Gas in Galaxy Mergers: More Important than You Think

Philip Hopkins

06/10/2009

Lars Hernquist, T. J. Cox, Rachel Somerville, Dusan Keres, Eliot Quataert, Chung-Pei Ma, Josh Younger, Volker Springel, Norm Murray, Kevin Bundy, Brant Robertson, John Kormendy, Tod Lauer, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Gordon Richards, Alison Coil, Barry Rothberg, Stijn Wuyts

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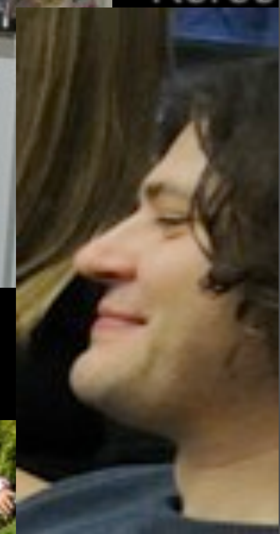


Dusan Keres

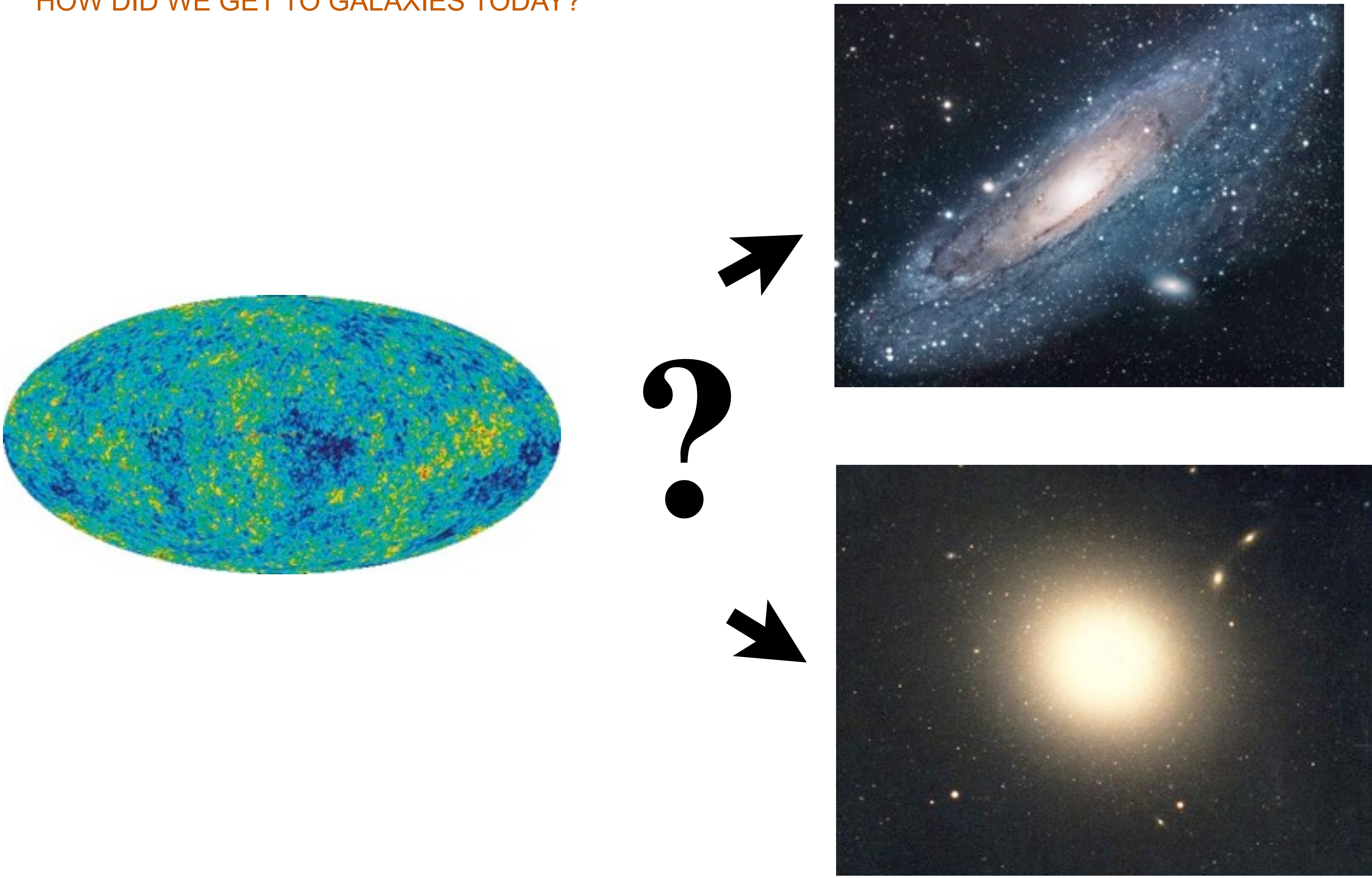
TJ Cox

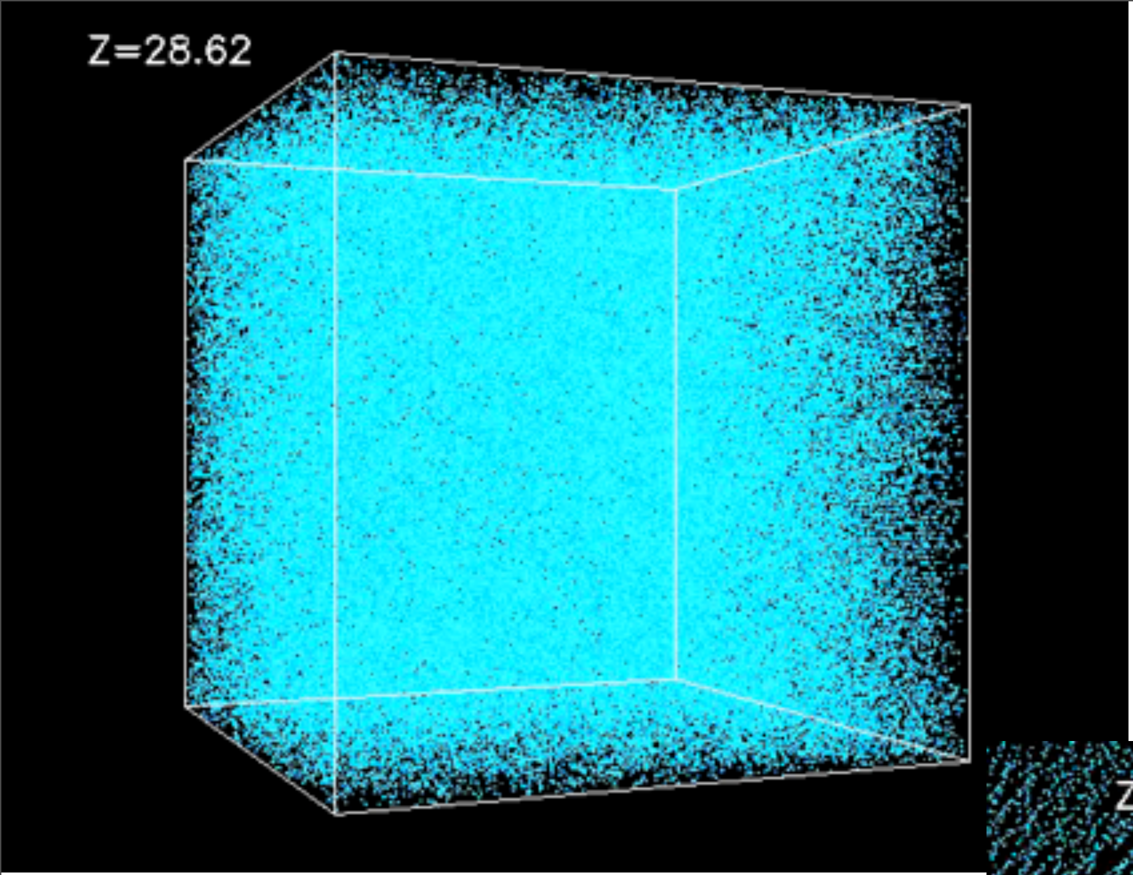
Eliot Quataert

Chris Hayward

Motivation

HOW DID WE GET TO GALAXIES TODAY?

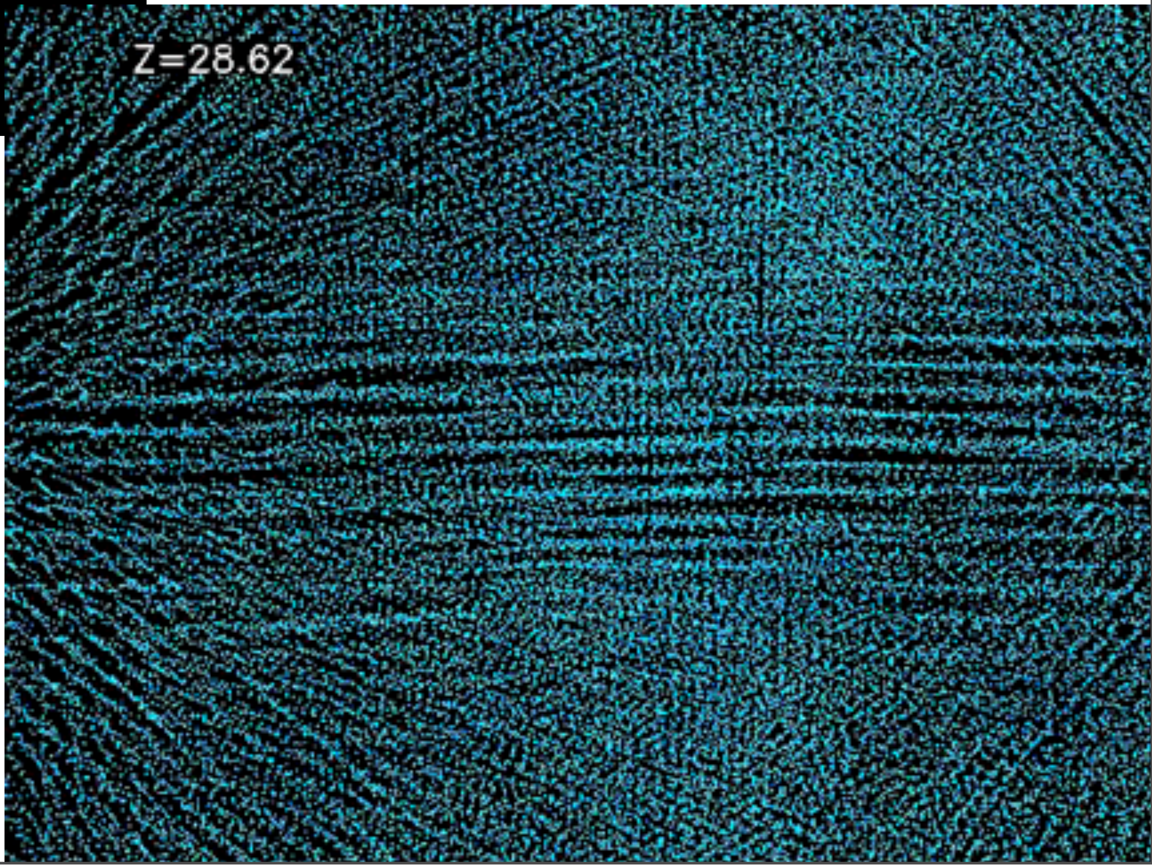




Motivation

HOW DID WE GET TO GALAXIES TODAY?

Kravtsov et al.

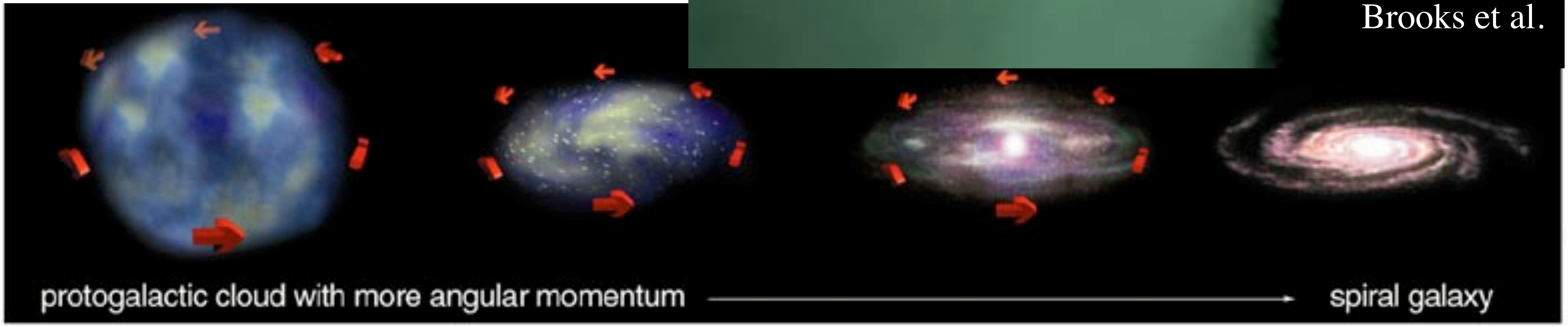


- Structure grows hierarchically: *must* understand mergers

Motivation

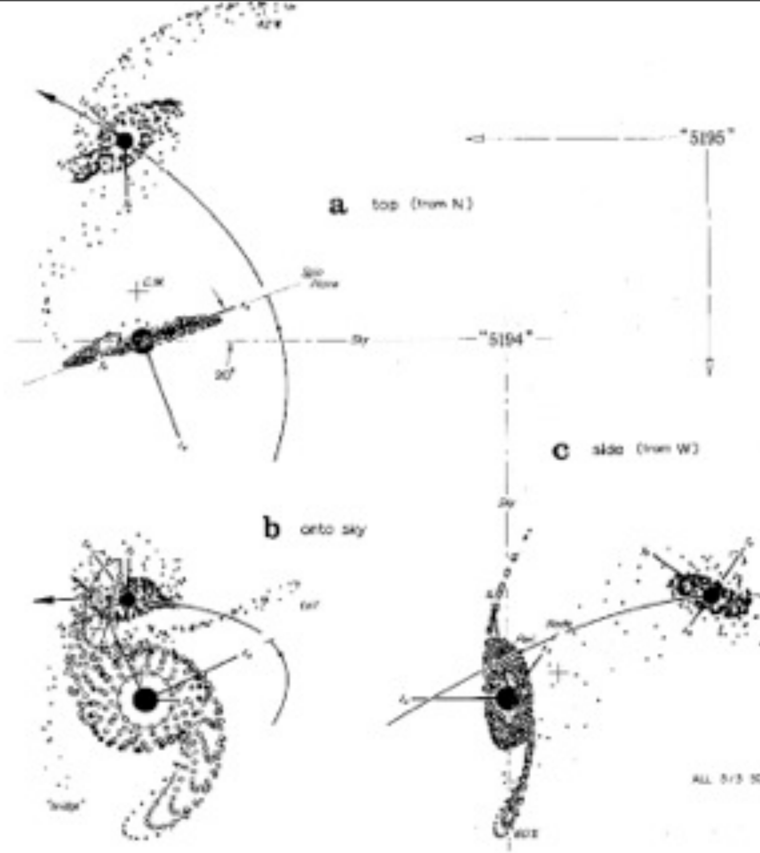
HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse: gas cools into a disk



- What happens when that starts colliding into other galaxies?

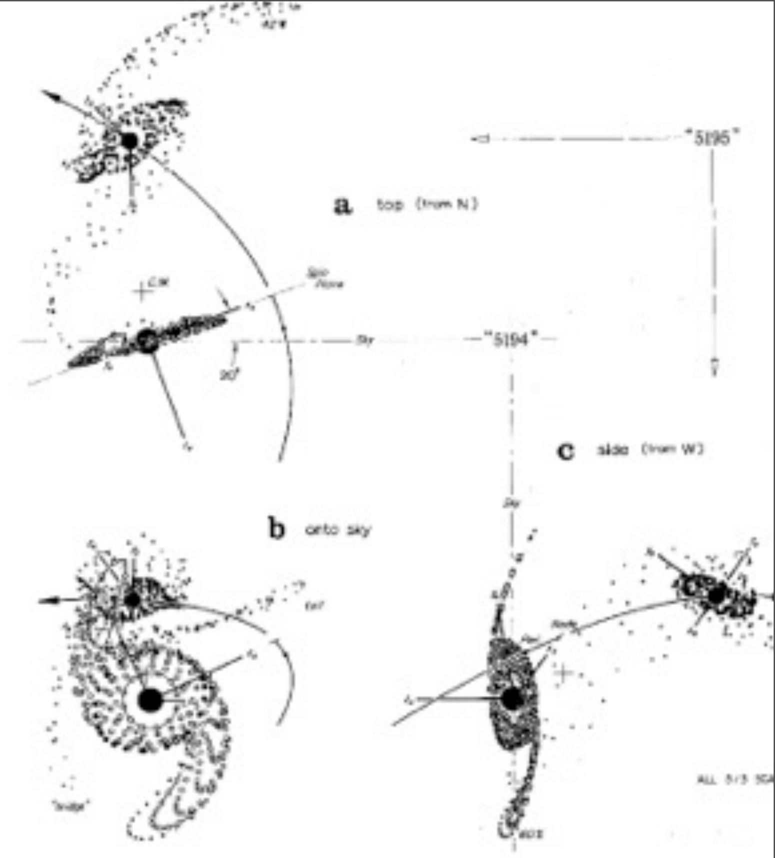
Our Conventional Wisdom (Toomre):



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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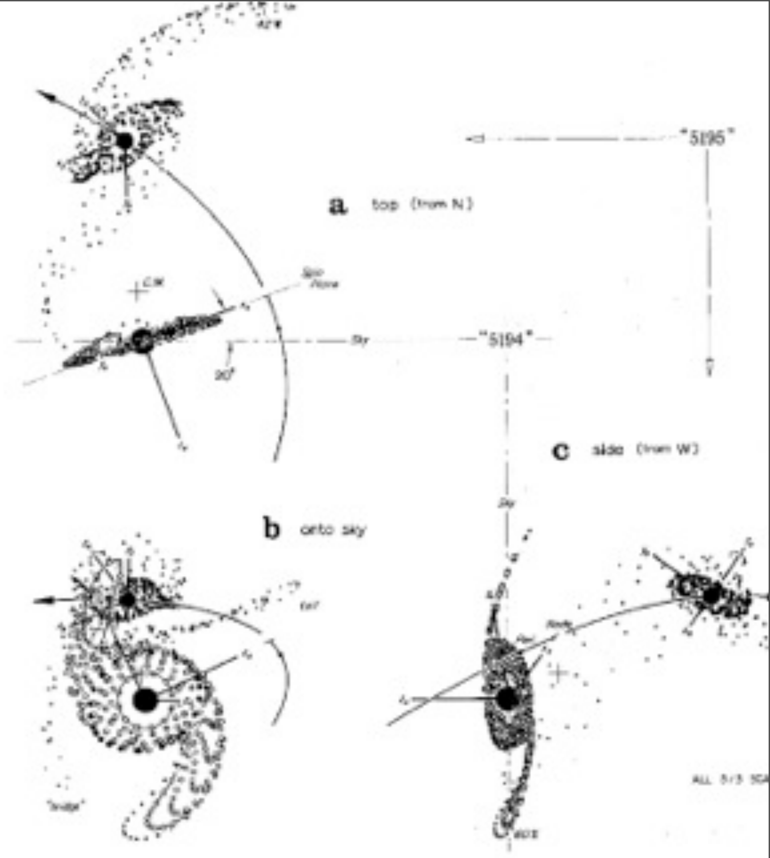
Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk



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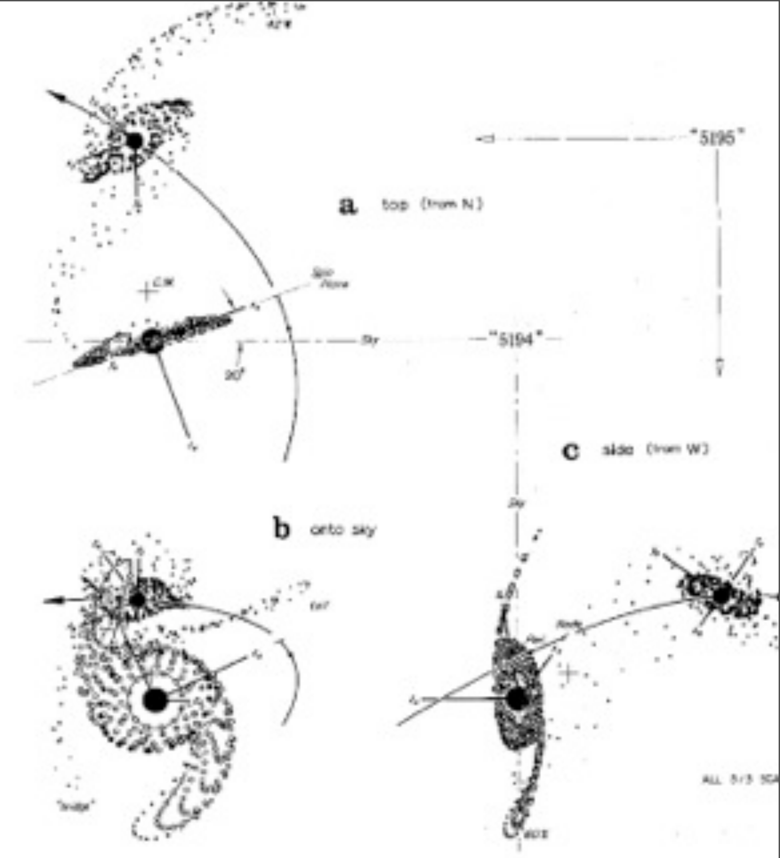
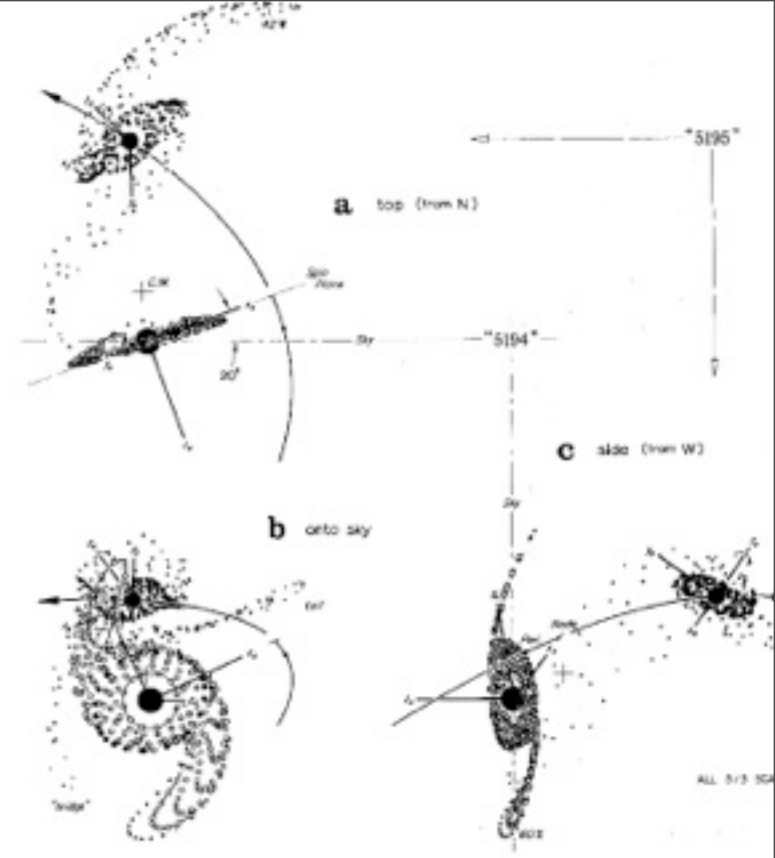


F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



F. Summers

Motivation

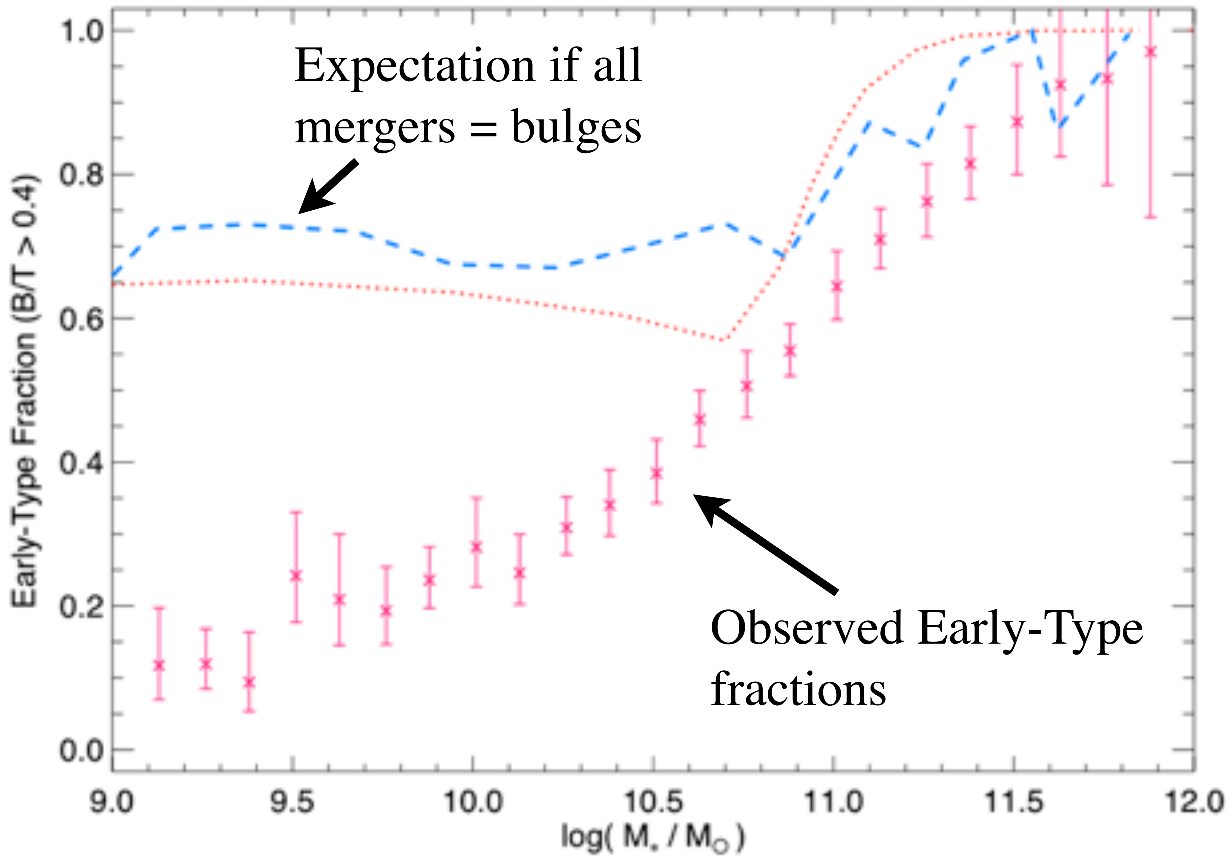
HOW DID WE GET TO GALAXIES TODAY?

Many of these are *problems*...

Too Many Mergers?

-- missing some physics

(Governato, Navarro, Scannapieco, Somer-Larson, et al.)

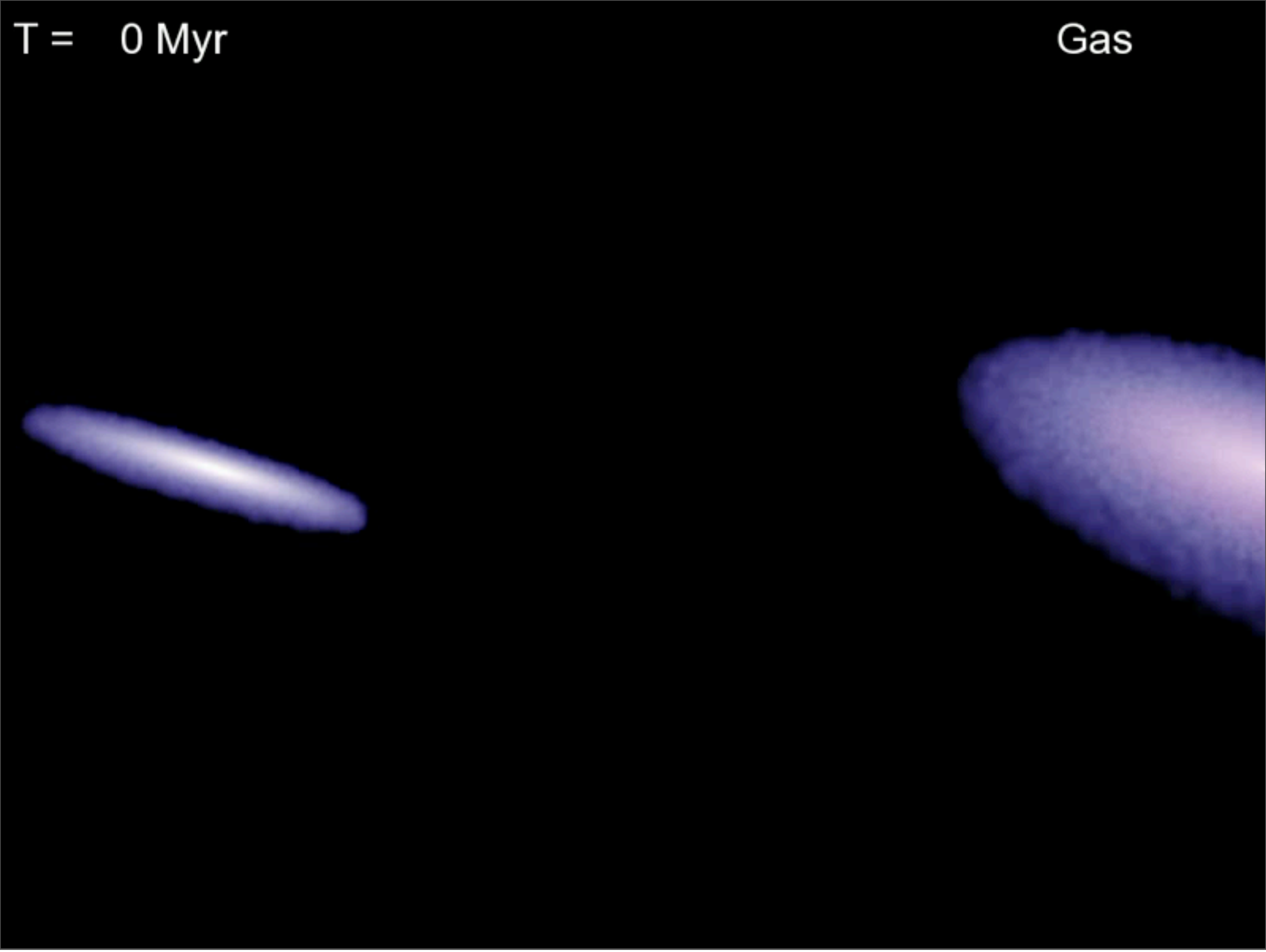


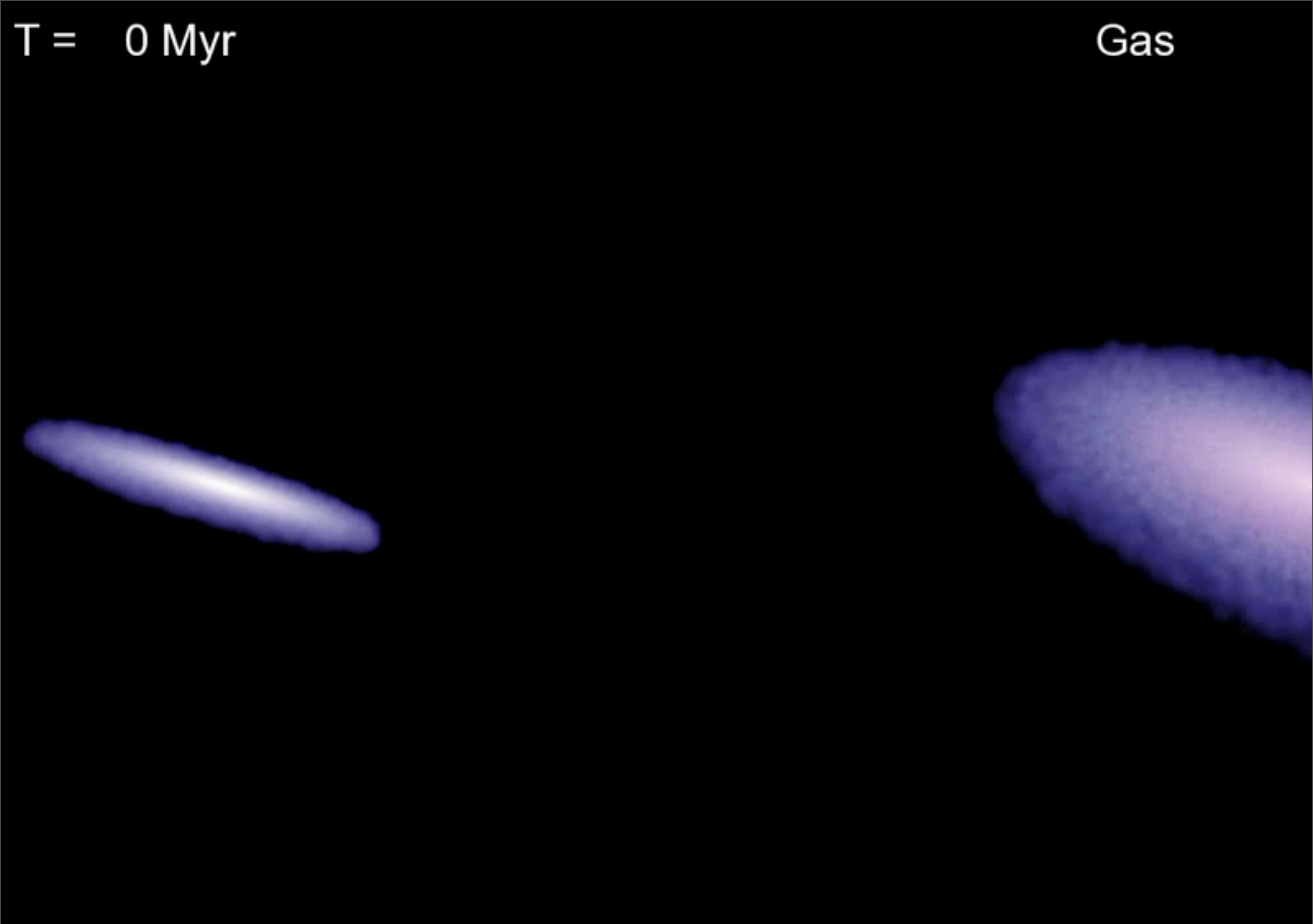
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

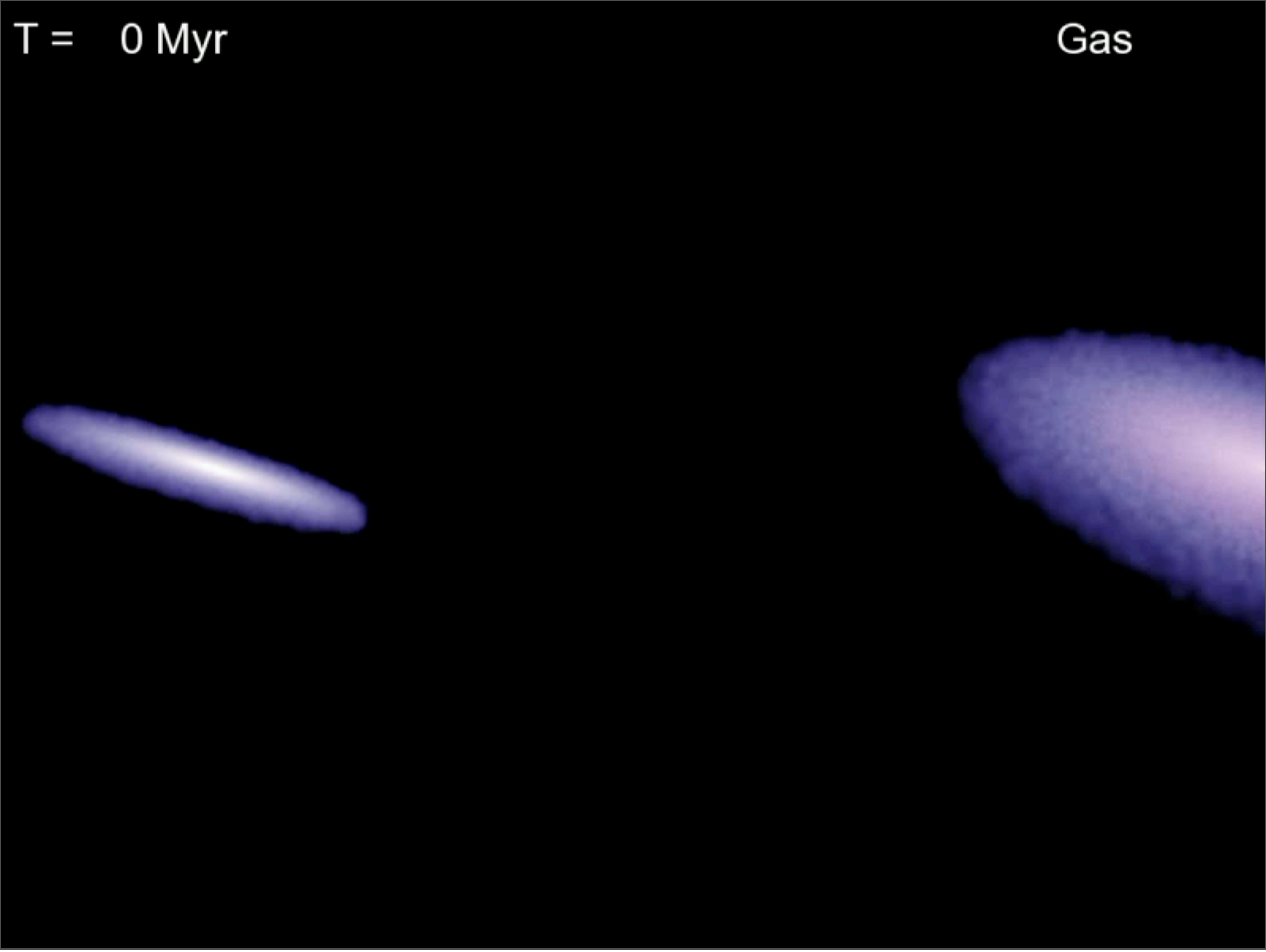
-- profiles too flat

-- shapes too flattened


T = 0 Myr
Gas



Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)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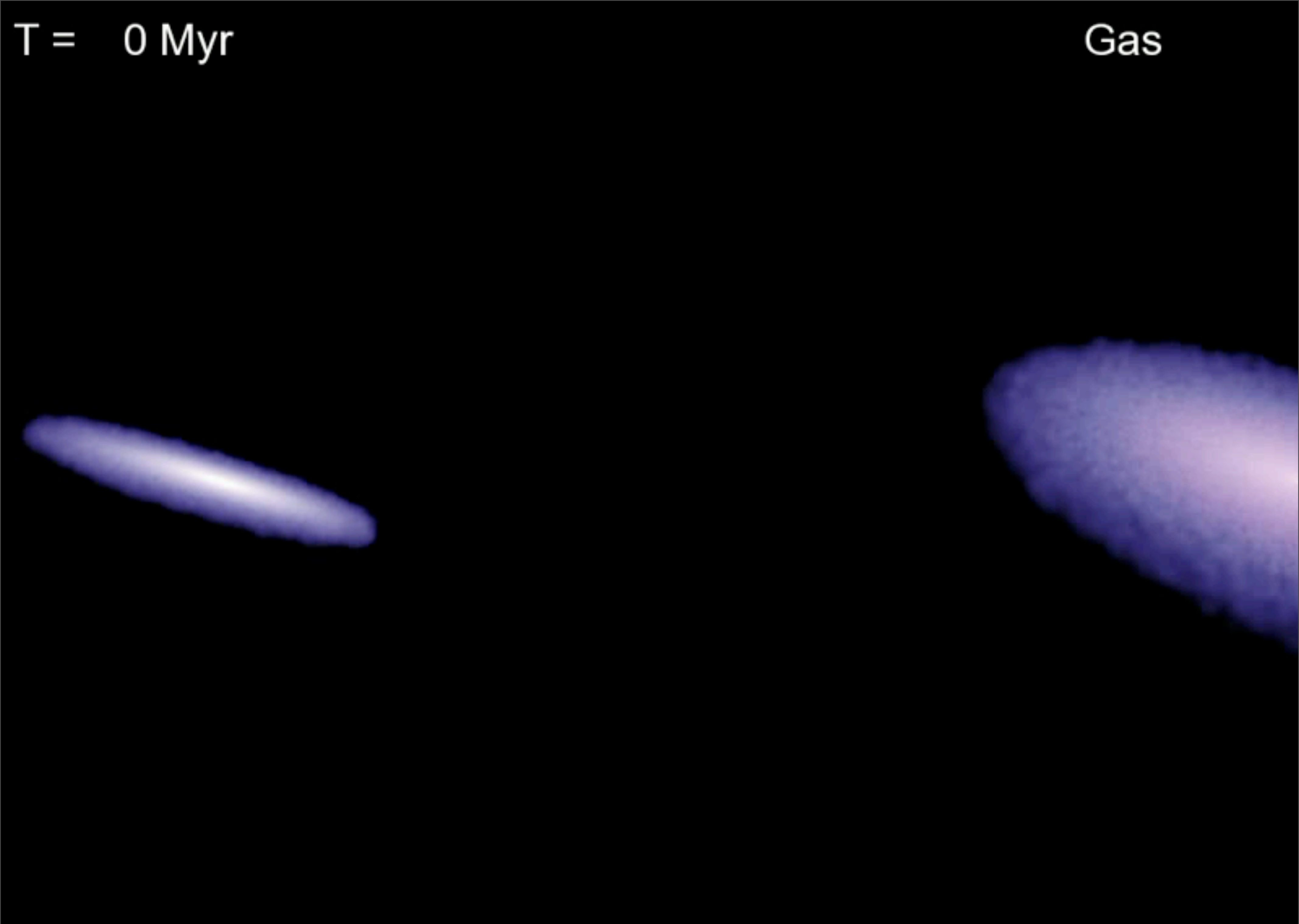
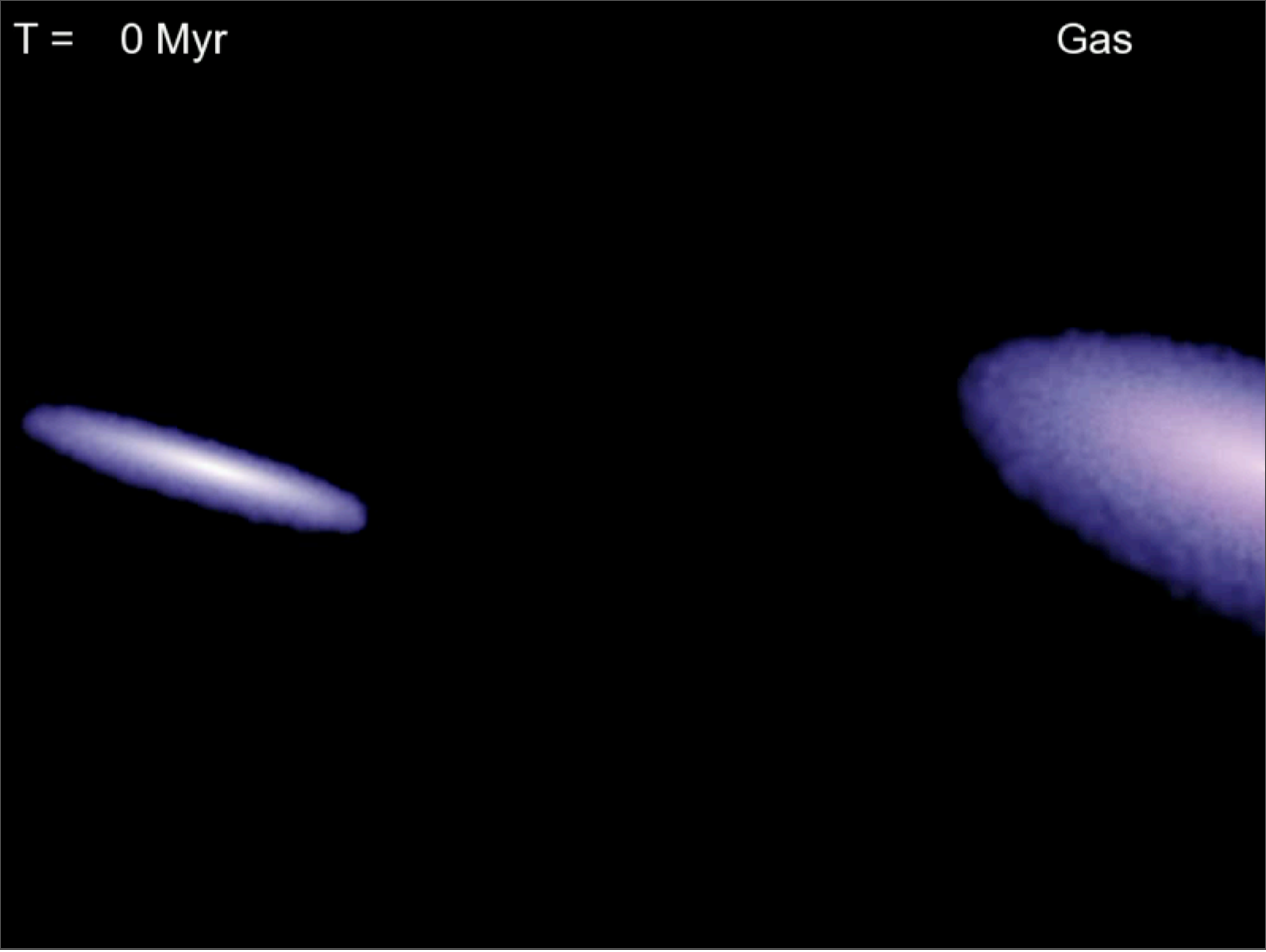


