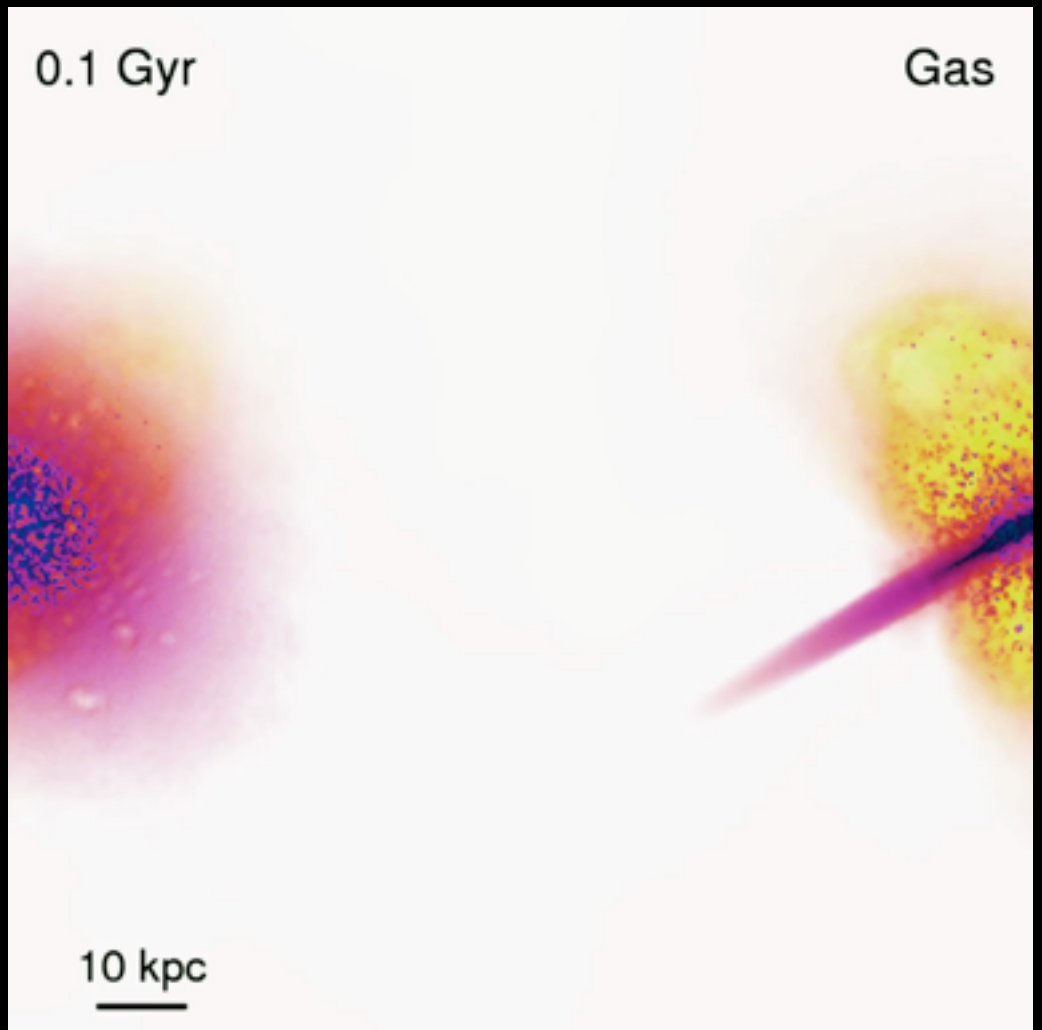
# Feedback: Now With Physics!*



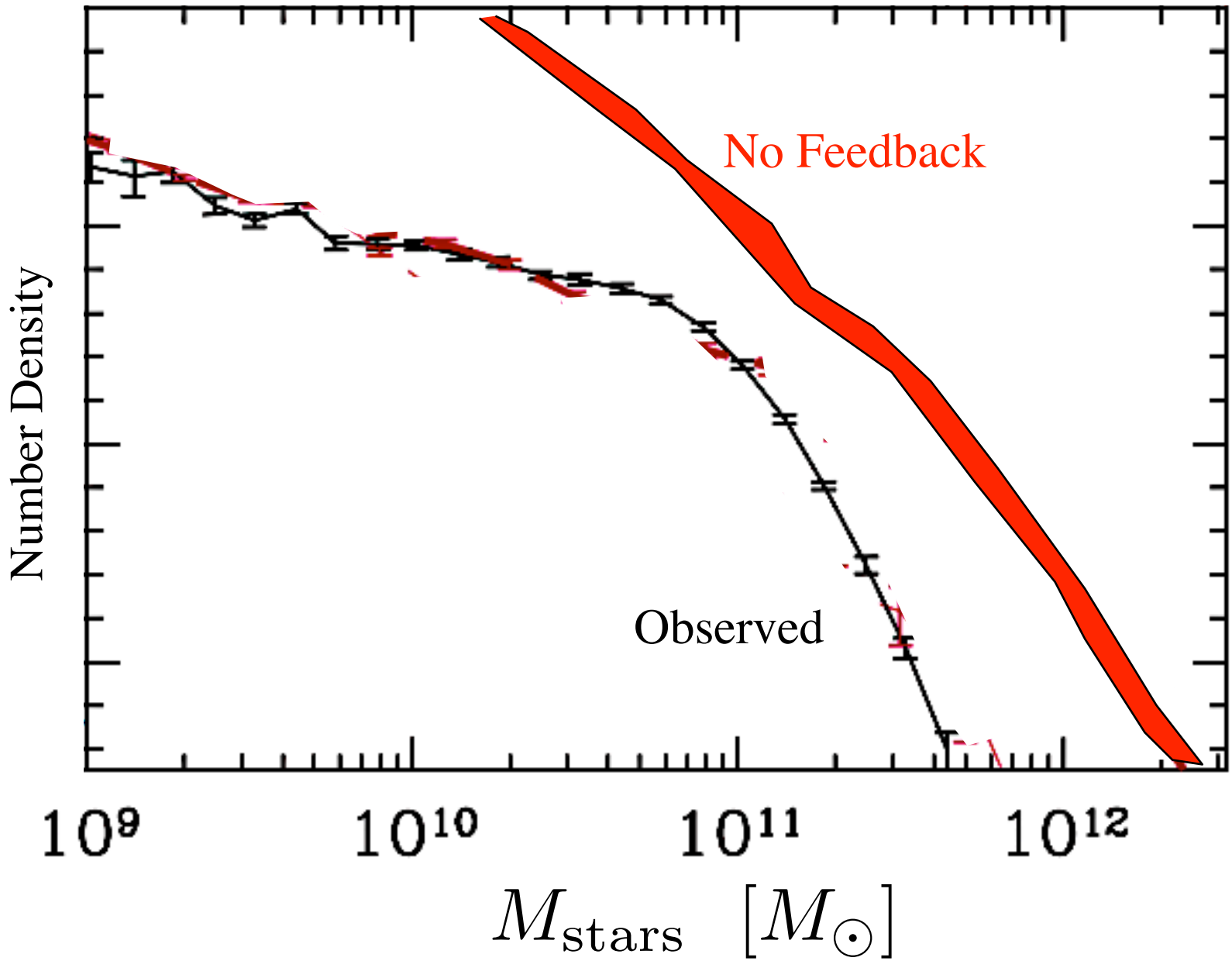


Philip Hopkins, Eliot Quataert, Norm Murray, Dusan Keres, Jose Onorbe

* *Real* physics not necessarily included

# Motivation

## Q: WHY IS STAR FORMATION SO INEFFICIENT?



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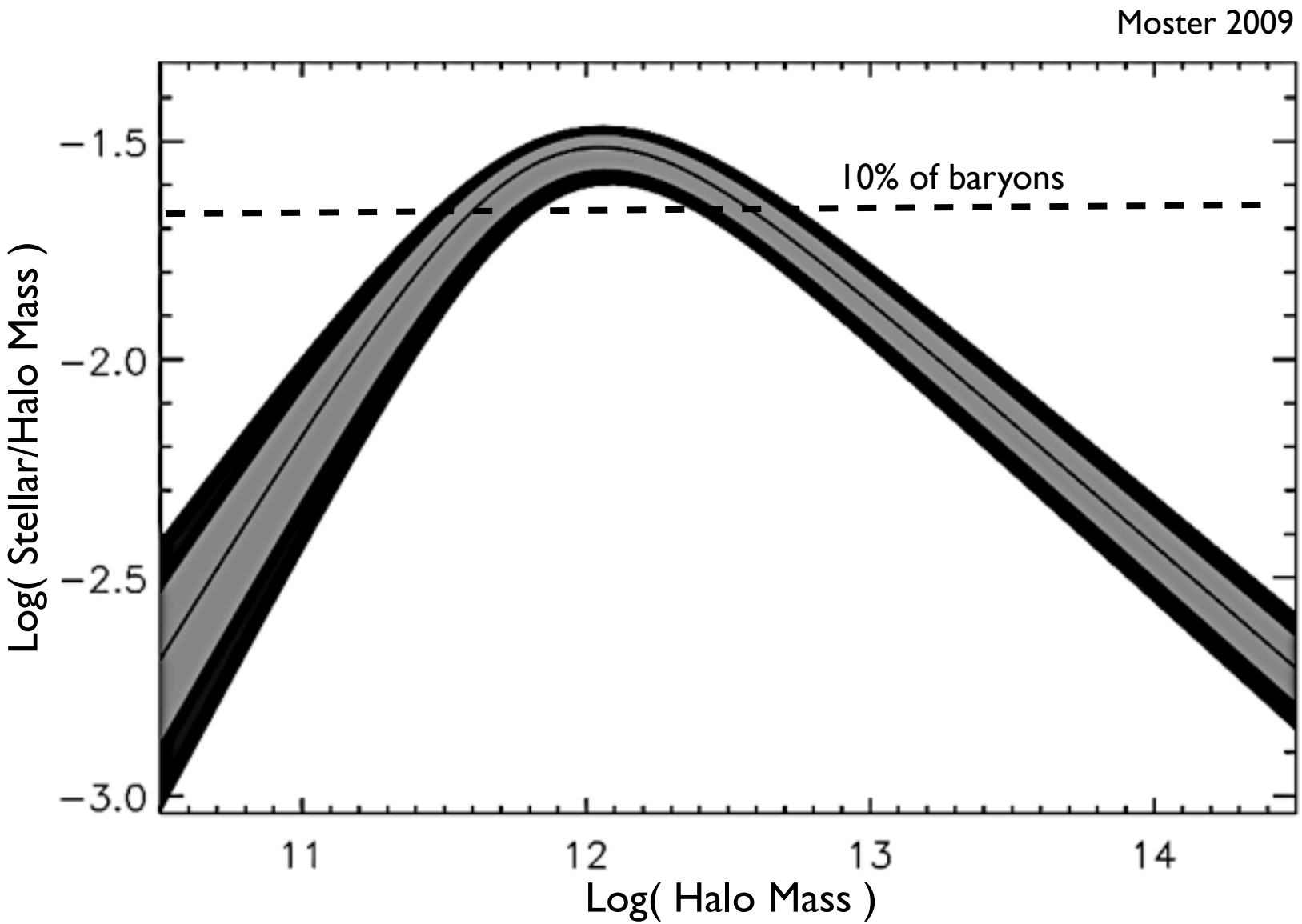

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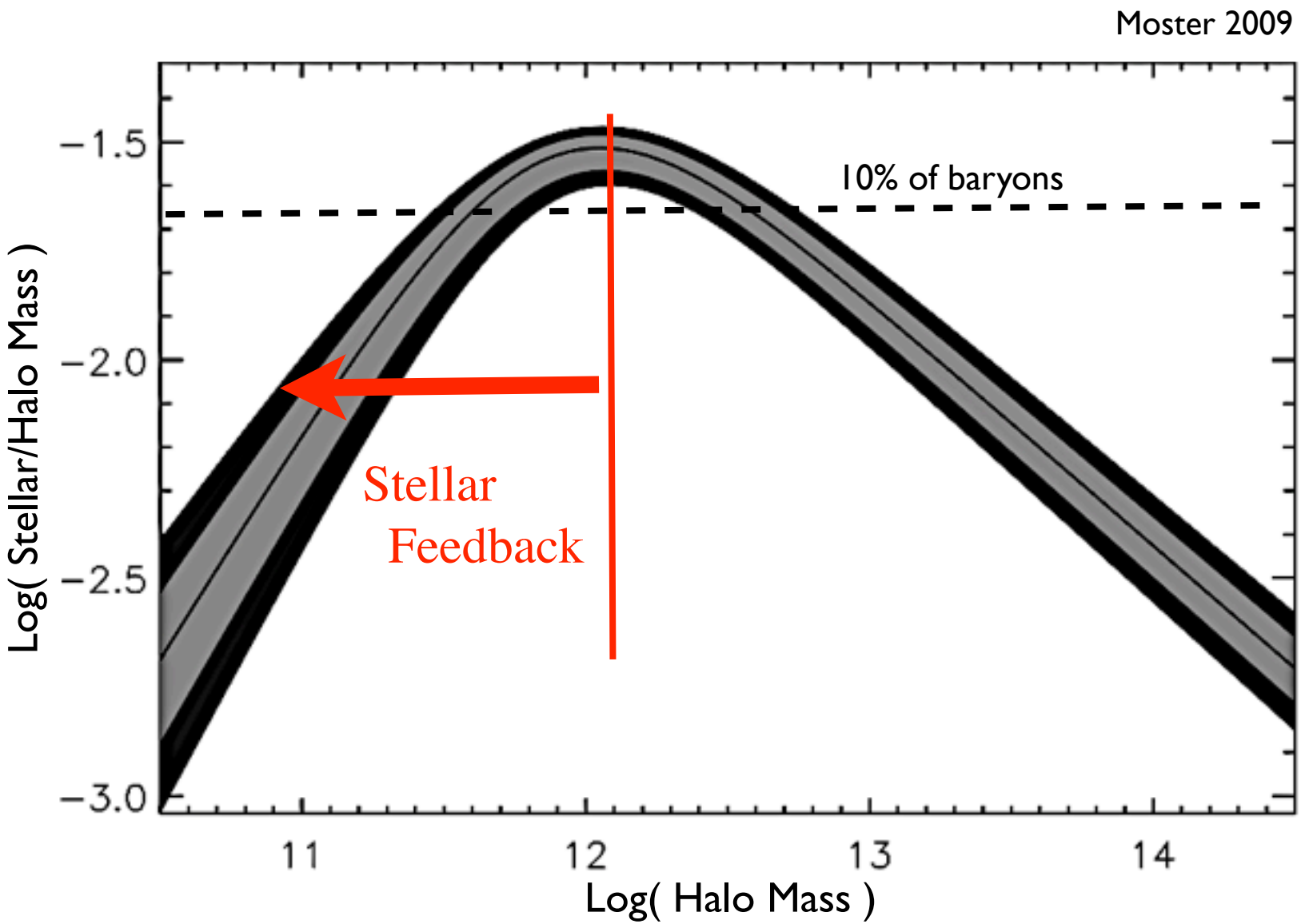

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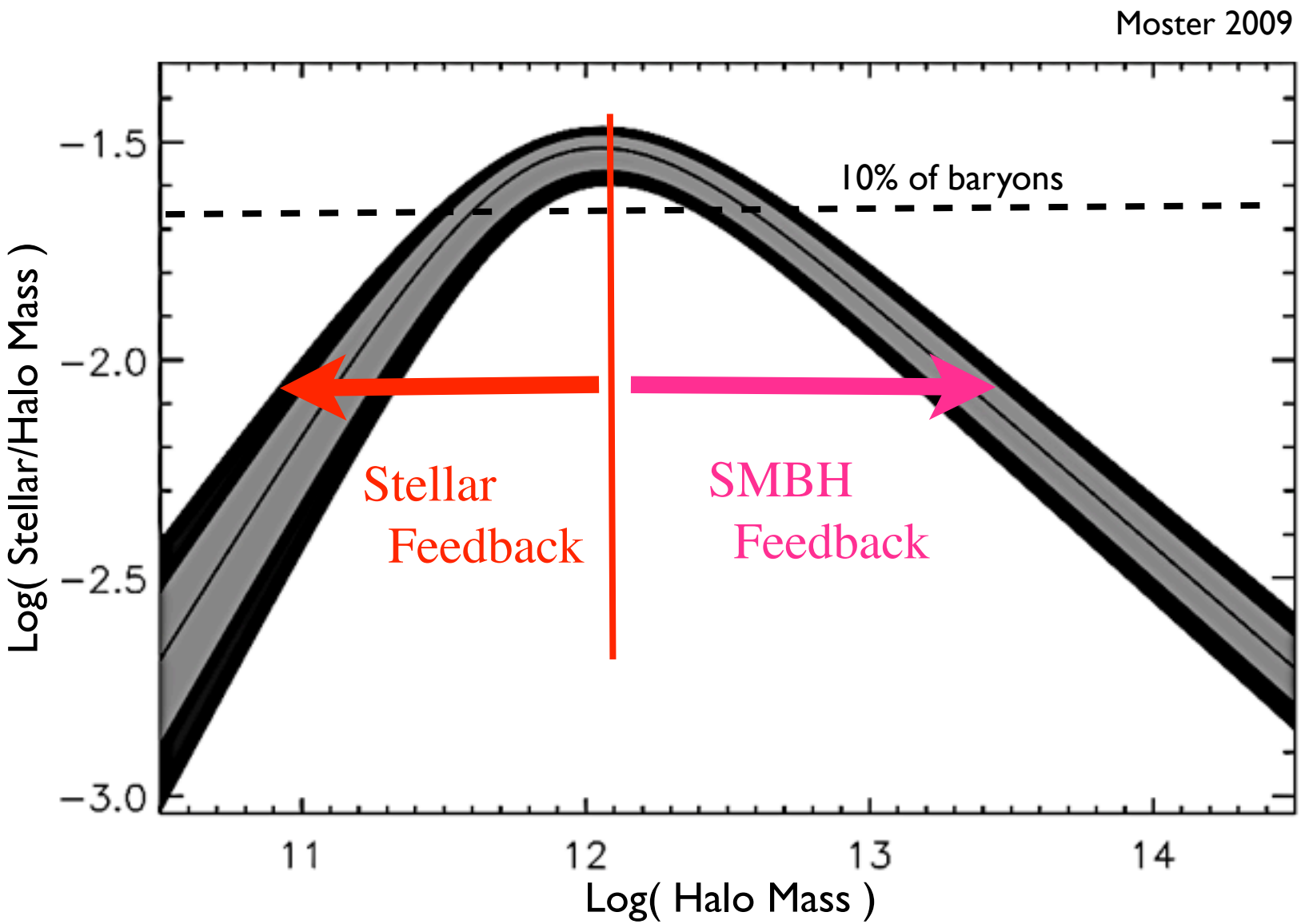


