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

Philip Hopkins

10/14/2009

Lars Hernquist, T. J. Cox, Rachel Somerville, 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, Barry Rothberg, Stijn Wuyts

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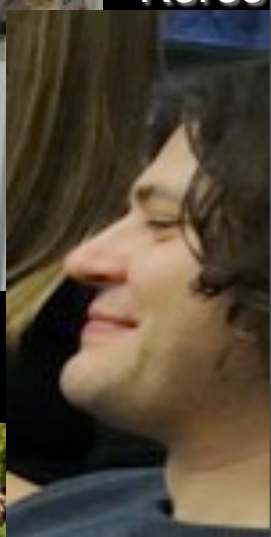


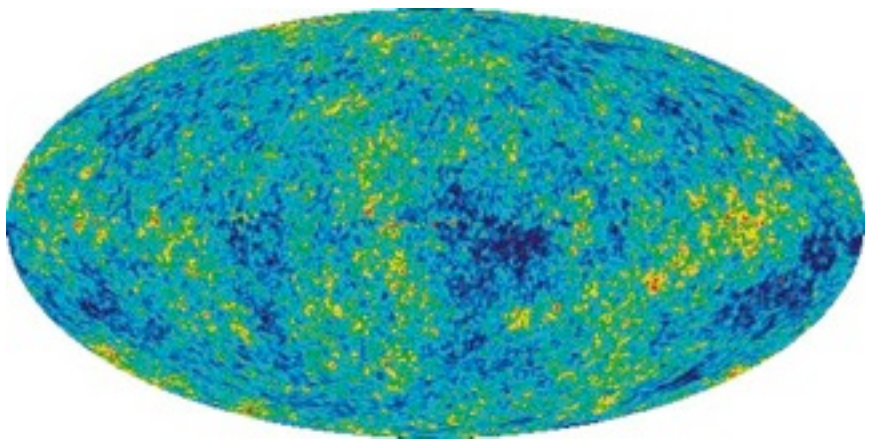
TJ Cox

Eliot Quataert

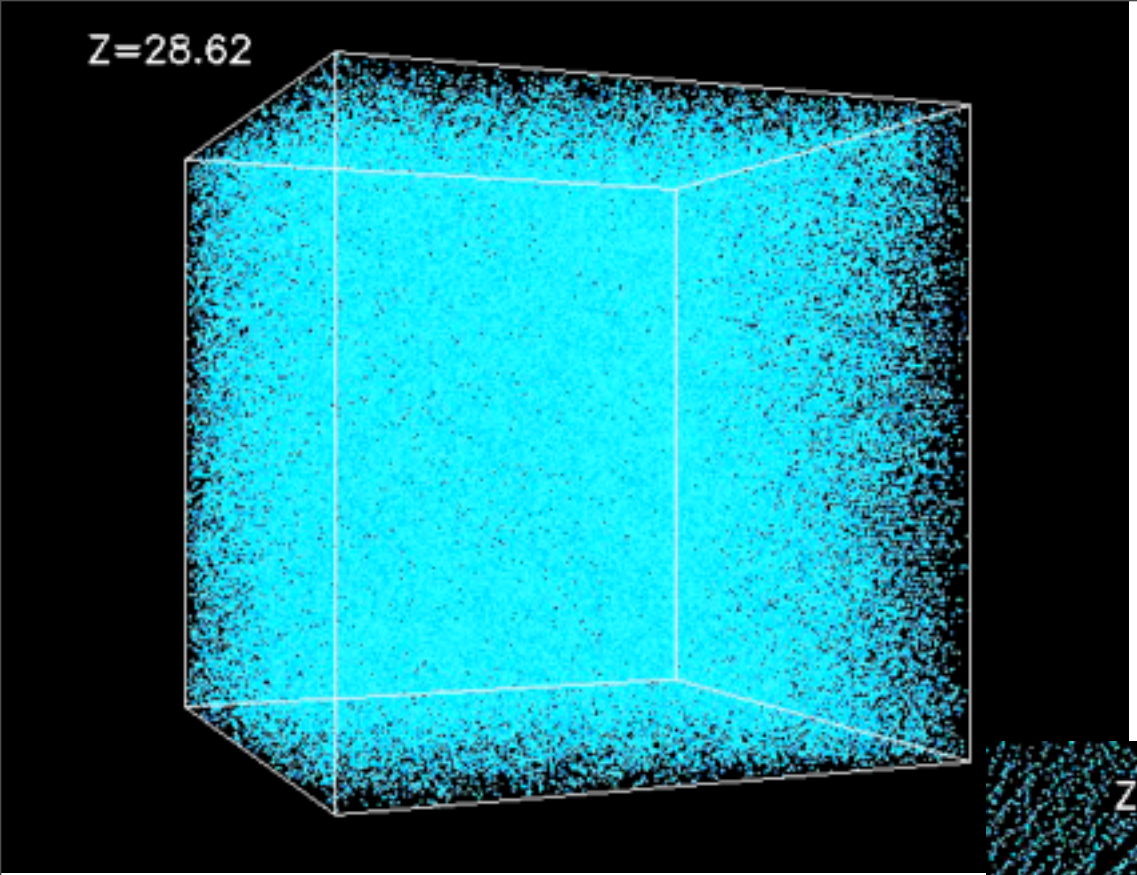
Chris Hayward

Motivation

HOW DID WE GET TO GALAXIES TODAY?



?



Motivation

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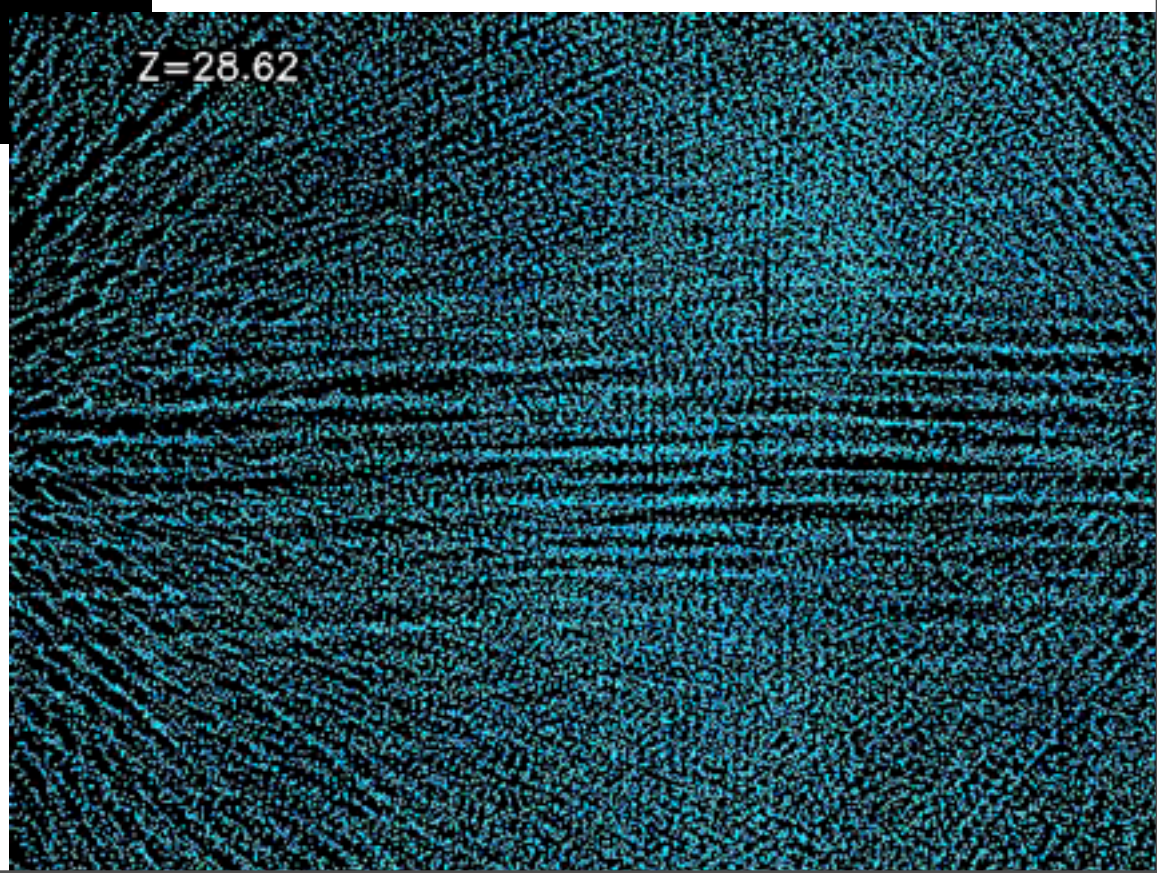
Kravtsov et al.

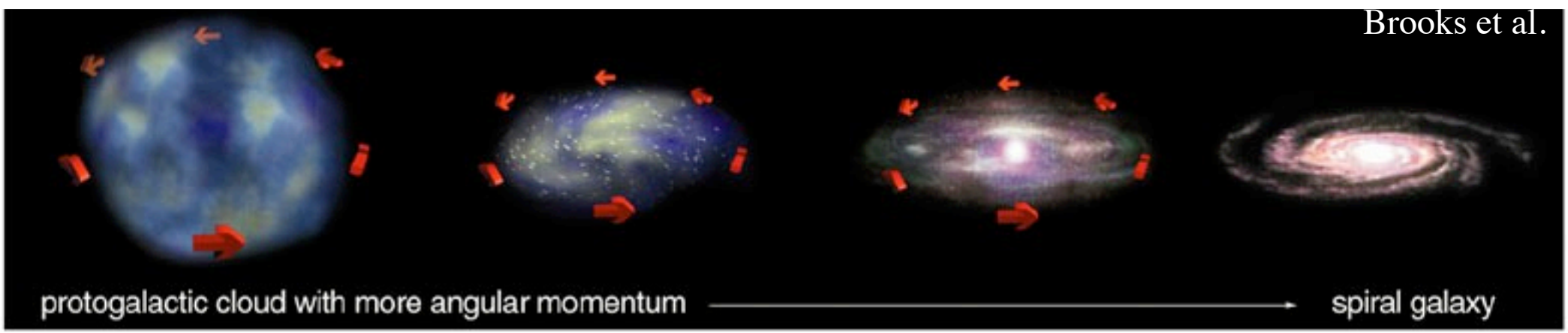


- Structure grows hierarchically:
  must understand mergers

Motivation

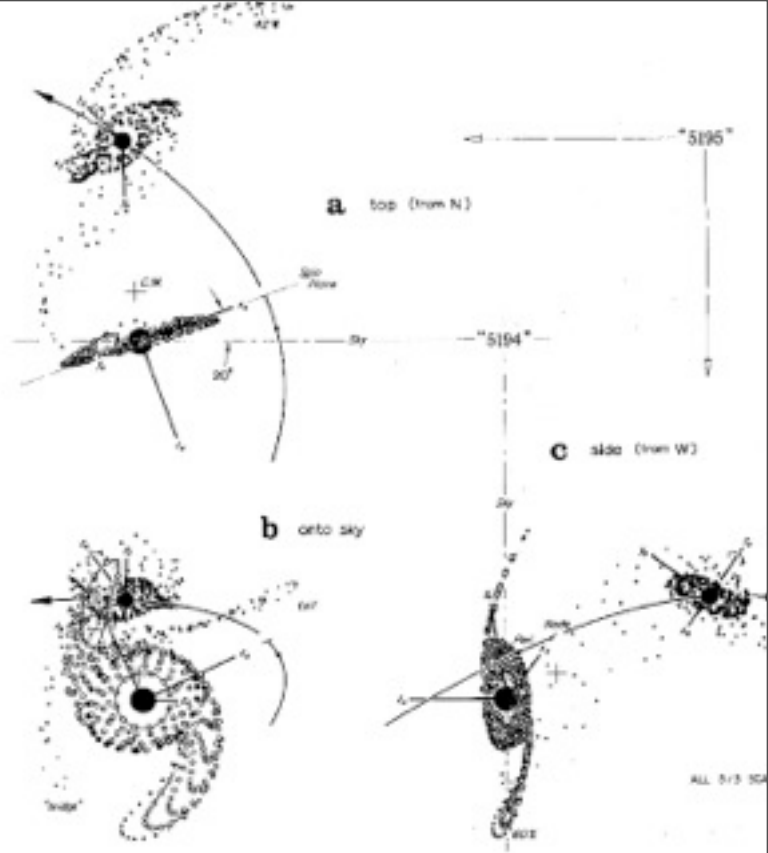
HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse:
  gas cools into a disk



- What happens when that starts colliding into other galaxies?

Our Conventional Wisdom (Toomre):



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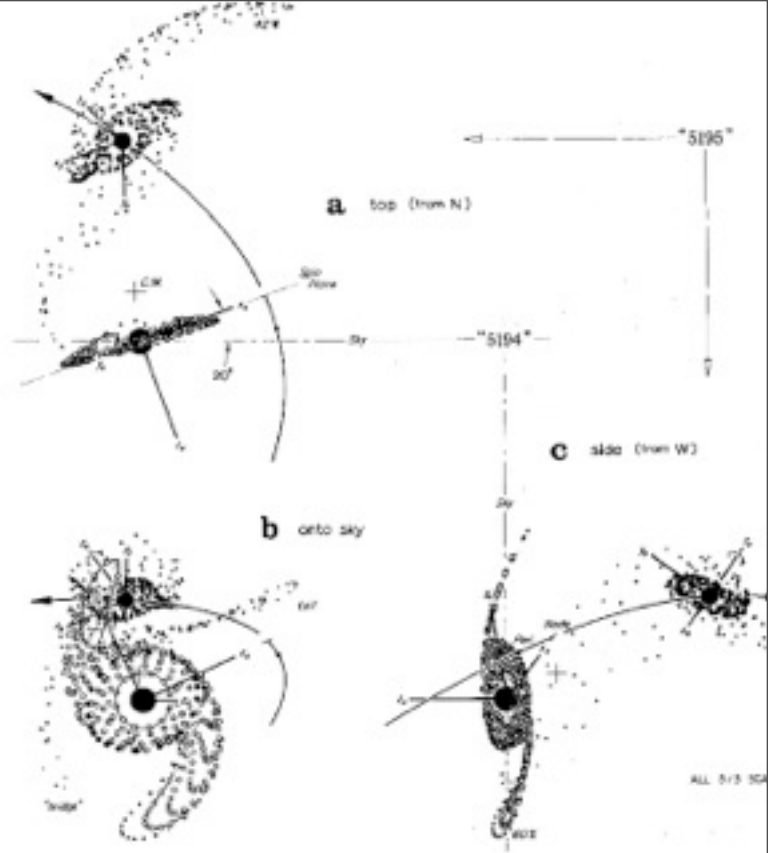
F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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Our Conventional Wisdom (Toomre):

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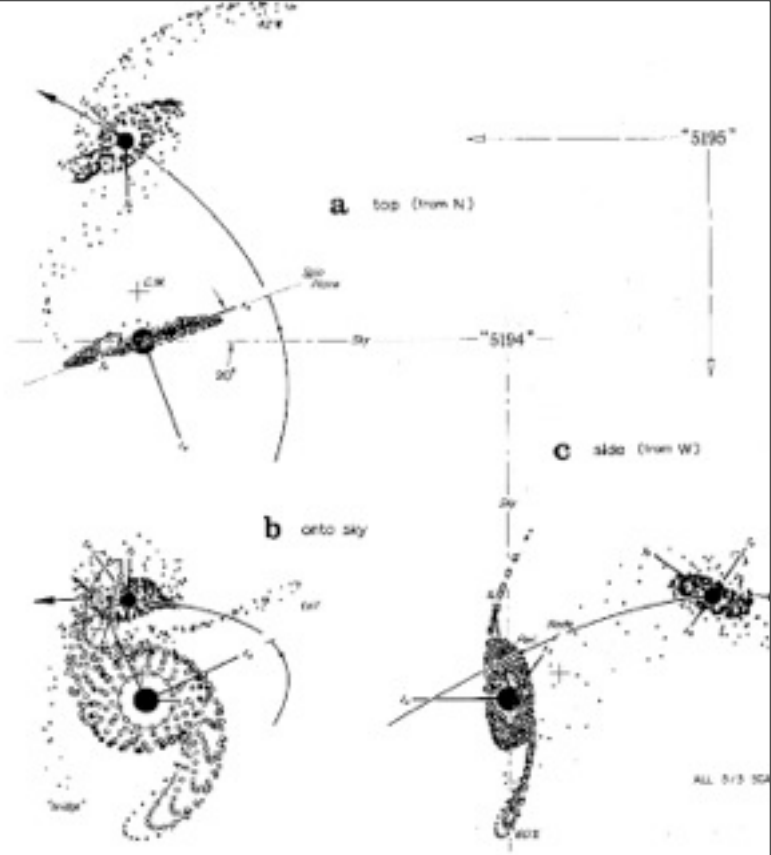

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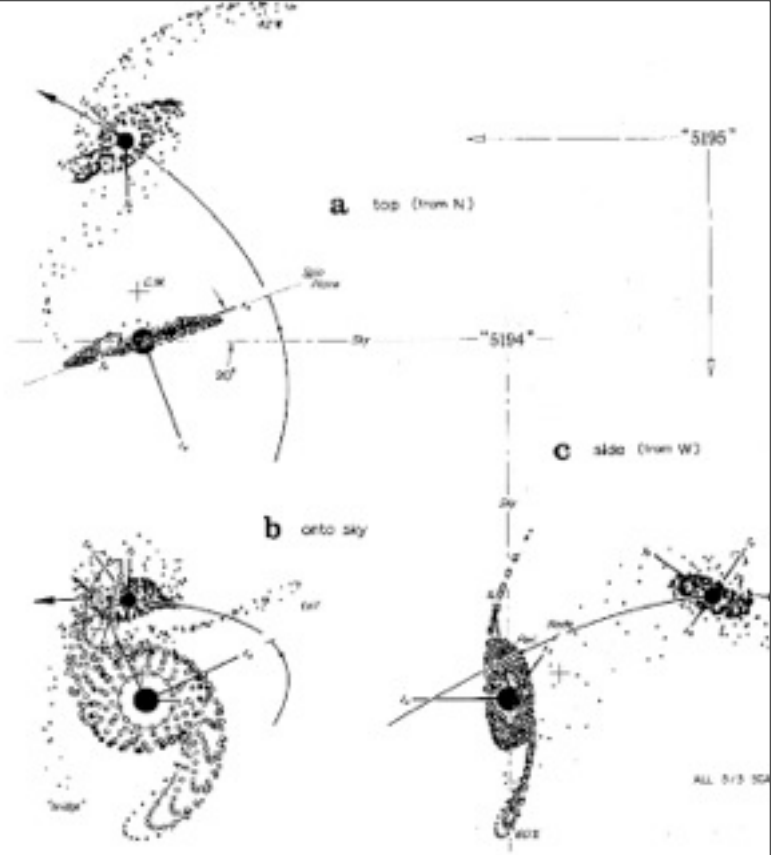
- Remnant has an $r^{1/4}$ law profile



F. Summers

Our Conventional Wisdom (Toomre):

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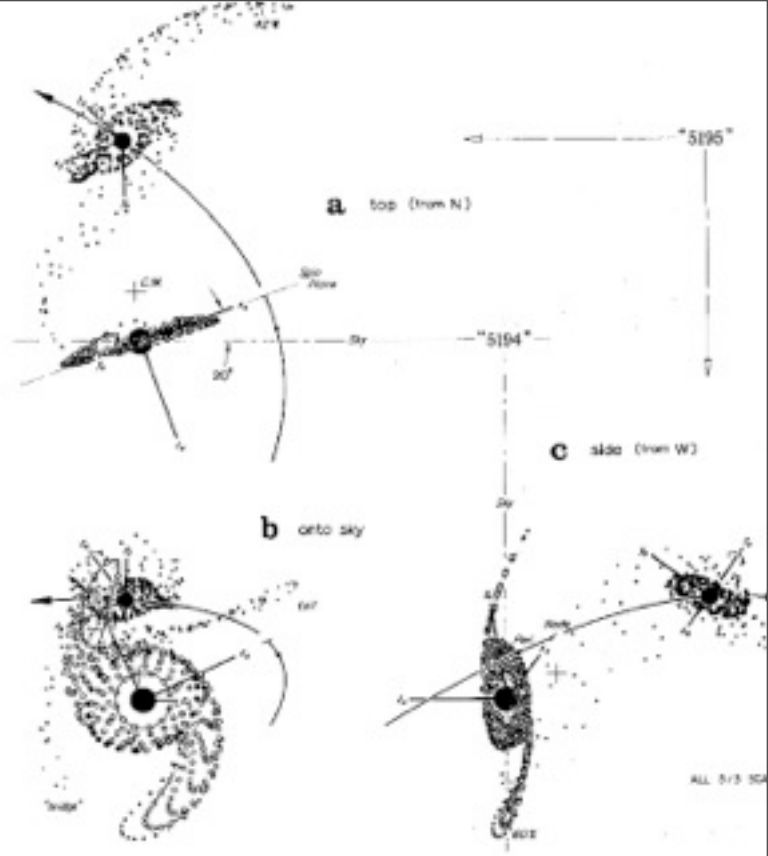
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



F. Summers

Motivation

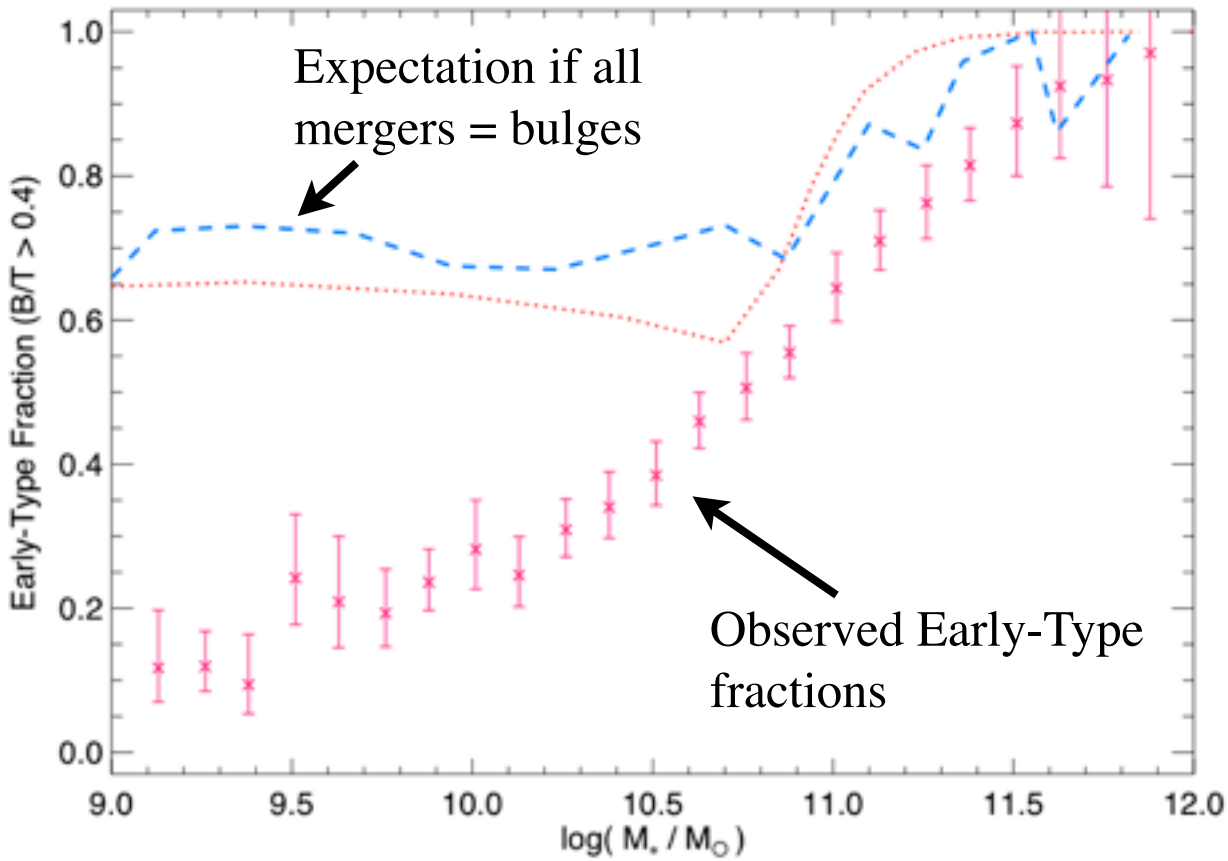
HOW DID WE GET TO GALAXIES TODAY?

Many of these are *problems*...

Too Many Mergers?

-- missing some physics

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

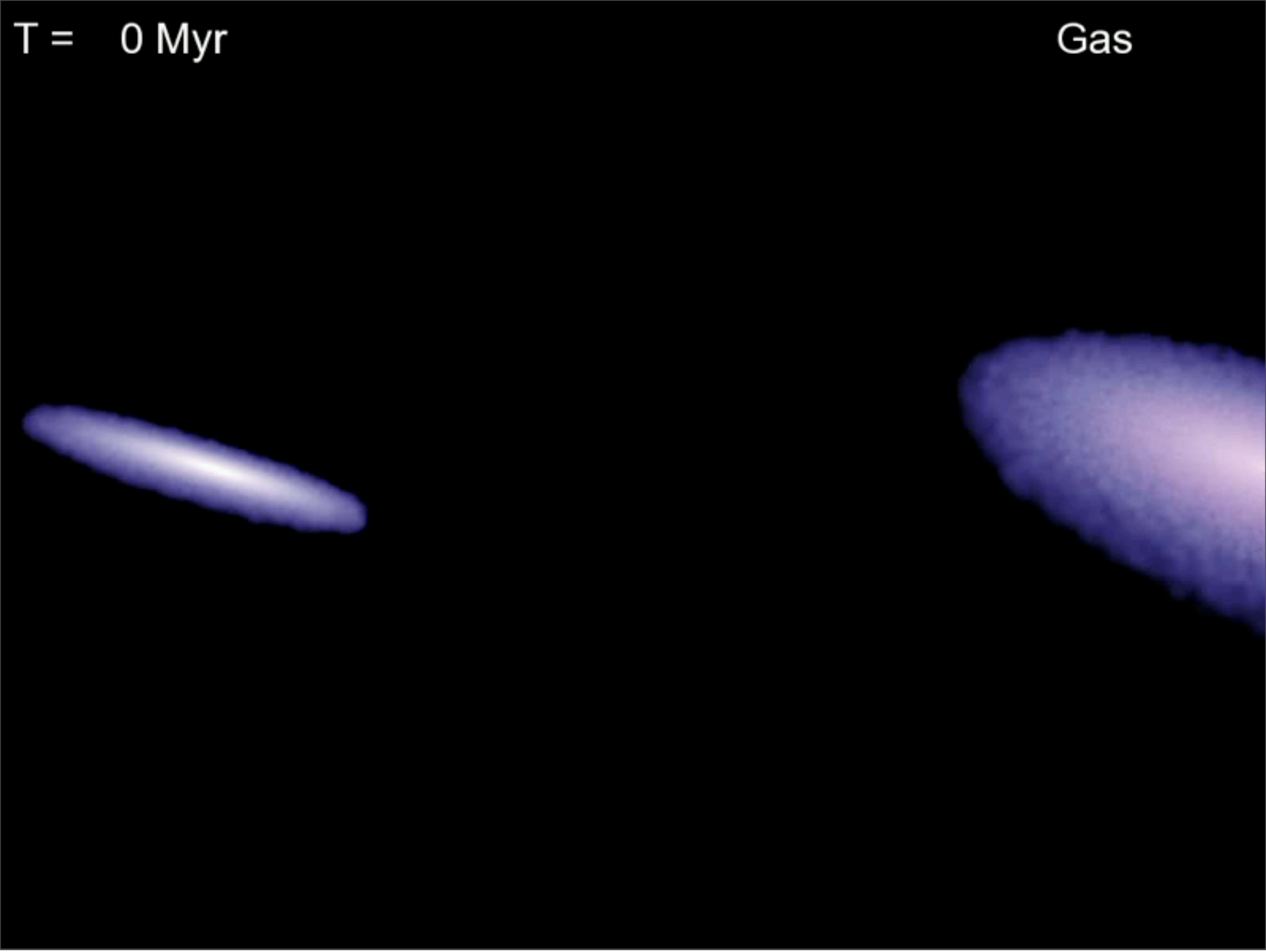


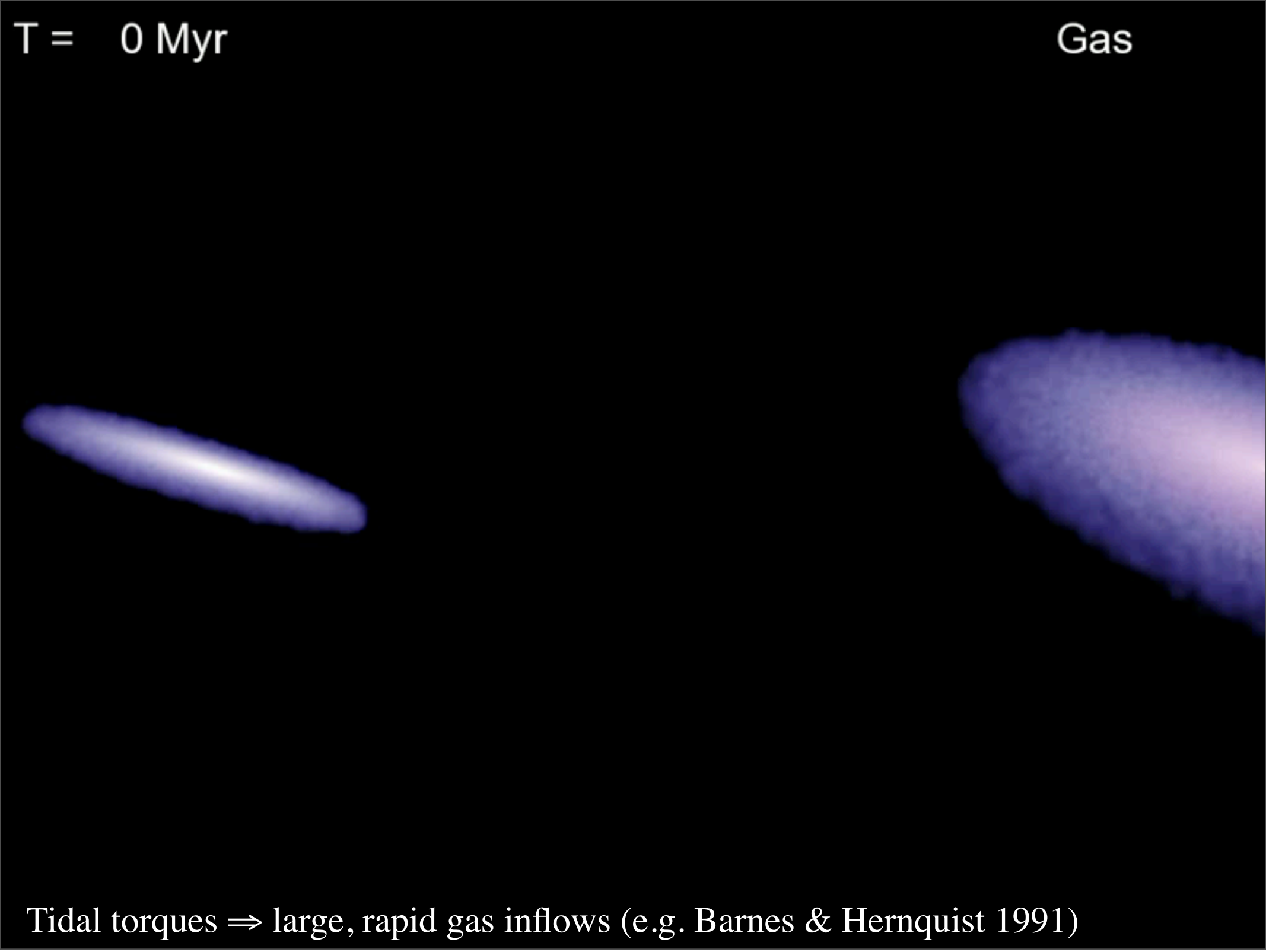
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

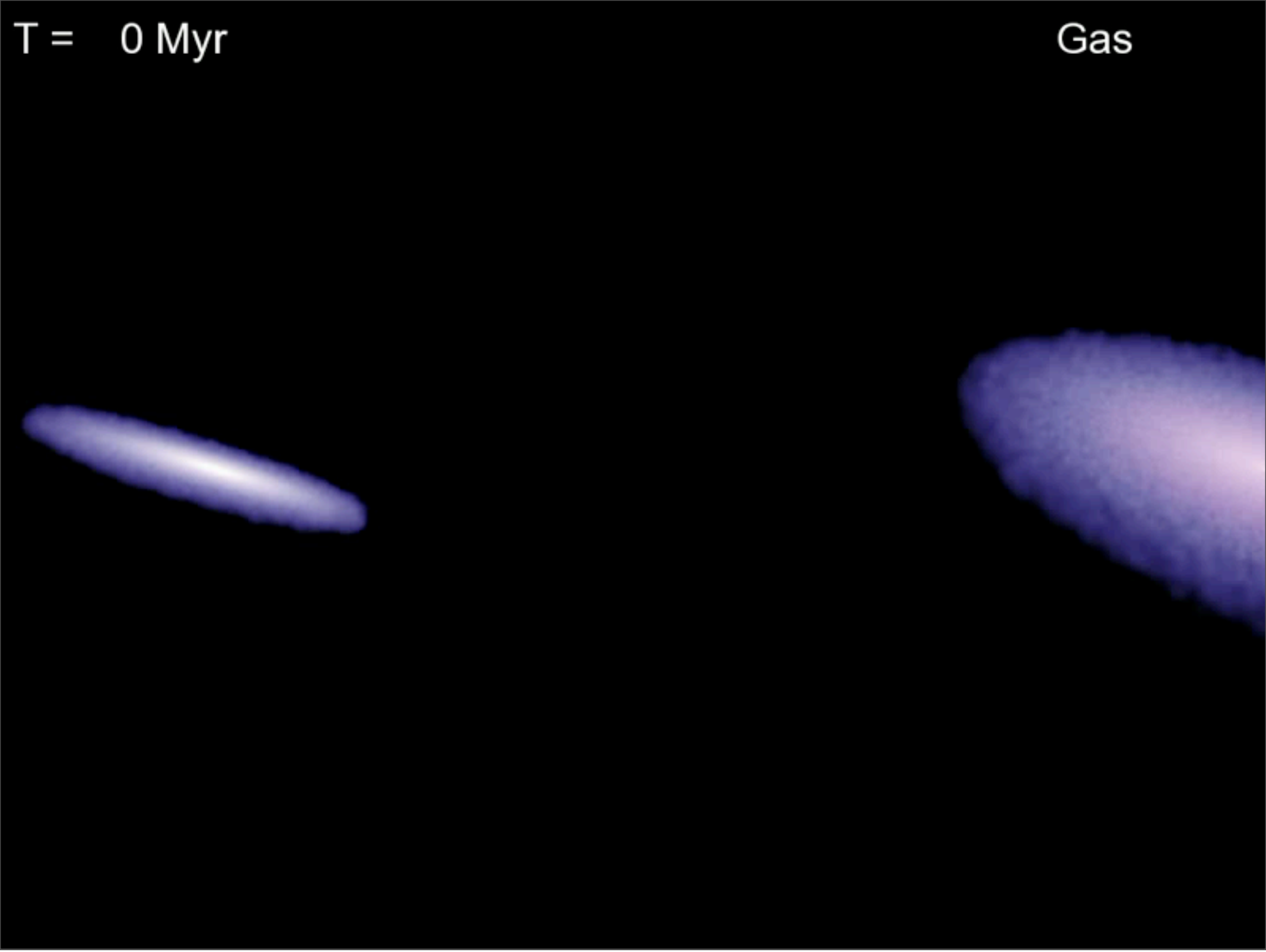
-- profiles too flat

-- shapes too flattened


T = 0 Myr
Gas



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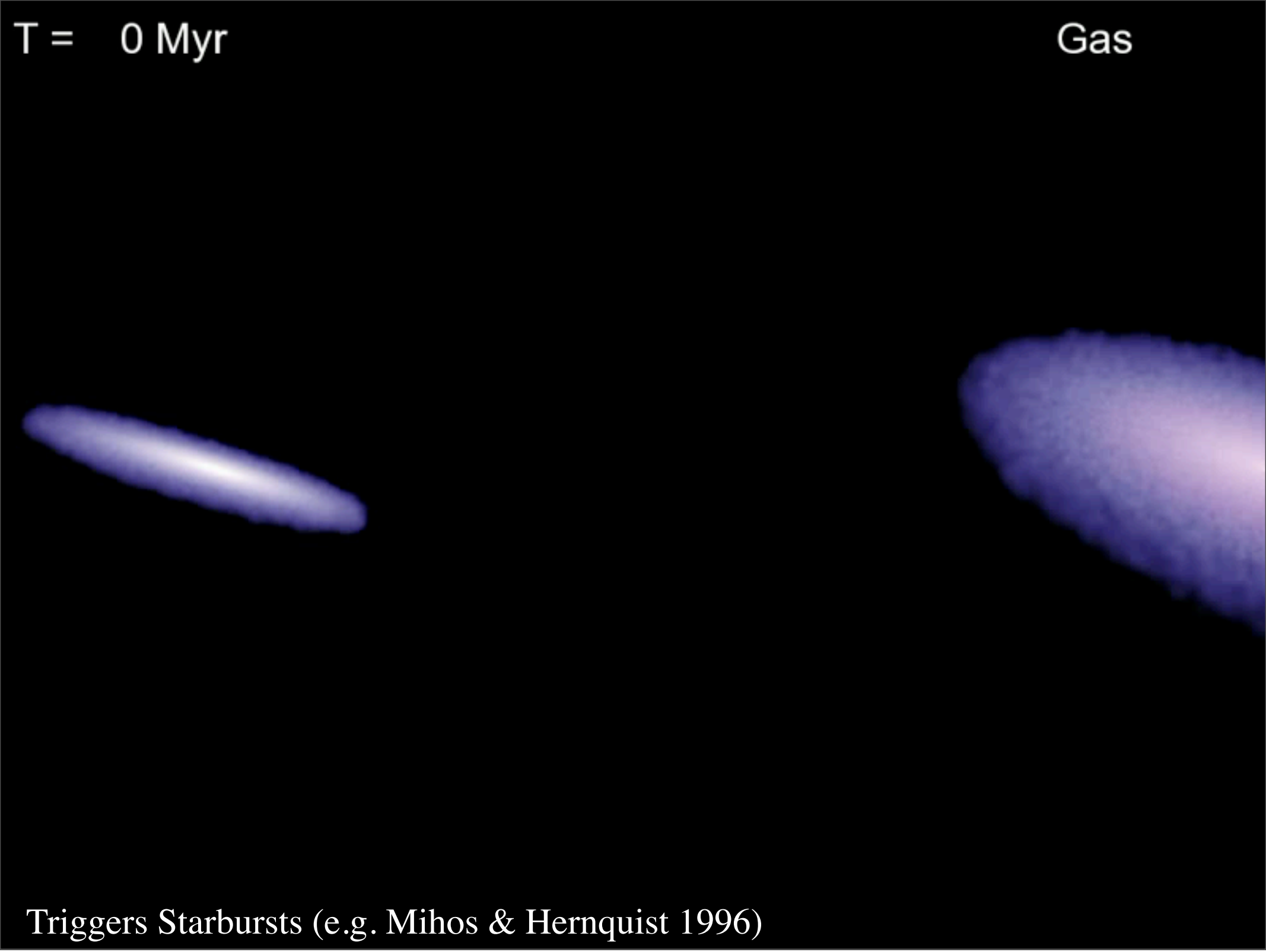
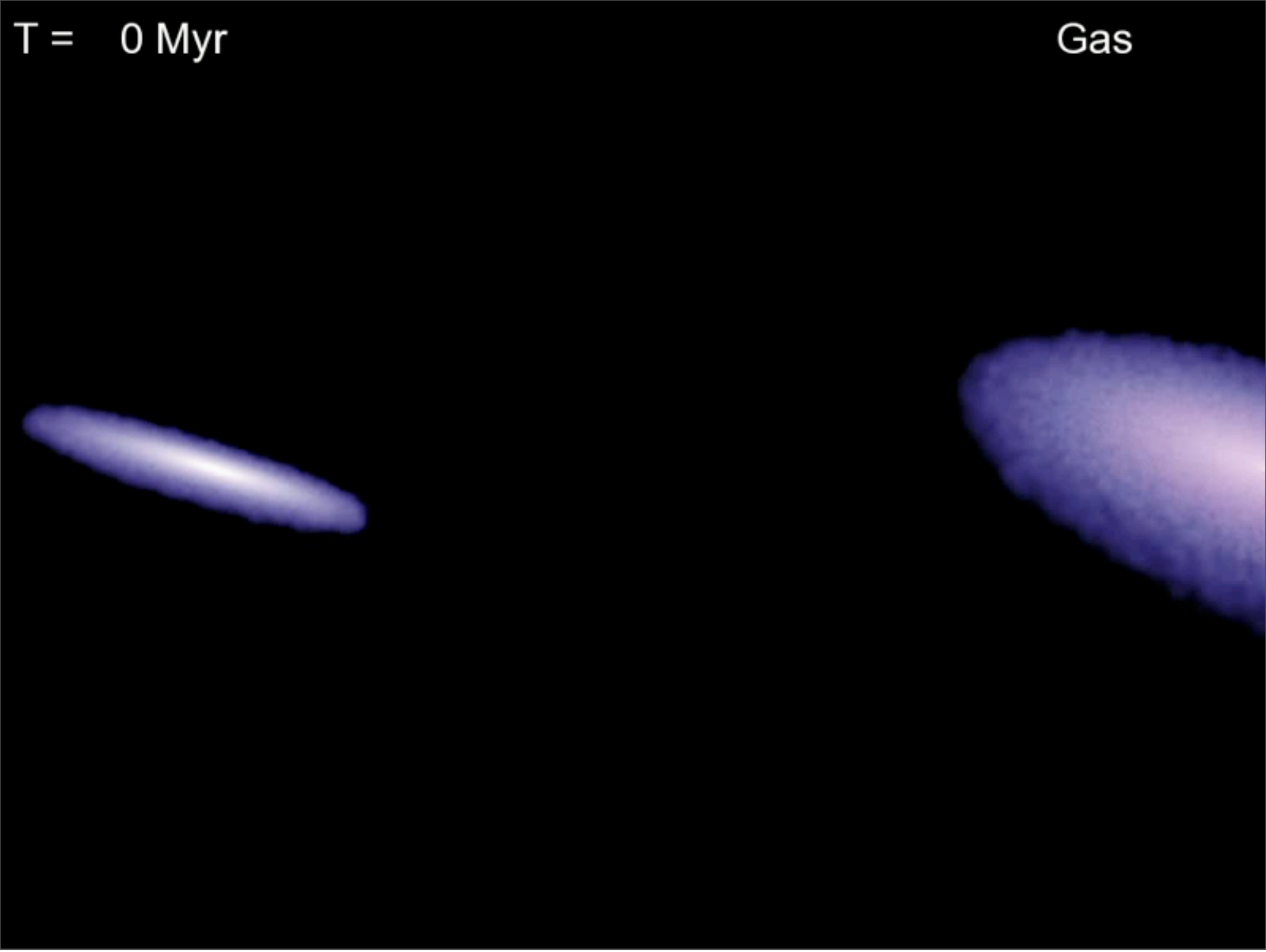


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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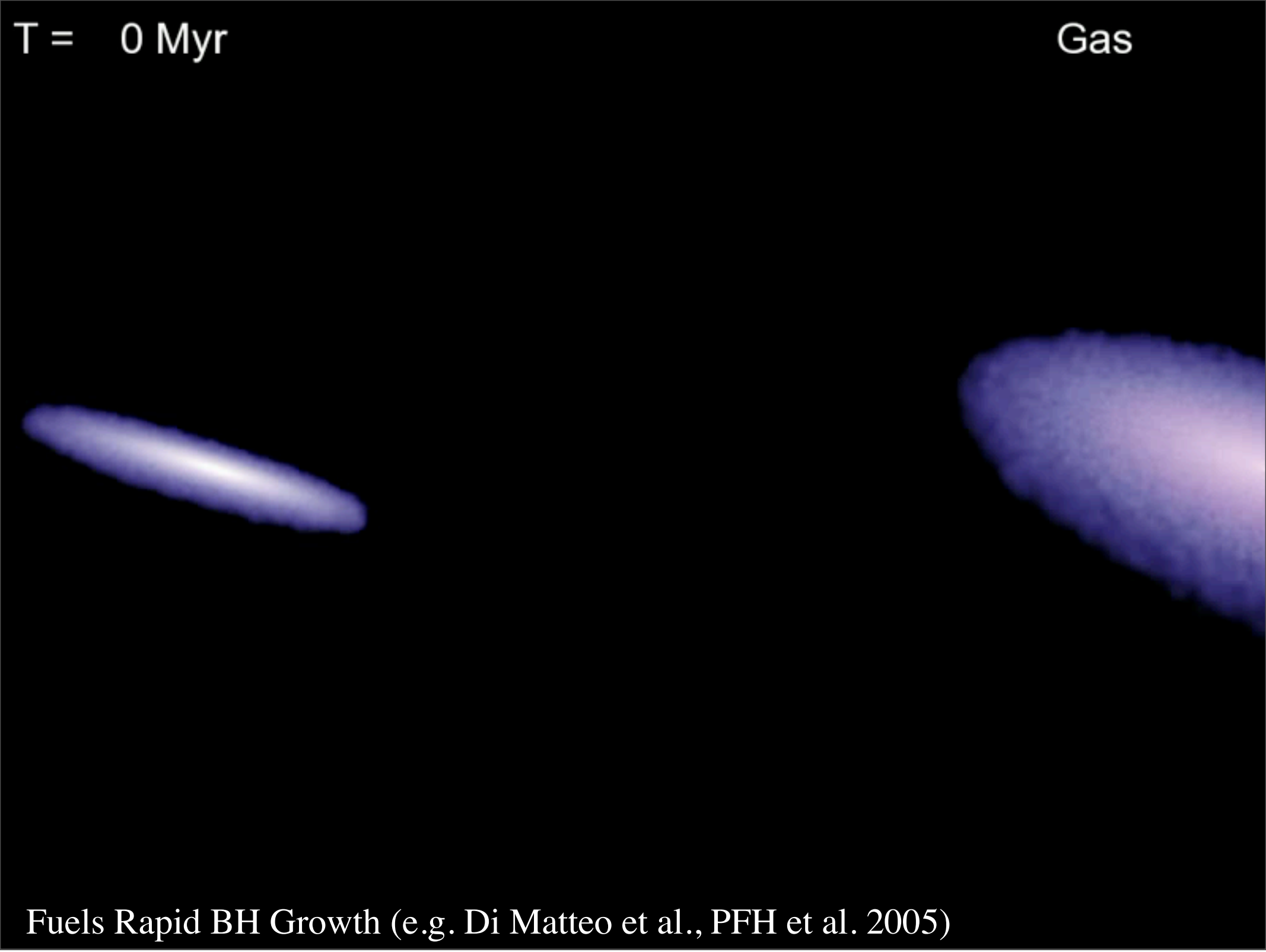
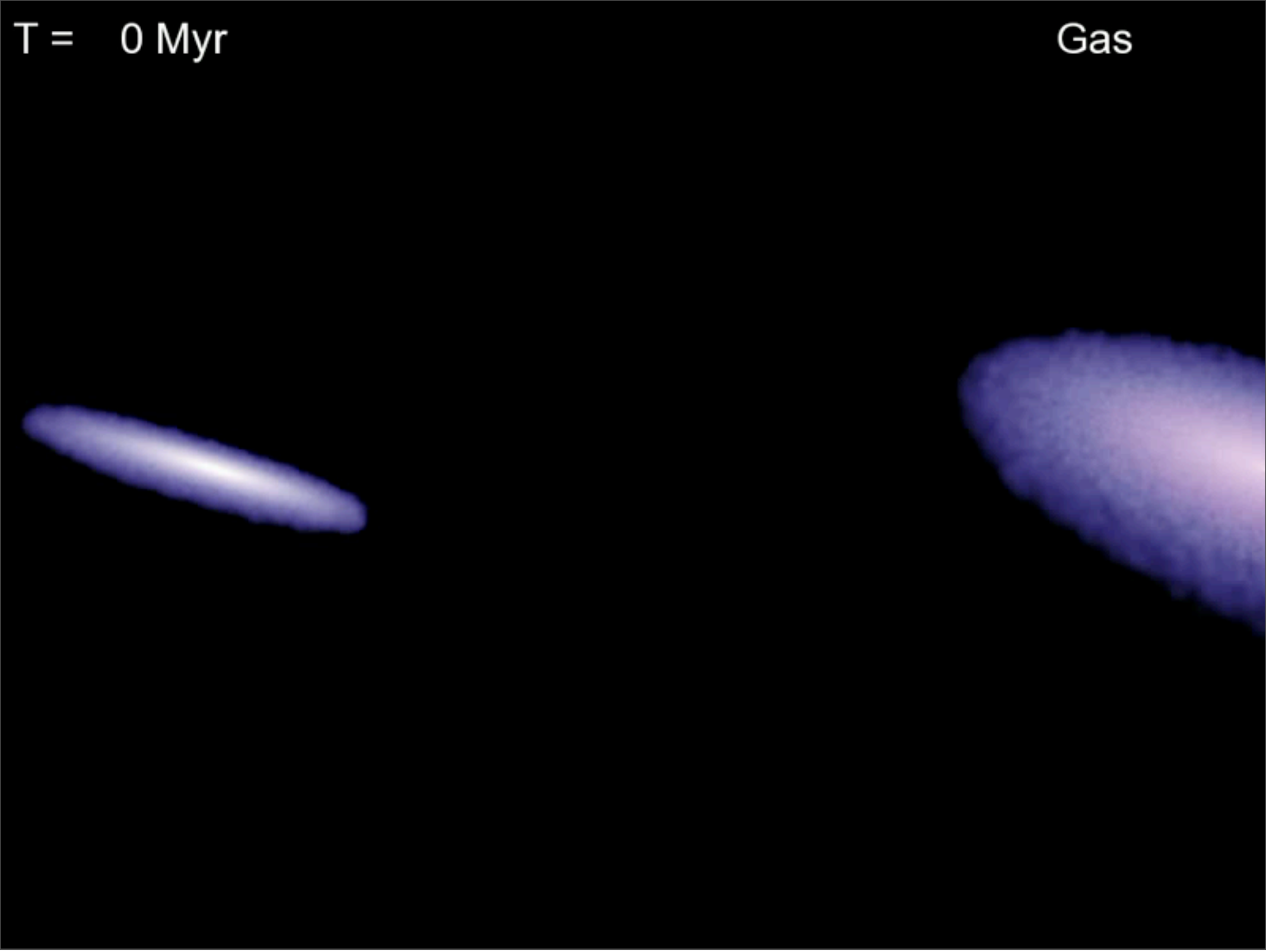


