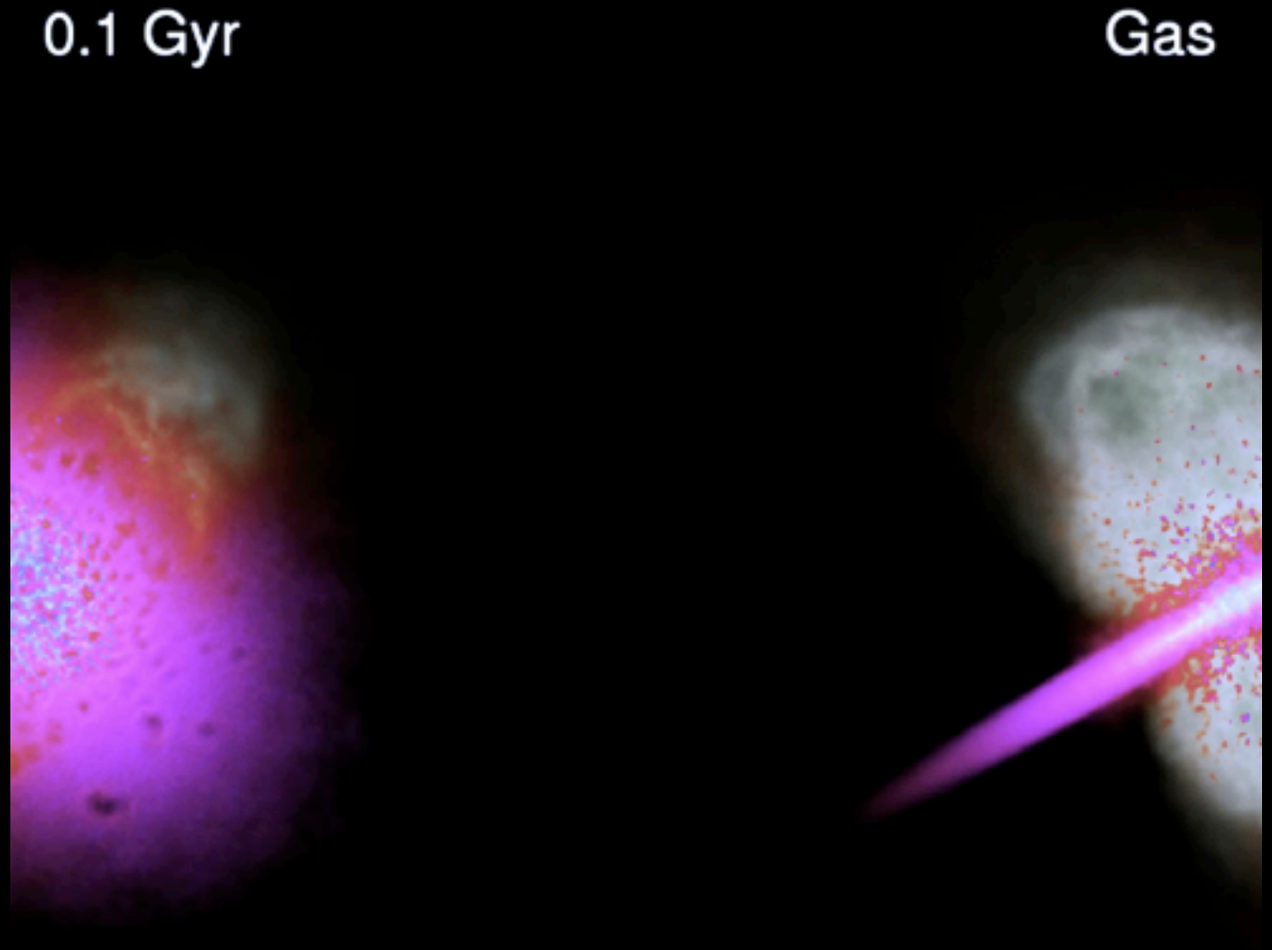
What *Doesn't* Quench Galaxy Formation?



Phil Hopkins

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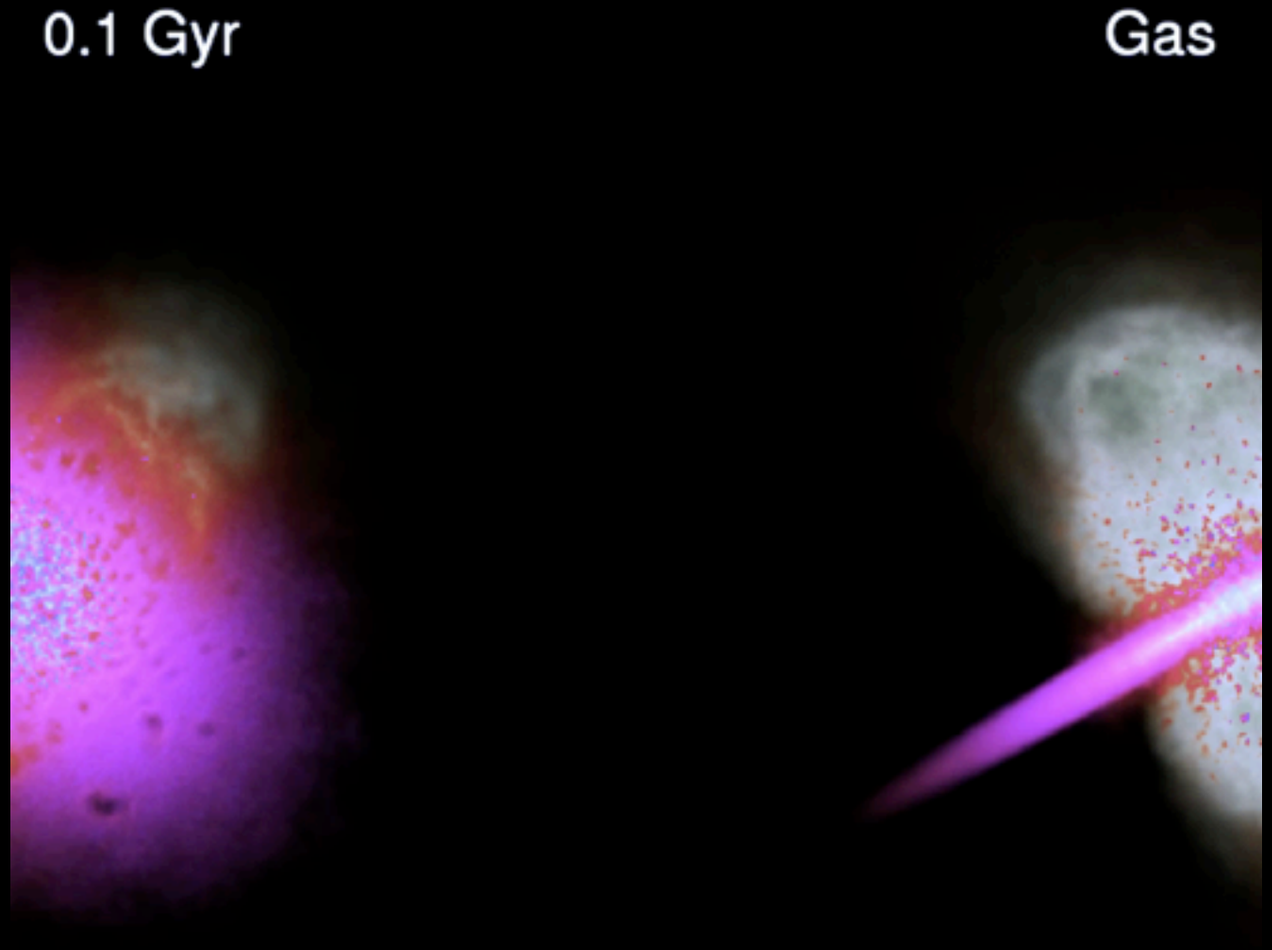

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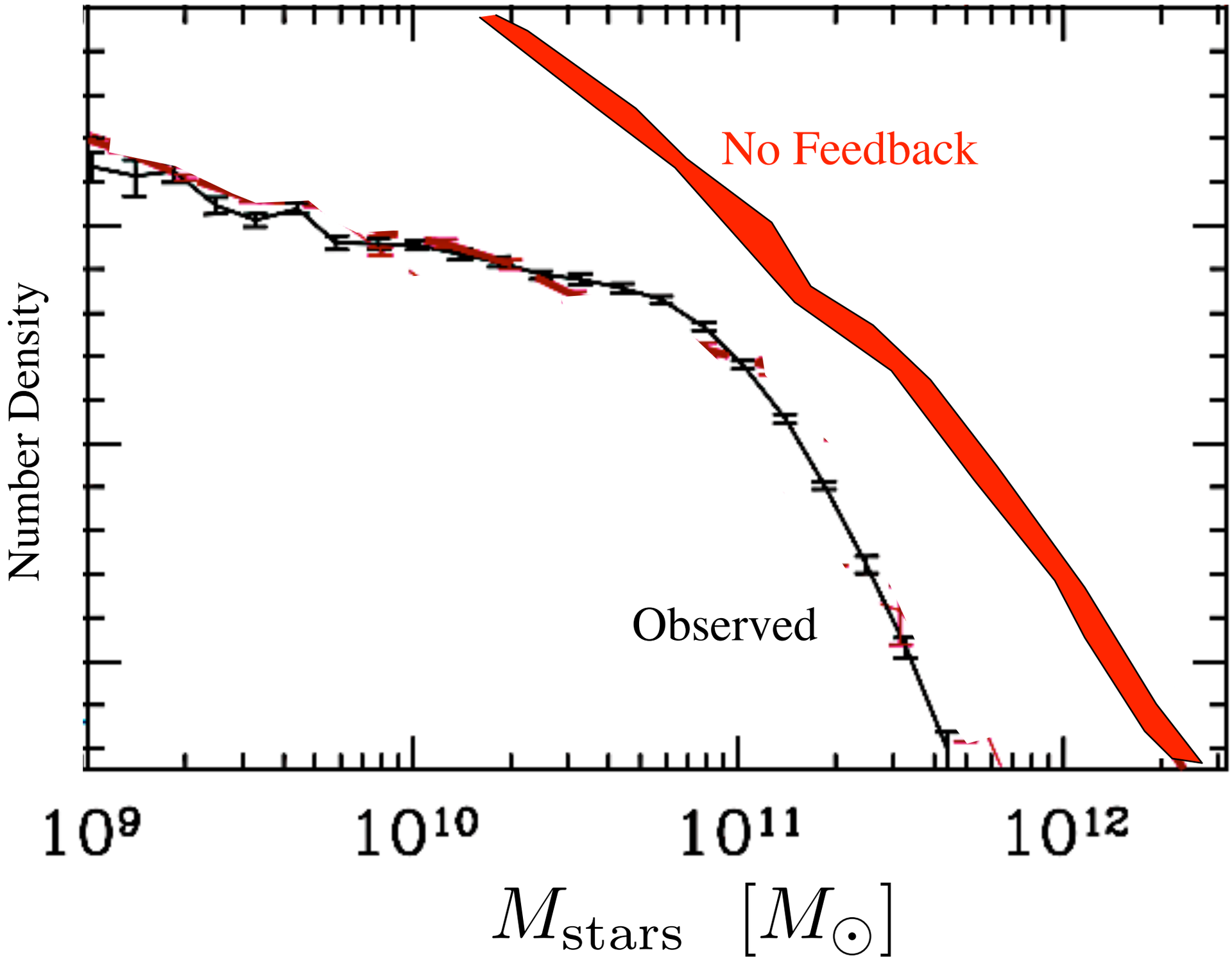
Q: WHY IS STAR FORMATION SO INEFFICIENT?



