Feedback: Now With Physics!*

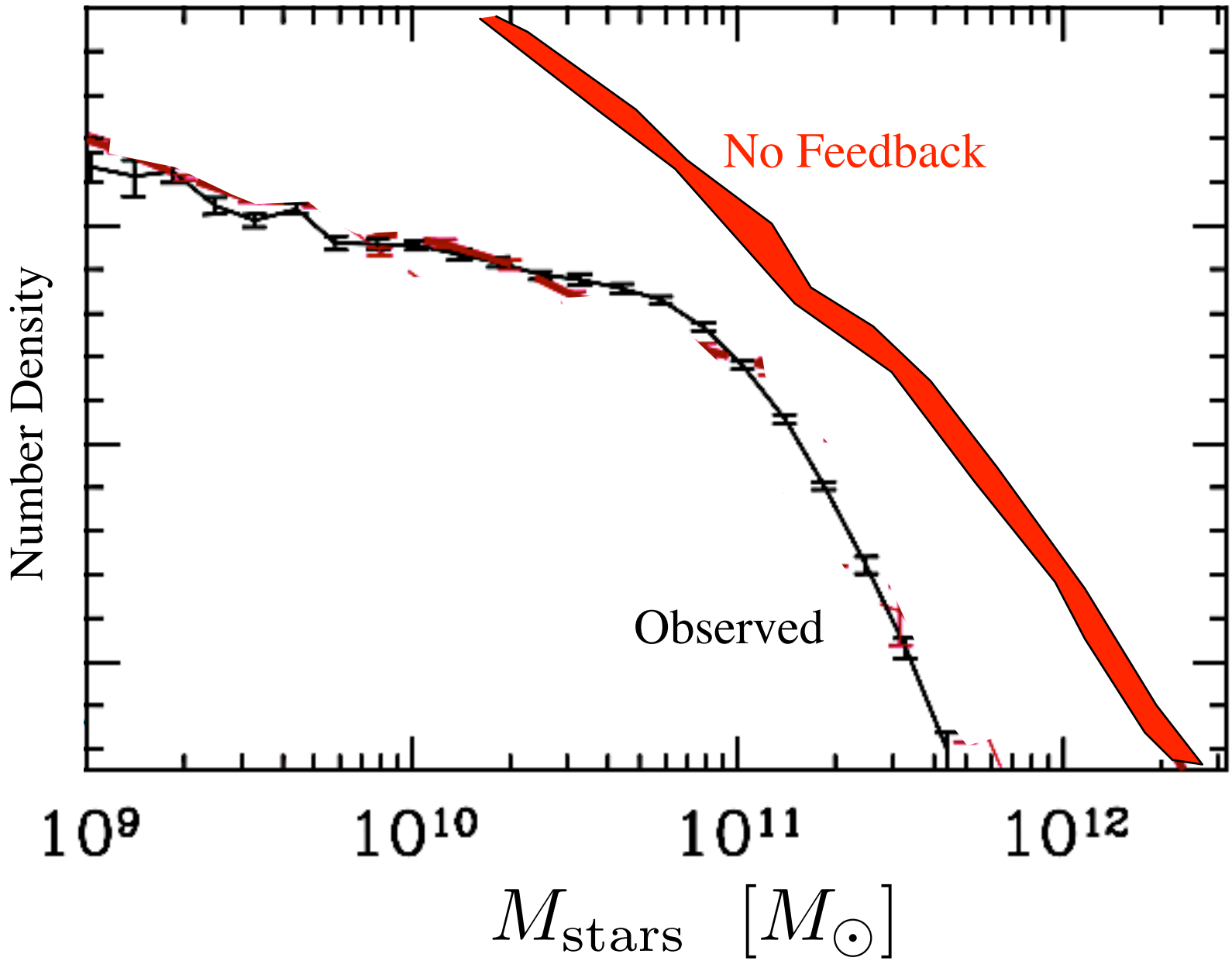
Dusan Keres

Philip Hopkins, Eliot Quataert, Norm Murray, Jose Onorbe

* *Real* physics not necessarily included

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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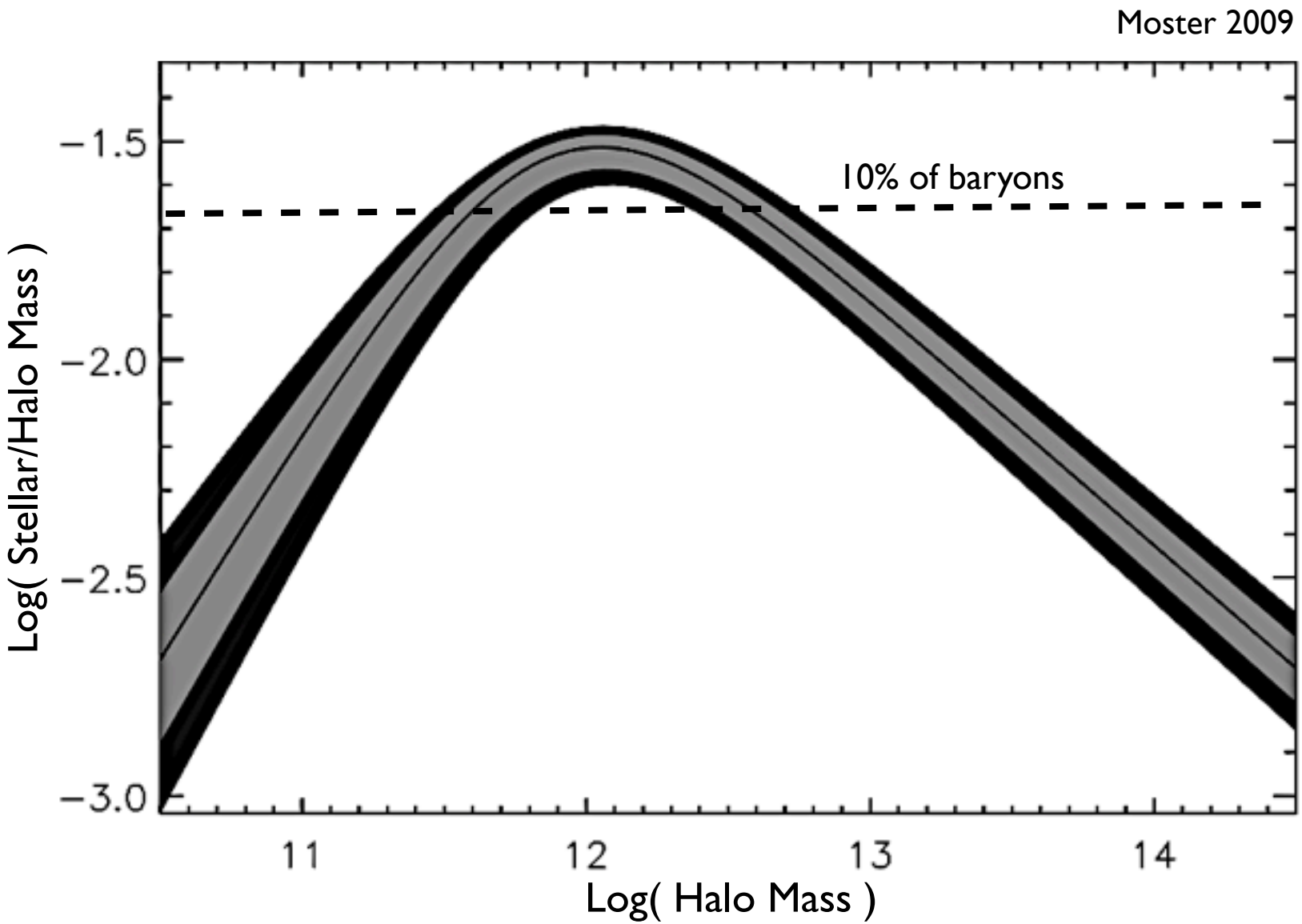

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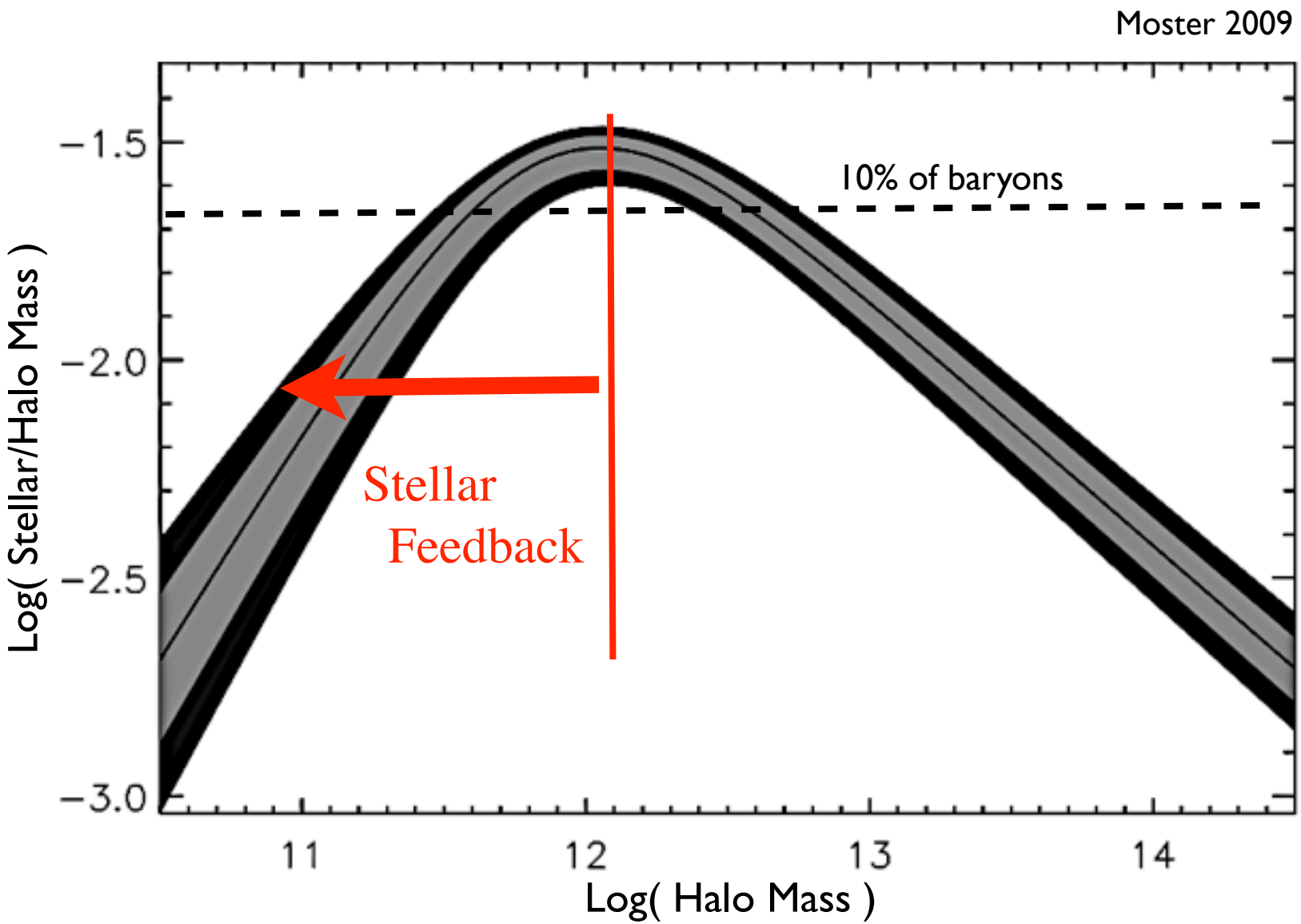

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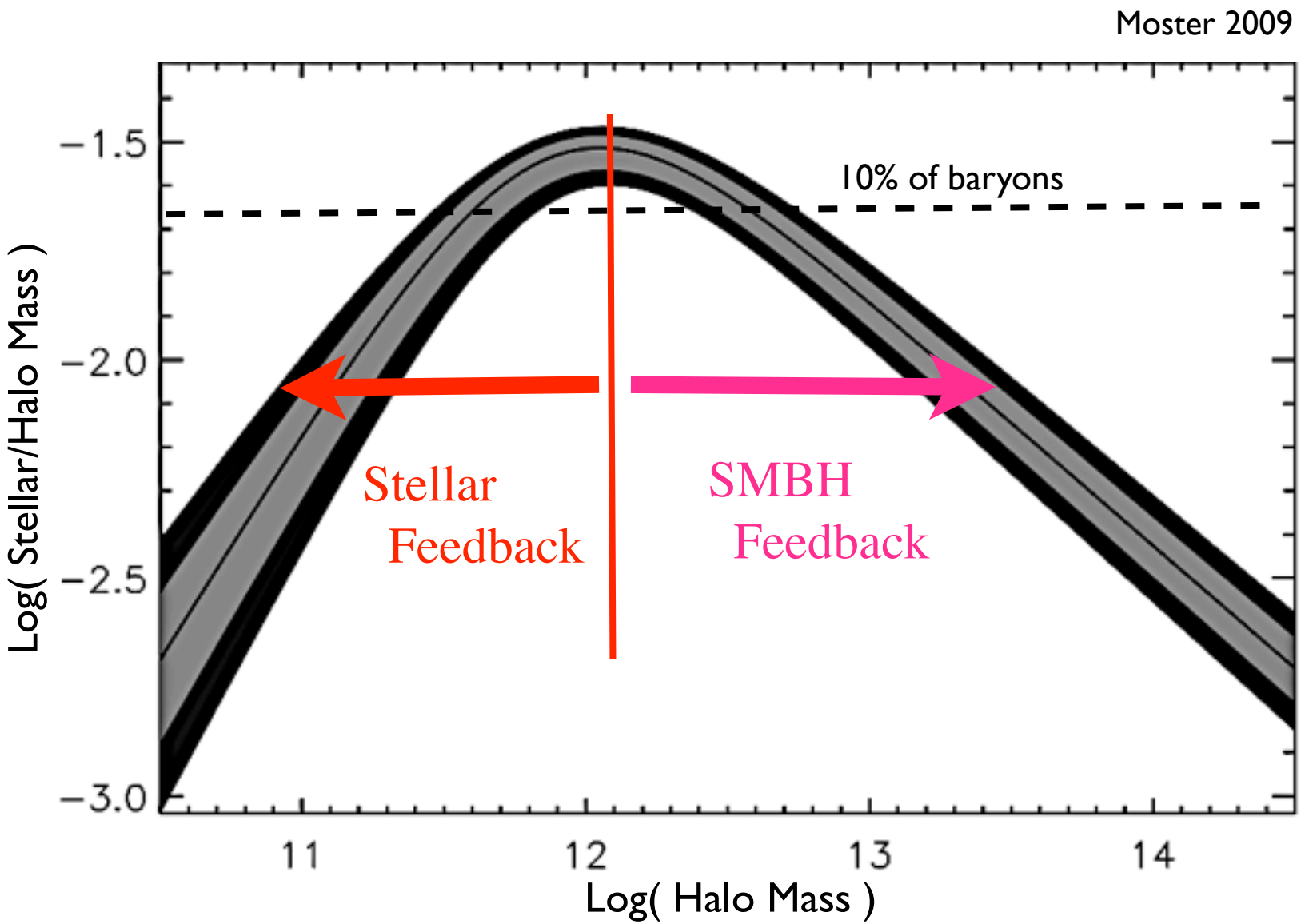


Stellar Feedback is the Key!

SO WHAT'S THE PROBLEM?

