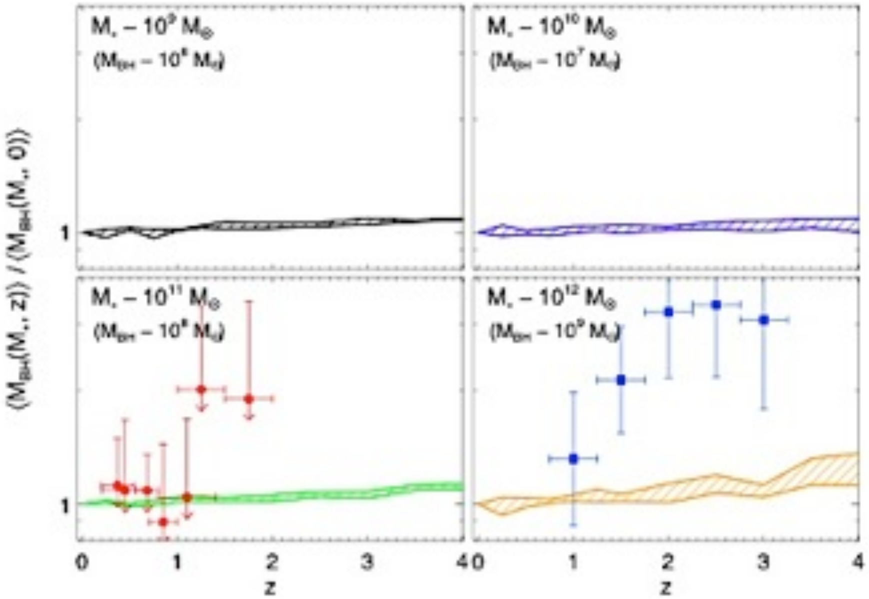


- So get more compact ellipticals

Implications for BH-Host Correlations

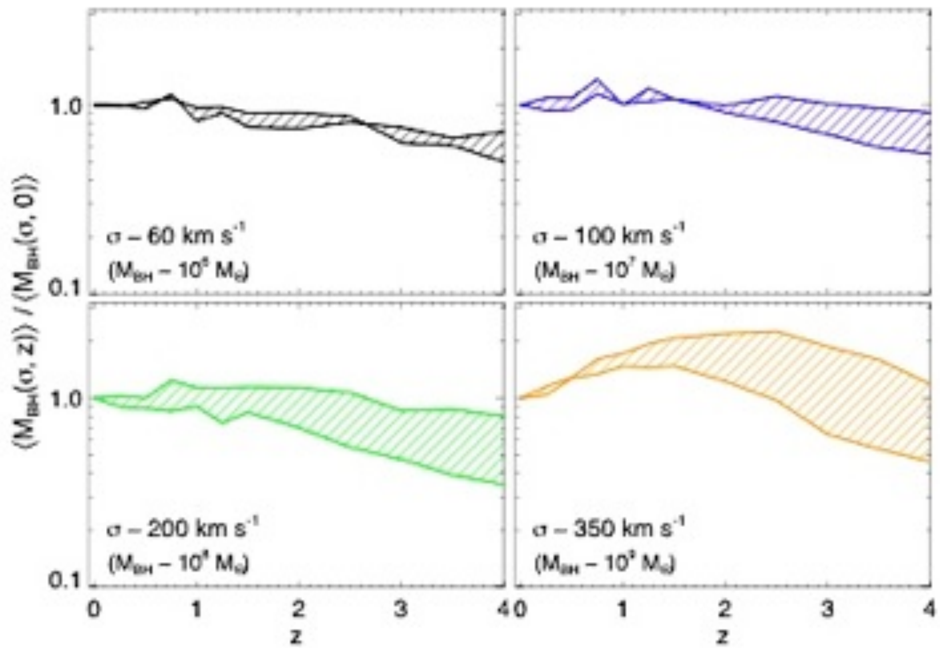
EVOLUTION WITH REDSHIFT





- (without dissipation=no evolution)