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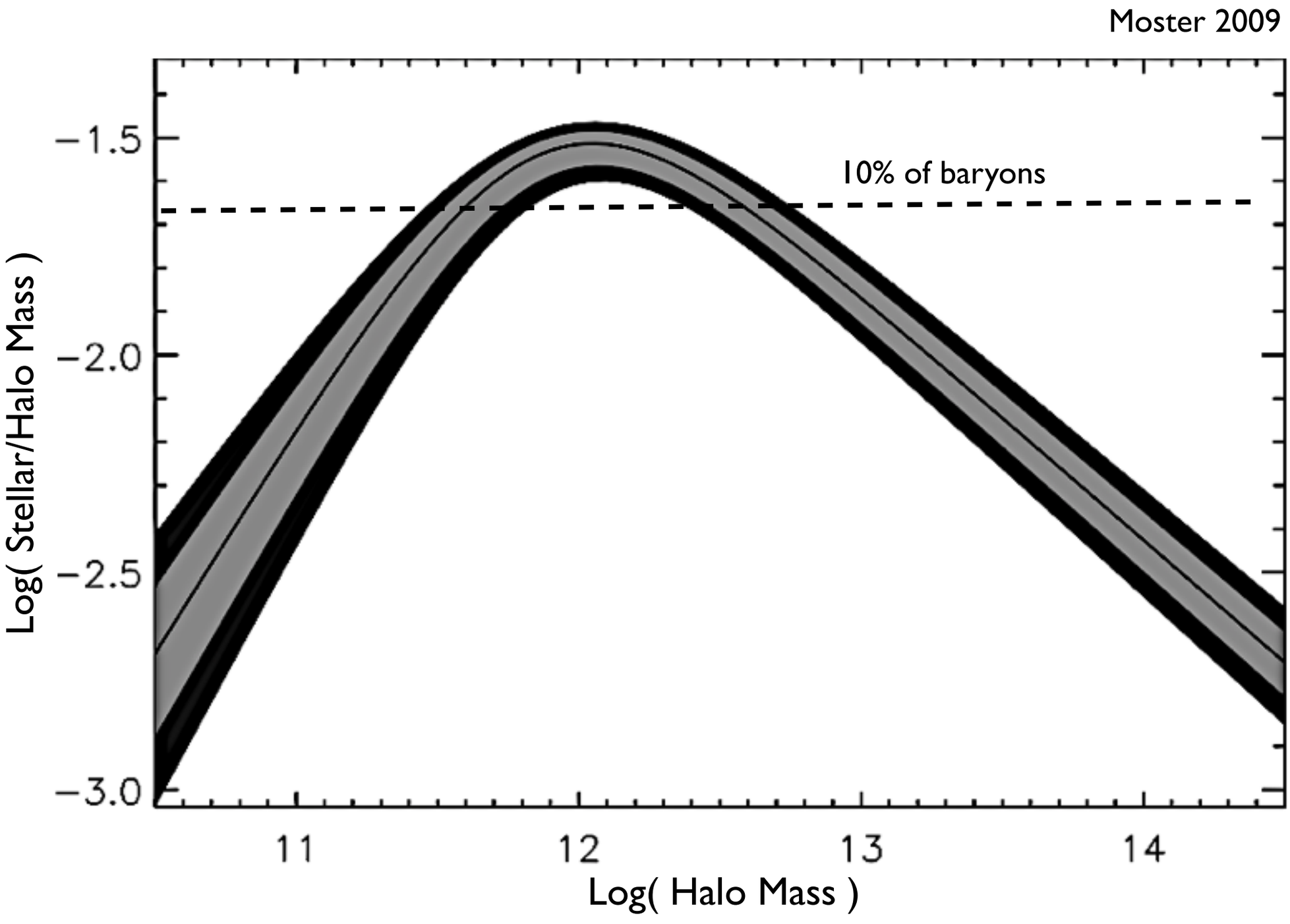

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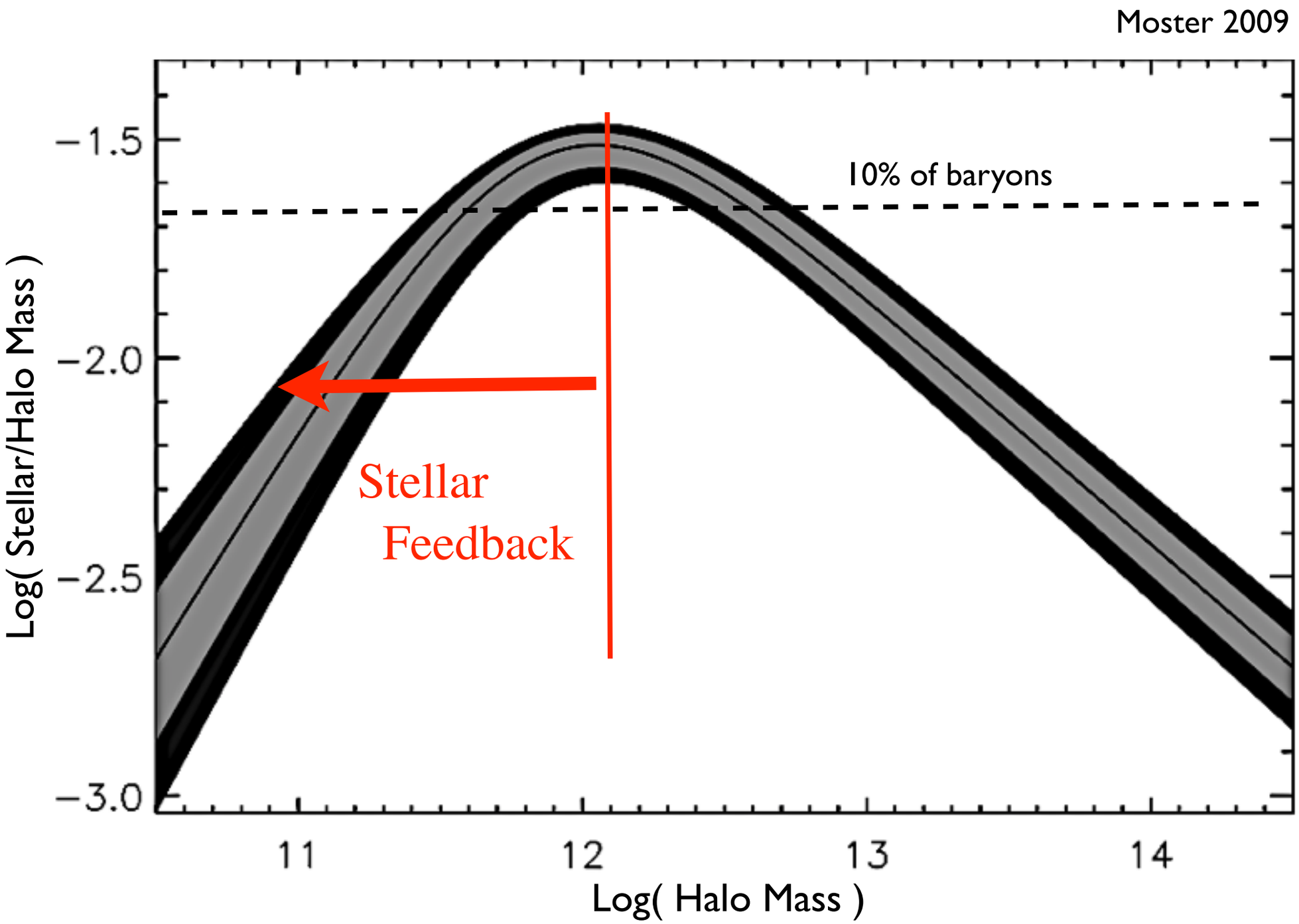