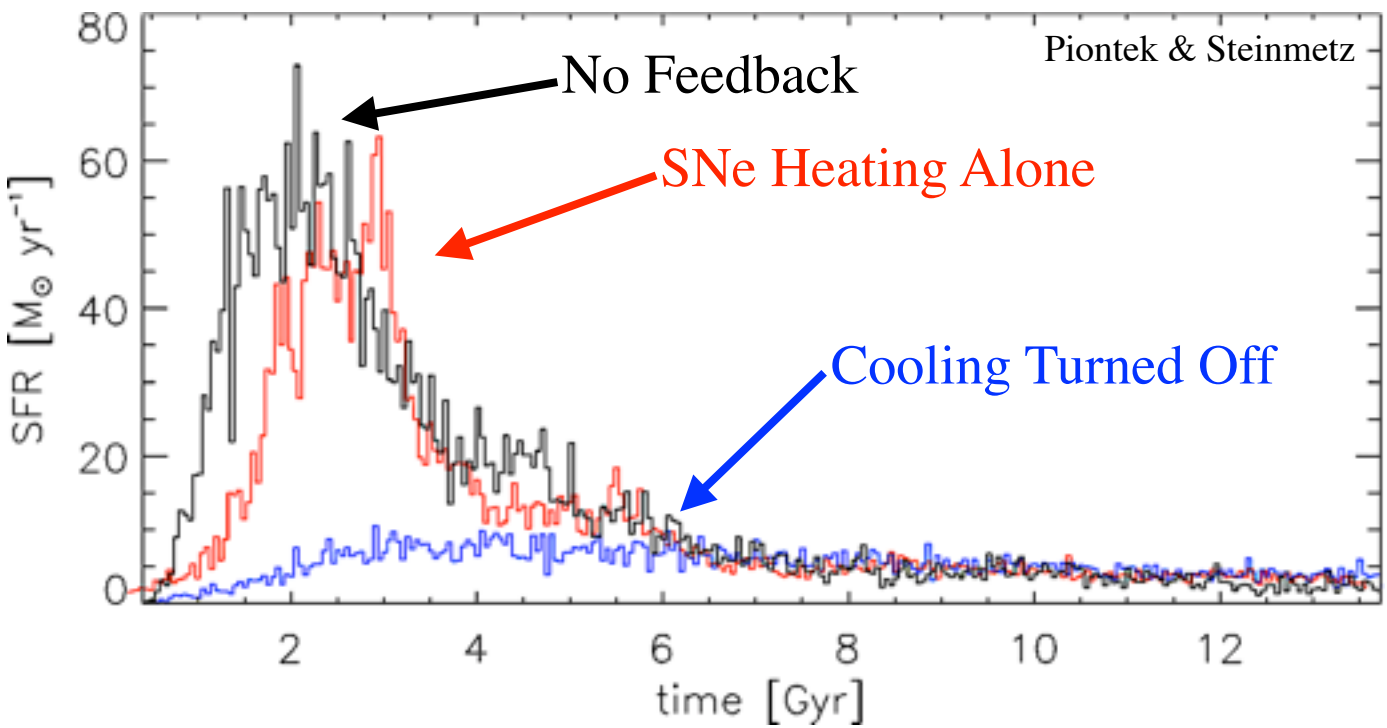
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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)



Stellar Feedback: Understanding the key Physics

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- "Energy Injection":
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  - Photoionization (HII) + Photoelectric

- *Explicit* Momentum Flux:
  - Radiation Pressure

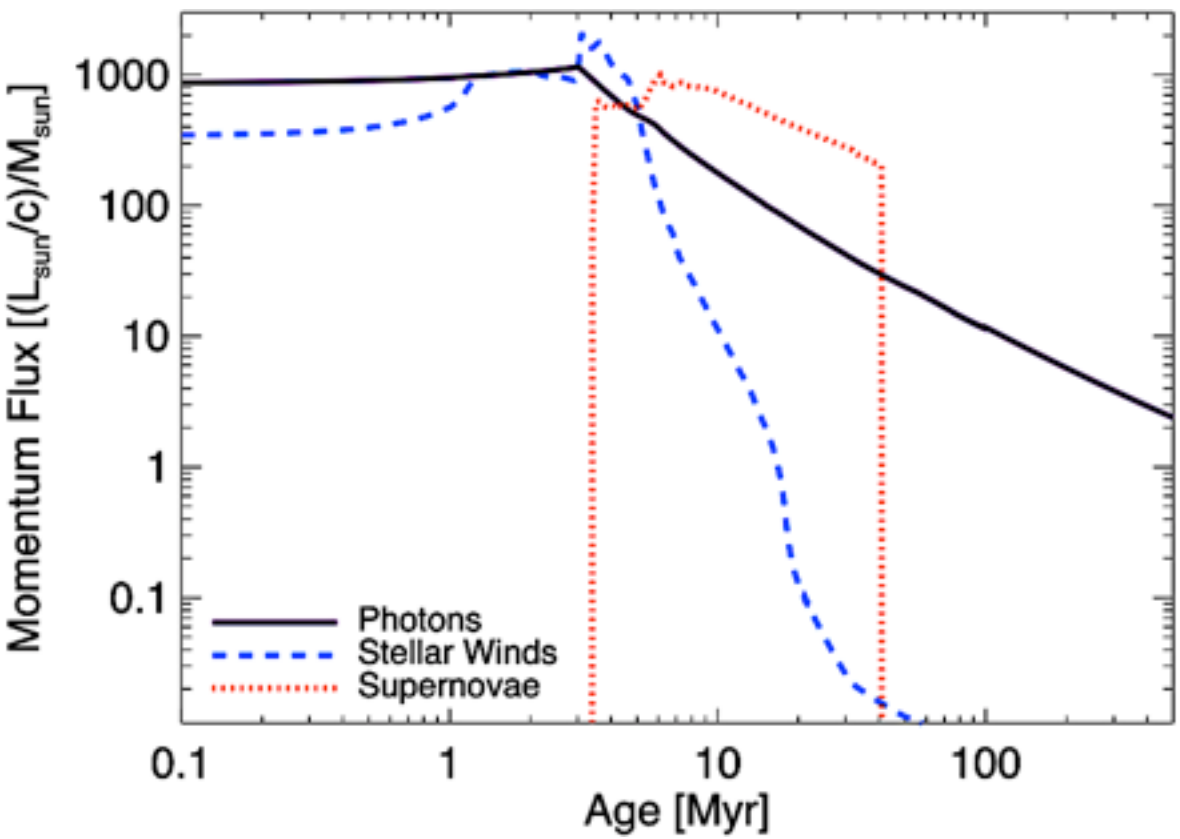
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

  - SNe

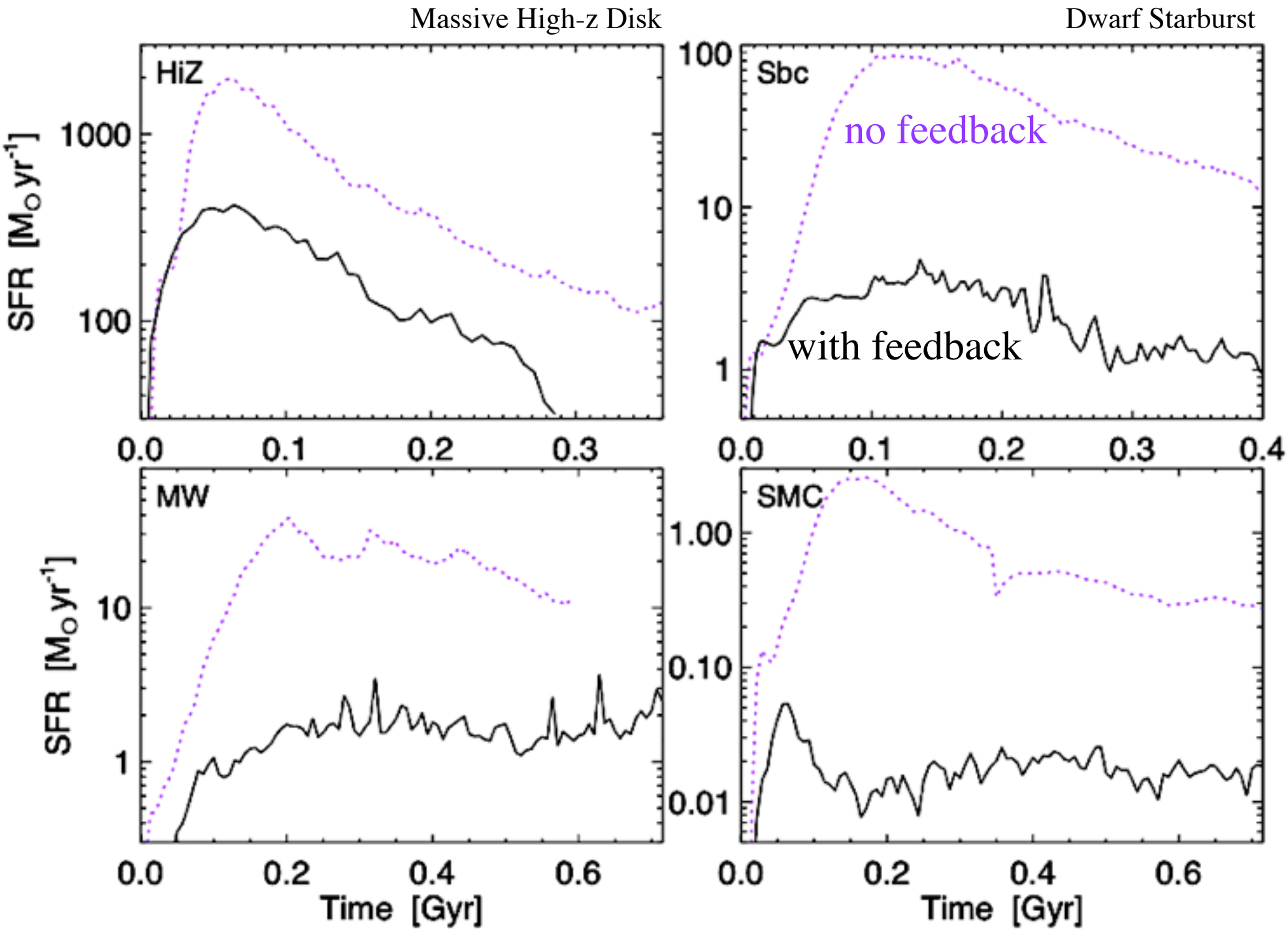
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

  - Stellar Winds

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



Stellar Feedback gives Self-Regulated Star Formation



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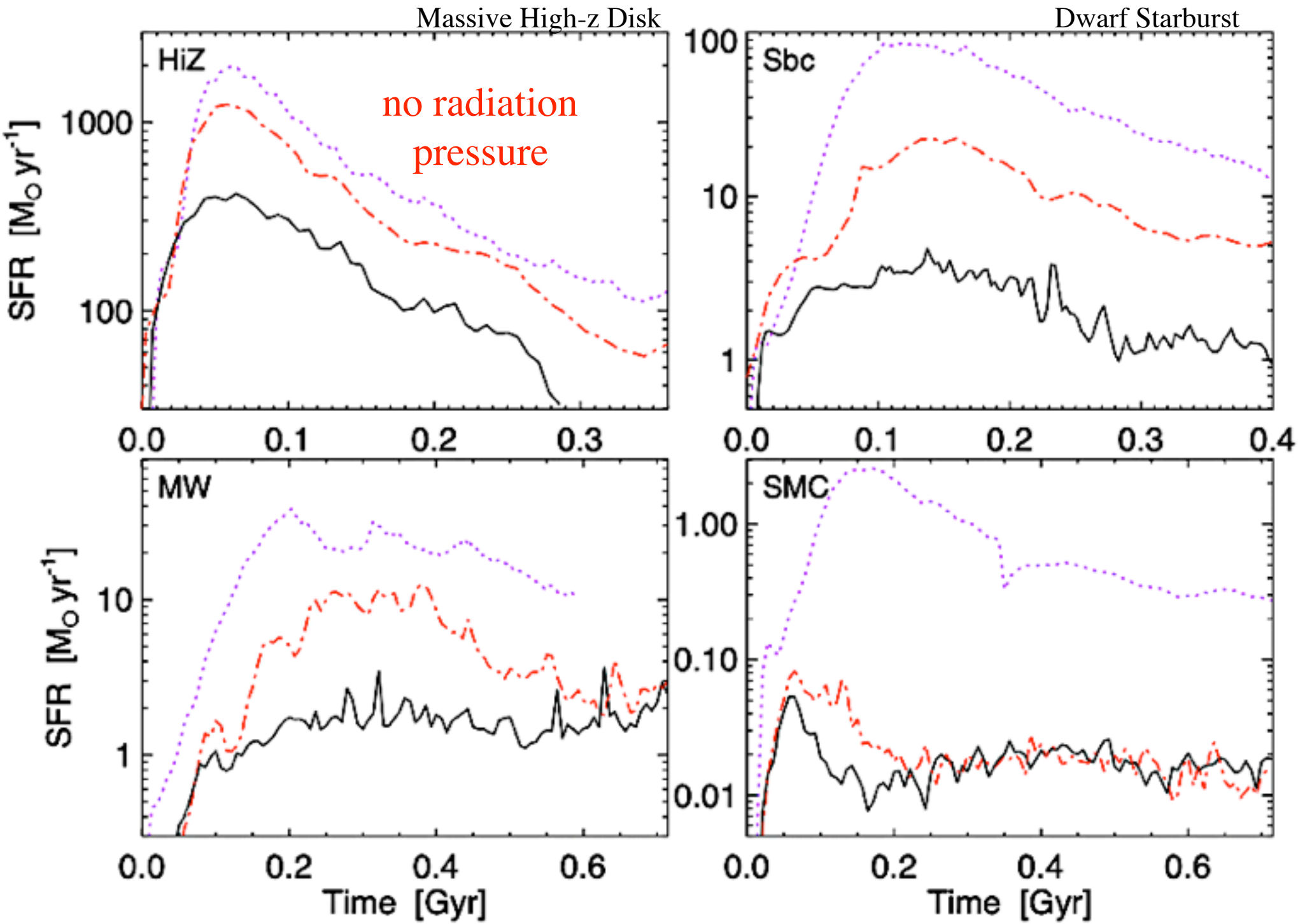

