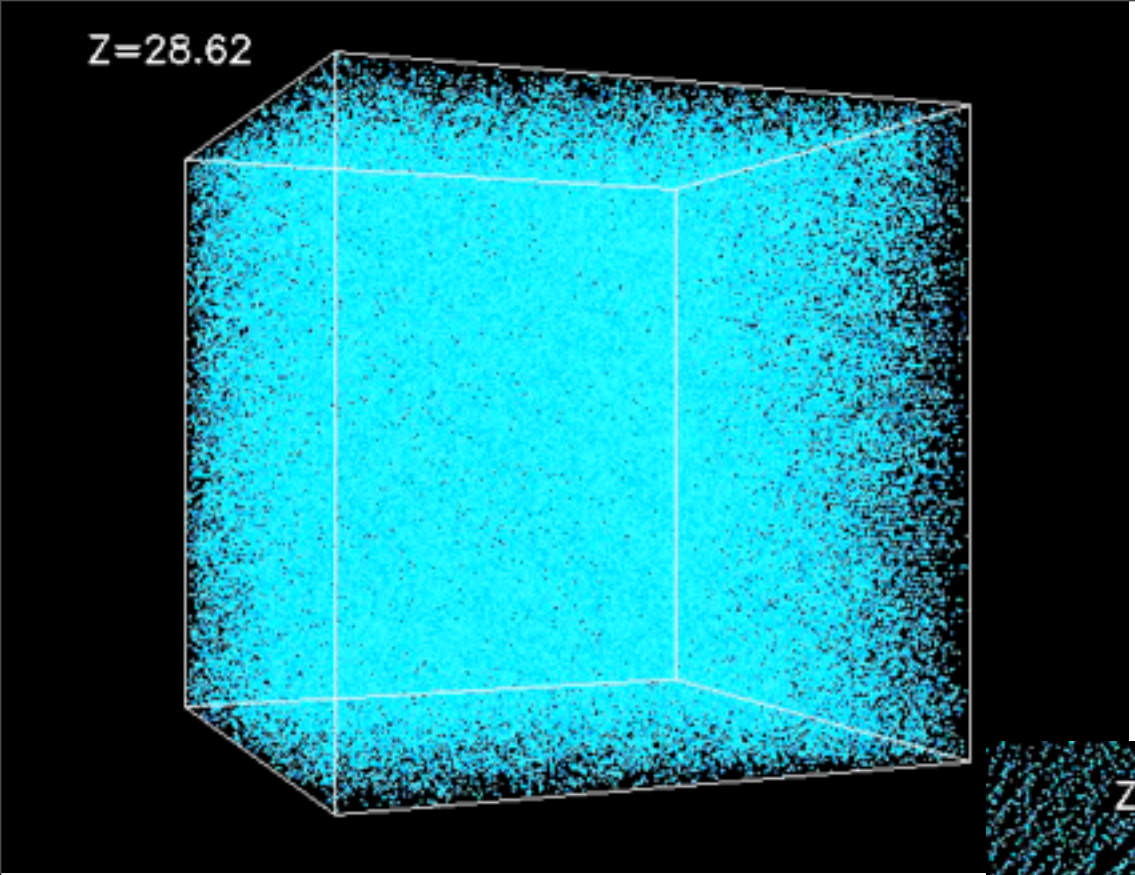
Gas in Galaxy Mergers: More Important than You Think

Philip Hopkins

09/24/09

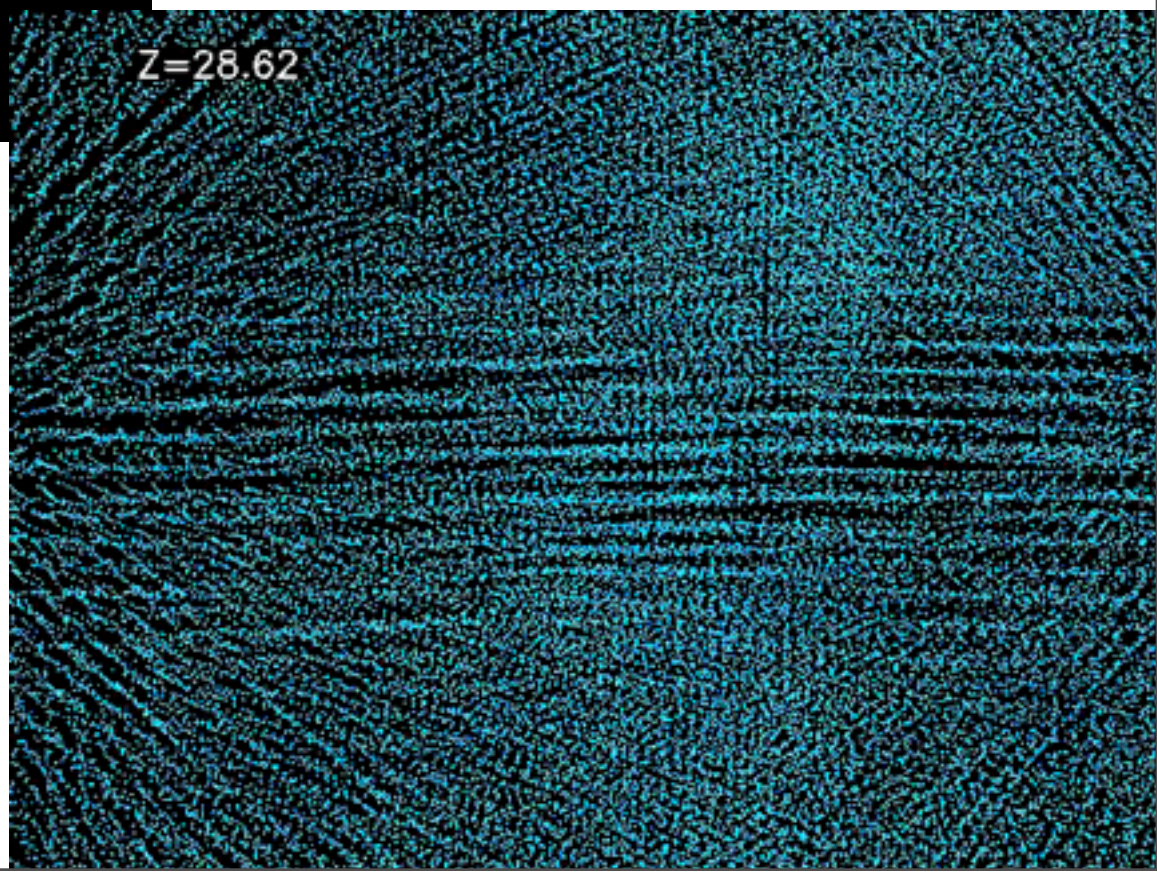
Lars Hernquist, T. J. Cox, Dusan Keres, Eliot Quataert, Chung-Pei Ma,
Josh Younger, Volker Springel, Norm Murray, Kevin Bundy,
Brant Robertson, John Kormendy, Tod Lauer, Adam Lidz, Tiziana Di Matteo,
Yuexing Li, Gordon Richards, Alison Coil, Adam Myers, and many more



Motivation

HOW DID WE GET TO GALAXIES TODAY?

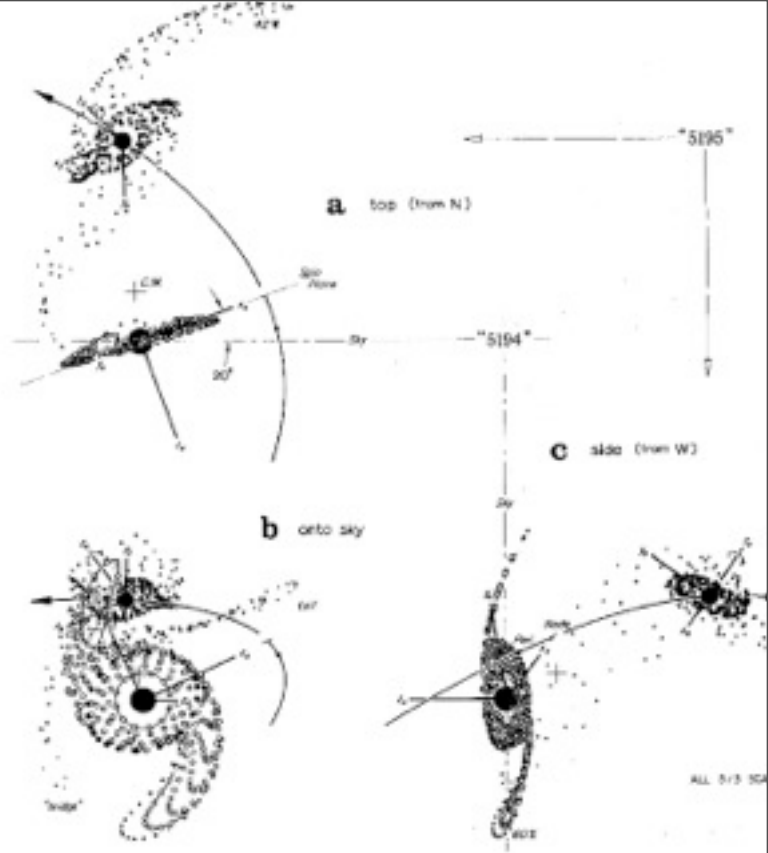
Kravtsov et al.



- Structure grows hierarchically:
  must understand mergers

(e.g. Navarro talk)

Our Conventional Wisdom (Toomre):

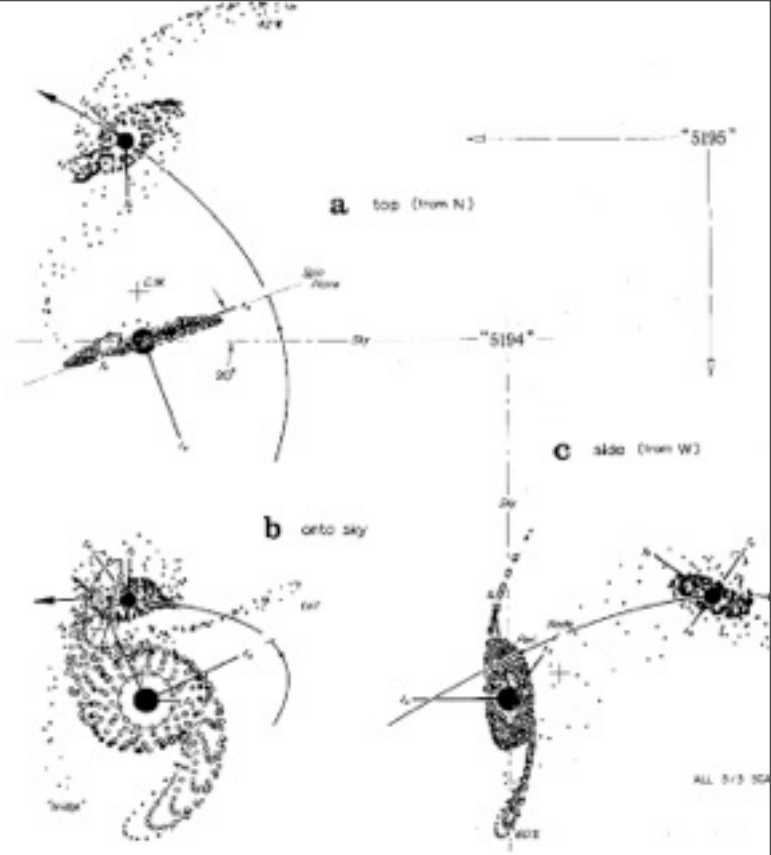


[redacted]

F. Summers

Our Conventional Wisdom (Toomre):

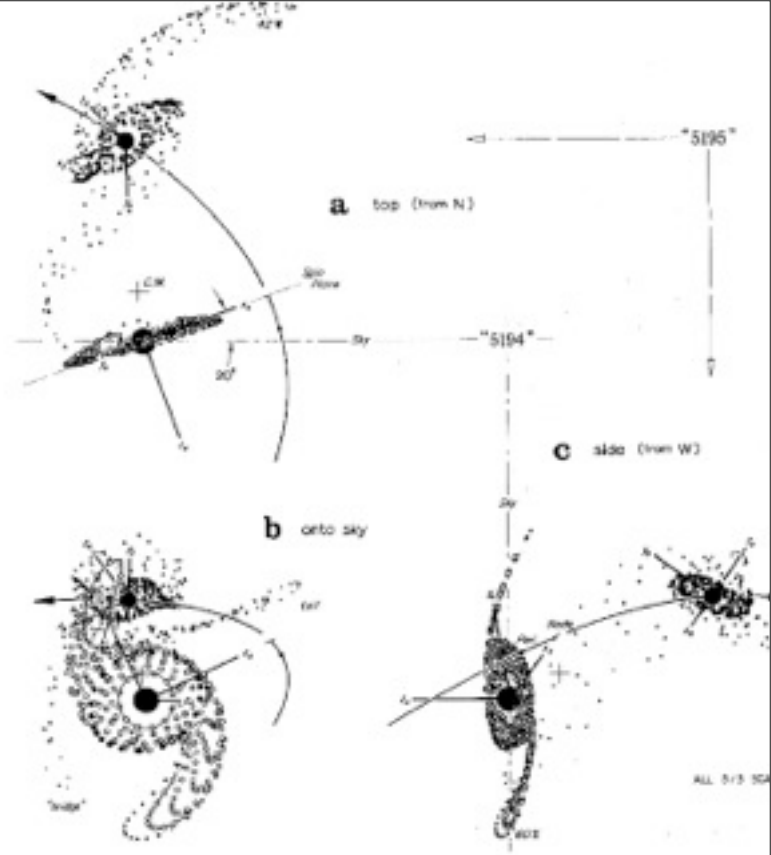
- Major mergers destroy disks



F. Summers

Our Conventional Wisdom (Toomre):

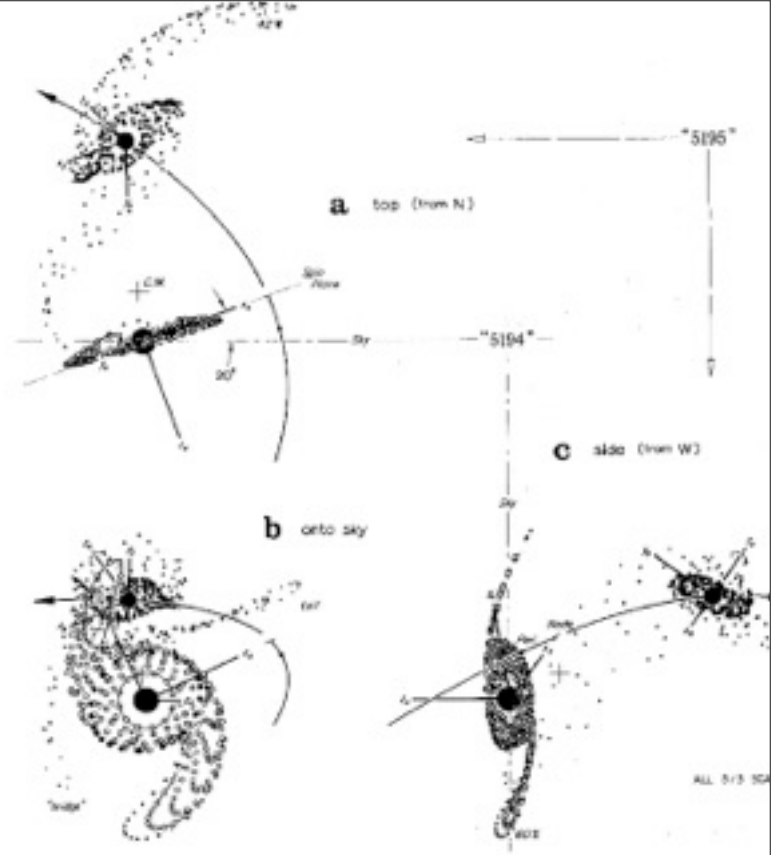
- Major mergers destroy disks
- Minor mergers make thick disk



F. Summers

Our Conventional Wisdom (Toomre):

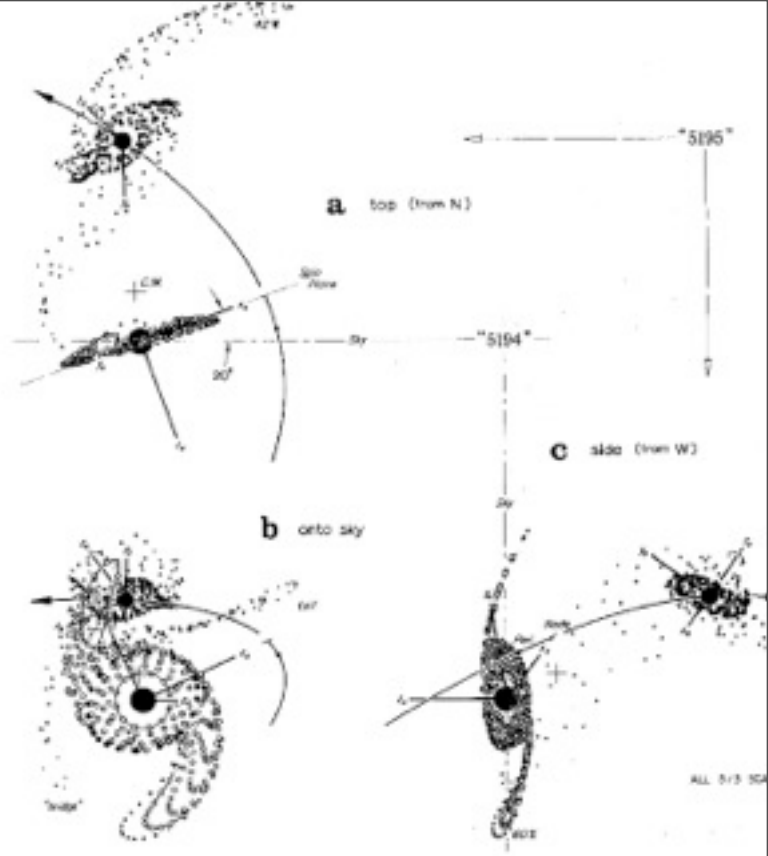
- Major mergers destroy disks
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile



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

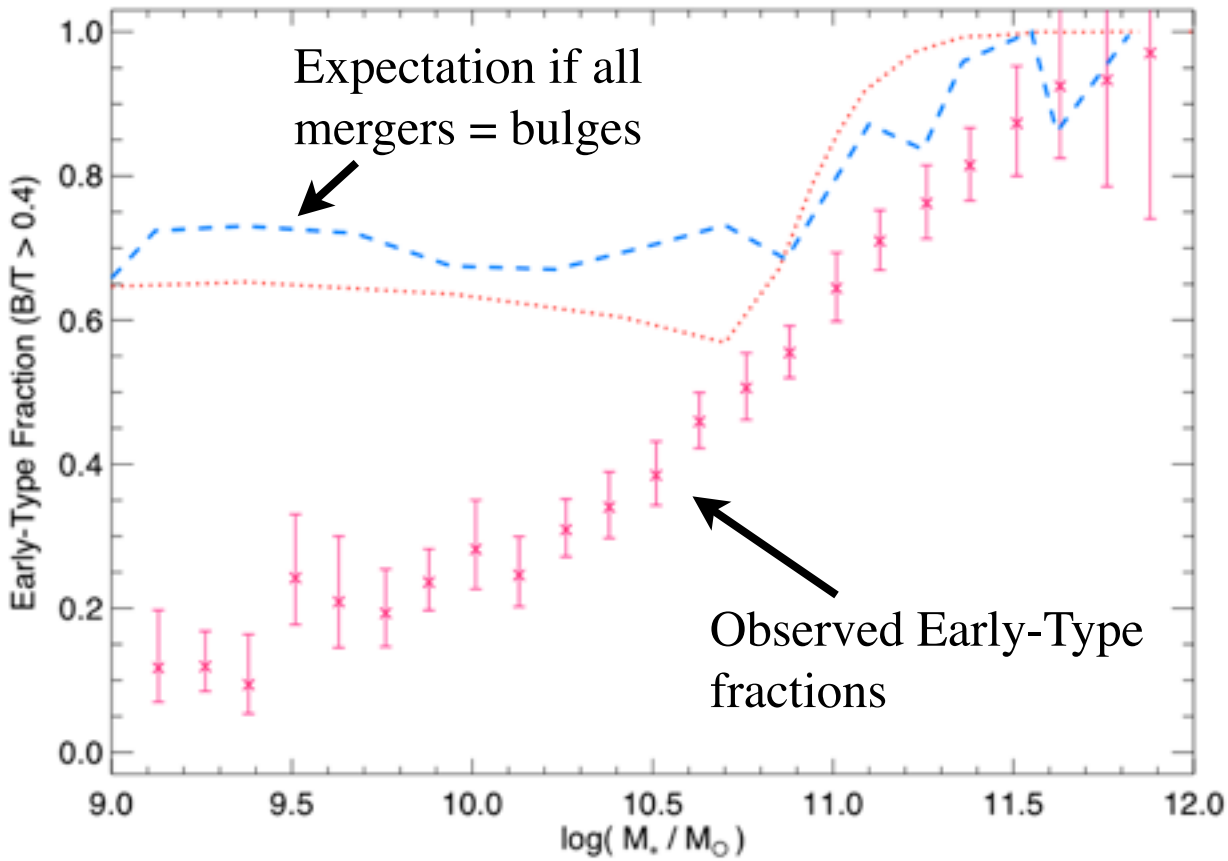
Motivation

HOW DID WE GET TO GALAXIES TODAY?

Many of these are *problems*...

Too Many Mergers?

-- missing some physics (see A. Brooks talk)

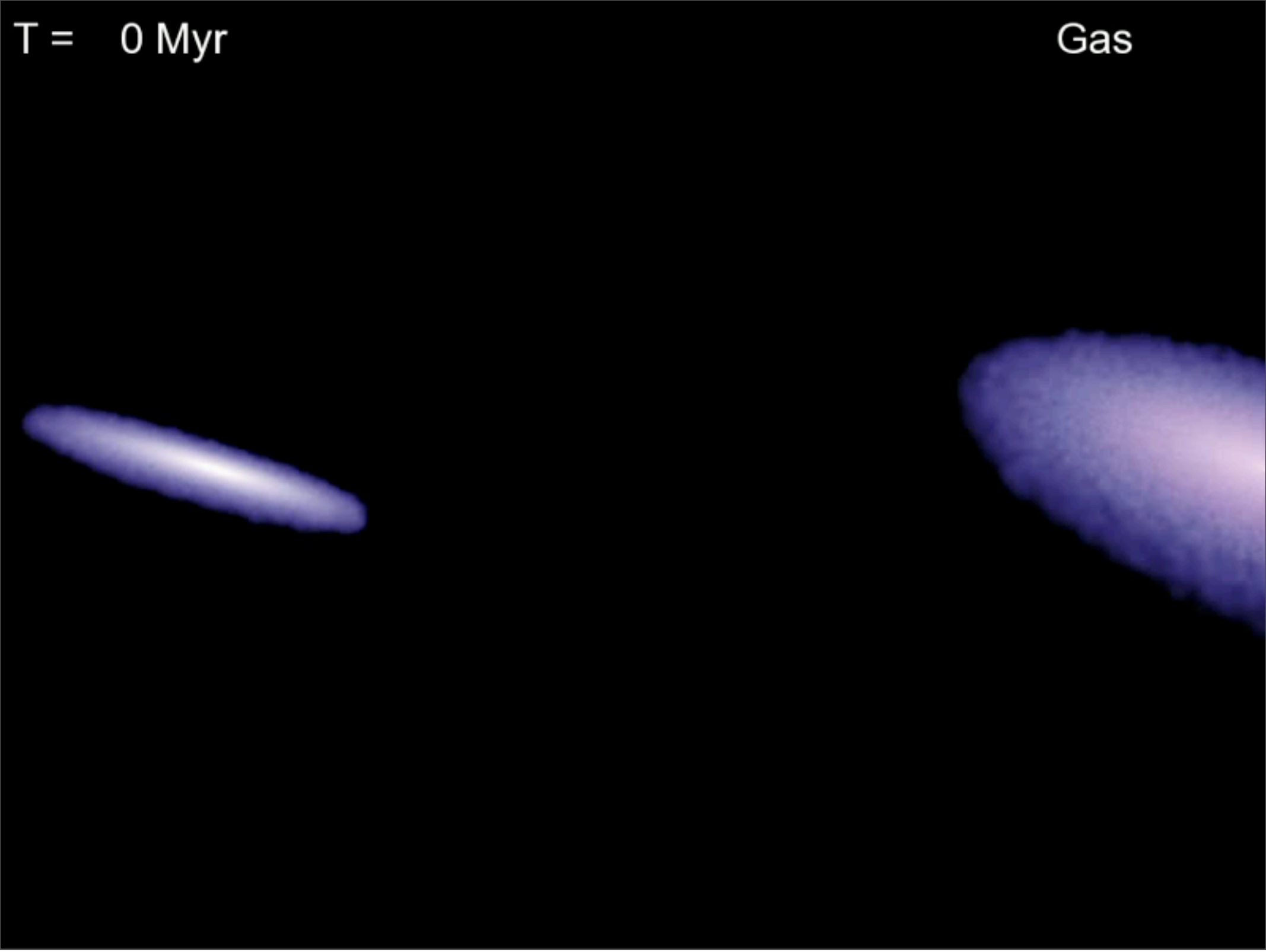


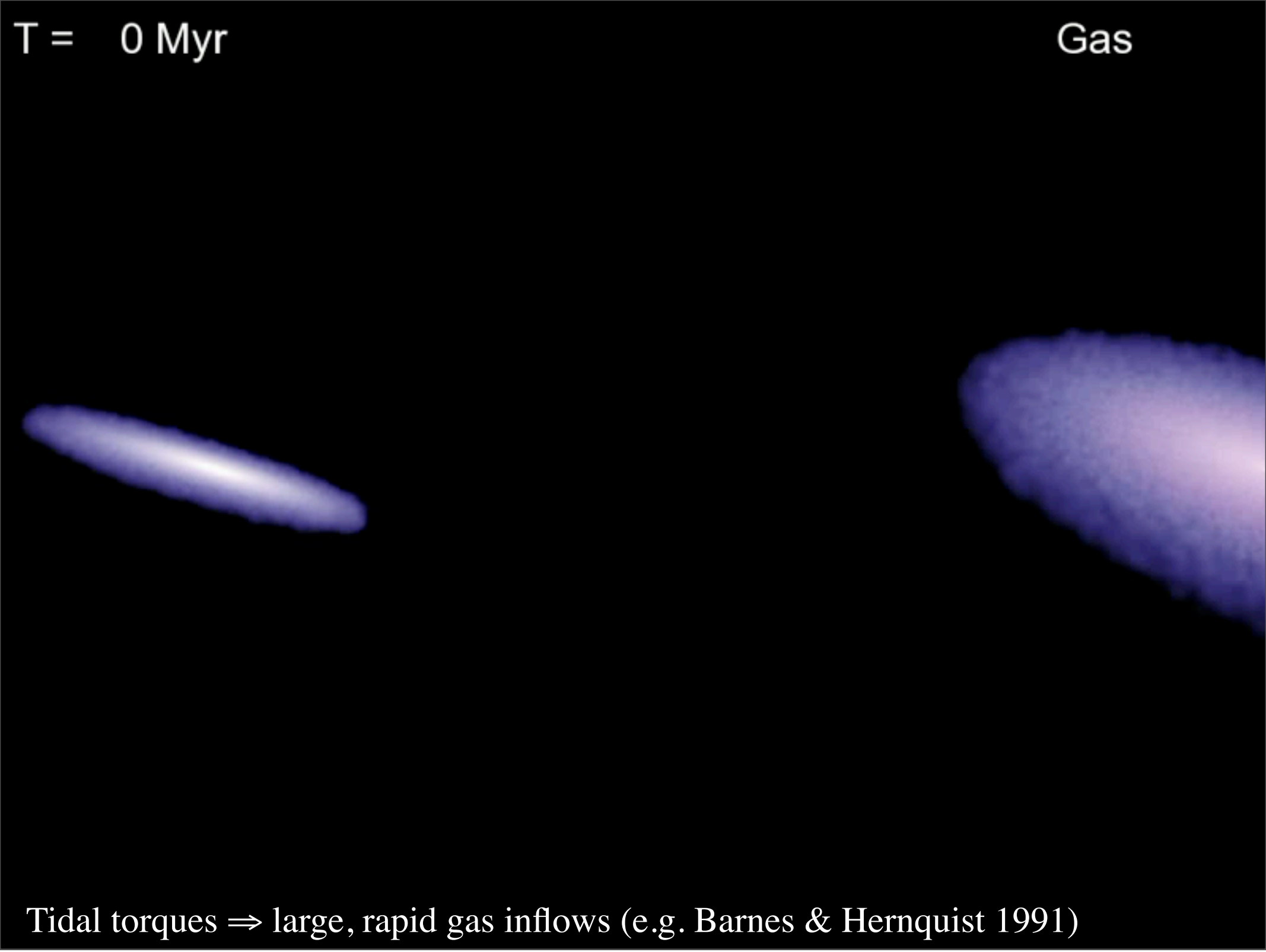
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

