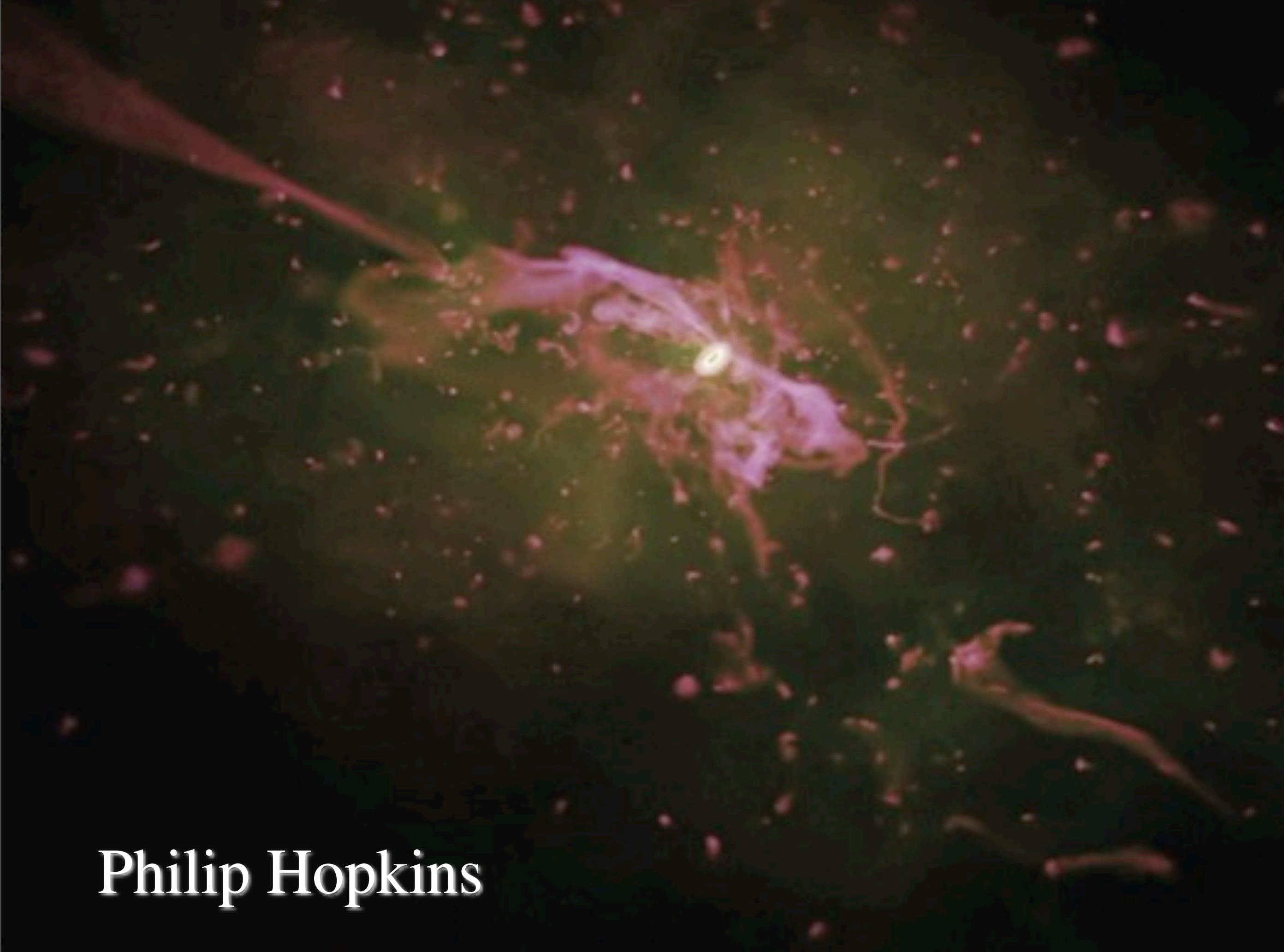
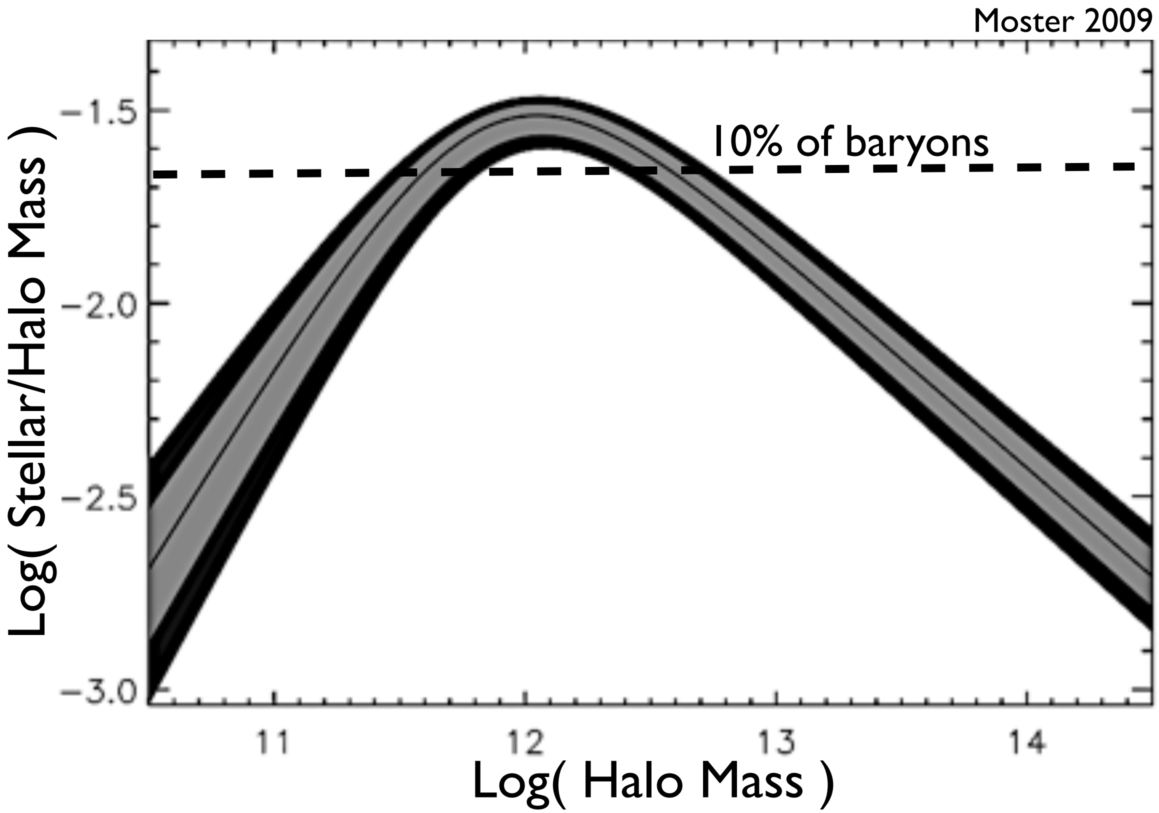
Feedback-Regulated Star Formation in Galaxies

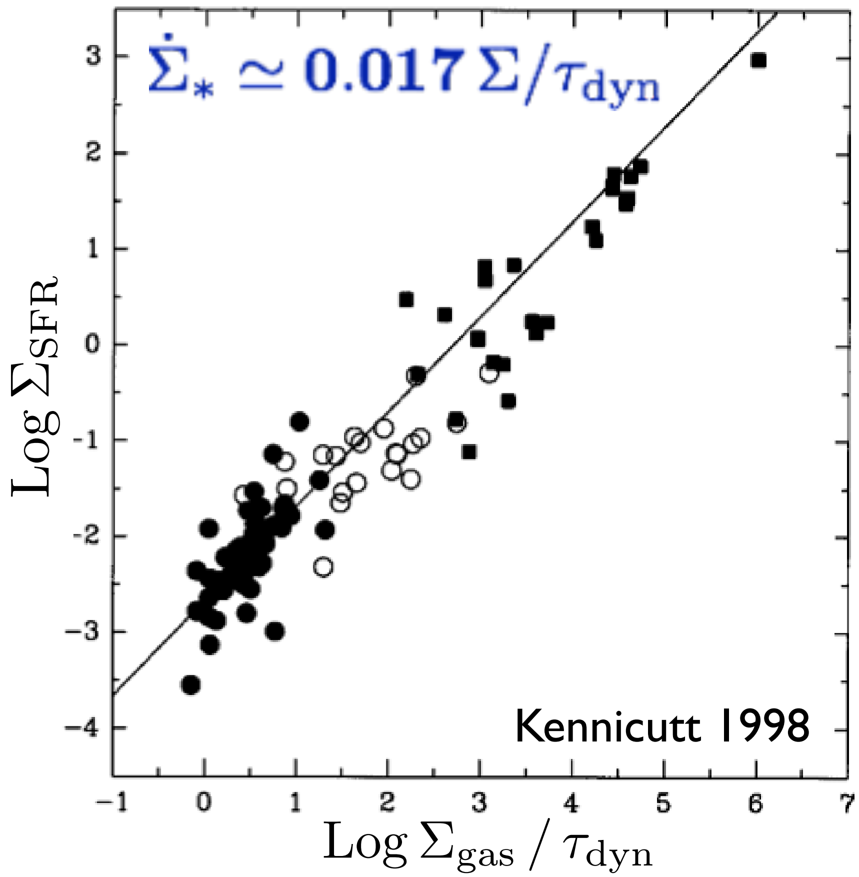


Philip Hopkins

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?

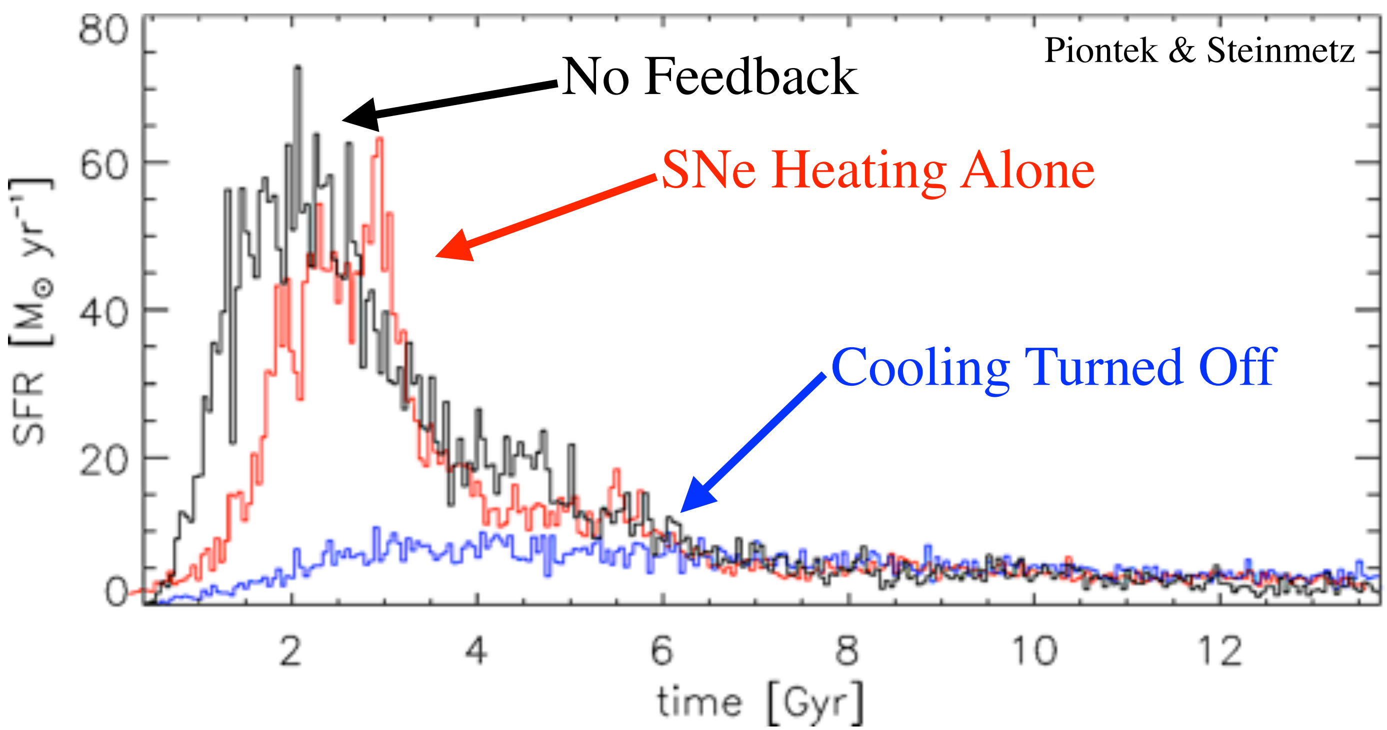
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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
  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

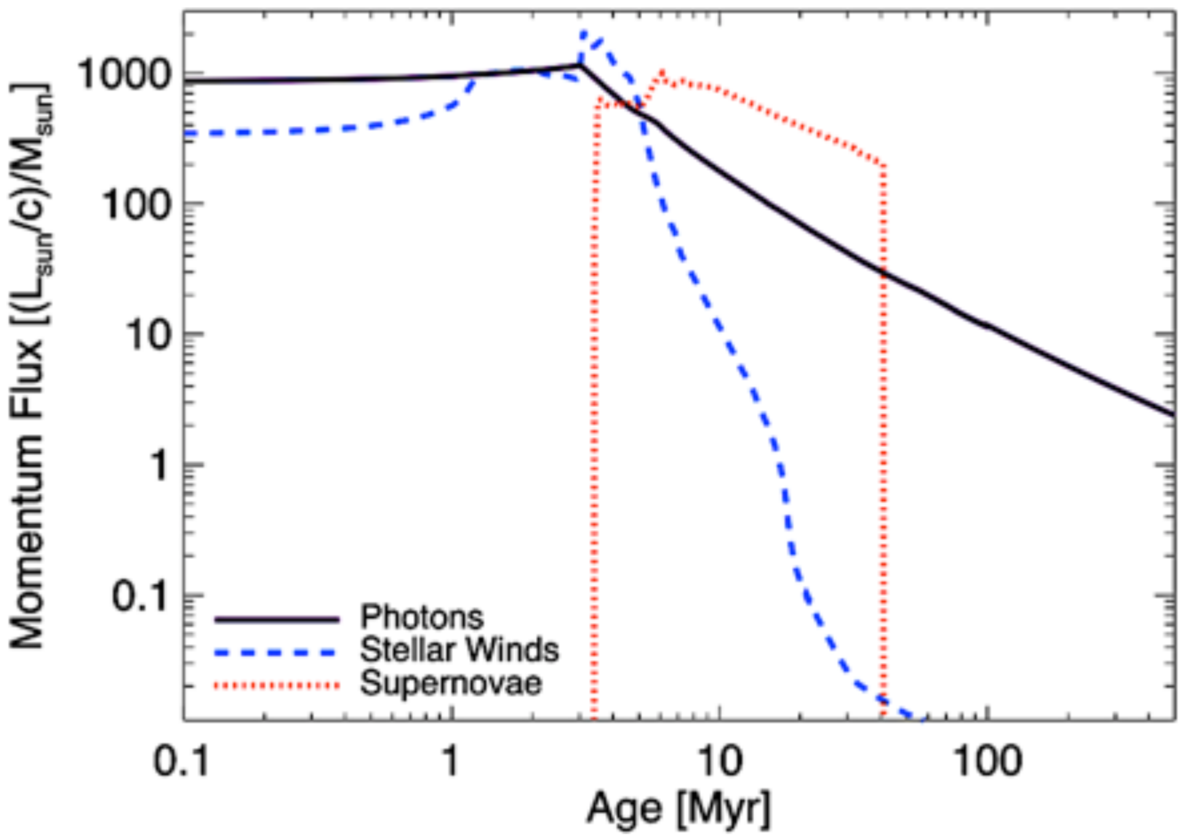
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

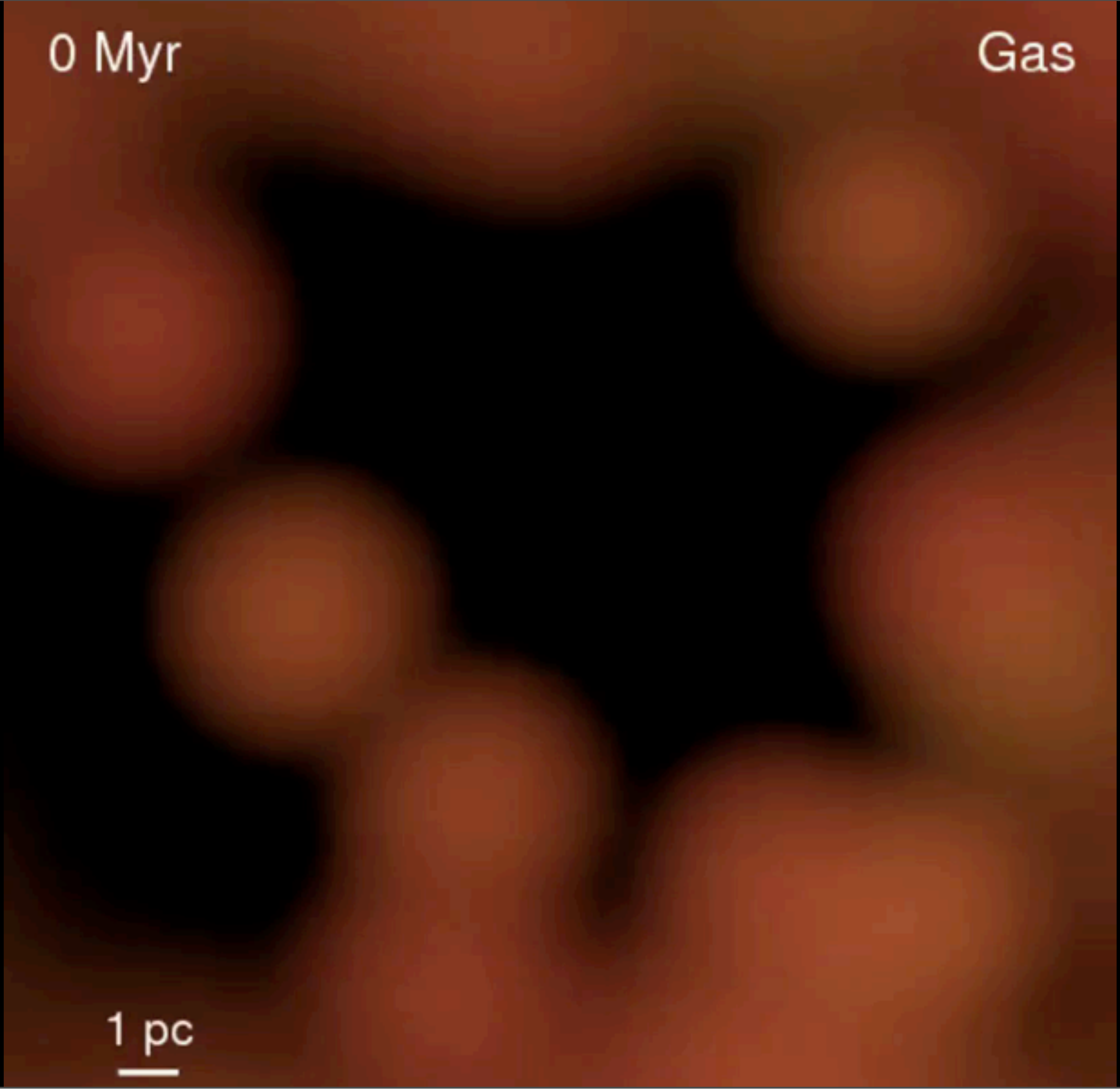
  - SNe

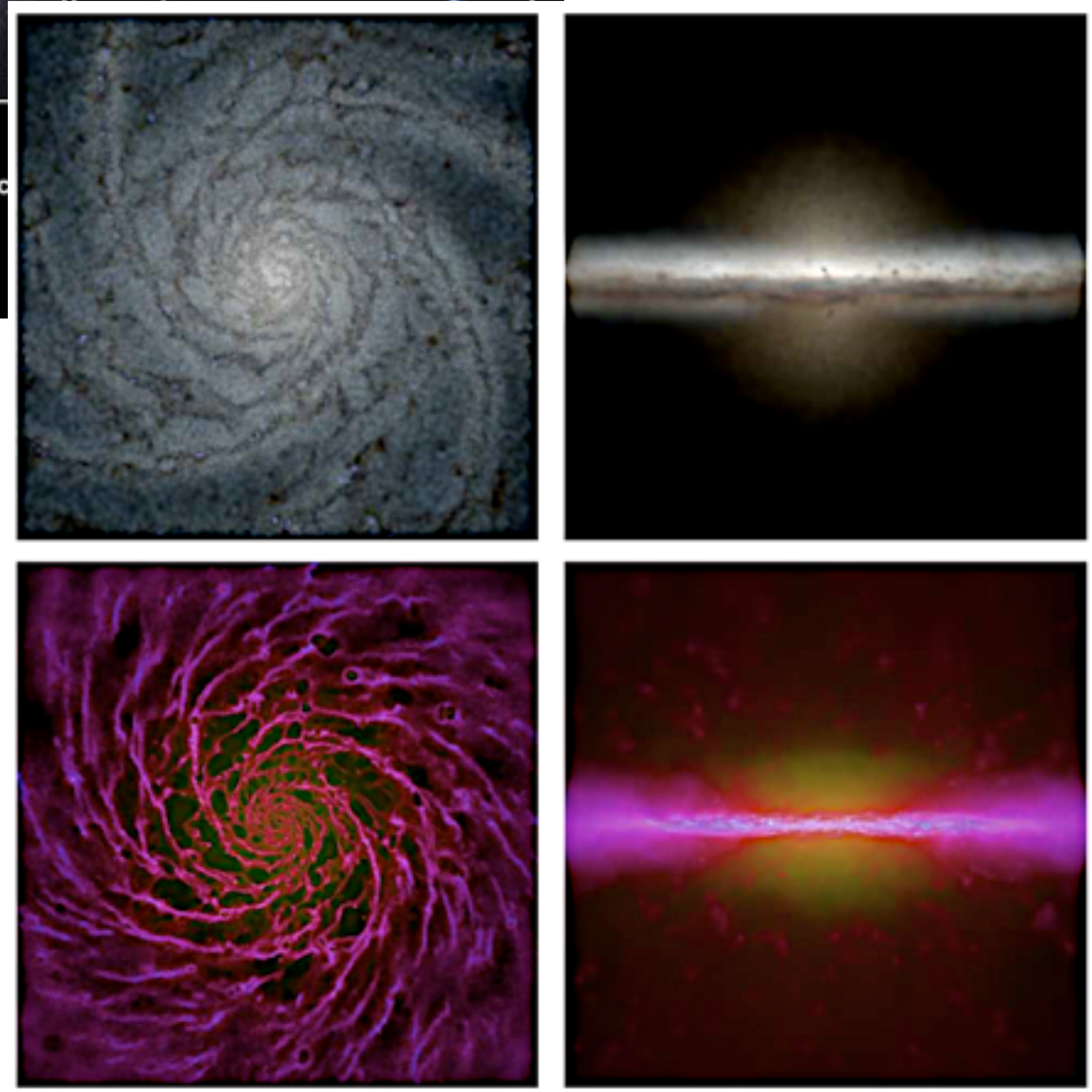
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