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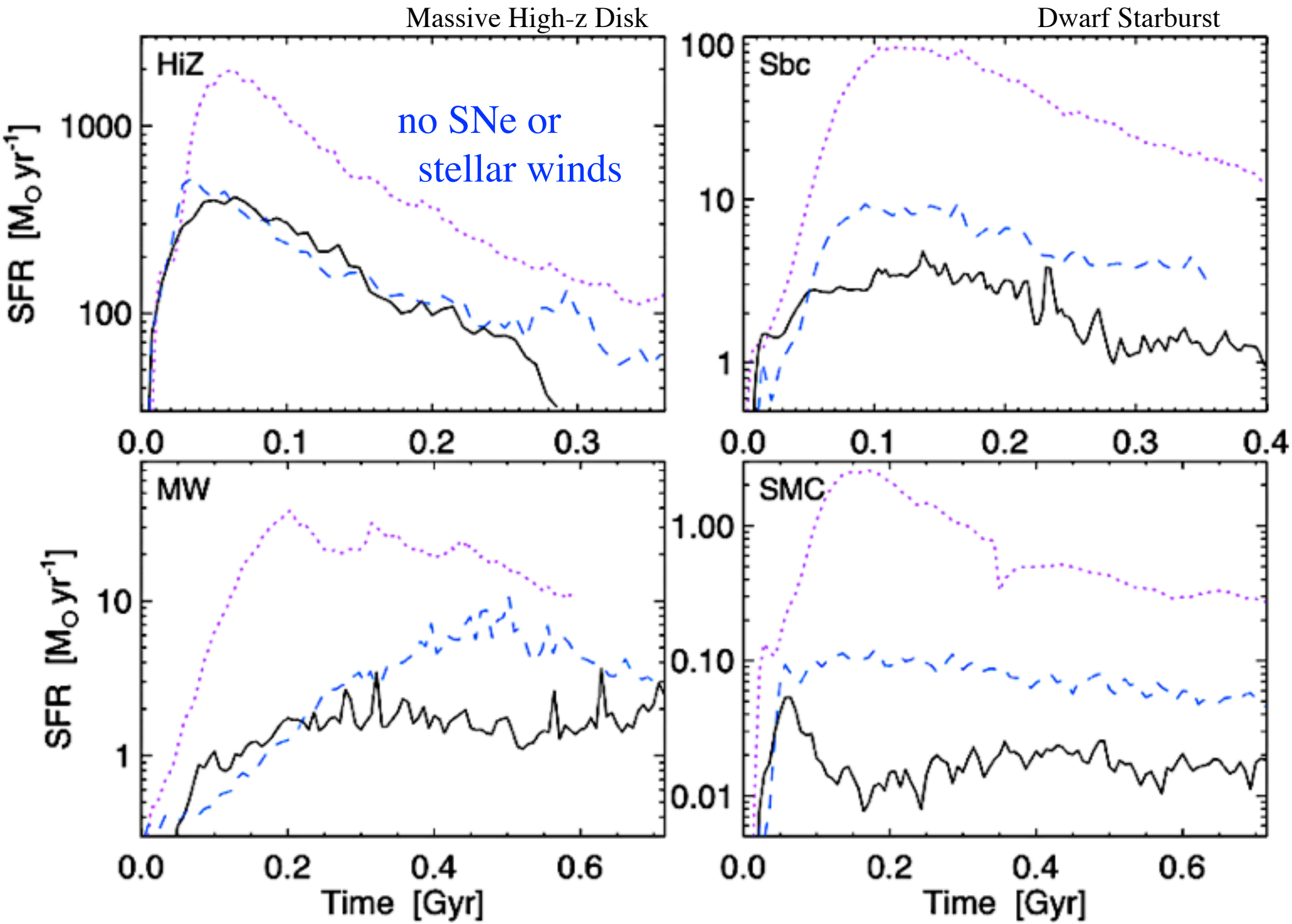
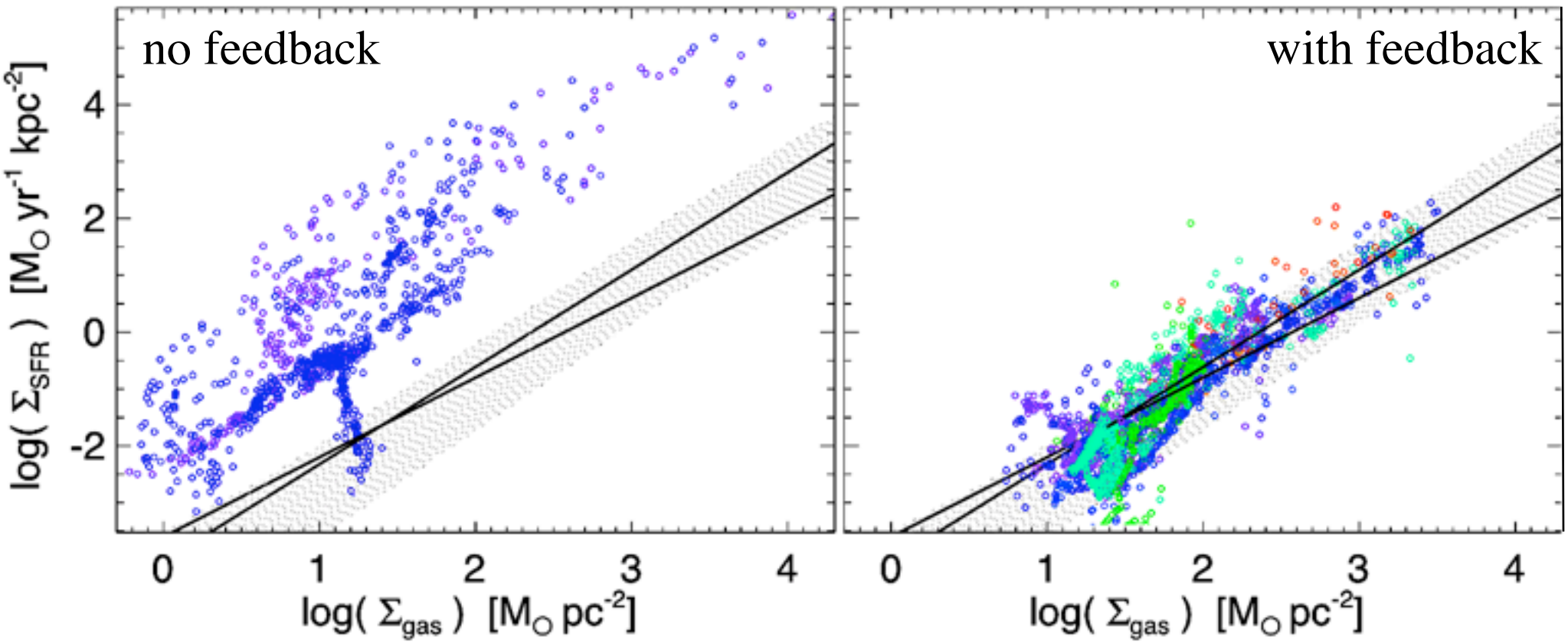


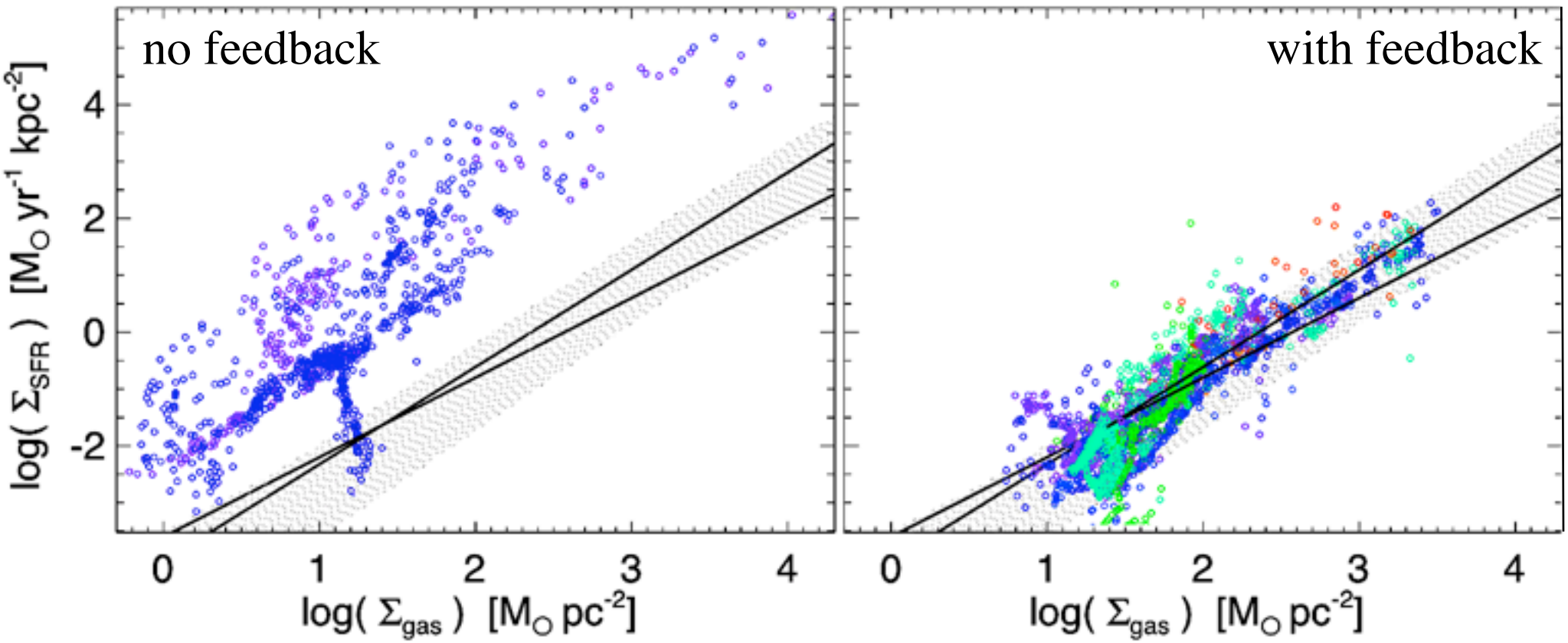
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally

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



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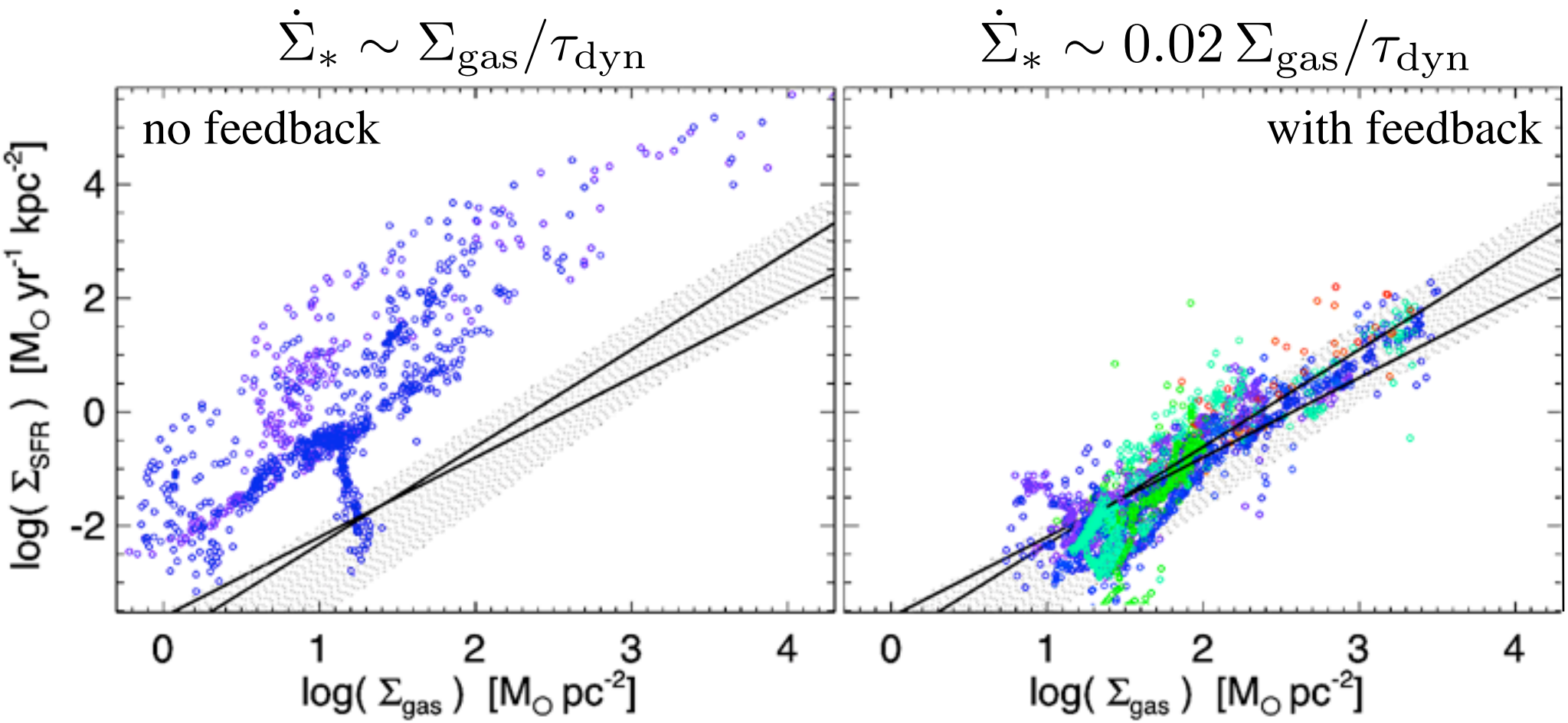

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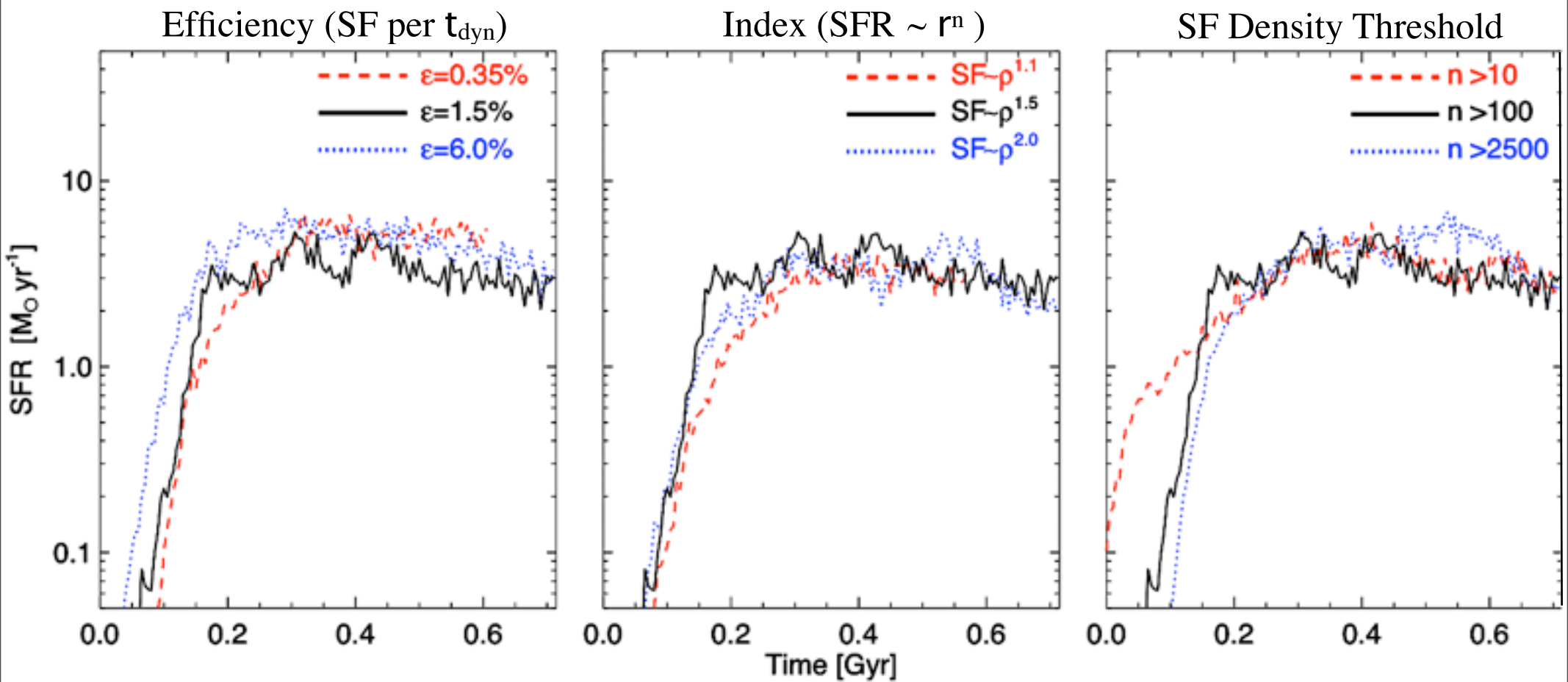
Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law



