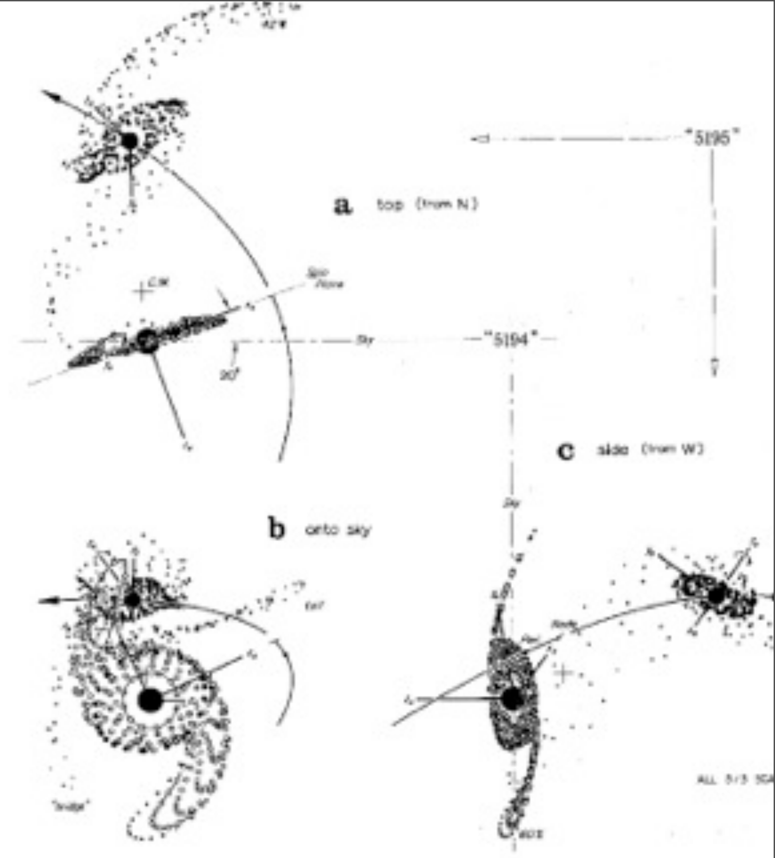
Gas & Galaxy Mergers: Driving an Evolving Hubble Sequence

Philip Hopkins

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

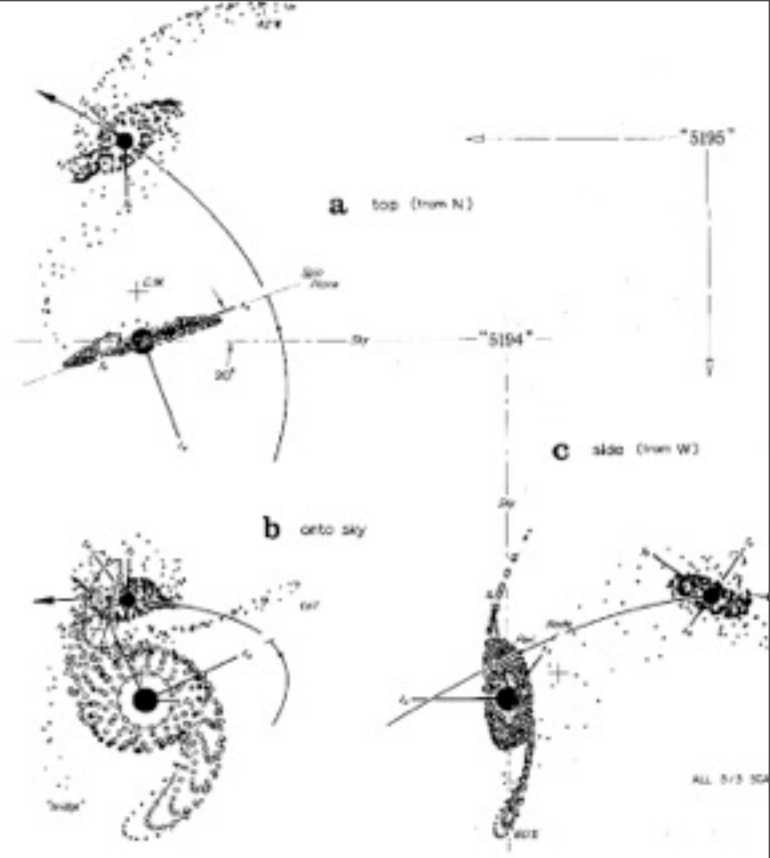
Our Conventional Wisdom (Toomre):



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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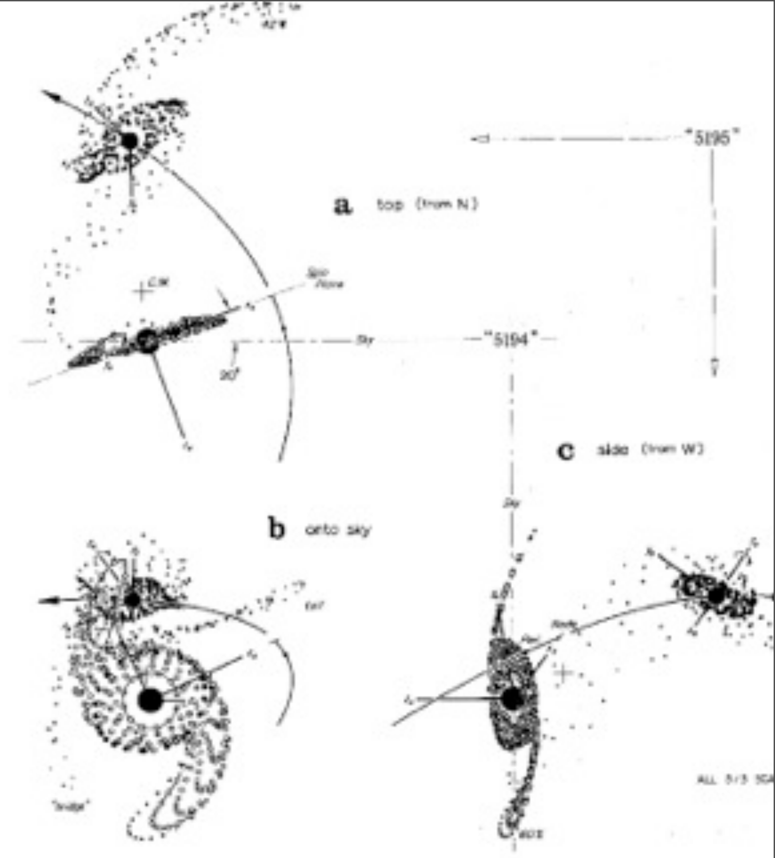

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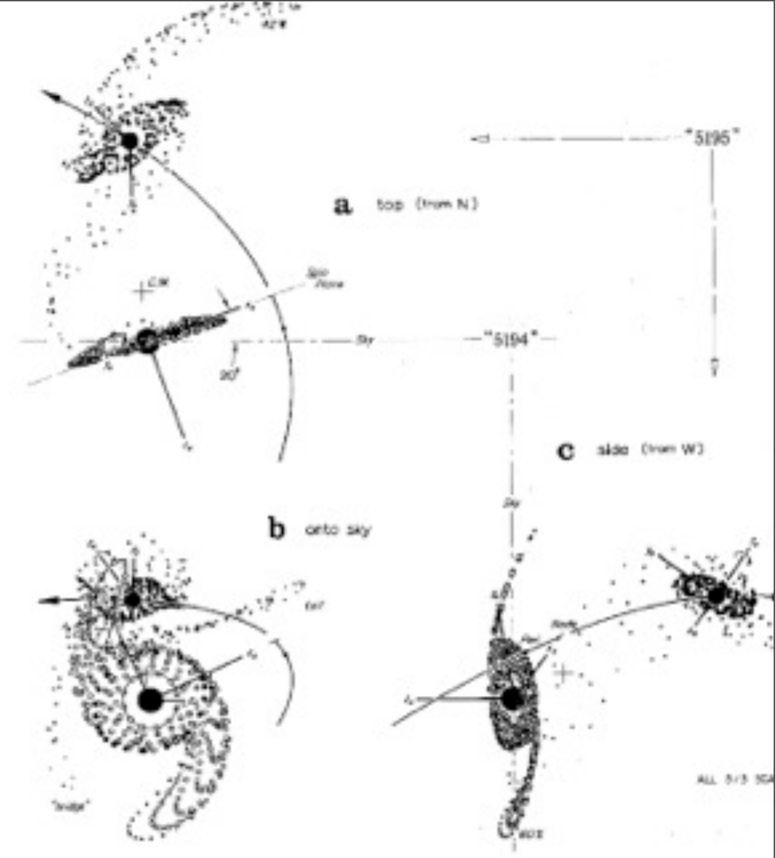

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Our Conventional Wisdom (Toomre):

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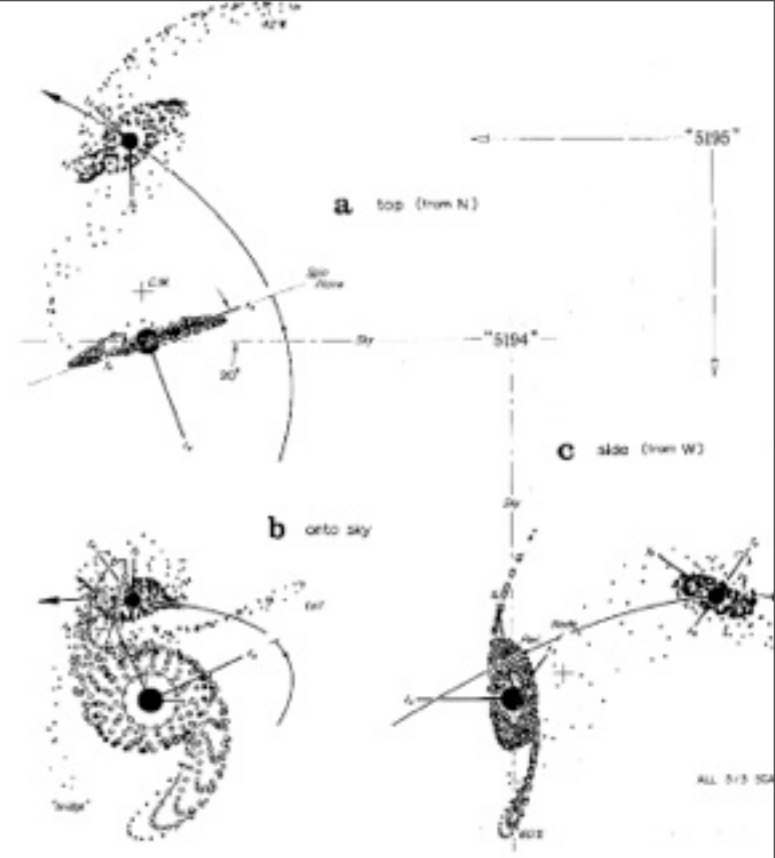
- Remnant has an $r^{1/4}$ law profile
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



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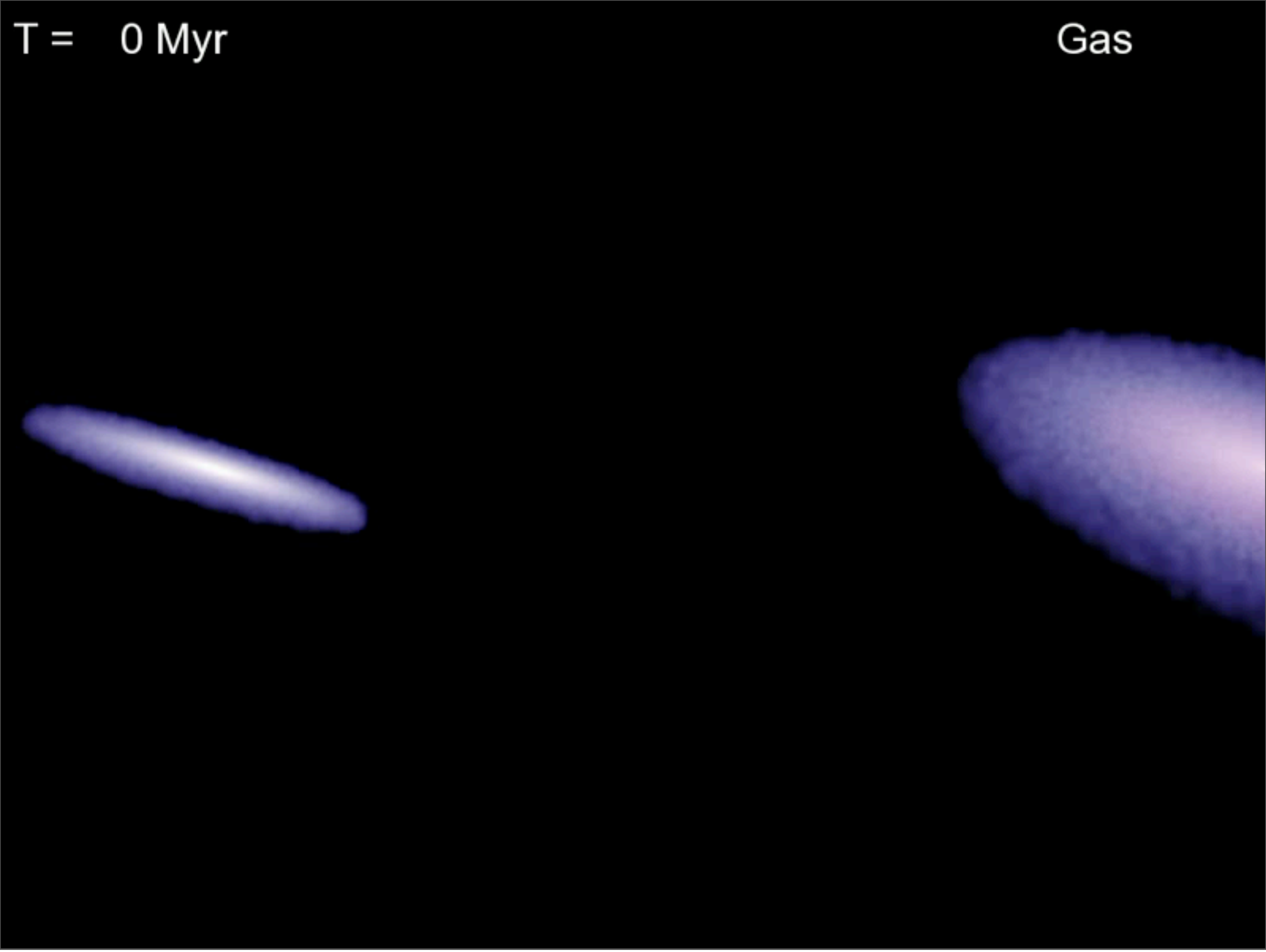
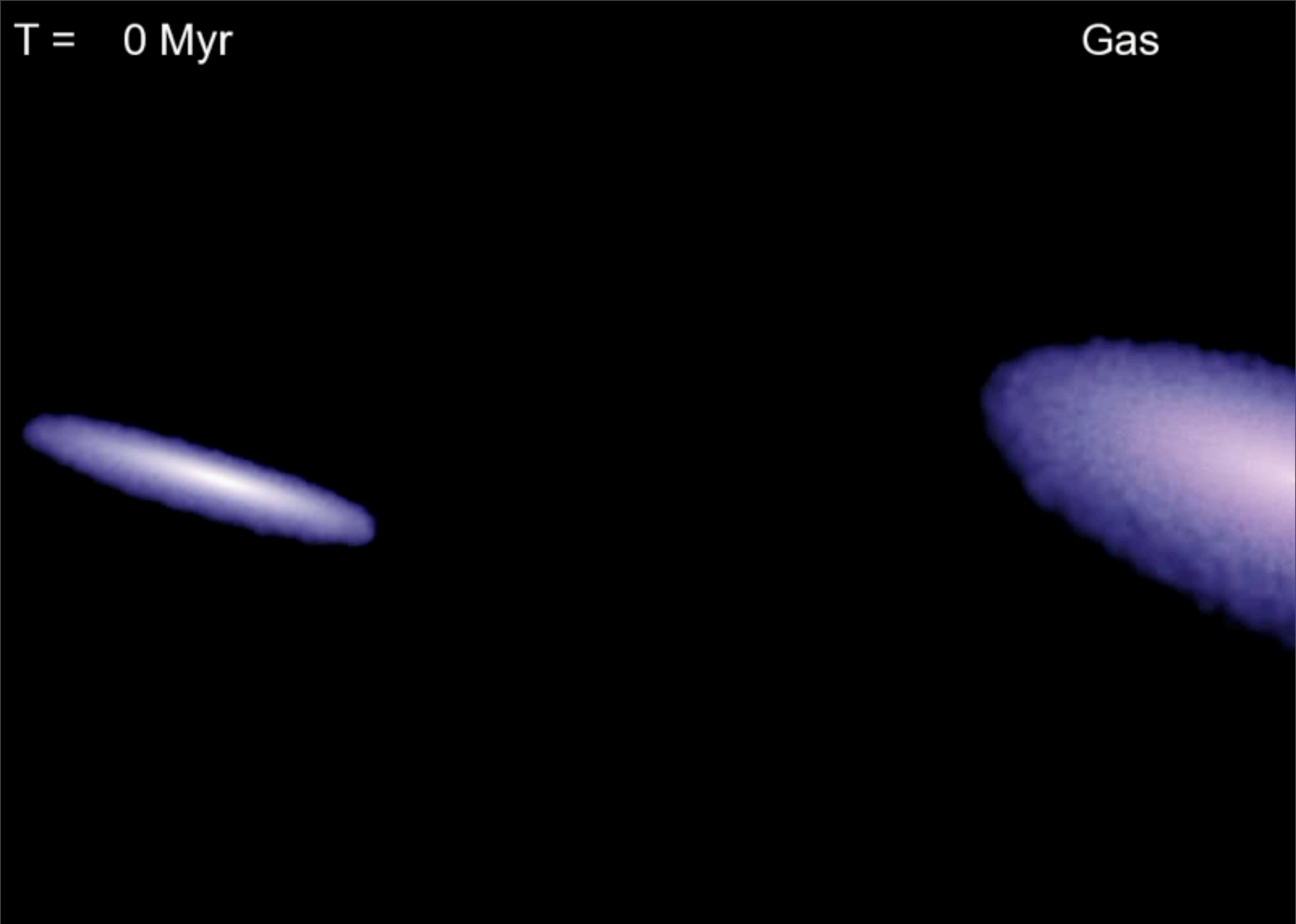
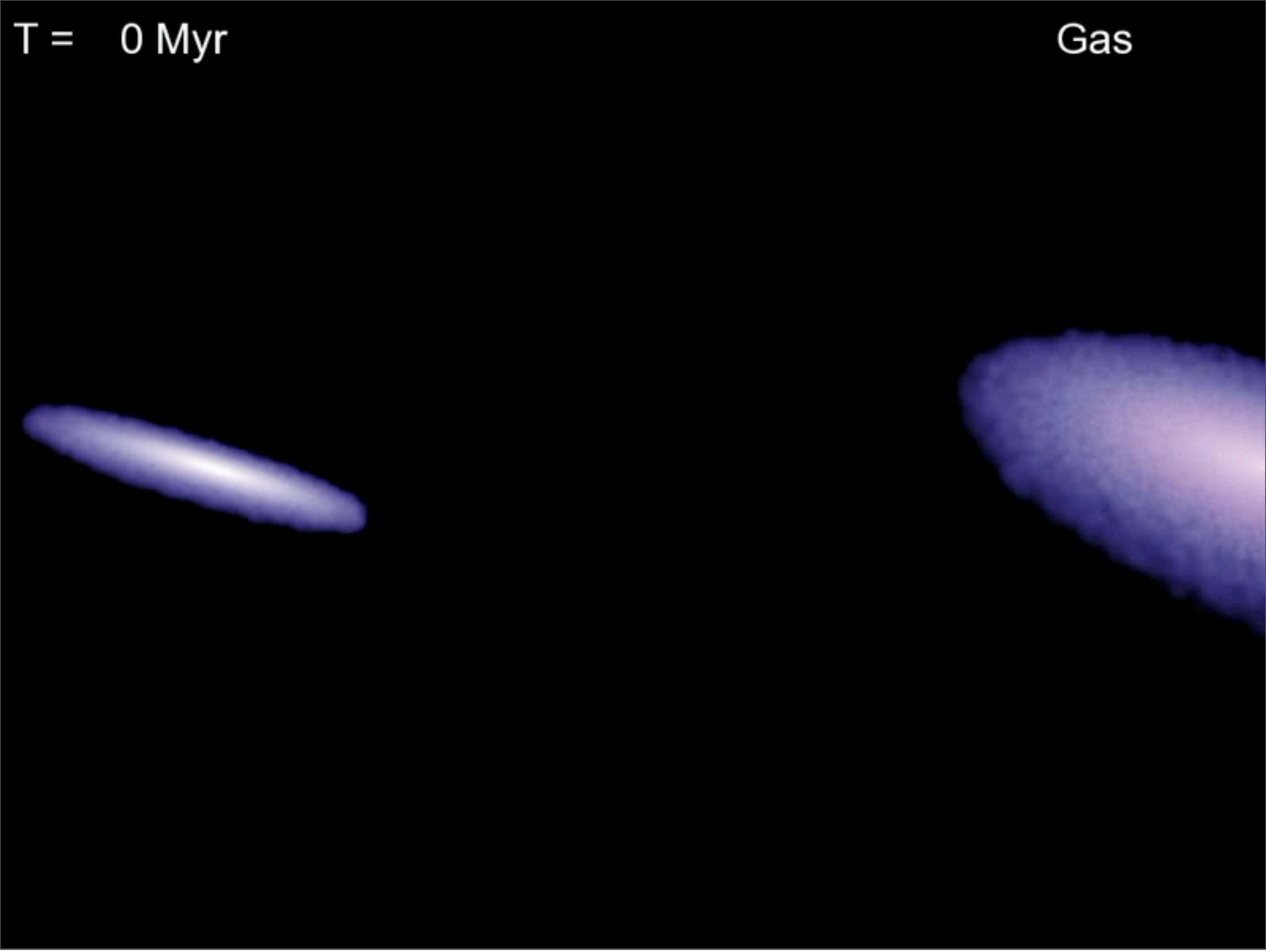