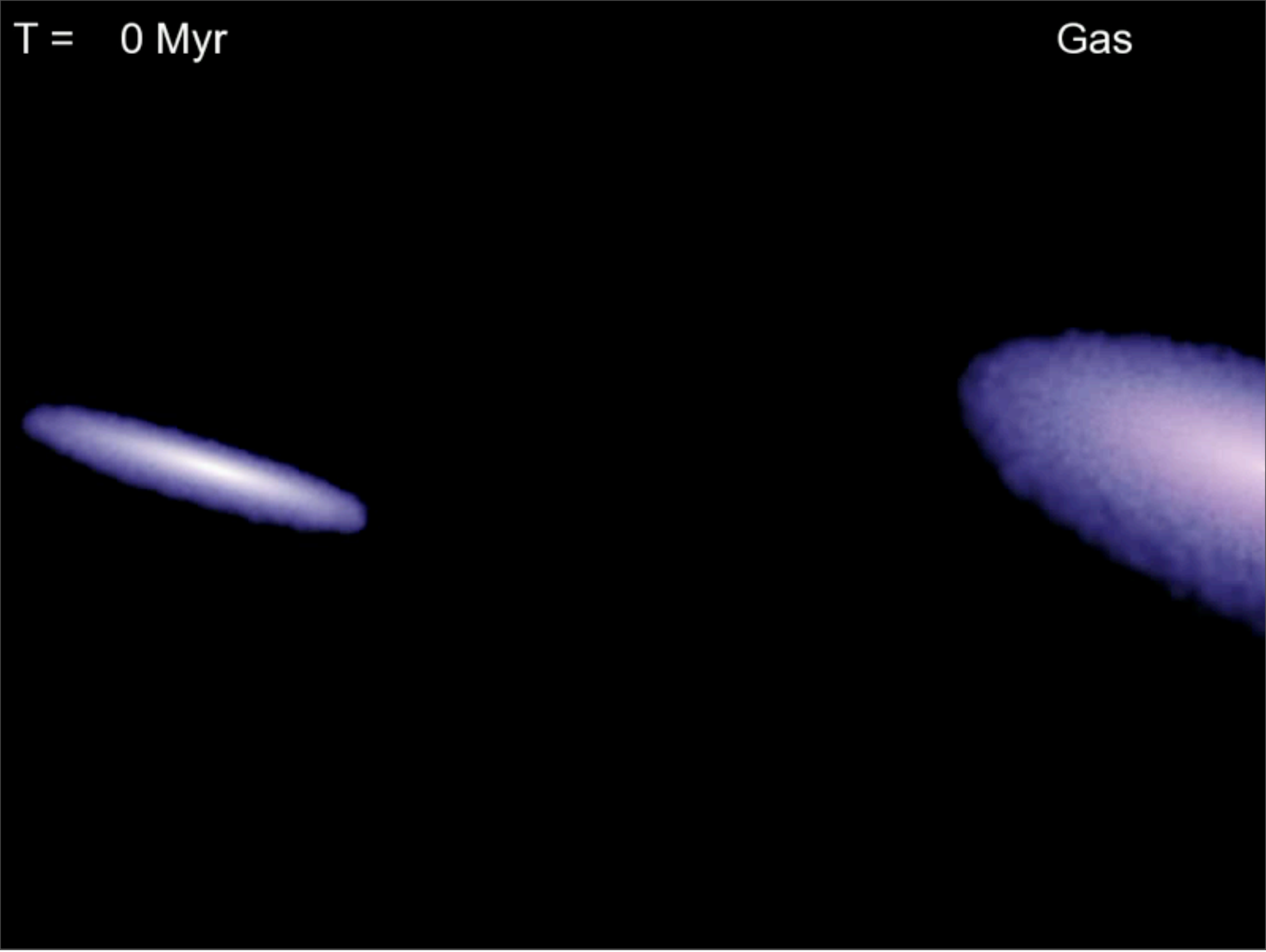
-- profiles too flat

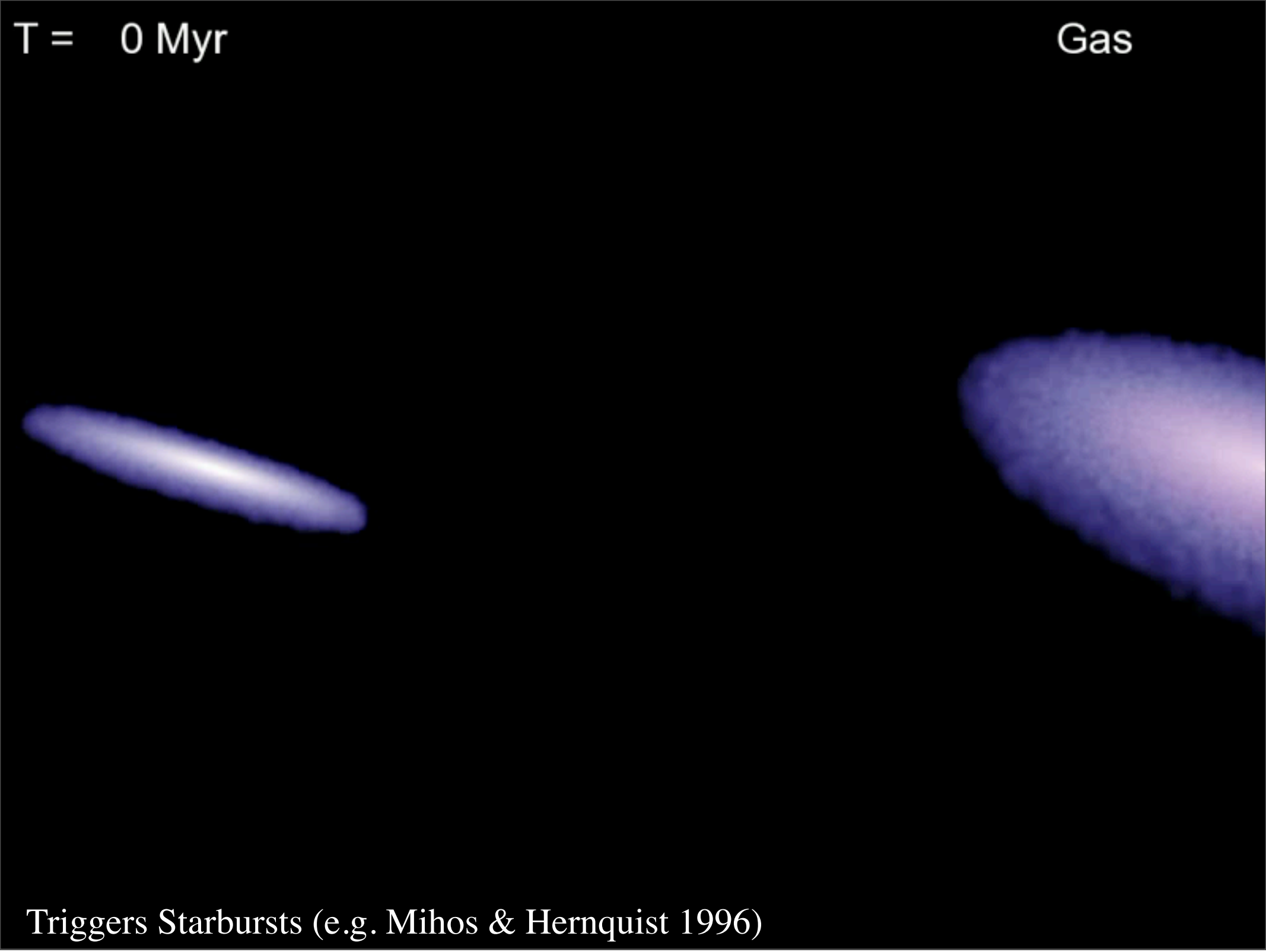
-- shapes too flattened


T = 0 Myr
Gas

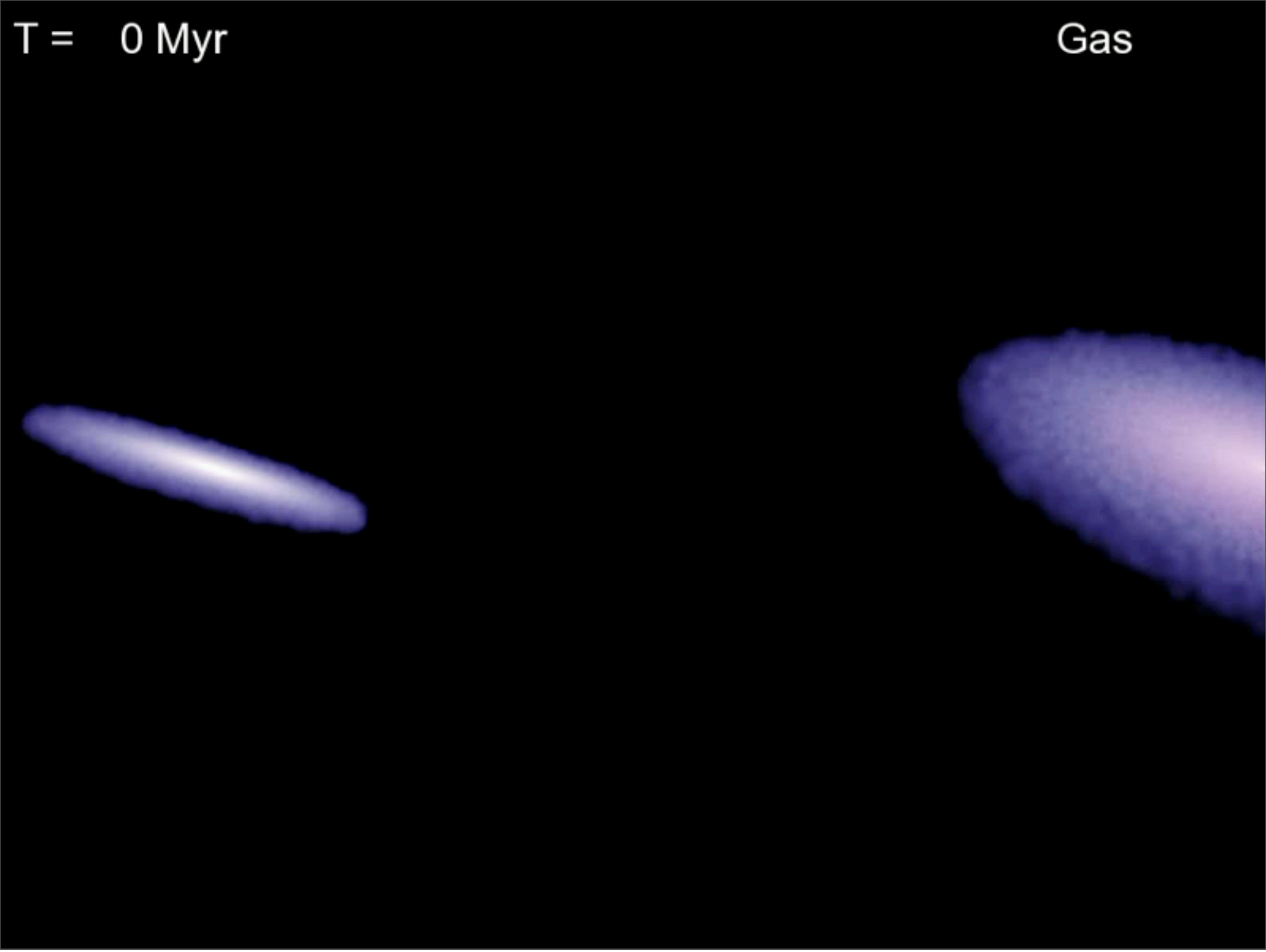


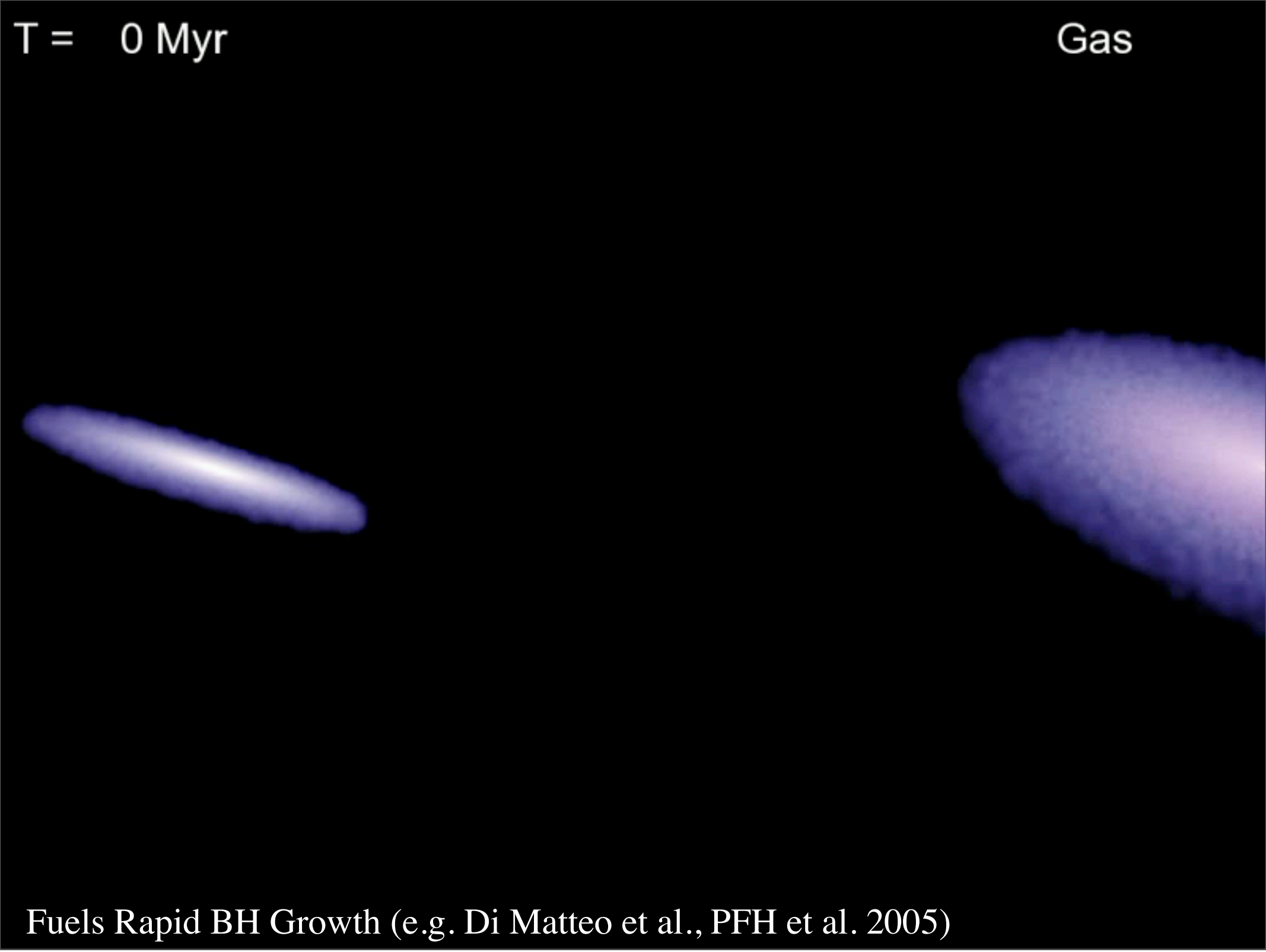
Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)


T = 0 Myr
Gas

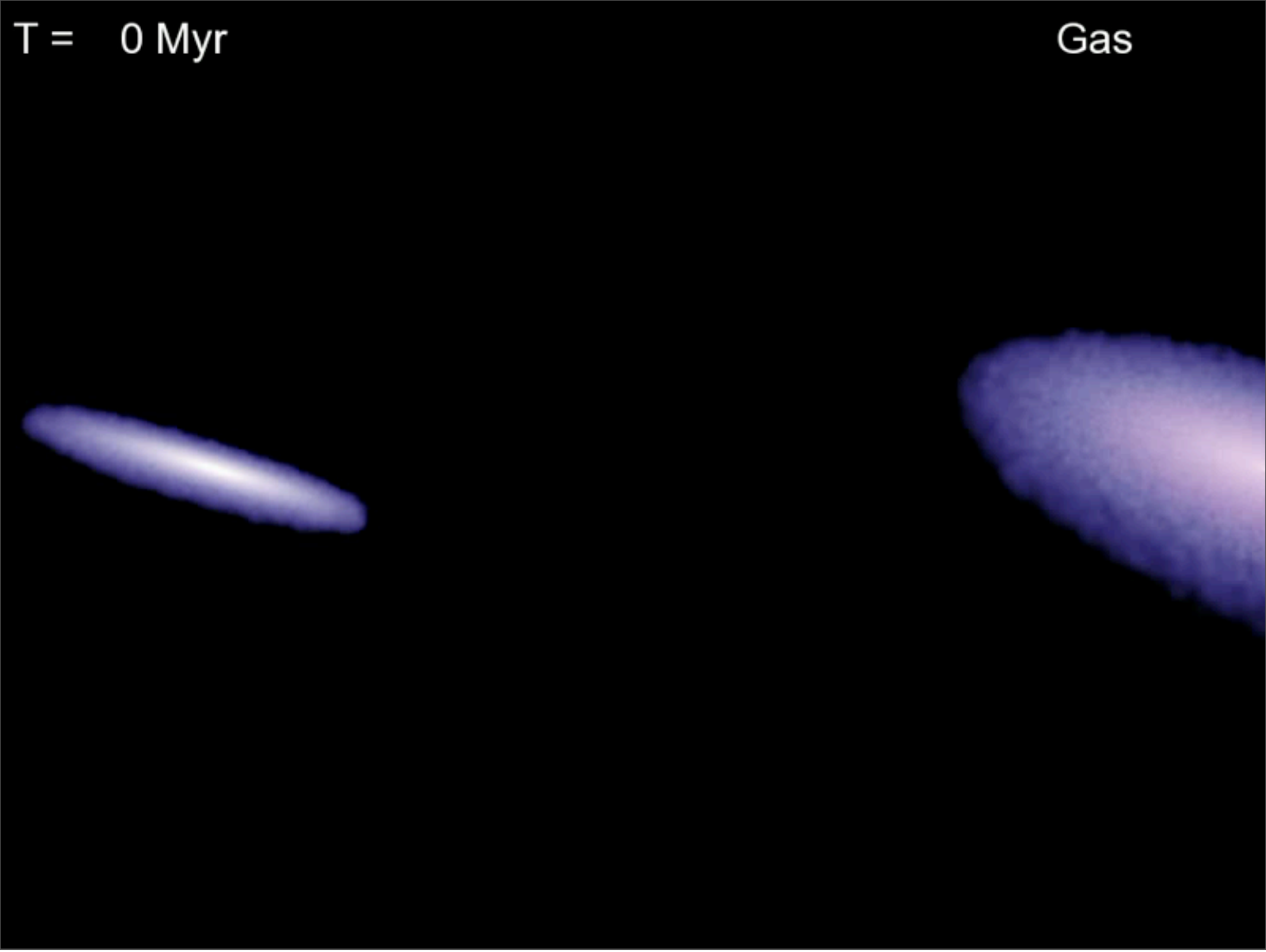


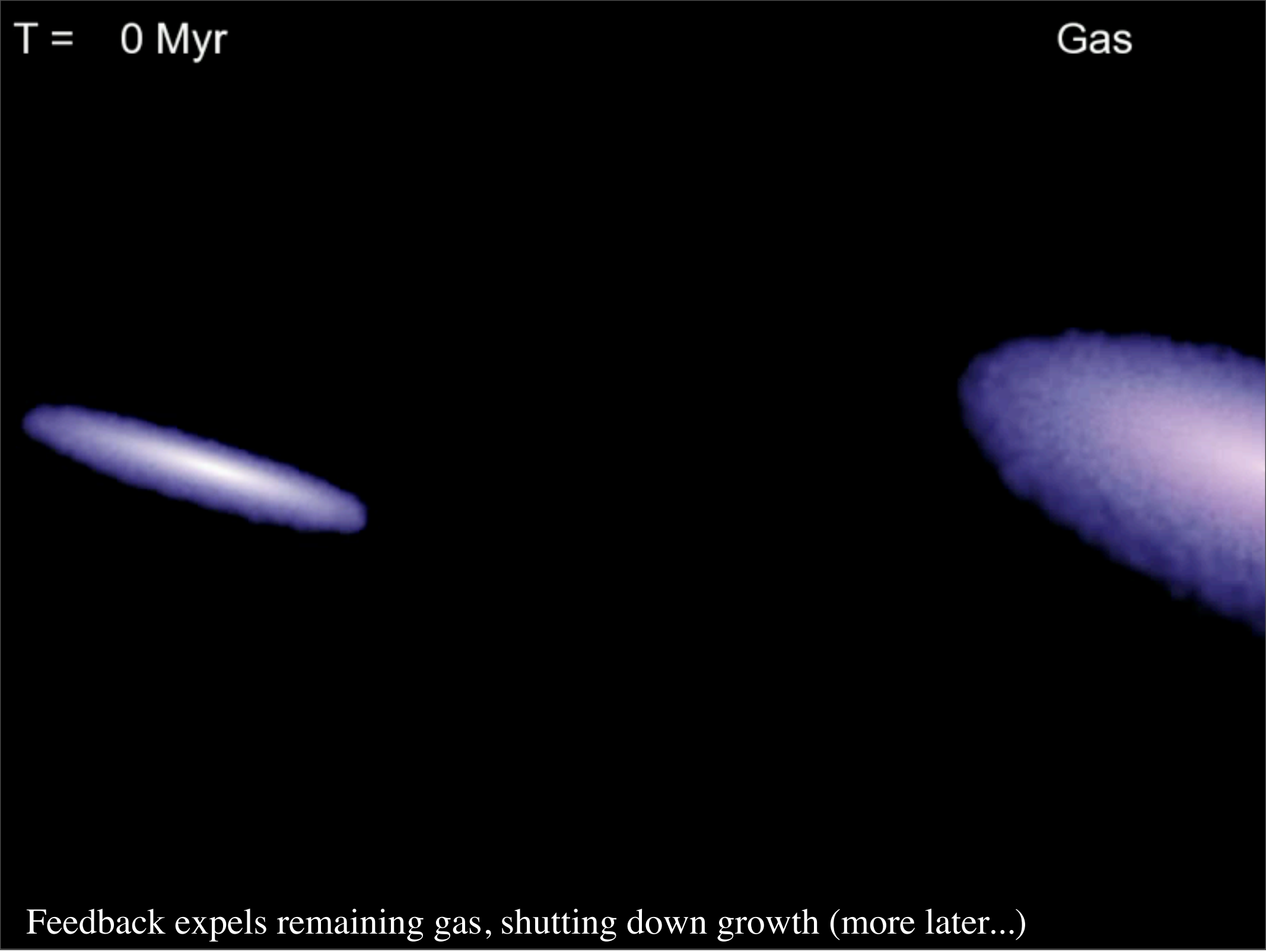
Triggers Starbursts (e.g. Mihos & Hernquist 1996)


T = 0 Myr
Gas

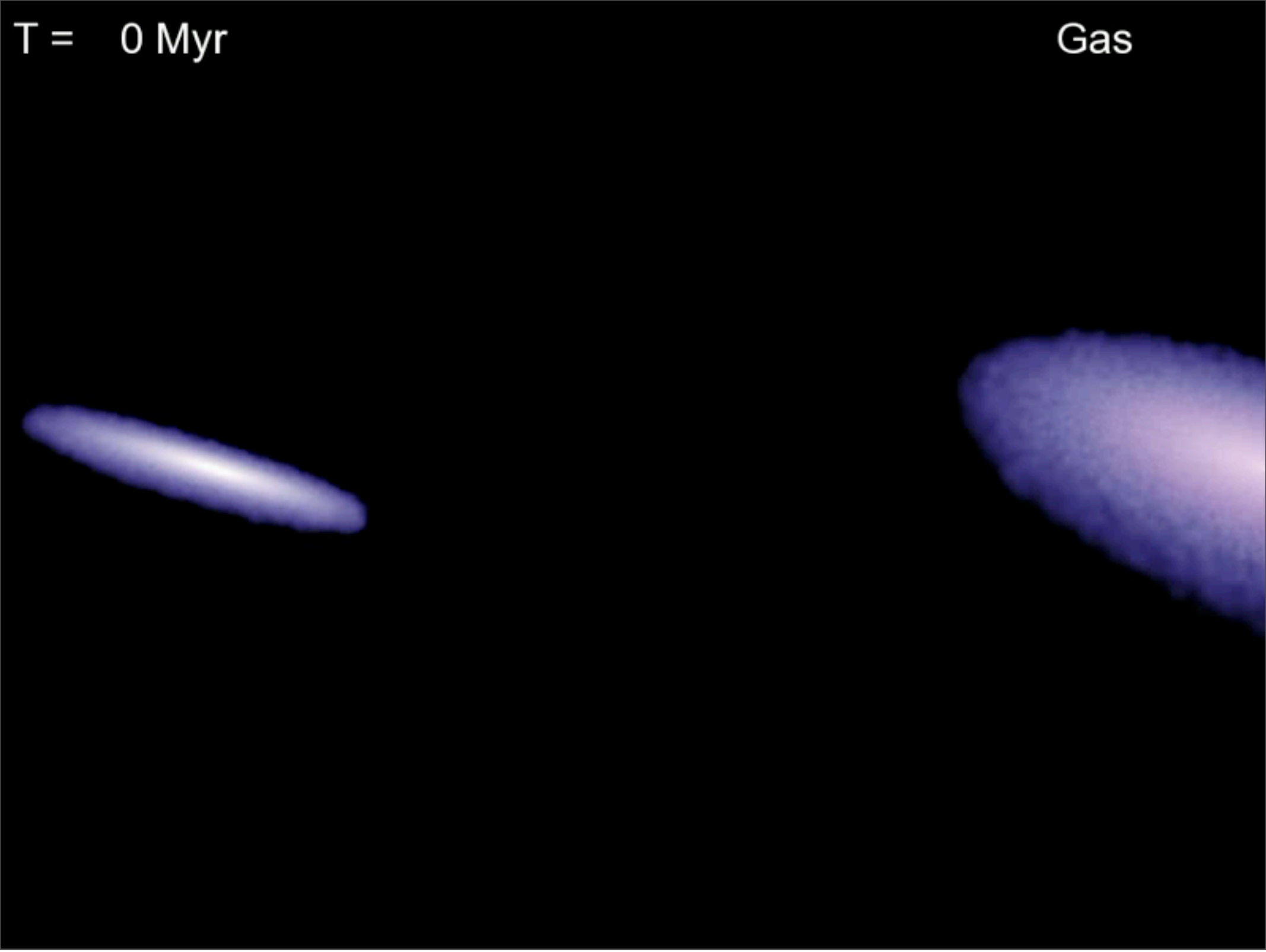


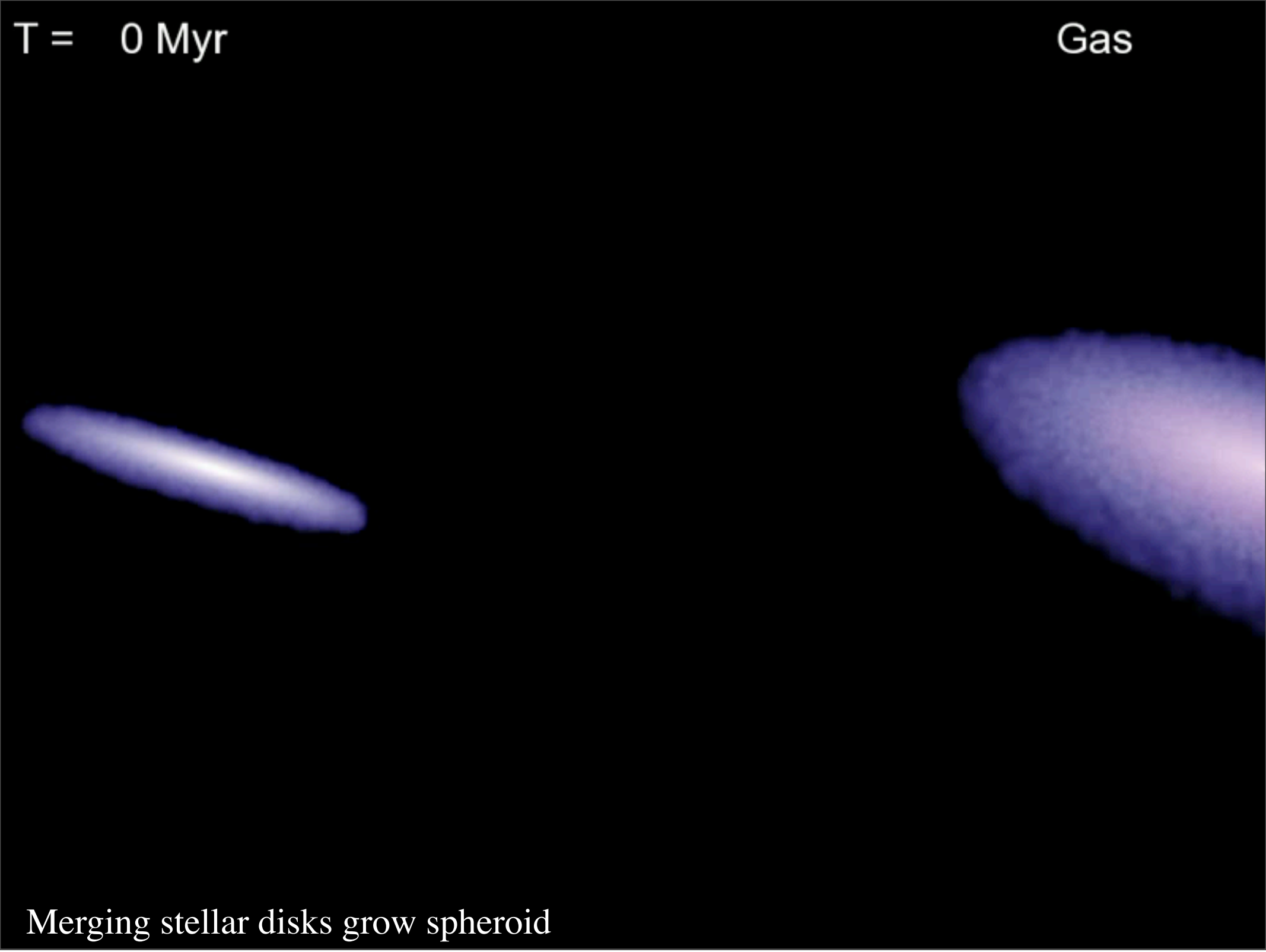
Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)


T = 0 Myr
Gas

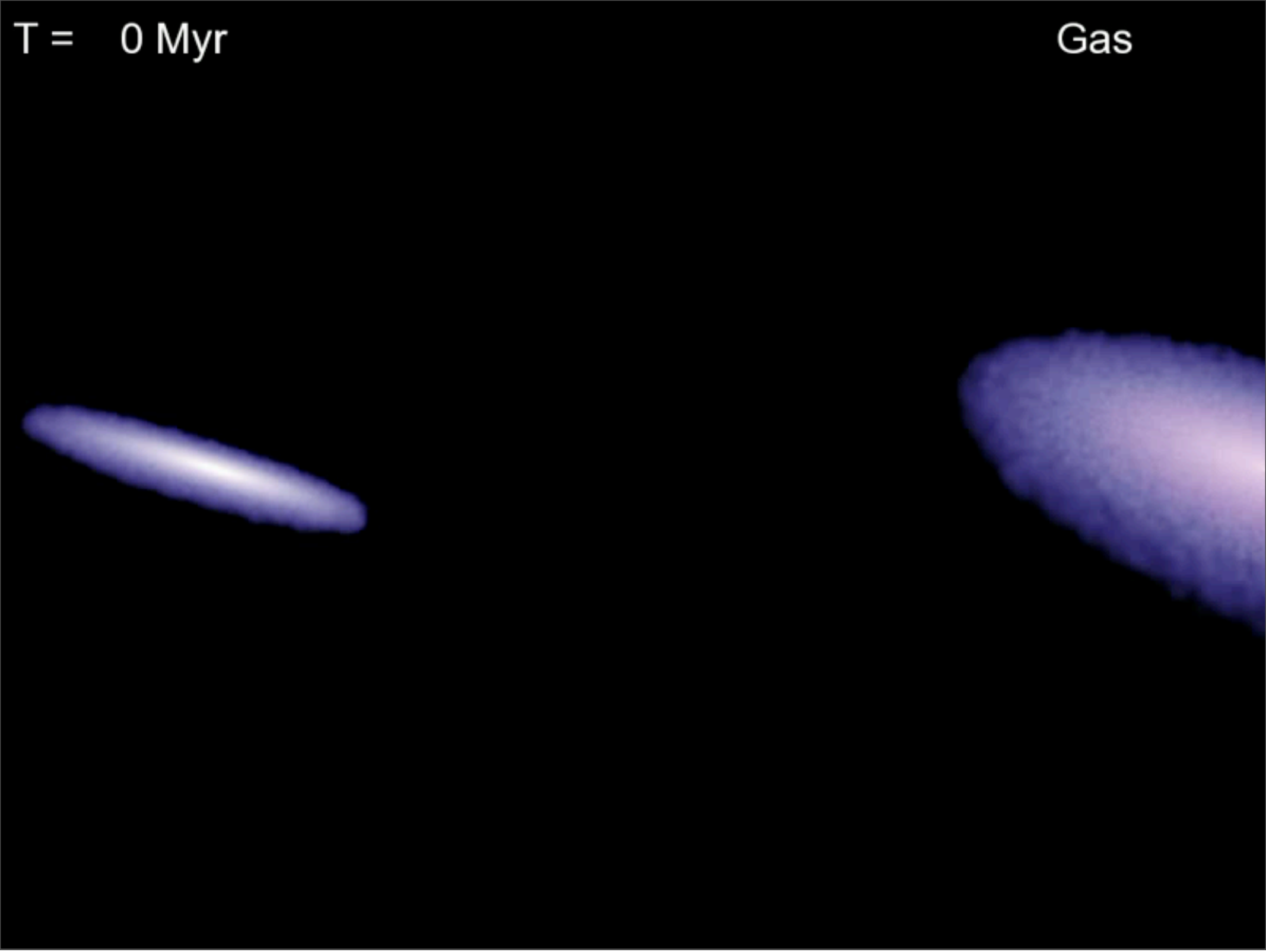


Feedback expels remaining gas, shutting down growth (more later...)