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)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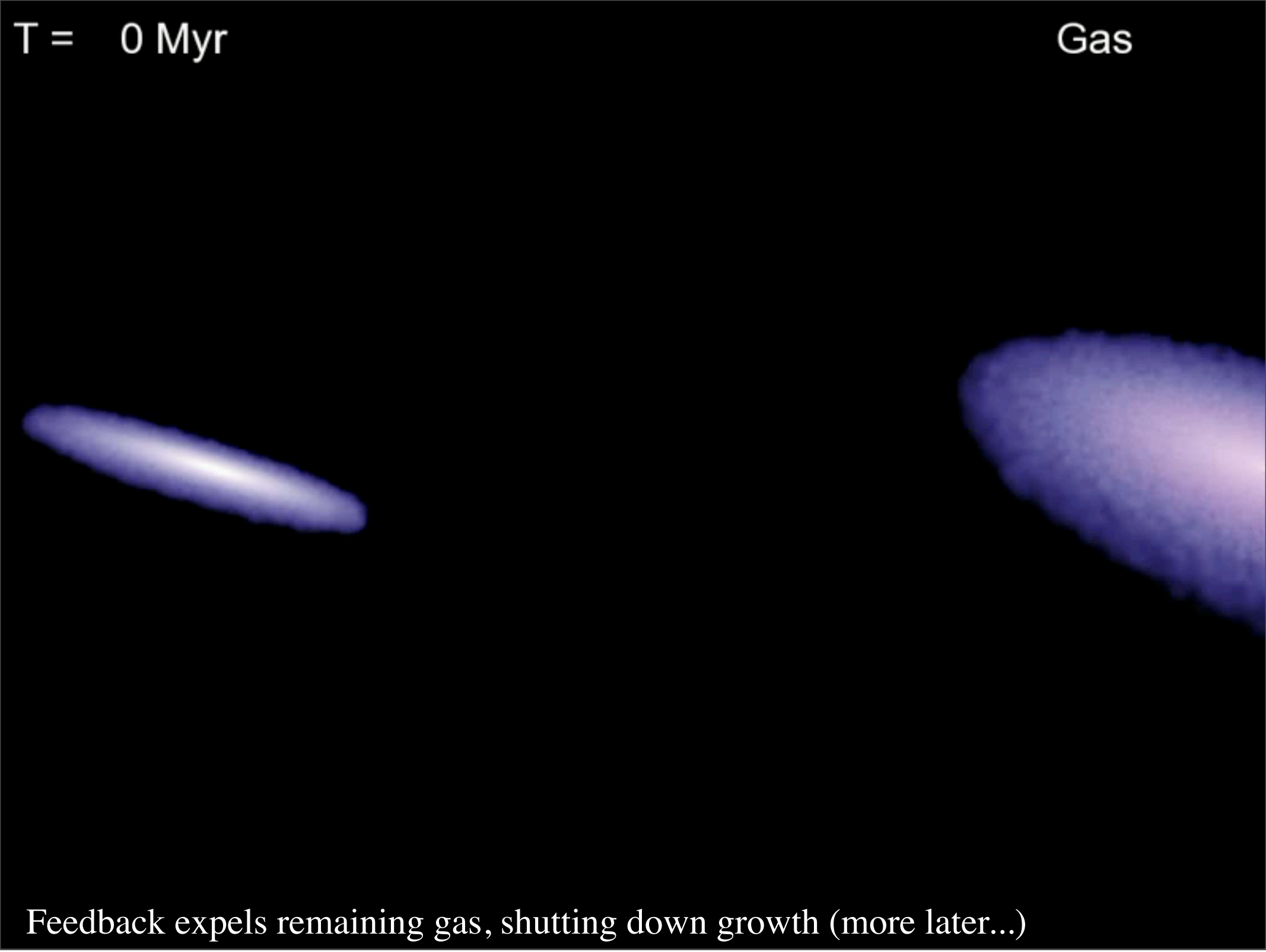
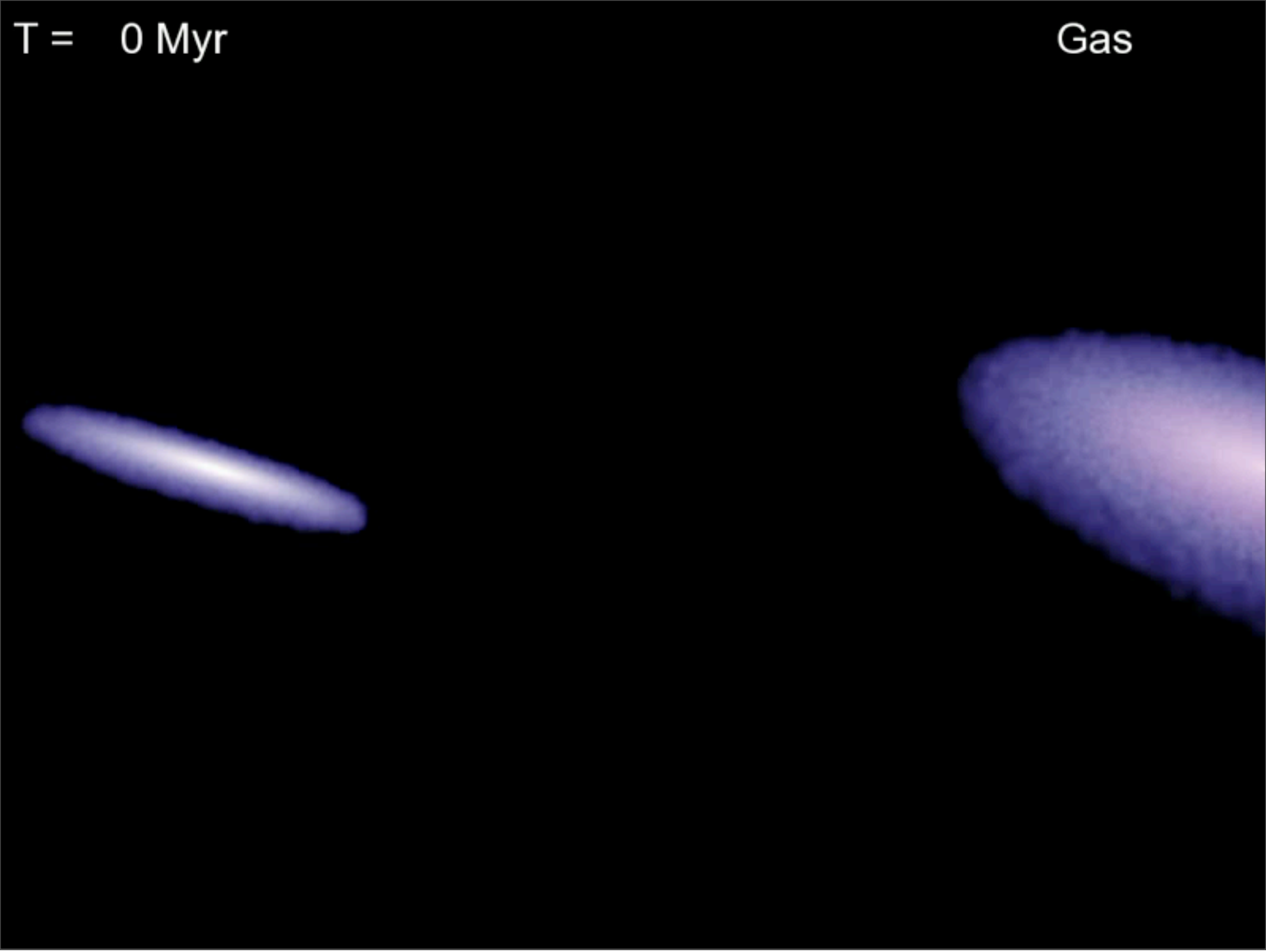


Feedback expels remaining gas, shutting down growth (more later...)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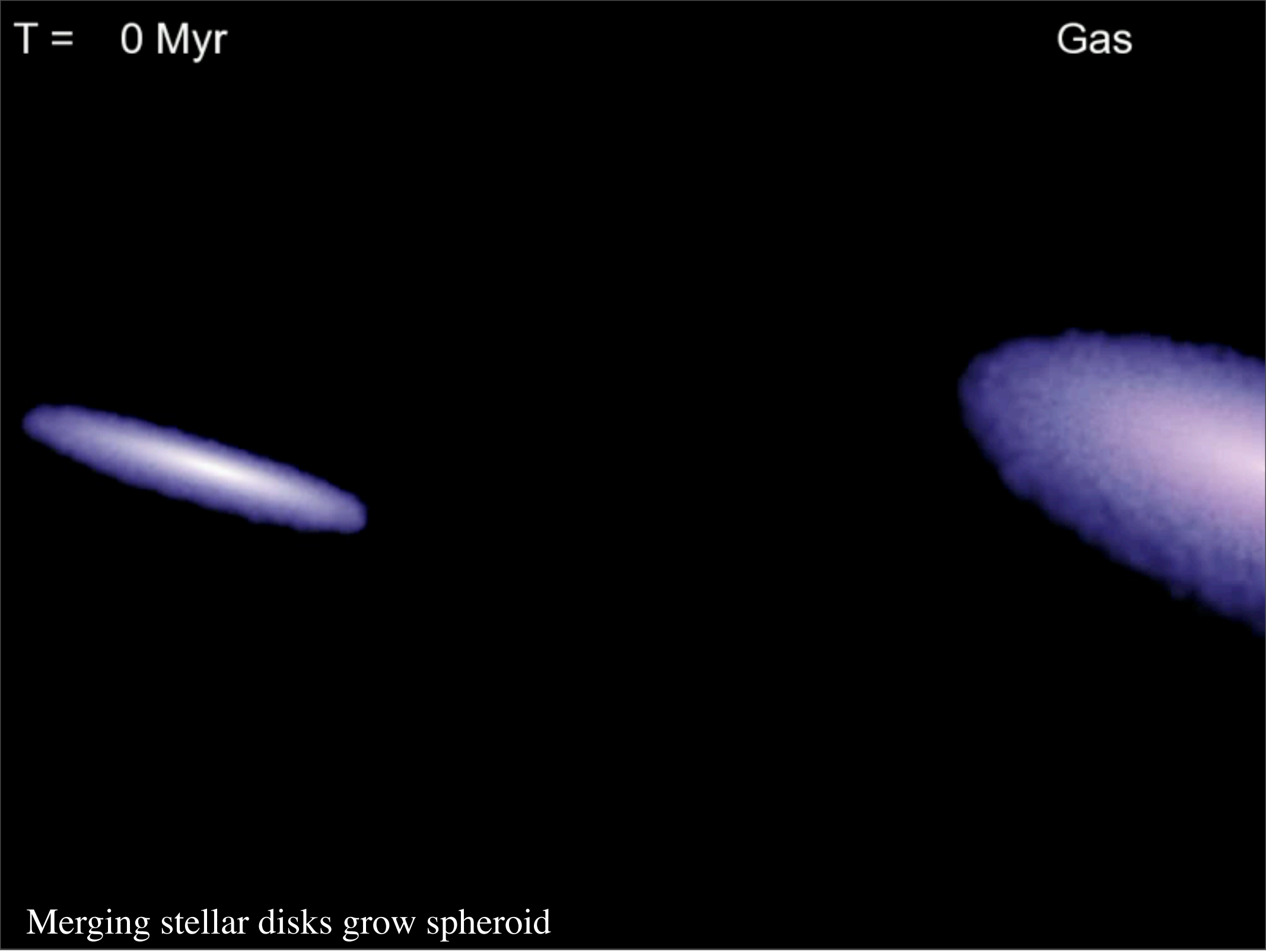
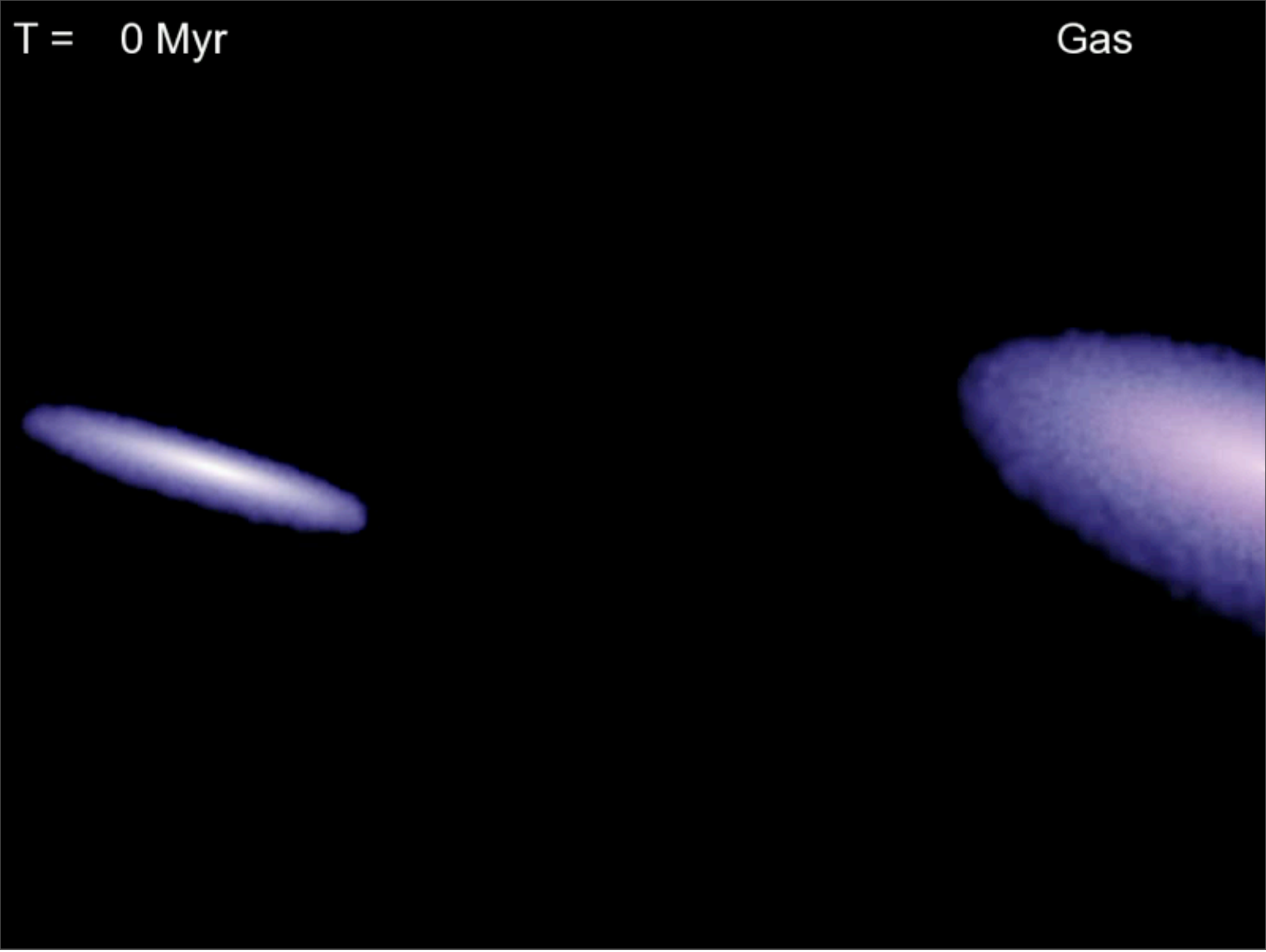


Merging stellar disks grow spheroid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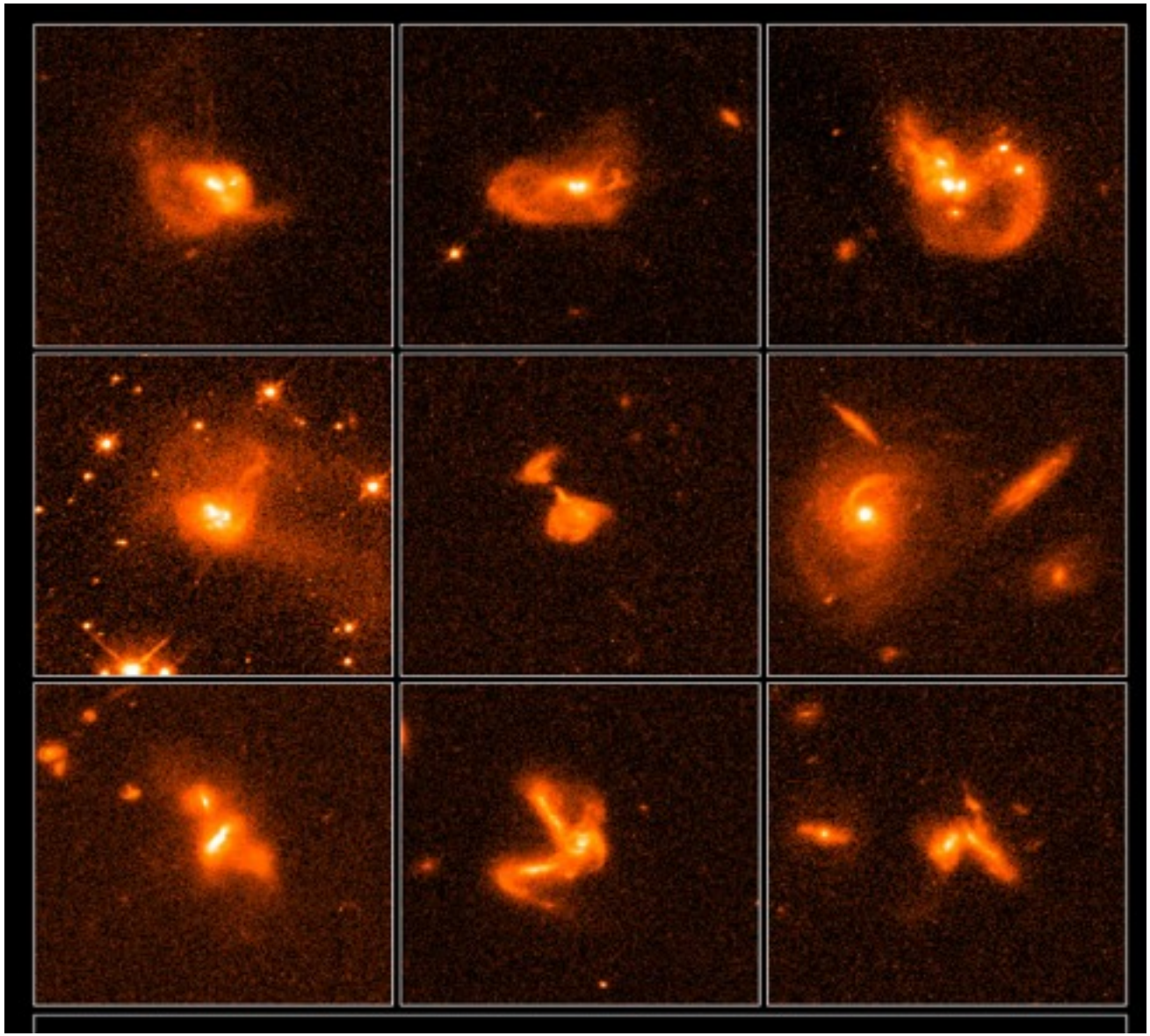
Gas

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

Borne et al., 2000



Funneled to the center → massive starbursts

Locally, *all* massive starbursts (> 100 M_{sun}/ yr) are late-stage mergers

Observe Compact Gas: ~10^{10} M_{sun} on <kpc scales

Are they the progenitors of ellipticals?

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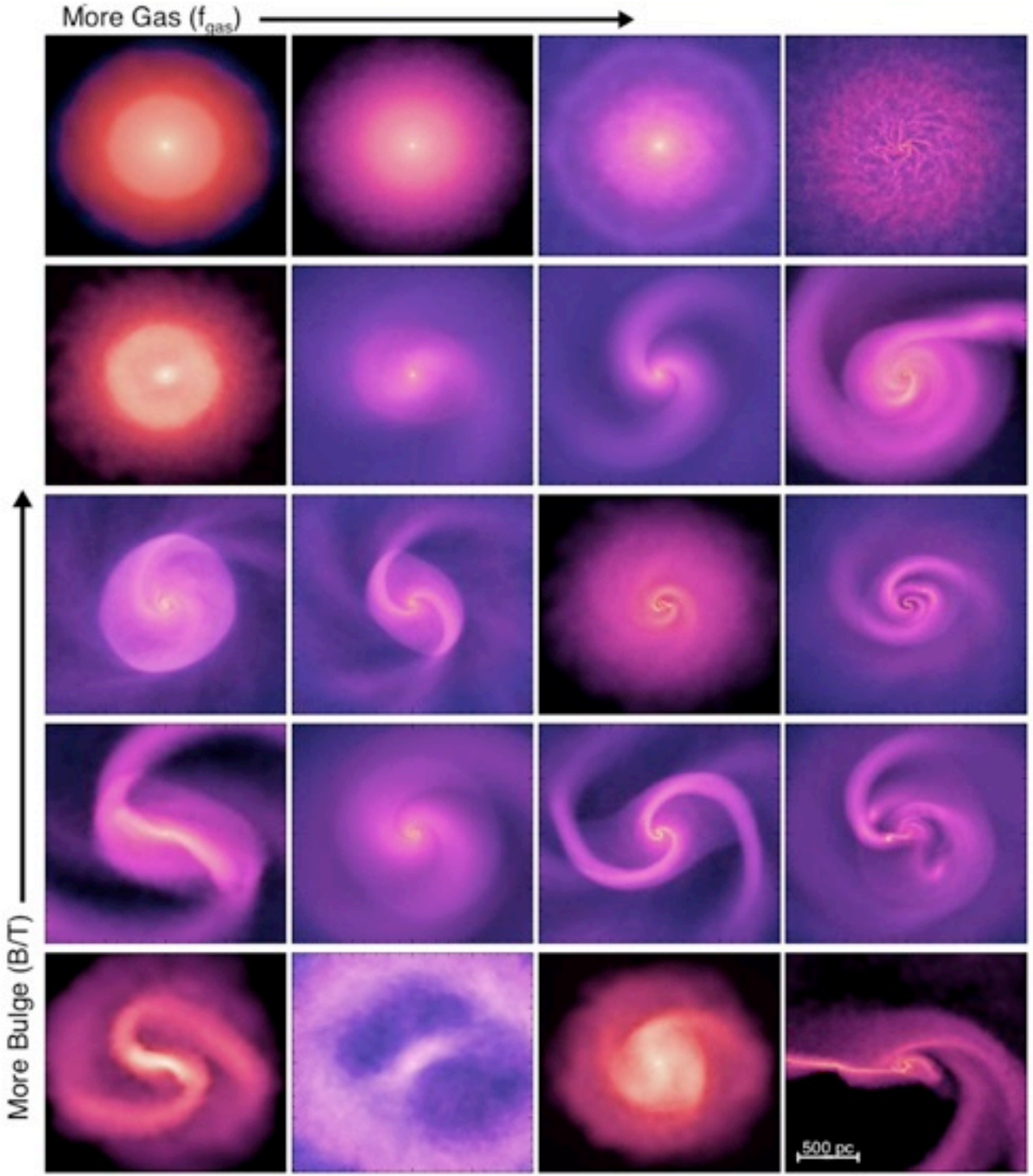

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New Work by

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
line transfer (polychromatic)
Mappings/CLOUDY model for
stellar birth clouds/PDRs

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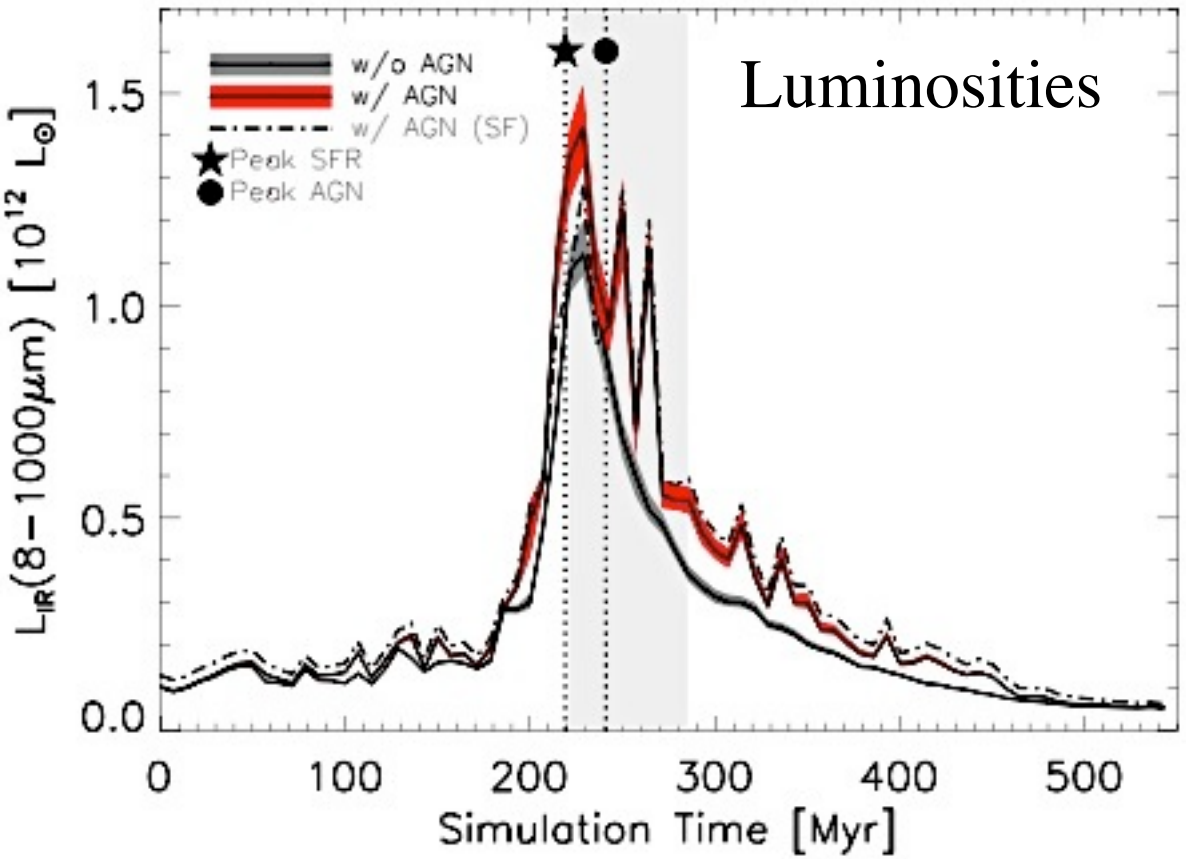

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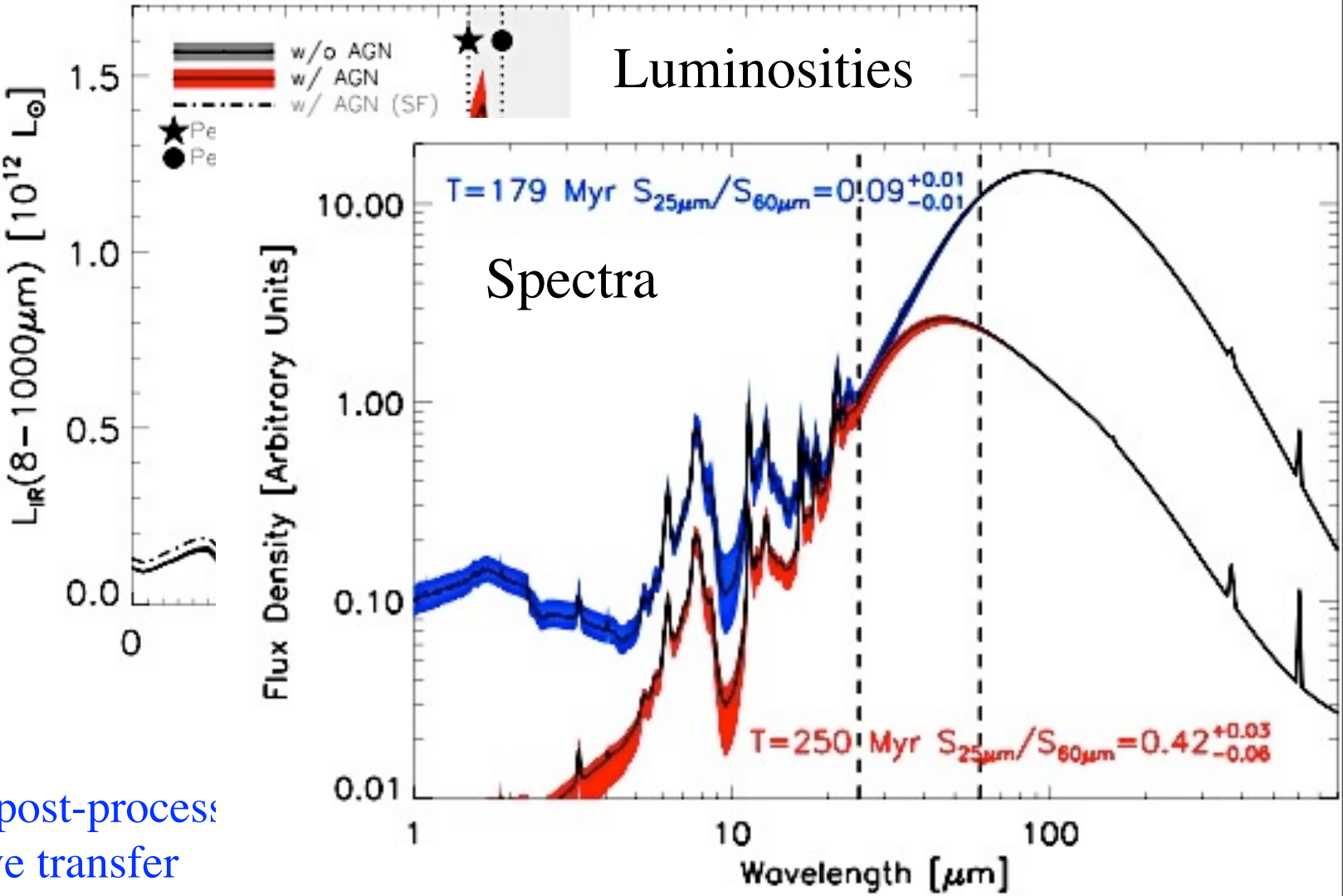

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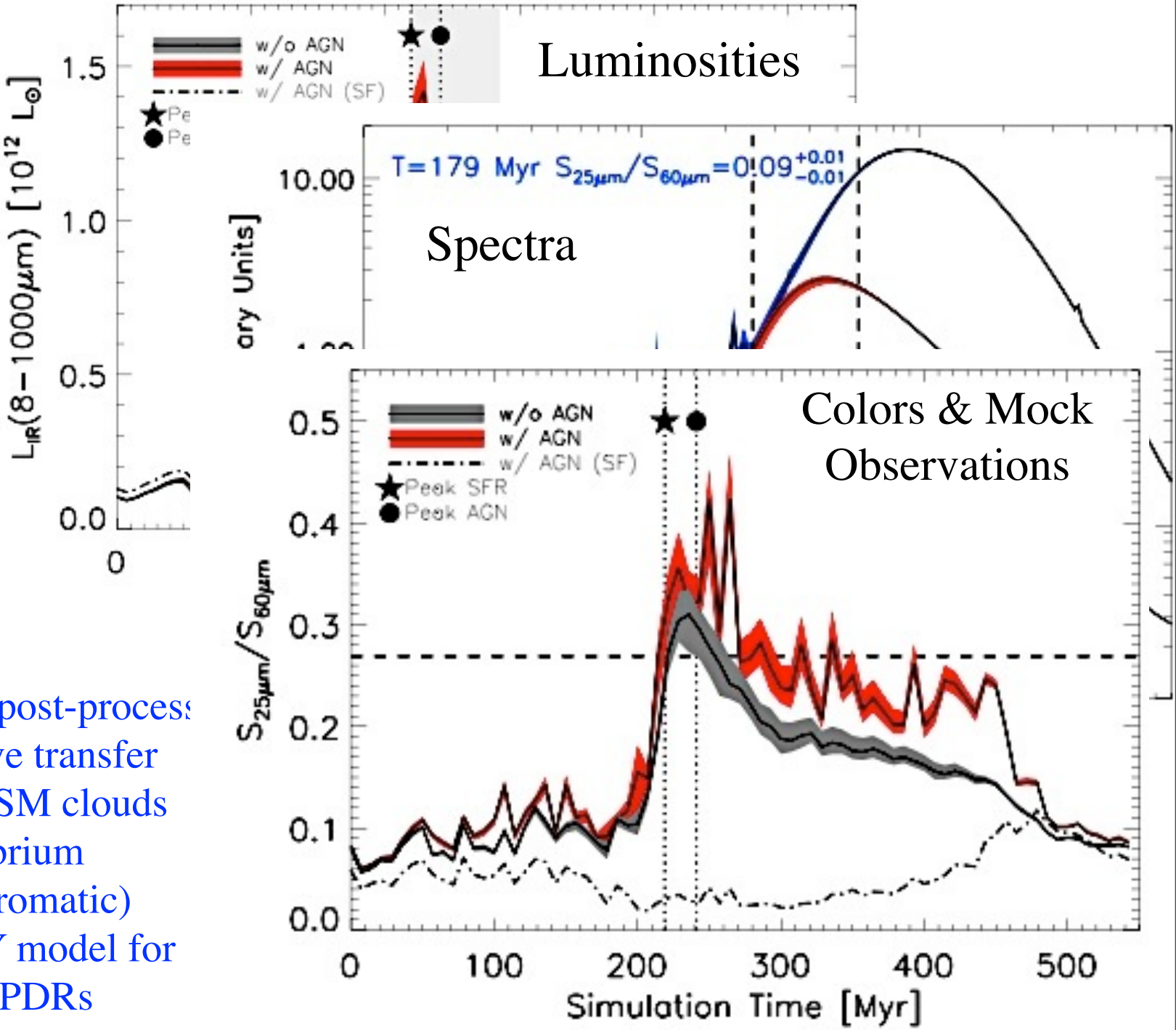

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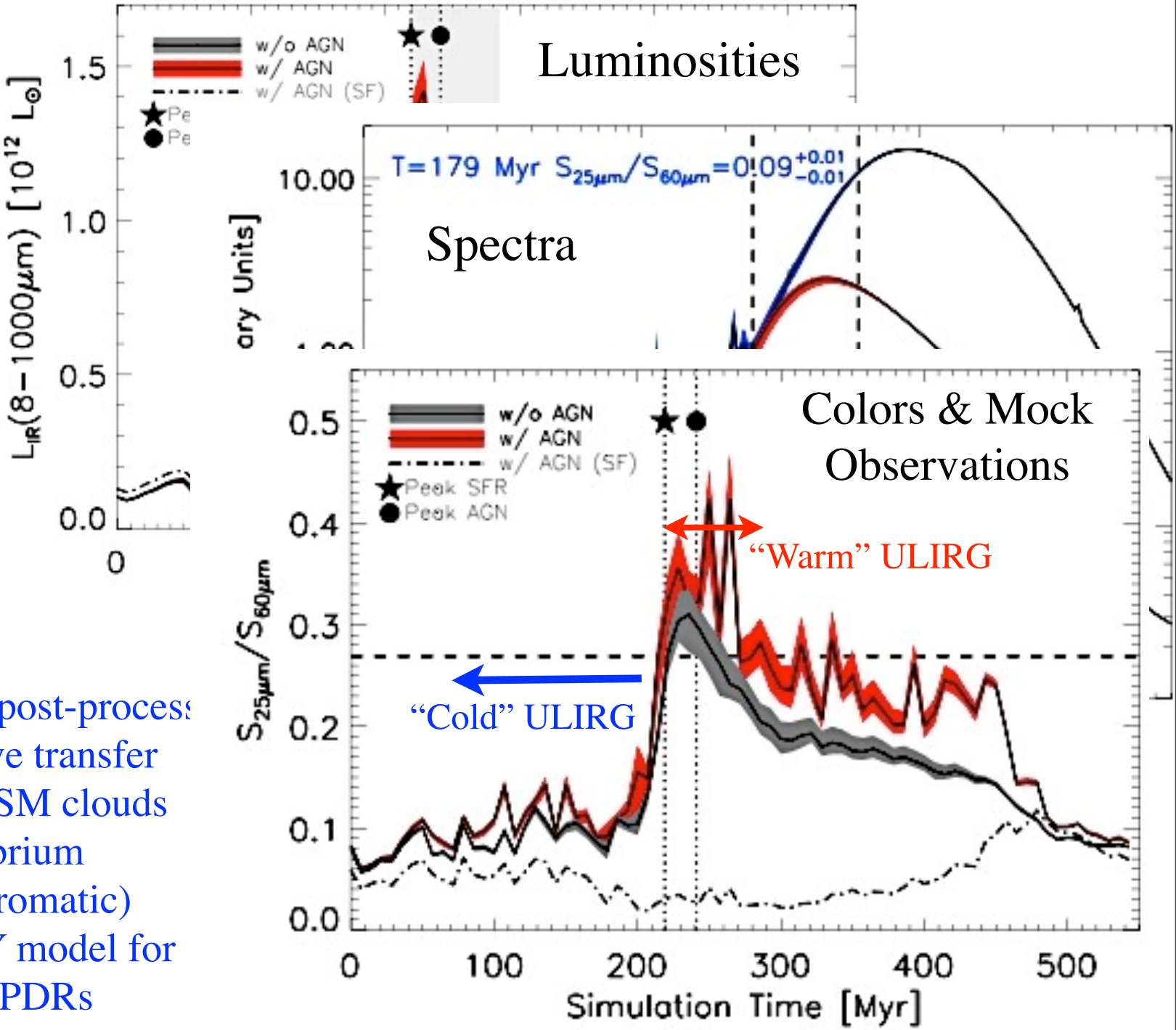

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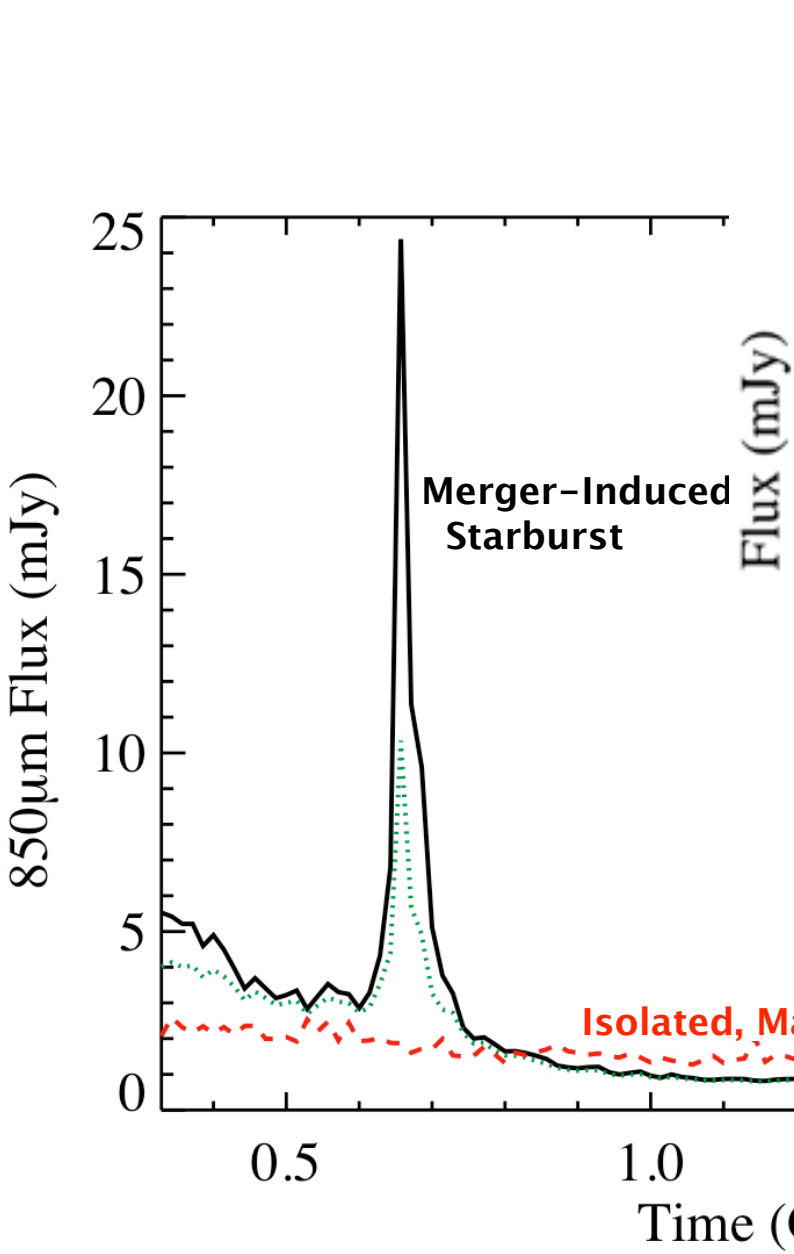
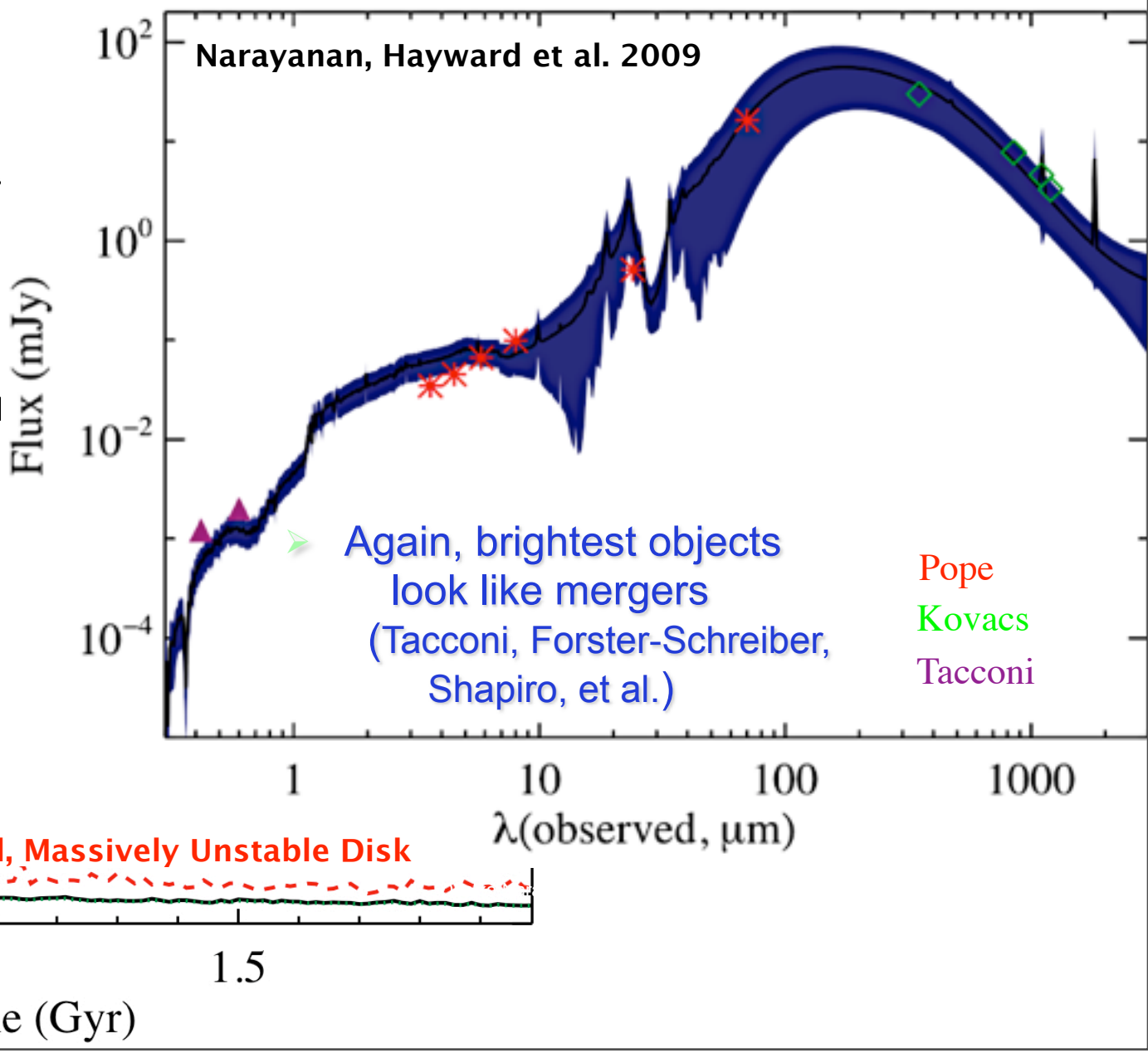
STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

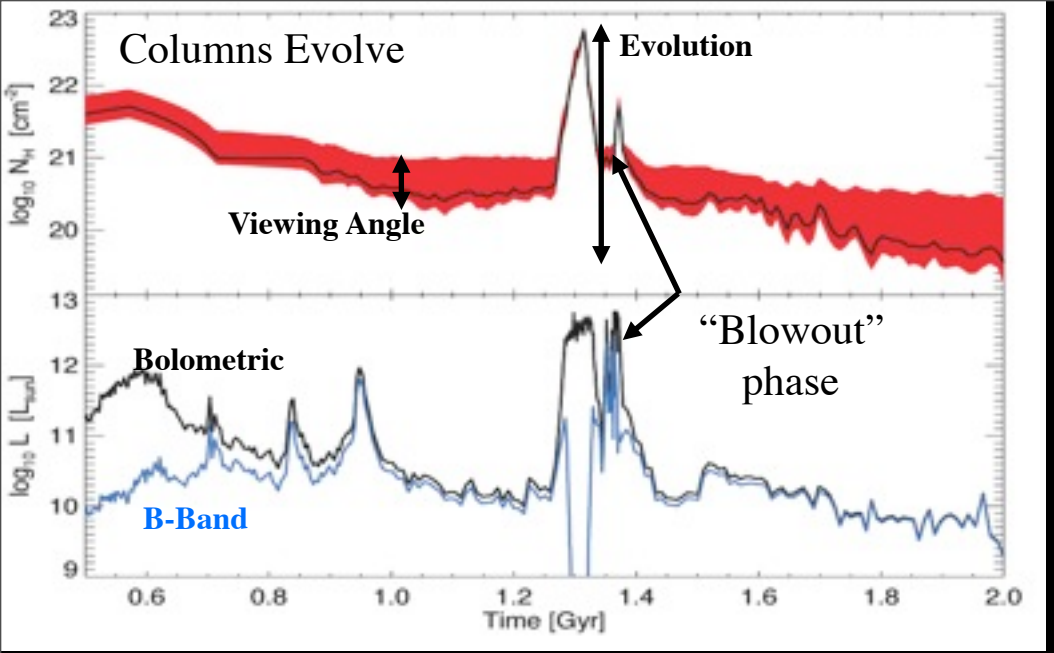
- Not just at z=0, but in high-redshift sub-millimeter galaxies





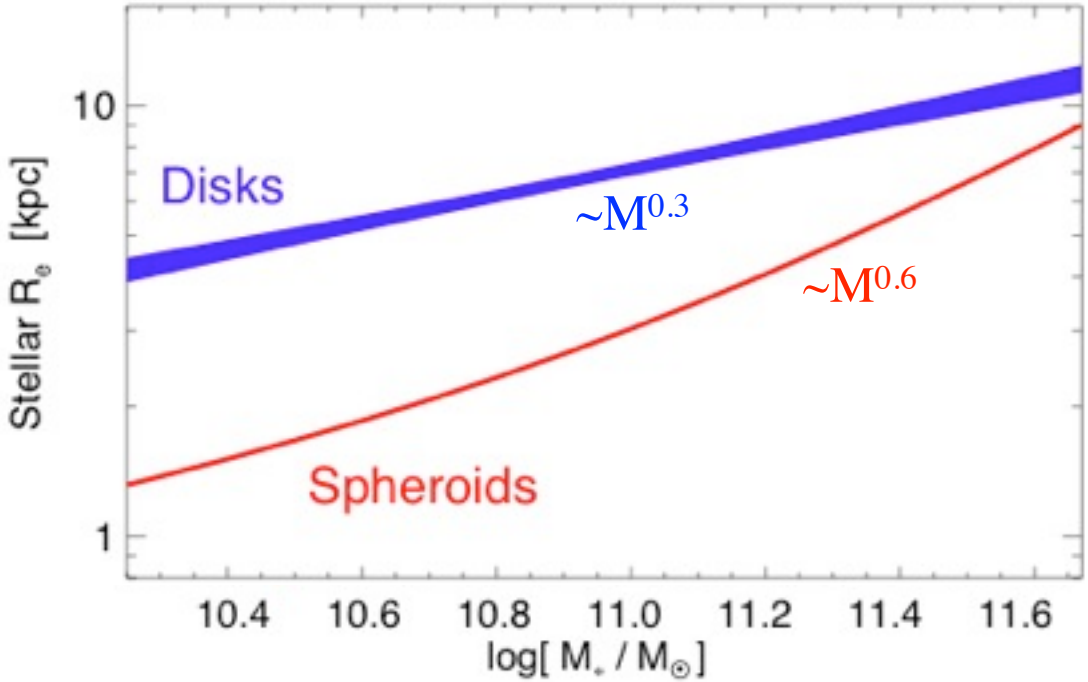
- Again, brightest objects look like mergers (Tacconi, Forster-Schreiber, Shapiro, et al.)

Pope
Kovacs
Tacconi

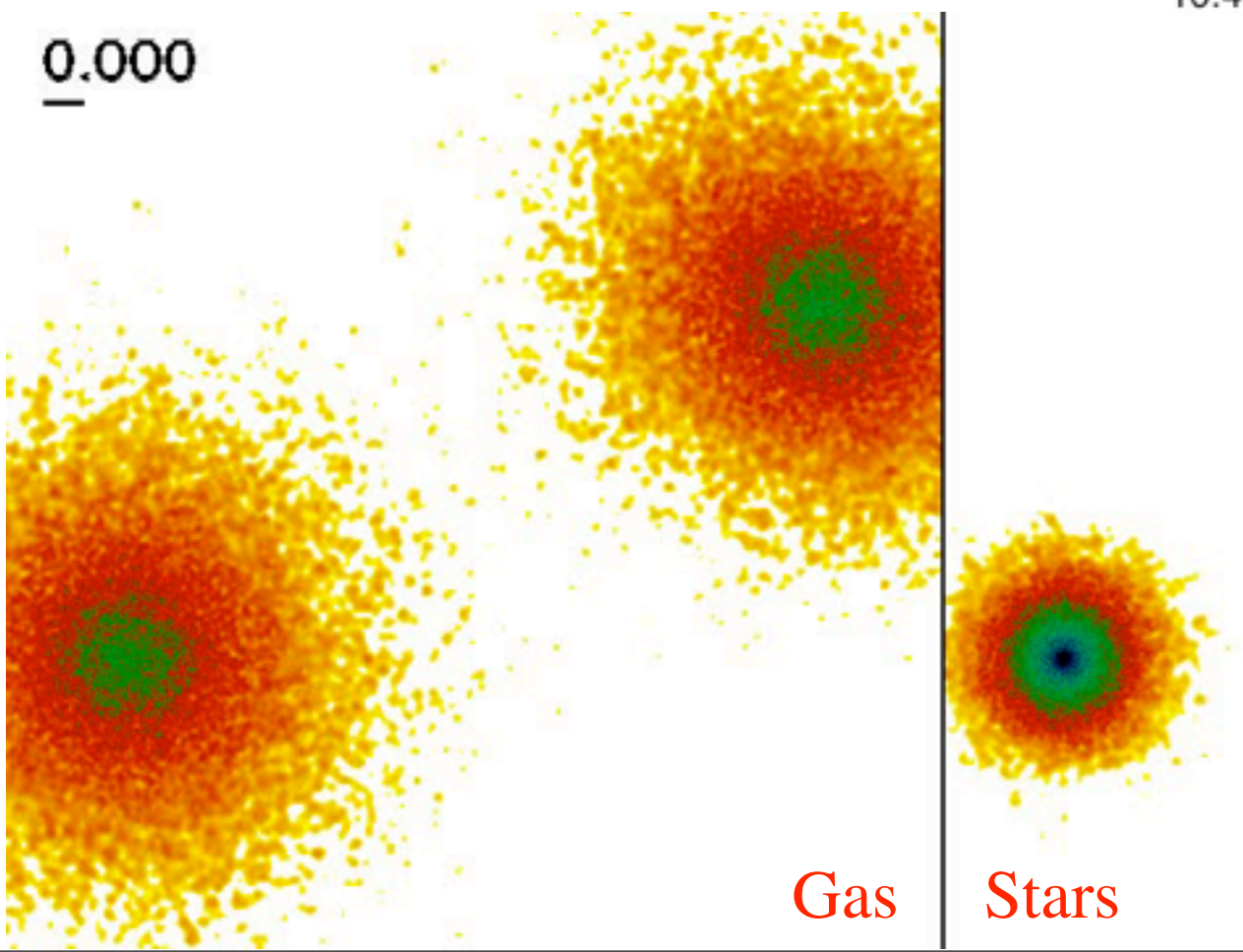

Columns Evolve
Evolution
Viewing Angle
"Blowout" phase
Bolometric
B-Band
log10 NH [cm-2]
log10 L [Lsun]
Time [Gyr]
23
22
21
20
13
12
11
10
9
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

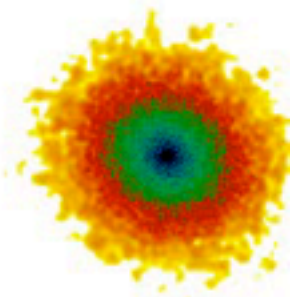
So What Difference Does this Starburst Make?

The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks?