  - Stellar Winds

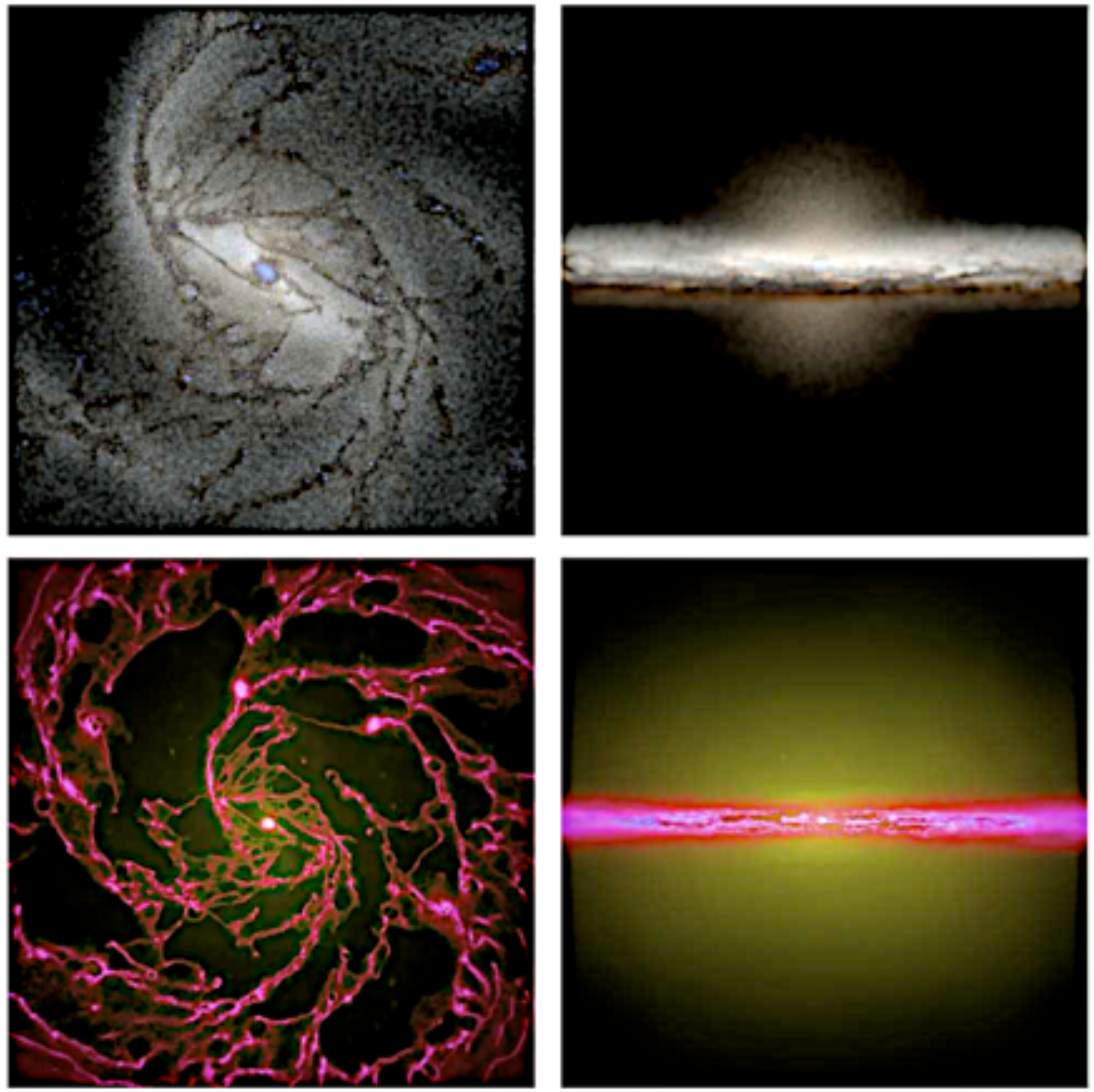
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




0 Myr
Gas
1 pc

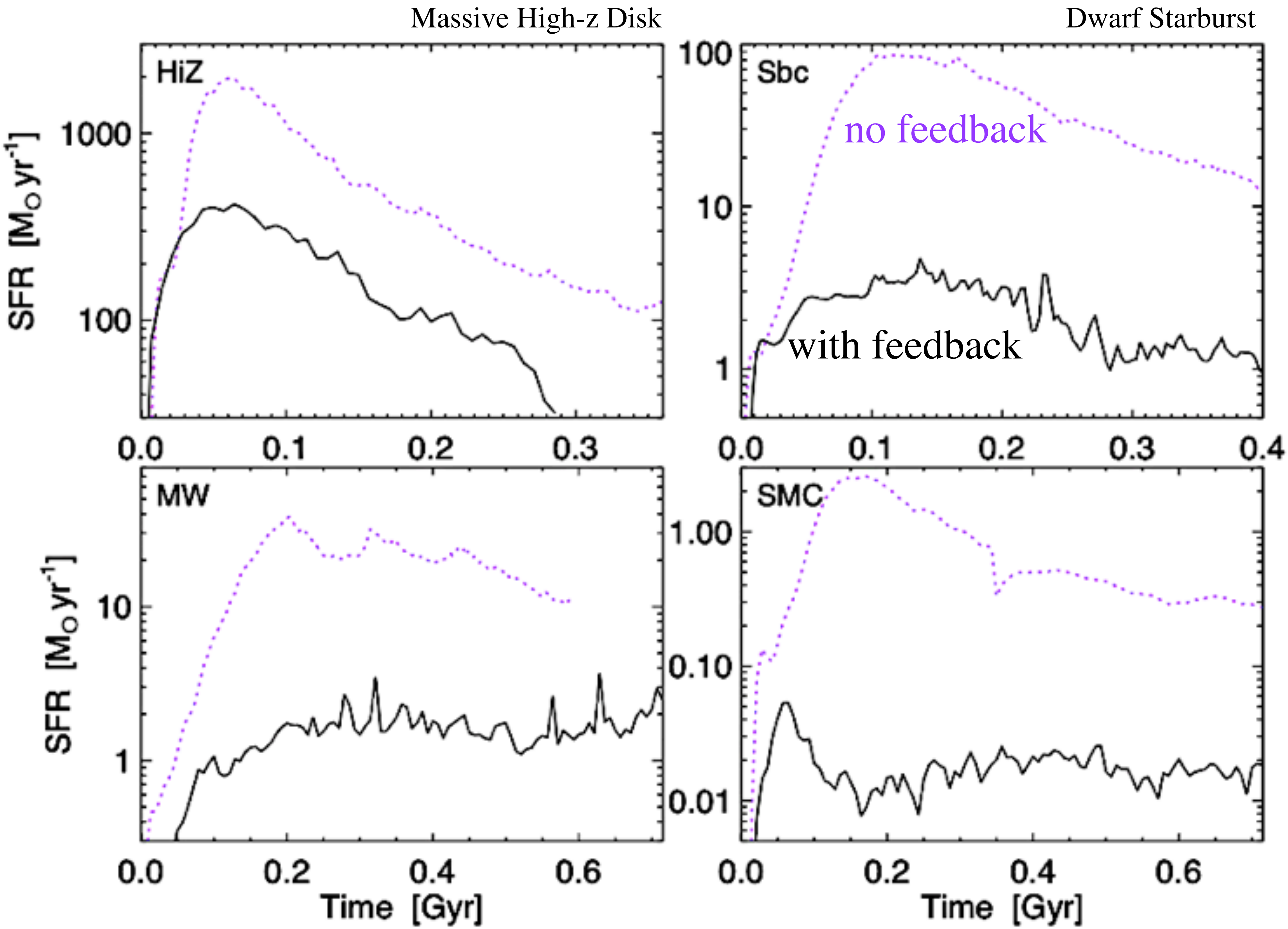


Hopkins, Quataert, & Murray, 2011



Hopkins, Quataert, & Murray, 2011

Stellar Feedback gives Self-Regulated Star Formation



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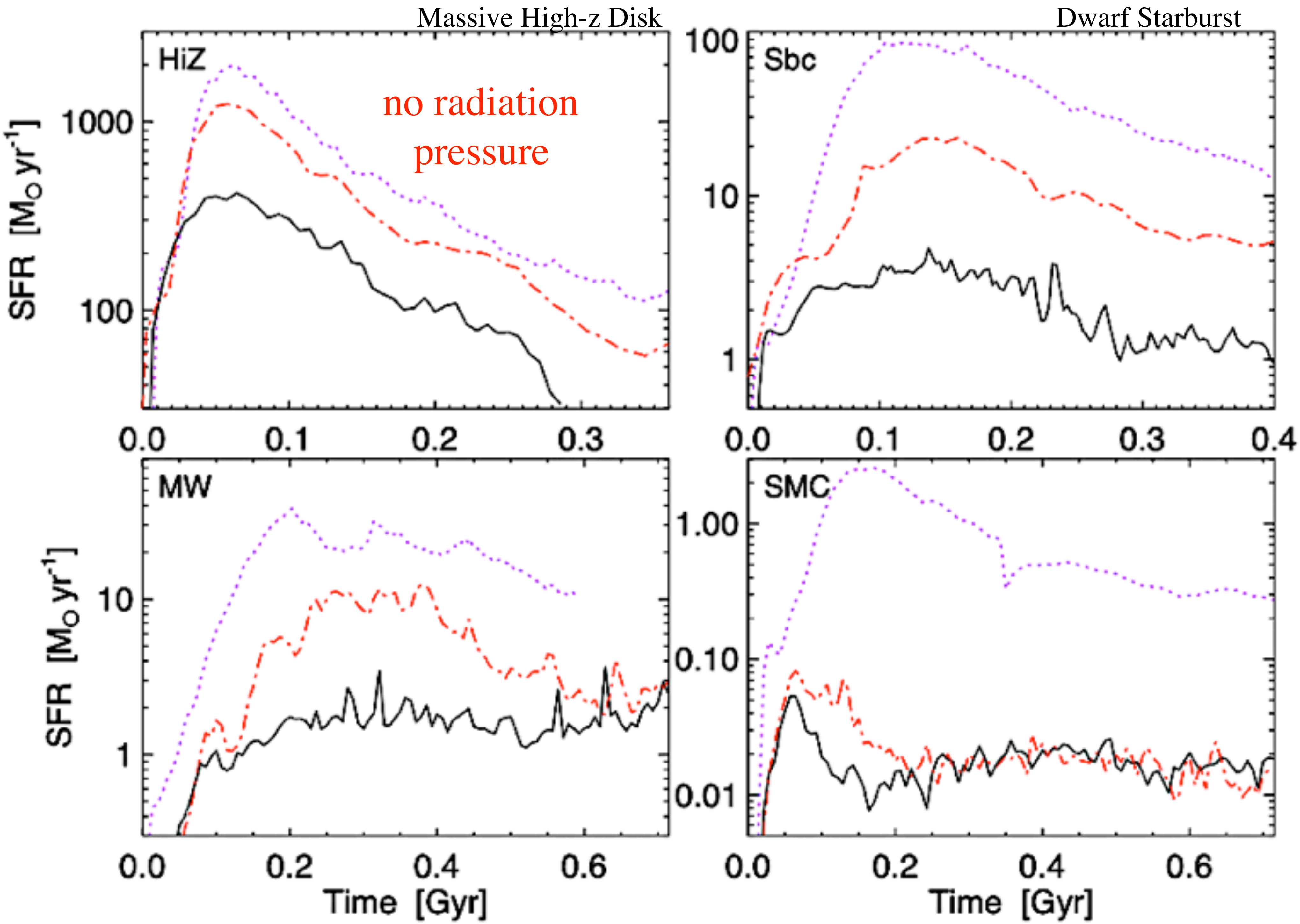

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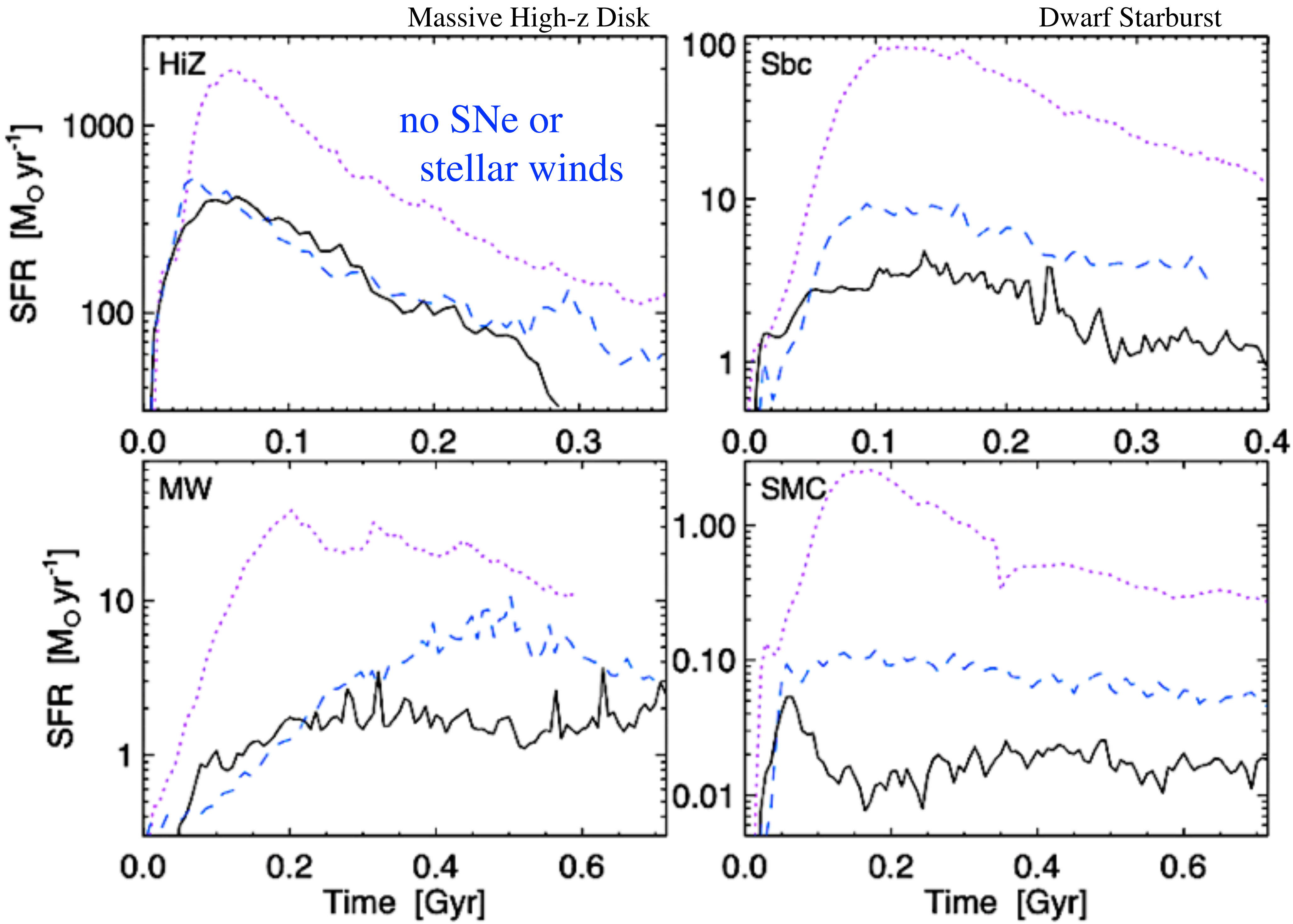
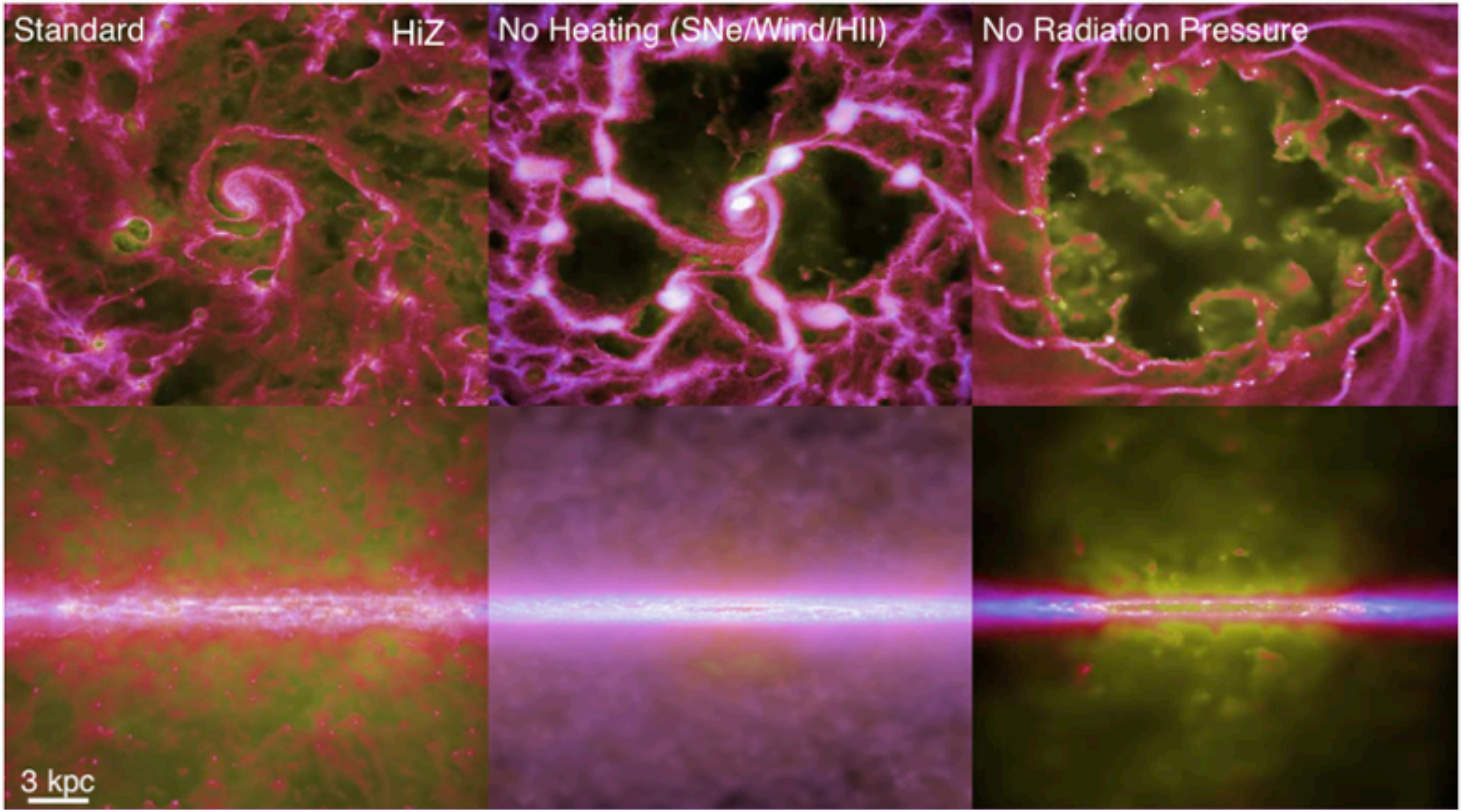


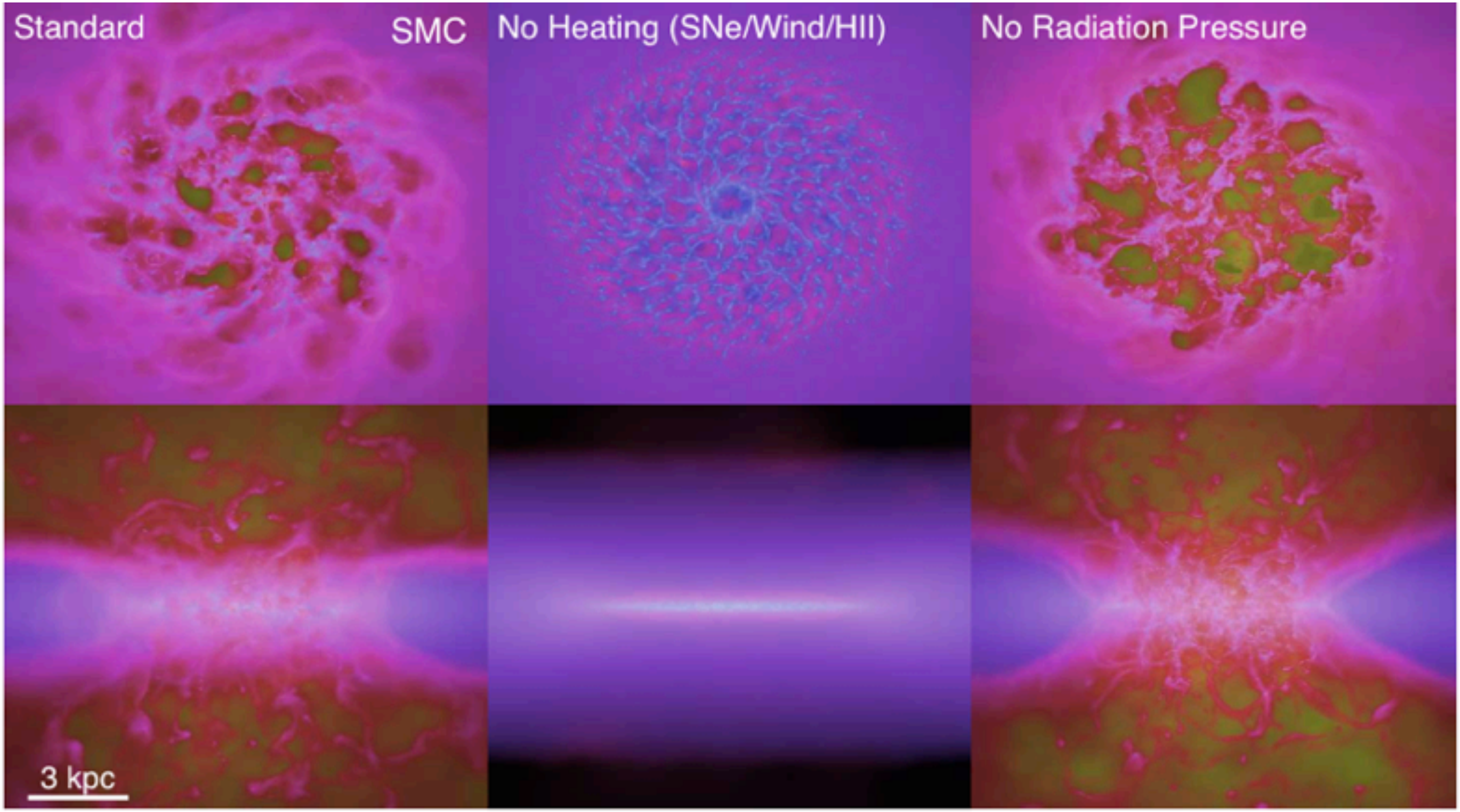
Stellar Feedback & Self-Regulation
WHICH MECHANISMS MATTER?



