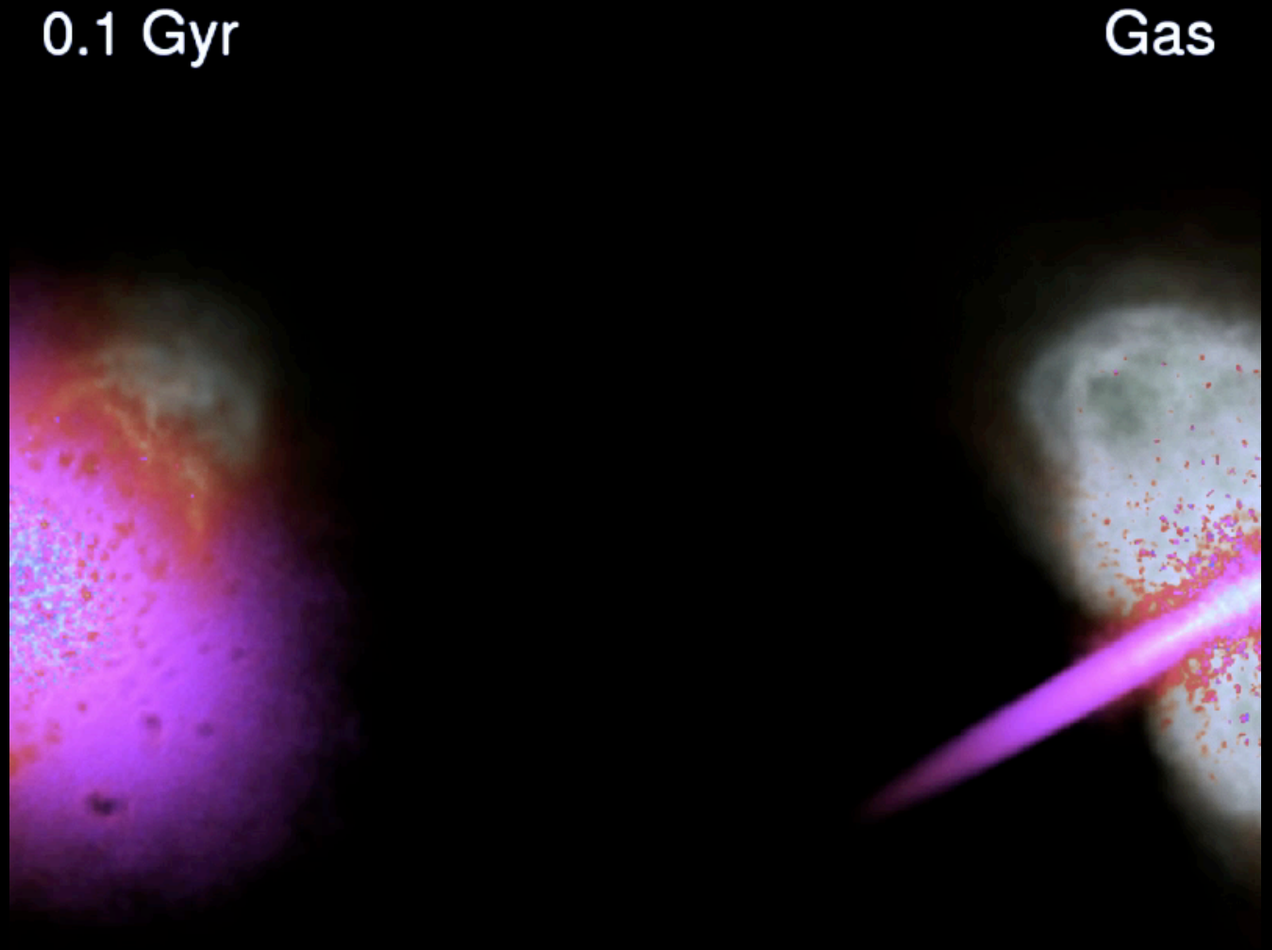
Cosmological Simulations: Now with Physics!

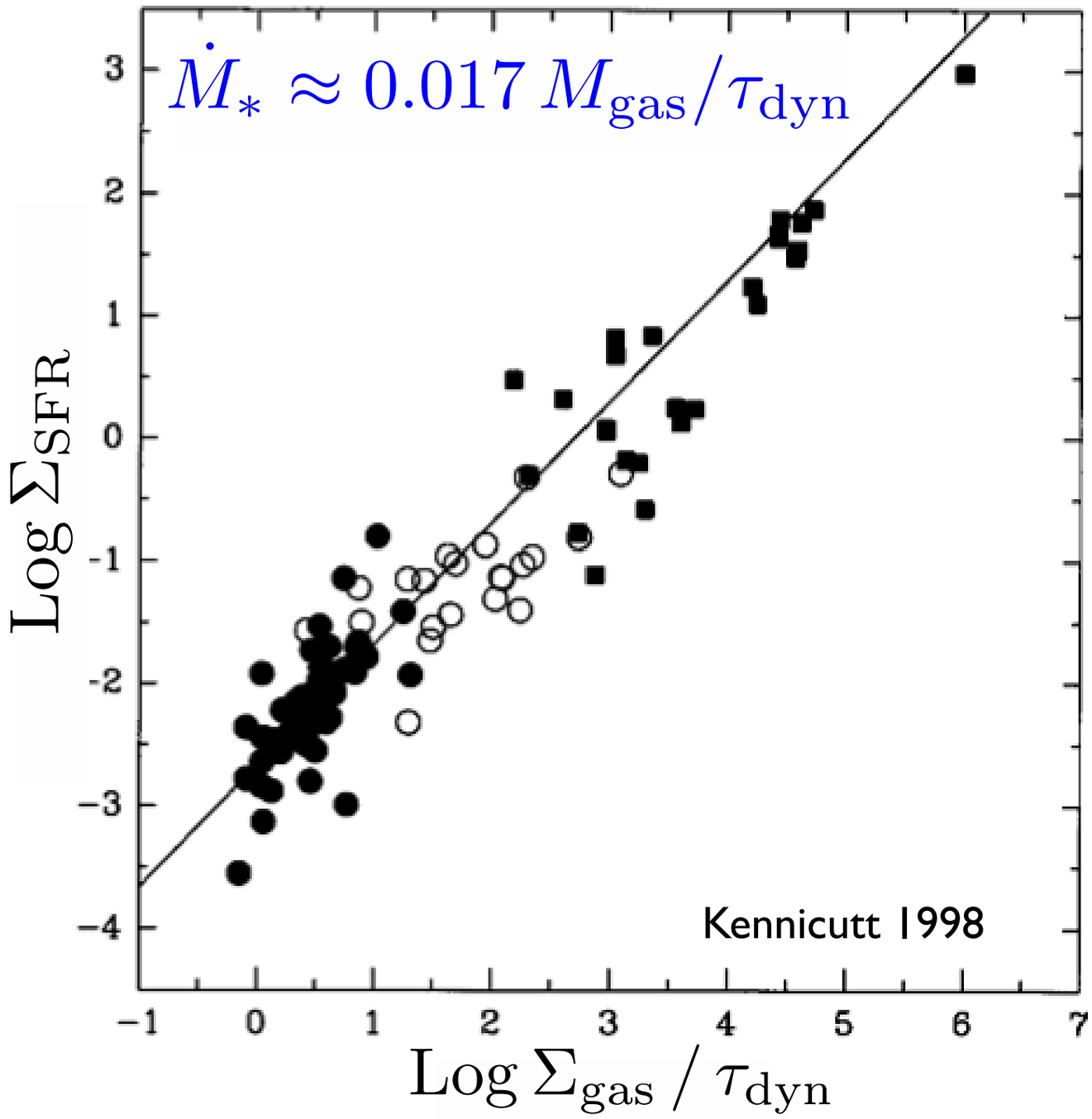


Phil Hopkins

Norm Murray, Eliot Quataert, Dusan Keres, Claude Faucher-Giguere, James Bullock, Jose Onorbe

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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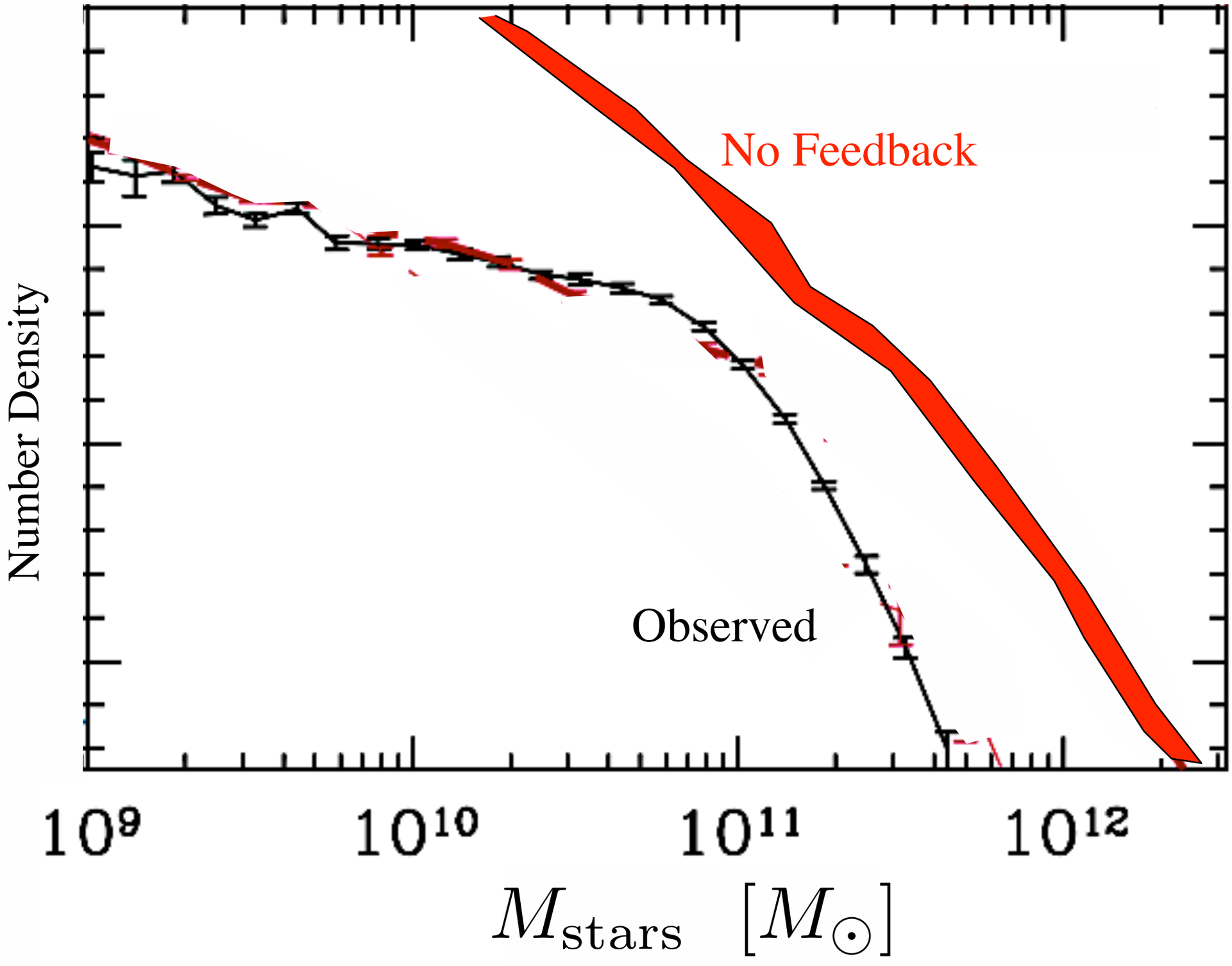

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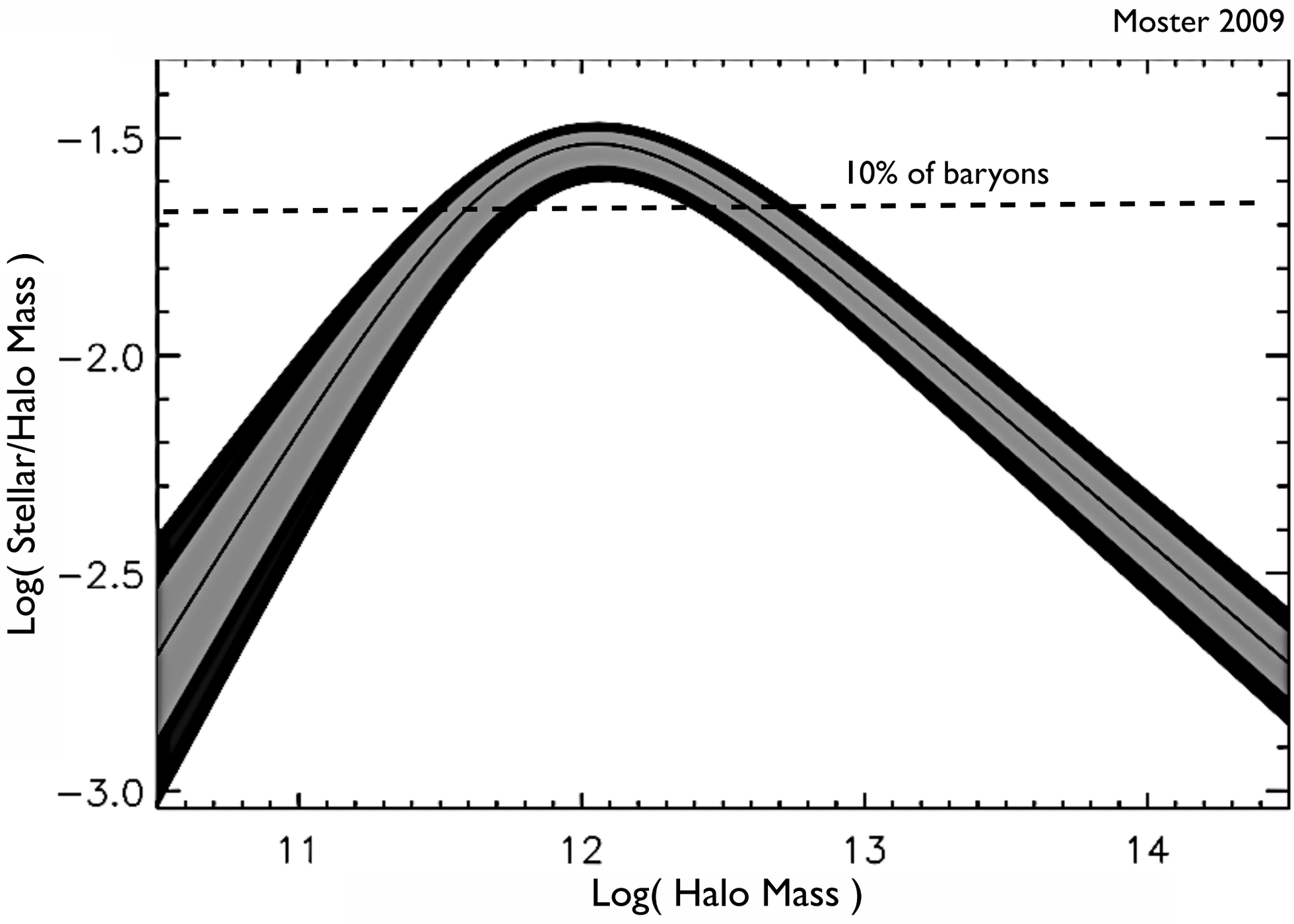

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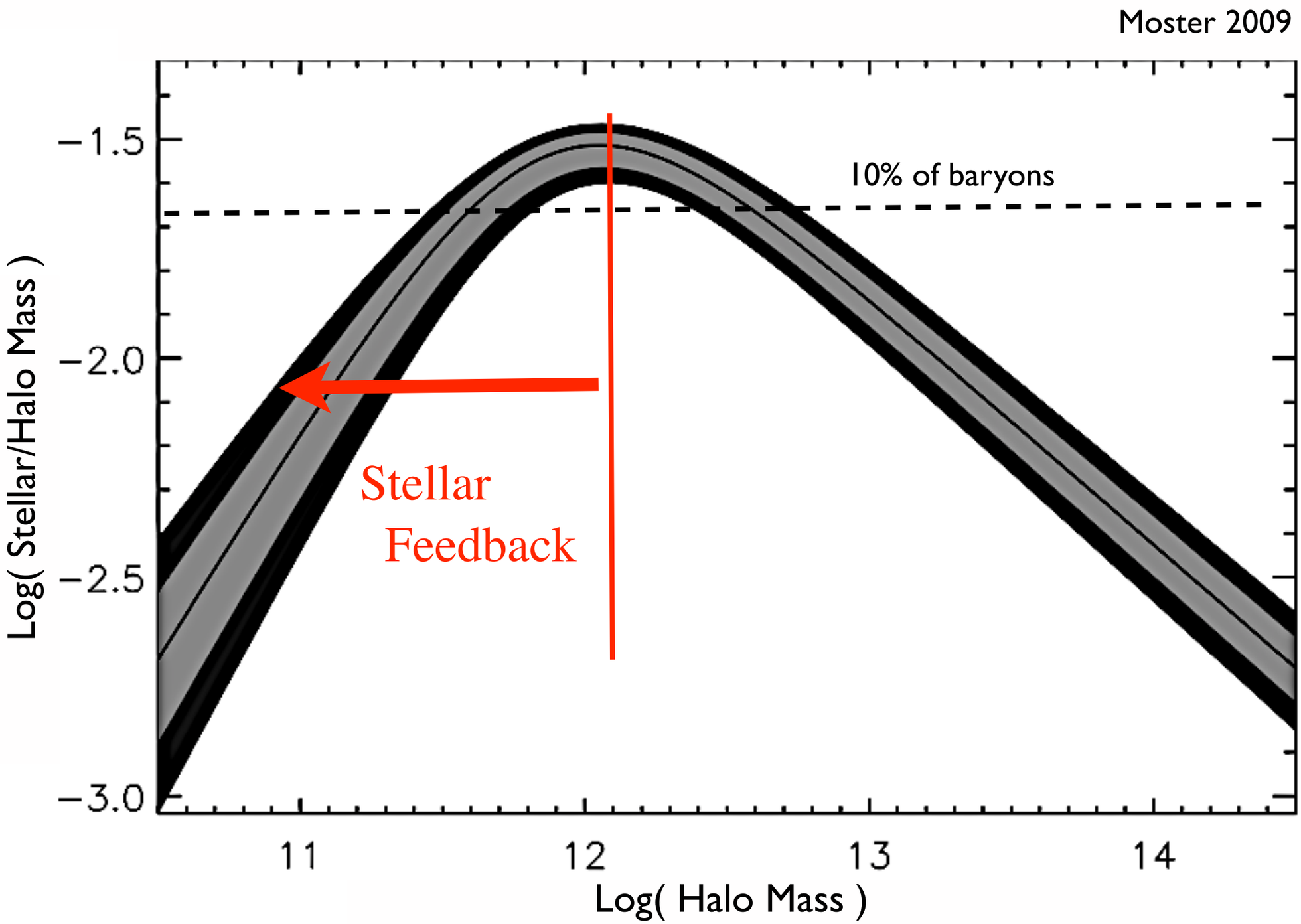

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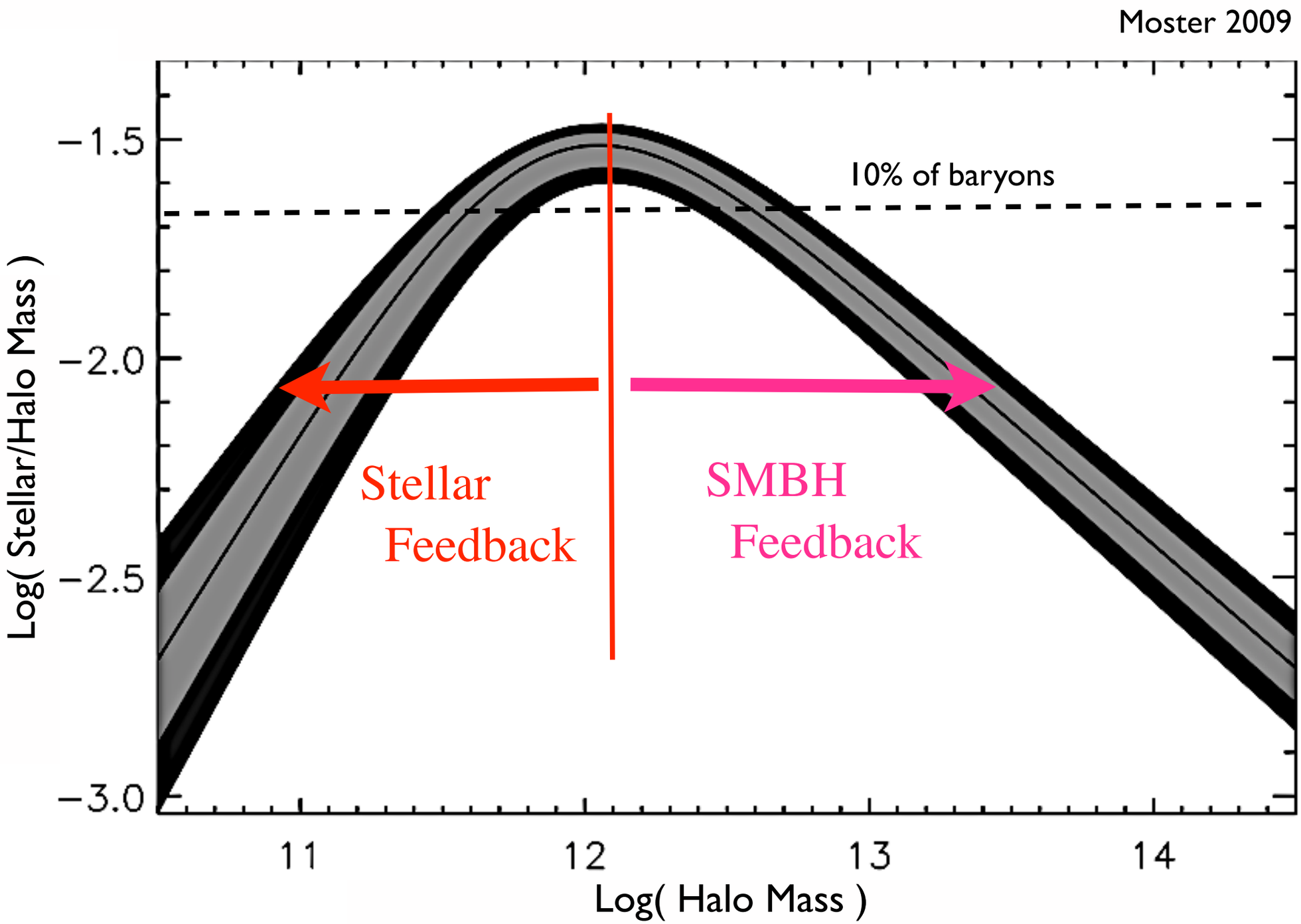


Feedback is the Key!

SO WHAT'S THE PROBLEM?

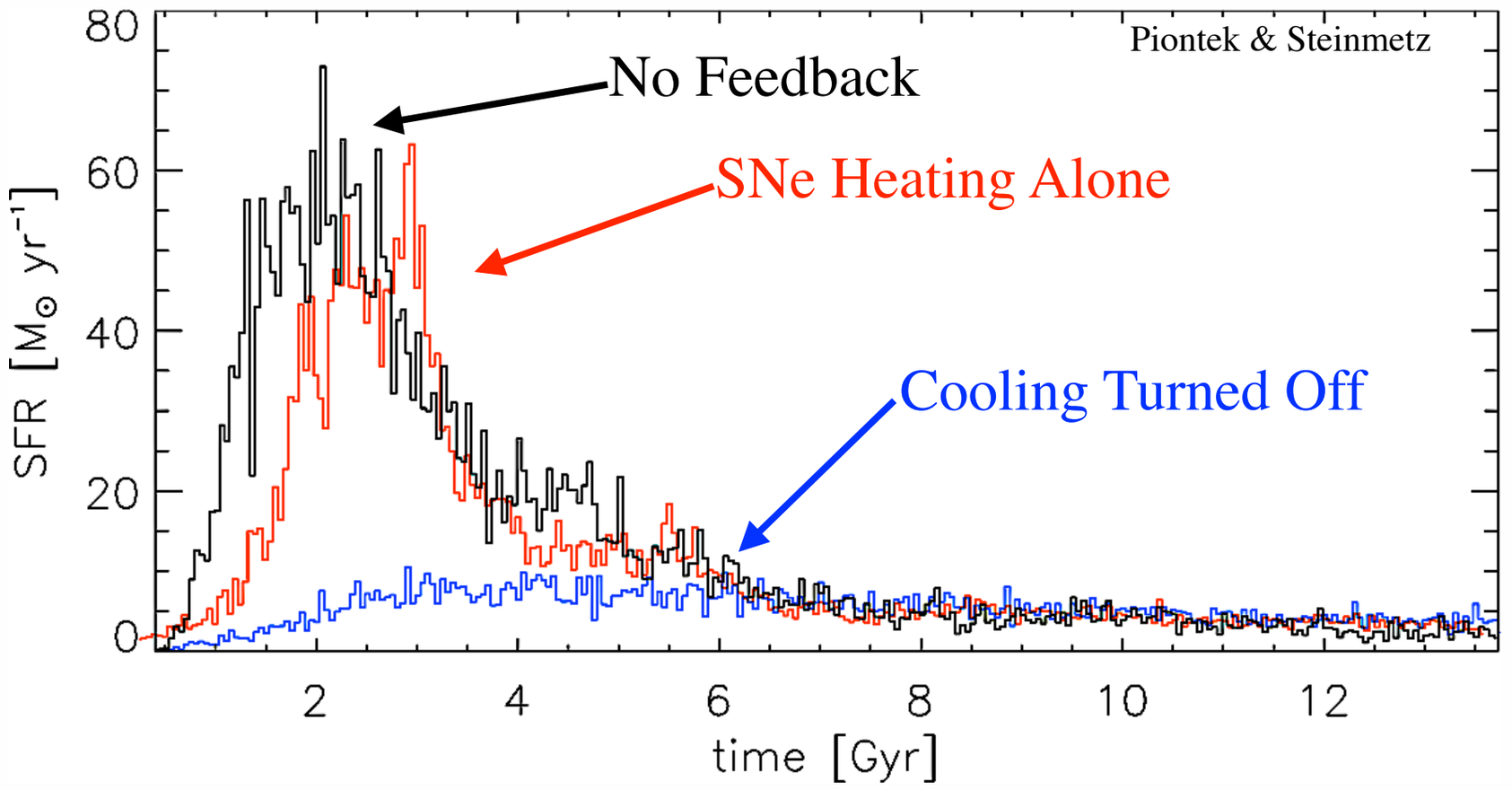
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- FAILS:

