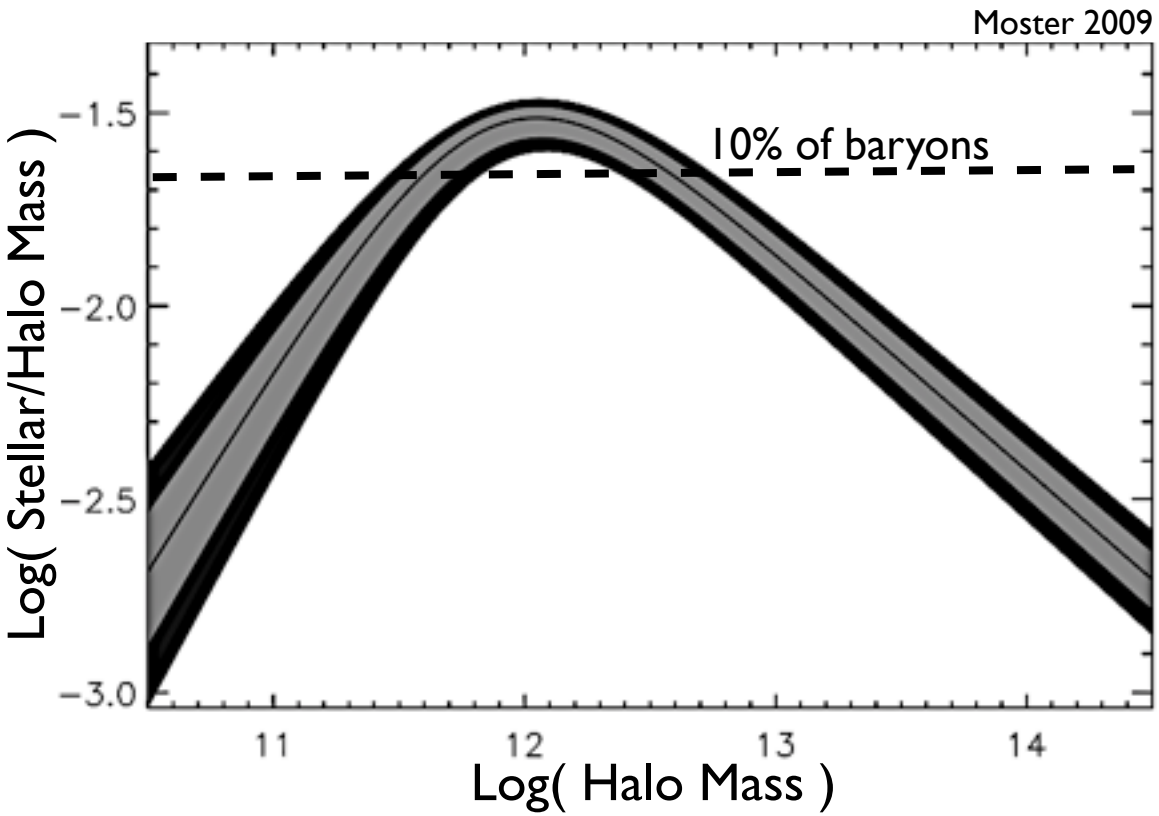
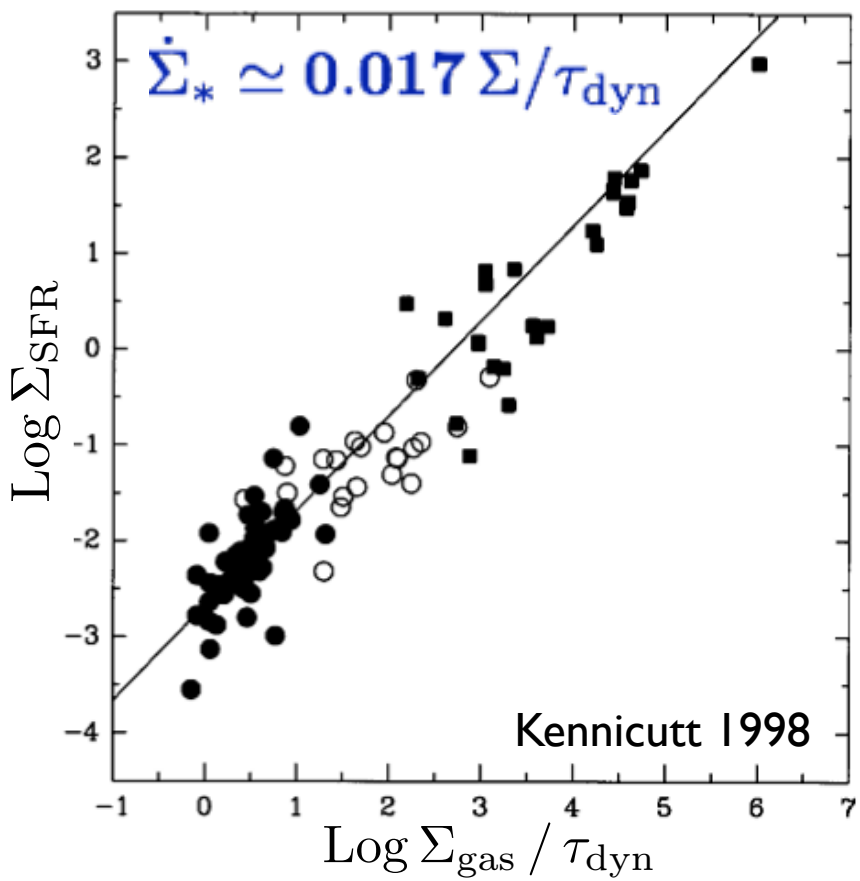
"Feedback," Star Formation, and AGN

Philip Hopkins

Eliot Quataert, Norm Murray,
Lars Hernquist, Dusan Keres, Todd Thompson, Desika Narayanan,
Dan Kasen, T. J. Cox, Chris Hayward, Kevin Bundy, & more

Q: WHY IS STAR FORMATION SO INEFFICIENT?





Stellar Feedback is (a/the) Key to Galaxy Formation!

SO WHAT'S THE PROBLEM?

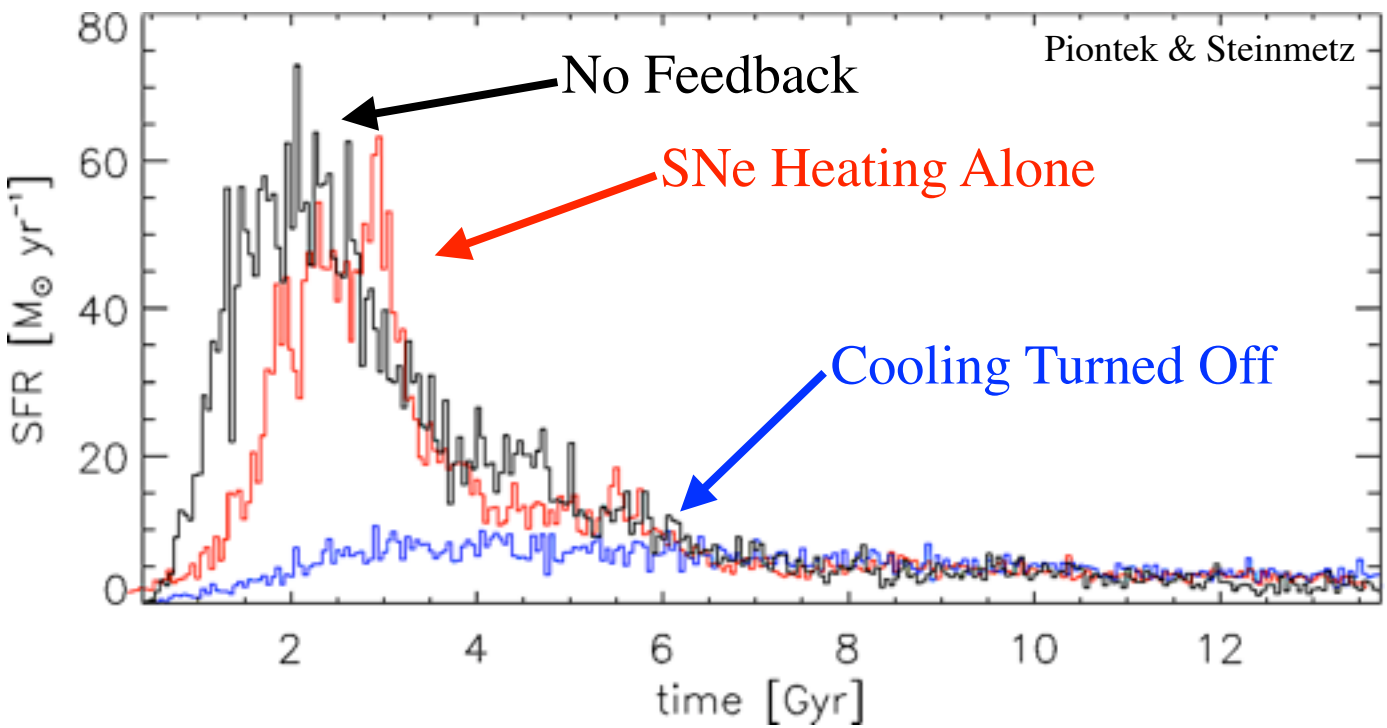
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- FAILS:

$$t_{\rm cool} \sim 4000\,{\rm yr}\left(\frac{n}{\rm cm^{-3}}\right)^{-1}$$

$$t_{\rm dyn} \sim 10^{8}\,{\rm yr}\left(\frac{n}{\rm cm^{-3}}\right)^{-1/2}$$

- "Cheat":
  - Turn off cooling
  - Force wind by hand
    ('kick' out of galaxy)



make really ~1 min

Stellar Feedback: How Can We Do Better?

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  - Stellar Winds
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- *Explicit* Momentum Flux:
  - Radiation Pressure

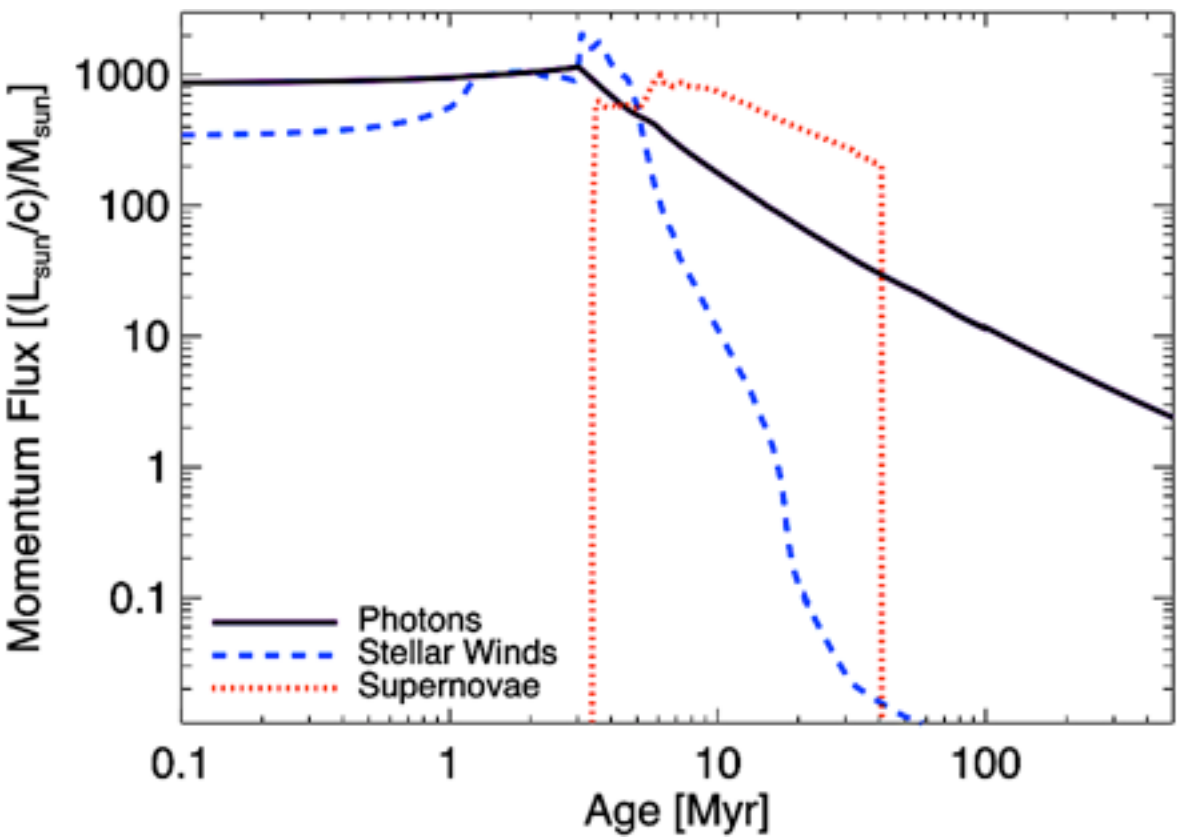
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

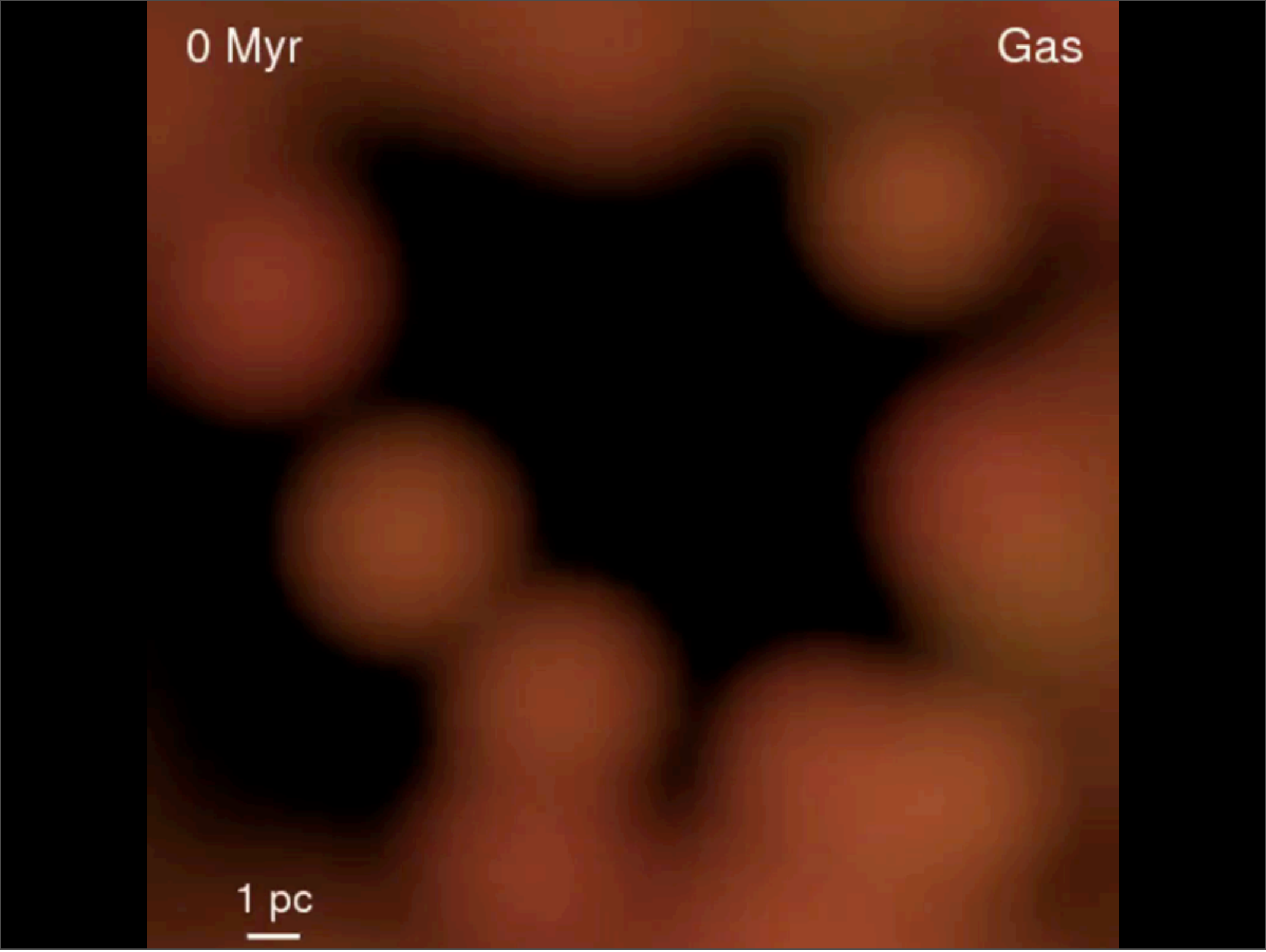
  - SNe

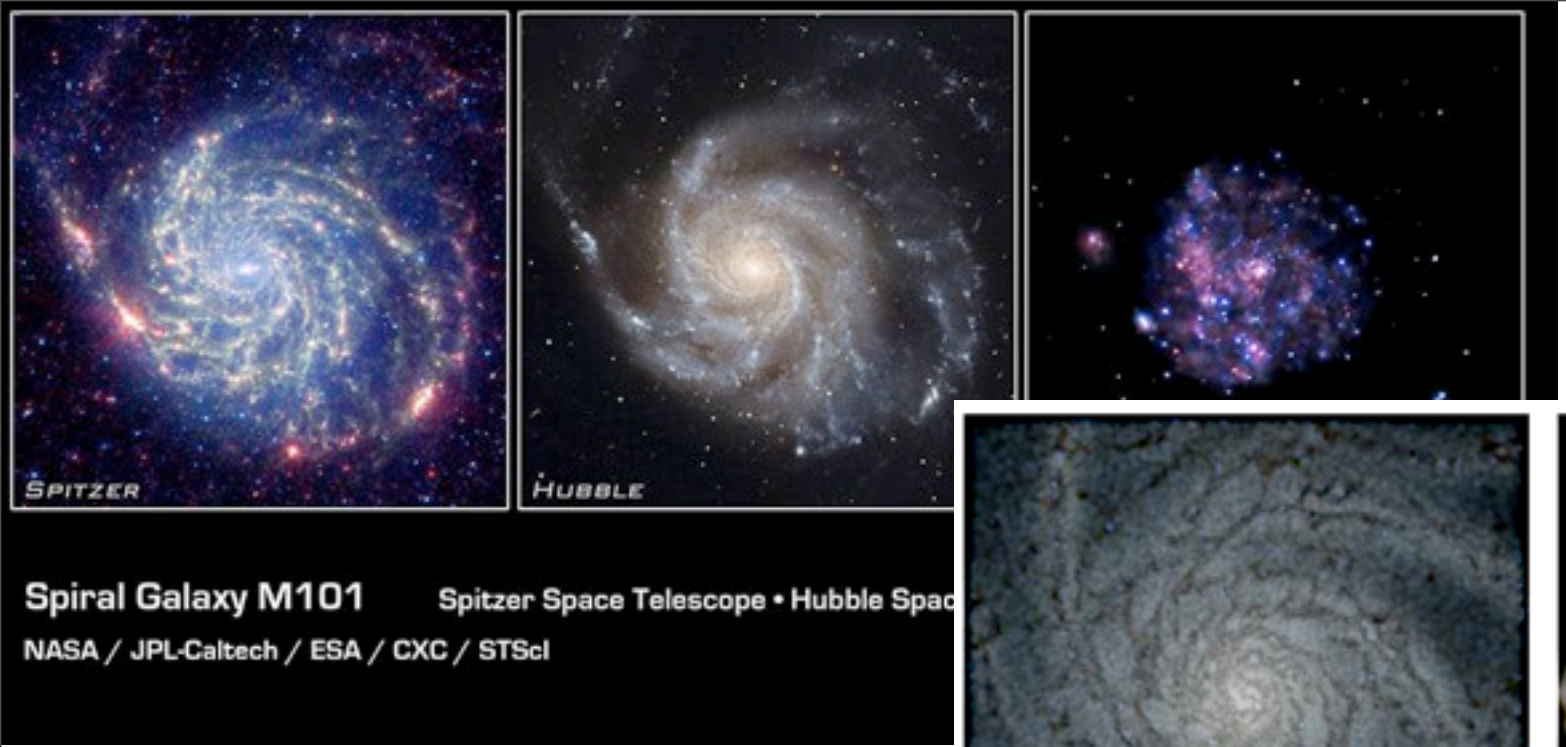
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

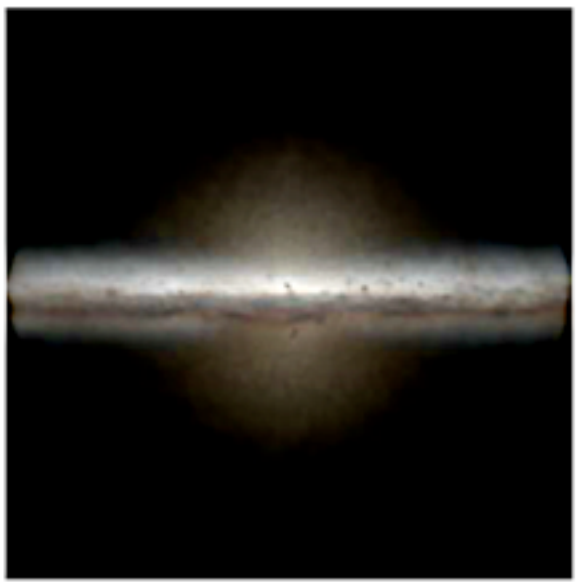
  - Stellar Winds

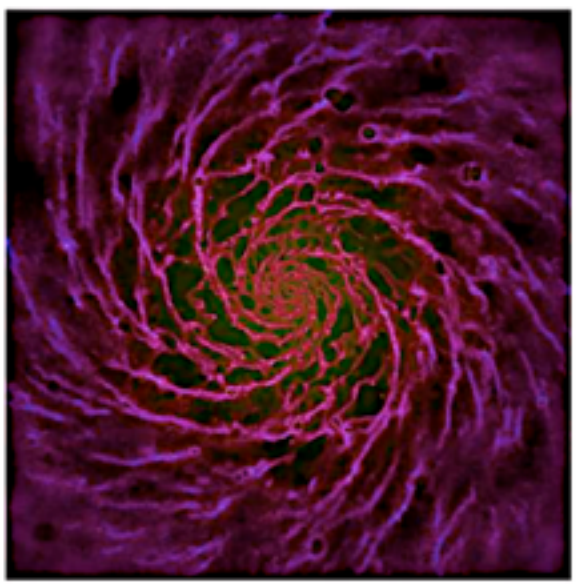
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

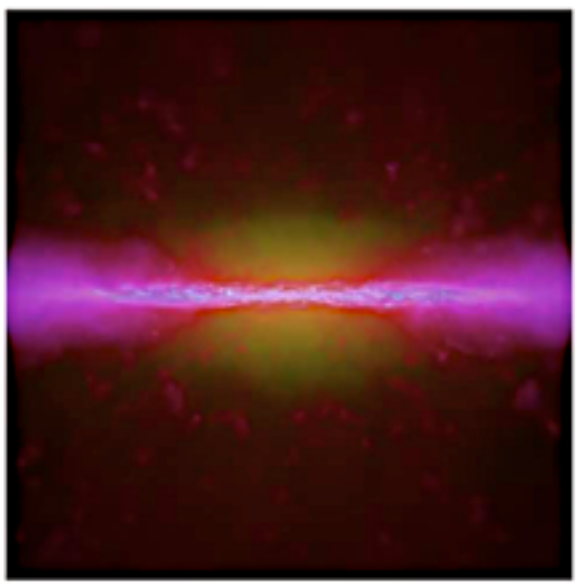



0 Myr
Gas
1 pc

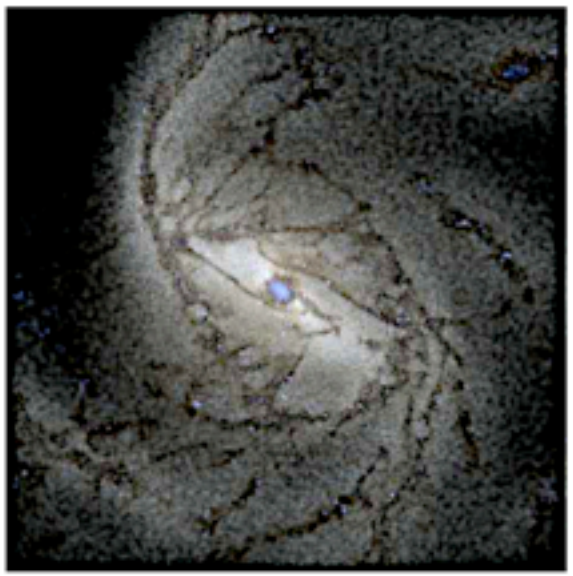


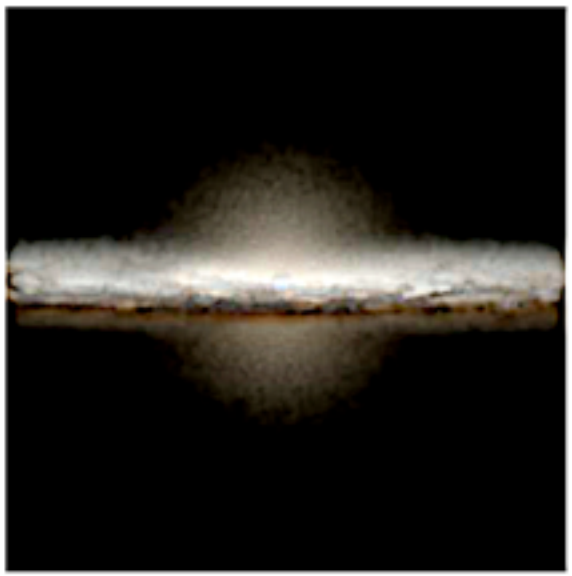


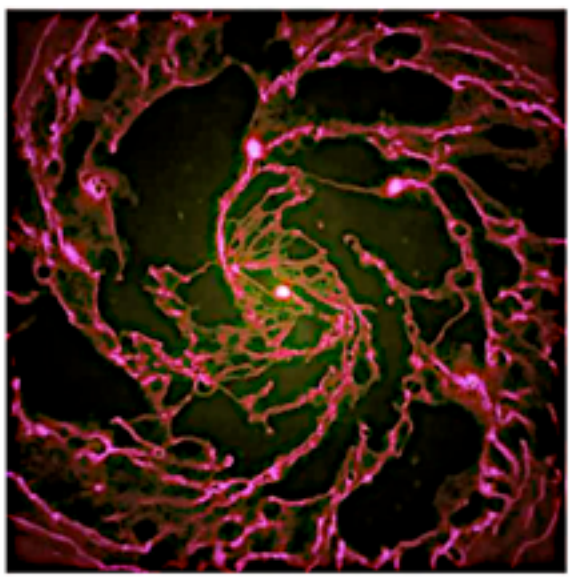


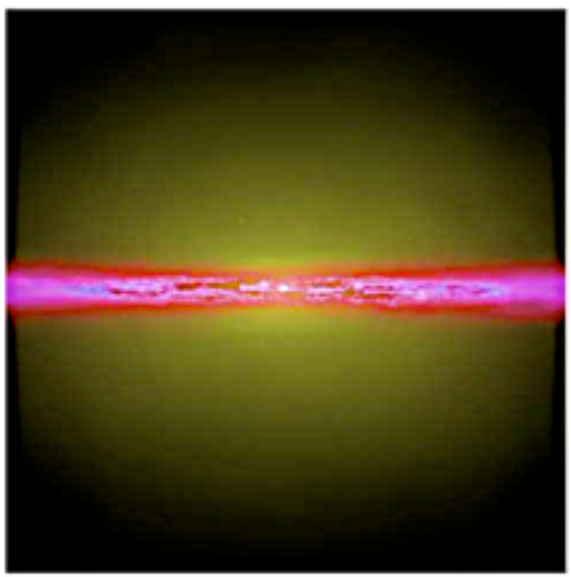


Hopkins, Quataert, & Murray, 2011









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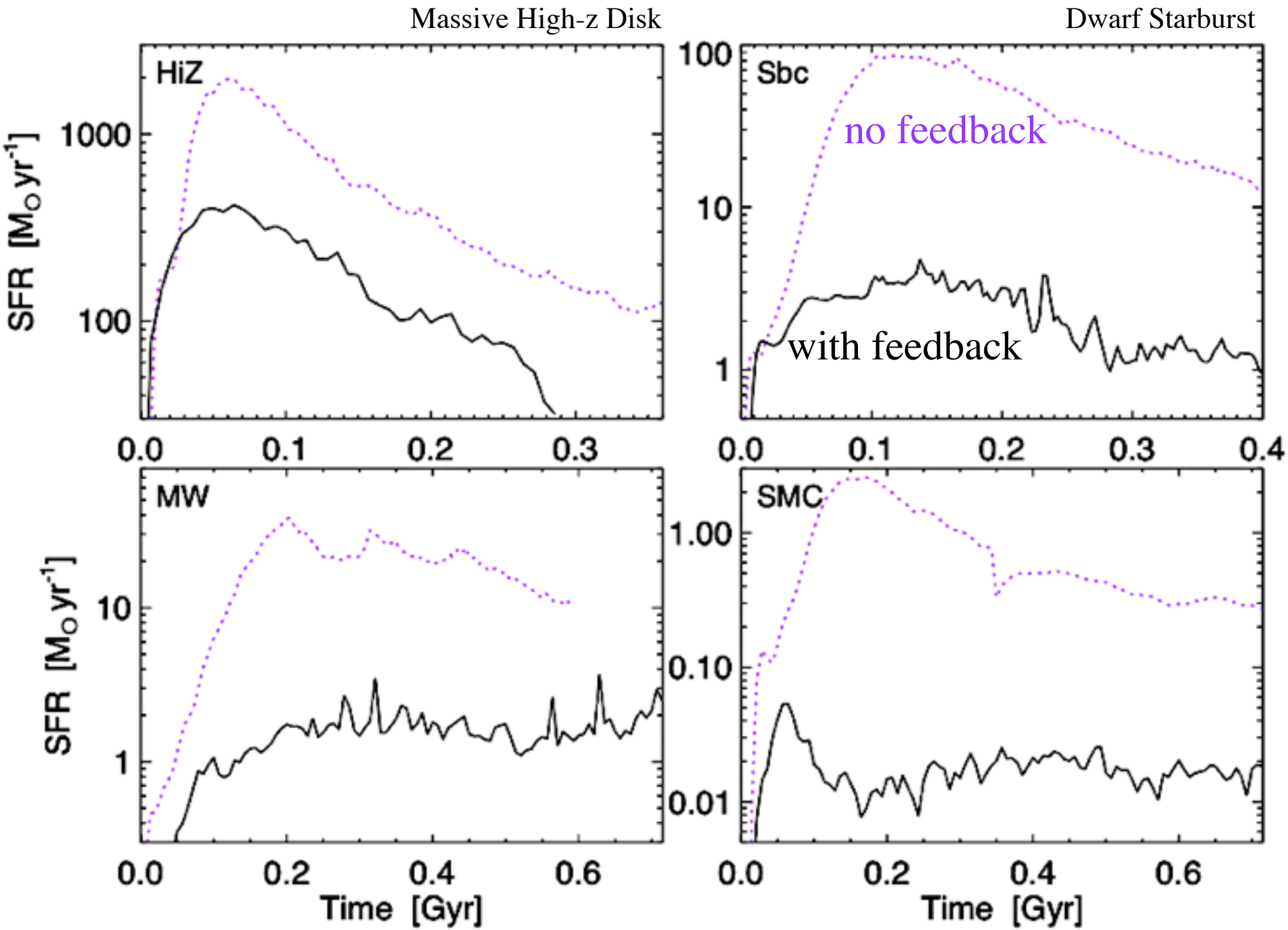
Stellar Feedback gives Self-Regulated Star Formation