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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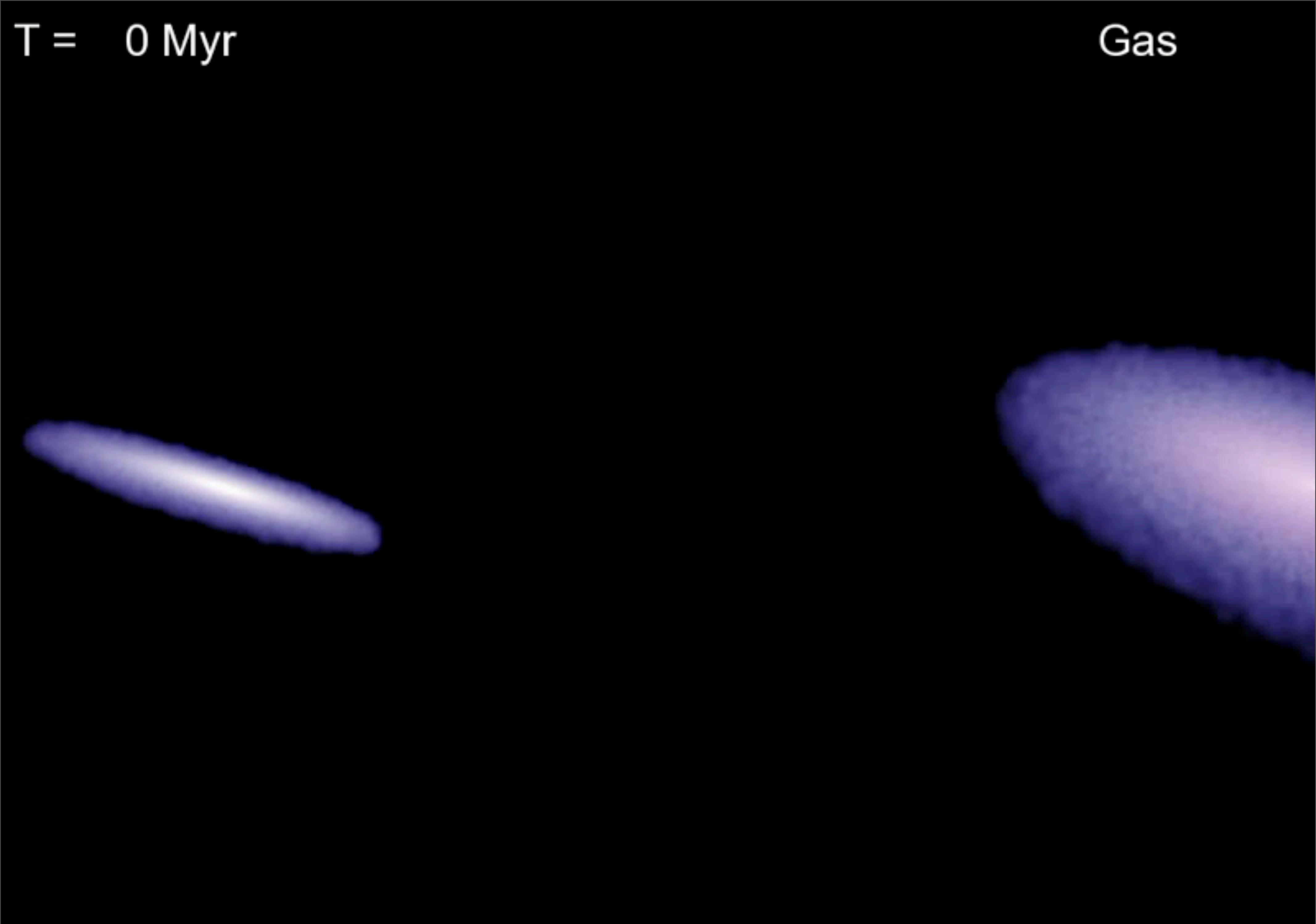
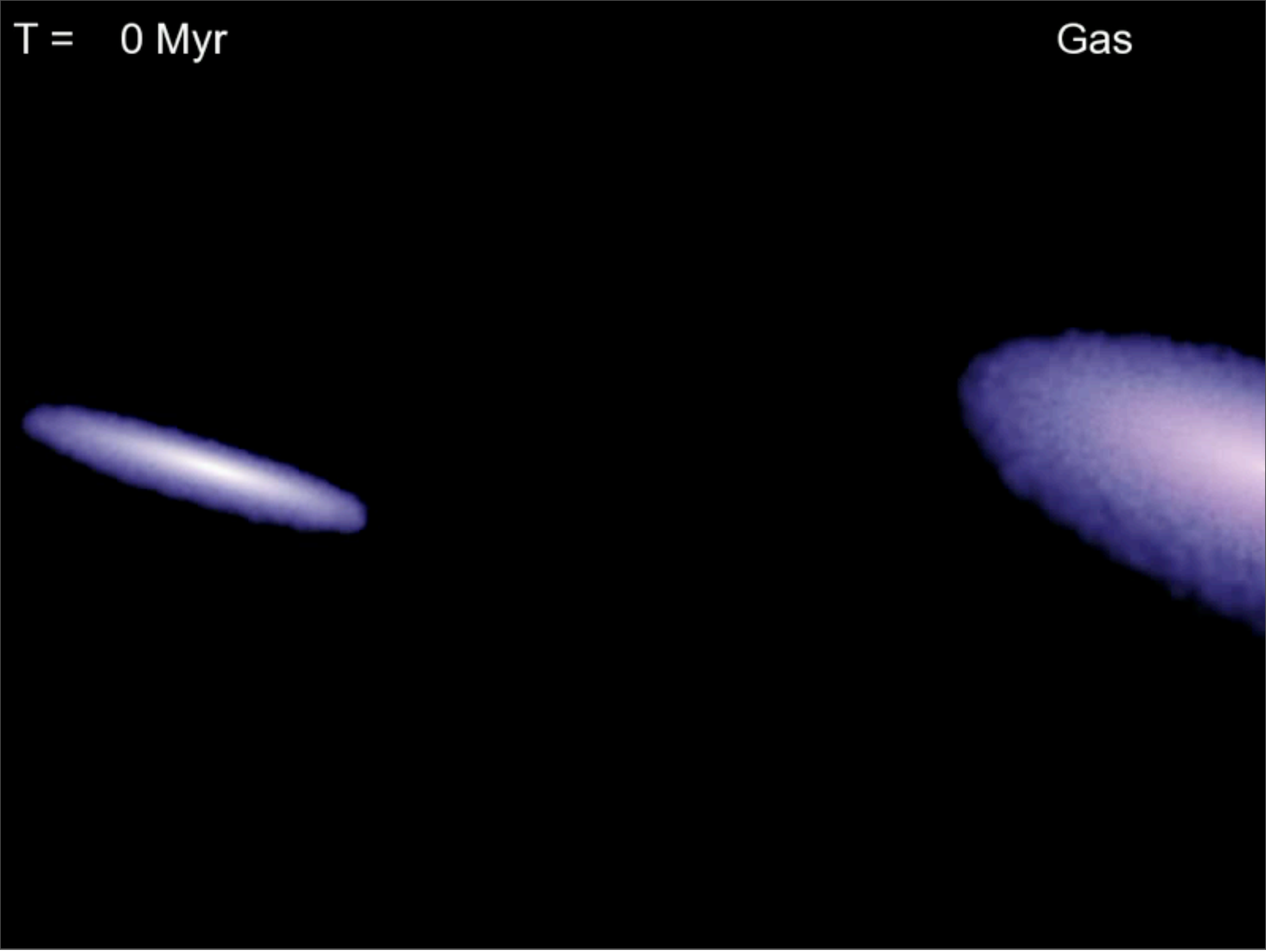


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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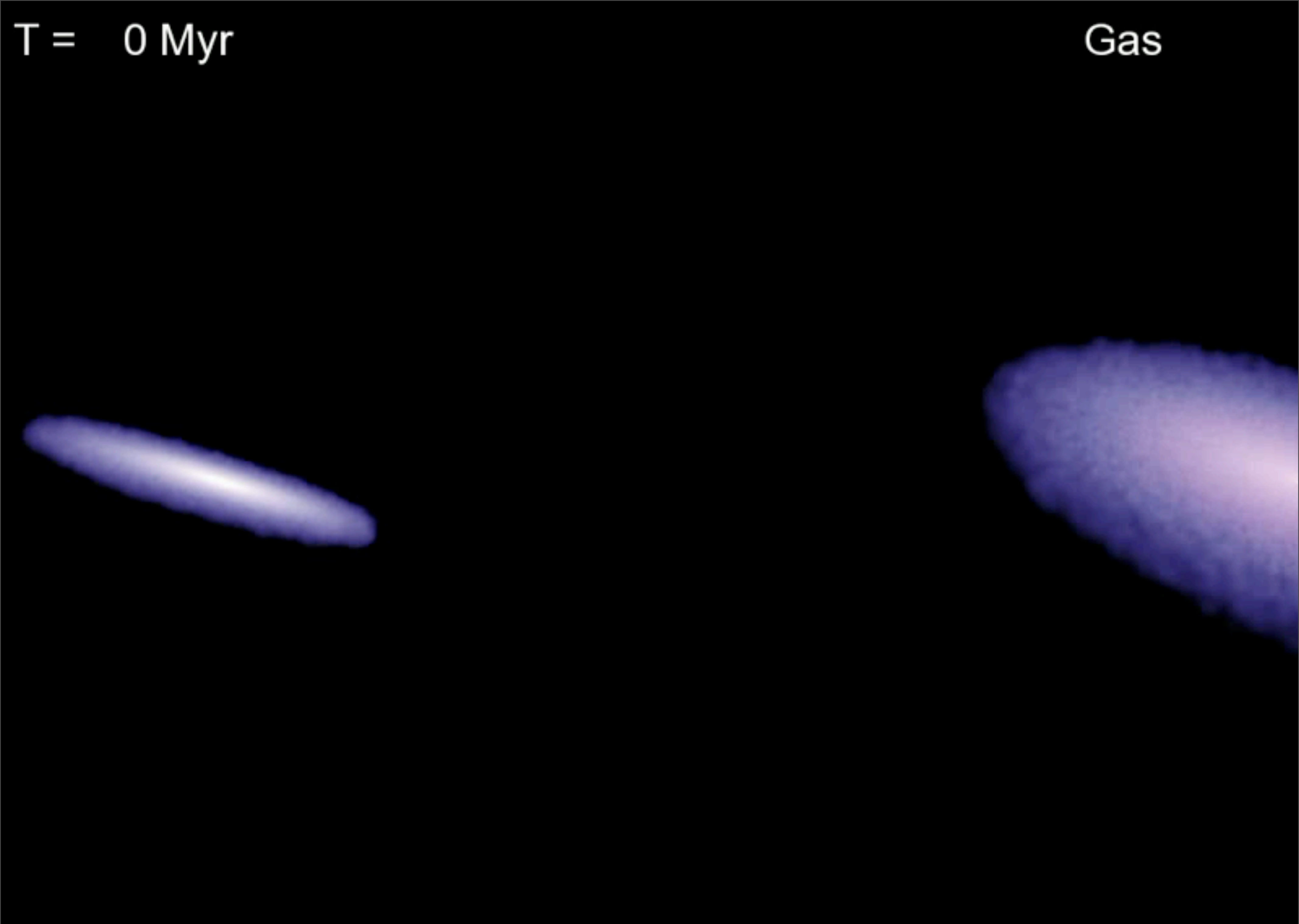
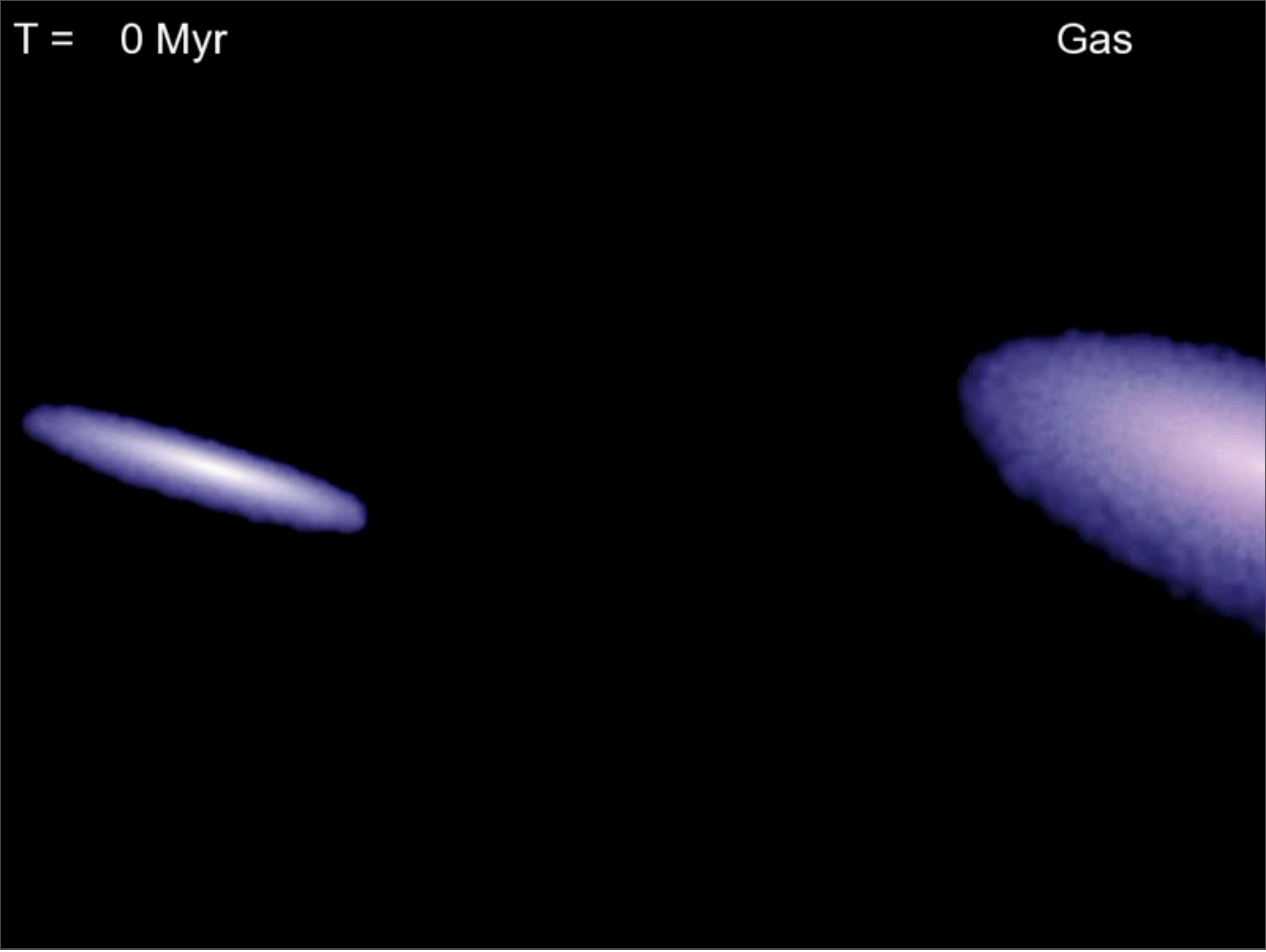


Feedback expels remaining gas, shutting down growth (more later...)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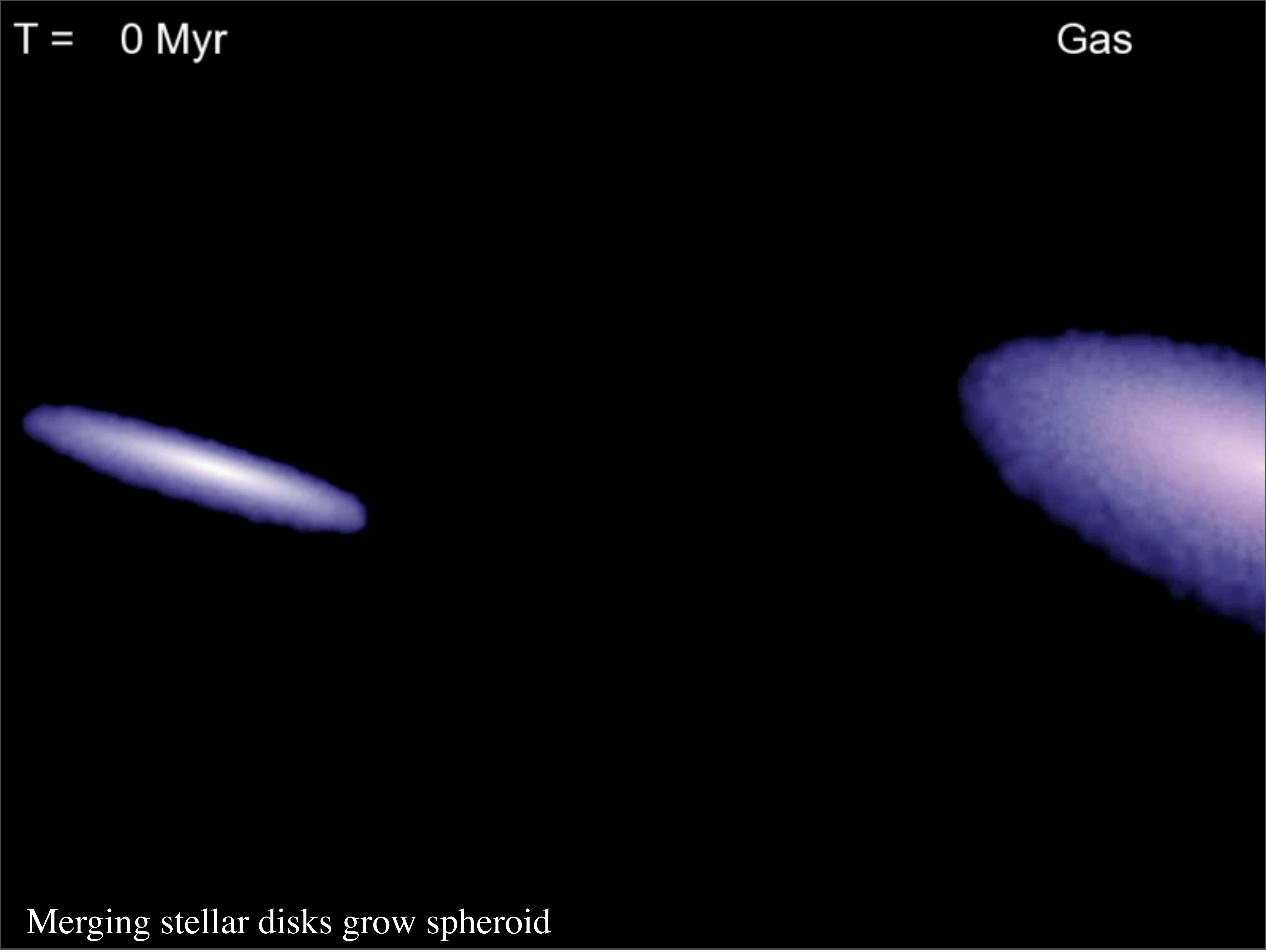
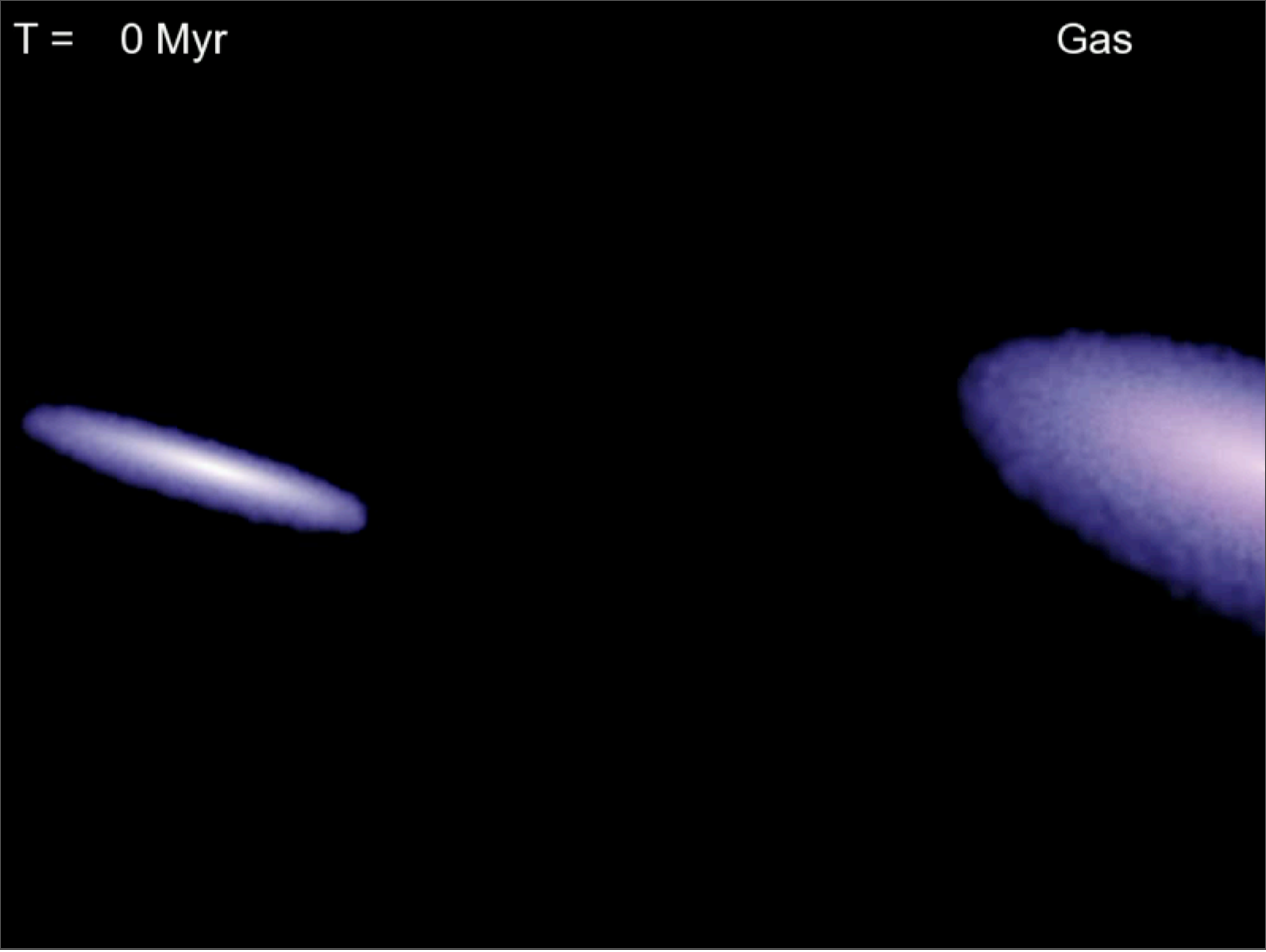


Merging stellar disks grow spheroid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What About the Gas that Does Lose Angular Momentum?

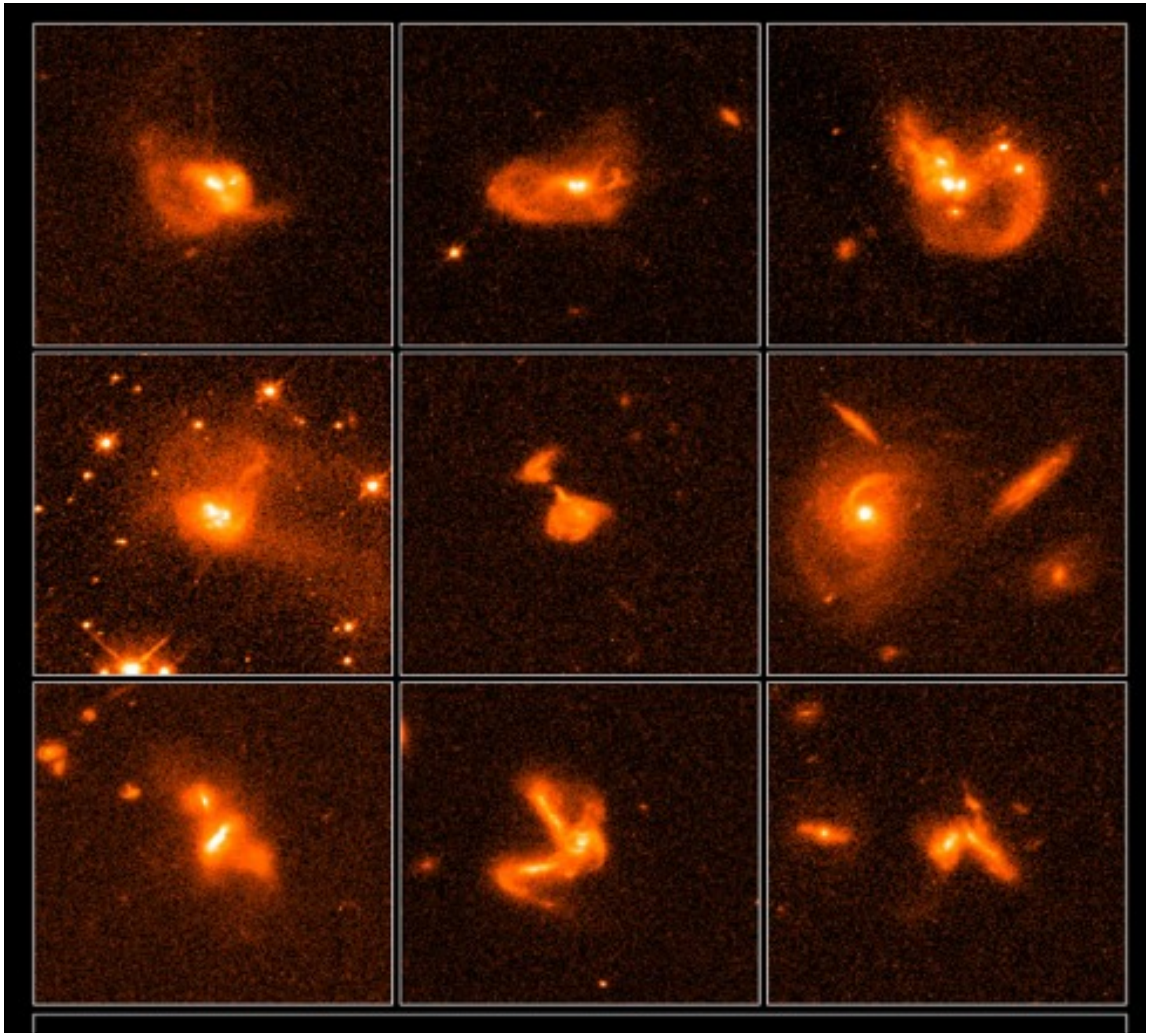
CAN WE MAKE A REAL ELLIPTICAL?

Borne et al., 2000

Funneled to the center → massive starbursts

Locally, *all* massive starbursts (> 100 M_{sun}/yr) are late-stage mergers

Observe Compact Gas: ~10^{10} M_{sun} on <kpc scales



Are they the progenitors of ellipticals?

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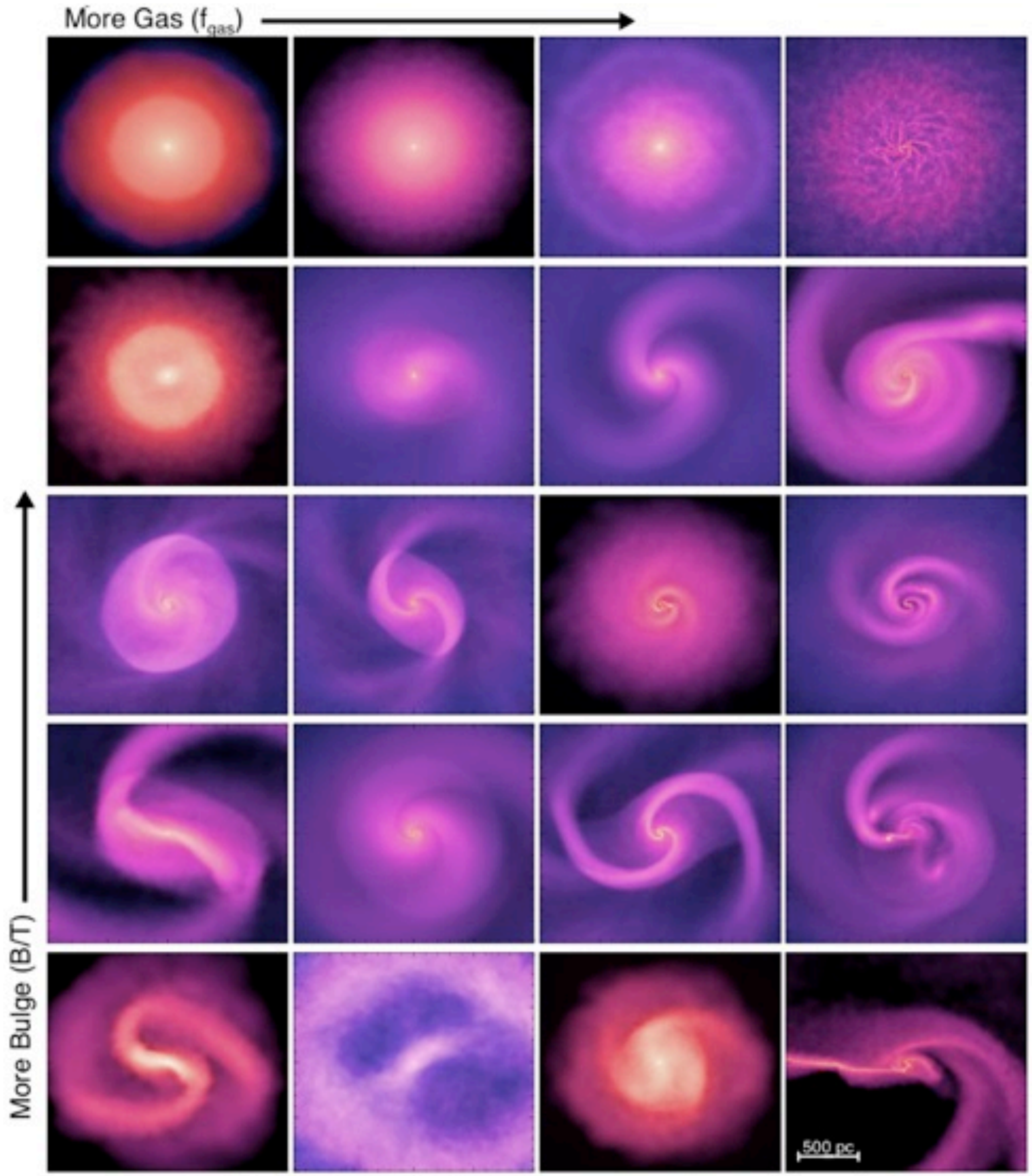

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New Work by

D. Narayanan,
C. Hayward,
P. Jonsson

SUNRISE code:

- 3-d, adaptive mesh (post-process)
- Monte Carlo radiative transfer
- sub-grid model for ISM clouds
- dust radiative equilibrium
- line transfer (polychromatic)
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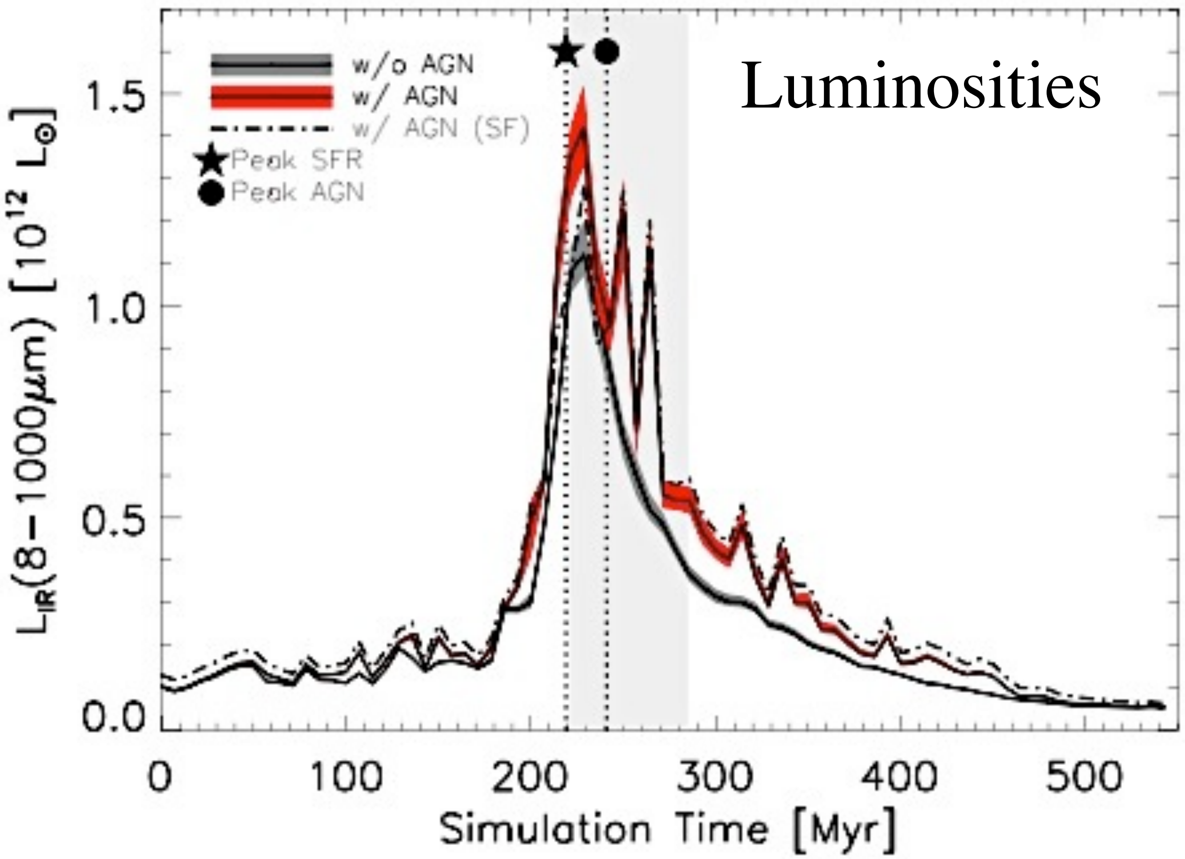