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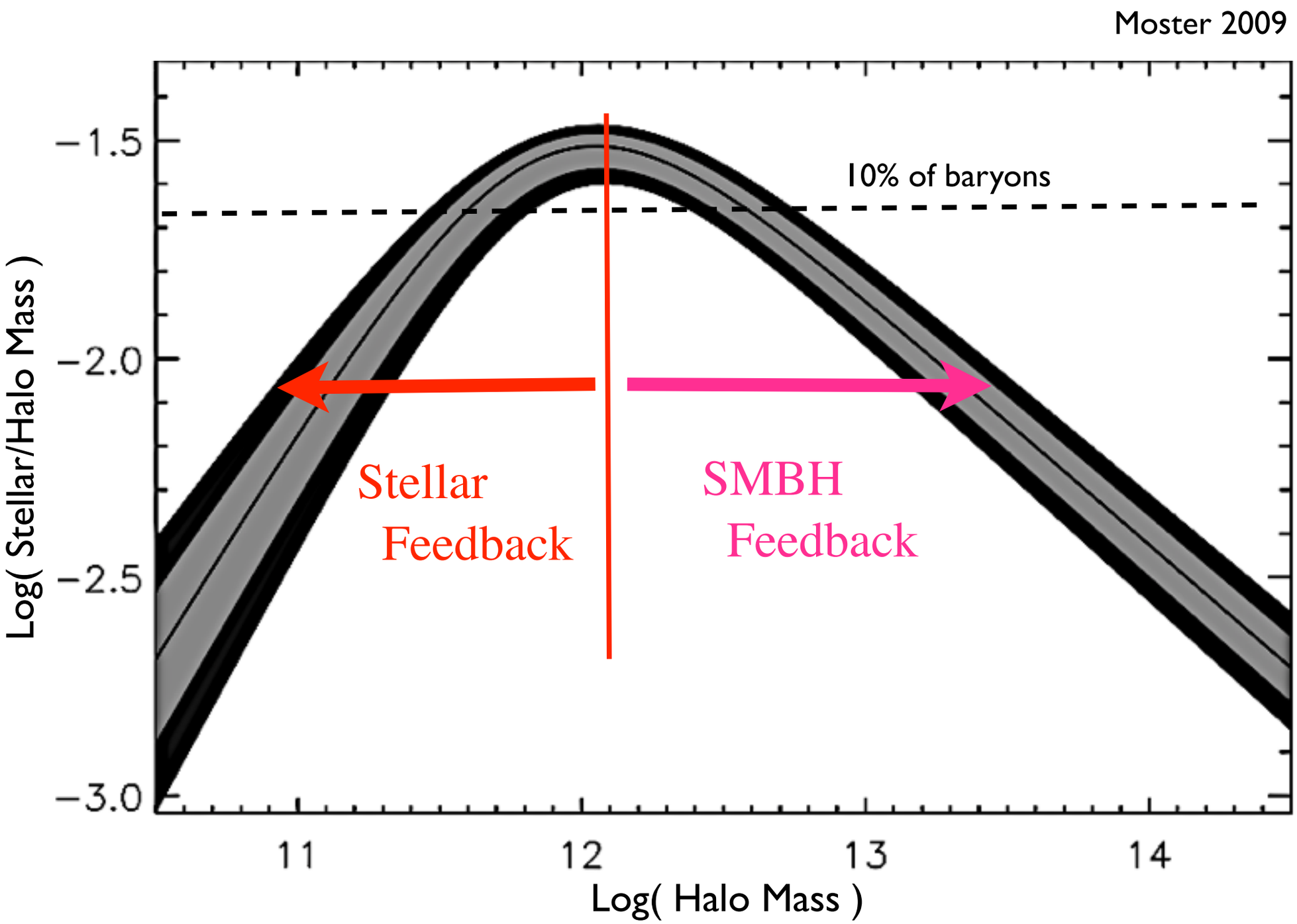
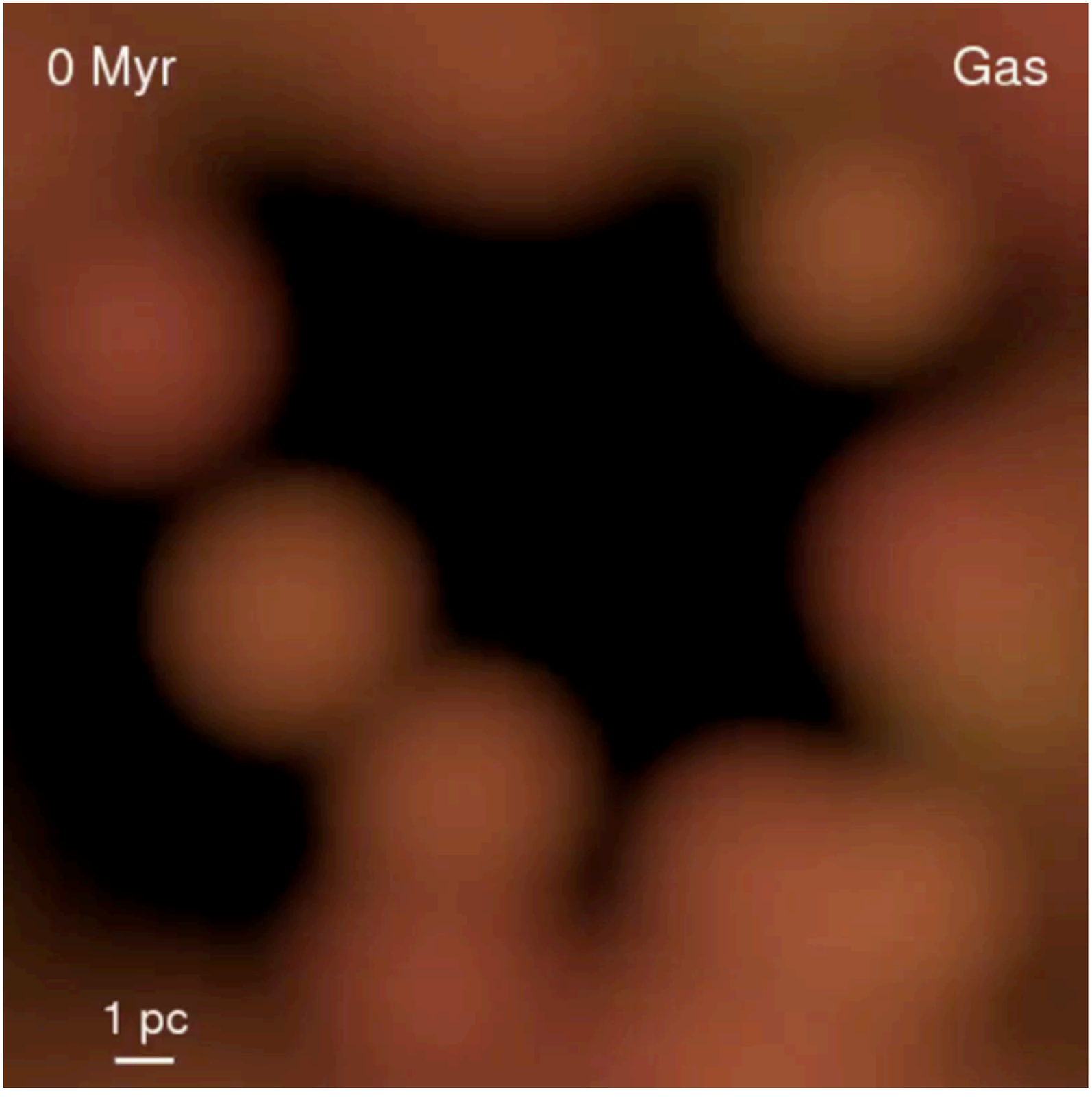


Stellar Feedback: How Can We Do Better?



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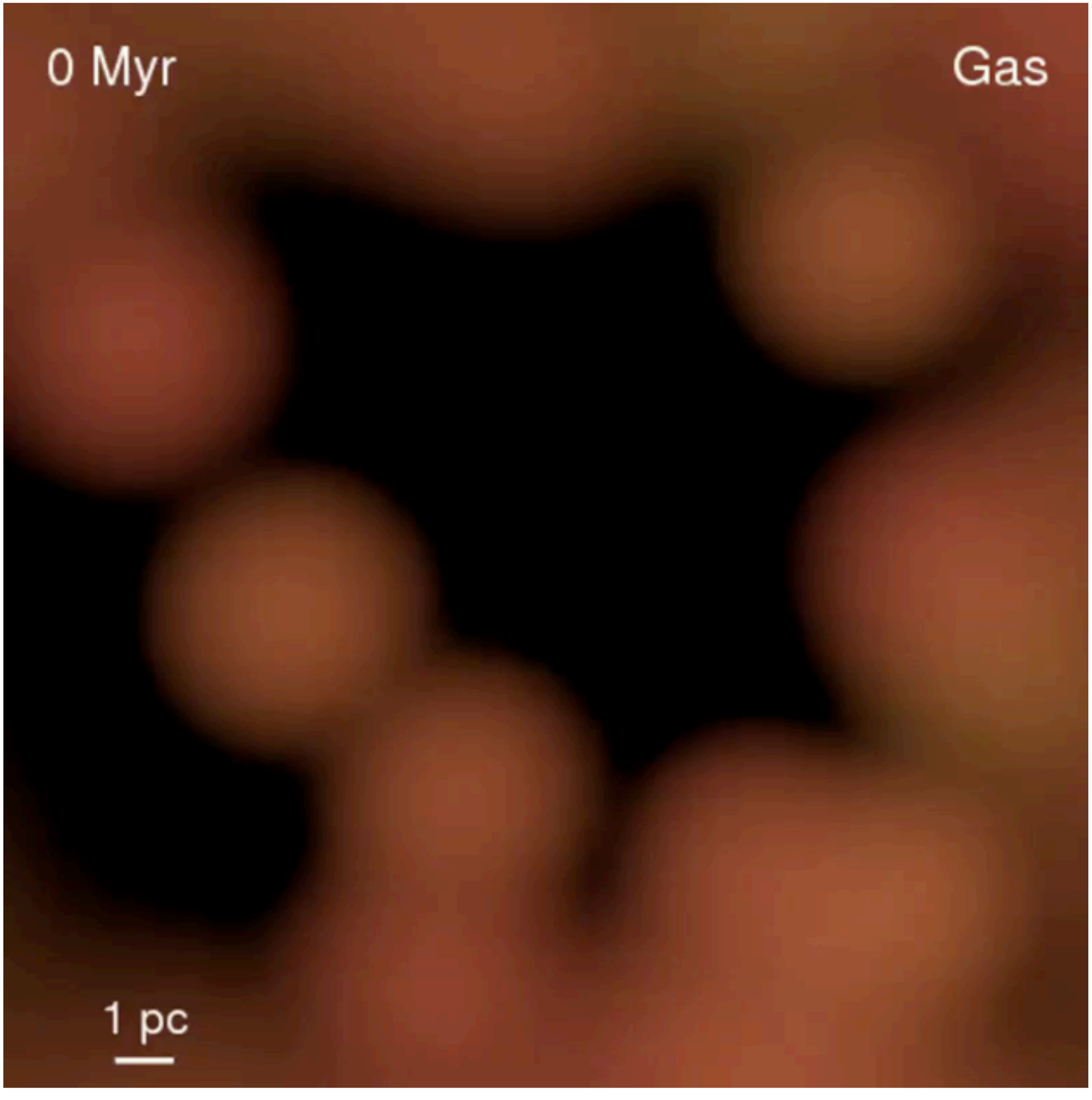

