P. Hopkins

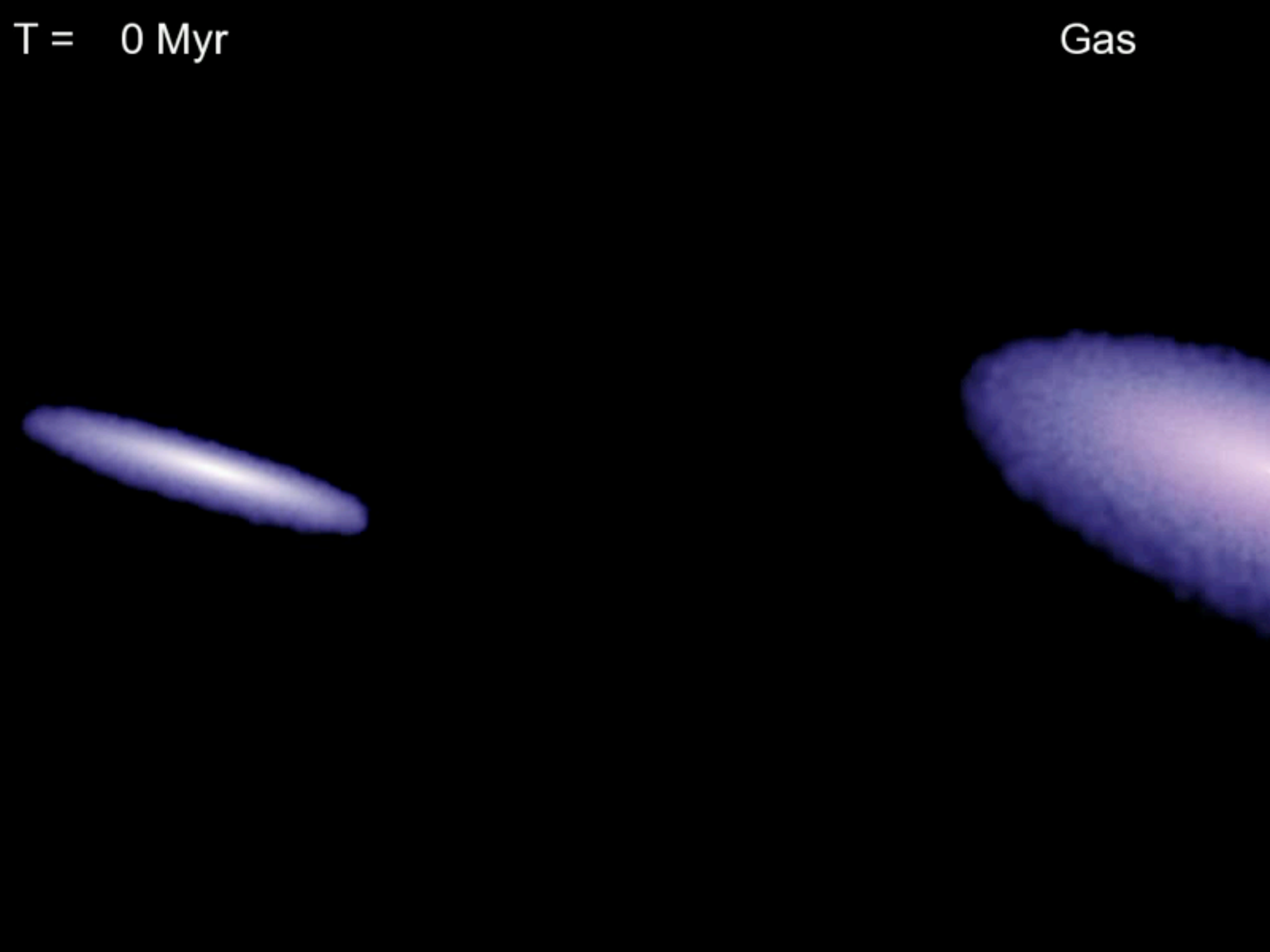
Gas, Galaxy Mergers, Starbursts, and AGN: Powering an Evolving Hubble Sequence

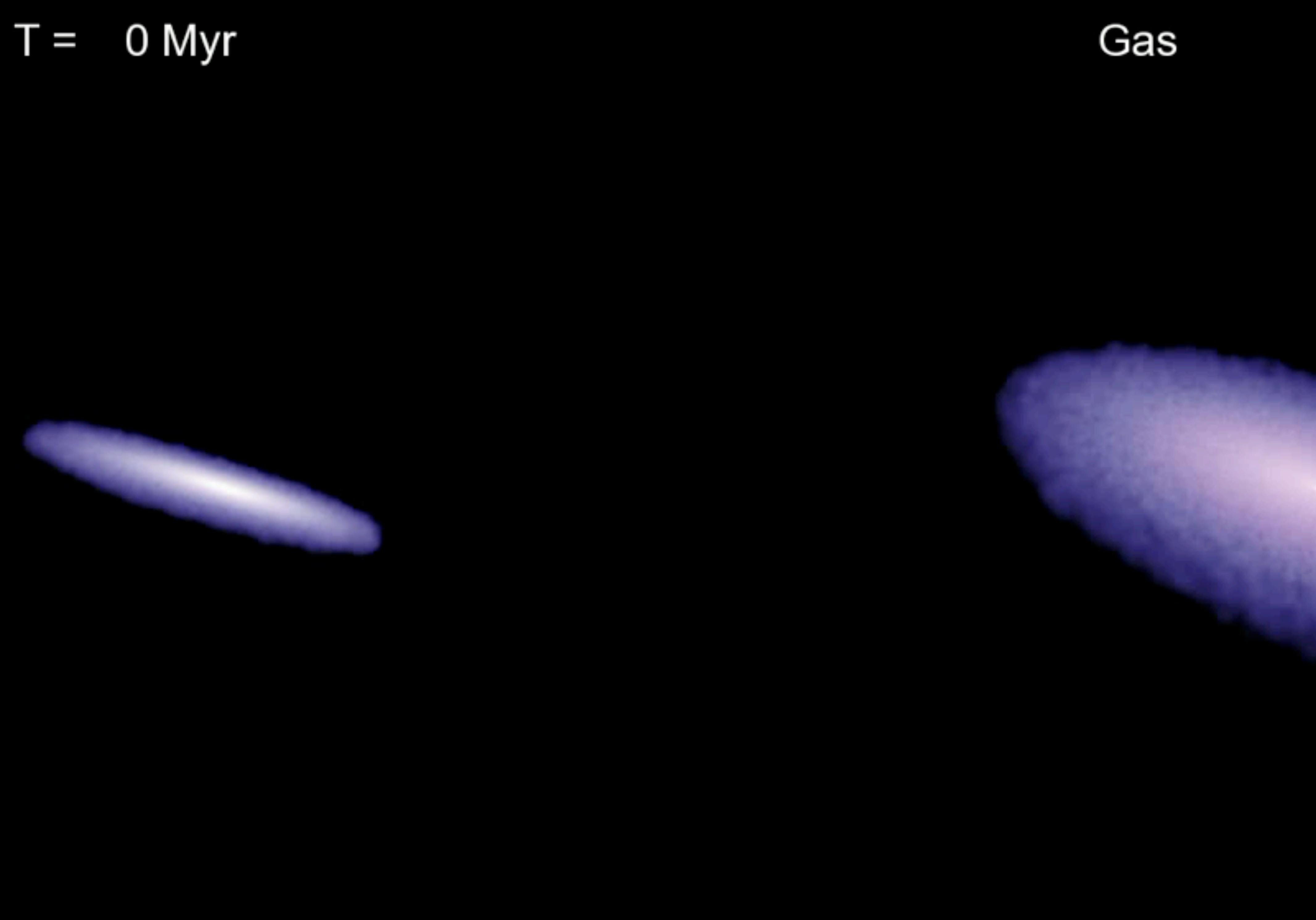
In the last few years, the combination of models that include realistic large gas supplies in galaxies, and prescriptions for feedback from both stellar evolution and super-massive BHs to maintain those gas reservoirs, have led to huge shifts in our understanding of galaxy formation. In particular, gas-richness, and the magnitude of starbursts driven by tidal action, may represent the most important driving factor in the net effects of galaxy-galaxy mergers on bulge structural properties, stellar populations, mass profiles, and kinematics; models with the appropriate gas content have finally begun to produce realistic bulges that resolve a number of discrepancies with observations. In the regime of very gas-rich mergers, expected at high redshift and/or low masses, gas can qualitatively change the character of mergers and starburst galaxies, making disks robust to destruction in mergers and providing a natural explanation for the observed morphology-mass relation. These processes provide a link between the 'relic' population seen today, low-redshift starburst populations, and rapidly star-forming galaxies at high redshifts. Feedback is critical in a number of ways: it regulates and maintains gas supplies, can 'shut down' the tail-end of starburst activity leaving 'quenched' galaxies, and may set a characteristic upper limit to the densities reached by any rapidly star-forming systems from the scales of star clusters to the most massive high-redshift starbursts.

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

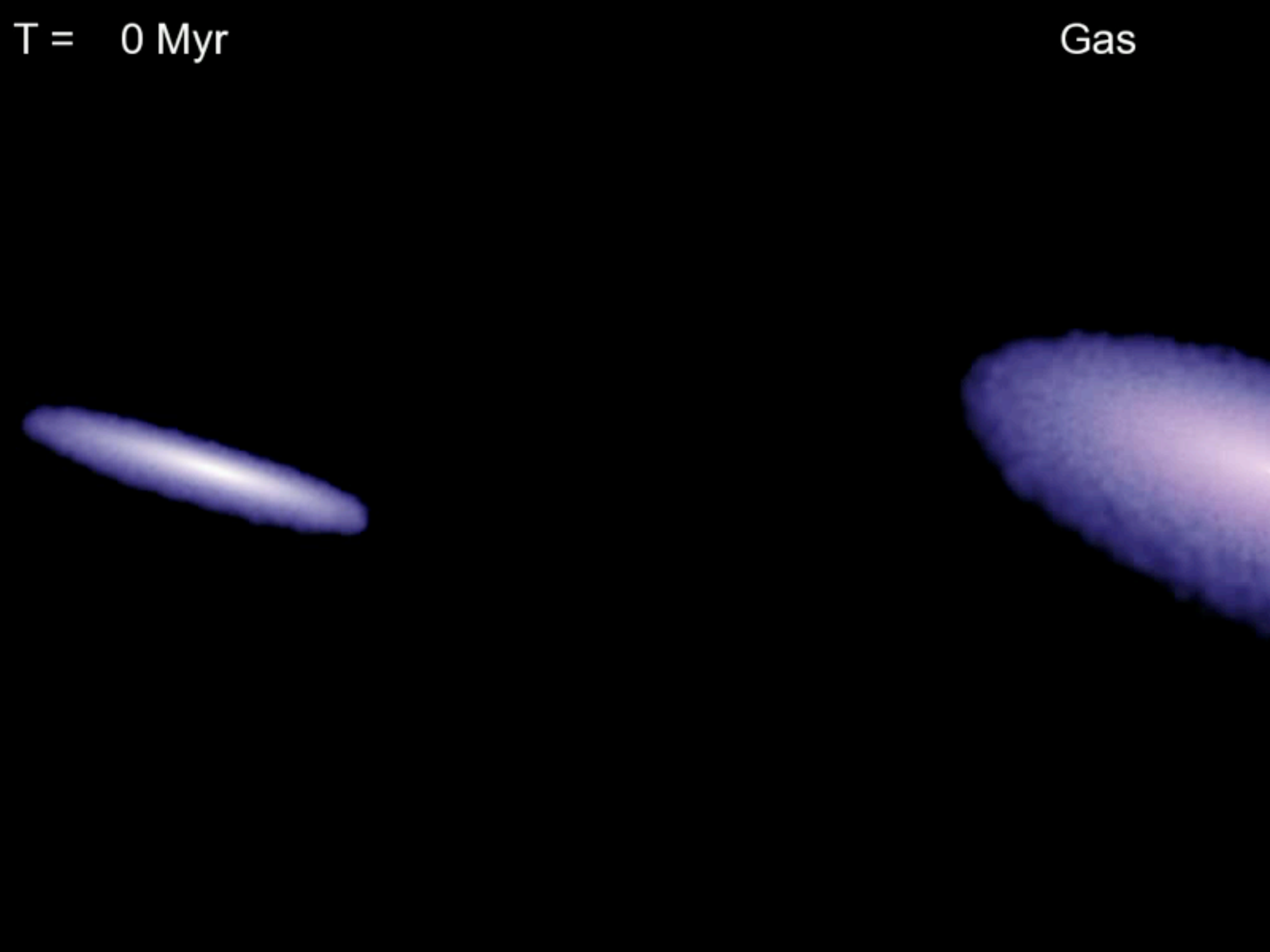
Philip Hopkins

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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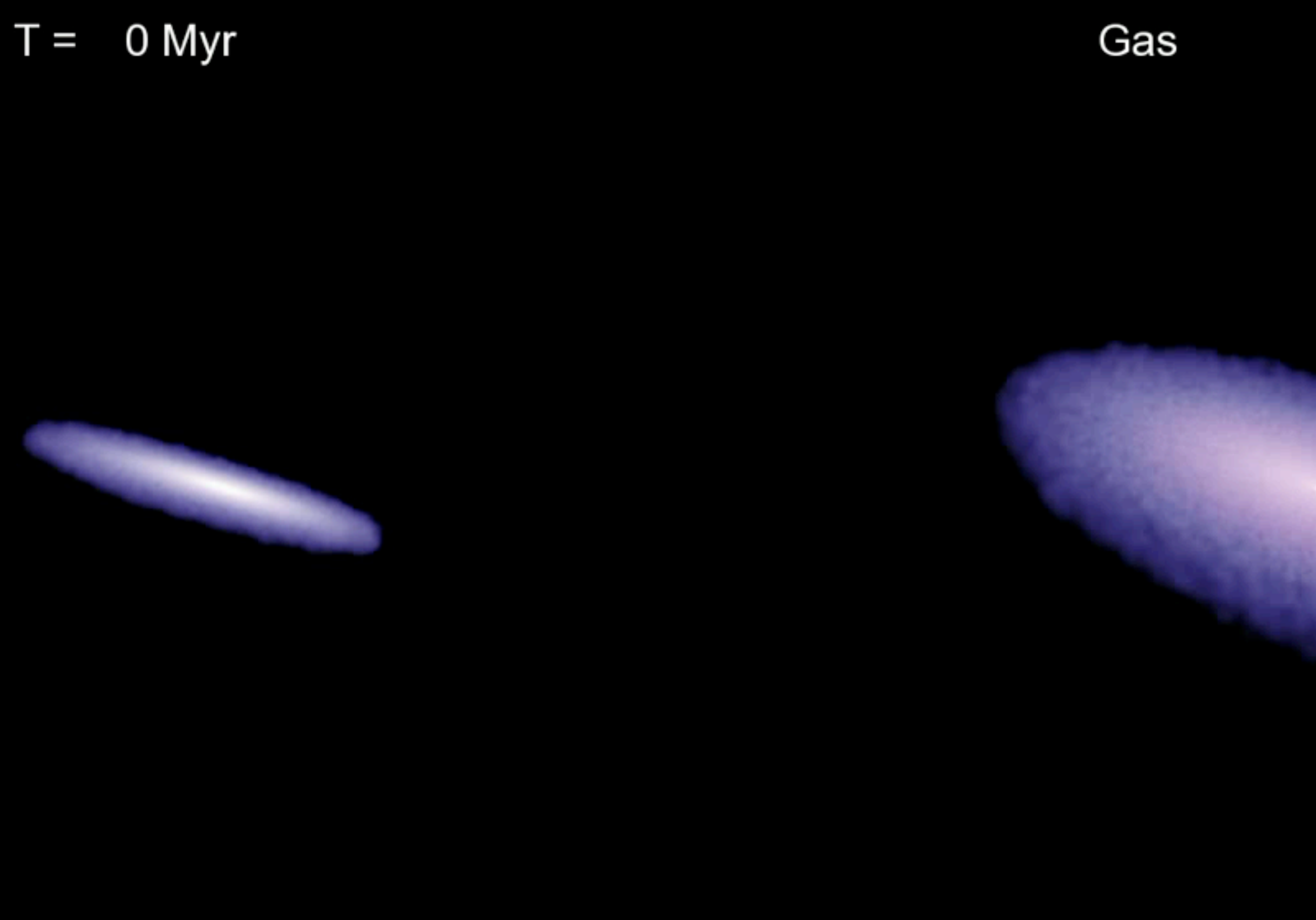
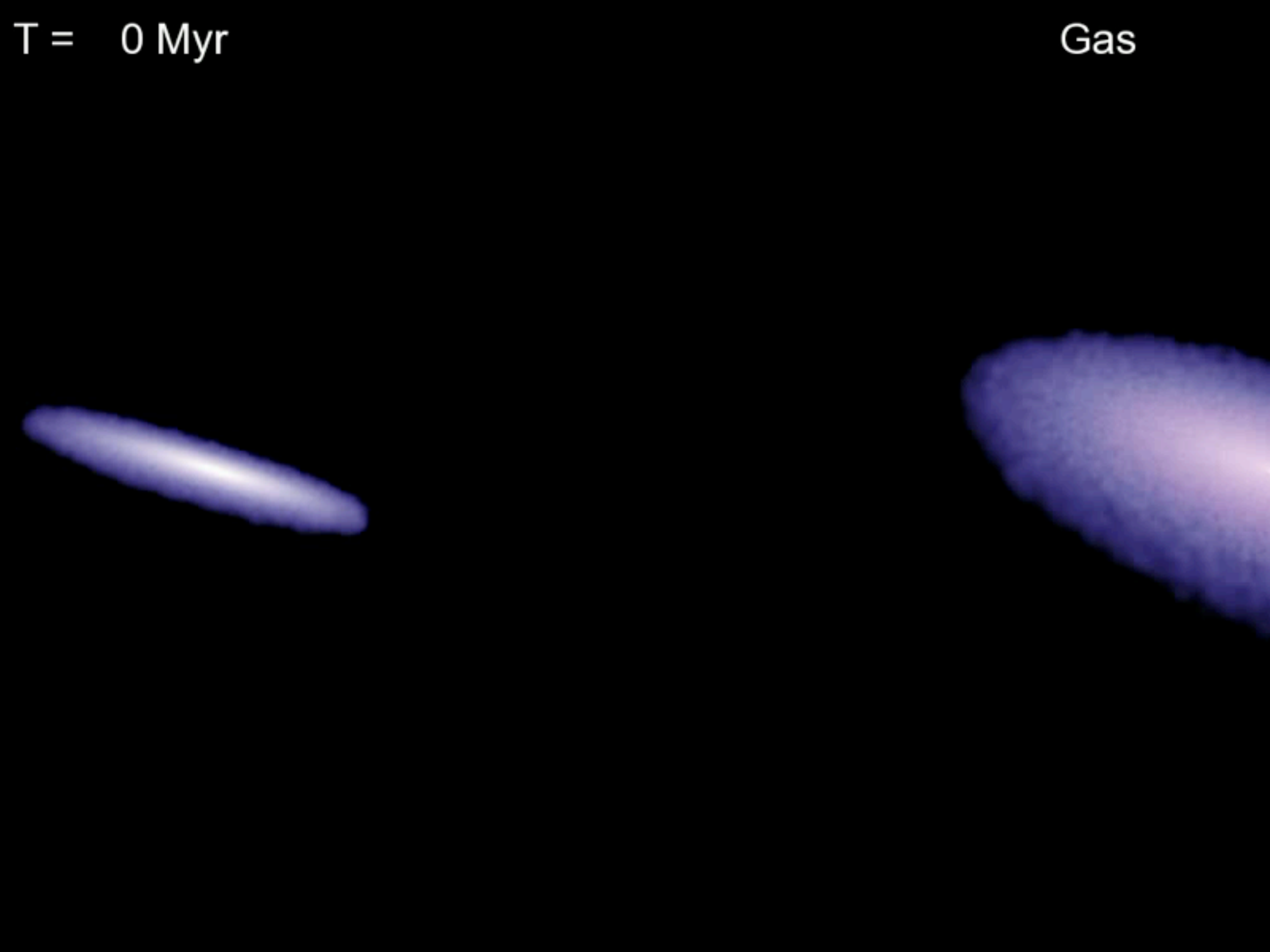


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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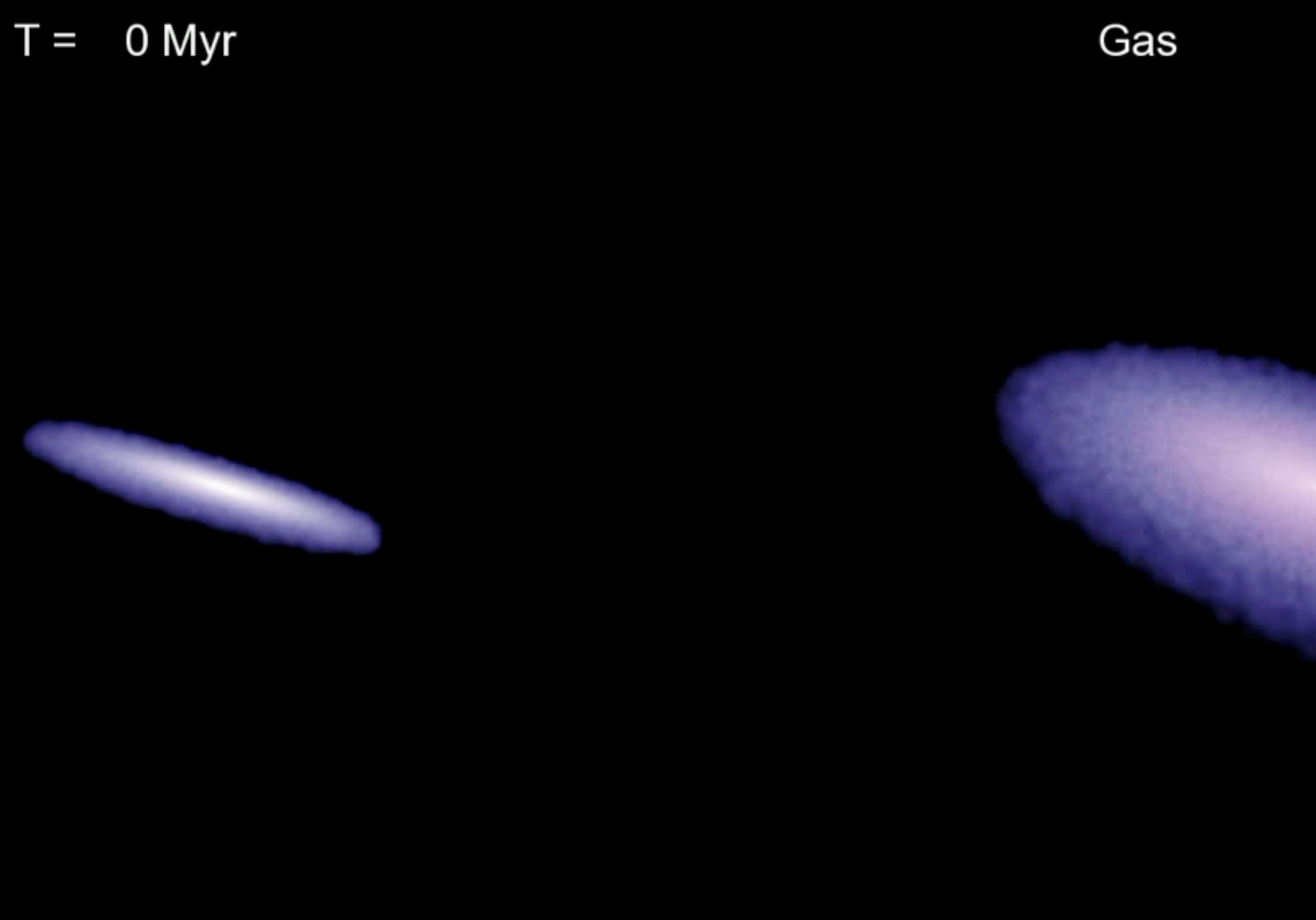
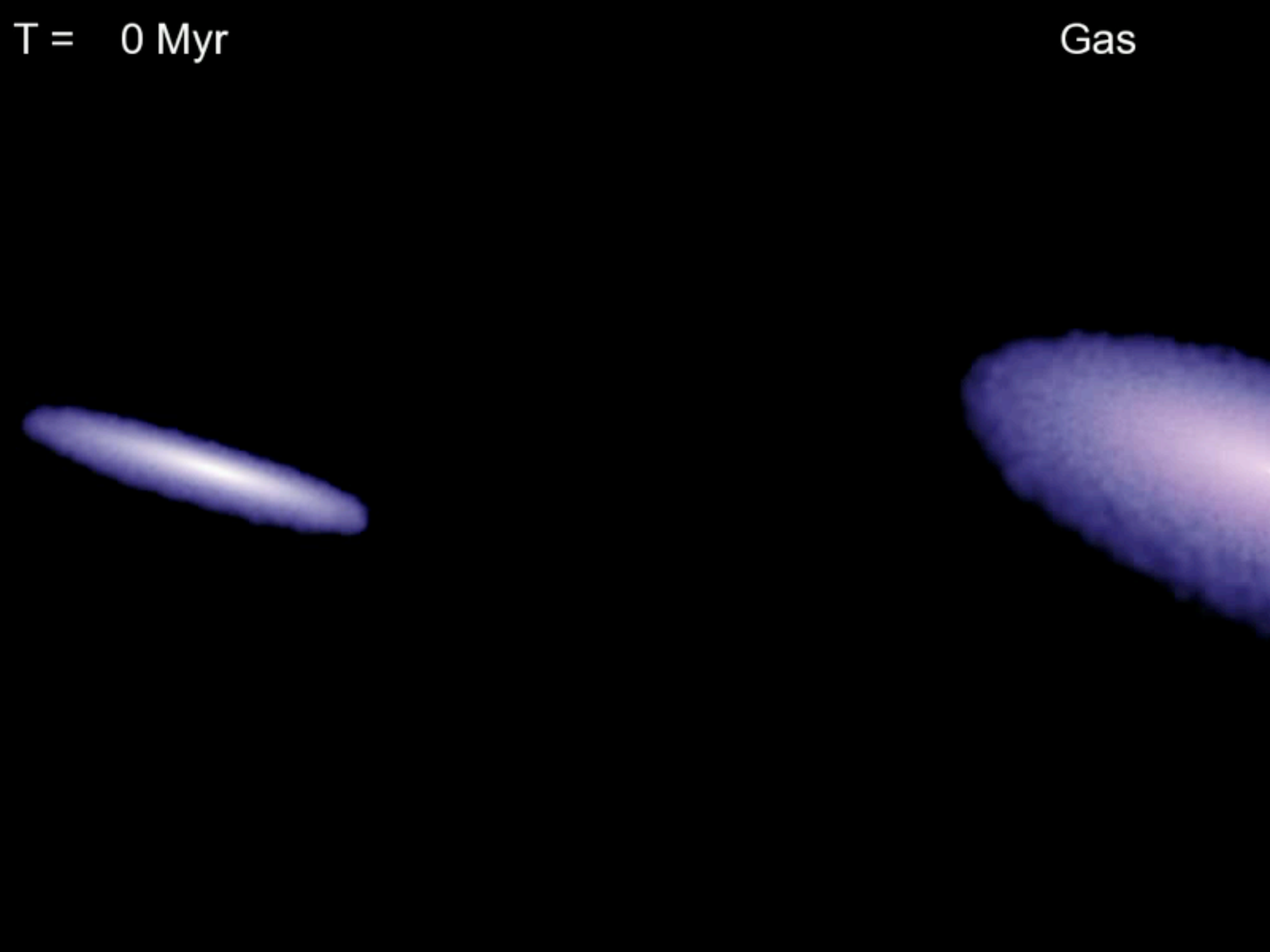


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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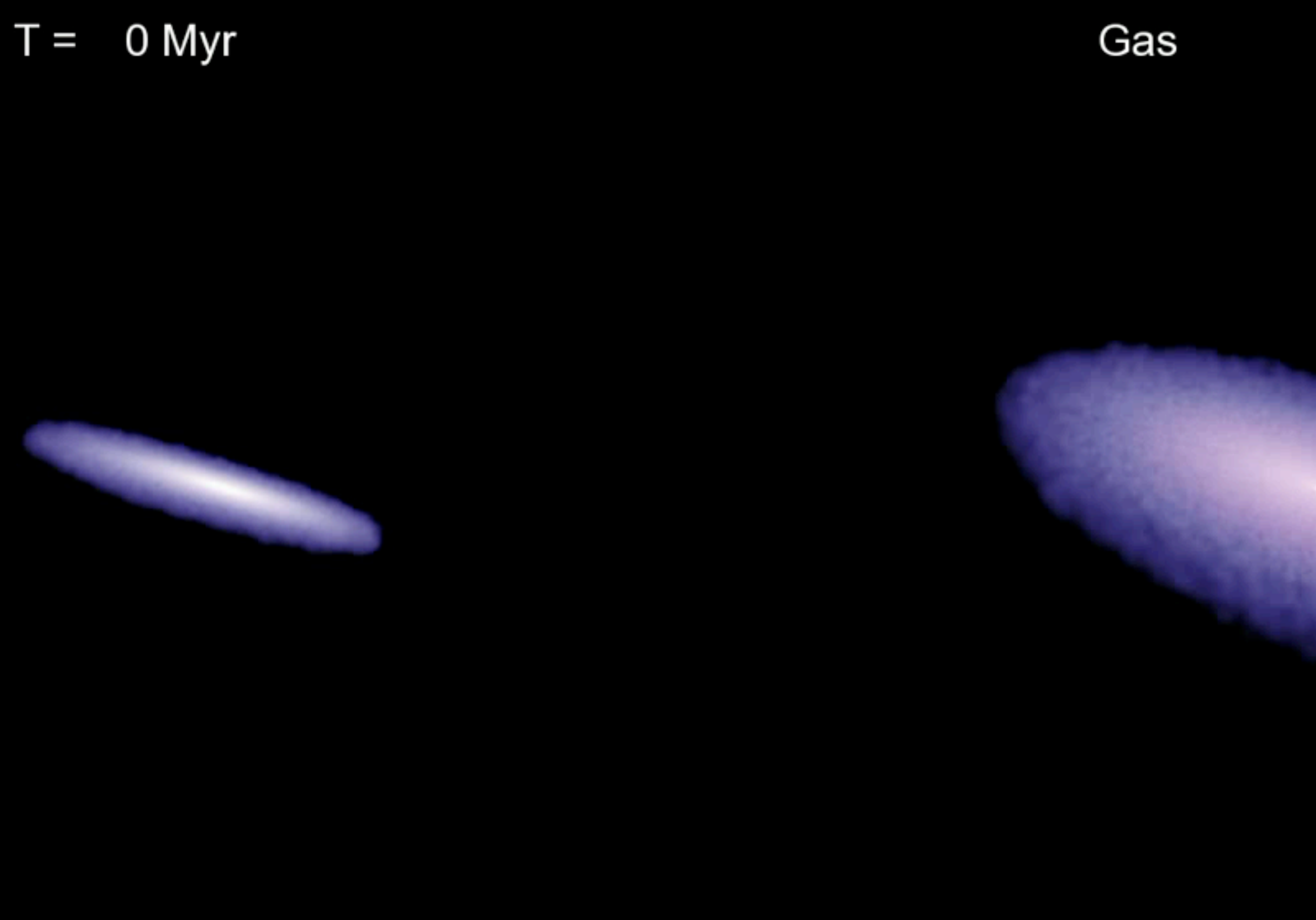
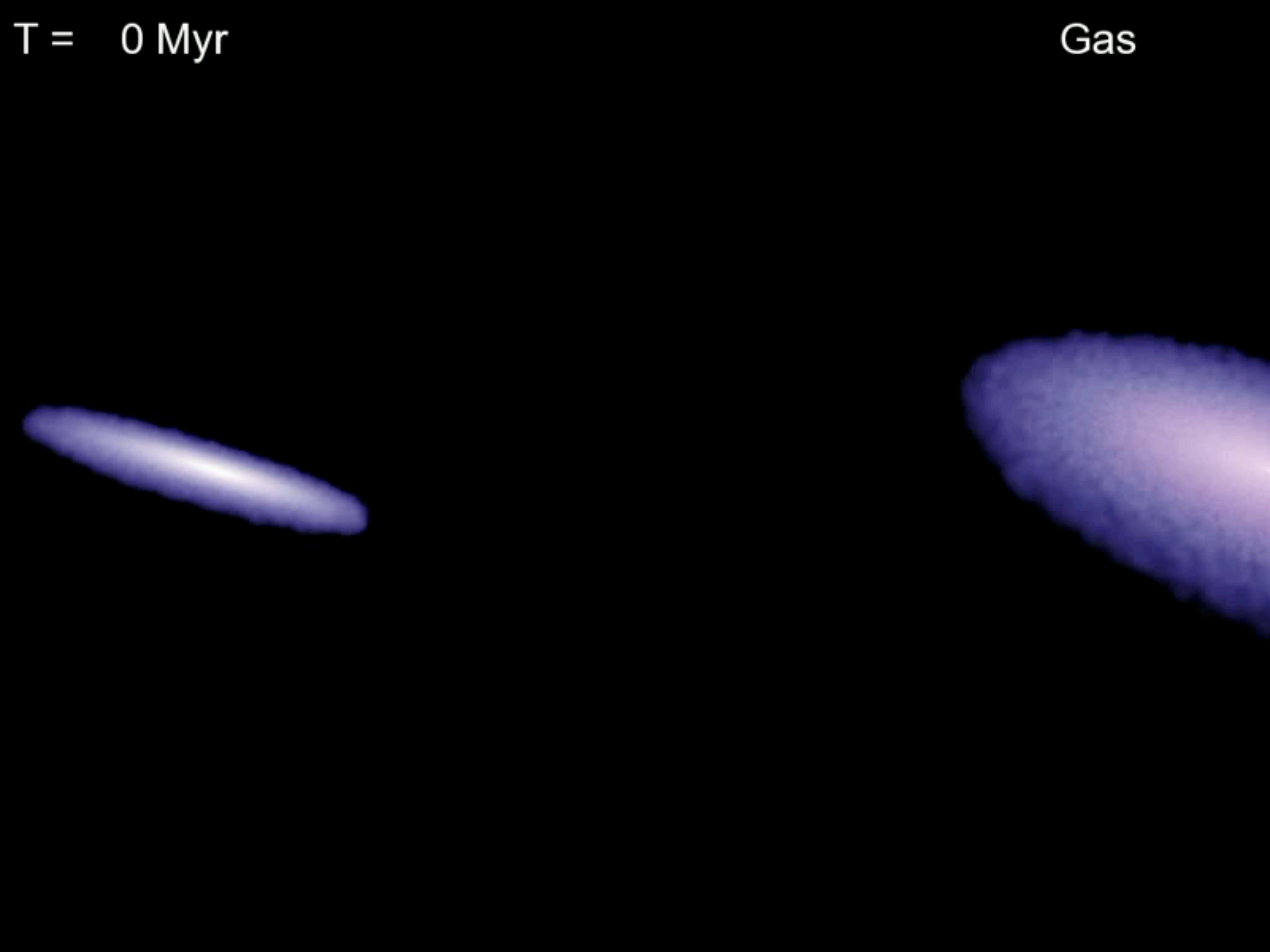


Feedback expels remaining gas, shutting down growth (more later...)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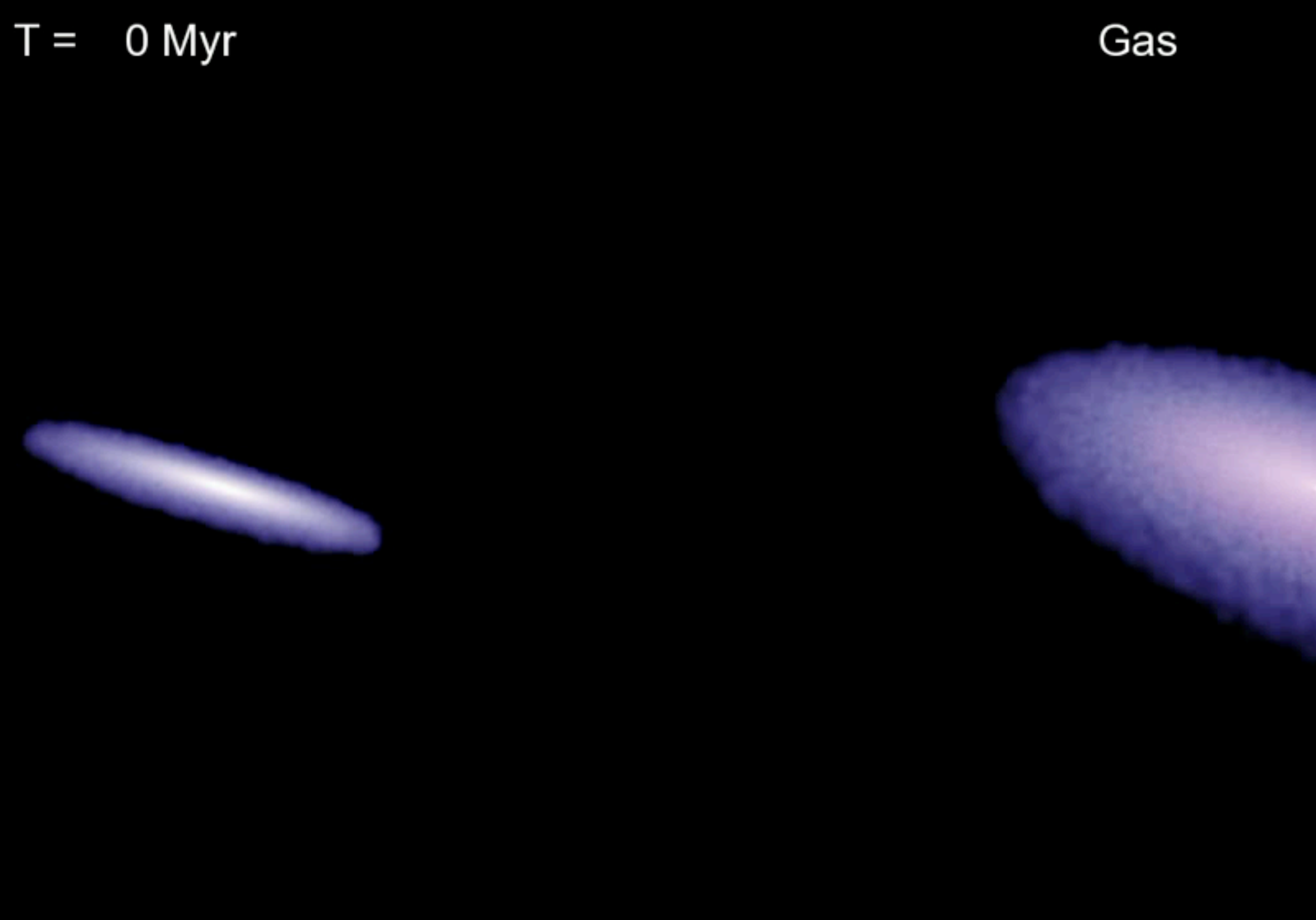
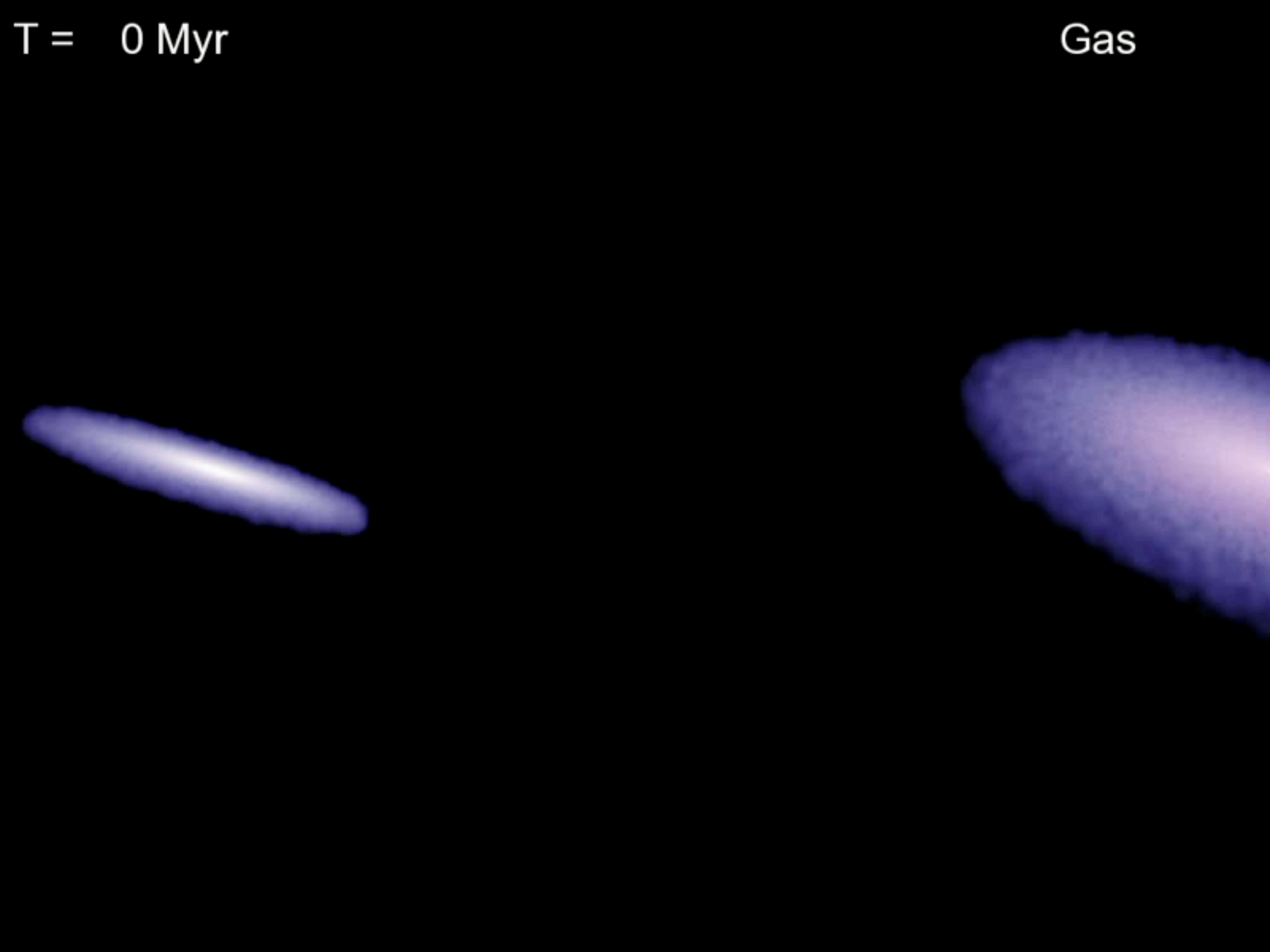