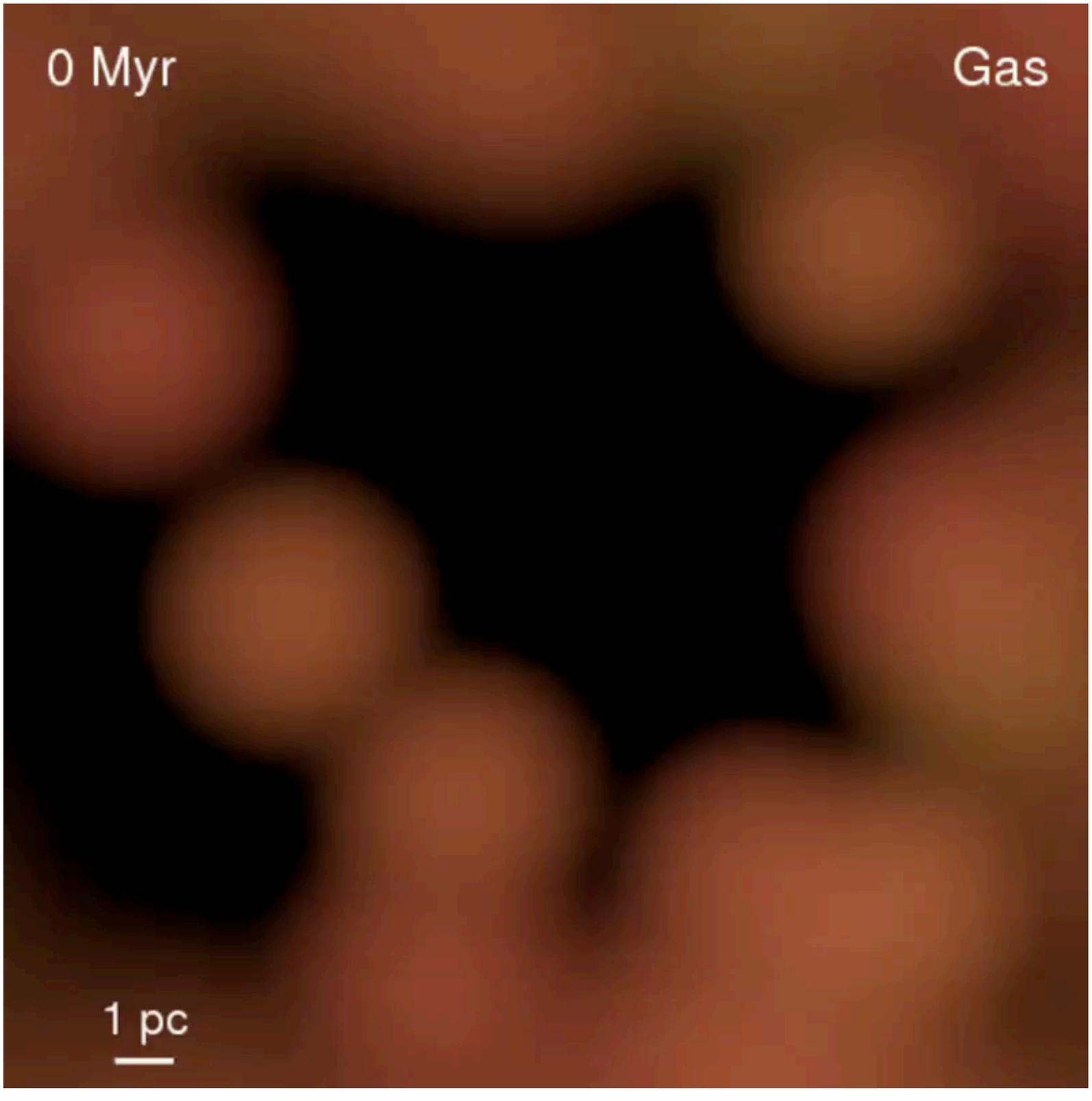
$$t_{\rm cool} \sim 4000\,{\rm yr}\left(\frac{n}{\rm cm^{-3}}\right)^{-1}$$

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

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

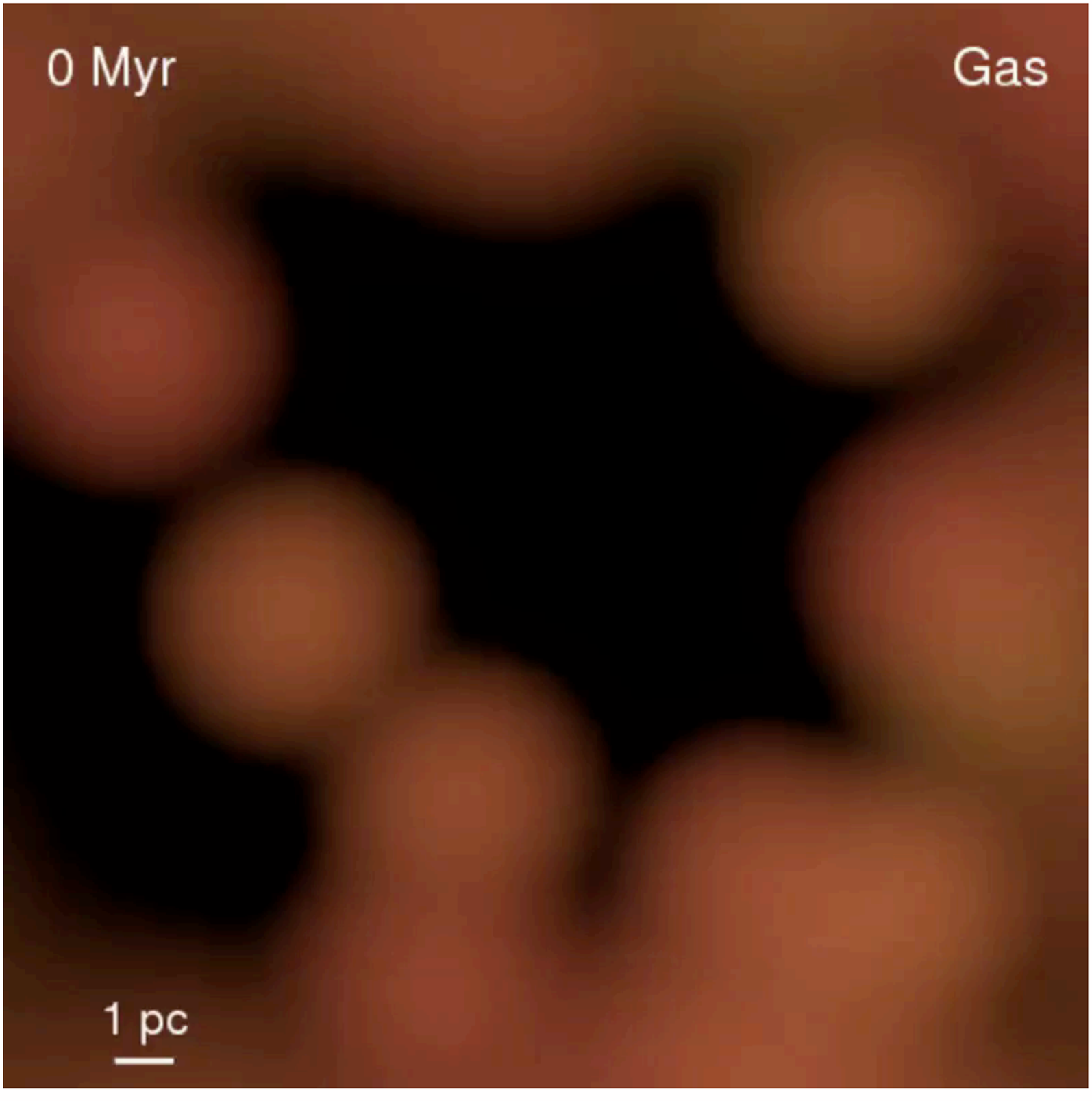


Stellar Feedback: How Can We Do Better?



Stellar Feedback: How Can We Do Better?

- High-resolution (~1-10 pc), molecular/metal cooling (~10 K), SF at $n_H > 100$ cm^{-3}



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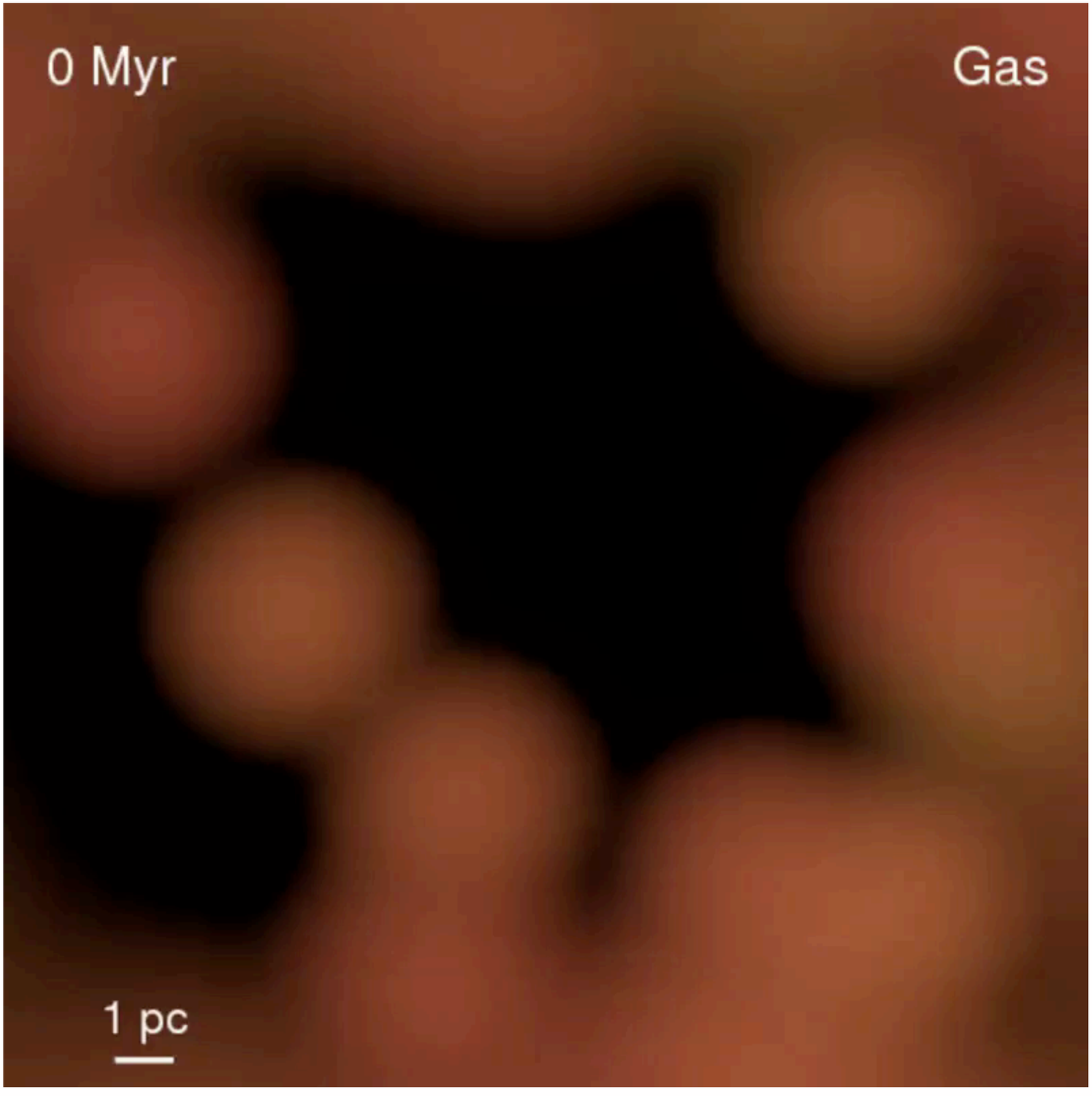

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  - Radiation Pressure

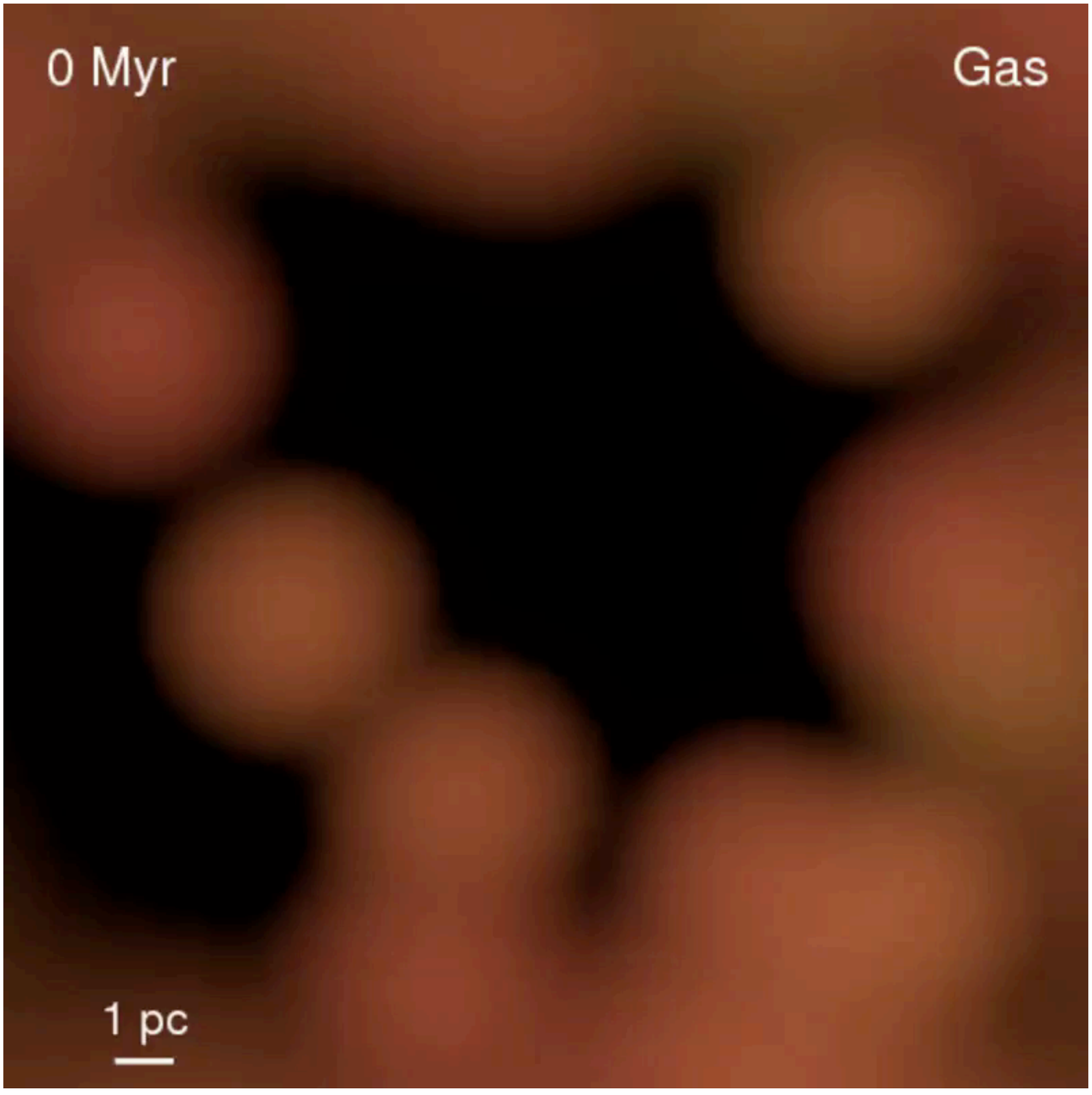
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

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



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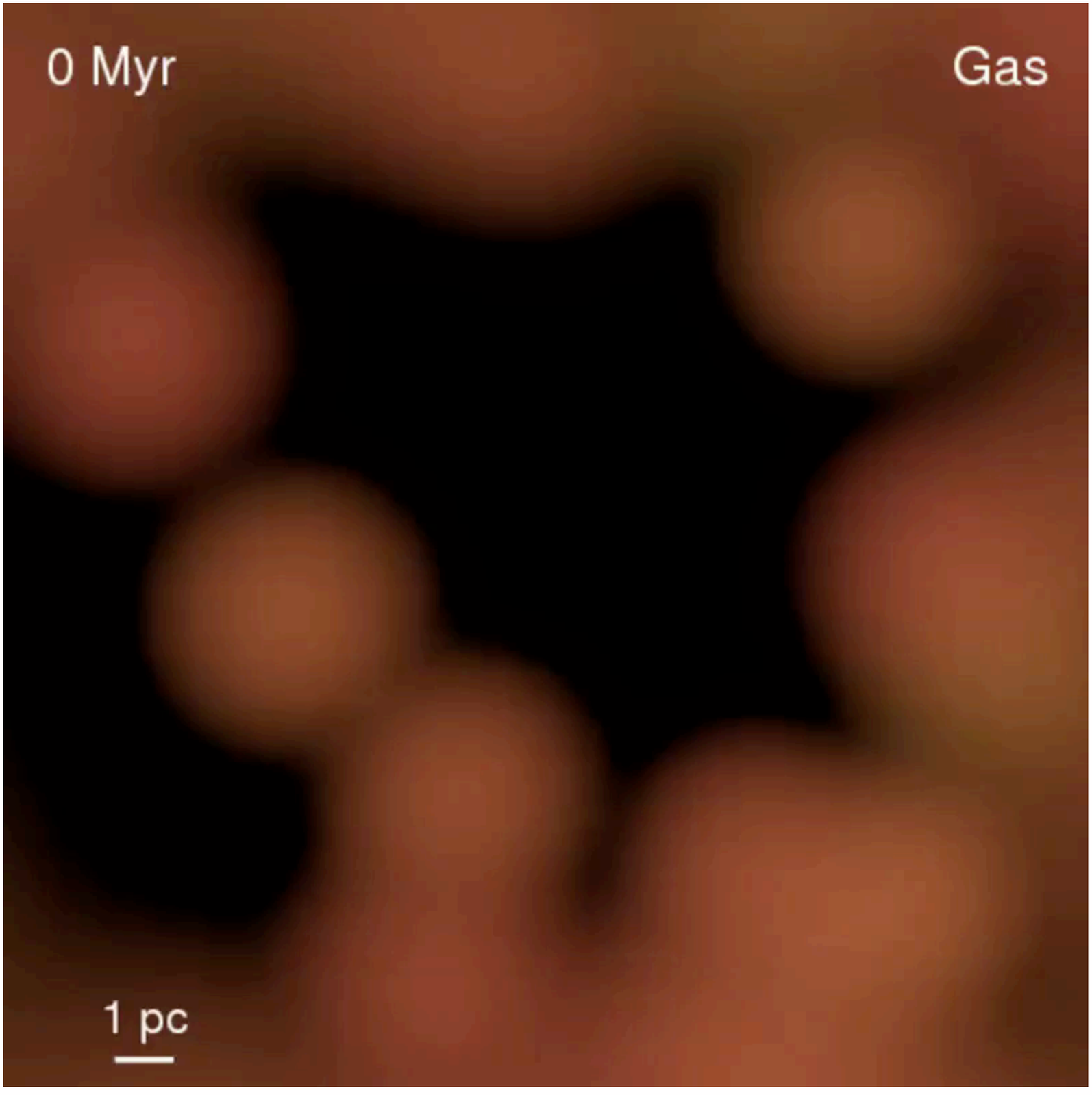
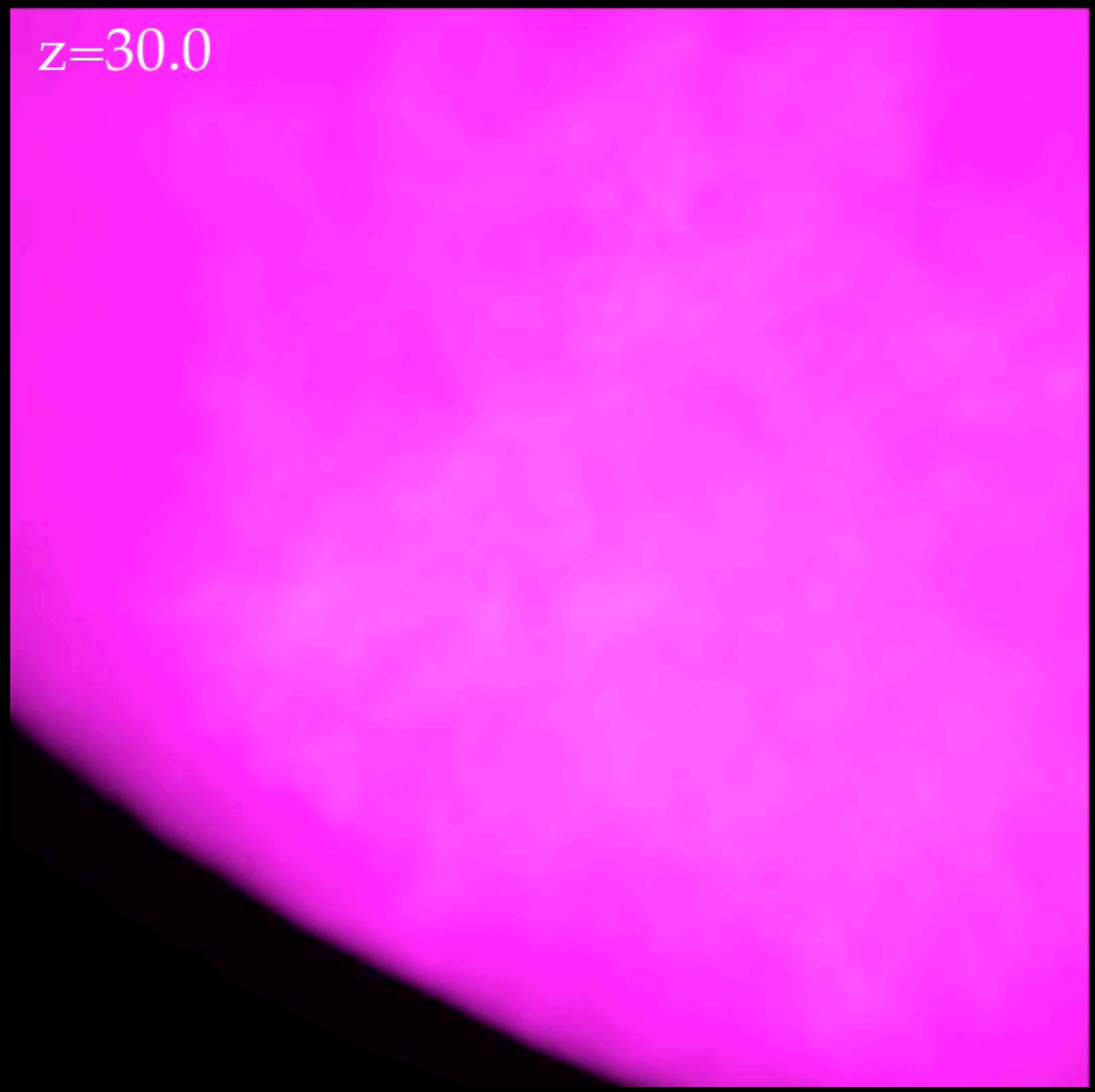


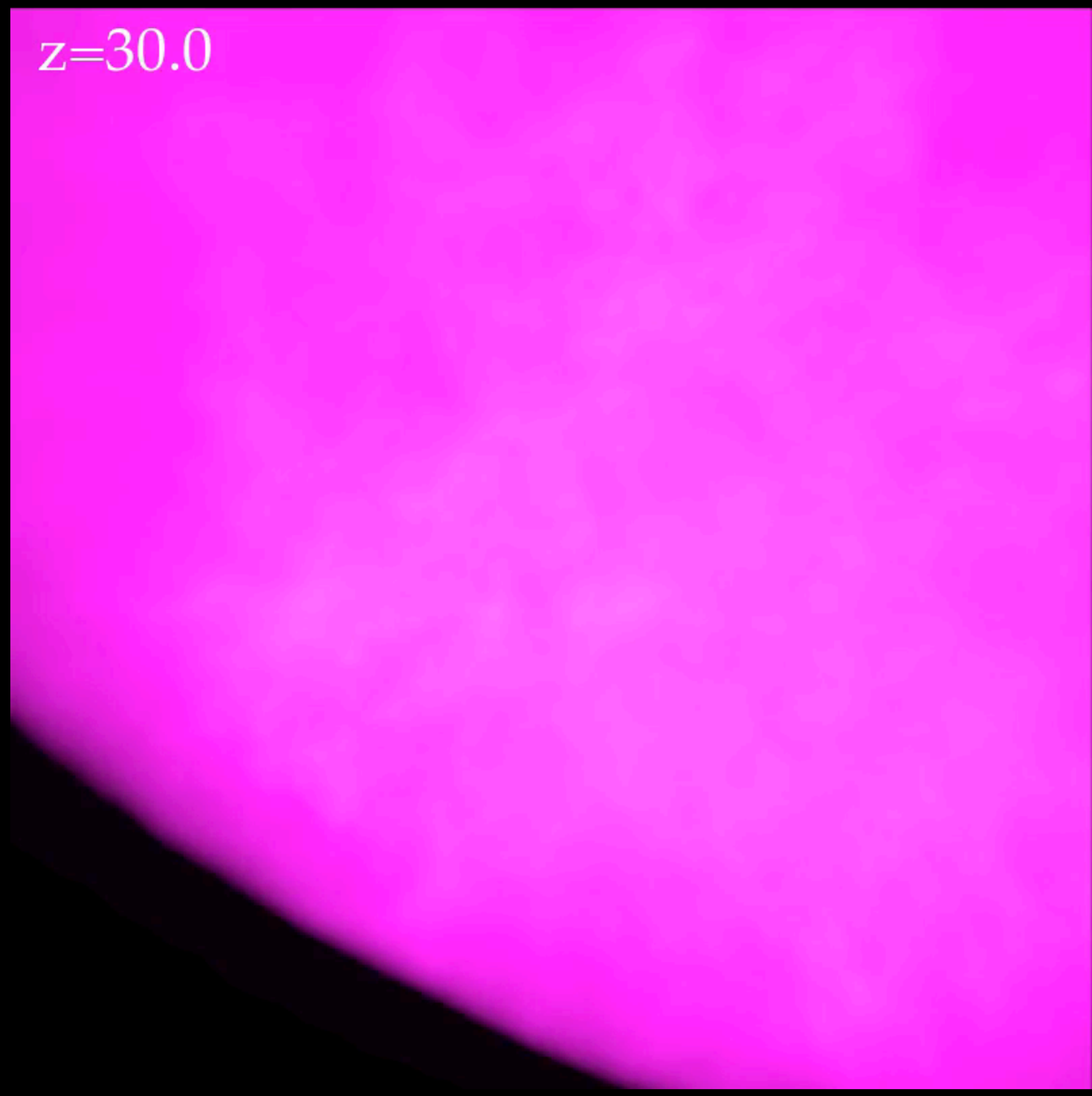
- (also MHD, anisotropic conduction, diffusion)

z=30.0



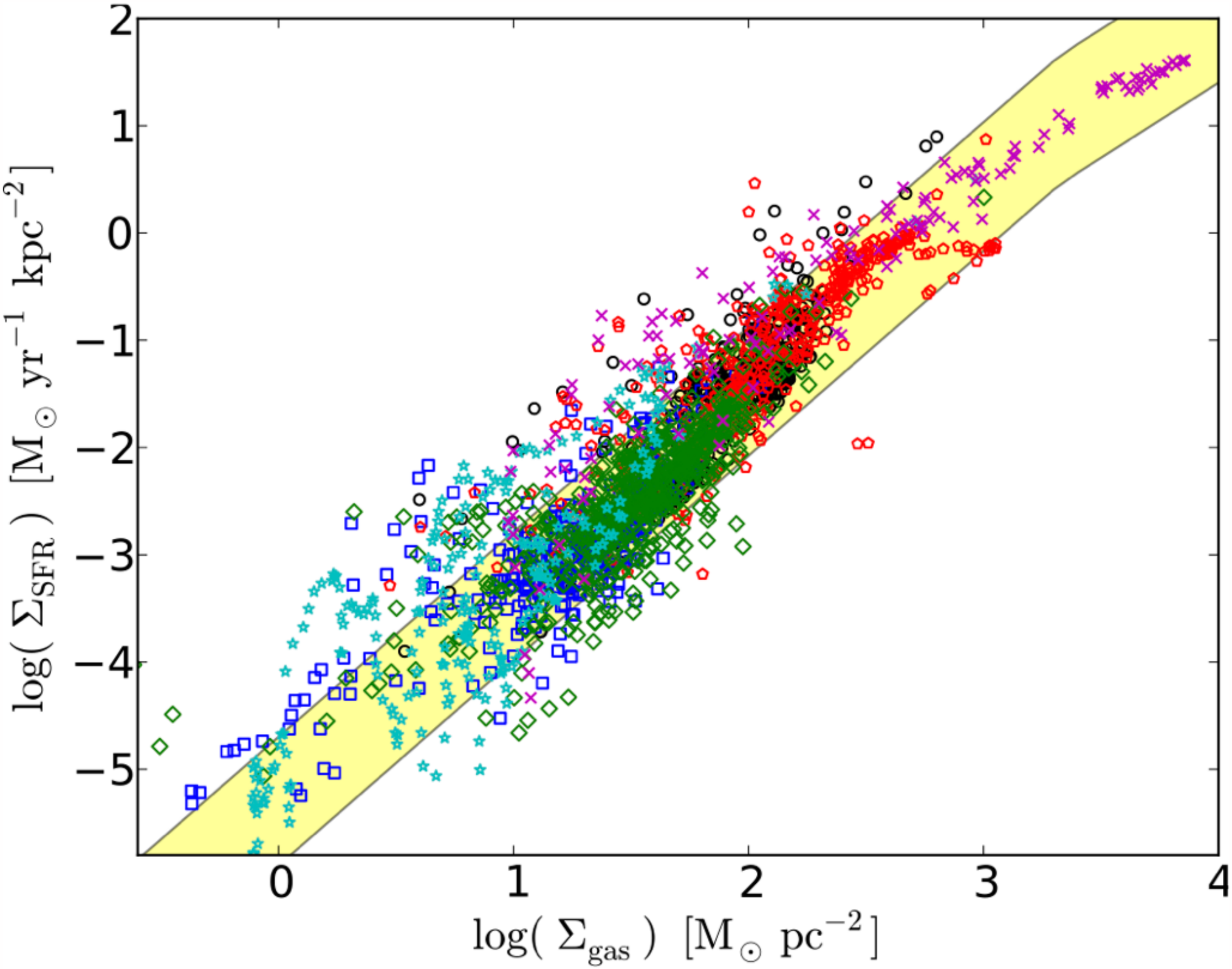
The FIRE Project: Cosmological Simulations at 1-10pc resolution

z=30.0



Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!



