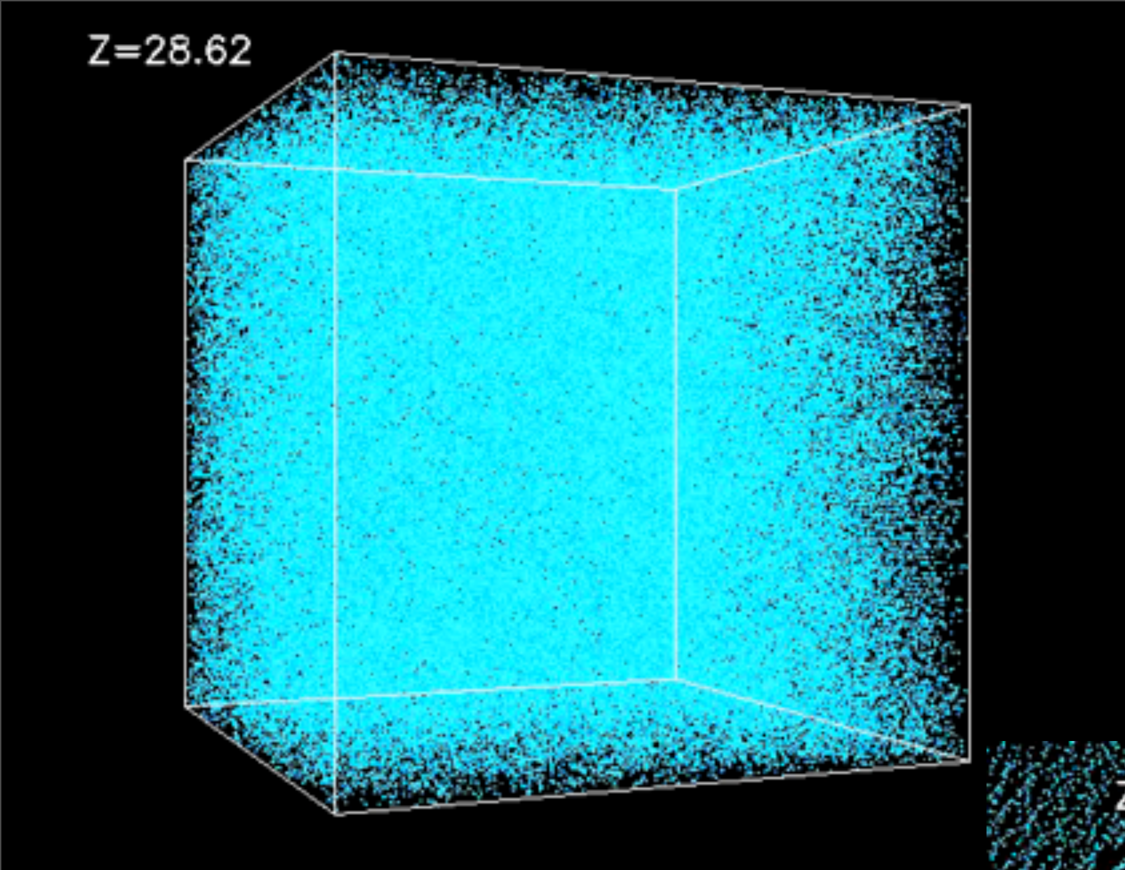
Gas & Galaxy Mergers: Driving an Evolving Hubble Sequence

Philip Hopkins

Lars Hernquist, T. J. Cox, 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, Adam Myers, and many more

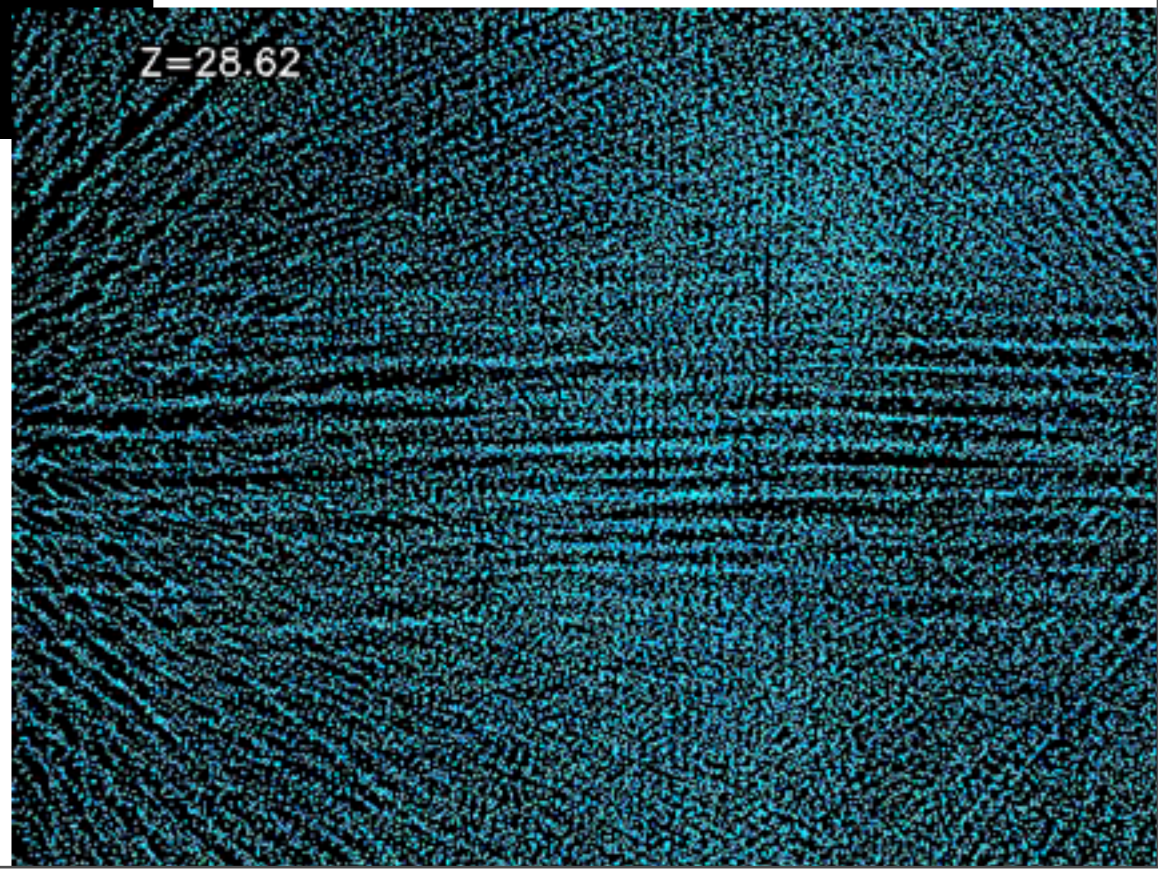

Adam
Lidz
TJ
Cox
Josh
Younger
Desika
Narayanan
Chris
Hayward
Gurtina
Besla
Dusan Keres
Lars
Hernquist
Eliot
Quataert



Motivation

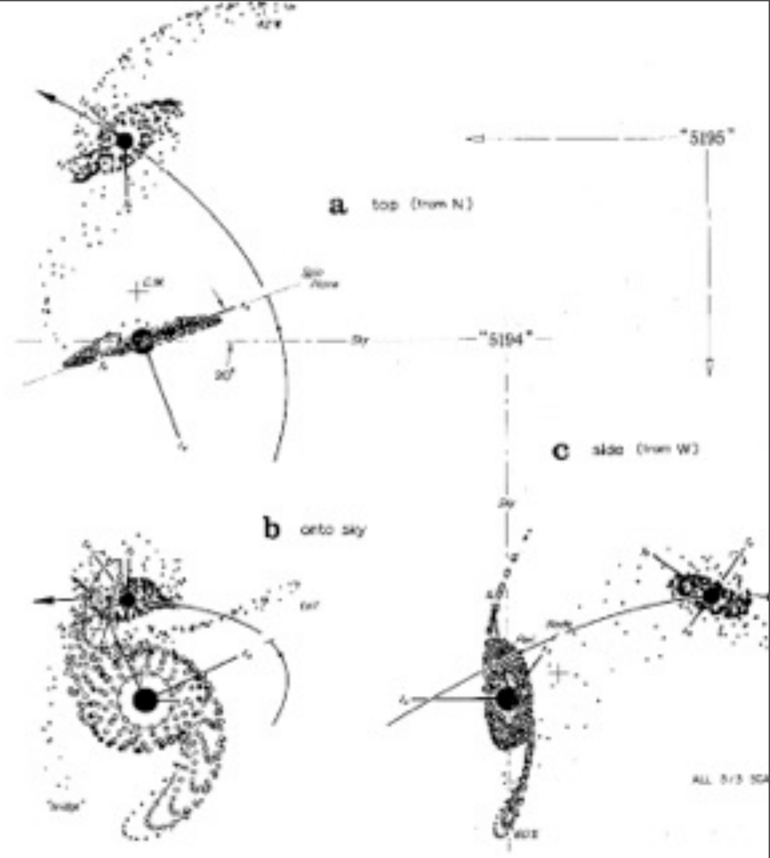
HOW DID WE GET TO GALAXIES TODAY?

Kravtsov et al.



- Structure grows hierarchically: must understand mergers

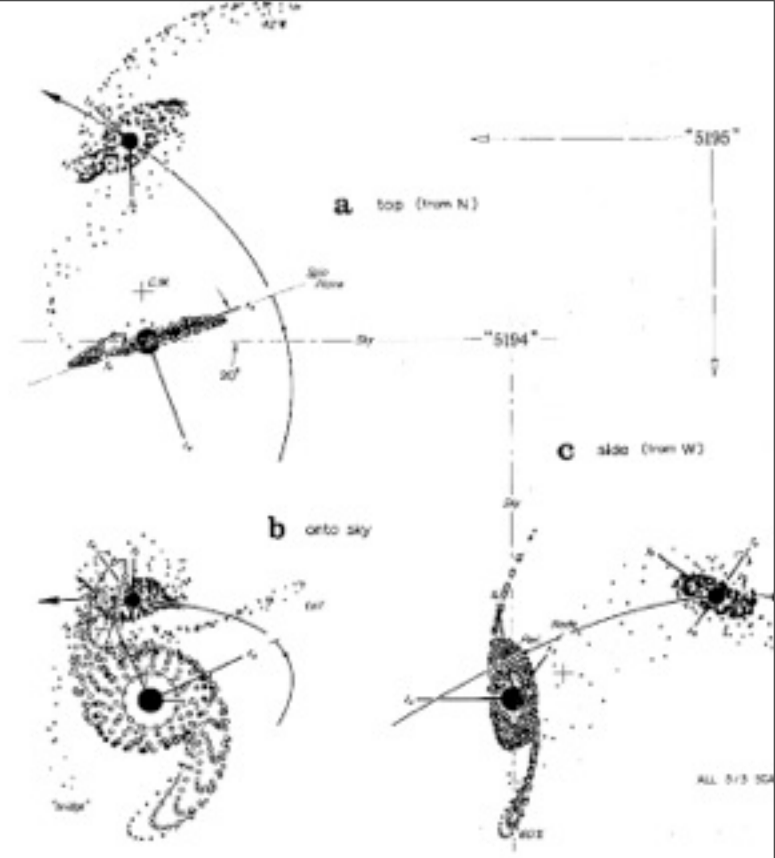
Our Conventional Wisdom (Toomre):



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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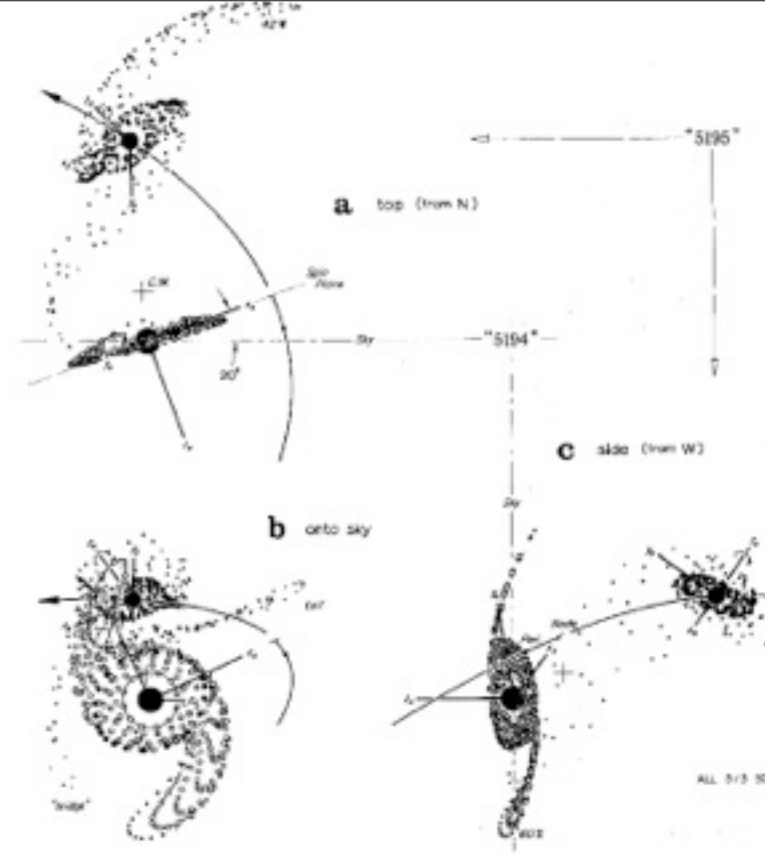
Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk



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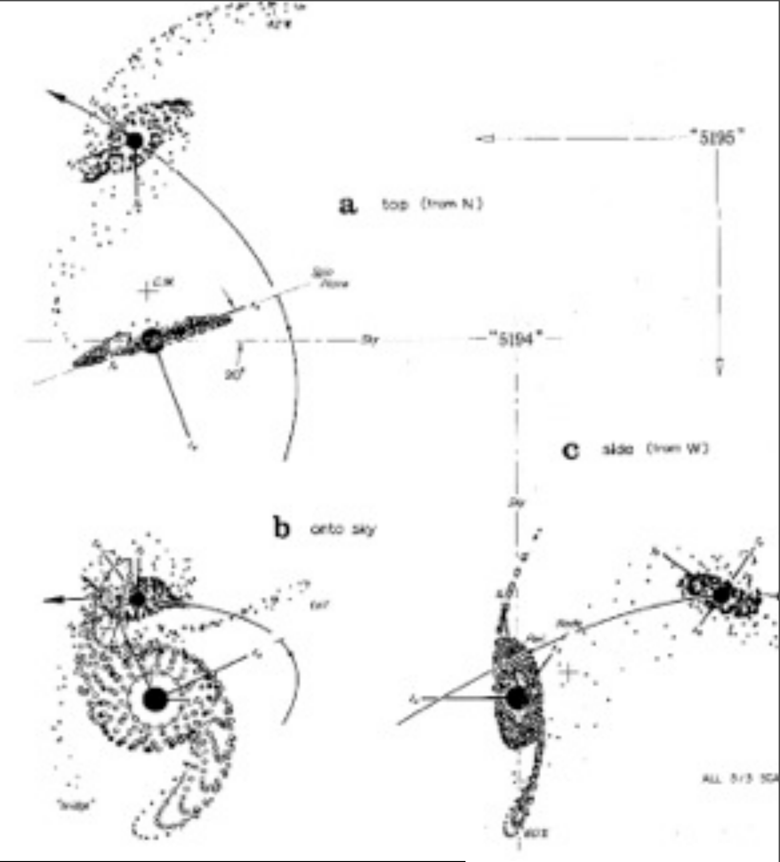
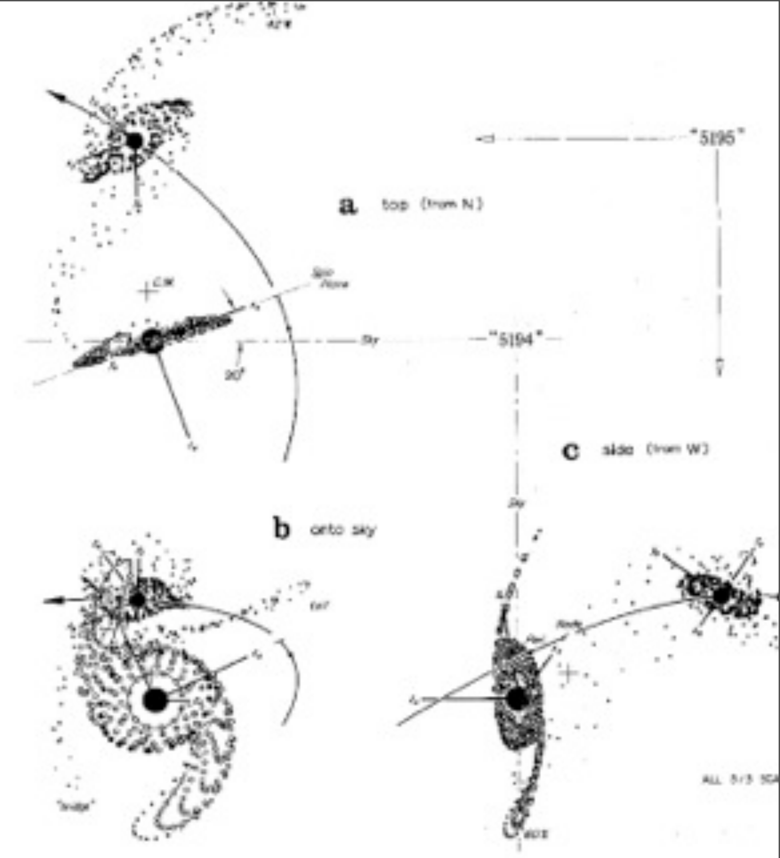


F. Summers

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"

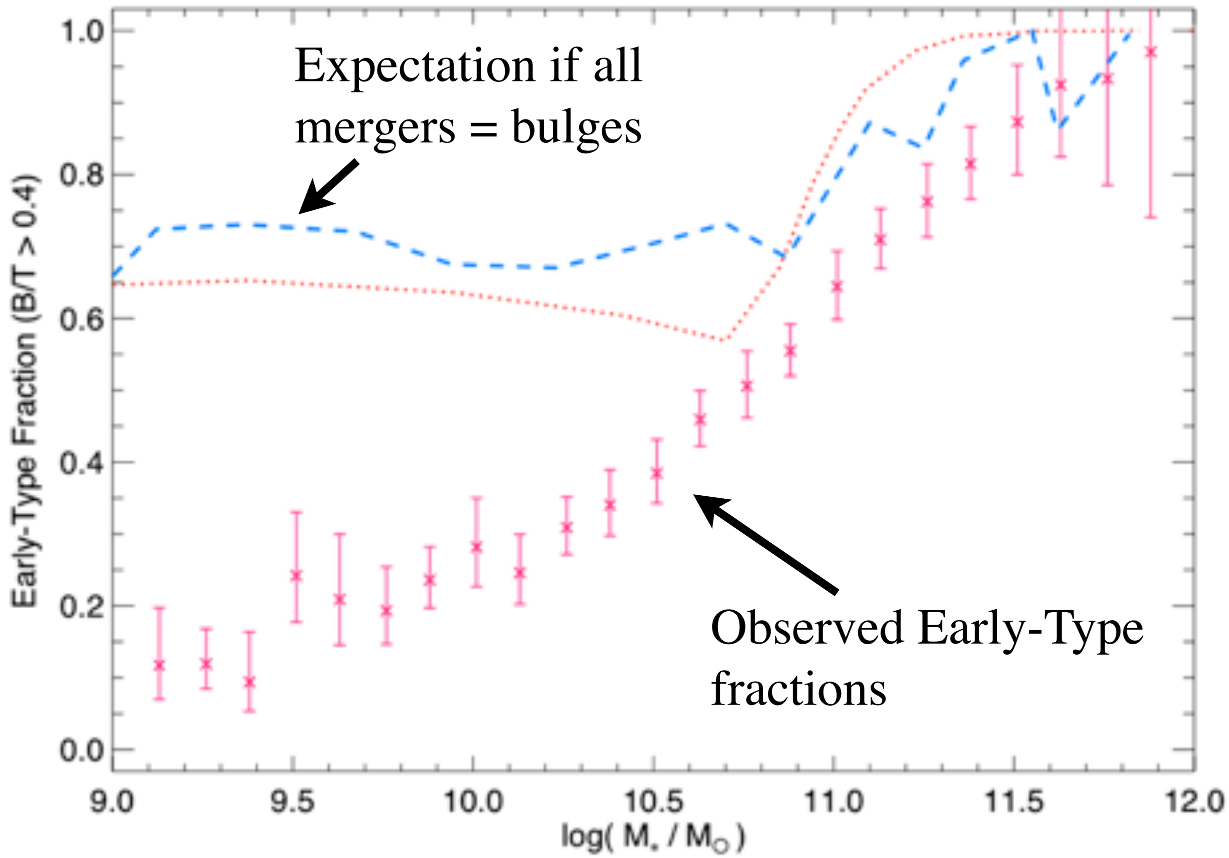


F. Summers

Today, many of these are *problems*...

Too Many Mergers?

-- missing some physics?



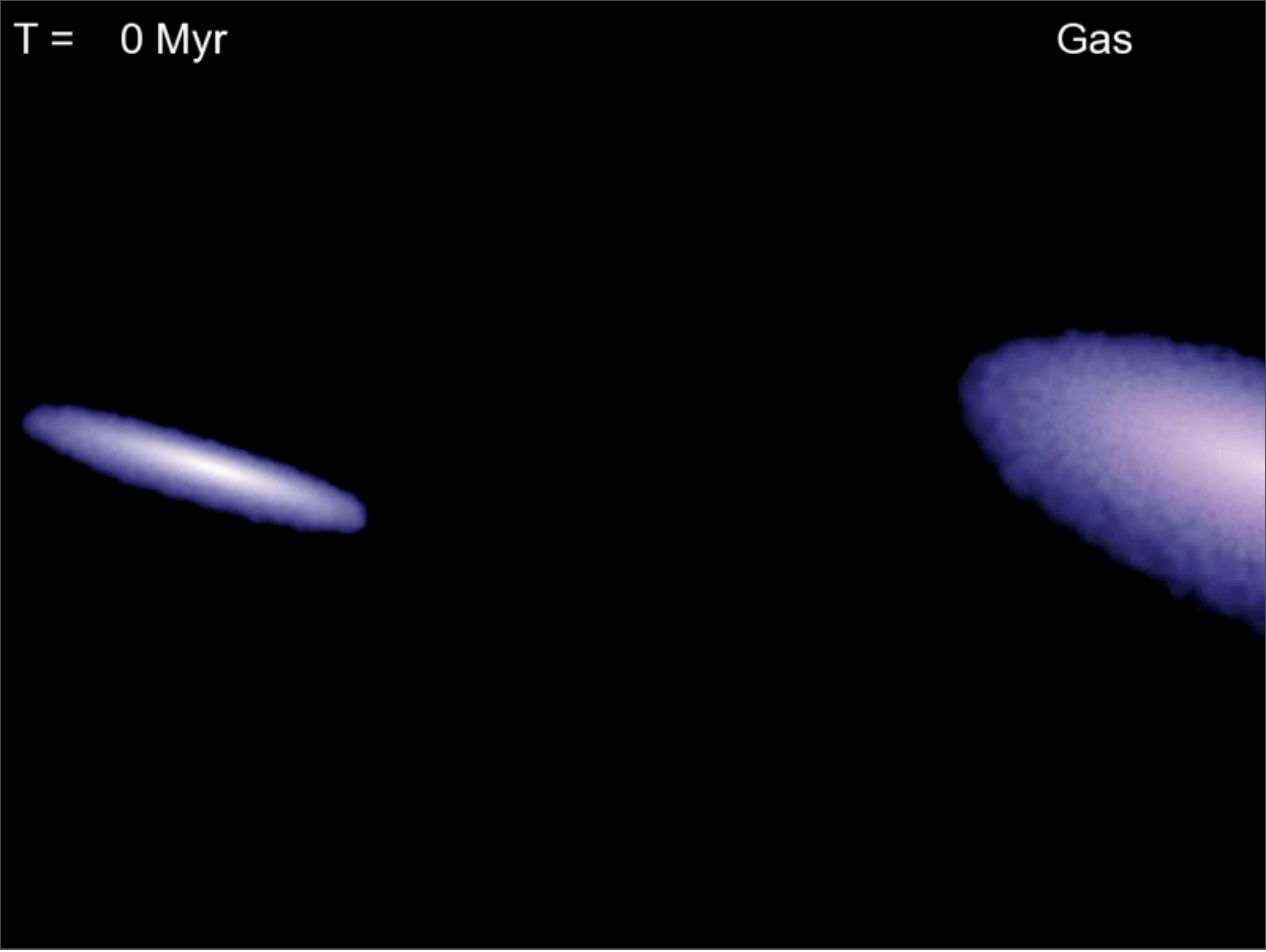
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

-- profiles too flat

-- shapes too flattened

So What About Today's Models is Different?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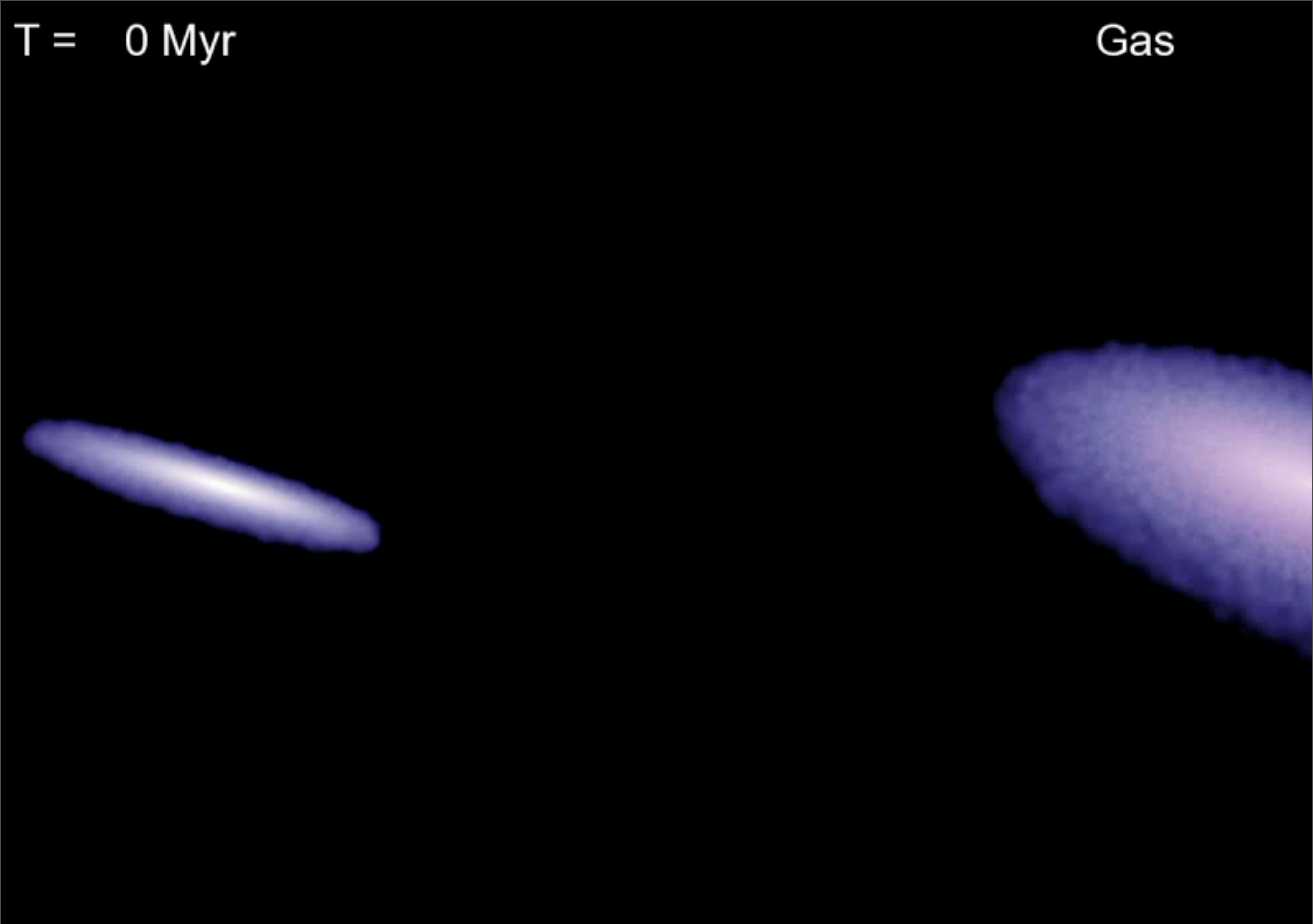
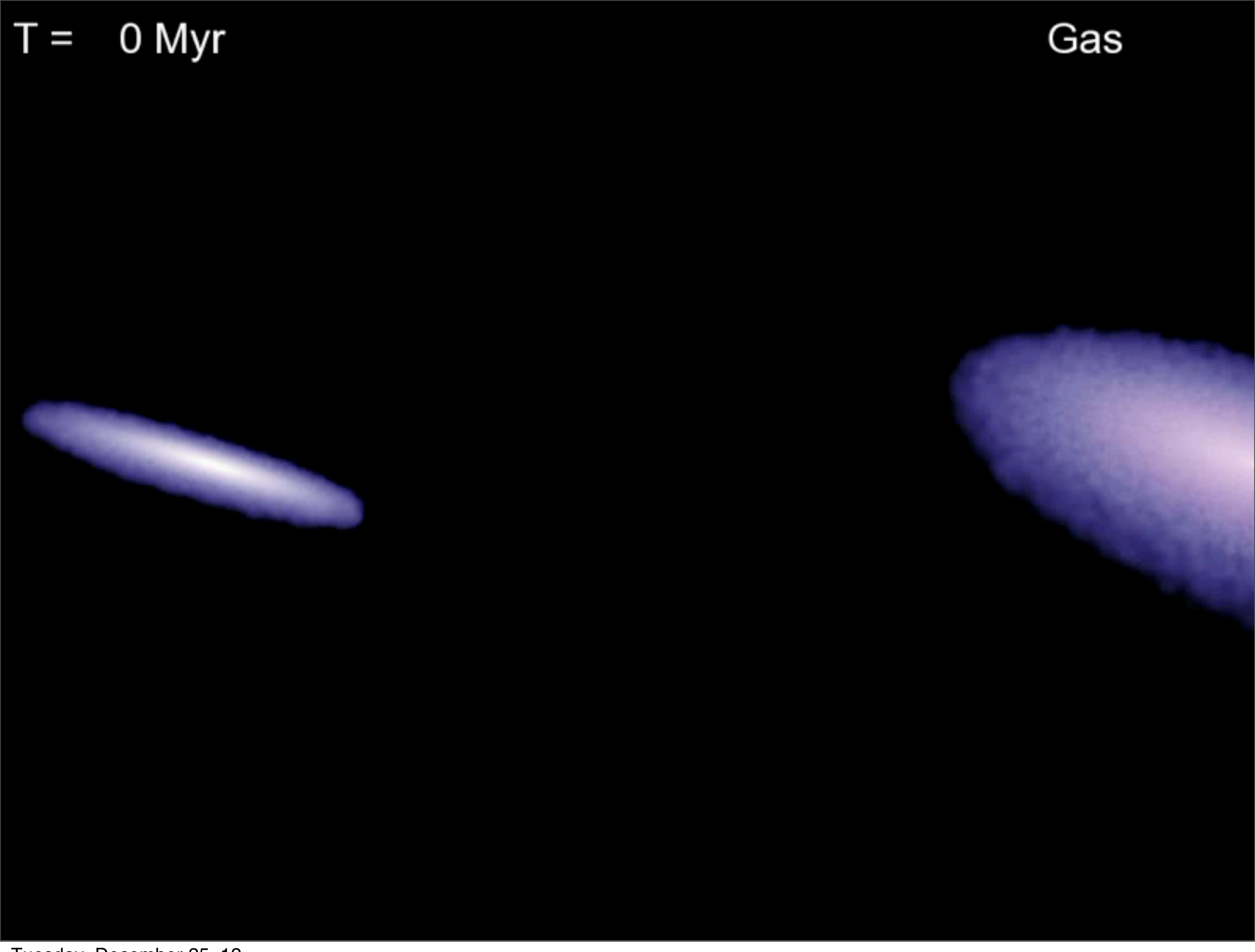
Gas



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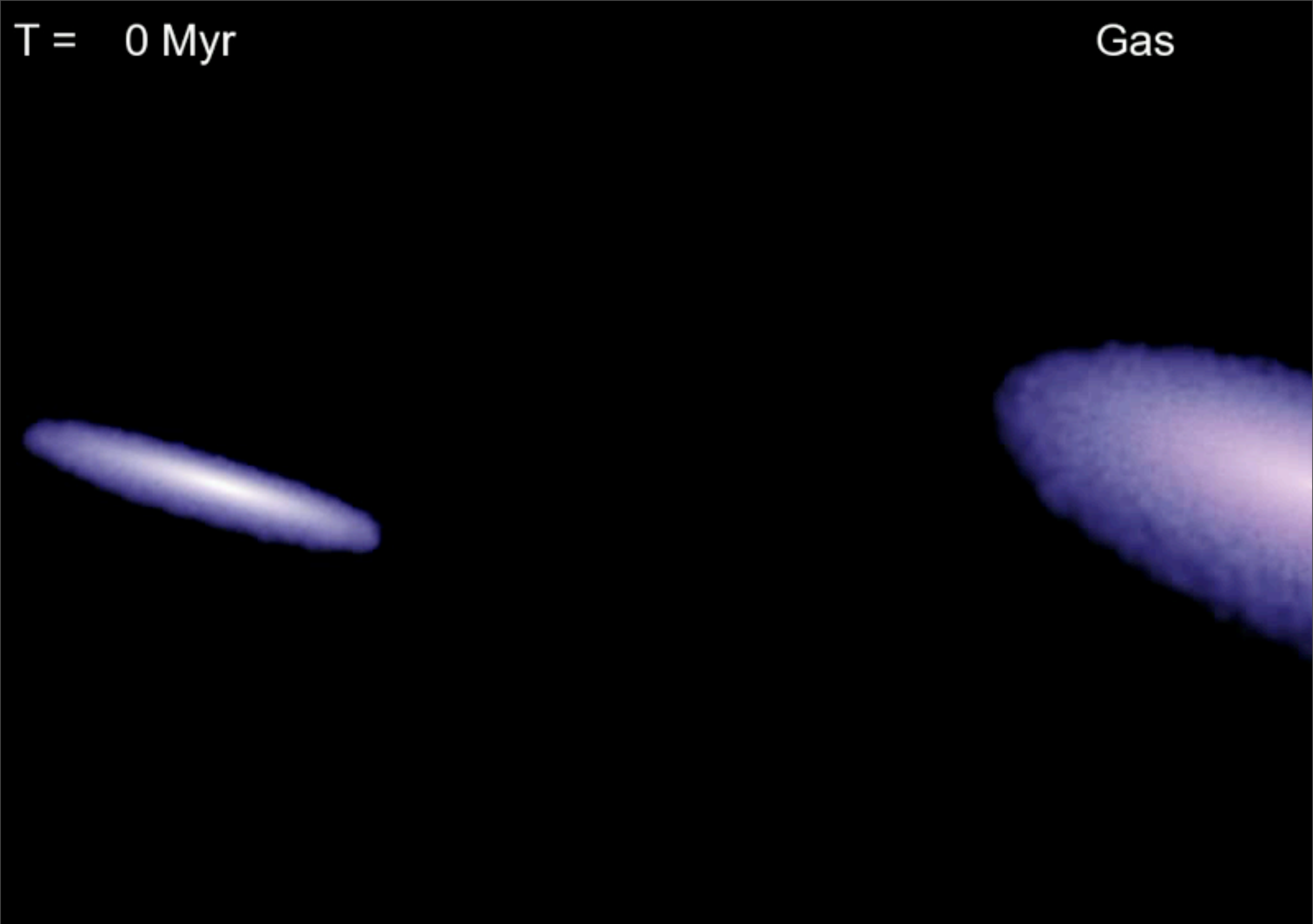
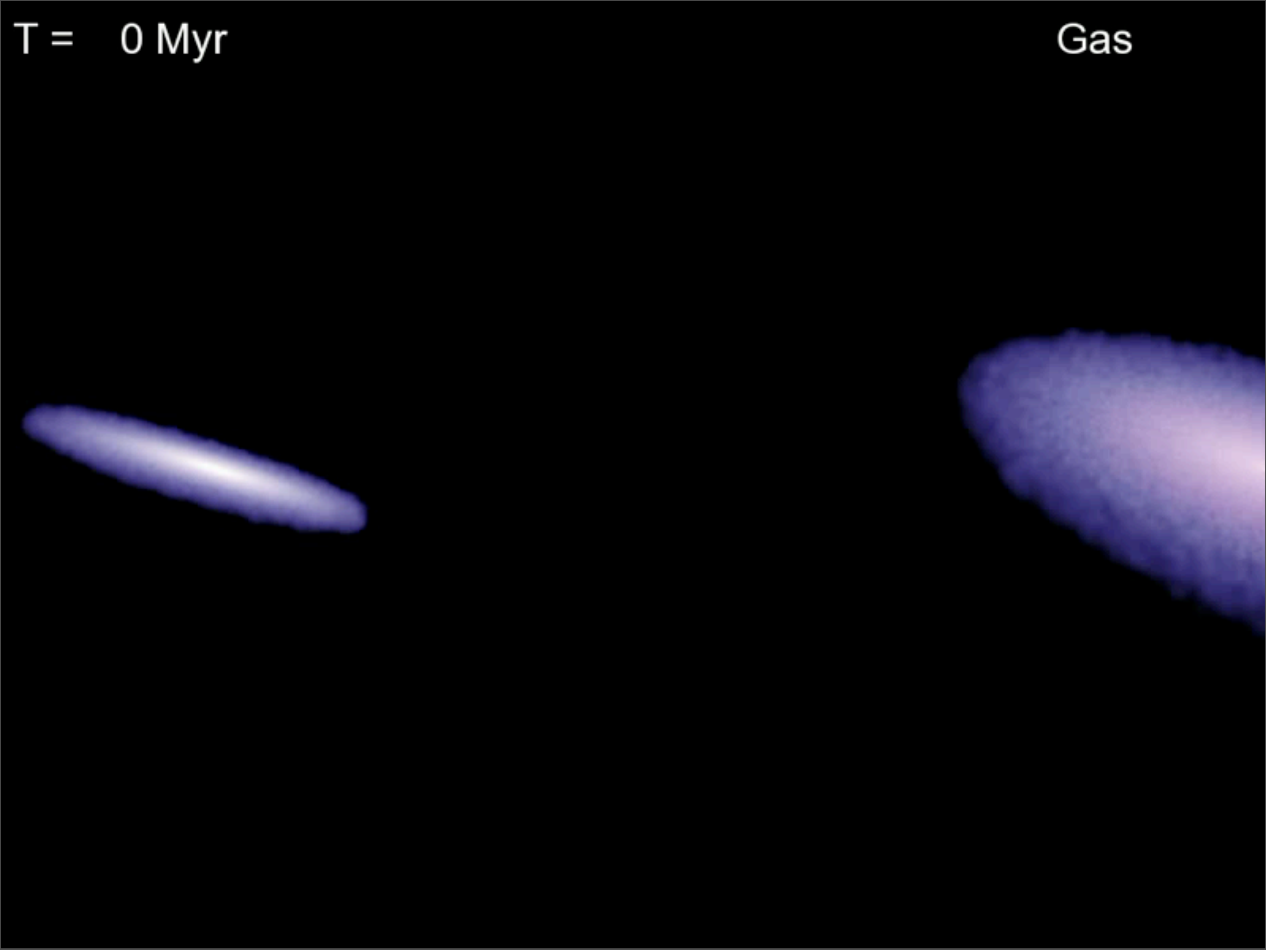