Merging stellar disks grow spheroid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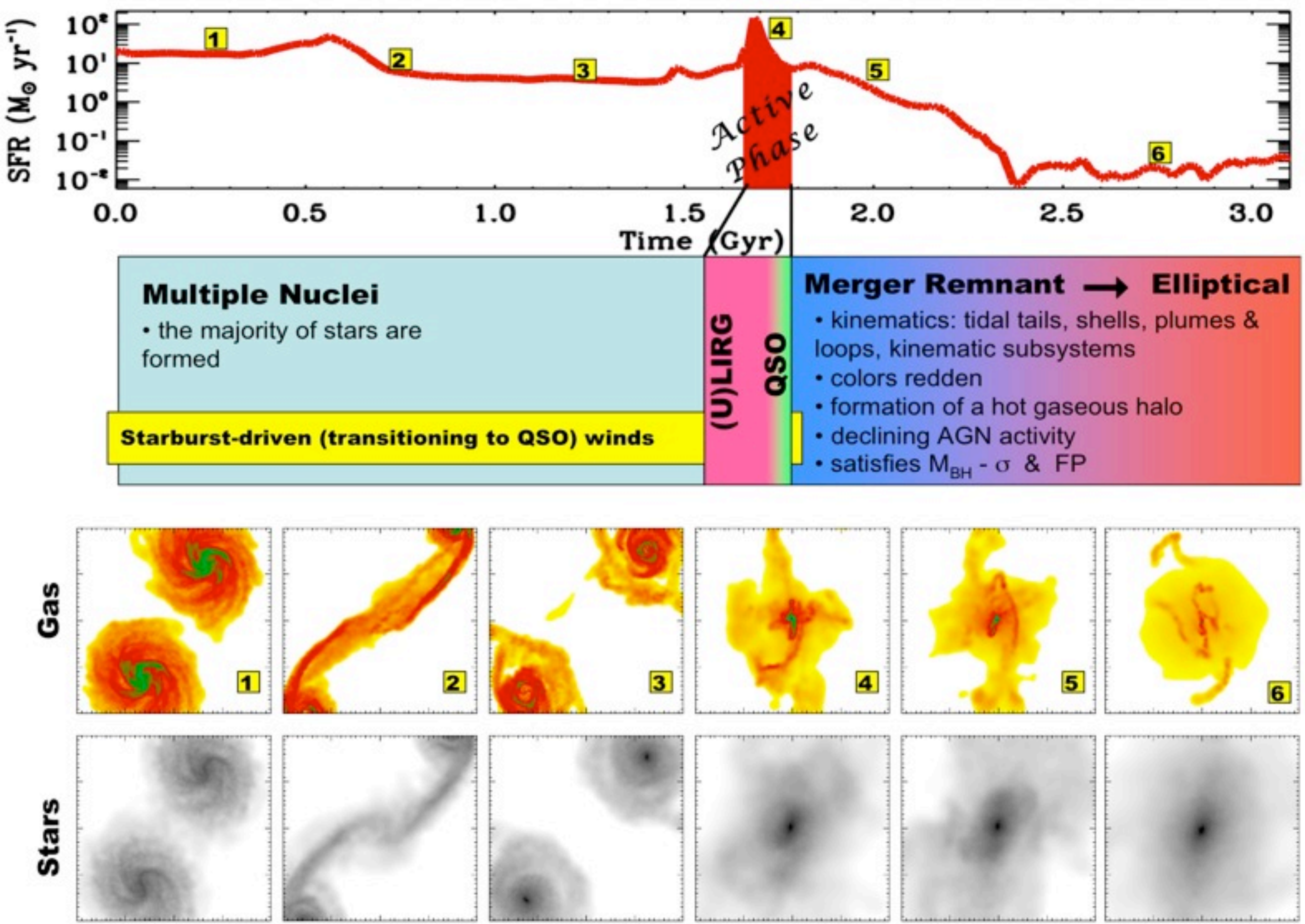
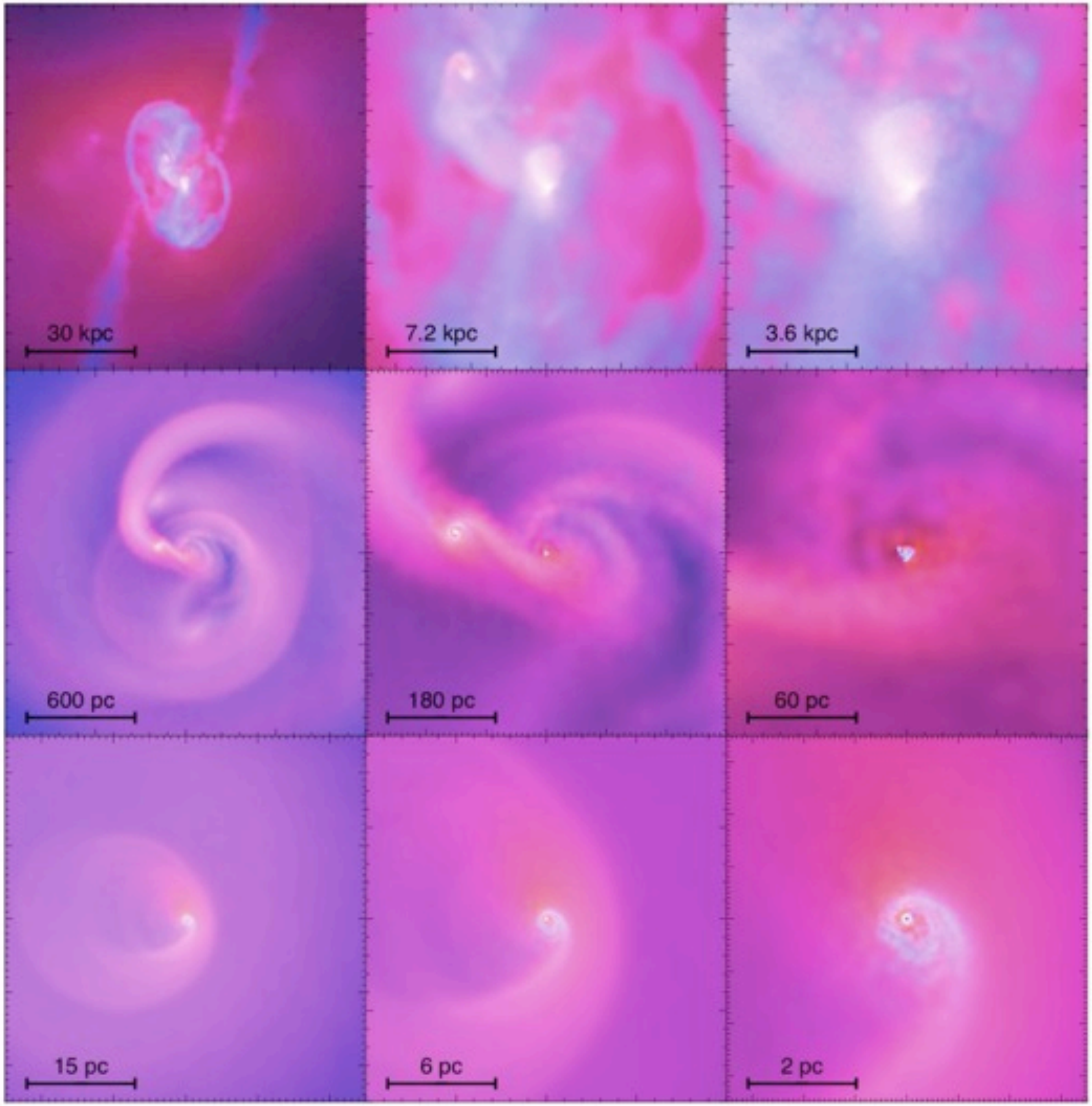

SFR ($M_\odot$ yr^{-1})
10^2
10^1
10^0
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
Active Phase
1
2
3
4
5
6
Multiple Nuclei
• the majority of stars are formed
Starburst-driven (transitioning to QSO) winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, 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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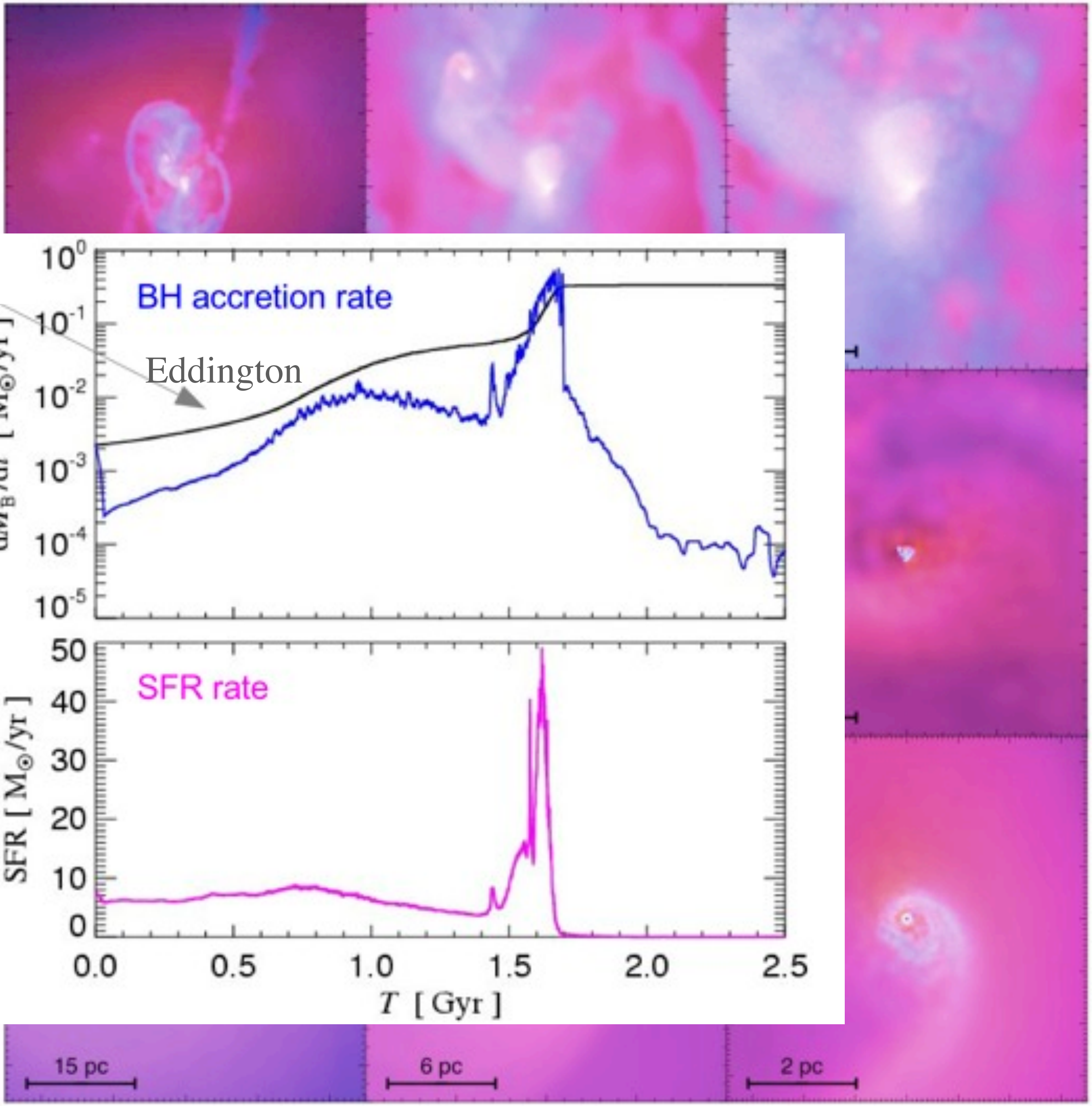

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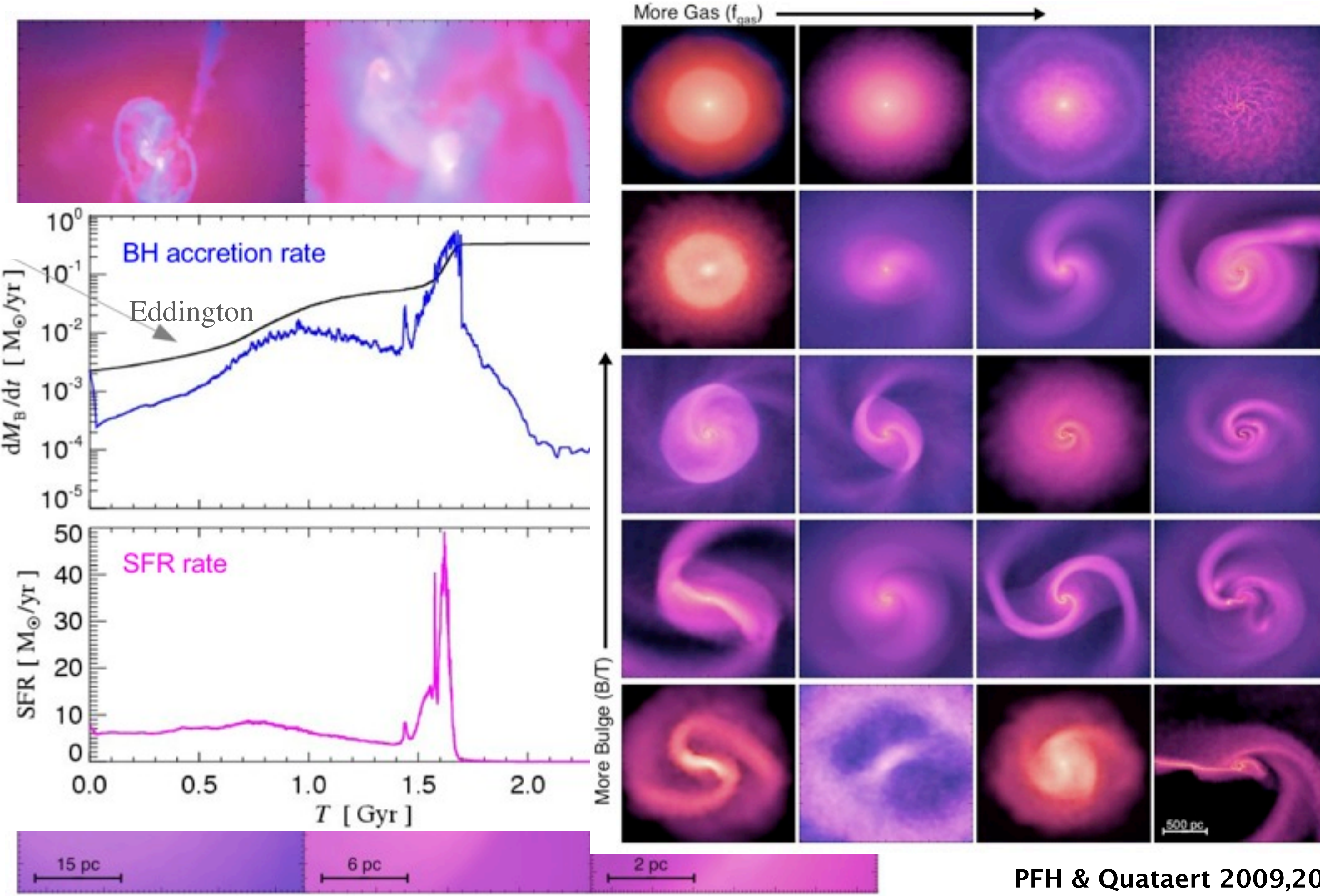


PFH & Quataert 2009,201

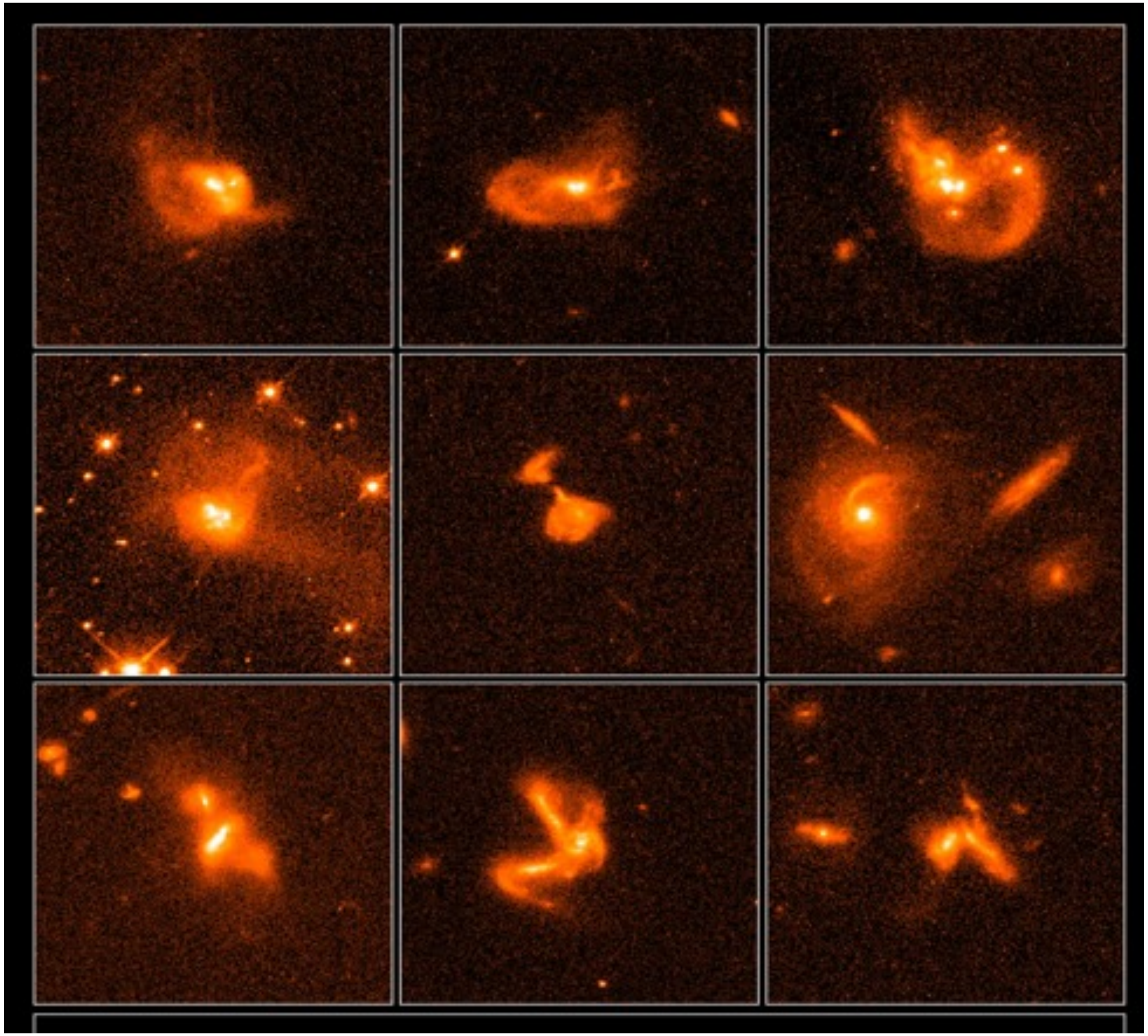
Sanders et al.,
& many others since
(many talks here):

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

Essentially all late-stage
merger remnants

Compact (~kpc scales)

Borne et al., 2000

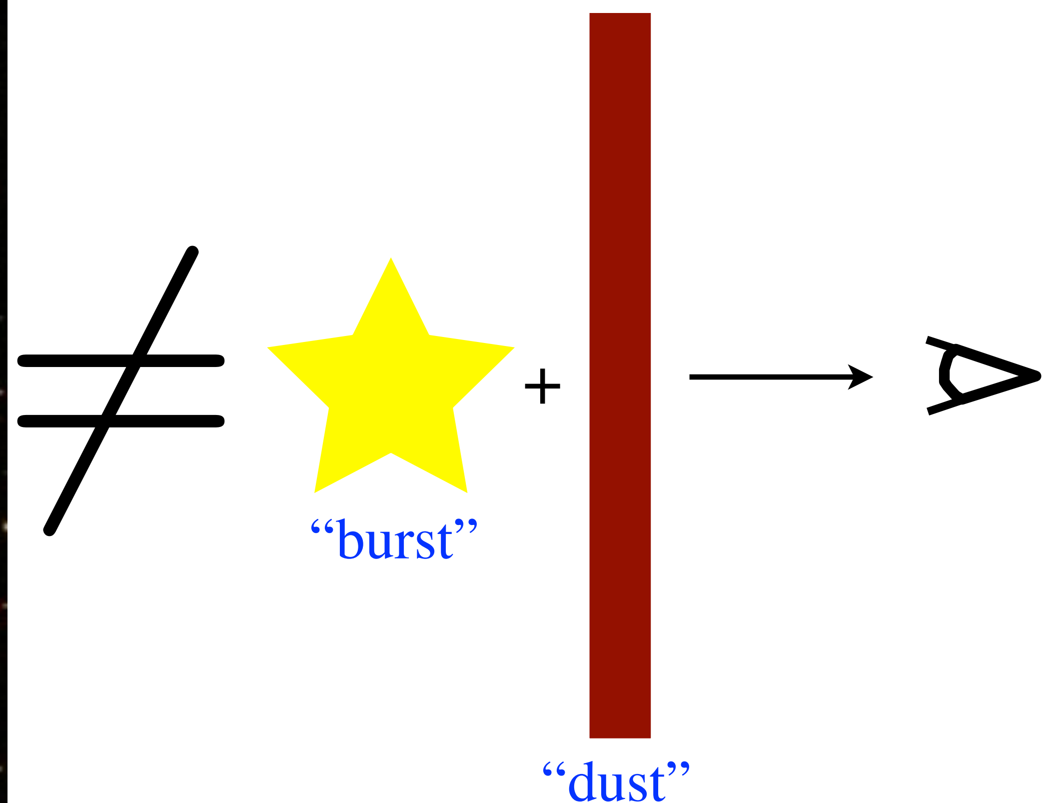


Are they the progenitors of ellipticals?

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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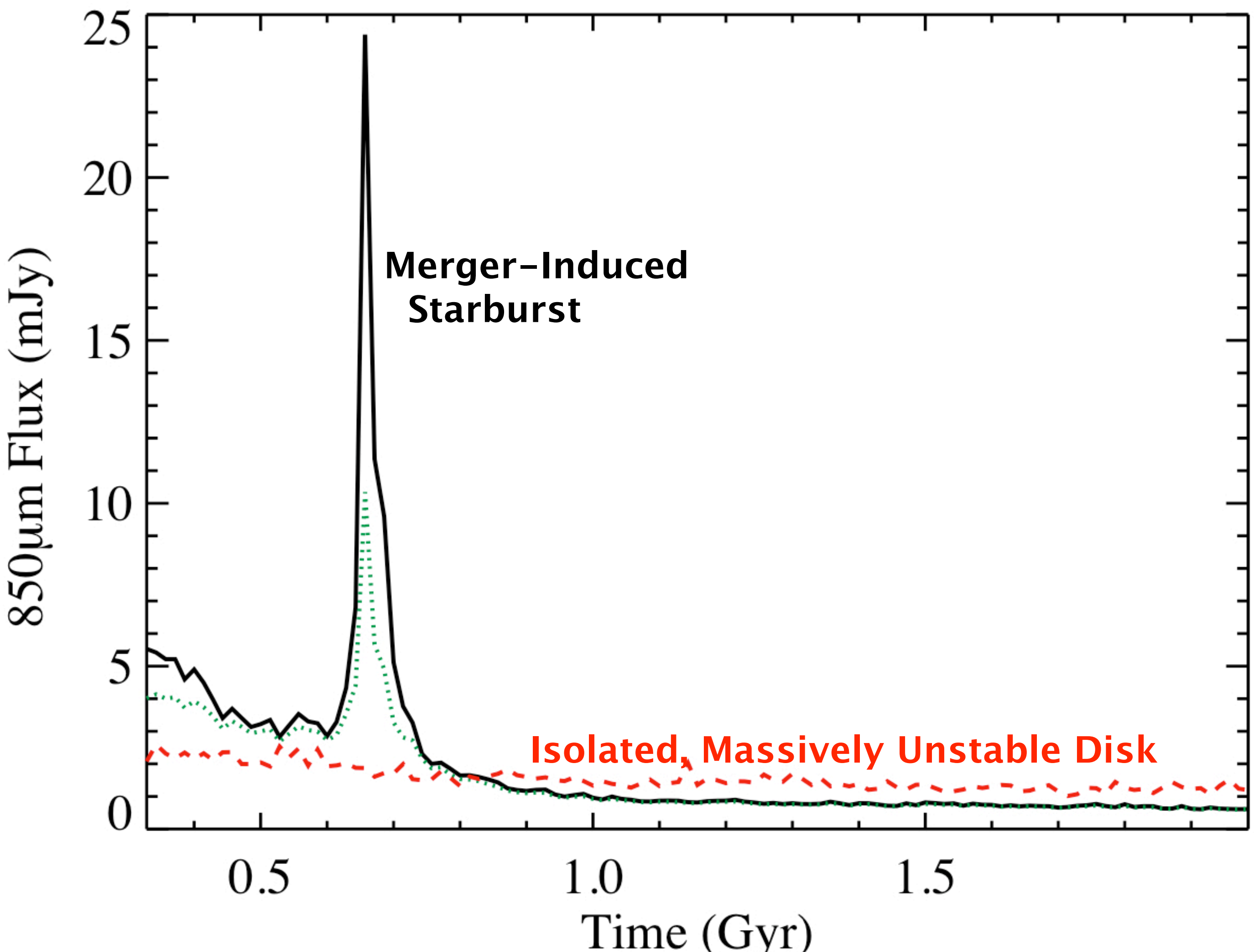

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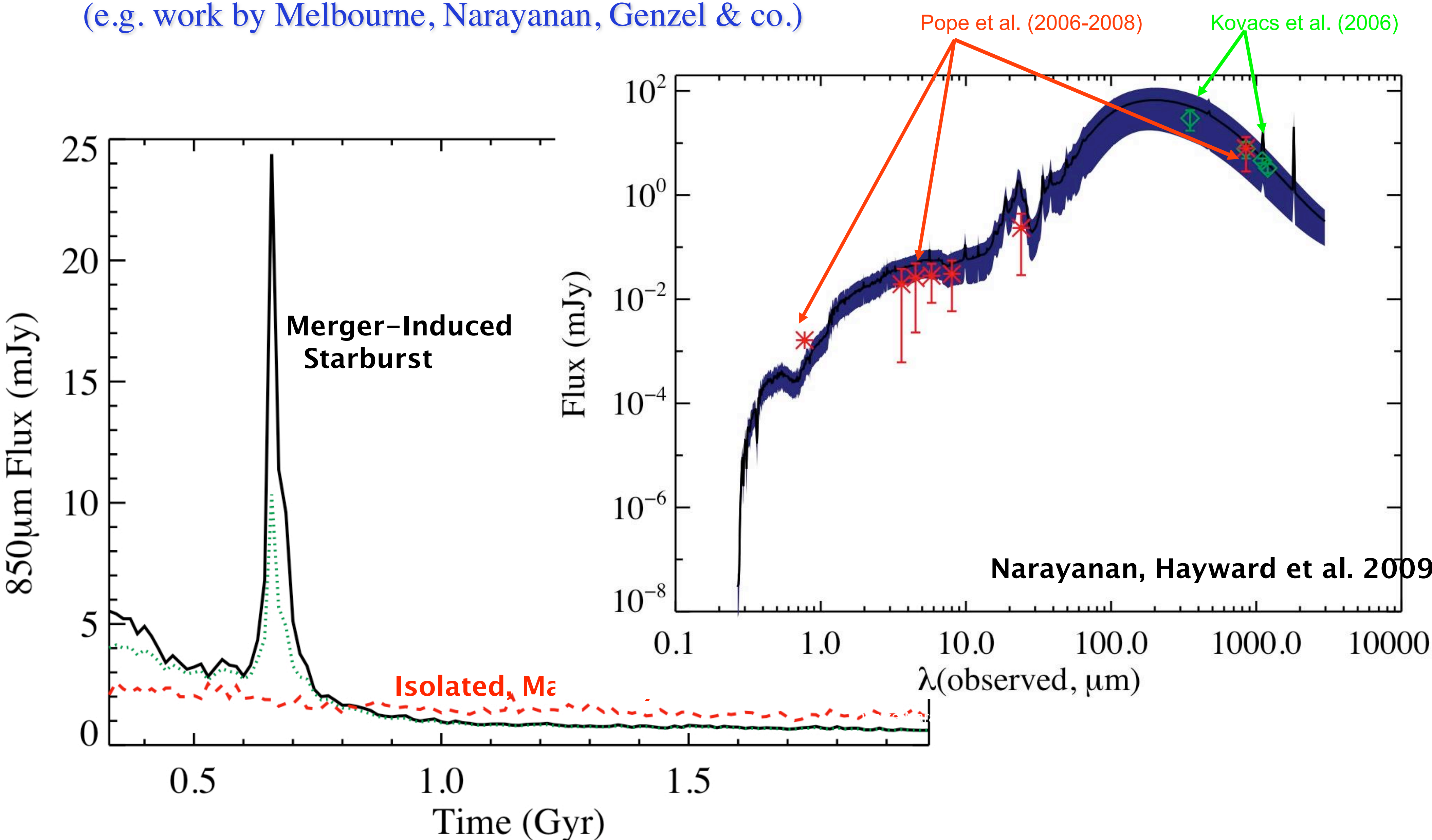
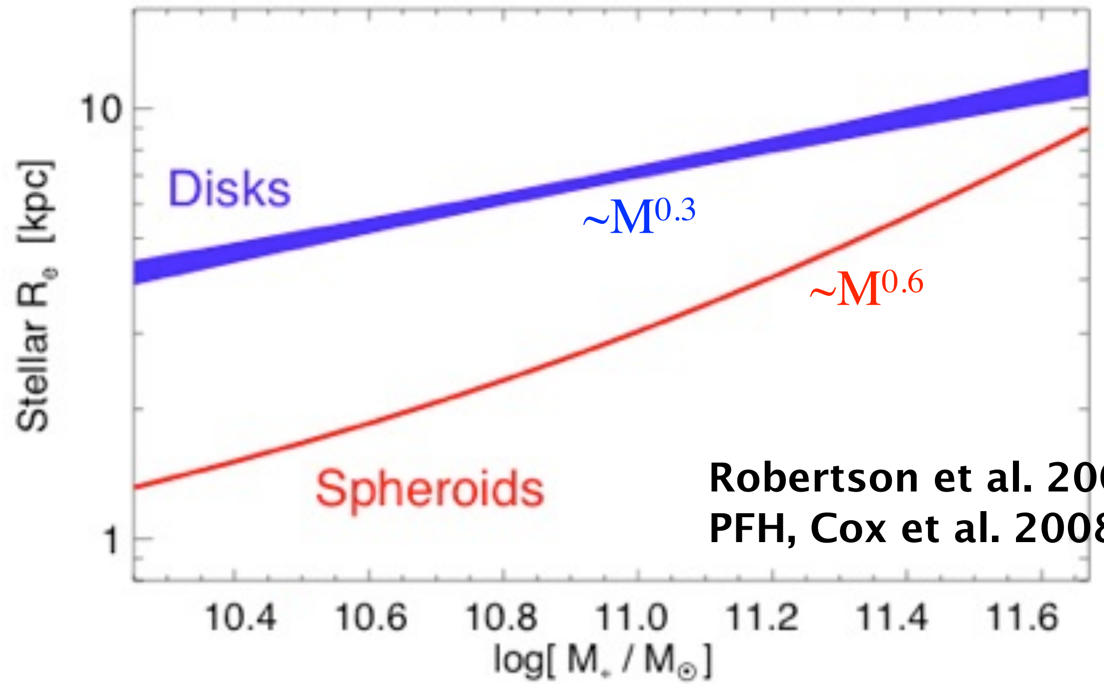
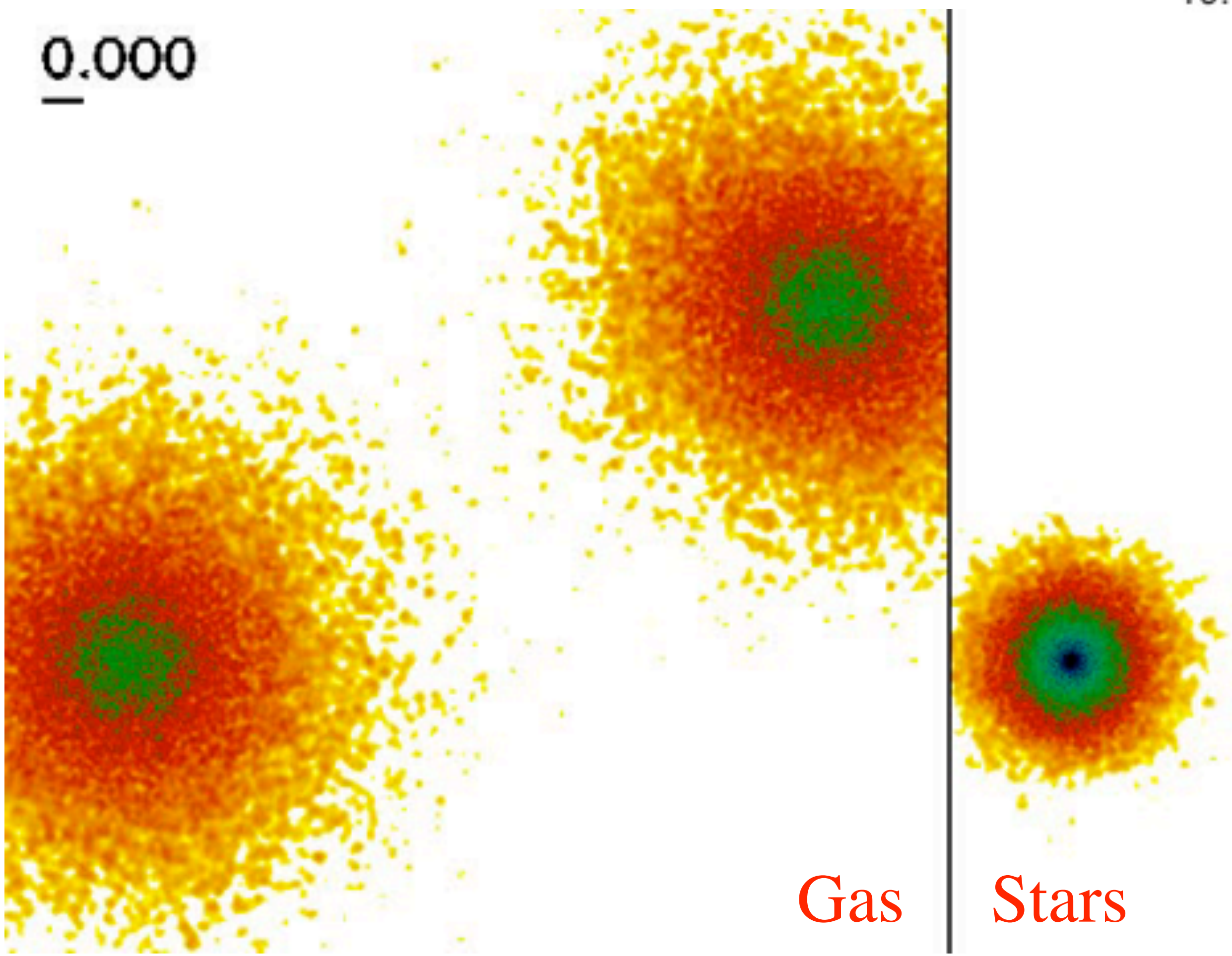


How does this relate to bulge formation?