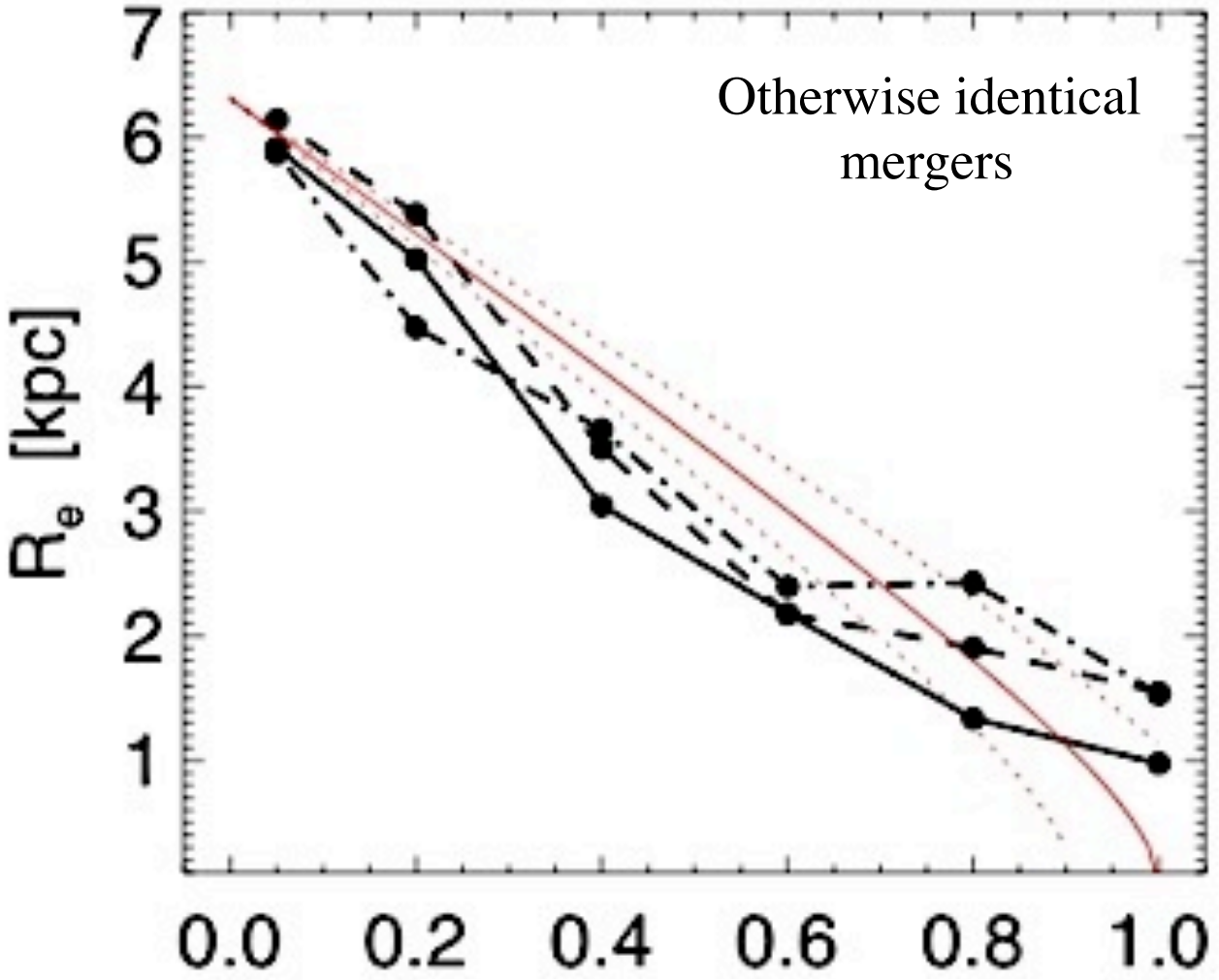


- Gas Dissipation

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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



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

PFH, Cox et al. 2008

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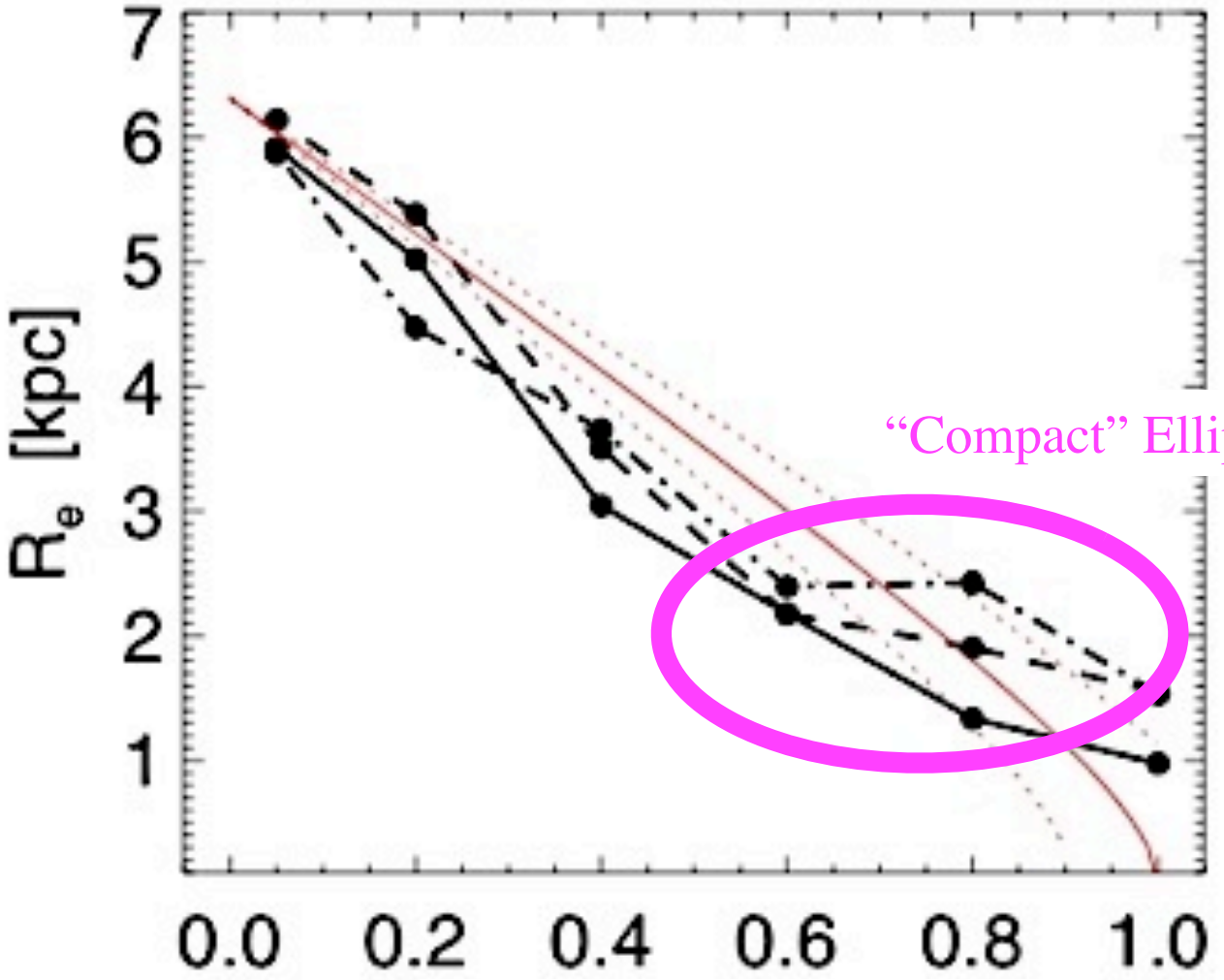

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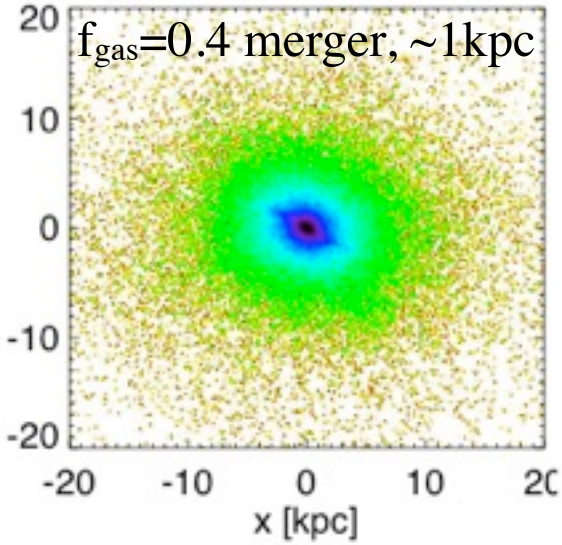
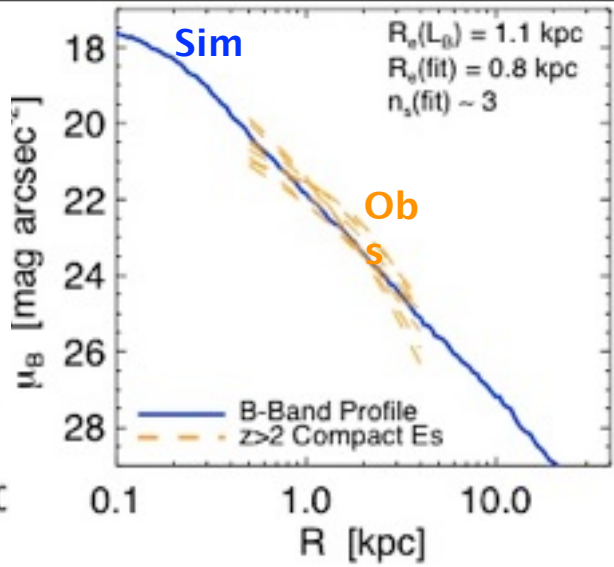
Compare: massive spheroids at z=2 to those today

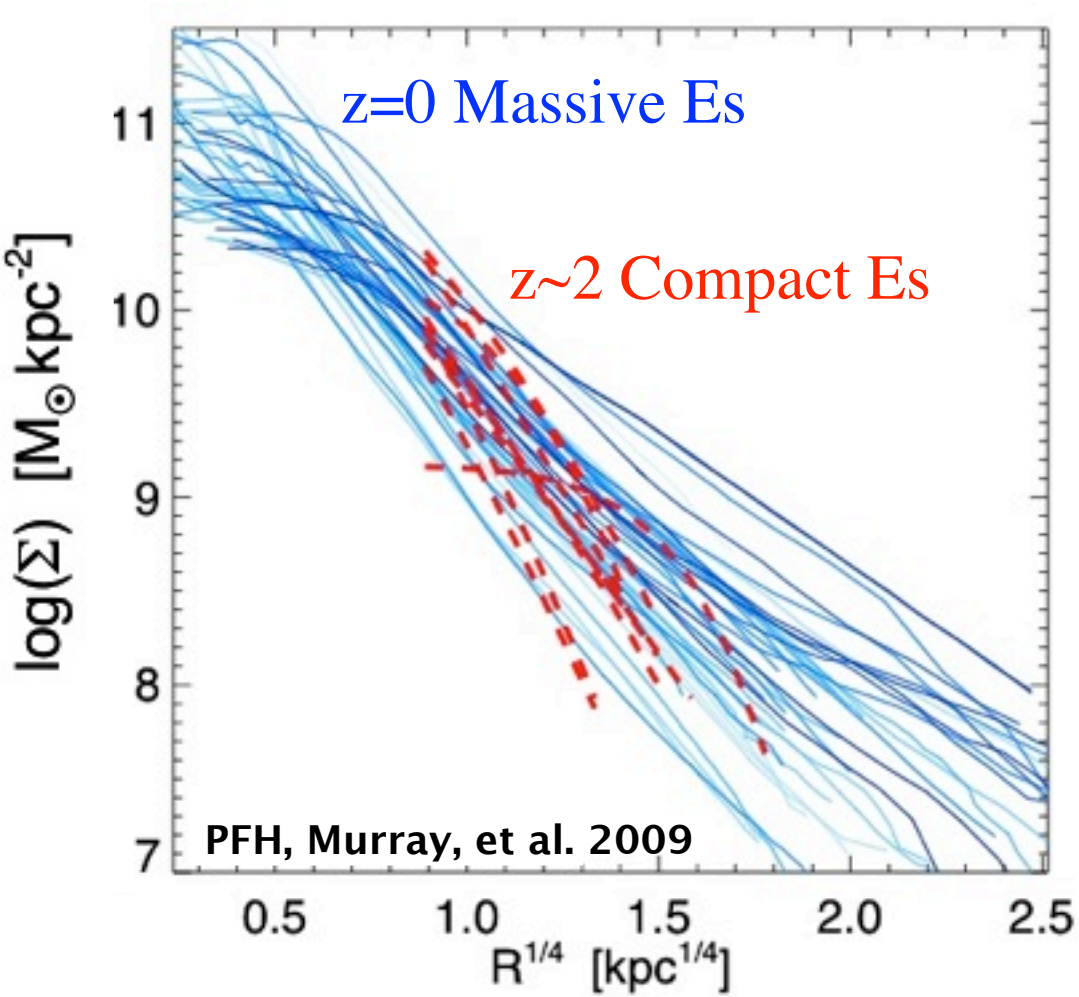
... vs gas-rich merger with later low-density/minor mergers





Observations: van Dokkum, Trujillo, Tacconi, Kormendy

(z=0)



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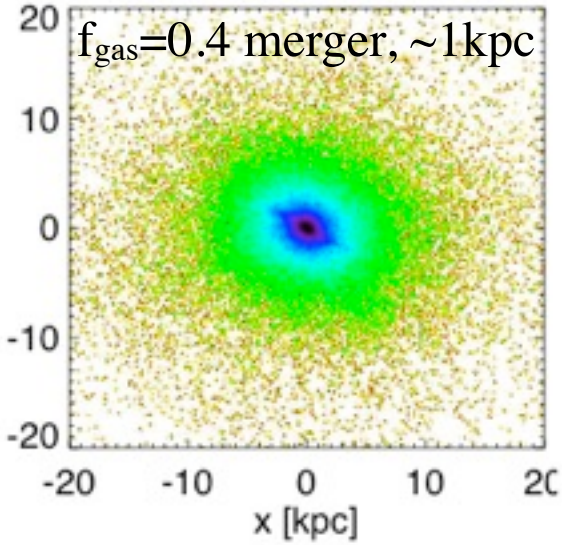

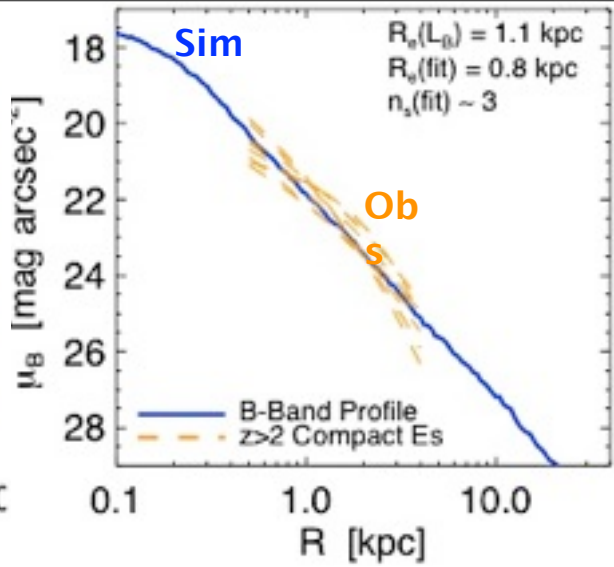

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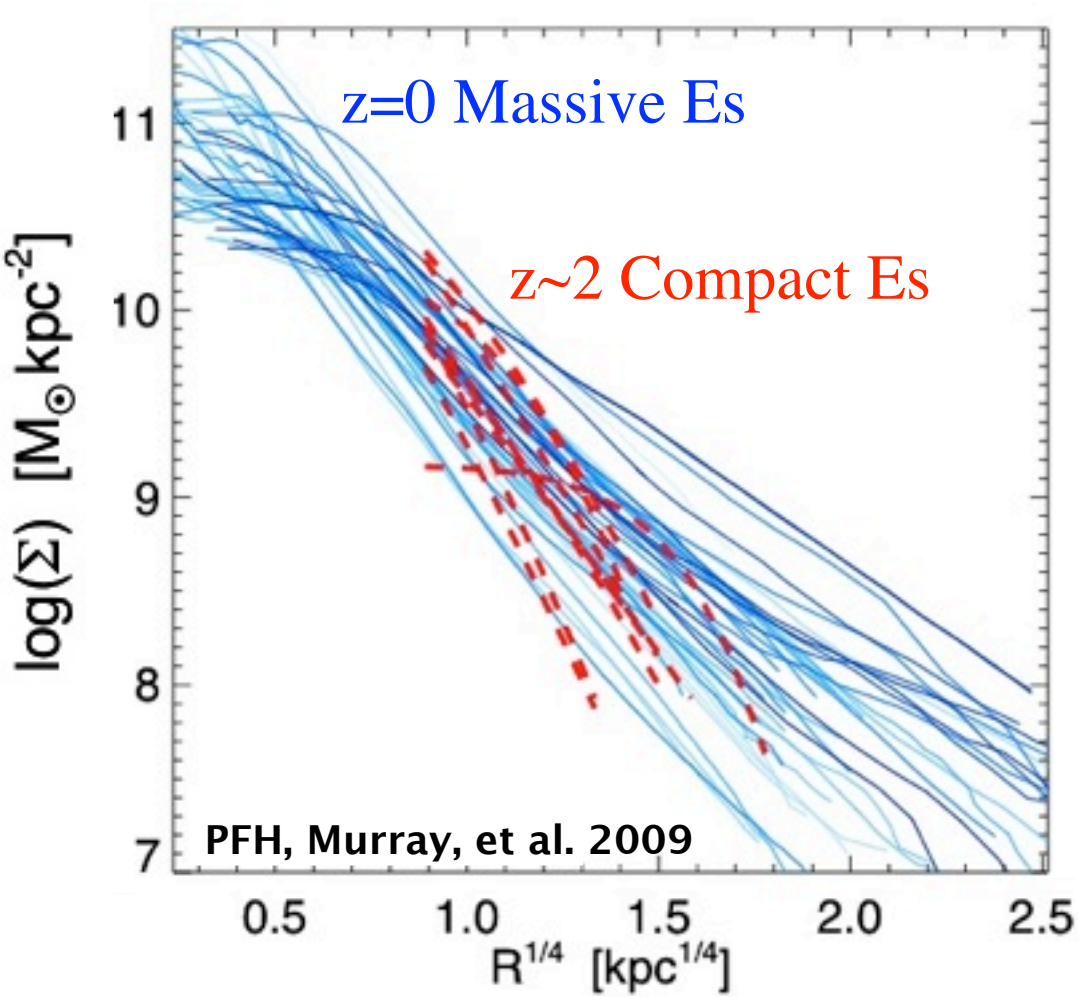

Outer "envelopes" build up after spheroid cores form

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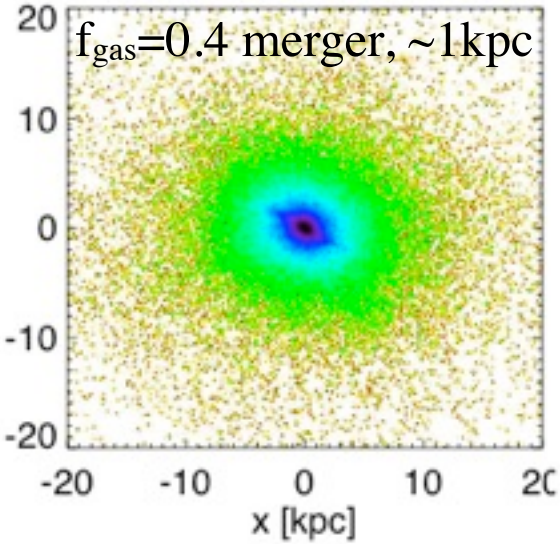
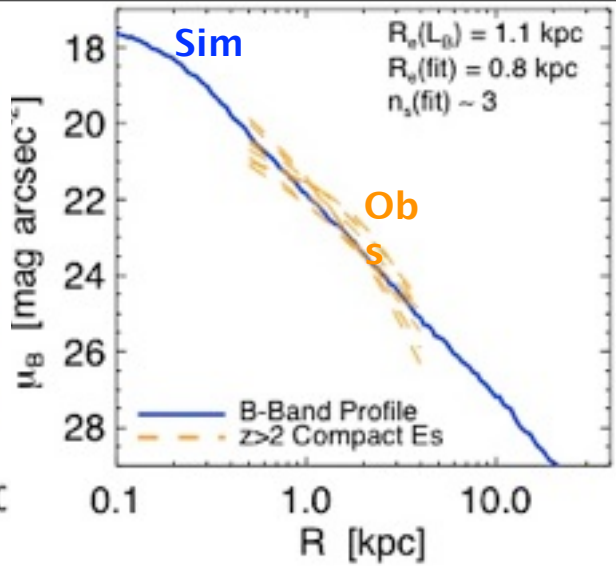
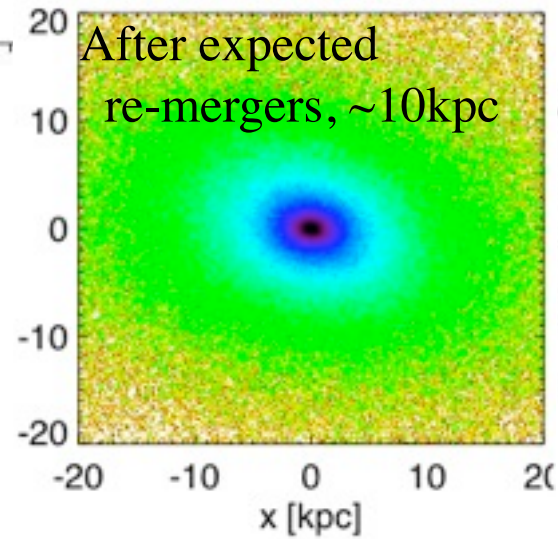
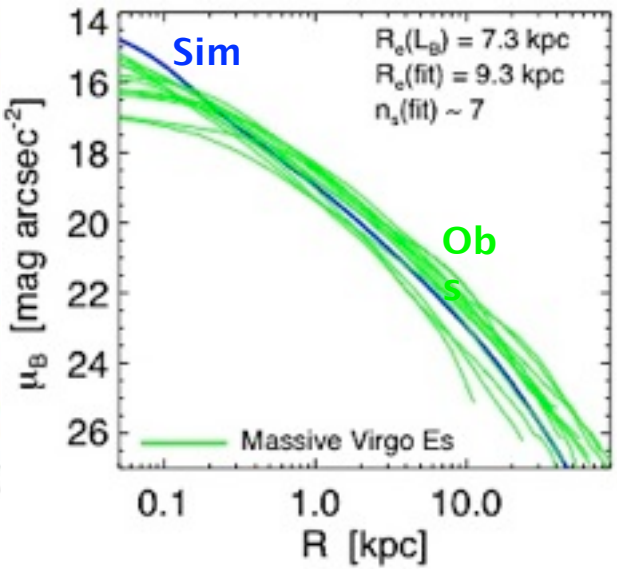
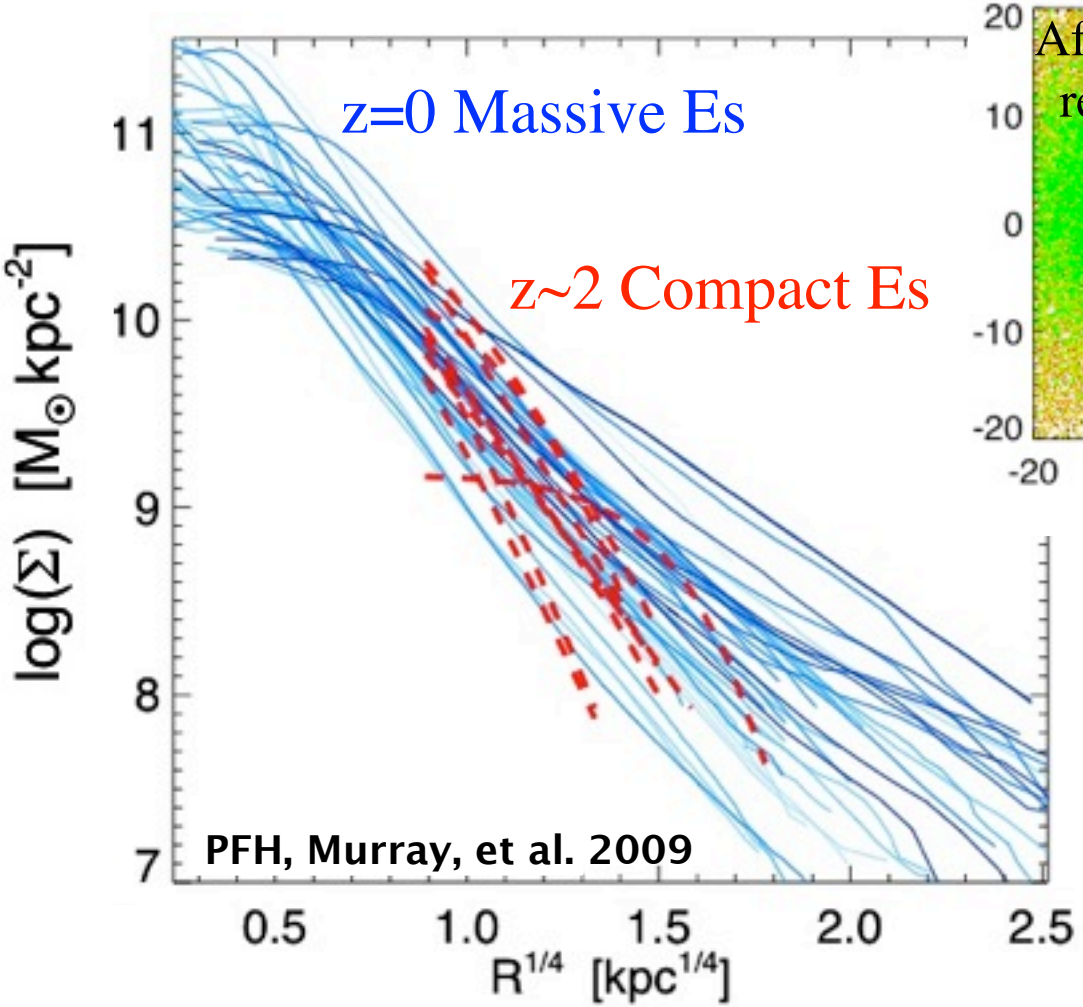
... vs gas-rich merger with later low-density/minor mergers









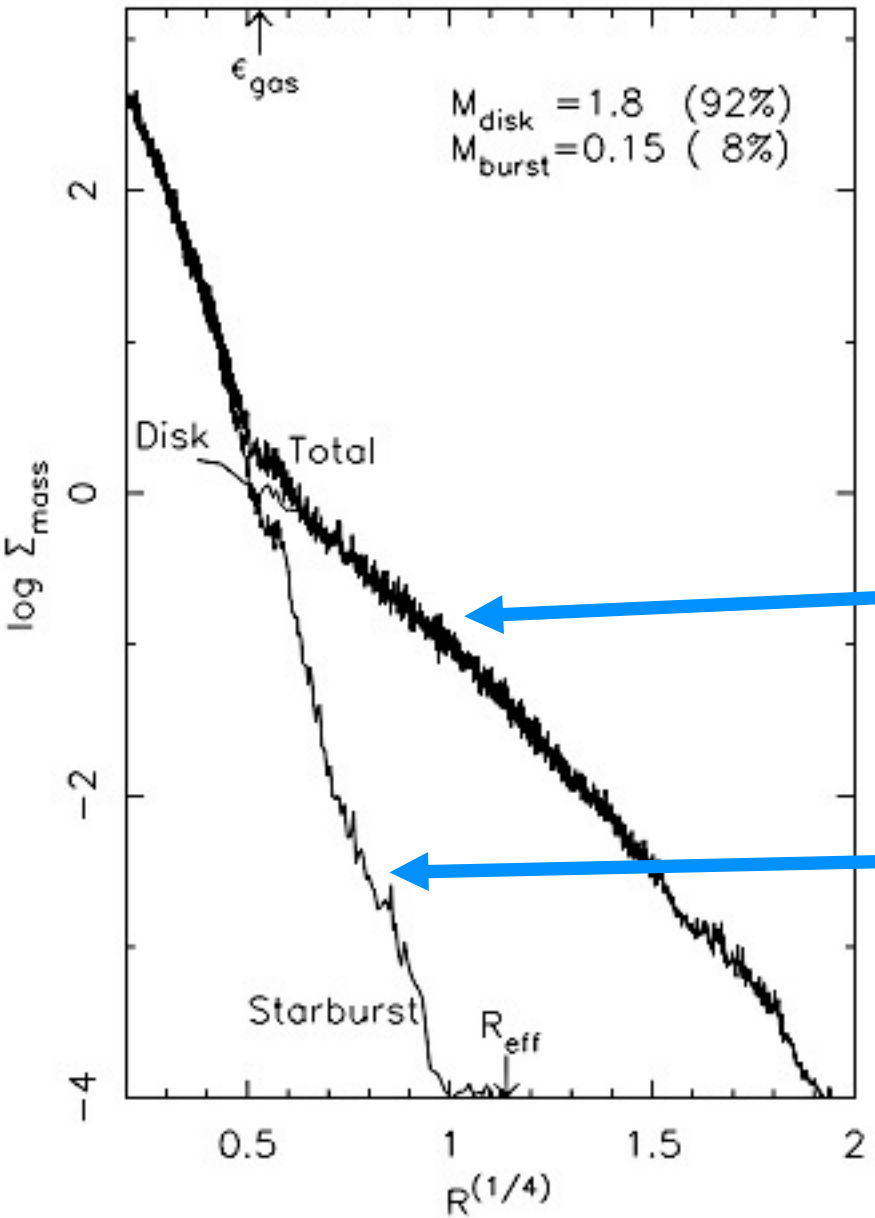


PFH, Bundy, et al. 2009

also Bezanso Naab et al.

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

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



Mihos & Hernquist 1994:

Merger remnant elliptical profiles should be fundamentally two-component:

Pre-starburst/Disk (dissipationless, violently relaxed)

Starburst (dissipational, no strong violent relaxation)

Not observed at the time:

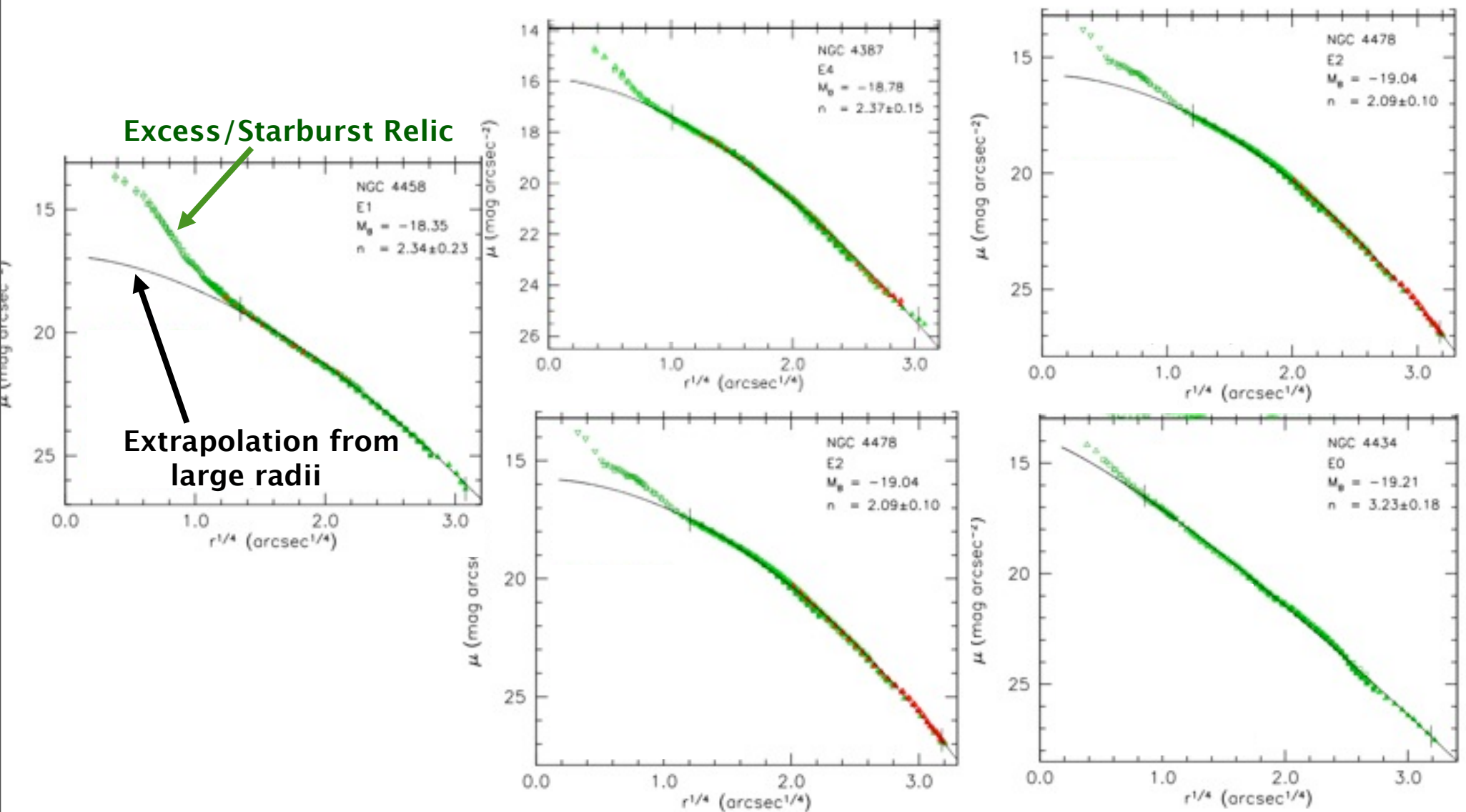
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

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

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...

Kormendy et al. 2008



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

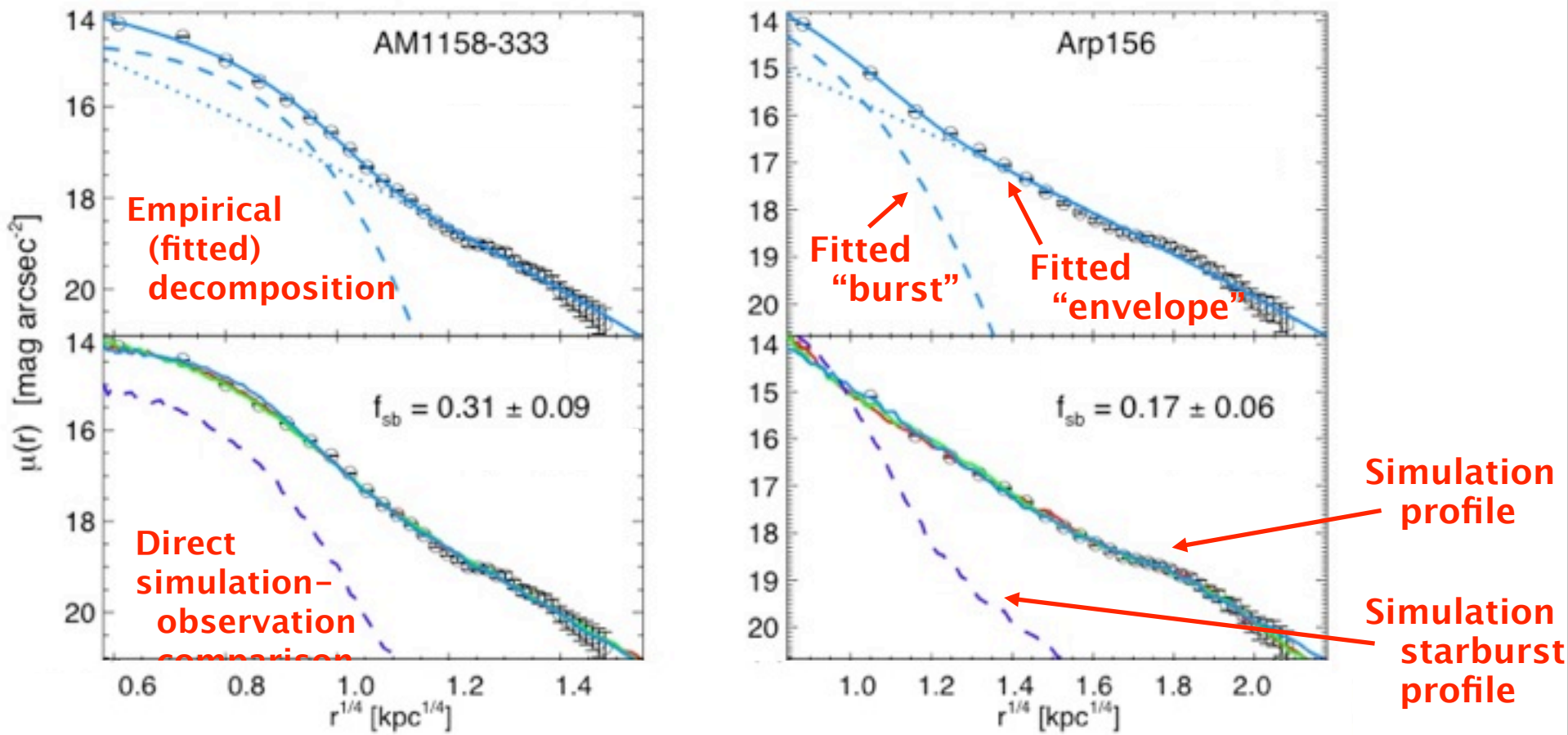
Application: Merger Remnants

RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

- Apply this to a well-studied sample of local merger remnants & ellipticals:



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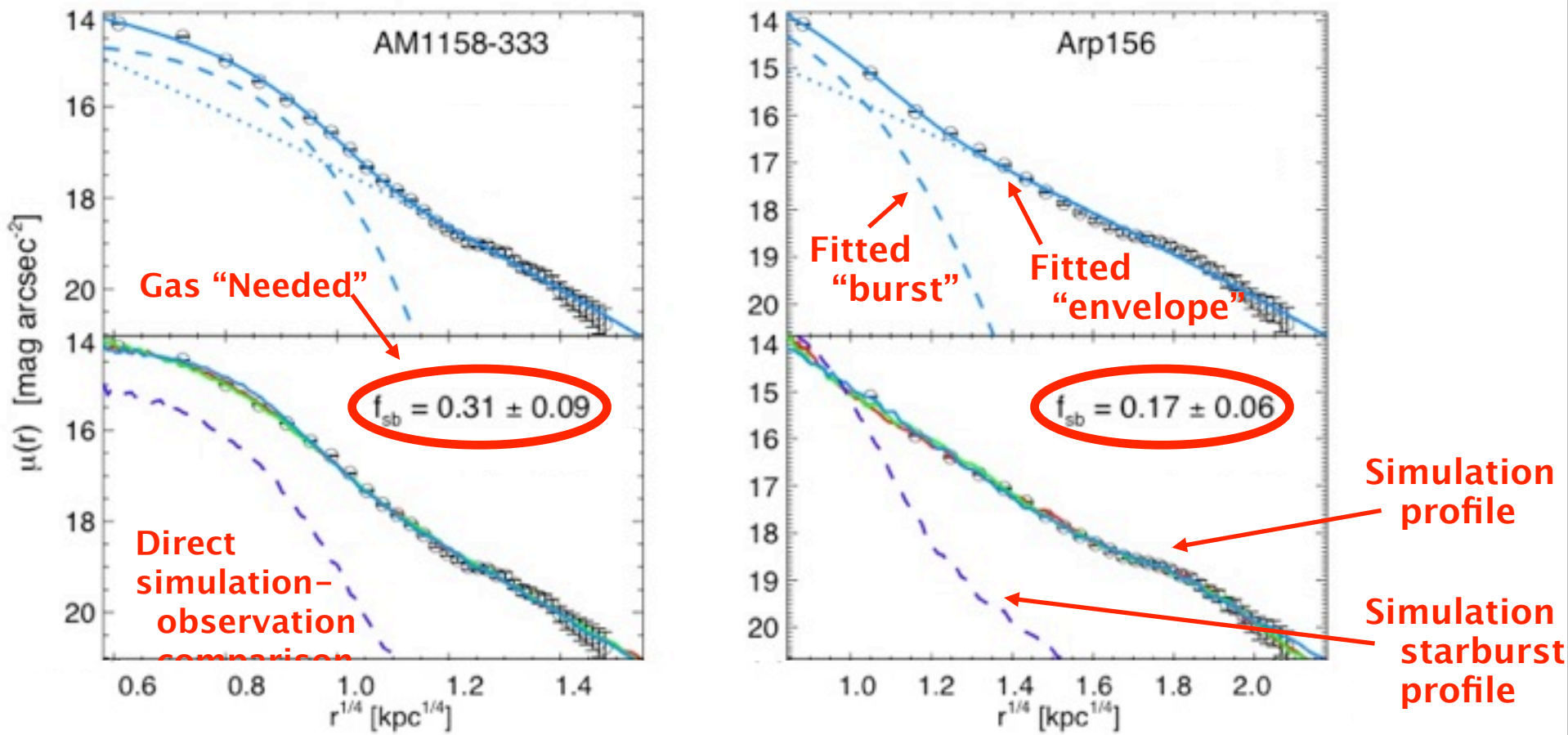

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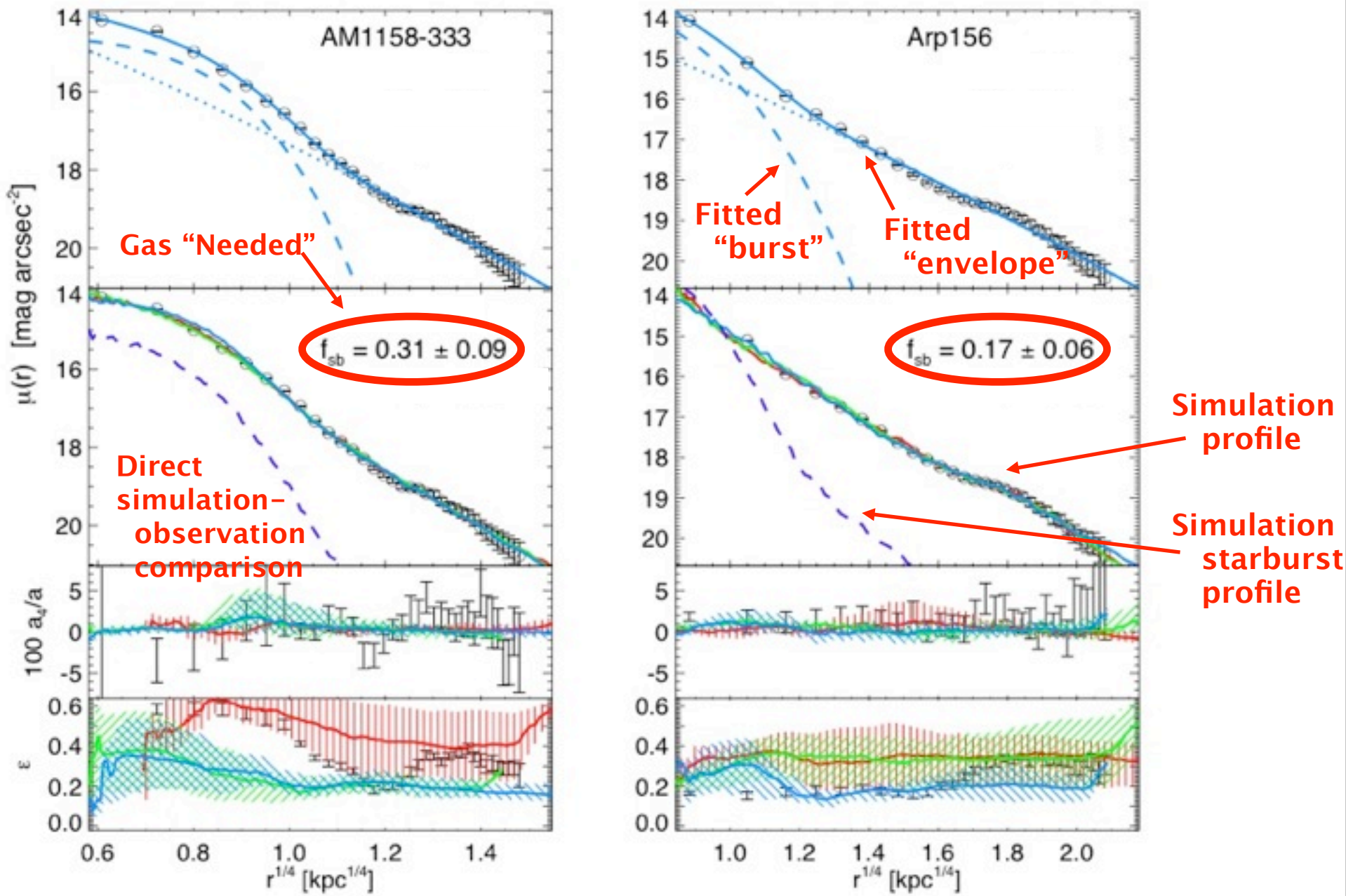


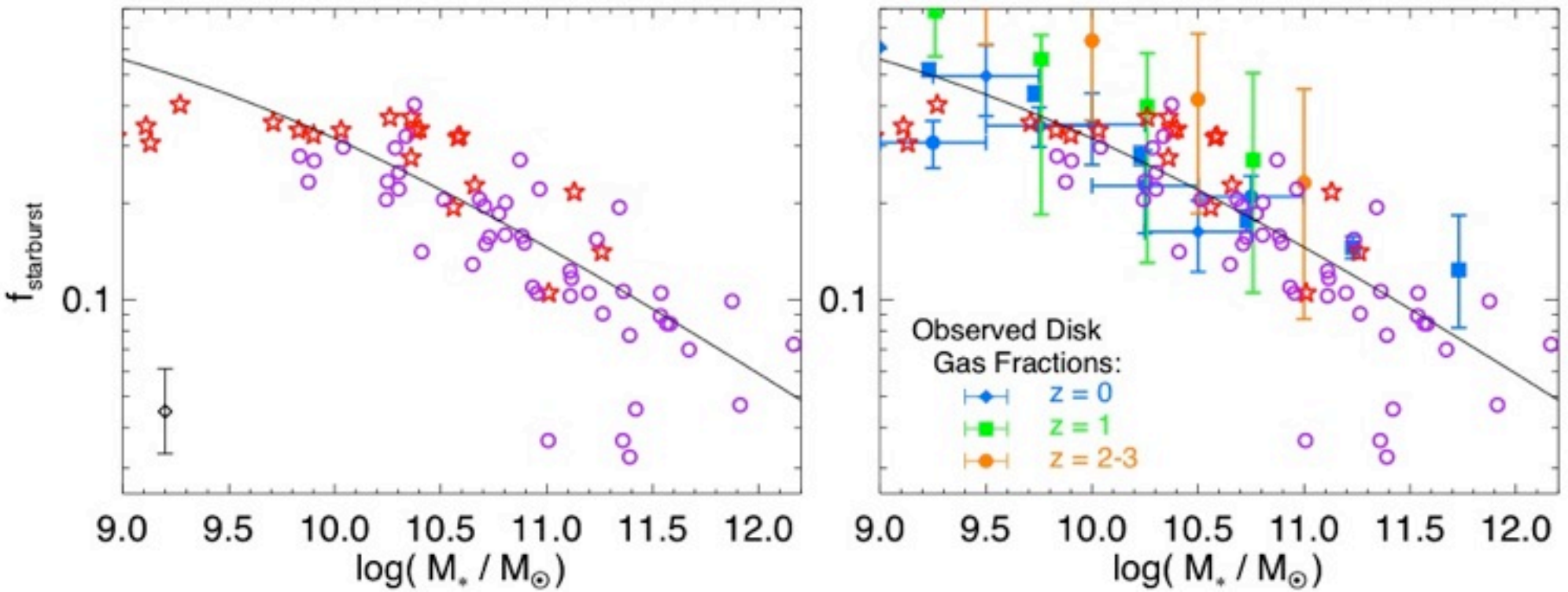
Structure in Elliptical Light Profiles

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):

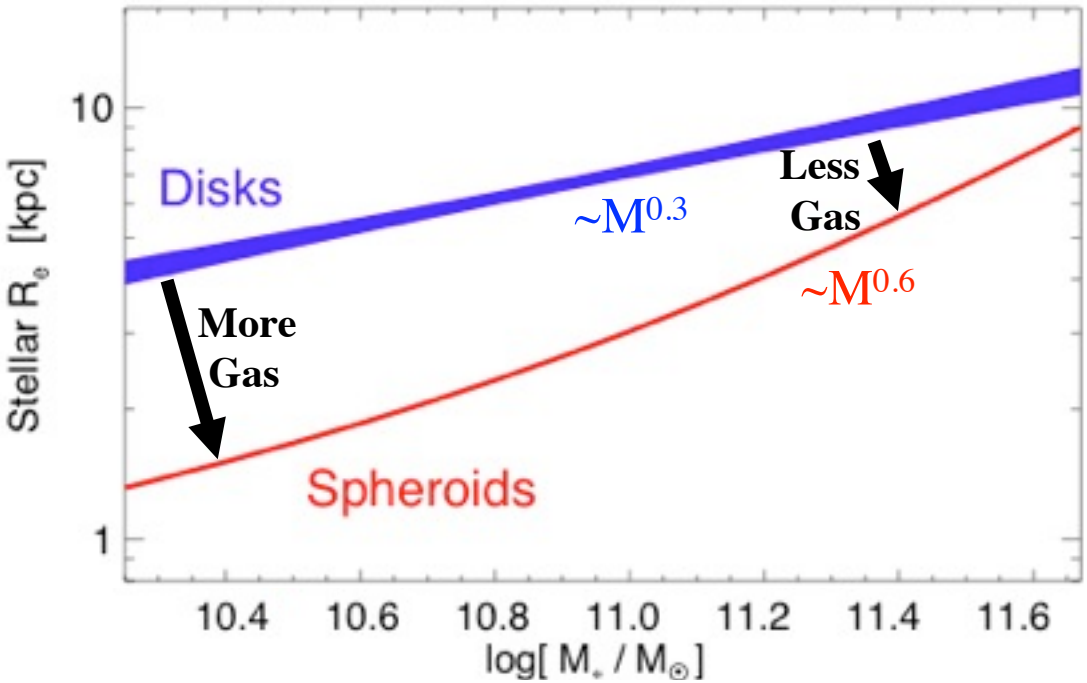


- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns

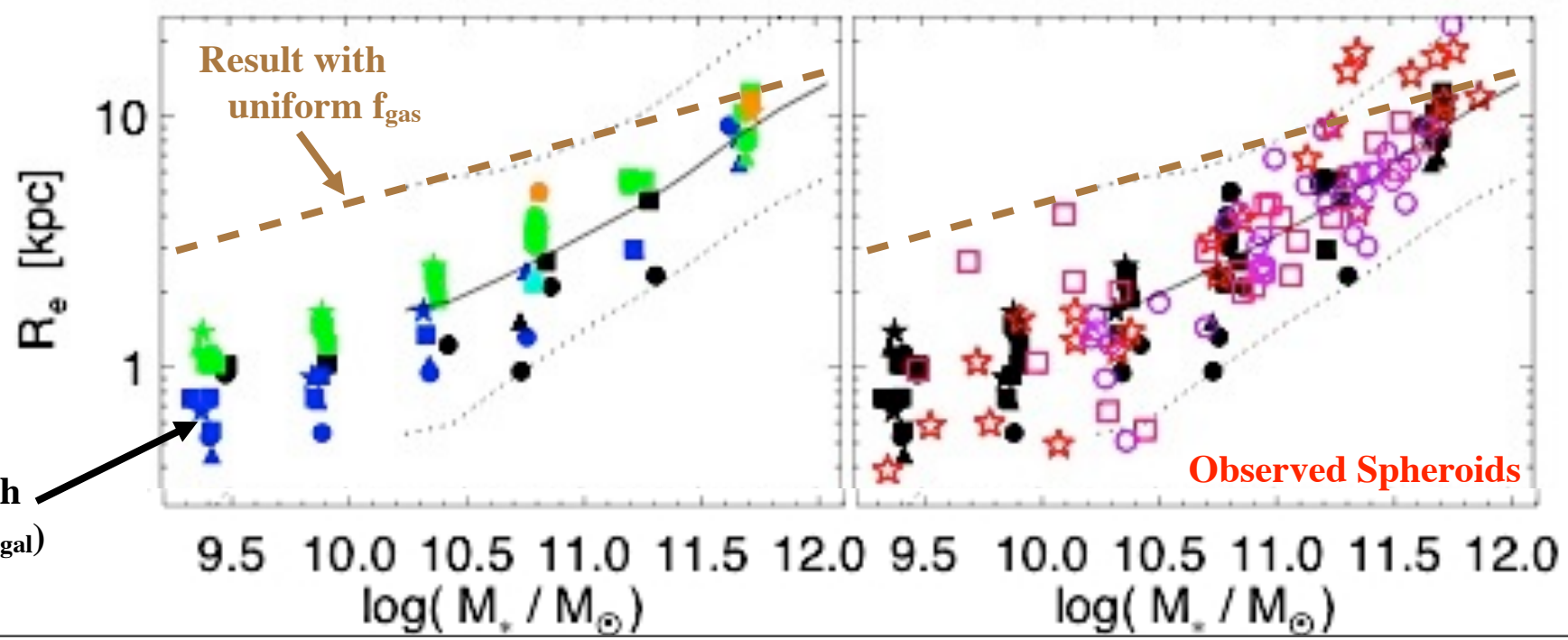
Structure in Elliptical Light Profiles

EXPLAINS THE "TILT" IN THE FP RELATIONS

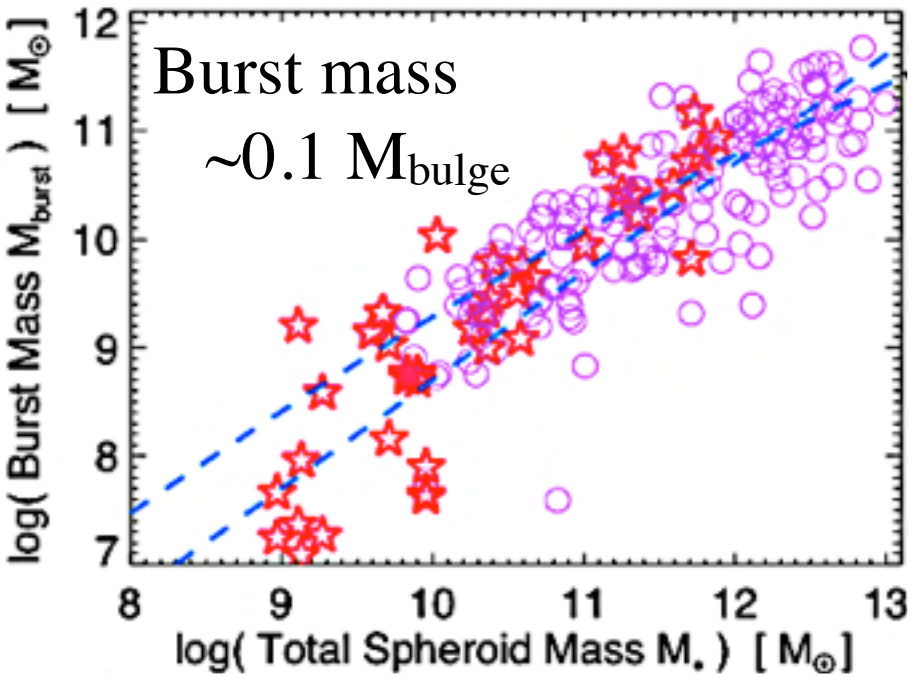
PFH, Cox, & Hernquist 2008



- Spheroid correlations "tilted" from disks because of f_{gas}-M_{gal} correlation