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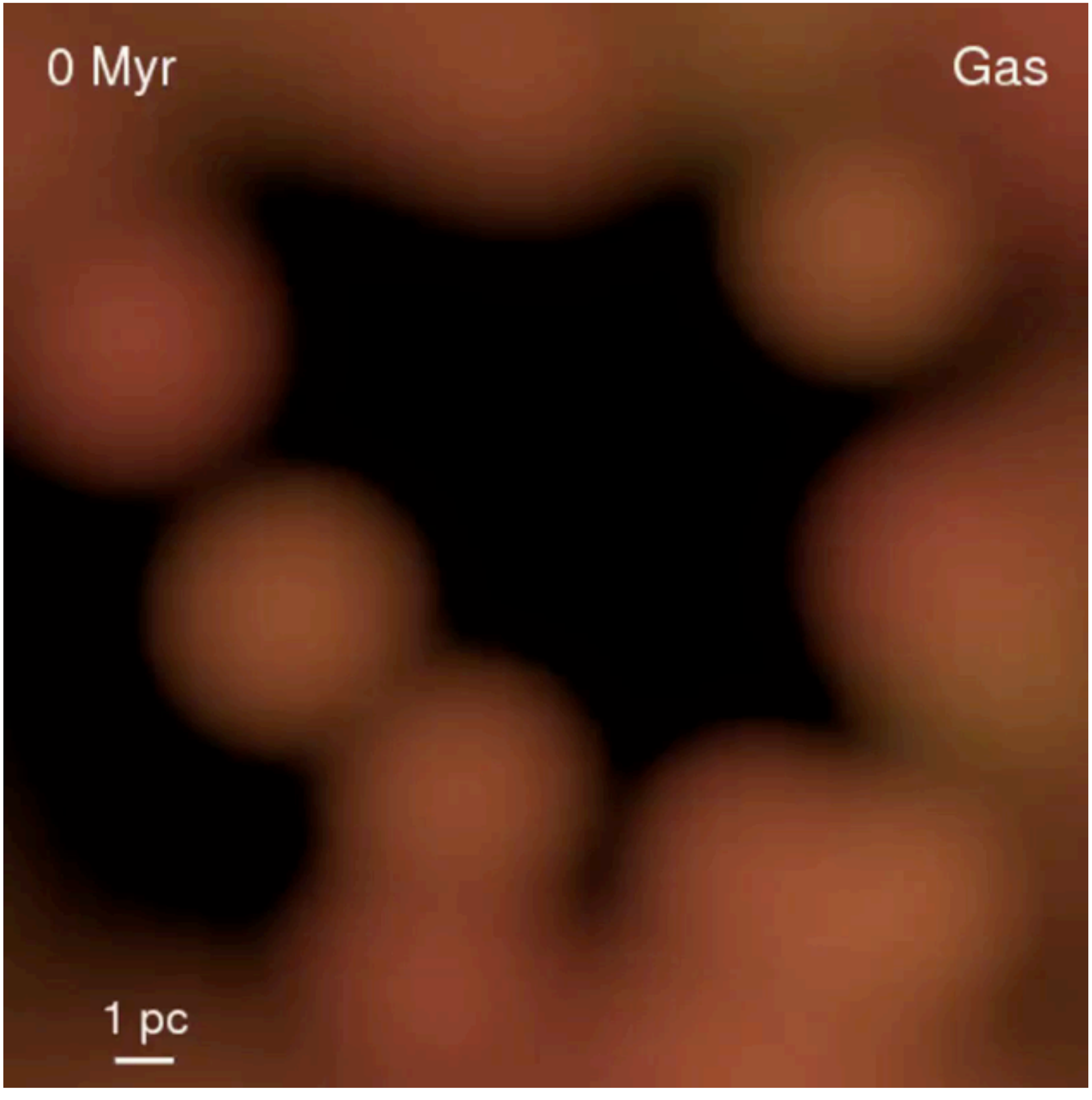

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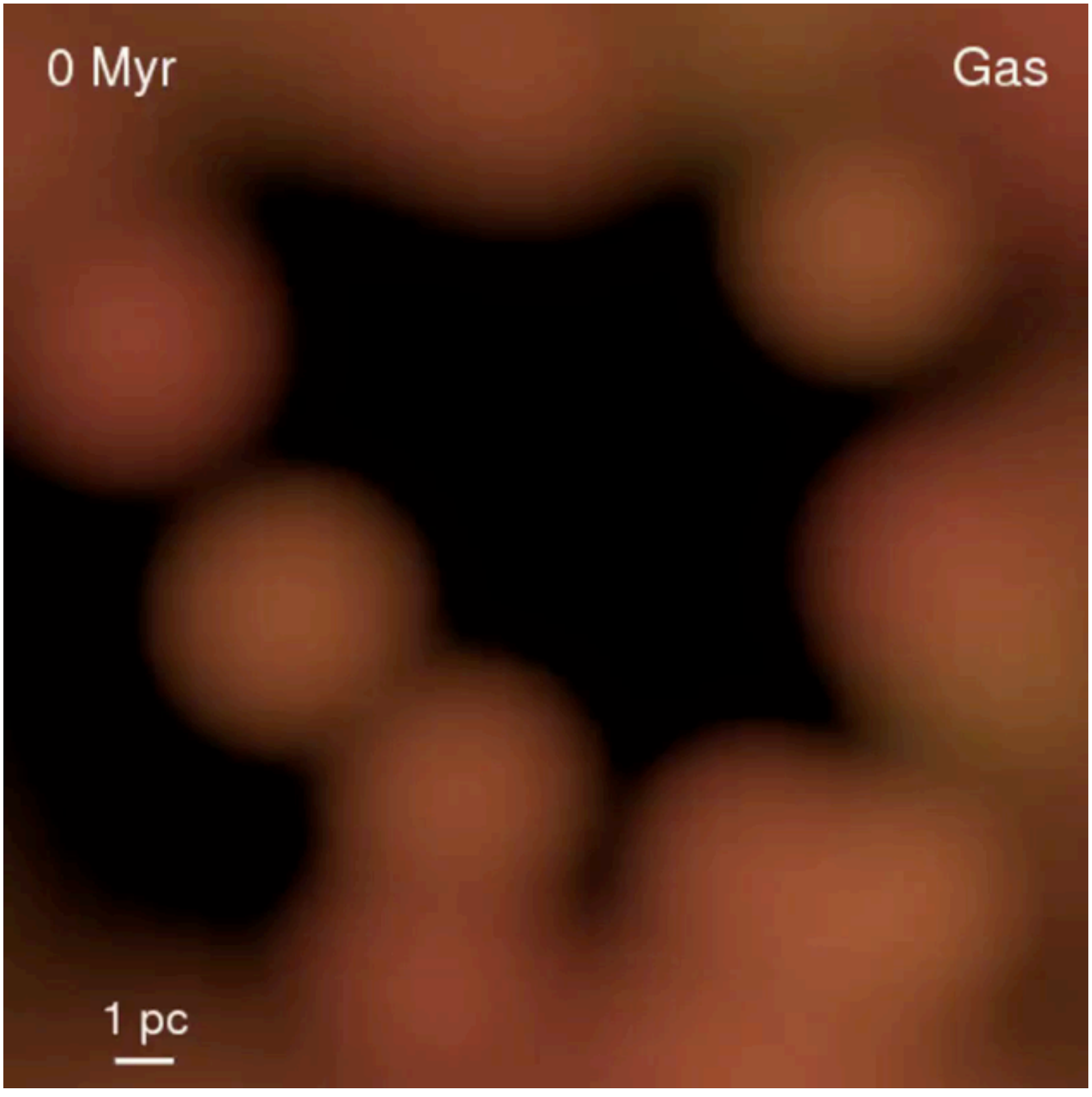

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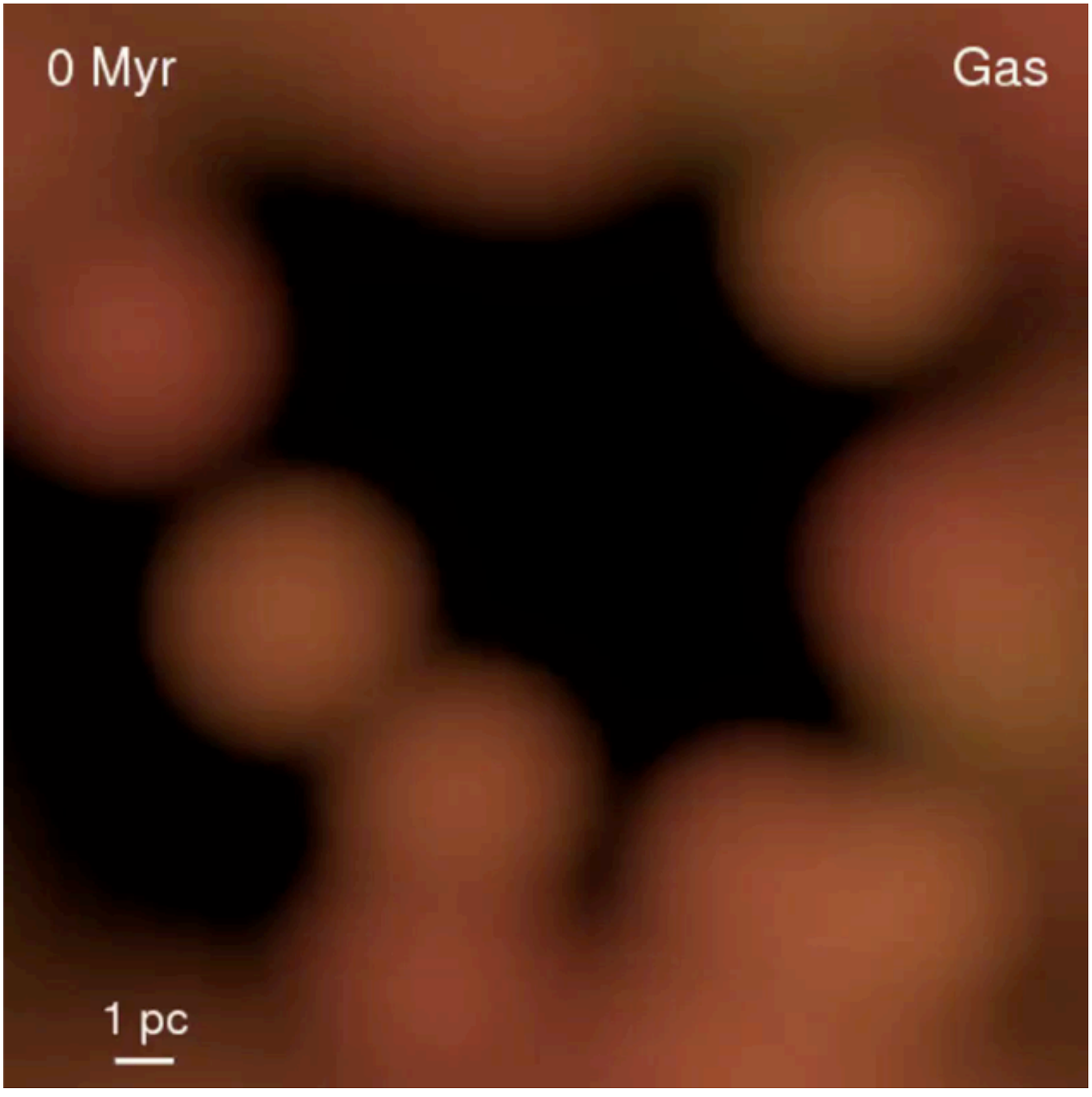