The Problem: The Fundamental Plane & Bulge Densities:

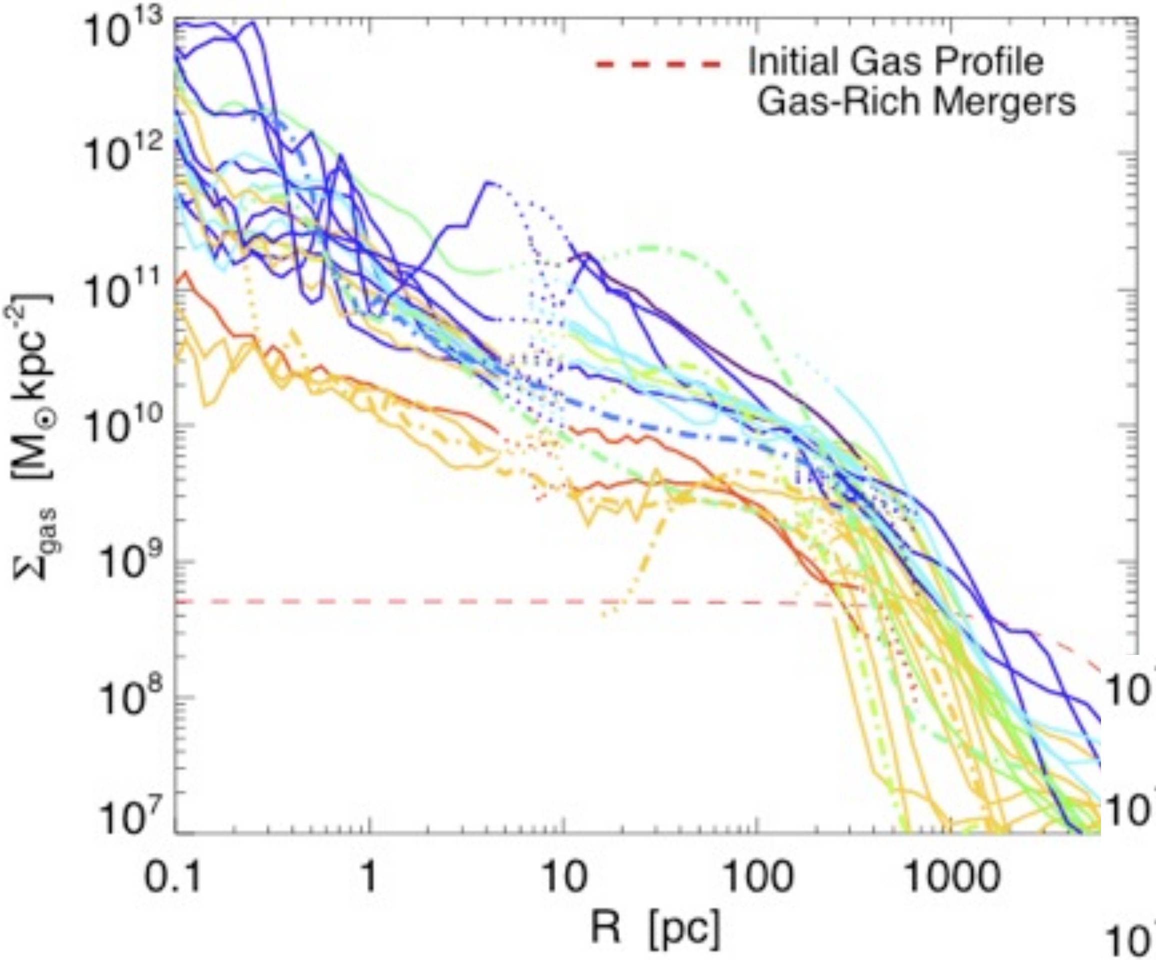
- Why are ellipticals smaller than disks? (Ostriker, Gunn, et al.)



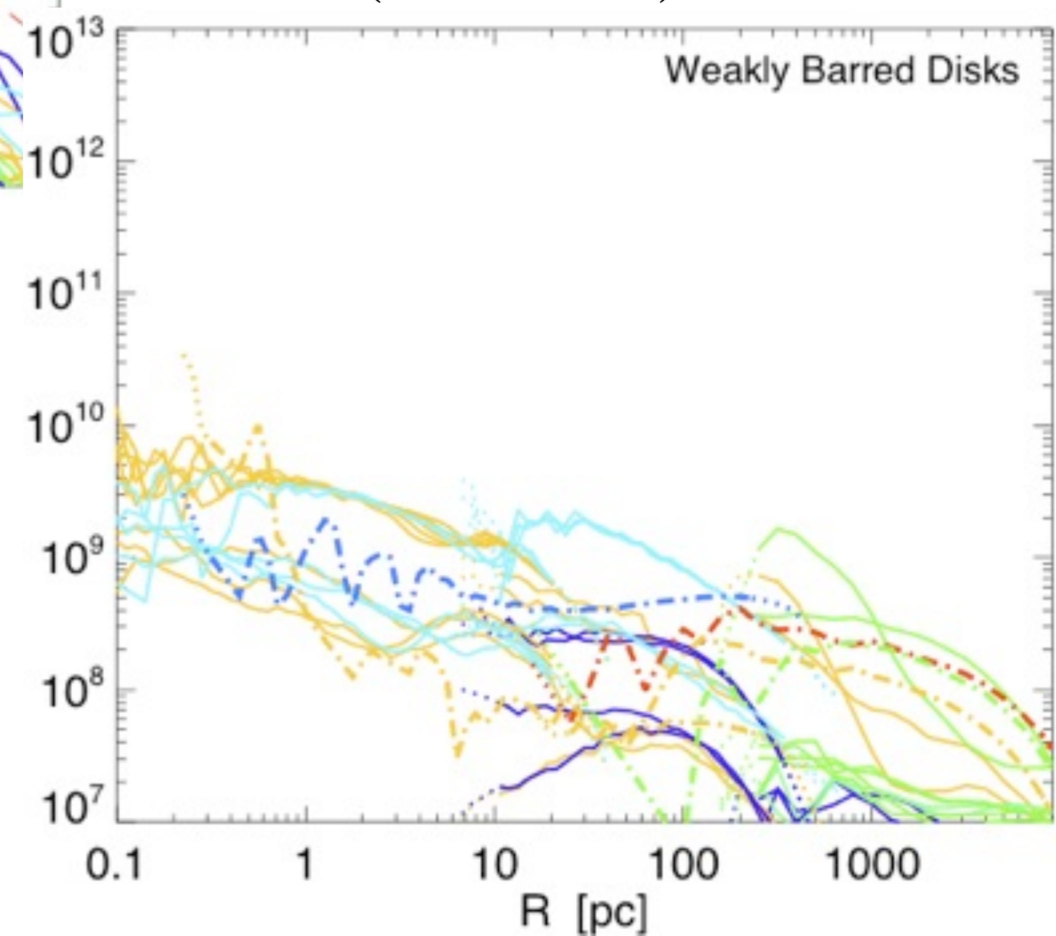


- Gas Dissipation

Gas-rich merger
(lots of inflow)



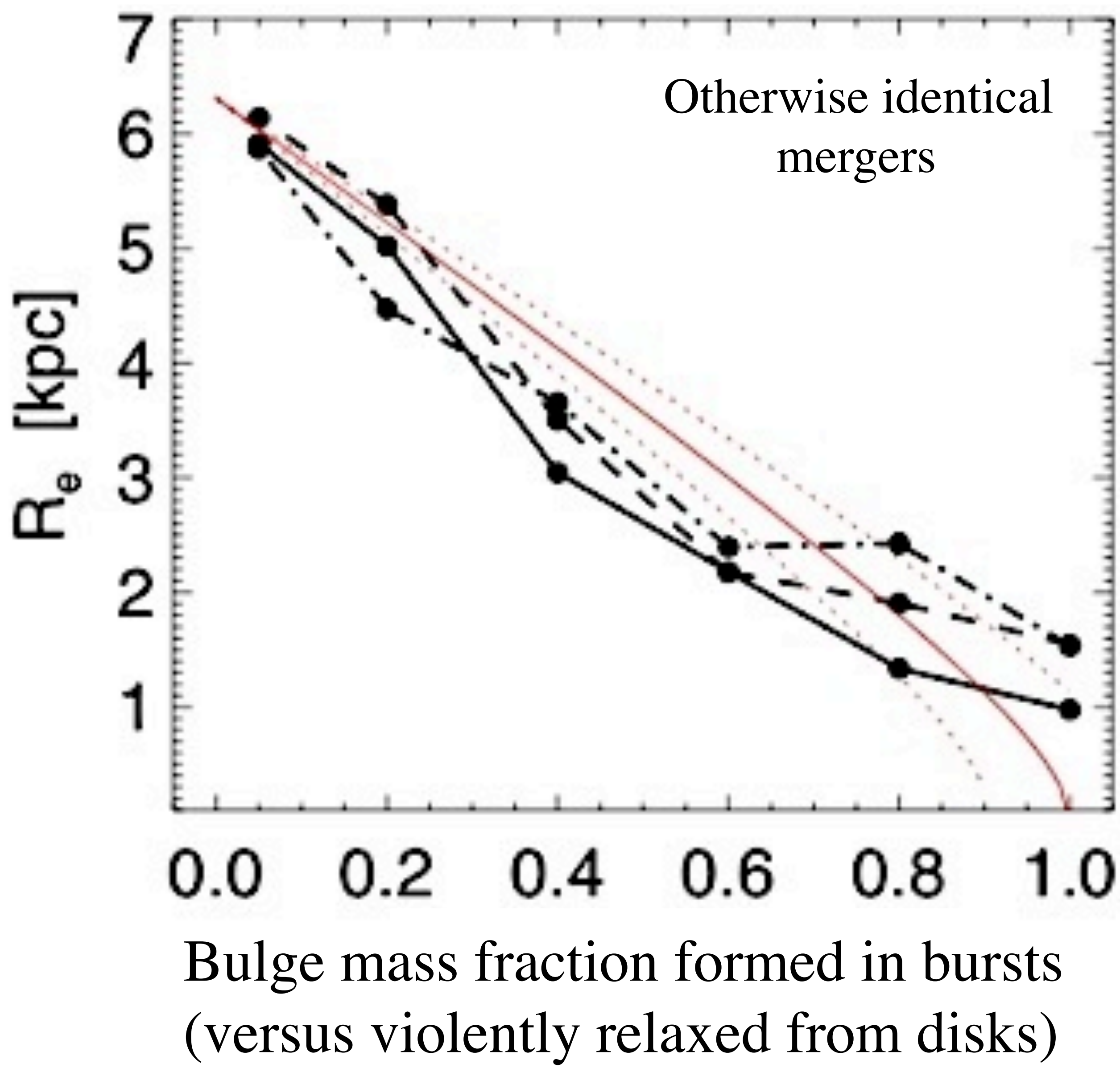
Weakly bar-unstable disk
(less inflow)



- Order-of-magnitude effect on central galaxy densities

The Solution: Gas-Rich Mergers

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



PFH, Cox et al. 2008

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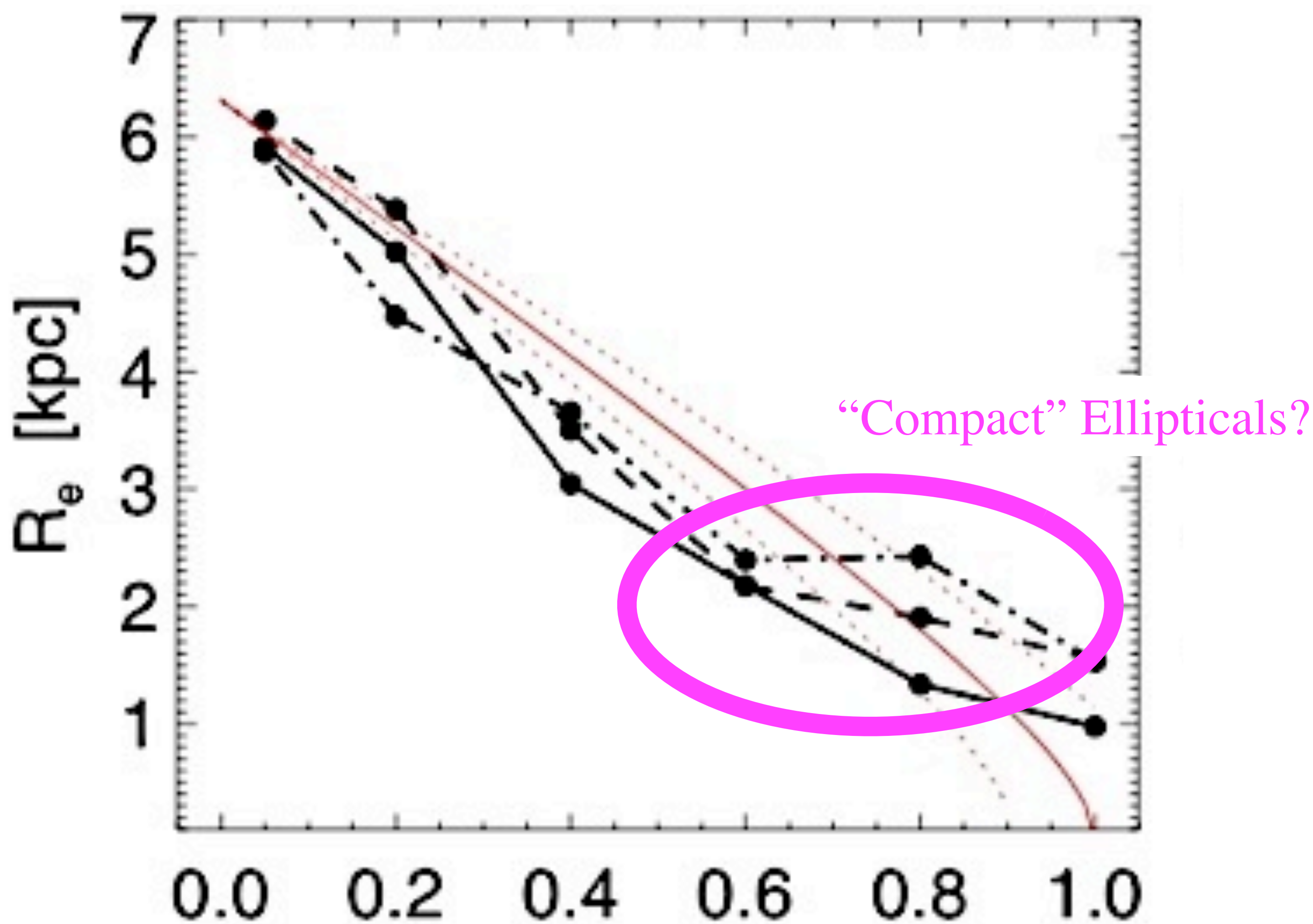
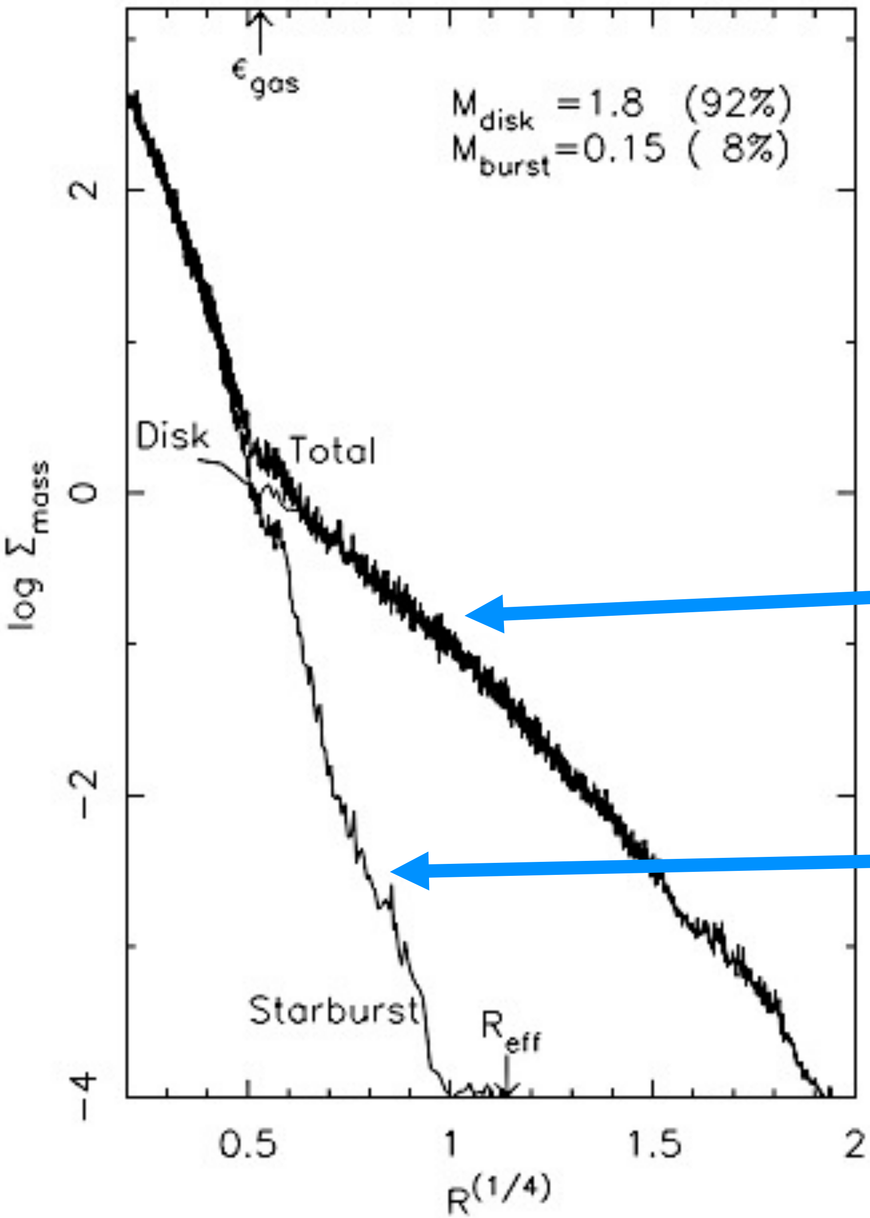


Bulge mass fraction formed in bursts (versus violently relaxed from disks)

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:

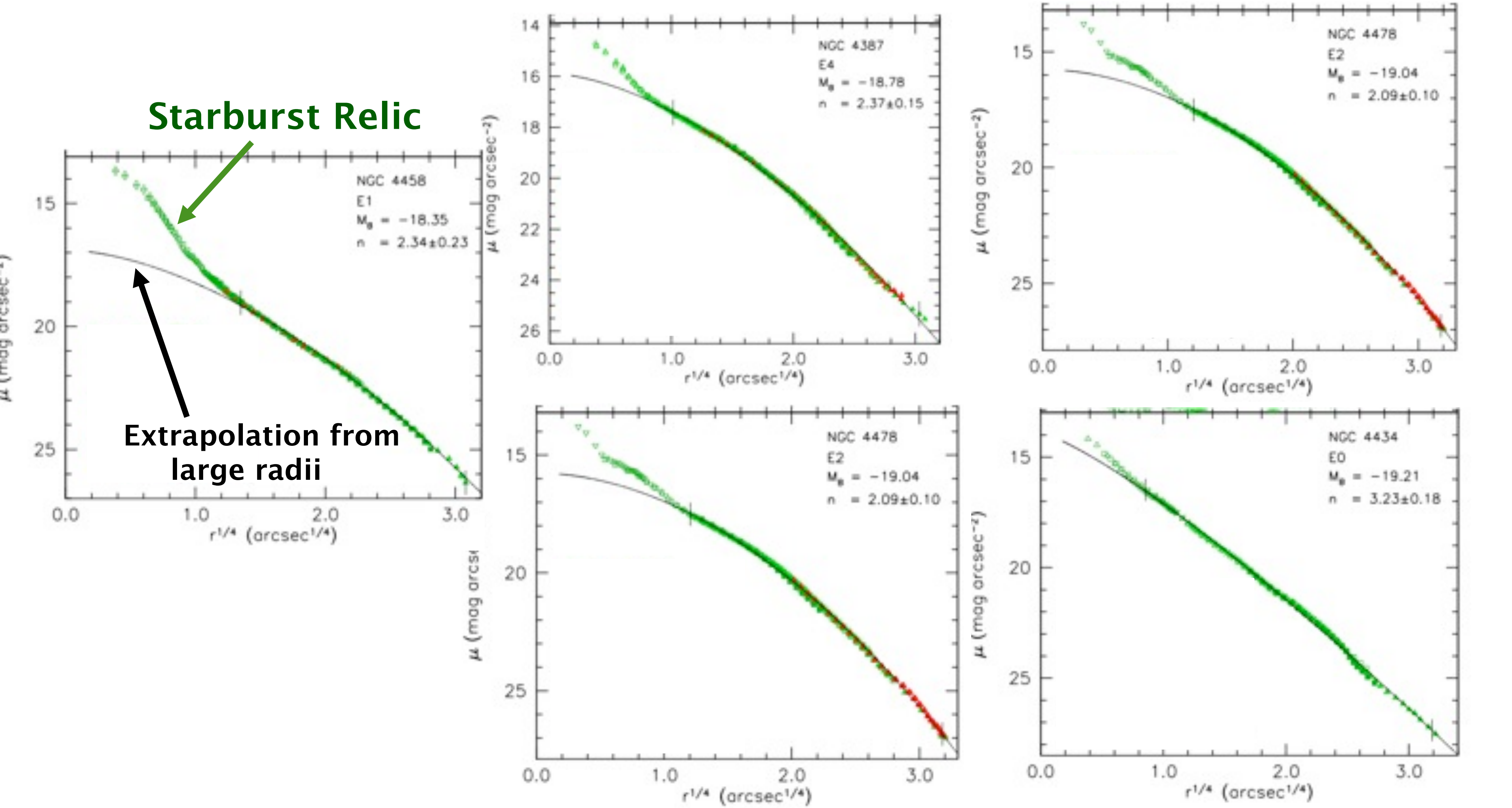
“Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?” (MH94)

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…

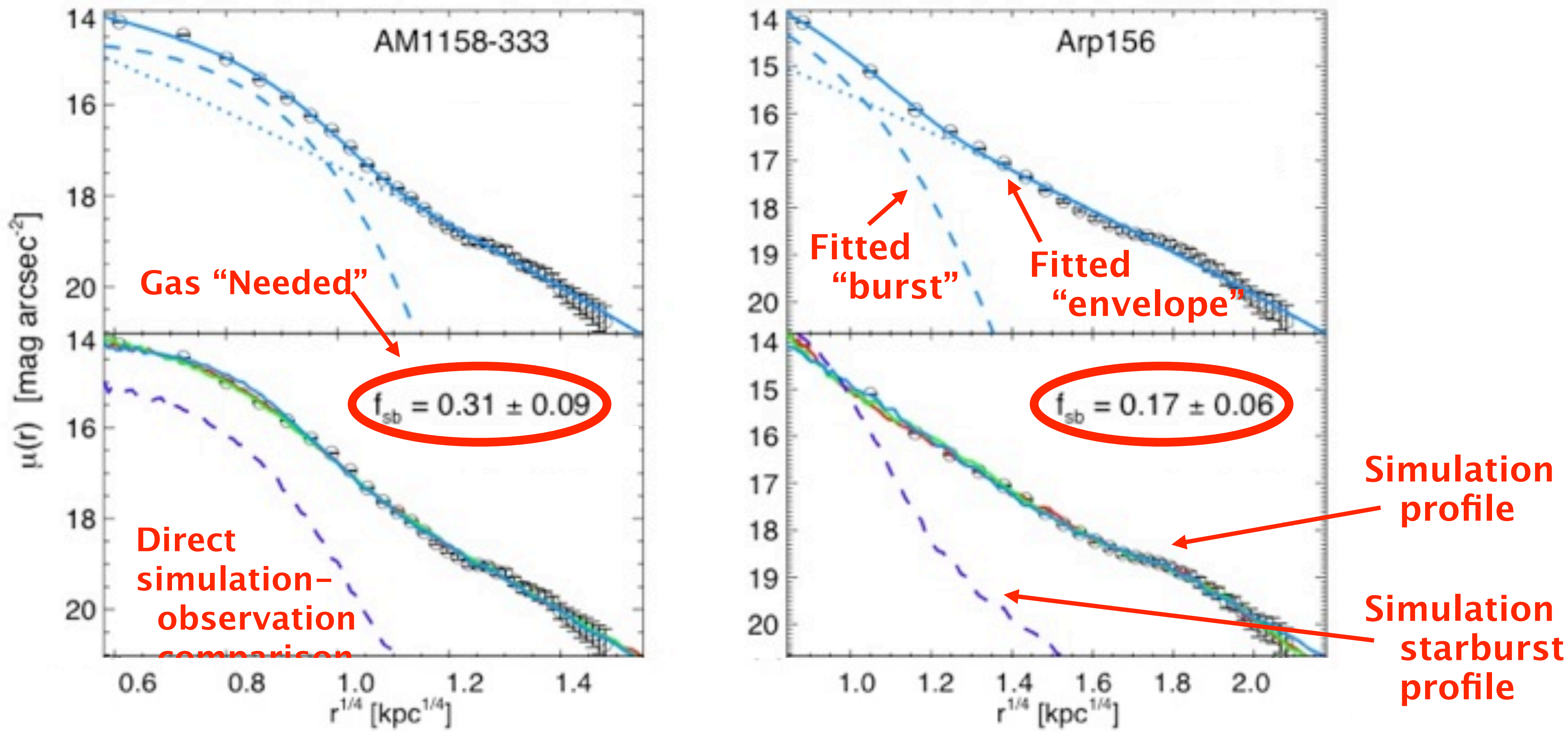


“Normal and low-luminosity ellipticals… in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles.”

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:



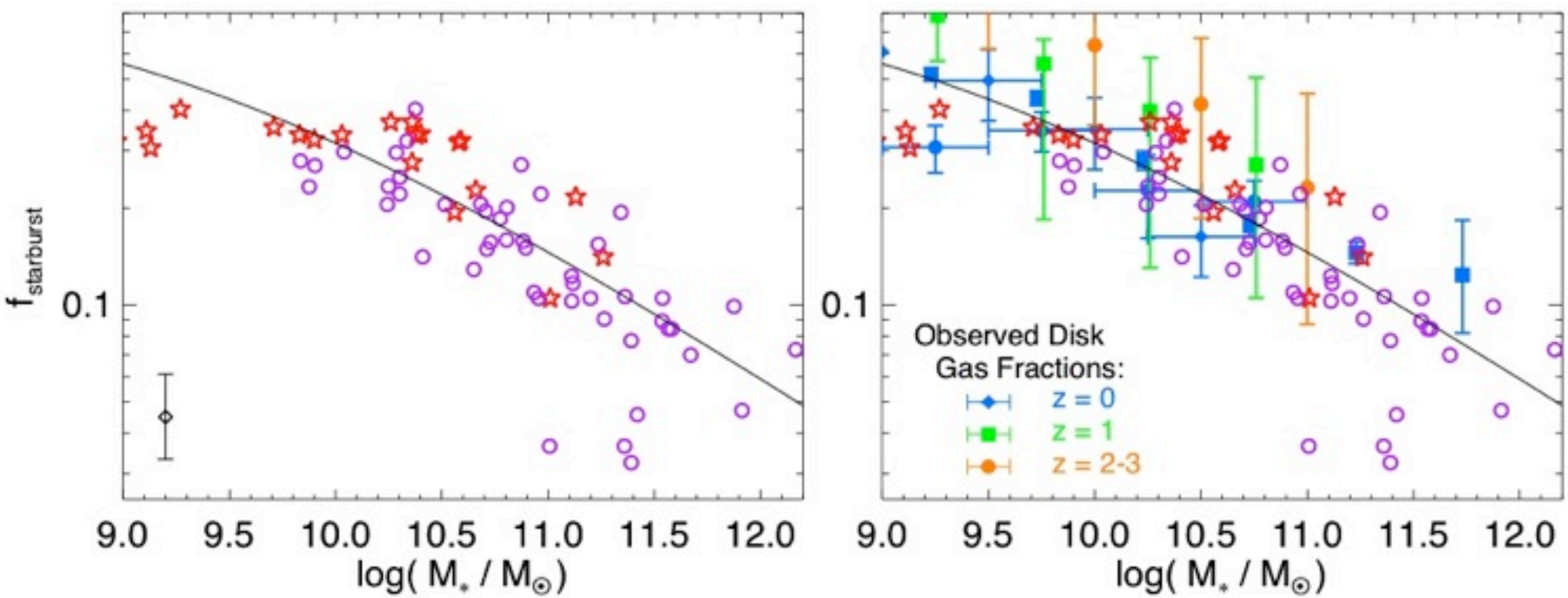
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

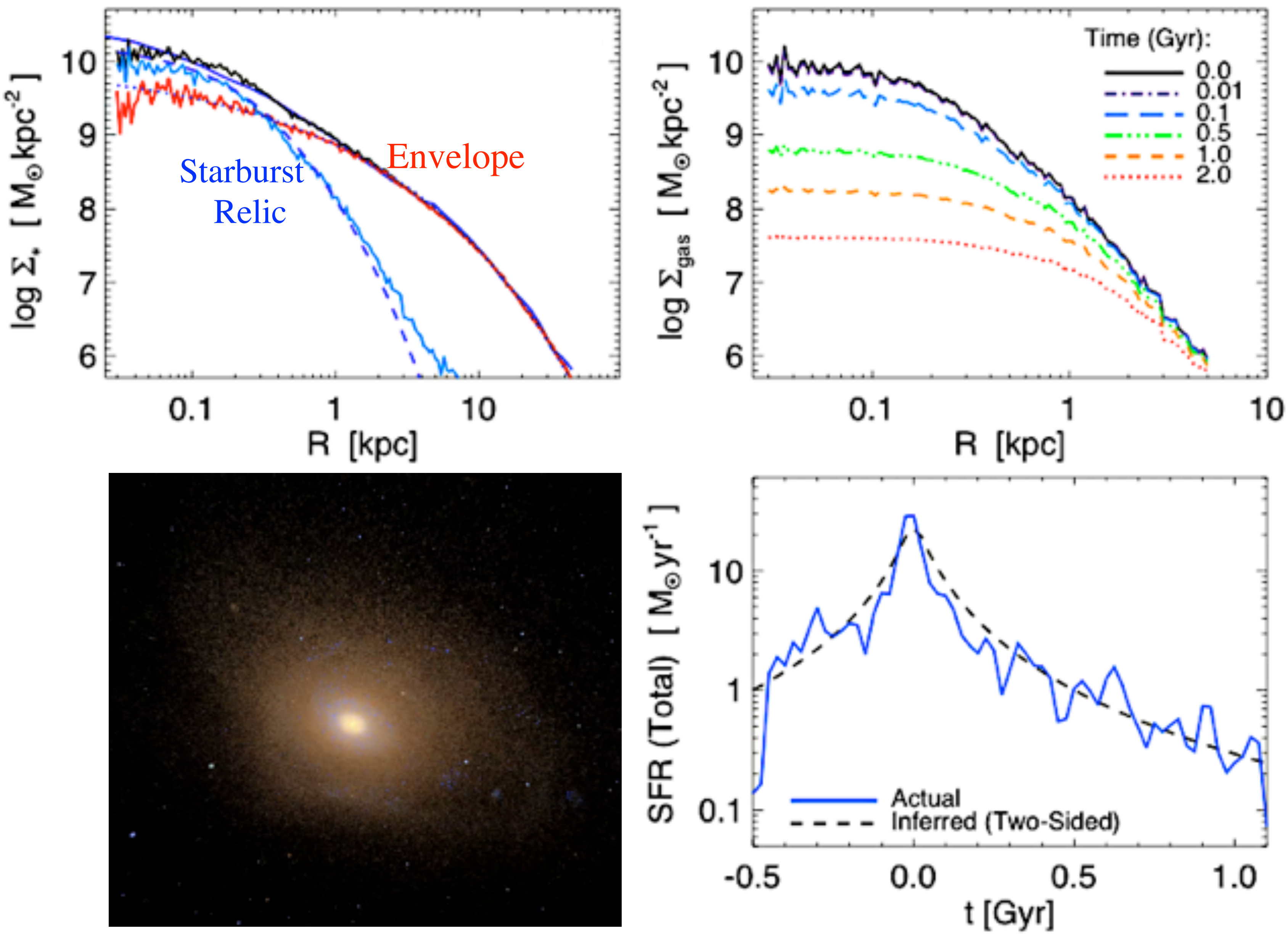
PFH, Kormendy, & Lauer et al. 2008

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



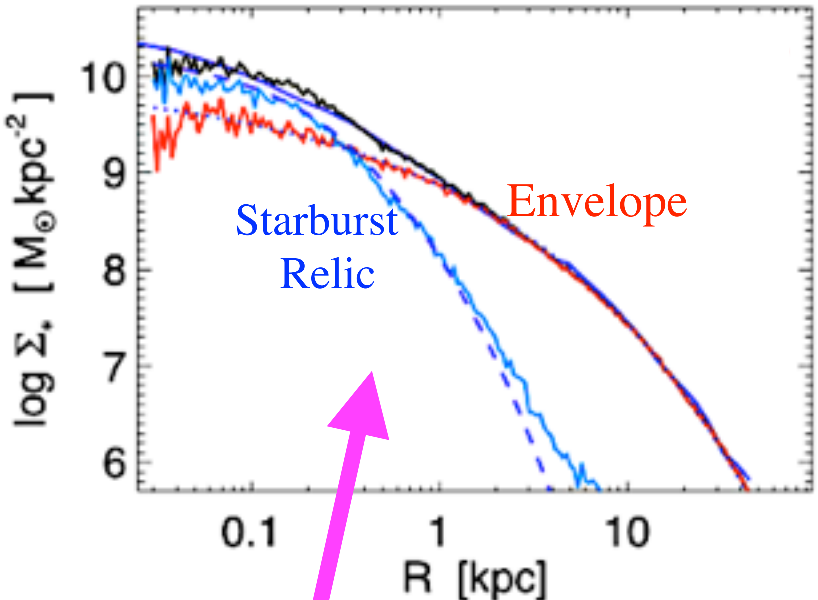
- You can and do get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns (Foster+, Forbes+, Lauer+, Hoffman+)

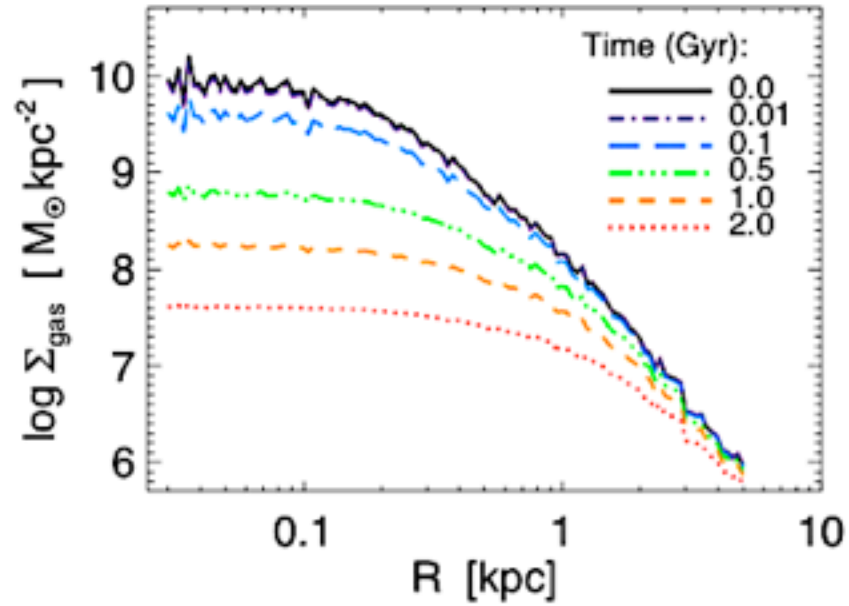
What else can we learn from the ‘relics’ of gas dissipation?

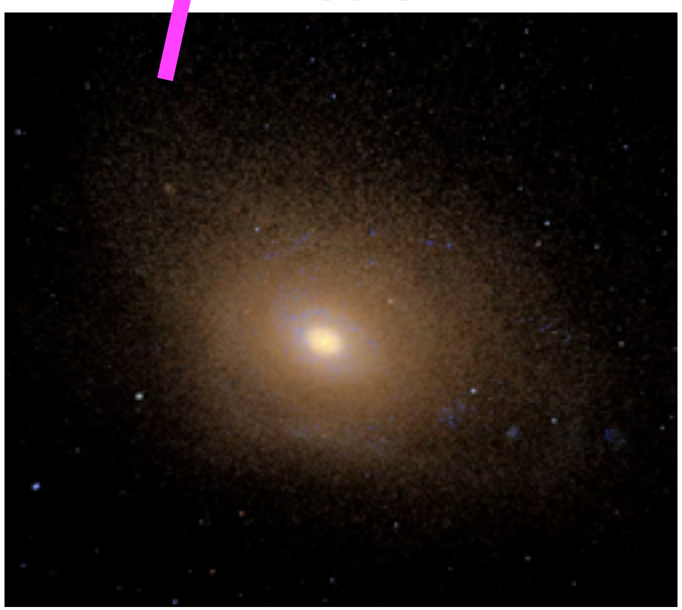


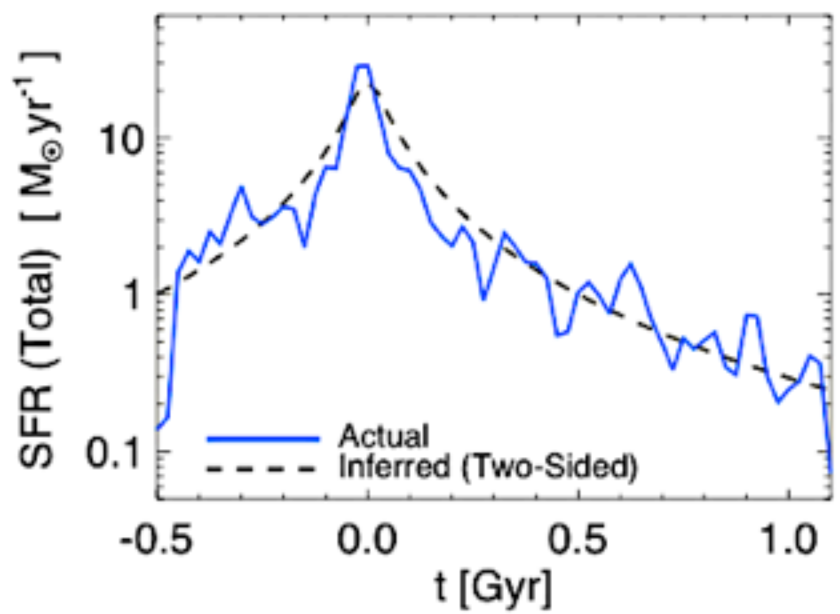
What else can we learn from the 'relics' of gas dissipation?