- SFR ~ 100+ M_{sun}/yr ($L \sim L_{EDD}$)
- Optically thick
- $\langle n \rangle \sim 100$ cm^{-3} $T_{cool} \sim 1000$ yr

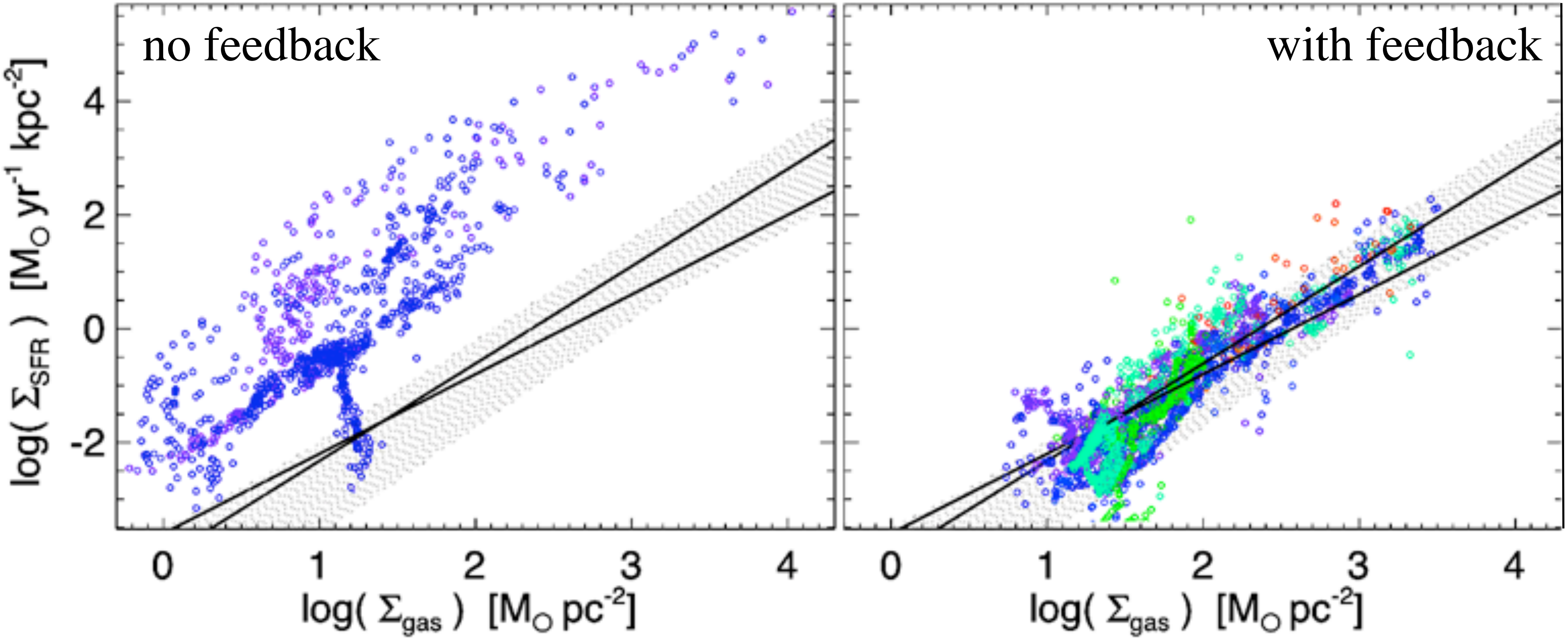
Stellar Feedback & Self-Regulation

WHICH MECHANISMS MATTER?



- SFR ~ 0.01 M_{sun}/yr (L << L_{EDD})
- Optically thin
- <n> ~ 0.1 cm^{-3} T_{cool} ~ Myr

Kennicutt-Schmidt relation emerges naturally



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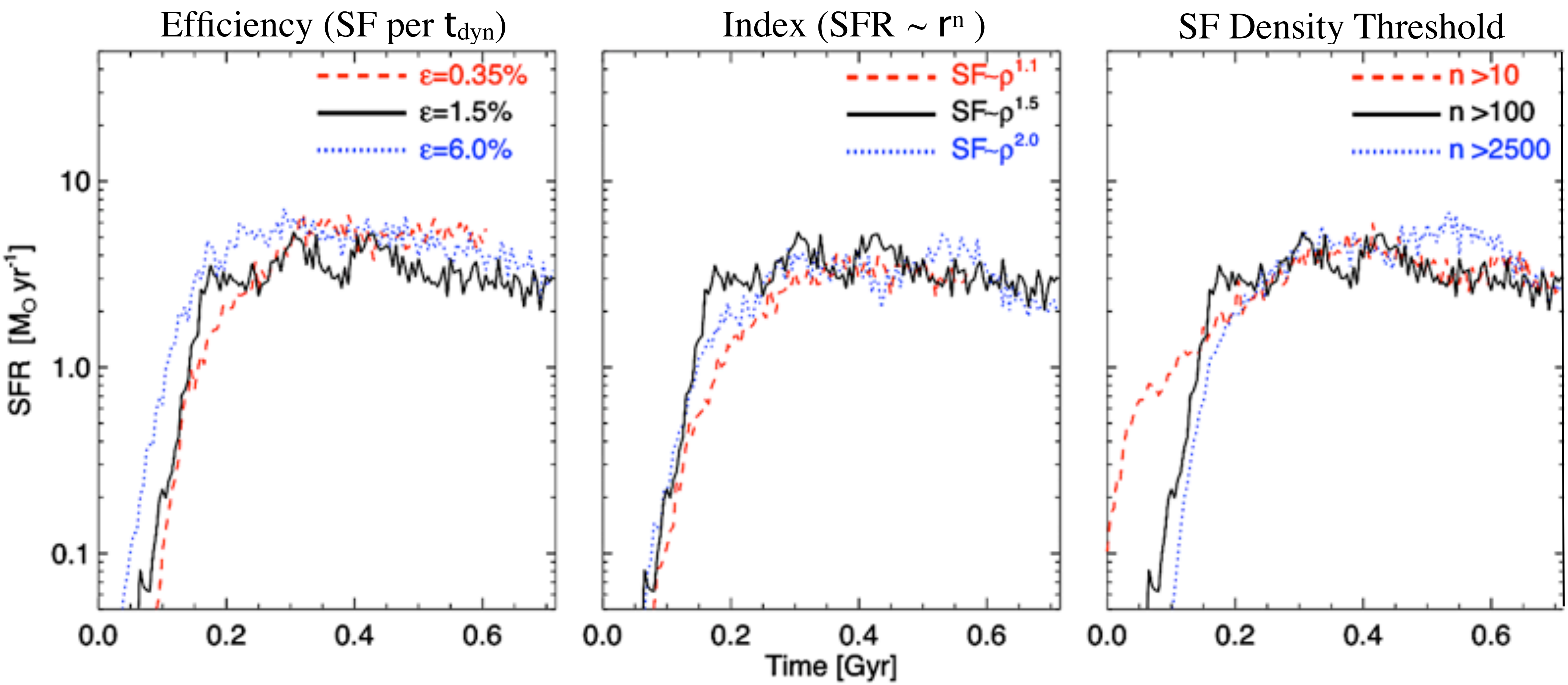
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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



Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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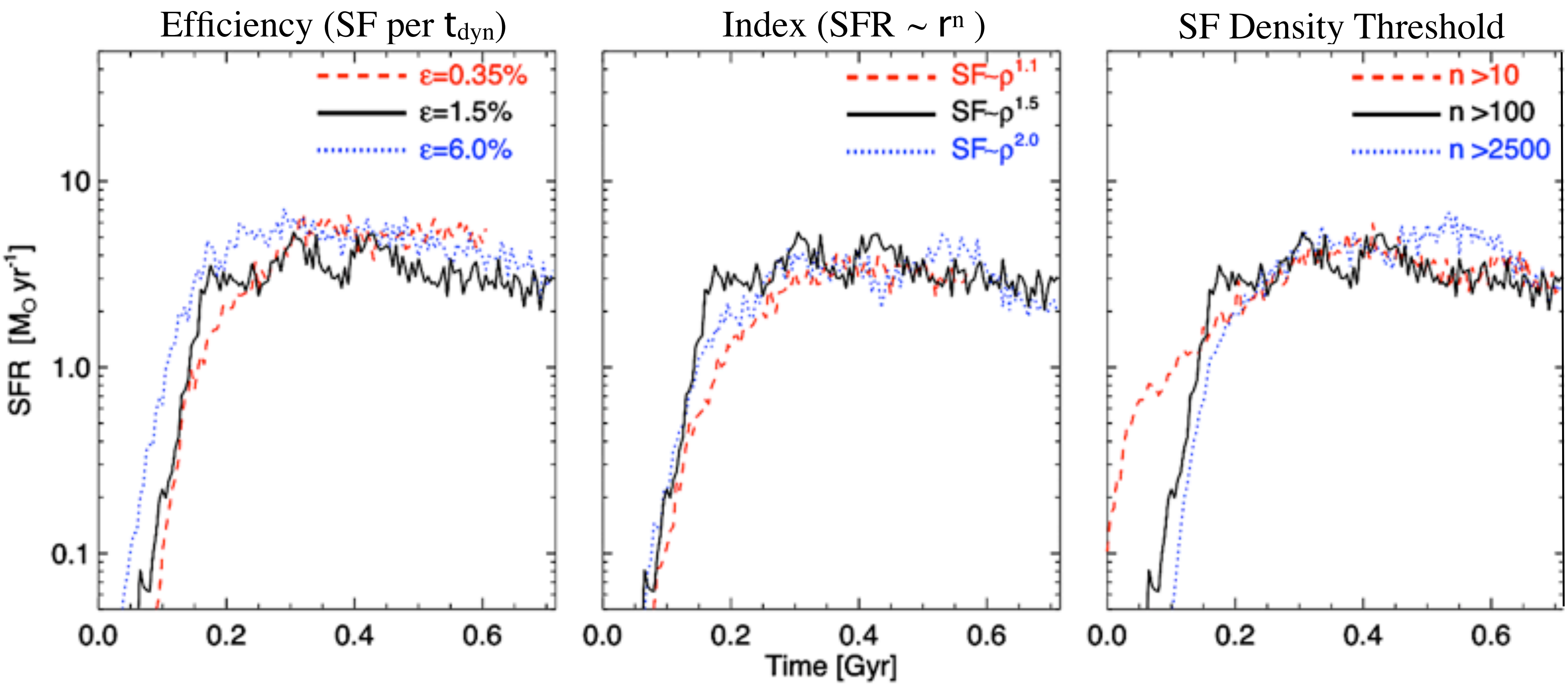
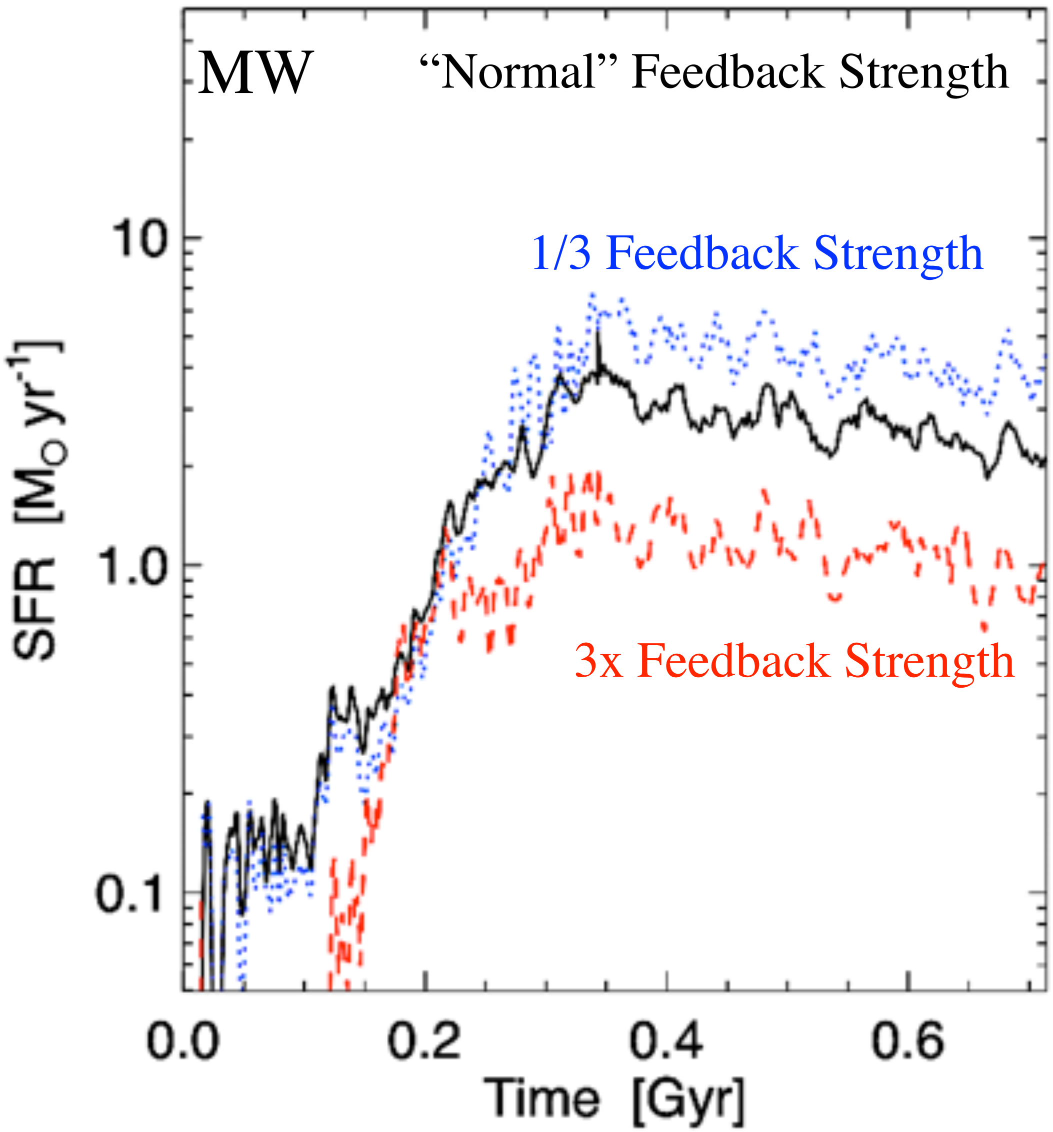


- Set by feedback (i.e. SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

Star Formation is Feedback-Regulated:
MORE FEEDBACK = LESS STAR FORMATION



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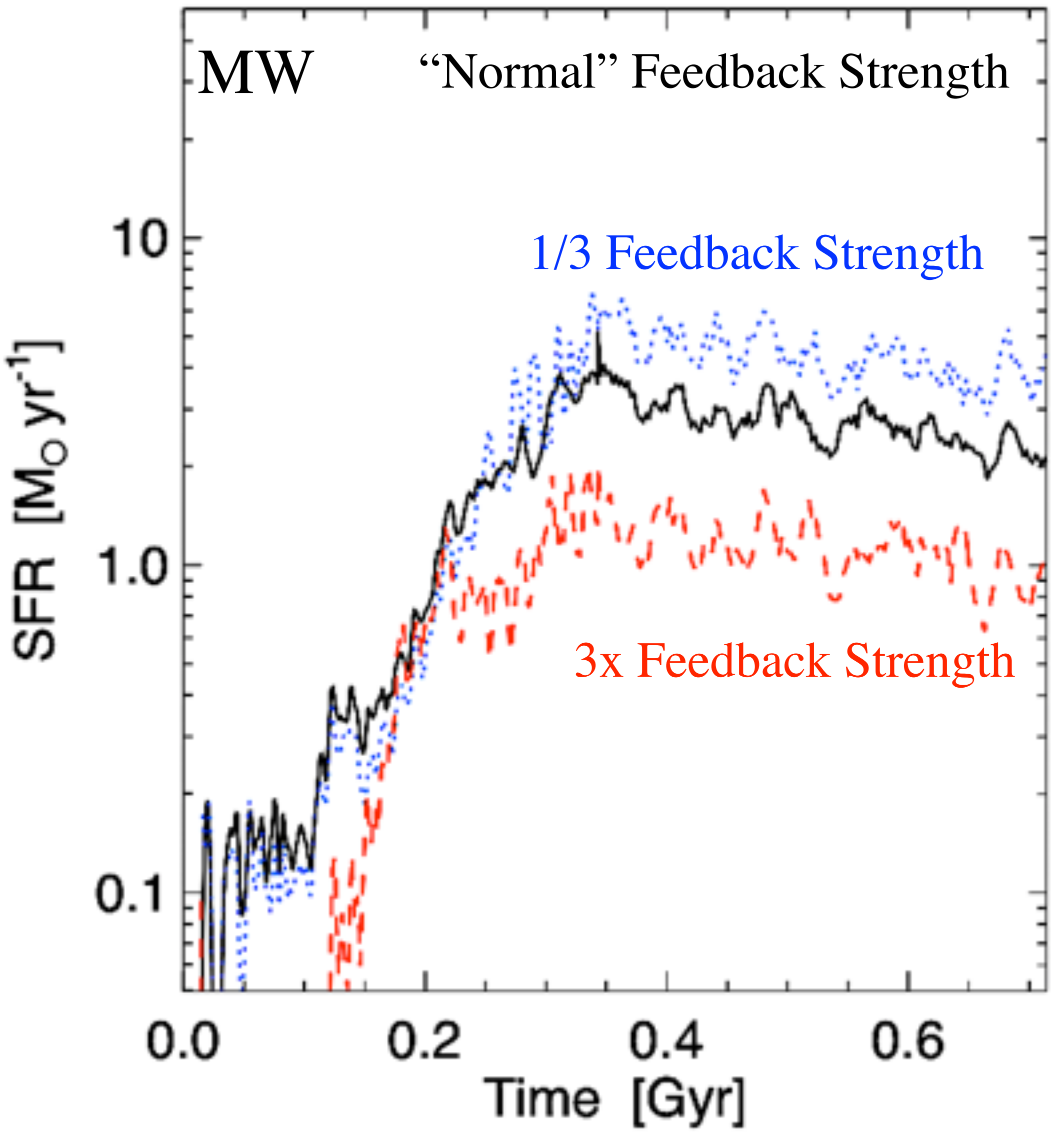
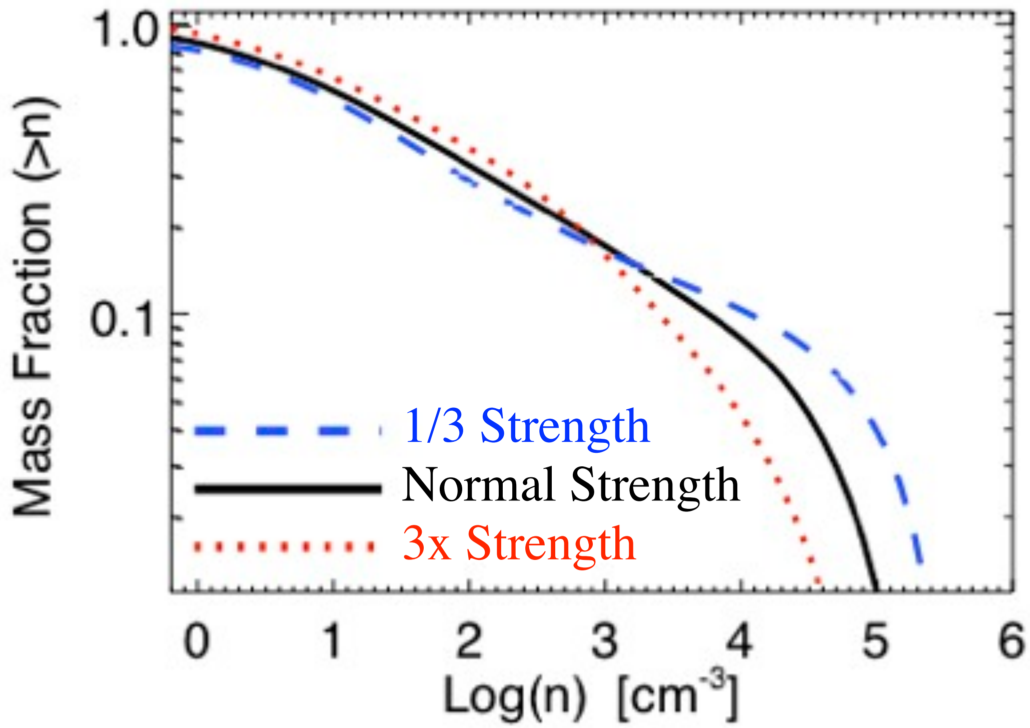
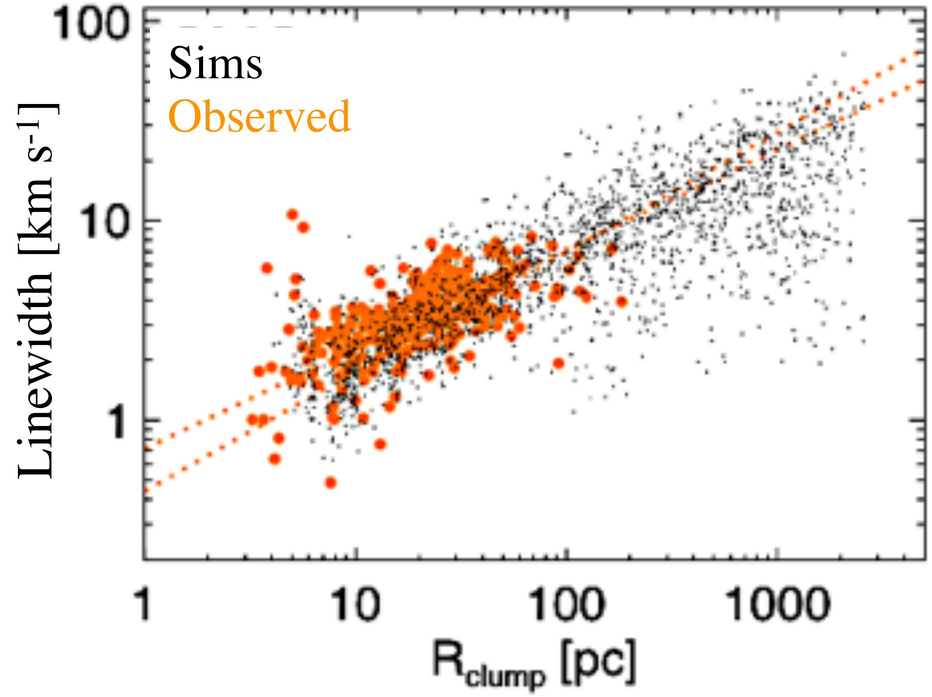
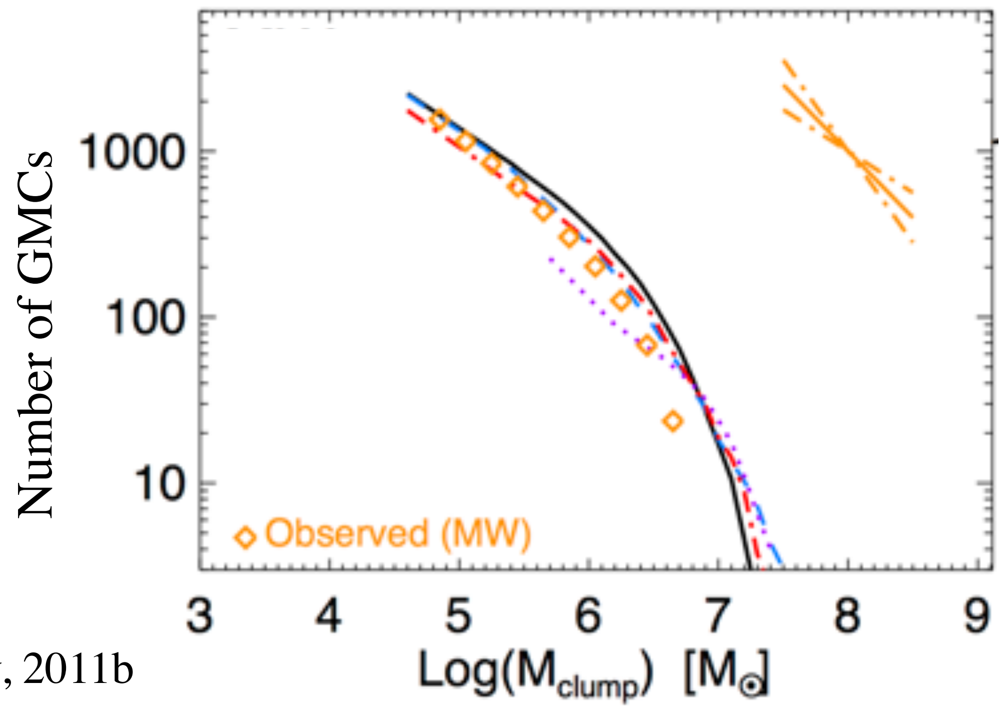
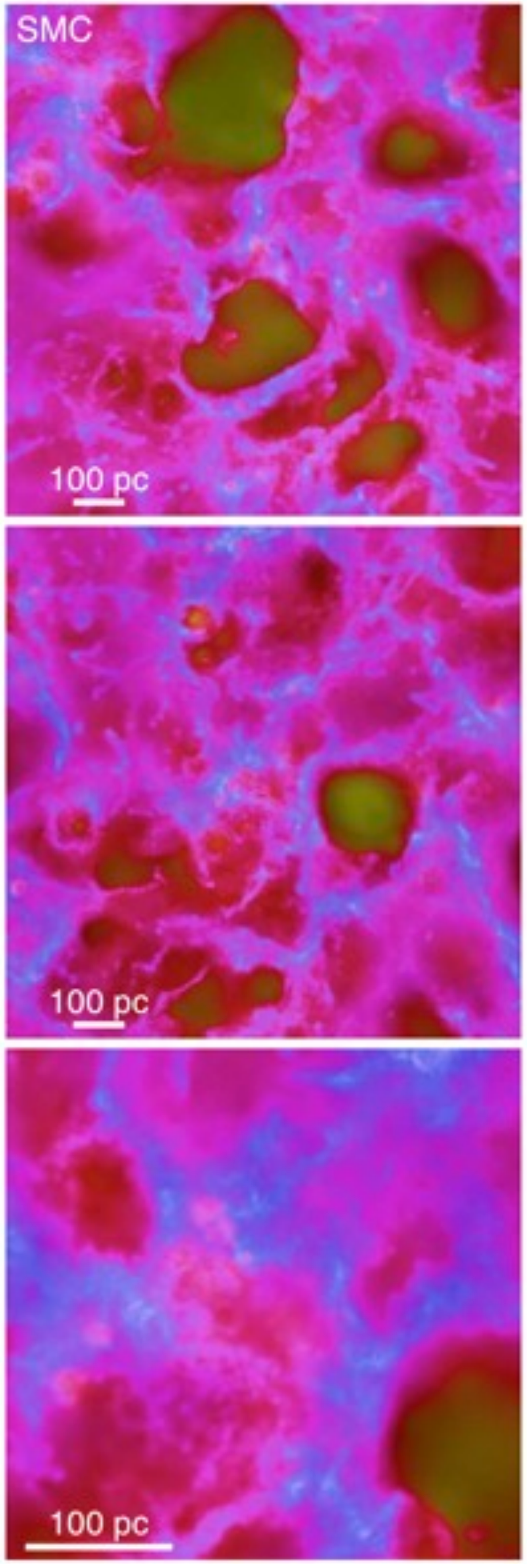




