

# Feedback: Now With Physics!\*

0.0 Gyr

Stars 0.1 Gyr

Stars

10 kpc

10 kpc

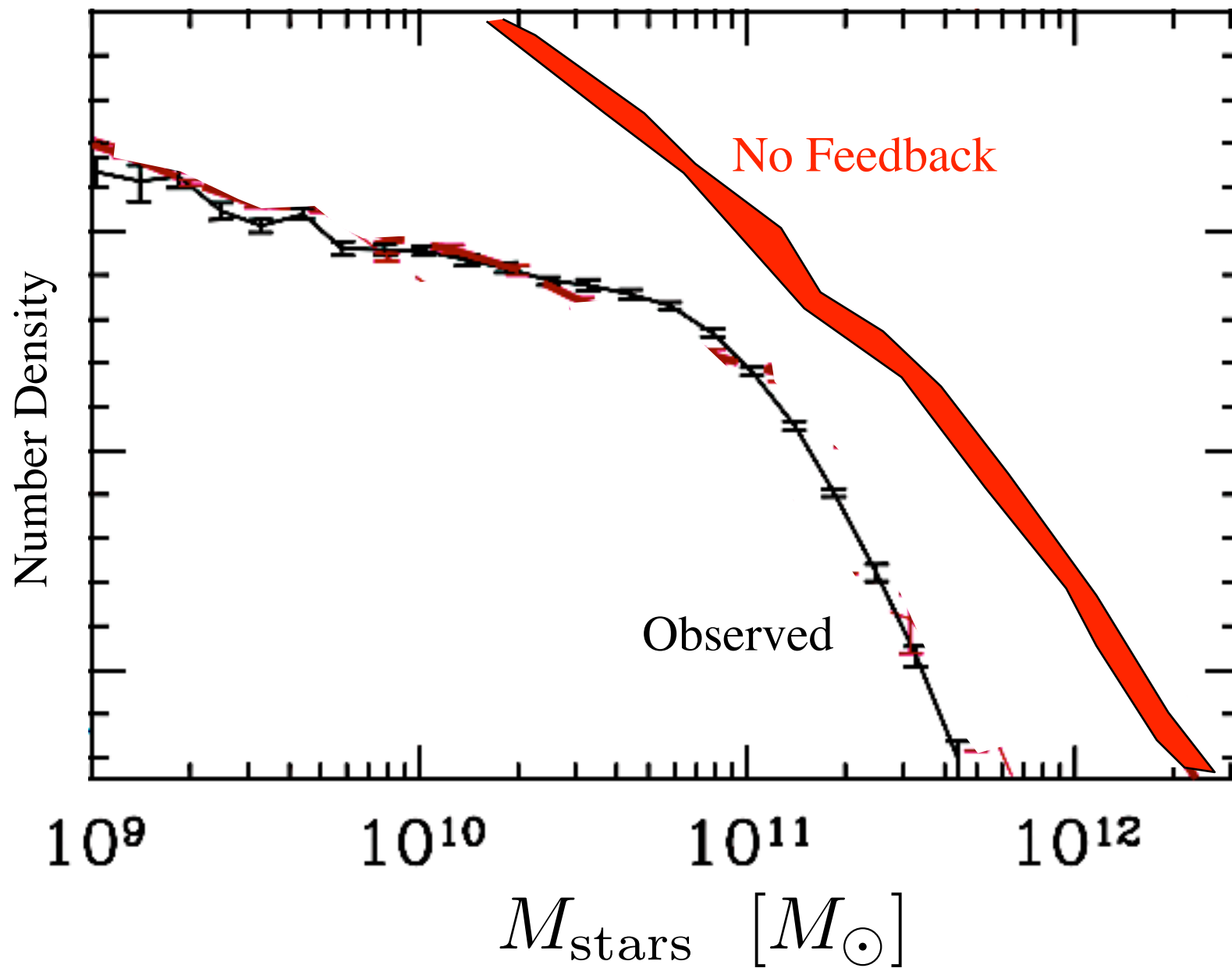
Dusan Keres

Philip Hopkins, Eliot Quataert, Norm Murray, Jose Onorbe

\* *Real physics may be pending*

## Motivation

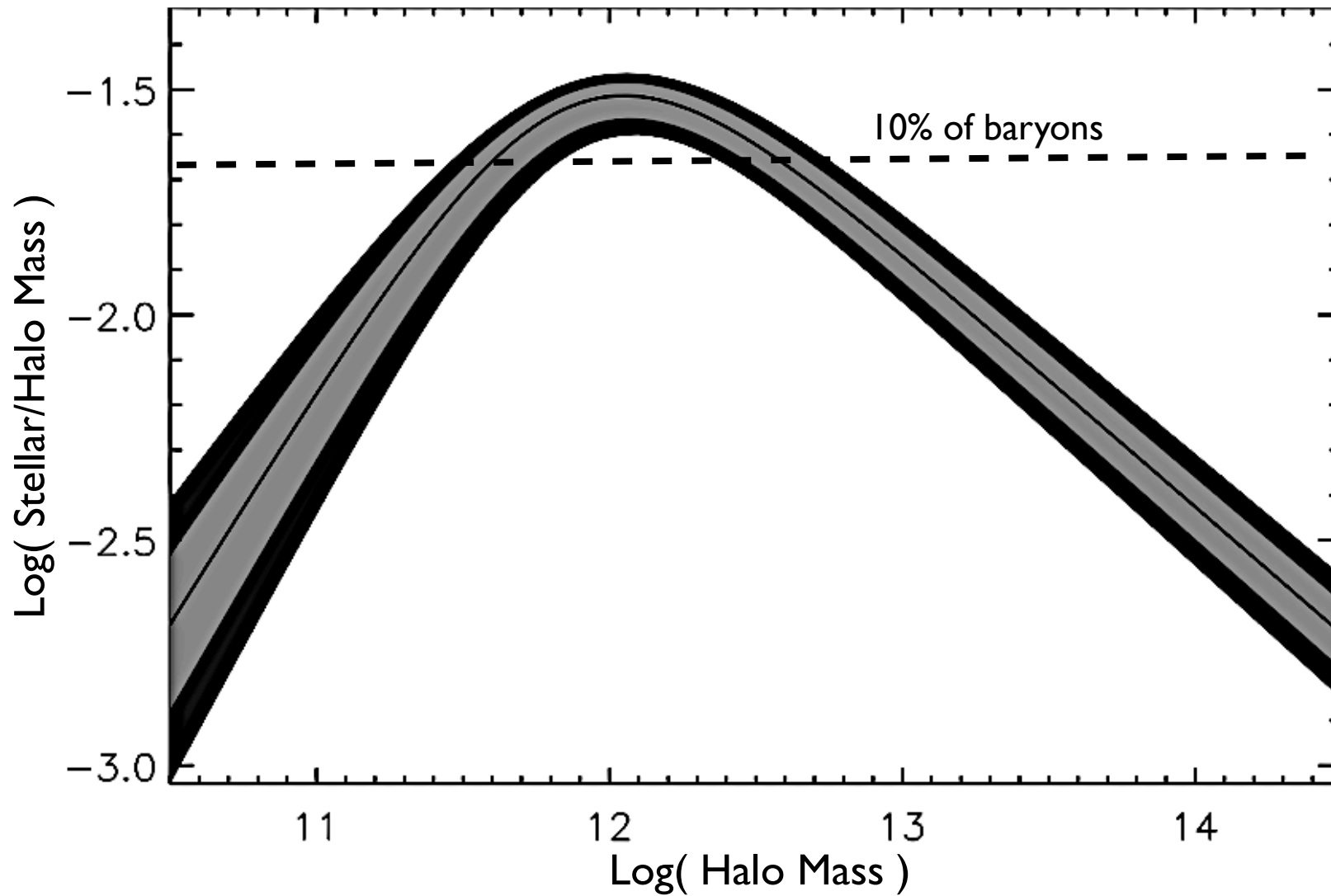
Q: WHY IS STAR FORMATION SO INEFFICIENT?



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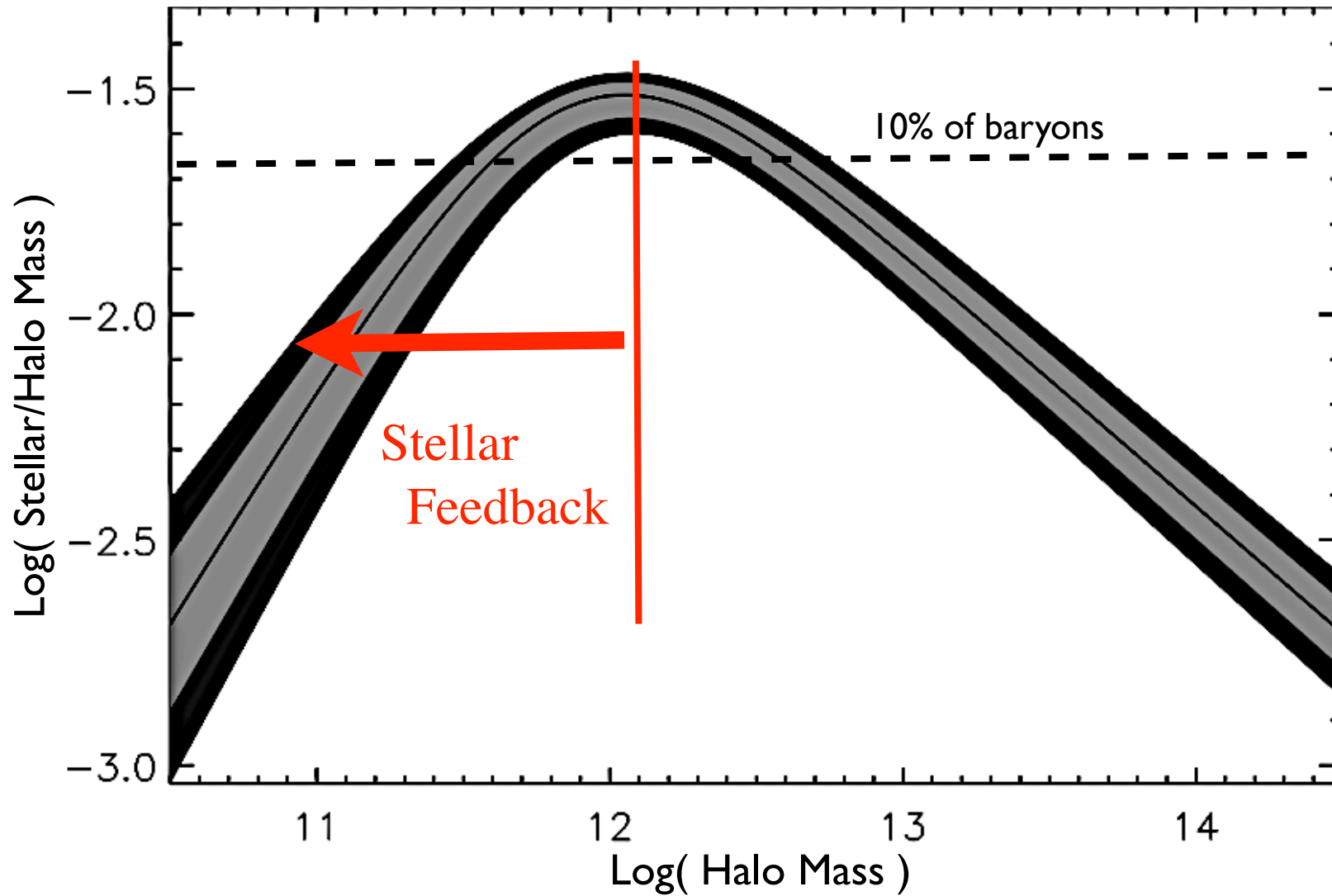
Moster 2009



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Q: WHY IS STAR FORMATION SO INEFFICIENT?

Moster 2009

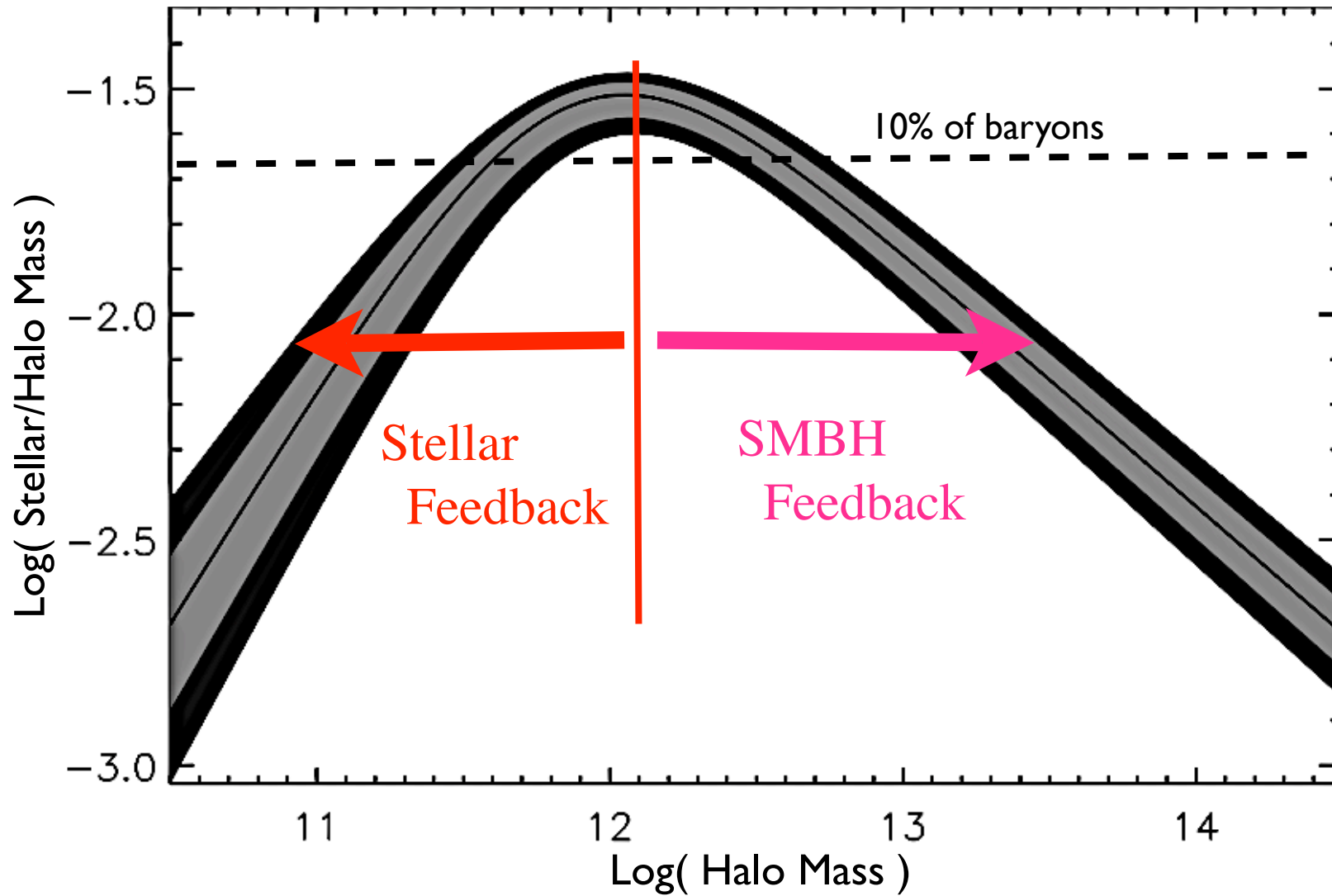




# Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?