PFH, Keres, et al. (arXiv:1311.2073)

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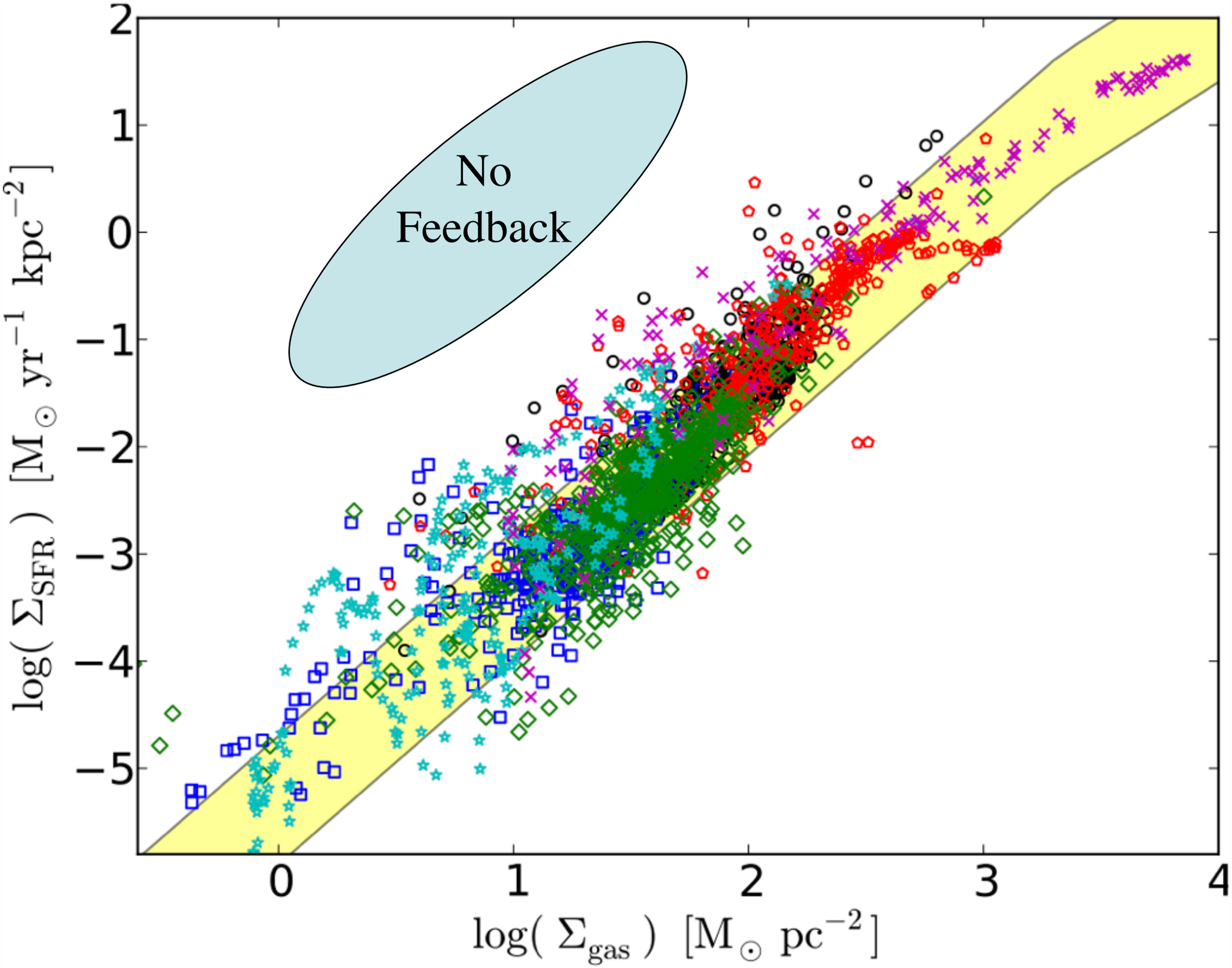

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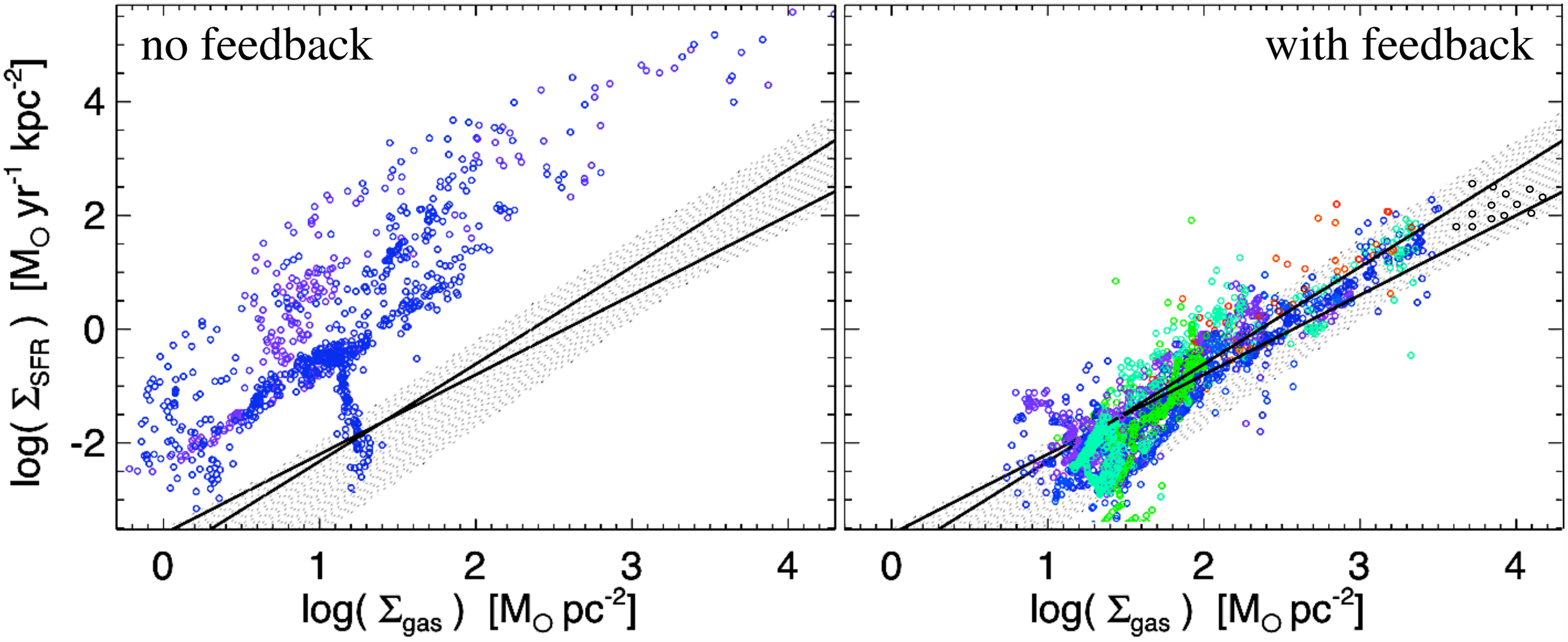
Kennicutt-Schmidt relation emerges naturally

ISOLATED GALAXIES



PFH, Quataert, & Murray, 2011a

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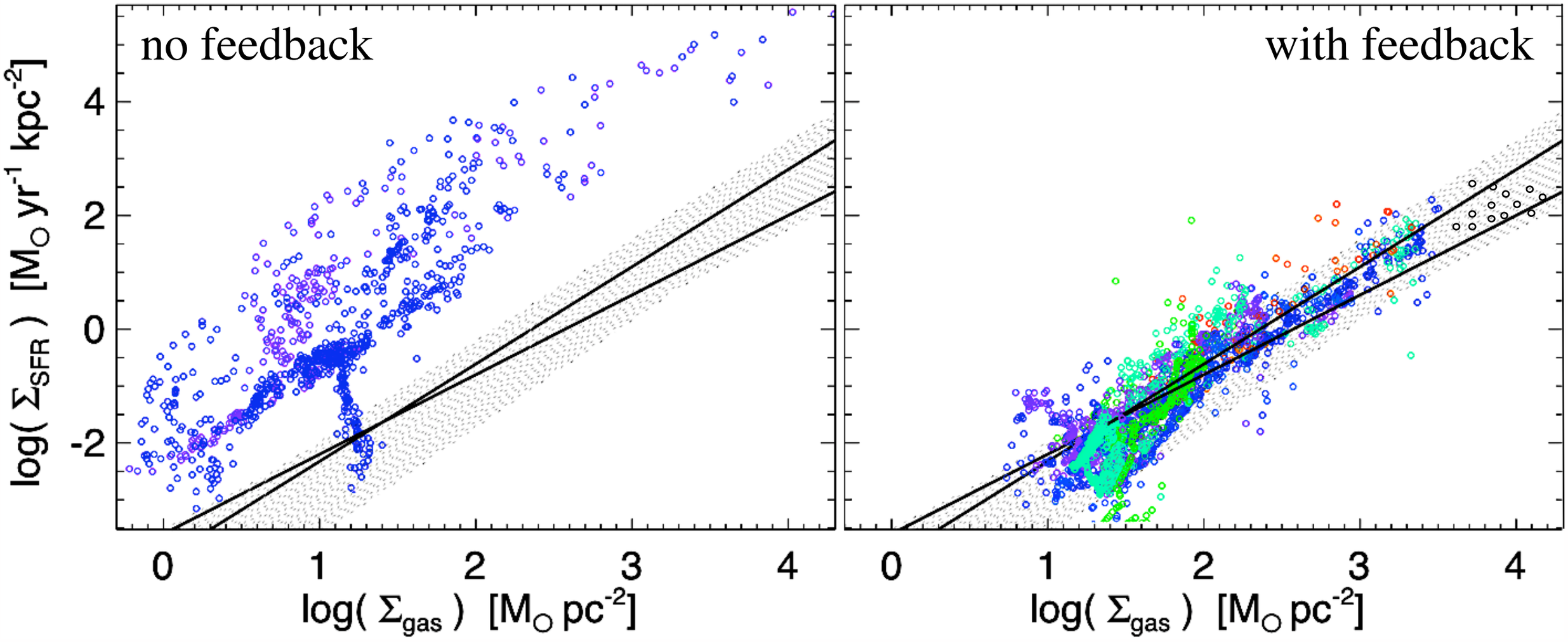
$$\dot{\Sigma}_* \sim \Sigma_{\rm gas}/\tau_{\rm dyn}$$



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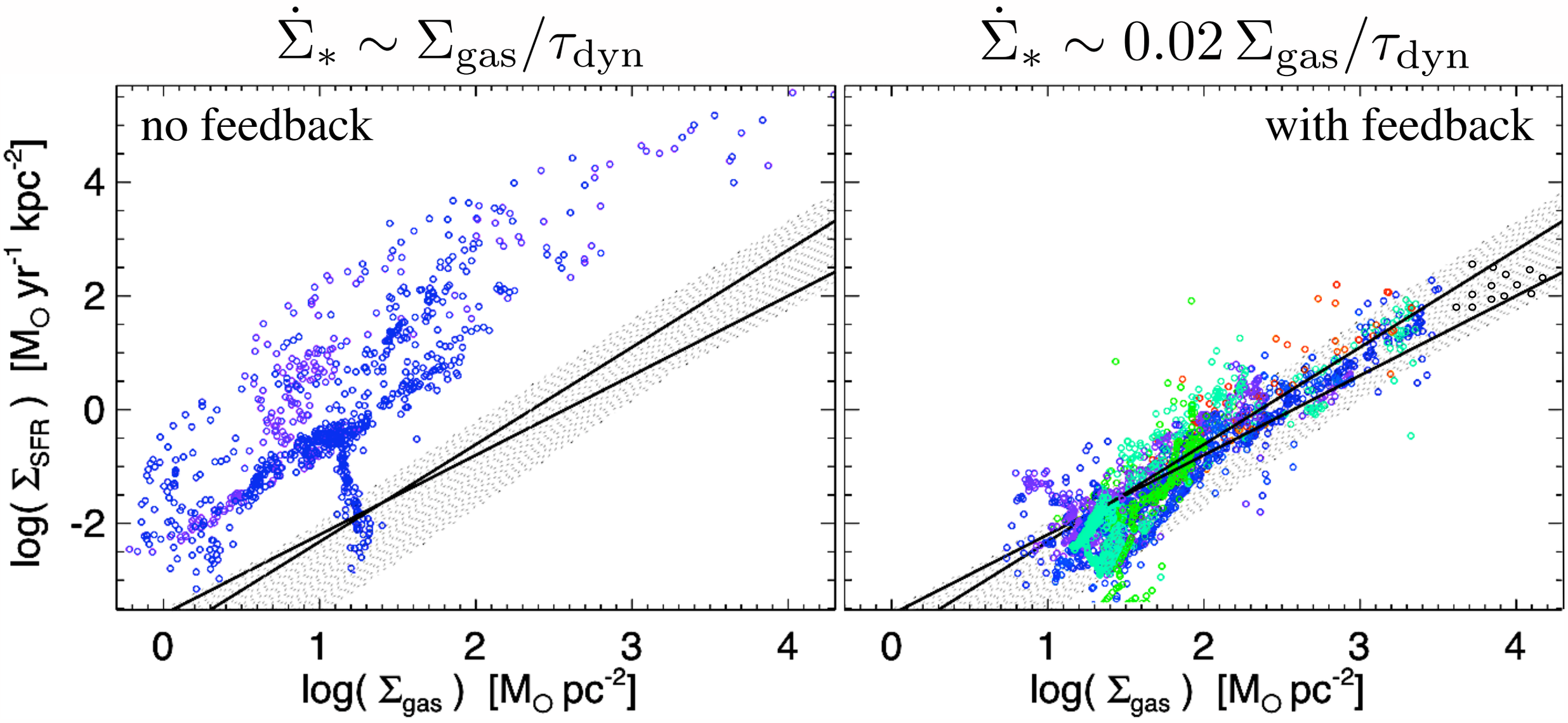

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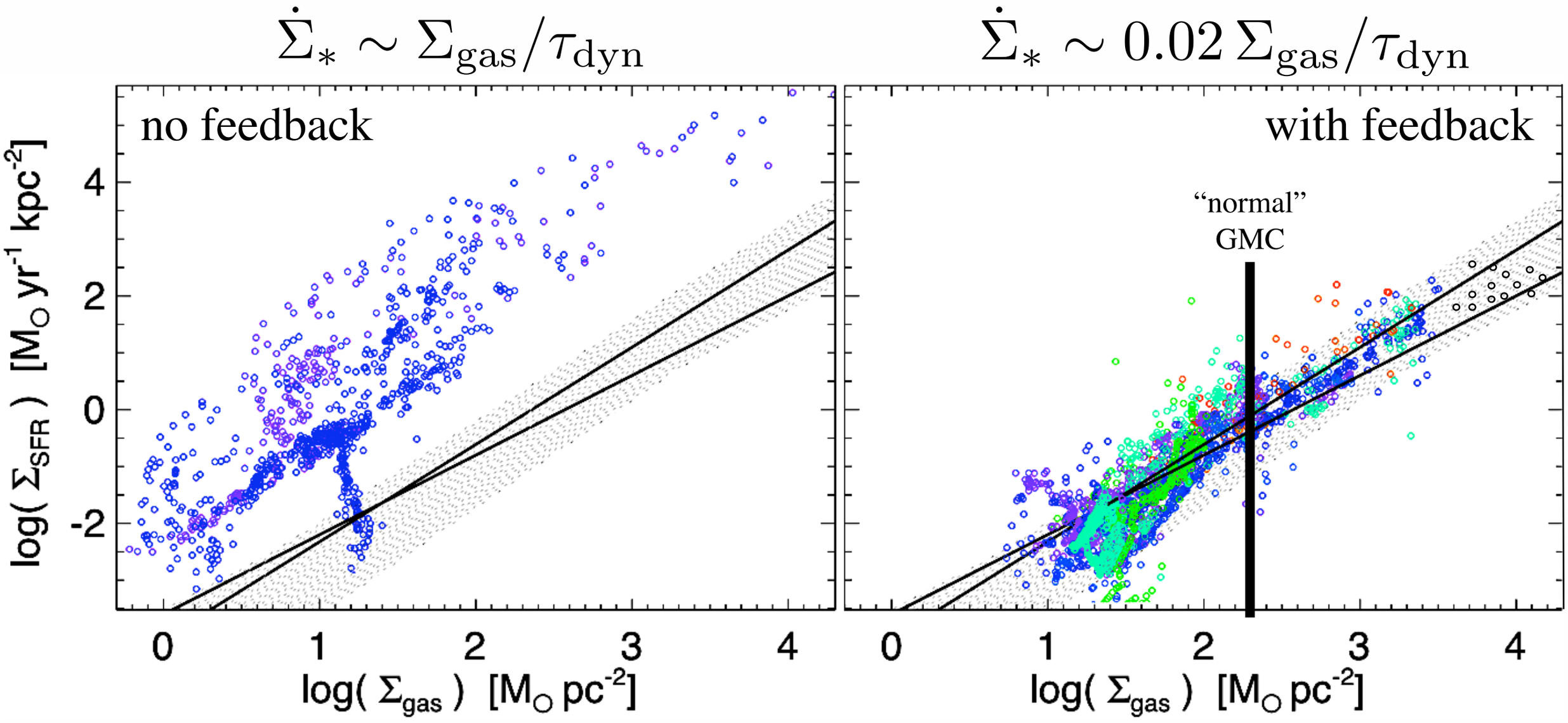

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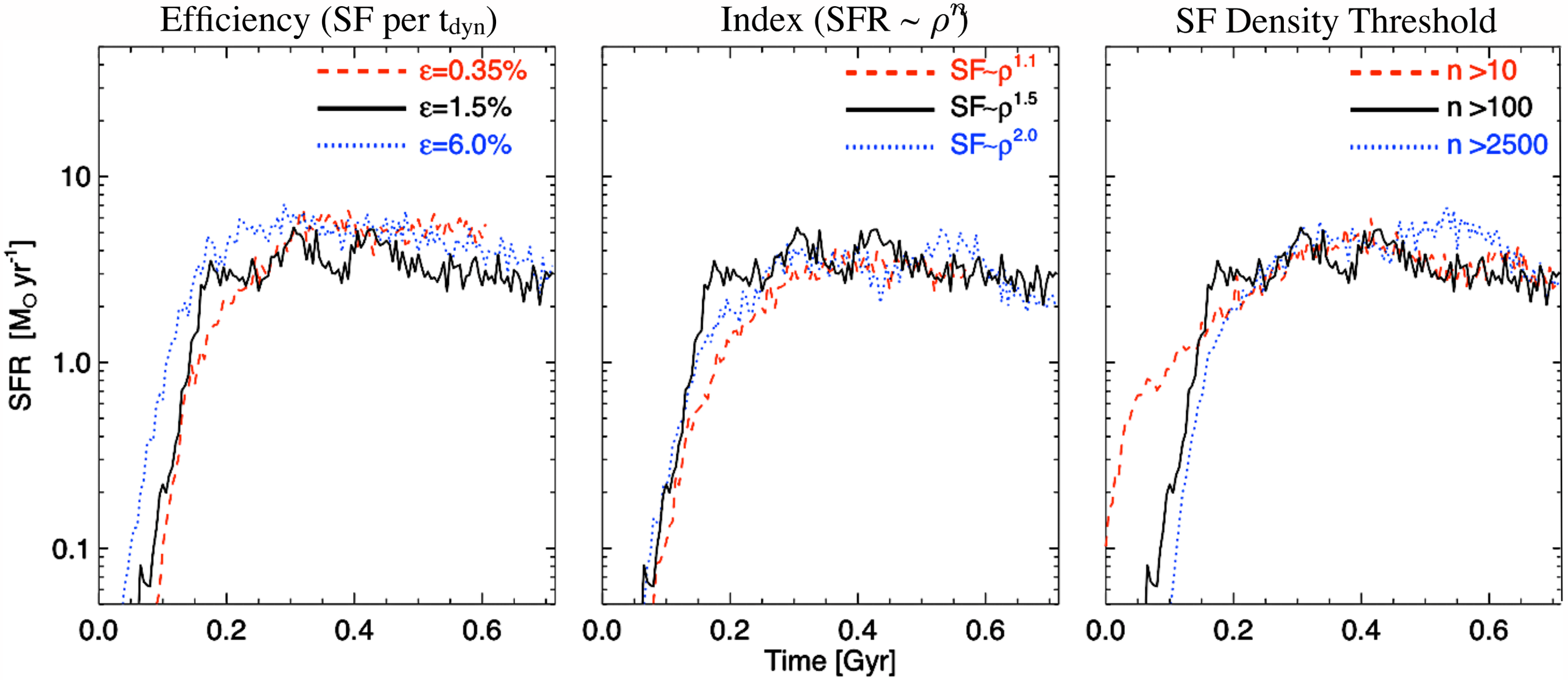
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!



Hopkins, Quataert, & Murray 2011
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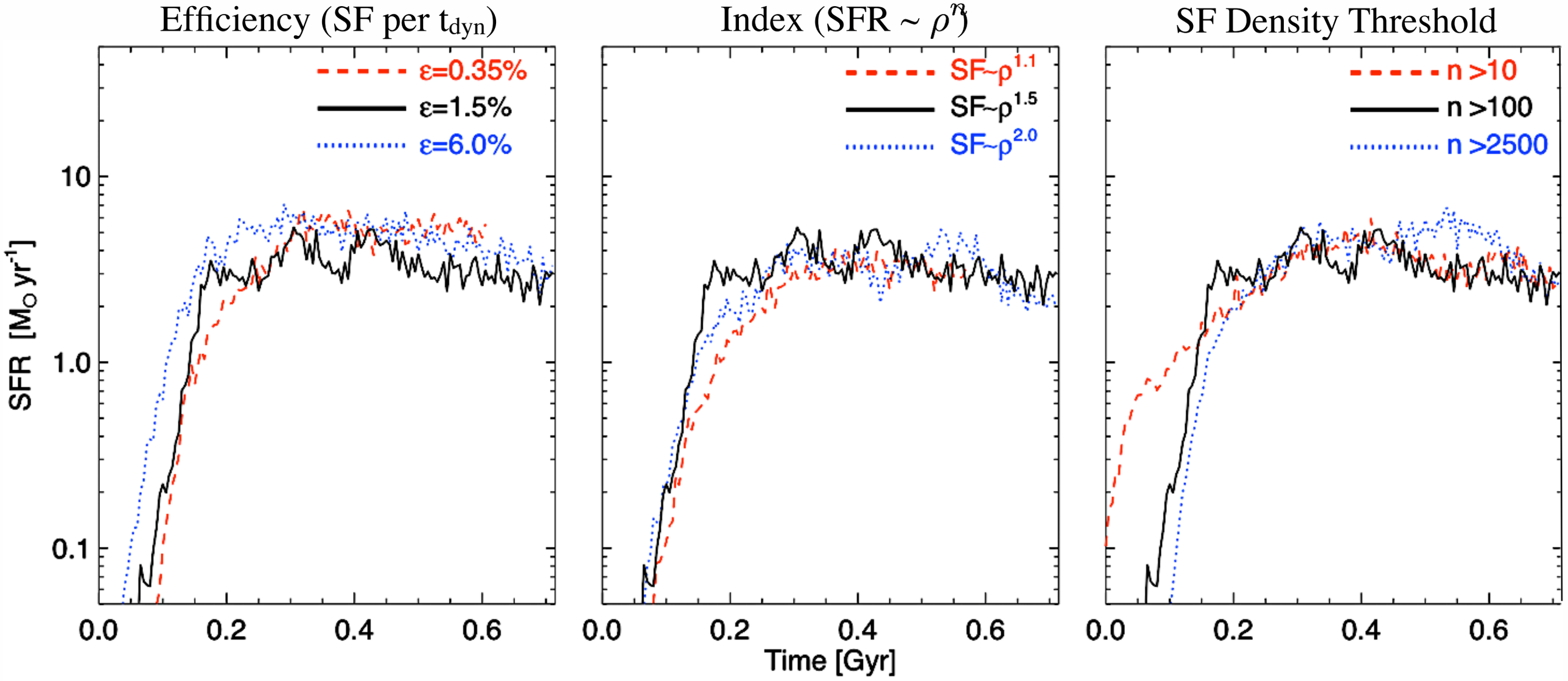