T = 0 Myr
Gas



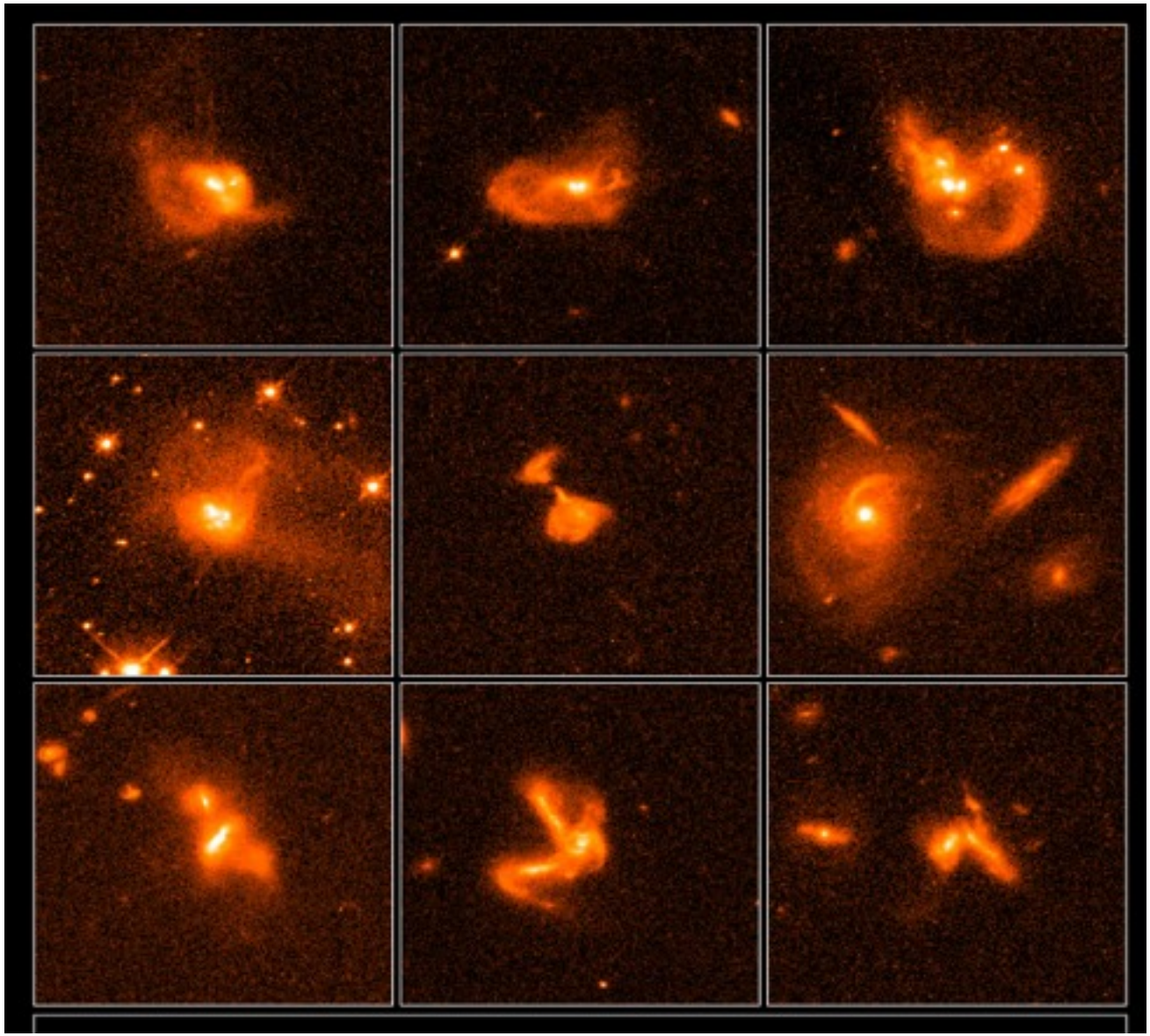
Merging stellar disks grow spheroid


T = 0 Myr
Gas

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)

Are they the progenitors of ellipticals?

What About the Gas that Does Lose Angular Momentum?

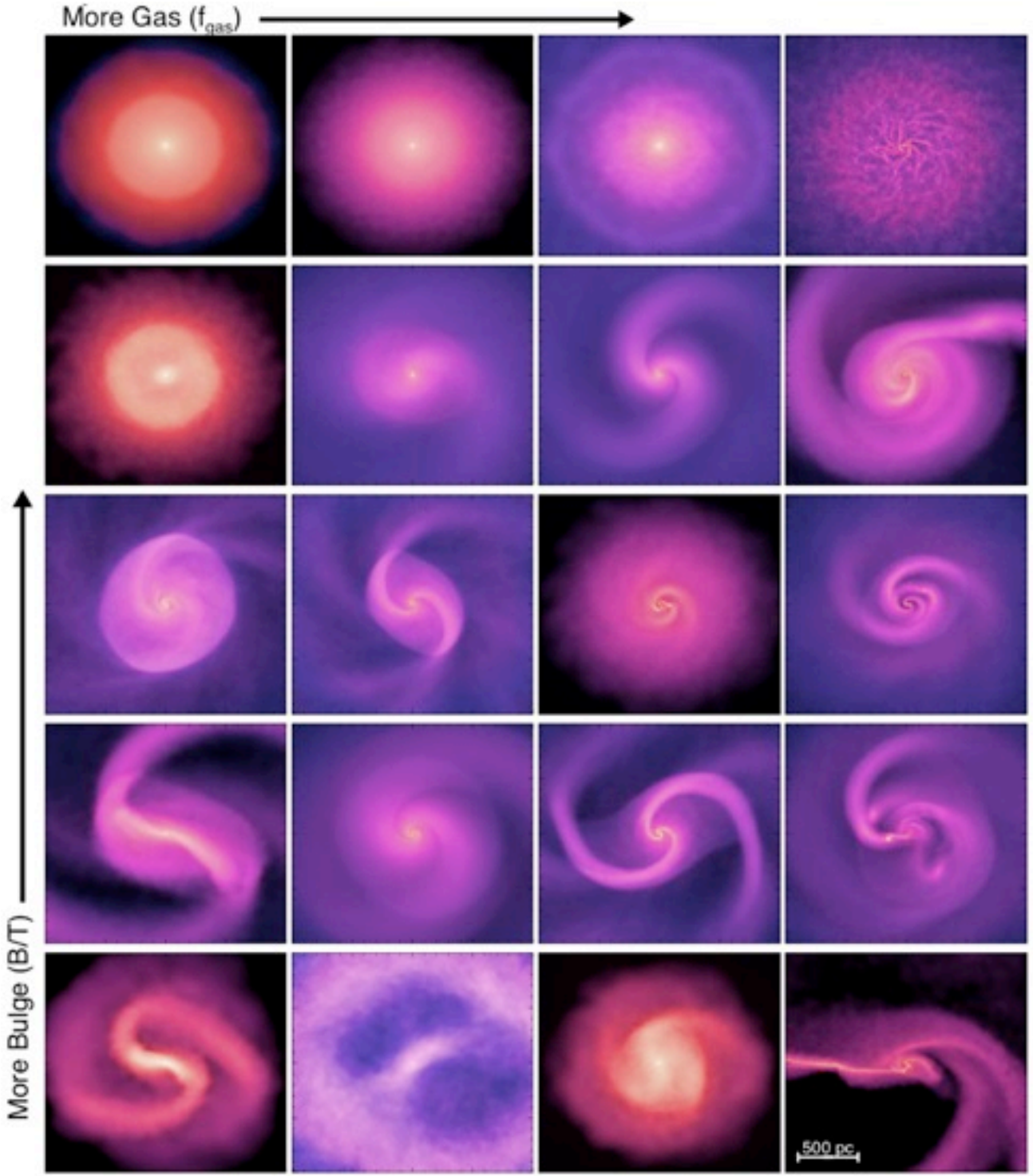
CAN WE MAKE A REAL ELLIPTICAL?

Funneled to the center
=> massive starbursts

Look at late-stage
merger remnants

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

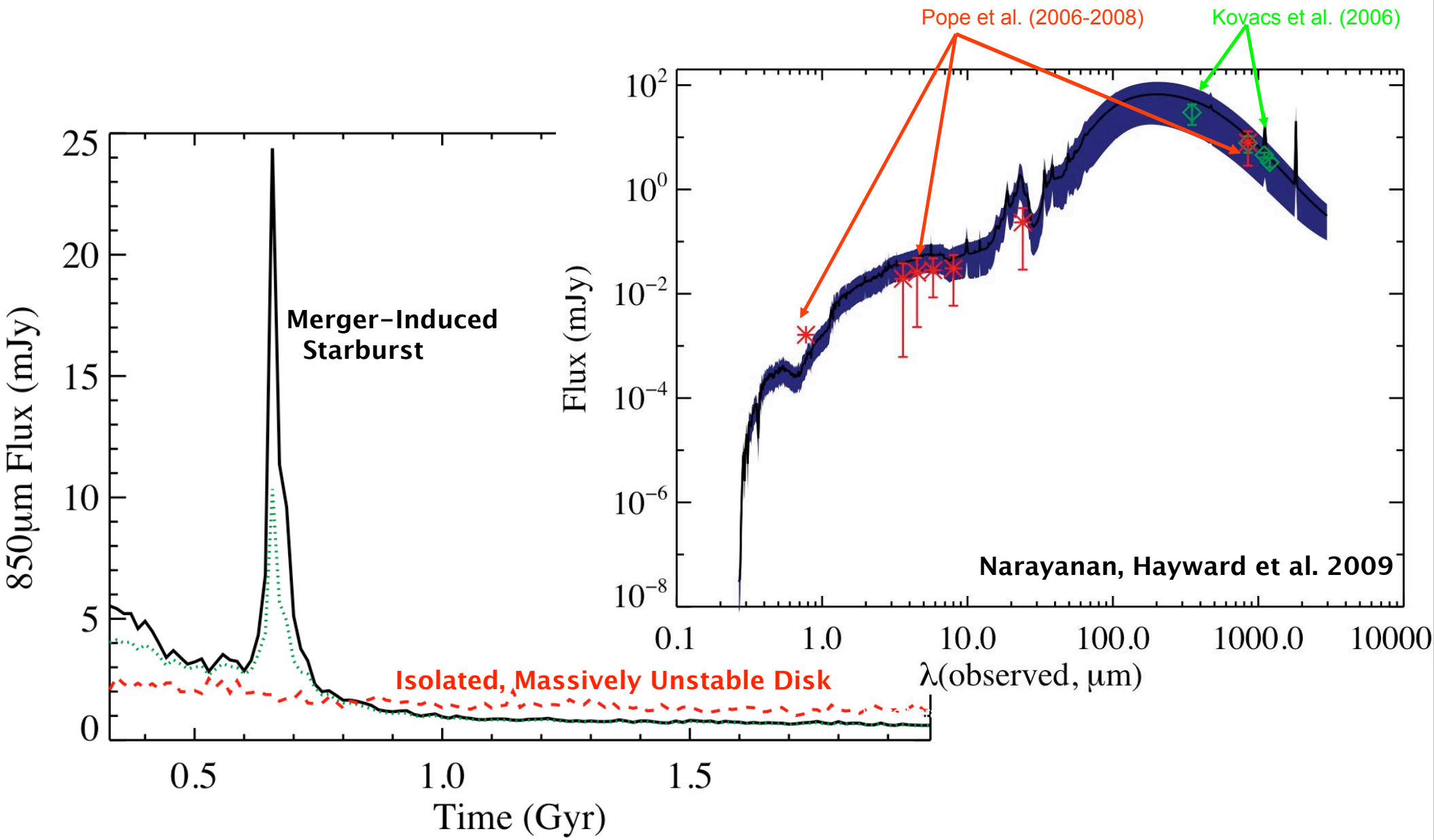
Compact (<kpc scales)



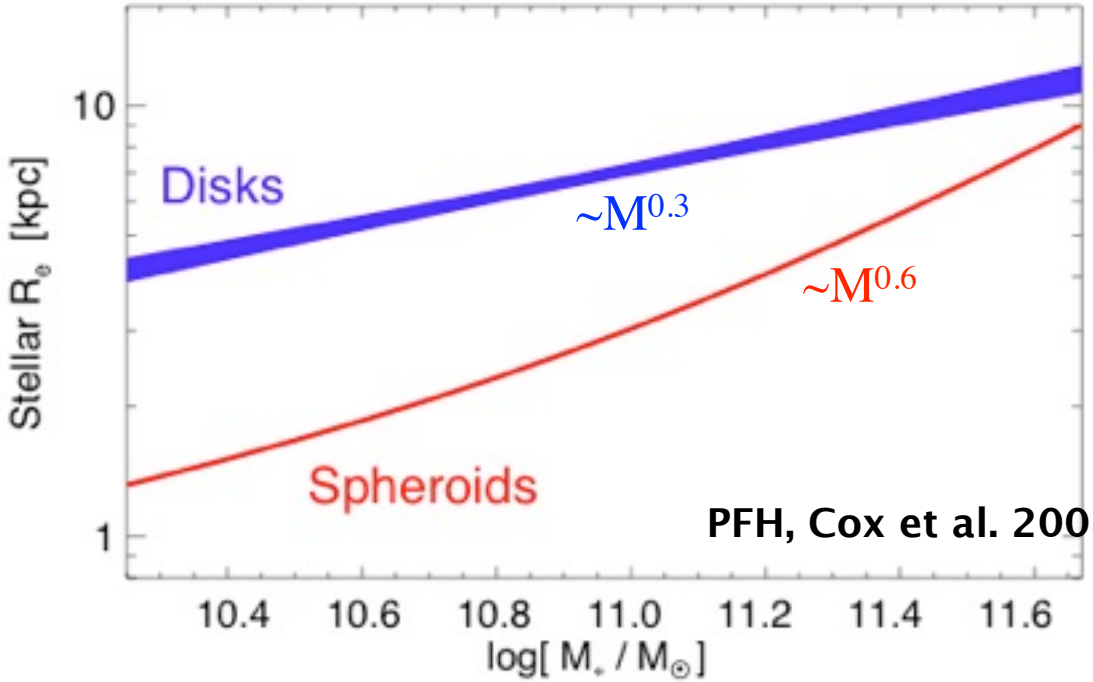
What About the Gas that Does Lose Angular Momentum?

STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

- Not just at z=0, but in high-redshift sub-millimeter galaxies (e.g. Shapiro, Melbourne, Narayanan talks...)

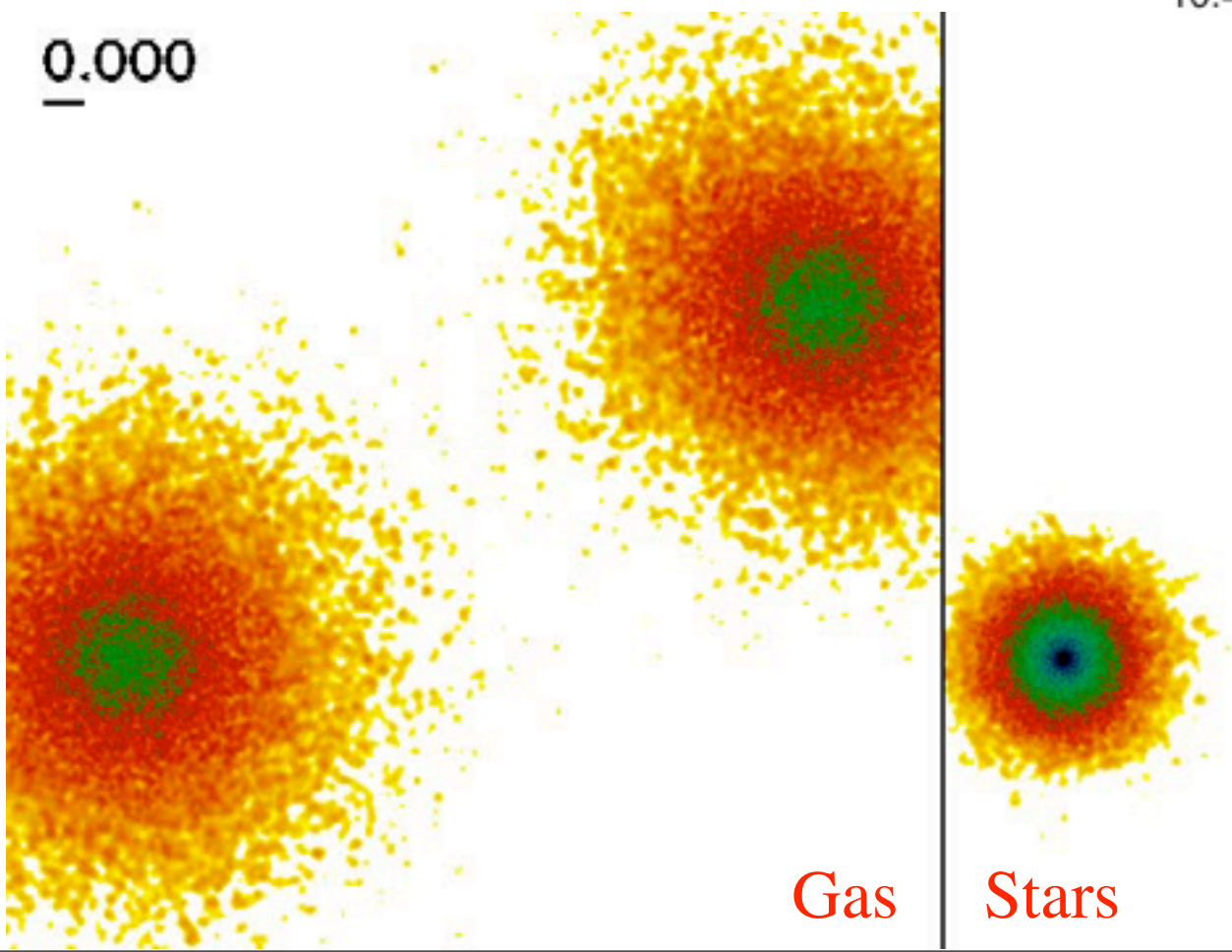


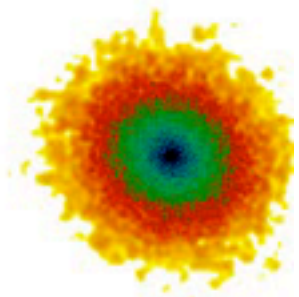
The Problem: The Fundamental Plane & Bulge Densities:



PFH, Cox et al. 200

- Why are ellipticals smaller than disks?

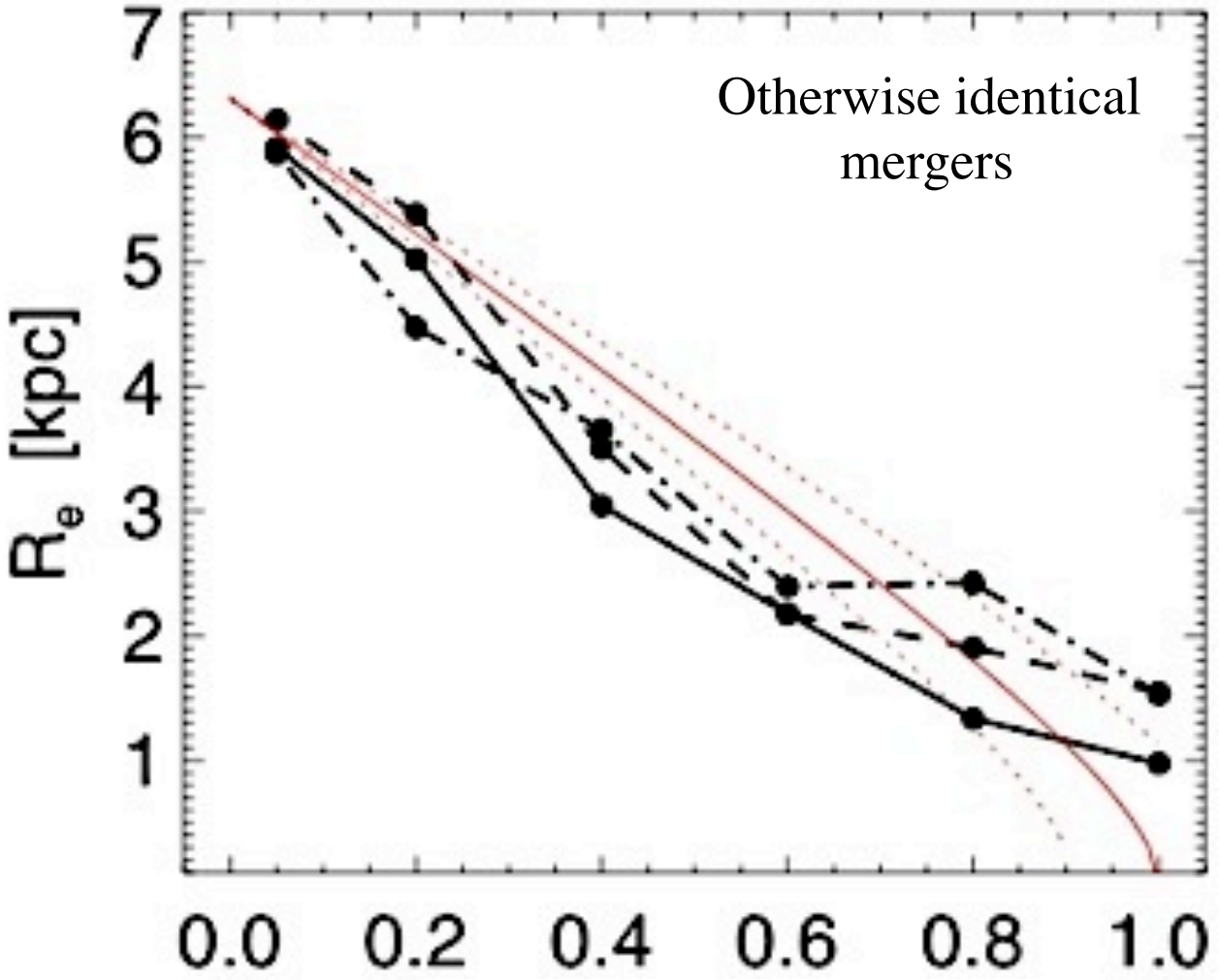




- Gas Dissipation

The Solution: Gas-Rich Mergers

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

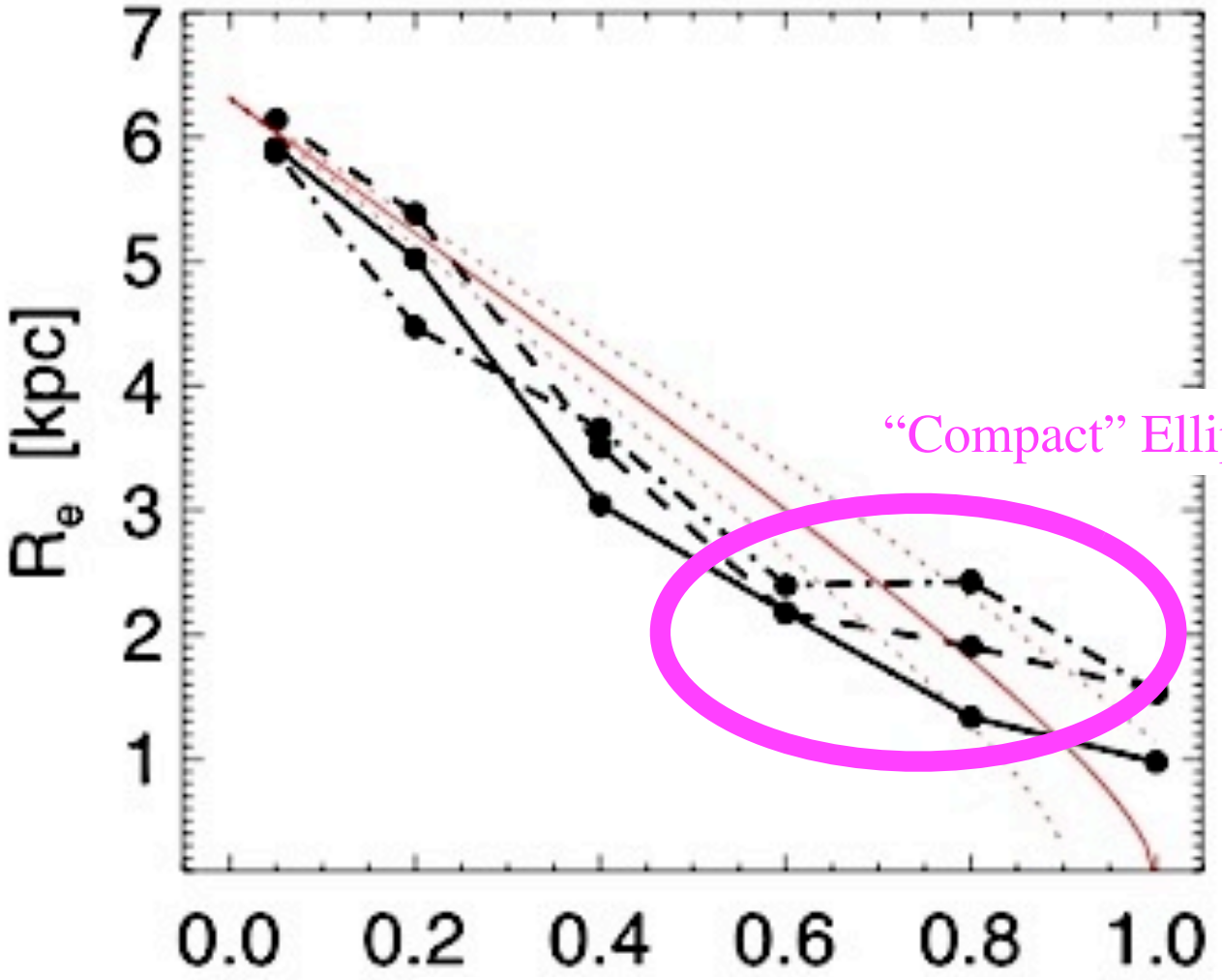


Bulge mass fraction formed in bursts (versus violently relaxed from disks)

PFH, Cox et al. 2008

The Solution: Gas-Rich Mergers

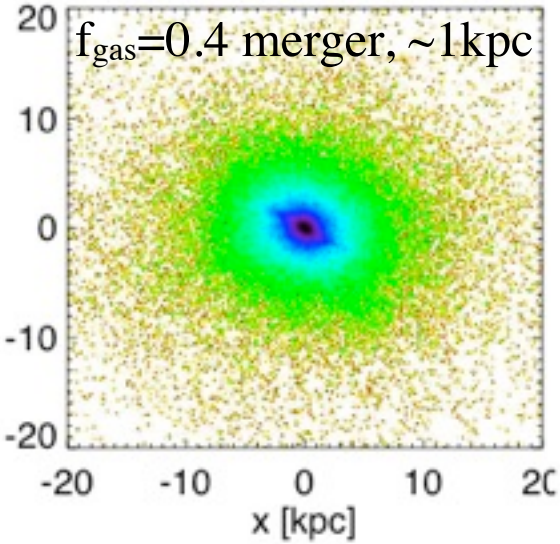
- Increased dissipation→smaller, more compact remnants (Cox; Khochfar; Naab; Robertson)