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









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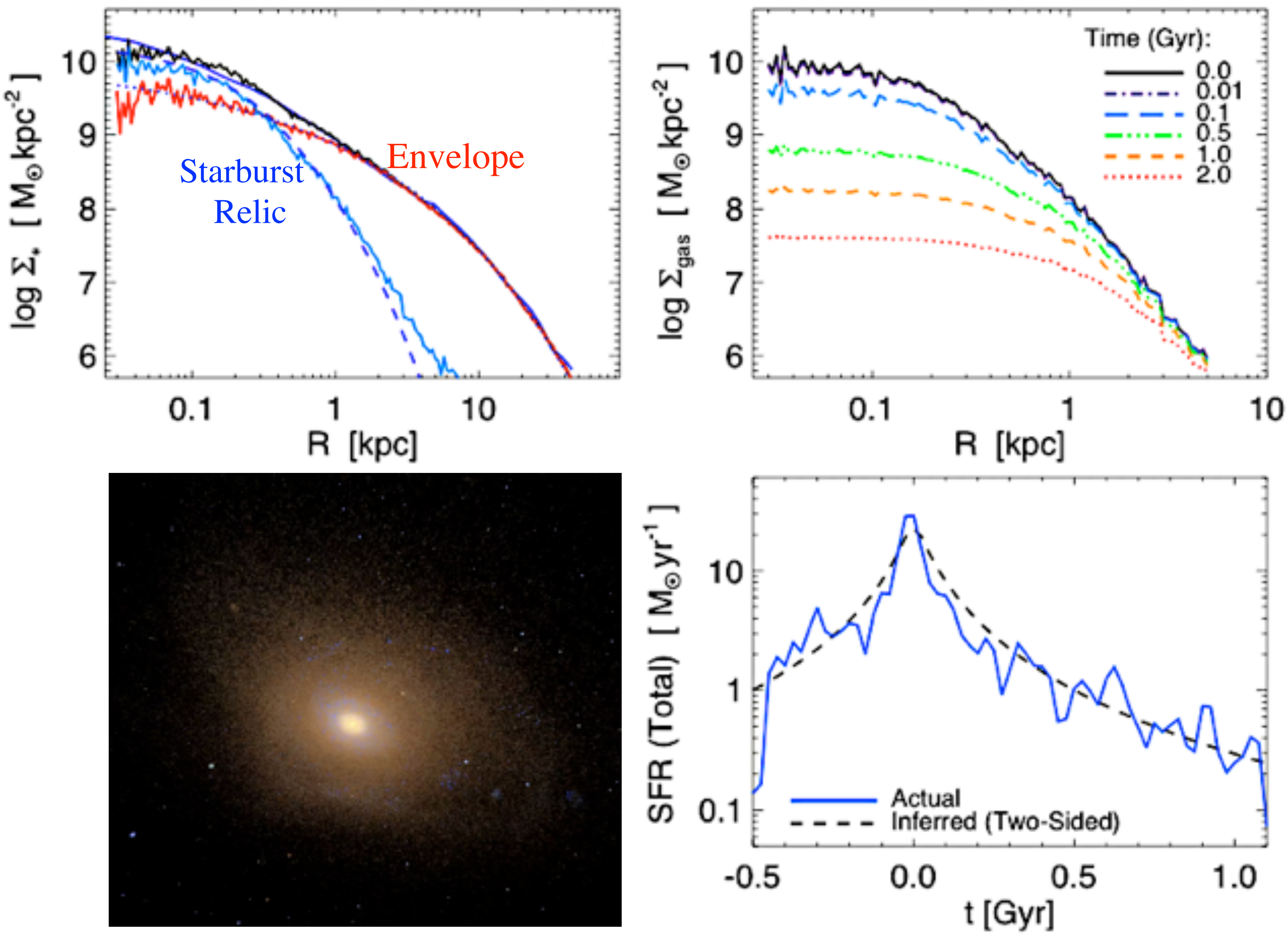
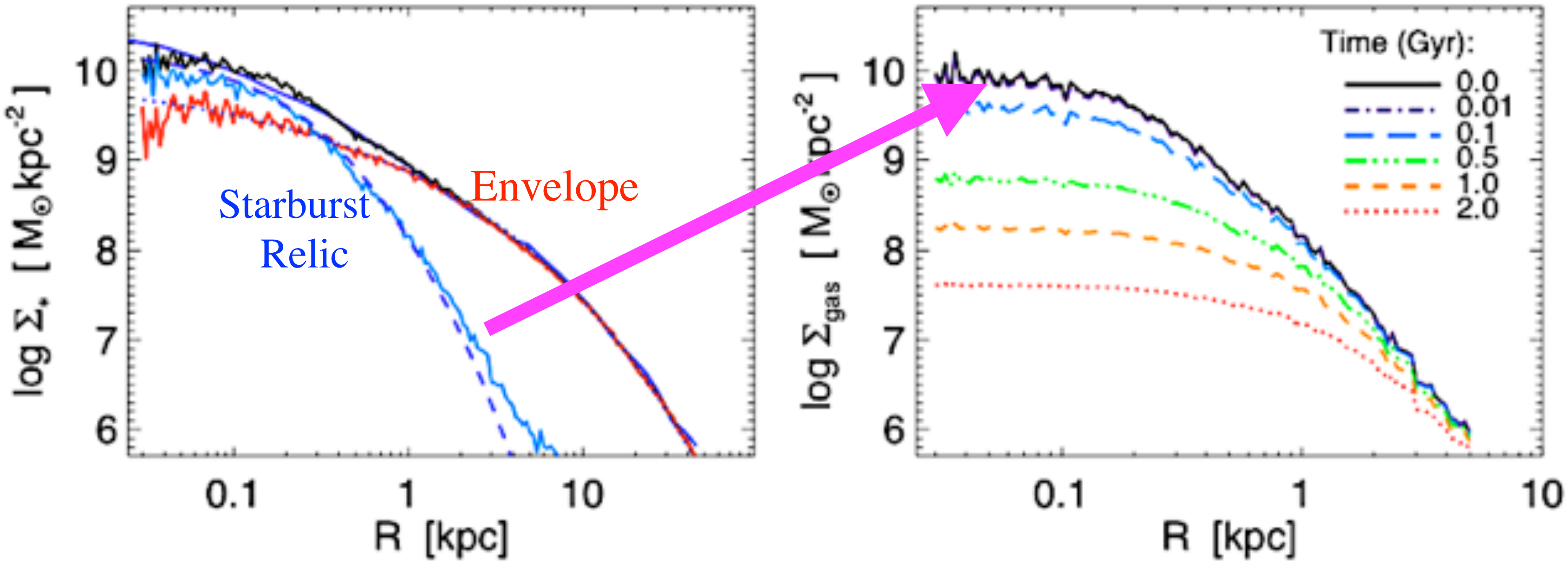
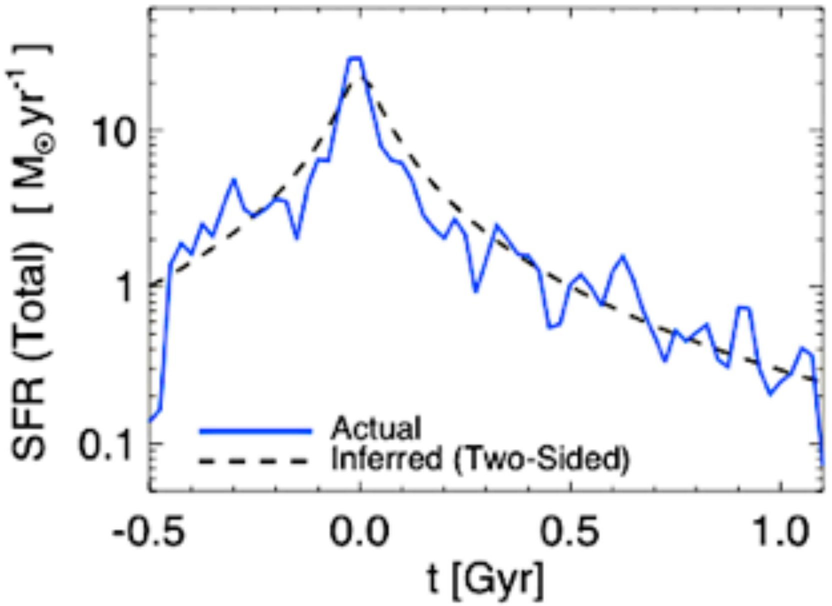


What else can we learn from the ‘relics’ of gas dissipation?

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

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





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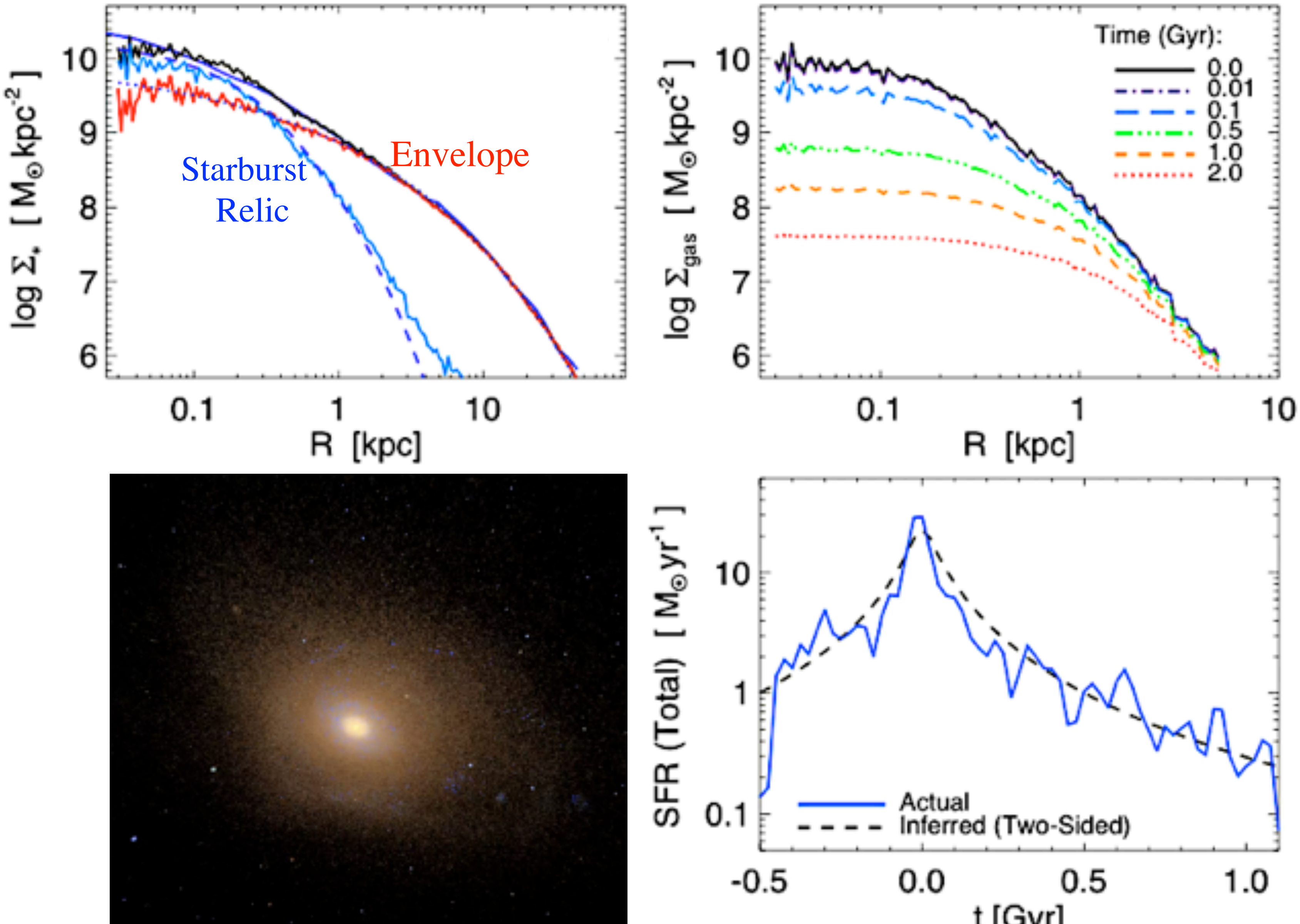
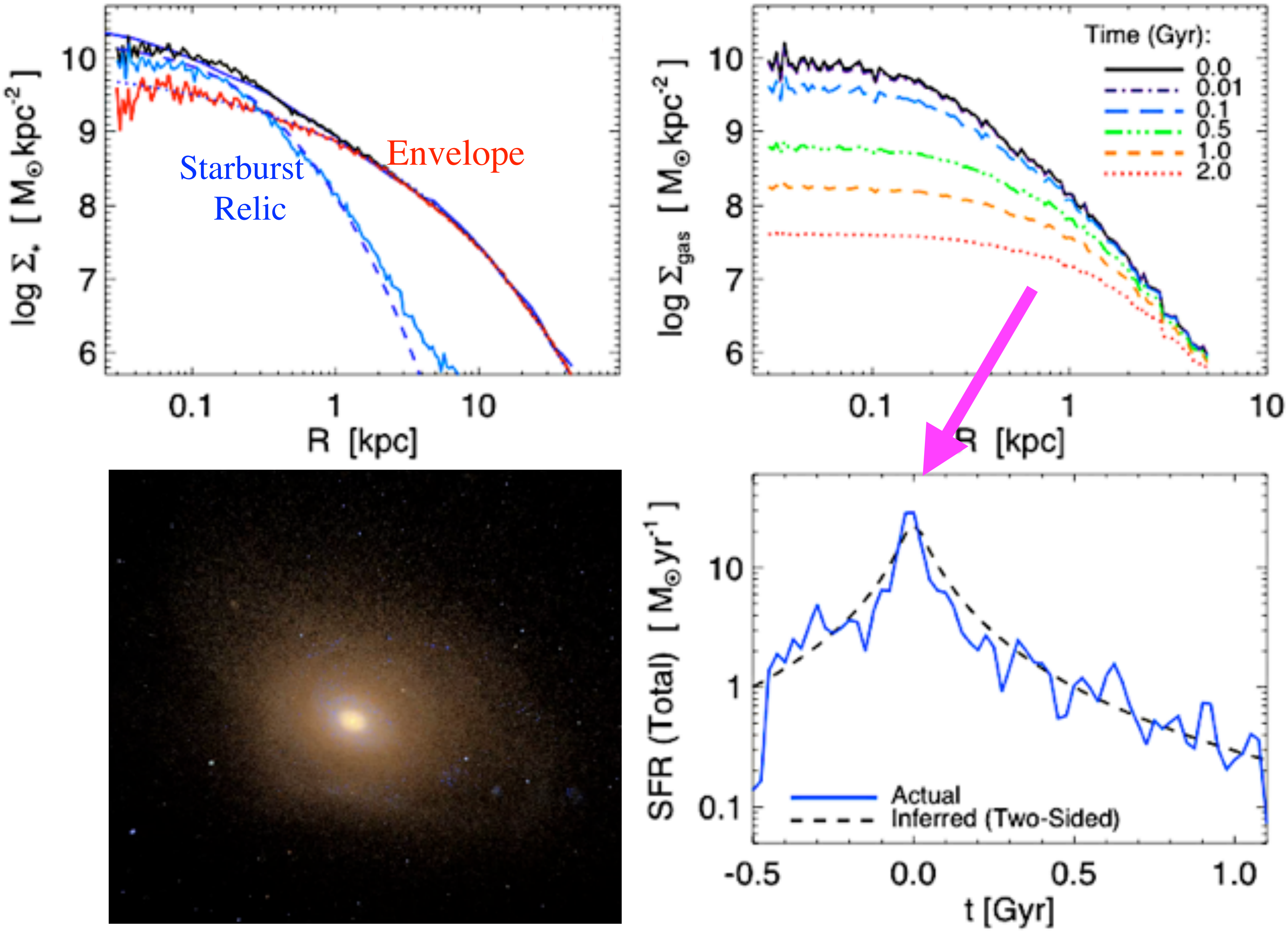


What else can we learn from the 'relics' of gas dissipation?

Assume Schmidt-Kennicutt law applies: Recover SFH

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



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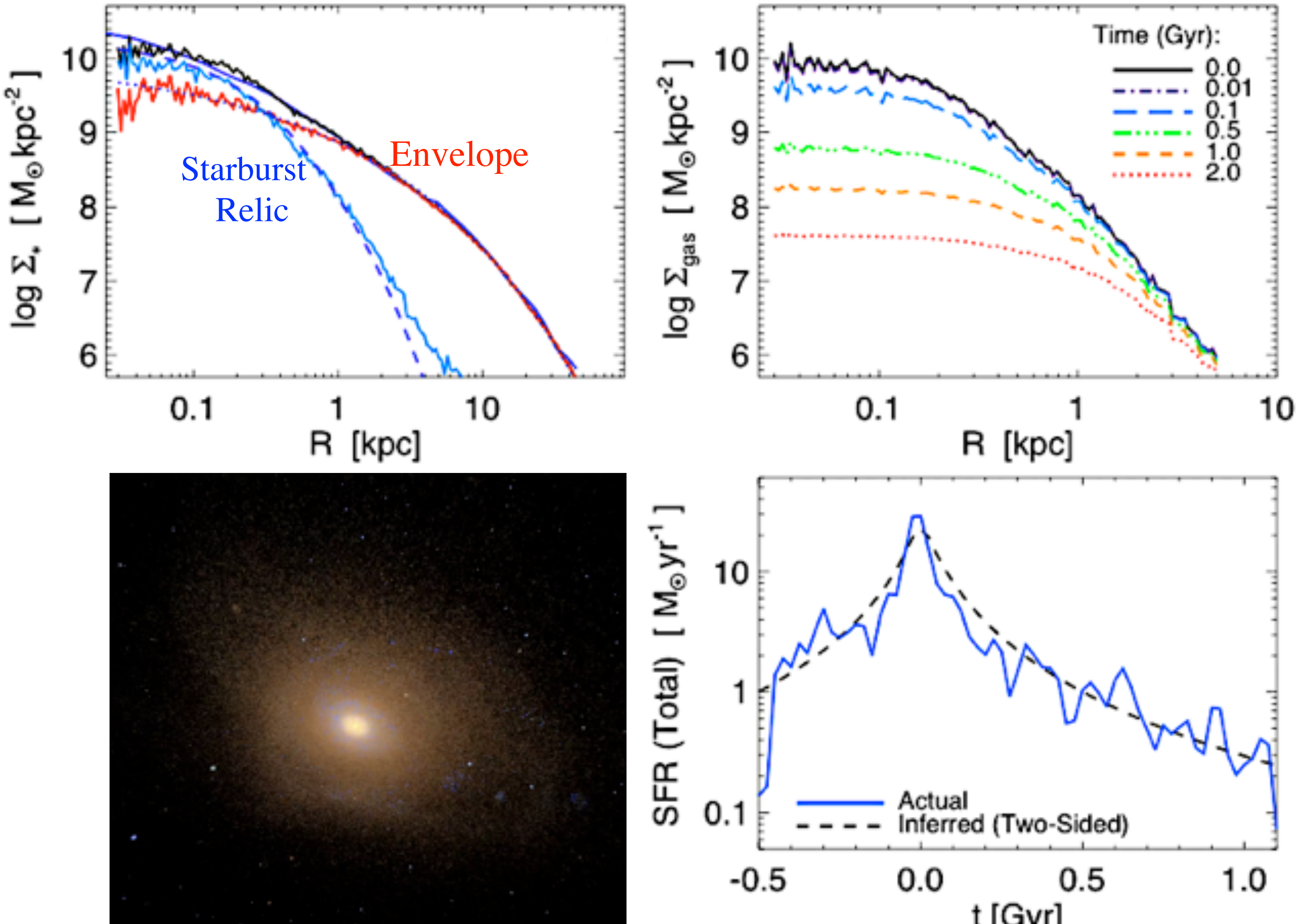

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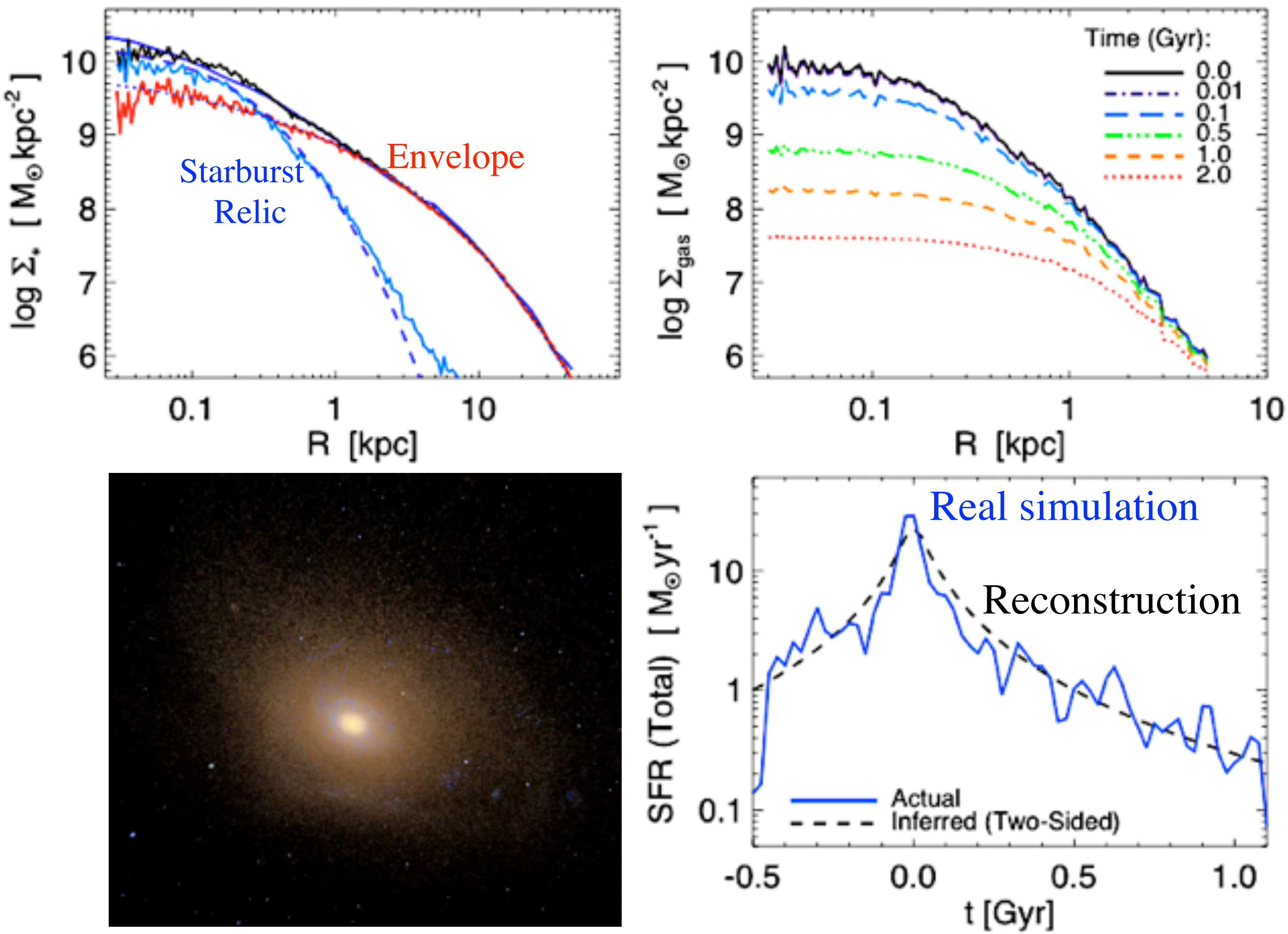

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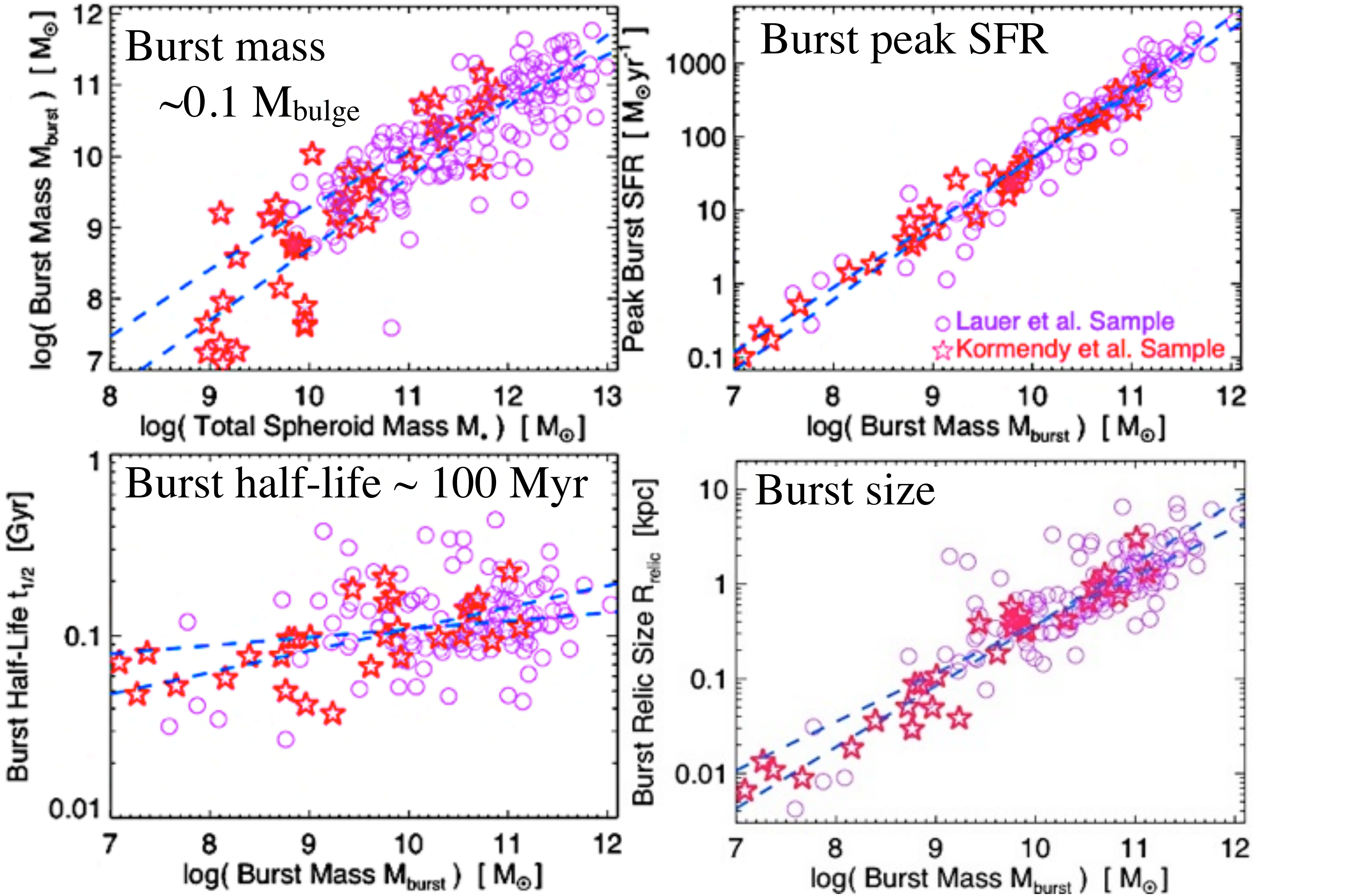

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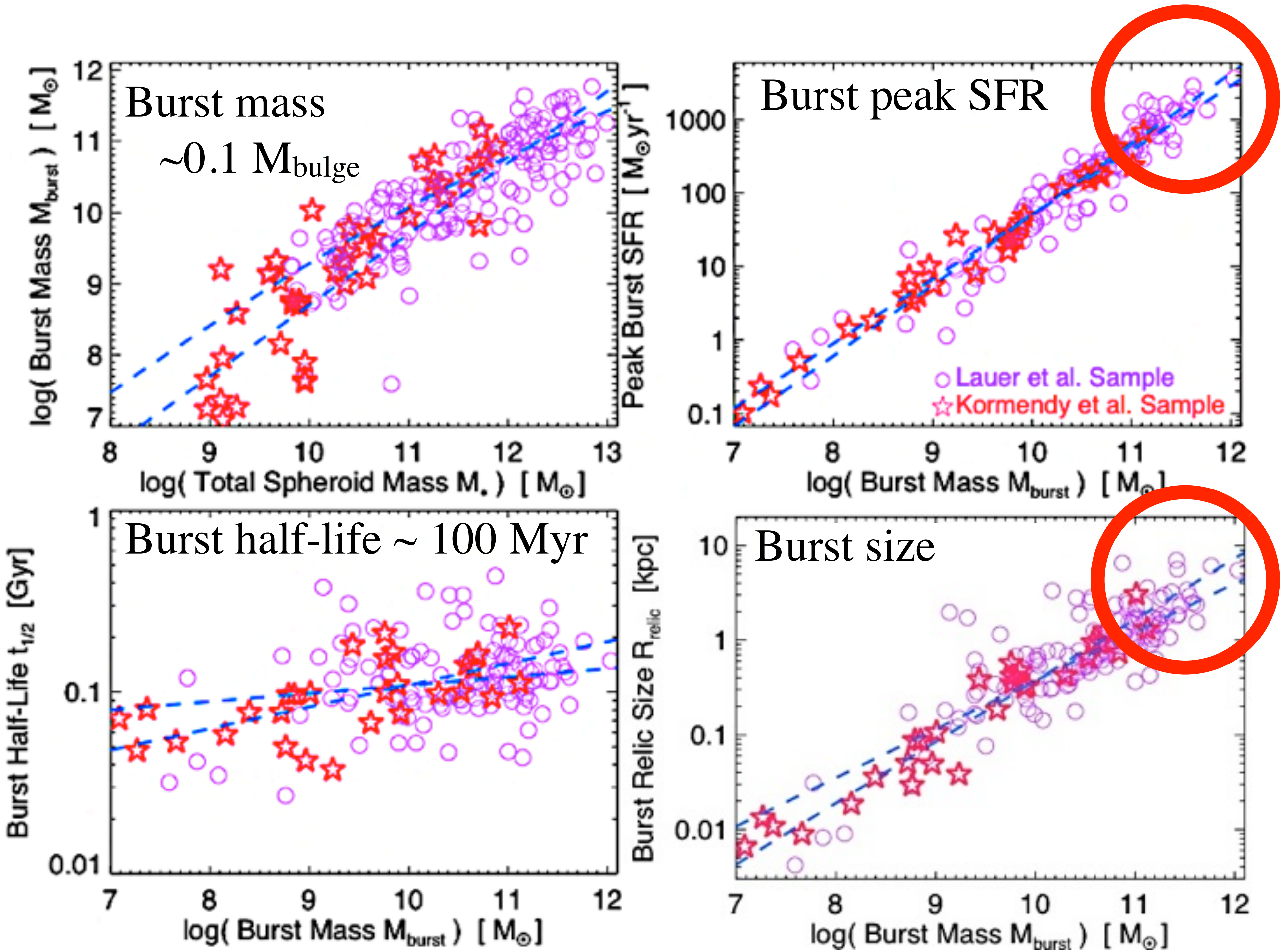
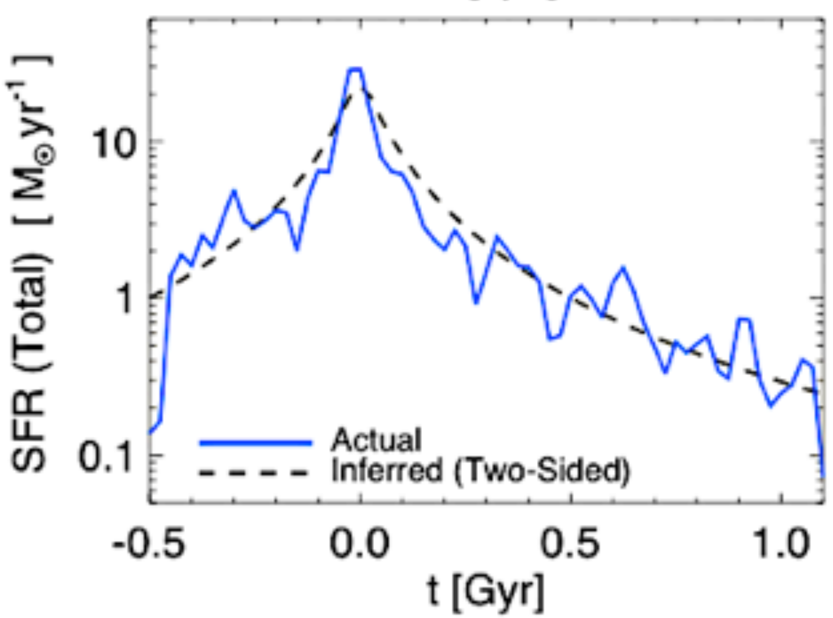
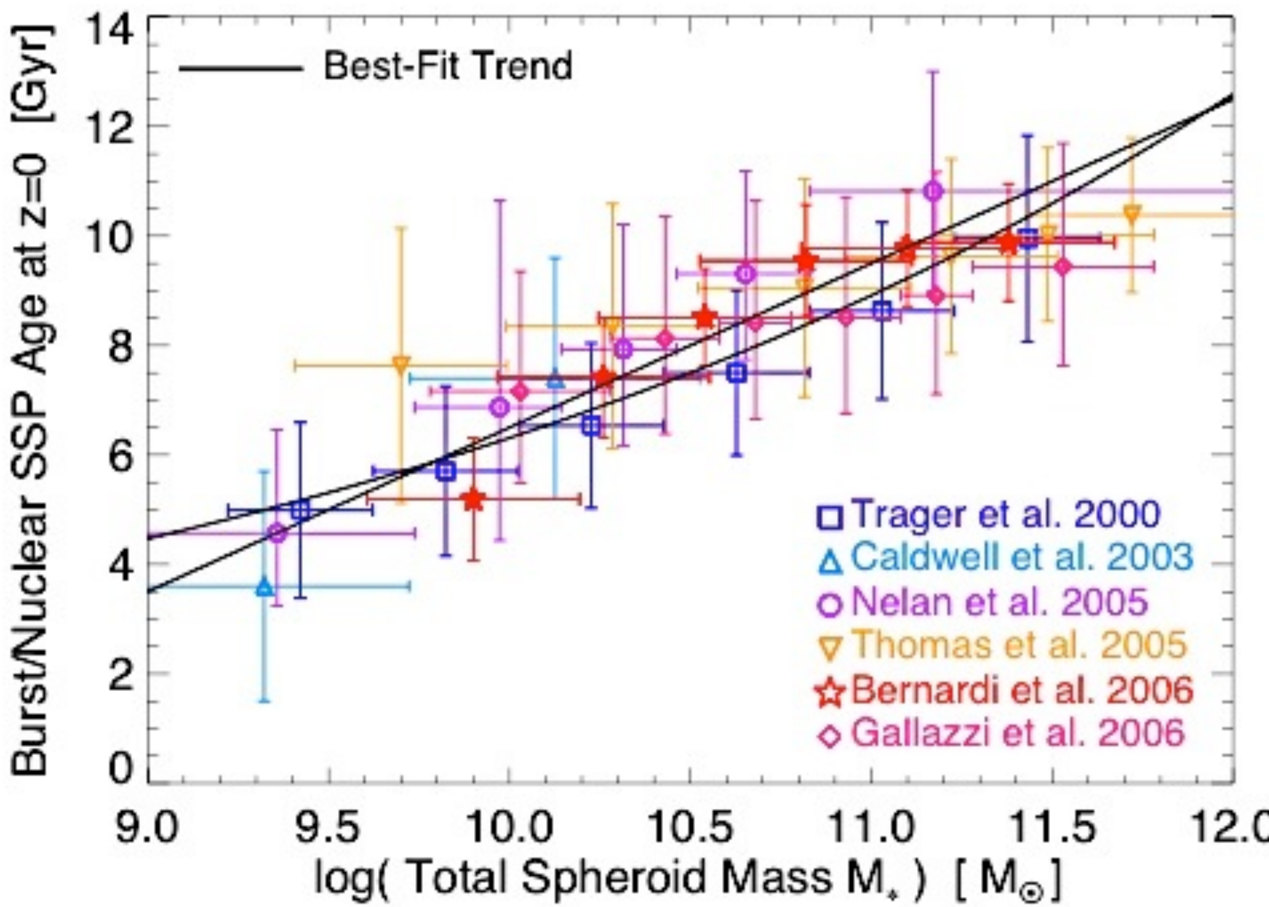


Re-construct SFR(t) for each burst :



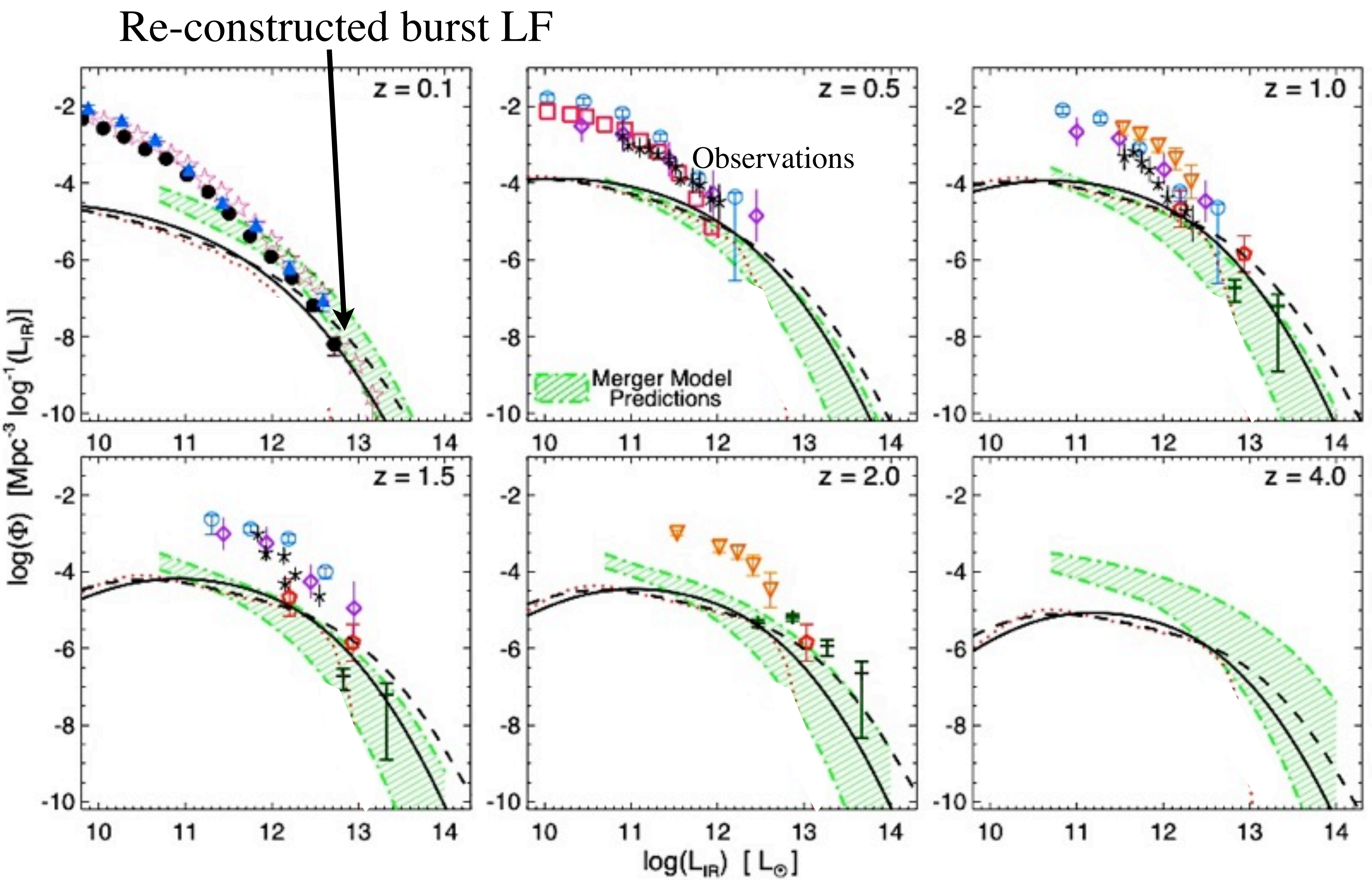
+ We know the nuclear SSP ages....