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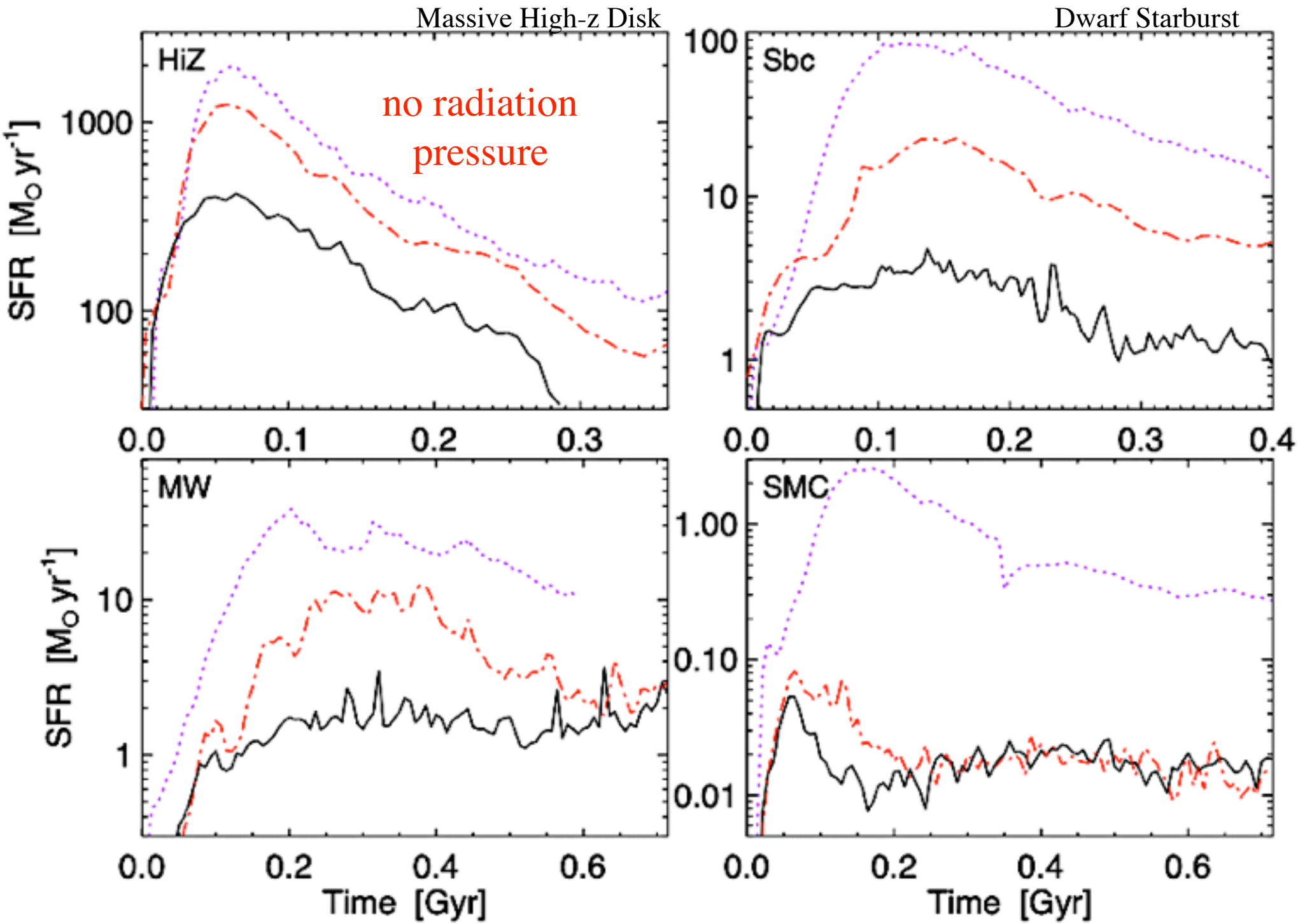

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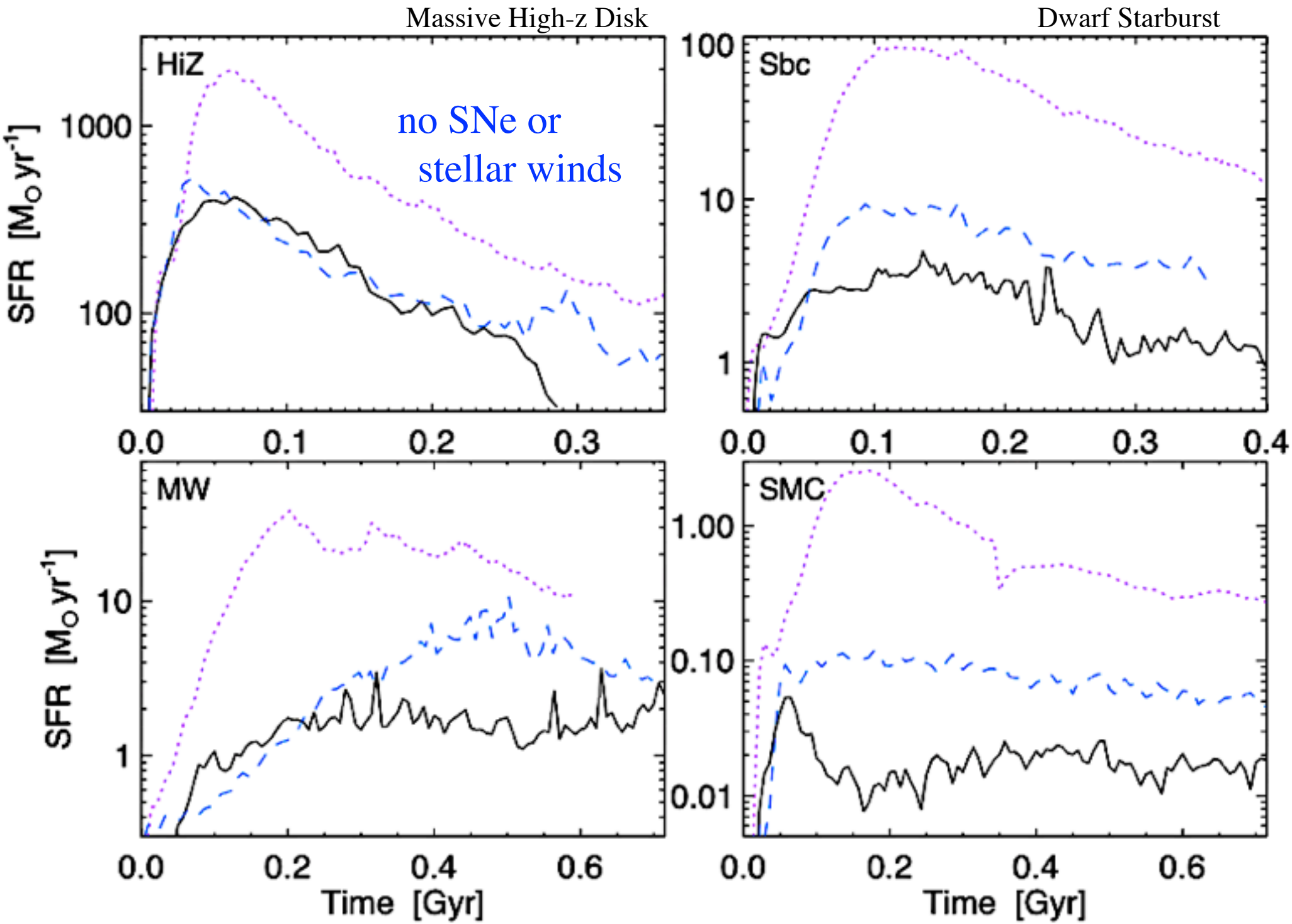
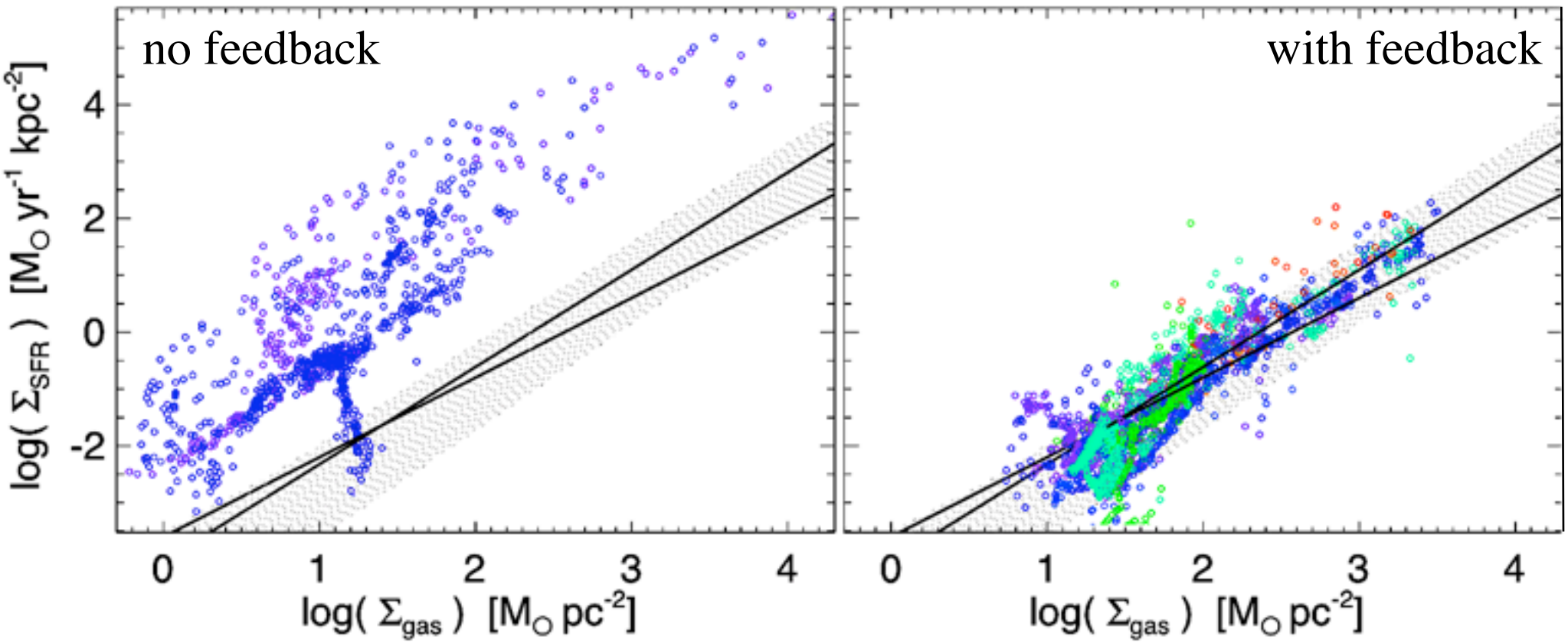


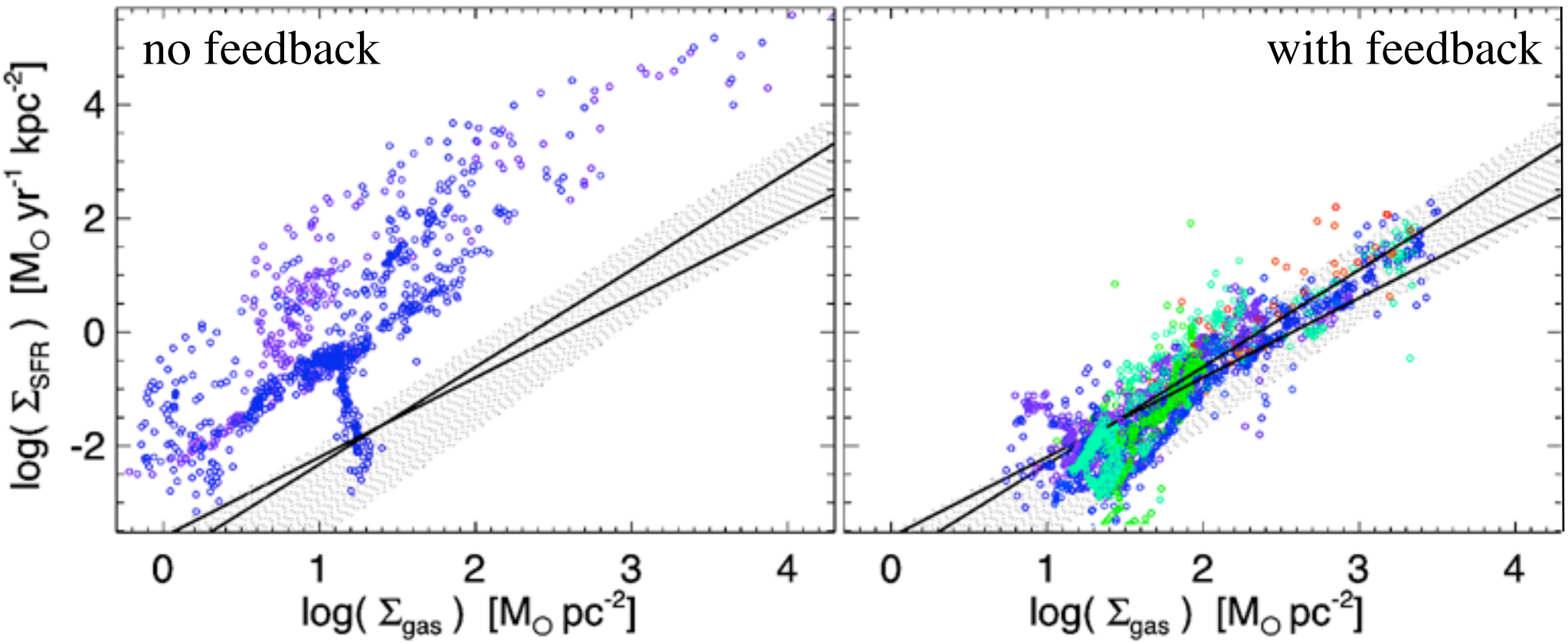
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally

$$\dot{\Sigma}_* \sim \Sigma_{\rm gas}/\tau_{\rm dyn}$$



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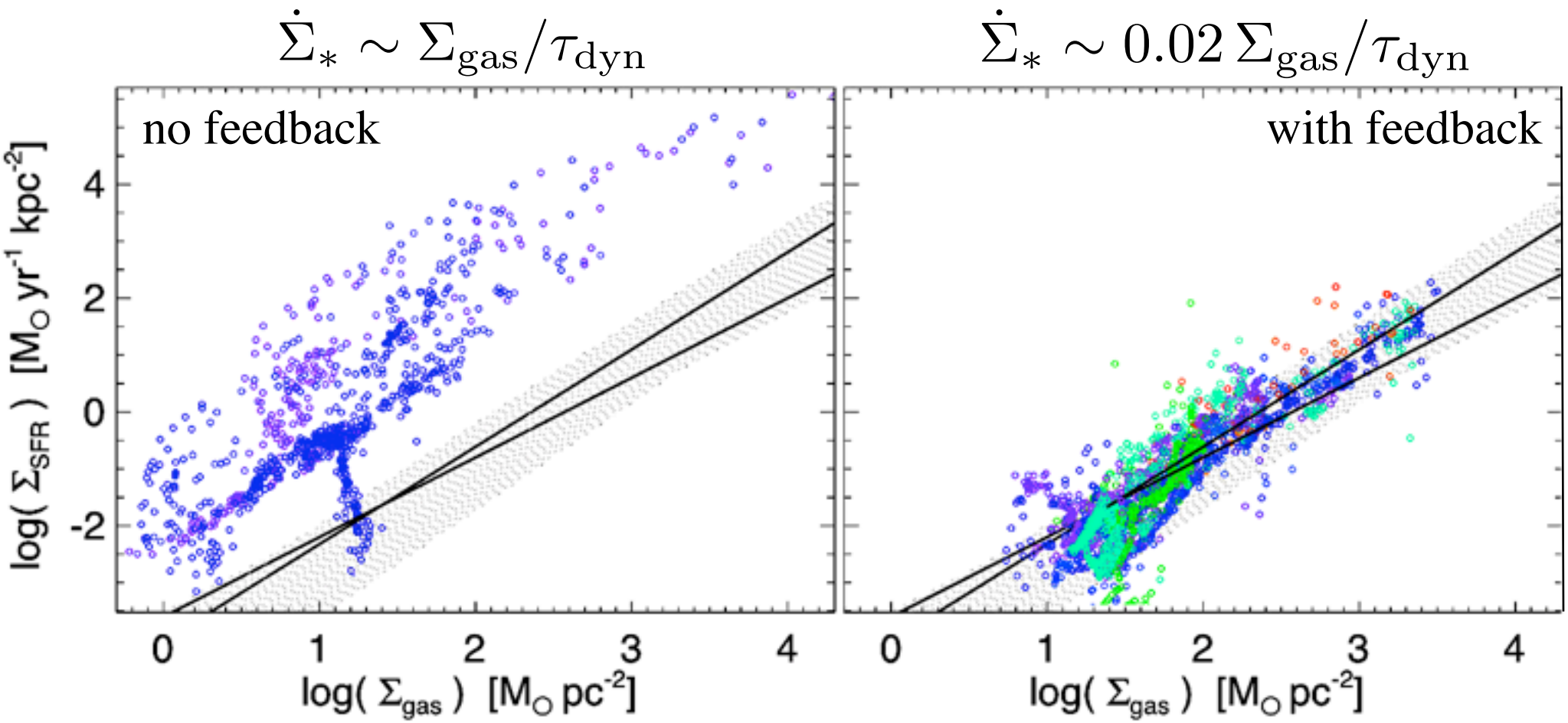

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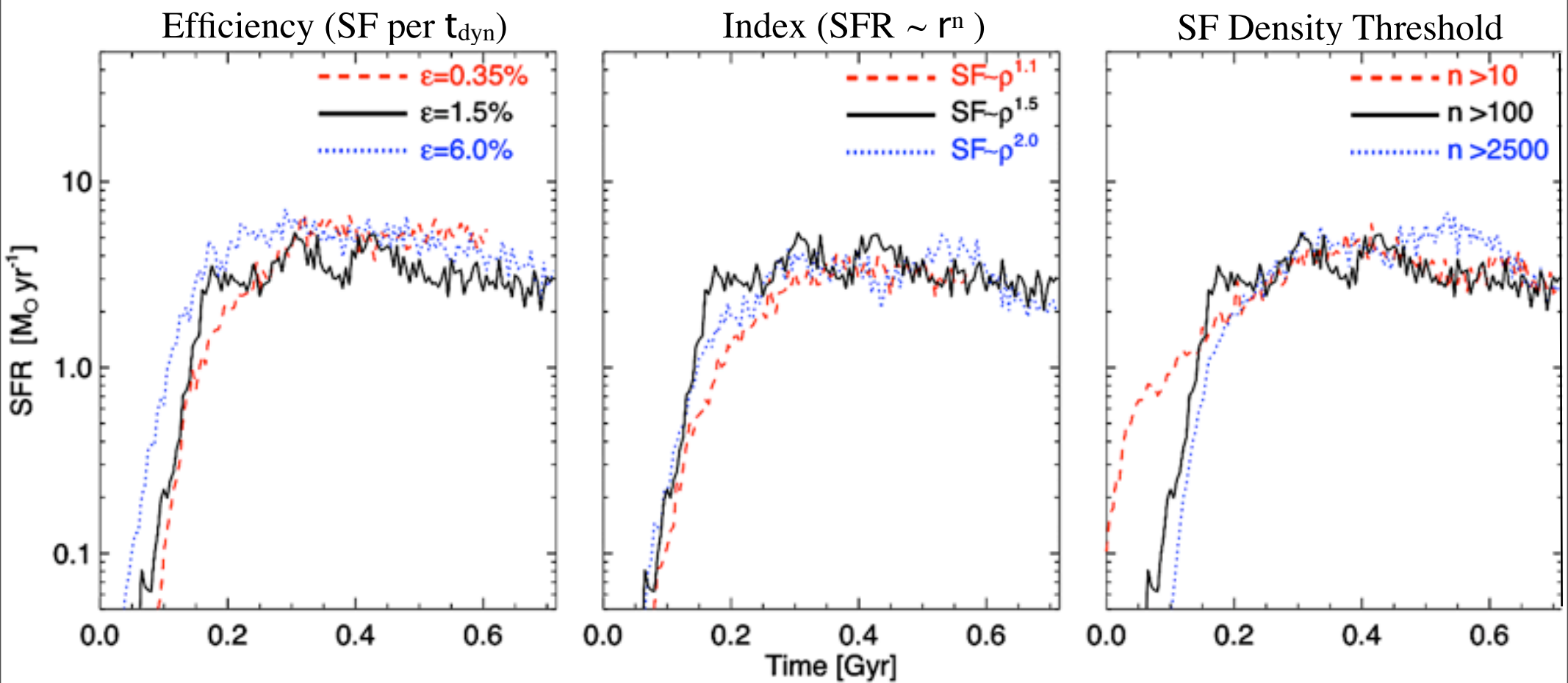
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas} \Omega \sim 0.02\, \Sigma_{\rm gas} \Omega$$

Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law



Hopkins, Quataert, & Murray 2011
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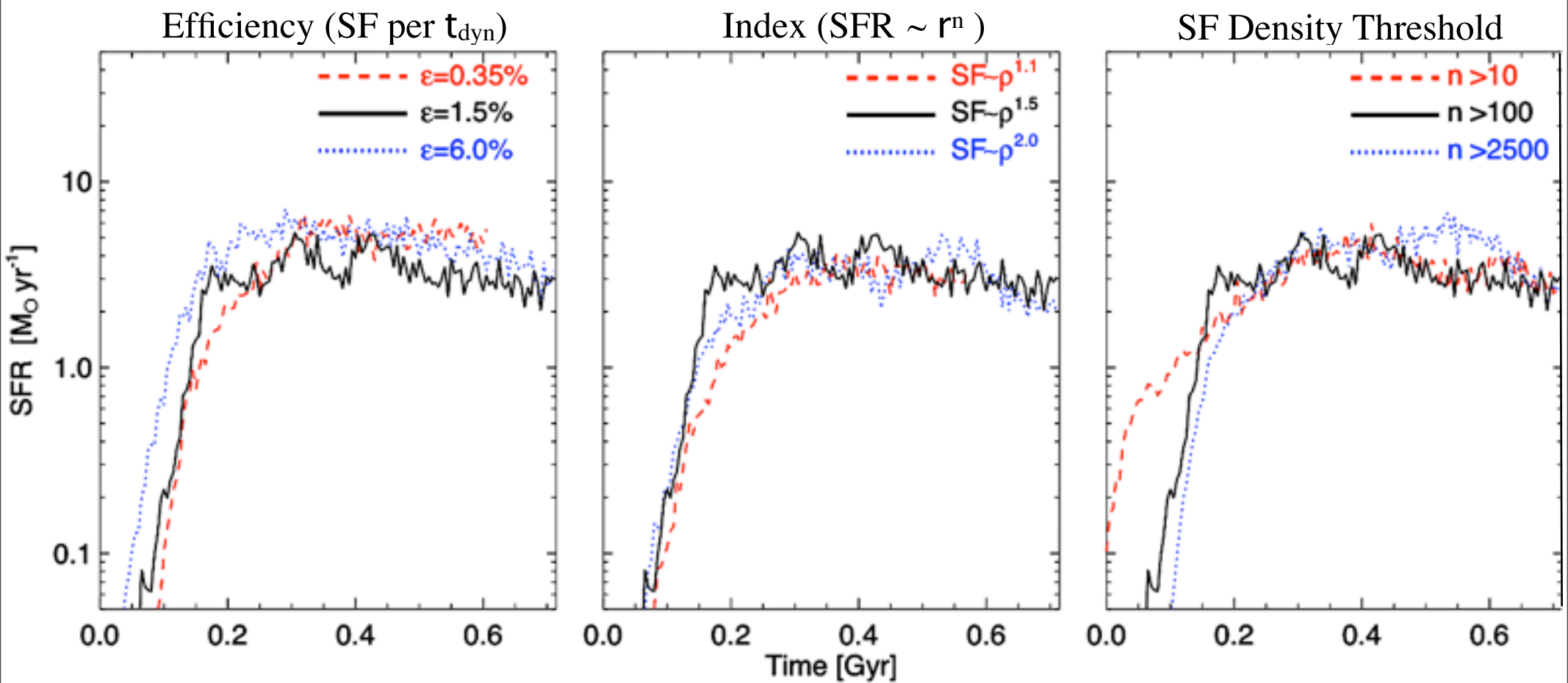

- Set by feedback (i.e. SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
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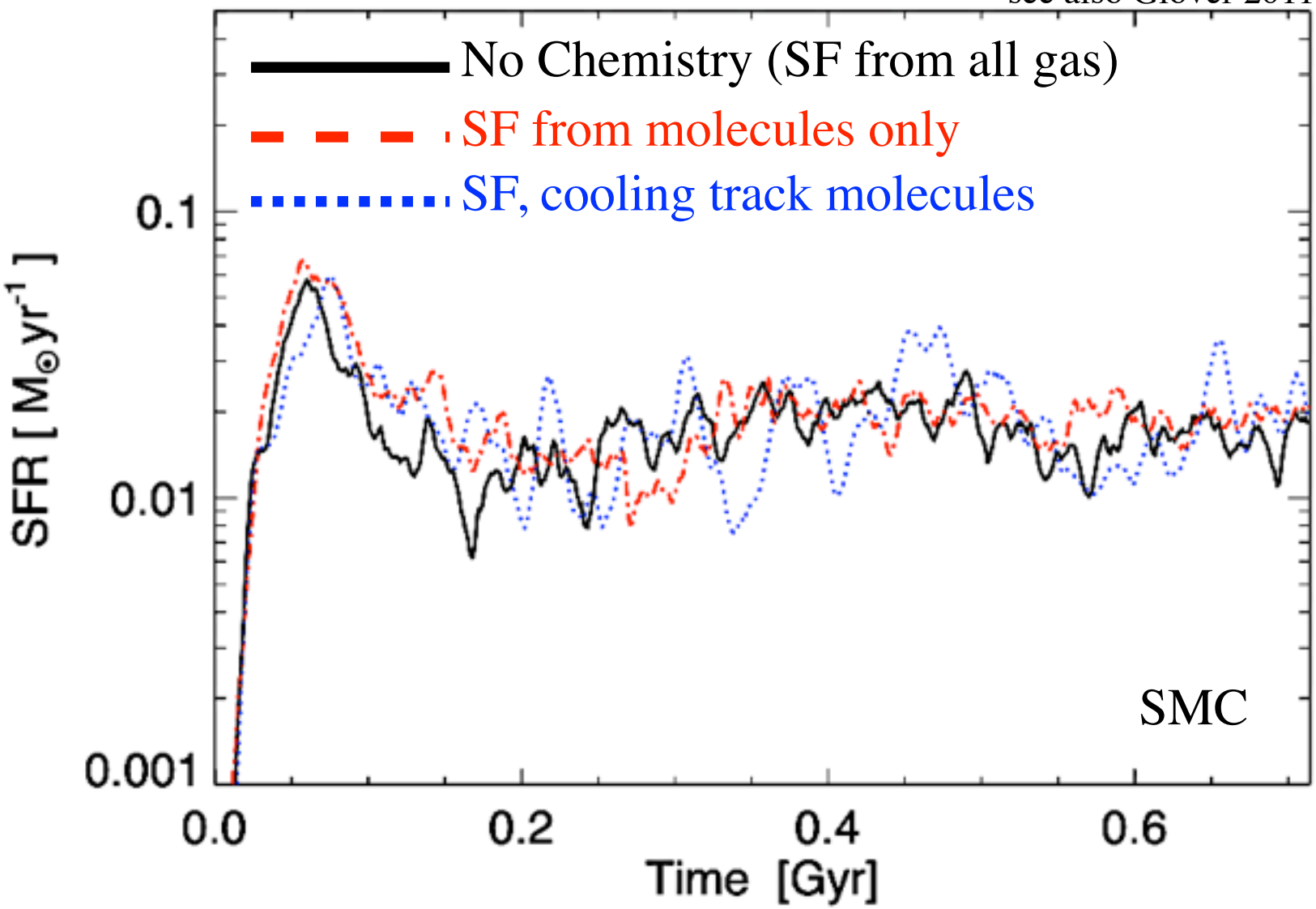
Molecular Chemistry doesn't change things above modest Metallicity