# Stellar Feedback is the Key!

## SO WHAT'S THE PROBLEM?

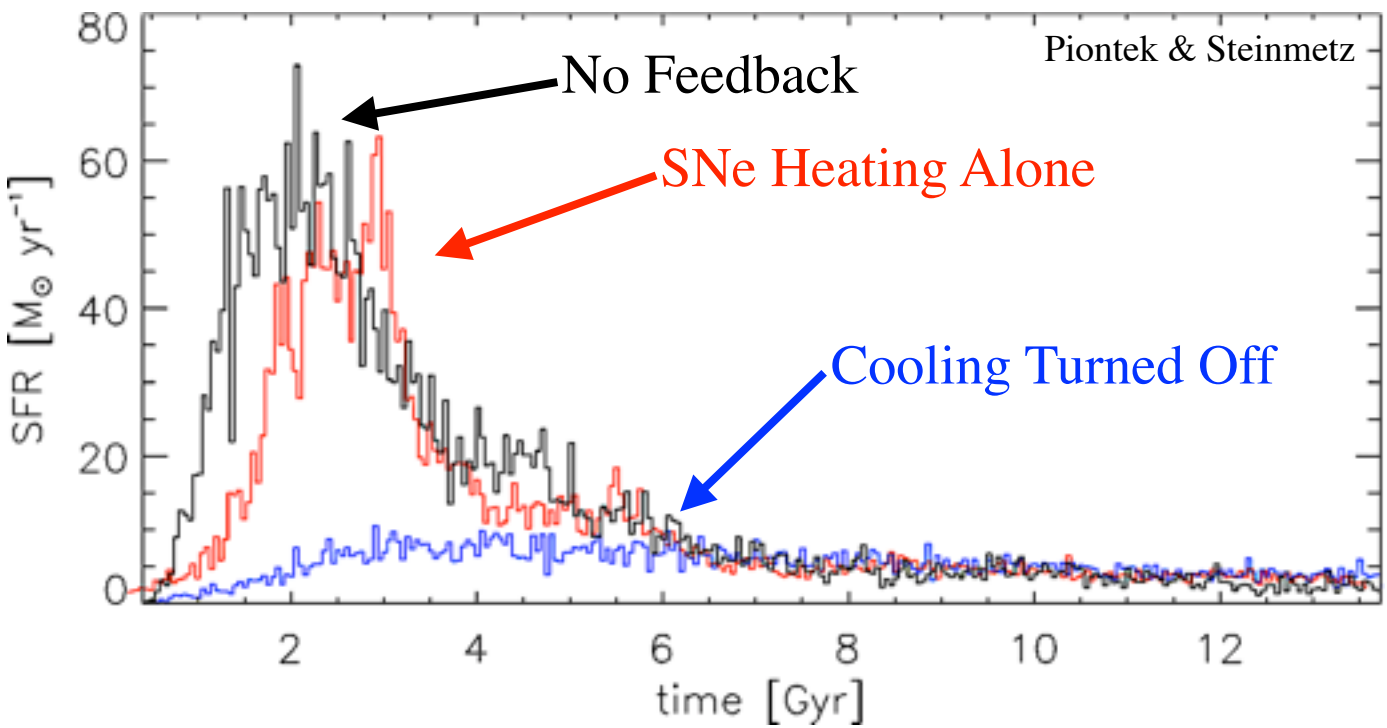
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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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- *Explicit* Momentum Flux:
  - Radiation Pressure

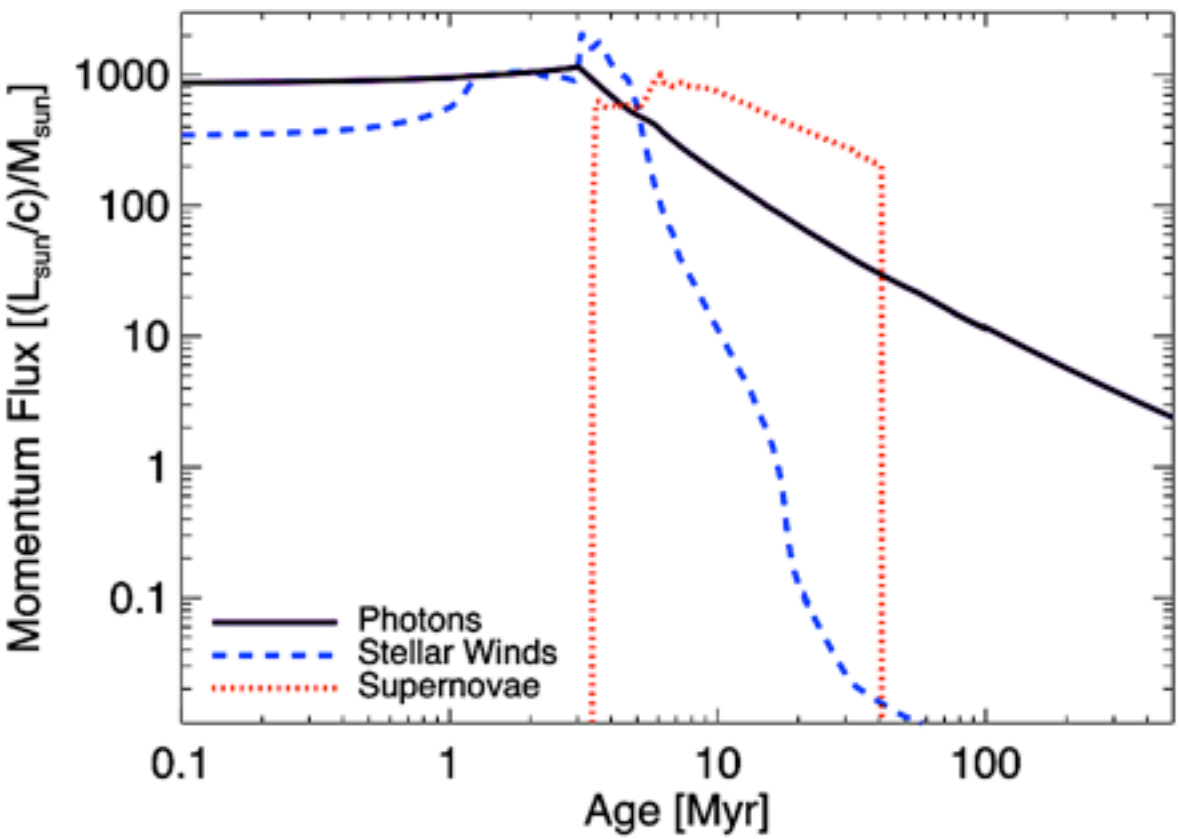
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

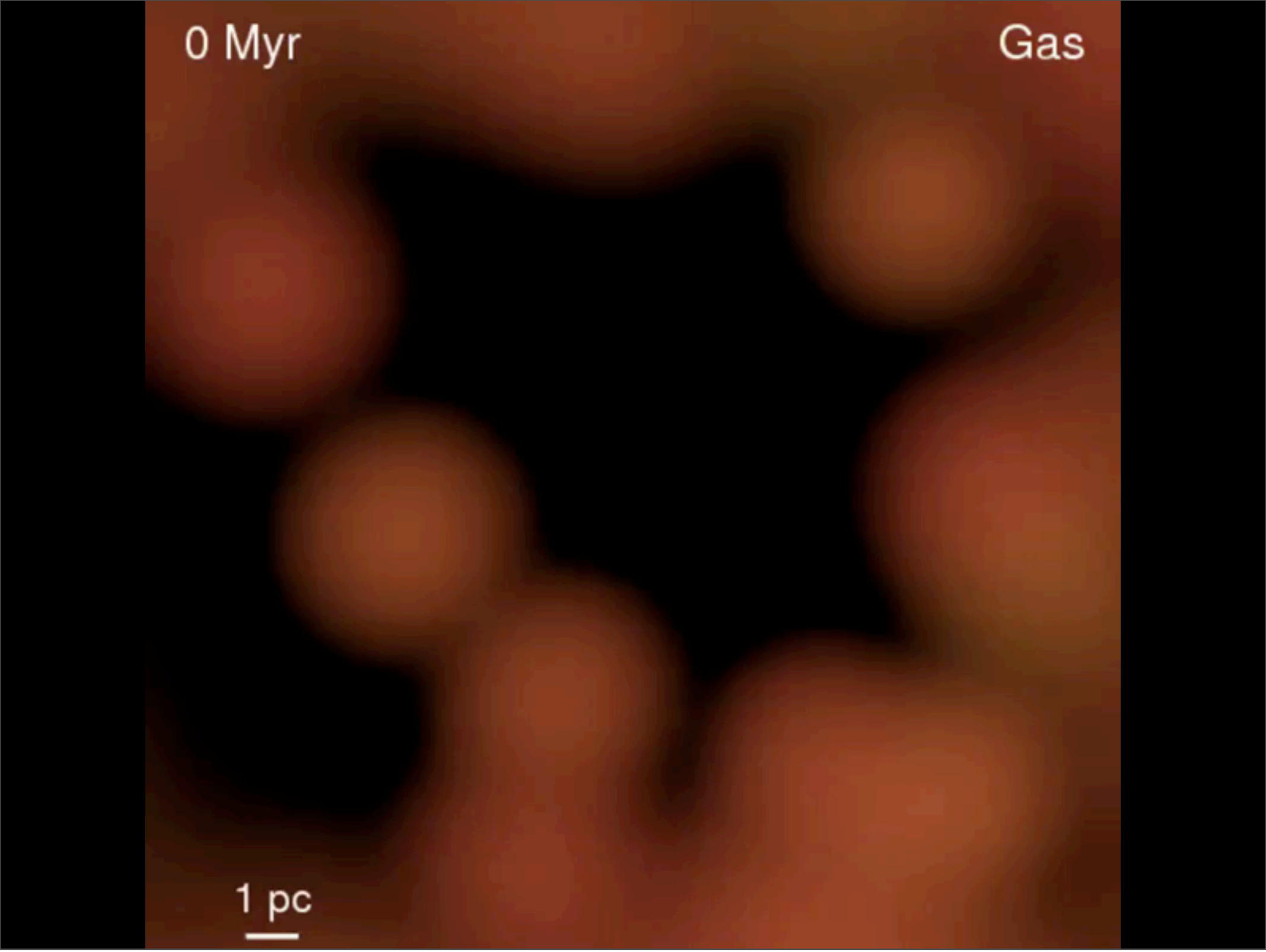
  - SNe

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

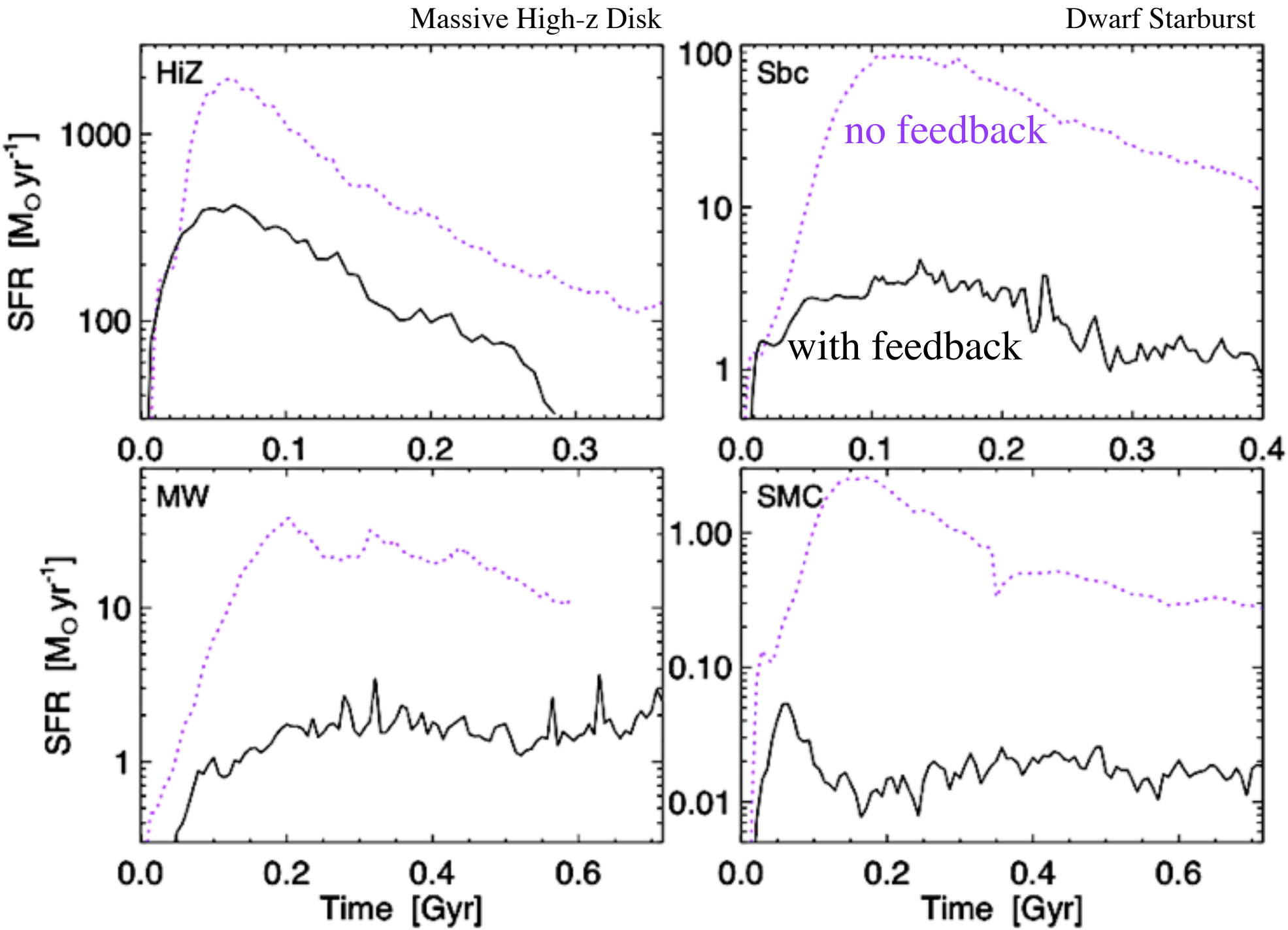
  - Stellar Winds

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




0 Myr
Gas
1 pc

# Stellar Feedback gives Self-Regulated Star Formation



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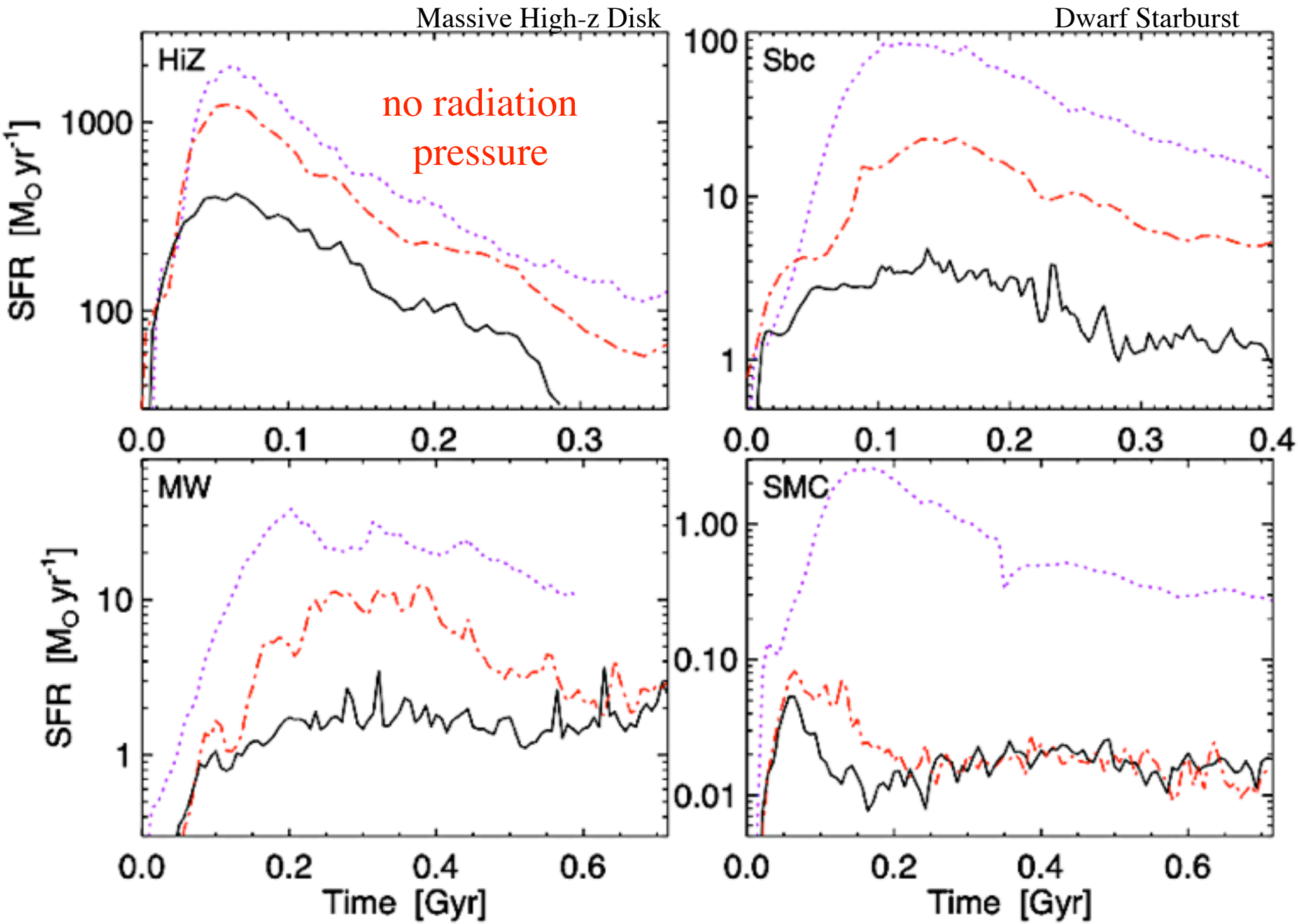