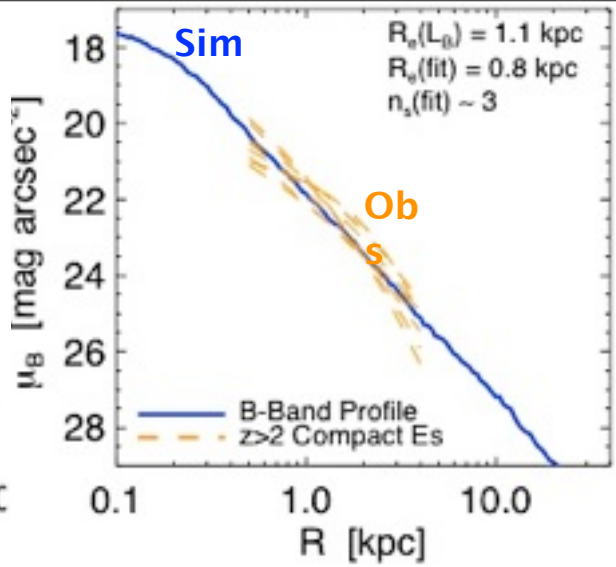


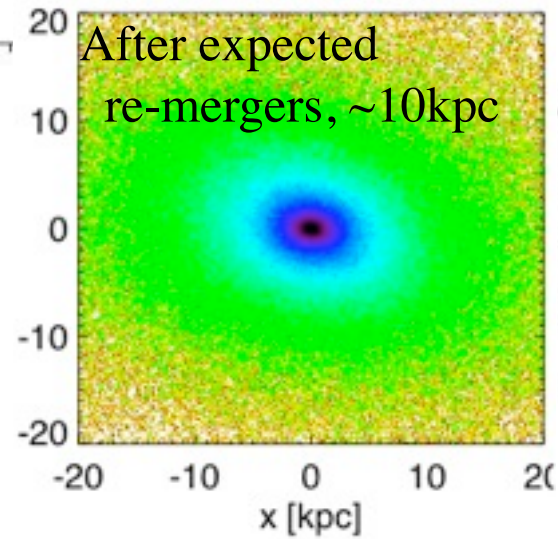
Bulge mass fraction formed in bursts
(versus violently relaxed from disks)

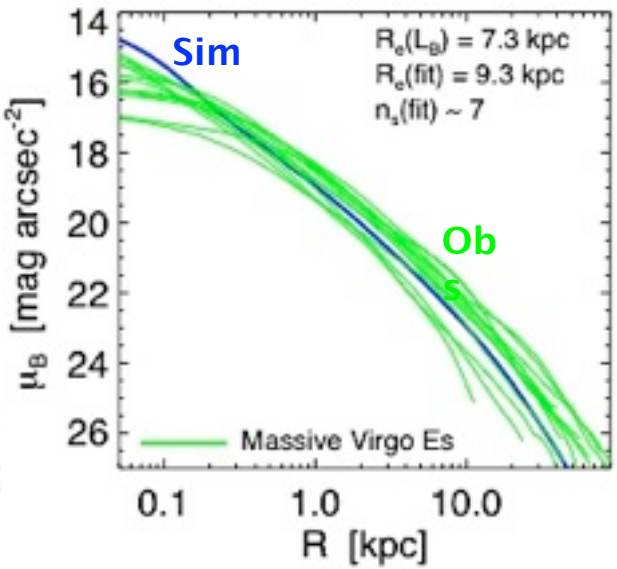
Compare: massive spheroids at z=2 to those today

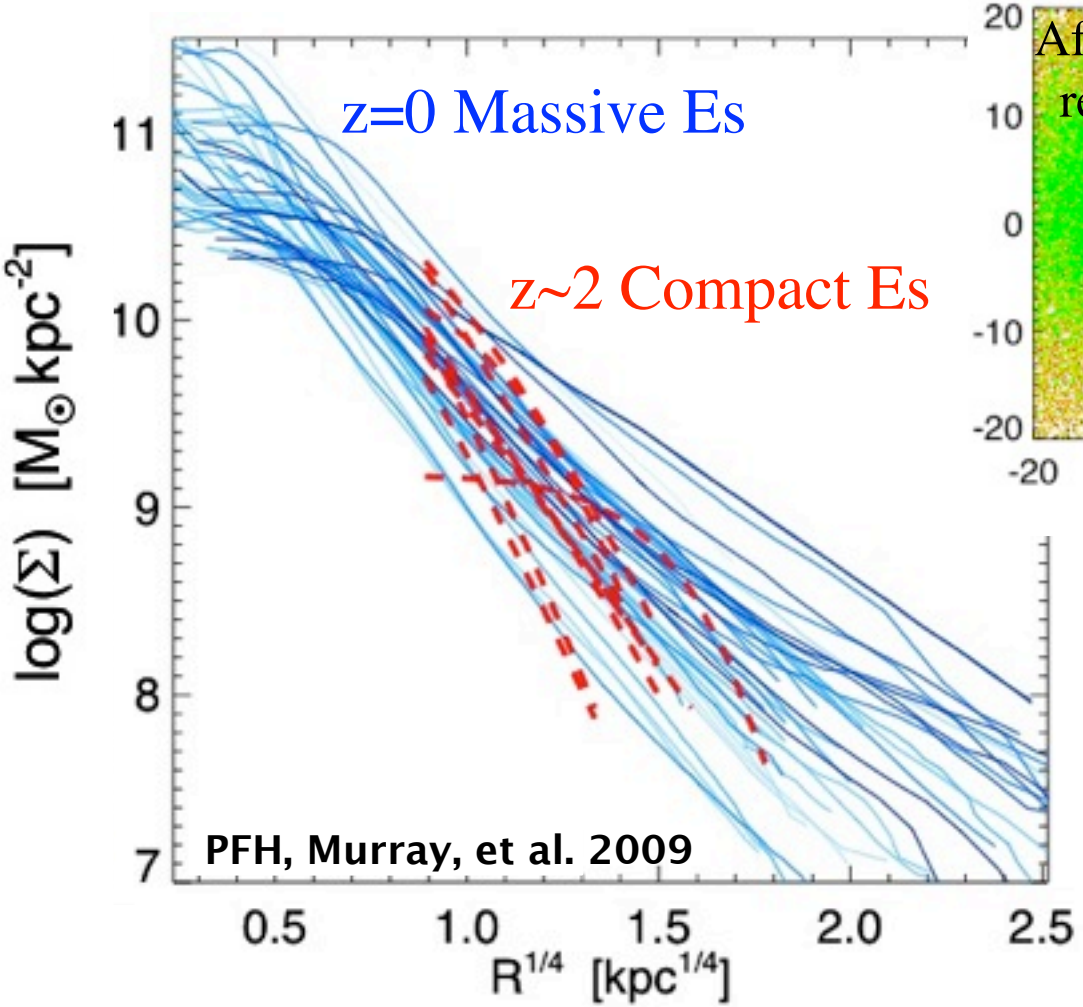
... vs gas-rich merger with later low-density/minor mergers









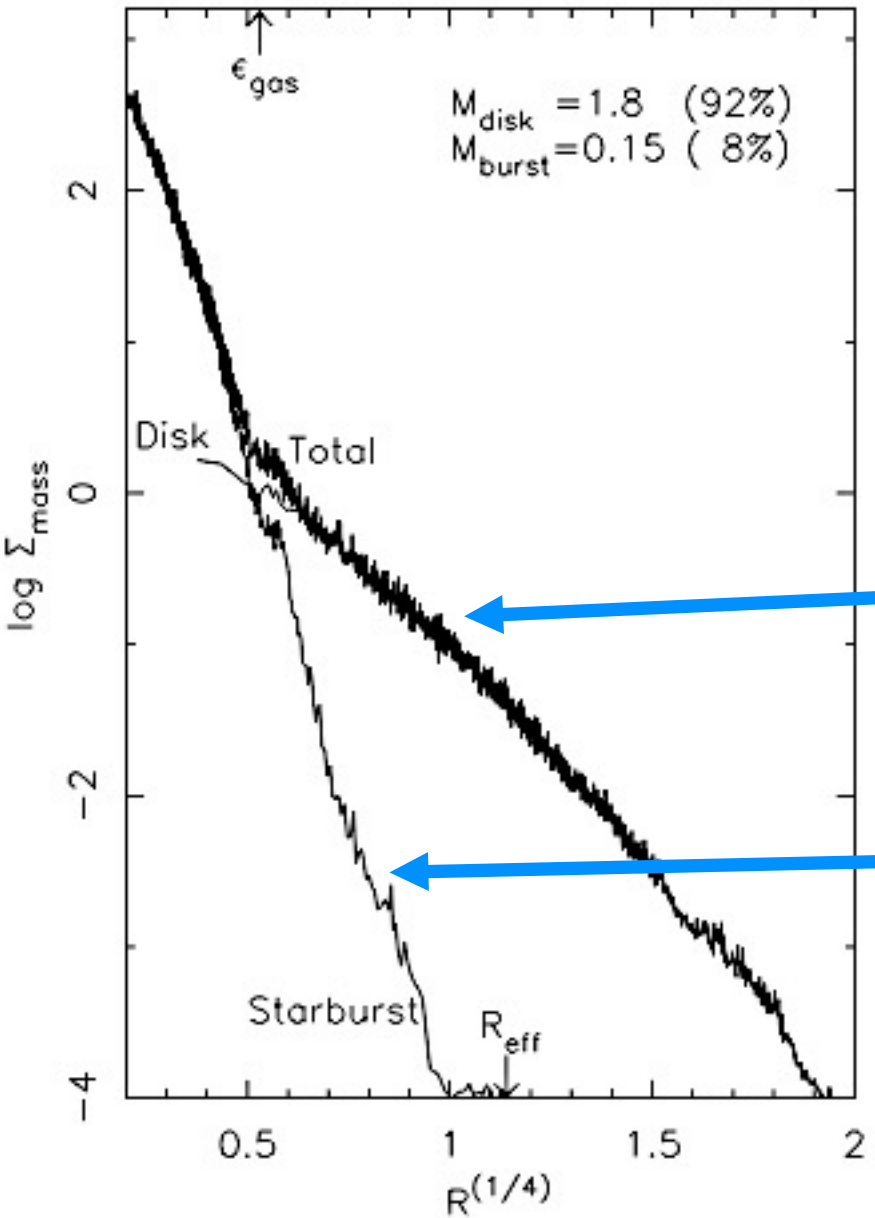


PFH, Bundy, et al. 2009

also Bezanso Naab et al.

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:

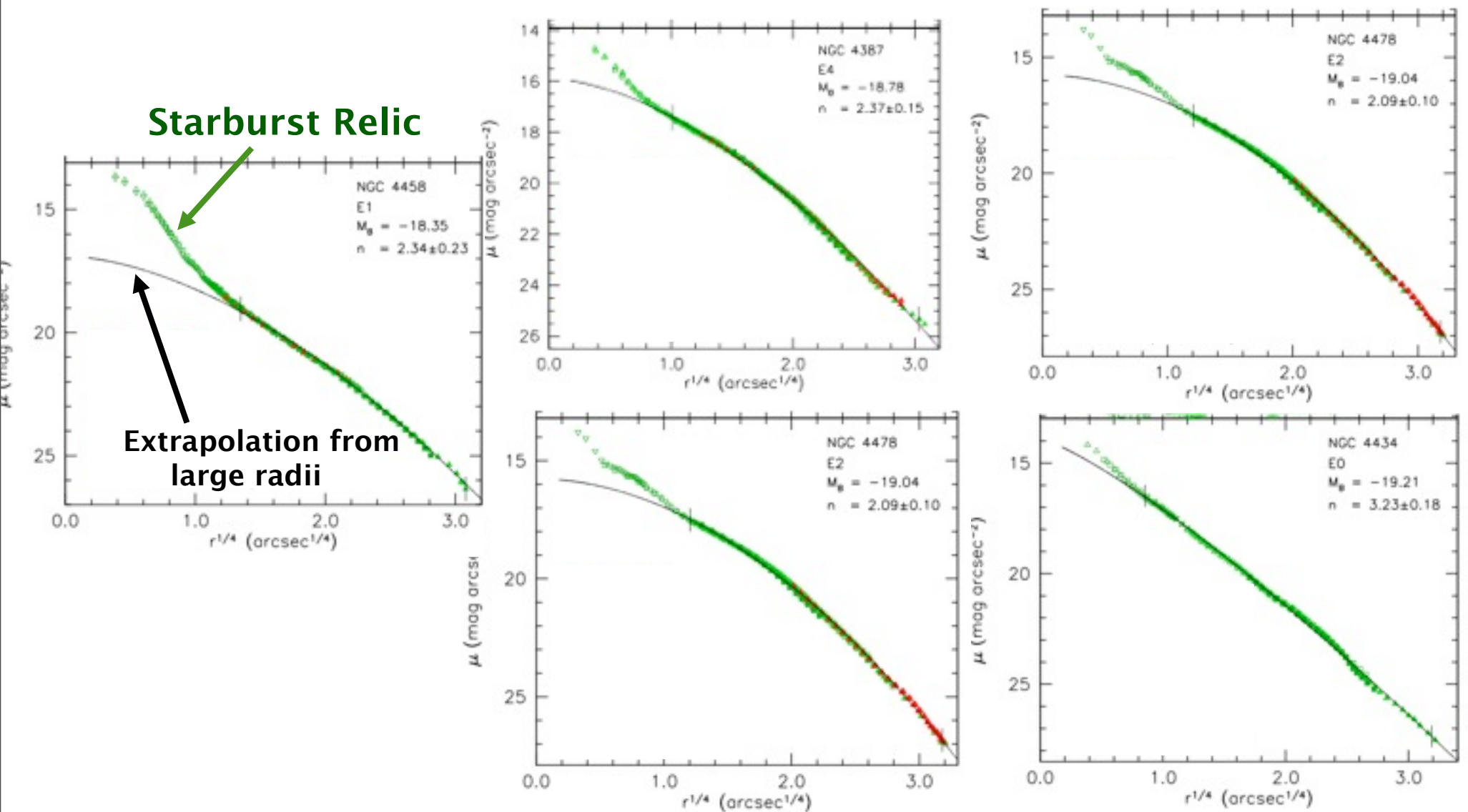
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

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

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...

Kormendy et al. 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."

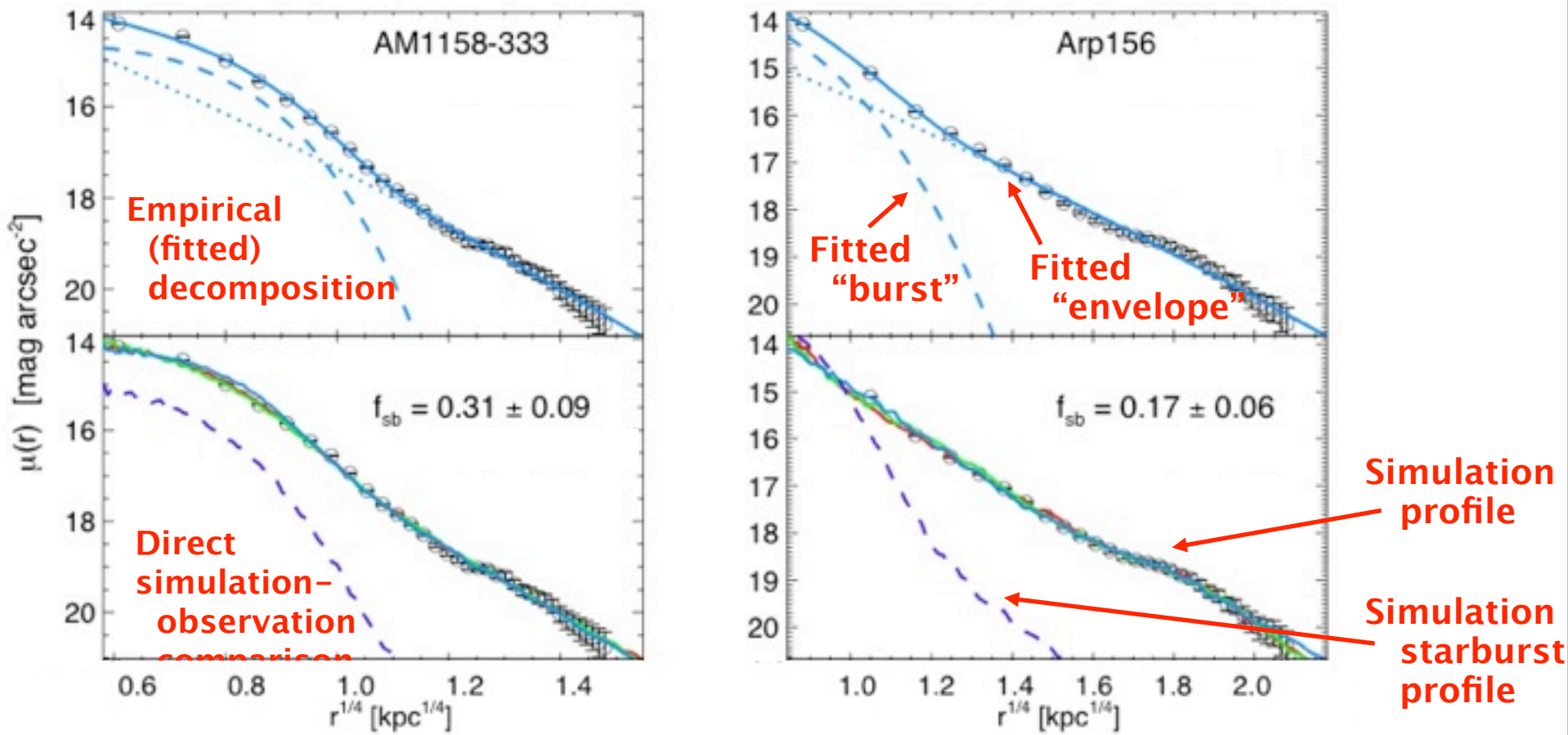
Application: Merger Remnants

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:



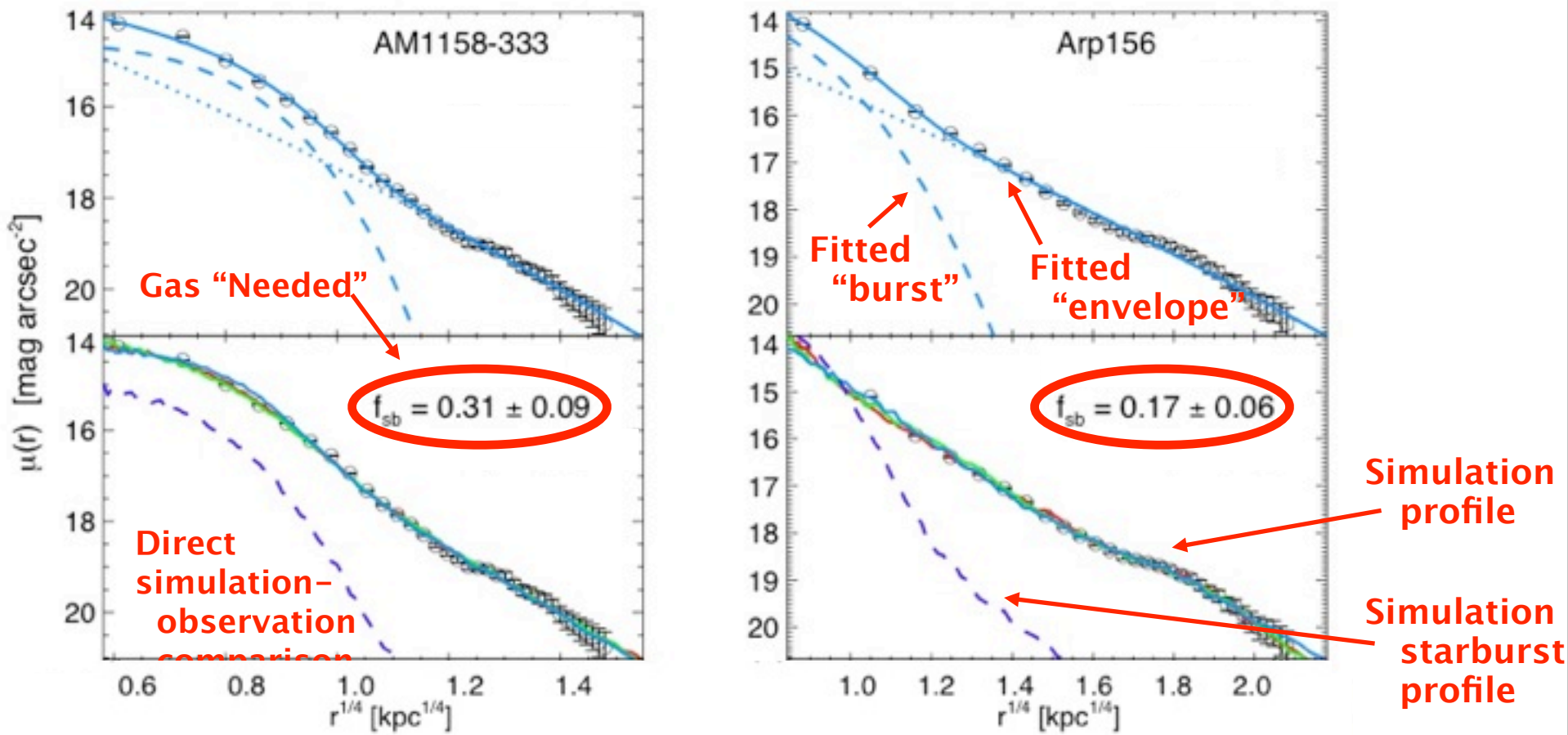
Application: Merger Remnants

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:



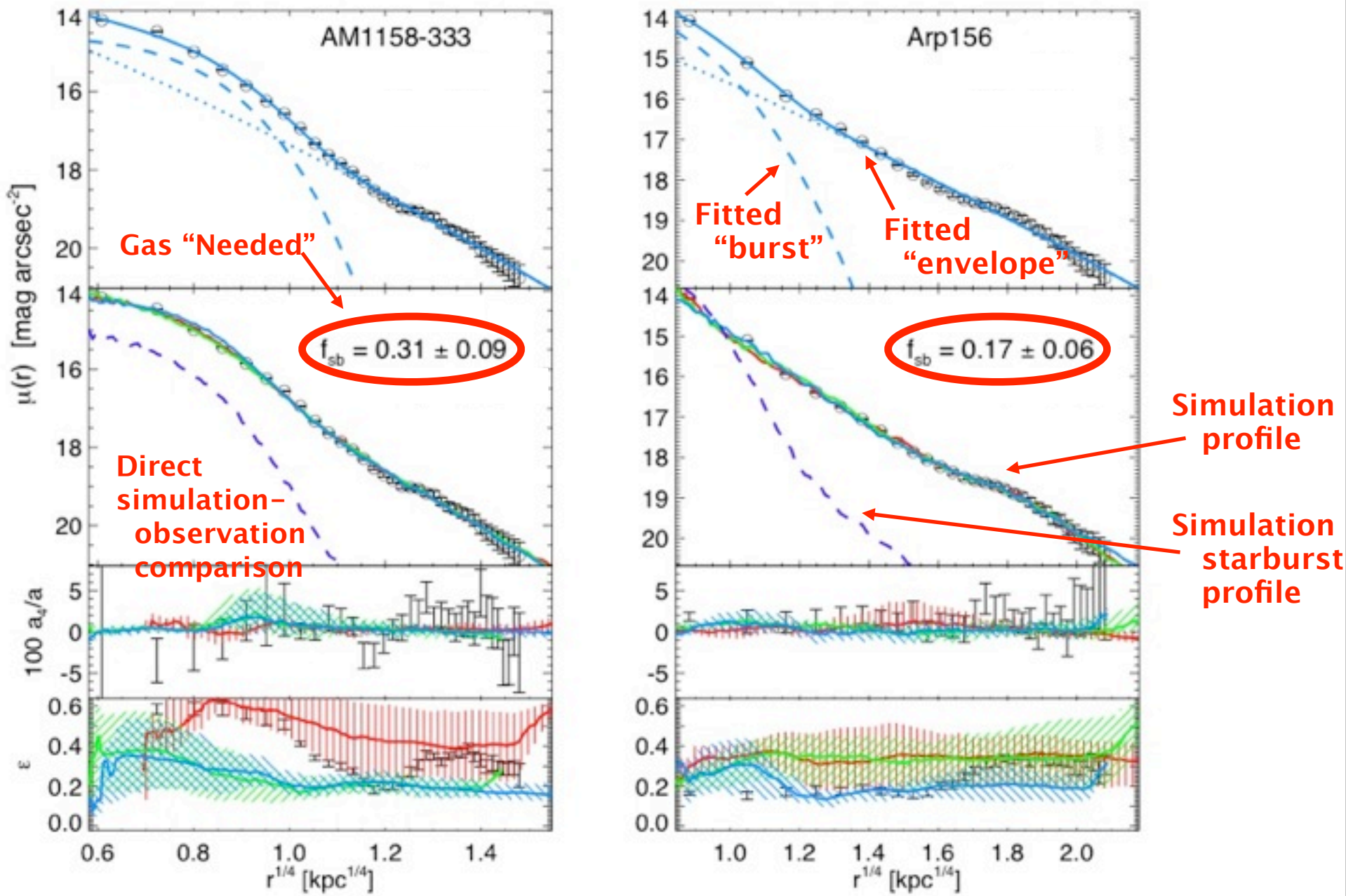
Application: Merger Remnants

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:



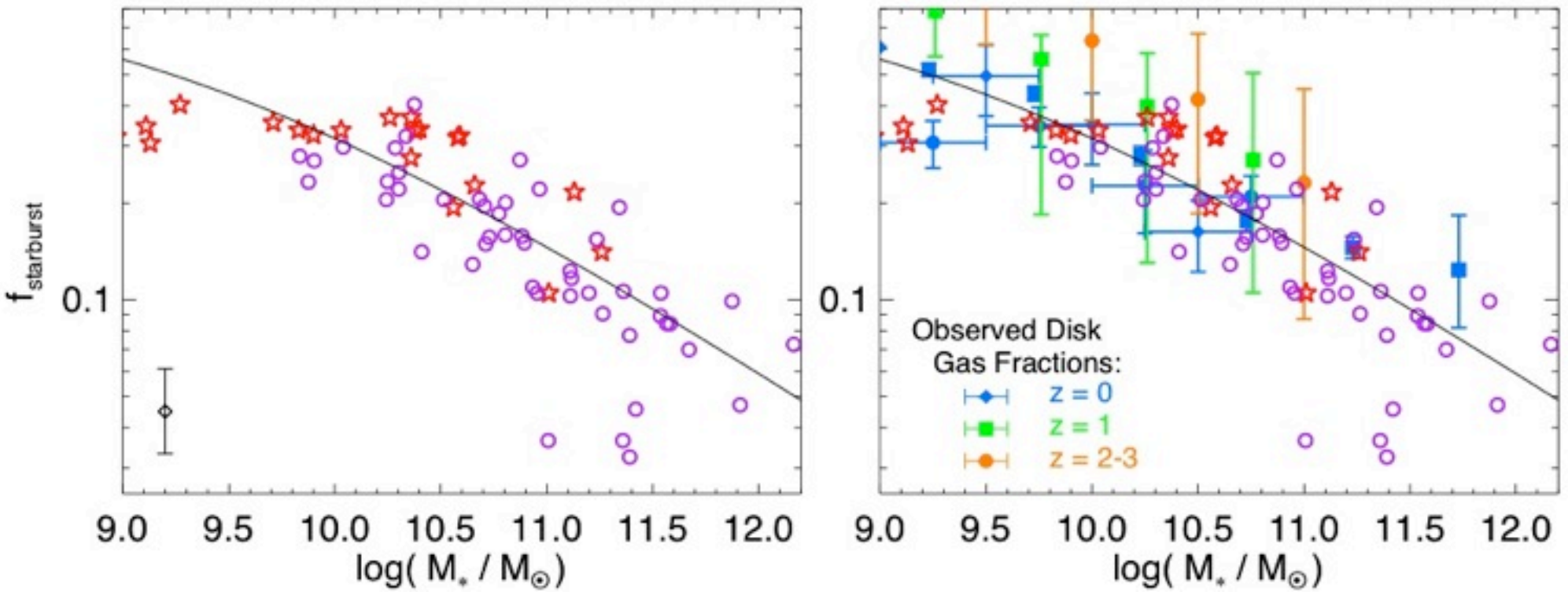
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

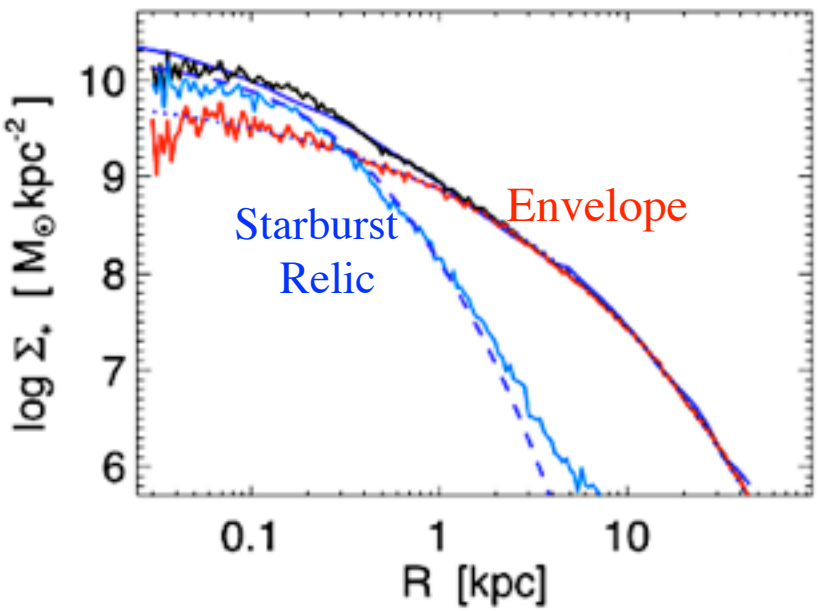
PFH, Kormendy, & Lauer et al. 2008

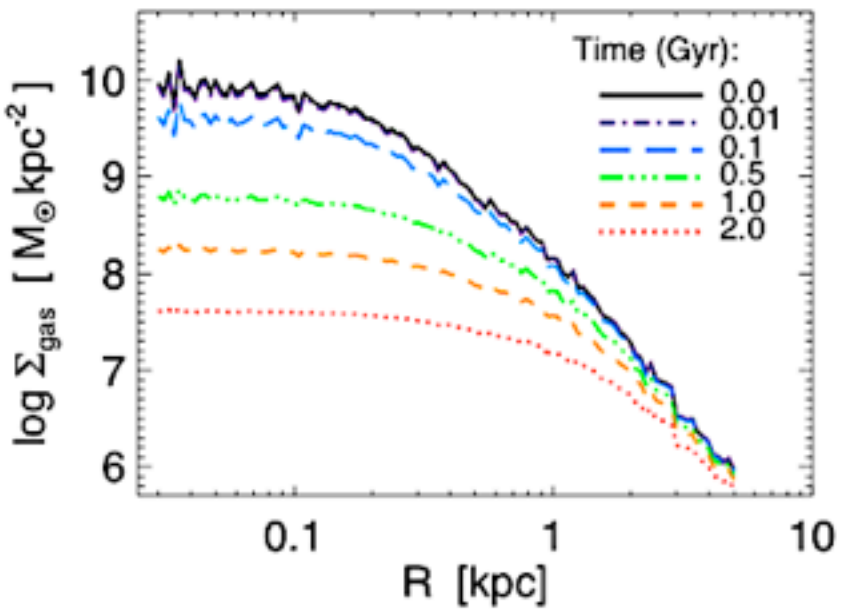
Starburst gas mass needed to match observed profile (or fitted to profile shape):