"place" each burst at the correct redshift

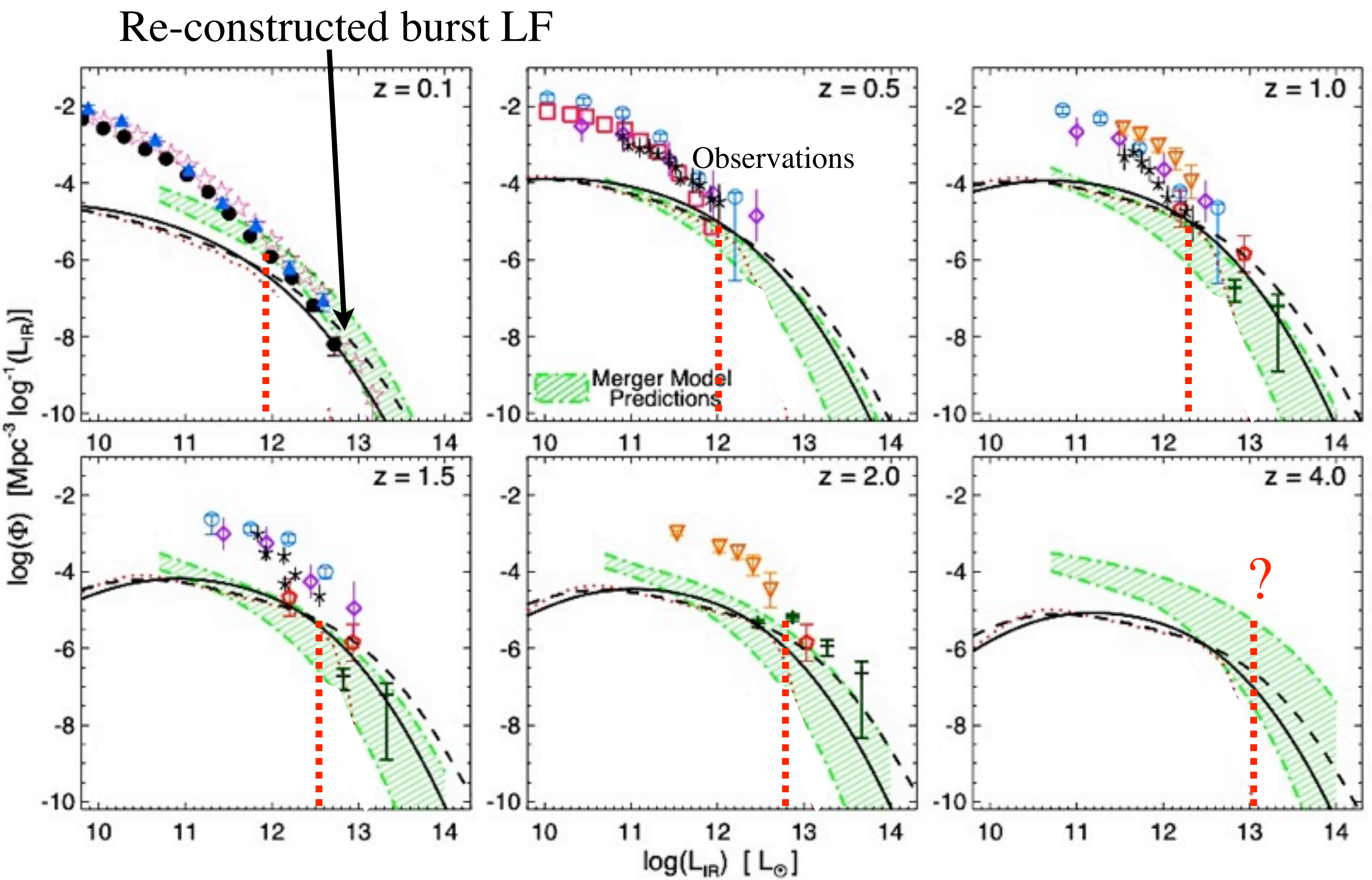
PFH & Hernquist 200

Recover the IR LF of dissipational starbursts!

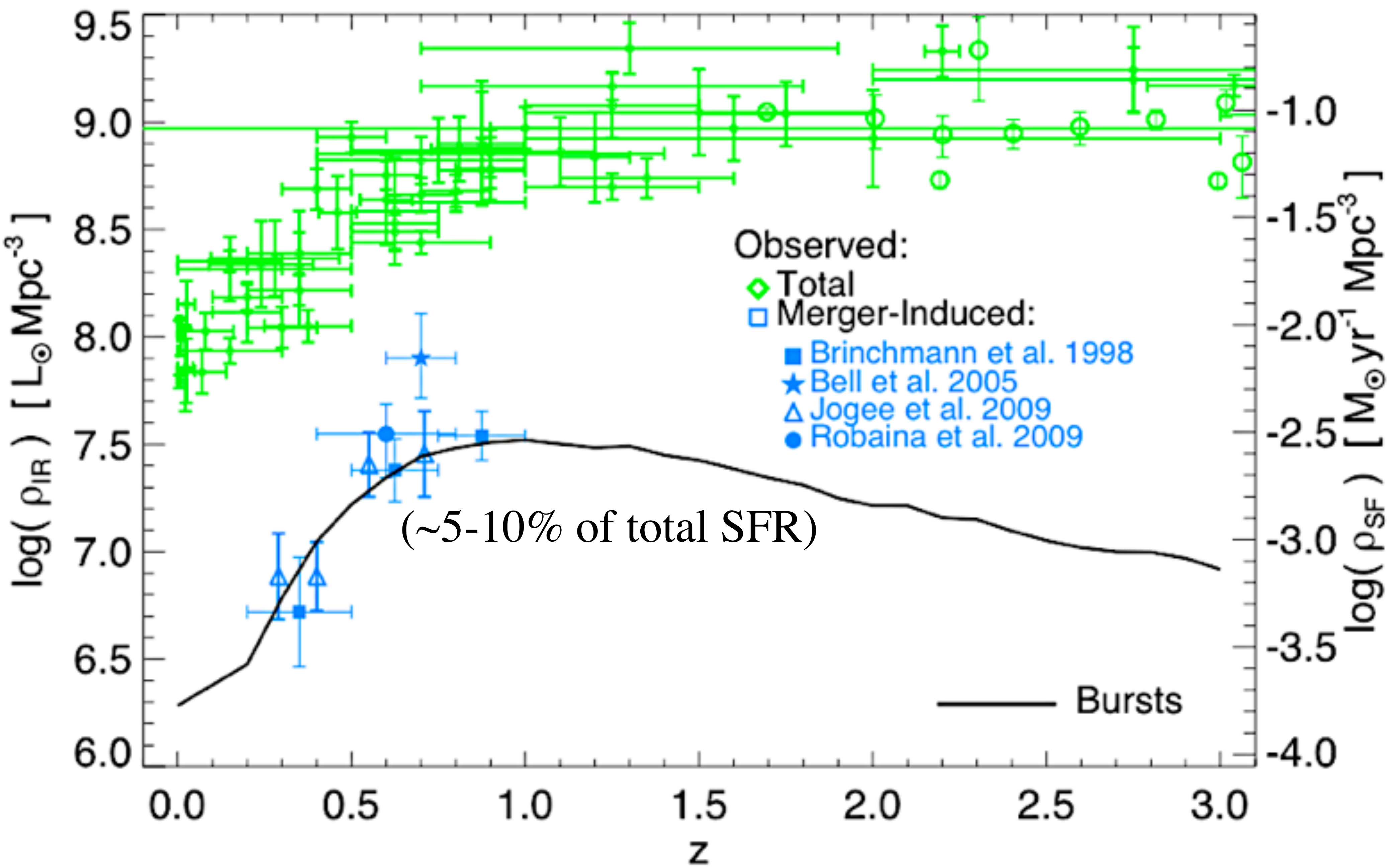


PFH & Hernquist 200

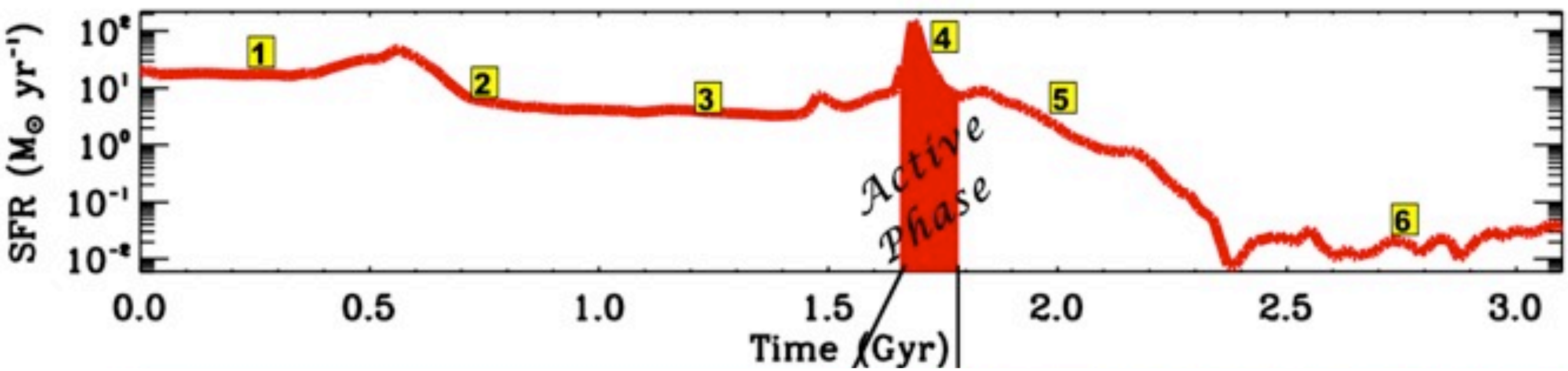
Bursts always dominate at high L, but the threshold shifts

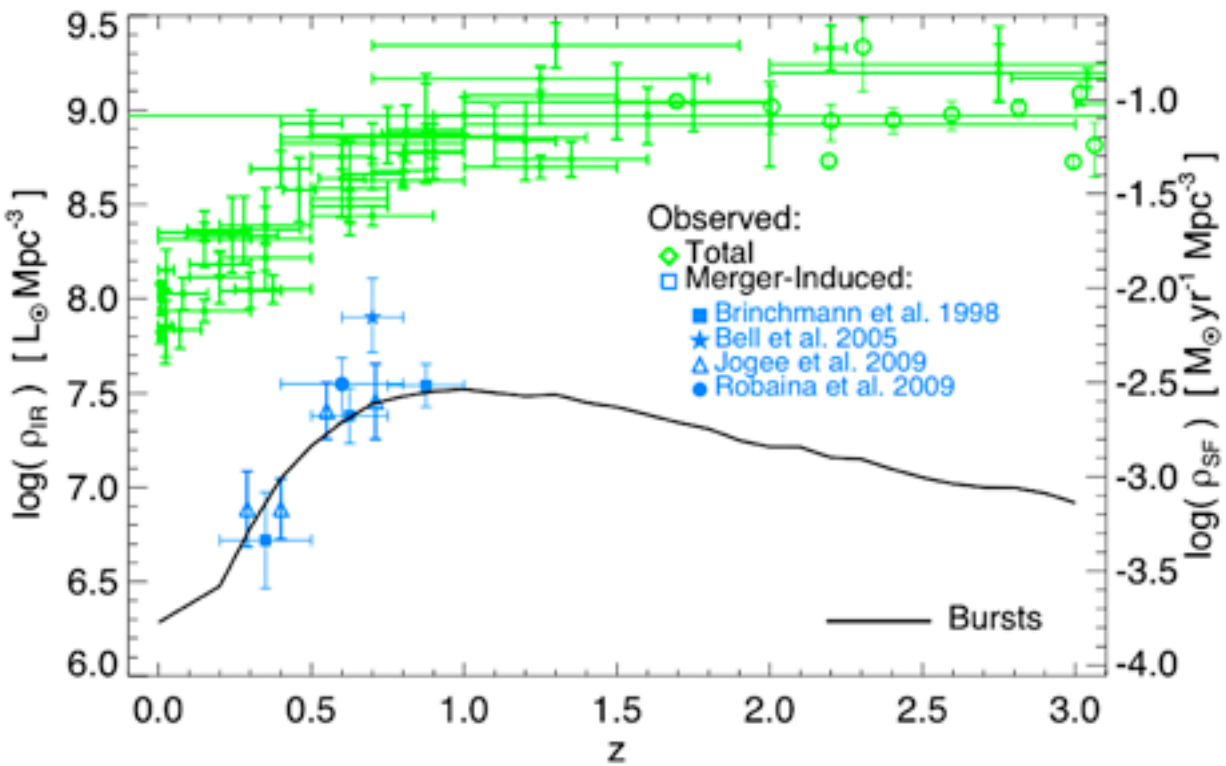


Bursts never dominate the SFR density!



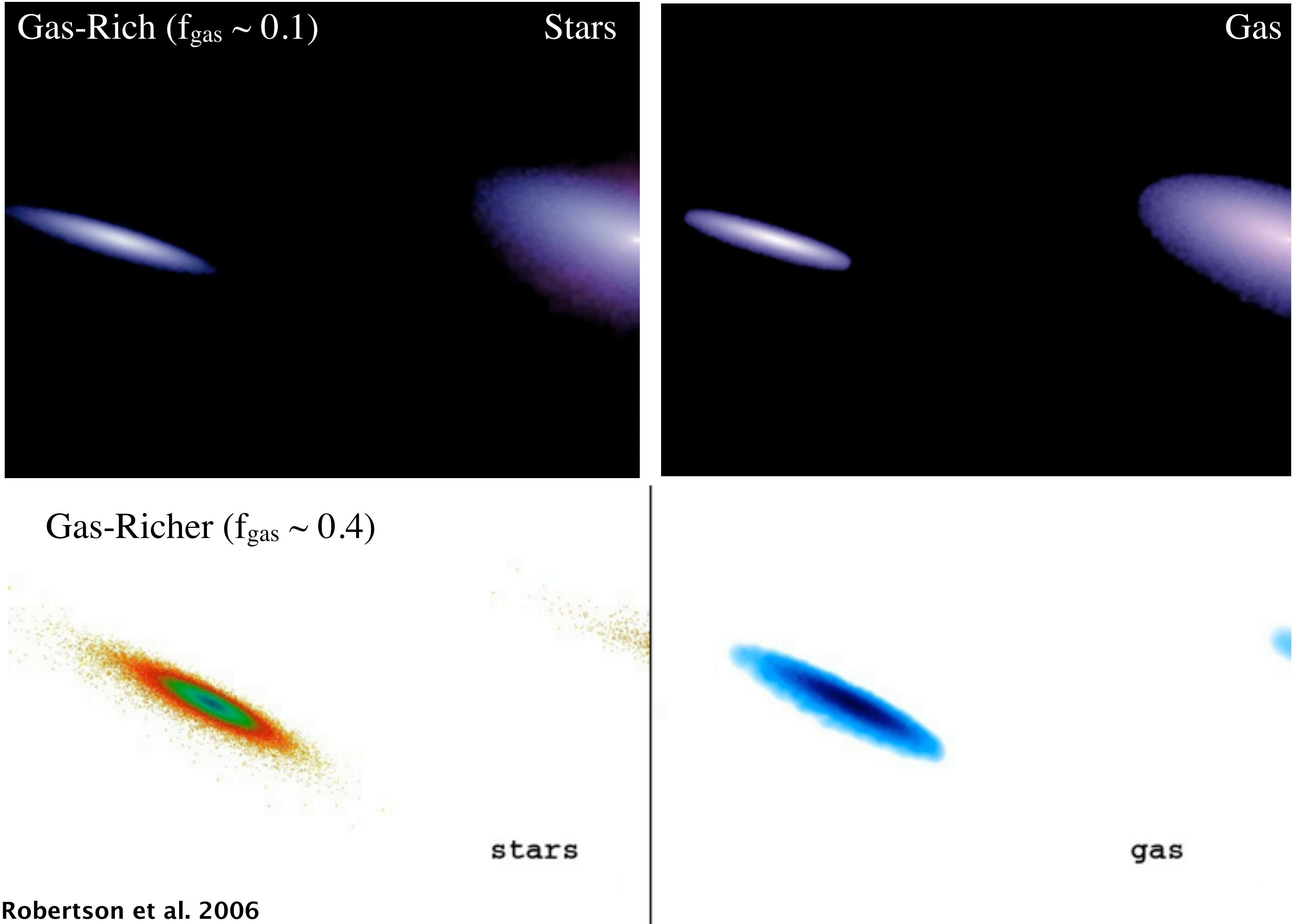
Triggered bursts never dominate the SFR density: why?





- 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

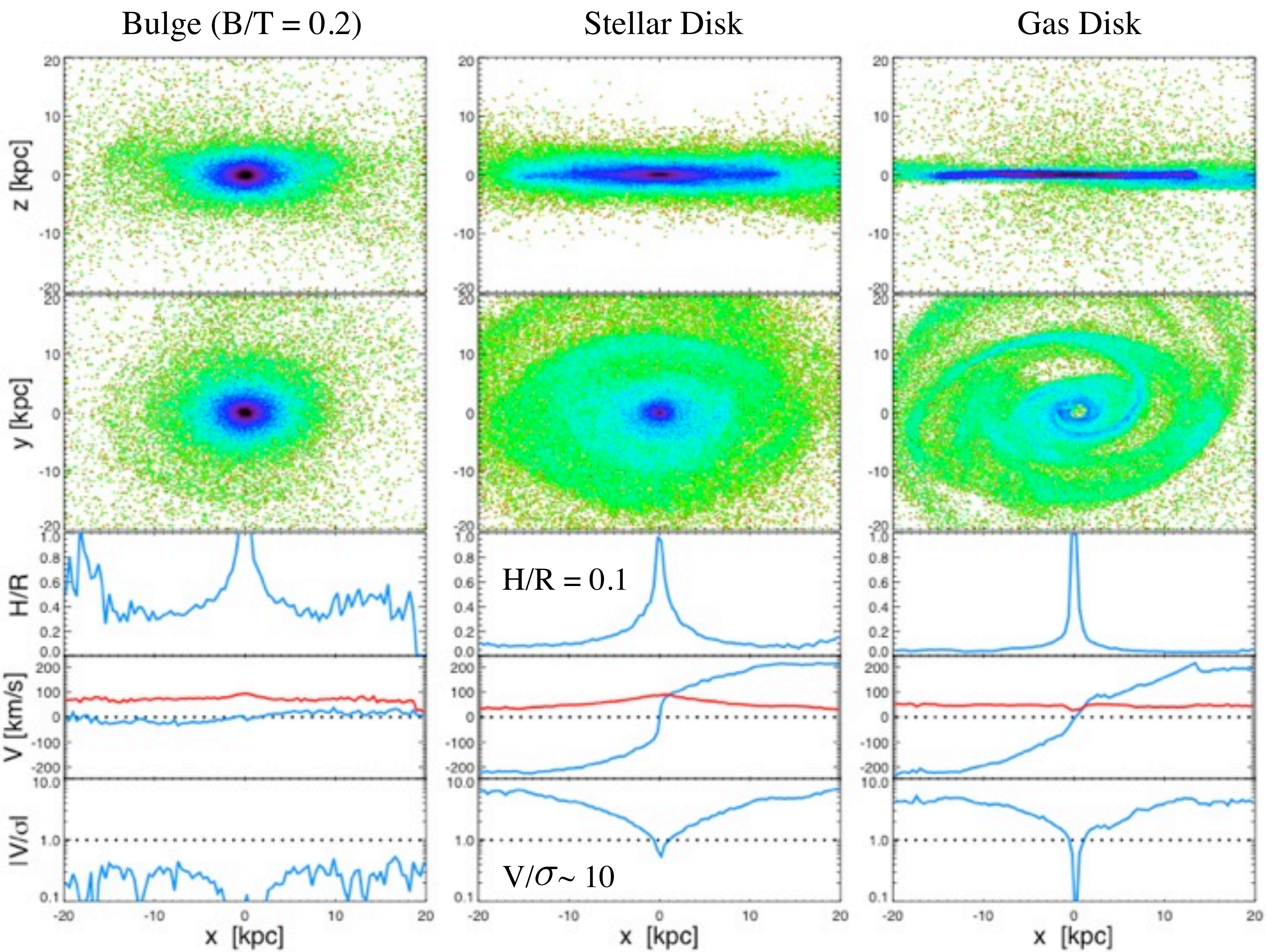
How Good Is Our Conventional Wisdom?



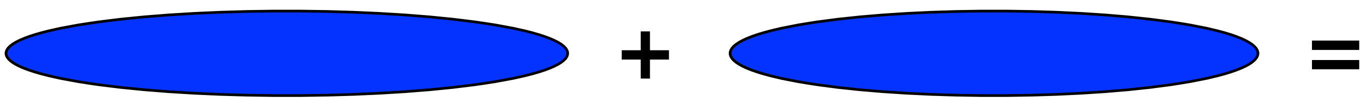
Robertson et al. 2006

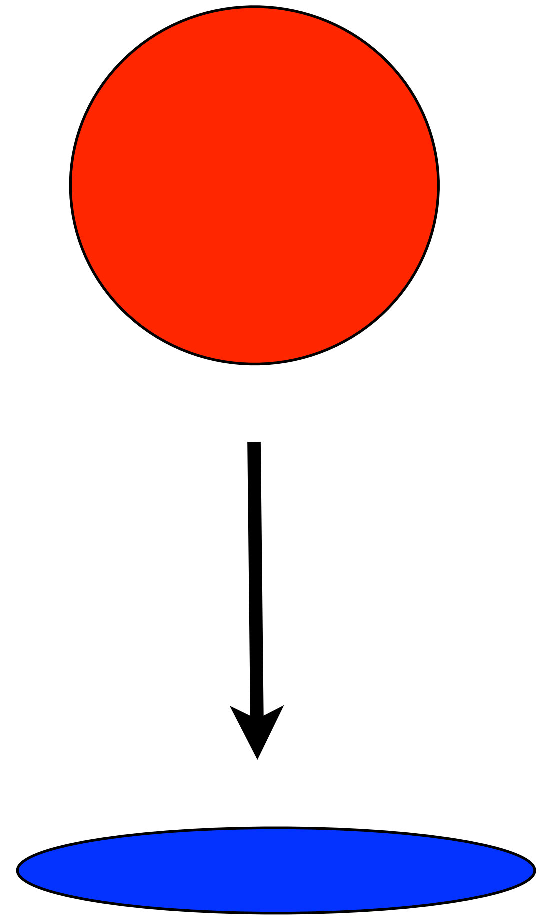
Major Merger Remnants

DO MERGERS DESTROY DISKS?



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



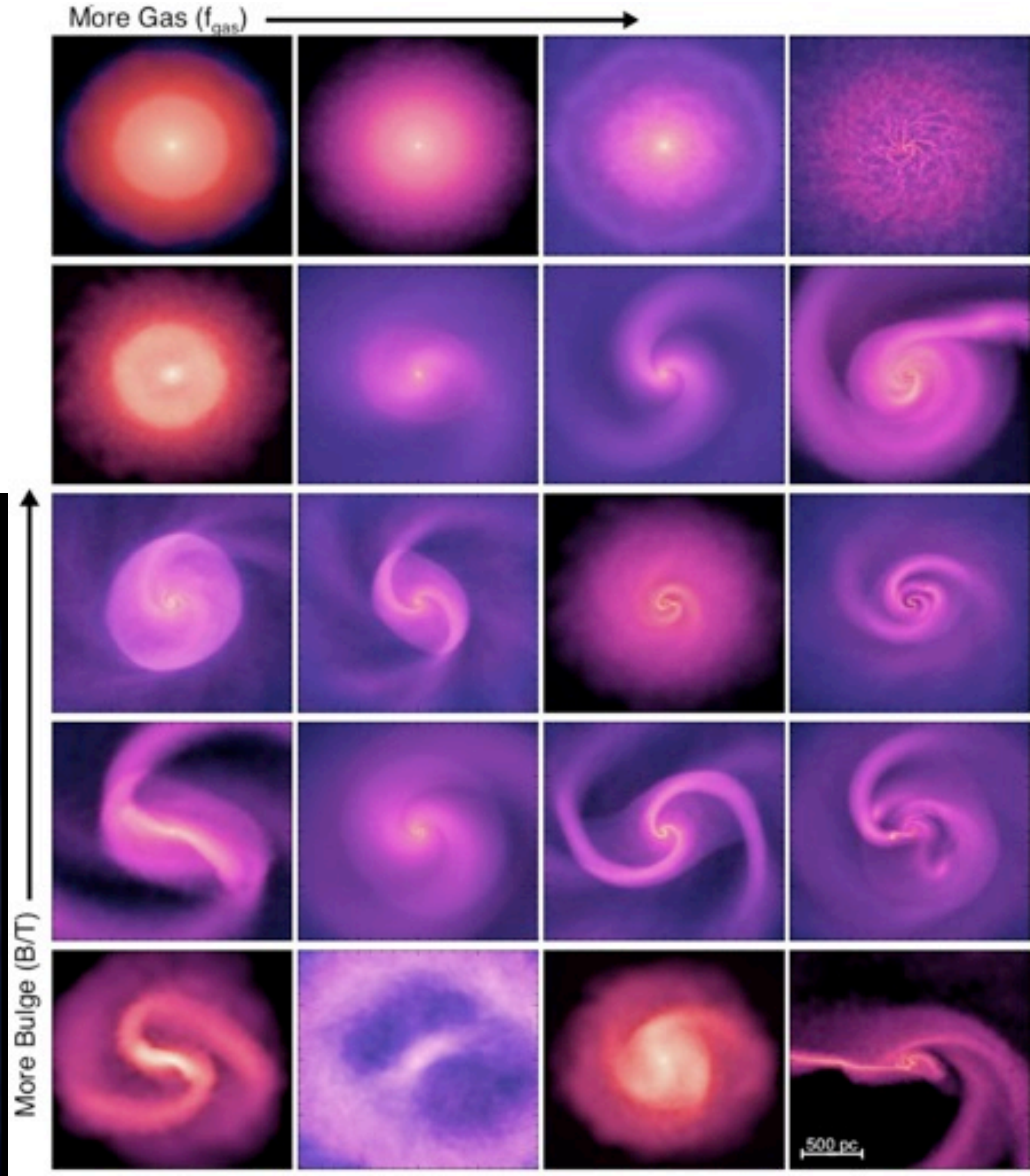


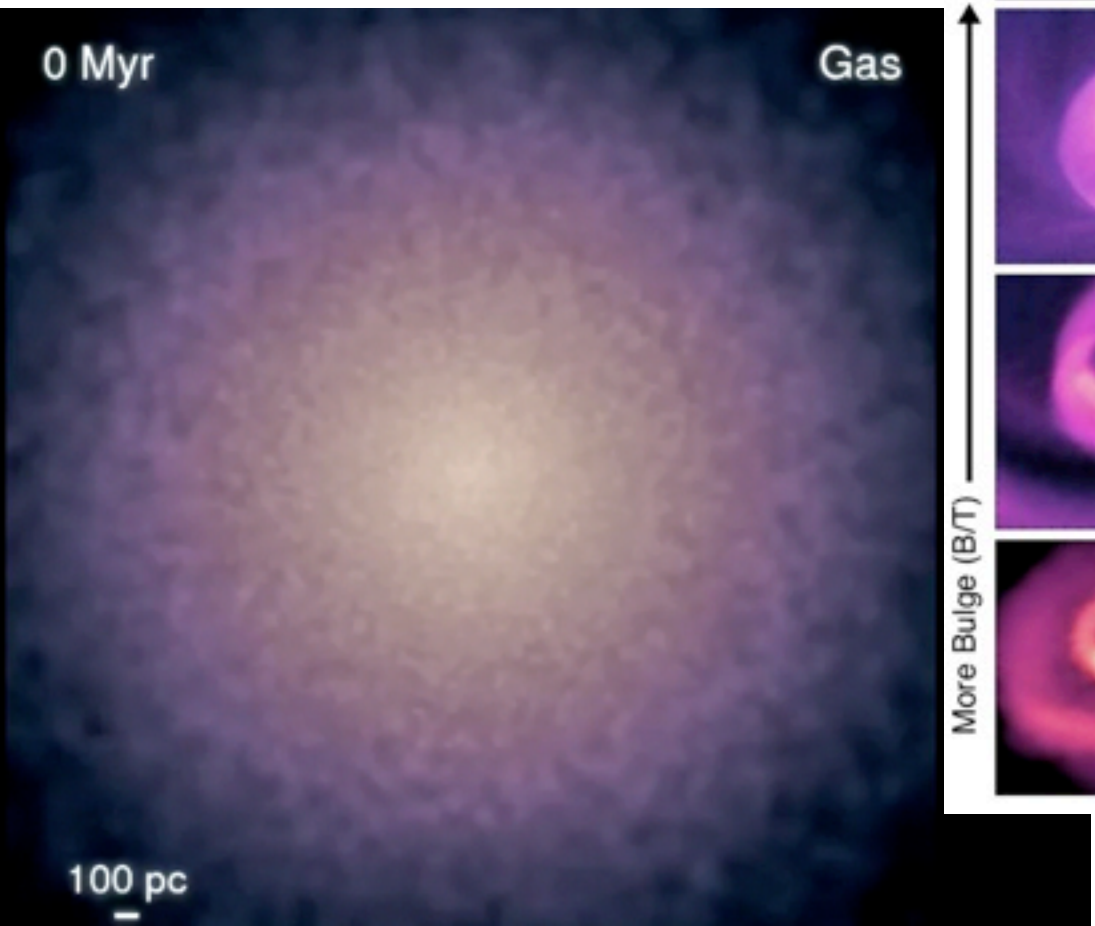
Brooks et al., Governato et al.

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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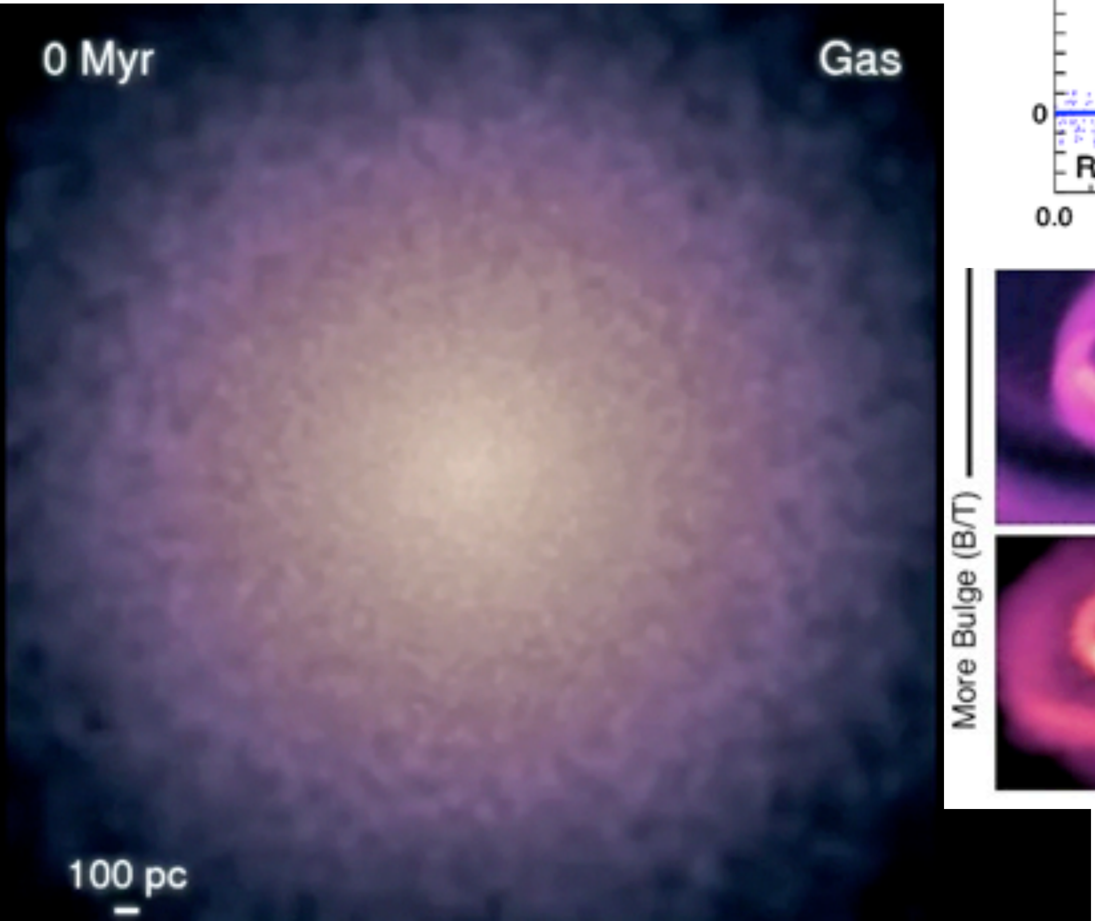
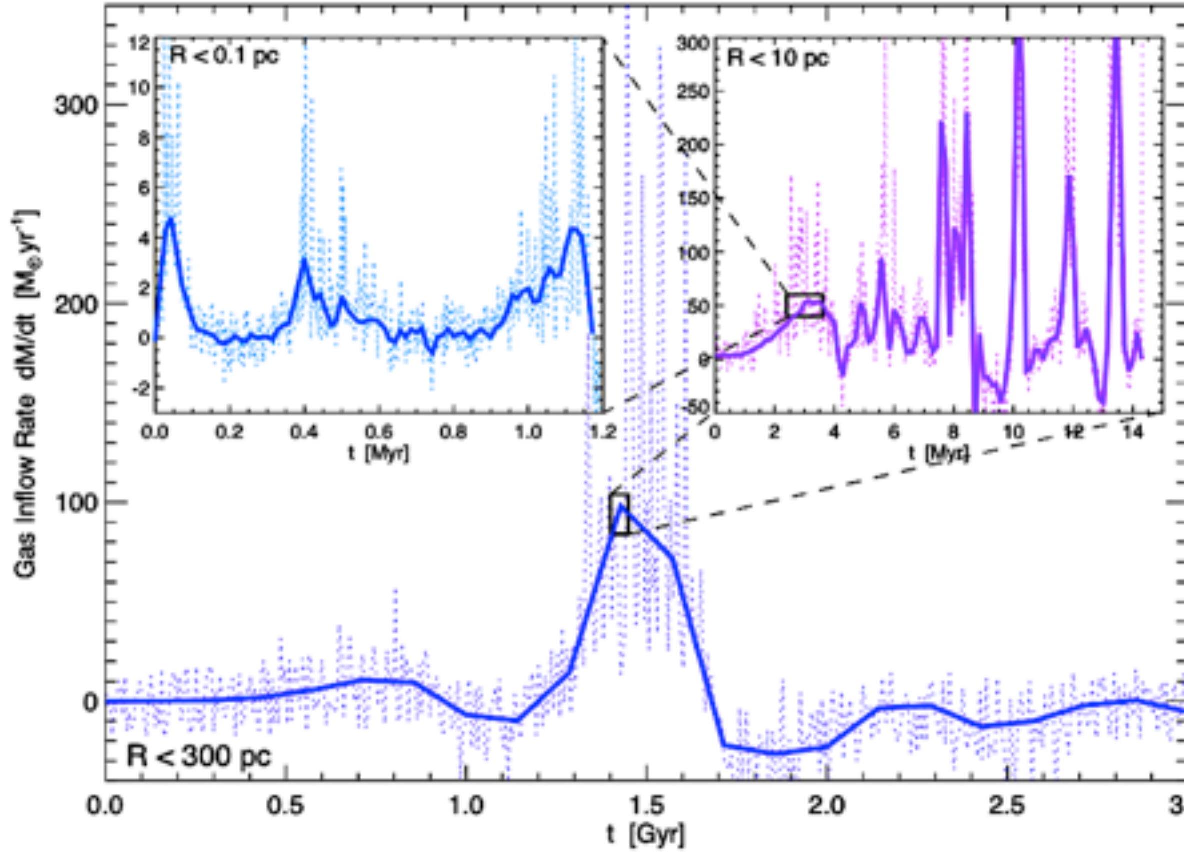
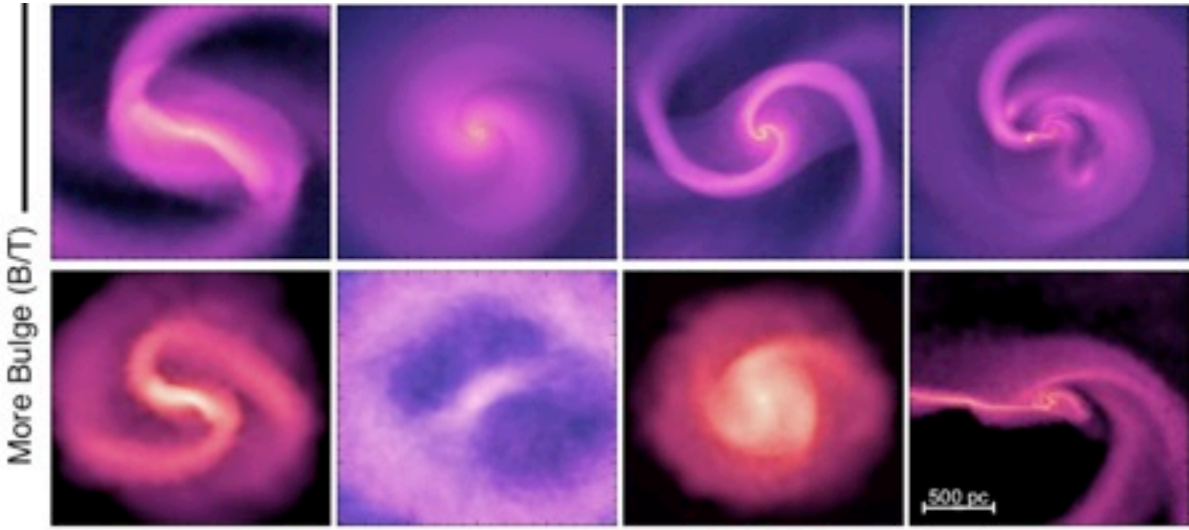
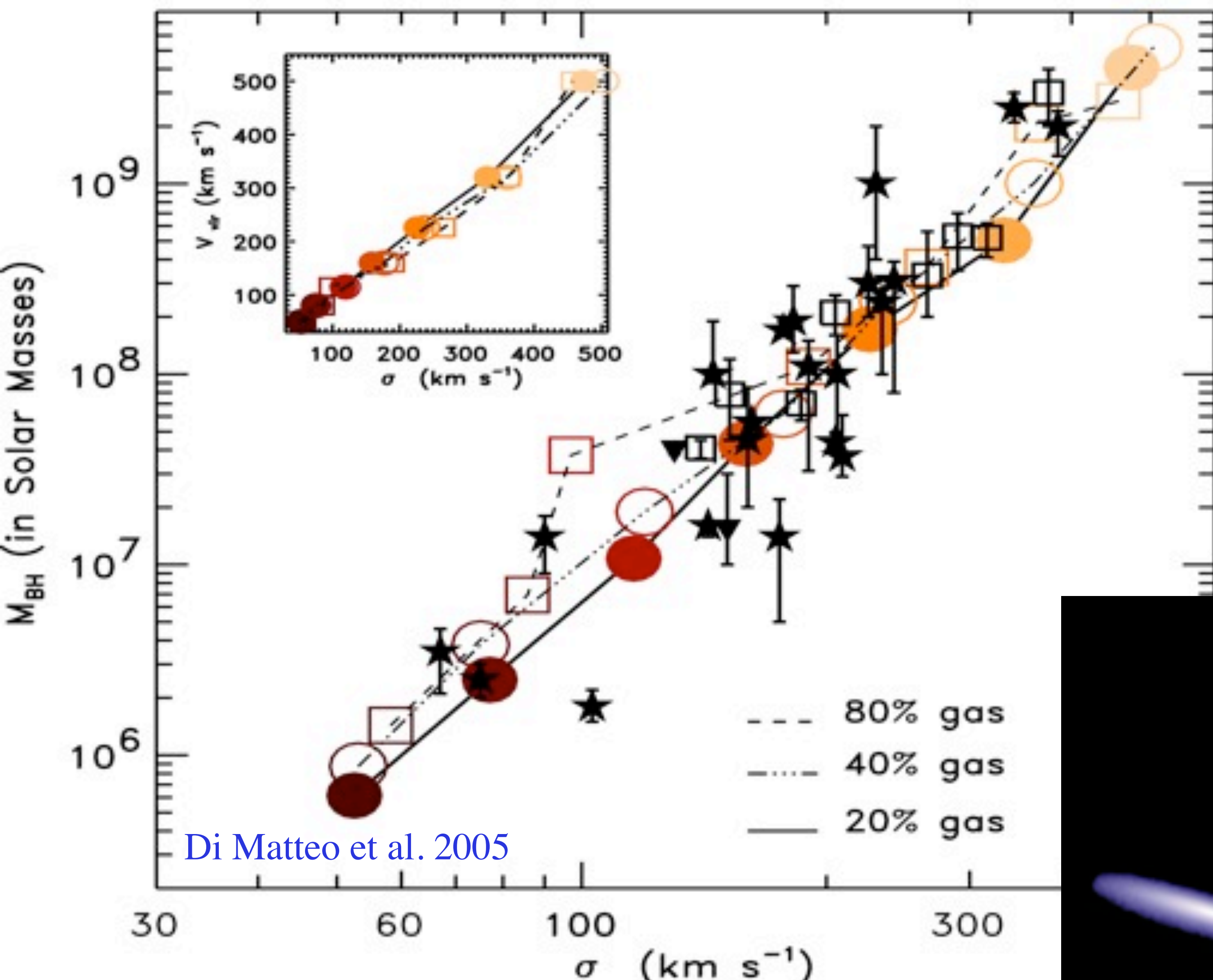