Moster 2009



# Stellar Feedback is the Key!

## SO WHAT'S THE PROBLEM?

- Standard (in Galaxy Formation):  
Couple SNe ( $\sim 1e51$  erg/SN)  
as “heating”/thermal energy

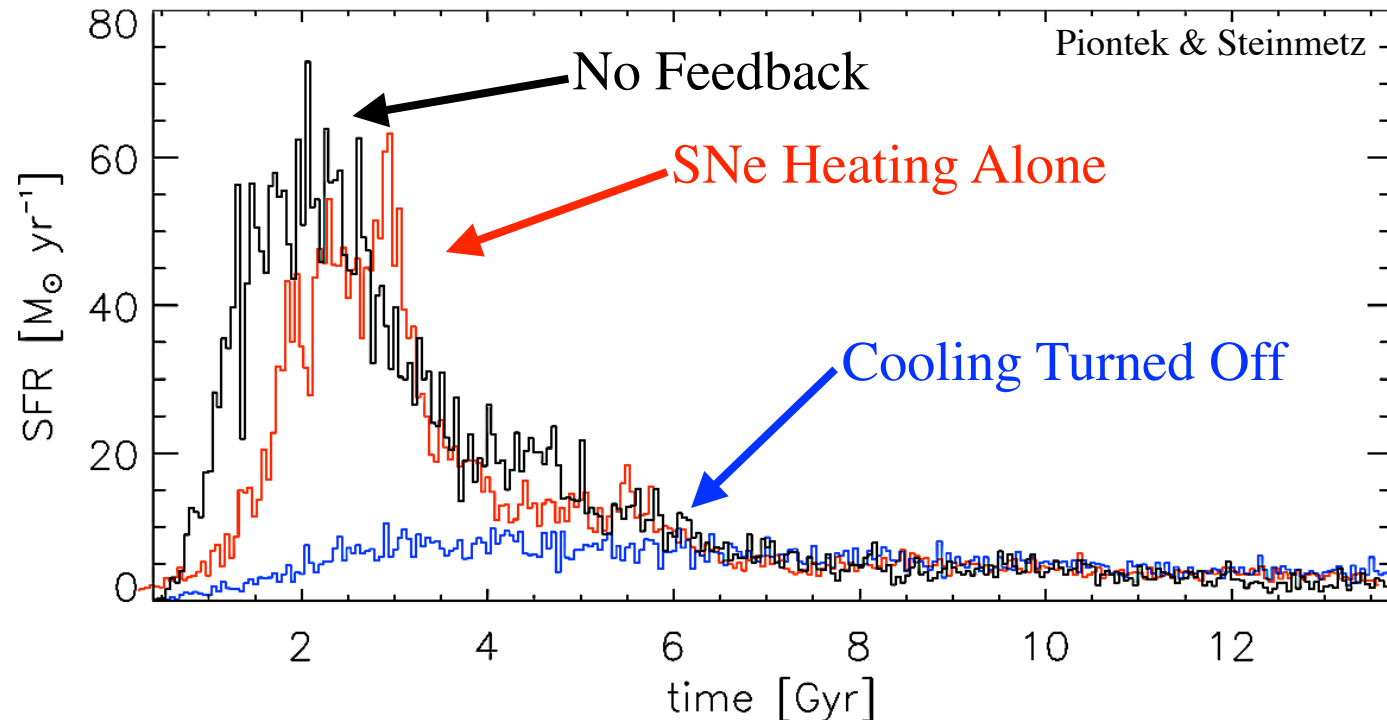
- FAILS:

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

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

- “Cheat”:

- Turn off cooling
- Force wind by hand  
(‘kick’ out of galaxy)



# Stellar Feedback: Understanding the key Physics



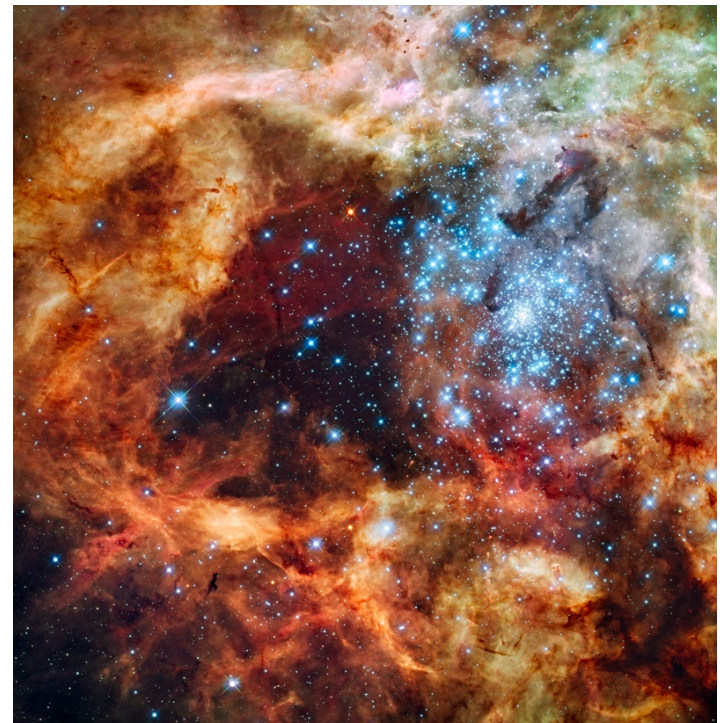
## Stellar Feedback: Understanding the key Physics

- High-resolution ( $\sim 1\text{pc}$ ), molecular cooling ( $< 100\text{ K}$ ), SF only at highest densities ( $n_{\text{H}} > 1000\text{ cm}^{-3}$ )



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  - SNe (II & Ia)
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- *Explicit* Momentum Flux:

- Radiation Pressure

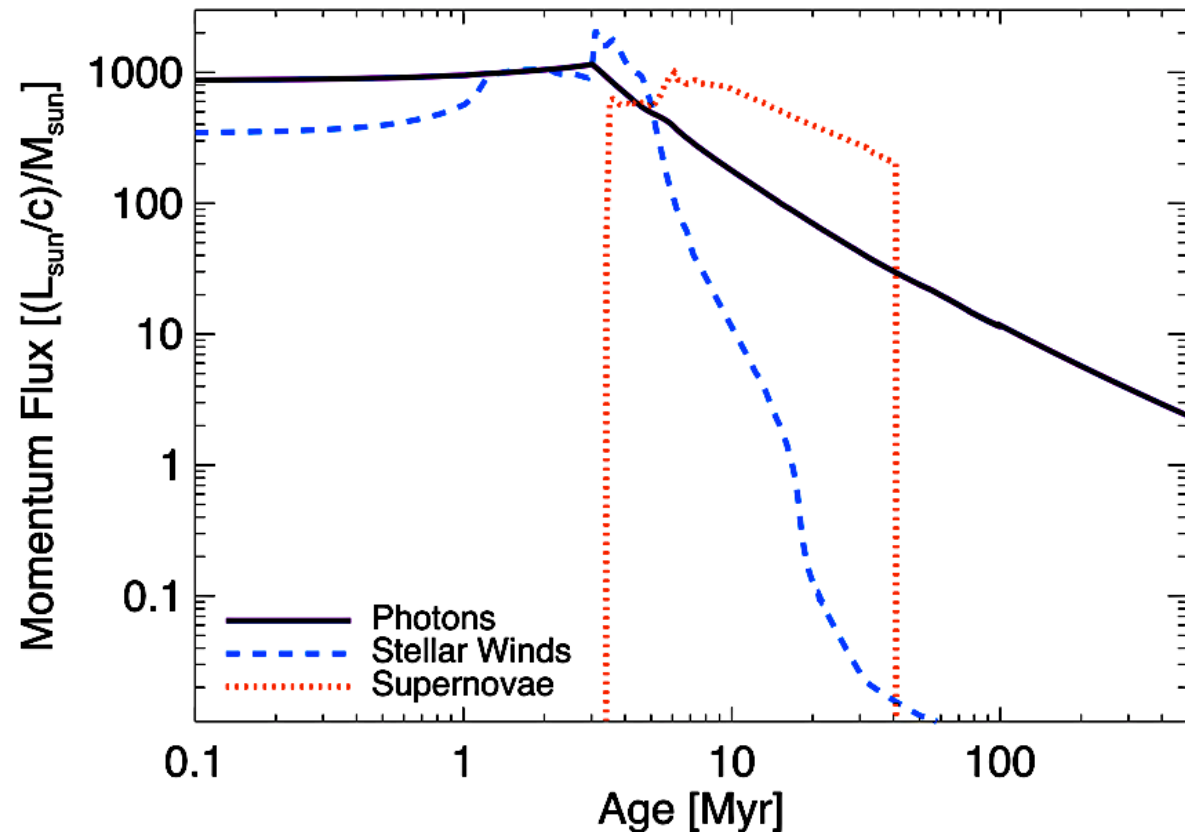
$$\dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}})$$

- SNe

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

- Stellar Winds

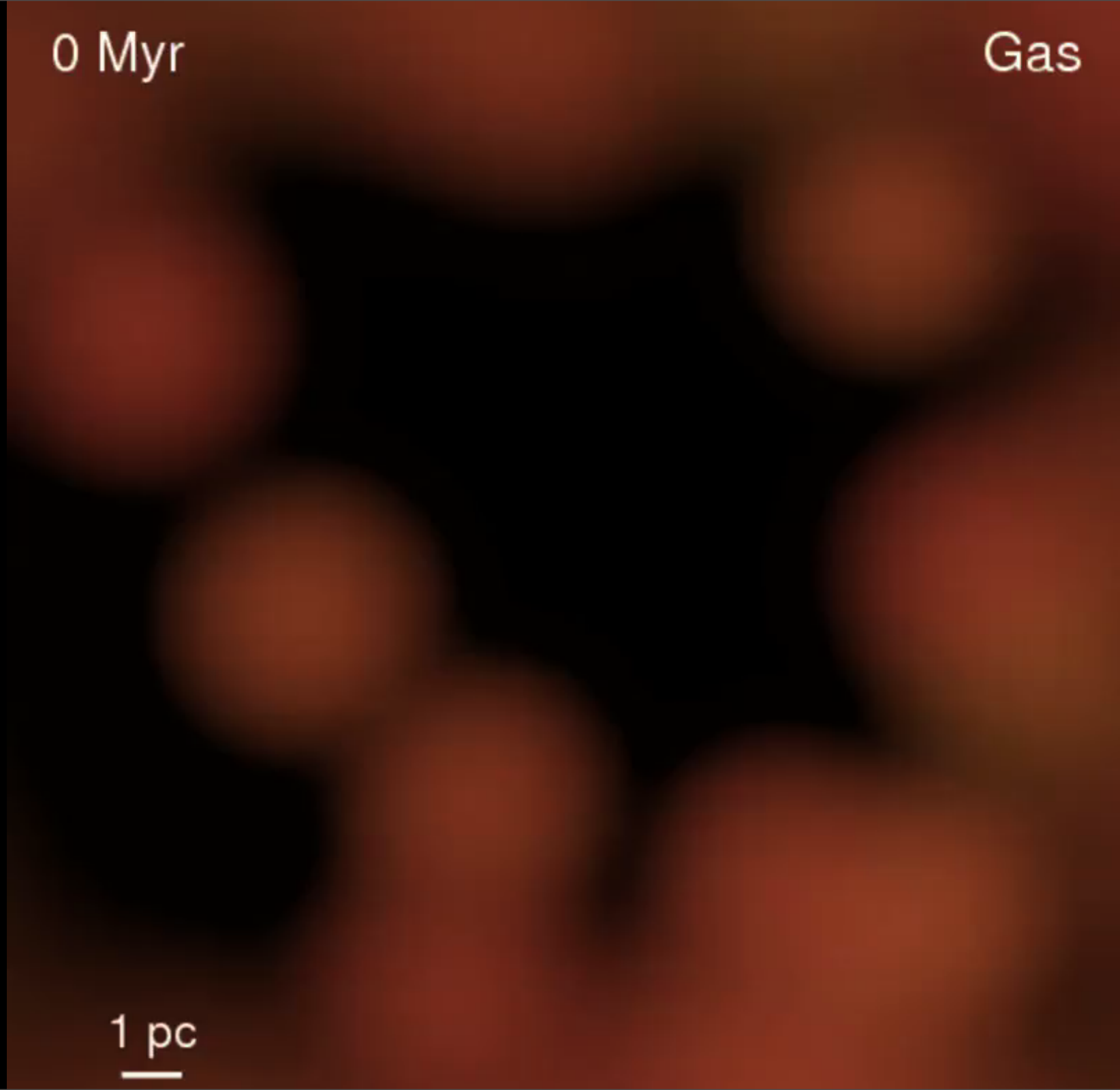
$$\dot{P}_{\text{W}} \sim \dot{M} v_{\text{wind}}$$



0 Myr

Gas

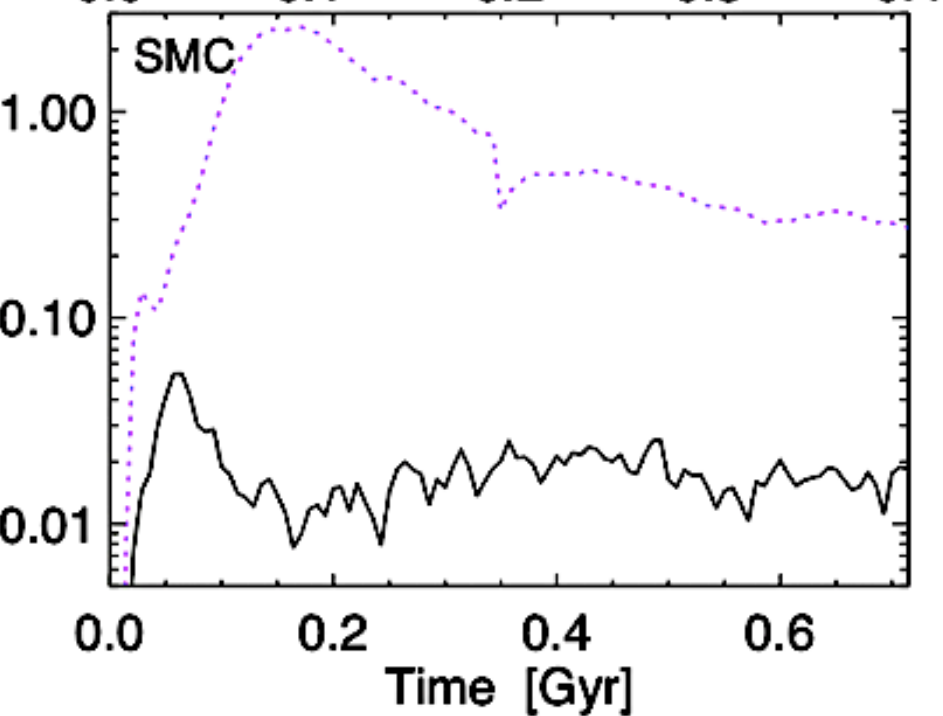
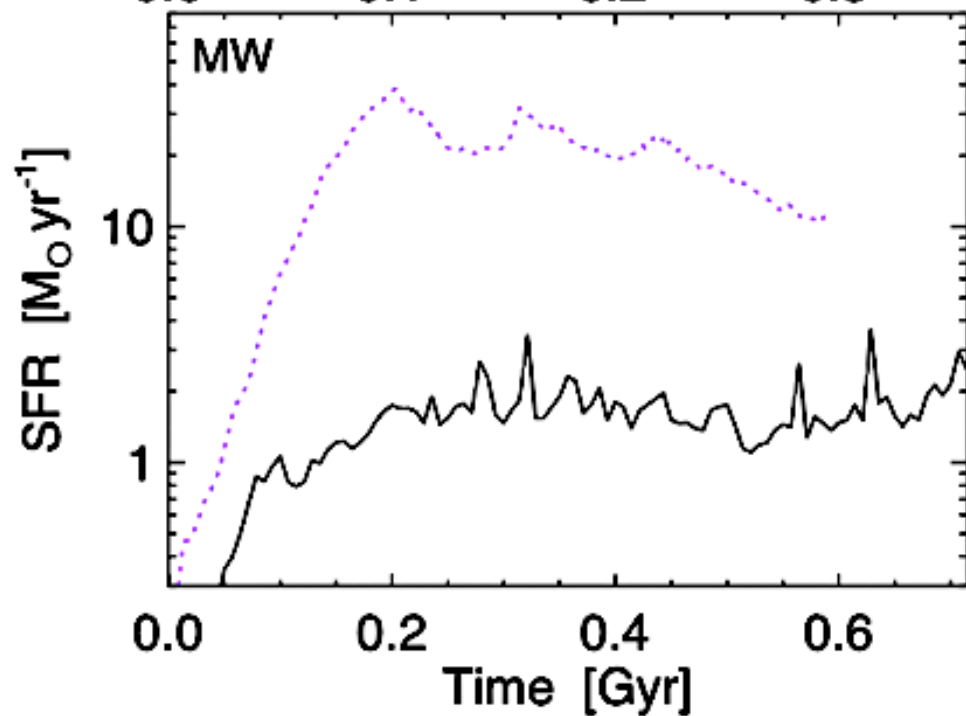
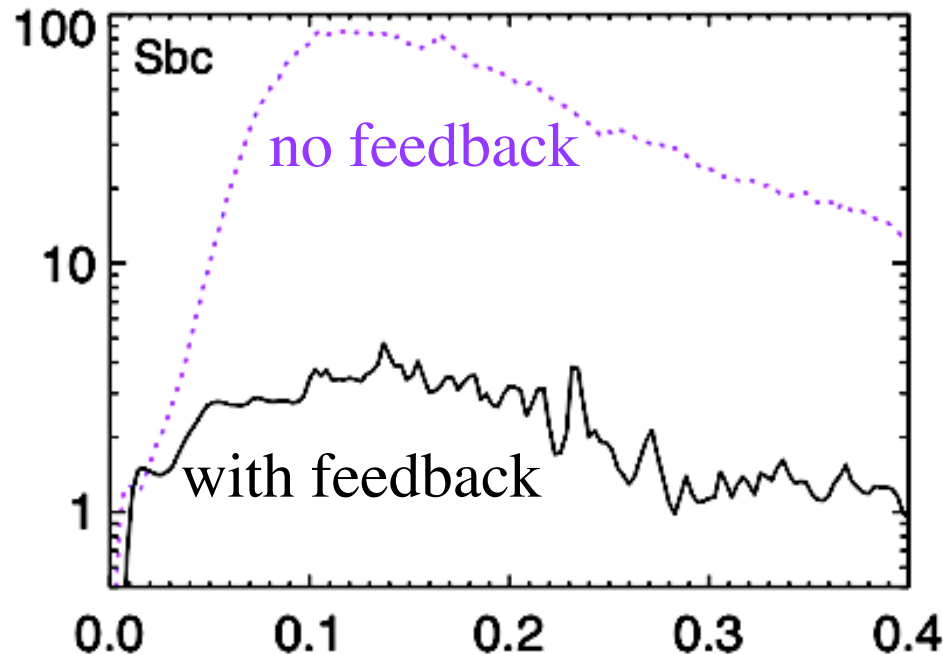
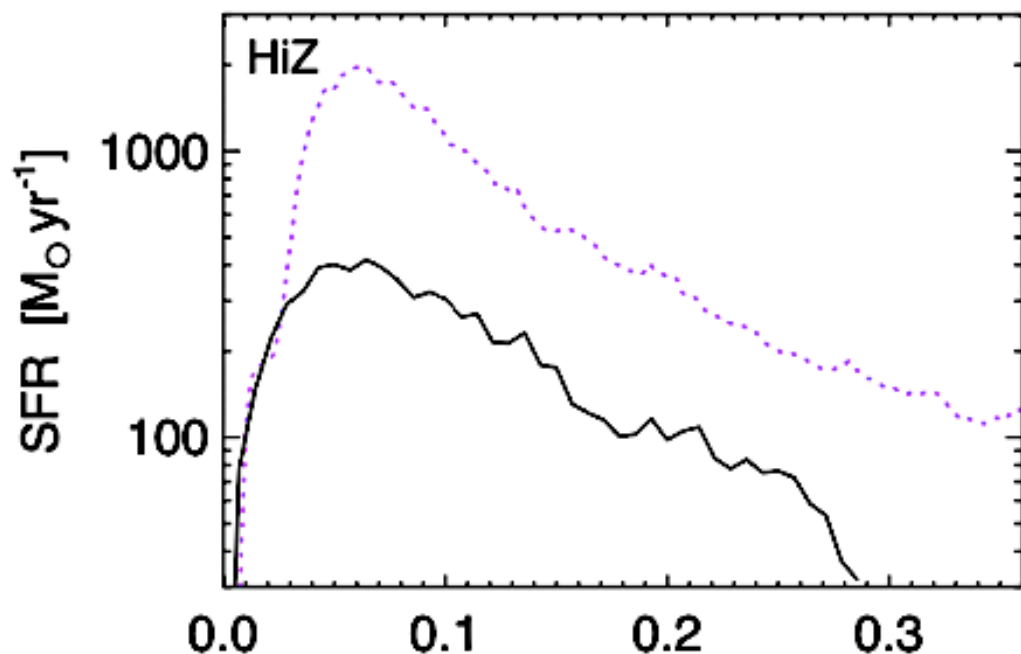
1 pc  
—