T = 0 Myr
Gas



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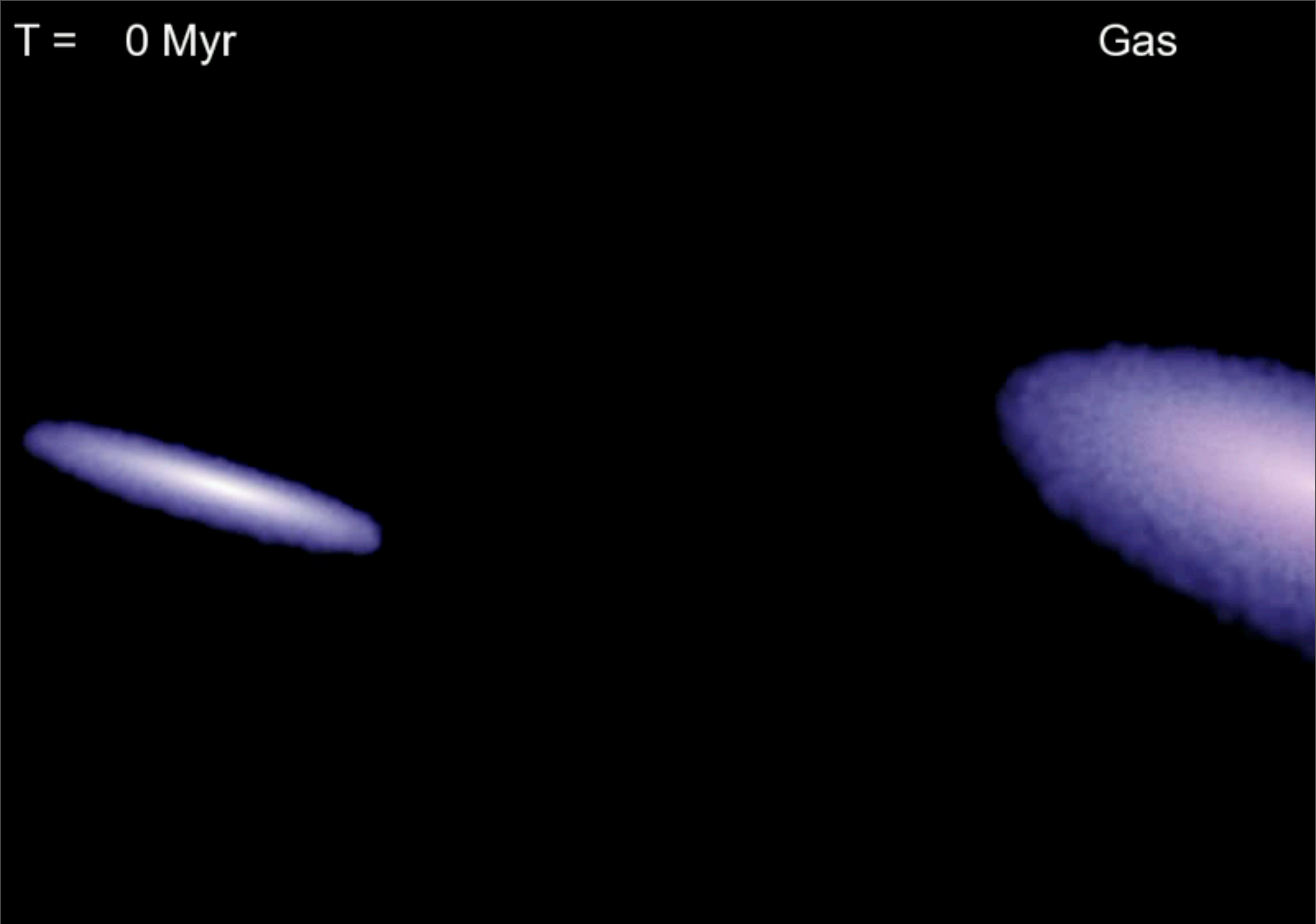
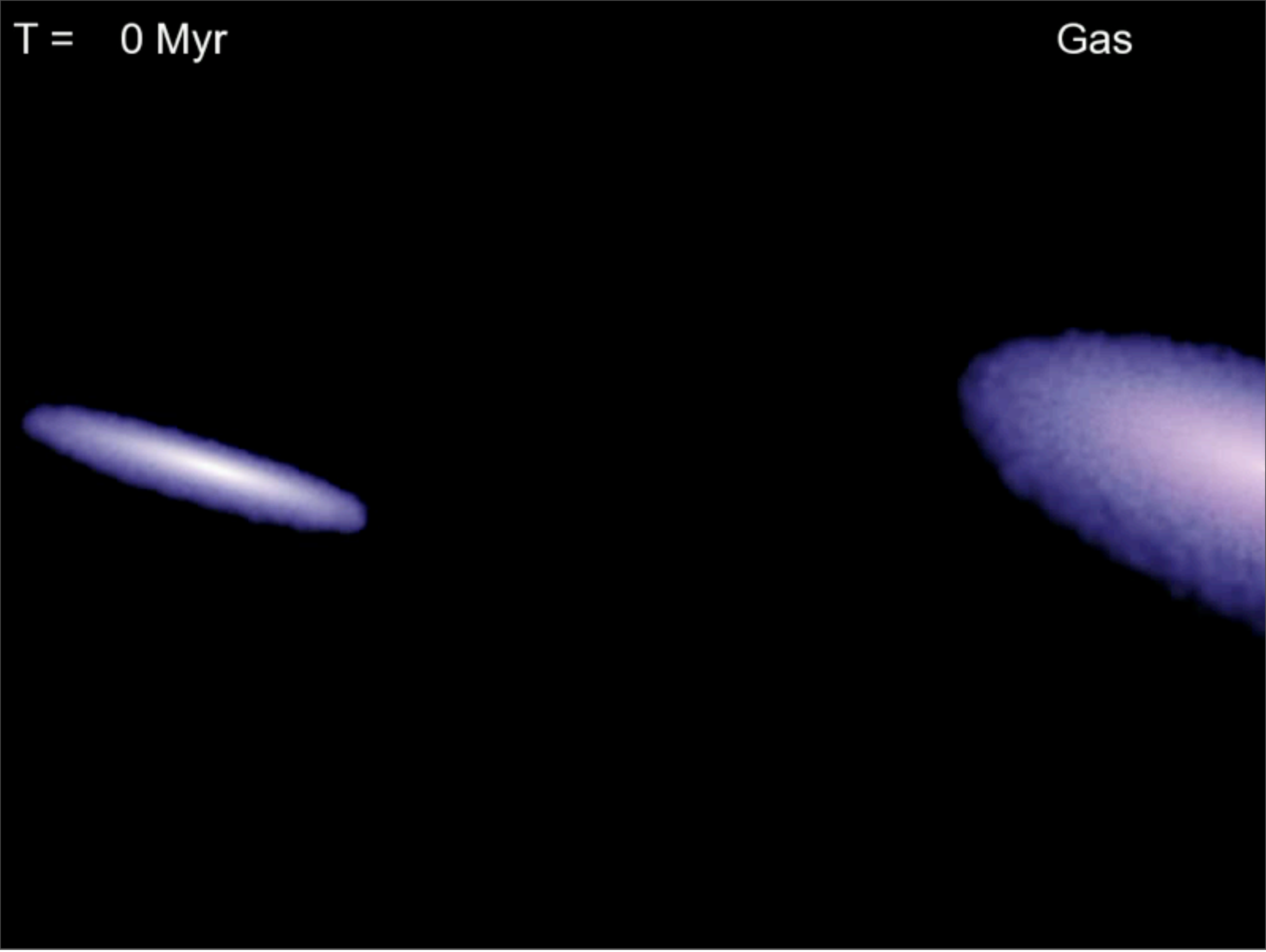


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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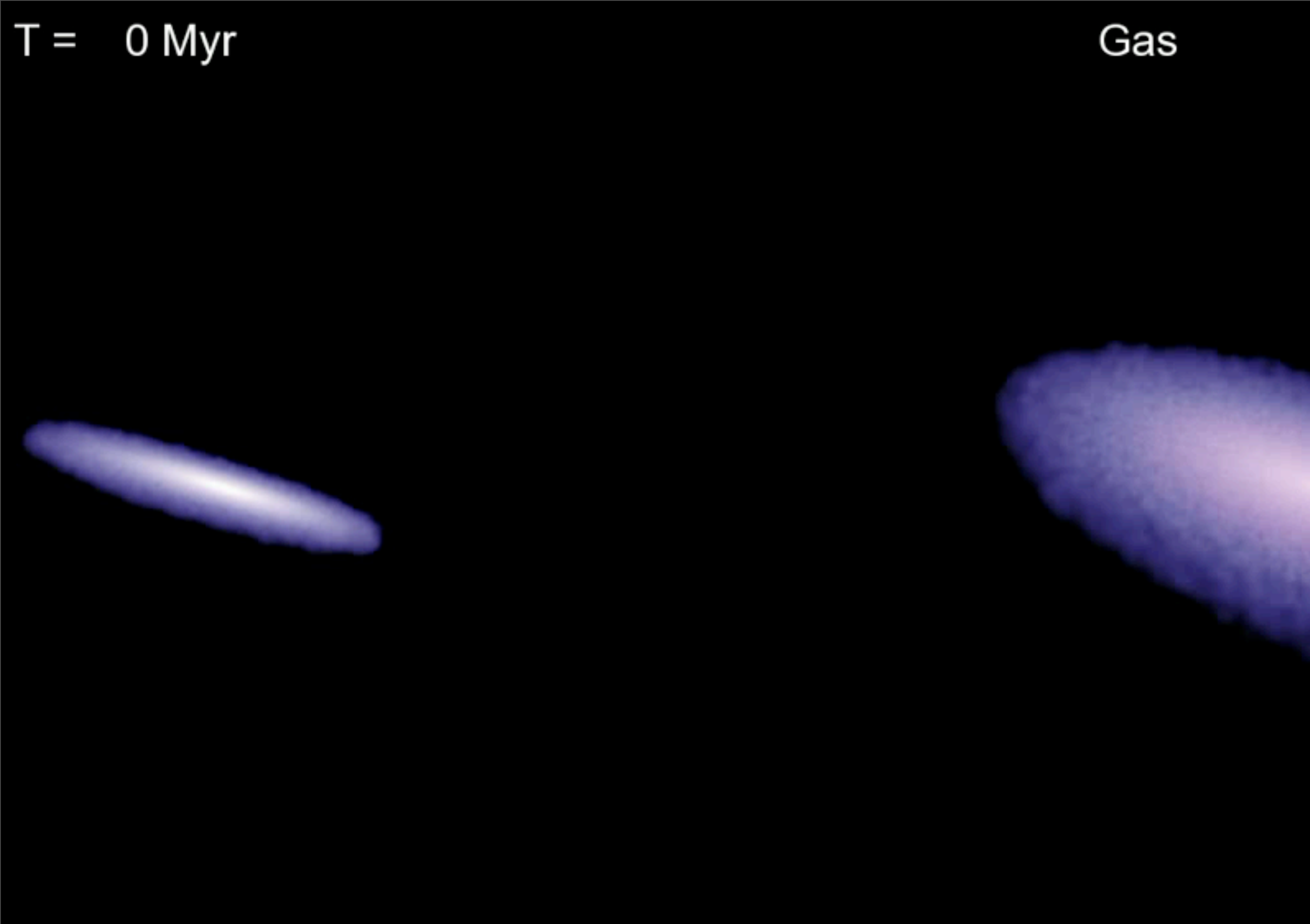
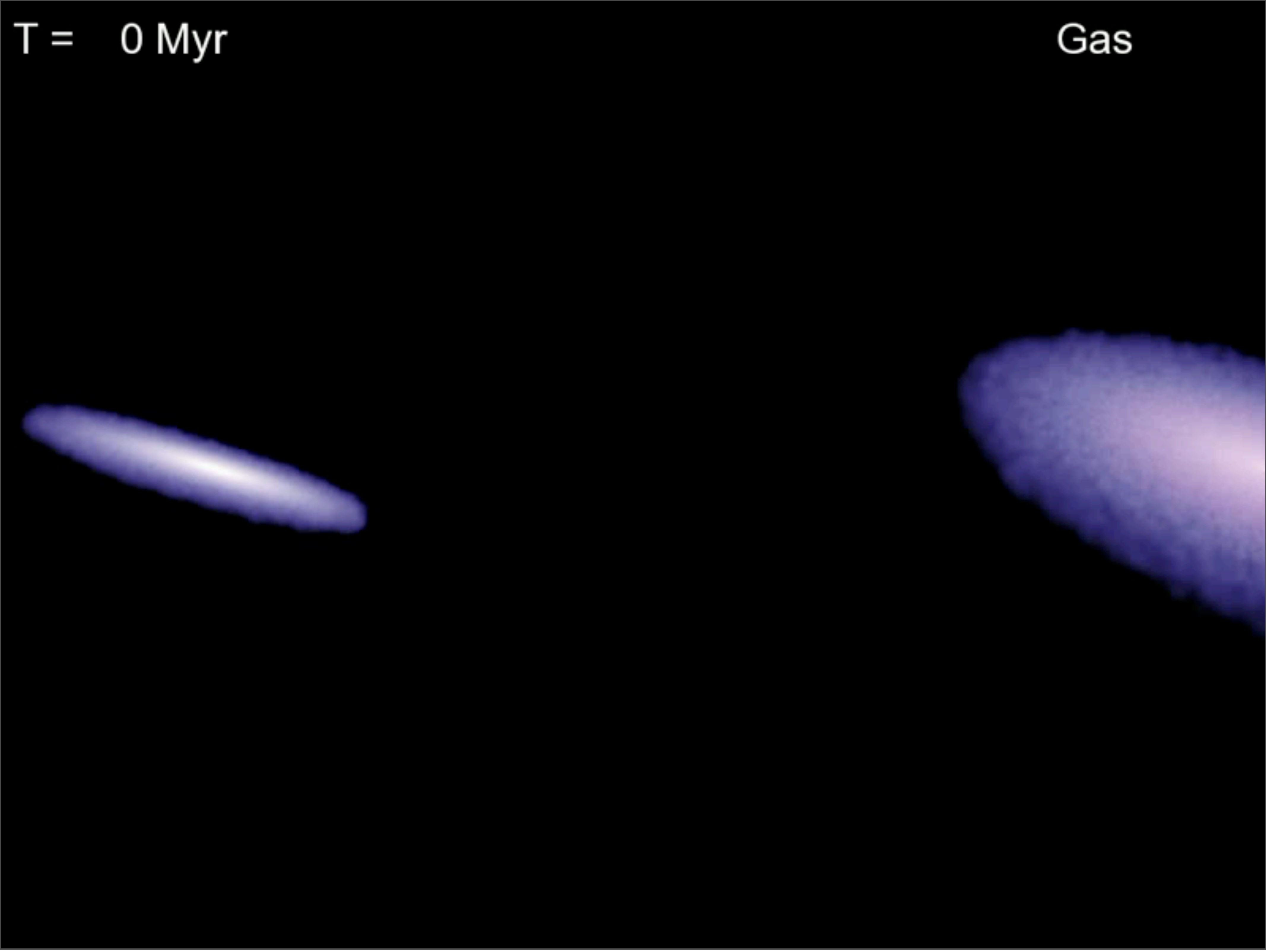


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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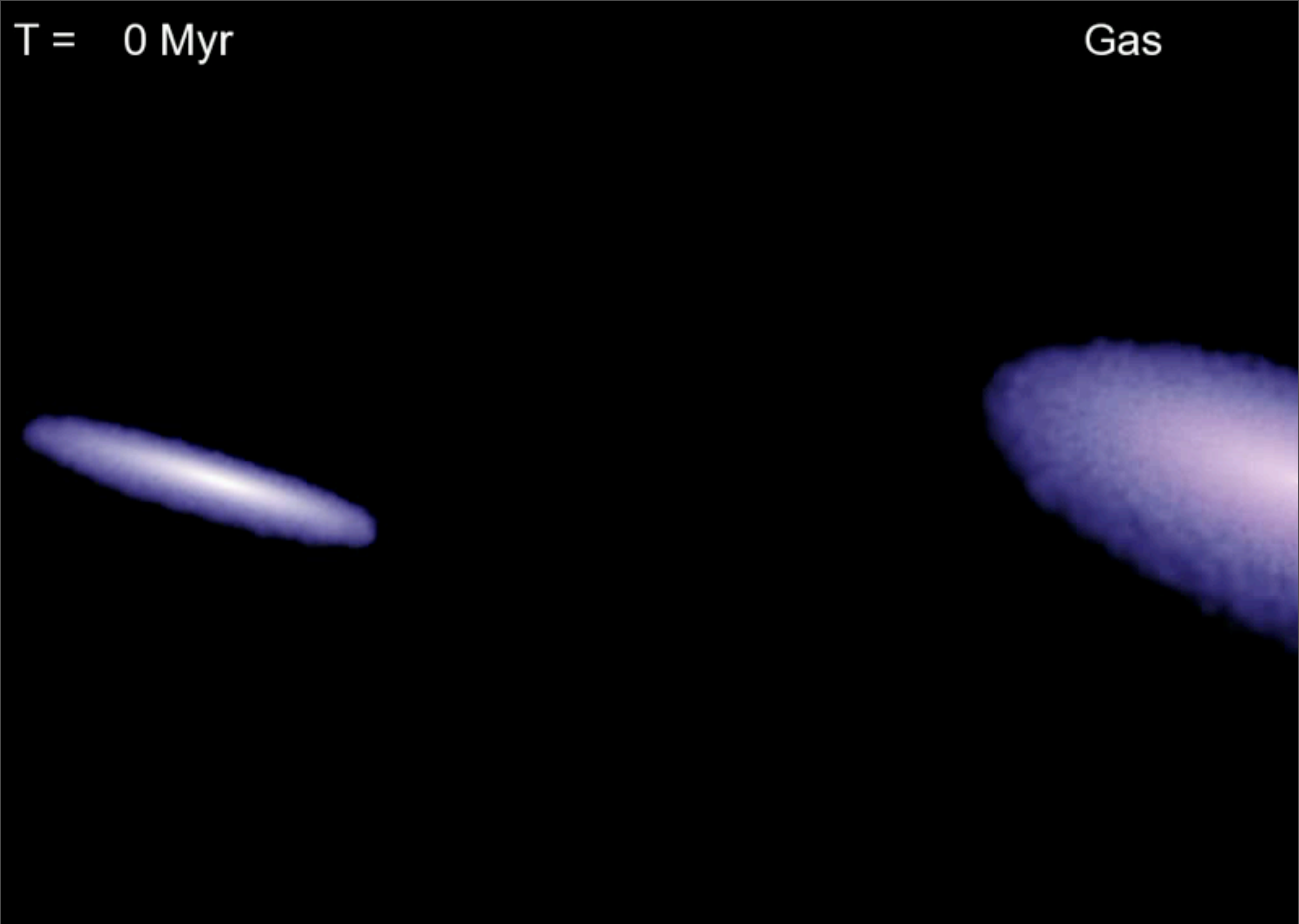
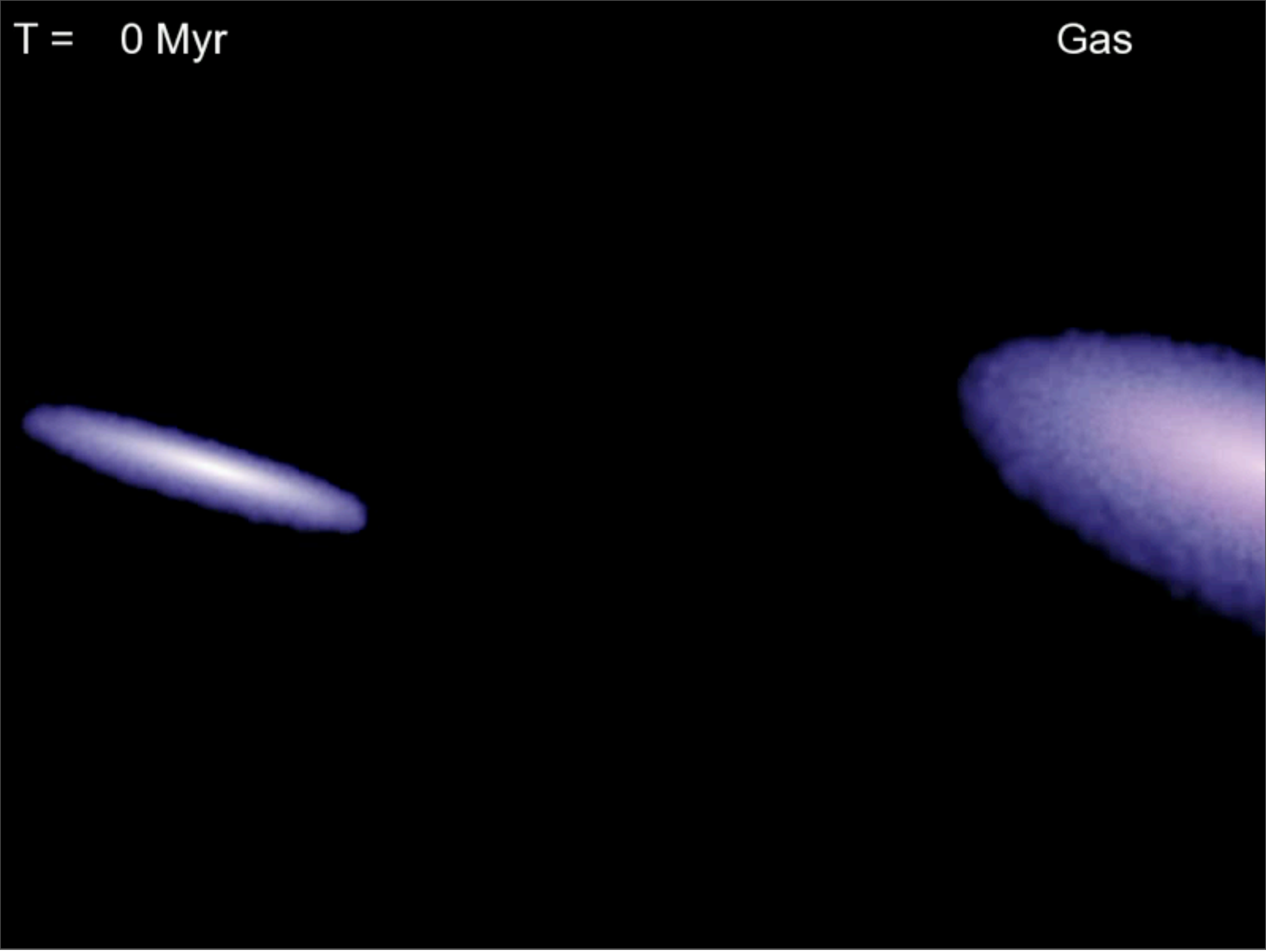