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



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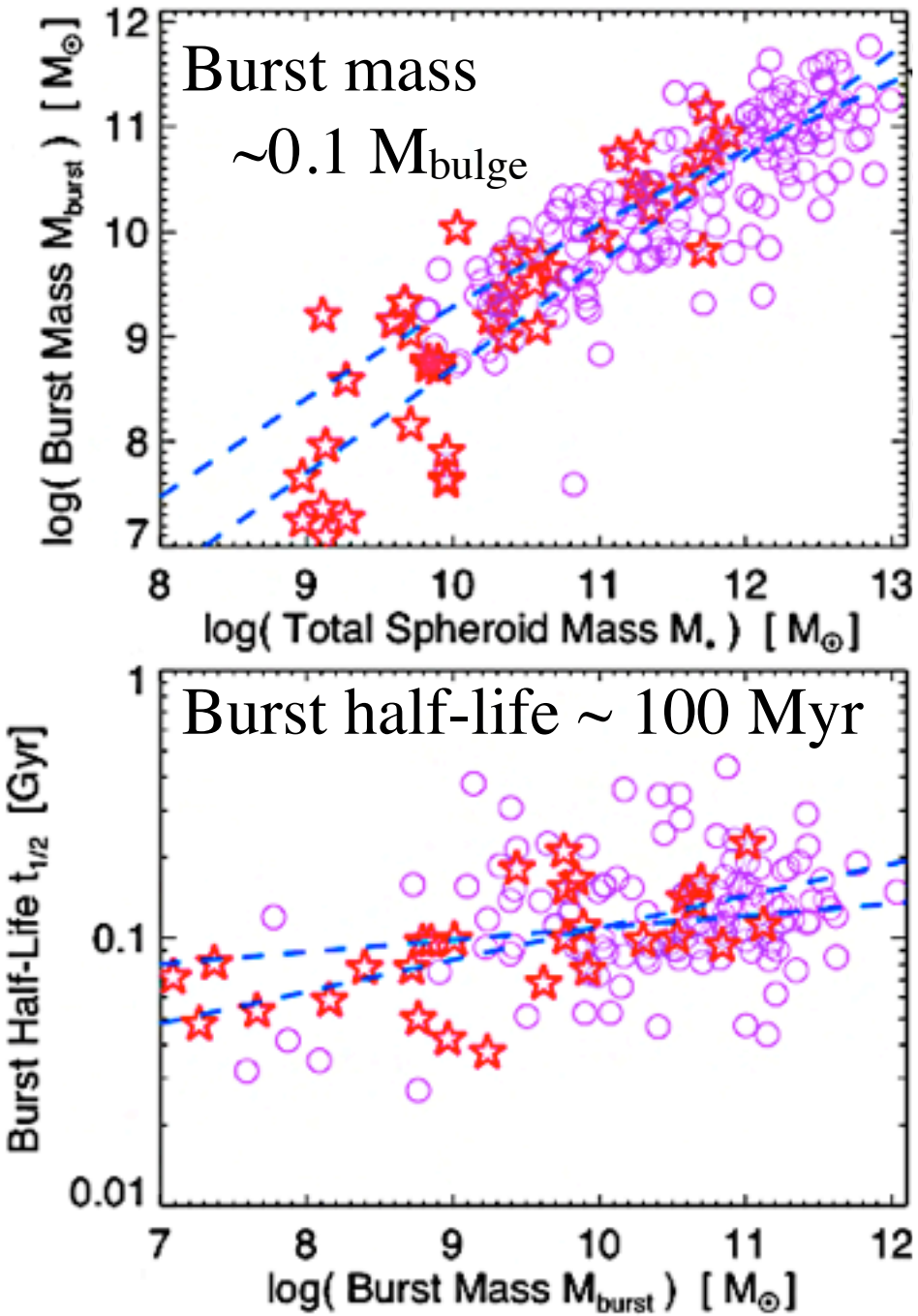

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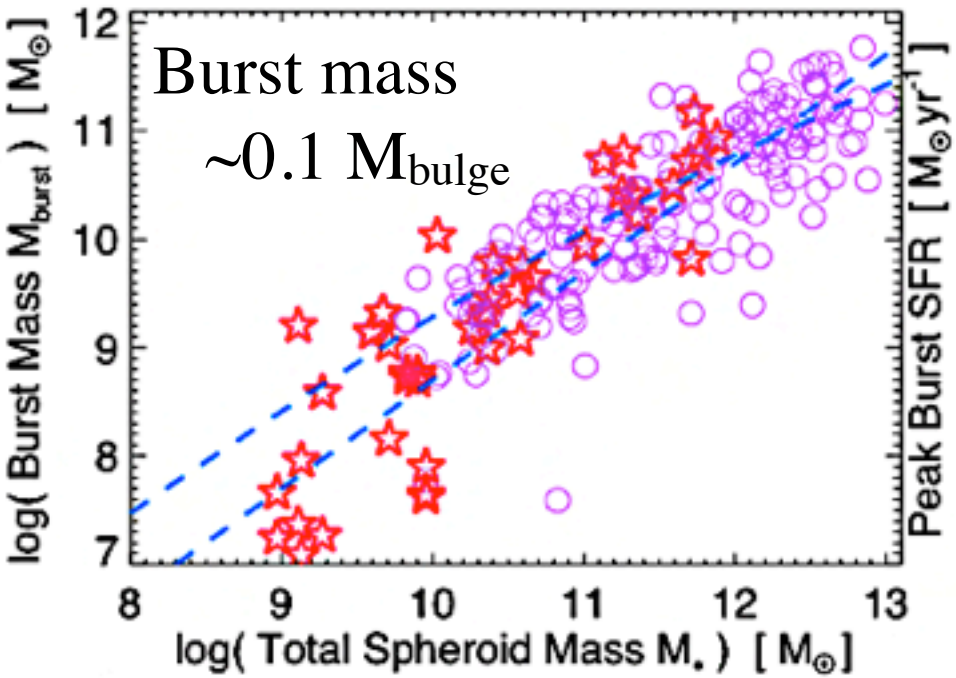

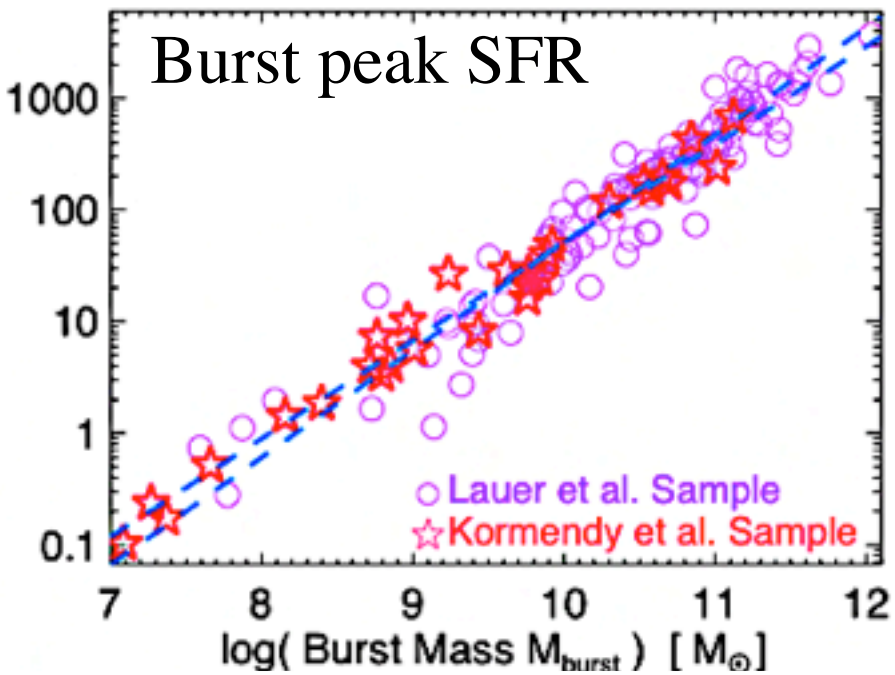

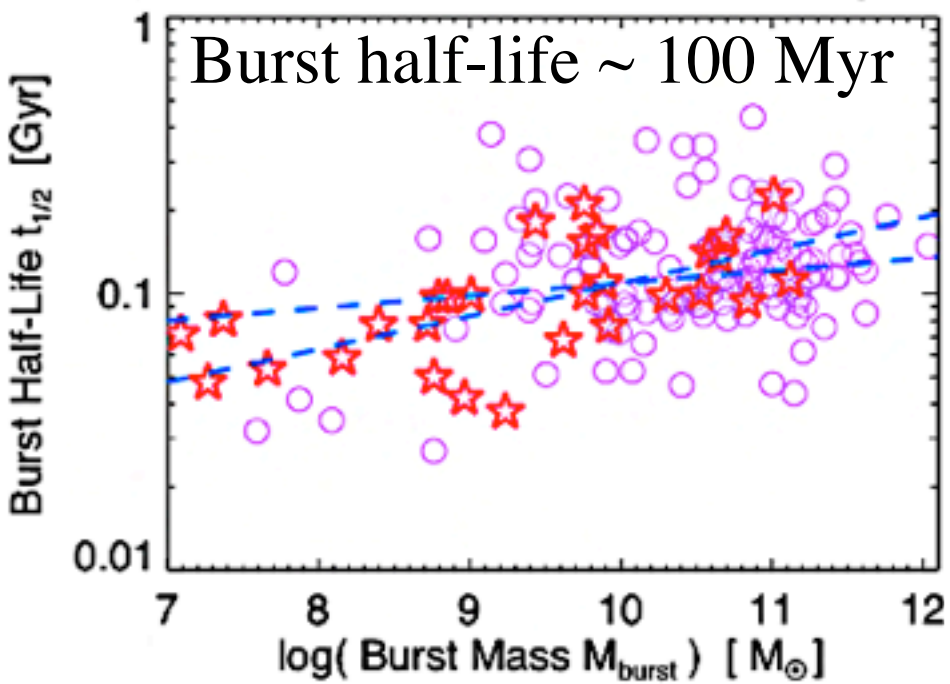

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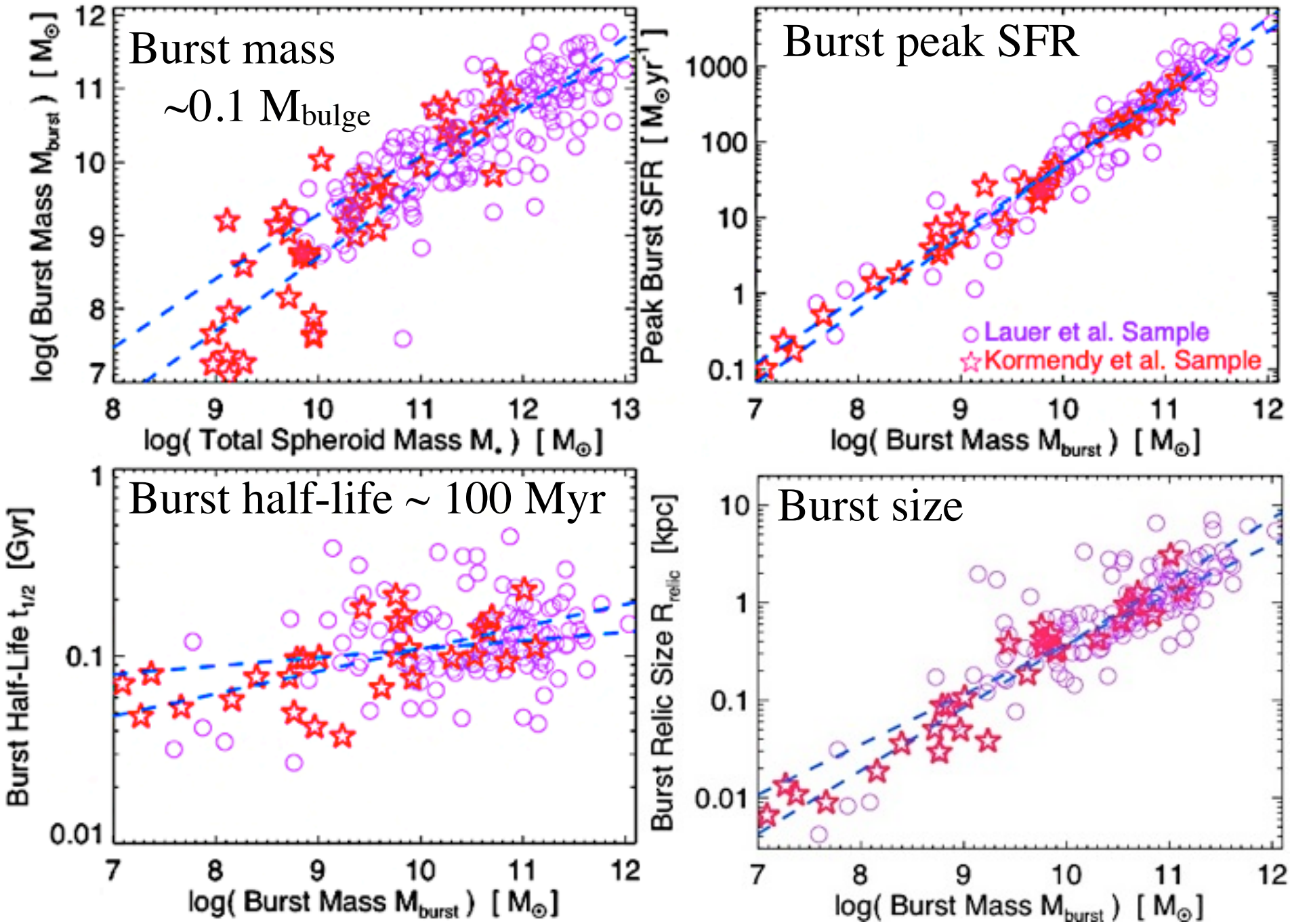

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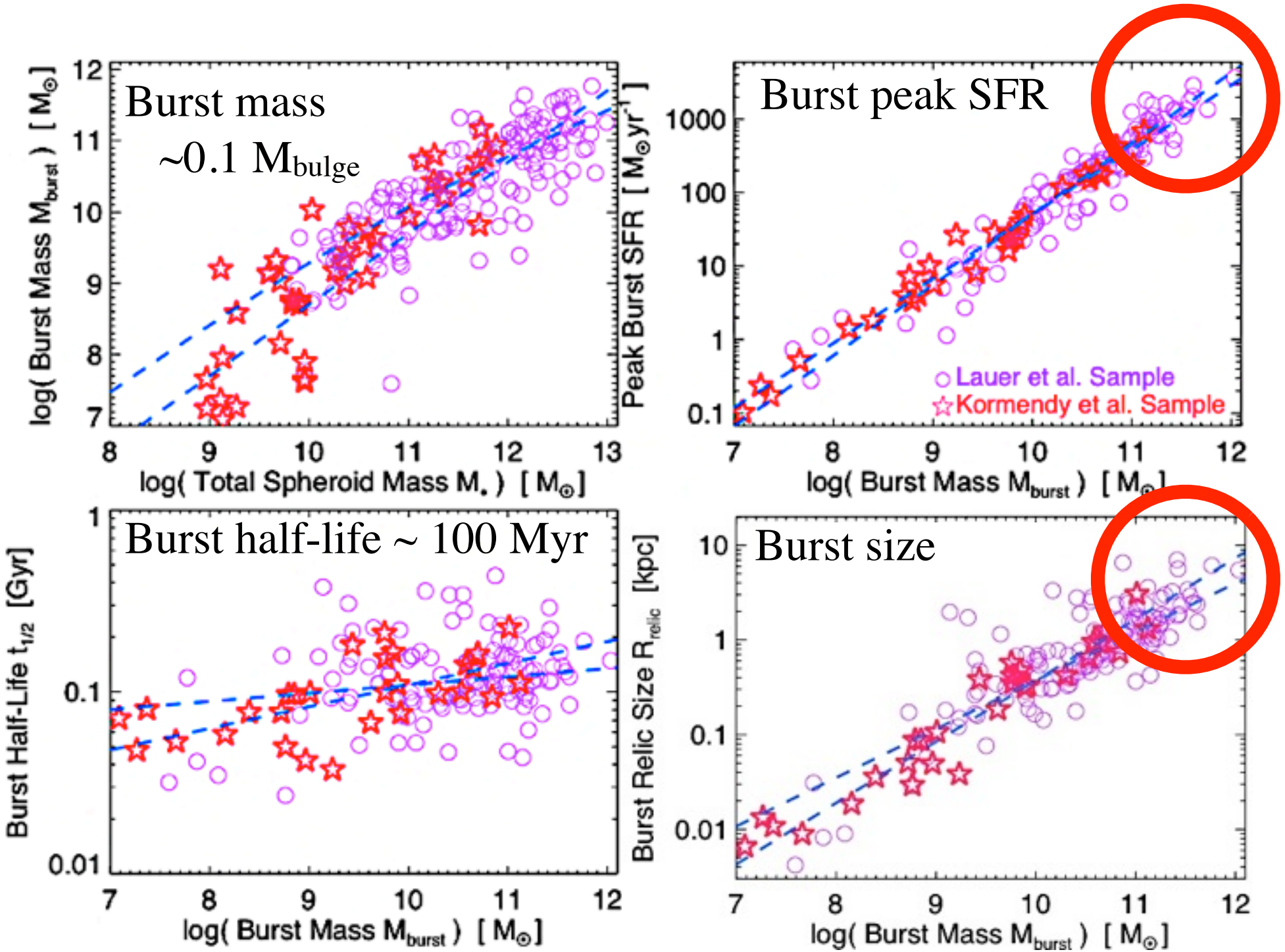
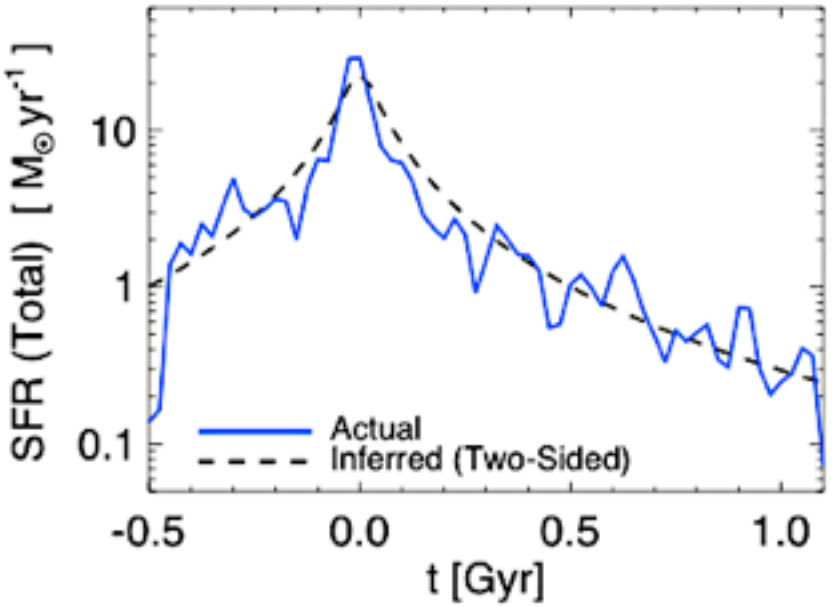
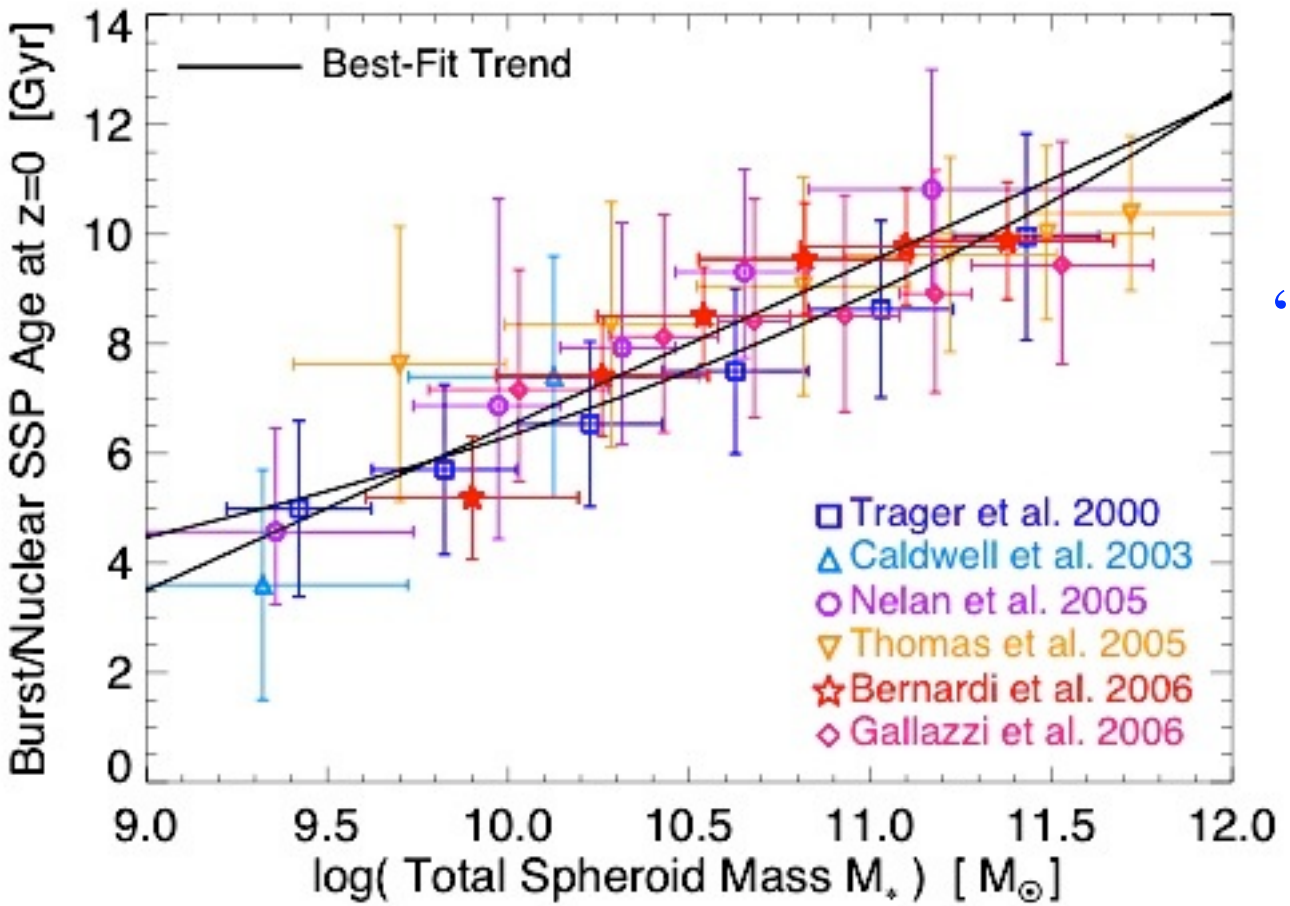


Re-construct SFR(t) for each burst :

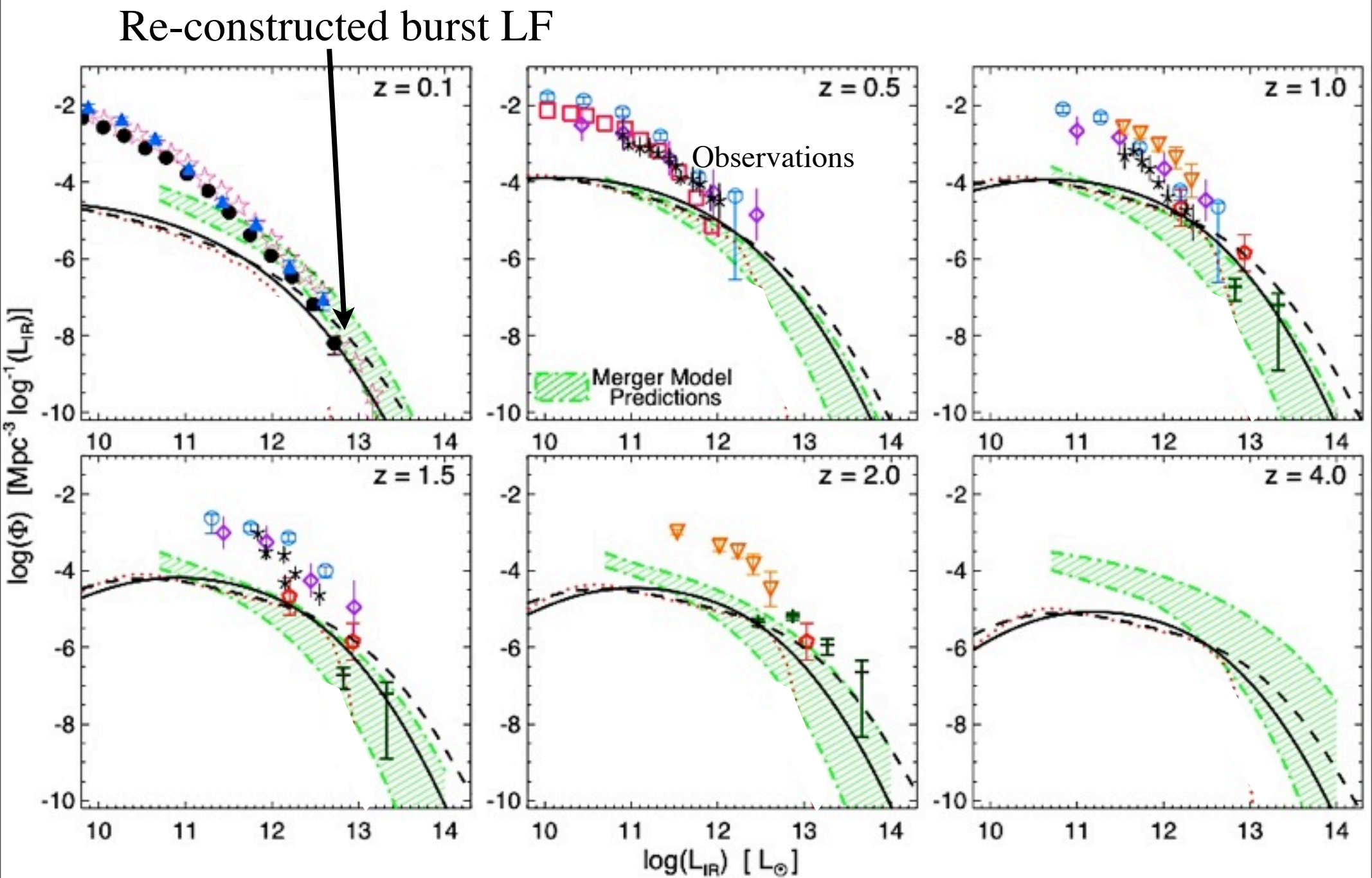


+ We know the nuclear SSP ages....

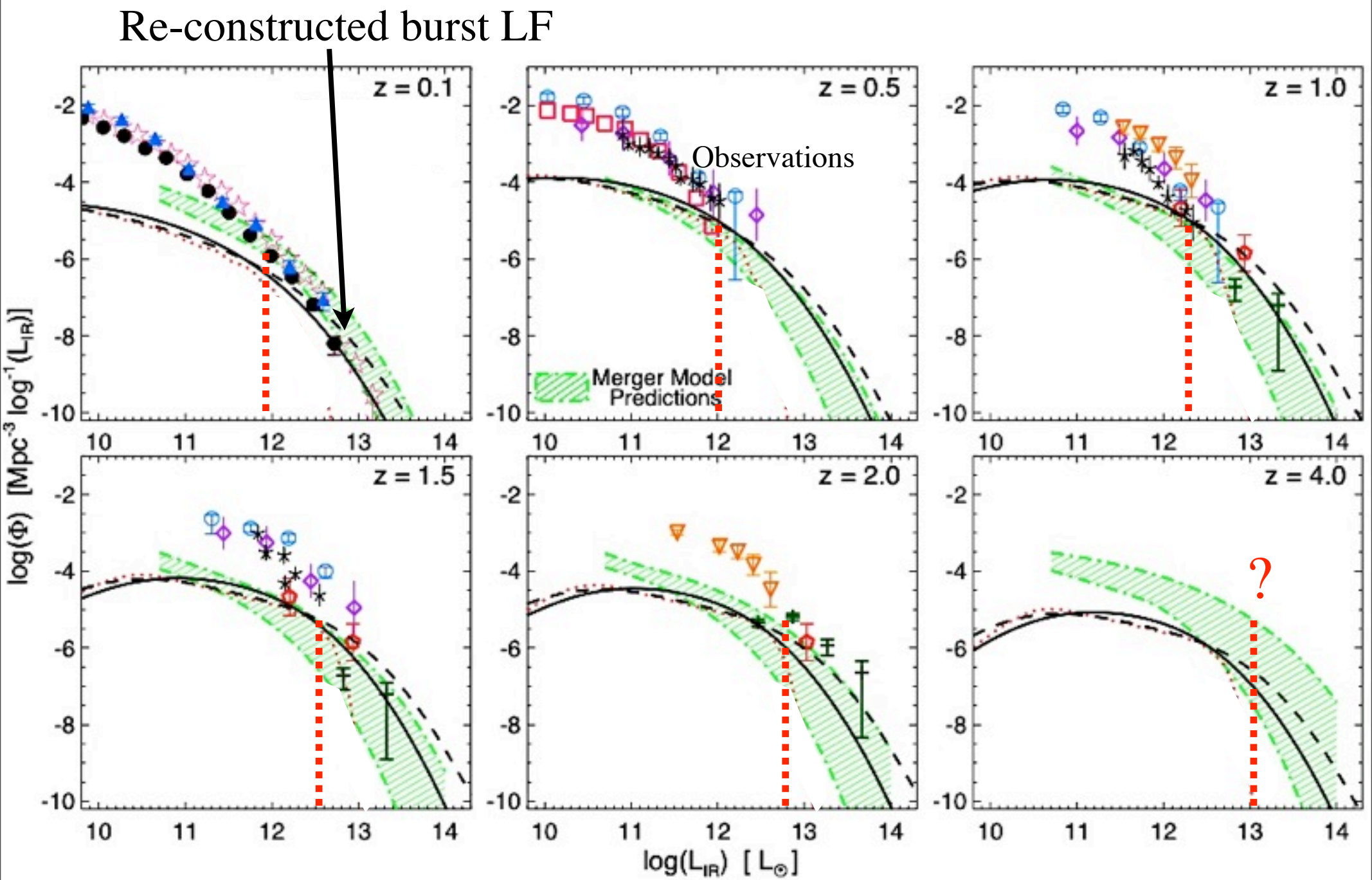


"place" each burst at the correct redshift

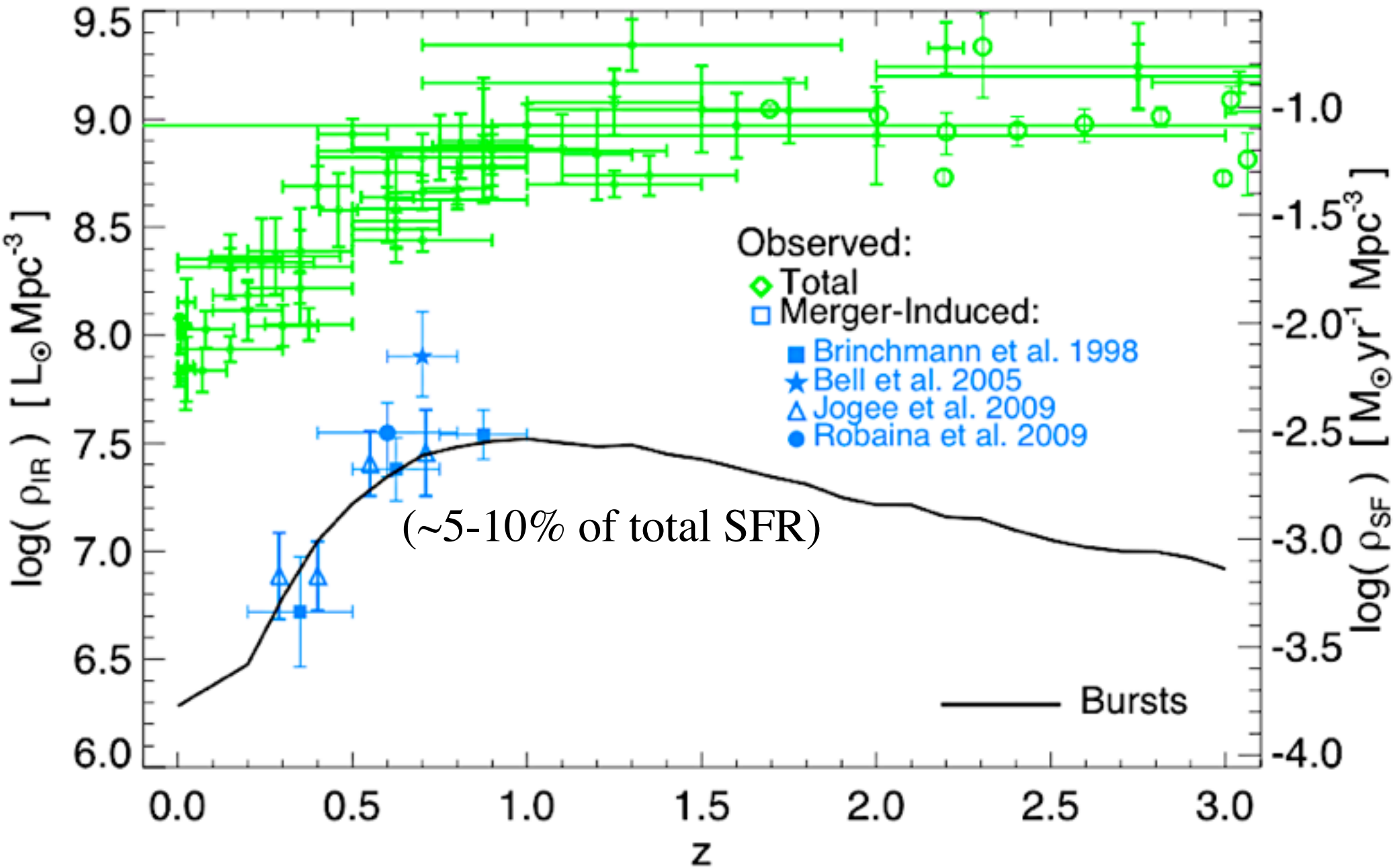
Recover the IR LF of dissipational starbursts!



Bursts always dominate at high L, but the threshold shifts

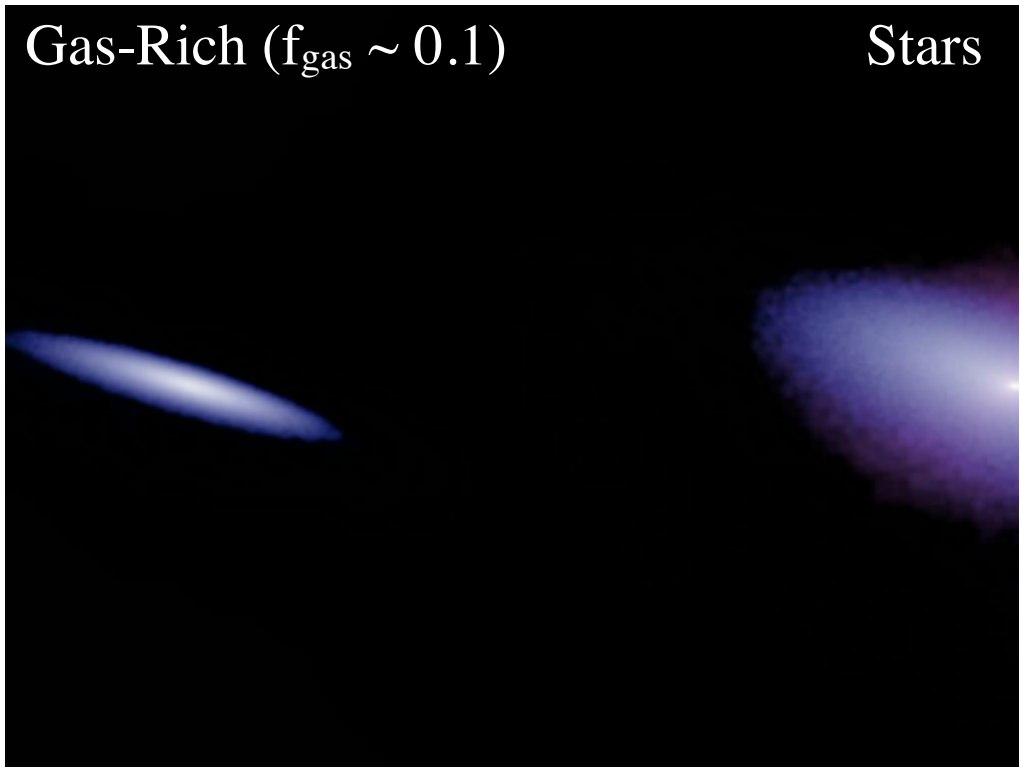


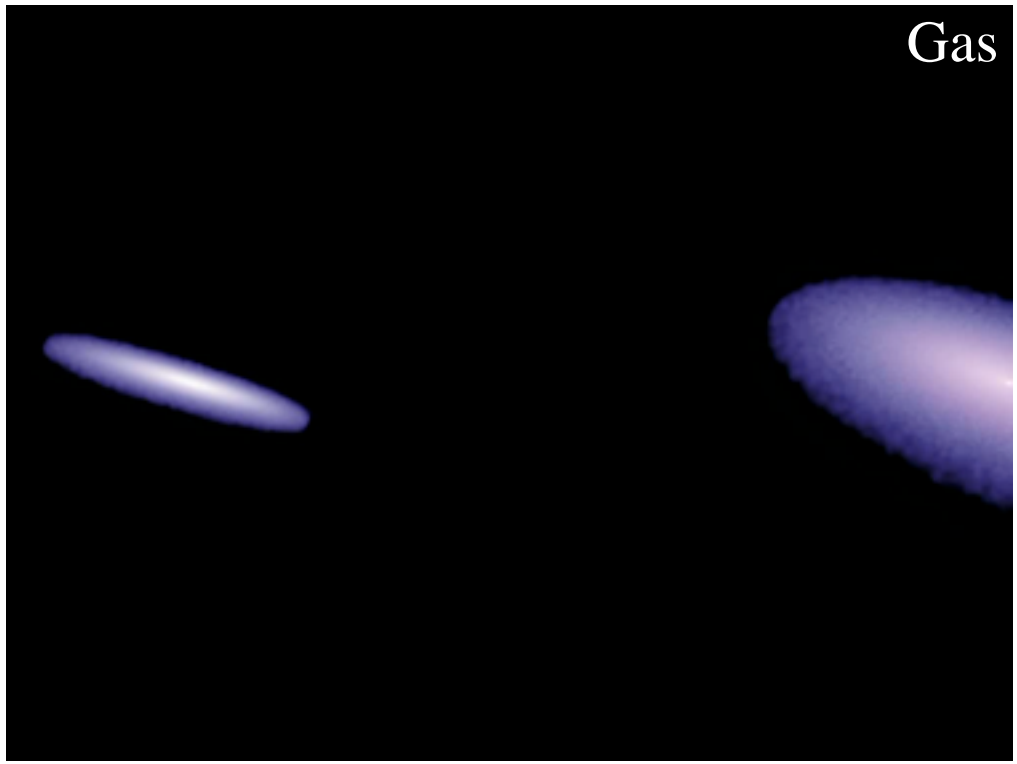
Bursts *never* dominate the SFR density!



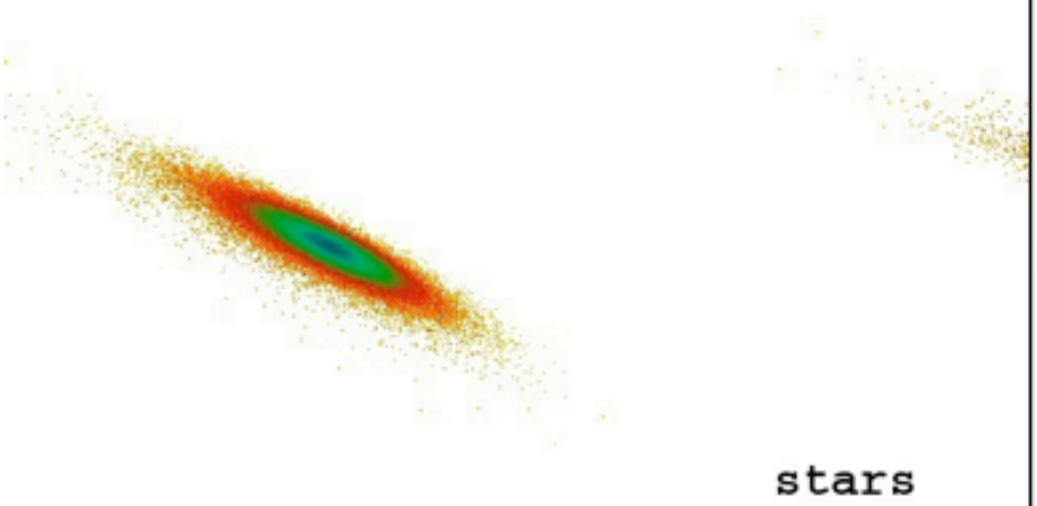
Why Is There Not Much More Efficient Gas Consumption at High Redshifts?

How Good Is Our Conventional Wisdom?



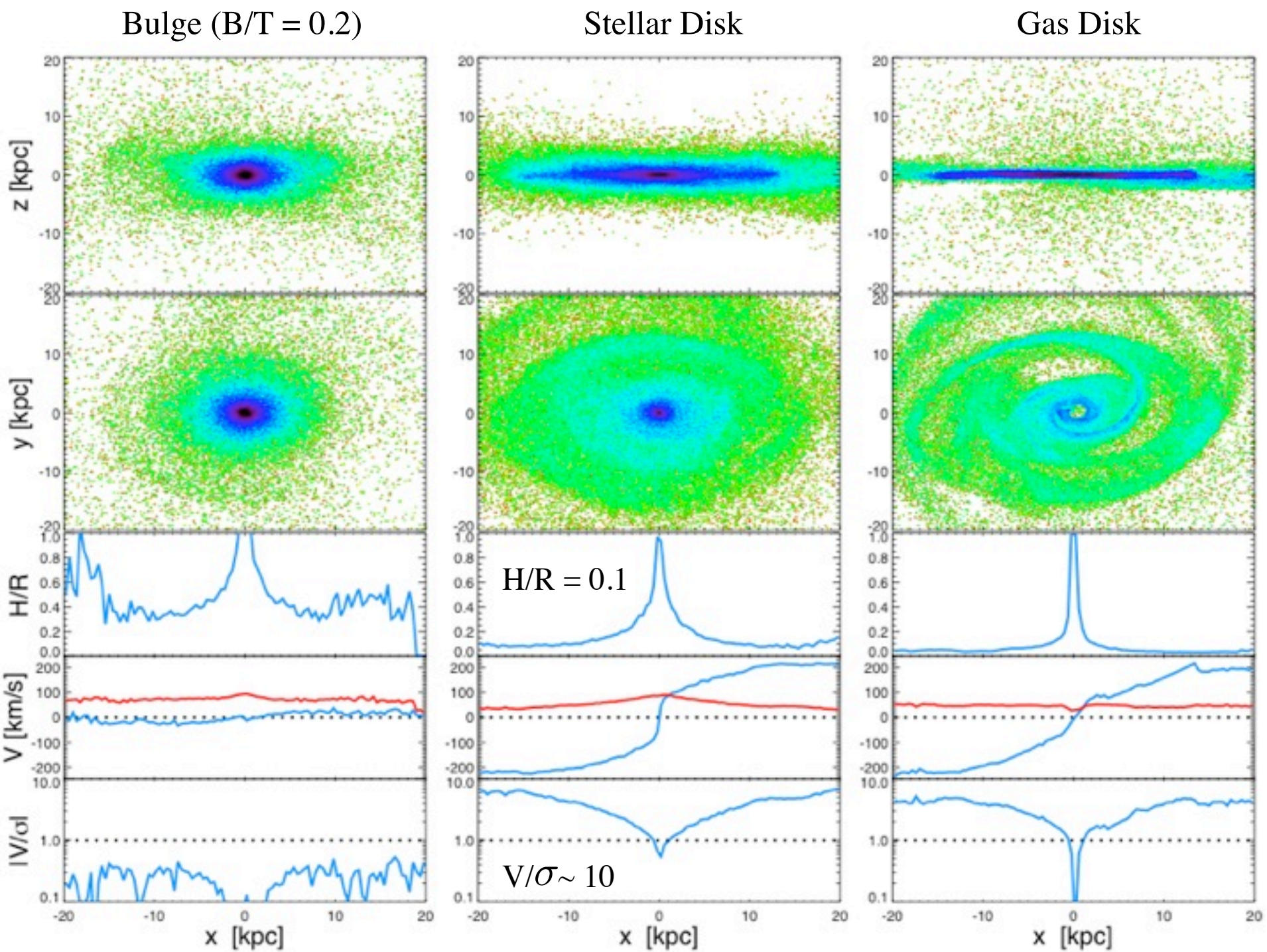


Gas-Richer ($f_{gas} \sim 0.4$)



Major Merger Remnants

DO MERGERS DESTROY DISKS?



The Unsolved Questions

HOW CAN A DISK SURVIVE?

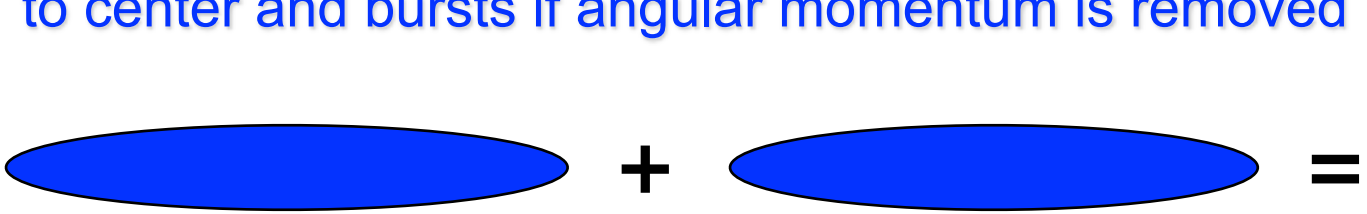
- Stellar disks are collisionless: they violently relax when they collide

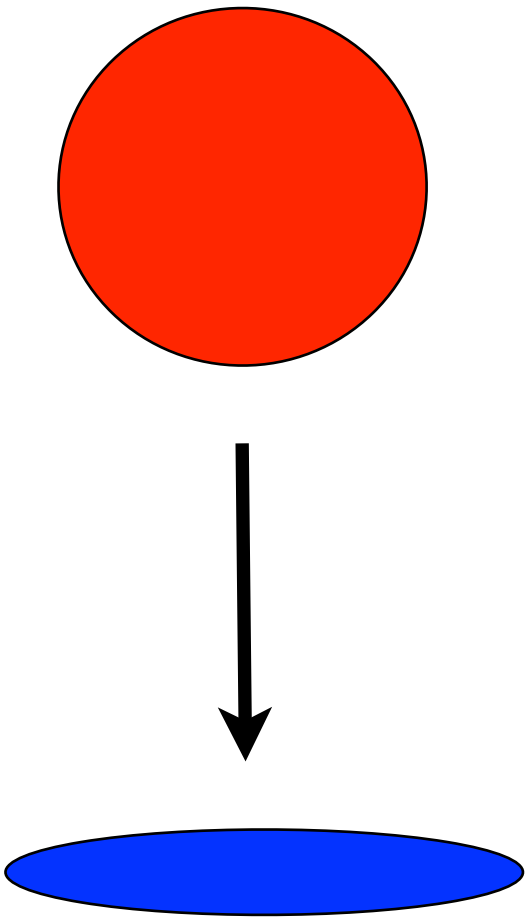
- Can’t “cool” into a new disk

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

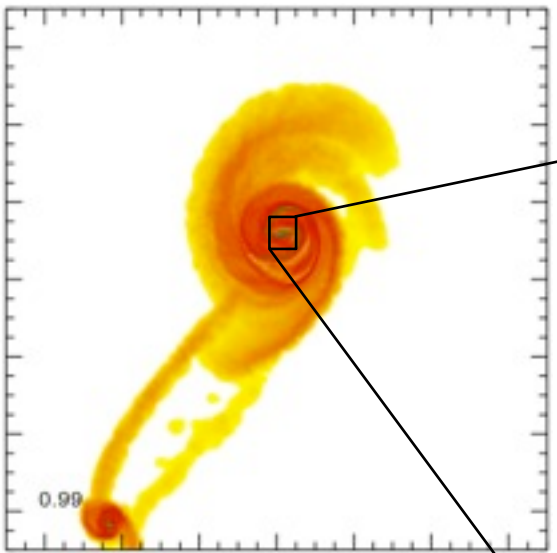


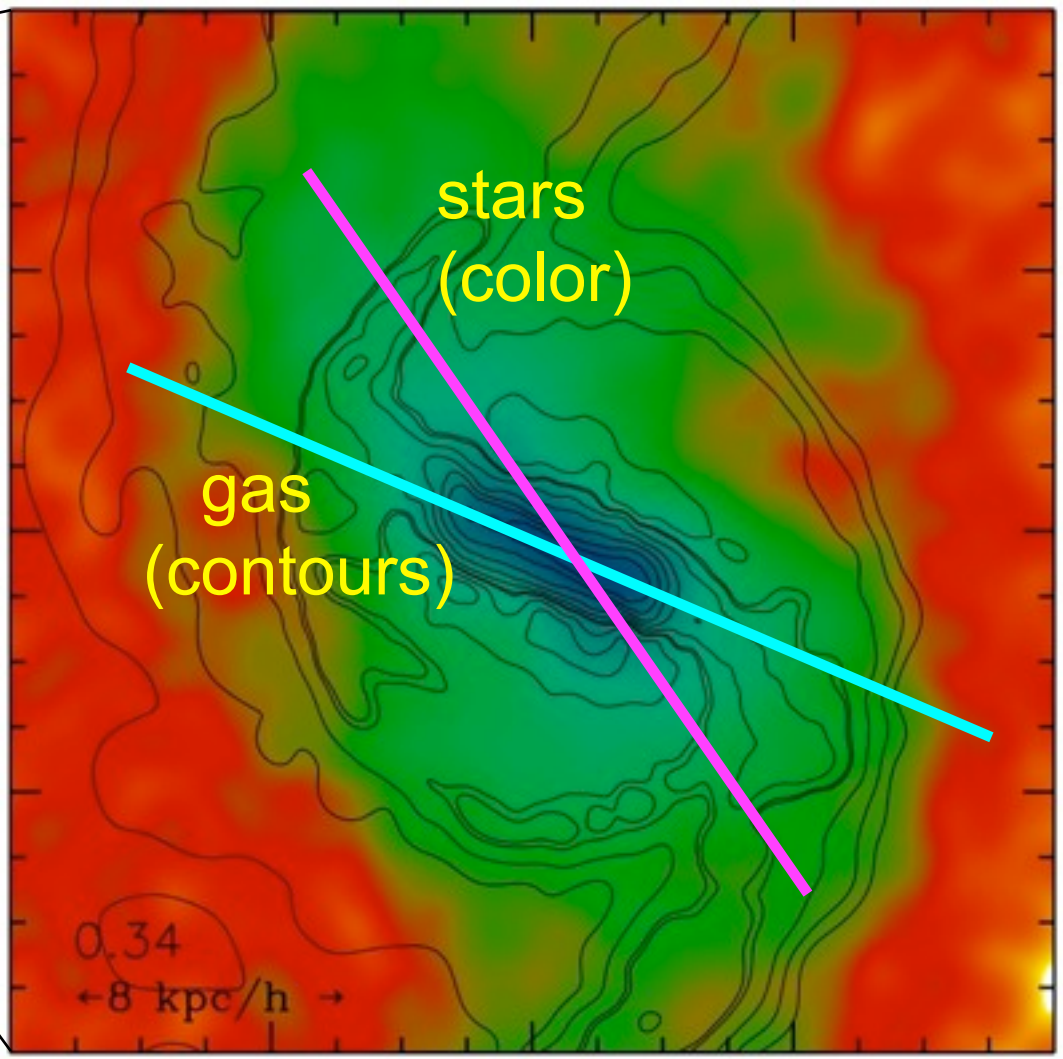


How Do Disks Survive Mergers?