# Stellar Feedback gives Self-Regulated Star Formation

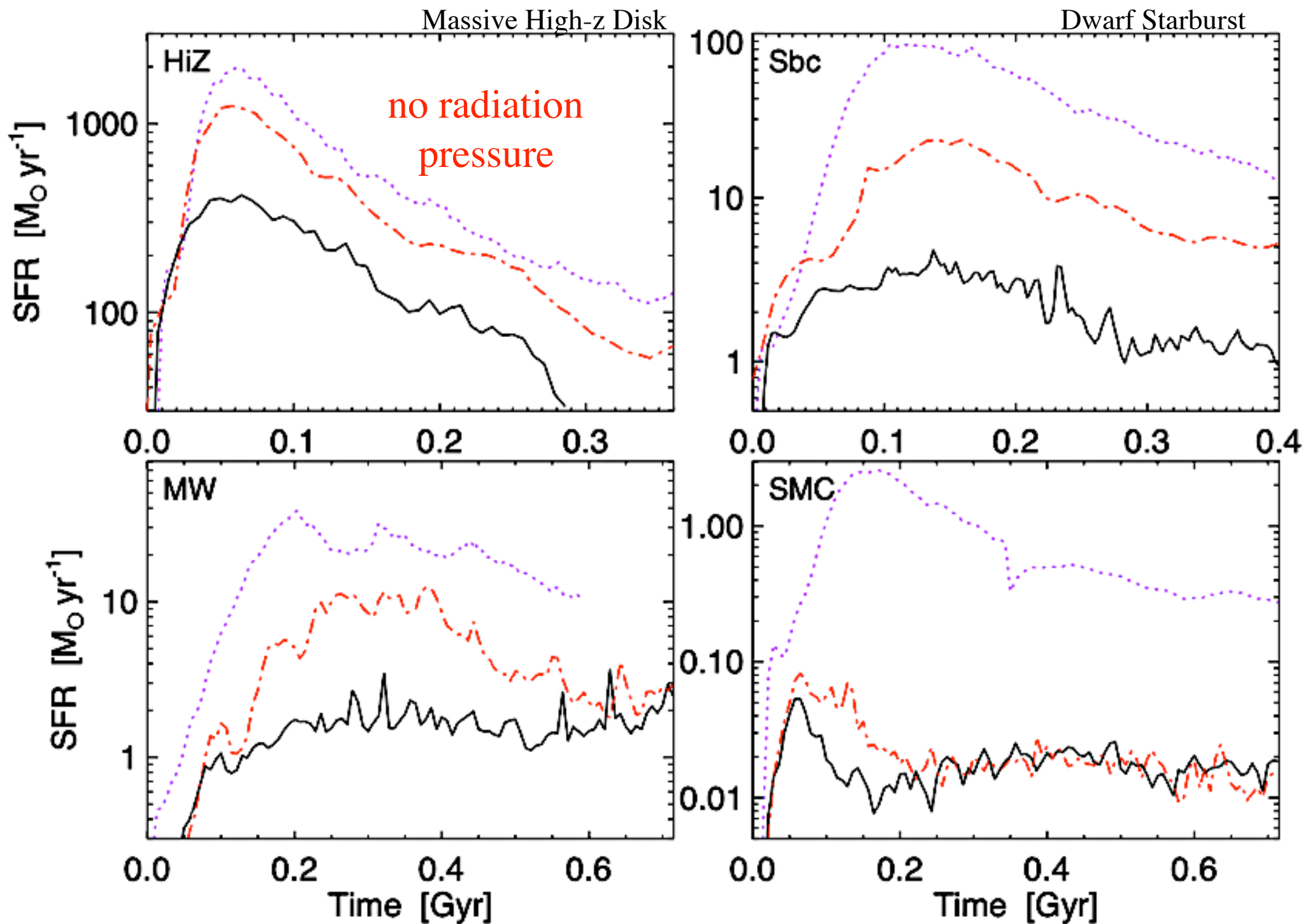
Massive High-z Disk

Dwarf Starburst

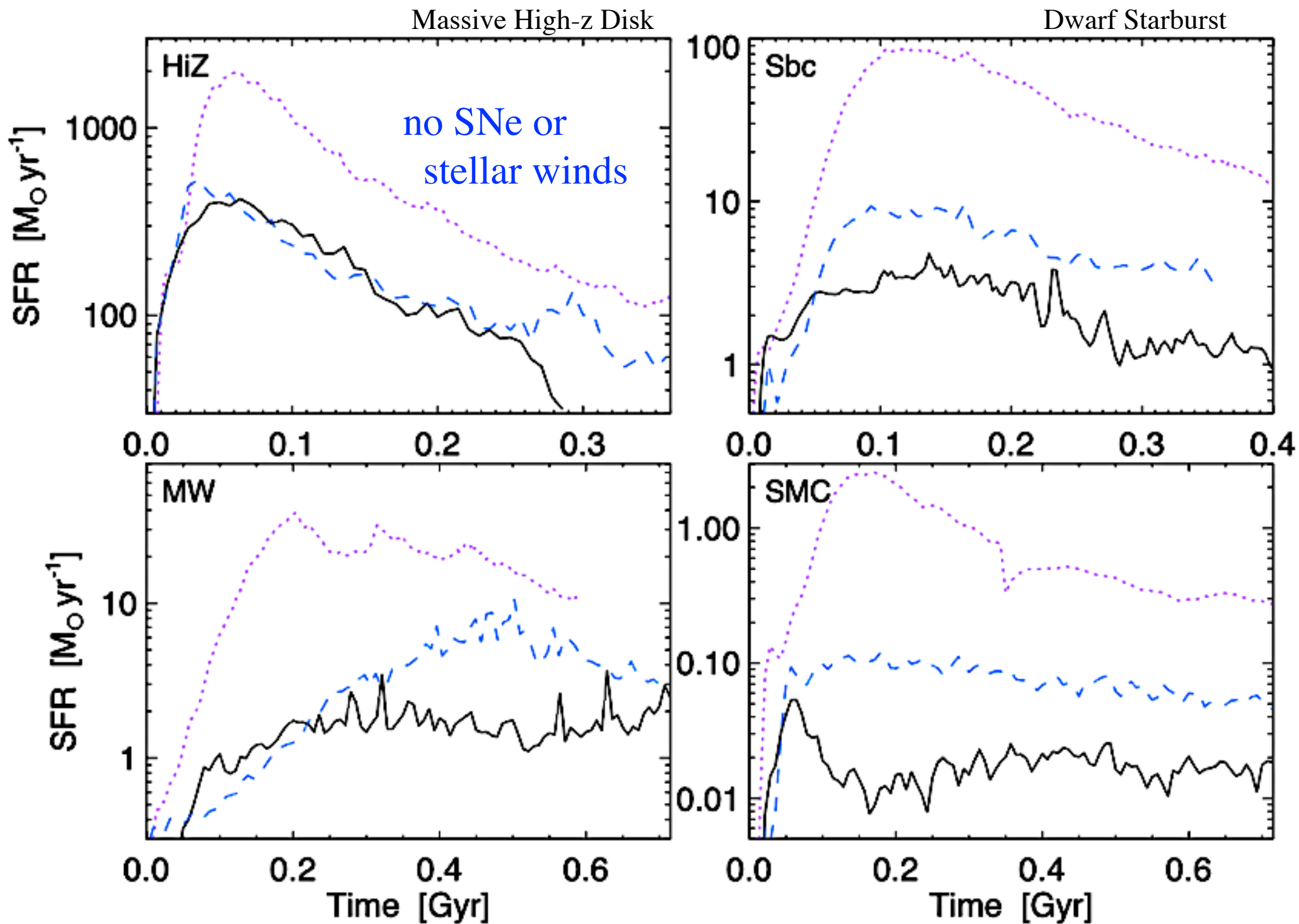




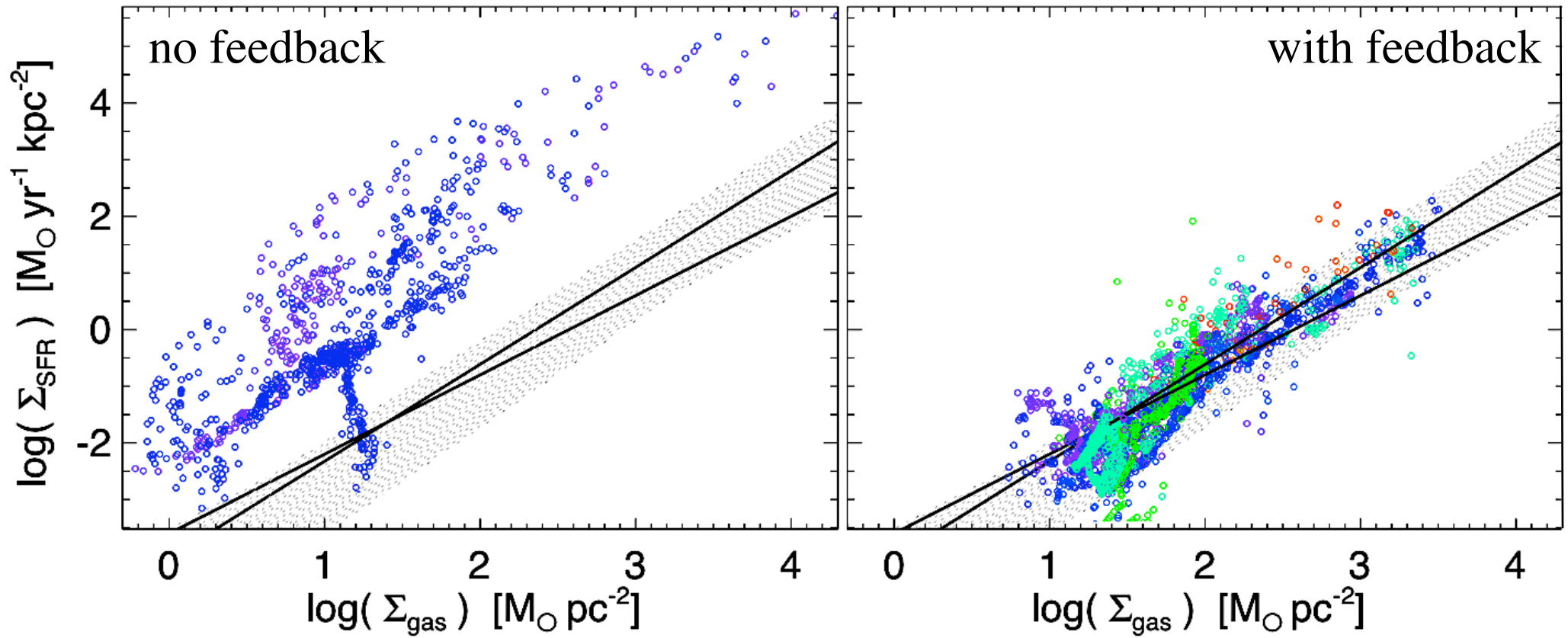
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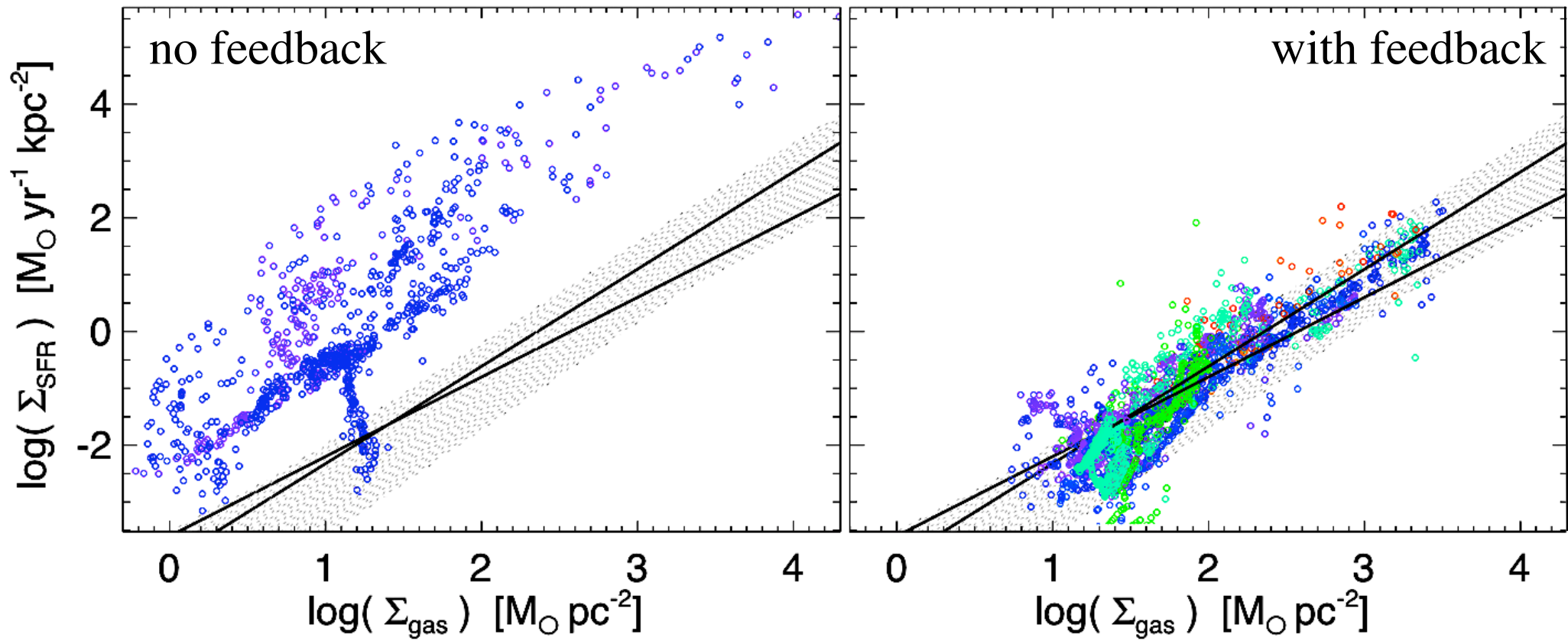


# Kennicutt-Schmidt relation emerges naturally



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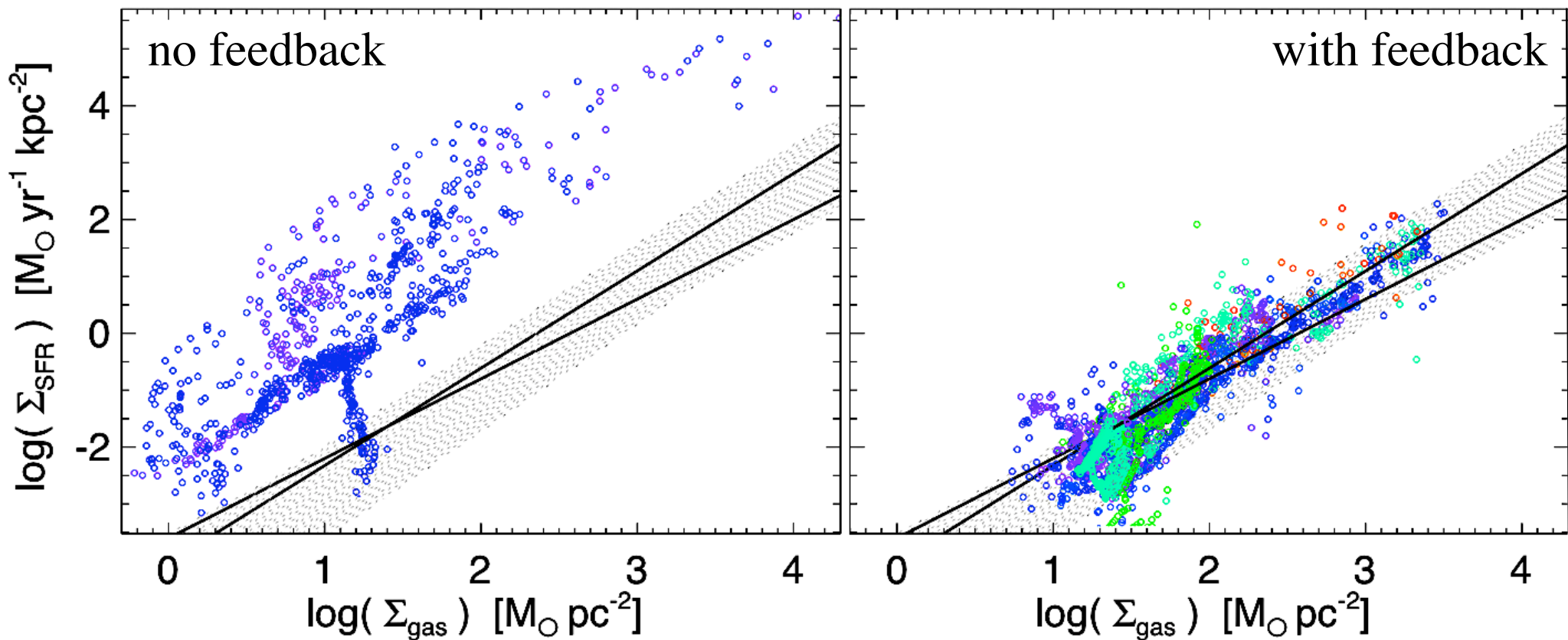
$$\dot{\Sigma}_* \sim \Sigma_{\text{gas}} / \tau_{\text{dyn}}$$