MOLECULES ARE A *TRACER*

see also Glover 2011



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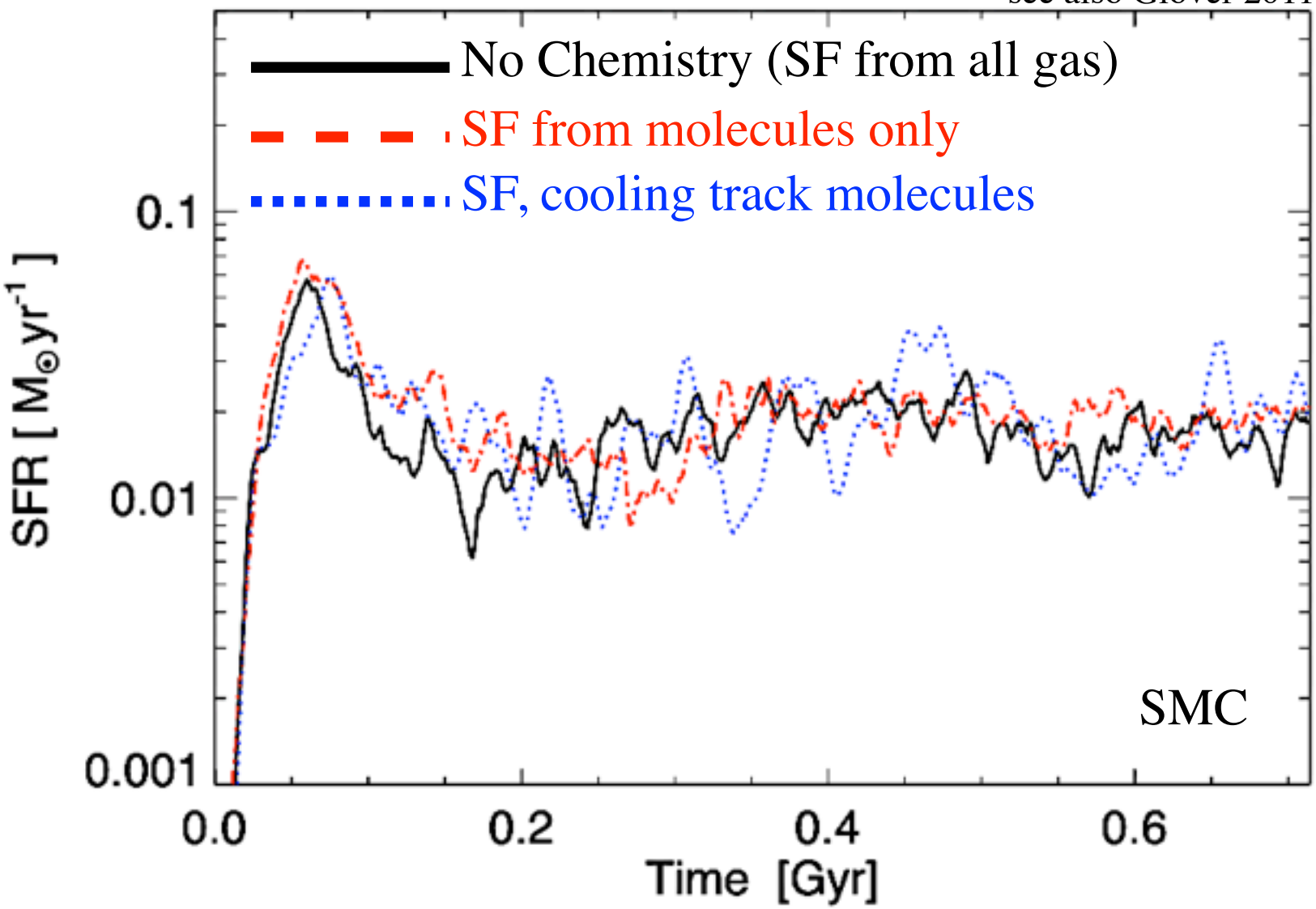
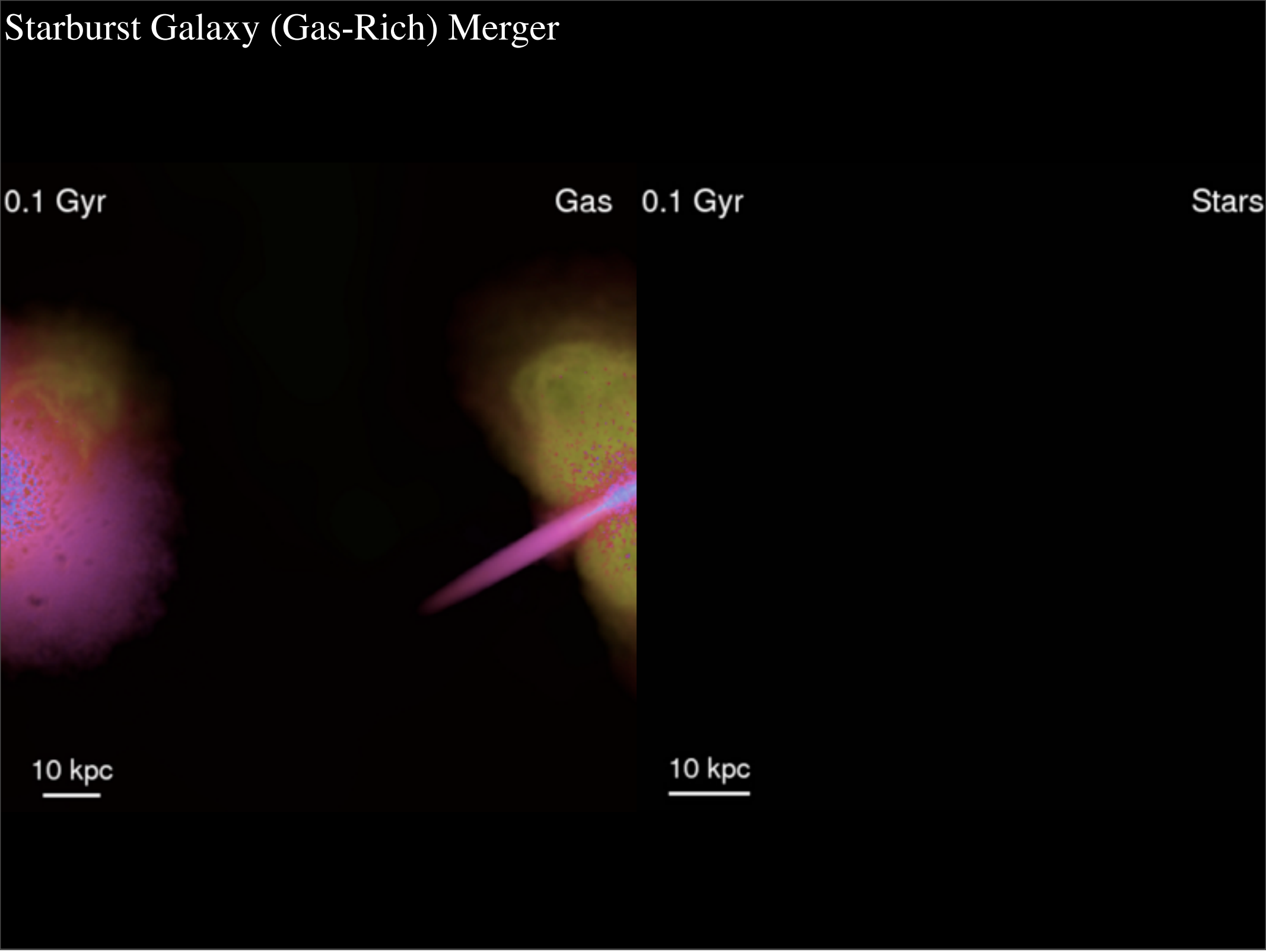


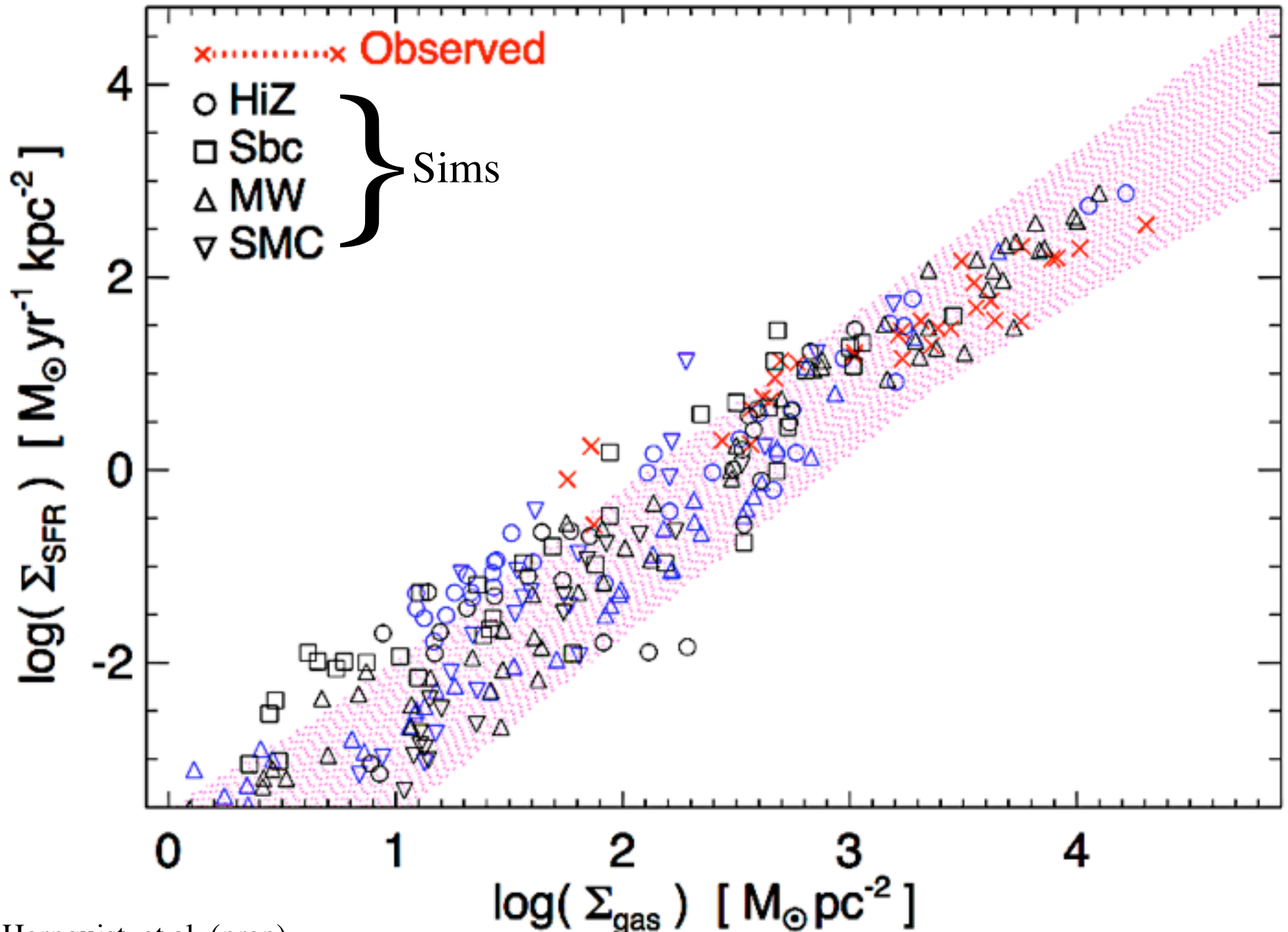
- Just need *some* cooling channel: changes at $M_{gal} < 10^6 M_{sun}$, $Z<0.01 Z_{sun}$

Starburst Galaxy (Gas-Rich) Merger



Galaxy Mergers

LABORATORY FOR STUDYING EXTREME CONDITIONS



PFH, Hernquist, et al. (prep)

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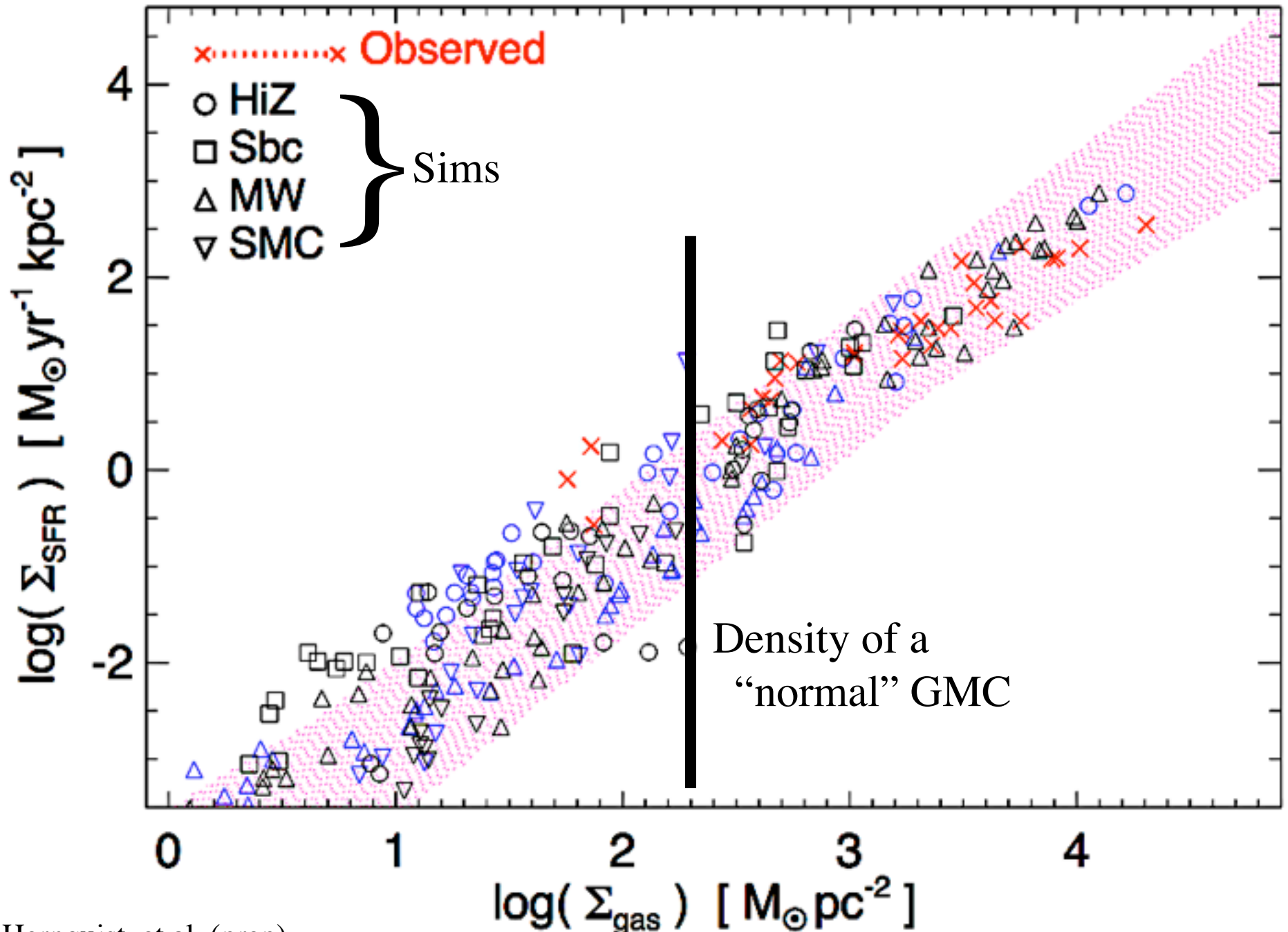
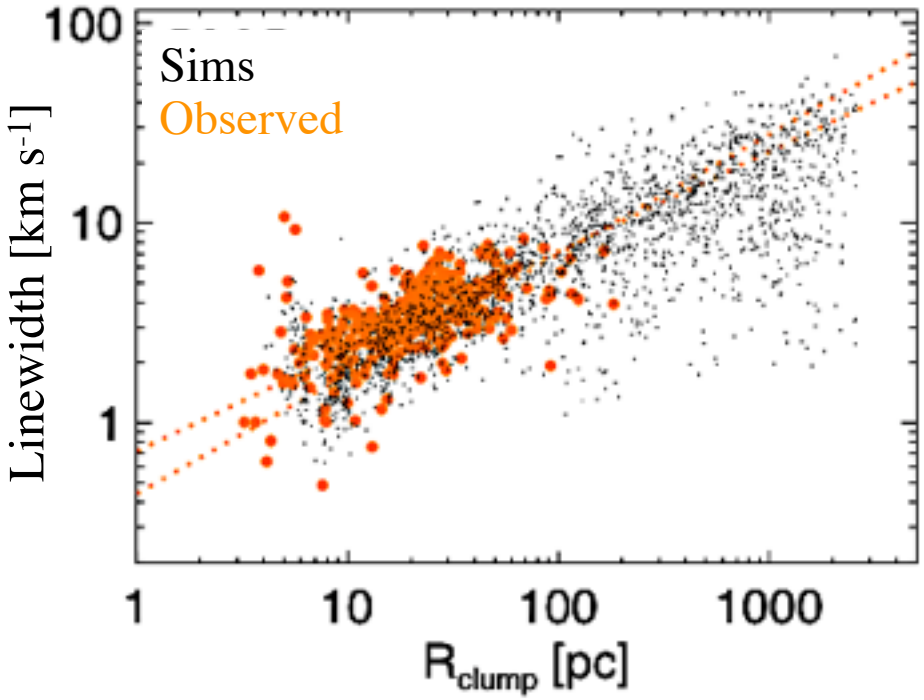
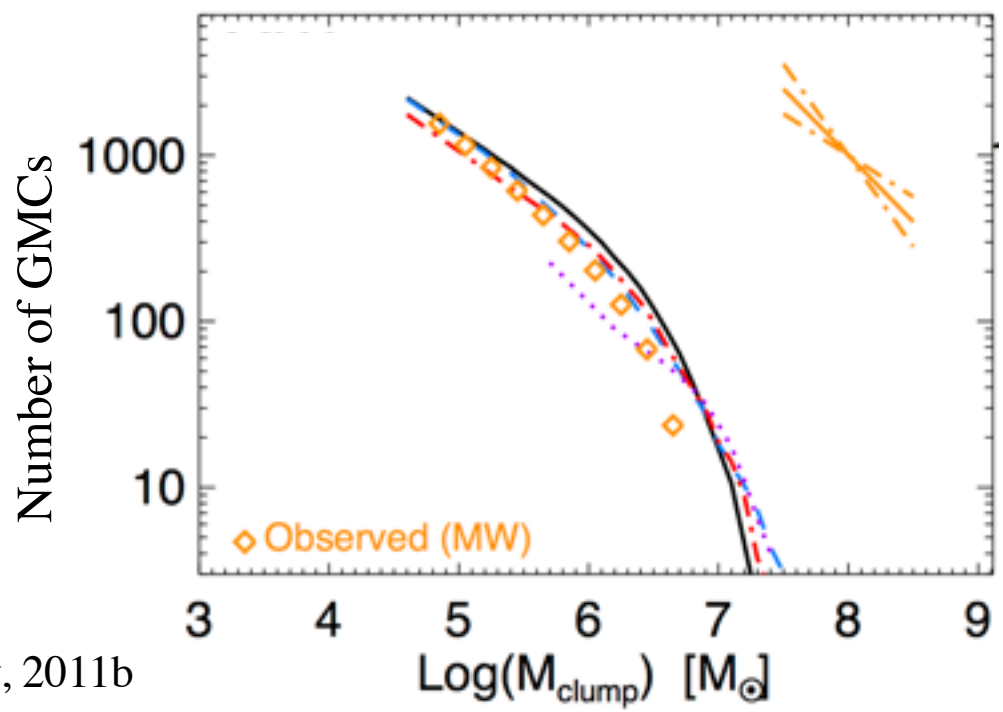
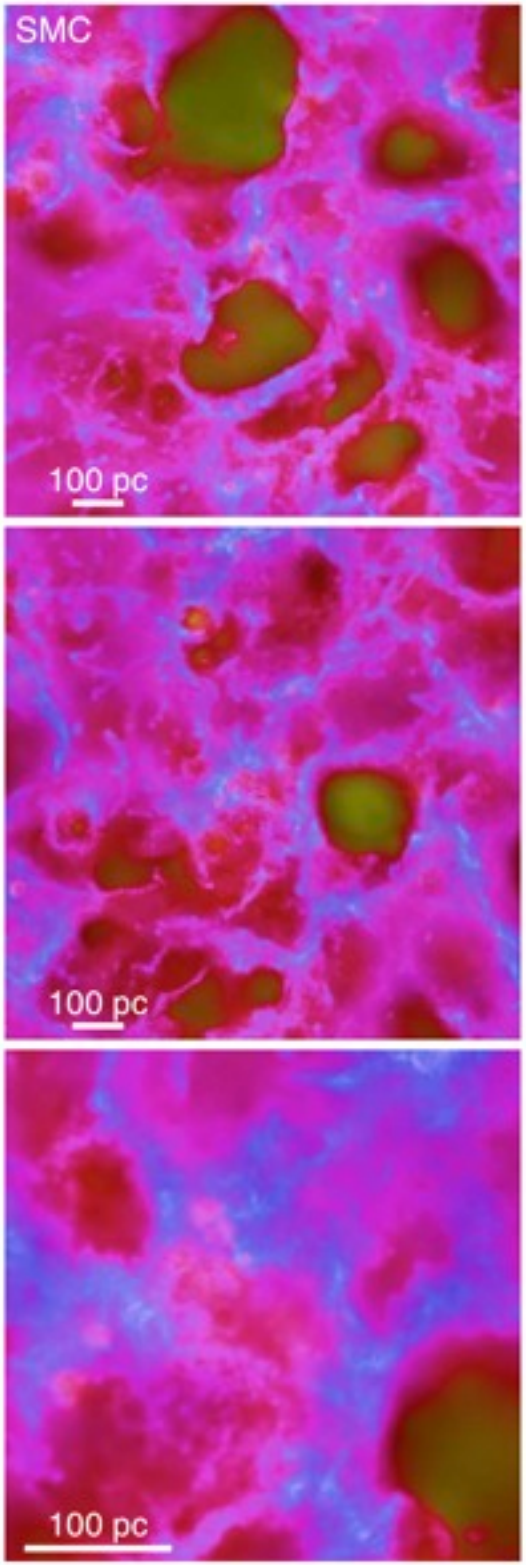


PFH, Hernquist, et al. (prep)

Properties of GMCs & Gas "Clumps"



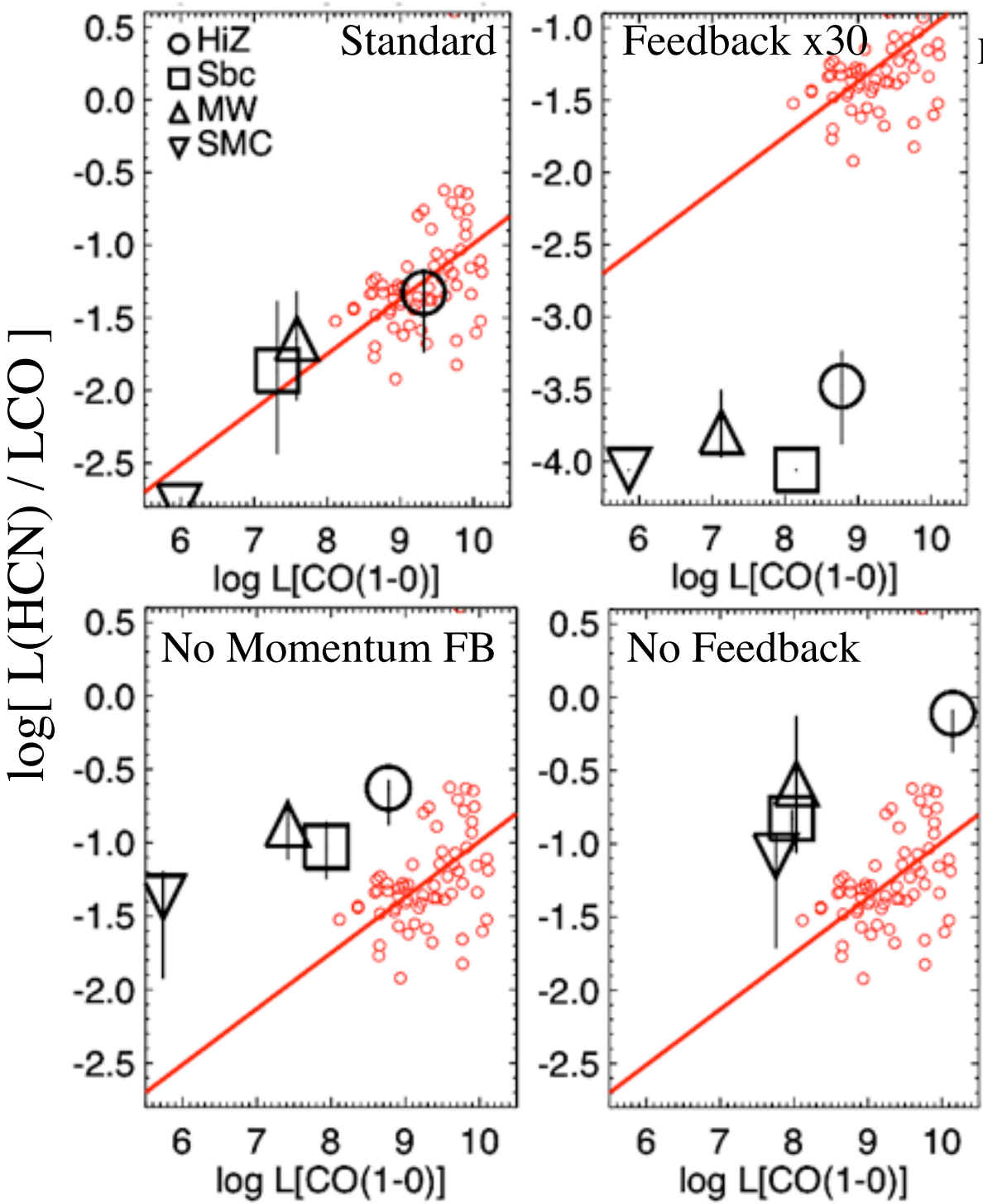




PFH, Quataert, & Murray, 2011b

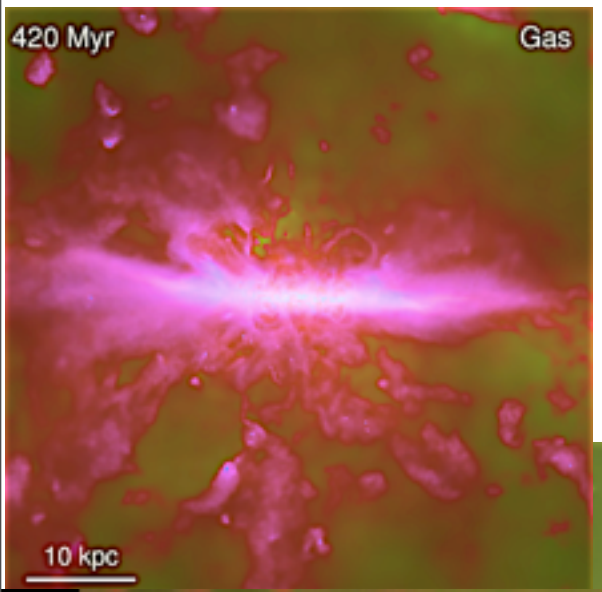
Feedback is Reflected in Dense Gas

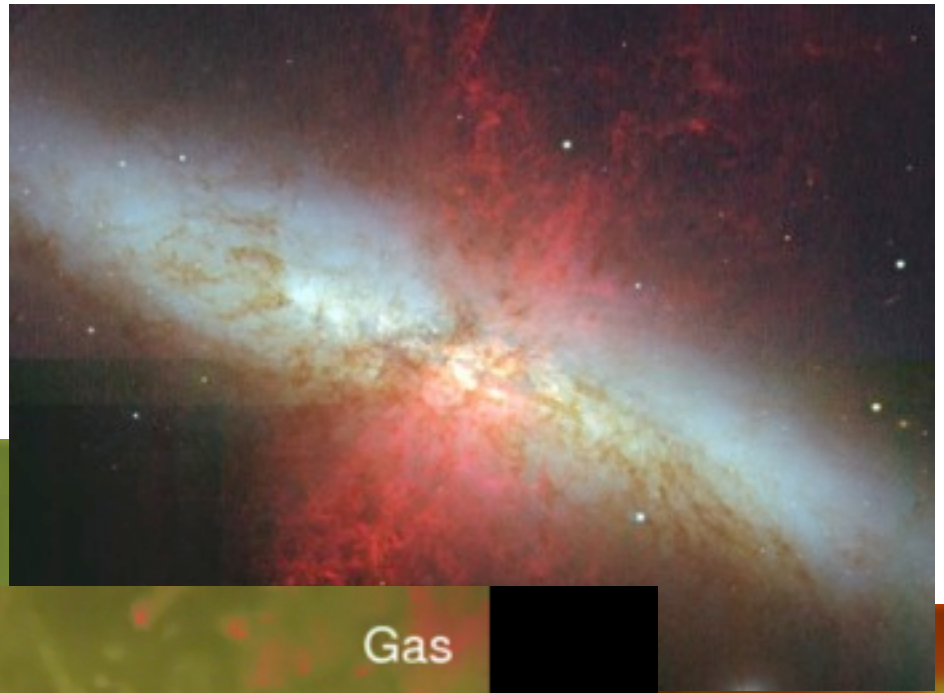
TRACERS OF STAR FORMATION EFFICIENCY

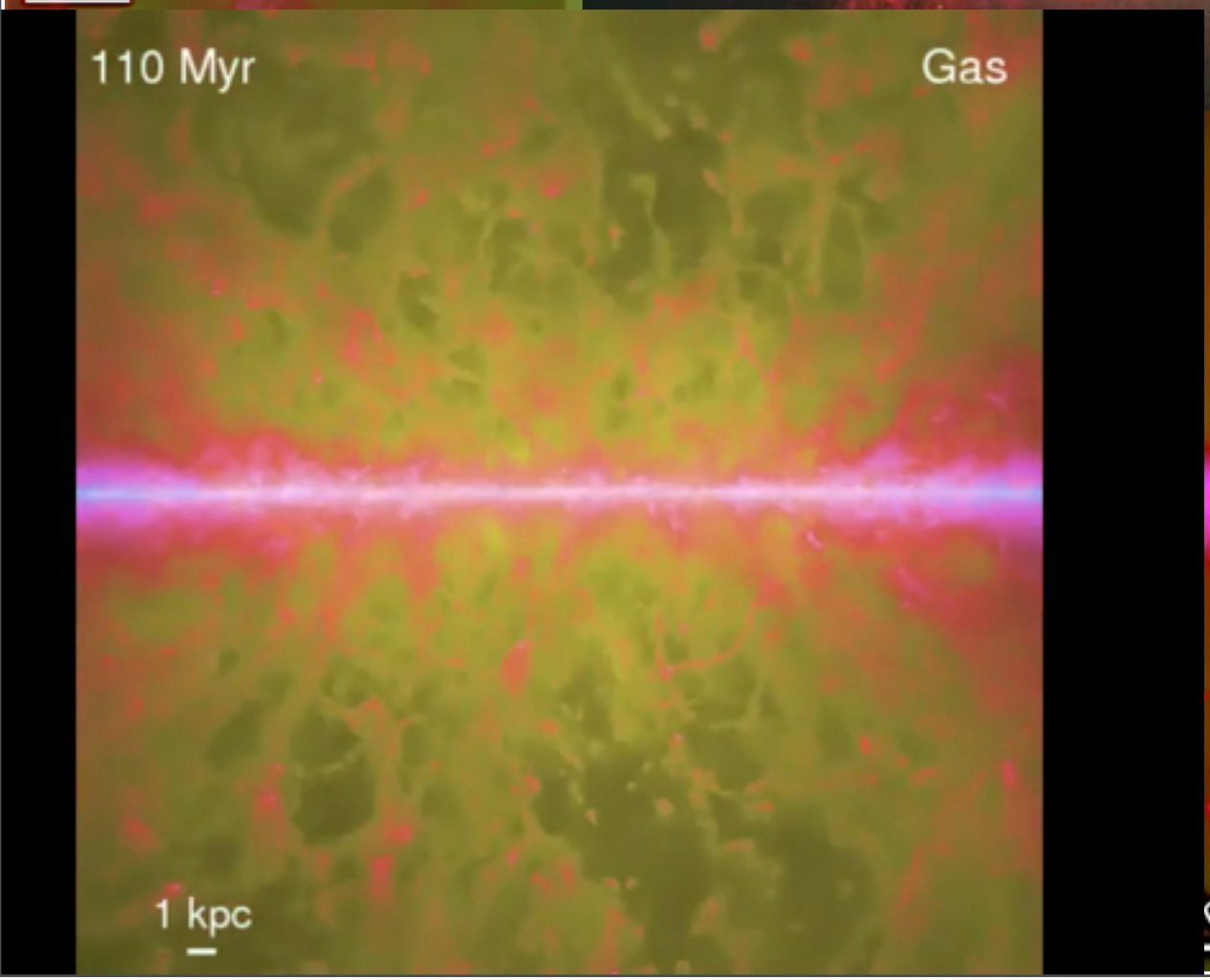


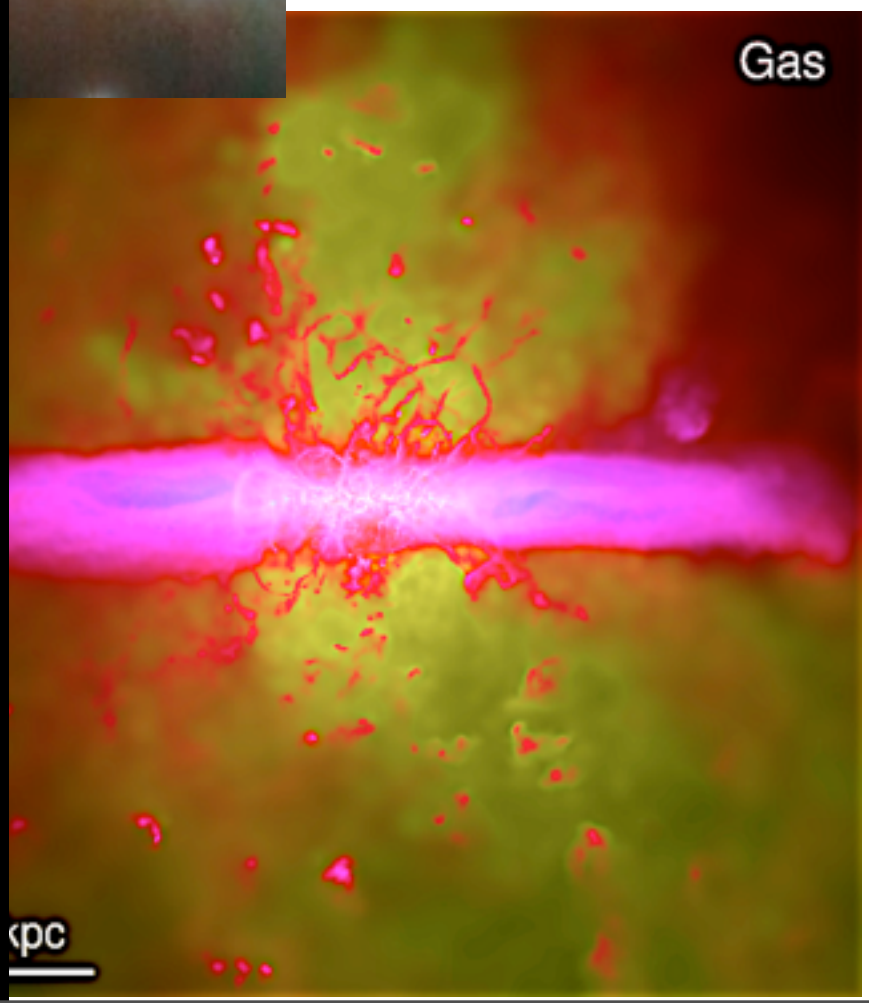
PFH, Narayanan et al. (prep)