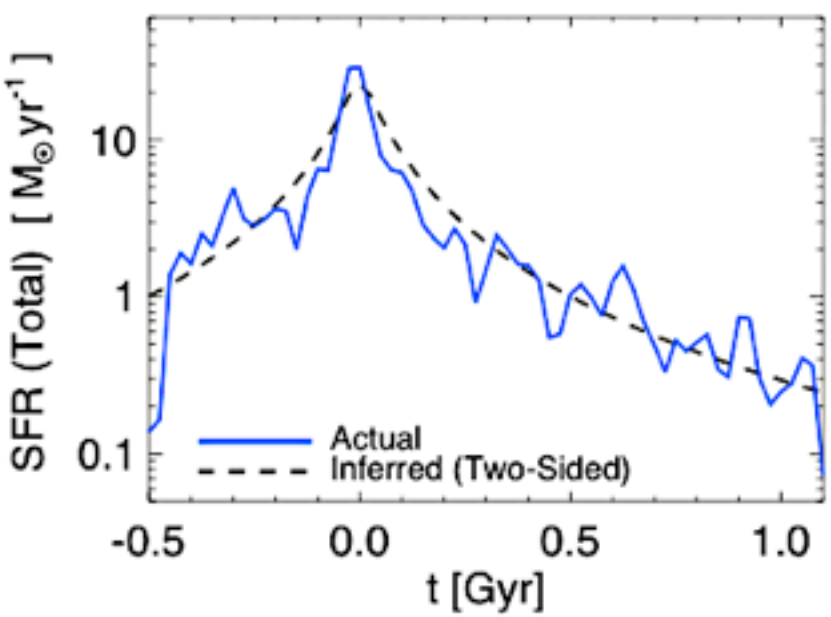


- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns

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

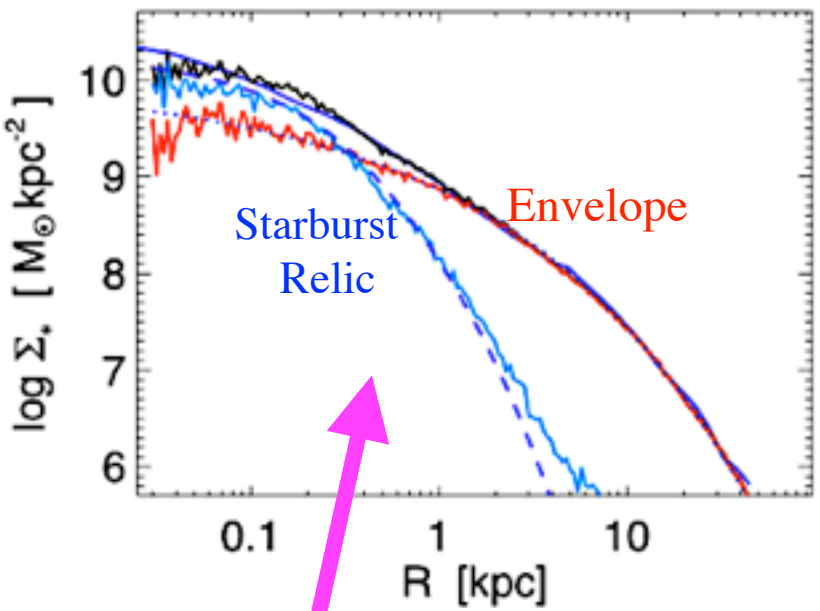


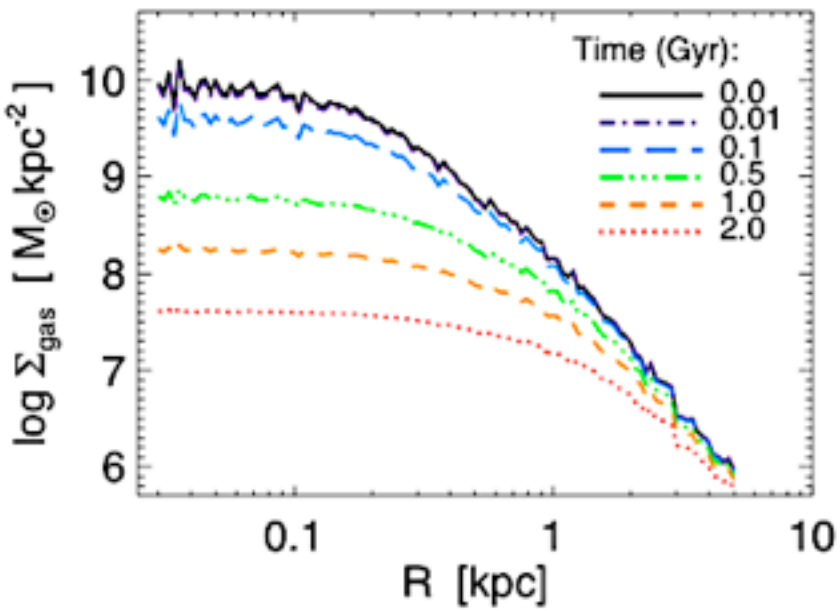


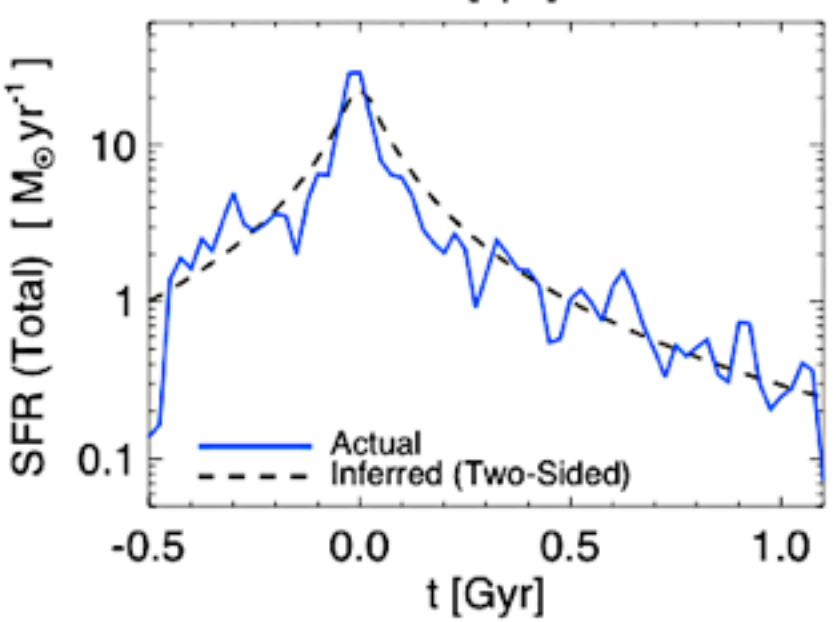


What else can we learn from the ‘relics’ of gas dissipation?

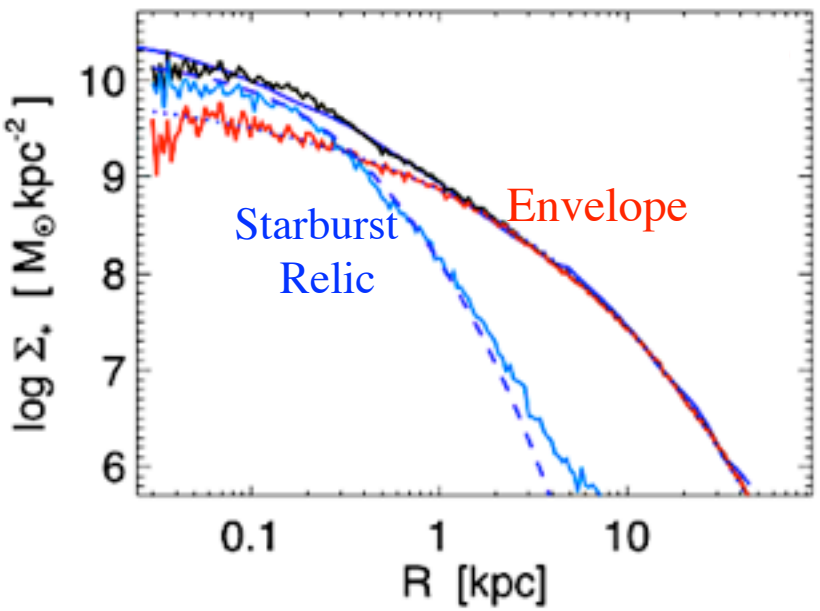
Given a galaxy, isolate ‘burst relic’ $\Sigma_{relic\ stars}(R)$

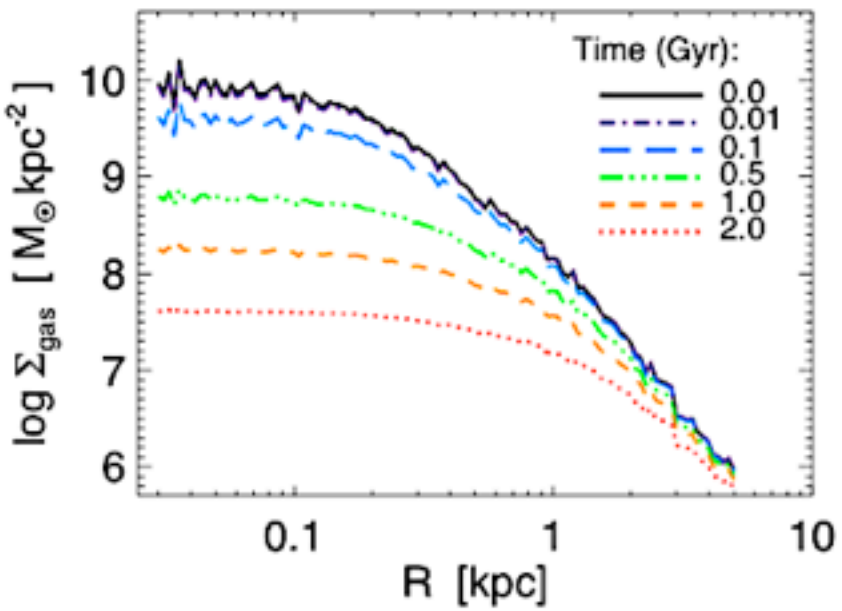


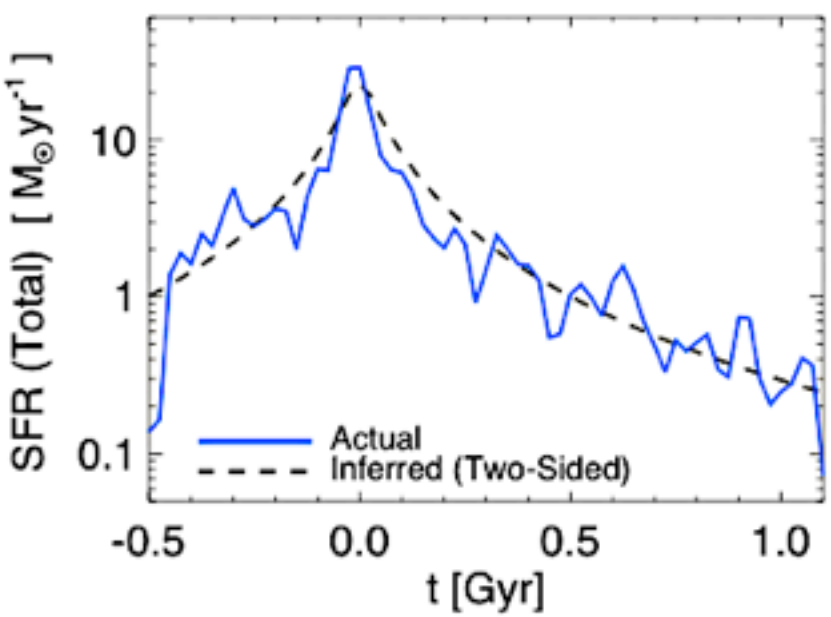




What else can we learn from the ‘relics’ of gas dissipation?



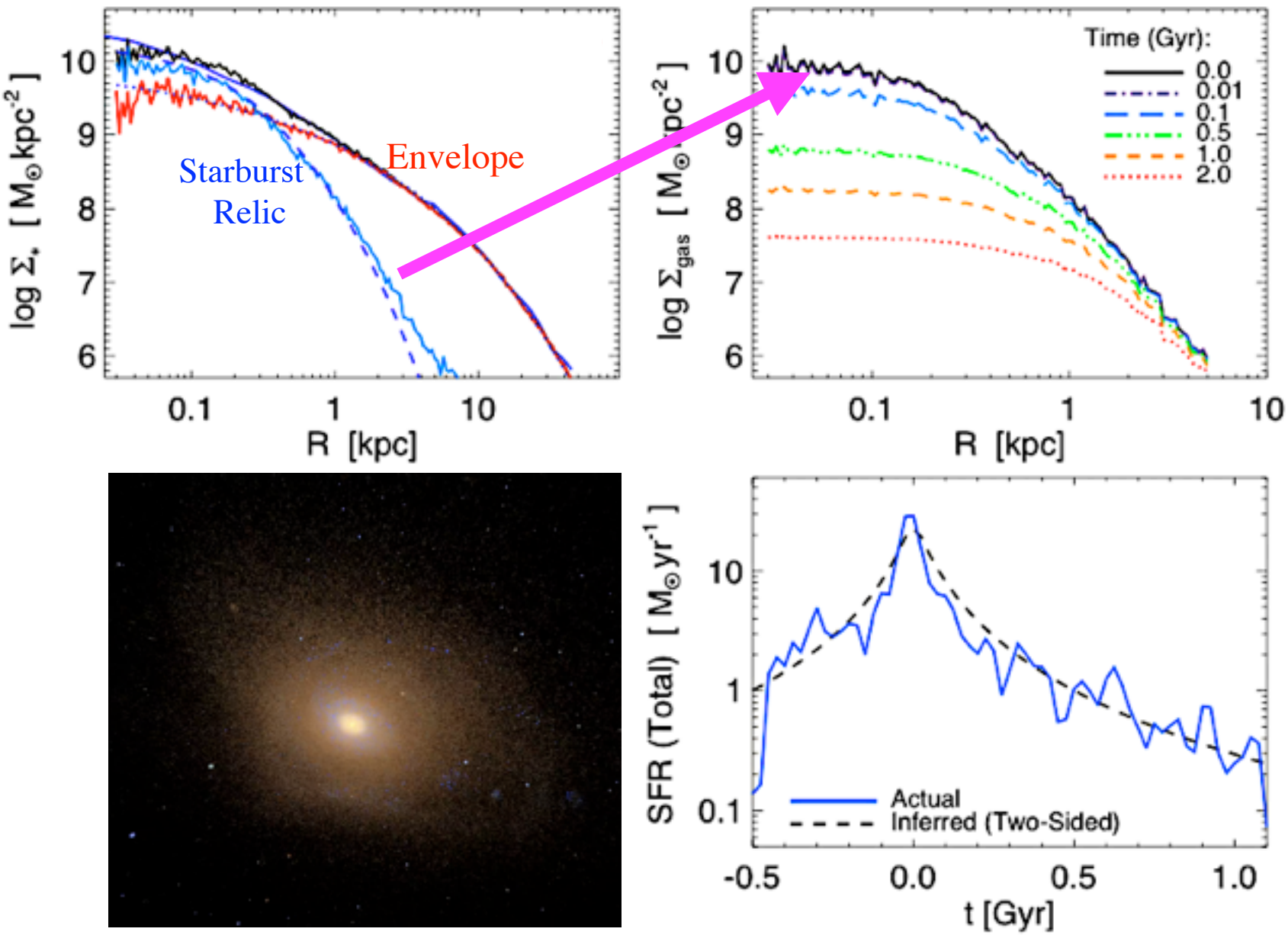




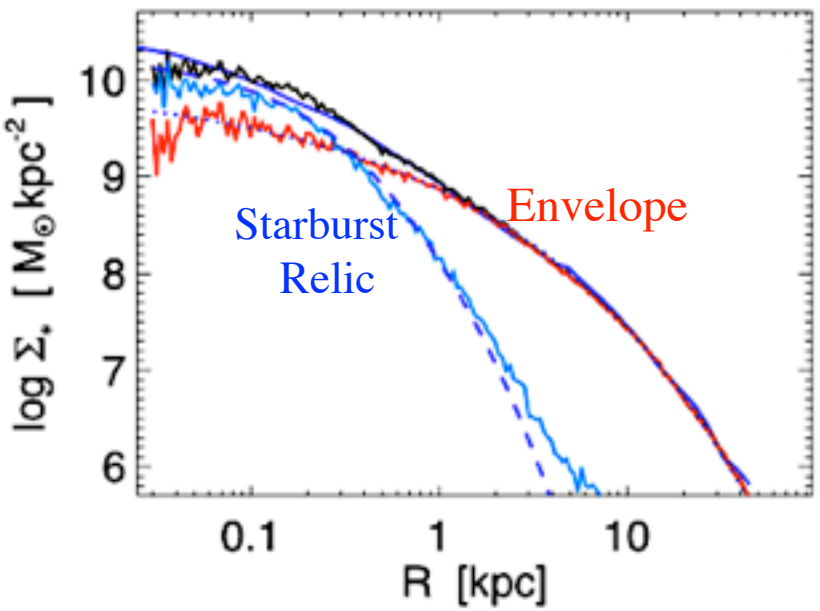
What else can we learn from the 'relics' of gas dissipation?

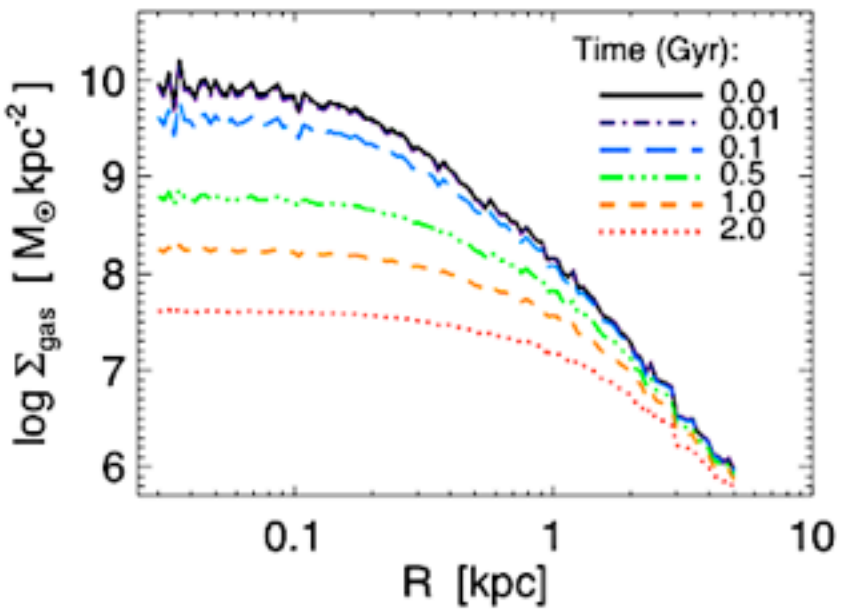
If formed dissipationally, then this reflects gas-star conversion "in situ"

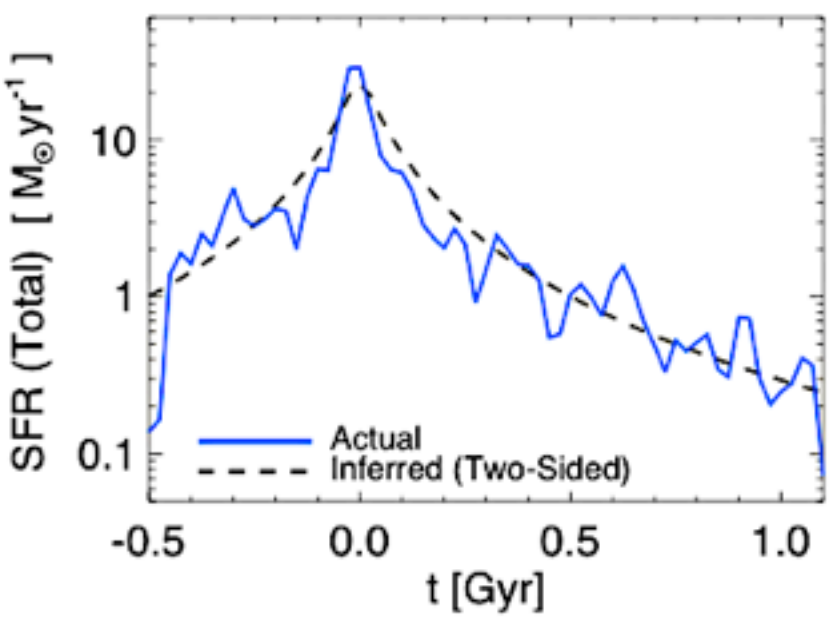
$$\Sigma_{relic\ stars}(R) \sim \Sigma_{gas\ for\ burst}(R, t = t_{burst})$$



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



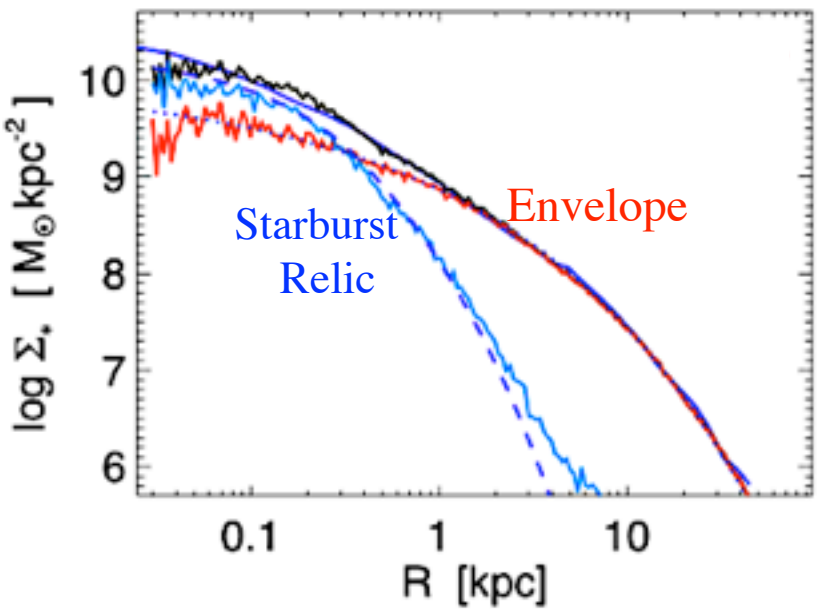


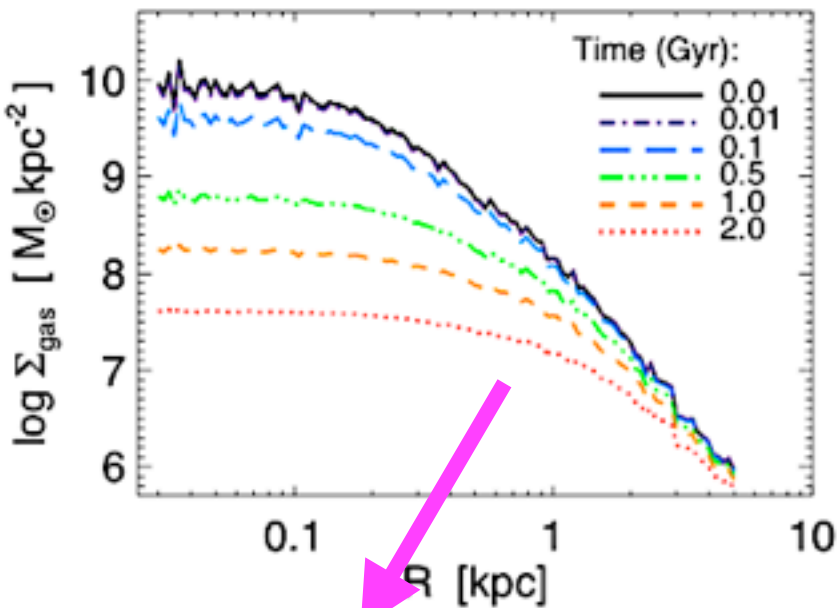


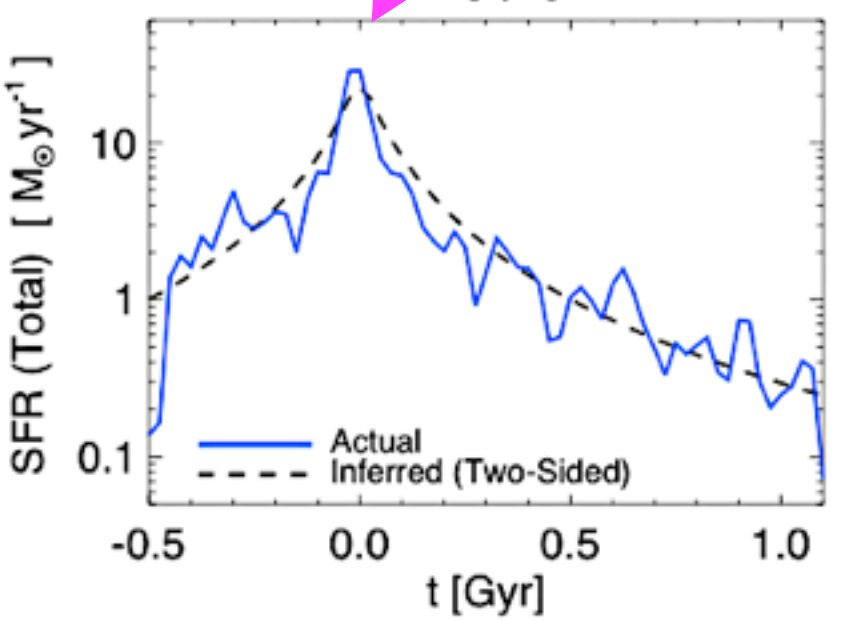
What else can we learn from the 'relics' of gas dissipation?

Assume Schmidt-Kennicutt law applies: Recover SFH

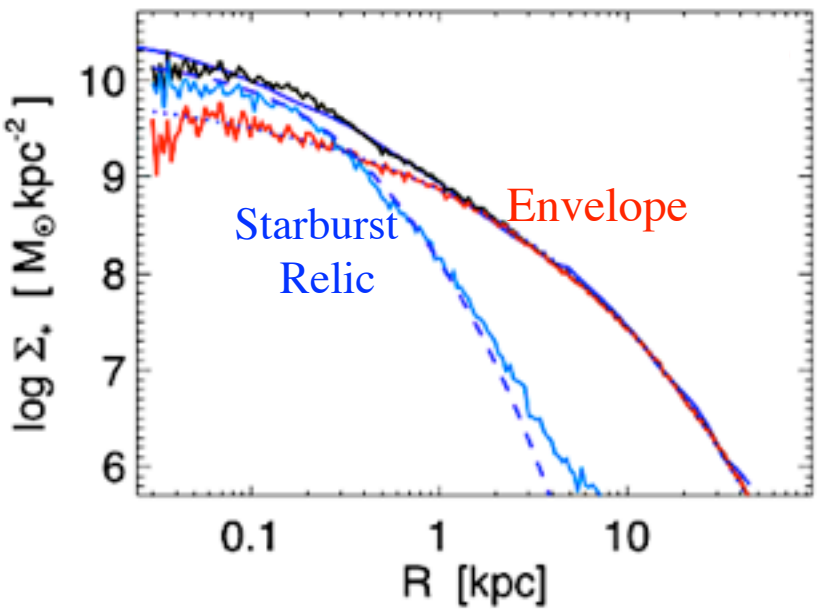
$$\Sigma_{gas}(R,t) \rightarrow \dot{\Sigma}_*(R,t) \rightarrow \Sigma_{gas}(R,t+\Delta t)$$

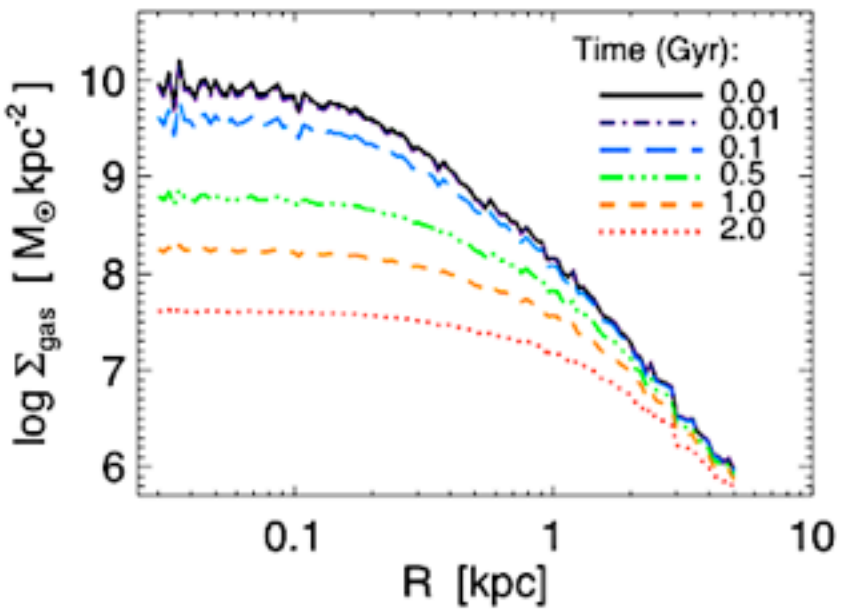


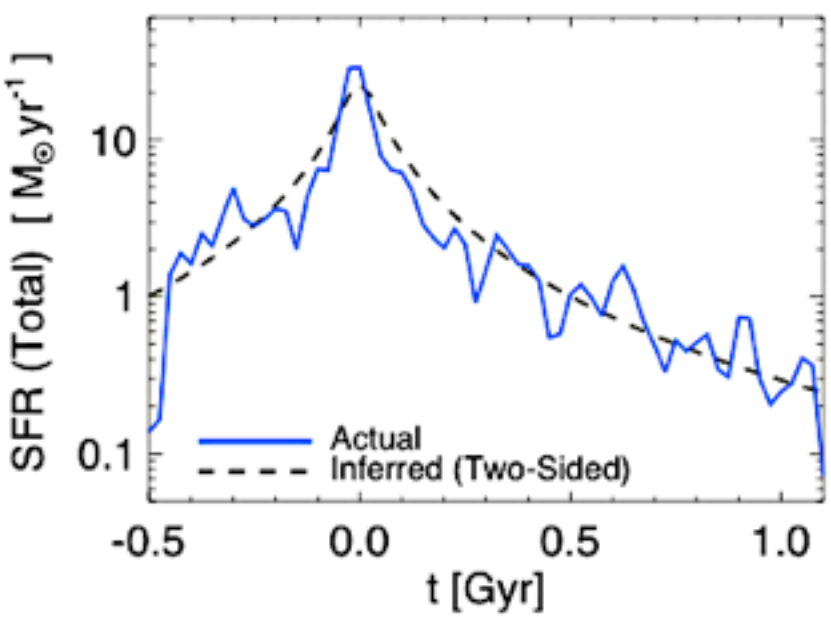




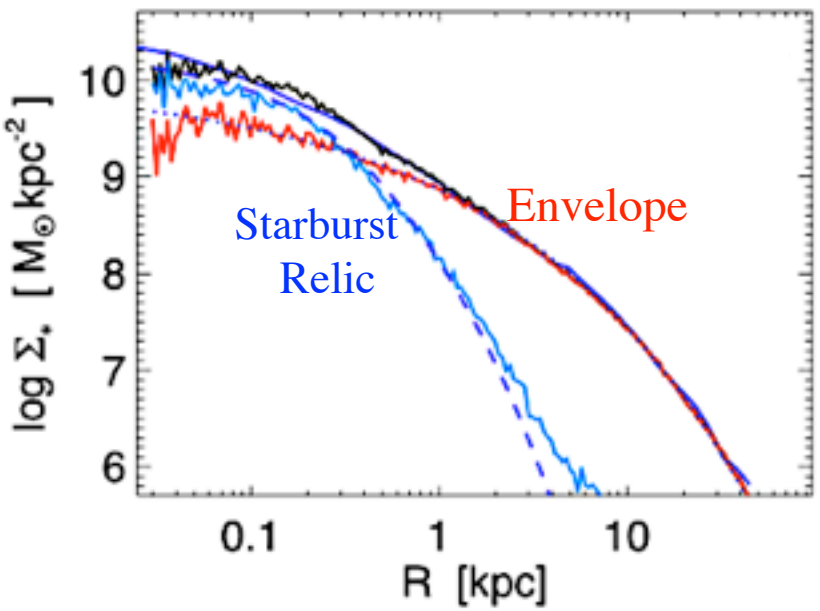
What else can we learn from the ‘relics’ of gas dissipation?