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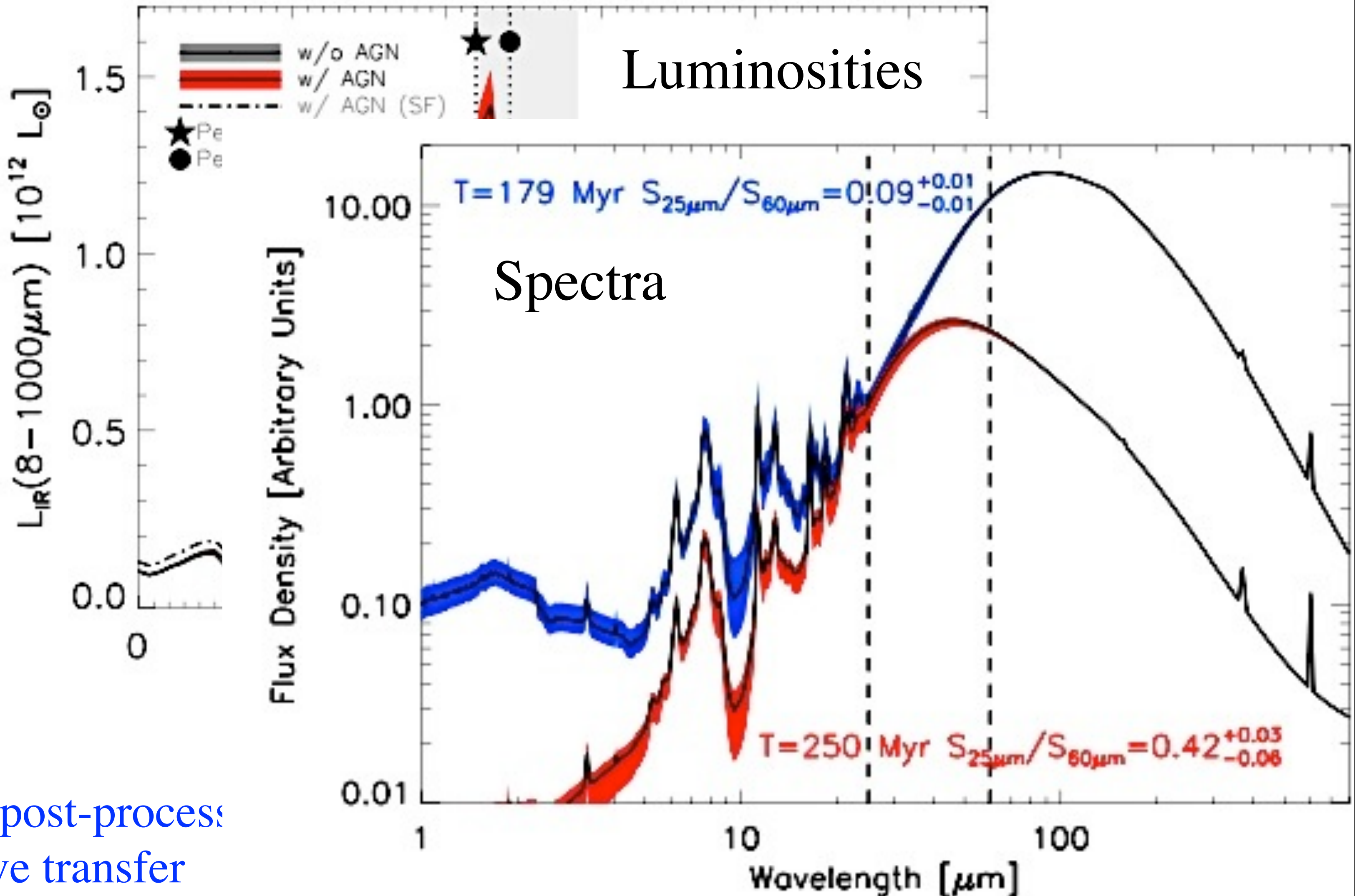

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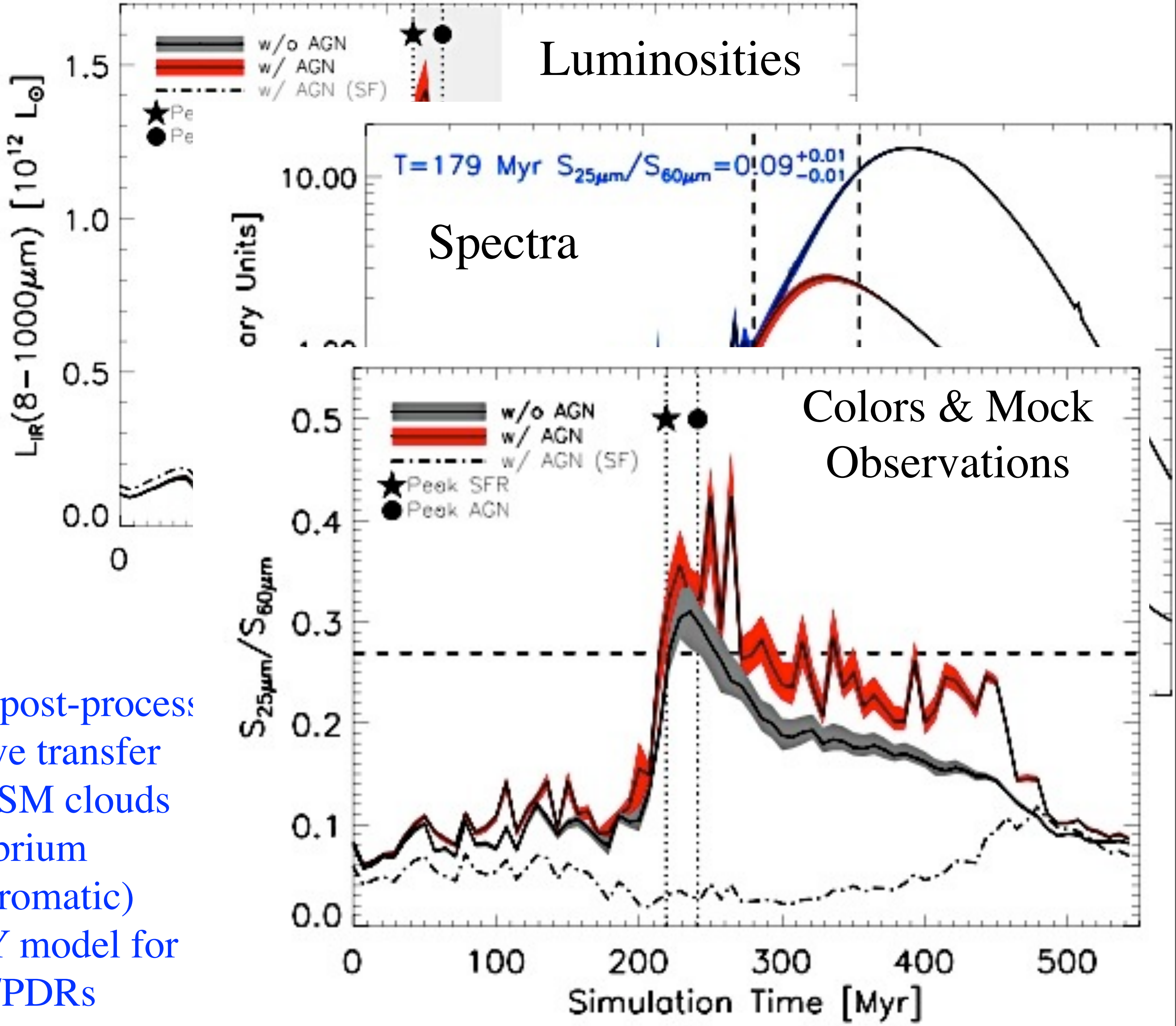

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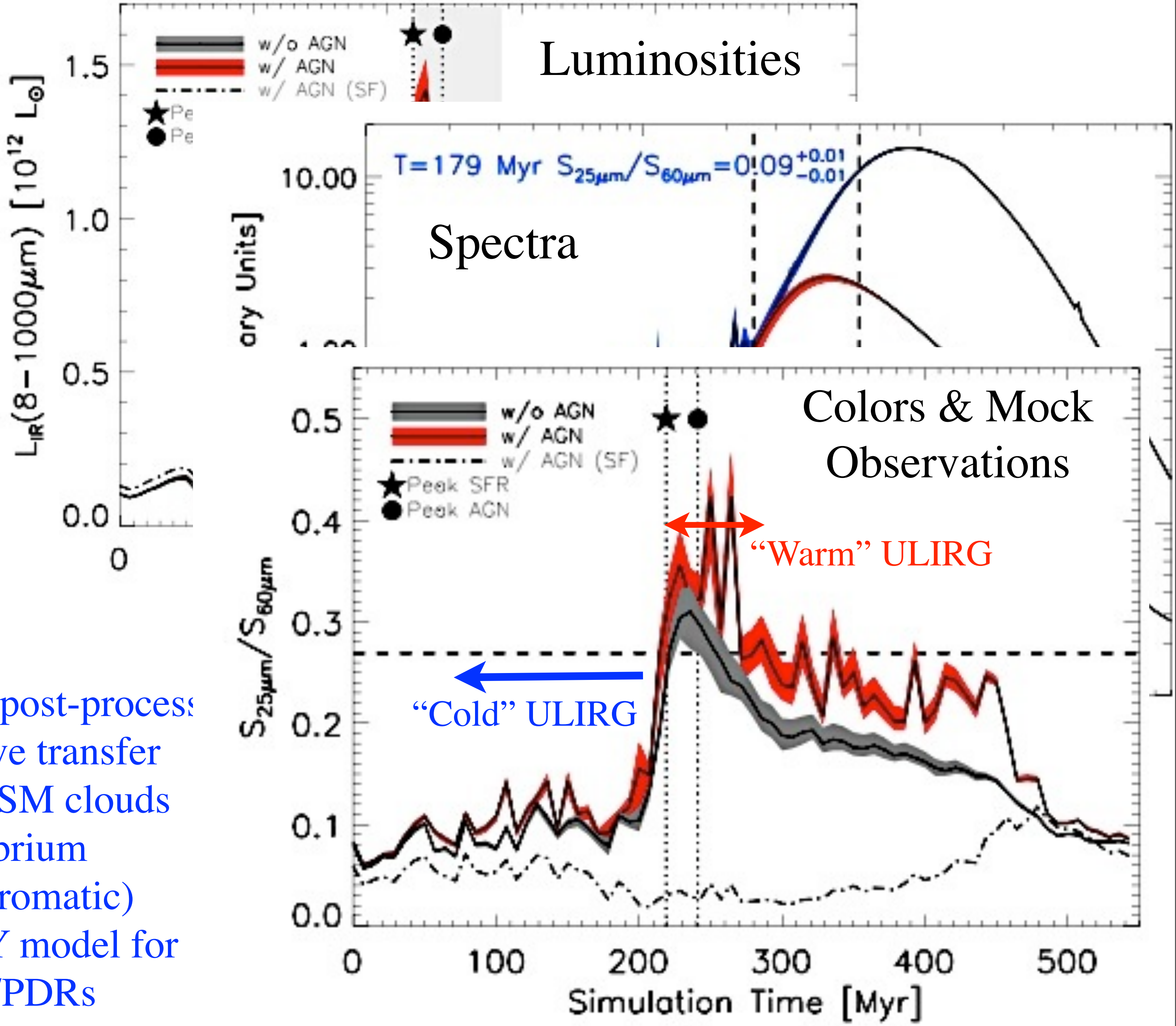
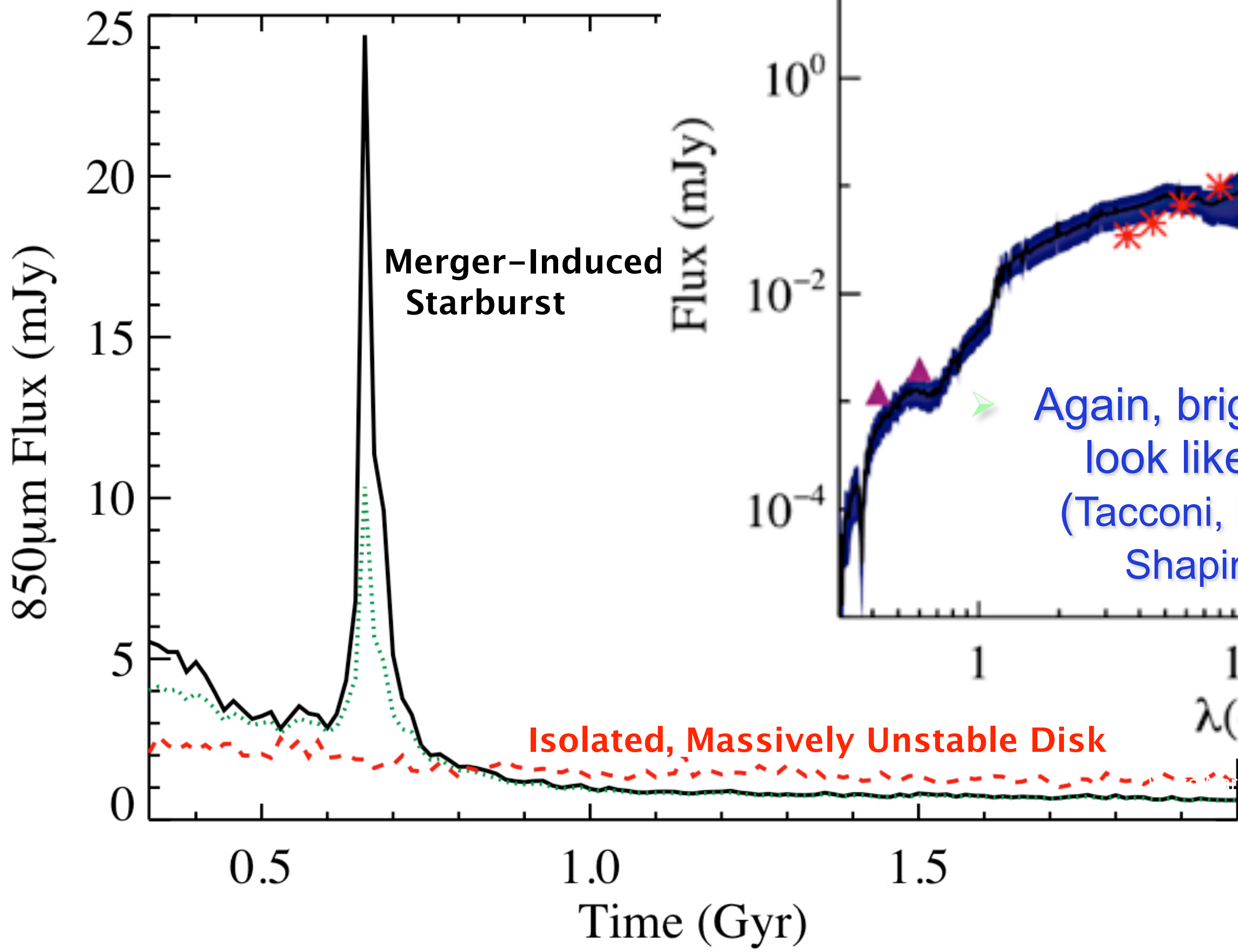
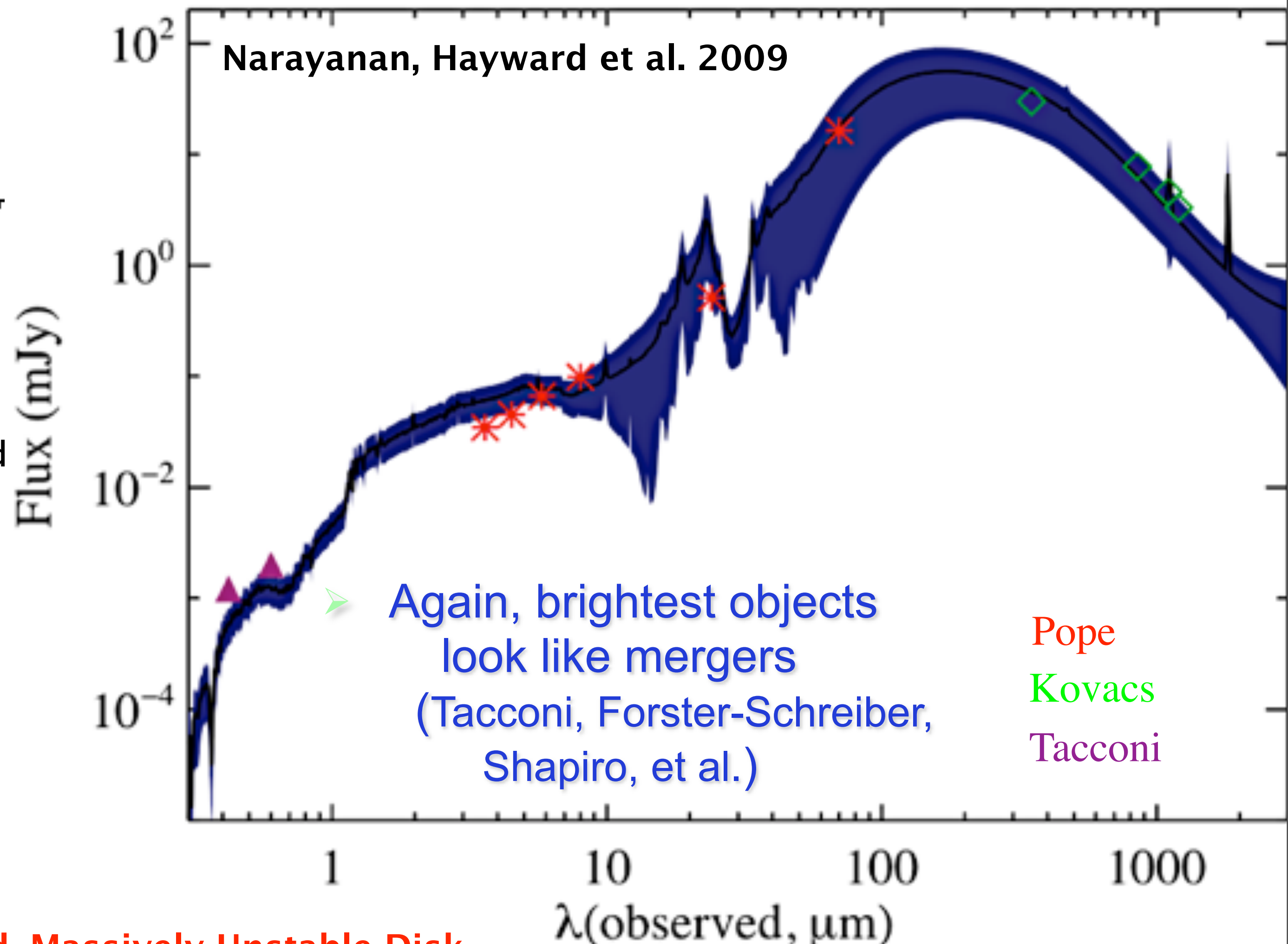


What About the Gas that Does Lose Angular Momentum?

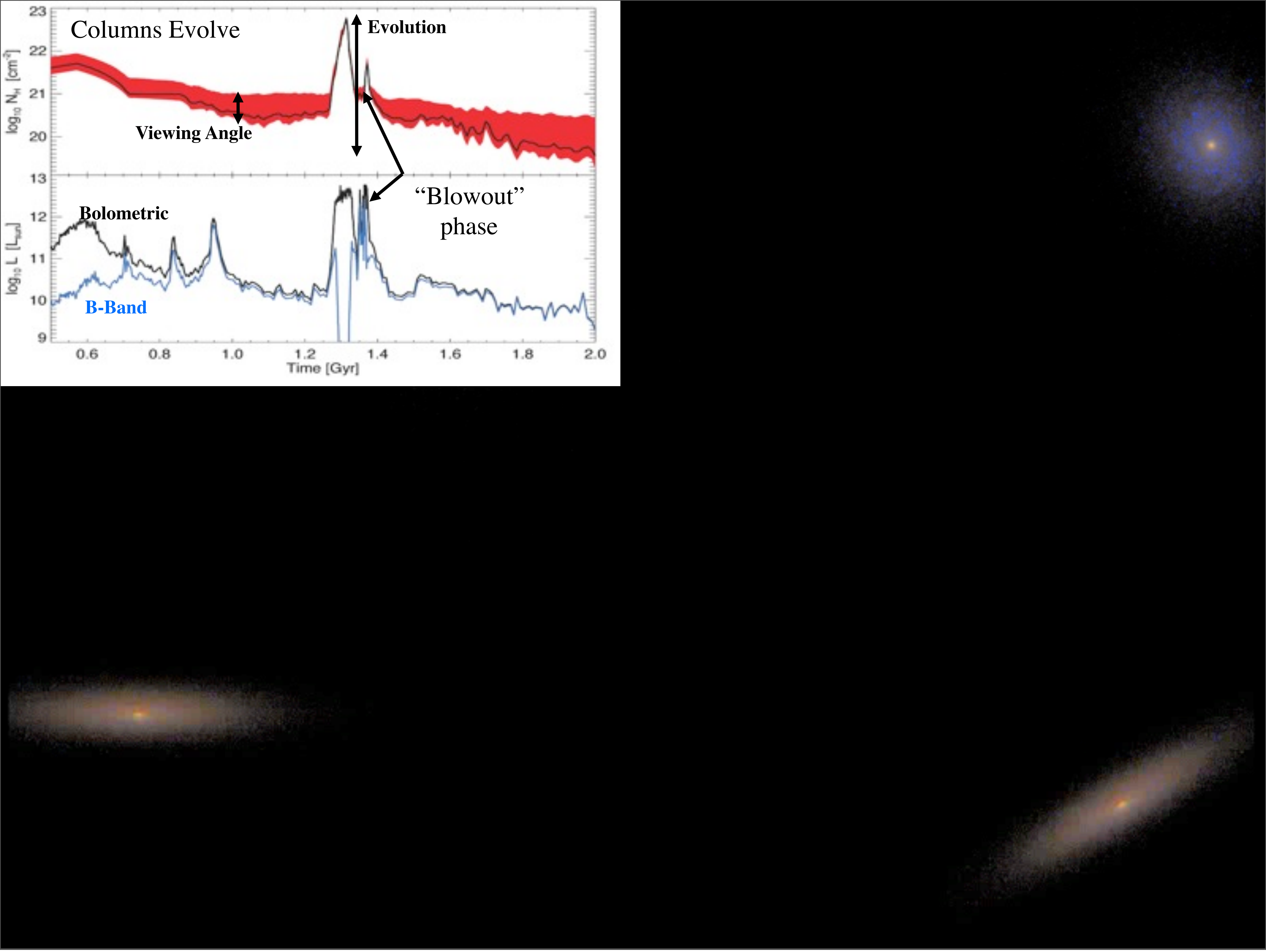
STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

- Not just at z=0, but in high-redshift sub-millimeter galaxies



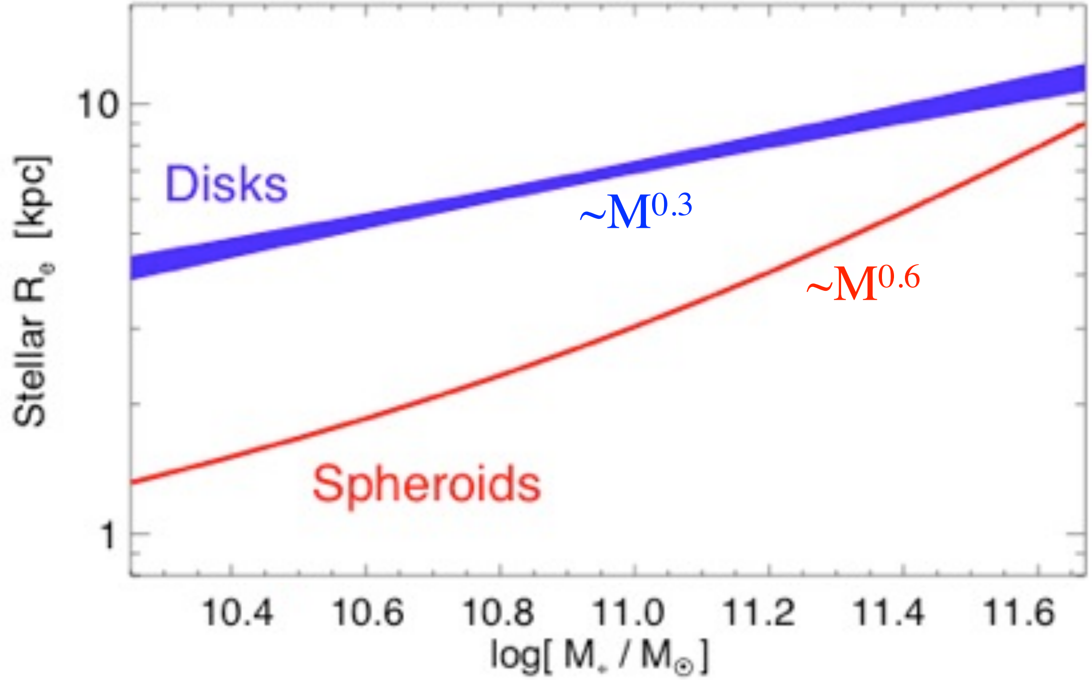


- Again, brightest objects look like mergers (Tacconi, Forster-Schreiber, Shapiro, et al.)

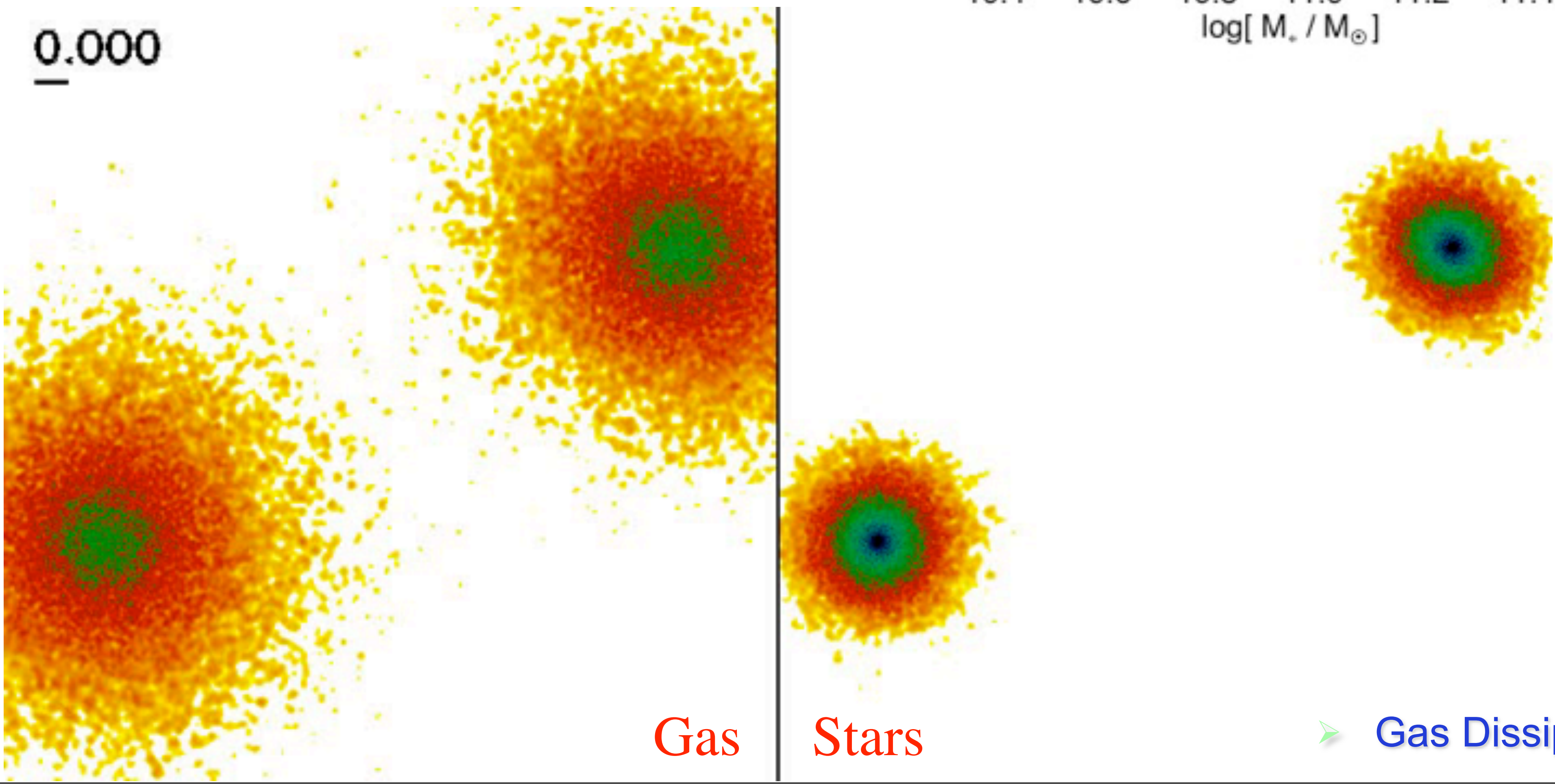

Columns Evolve
Evolution
Viewing Angle
"Blowout"
phase
Bolometric
B-Band
log10 NH [cm-2]
log10 L [Lsun]
Time [Gyr]
23
22
21
20
13
12
11
10
9
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

So What Difference Does this Starburst Make?

The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks?

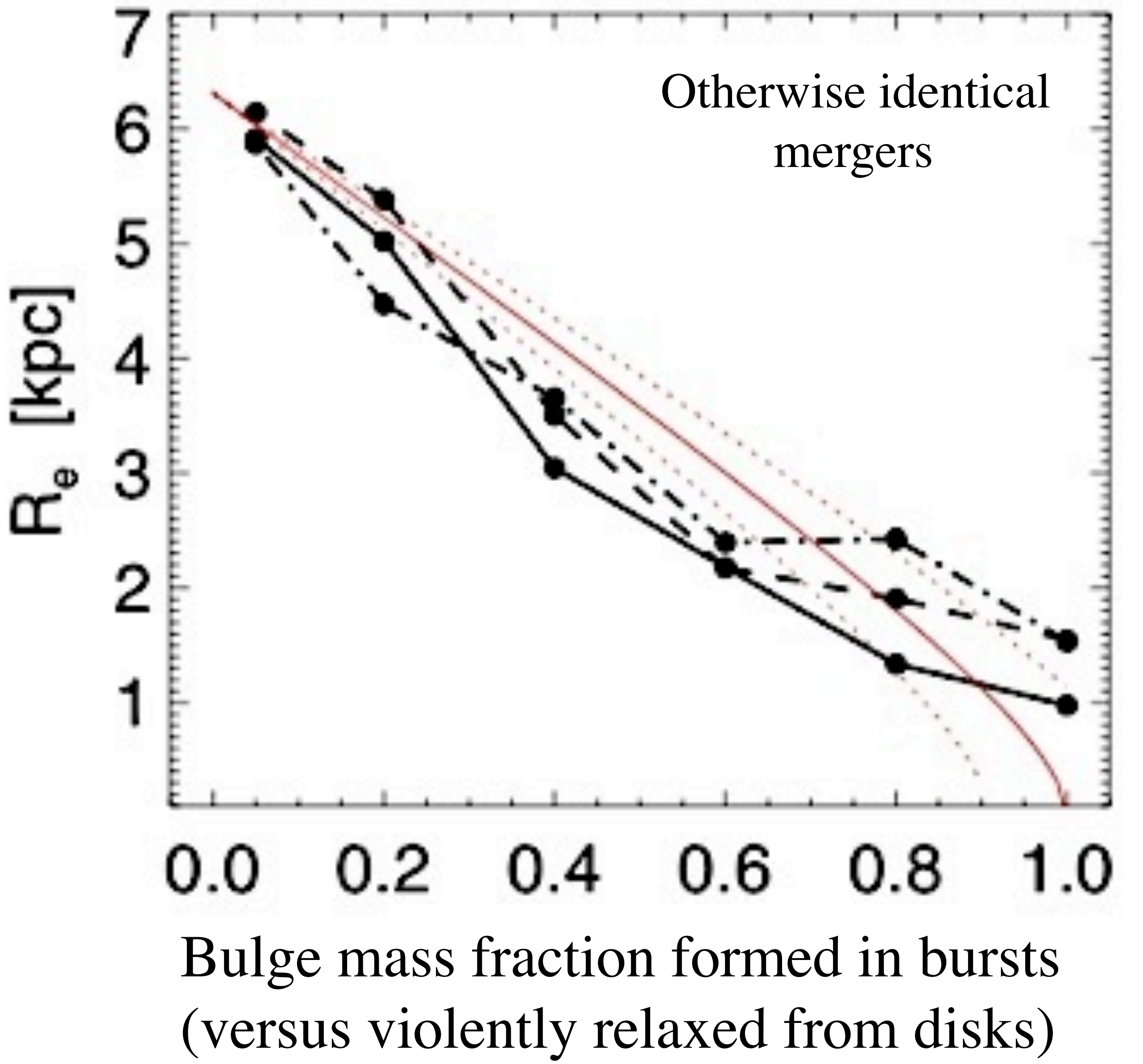


- Gas Dissipation

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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



PFH, Cox et al. 2008

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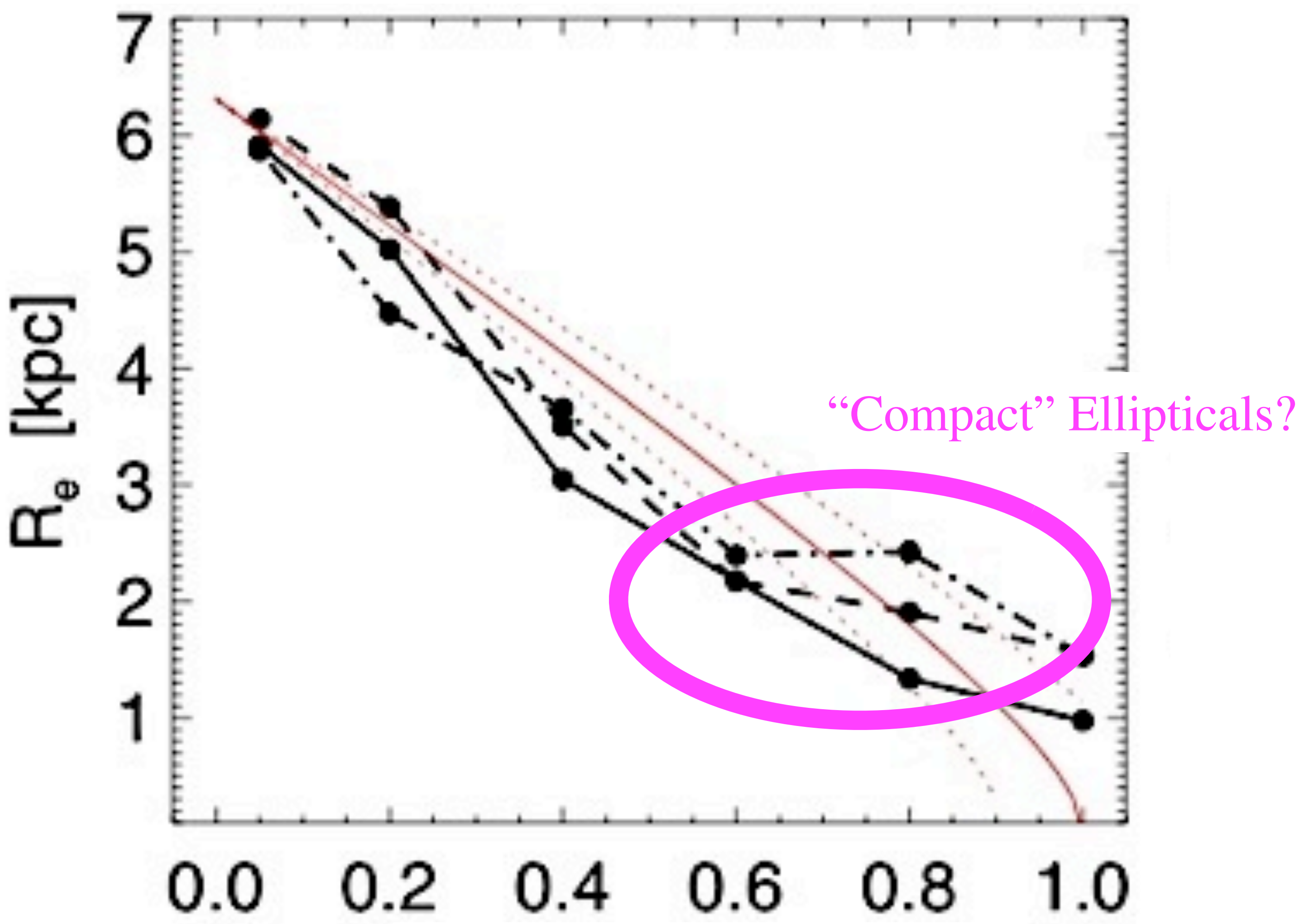
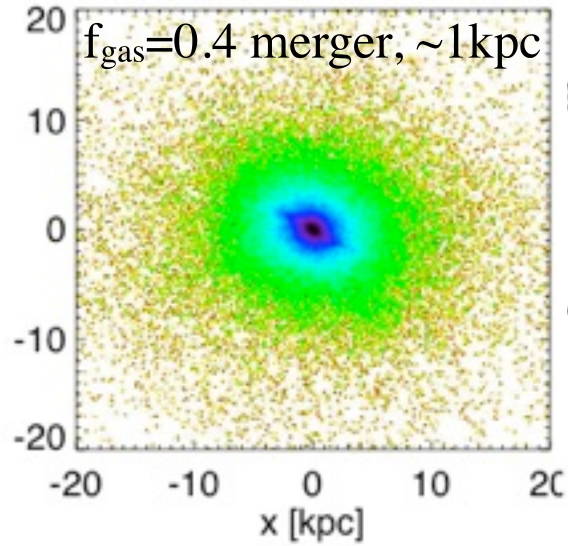
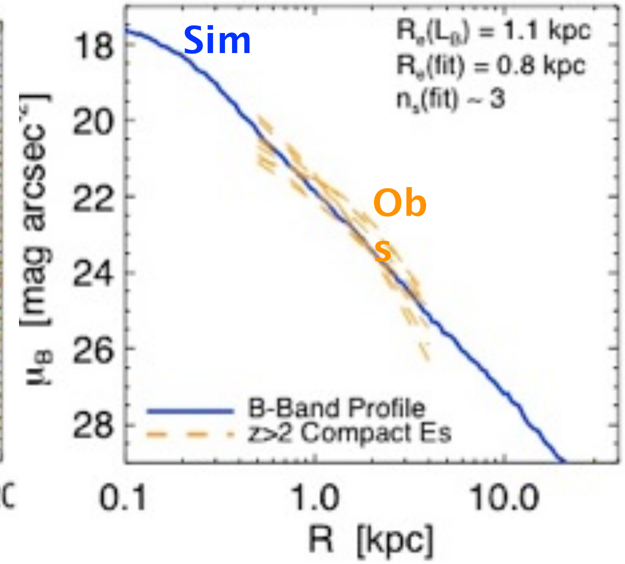


Bulge mass fraction formed in bursts
(versus violently relaxed from disks)

Compare: massive spheroids
at z=2 to those today

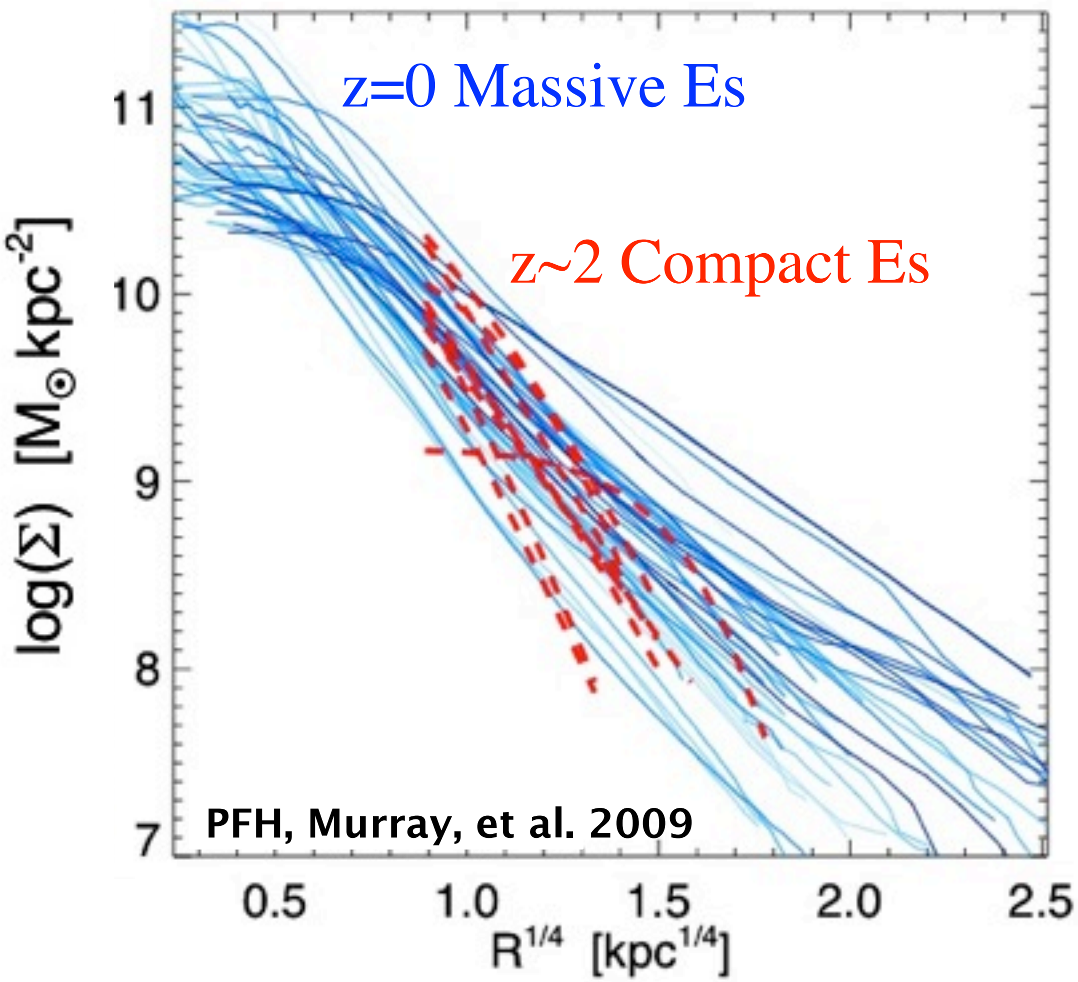
... vs gas-rich merger with later
low-density/minor mergers