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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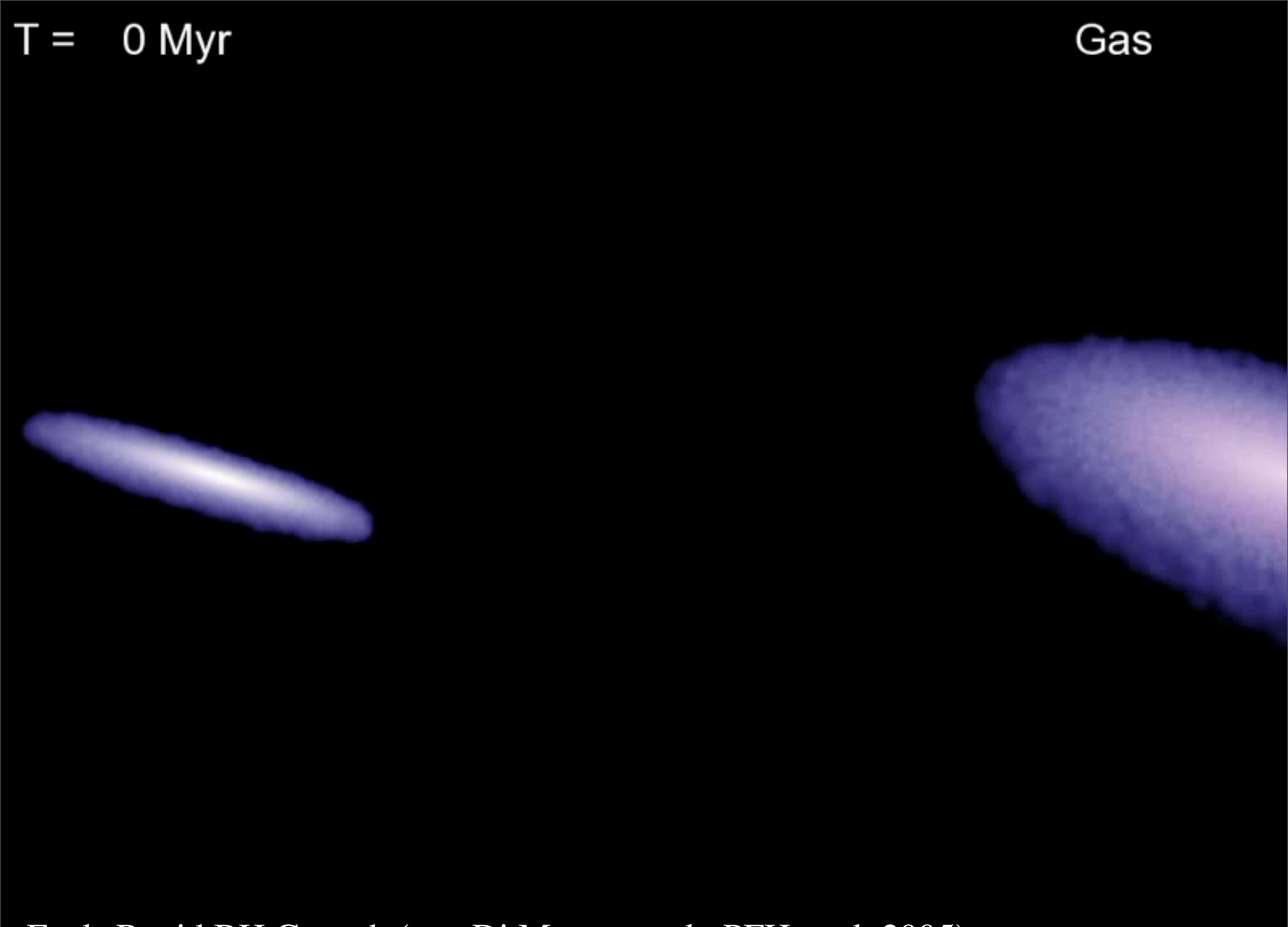
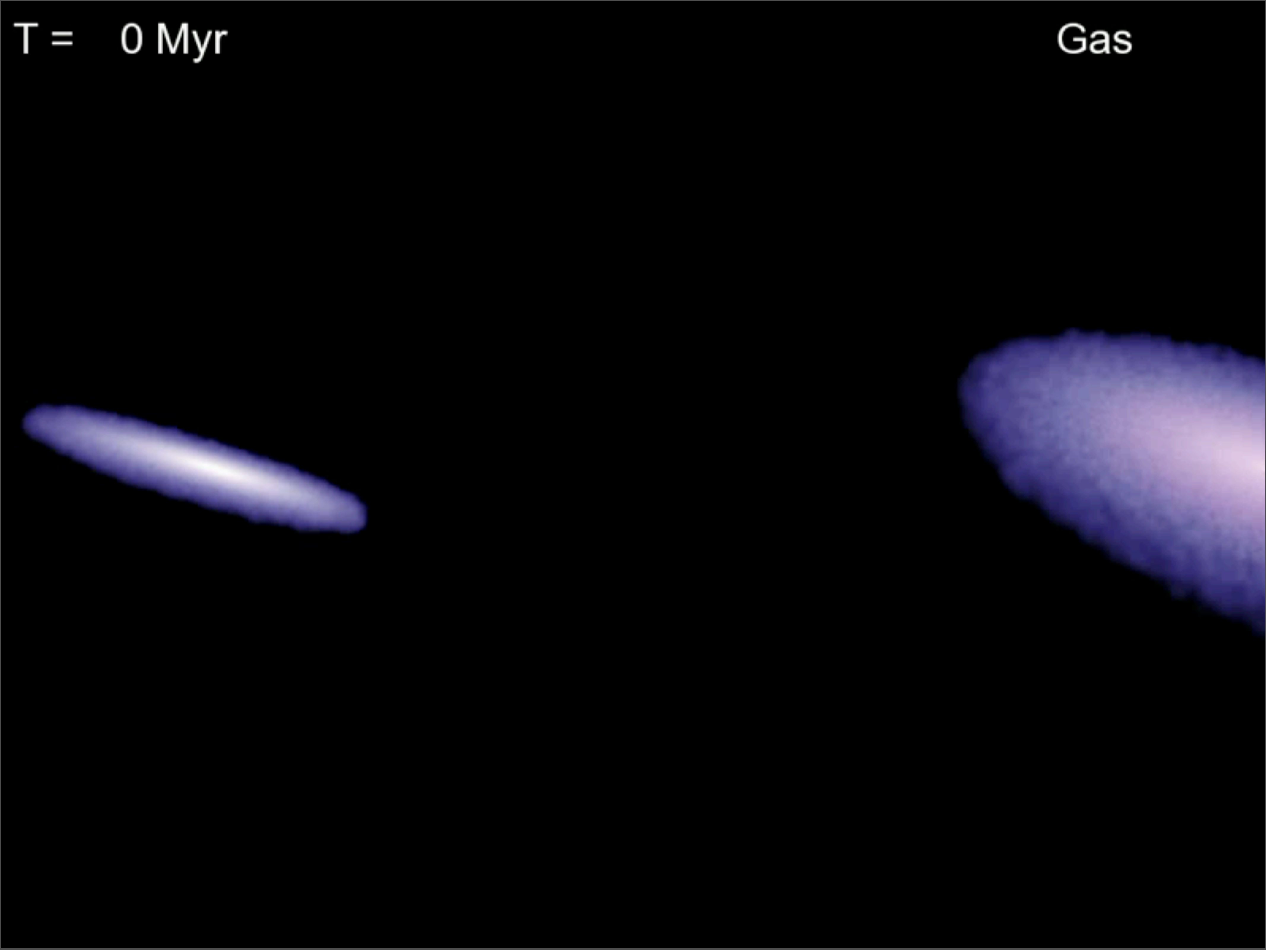


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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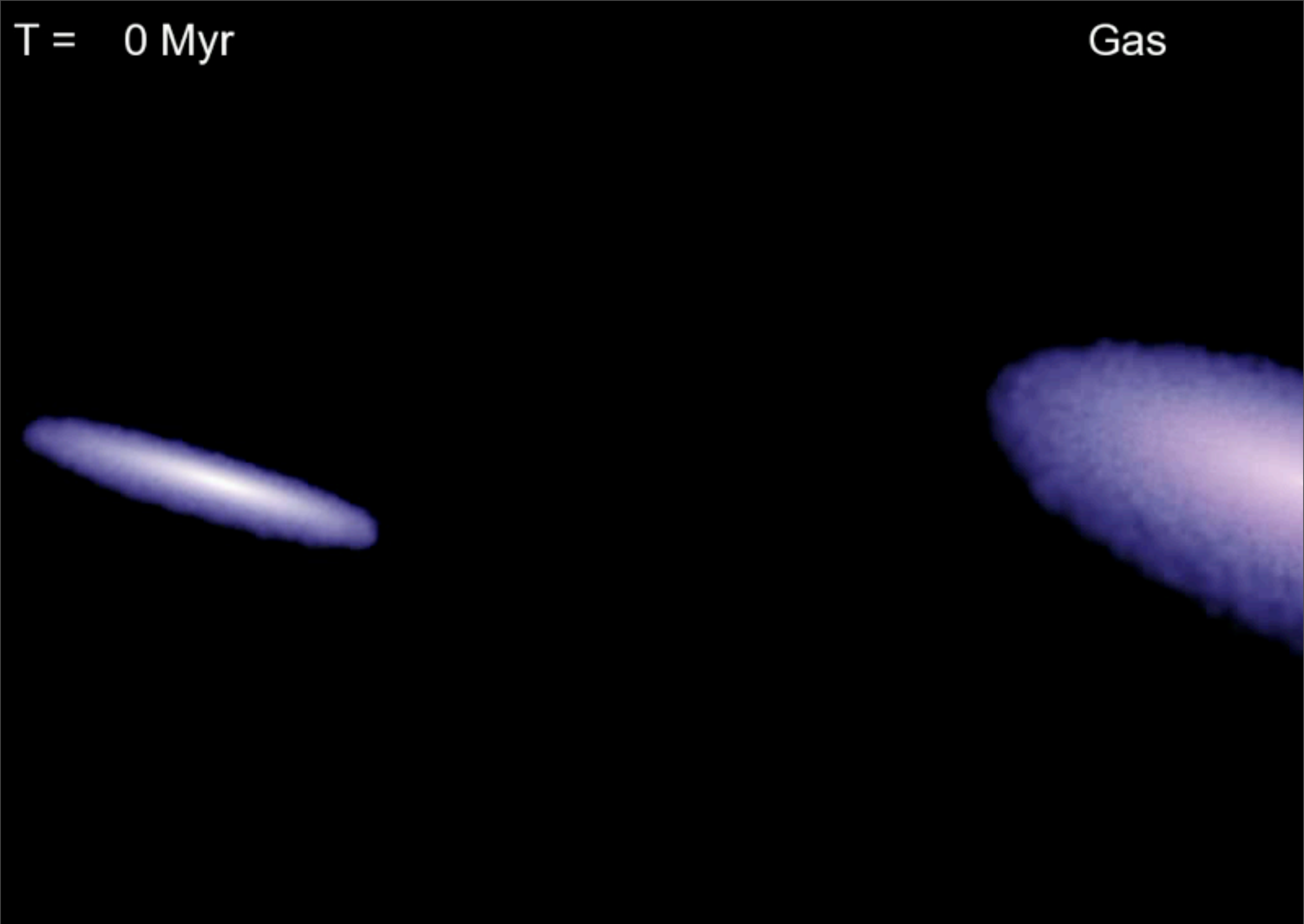
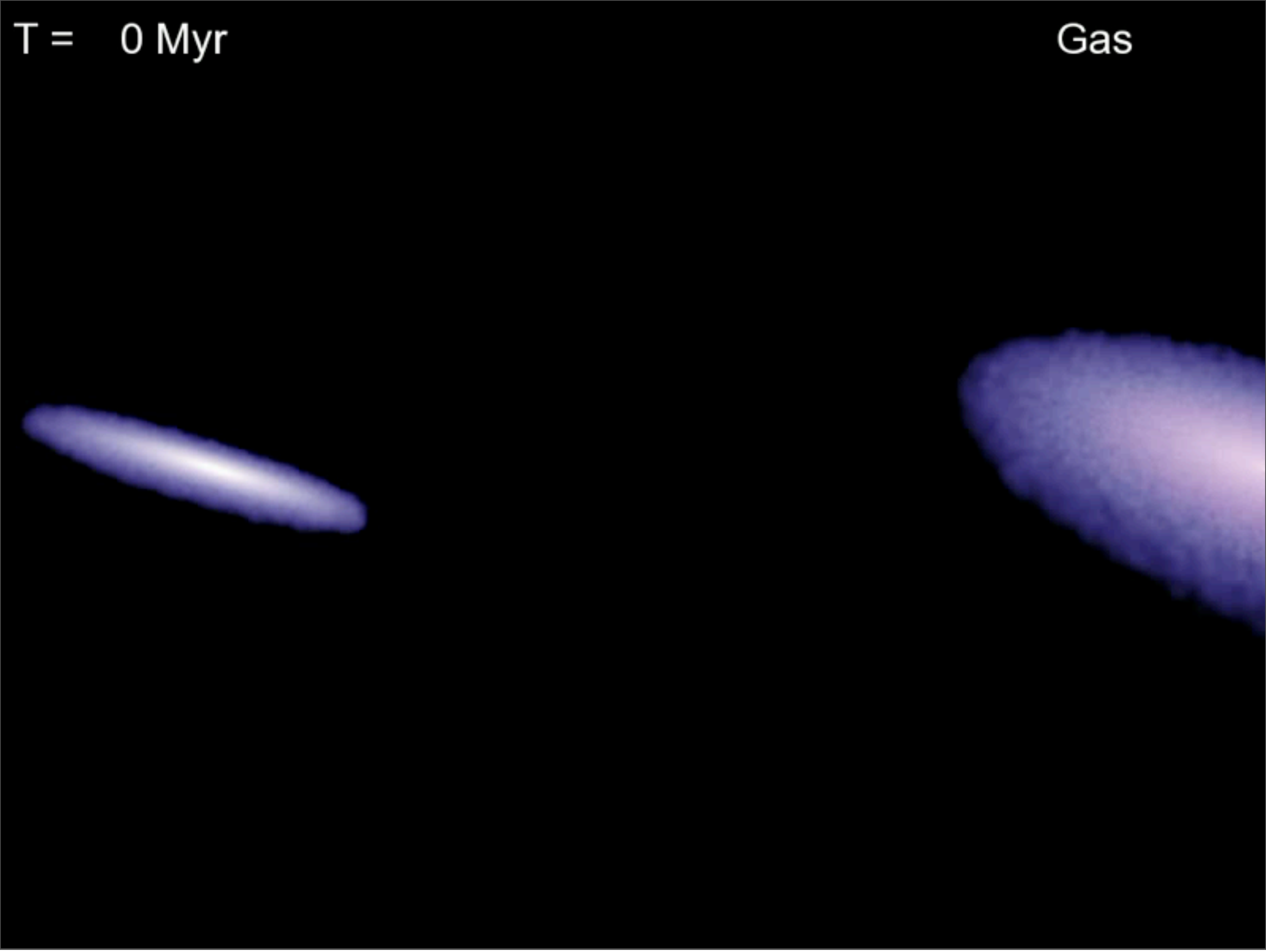


Feedback expels remaining gas, shutting down growth (more later...)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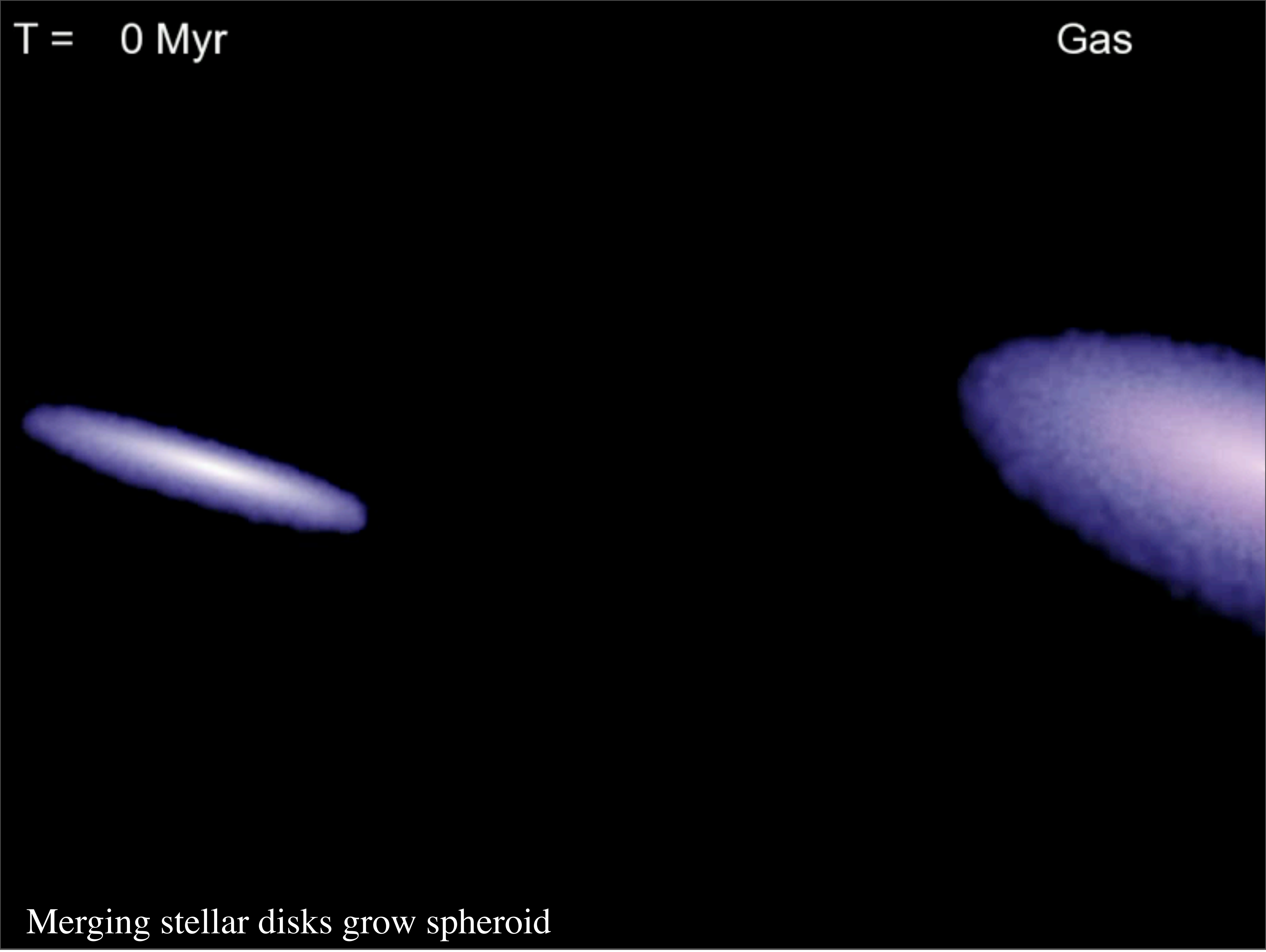
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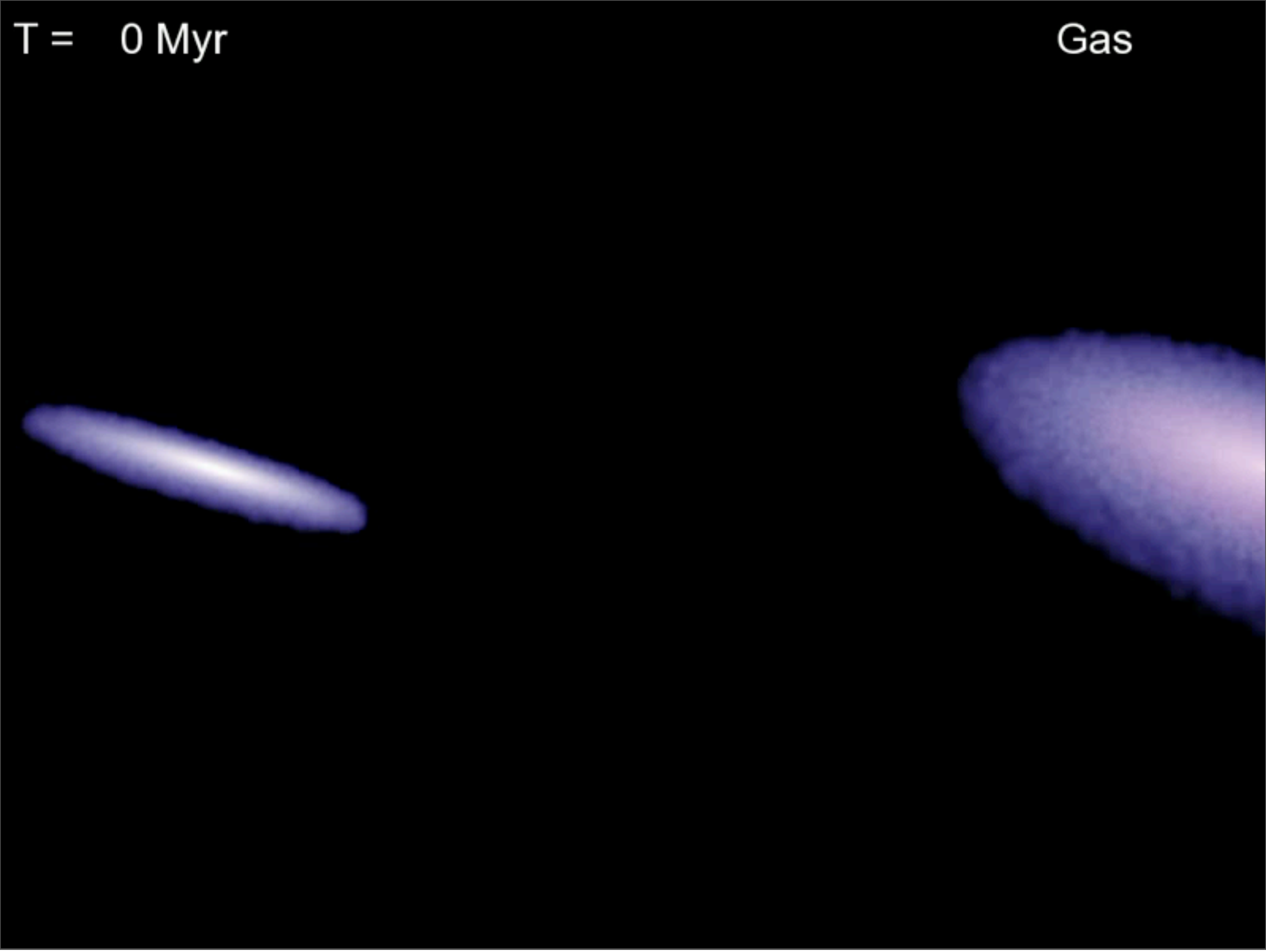
Gas
Merging stellar disks grow spheroid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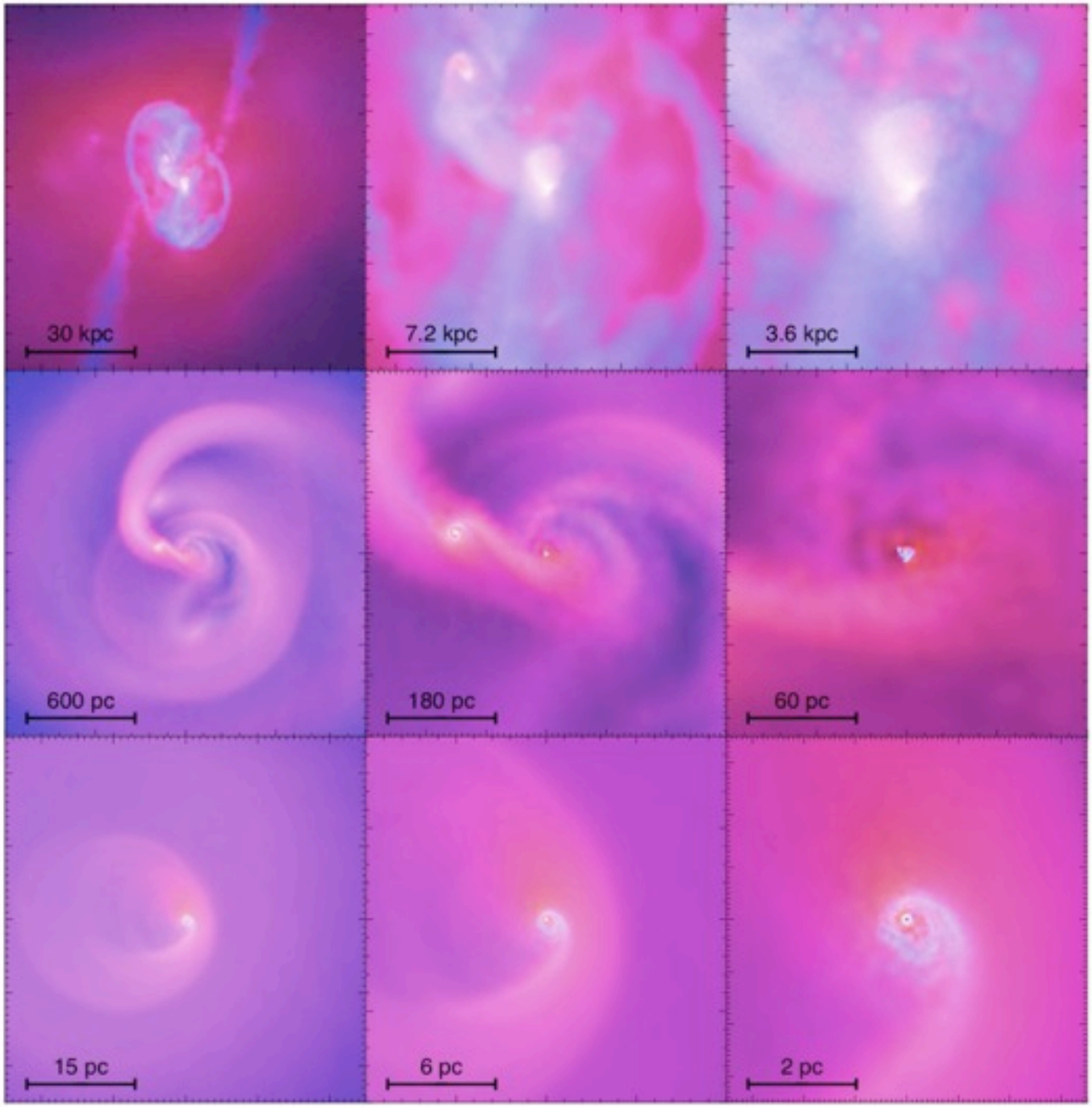
Gas Loses Angular Momentum: Participates in a Massive Starburst

(NOW SIMULATIONS CAN FOLLOW FROM ~ KPC to ~ 0.1 PC)



- Follow gas from 10s of kpc to ~0.1 pc
- Cascade of instabilities: merger itself not dominant inside of a kpc
- Instabilities change form at BH radius of influence: continue on to fuel SMBH

PFH & Quataert 2009,201

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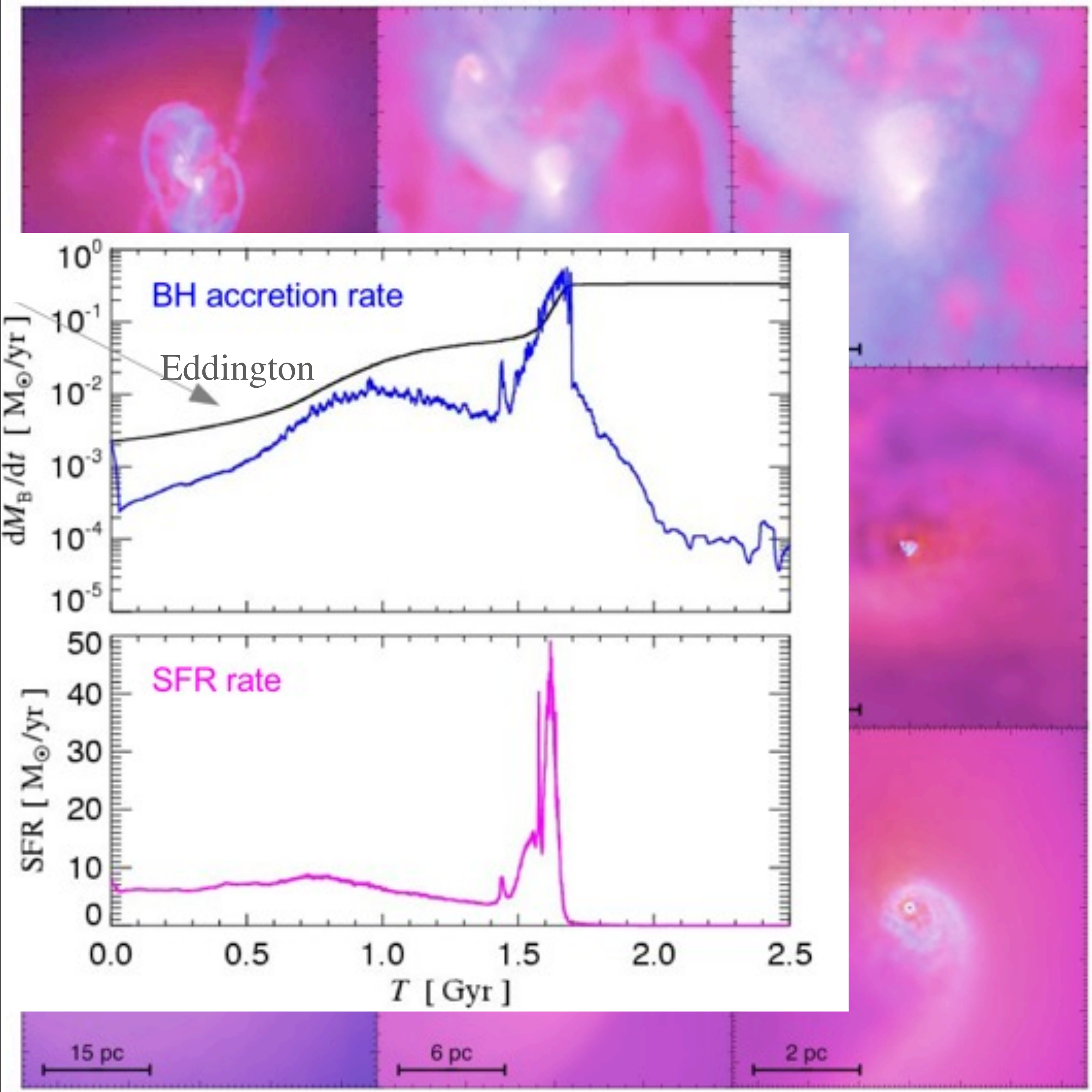

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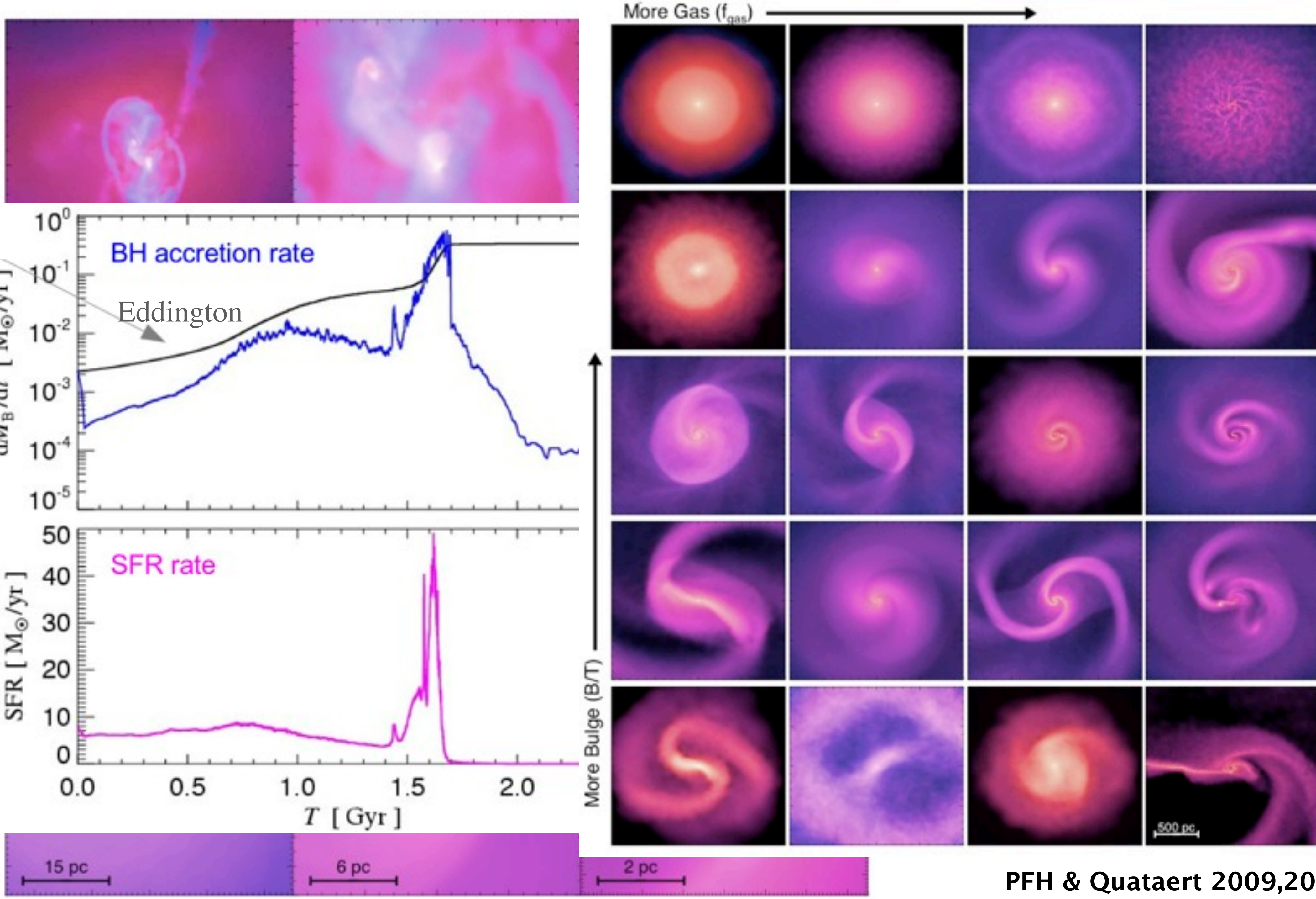


PFH & Quataert 2009,201

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

Sanders, Scoville, Soifer,
& others since:

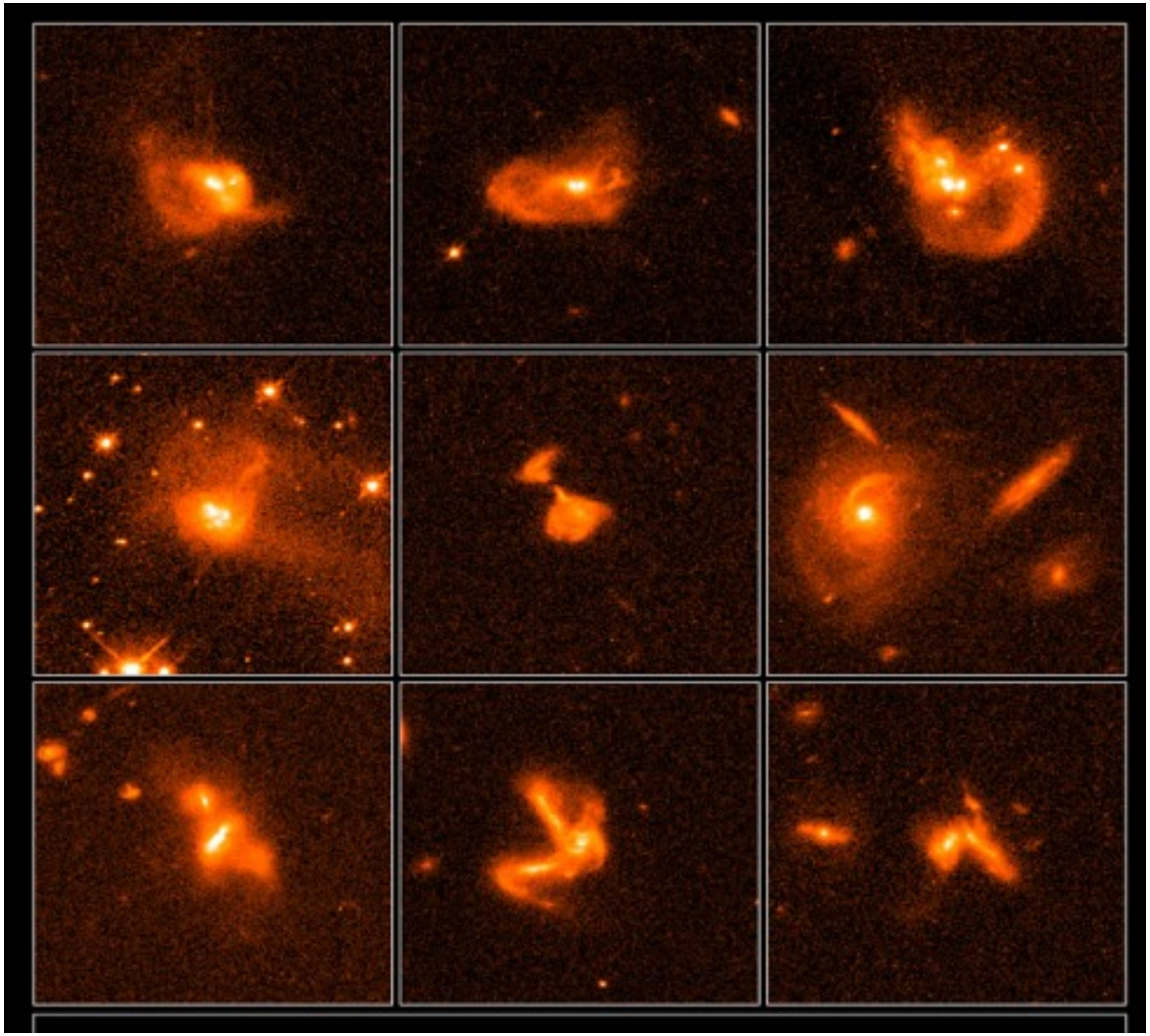
Compare local starburst
ULIRGs: SFR up to $>100\ M_{sun}/yr$

Essentially all late-stage
merger remnants

Compact (~kpc scales)

Evidence for SB-QSO
transition?

Borne et al., 2000



Are they the progenitors of ellipticals?