Galactic Super-Winds



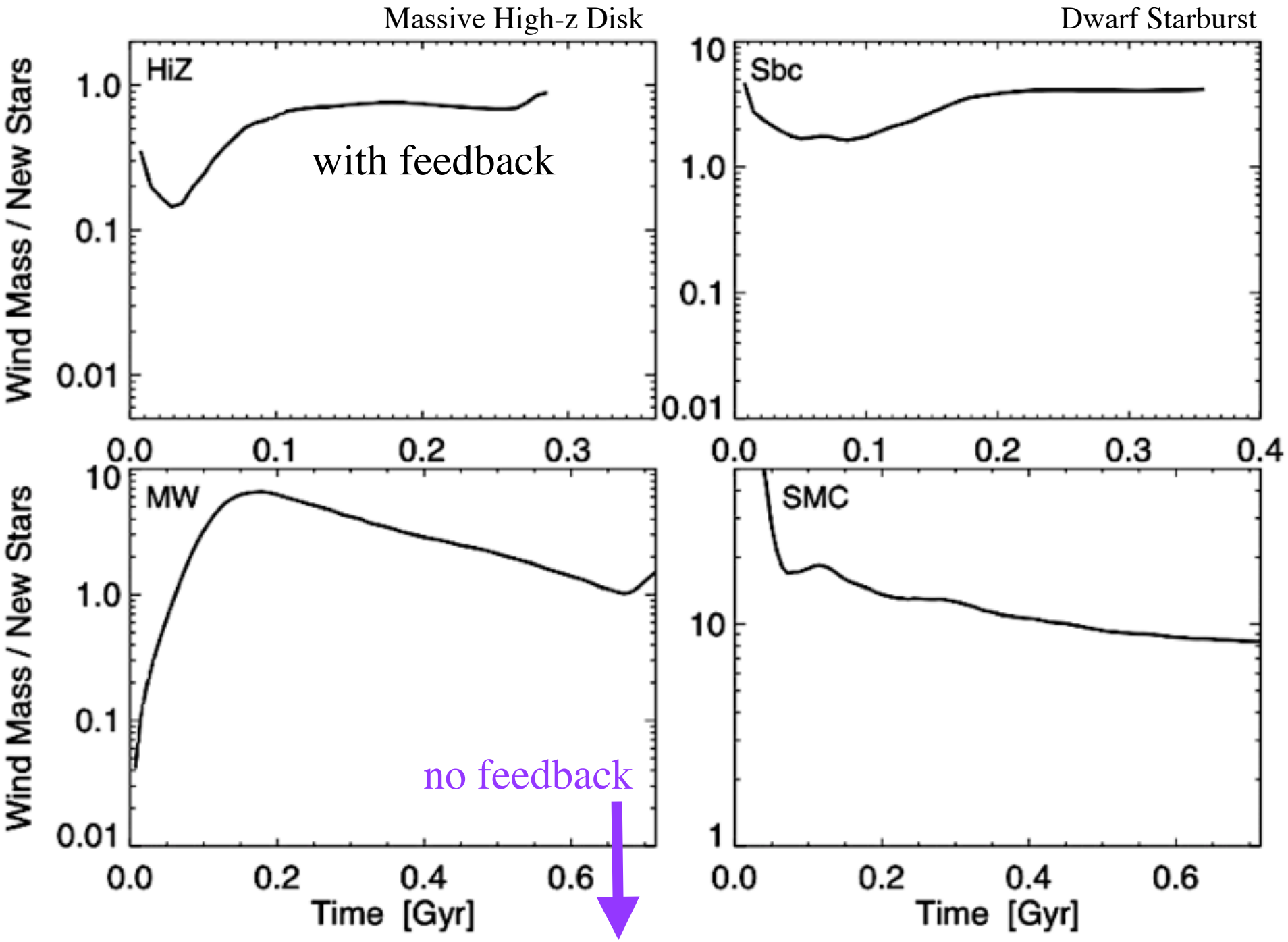






How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?



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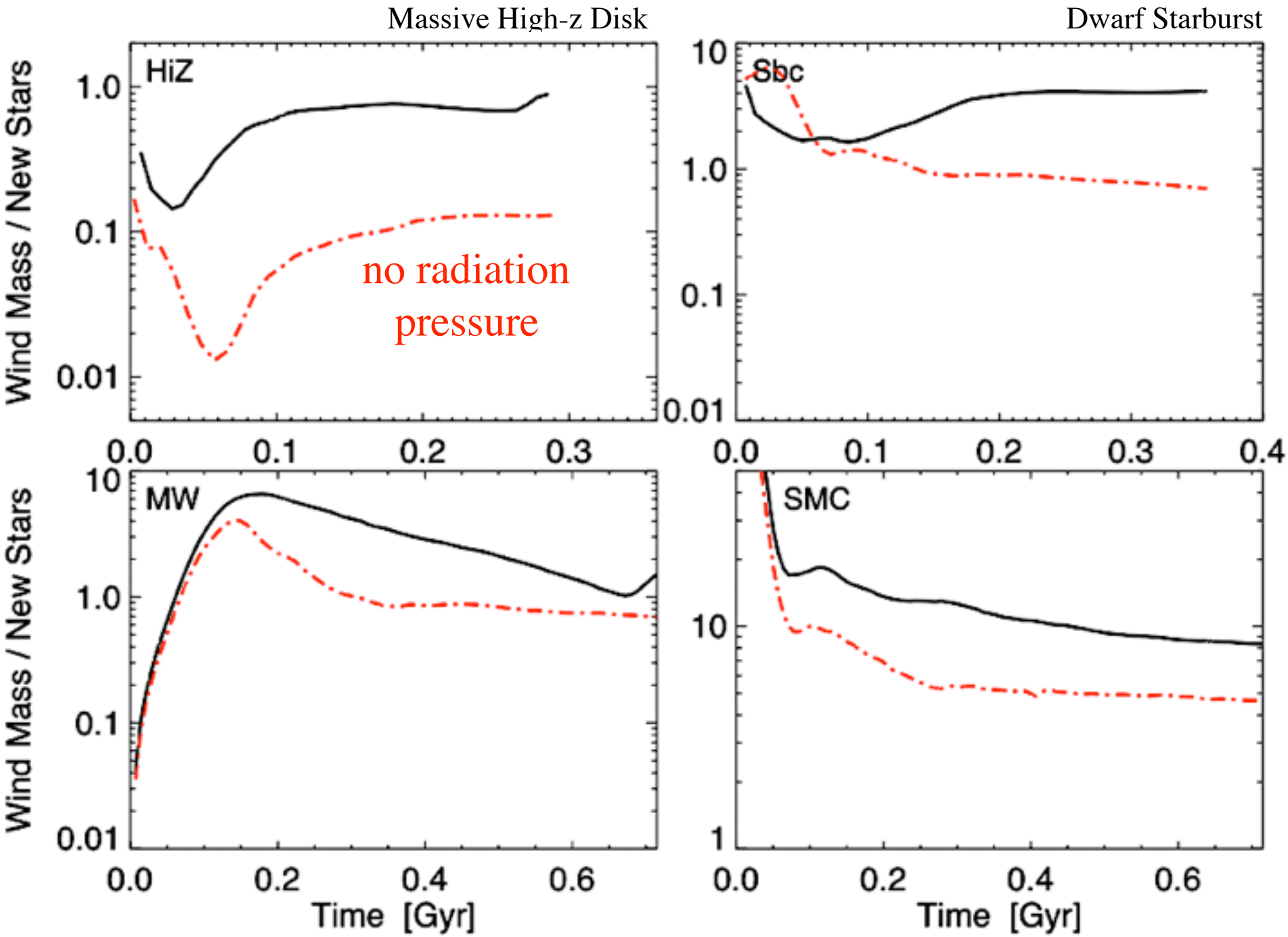

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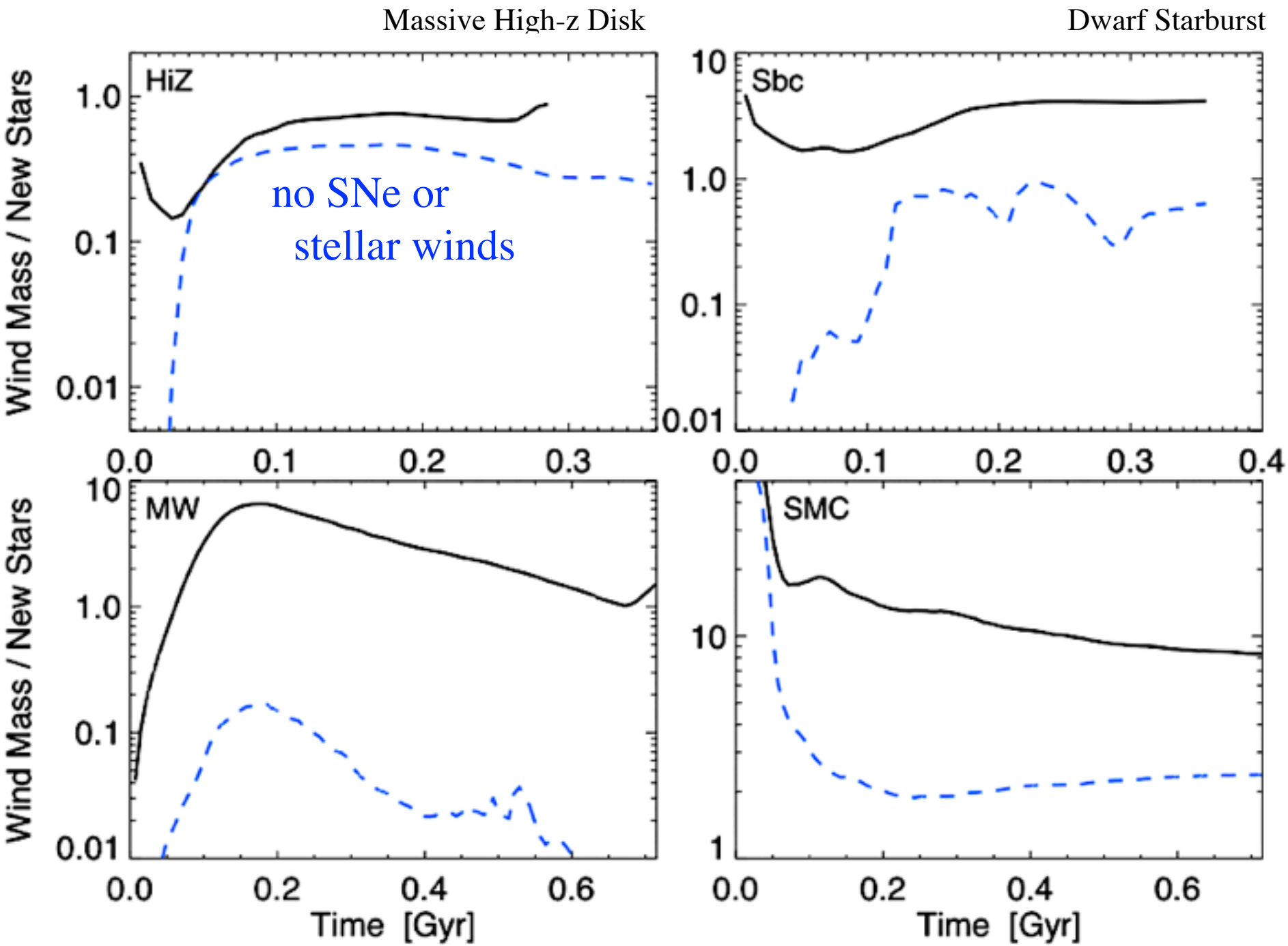

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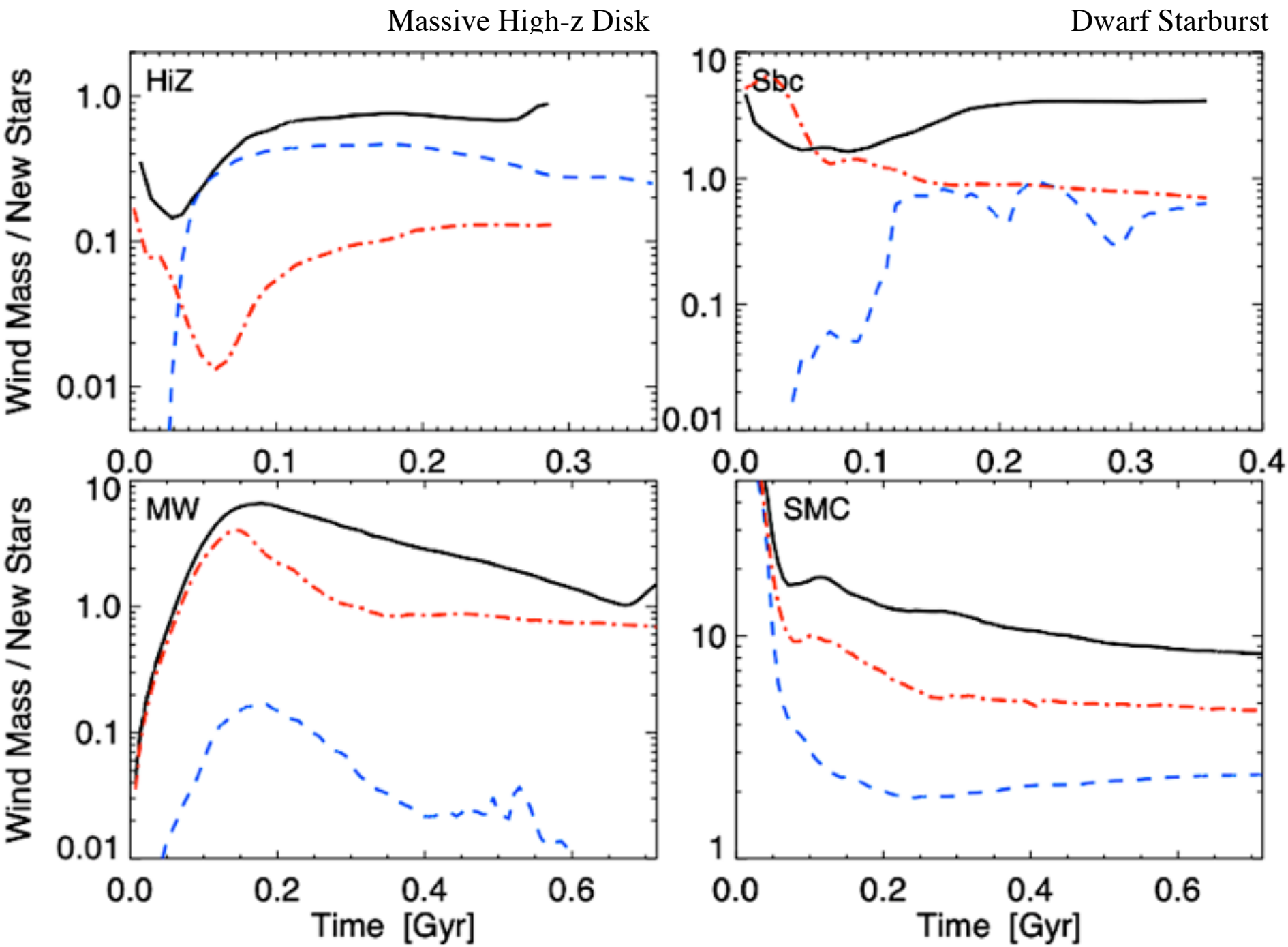

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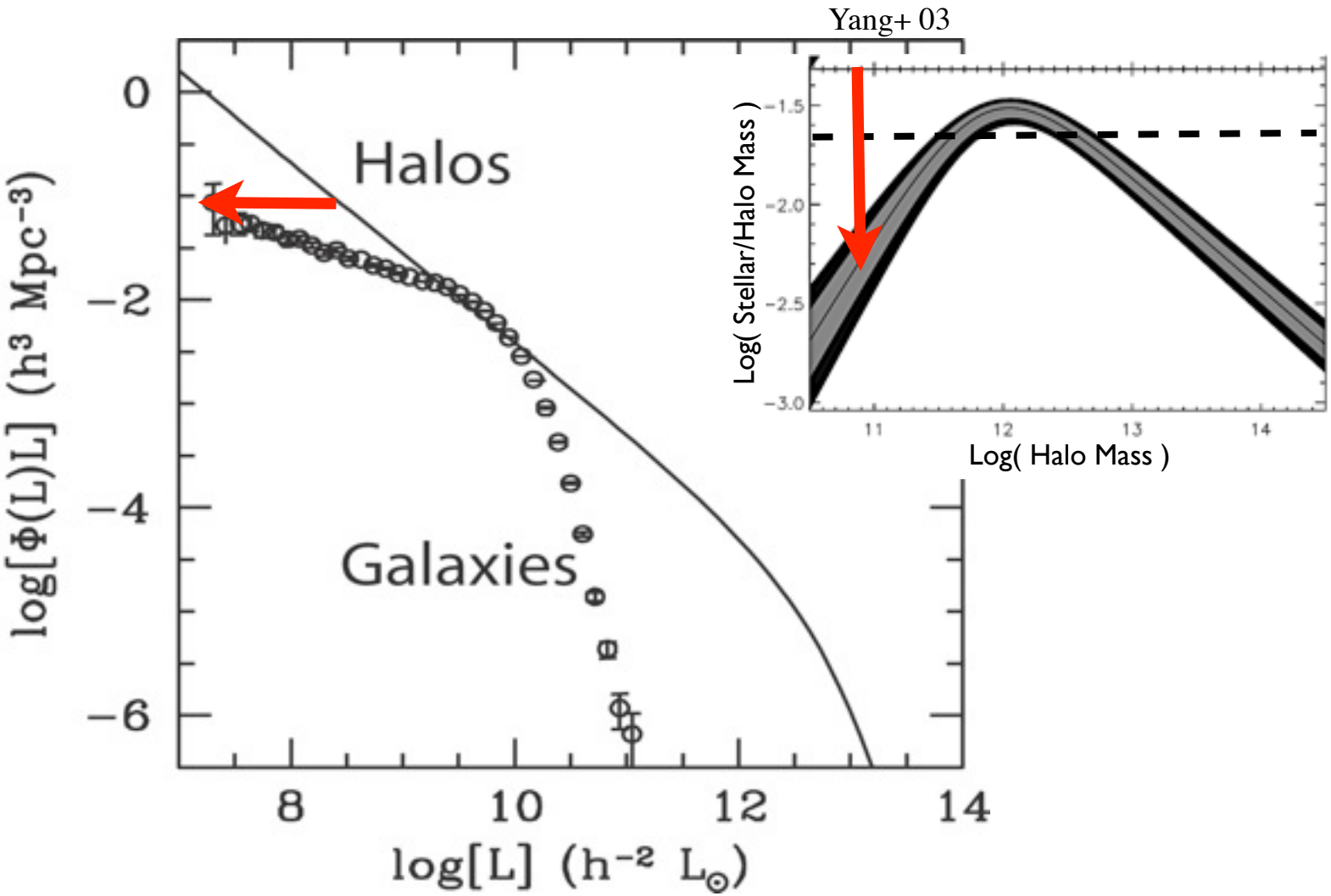

- Large mass-loading:

$$\dot{M}_{\rm wind} \approx 10\,\dot{M}_* \left(\frac{V_c}{100\,{\rm km\,s^{-1}}}\right)^{-1.1} \left(\frac{\Sigma_{\rm gas}}{10\,{\rm M_\odot\,pc^{-2}}}\right)^{-0.5}$$

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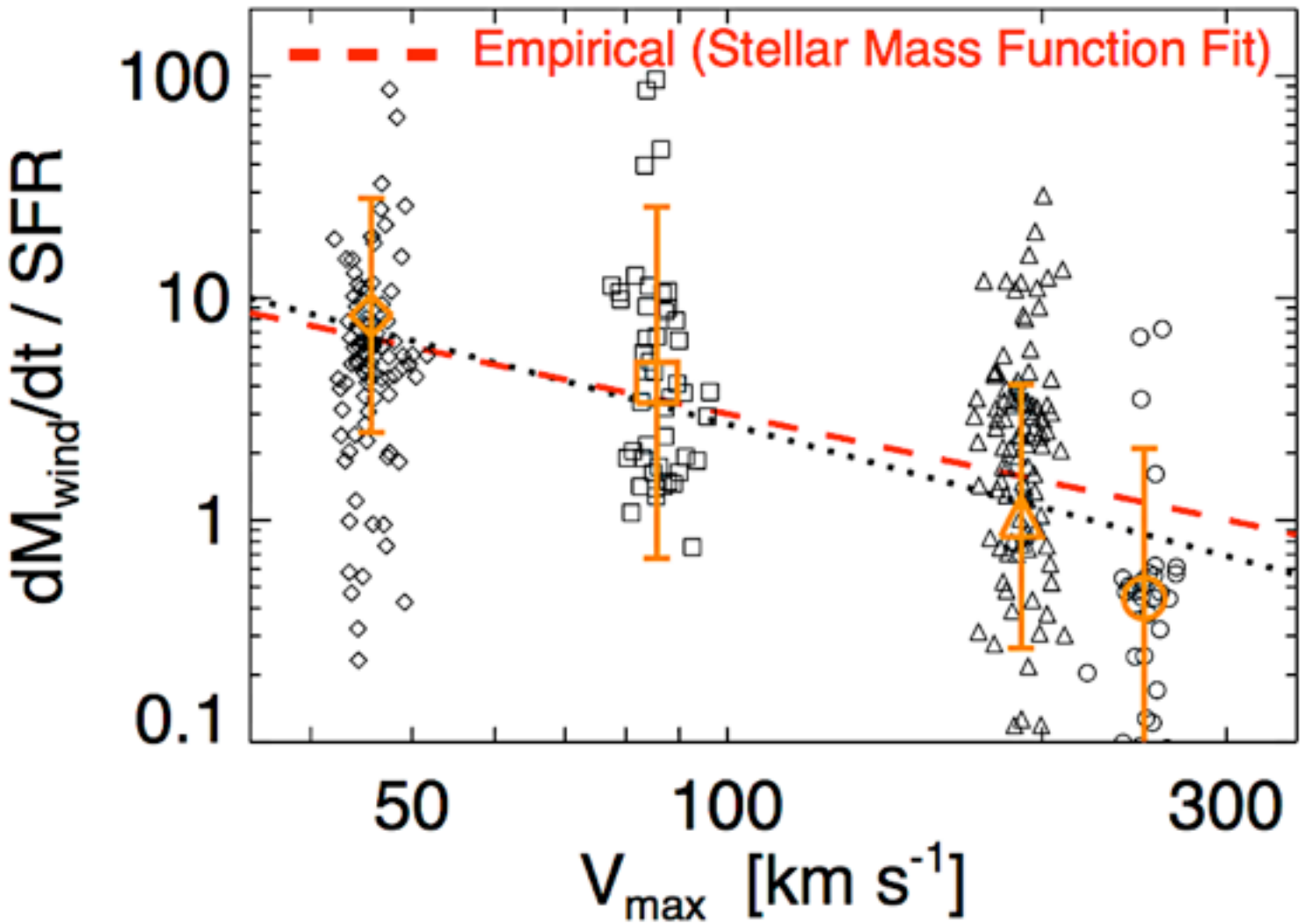

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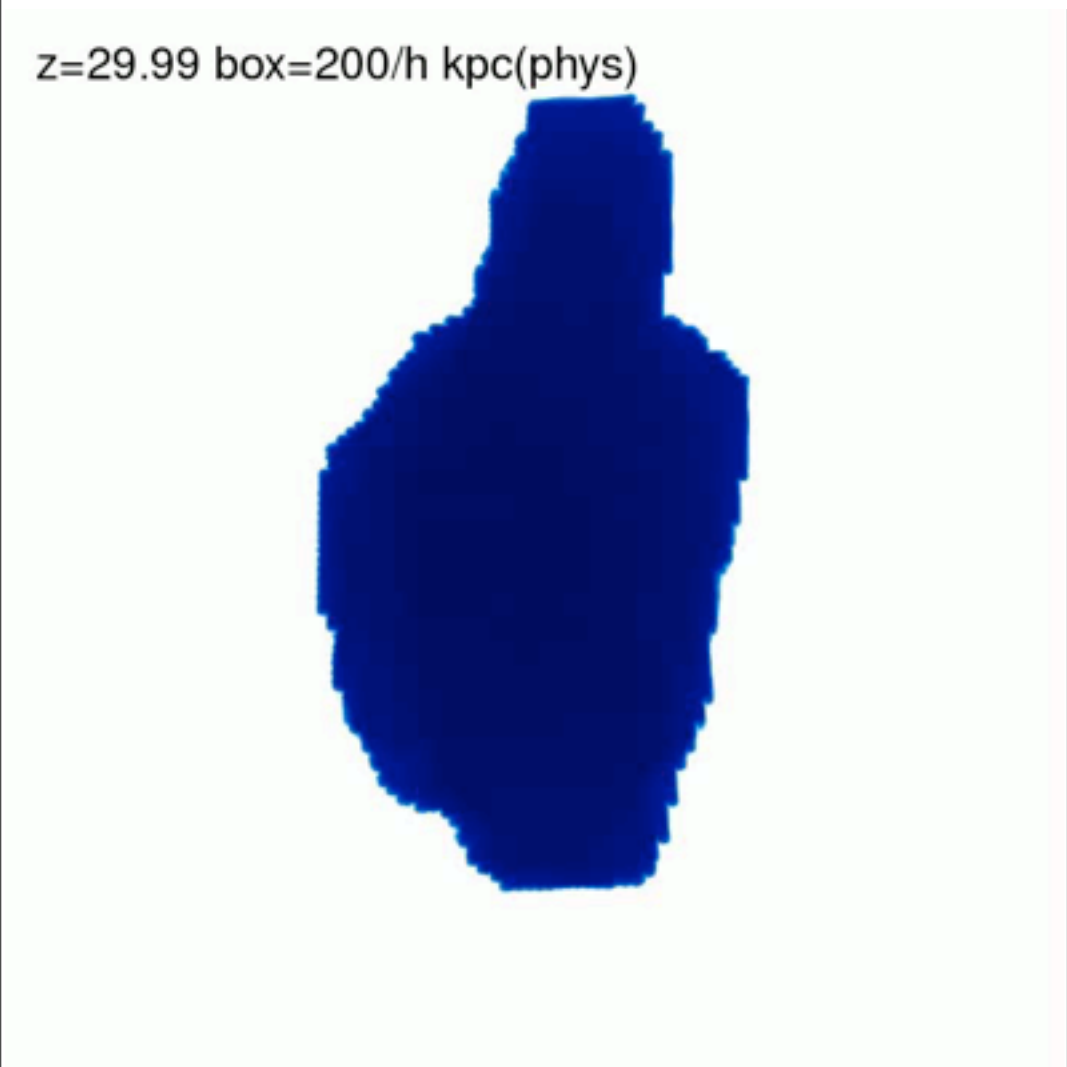
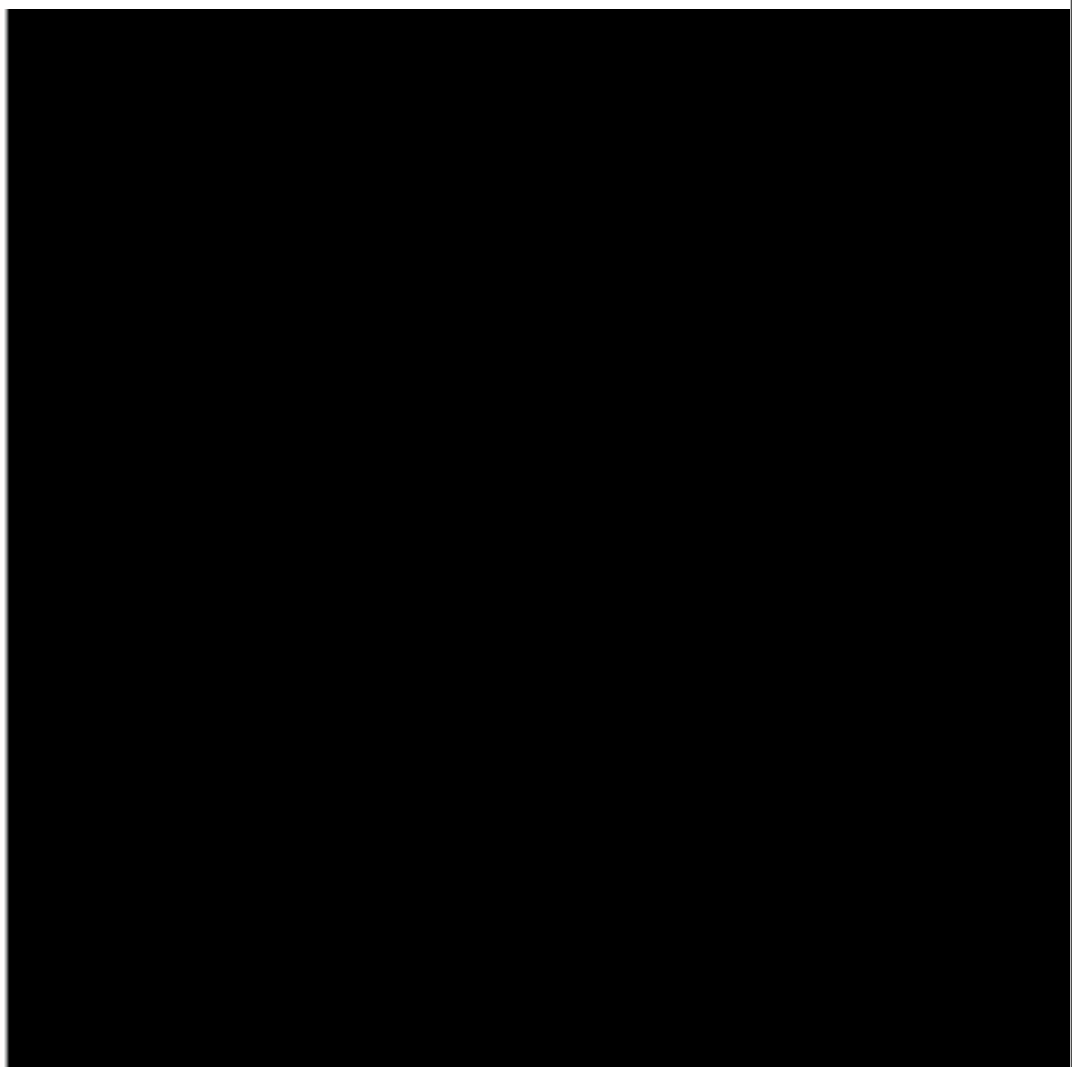
Cosmological Simulations