- Set by feedback (SFR) needed to maintain marginal stability

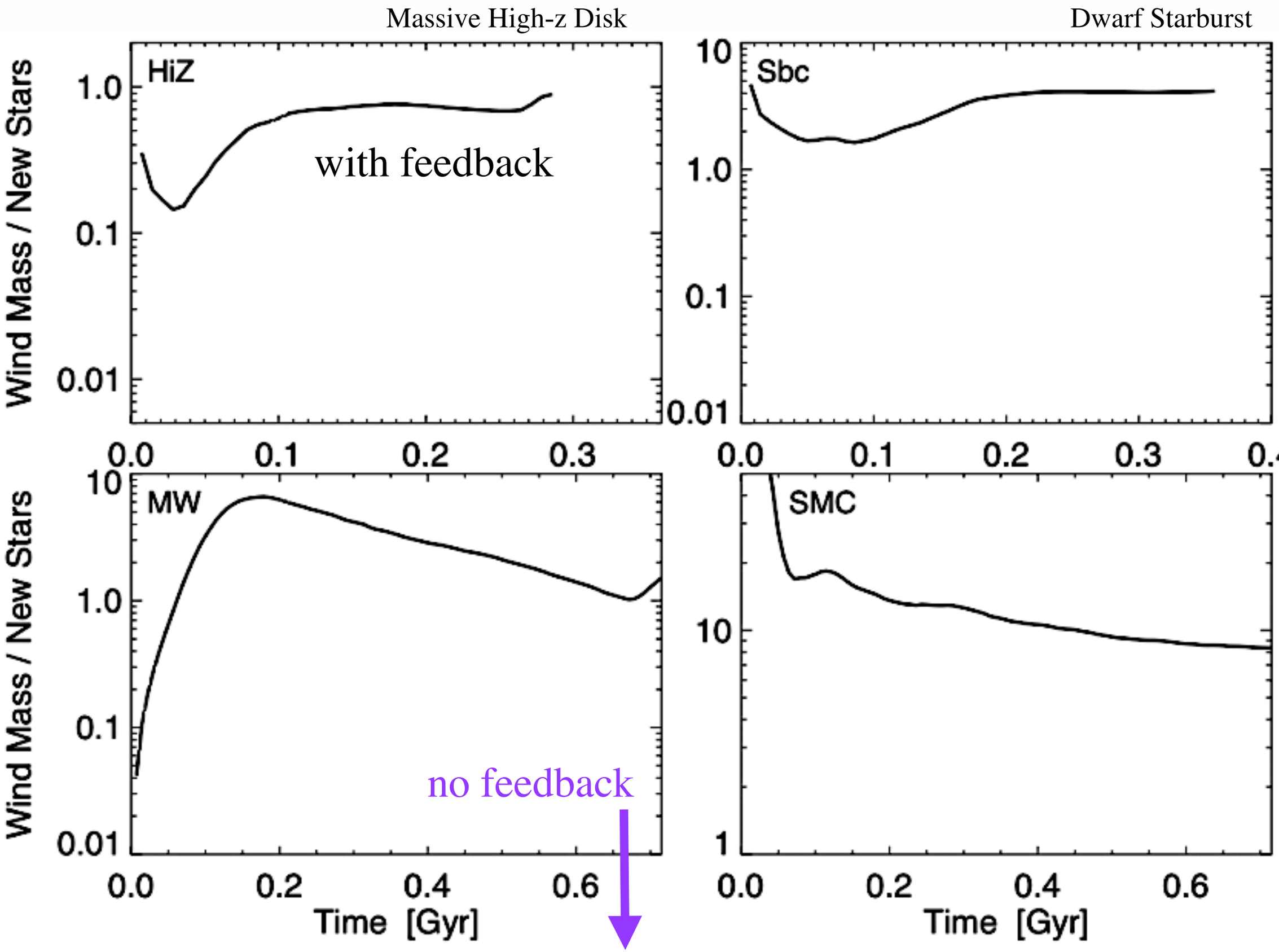
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

Inflows & Outflows

How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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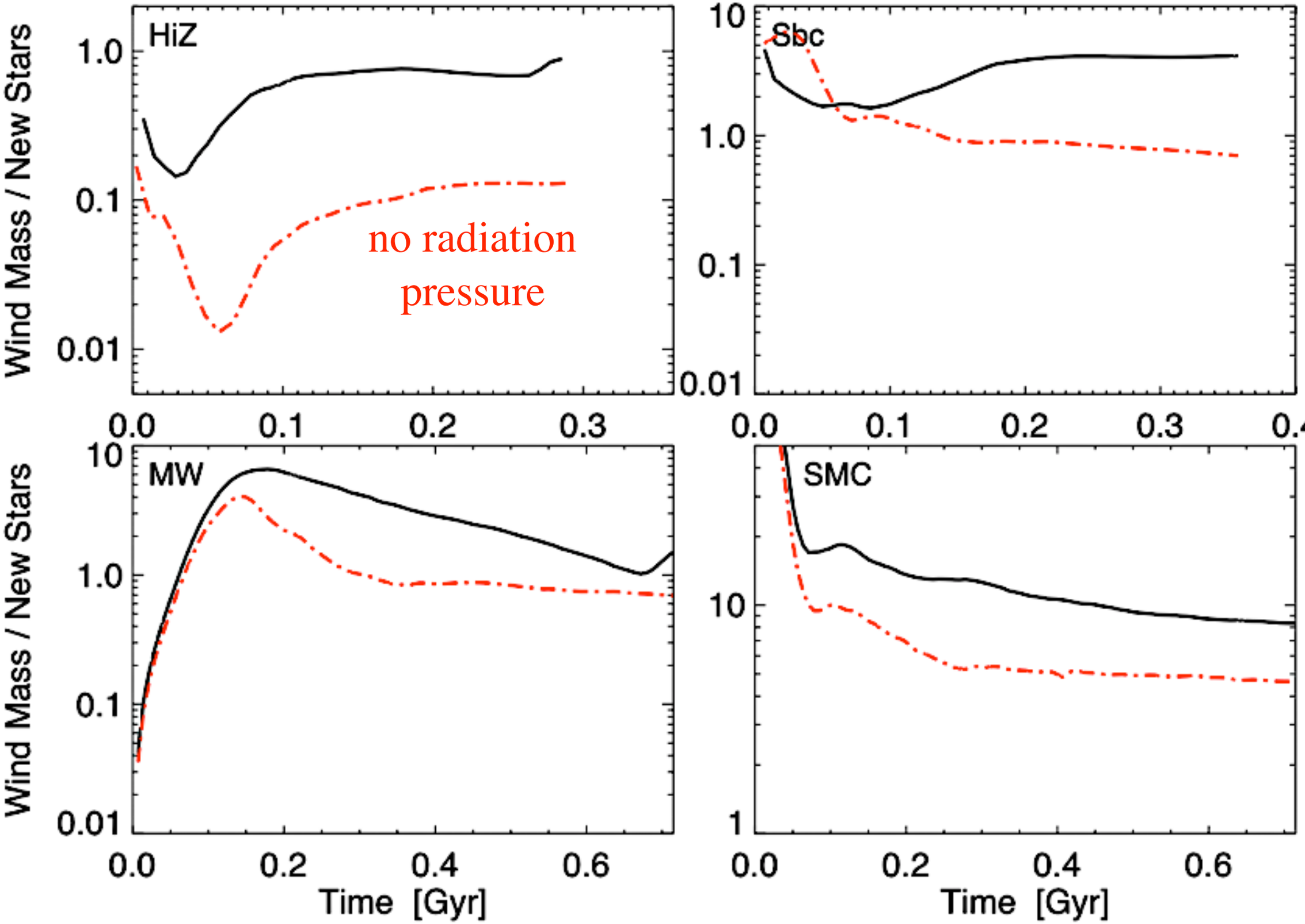
PFH, Quataert, & Murray, 2011c

Massive High-z Disk

Dwarf Starburst



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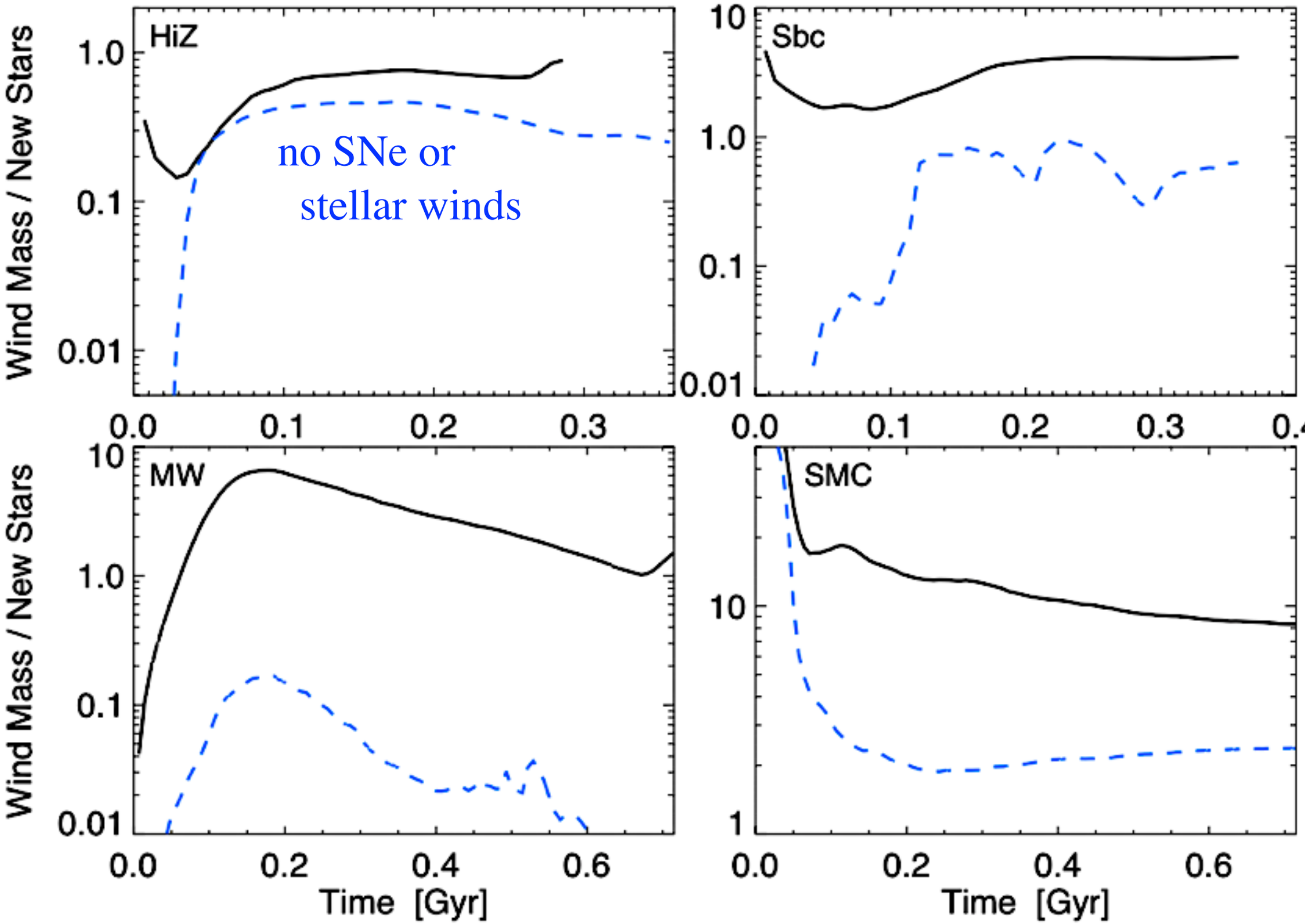

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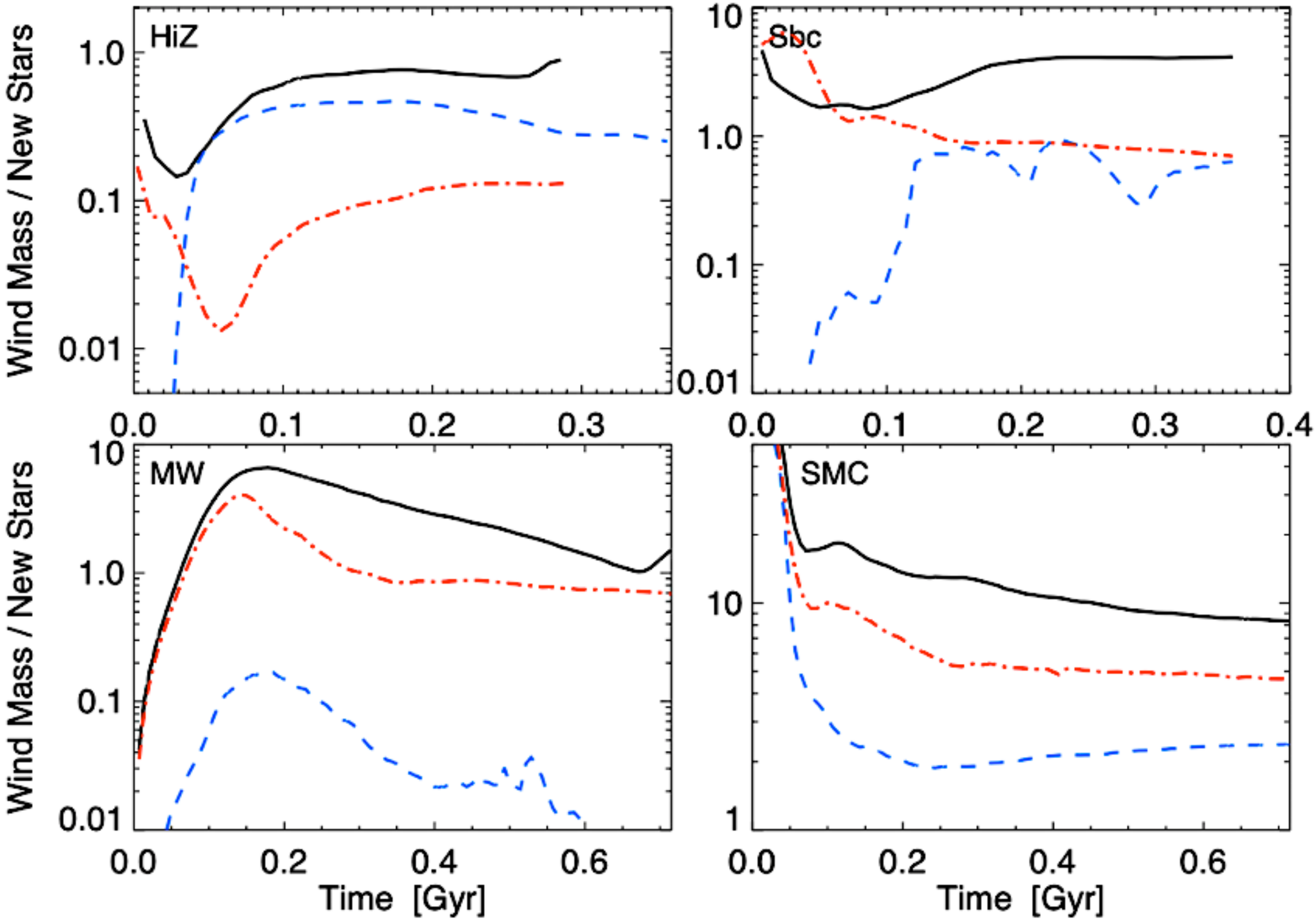
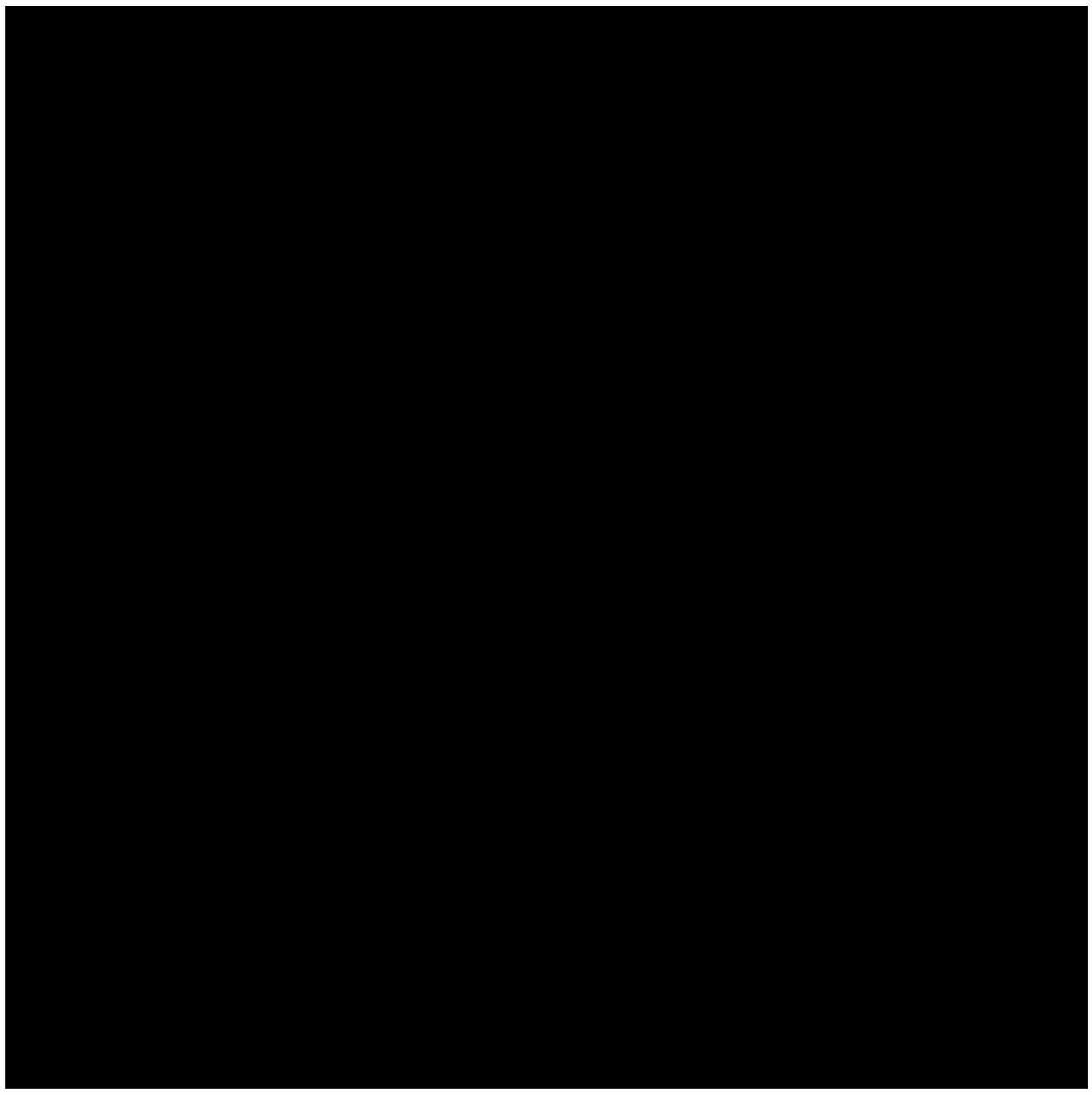
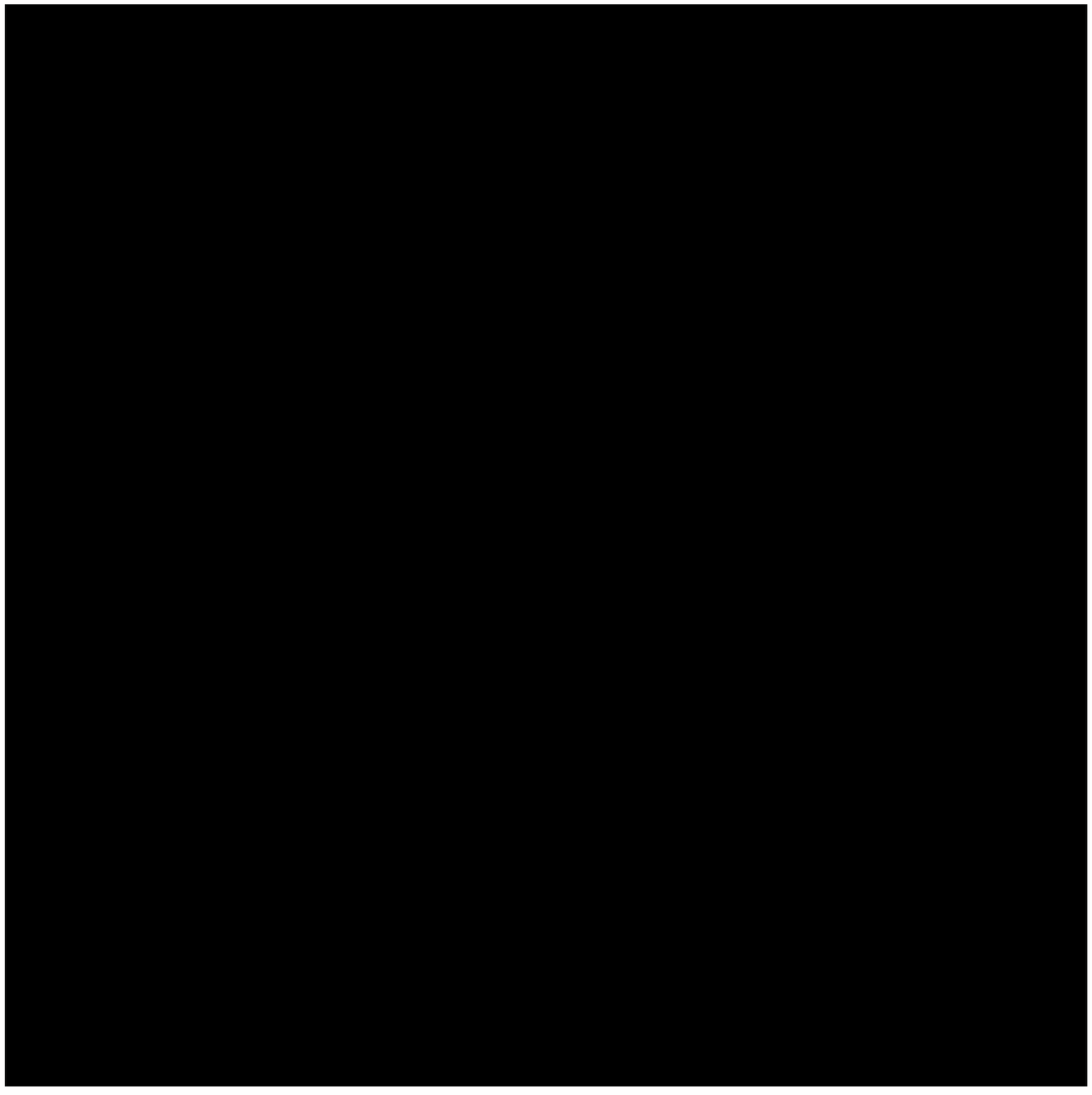


Proto-MW: Gas Temperature:

No Feedback



Following Full Feedback

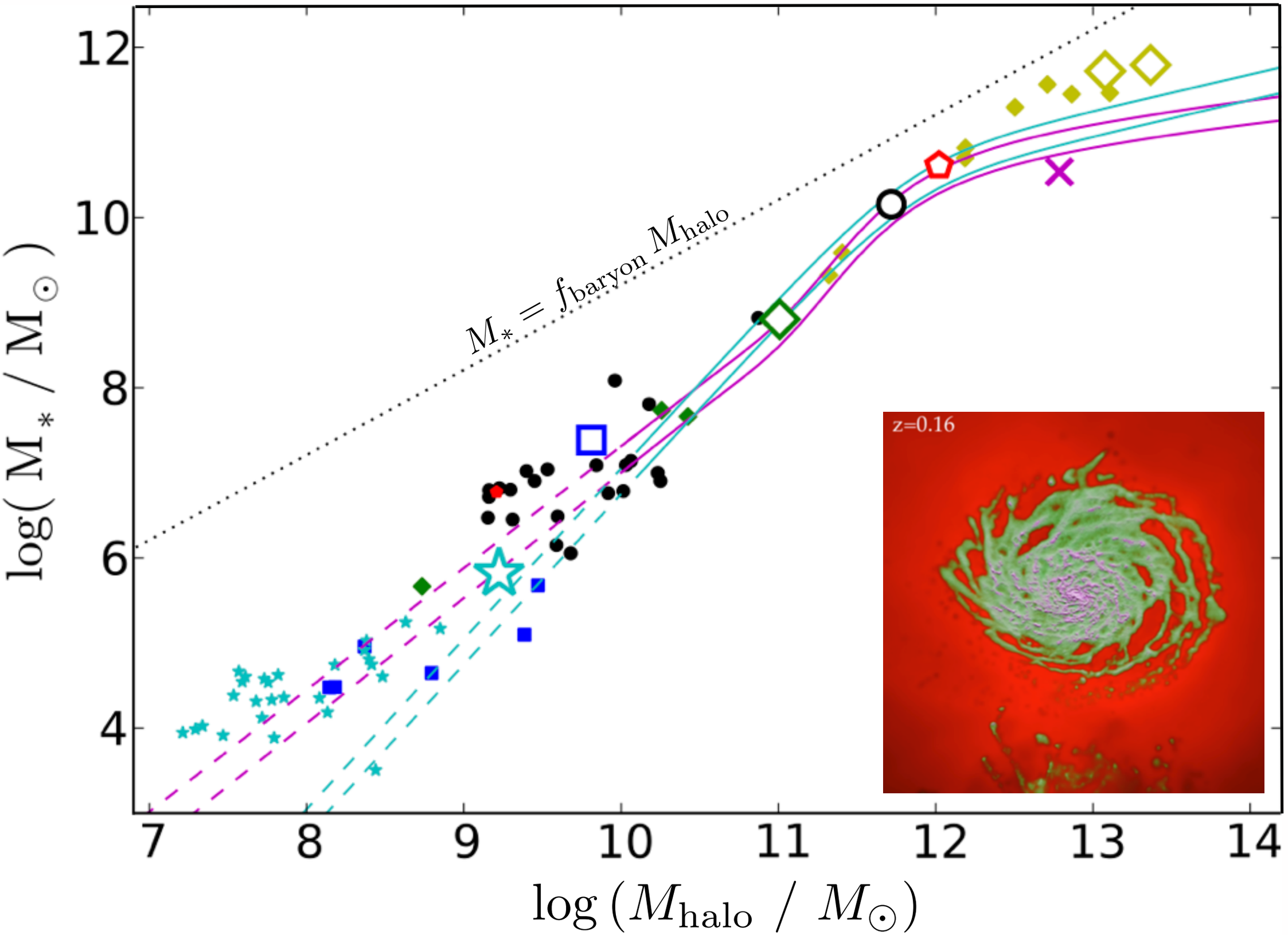


Faucher-Giguere, PFH, in prep

Does Stellar Feedback Explain the Mass Function?

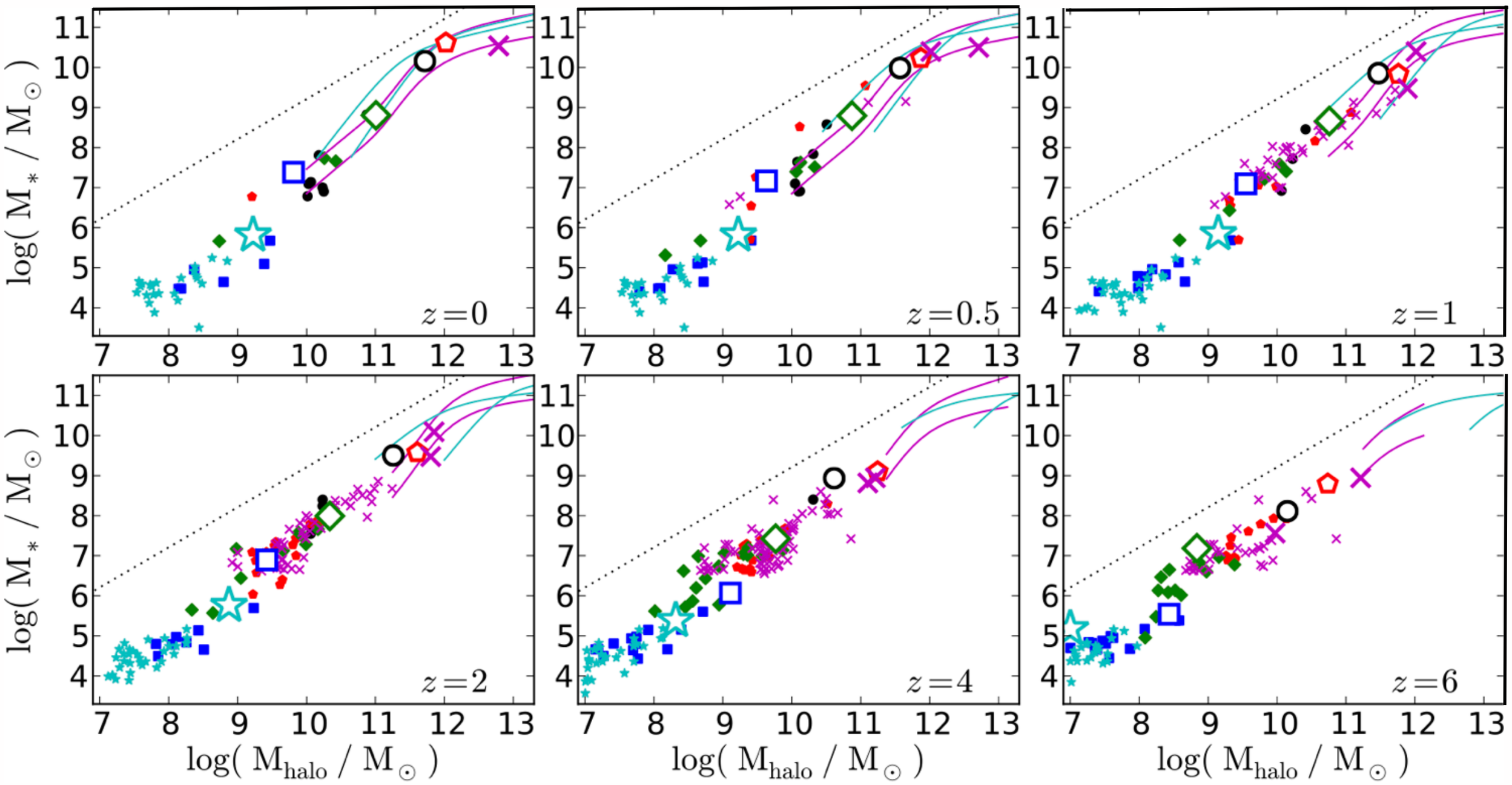
HOW EFFICIENT ARE GALACTIC WINDS?

