Galaxy Mergers: A Factory for Quasars, Feedback, Ellipticals, and even Disks?

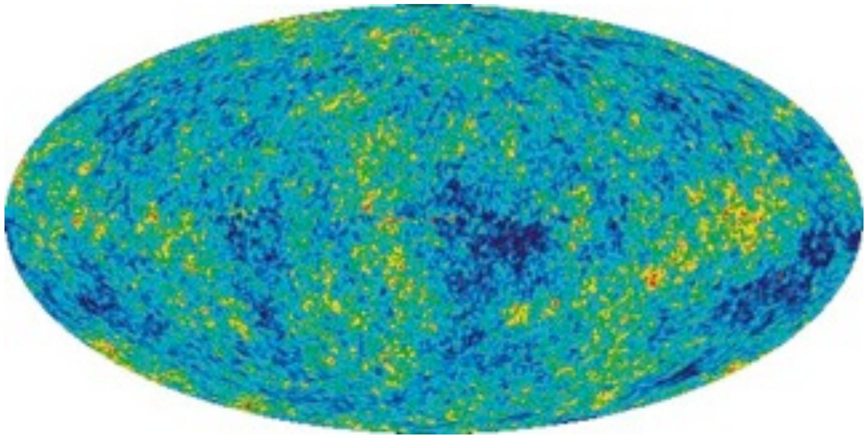
Philip Hopkins

30/09/2009

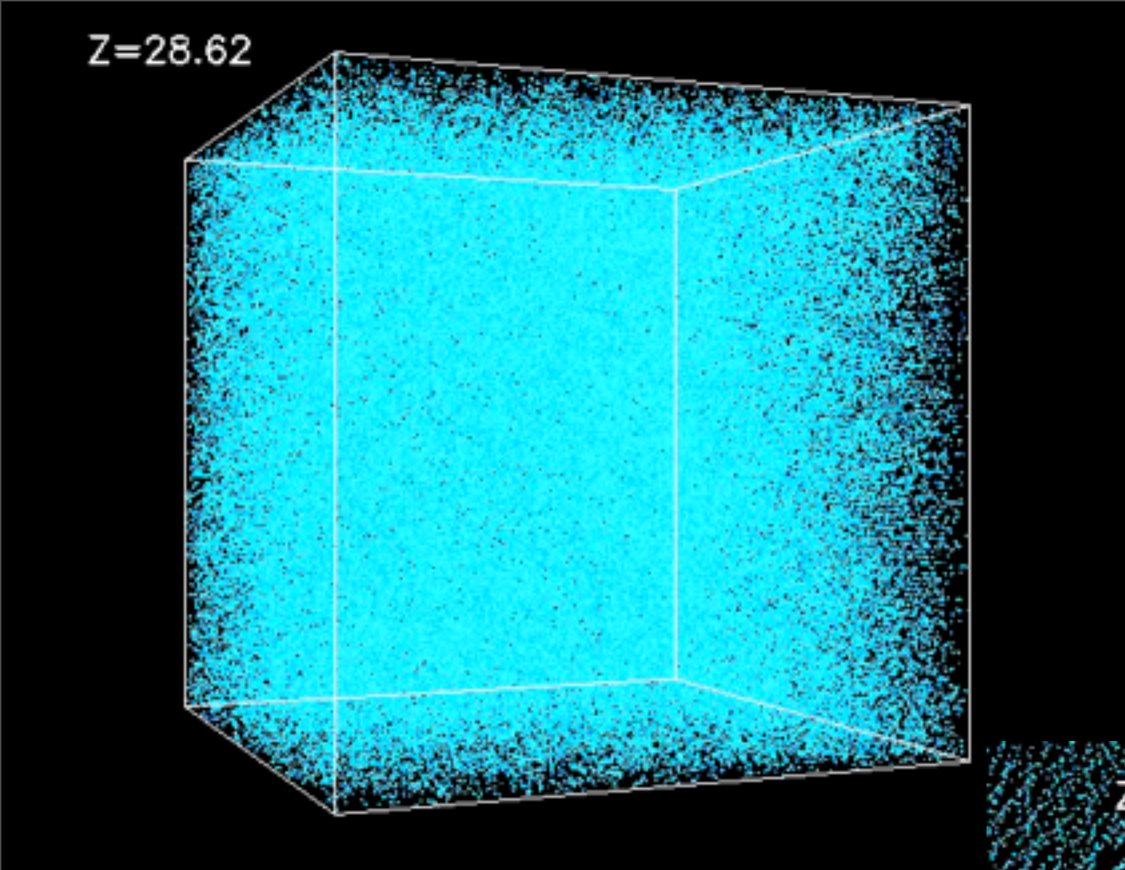
Lars Hernquist, T. J. Cox, Dusan Keres, Eliot Quataert, Chung-Pei Ma,
Josh Younger, Volker Springel, Norm Murray, Kevin Bundy,
Brant Robertson, John Kormendy, Tod Lauer, Adam Lidz, Tiziana Di Matteo,
Yuexing Li, Gordon Richards, Alison Coil, Adam Myers, and many more

Motivation

HOW DID WE GET TO GALAXIES TODAY?



?



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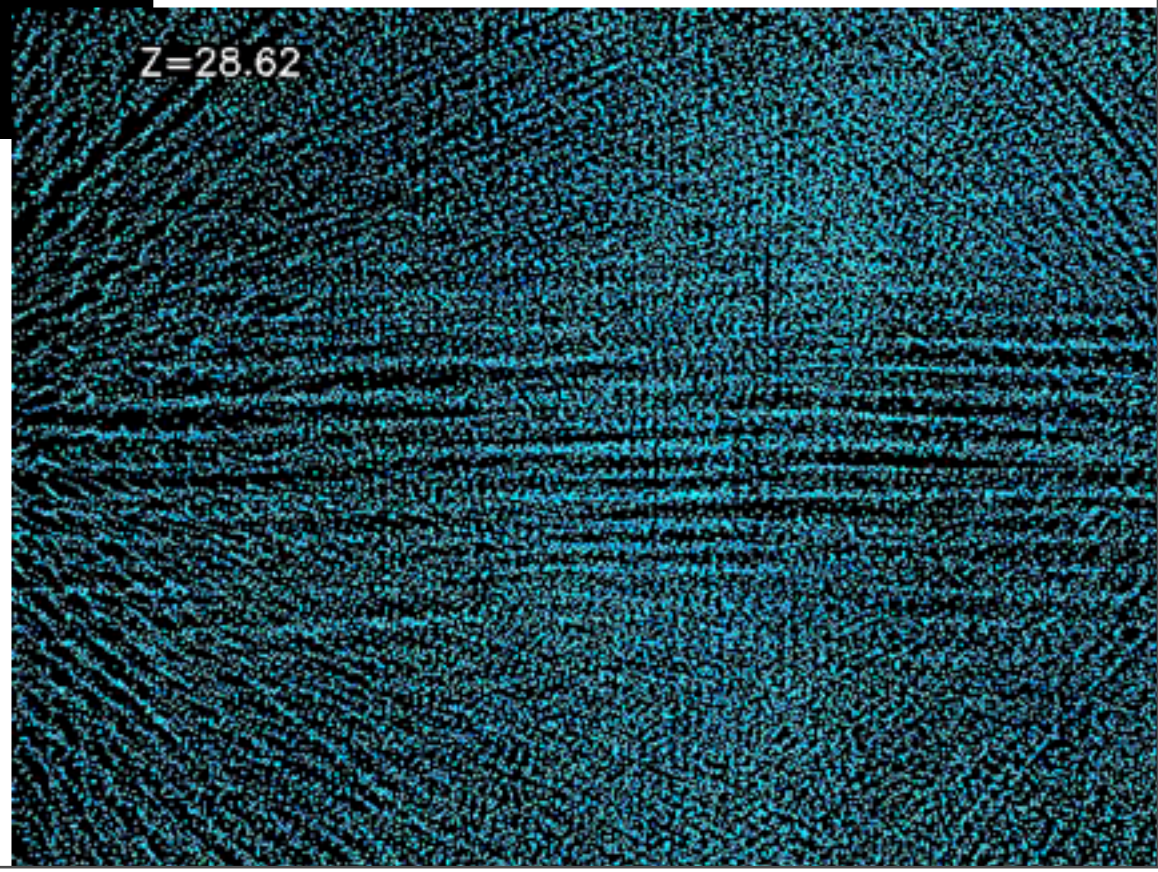
Kravtsov et al.



- Structure grows hierarchically: *must* understand mergers

Motivation

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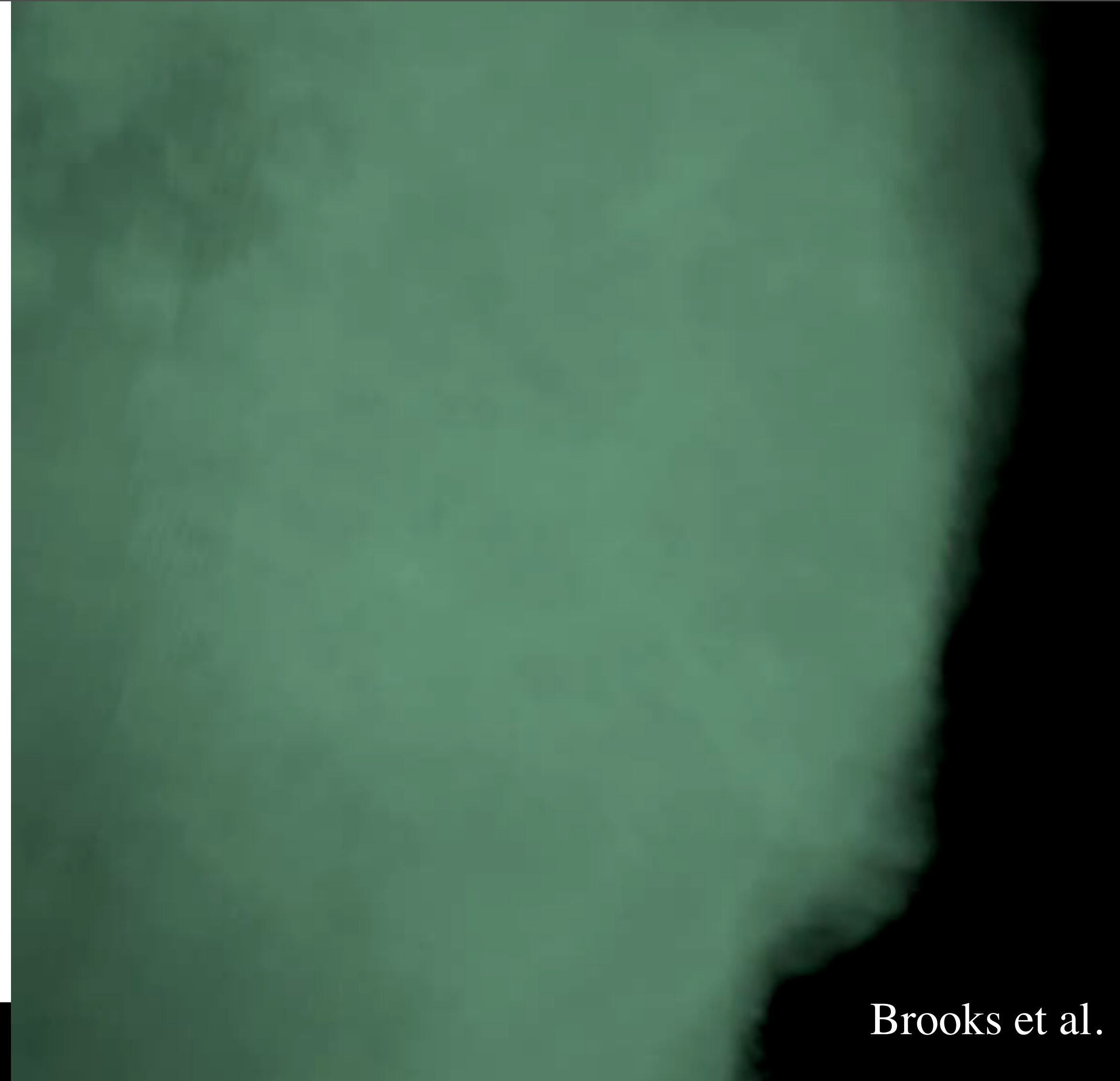
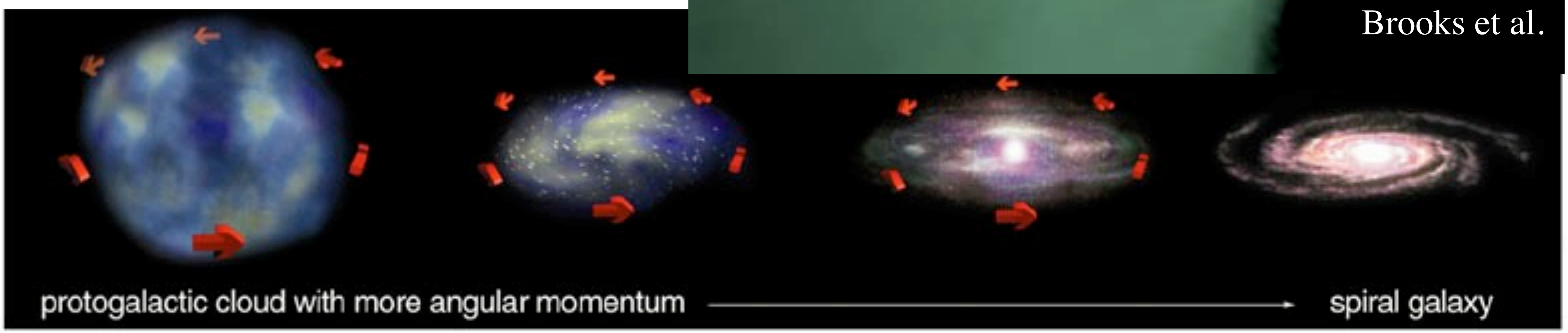
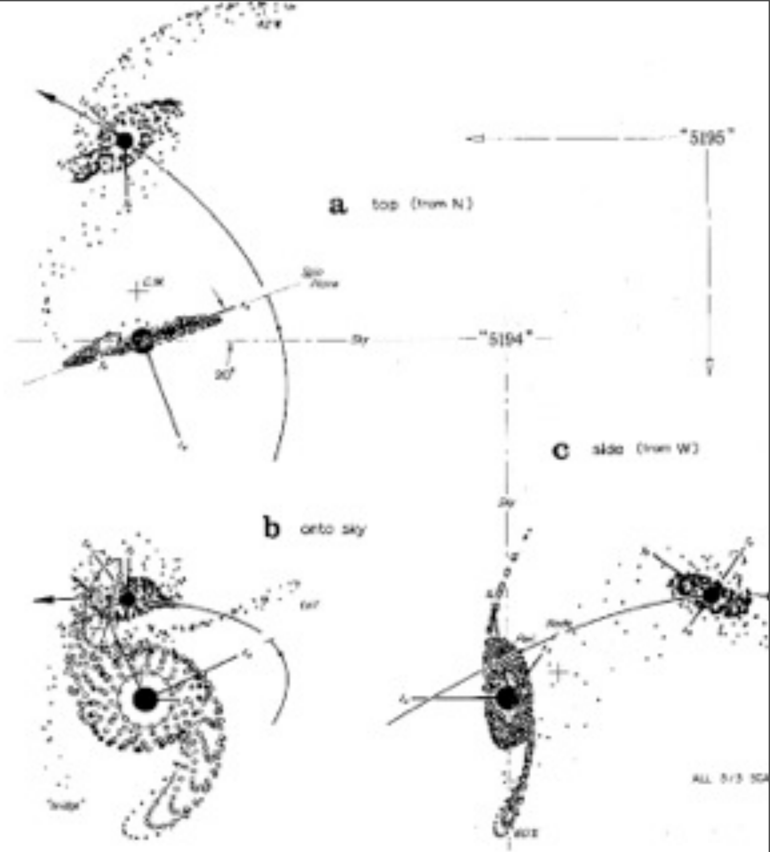


- Dark matter halos collapse: gas cools into a disk



- What happens when that starts colliding into other galaxies?

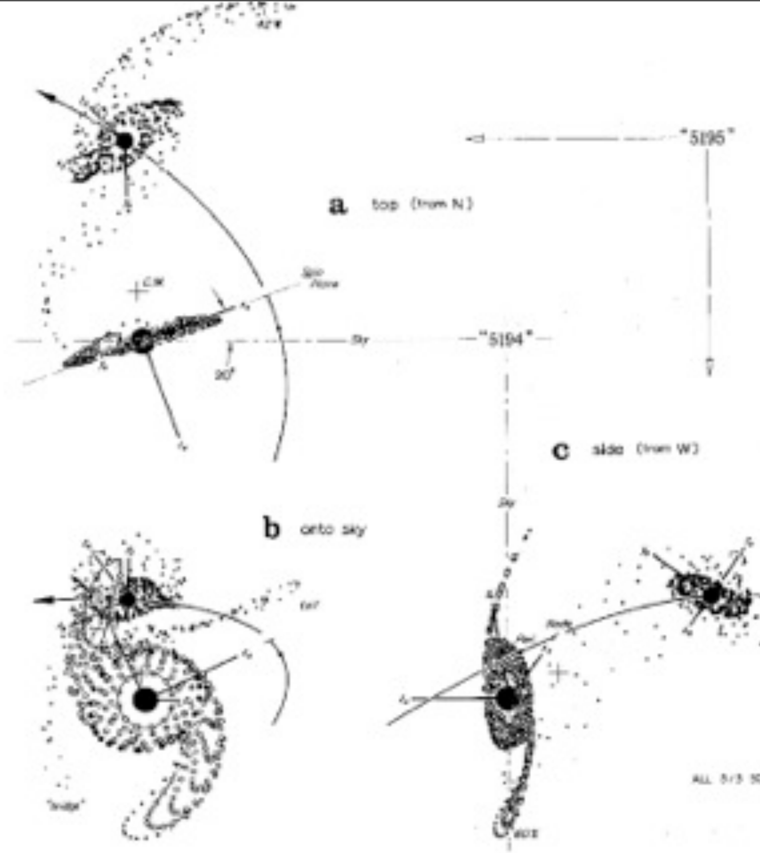
Our Conventional Wisdom (Toomre):



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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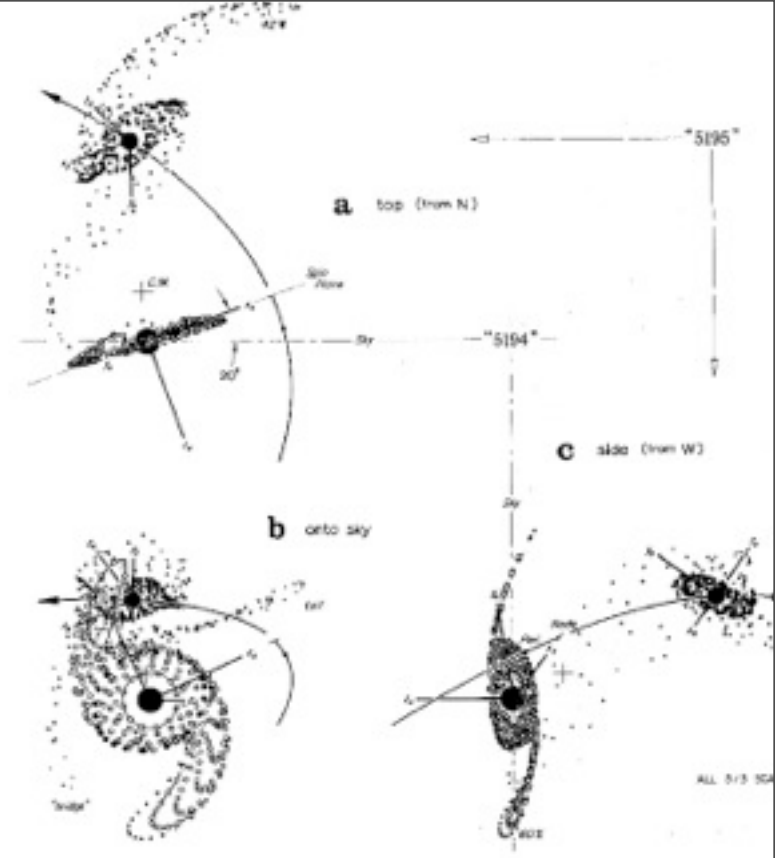
Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk



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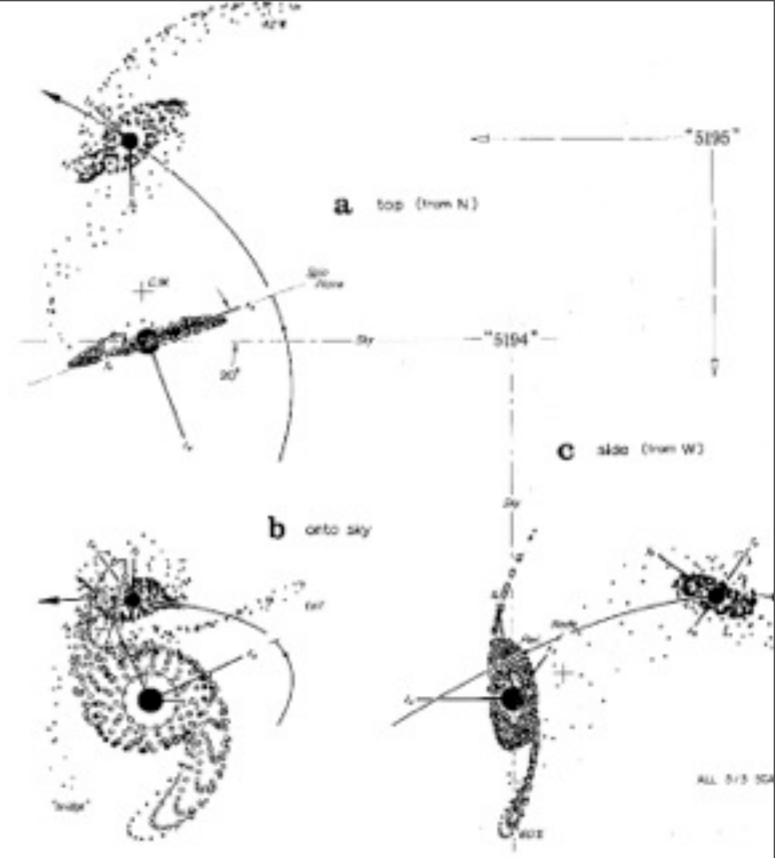

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Our Conventional Wisdom (Toomre):

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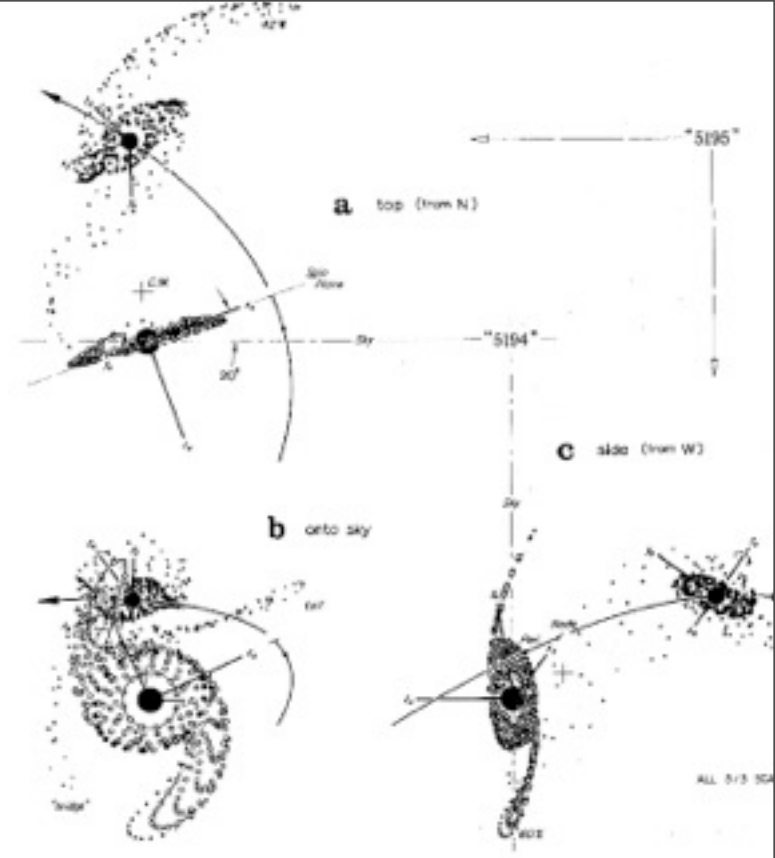
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



F. Summers

Motivation

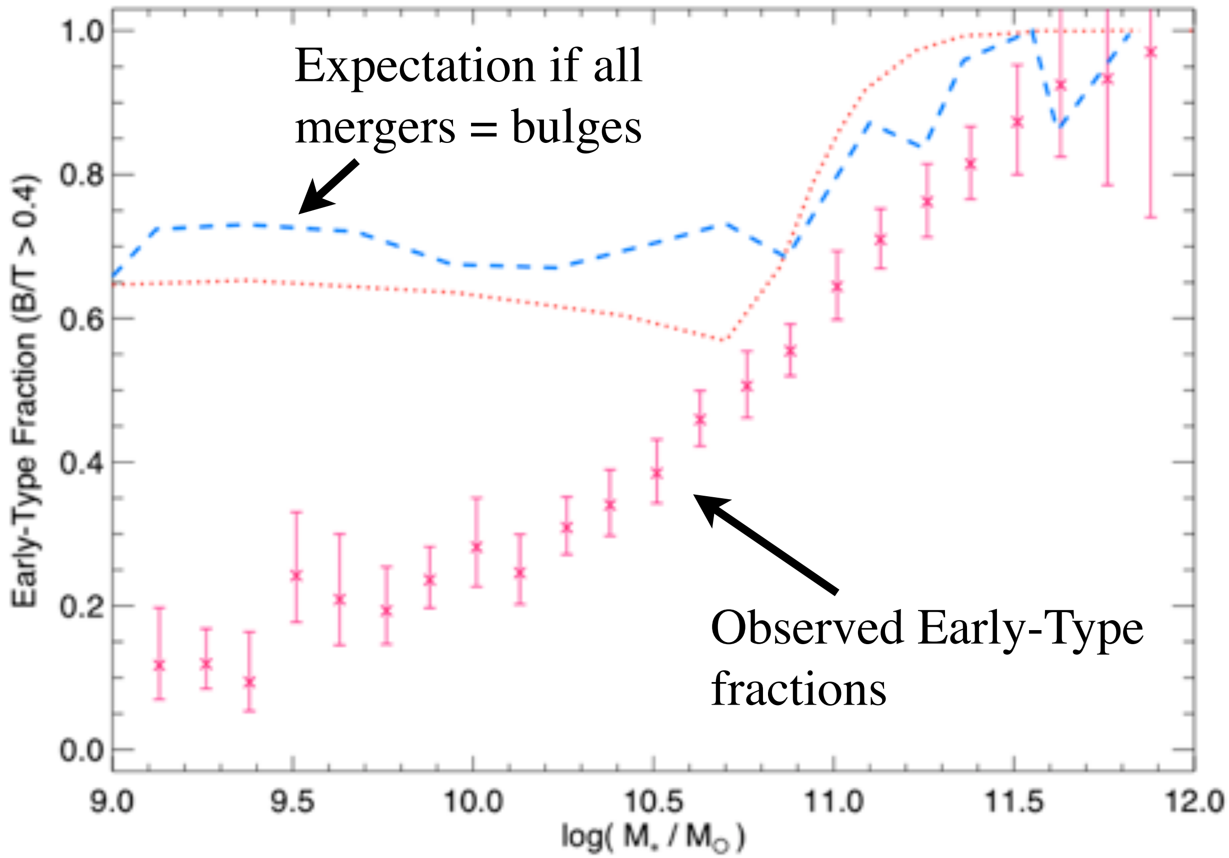
HOW DID WE GET TO GALAXIES TODAY?

Many of these are *problems*...

Too Many Mergers?

-- missing some physics

(Governato, Navarro, Scannapieco, Somer-Larson, et al.)

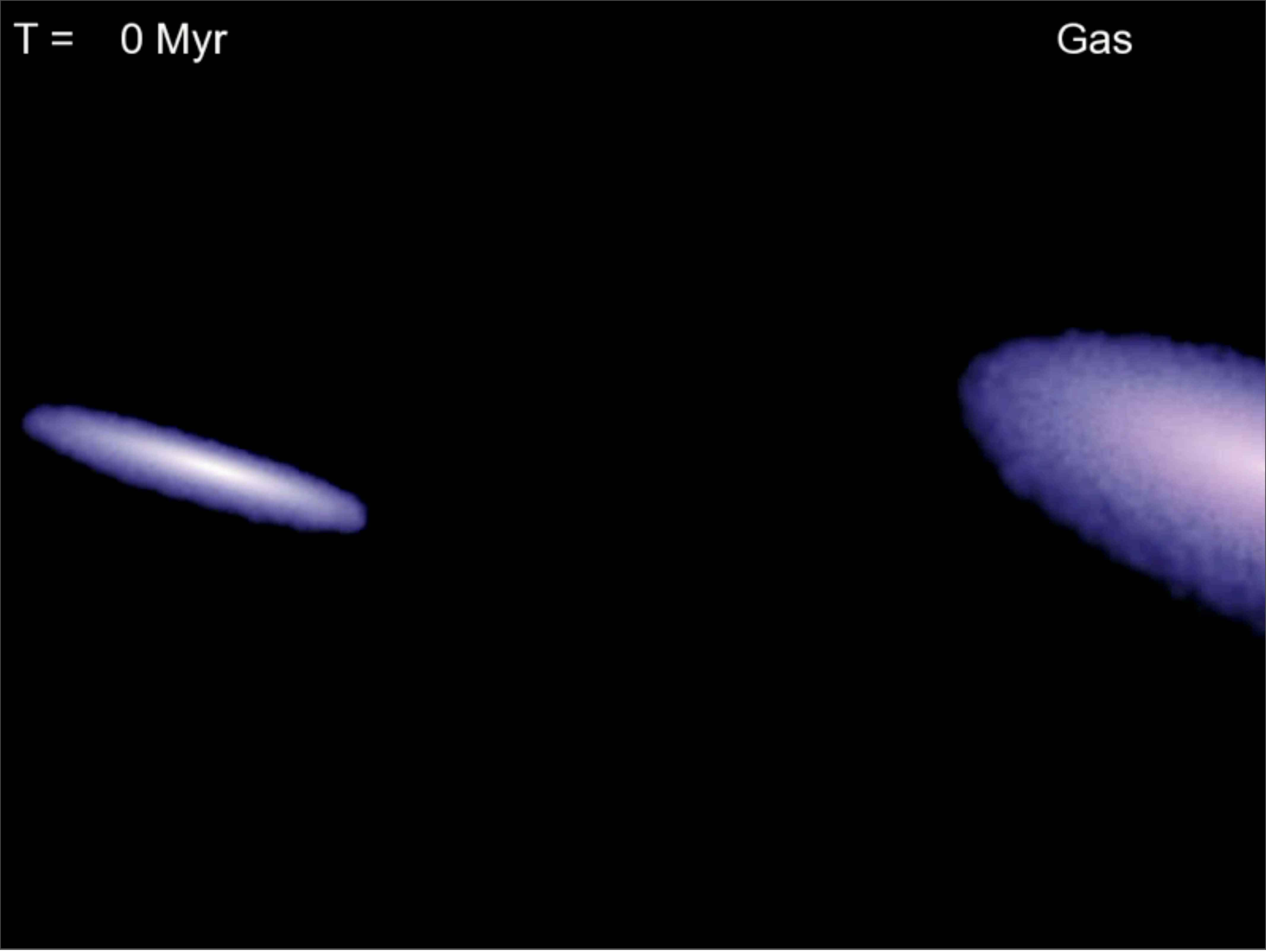


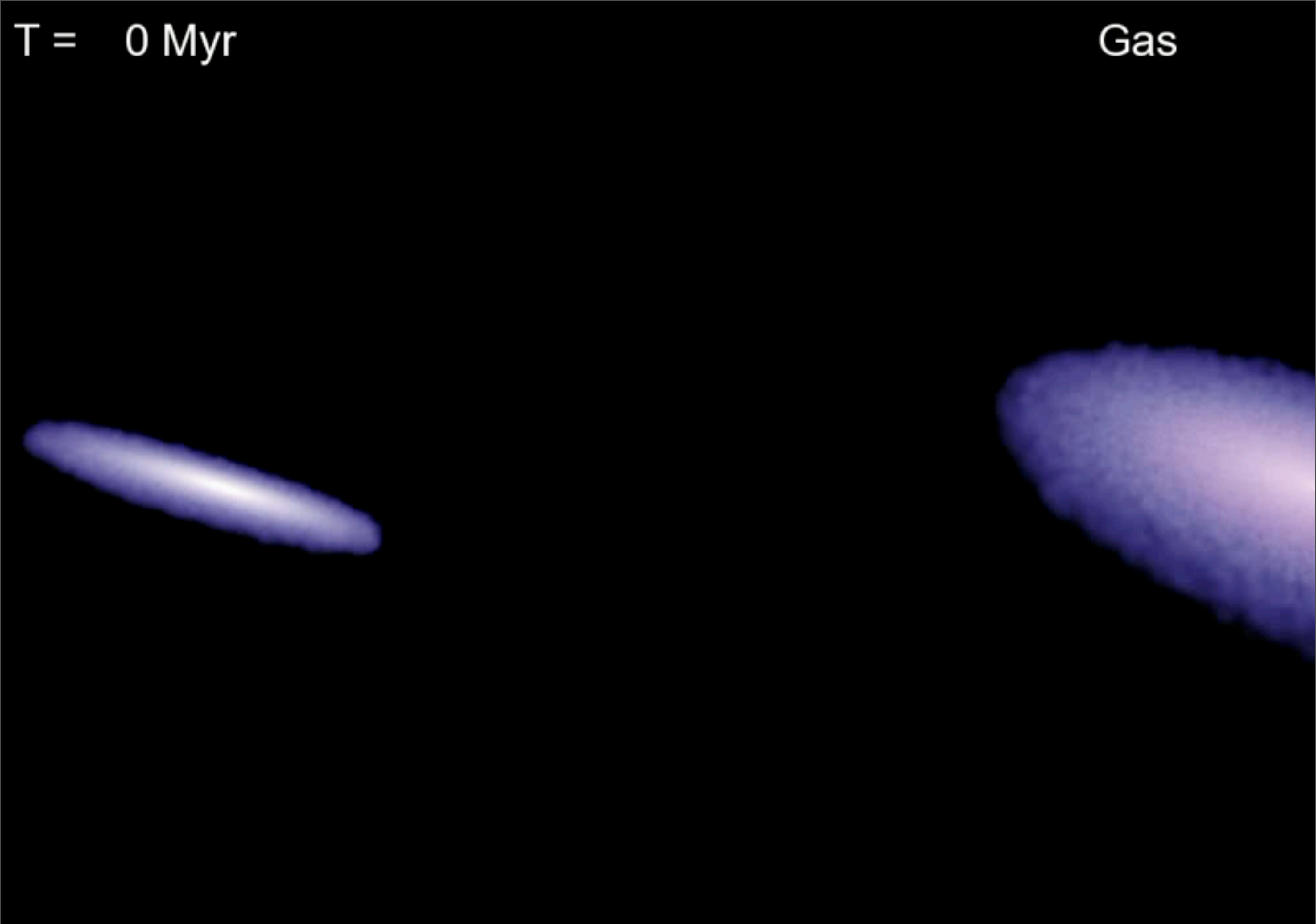
Stellar disk-disk merger remnants don’t look like bulges!

-- sizes too large

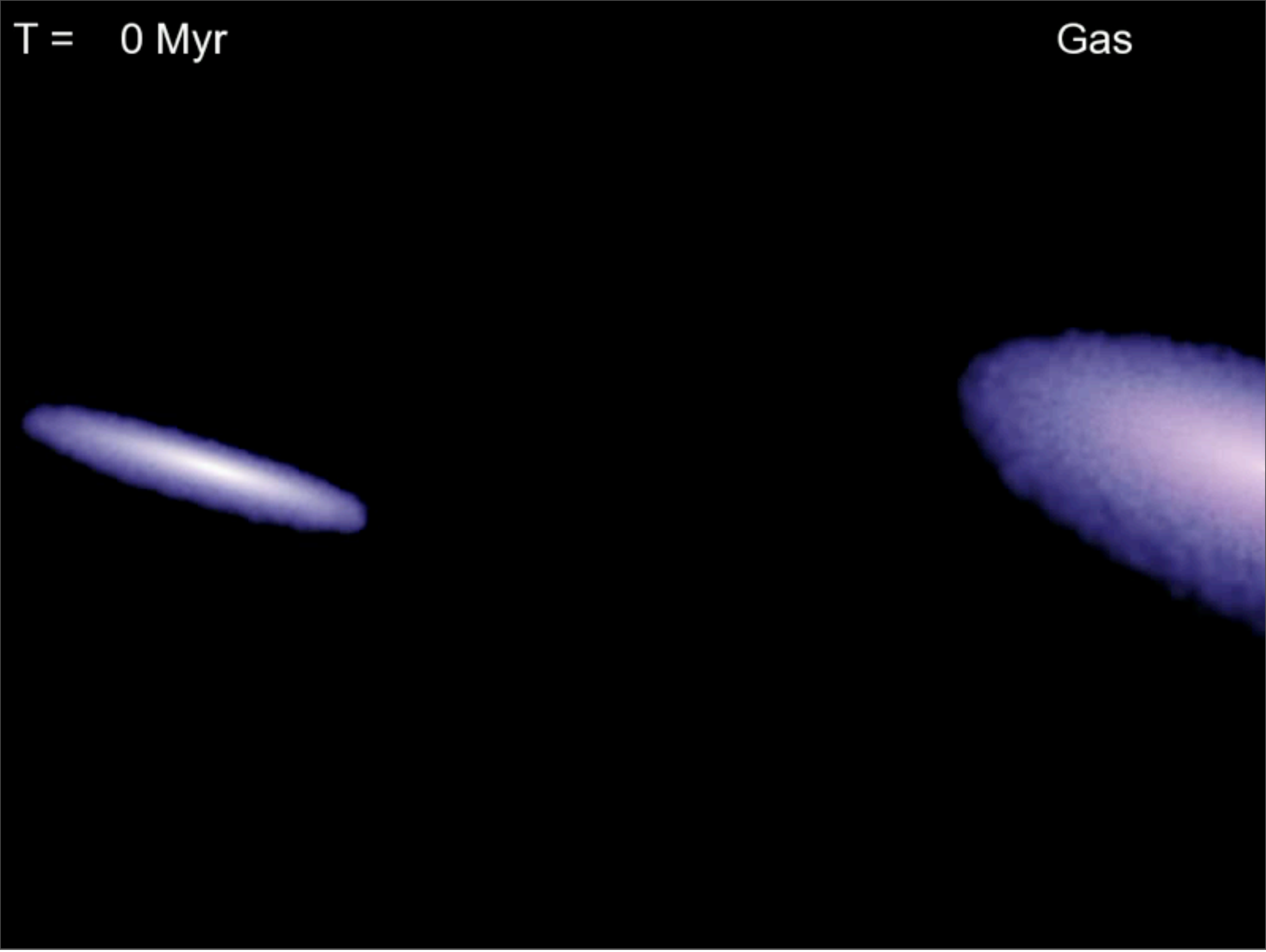
-- profiles too flat

-- shapes too flattened


T = 0 Myr
Gas



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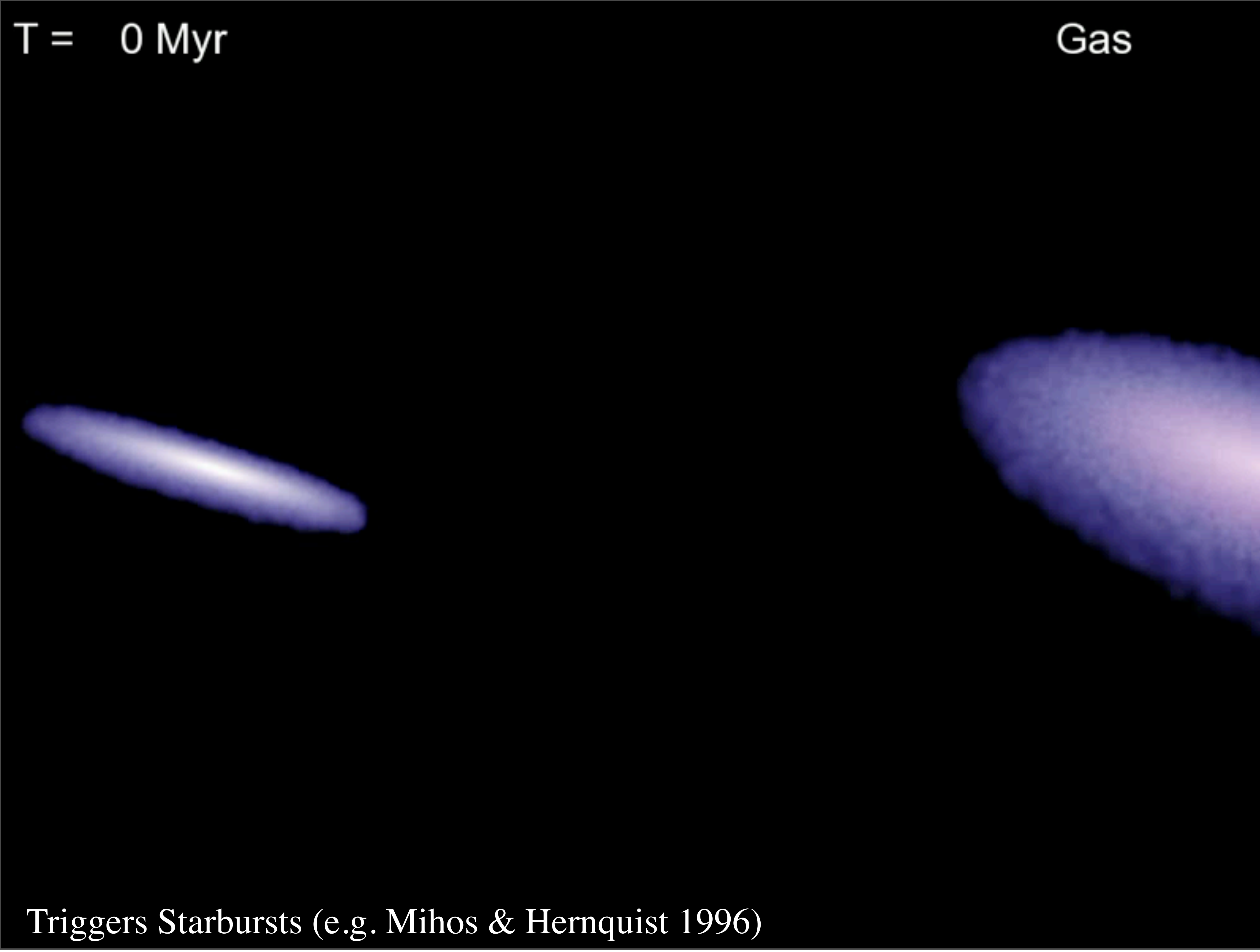
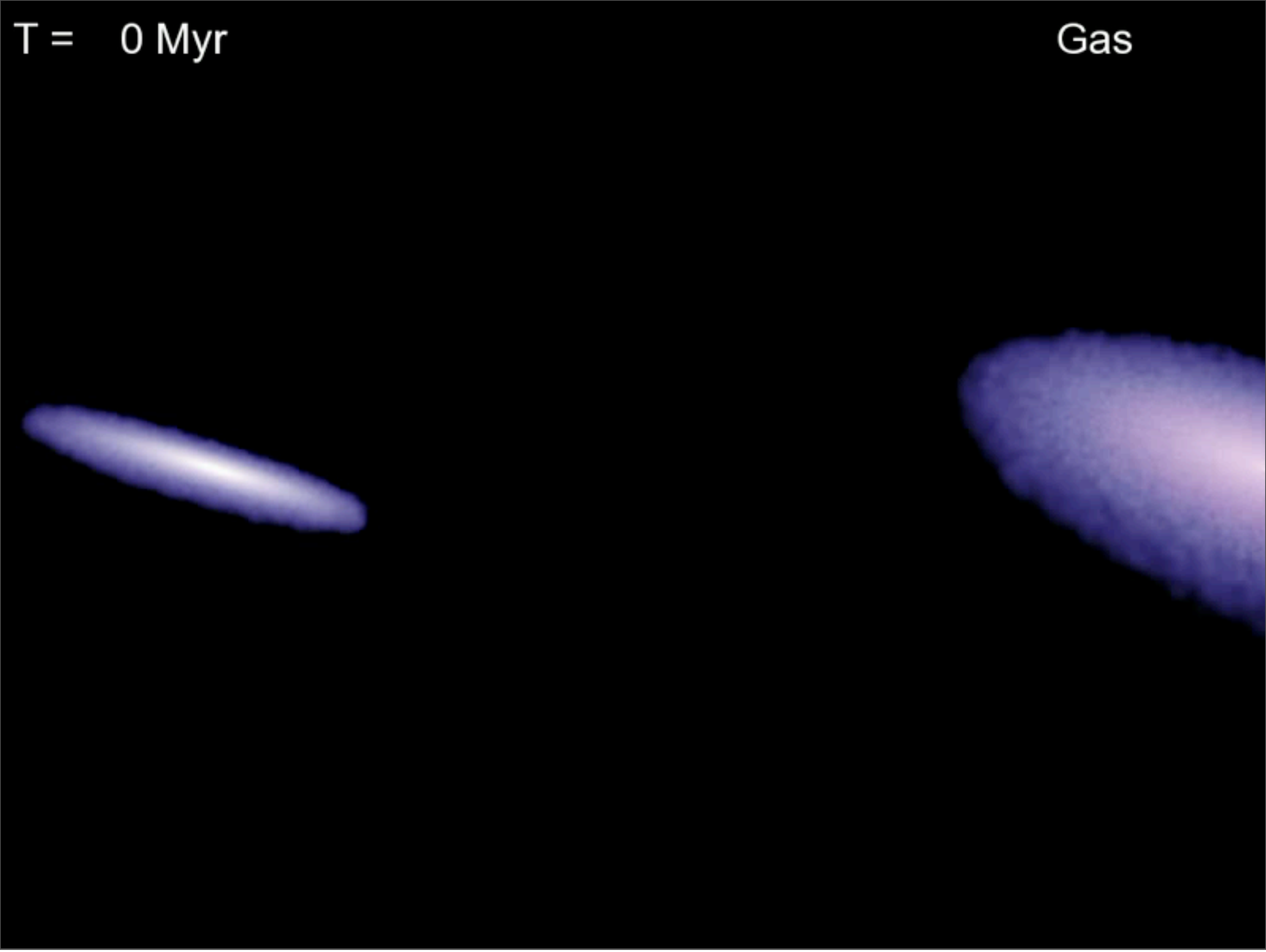