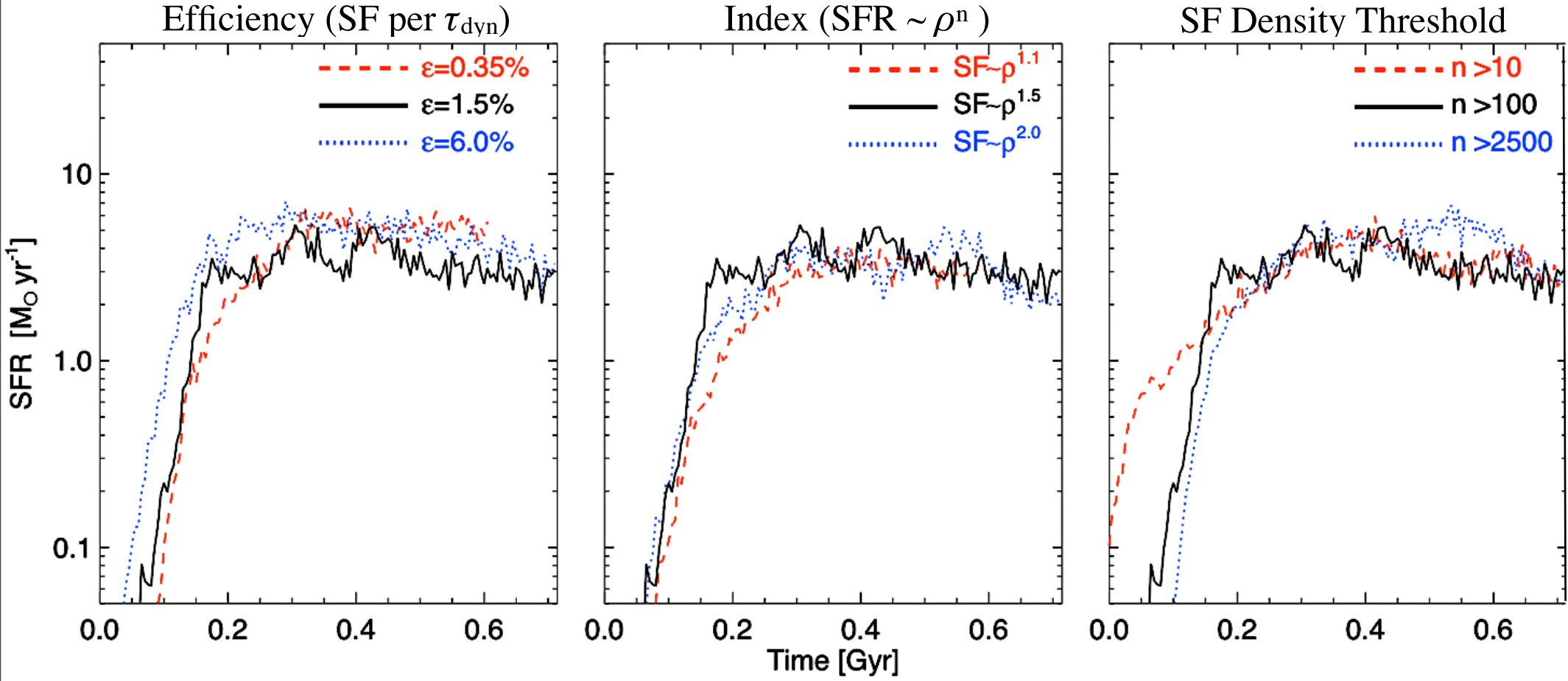
# Kennicutt-Schmidt relation emerges naturally

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

$$\dot{\Sigma}_* \sim 0.02 \Sigma_{\text{gas}} / \tau_{\text{dyn}}$$



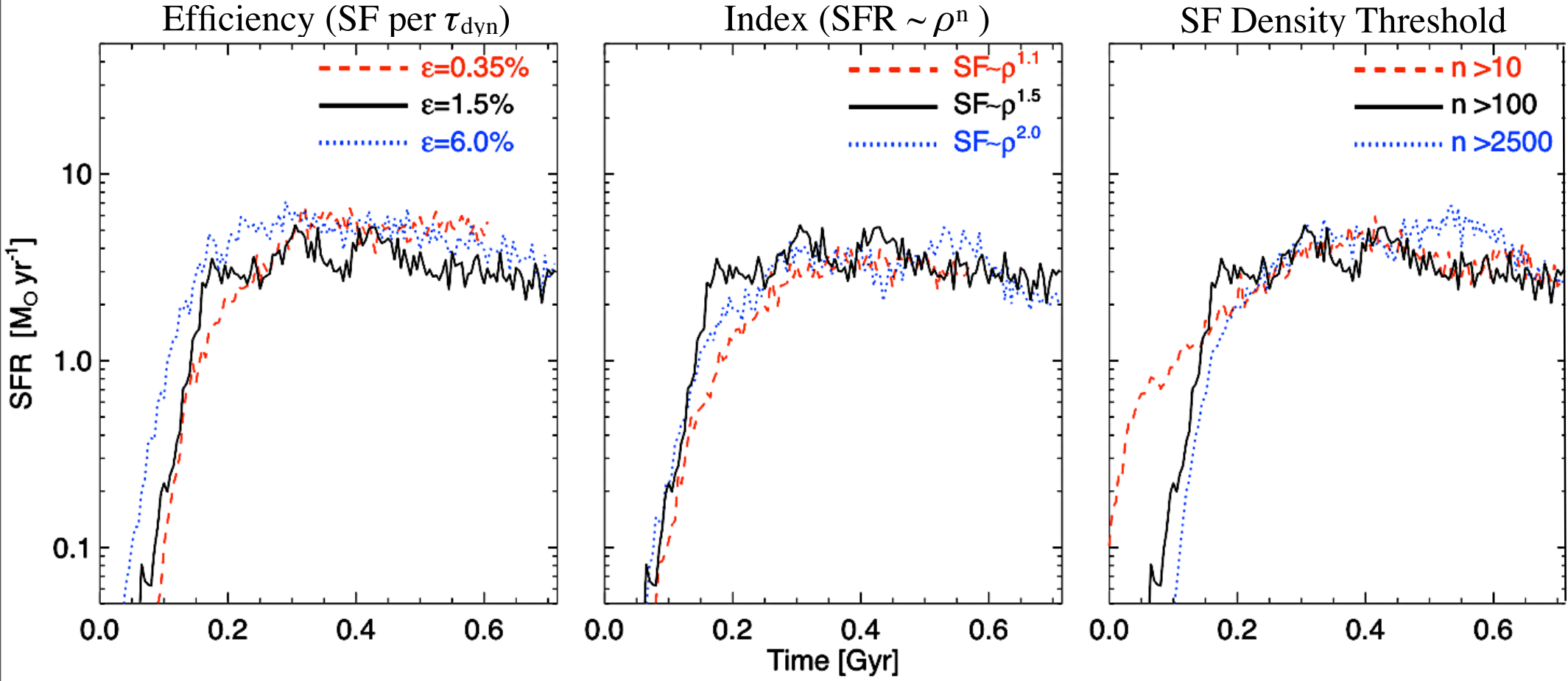
# Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law



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



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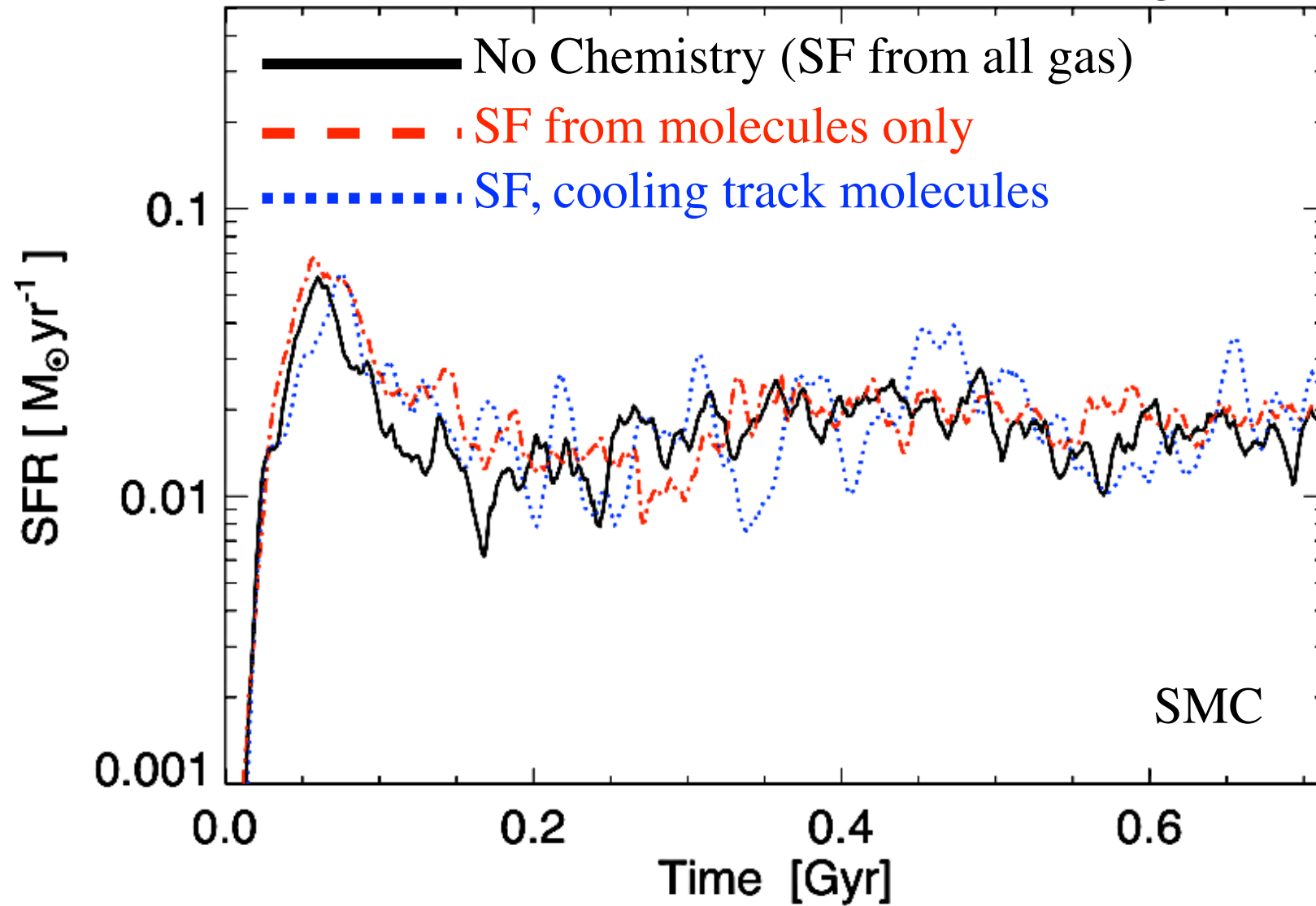