PFH, Keres, et al. (arXiv:1311.2073)



Weak Redshift Evolution

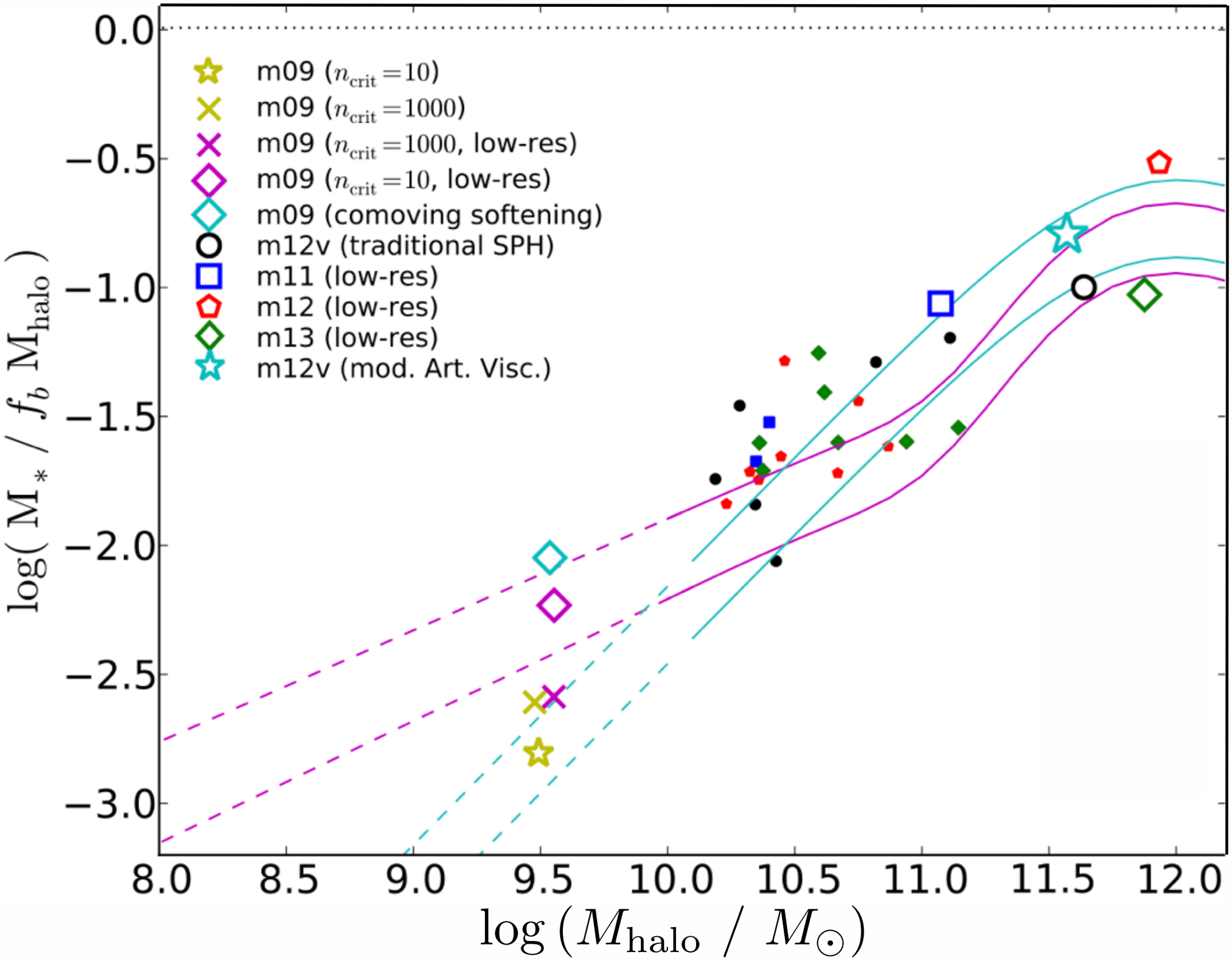
PFH, Keres, et al. (arXiv:1311.2073)



Weak Numerical Dependence

"ALGORITHMIC" CHOICES NOT DOMINANT

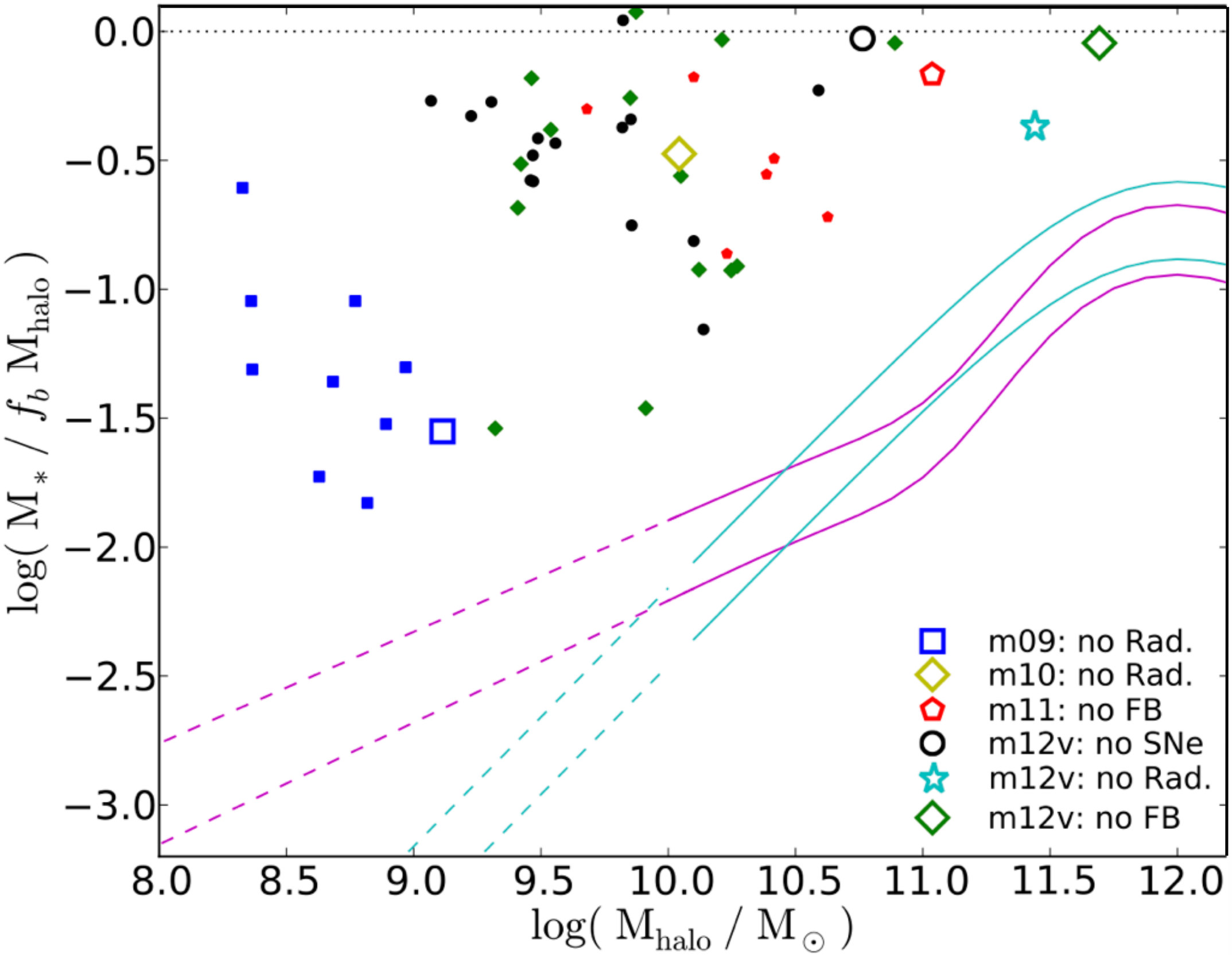
PFH, Keres, et al. (arXiv:1311.2073)



But Feedback *Does* Matter

MULTIPLE FEEDBACK MECHANISMS ARE CRITICAL

PFH, Keres, et al. (arXiv:1311.2073)



Non-SNe Feedback: Key in Dwarfs and High-z Galaxies

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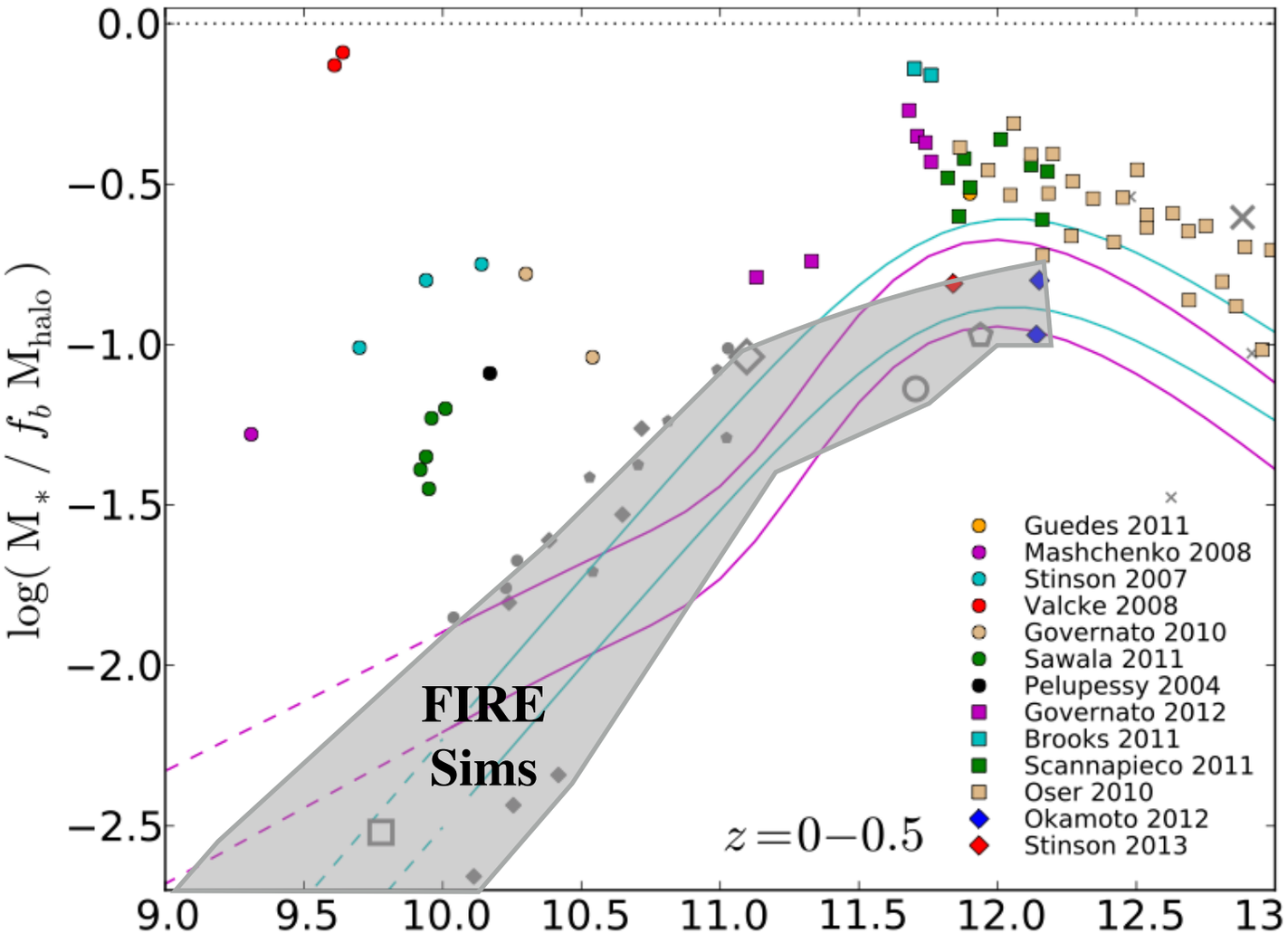

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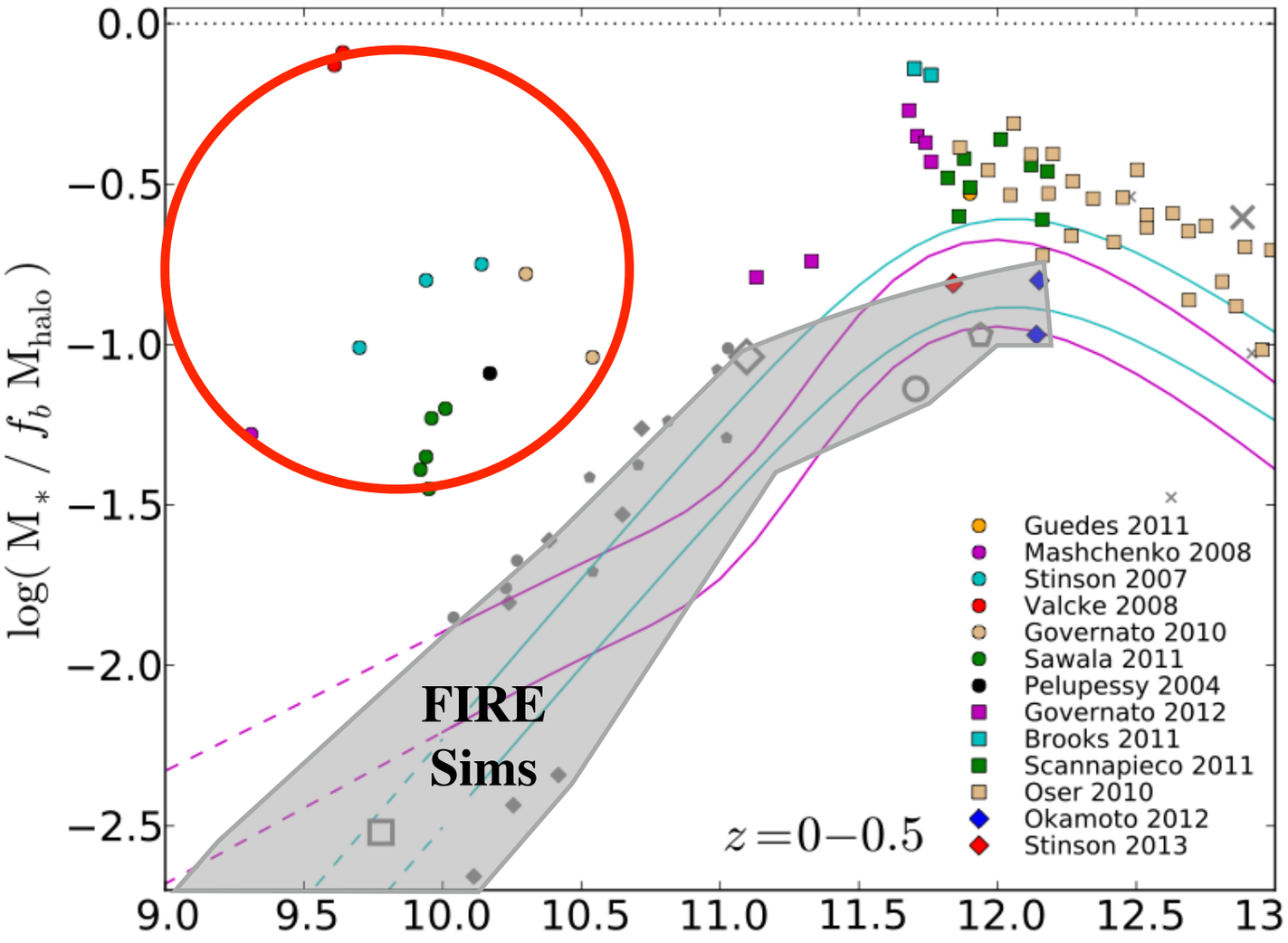

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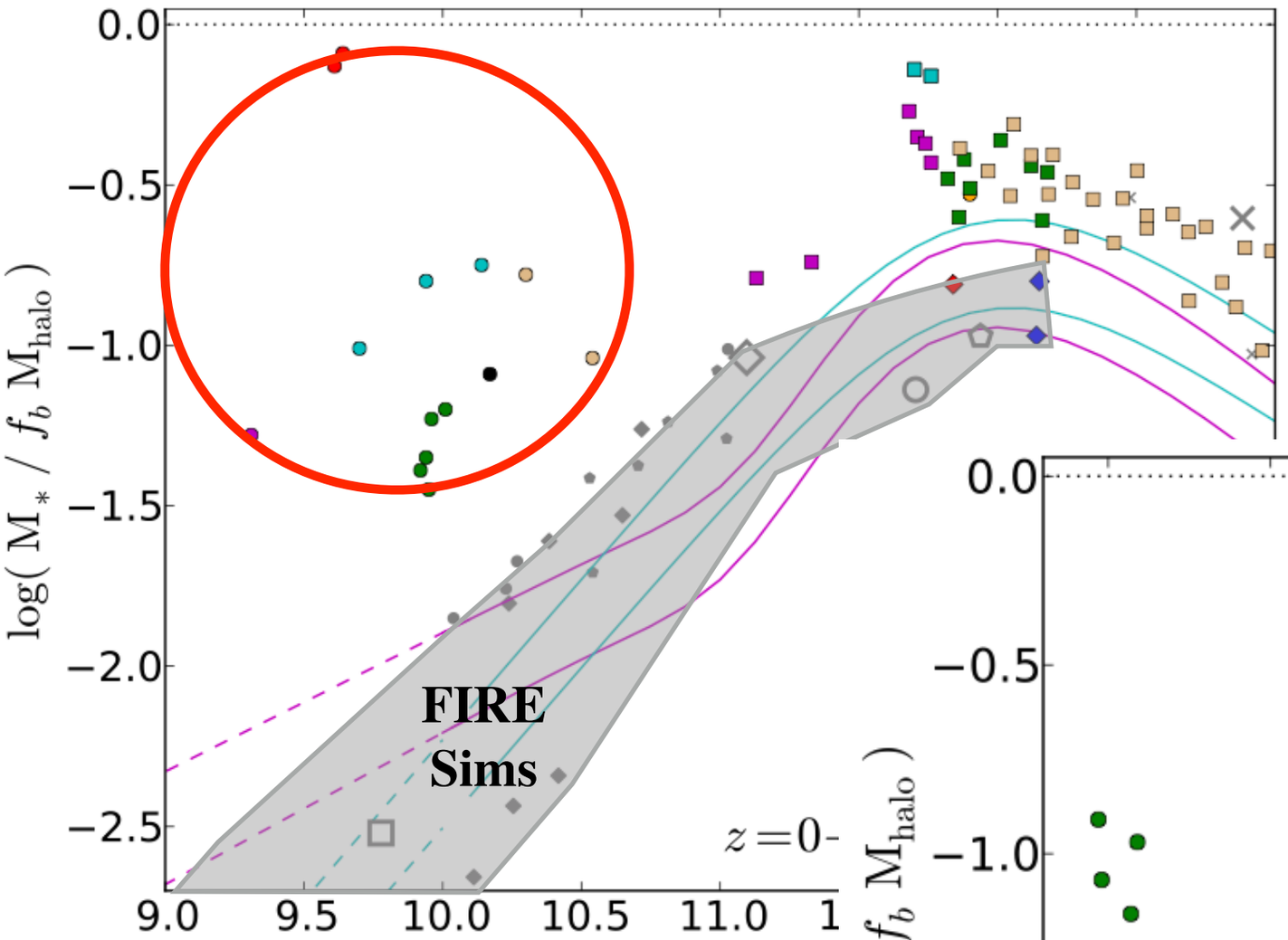

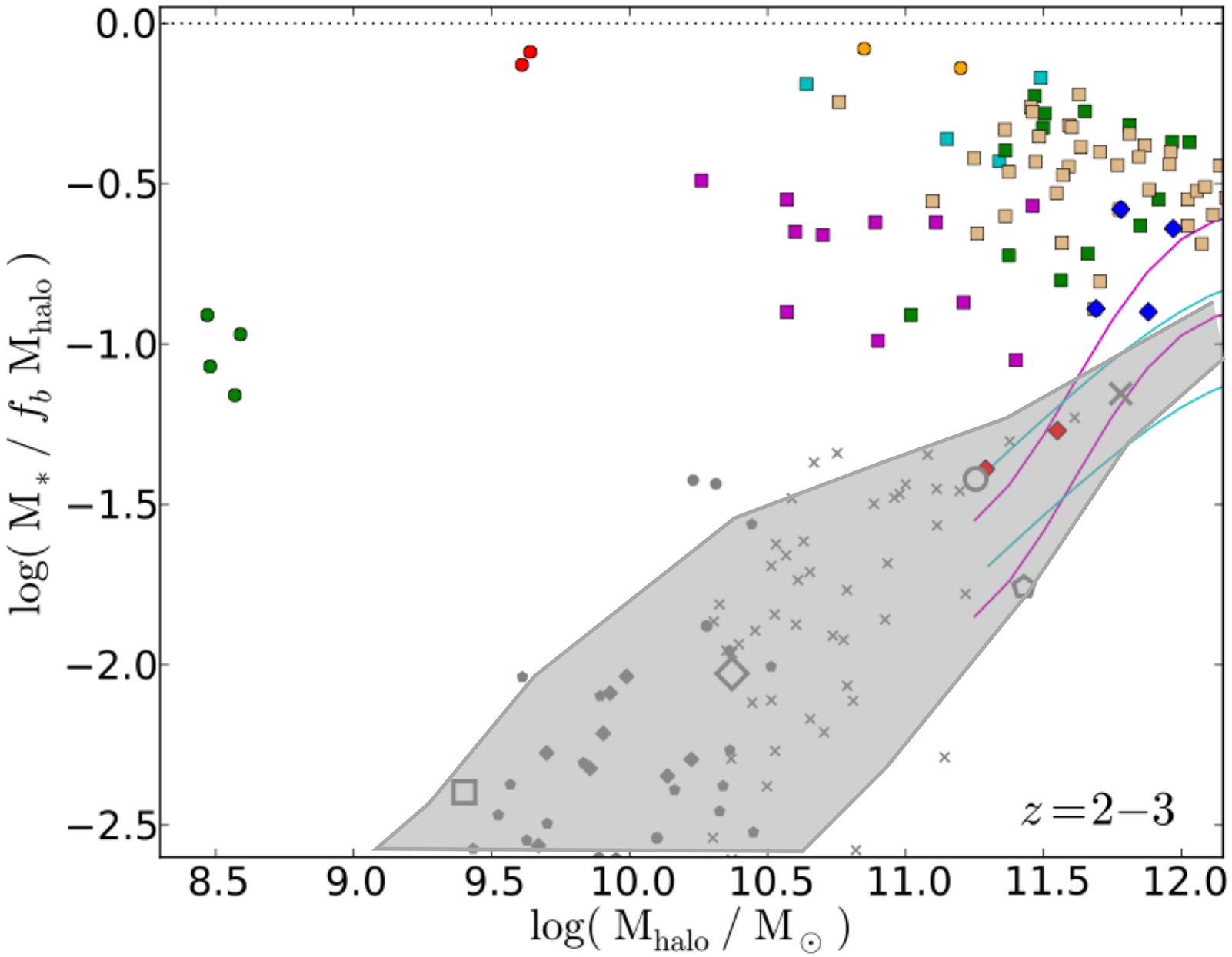

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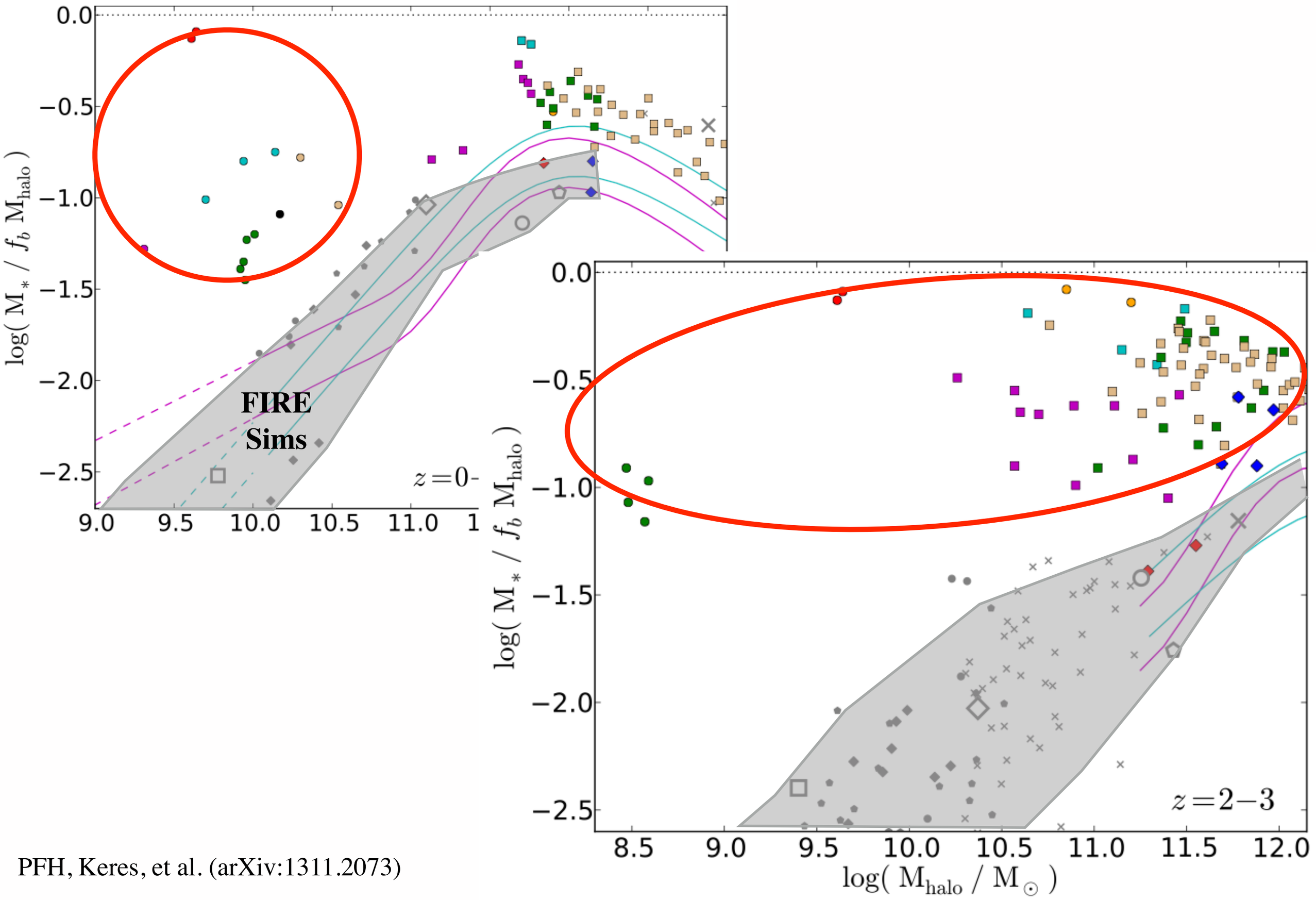