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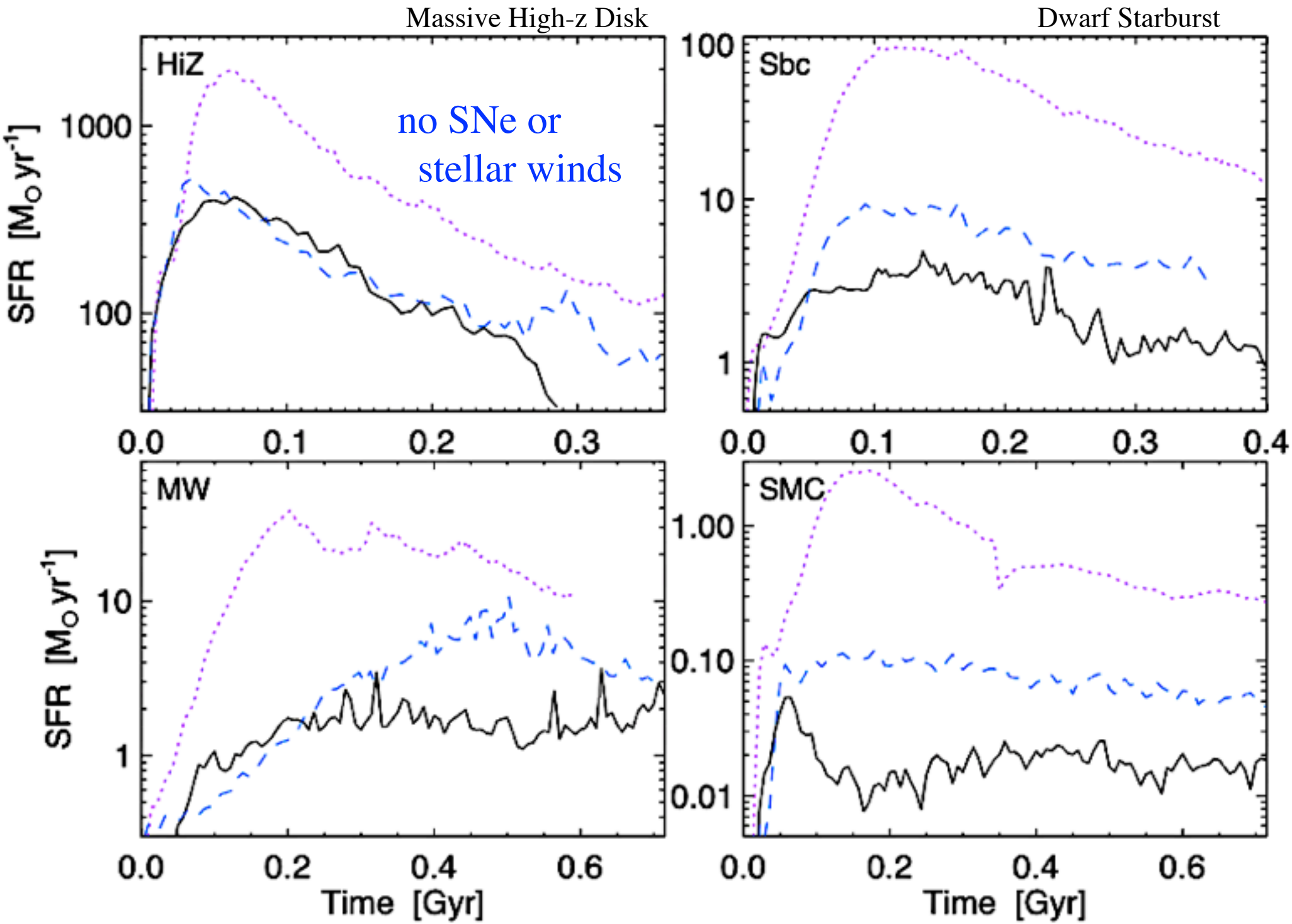
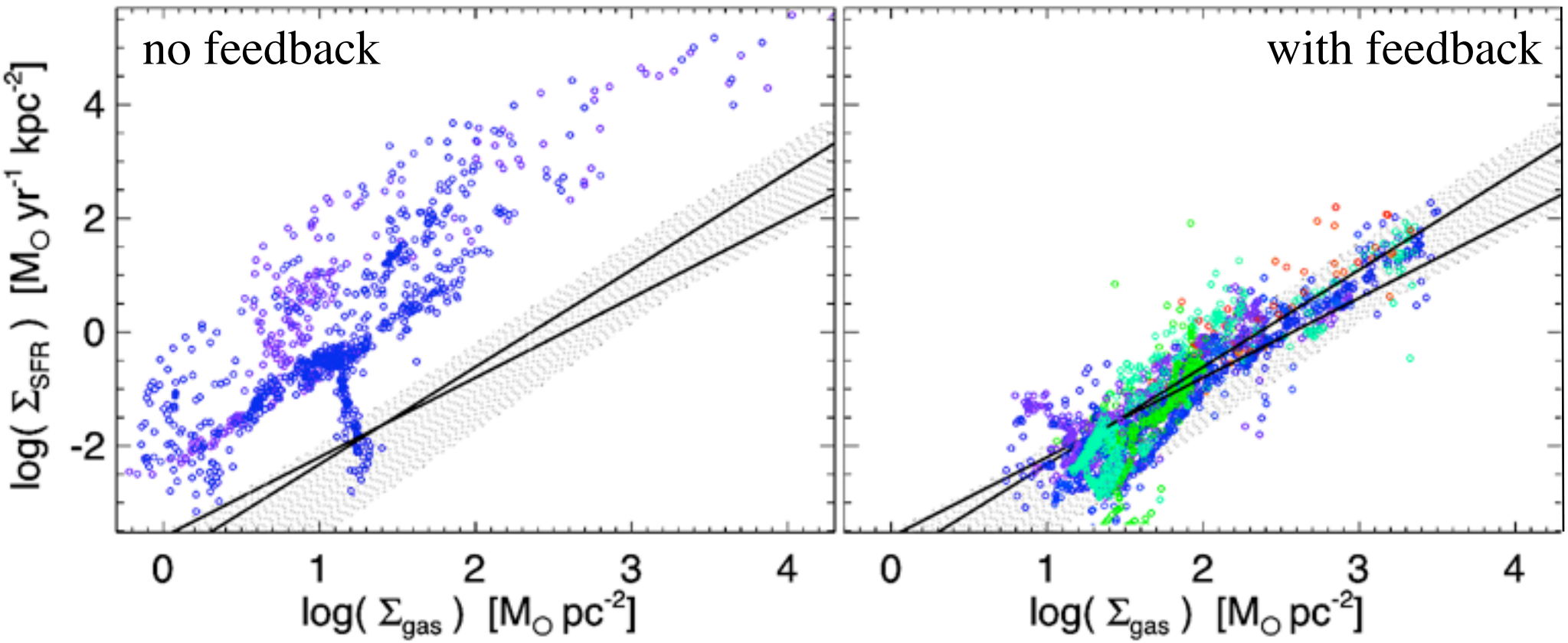


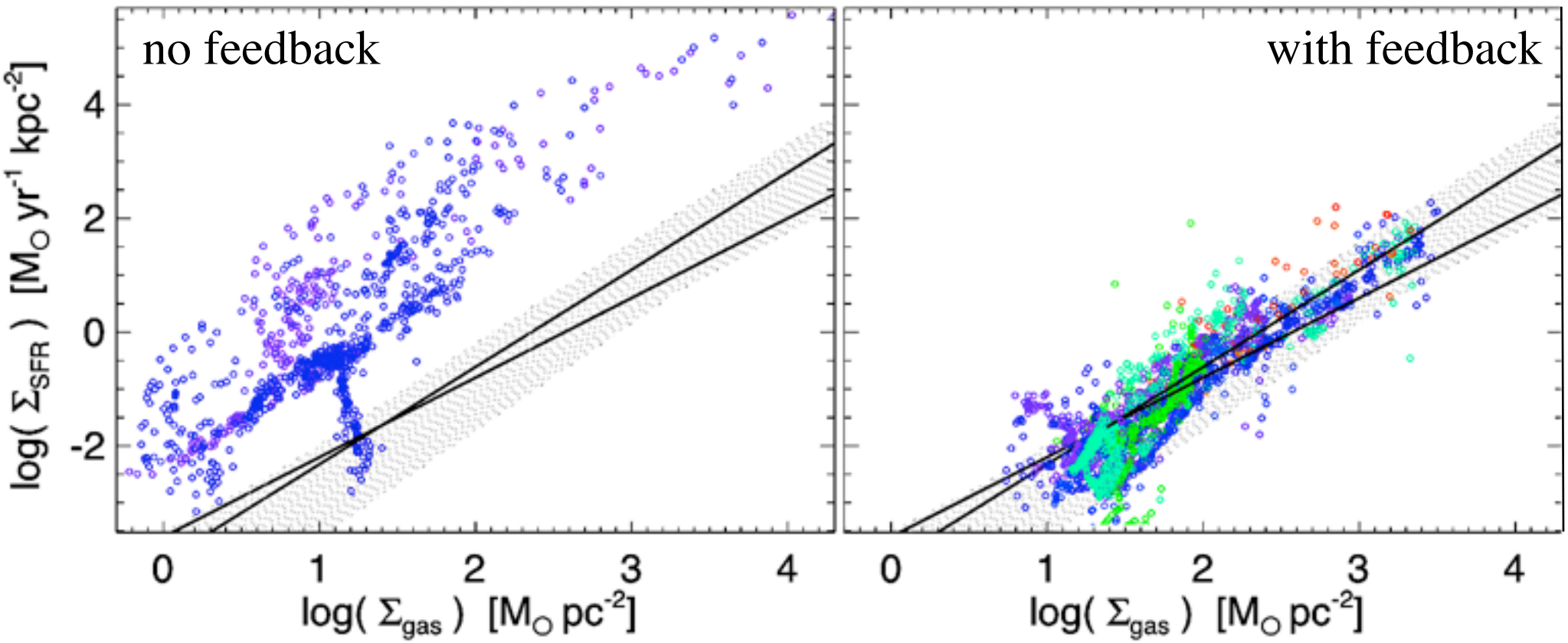
# Kennicutt-Schmidt relation emerges naturally




PFH, Quataert, & Murray, 2011a

# Kennicutt-Schmidt relation emerges naturally

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

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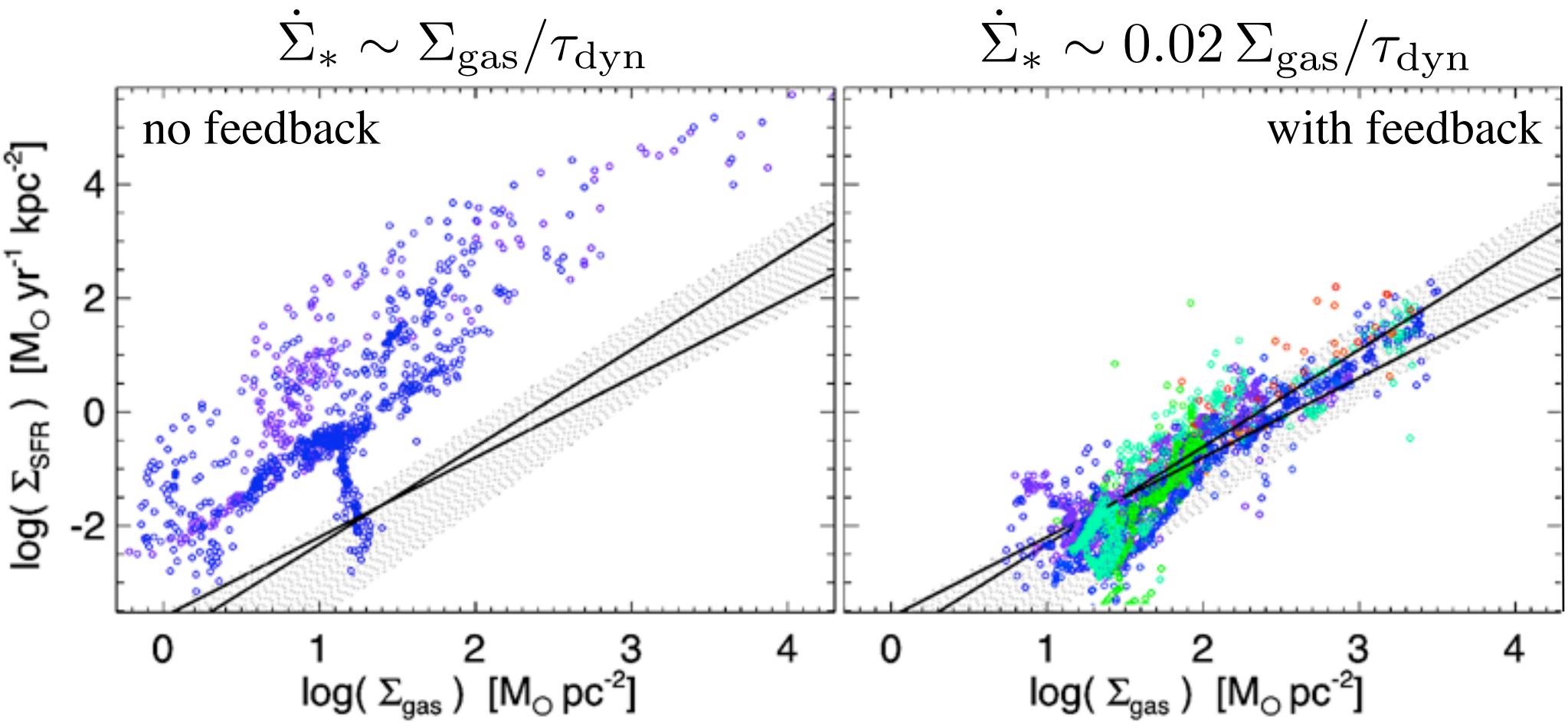


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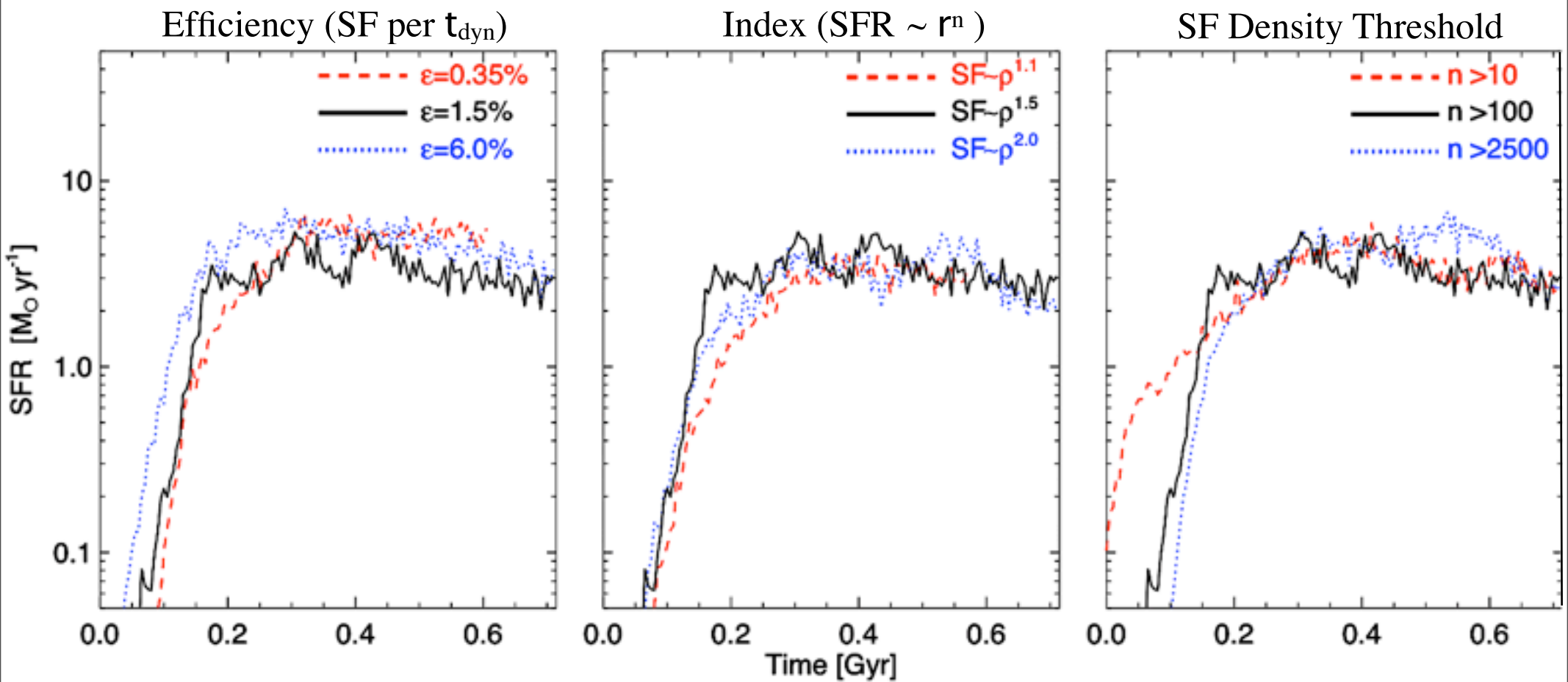
# Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law