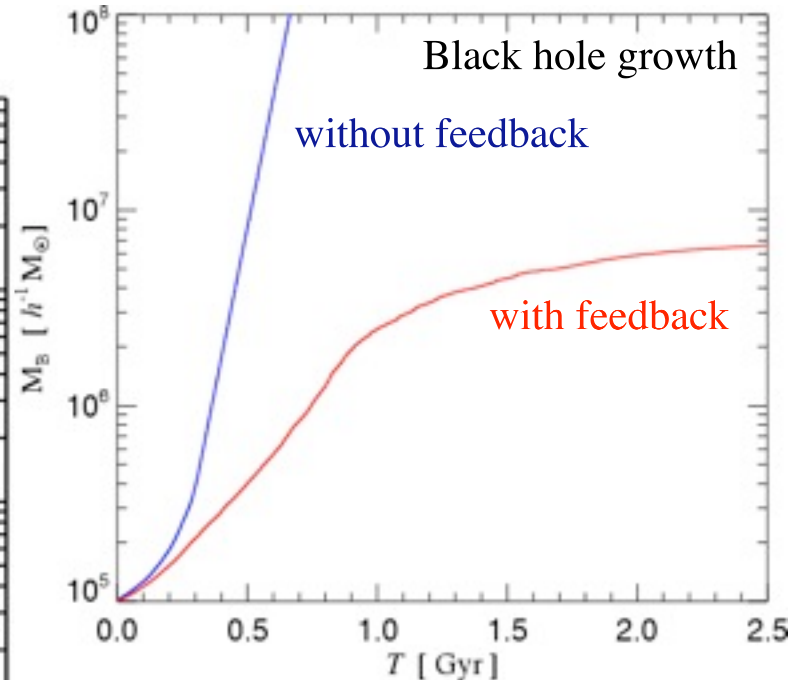


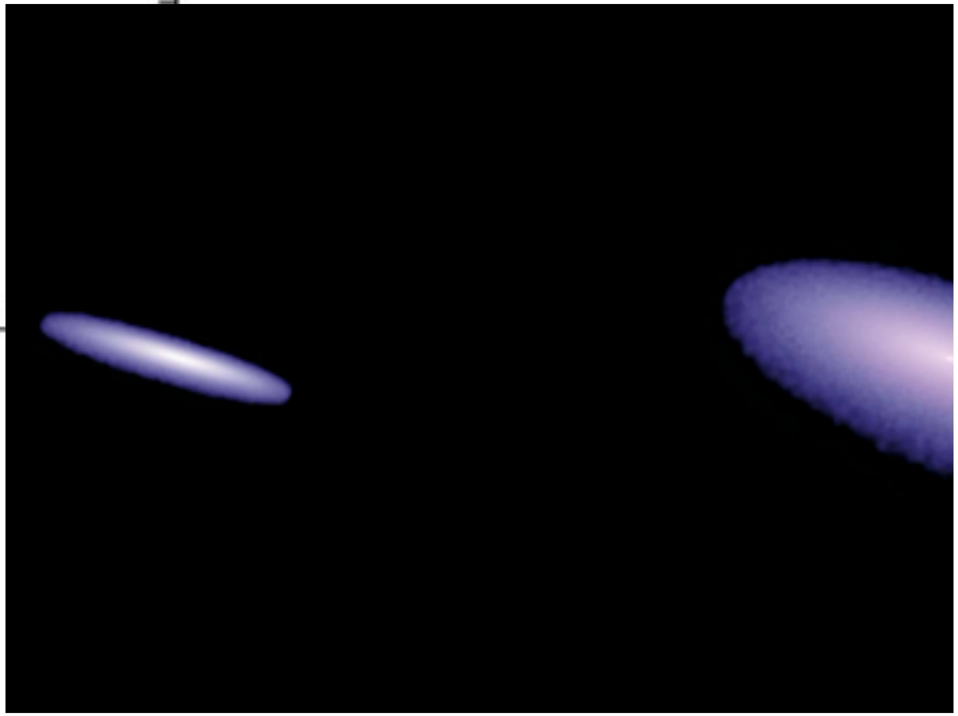


AGN Feedback Primarily Regulates... the AGN!

PREVENTS RUNAWAY BLACK HOLE GROWTH



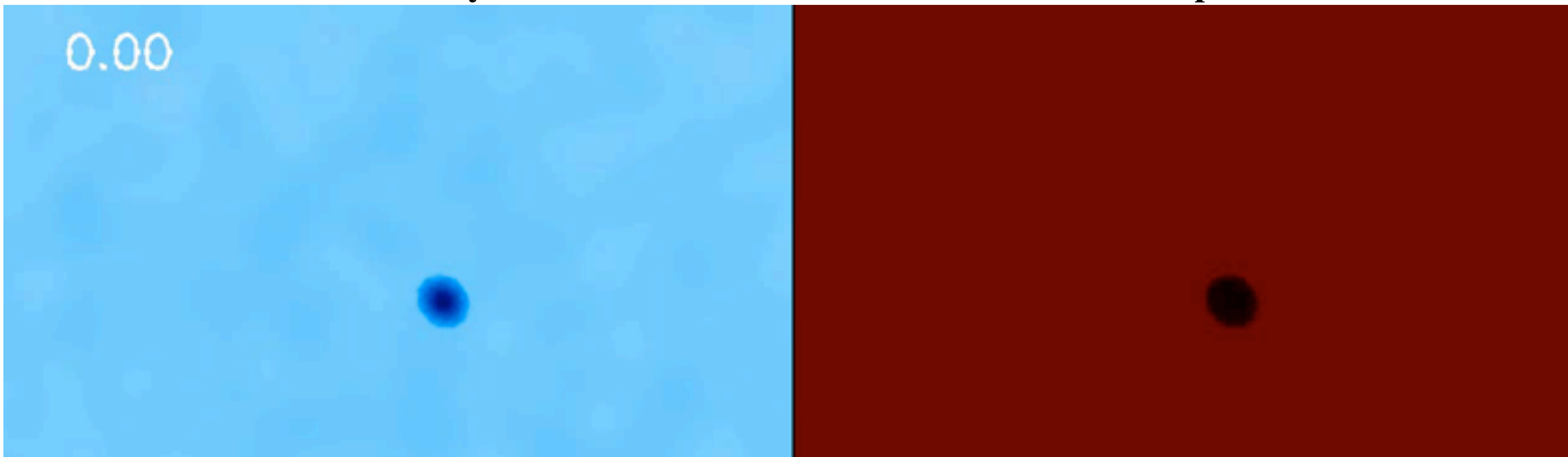


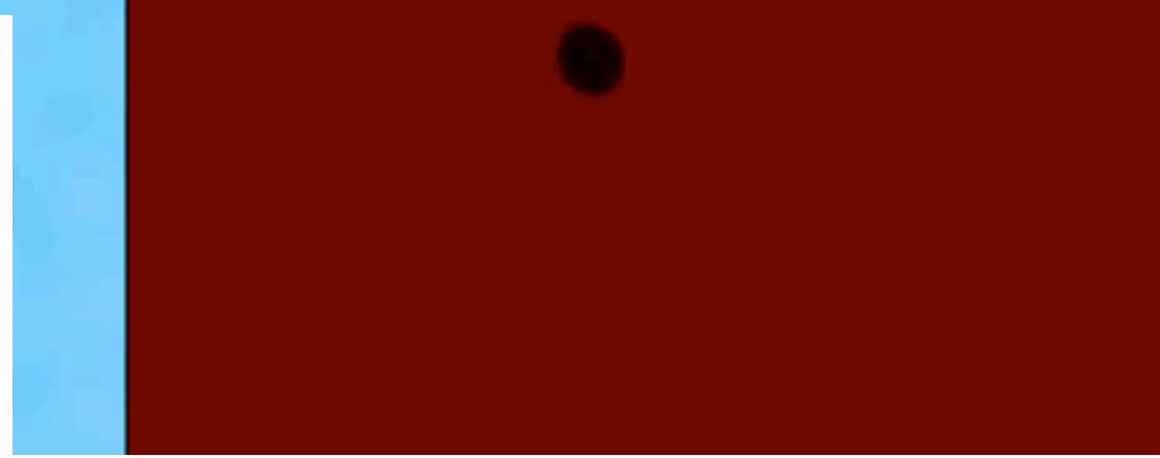


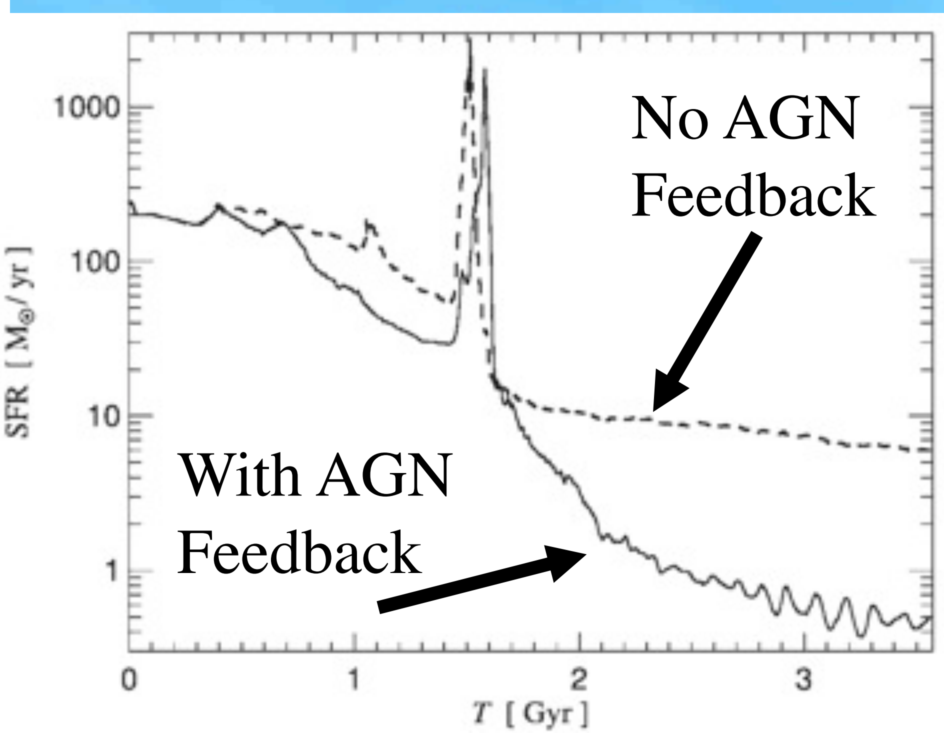
Quasar Outflows May Be Significant for the ICM & IGM

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

Gas Density **Gas Temperature**







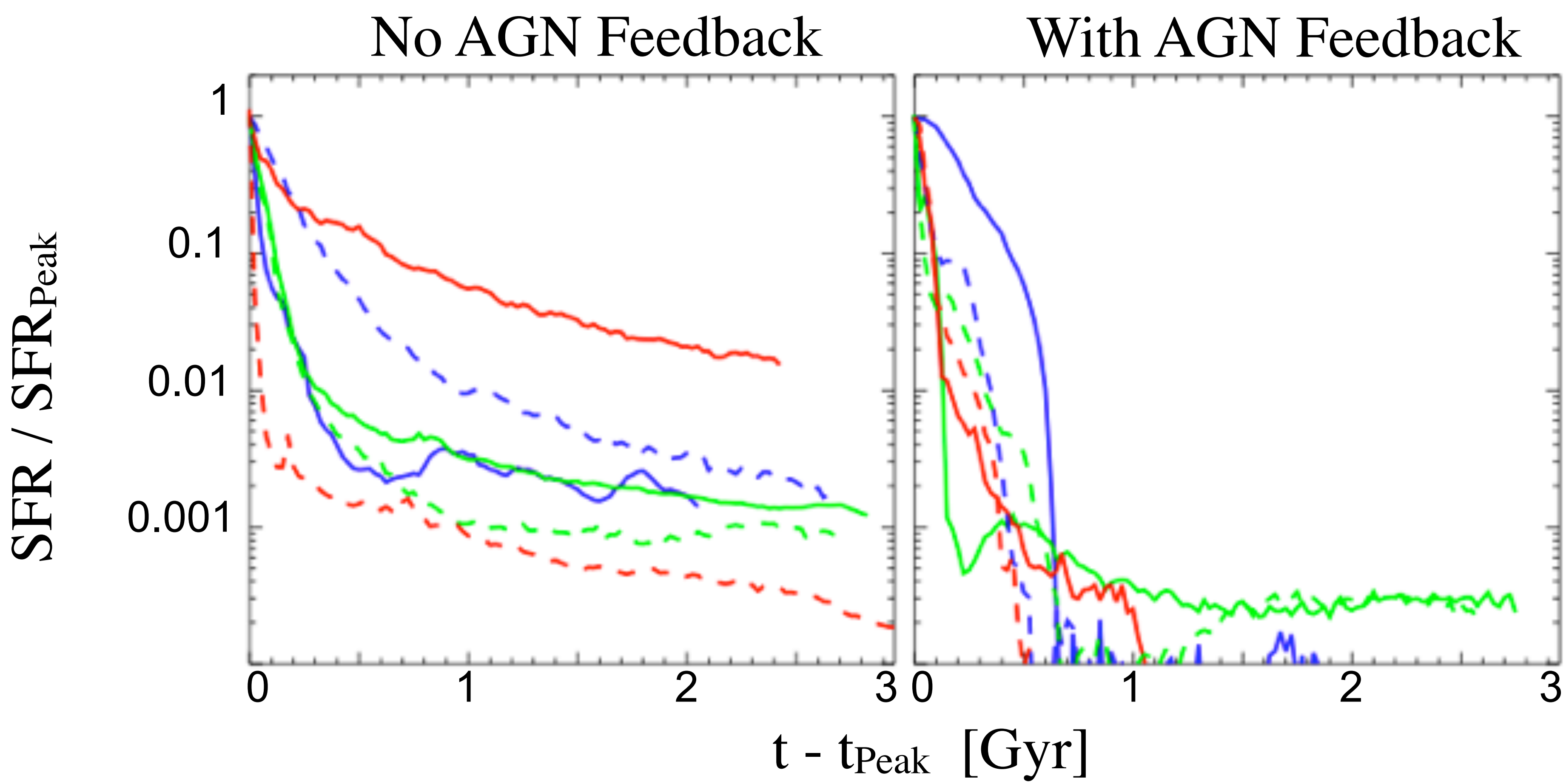
Springel et al. 2005

PFH, Keres et al. 2008

Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

... but ...

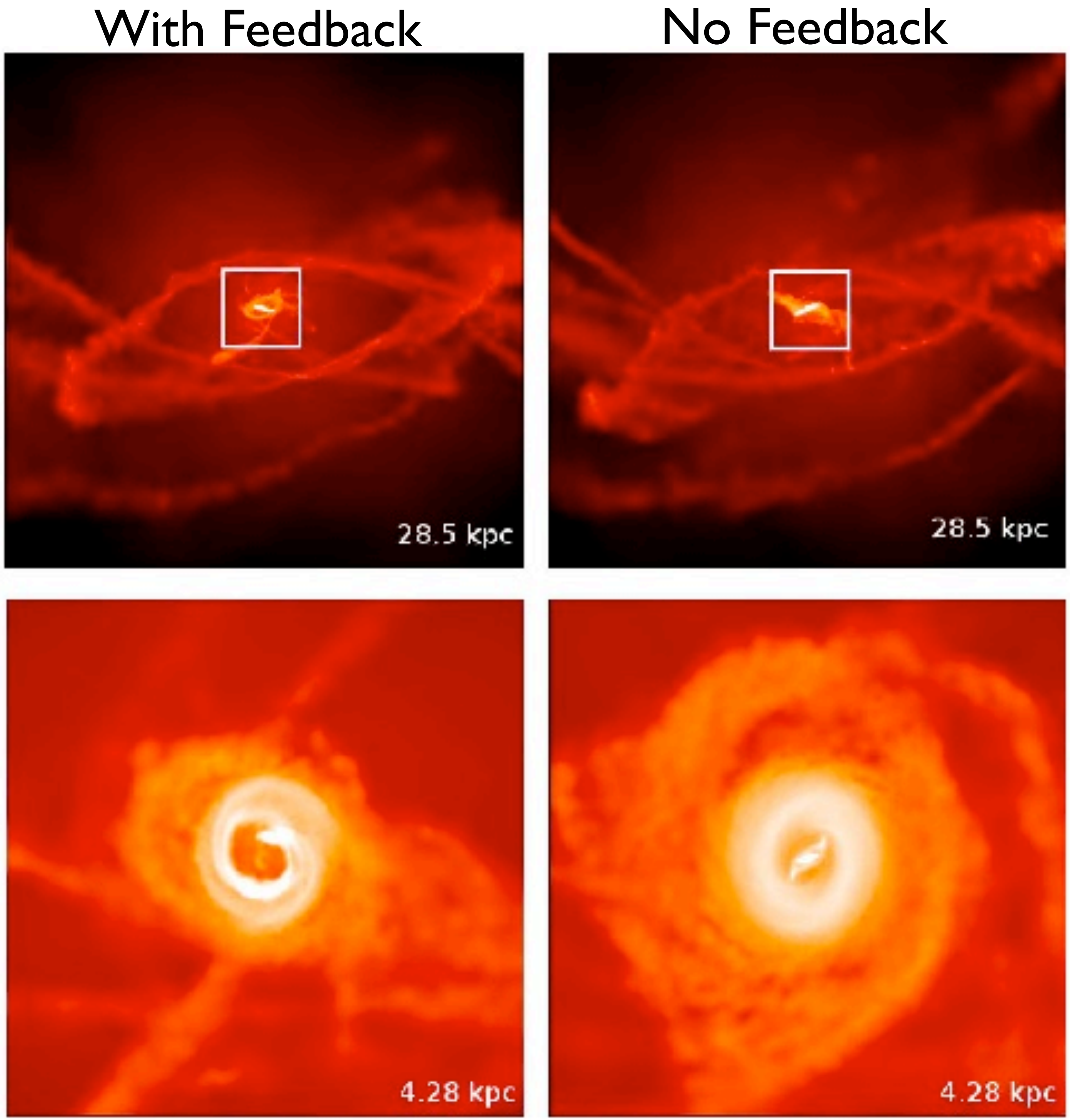


... MOST of the work is still done by star formation/stellar feedback

- 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"!

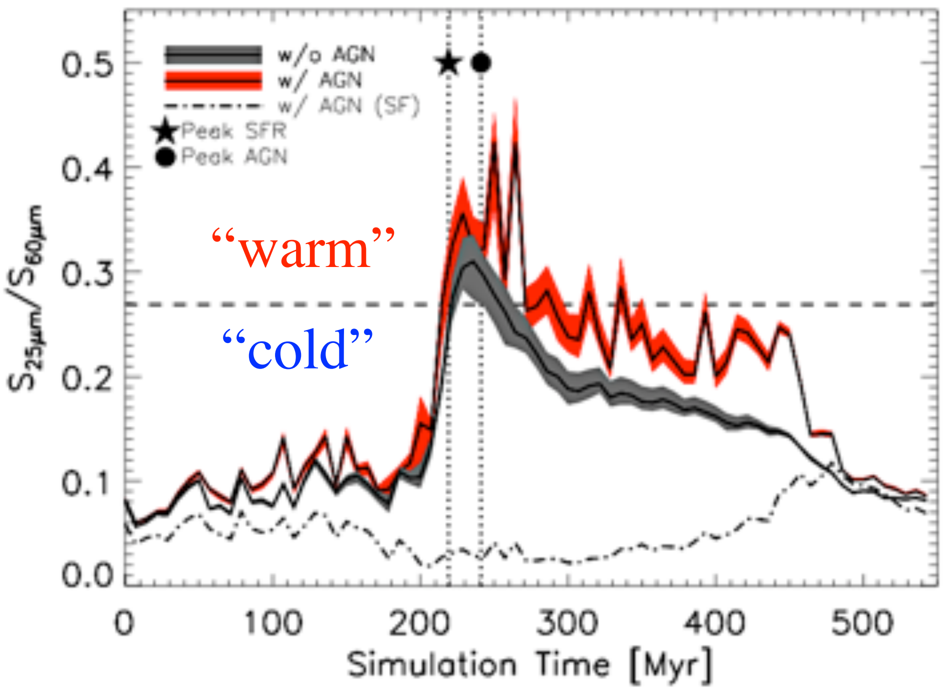


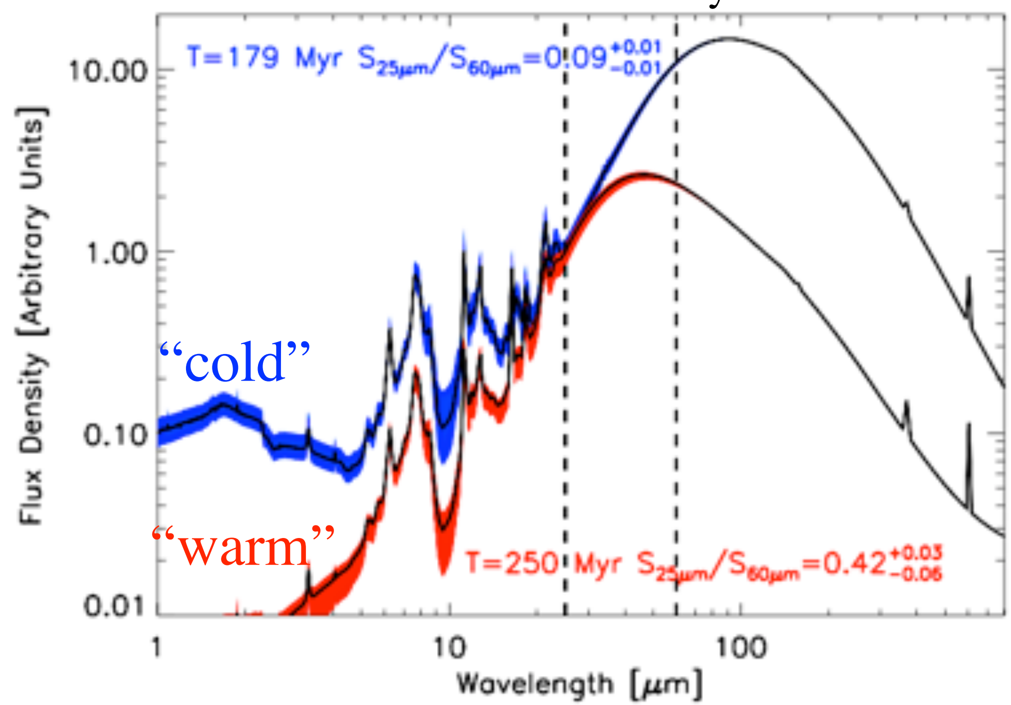
The Role of the AGN…

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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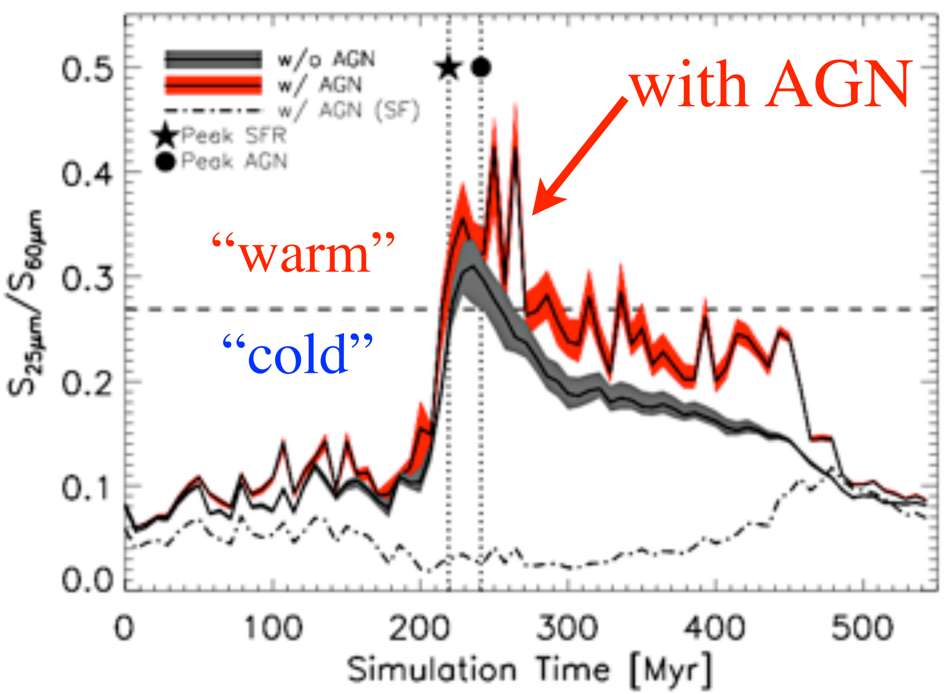

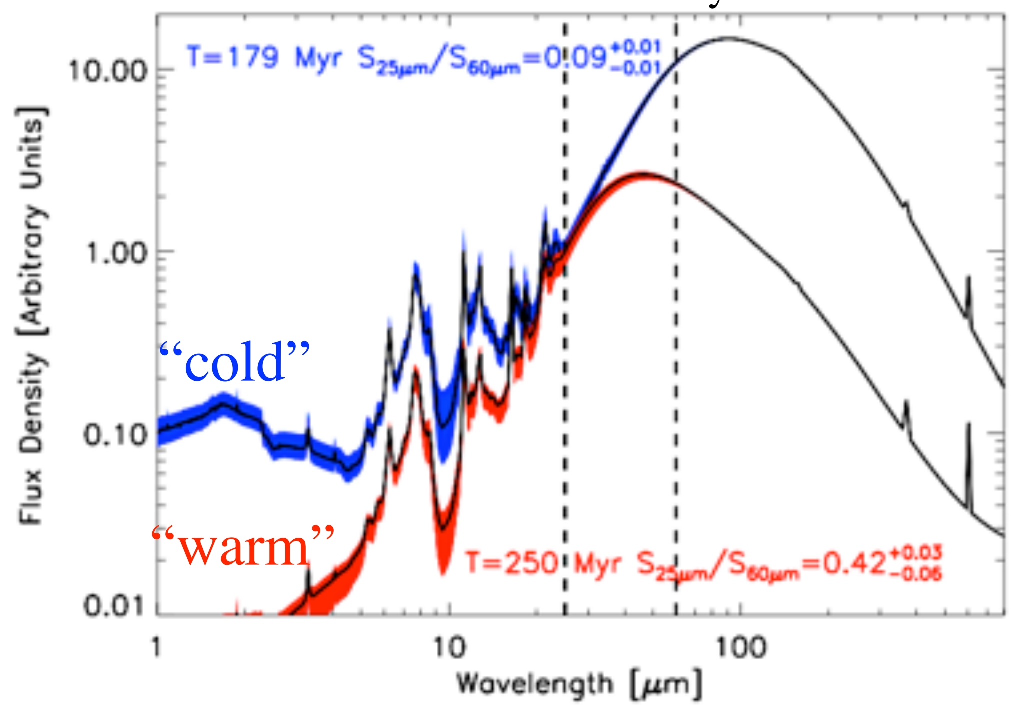

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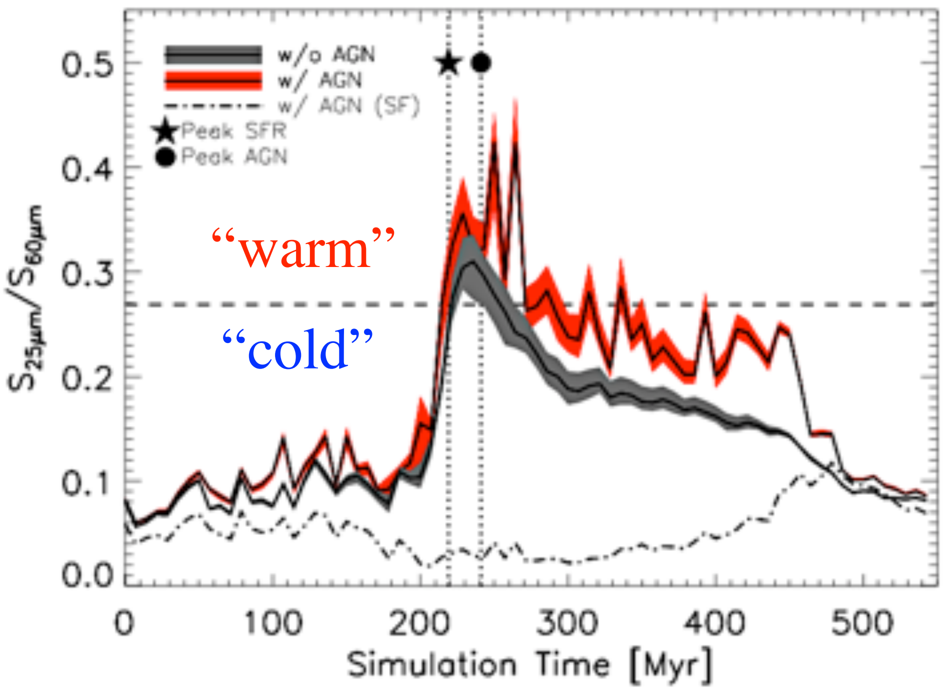

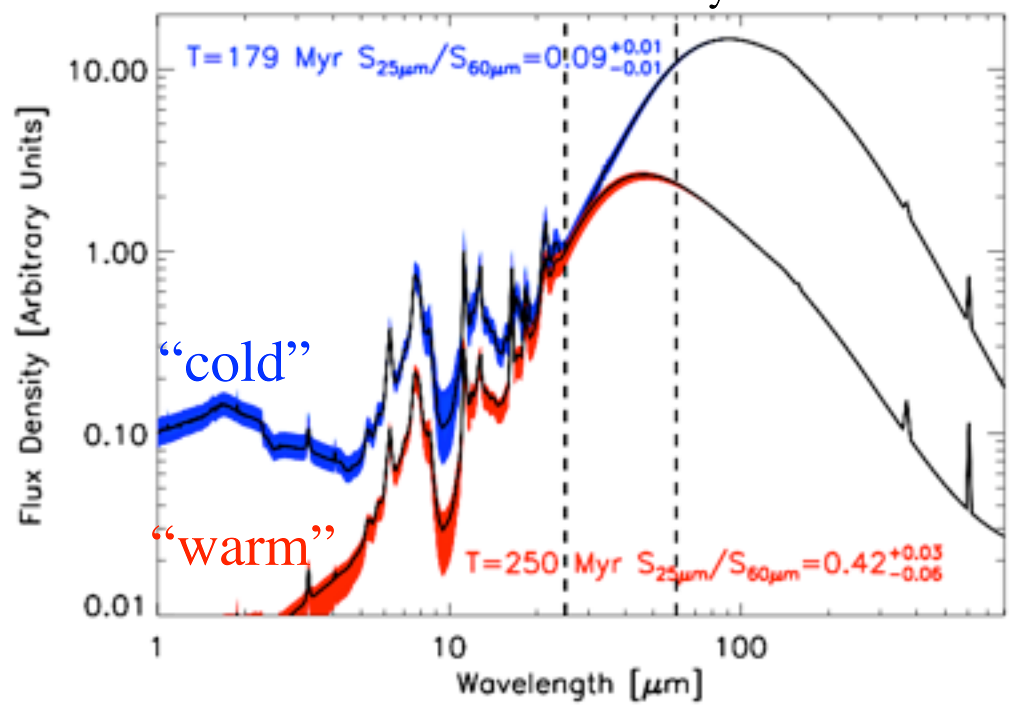

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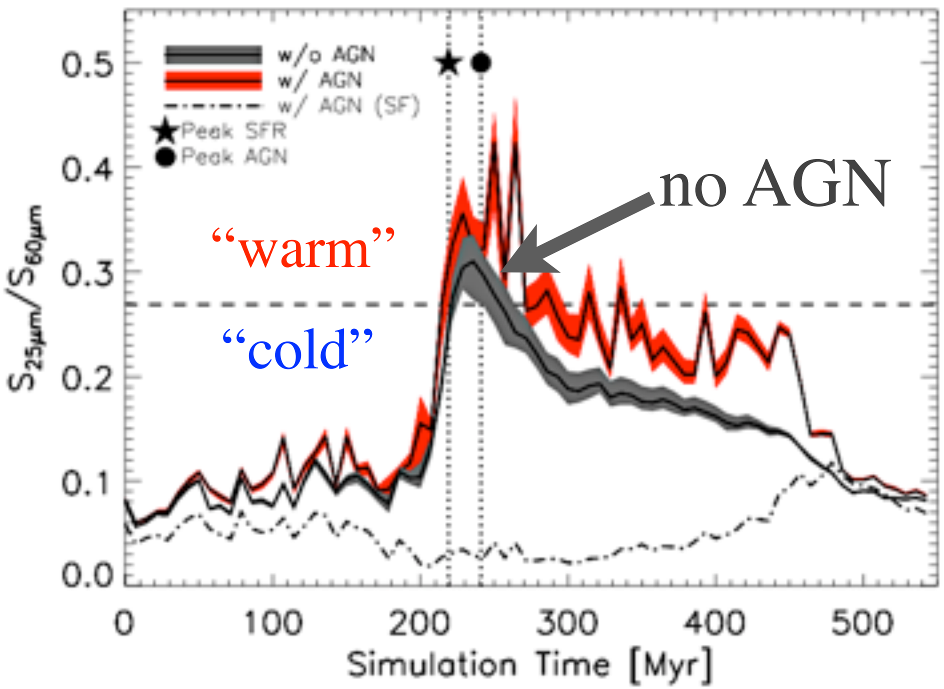