Properties of GMCs & Gas "Clumps"

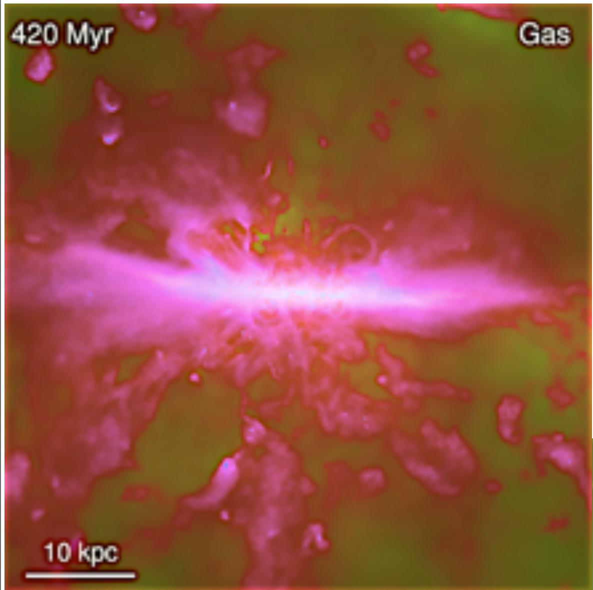


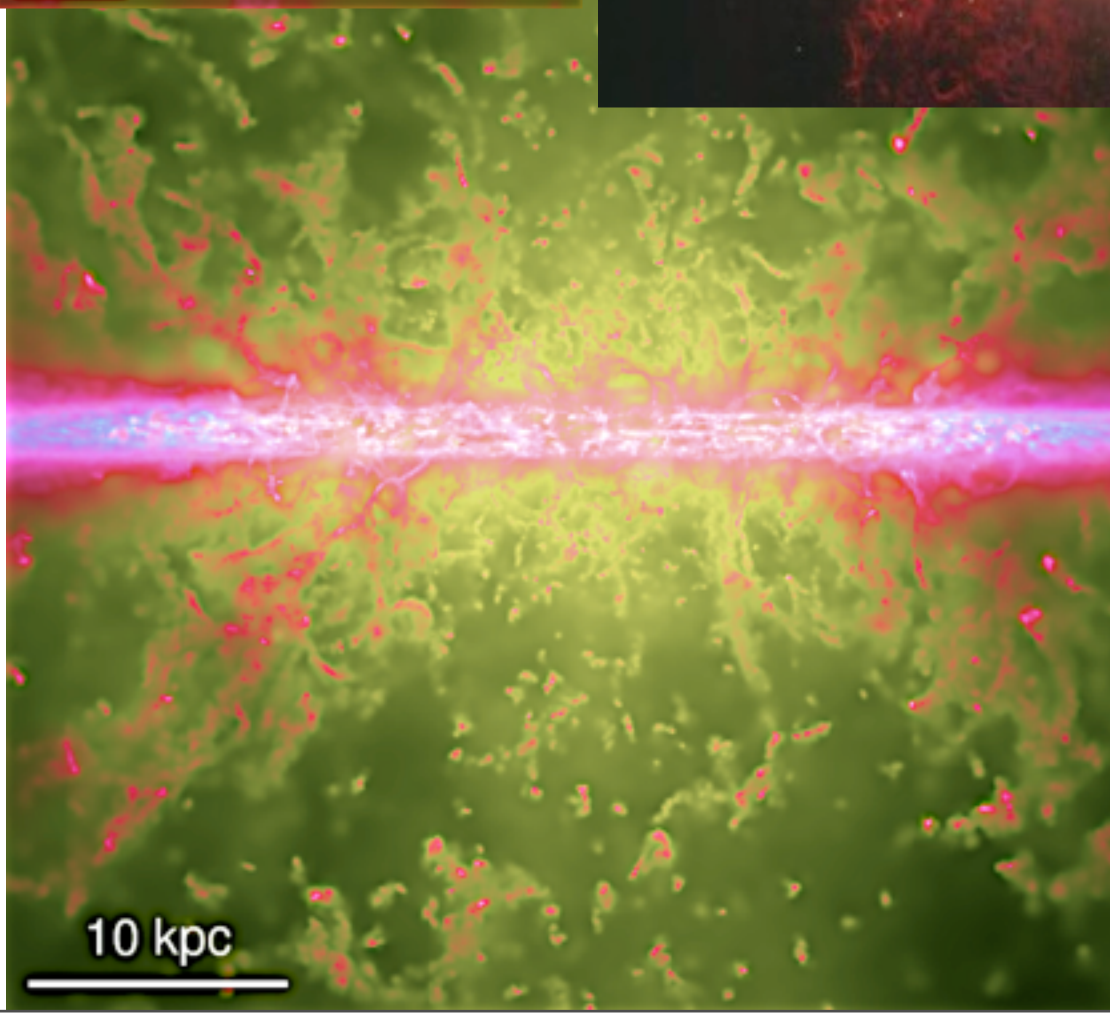


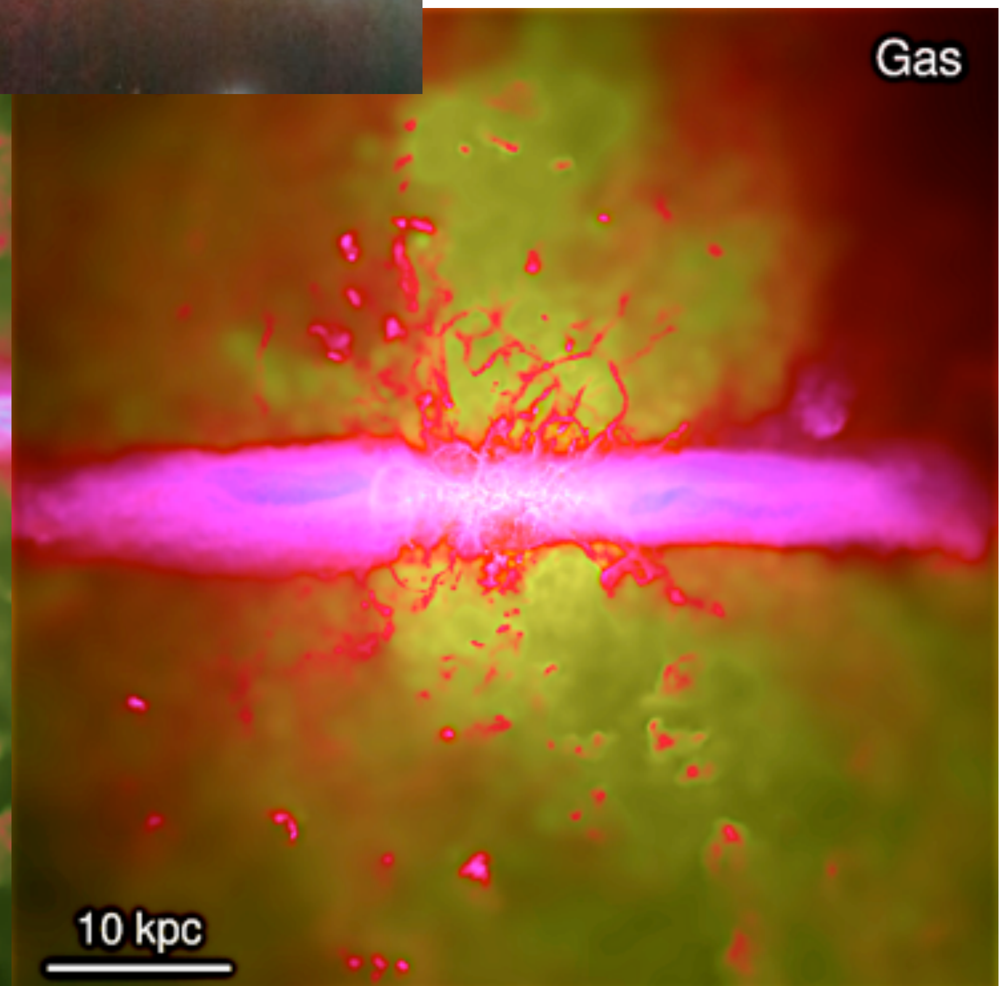


PFH, Quataert, & Murray, 2011b

Galactic Super-Winds







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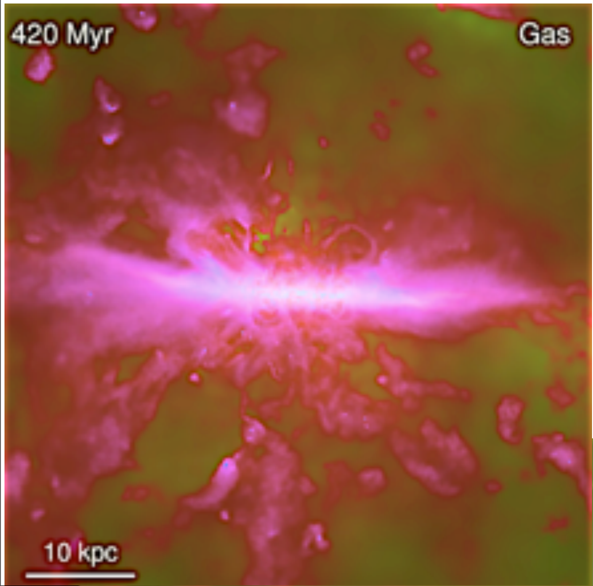
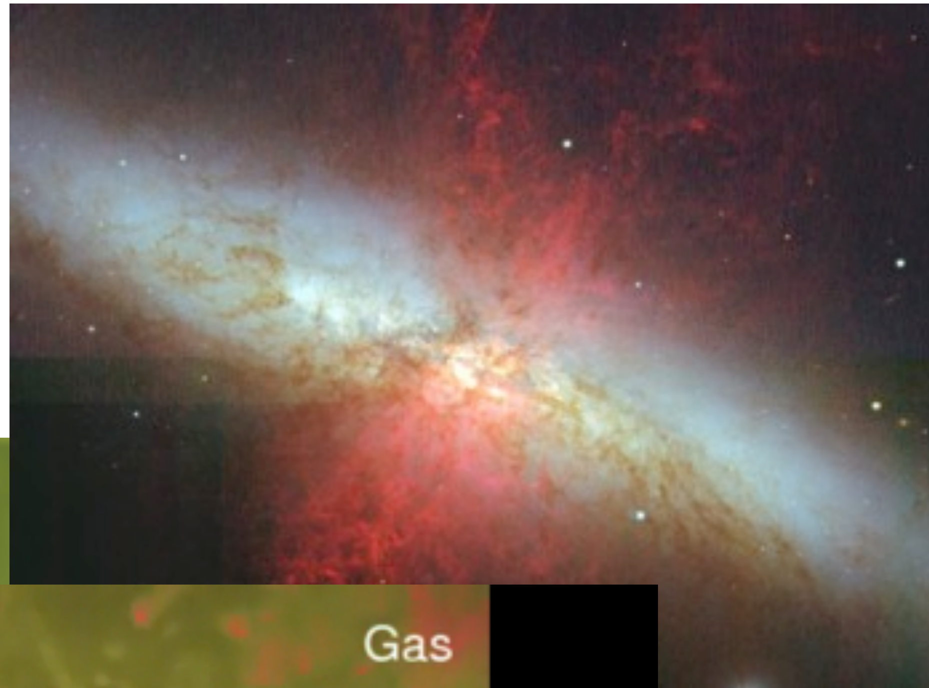
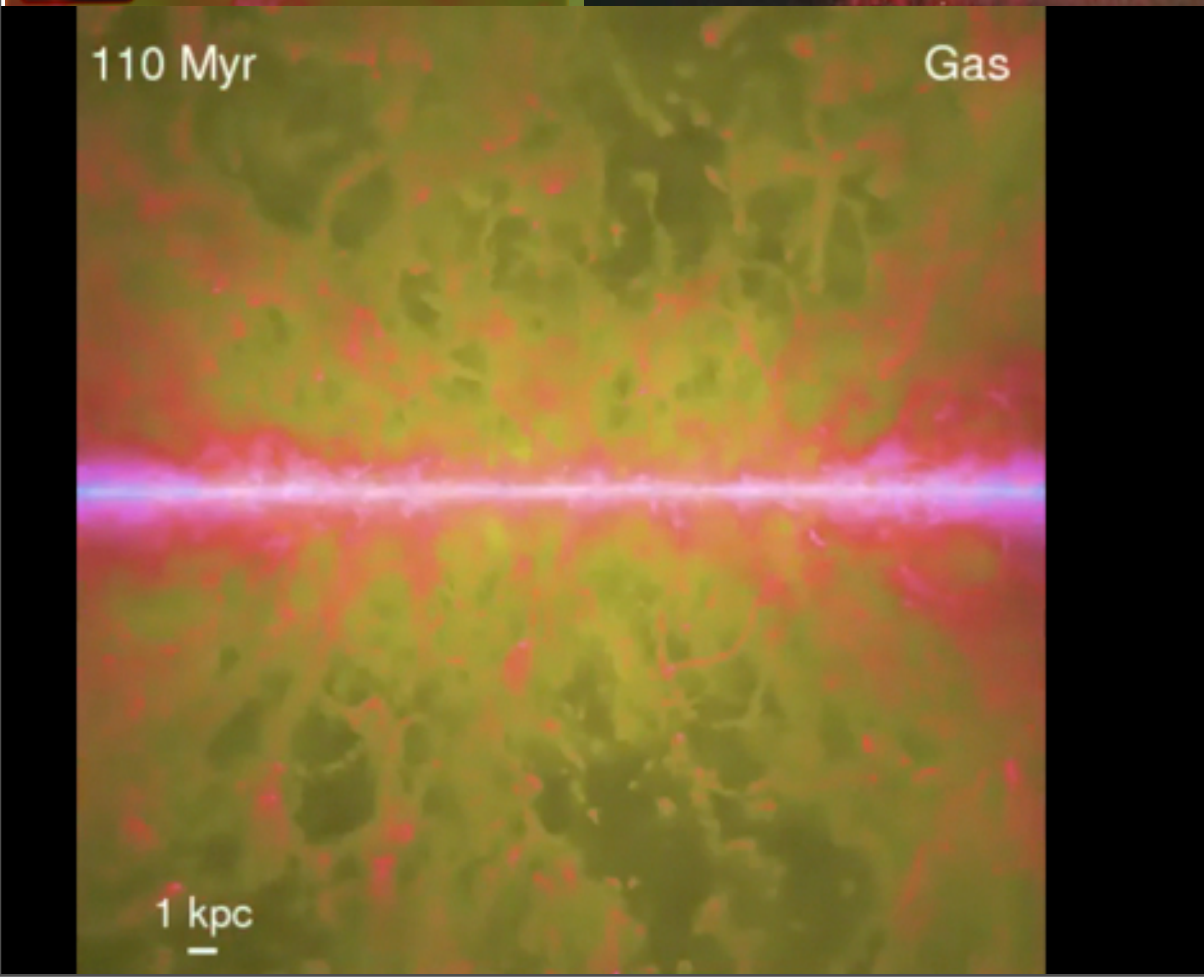
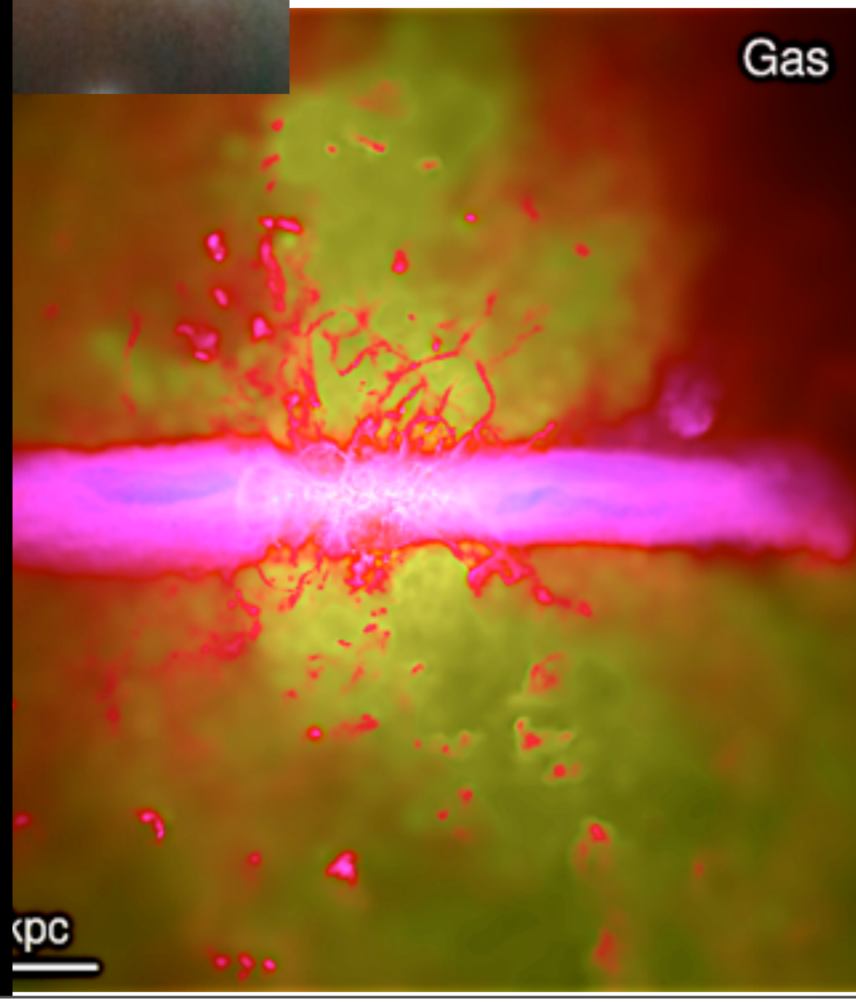
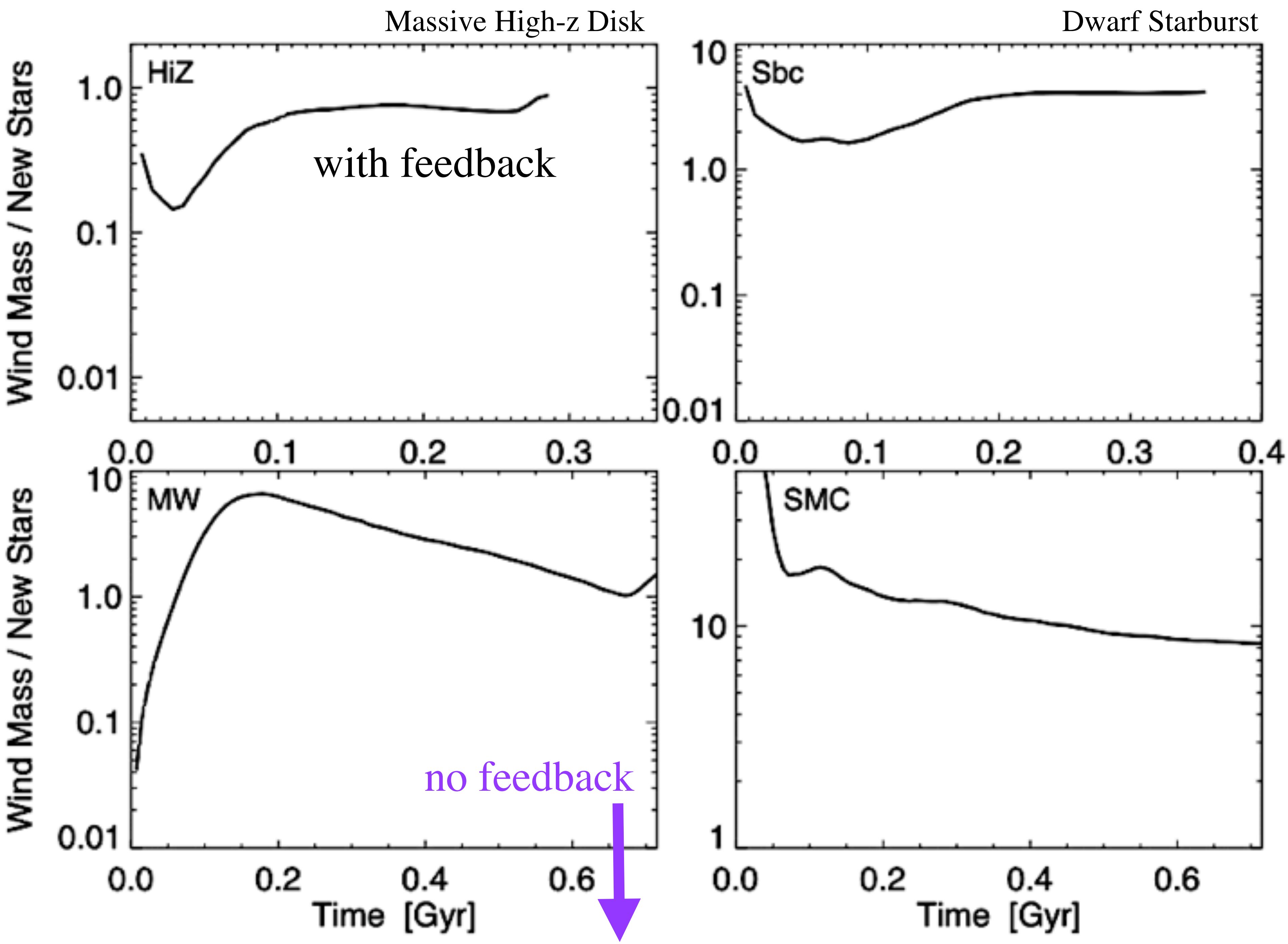








How Efficient Are Galactic Super-Winds?
AND WHAT MECHANISMS DRIVE THEM?