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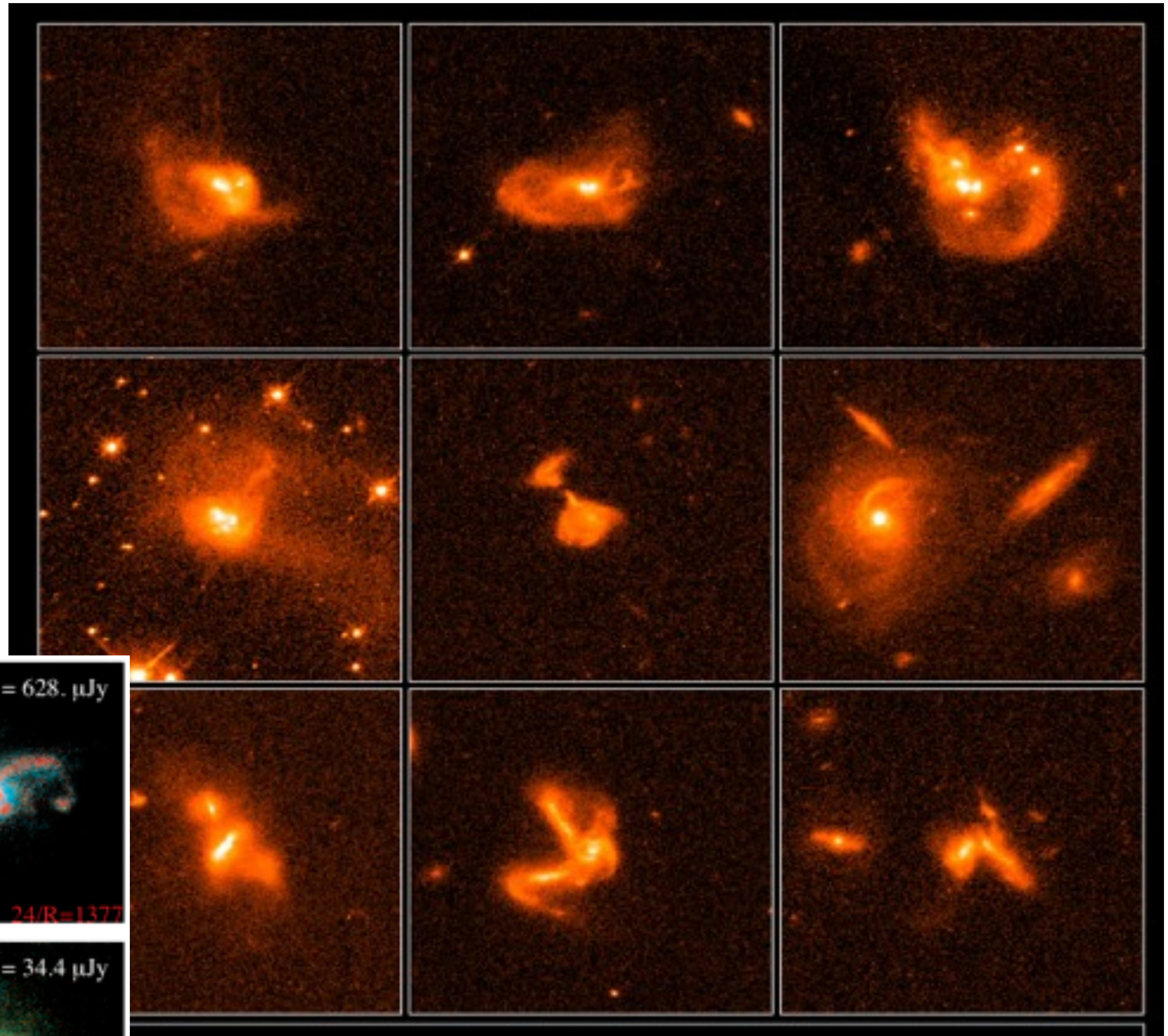

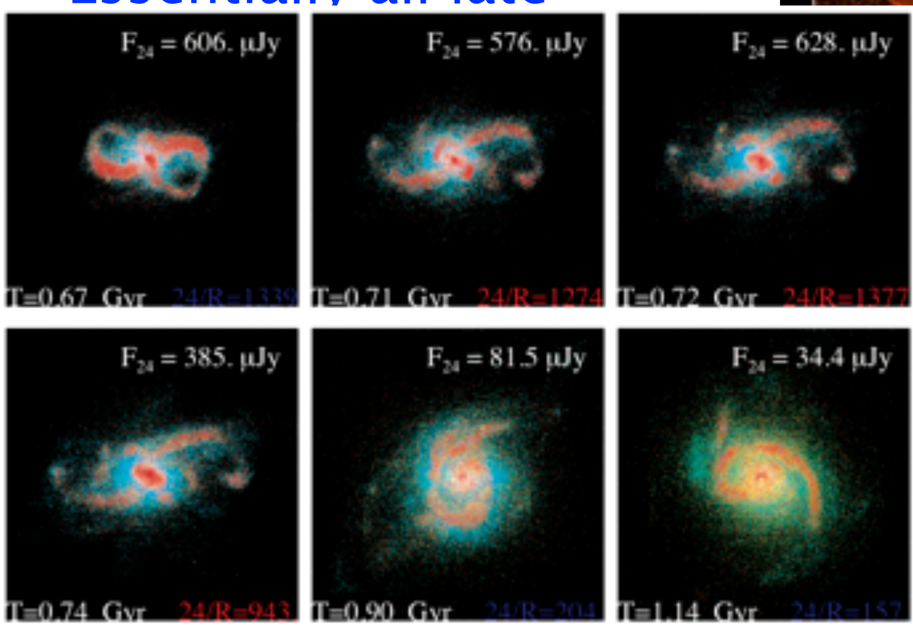

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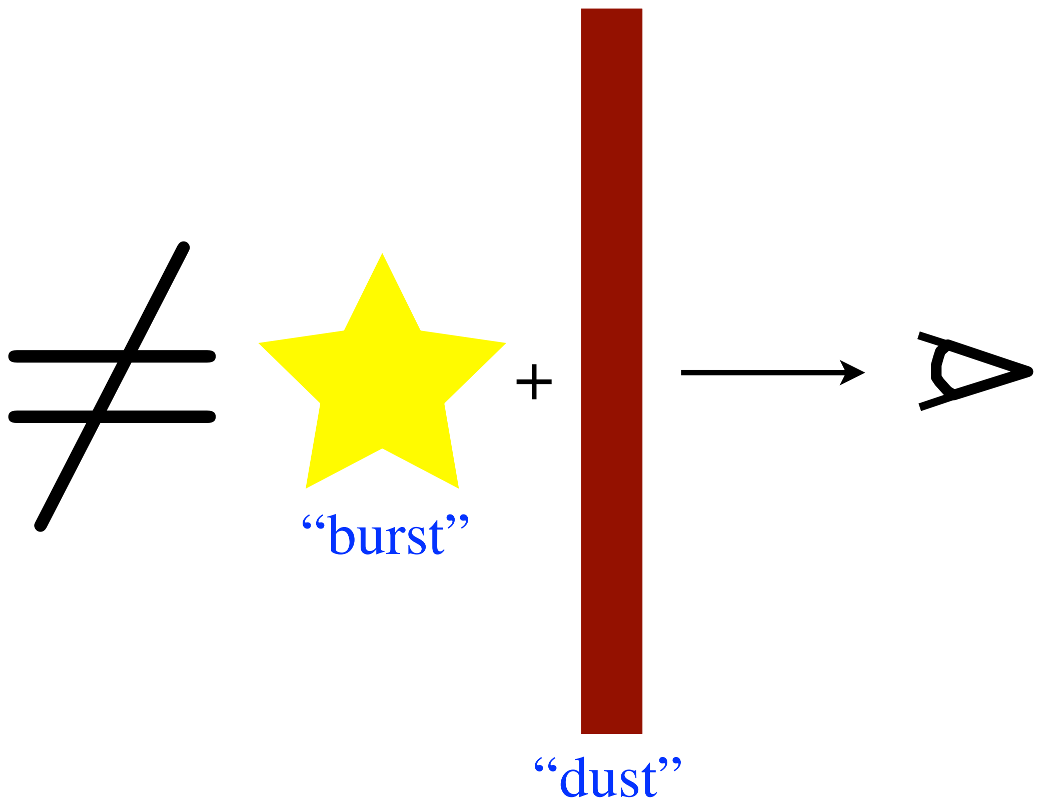
What About the Gas that Does Lose Angular Momentum?

STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

- Radiative Transfer: SUNRISE by P. Jonsson
- Not just at z=0, but in high-redshift sub-millimeter galaxies (e.g. work by Melbourne, Narayanan, Genzel & co.)



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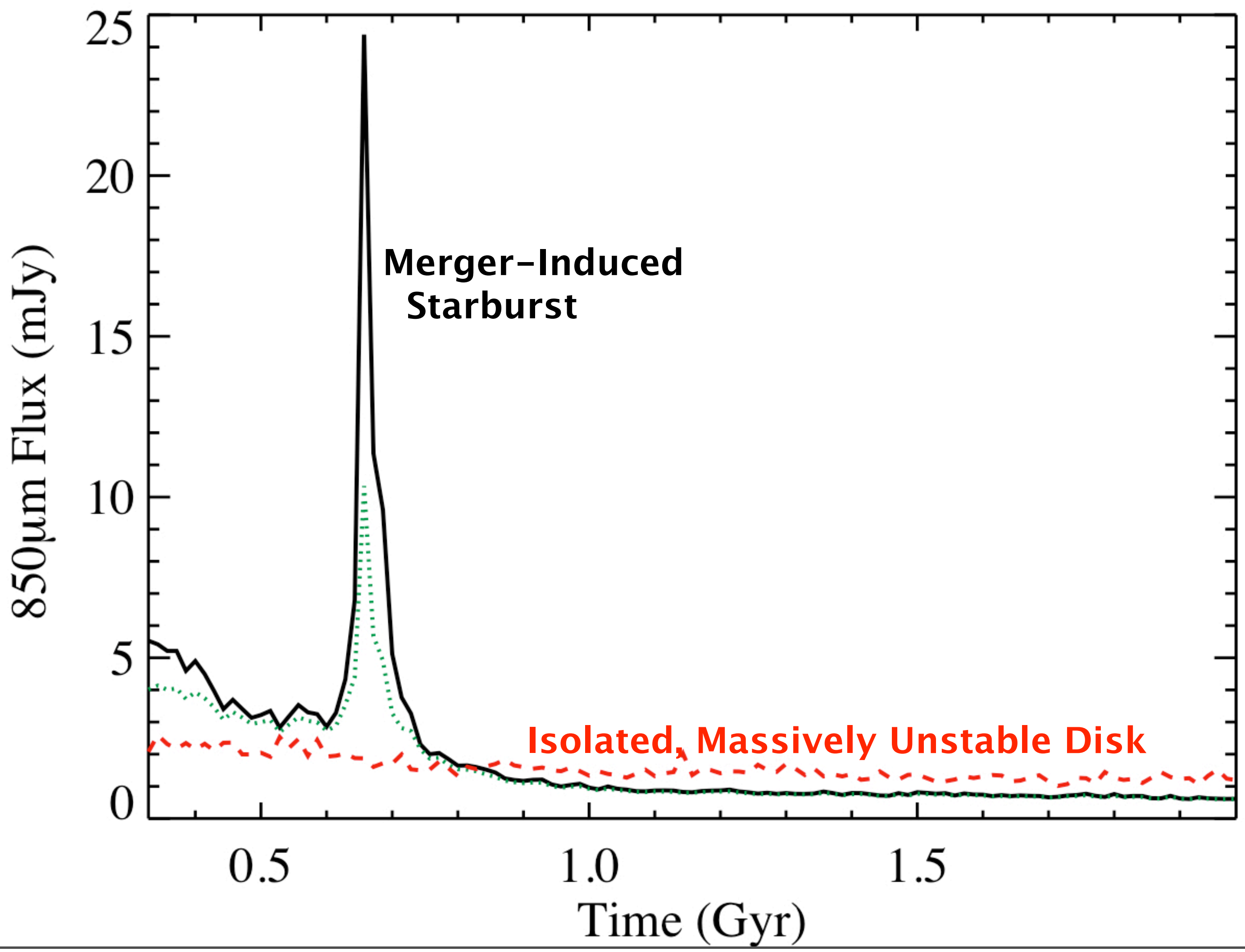

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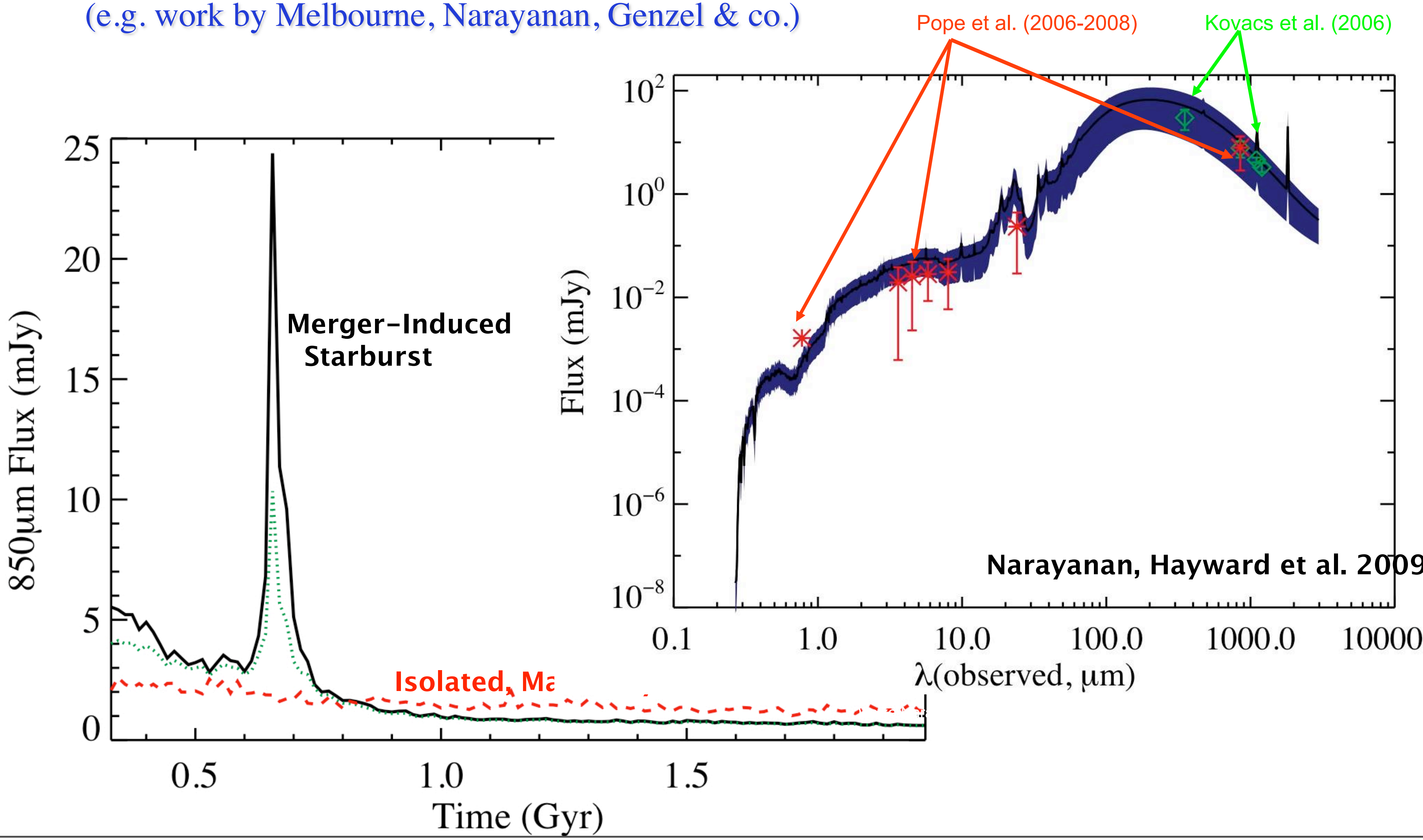

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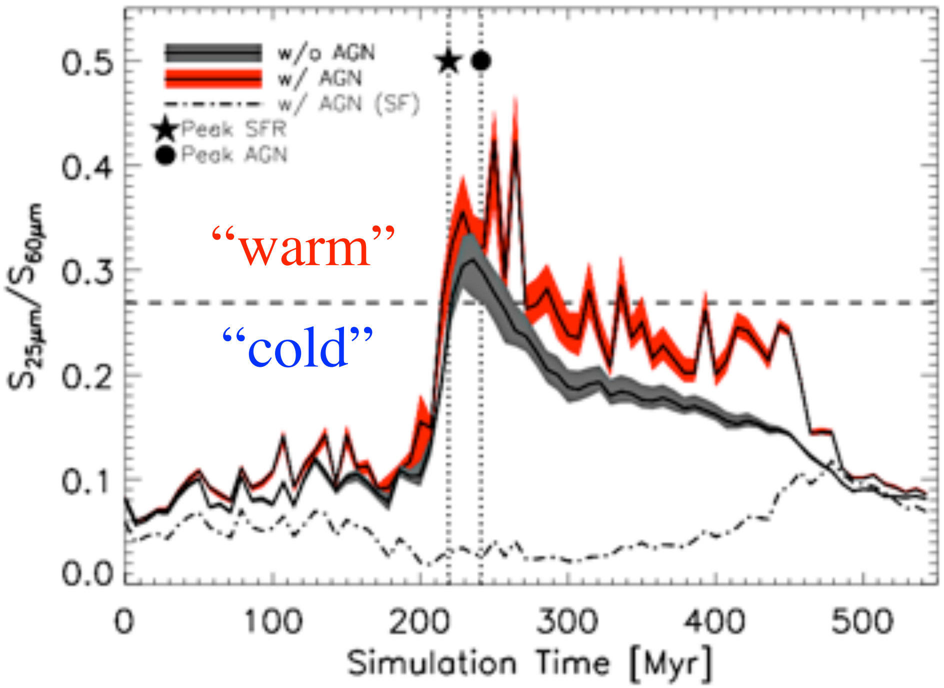
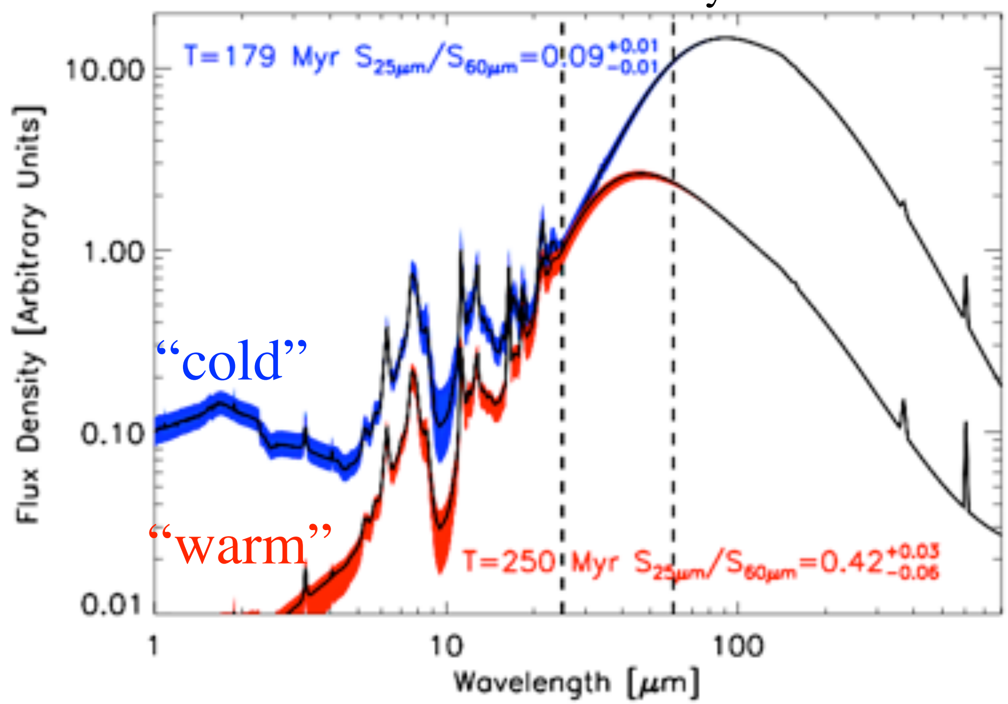
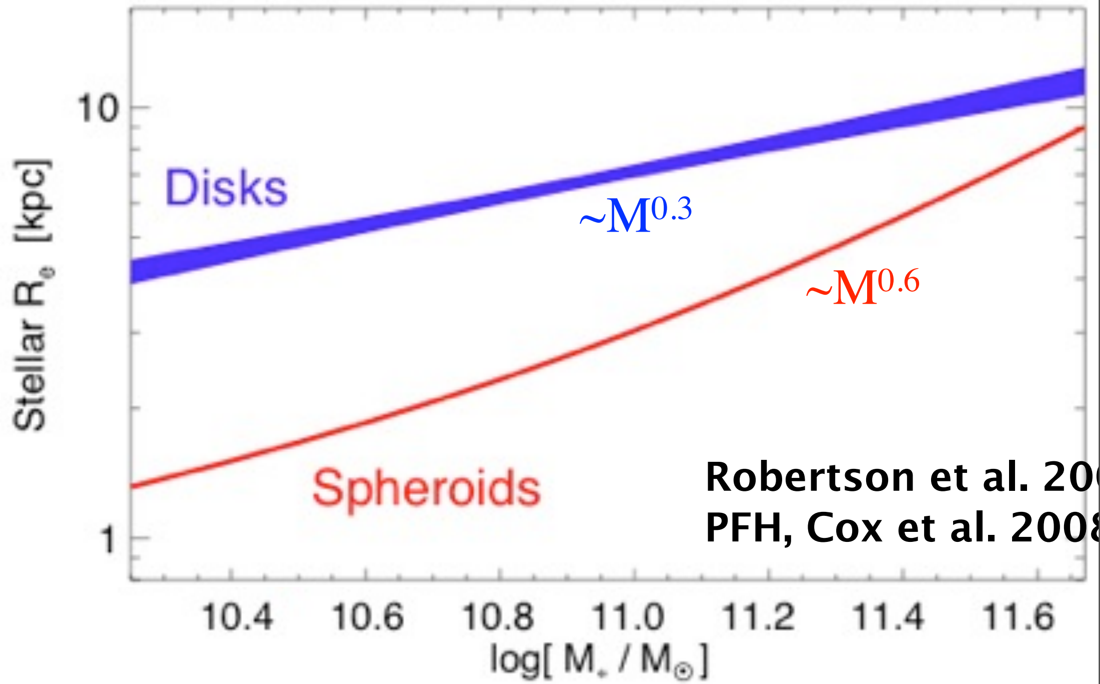
Younger et al. 2009, Narayanan et al. 2010



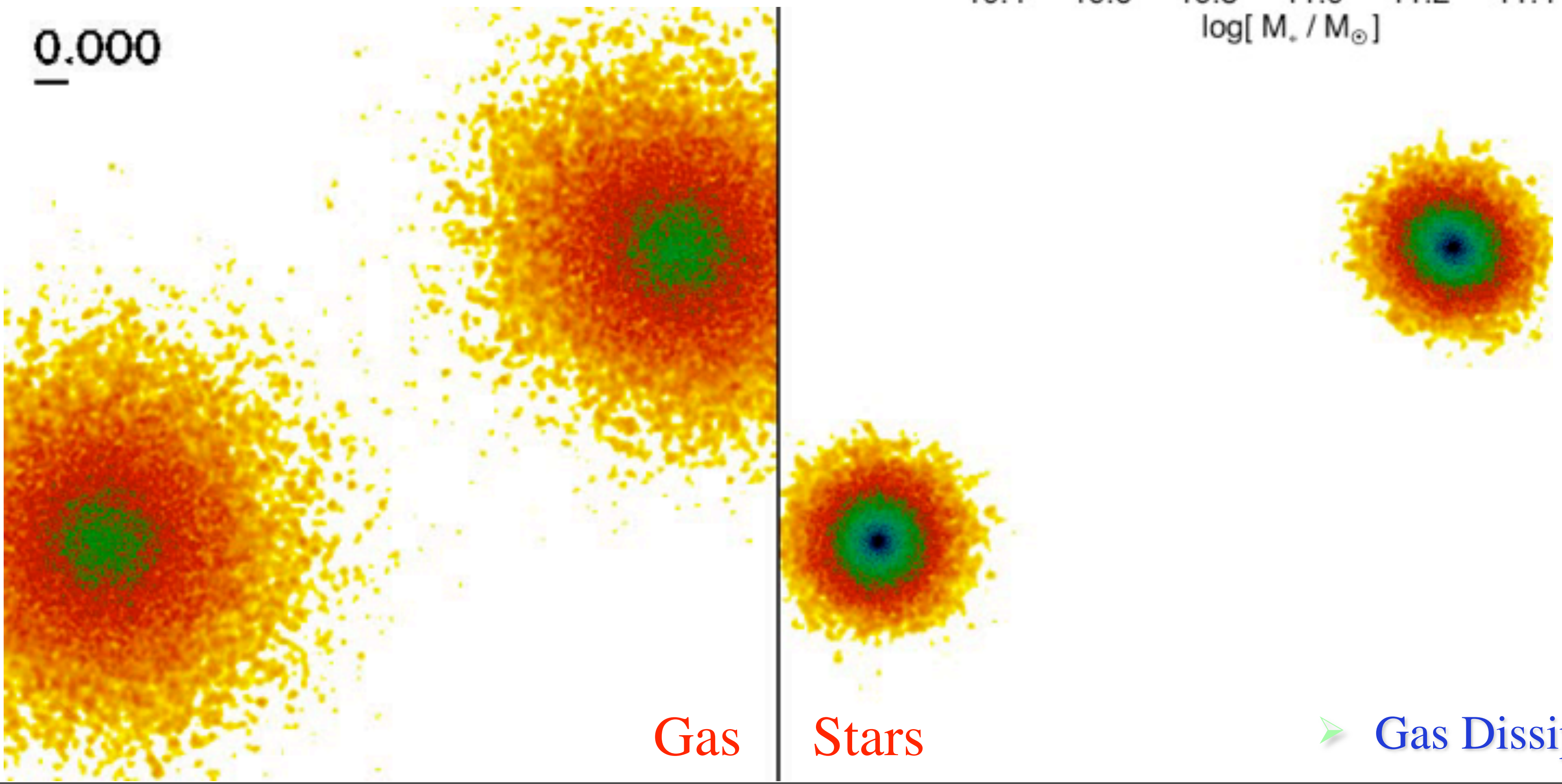


How does this relate to bulge formation?

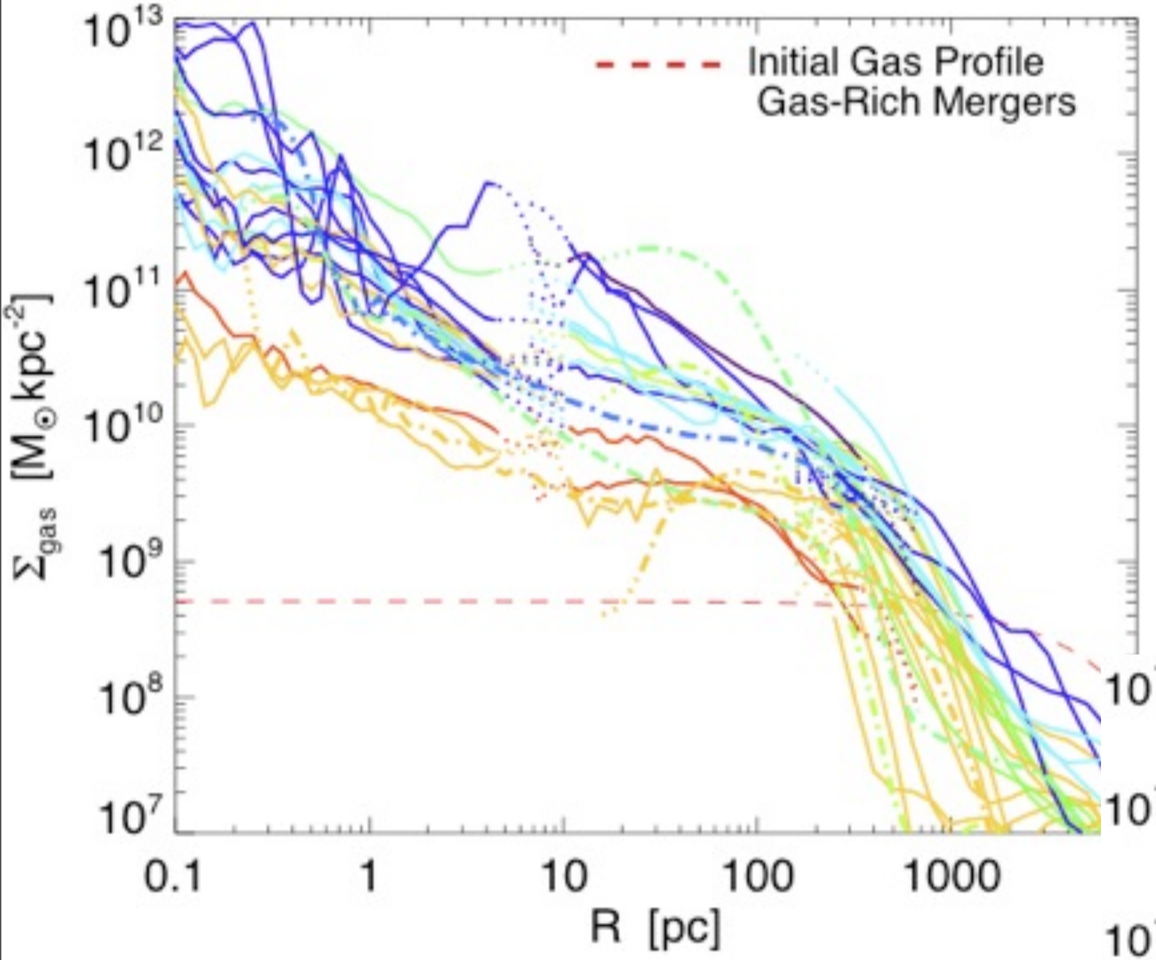
The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks? (Ostriker, Gunn, et al.)

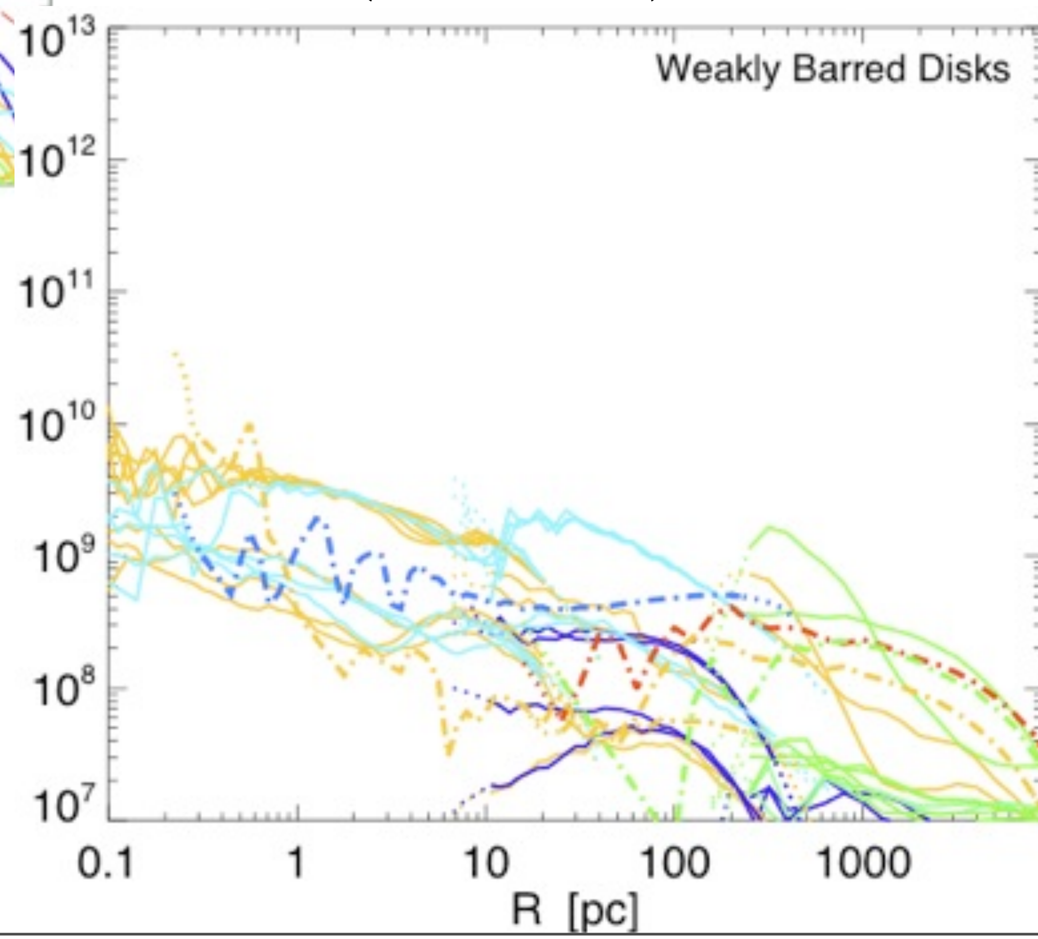


- Gas Dissipation



Gas-rich merger
(lots of inflow)

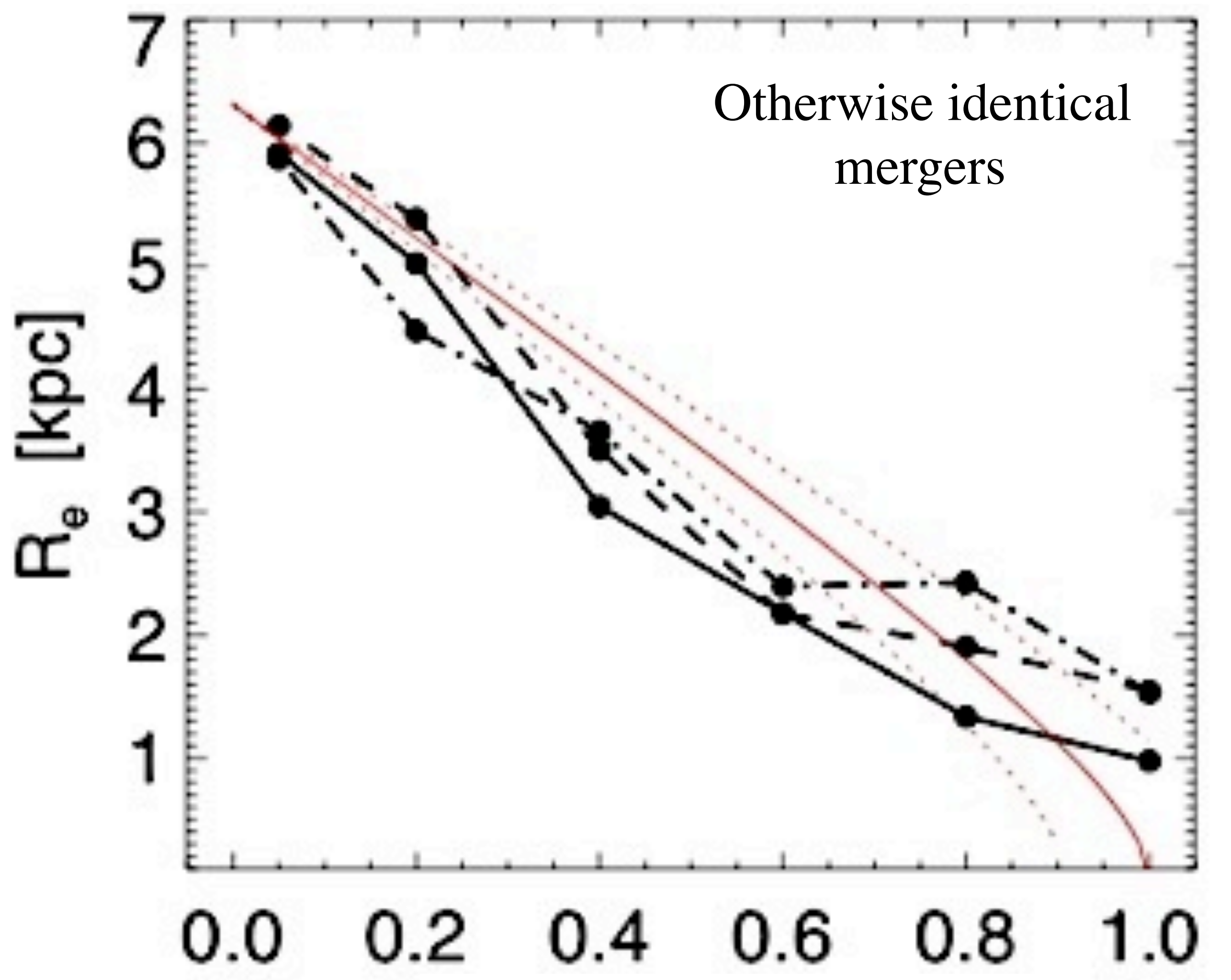
Weakly bar-unstable disk
(less inflow)



- Order-of-magnitude effect on central galaxy densities

The Solution: Gas-Rich Mergers

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



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

PFH, Cox et al. 2008

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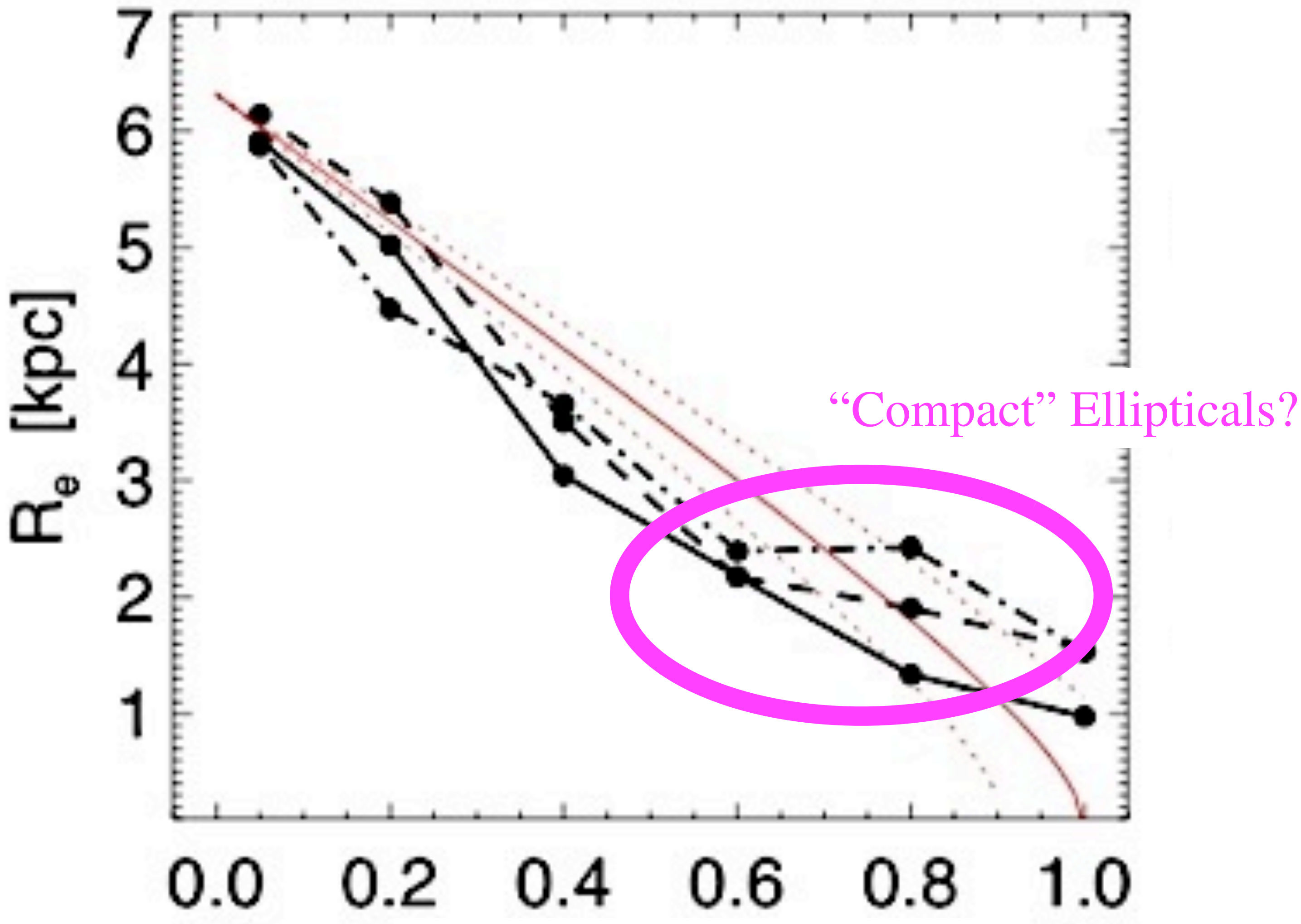

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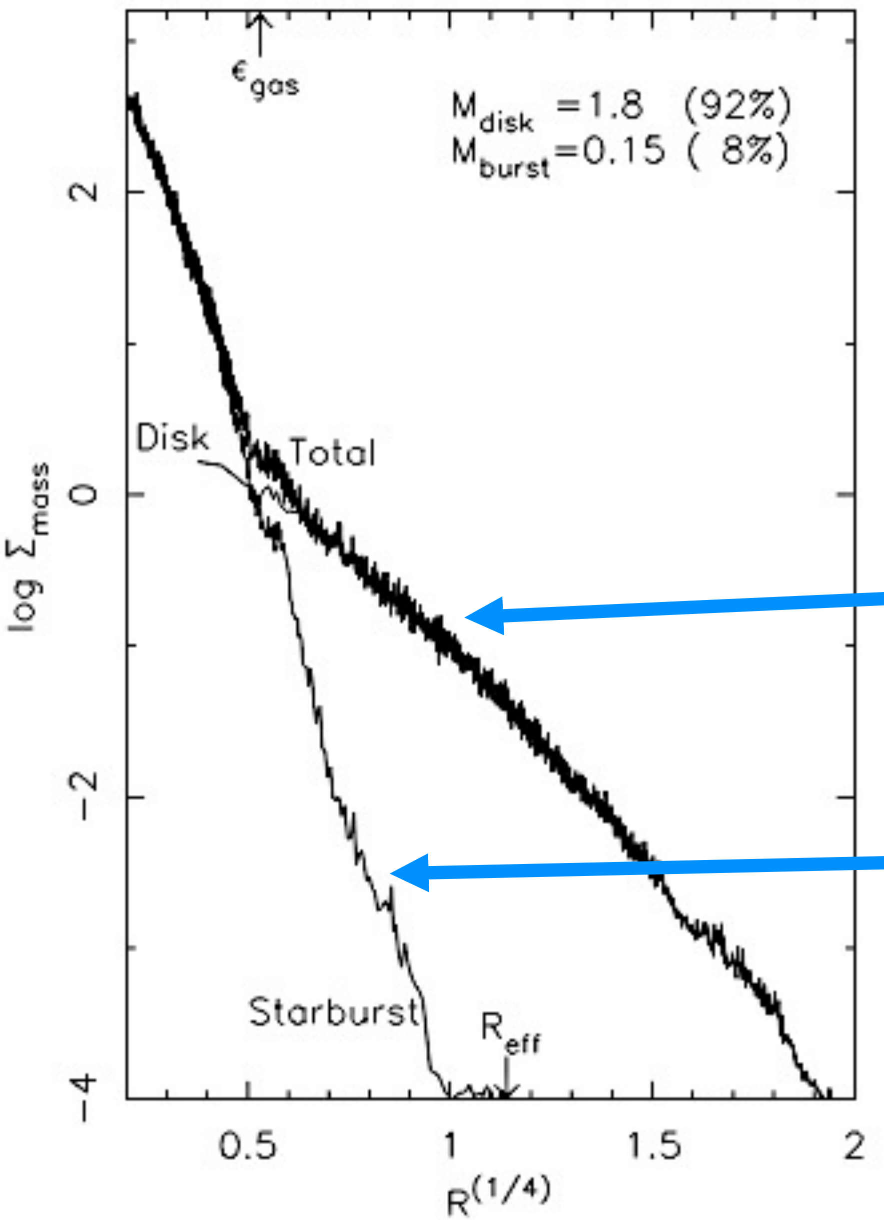
Starburst Stars Leave a "Footprint" on the Profile



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:

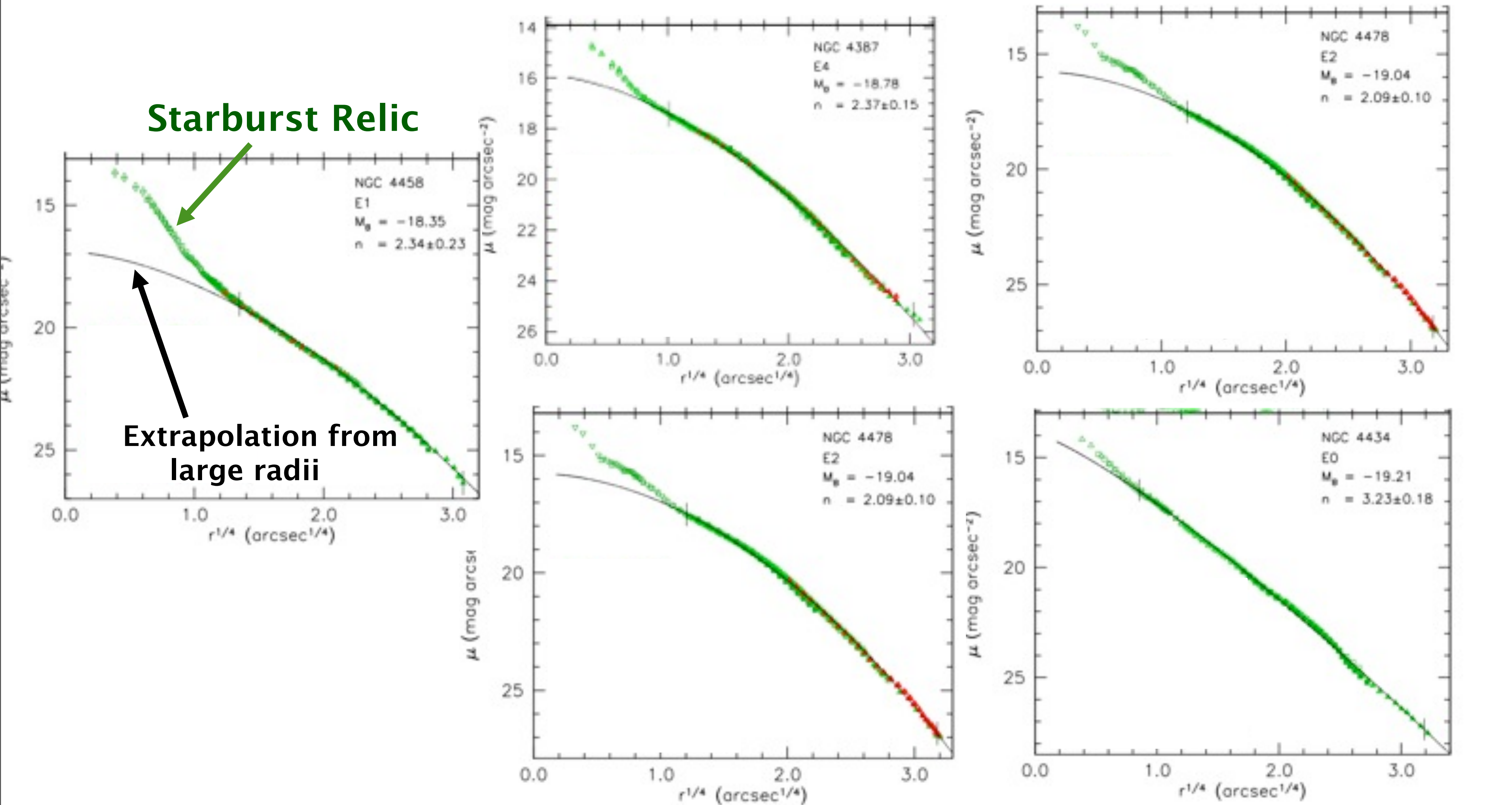
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

Starburst Stars Leave a “Footprint” on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Kormendy et al. 2008
(also Hibbard & Yun,
Rothberg & Joseph,
Lauer et al., Cote et al.,
Ferrarese et al.)