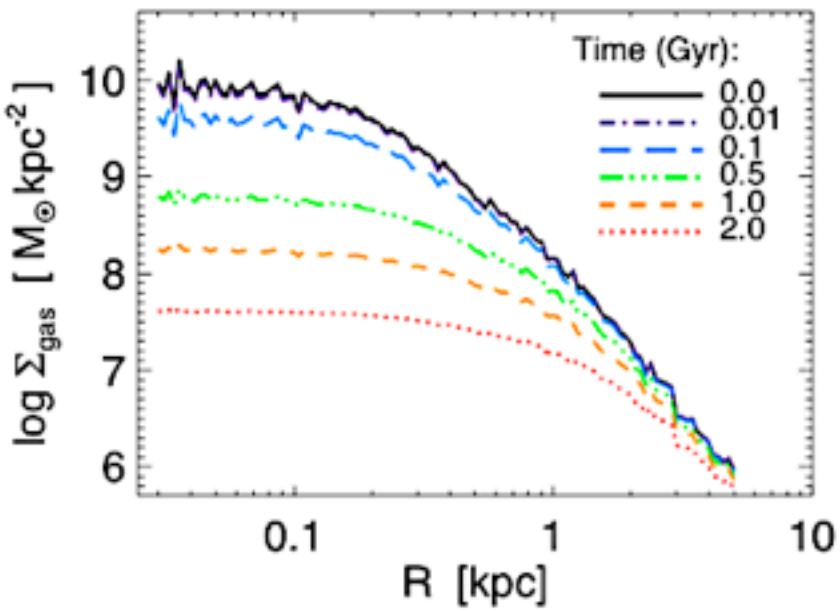


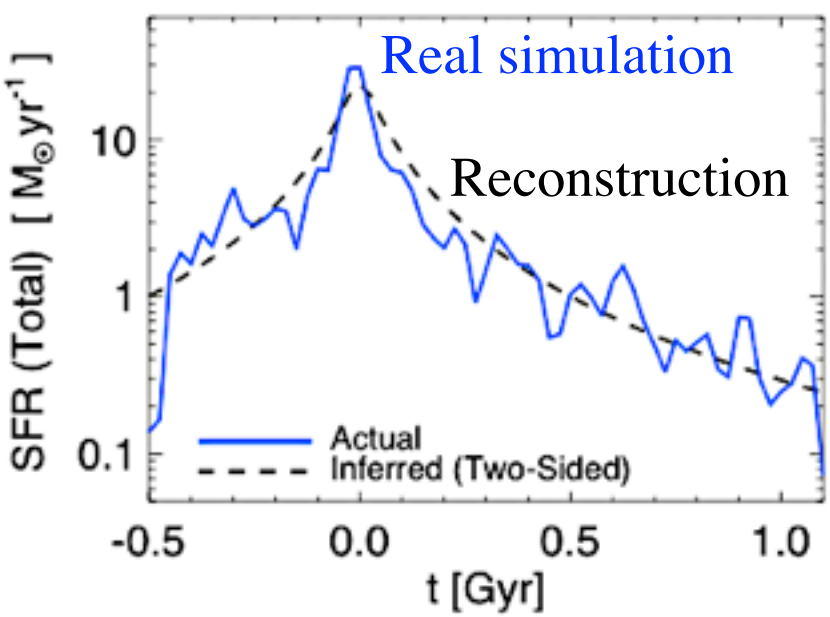




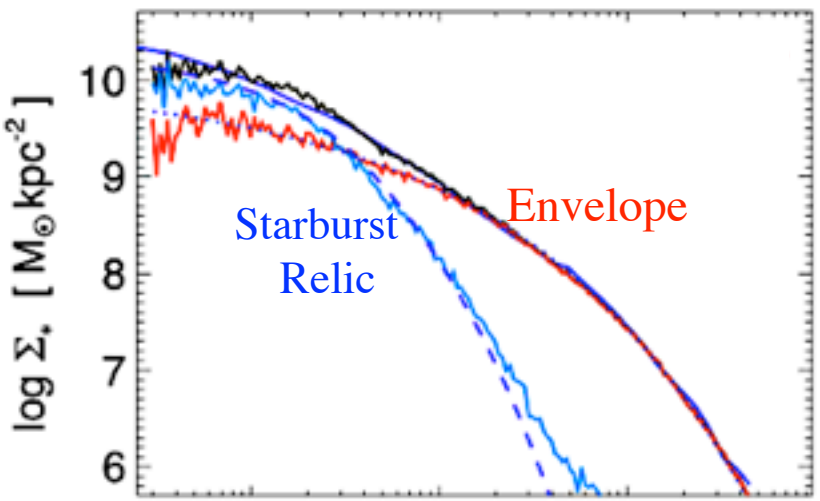
What else can we learn from the ‘relics’ of gas dissipation?

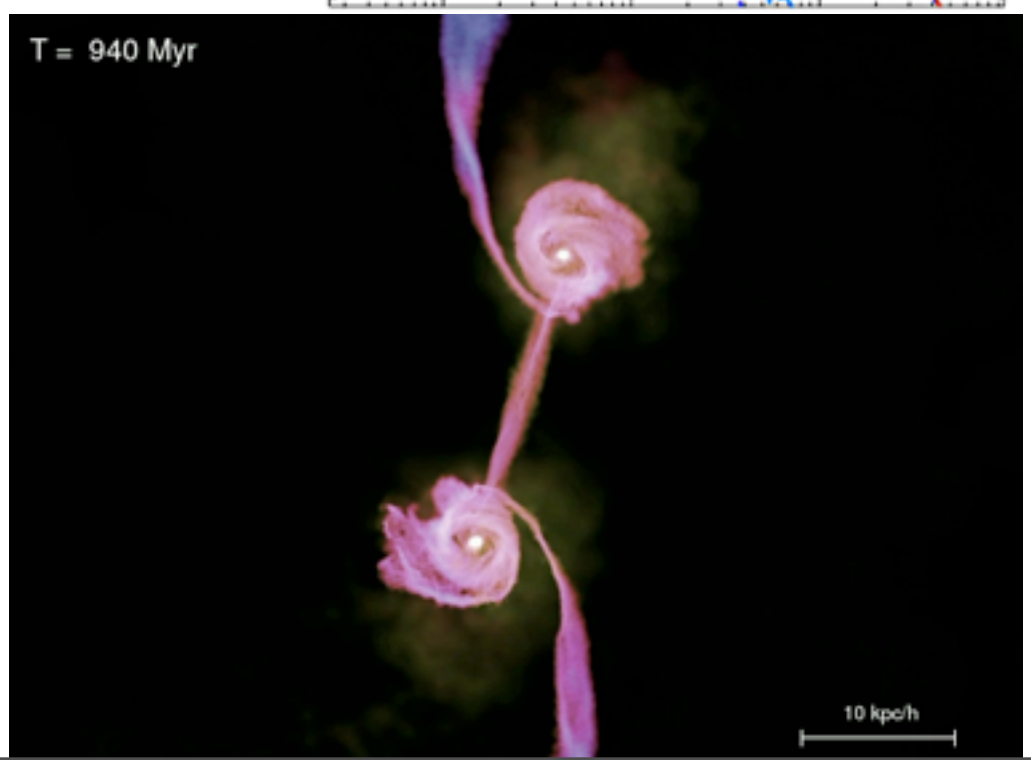


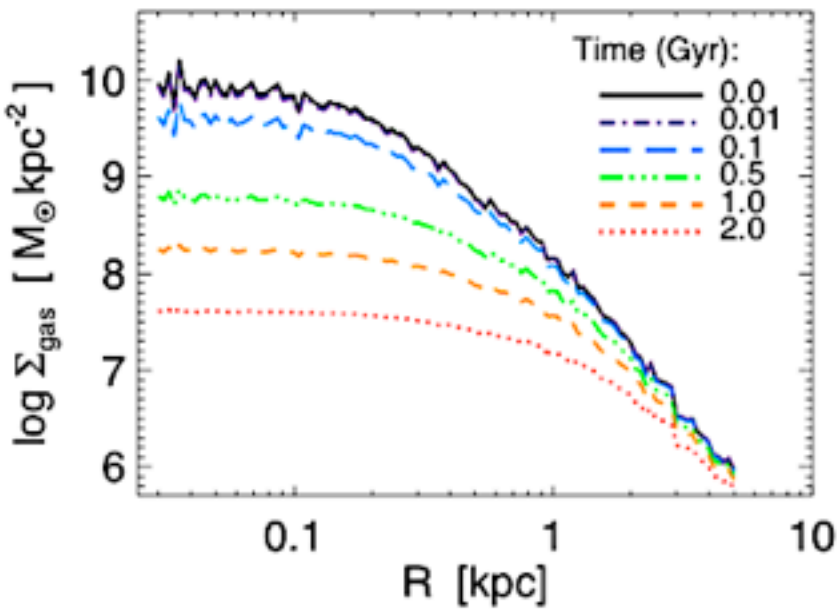


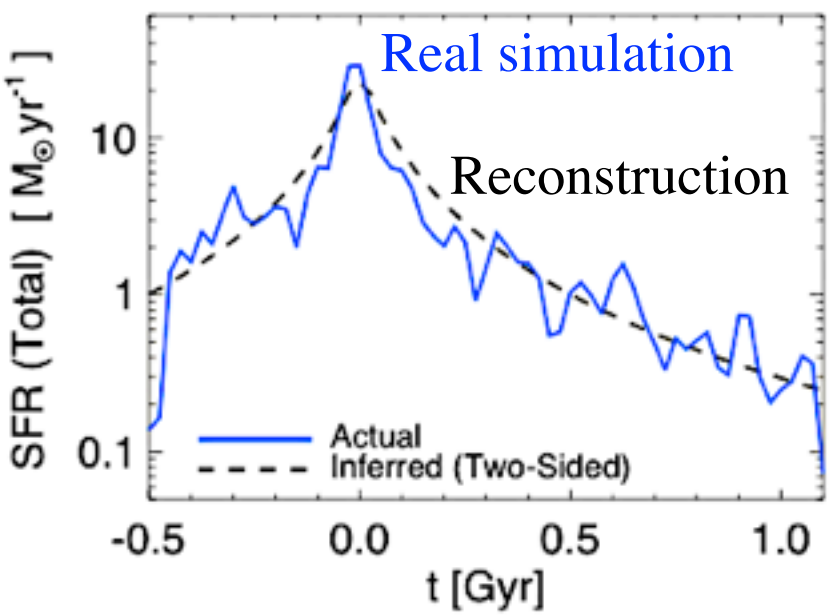


What else can we learn from the ‘relics’ of gas dissipation?

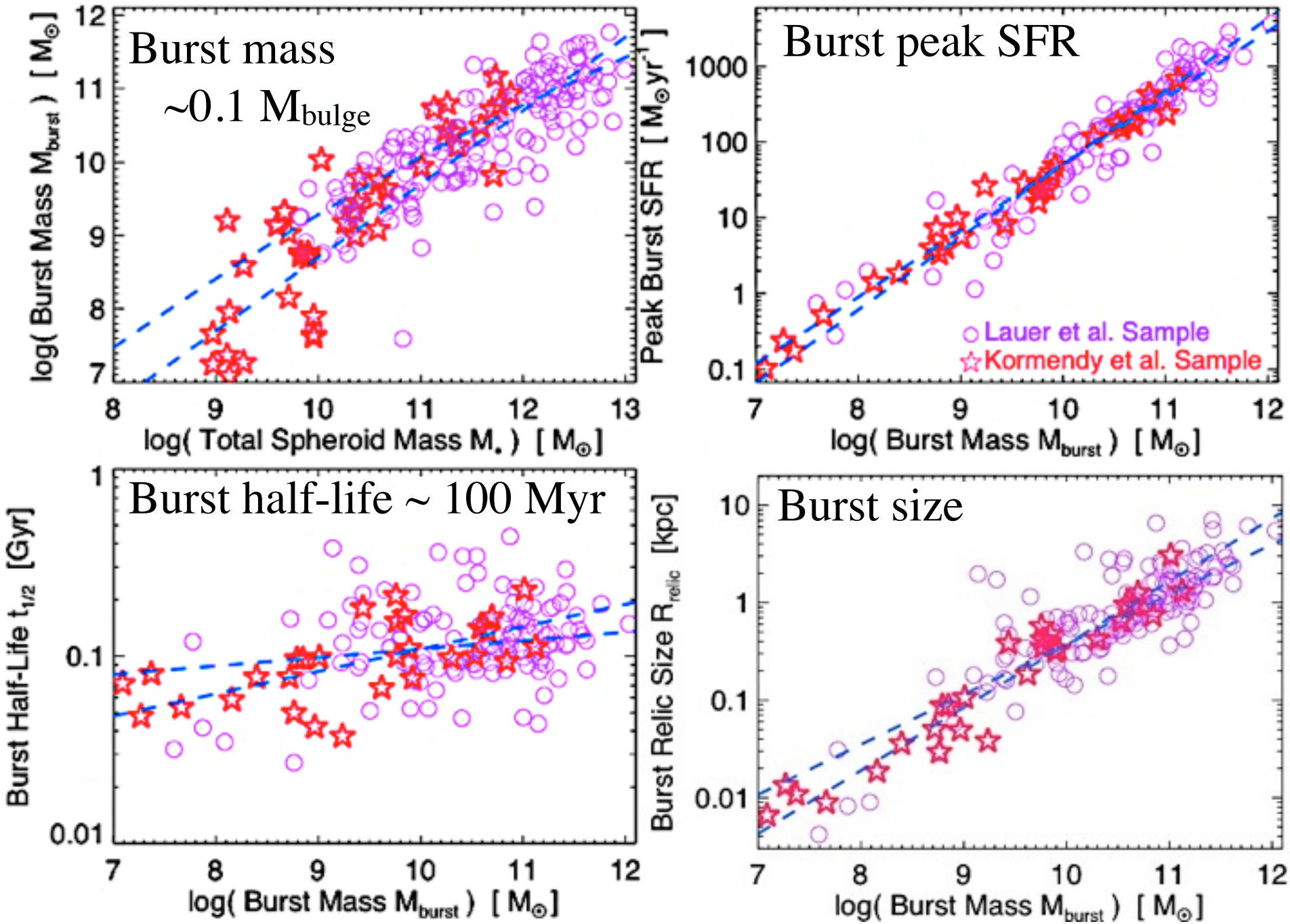




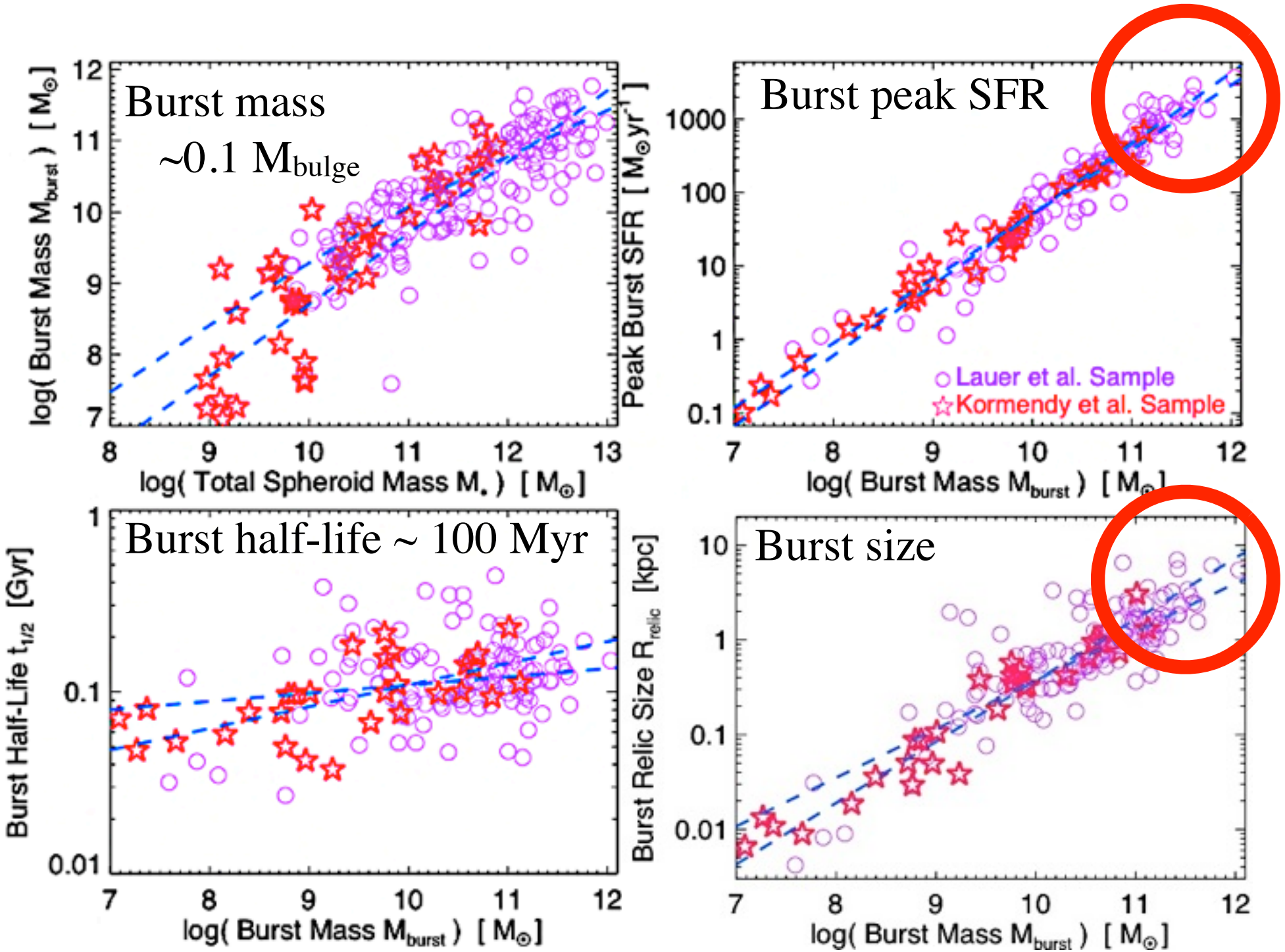




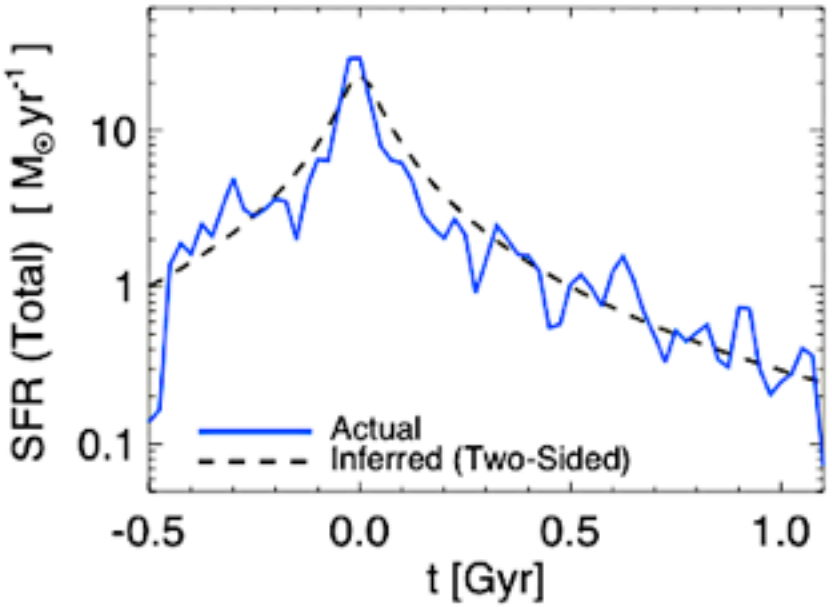
What else can we learn from the 'relics' of gas dissipation?



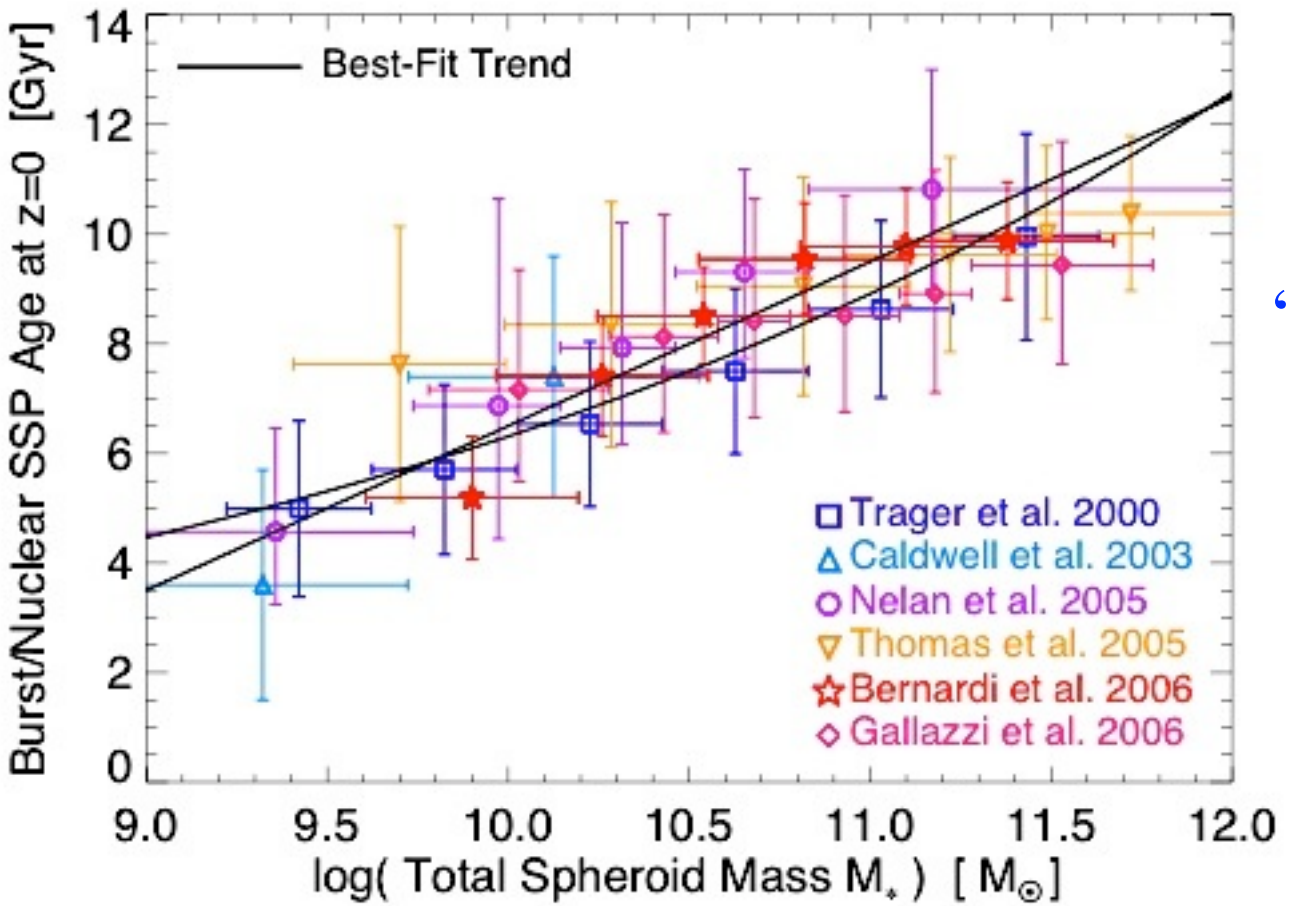
What else can we learn from the 'relics' of gas dissipation?



Re-construct SFR(t) for each burst :

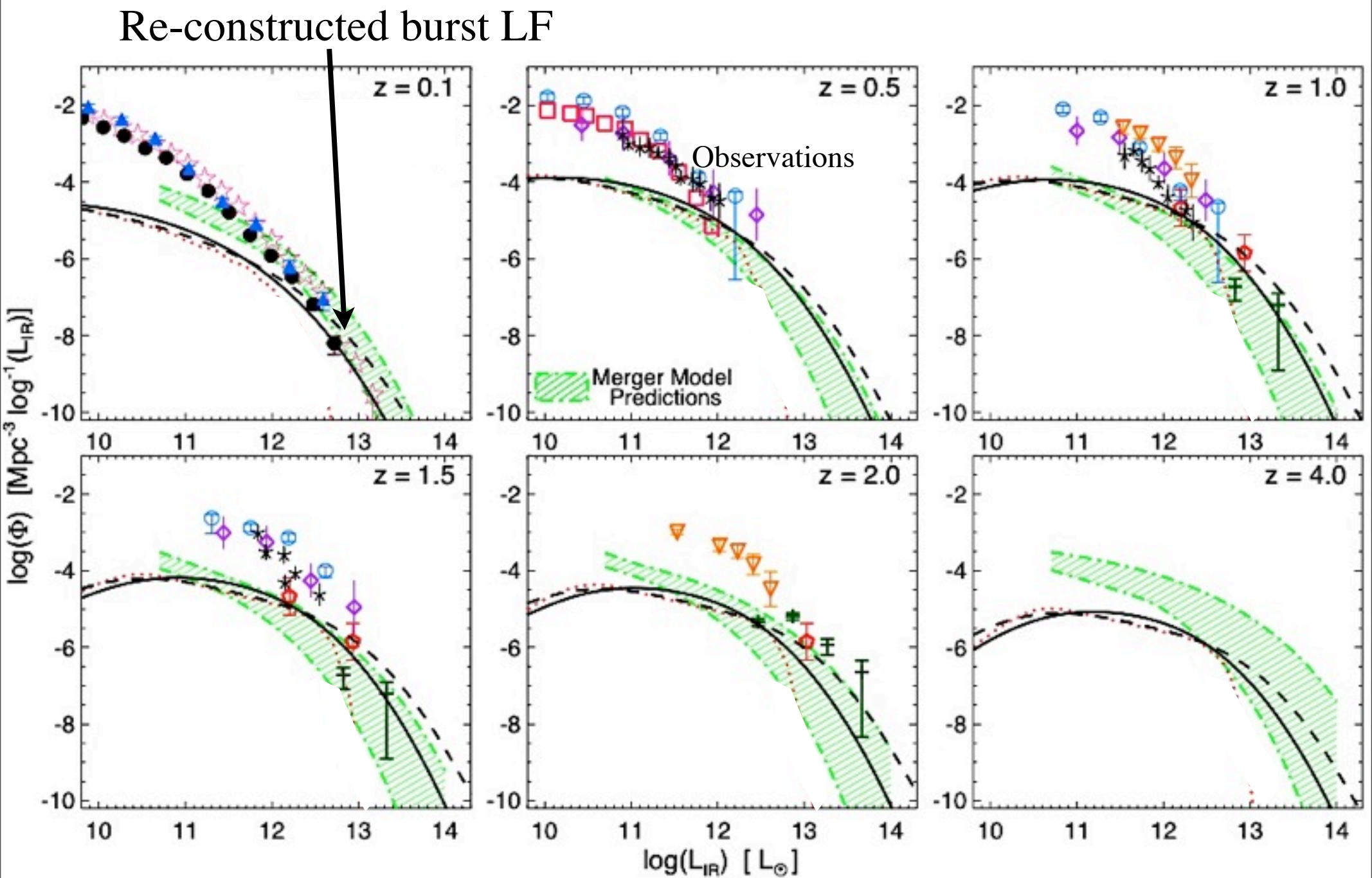


+ We know the nuclear SSP ages....