Feedback expels remaining gas, shutting down growth (more later...)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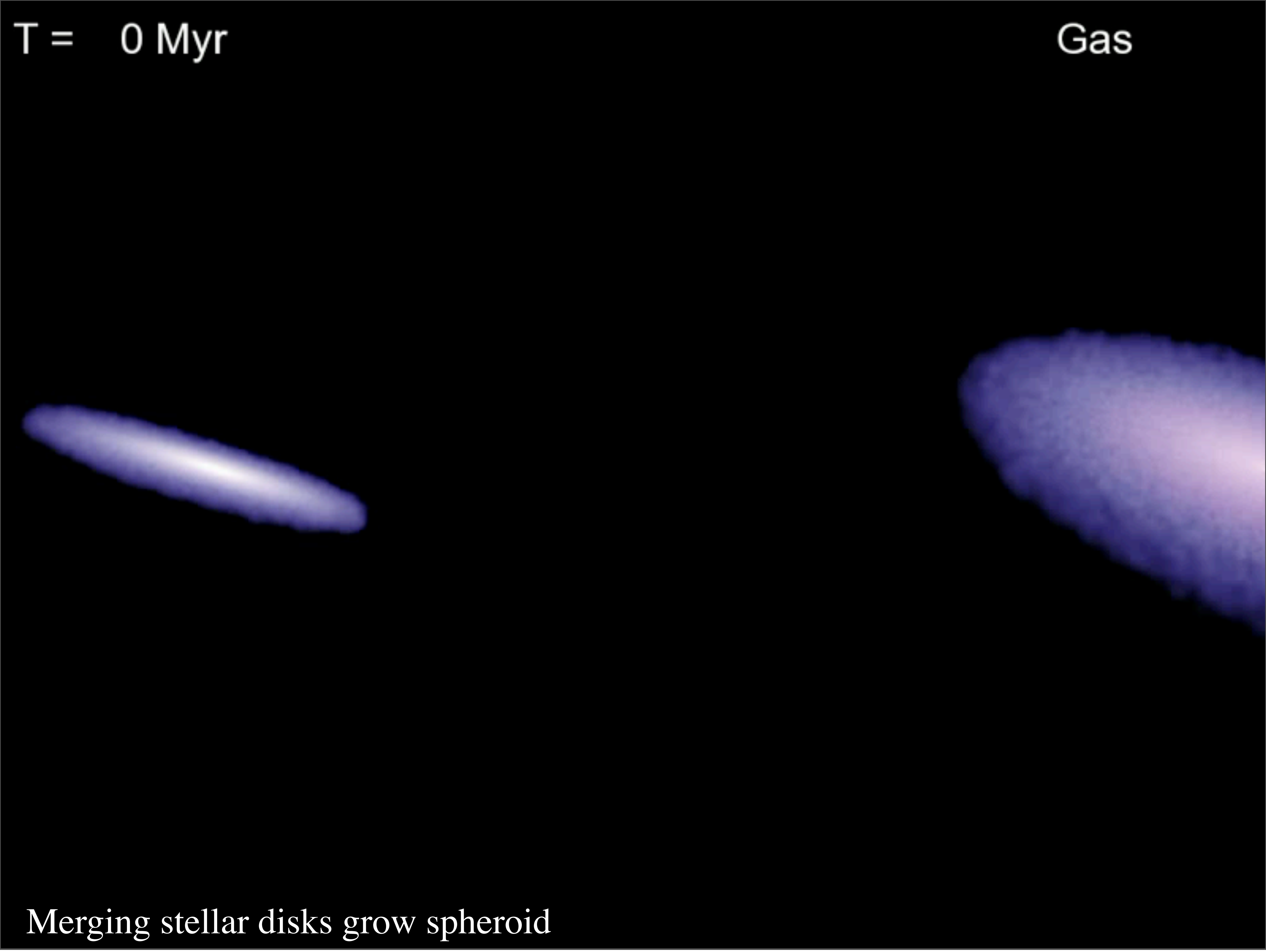
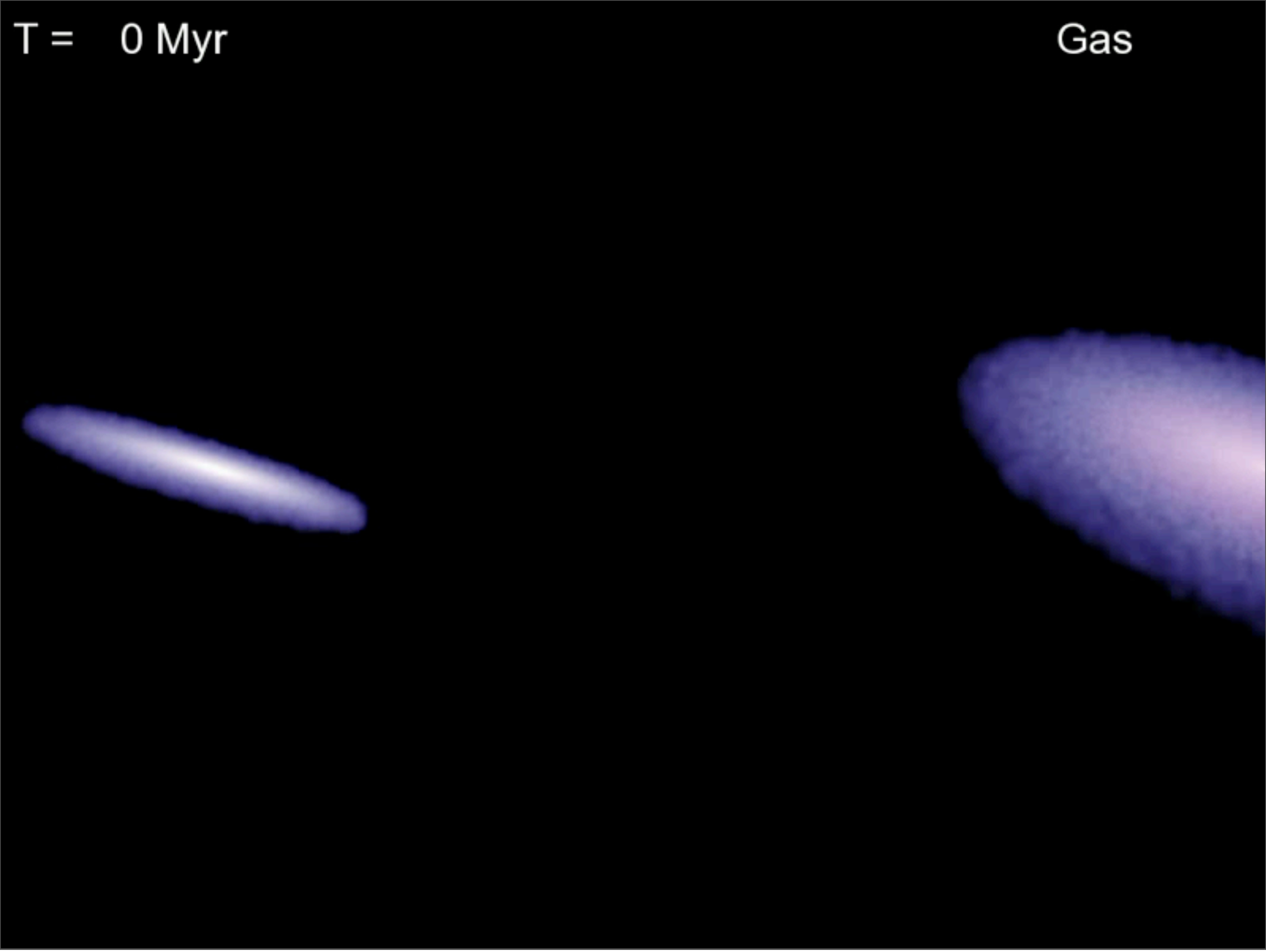

T = 0 Myr
Gas
Merging stellar disks grow spheroid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Gas

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

Sanders, Scoville, Soifer,
& others since:

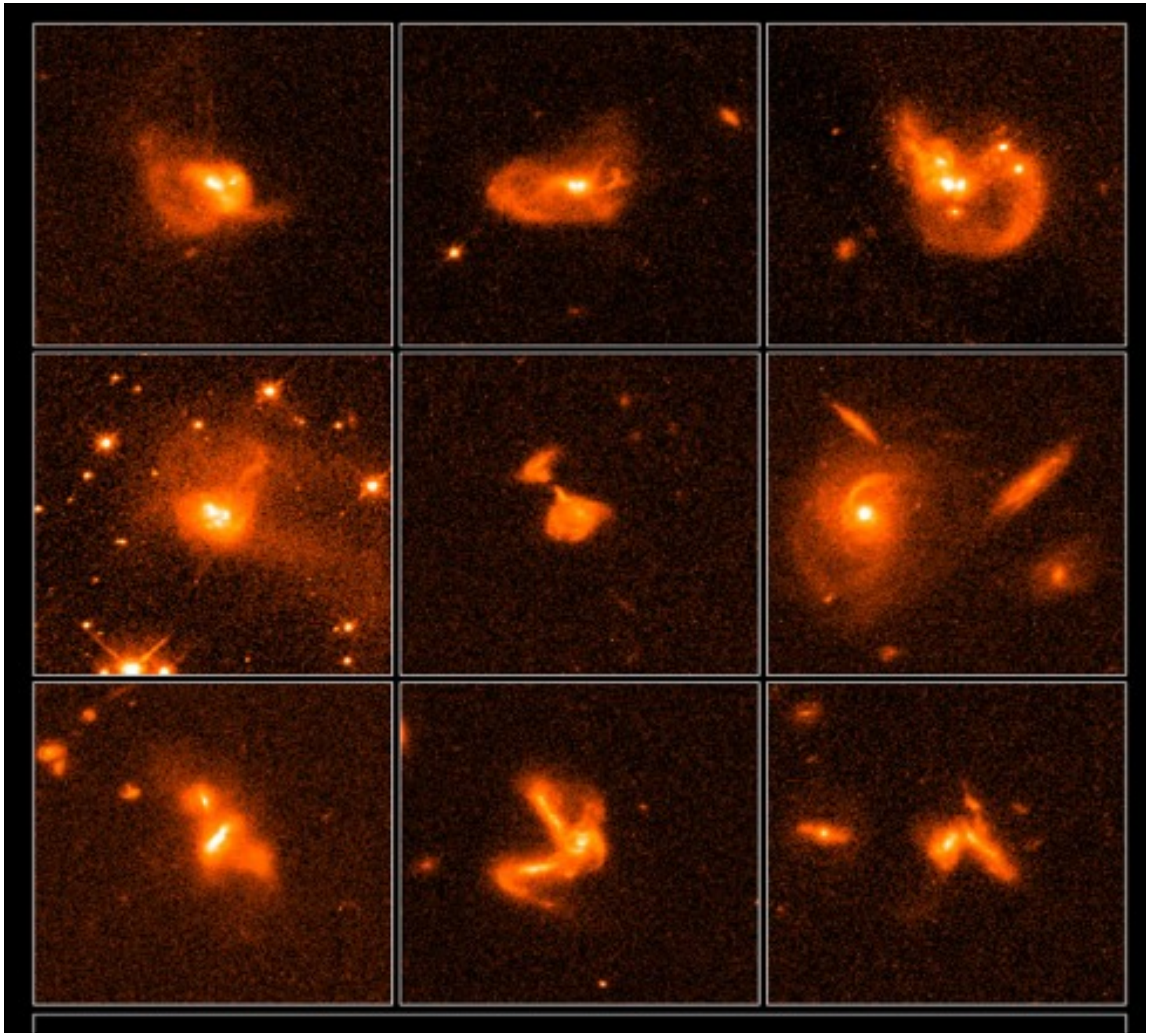
Compare local starburst
ULIRGs: SFR up to >100 M_{sun}/yr

Essentially all late-stage
merger remnants

Compact (~kpc scales)

Evidence for SB-QSO
transition?

Borne et al., 2000

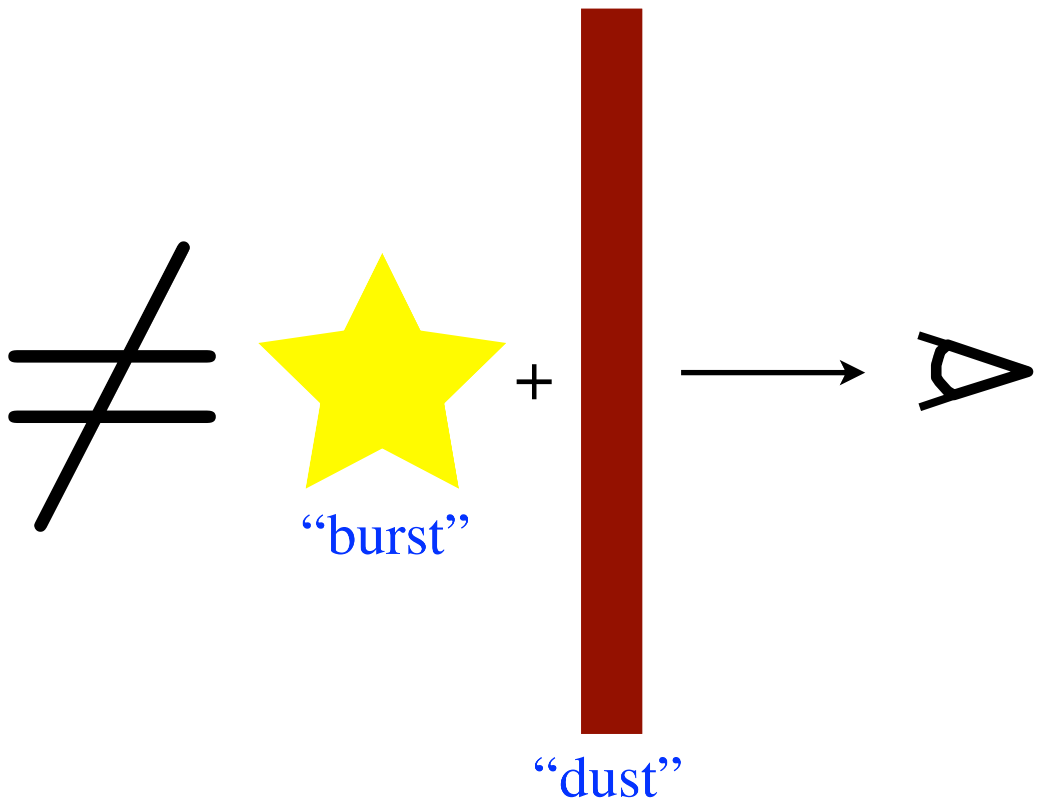


Are they the progenitors of ellipticals?

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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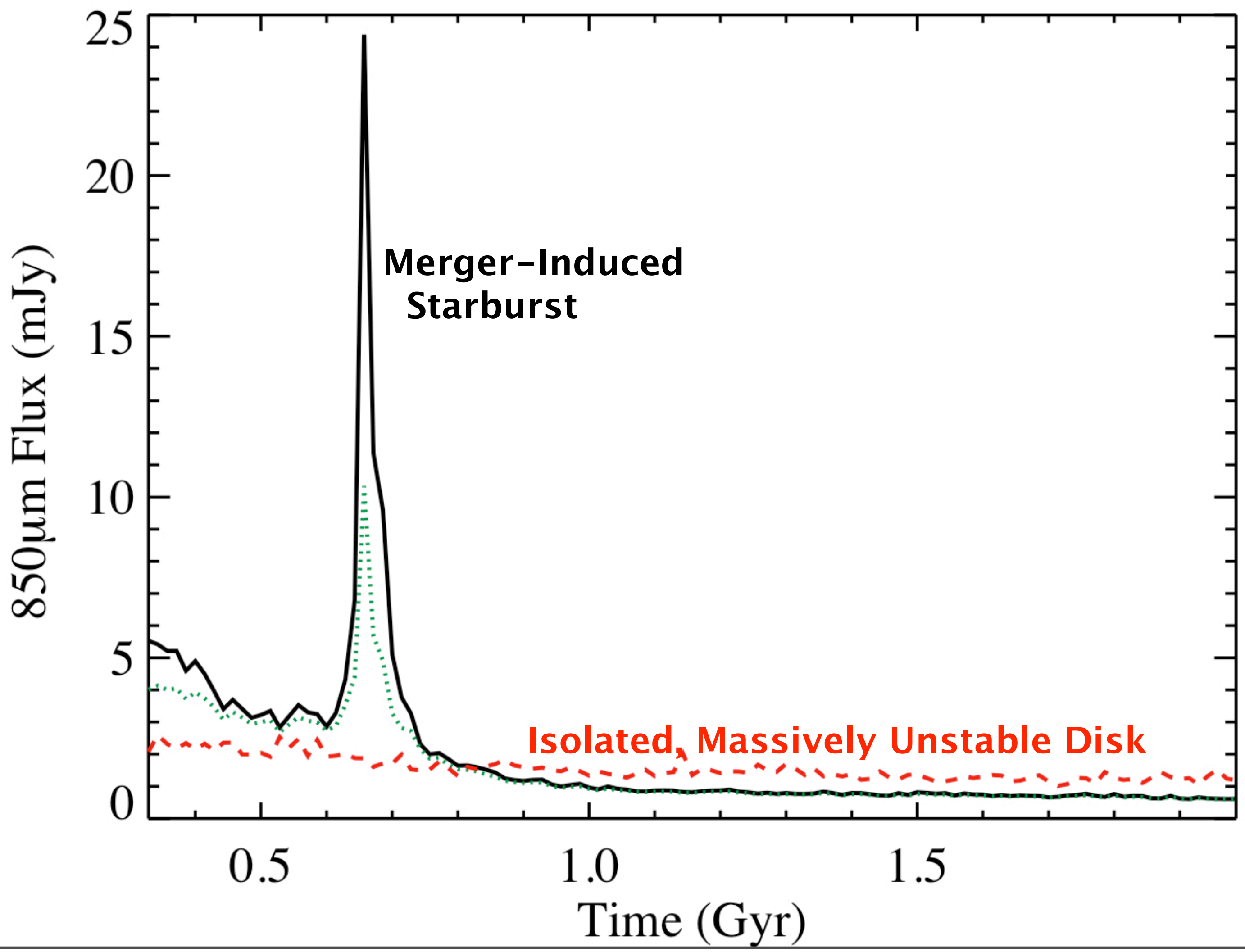

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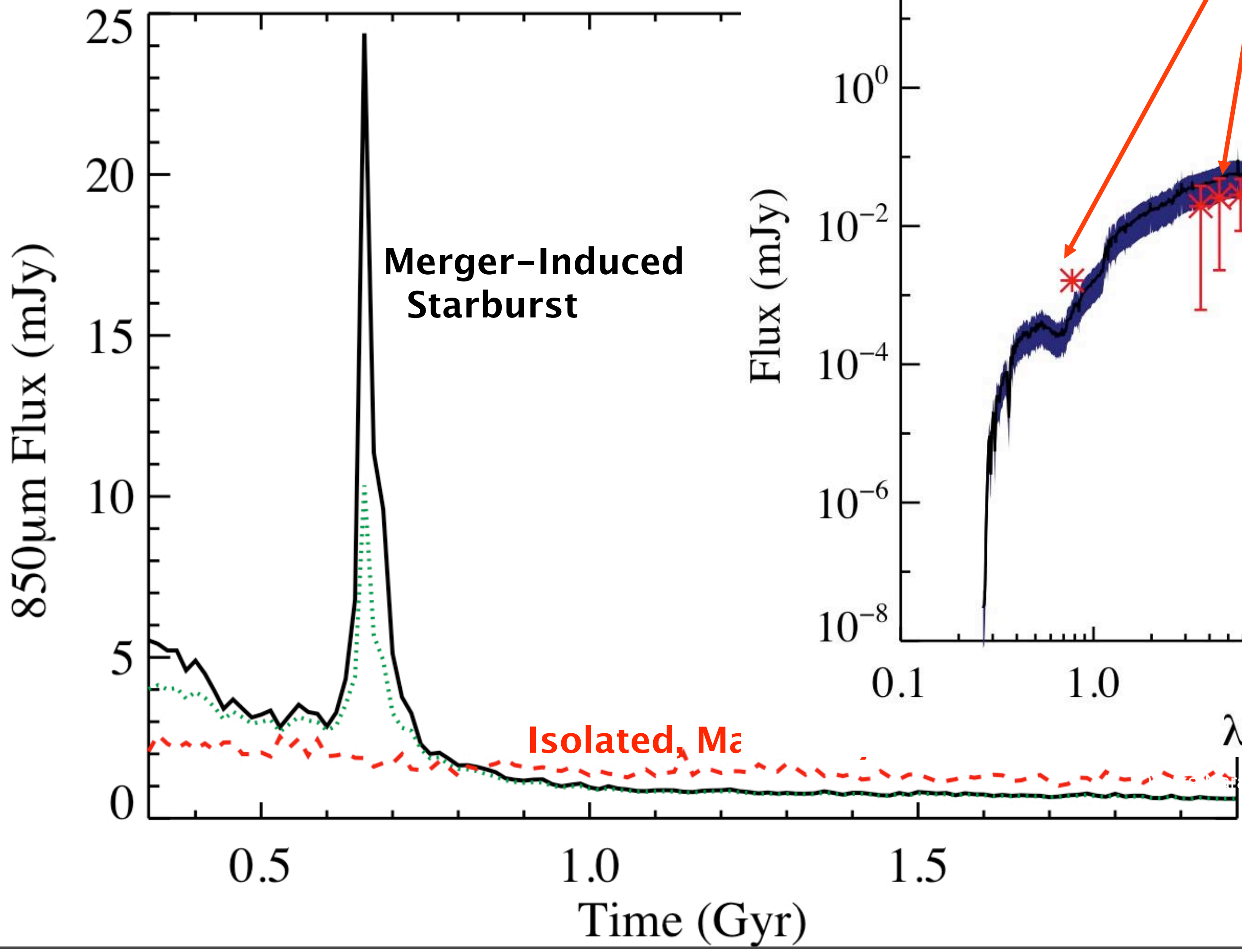
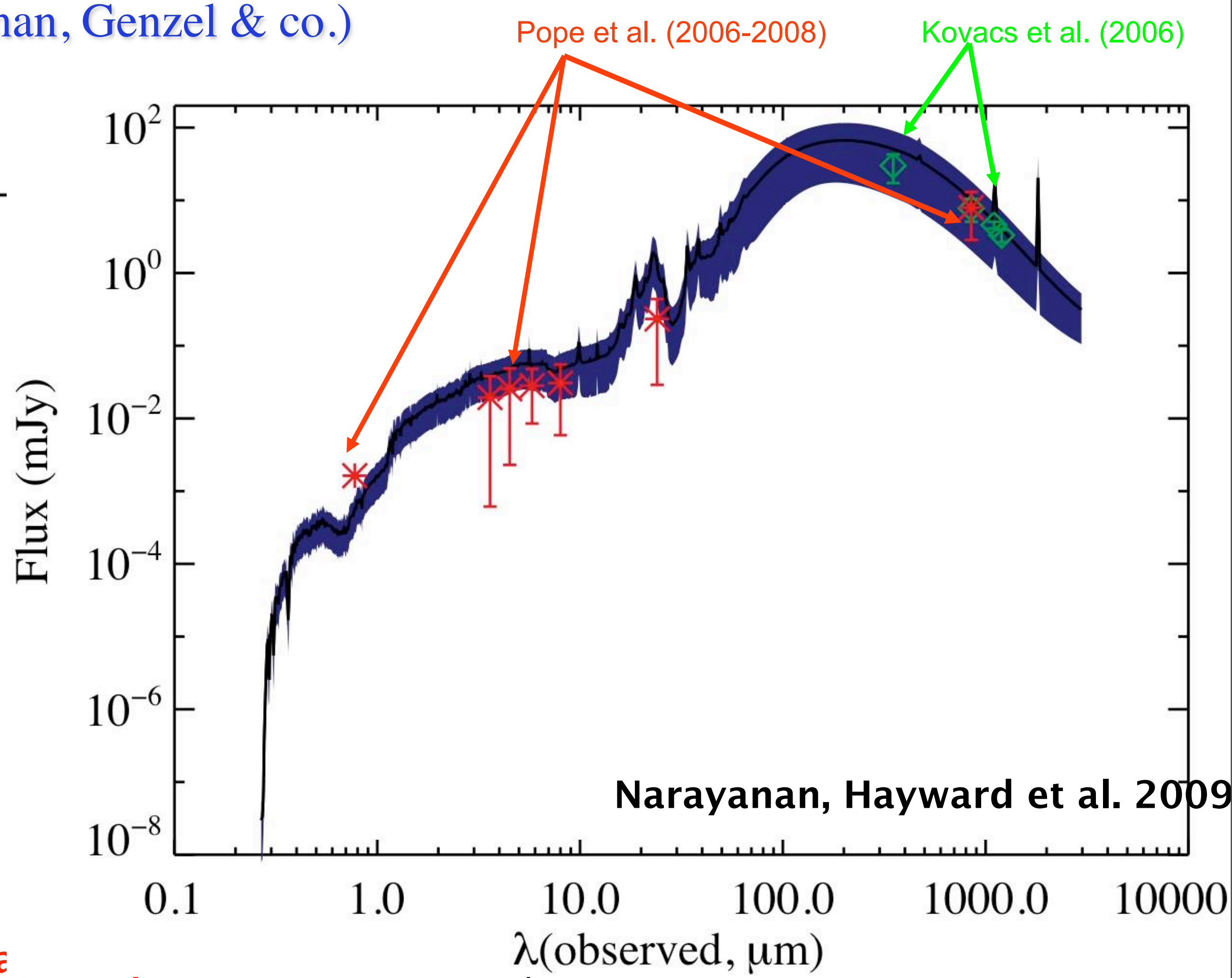
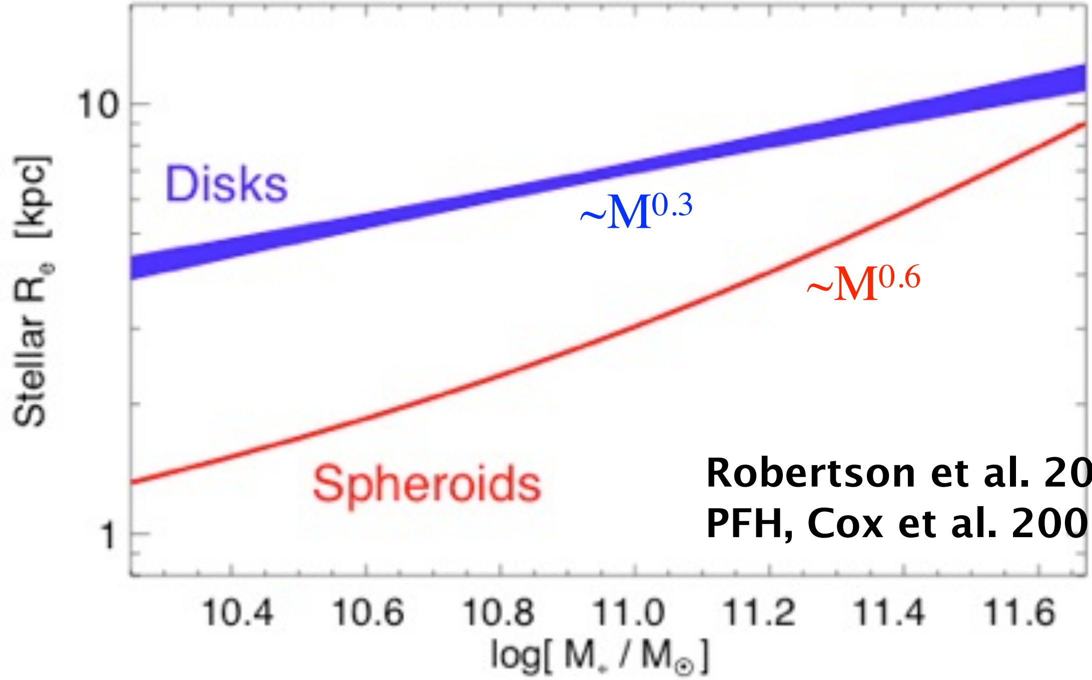


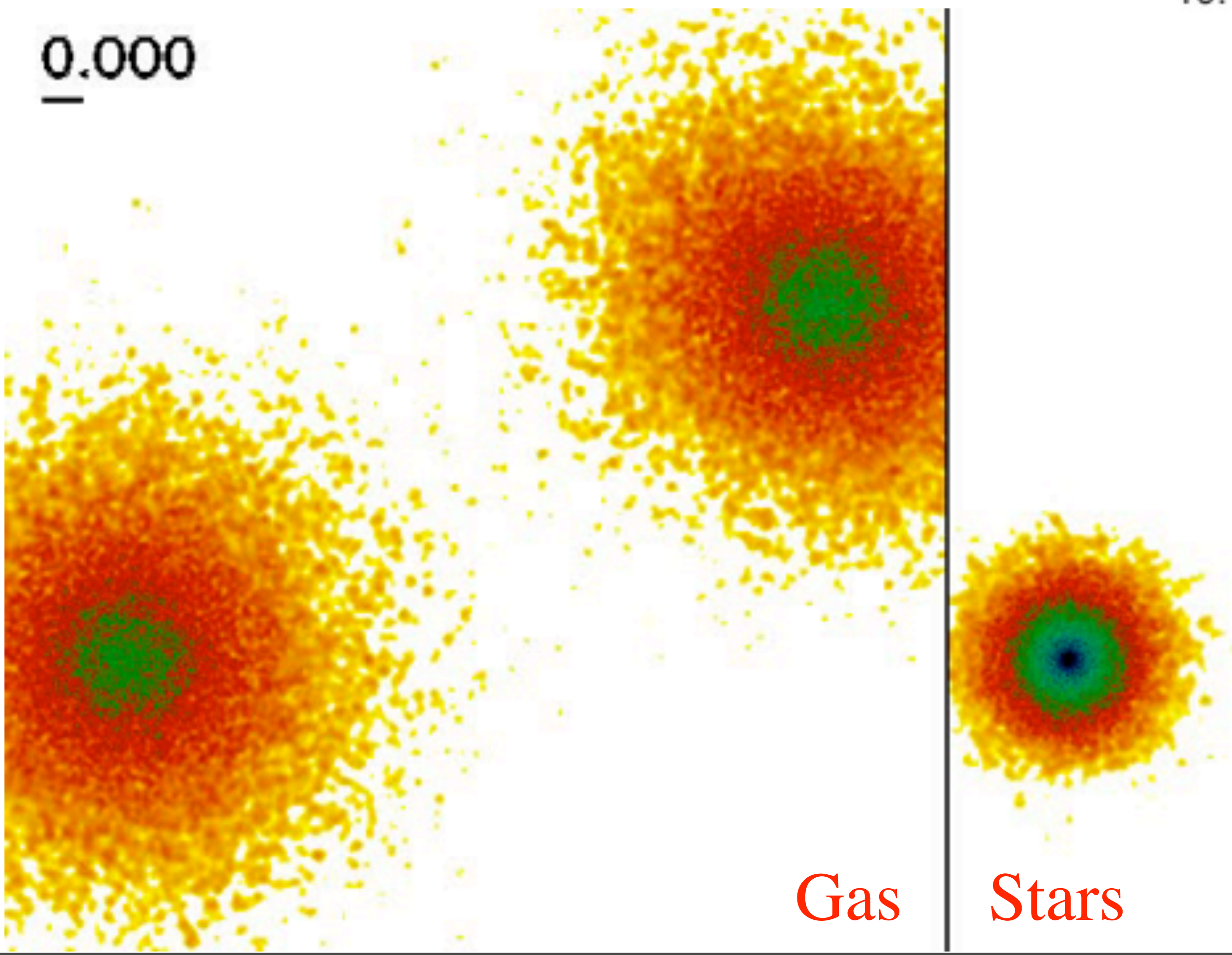


How does this relate to bulge formation?

The Problem: The Fundamental Plane & Bulge Densities:



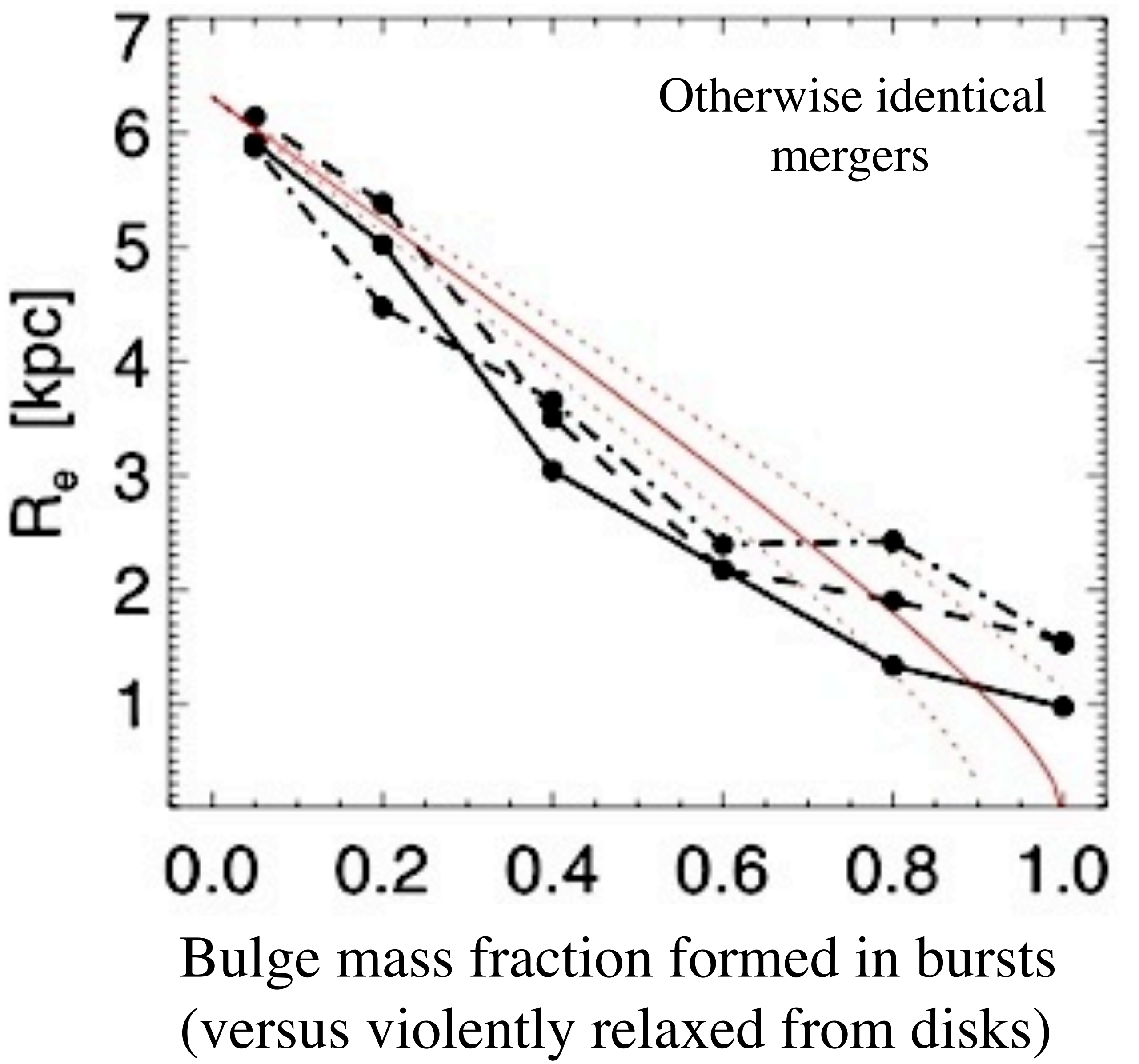
- Why are ellipticals smaller than disks? (Ostriker, Gunn, et al.)



- Gas Dissipation

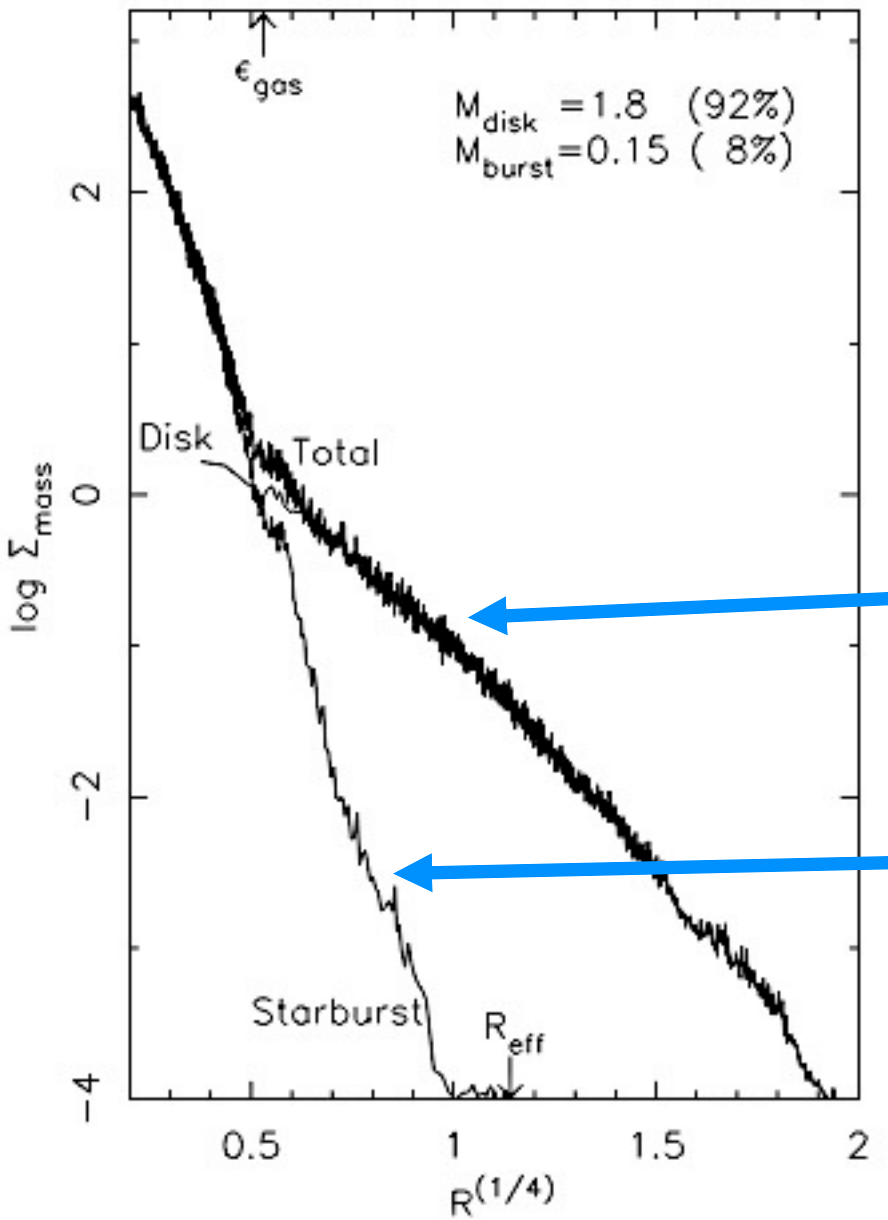
The Solution: Gas-Rich Mergers

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



PFH, Cox et al. 2008

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:

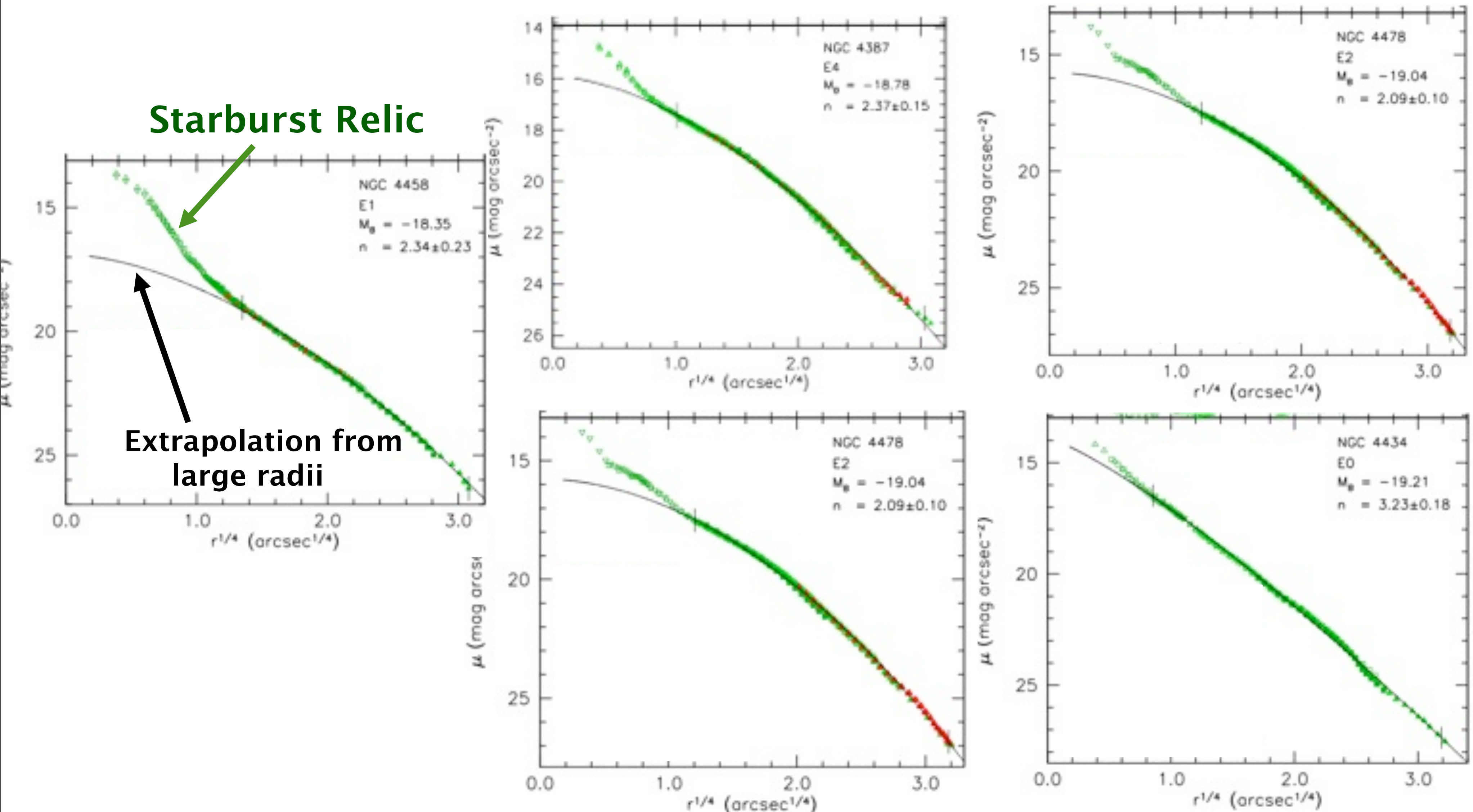
“Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?” (MH94)

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.”

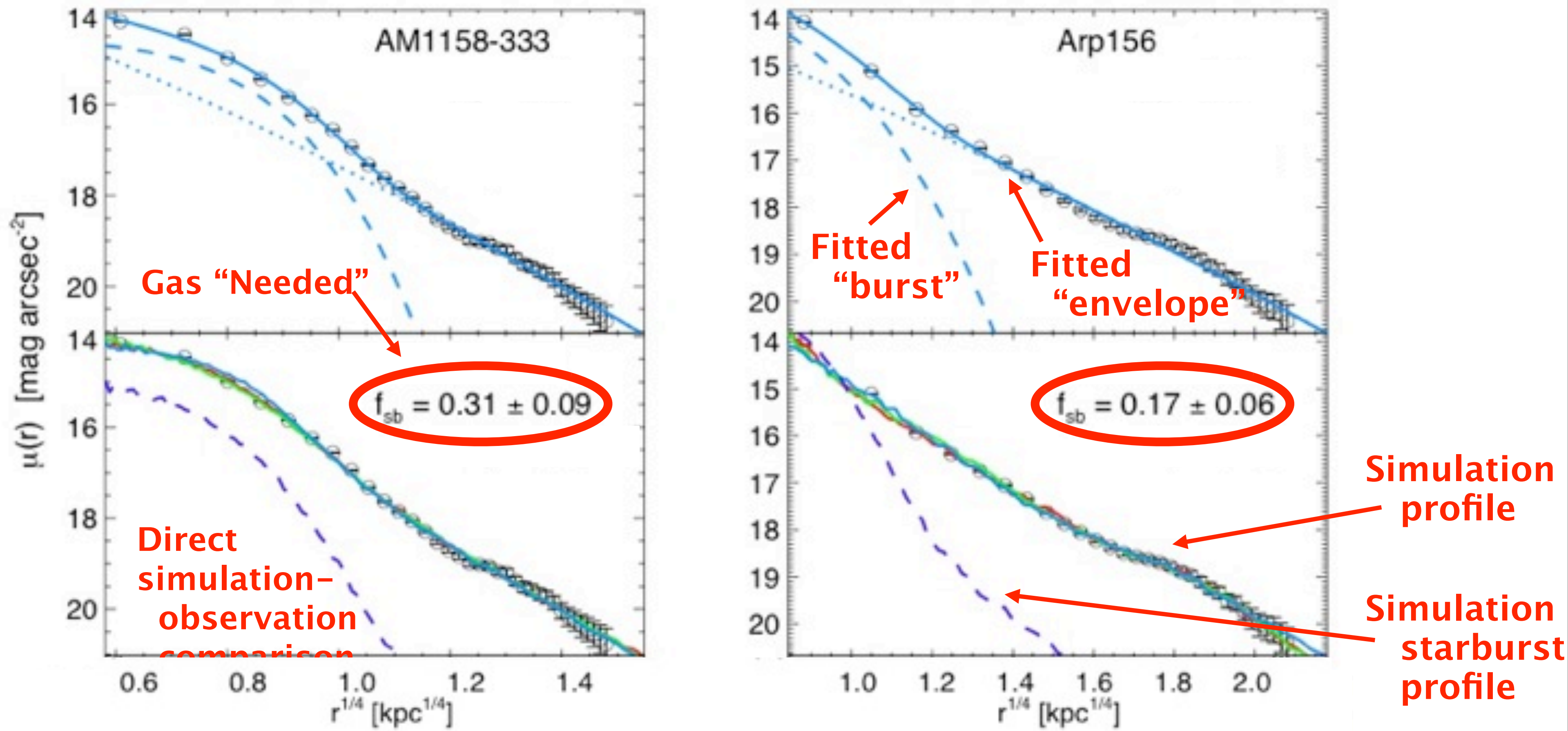
Application: Merger Remnants

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:



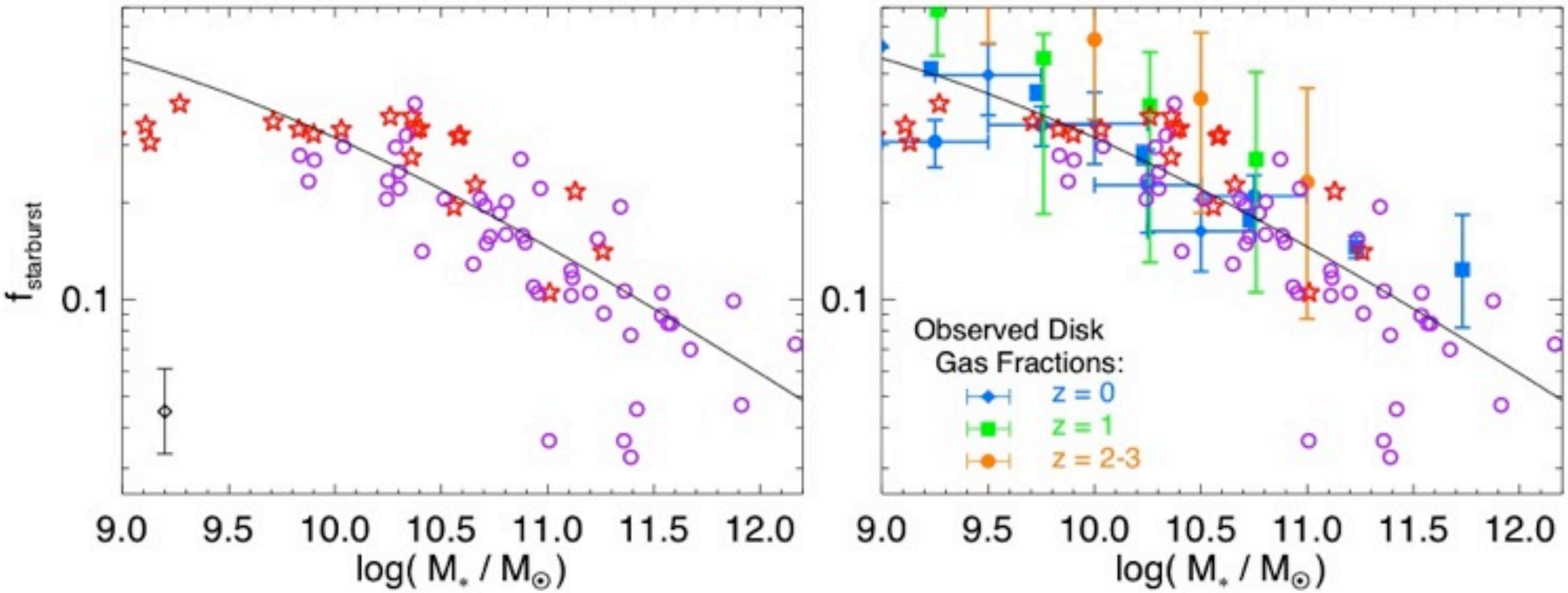
Structure in Elliptical Light Profiles

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

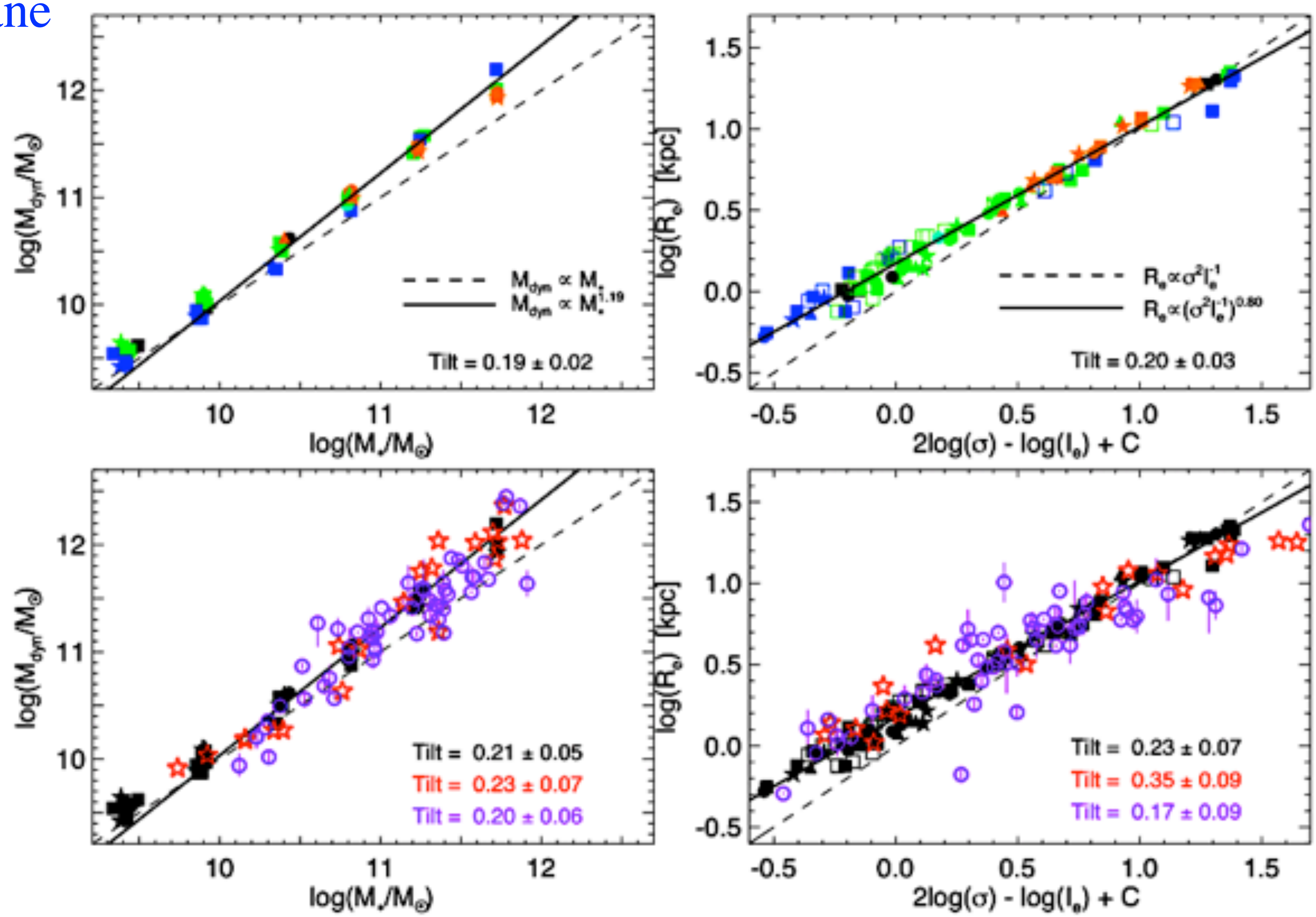
PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

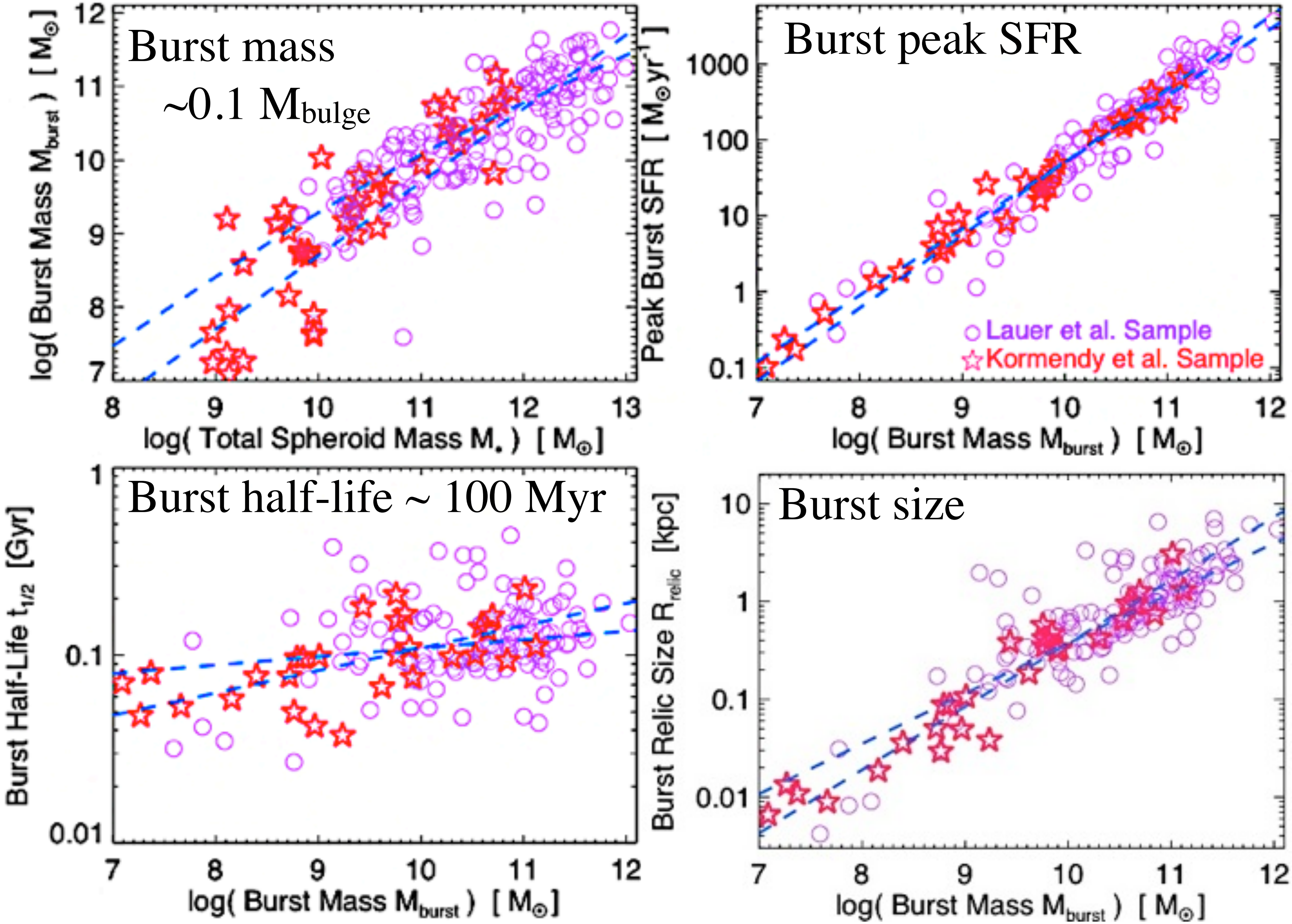
Decreasing of gas/burst fraction with mass

→ Increasing dark matter fractions

→ Fundamental Plane
(for free!)



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



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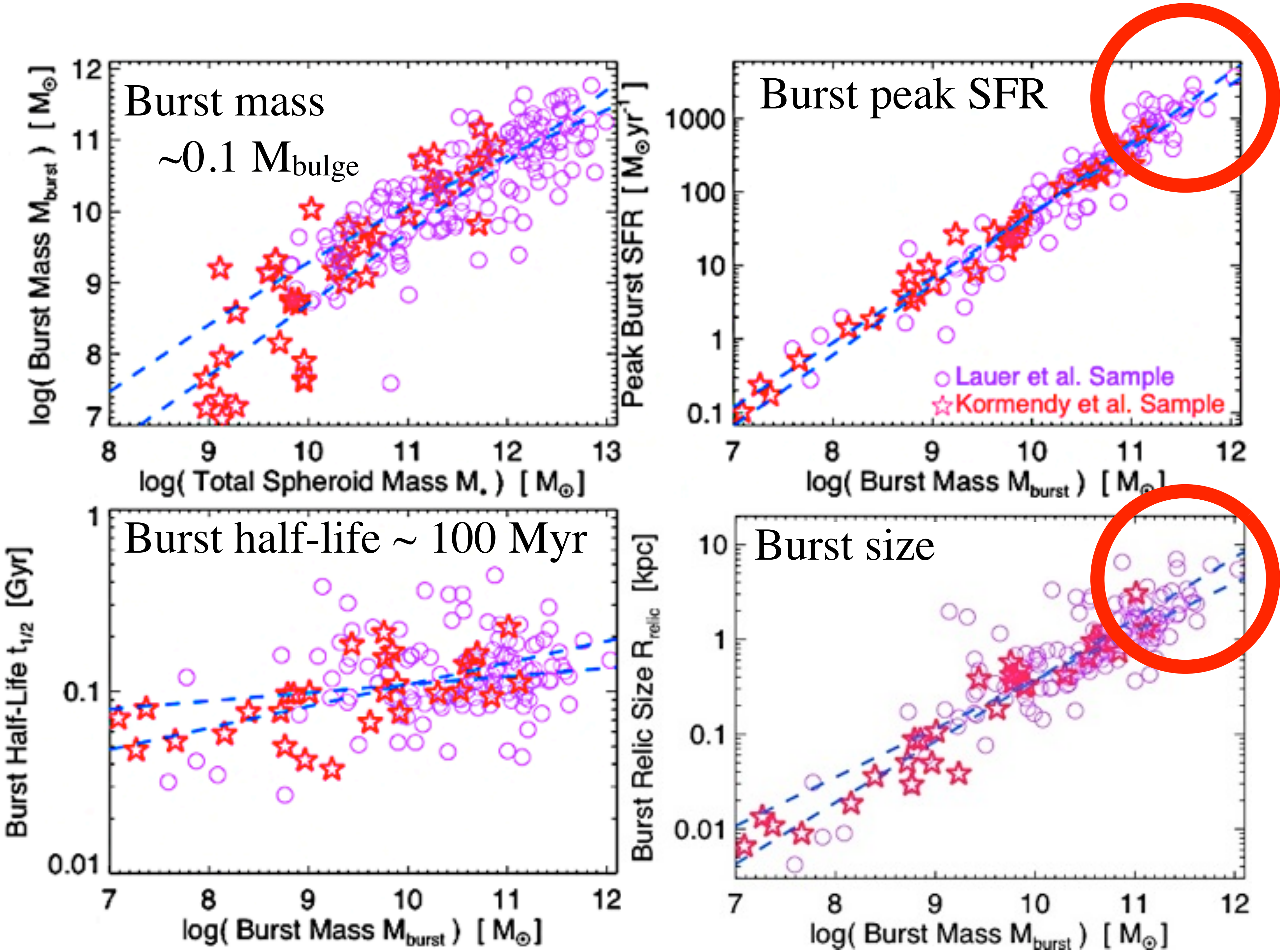
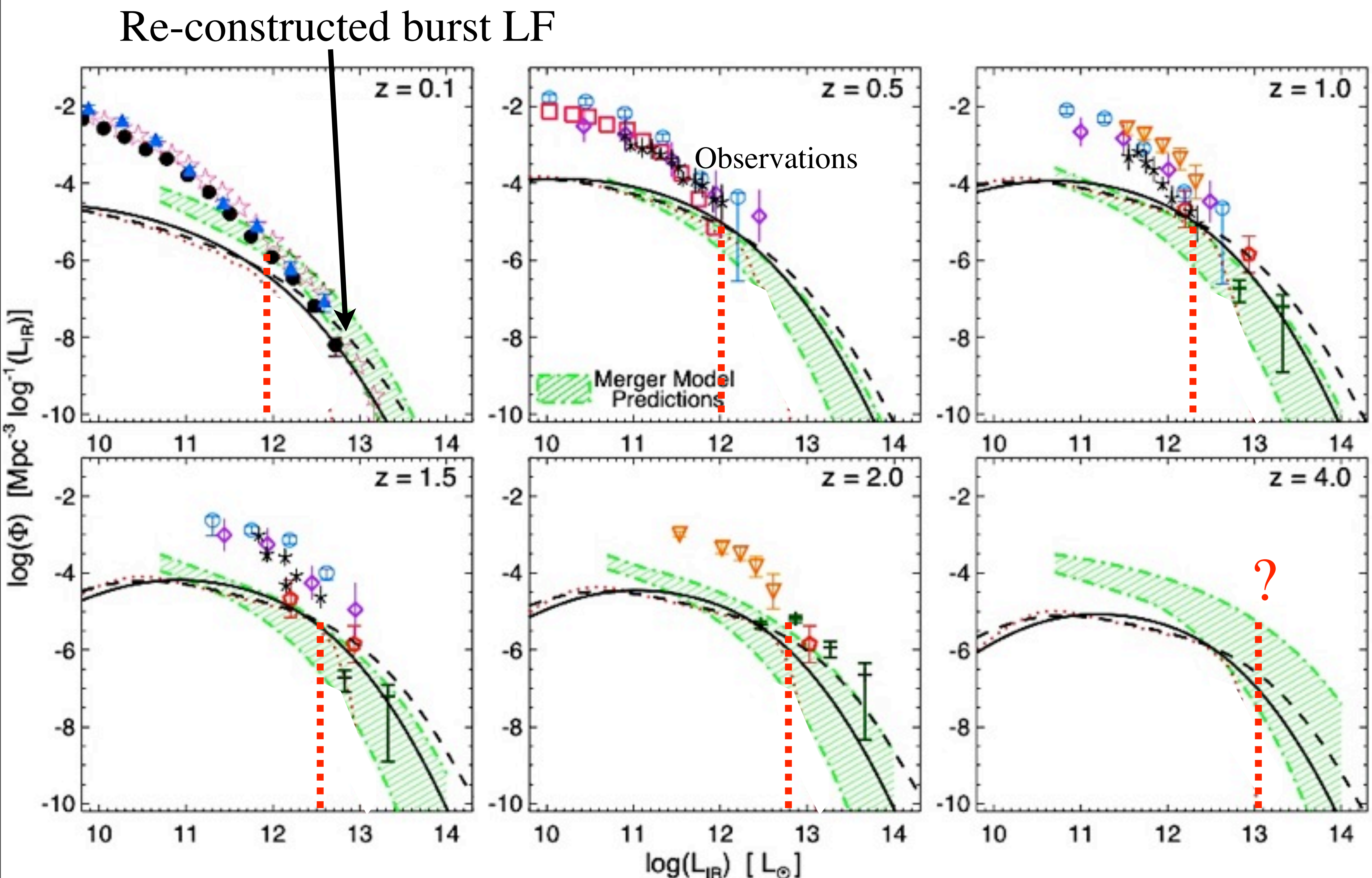
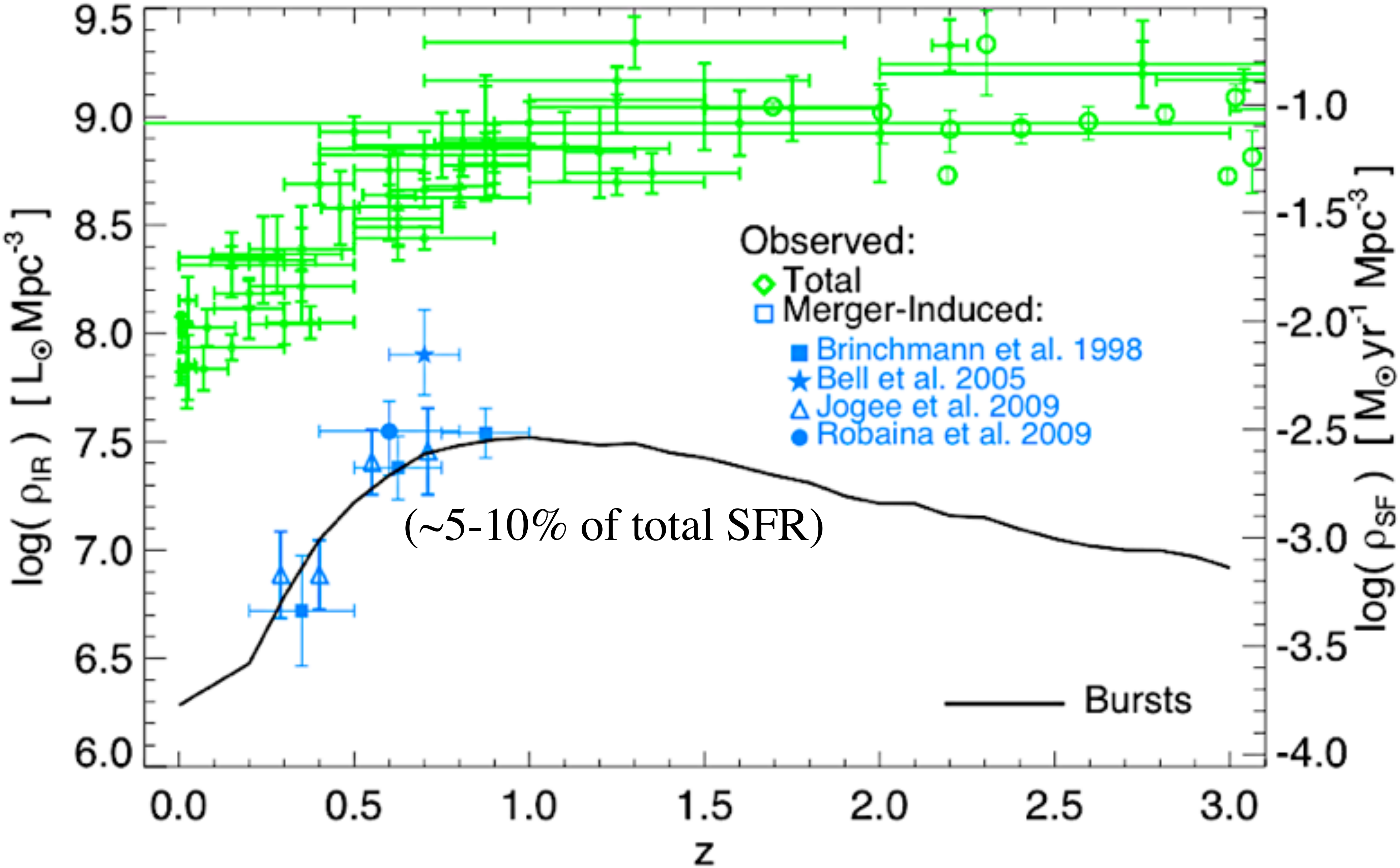


Bursts always dominate at high L, but the threshold shifts

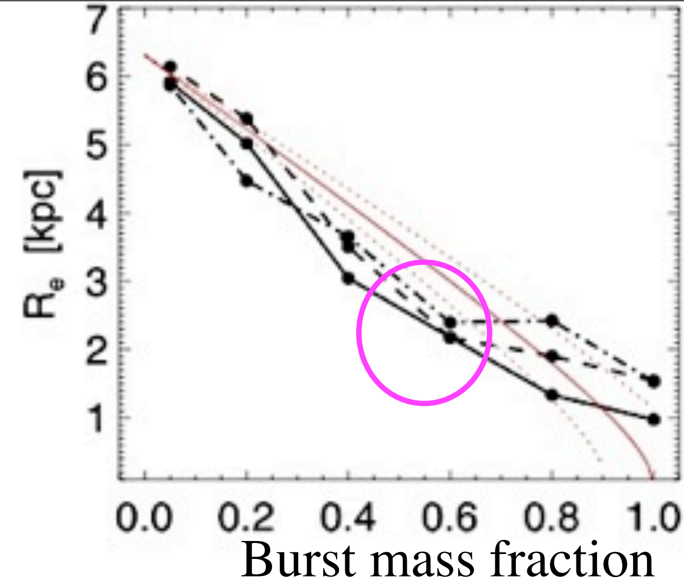


Bursts never dominate the SFR density!