- Since then...

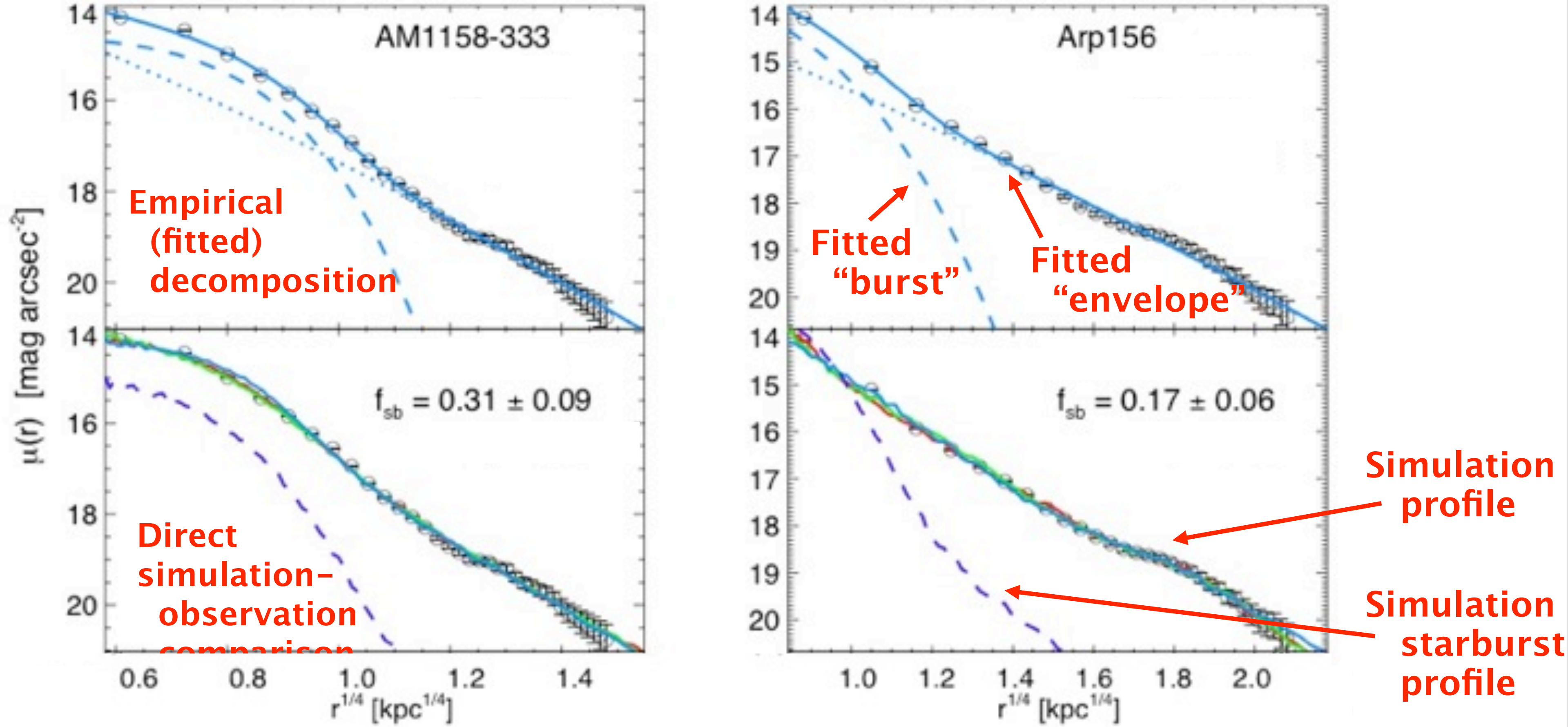


“Normal and low-luminosity ellipticals... in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles.”

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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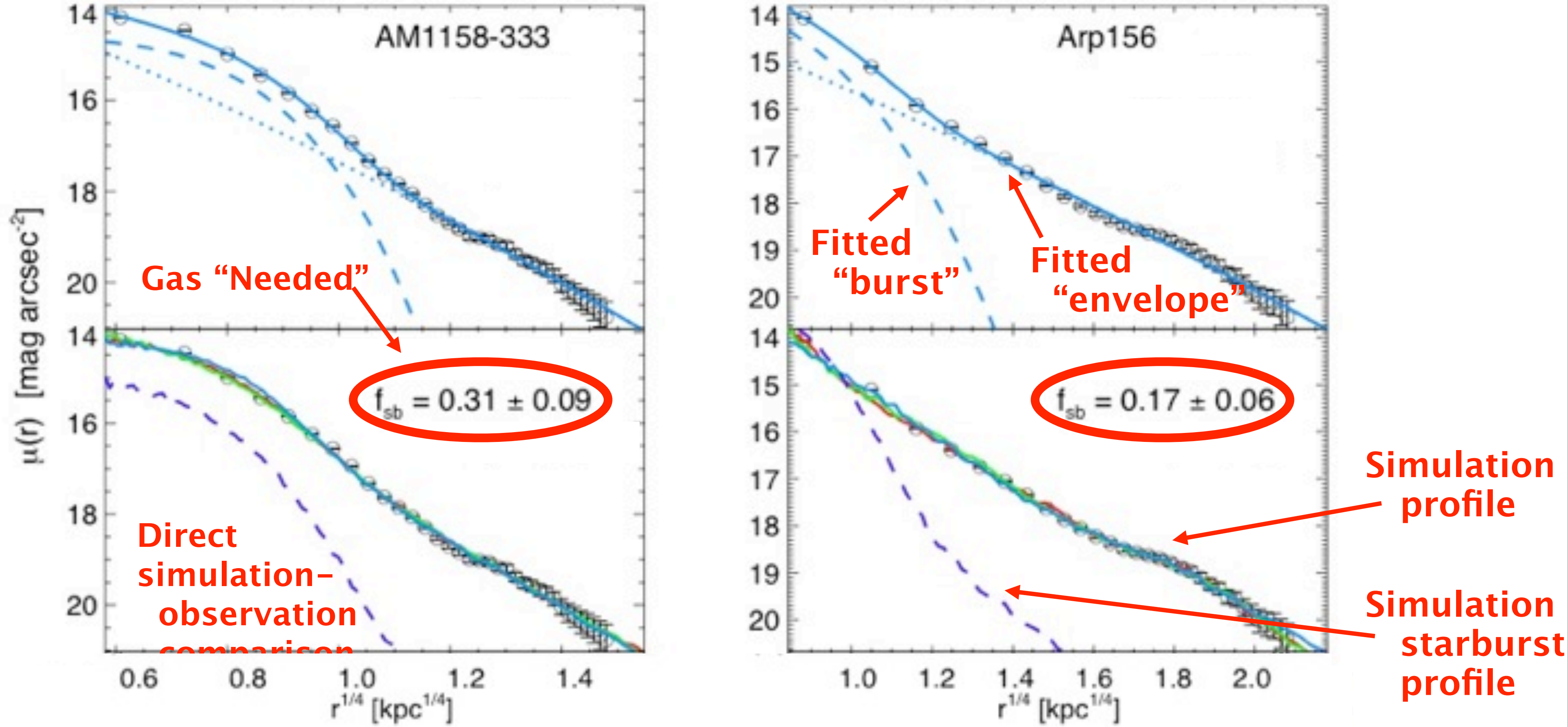

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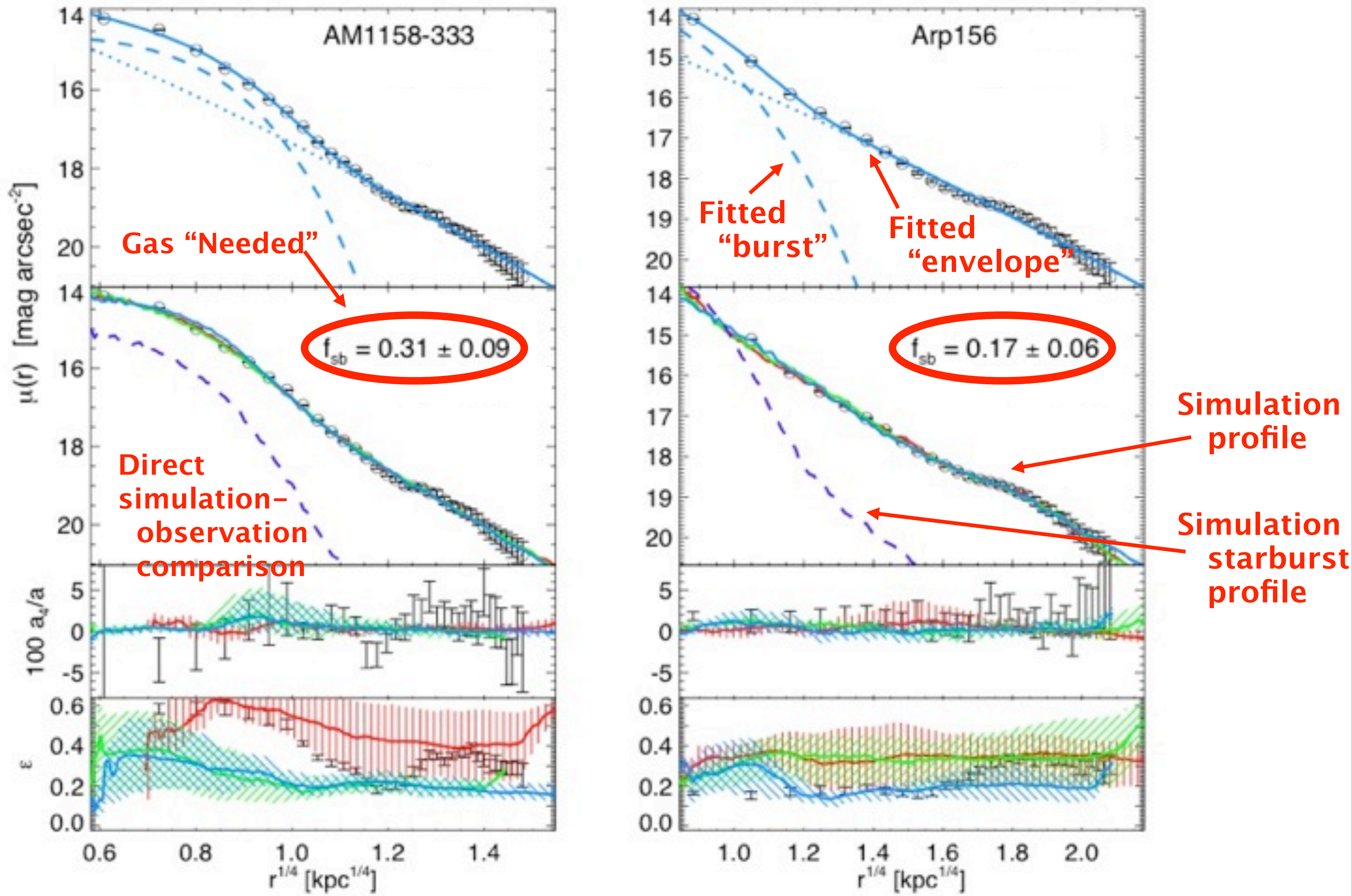

Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

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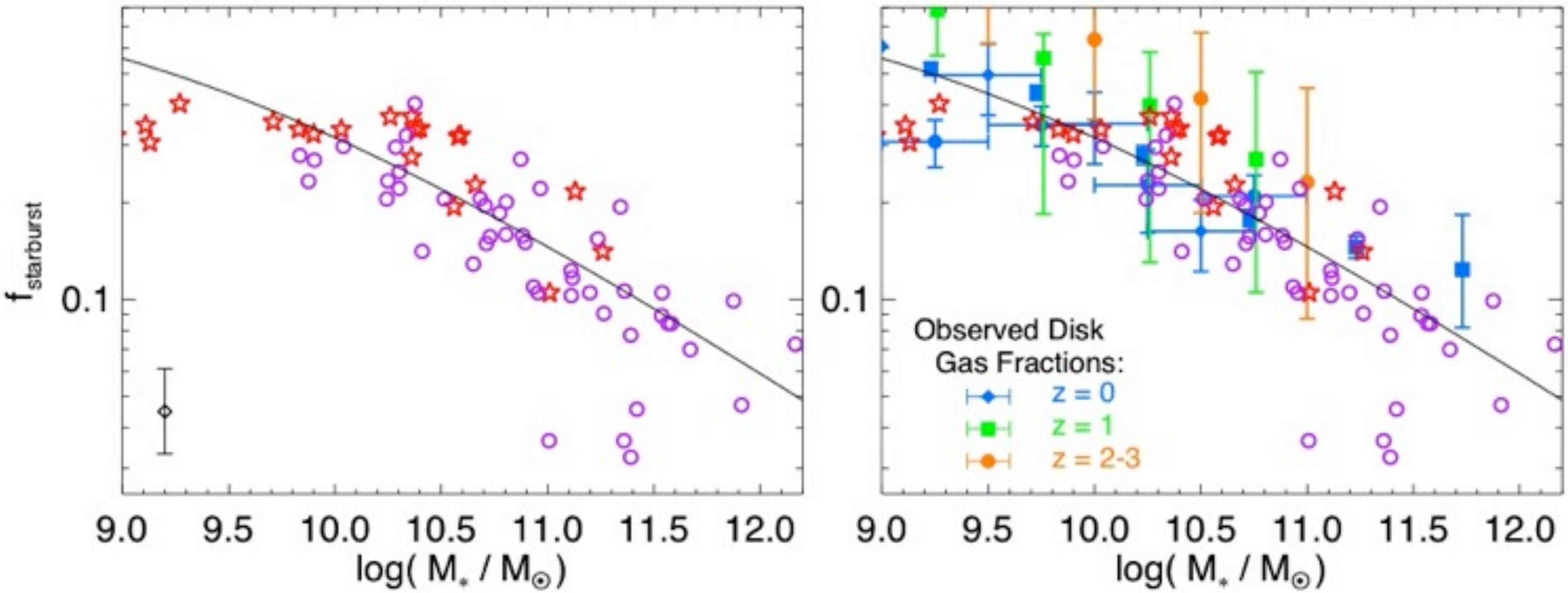
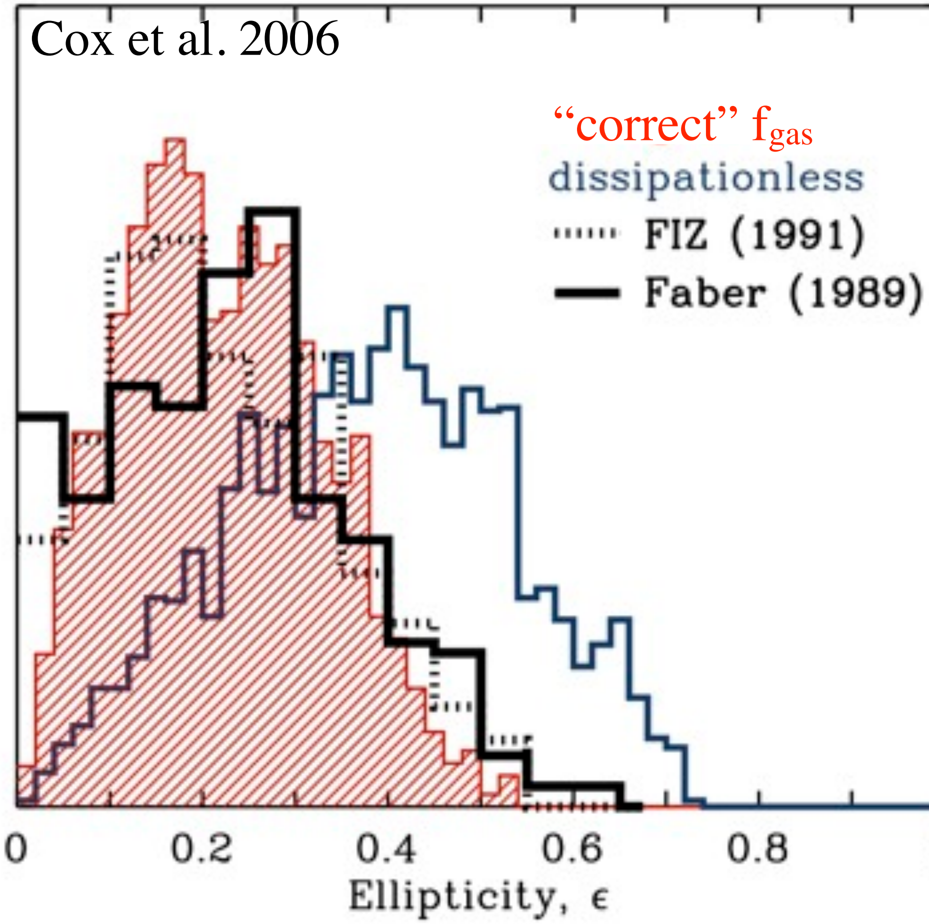
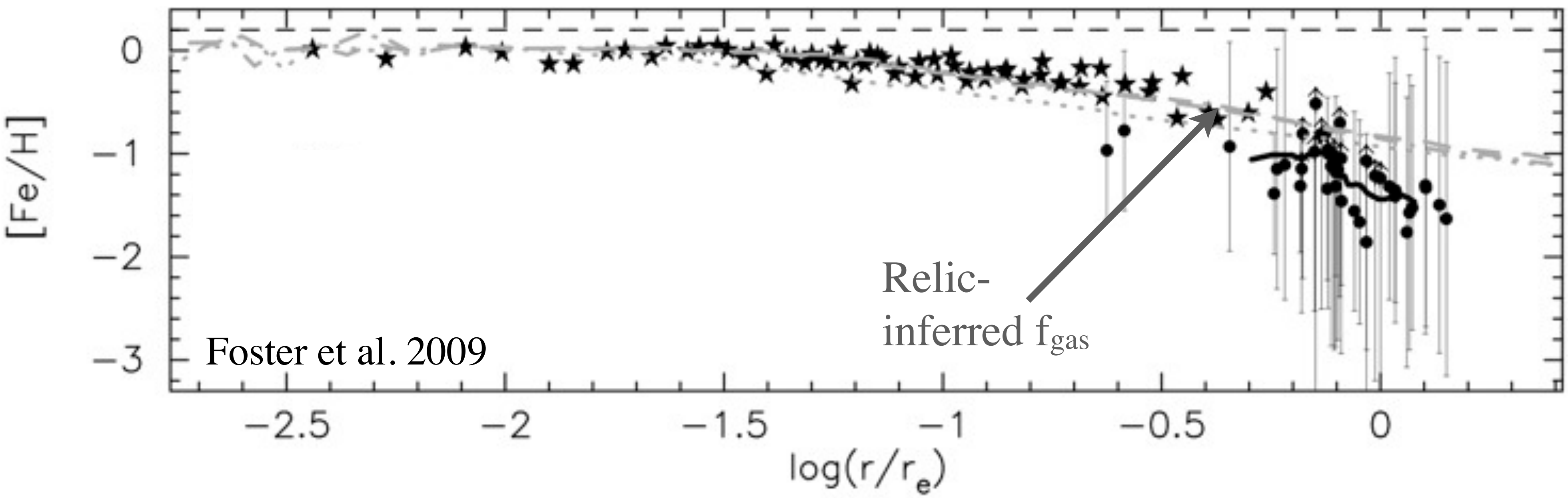
PFH, Kormendy, & Lauer et al. 2008

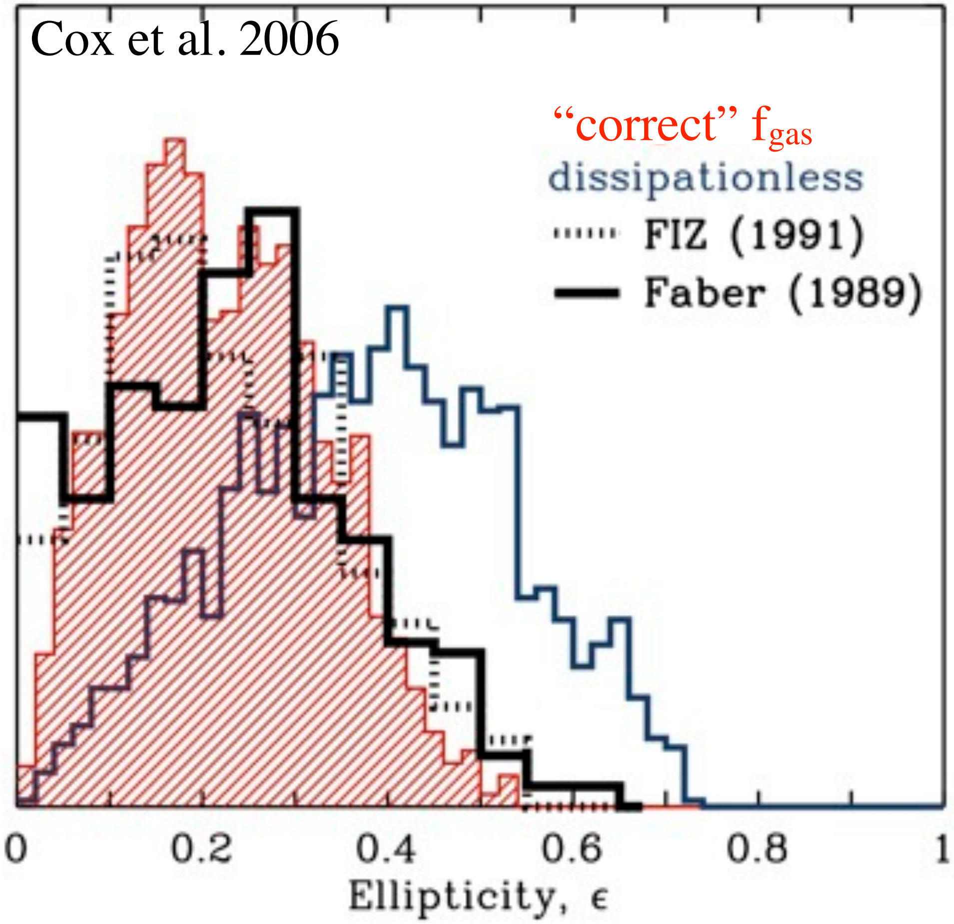
Starburst gas mass needed to match observed profile (or fitted to profile shape):



- 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 (Foster+, Forbes+, Lauer+, Hoffman+)


Cox et al. 2006
"correct" f_{gas}
dissipationless
FIZ (1991)
Faber (1989)
0
0.2
0.4
0.6
0.8
1
Ellipticity, ε


[Fe/H]
0
−1
−2
−3
Foster et al. 2009
Relic-
inferred f_{gas}
−2.5
−2
−1.5
−1
−0.5
0
log(r/r$_e$)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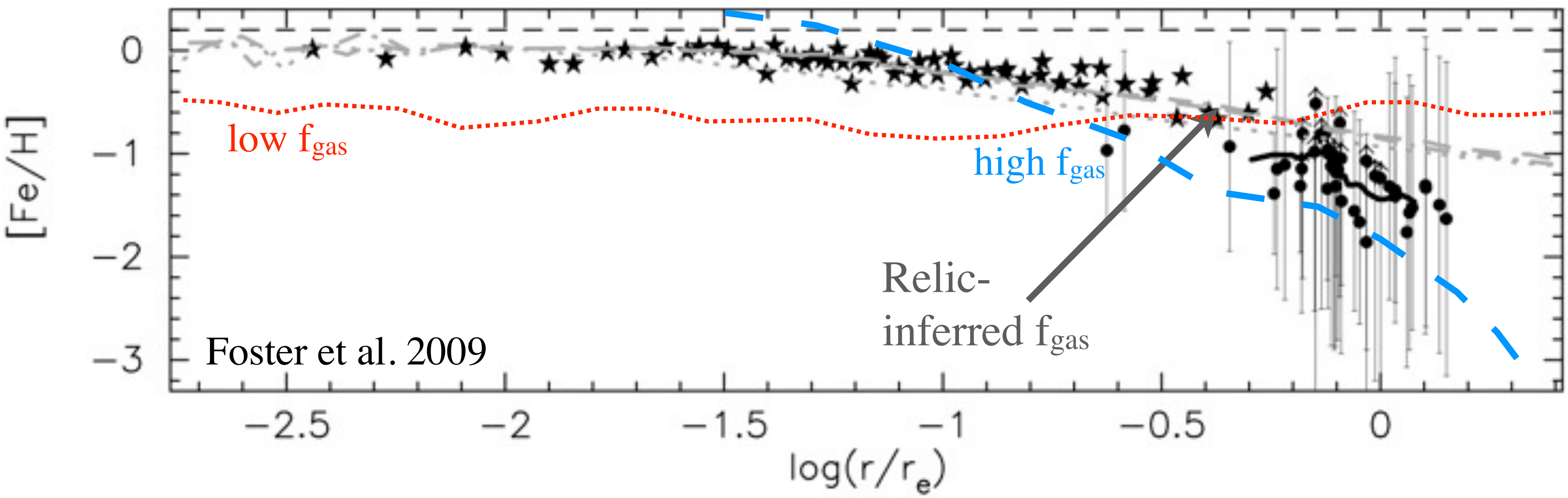
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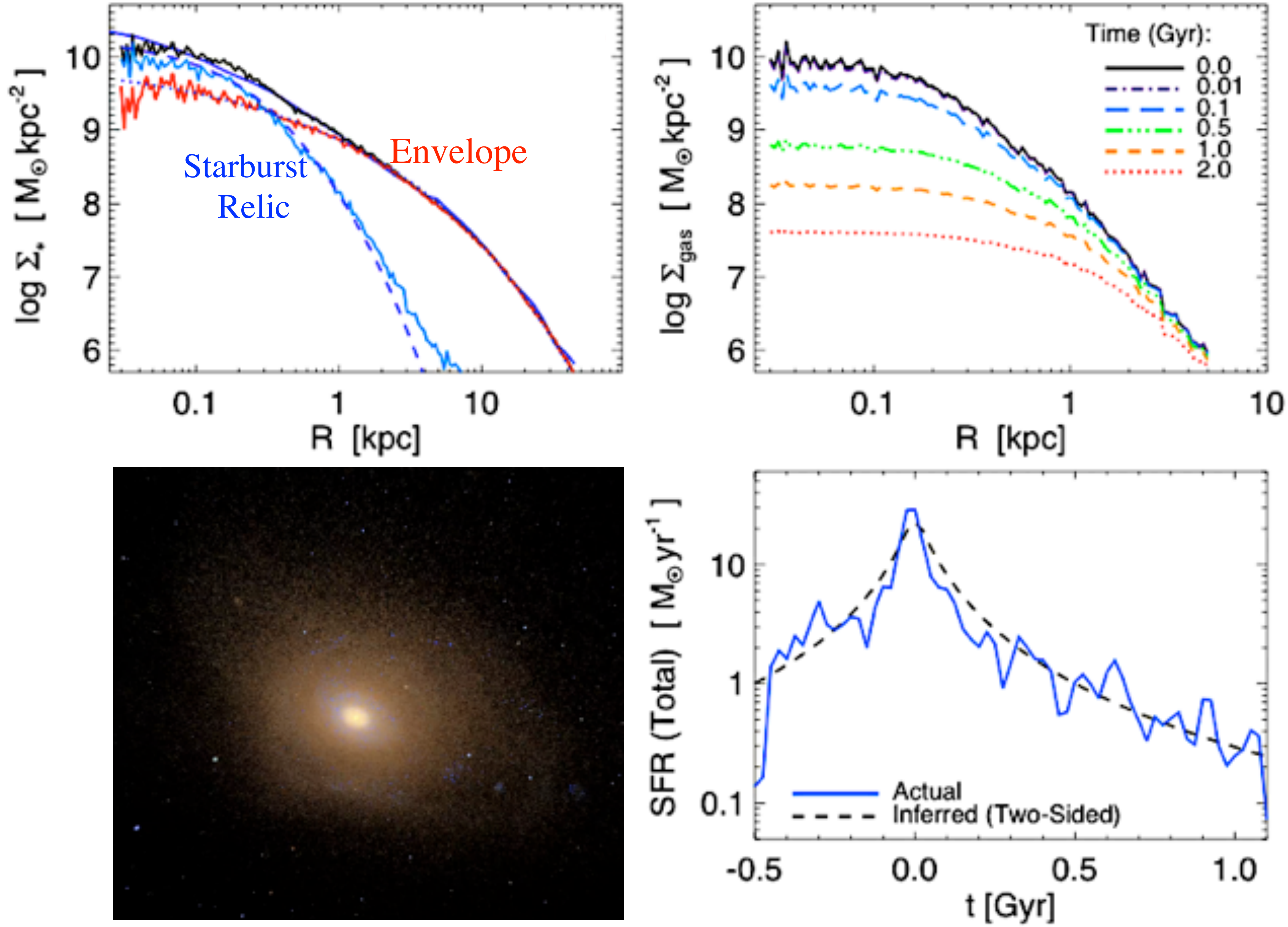
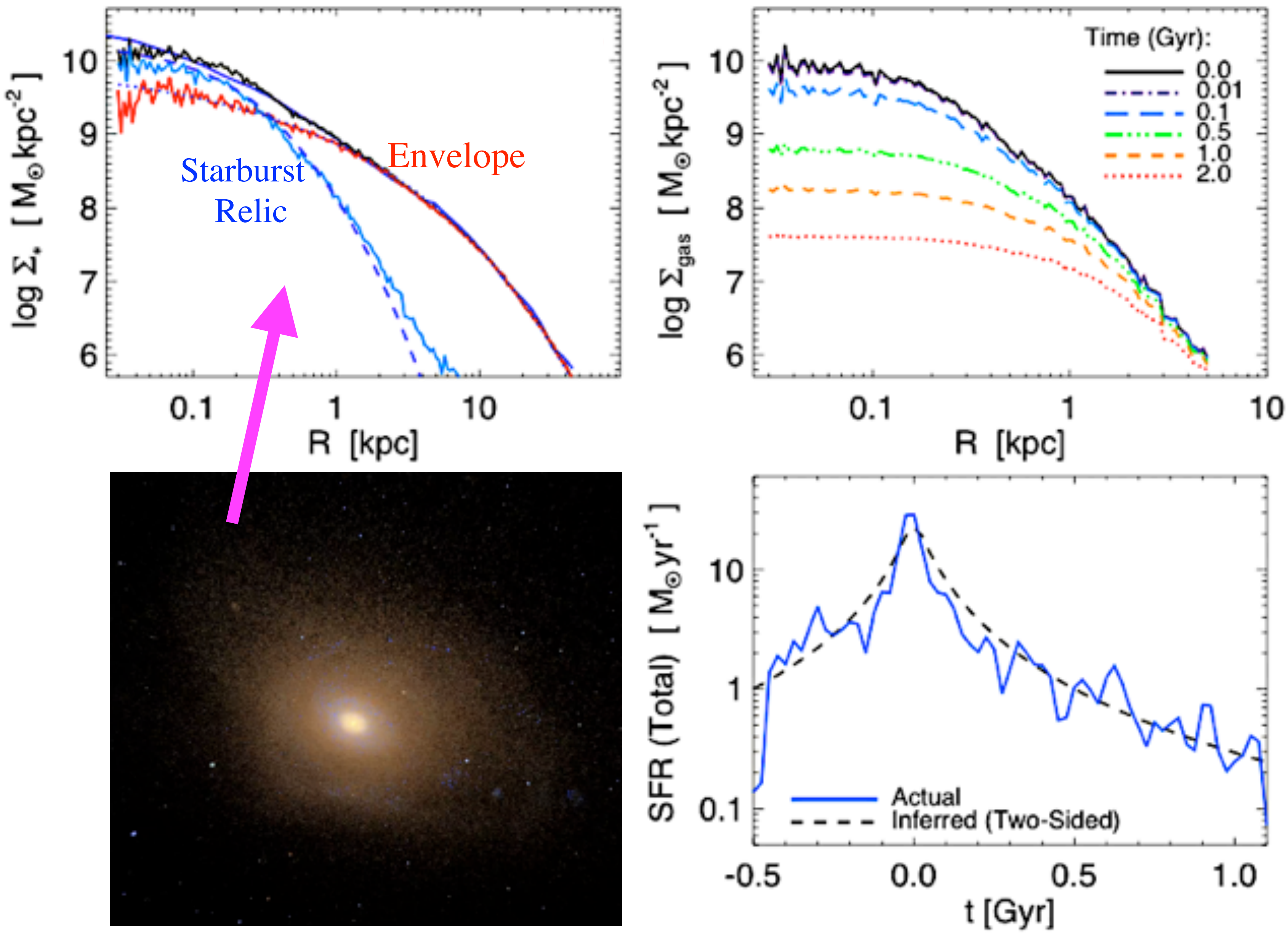
What else can we learn from the ‘relics’ of gas dissipation?



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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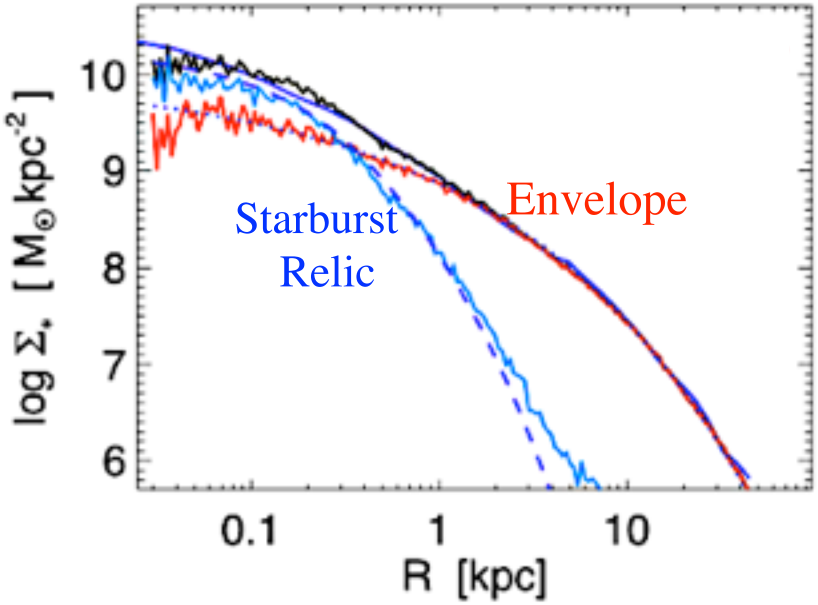
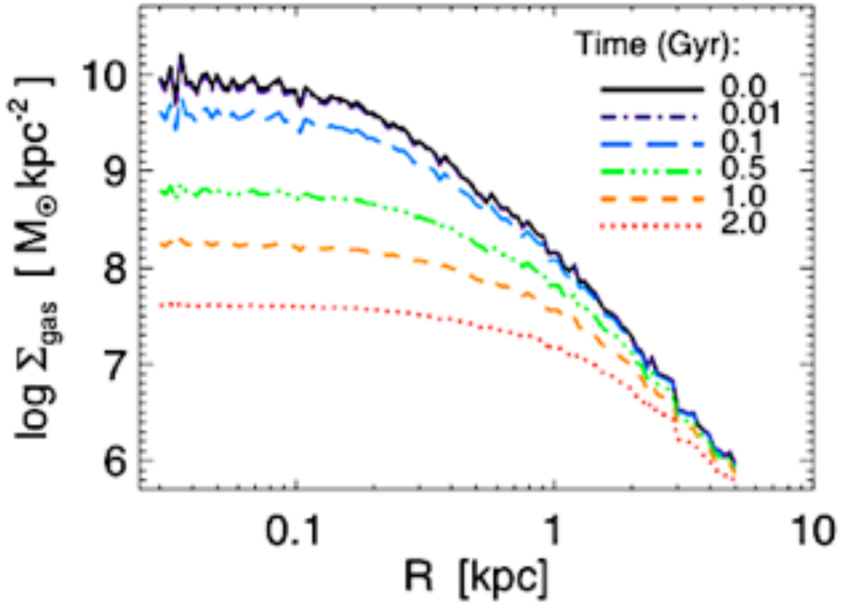
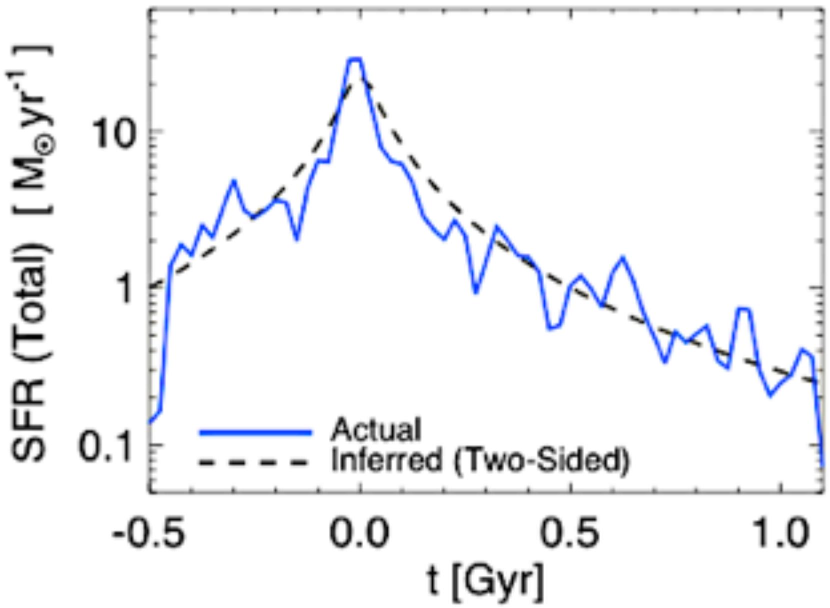


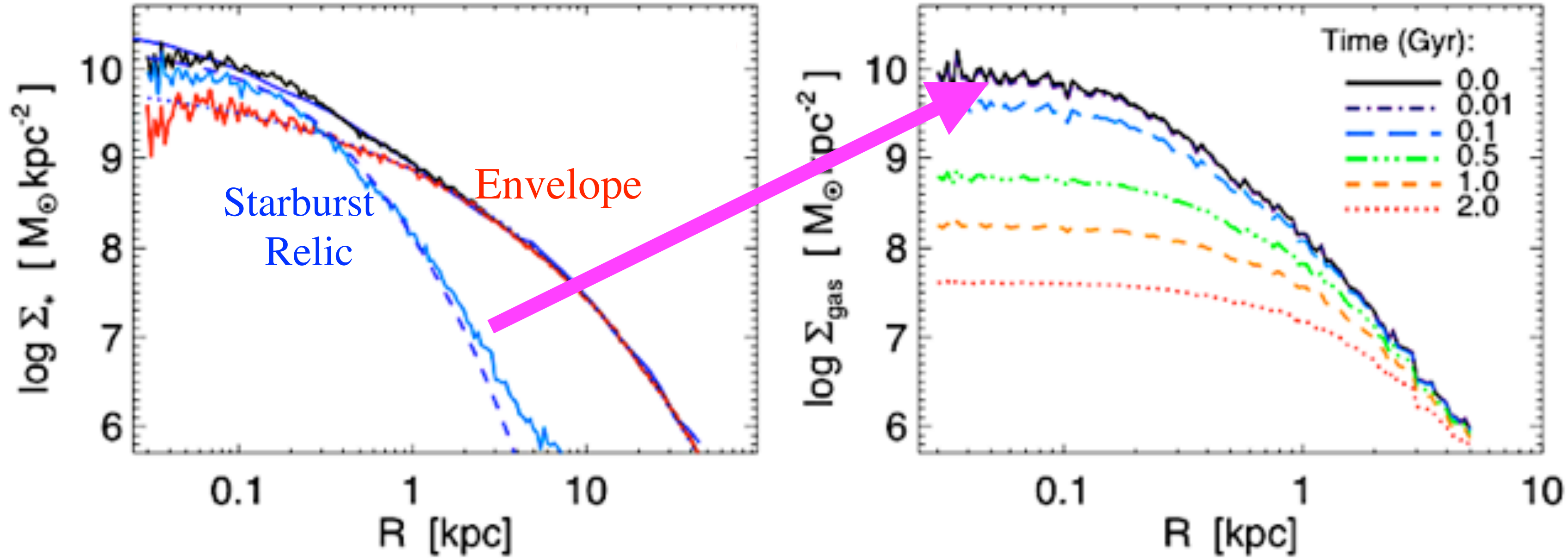


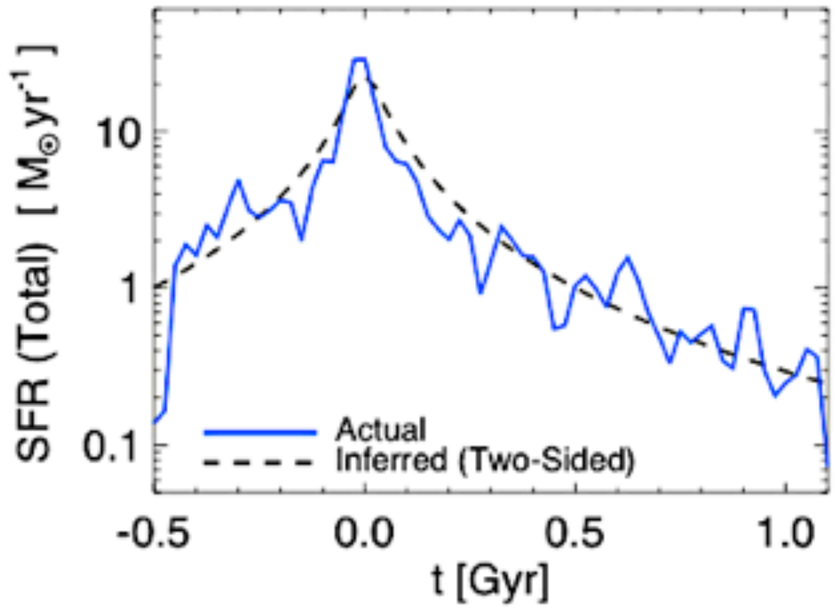


What else can we learn from the ‘relics’ of gas dissipation?