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

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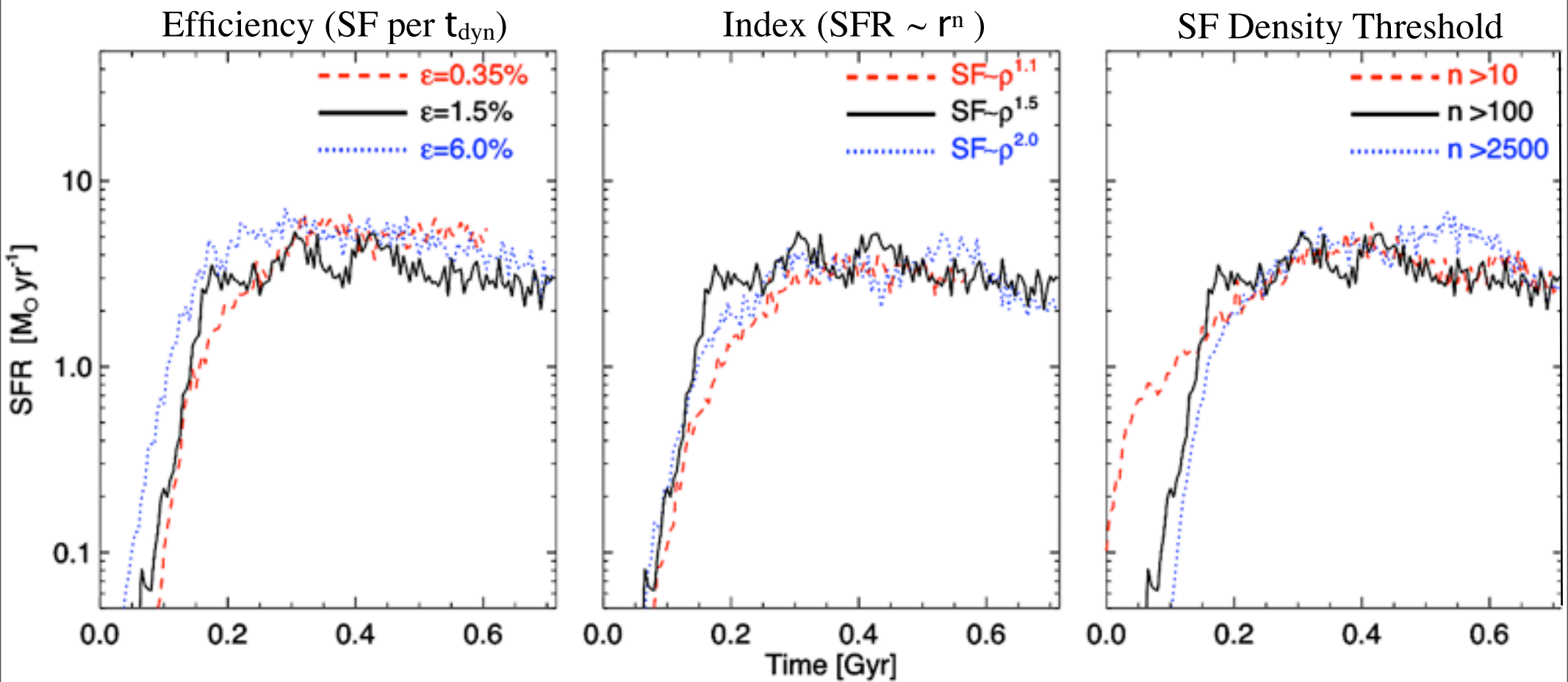


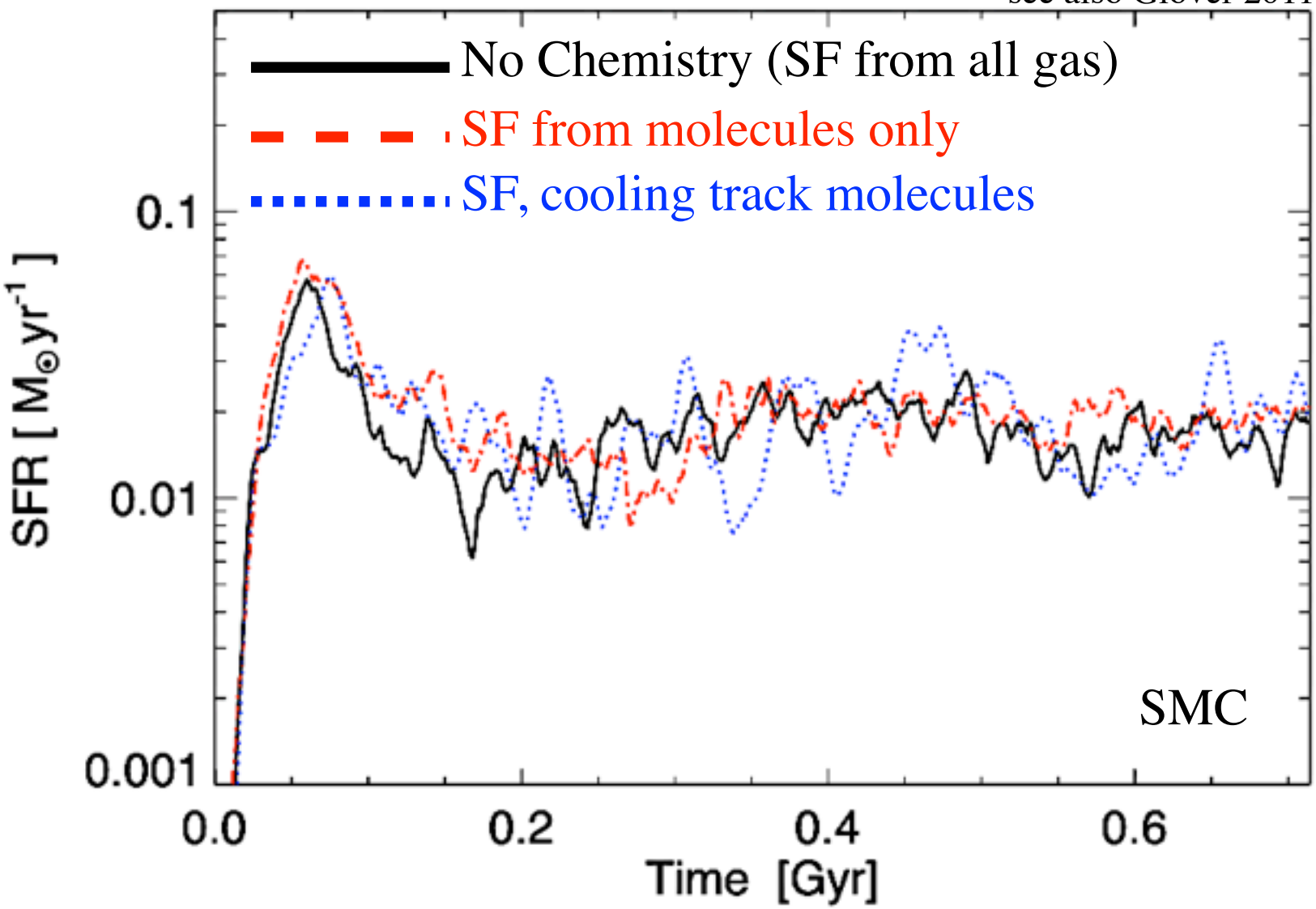
- Set by feedback (i.e. SFR) needed to maintain marginal stability

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

Molecular Chemistry doesn't change things above modest Metallicity

MOLECULES ARE A *TRACER*

see also Glover 2011



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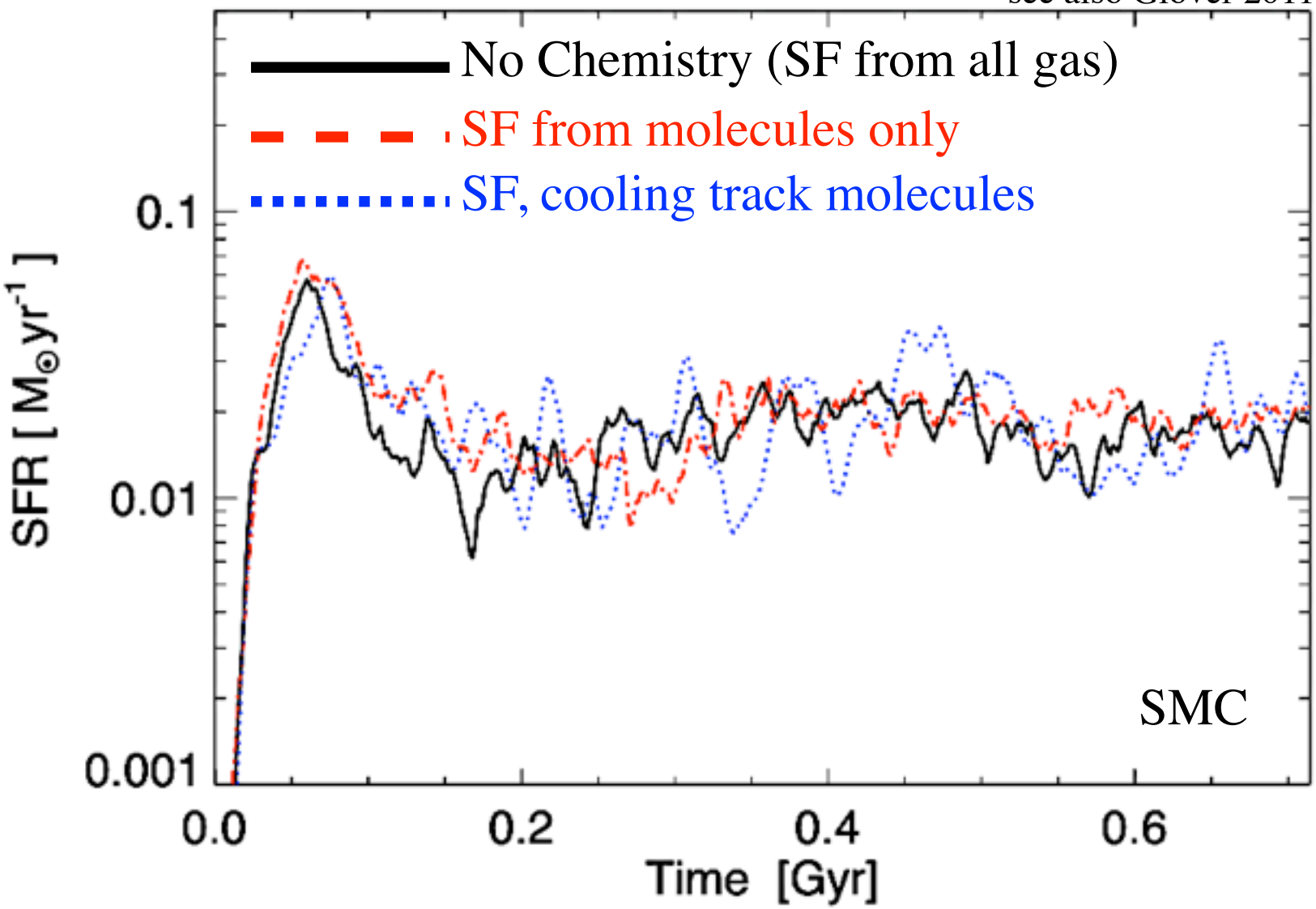
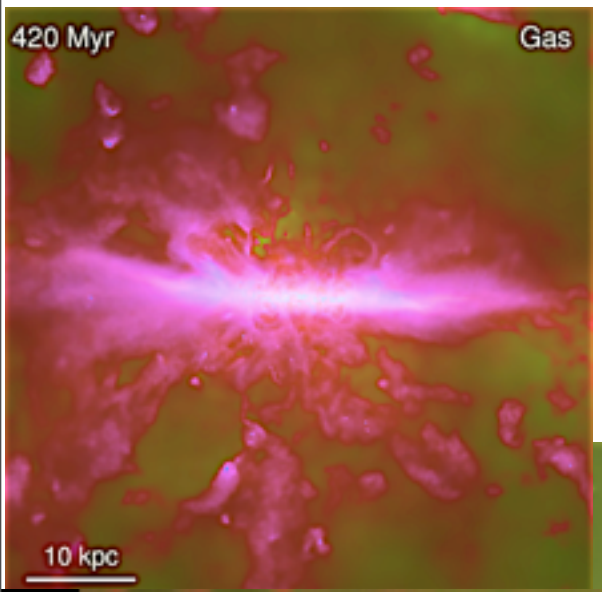
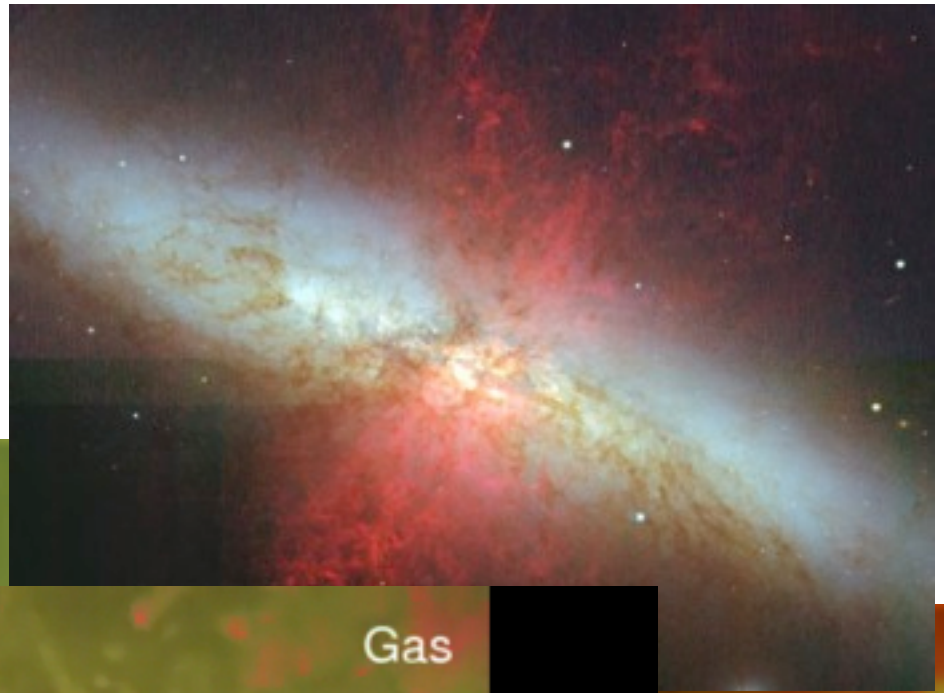
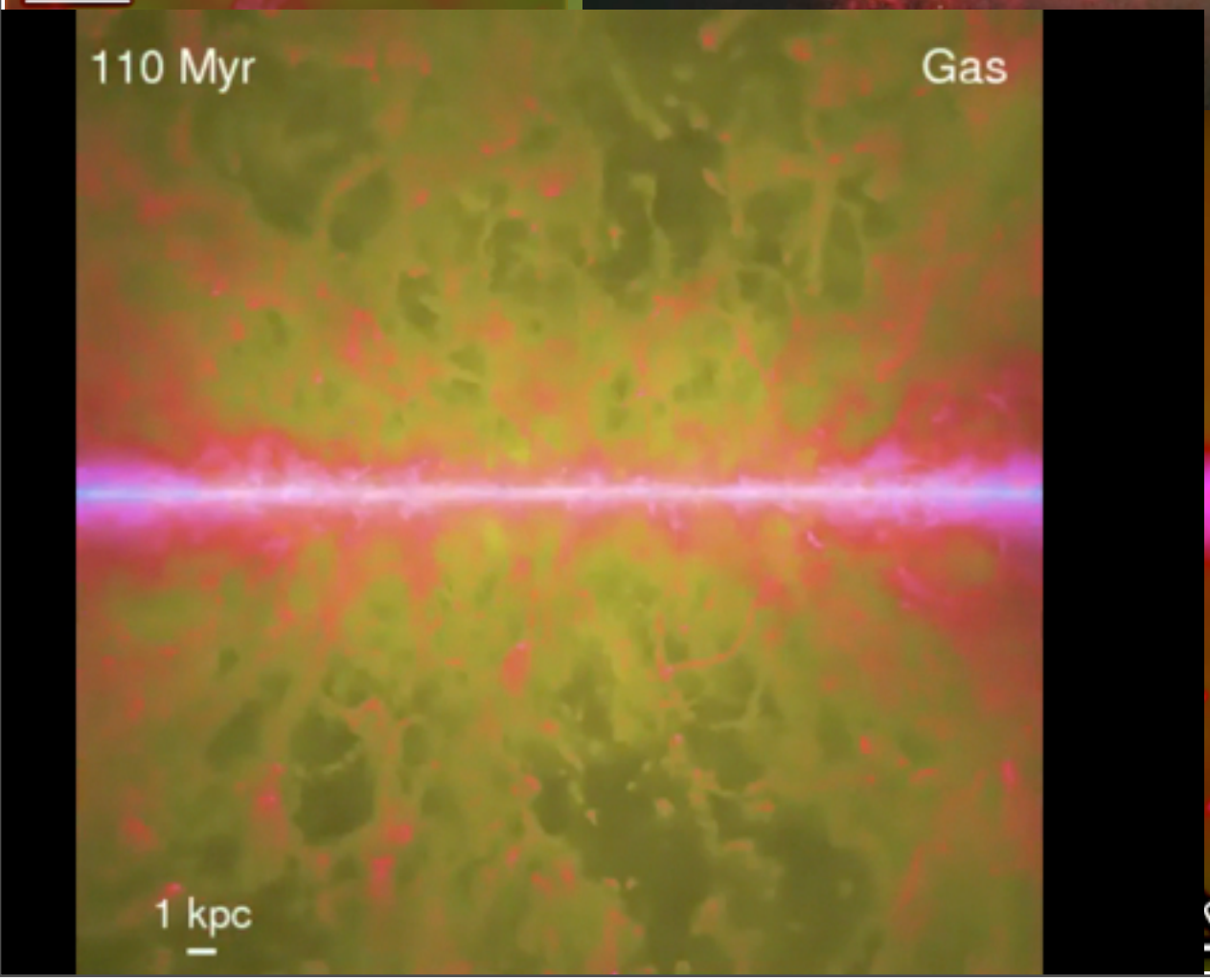