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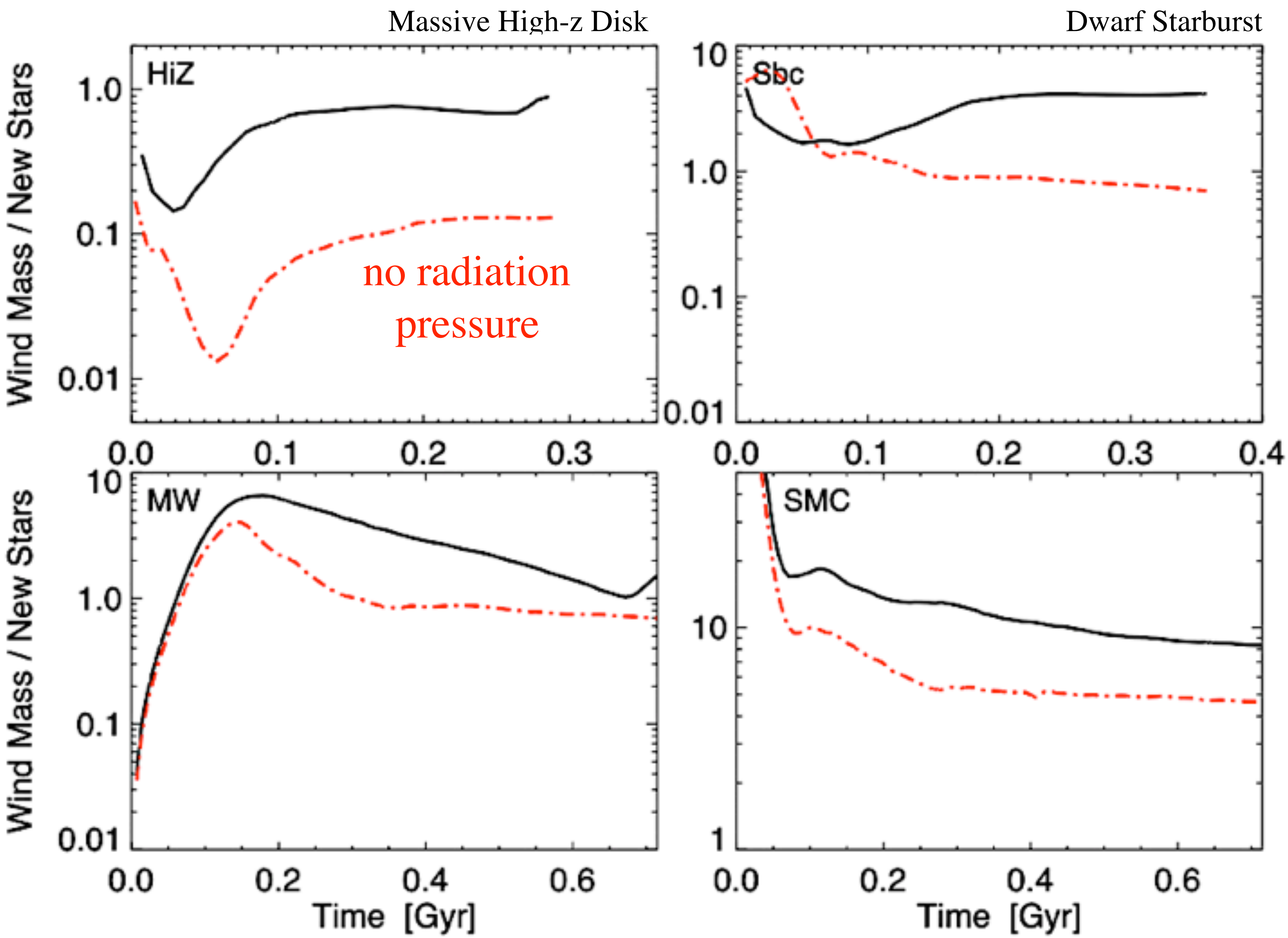

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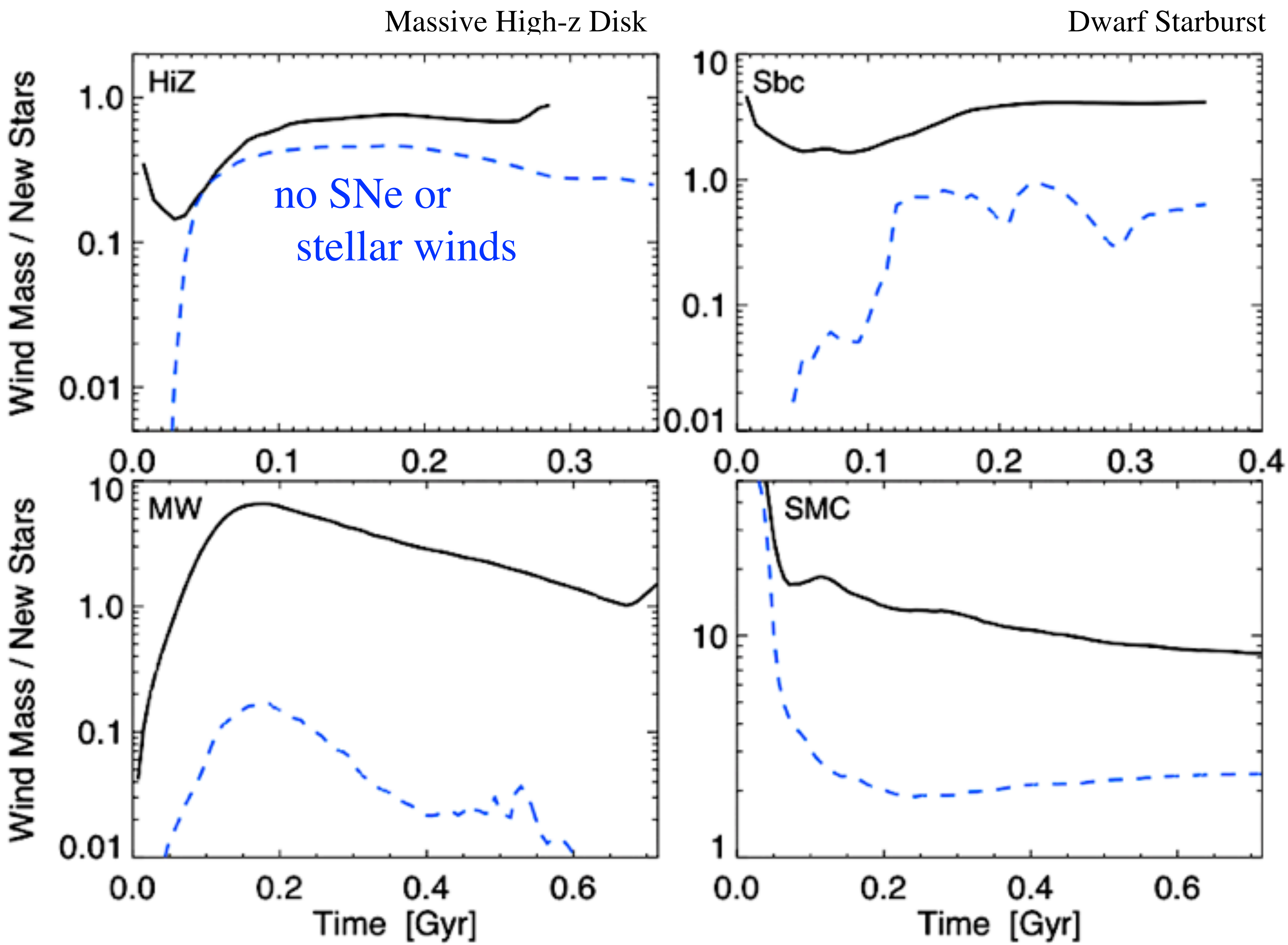

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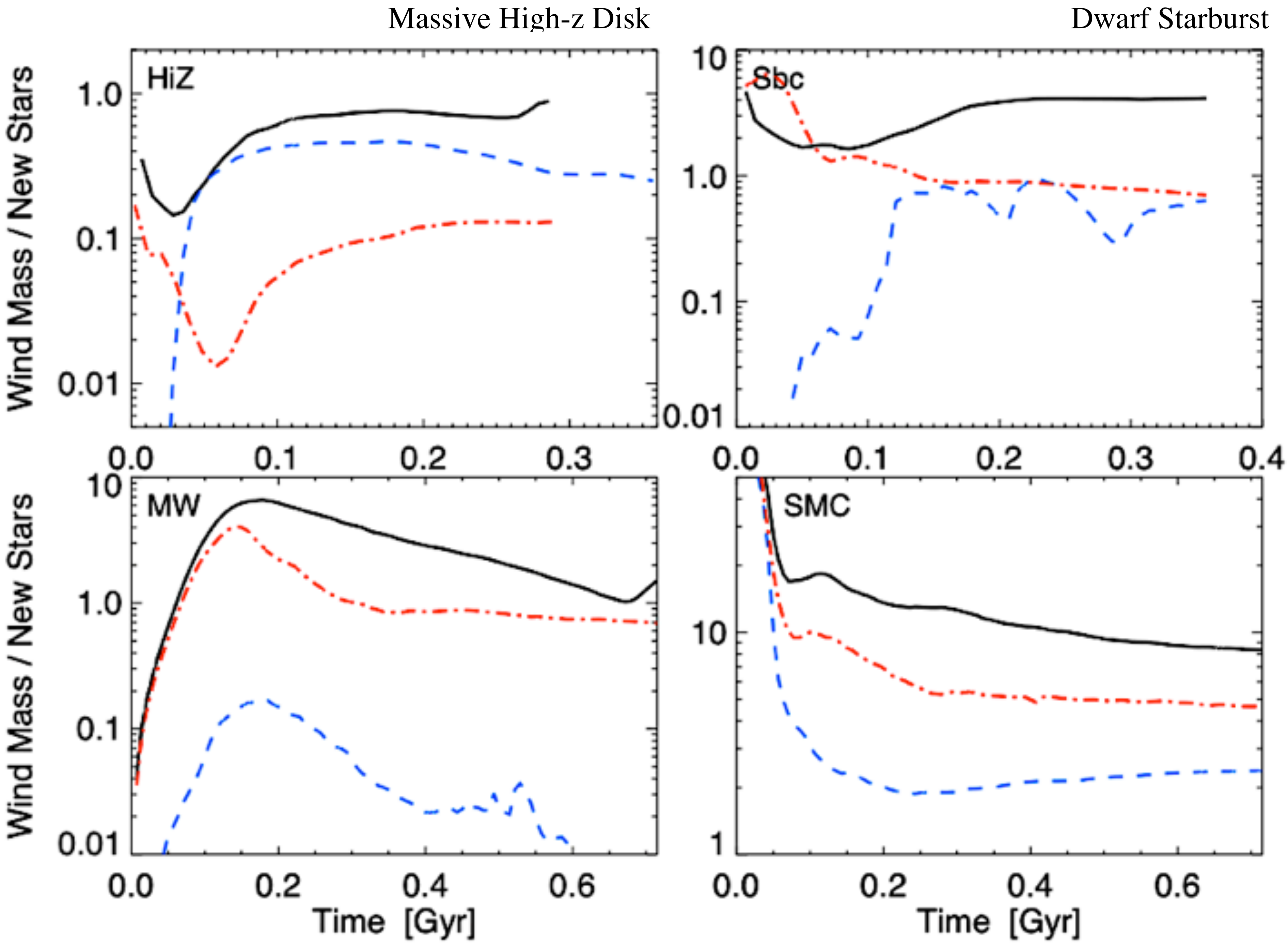

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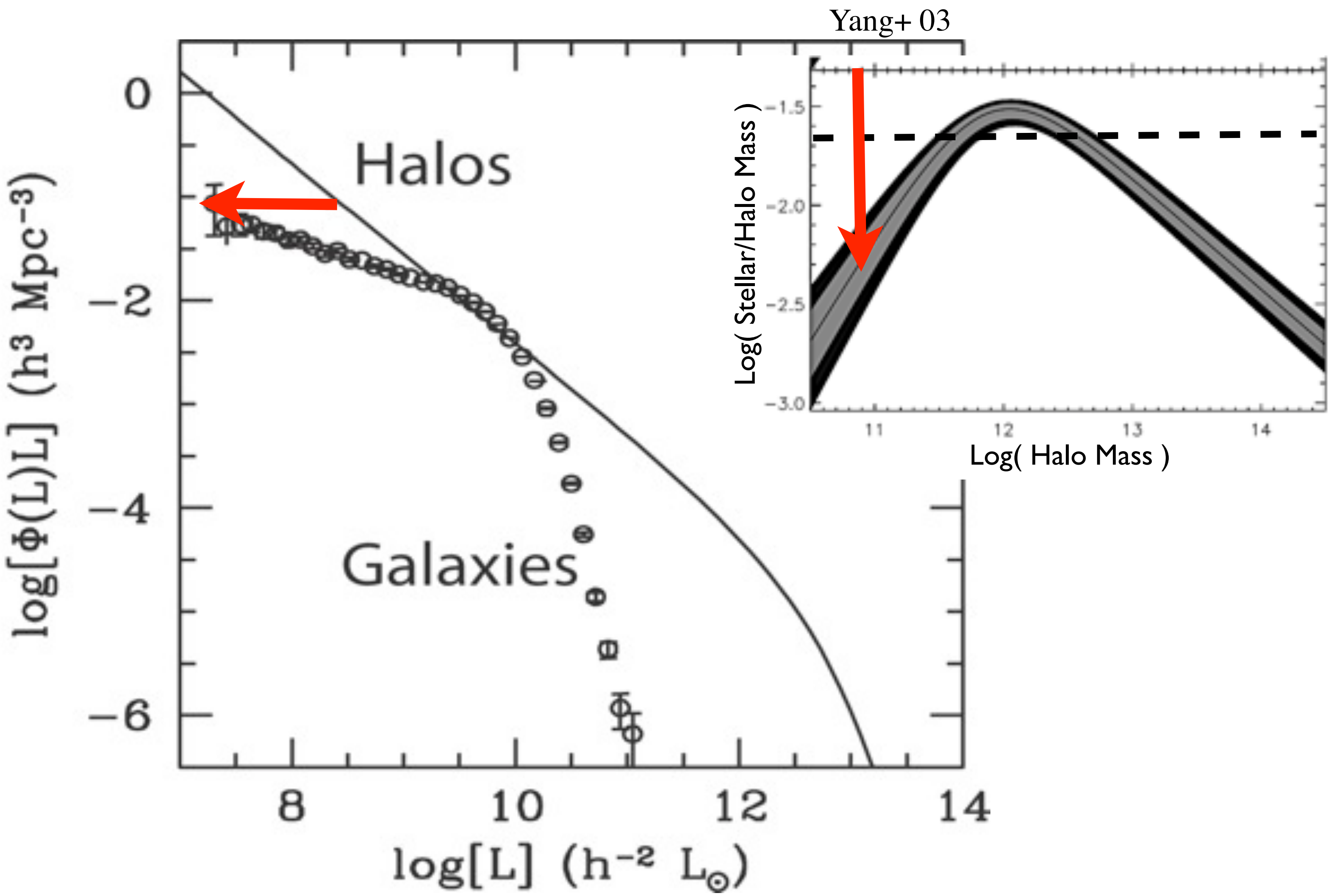

- Large mass-loading:

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

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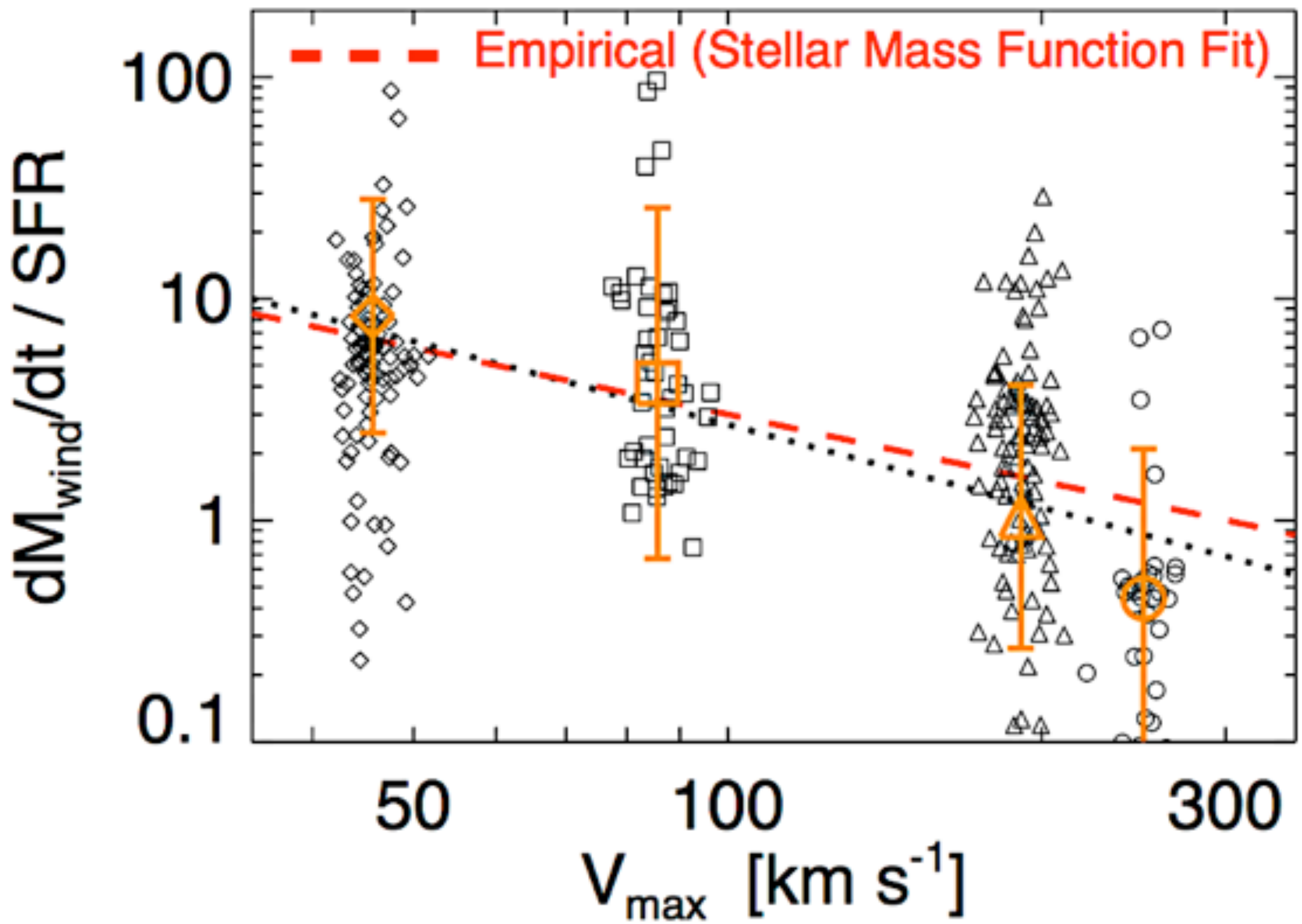