PFH et al. 2008

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

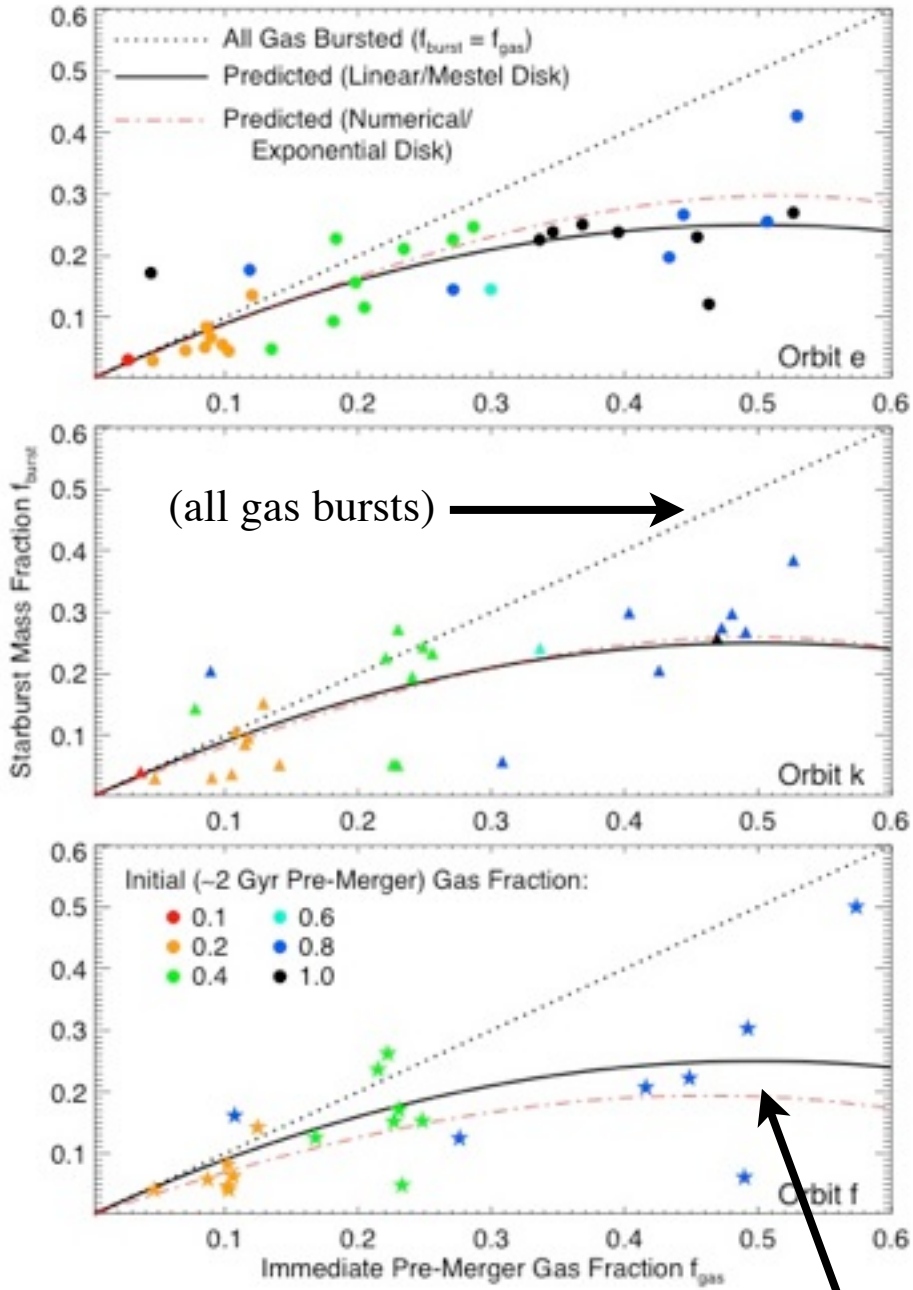




- What does the torquing?
  - *Stars* in the same galaxy

How Do Disks Survive Mergers?

Burst mass vs. f_{gas}



Torque on gas:

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

For the same merger/perturbation:

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

(gas-dependent prediction)

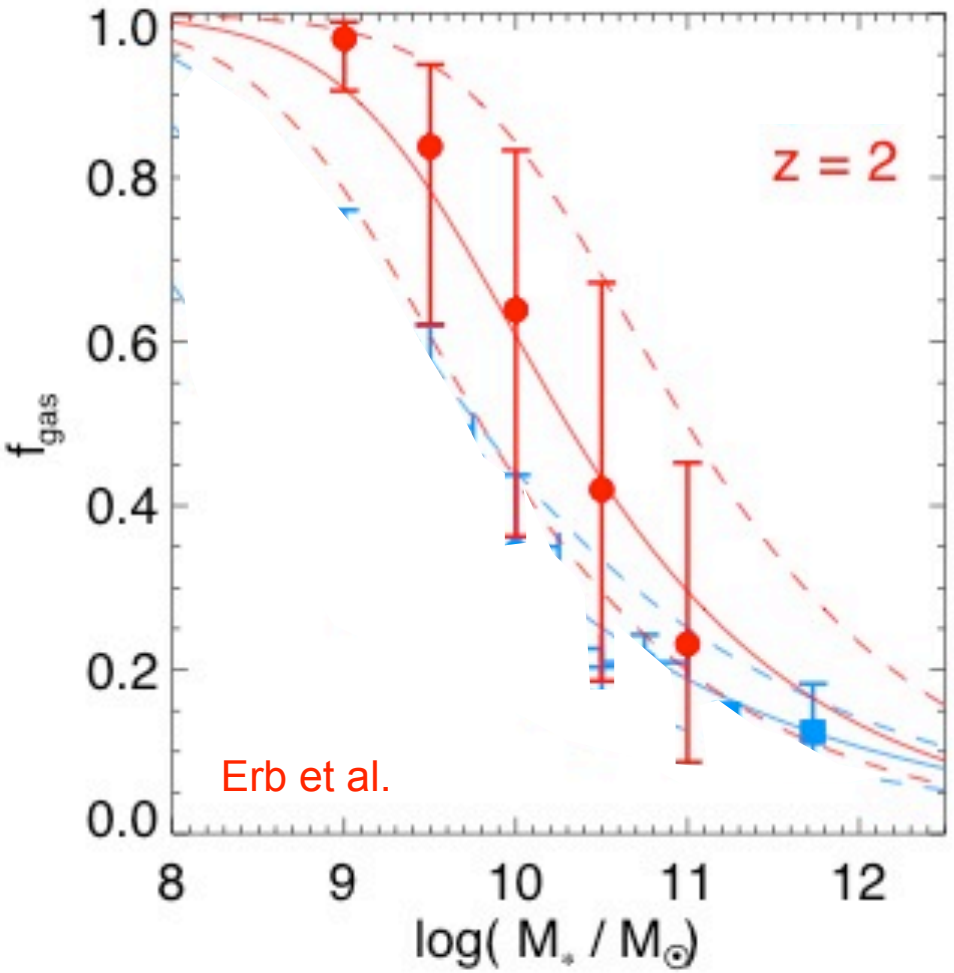
PFH et al. 2008 ("How Do Disks Survive Mergers?")

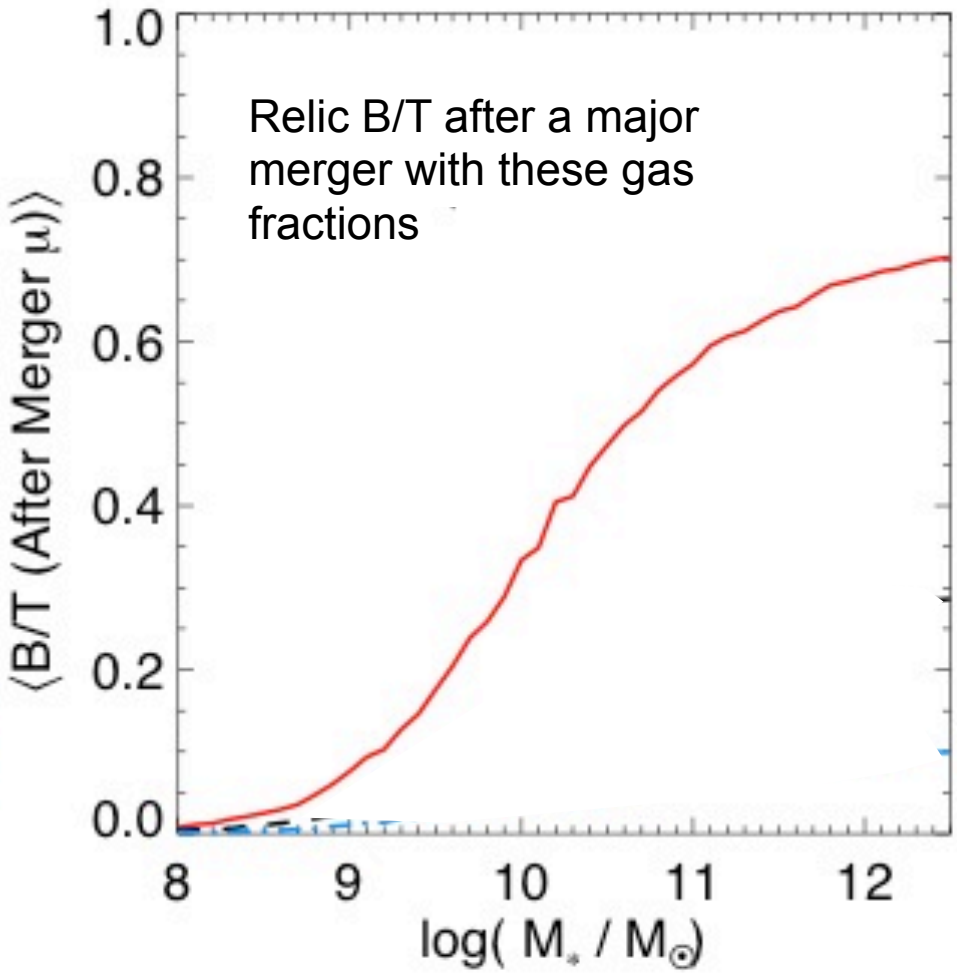
Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 200

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

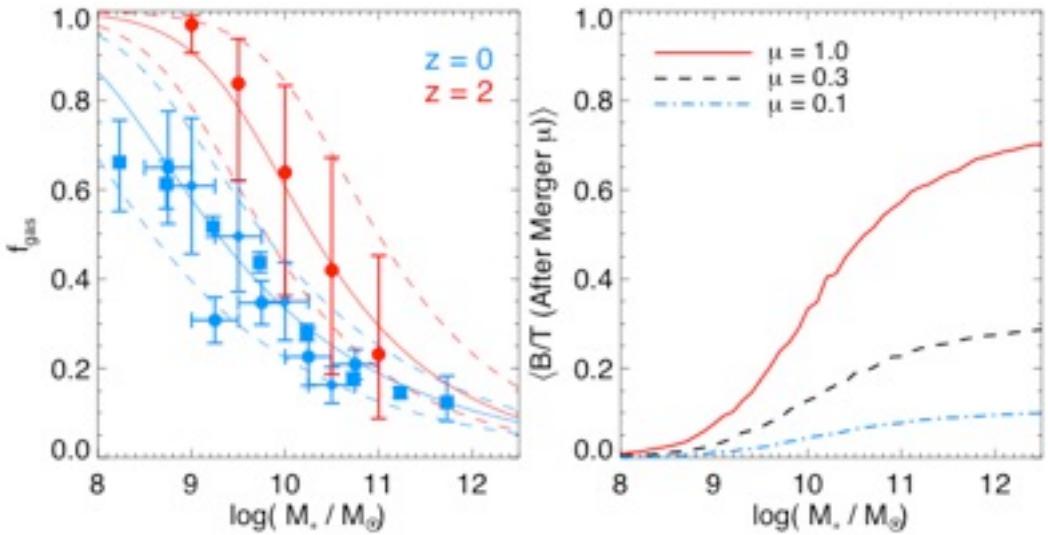




- Low-mass galaxies have high gas fractions: less B/T for the same mergers

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



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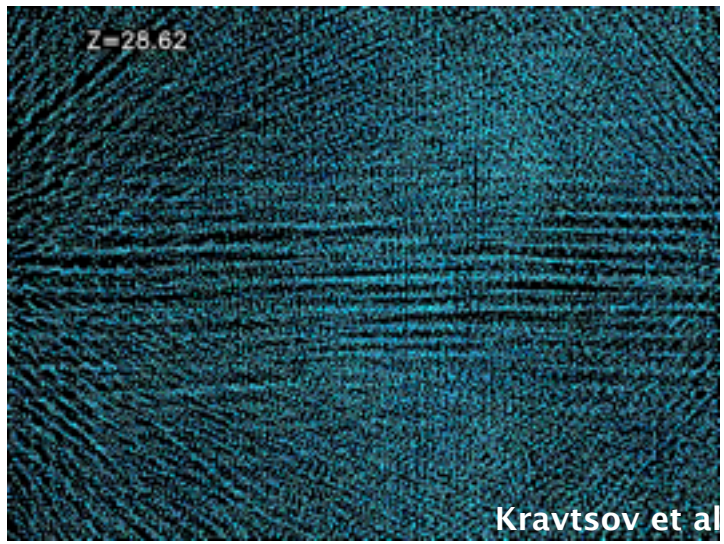

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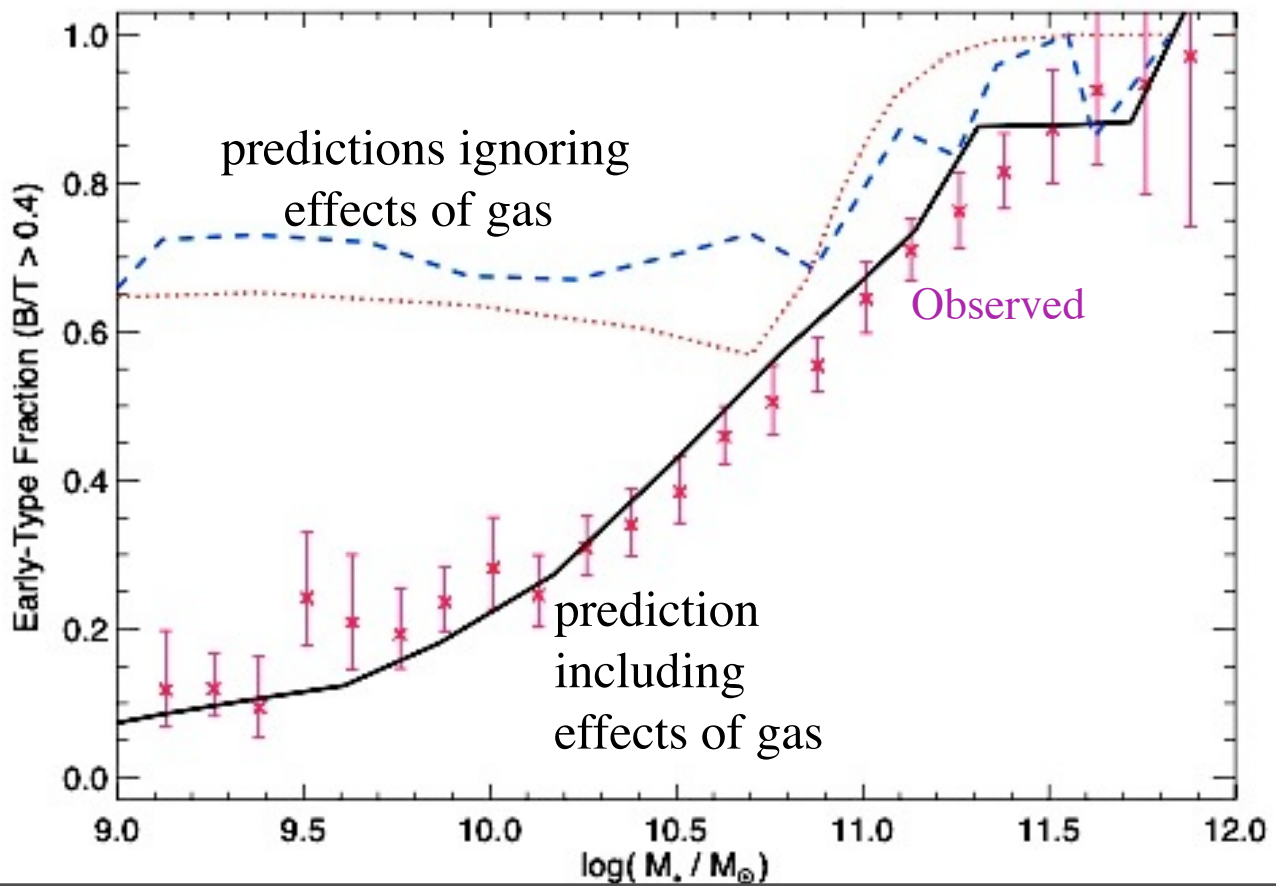
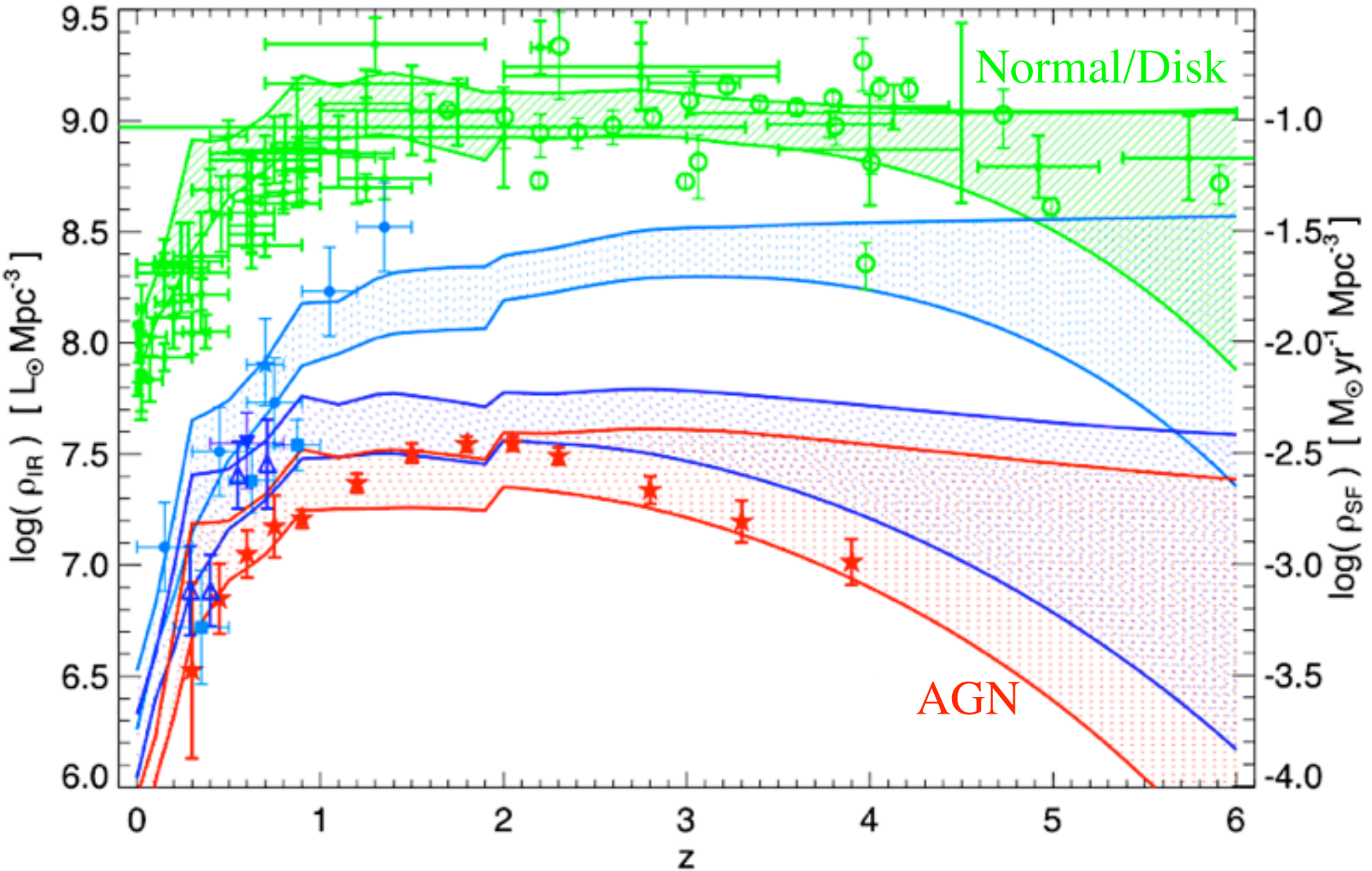


PFH & Somerville et al. 2009

Have burst predictions -- why not use them?

PFH, Younger et al. 20

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



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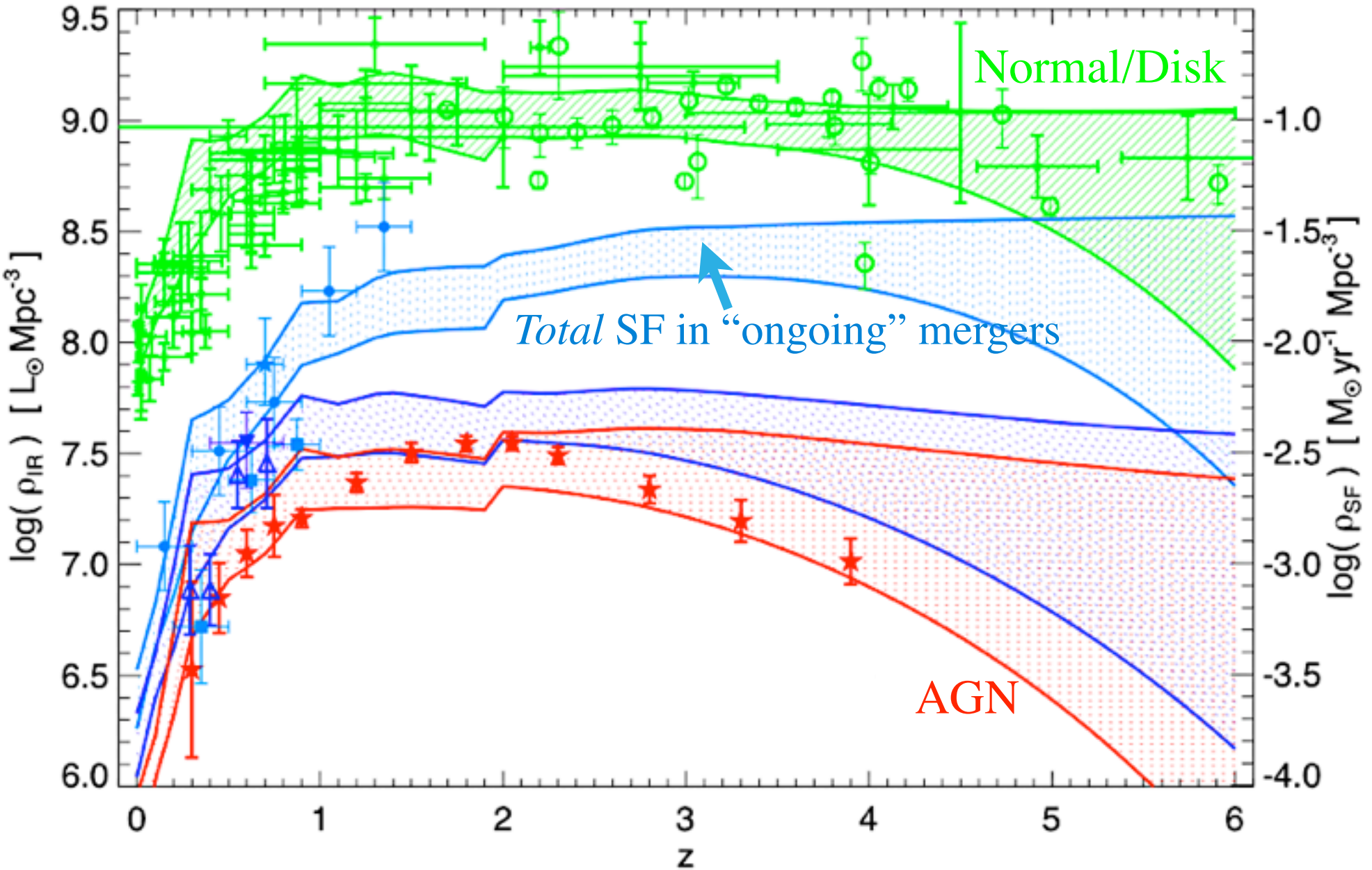

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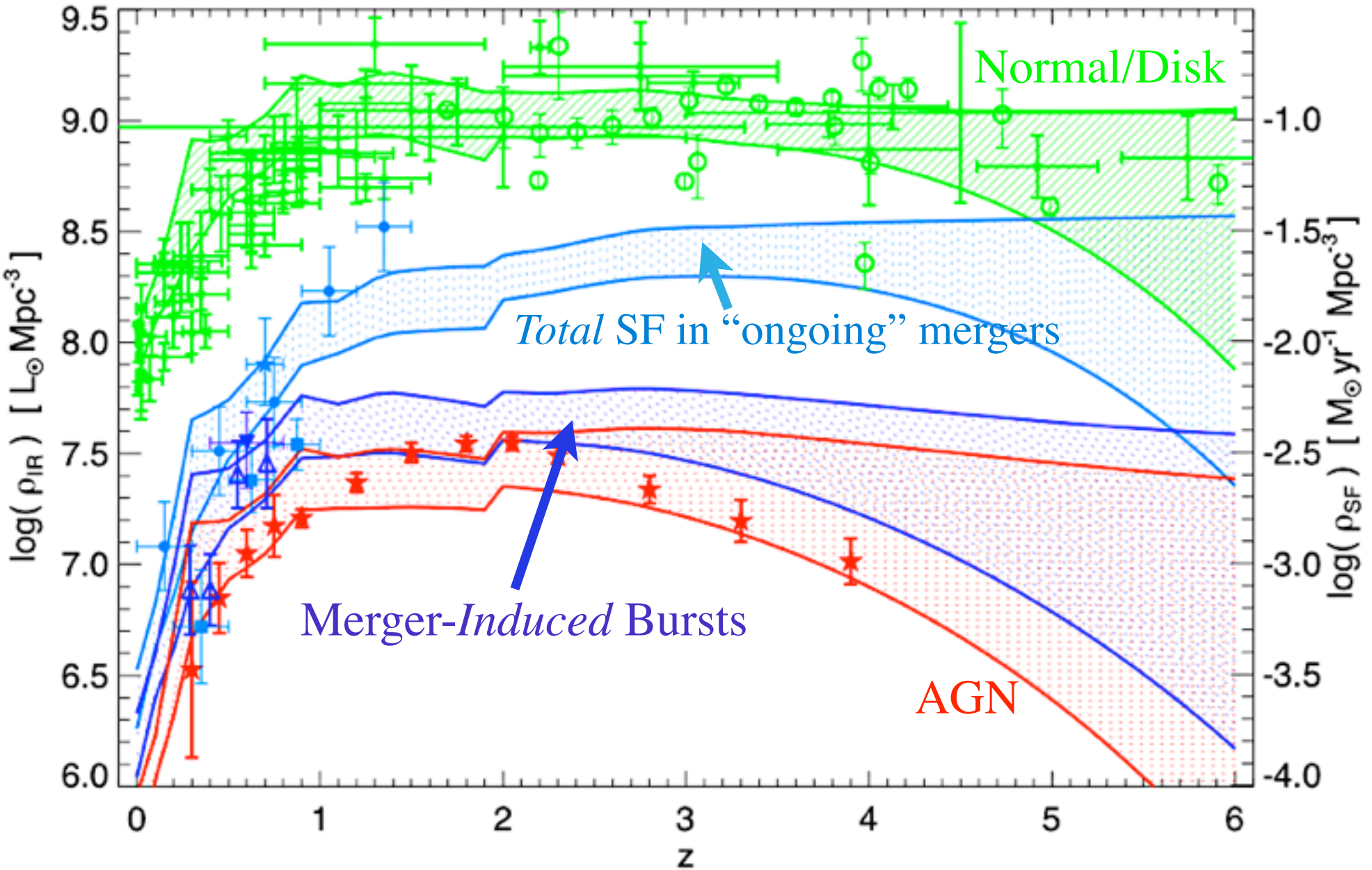
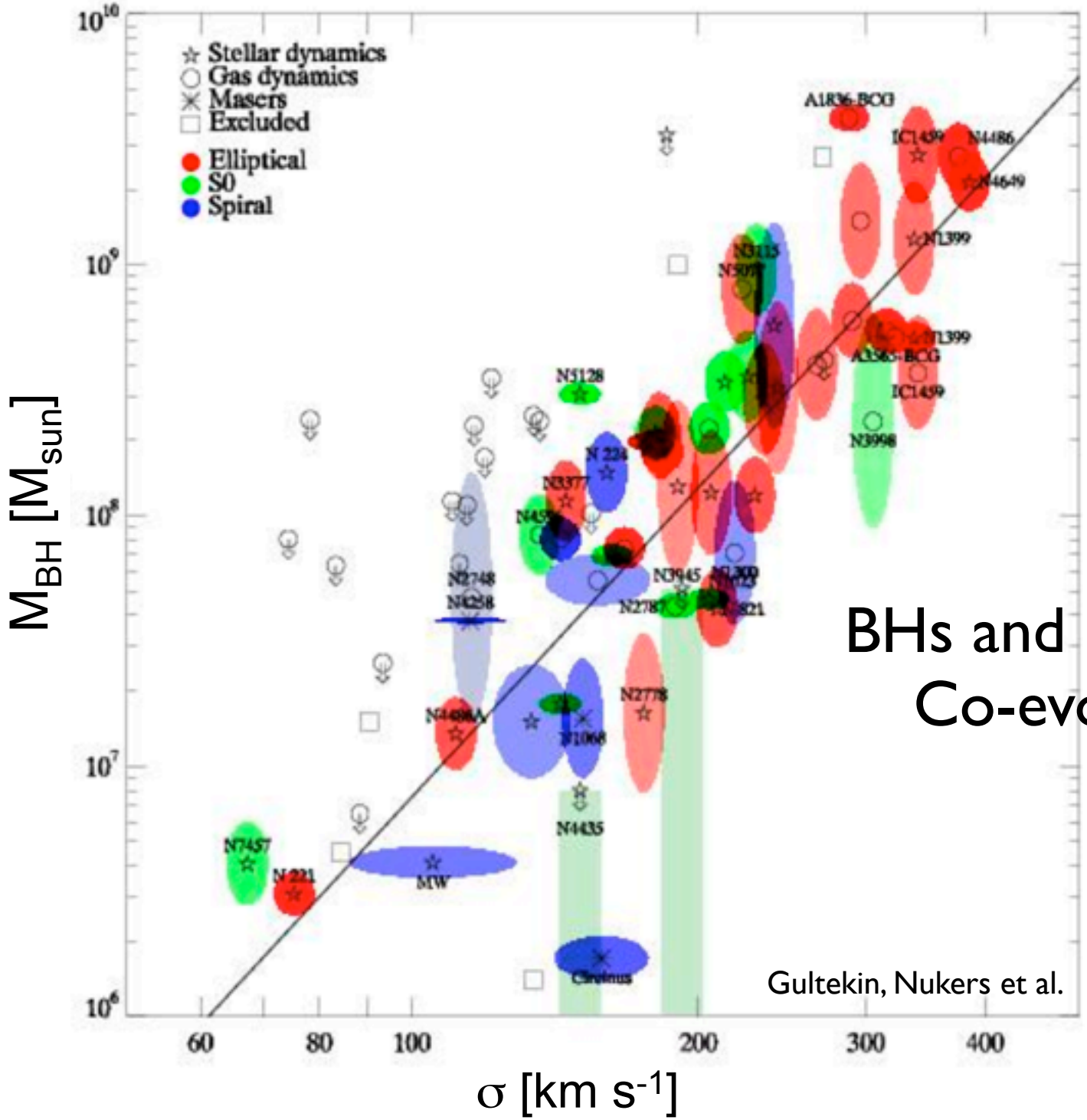


With all this gas getting to the center of the galaxy, what is the black hole doing?

Black Holes are Tightly Coupled to Bulge Properties...



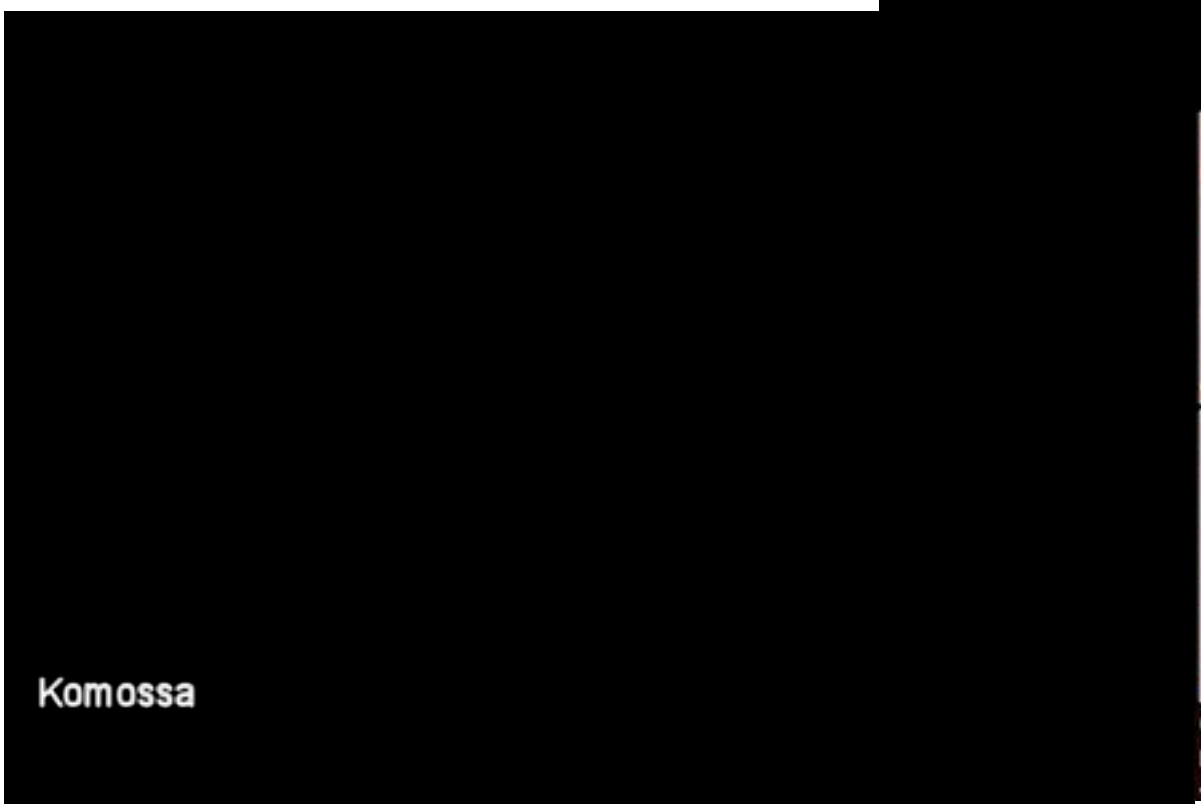
BHs and Bulges Co-evolve

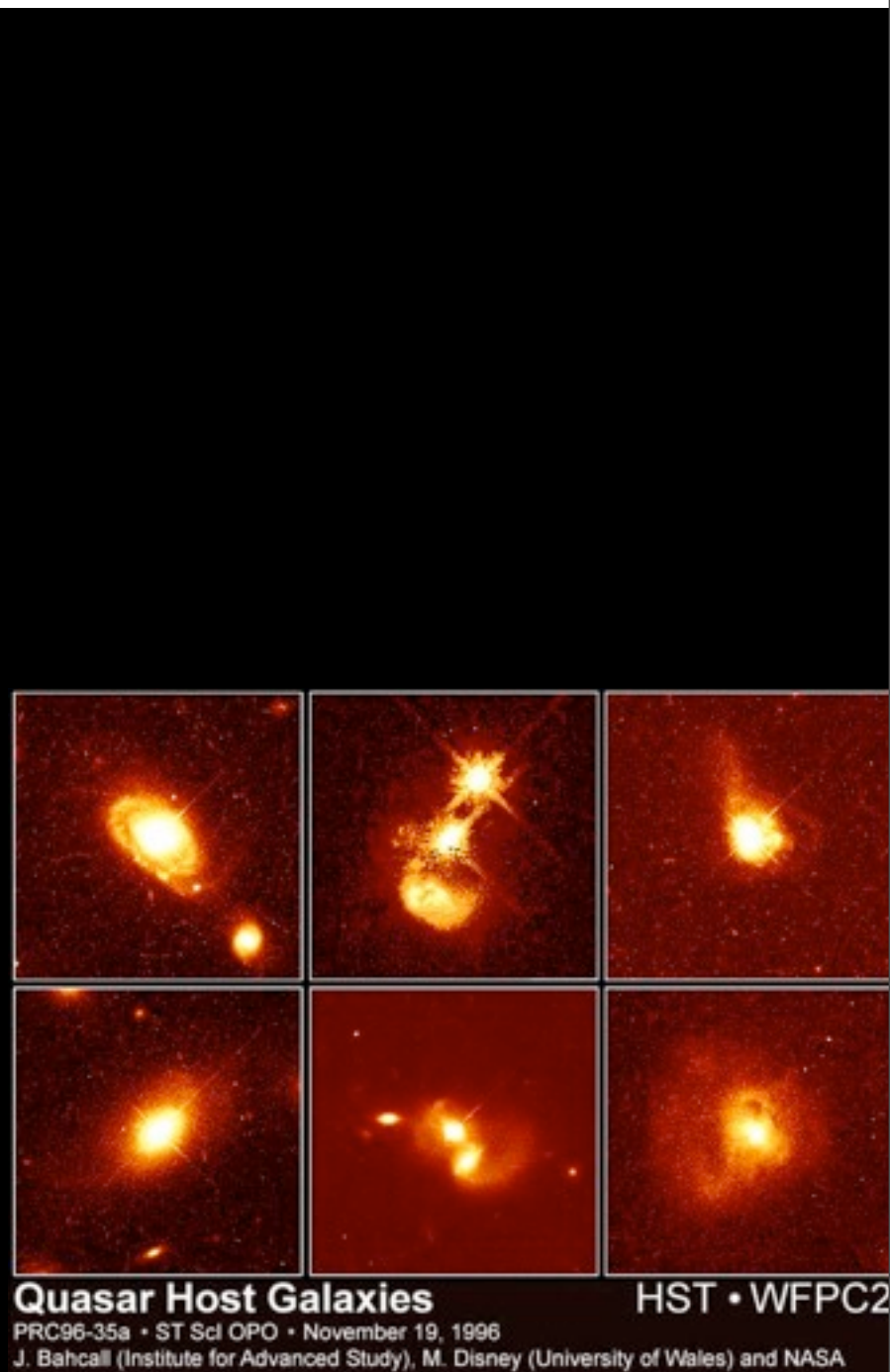
Implications for Fueling: "Feeding the Monster"

WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

- Galaxy merger: good way to get lots of gas to small scales!

- *If* BHs trace spheroids, then *most* mass added in violent events that also build bulges

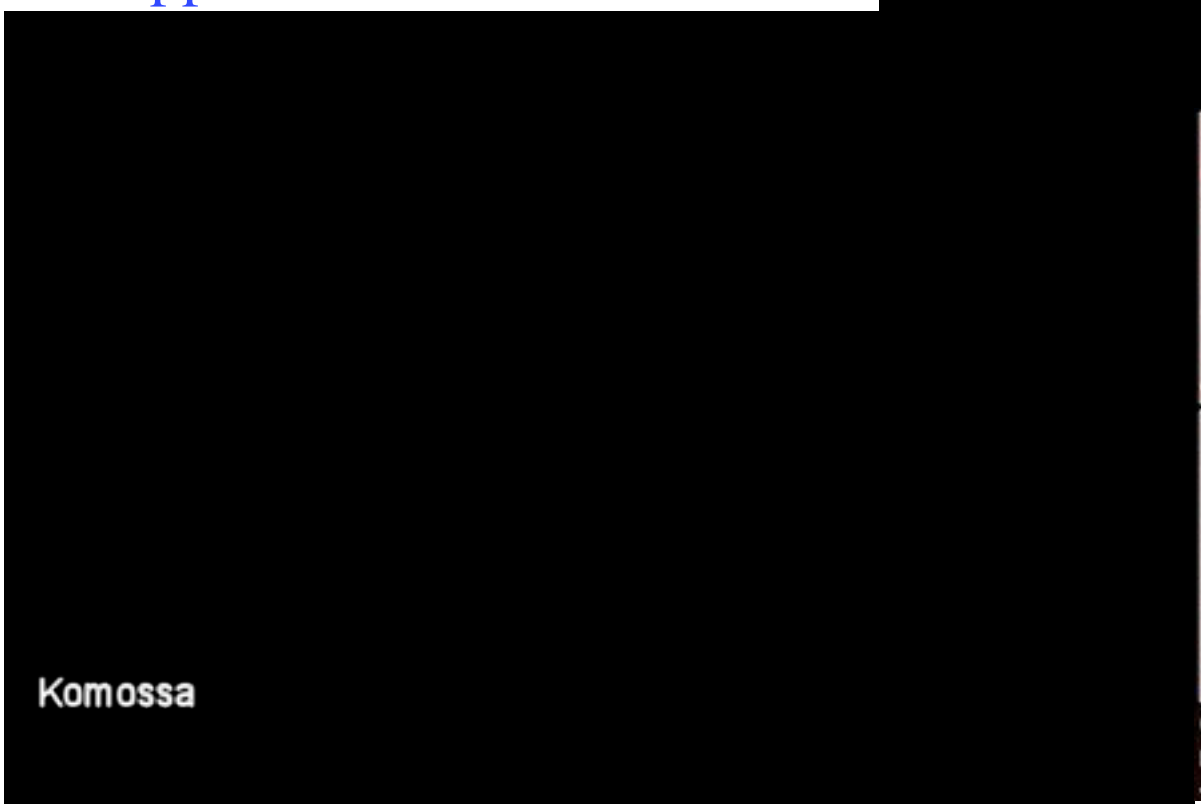


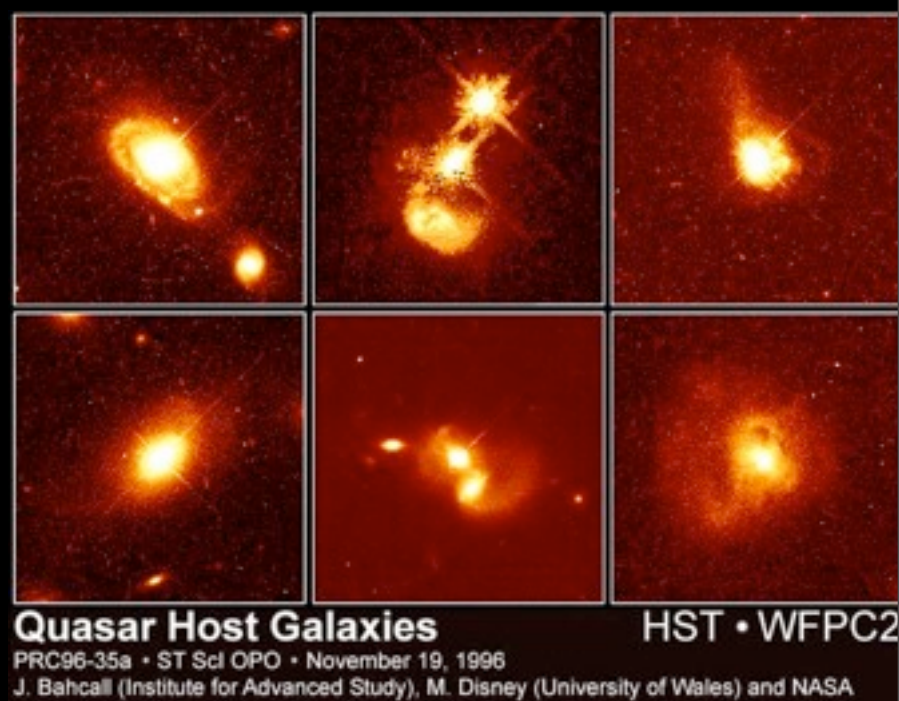


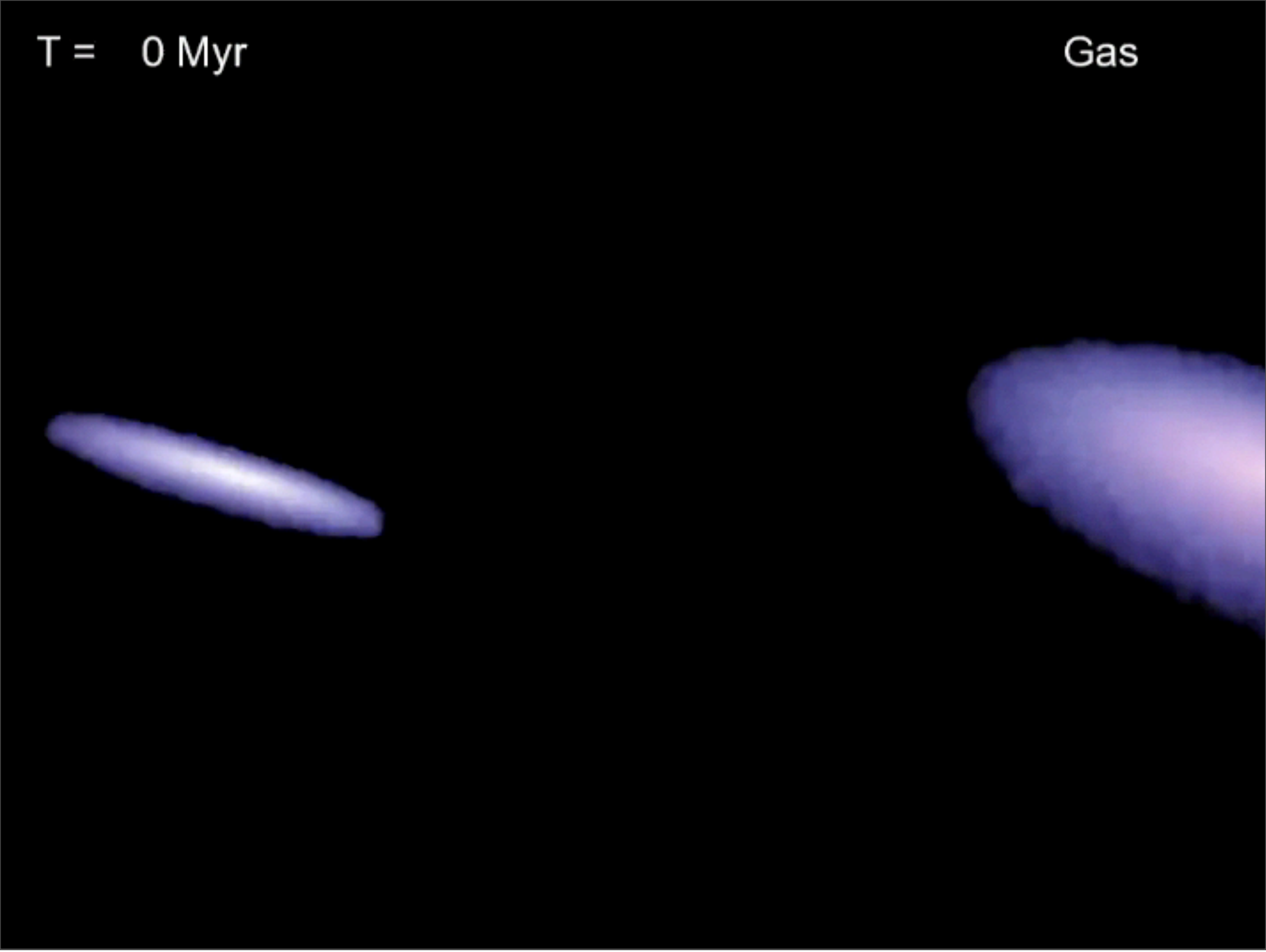
Implications for Fueling: "Feeding the Monster"

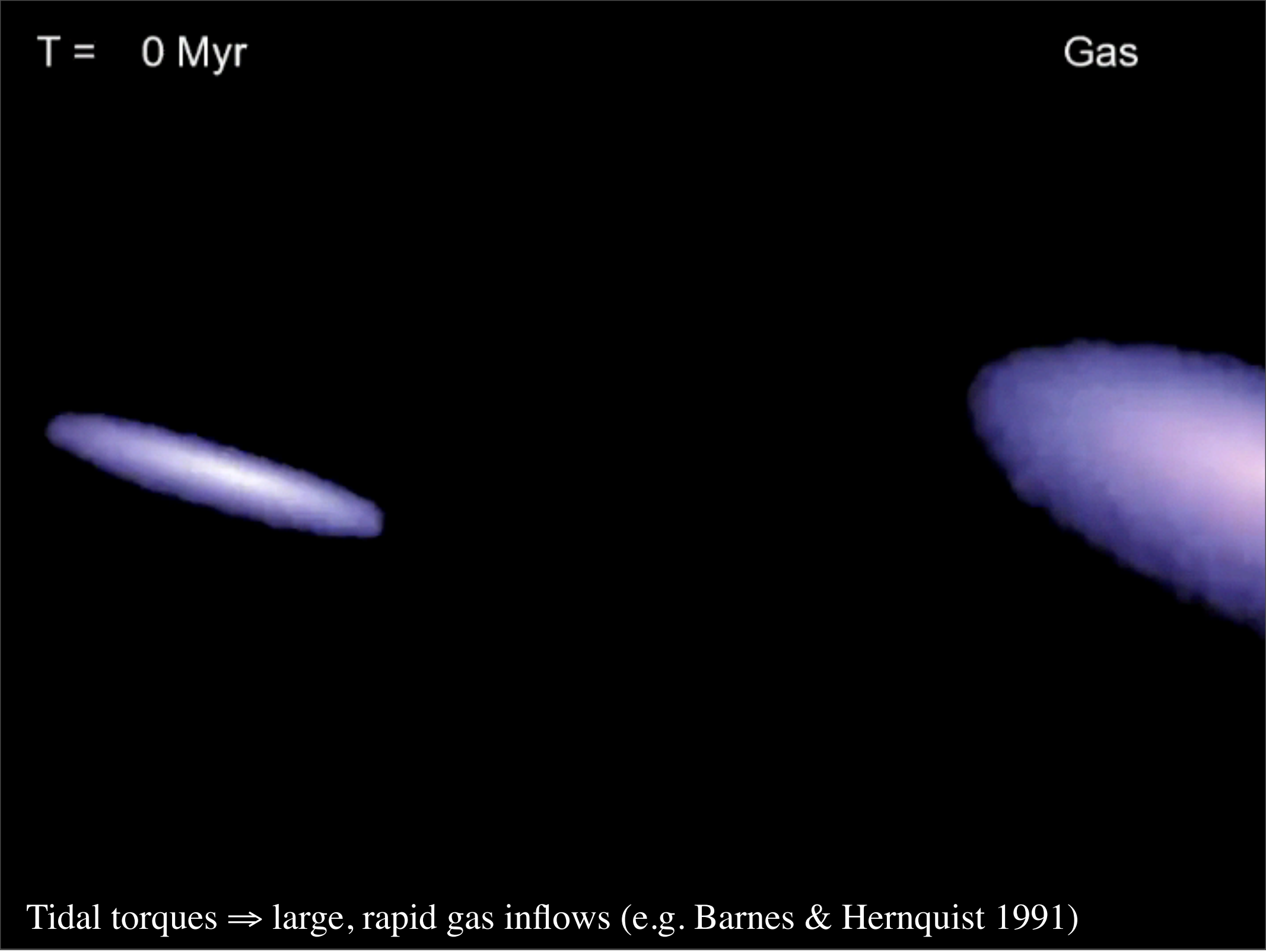
WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

- Problem:
  Scale of merger: ~100 kpc
  Viscous disk: ~0.1 pc
- Solution 1: simple prescription
- Solution 2: re-simulate ("zoom in") and see what happens!