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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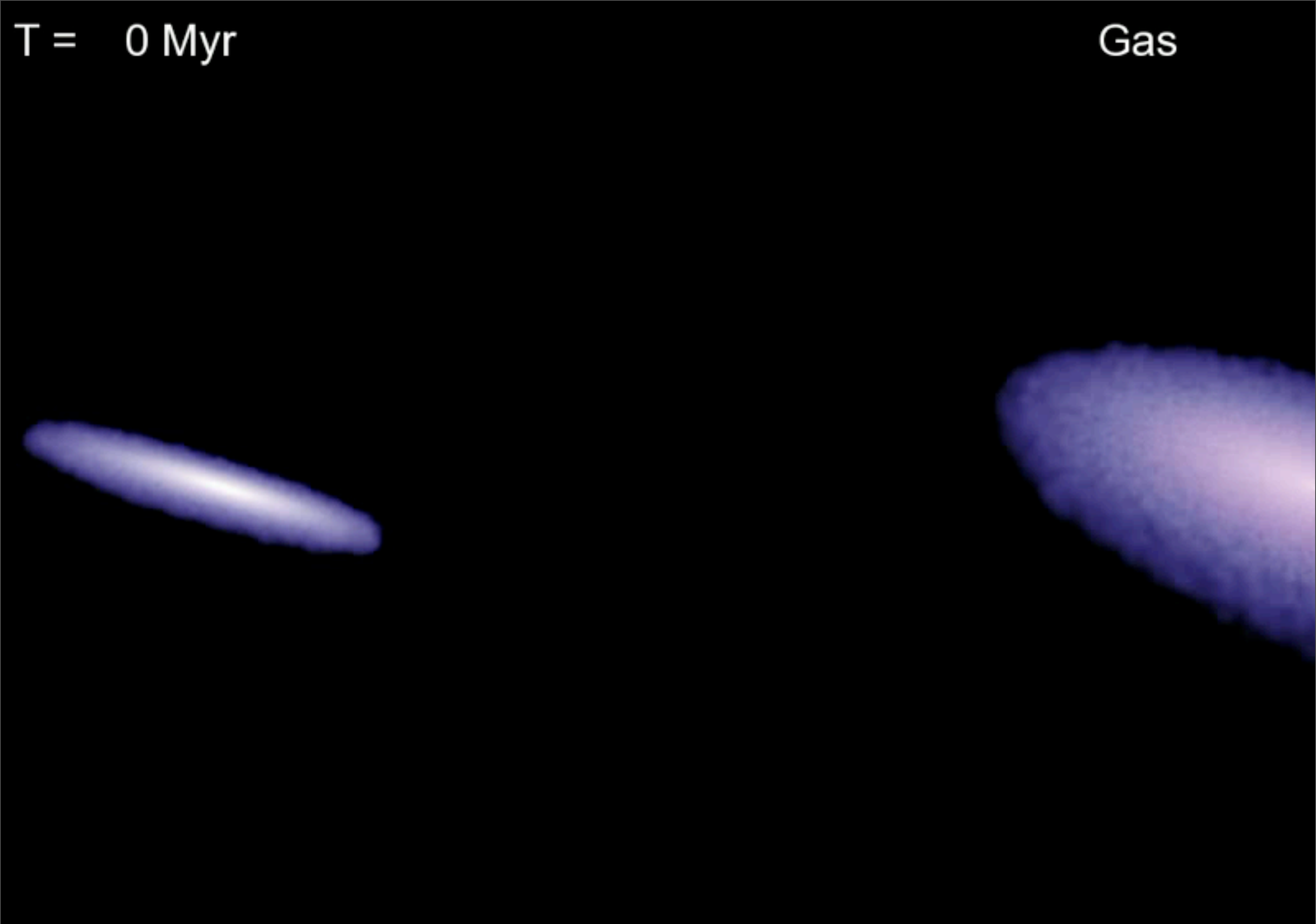
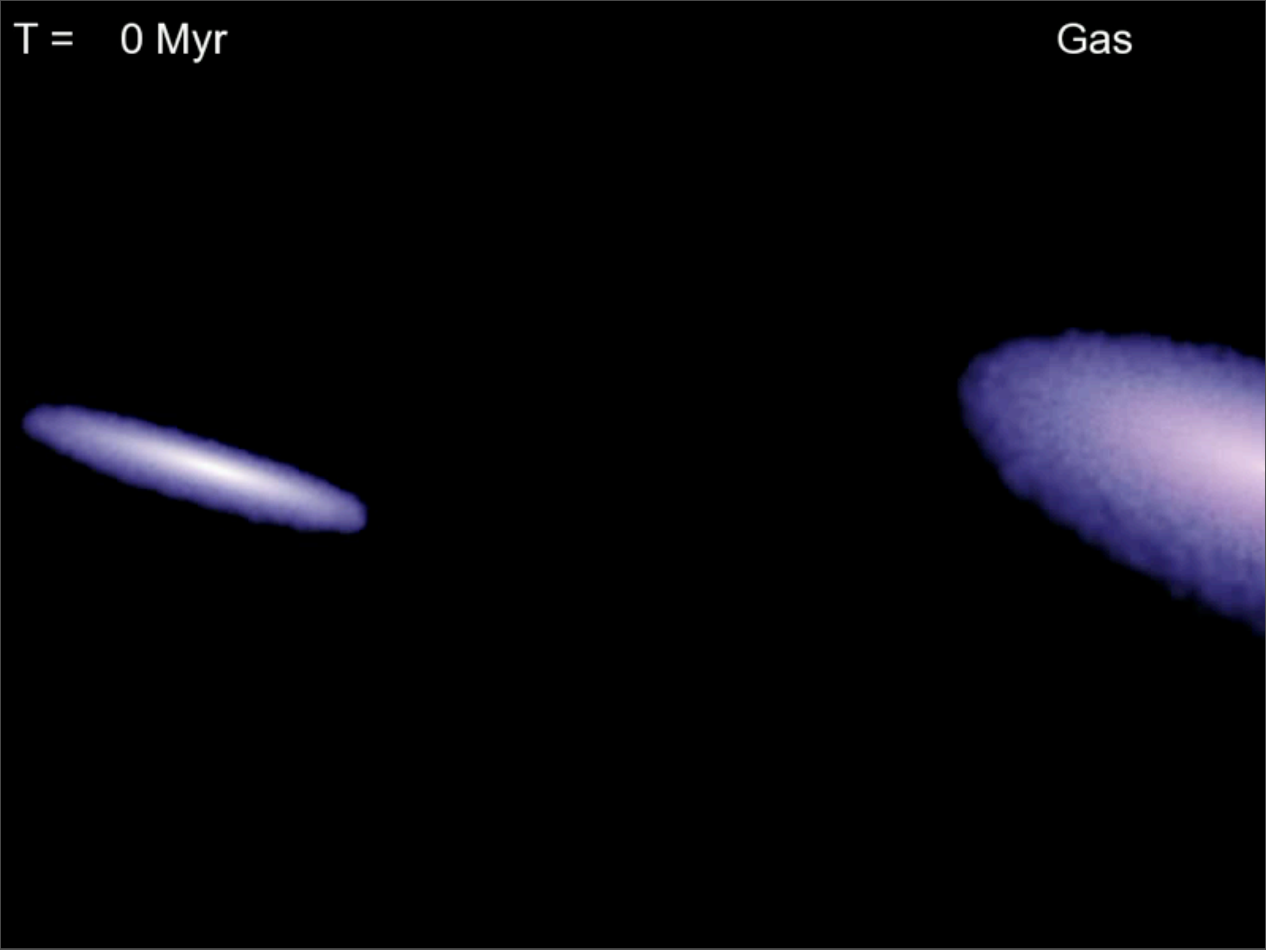


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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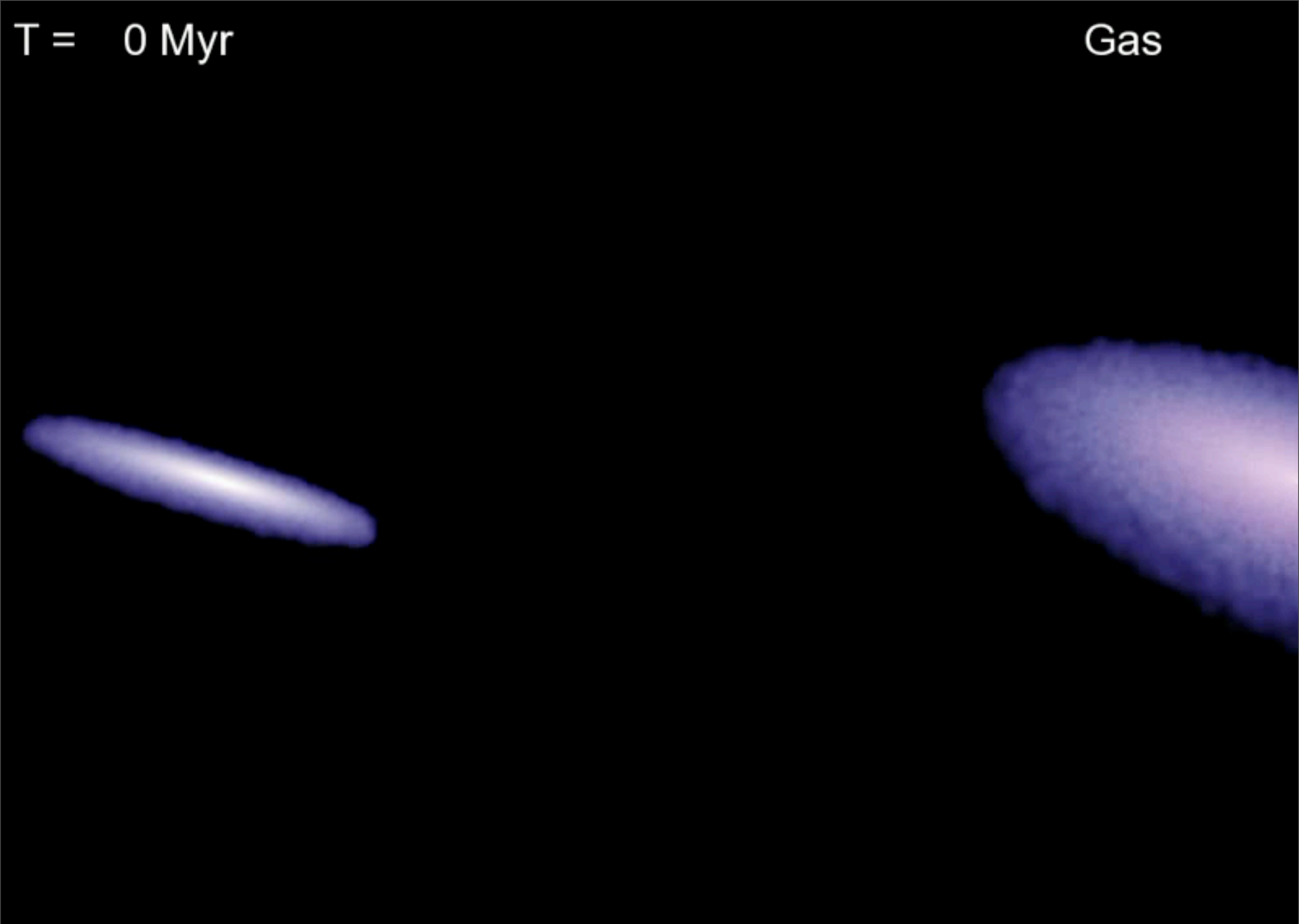
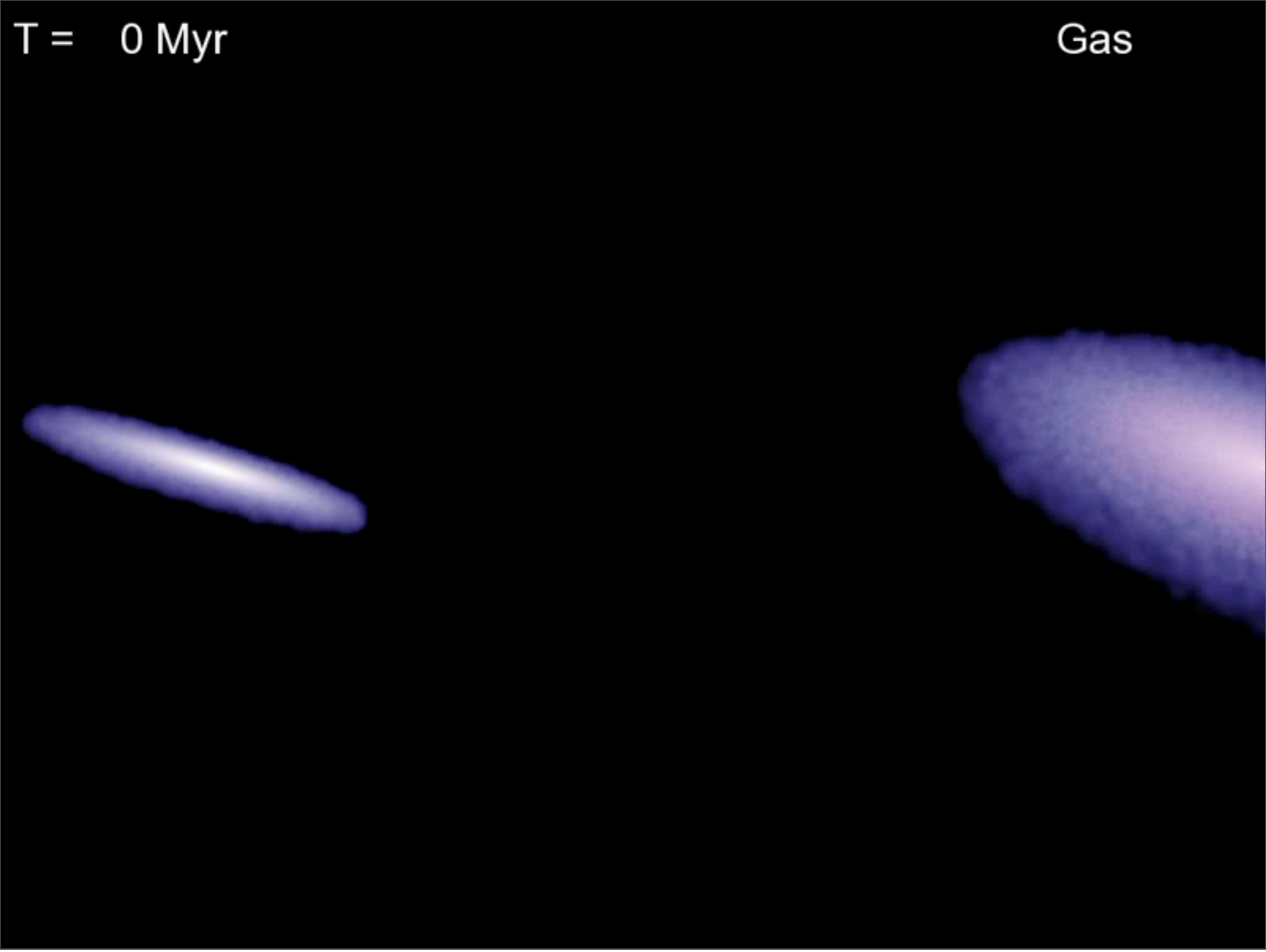


Feedback expels remaining gas, shutting down growth (more later...)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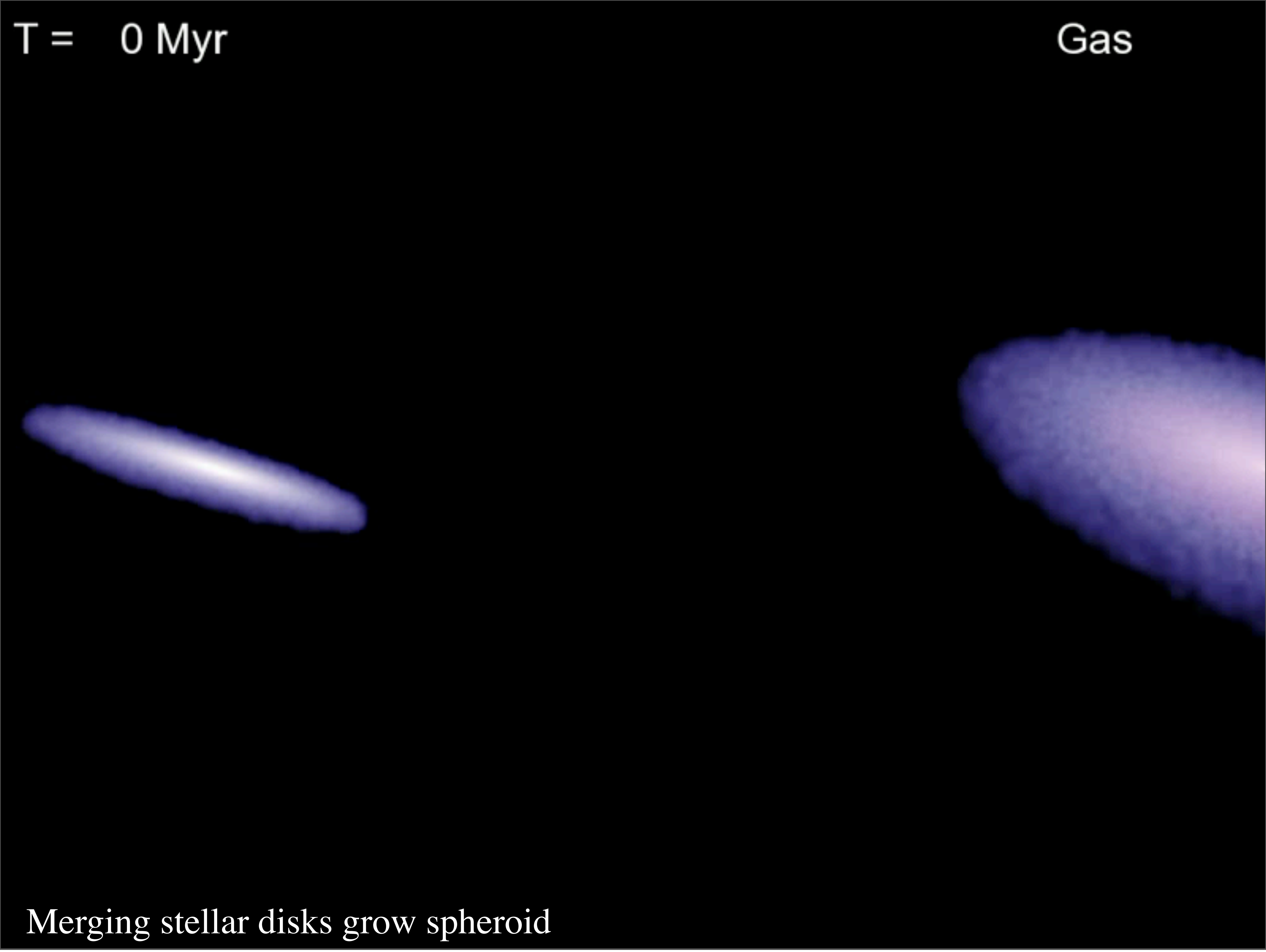
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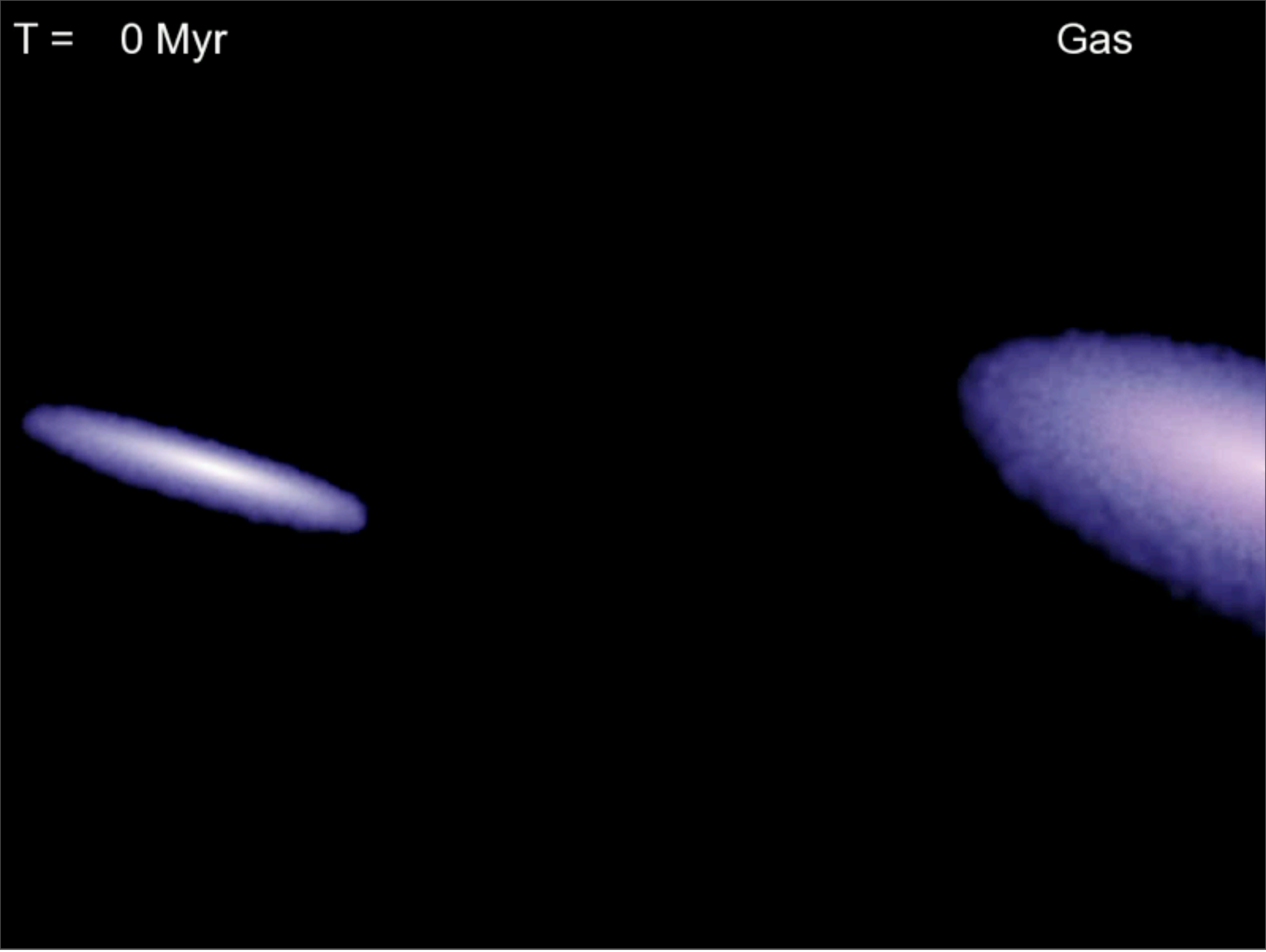
Gas
Merging stellar disks grow spheroid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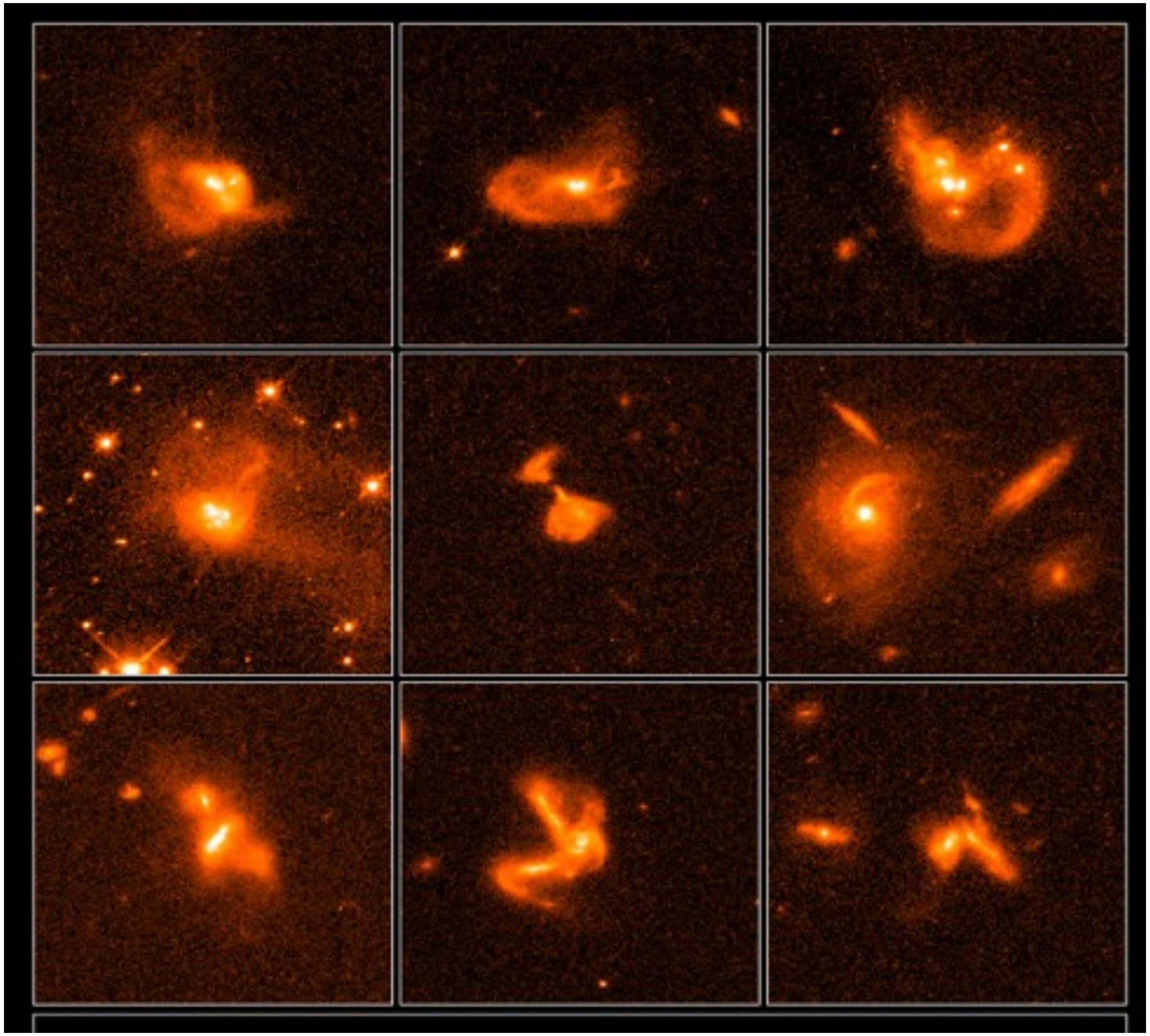
What About the Gas that Does Lose Angular Momentum?

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?

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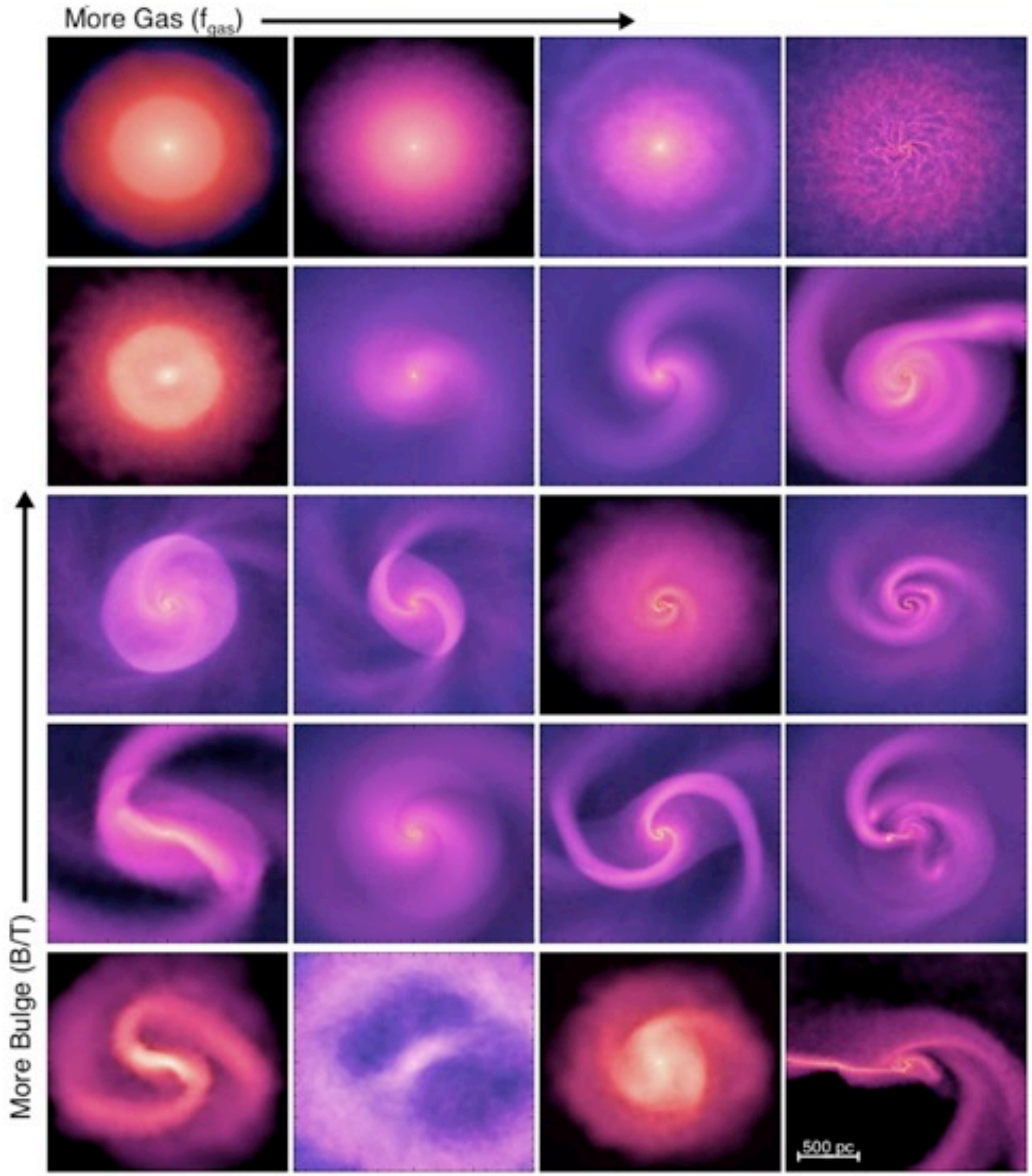

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New Work by

D. Narayanan,
C. Hayward,
P. Jonsson

SUNRISE code:
- 3-d, adaptive mesh (post-process)
- Monte Carlo radiative transfer
- sub-grid model for ISM clouds
- dust radiative equilibrium
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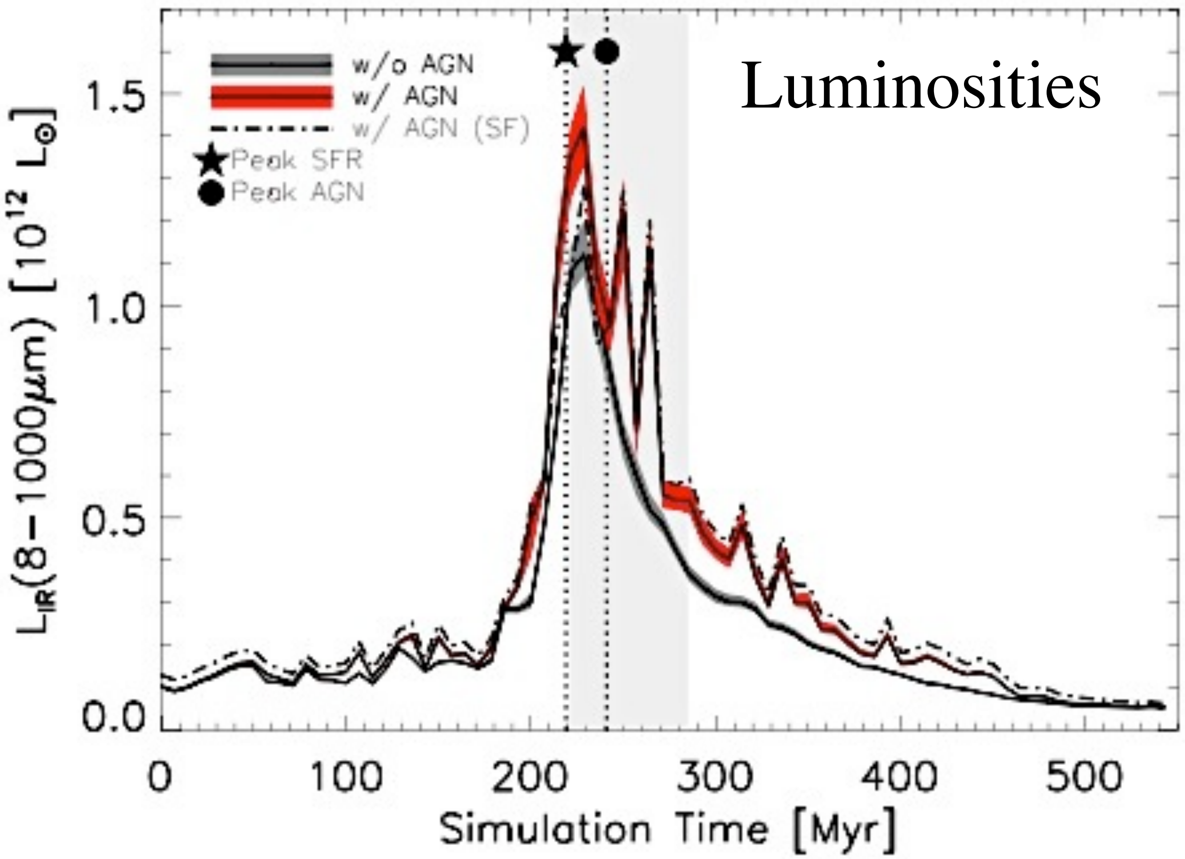

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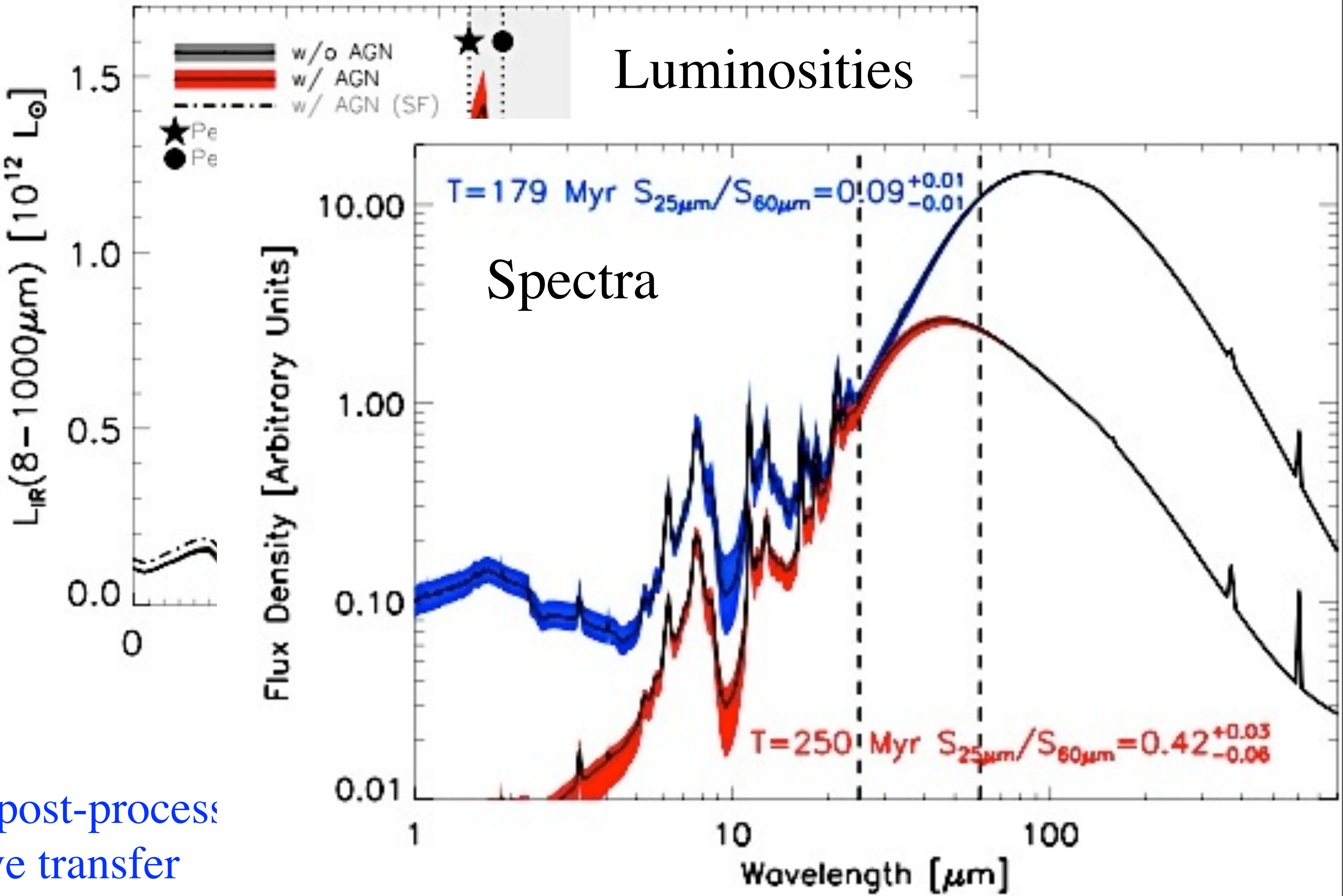

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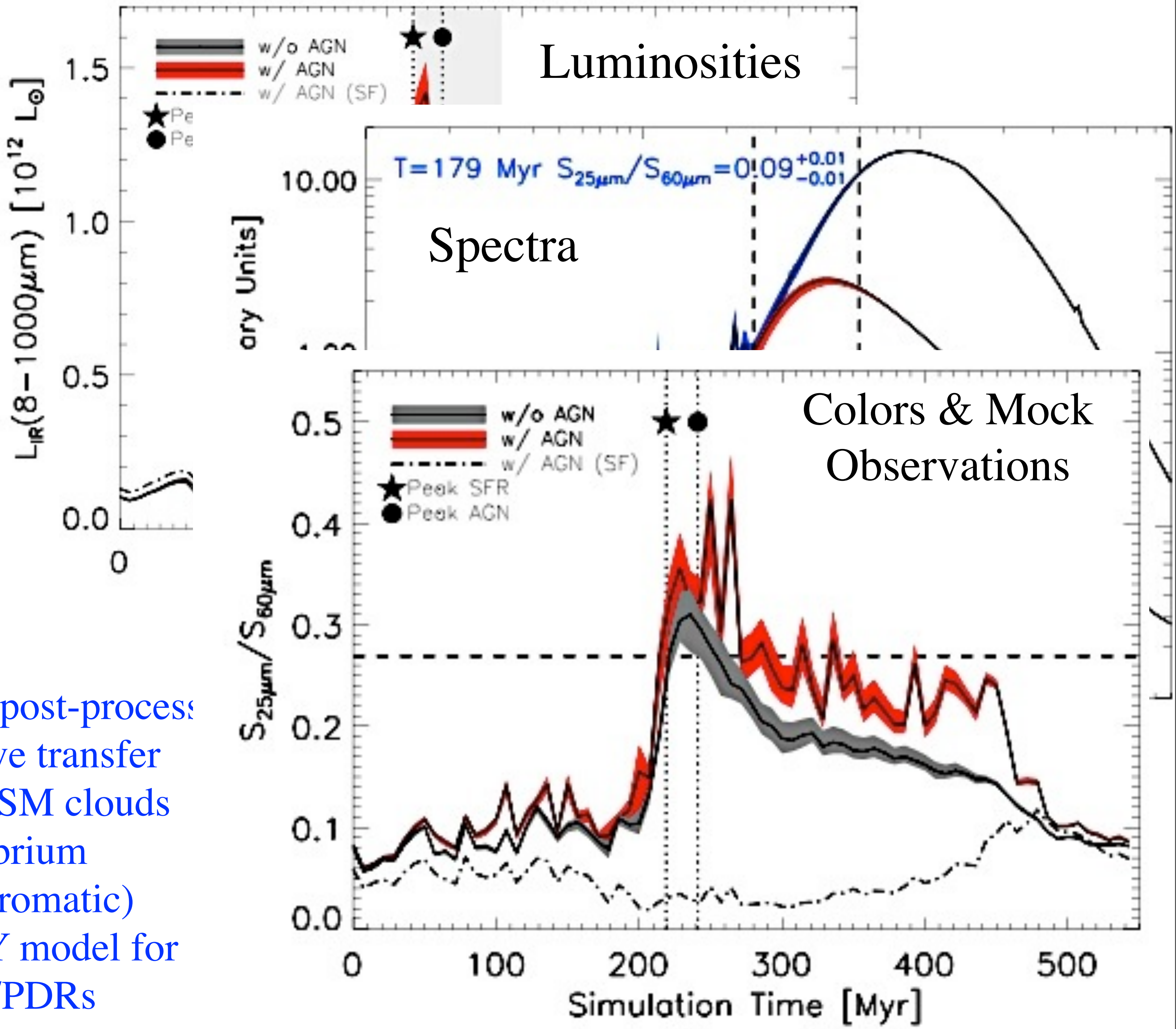