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

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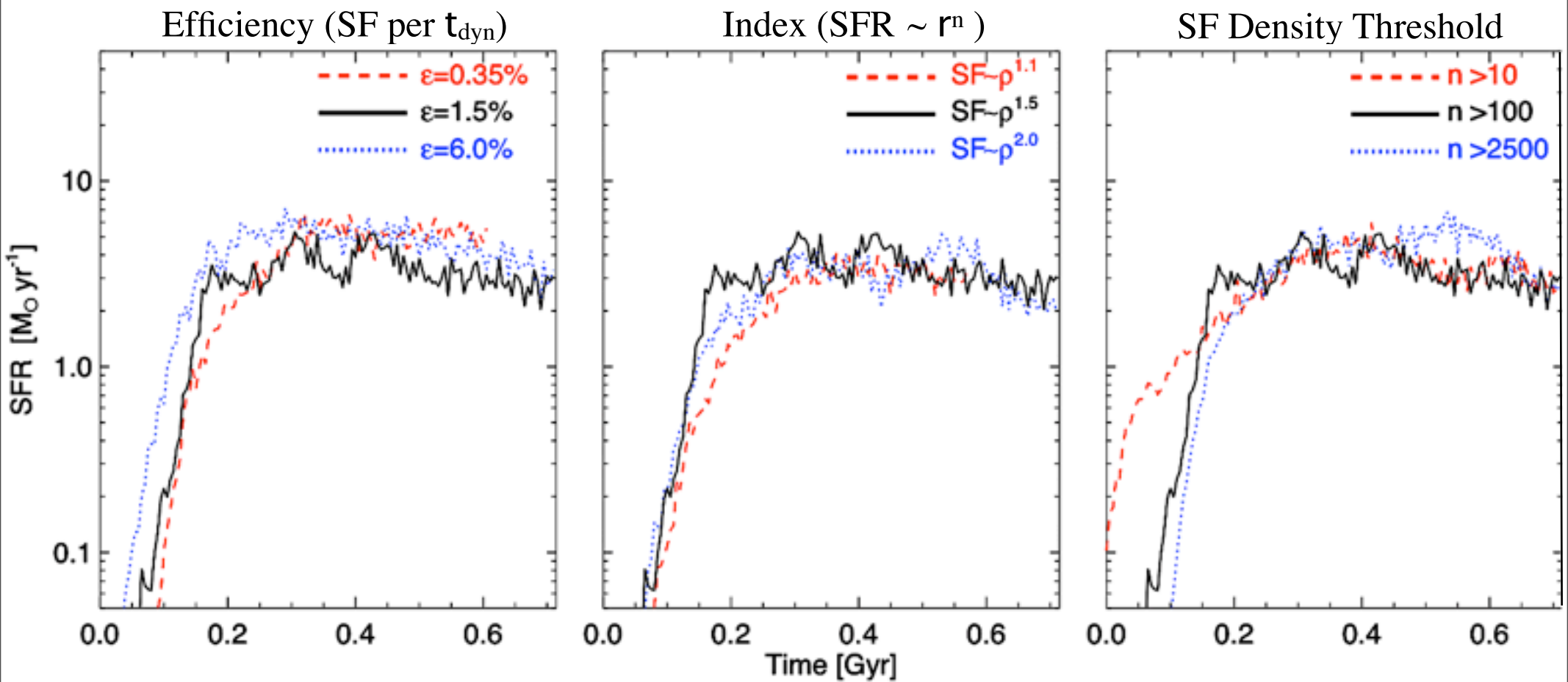
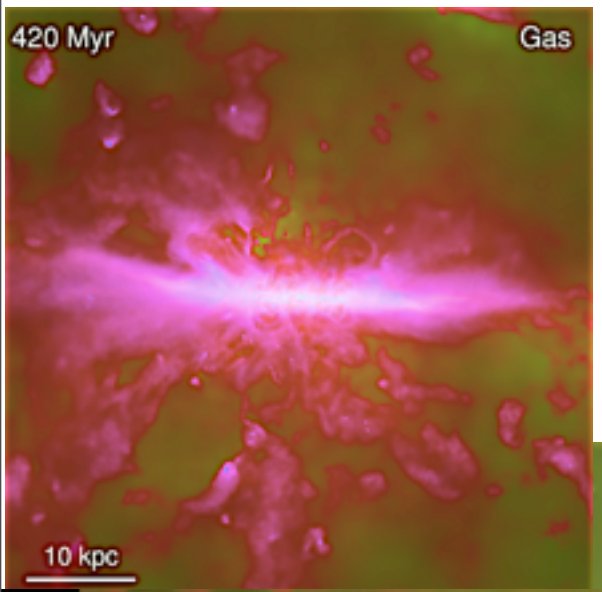
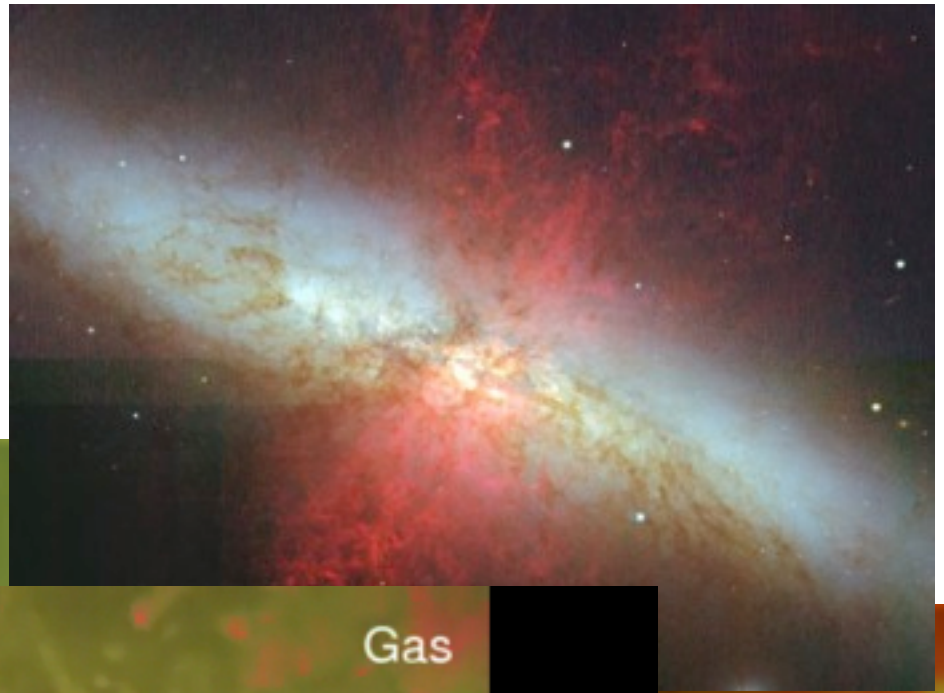


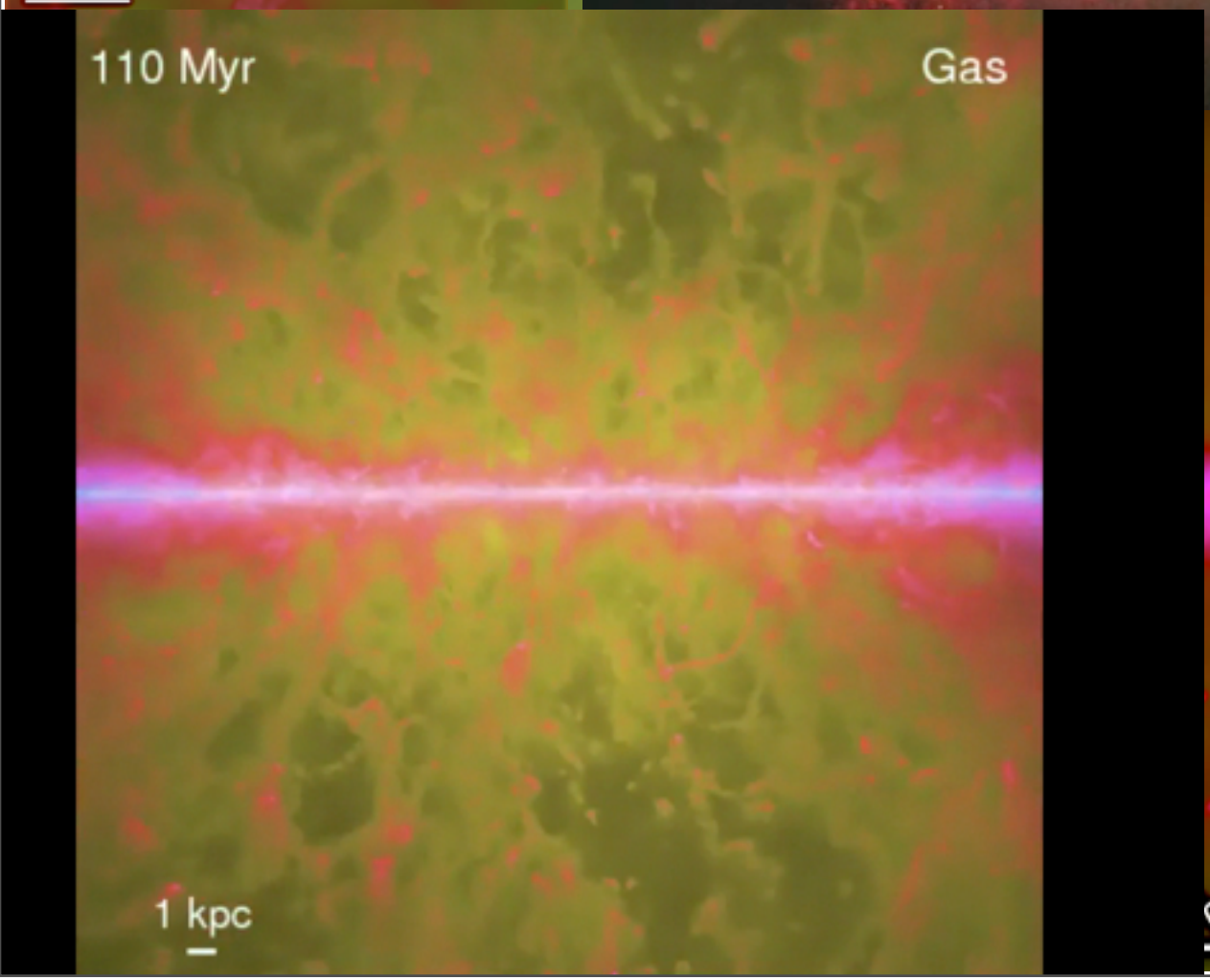

- Set by feedback (i.e. SFR) needed to maintain marginal stability

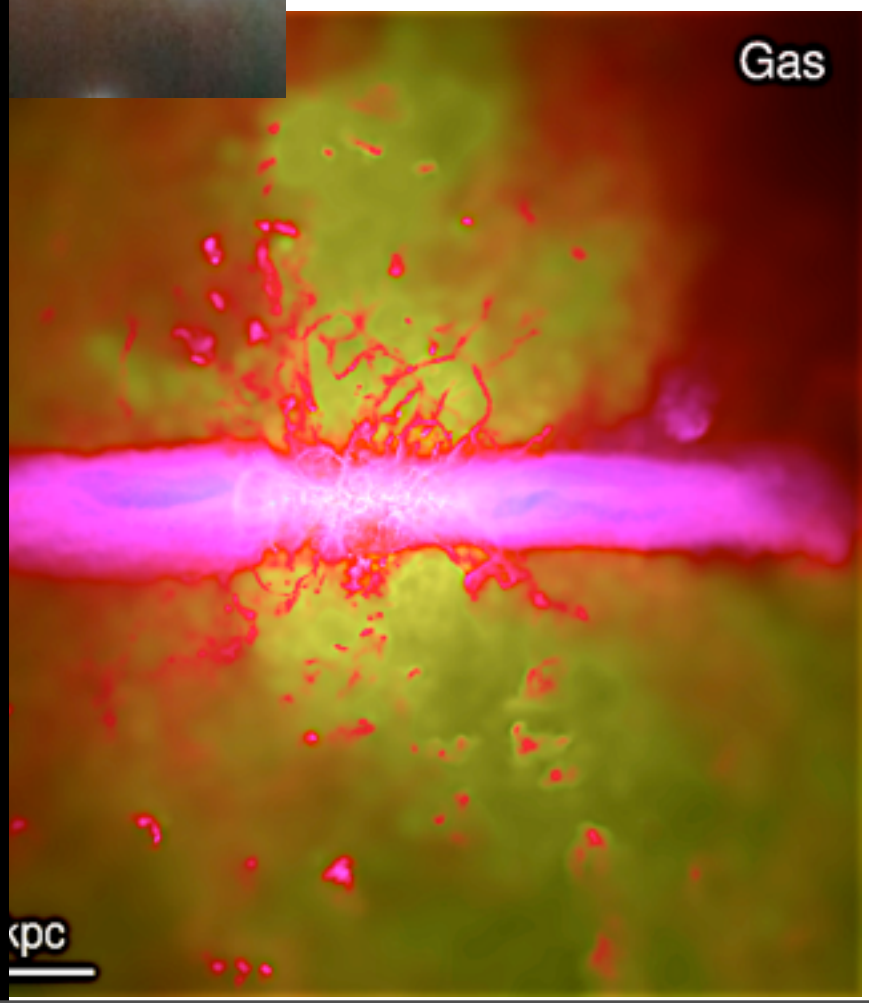
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

# Galactic Super-Winds

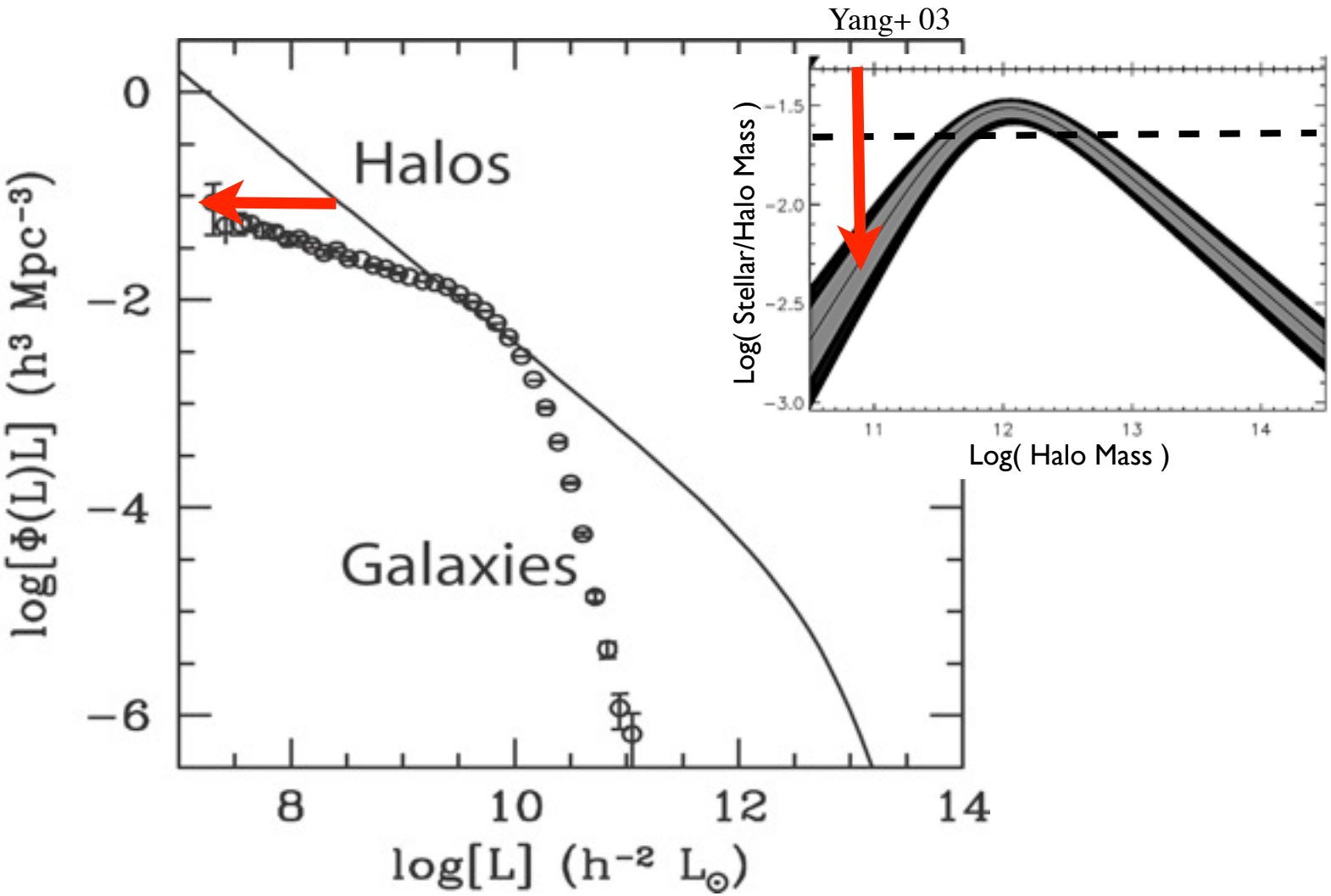




# How Efficient Are Galactic Super-Winds?




- 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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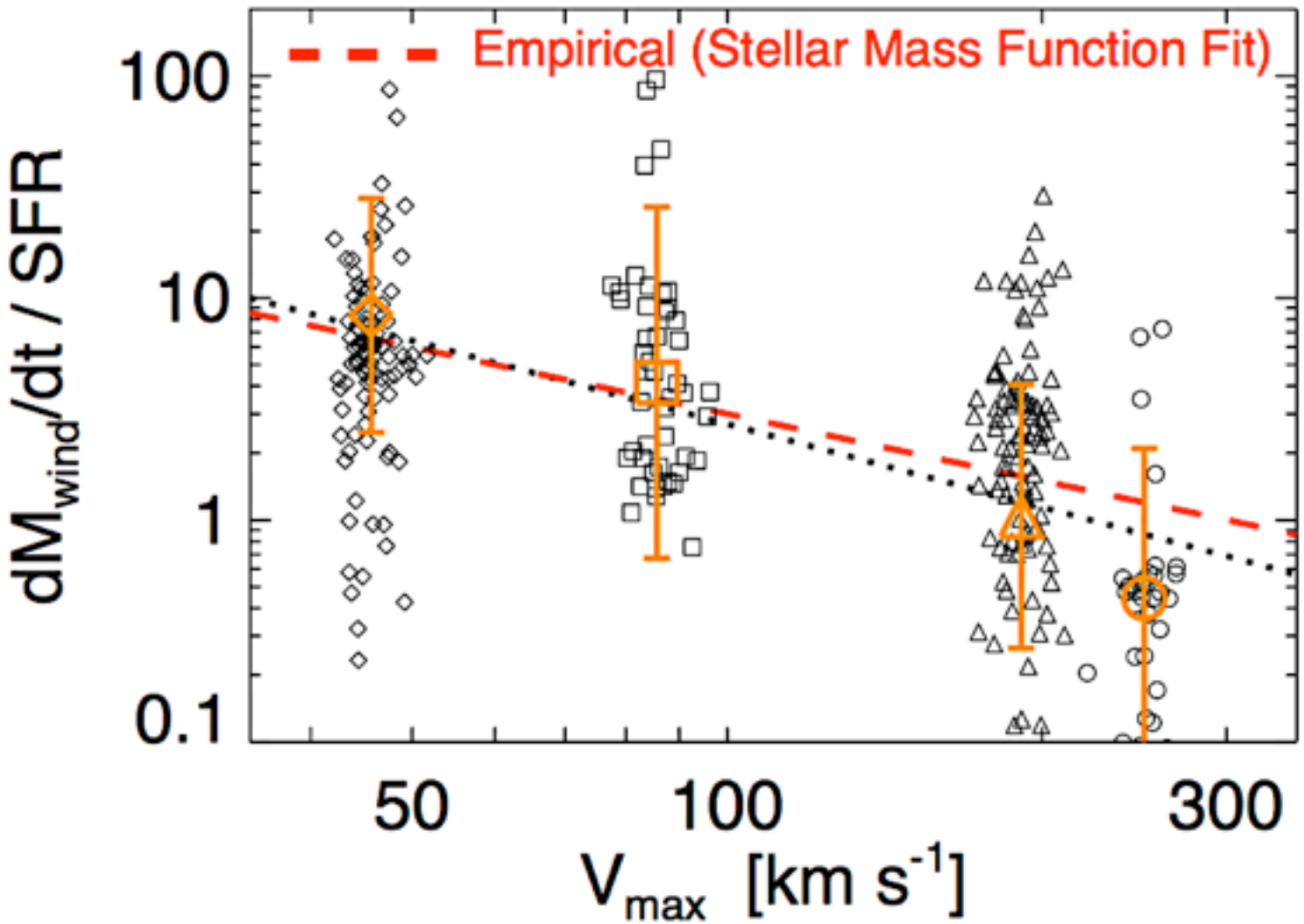