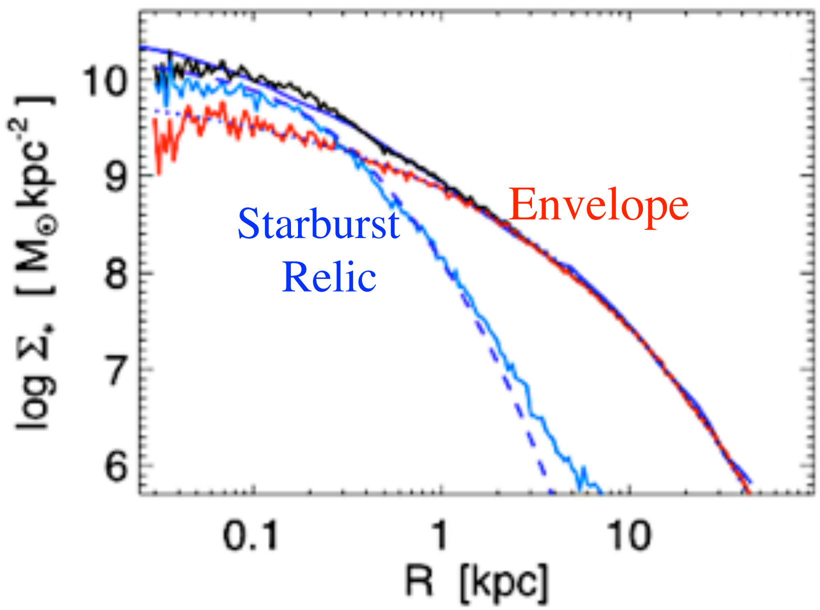
If formed dissipationally, then this reflects gas-star conversion “in situ”

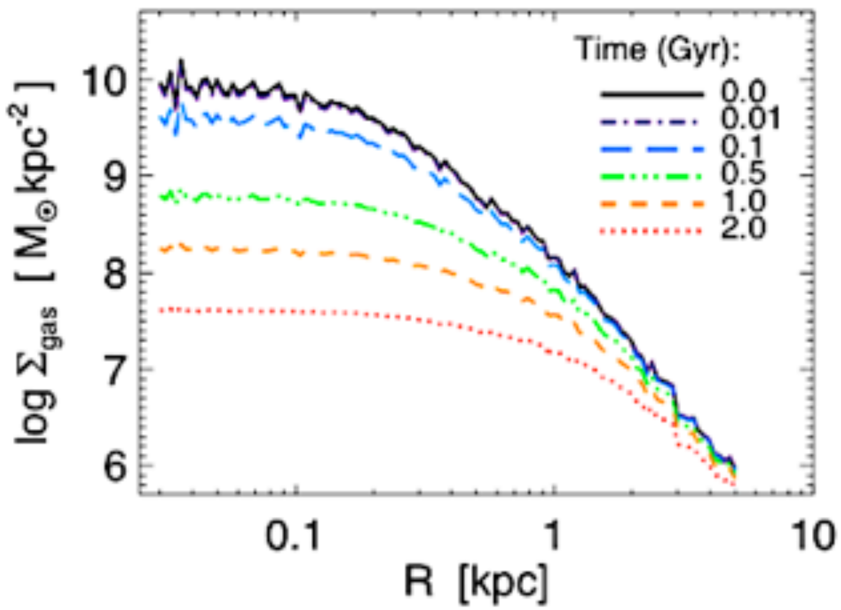
$$\Sigma_{relic\ \ stars}(R)\ \sim\ \Sigma_{gas\ \ for\ \ burst}(R, t = t_{burst})$$

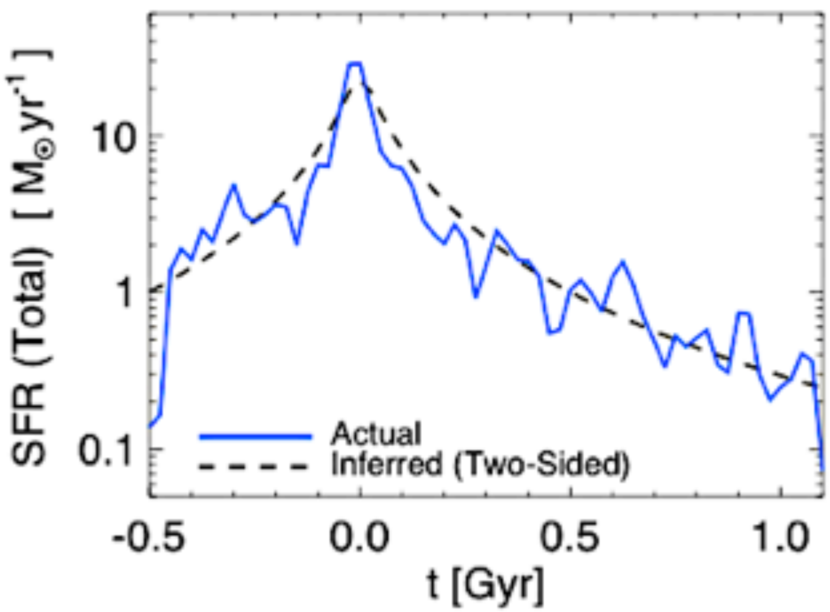




What else can we learn from the ‘relics’ of gas dissipation?



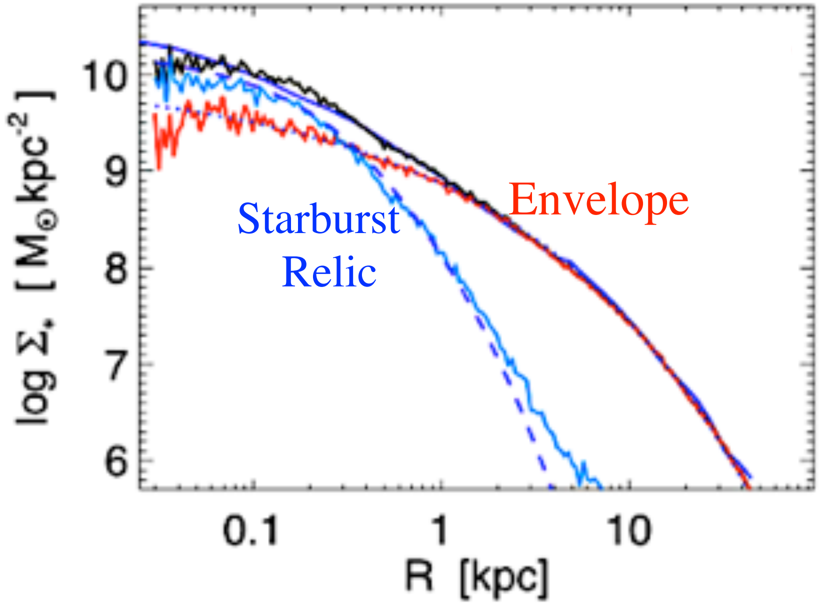


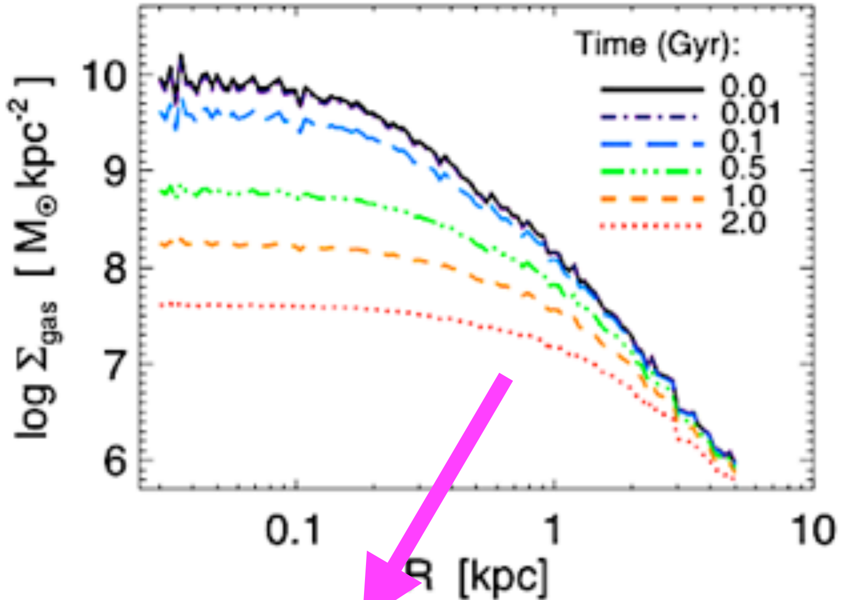


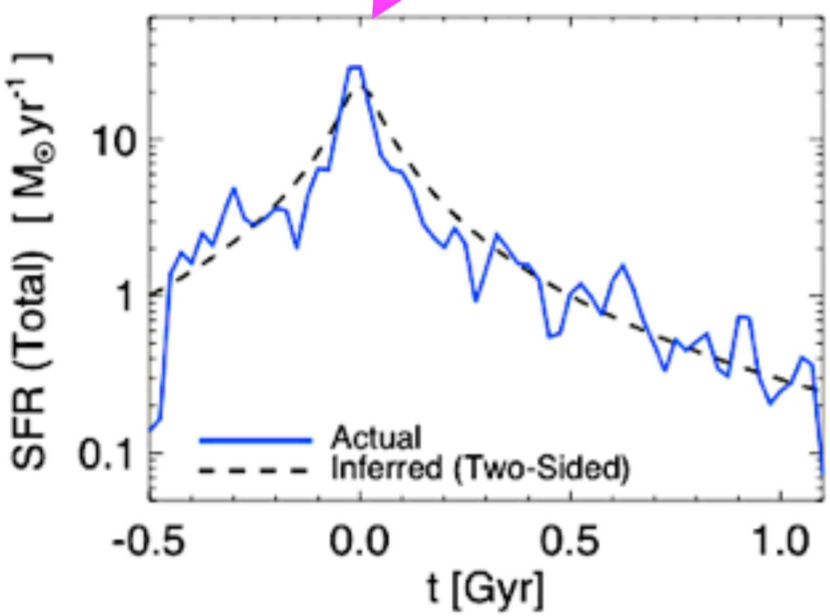
What else can we learn from the ‘relics’ of gas dissipation?

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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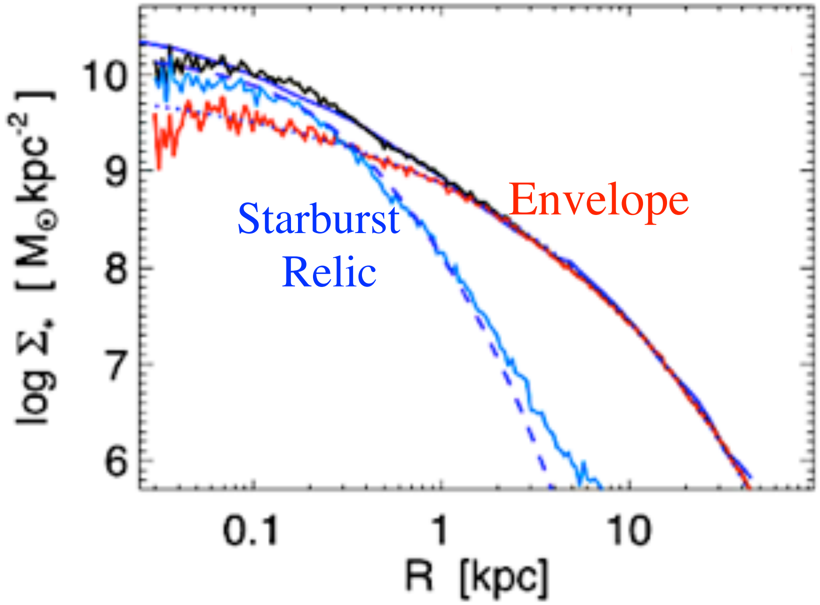

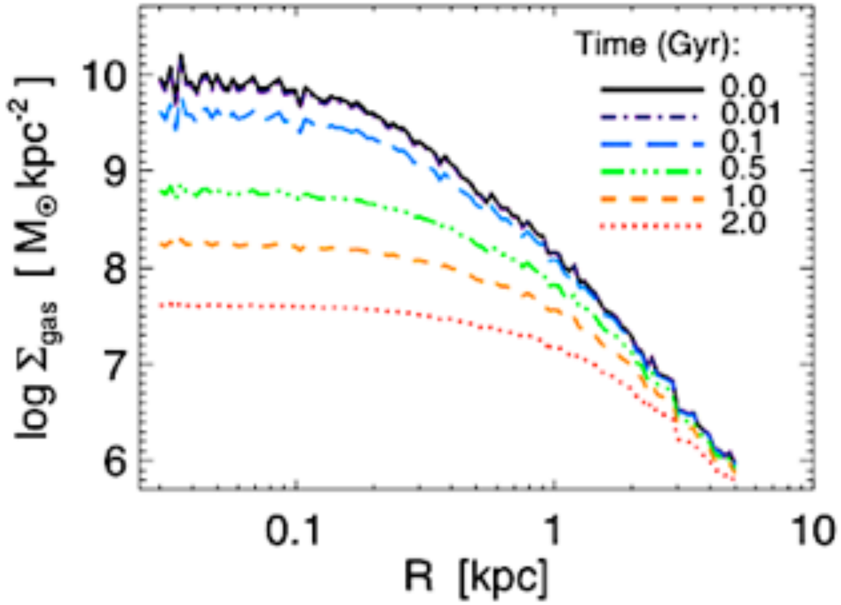

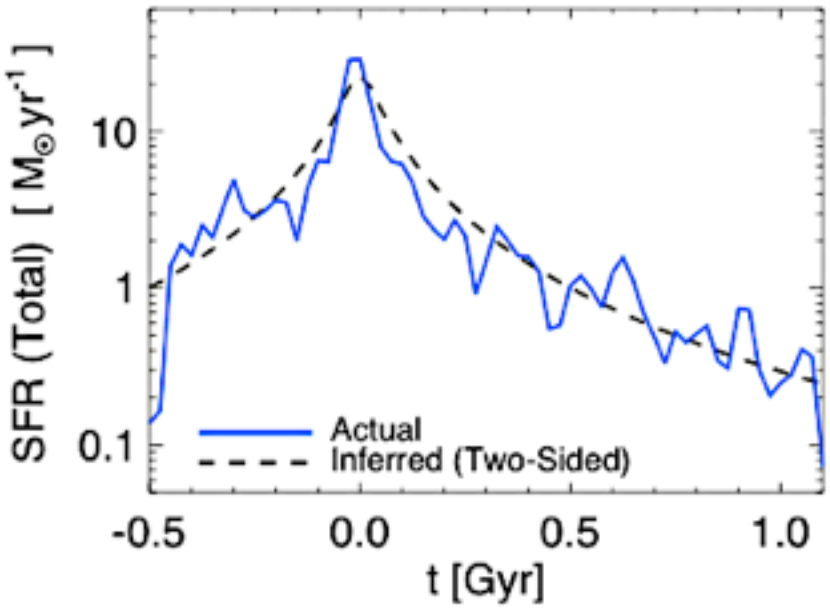

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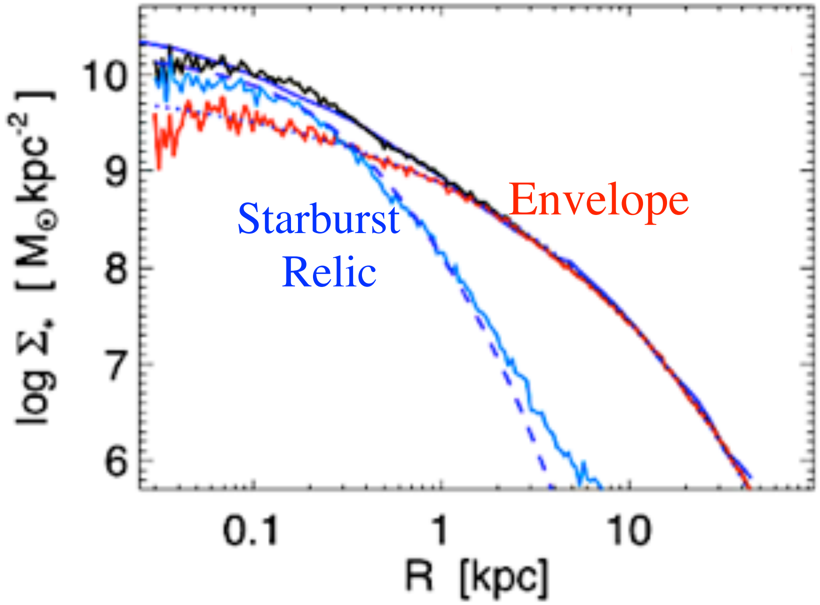

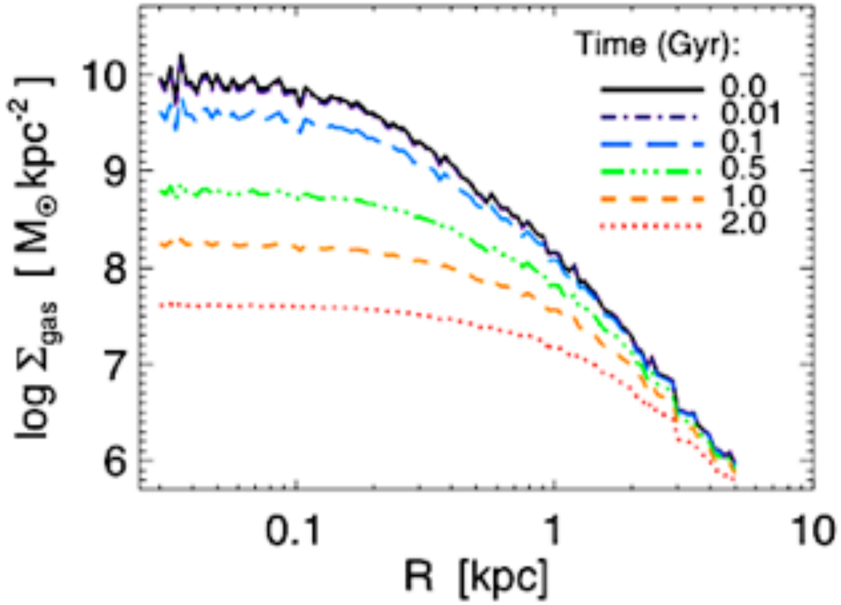

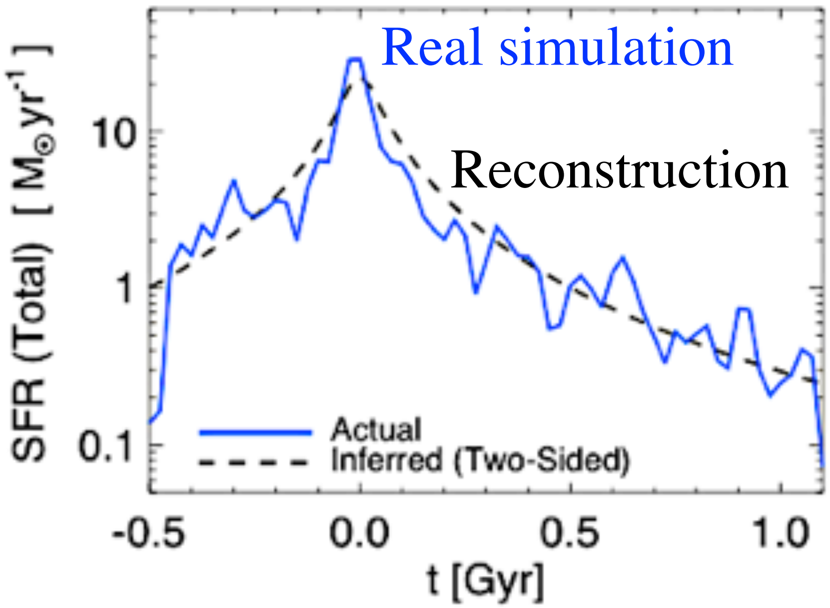

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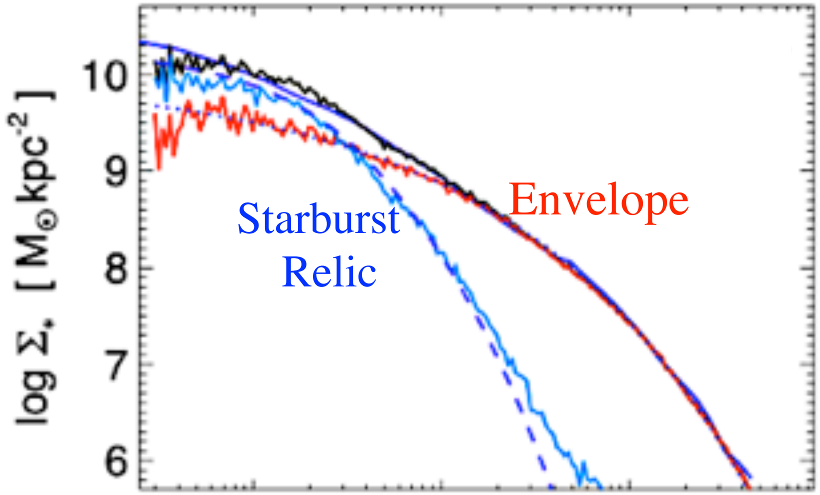

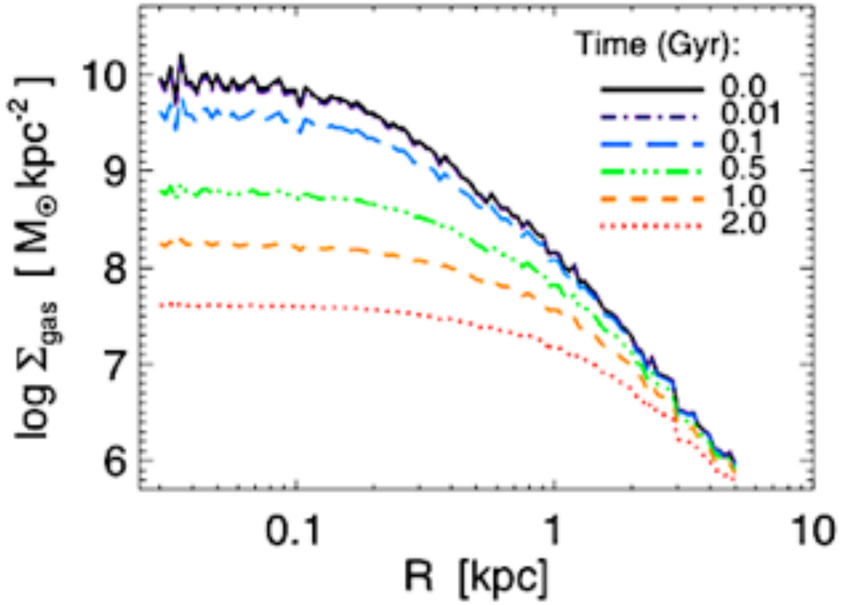

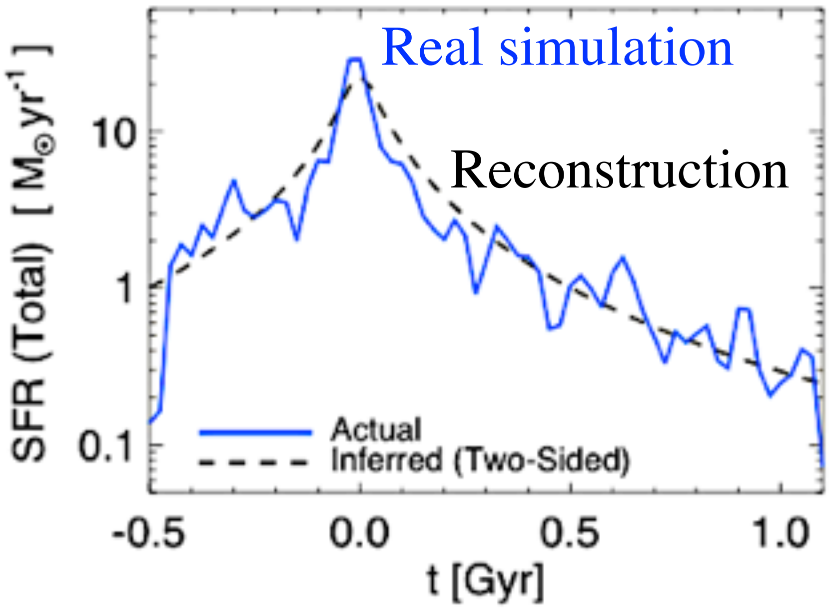

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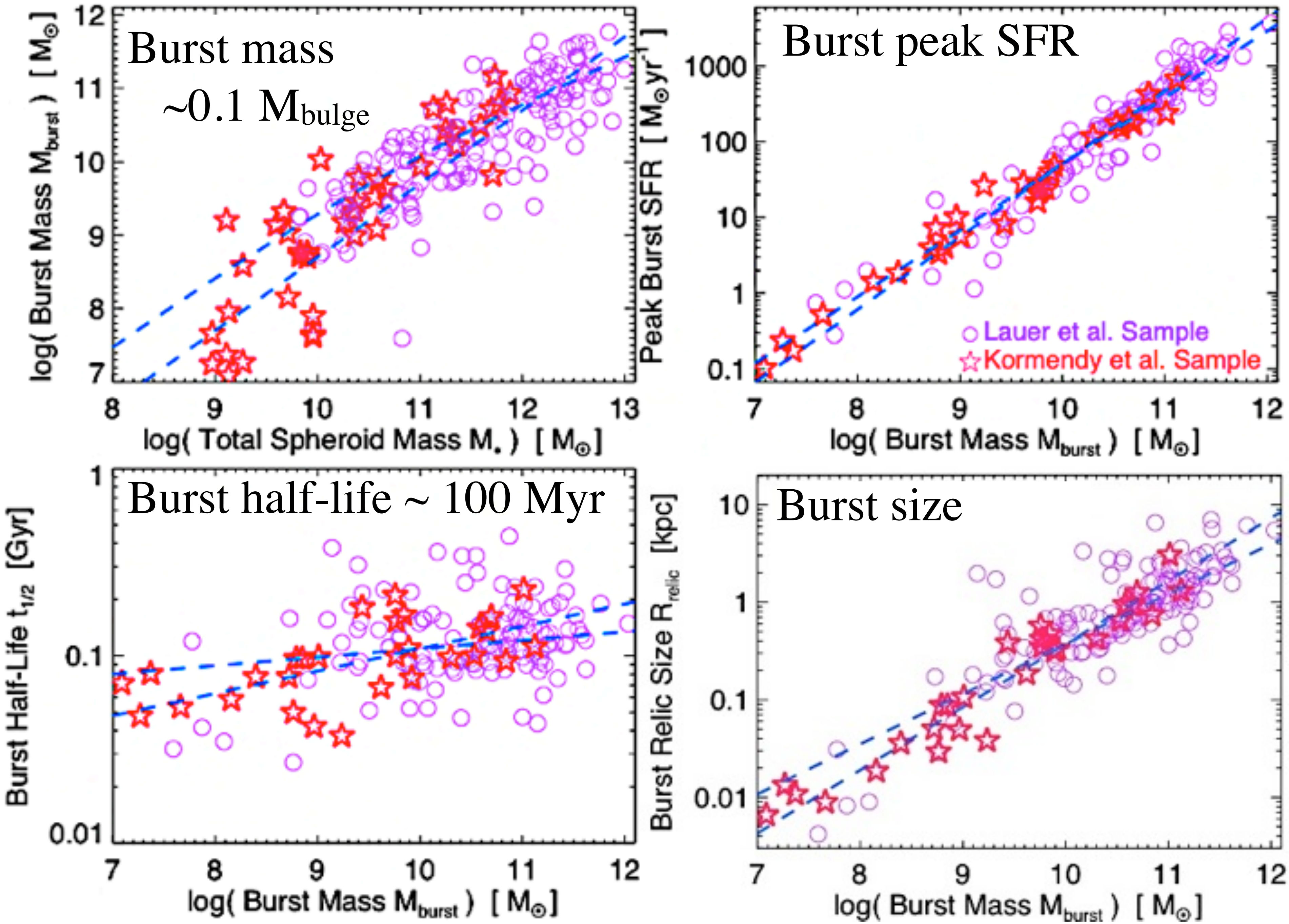

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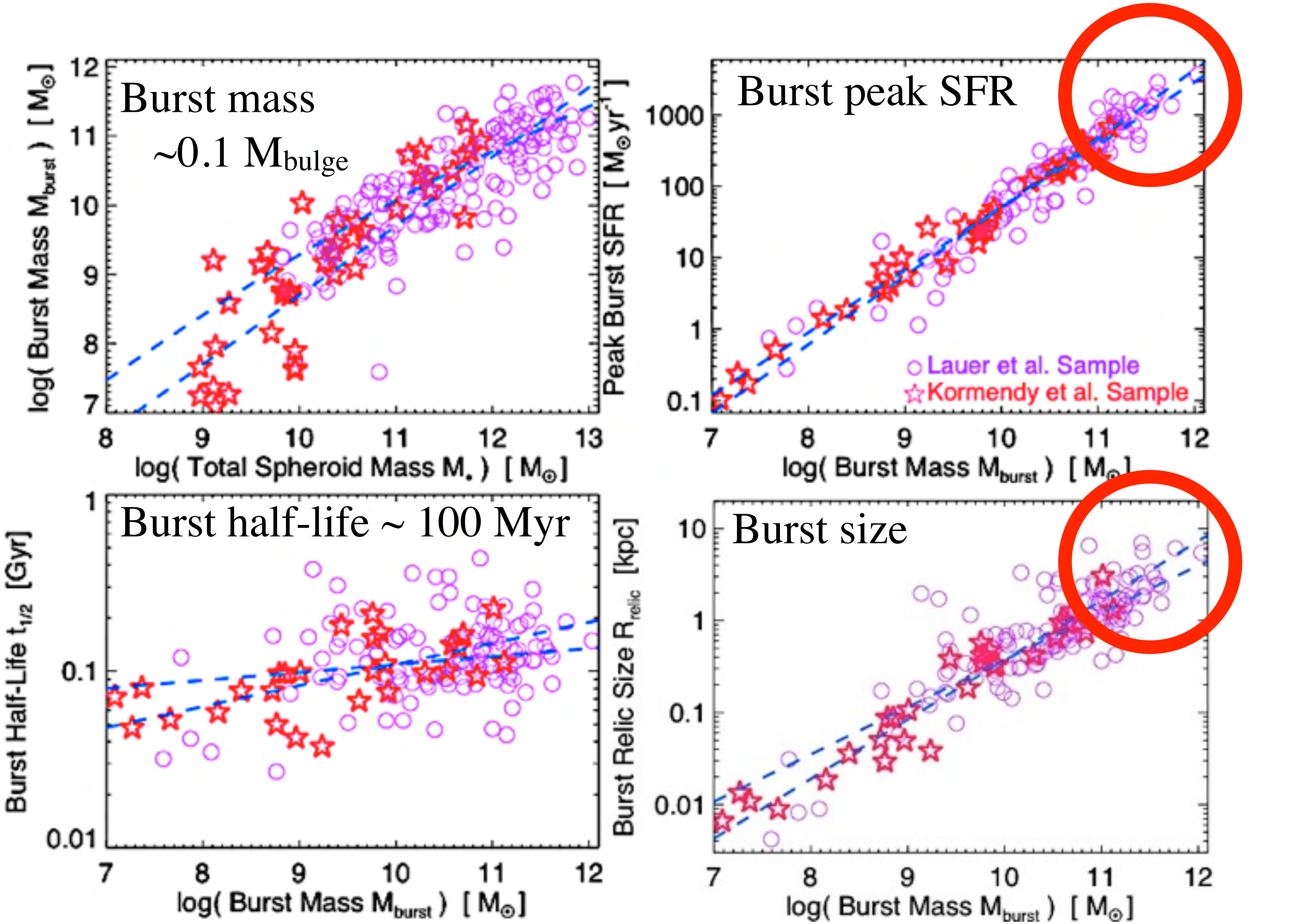
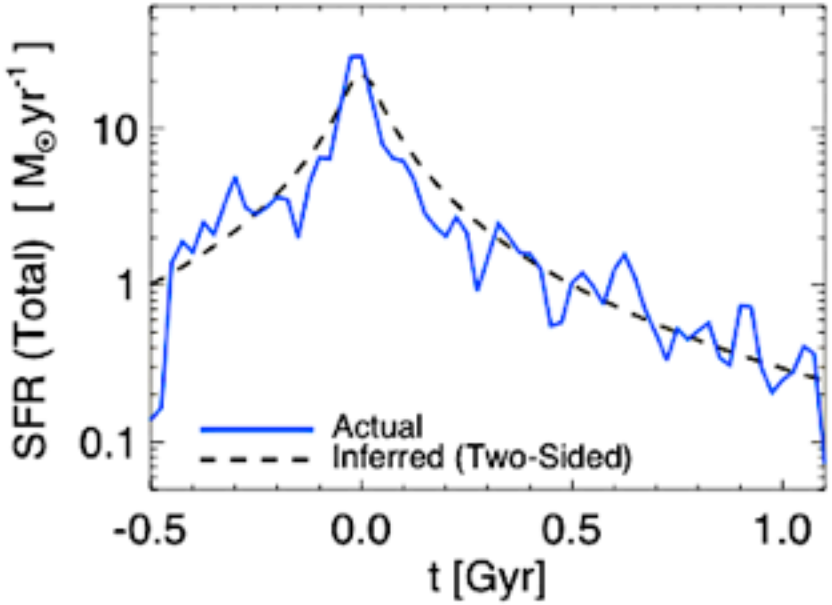
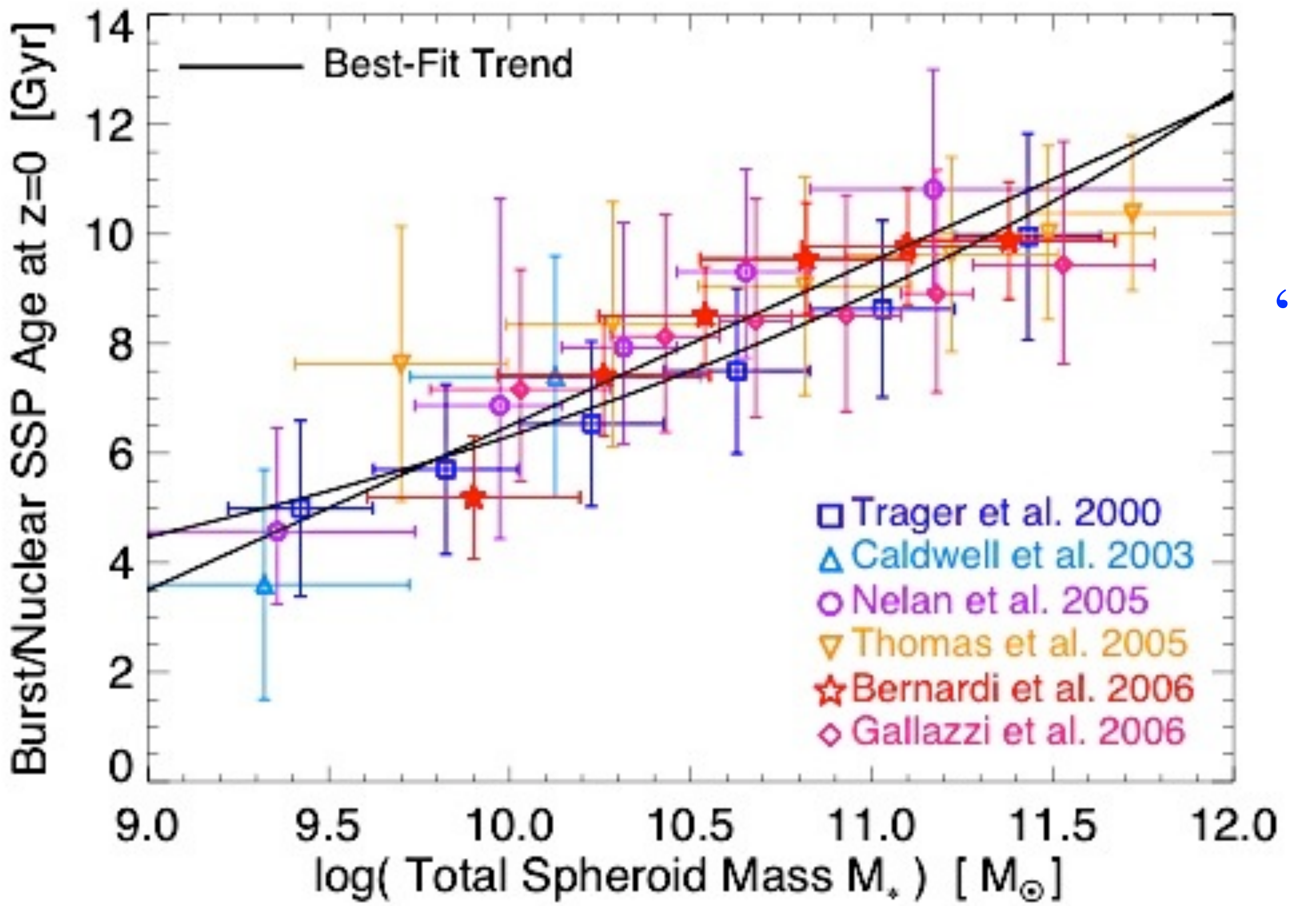


Re-construct SFR(t) for each burst :

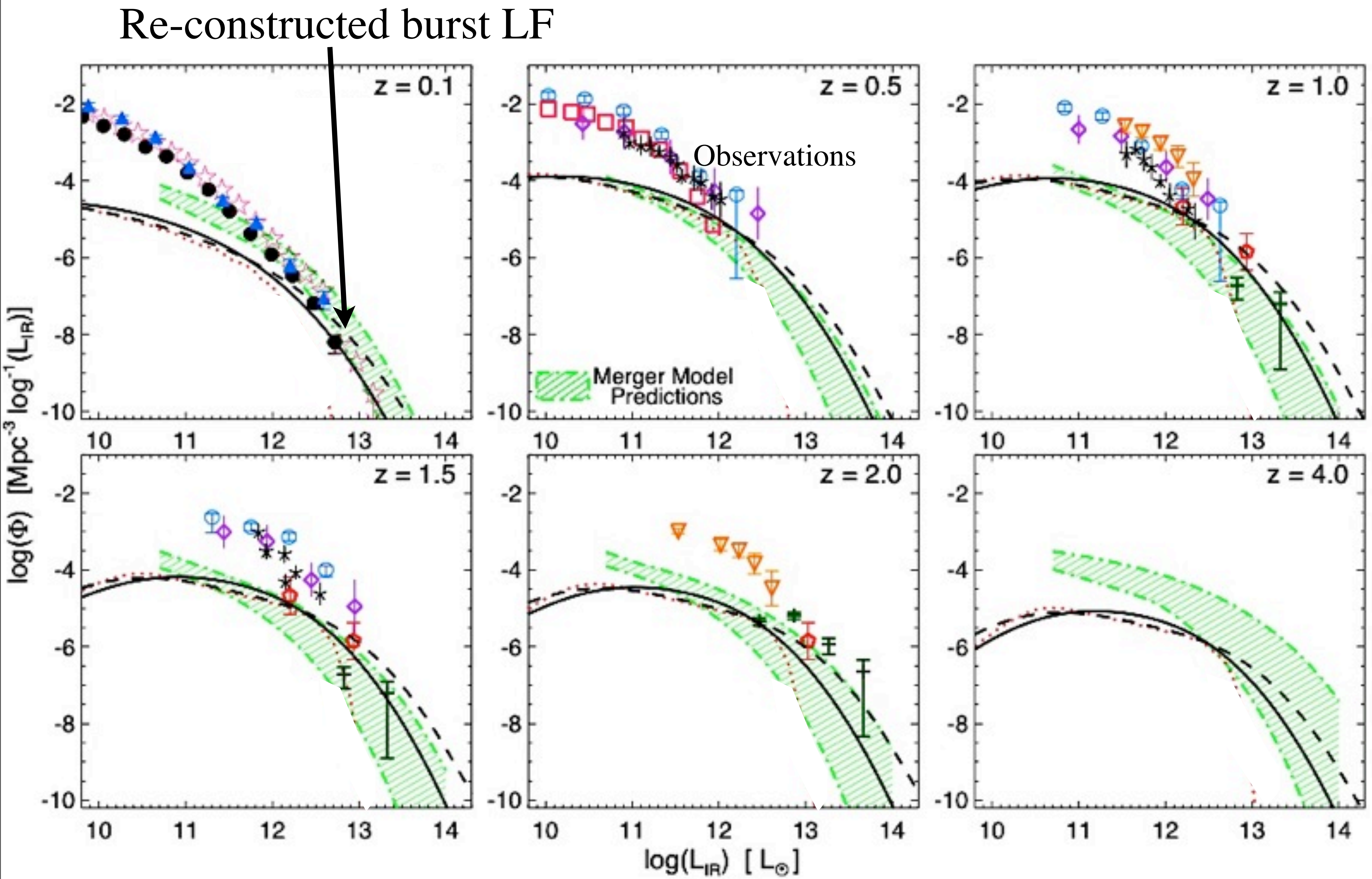


+ We know the nuclear SSP ages....