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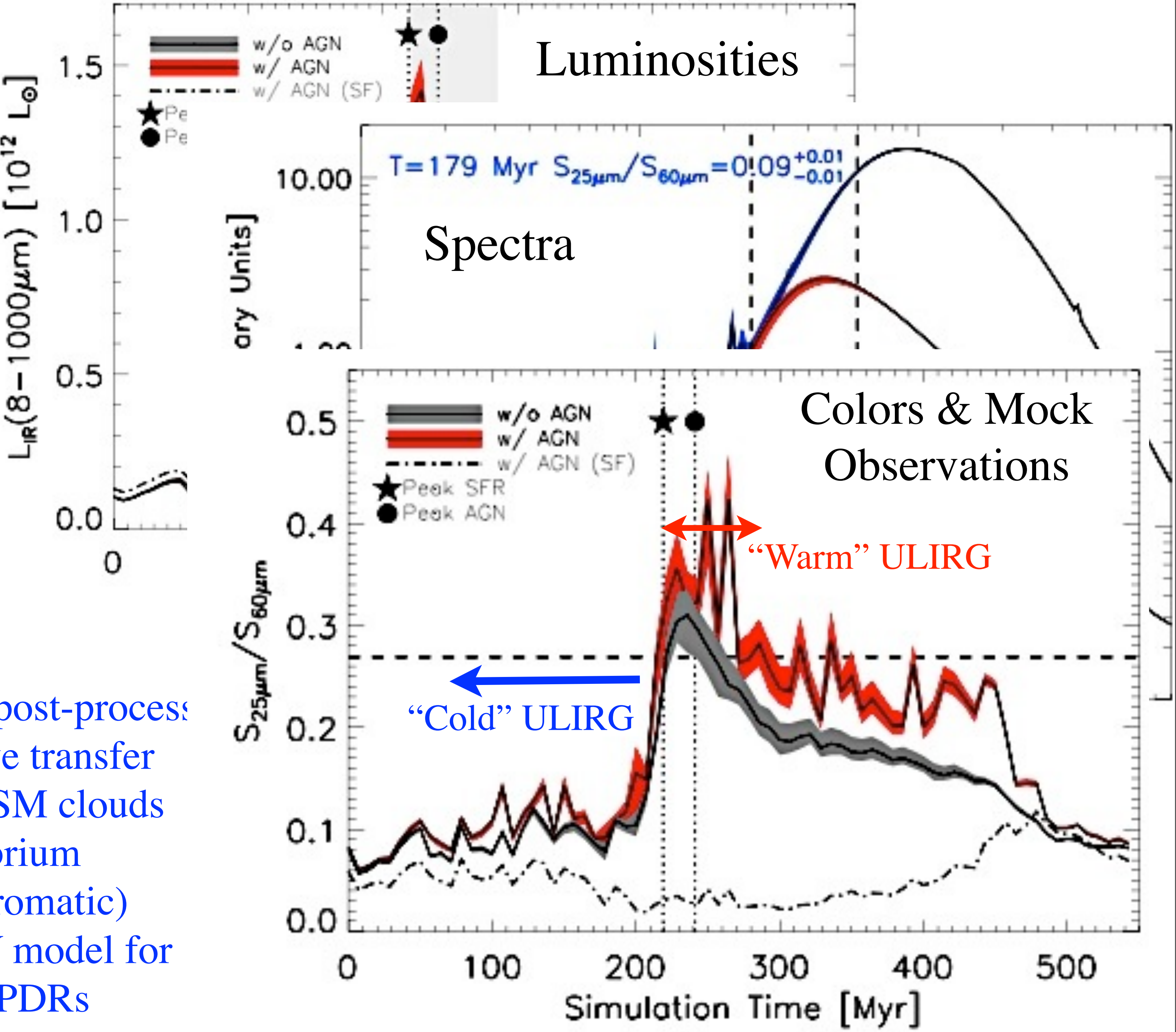
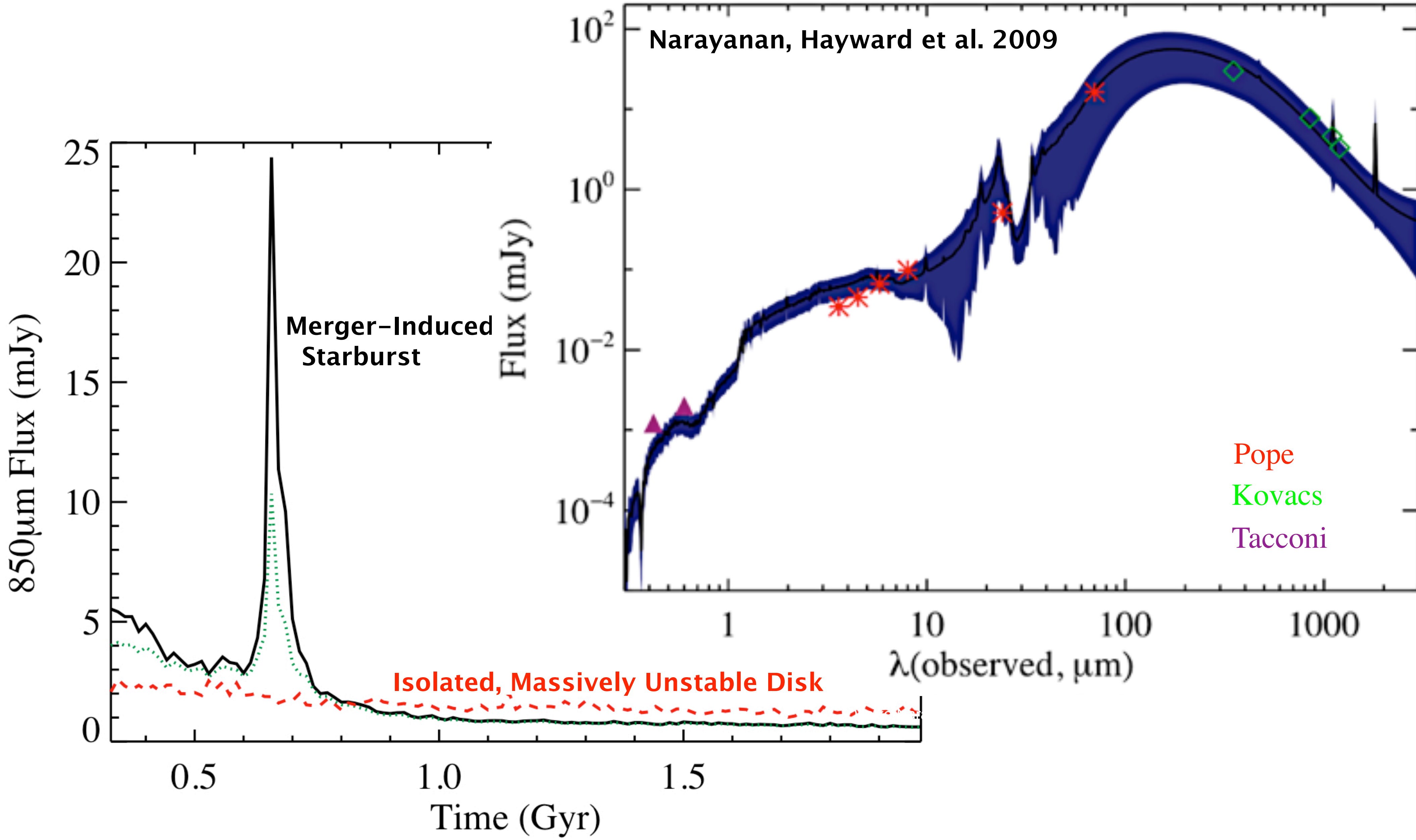
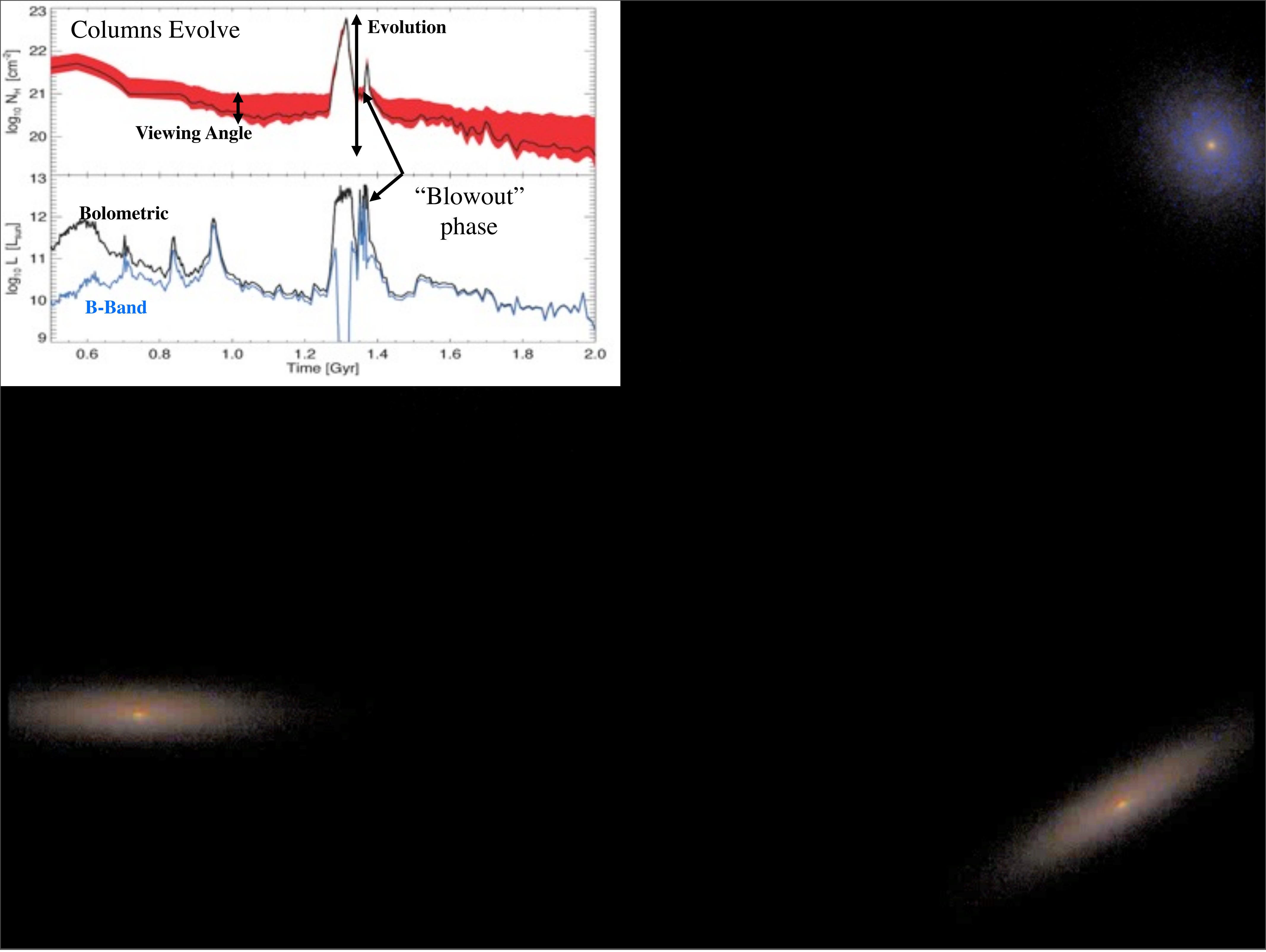


What About the Gas that Does Lose Angular Momentum?

STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

- Not just at z=0, but in high-redshift sub-millimeter galaxies

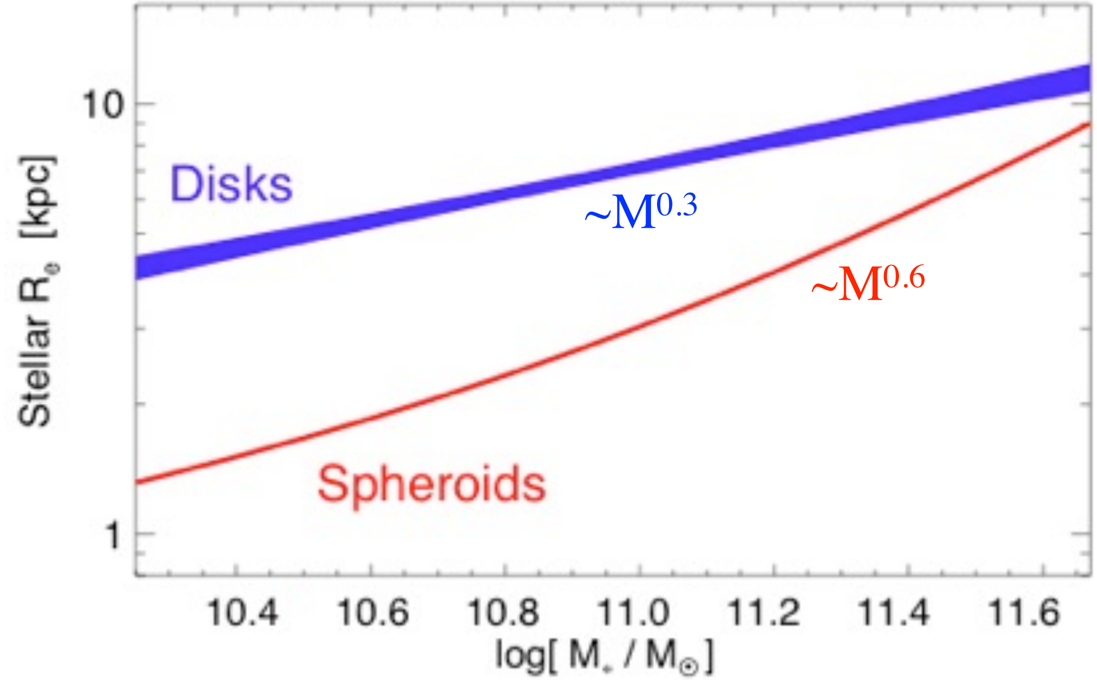




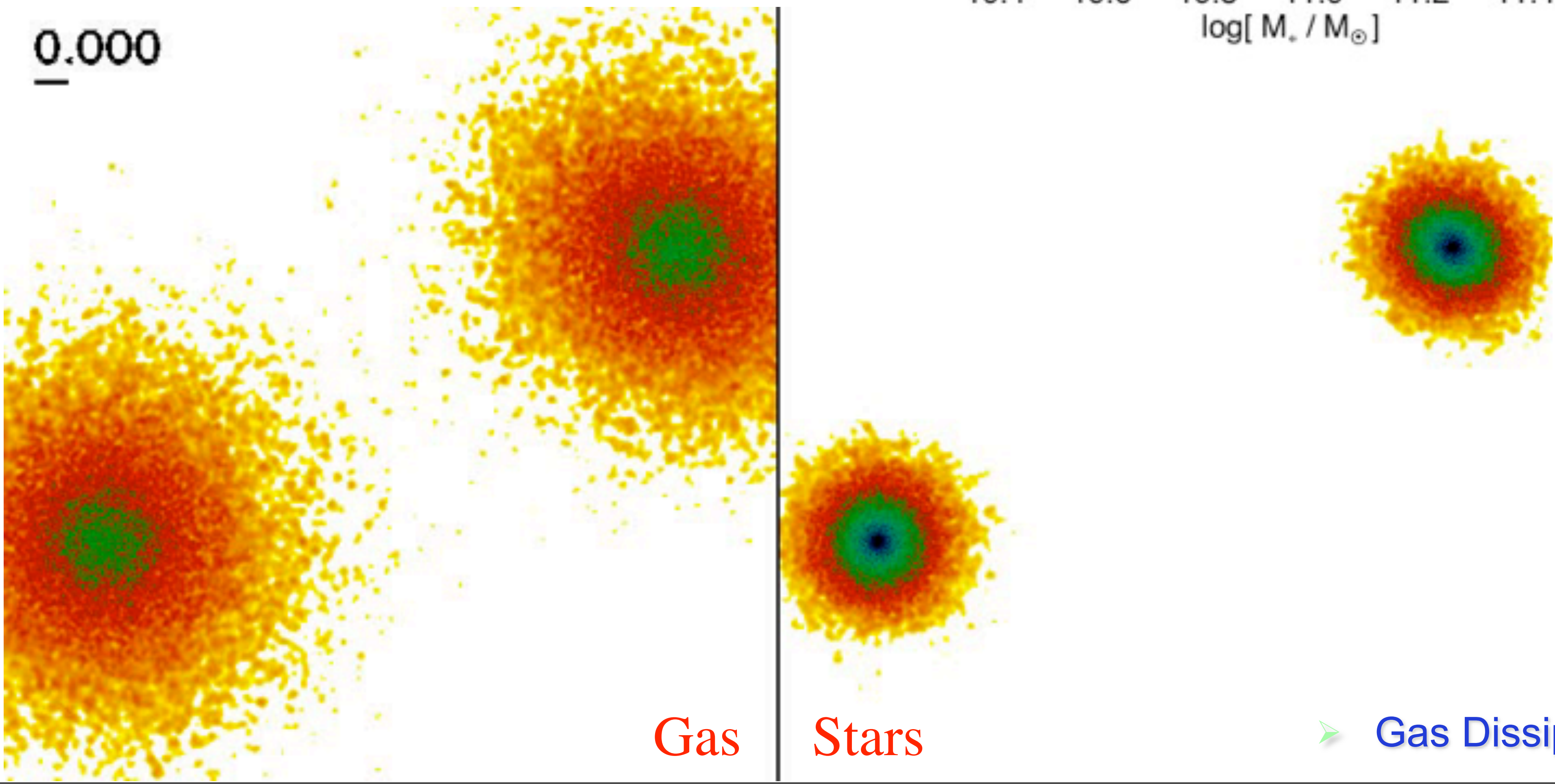
Columns Evolve
Evolution
Viewing Angle
"Blowout" phase
Bolometric
B-Band
$\log_{10} N_H$ [cm^{-2}]
$\log_{10}$ L [L_{sun}]
Time [Gyr]

So What Difference Does this Starburst Make?

The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks?

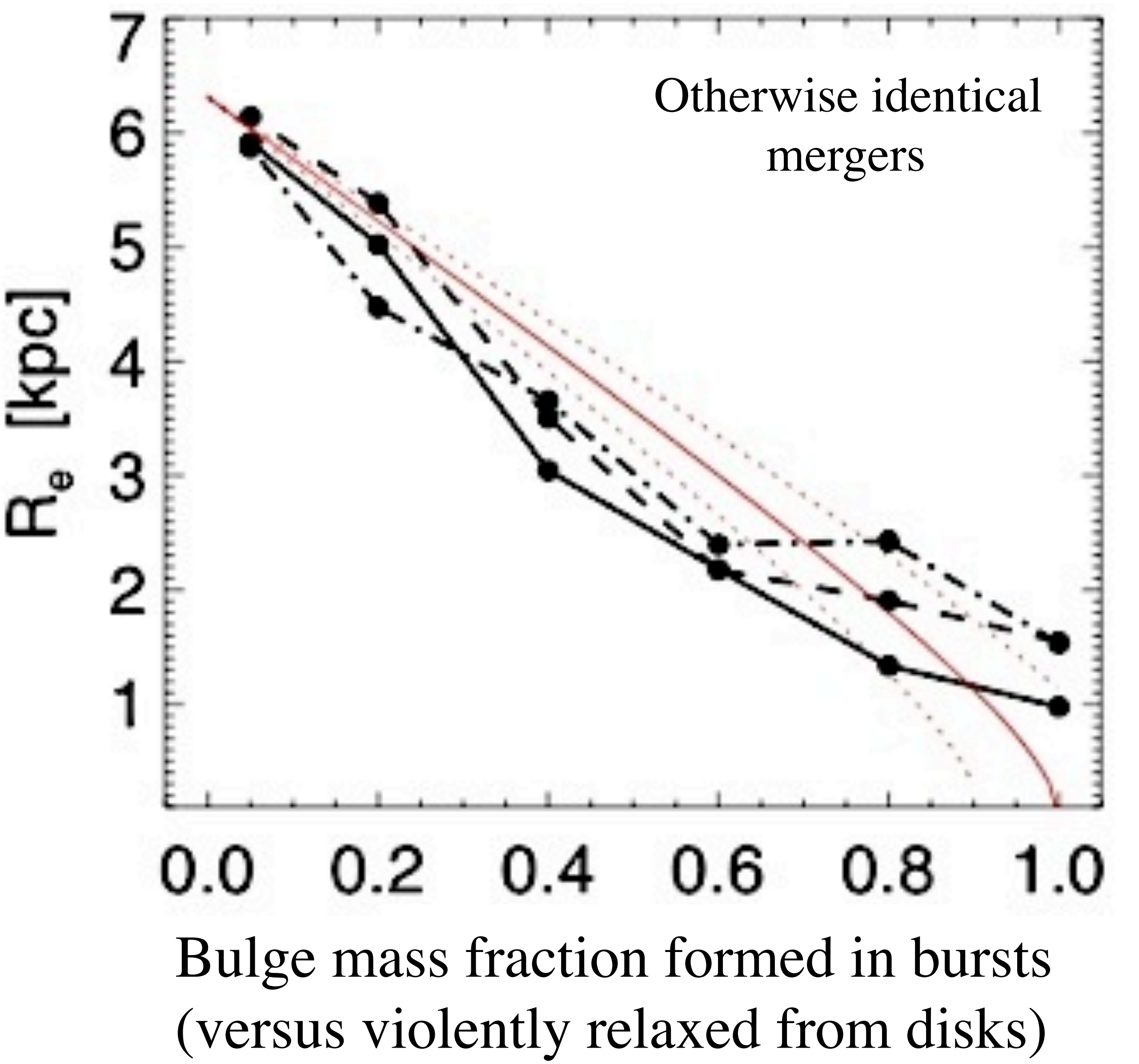


- Gas Dissipation

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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



PFH, Cox et al. 2008

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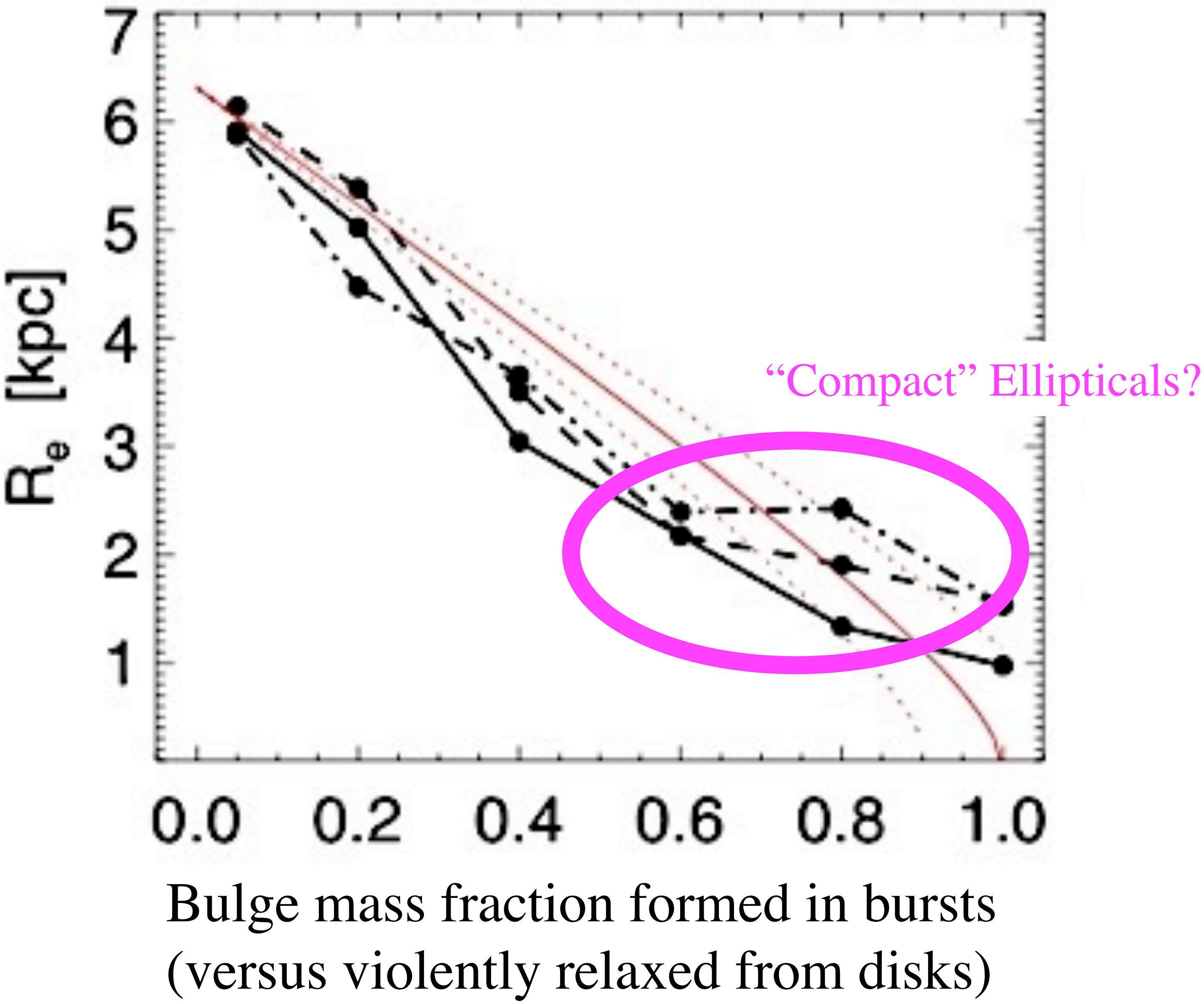
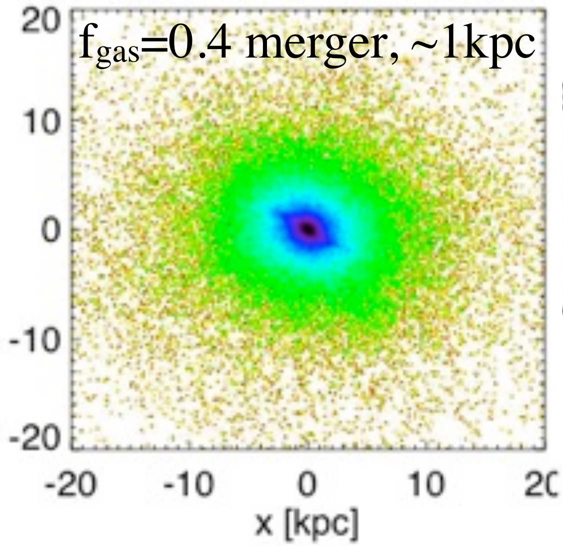
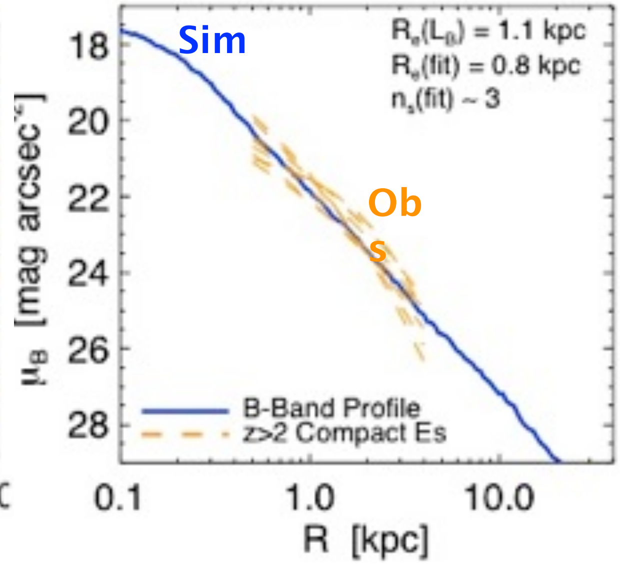
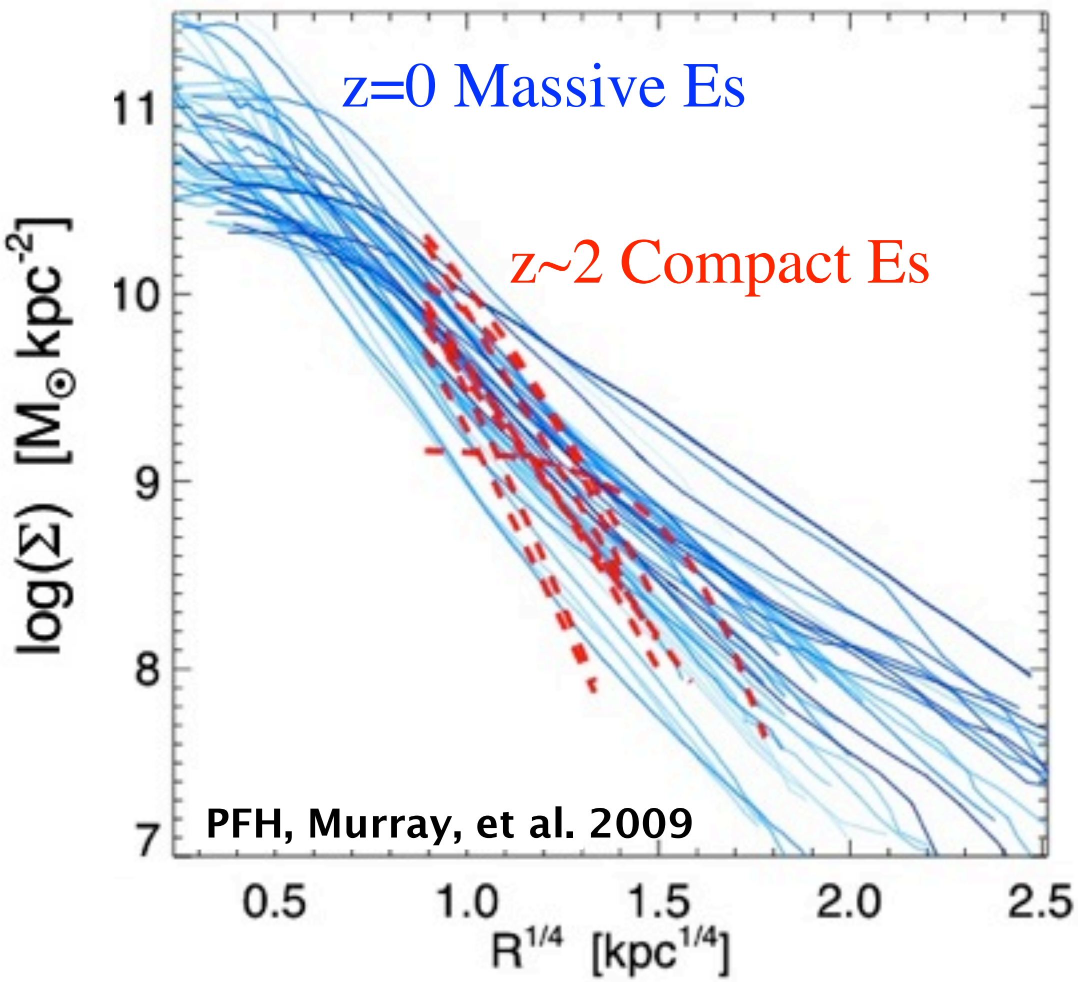


Compare: massive spheroids at z=2 to those today

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








20
Sim
$R_e(L_B)$ = 1.1 kpc
$R^{1/4}$ [$kpc^{1/4}$]

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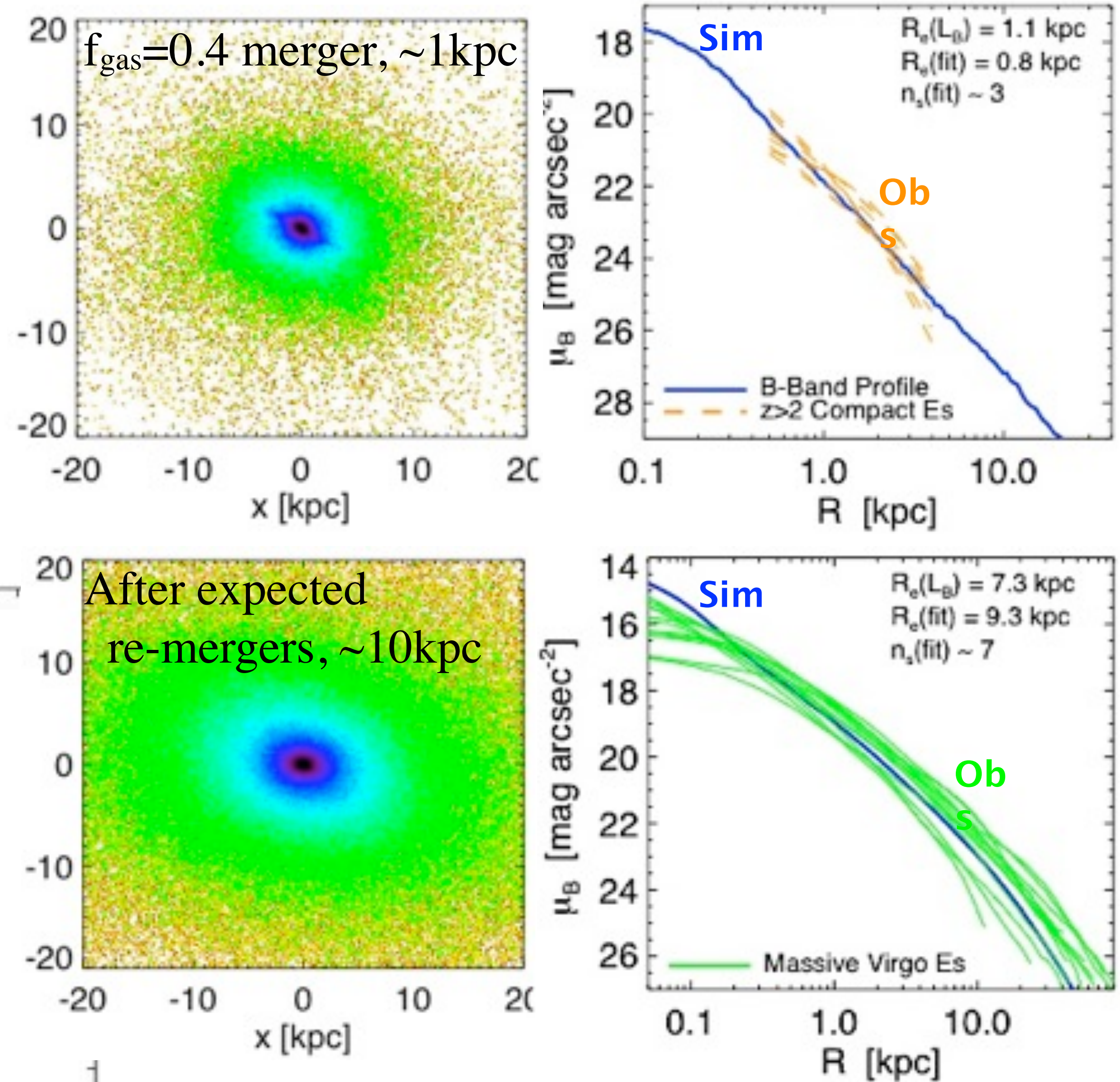
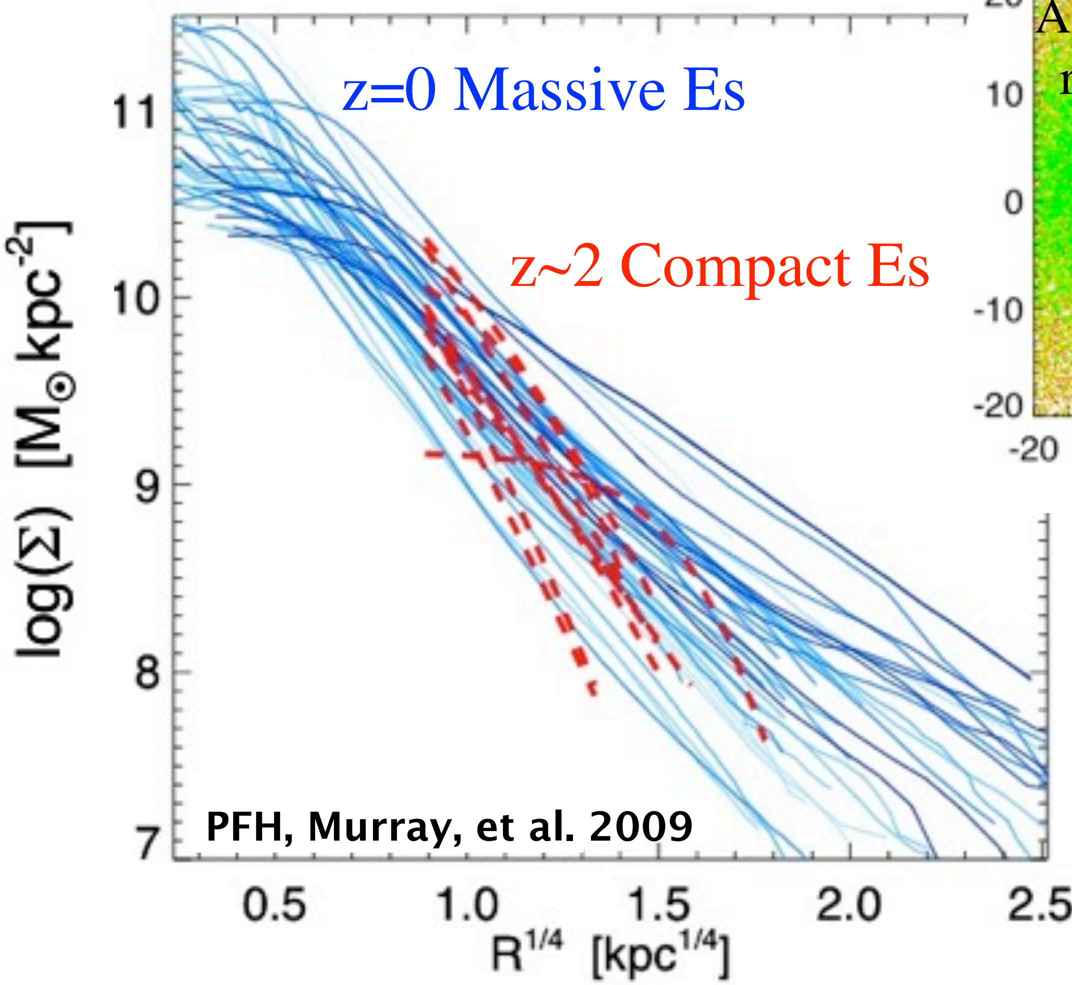


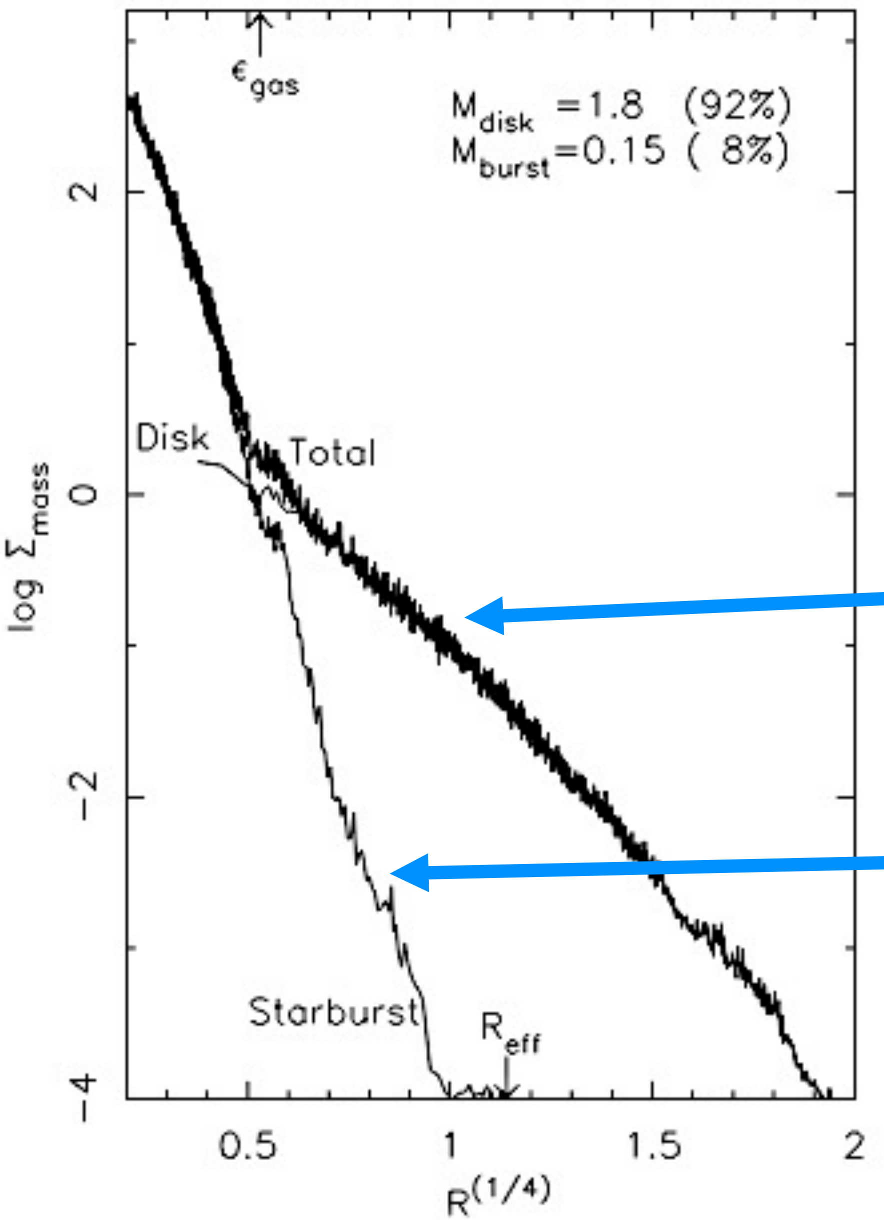


PFH, Bundy, et al. 2009

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)

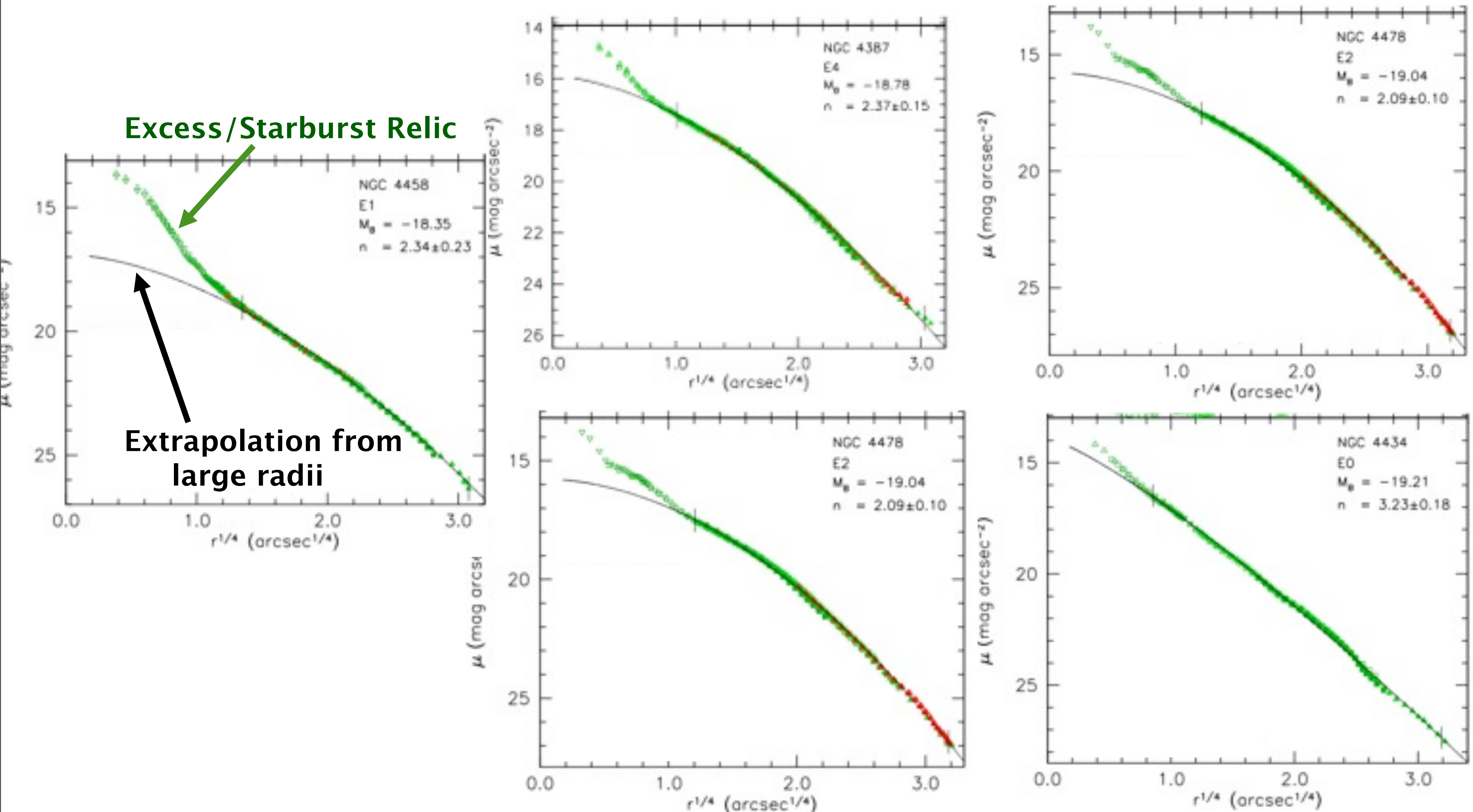
Not observed at the time:

"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

- 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.”