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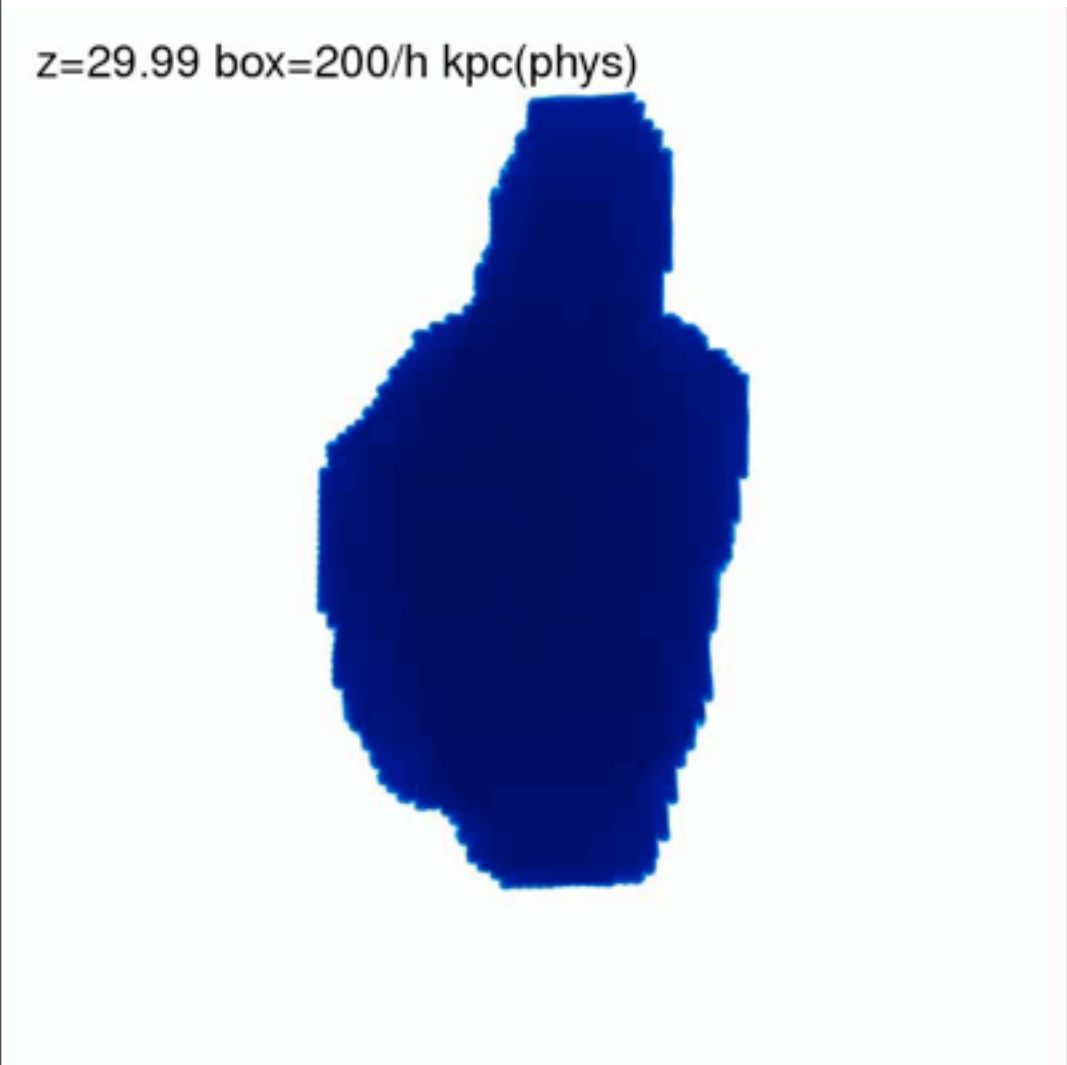
# The Cosmological Inflow/Outflow Cycle

# Cosmological Simulations

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




IGM Density

IGM Temperature

**Keres & PFH et al**

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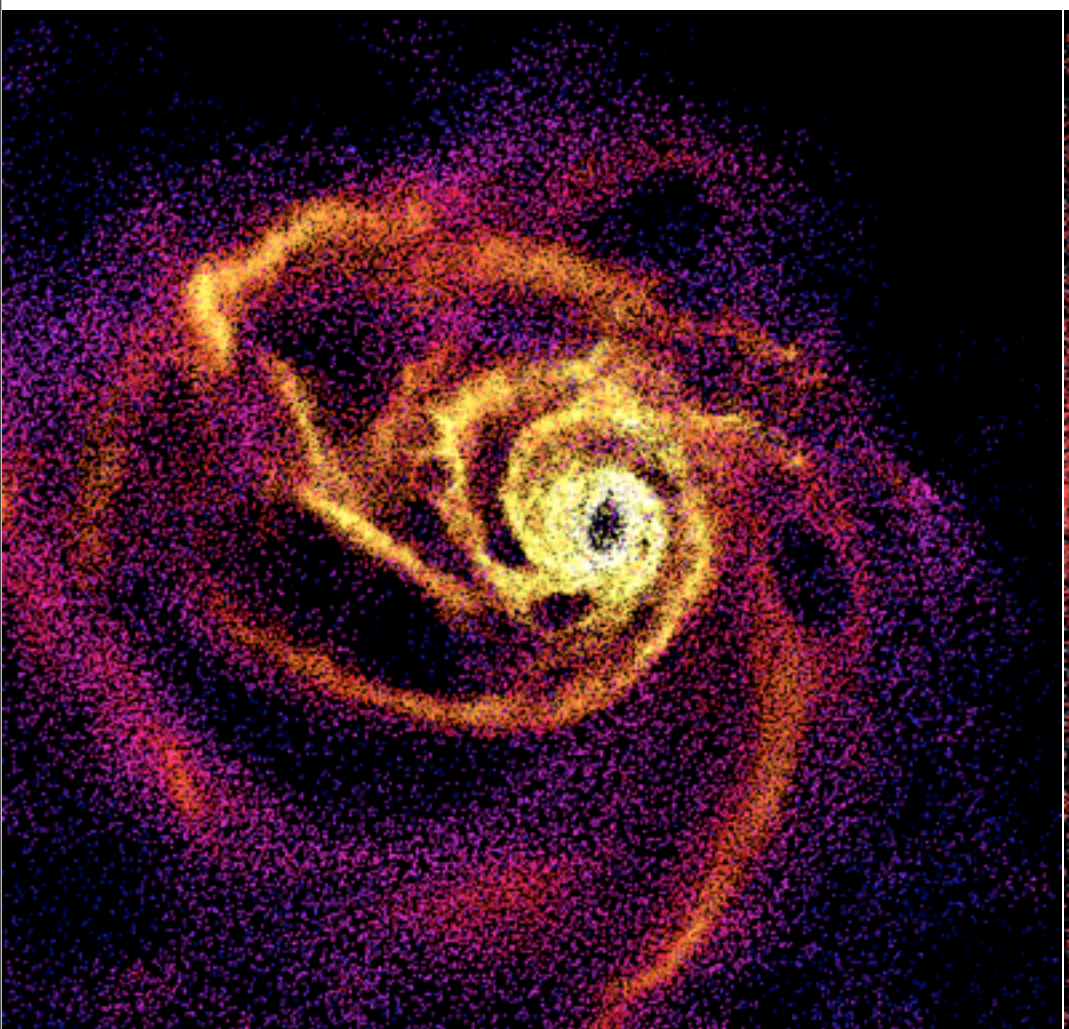
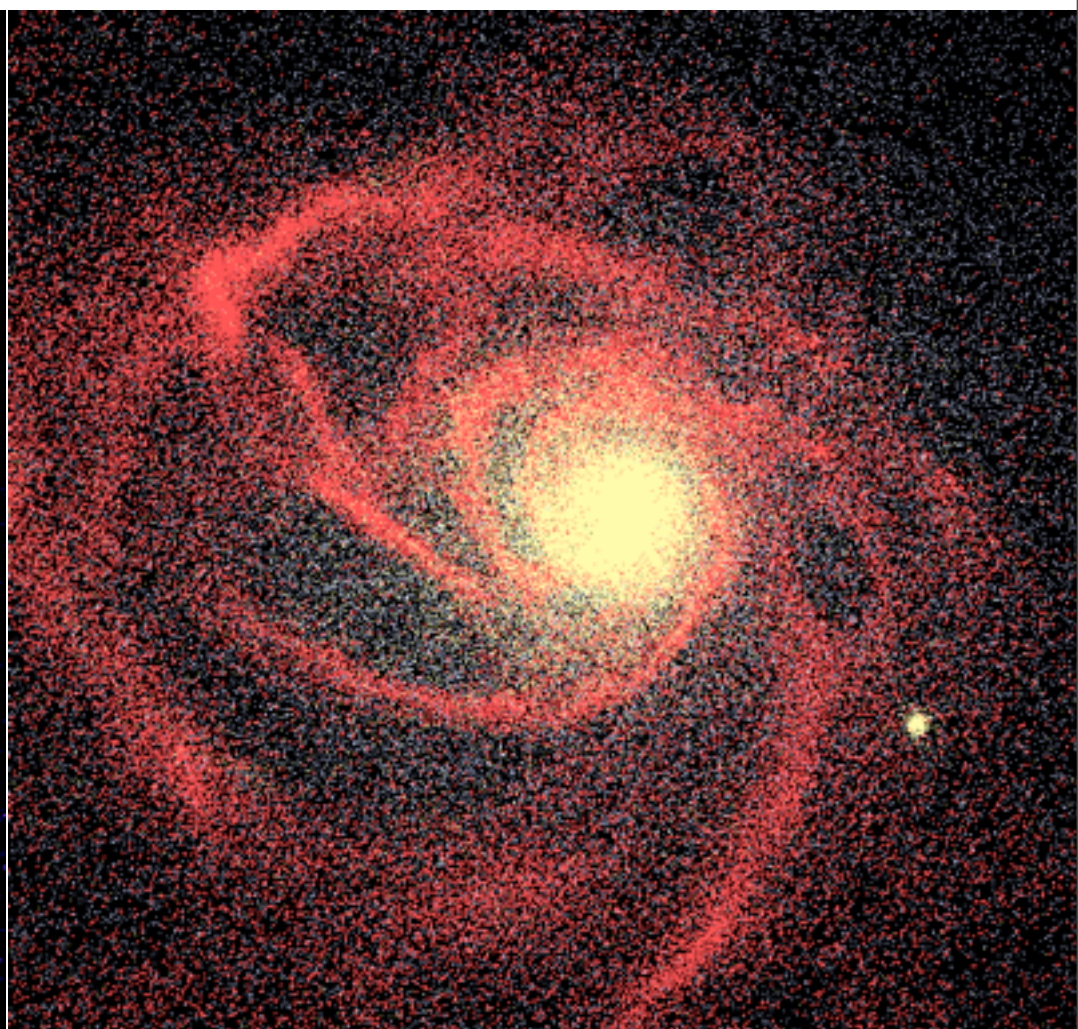