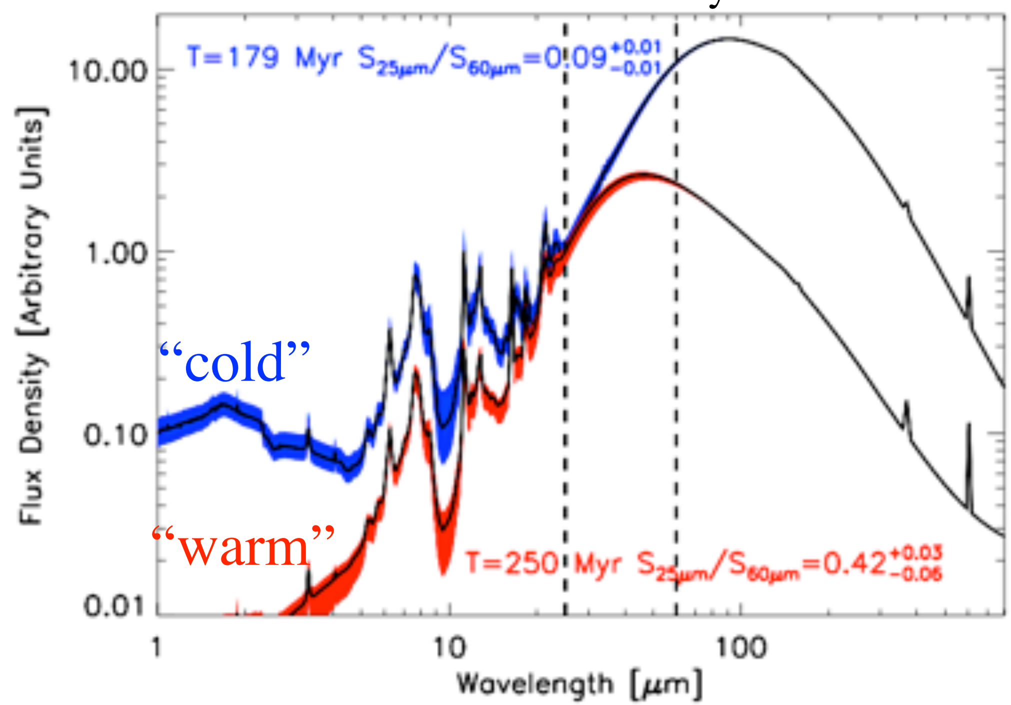

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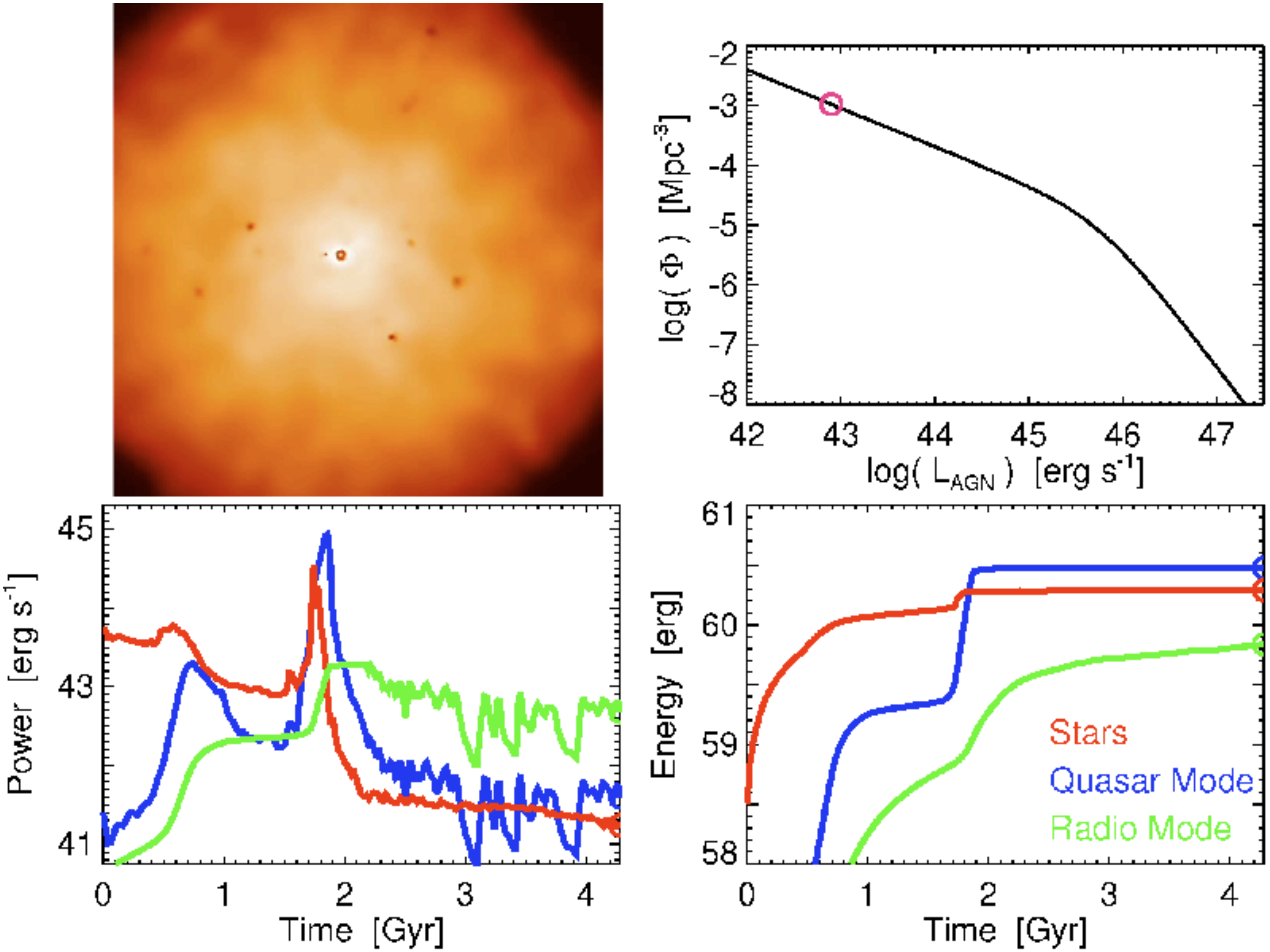
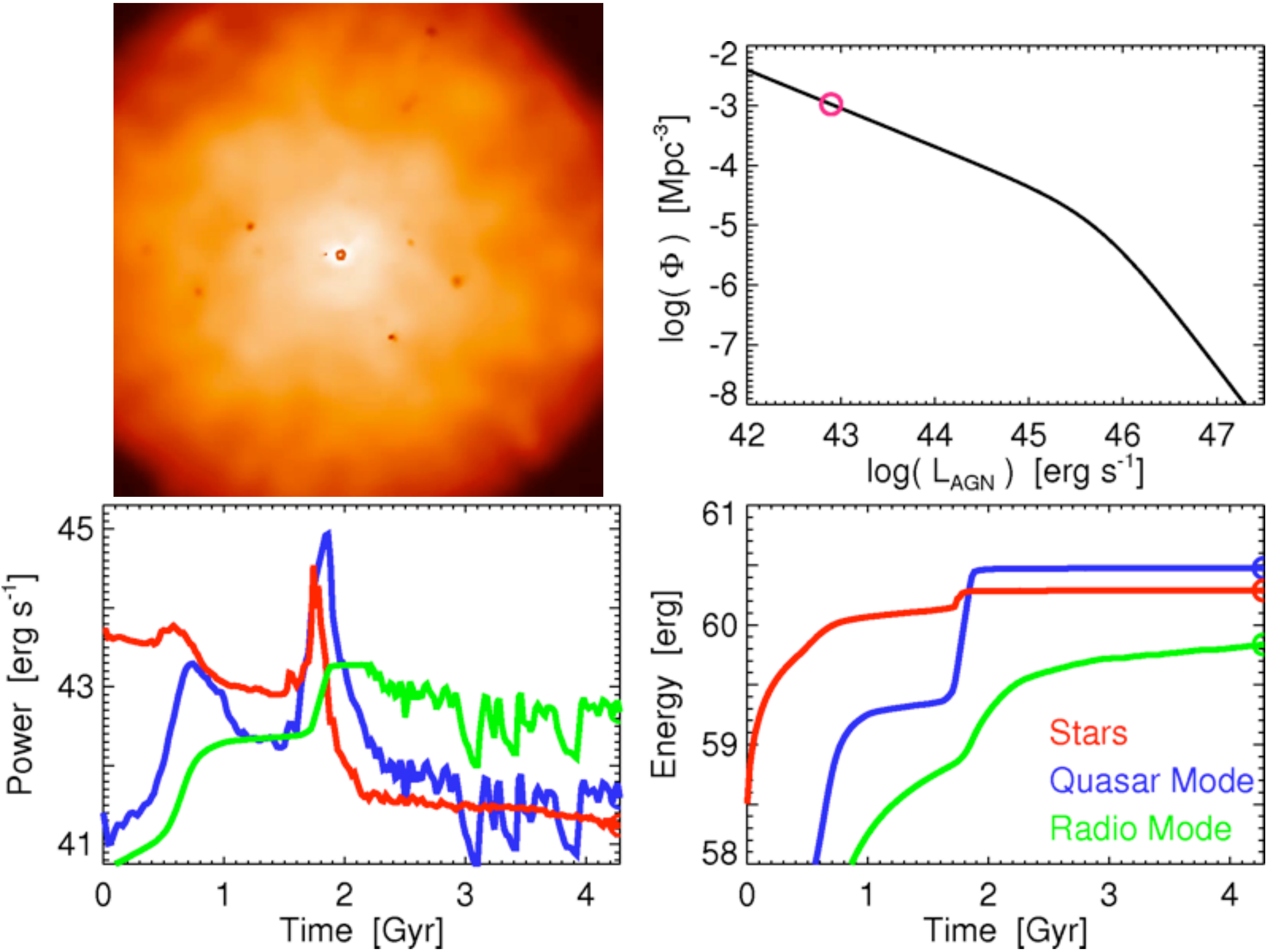
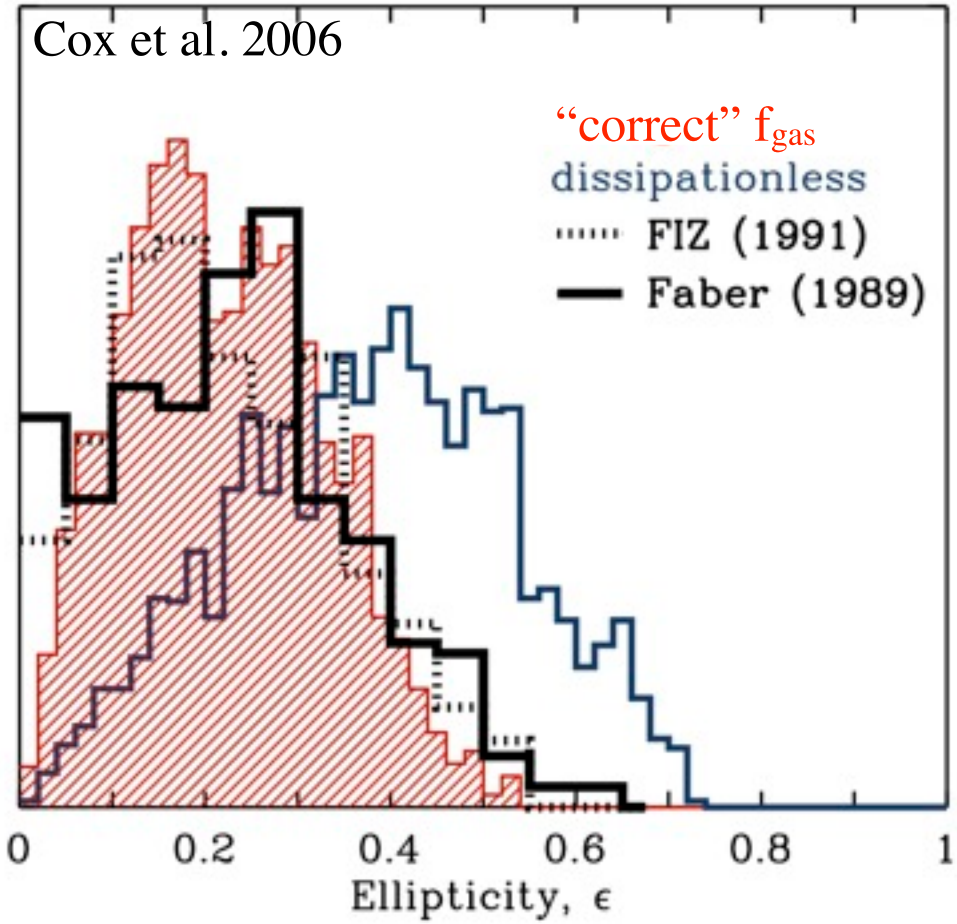
Summary

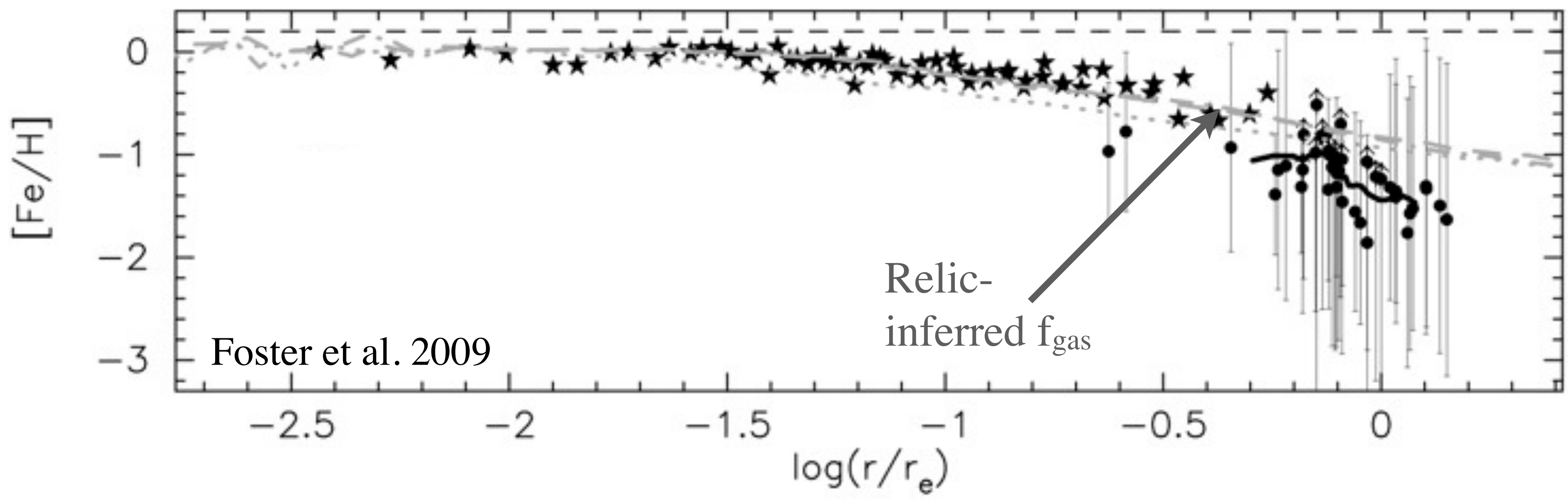
- Gas Dissipation and Star Formation Are Critical to Understand Galaxy Structure
  - Gas! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed ($f_{gas} \sim 0.1 - 0.5$)
  - Explains compact z~2 sizes, and evolution to today?
- Relics of starbursts 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

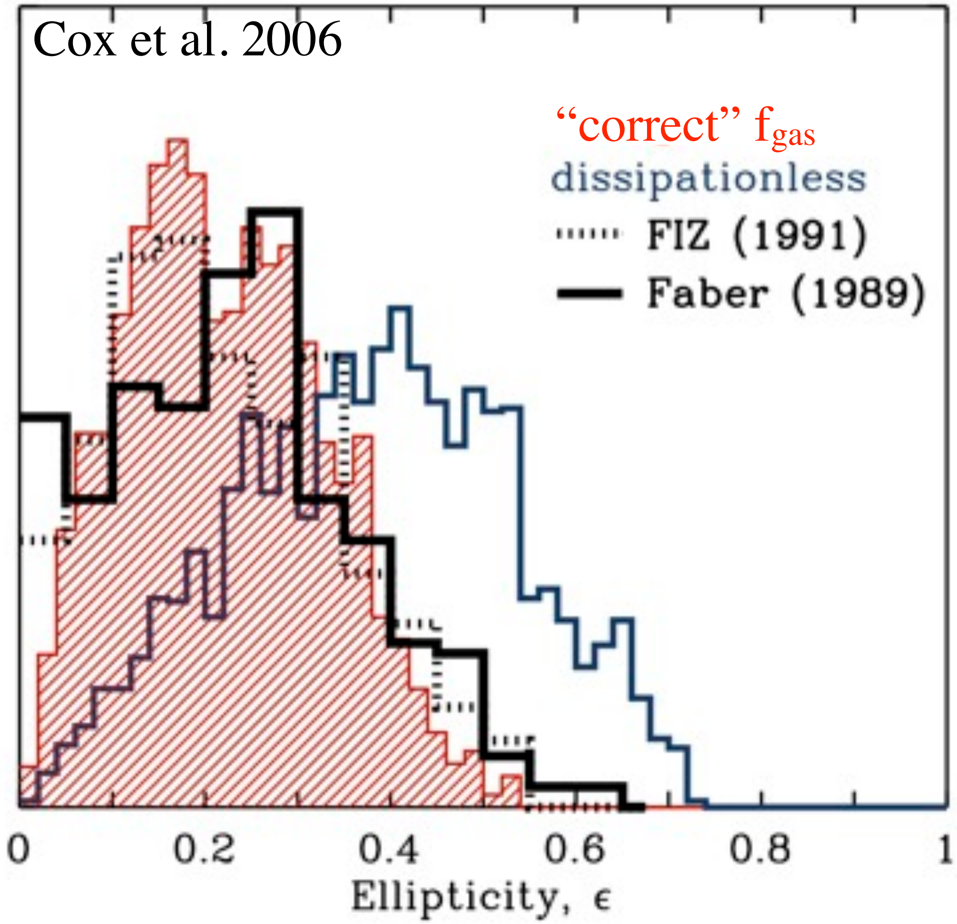


log(Φ) [Mpc^-3]
log(L_AGN) [erg s^-1]
Power [erg s^-1]
Time [Gyr]
Energy [erg]
Time [Gyr]
Stars
Quasar Mode
Radio Mode


-2
-3
-4
-5
-6
-7
-8
log(Φ) [Mpc^{-3}]
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]
45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]
61
60
59
58
Energy [erg]
0
1
2
3
4
Time [Gyr]
Stars
Quasar Mode
Radio Mode


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


0
−1
−2
−3
[Fe/H]
Relic-
inferred f_{gas}
Foster et al. 2009
−2.5
−2
−1.5
−1
−0.5
0
log(r/r$_e$)



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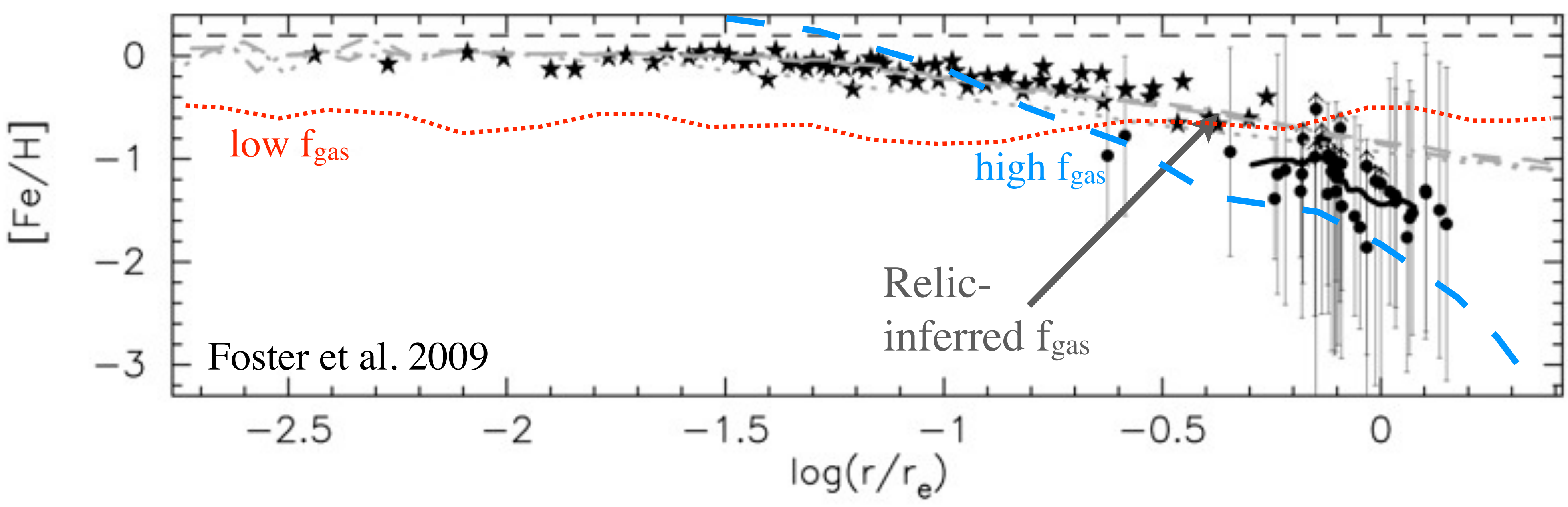

0
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−1
−0.5
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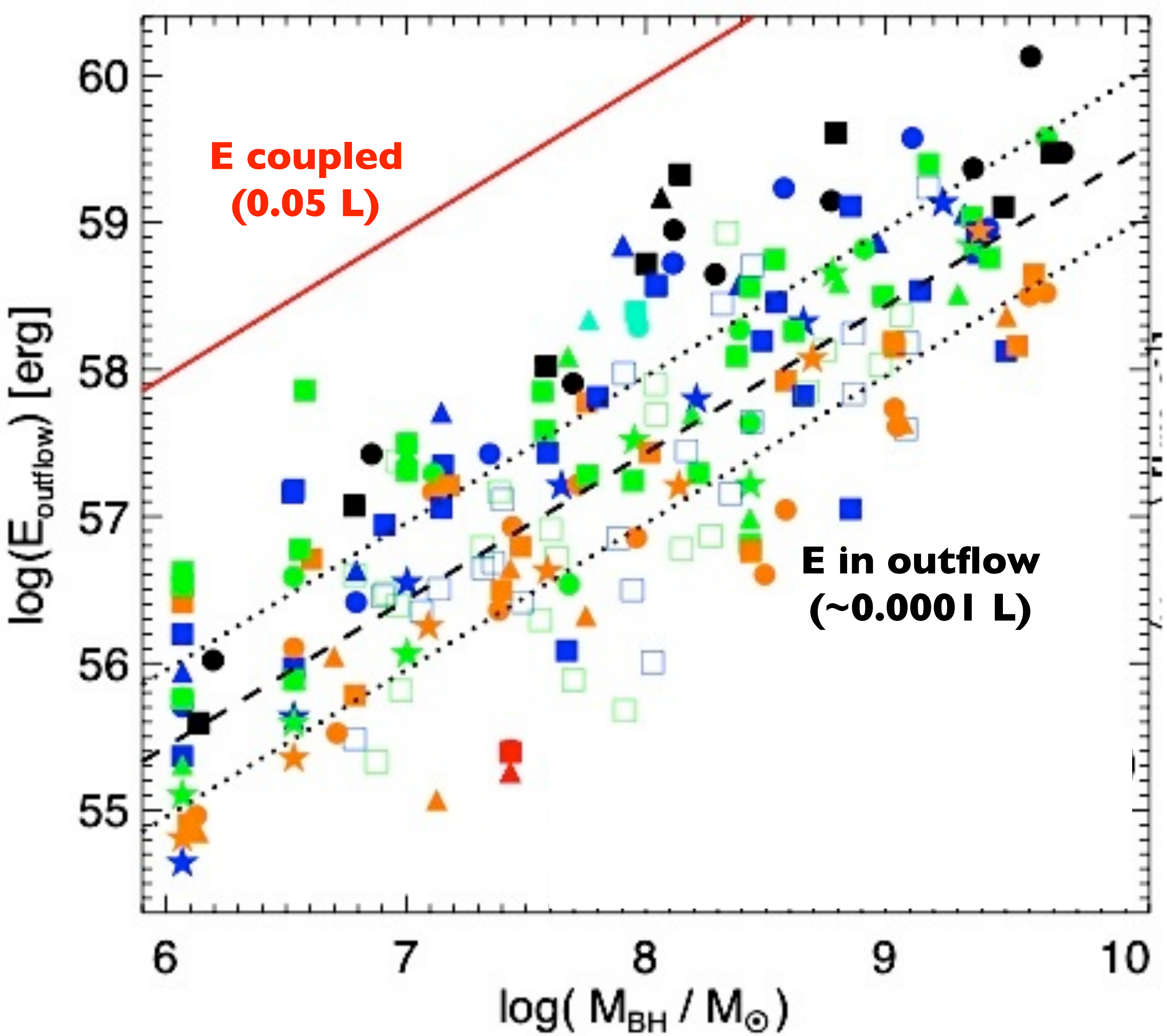
log(r/r$_e$)

CAUTION: Energy-Driven Outflows are *NOT* Energy-Conserving

MOMENTUM IS WHAT MATTERS ON LARGE SCALES!



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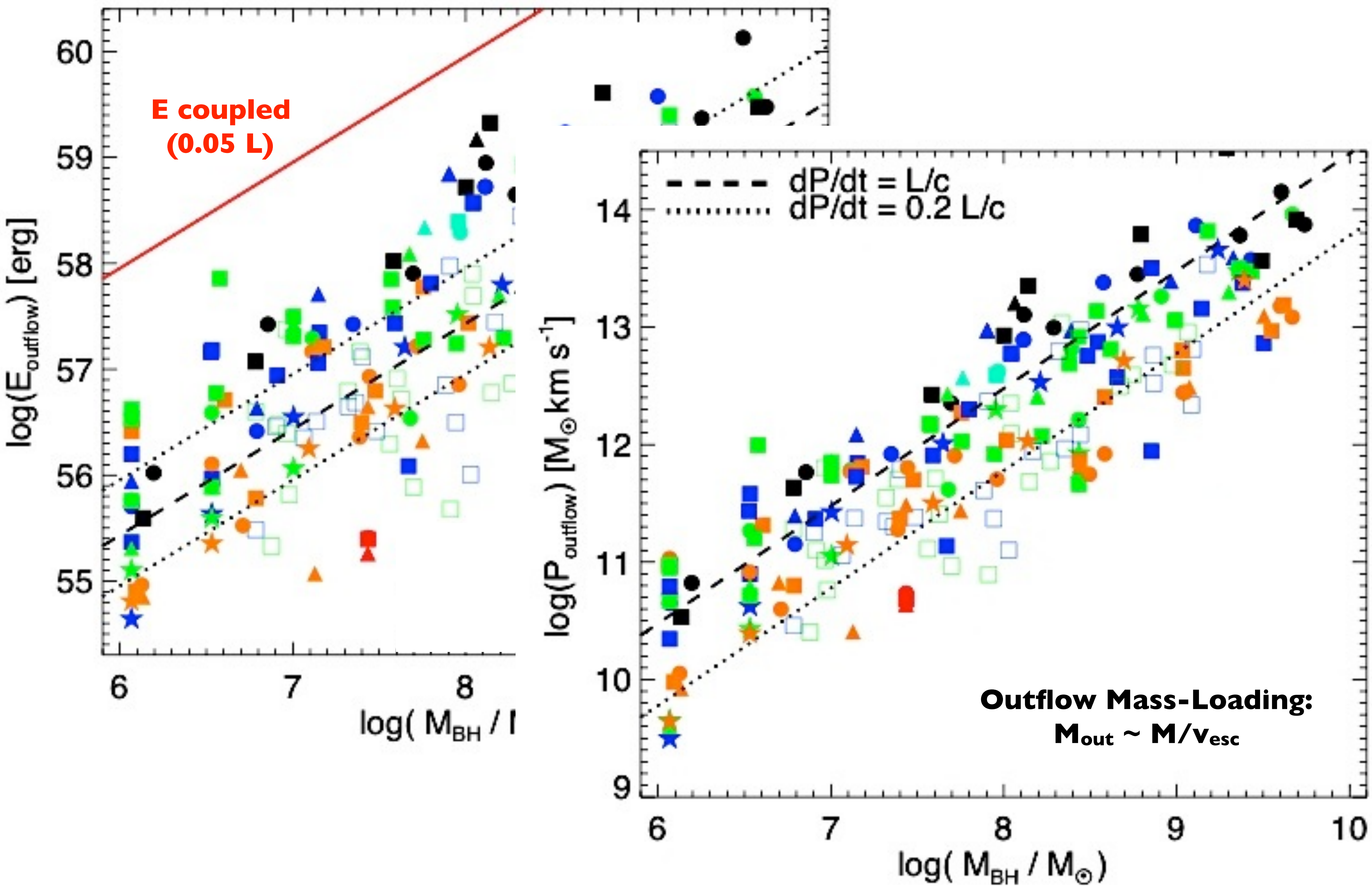


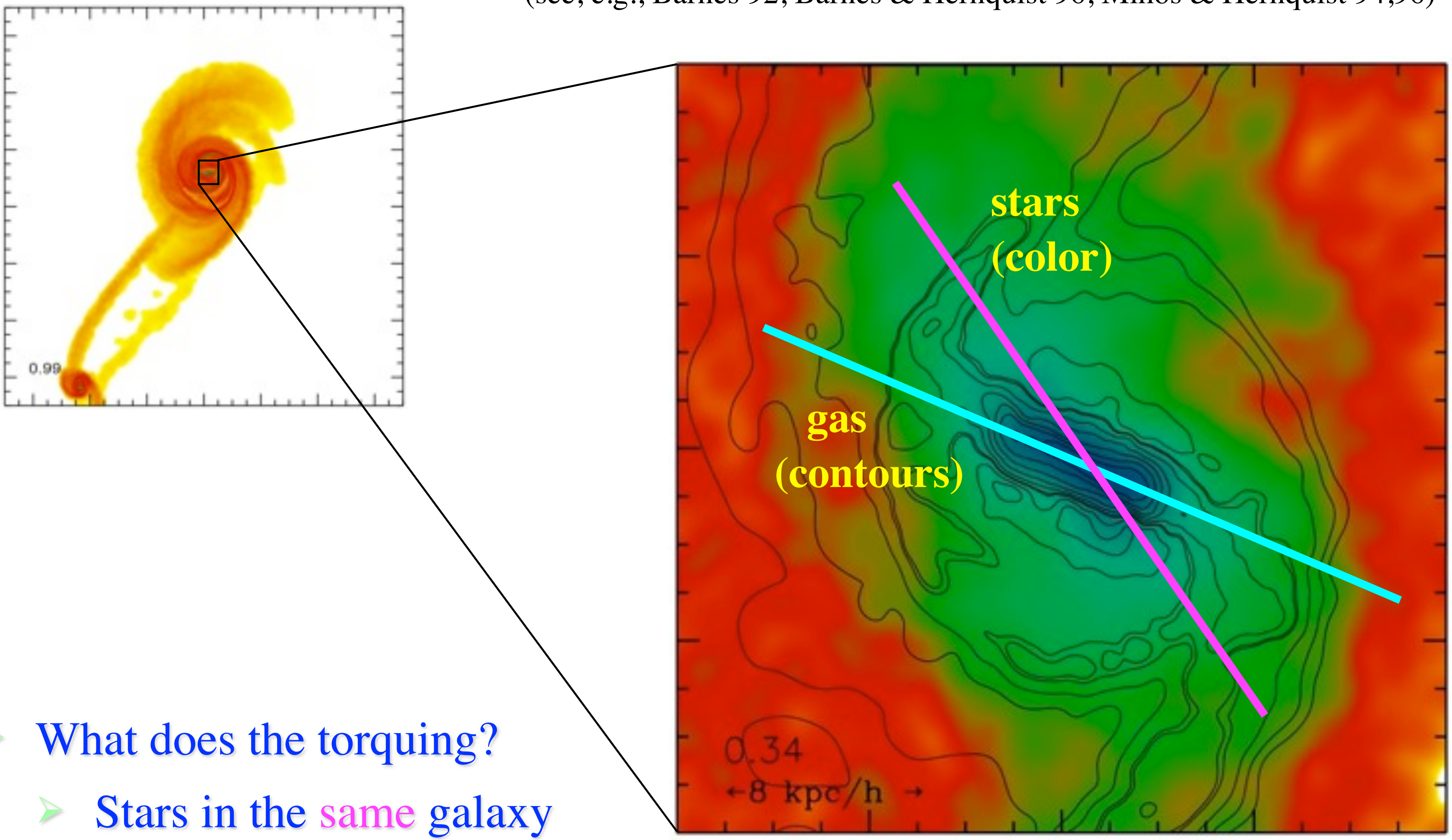
But what about the highest gas fractions?

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)



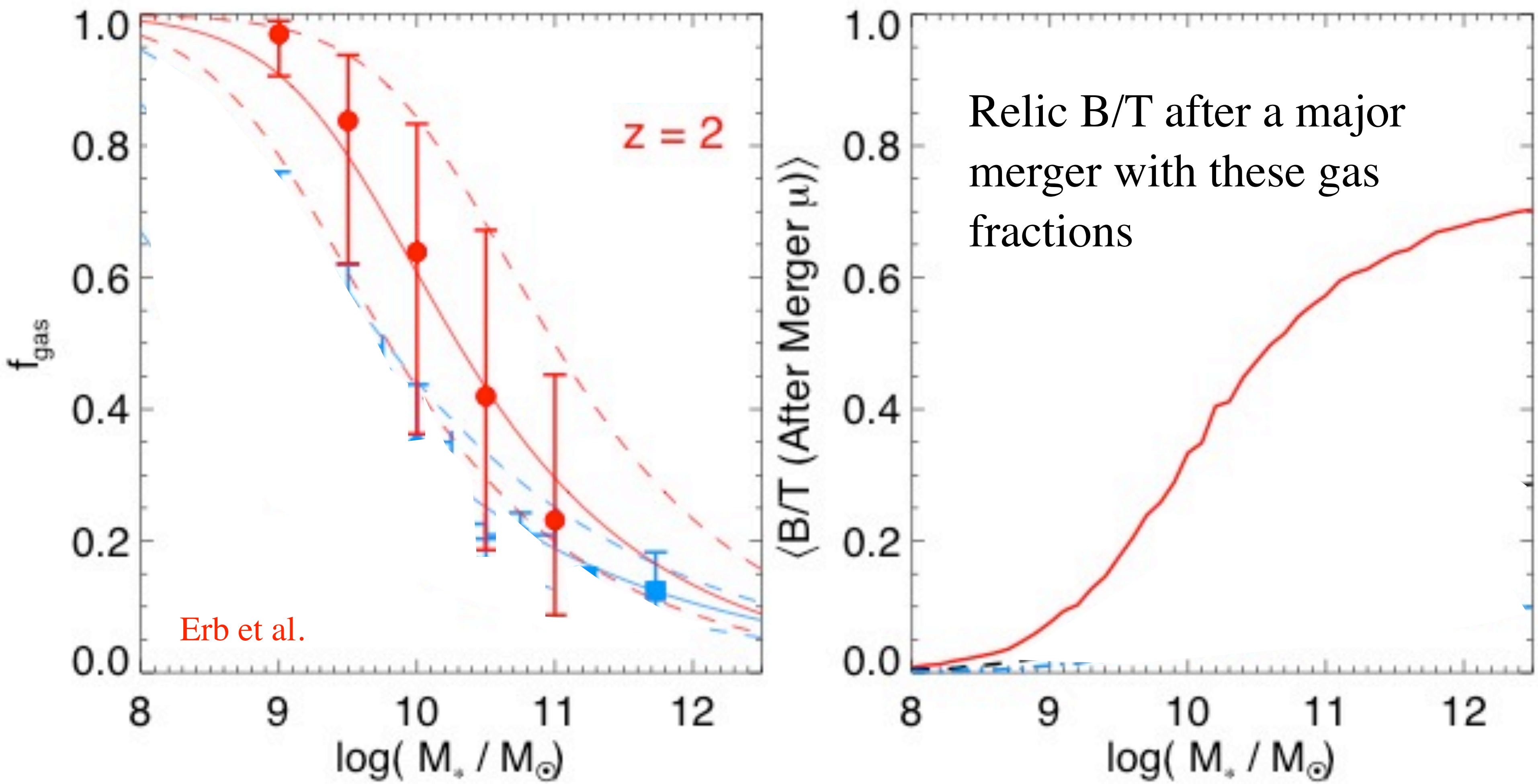
- What does the torquing?
  - Stars in the same galaxy

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 2009

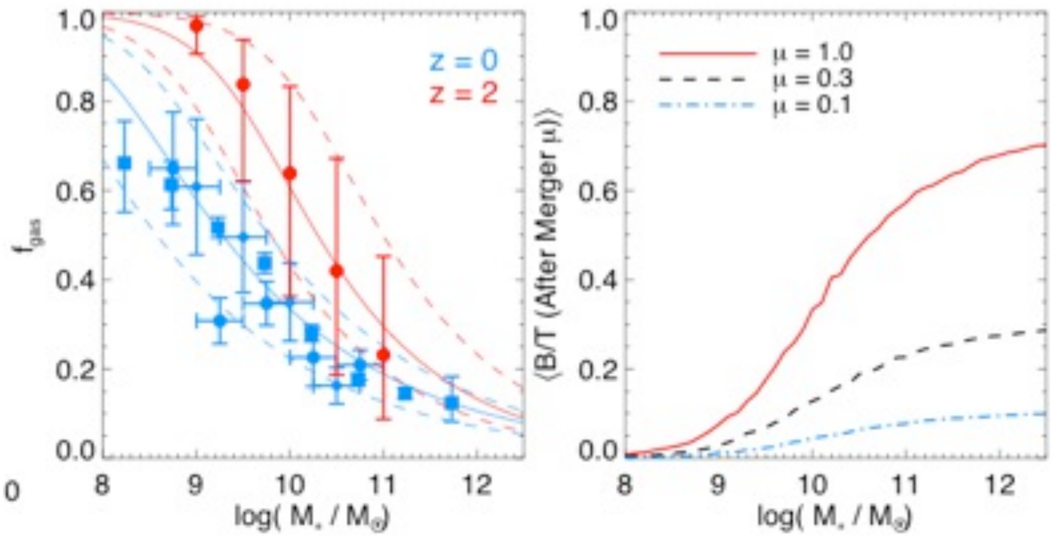
- Fold this into a cosmological model: why do we care?