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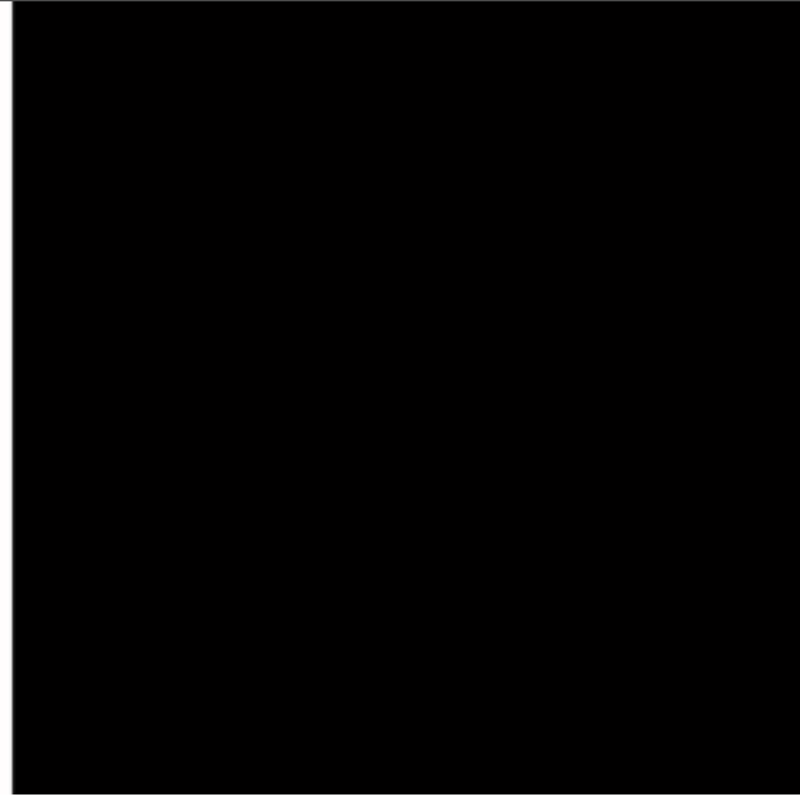
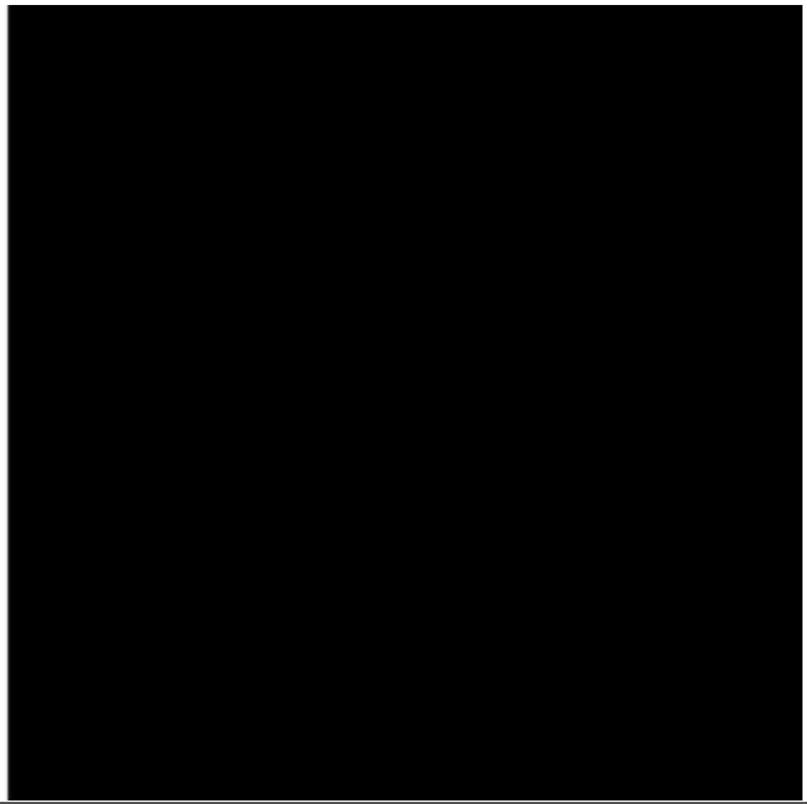


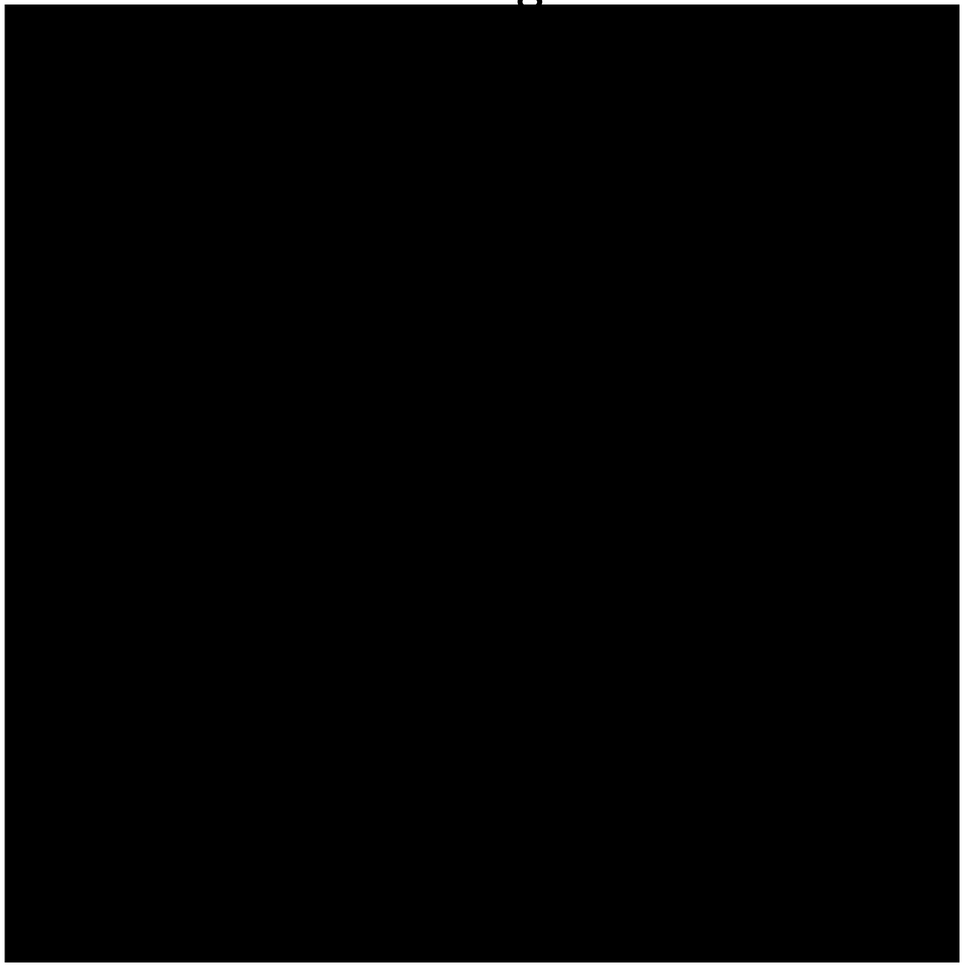
Full Feedback



Weak Feedback

Proto-MW: Gas Temperature:

Phenomenological Winds



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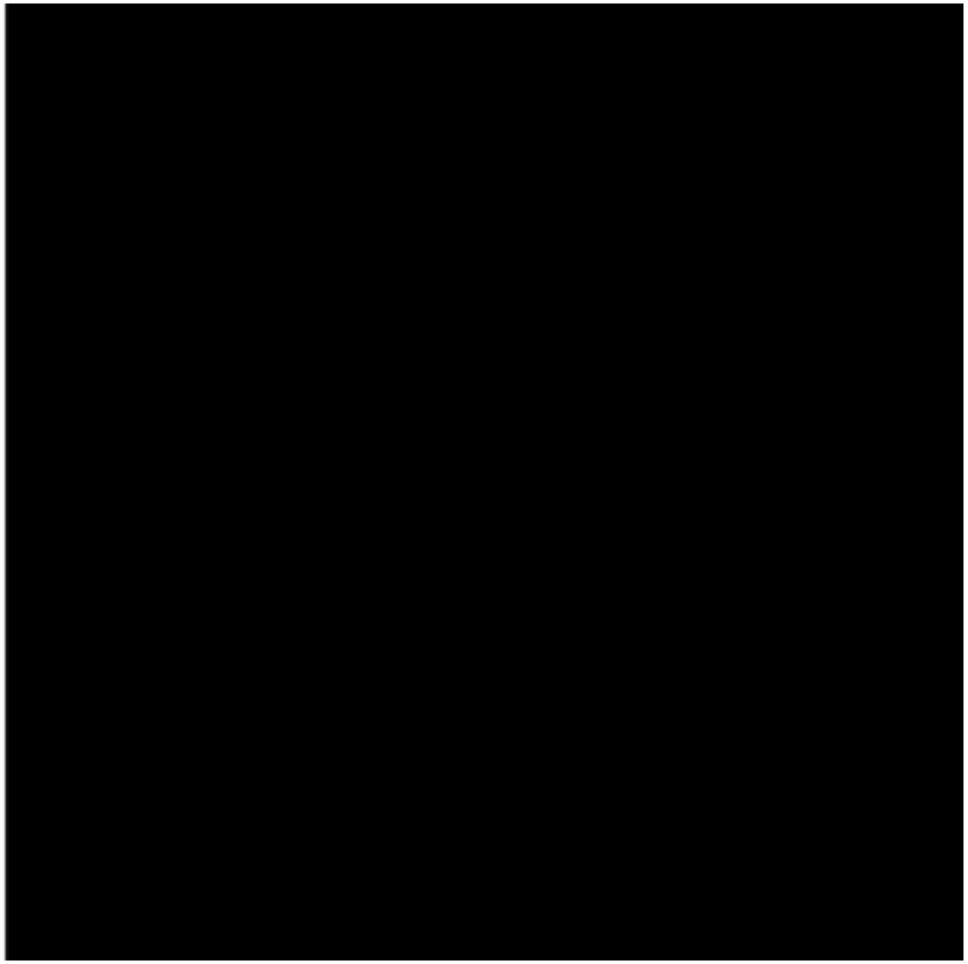
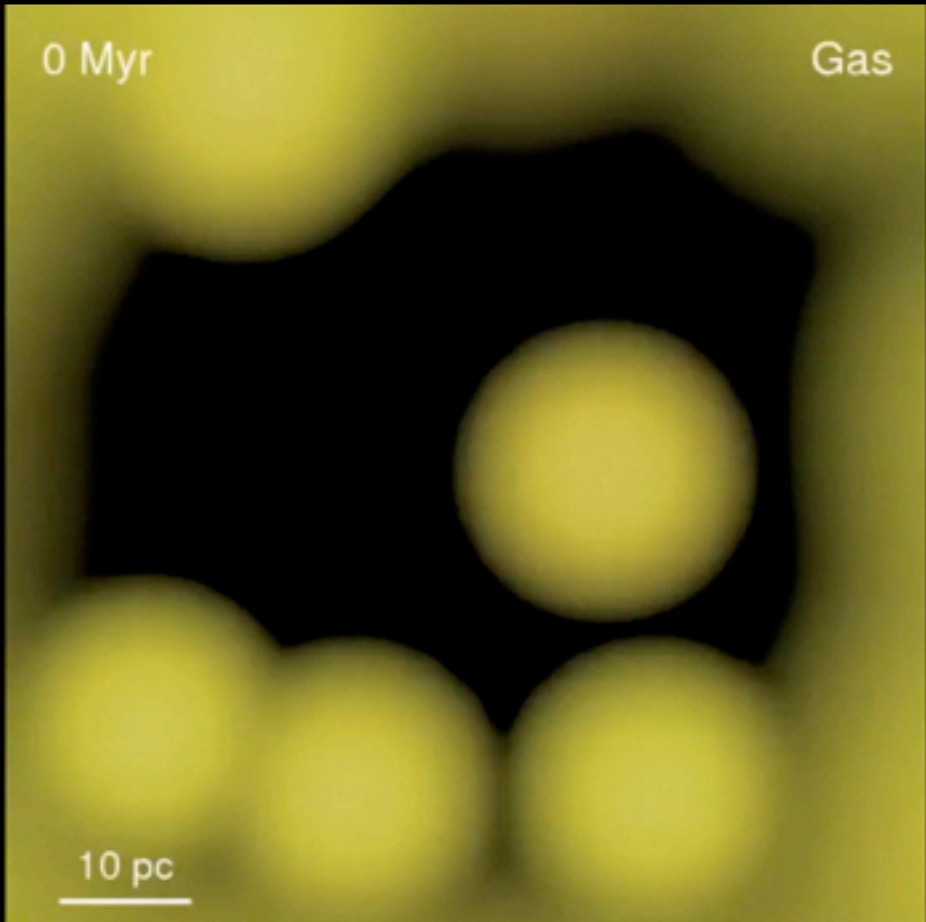
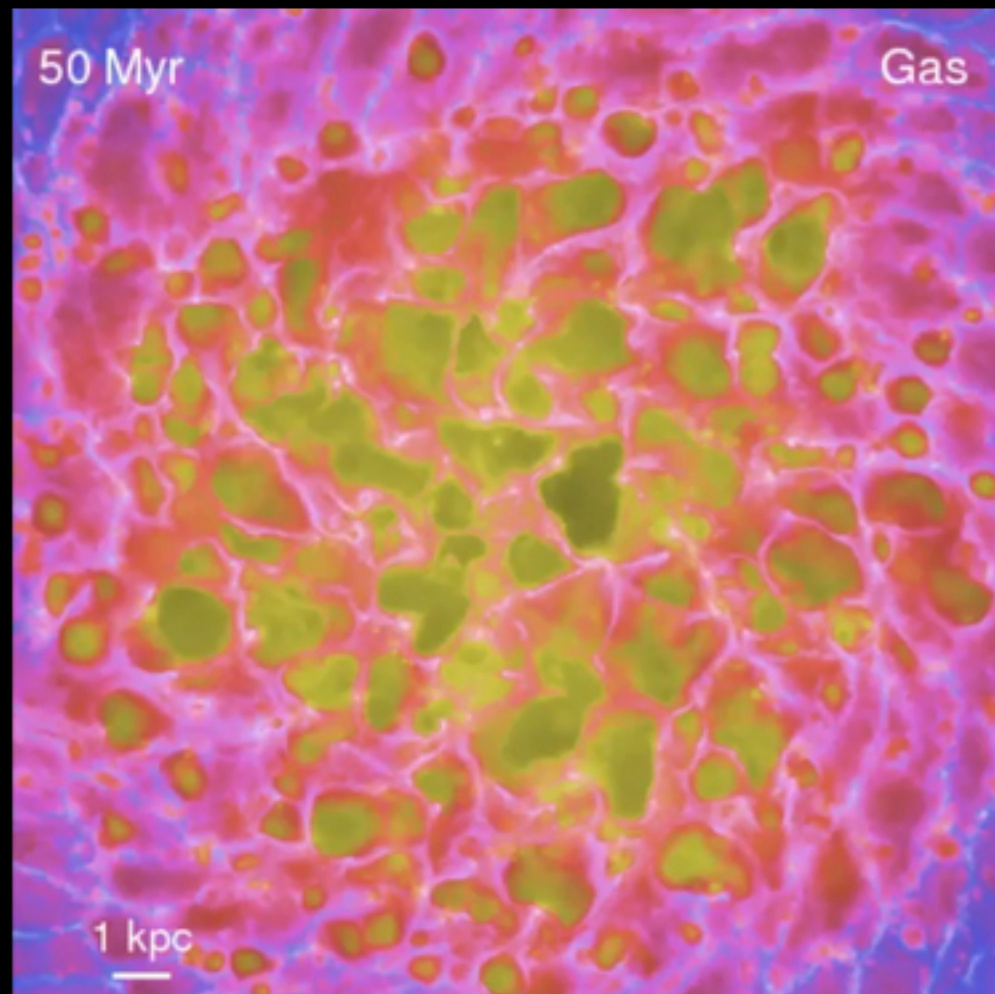
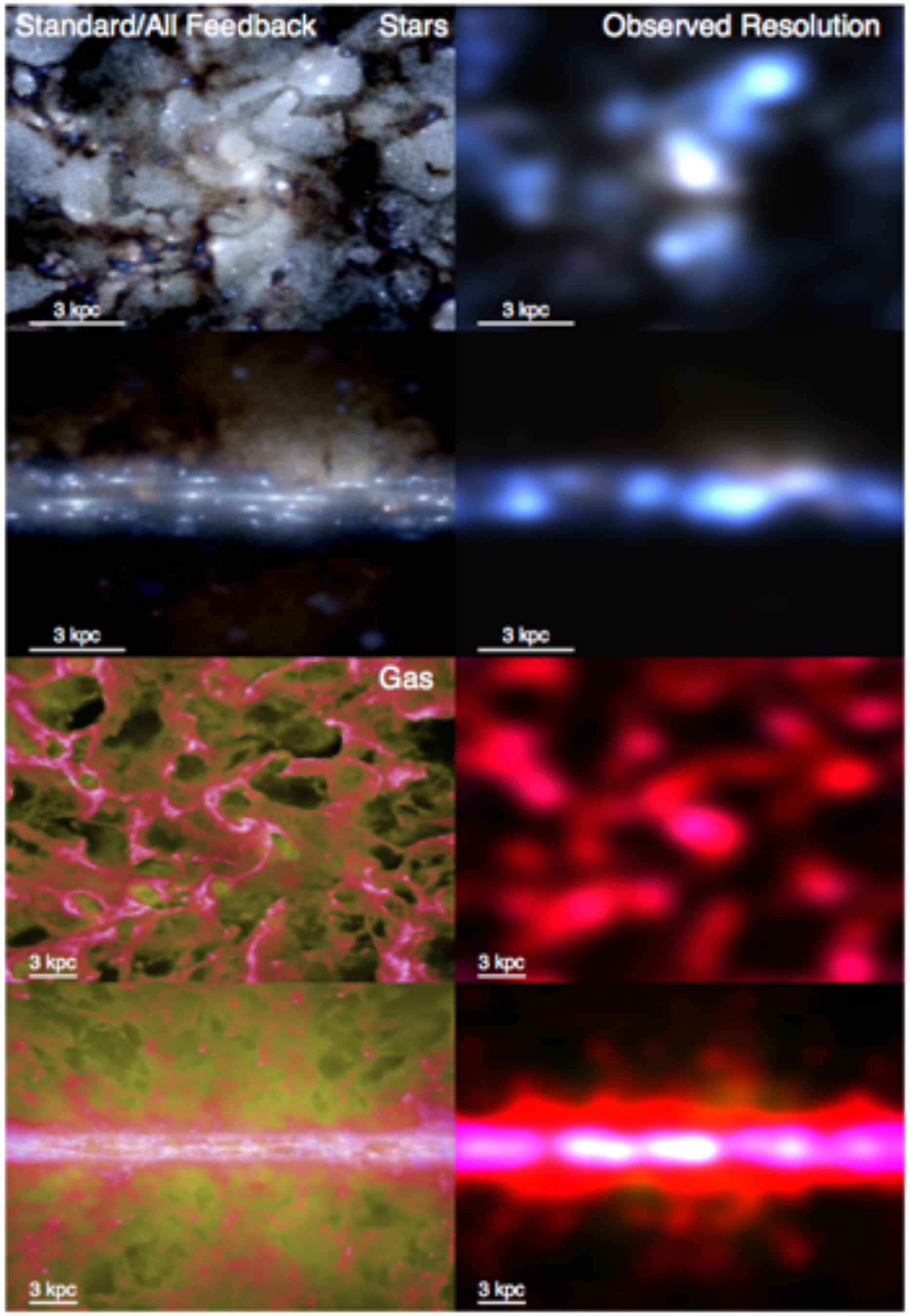