- Deeper potential wells at fixed M

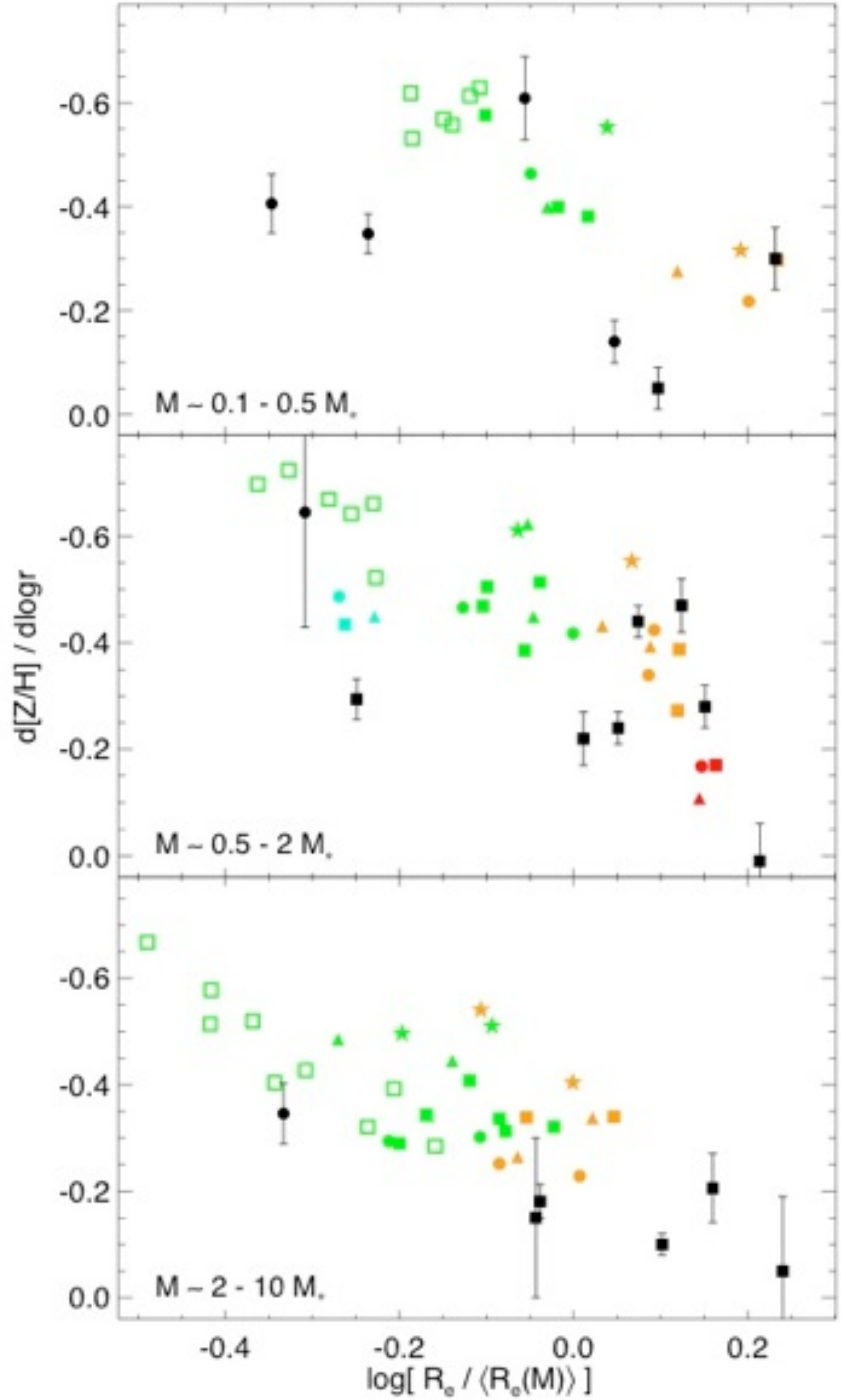


- (Weaker in sigma)