➤ Set by feedback (i.e. SFR) needed to maintain marginal stability

# Molecular Chemistry doesn't change things above modest Metallicity

MOLECULES ARE A *TRACER*

see also Glover 2011

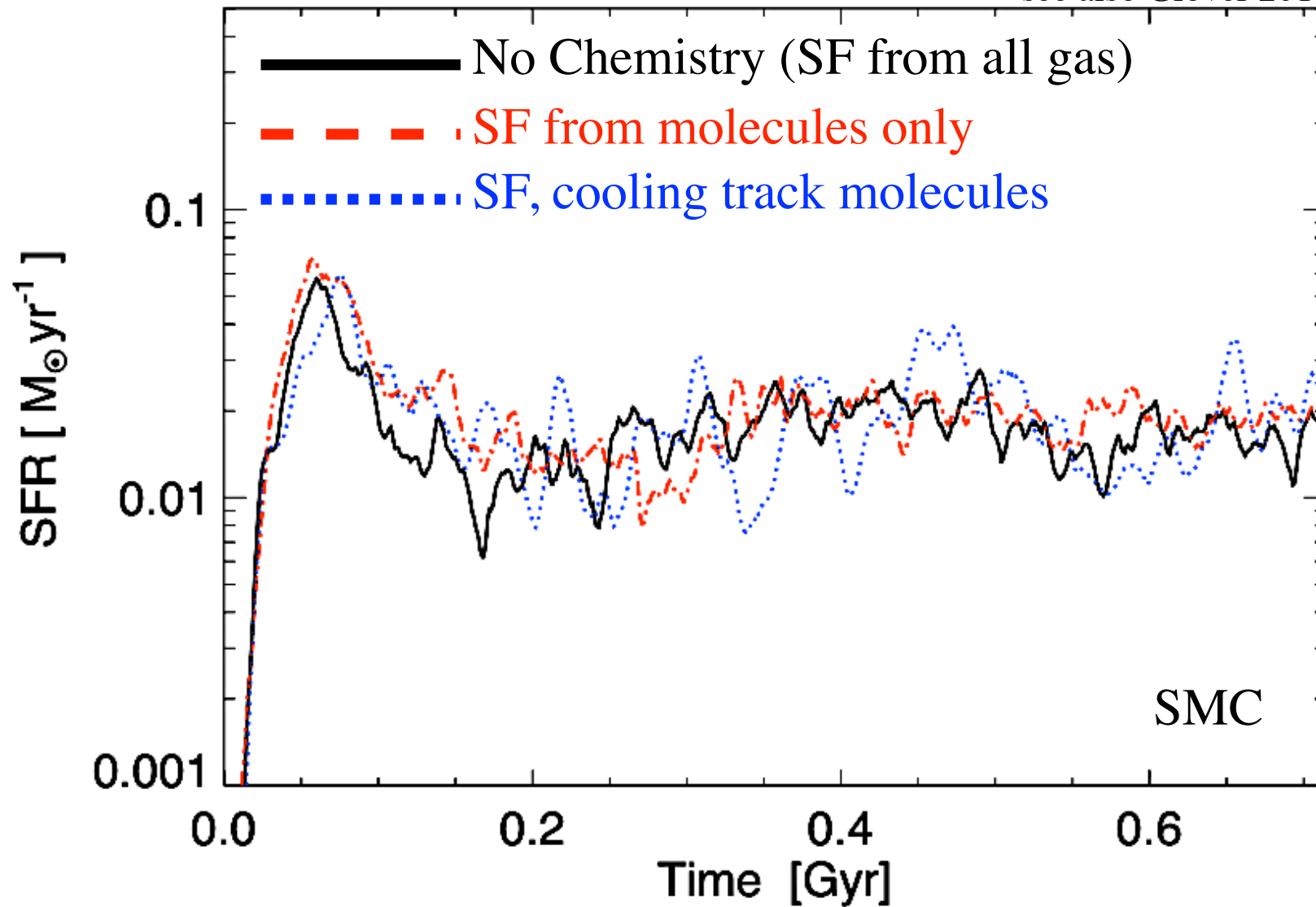




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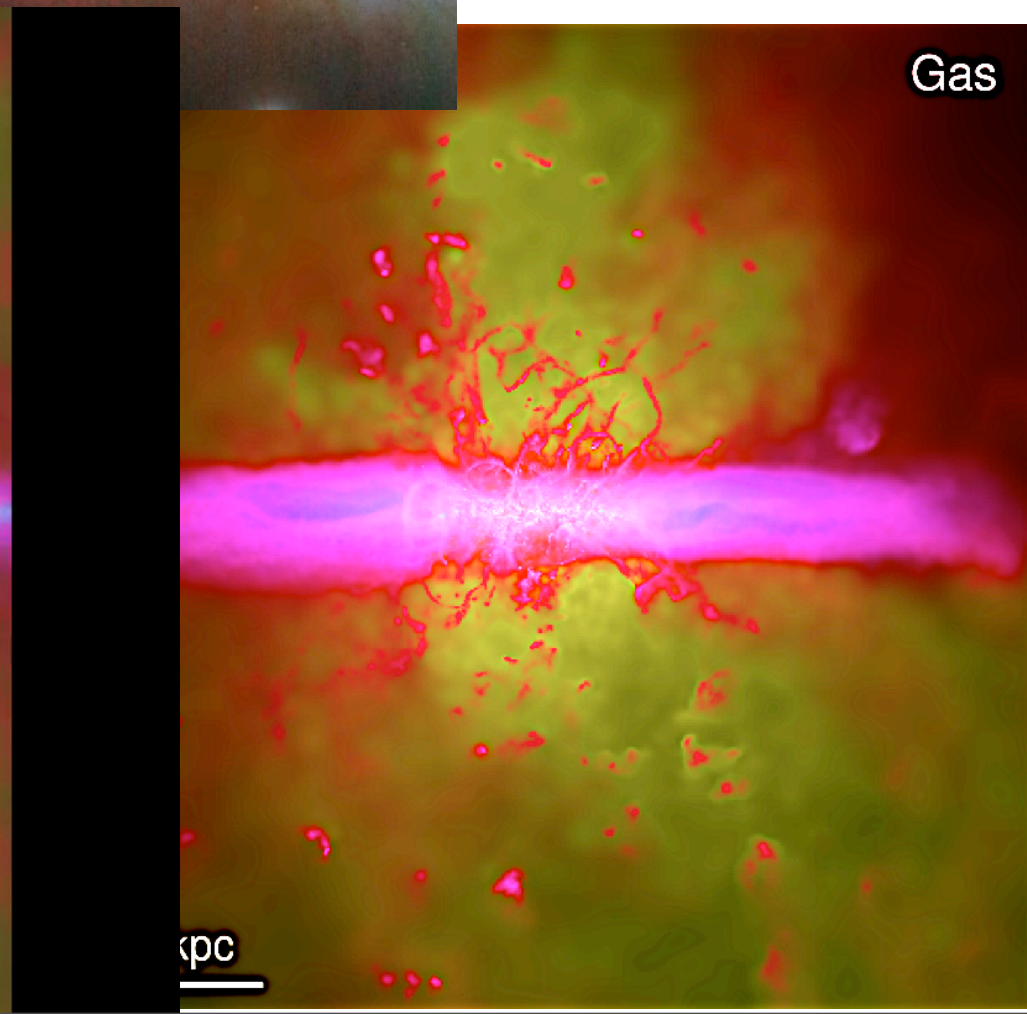
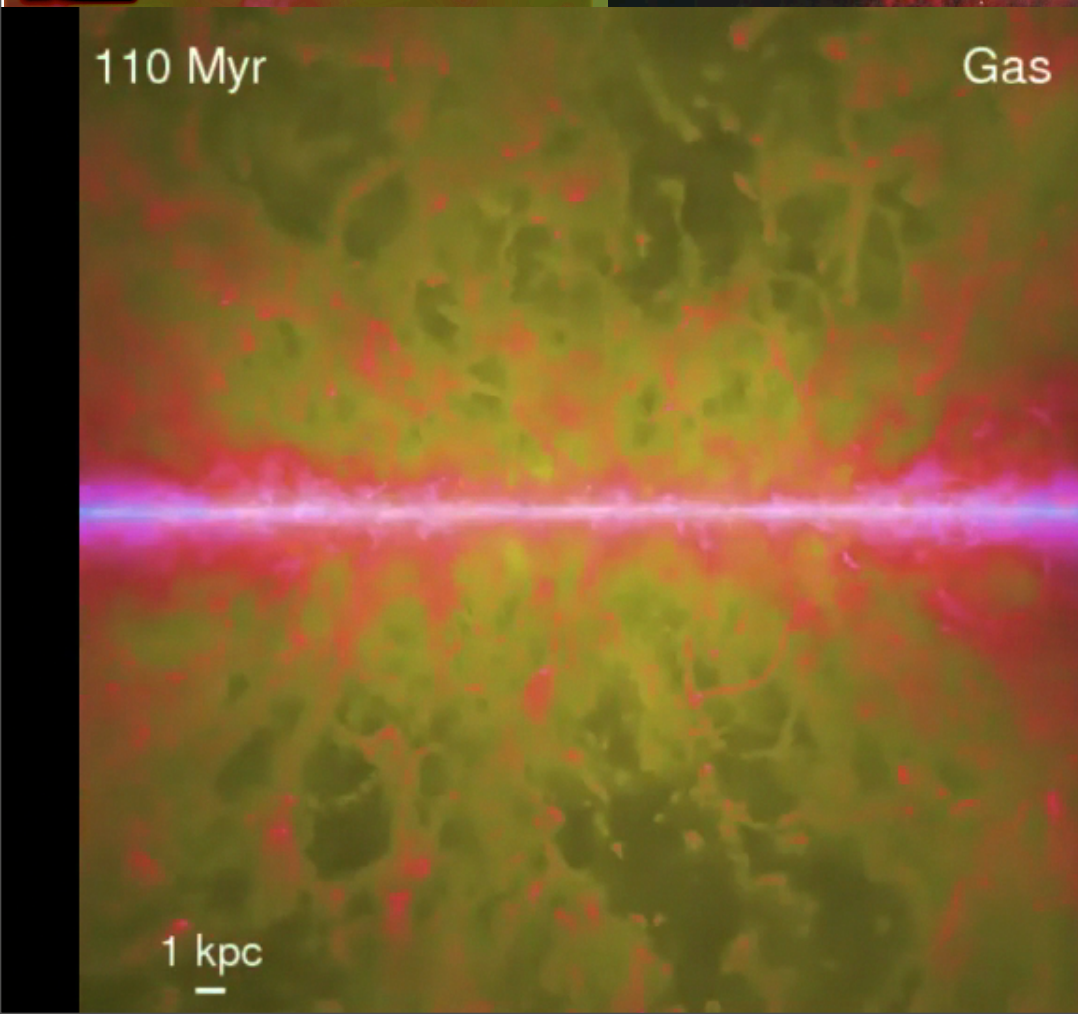
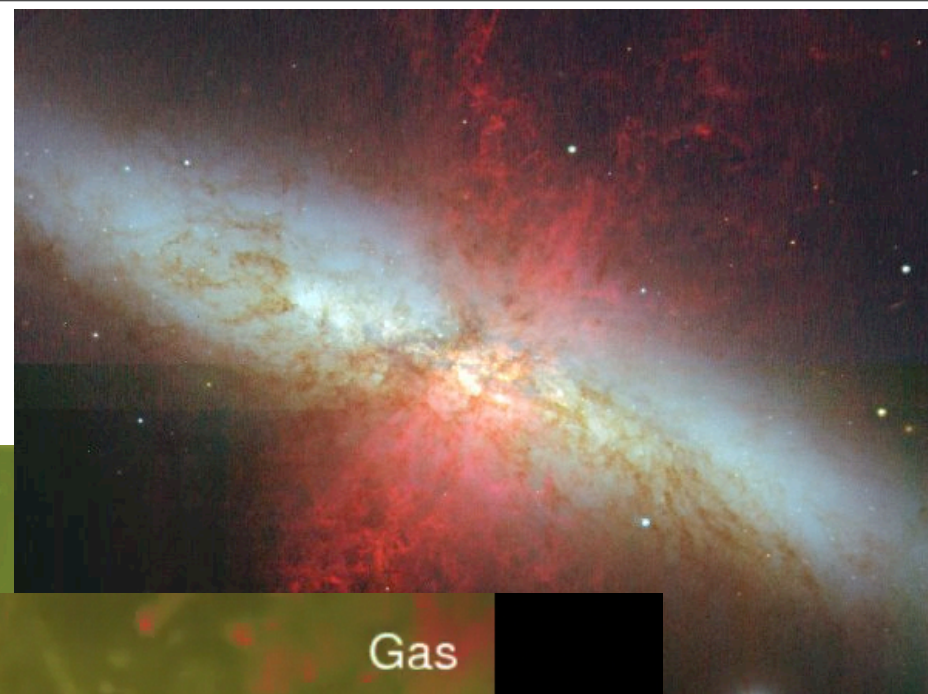
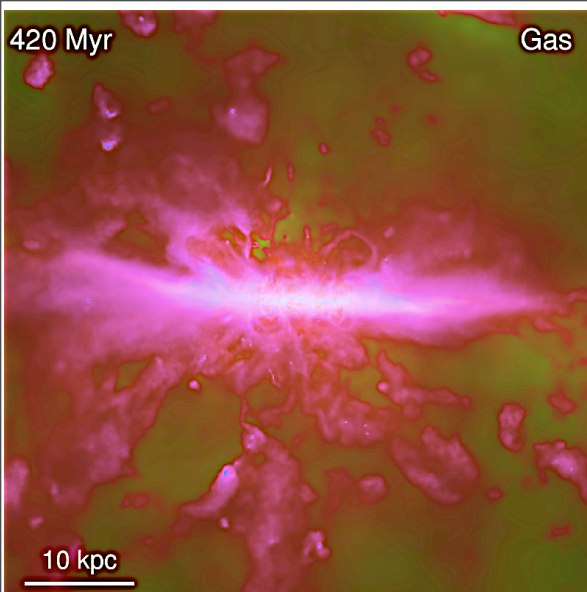
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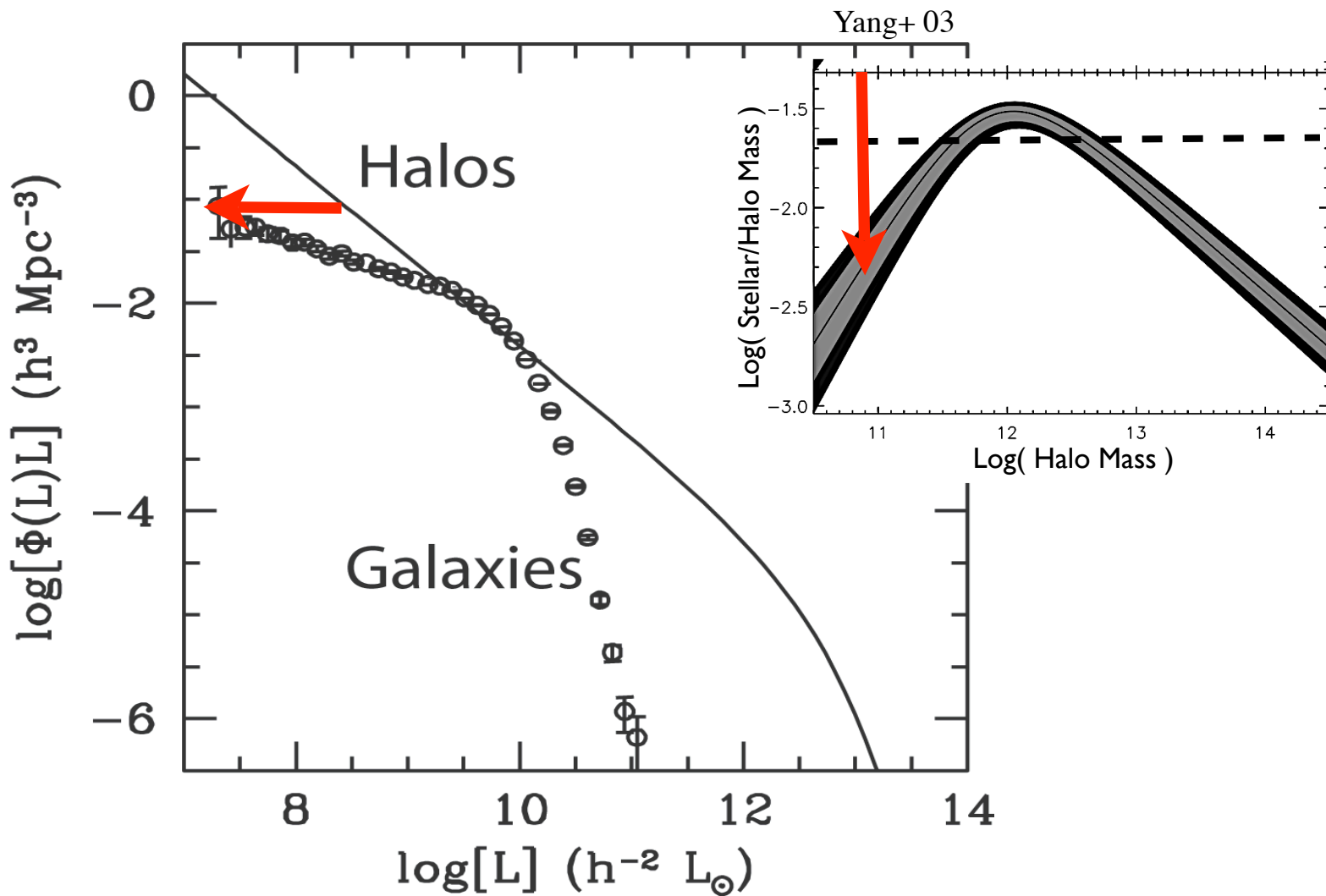


- Just need *some* cooling channel: changes at  $M_{\text{gal}} < 10^6 M_{\text{sun}}$ ,  $Z < 0.01 Z_{\text{sun}}$

# Galactic Super-Winds



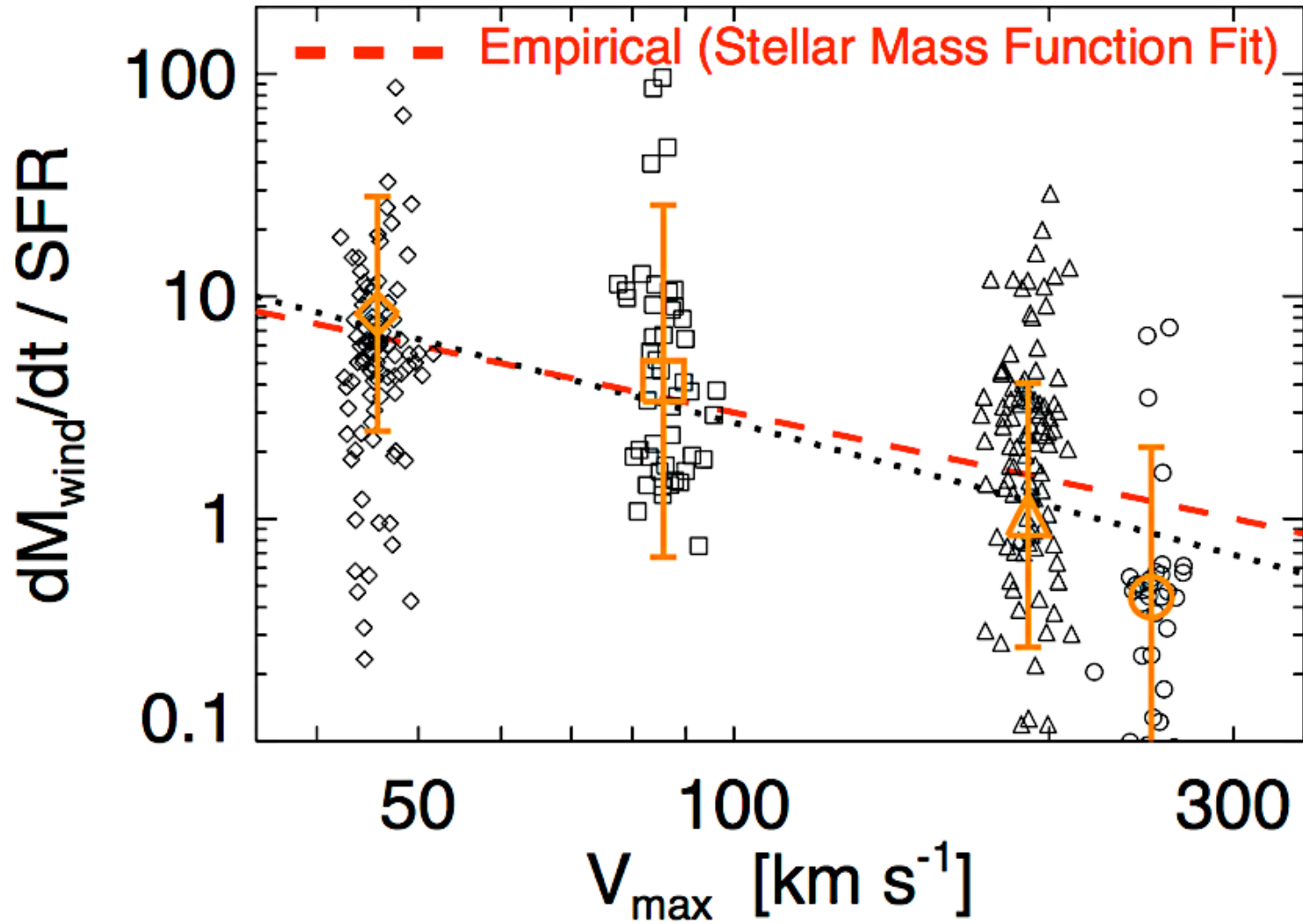
# How Efficient Are Galactic Super-Winds?