Observations: van Dokkum, Trujillo, Tacconi, Kormendy

(z=0)



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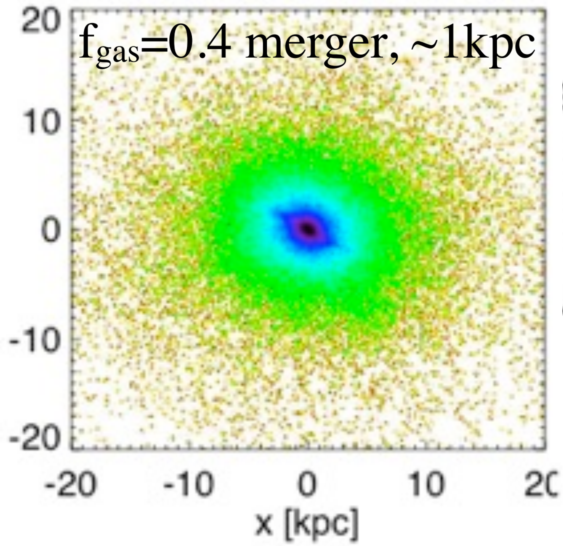

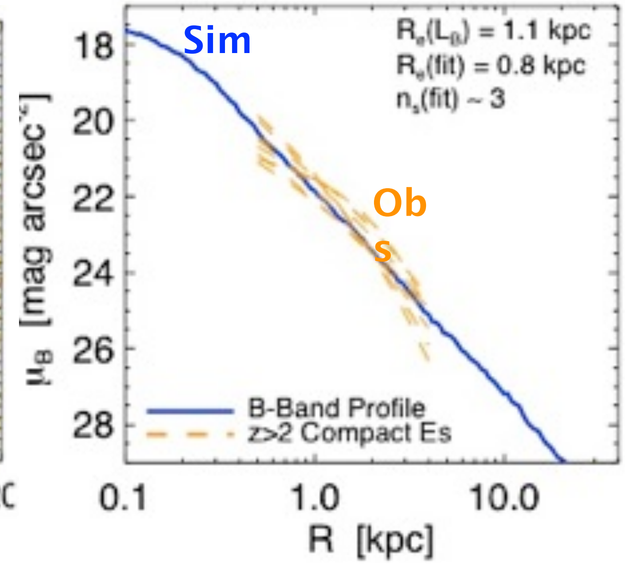

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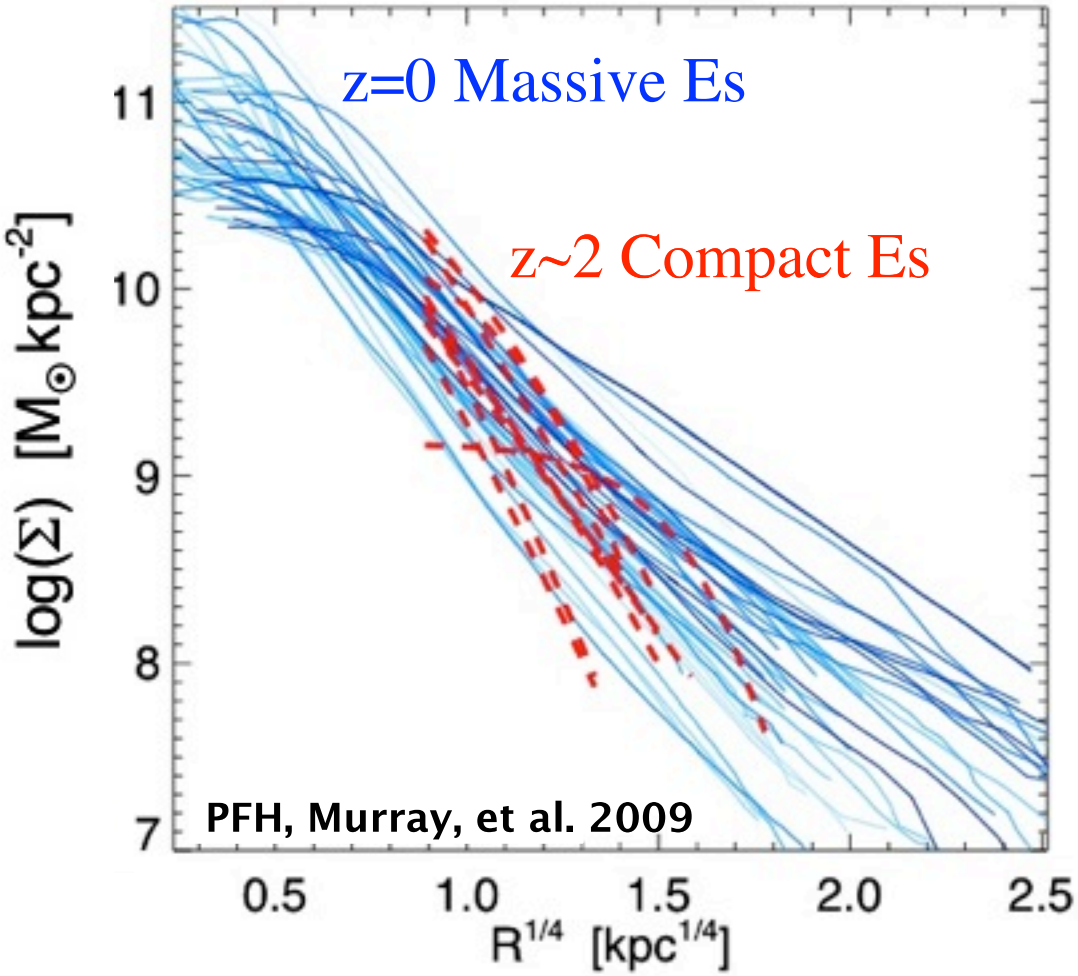

Outer “envelopes” build
up after spheroid cores
form


T. Naab et al.

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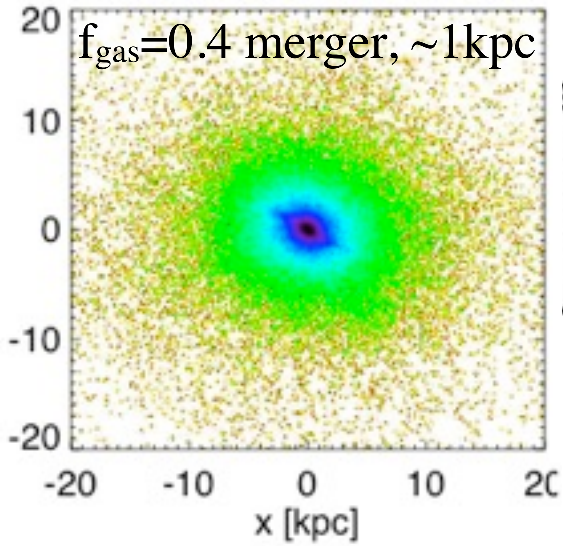
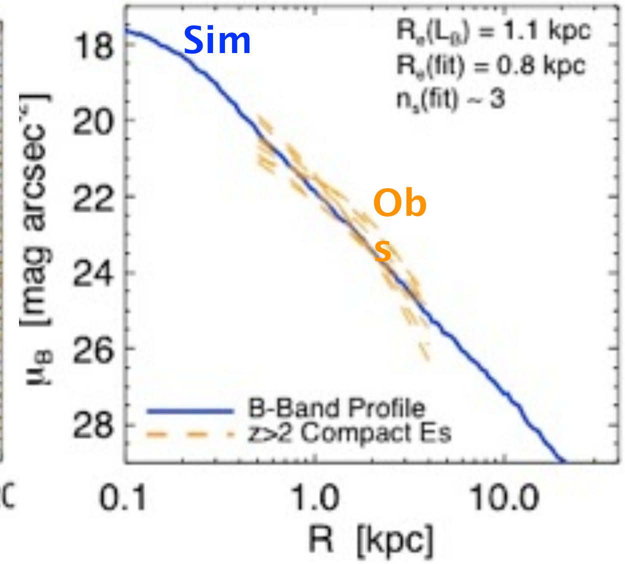
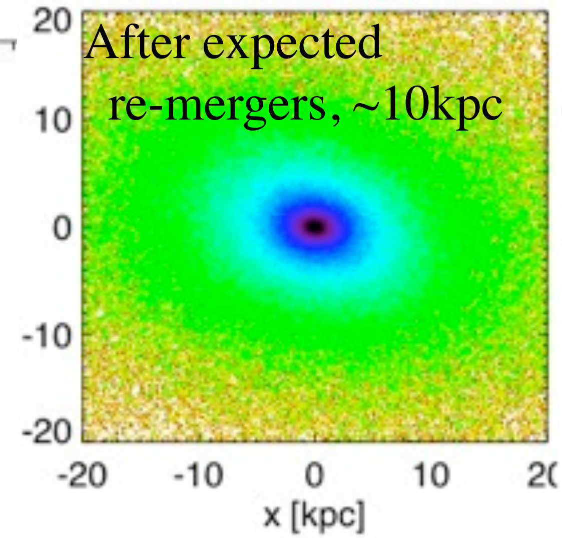
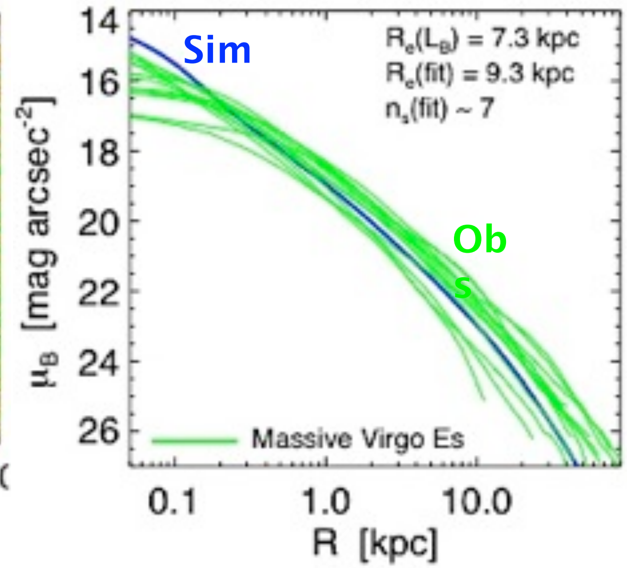
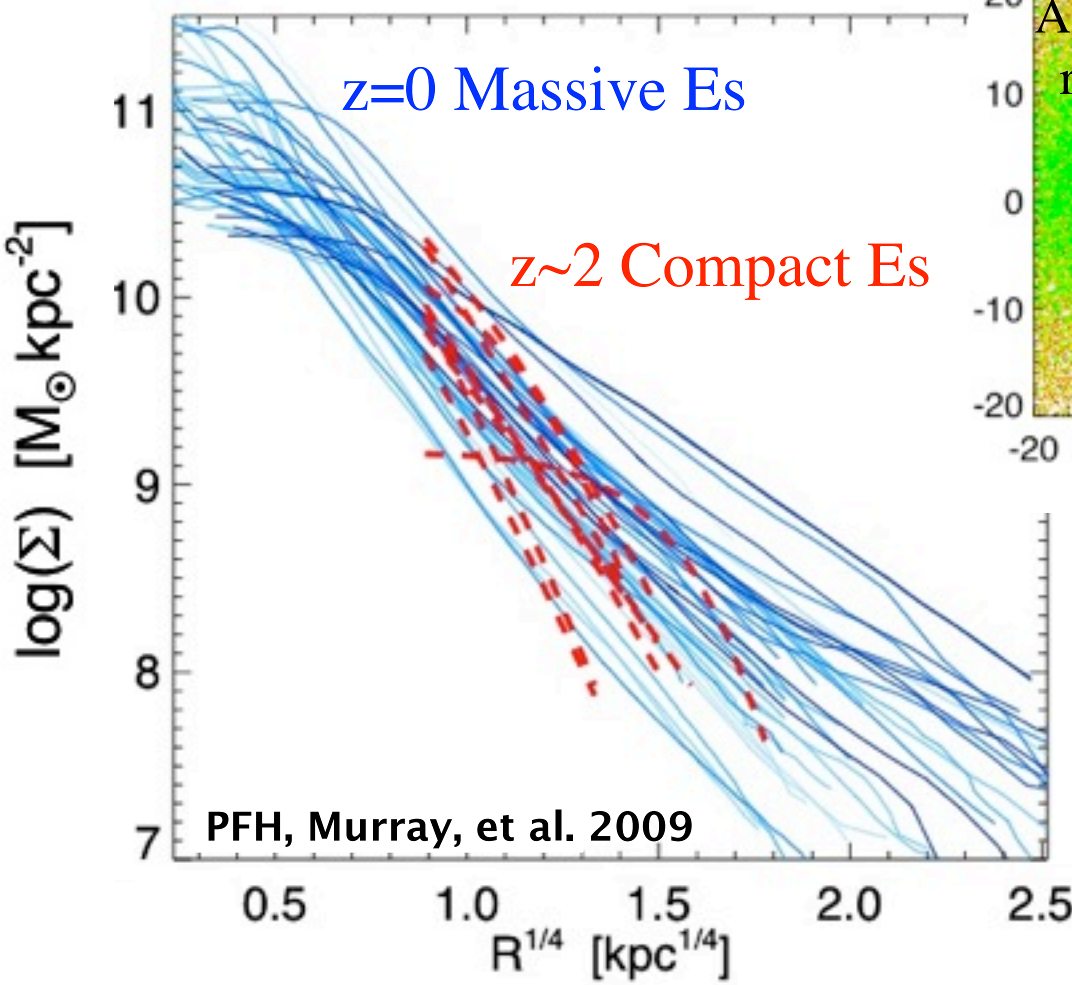






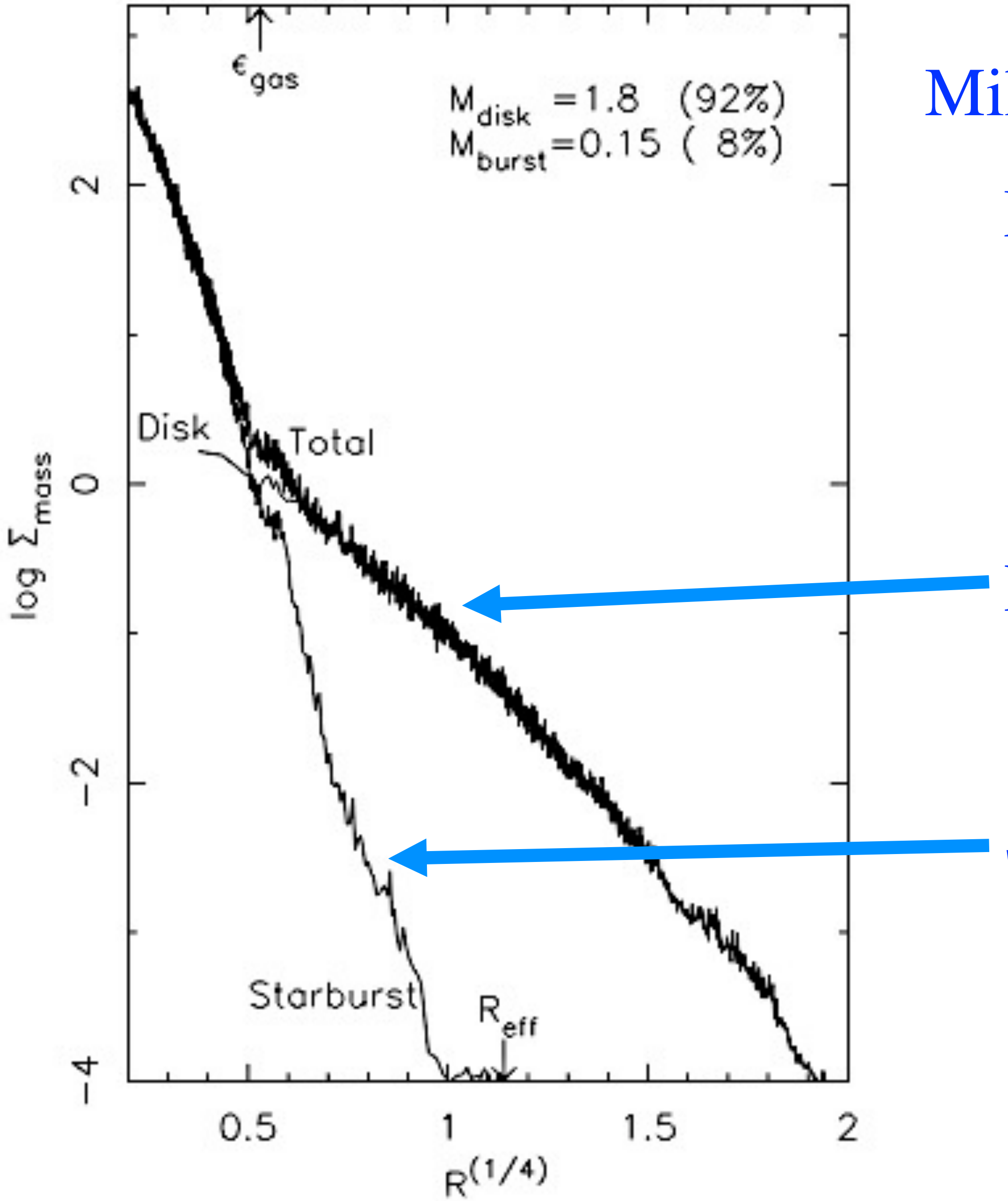




PFH, Bundy, et al. 2009

also Bezanso Naab et al.

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:

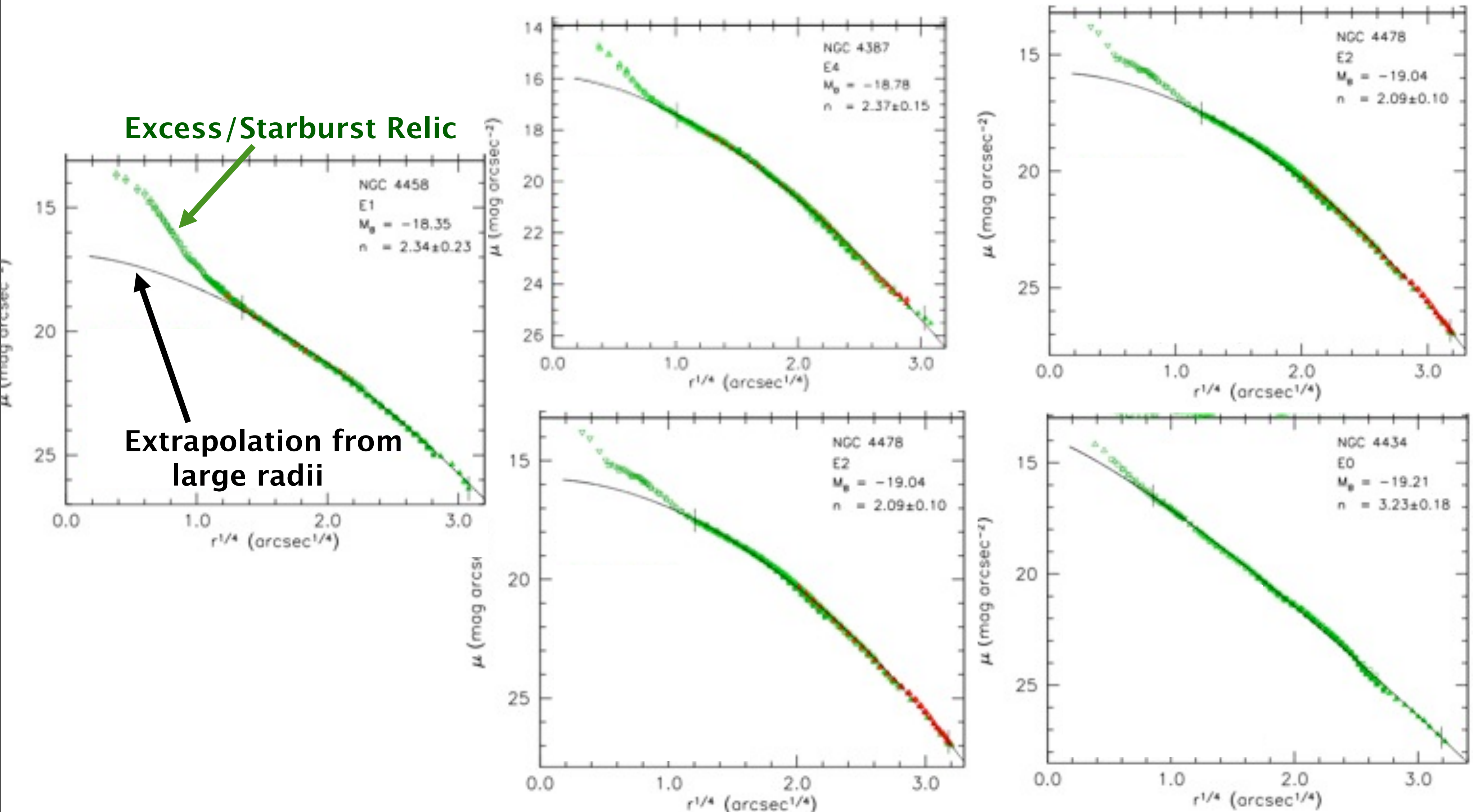
“Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?” (MH94)

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

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...

Kormendy et al. 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."

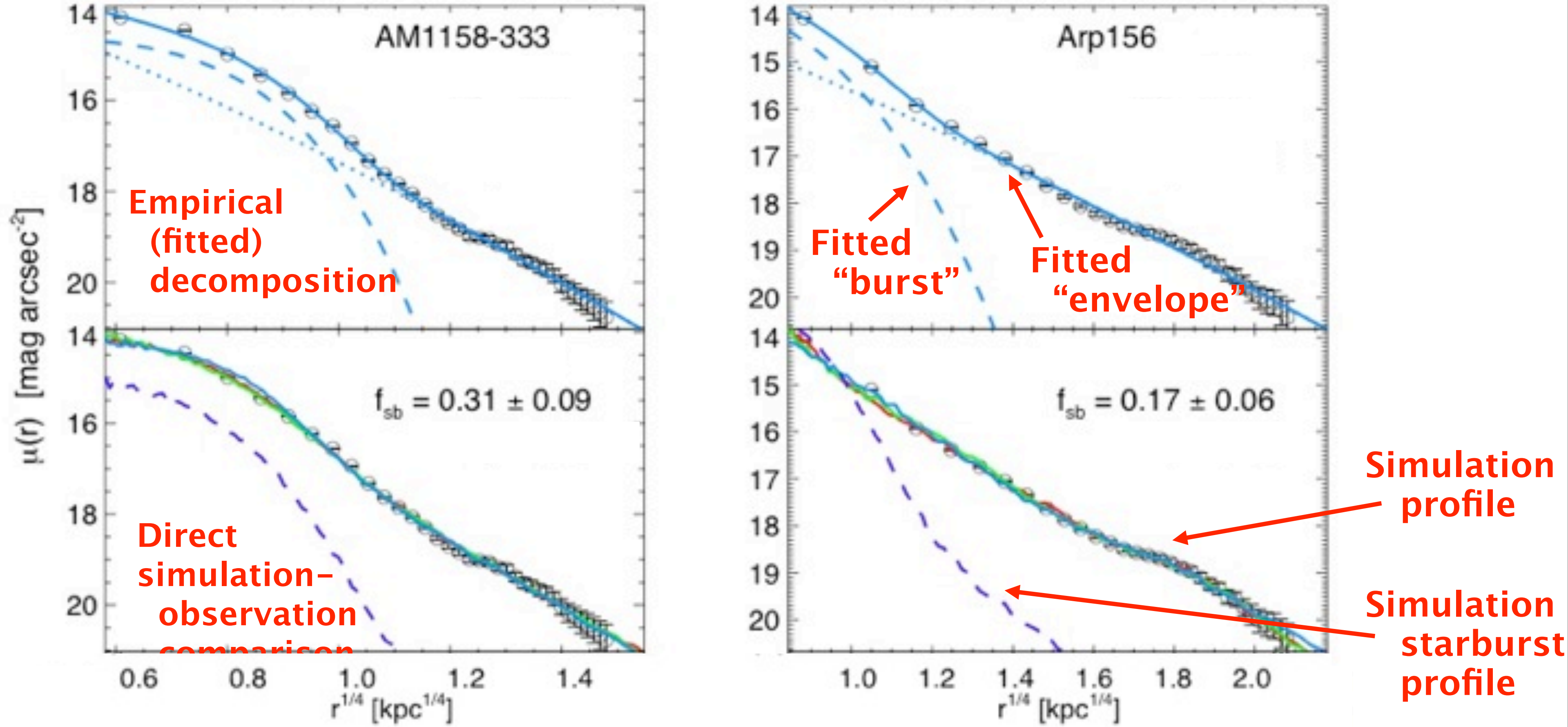
Application: Merger Remnants

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:



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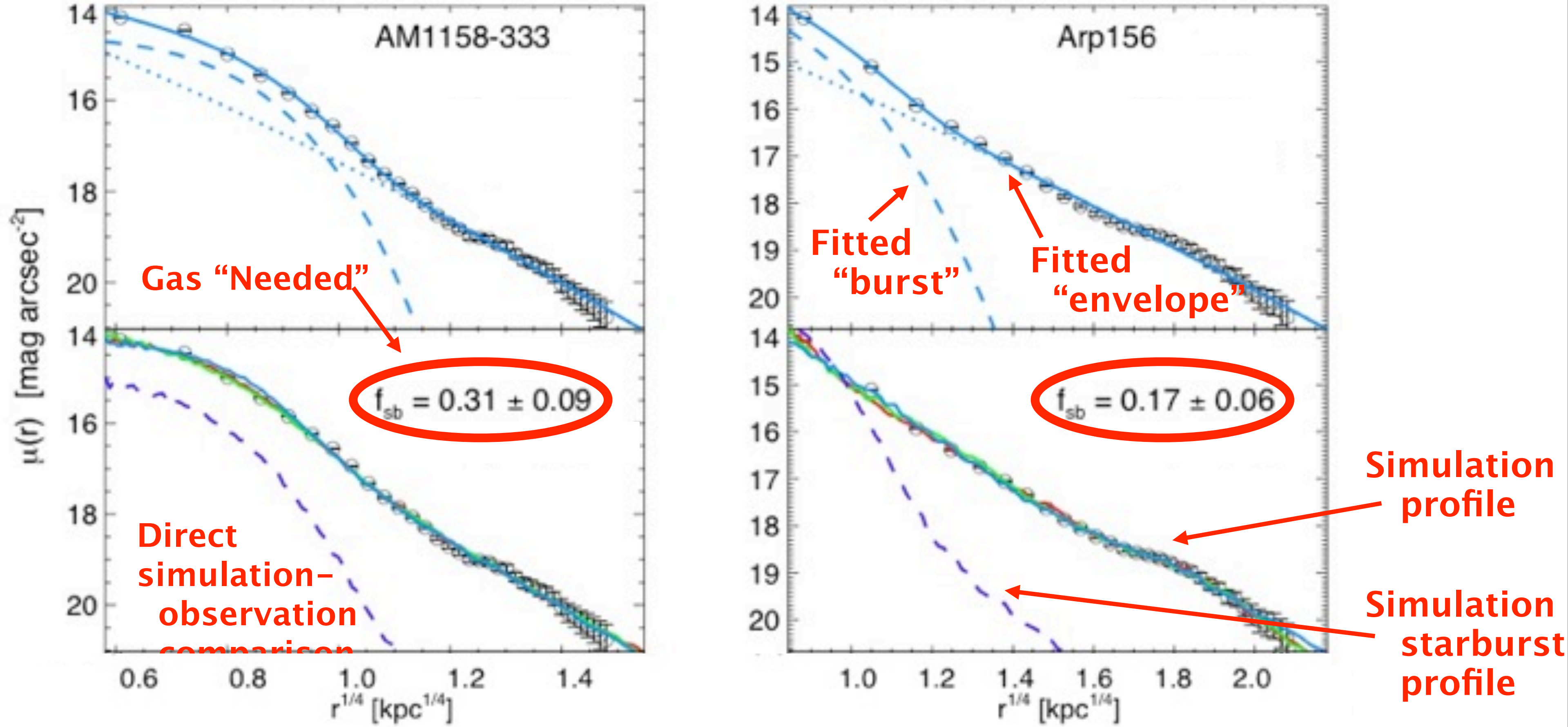

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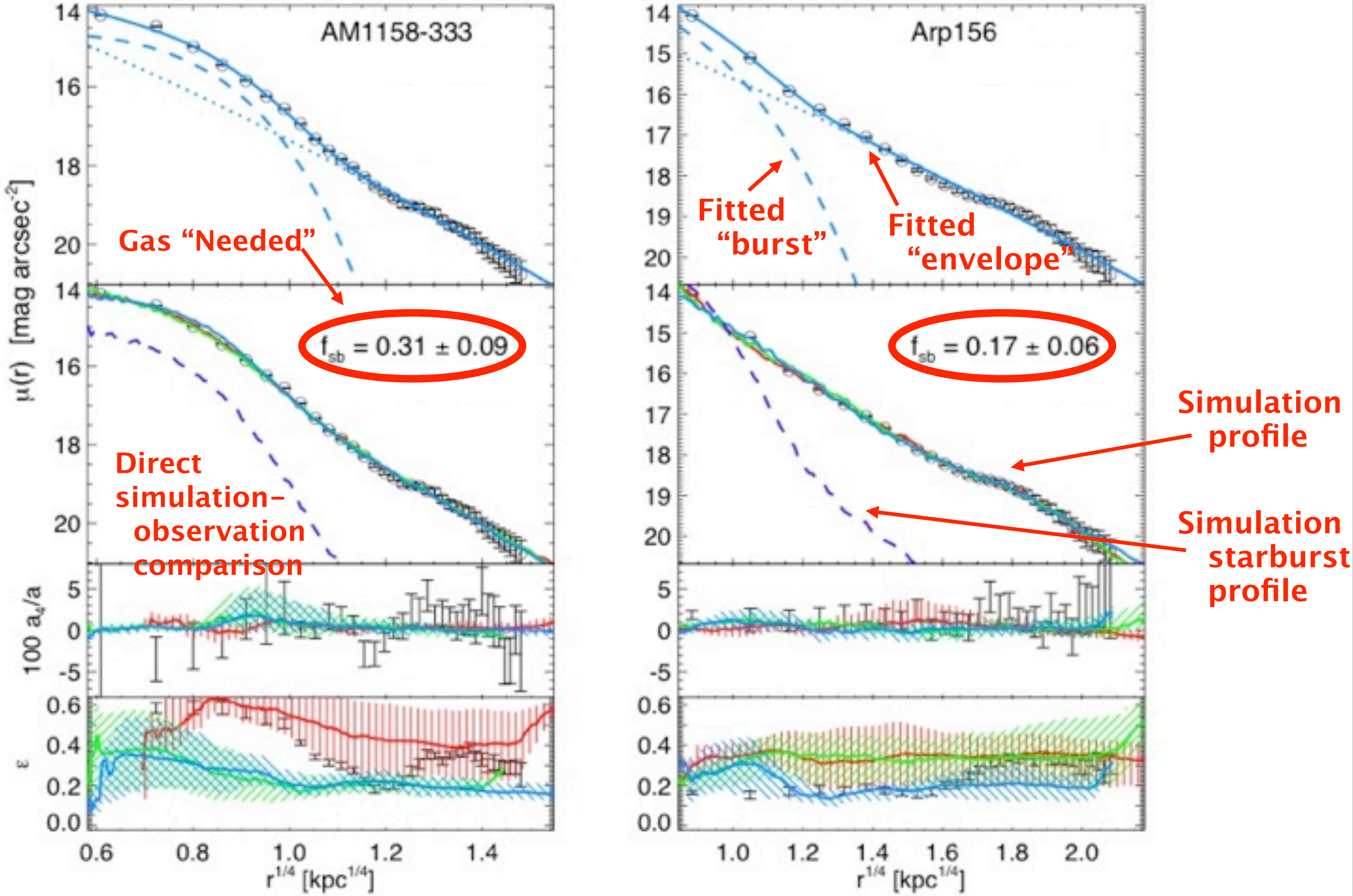


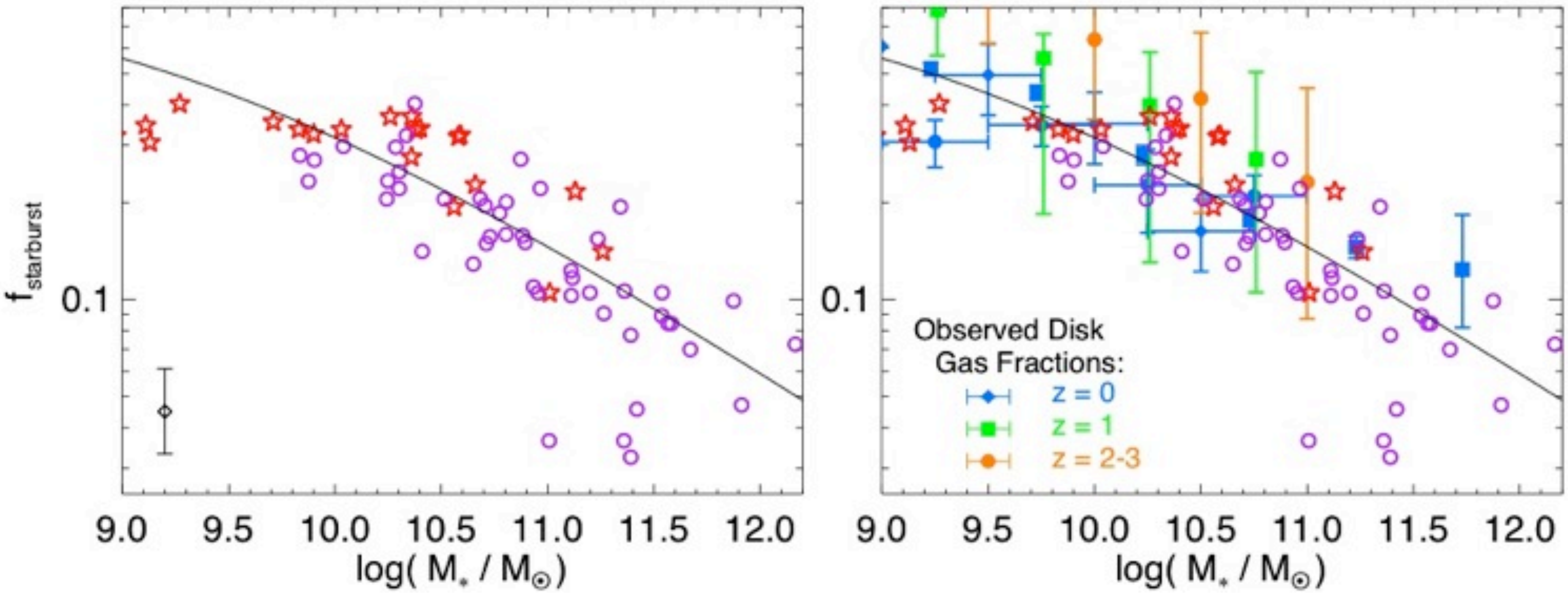
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

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

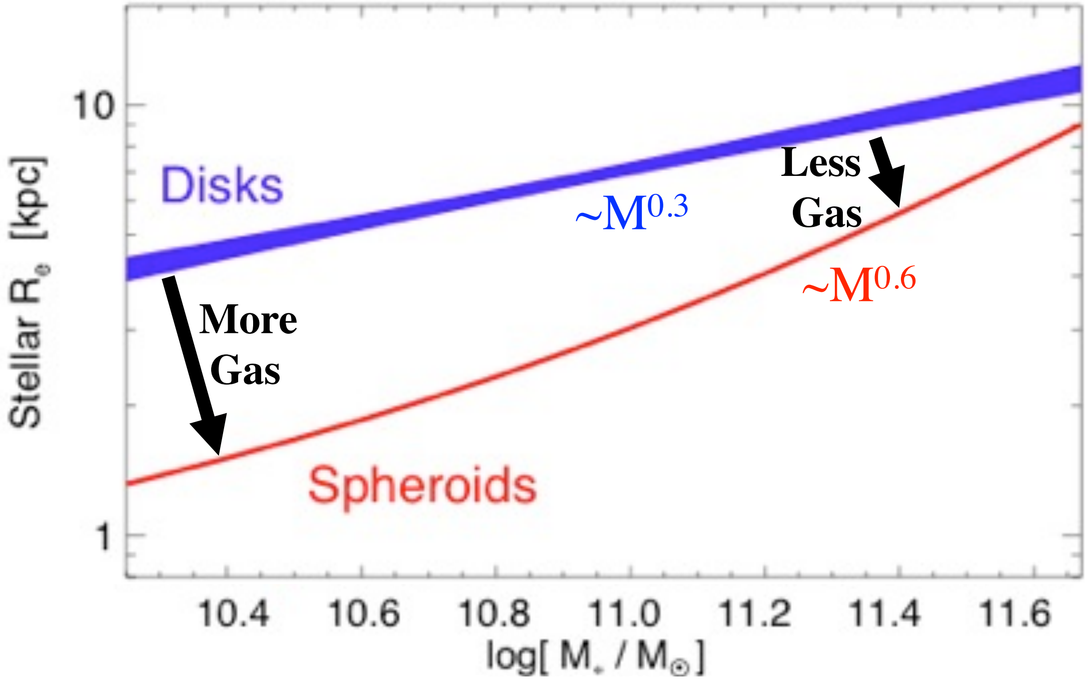


- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns

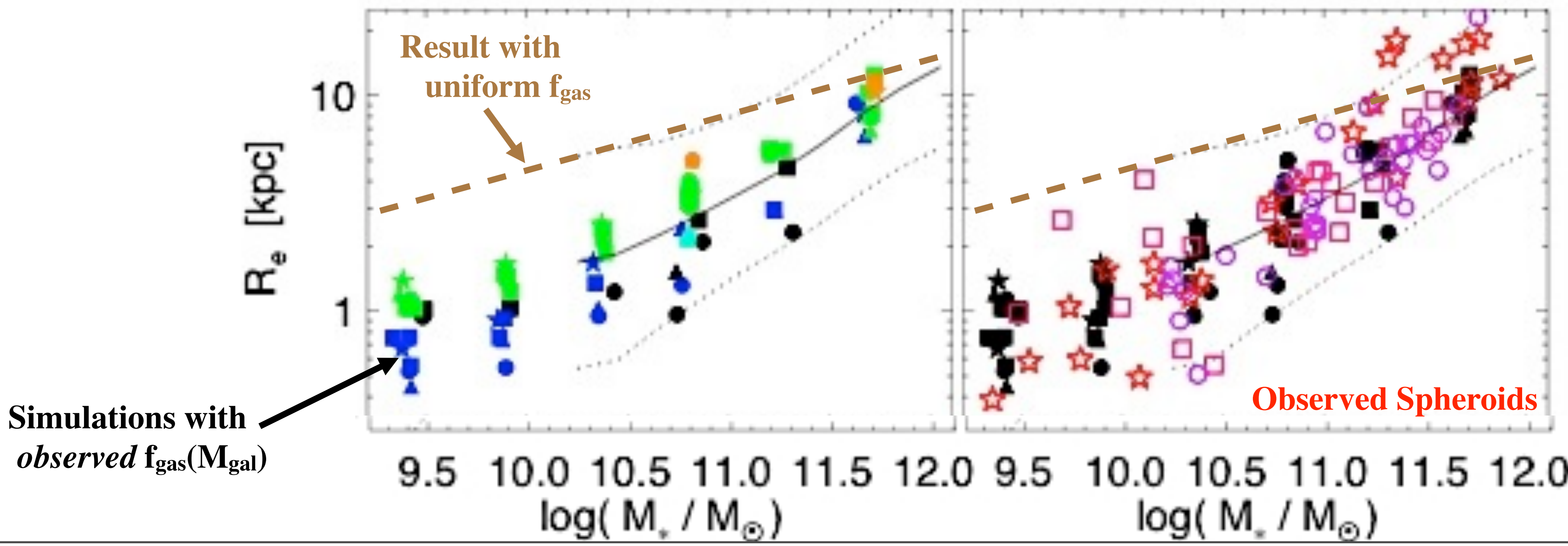
Structure in Elliptical Light Profiles

PFH, Cox, & Hernquist 2008

EXPLAINS THE "TILT" IN THE FP RELATIONS



- Spheroid correlations "tilted" from disks because of f_{gas}-M_{gal} correlation

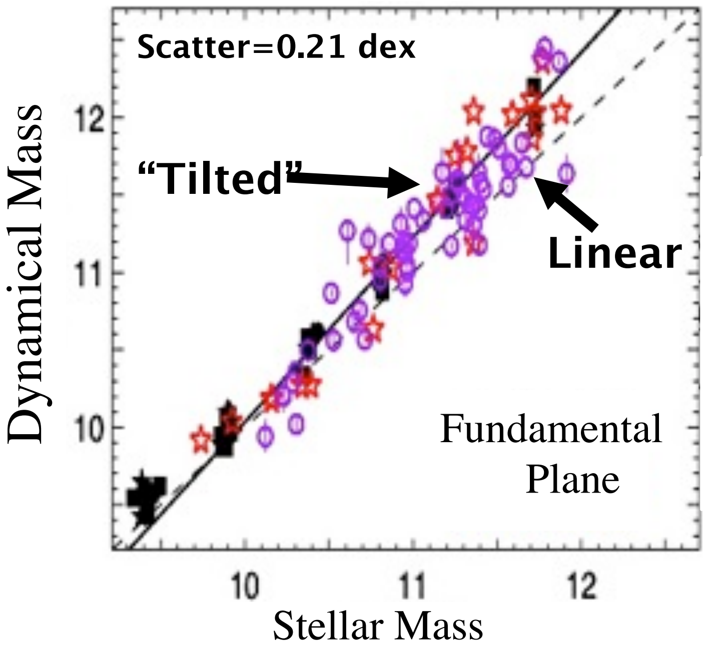


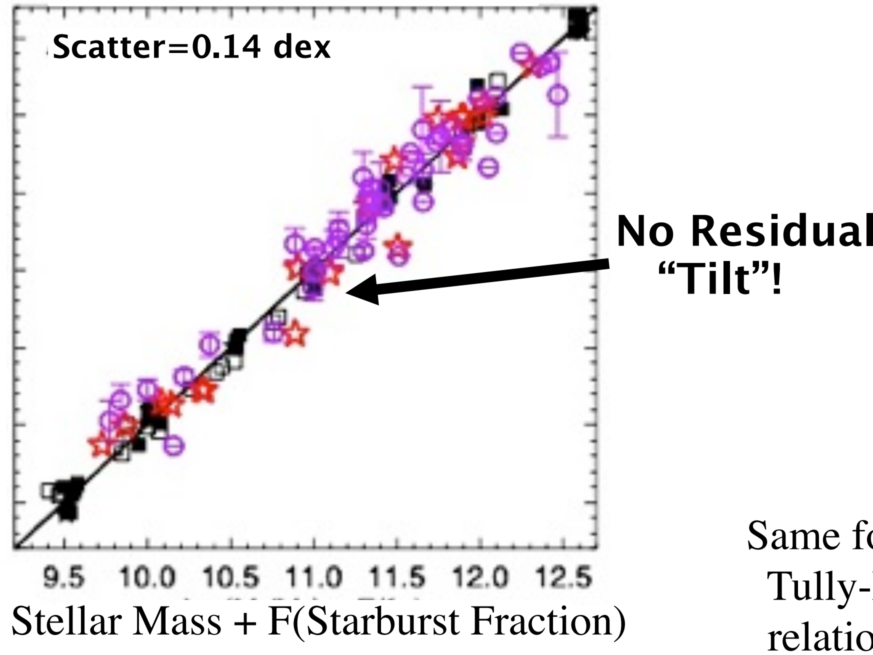
Fundamental Plane Tilt

PFH, Cox, & Hernquist 2008

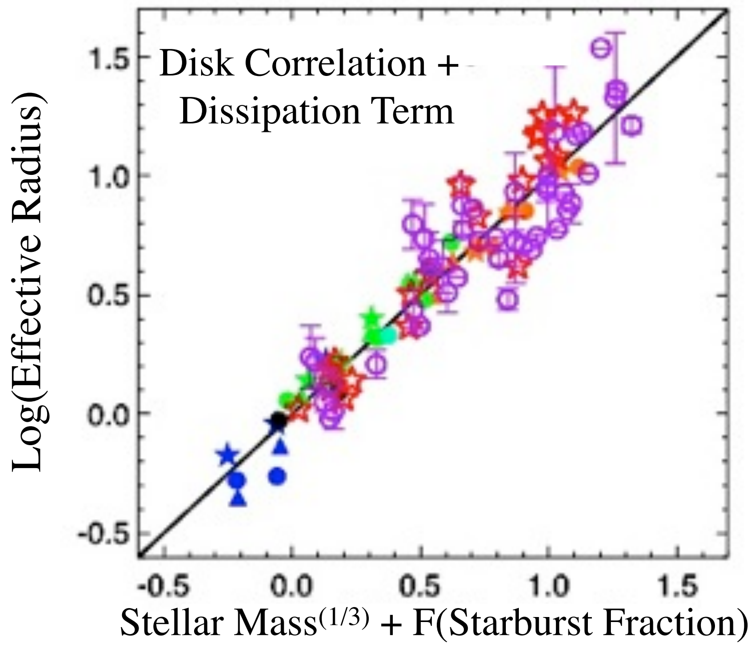
WHERE DOES IT COME FROM?