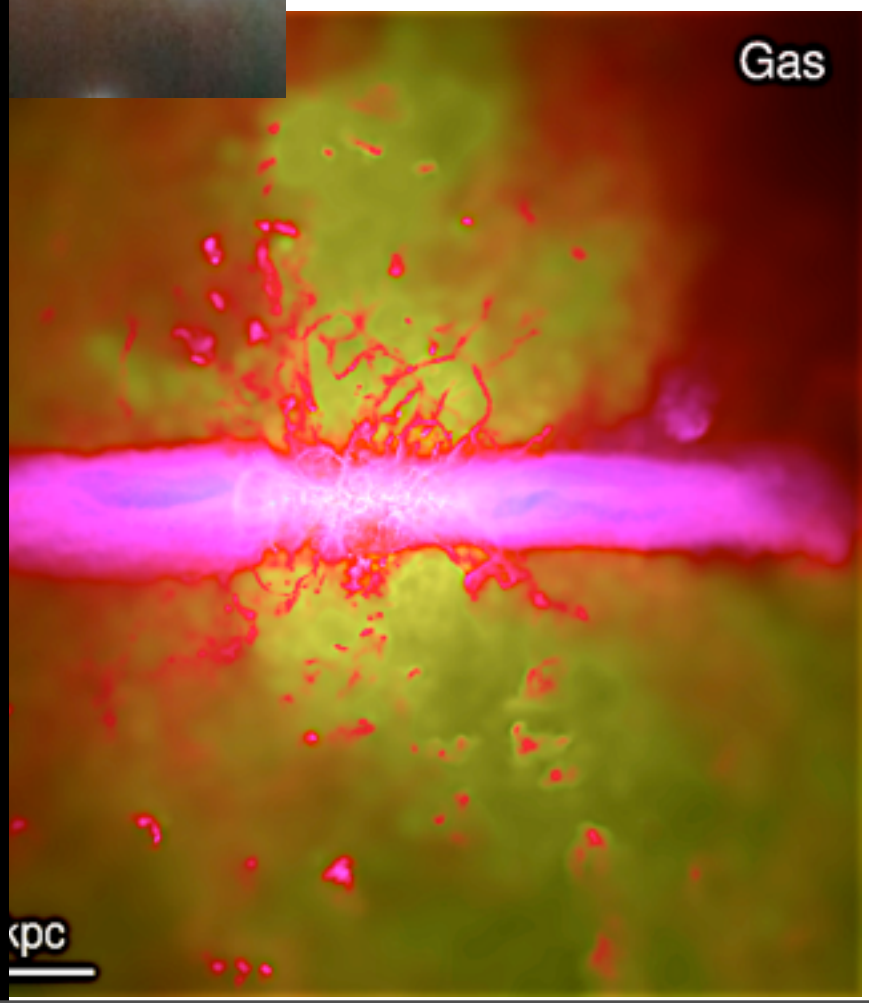
- Just need *some* cooling channel: changes at $M_{gal} < 10^6 M_{sun}$, $Z<0.01 Z_{sun}$

Galactic Super-Winds

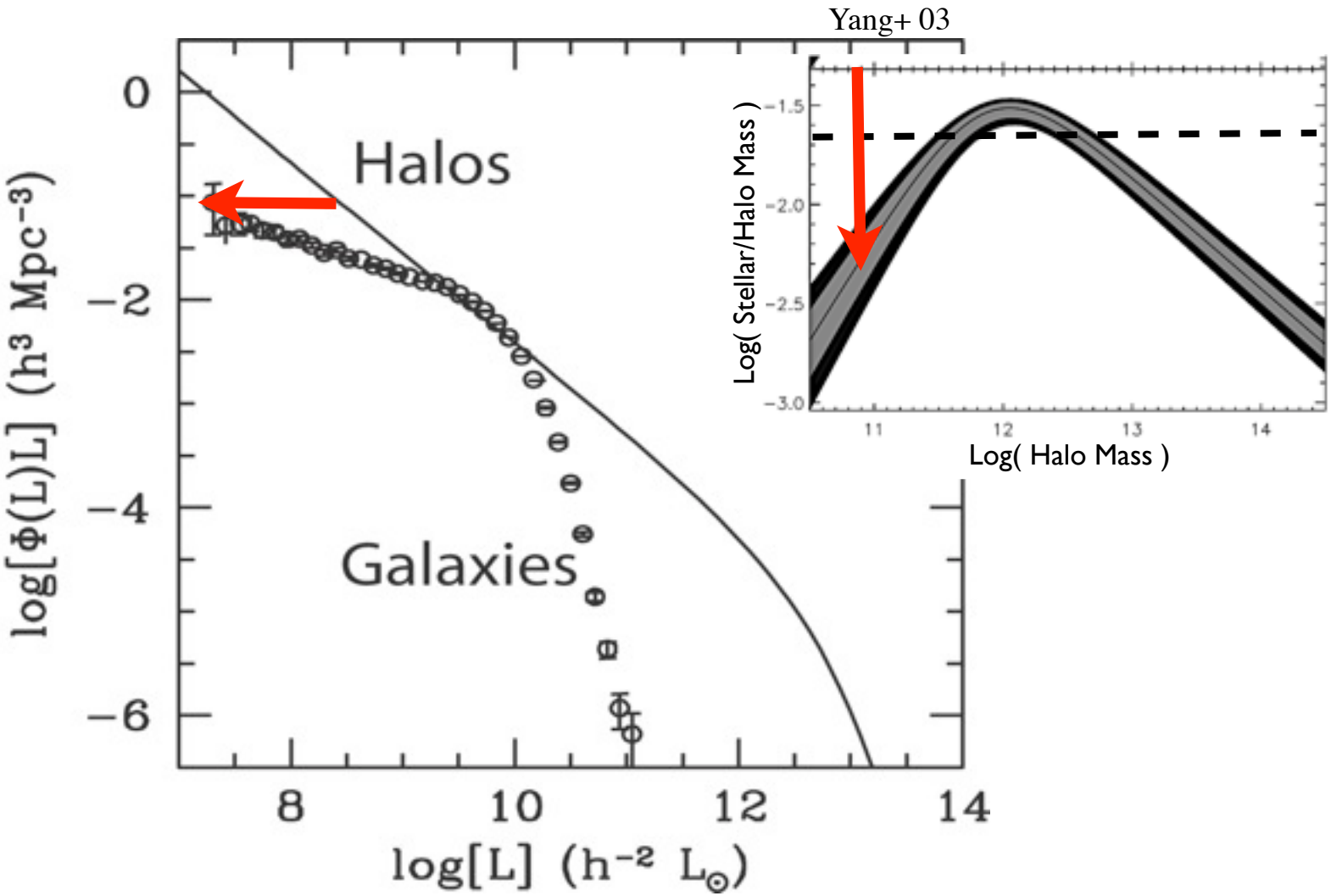








How Efficient Are Galactic Super-Winds?



- 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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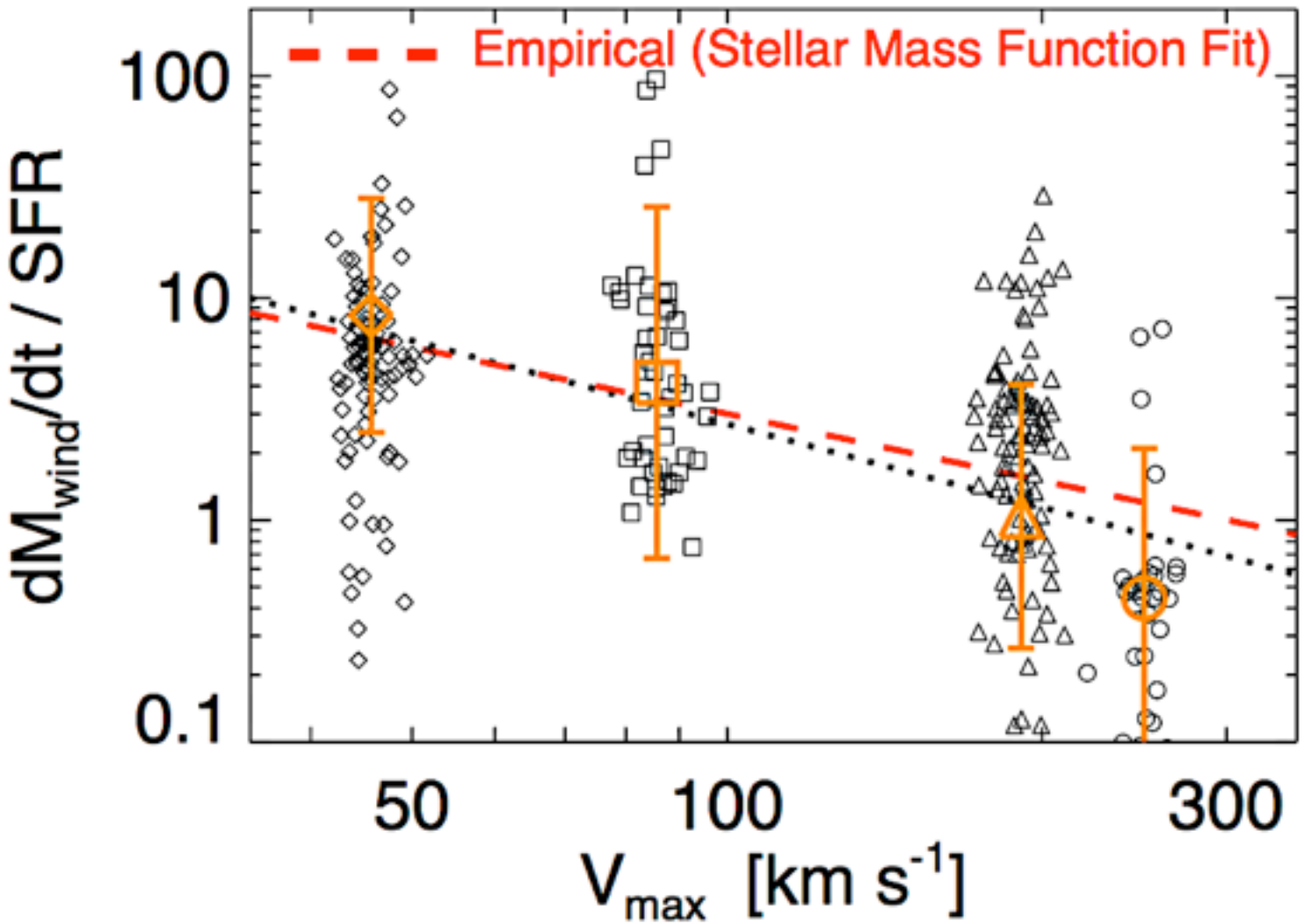

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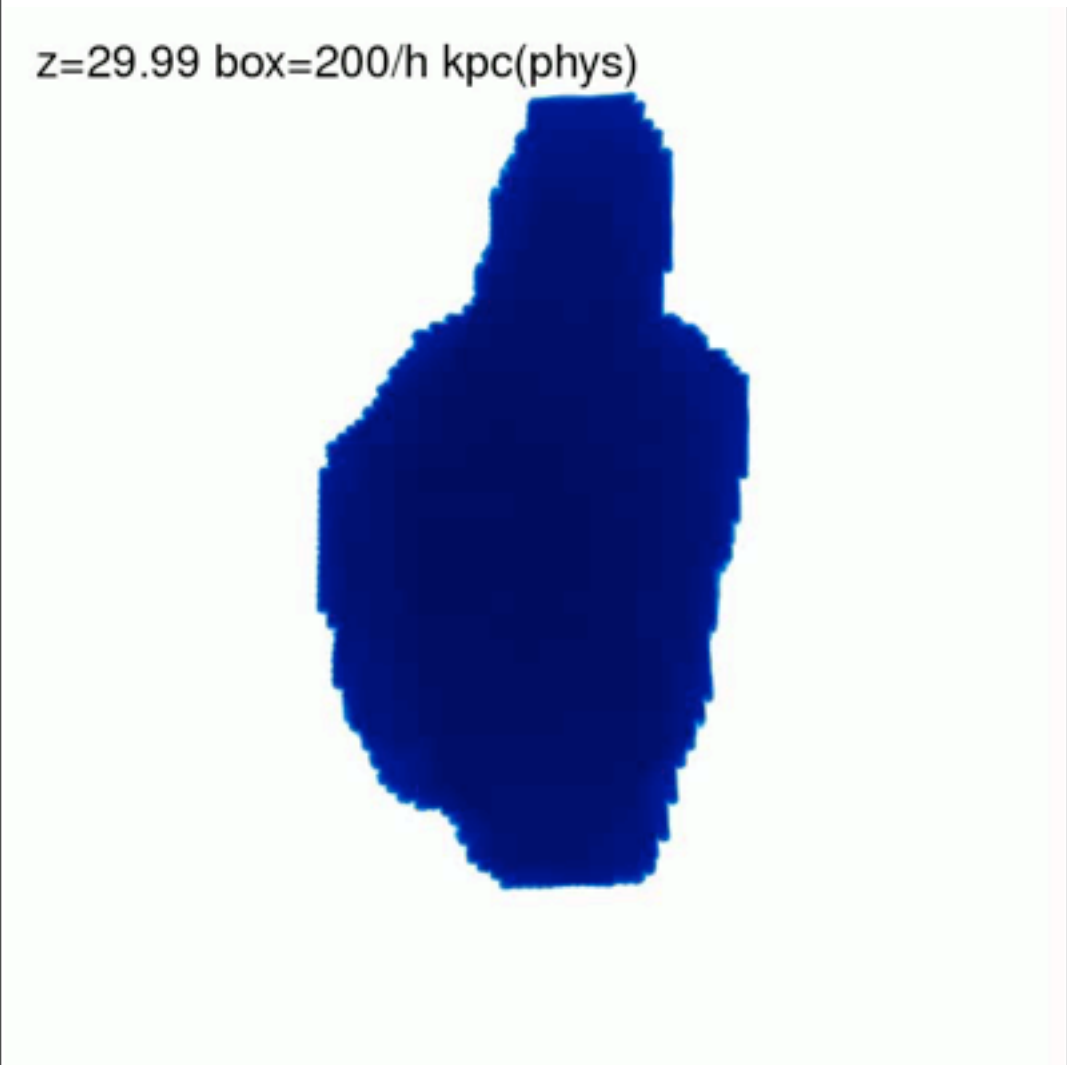
The Cosmological Inflow/Outflow Cycle