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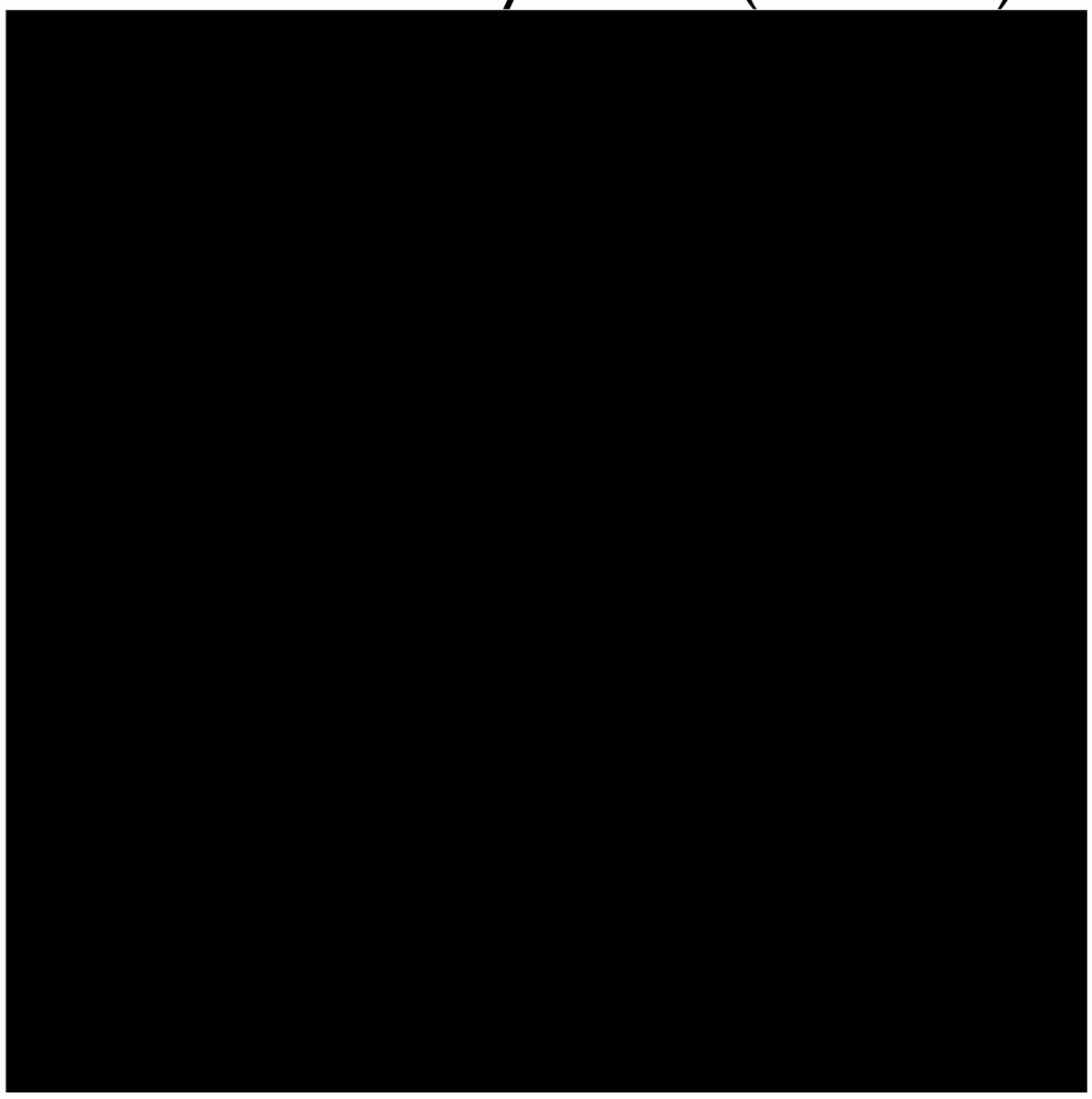
Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)



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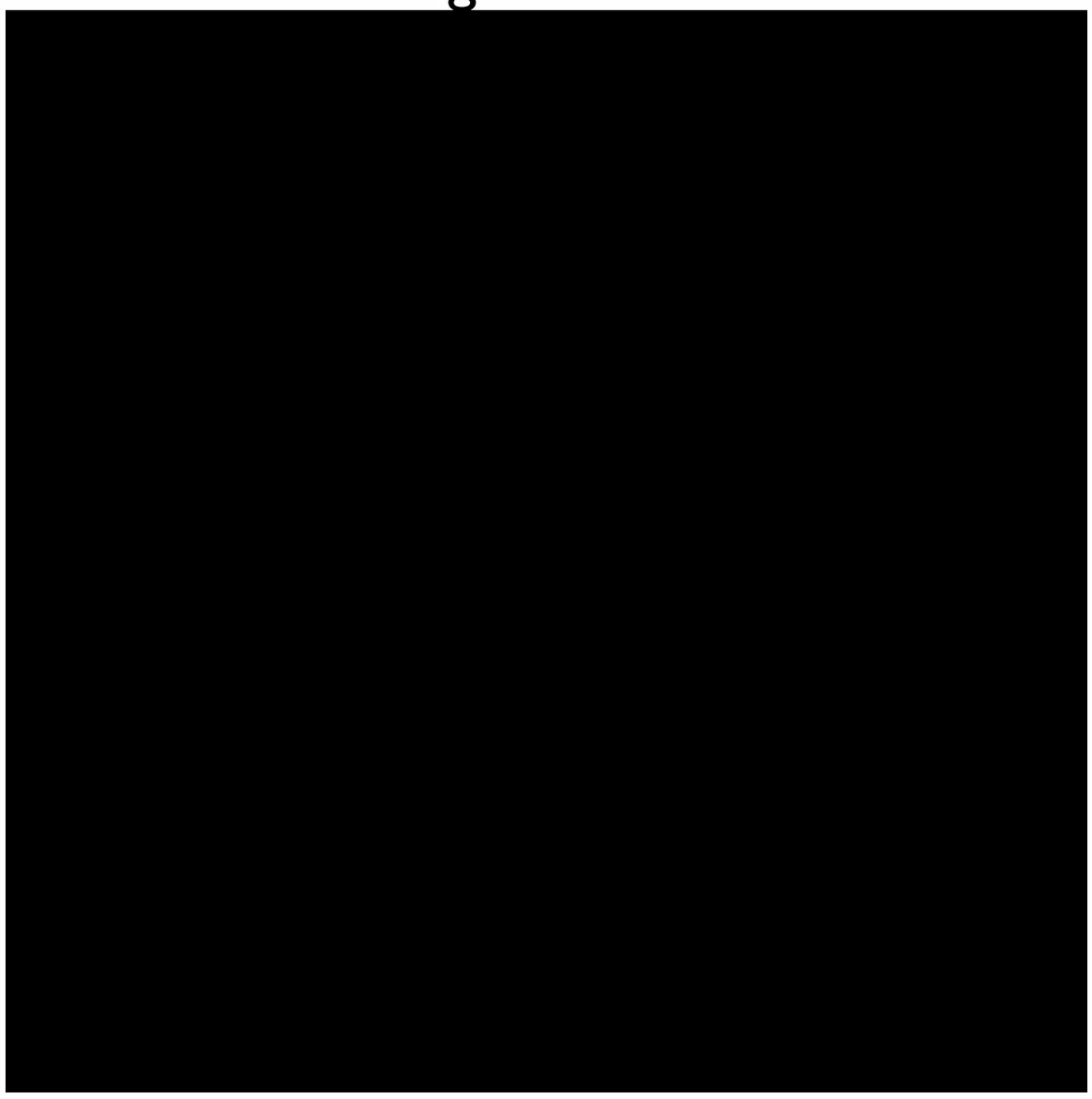

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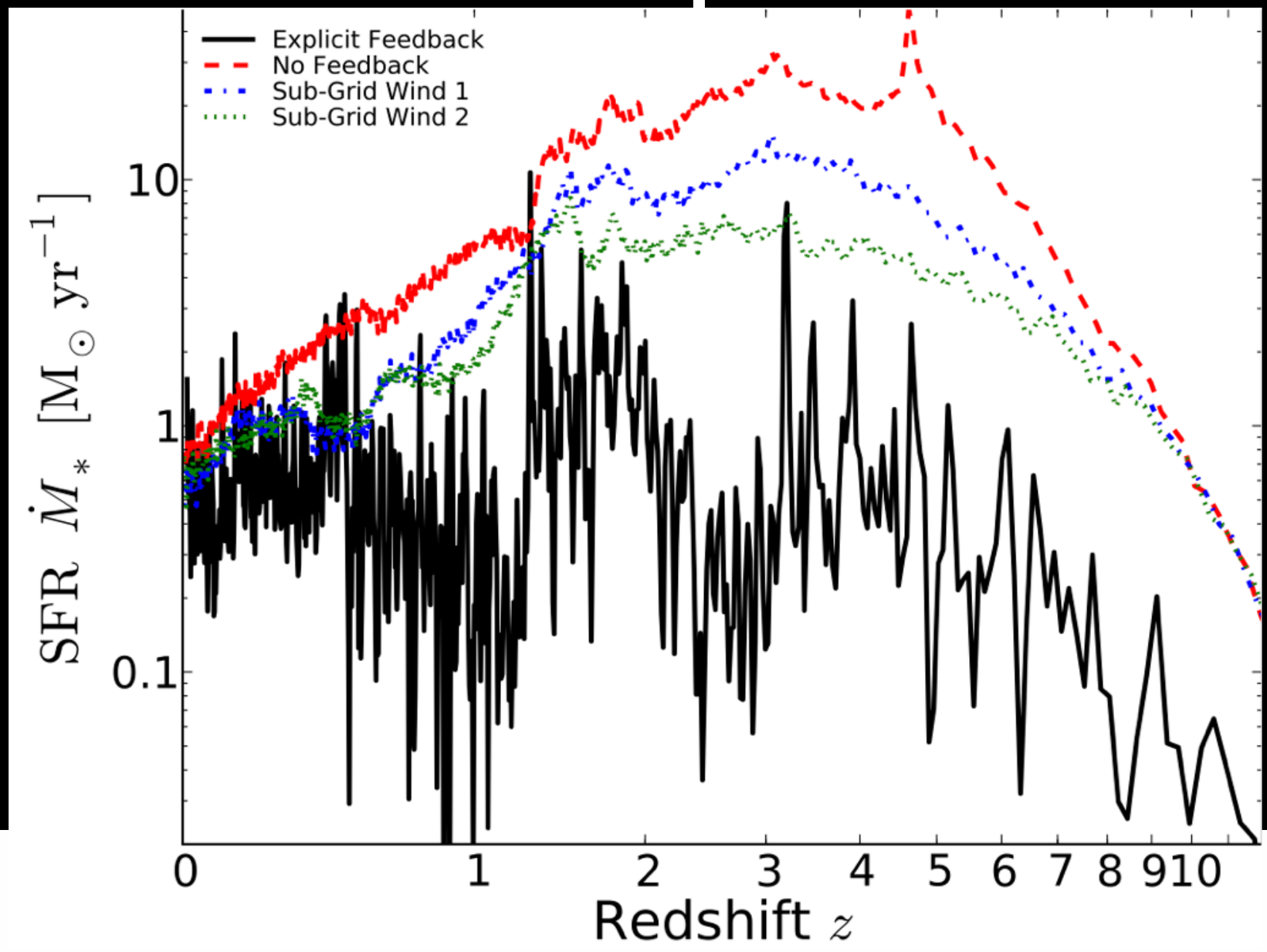

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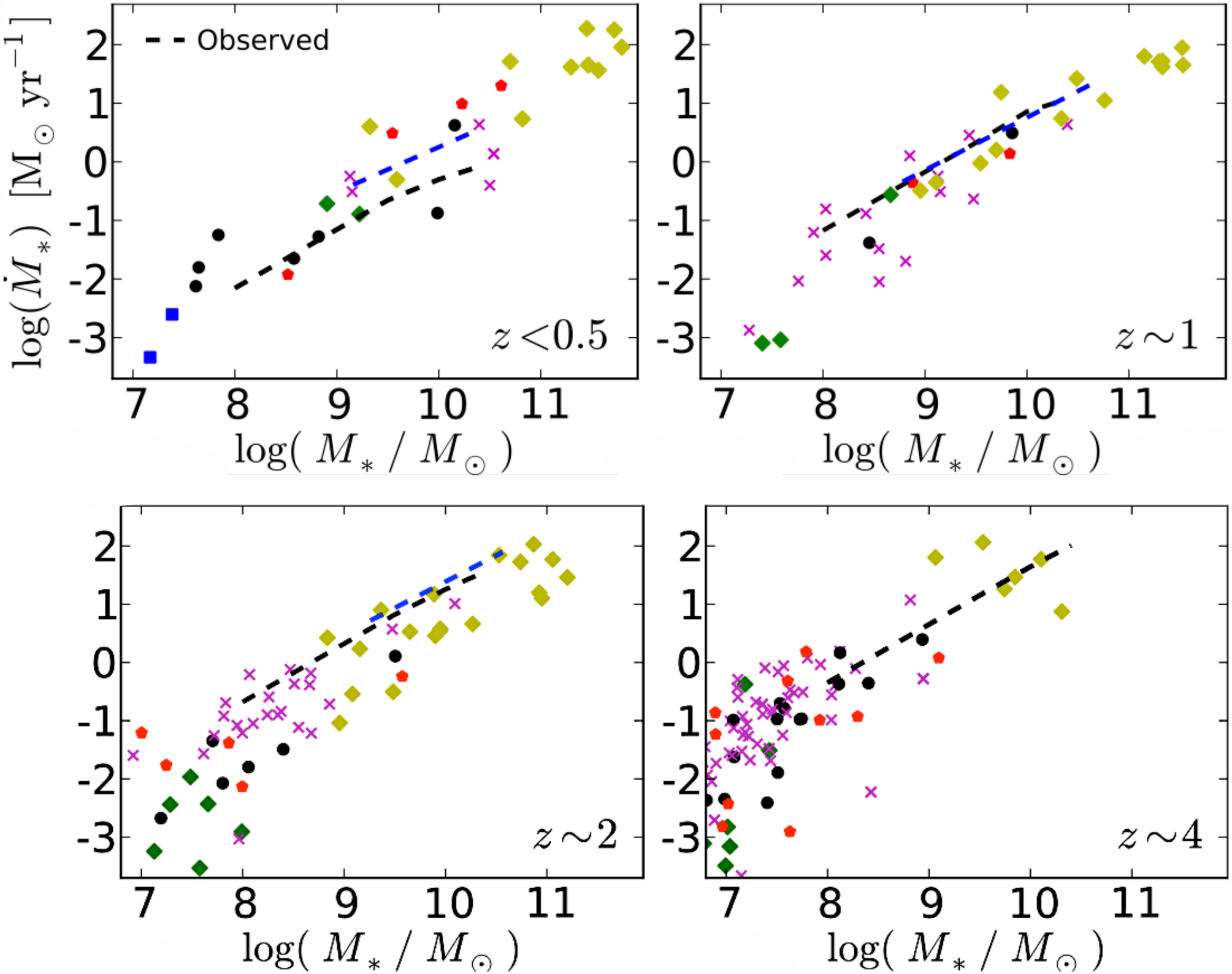
z=30.0

z=30.0

Star Formation "Main Sequence" & Specific SFRs:

NOT A STRONG CONSTRAINT



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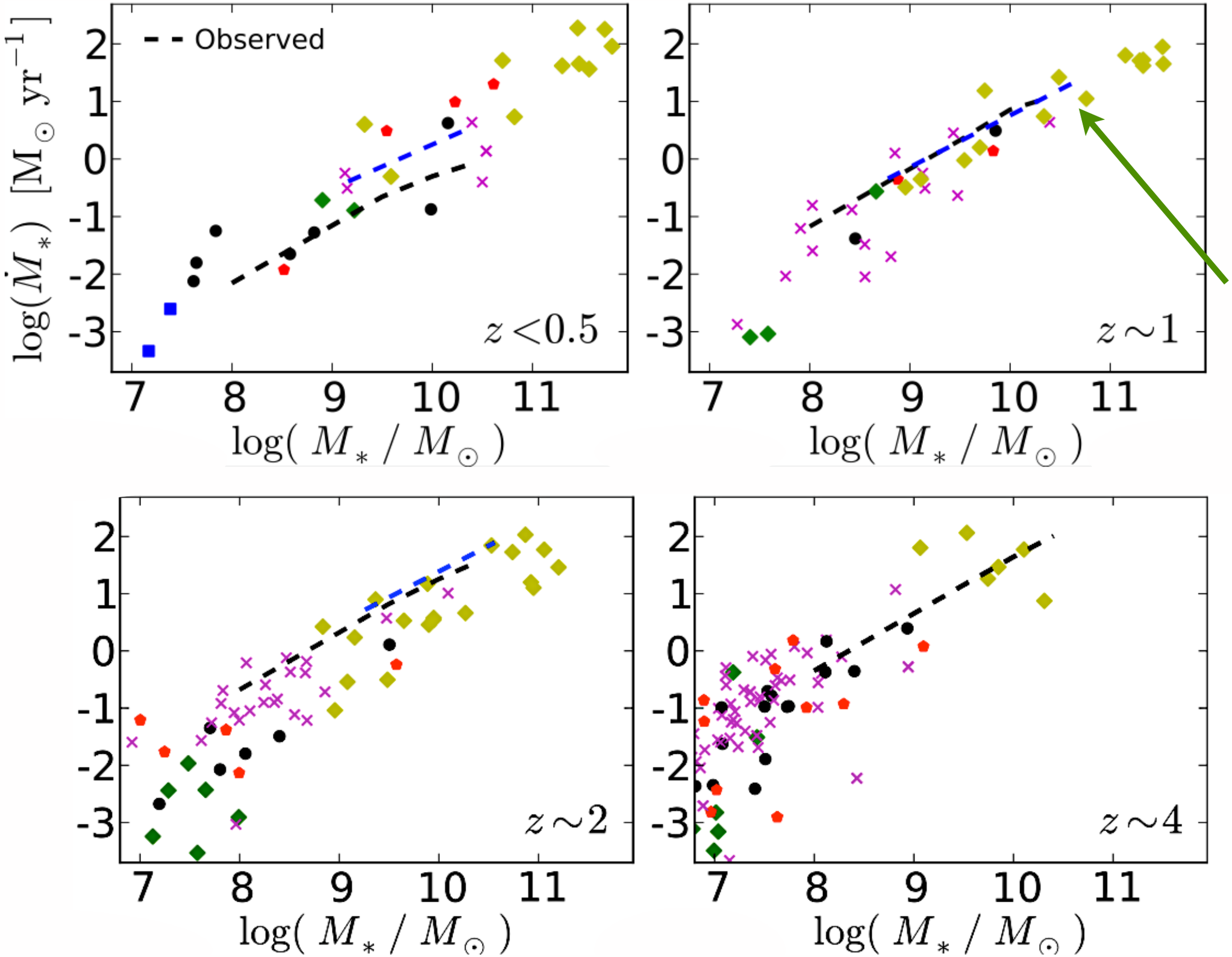
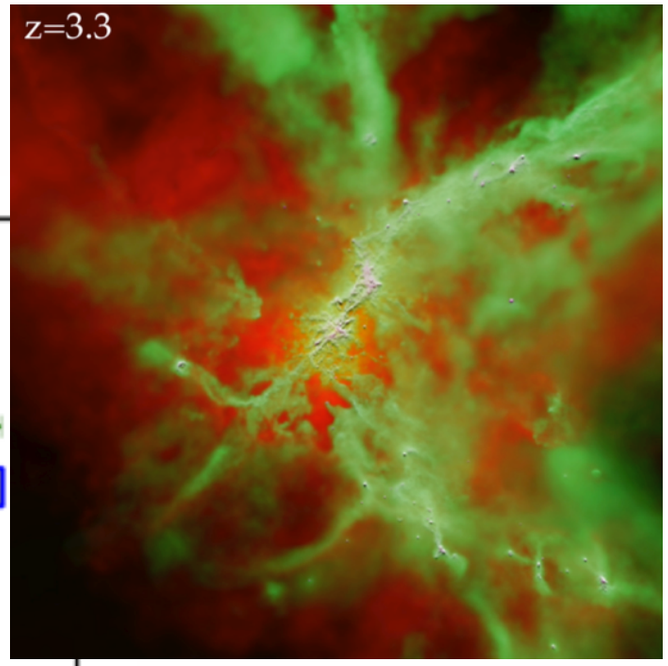
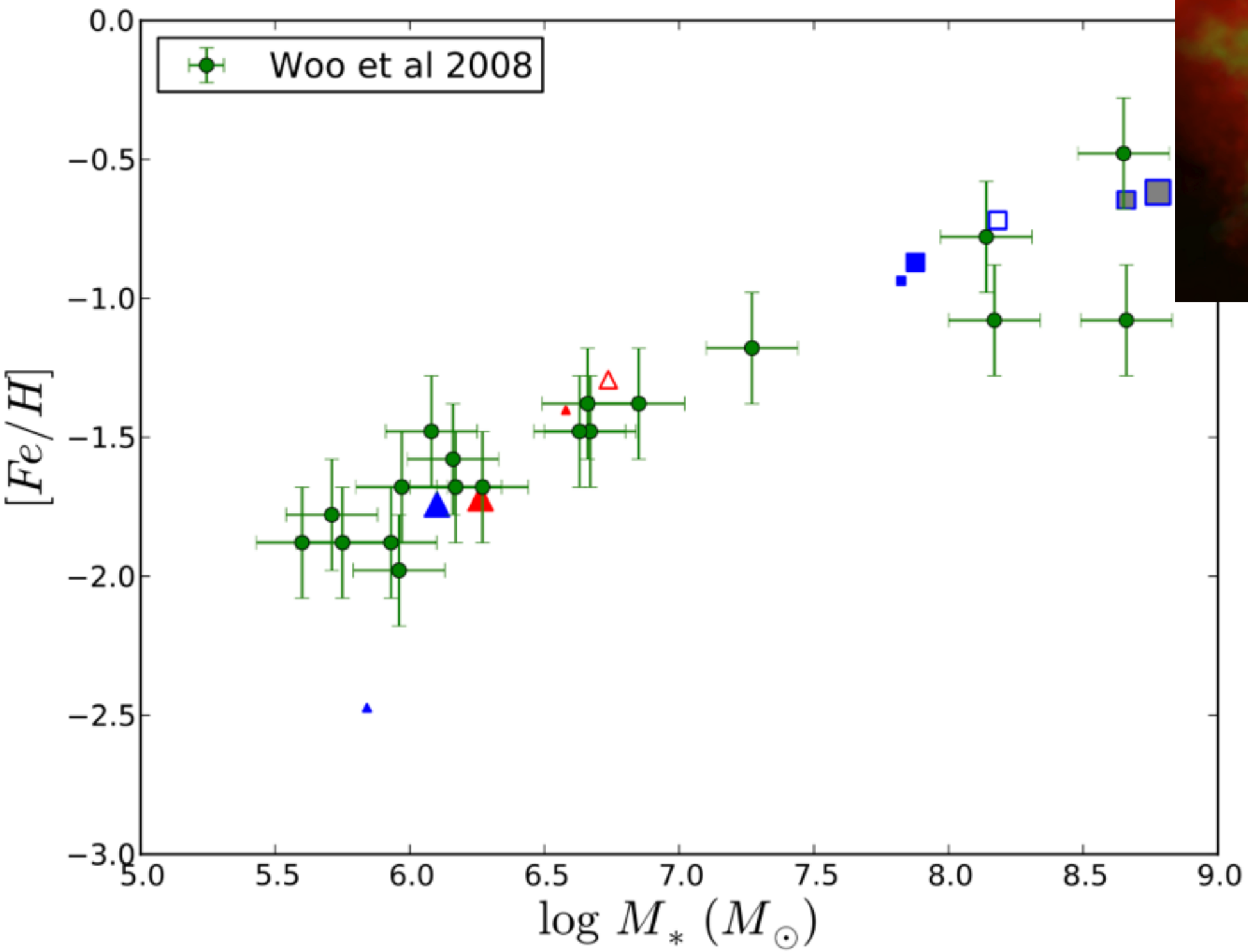


But, Mass-Metallicity Relation is Sensitive to Feedback

DETAILS MATTER





Torrey, PFH, in prep.