- Fundamental plane: "tilt" driven by amount of dissipation



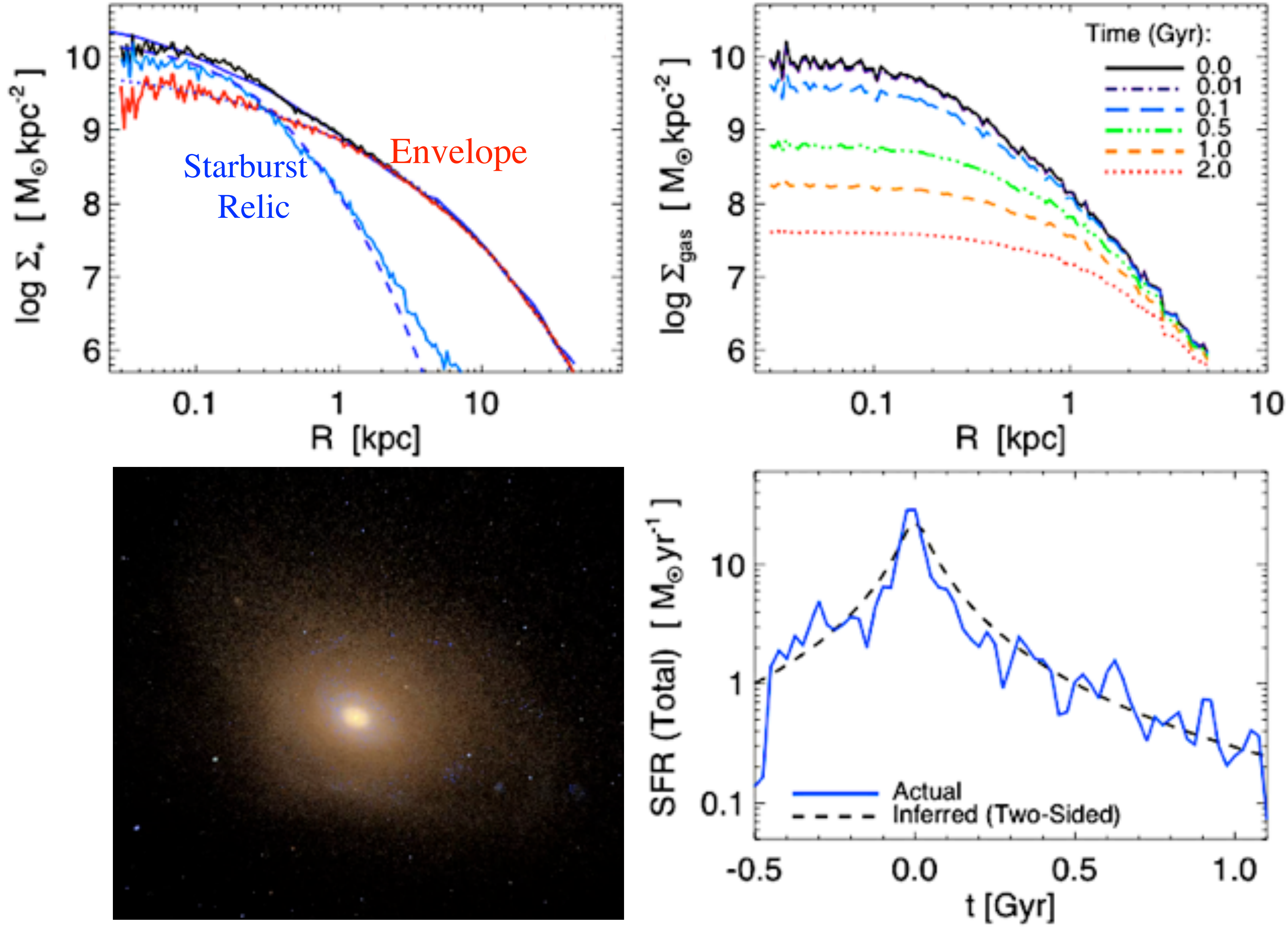


Same for size-mass and Tully-Fisher/Faber-Jackson relations



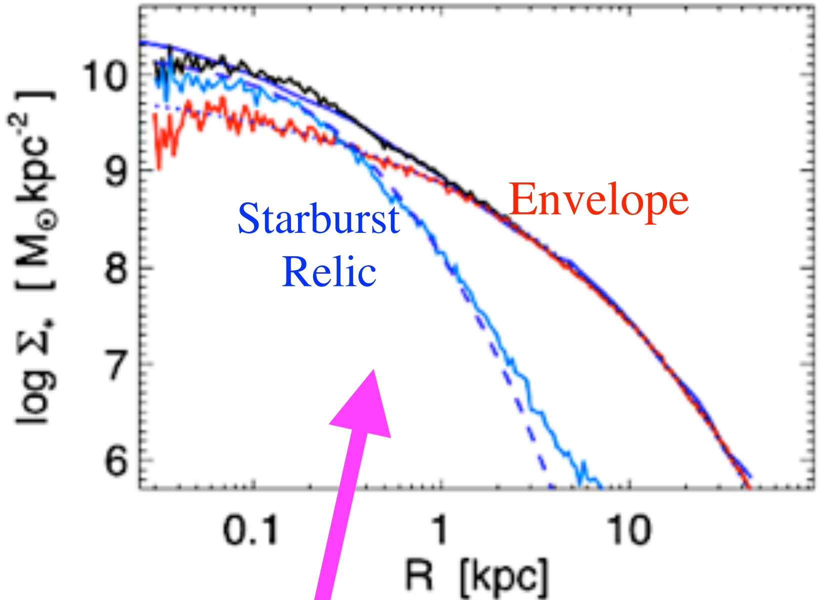
- At FIXED $f_{dissipational}$, there is NO TILT: look just like disks on these correlations!
  - Spheroid correlations can be entirely restated as disks+dissipation

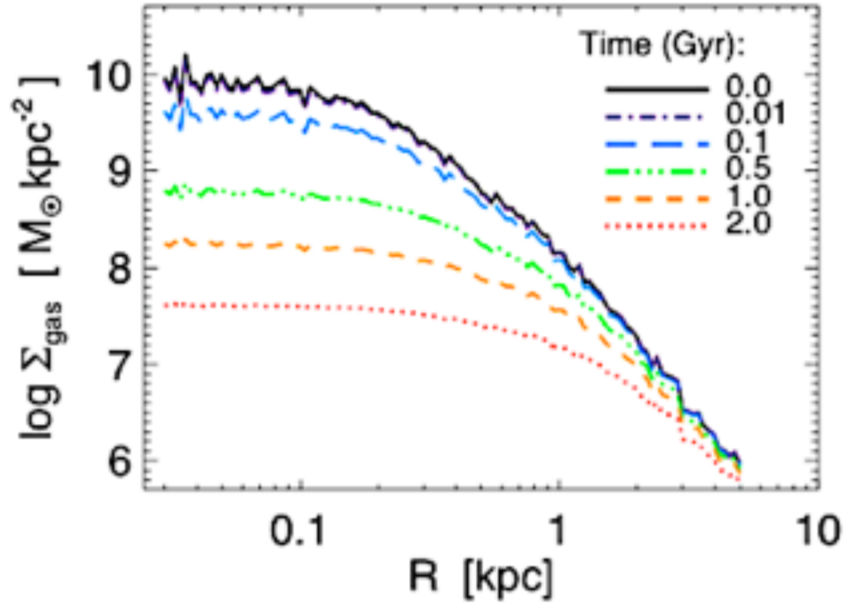
What else can we learn from the ‘relics’ of gas dissipation?

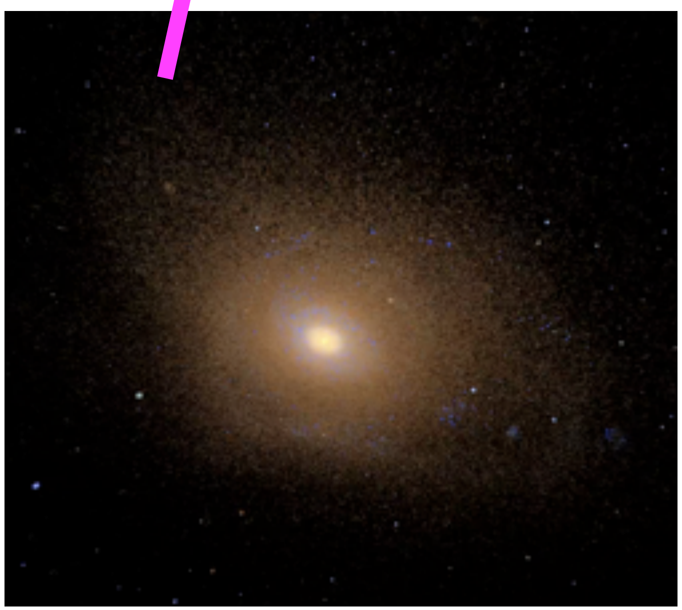


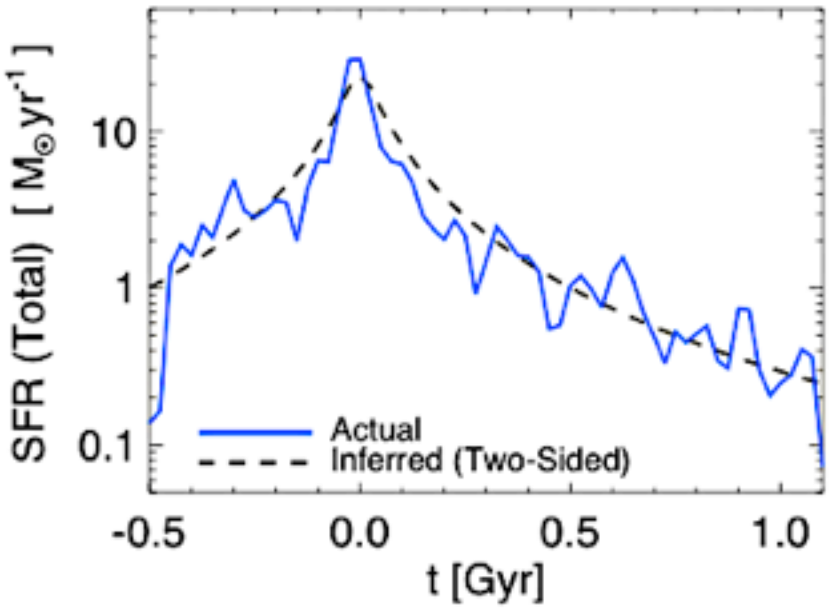
What else can we learn from the ‘relics’ of gas dissipation?

Given a galaxy, isolate ‘burst relic’ $\Sigma_{relic\ stars}(R)$









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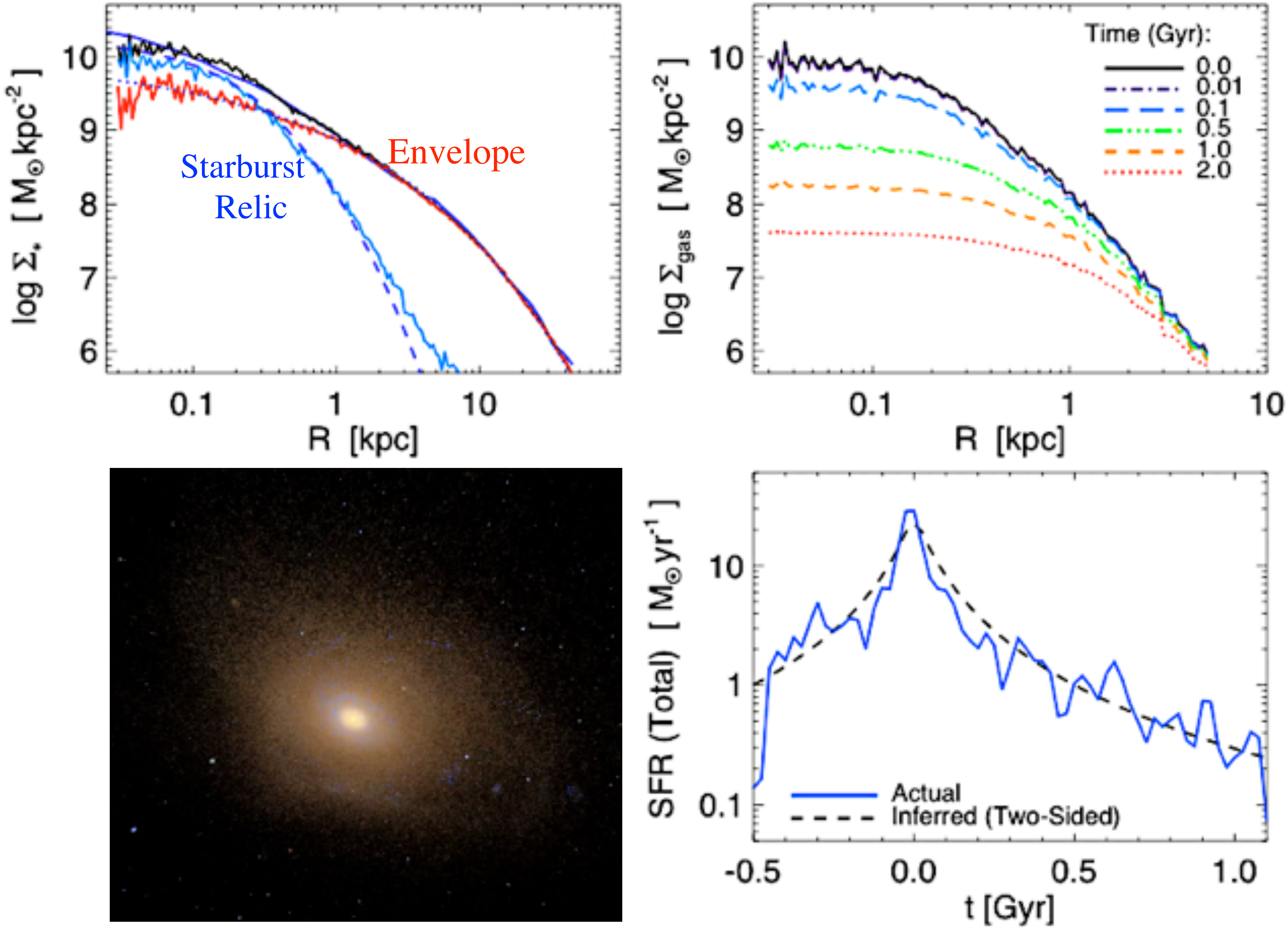
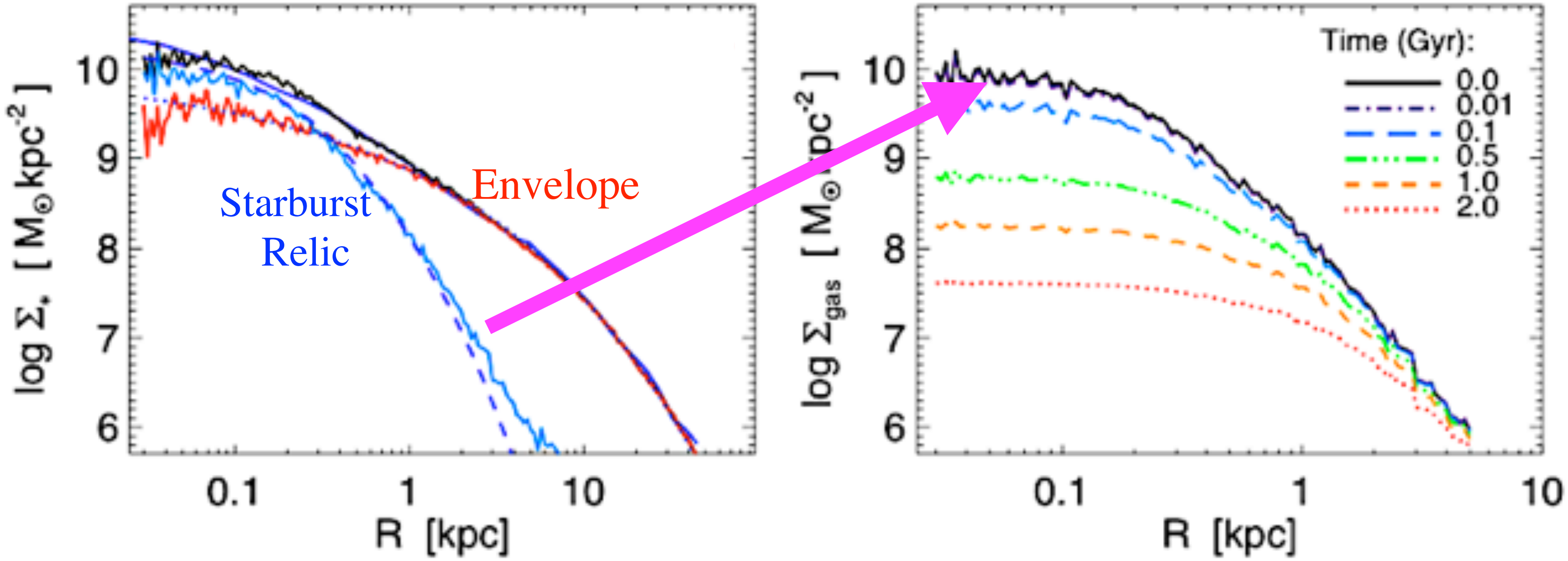
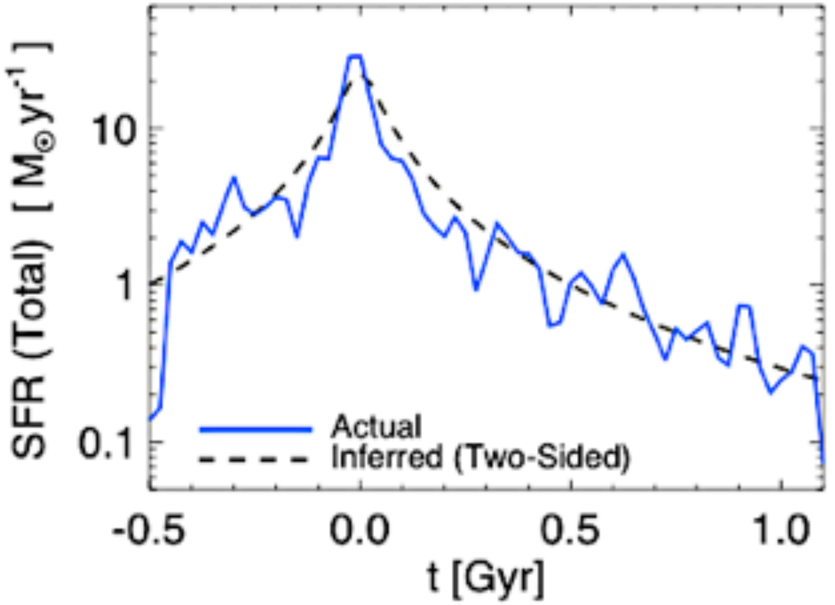


What else can we learn from the 'relics' of gas dissipation?

If formed dissipationally, then this reflects gas-star conversion "in situ"

$$\Sigma_{relic\ stars}(R) \sim \Sigma_{gas\ for\ burst}(R, t = t_{burst})$$





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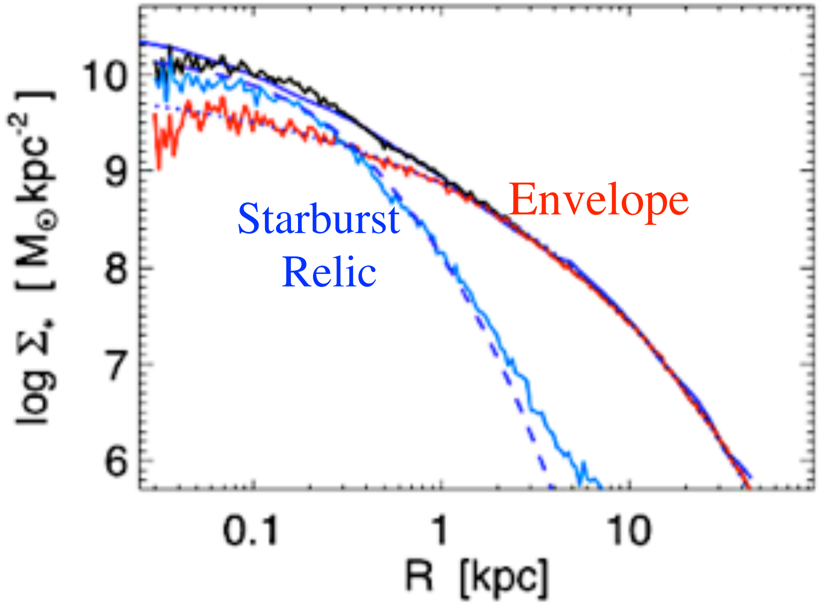
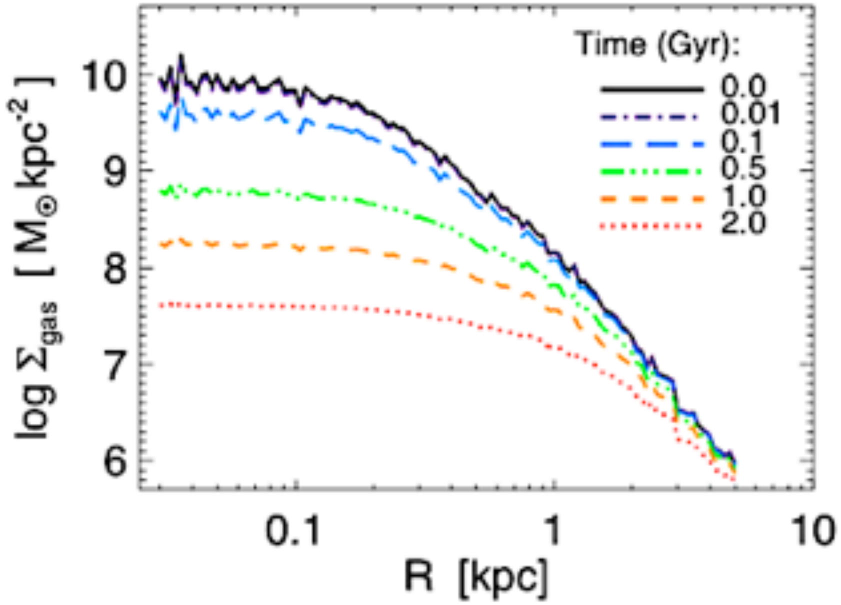
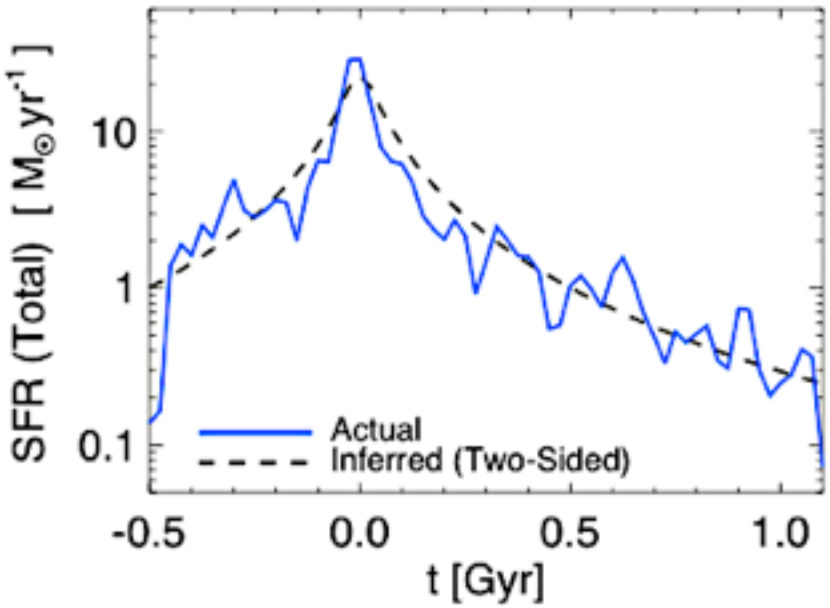


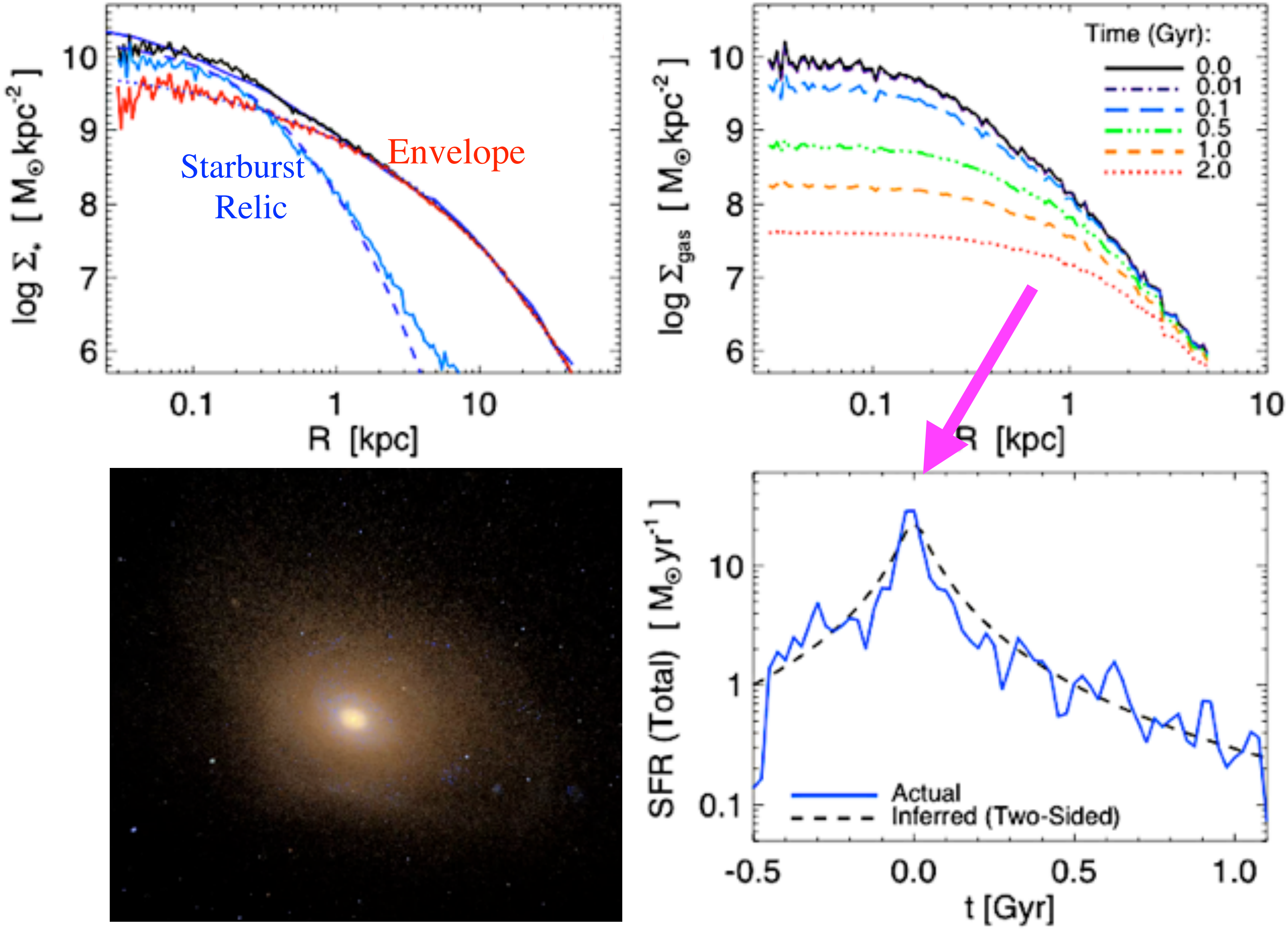




What else can we learn from the ‘relics’ of gas dissipation?

Assume Schmidt-Kennicutt law applies: Recover SFH

$$\Sigma_{gas}(R,t) \rightarrow \dot{\Sigma}_*(R,t) \rightarrow \Sigma_{gas}(R,t+\Delta t)$$



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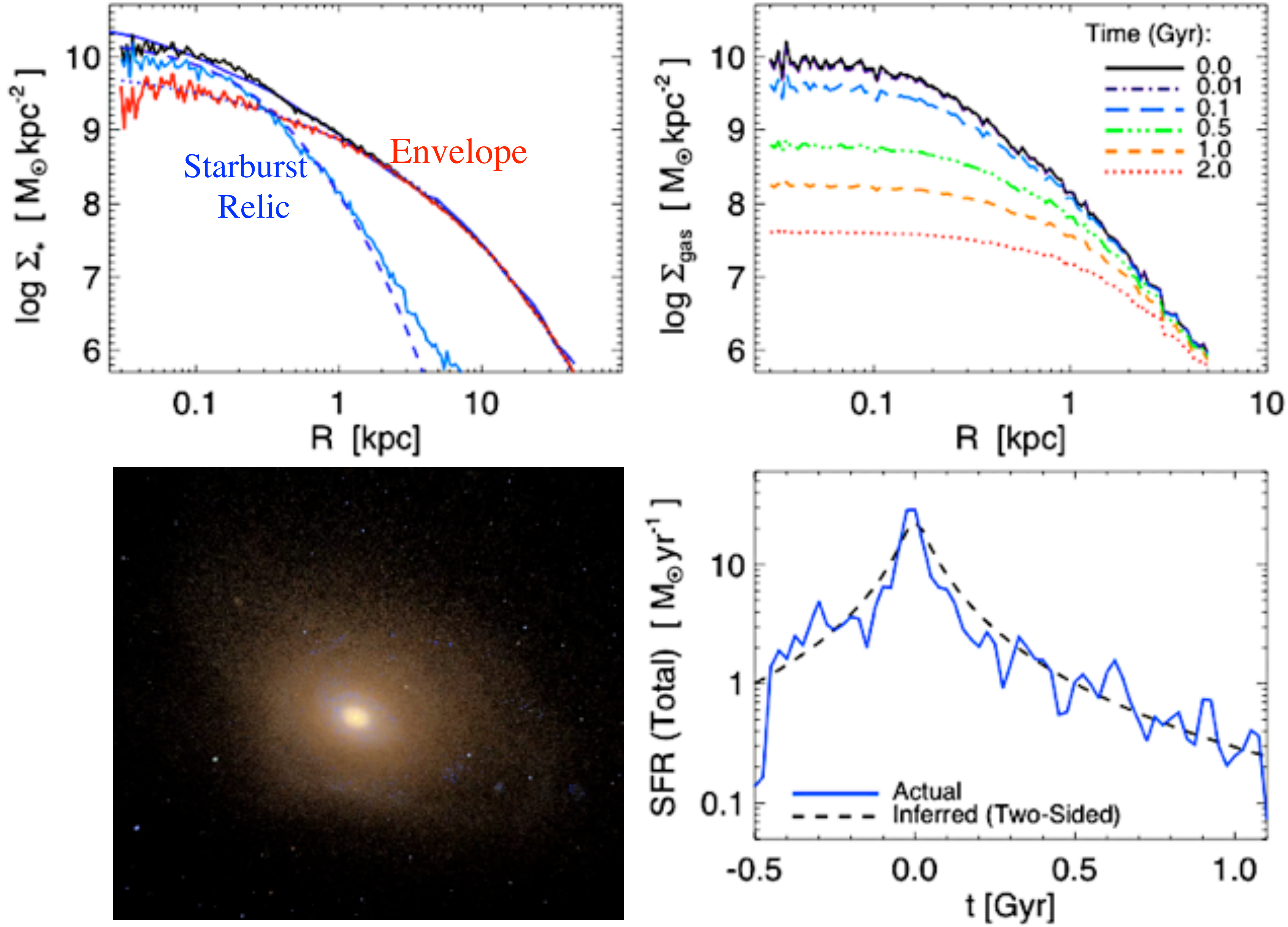

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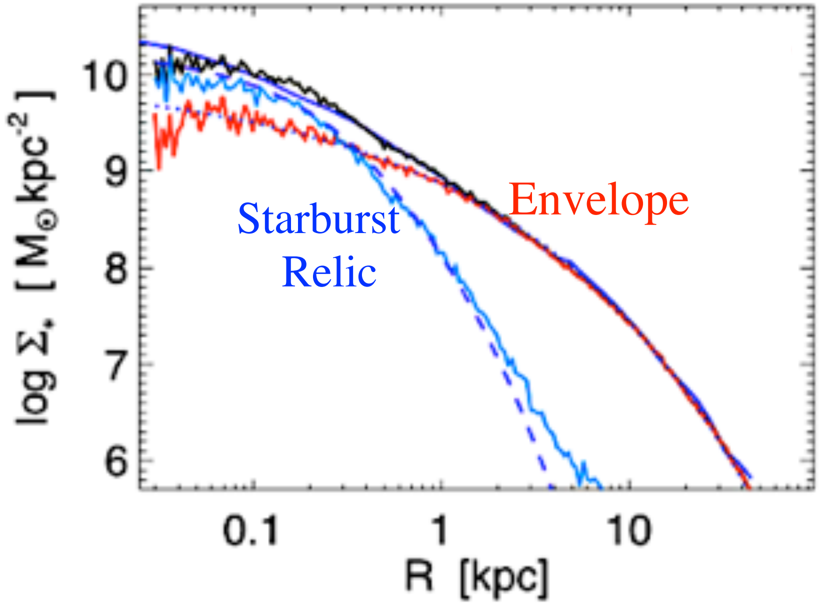

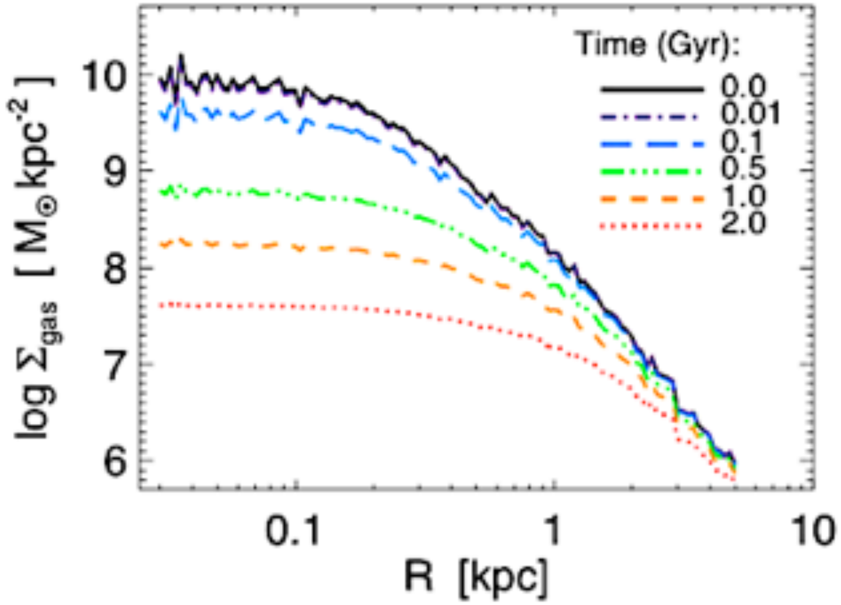

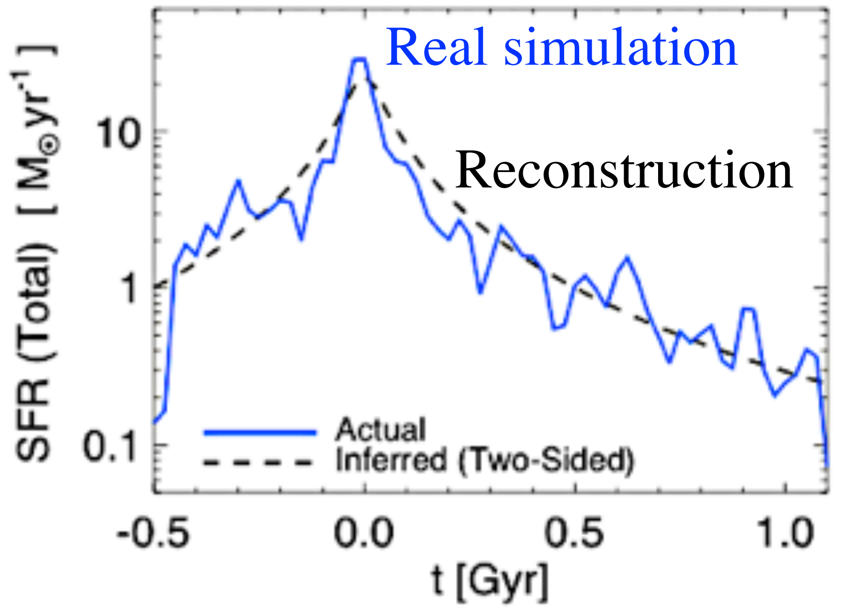

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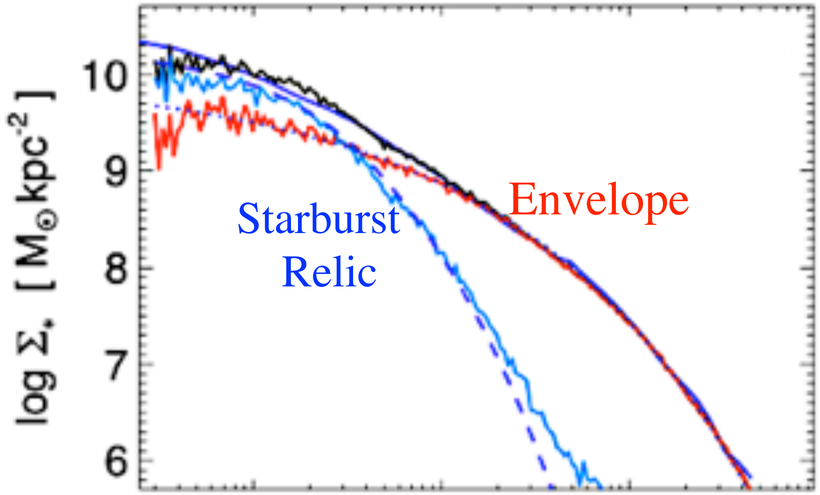

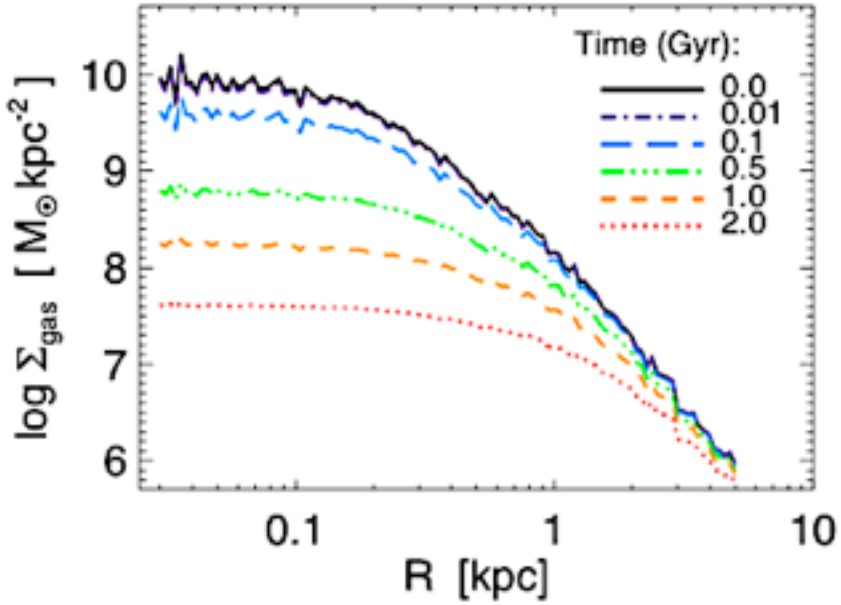

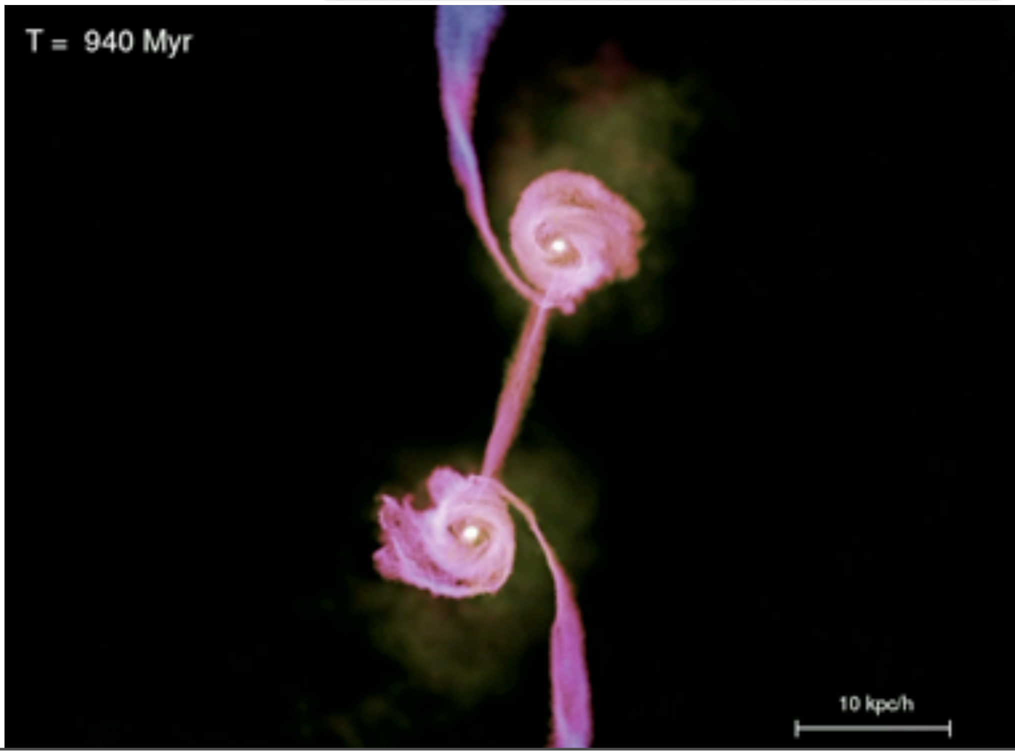

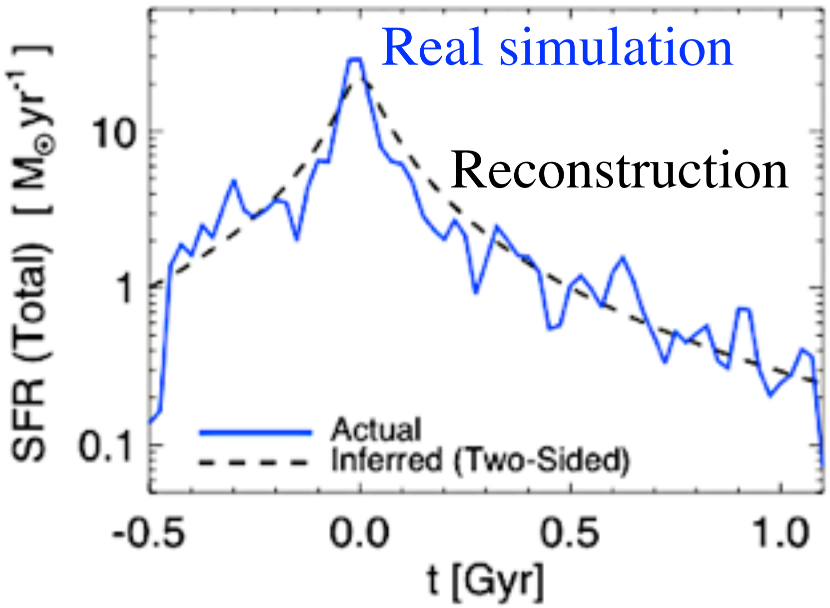

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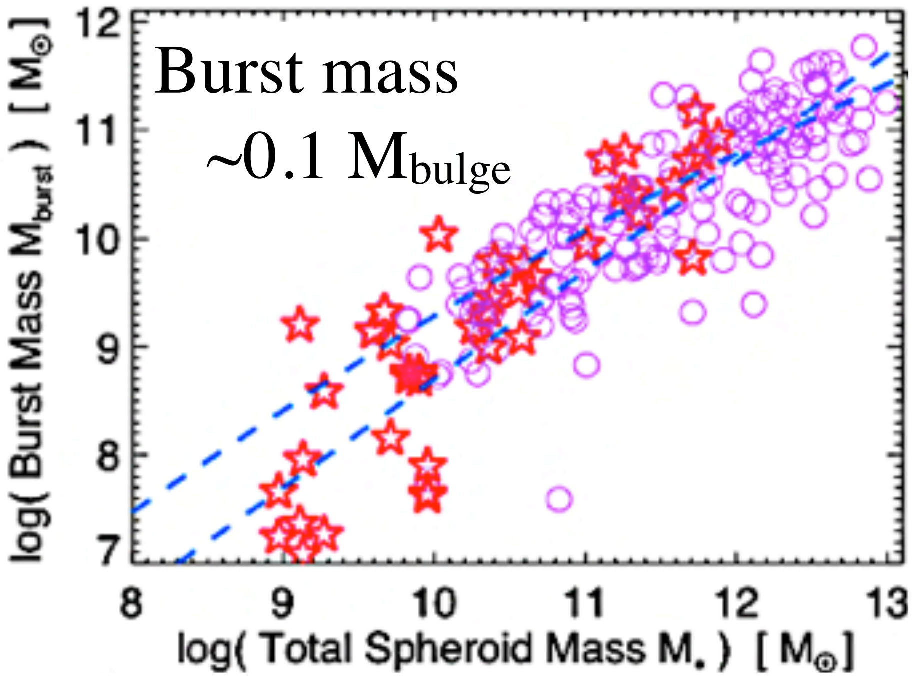

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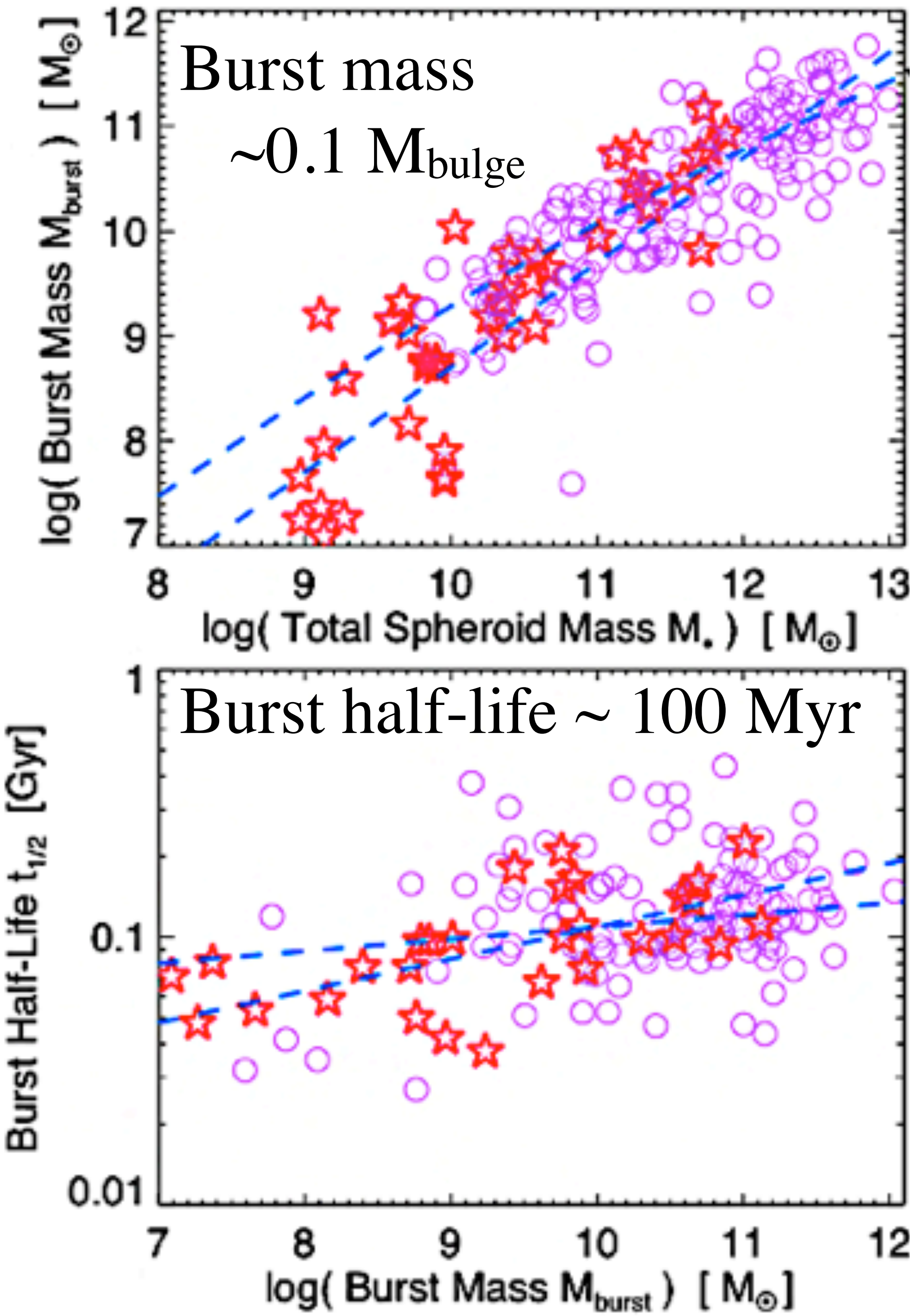

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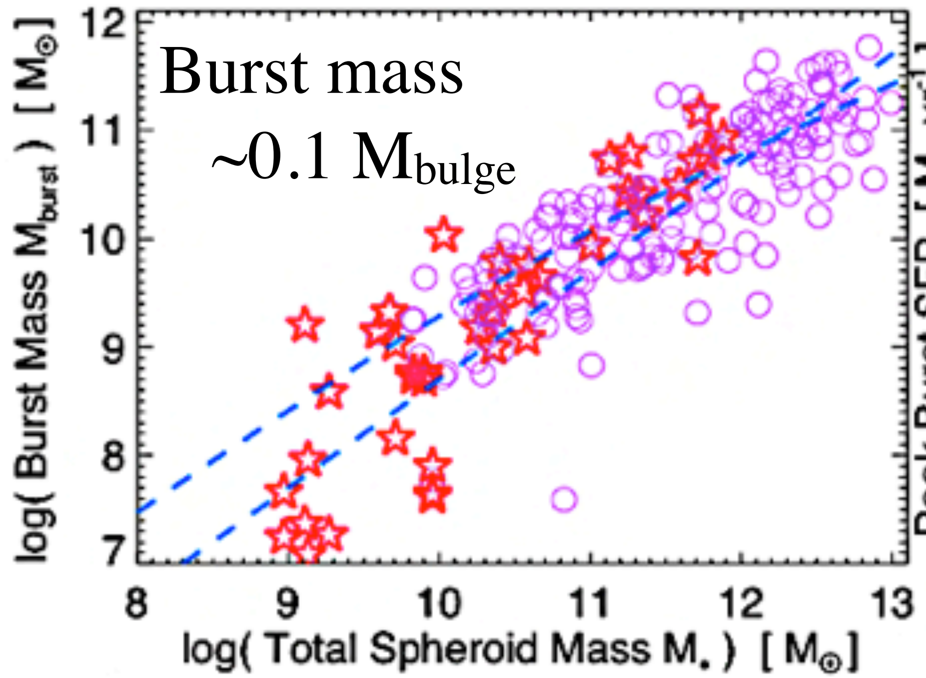

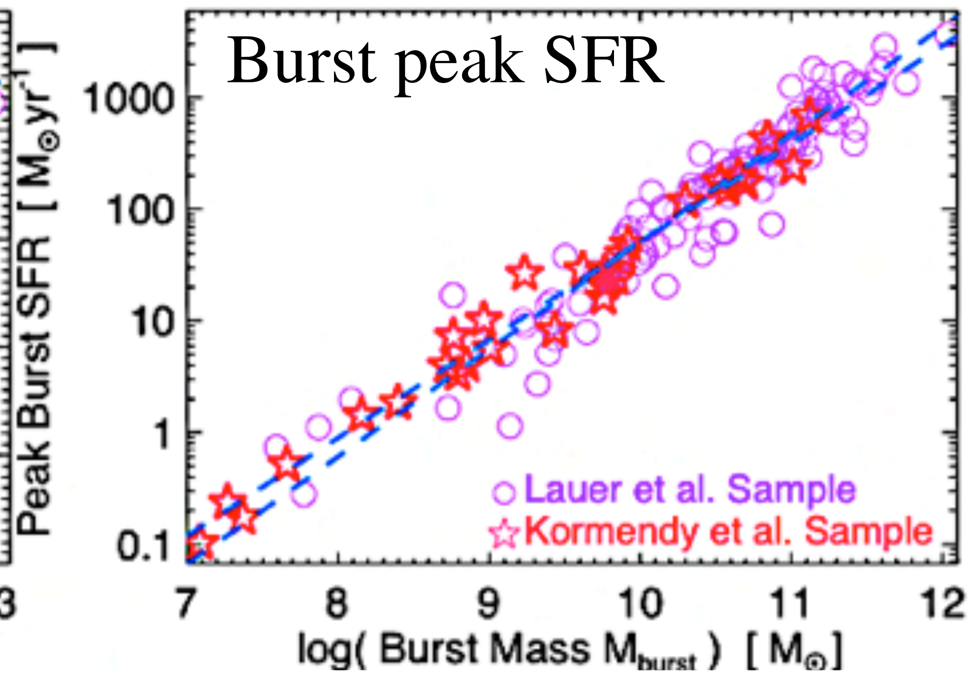

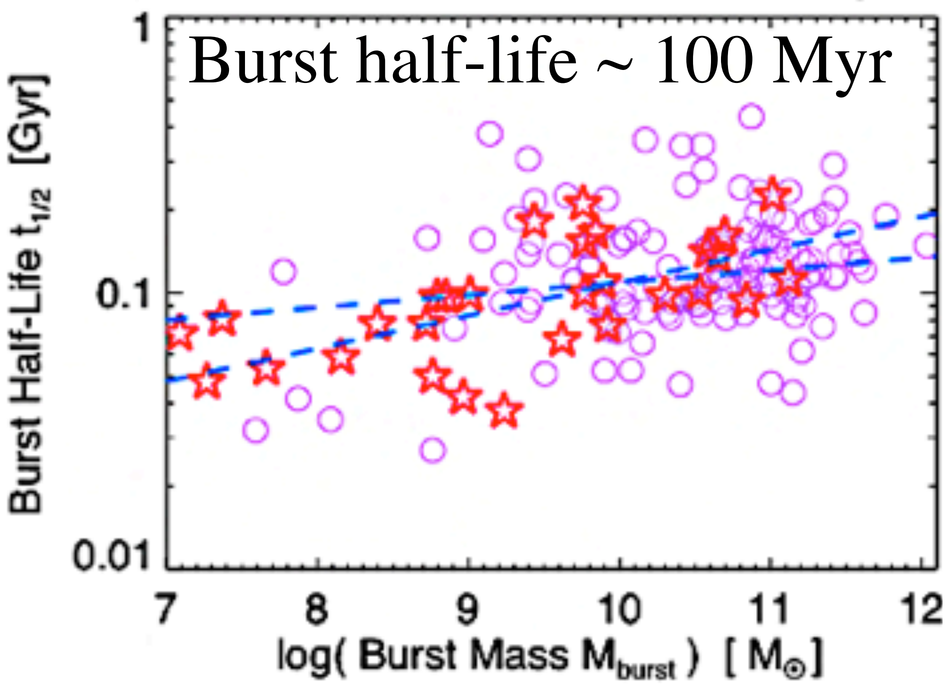

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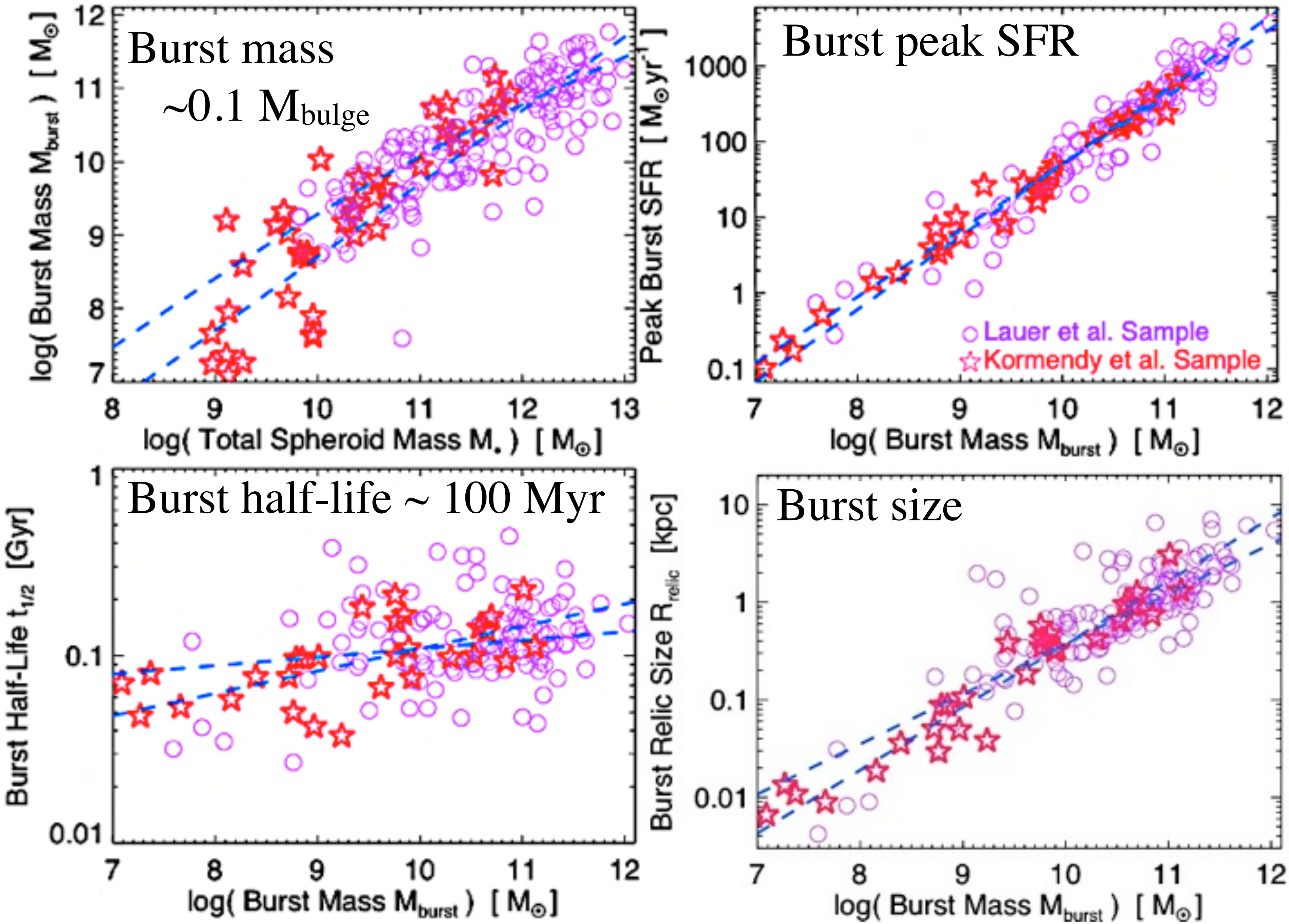

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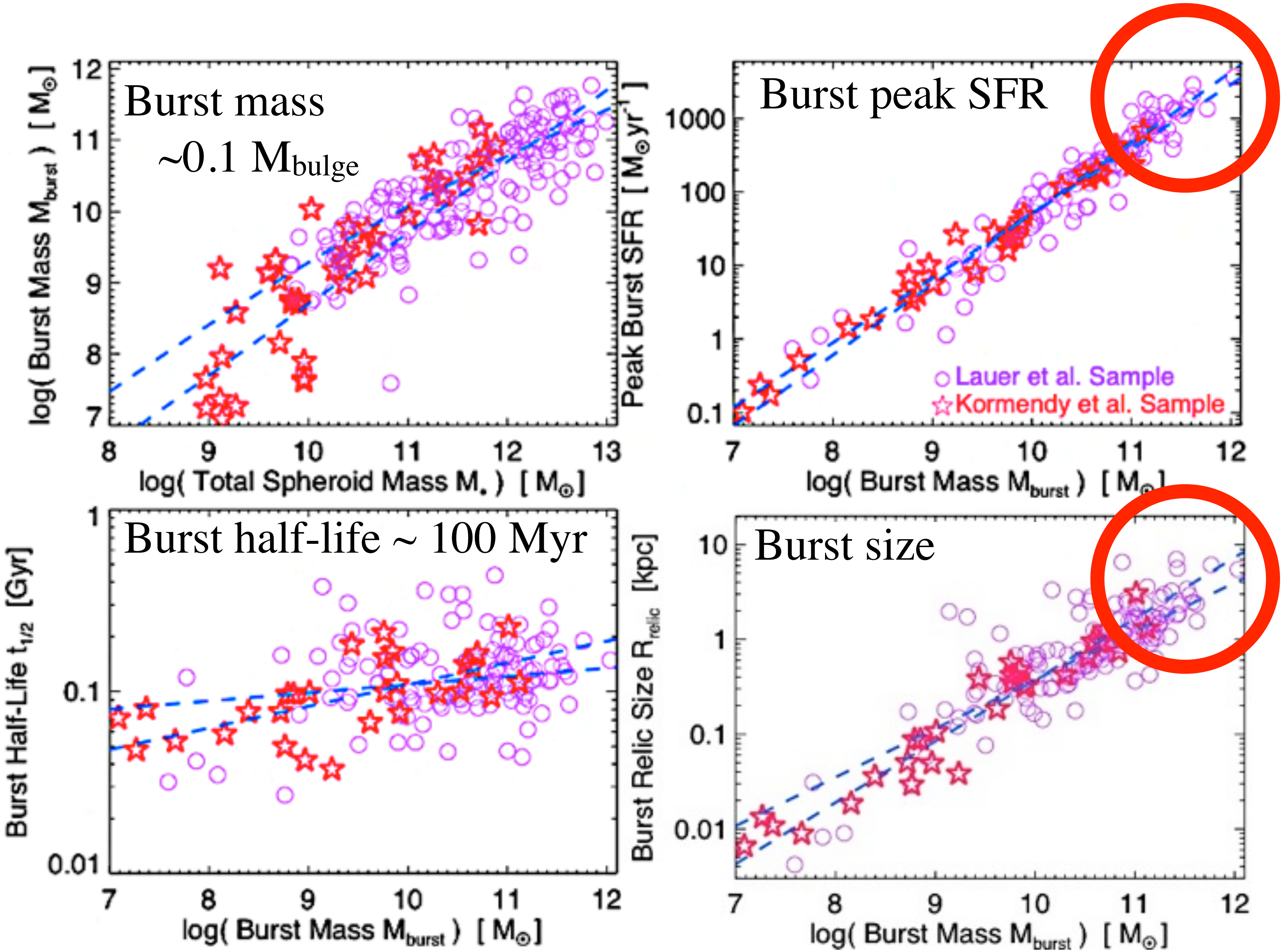
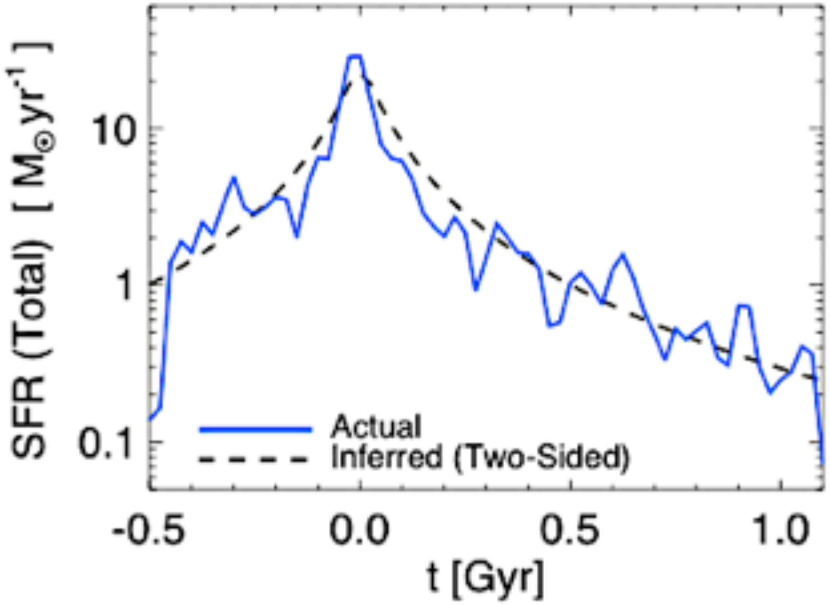
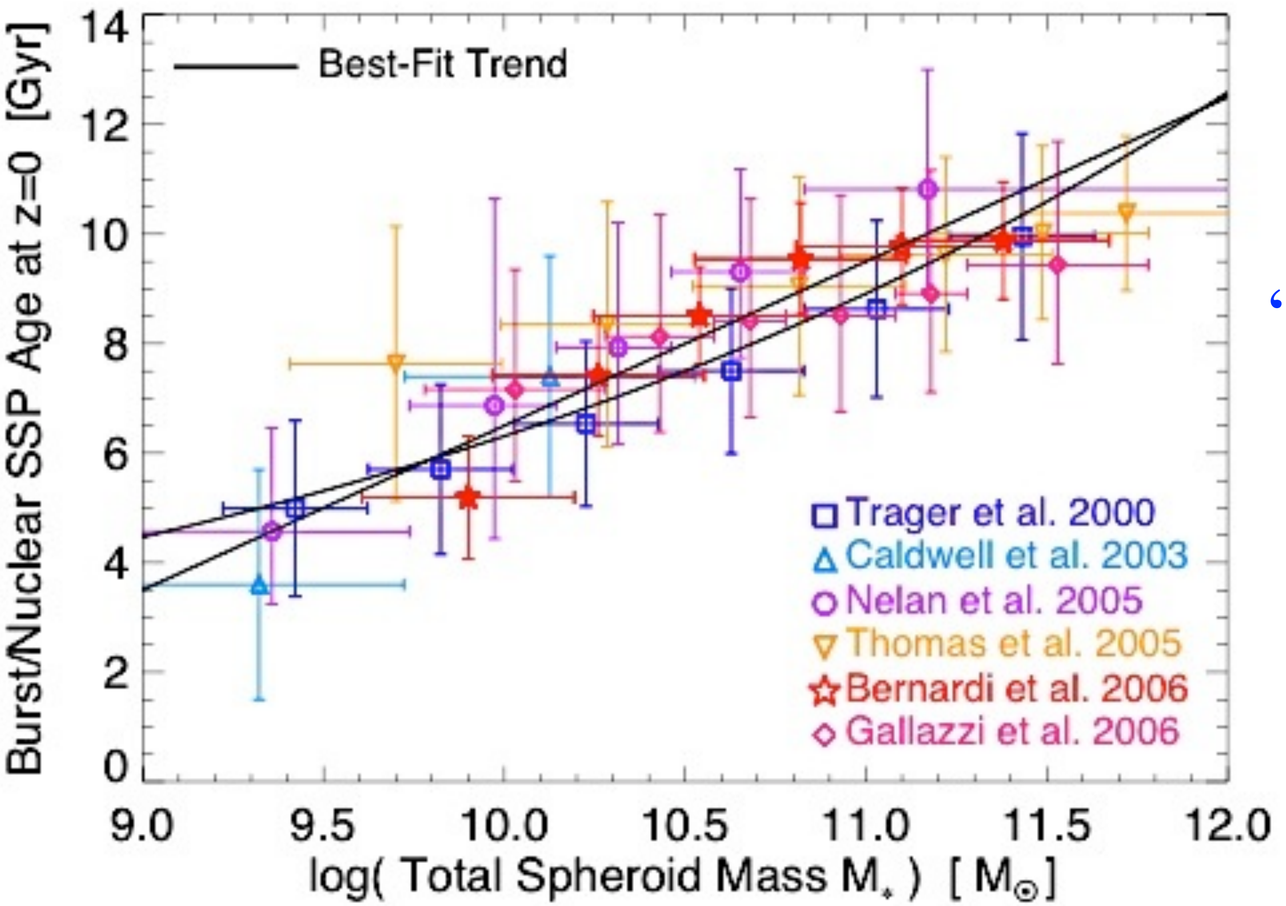


Re-construct SFR(t) for each burst :



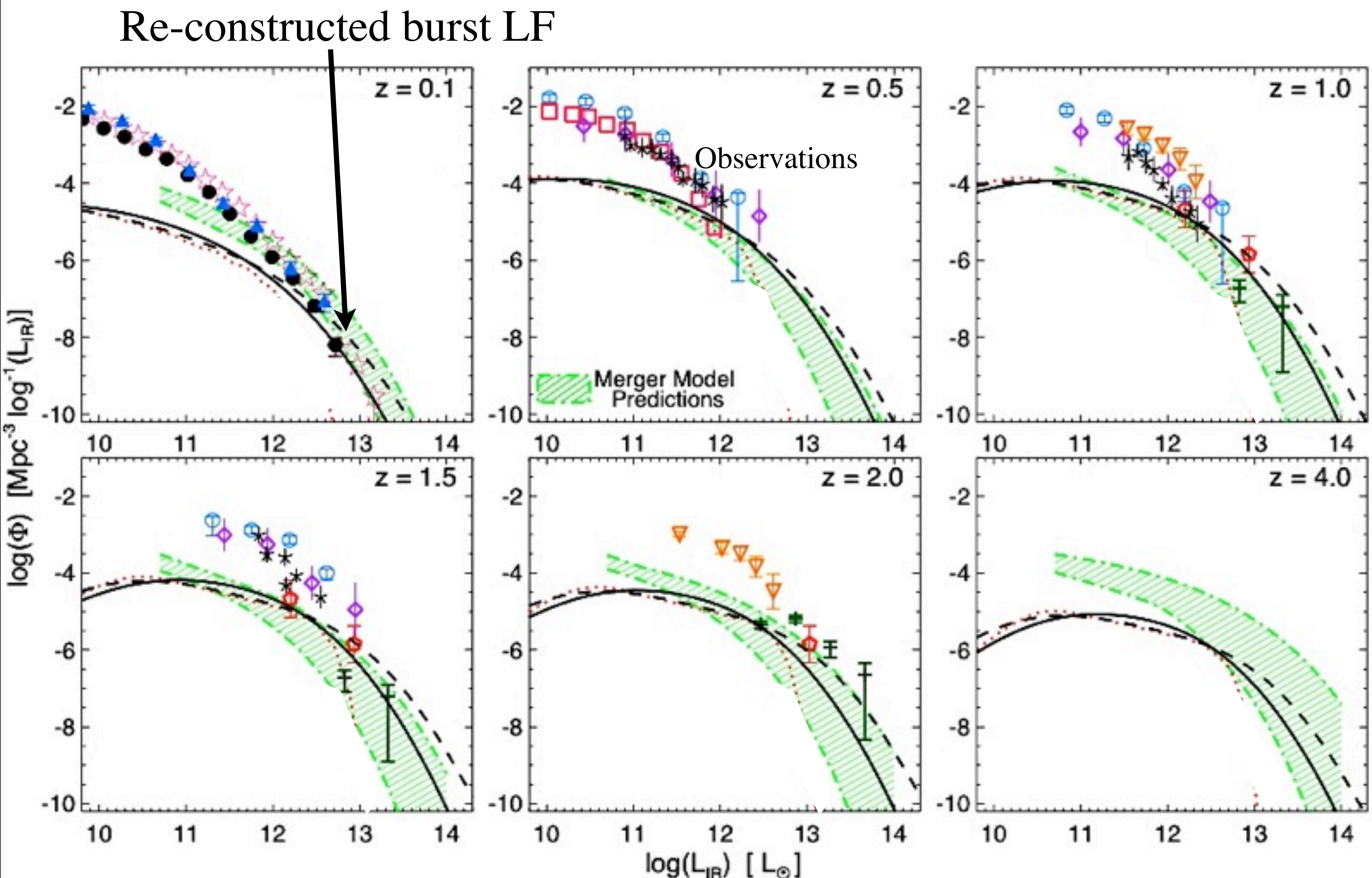
+ We know the nuclear SSP ages....