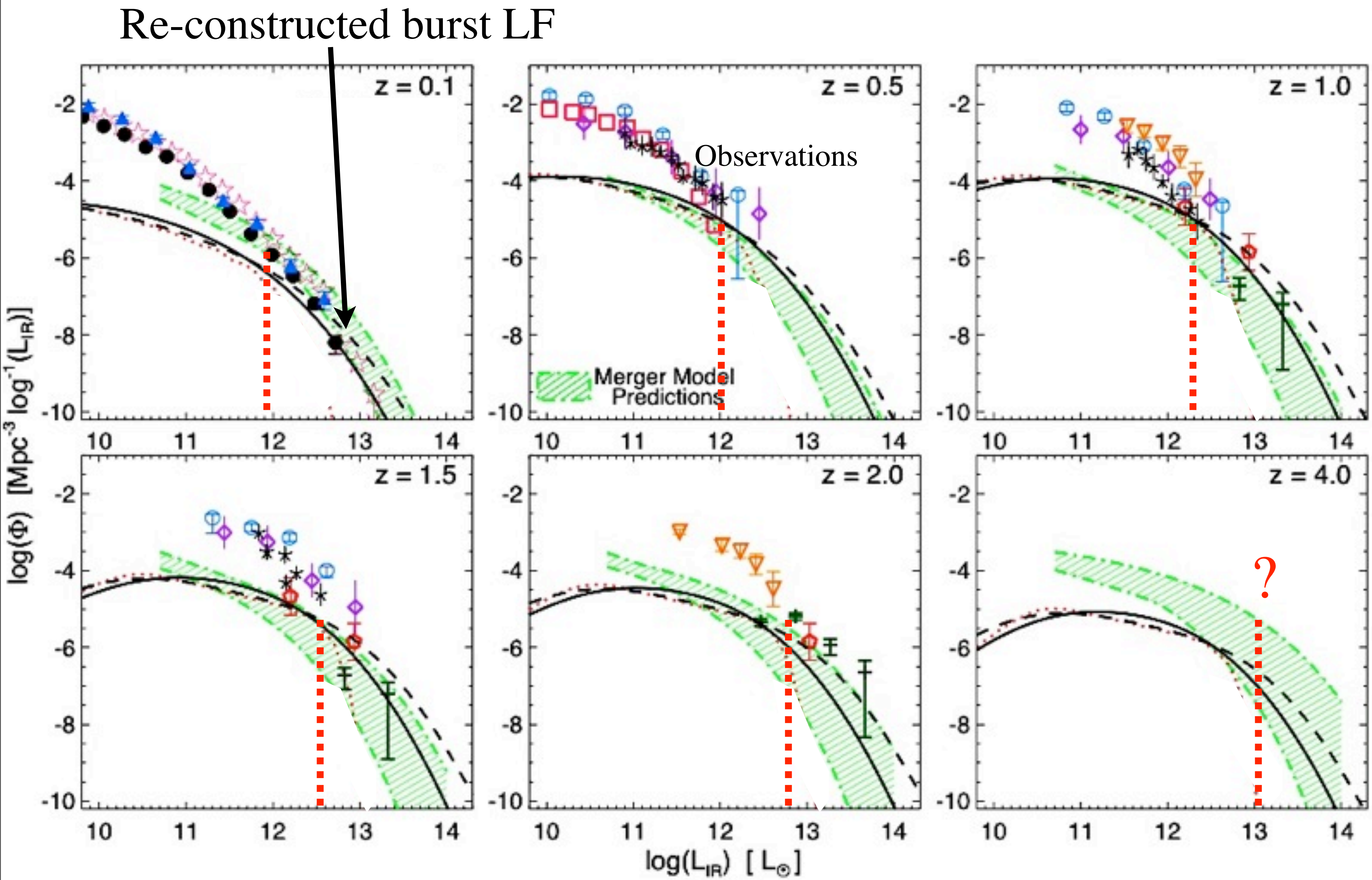


"place" each burst at the correct redshift

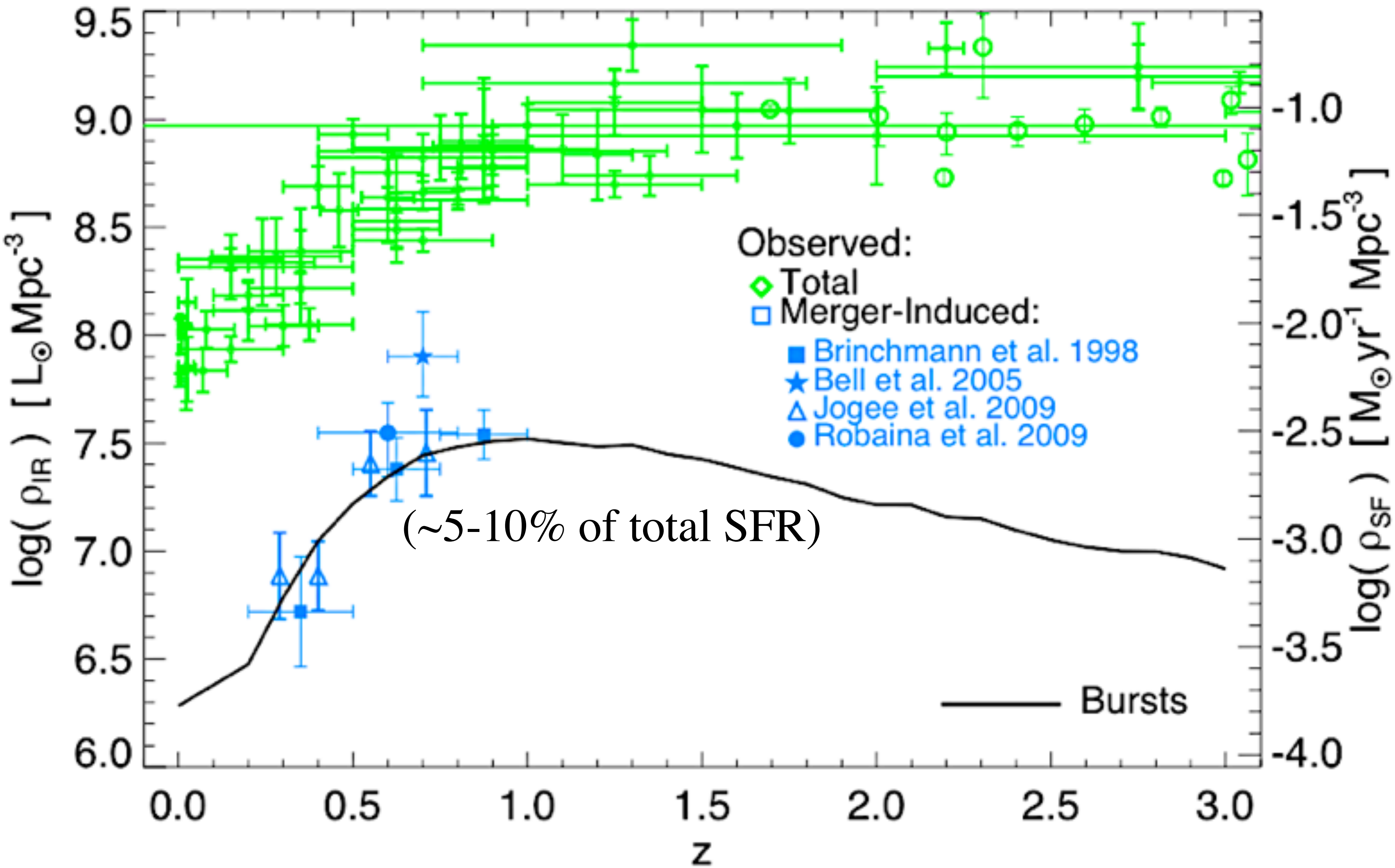
Recover the IR LF of dissipational starbursts!



Bursts always dominate at high L, but the threshold shifts

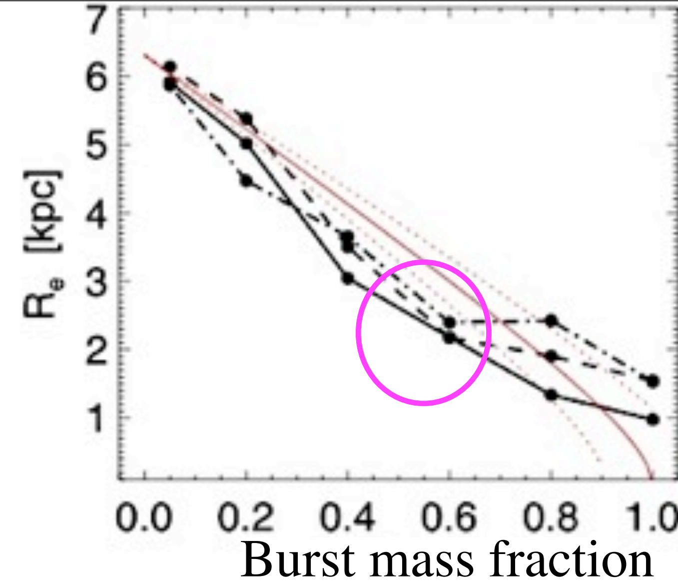


Bursts never dominate the SFR density!

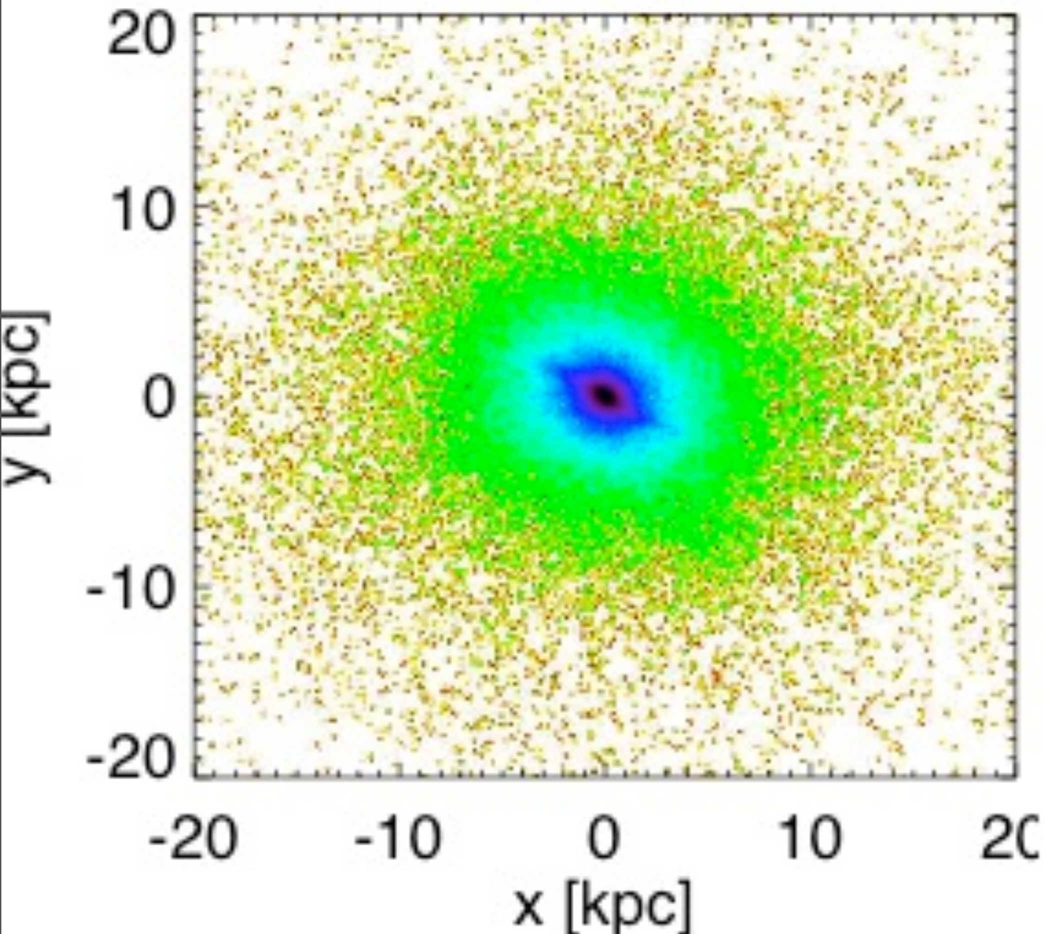


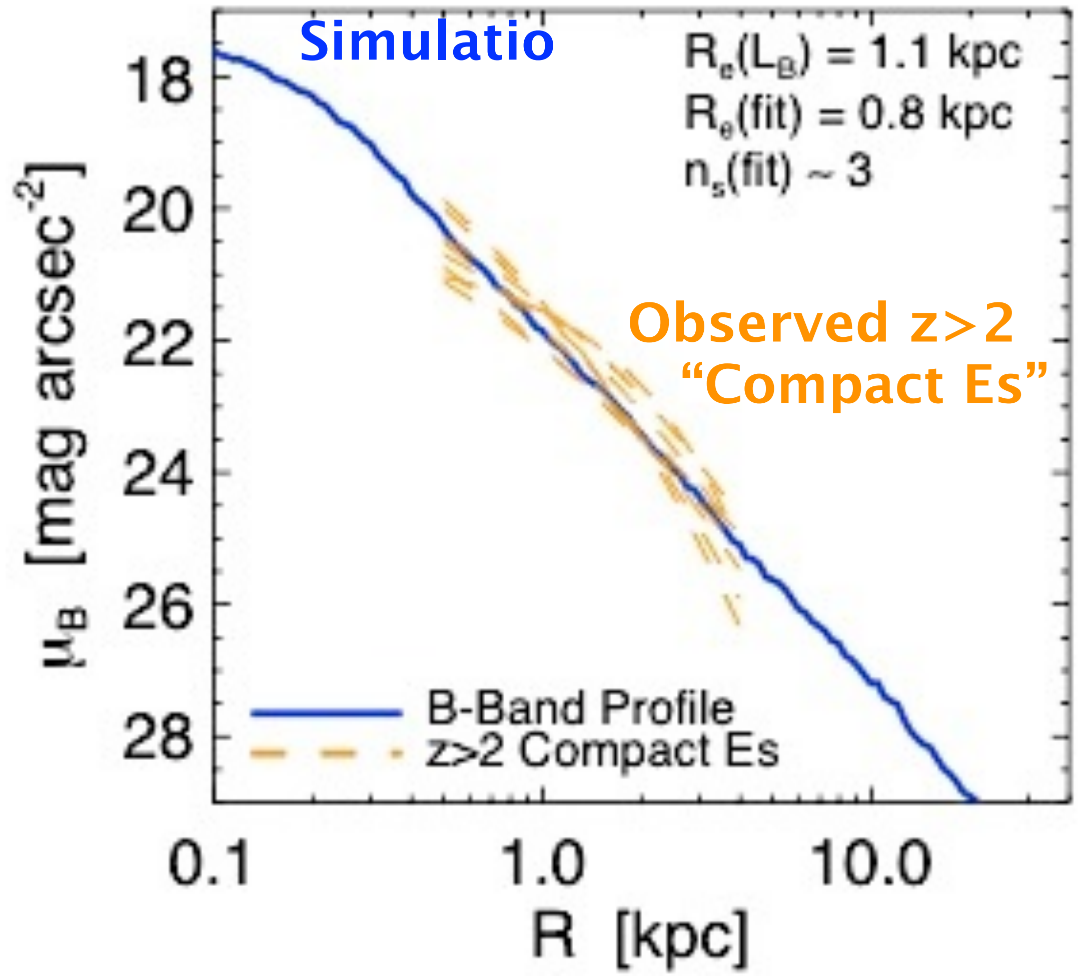
What happens in an “extreme” case?

- Typical f_{gas} in high-z massive disks up to ~40% (Erb+, Tacconi+, Manucci+)



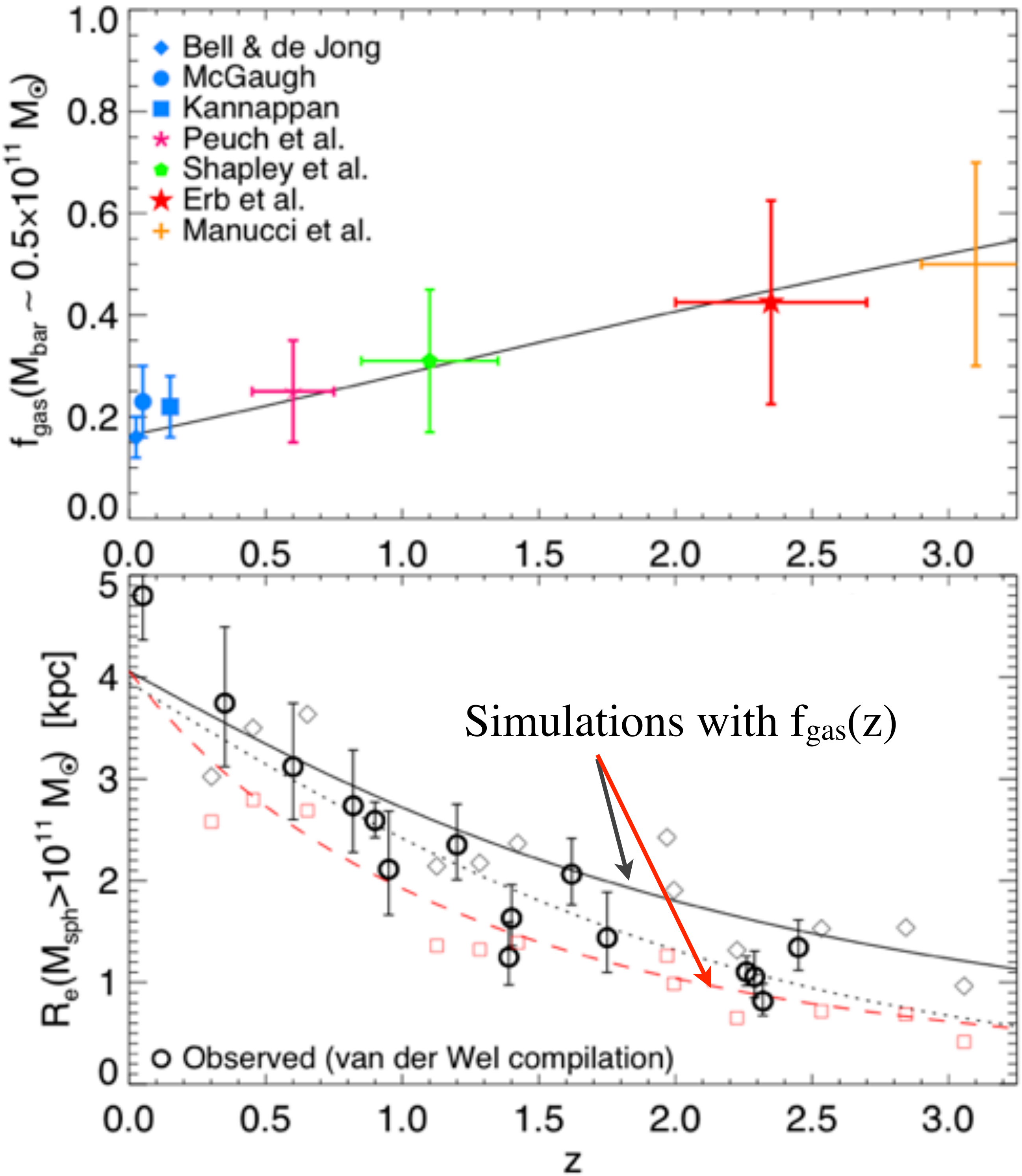
f_{gas}=0.4 merger, ~1kpc





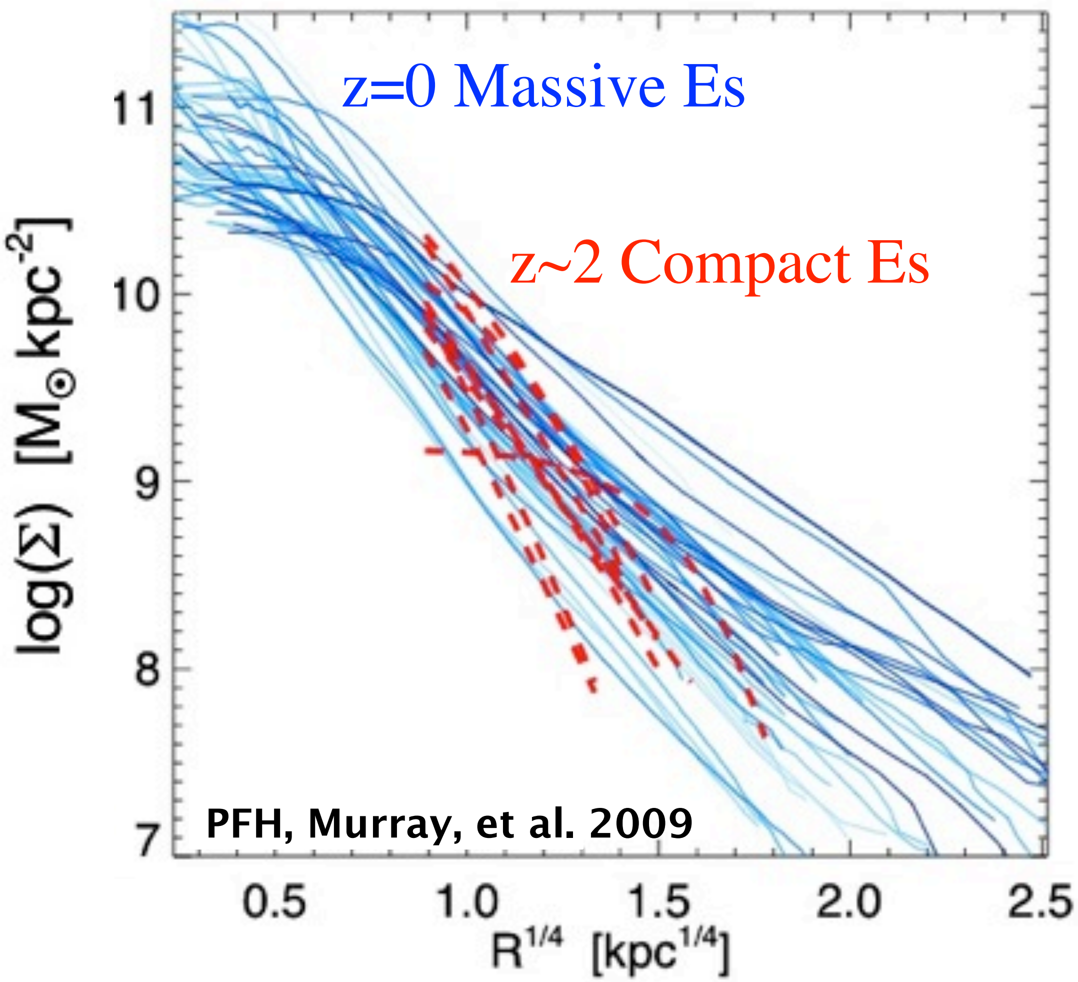
PFH, Bundy, et al. 2009

- Spheroid size evolution corresponds to the expectation from evolving gas fractions!



- Do we see the 'footprint' today?

- How did the high-z systems evolve to be 'normal' at z=0?



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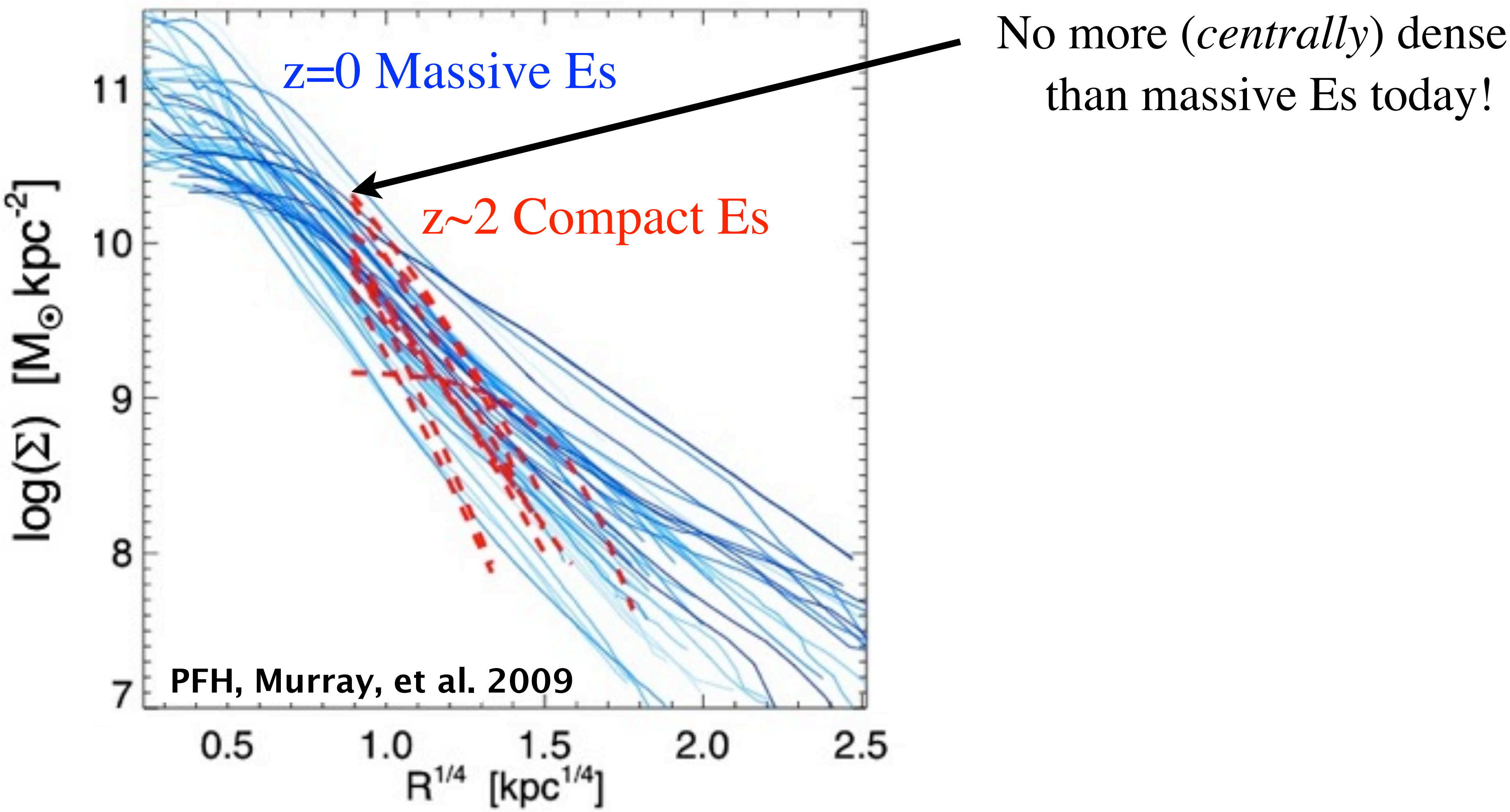
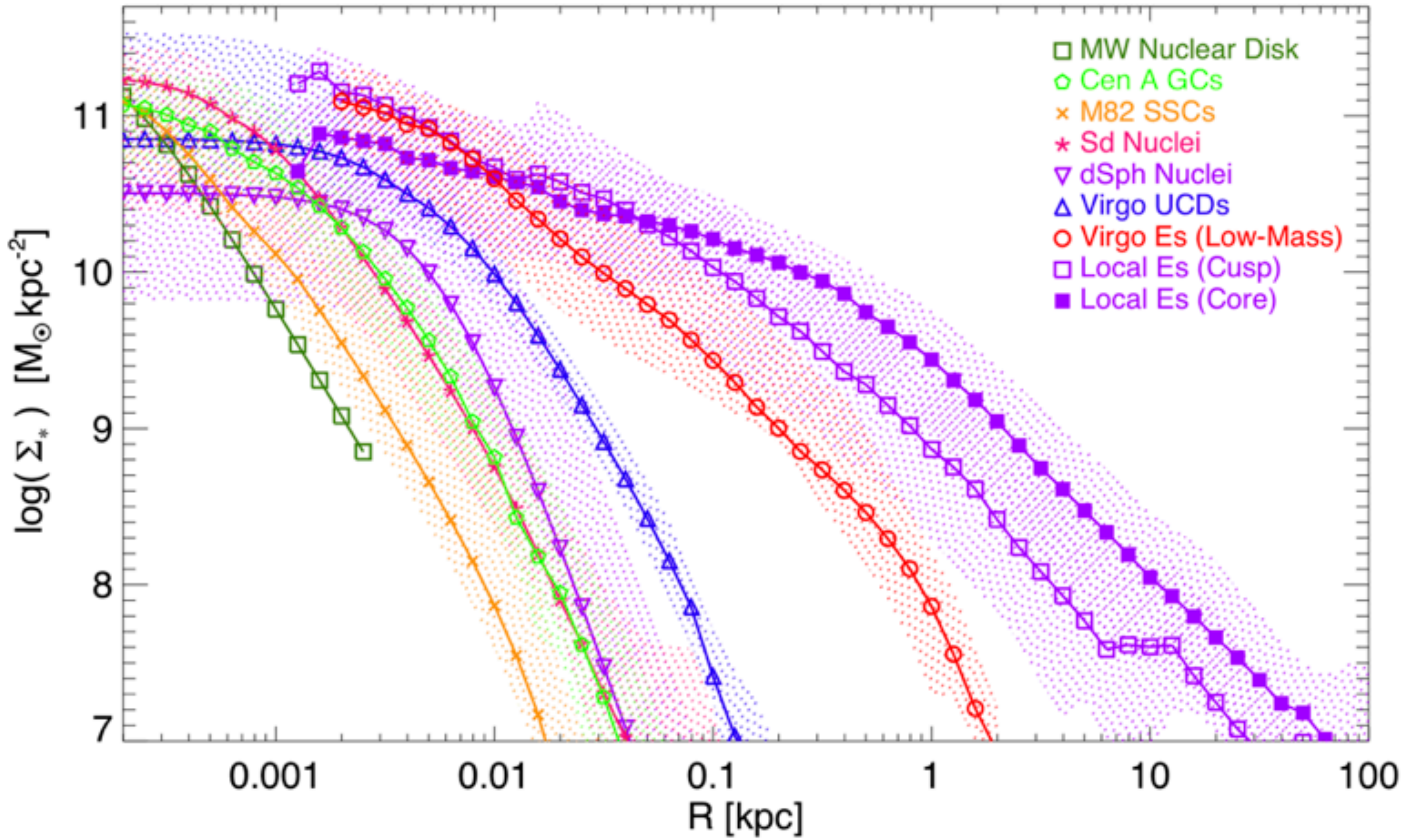


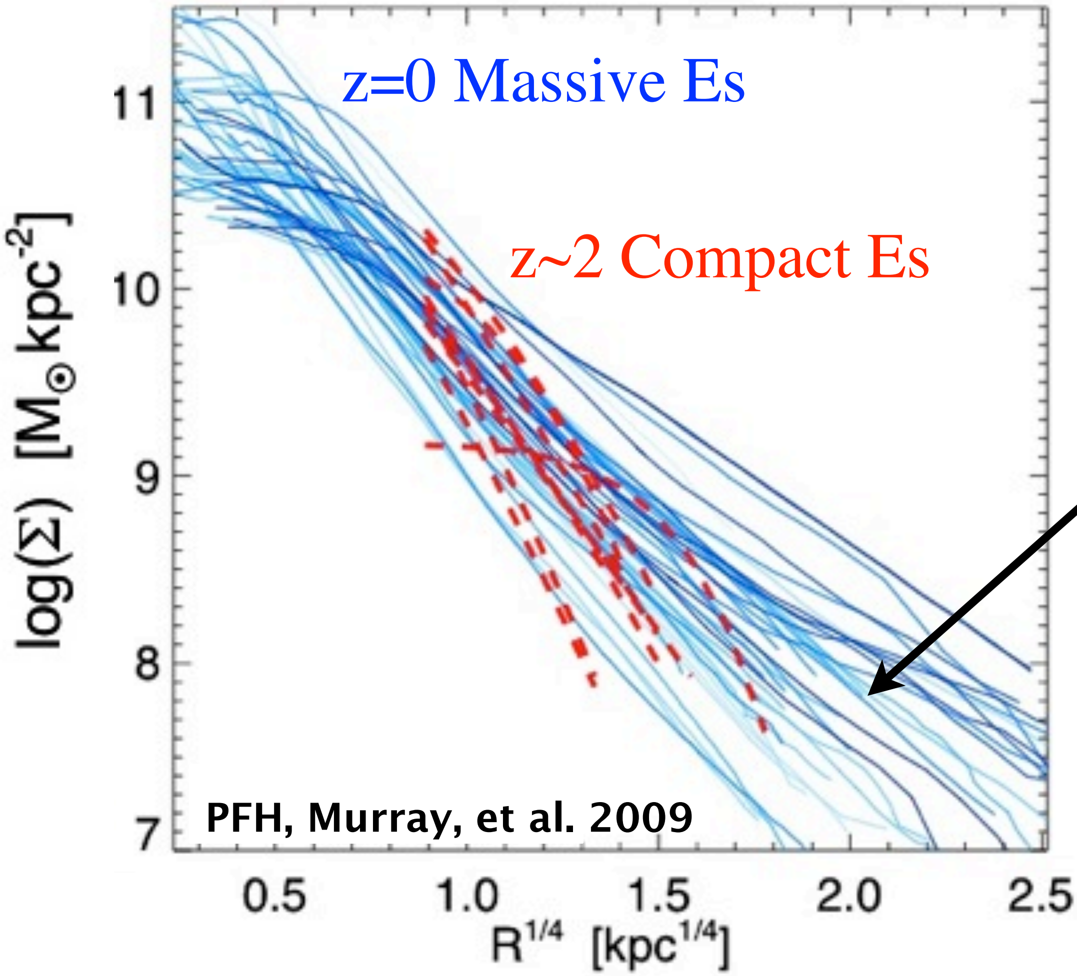


In fact, never see much higher densities.....
.... feedback?

PFH, Murray, Thomps
et al. 2009

- Do we see the 'footprint' today?

- How did the high-z systems evolve to be 'normal' at z=0?

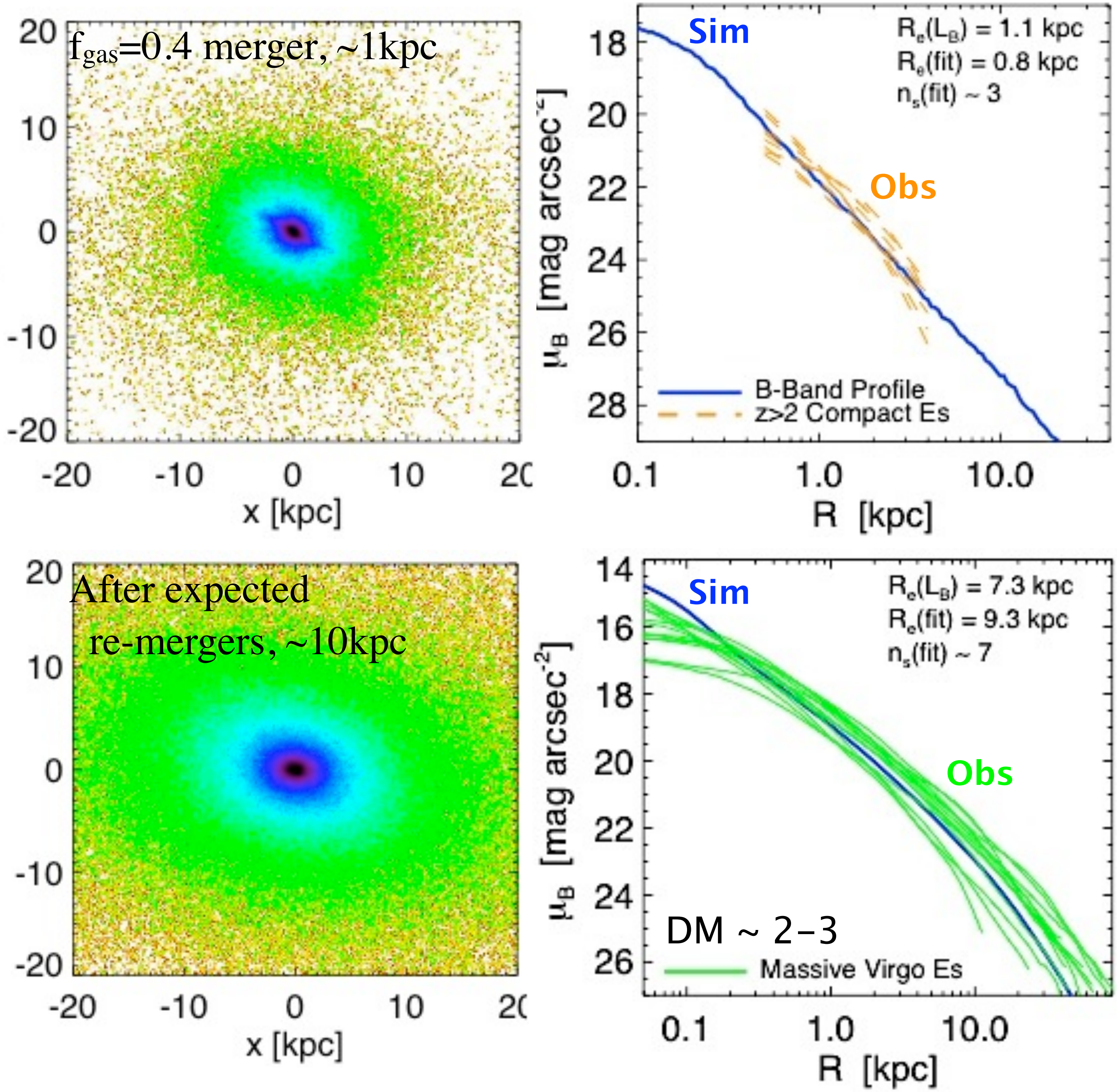


Missing the low-density "wings":

Only need to accrete ~M_{gal} in "fluff", to increase R_e by a factor ~6!