➤ Large mass-loading:

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

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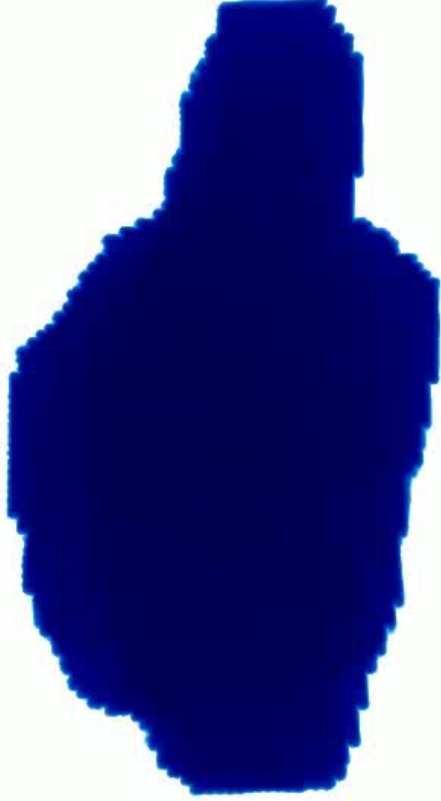
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# The Cosmological Inflow/Outflow Cycle

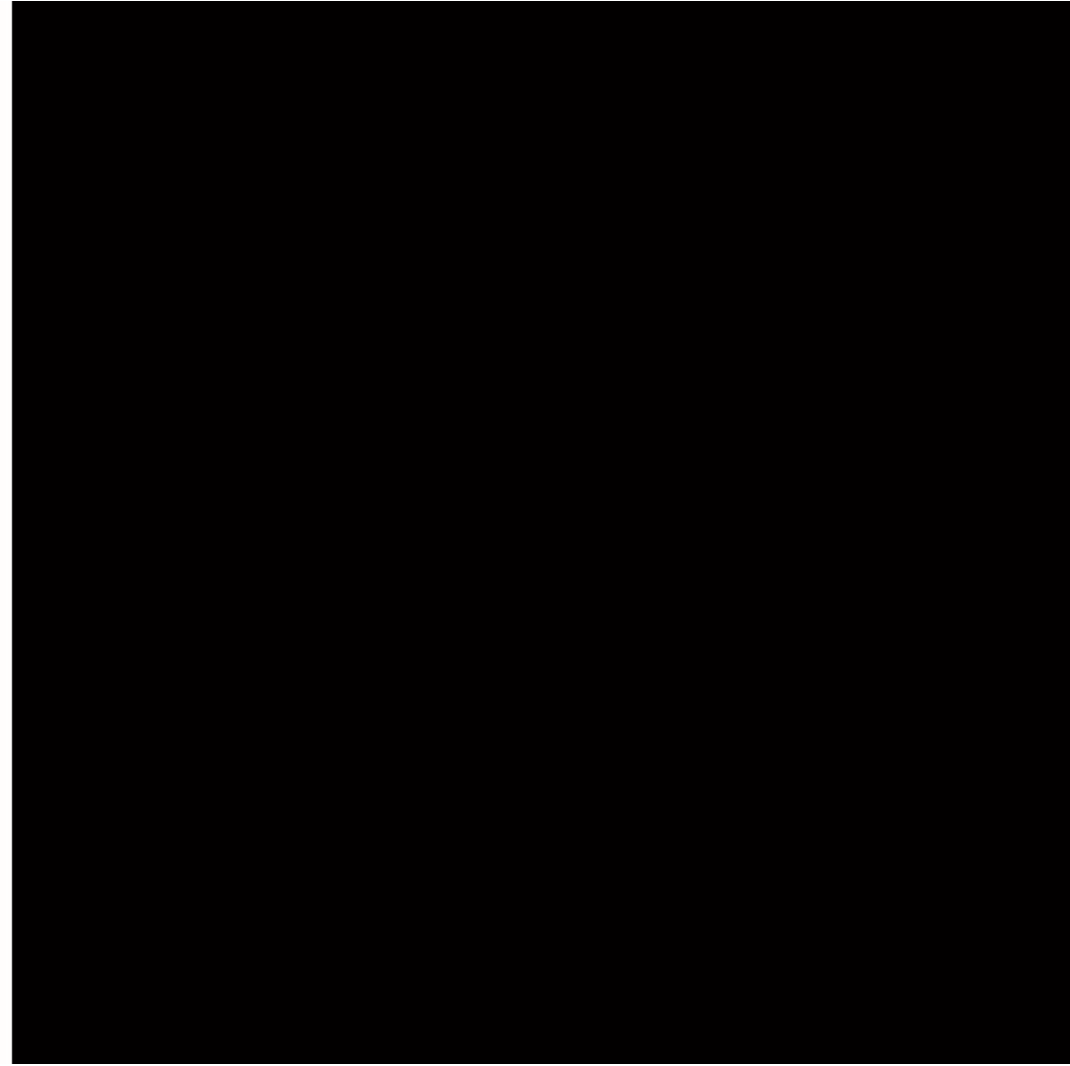
# Cosmological Simulations

## “ZOOM-IN” ON THE FORMATION OF A MASSIVE GALAXY

$z=29.99$  box= $200/h$  kpc(phys)



IGM Density

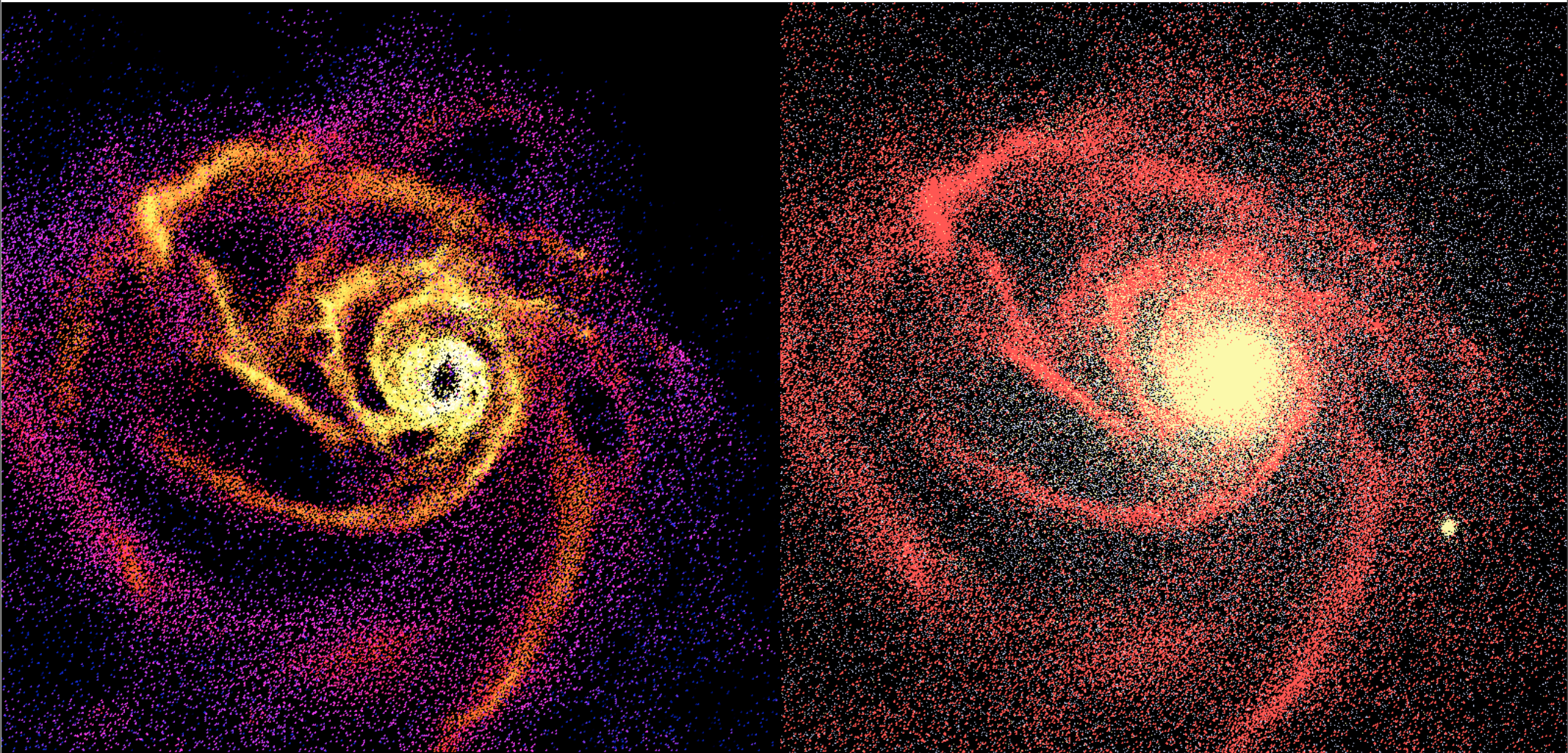


IGM Temperature



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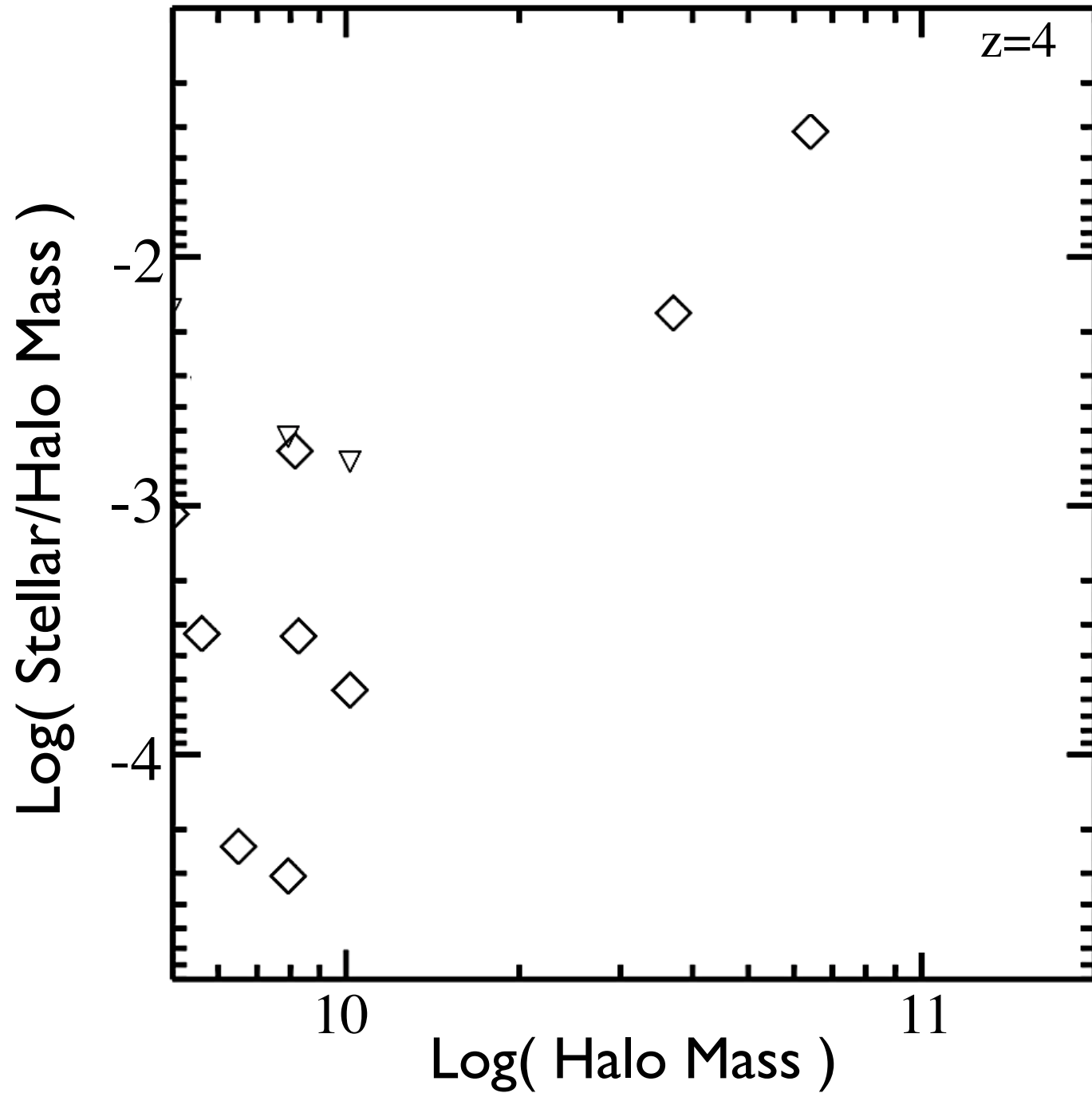


Gas Density

Stars

# How Inefficient is Galaxy Formation?

HELP WITH THE \*FORMING-TOO-MANY-STARS-AT-HIGH-REDSHIFT-CATASTROPHE\*?

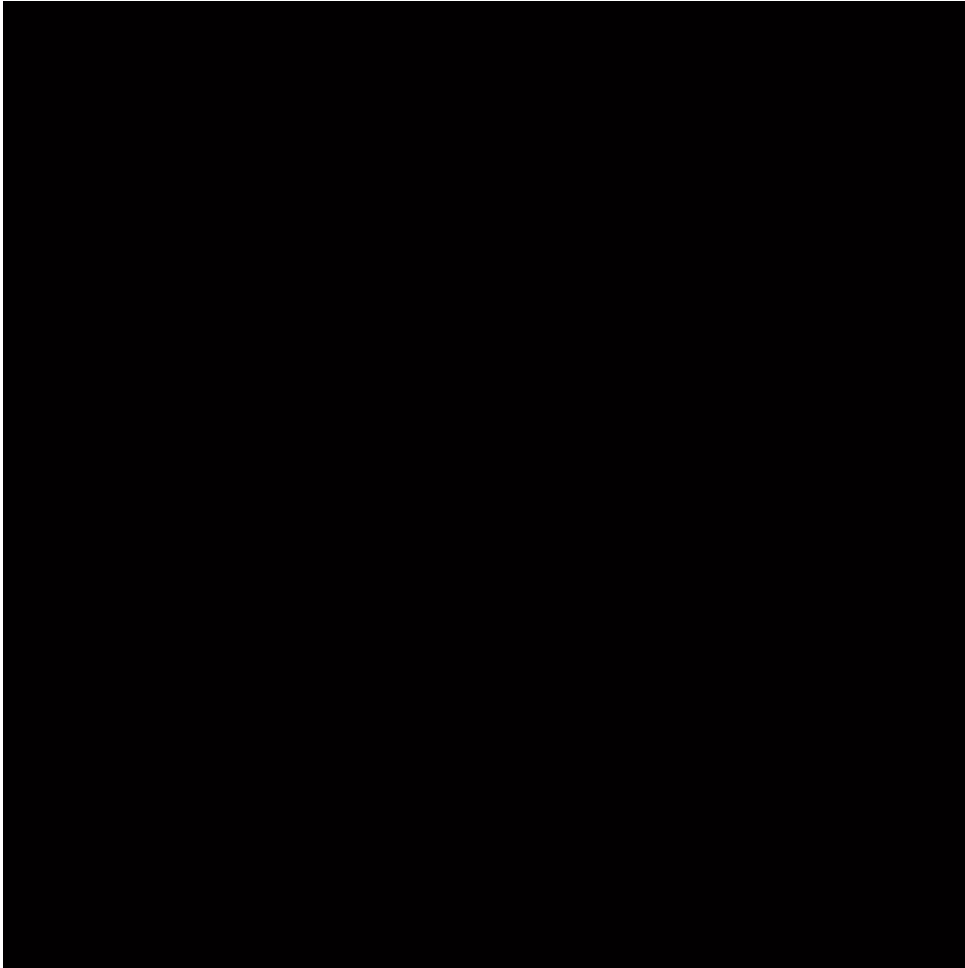


Keres & PFH et al.  
Bullock,  
& Onorbe et al.