Structure in Elliptical Light Profiles

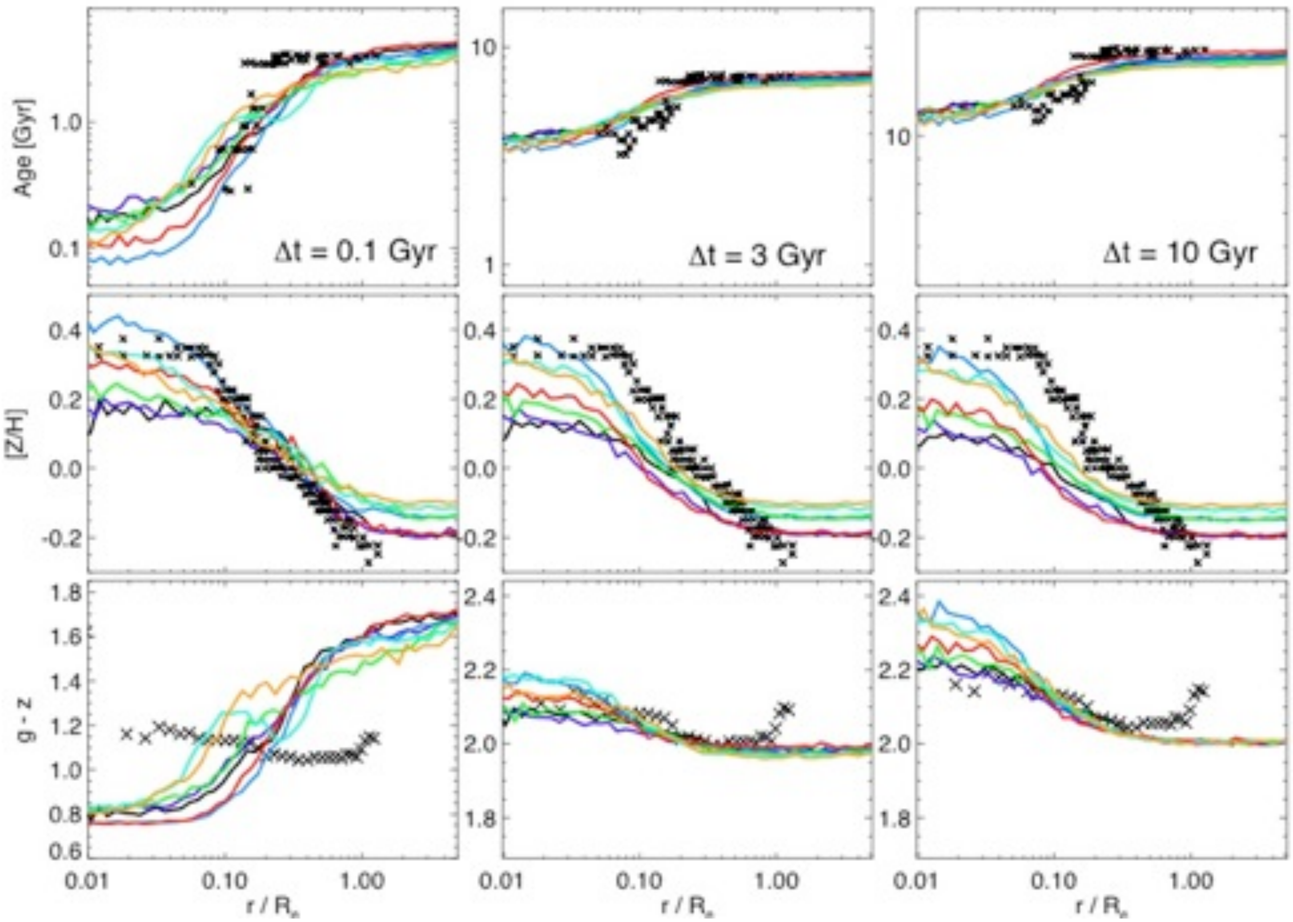
RECOVERING THE ROLE OF GAS

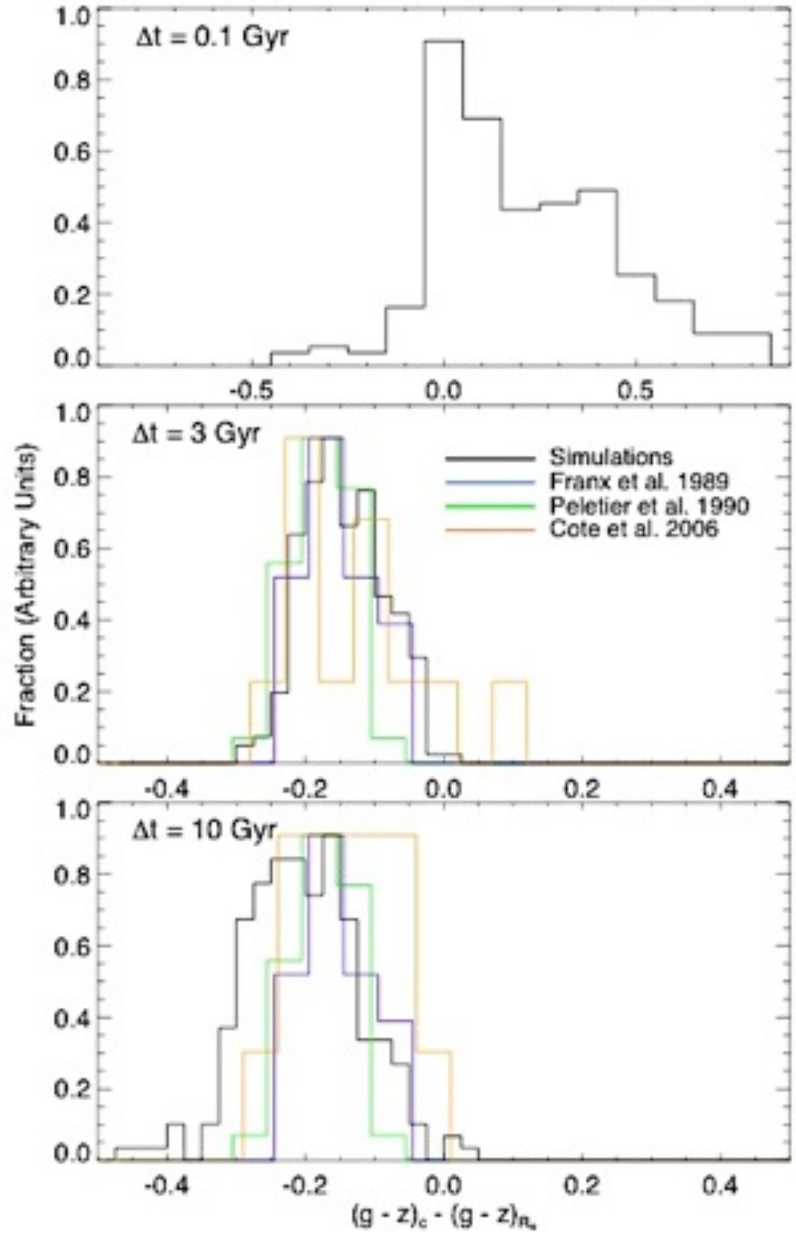
- Get accompanying predictions for how stellar populations & their gradients should scale with size, luminosity, etc.



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS





Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS