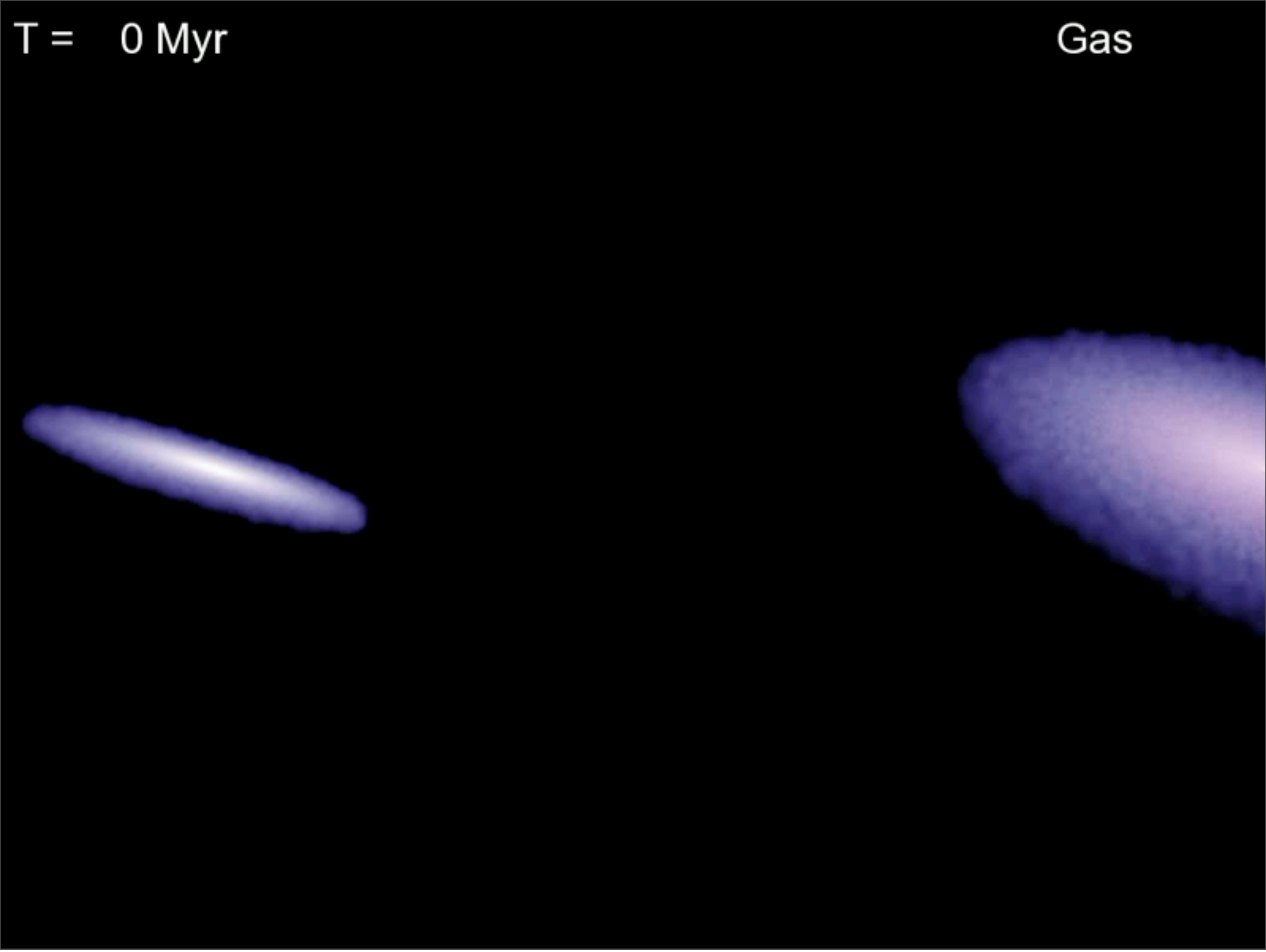
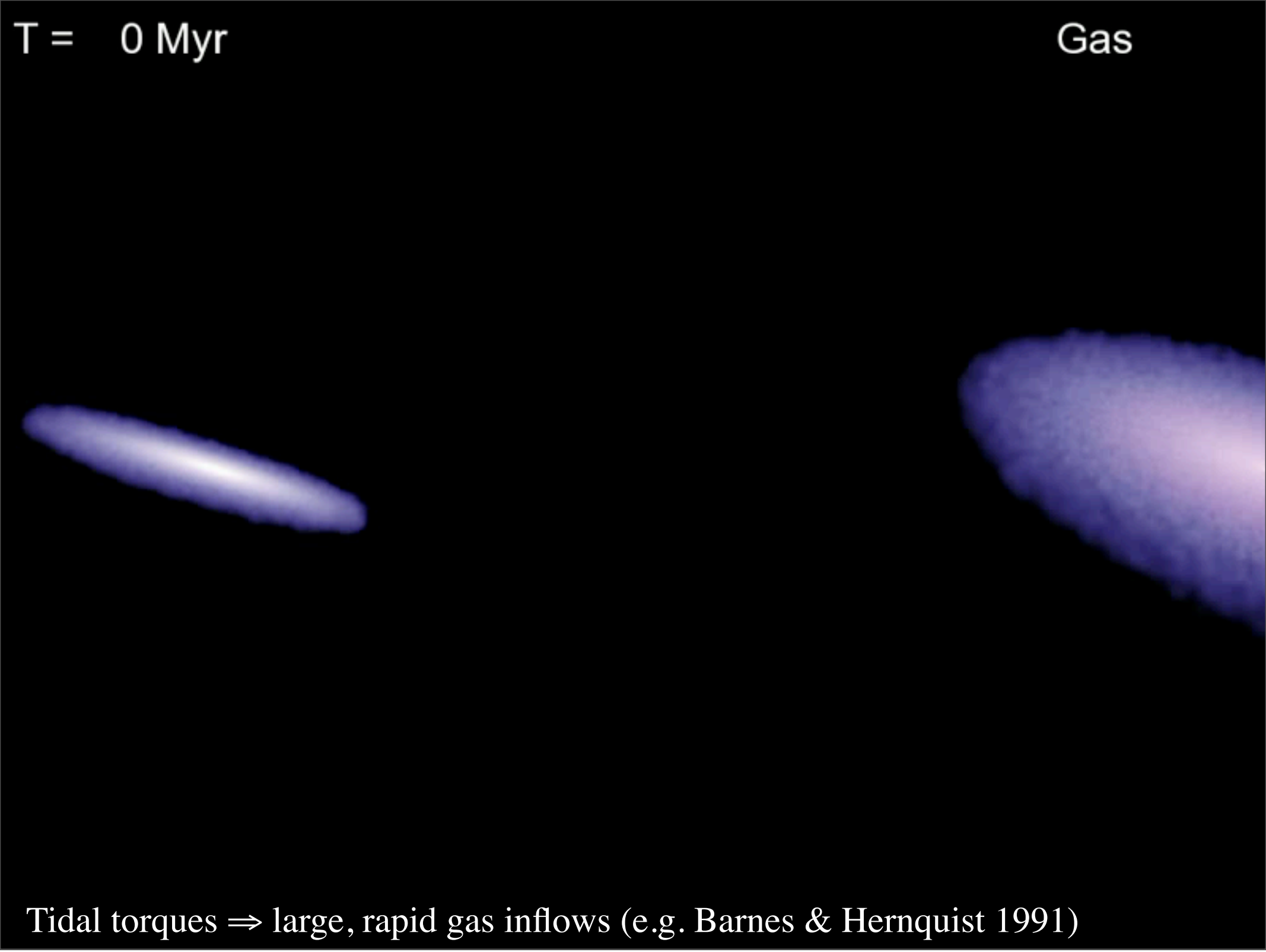
Gas, Galaxy Mergers, & Feedback: Driving an Evolving Hubble Sequence

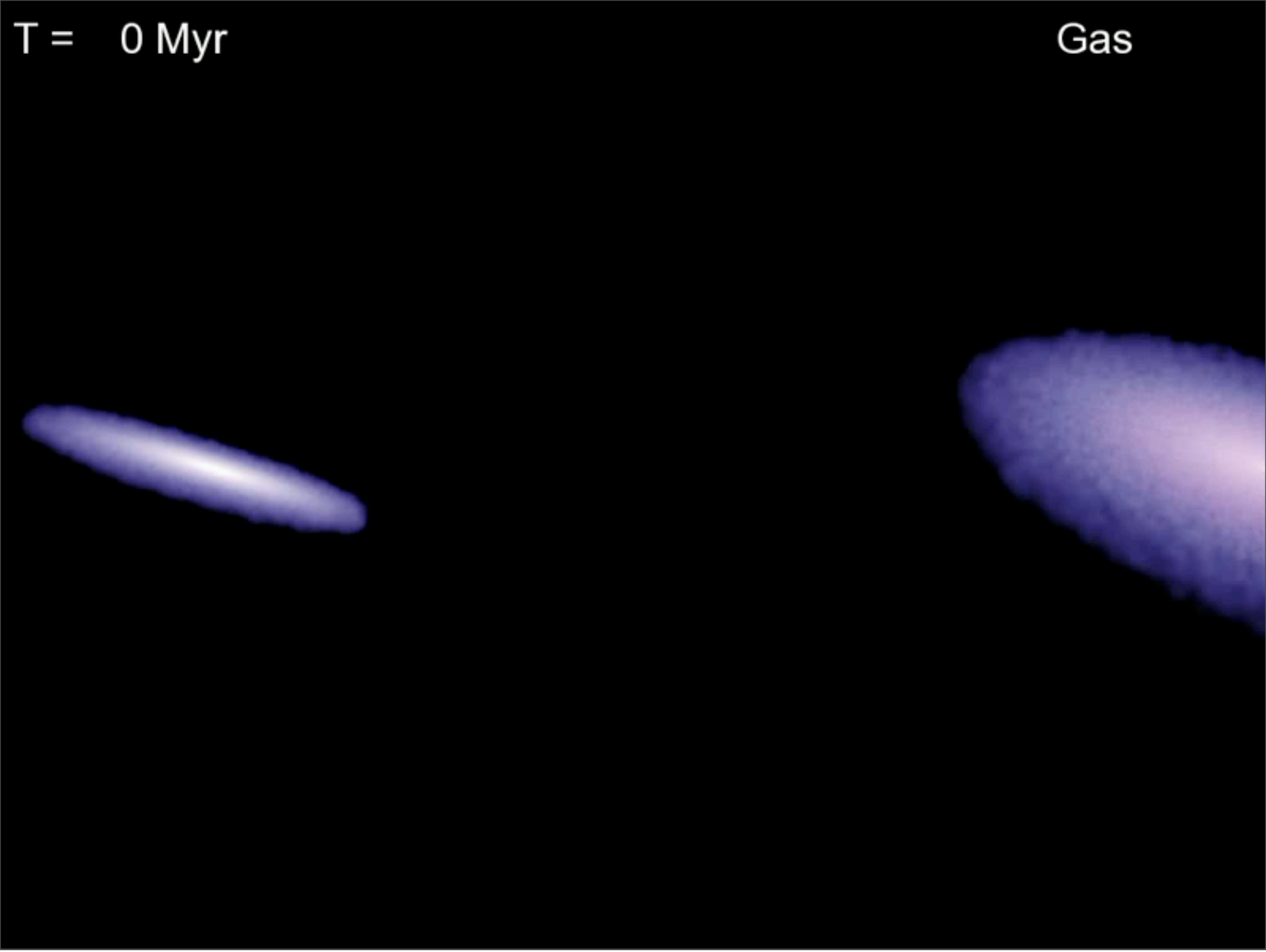
Philip Hopkins

Lars Hernquist, Eliot Quataert, T. J. Cox, Brant Robertson, Dusan Keres, 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


T = 0 Myr
Gas



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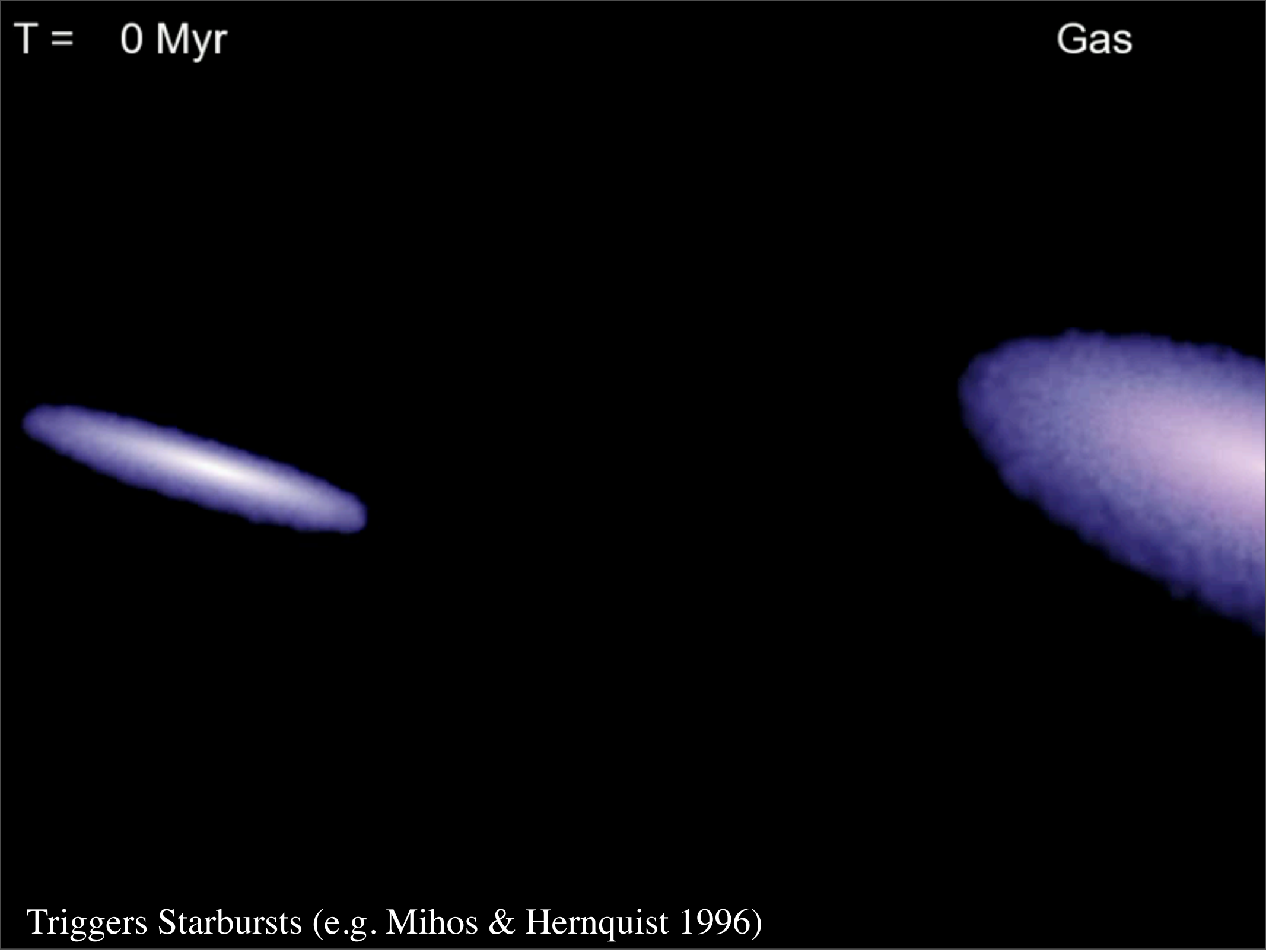
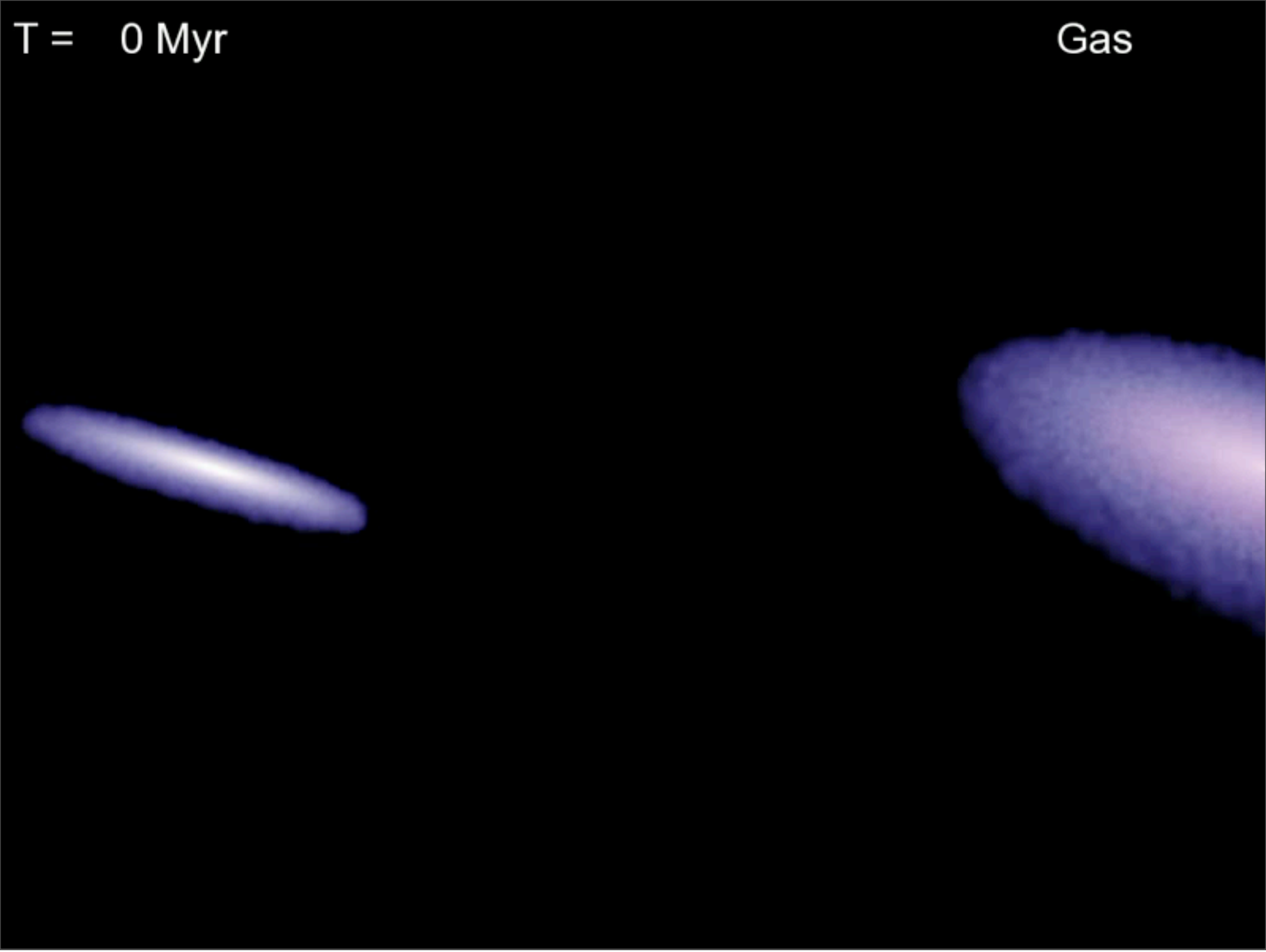


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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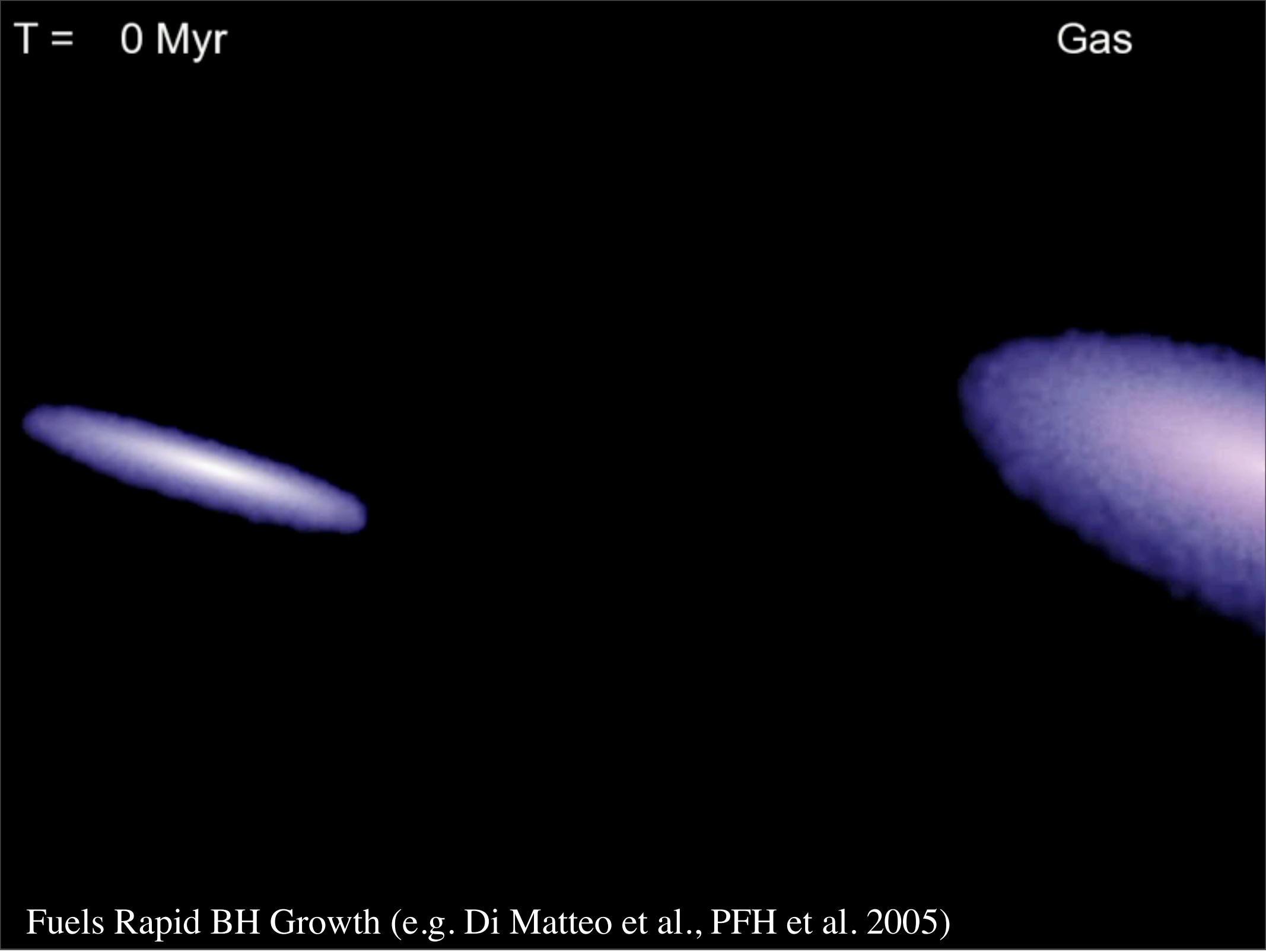
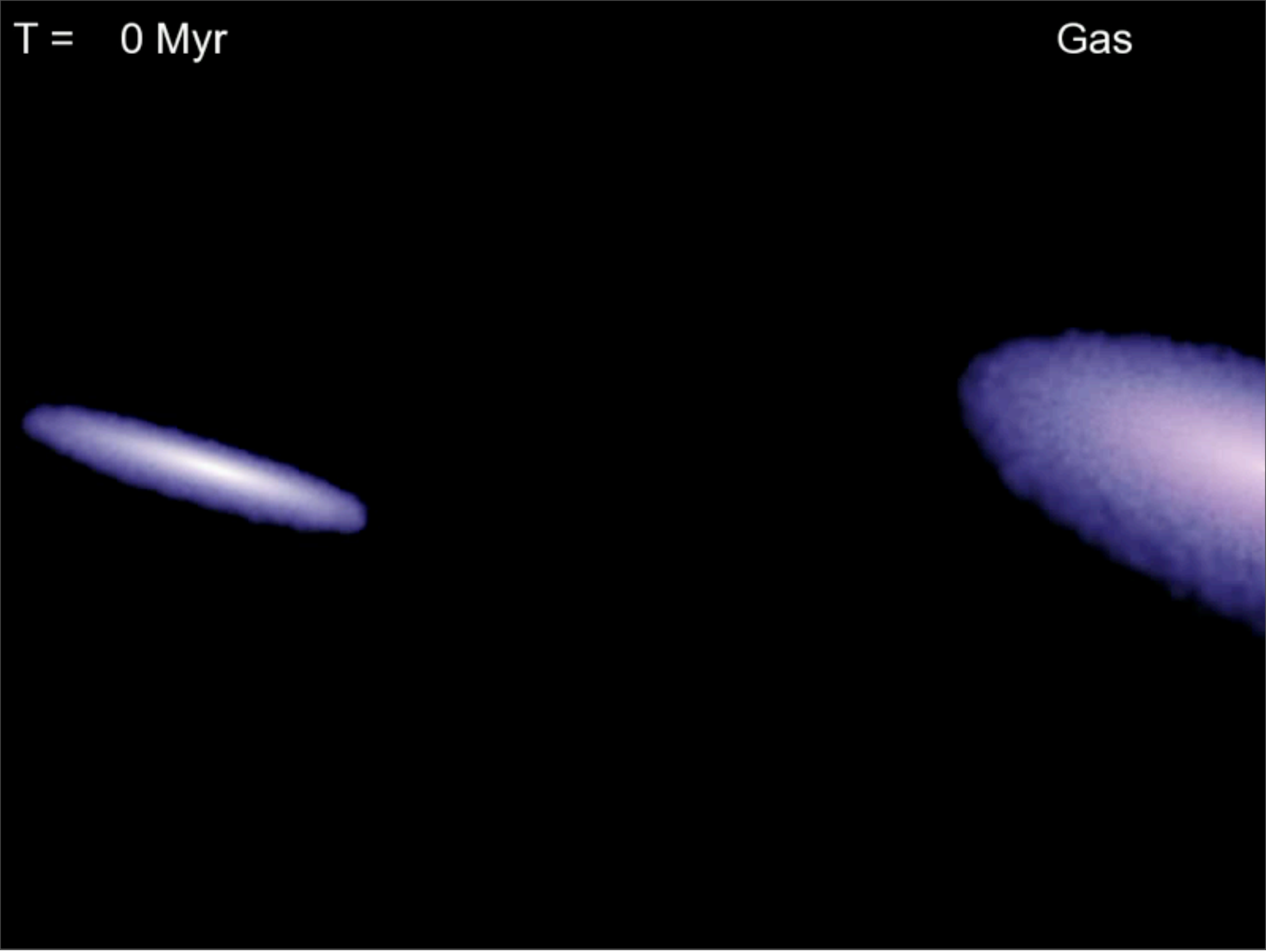


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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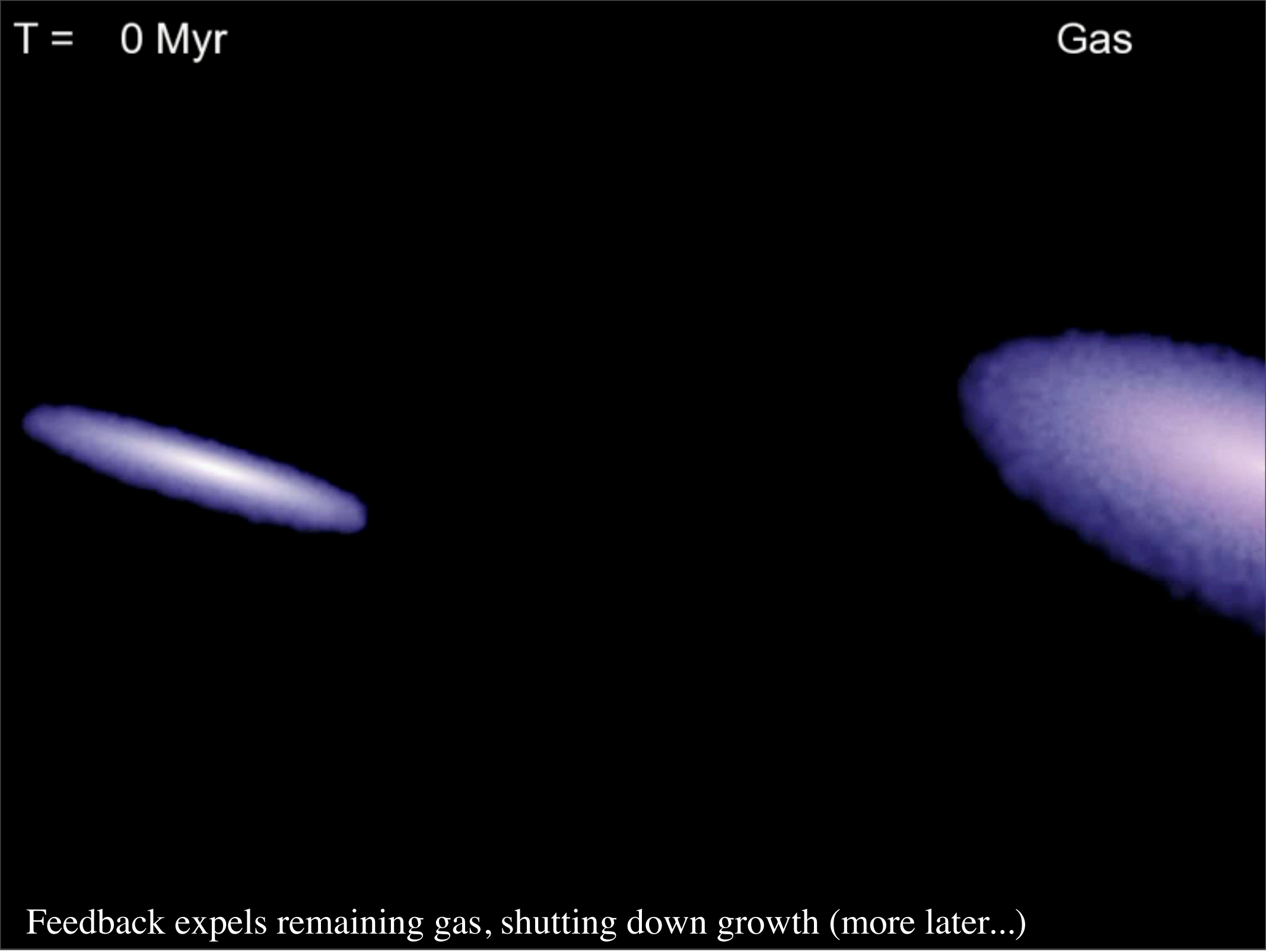
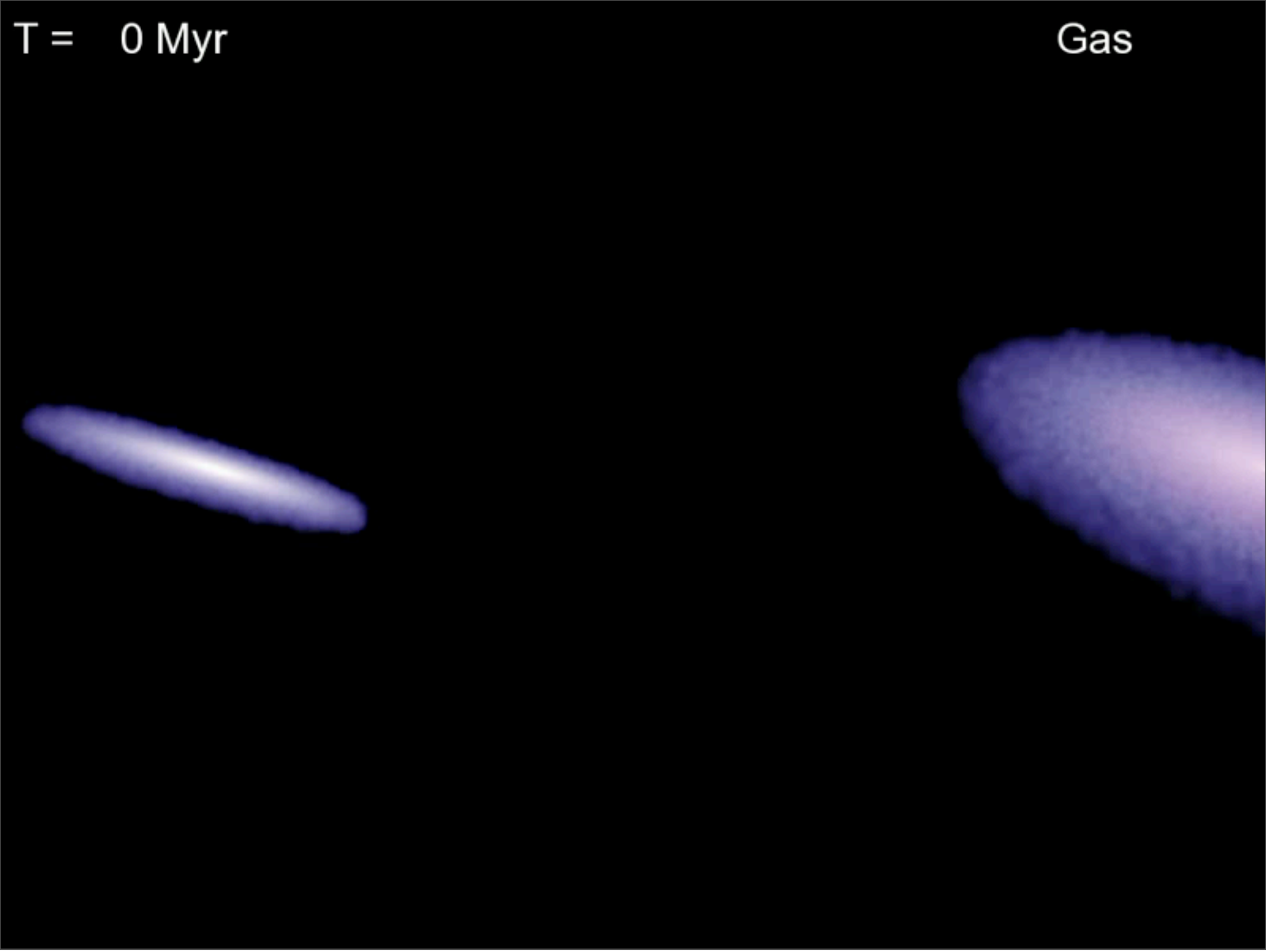


Feedback expels remaining gas, shutting down growth (more later...)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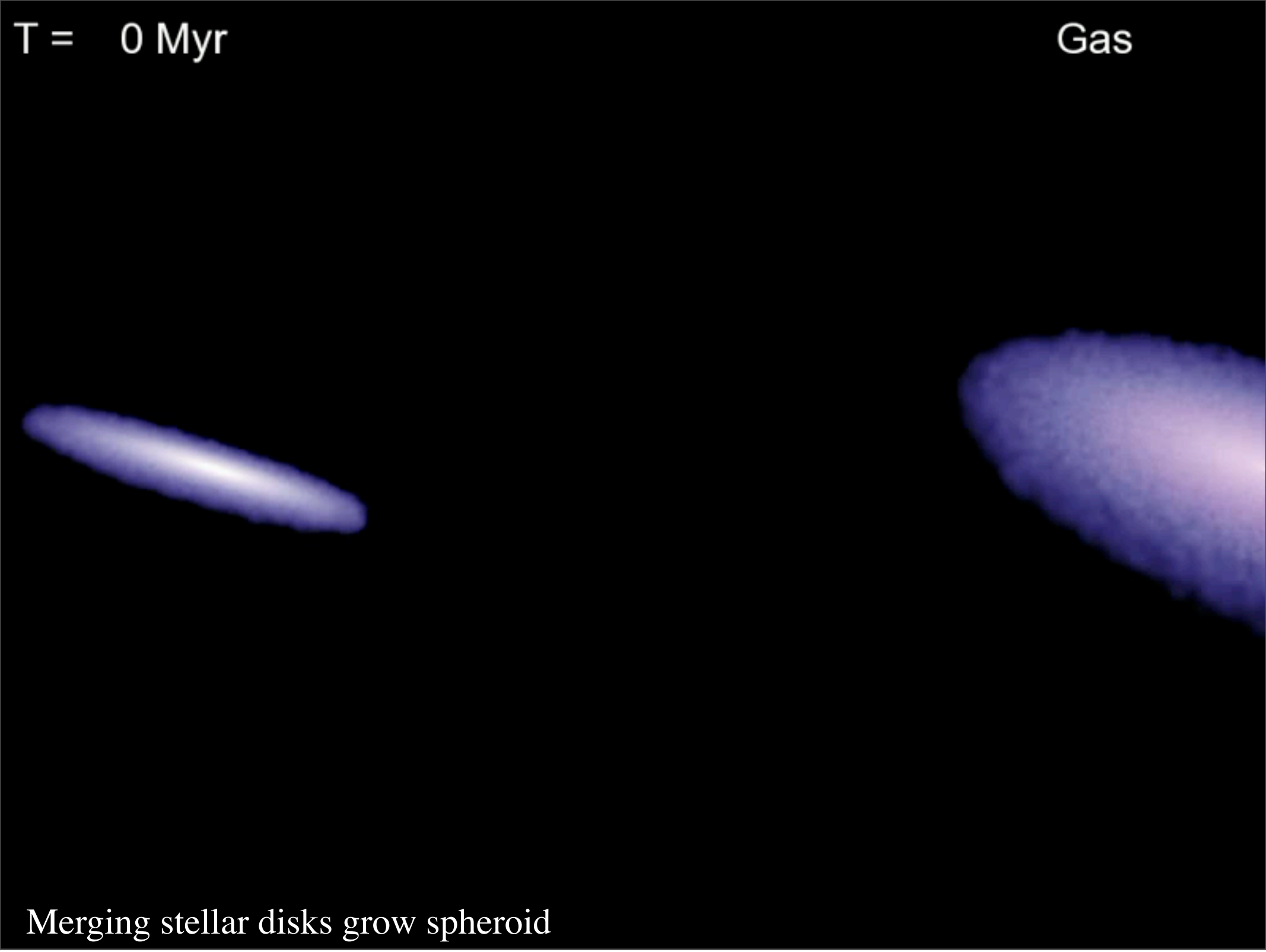
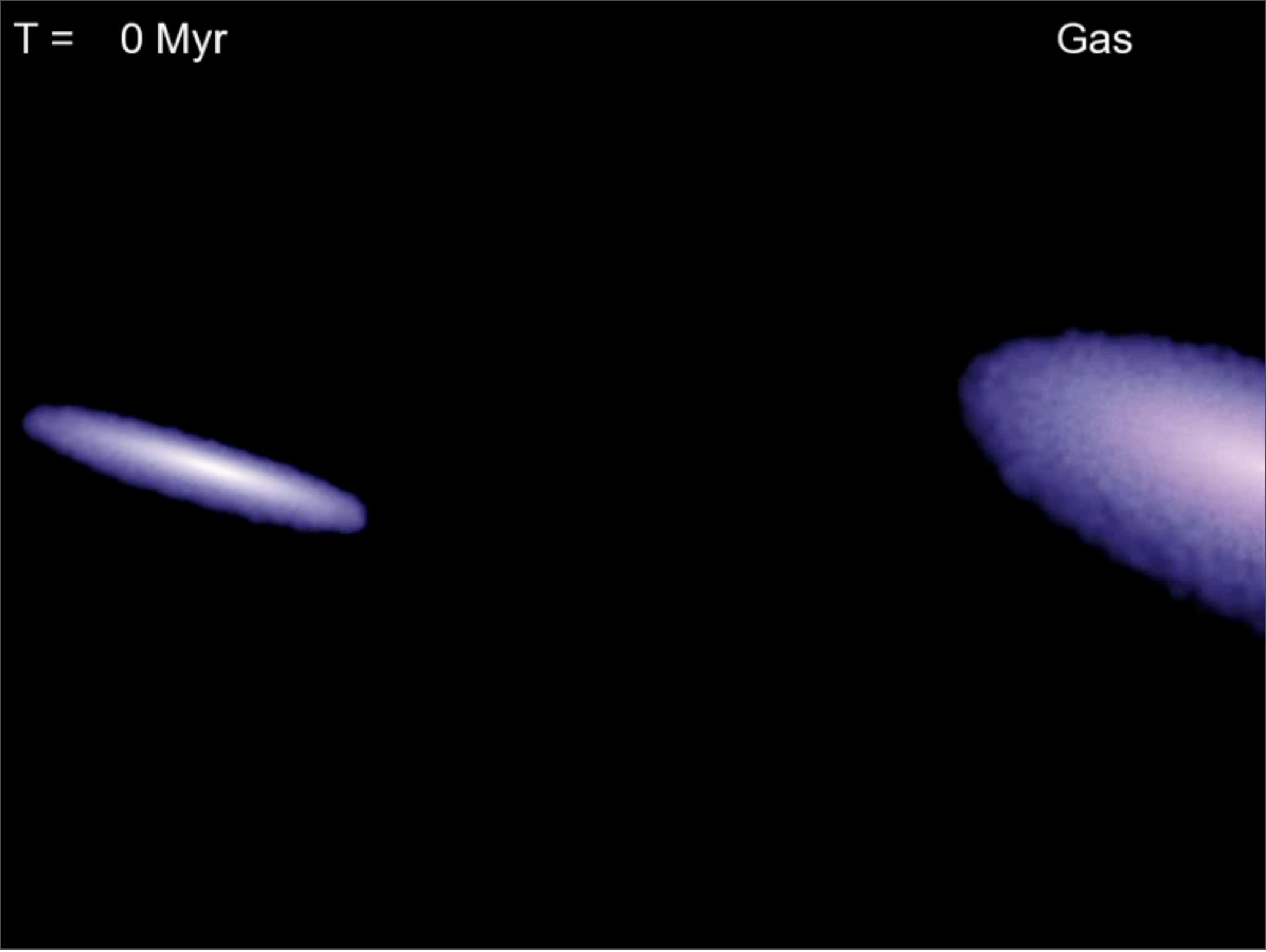


Merging stellar disks grow spheroid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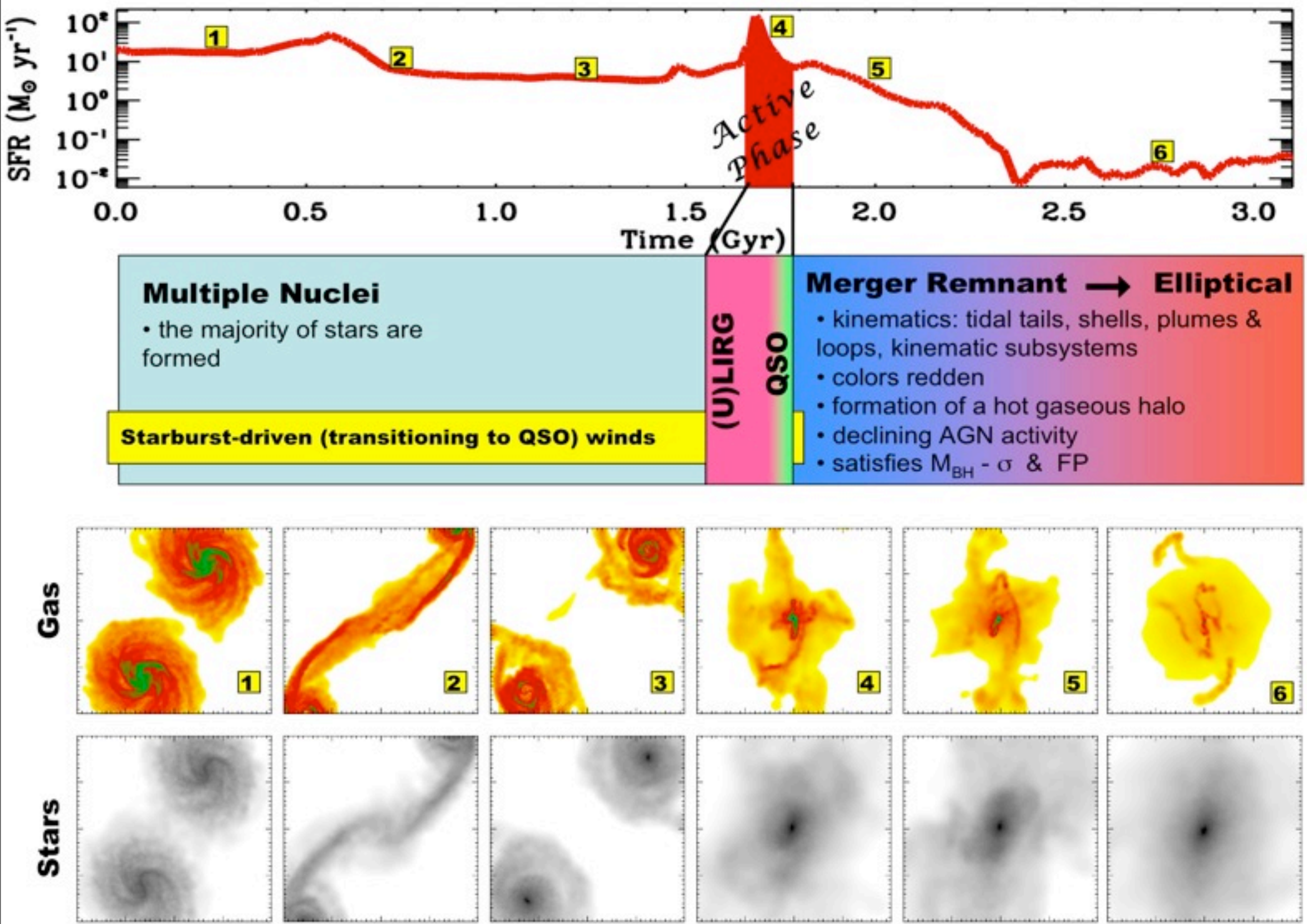
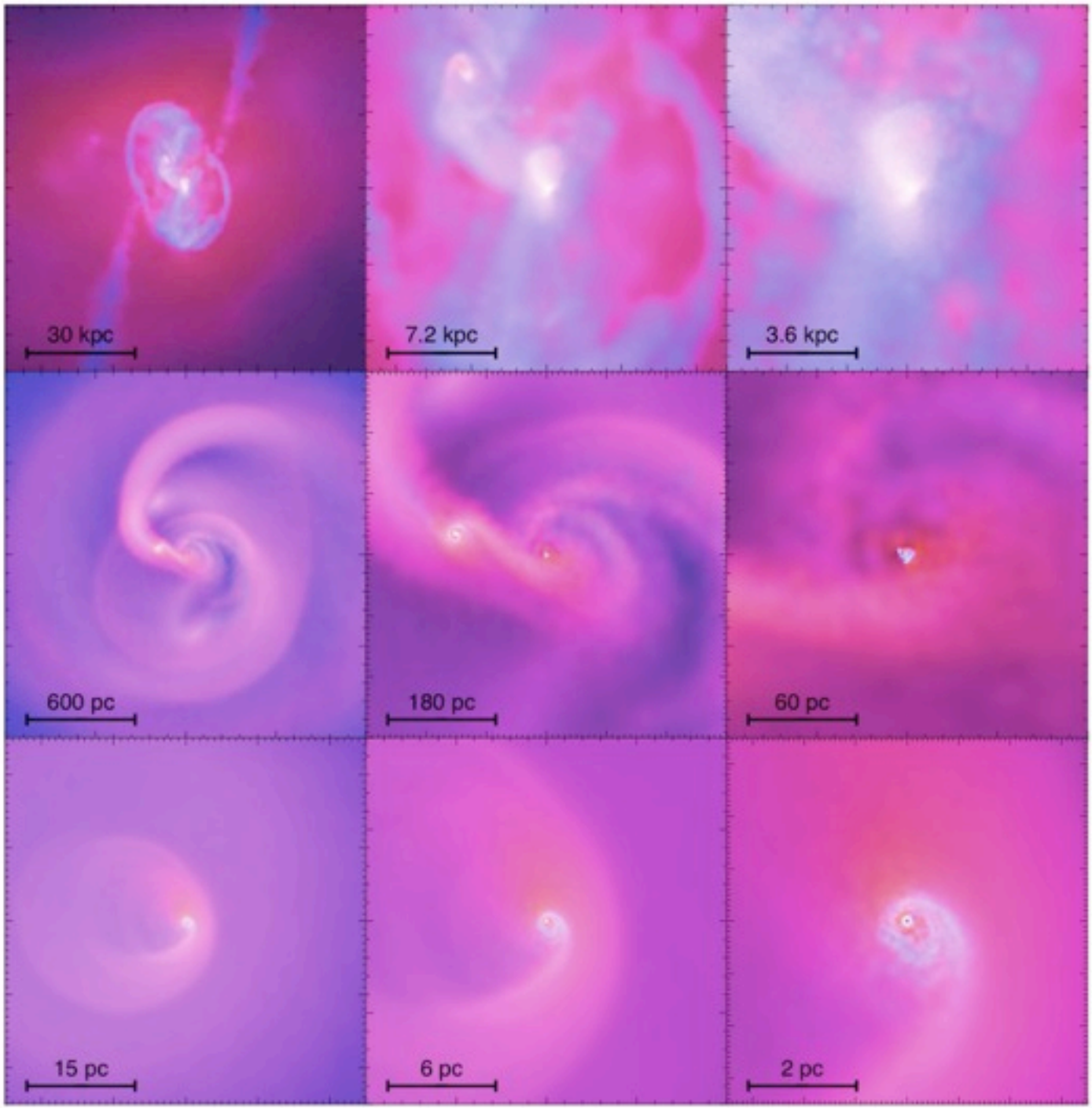

SFR ($M_\odot$ yr^{-1})
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
1
2
3
4
5
6
Active Phase
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
Multiple Nuclei
• the majority of stars are formed
Starburst-driven (transitioning to QSO) winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

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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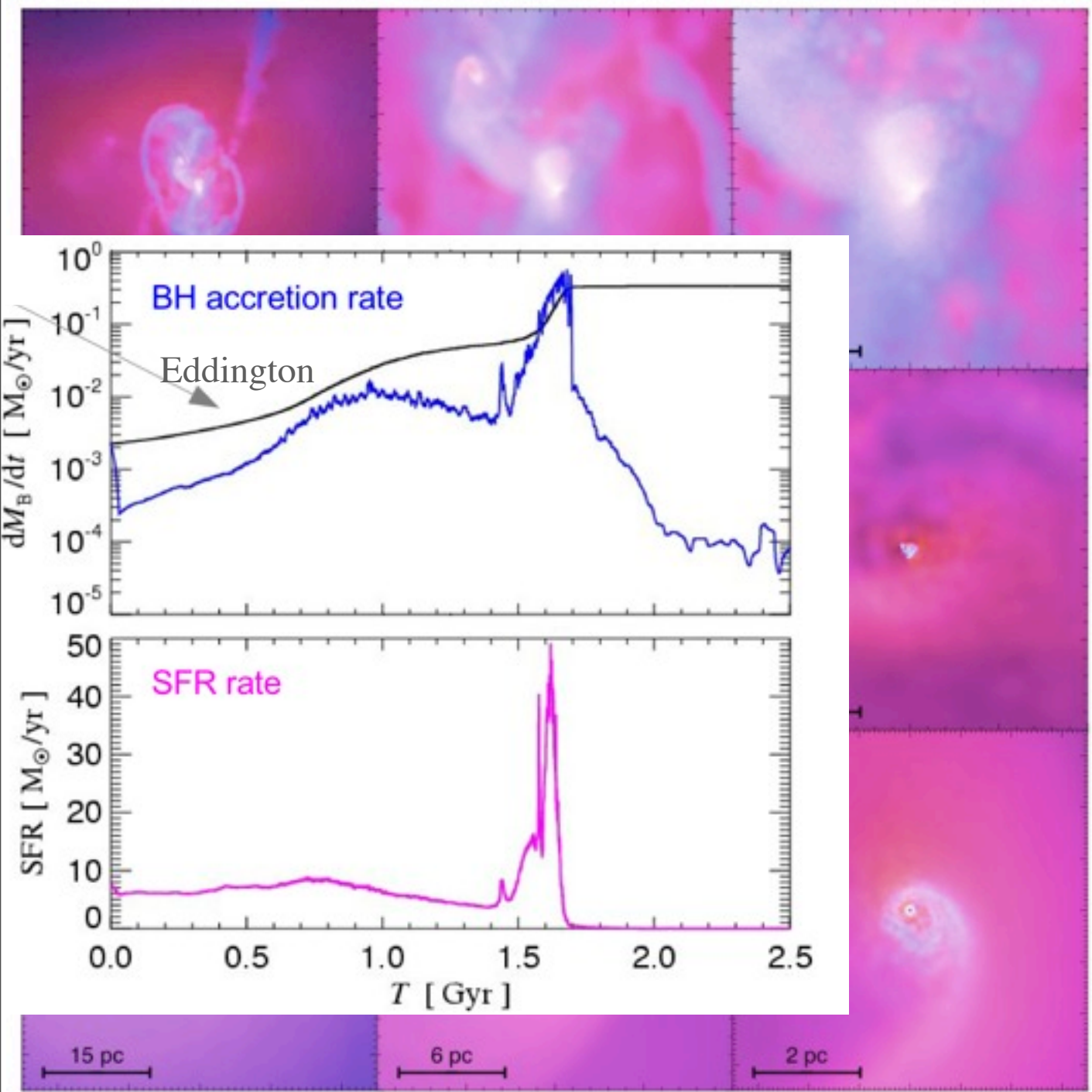

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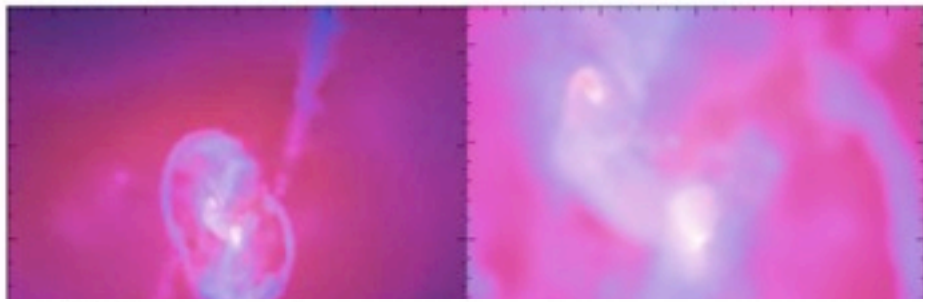
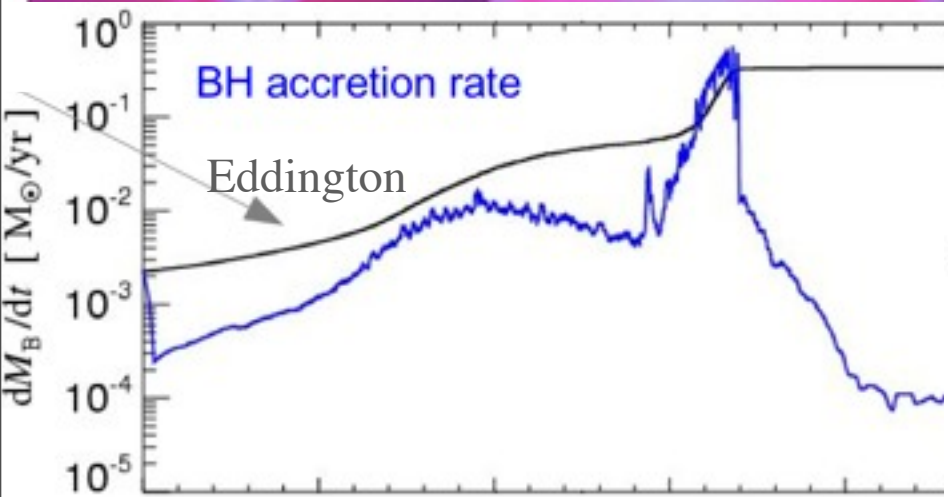
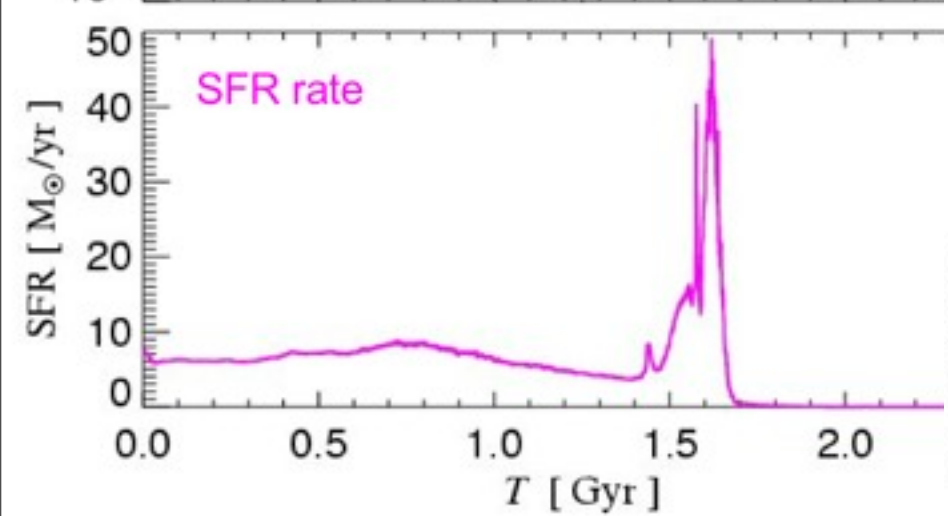
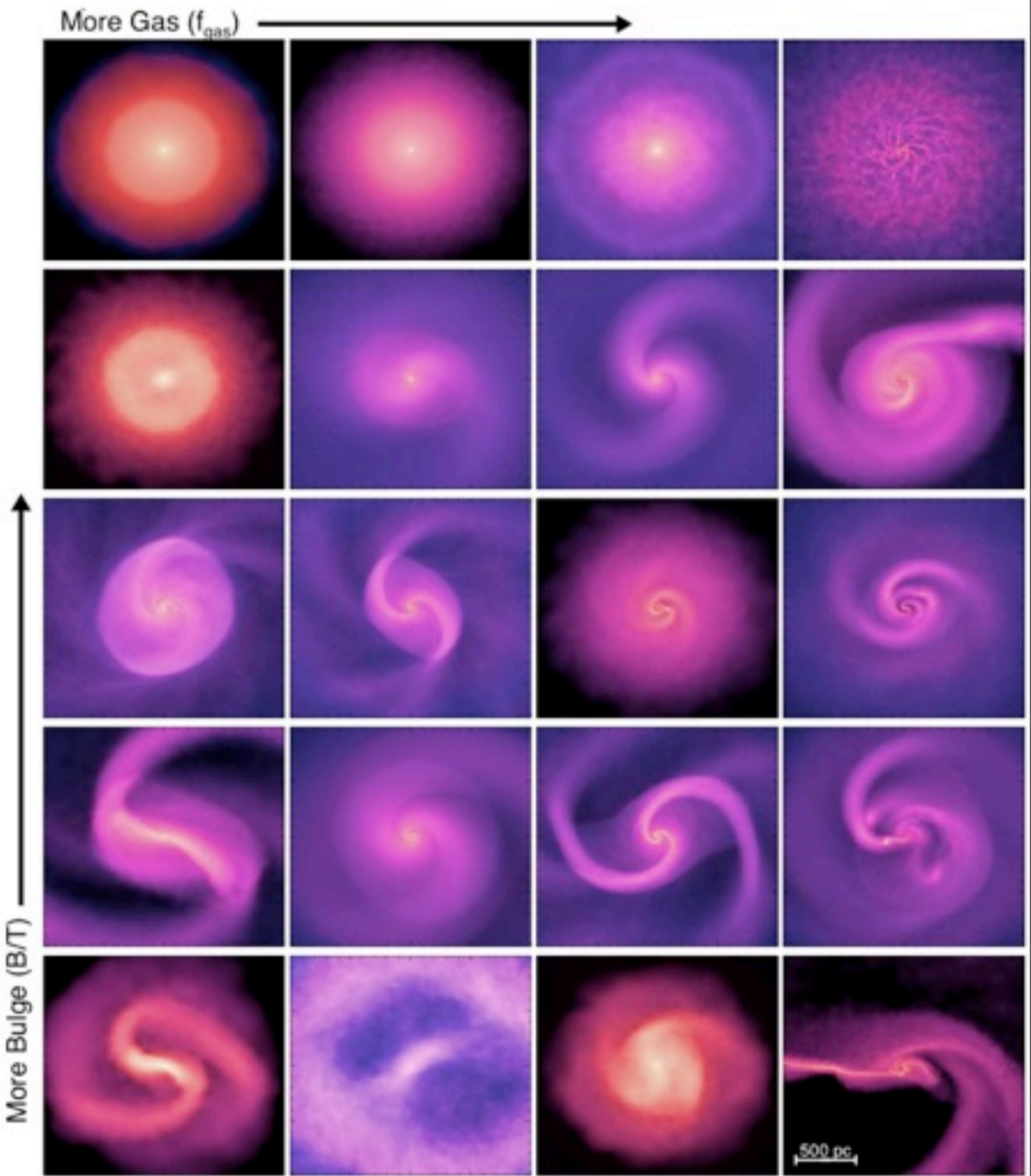








PFH & Quataert 2009,201

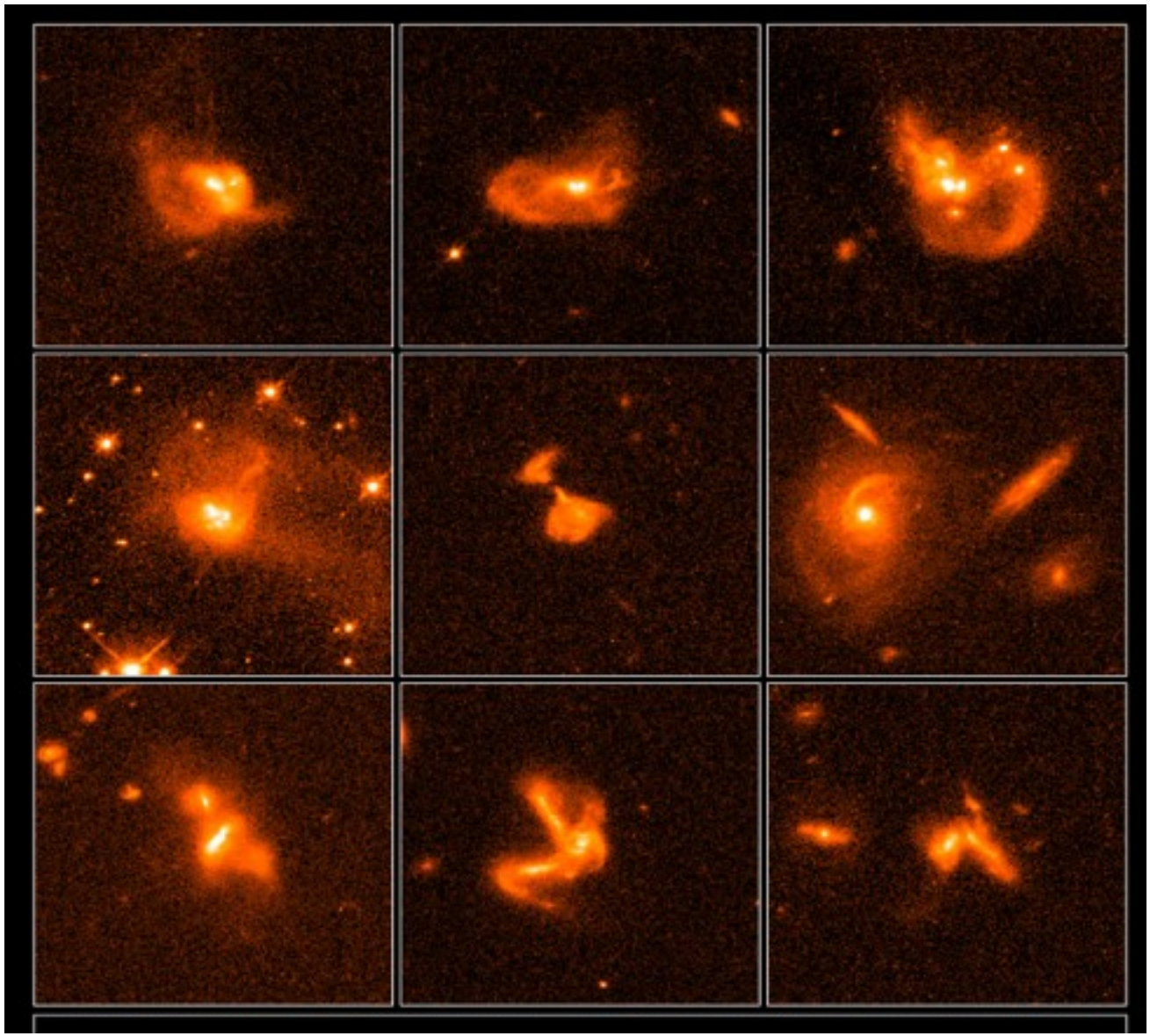
Sanders et al.,
& many others since
(many talks here):

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

Essentially all late-stage
merger remnants

Compact (~kpc scales)

Borne et al., 2000

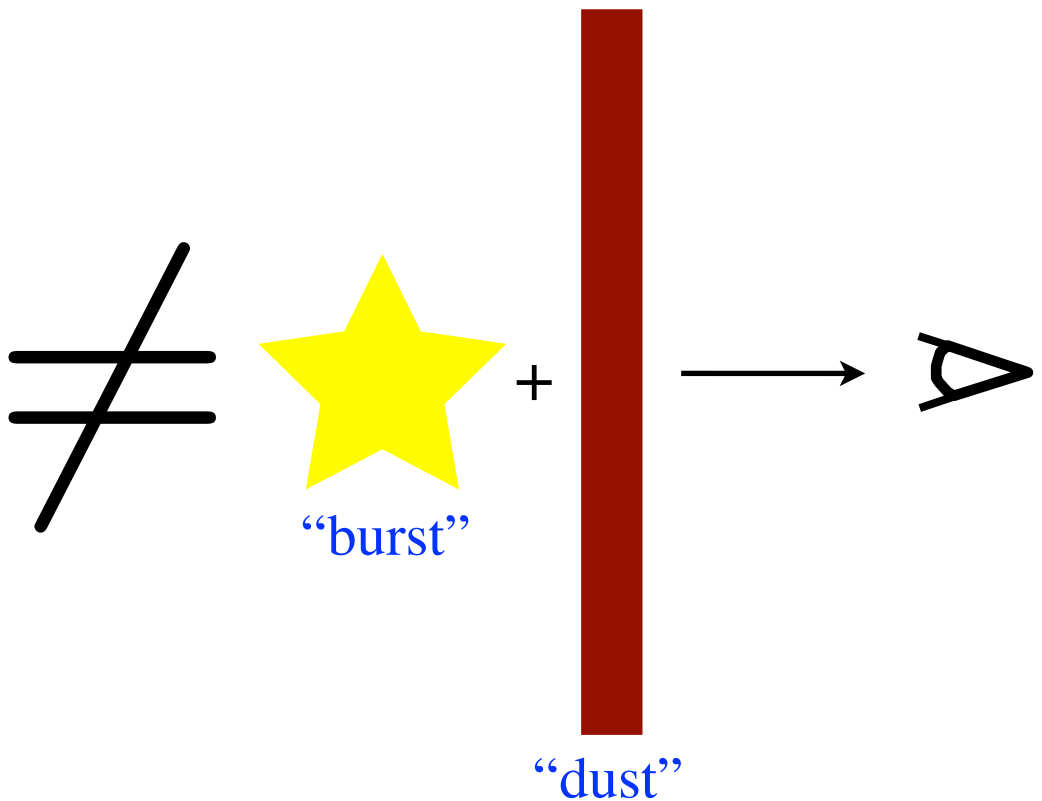


Are they the progenitors of ellipticals?

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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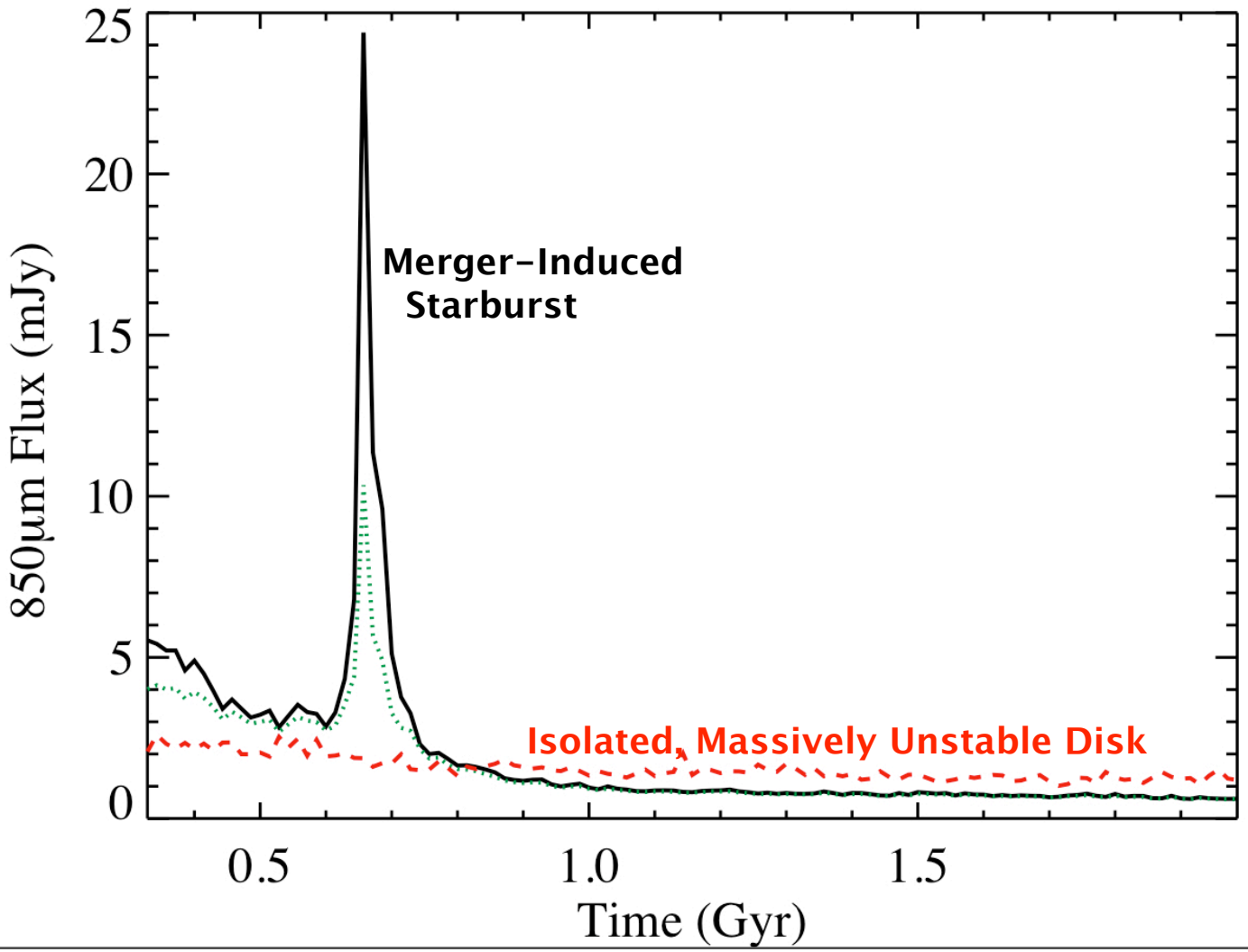

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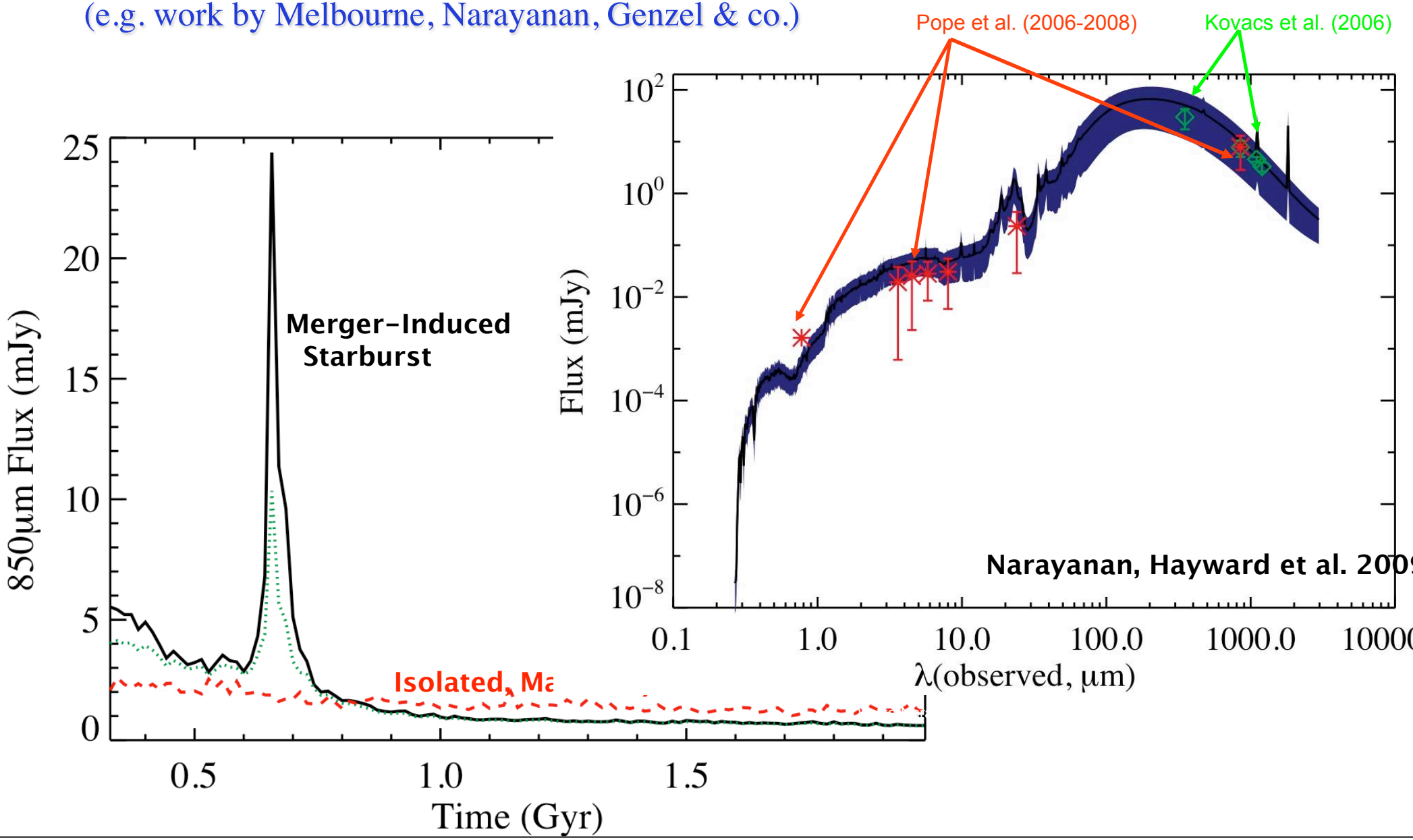
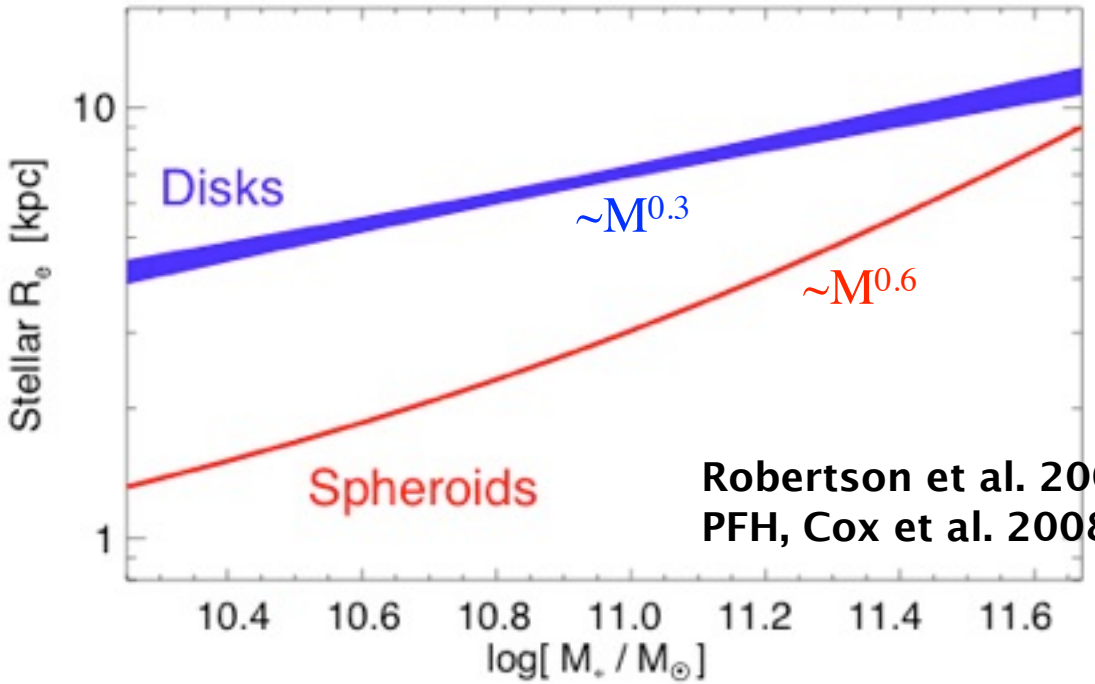
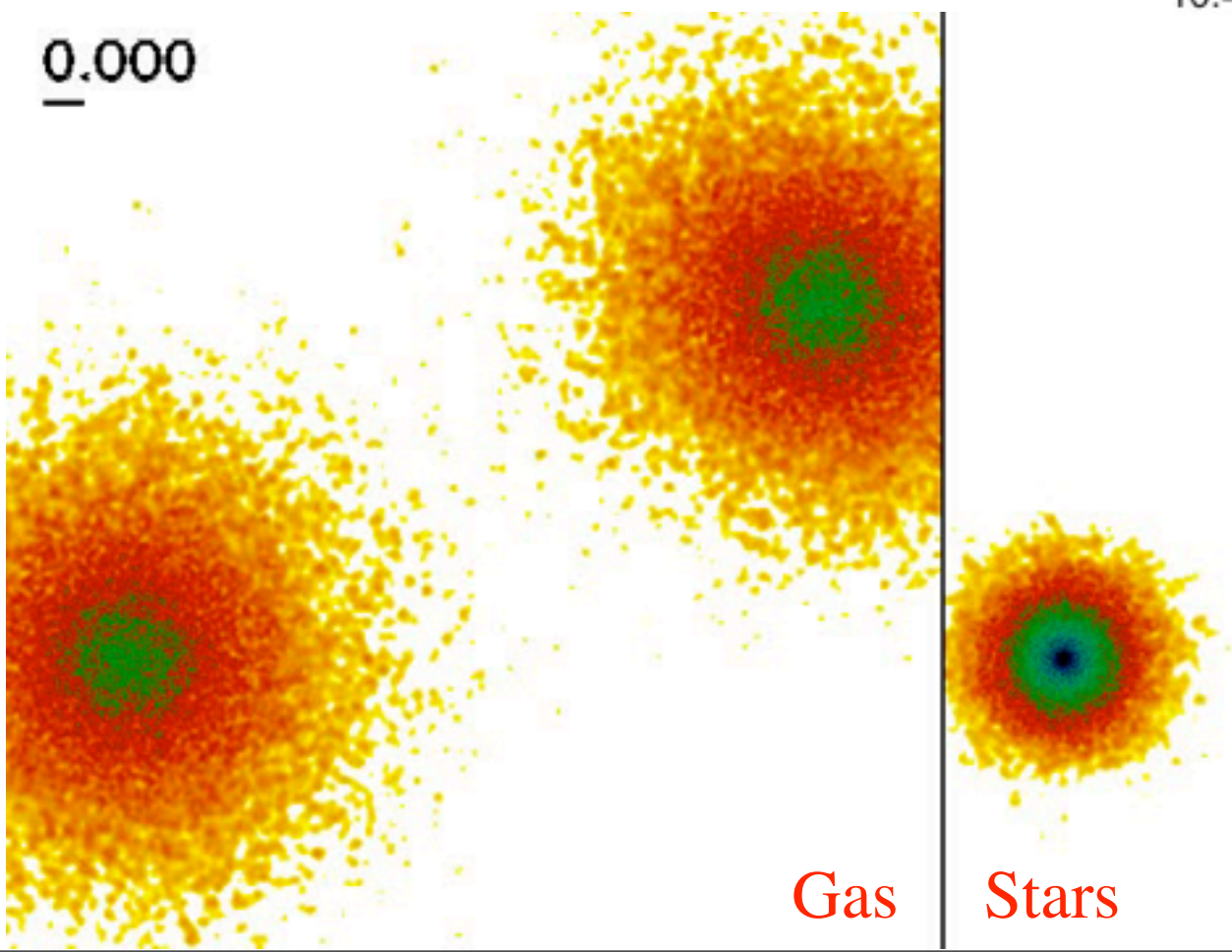


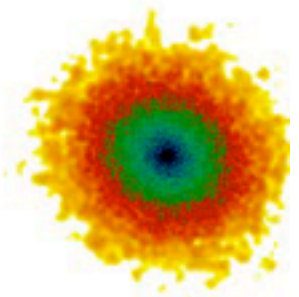
How does this relate to bulge formation?

The Problem: The Fundamental Plane & Bulge Densities:

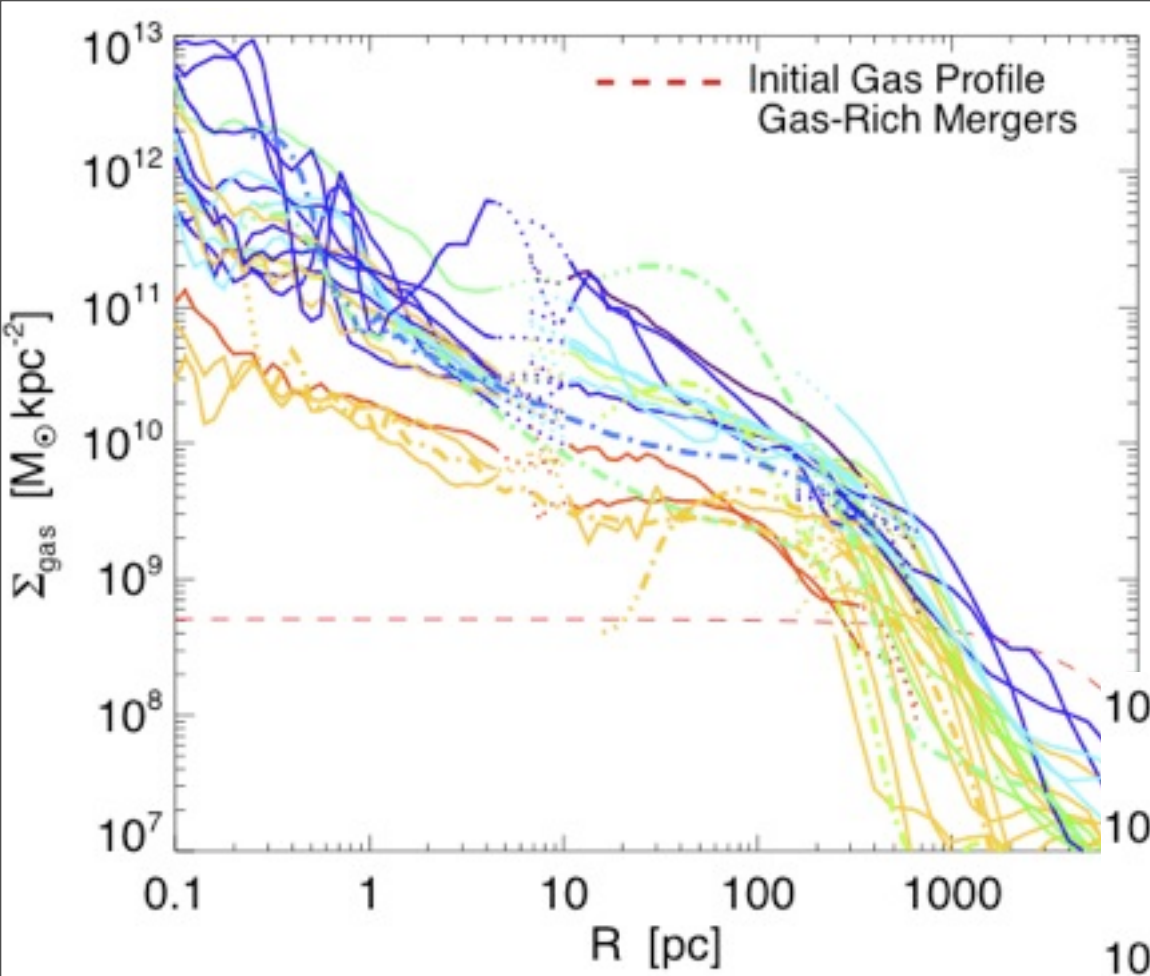


- Why are ellipticals smaller than disks? (Ostriker, Gunn, et al.)



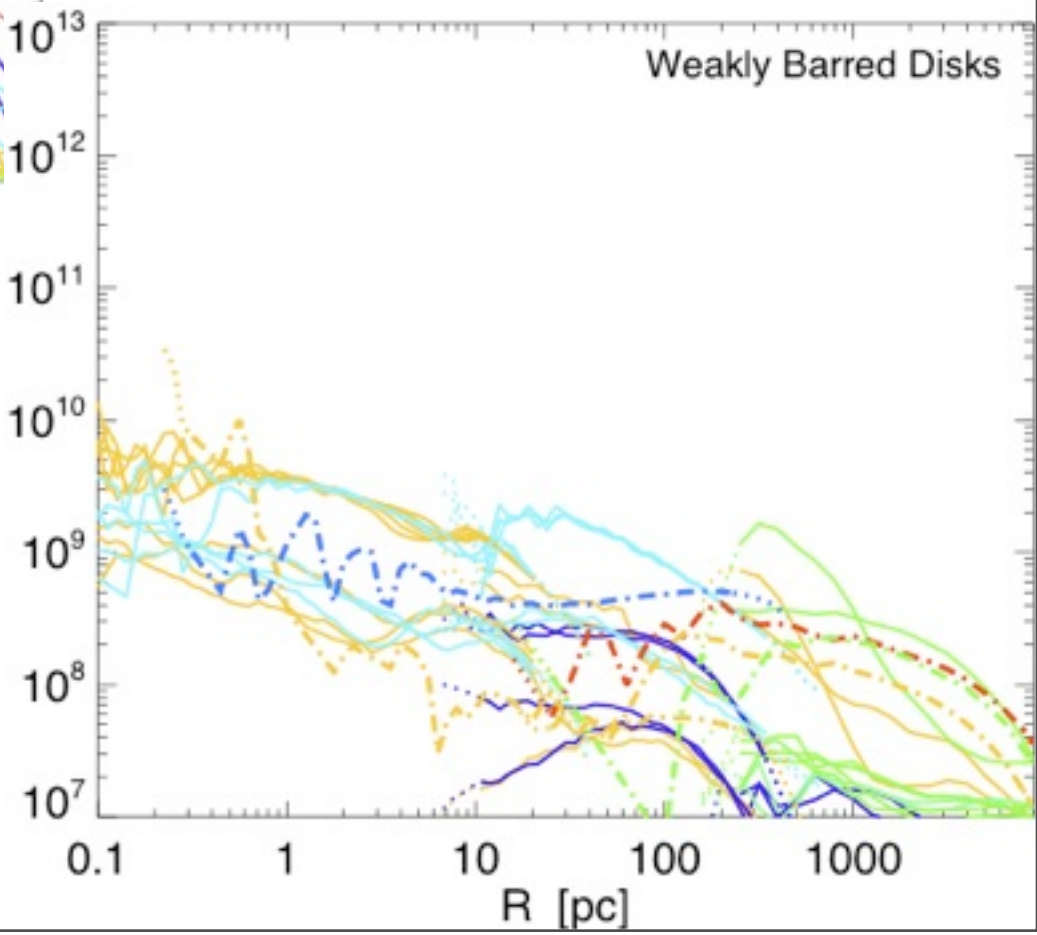


- Gas Dissipation



Gas-rich merger
(lots of inflow)

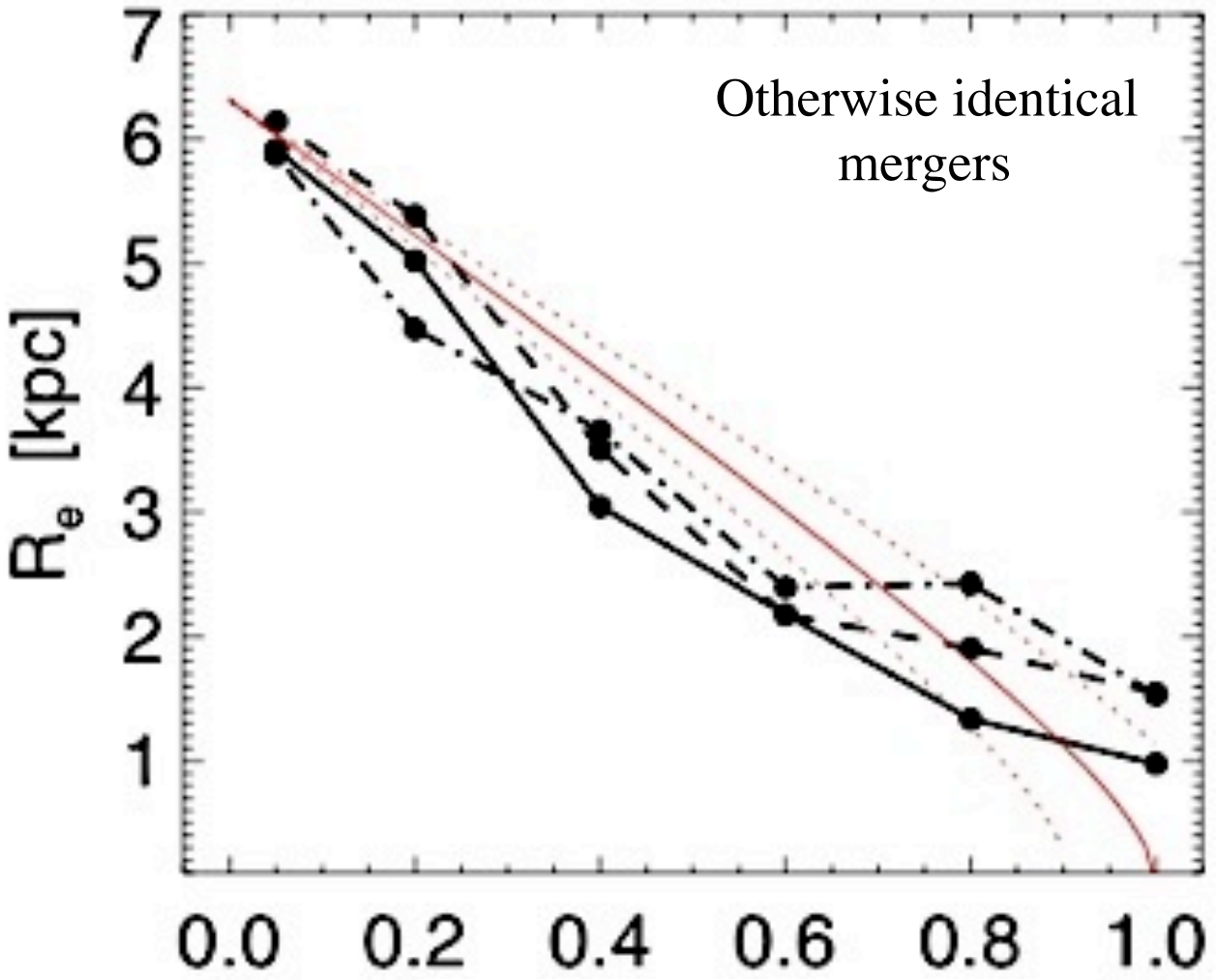
Weakly bar-unstable disk
(less inflow)



- 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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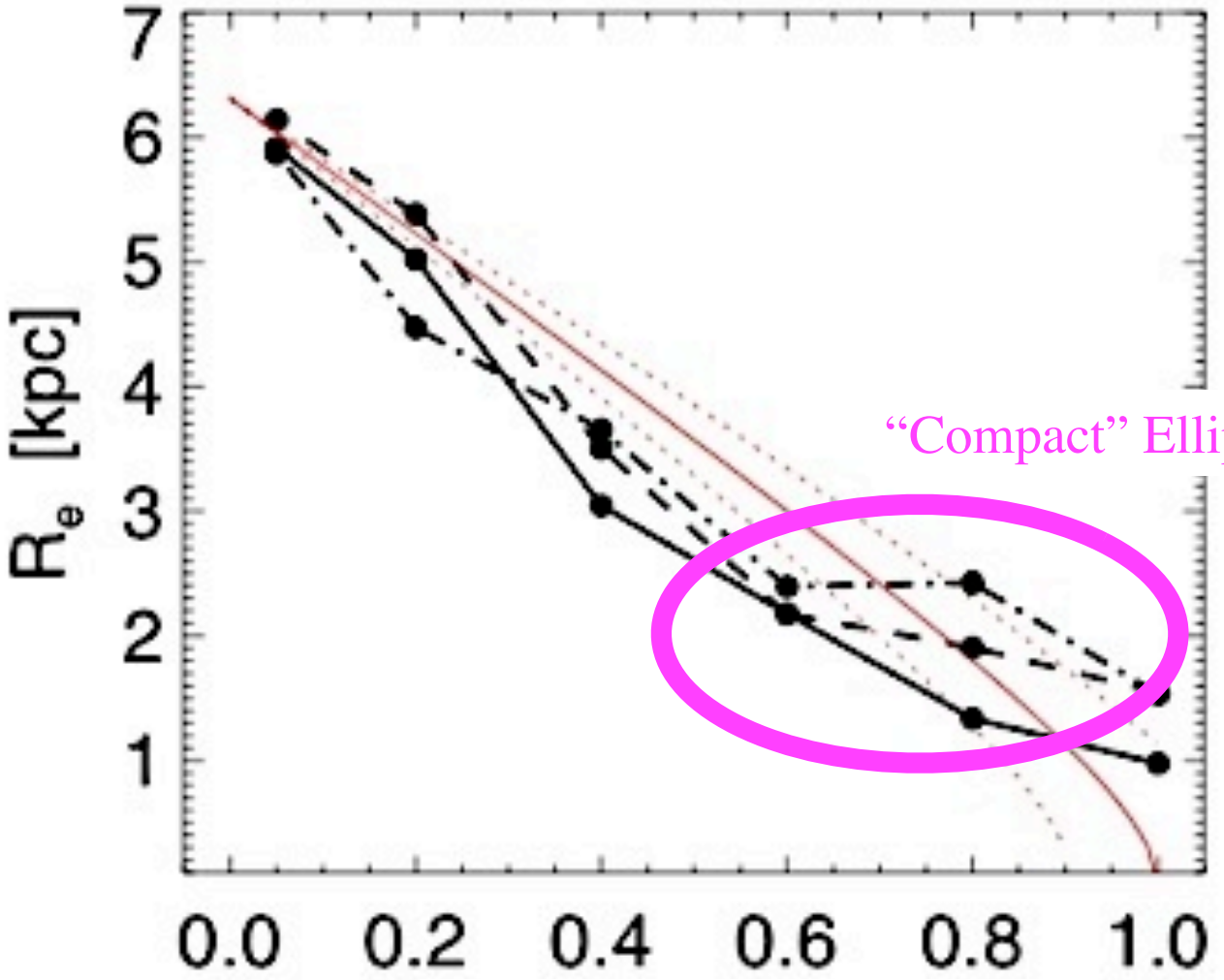

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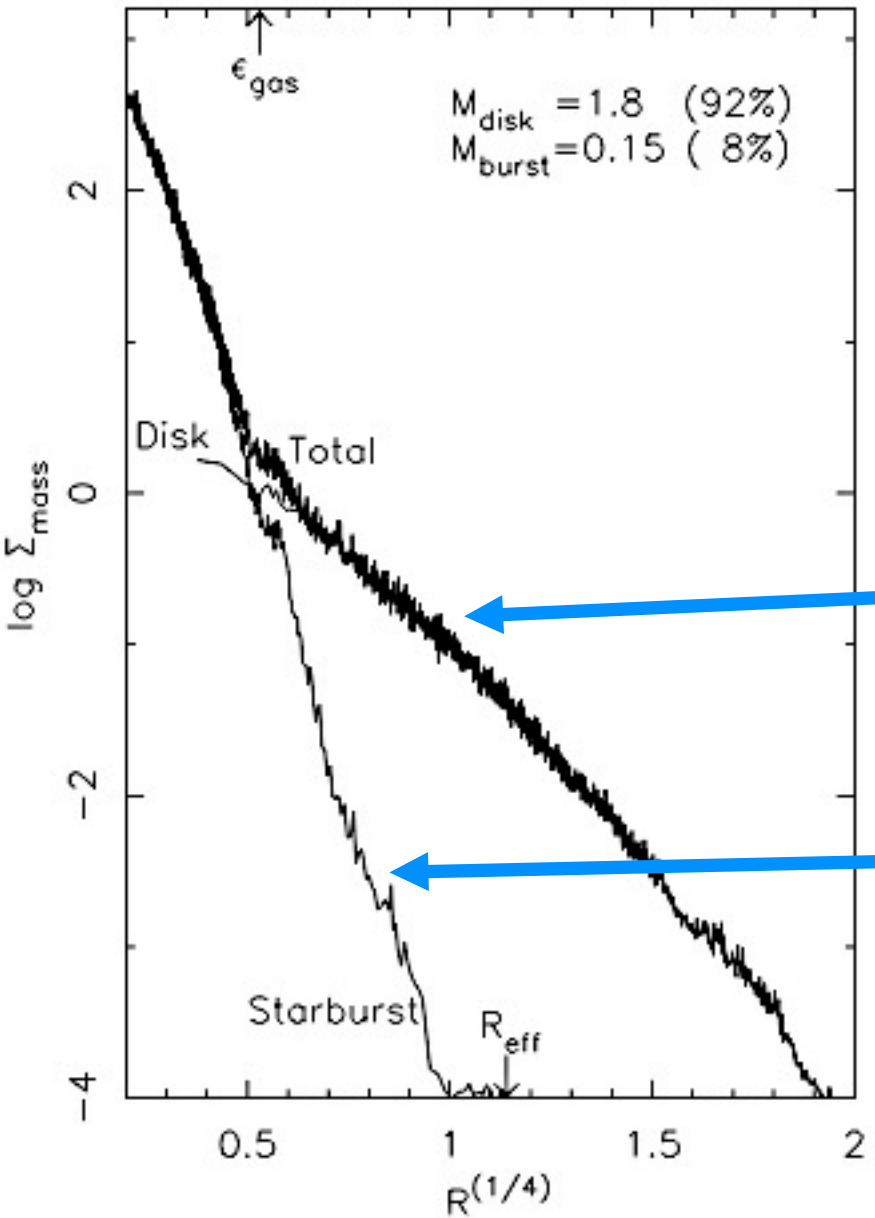
PFH, Cox et al. 2008

Starburst Stars Leave a "Footprint" 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:

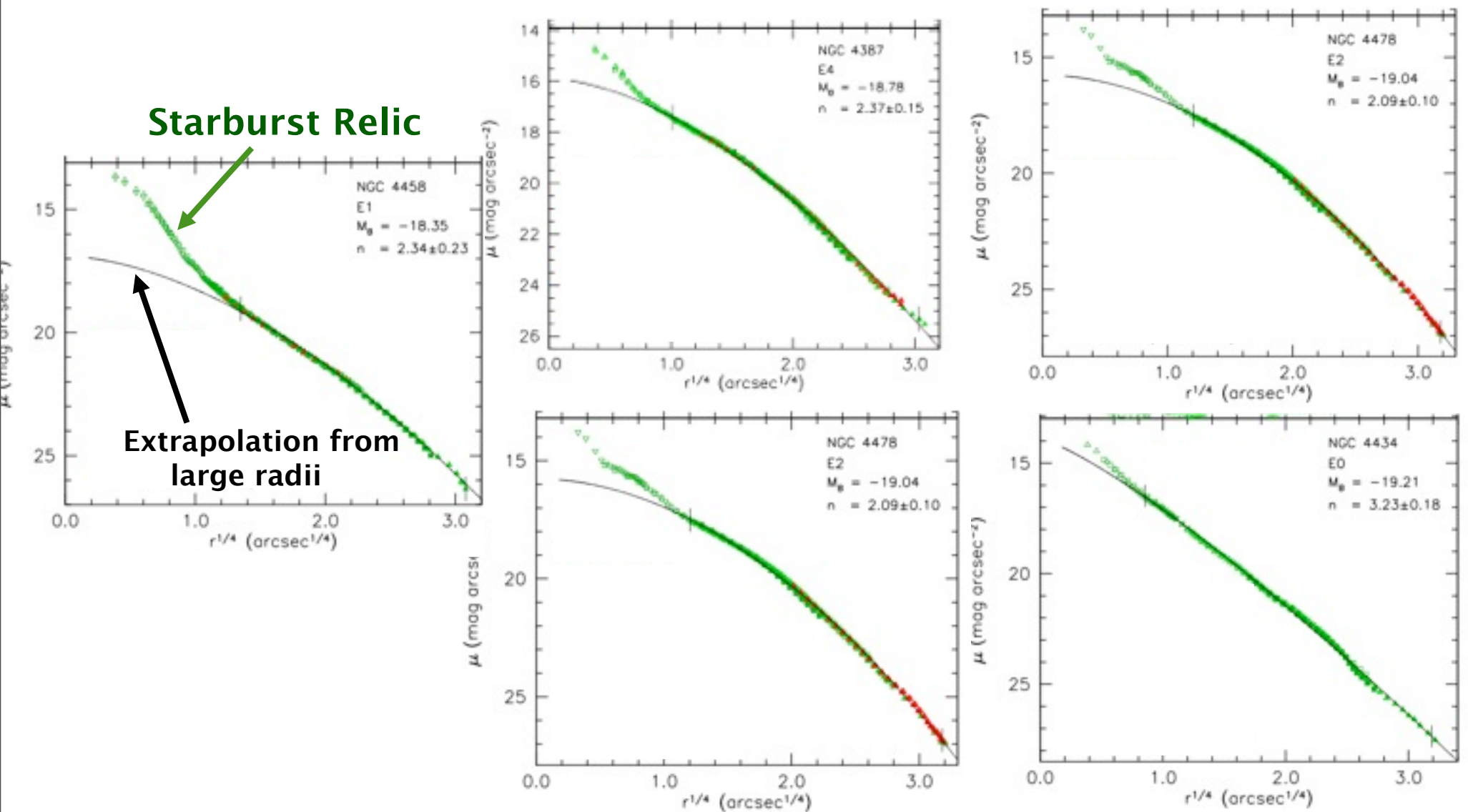
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

Starburst Stars 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...

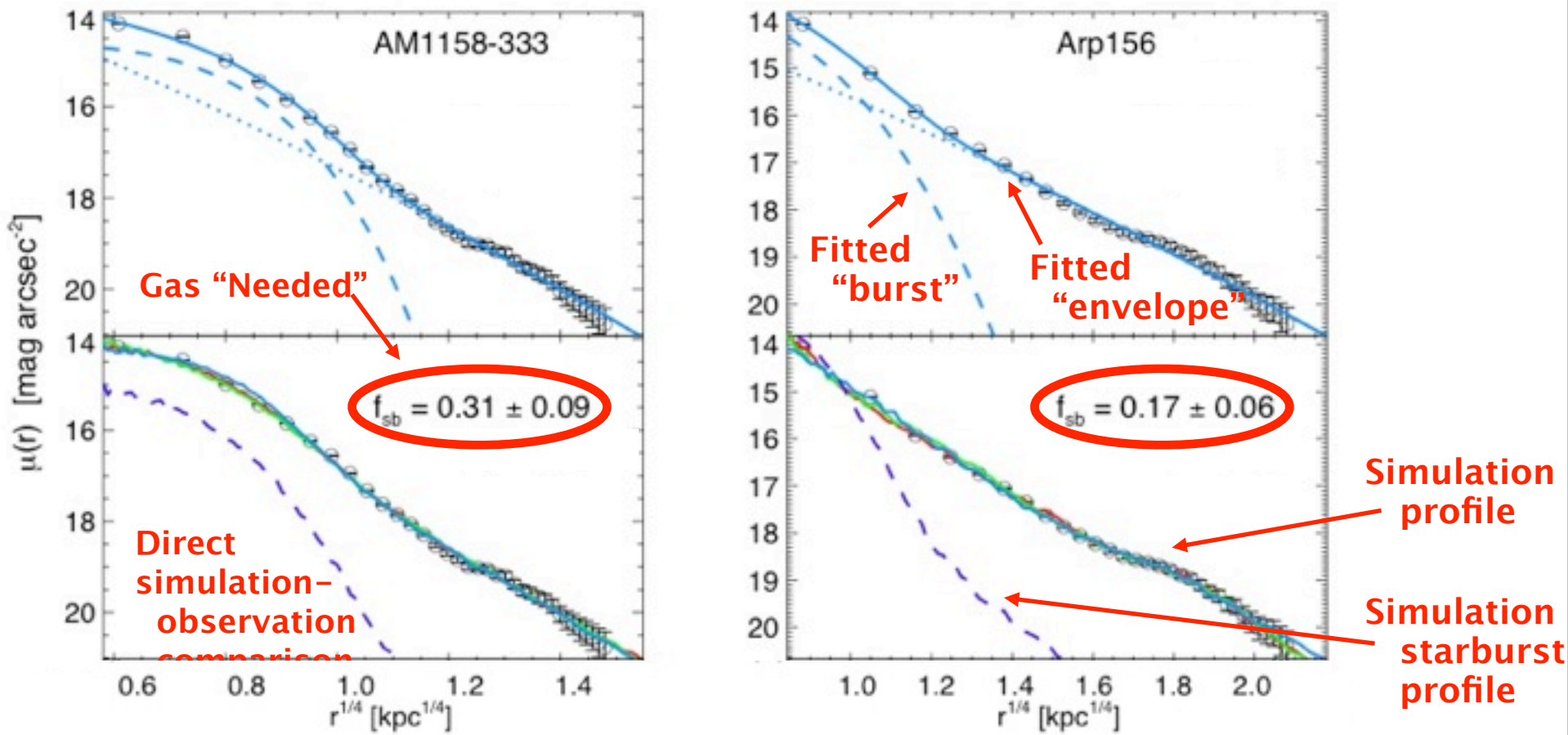


"Normal and low-luminosity ellipticals... in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles."

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:



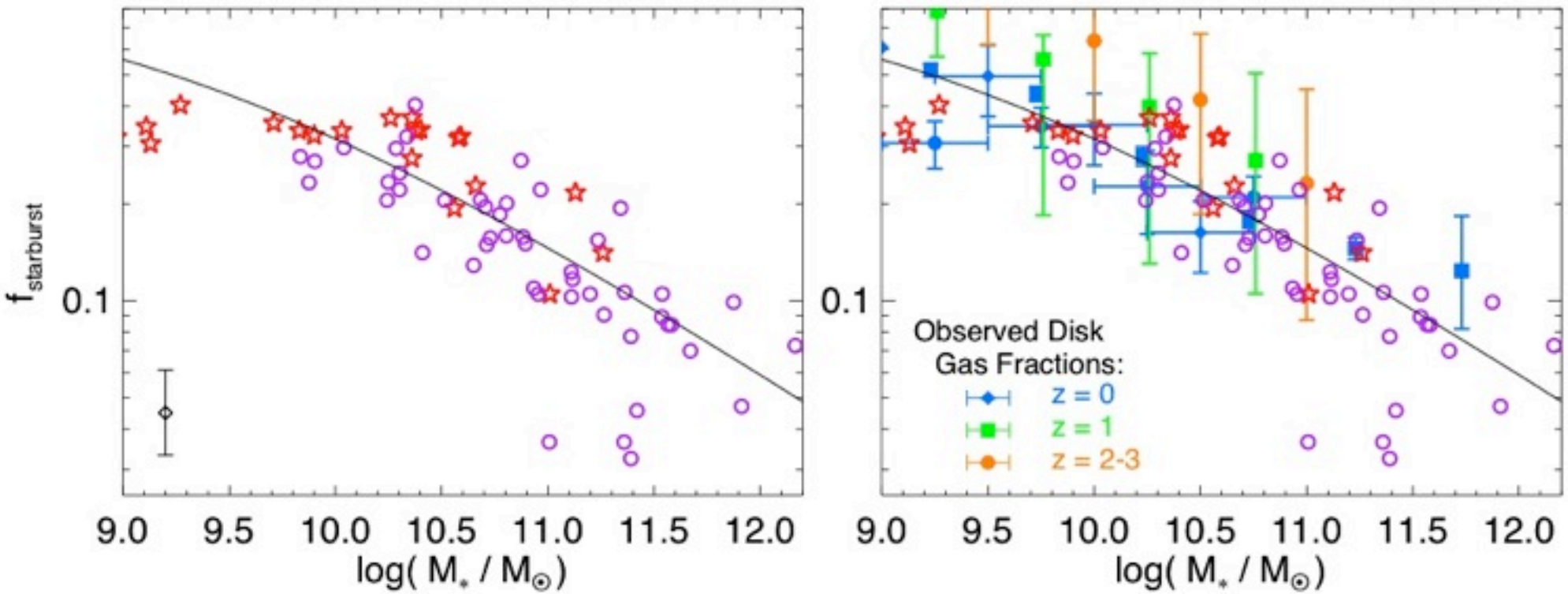
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

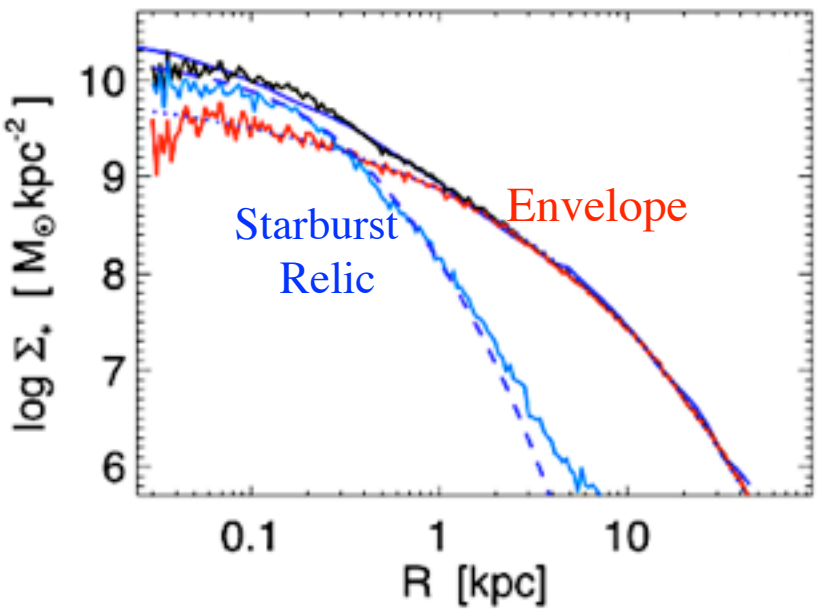
PFH, Kormendy, & Lauer et al. 2008

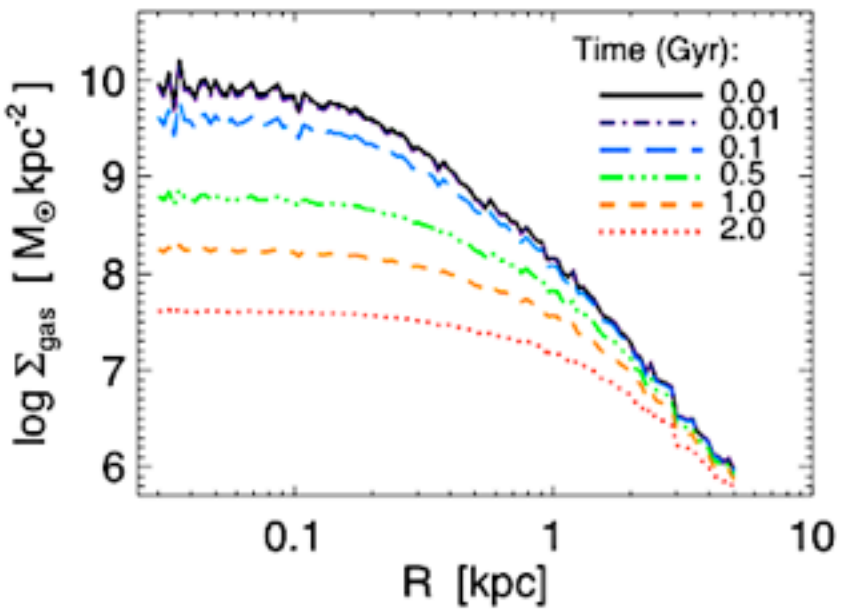
Starburst gas mass needed to match observed profile (or fitted to profile shape):

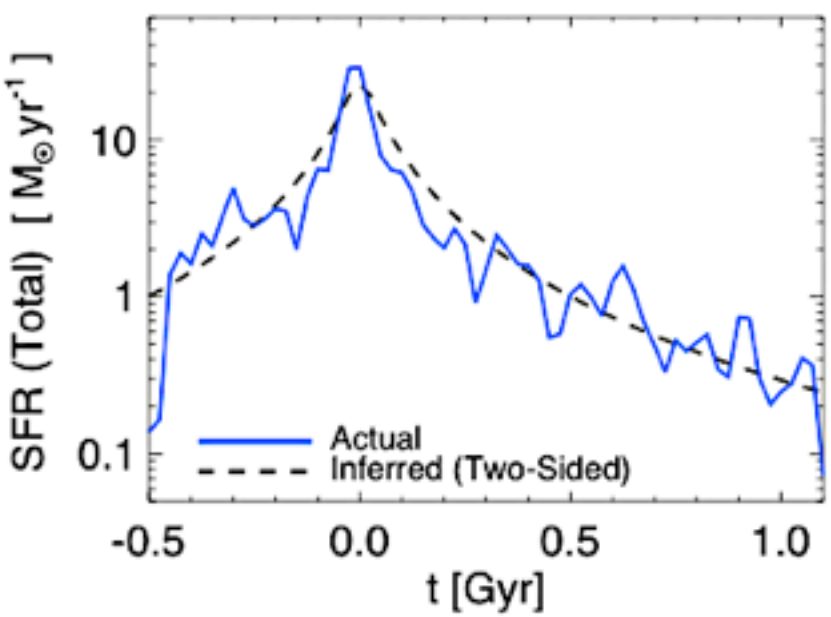


- You can and do get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns (Foster+, Forbes+, Lauer+, Hoffman+)

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







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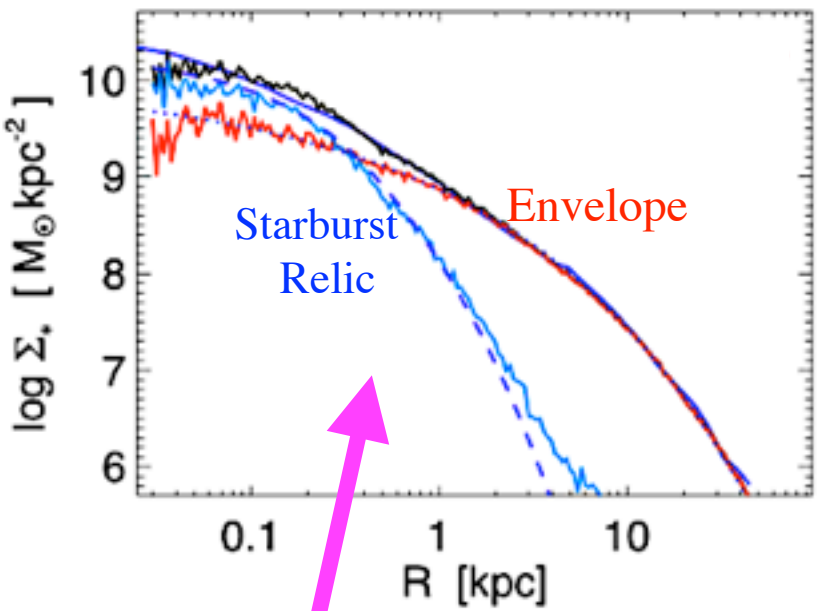
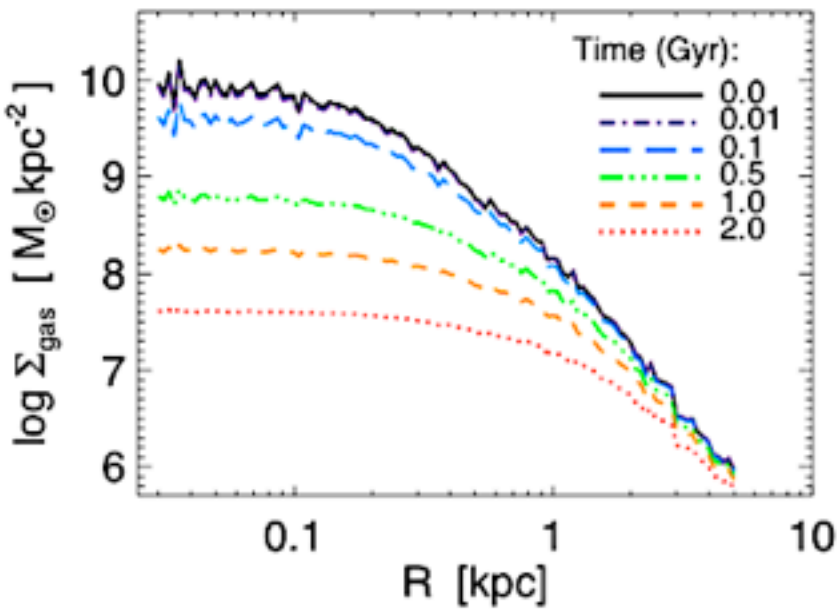
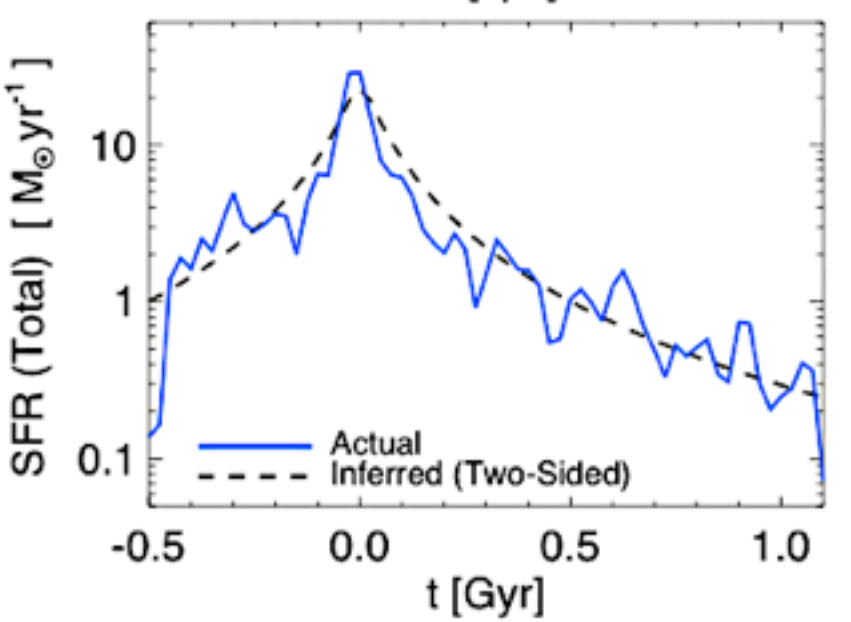
Given a galaxy, isolate 'burst relic' $\Sigma_{relic\ stars}(R)$







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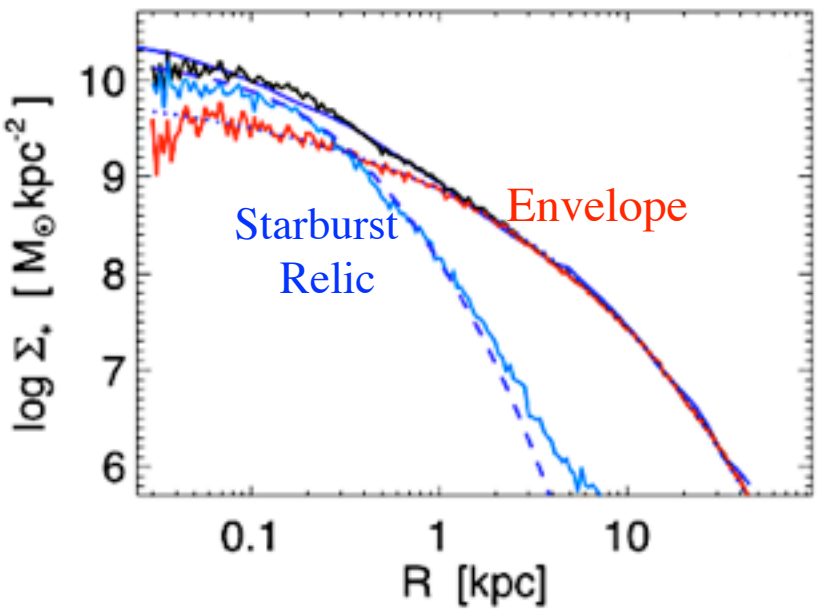

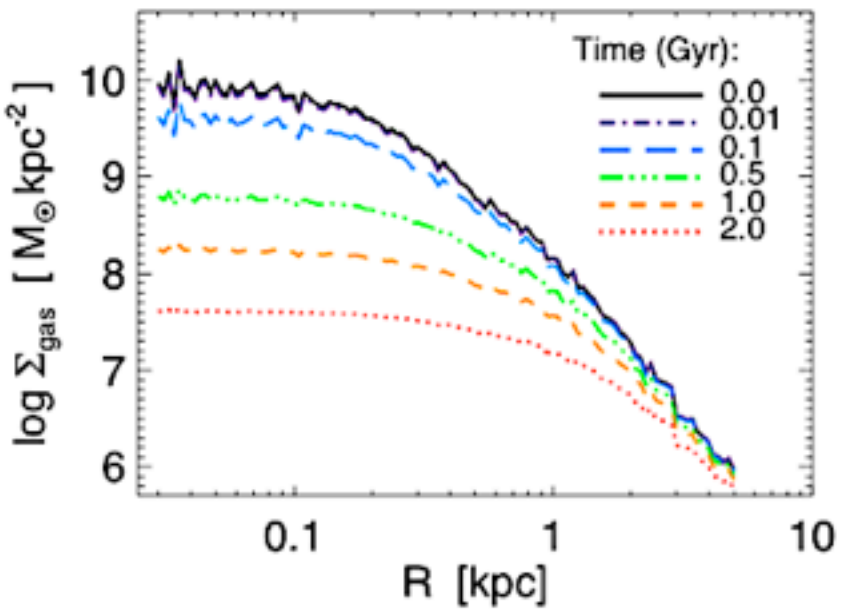

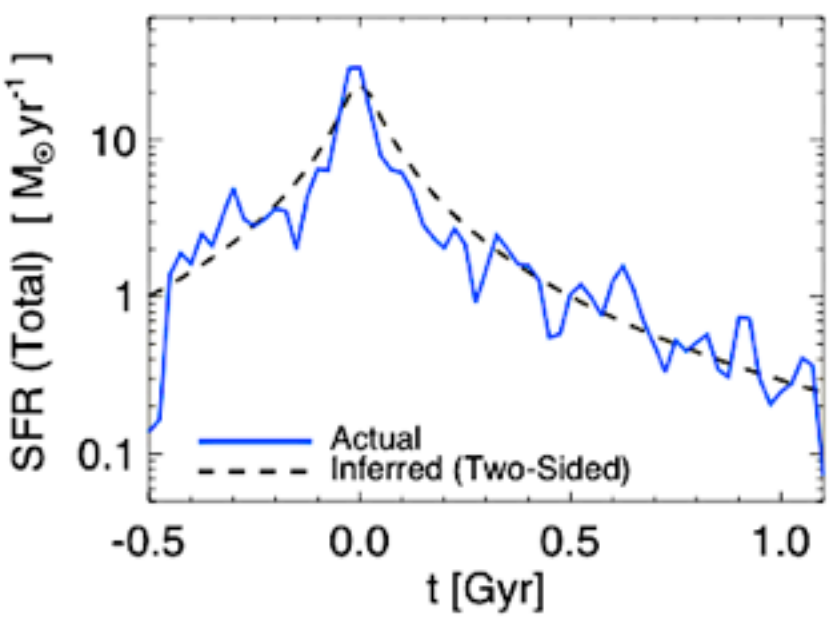

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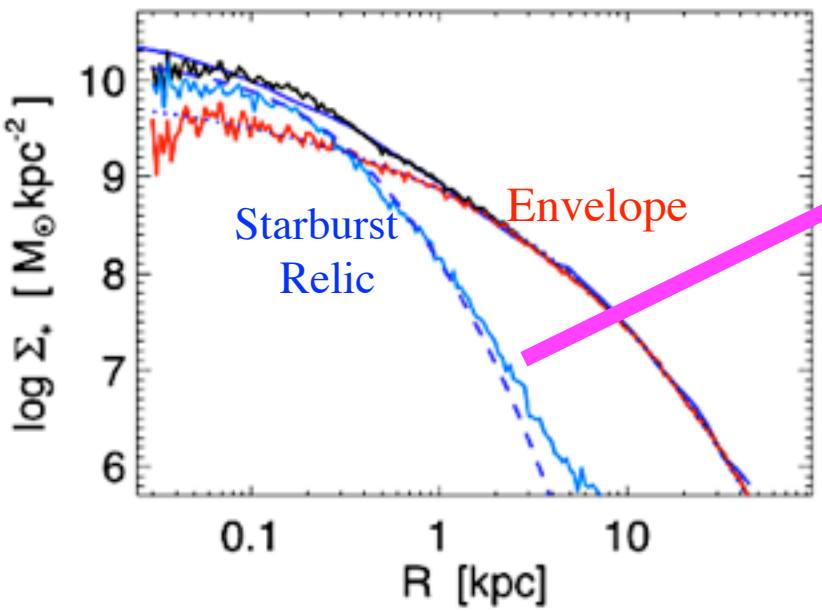
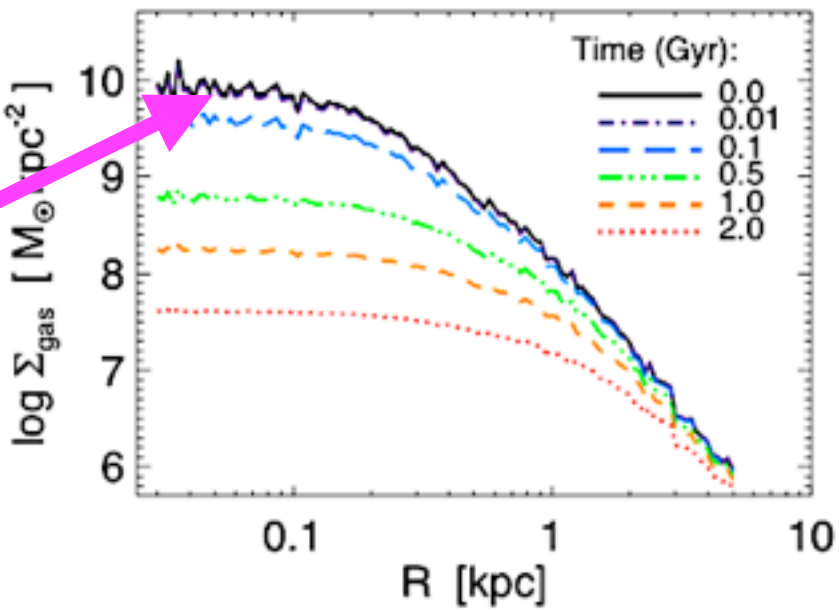
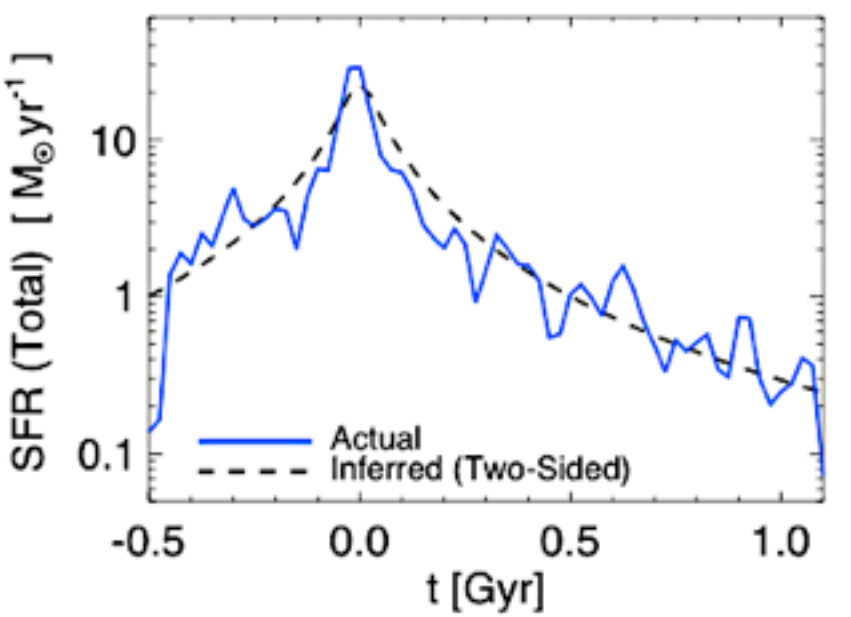
If formed dissipationally, then this reflects gas-star conversion "in situ"

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







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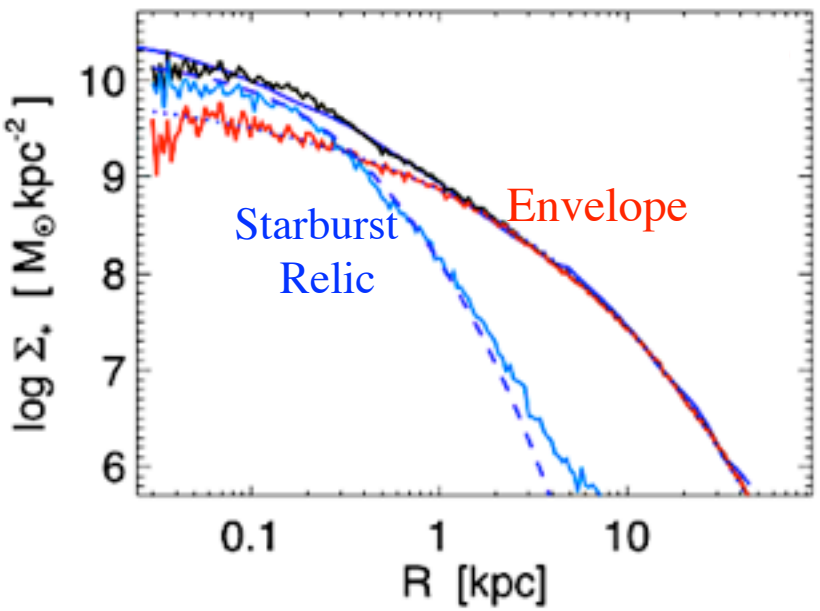
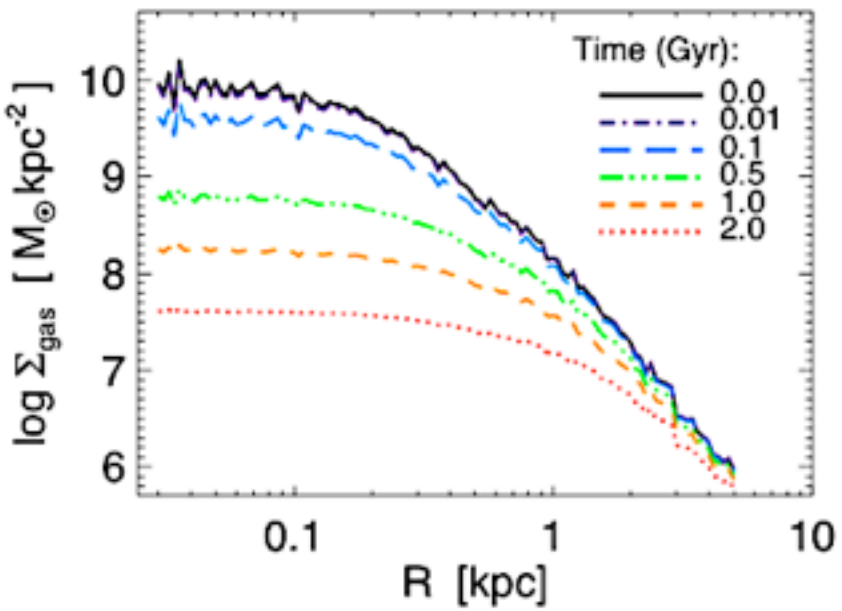
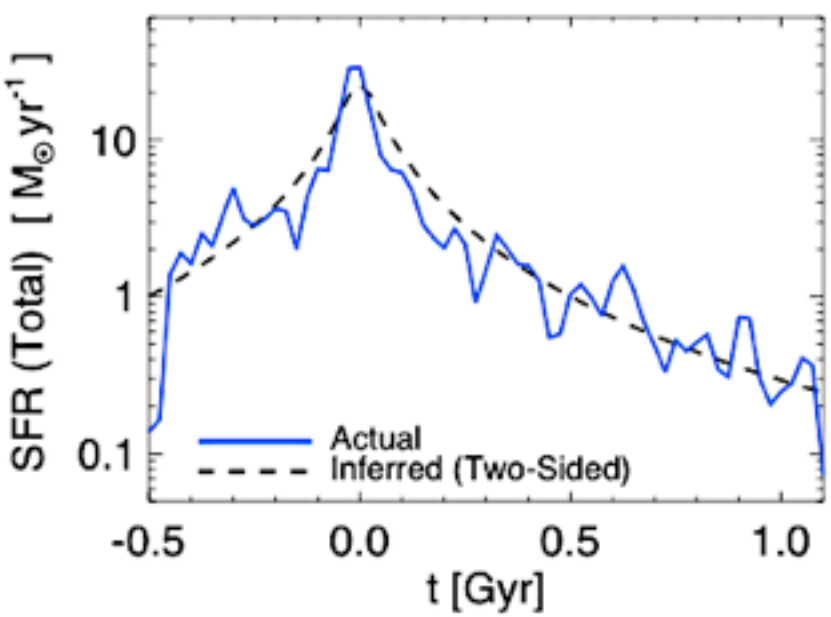


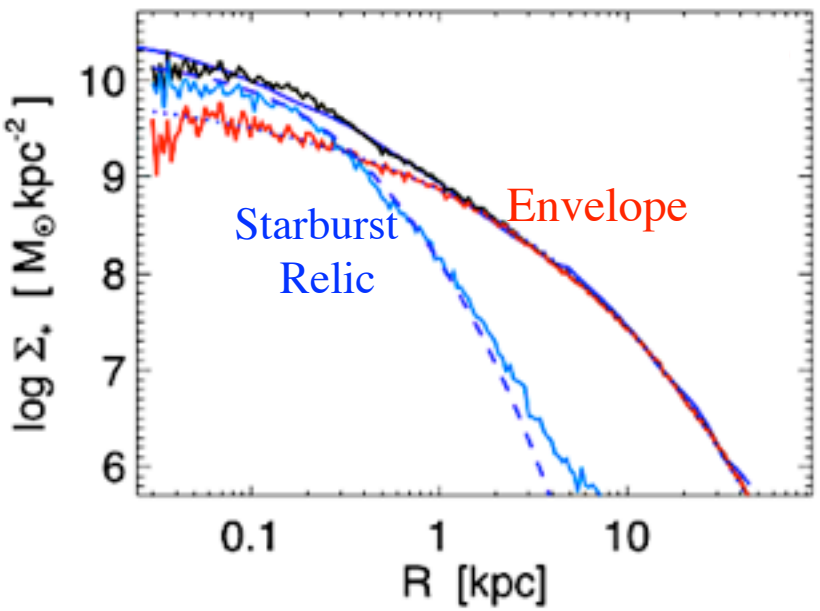


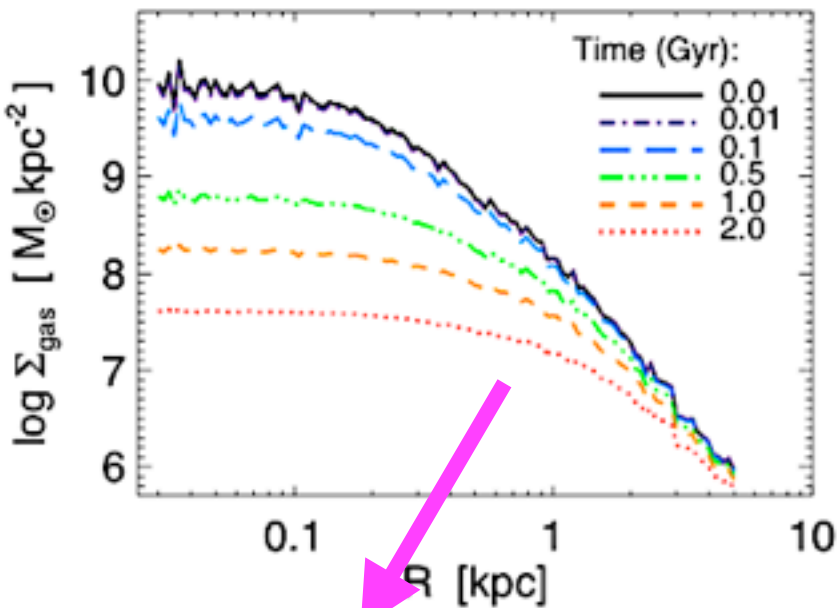


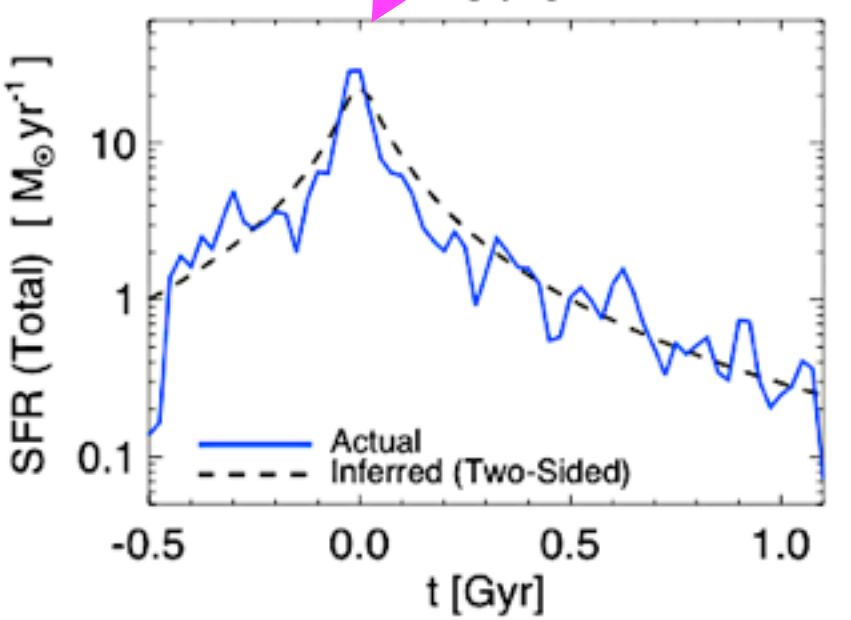
What else can we learn from the 'relics' of gas dissipation?

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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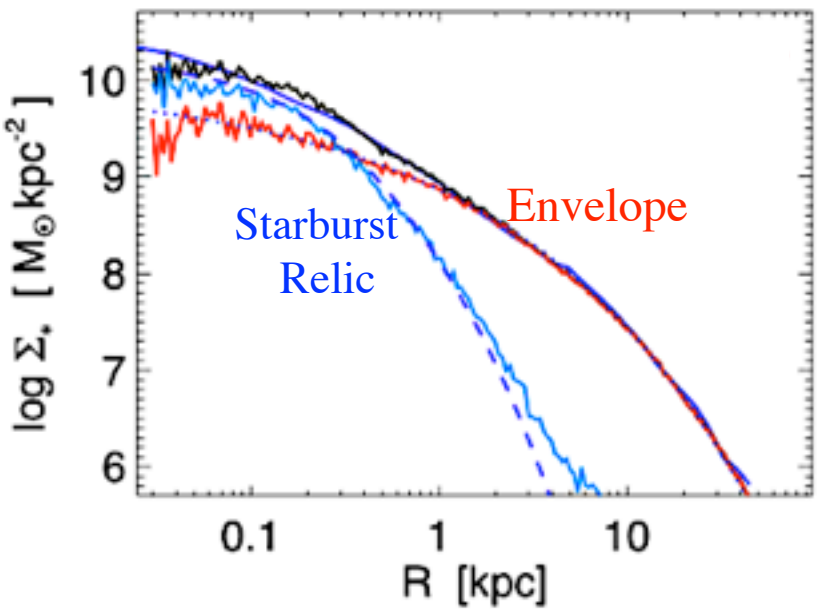

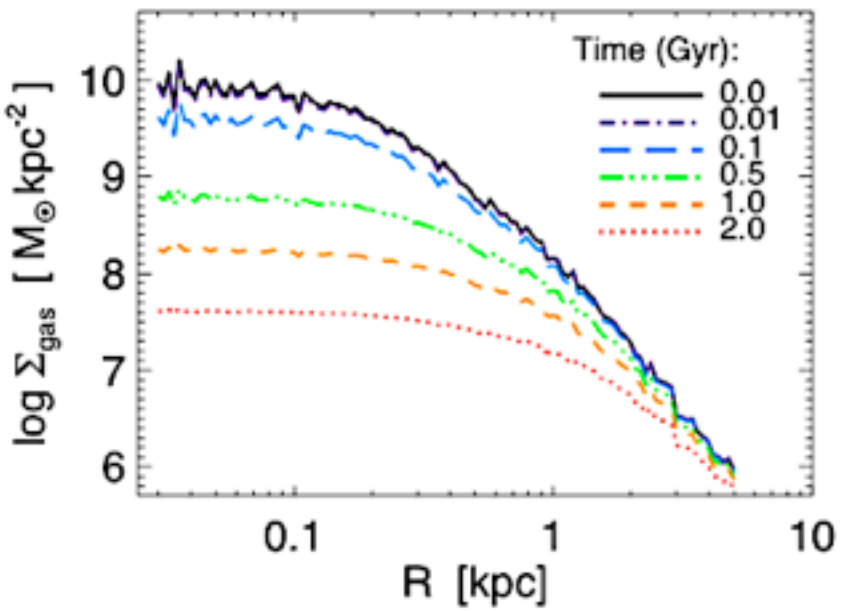

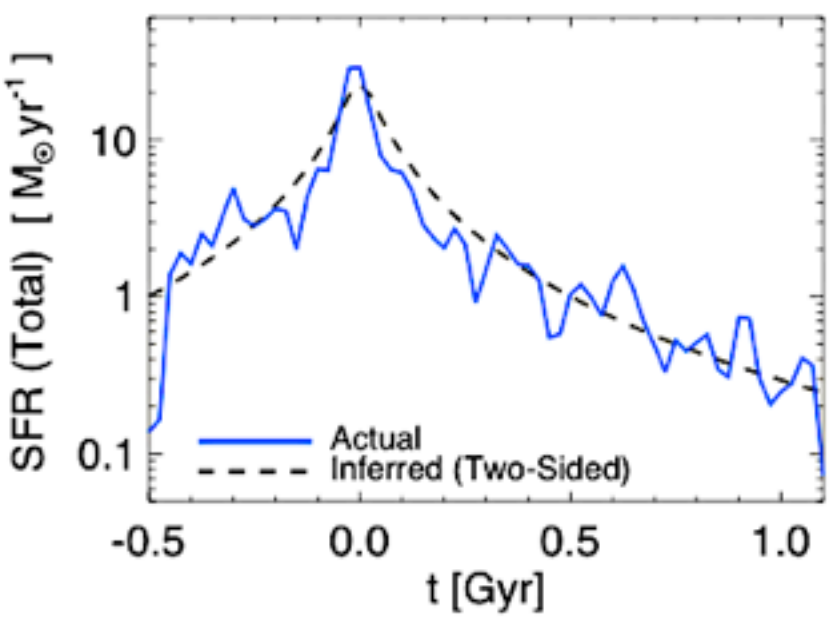

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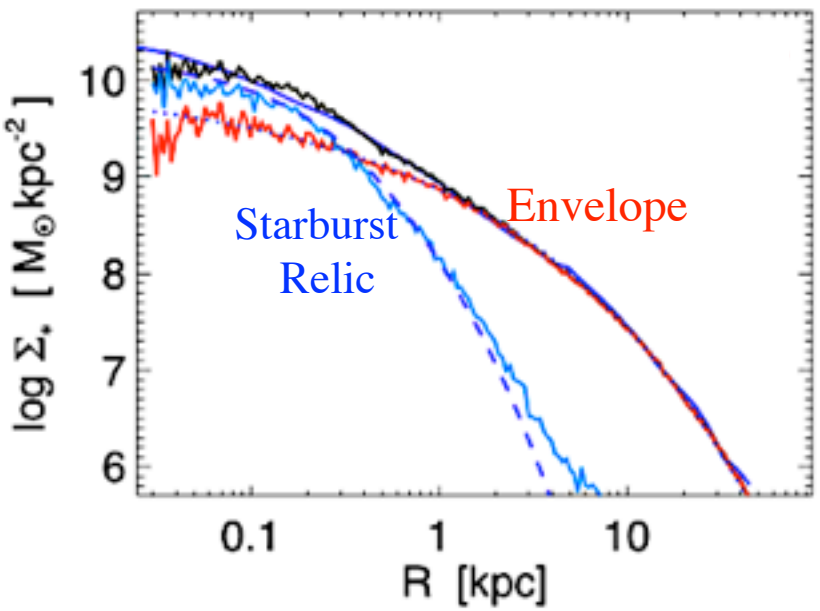

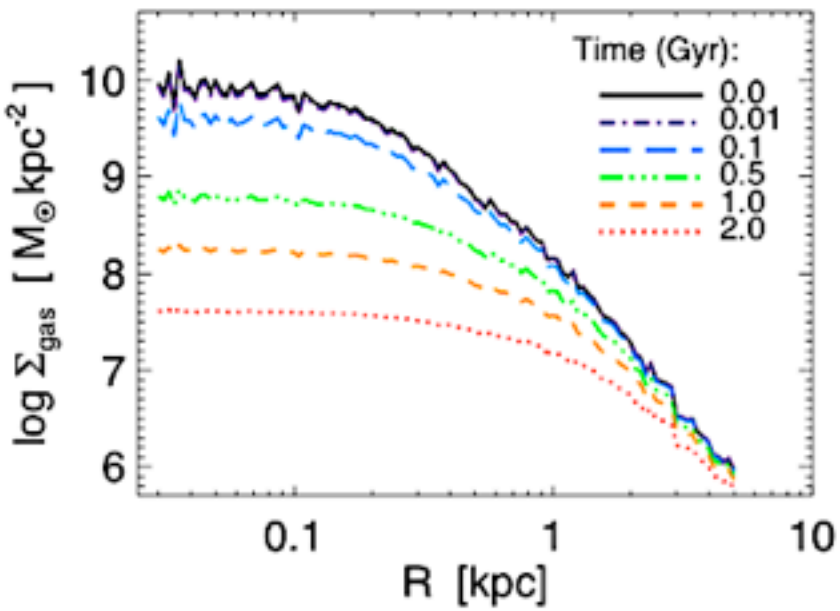

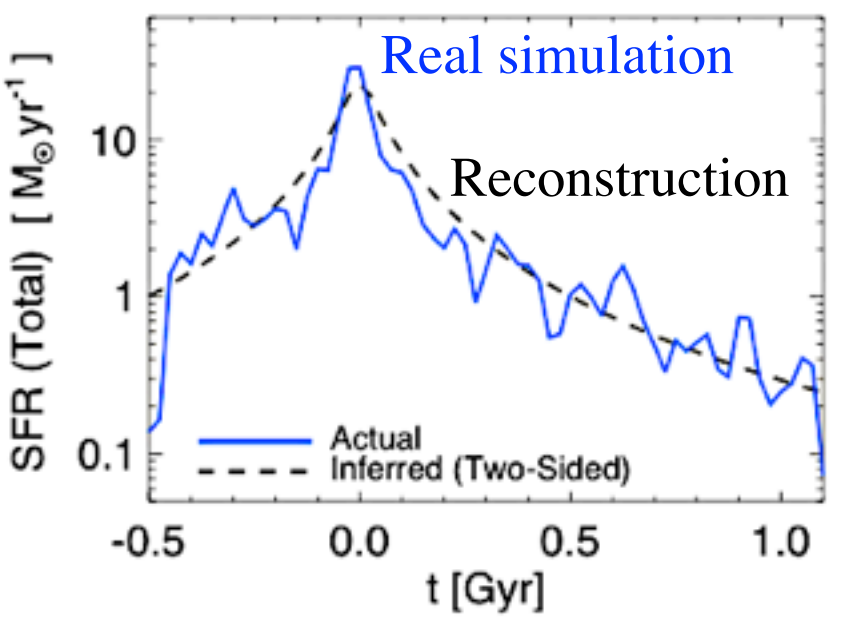

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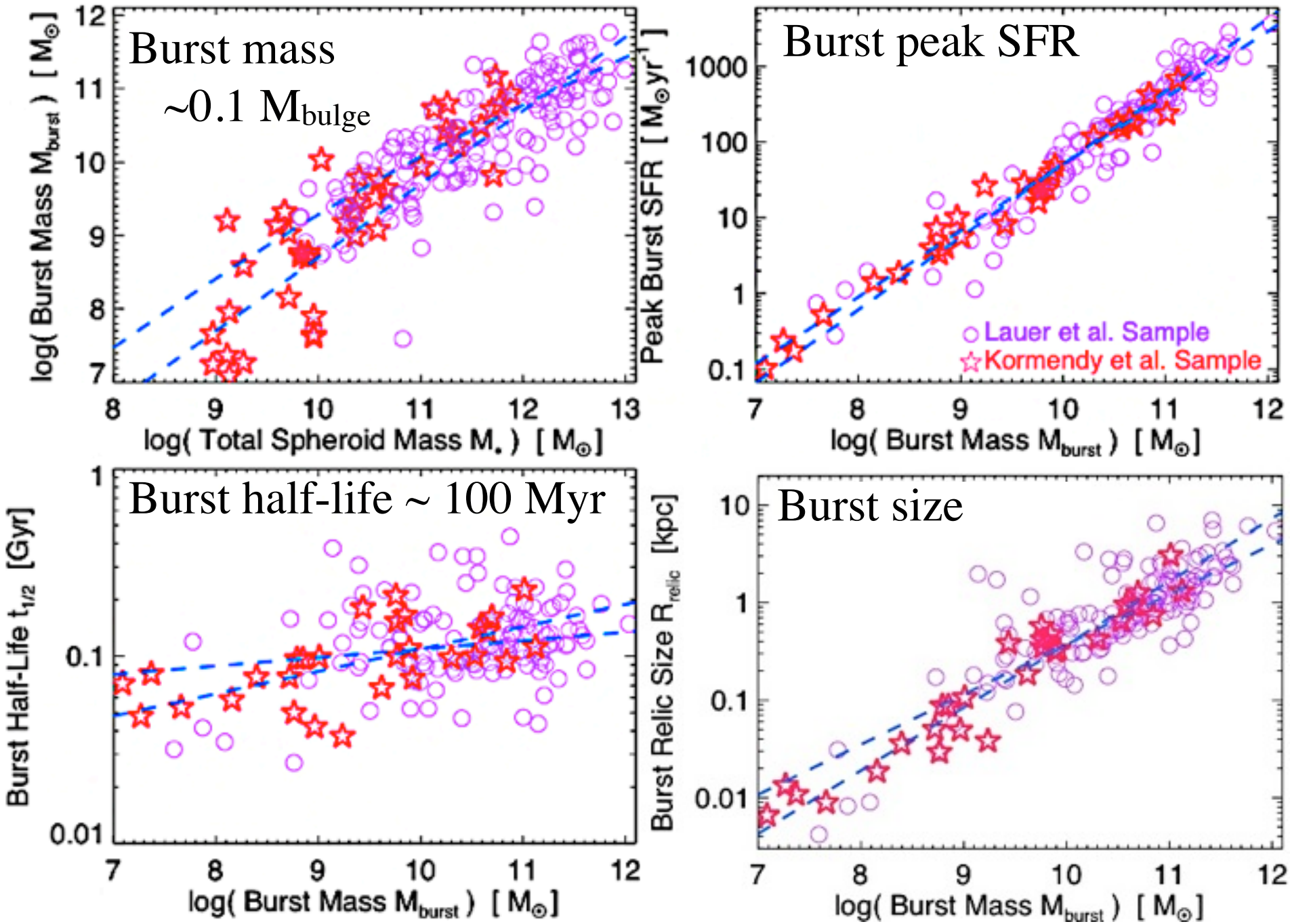

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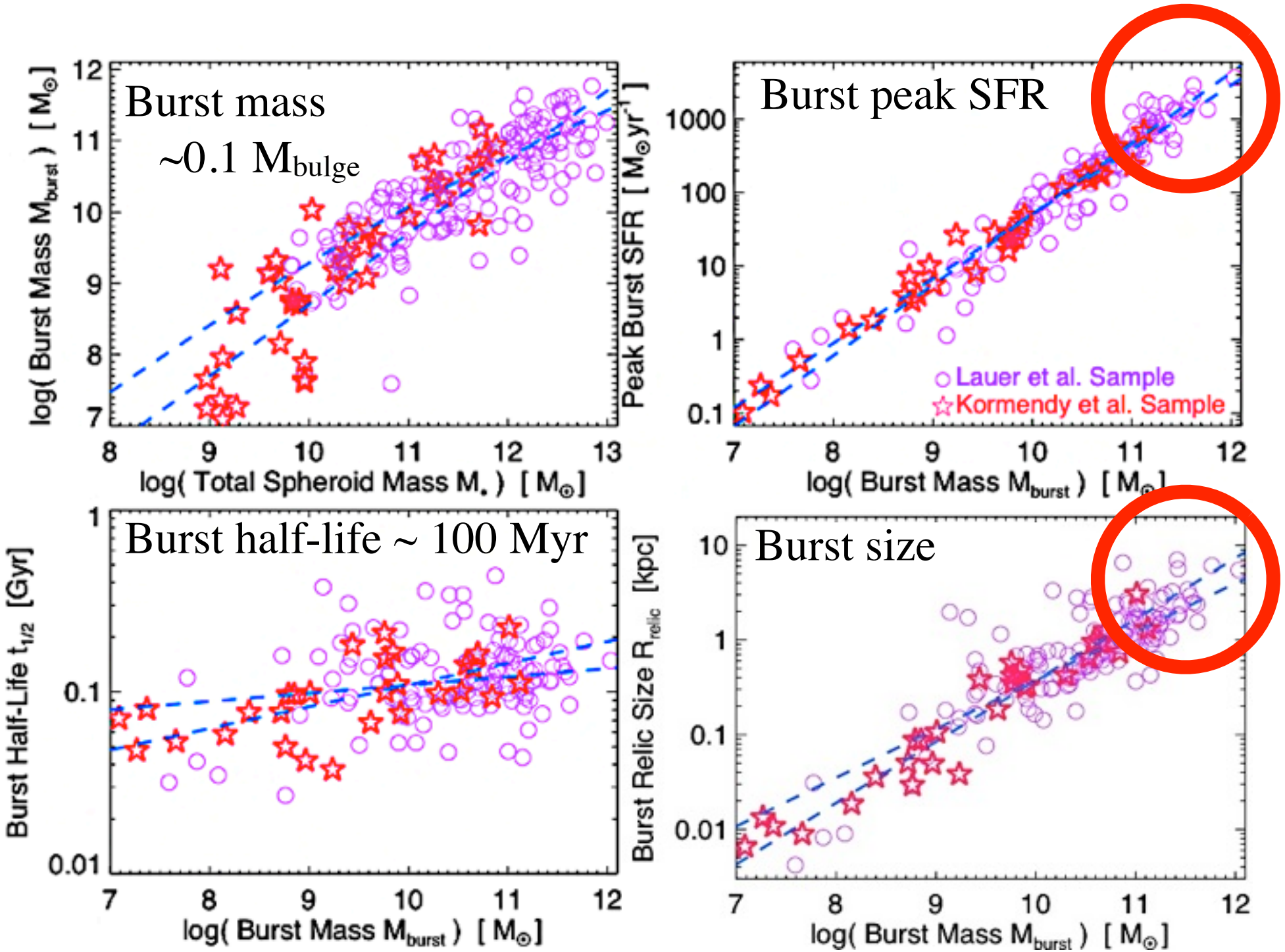
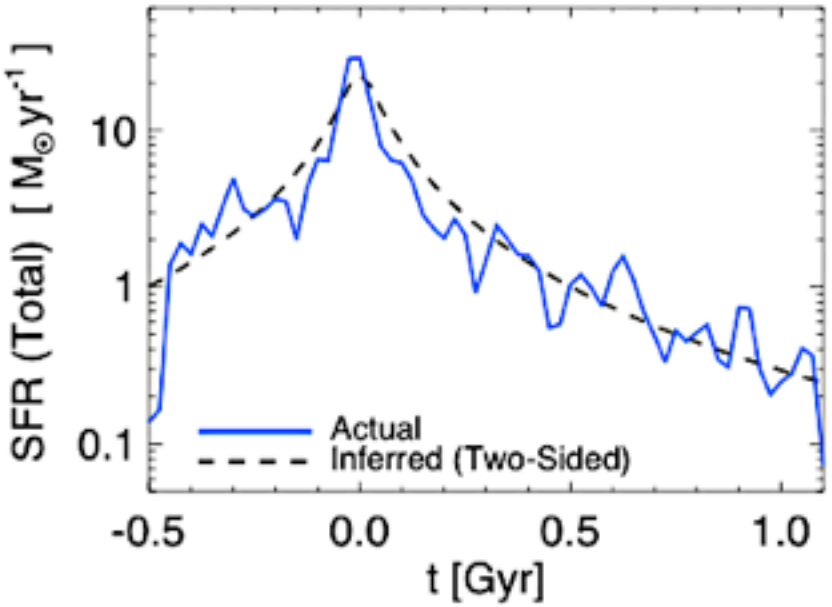
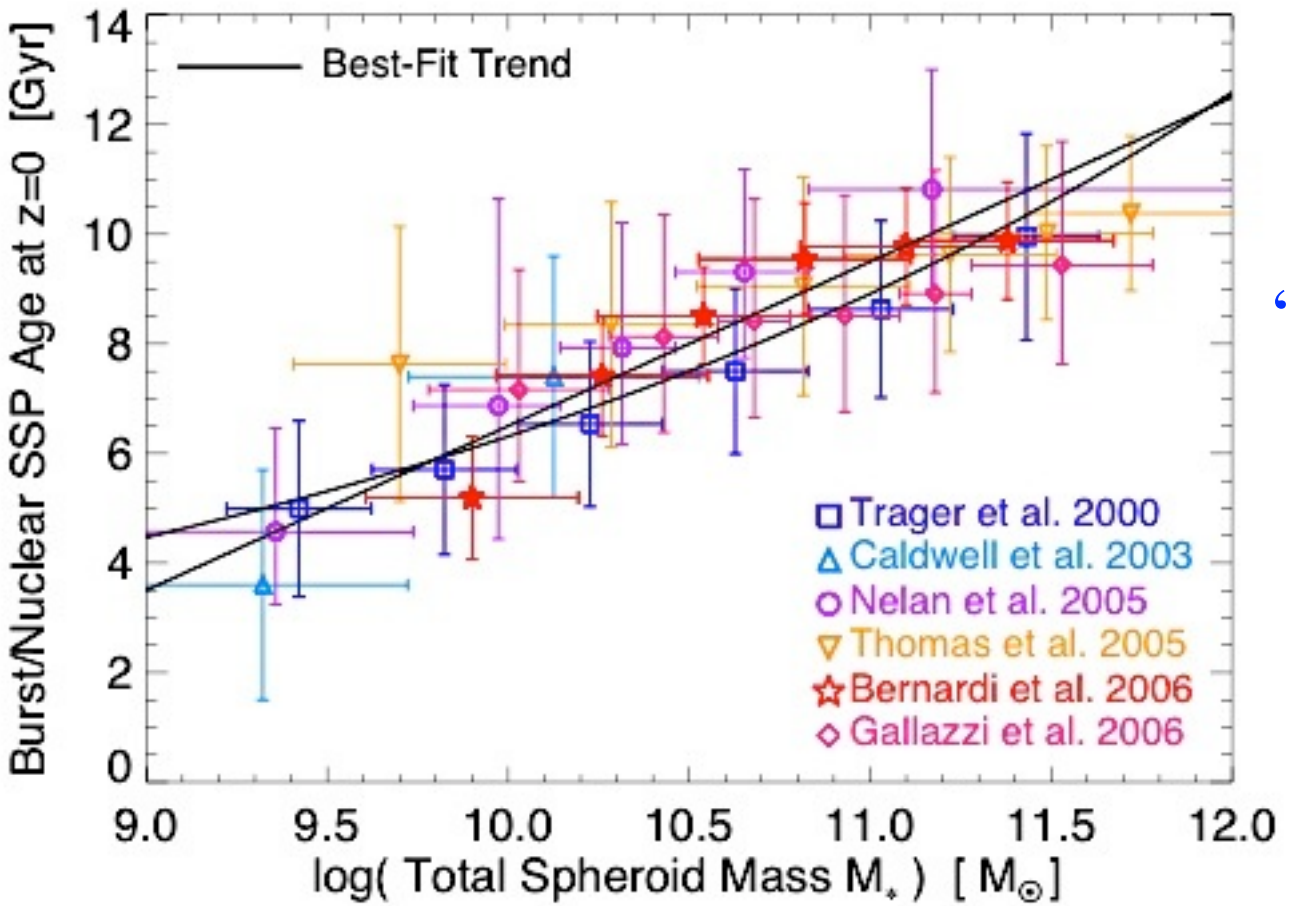


Re-construct SFR(t) for each burst :

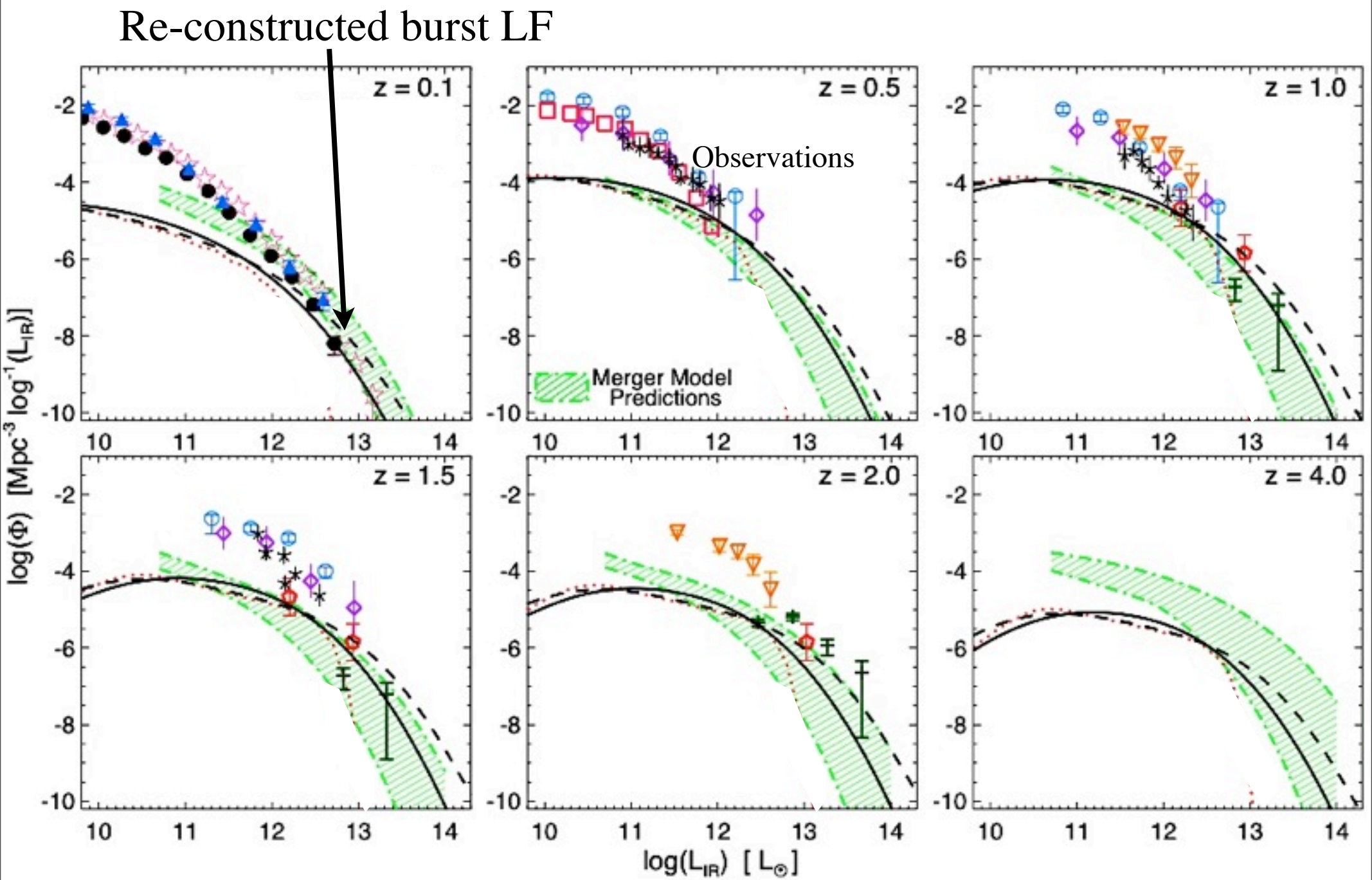


+ We know the nuclear SSP ages....

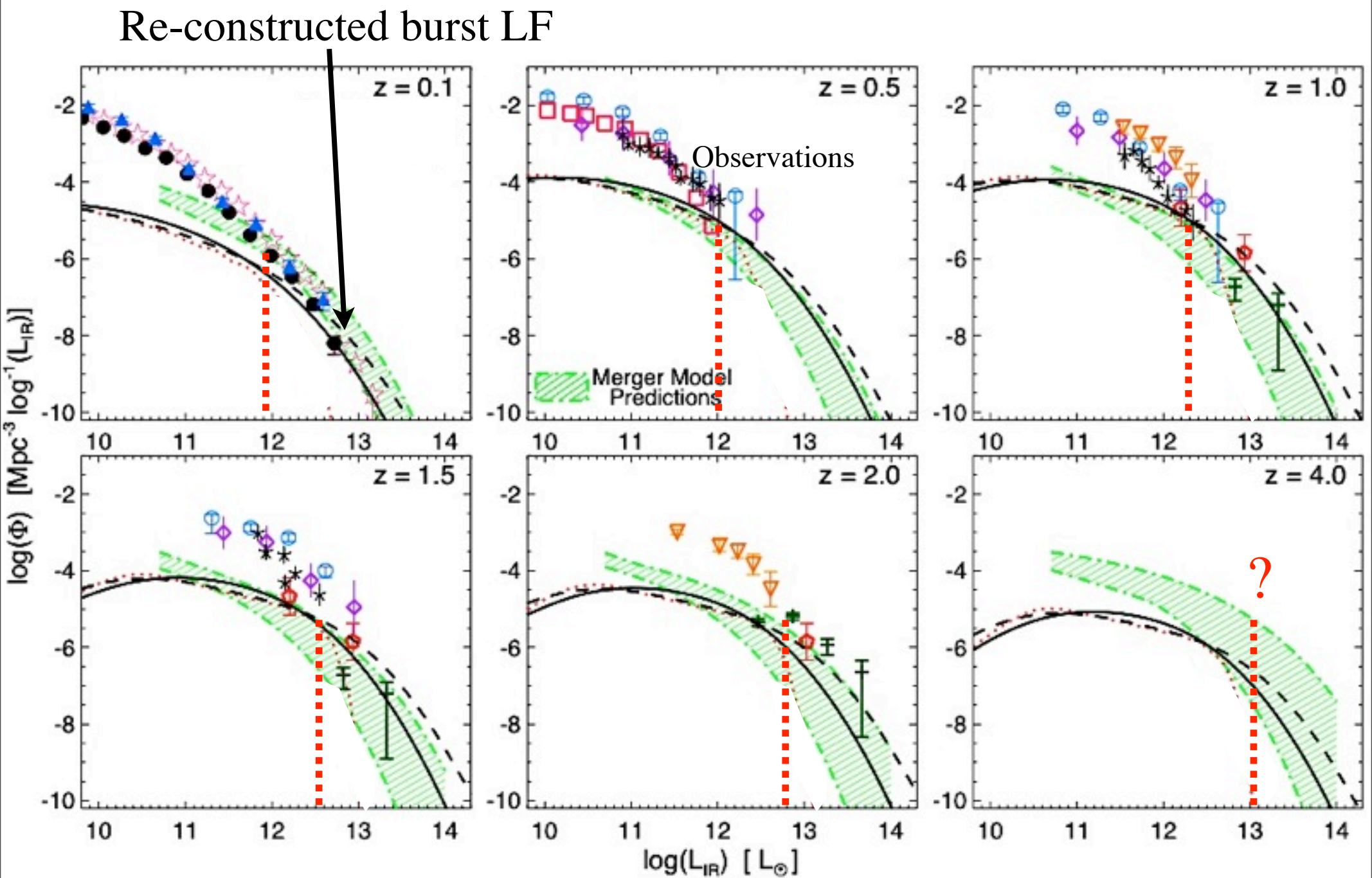


"place" each burst at the correct redshift

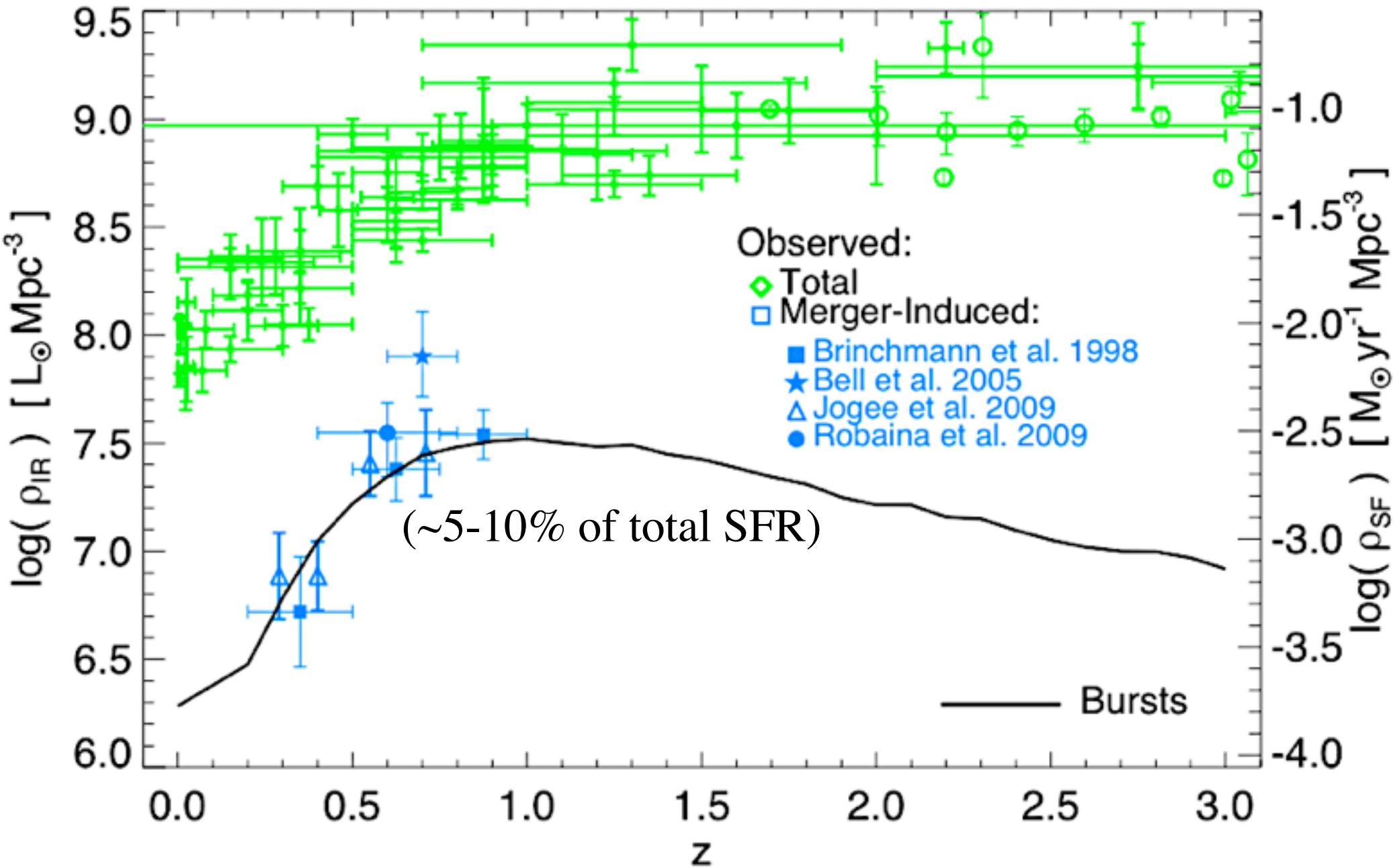
Recover the IR LF of dissipational starbursts!



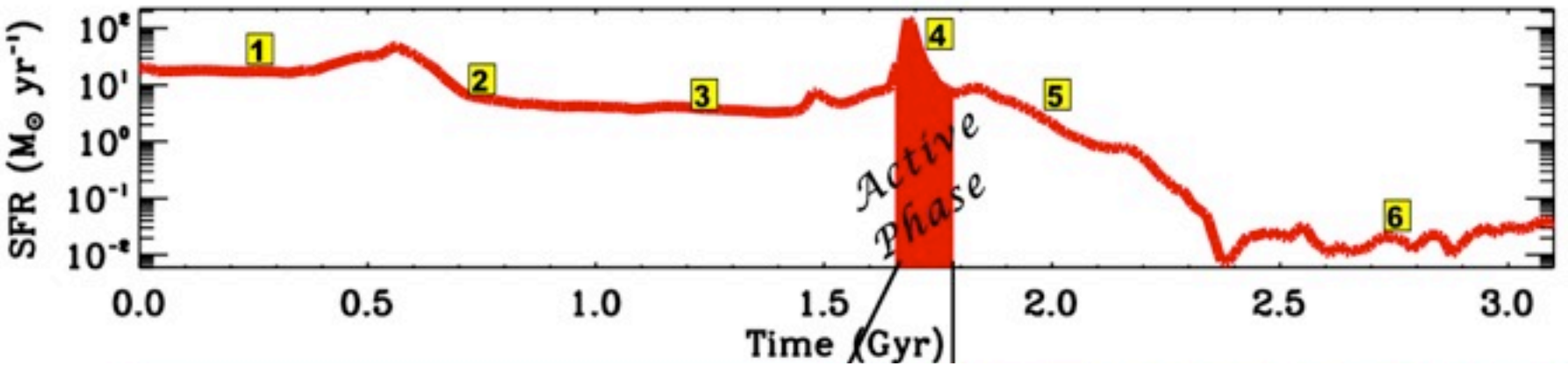
Bursts always dominate at high L, but the threshold shifts

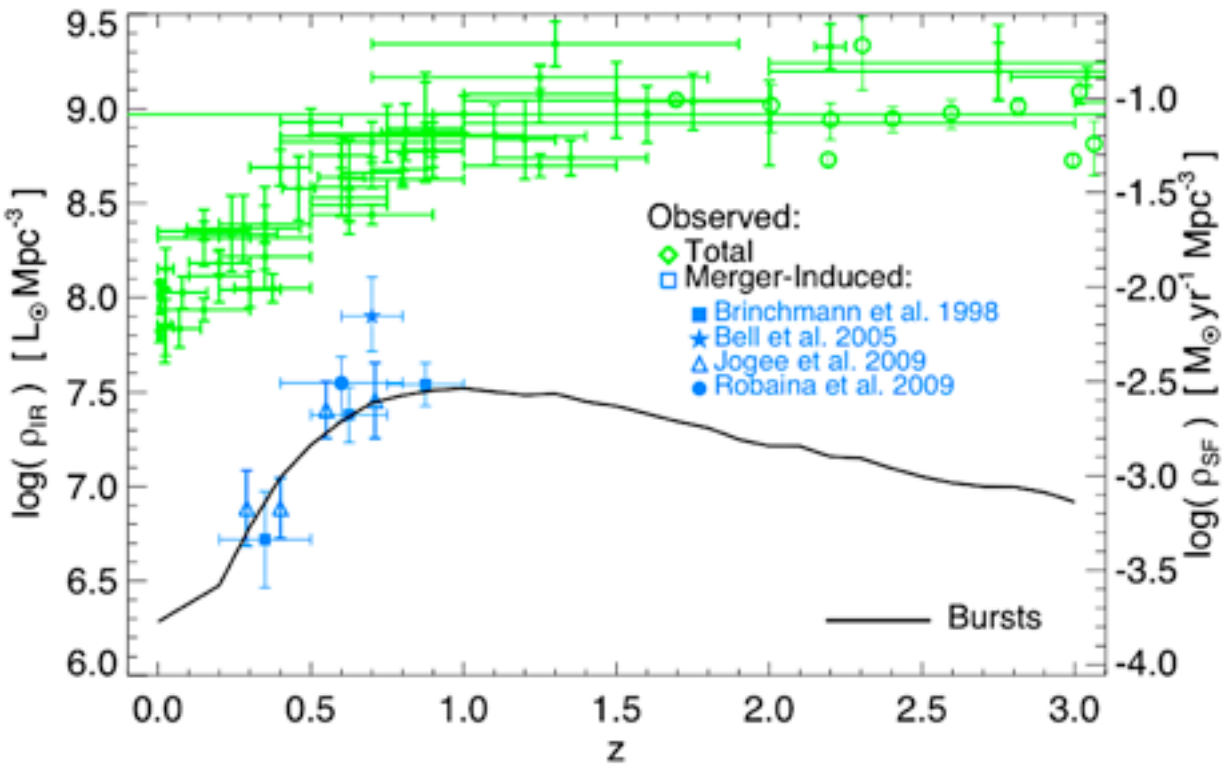


Bursts never dominate the SFR density!



Triggered bursts never dominate the SFR density: why?



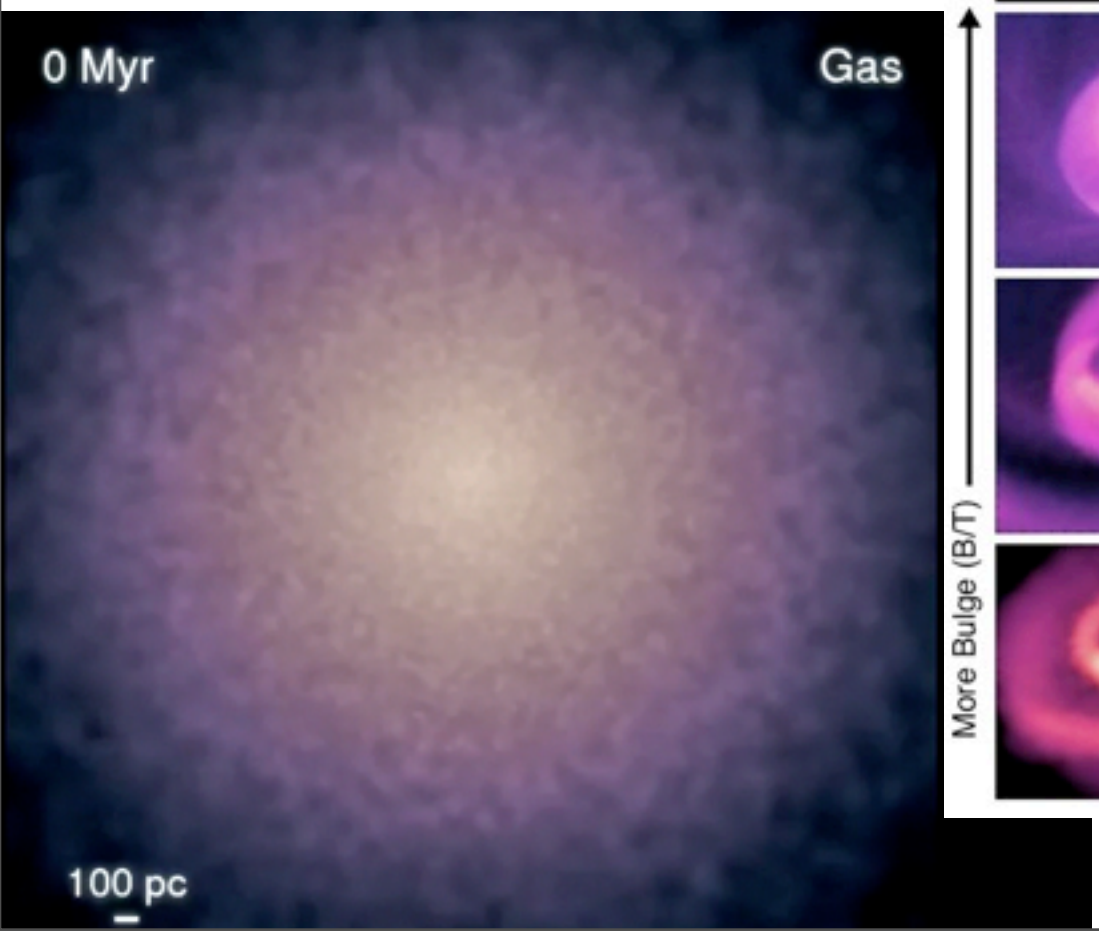


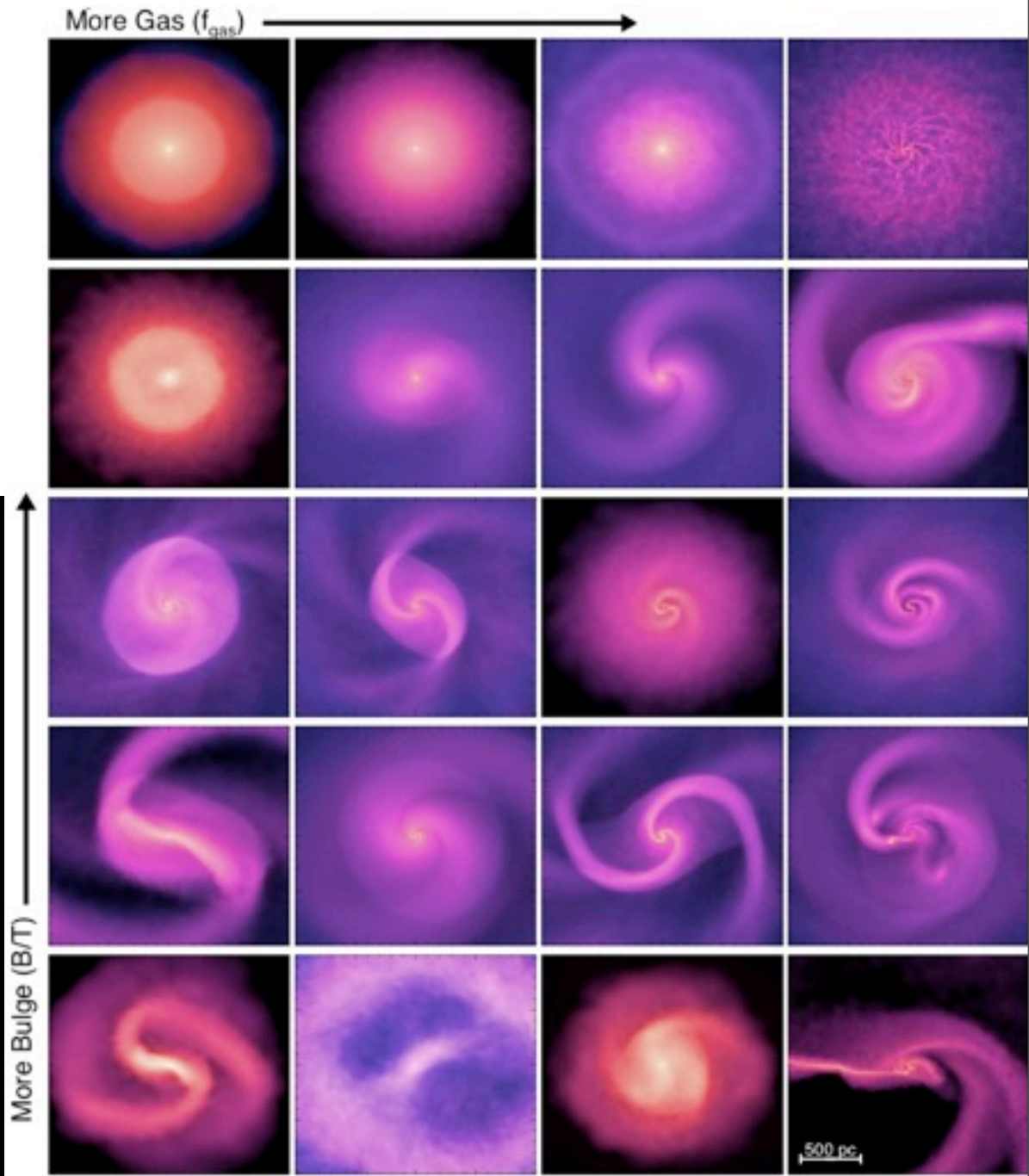
- Better definition of 'burst'
- Lower merger rates at high-z when you actually *match* the observed stellar mass functions
- Less efficient 'bursts' in the most gas-rich systems

Meanwhile, what's happening with the AGN?

Sub-kpc scales: "Stuff within Stuff"

- Diverse morphologies on sub-kpc scales: not just bars!
- Inflow is *not* smooth/continuous





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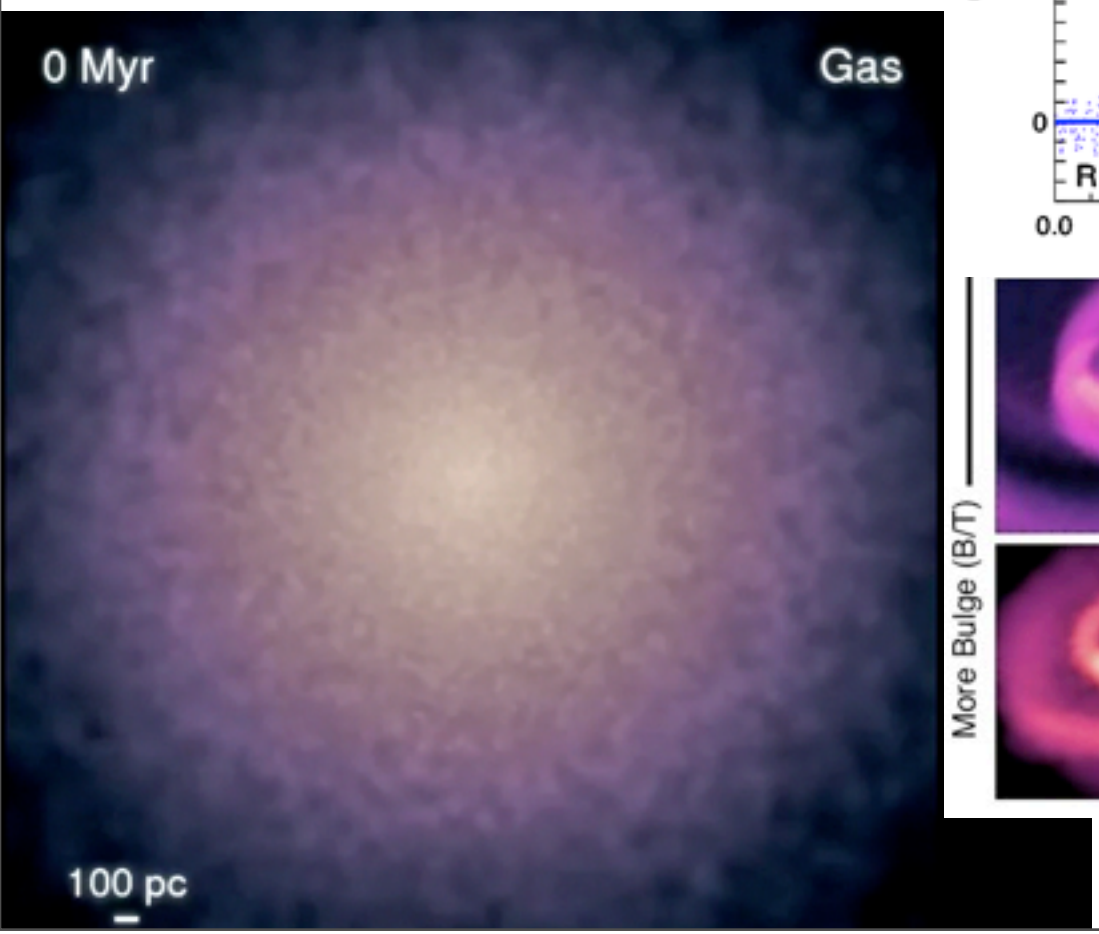
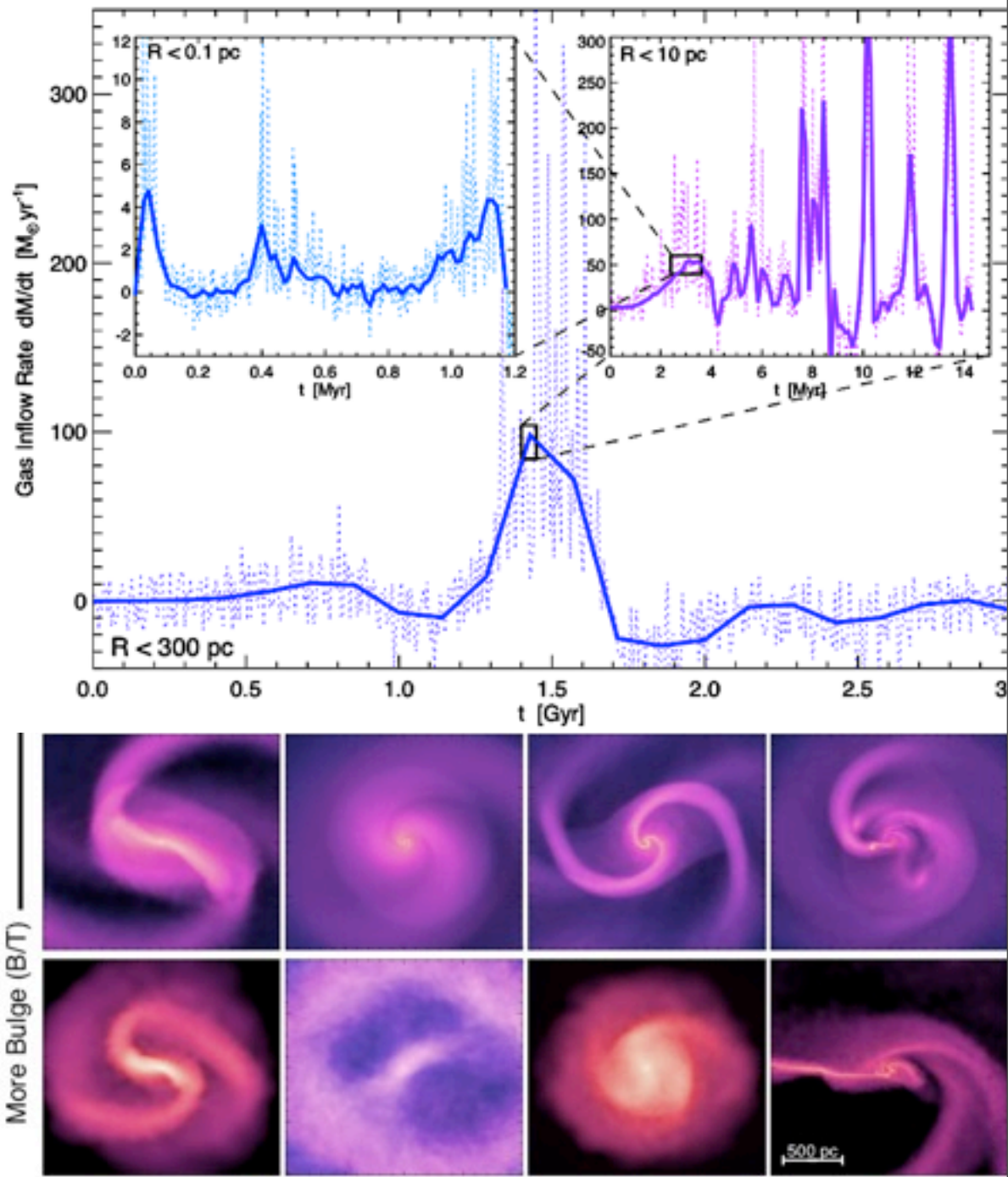
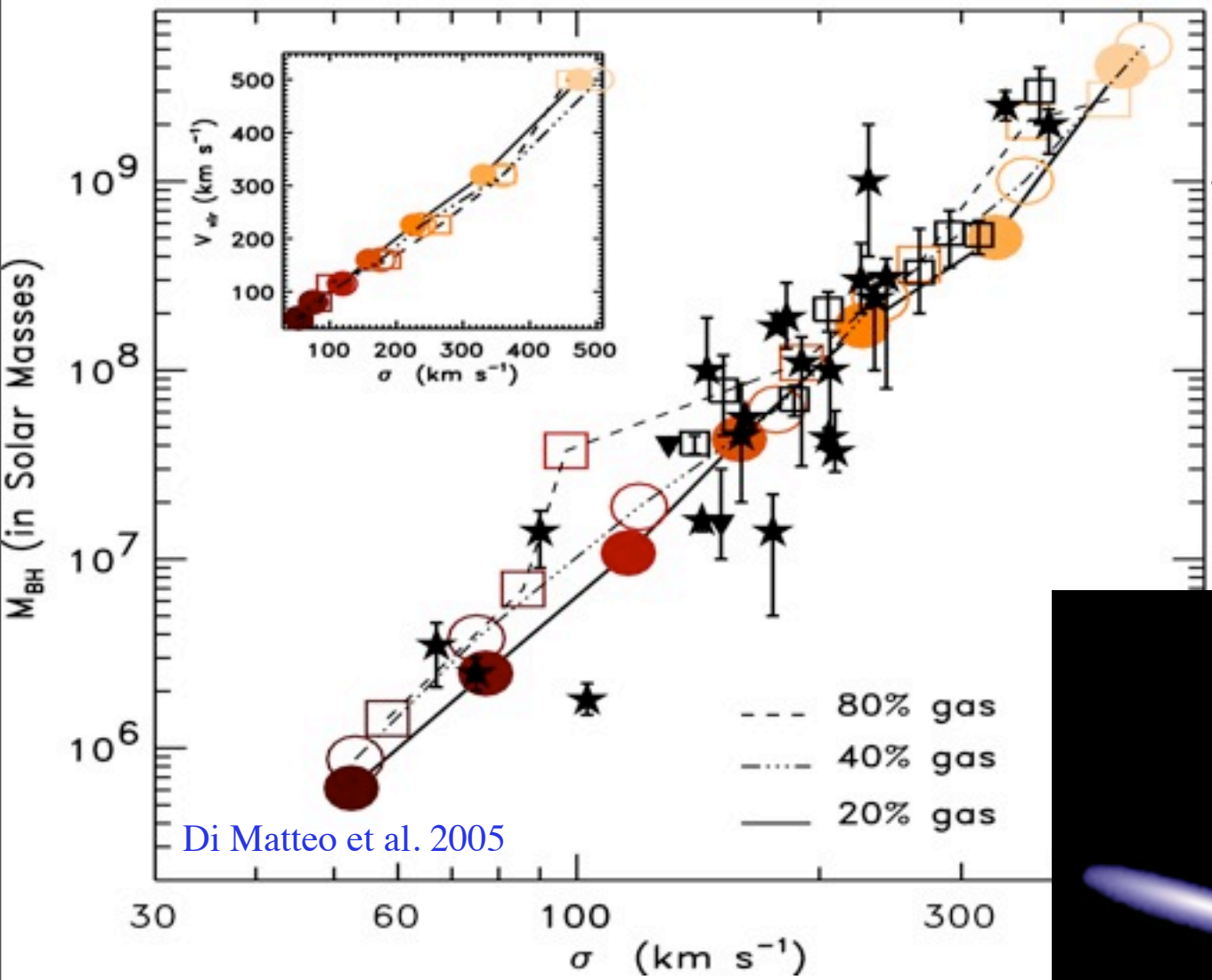
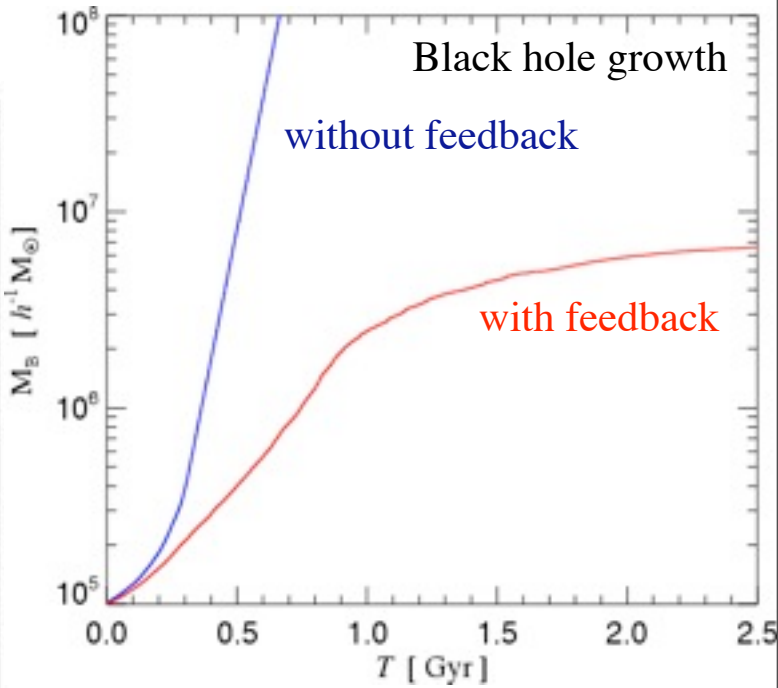


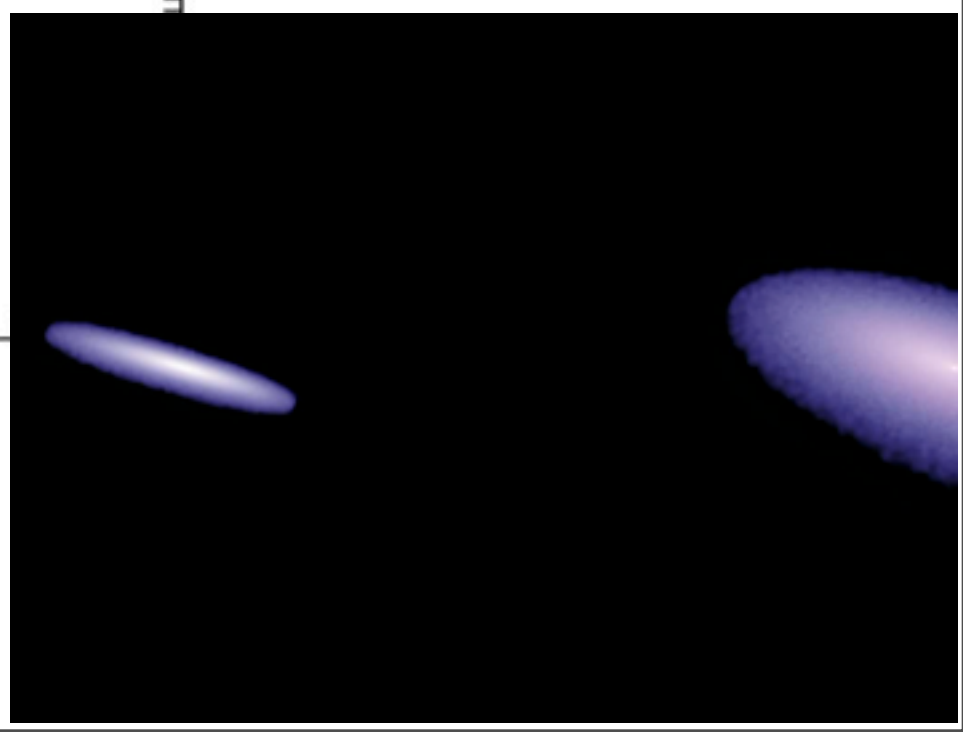


AGN Feedback Primarily Regulates... the AGN!

PREVENTS RUNAWAY BLACK HOLE GROWTH





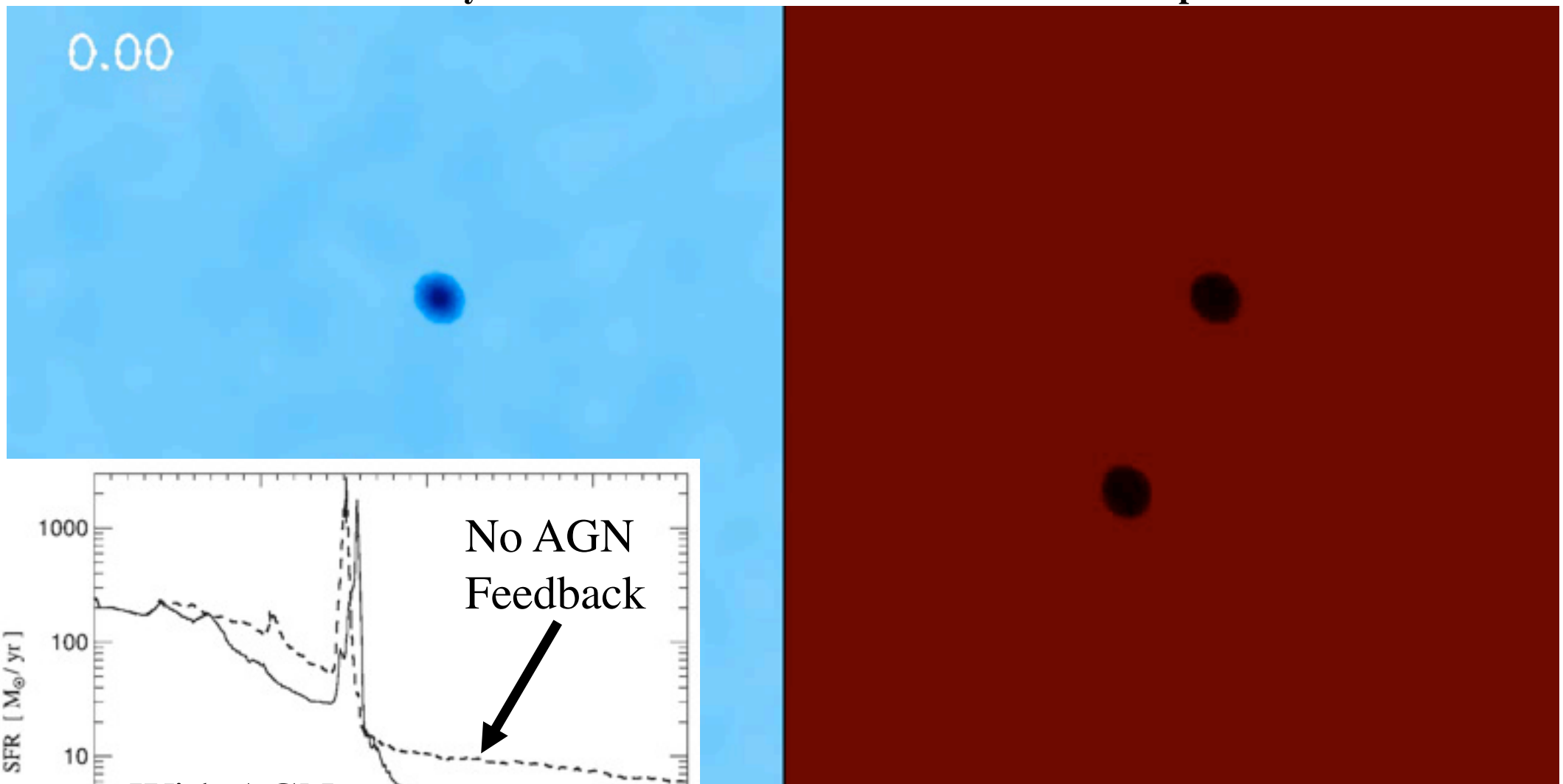


Quasar Outflows May Be Significant for the ICM & IGM

SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?

Gas Density

Gas Temperature



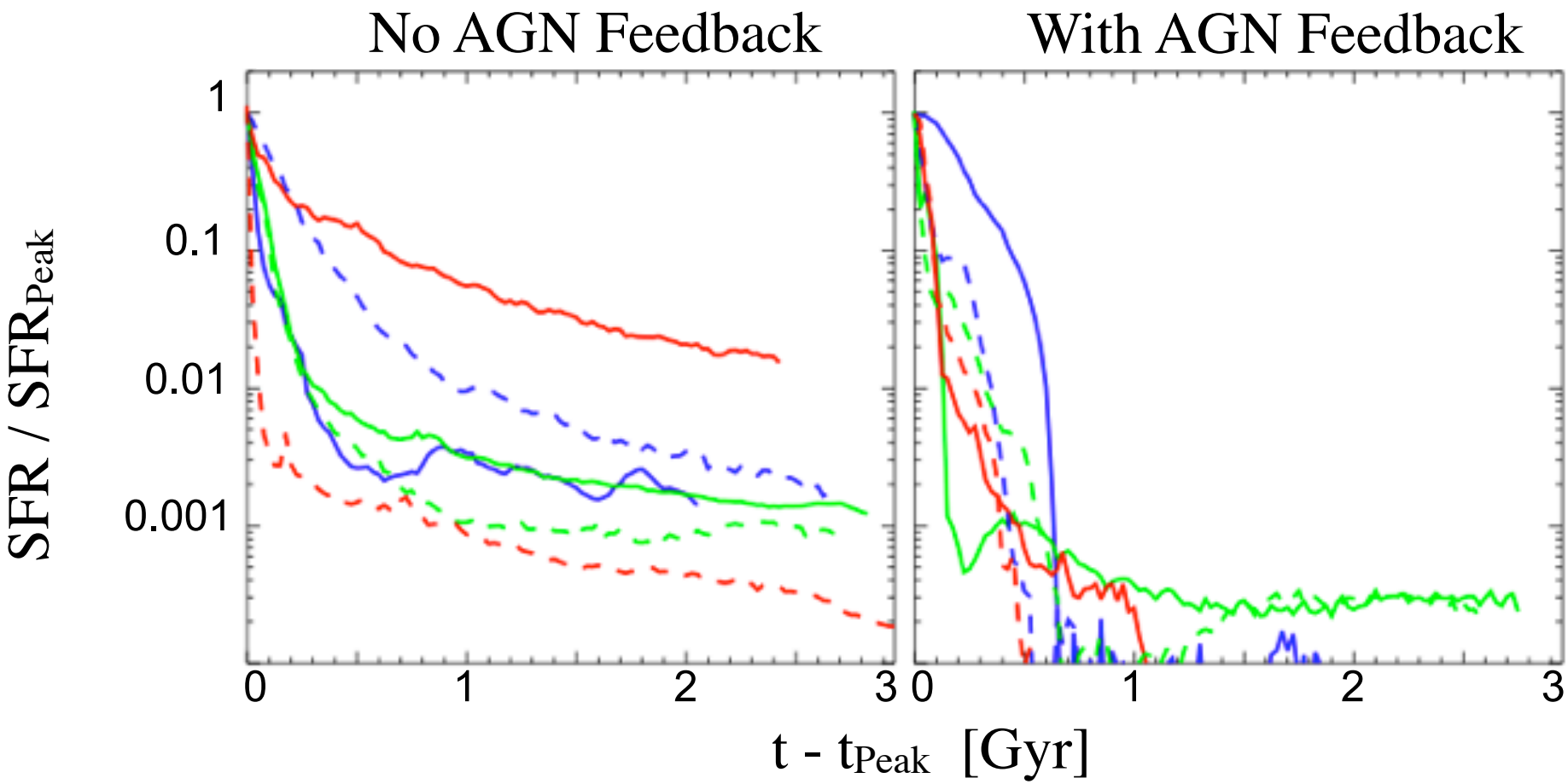
Springel et al. 2005

Expulsion of Gas Turns off Star Formation

PFH, Keres et al. 2008

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?

... but ...

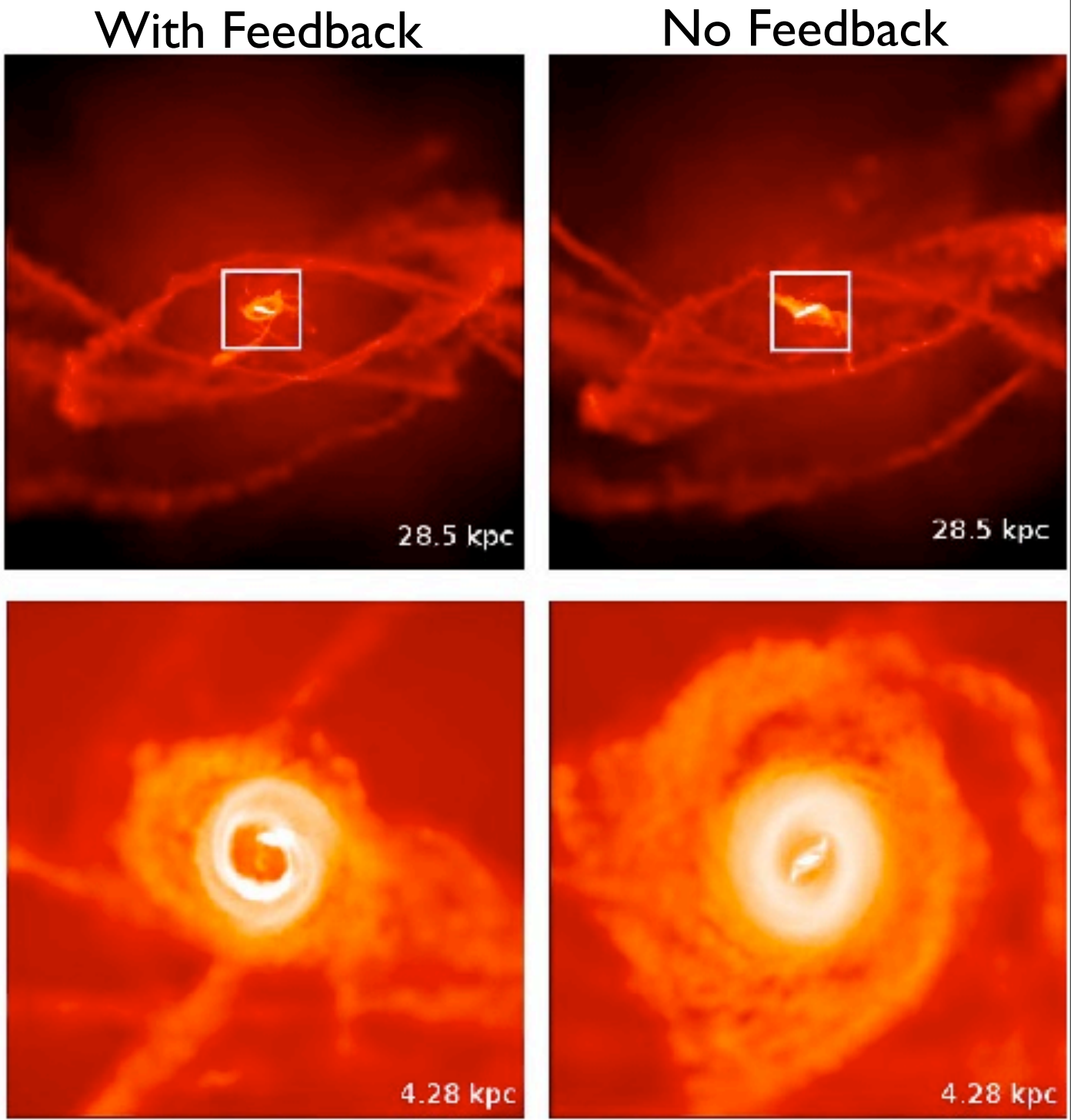


... MOST of the work is still done by star formation/stellar feedback

- but over a longer period of time -

And what if we change the feedback?

- DeBuhr et al. 2010:
  - Momentum-based feedback
- BH growth self-regulates on ~kpc scales, but with no galaxy scale "blowout"!

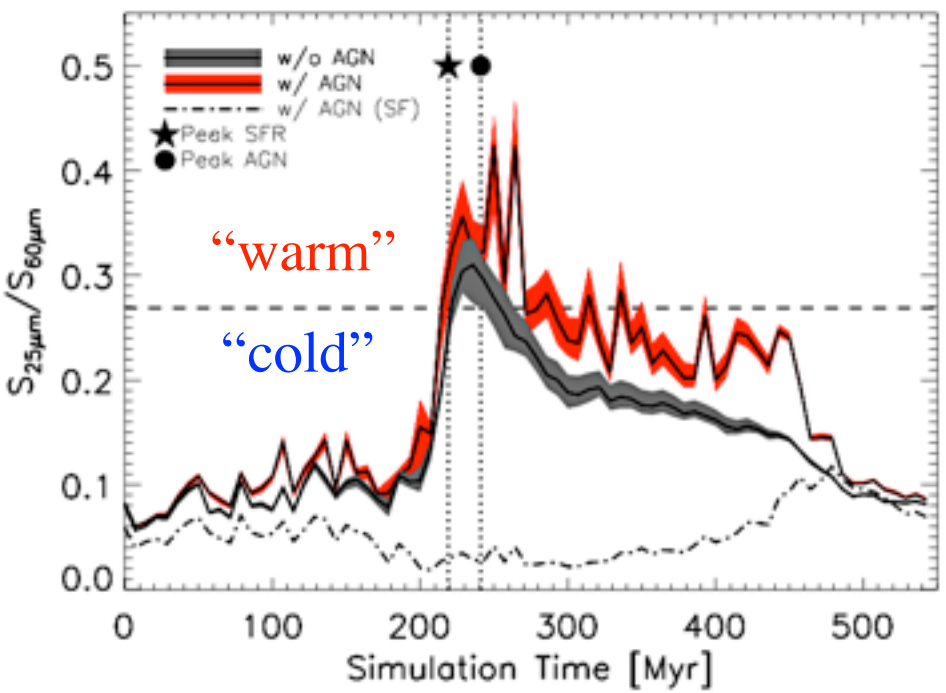


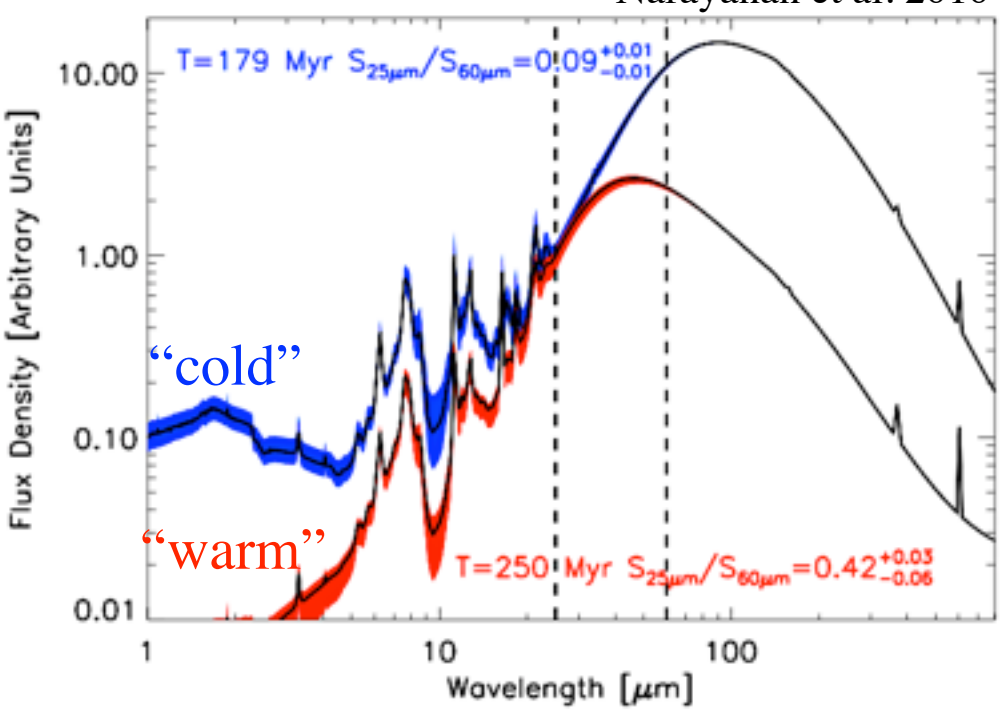
The Role of the AGN...

HOW IMPORTANT IS IT TO THE STARBURST?

- Radiative Transfer: SUNRISE by P. Jonsson

Younger et al. 2009,
Narayanan et al. 2010





- Cold/Warm transition: see the AGN growing....
  but may not rely on feedback

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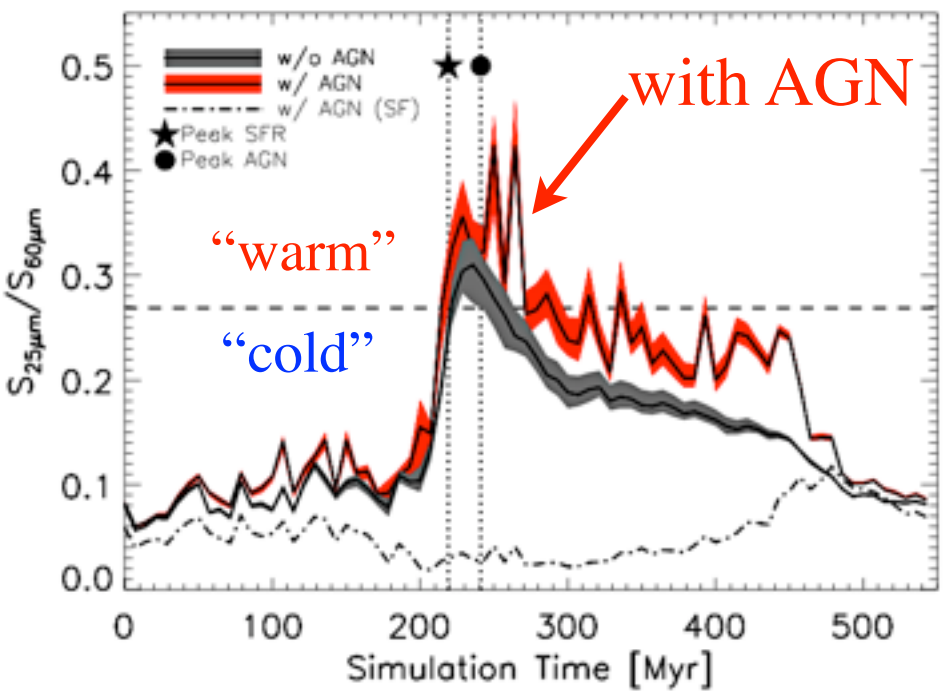

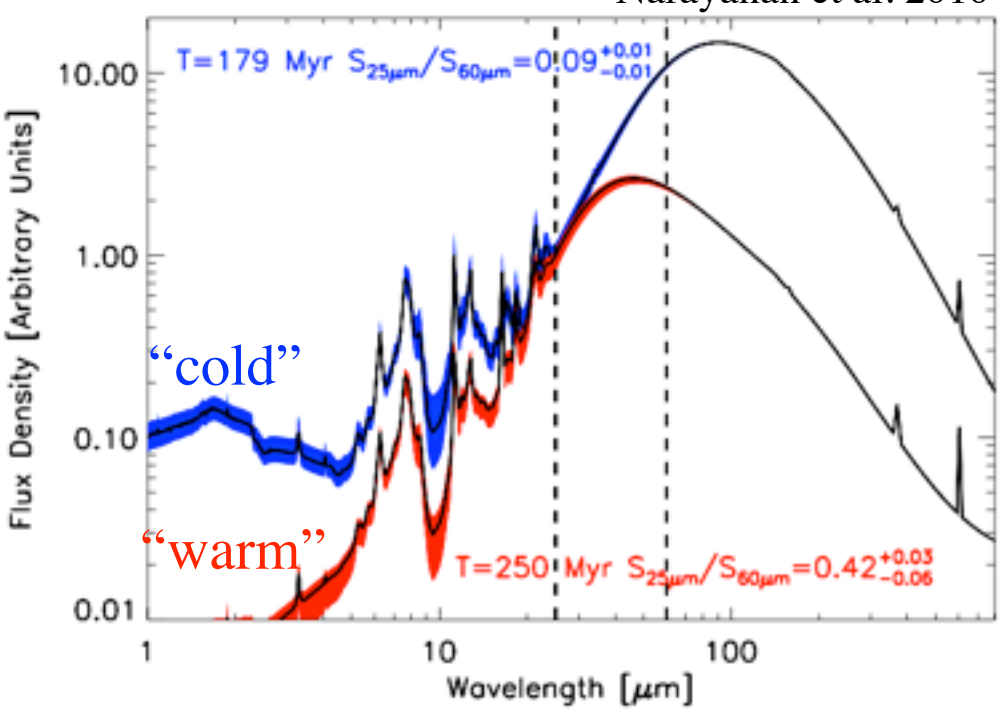

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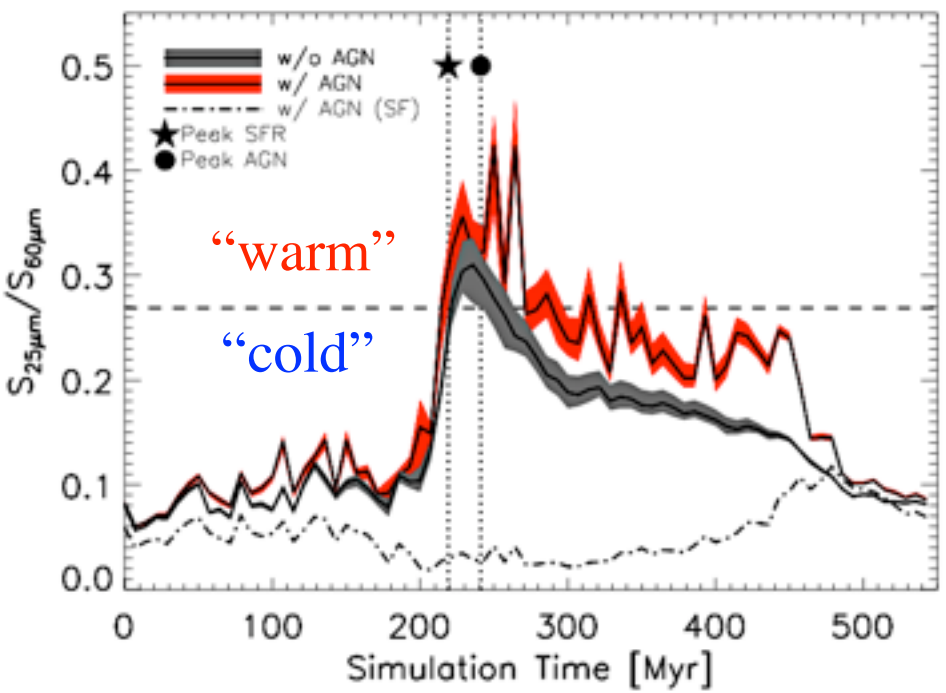

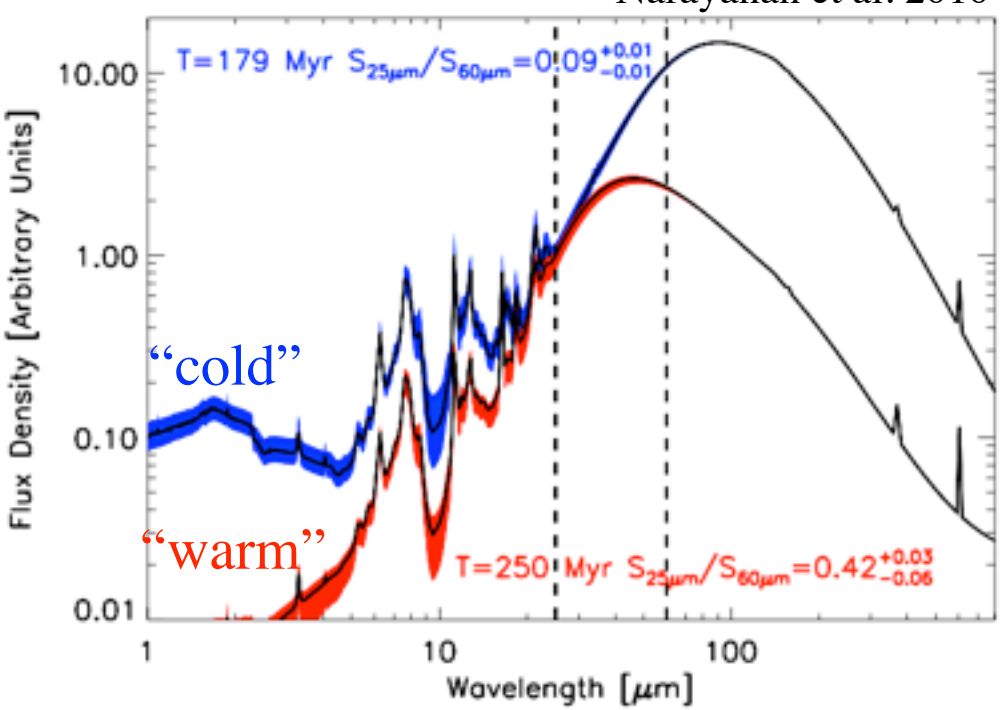

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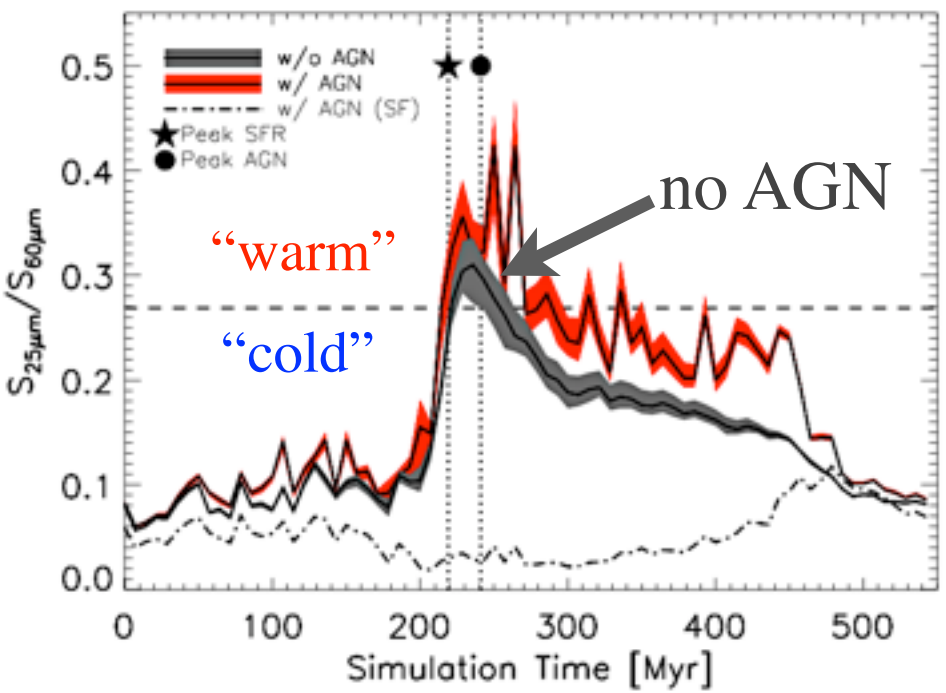

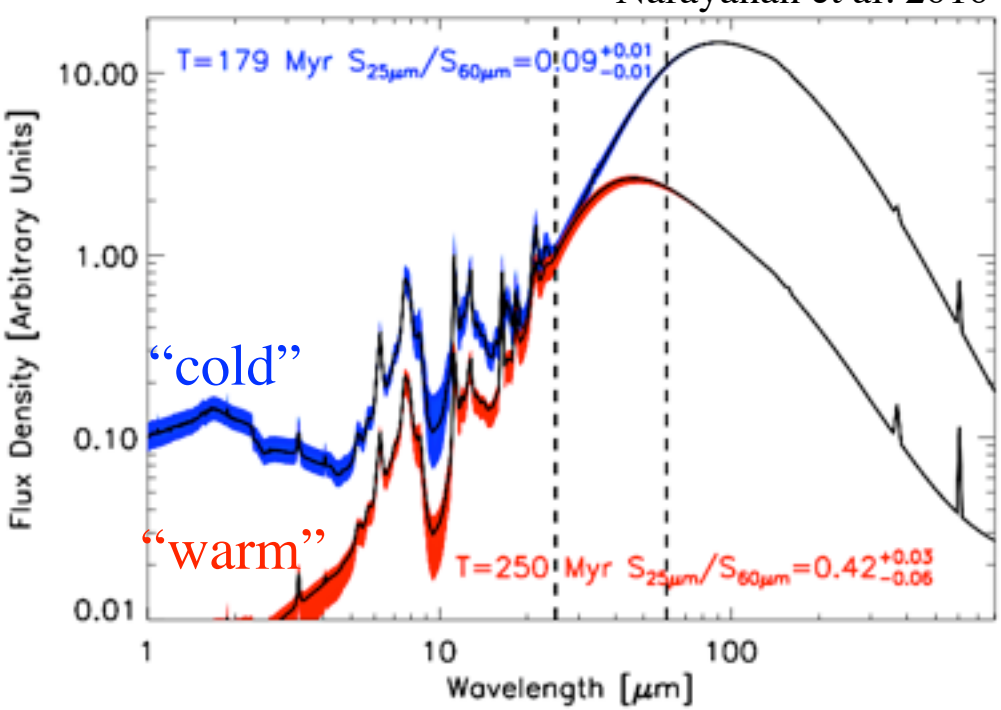

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Summary

- Gas Dissipation and Star Formation Are Critical to Understand Galaxy Structure
  - 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 today match the population of IR-luminous starbursts now being seen at high-z
  - Mergers are always the brightest/most violent things, *but* as gas fractions and cooling rates increase, *everything* scales up similarly
- Dynamics may change at the highest gas fractions
  - Gas! No stars = No angular momentum loss
- AGN Feedback is critical *for AGN*, and may be critical for quenching, but:
  - Doesn't do much to the galaxy structure, or the starburst
  - Gas exhaustion dictates the central structure, SFR(t), and cold/warm transition