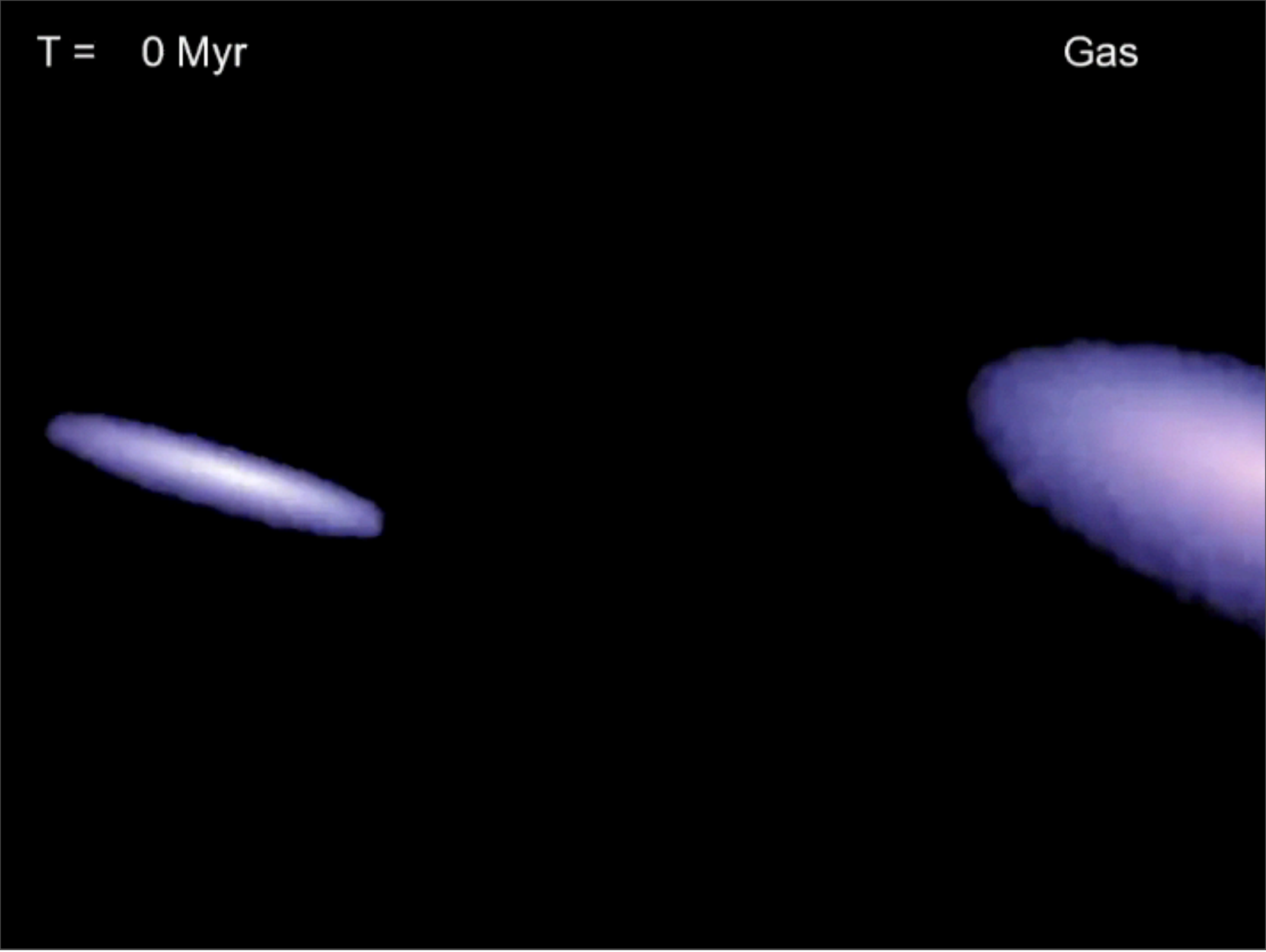




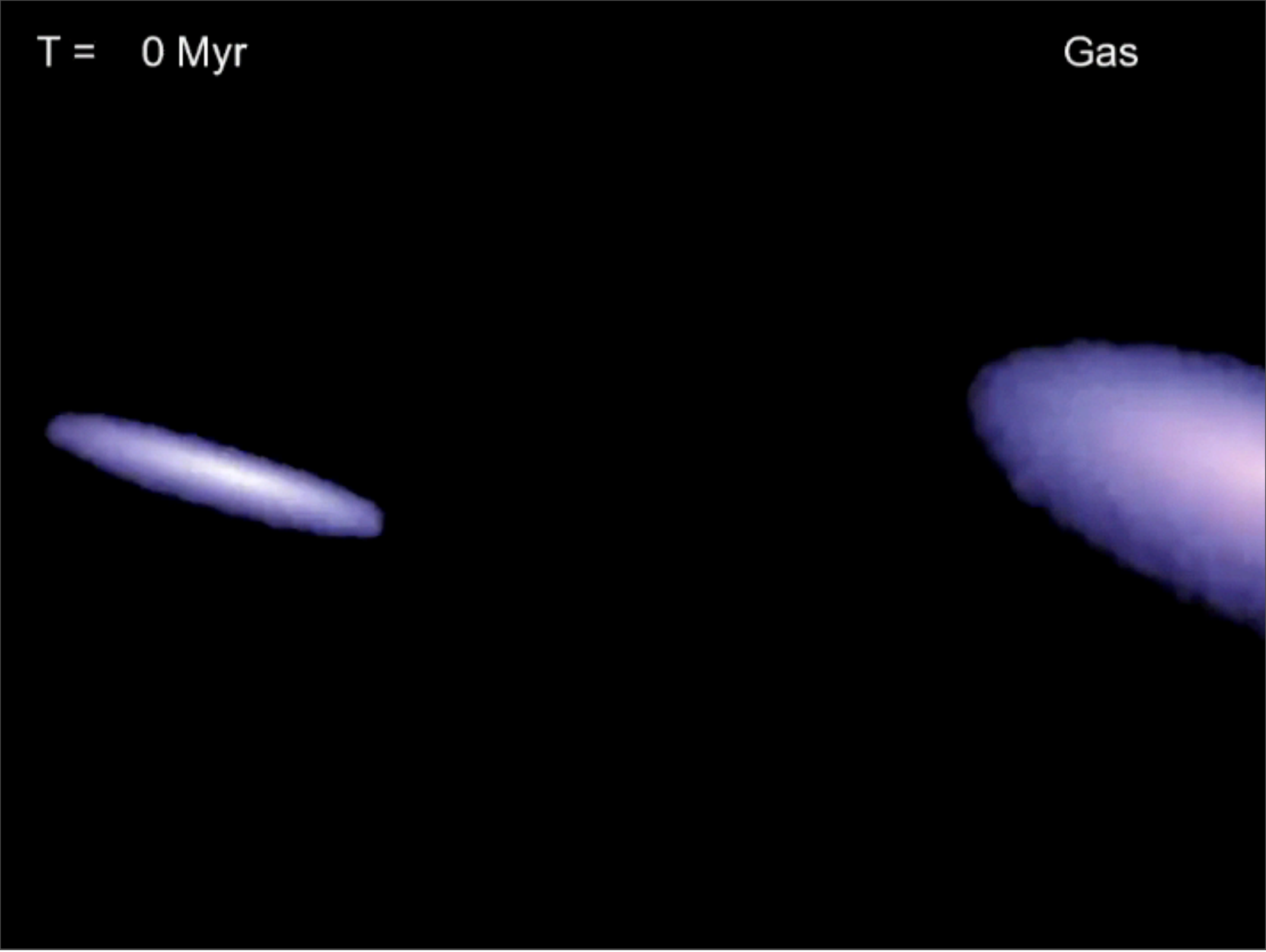

T = 0 Myr
Gas

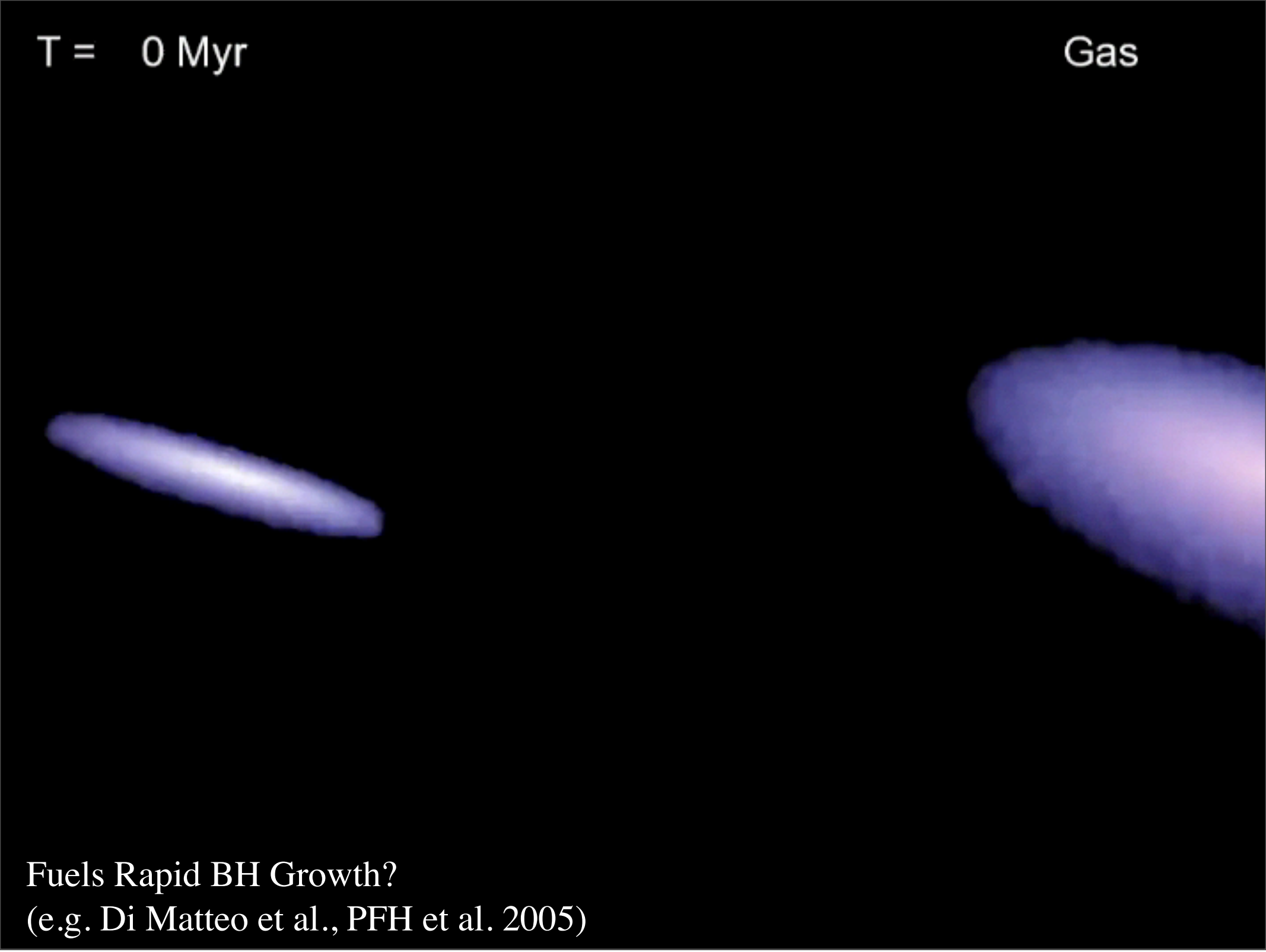


Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)

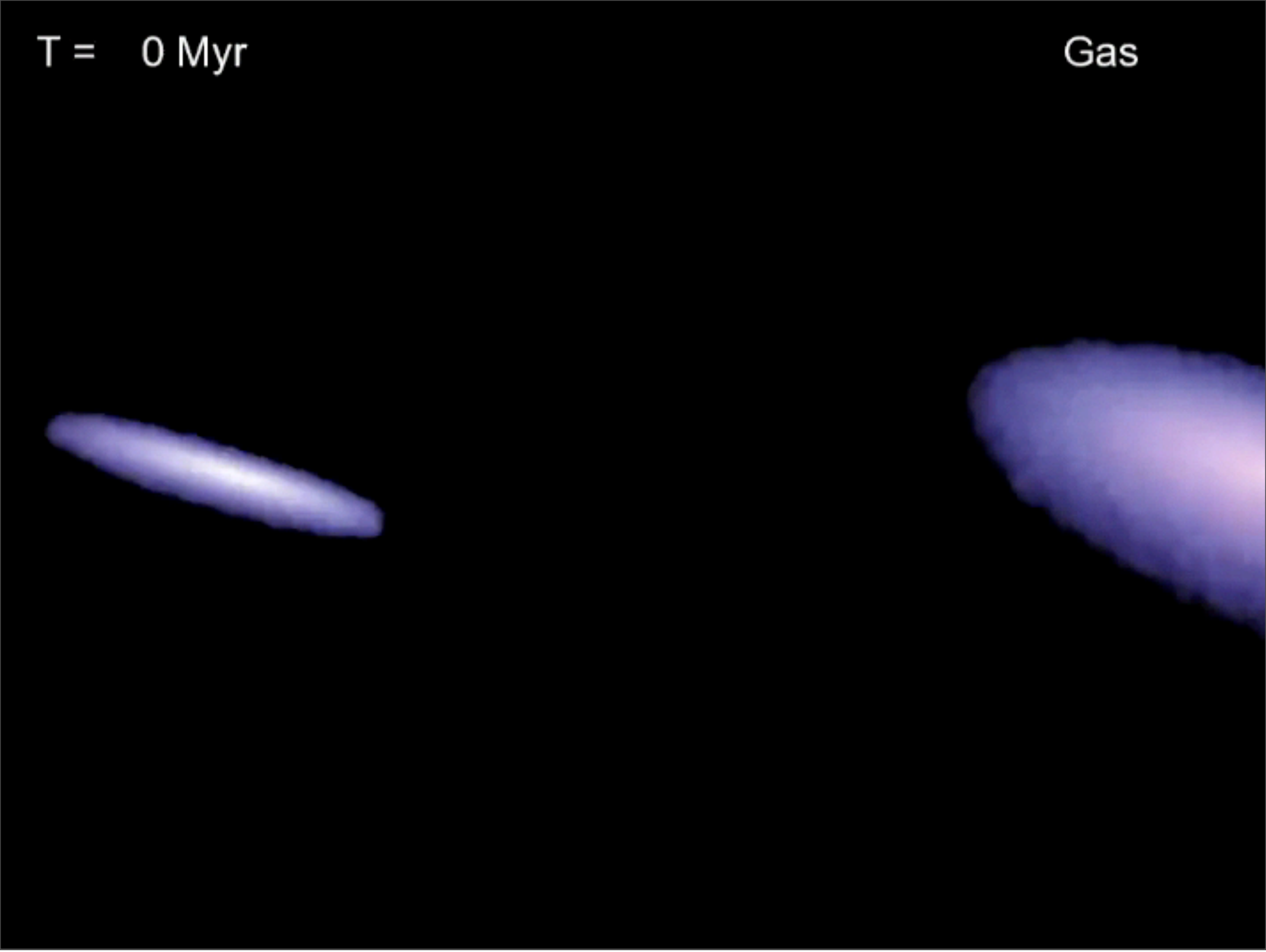

T = 0 Myr
Gas

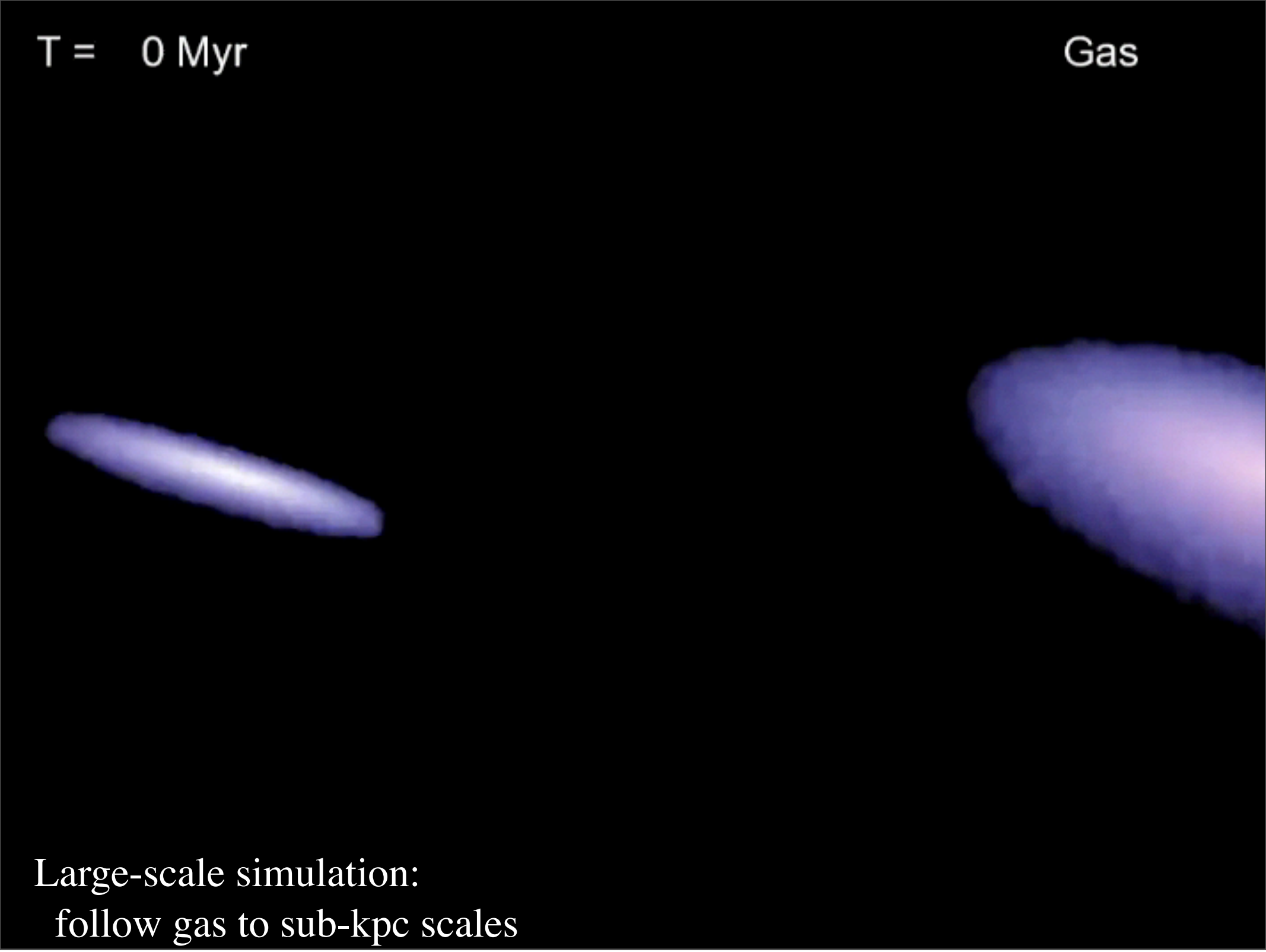
Triggers Starbursts (e.g. Mihos & Hernquist 1996)


T = 0 Myr
Gas

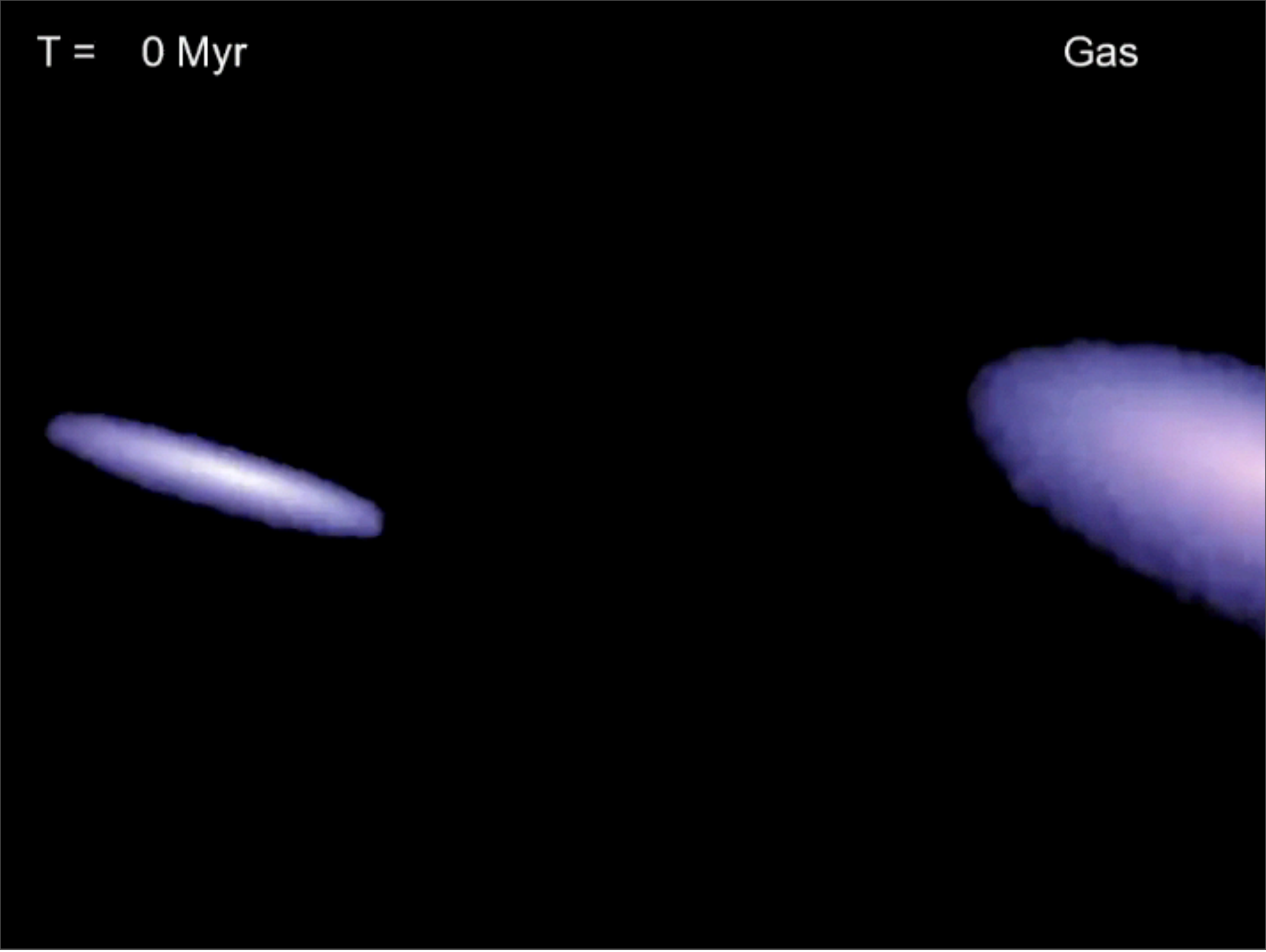


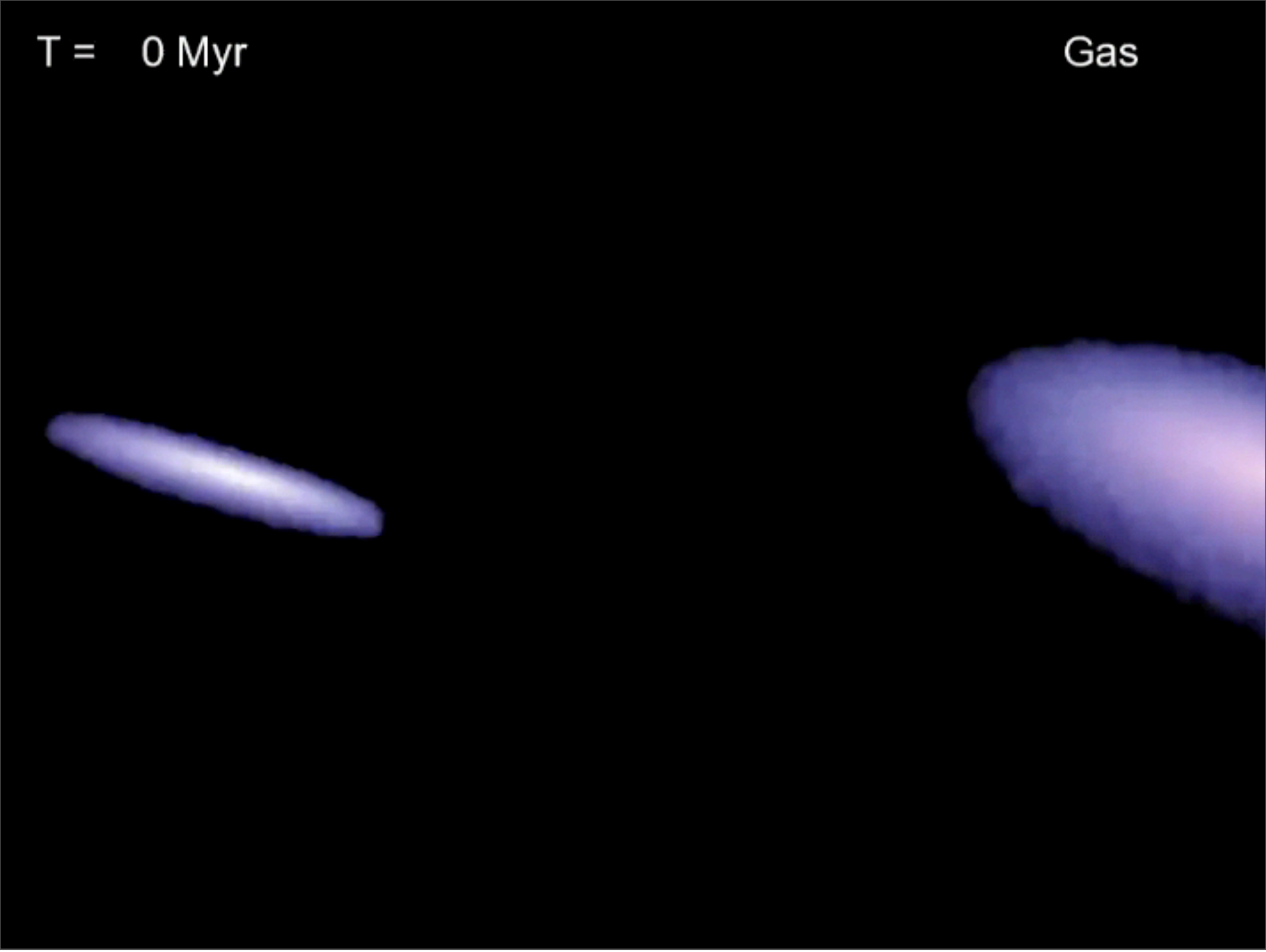
Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)

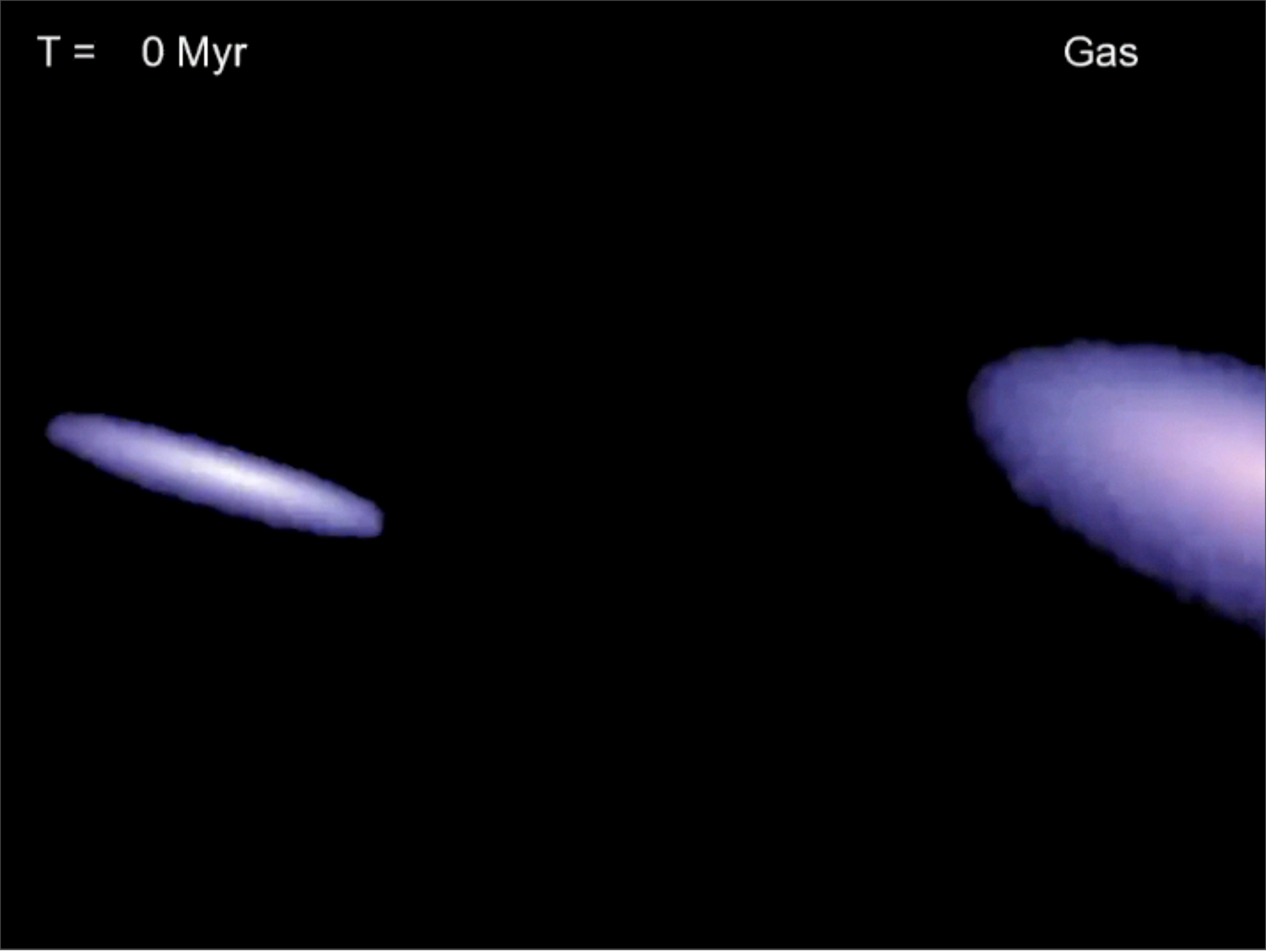

T = 0 Myr
Gas



Large-scale simulation:
follow gas to sub-kpc scales


T = 0 Myr
Gas


T = 0 Myr
Gas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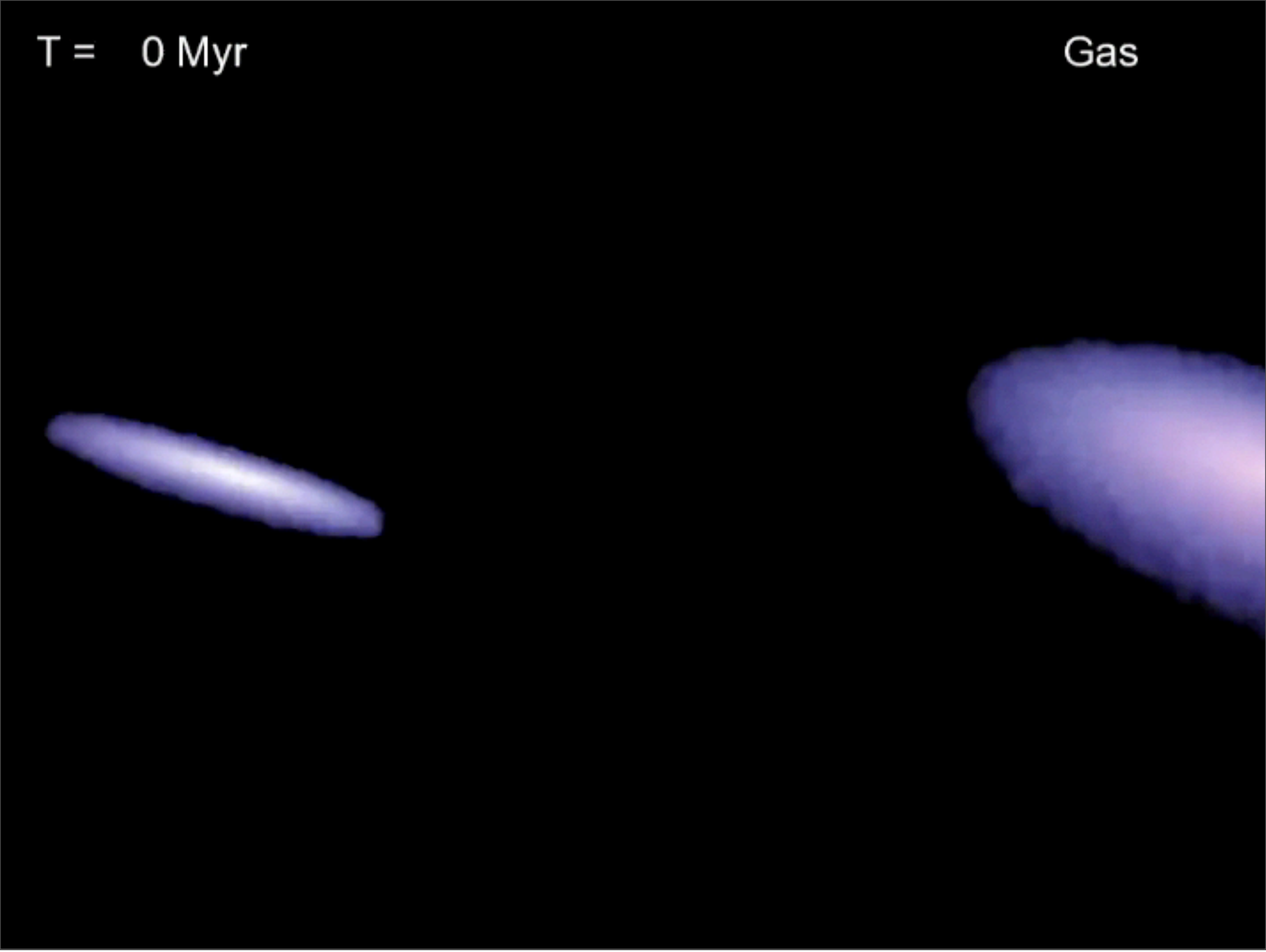
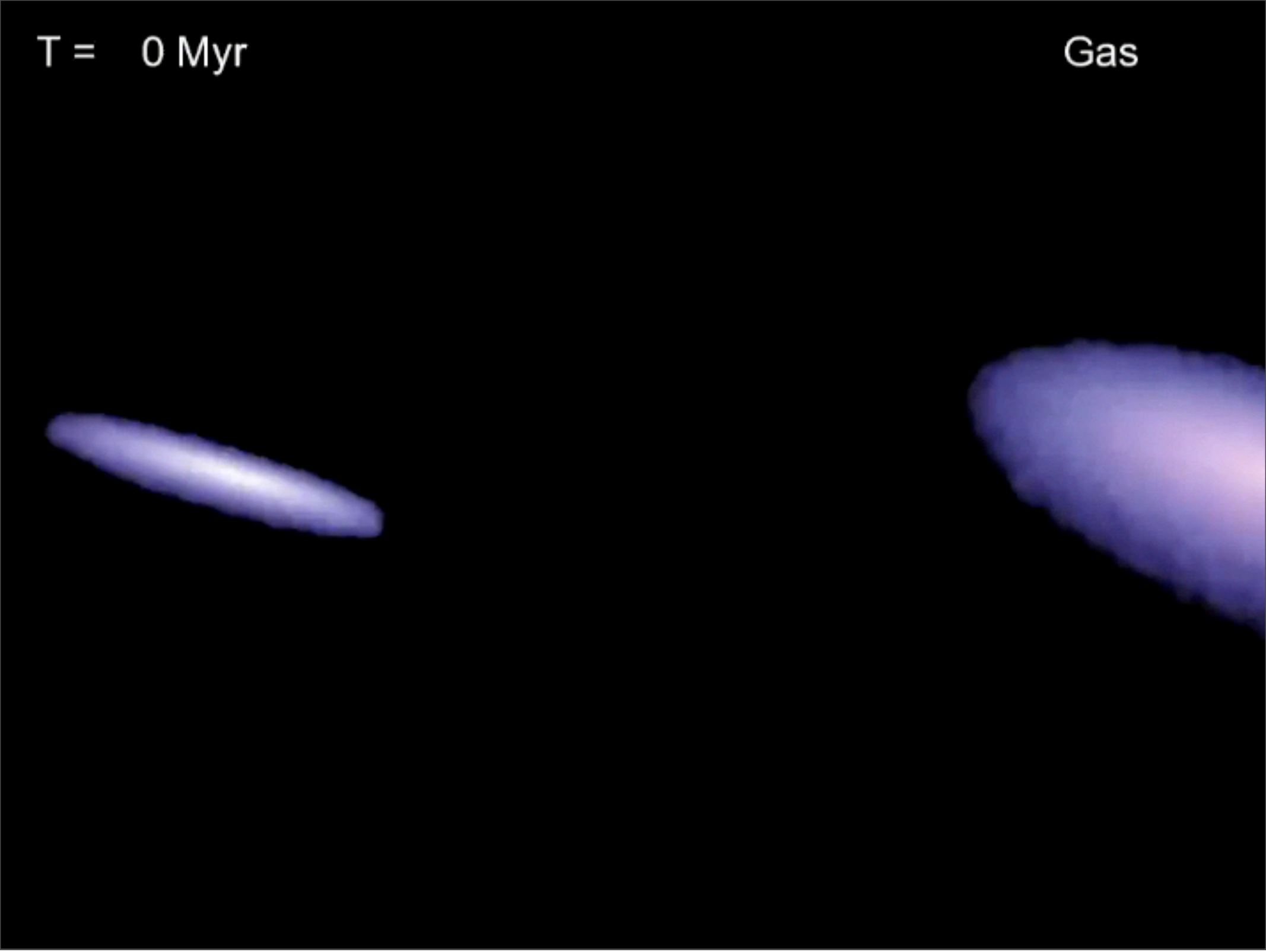
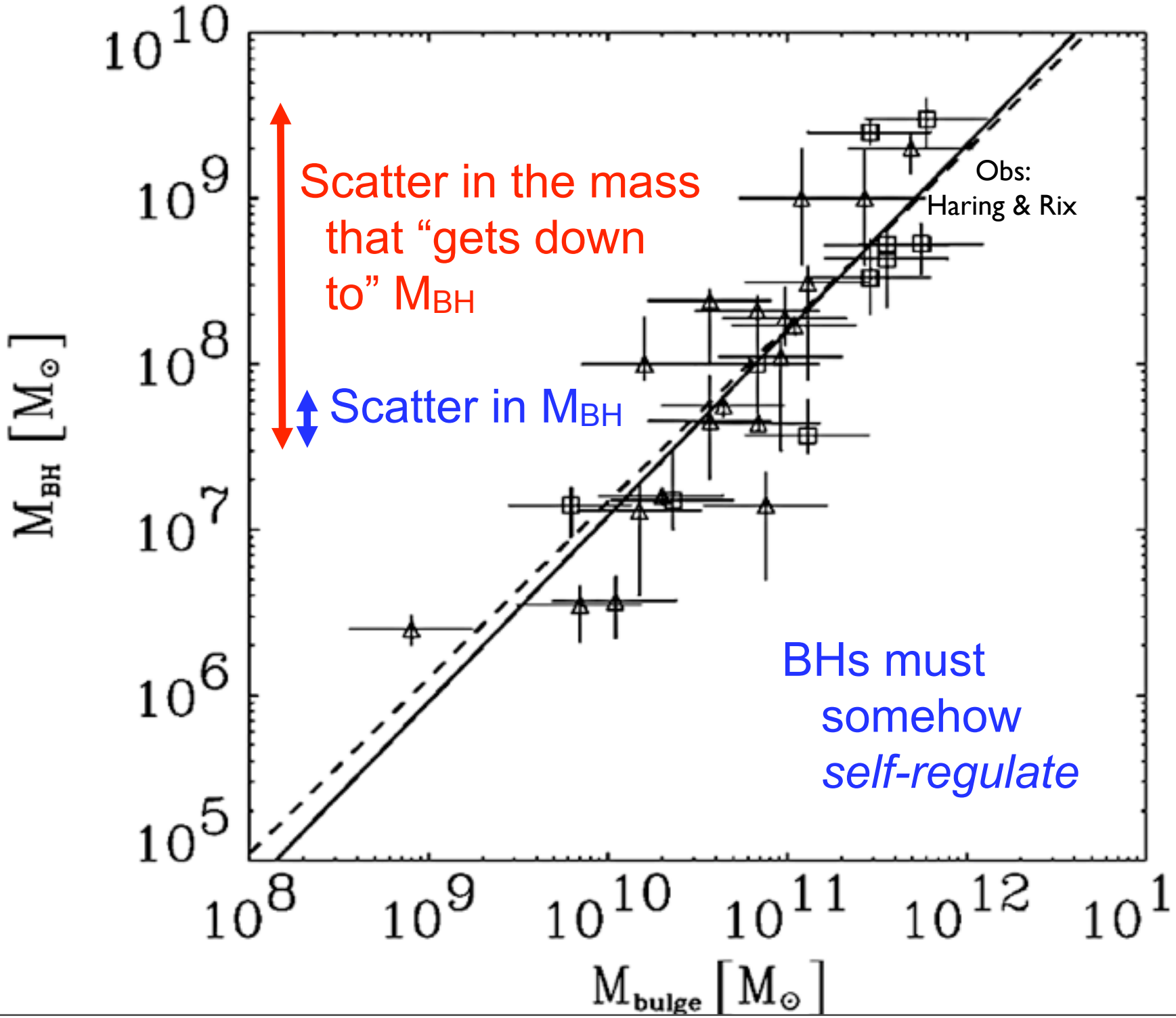
Gas


T = 0 Myr
Gas


T = 0 Myr
Gas

M-sigma is NOT the simplest expectation!



Simplest Idea:

FEEDBACK ENERGY/MOMENTUM BALANCE (SILK & REES '98)

- Accretion disk radiates:

$$L = \epsilon_r \, (\mathrm{d}M_{\rm BH}/\mathrm{d}t) \, c^2 \quad (\epsilon_r \sim 0.1)$$

- Total energy radiated (typical ~10^8 $M_{\rm sun}$ system)

$$\sim 0.1 \, M_{\rm BH} \, c^2 \sim 10^{61} \, \mathrm{ergs}$$

- Compare to gravitational binding energy of galaxy:

$$\sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_{\rm sun}) \, (200 \, \mathrm{km/s})^2 \sim 10^{59} \, \mathrm{erg}$$

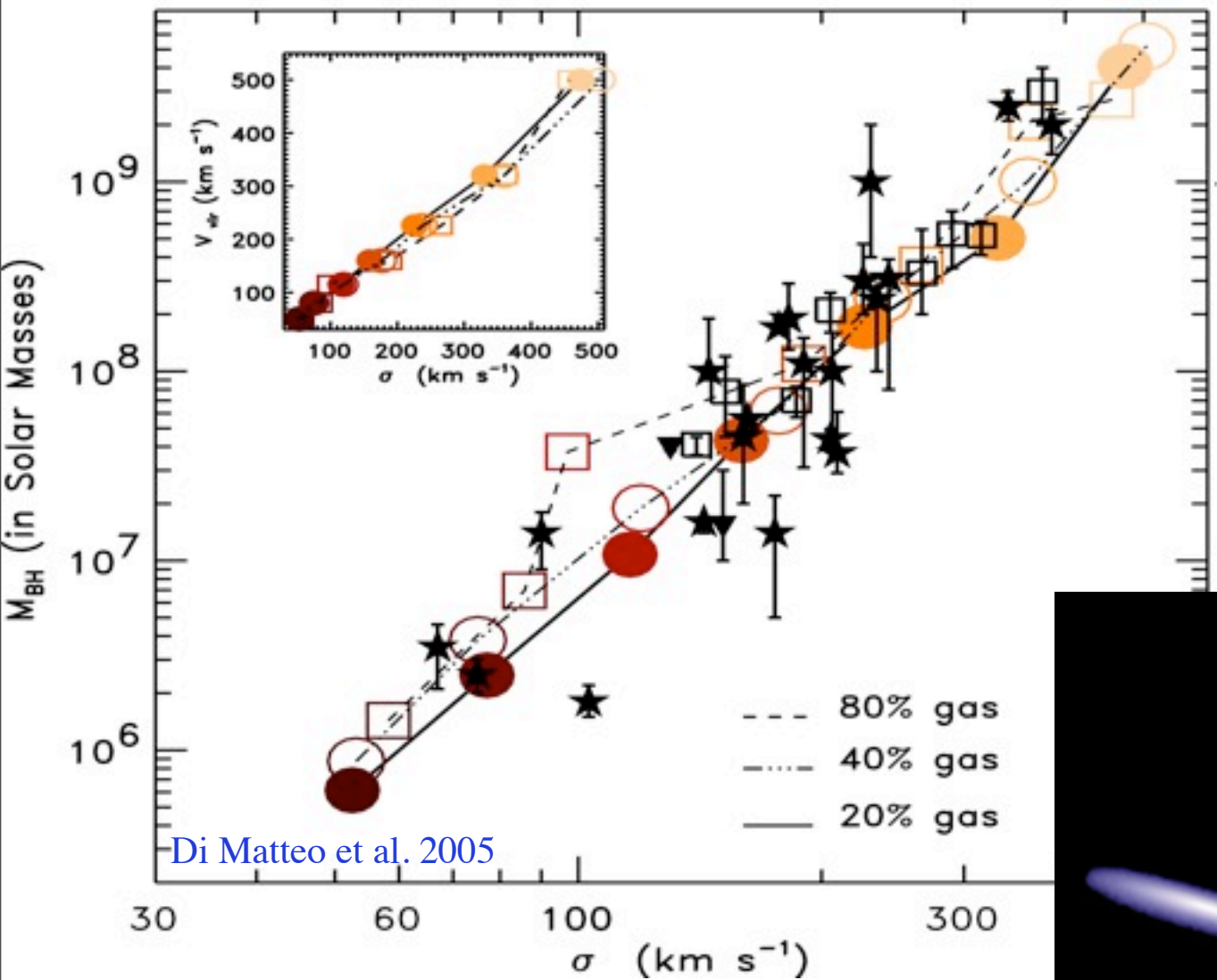
- If only a few percent of the luminous energy coupled, it would unbind the baryons!

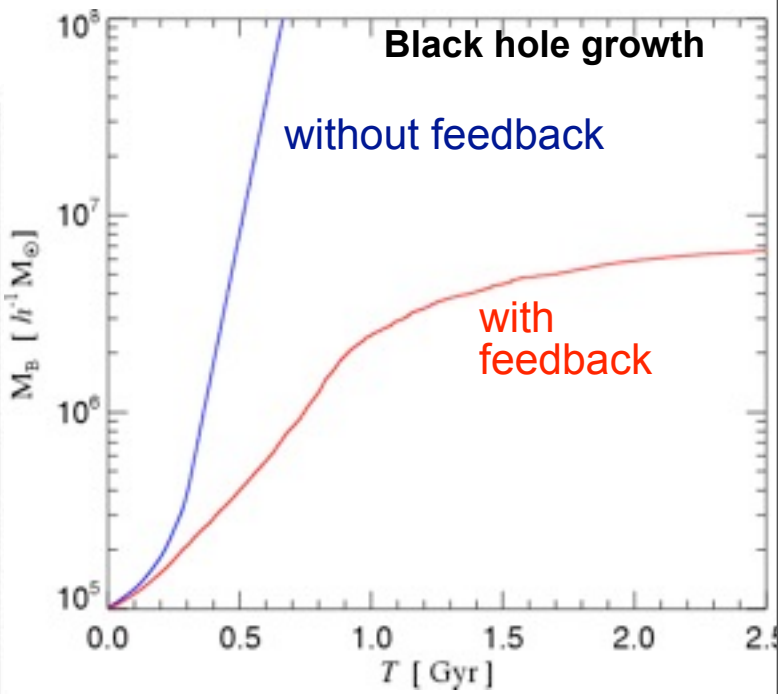
- Turn this around: *if* some fraction f ~ 1-5% of the luminosity can couple, then accretion stops when

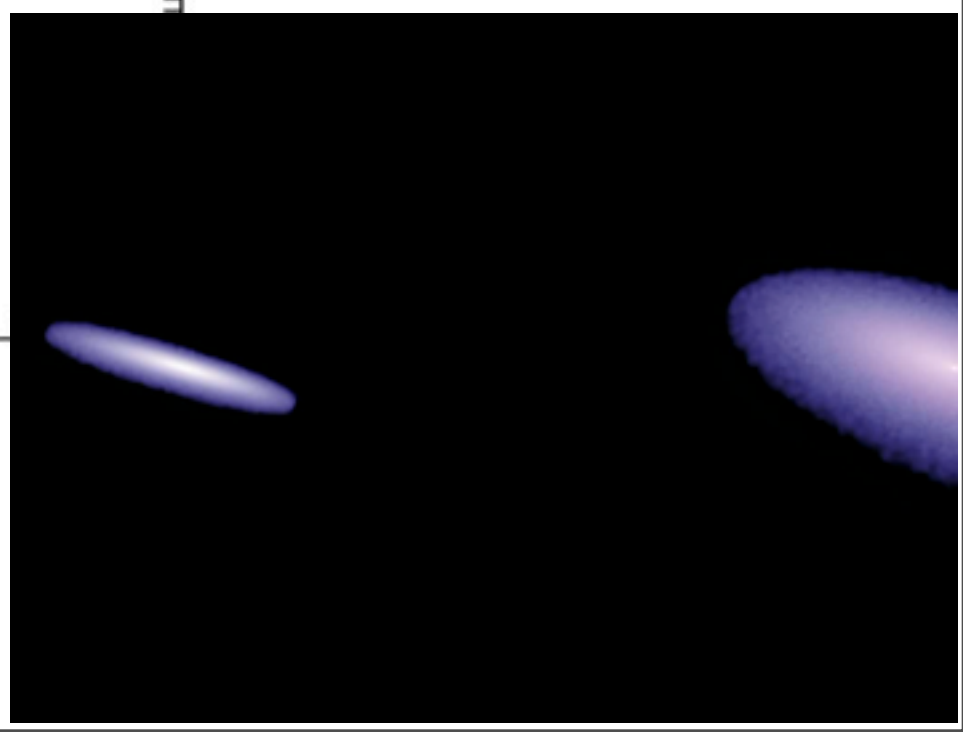
$$M_{\rm BH} \sim (1/f\epsilon_r) \, M_{\rm gal} \, (\sigma/c)^2 \sim 0.002 \, M_{\rm gal}$$

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

PREVENTS RUNAWAY BLACK HOLE GROWTH



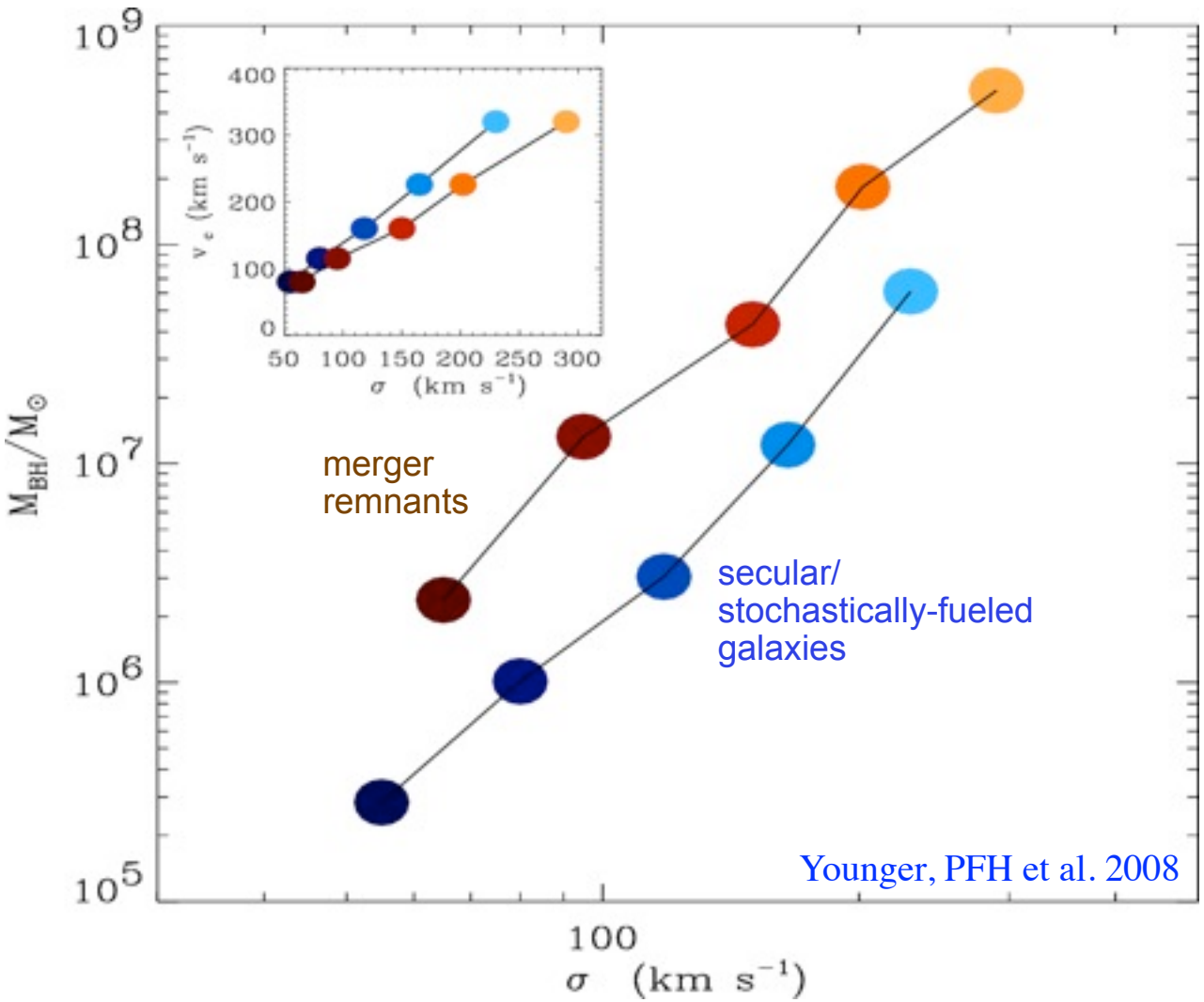




Observations & Simulations Suggest this Simple Picture Works

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.)