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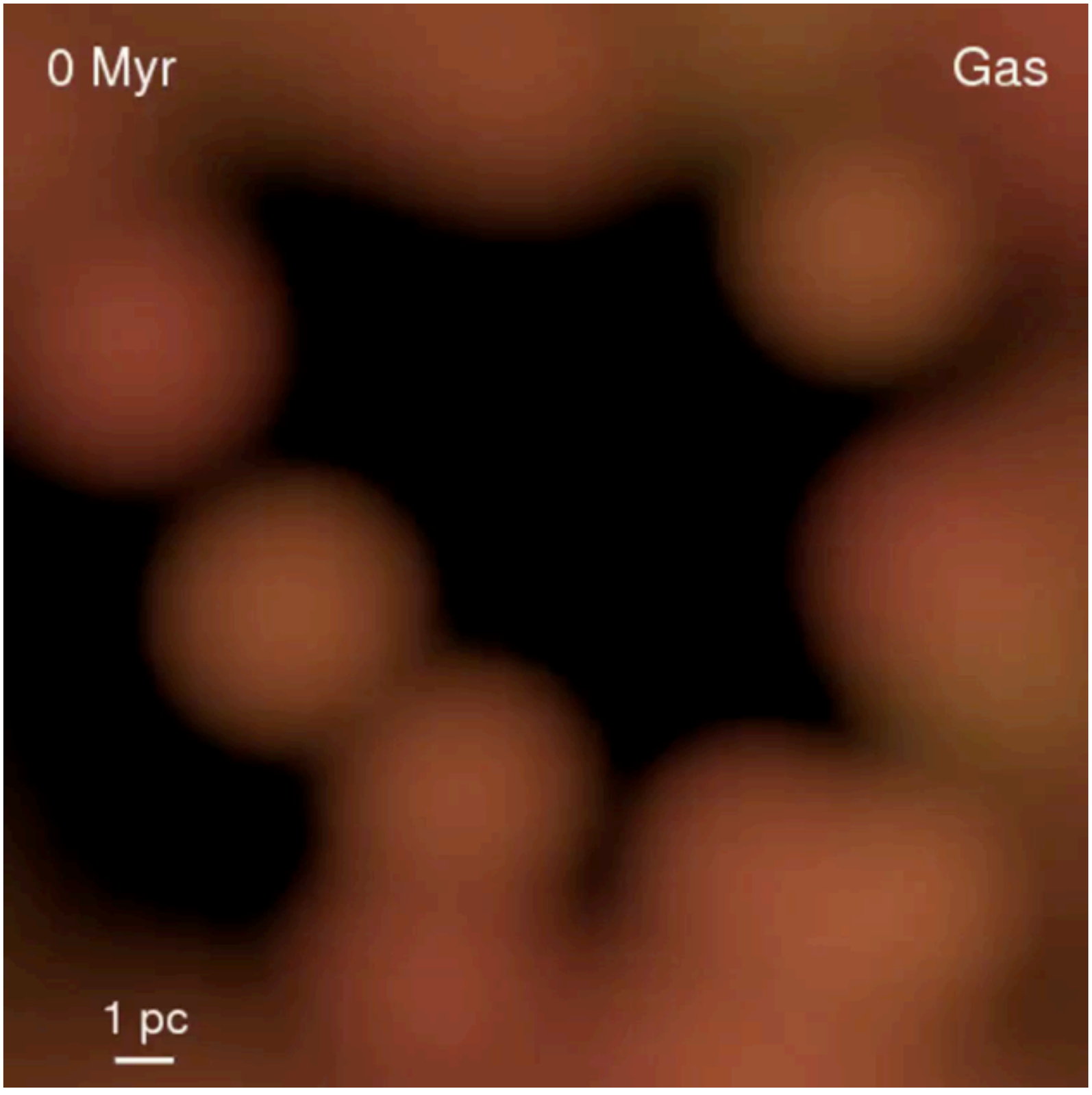
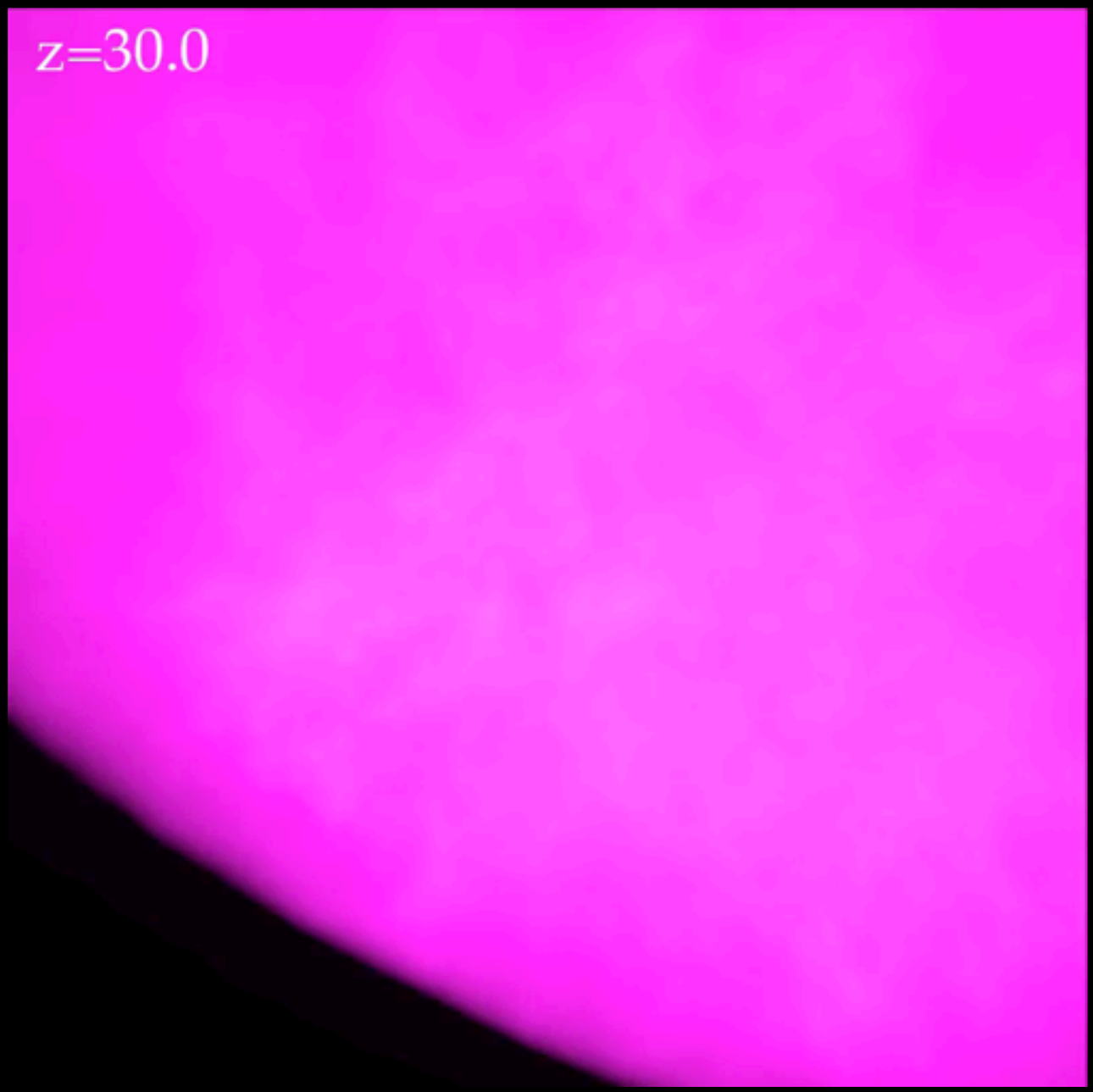


- (also MHD, anisotropic conduction, diffusion)