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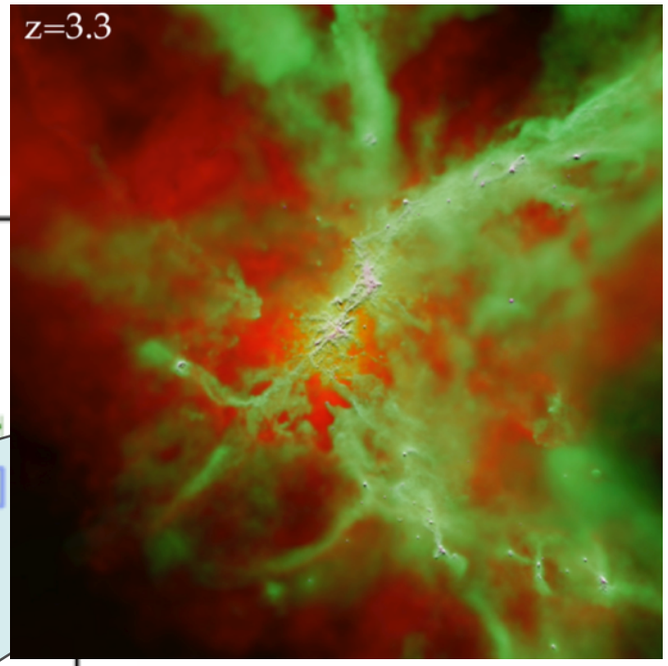

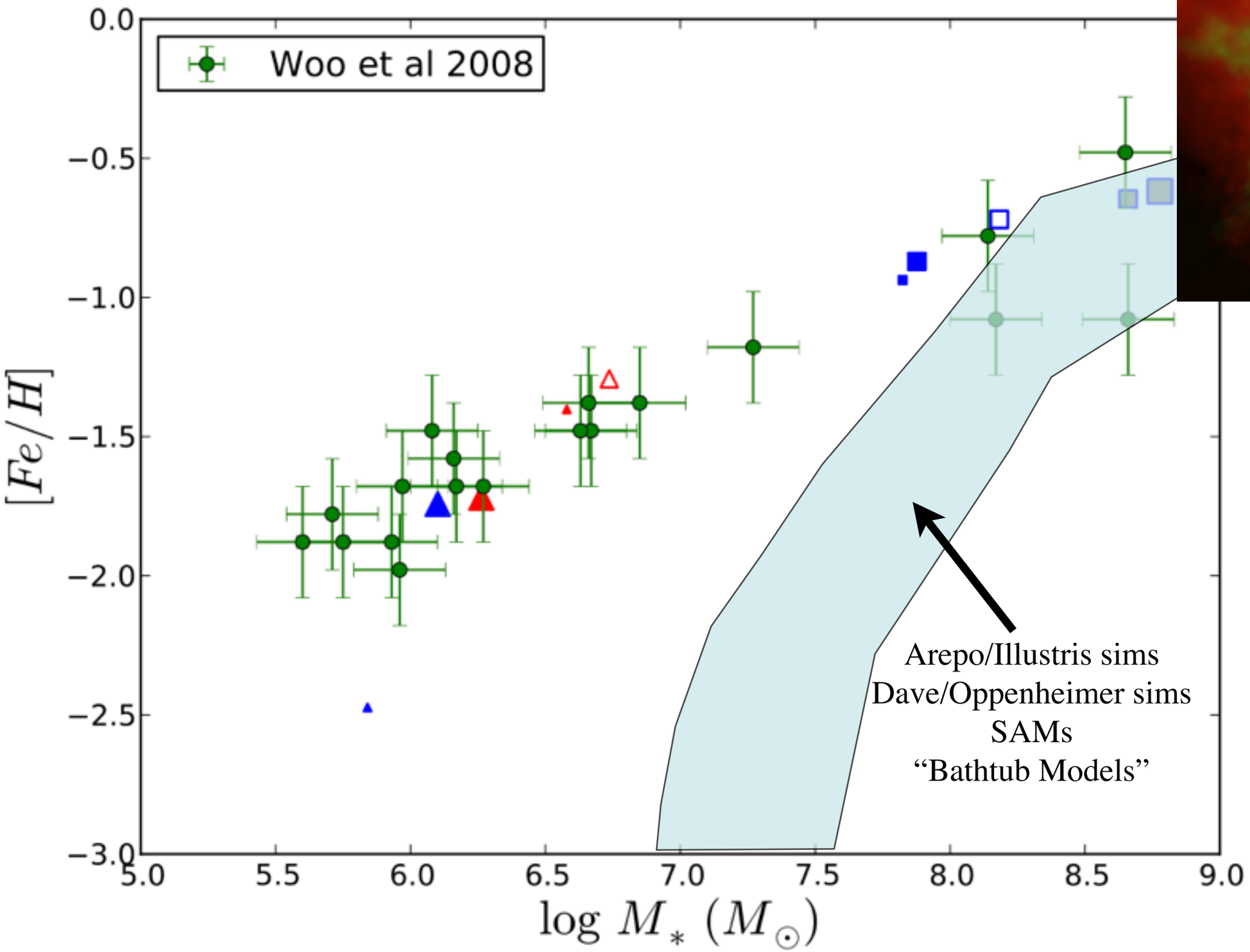

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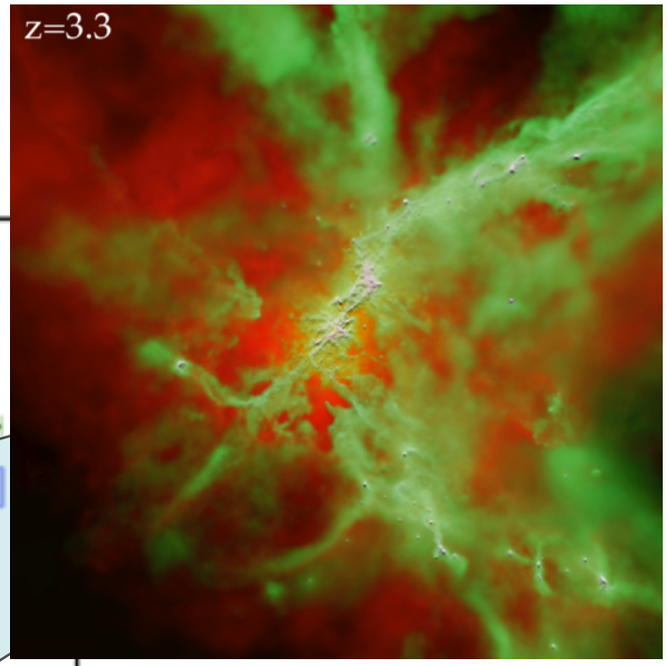
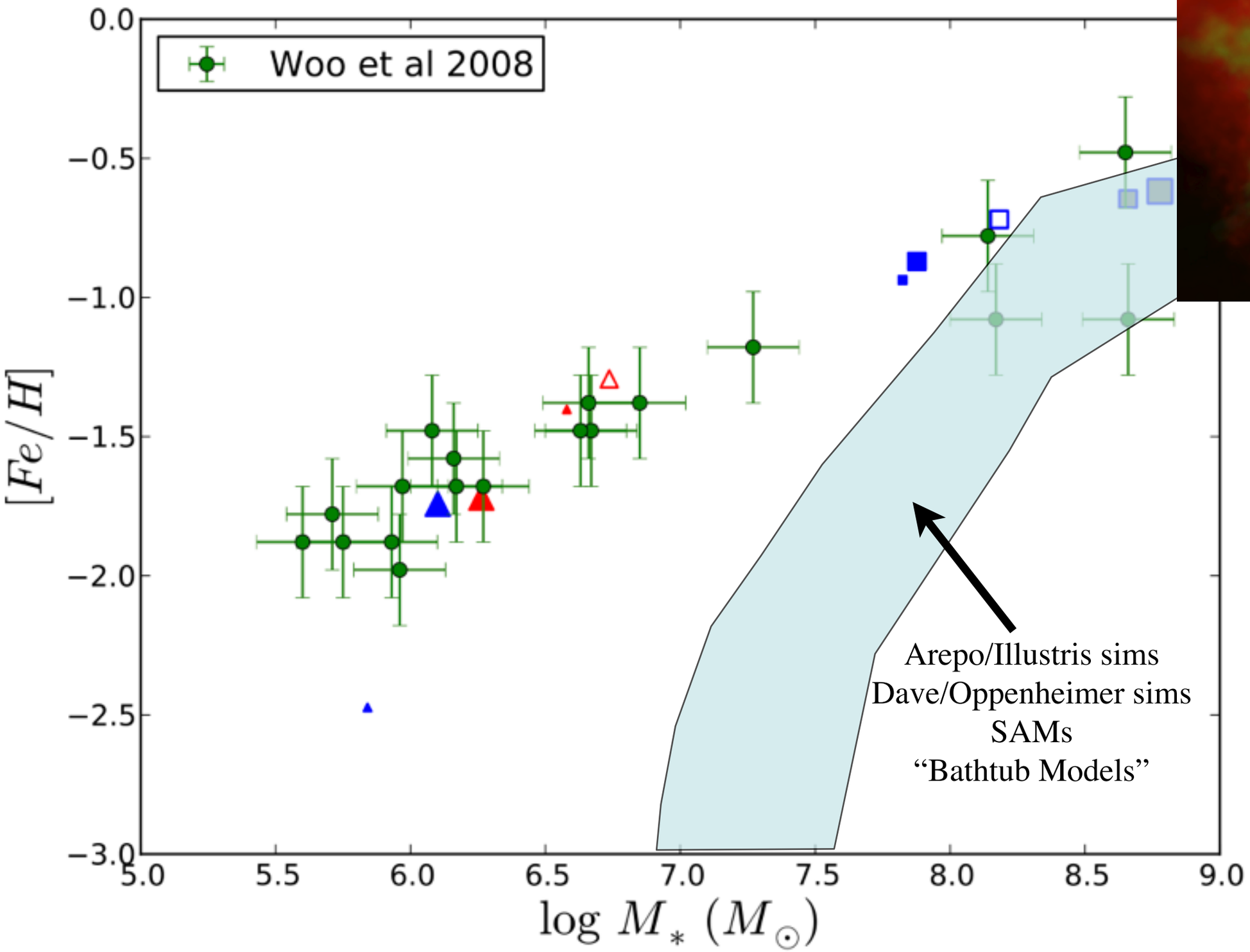


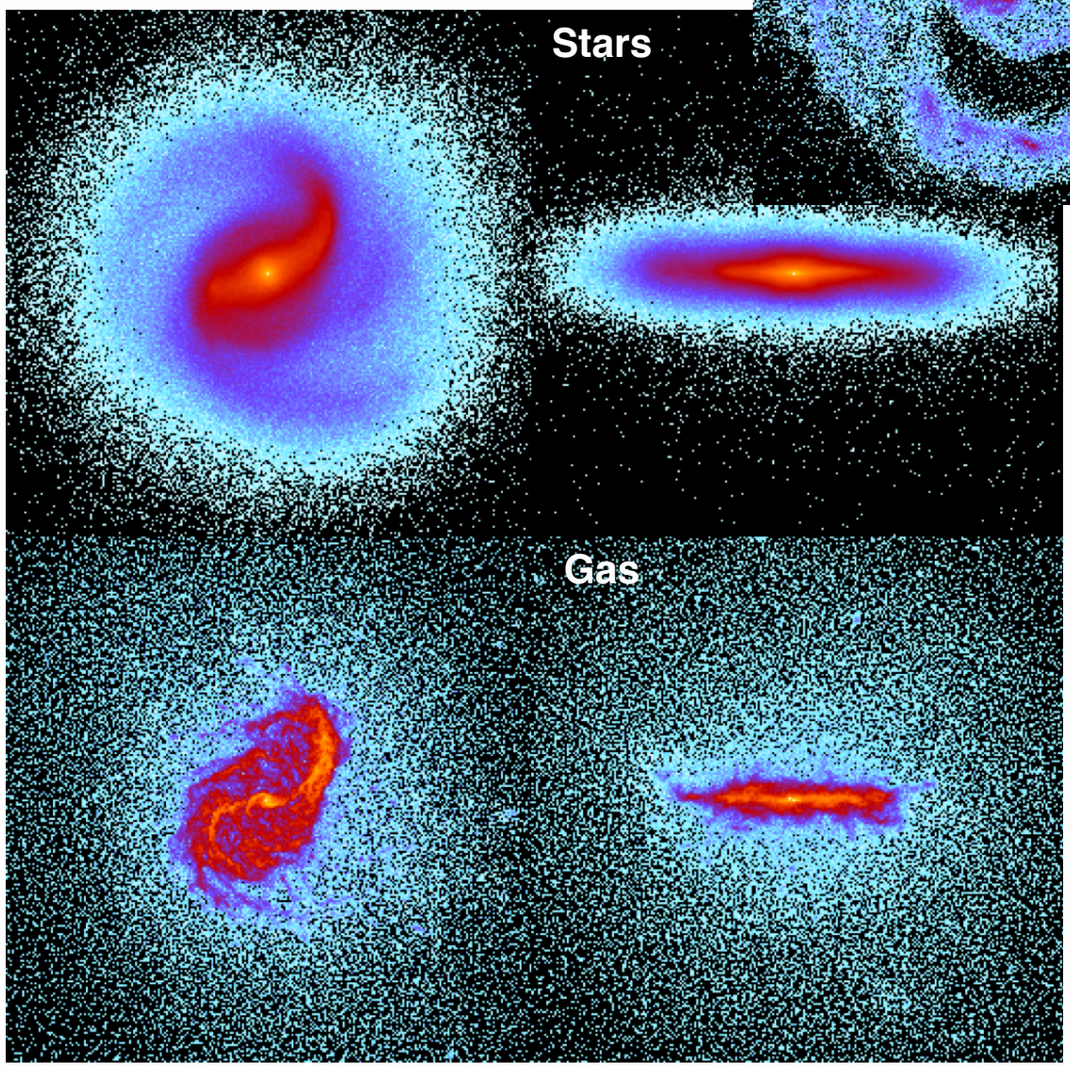


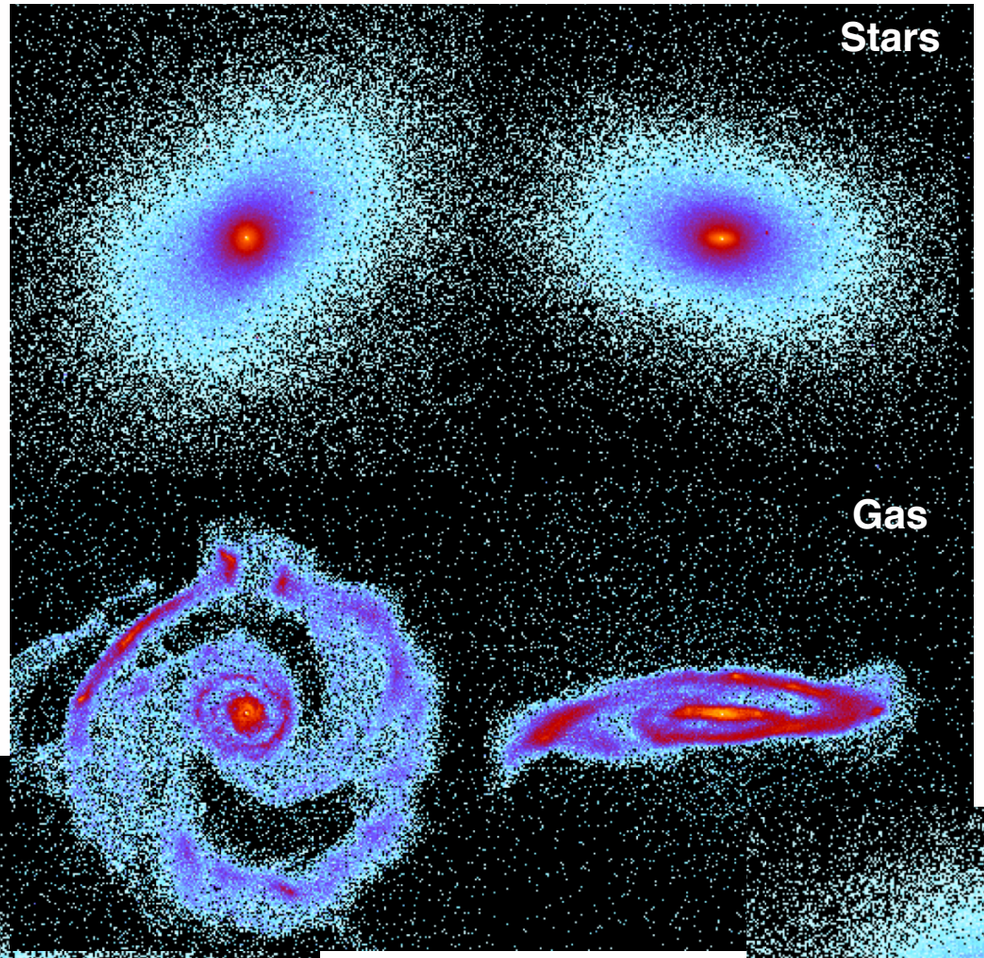
- Outflows suppress "new" infall of pristine material
- Metal-rich gas preferentially re-accretes in fountains

Torrey, PFH, in prep.

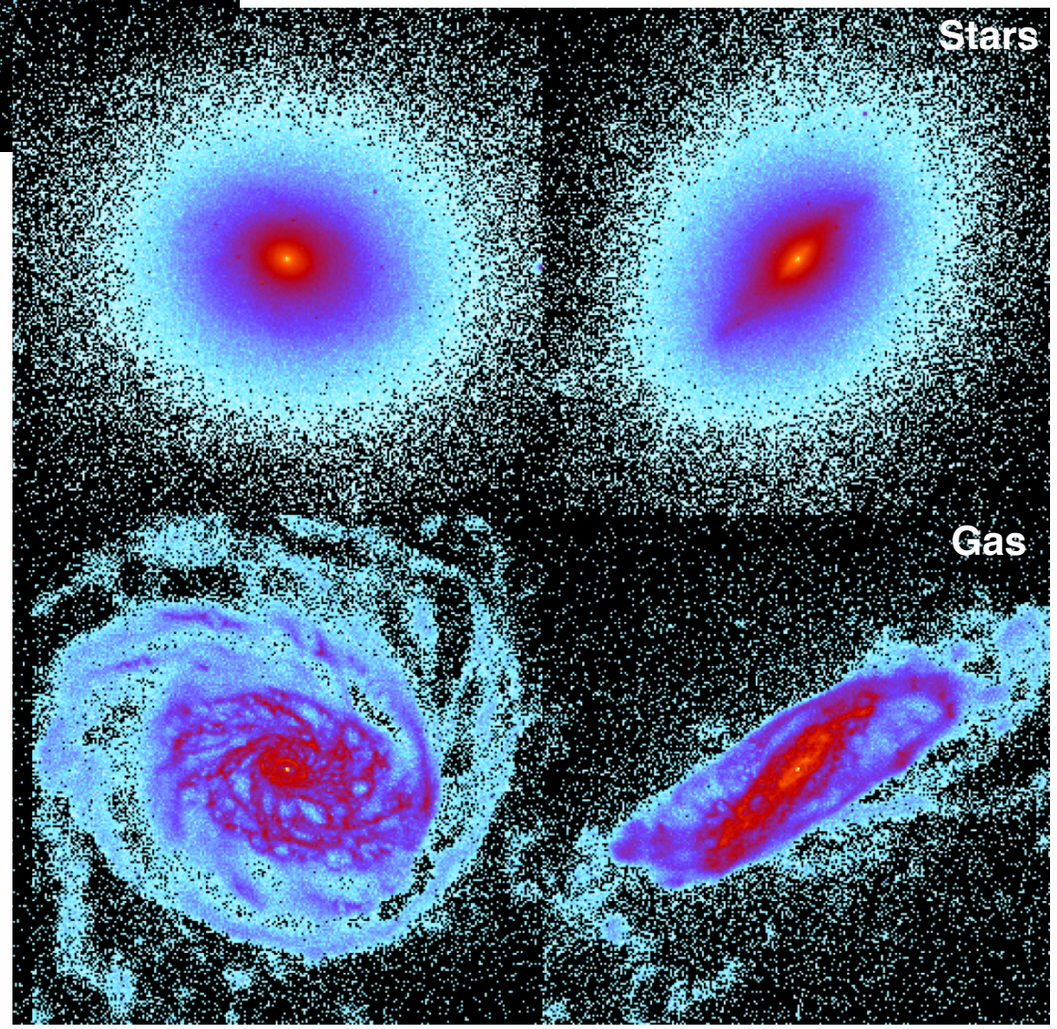
Morphology is *Very* Sensitive to Feedback

DETAILS MATTER



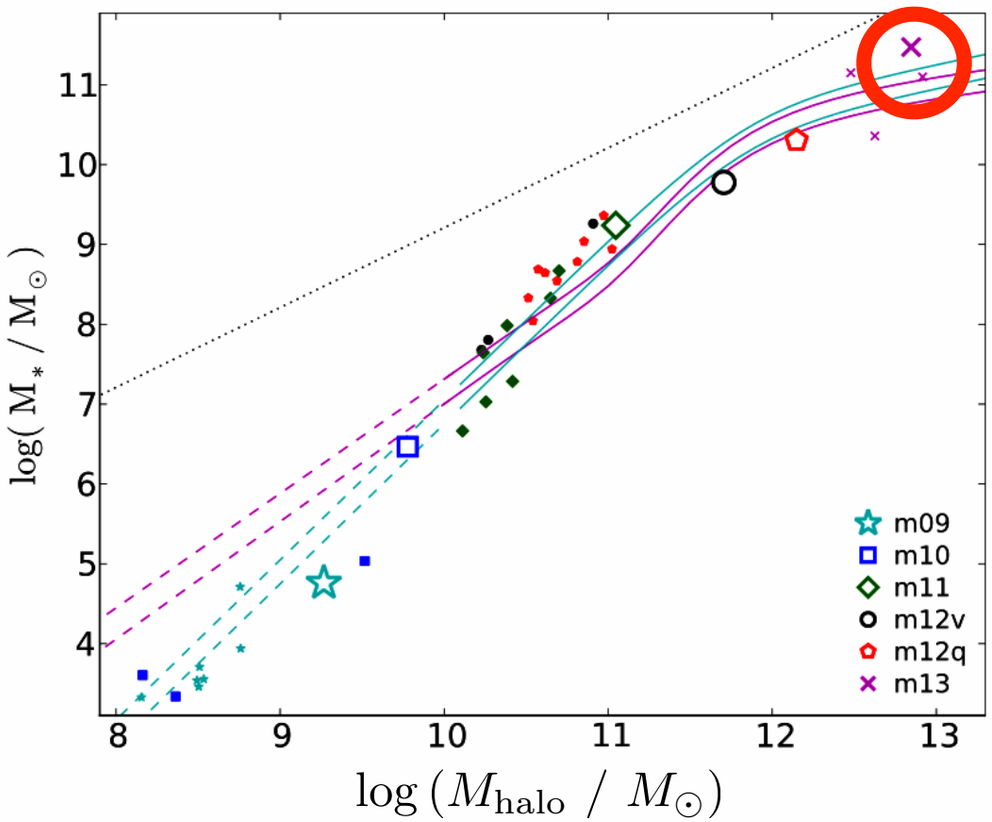


van de Voort, PFH, in prep.



Quenching: Non-AGN Mechanisms *FAIL*

MORE THAN GRAVITY, COOLING, STARS, & MHD



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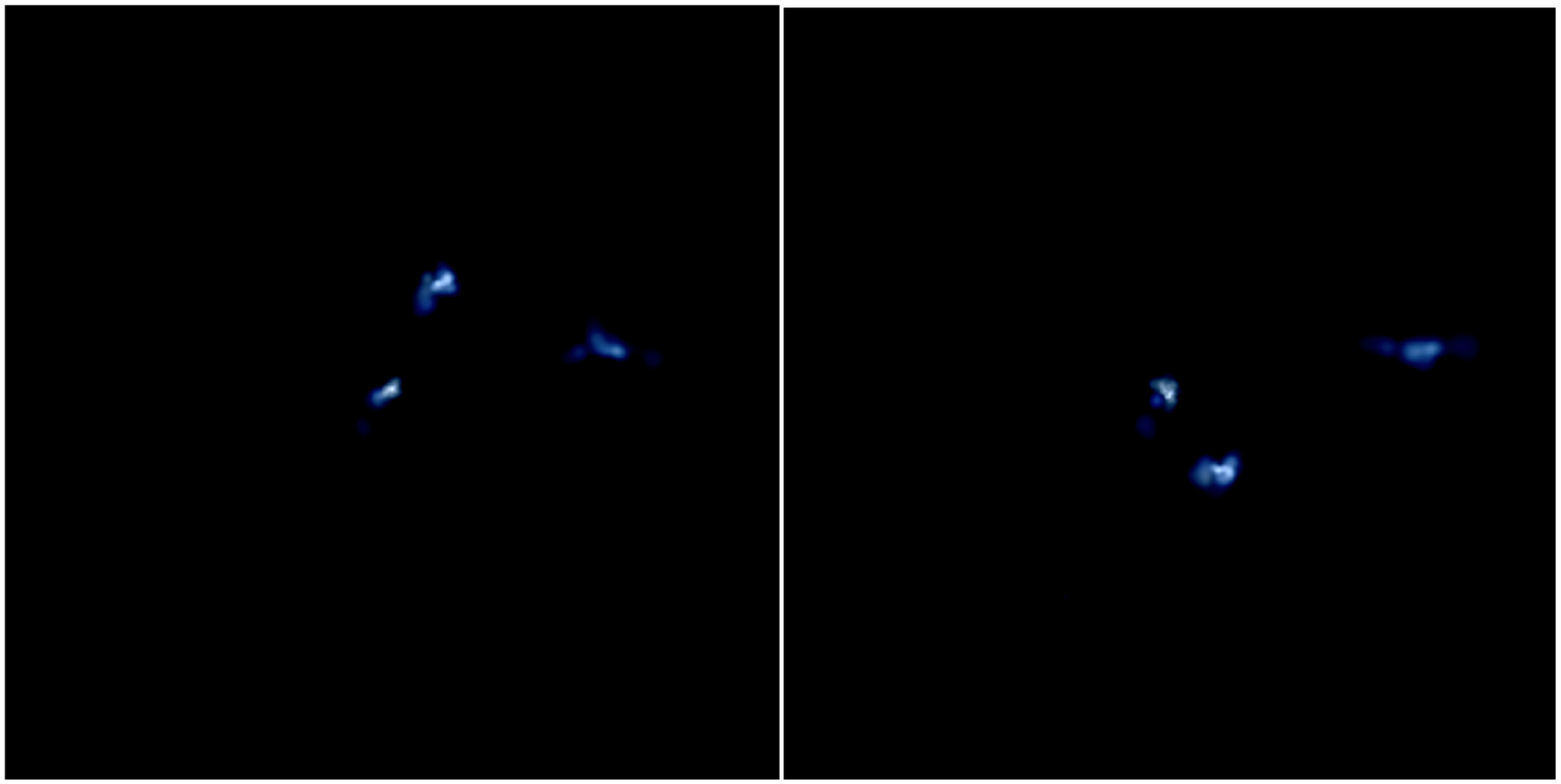

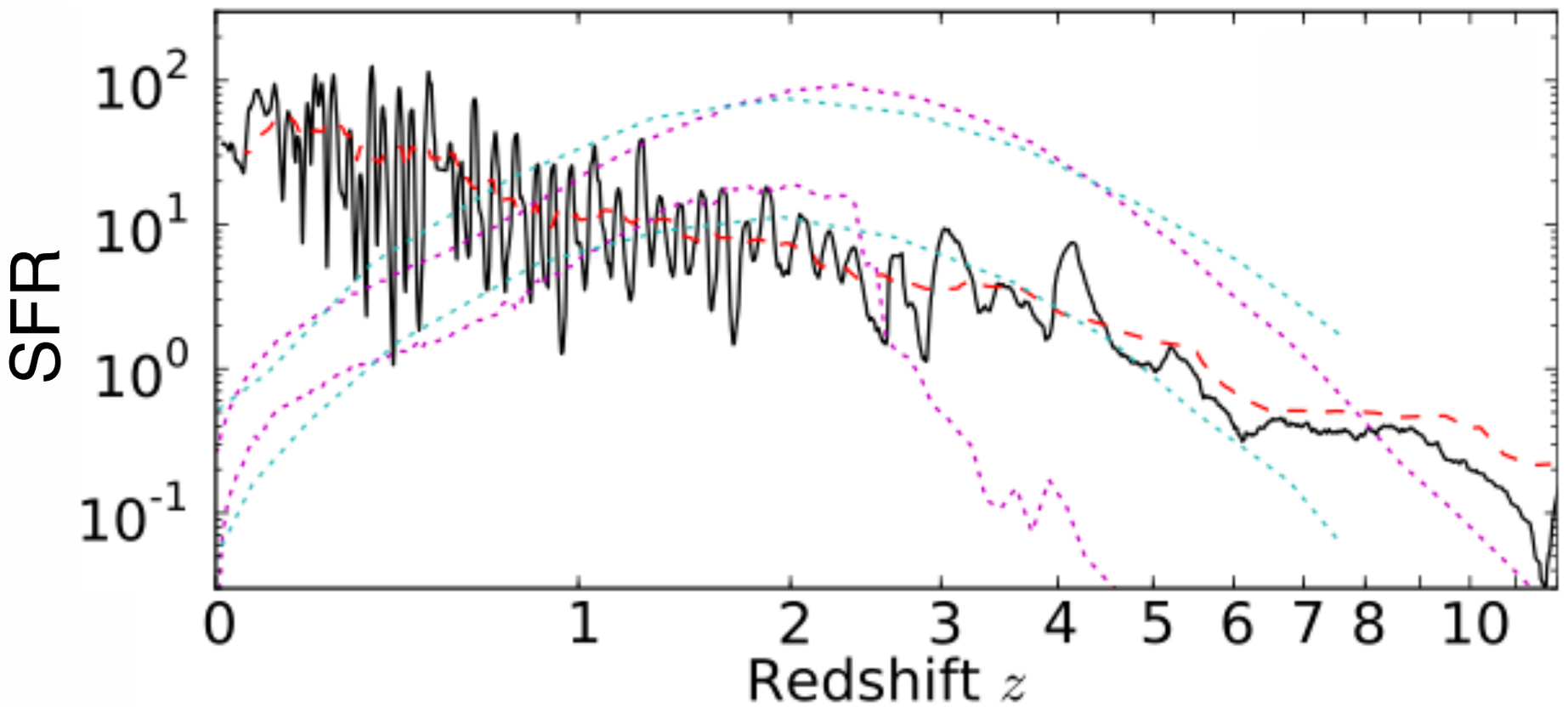

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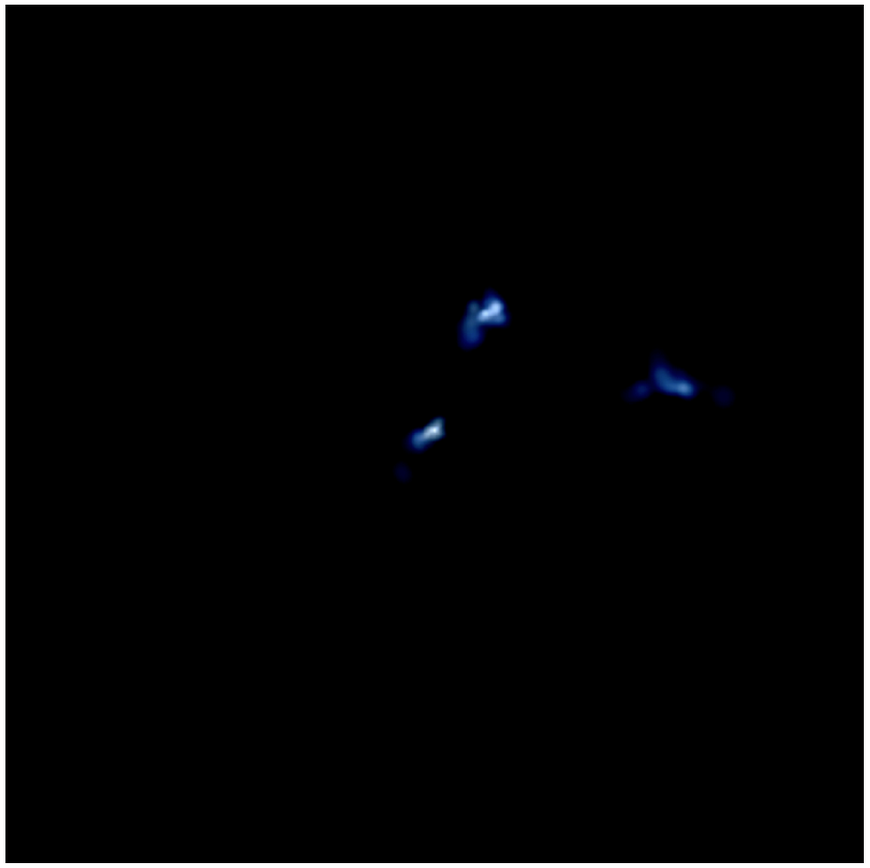