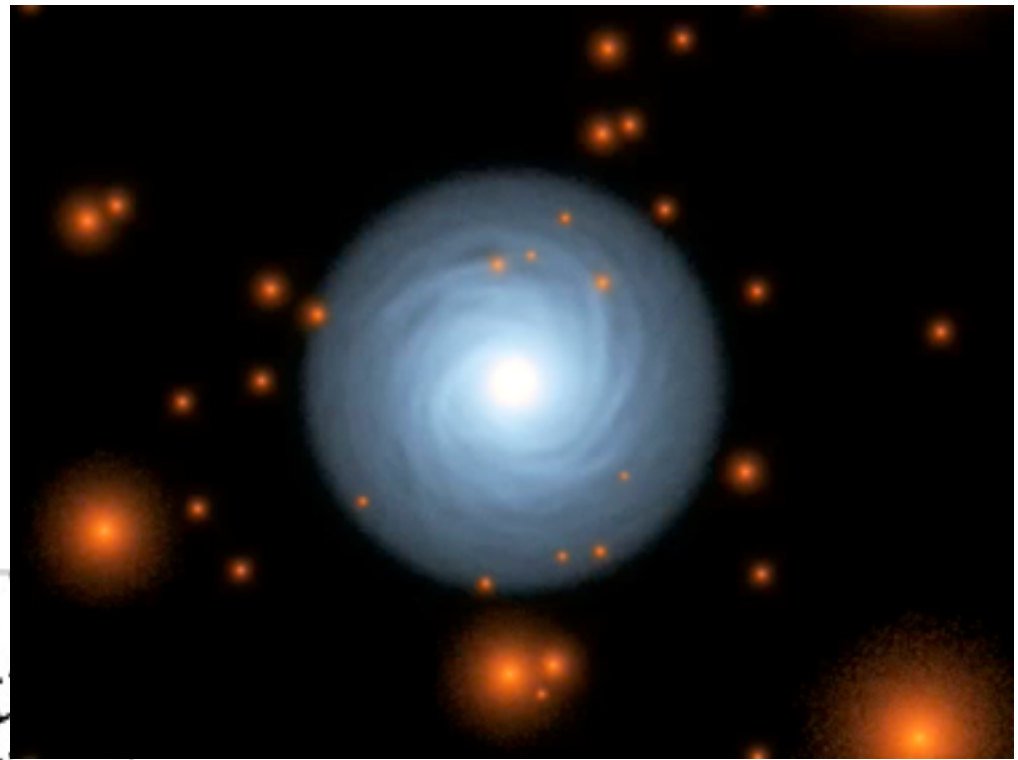


- Basic argument:
  - BH feedback self-regulates growth in ~fixed potential

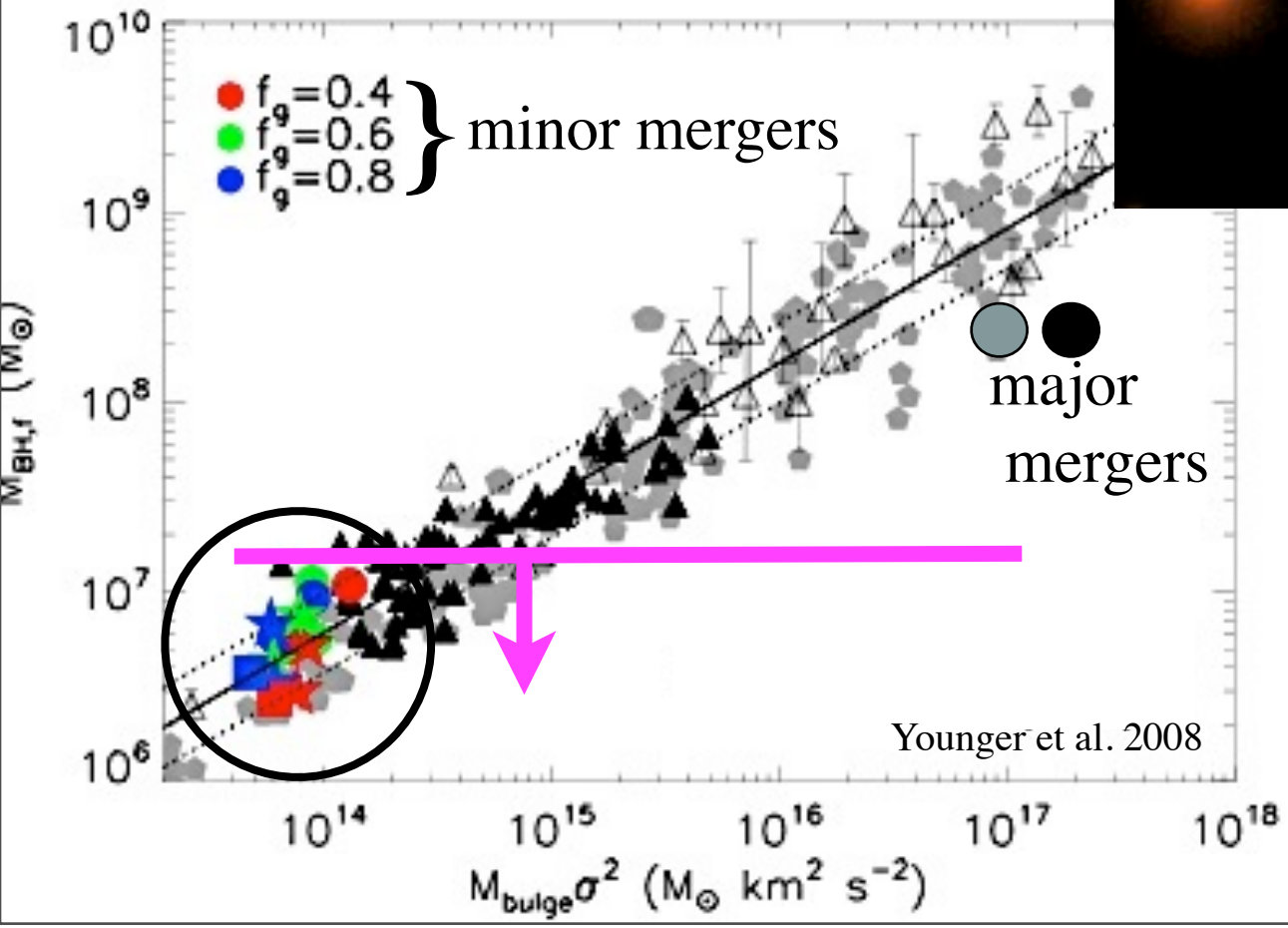
Of Course, Not *Every* AGN Needs a Merger

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?

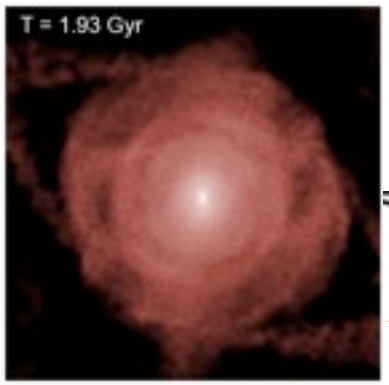


Dubinski

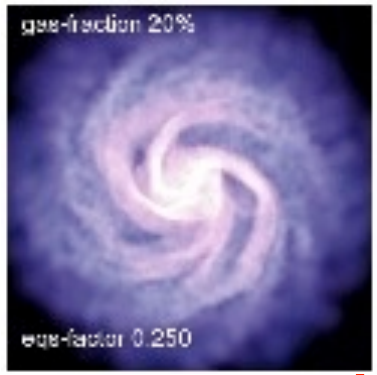


Younger et al. 2008

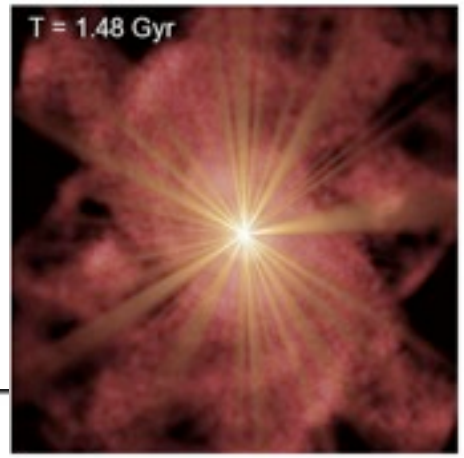
- If you don't build massive bulges, doesn't matter if you can get the gas in!



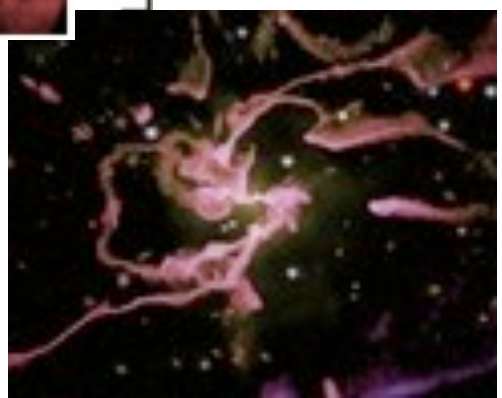
"Dead" Bulges (stellar wind/hot gas halo accretion)



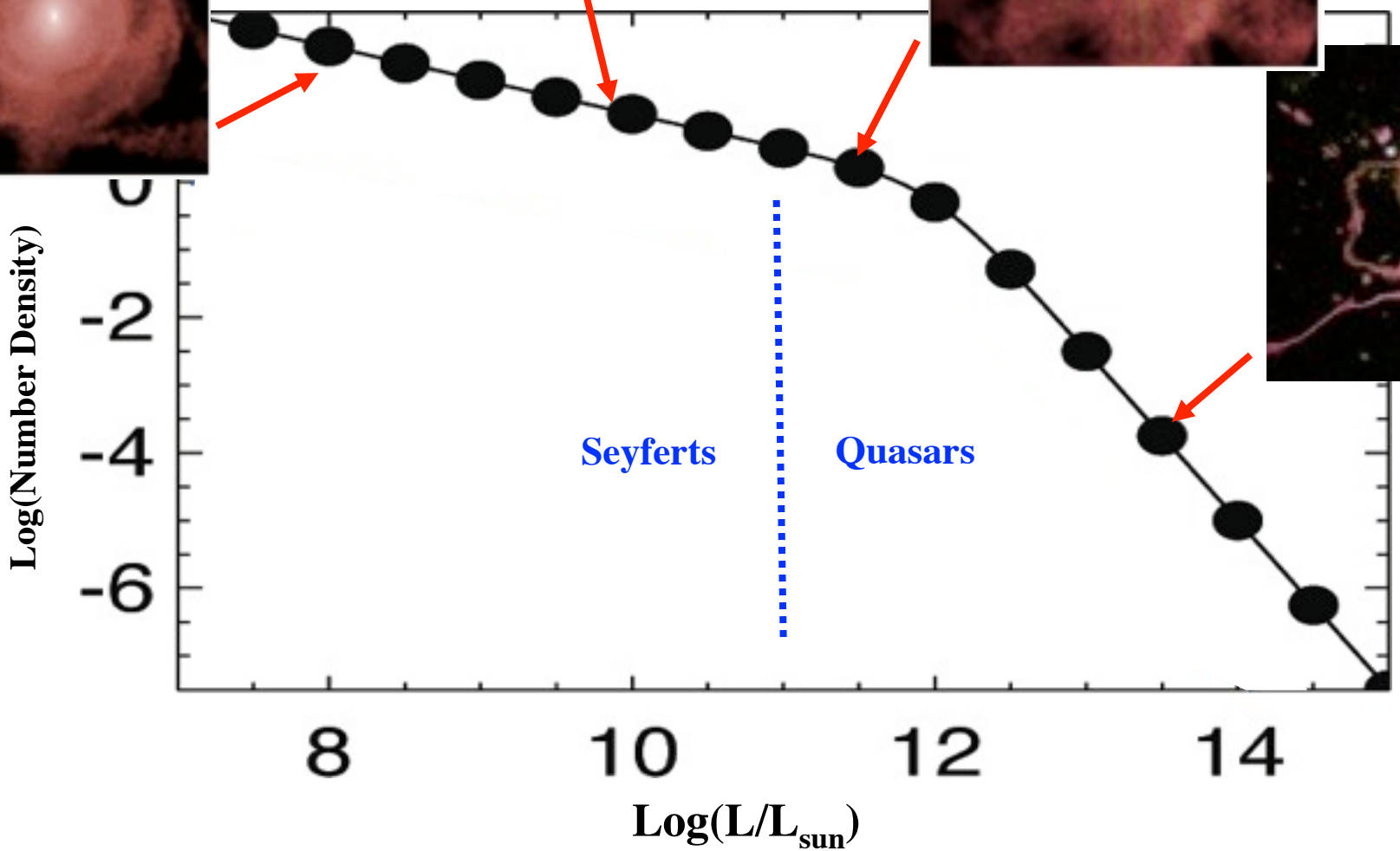
"Seyferts" (disk-dominated, secular/minor mergers)



"Fading" Mergers (post-starburst spheroids)



"Blowout" (Bright Mergers)

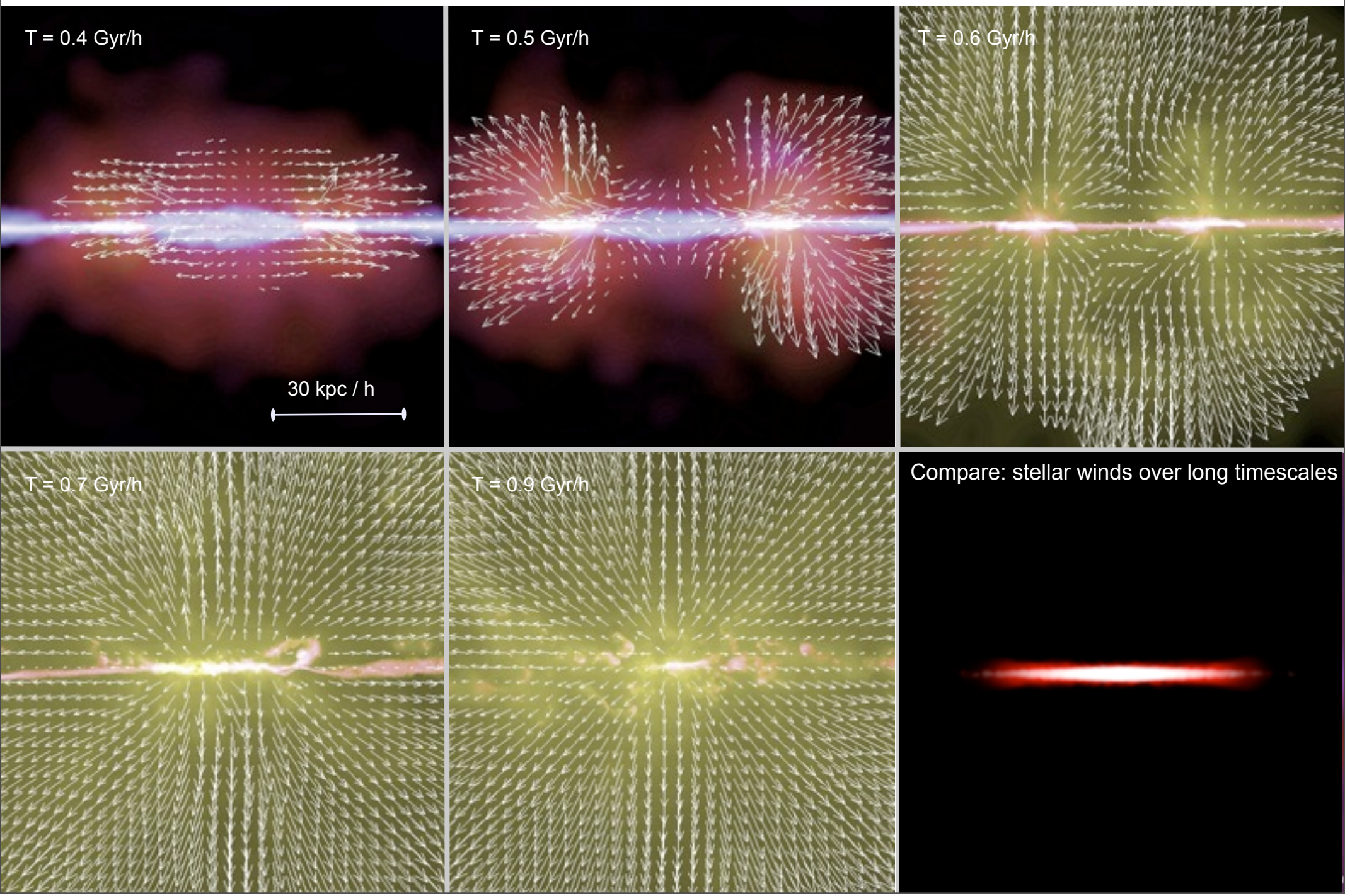


- Observed luminosity function: populations at different *evolutionary* stages

Where Does the Energy/Momentum Go?

QUASAR-DRIVEN OUTFLOWS?

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



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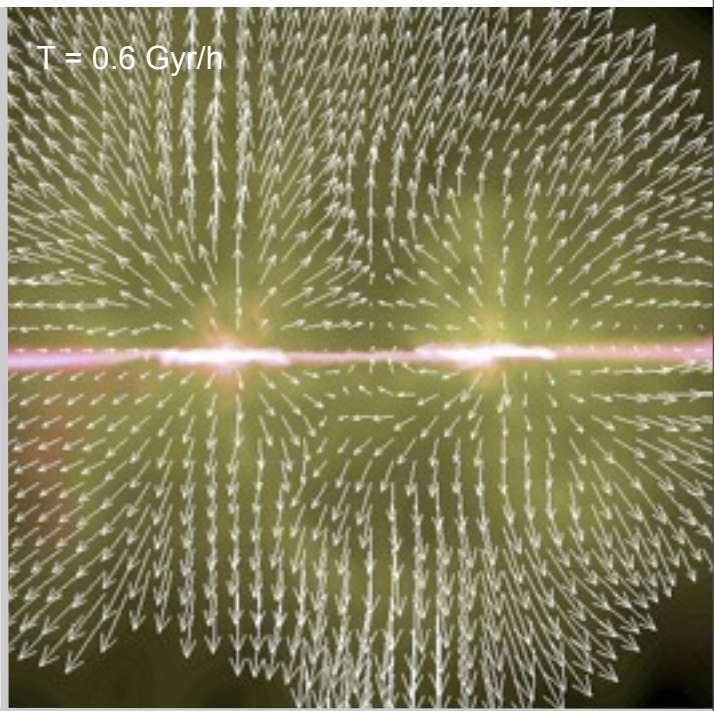

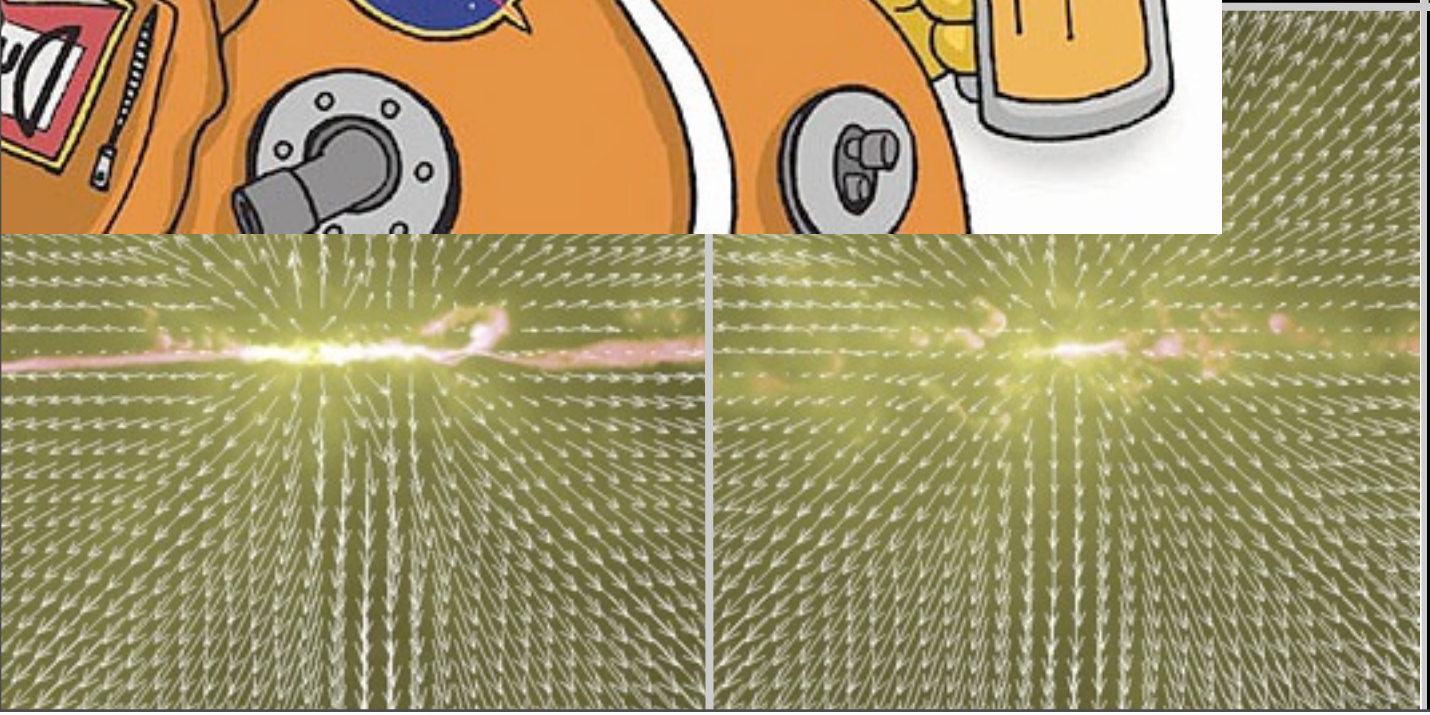

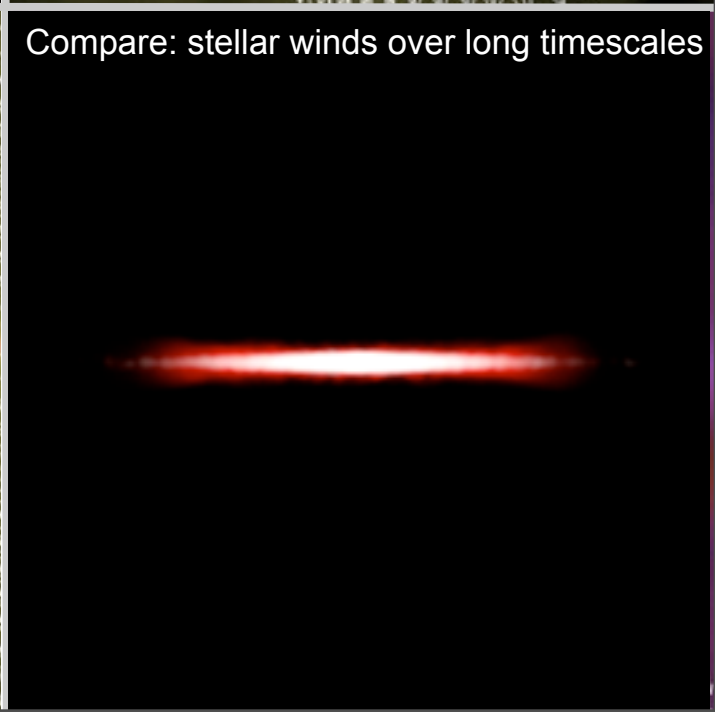

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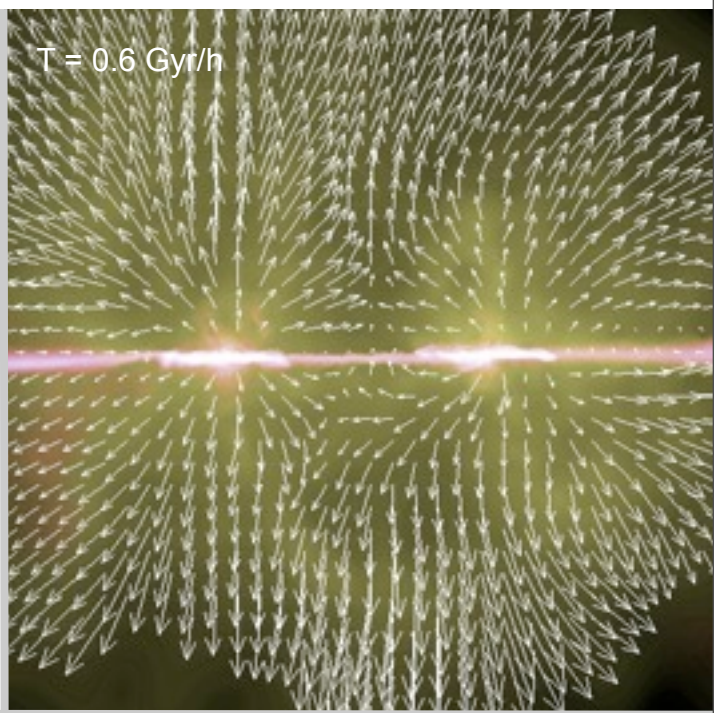

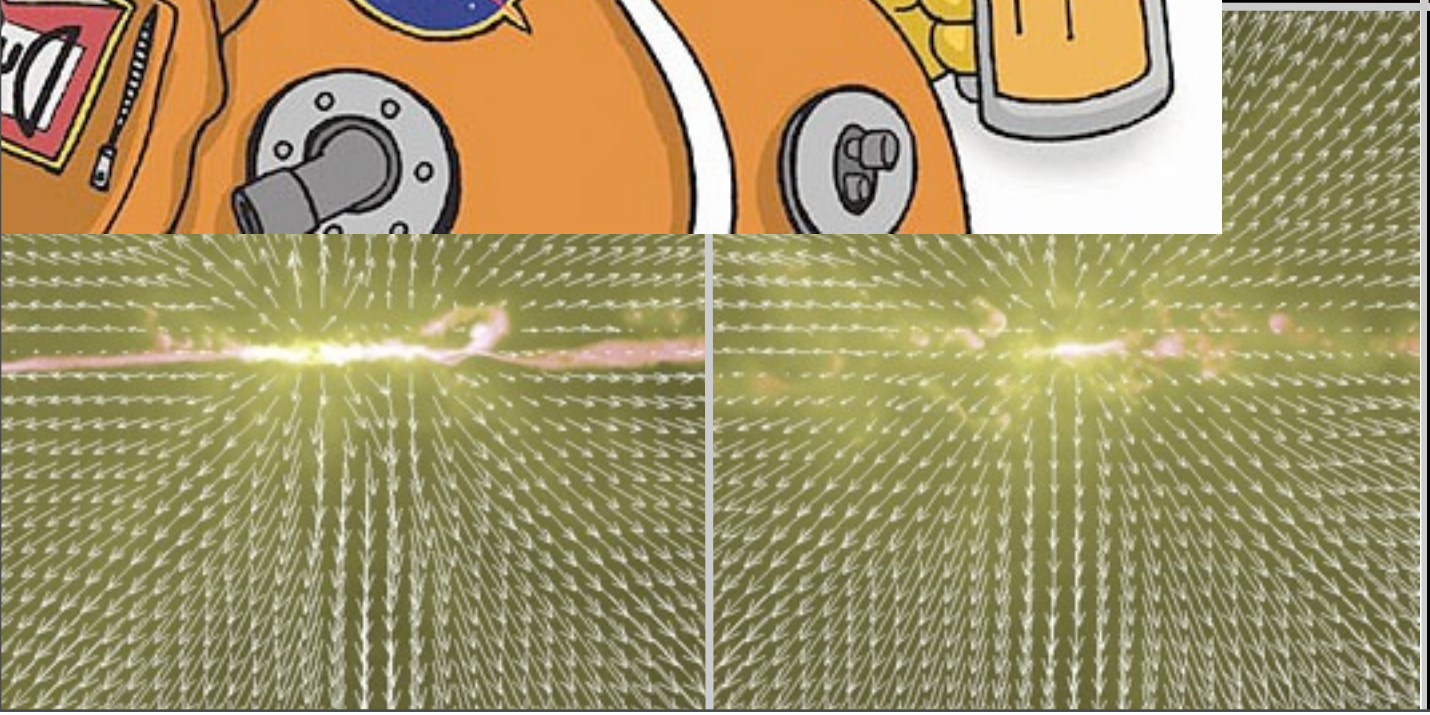

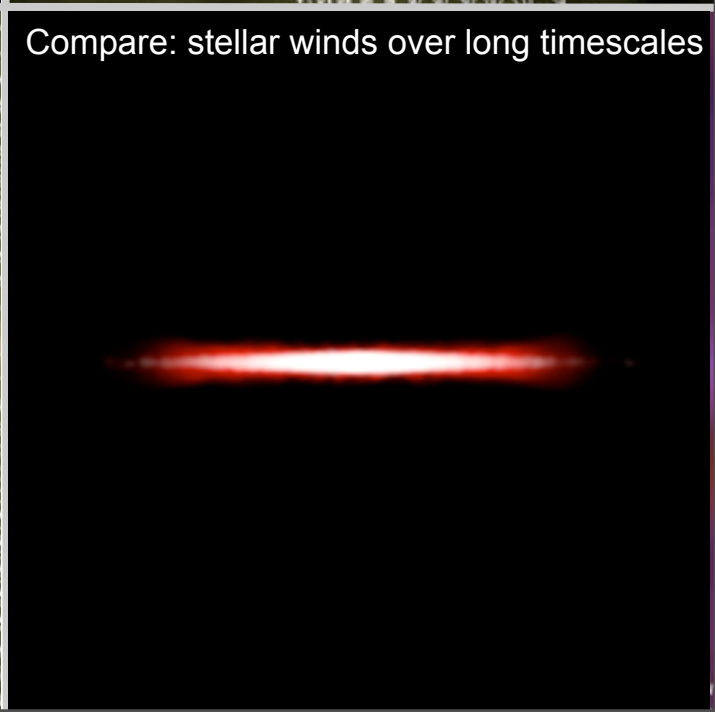

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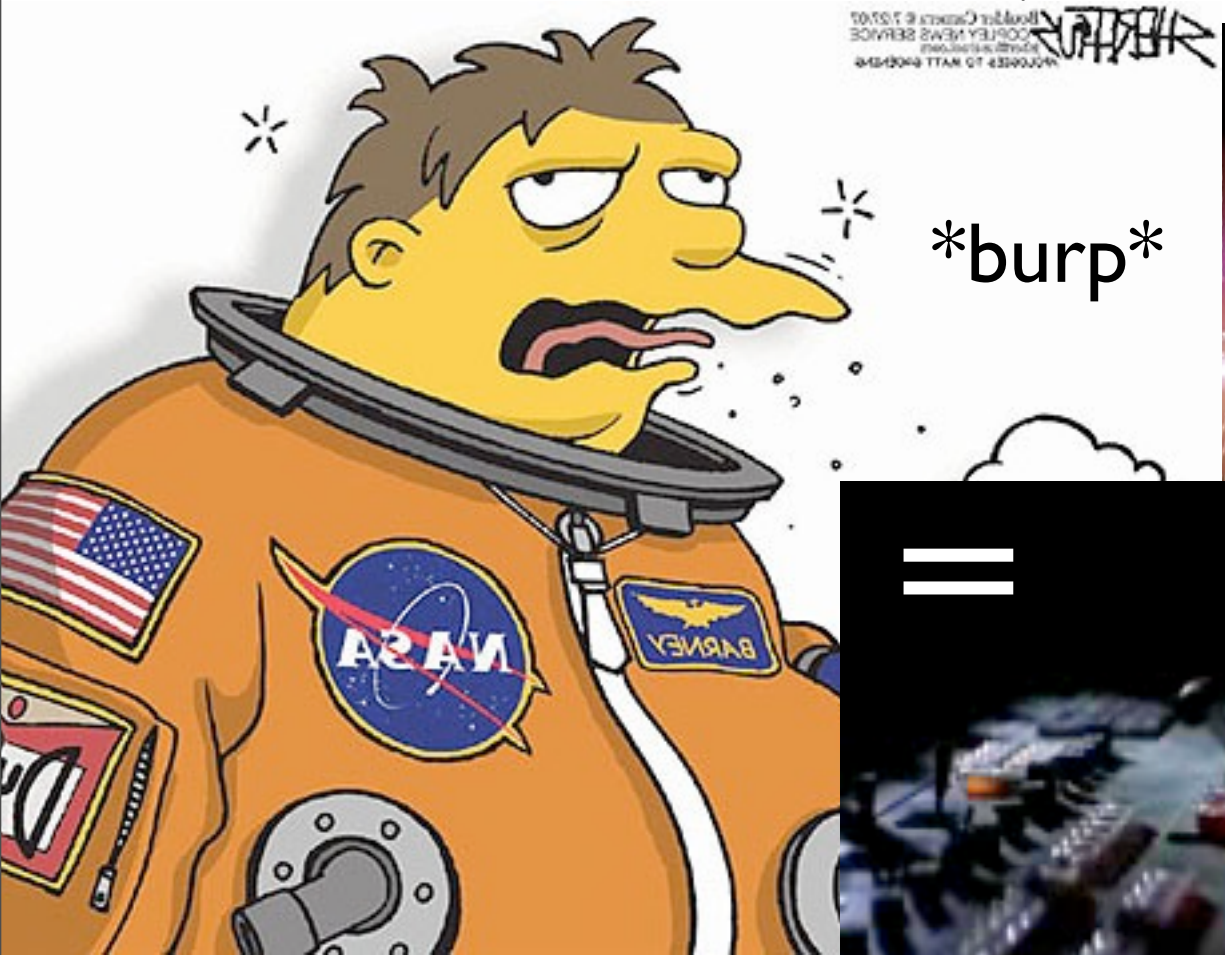
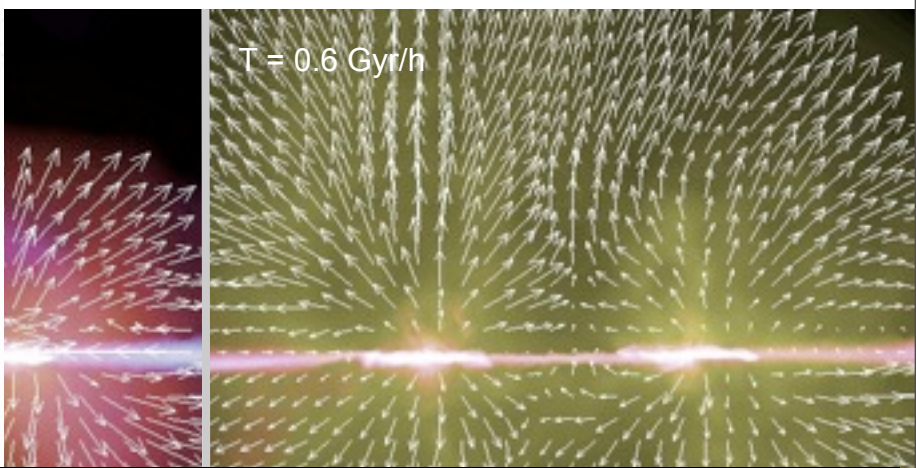


burp



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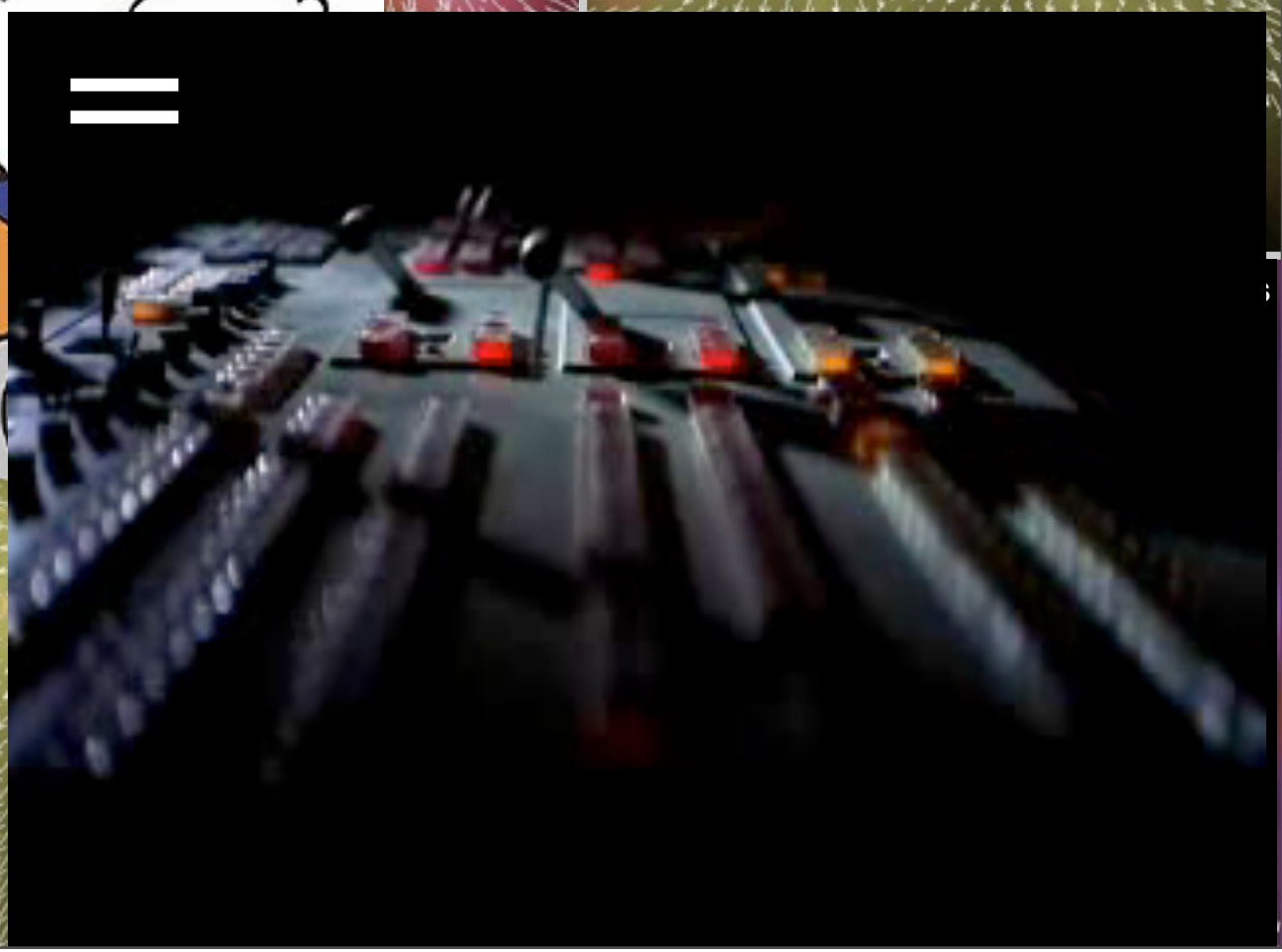
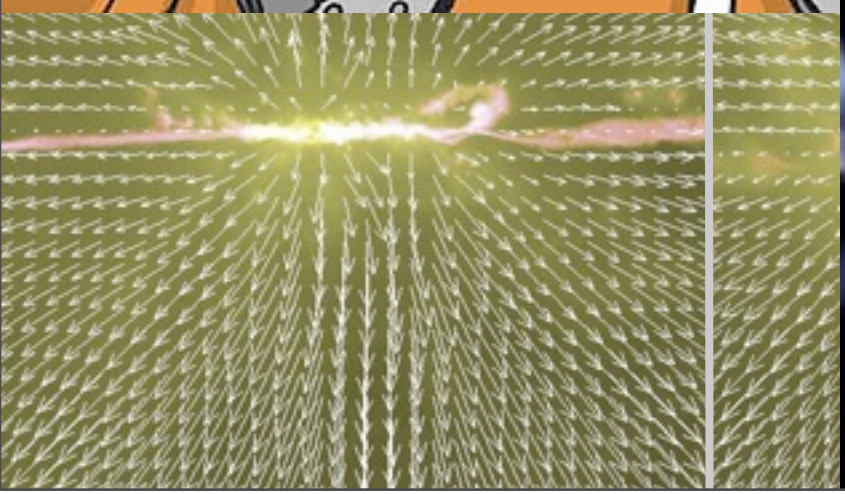
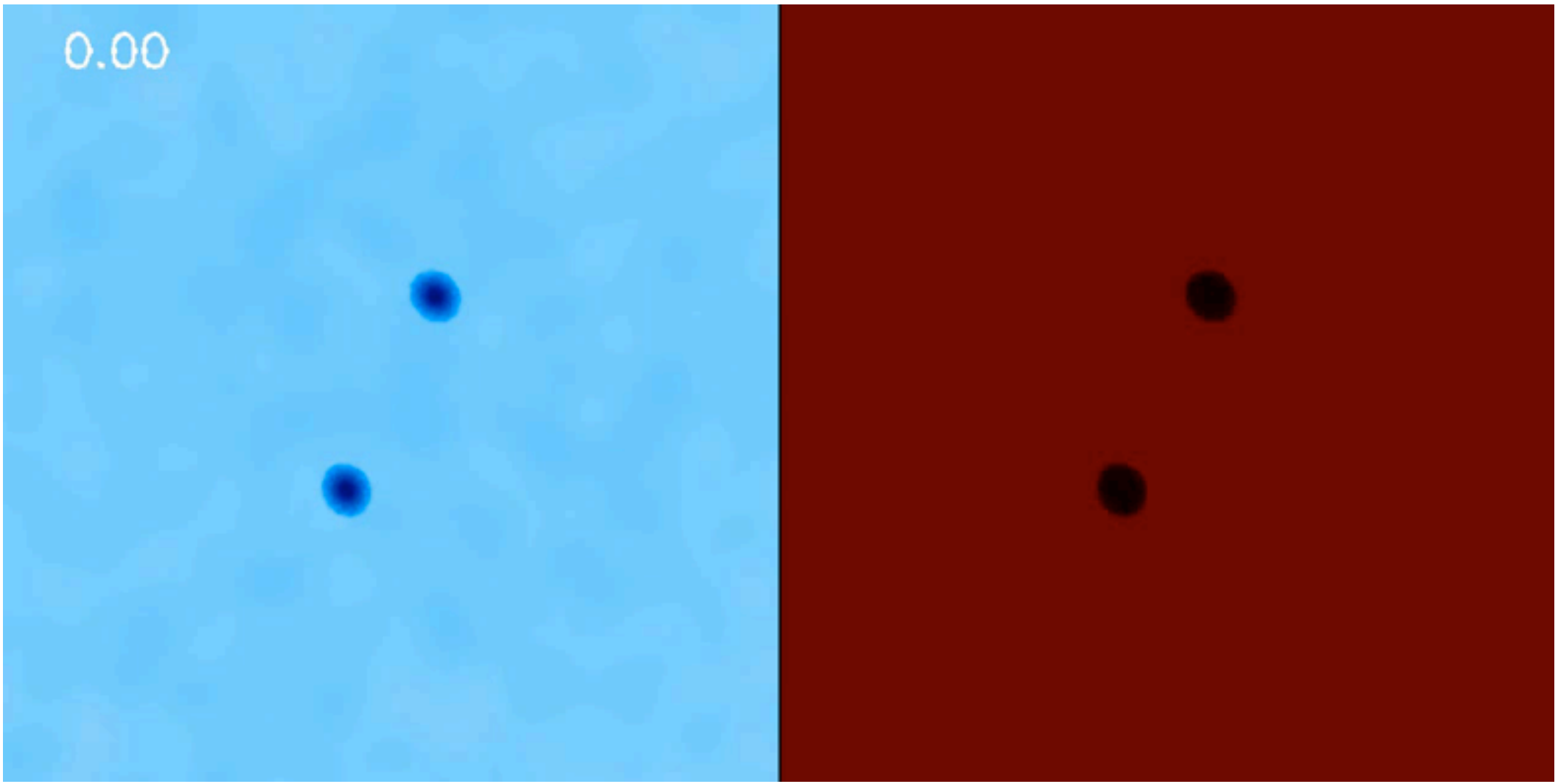




Quasar Outflows May Be Significant for the ICM & IGM

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

Gas Density | **Gas Temperature**



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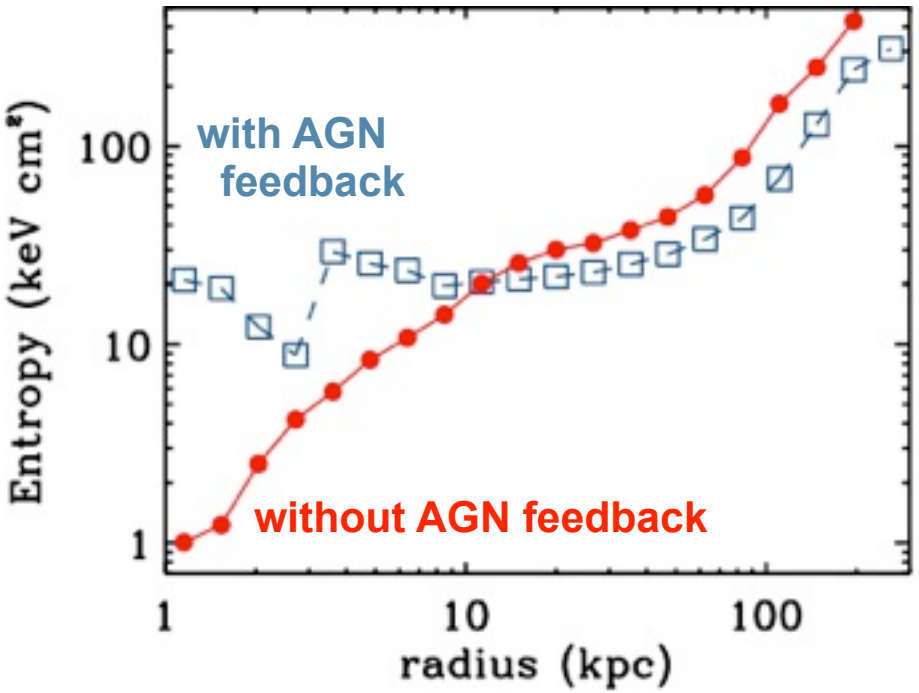
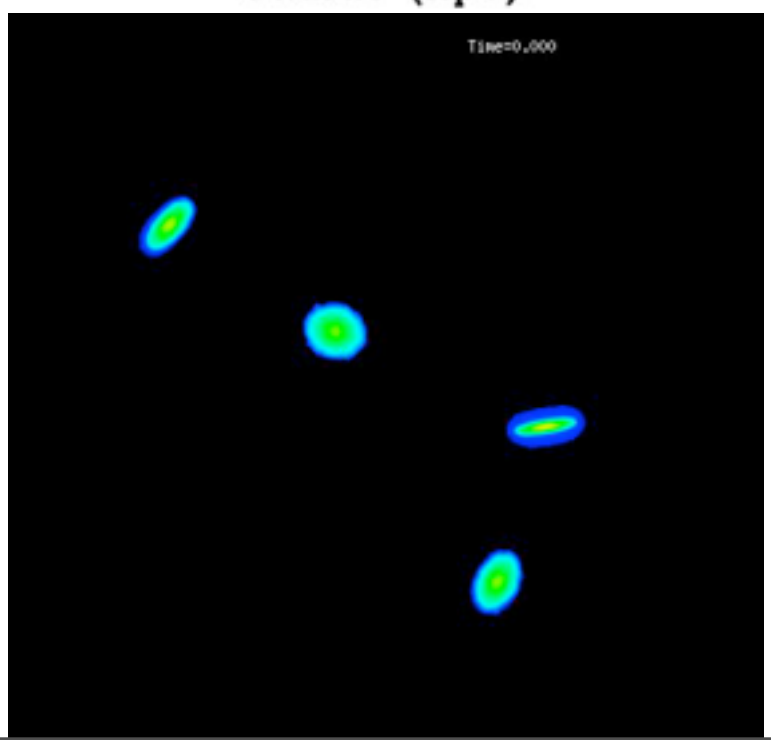
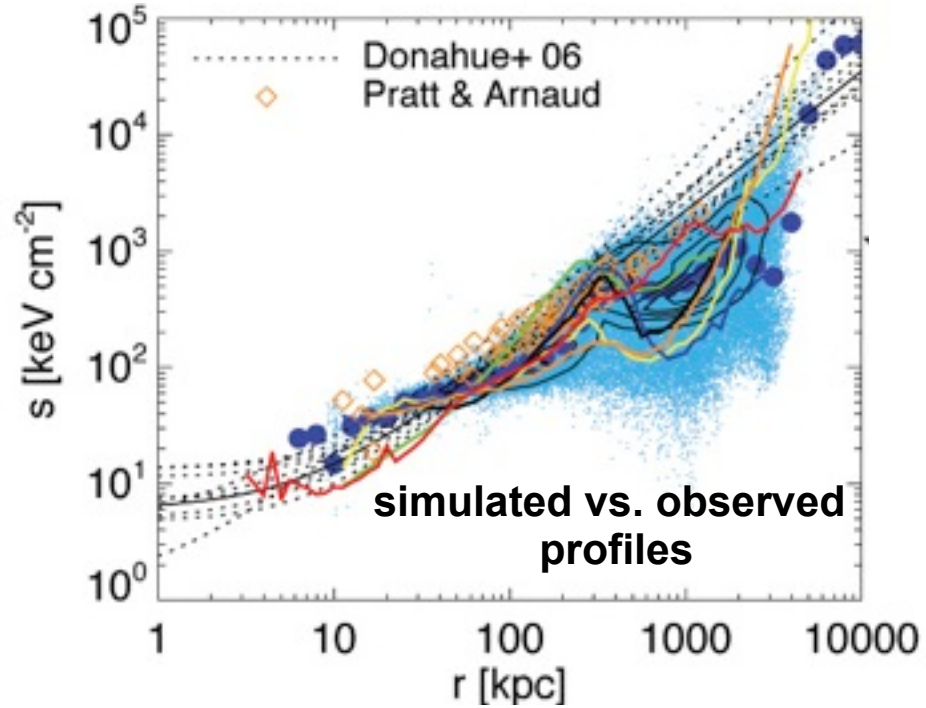
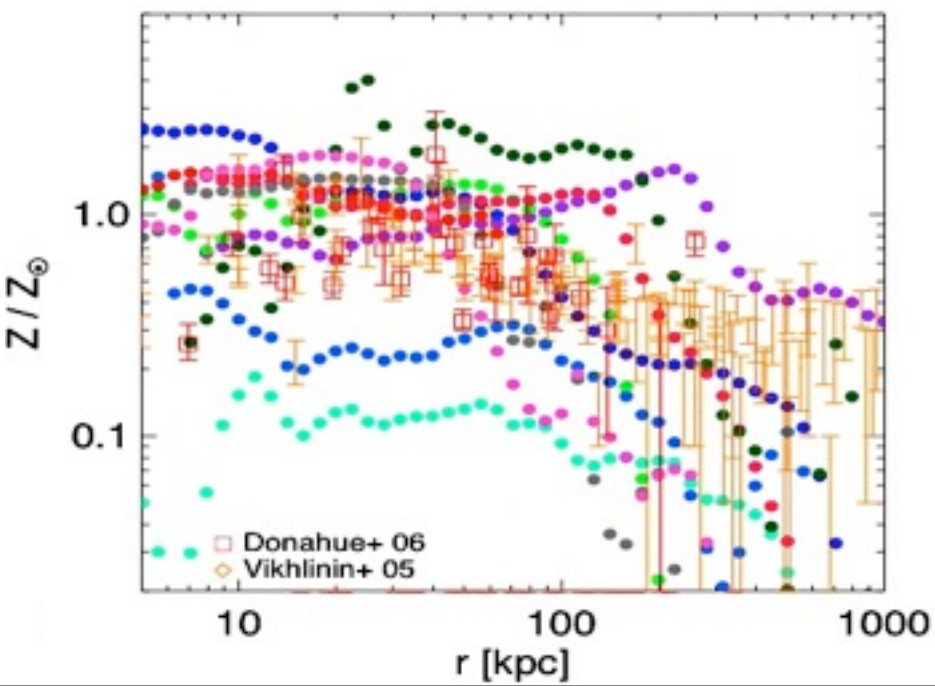


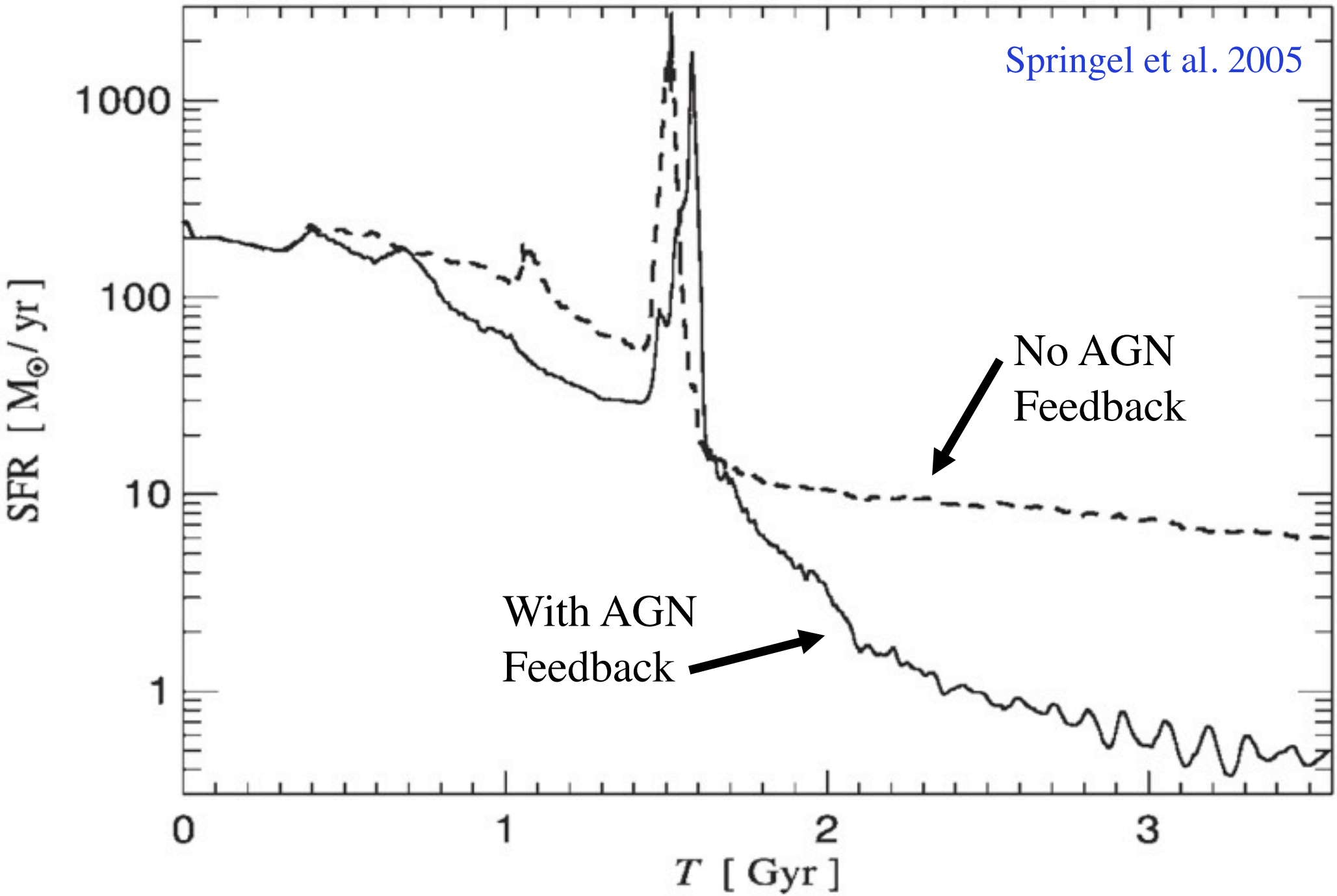






Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



BUT, This is Not the Only Possibility!