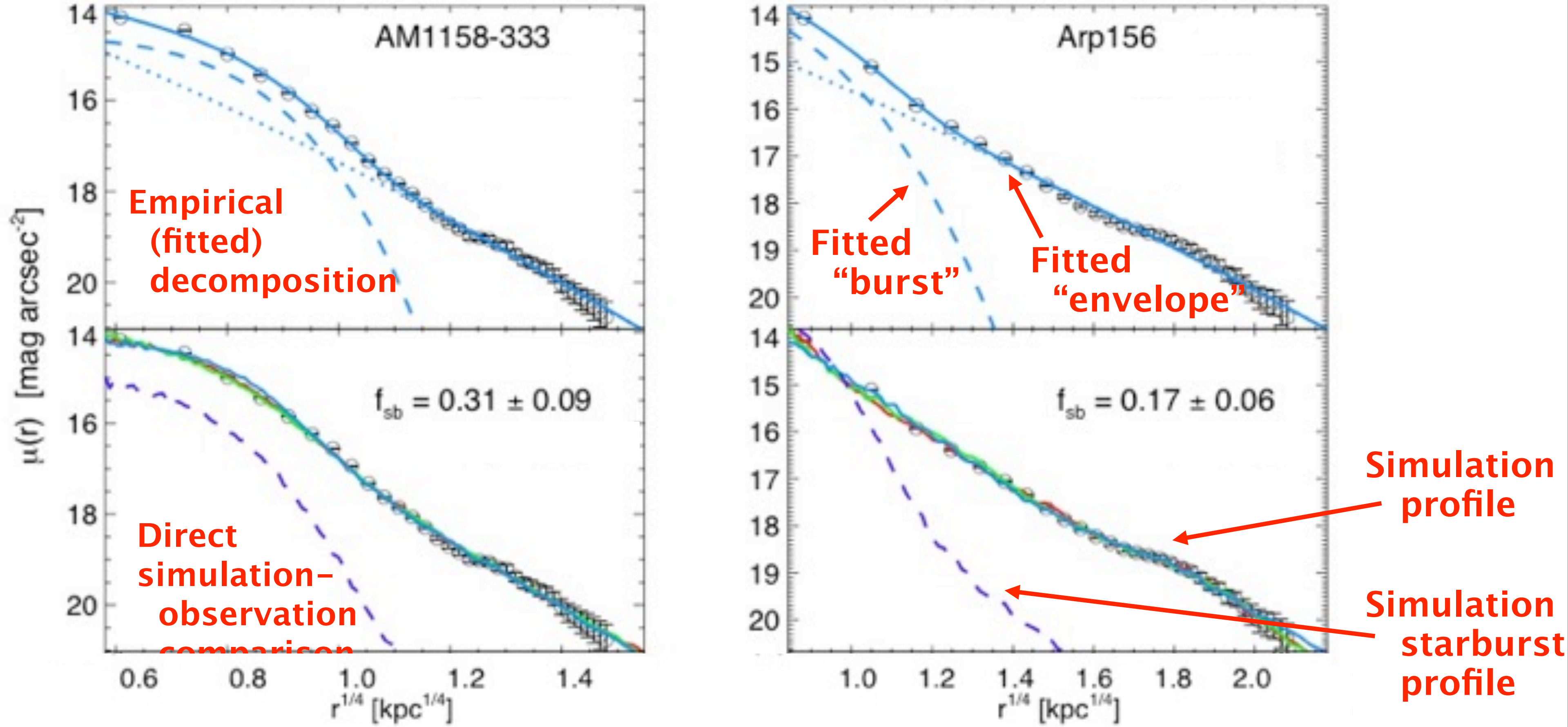
Application: Merger Remnants

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:



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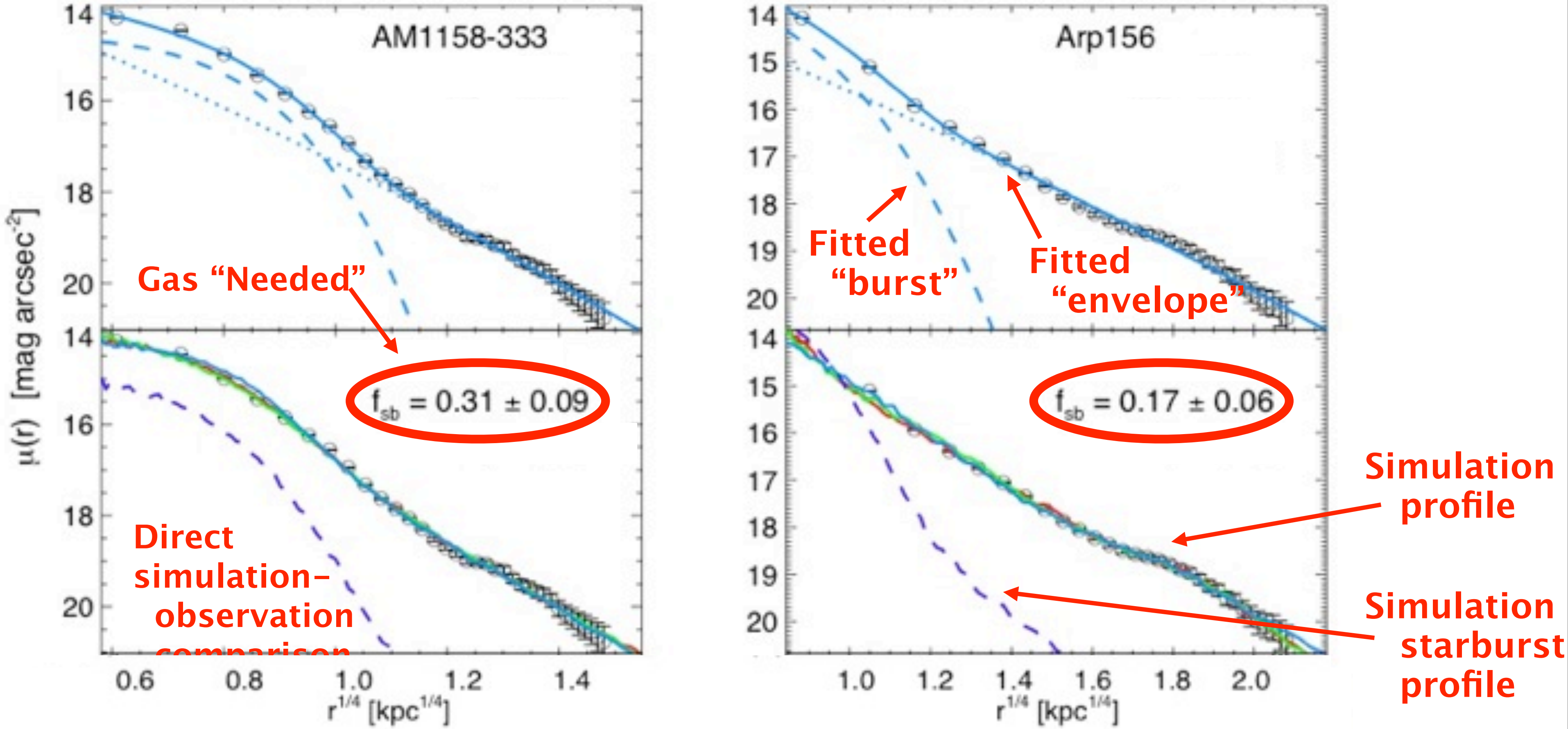

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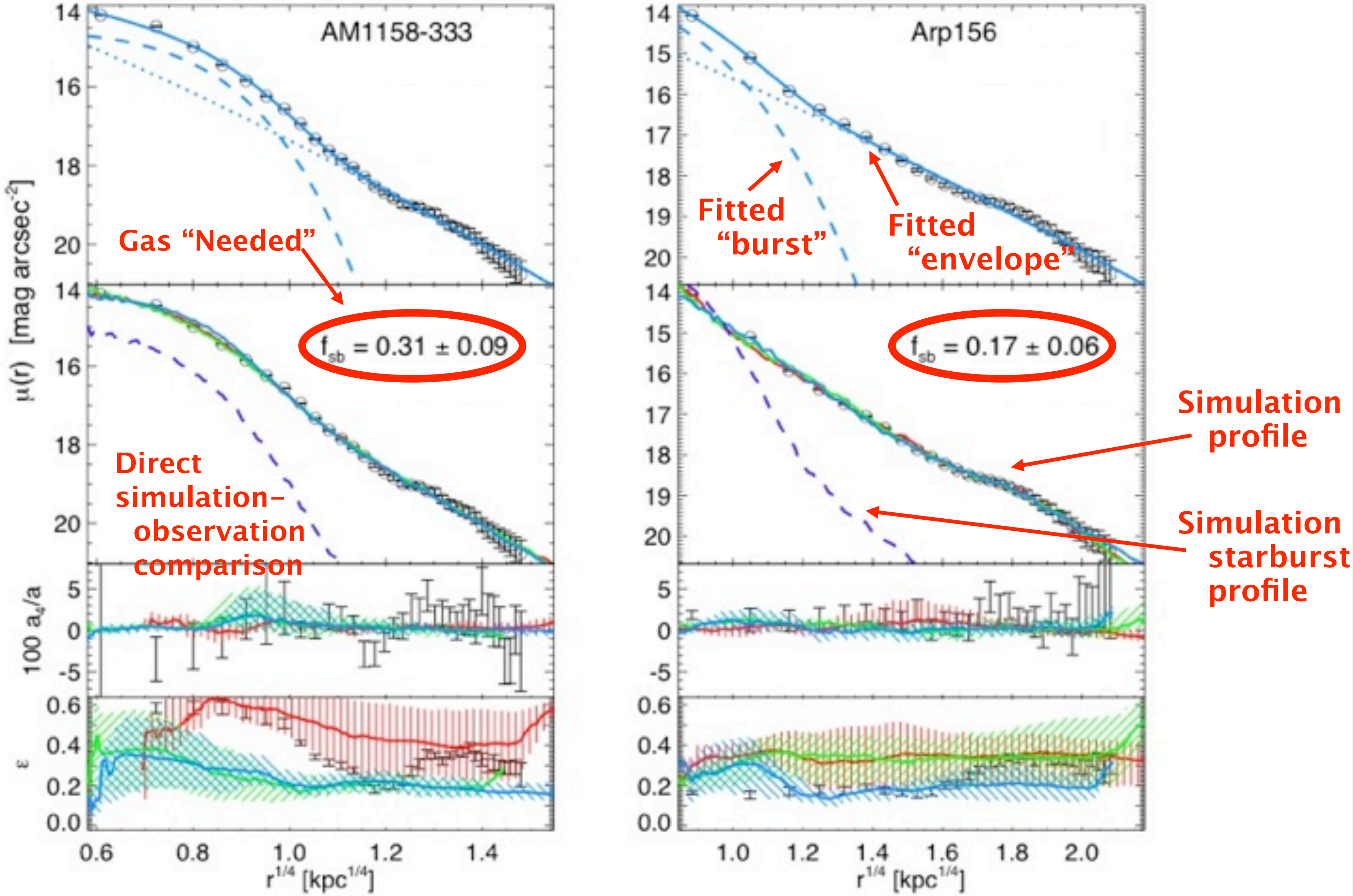

Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

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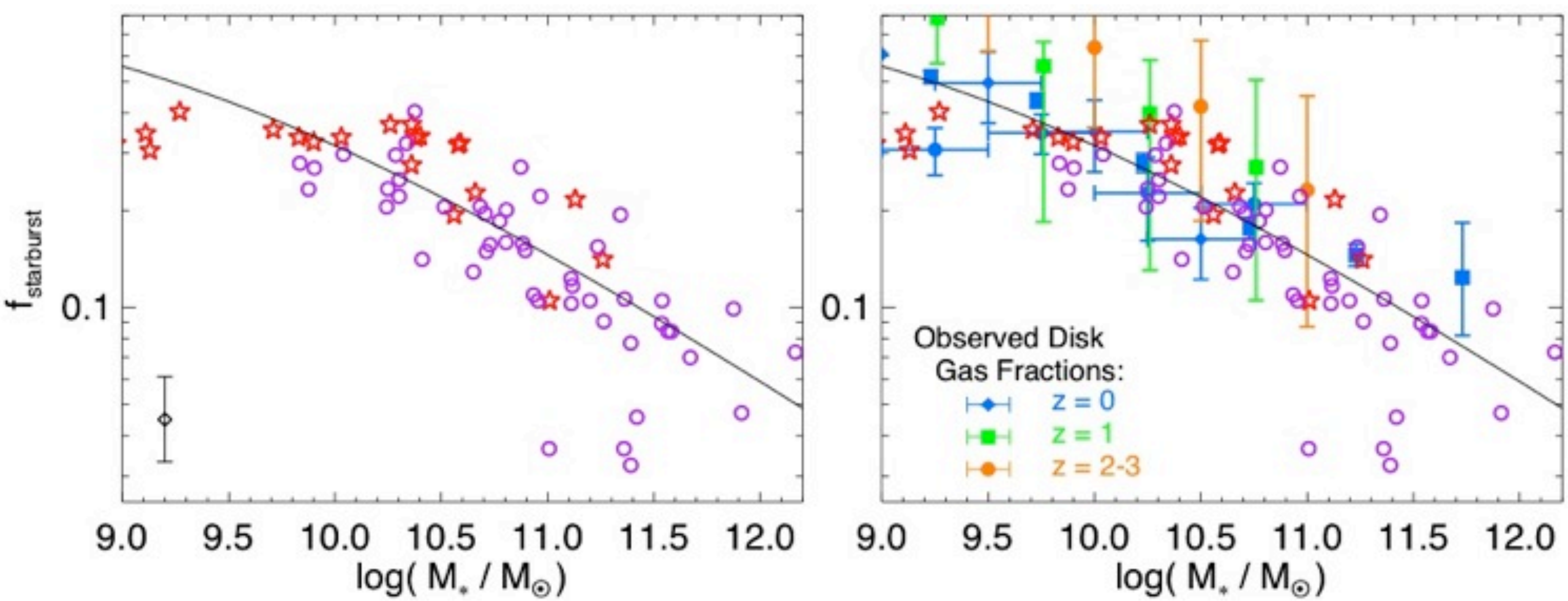
PFH, Kormendy, & Lauer et al. 2008

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



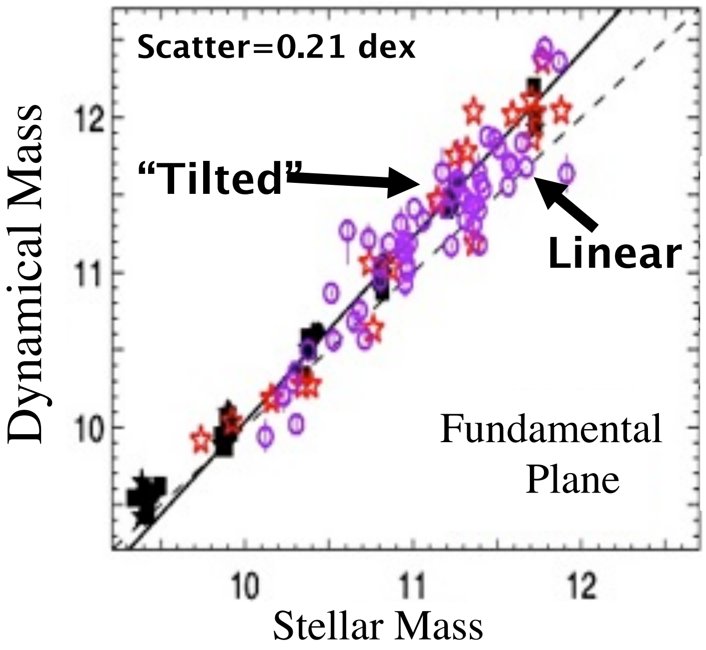
- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns

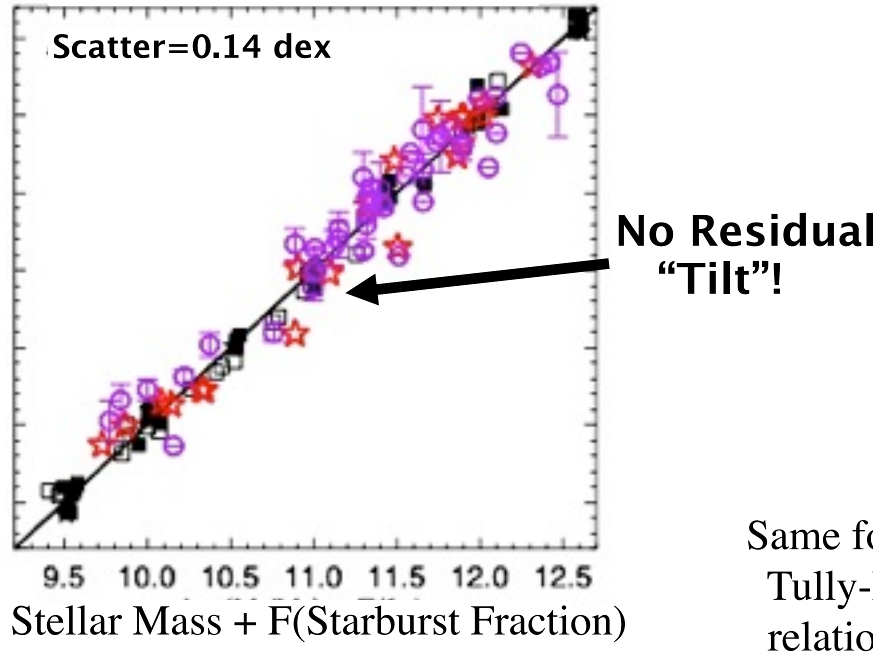
Fundamental Plane Tilt

PFH, Cox, & Hernquist 2008

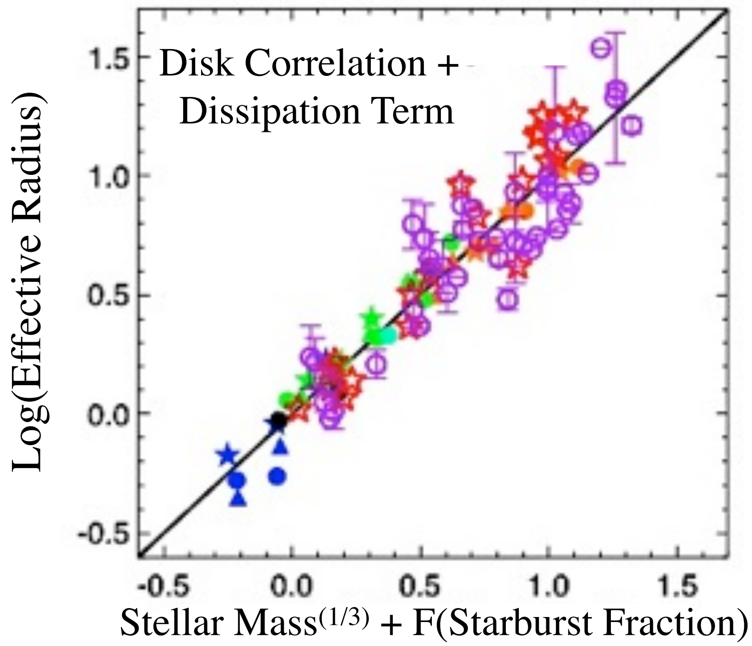
WHERE DOES IT COME FROM?

- Fundamental plane: “tilt” driven by amount of dissipation





Same for size-mass and Tully-Fisher/Faber-Jackson relations

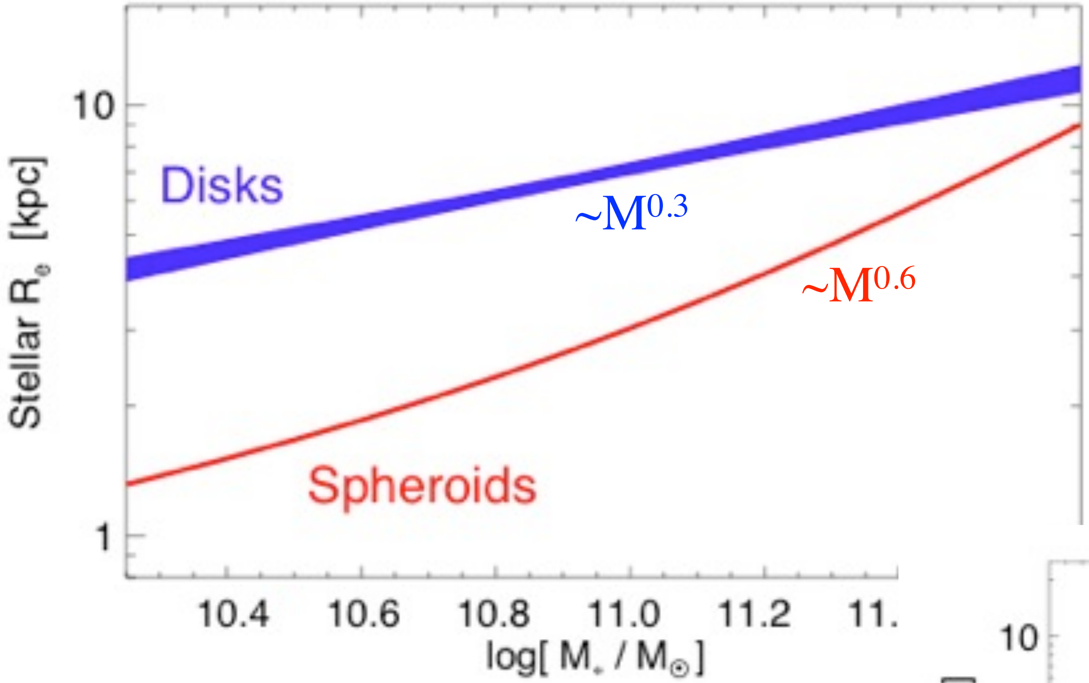


- At FIXED $f_{dissipational}$, there is NO TILT: look just like disks on these correlations!
  - Spheroid correlations can be entirely restated as disks+dissipation

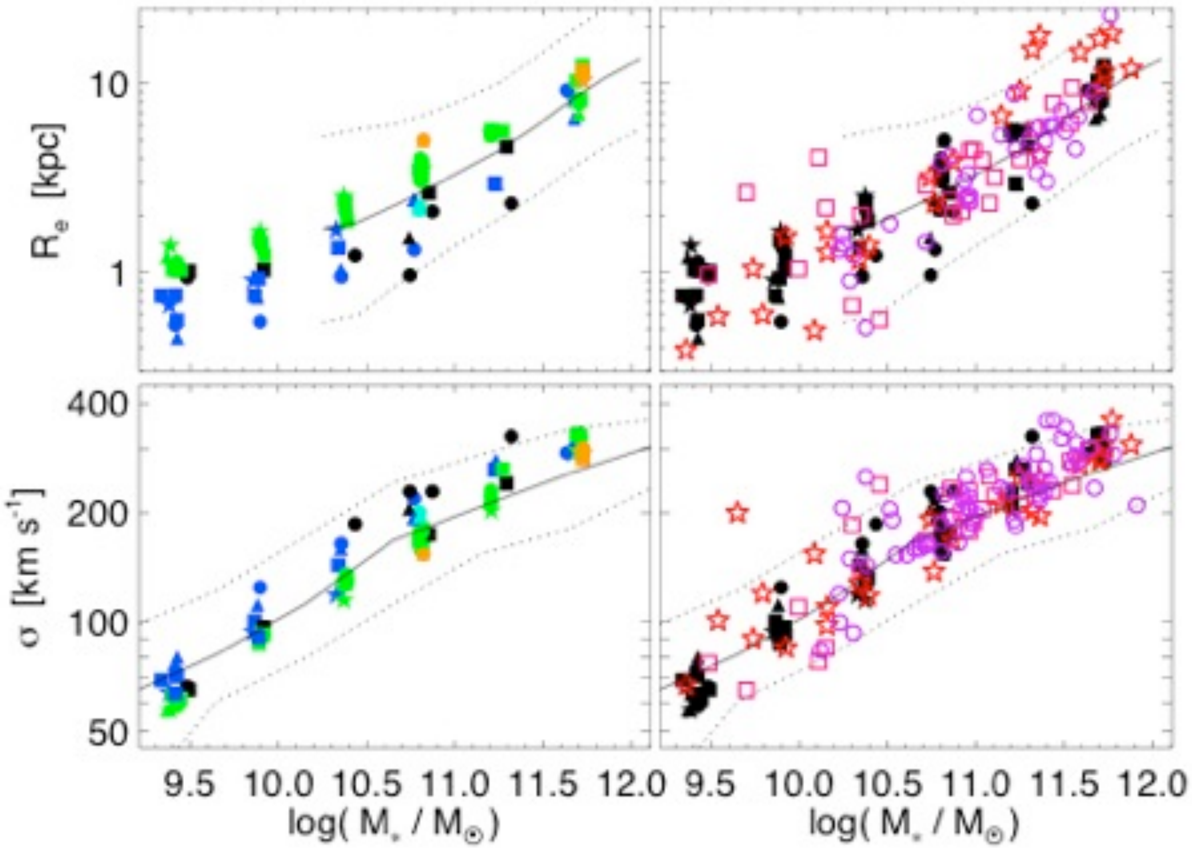
Structure in Elliptical Light Profiles

PFH, Cox, & Hernquist 2008

THE ROLE OF GAS IN THE SIZE-MASS RELATION

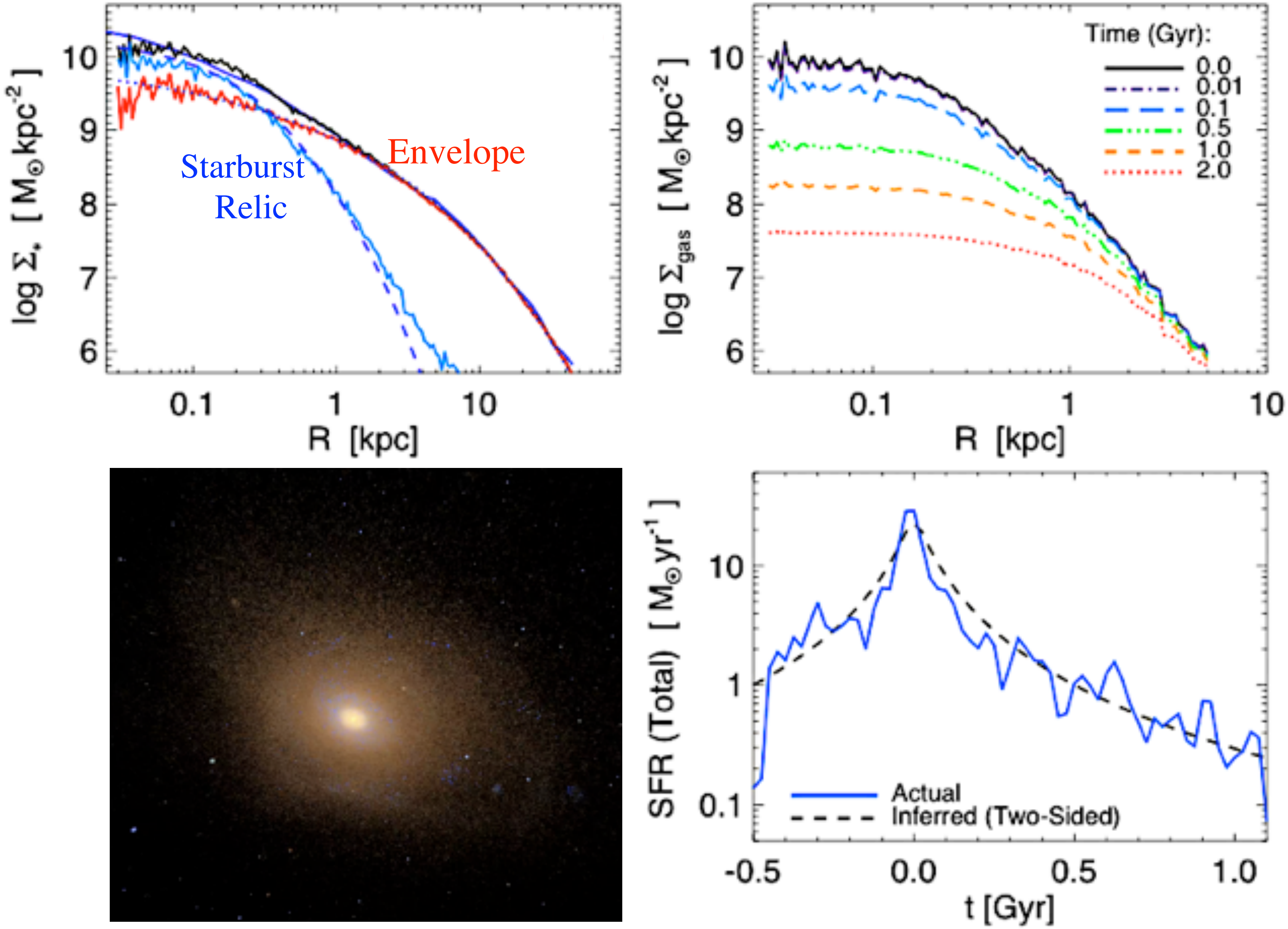


- Recall, low-M ellipticals are more compact than disks of similar mass



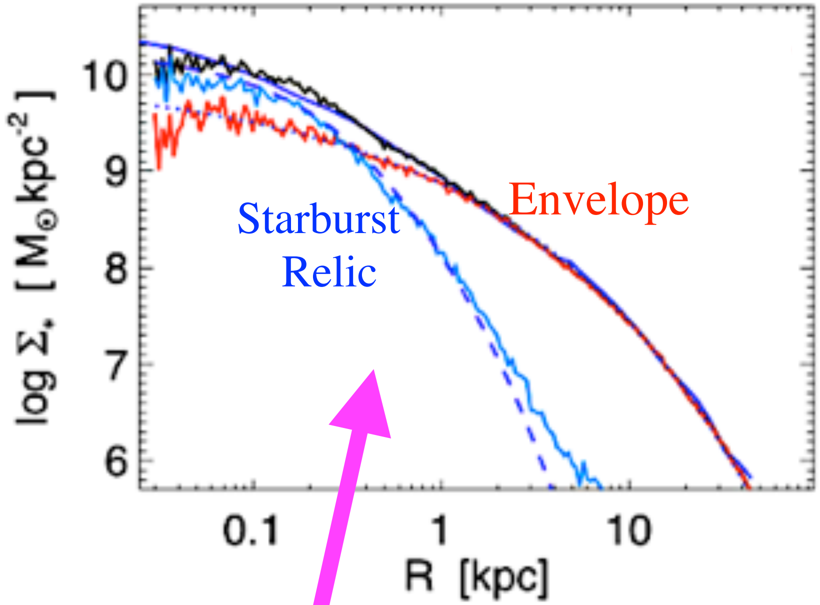
- Include effects of gas: reproduce fundamental plane, sizes, etc. of ellipticals

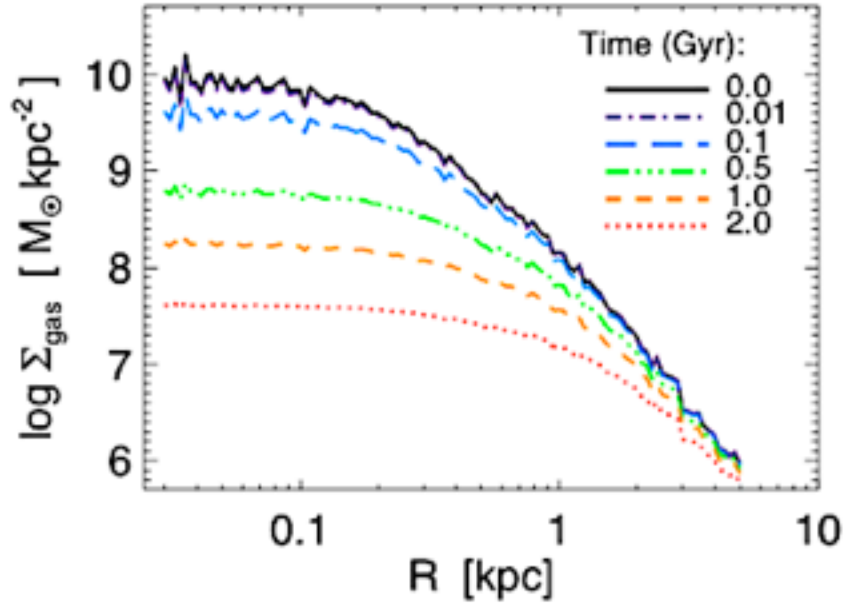
What else can we learn from the ‘relics’ of gas dissipation?

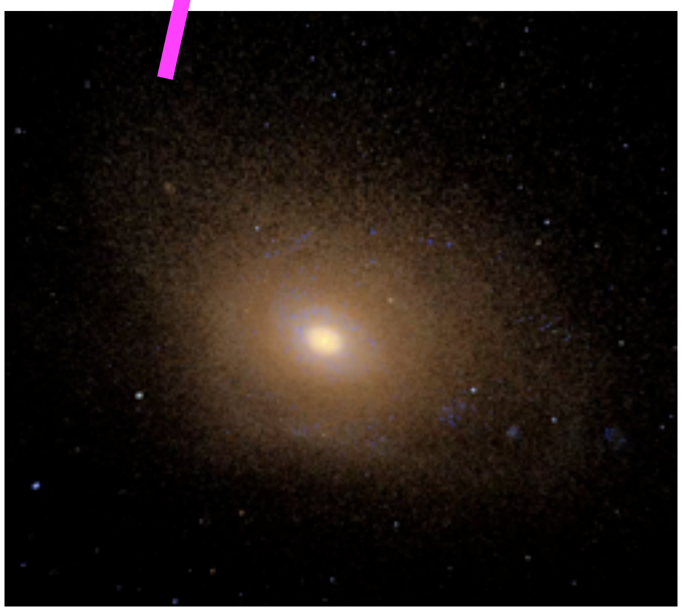


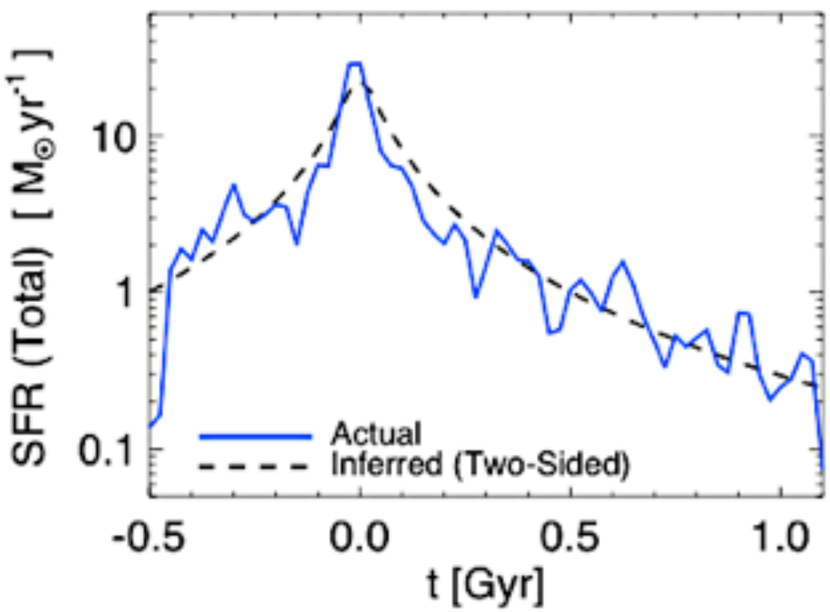
What else can we learn from the ‘relics’ of gas dissipation?

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

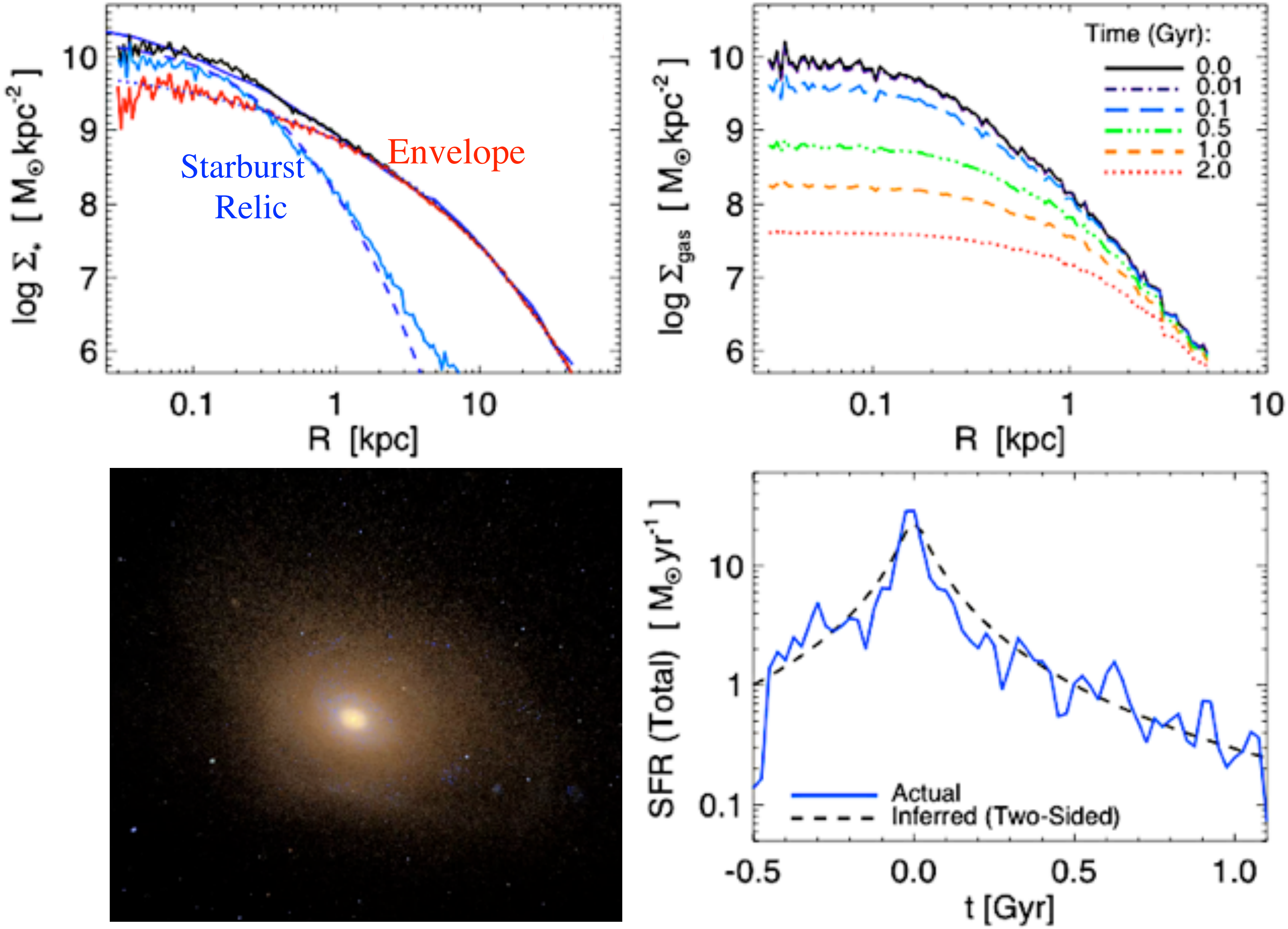








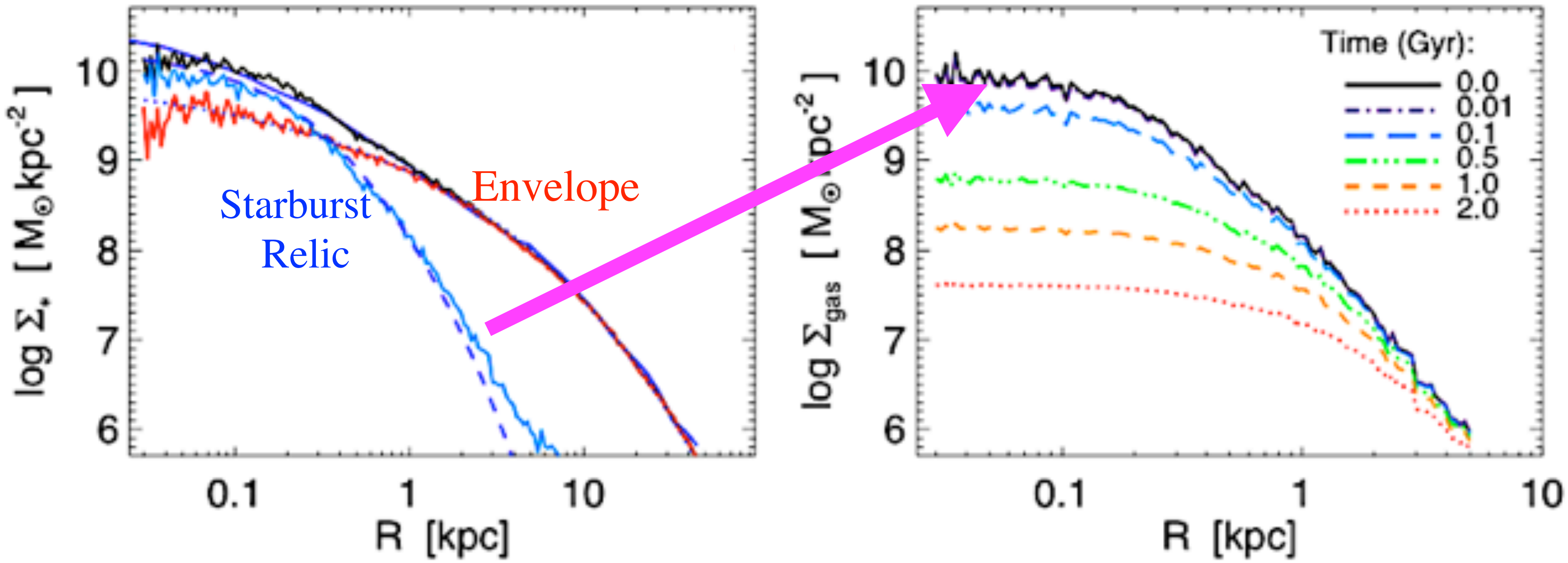
What else can we learn from the ‘relics’ of gas dissipation?

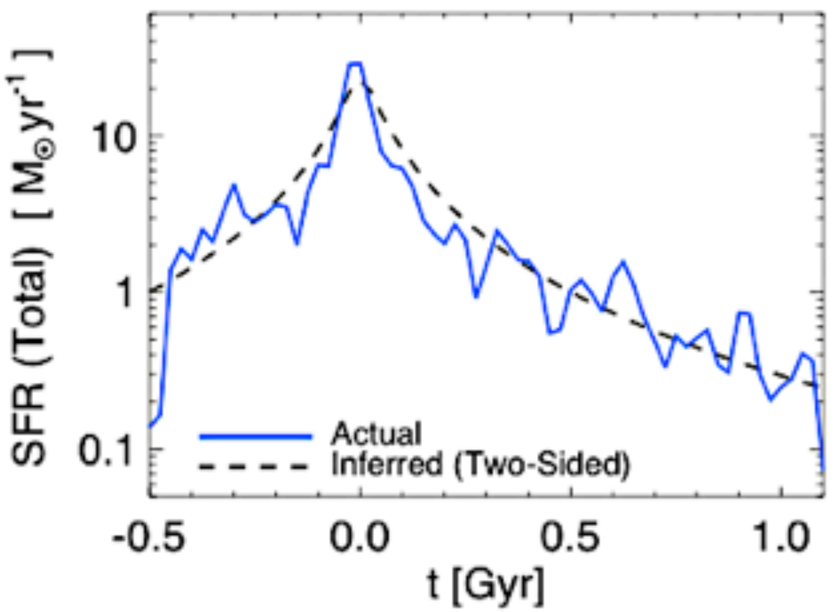


What else can we learn from the ‘relics’ of gas dissipation?