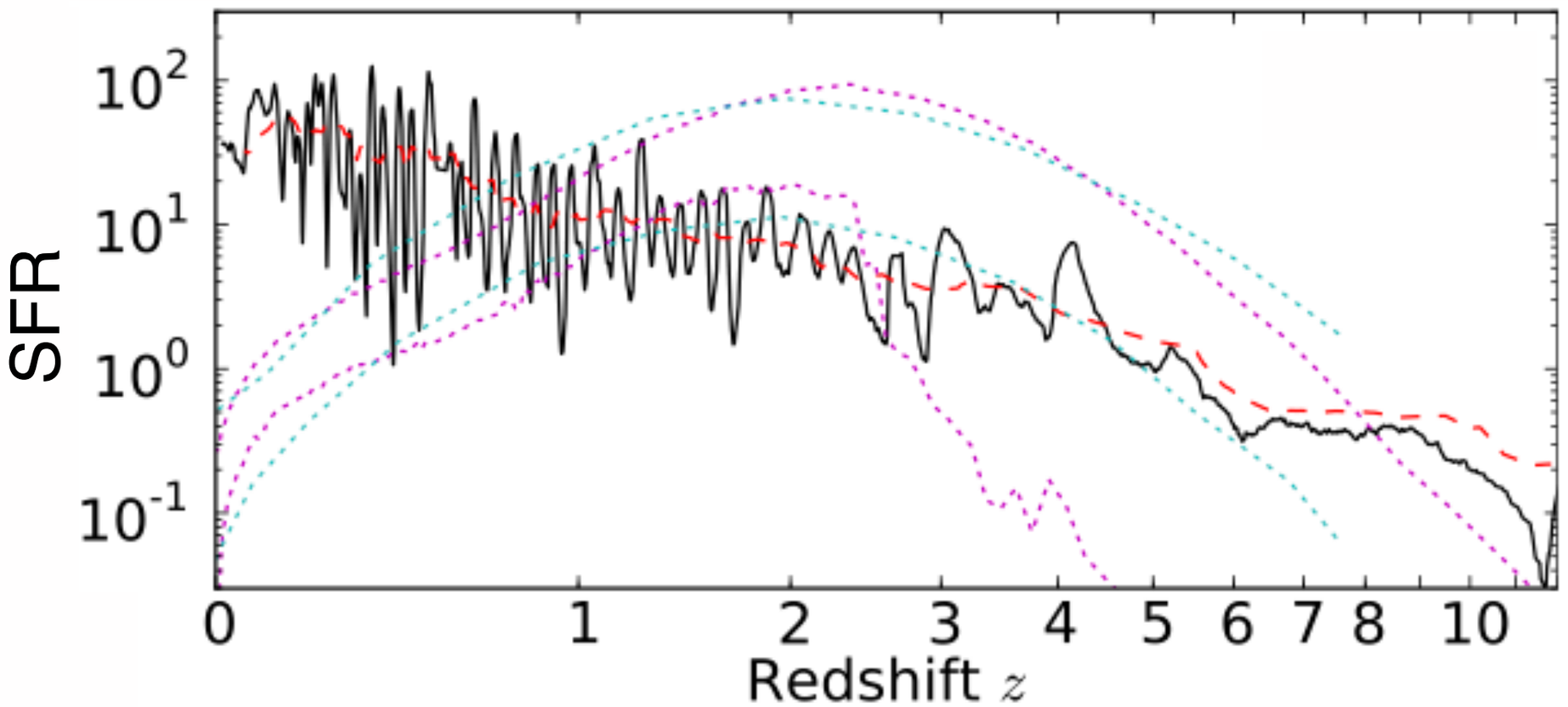

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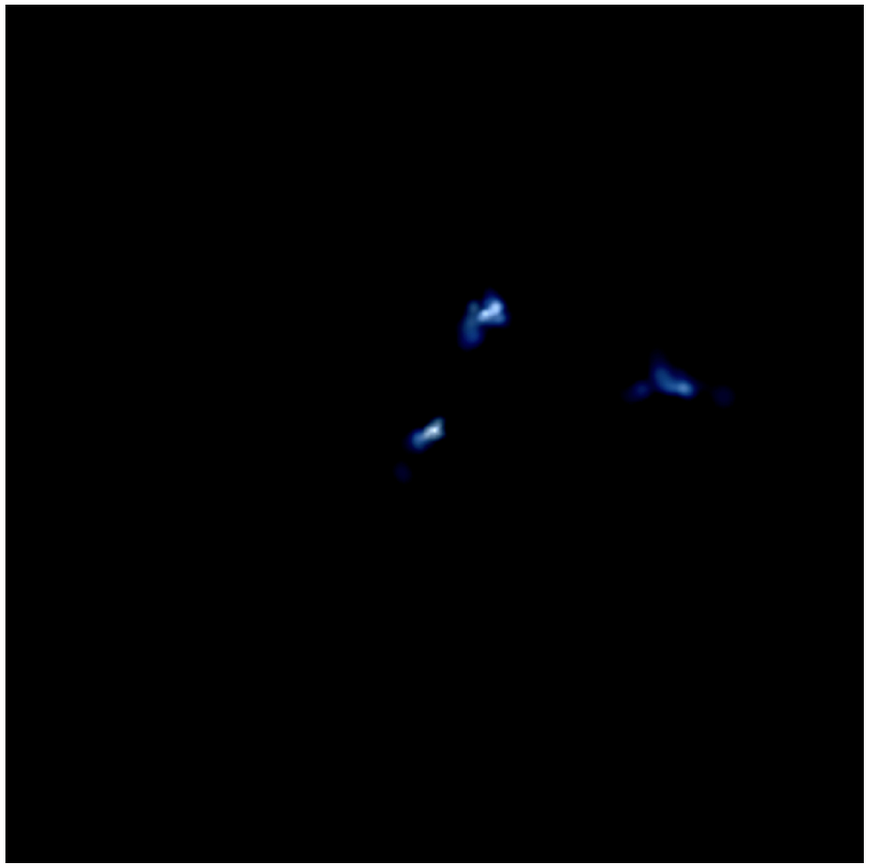
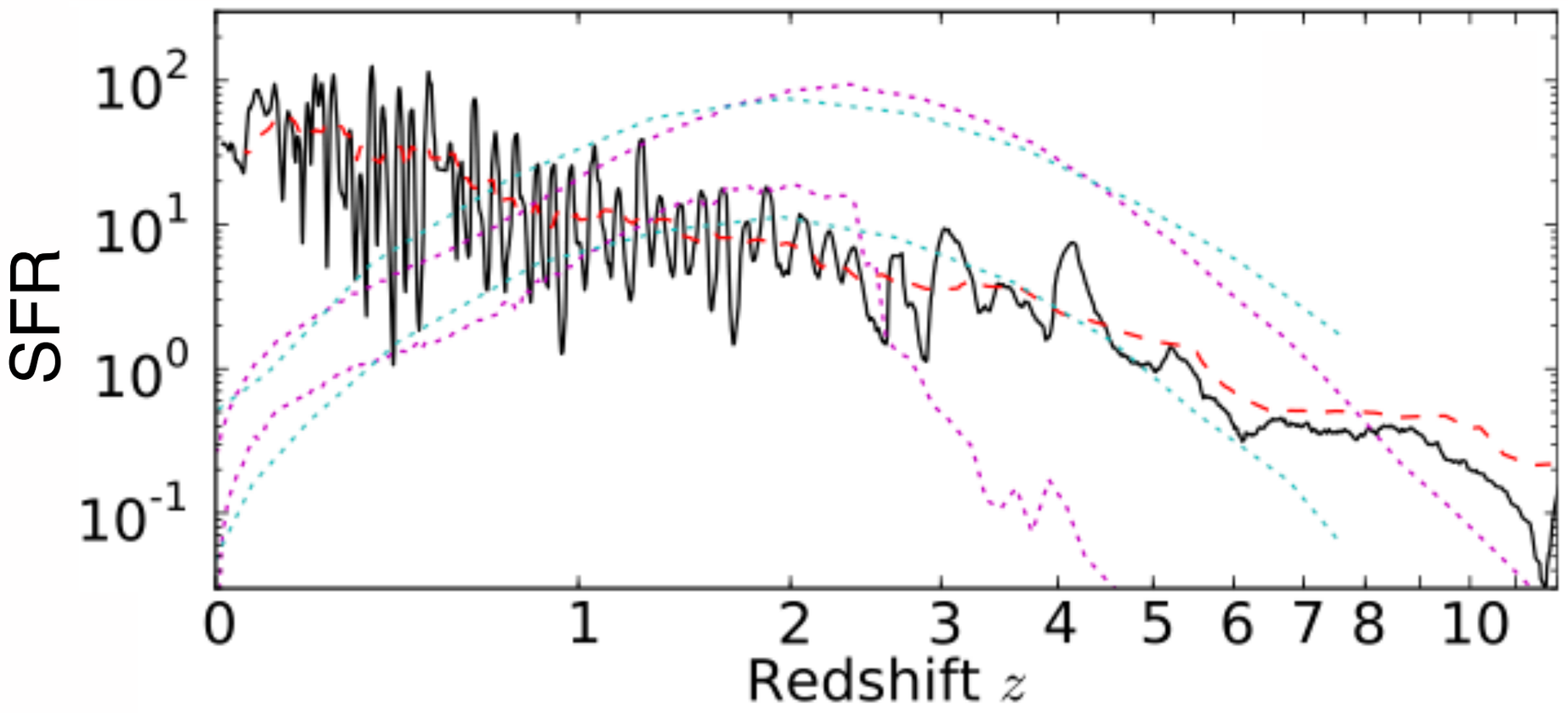


- "Morphological Quenching" (Martig+)
  - Morphology $\neq$ cooling
  - Original ignored low-T gas



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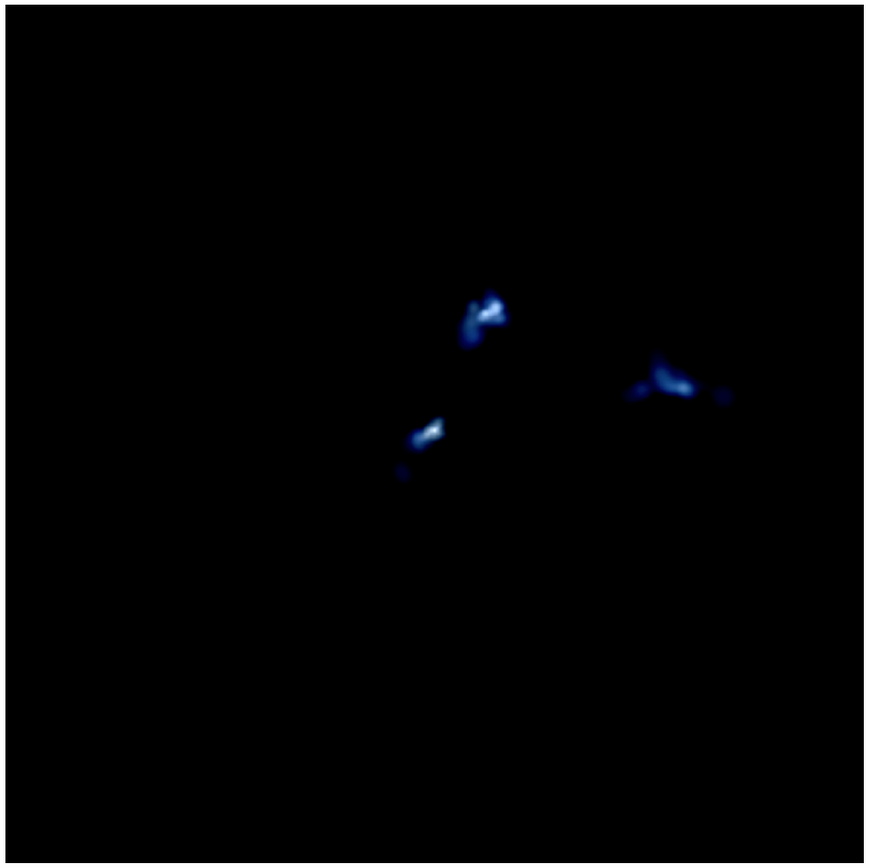

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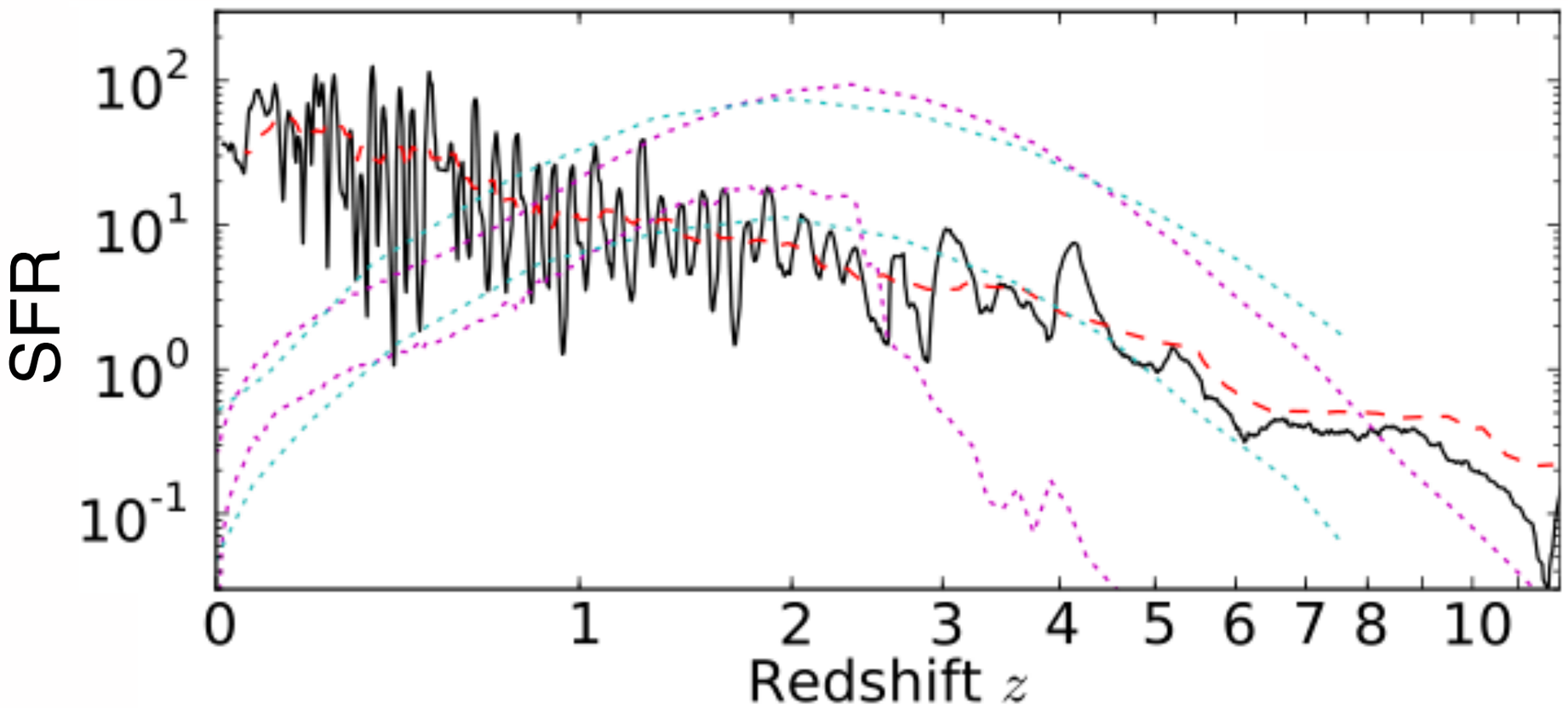
  - Heats ~R_{VIR} "cooling flows" at *center*
  - Coupling inefficient: res.~100x better than "needed"



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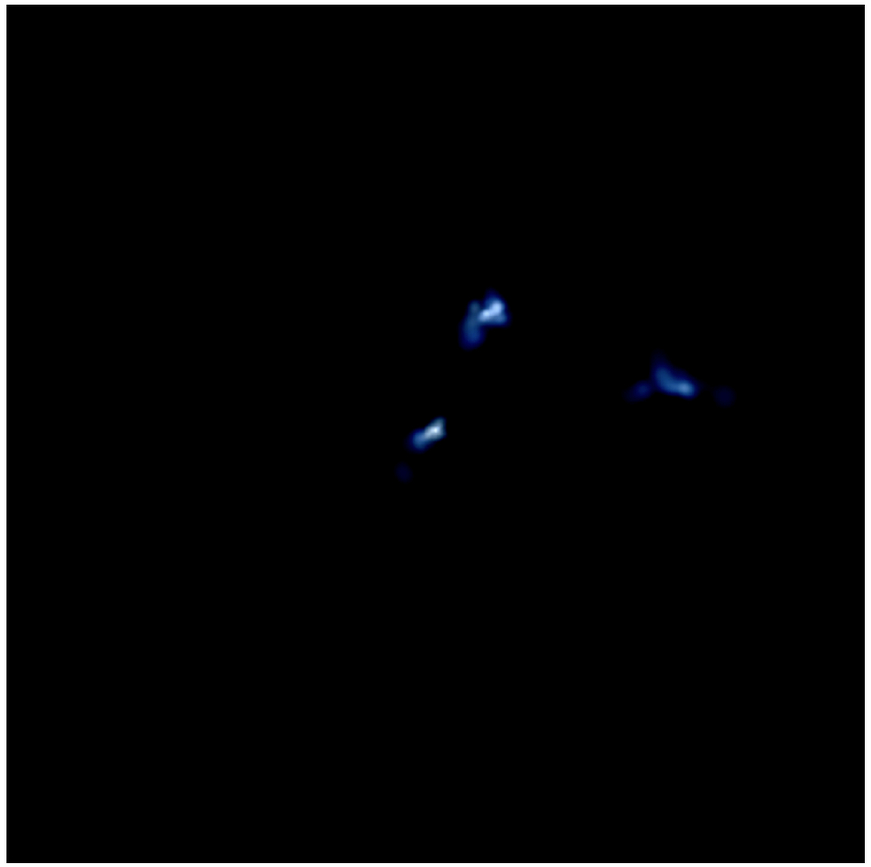

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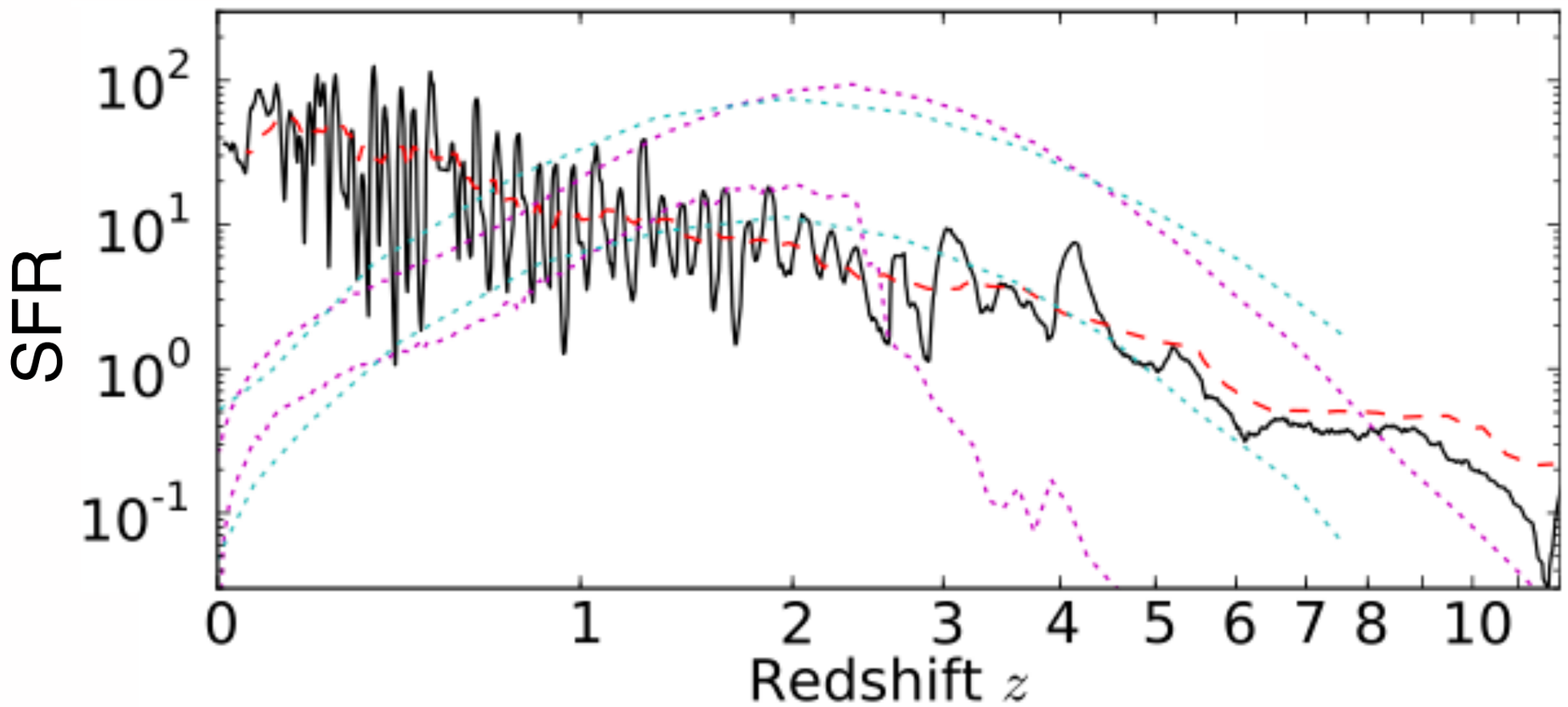
- Conduction:
  - Magnetic Instabilities (HBI; Quataert '08)
  - Inefficient in halos < 10^{14} M_{SUN}



- **Star formation is Feedback-Regulated**: *independent* of small-scale SF
  - Enough stars to offset gravity = Kennicutt relation
- Different mechanisms dominate different regimes: **No *one* mechanism works**
  - High-ρ: rad. pressure & photo-heating
  - Low-ρ: SNe & stellar winds
- Cosmologically: ***Accretion does not regulate star formation***
  - **Winds** determine **IGM enrichment, temperature, & subsequent inflow**
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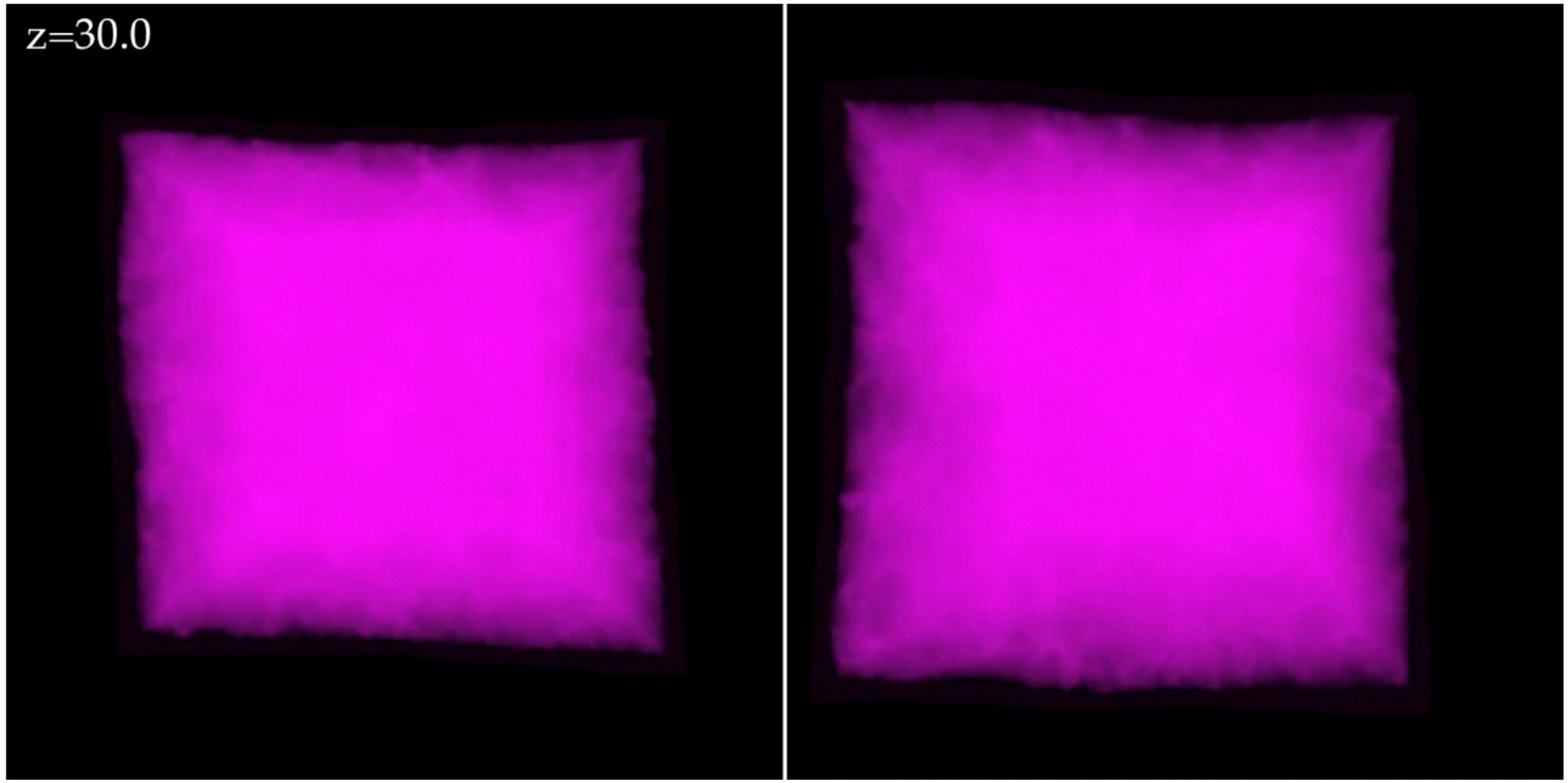
    - Mass-metallicity, SFHs, morphology *not the same*
- **Something else** needed to "quench"



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