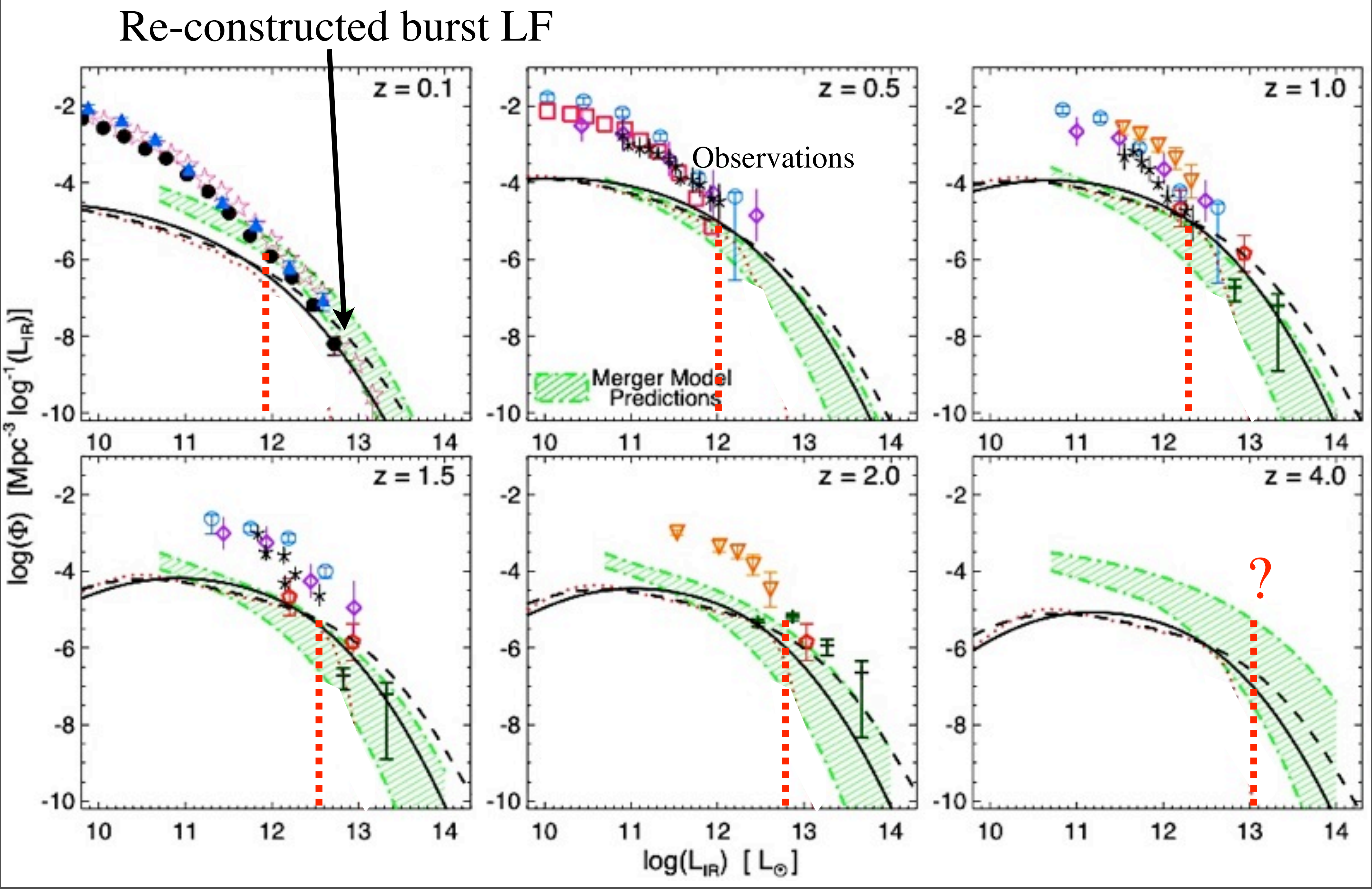
"place" each burst at the correct redshift

PFH & Hernquist 200

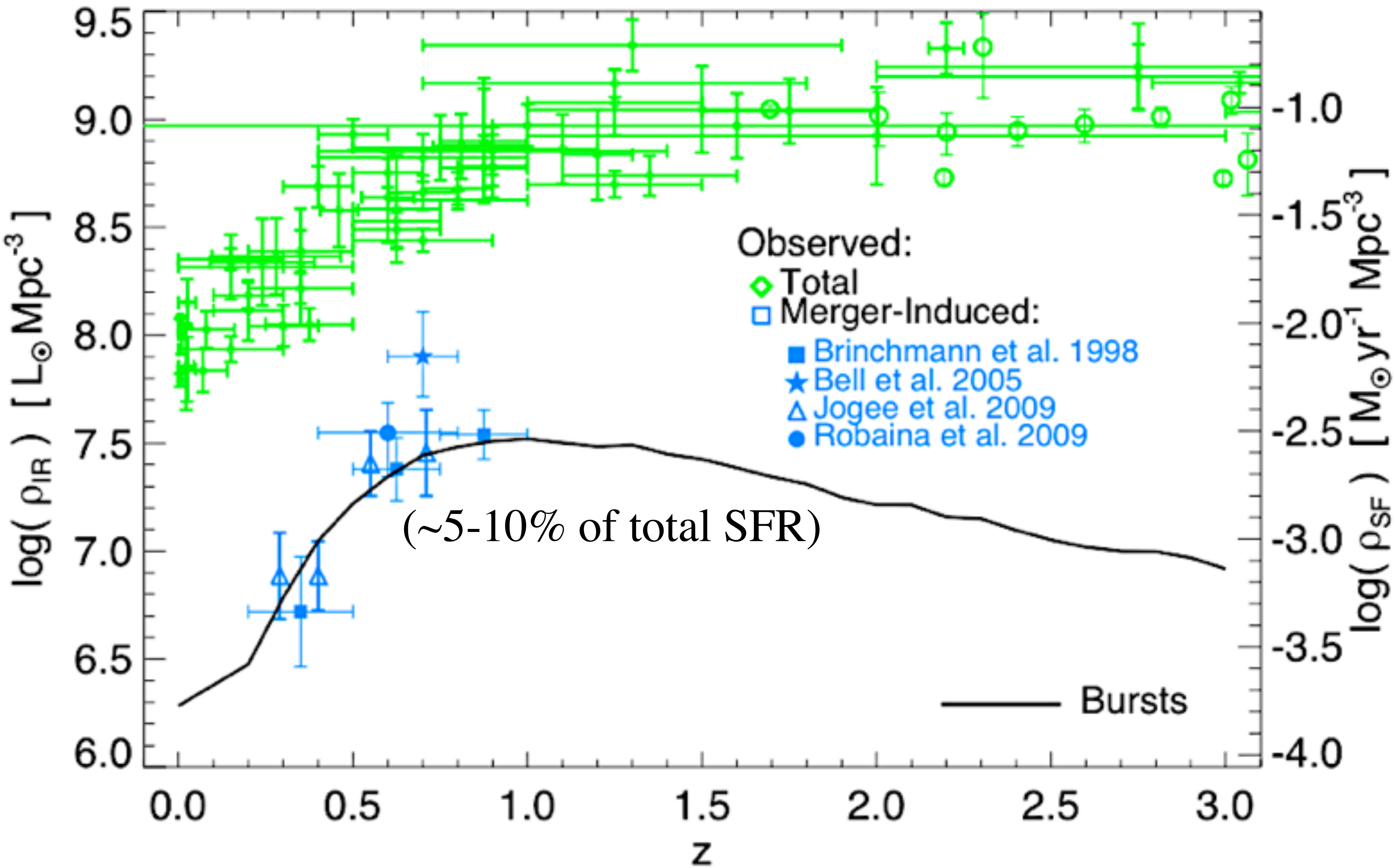
Recover the IR LF of dissipational starbursts!



Bursts always dominate at high L, but the threshold shifts

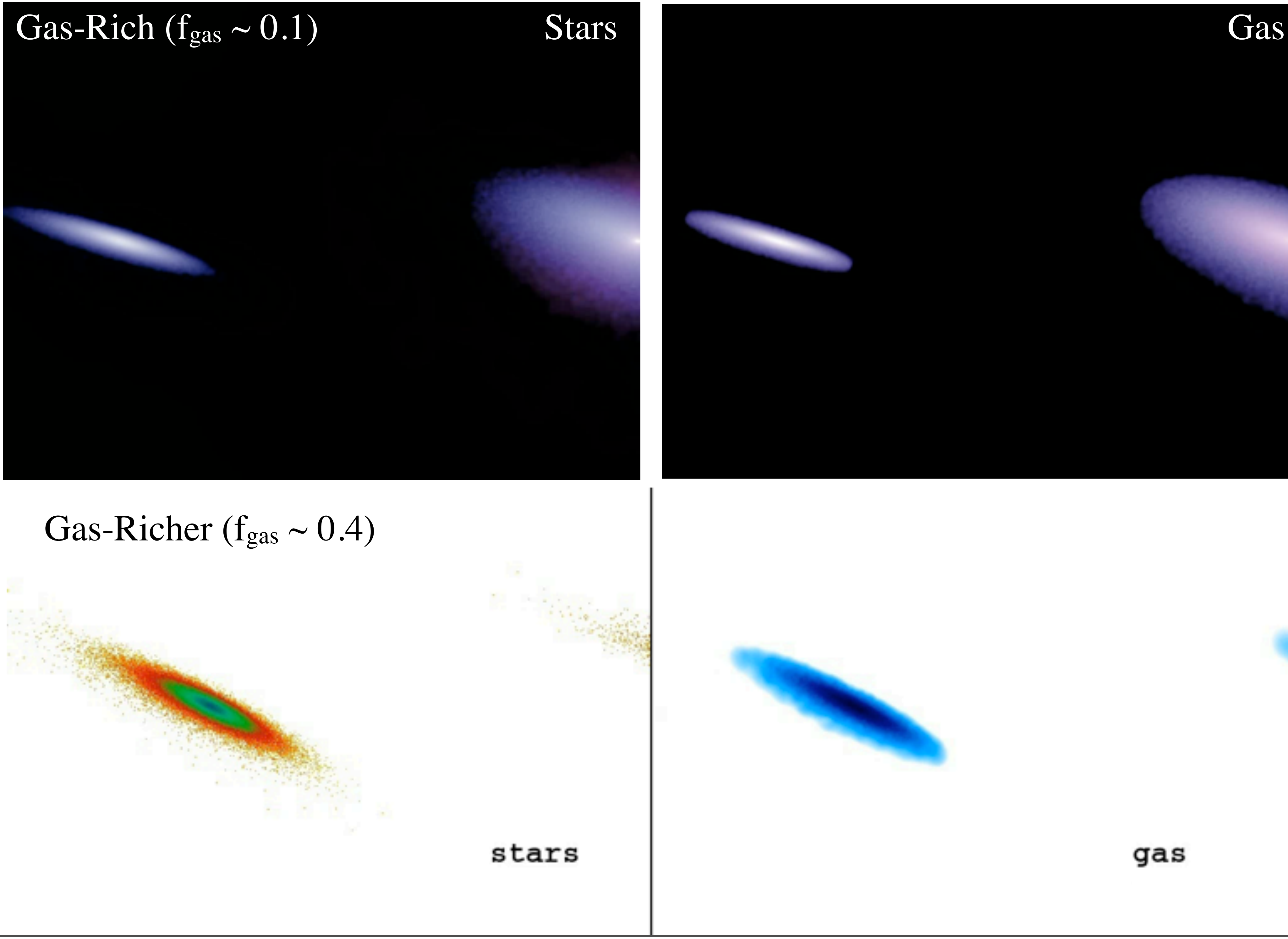


Bursts *never* dominate the SFR density!



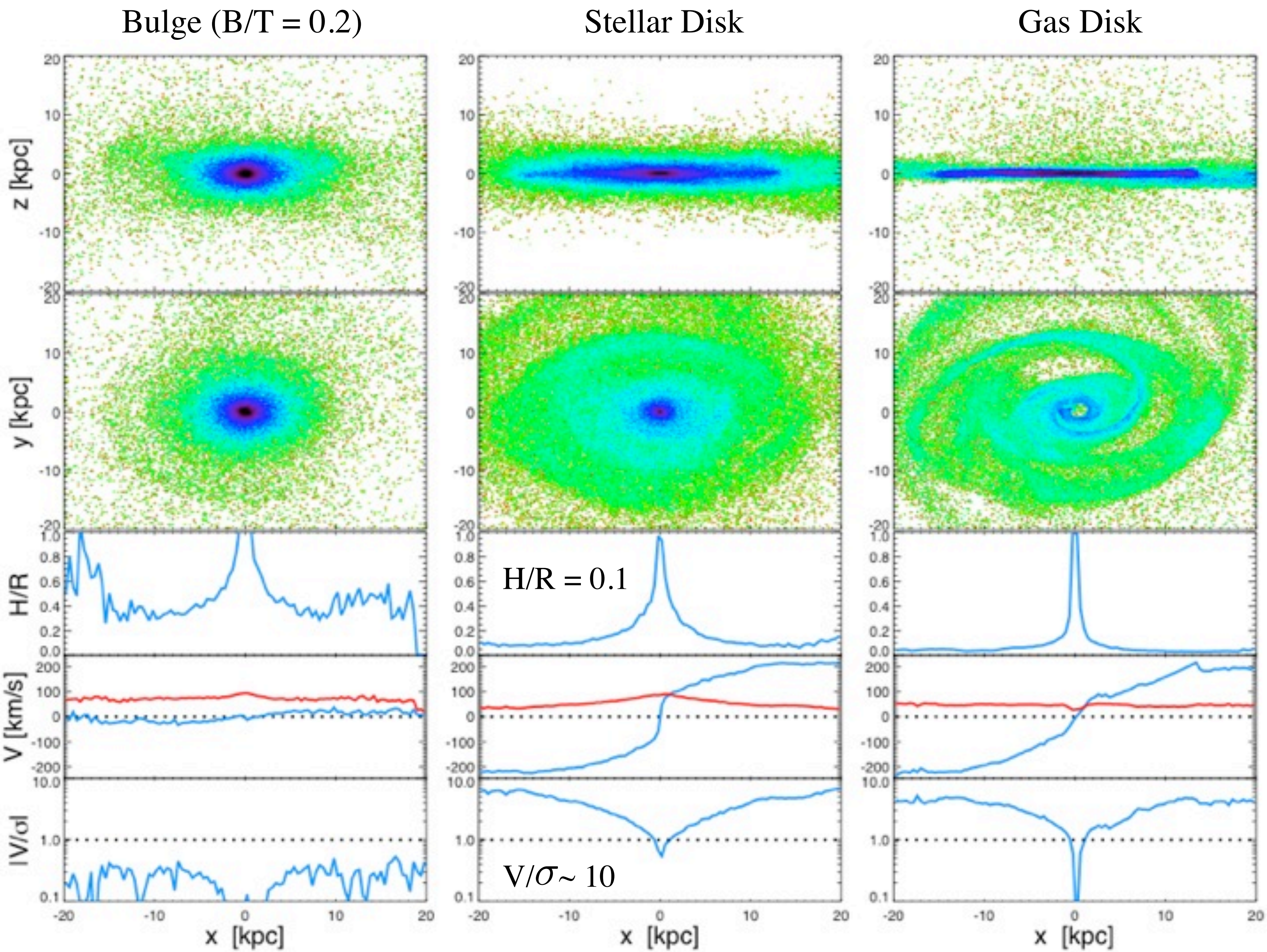
Why Is There Not Much More Efficient Gas Consumption at High Redshifts?

How Good Is Our Conventional Wisdom?



Major Merger Remnants

DO MERGERS DESTROY DISKS?



The Unsolved Questions

HOW CAN A DISK SURVIVE?

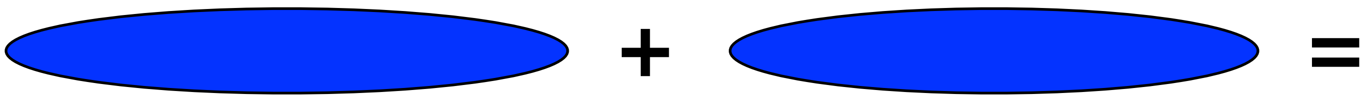
- Stellar disks are collisionless: they violently relax when they collide

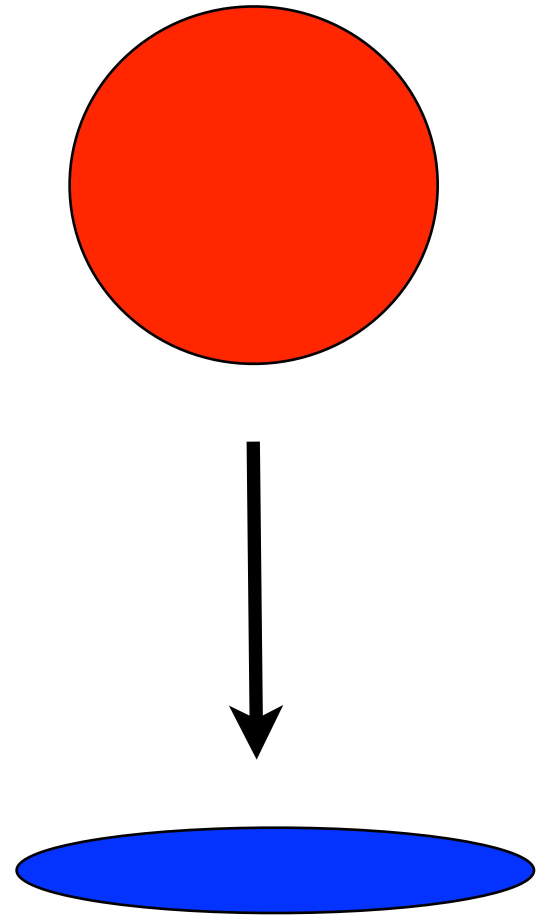
- Can’t “cool” into a new disk

The Unsolved Questions

HOW CAN A DISK SURVIVE?

- Gas, however, is collisional (will cool into new disk): only goes to center and bursts if angular momentum is removed



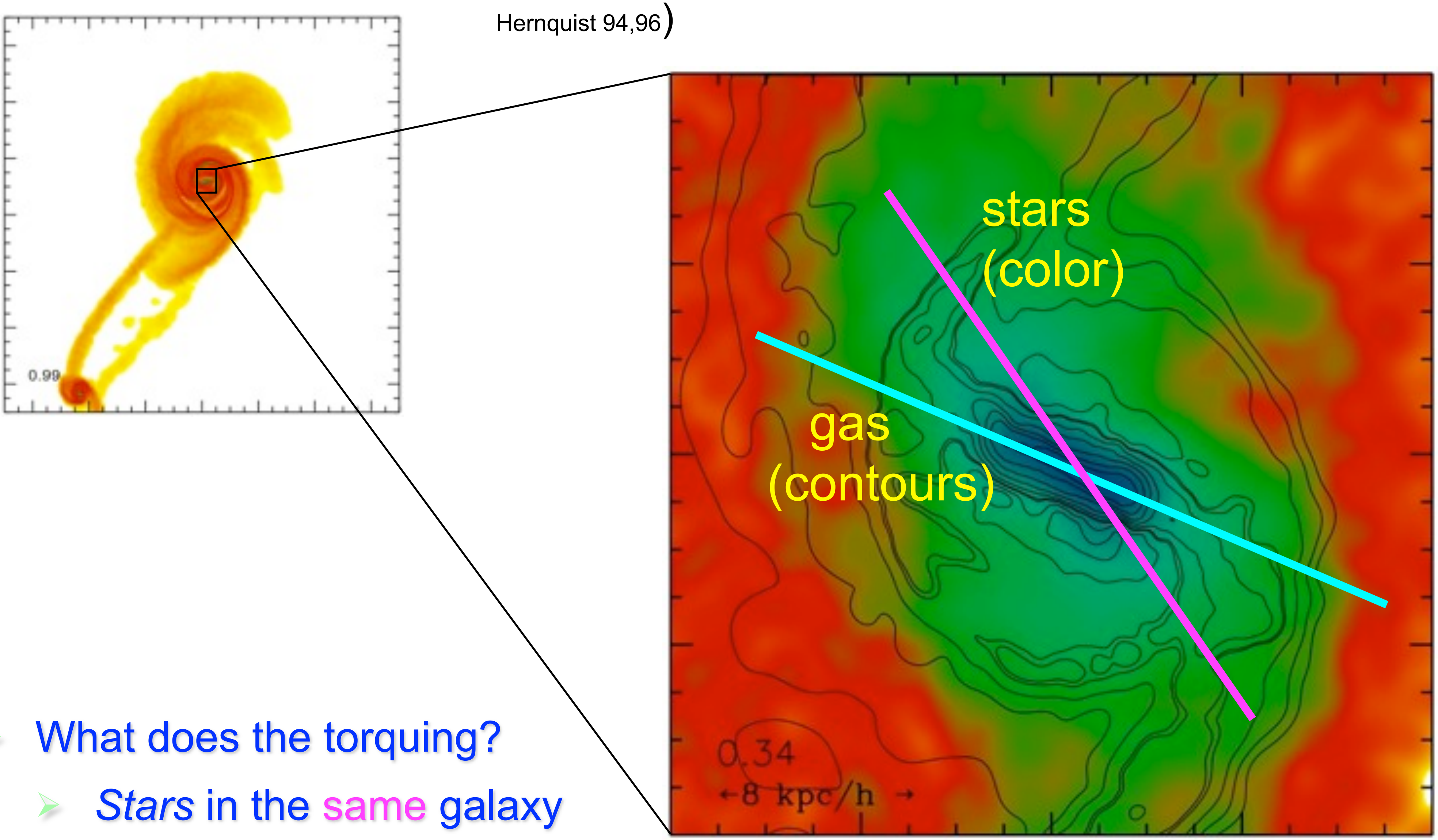


Governato et al.

How Do Disks Survive Mergers?

PFH et al. 2008

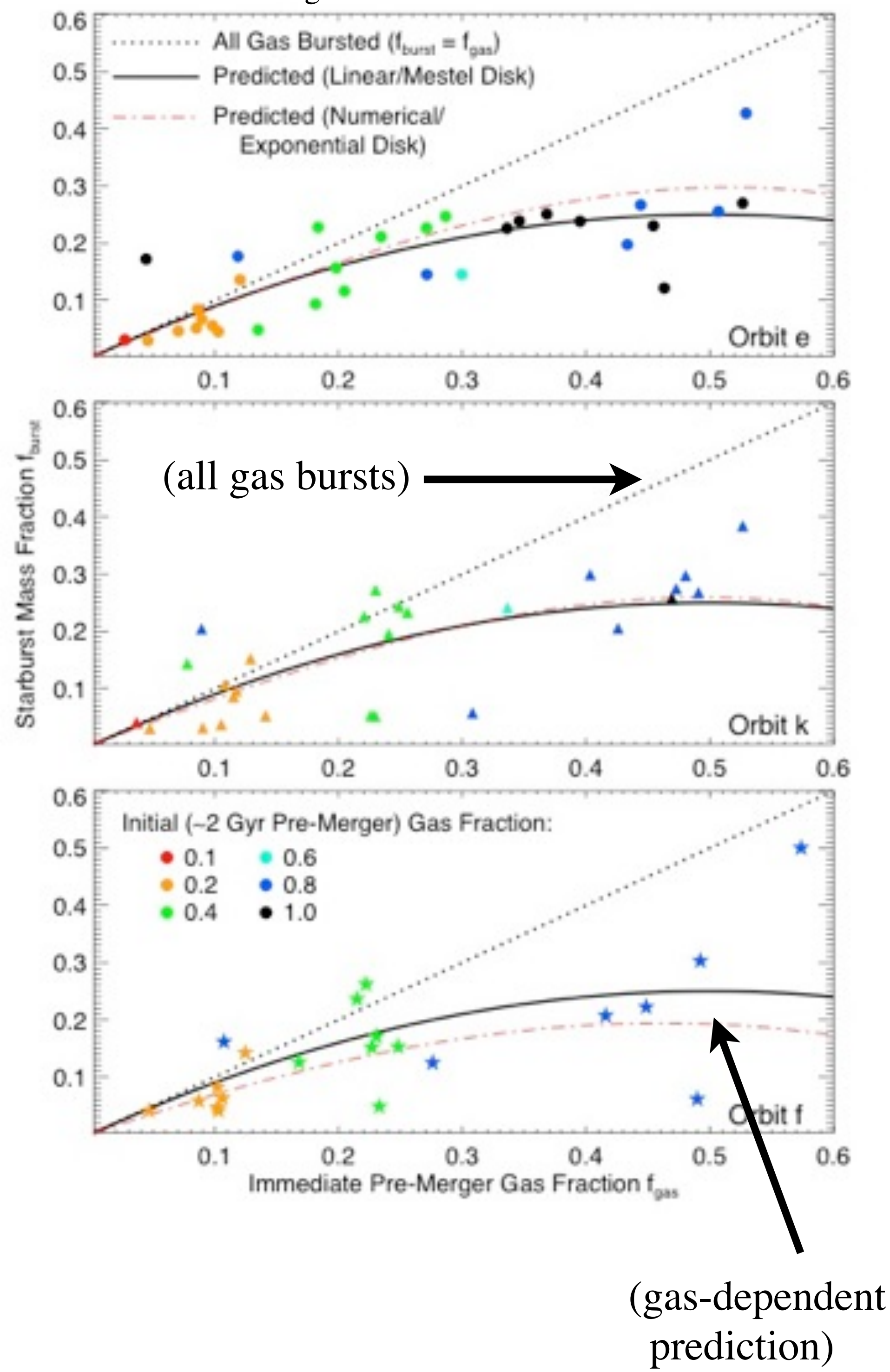
companions -- bars -- gas/star offset -- torques -- gas inflow (see, e.g., Barnes 92, Barnes & Hernquist 96, Mihos & Hernquist 94,96)



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

How Do Disks Survive Mergers?

Burst mass vs. f_{gas}



Torque on gas:

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

For the same merger/perturbation:

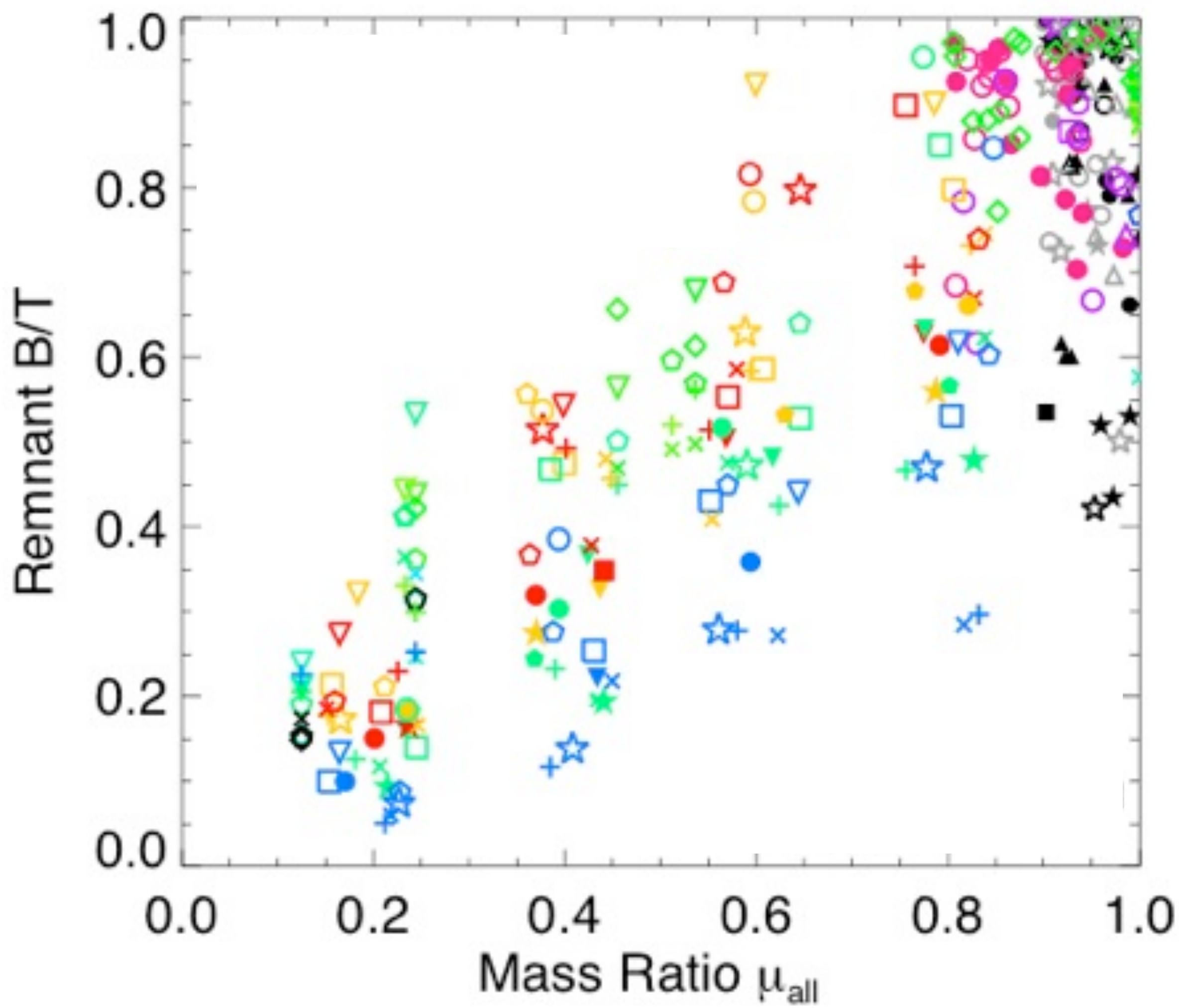
$M_{\text{stellar distortion}} \propto M_{\text{stellar}} \propto (1 - f_{gas})$

PFH et al. 2008 ("How Do Disks Survive Mergers?")

How Do Disks Survive Mergers?

Can analytically determine burst masses and properties as a function of e.g. orbital parameters, f_{gas}, merger mass ratio, etc.

Need to know these parameters to say what mergers "do"



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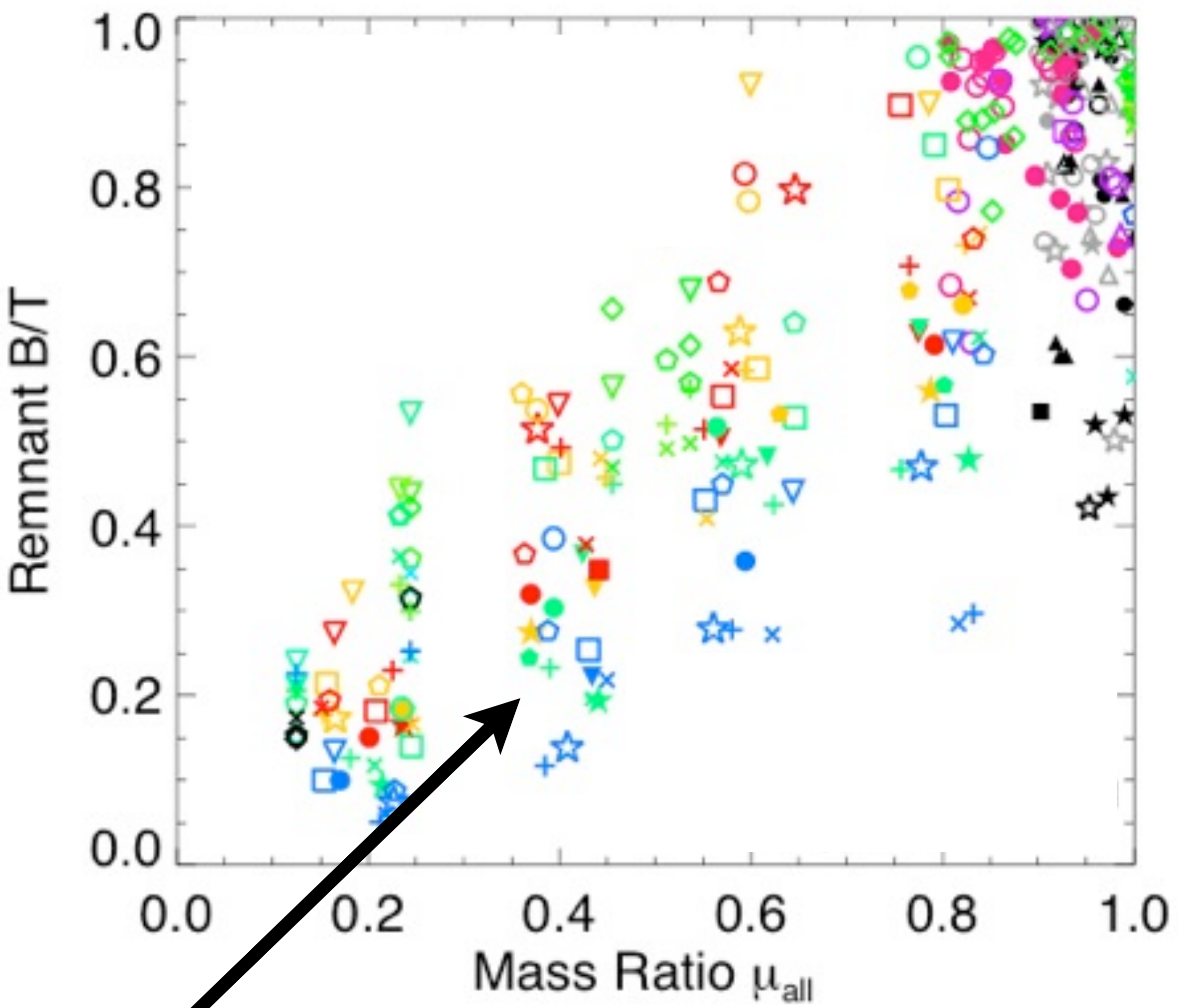

Not a step function!

PFH et al. 2008 ("How Do Disks Survive Mergers?")

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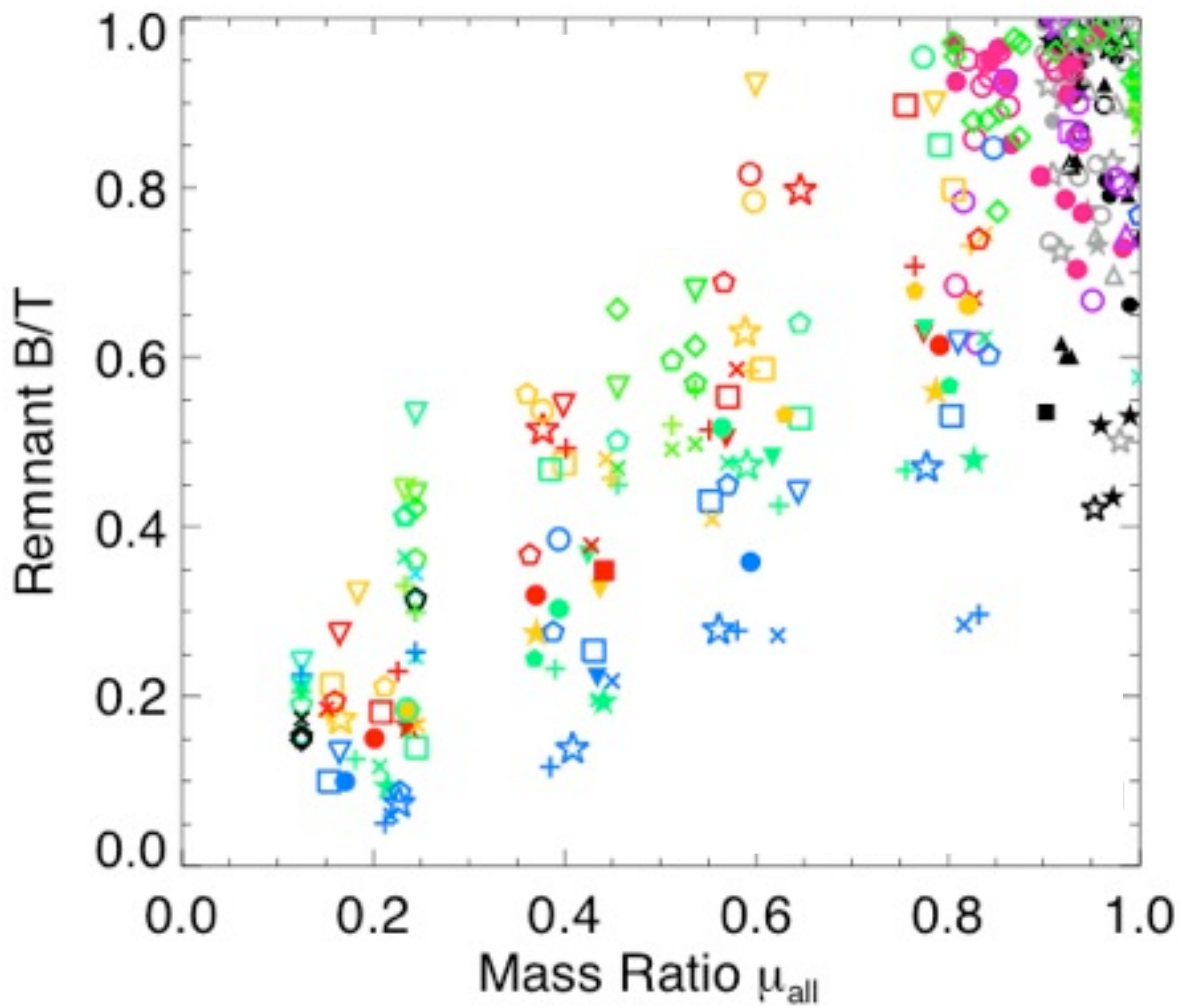

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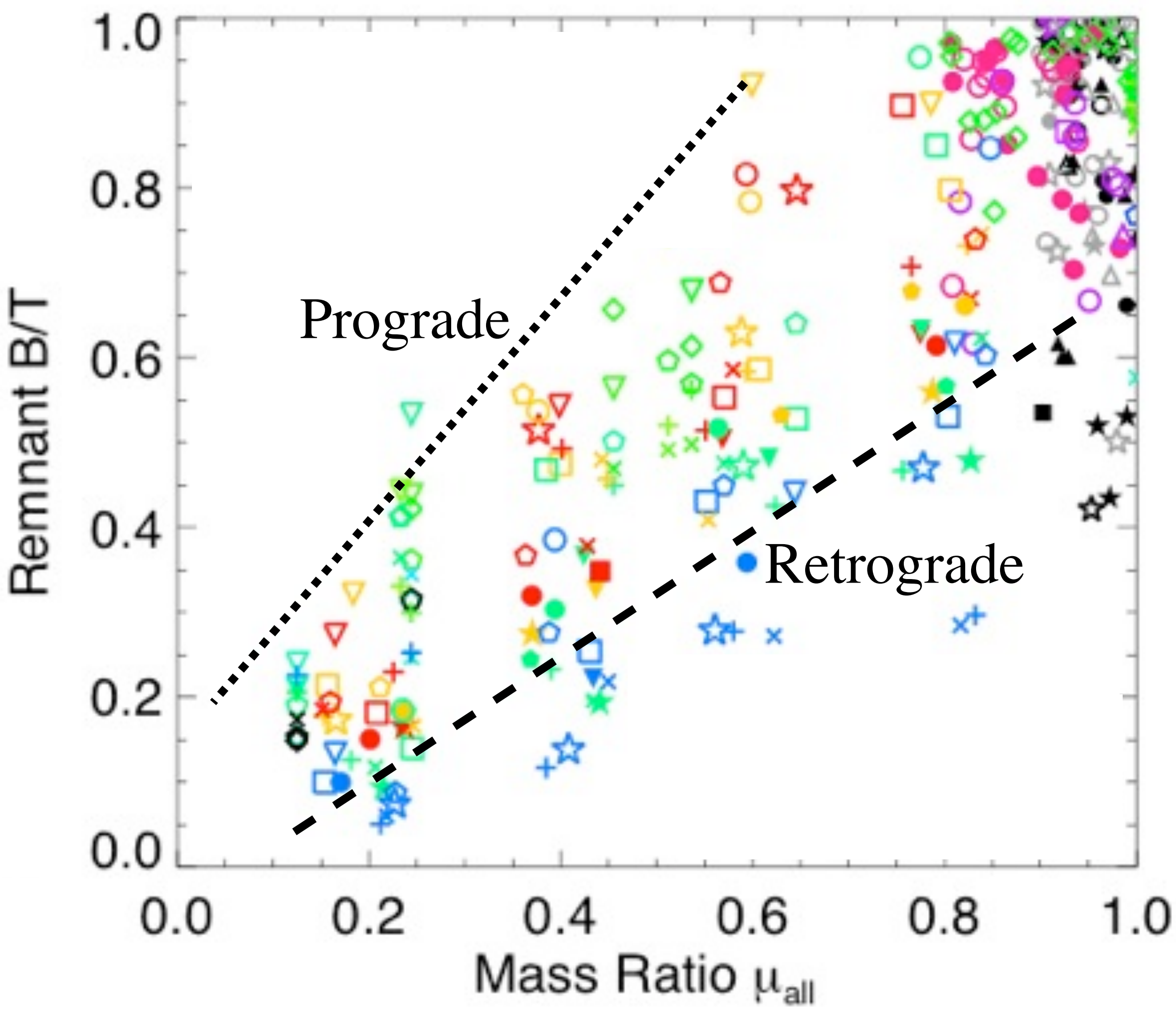

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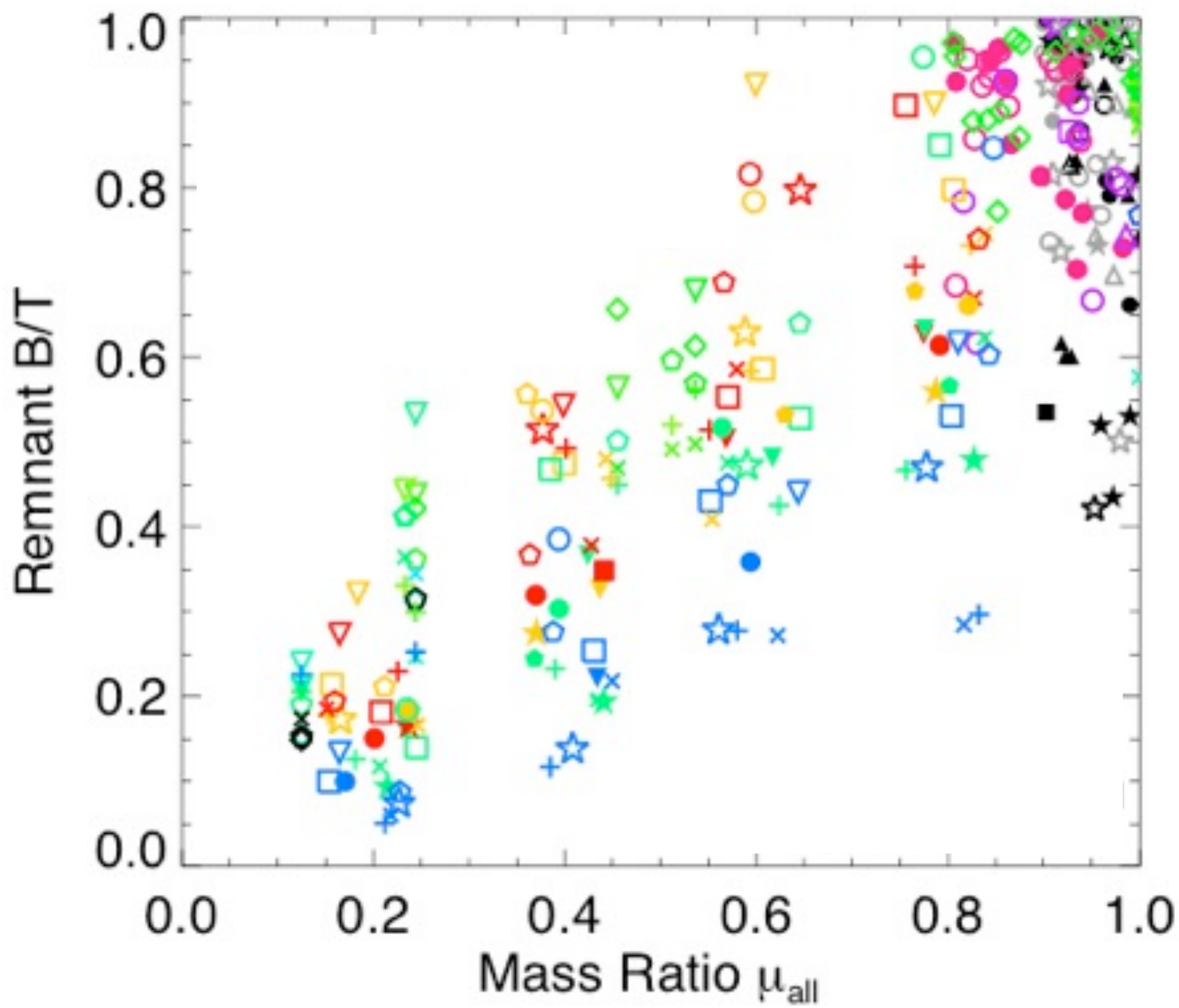