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

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





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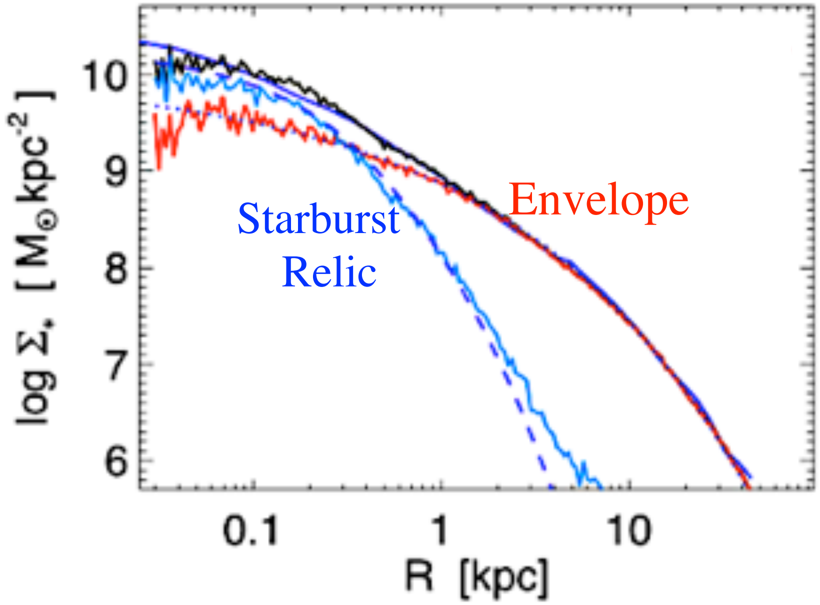
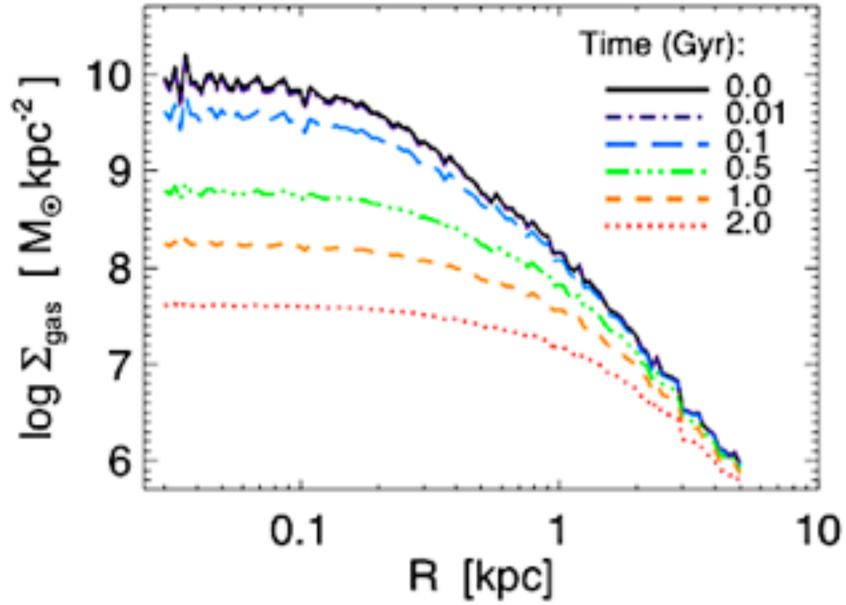
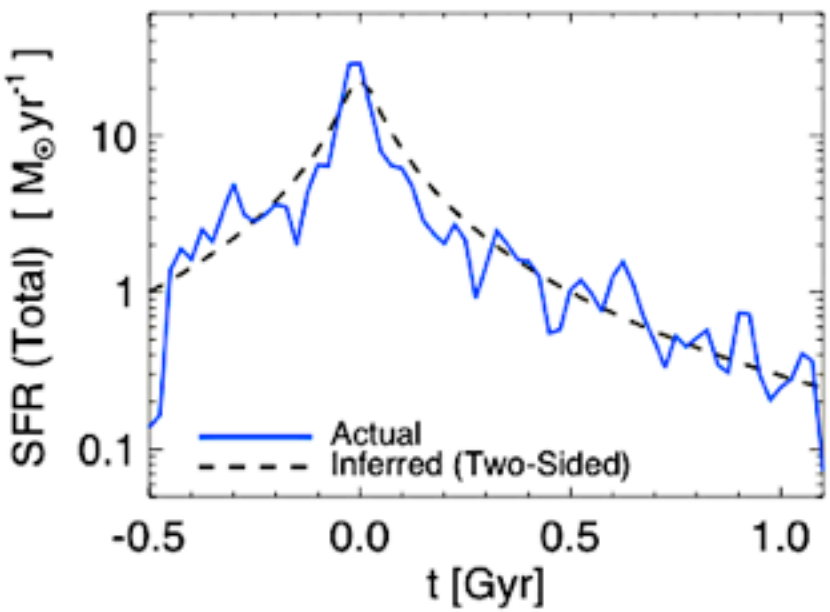


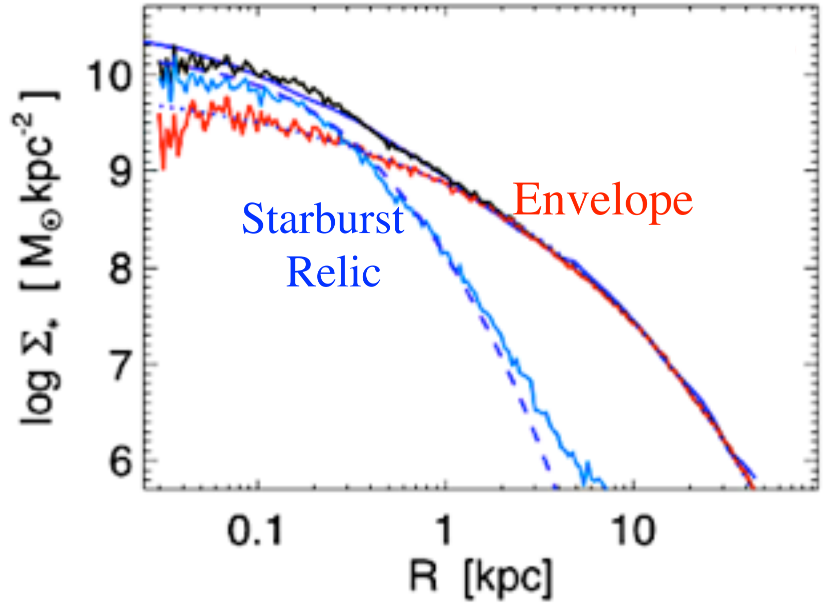


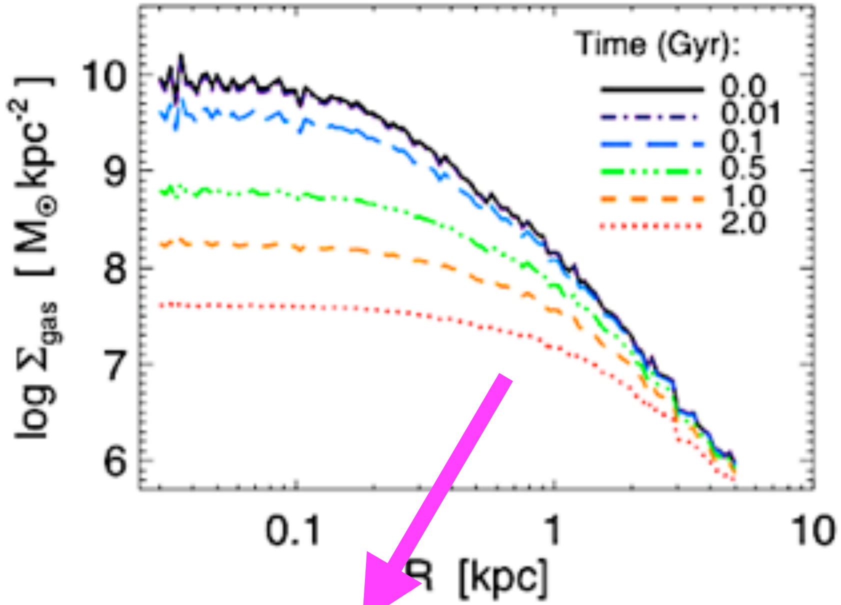


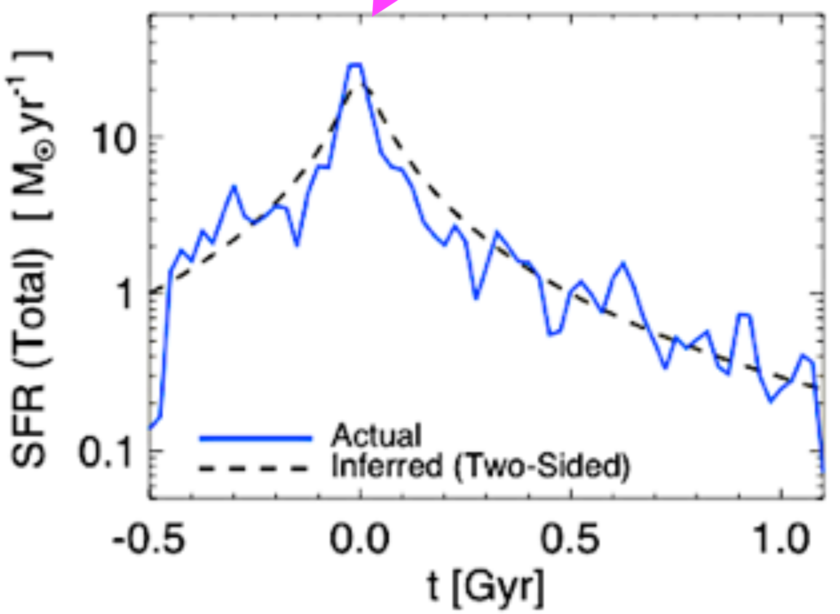
What else can we learn from the ‘relics’ of gas dissipation?

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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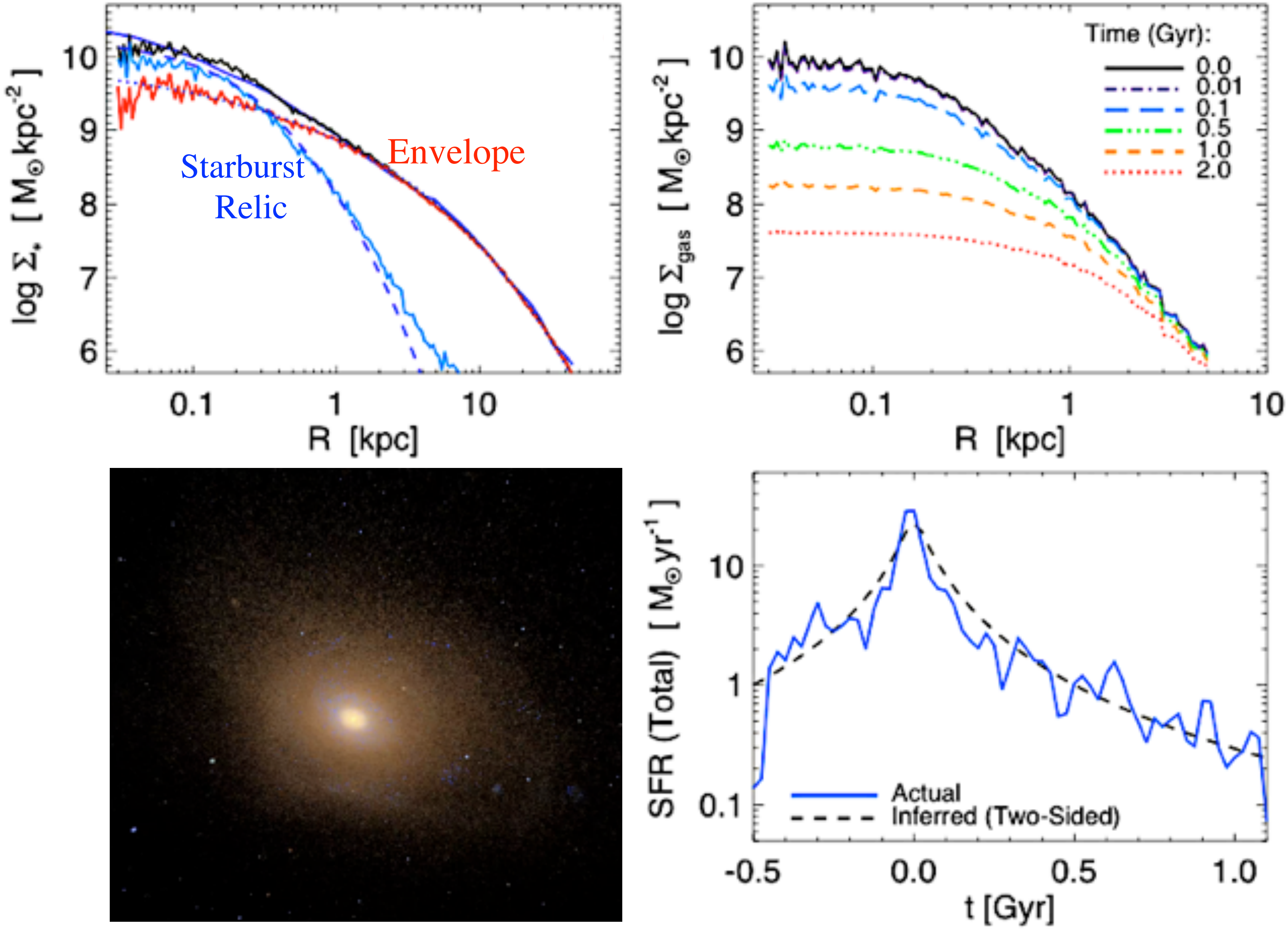

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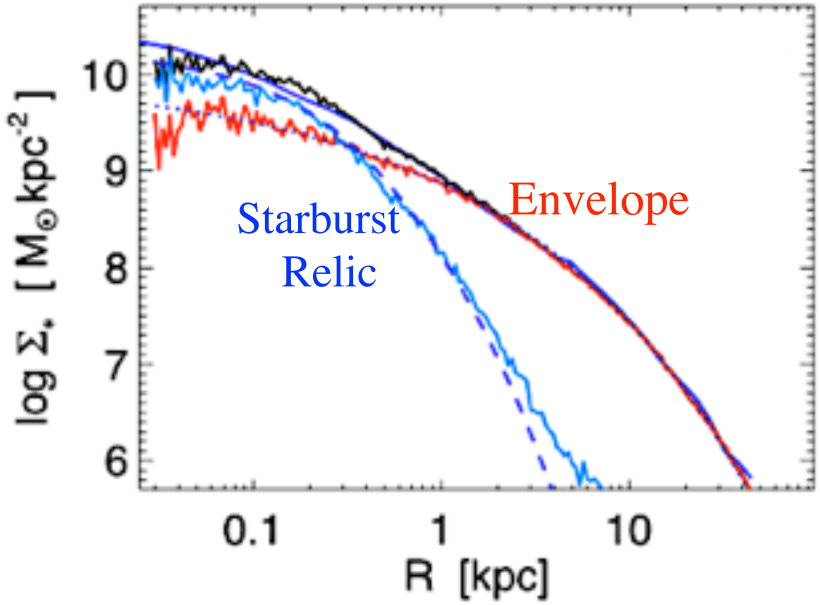

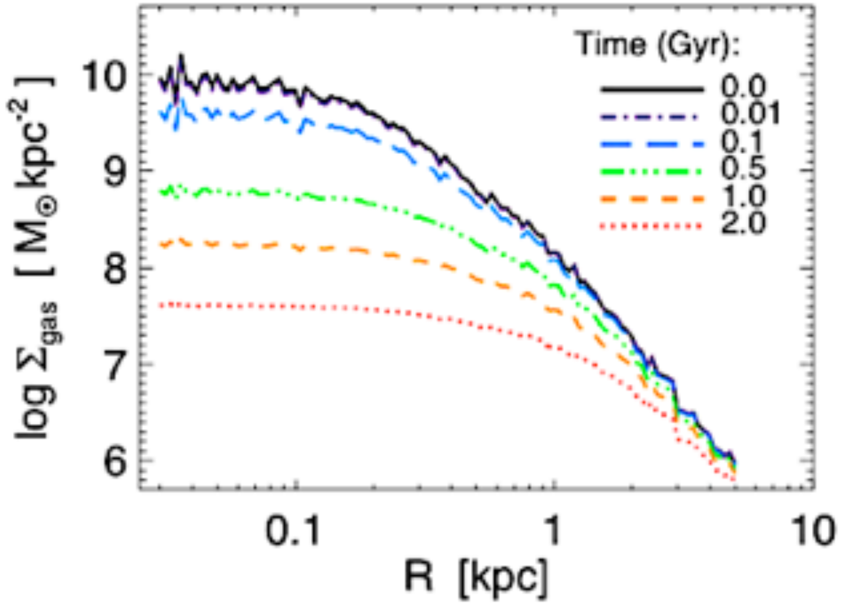

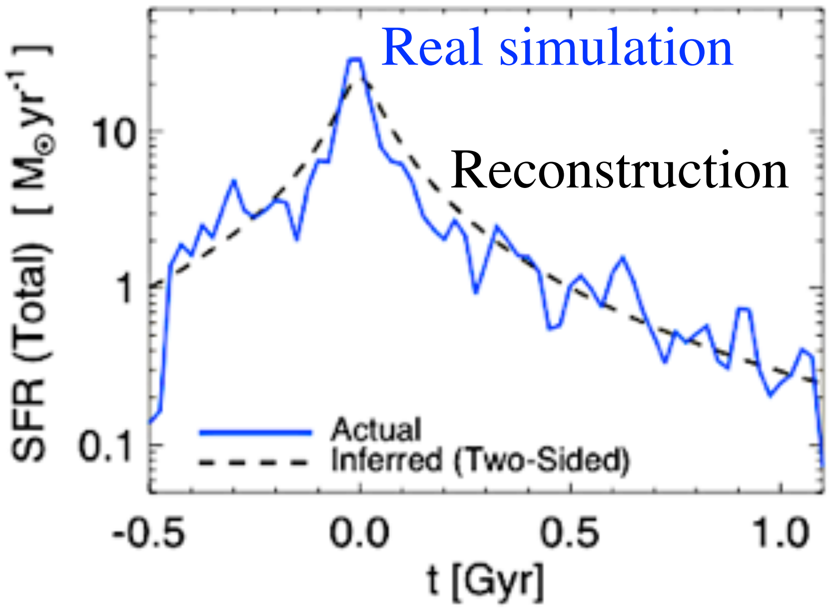

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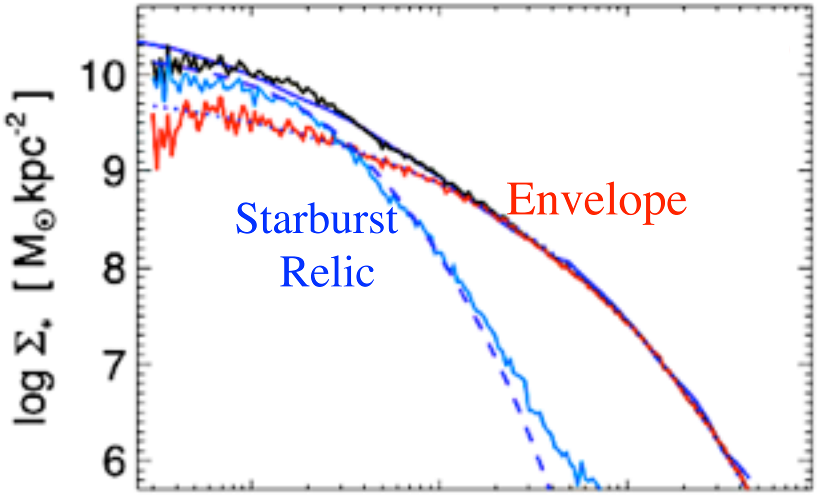

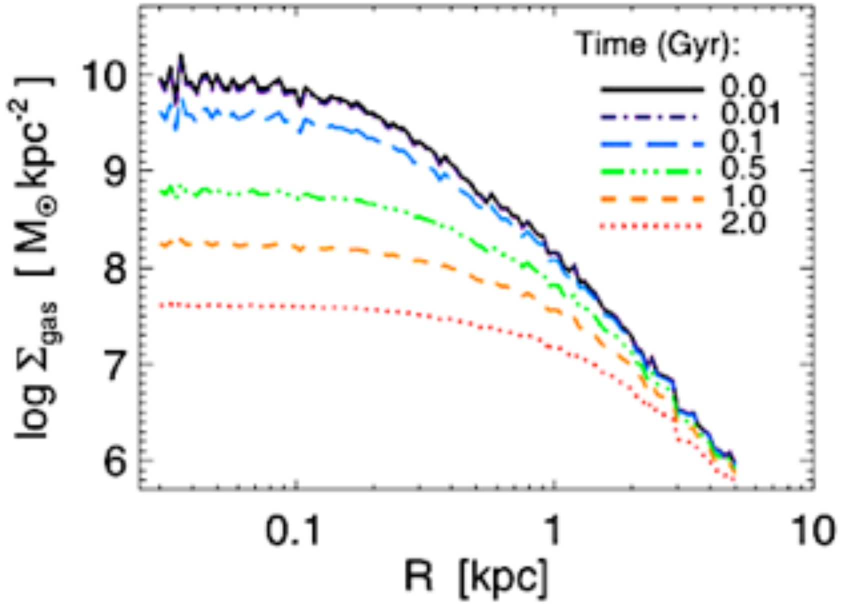

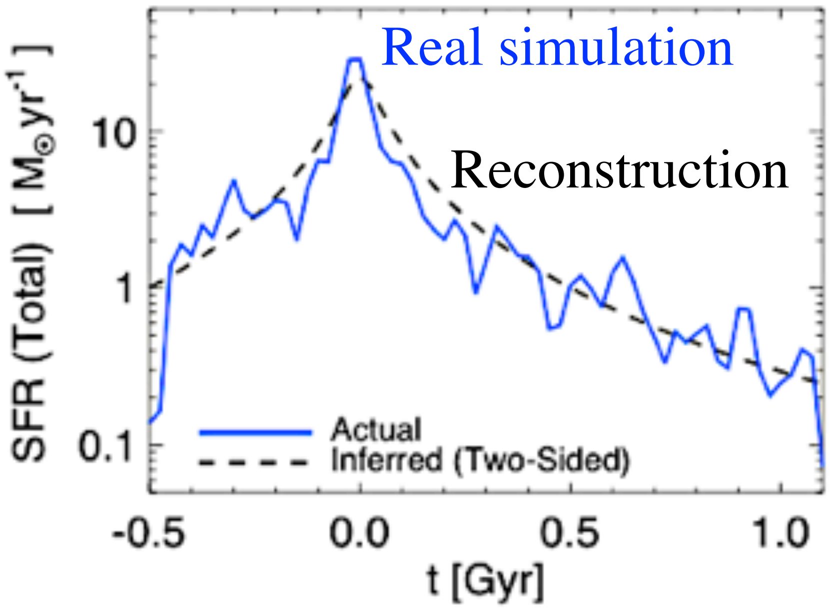

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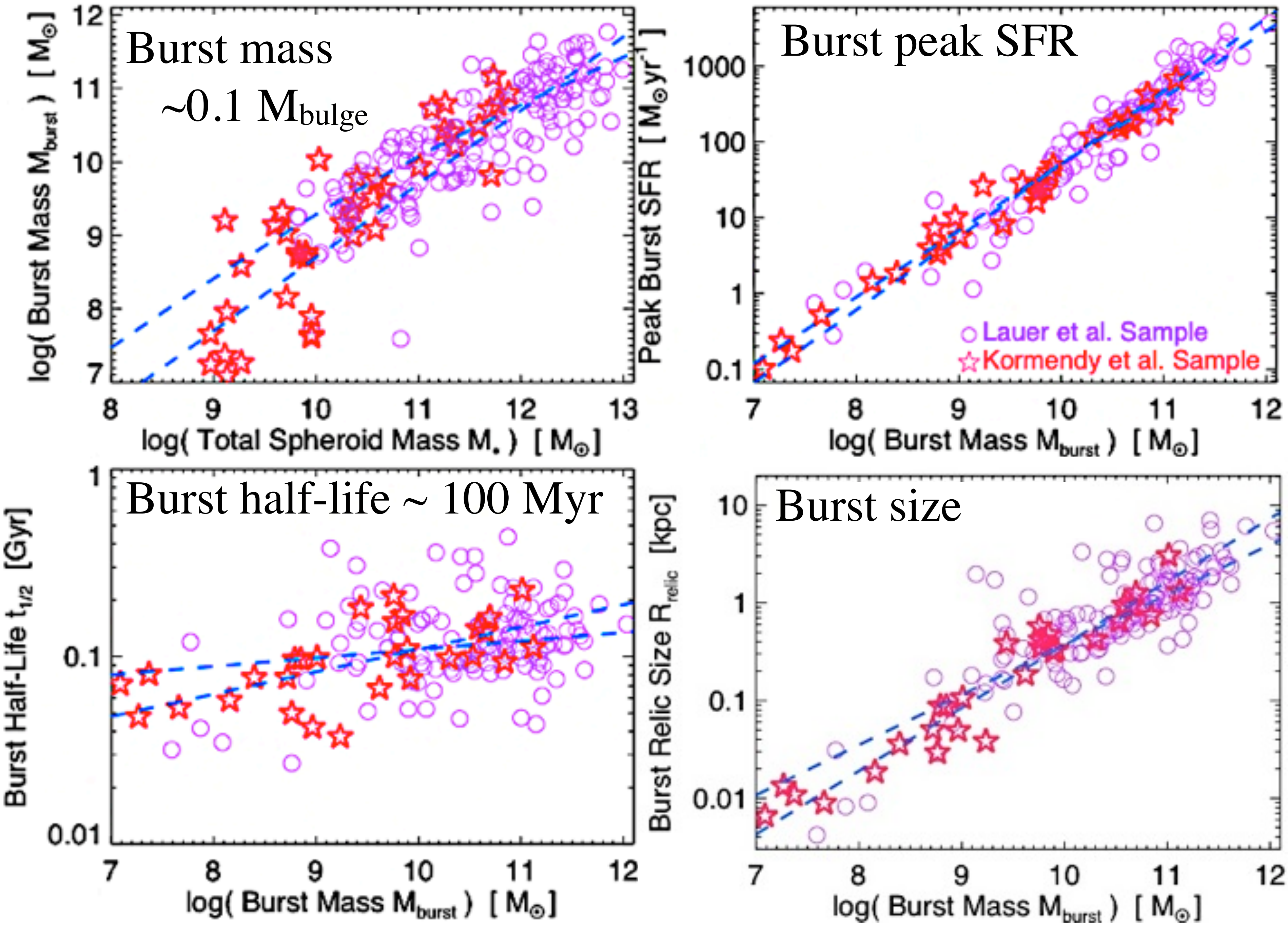

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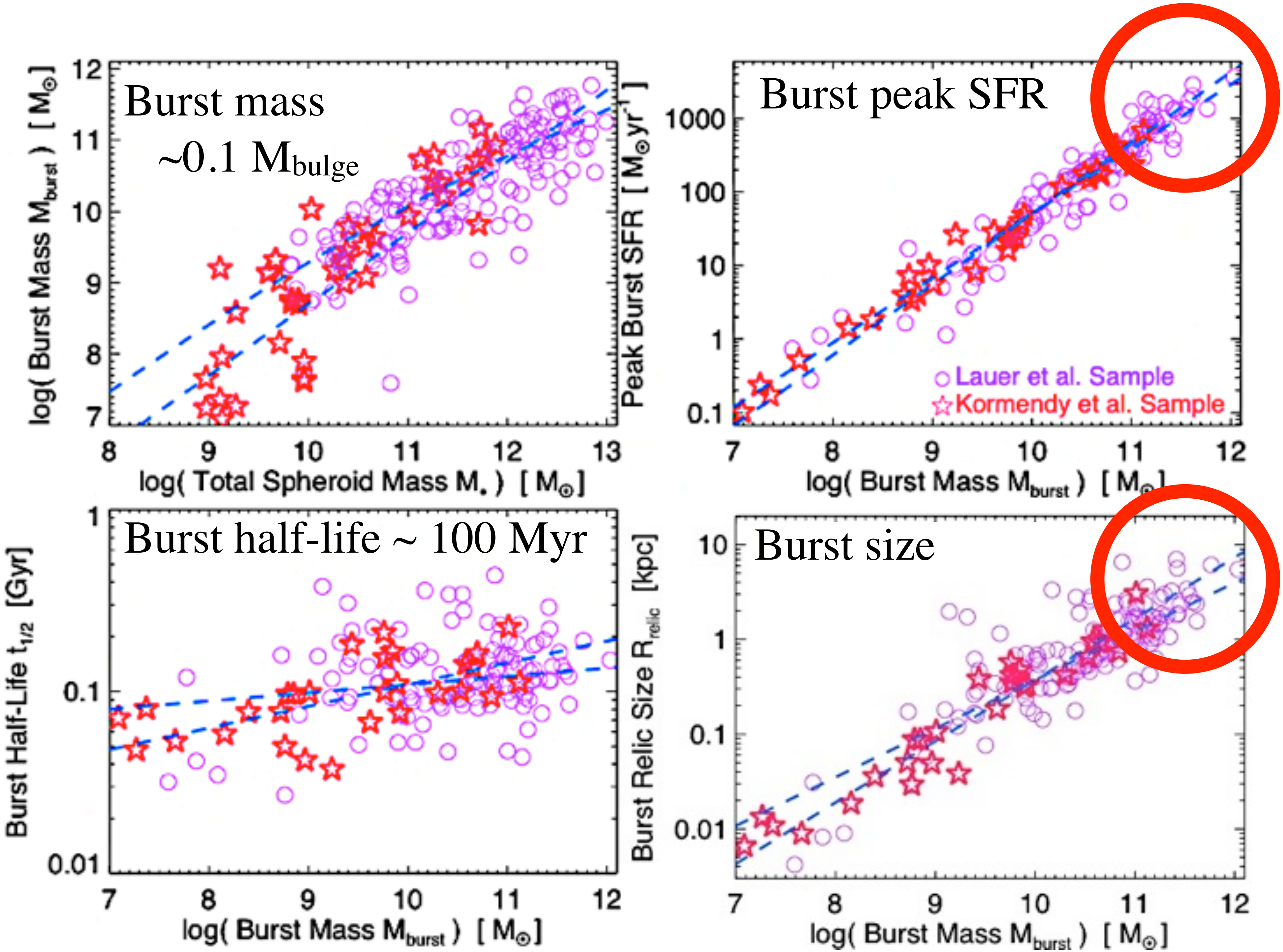
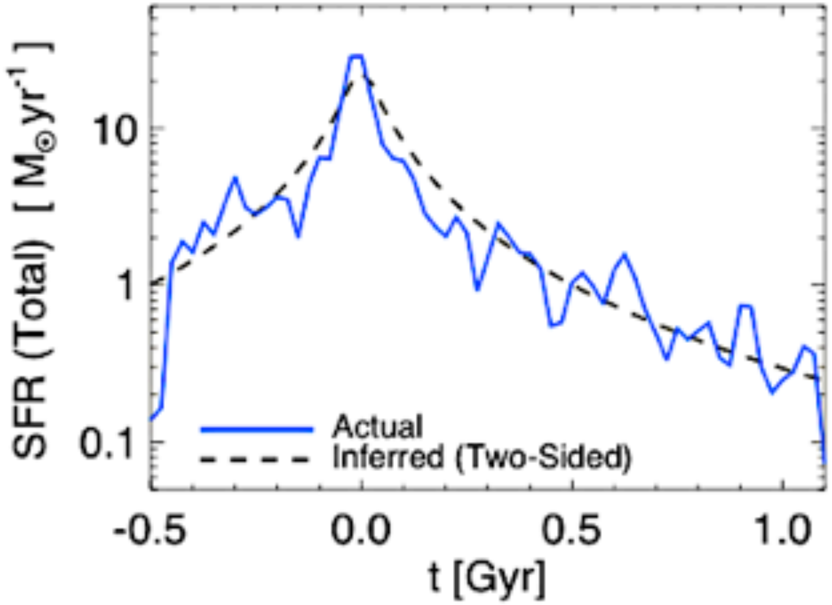
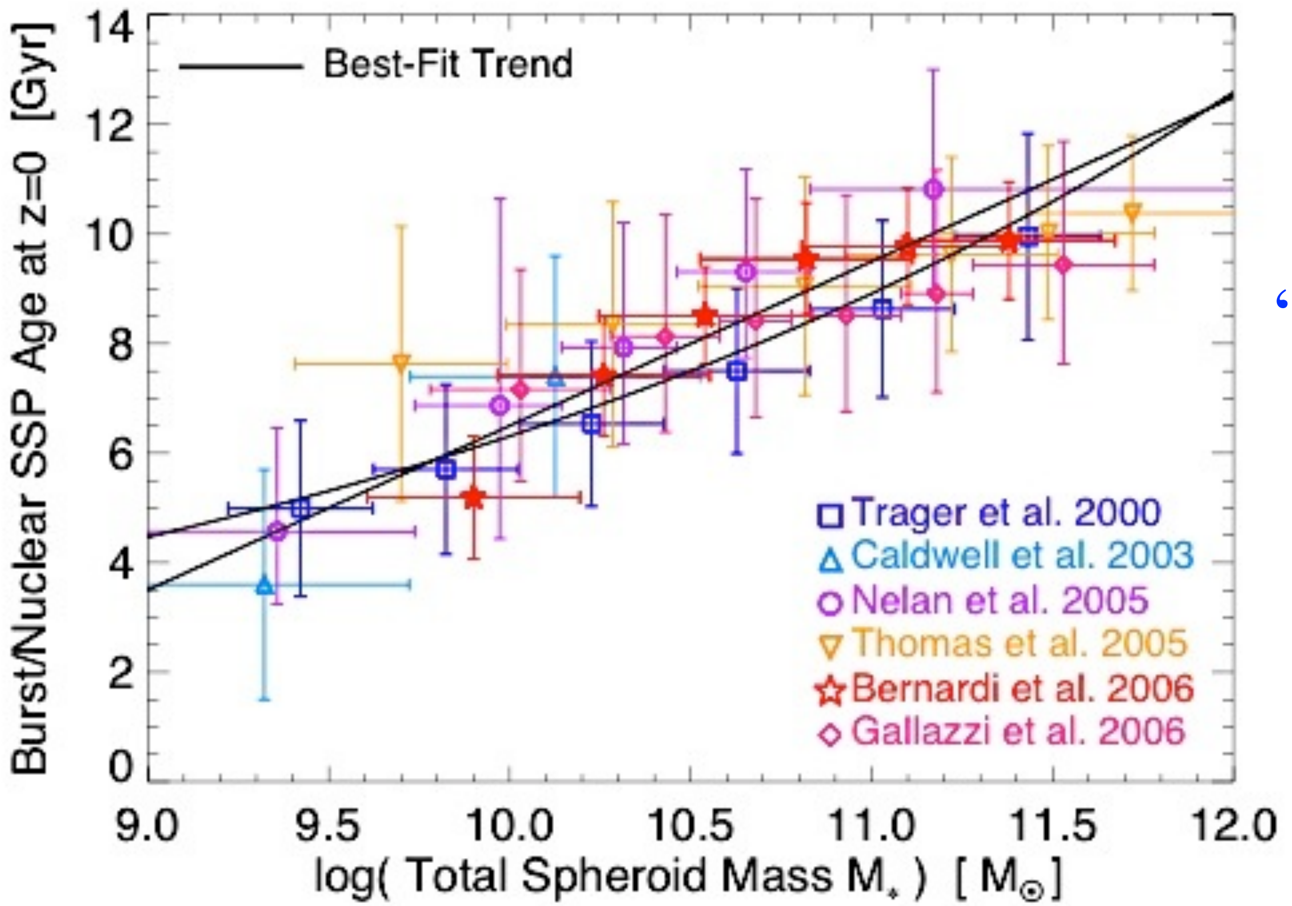


Re-construct SFR(t) for each burst :



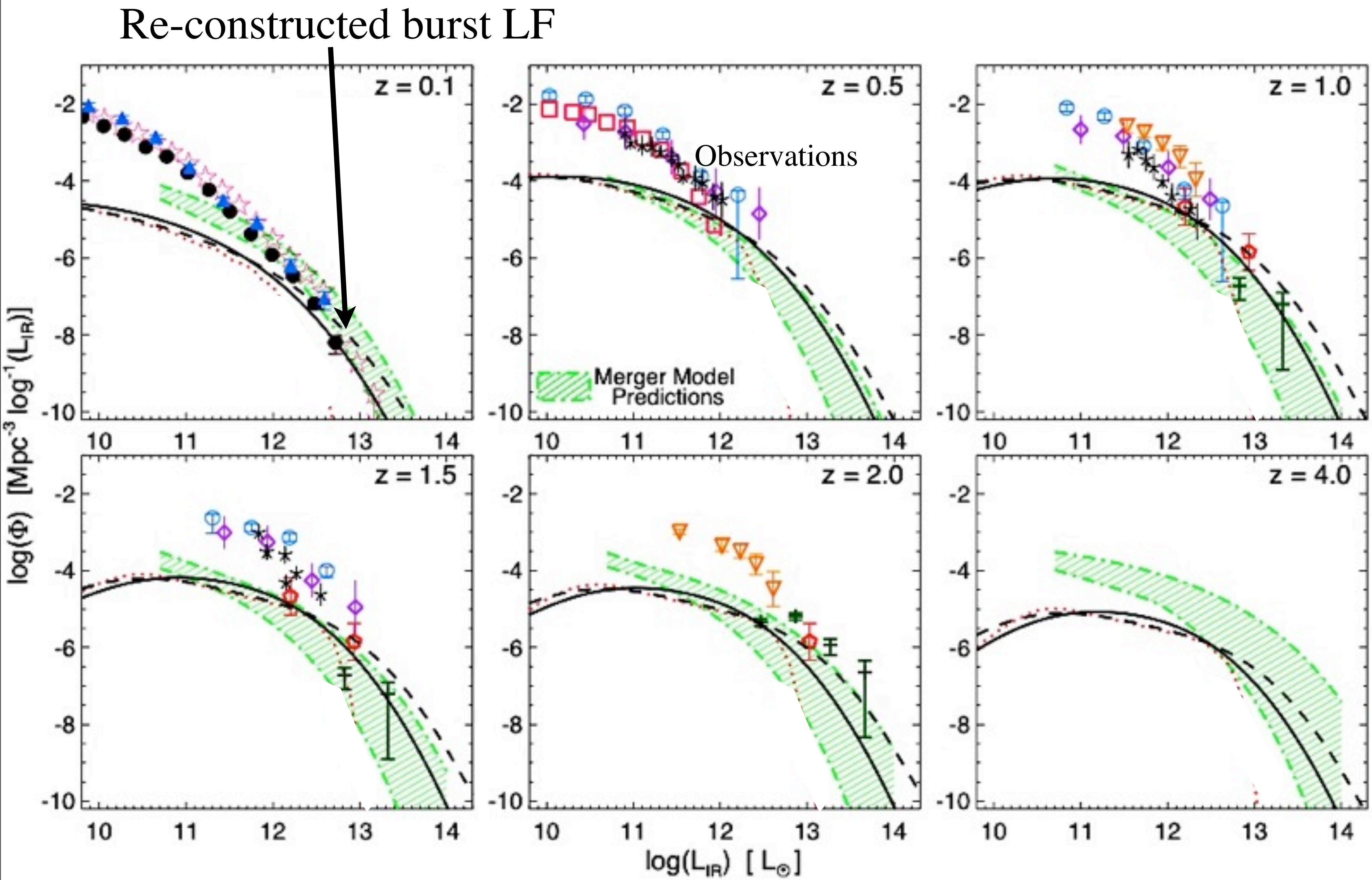
+ We know the nuclear SSP ages....



"place" each burst at the correct redshift

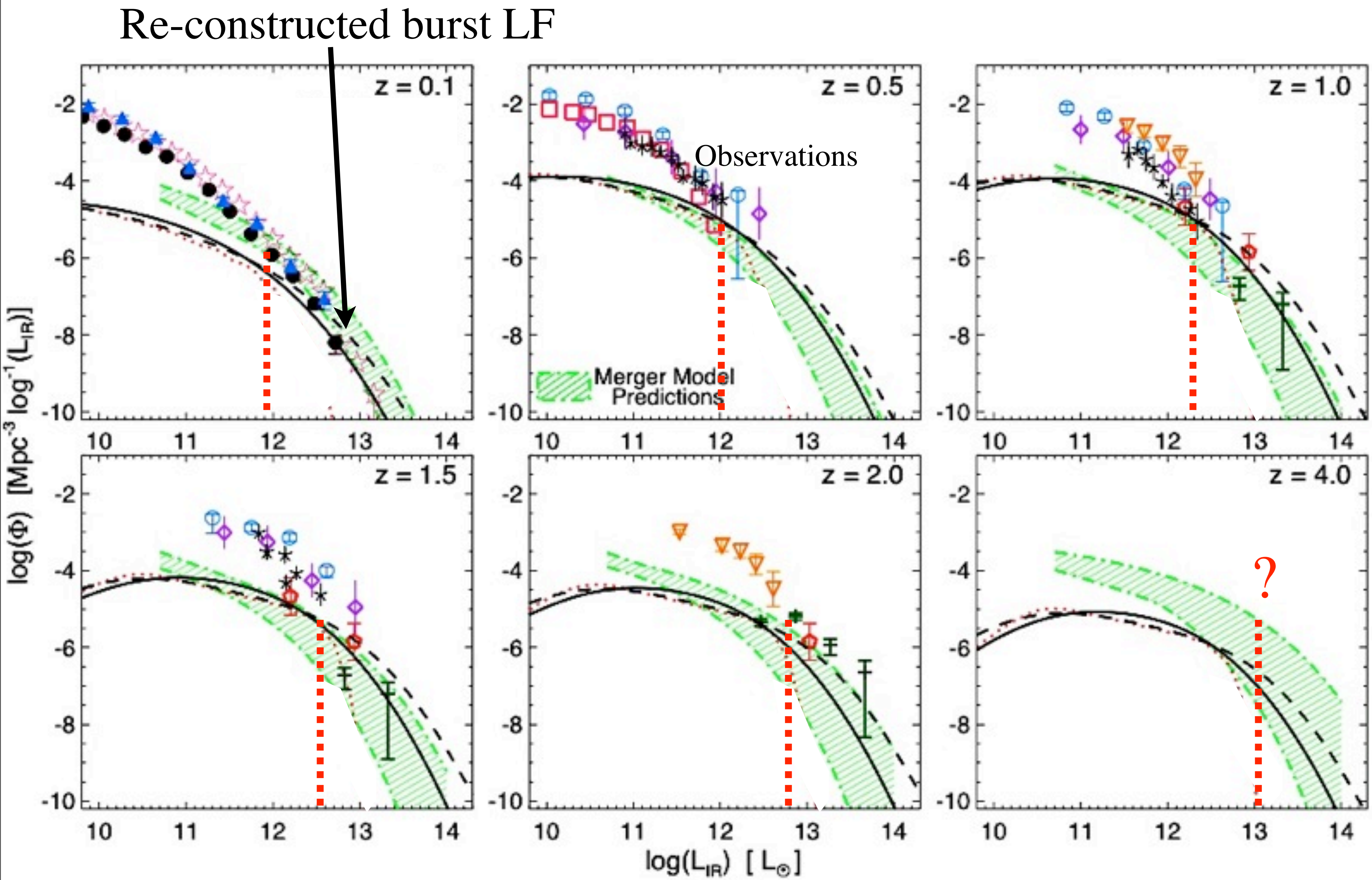
PFH & Hernquist 200

Recover the IR LF of dissipational starbursts!