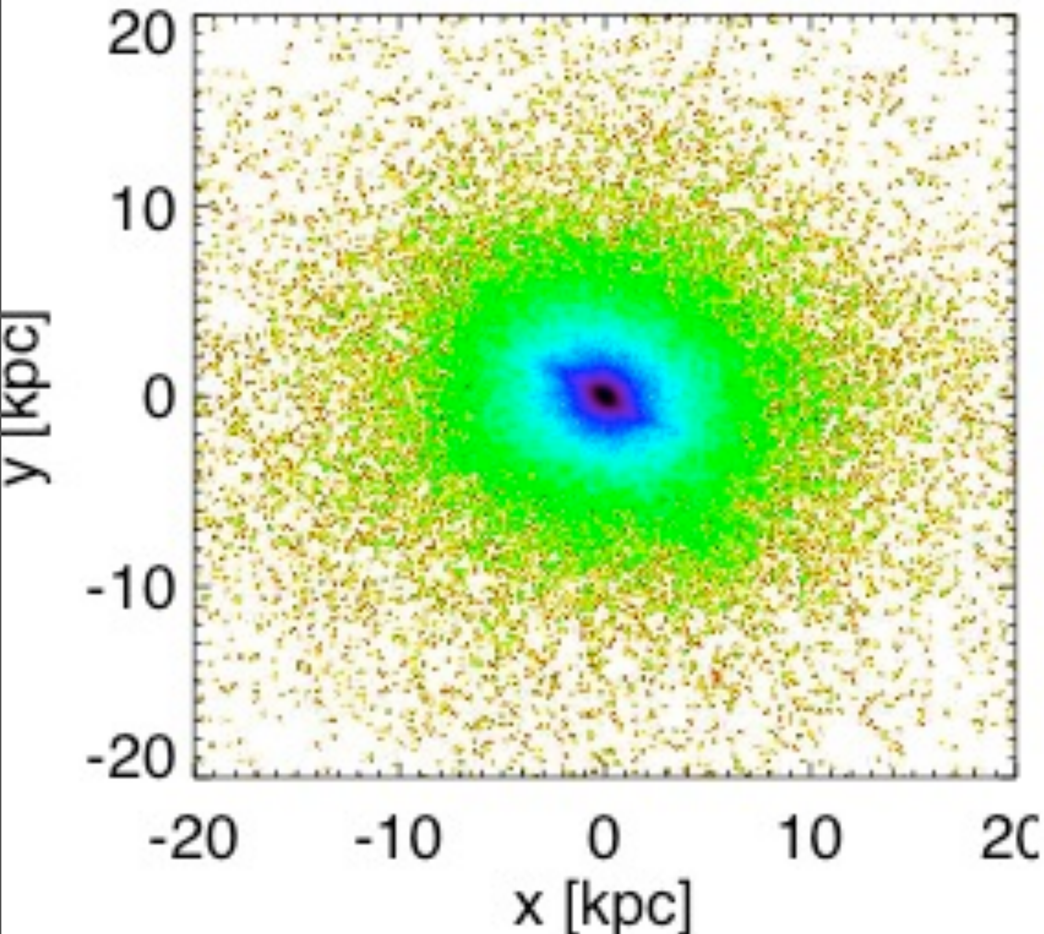


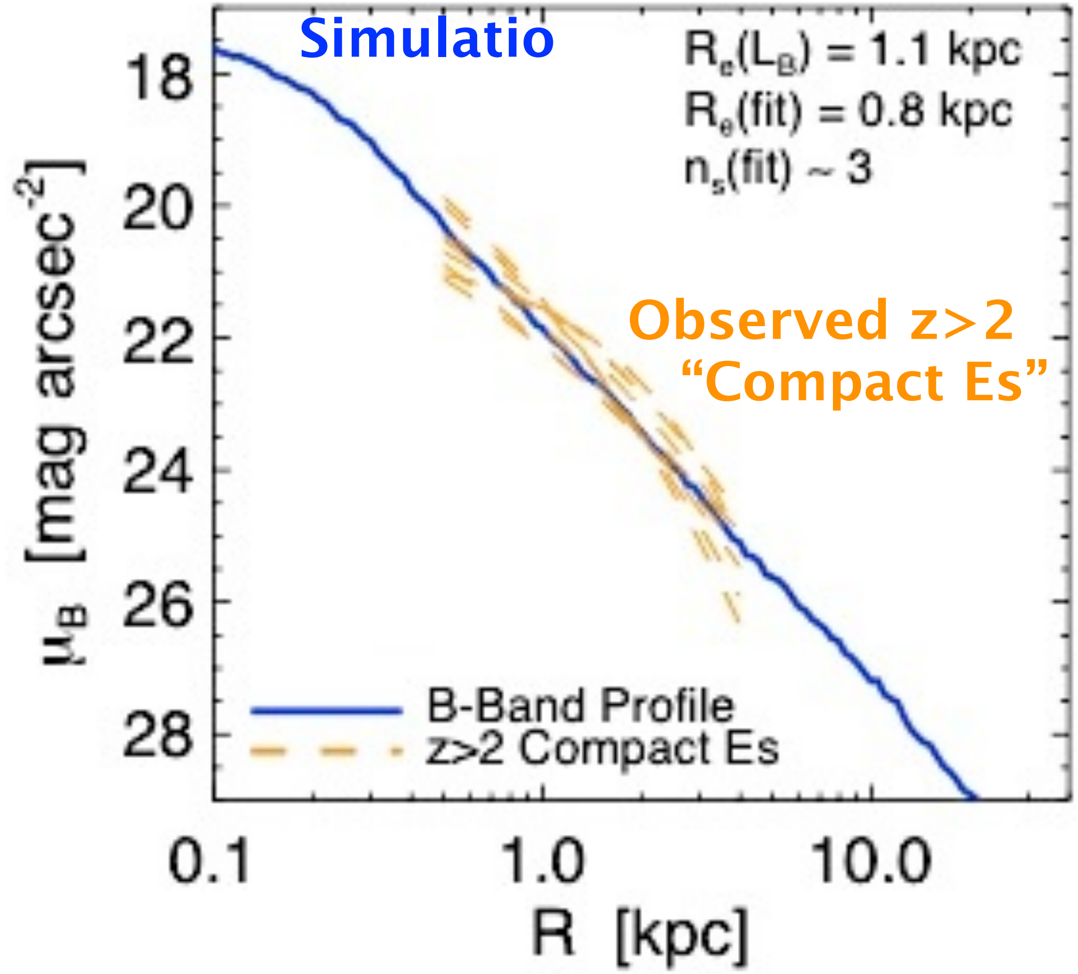
What happens as we scale up with redshift?

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



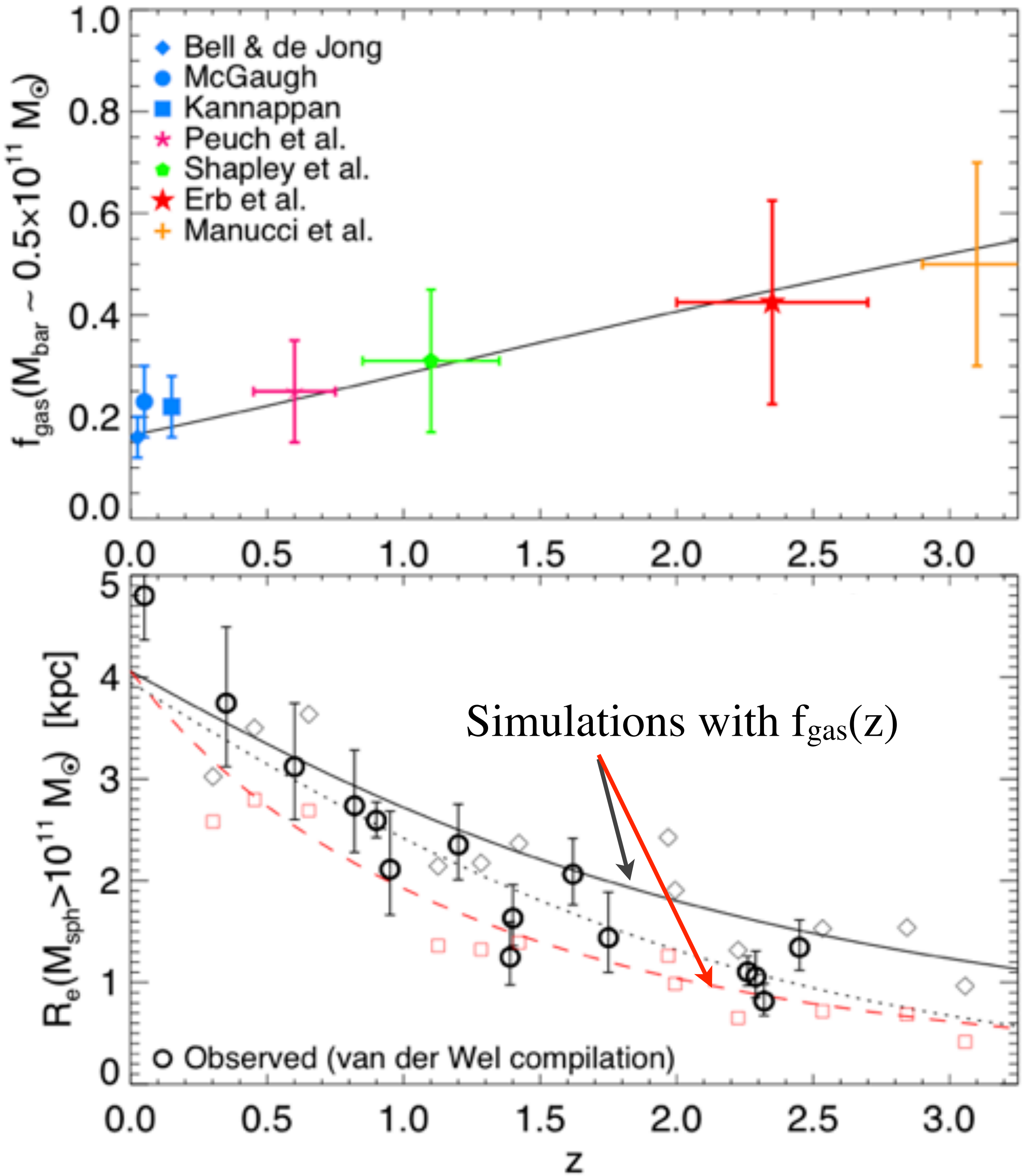
f_{gas}=0.4 merger, ~1kpc





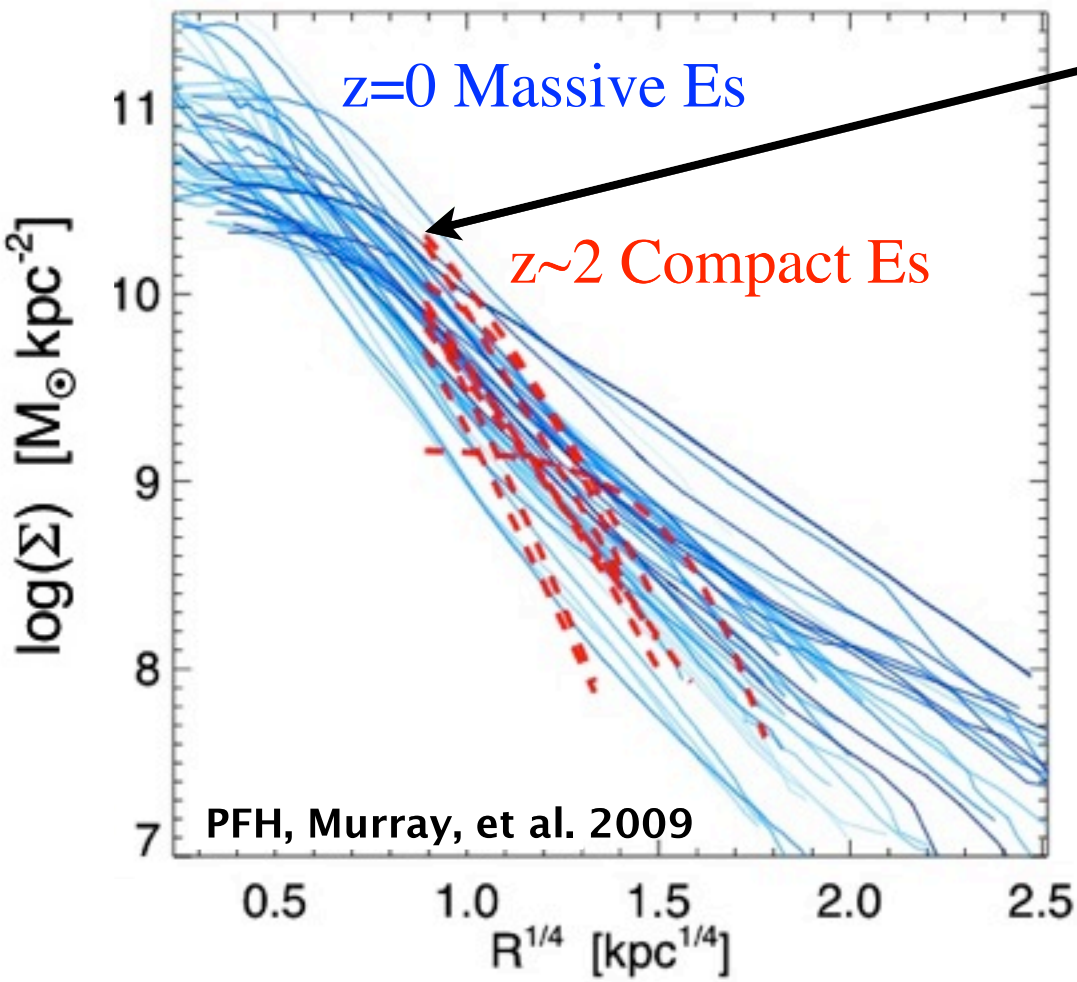
PFH, Bundy, et al. 2009

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



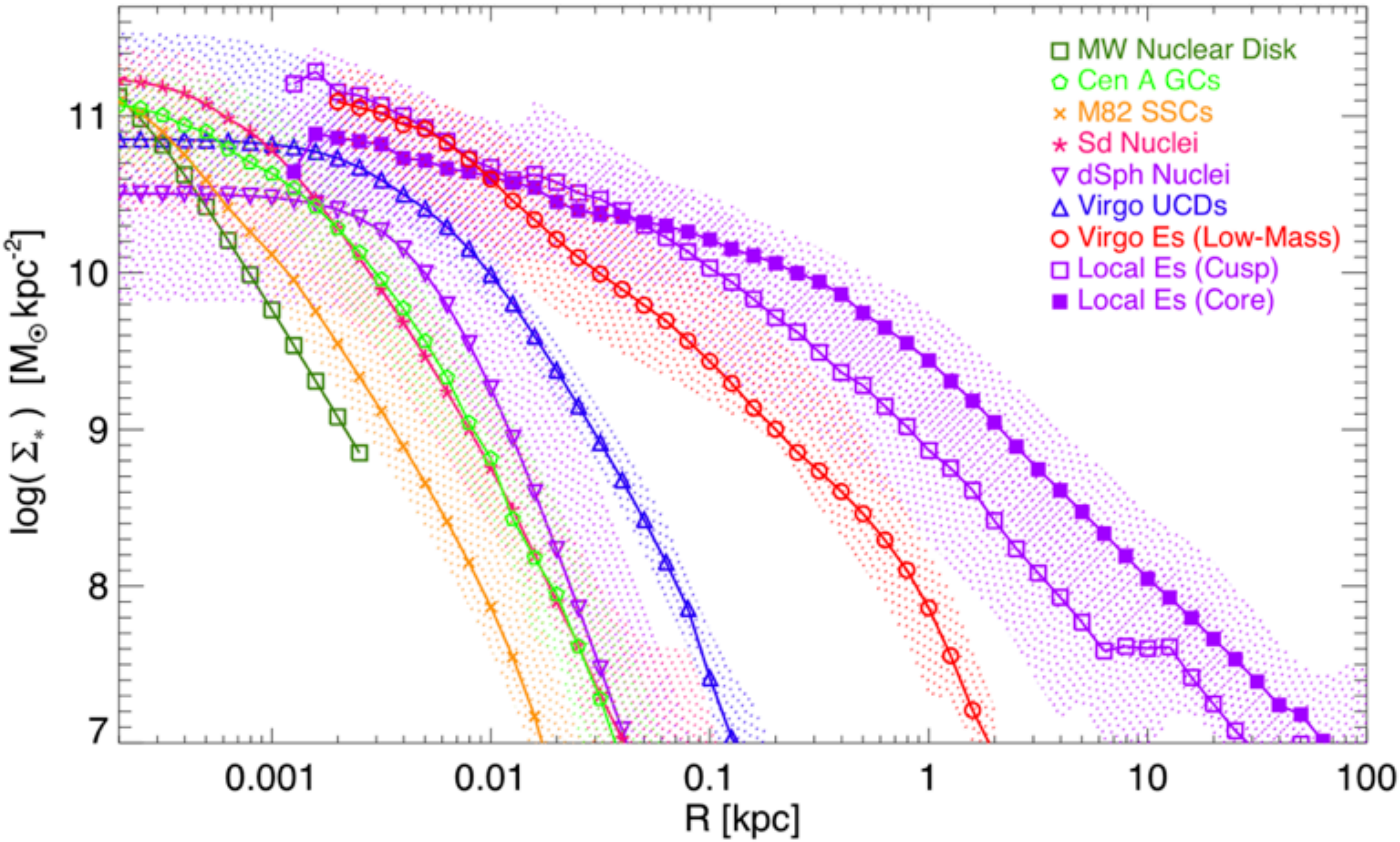
- Do we see the 'footprint' today?

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



No more (*centrally*) dense than massive Es today!

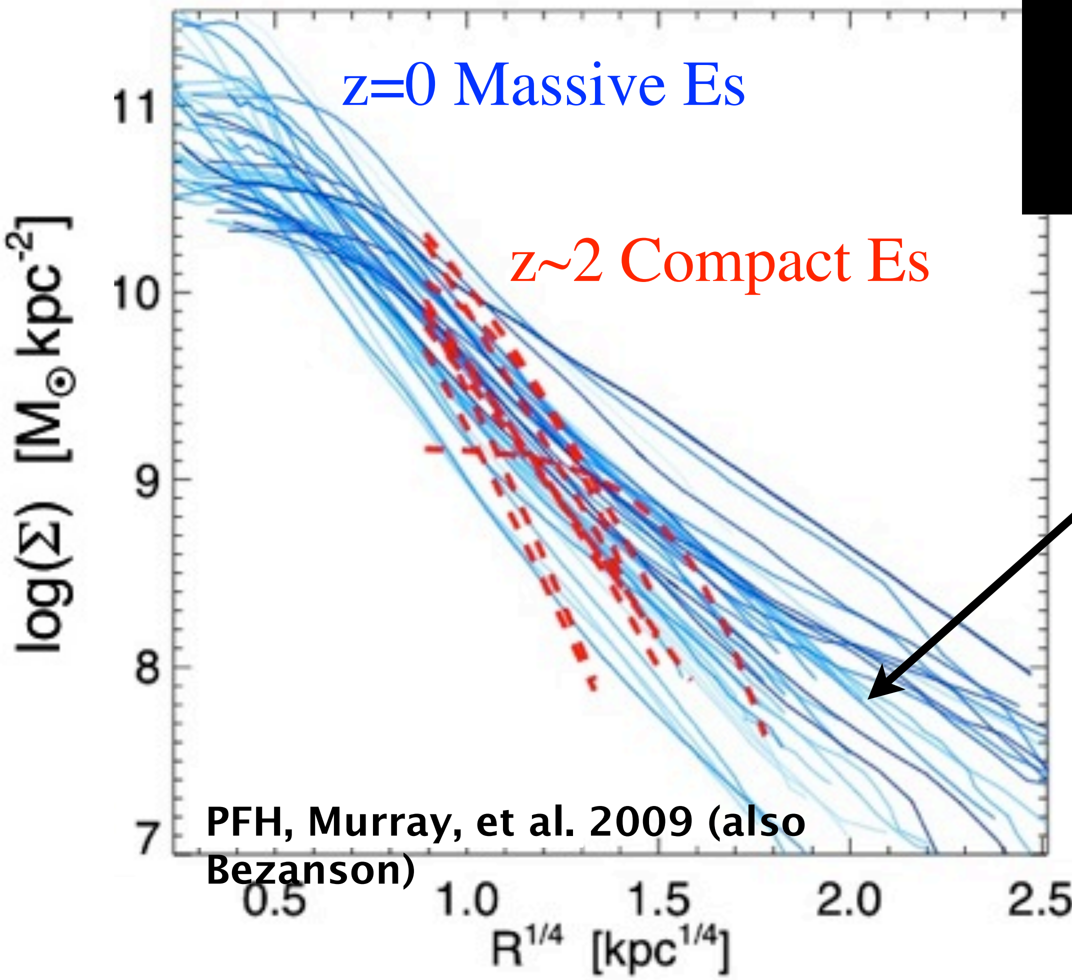
(Bezanson et al., 2009)



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?