"ZOOM-IN" ON THE FORMATION OF A MASSIVE GALAXY



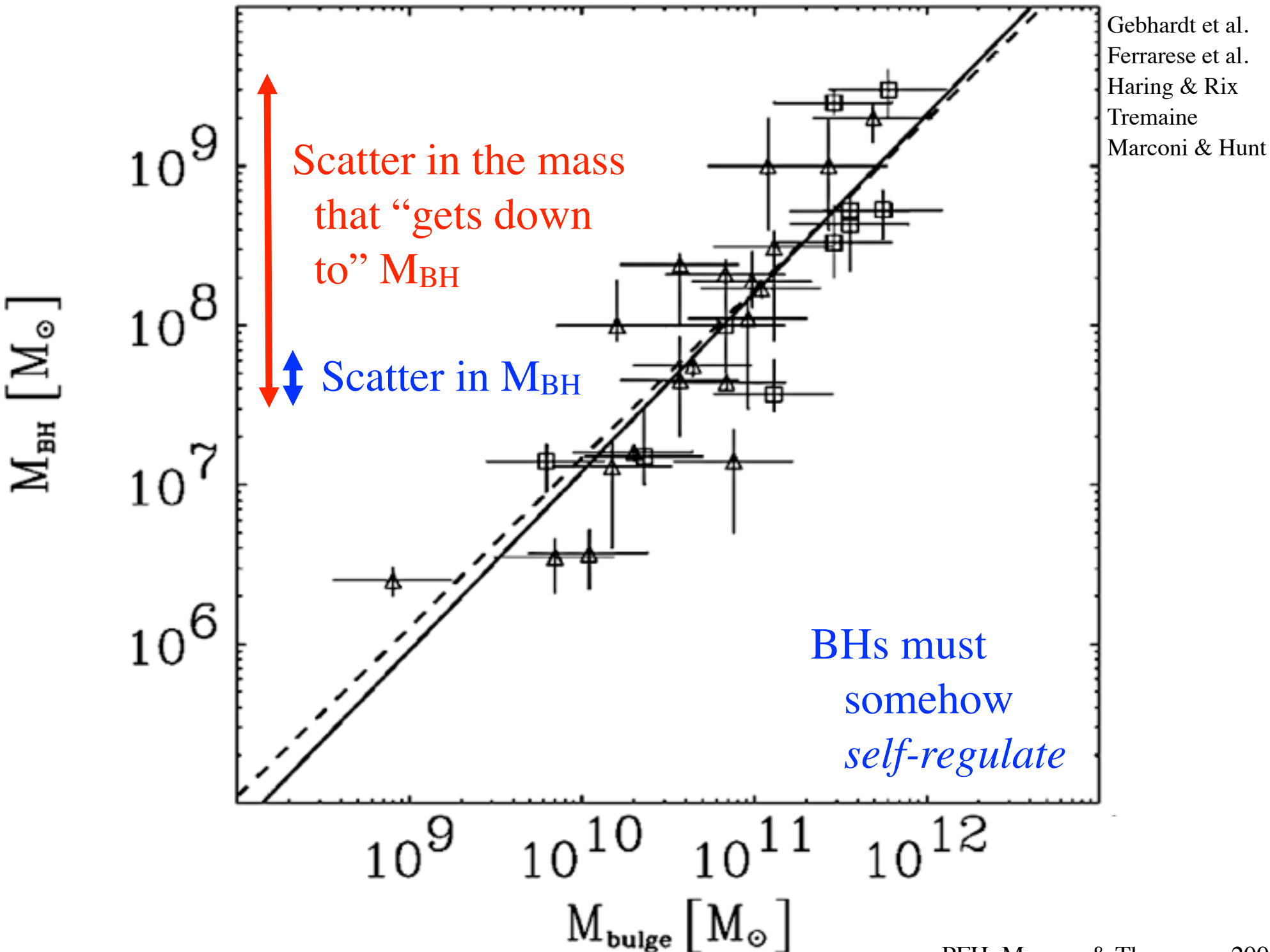
IGM Density



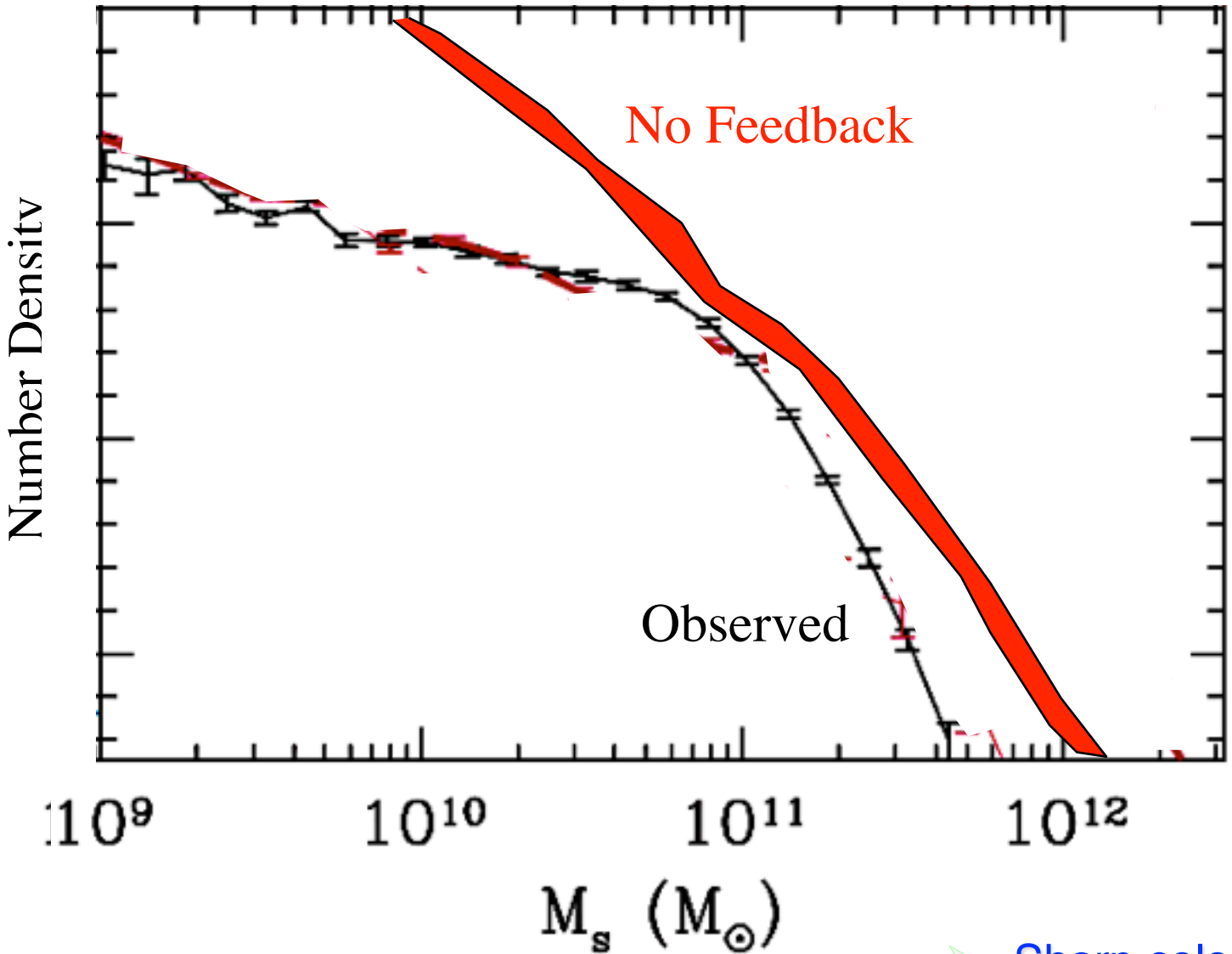
IGM Temperature

PFH & Keres et al

What About the AGN?

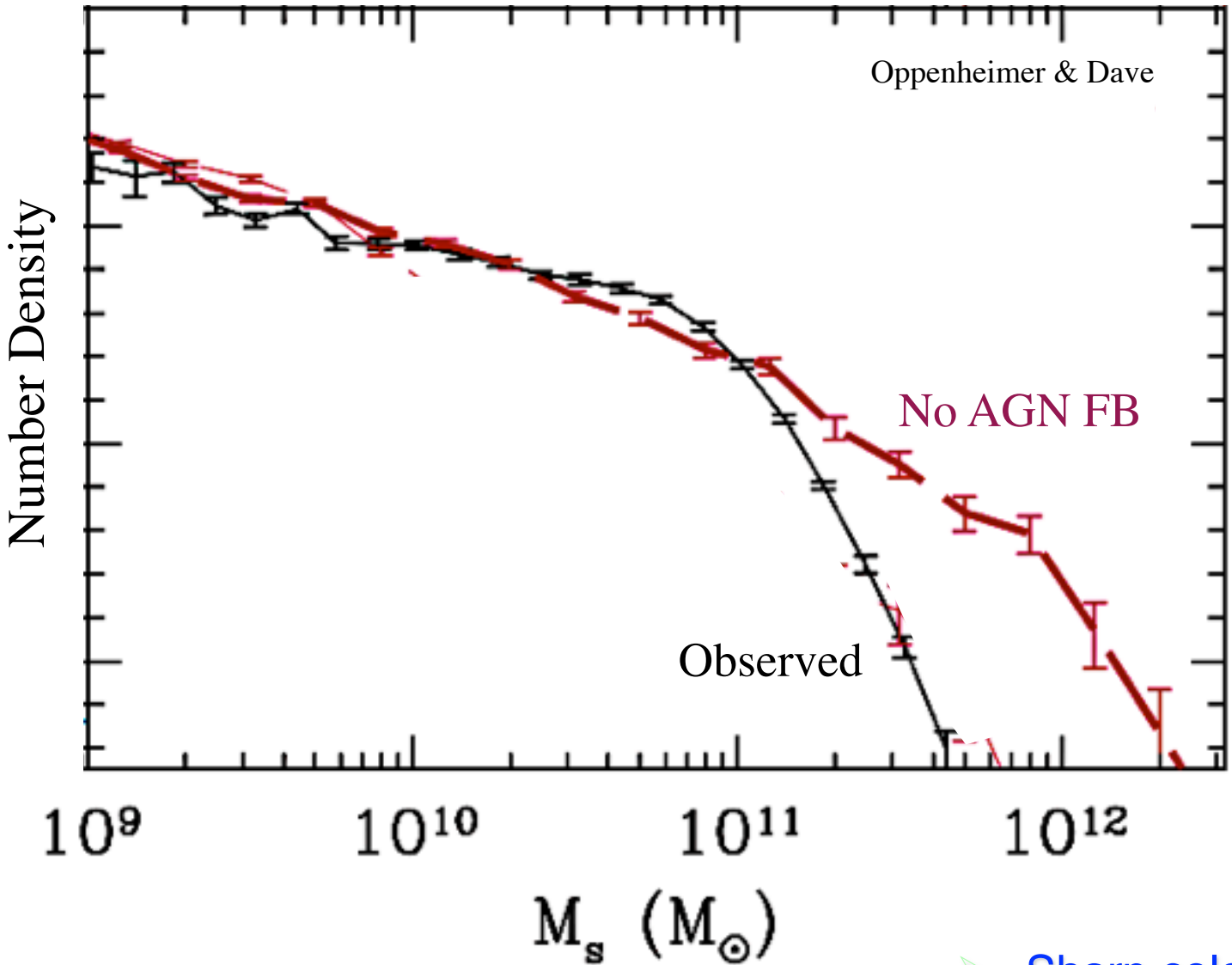

Gebhardt et al.
Ferrarese et al.
Haring & Rix
Tremaine
Marconi & Hunt
Scatter in the mass that "gets down to" M_{BH}
Scatter in M_{BH}
BHs must somehow *self-regulate*
M_{BH} [$M_\odot$]
10^9
10^8
10^7
10^6
10^9
10^{10}
10^{11}
10^{12}
M_{bulge} [$M_\odot$]
PFH, Murray, & Thompson 2009

What can AGN Feedback Do For You?



- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

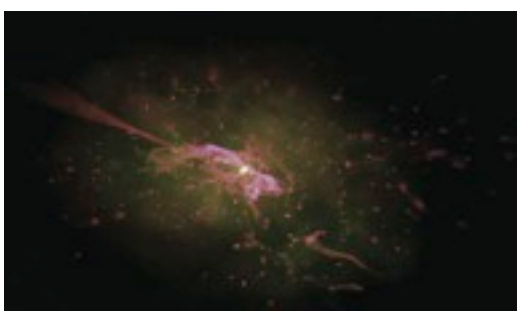
What can AGN Feedback Do For You?



- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

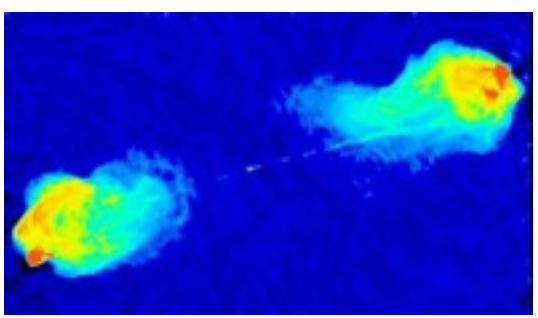
"Transition" vs. "Maintenance"

- "**Quasar**" mode (high mdot)
- Move mass from Blue to Red?
- Rapid (~10^7 yr)
- Small(er) scales (~pc-kpc)
- Morphological Transformation
- Gas-rich/Dissipational Mergers?



- Regulates *Black Hole* Mass

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

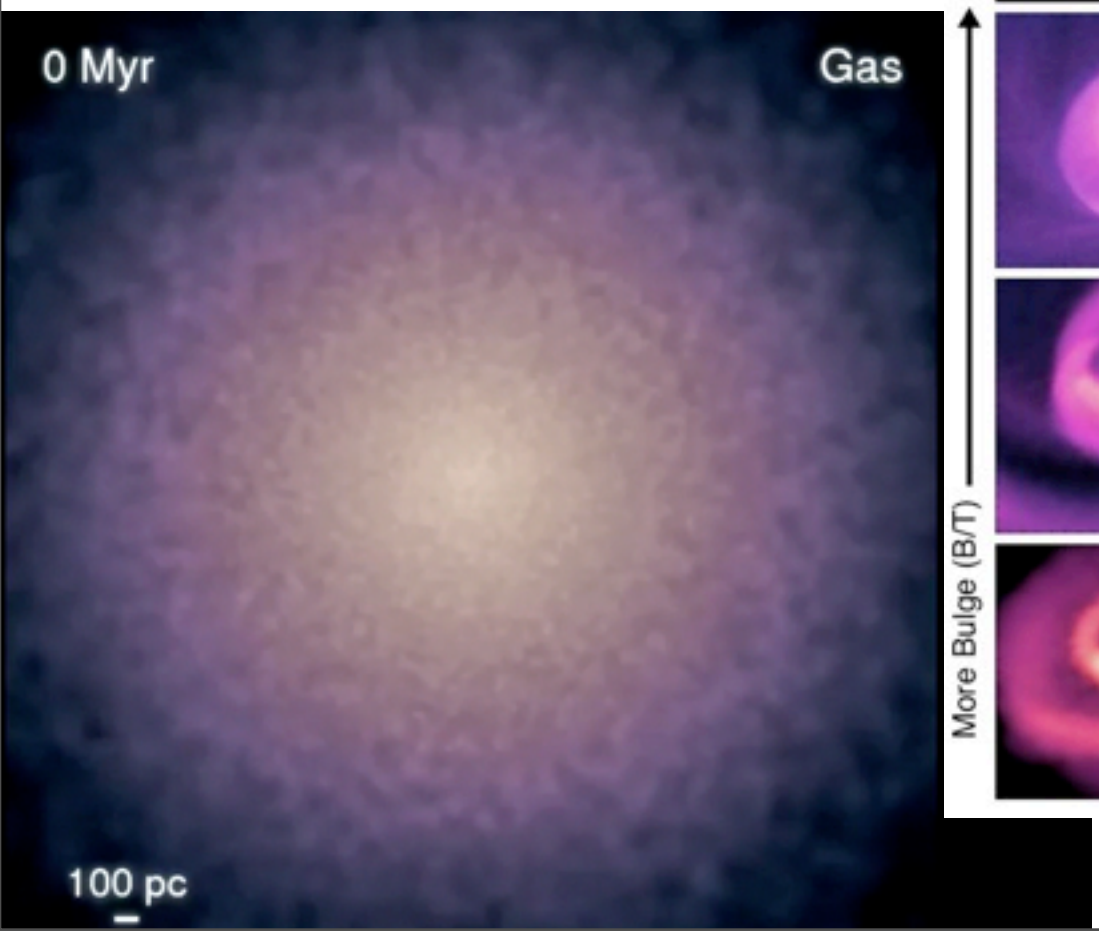


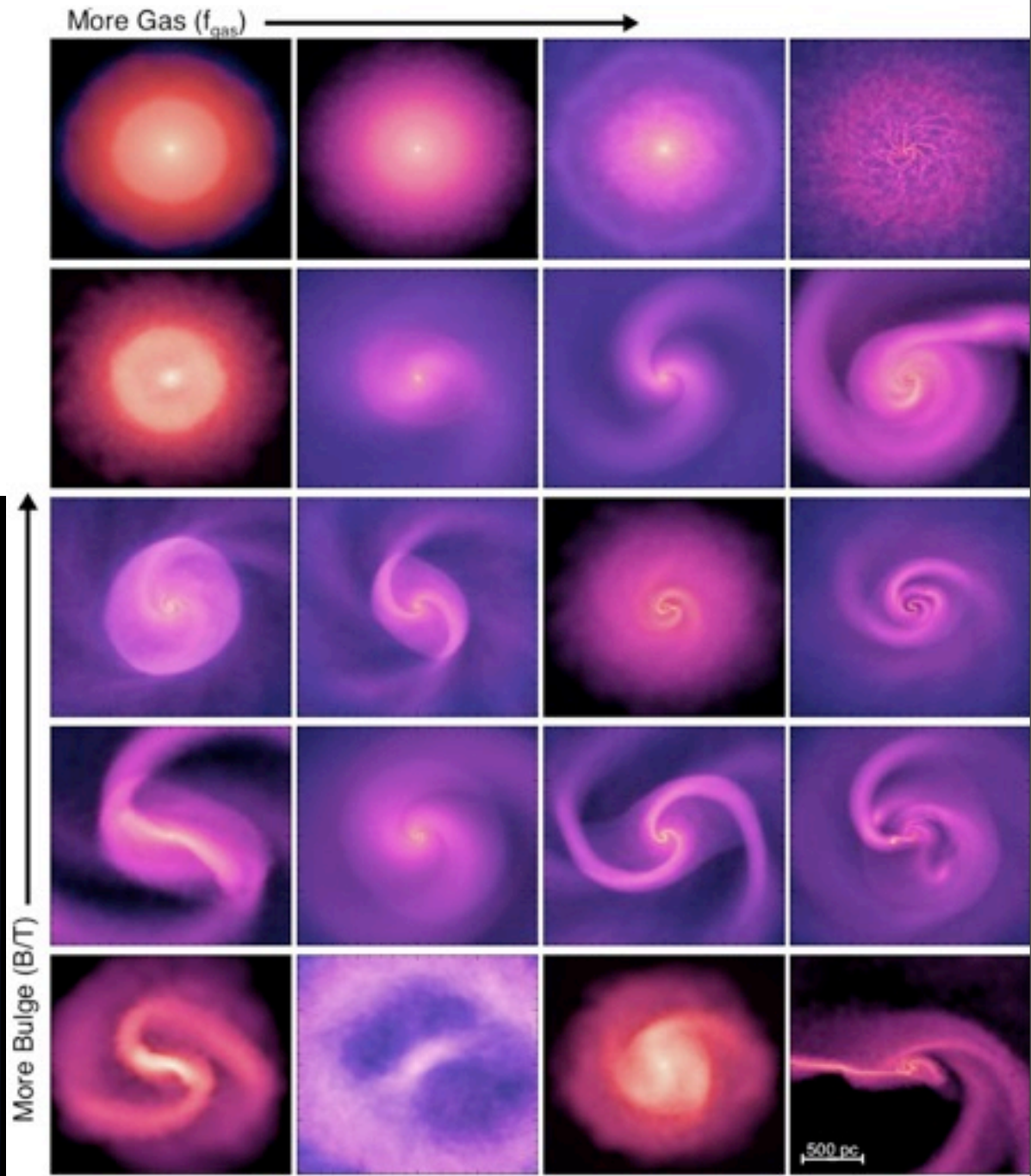
- Regulates *Galaxy* Mass

Step 1: Inflow

- Beginning to directly follow inflow to sub-pc scales

PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10





Step 1: Inflow

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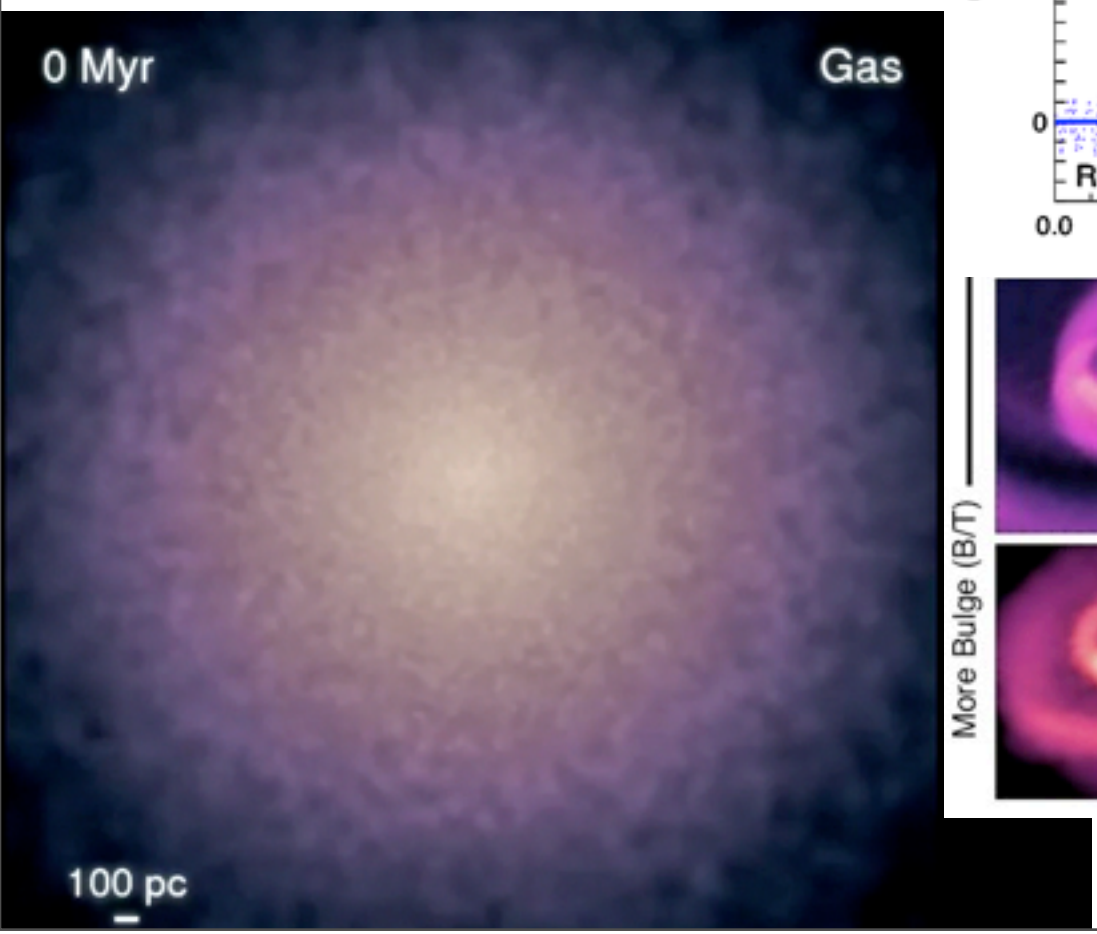
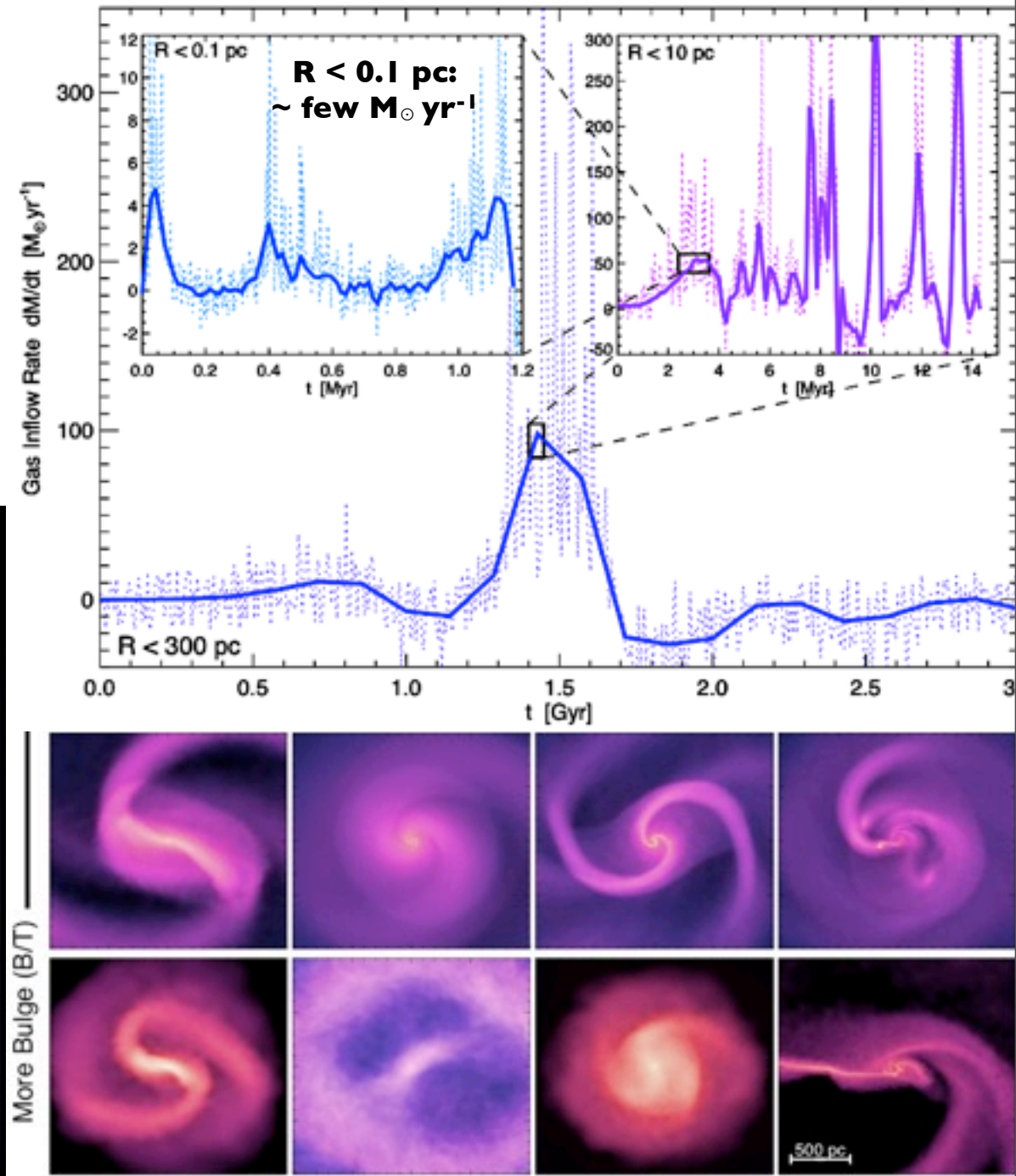
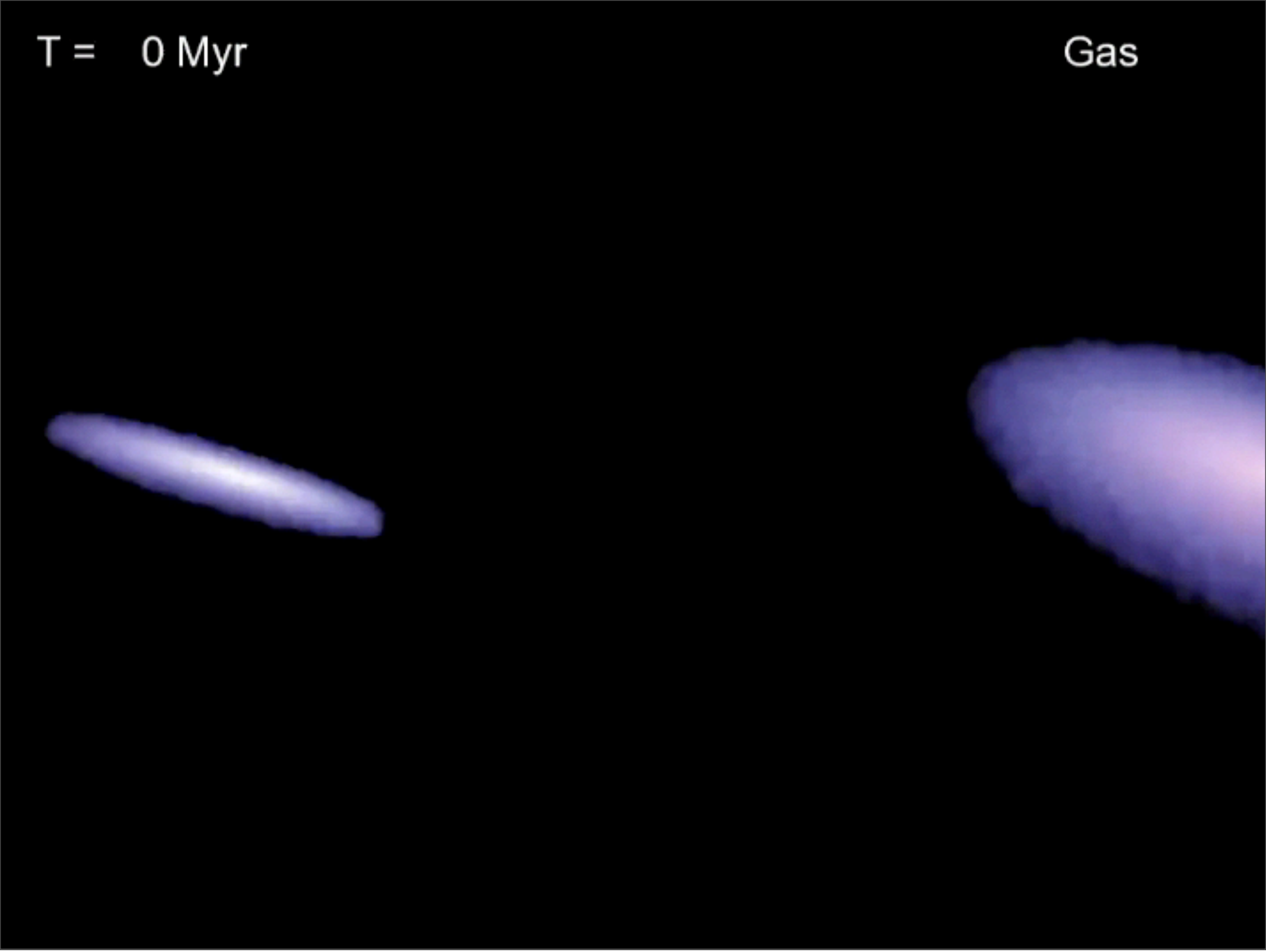
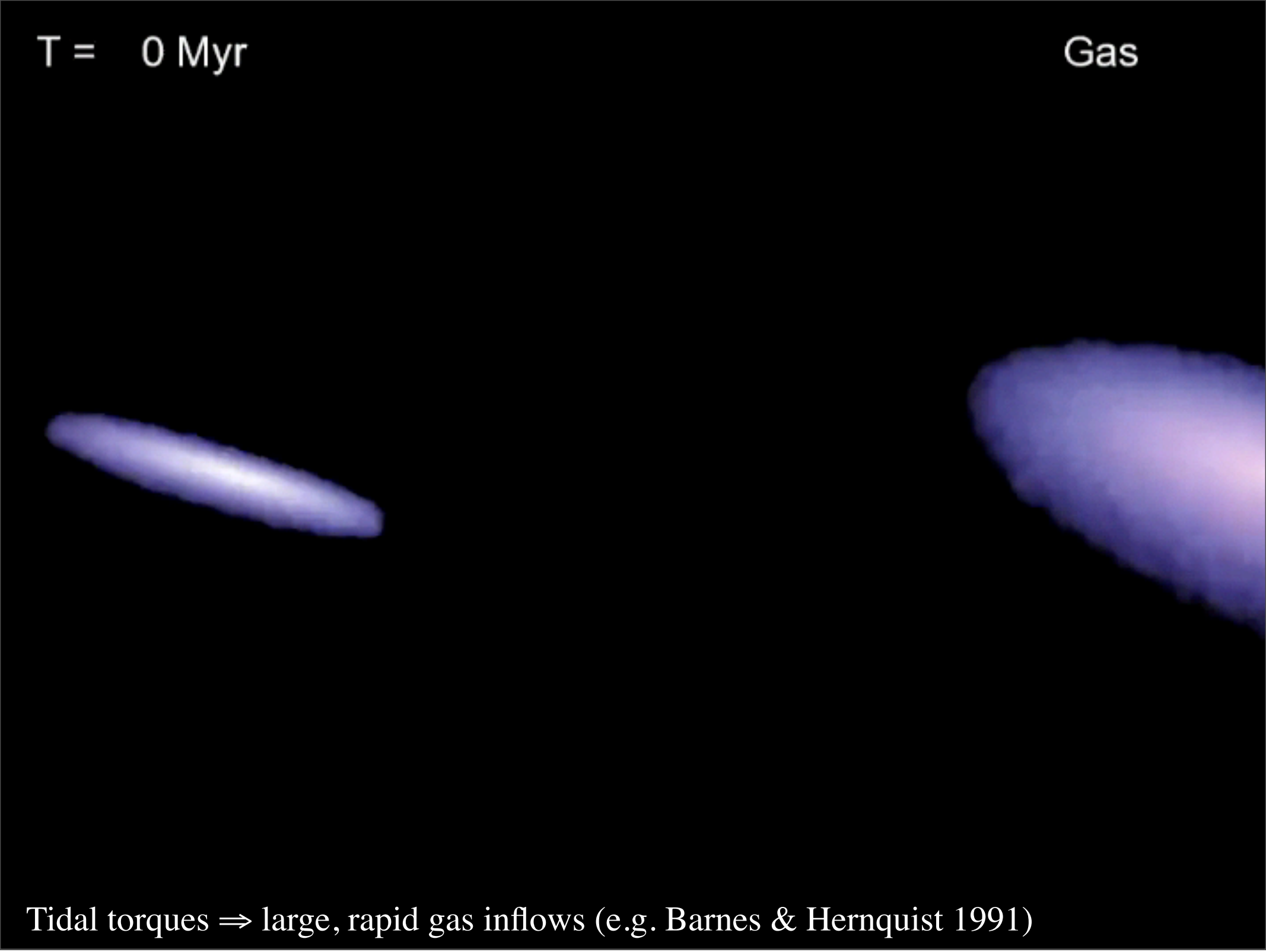
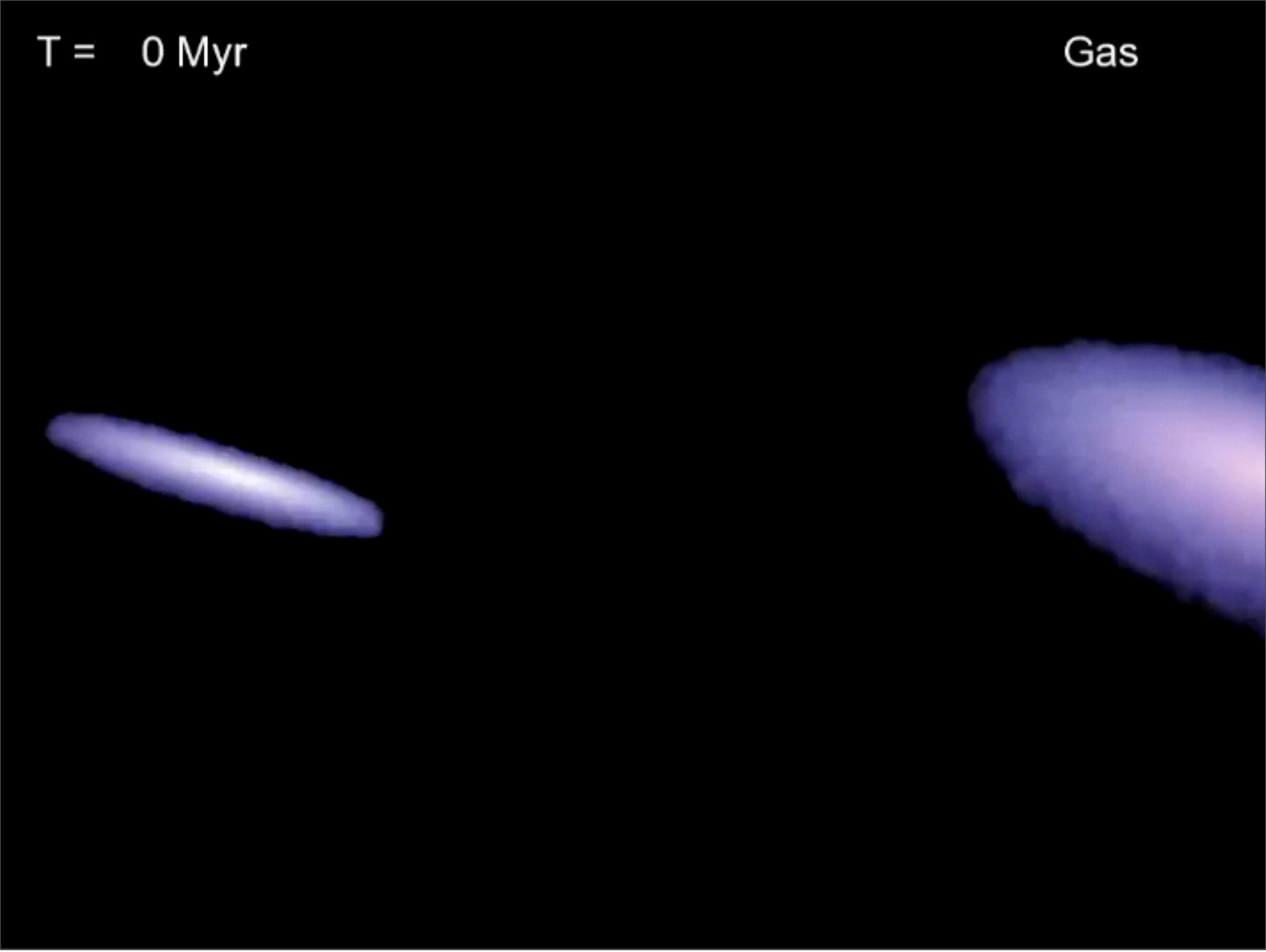