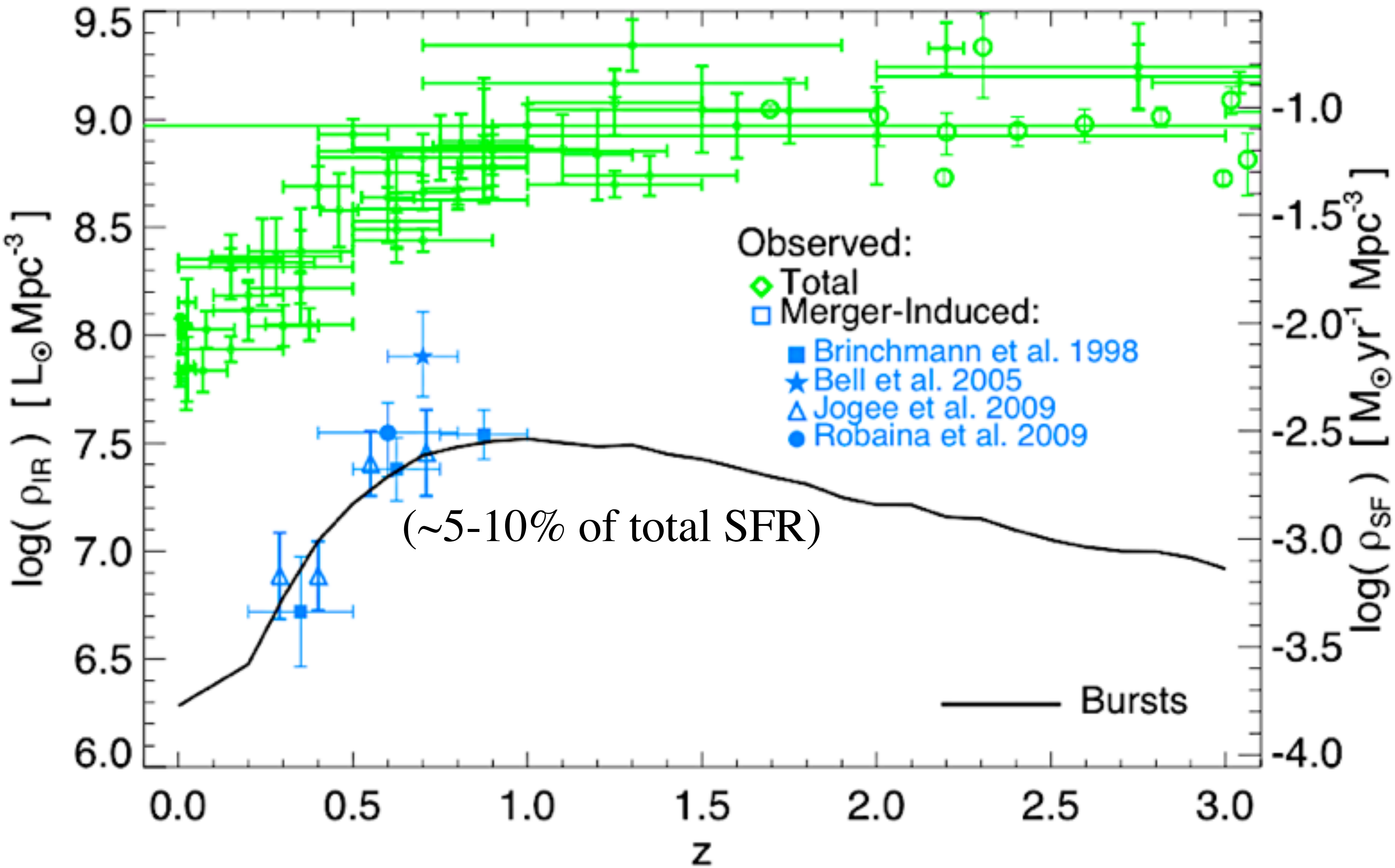


PFH & Hernquist 200

Bursts always dominate at high L, but the threshold shifts

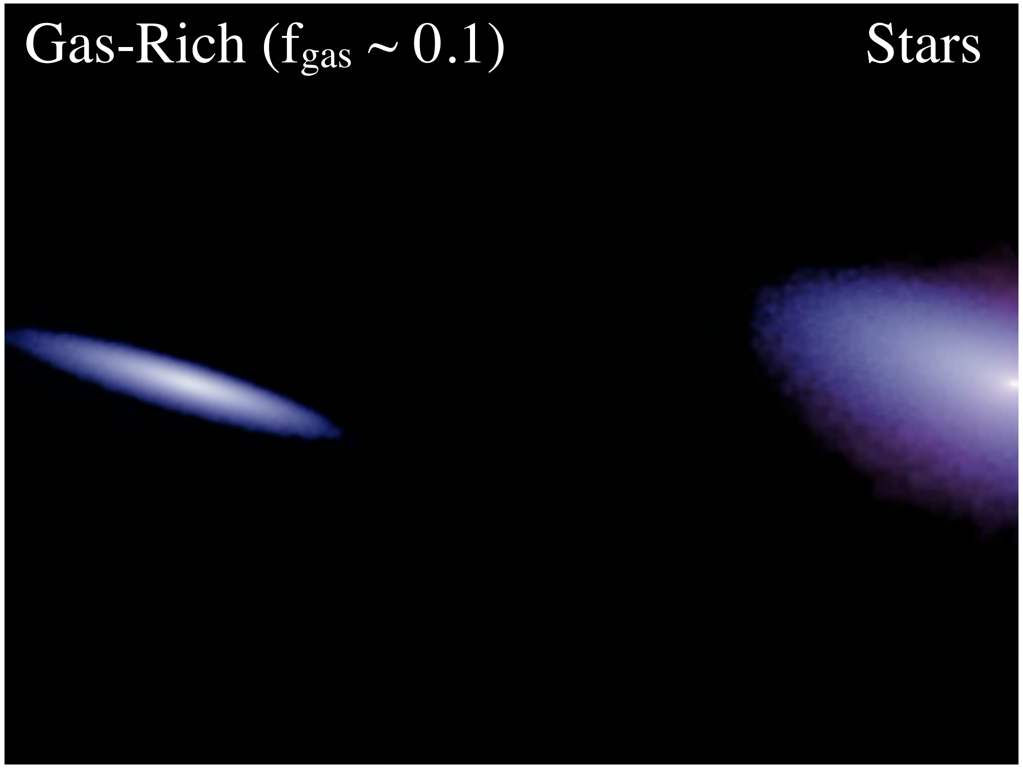


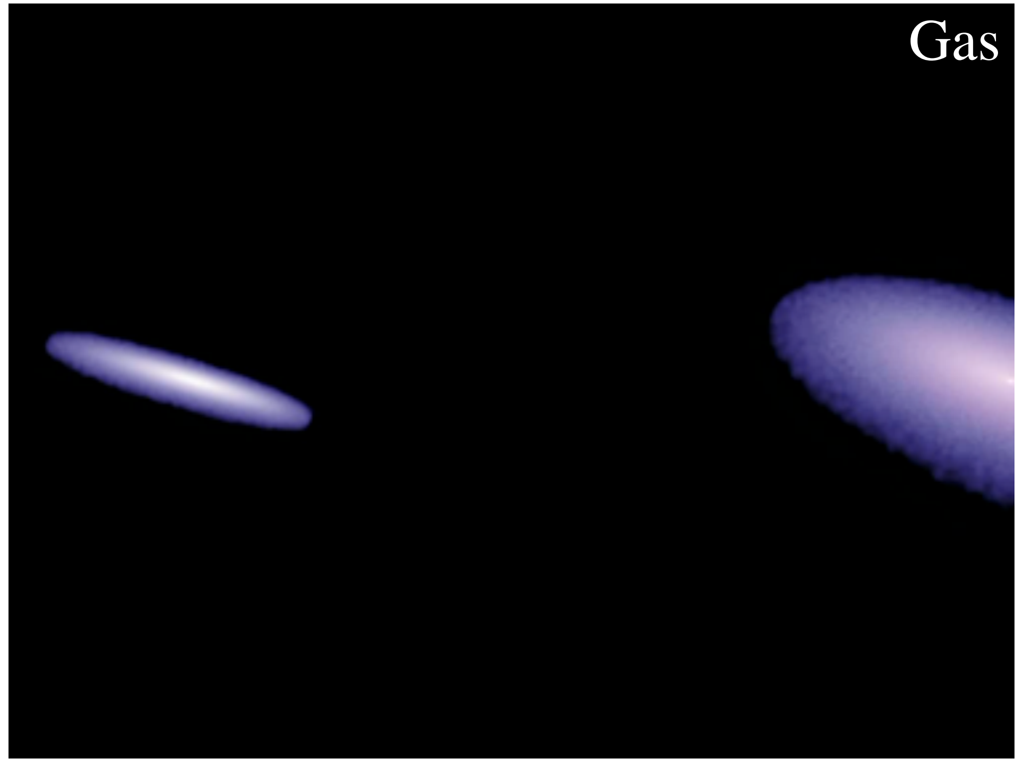
Bursts *never* dominate the SFR density!



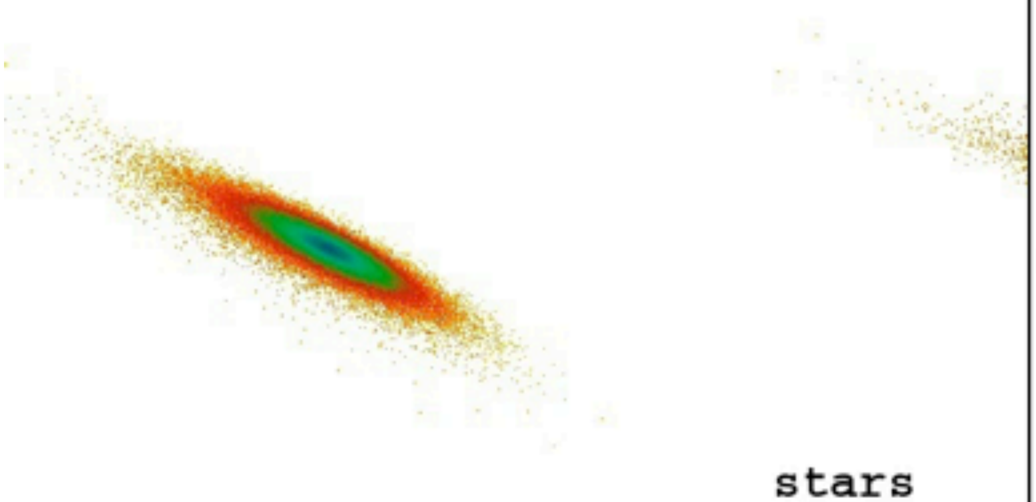
Why Is There Not Much More Efficient Gas Consumption at High Redshifts?

How Good Is Our Conventional Wisdom?



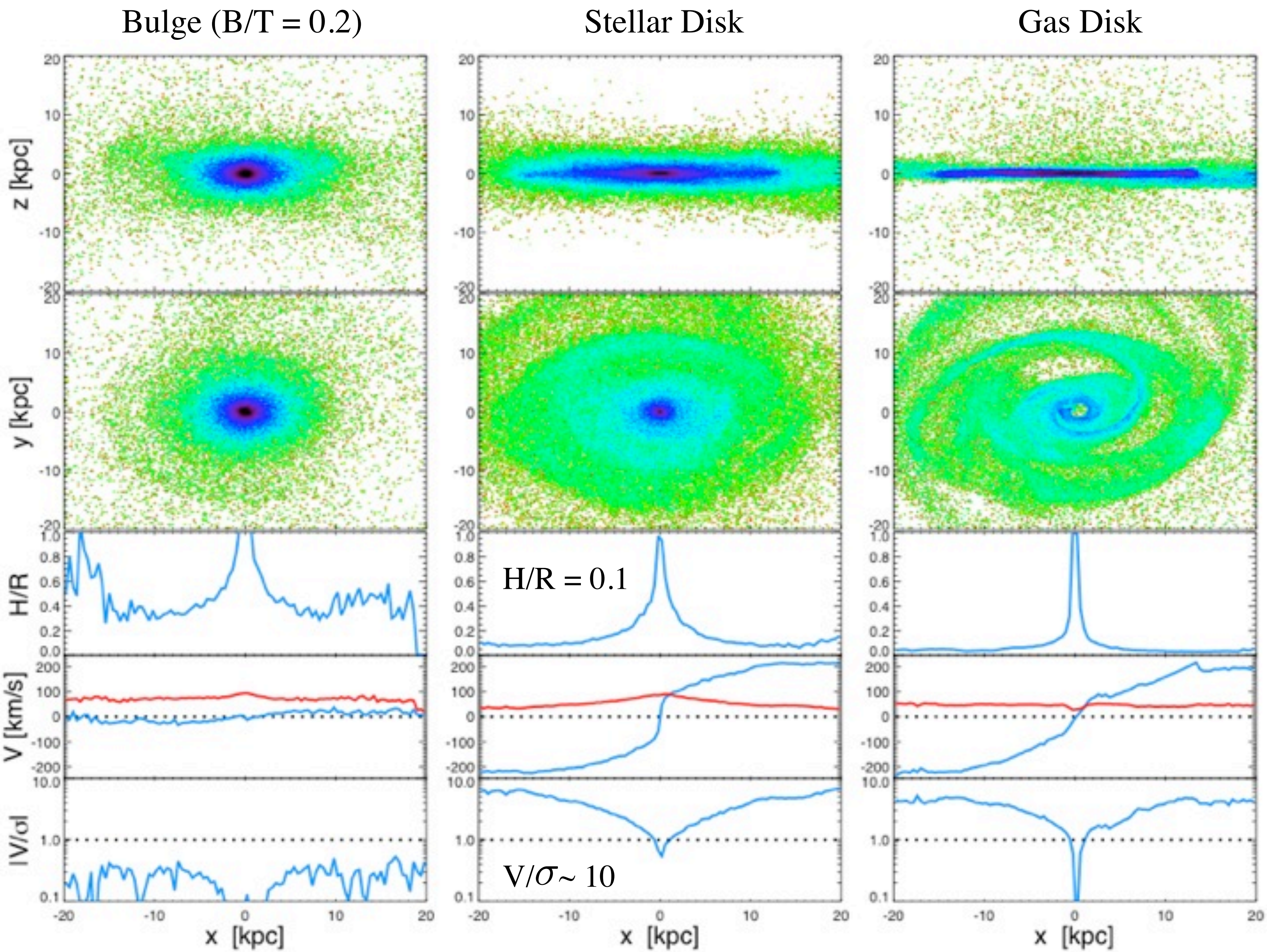


Gas-Richer (f_{gas} ~ 0.4)



Major Merger Remnants

DO MERGERS DESTROY DISKS?



The Unsolved Questions

HOW CAN A DISK SURVIVE?

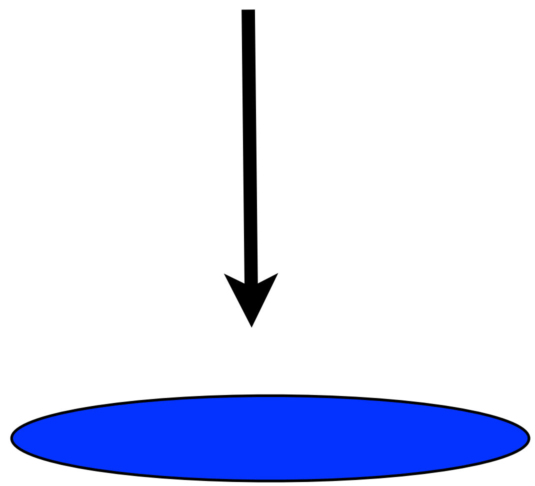
- Stellar disks are collisionless: they violently relax when they collide

- Can’t “cool” into a new disk

The Unsolved Questions

HOW CAN A DISK SURVIVE?

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

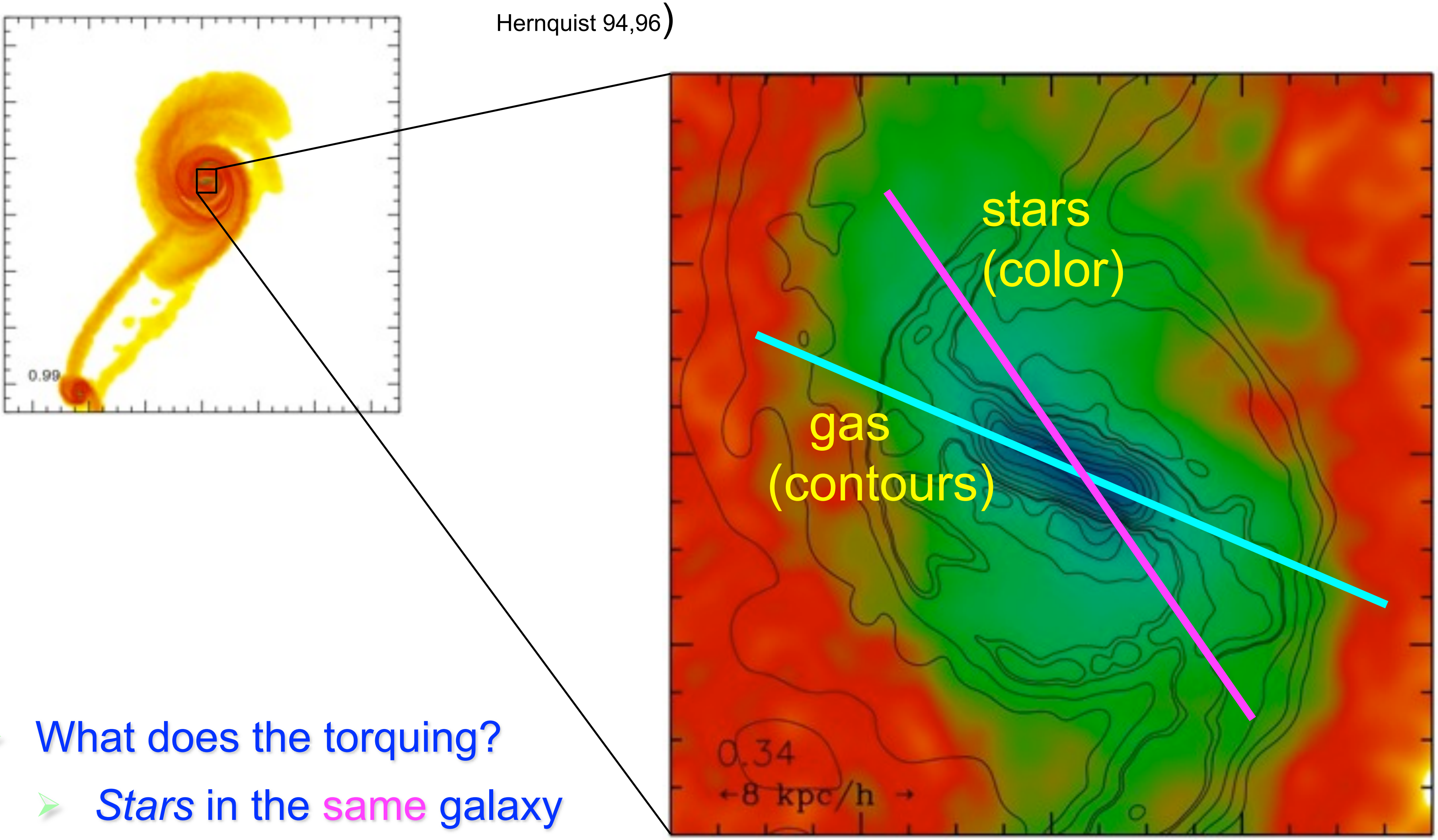


Governato et al.

How Do Disks Survive Mergers?

PFH et al. 2008

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



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

How Do Disks Survive Mergers?

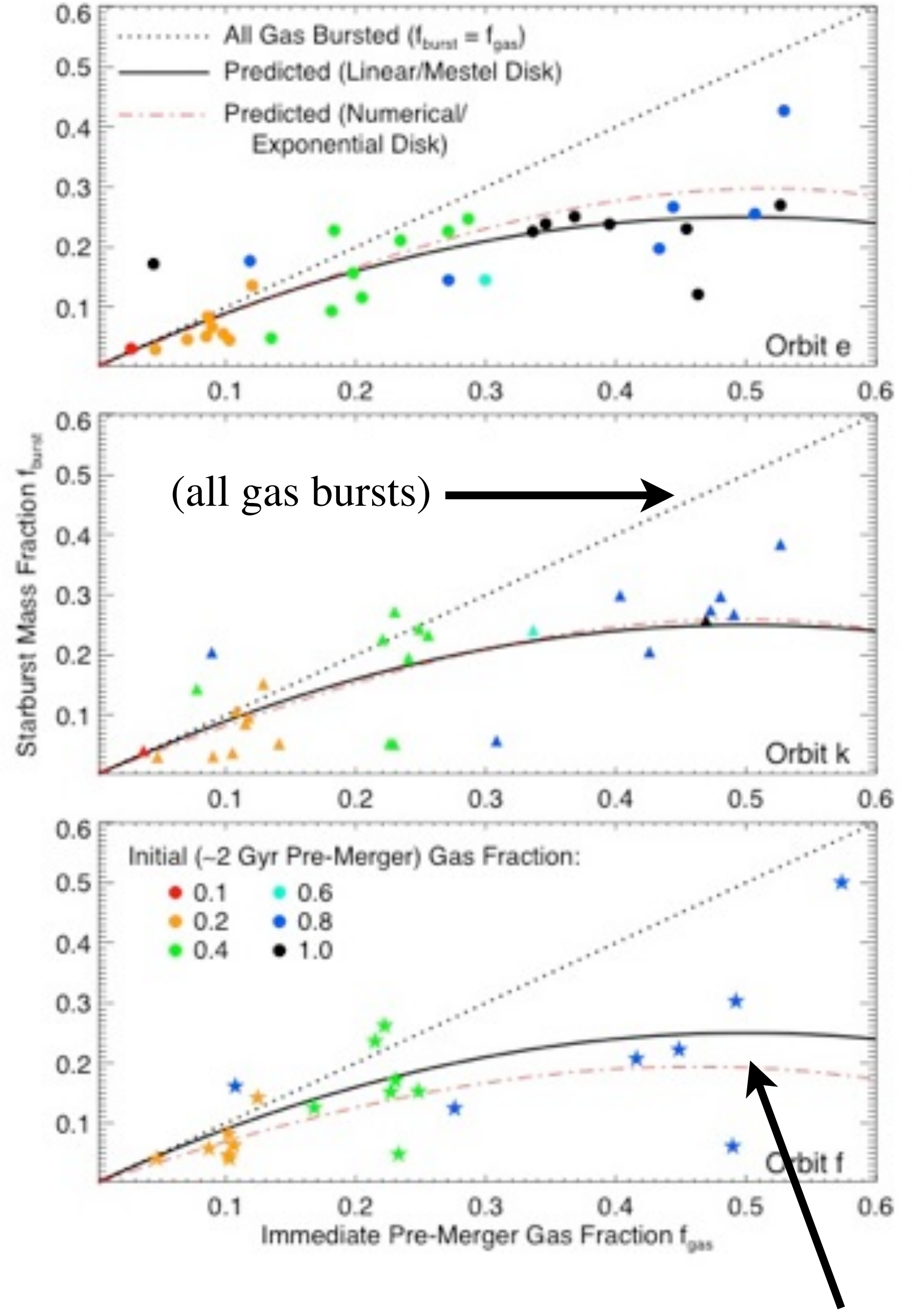
Torque on gas:

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

For the same merger/perturbation:

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

Burst mass vs. f_{gas}

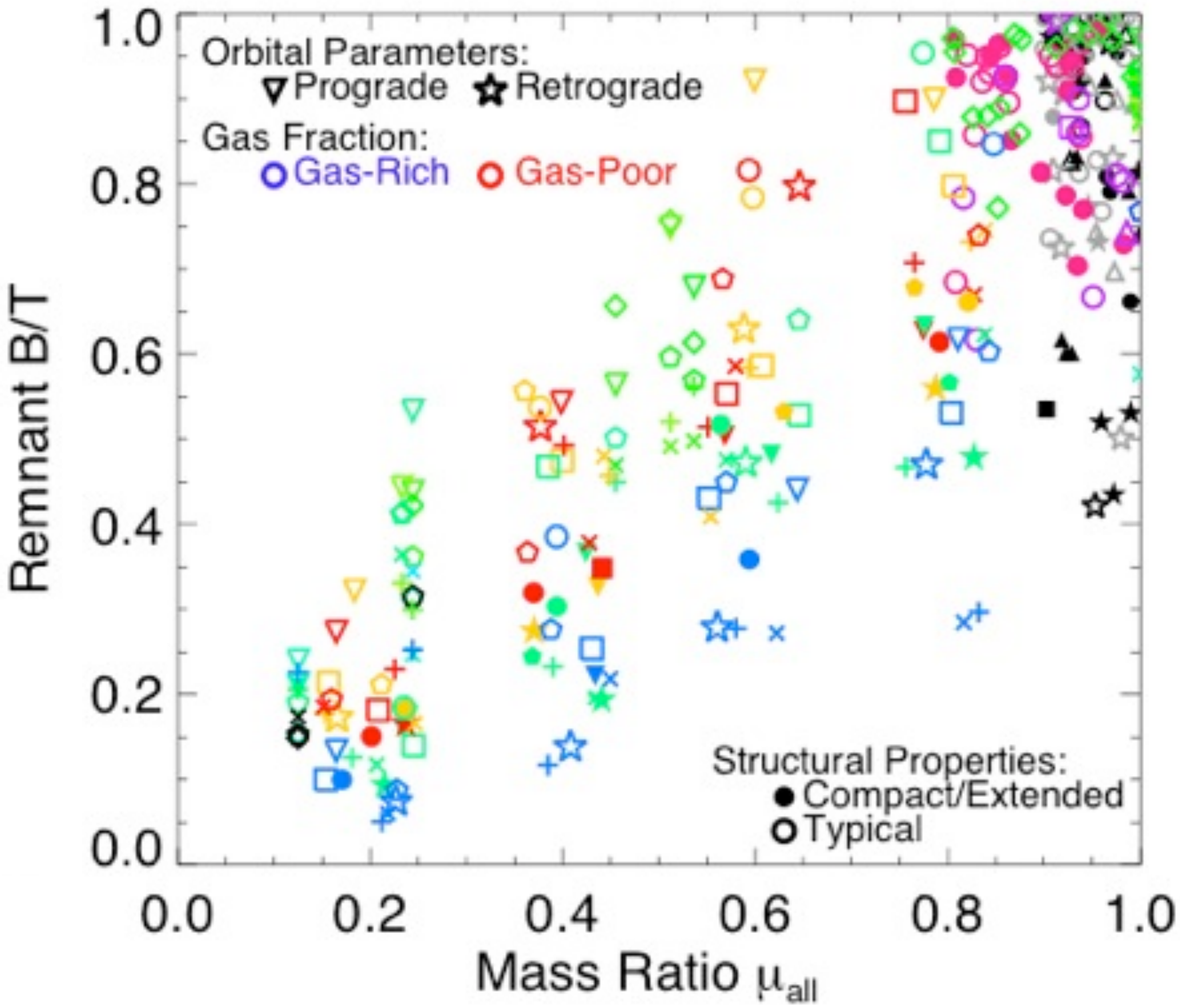


(gas-dependent prediction)

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.



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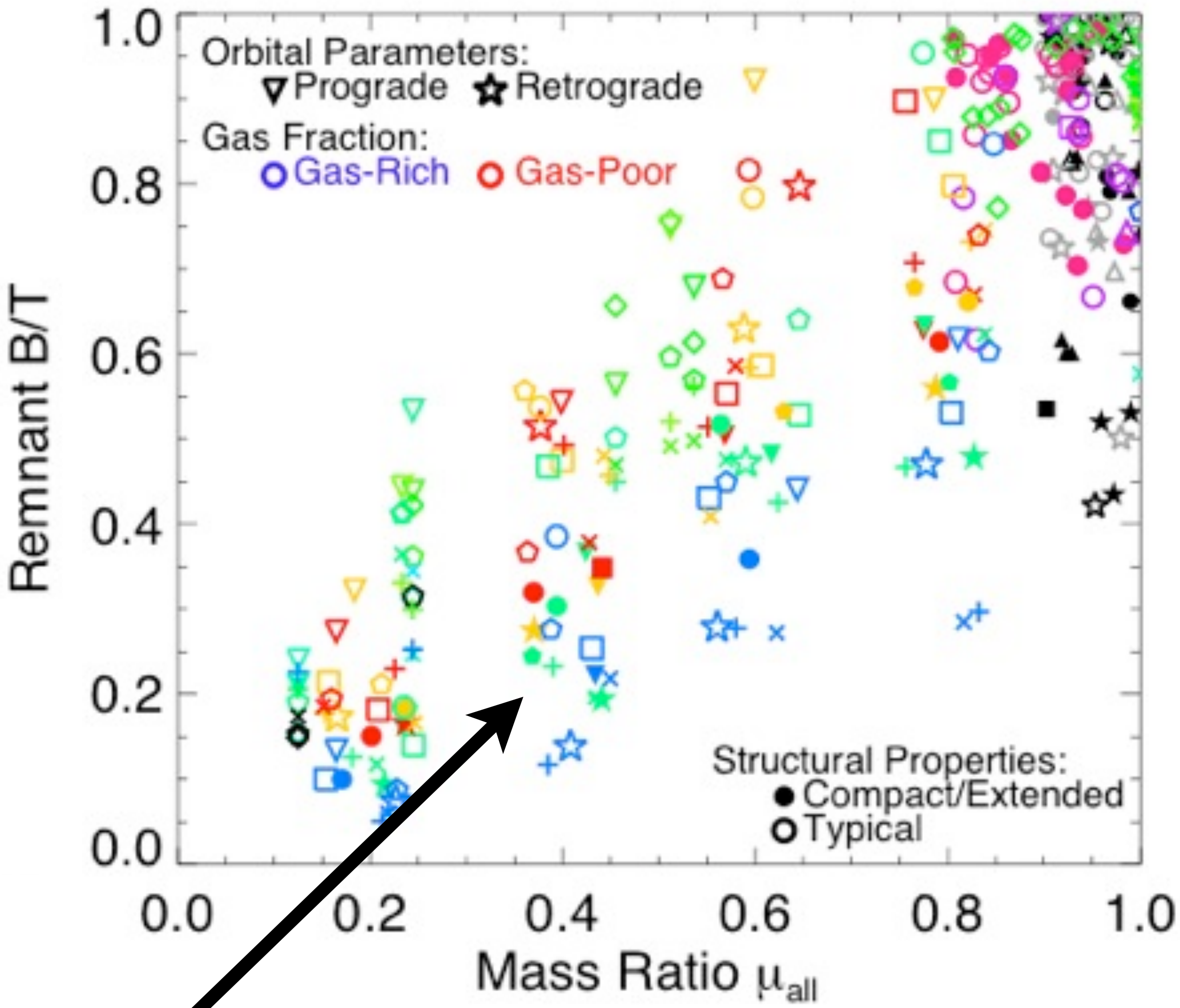


REALLY IMPORTANT!!!

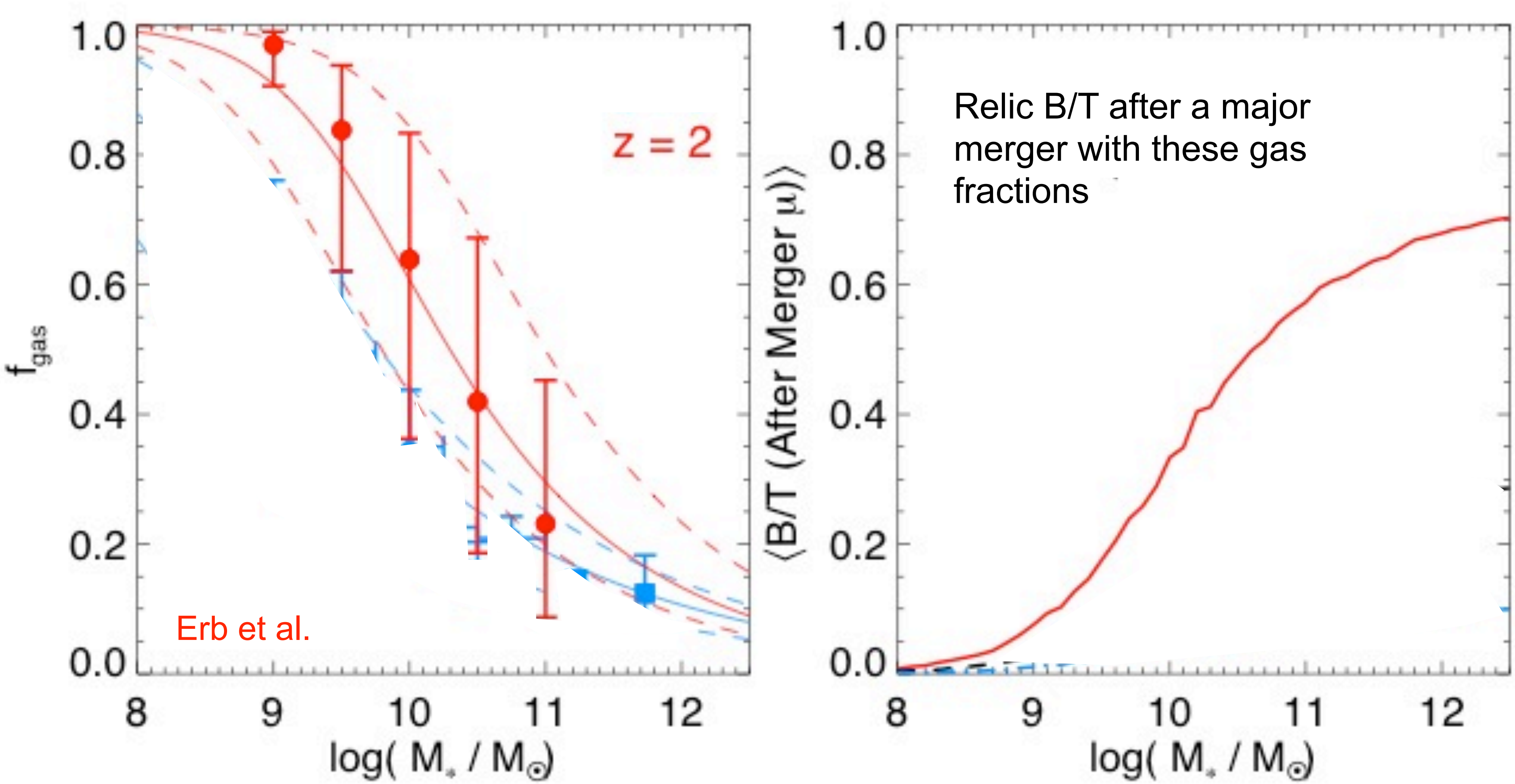
PFH et al. 2008 ("How Do Disks Survive Mergers?")

Why Do We Care?

PFH & Somerville et al. 2009

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

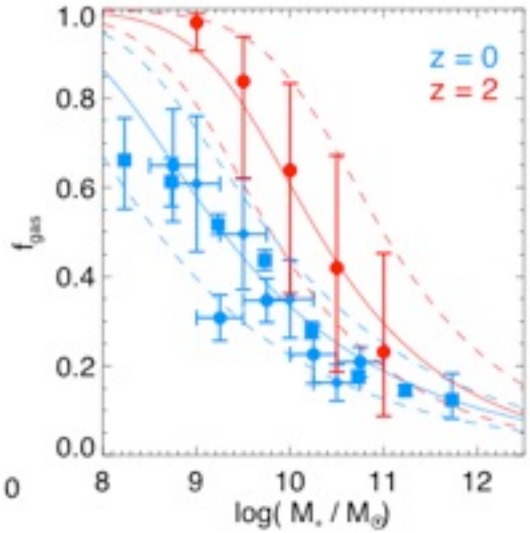
- Fold this into a cosmological model: why do we care?

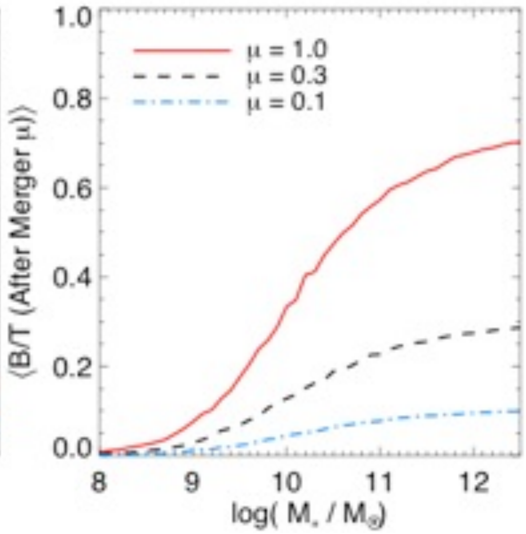


- Low-mass galaxies have high gas fractions: less B/T for the same mergers

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT





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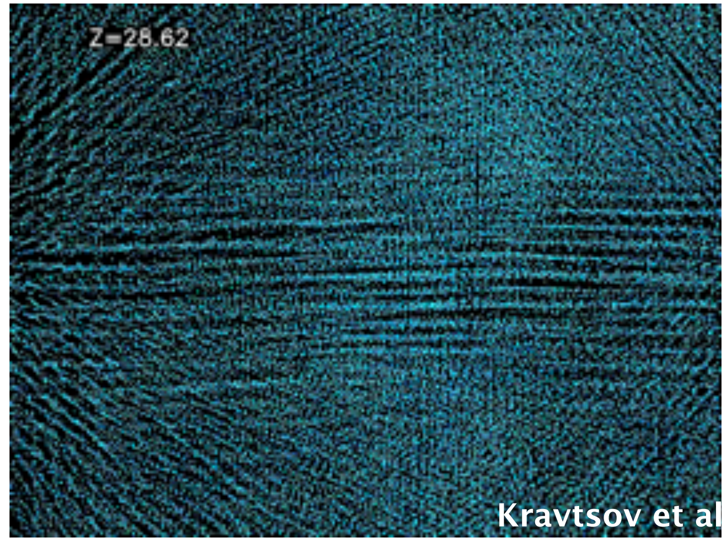

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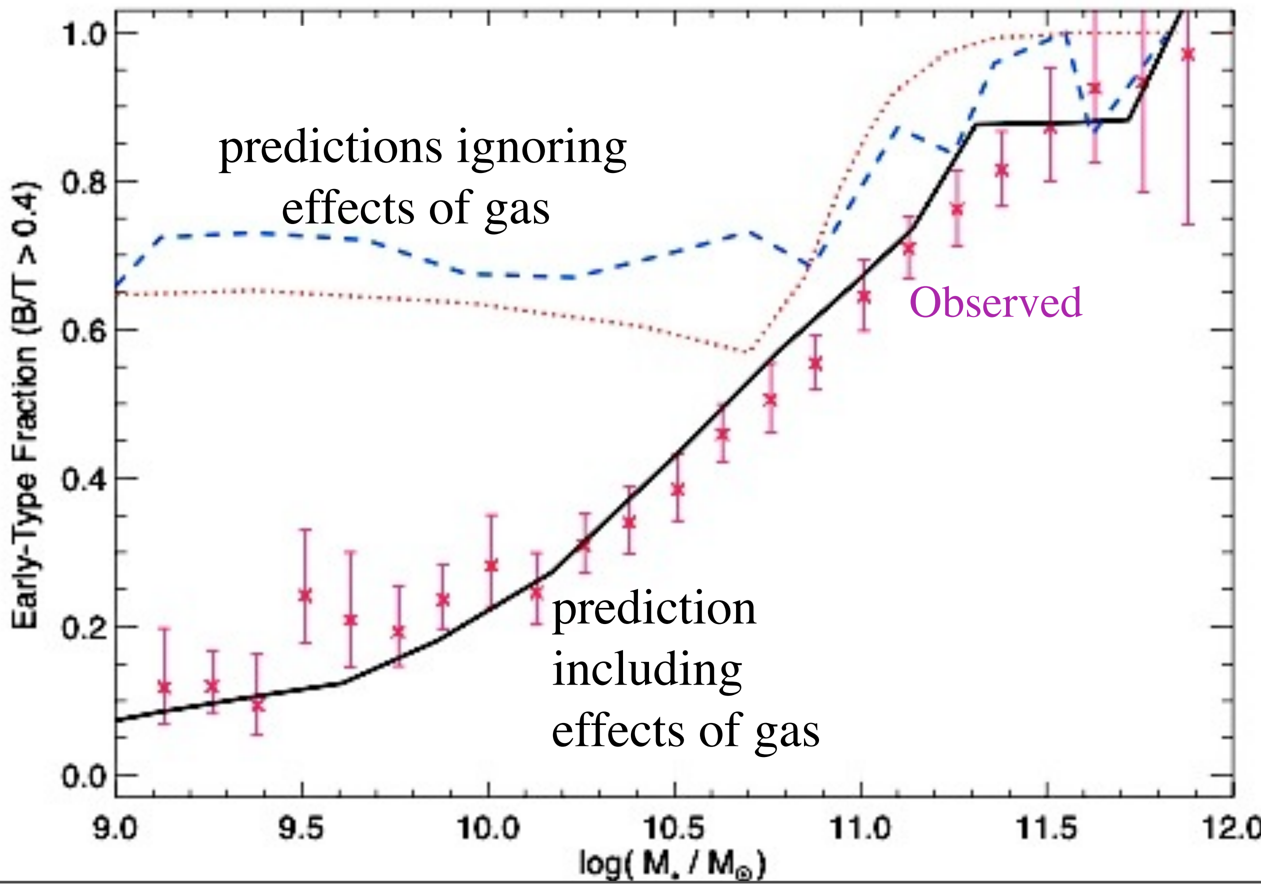


PFH & Somerville et al. 2009

Why Do We Care?

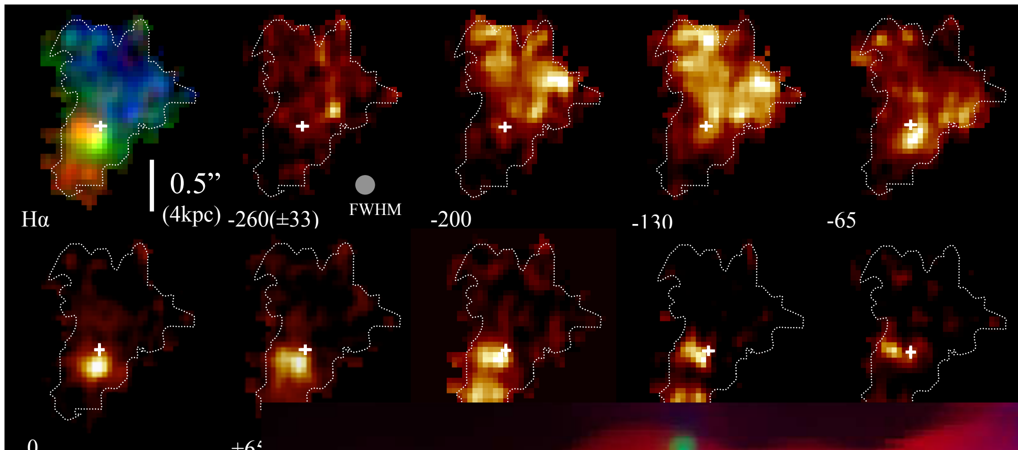
HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 2009

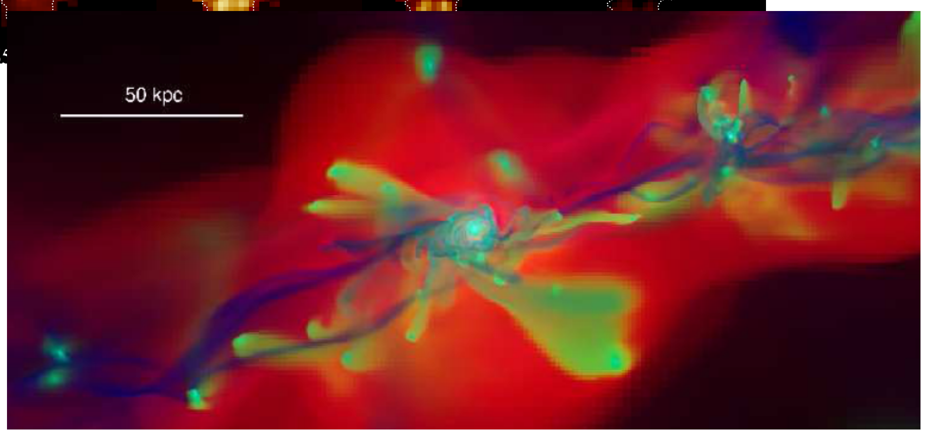
Predict lots of high-z disks!

- Needed for their existence
  - We see them
  - (Genzel, Tacconi, Erb, Law, et al.)