PFH, Bundy, et al. 2009

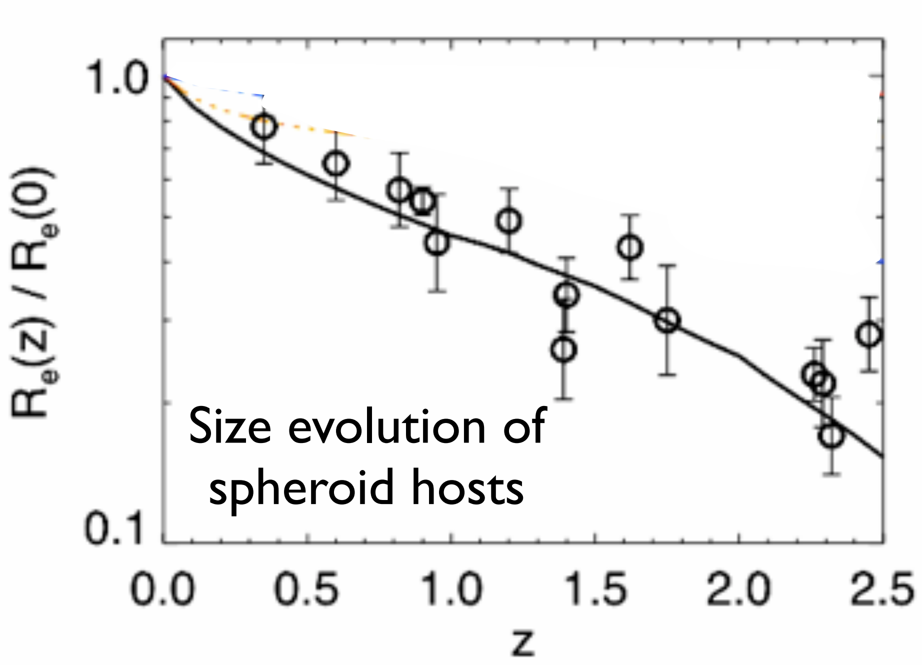
also Bezanson, Naab et al.

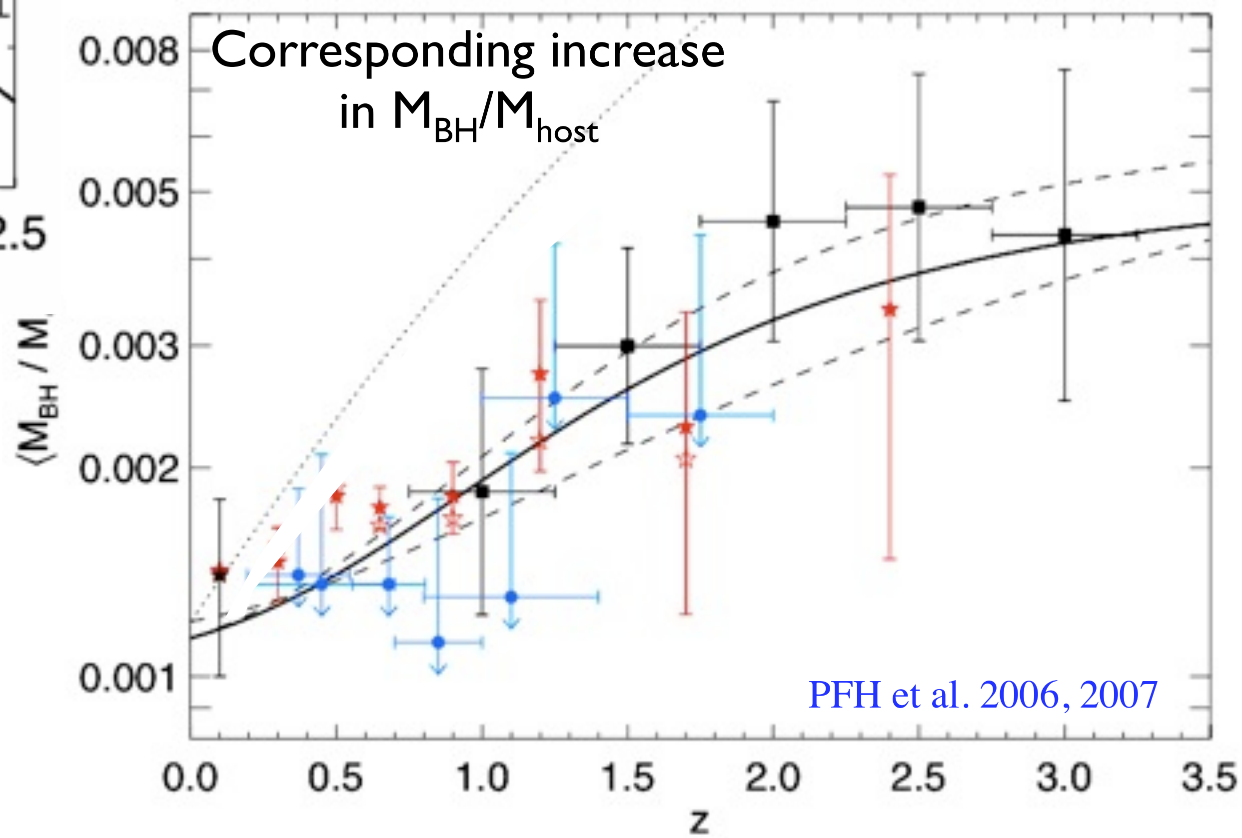


PFH, Bundy, et al. 2009

Implications for Evolution in BH-Host Correlations

- In self-regulated models: BH stops growing when energy released ~ binding energy
  - Hosts more gas rich/compact at high-z → more "work" for the BH before self-regulation

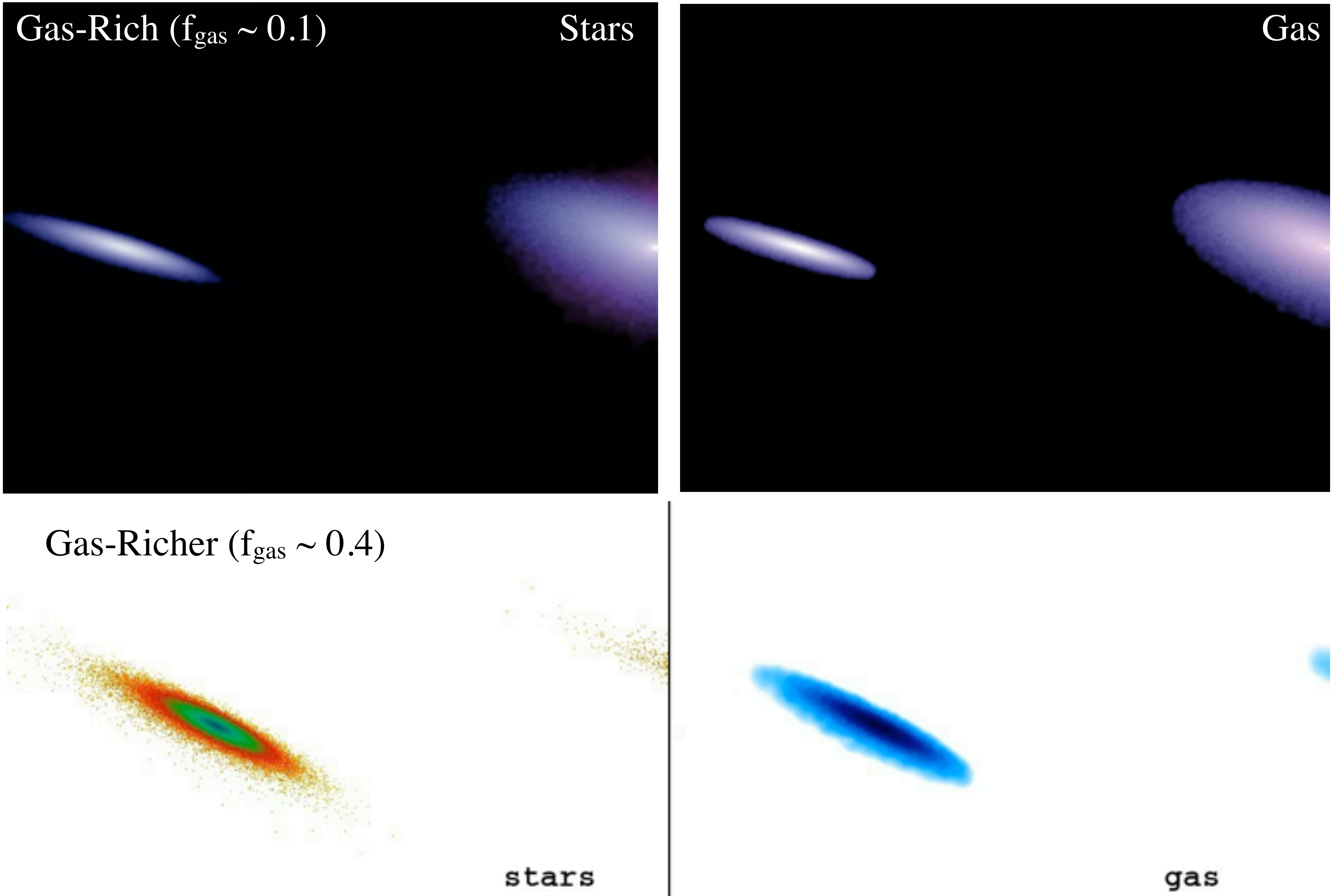




- Doesn't mean that BHs grew "before" their bulges

But what about the highest gas fractions?

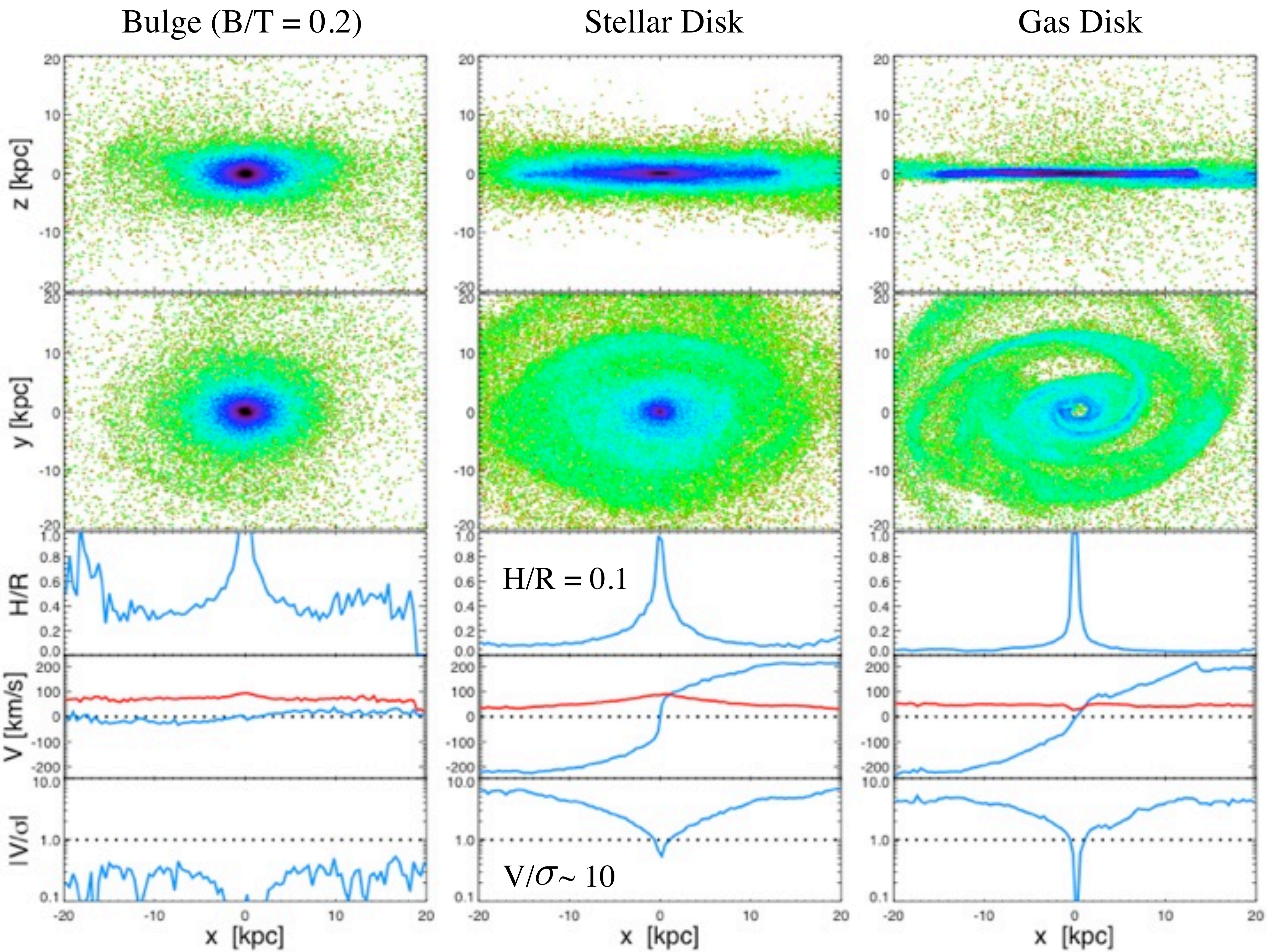
How Good Is Our Conventional Wisdom?



Robertson et al. 2006

Major Merger Remnants

DO MERGERS DESTROY DISKS?



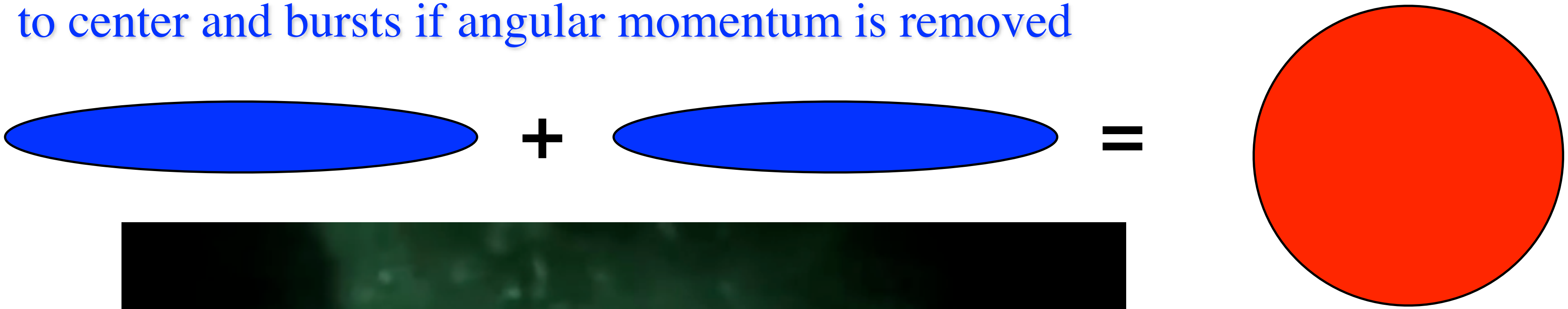
The Unsolved Questions

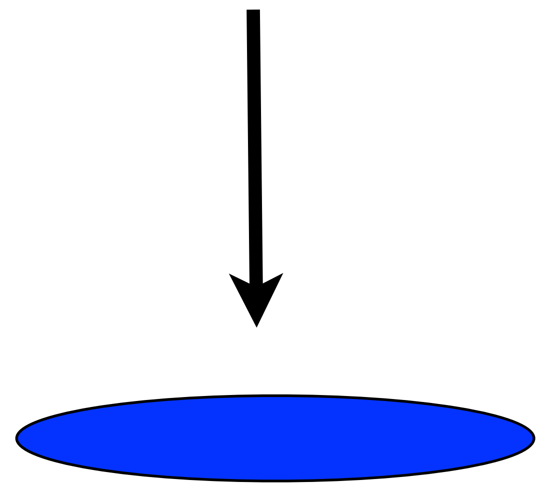
HOW CAN A DISK SURVIVE?

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

- Can’t “cool” into a new disk

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





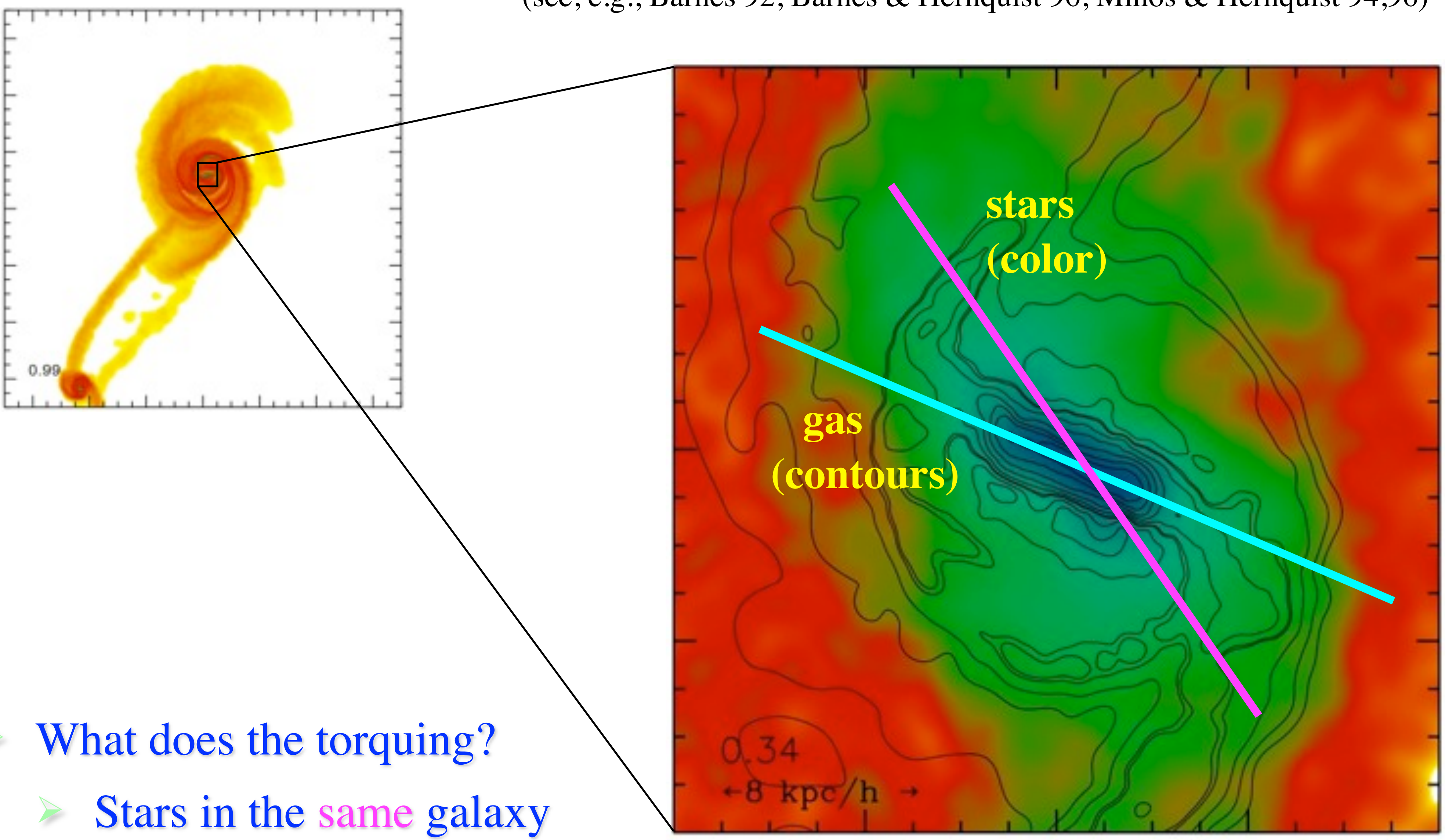
Brooks et al., Governato et al.

How Do Disks Survive Mergers?

PFH et al. 2008

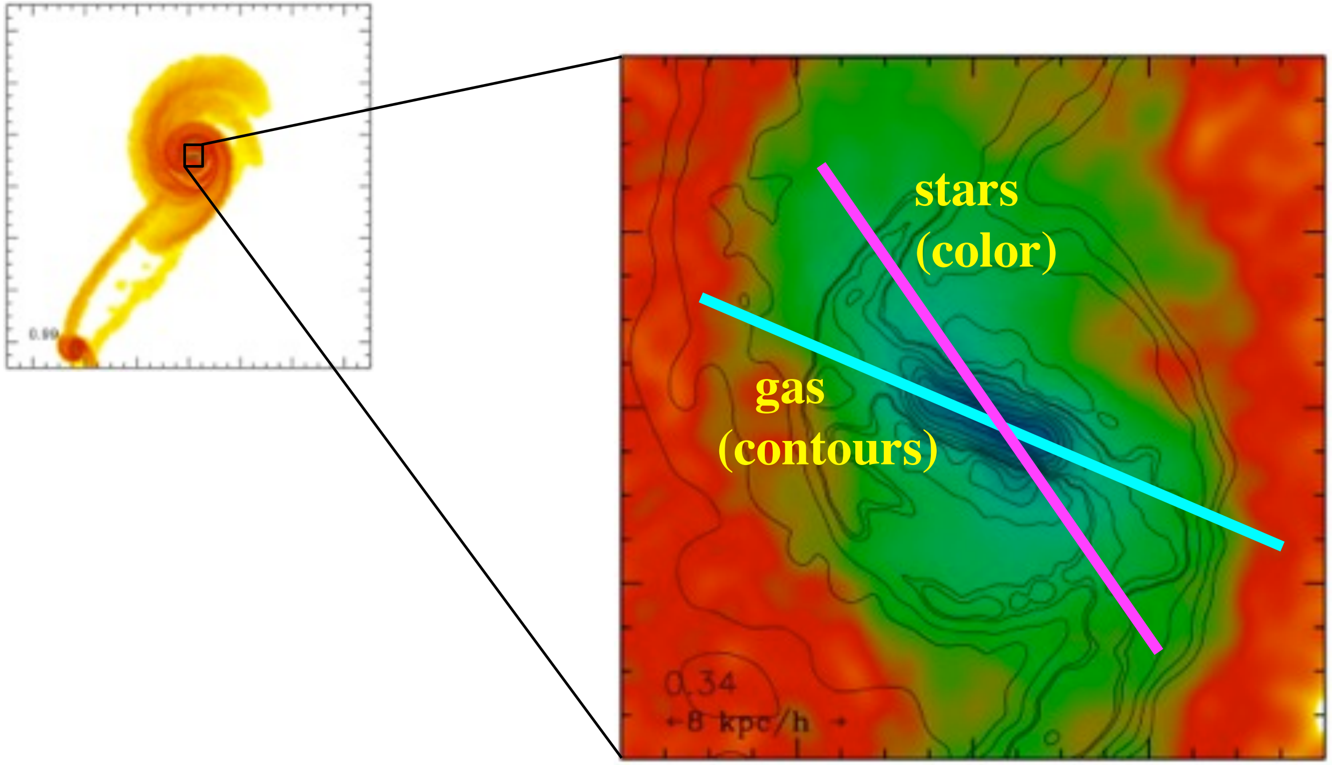
companions -- bars -- gas/star offset -- torques -- gas inflow

(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?



Compare:

Self-torque in gas disk (Lynden-Bell & Kalnajs 1972):

$$v_{\mathrm{inflow}} \sim (0.01 - 0.1)\,|a|^2\,c_s$$

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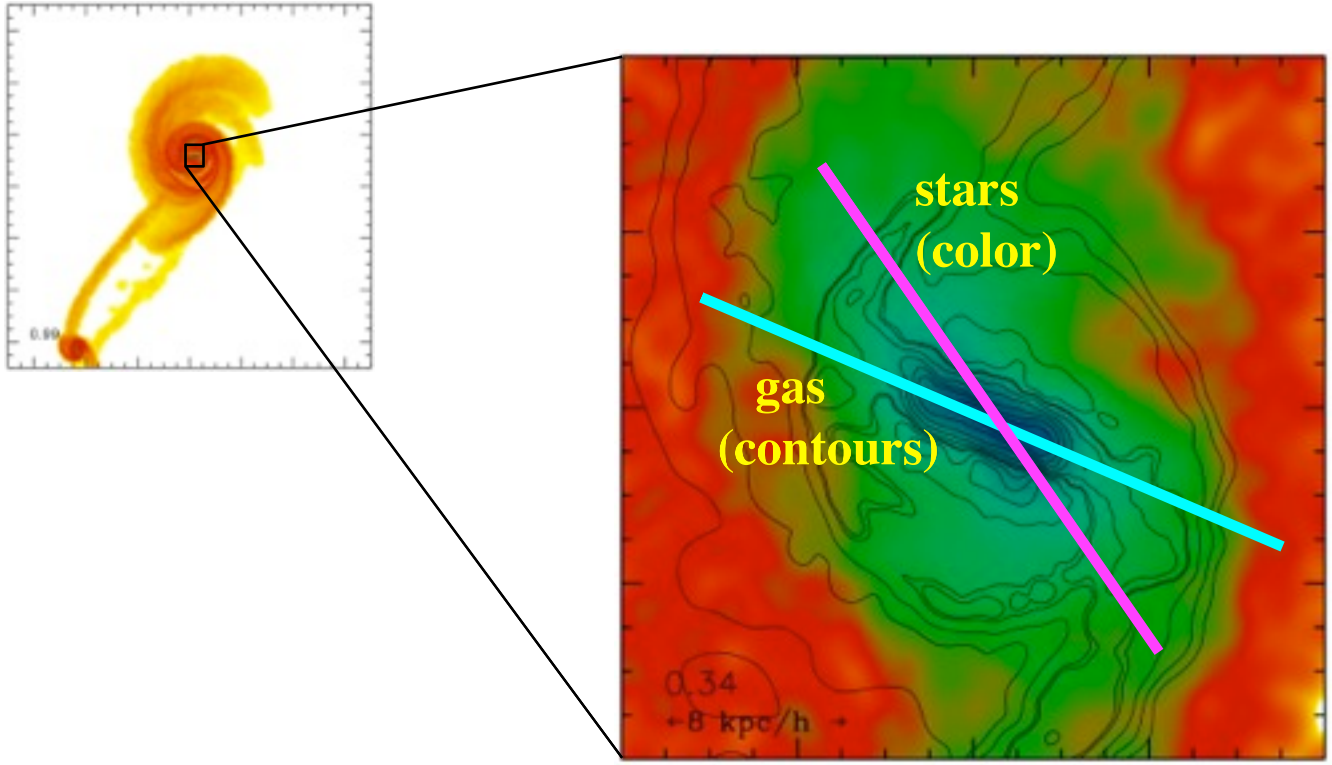

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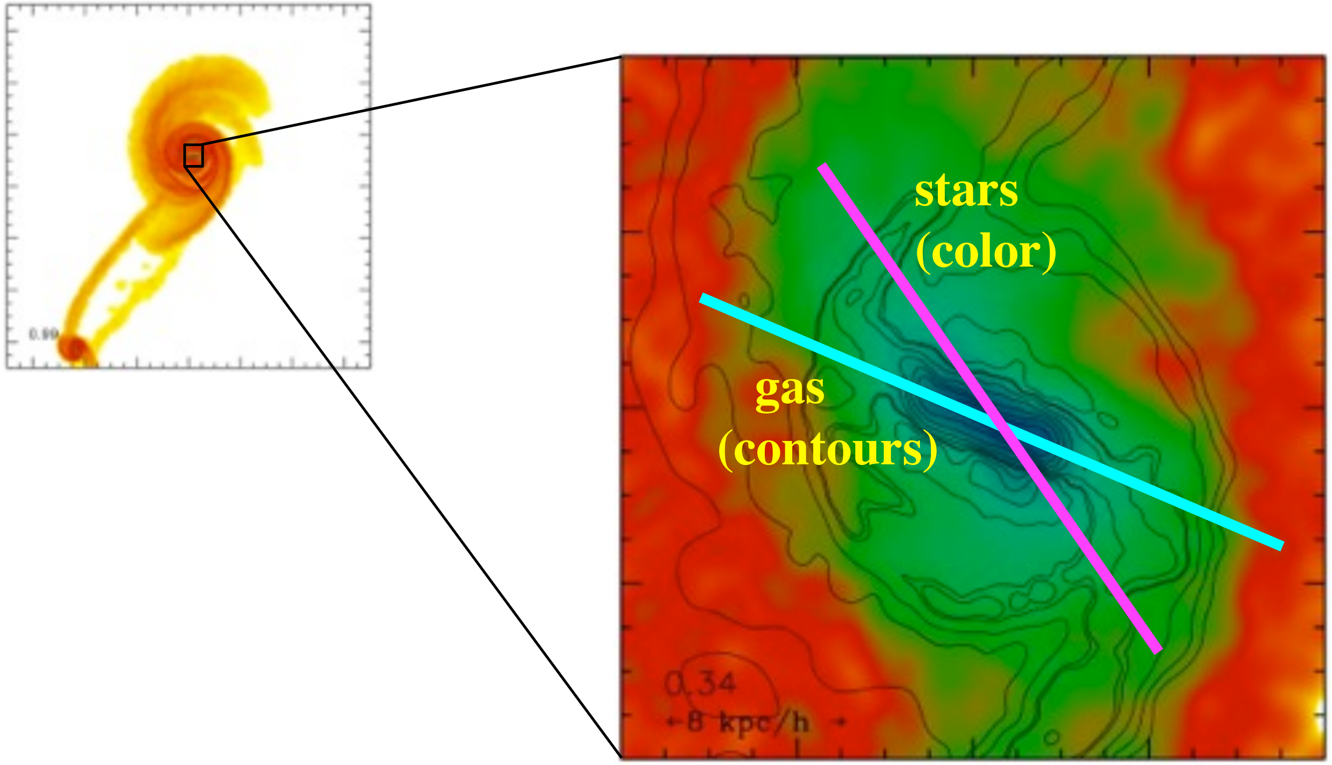
(~ 0.1) → $|a|^2$; $(\sim 0.1\,V_c)$ → c_s

How Do Disks Survive Mergers?



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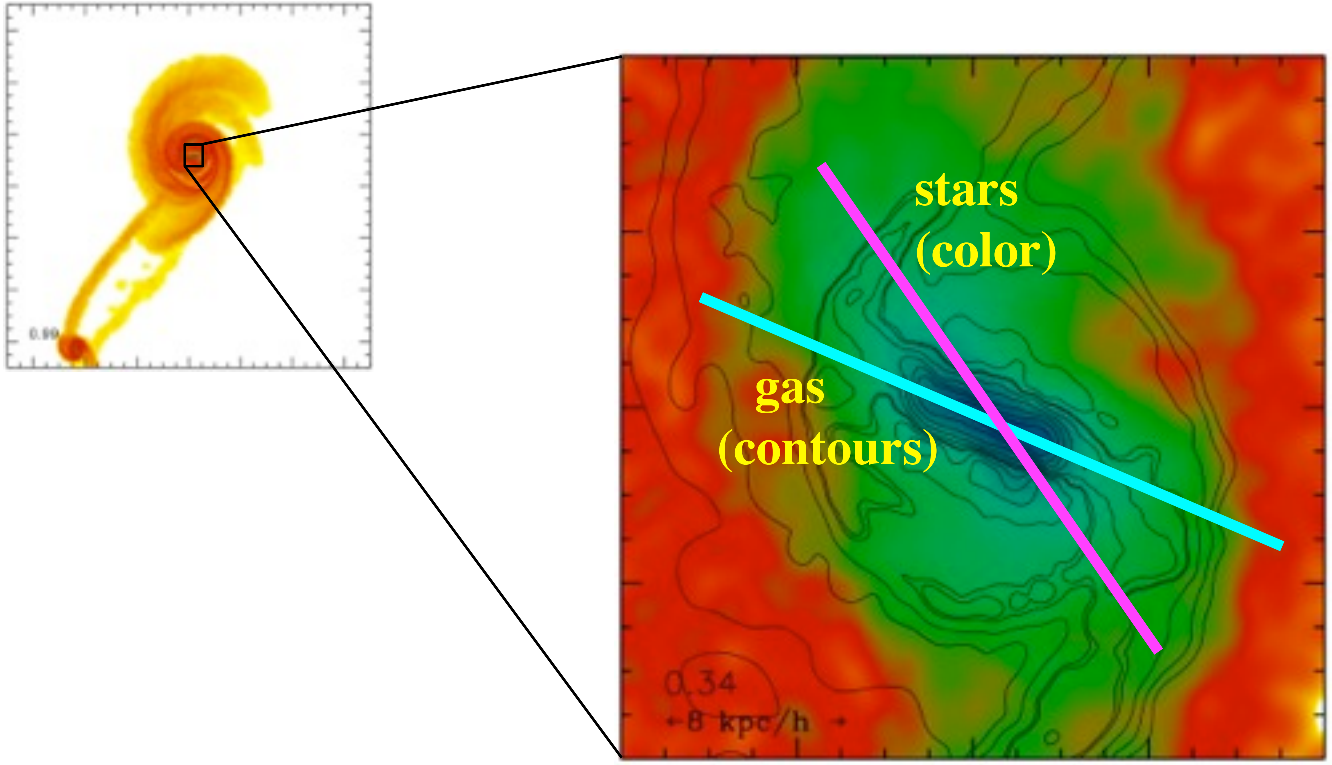

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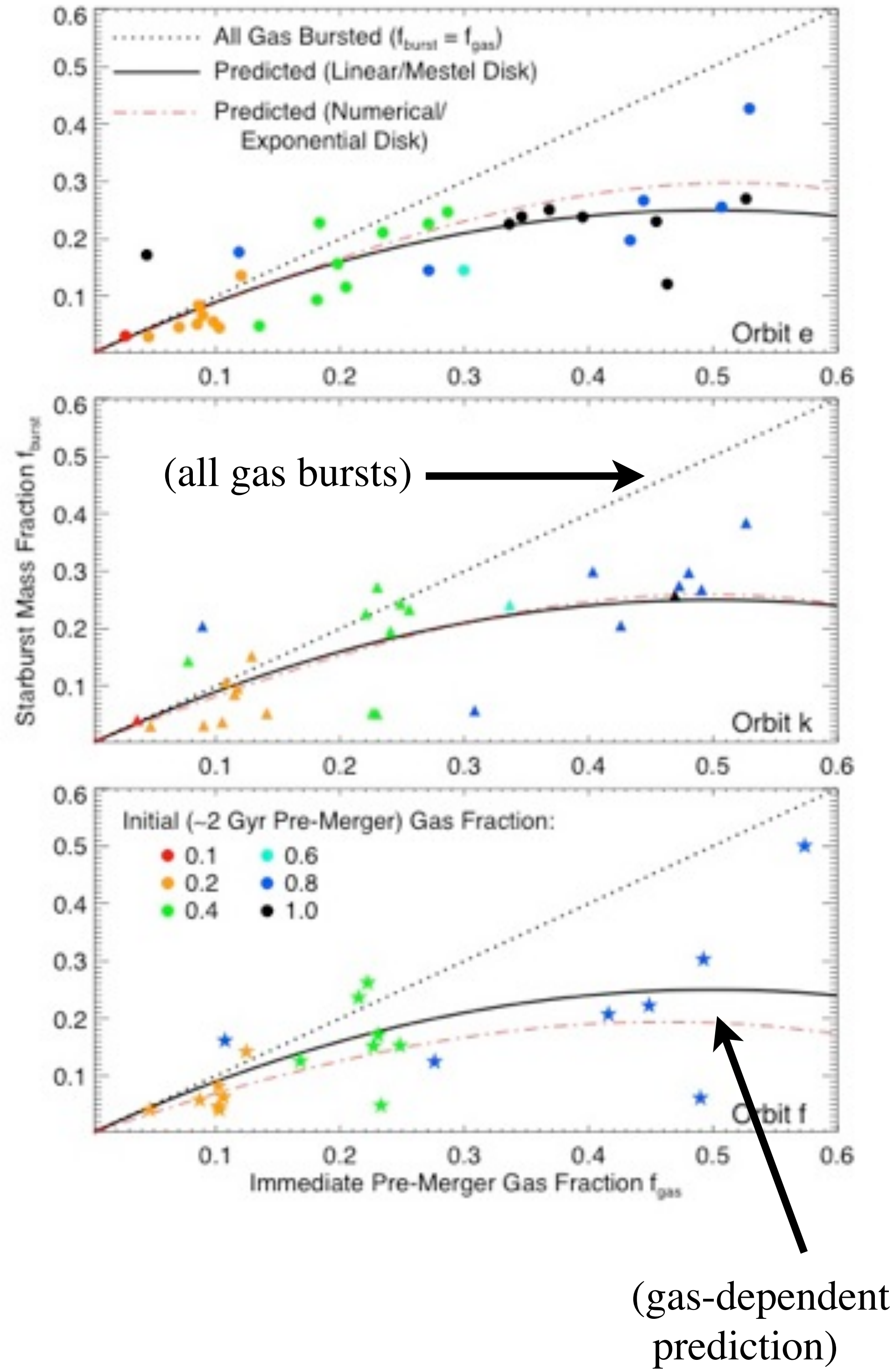
$$v_{\rm inflow} \sim (0.01 - 0.1)\,|a|^2\,c_s$$

Torques from stars when strong shocks induced (PFH & EQ, in prep):

$$v_{\rm inflow} \sim |a|\,V_c$$ (~100-1000x larger!)

How Do Disks Survive Mergers?

Burst mass vs. f_{gas}



Torque on gas:

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

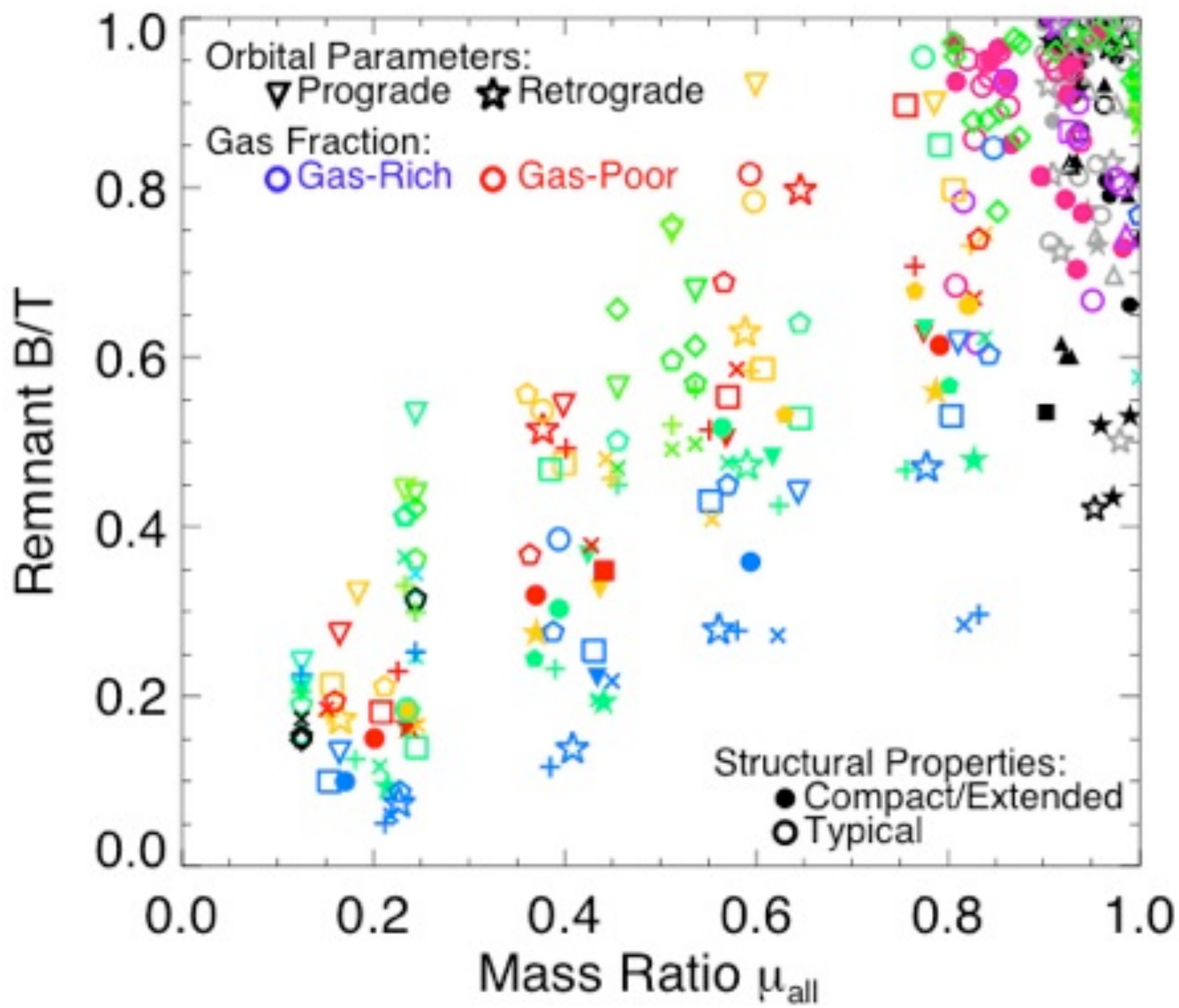
For the same merger/perturbation:

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

PFH et al. 2008

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.