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

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



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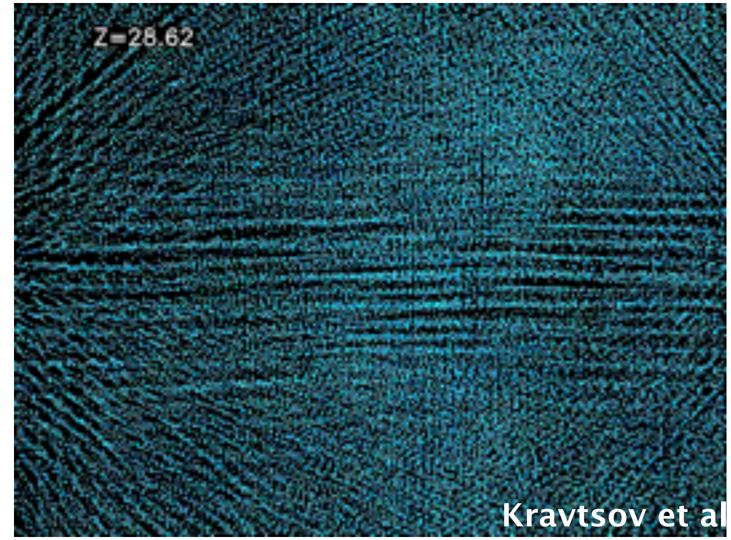

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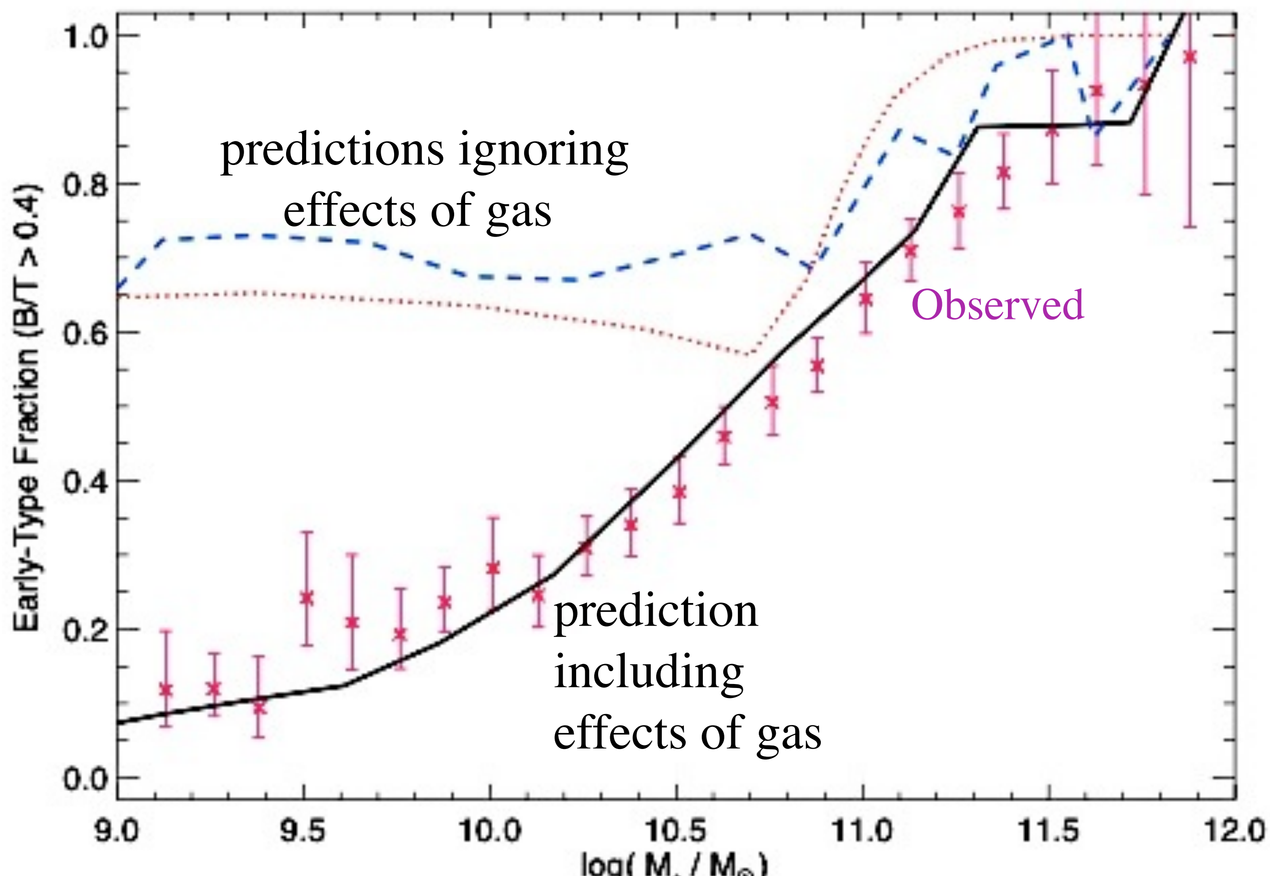
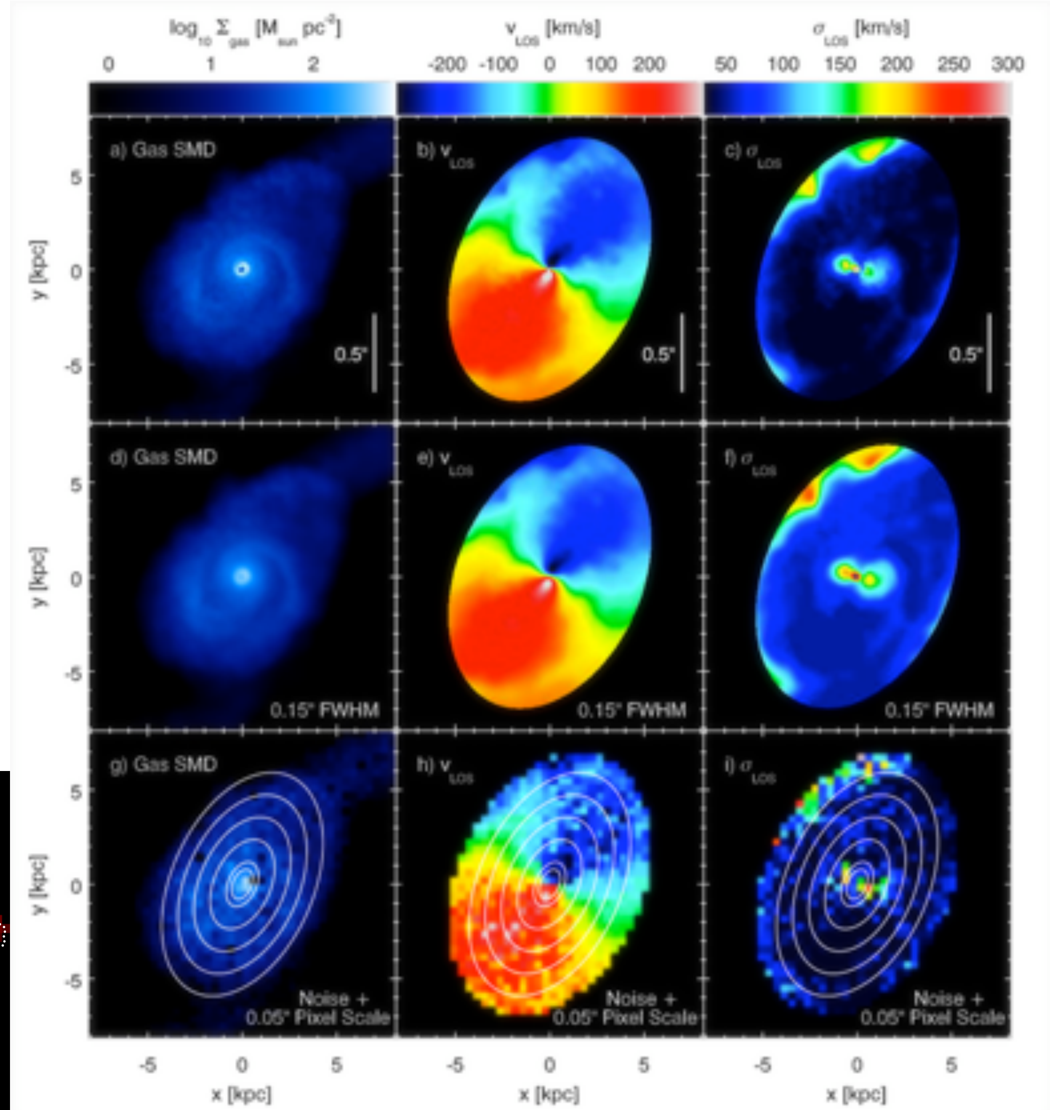


PFH & Somerville et al. 2009

High-Redshift:
WILL ONLY INCREASE IN IMPORTANCE

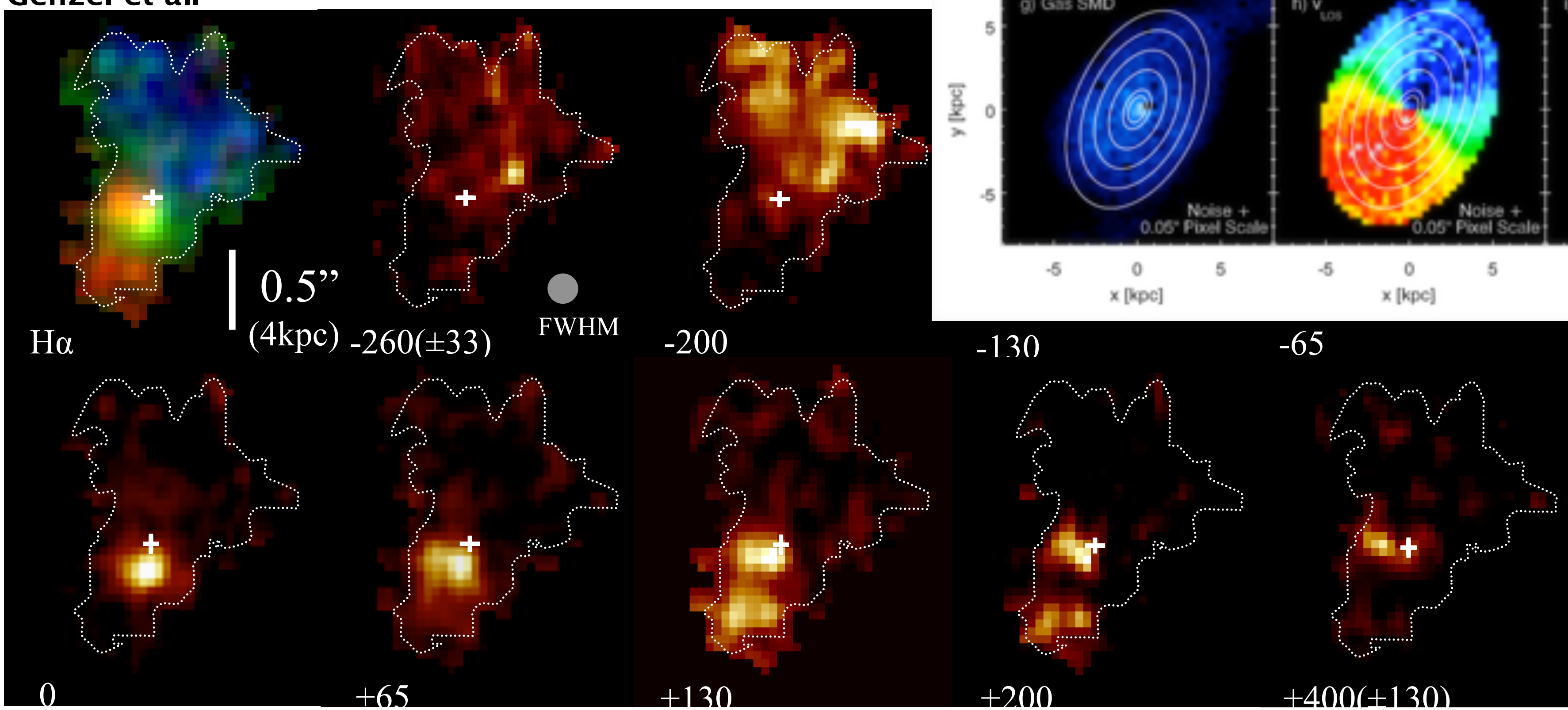
Need to explain high-z massive disks
- We see them
- (Genzel, Tacconi, Erb, Law, et al.)

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



Robertson & Bullock 2008

Genzel et al.



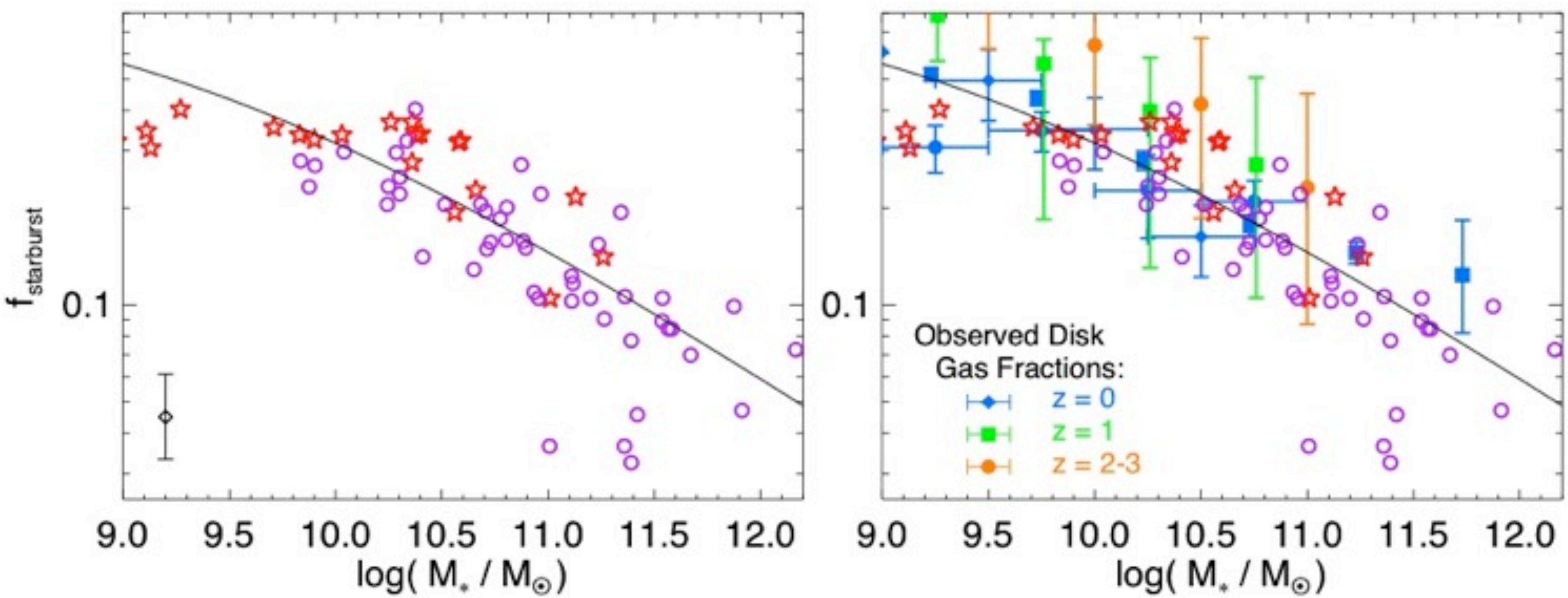
Structure in Elliptical Light Profiles

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+)

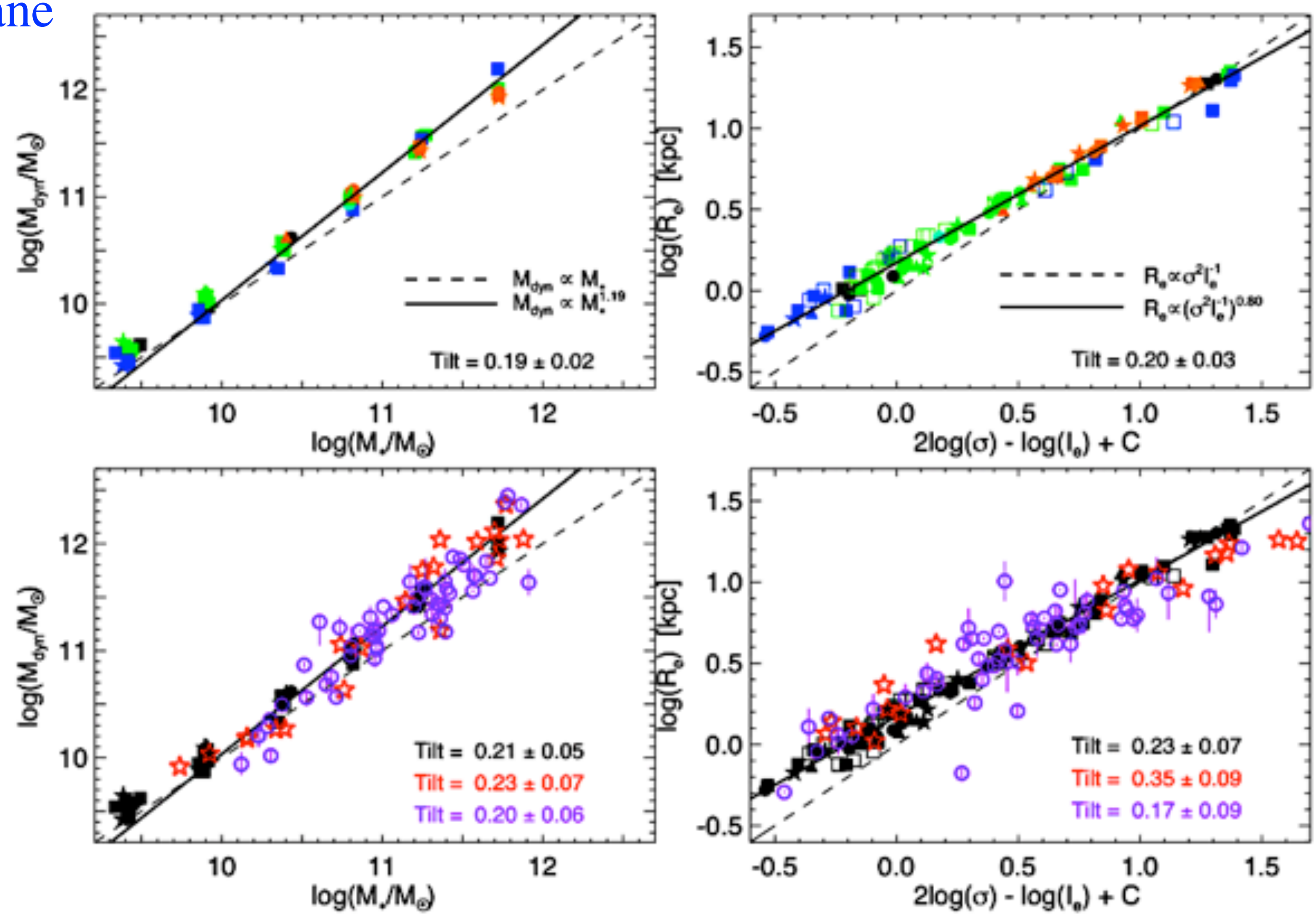
PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

Decreasing of gas/burst fraction with mass

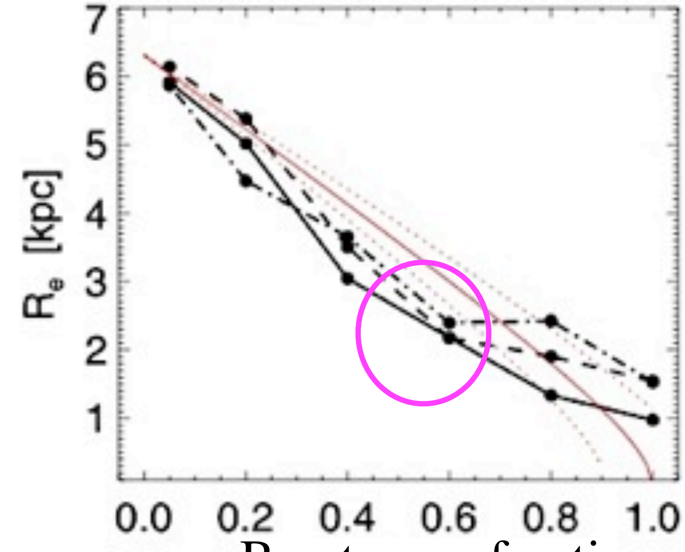
→ Increasing dark matter fractions

→ Fundamental Plane
(for free!)

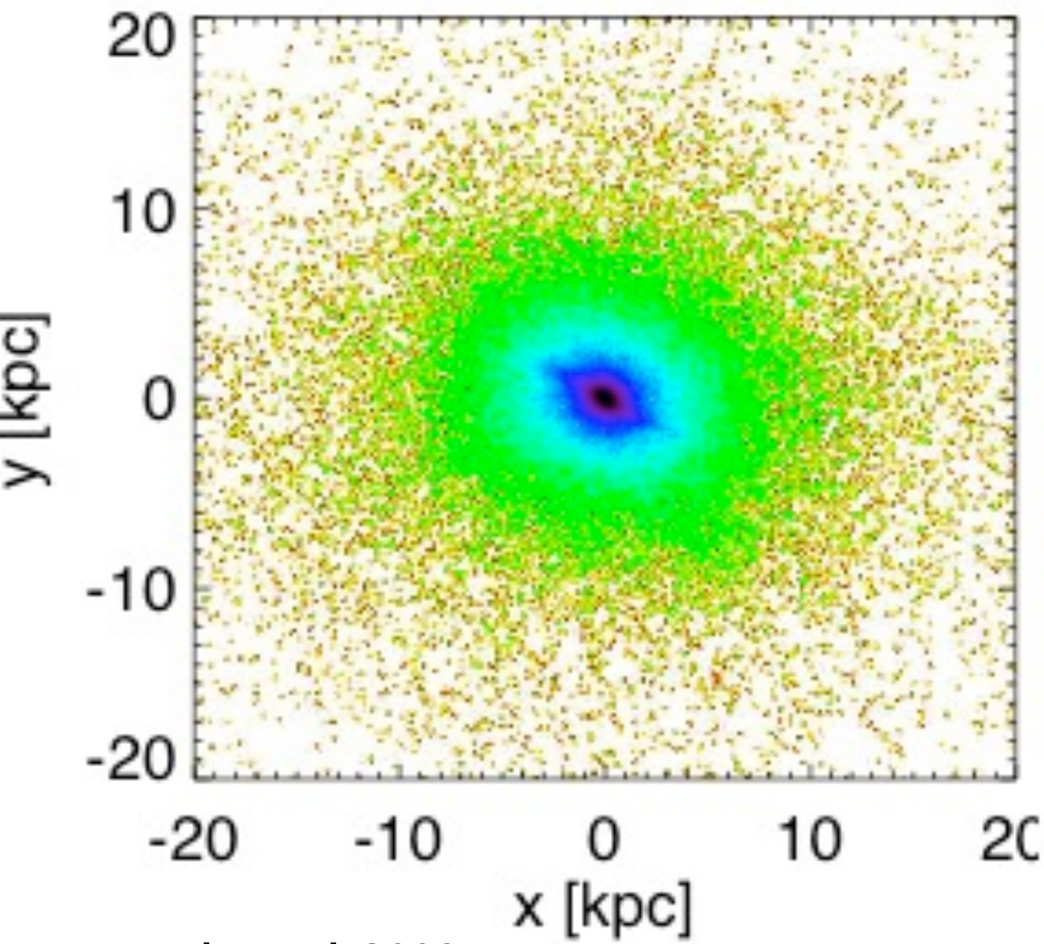


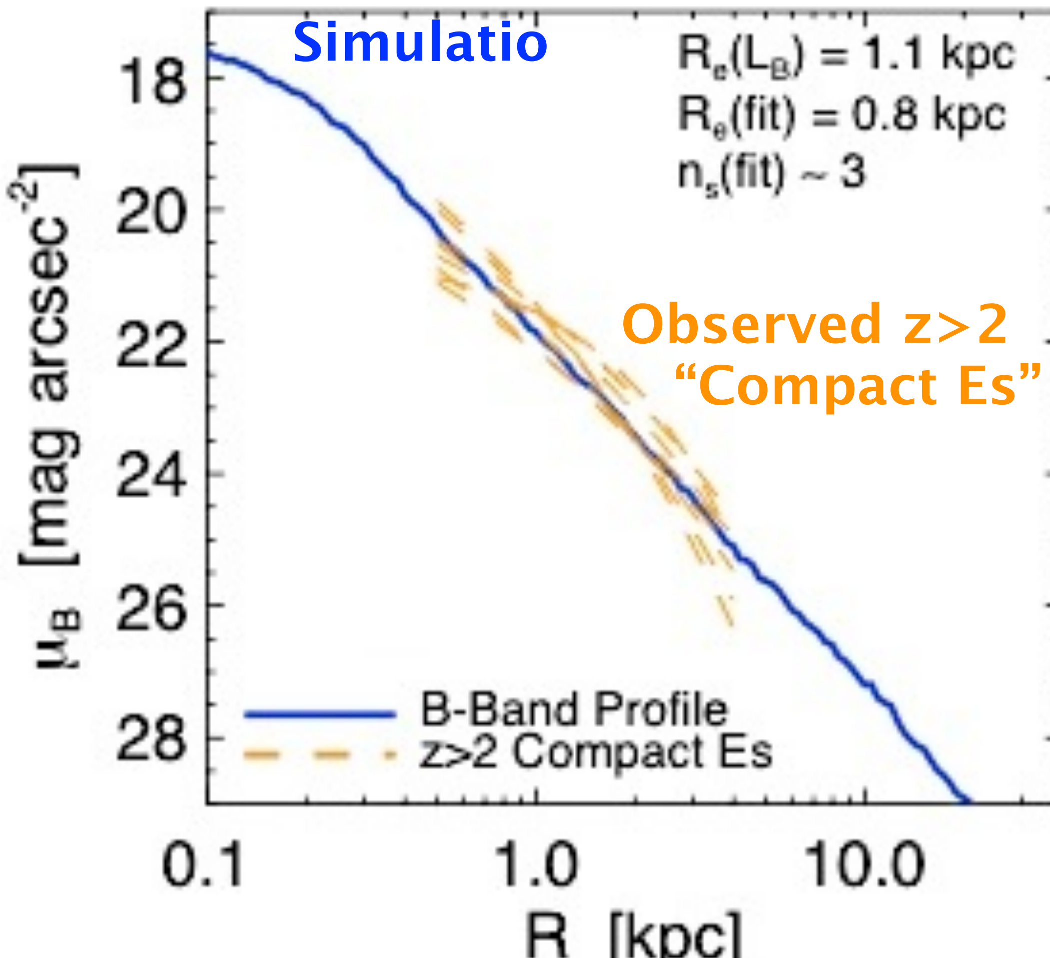
What happens as we scale up with redshift?

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



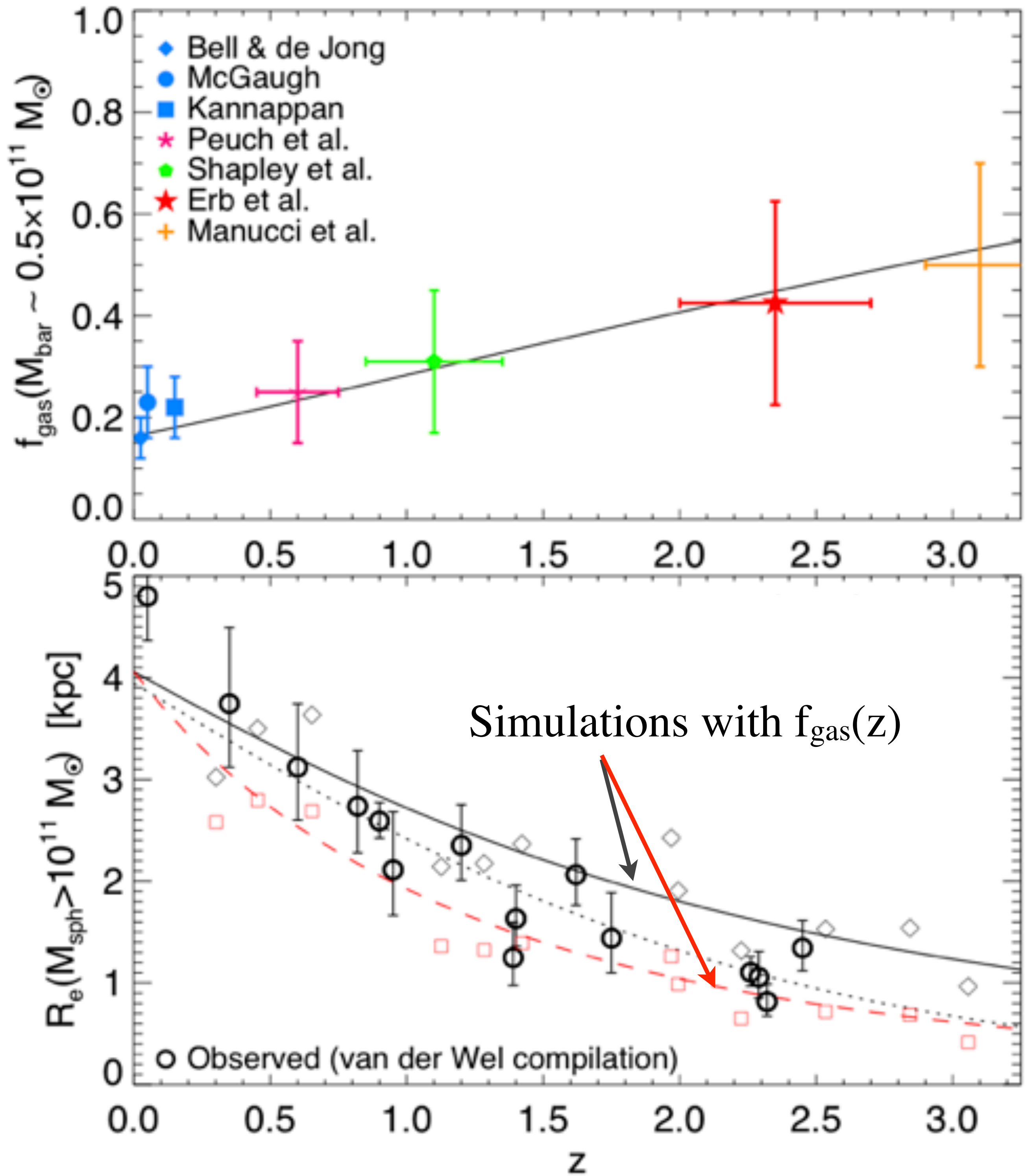
f_{gas}=0.4 merger, ~1kpc





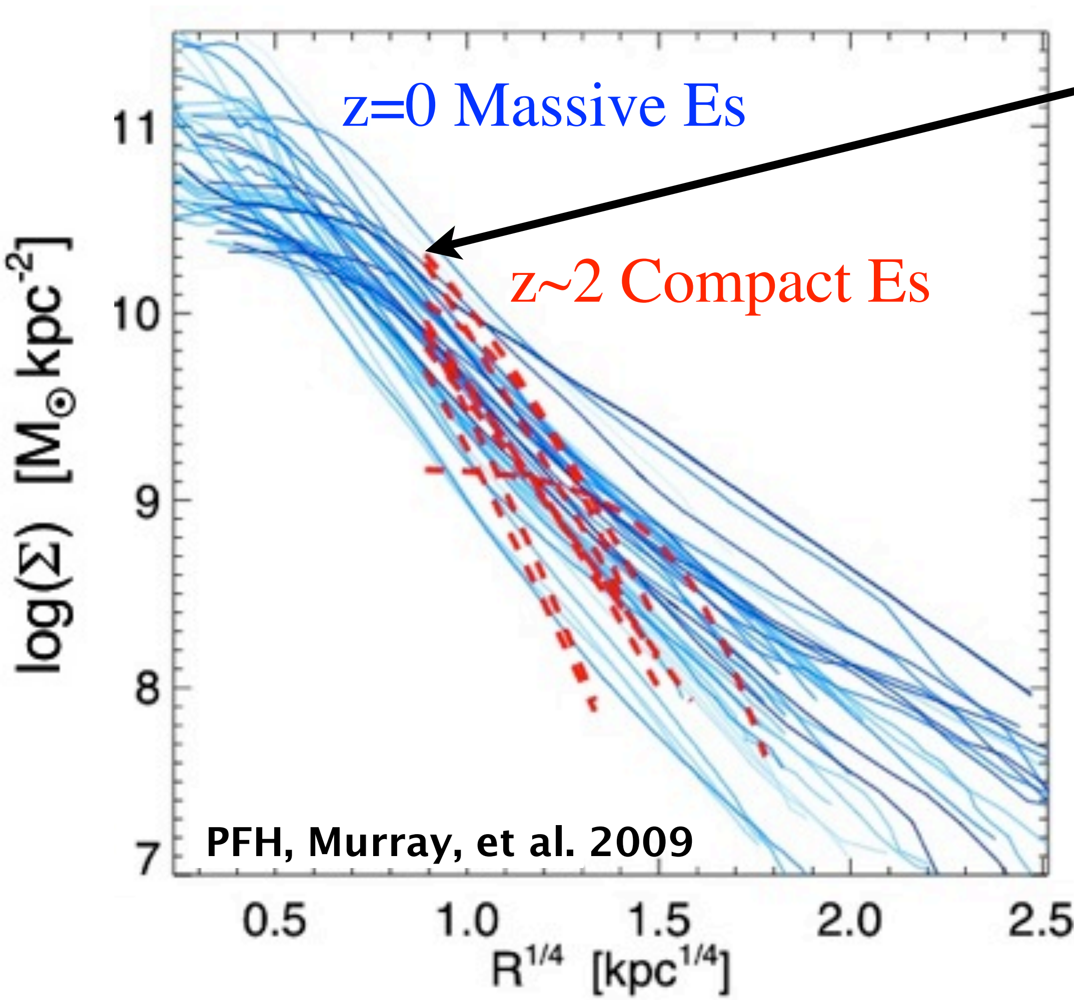
PFH, Bundy, et al. 2009

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



- Do we see the 'footprint' today?

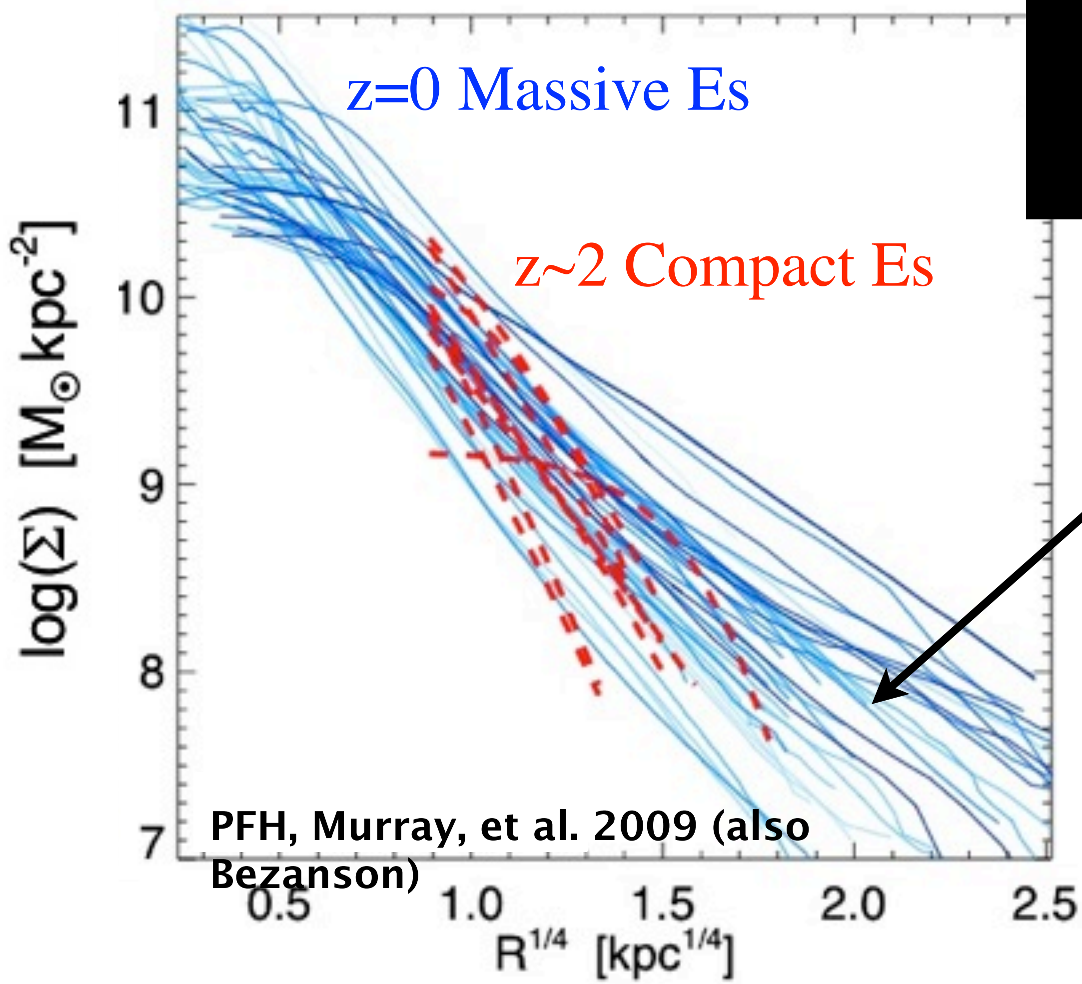
- How did the high-z systems evolve to be 'normal' at z=0?



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

(Bezanson et al., 2009)

- Do we see the 'footprint' today?
- How did the high-z systems evolve to be 'normal' at z=0?



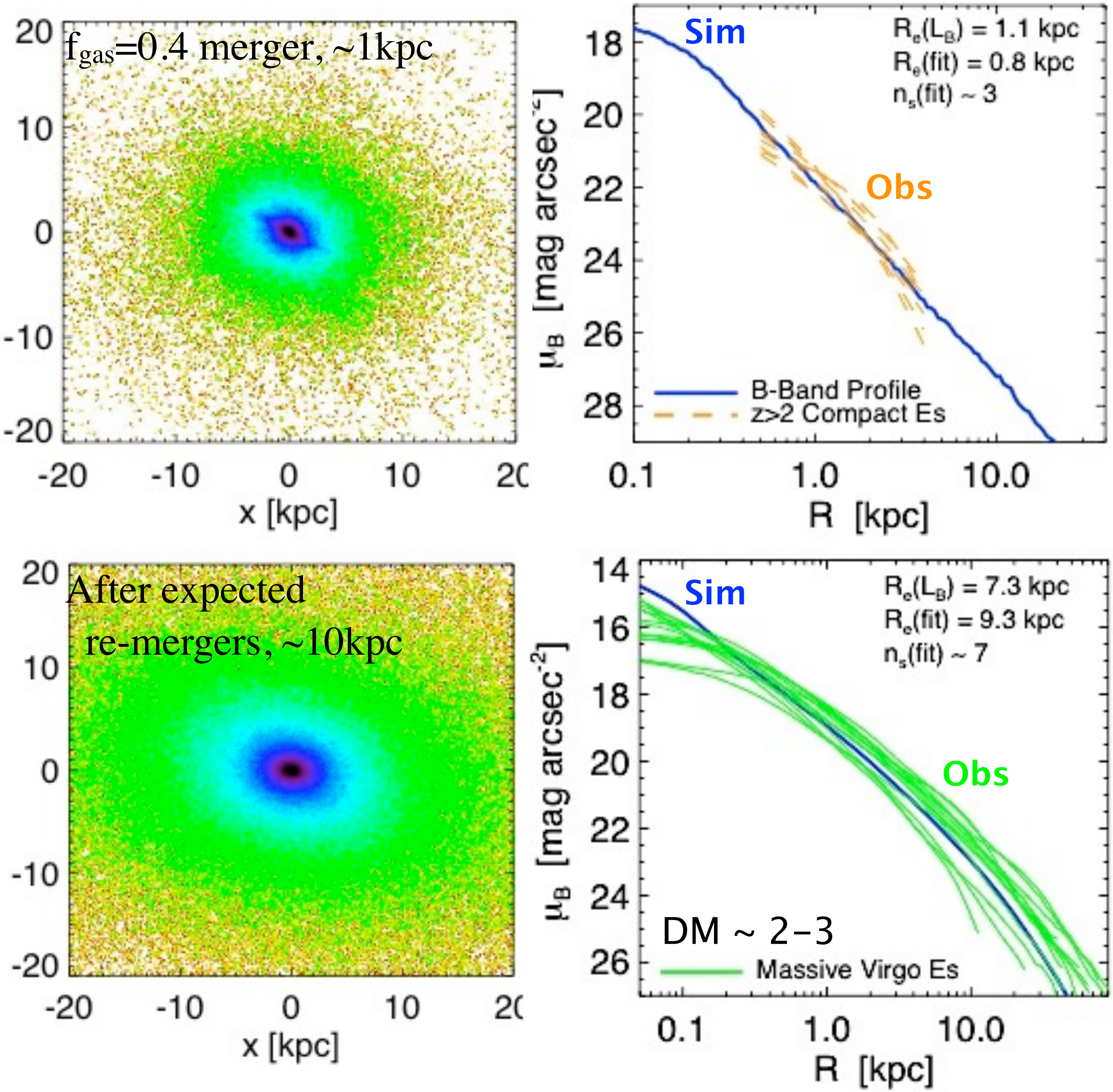
PFH, Murray, et al. 2009 (also Bezanson)

Missing the low-density "wings":

Only need to accrete $\sim M_{gal}$ 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