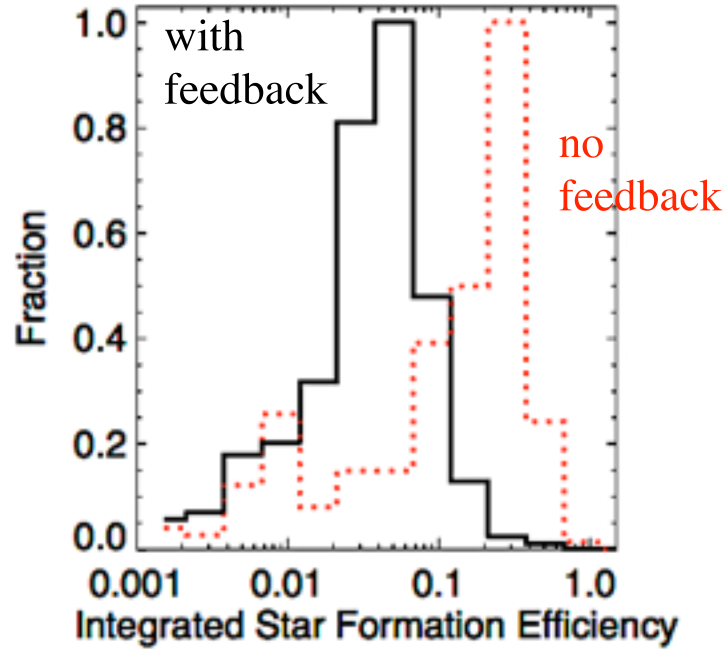

0 Myr
Gas
10 pc

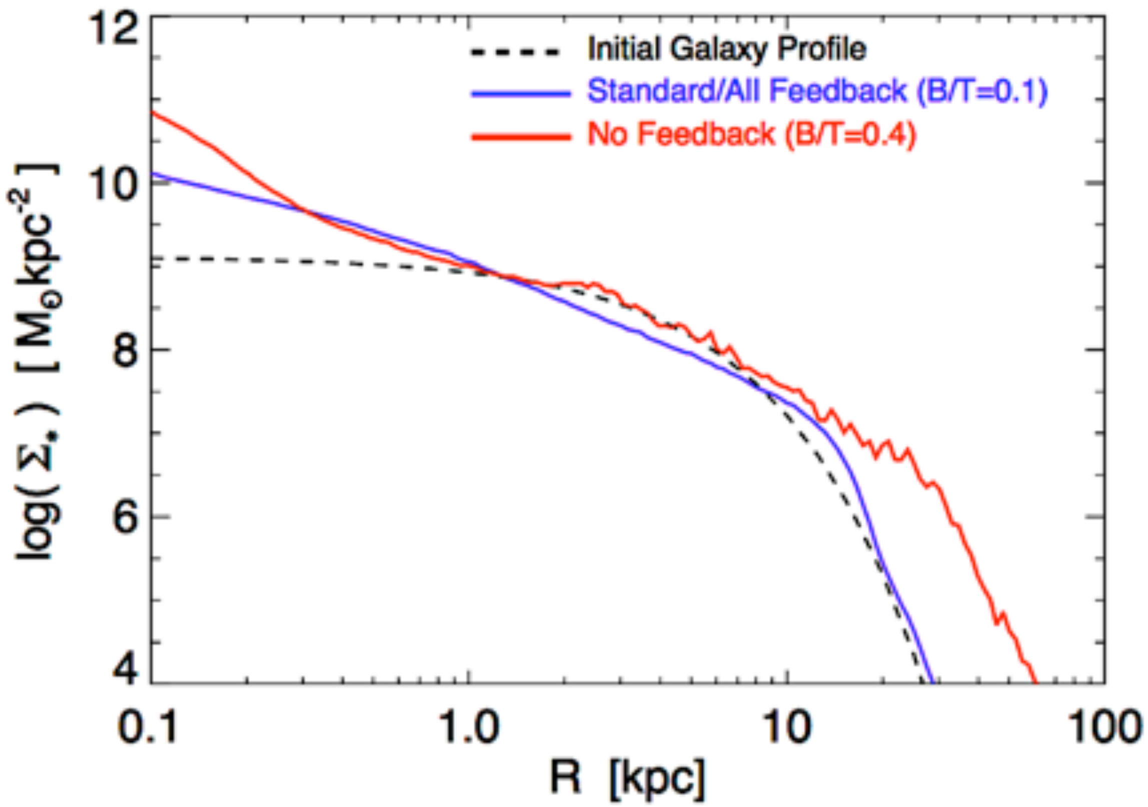

50 Myr
Gas
1 kpc

“Clumpy” Disks

FEEDBACK SUPPRESSES CLUMP INSPIRAL







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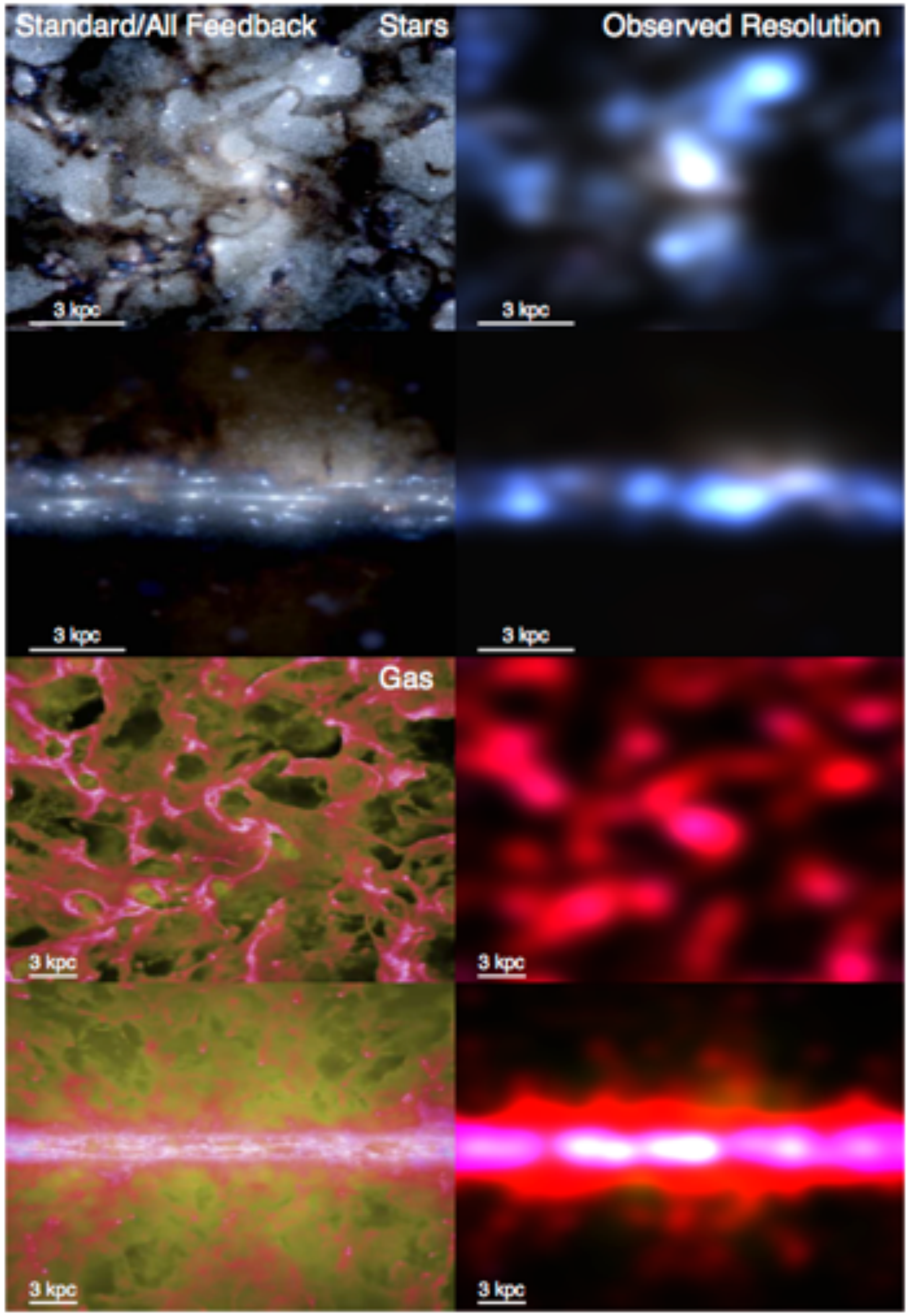
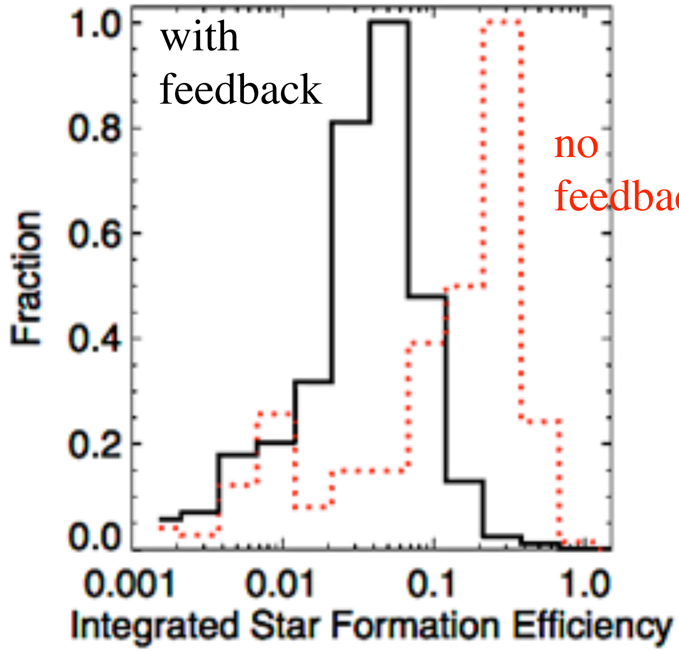
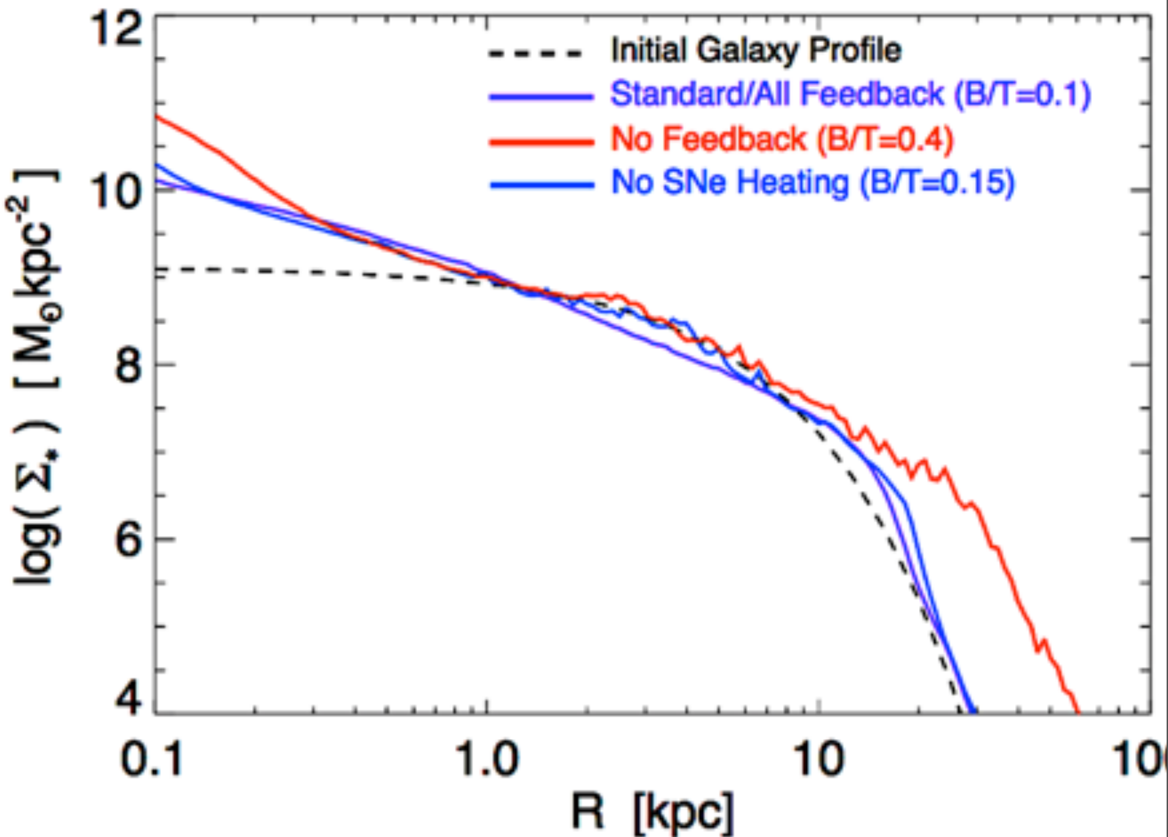
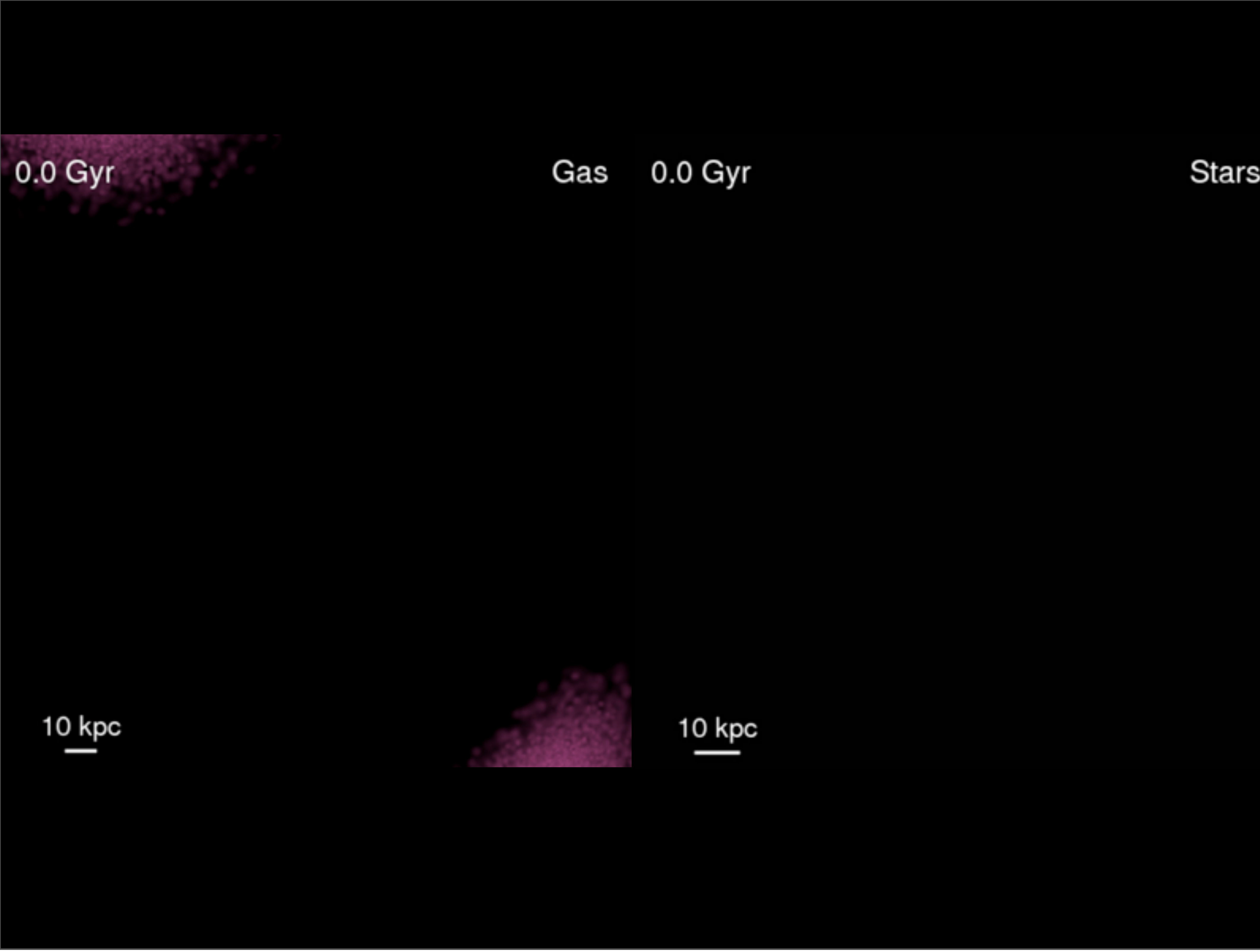




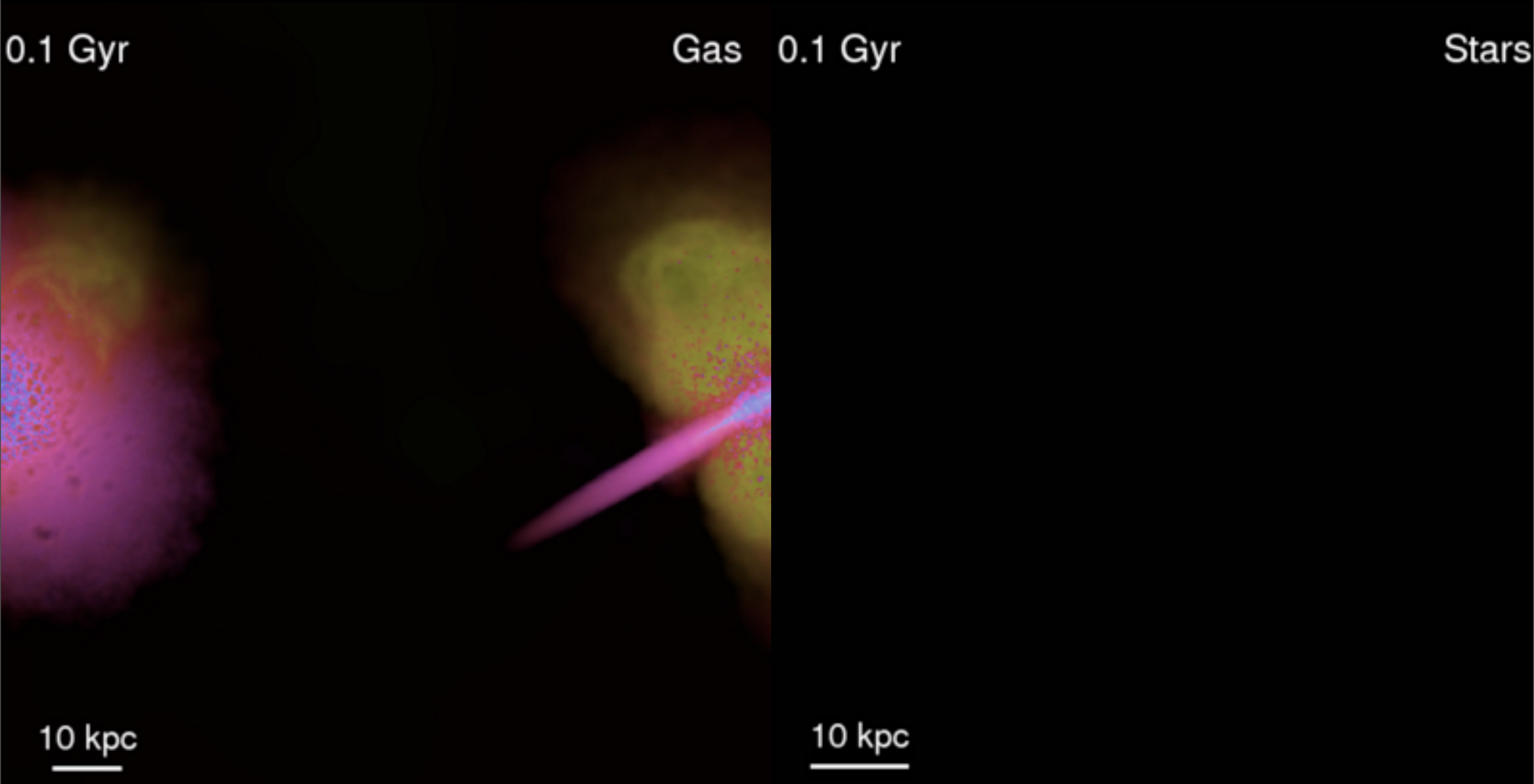



0.0 Gyr
Gas
0.0 Gyr
Stars
10 kpc
10 kpc

Galaxy Mergers

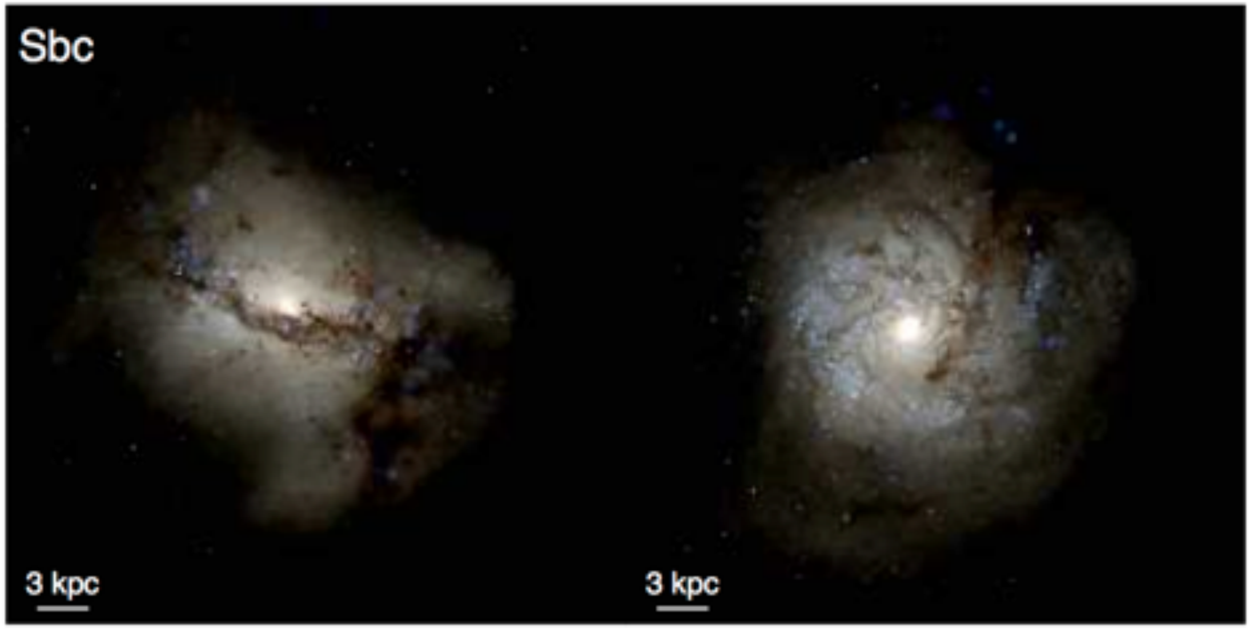
LABORATORY FOR STUDYING EXTREME CONDITIONS

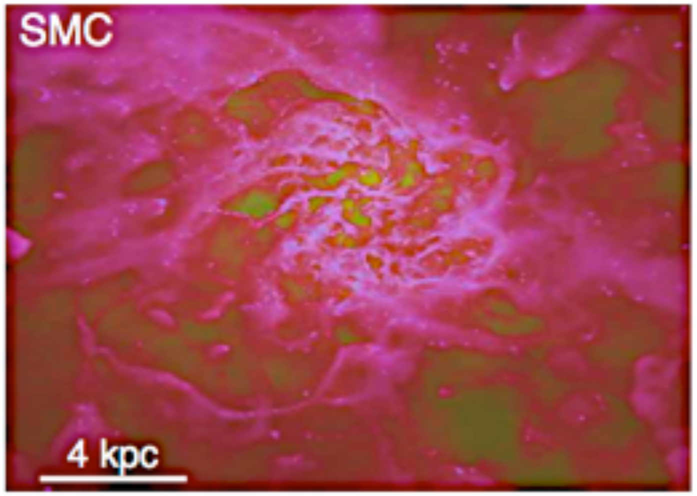
- Global conclusions similar to old models:
  - 10% SF in mergers (Hernquist & Spergel 91)
  - sizes/structure/profiles
  - burst dominated by inflows to nuclei
- Enhanced SF in tails/bridges/shocks
- Super-winds: ~10-500 M_{sun}/yr

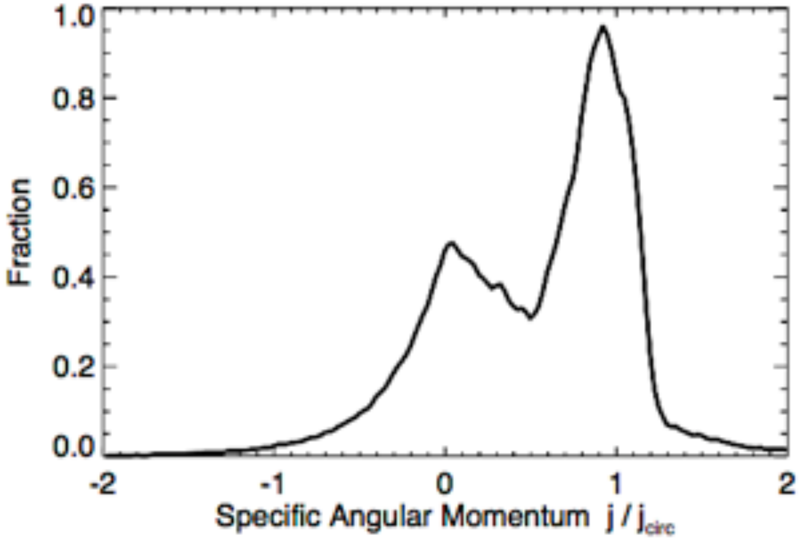

0.1 Gyr
Gas
10 kpc
0.1 Gyr
Stars
10 kpc

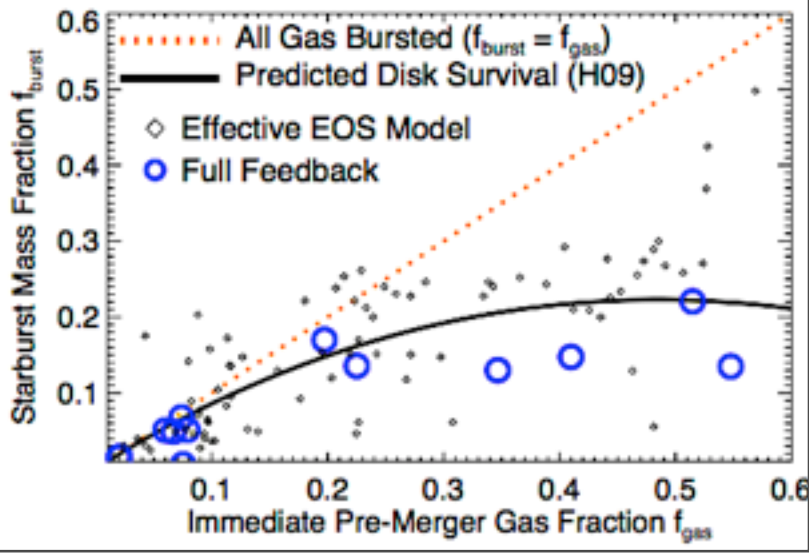
Disk Survival

REMAINS EFFICIENT!