PFH et al. 2008

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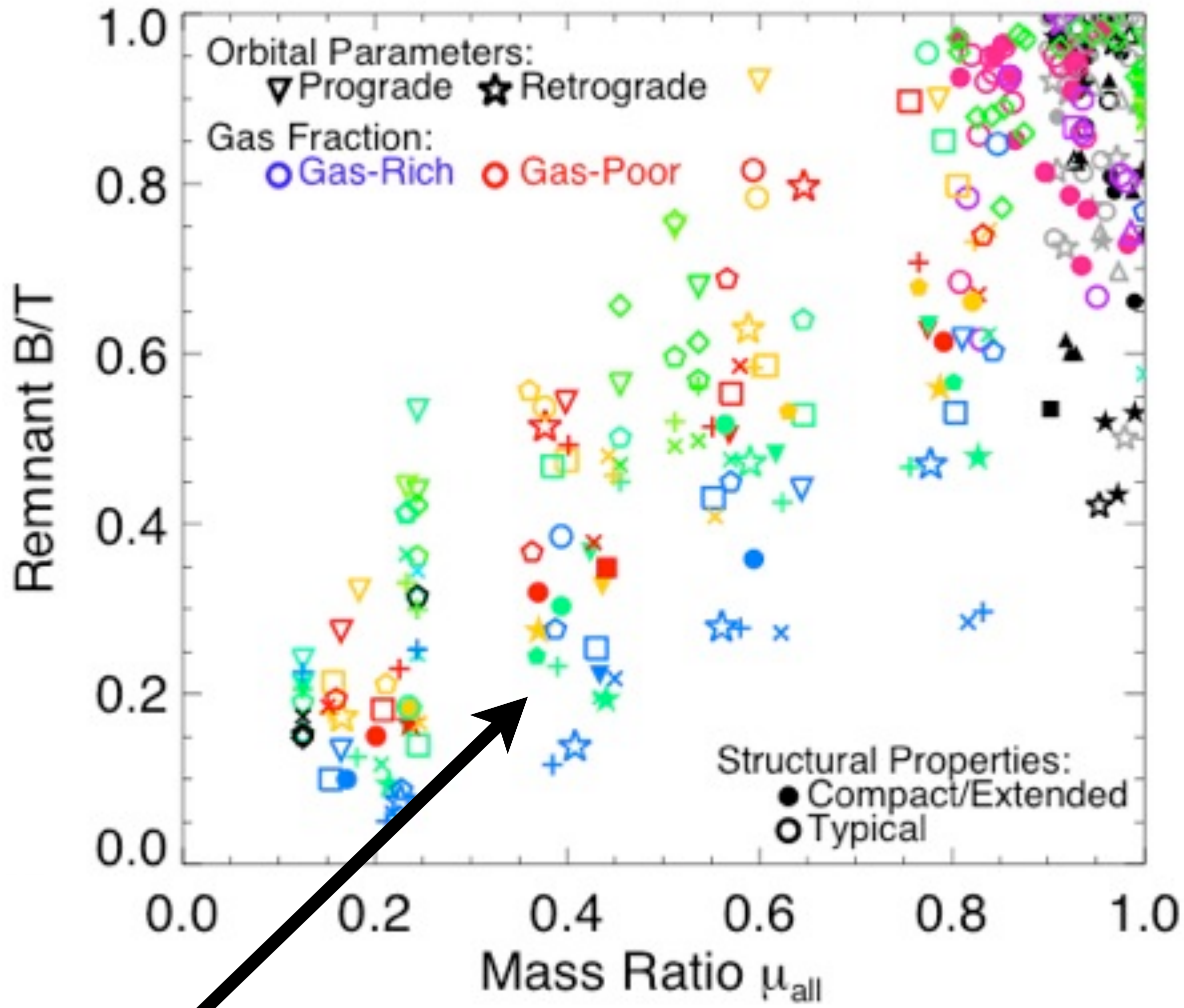


REALLY IMPORTANT!!!

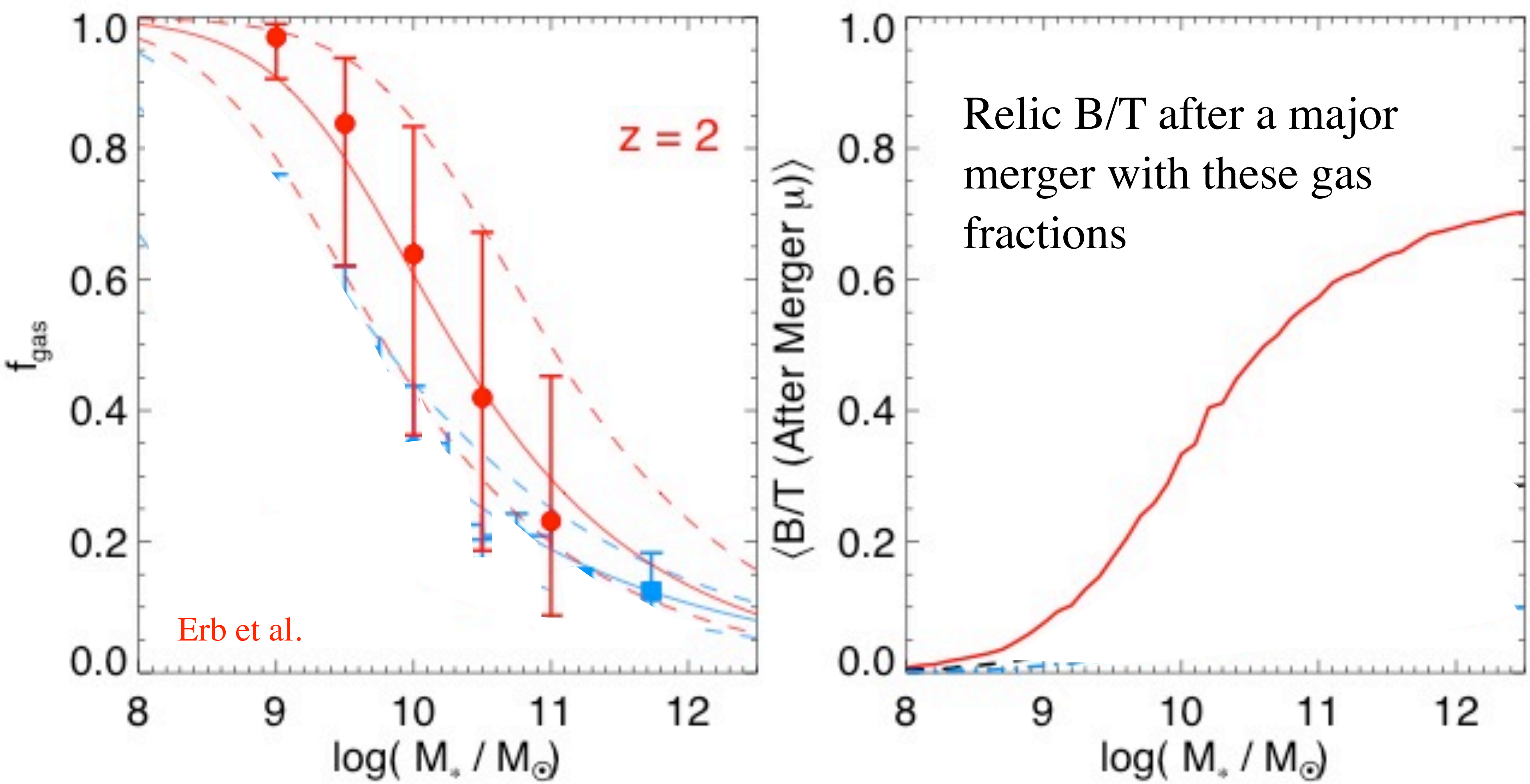
PFH et al. 2008

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 2009

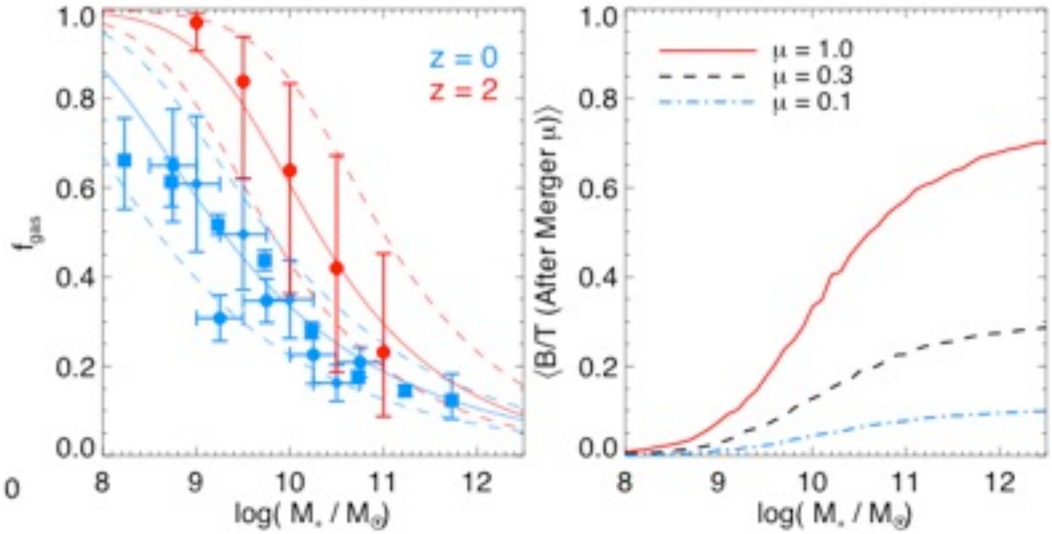
- Fold this into a cosmological model: why do we care?



- 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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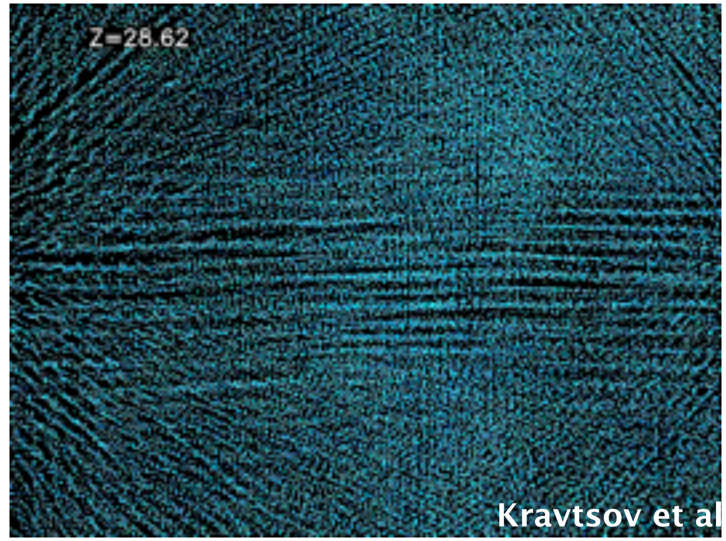

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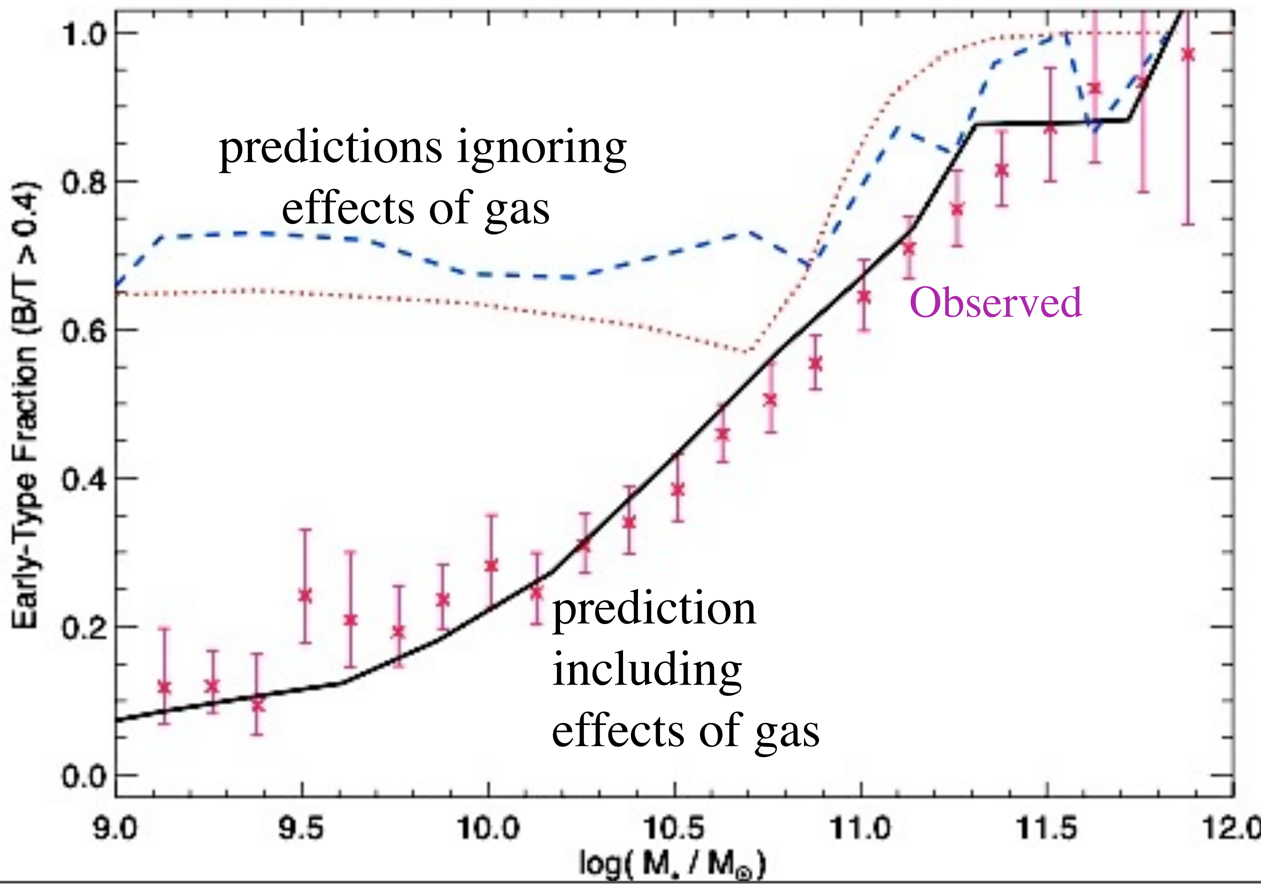
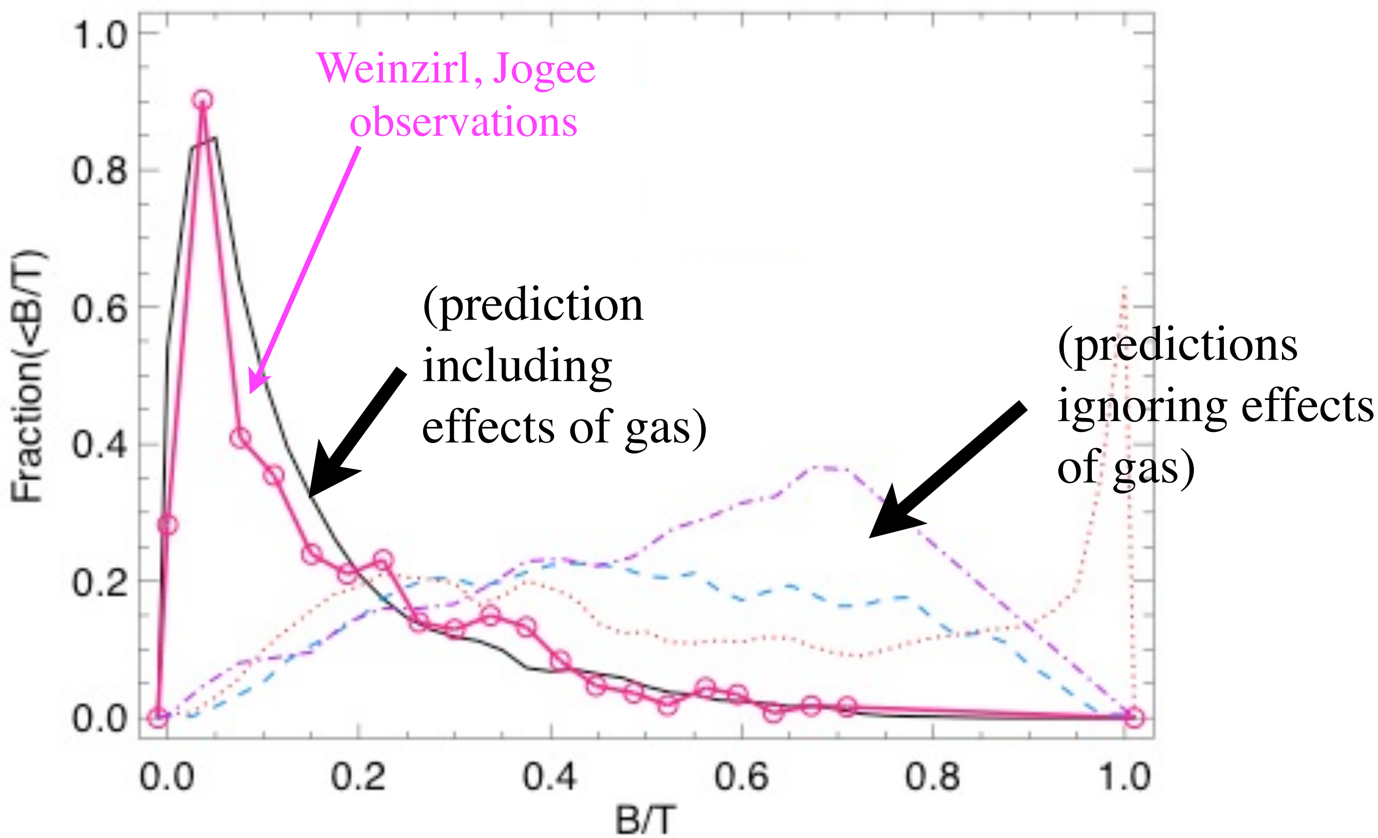


PFH & Somerville et al. 2009

Why Do We Care?
HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

- Mergers don’t bring most mass into disks, but can remove it
- Morphology Mass Relation:
  - Emerges naturally *if* low-mass galaxies keep more gas around

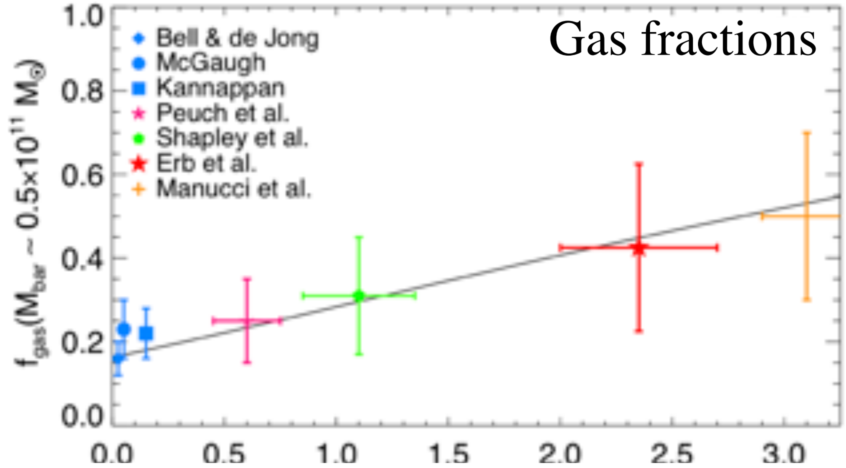


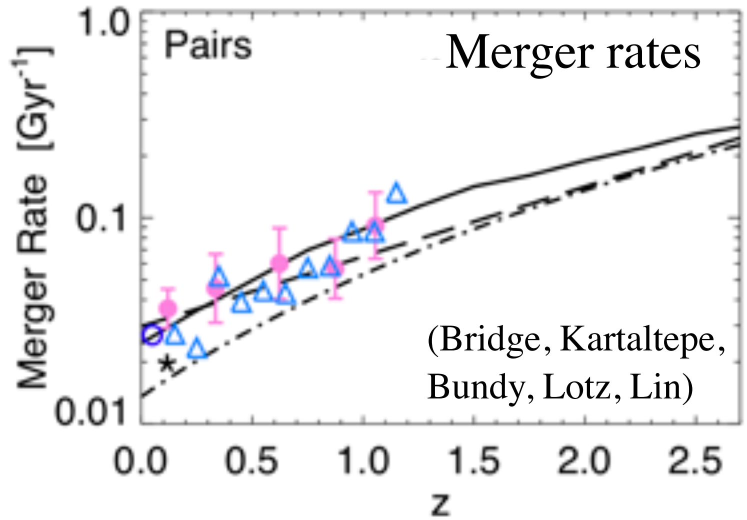
PFH & Somerville et al. 2009

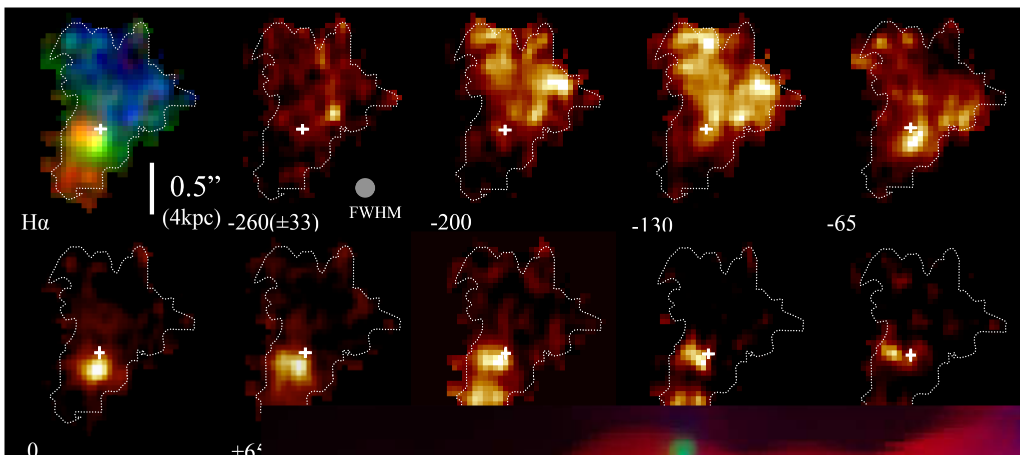
High-Redshift:
WILL ONLY INCREASE IN IMPORTANCE

Need to explain high-z massive disks
- We see them
- (Genzel, Tacconi, Erb, Law, et al.)

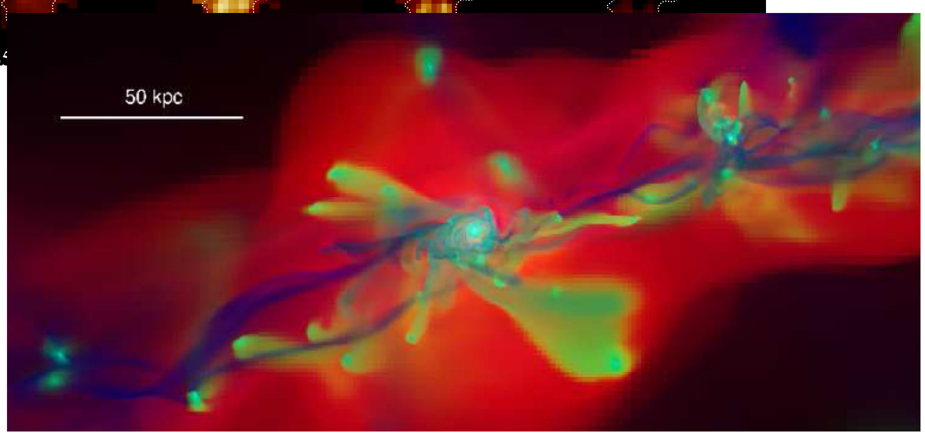
May explain some properties (turbulence etc.)
- (Robertson & Bullock, 2009)



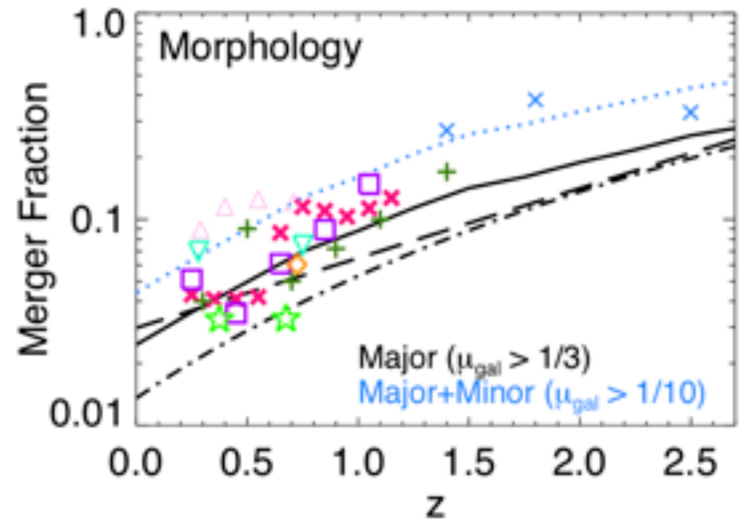




Genzel et al.



Keres, Dekel. Moore



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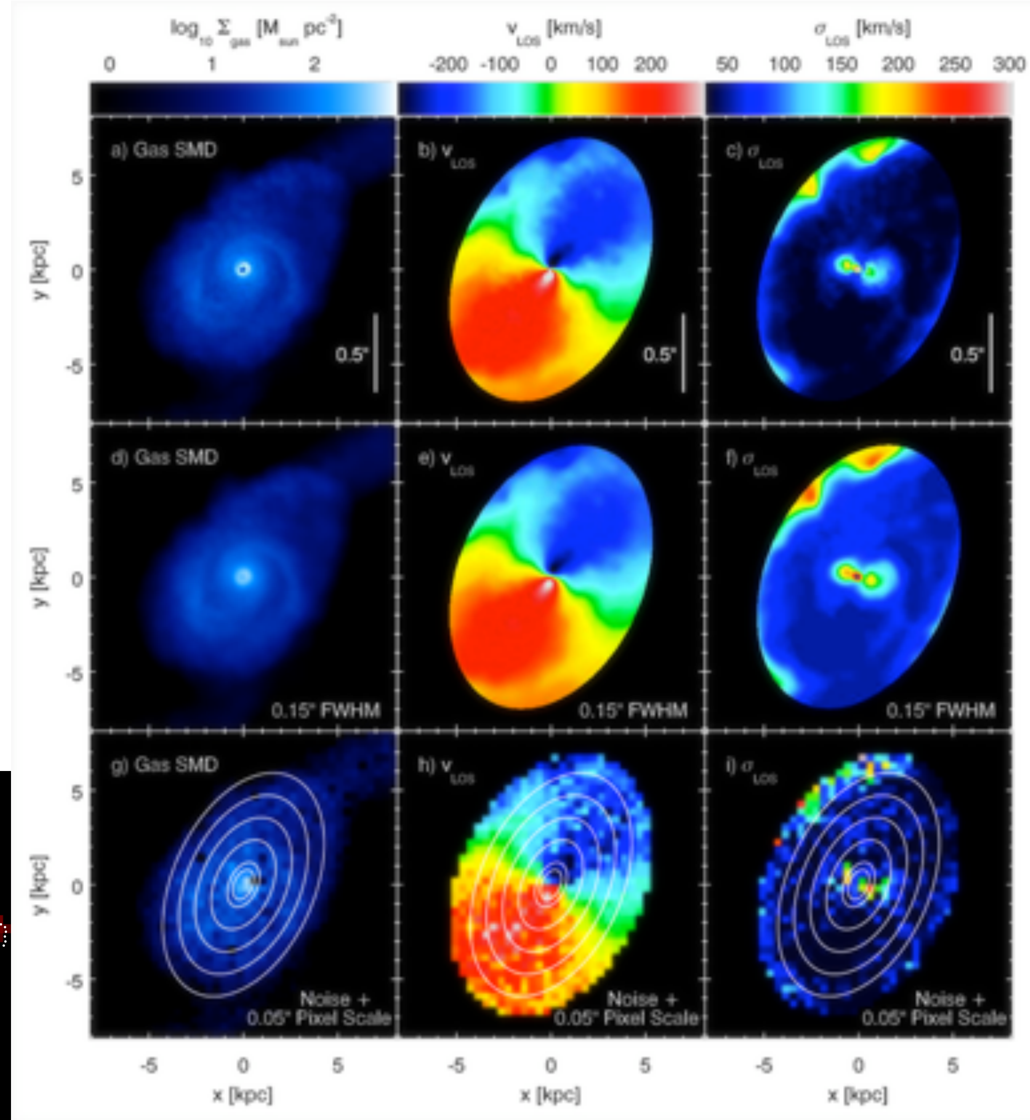
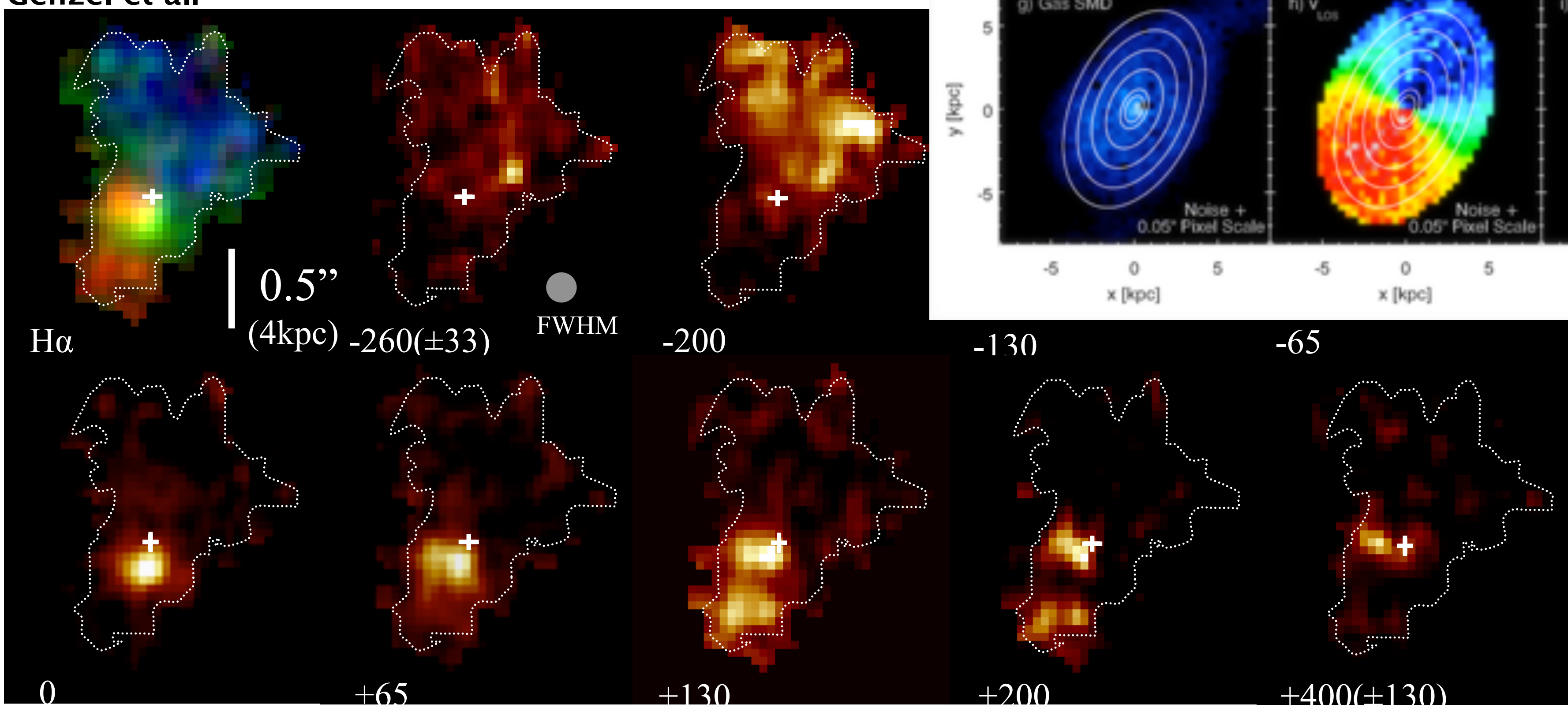


Robertson & Bullock 2008

Genzel et al.



What About Disk Heating?

WON'T YOU OVER-PRODUCE THE THICK DISK?

- Toth & Ostriker (1992): Rigid satellite in static potential, decay by dynamical friction on circular orbit:

$$\text{Heating :} \quad \frac{\Delta H}{R} \propto \frac{M_2}{M_1}$$

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- Toth & Ostriker (1992): Rigid satellite in static potential, decay by dynamical friction on circular orbit:

Heating : $$\frac{\Delta H}{R} \propto \frac{M_2}{M_1}$$

- Satellite mass functions: $$\frac{dN}{dlog(M_2/M_1)} \propto \left(\frac{M_2}{M_1}\right)^{-1}$$

Equal contributions to thick disk from all intervals in M_2/M_1!

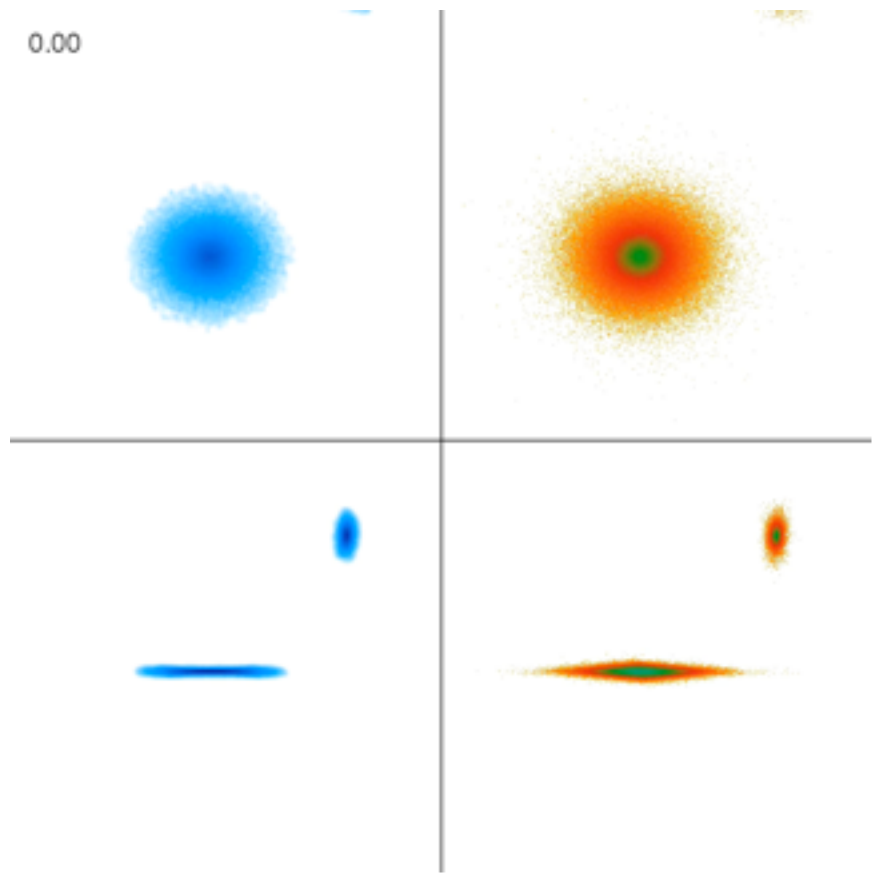
- No more than ~10% MW growth from any mass ratios since z~1-2!

What About Disk Heating?
WON'T YOU OVER-PRODUCE THE THICK DISK?

- In fact, orbits are radial, satellites strip, potentials are live:

Gives: $$\frac{\Delta H}{R} \propto \left(\frac{M_2}{M_1}\right)^2$$

Younger et al.



Dubinski et al.

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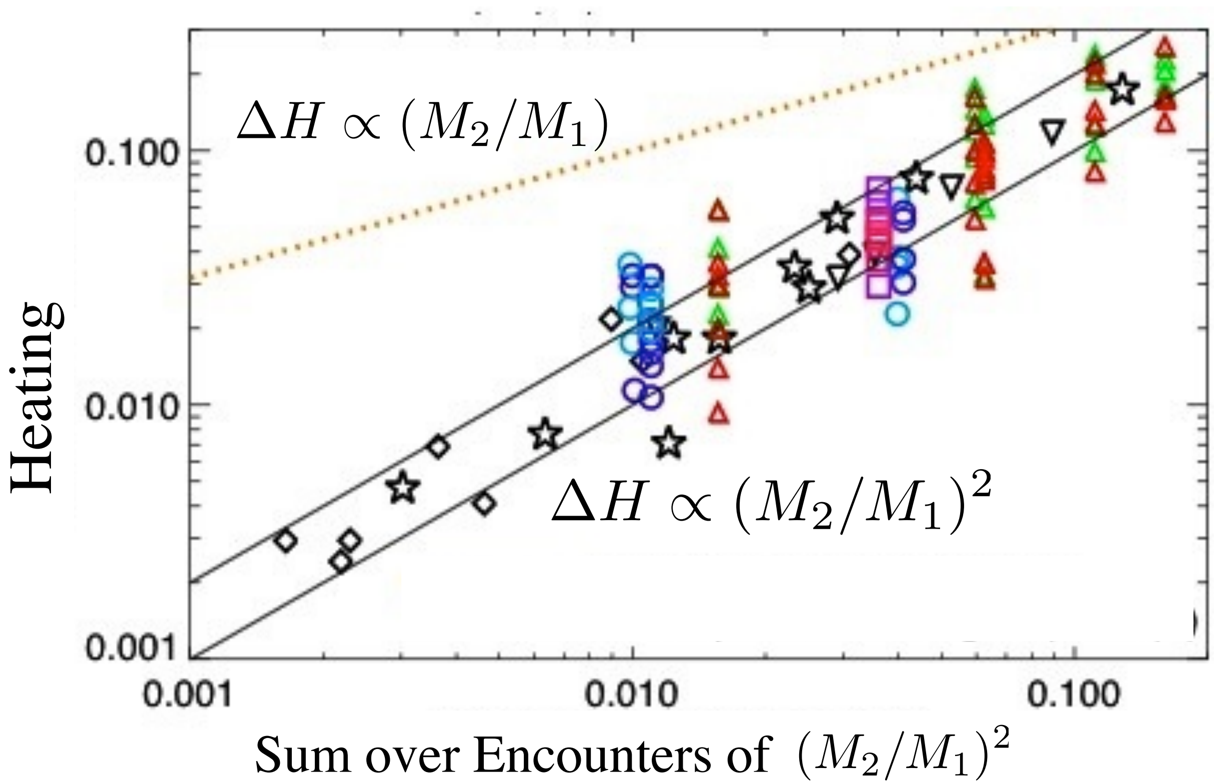

See in "live" simulations:
Velazquez & White,
Villalobos & Helmi

& with cosmological ICs:
Purcell et al.,
Kazantzidis et al.

What About Disk Heating?

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Gives: $$\frac{\Delta H}{R} \propto \left(\frac{M_2}{M_1}\right)^2$$

- Heating dominated by few big events
  - Super-thin disks can exist
  - More variation in thick disks

- Thick disk doesn't constrain total MW growth, does constrain the biggest event MW could have experienced

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 ($f_{gas} \sim 0.1 - 0.5$)
  - Explains compact z~2 sizes, and evolution to today?
- Relics of starbursts are important in today's Universe
  - They match the population of IR-luminous starbursts now being seen at high-z
- How do disks survive mergers? (How do we avoid making all ellipticals?)
  - Gas! No stars = No angular momentum loss
  - Particularly important at high-z: May see unique kinematic signatures
  - Drives the starburst history of the Universe, but not always as you'd expect
- Don't forget about black holes and AGN (a talk for another day...)