Gas Density

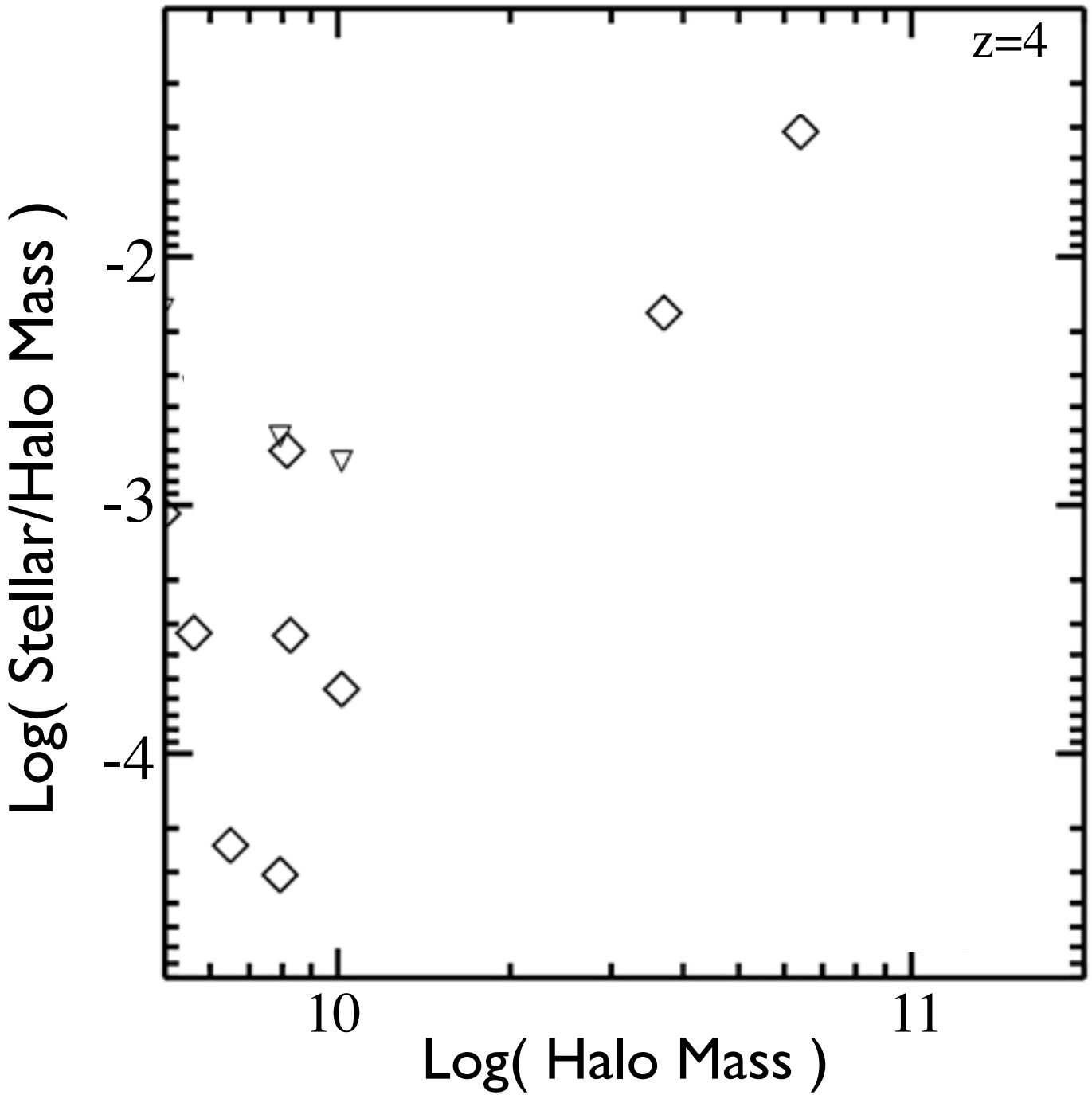


Stars

**Keres & PFH et al**

# How Inefficient is Galaxy Formation?

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

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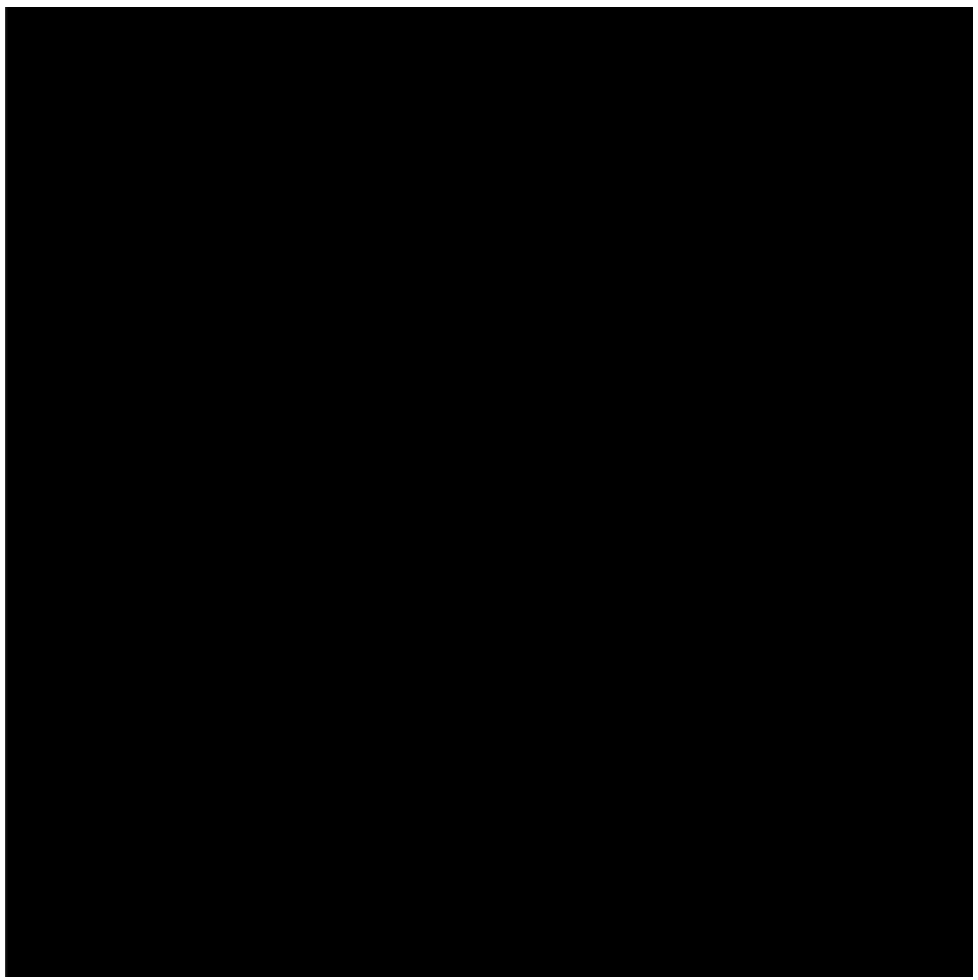
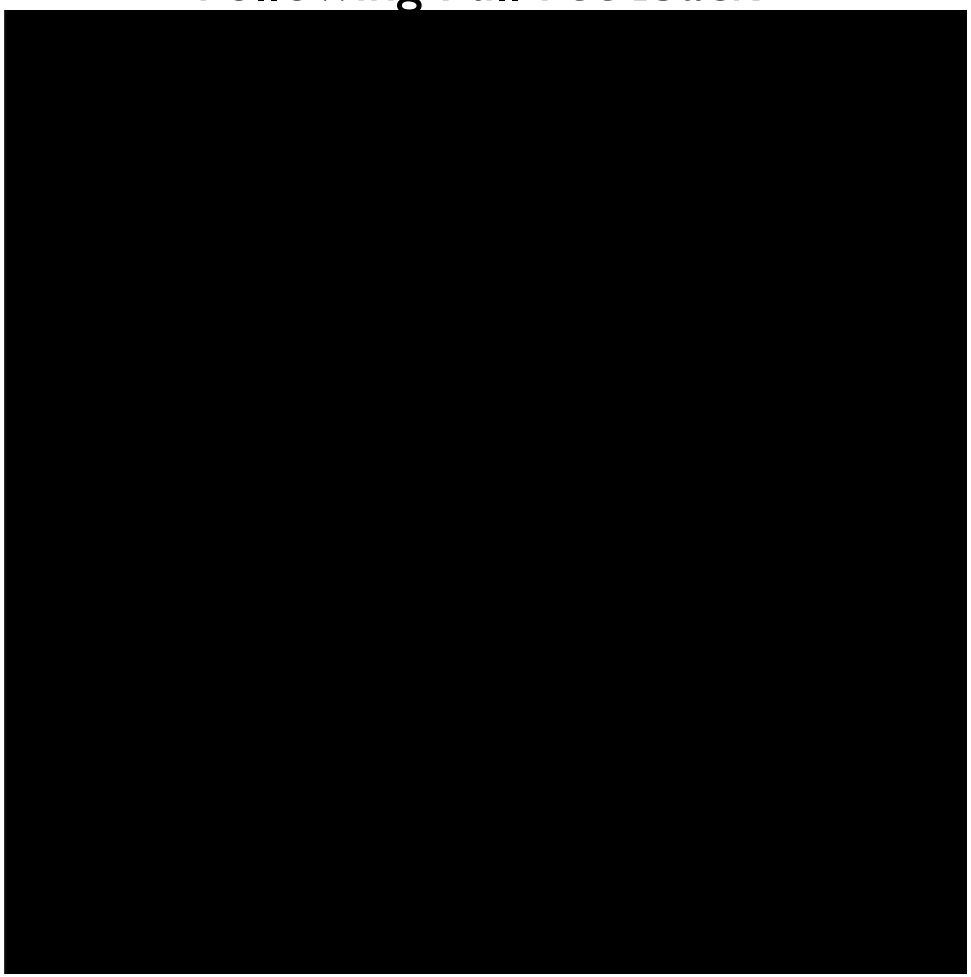
& Onorbe et a

# Proto-MW: Gas Temperature:

No Feedback



Following Full Feedback

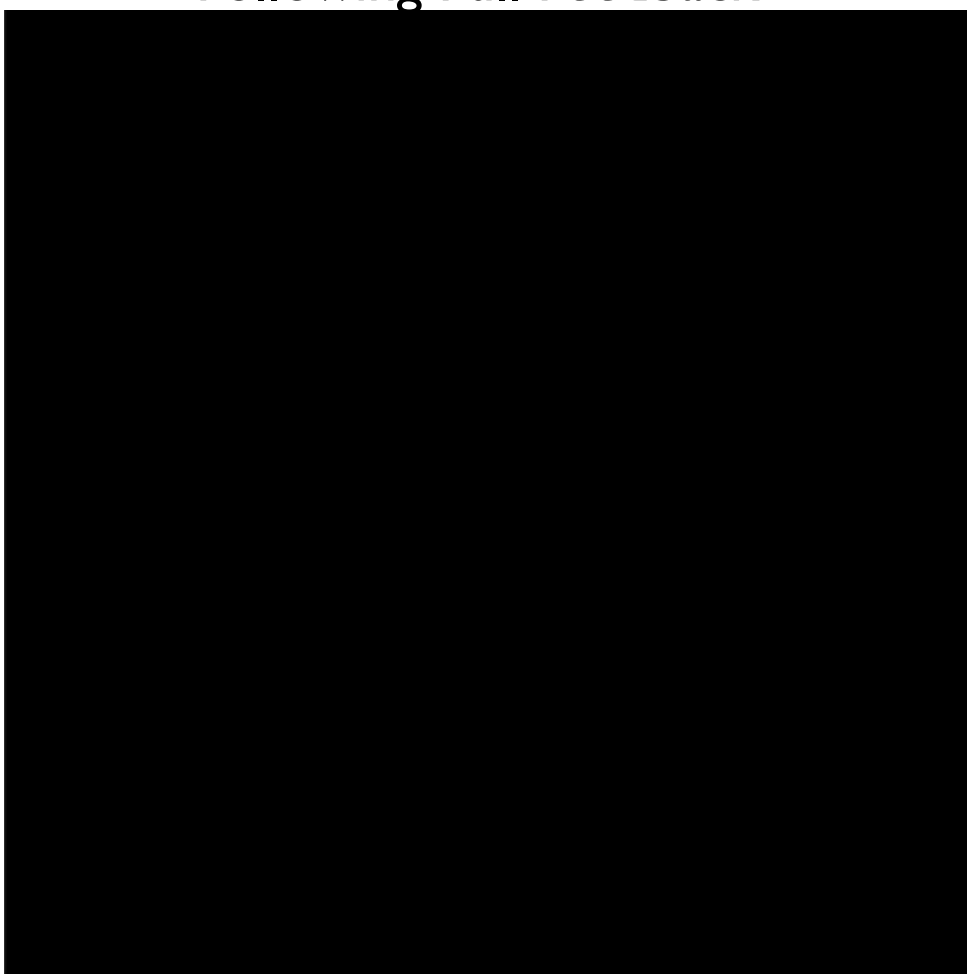


**Keres & PFH et al**

# Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

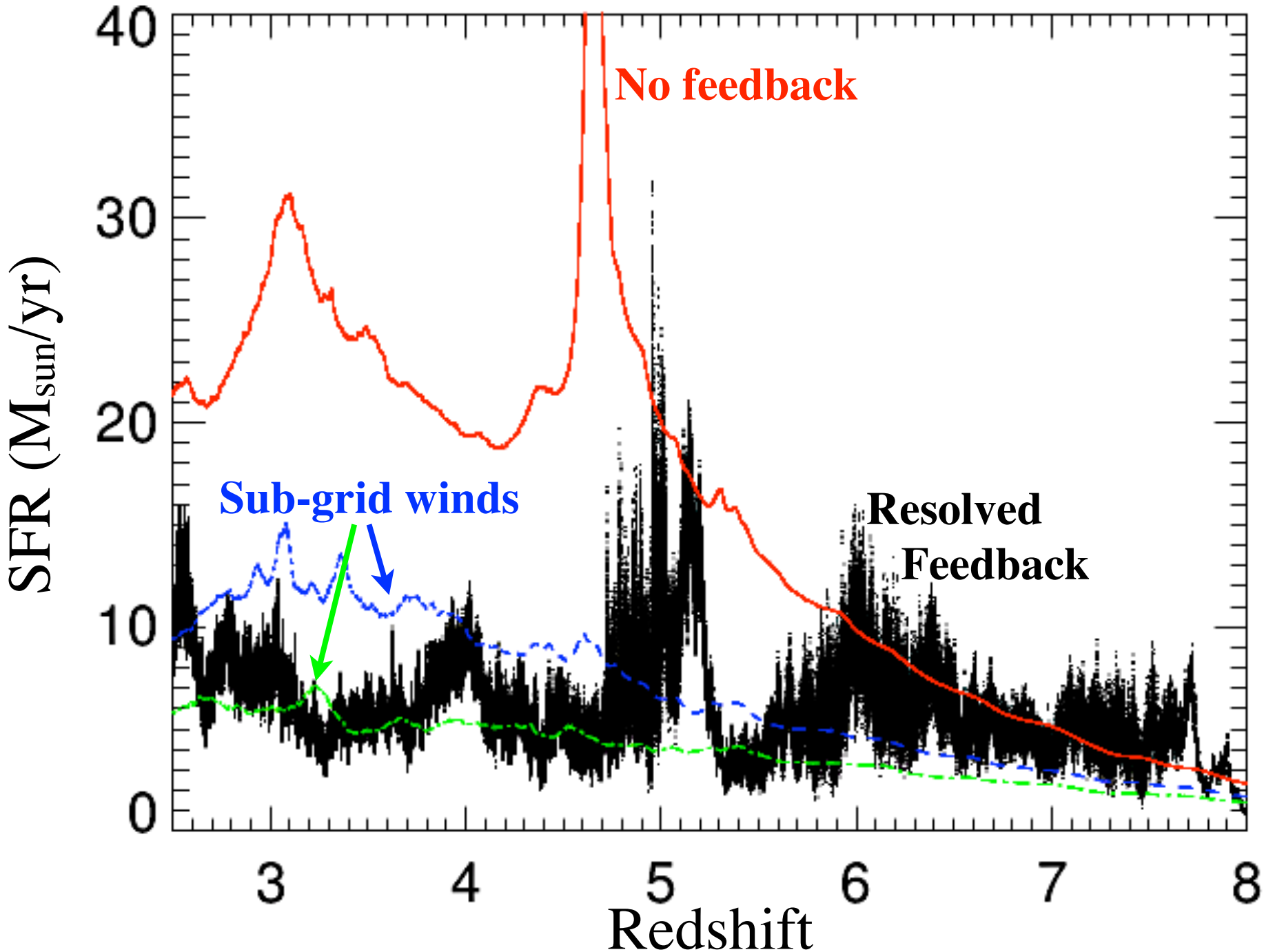
Following Full Feedback



Keres & PFH et al

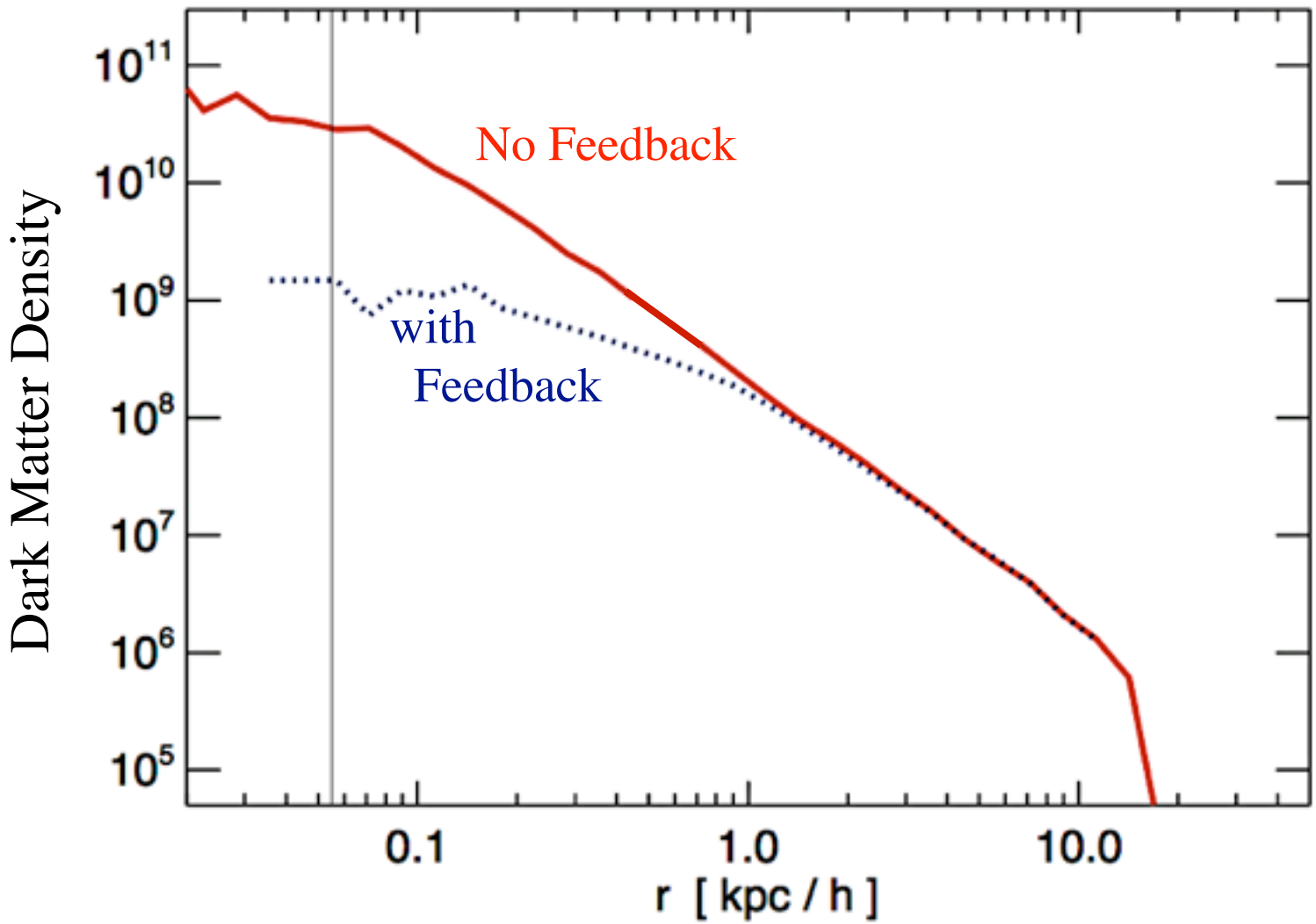
# Starburst-Driven Winds

## SUB-GRID vs. RESOLVED MATTERS!



# Dark Matter Profiles: Baryons or Cosmology?

## DO RESOLVED WINDS ACTUALLY MAKE CORES?

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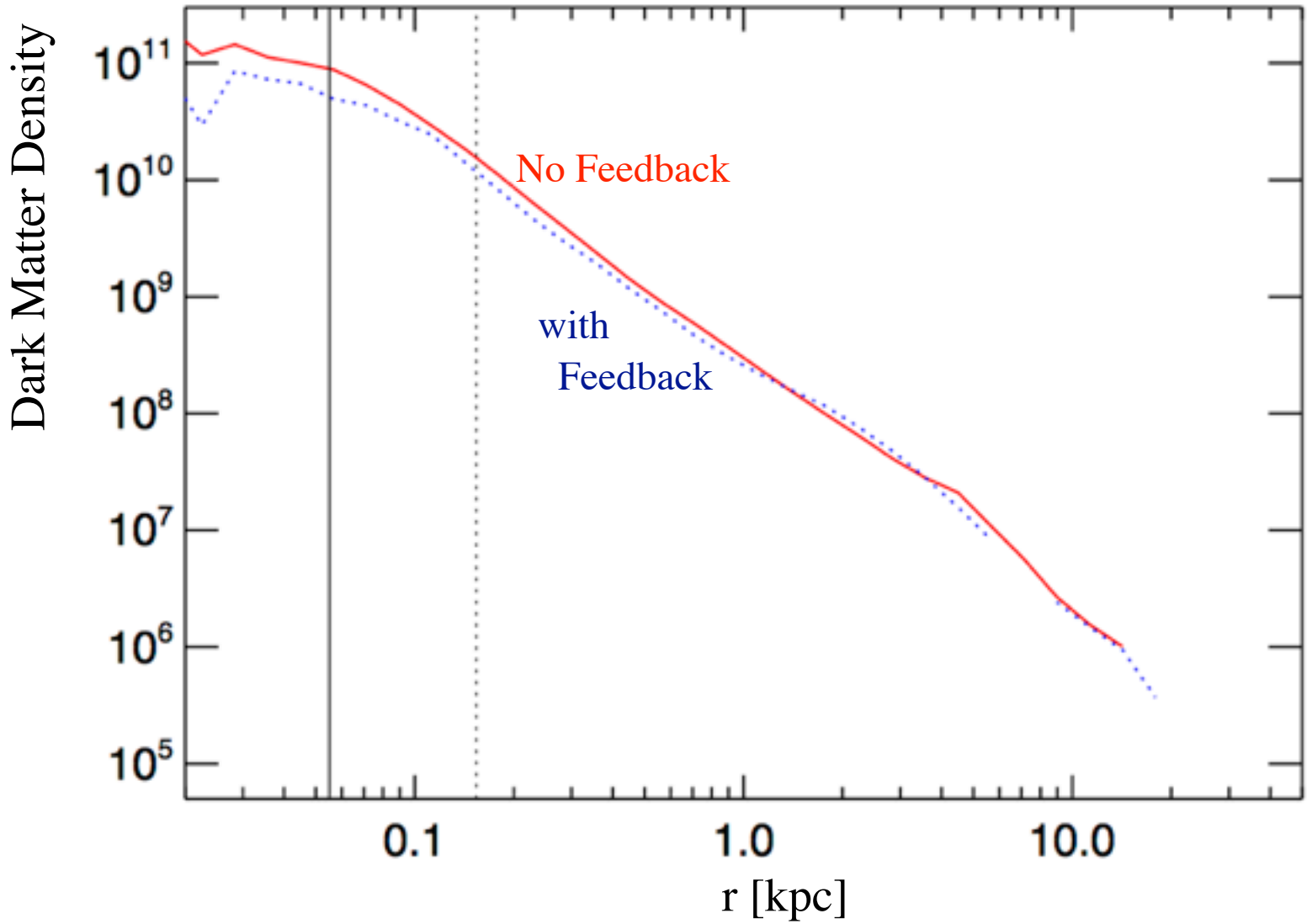
Bullock,
& Onorbe et a