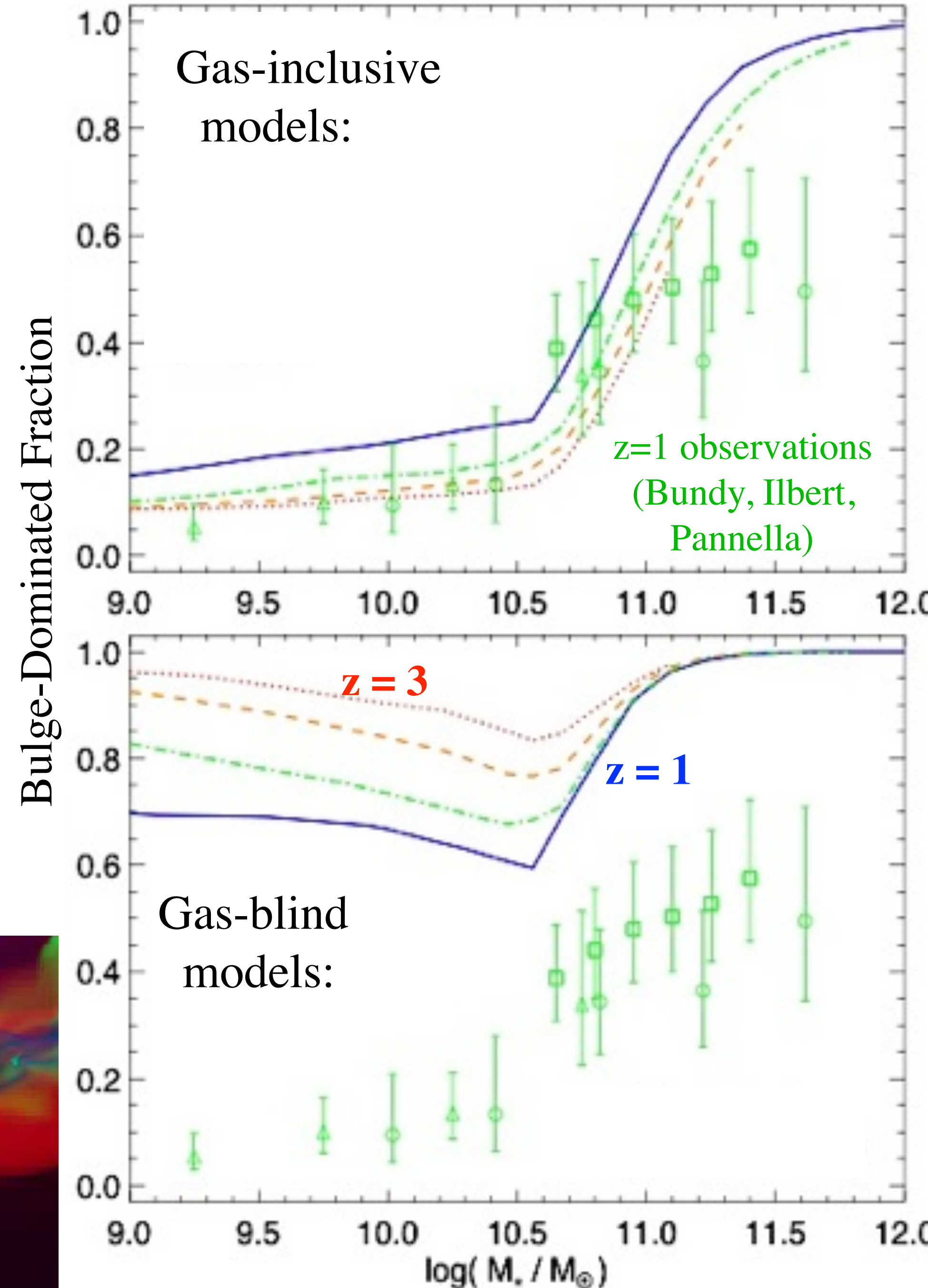
- *May* explain some properties (turbulence etc.)
  - (Robertson & Bullock, 2009)



Genzel et al.

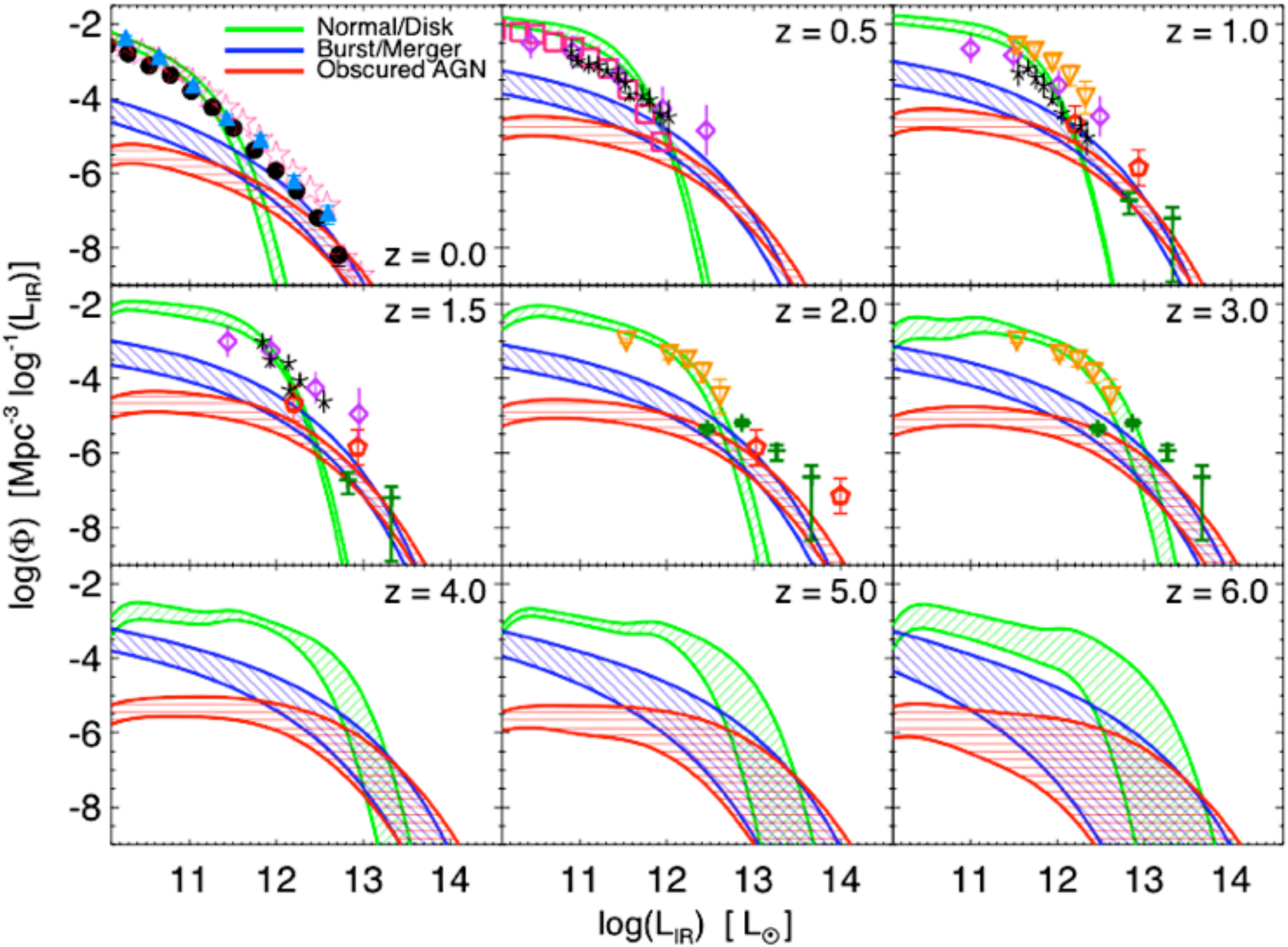


Keres, Dekel. Moore



Have burst predictions -- why not use them?

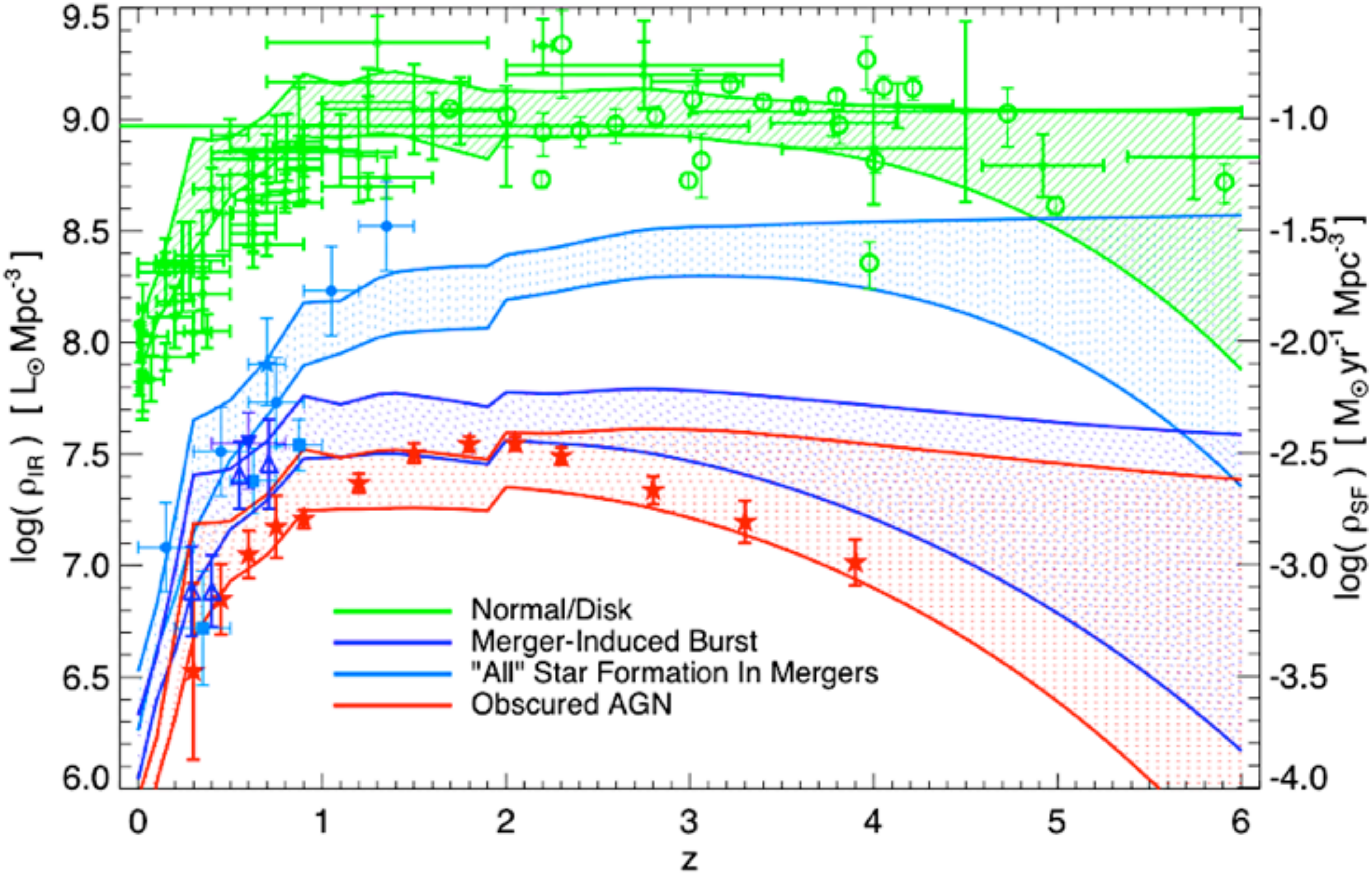
PFH, Younger et al. 20



Have burst predictions -- why not use them?

PFH, Younger et al. 20

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

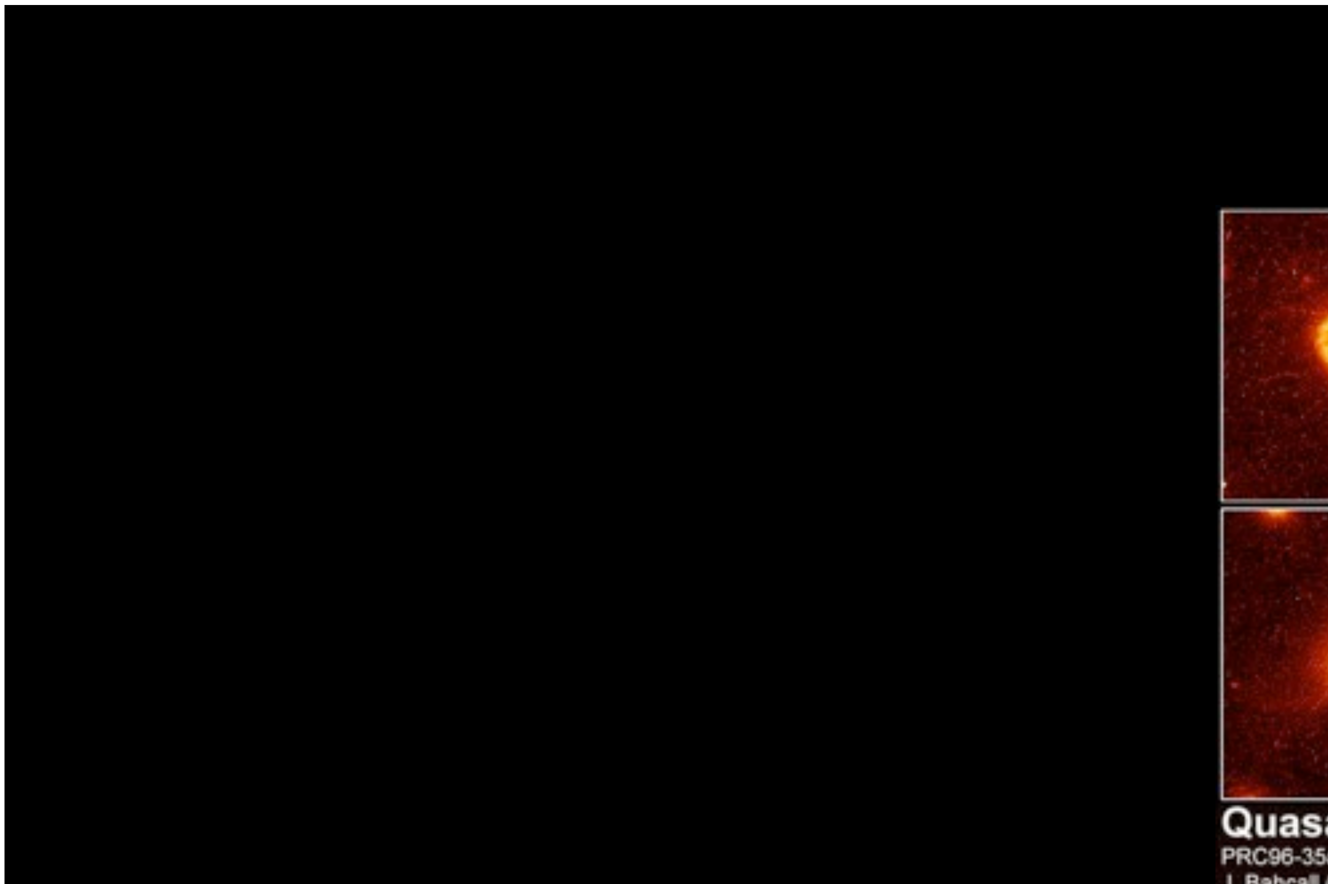


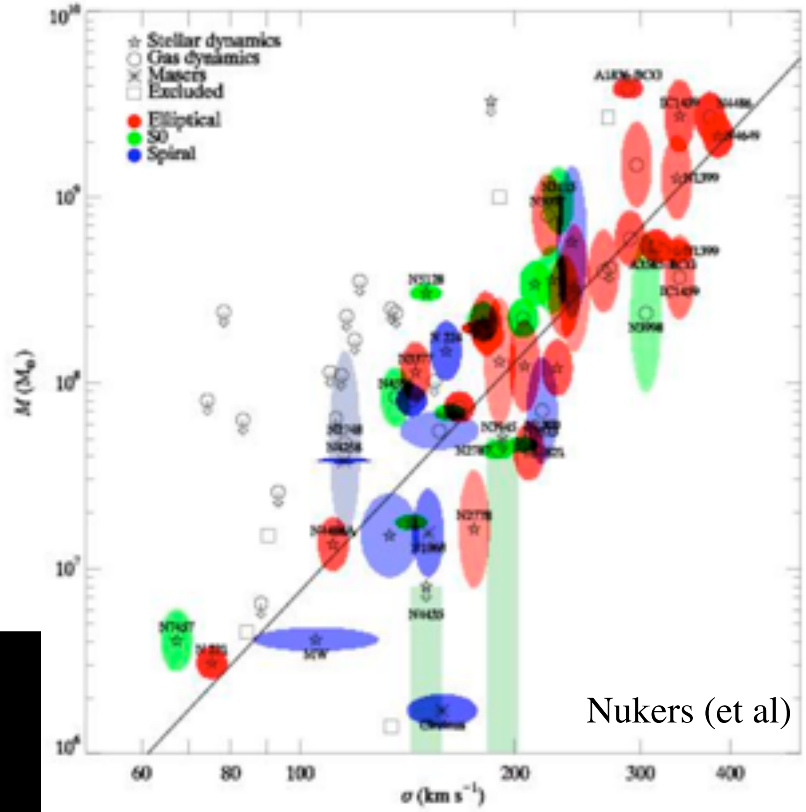
With all this gas getting to the center of the galaxy, what is the black hole doing?

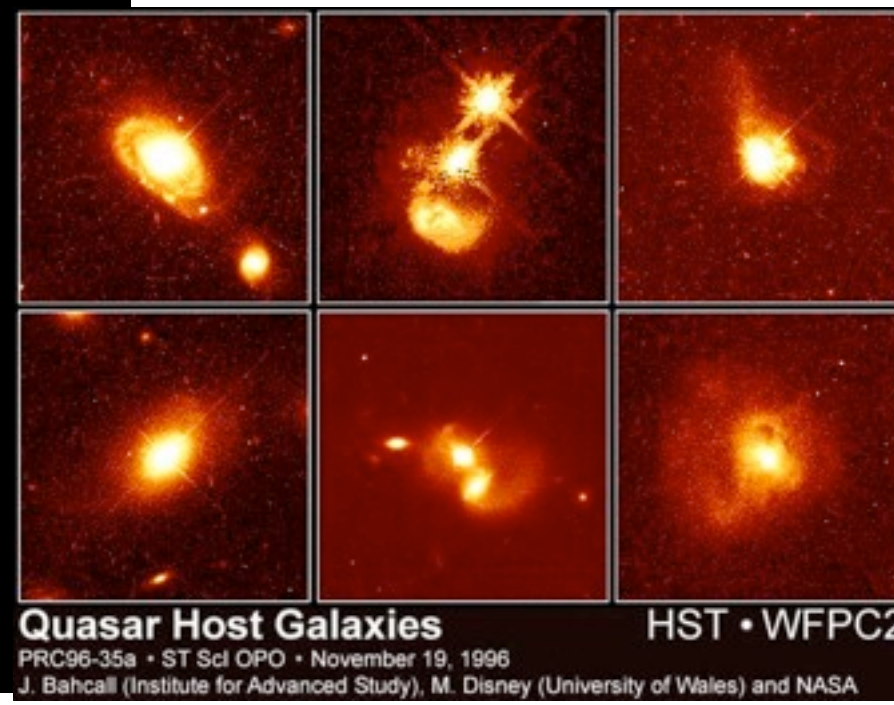
Triggering & Fueling: “Feeding the Monster”

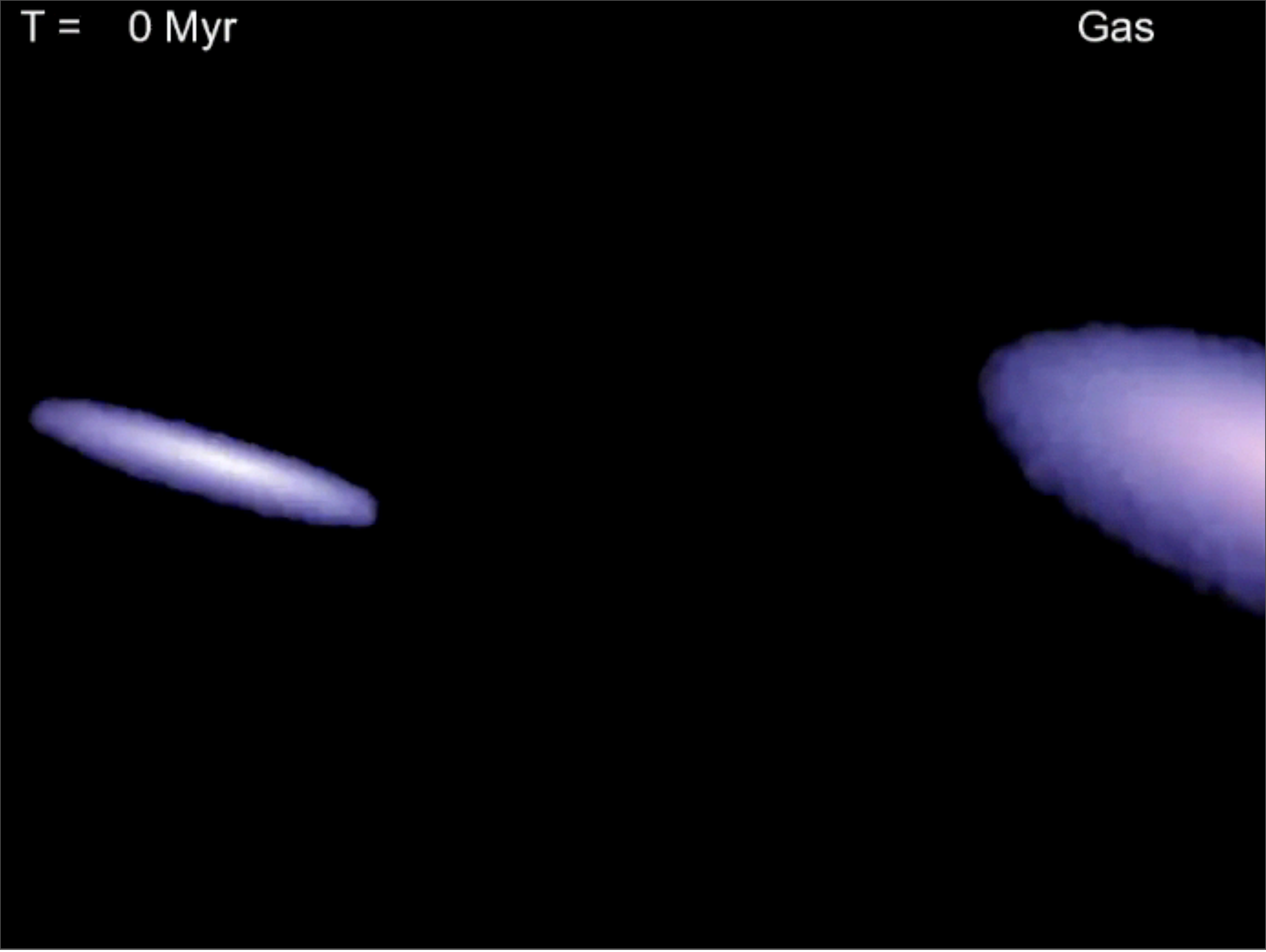
WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

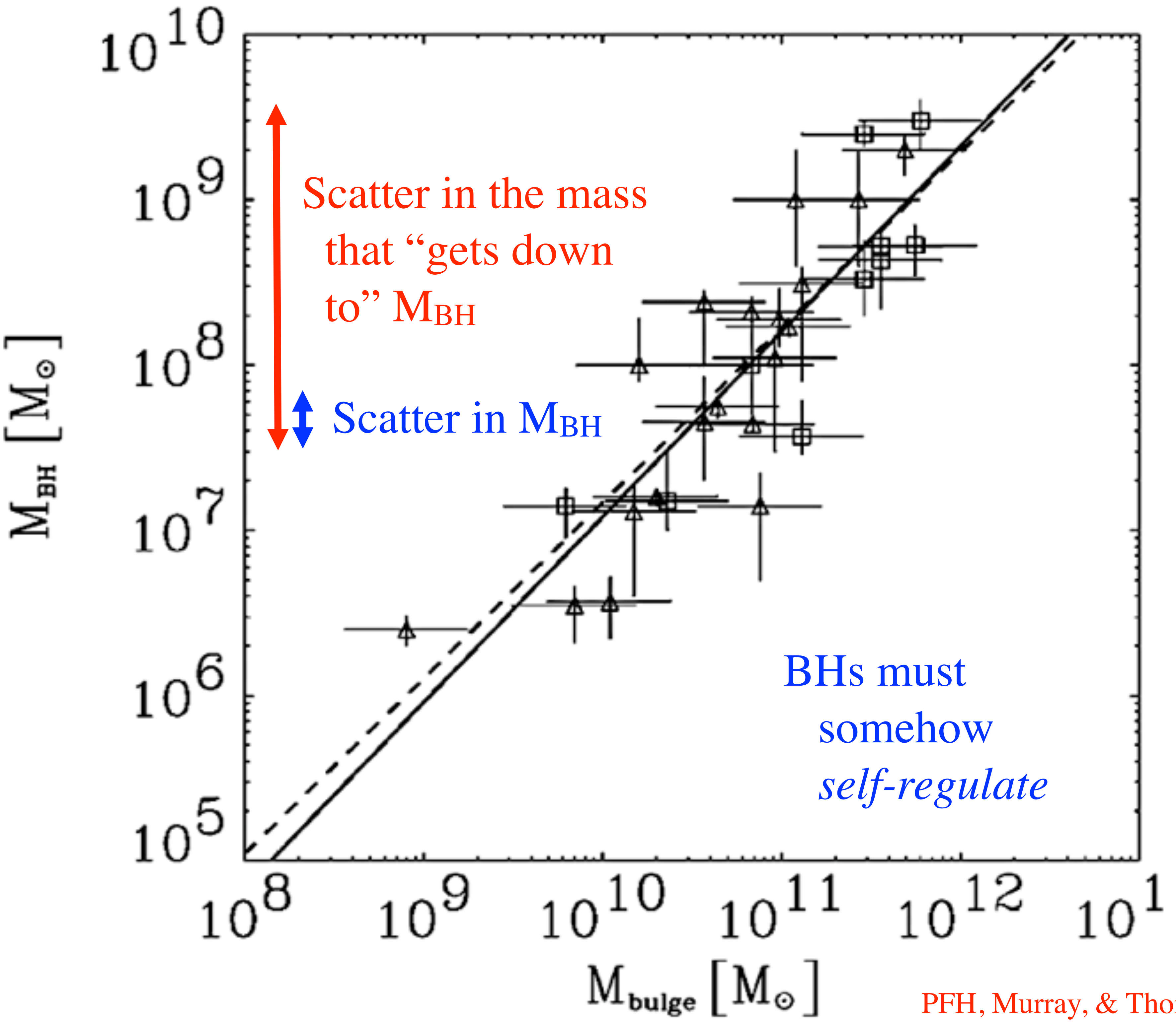
- If BHs trace spheroids, then
  most mass added in mergers








T = 0 Myr
Gas



PFH, Murray, & Thompson 2009

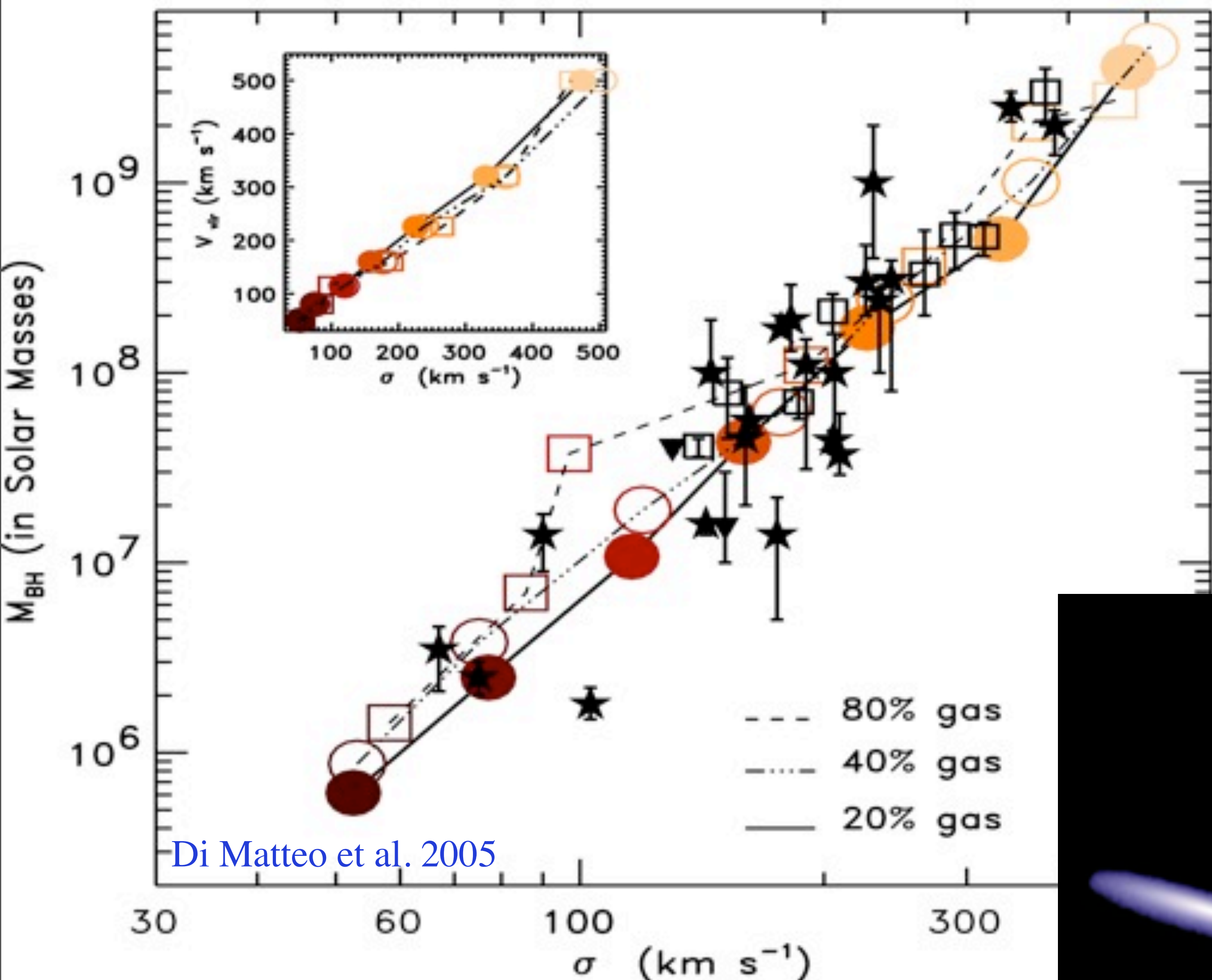
Simplest Idea:

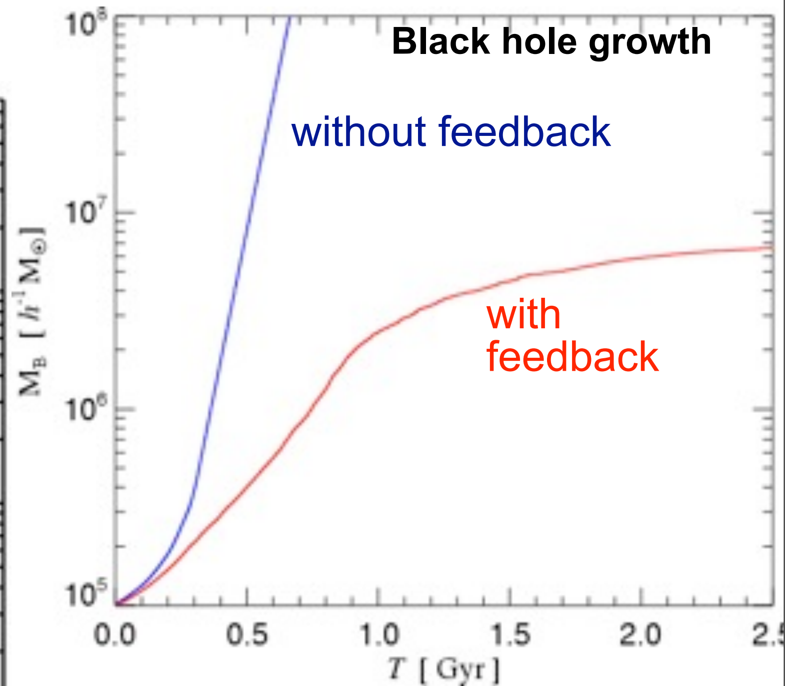
FEEDBACK ENERGY BALANCE (SILK & REES '98)

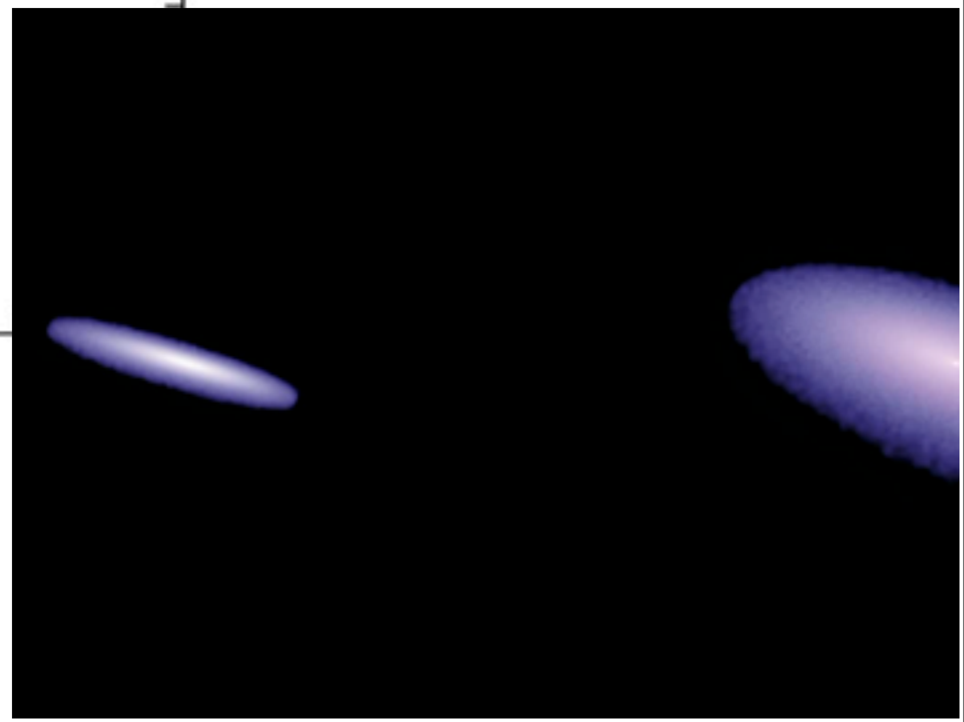
- Accretion disk radiates:
  - $L = e_r (dM_{BH}/dt) c^2$ ($e_r \sim 0.1$)
- Total energy radiated:
  - $\sim 0.1 M_{BH} c^2 \sim 10^{61}$ ergs in typical $\sim 10^8 M_{sun}$ system
- Compare to gravitational binding energy of galaxy:
  - $\sim M_{gal} s^2 \sim (10^{11}$ Msun$)$ $(200$ km/s$)^2 \sim 10^{59}$ erg!
- If only a few percent of the luminous energy coupled, it would unbind the baryons!
  - Turn this around: *if* some fraction h ~ 1-5% of the luminosity can couple, then accretion stops when
    - $M_{BH} \sim (a/he_r) M_{gal} (s/c)^2 \sim 0.002 M_{gal}$

M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



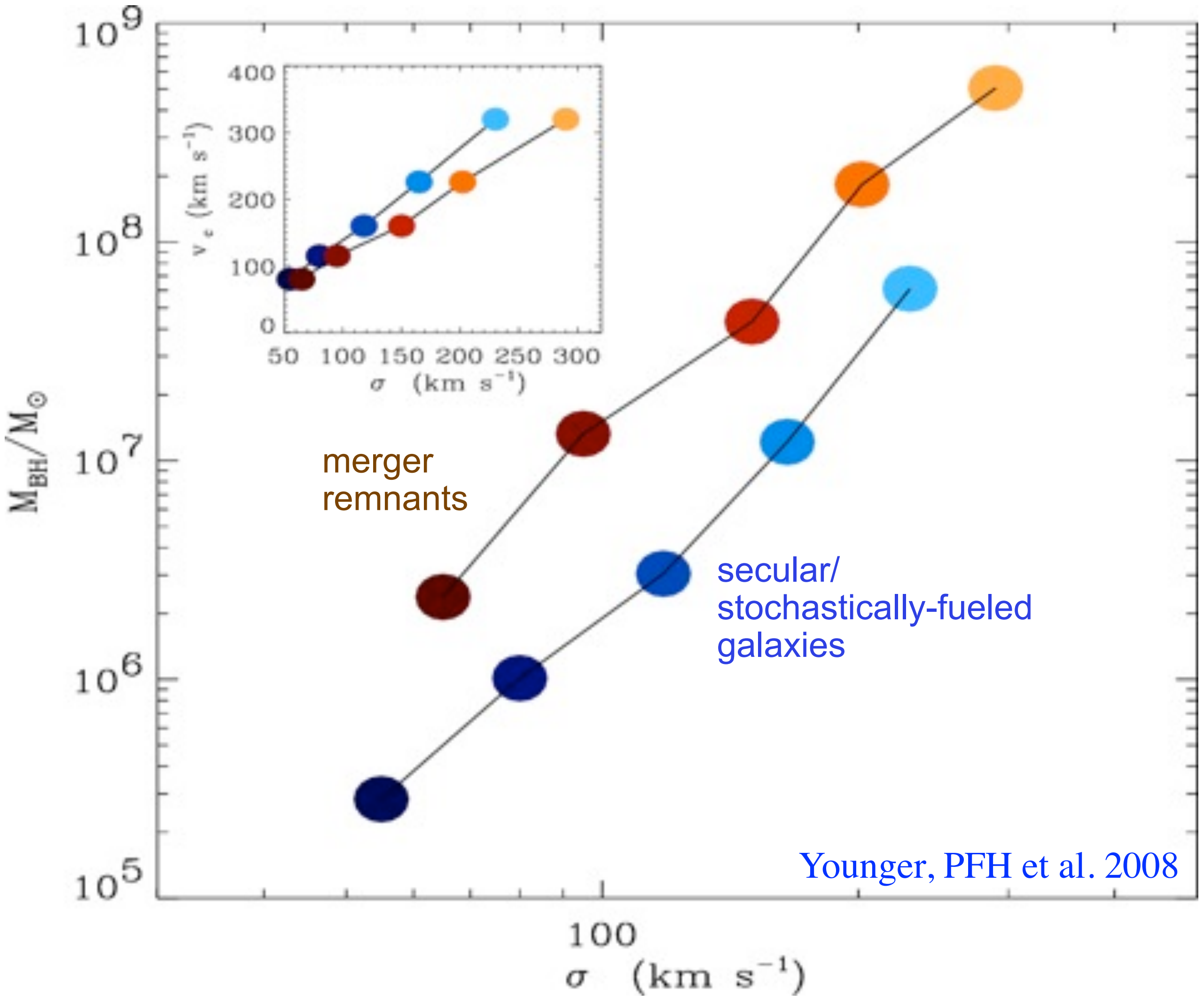




Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- What is the “fundamental” correlation? M_{BH}-$E_{binding}$: BH “fundamental plane” (PFH et al.)
- Different correlation for “classical” and “pseudobulges”
  - Both tentatively observed (Aller & Richstone; Greene et al.; Hu; Gadotti et al.)