z=30.0



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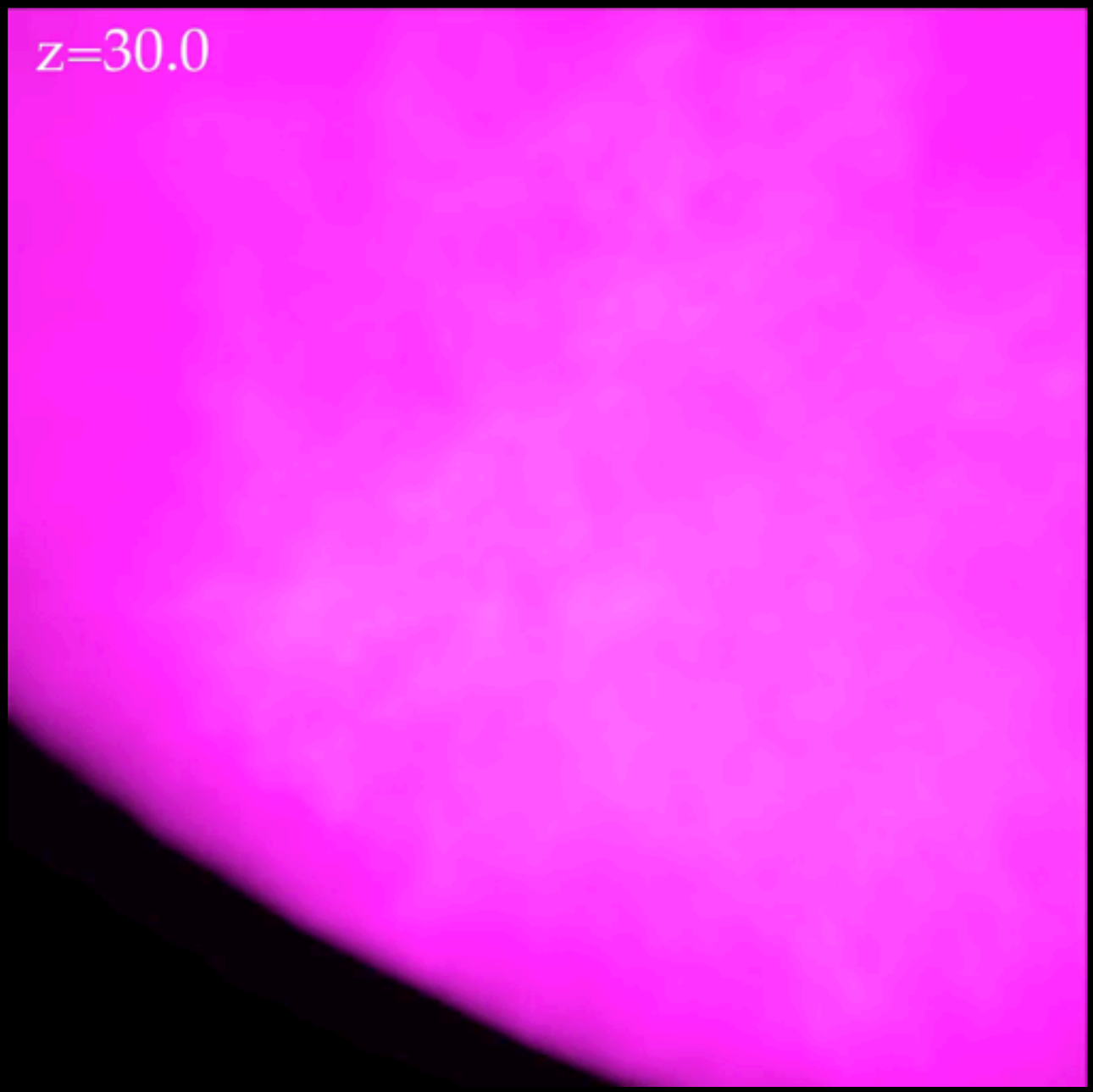
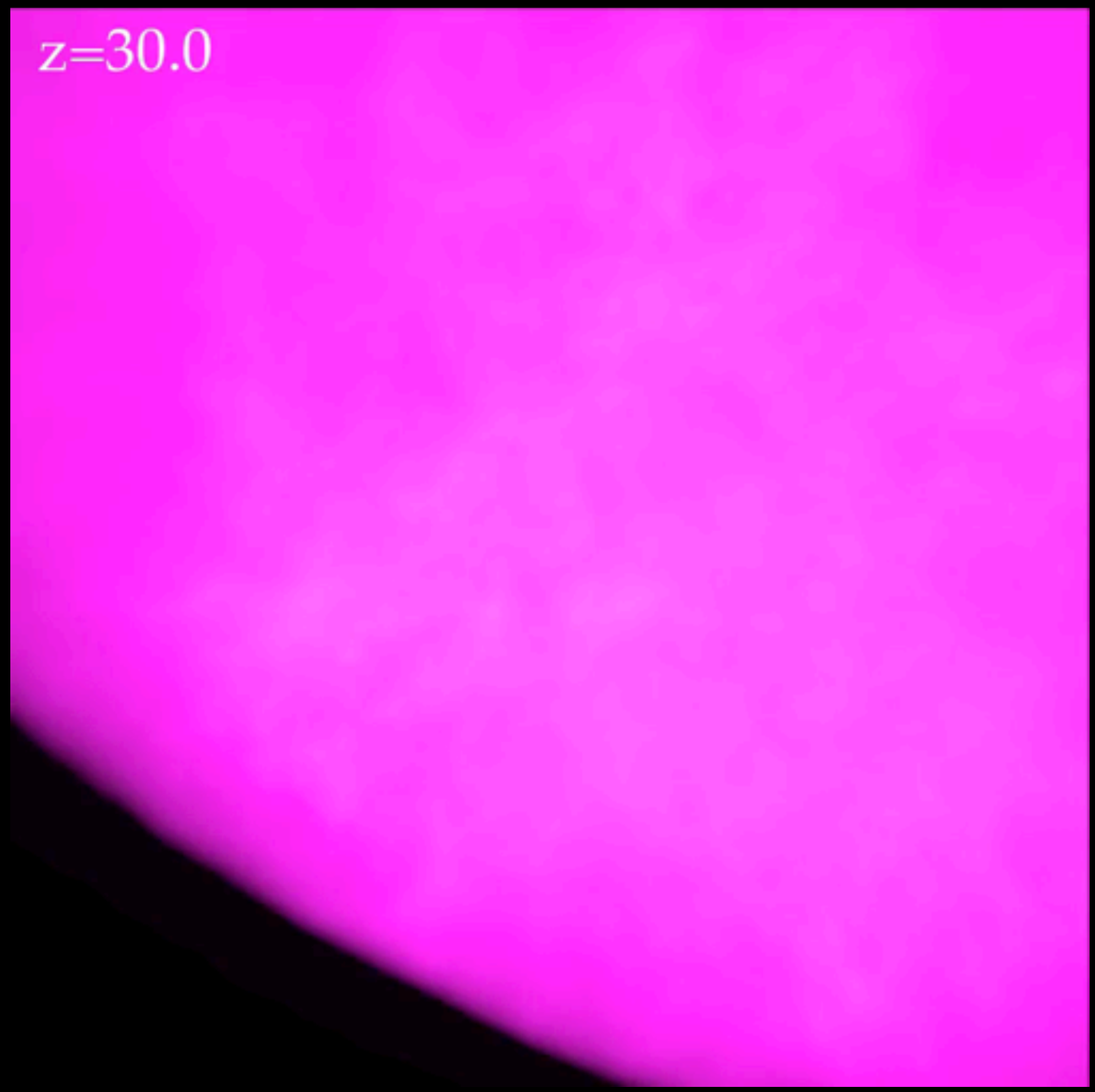


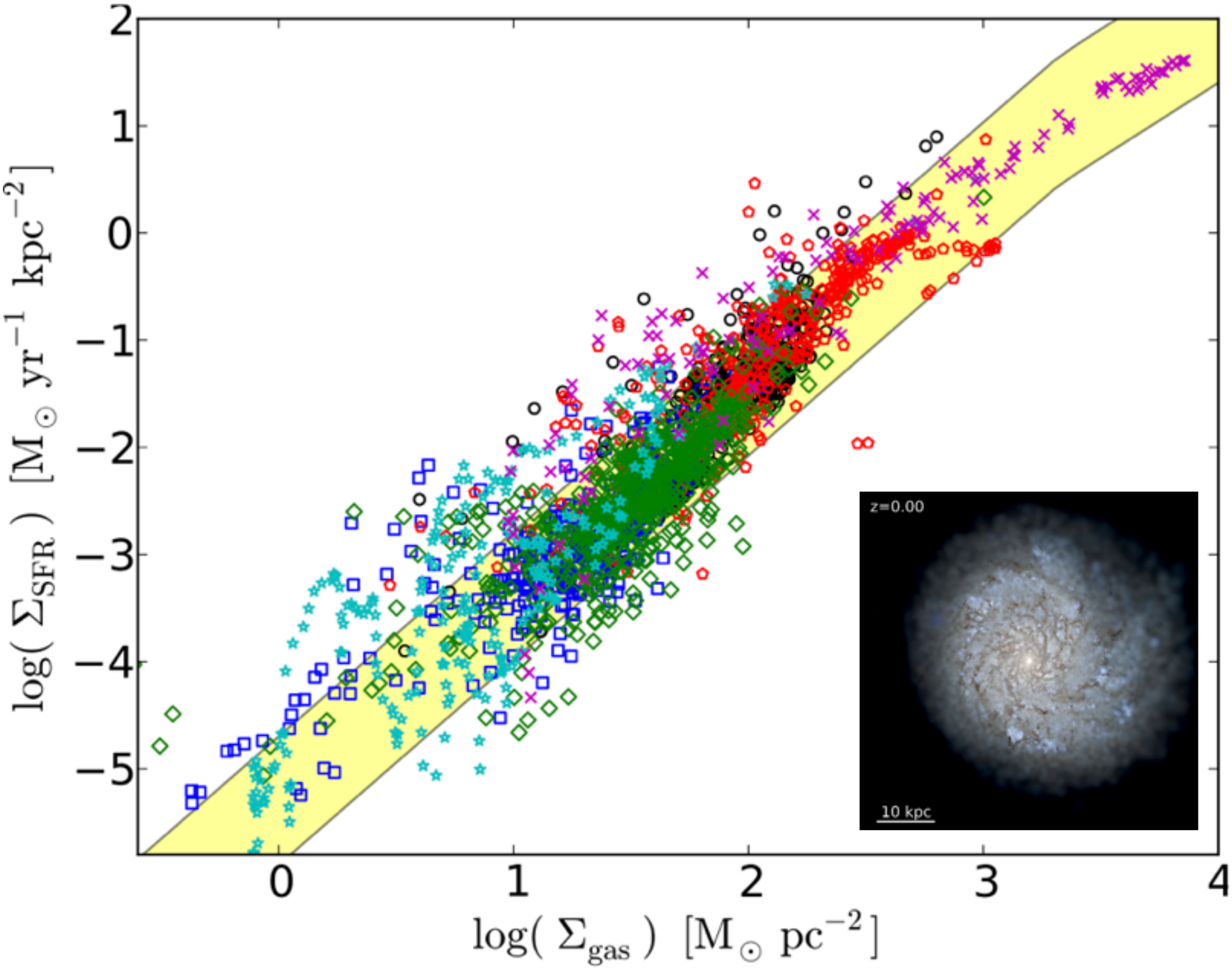
The FIRE Project: Cosmological Simulations at 1-10pc resolution

z=30.0



Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!



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

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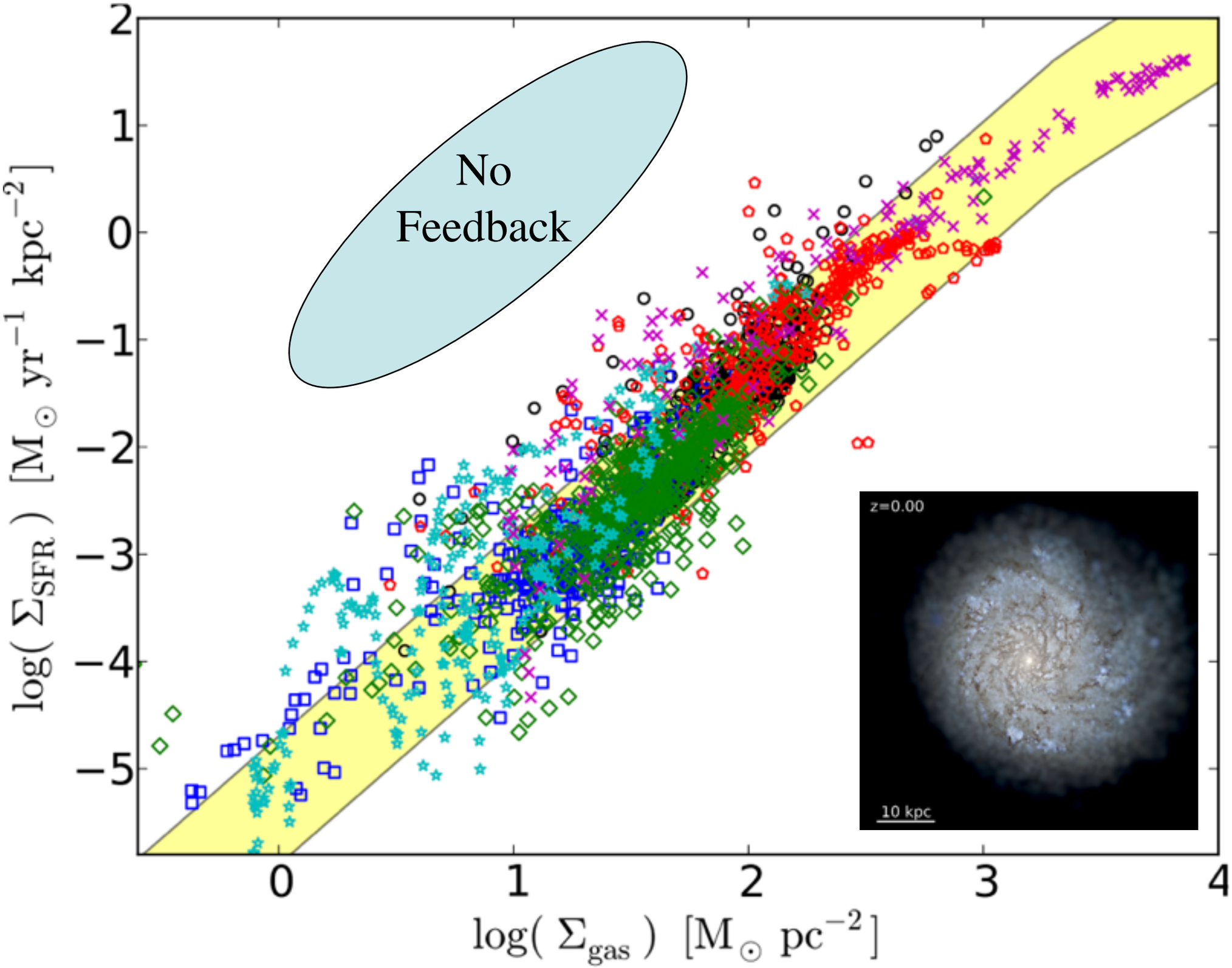