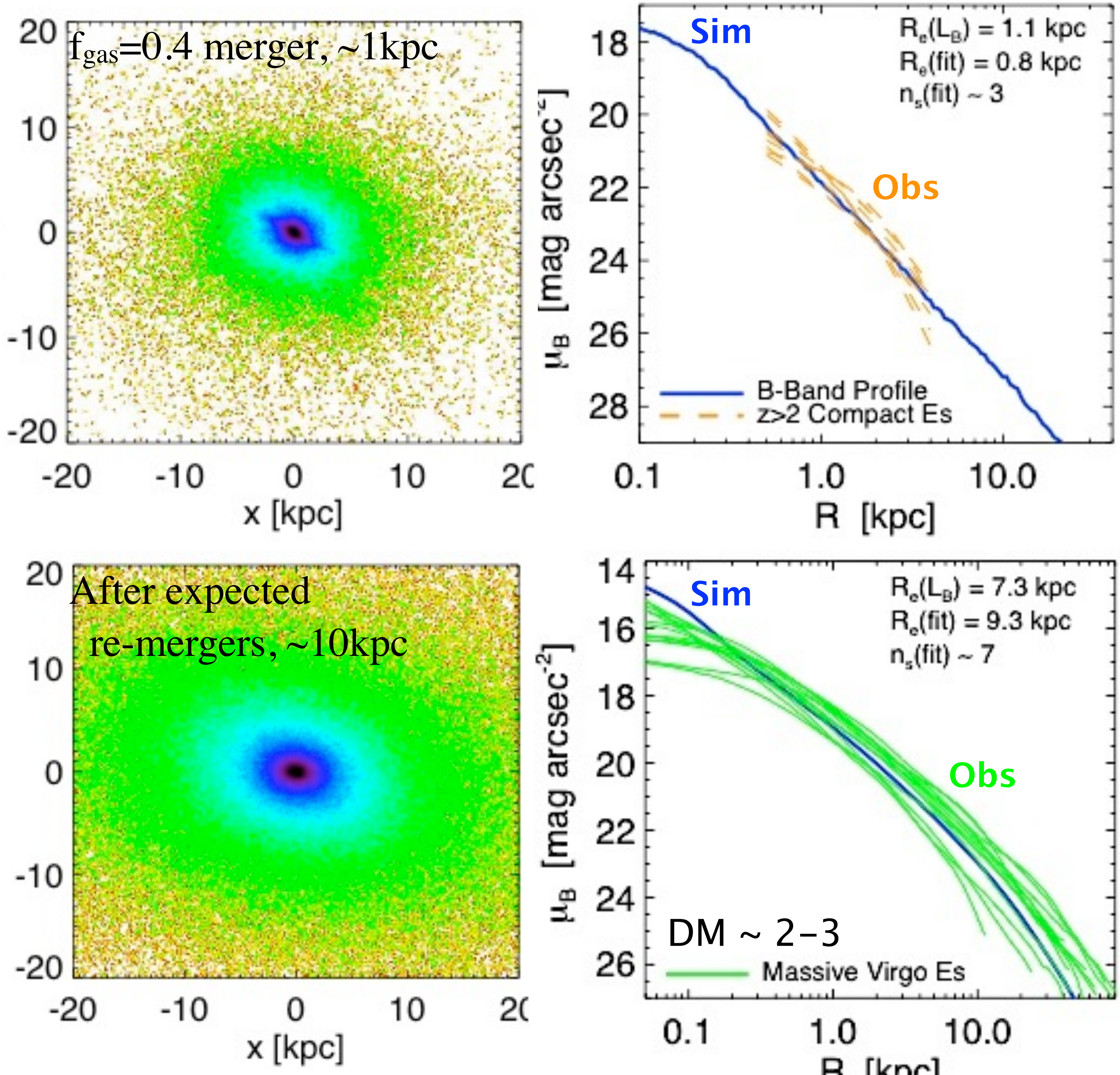
PFH, Murray, et al. 2009 (also Bezanson)

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

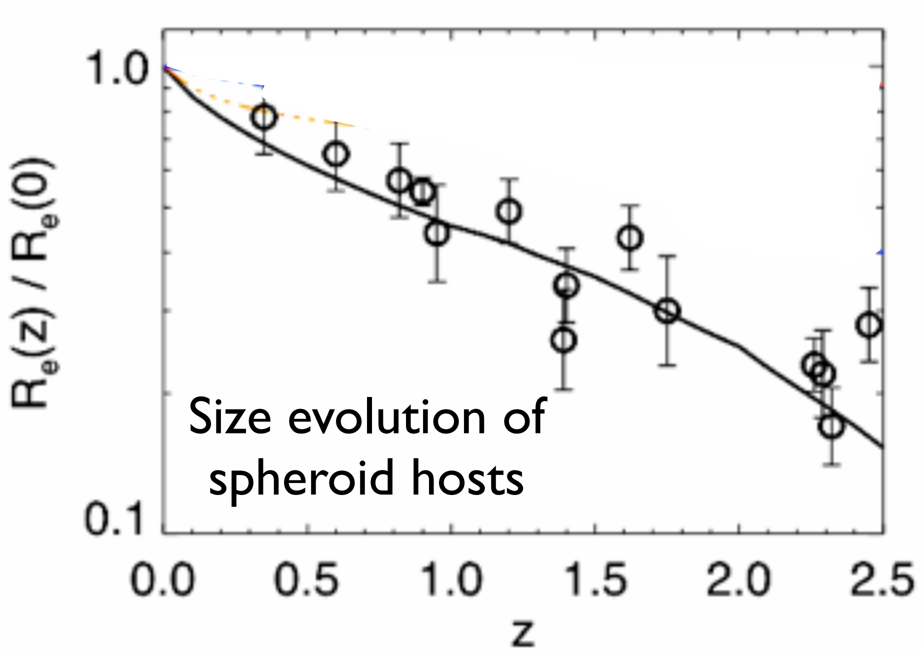
Naab et al. 2009 (& in pre

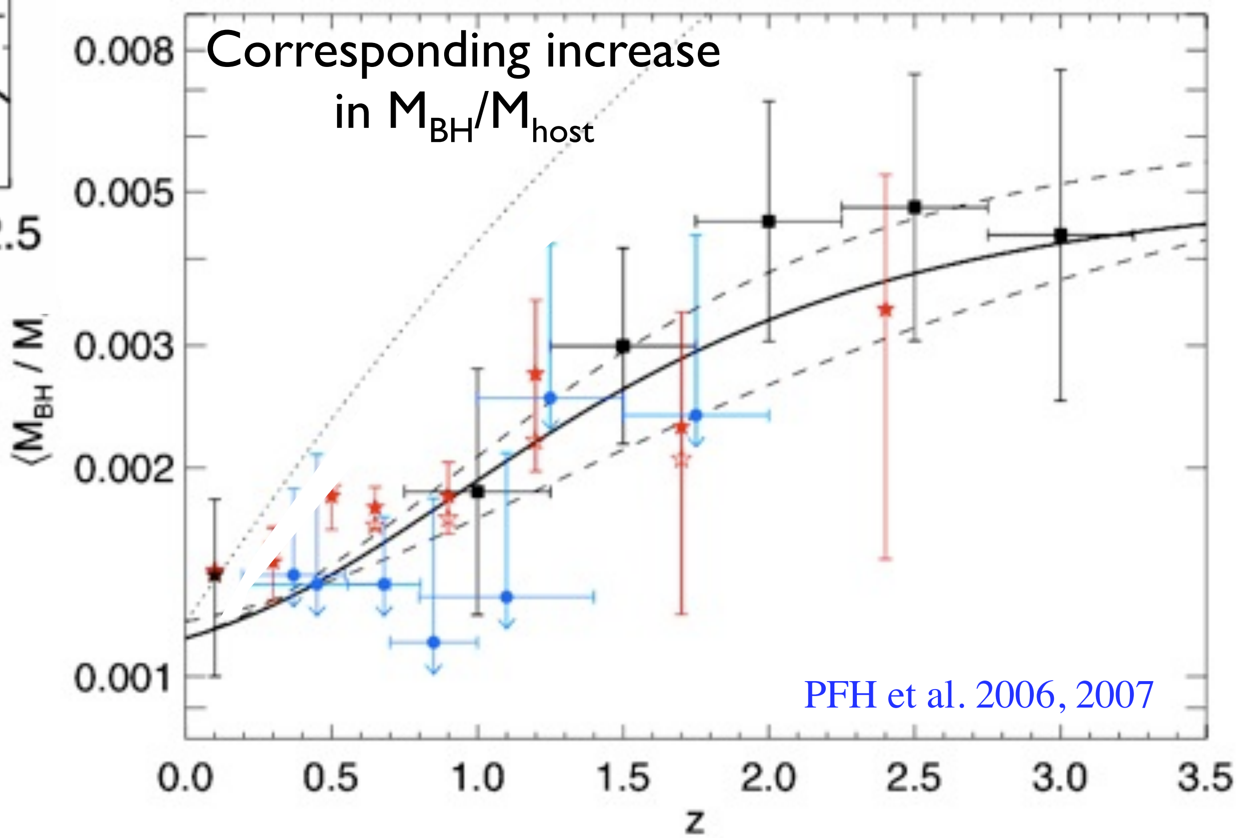


PFH, Bundy,
et al. 2009

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

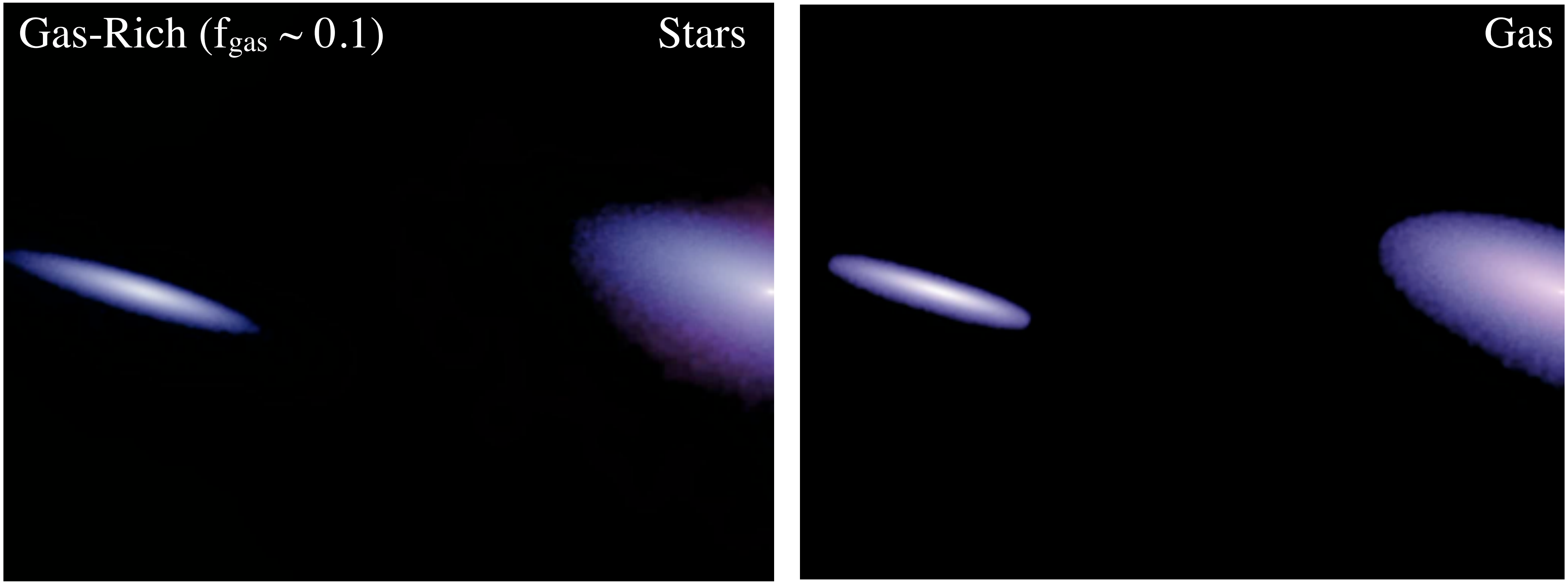




- Doesn't mean that BHs grew "before" their bulges

But what about the highest gas fractions?

How Good Is Our Conventional Wisdom?

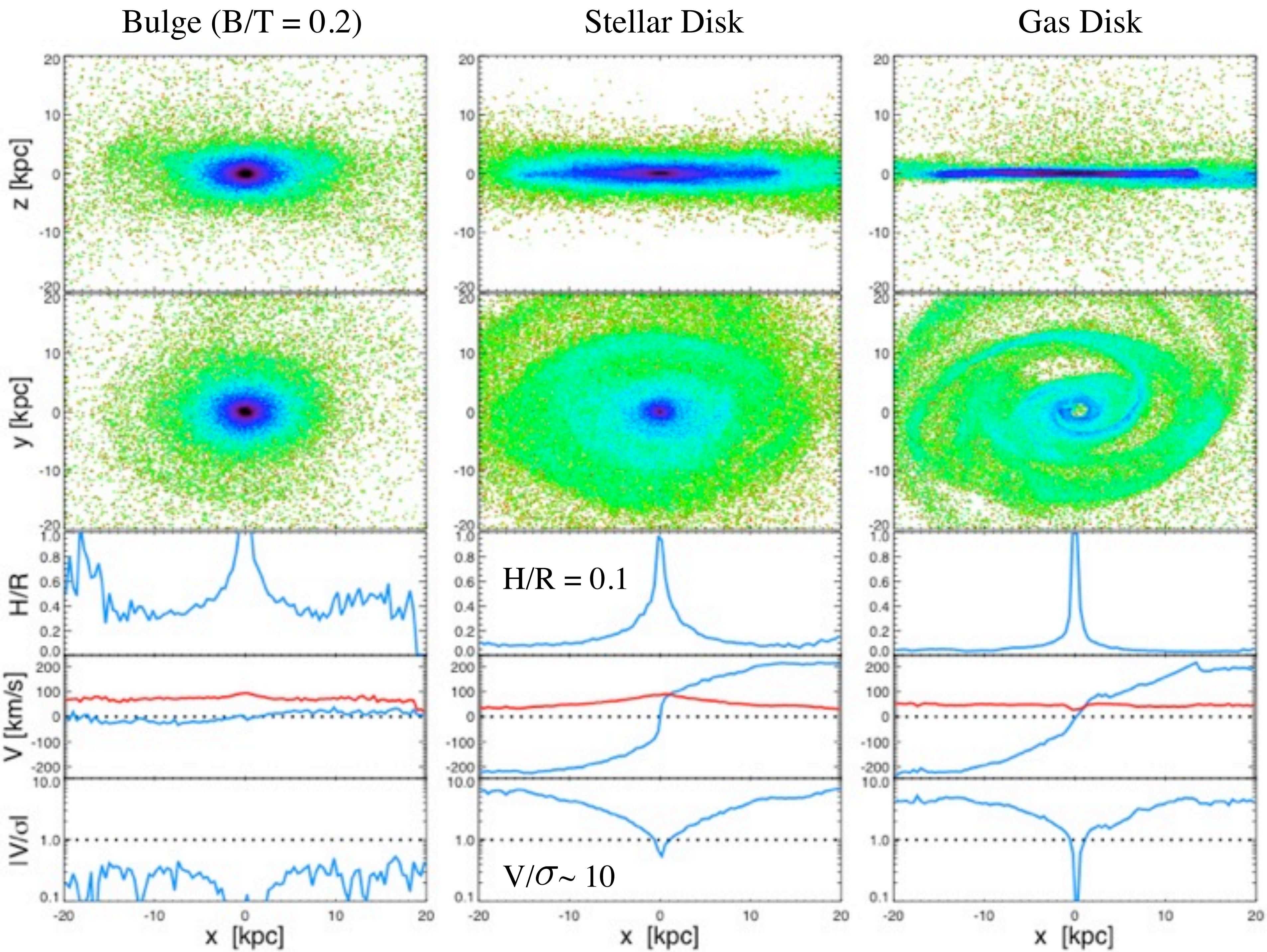


Gas-Richer ($f_{gas} \sim 0.4$)

Robertson et al. 2006

Major Merger Remnants

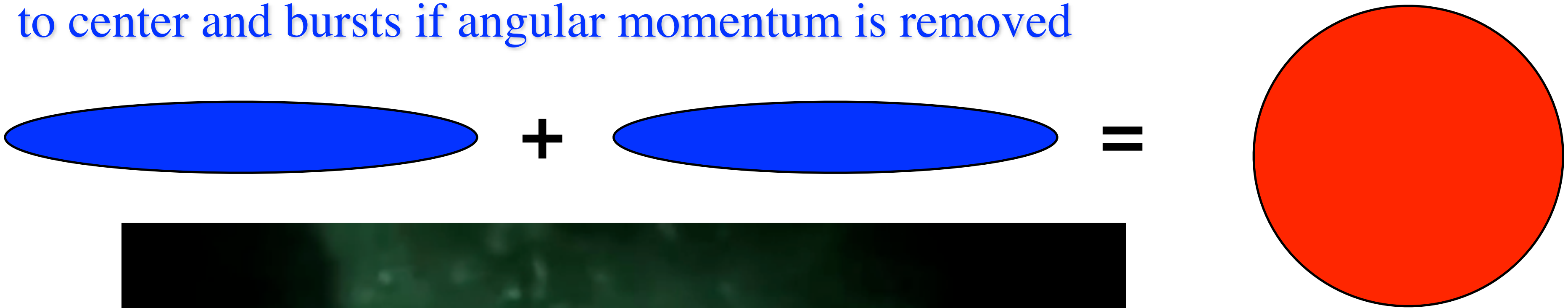
DO MERGERS DESTROY DISKS?

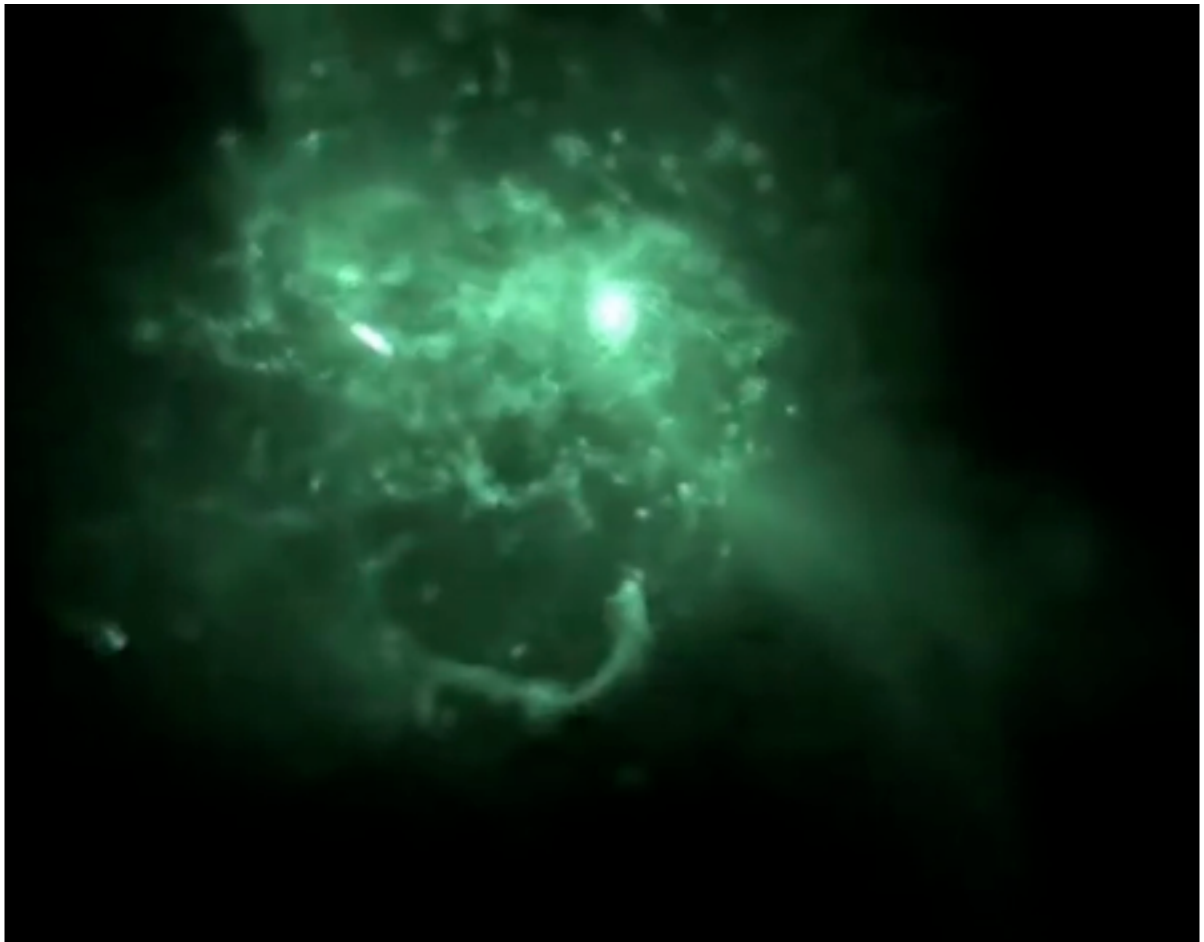


The Unsolved Questions

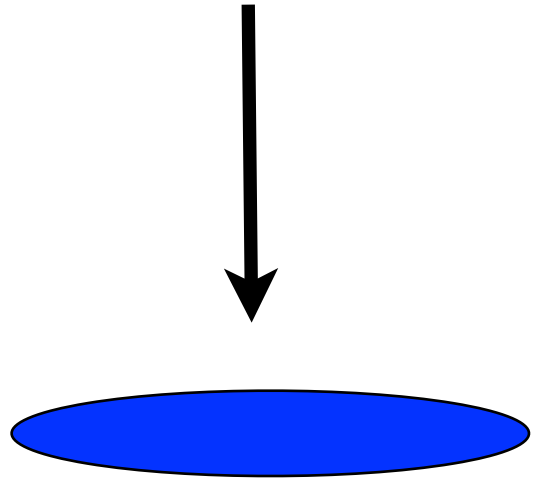
HOW CAN A DISK SURVIVE?

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





Brooks et al., Governato et al.