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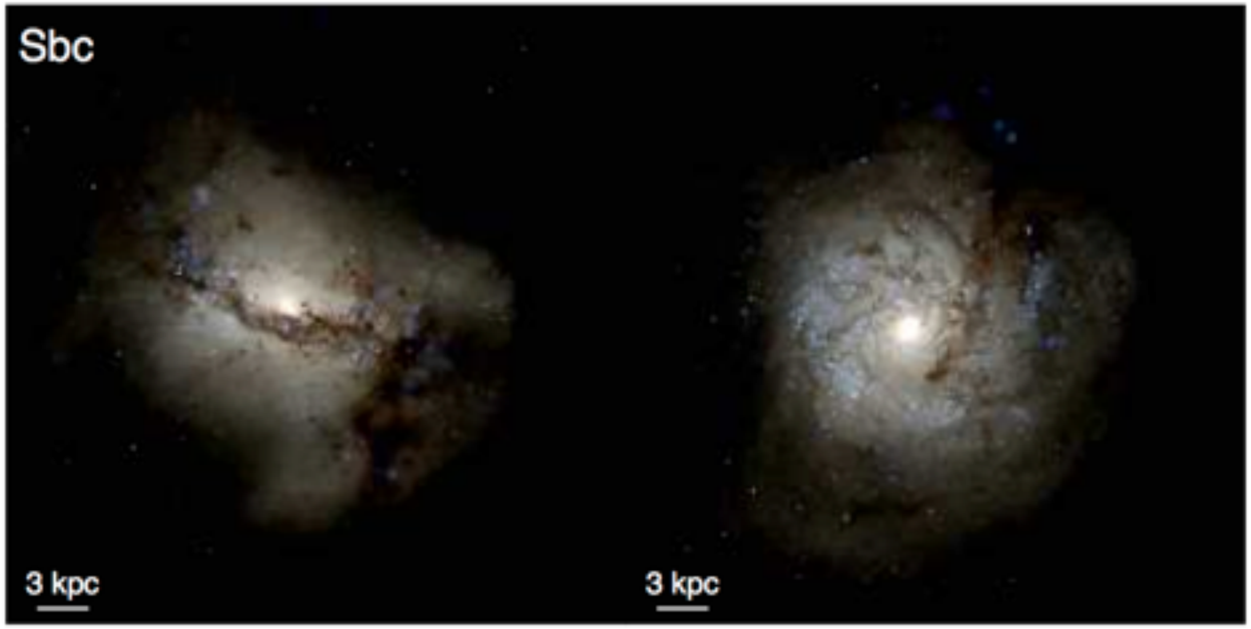
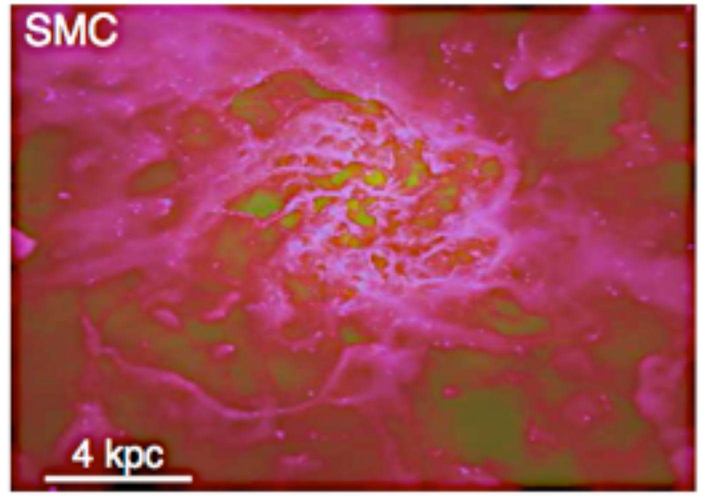
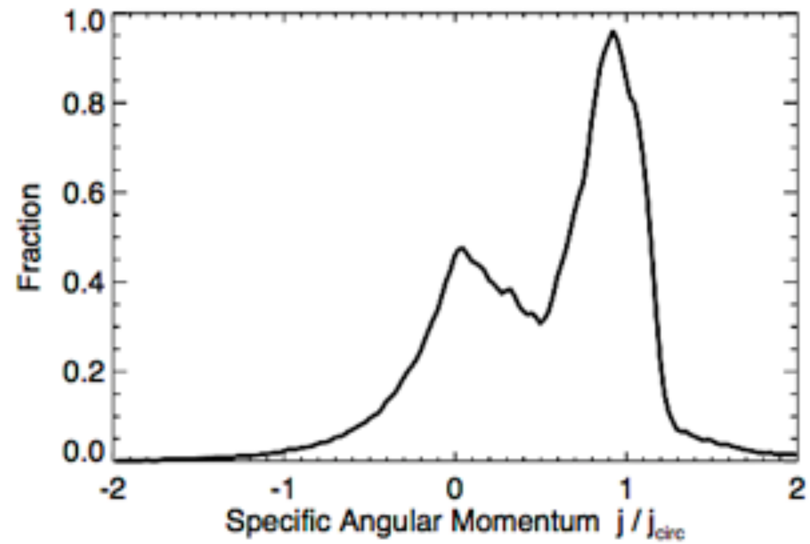
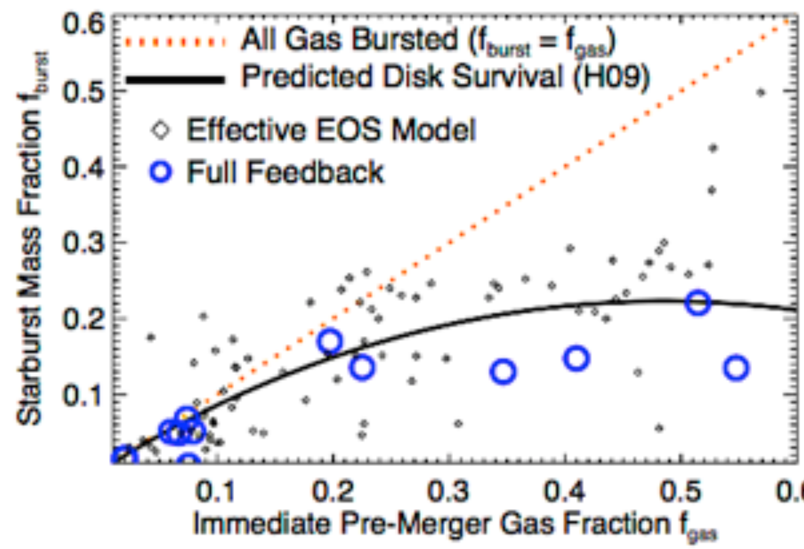
REMAINS EFFICIENT!

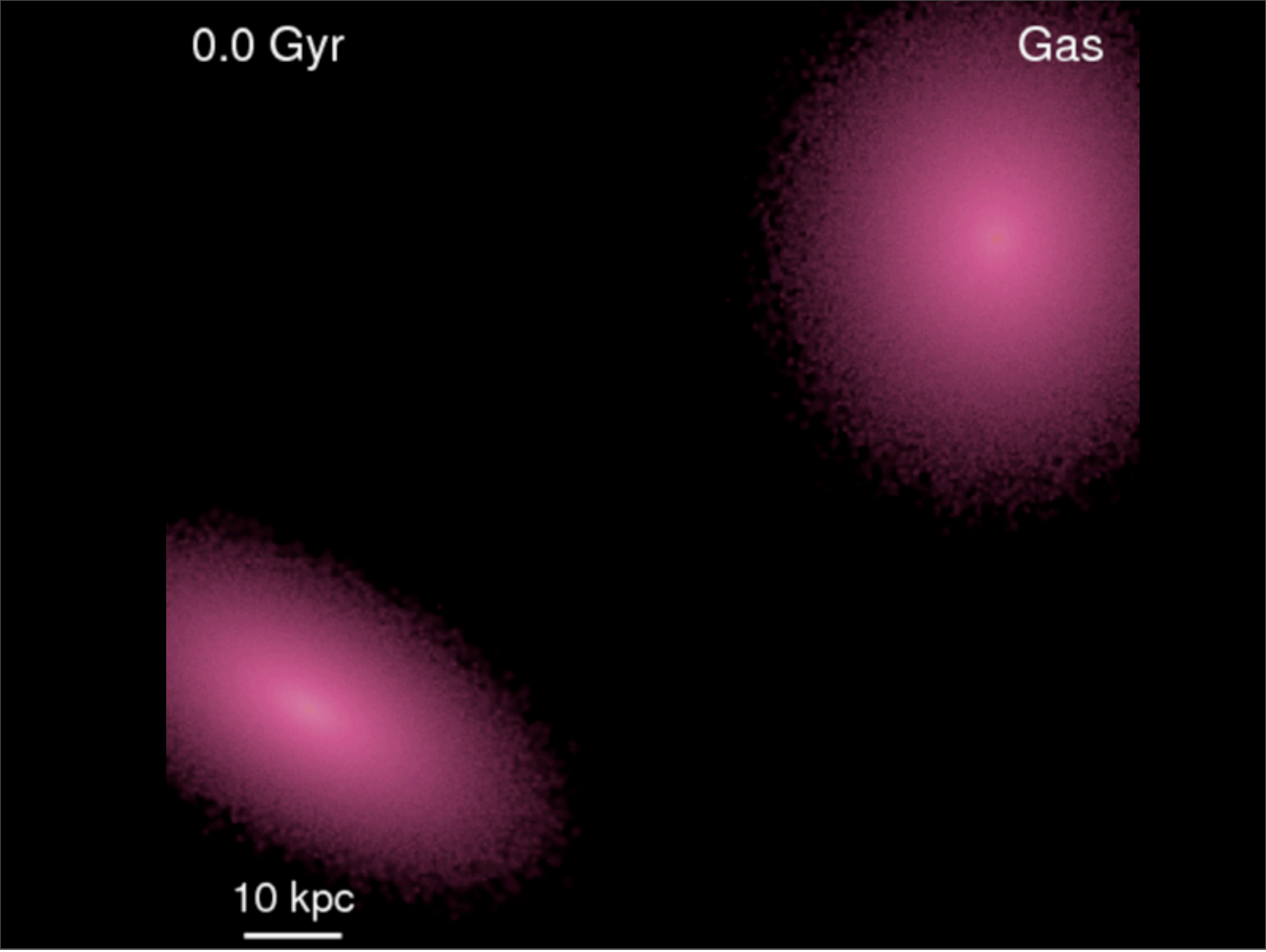




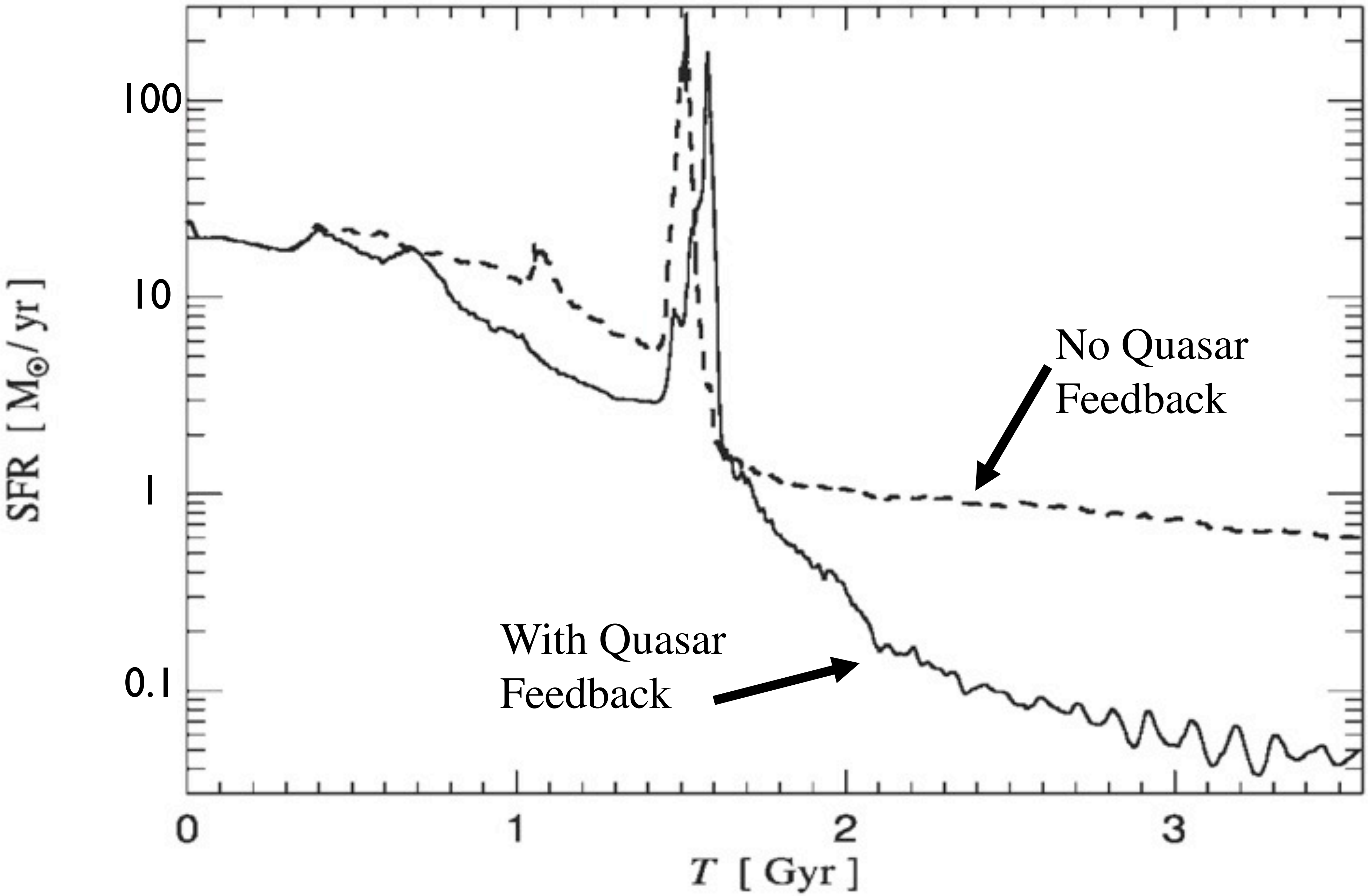




- More efficient in gas-rich mergers
- Large fraction of high-*z* merger remnants will be “disks/disky”


0.0 Gyr
Gas
10 kpc

Do we need 'Quasar Mode' Feedback?



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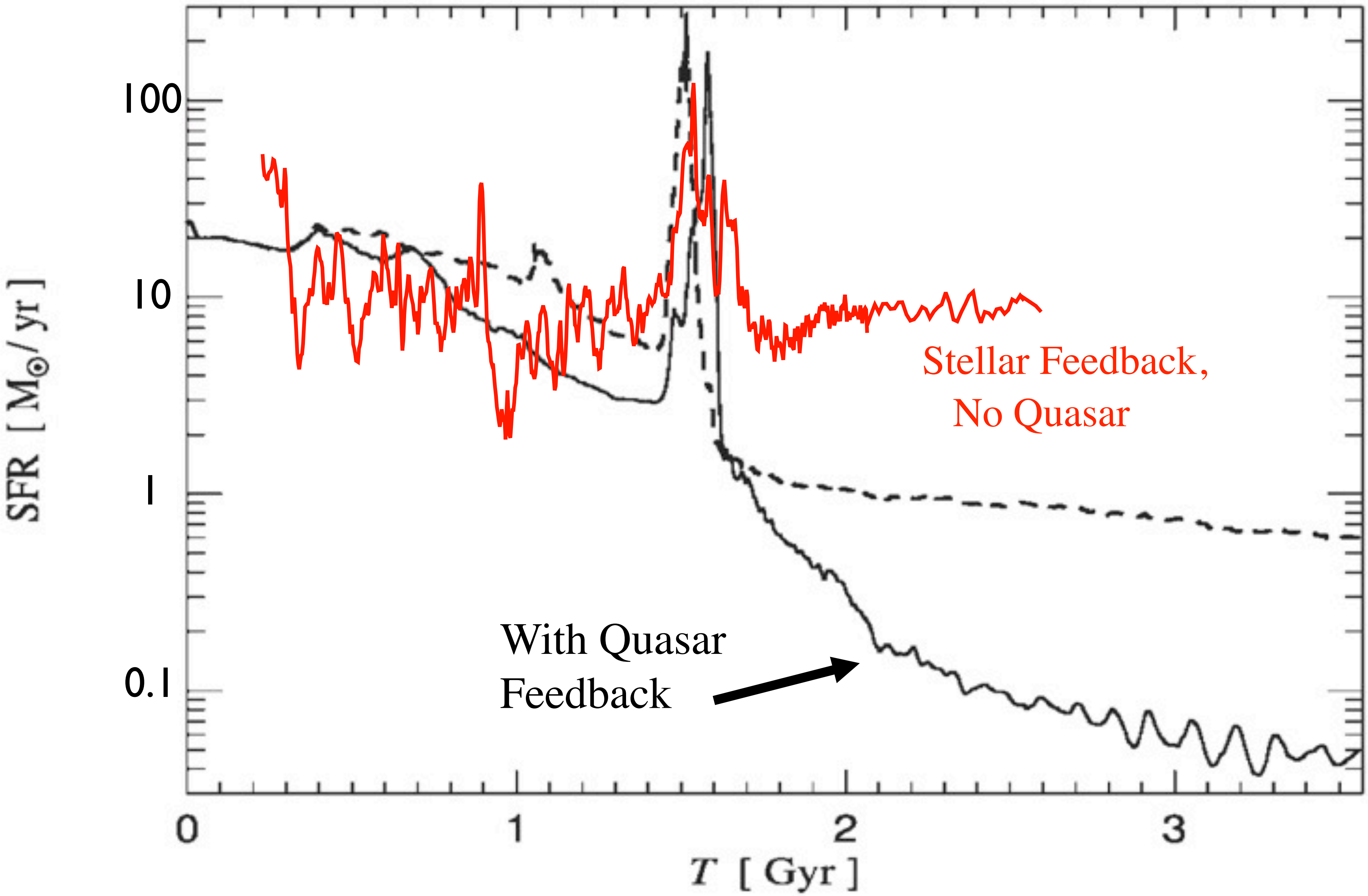
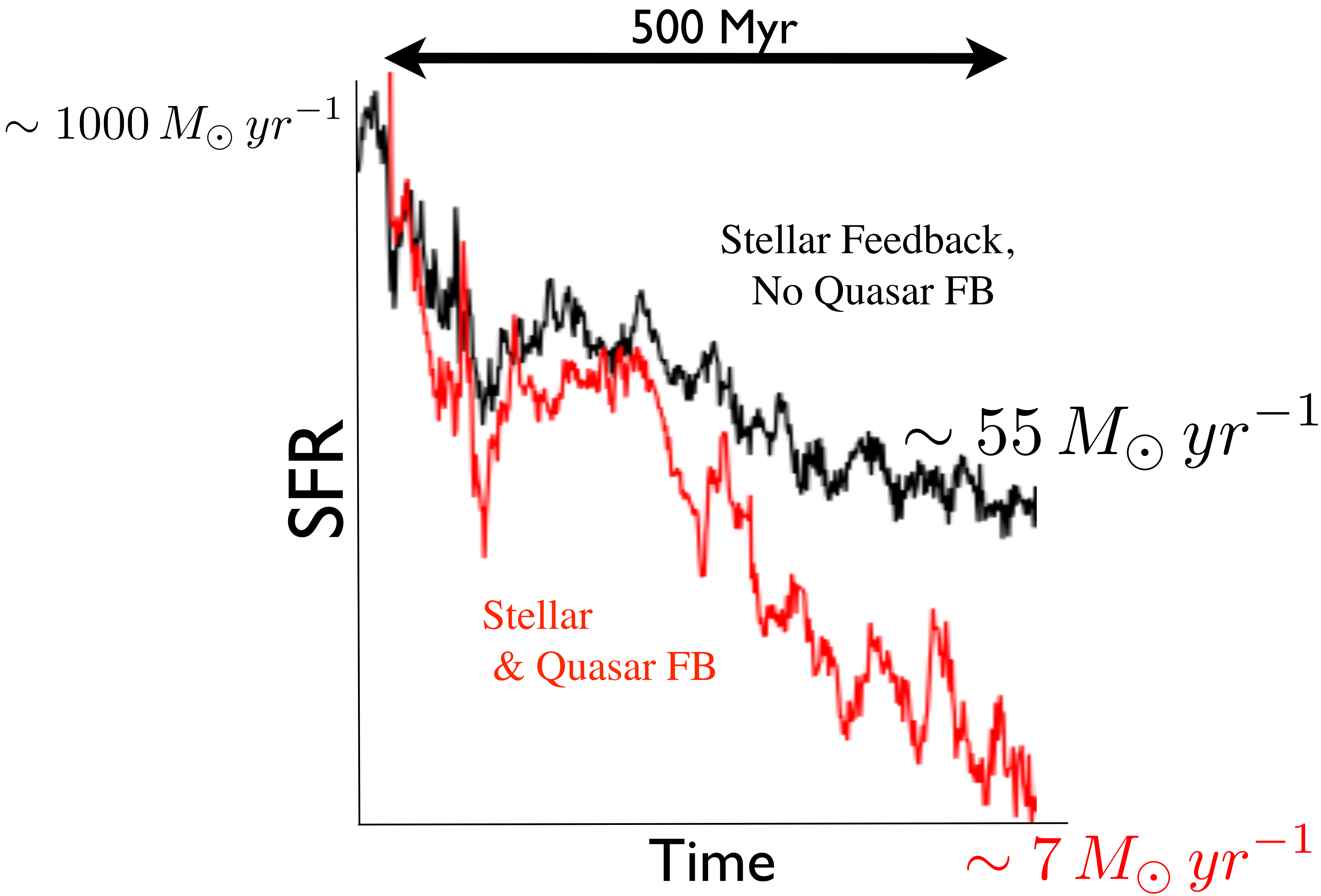


Do we need 'Quasar Mode' Feedback?



Summary:

- Global **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
    - Need 'enough' stars to offset dissipation (set by gravity)

- Feedback leads to Kennicutt relation & **super-winds**:

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

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

- Giant Clumps: *Mostly* **transient** features of unstable, gas-rich disks

- Mergers: Broadly similar conclusions
    - **Efficient disk survival**
    - Super-winds with ~10-500 M_{sun}/yr: consistent *per unit SFR* with isolated disks

- **Can't Quench Without "Impulsive" Feedback**!
    - Quasar BAL Winds: Explain M_{BH}-σ, and *WILL* suppress SFRs