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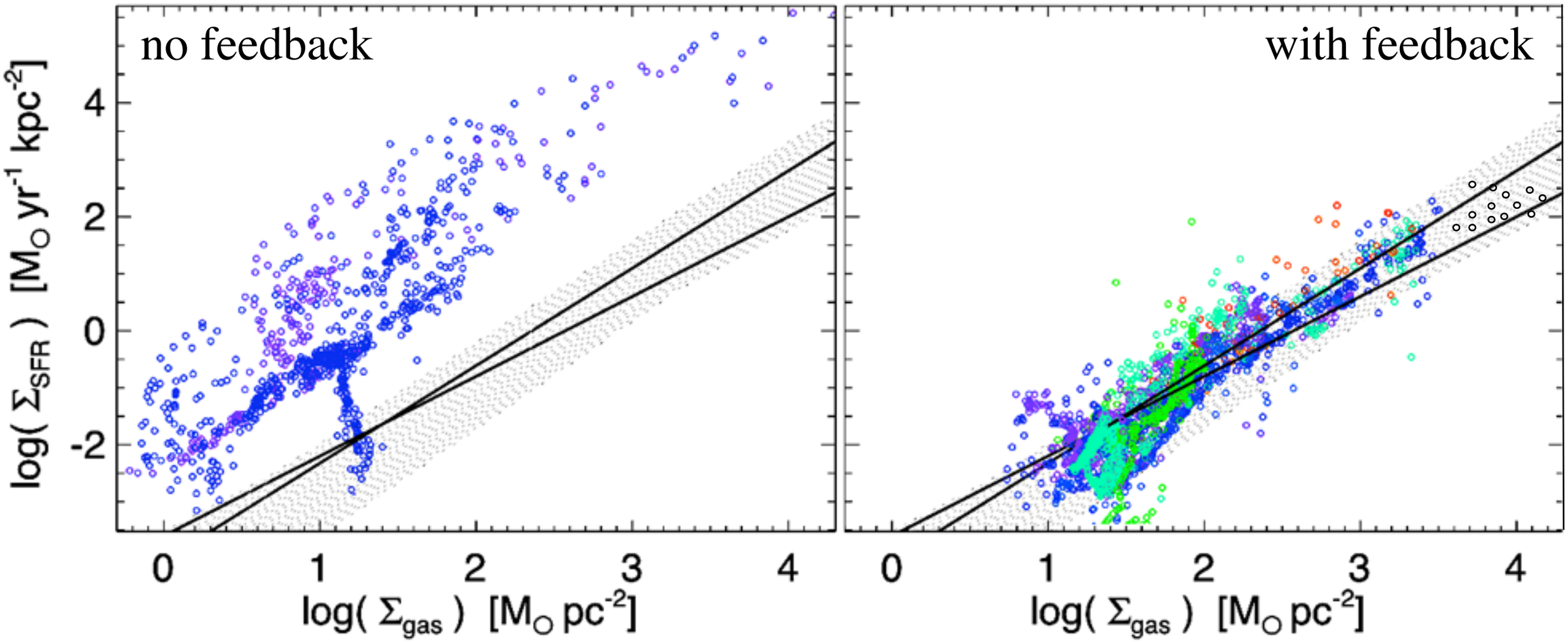
Kennicutt-Schmidt relation emerges naturally

ISOLATED GALAXIES



PFH, Quataert, & Murray, 2011a

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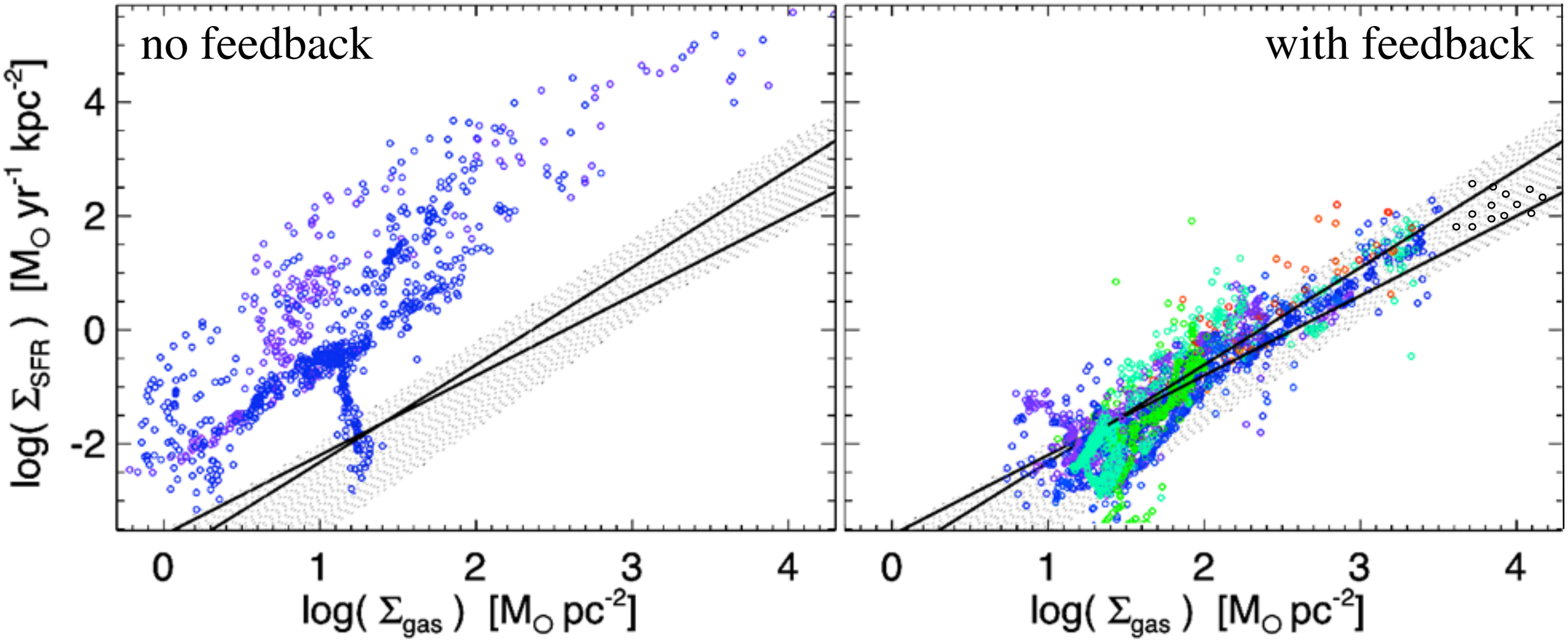
$$\dot{\Sigma}_* \sim \Sigma_{\rm gas}/\tau_{\rm dyn}$$



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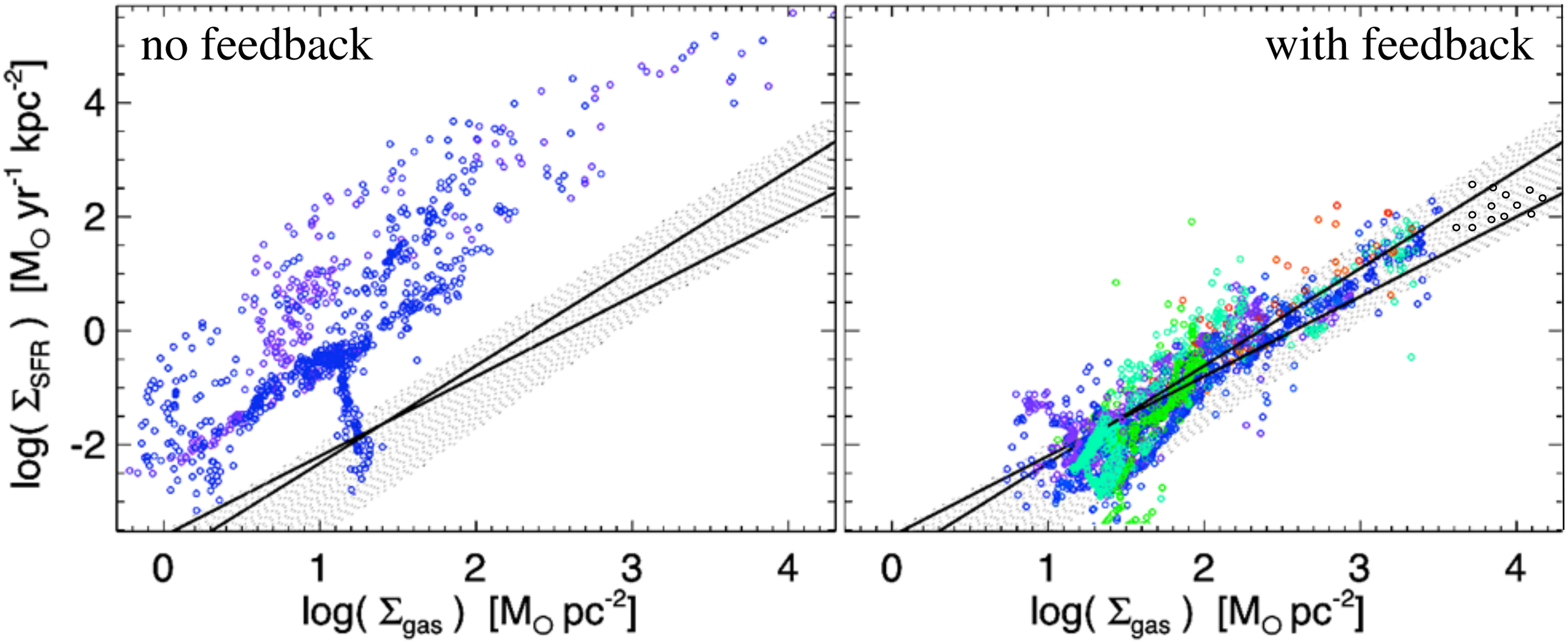