EXPERIMENTS WITH RADIATION PRESSURE

- Problem: Cooling times at densities near BH ~ 0
- BUT, photons have an irreducible momentum

Dust in host absorbs radiation

$$F_{\rm rad} = \tau \frac{L}{c}$$

Set equal to $F_{gravity}$, get a galaxy-scale Eddington limit:

$$L_{\rm max} \sim \frac{4\, f_{\rm gas}\, \sigma^4\, c}{G}$$

Why Not Just Couple the Momentum Directly?

EXPERIMENTS WITH RADIATION PRESSURE

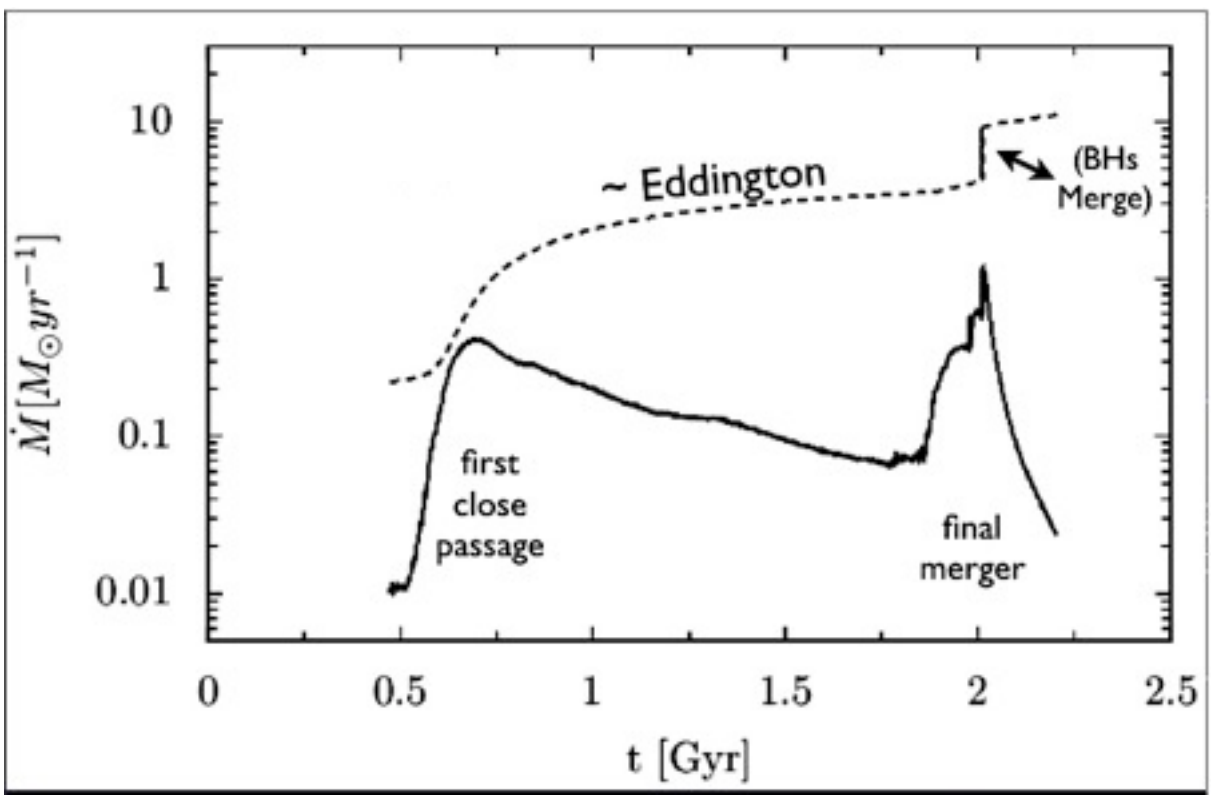
- New simulations in DeBuhr et al. 2009: add feedback force from radiation:

$$F_{\rm rad} = \tau \frac{L}{c}$$

$\tau \sim 10$

Radial momentum flux

Couple to nearest ~500-2000 particles

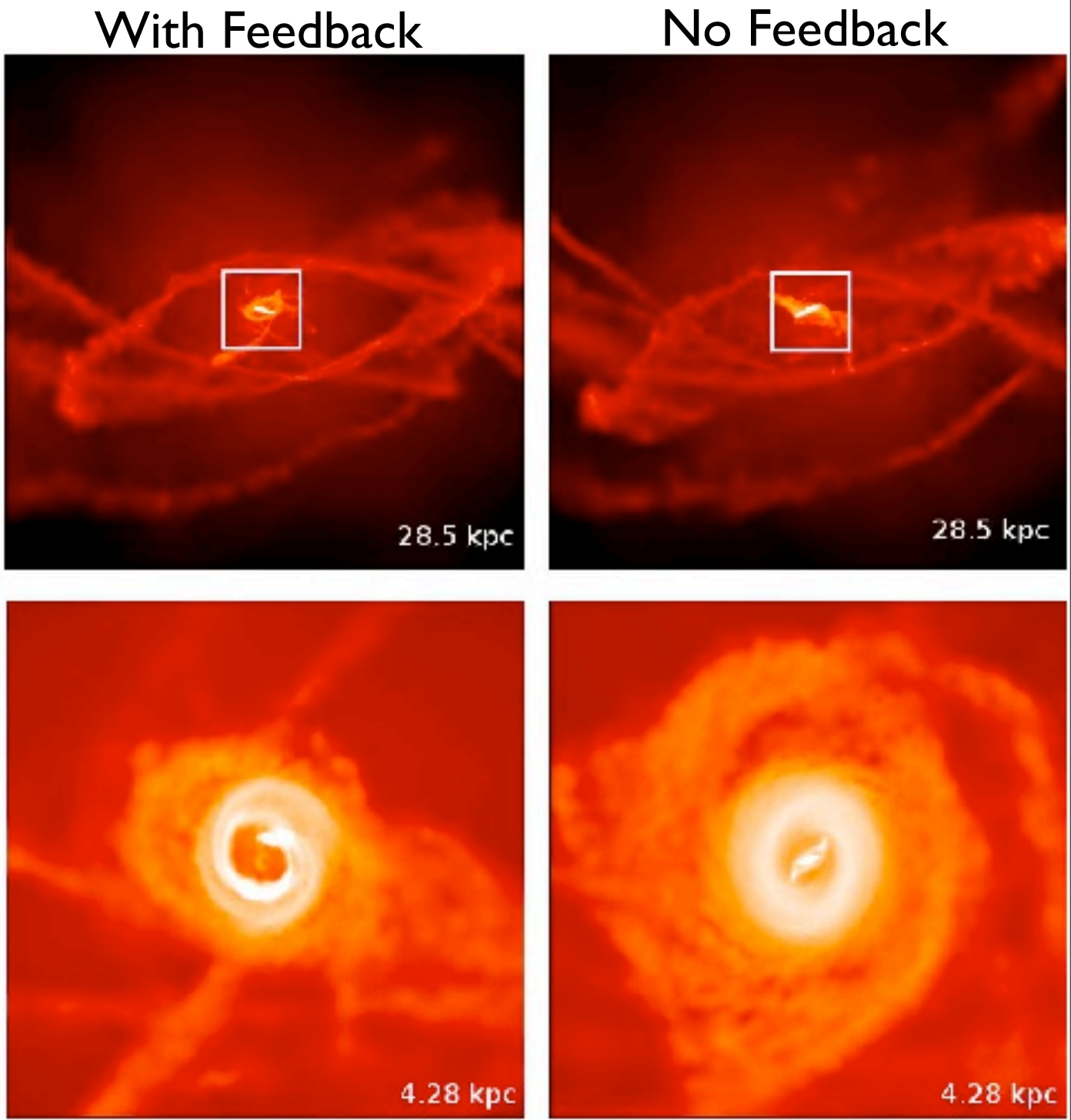


- Get self-regulated BH growth!

But.....

- BH growth self-regulates on ~kpc scales, but with no galaxy scale "blowout"!

- Depending on FB & accretion rate couplings, can simply "hold up" the gas at intermediate scales



Q. Despite this, can we say some global things about AGN feedback and galaxies?

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A. Yes.

Q. Despite this, can we say some global things about AGN feedback and galaxies?

A. Yes. I Think.

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?

1. Even with the most optimistic assumptions, stellar FB dominates over AGN FB in star-forming, disk-dominated galaxies

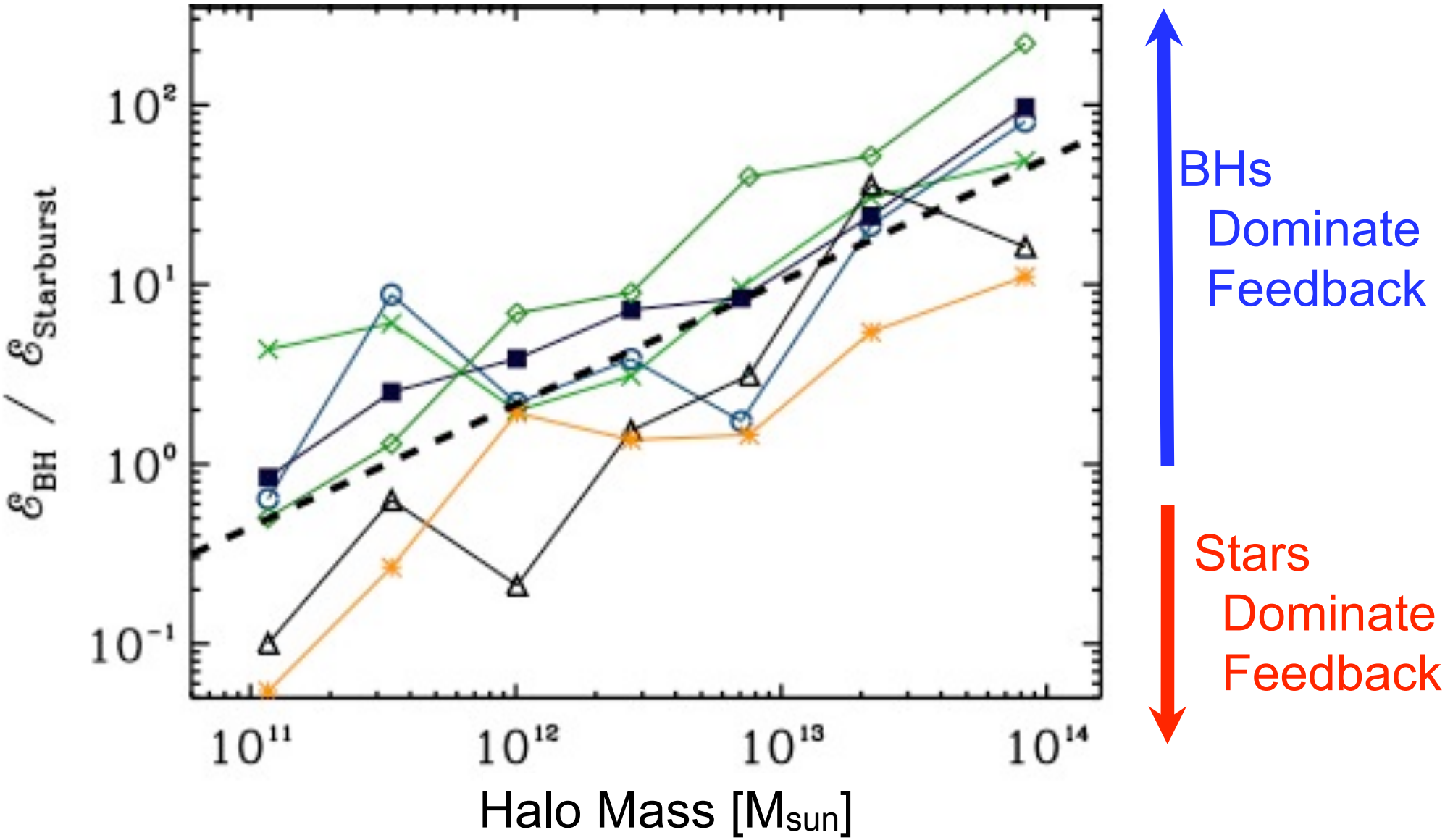
Total $E_{AGN} \sim E_{Supernovae}$ for a bulge-dominated galaxy.

But the E_{AGN} comes in a very short burst

PFH, Cox et al. 2007

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?



PFH, Cox et al. 2007

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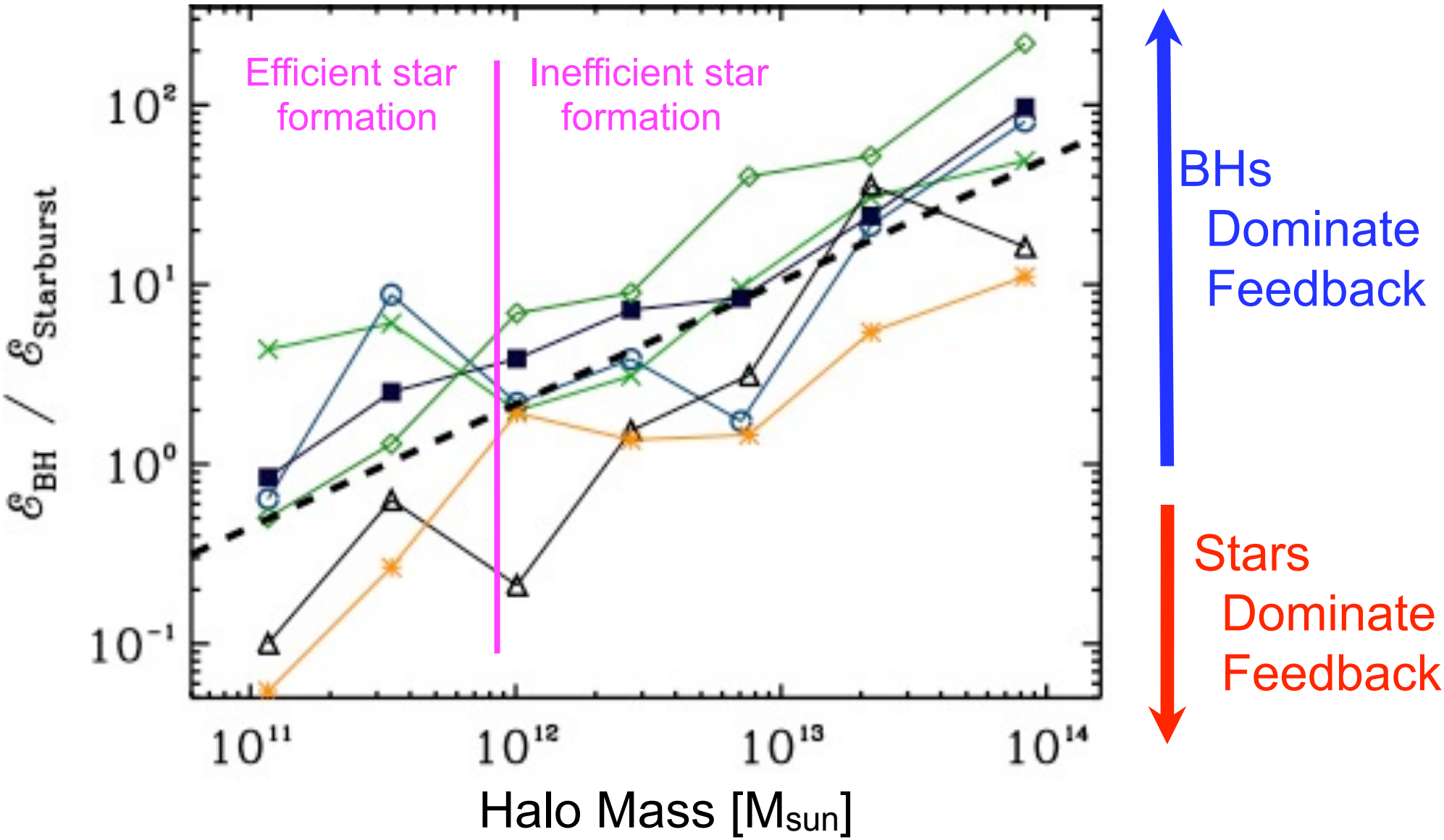

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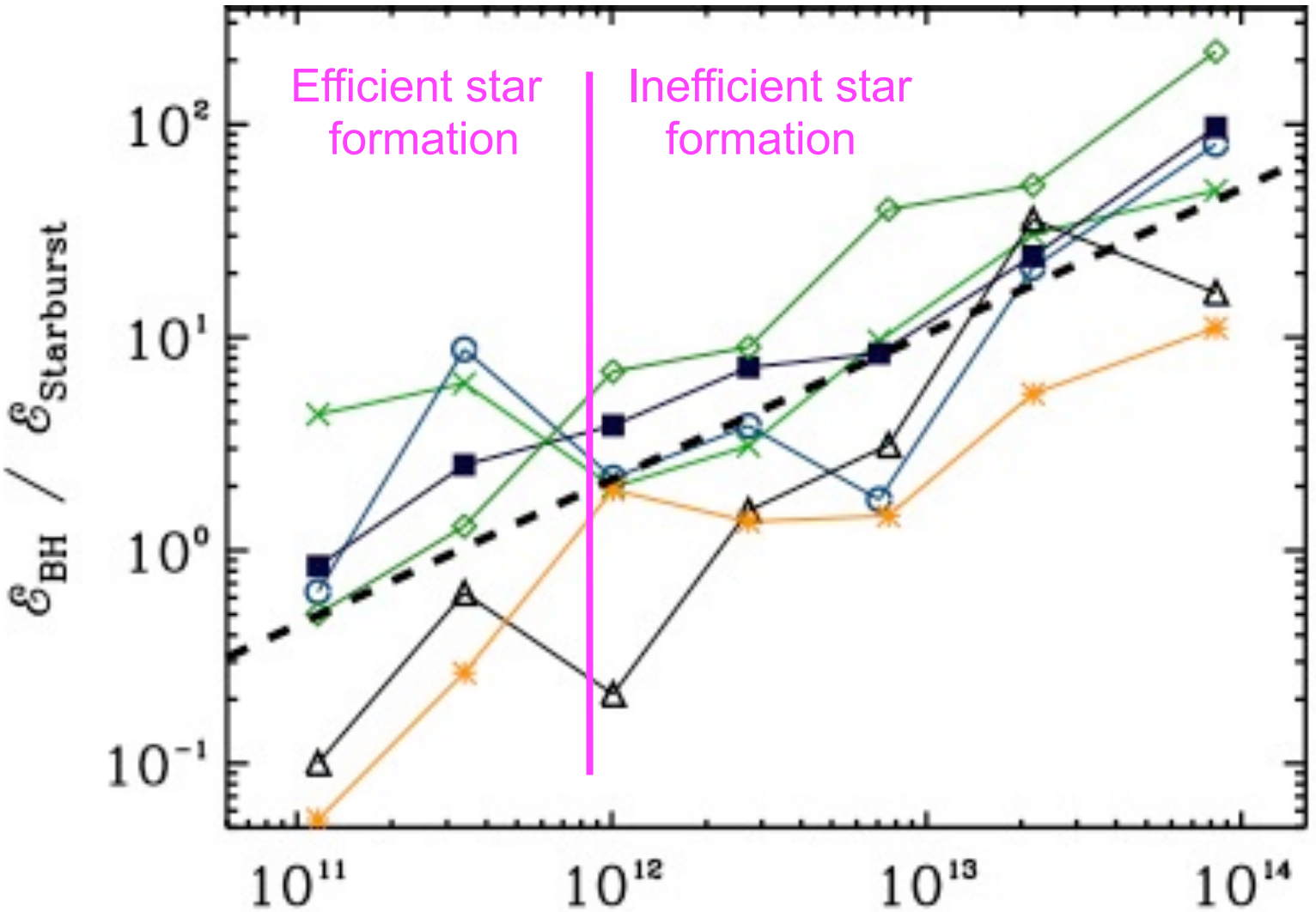


BHs Dominate Feedback

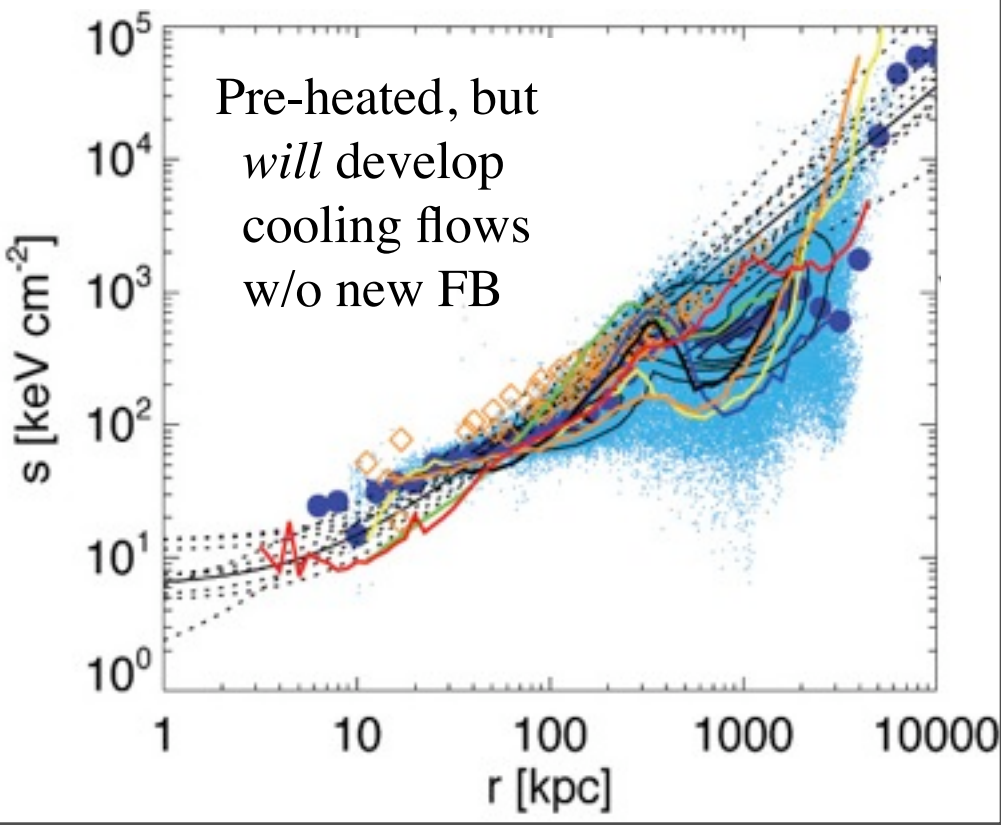
Stars Dominate Feedback

How is this inefficient star formation *maintained*?

2. Quasar-mode feedback will not solve the cooling-flow problem

Clusters with cooling flows do *not* have quasars!

Even optimistic models cannot halt ~10 Gyr of future cooling



"Transition" vs. "Maintenance"

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

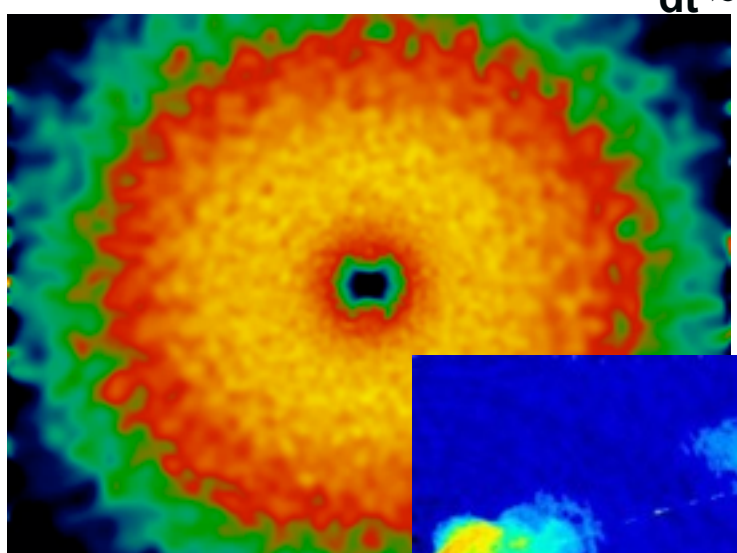
Proga et al.

dt ~ 10^6 yr

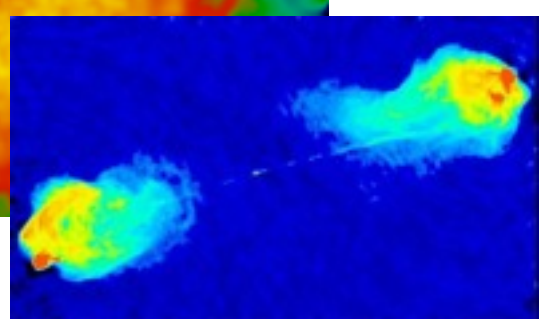
- Regulates *Black Hole* Mass

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

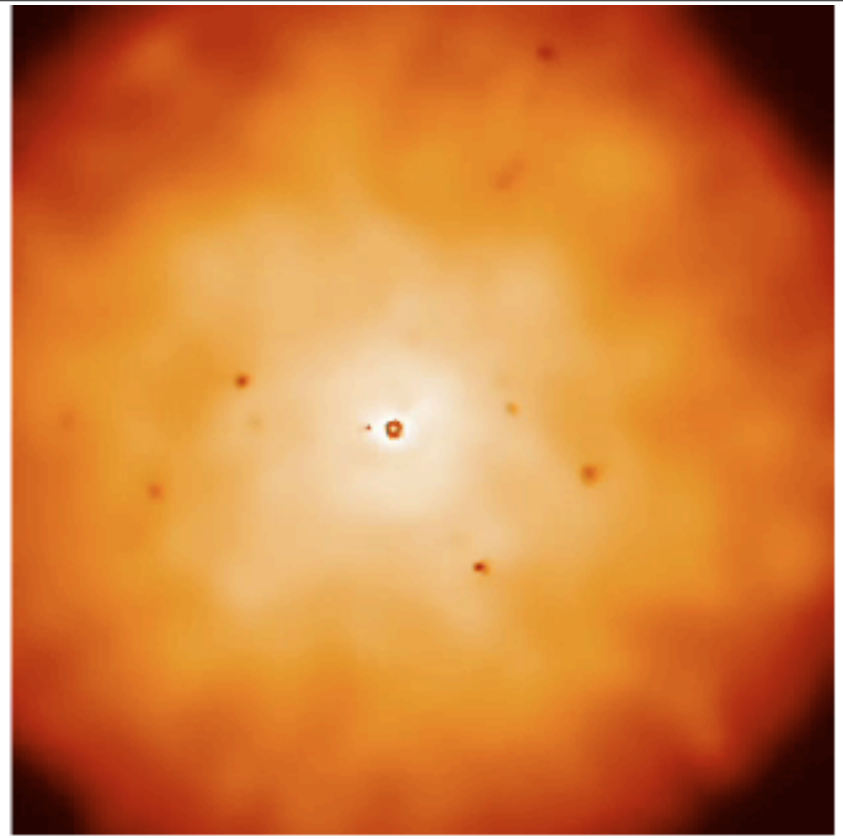
dt ~ 10^{10} yr

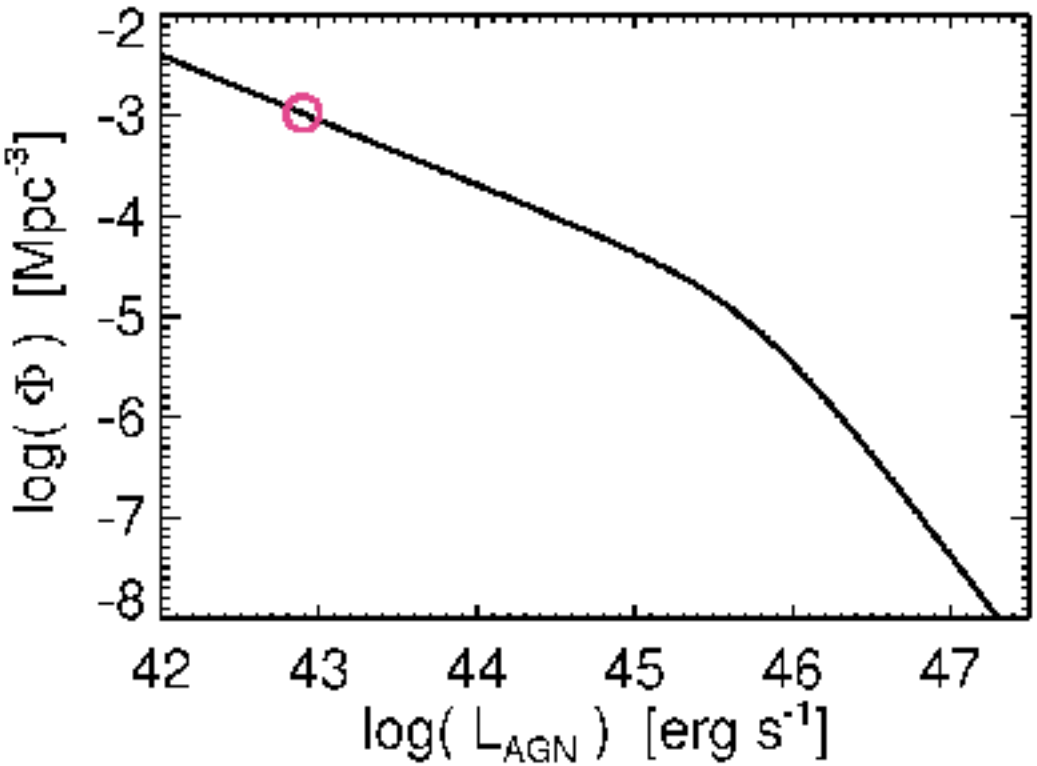


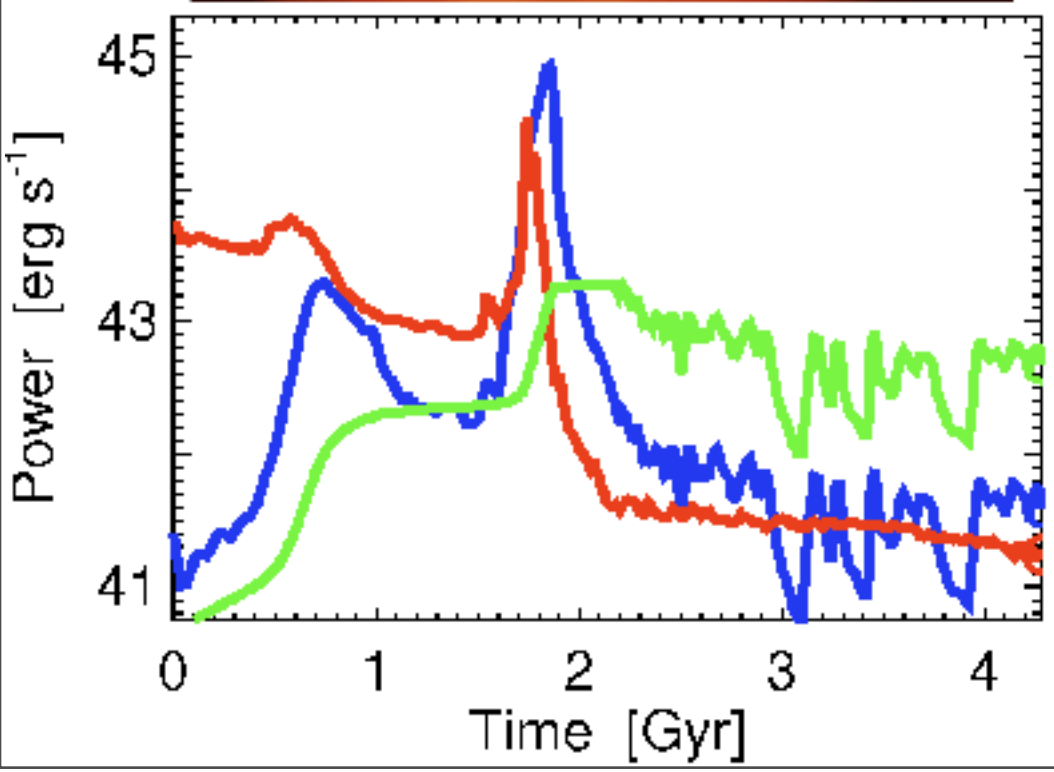
Sijacki et al.

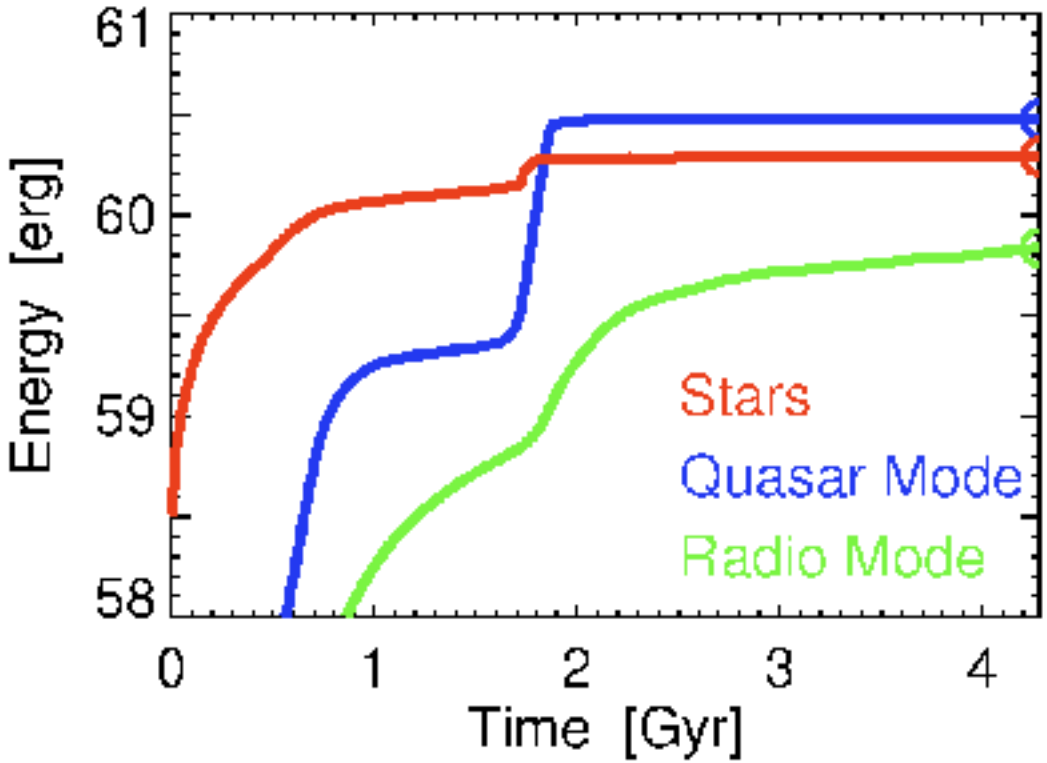


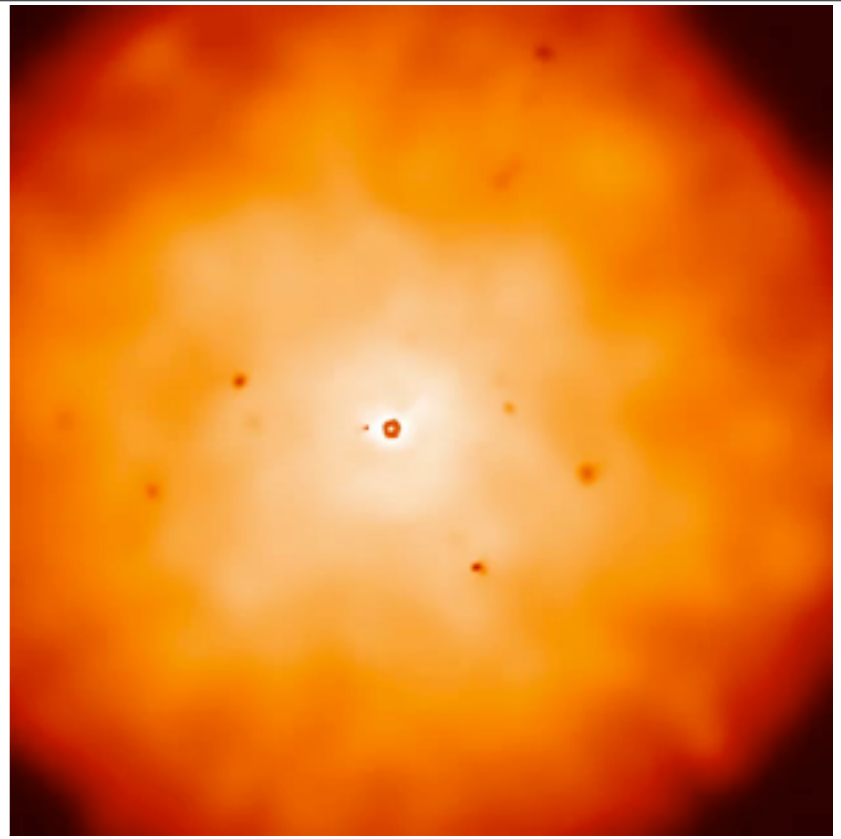
- Regulates *Galaxy* Mass

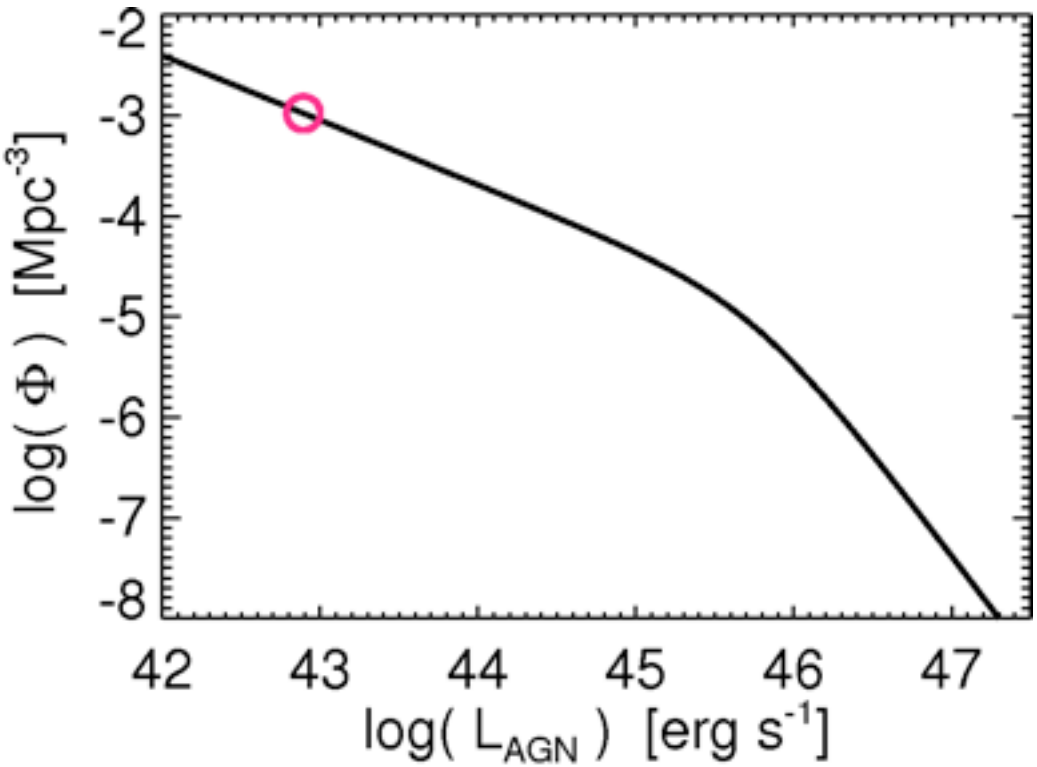


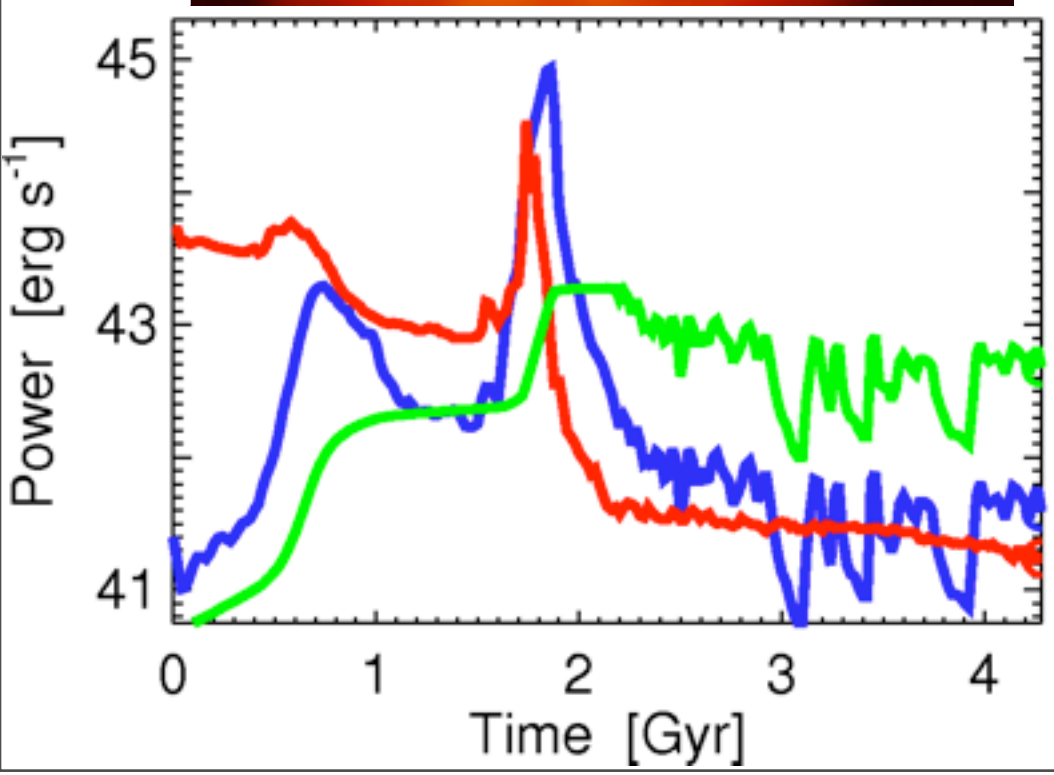

log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]

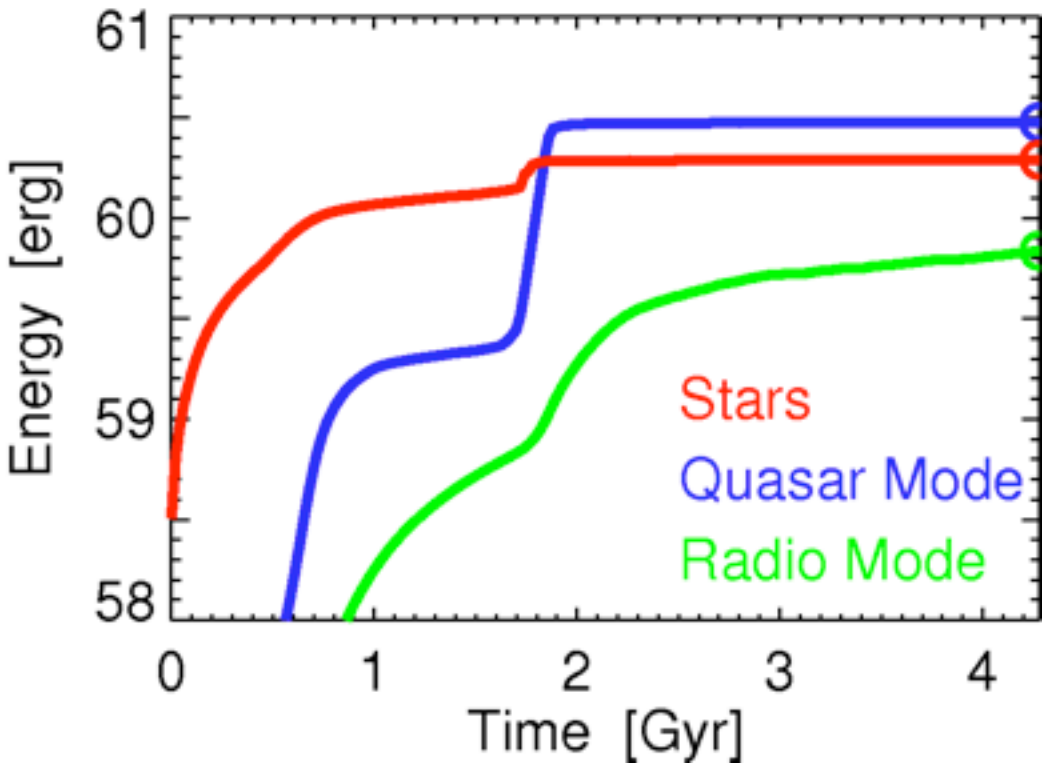

Power [erg s^{-1}]
45
43
41
0
1
2
3
4
Time [Gyr]


Energy [erg]
61
60
59
58
0
1
2
3
4
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

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: Inside-out formation via mergers

- How do disks *survive* mergers? (How do we ***avoid*** making all ellipticals?)
  - Gas! No stars = No angular momentum loss
  - Particularly important at high-*z*
  - Drives the starburst history of the Universe... but not always as you'd expect

- Don't forget about black holes and AGN!
  - M-sigma implies BHs formed in mergers?
  - Implies feedback: quasar-mode vs. radio-mode
  - Non-trivial AGN lifetimes & lightcurves

Can understanding the structure and scalings of galaxies be reduced to understanding their gas-consumption histories?