# BUT...

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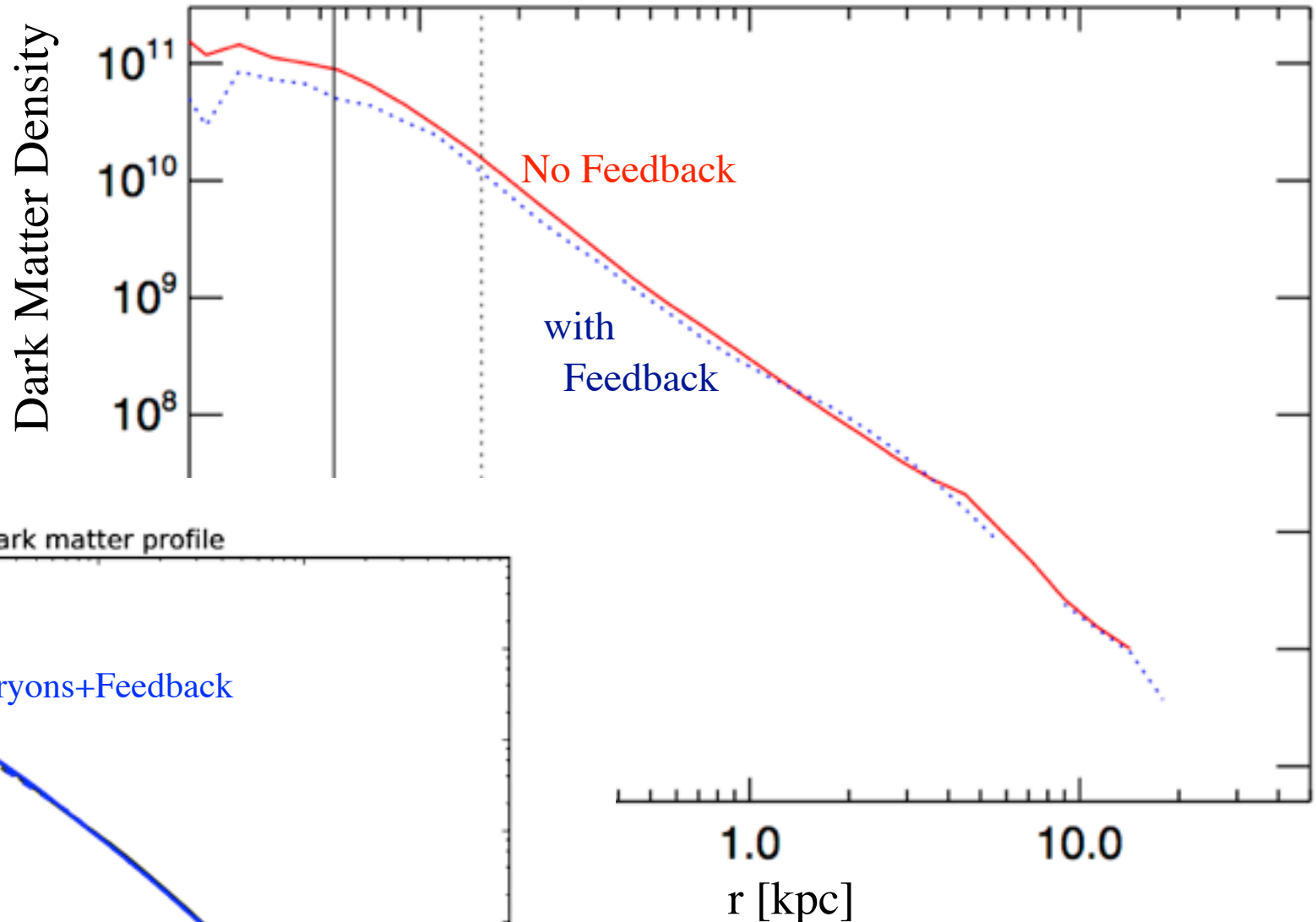


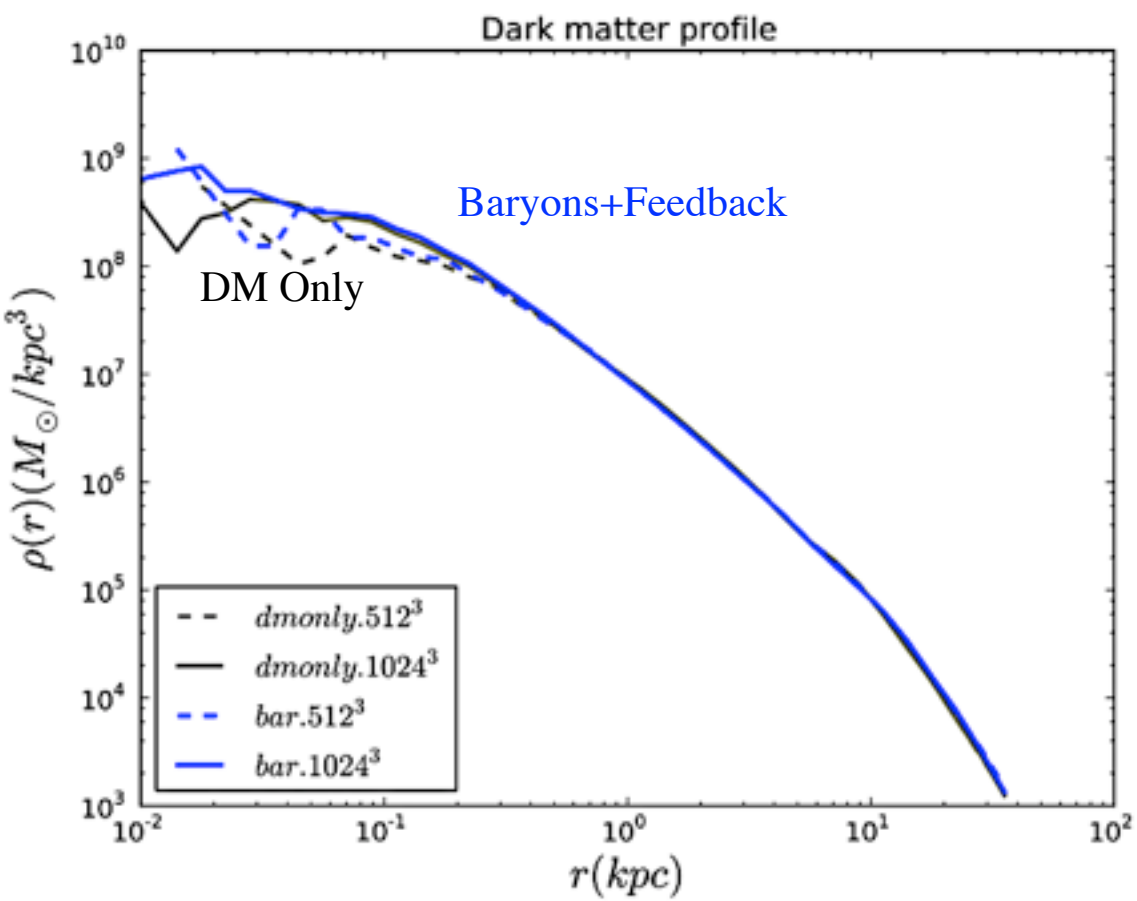


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Bullock,
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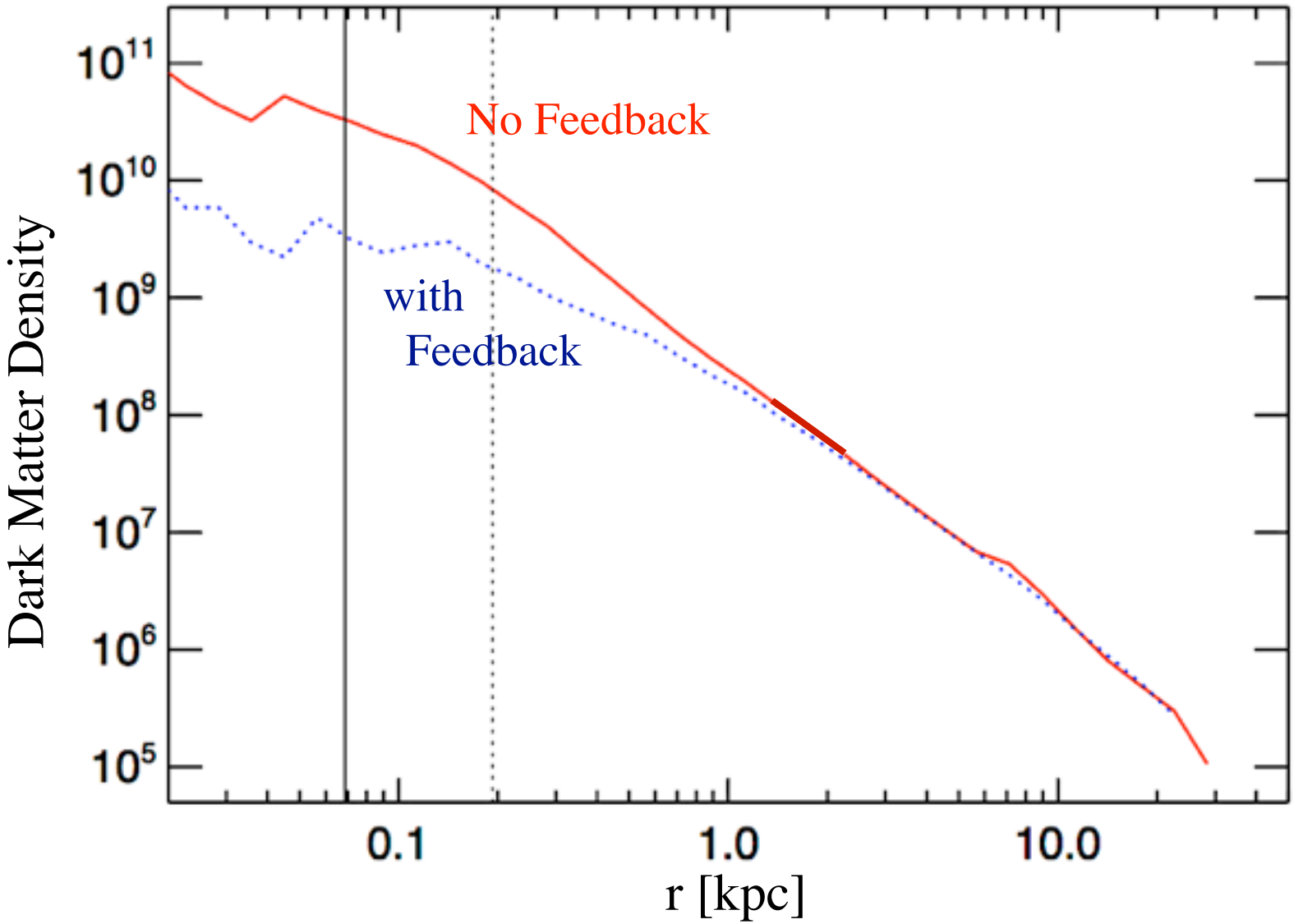


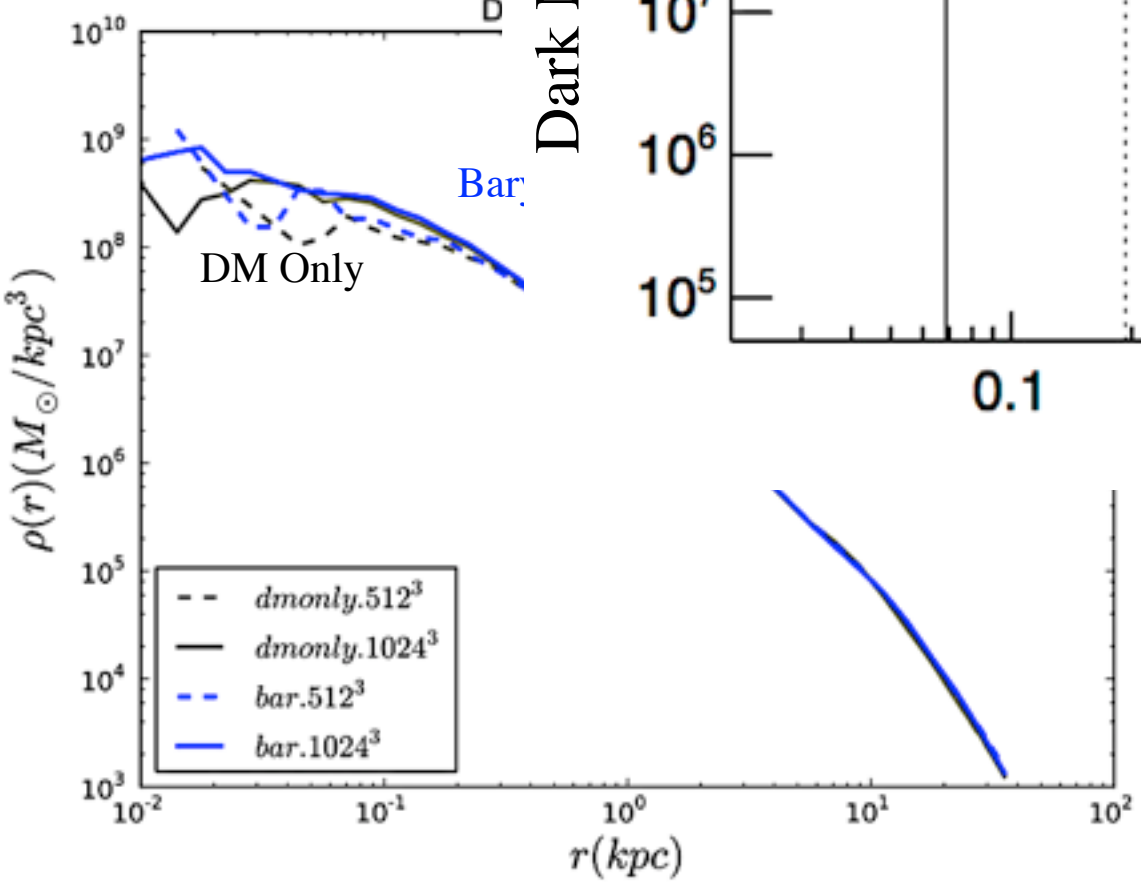


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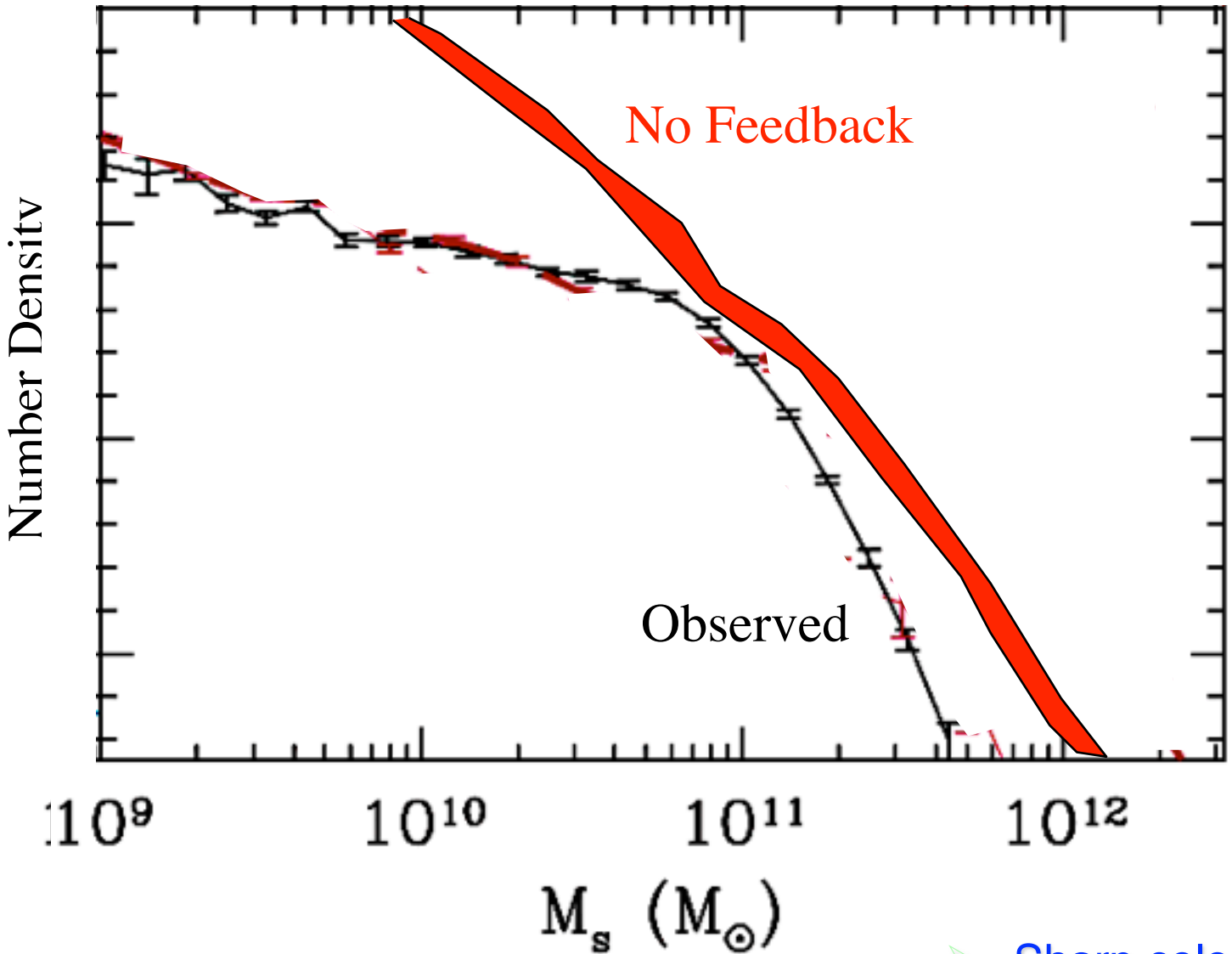
# What About the AGN?