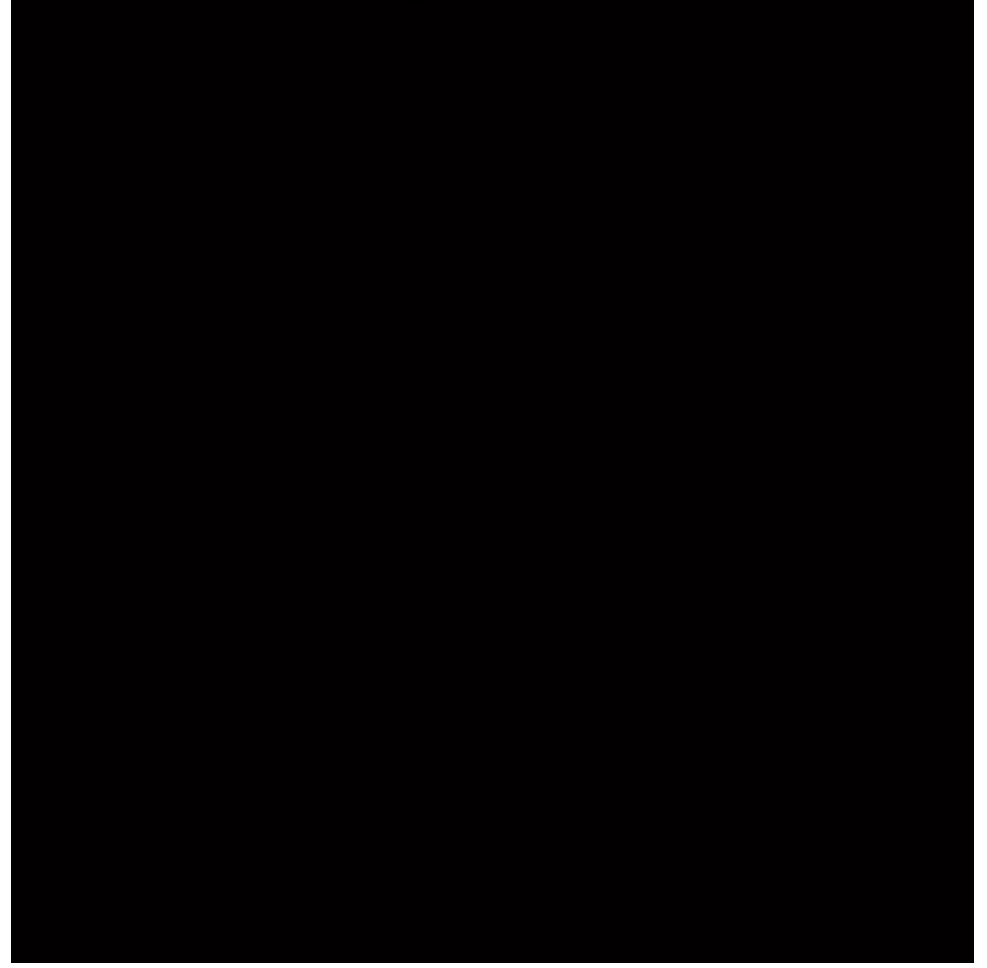


## Proto-MW: Gas Temperature:

No Feedback

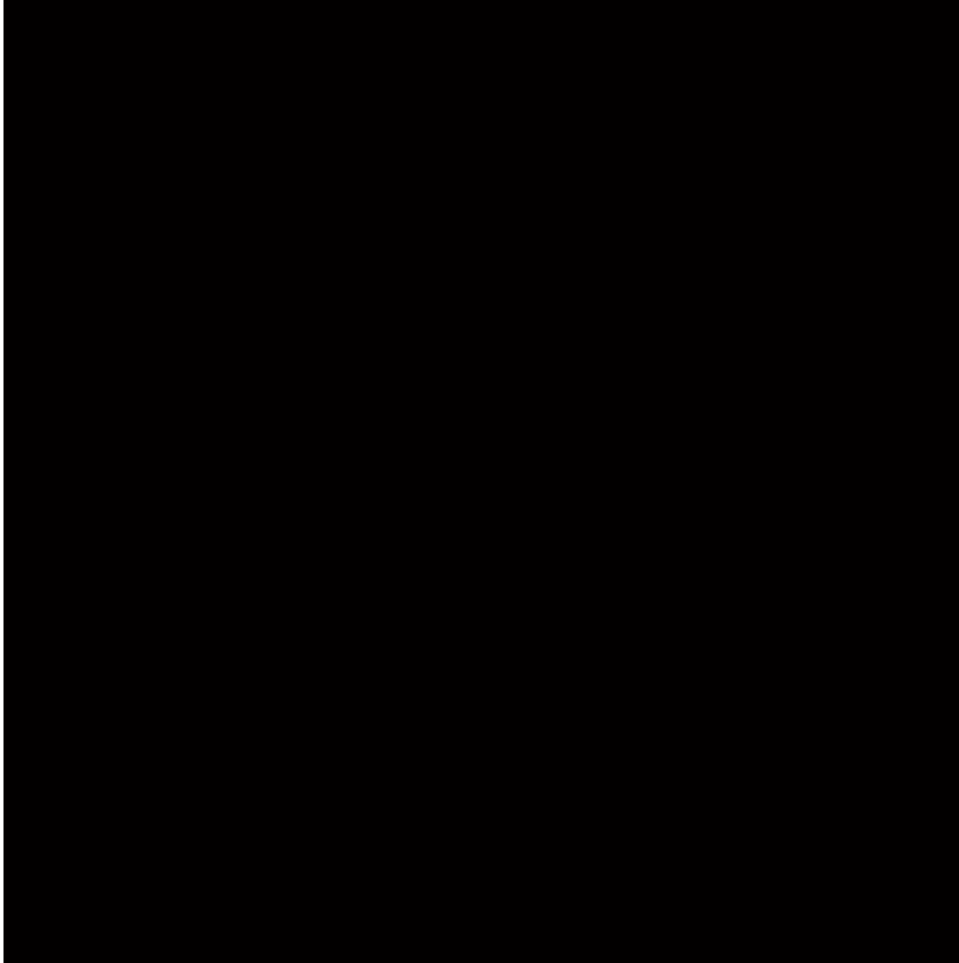


Following Full Feedback

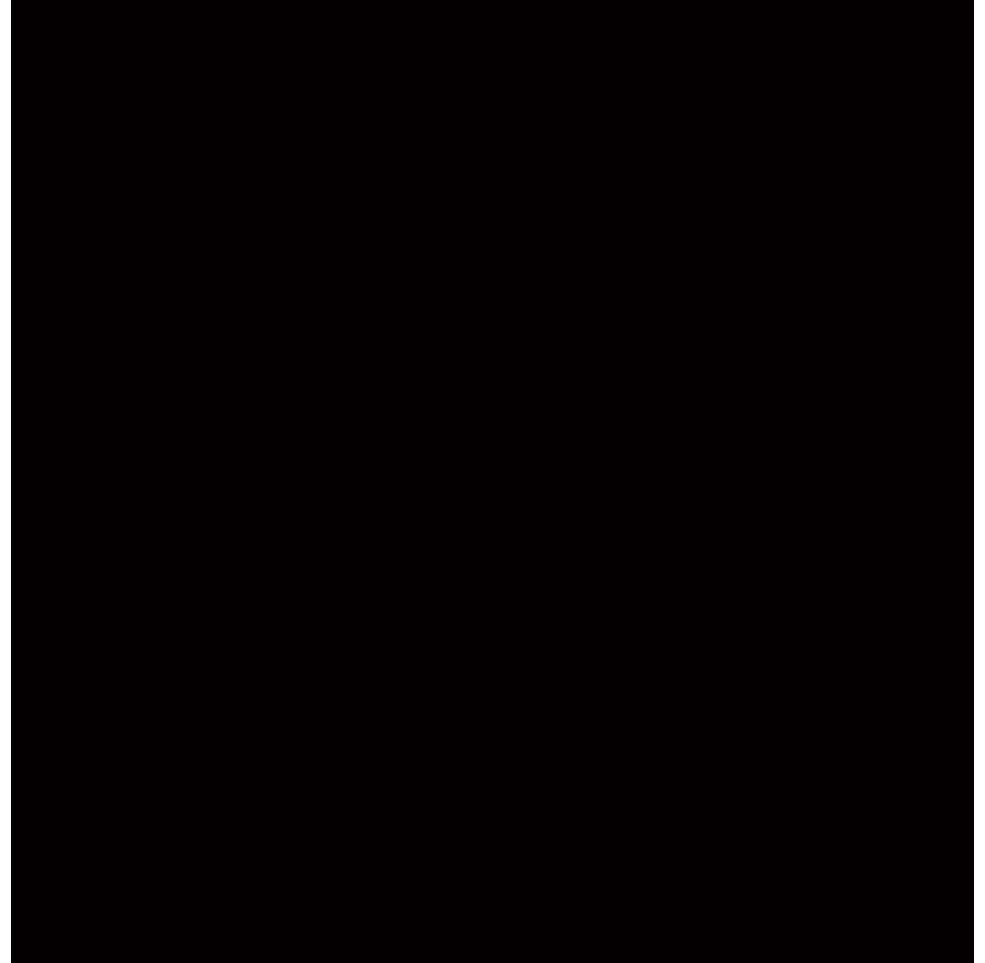


## Proto-MW: Gas Temperature:

Insert Winds “By Hand” (Sub-Grid)

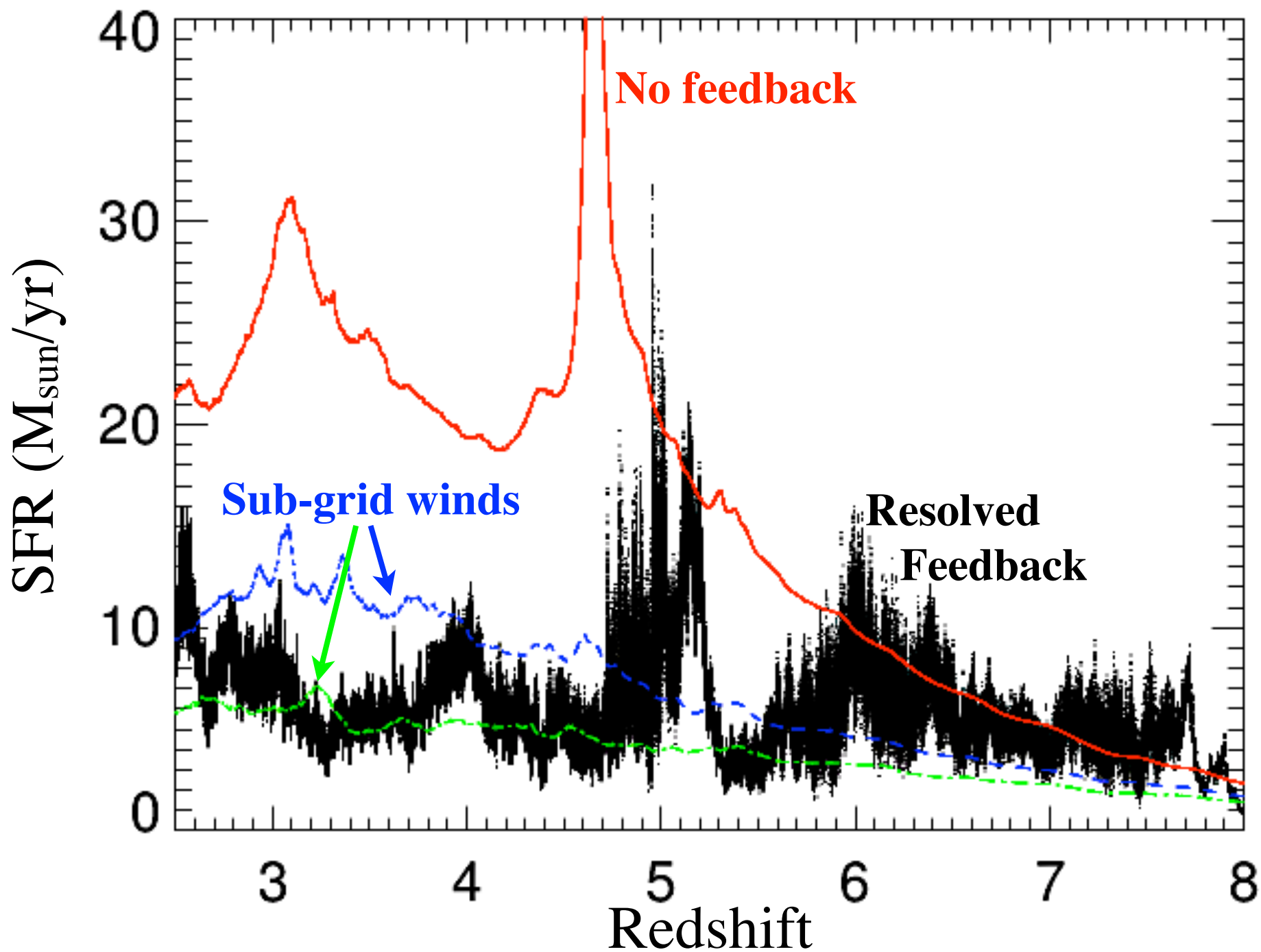


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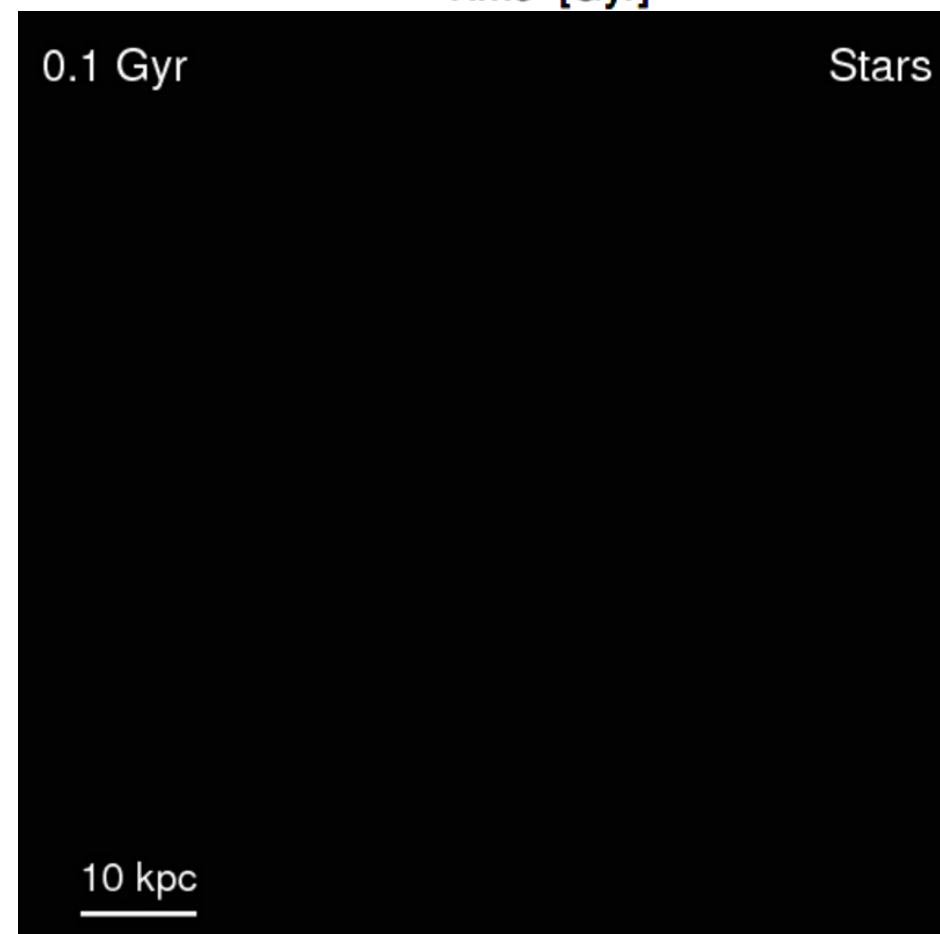
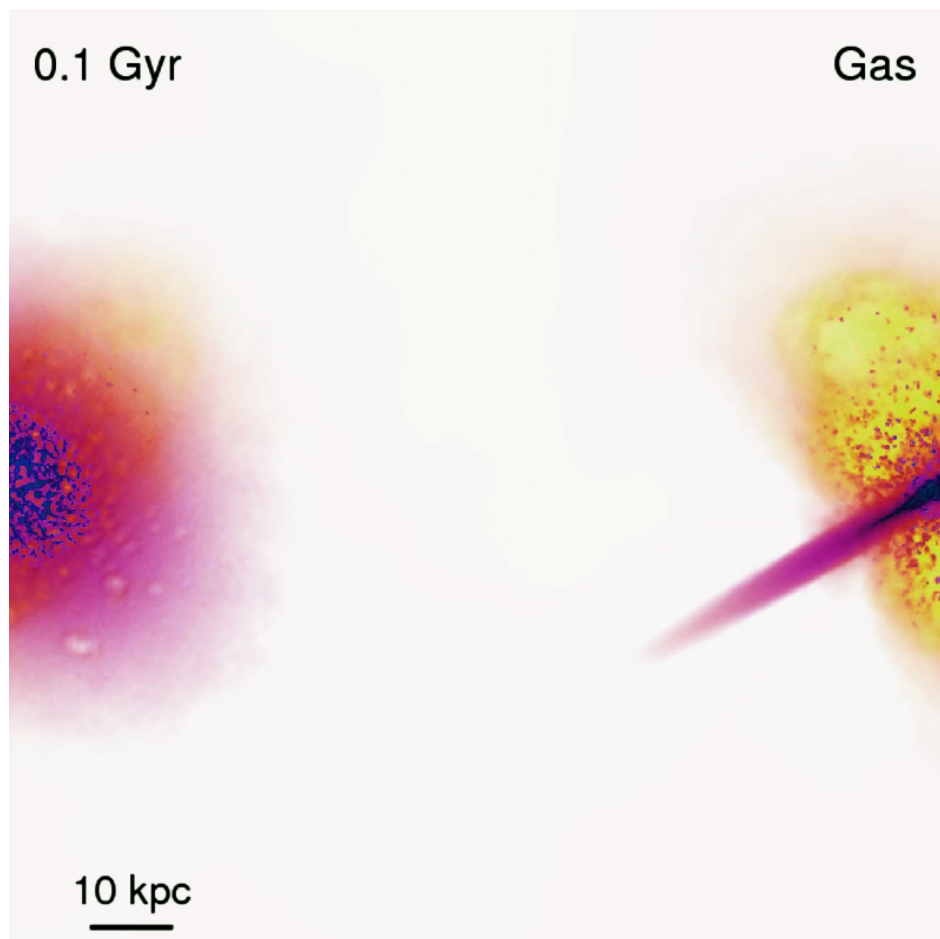
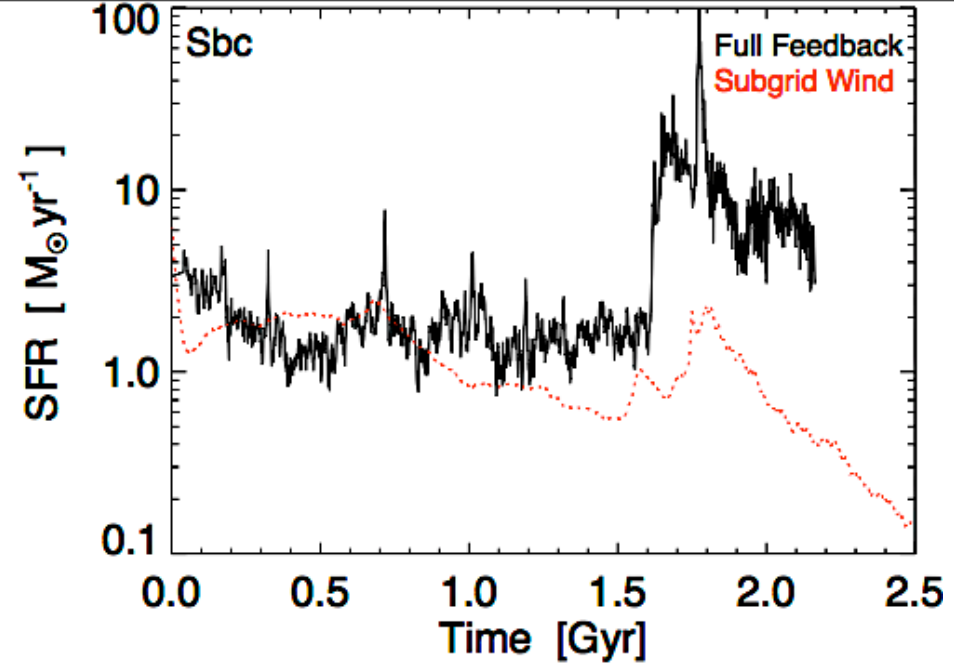
# Starburst-Driven Winds

SUB-GRID vs. RESOLVED MATTERS!