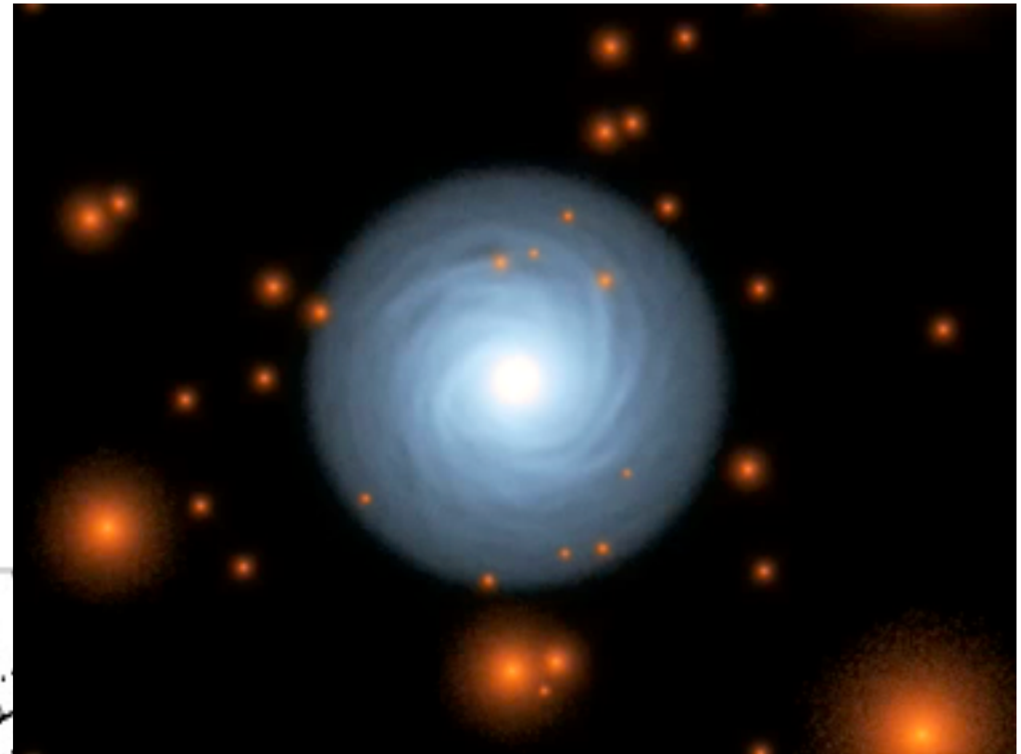


- Basic argument:
  - BH feedback self-regulates growth in ~fixed potential

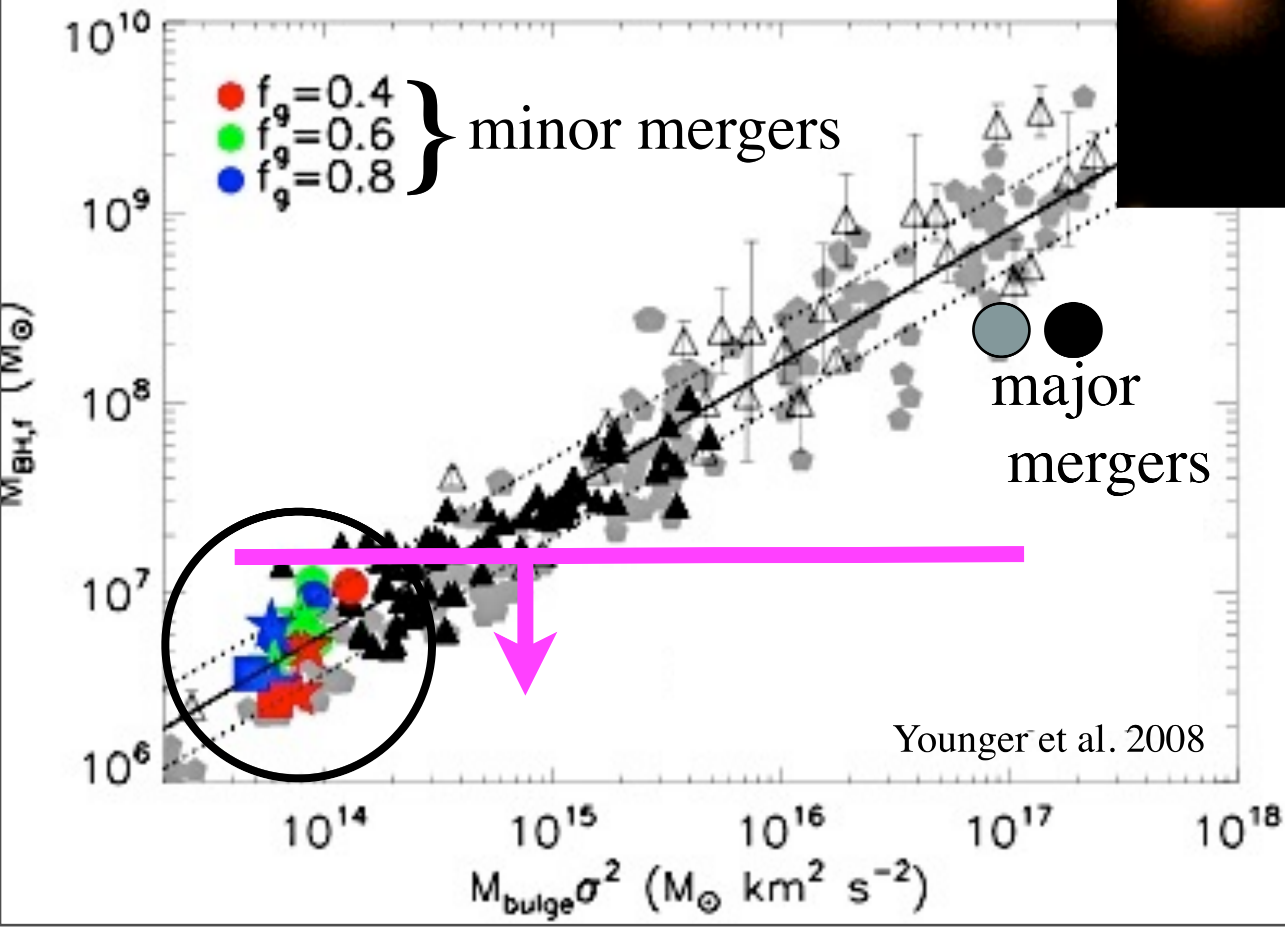
Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

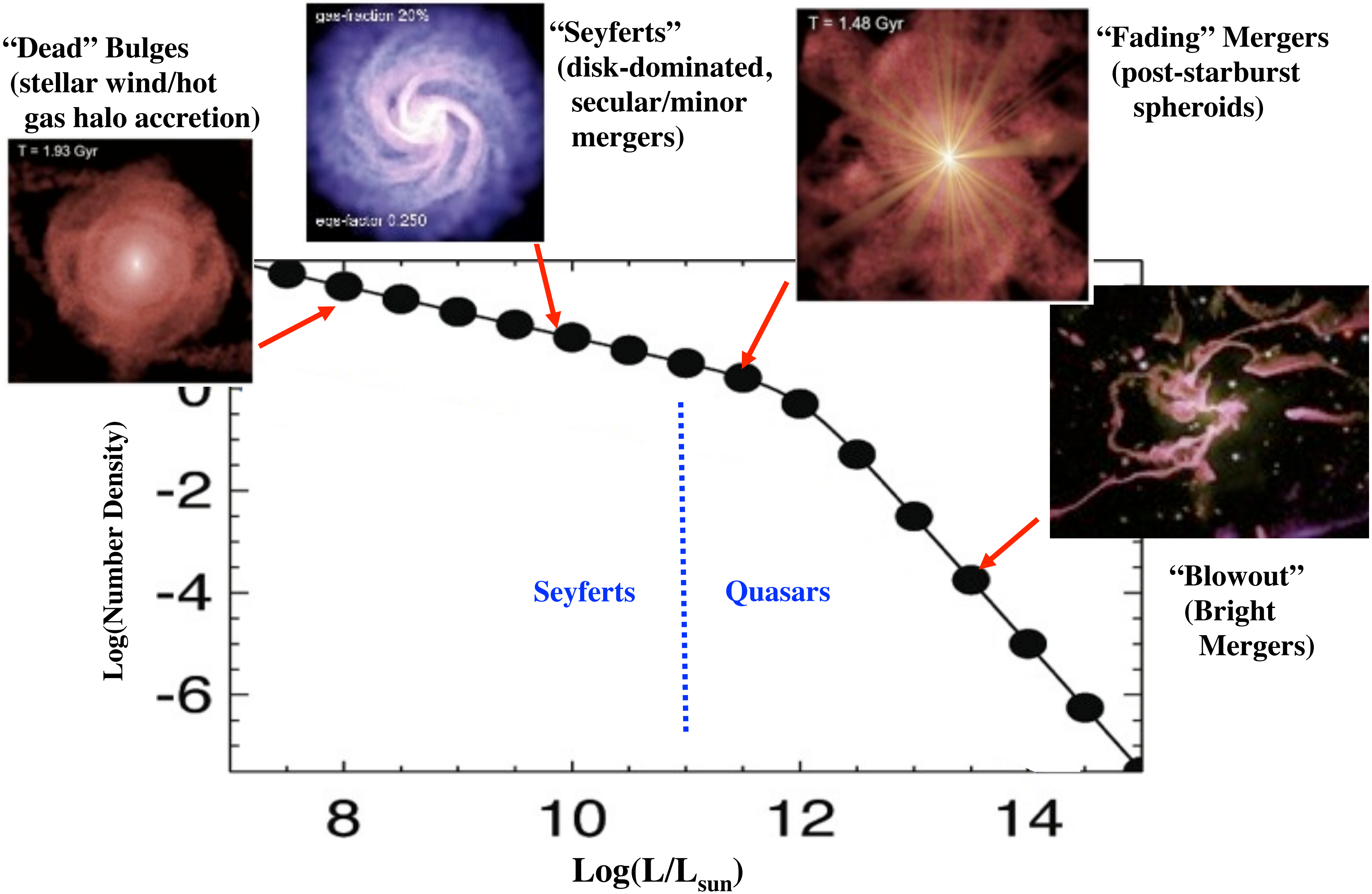
- z~2 QSO: 10^{11} M_{sun} in <10pc in ~t_{dyn}
- Seyfert: only $10^{7\text{-}8}$ M_{sun} ~ GMC
  - Minor mergers?
  - Secular instabilities/bars?



Dubinski



- If you don't build massive bulges, doesn't matter if you can get the gas in!

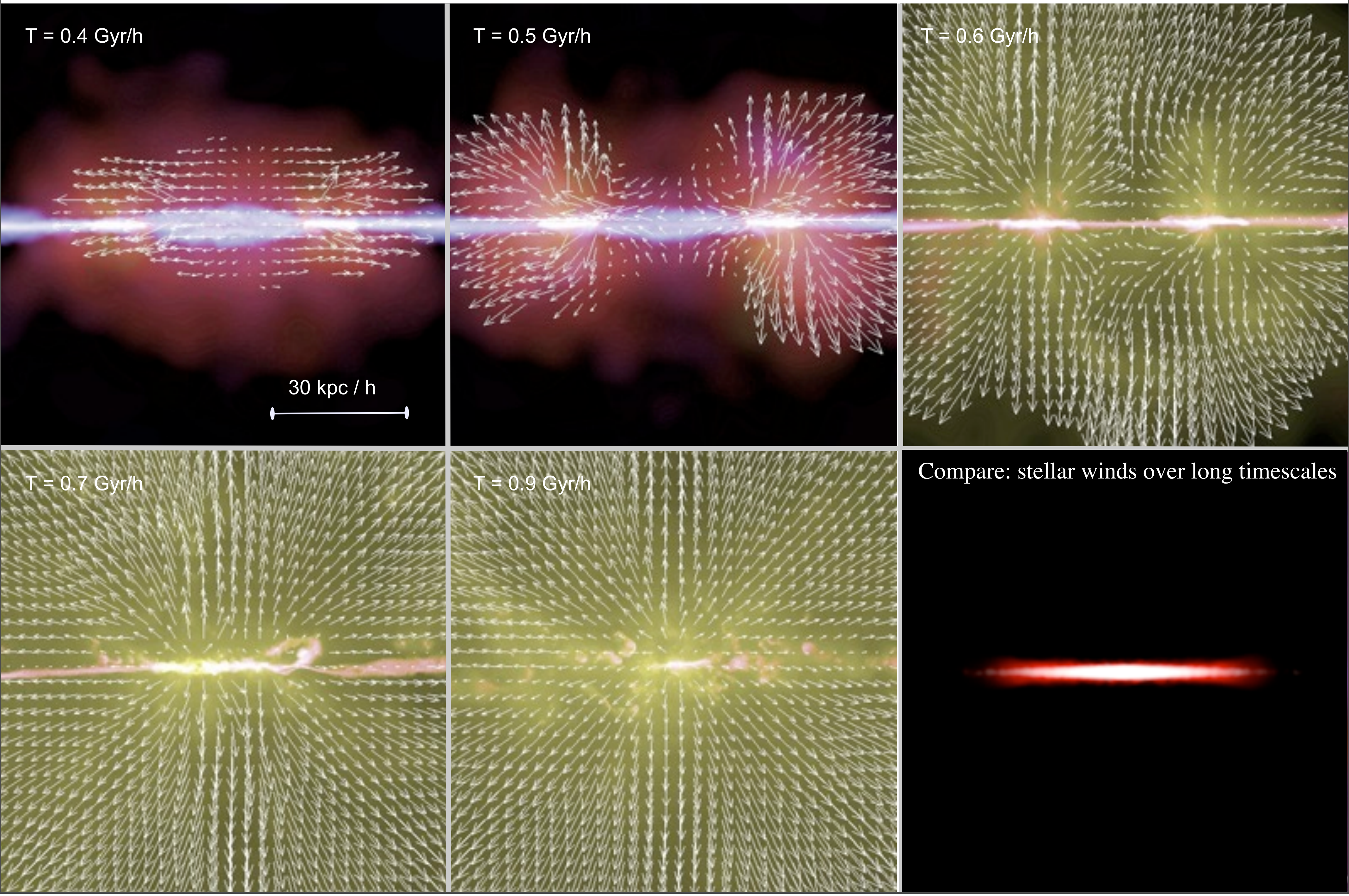


- Observed luminosity function: populations at different *evolutionary* stages

Where Does the Energy/Momentum Go?

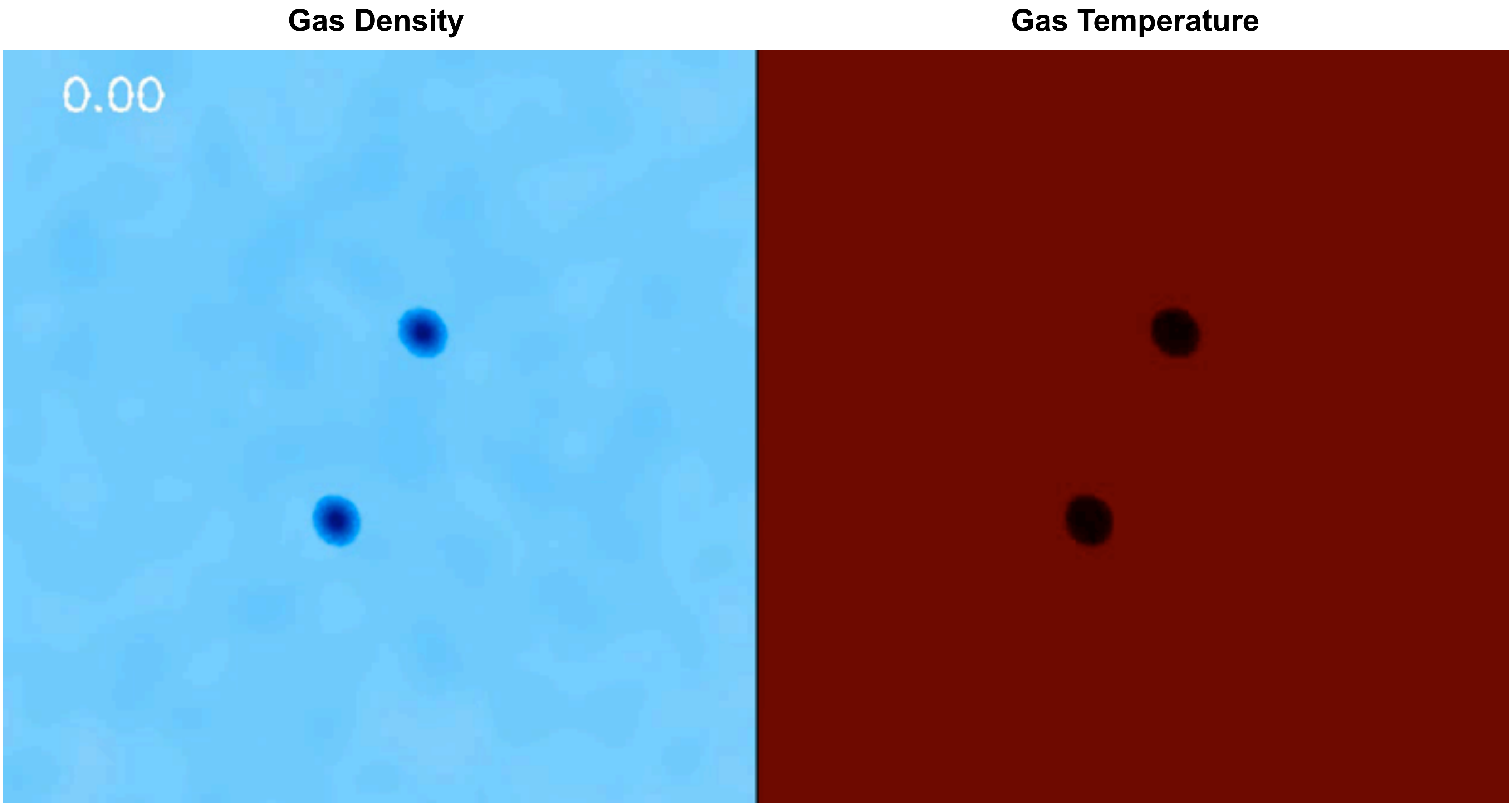
QUASAR-DRIVEN OUTFLOWS?

(outflow reaches speeds of up to ~1800 km/sec)



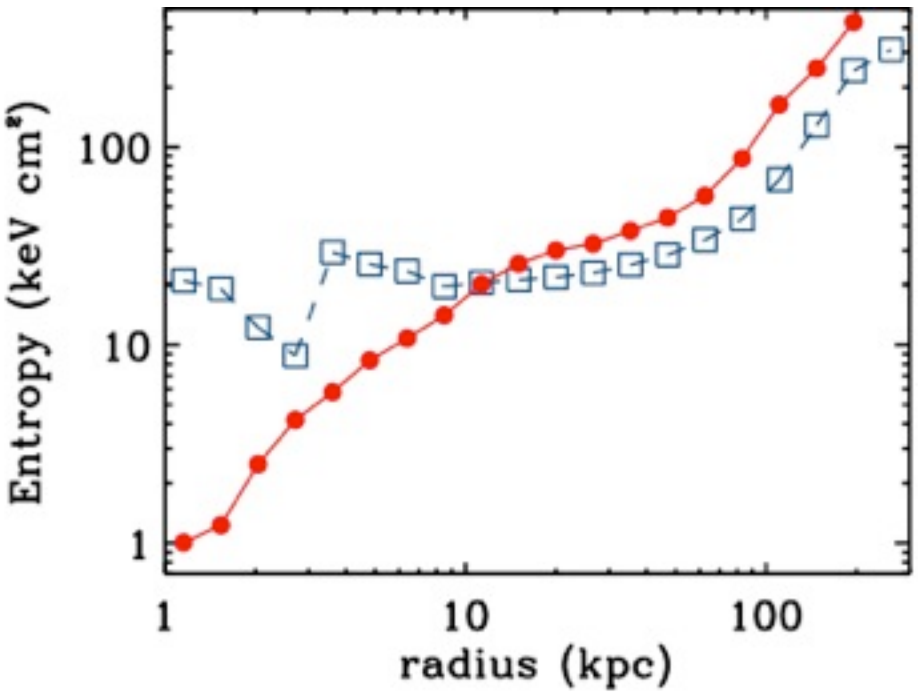
Quasar Outflows May Be Significant for the ICM & IGM

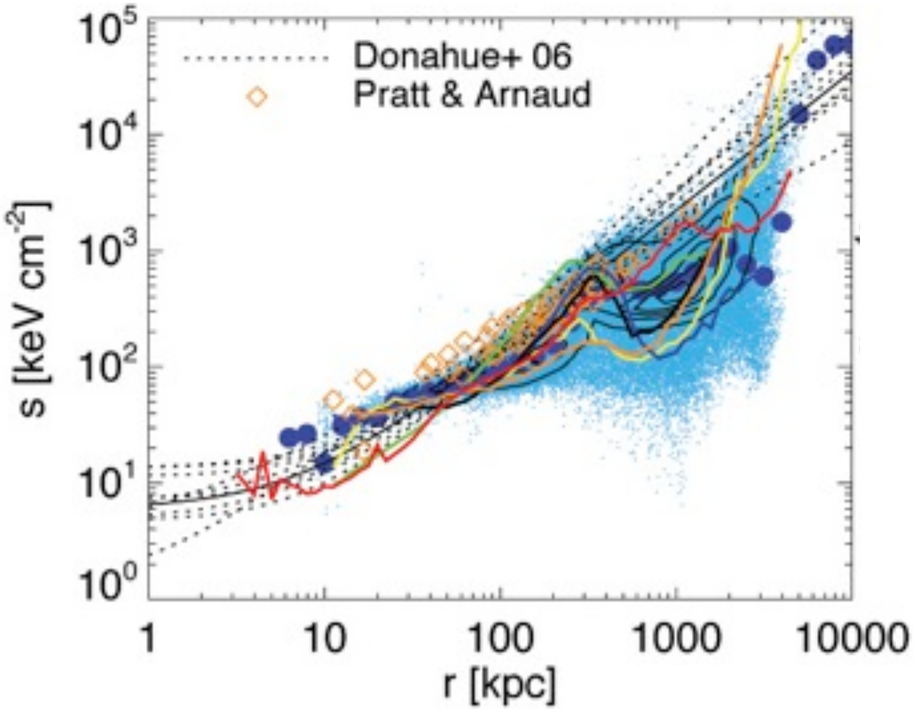
SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?

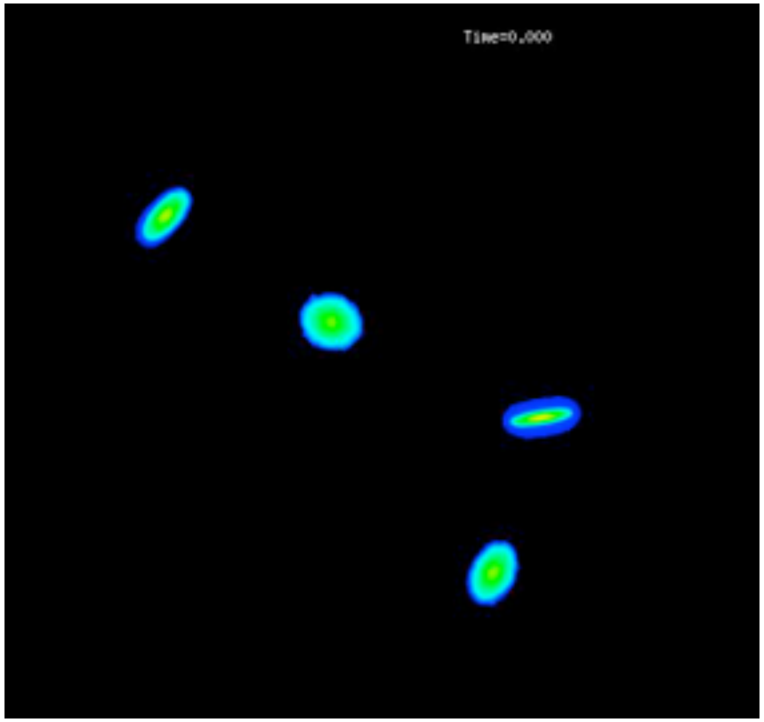


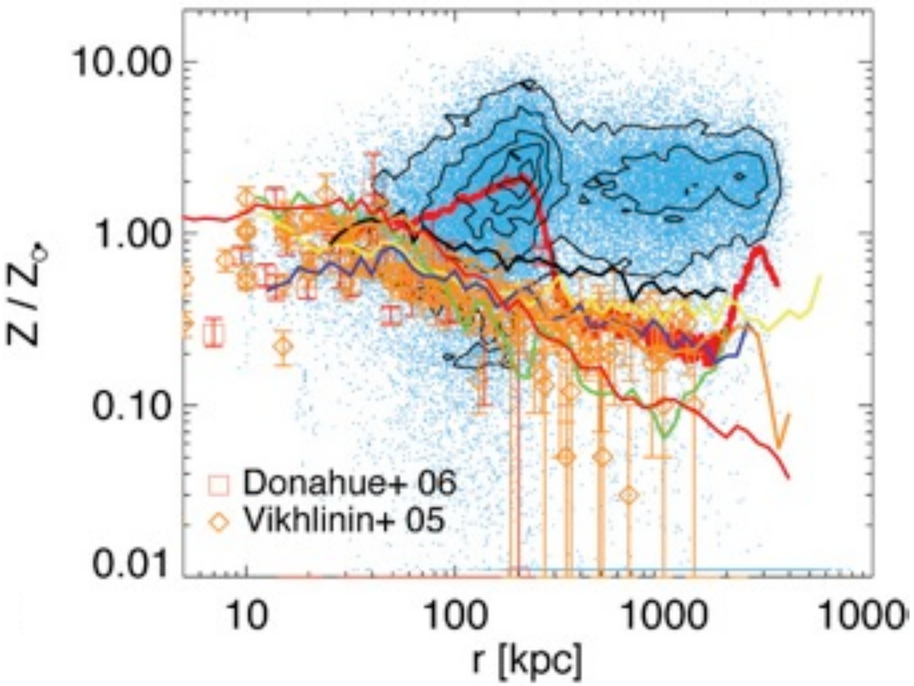
Quasar Outflows May Be Significant for the ICM & IGM

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



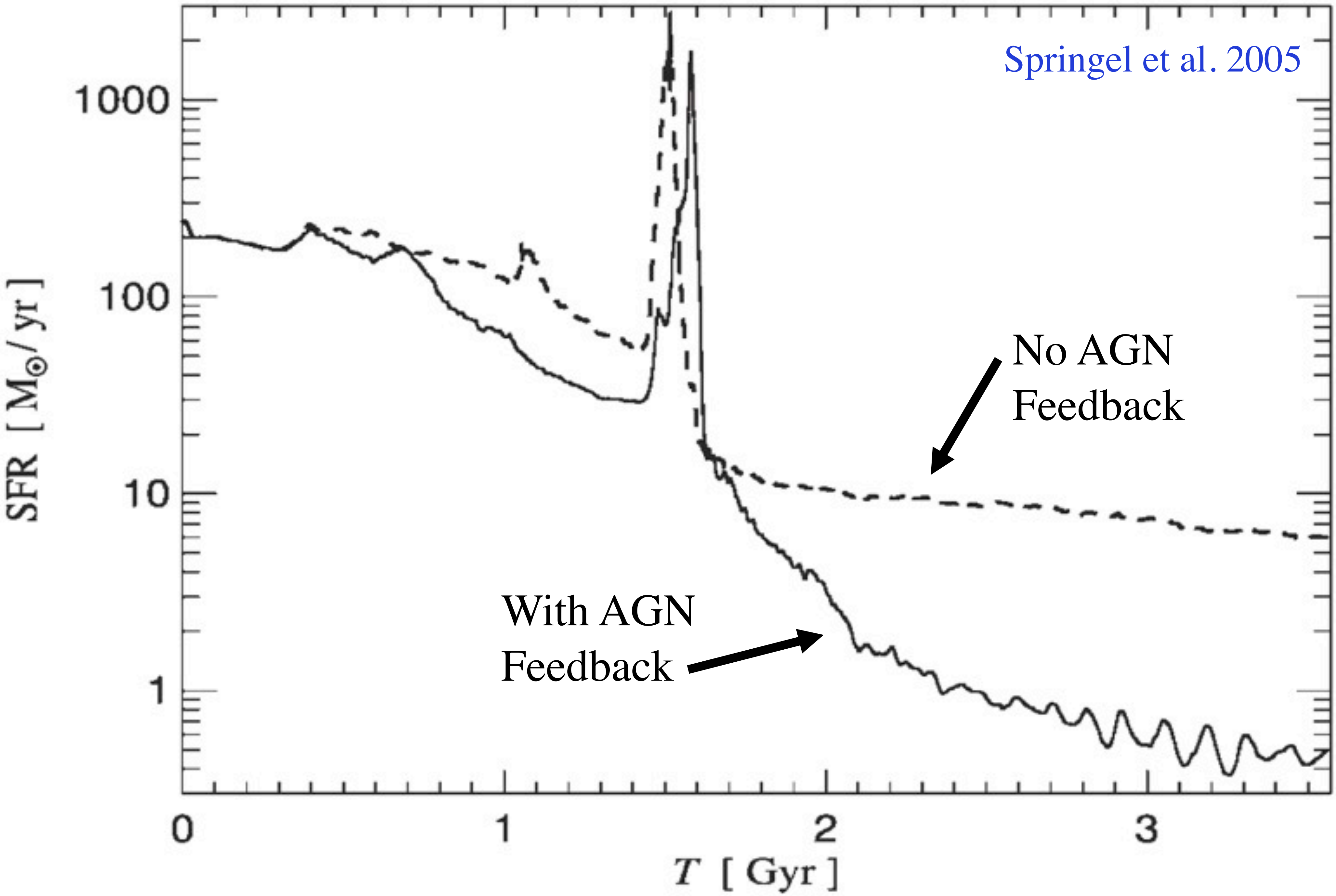






Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

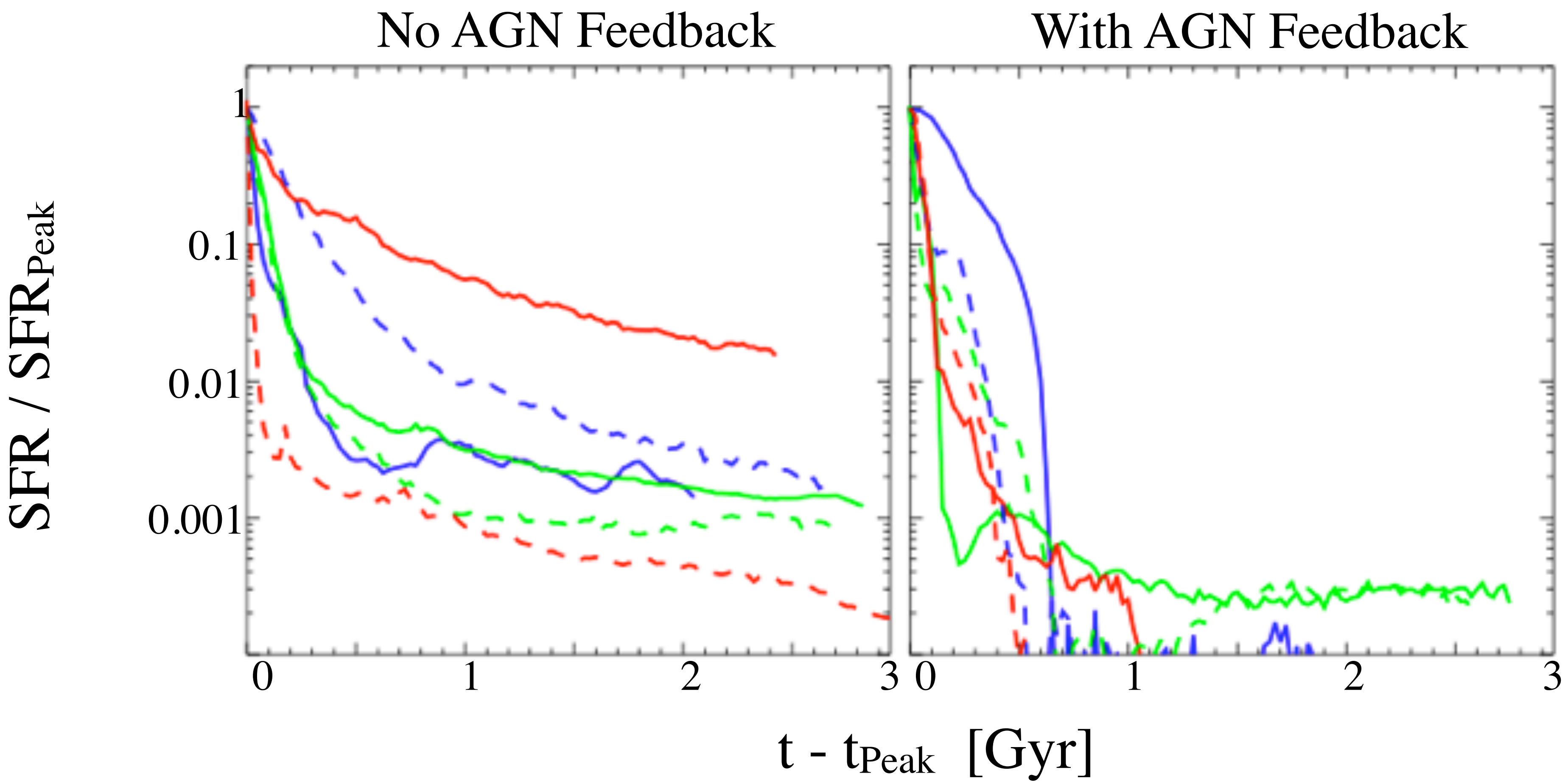


Expulsion of Gas Turns off Star Formation

PFH, Keres et al. 2008

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

... but ...

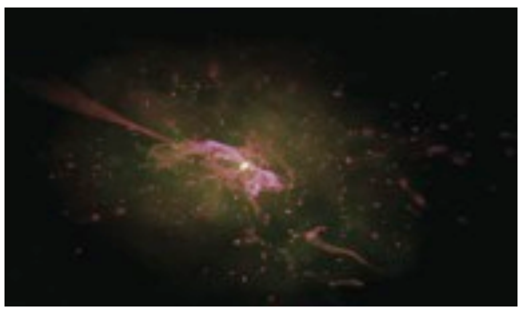


... MOST of the work is still done by star formation/stellar feedback

“Transition” vs. “Maintenance”

“Transition”

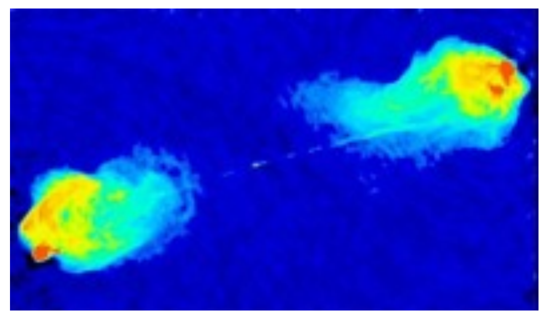
- Move mass from Blue to Red
- Rapid
- Small scales
- “Quasar” mode (high mdot)
- Morphological Transformation
- Gas-rich/Dissipational Mergers



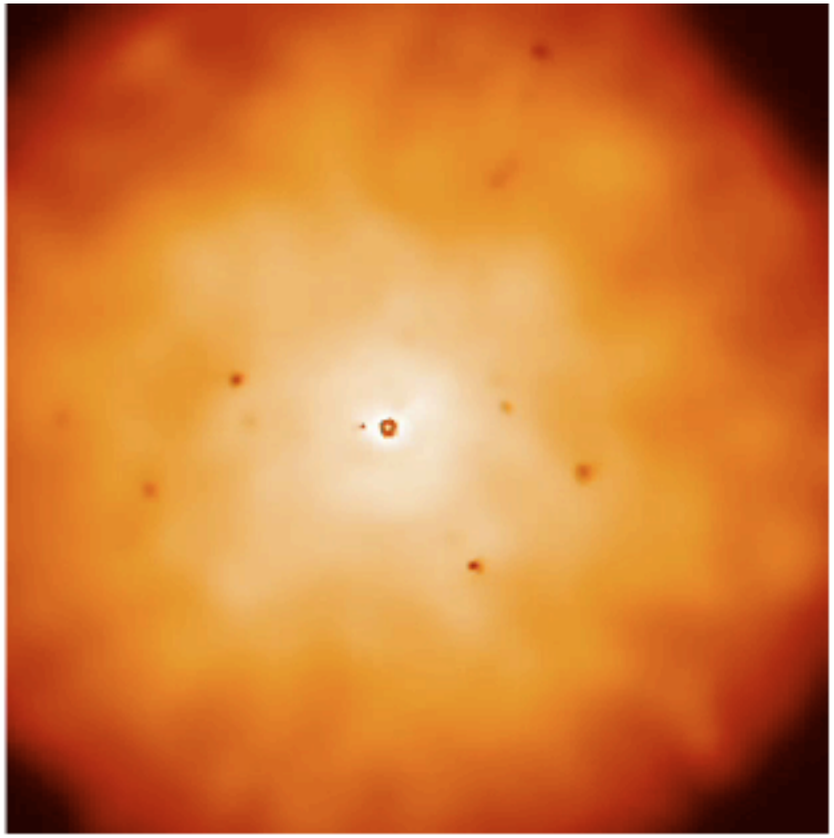
- Regulates *Black Hole* Mass

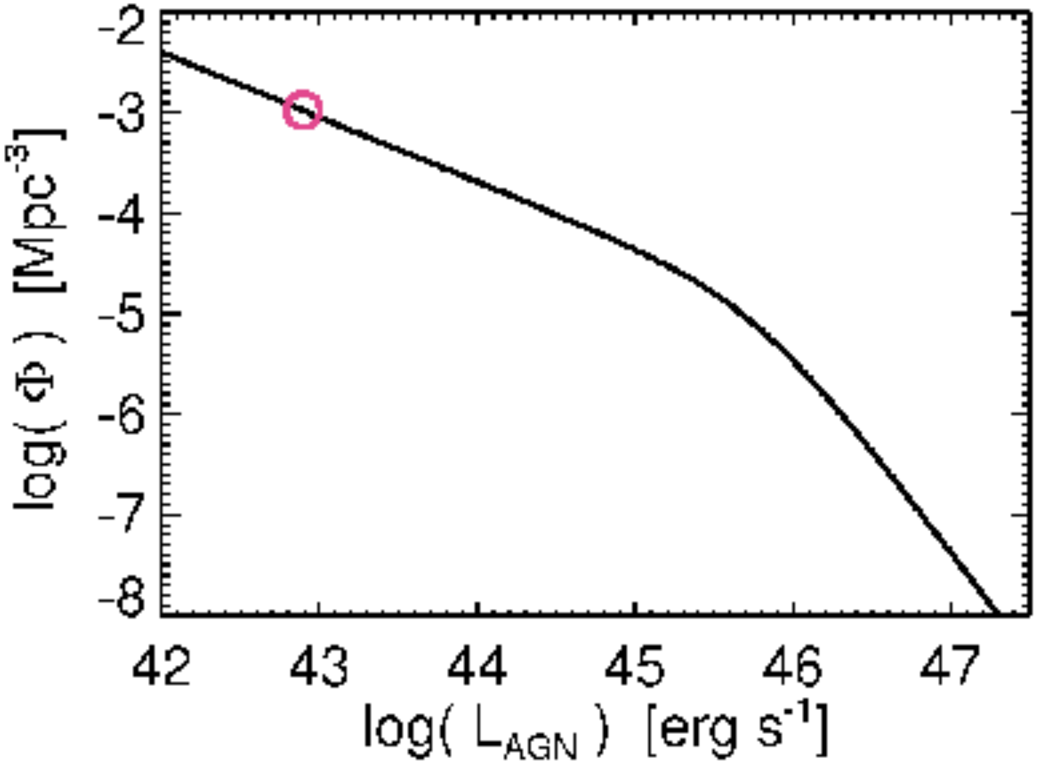
“Maintenance”

- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- “Radio” mode (low mdot)
- Subtle morphological change
- Hot Halos & Dry Mergers

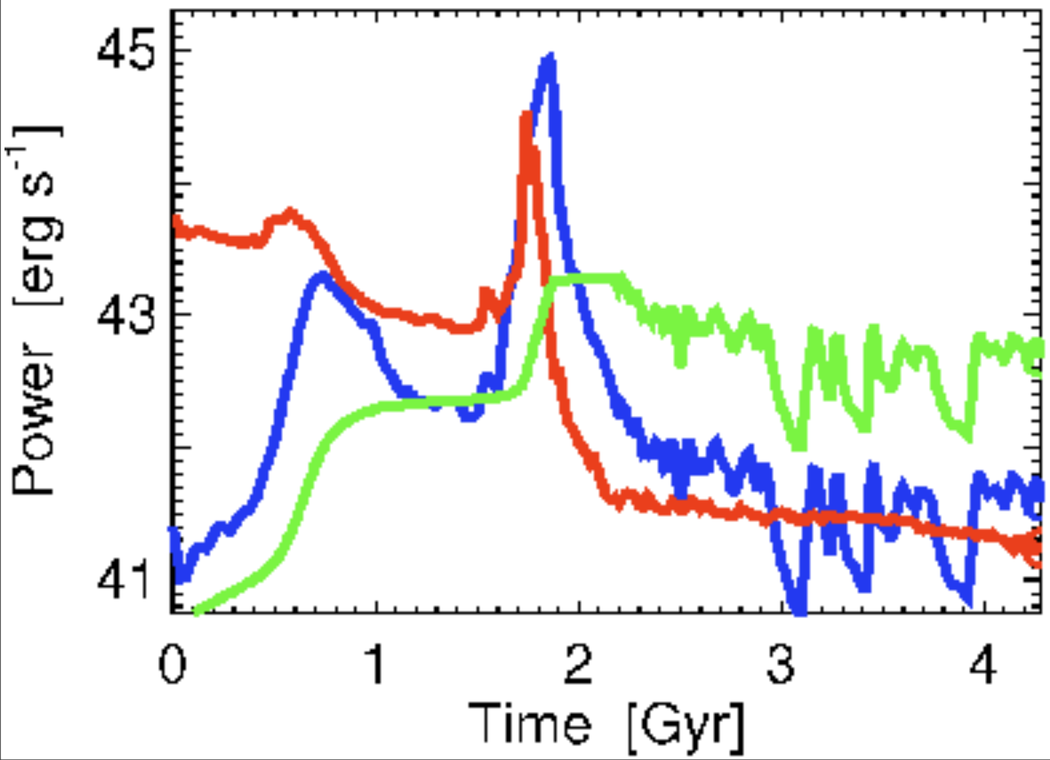


- Regulates *Galaxy* Mass

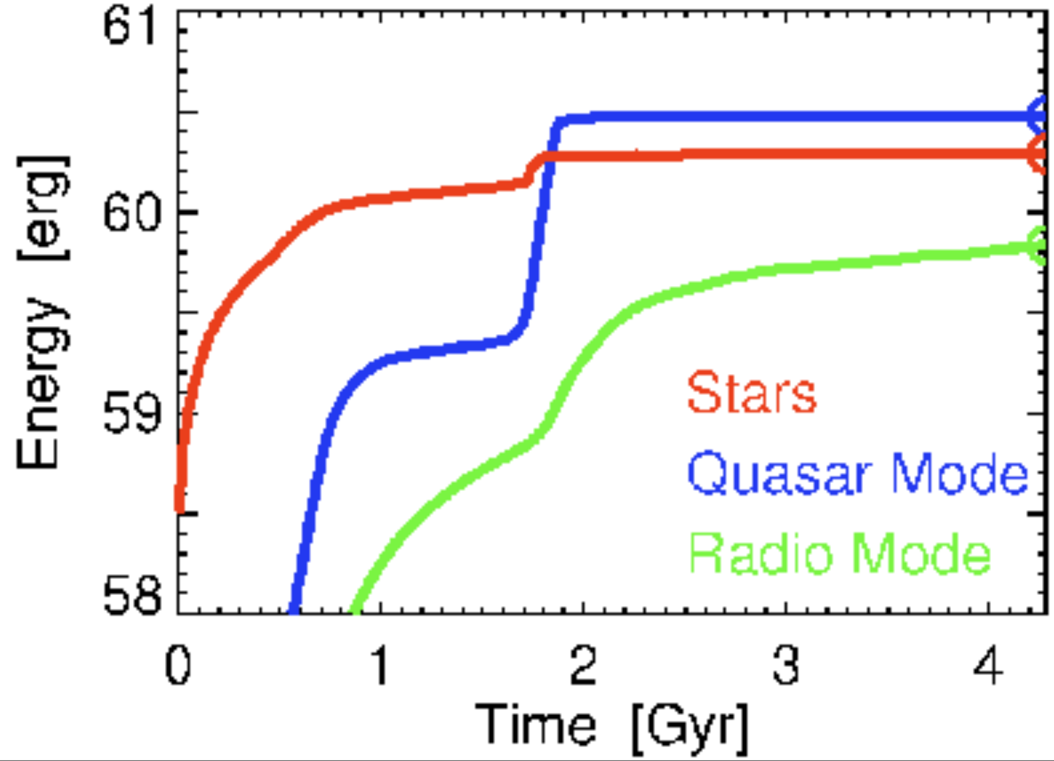




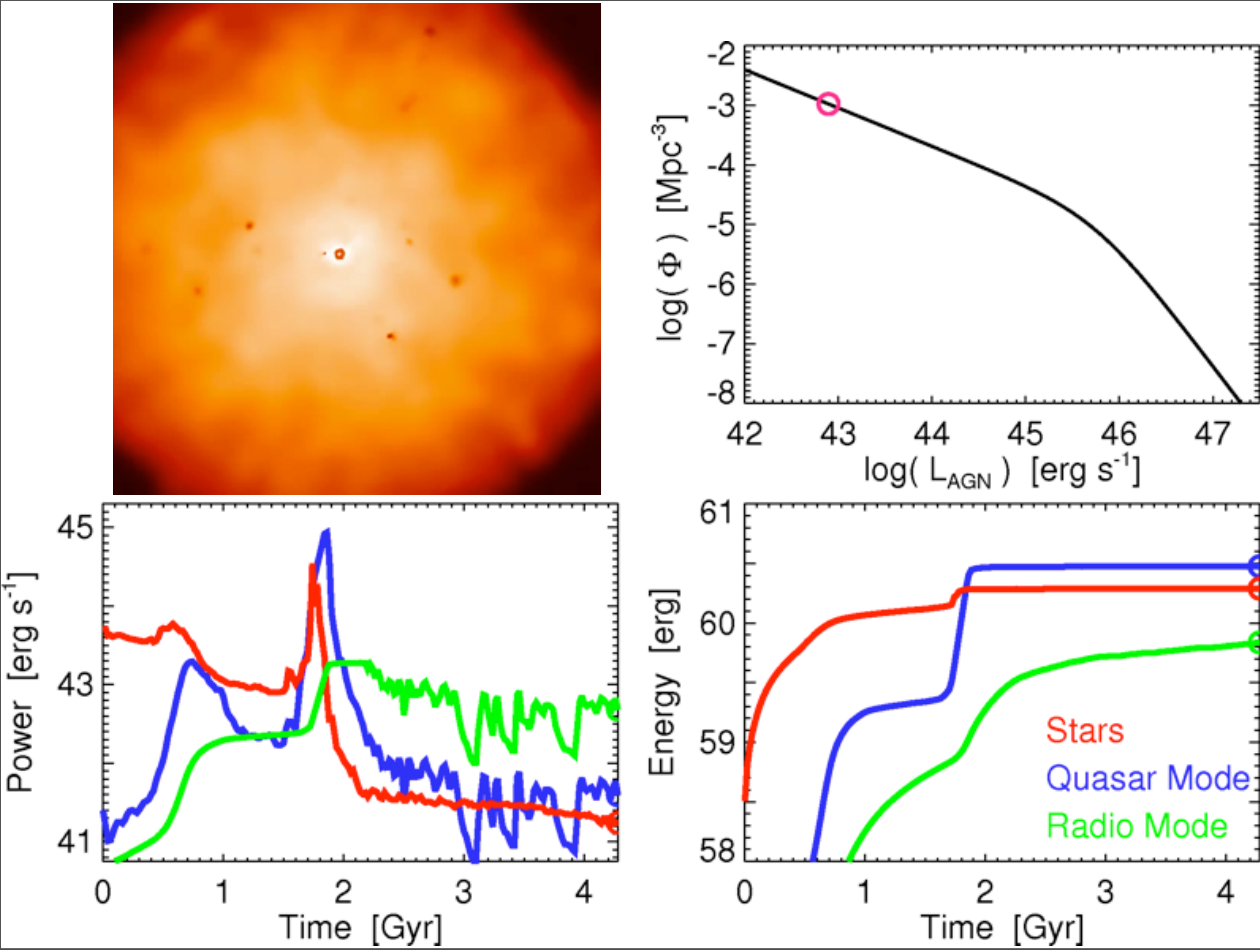
log(Φ) [Mpc^-3]
log(L_AGN) [erg s^-1]



Power [erg s^-1]
Time [Gyr]



Energy [erg]
Stars
Quasar Mode
Radio Mode
Time [Gyr]



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

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 ***<u>avoid</u>*** 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!
  - M-sigma implies BHs formed in mergers? "Stuff within stuff"?
  - Also implies feedback: quasar-mode for BH mass
radio-mode for galaxy mass
  - Non-trivial AGN lifetimes & lightcurves