# What can AGN Feedback Do For You?




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

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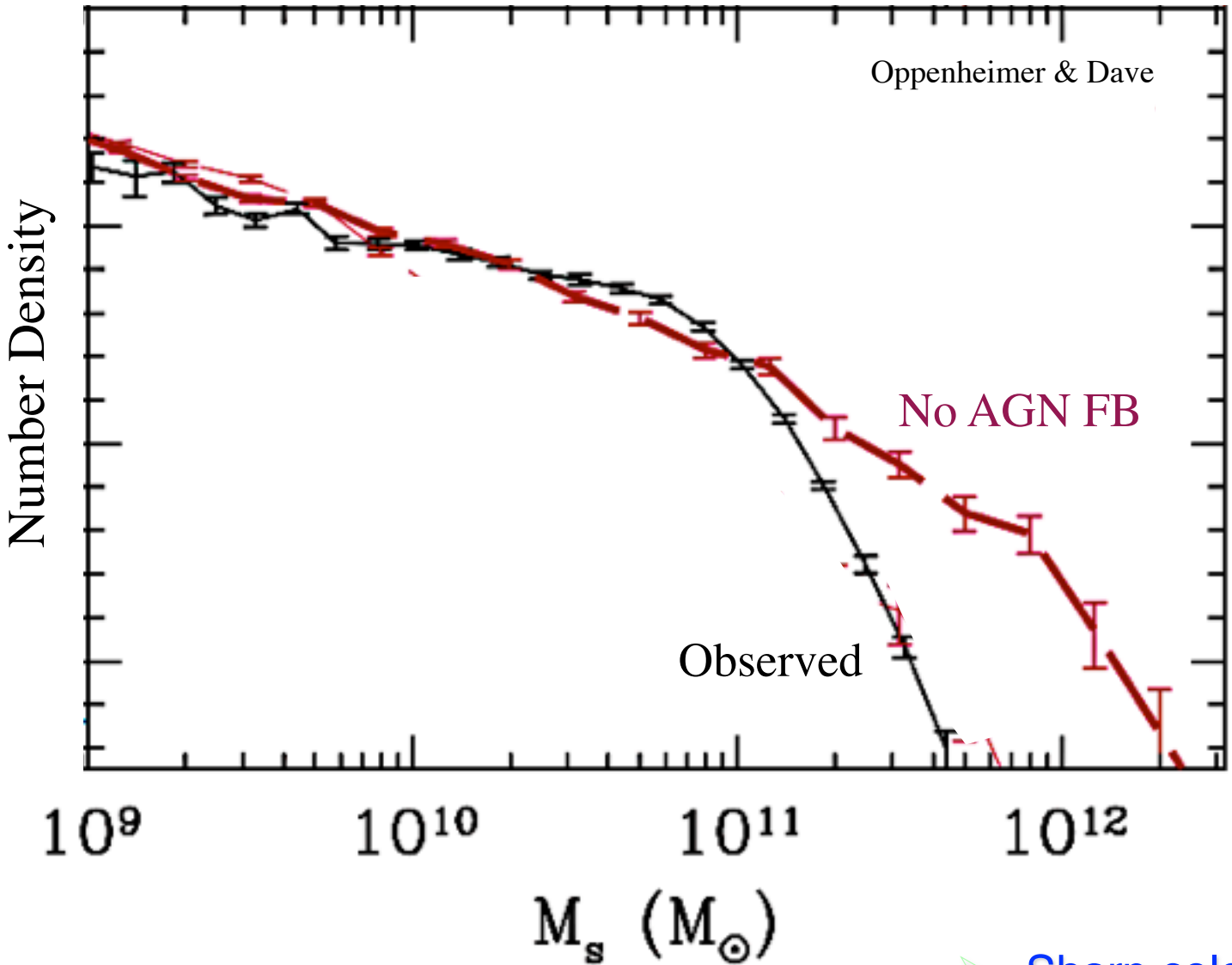


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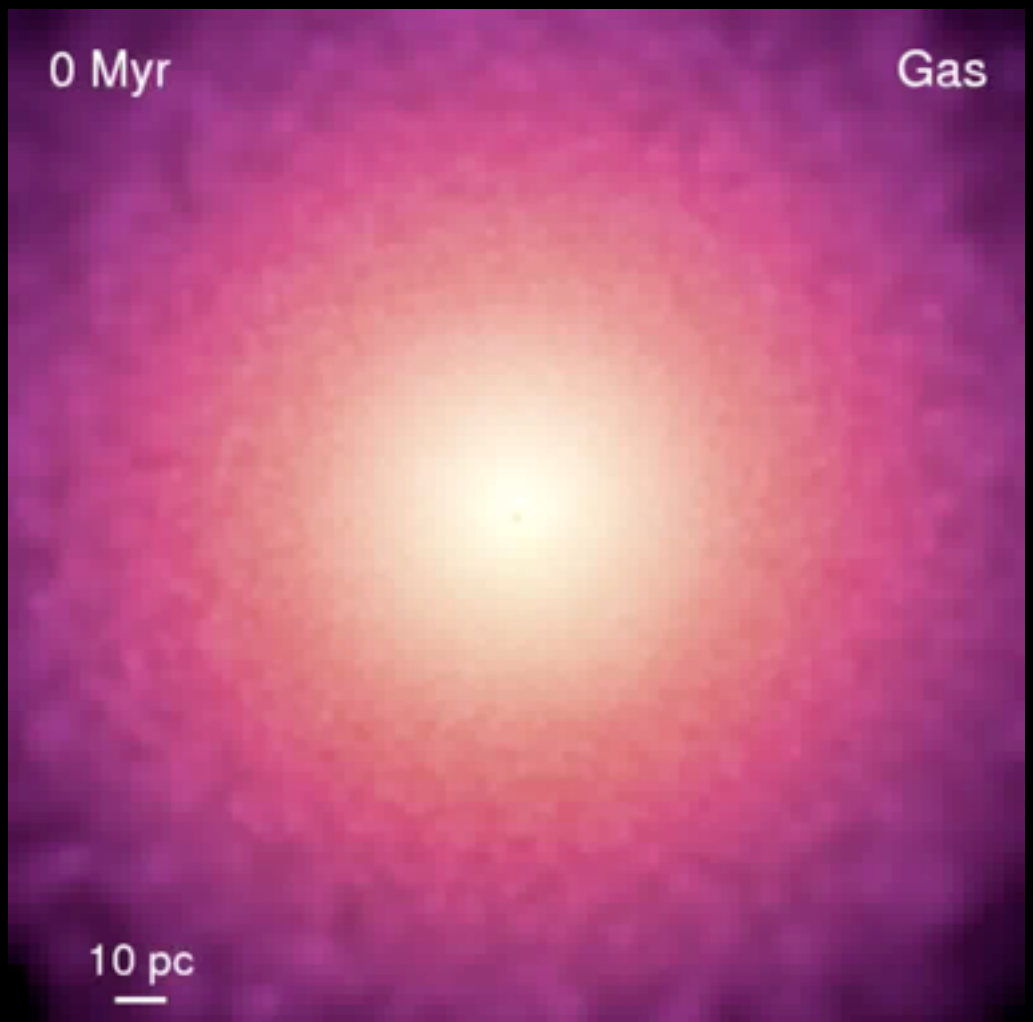
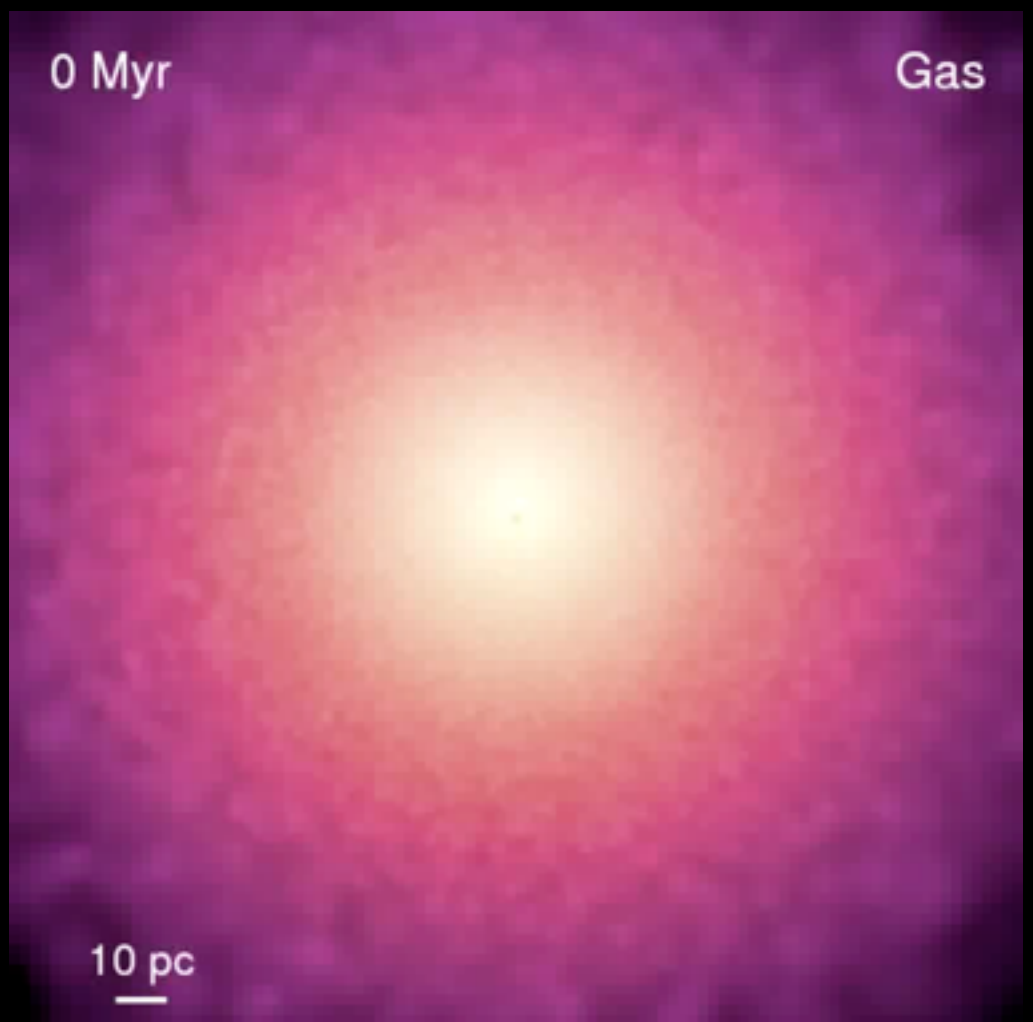
# BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds



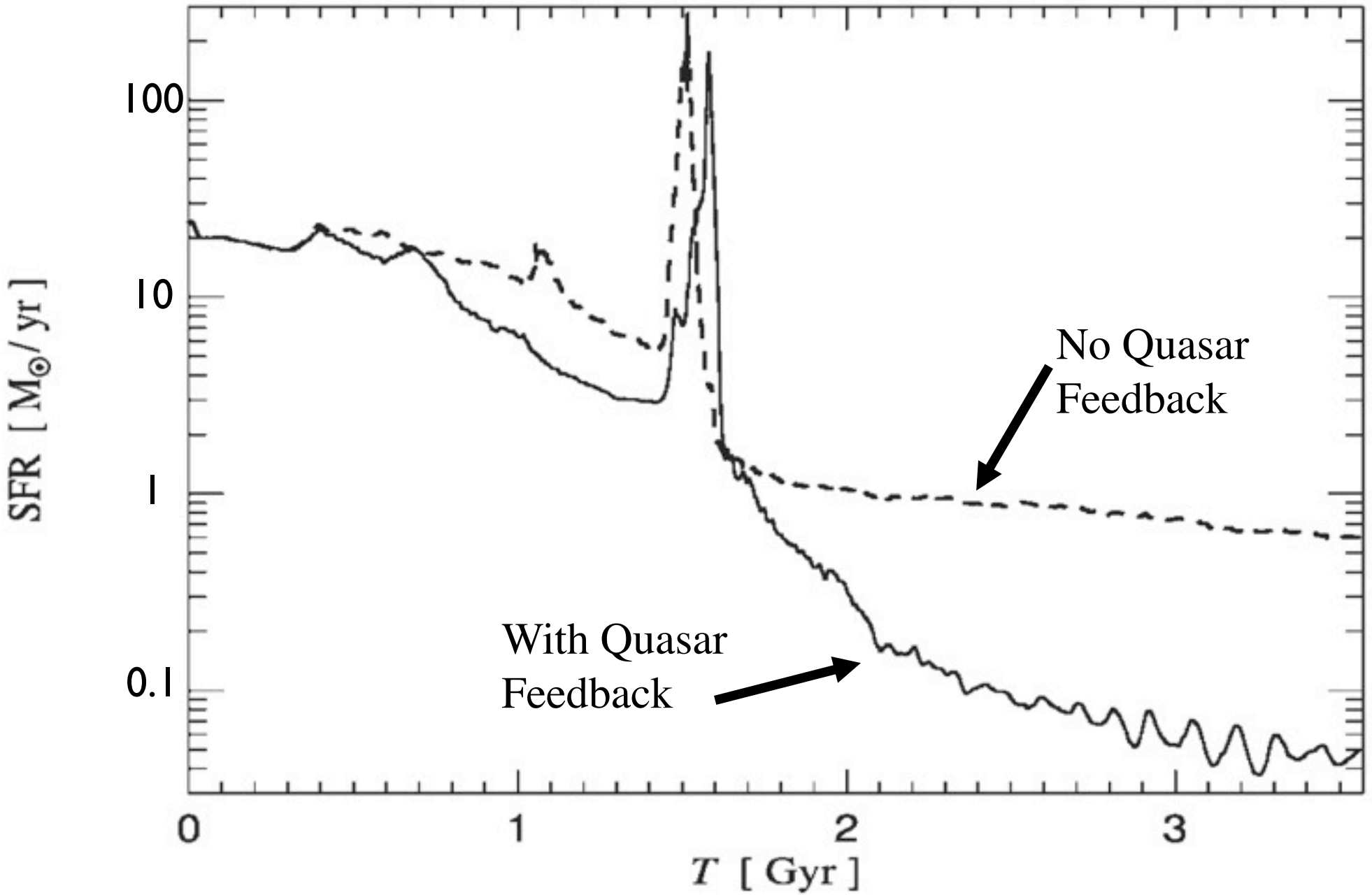

With BAL Winds




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

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

# Do we need 'Quasar Mode' Feedback?



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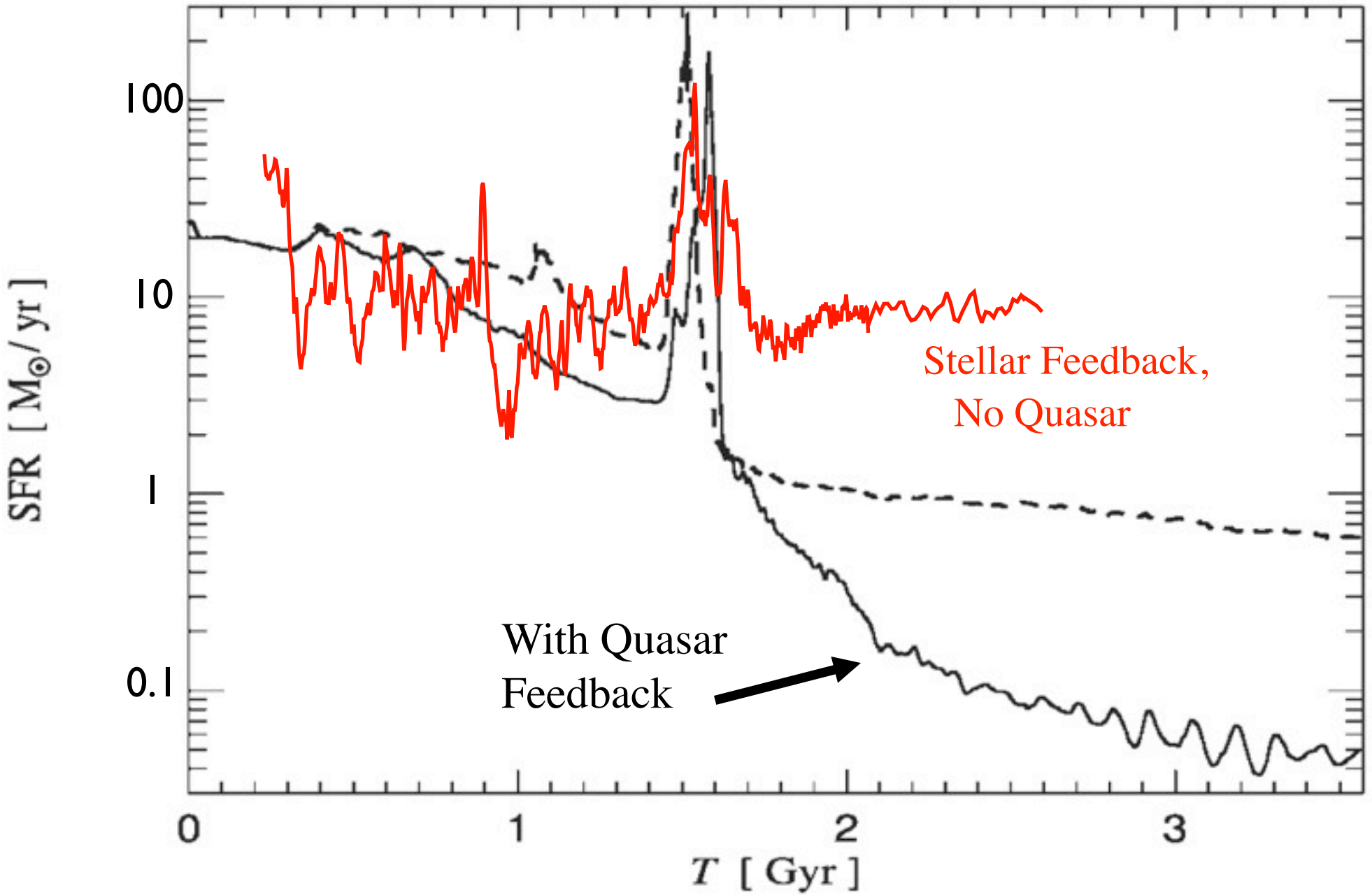

# Summary:

- **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!