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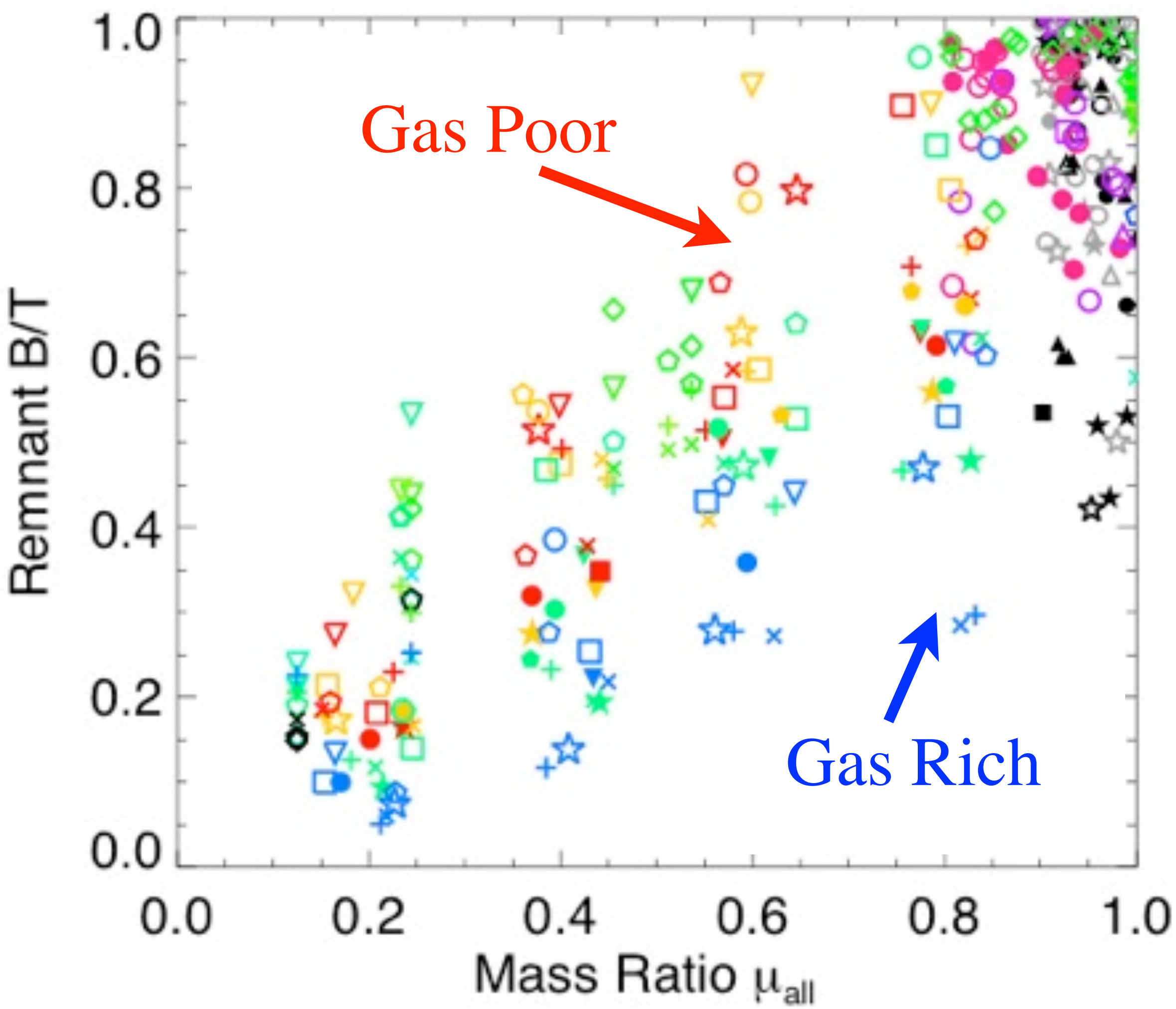
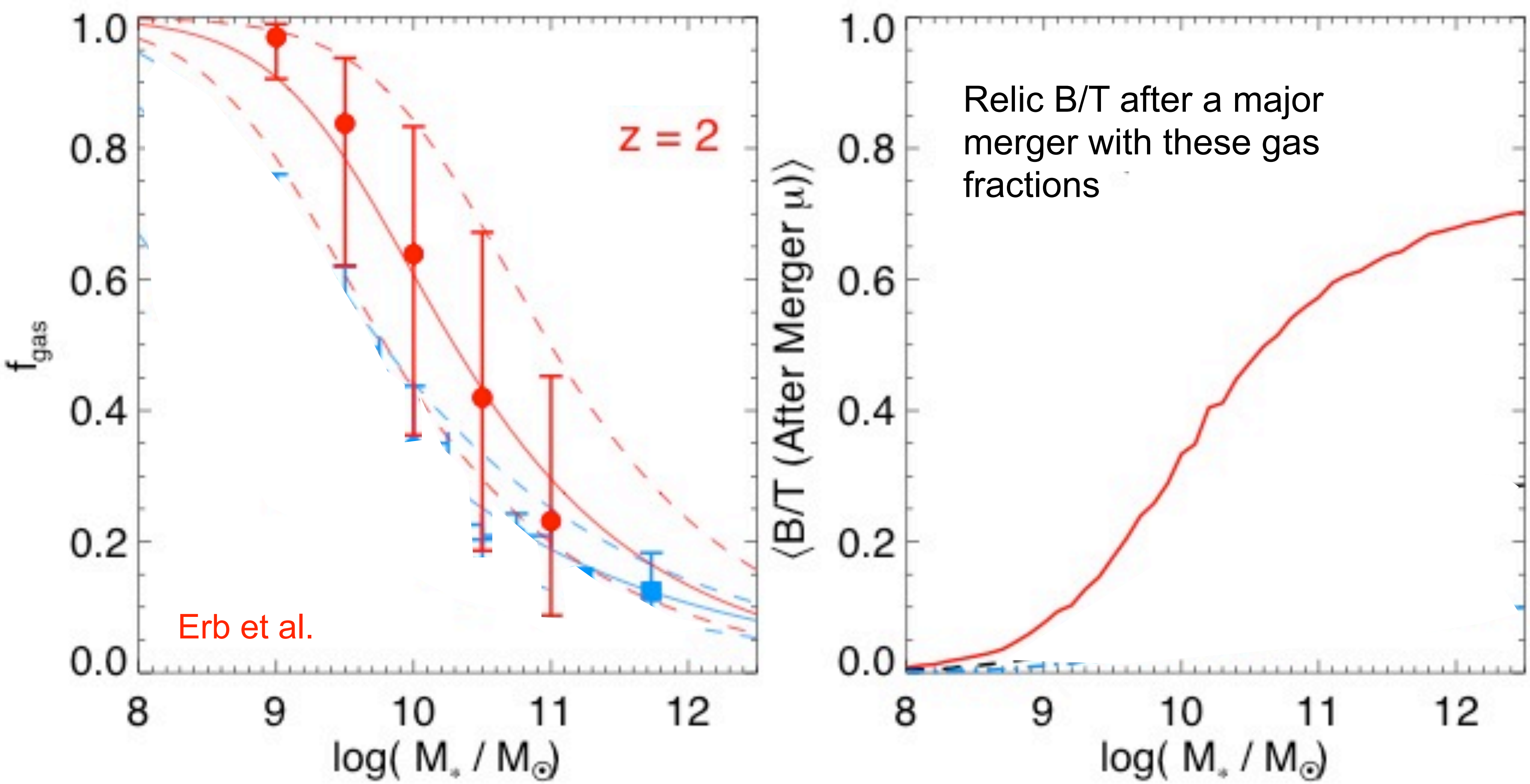


PFH et al. 2008 ("How Do Disks Survive Mergers?")

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

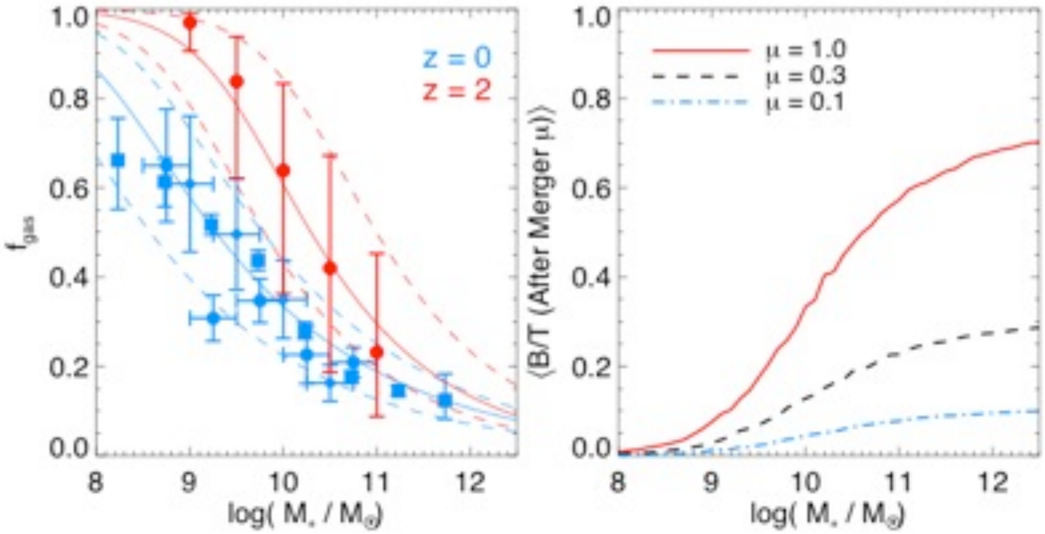
- Fold this into a cosmological model: why do we care?



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

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



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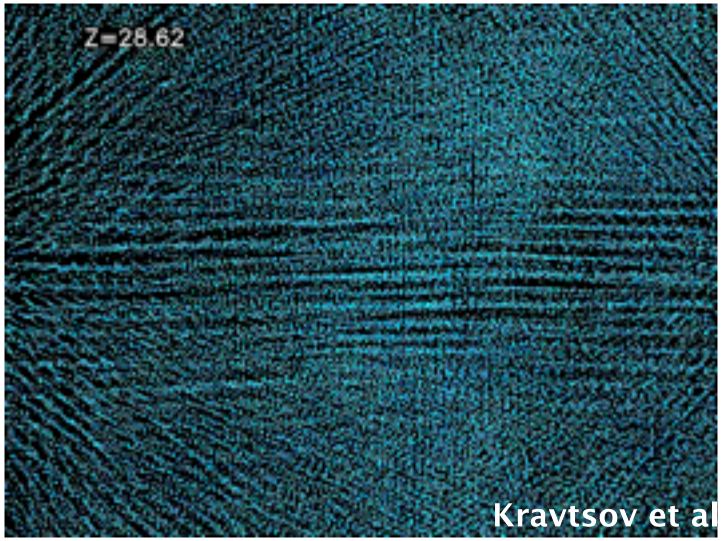

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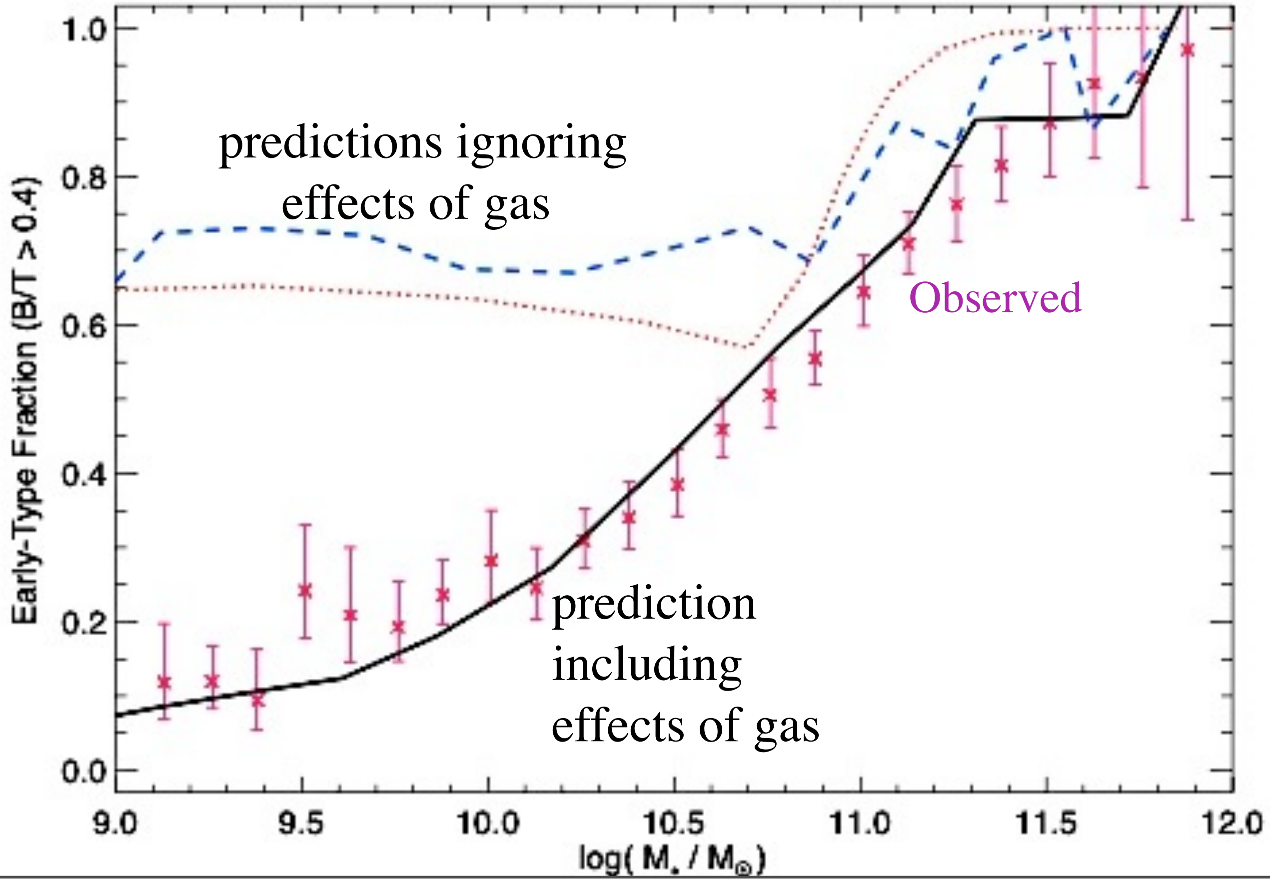


PFH & Somerville et al. 2009

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 2009

Predict lots of high-z disks!

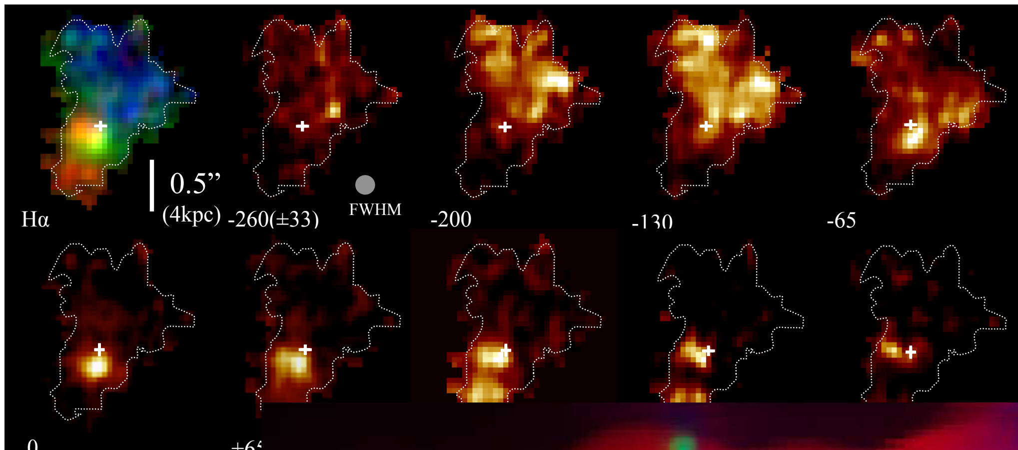
Needed for their existence

We see them

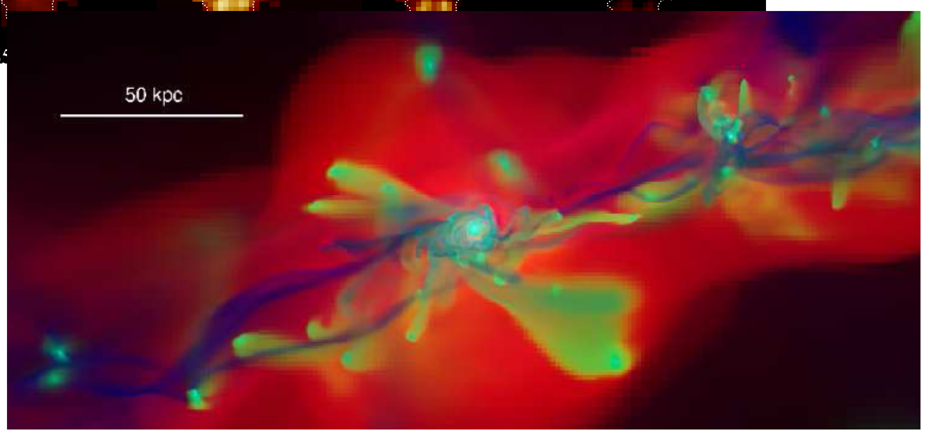
(Genzel, Tacconi, Erb, Law, et al.)

May explain some properties (turbulence etc.)

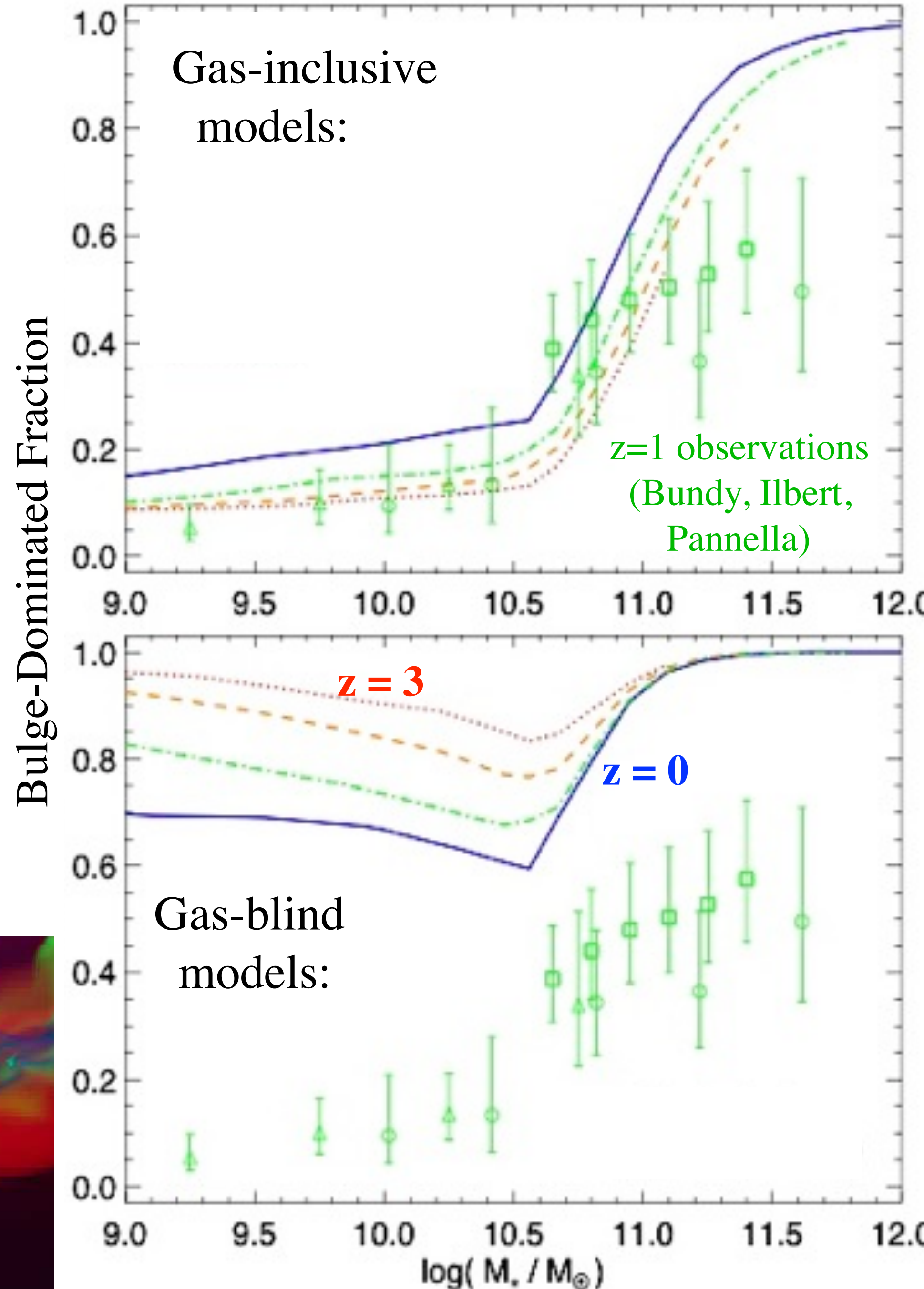
(Robertson & Bullock, 2009)



Genzel et al.



Keres, Dekel. Moore

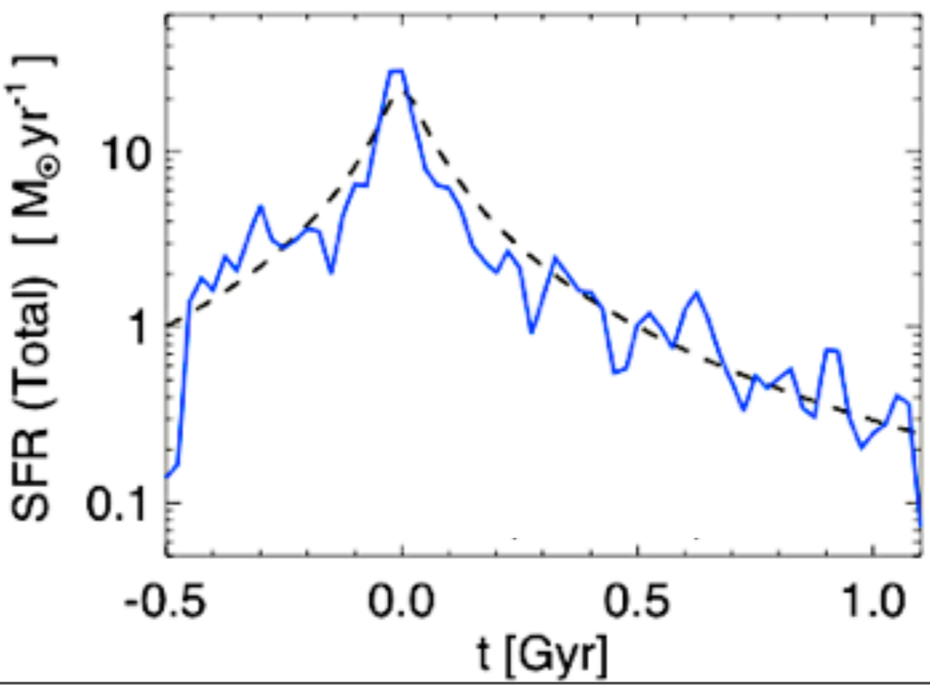


How does this relate to starbursts?

SAME MODEL GIVES STARBURST PROPERTIES FOR EACH MERGER

For each merger, can estimate mass in:

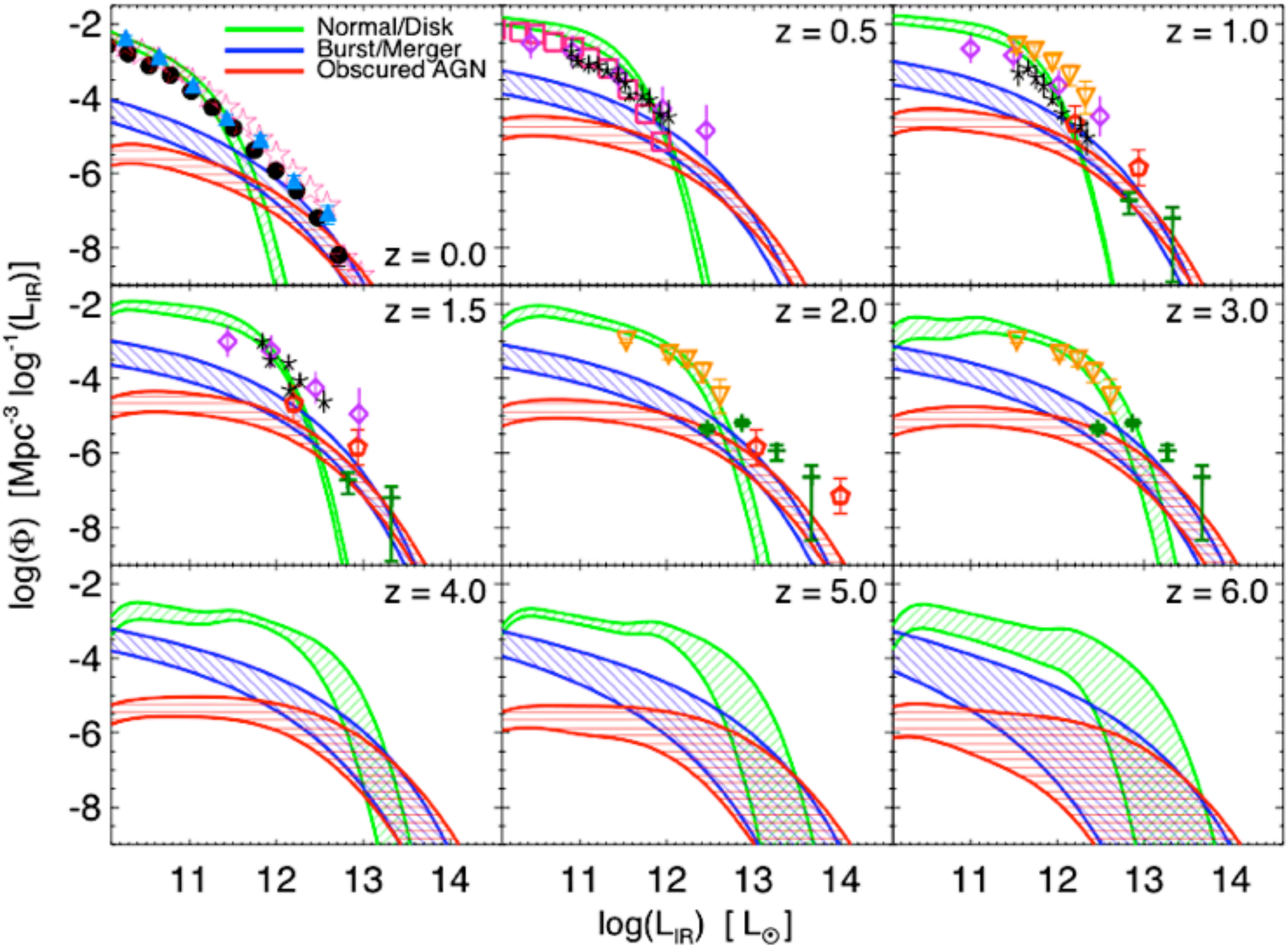
- Surviving disk
- Violently relaxed (from disk stars)
- Starburst (from disk gas)



Given M_{burst}, SFR(t) well-defined

Burst versus "Normal" (Non-Merger) Luminosity Functions

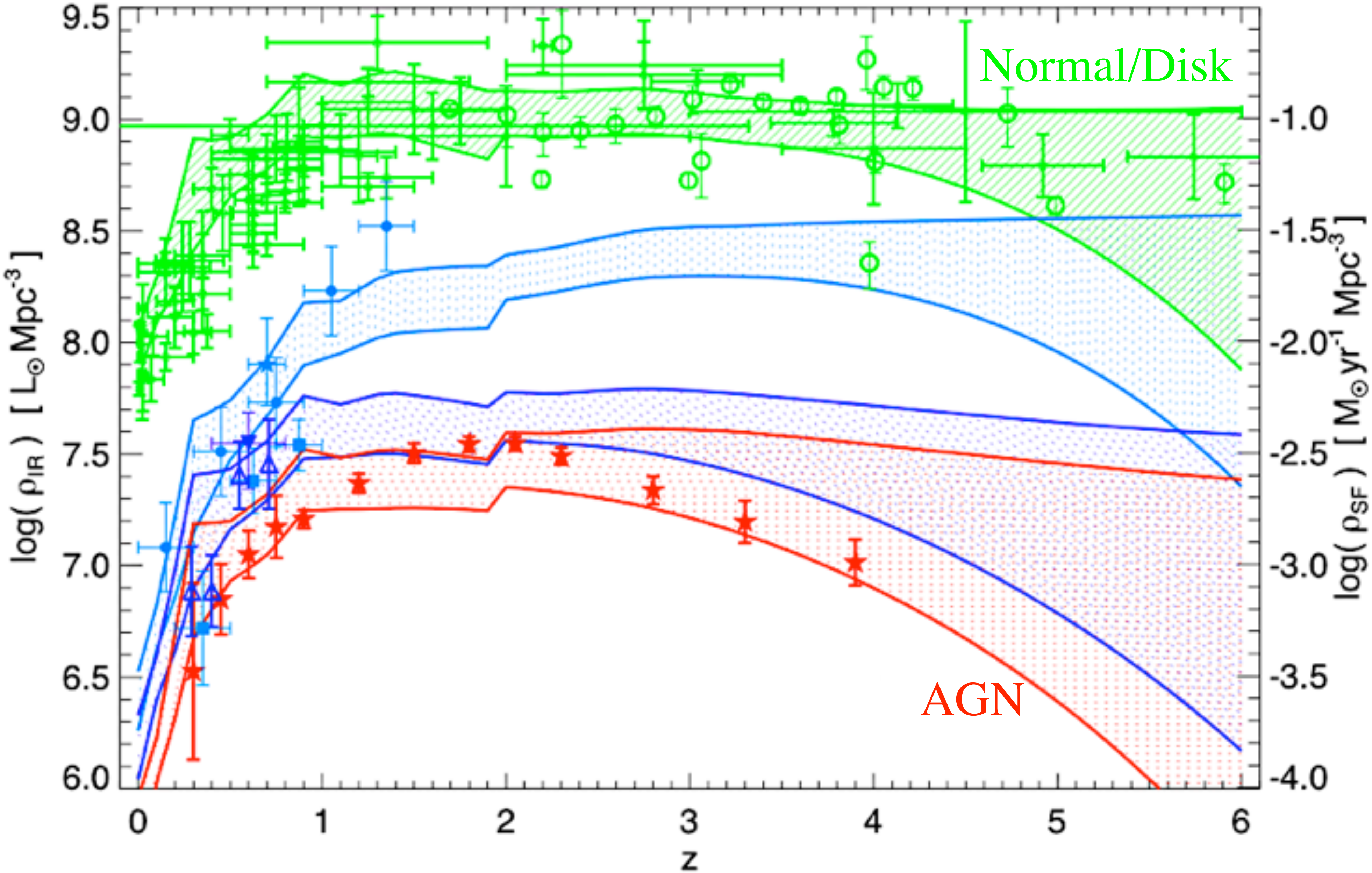
PFH, Younger et al. 20



Have burst predictions -- why not use them?

PFH, Younger et al. 20

All SF in Merging Systems ≠ All SF *Induced* by Mergers



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PFH, Younger et al. 20

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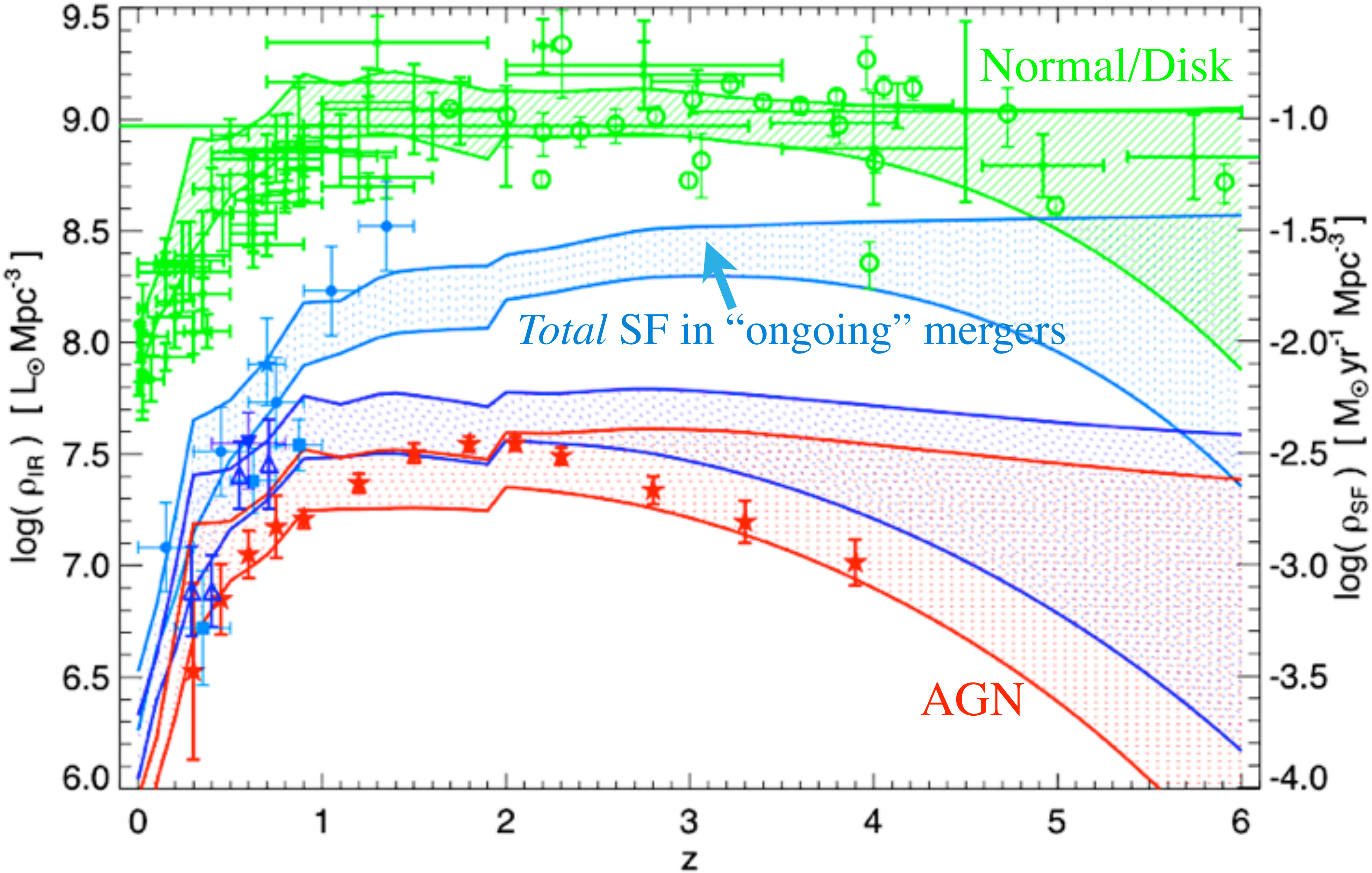

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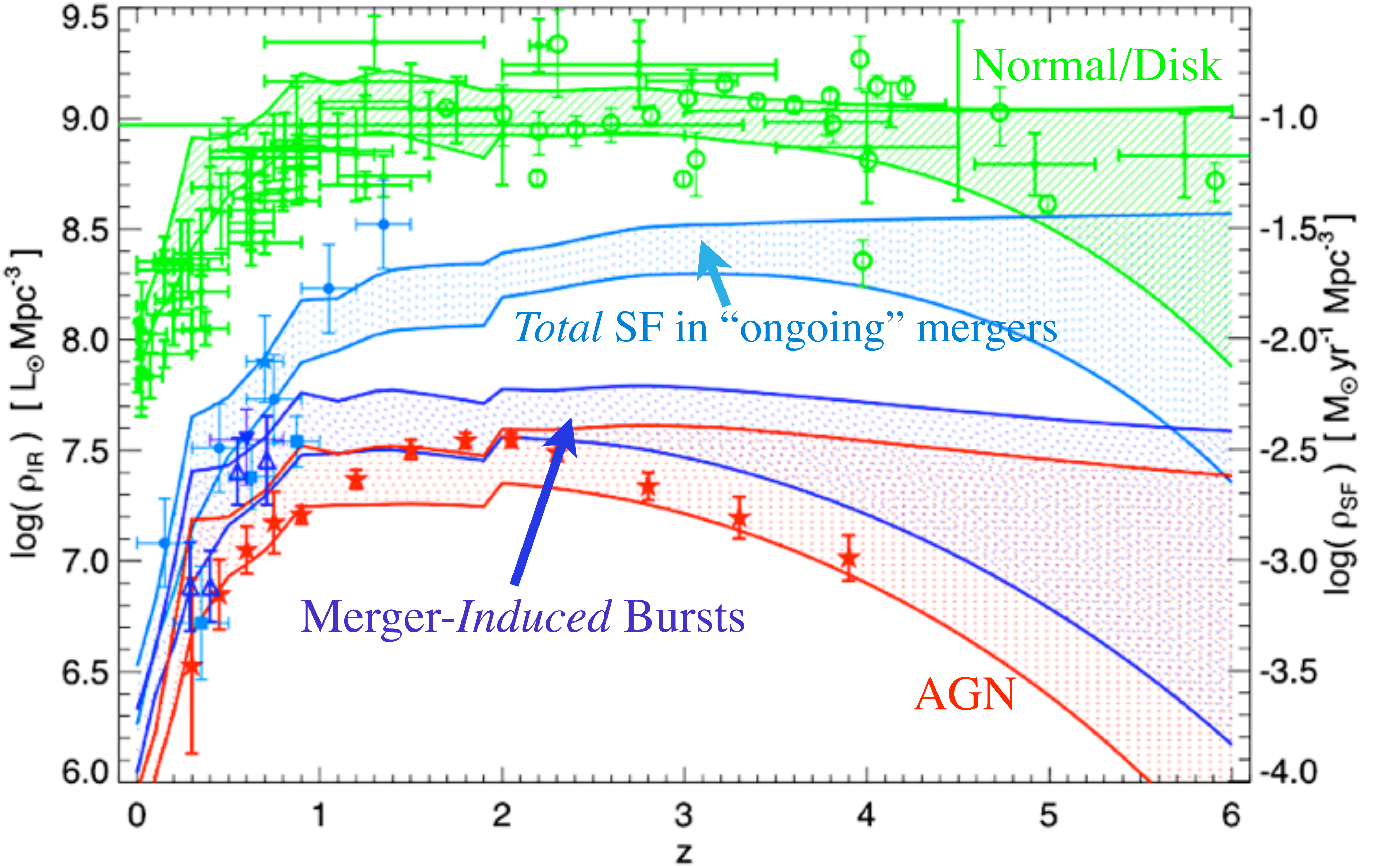
PFH, Younger et al. 20

All SF in Merging Systems ≠ All SF *Induced* by Mergers



Summary

- Ellipticals are *smaller* than spirals! How do we make a *real* elliptical?
  - Gas! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed (f_{gas} ~ 0.1 - 0.5)
  - Explains compact z~2 galaxy and SMG sizes: Inside-out formation via mergers
- Relics of starbursts are important in today's Universe
  - What to expect at high redshifts: naturally link today's spheroids with high-z starbursts
- How do disks *survive* mergers? (How do we ***avoid*** making all ellipticals?)
  - Gas! No stars = No angular momentum loss
  - Particularly important at high-z
  - Drives the starburst history of the Universe... but not always as you'd expect

Understanding the structure and scalings of galaxies can be reduced to understanding their gas-consumption histories...