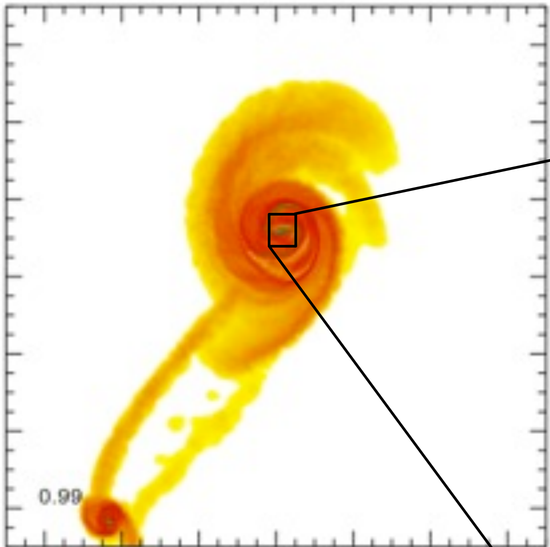


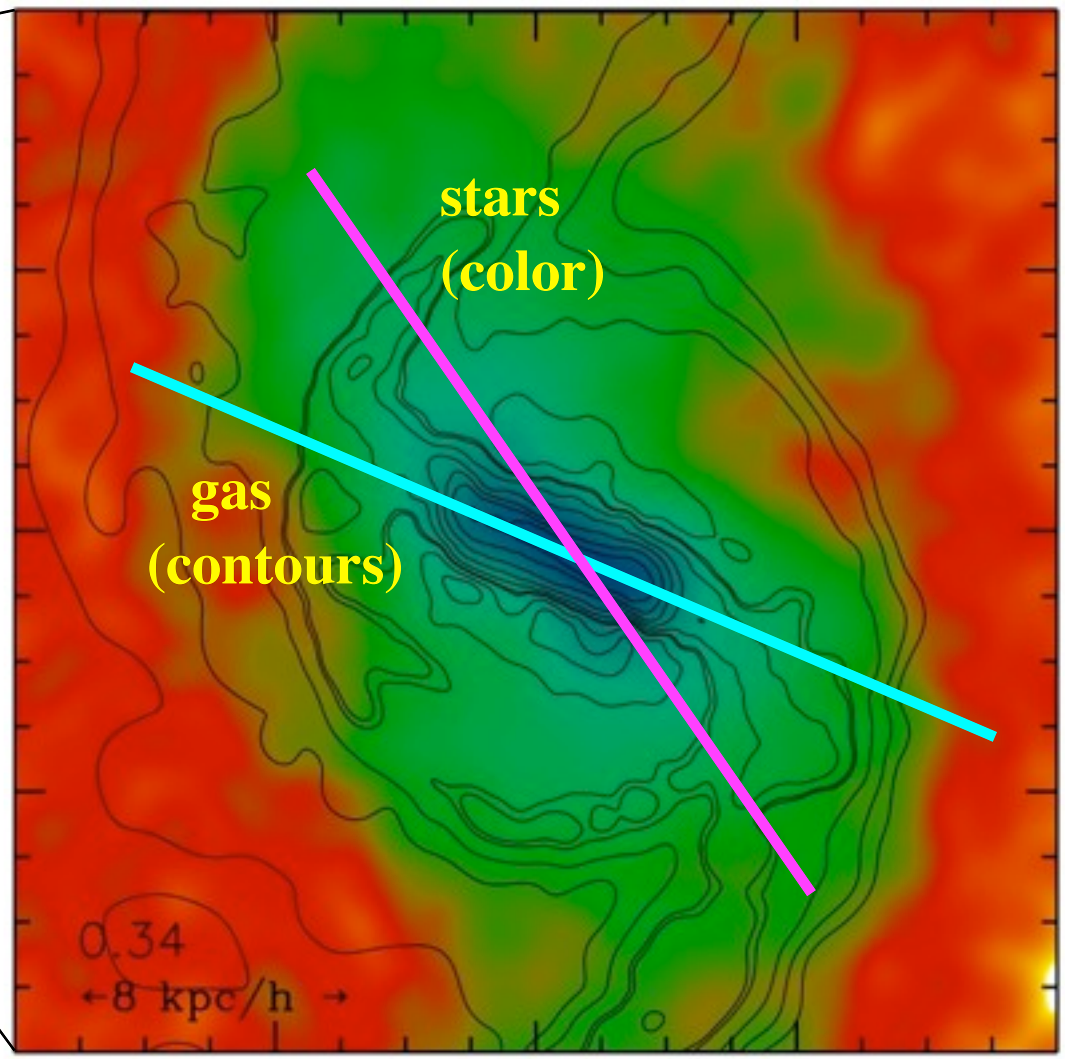
How Do Disks Survive Mergers?

PFH et al. 2008

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

(see, e.g., Barnes 92, Barnes & Hernquist 96, Mihos & Hernquist 94,96)





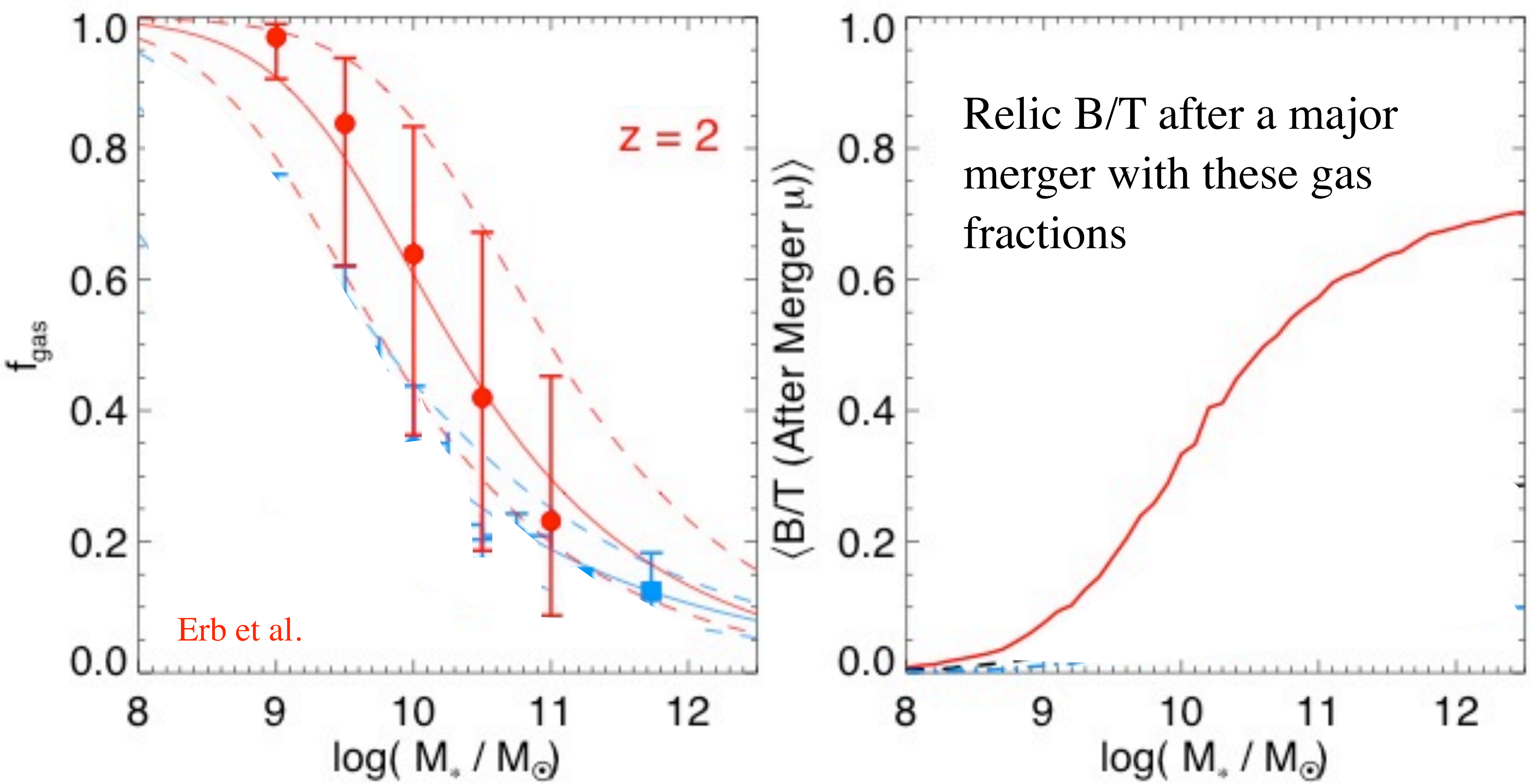
- What does the torquing?
  - Stars in the same galaxy

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

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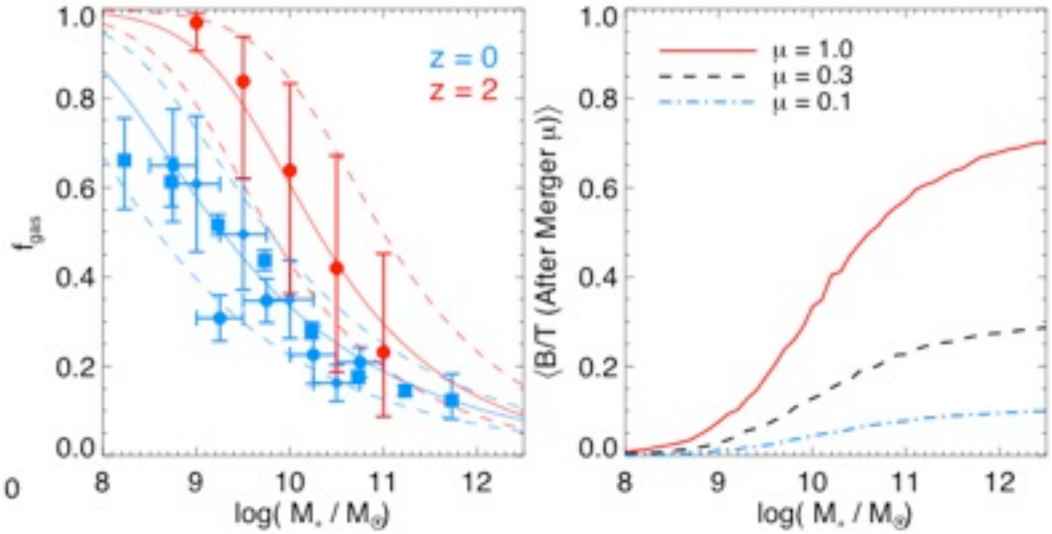
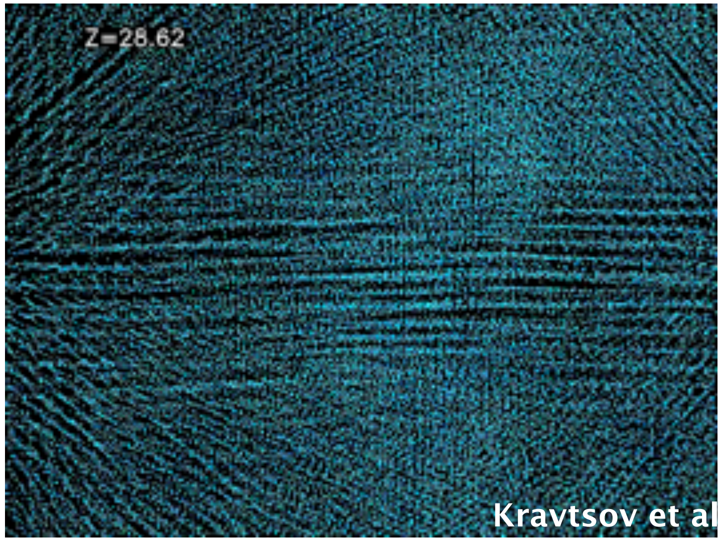
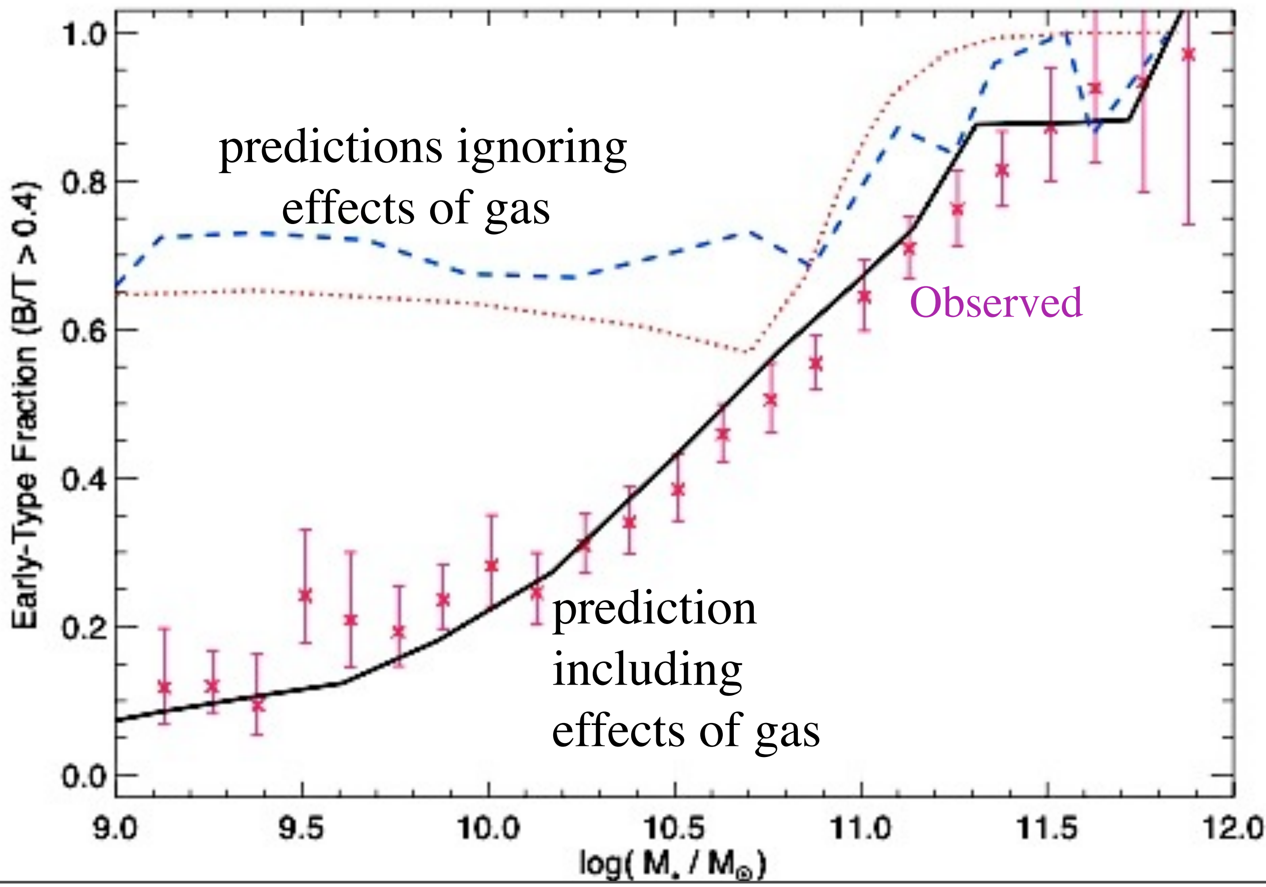






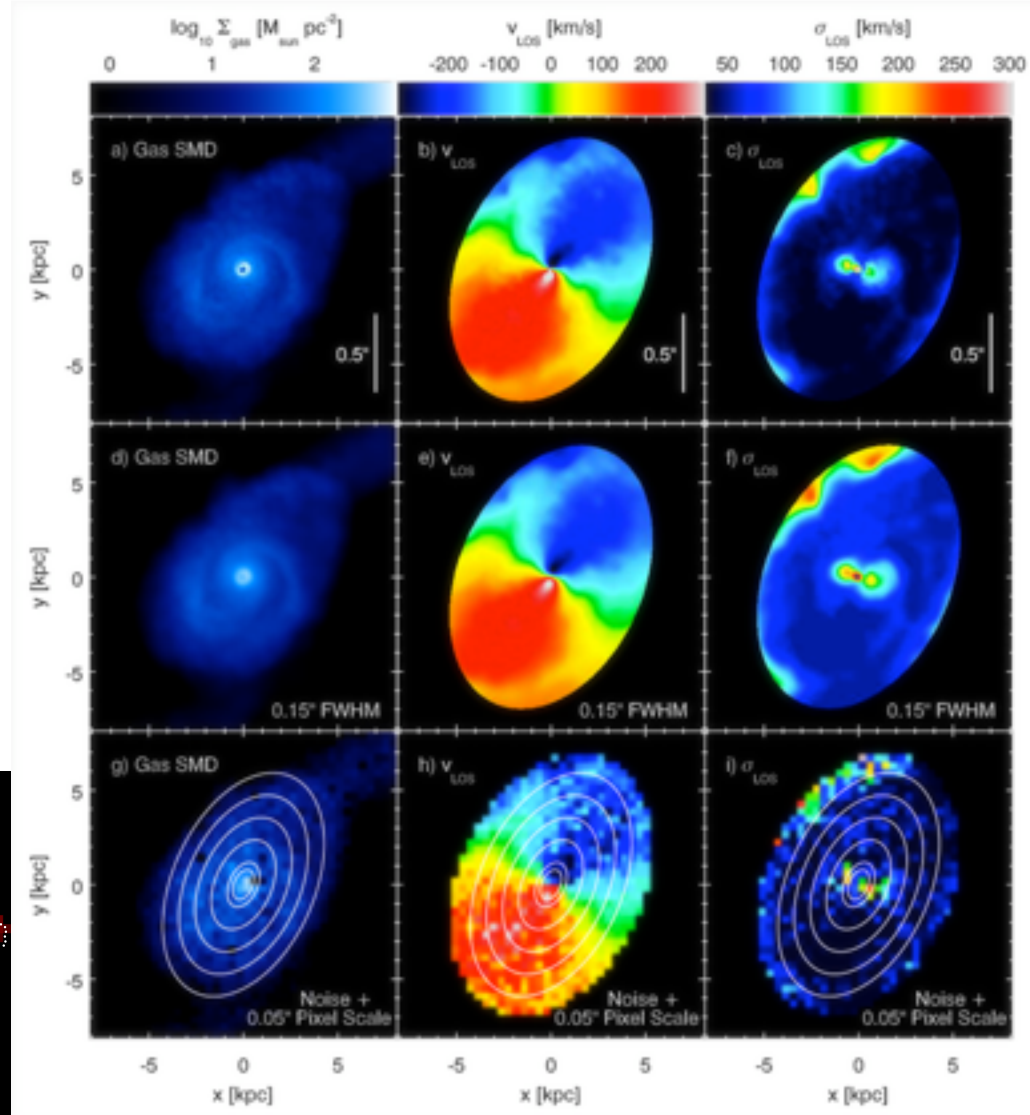
PFH & Somerville et al. 2009

High-Redshift:

WILL ONLY INCREASE IN IMPORTANCE

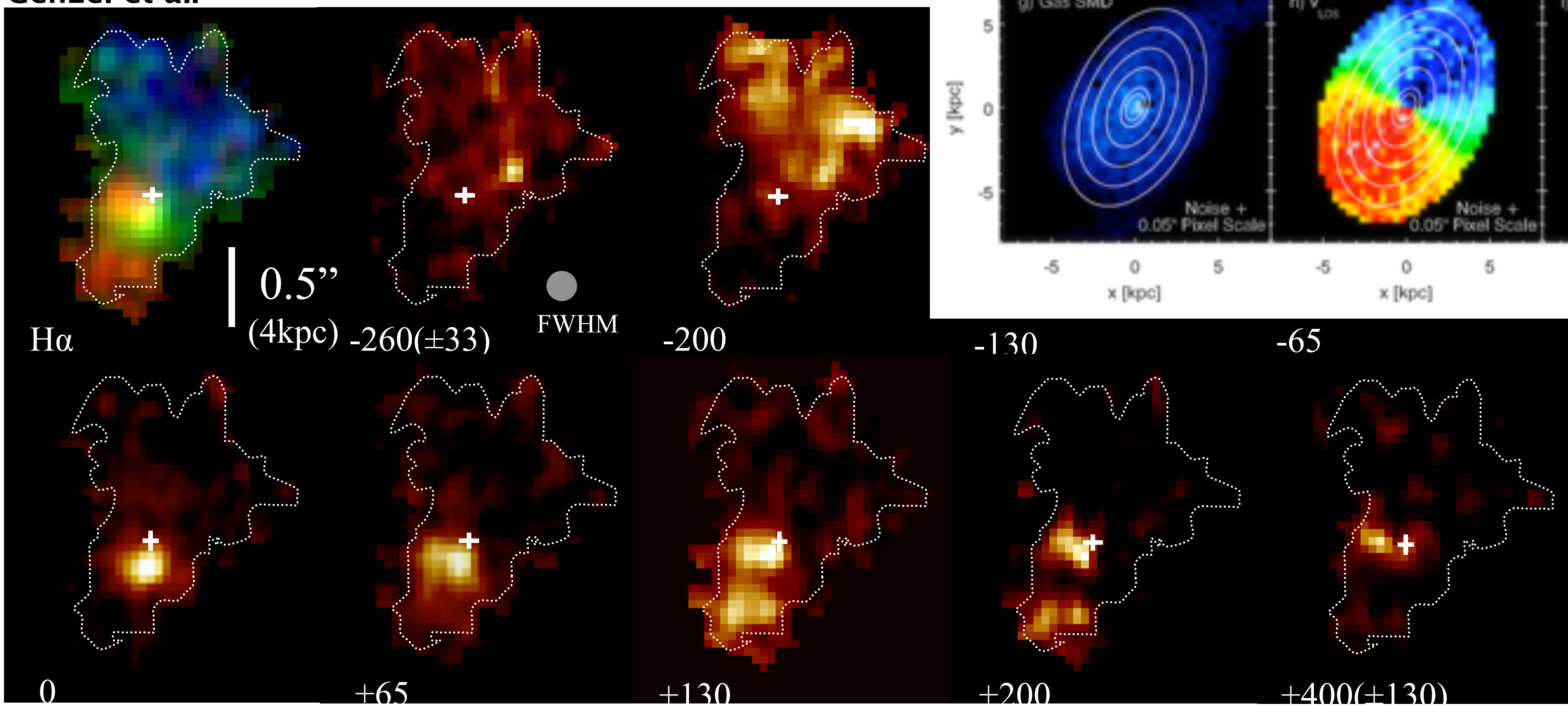
Need to explain high-z massive disks
 We see them
 (Genzel, Tacconi, Erb, Law, et al.)

May explain properties (turbulence etc.)
 (Robertson & Bullock 2008)



Robertson & Bullock 2008

Genzel et al.



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...)