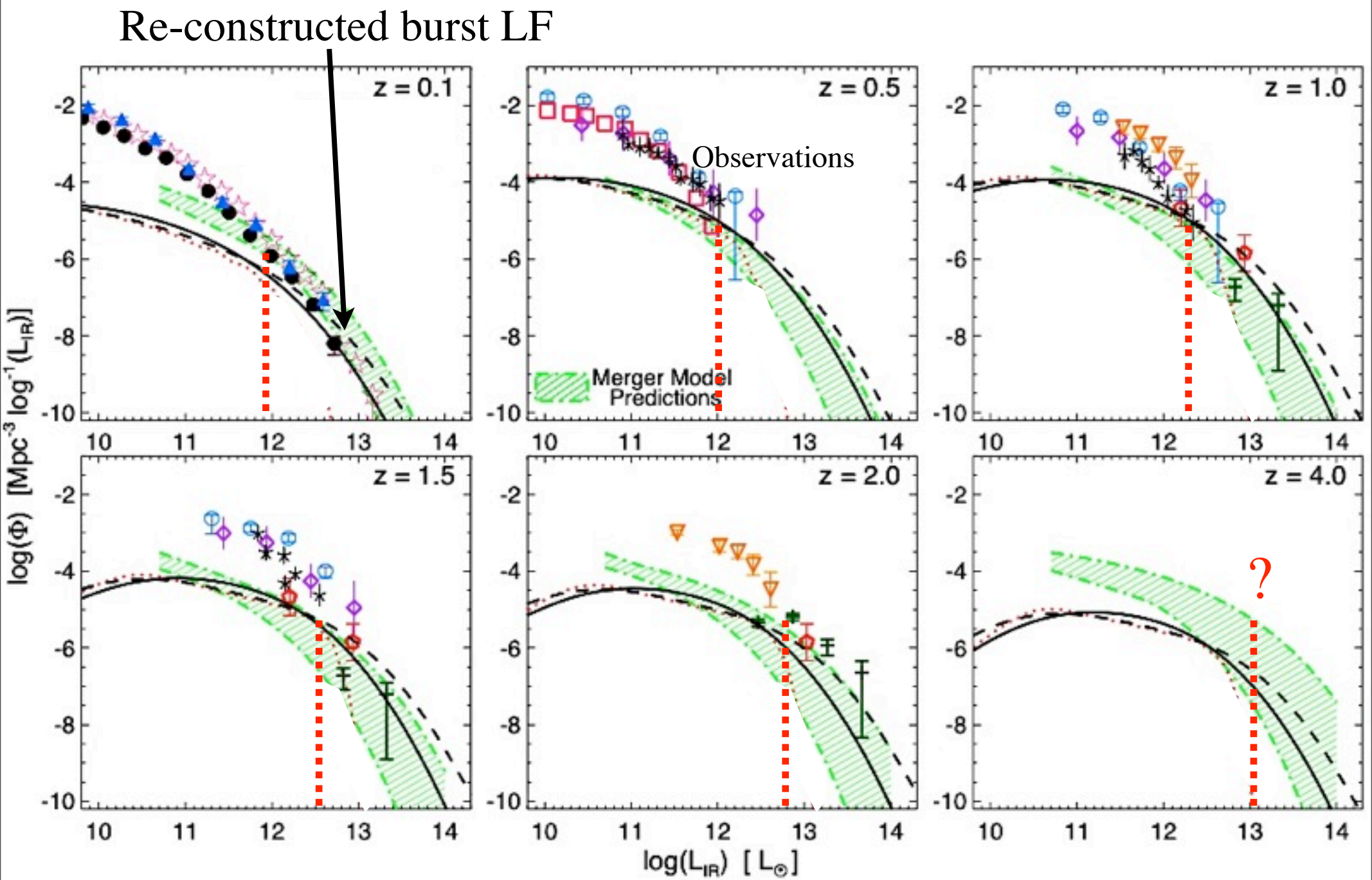


"place" each burst at the correct redshift

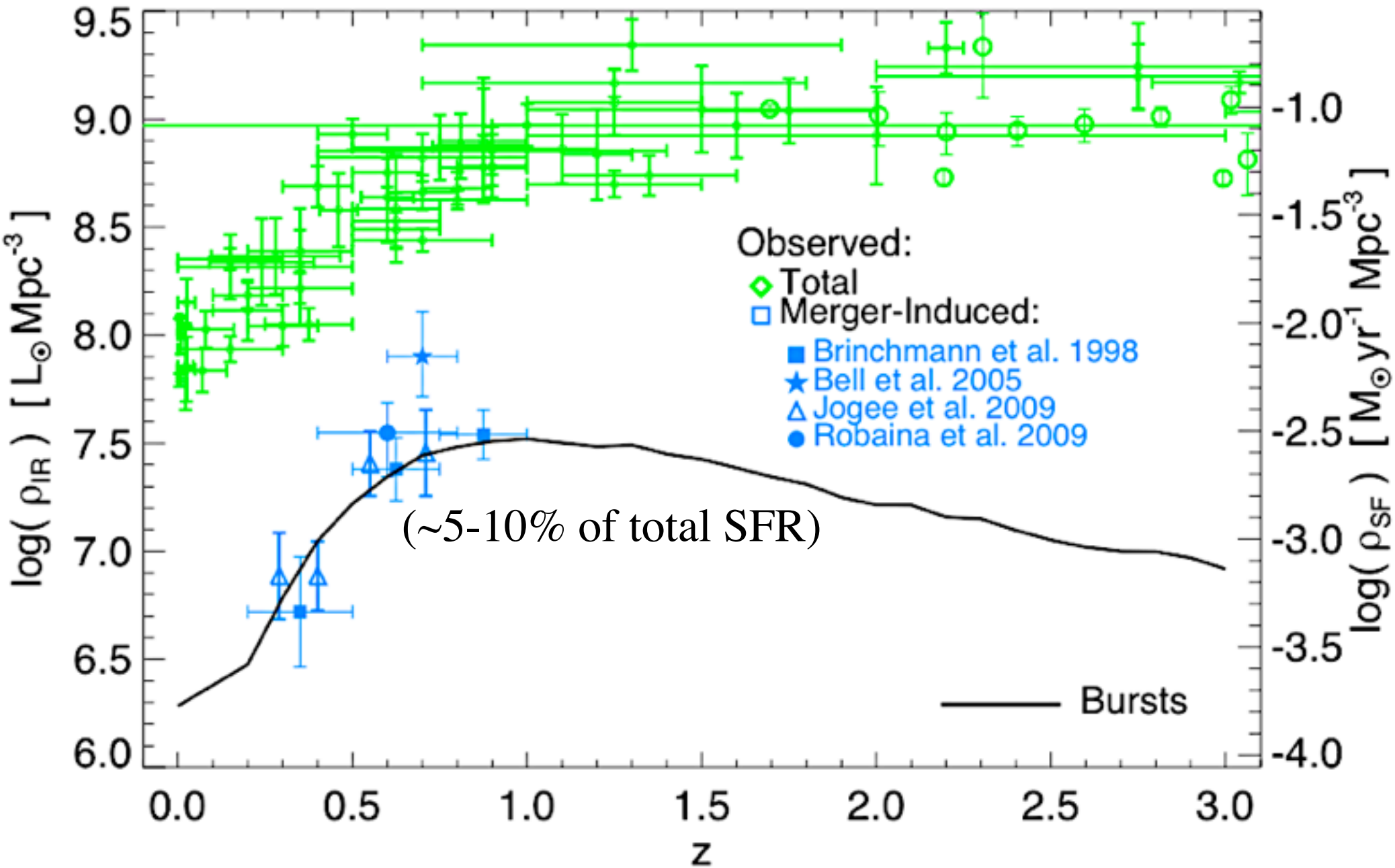
Recover the IR LF of dissipational starbursts!



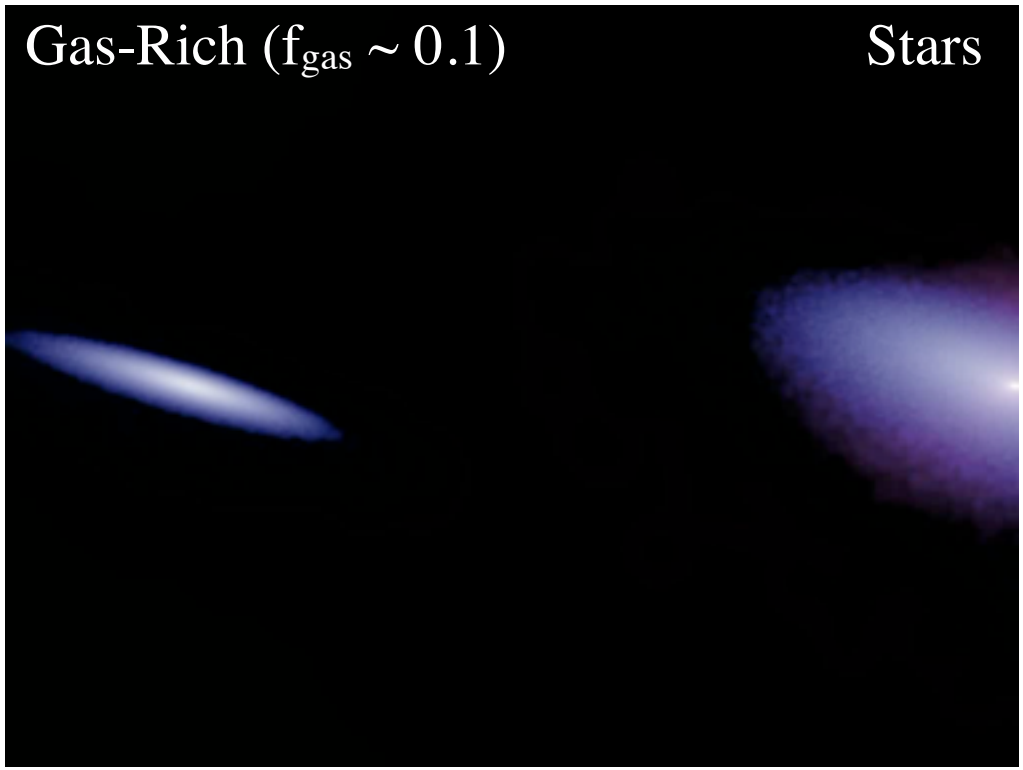
Bursts always dominate at high L, but the threshold shifts

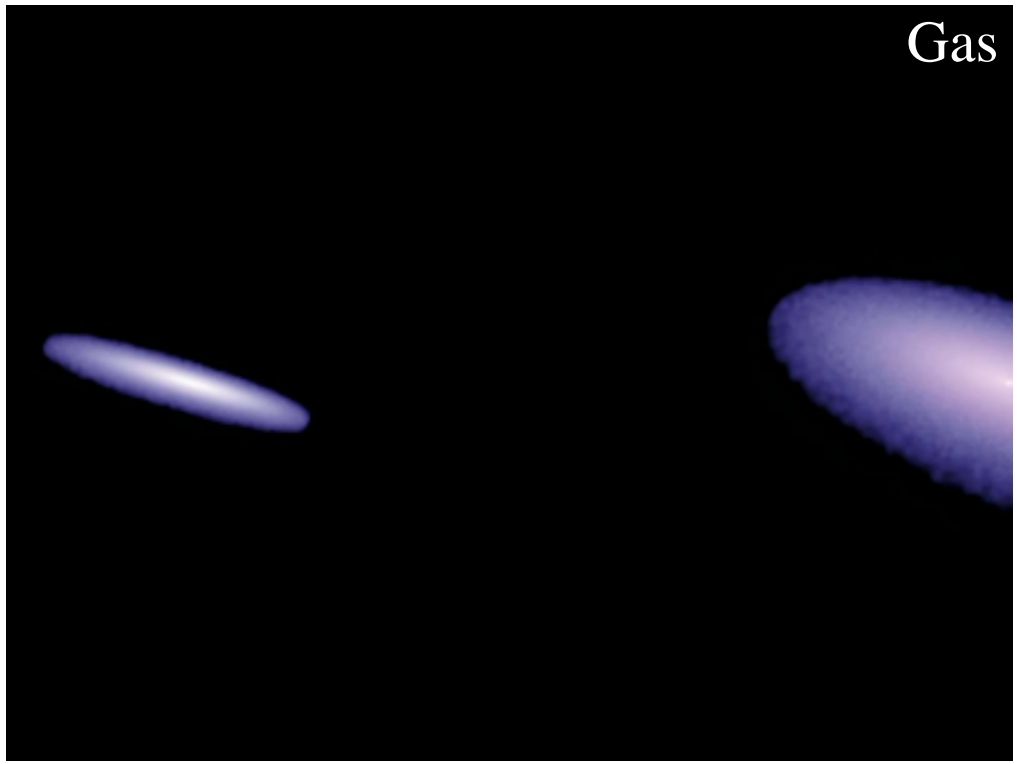


Bursts *never* dominate the SFR density!

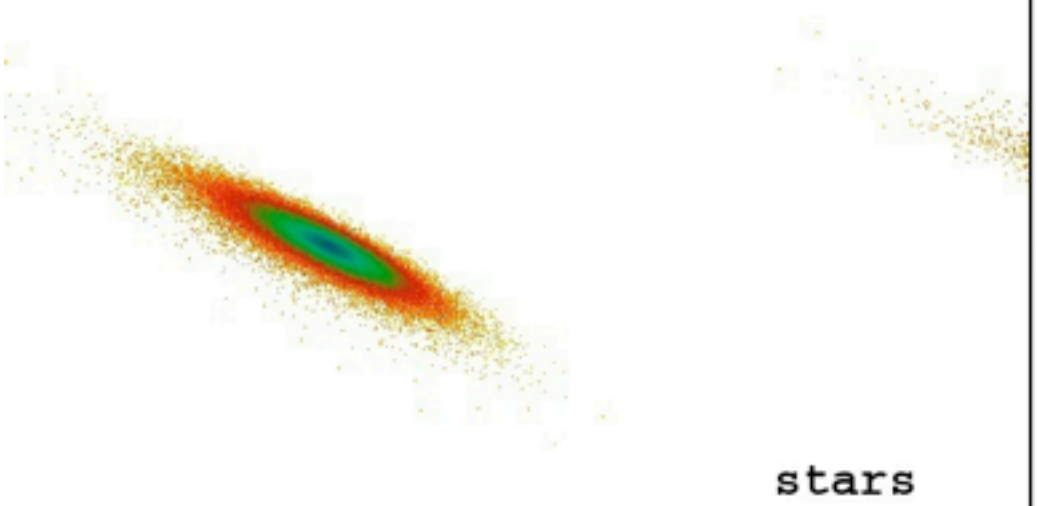


How Good Is Our Conventional Wisdom?



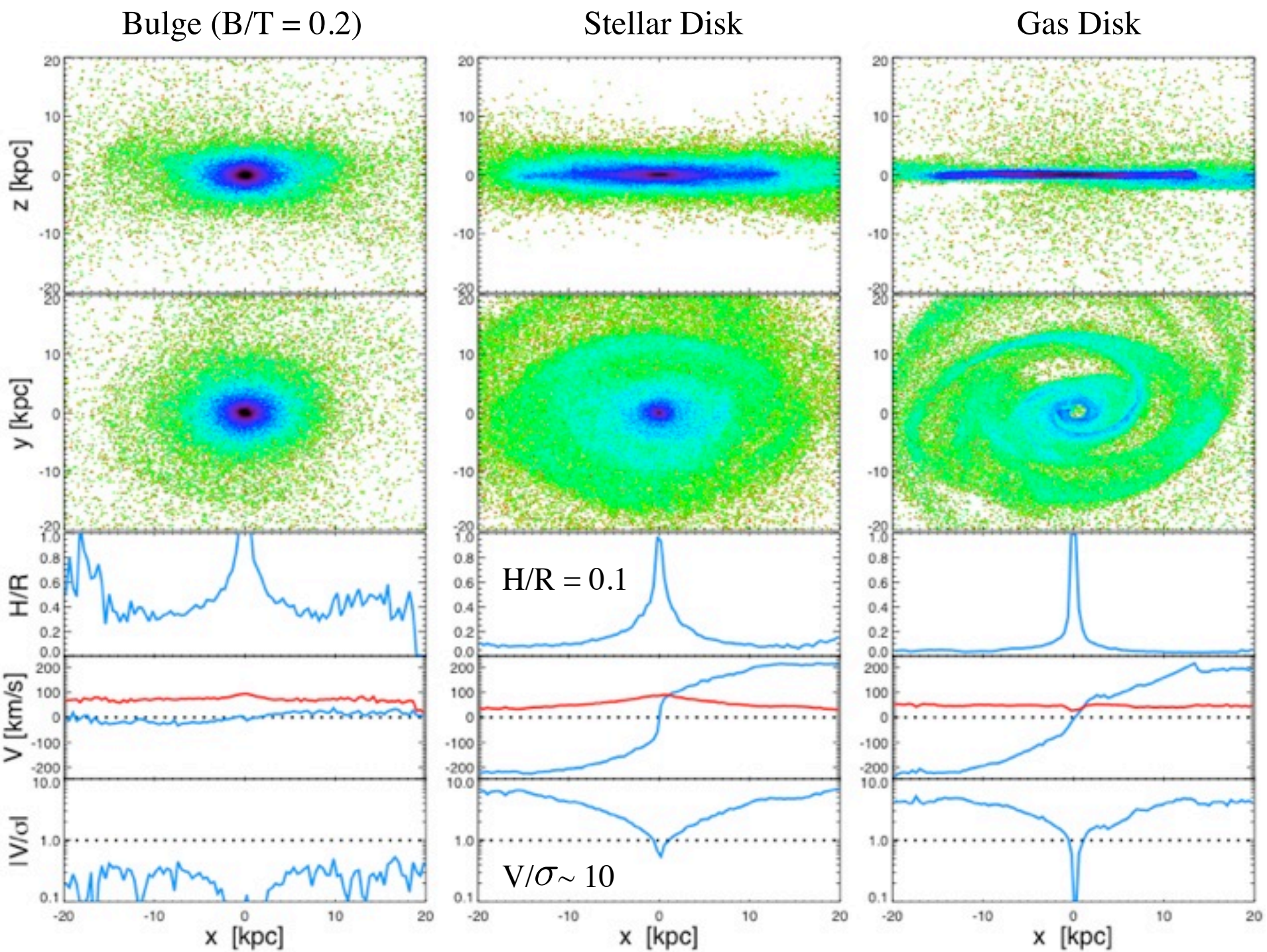


Gas-Richer ($f_{gas} \sim 0.4$)



Major Merger Remnants

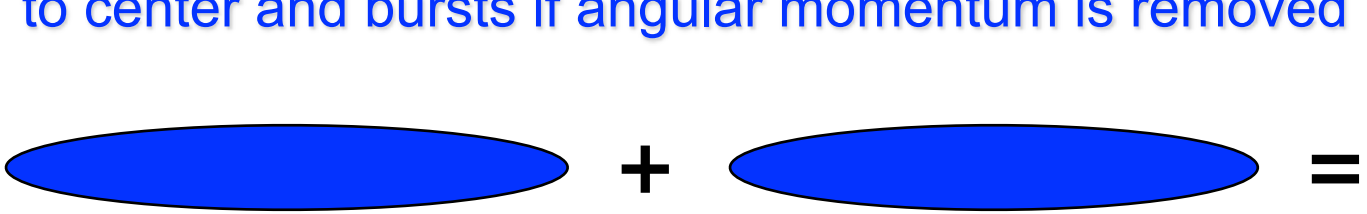
DO MERGERS DESTROY DISKS?

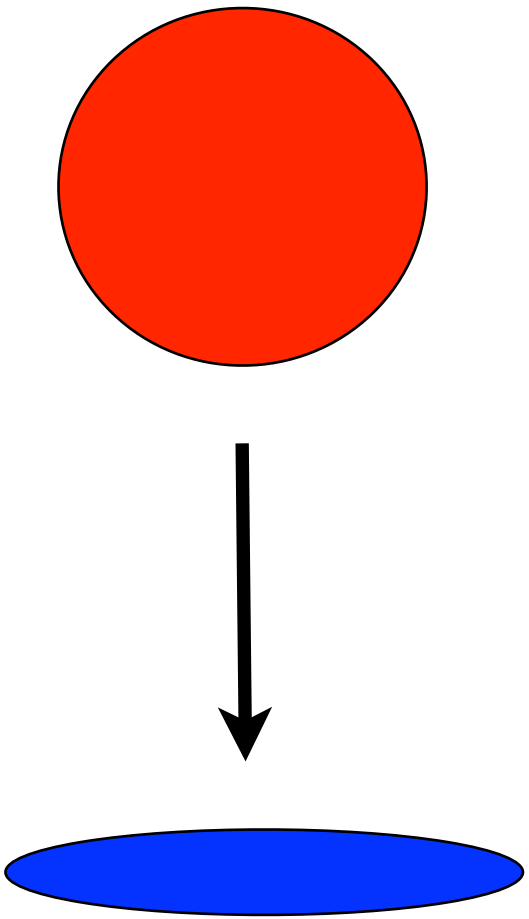


The Unsolved Questions

HOW CAN A DISK SURVIVE?

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

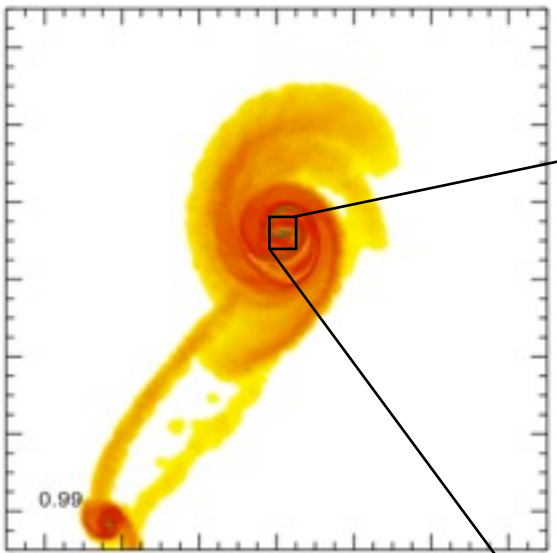


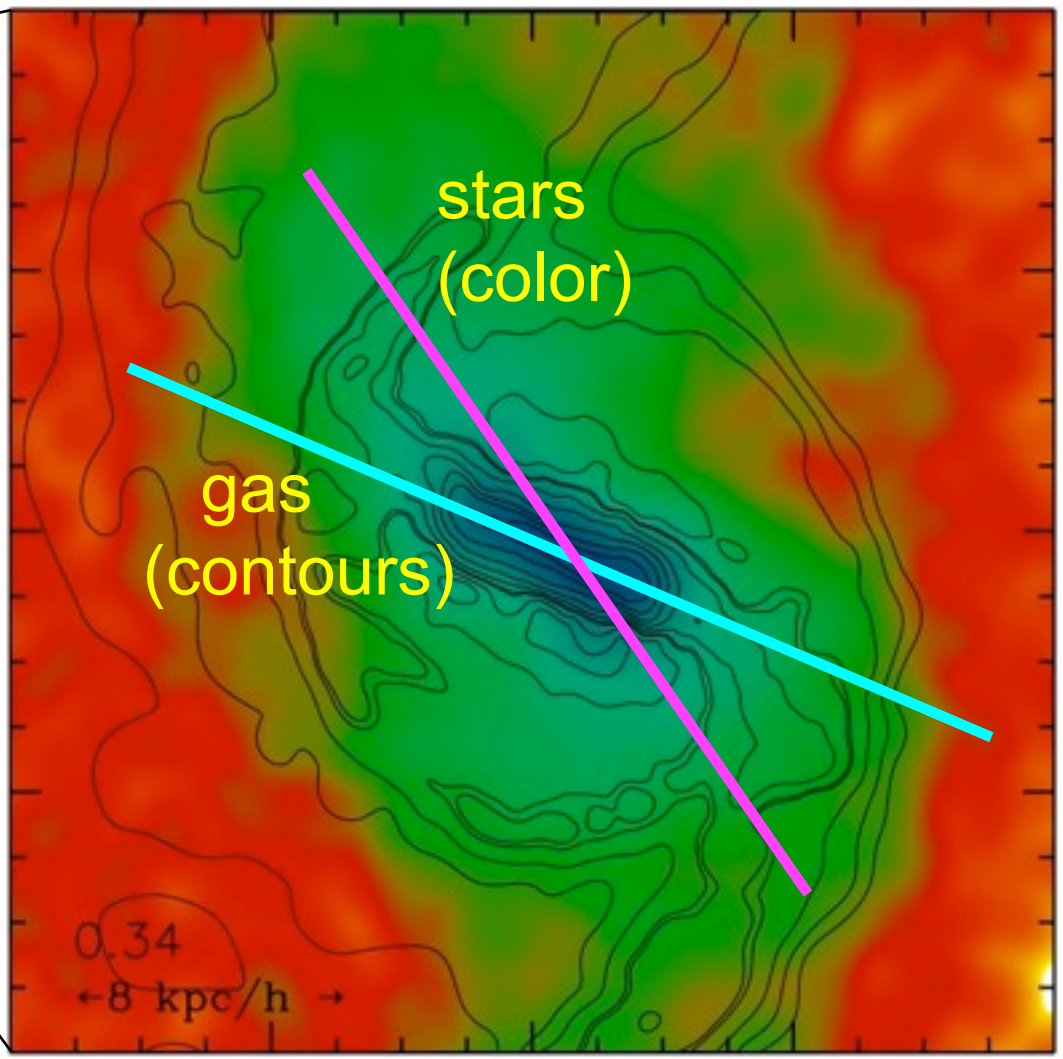


How Do Disks Survive Mergers?

PFH et al. 2008

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

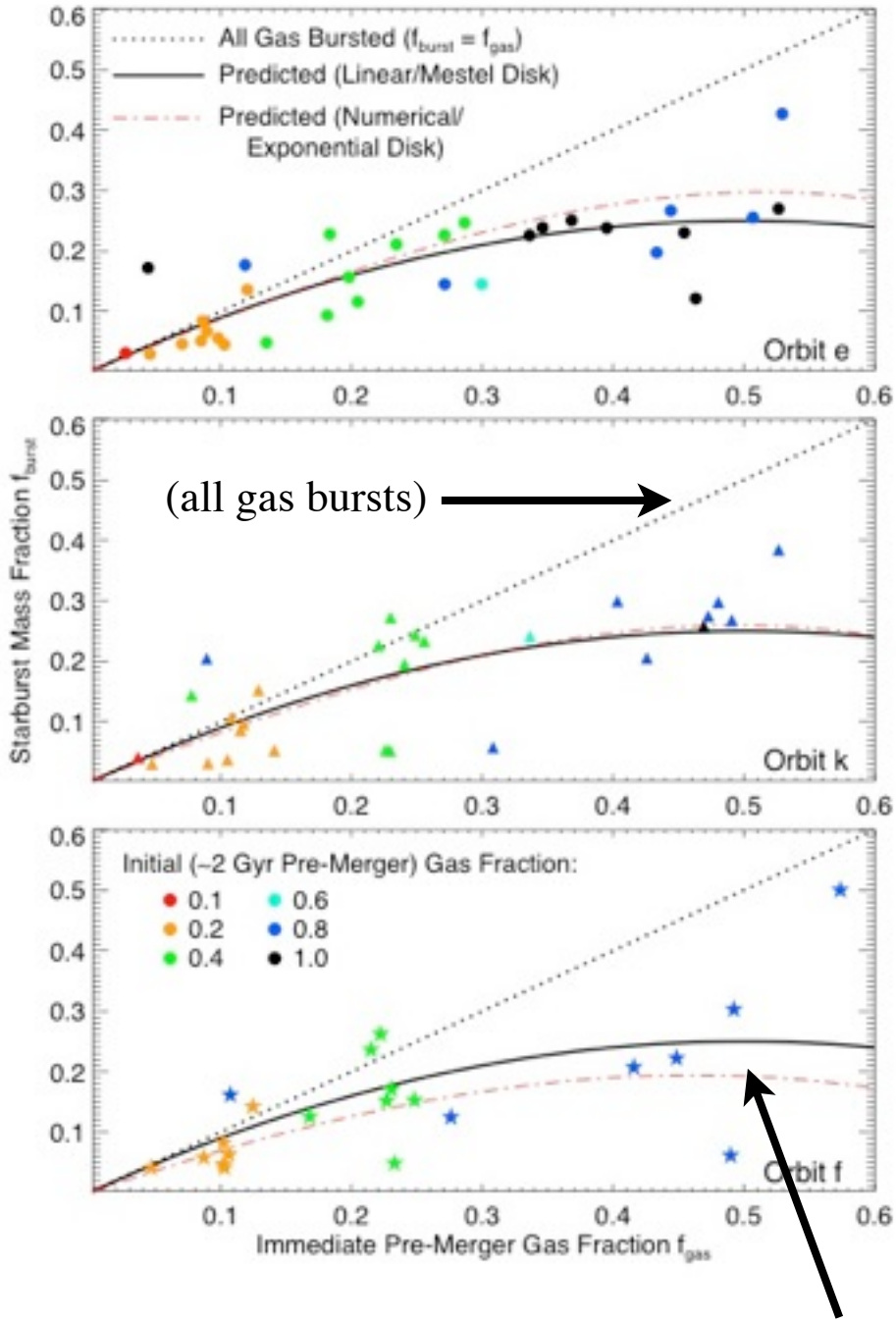




- What does the torquing?
  - *Stars* in the same galaxy

How Do Disks Survive Mergers?

Burst mass vs. f_{gas}



(all gas bursts)

Torque on gas:

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

For the same merger/perturbation:

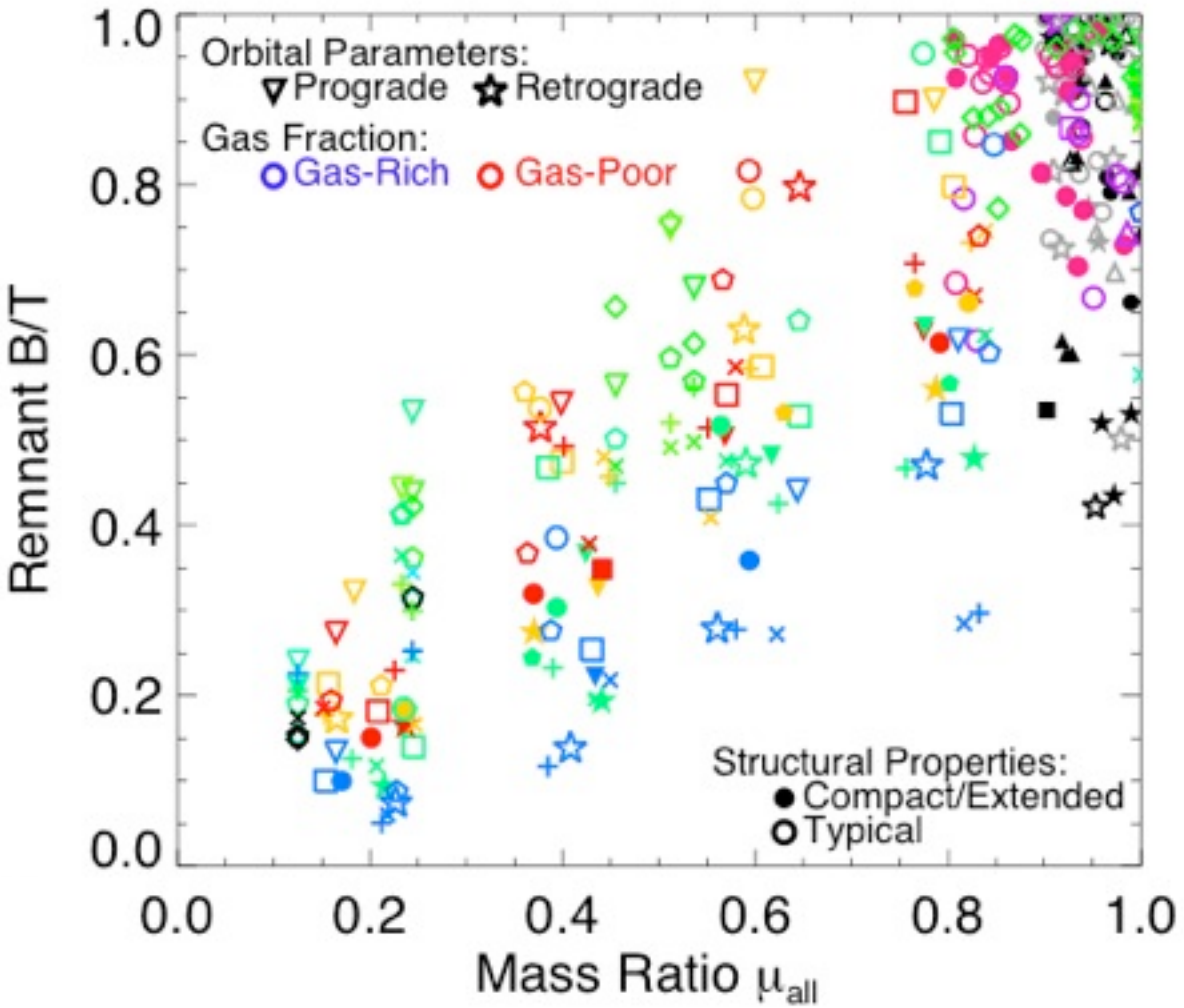
$M_{stellar\ bar} \propto M_{stellar} \propto (1 - f_{gas})$

(gas-dependent prediction)

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

How Do Disks Survive Mergers?