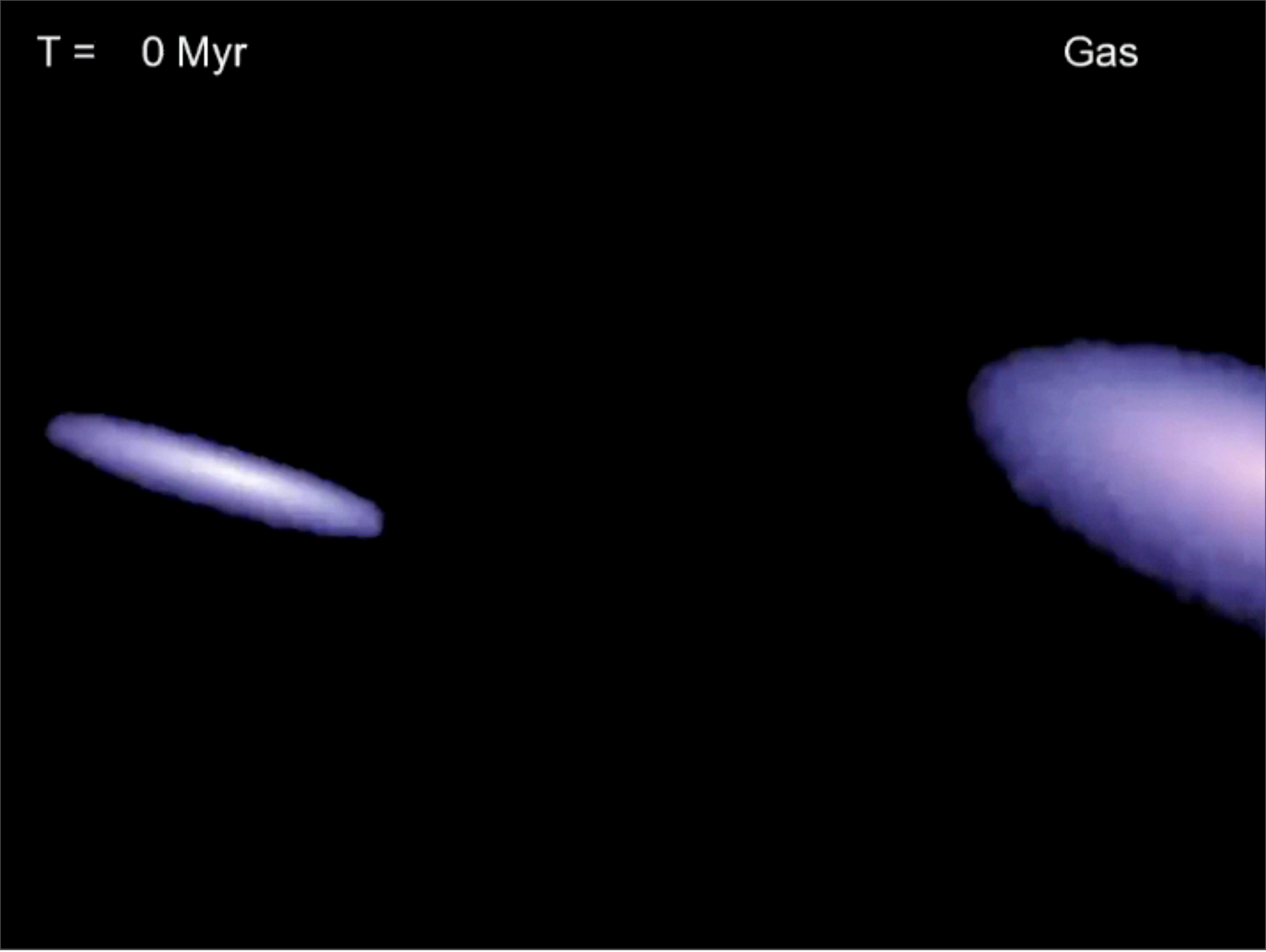

T = 0 Myr
Gas



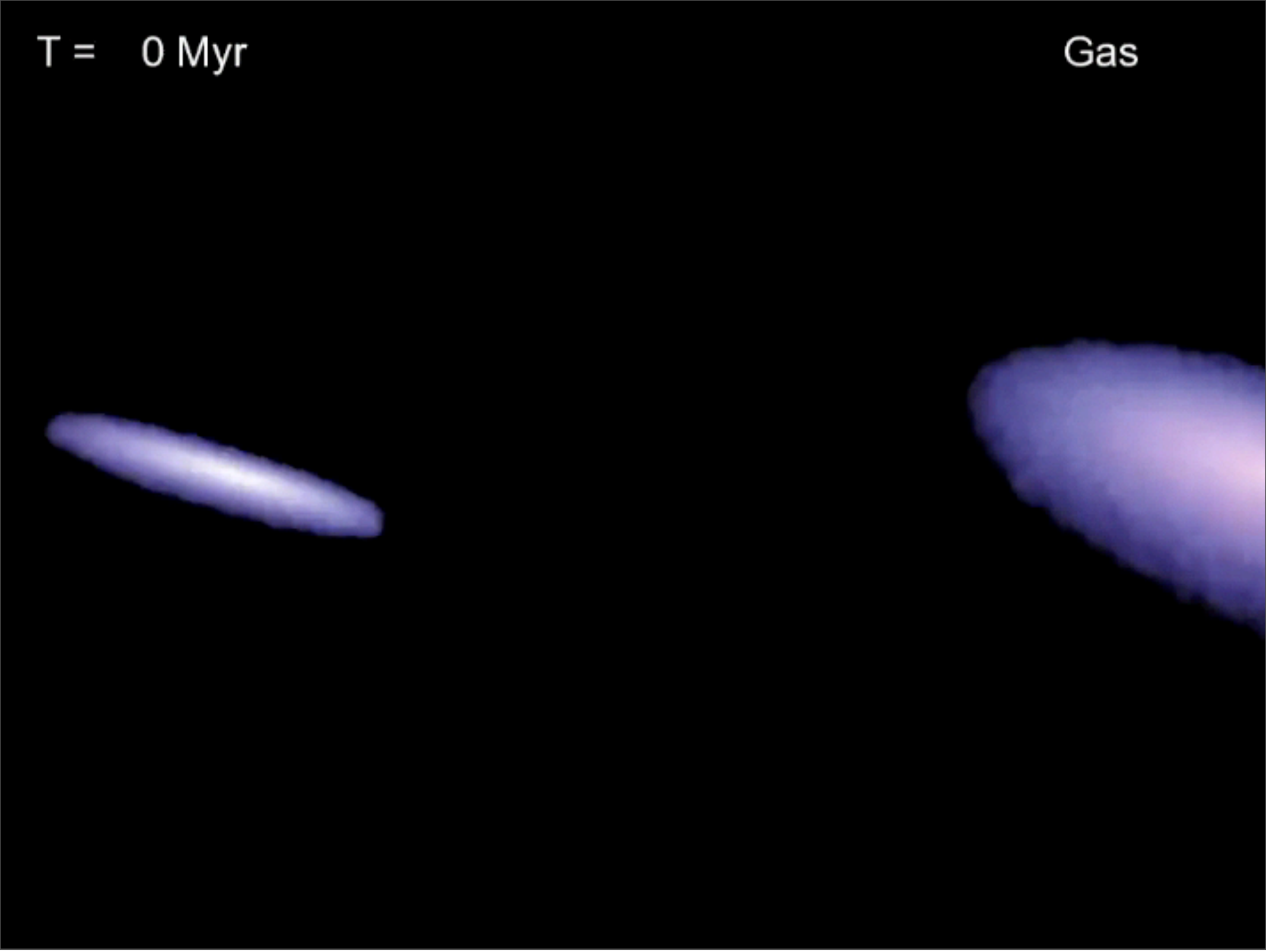
Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)

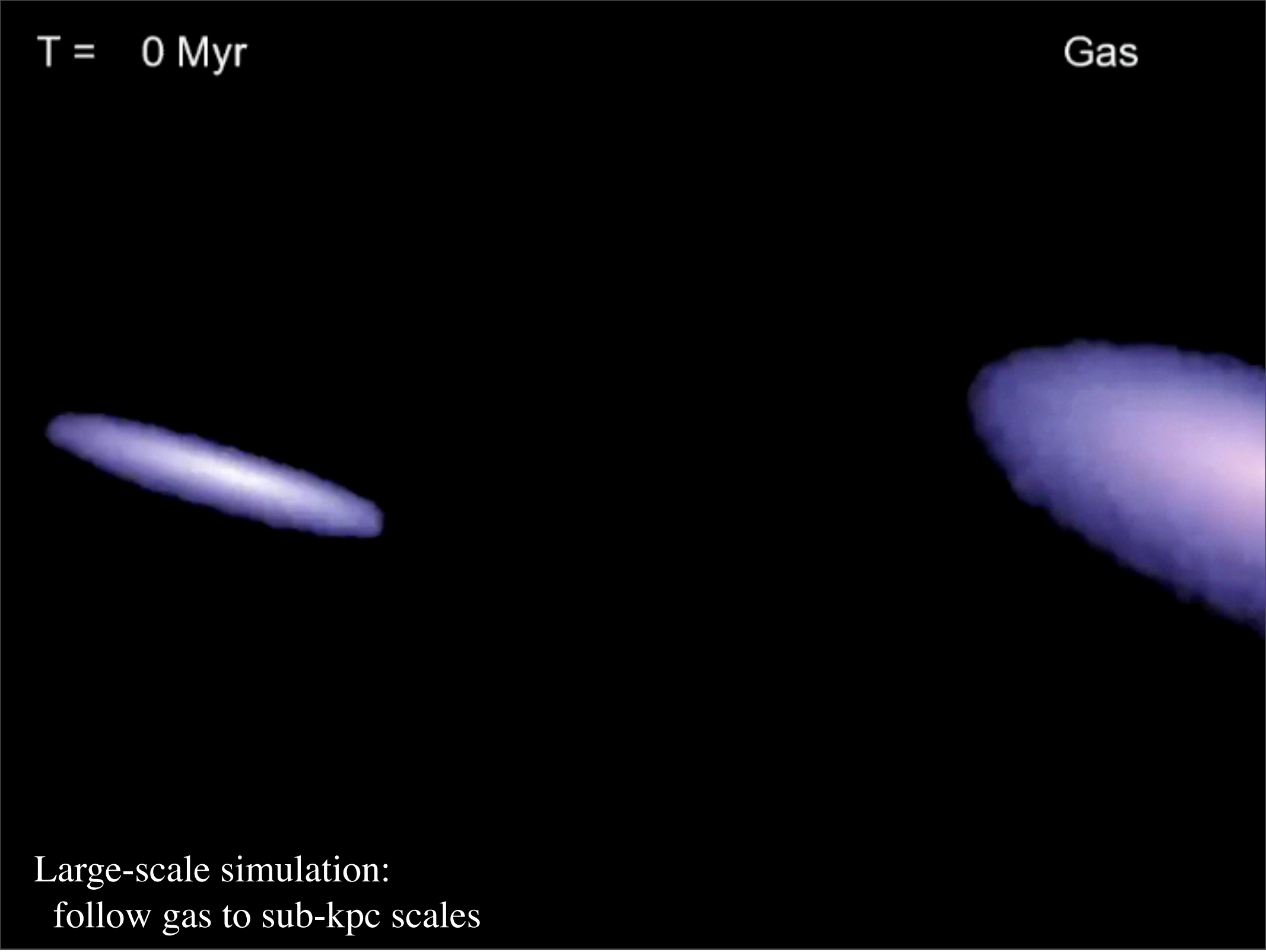

T = 0 Myr
Gas

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

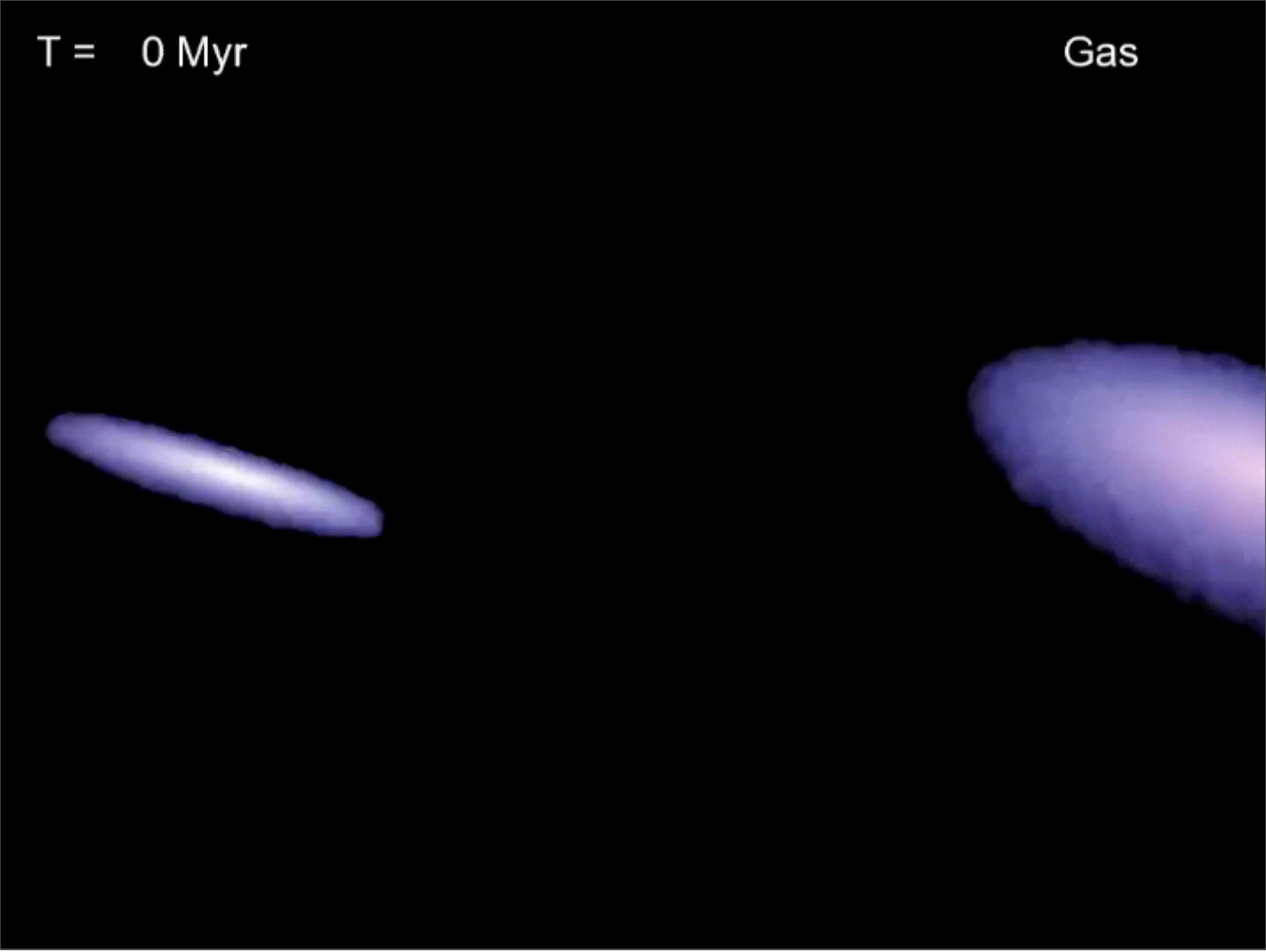

T = 0 Myr
Gas

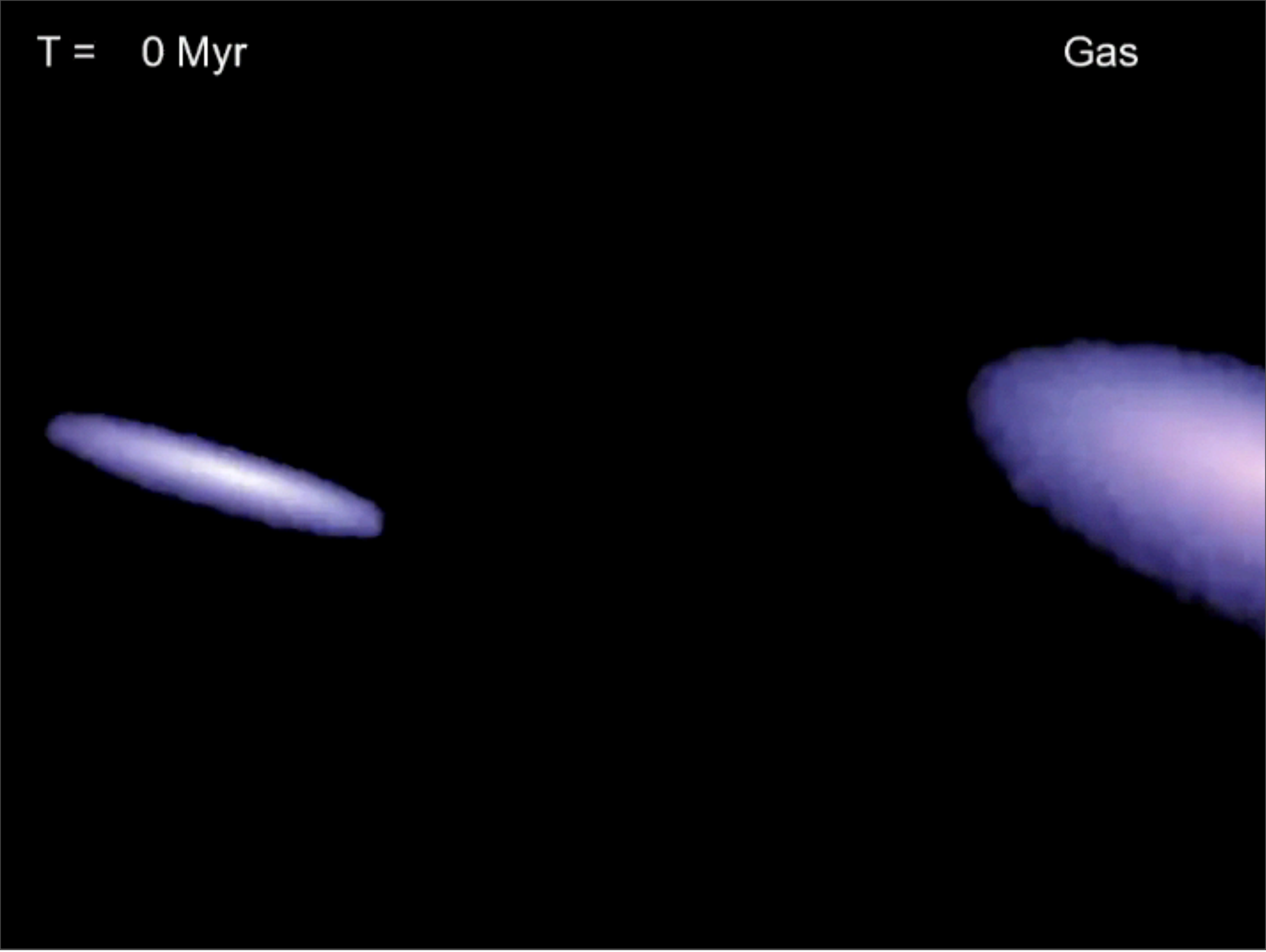
Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)