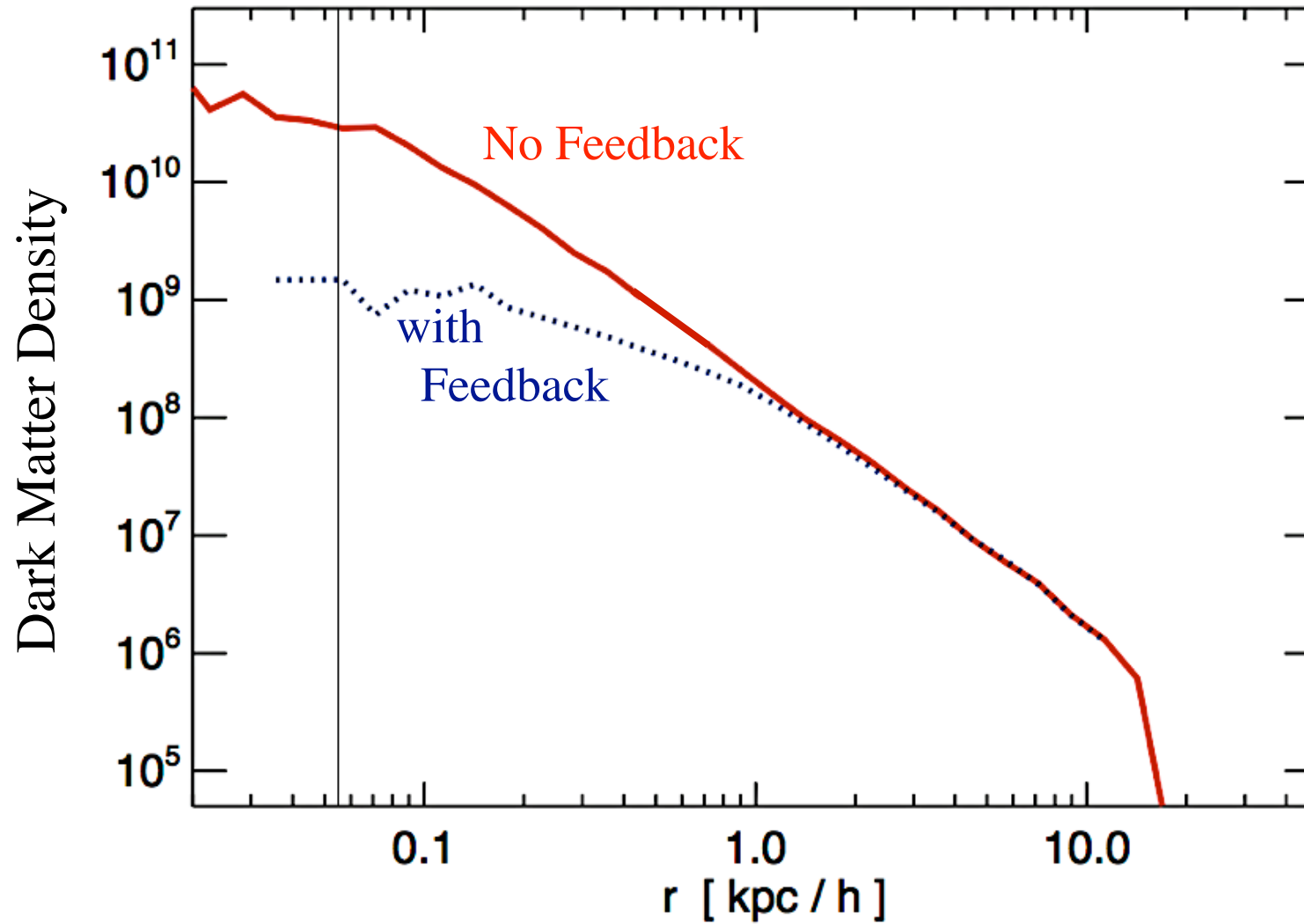
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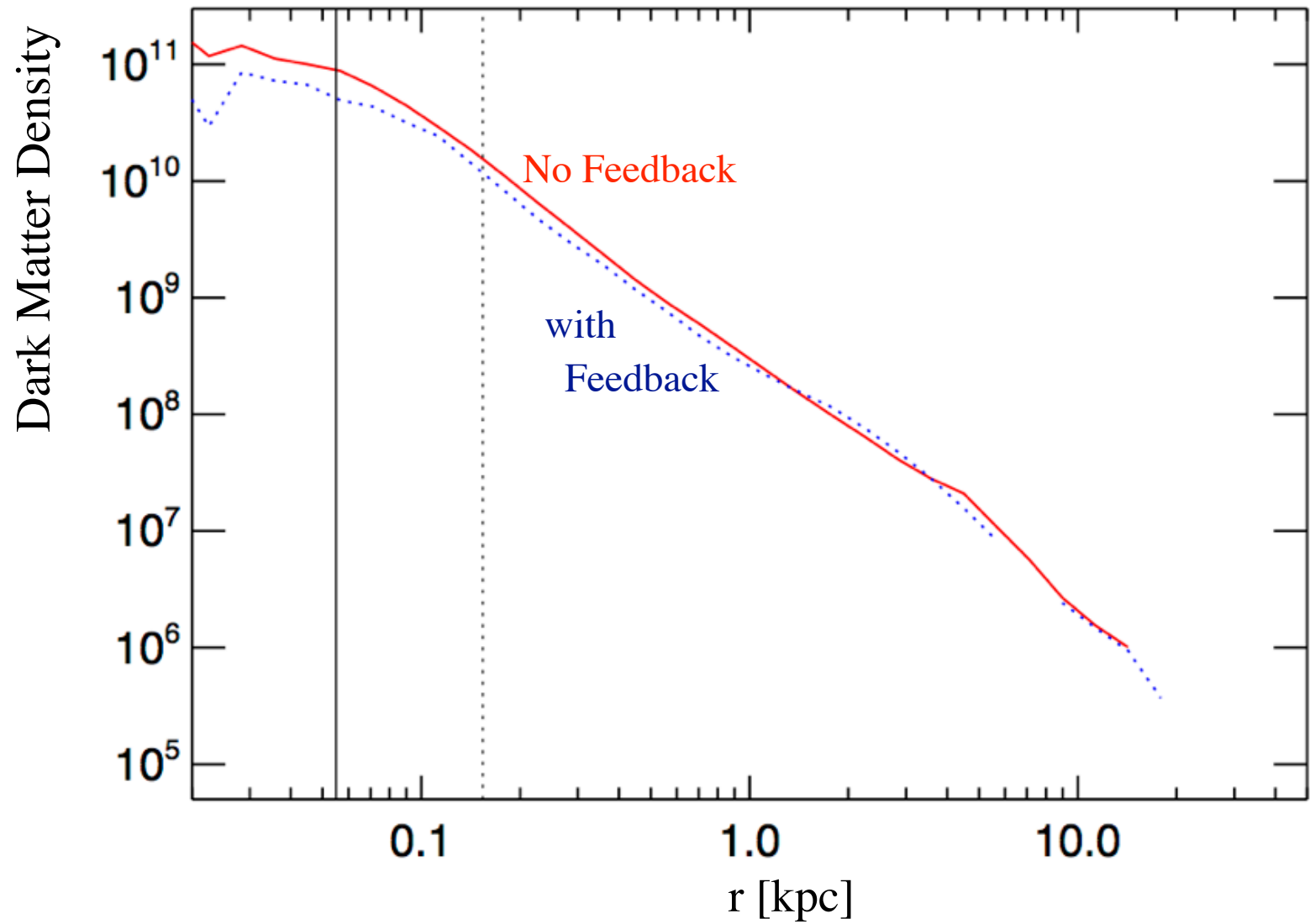
# Dark Matter Profiles: Baryons or Cosmology?

DO RESOLVED WINDS ACTUALLY MAKE CORES?



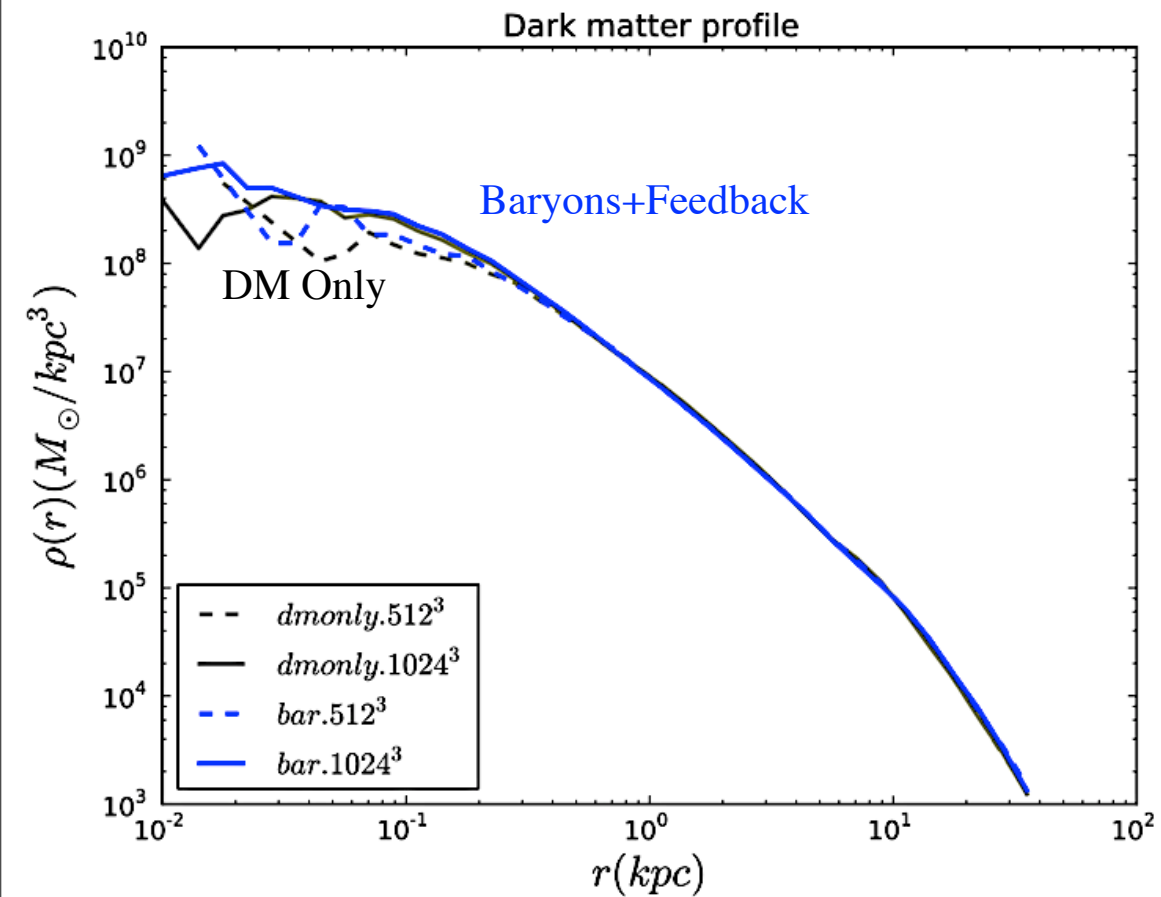
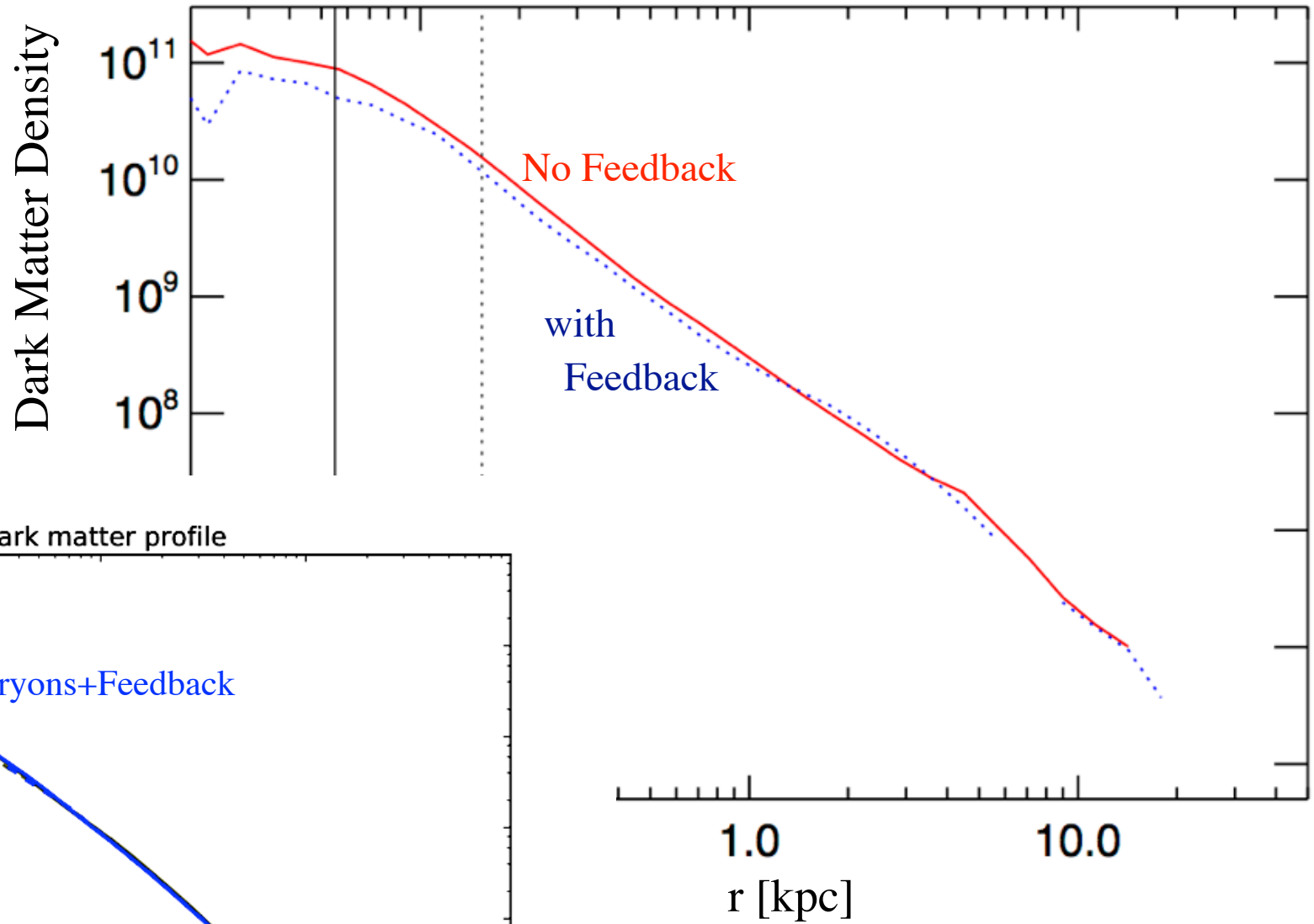
Keres & PFH et al.  
Bullock,  
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BUT...



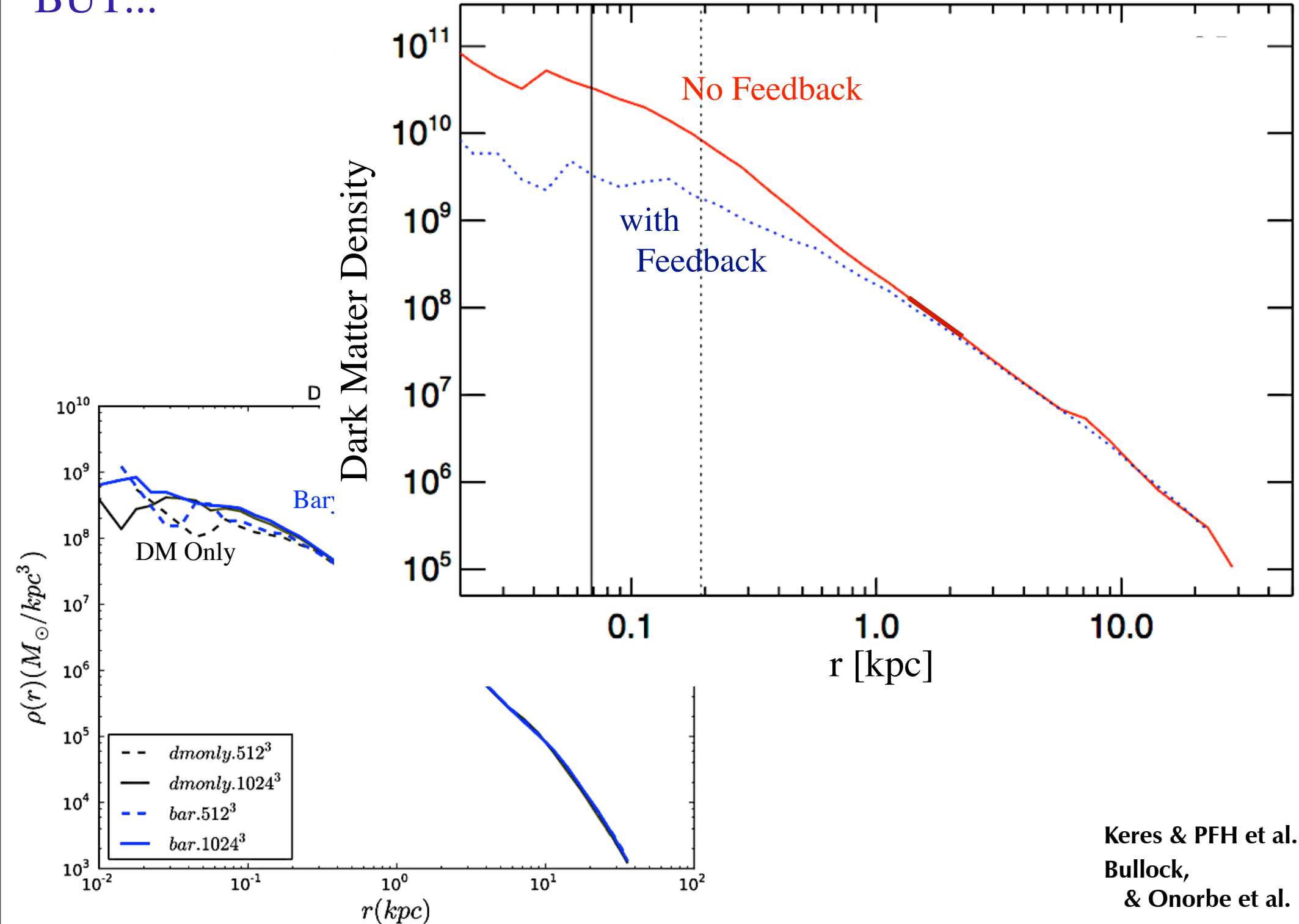
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BUT...





## Summary:

- **Star formation is Feedback-Regulated:** *independent* of small-scale SF ‘law’
  - Need enough stars to offset dissipation (gravity)
  - Leads to Kennicutt relation & **super-winds**
- Different mechanisms dominate different regimes:
  - High- $\rho$ : radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low- $\rho$ : SNe & stellar wind shock-heating
    - **No *one* mechanism works**
- Cosmologically: *Not* just top-down inflows:
  - Winds determine **IGM enrichment, temperature, & subsequent inflow** structure
  - Cores? Be VERY careful!