Cosmological Simulations

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



IGM Density

IGM Temperature

Keres & PFH et al

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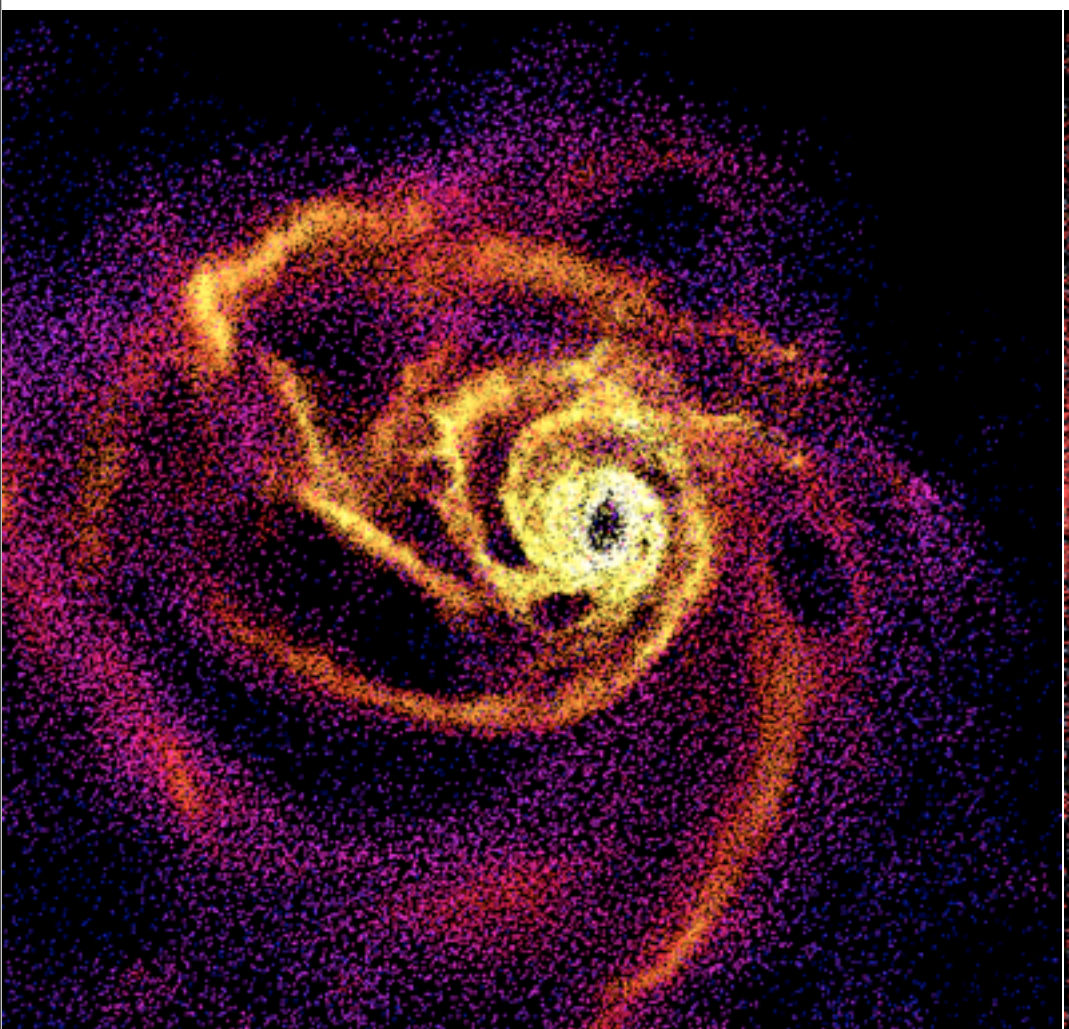
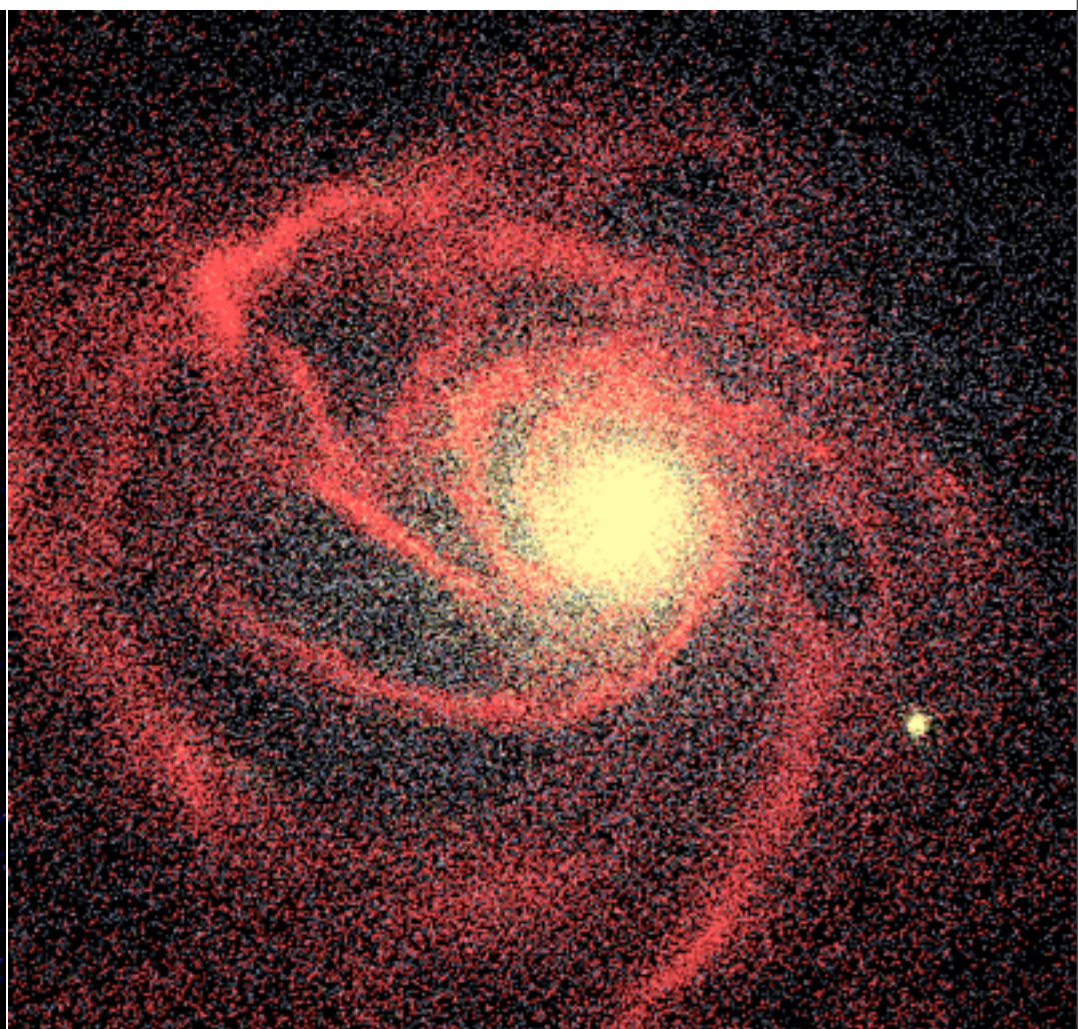


Gas Density



Stars

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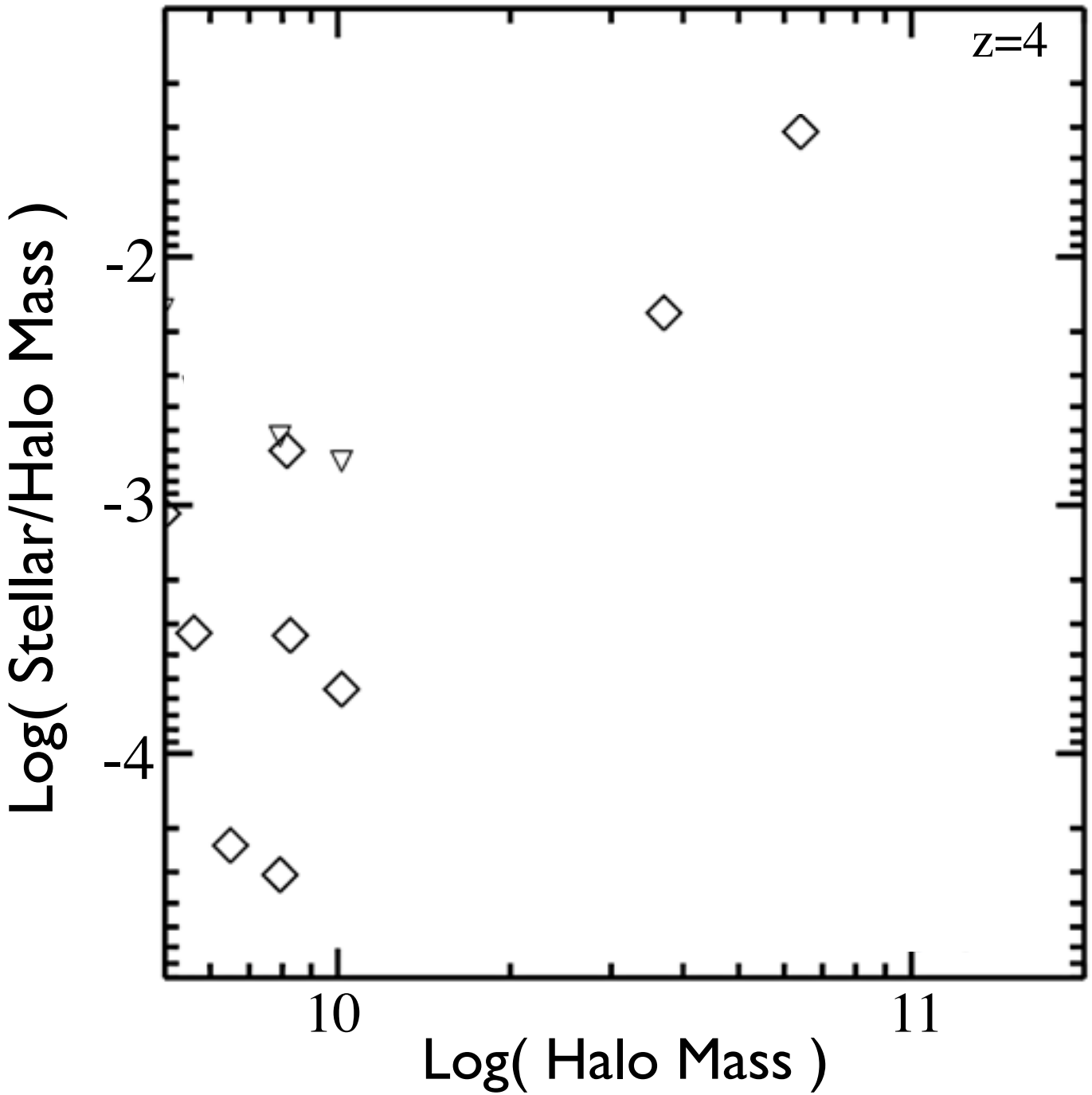
How Inefficient is Galaxy Formation?

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



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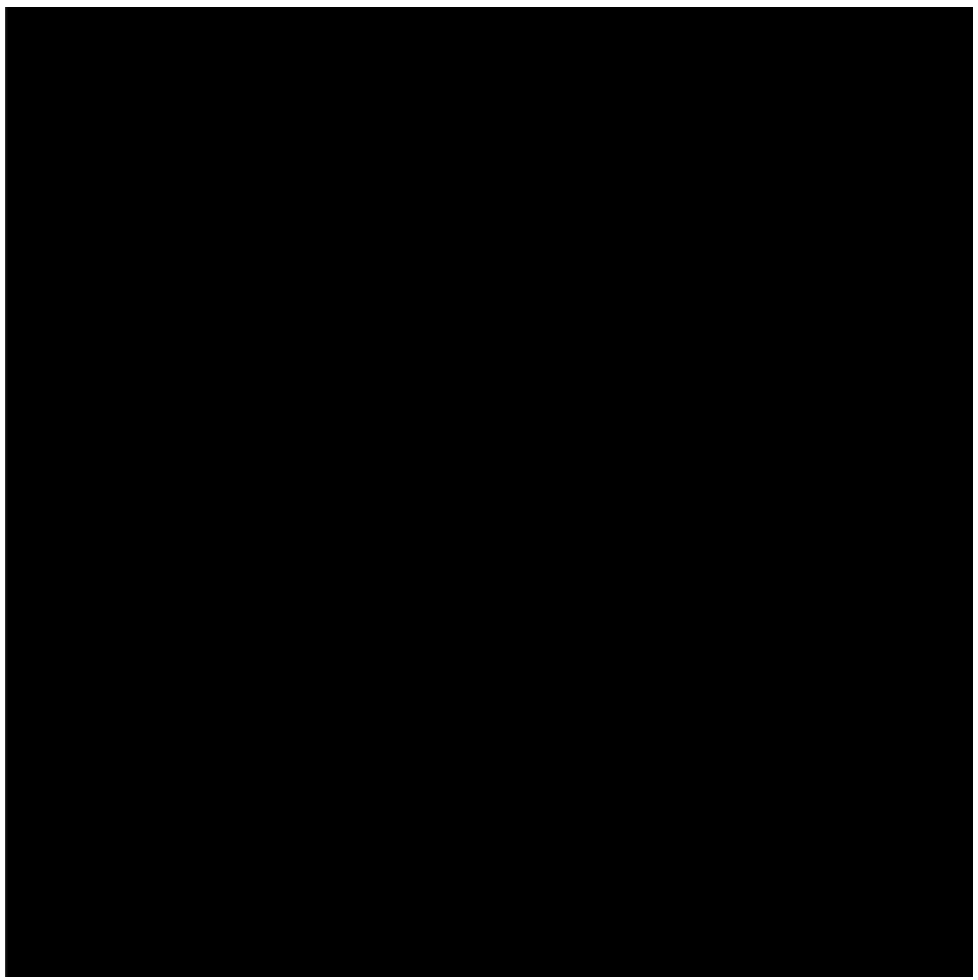
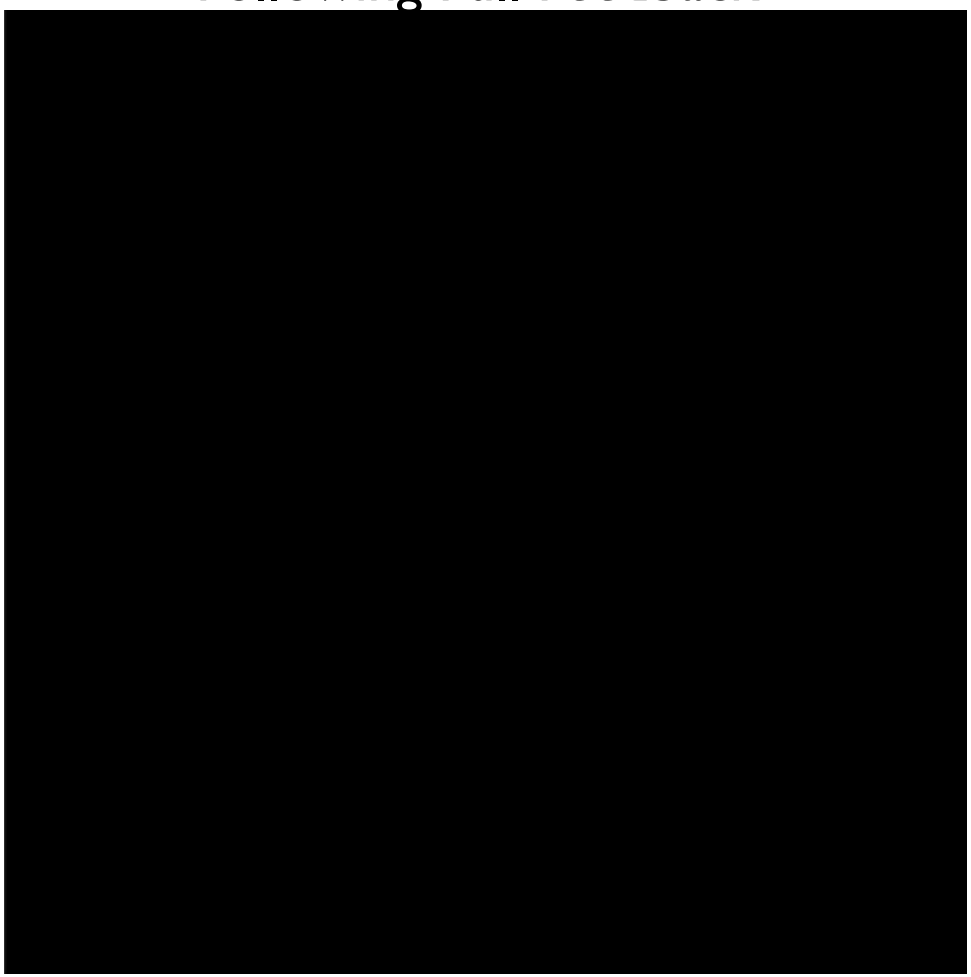
Proto-MW: Gas Temperature:

No Feedback



Following Full Feedback



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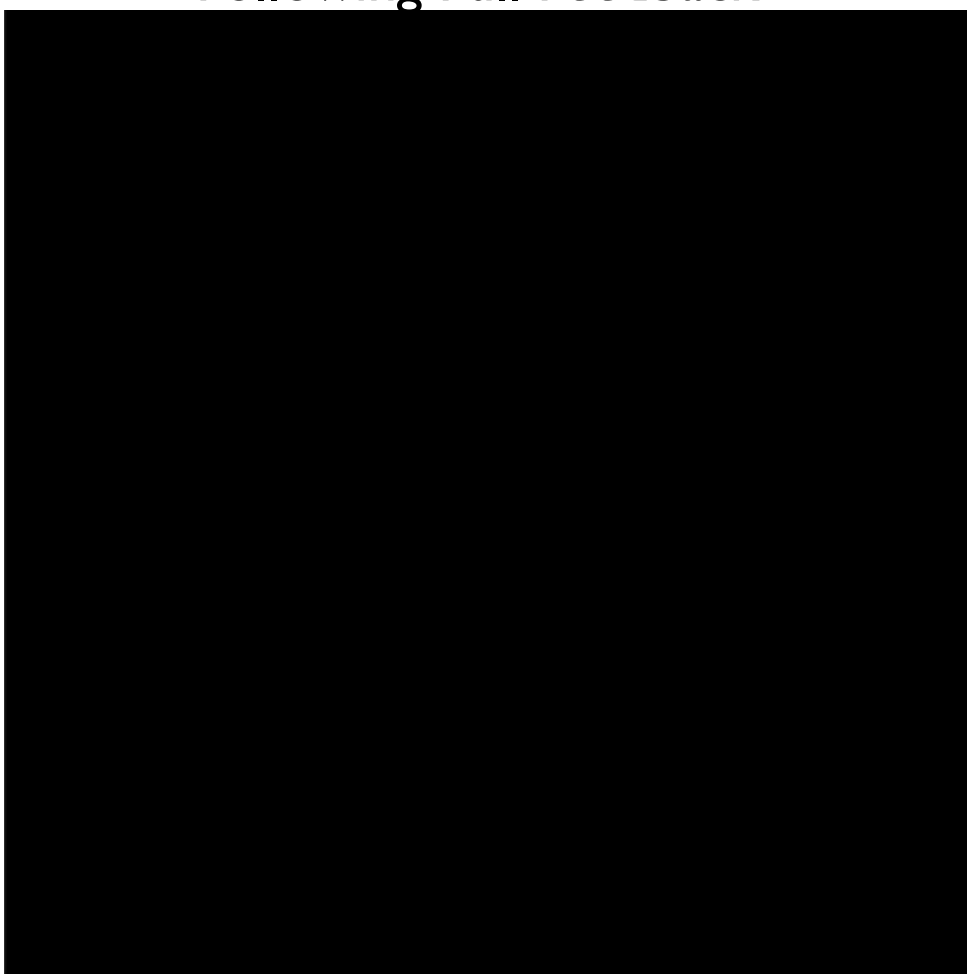
Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

Following Full Feedback



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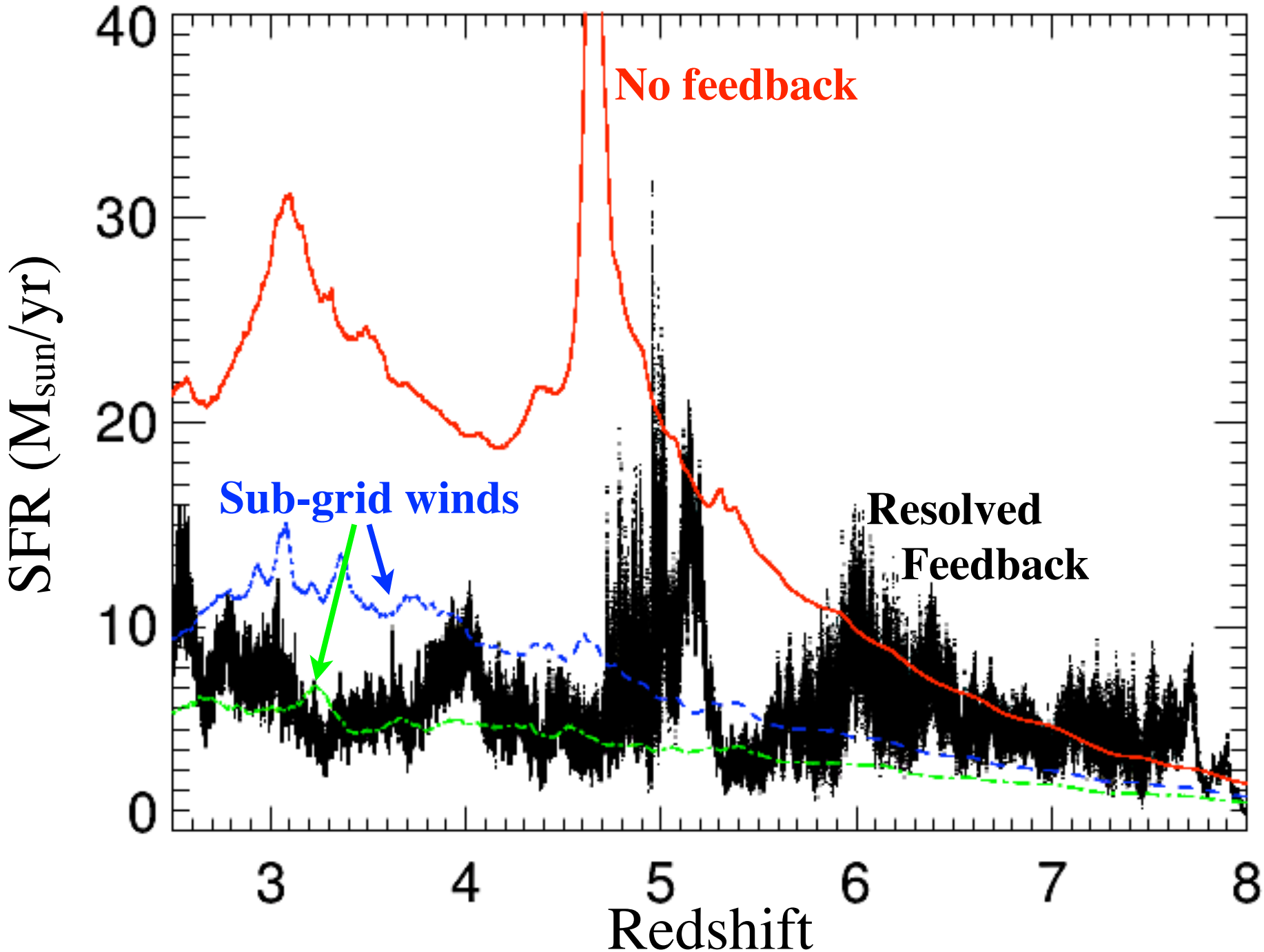
Starburst-Driven Winds

SUB-GRID vs. RESOLVED MATTERS!



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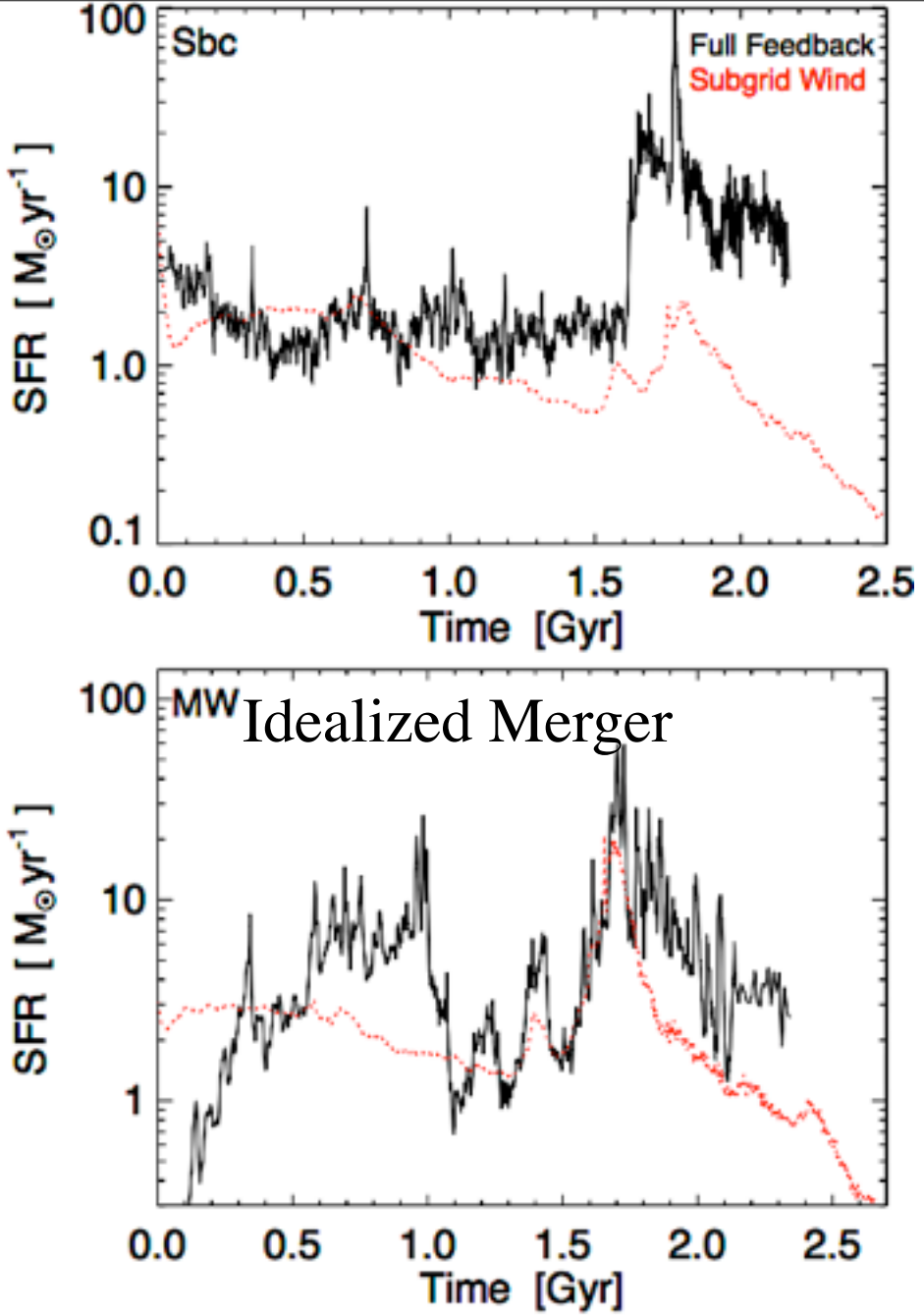
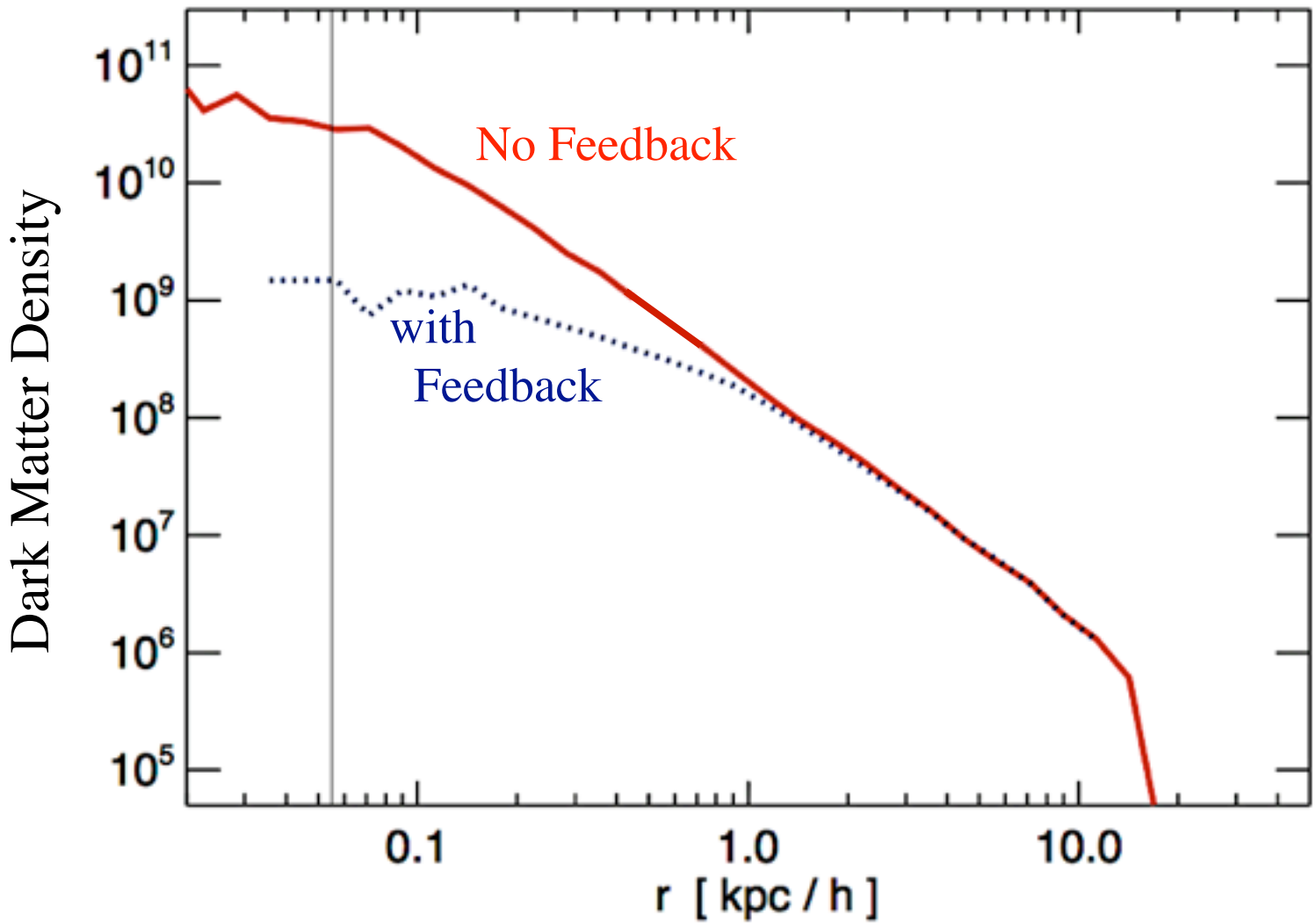


Dark Matter Profiles: Baryons or Cosmology?

DO RESOLVED WINDS ACTUALLY MAKE CORES?