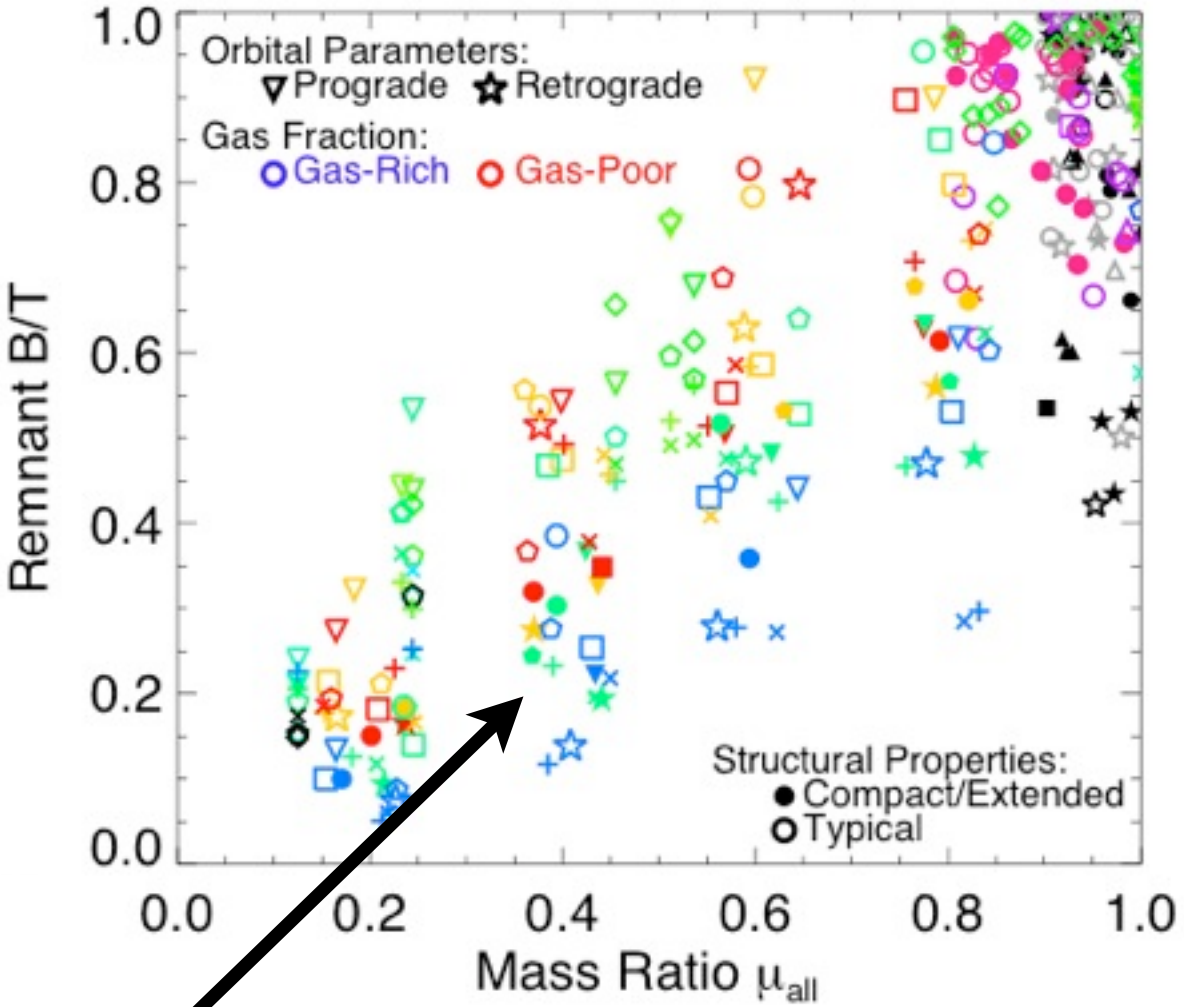
Can analytically determine burst masses and properties as a function of e.g. orbital parameters, f_{gas}, merger mass ratio, etc.



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.



REALLY IMPORTANT!!!

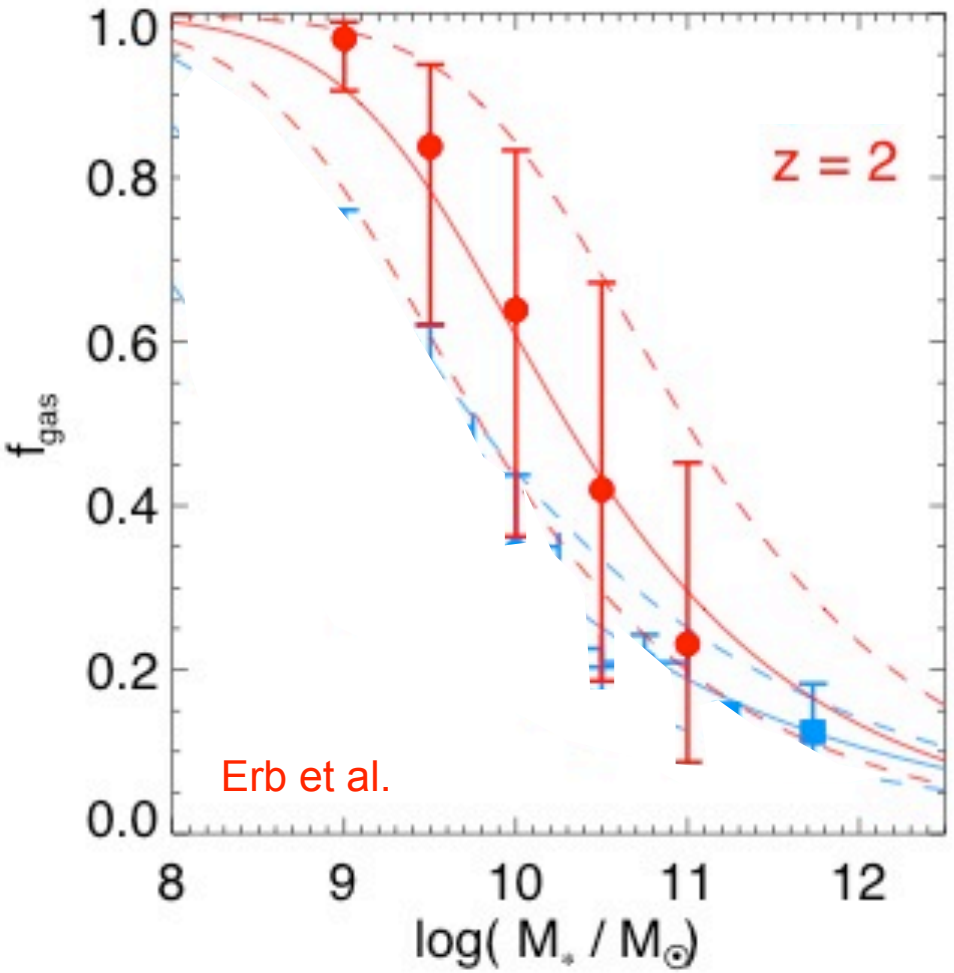
PFH et al. 2008 ("How Do Disks Survive Mergers?")

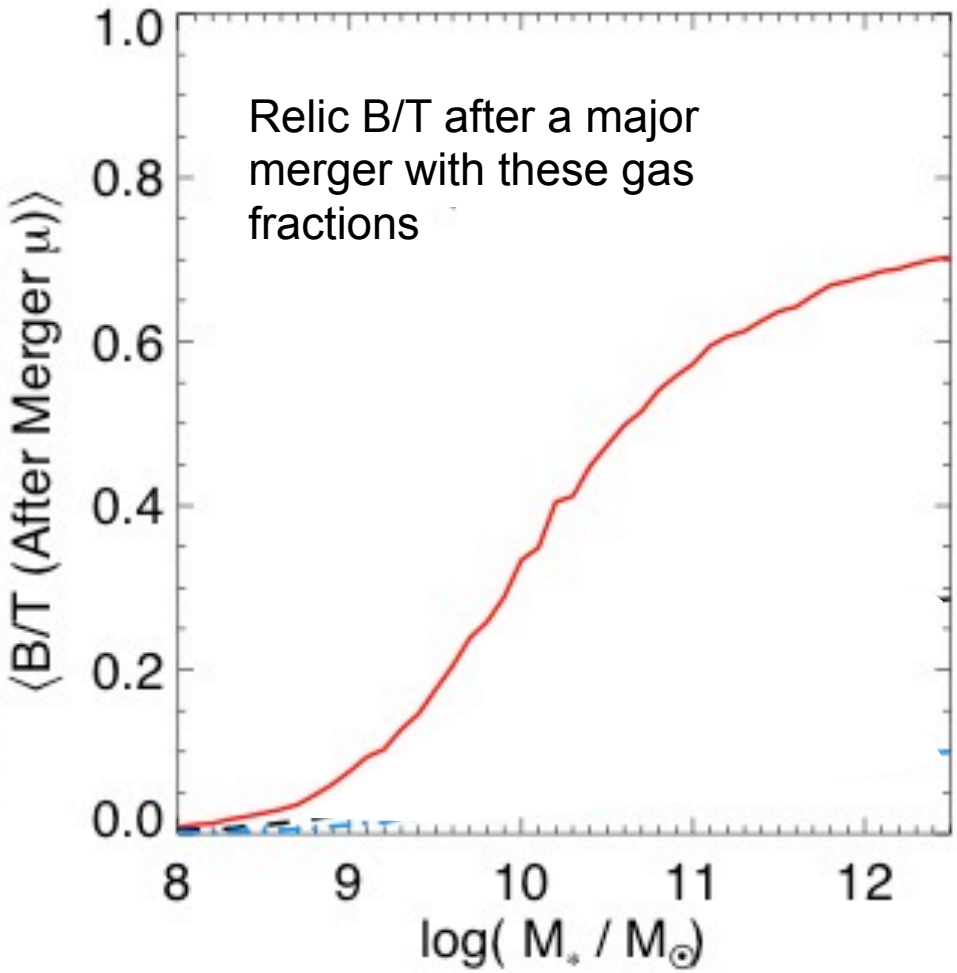
Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 200

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

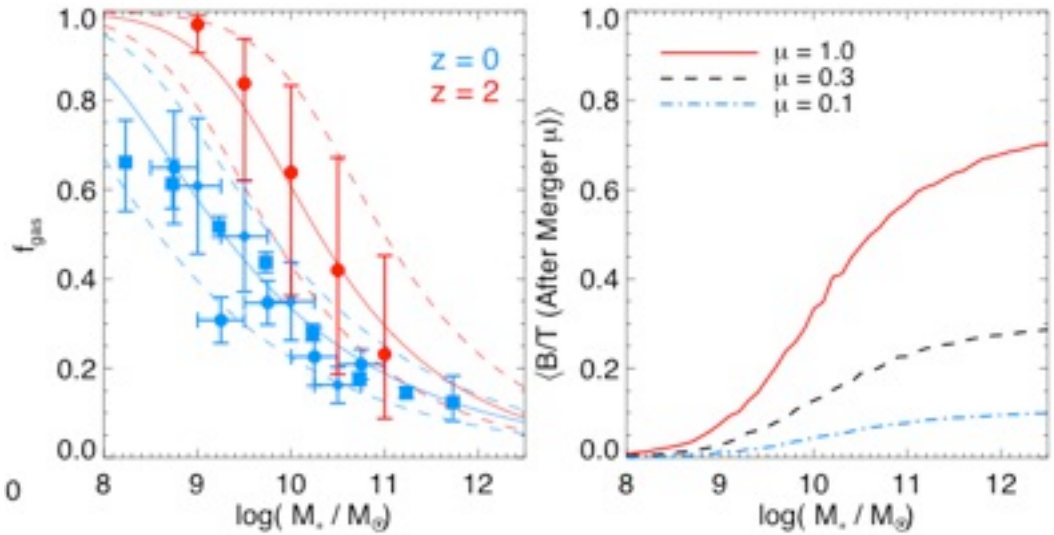




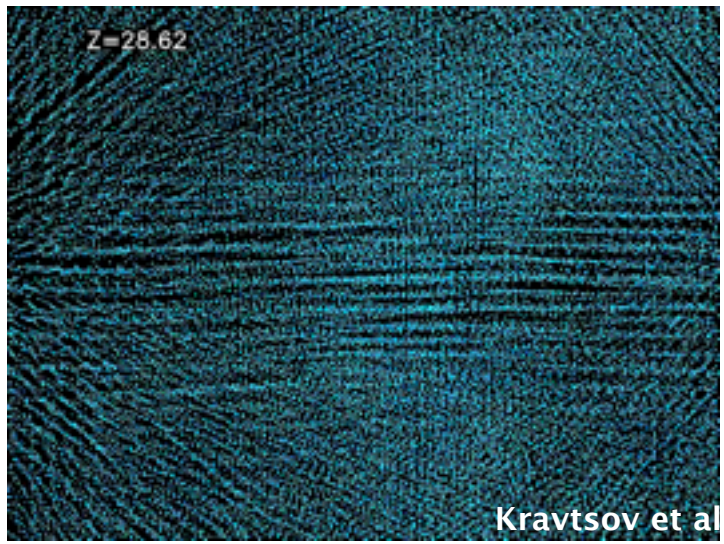
- Low-mass galaxies have high gas fractions: less B/T for the same mergers

Why Do We Care?

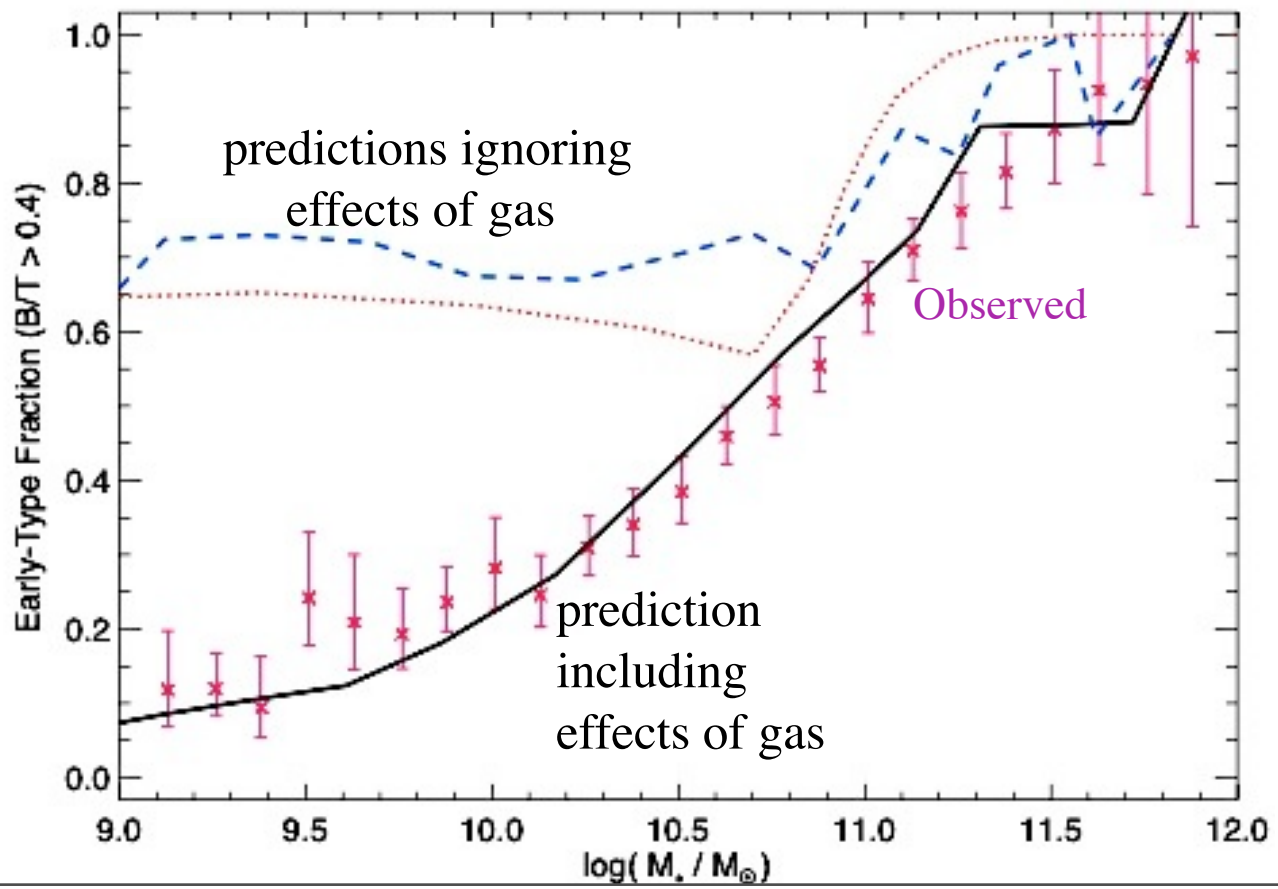
HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



+



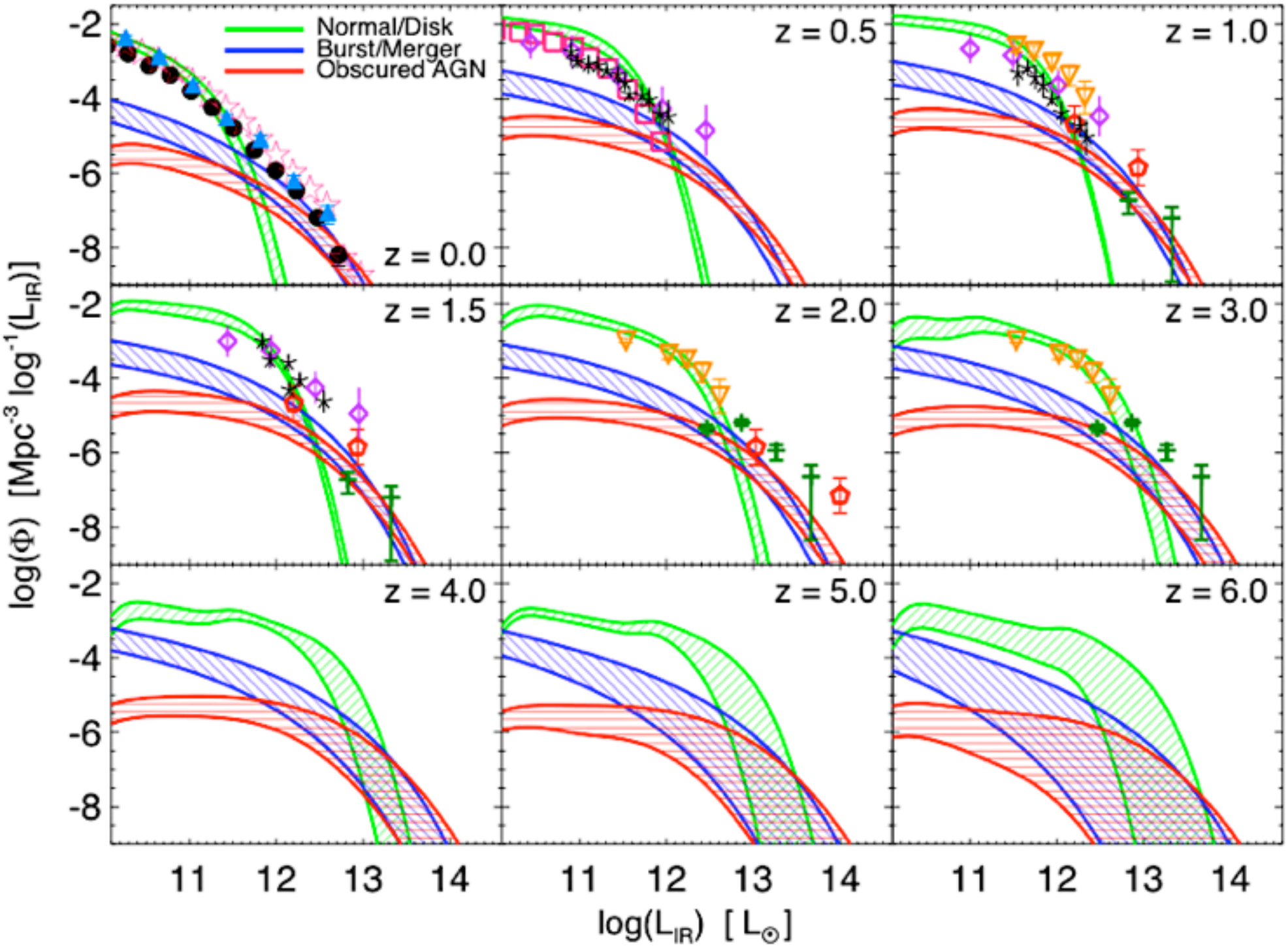
=



PFH & Somerville et al. 2009

Have burst predictions -- why not use them?

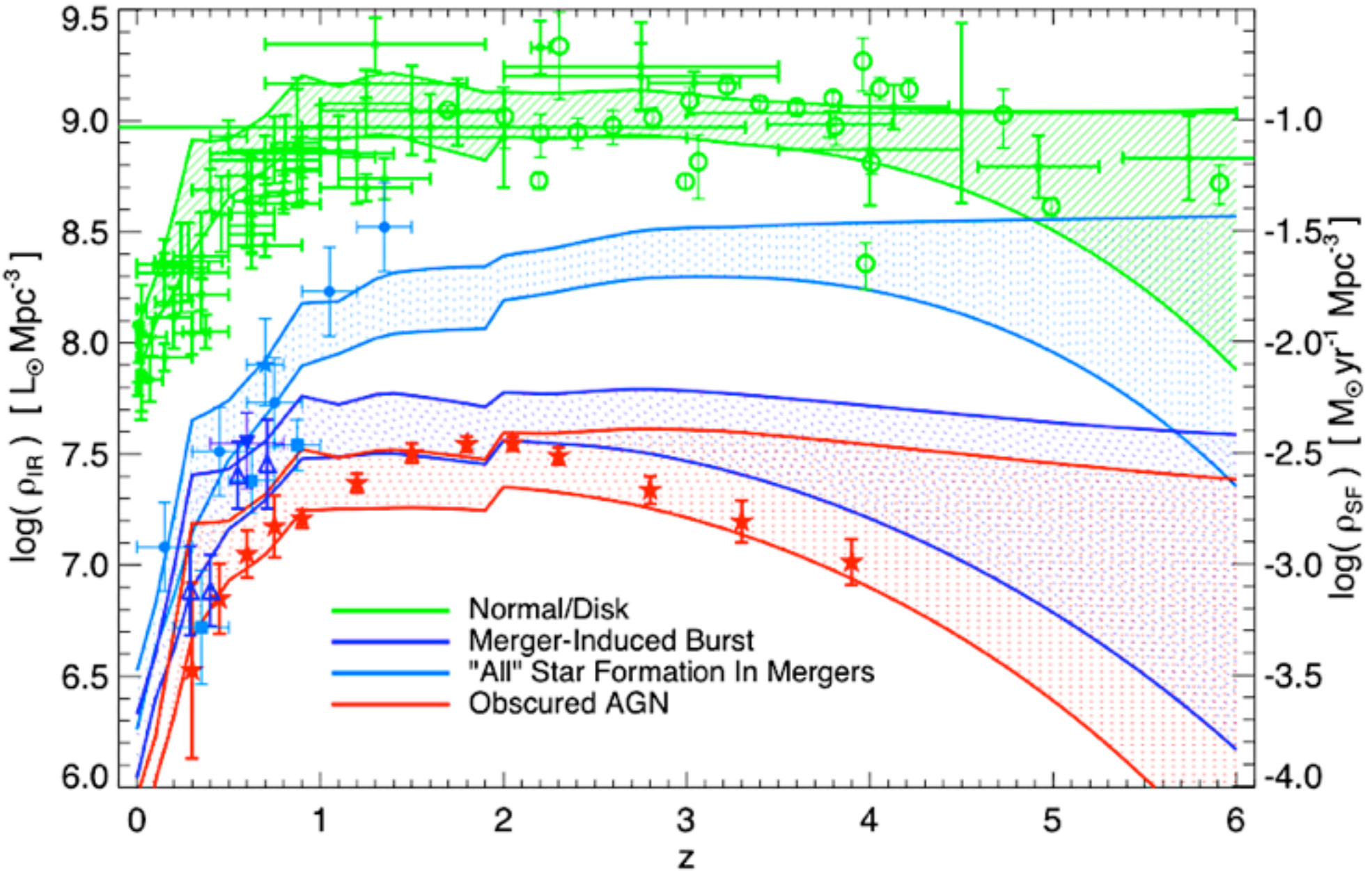
PFH, Younger et al. 20



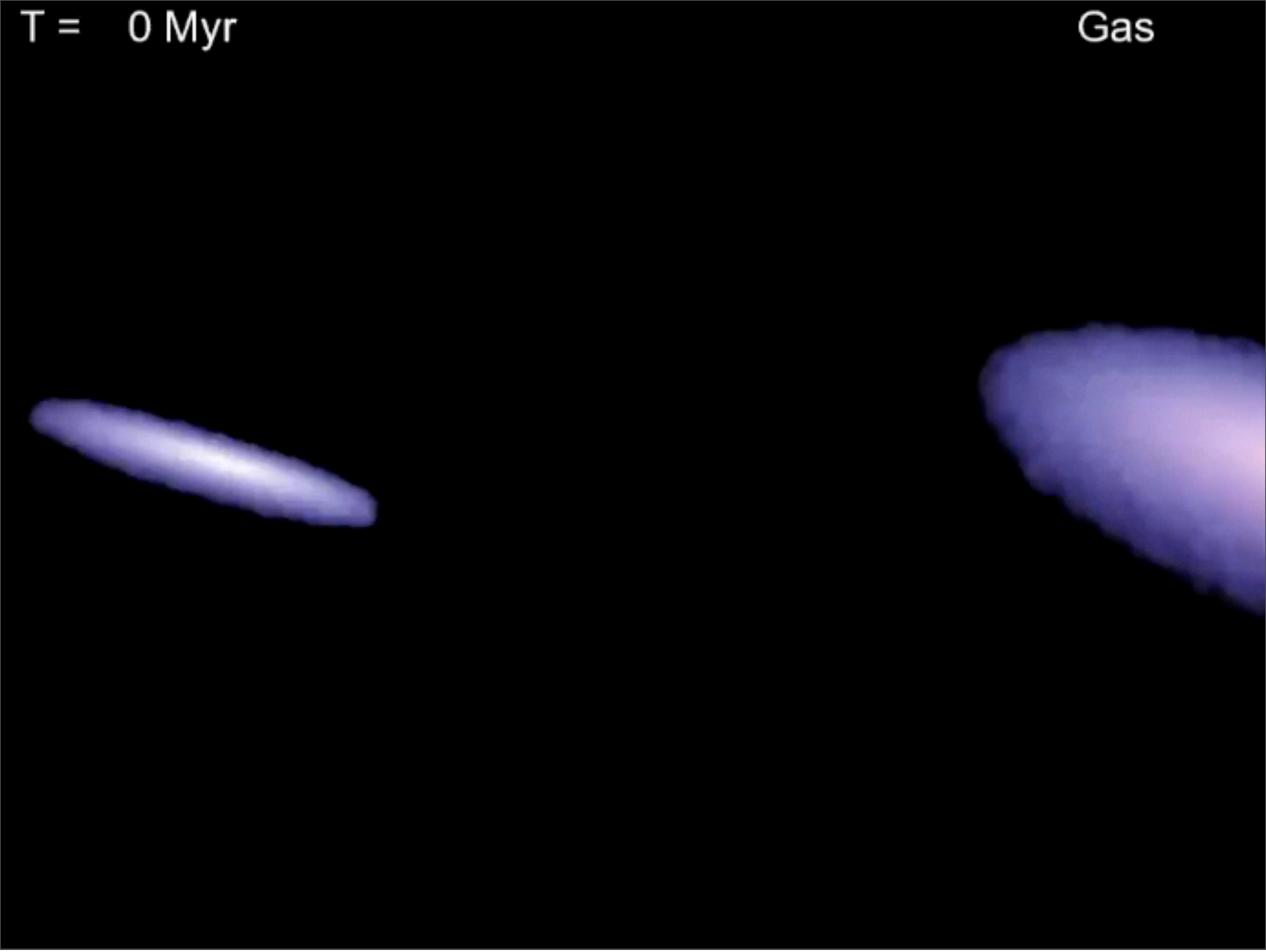
Have burst predictions -- why not use them?

PFH, Younger et al. 20

All SF in Merging Systems $\neq$ All SF *Induced* by Mergers



With all this gas getting to the center of the galaxy, what is the black hole doing?


T = 0 Myr
Gas

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?
- Relics of starbursts are important in today's Universe
  - What to expect at high redshifts?
- 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
- Don't forget about black holes and AGN!