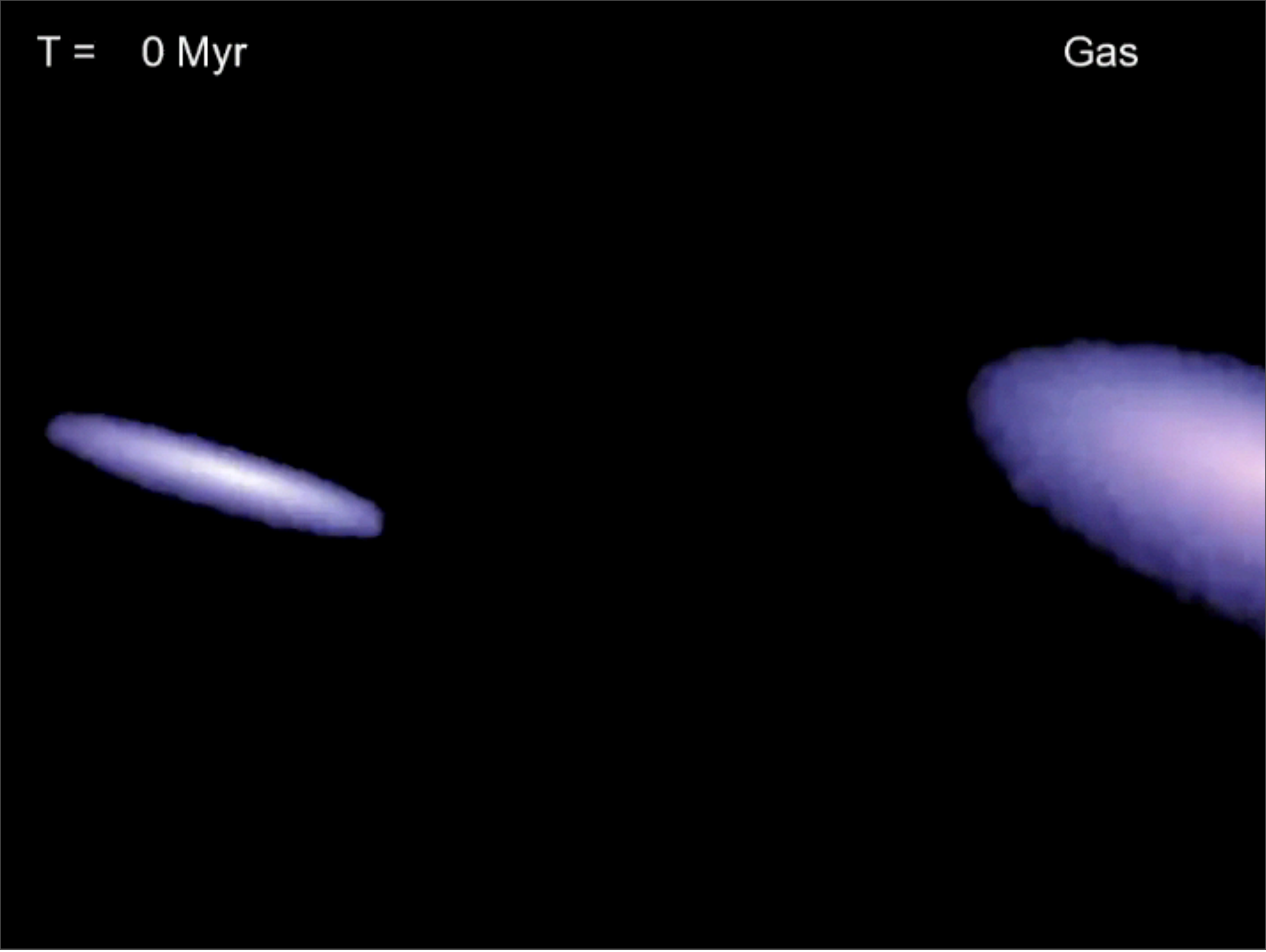

T = 0 Myr
Gas

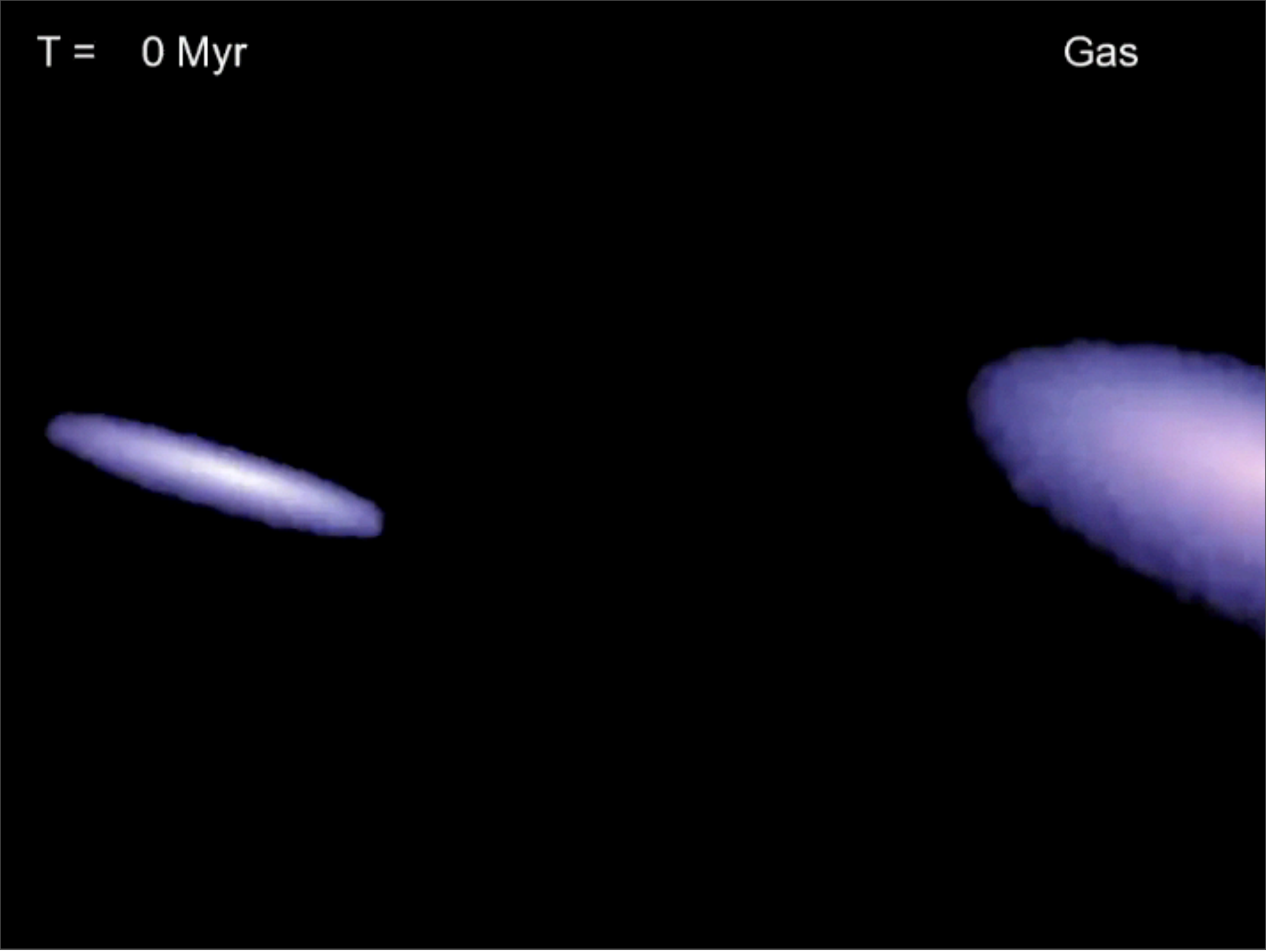


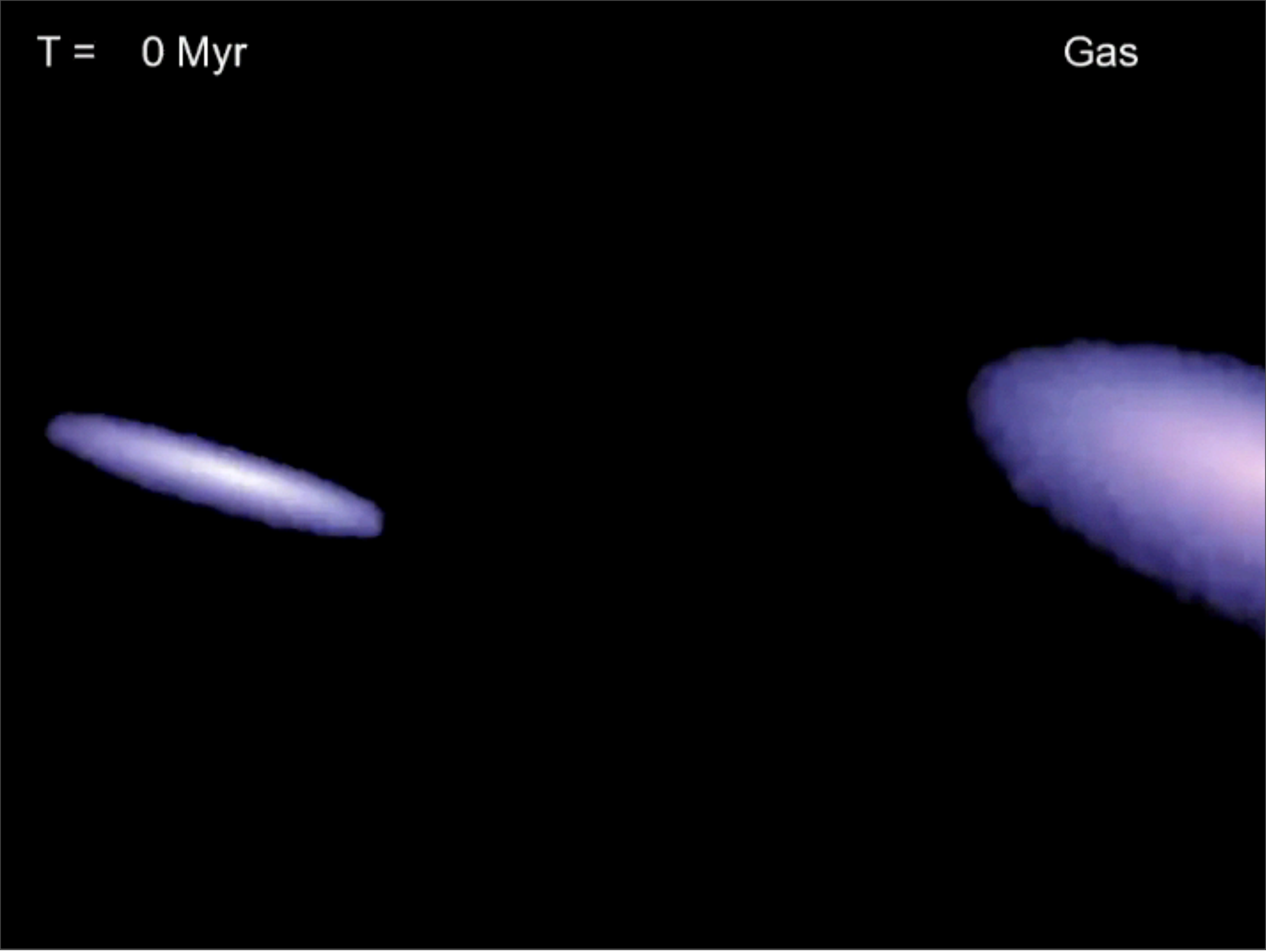
Large-scale simulation:
follow gas to sub-kpc scales


T = 0 Myr
Gas


T = 0 Myr
Gas


T = 0 Myr
Gas


T = 0 Myr
Gas


T = 0 Myr
Gas

Step 2: *Stellar* Feedback & the ISM

- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

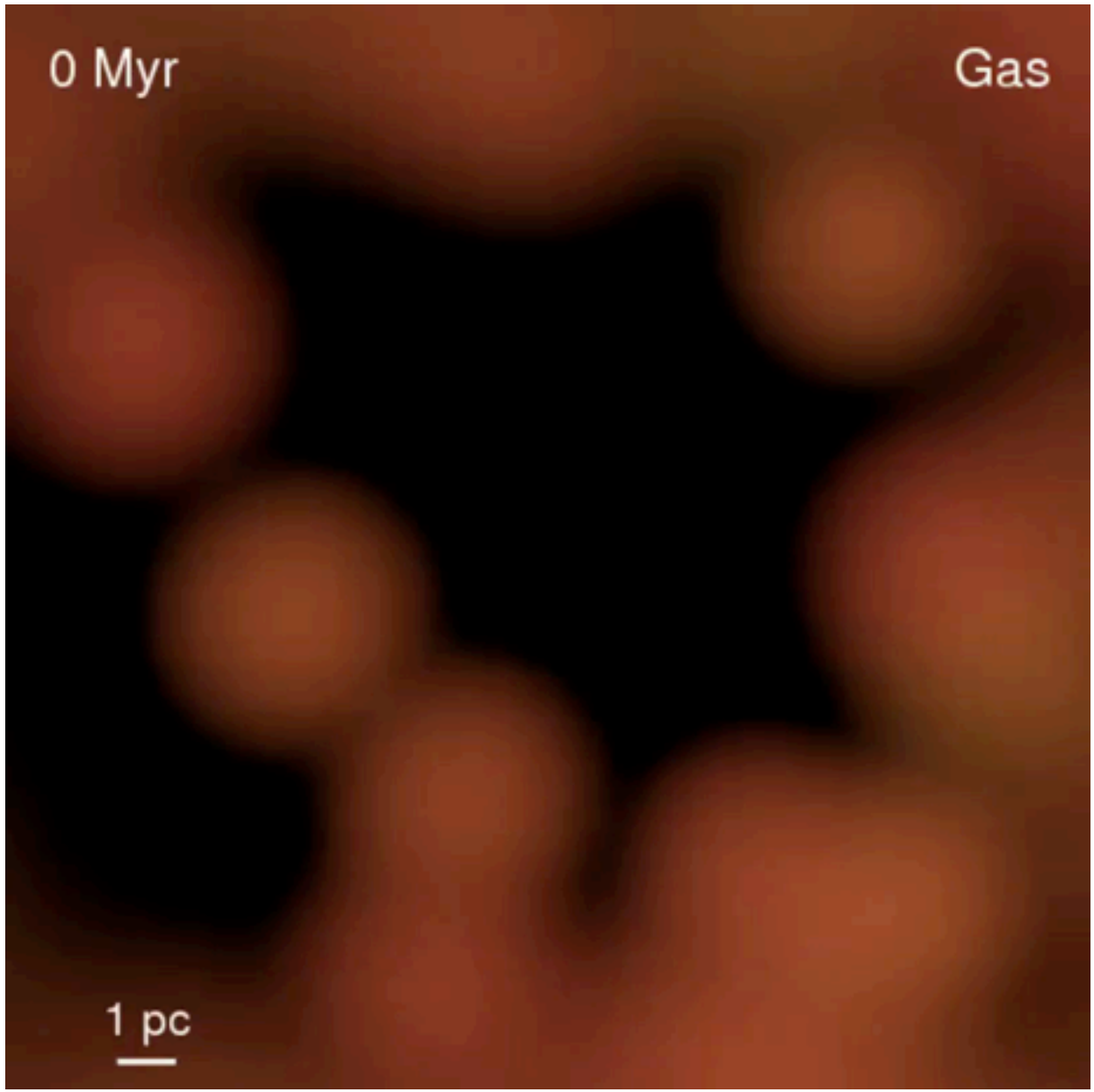
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

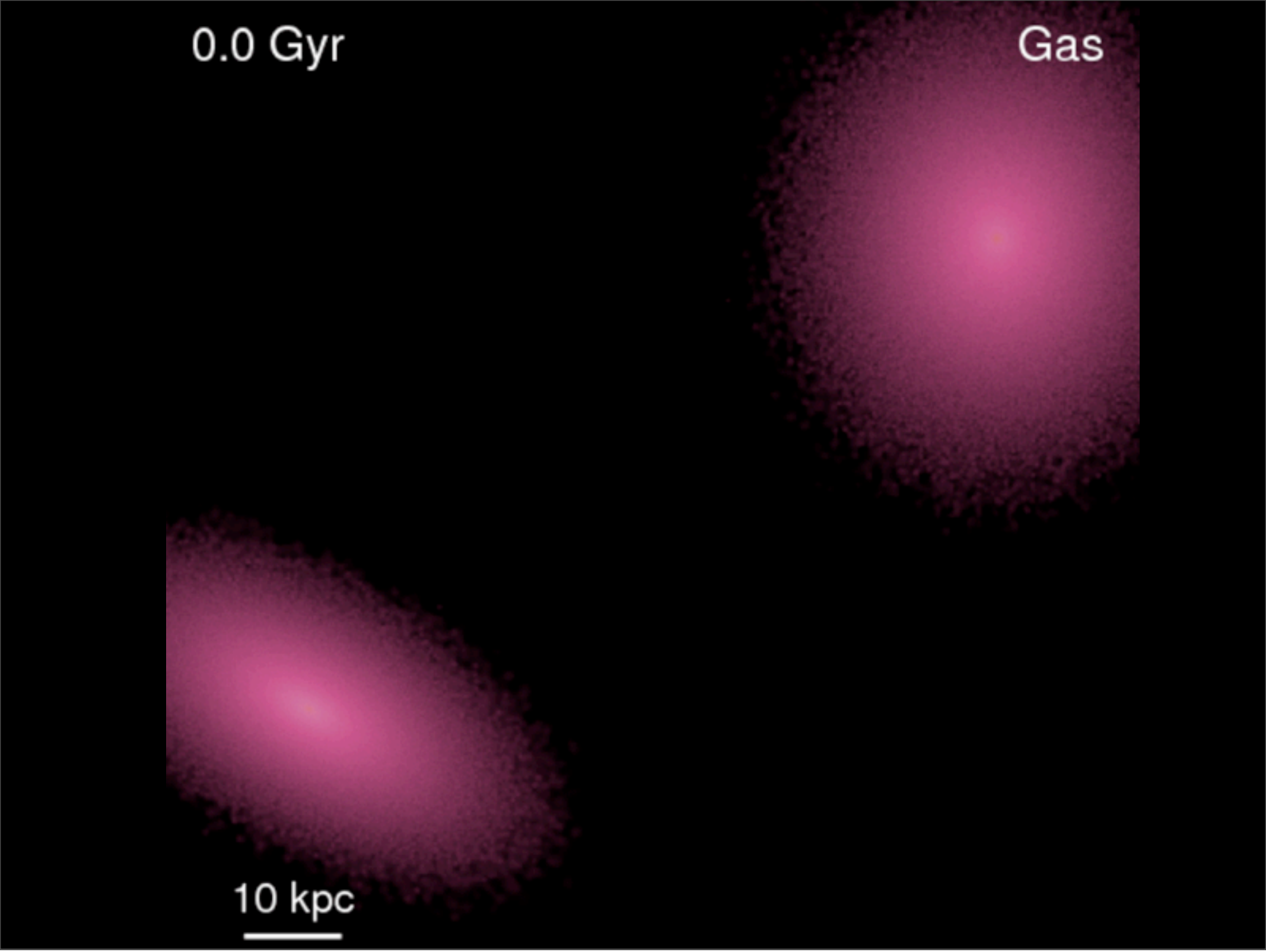
  - SNe

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

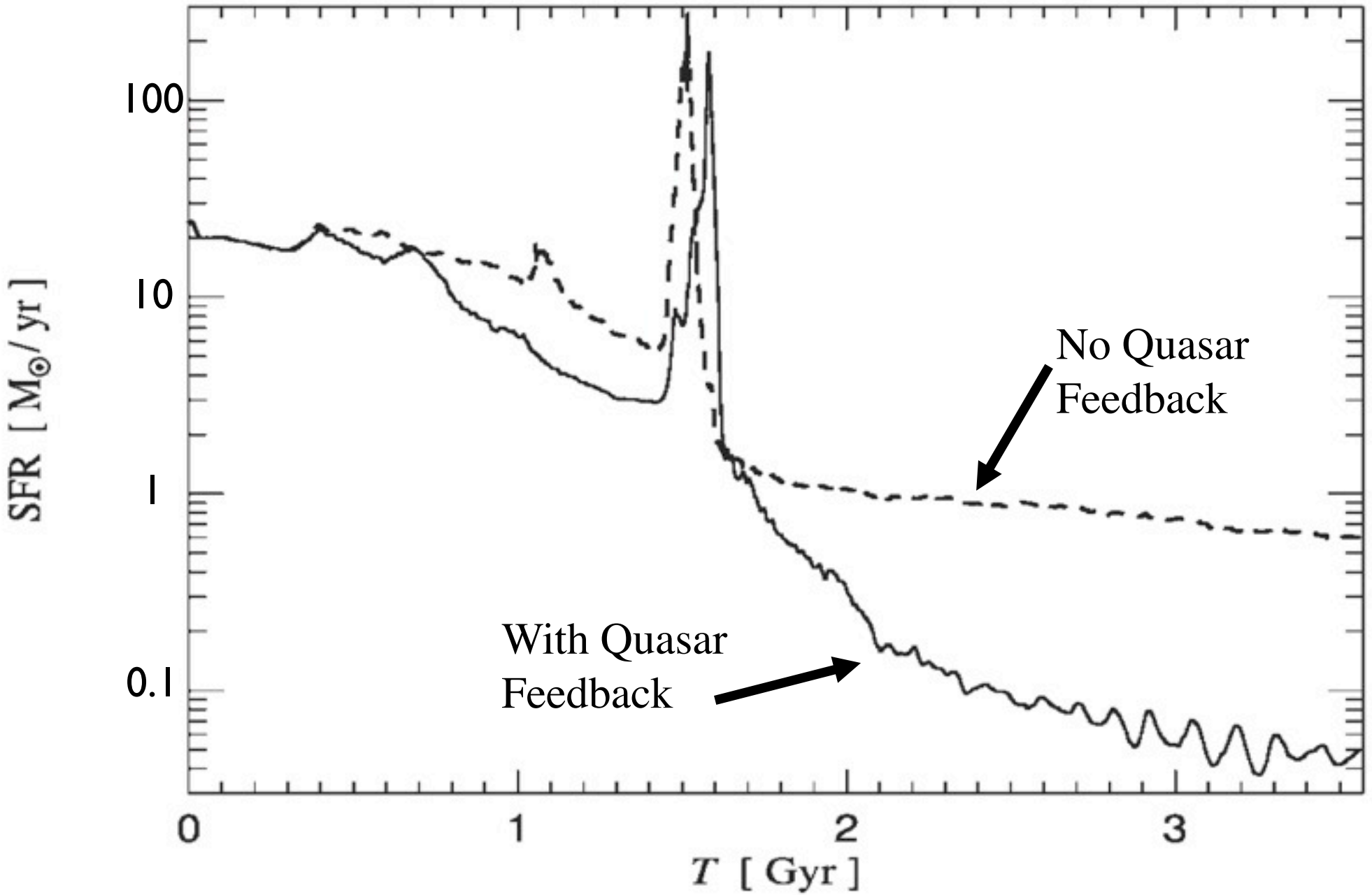
  - Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

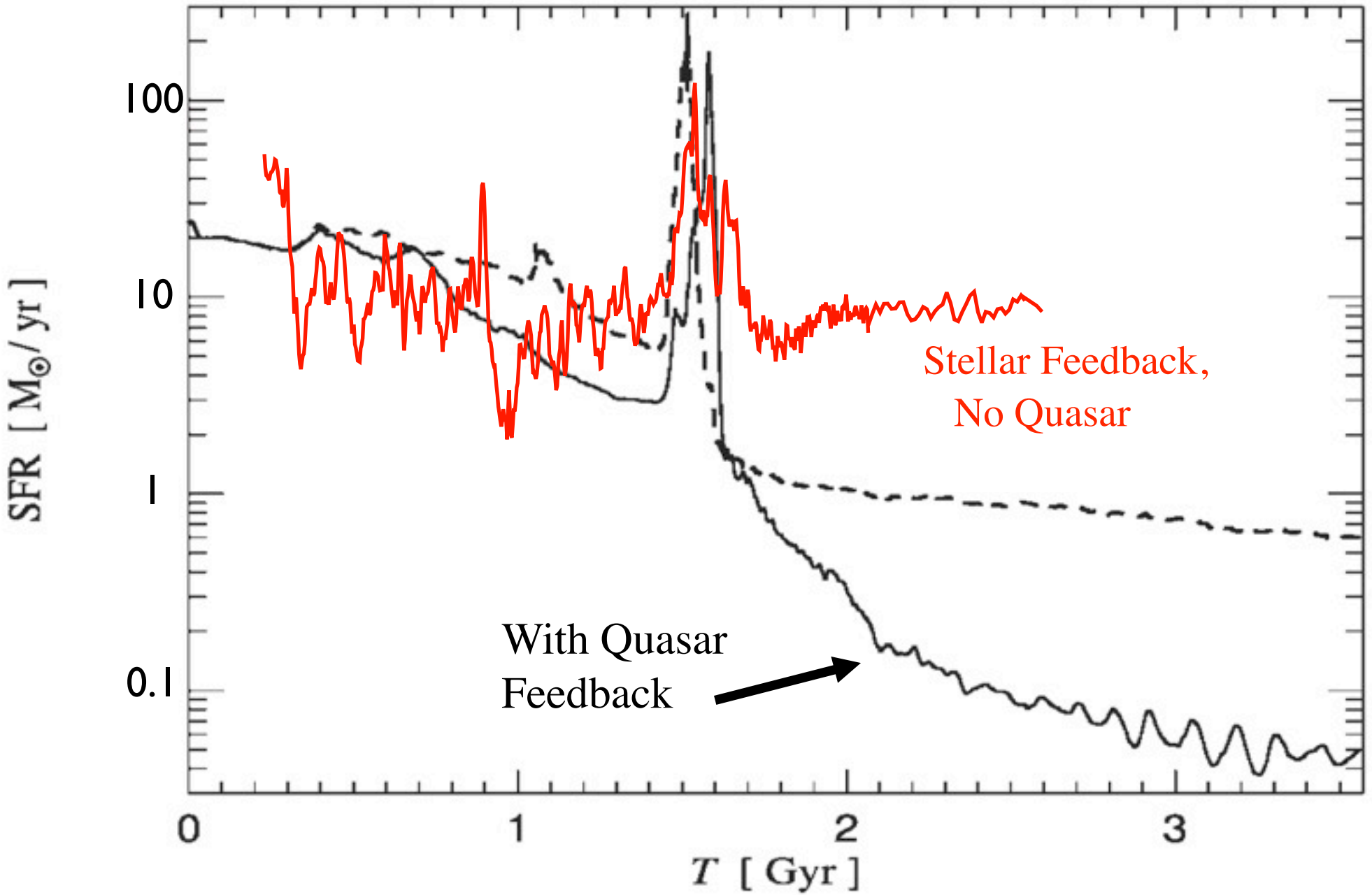



0.0 Gyr
Gas
10 kpc

Do we need 'Quasar Mode' Feedback?

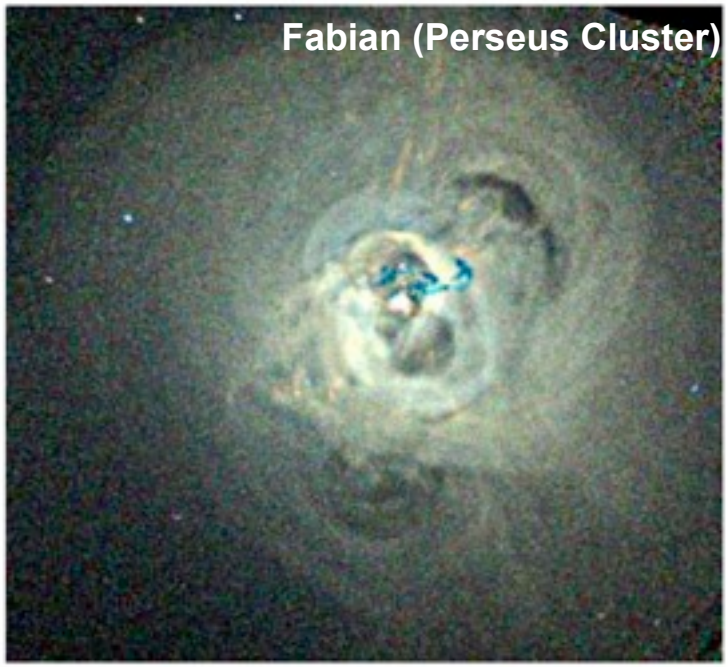


Do we need 'Quasar Mode' Feedback?

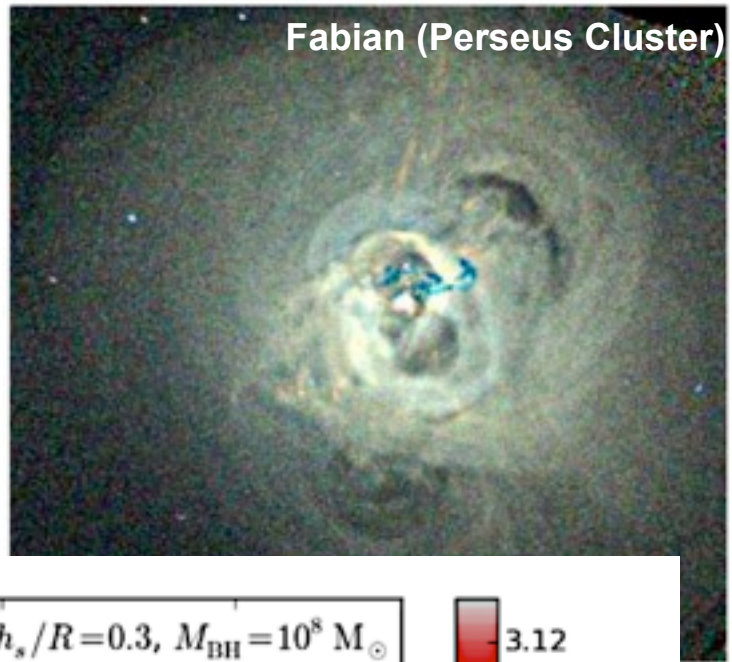


Step 3: Observed Sources of AGN Feedback

- Jets
  - heat IGM/ICM (low-density), but not dense ISM

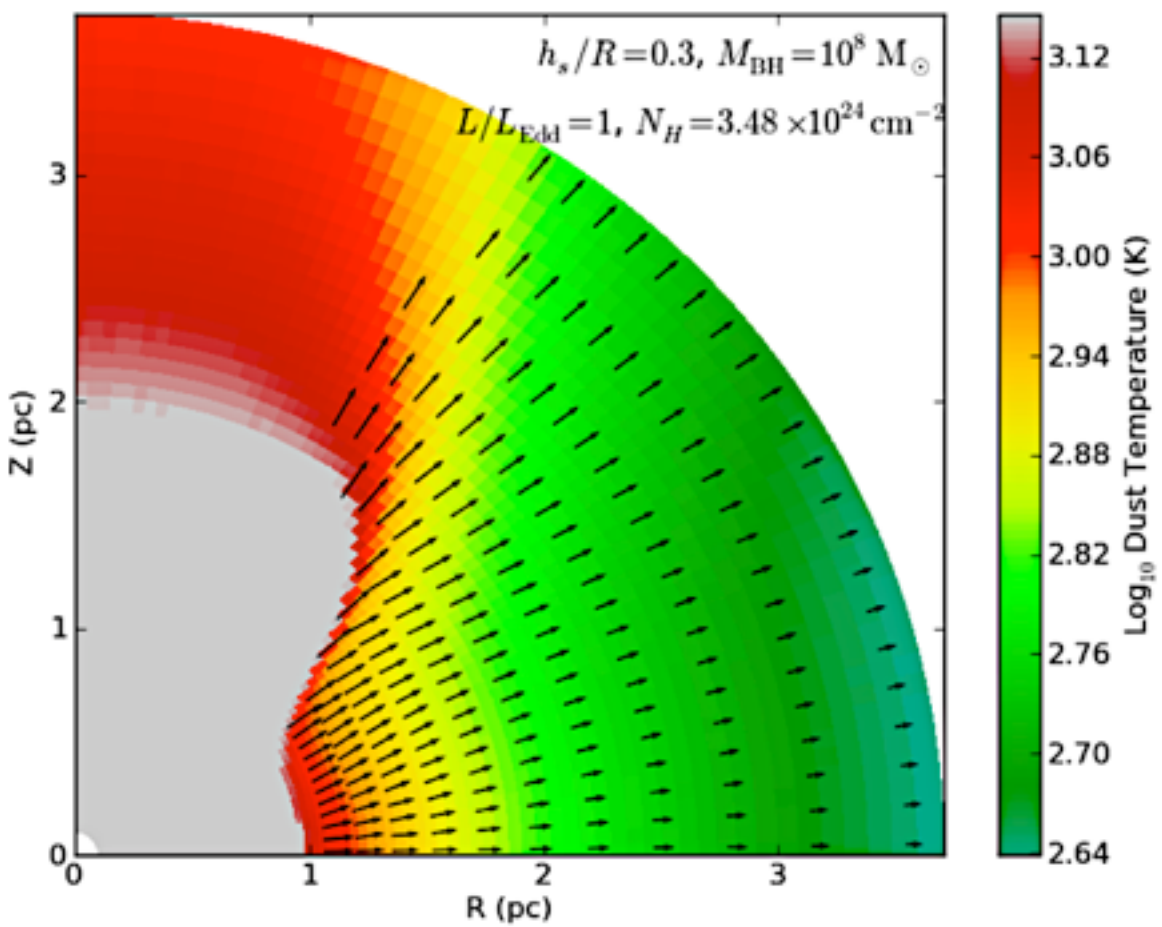


Step 3: Observed Sources of AGN Feedback



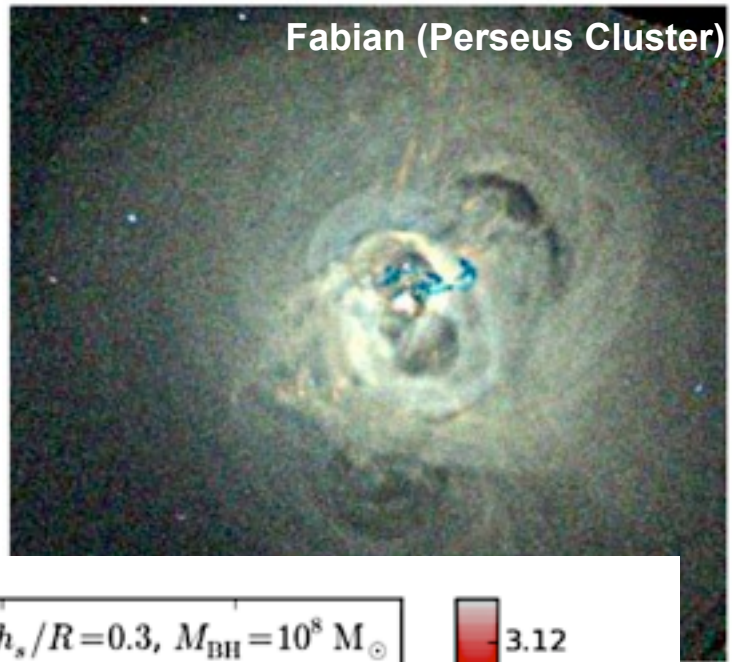
- Jets
  - heat IGM/ICM (low-density), but not dense ISM