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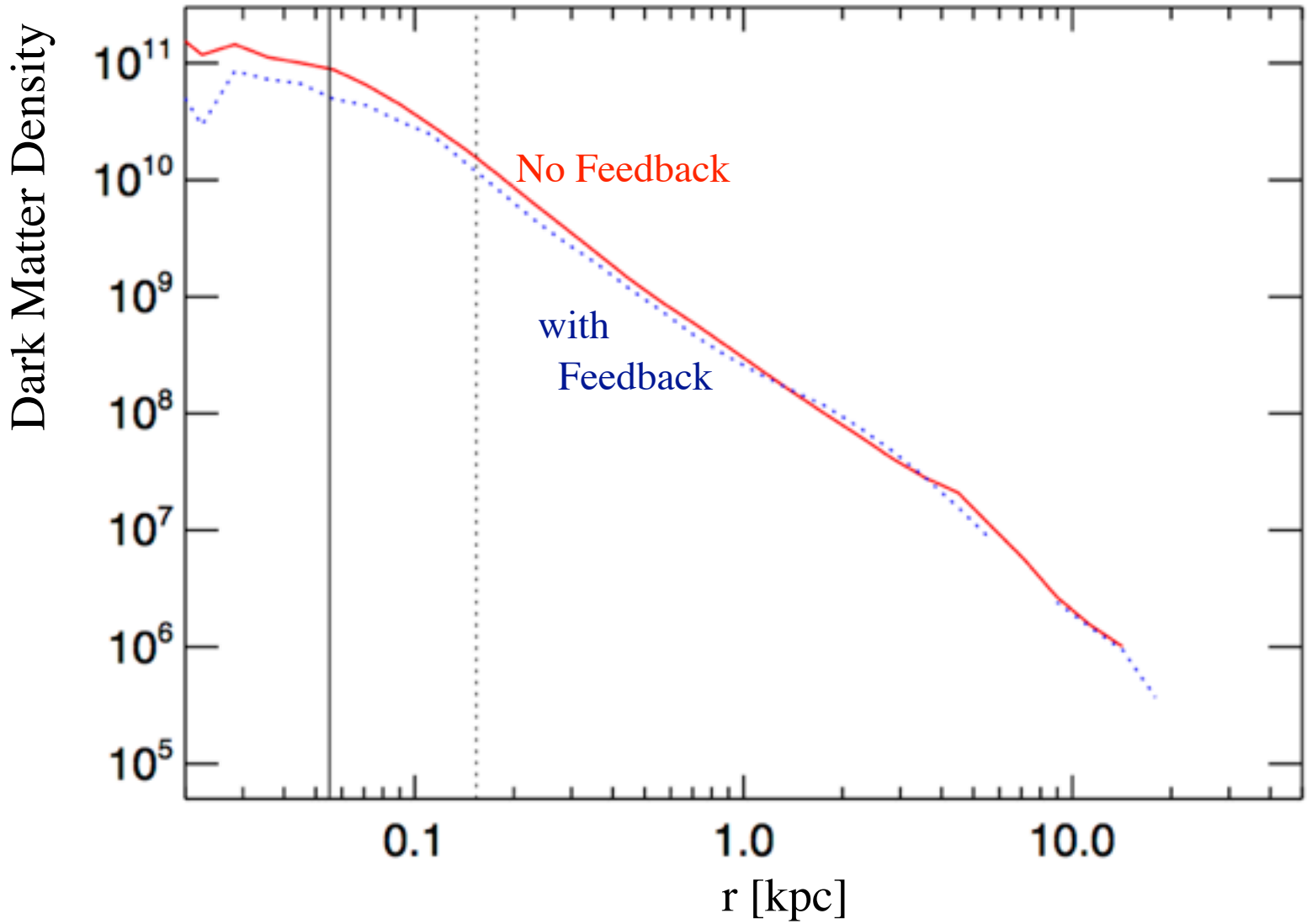

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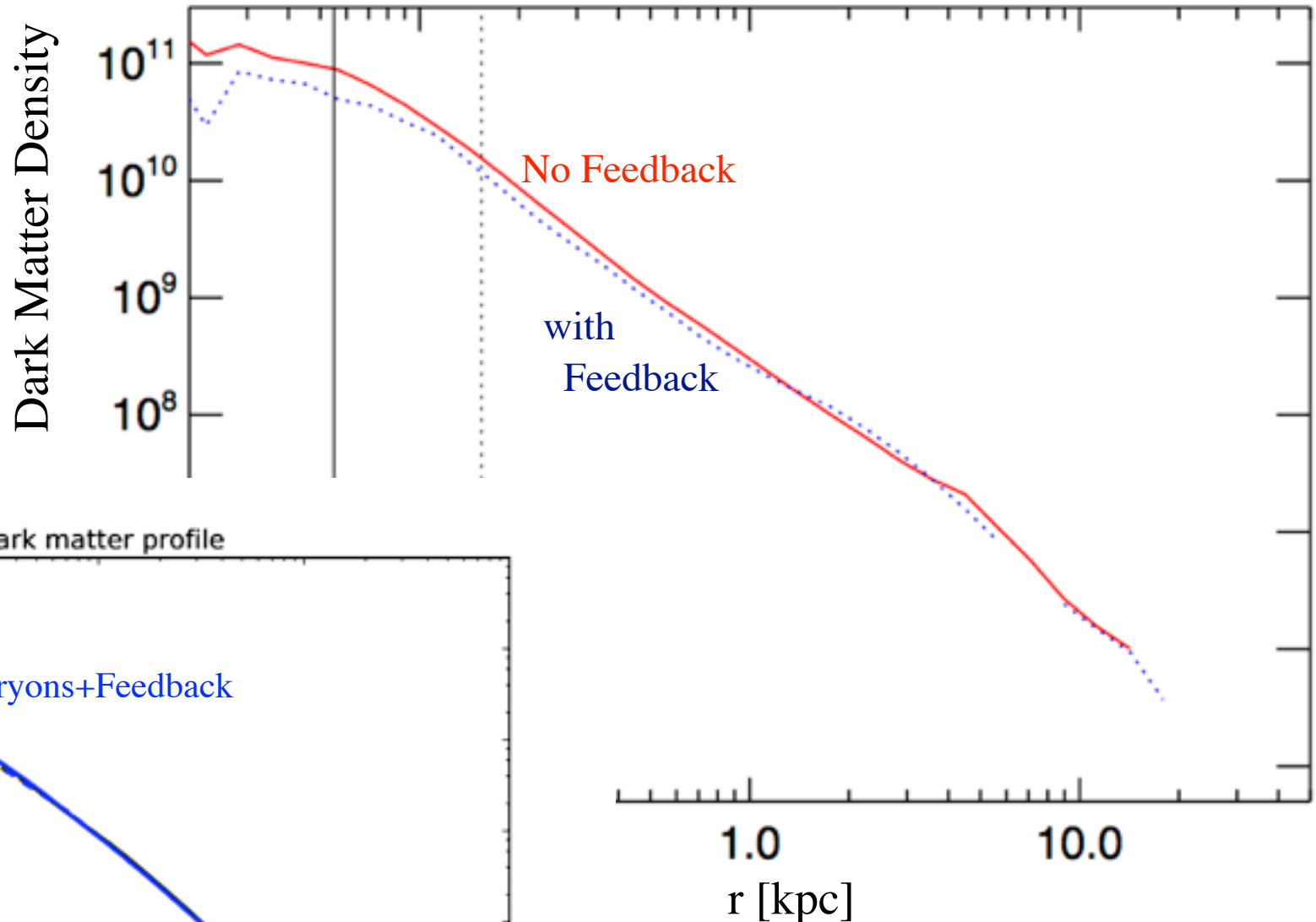

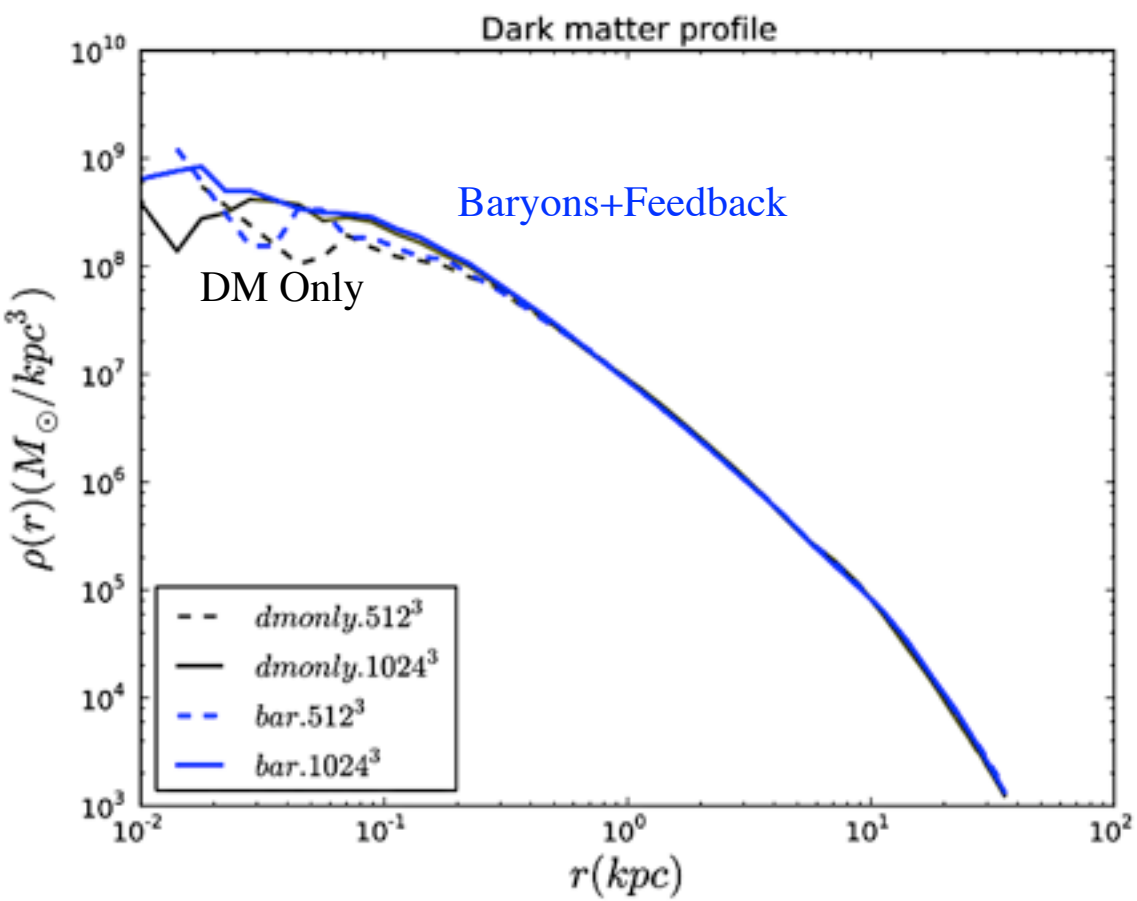

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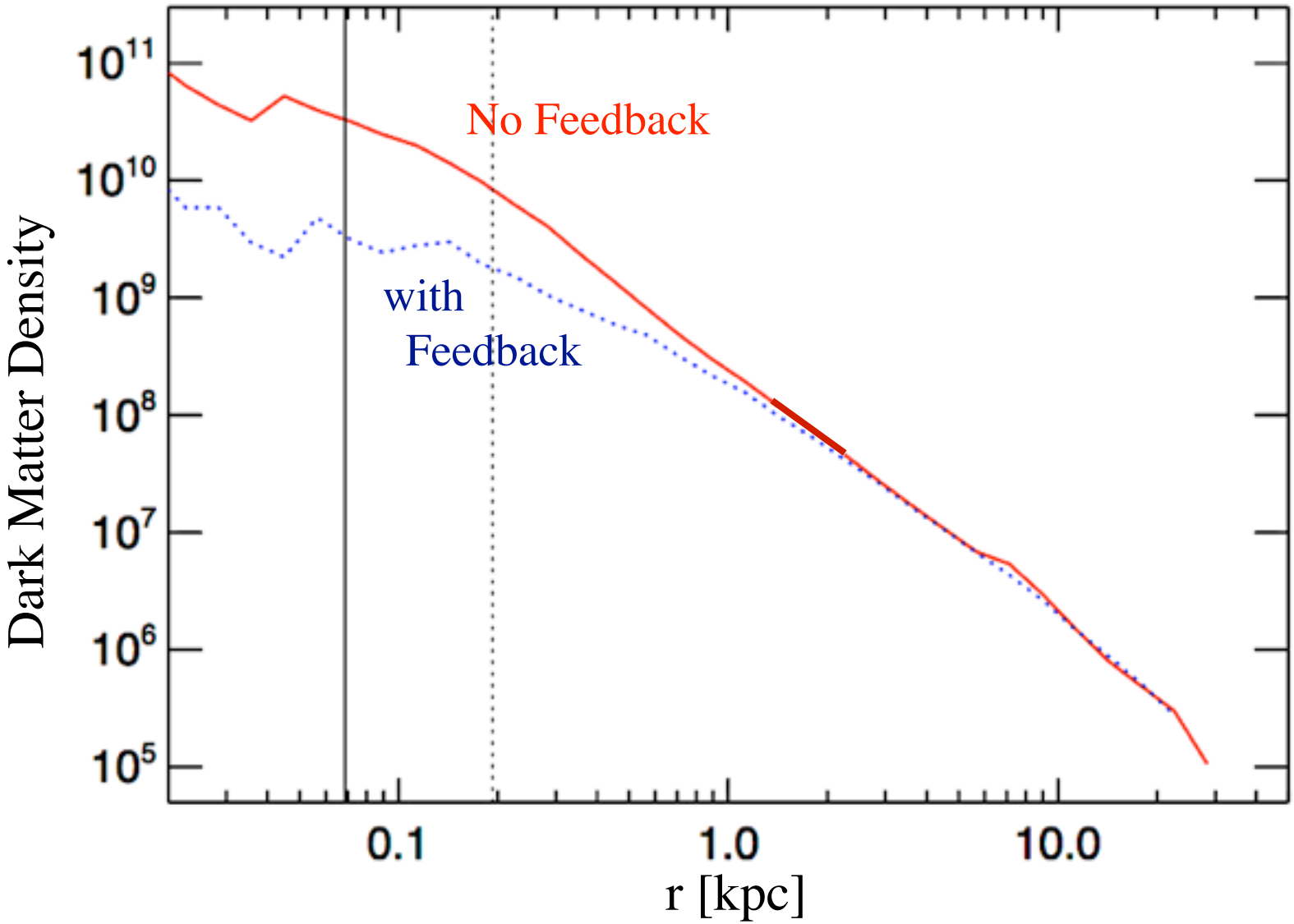

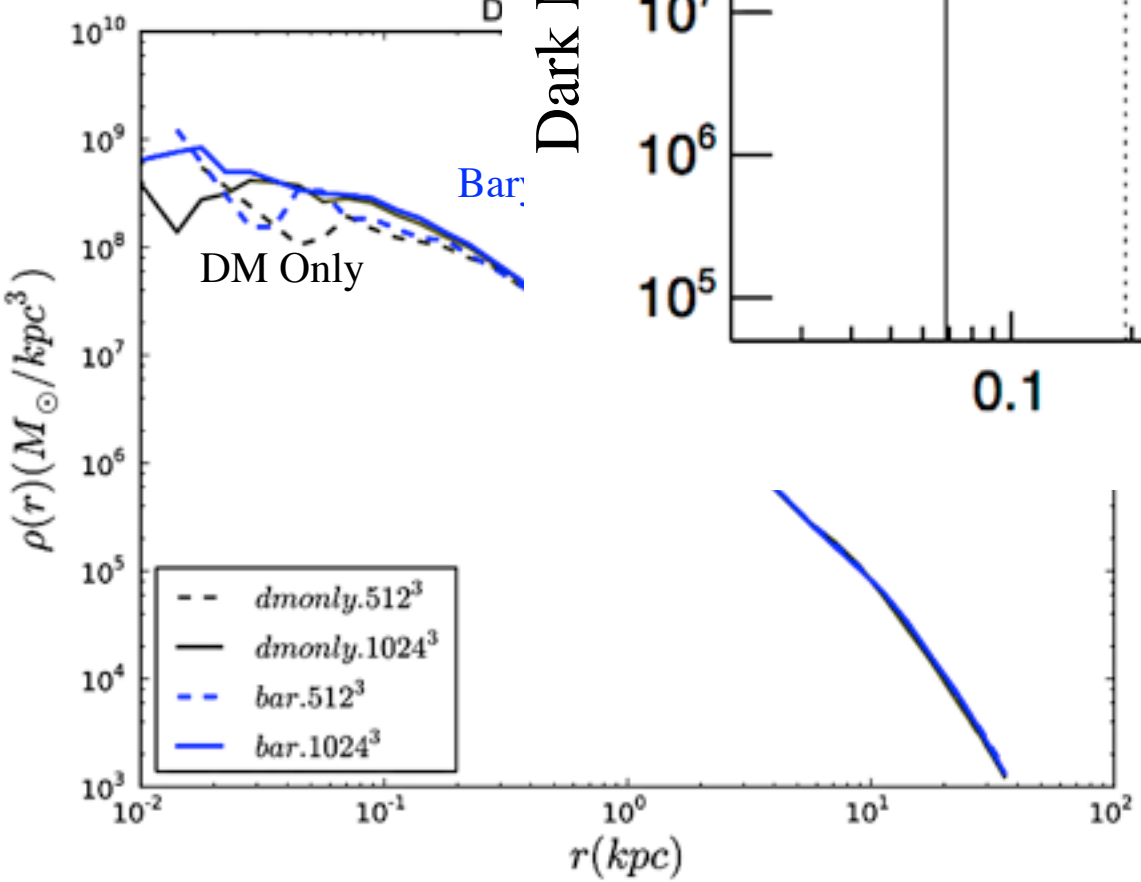

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Summary:

- **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-r: radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low-r: 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!