- Radiation Pressure
  - $L_{AGN} >> L_{stars}$

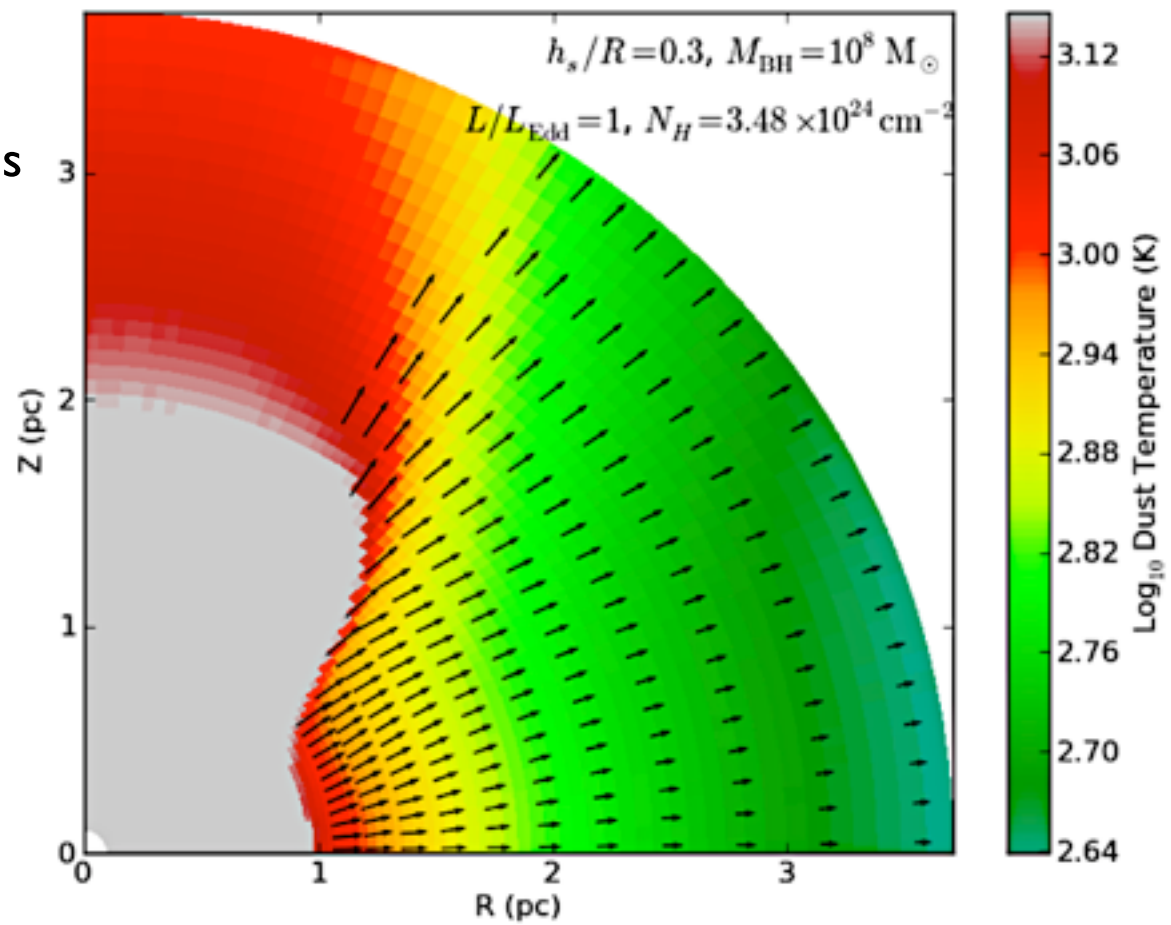


Roth, Kasen, Quataert, PFH in prep

Step 3: Observed Sources of AGN Feedback



- Jets
  - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
  - Broad Absorption Line Winds

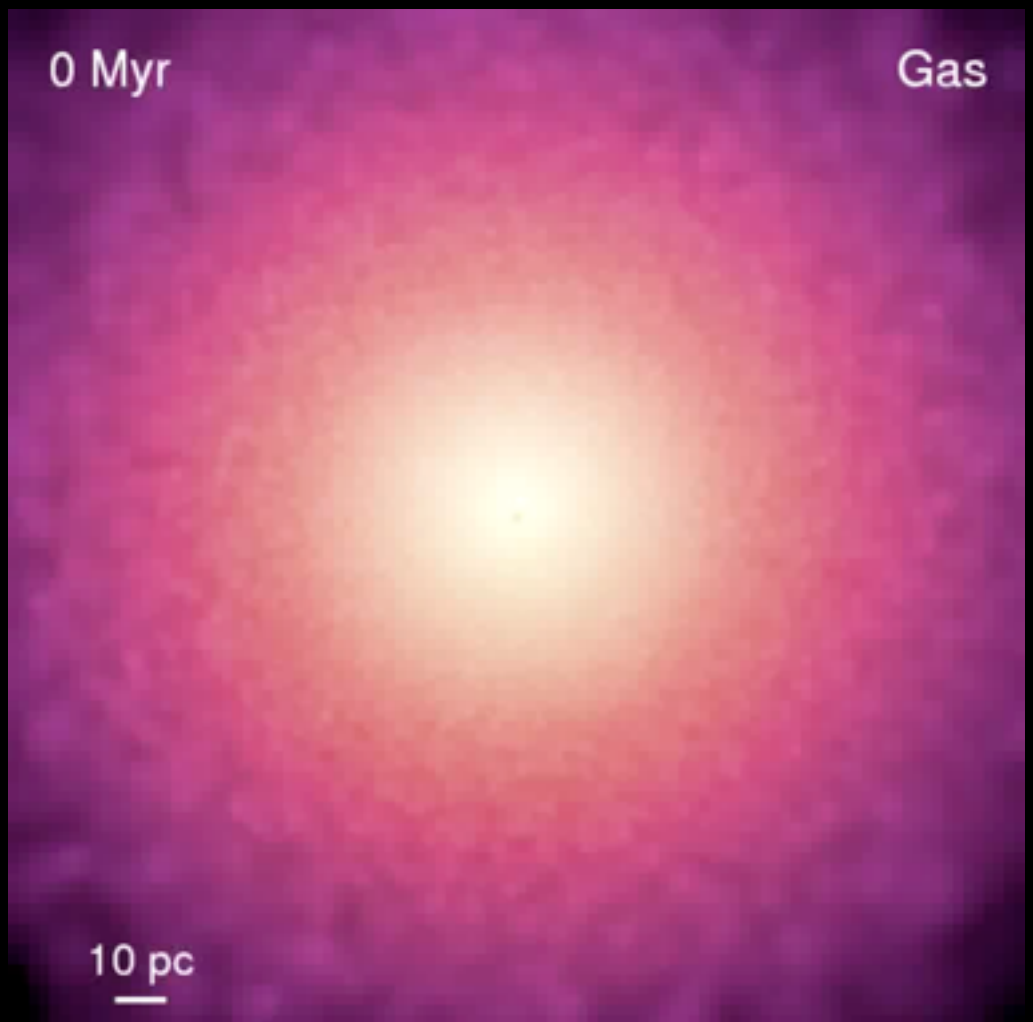


Roth, Kasen, Quataert, PFH in prep

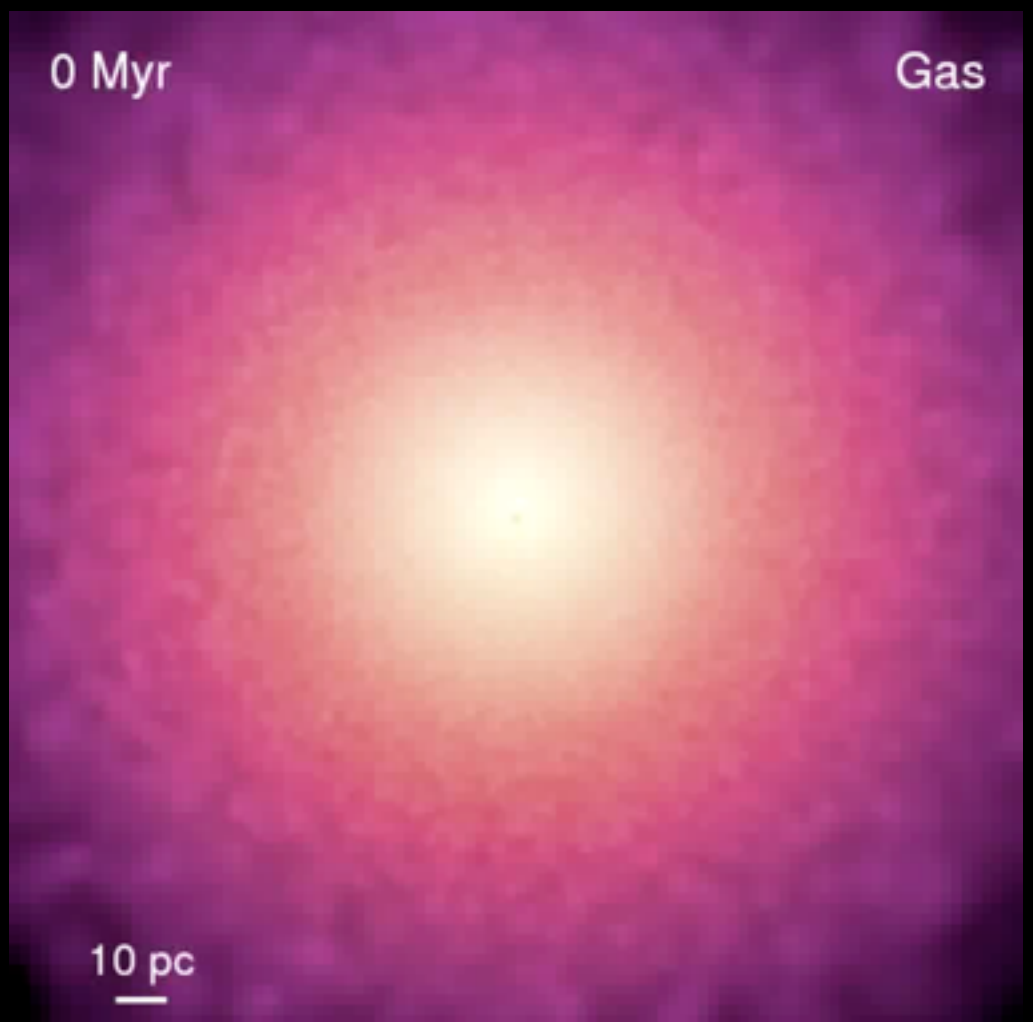
BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds

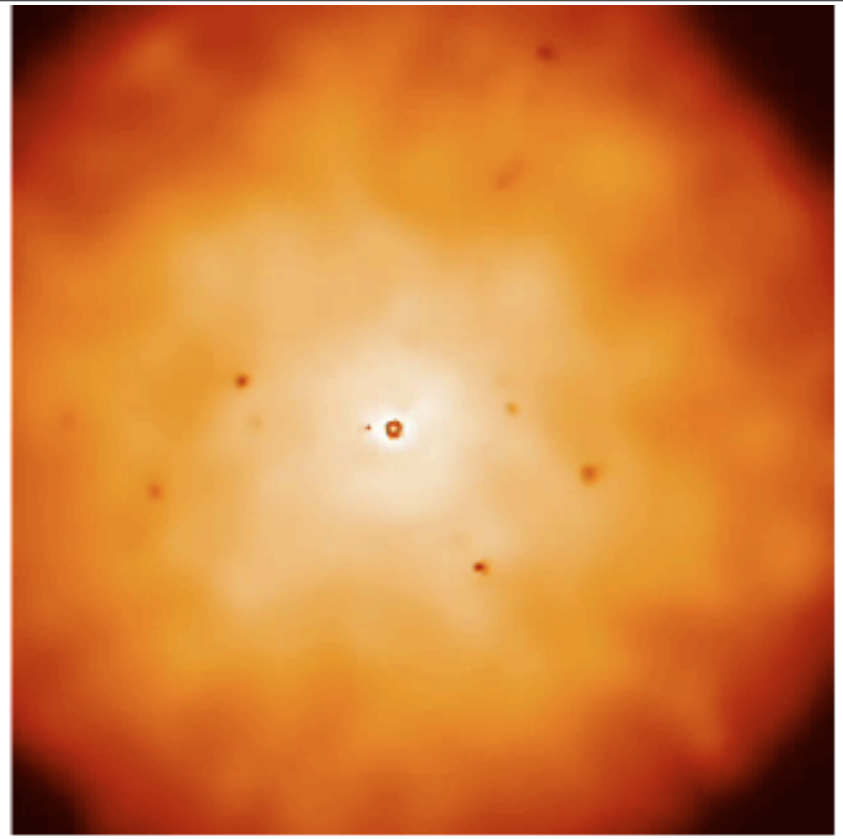


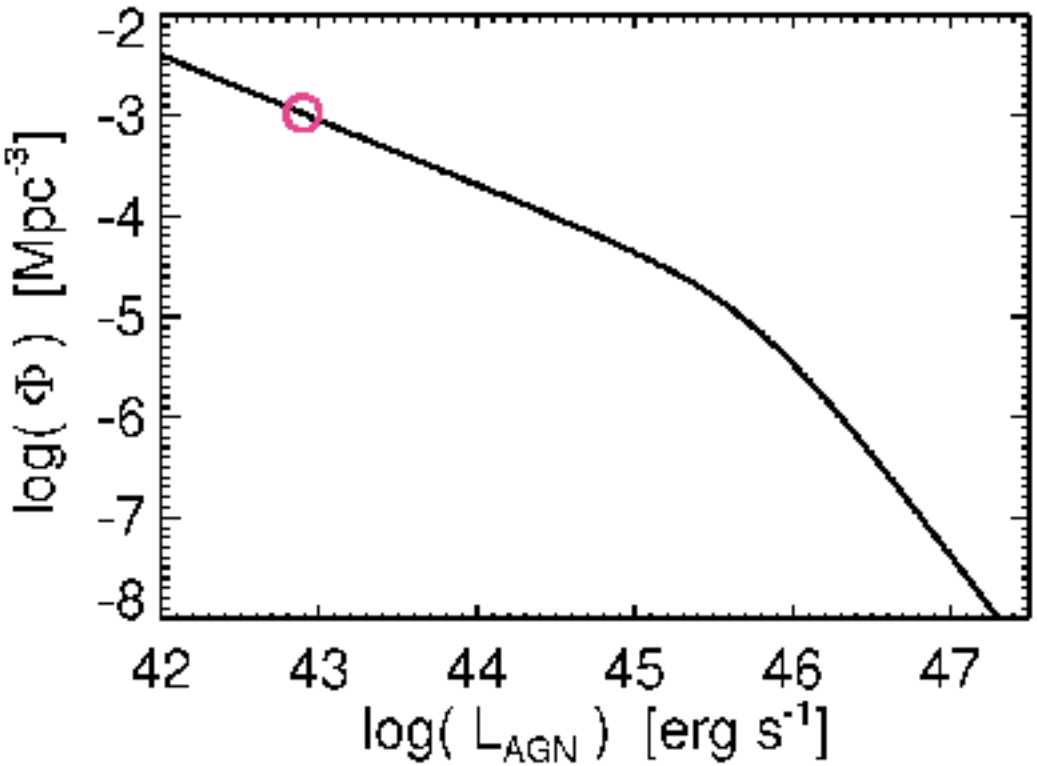
With BAL Winds

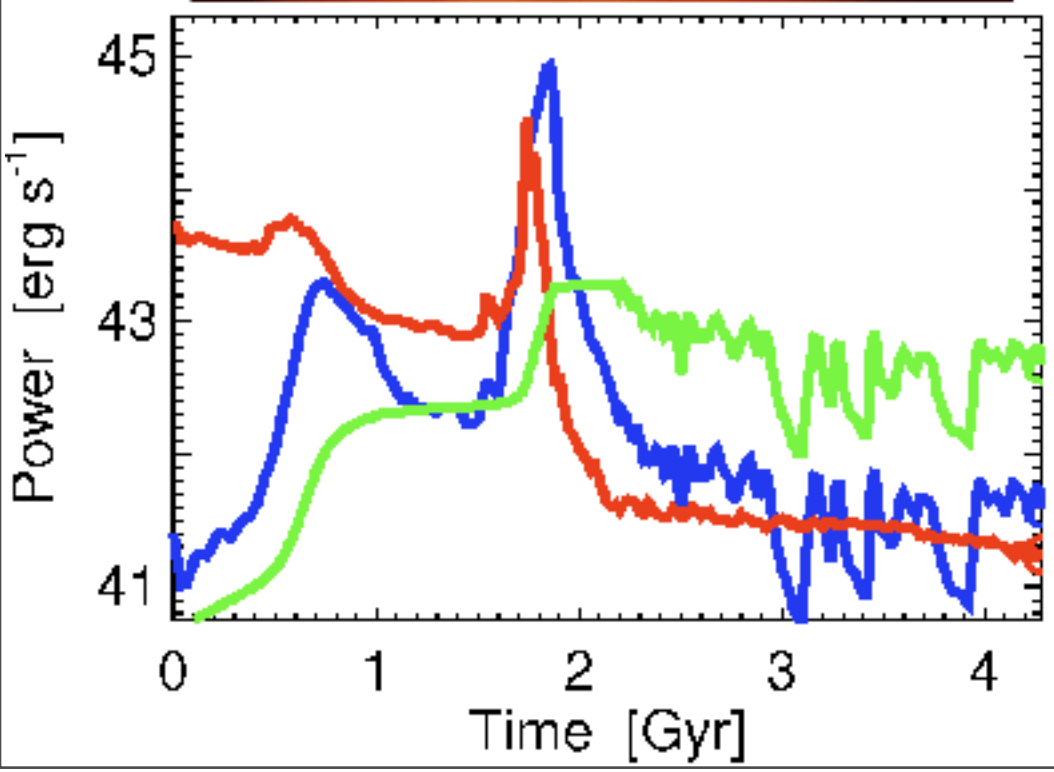


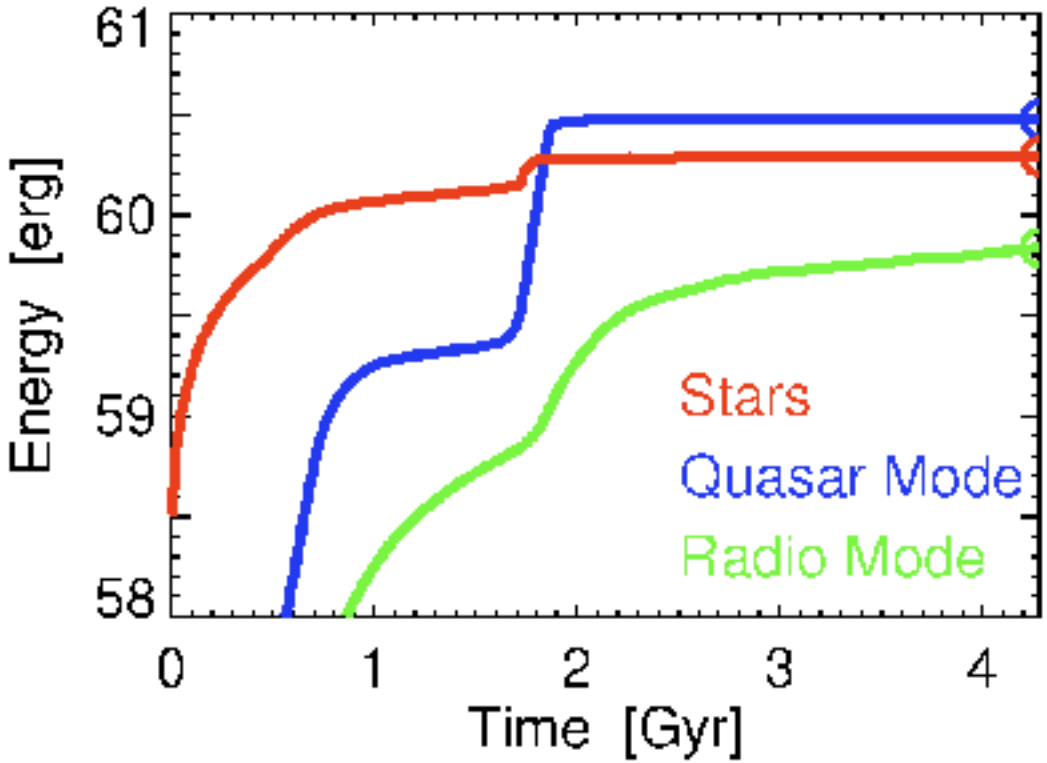
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

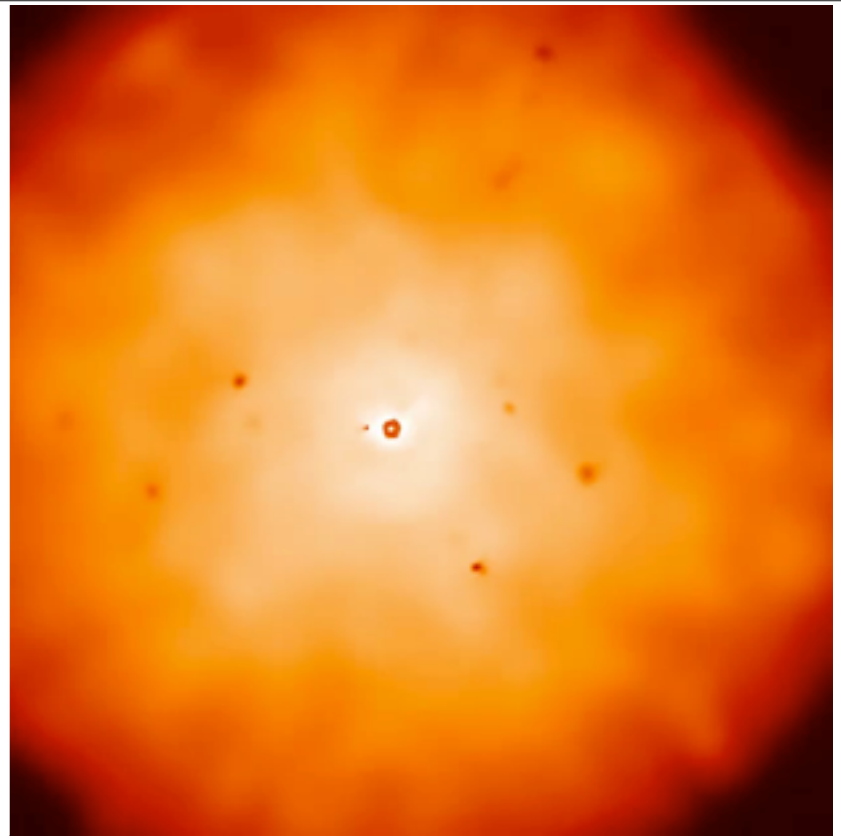
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

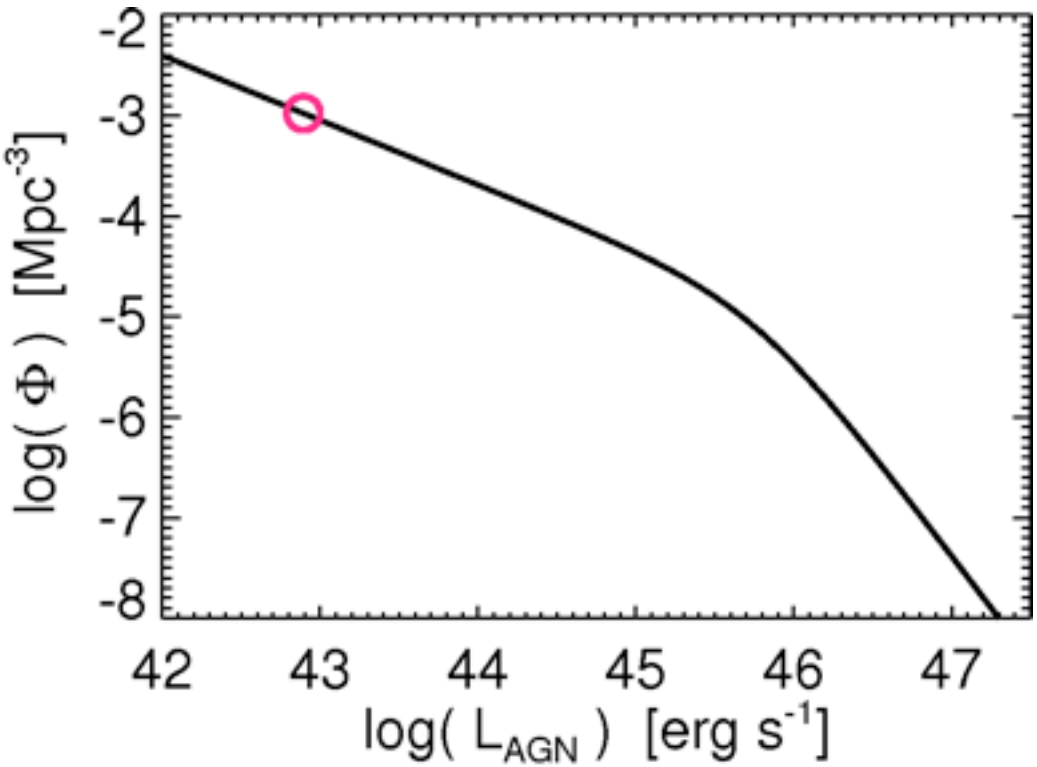


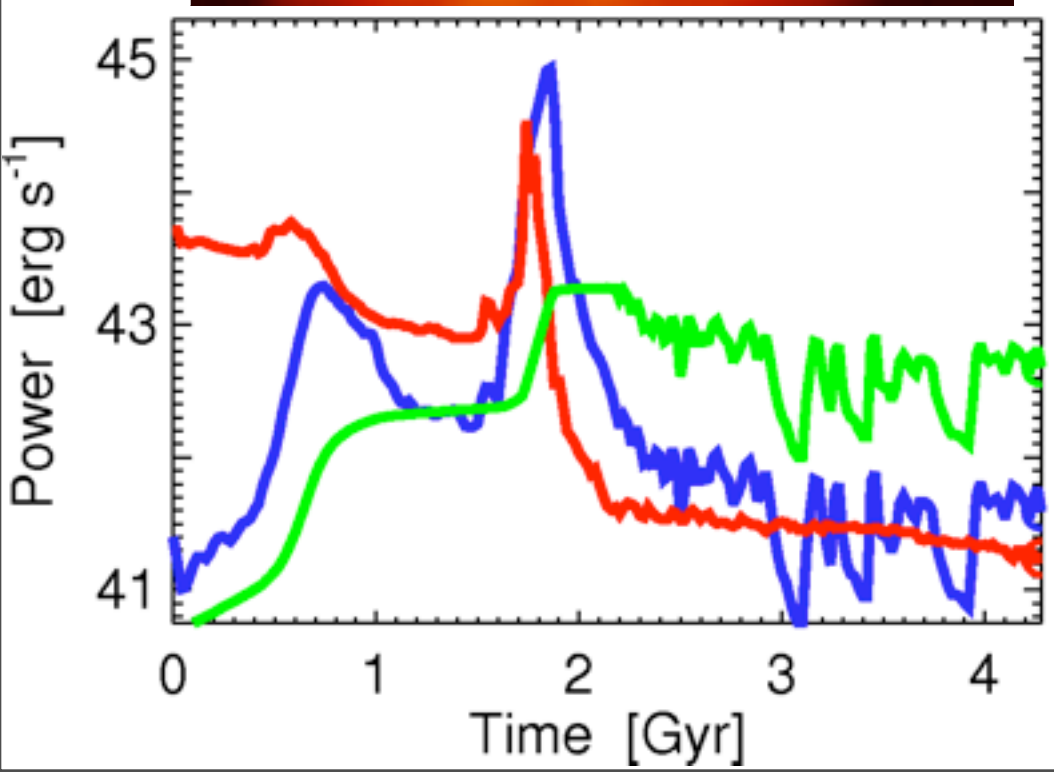

log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]

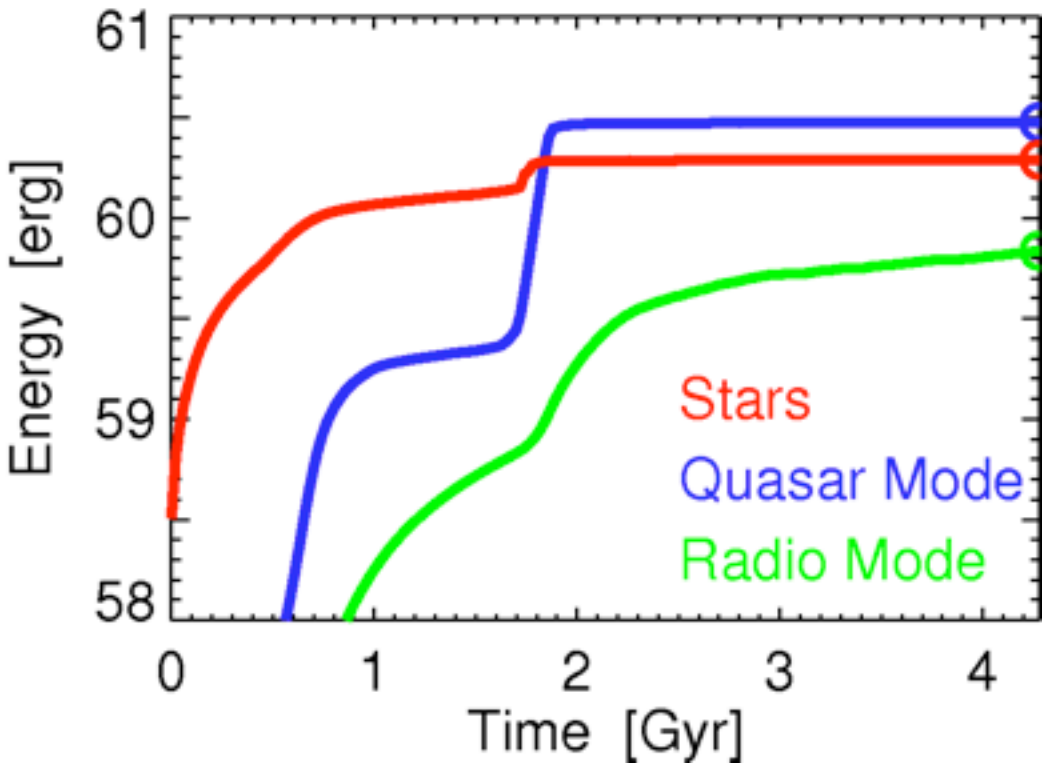

Power [erg s^{-1}]
45
43
41
0
1
2
3
4
Time [Gyr]


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:

- **Star formation is Feedback-Regulated**:
  - *Independent* of small-scale SF 'law' & chemistry
  - Leads to Kennicutt relation & **super-winds**

- Different mechanisms dominate different regimes:
  - High-r: radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low-r: SNe & stellar wind shock-heating
    - **No *one* mechanism works**

- Mergers: Extreme laboratory (>100x GMC densities!)
  - **No "unique" physics**
  - Super-winds: ~10-500 M_{sun}/yr

- Most **Massive Galaxies: Need "AGN" Feedback**!
  - Disk Winds+Radiation Pressure+Jets: Explain M_{BH}-s & suppress SF
  - "Radio Mode": What's doing the work?