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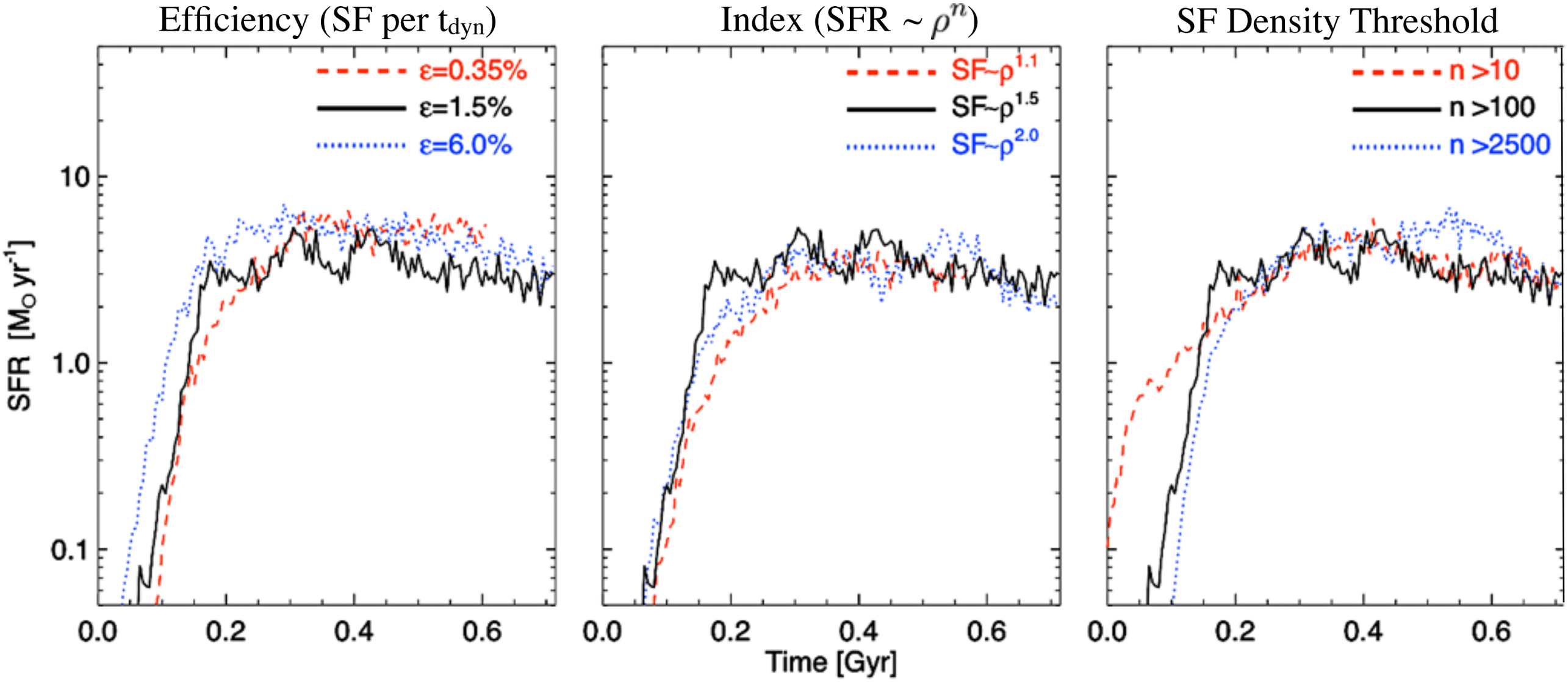
(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!



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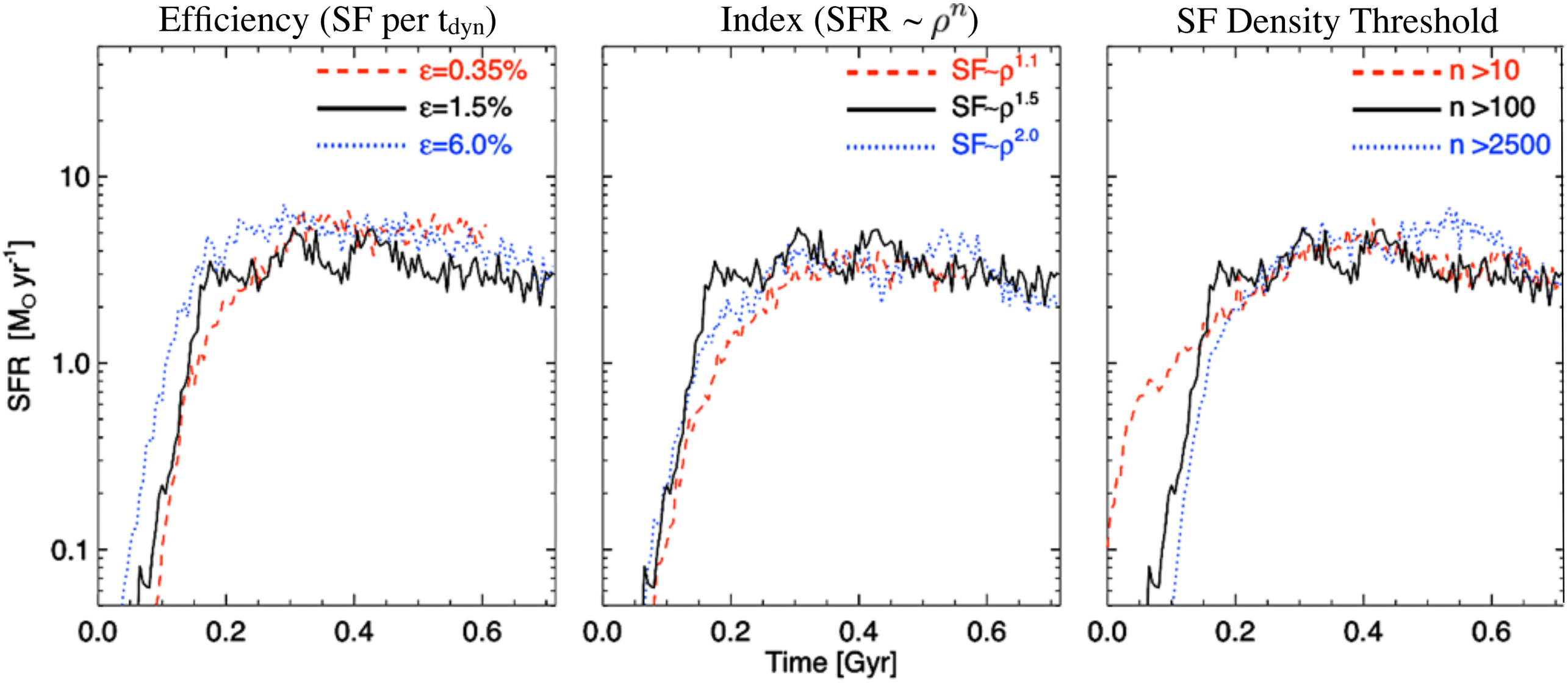

- Set by feedback (SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
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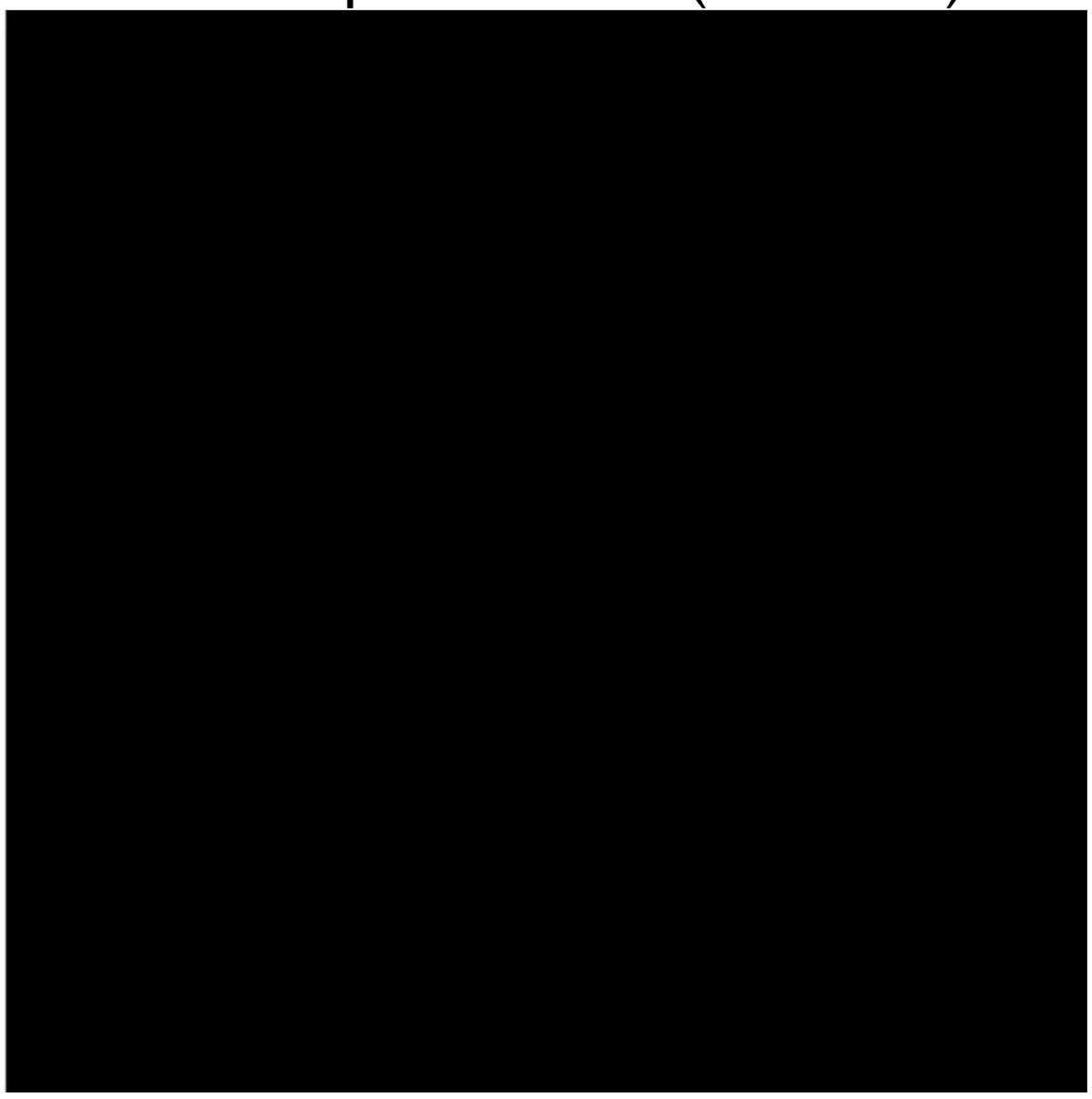
Inflows & Outflows

Simplest Sub-Grid Is Not Enough

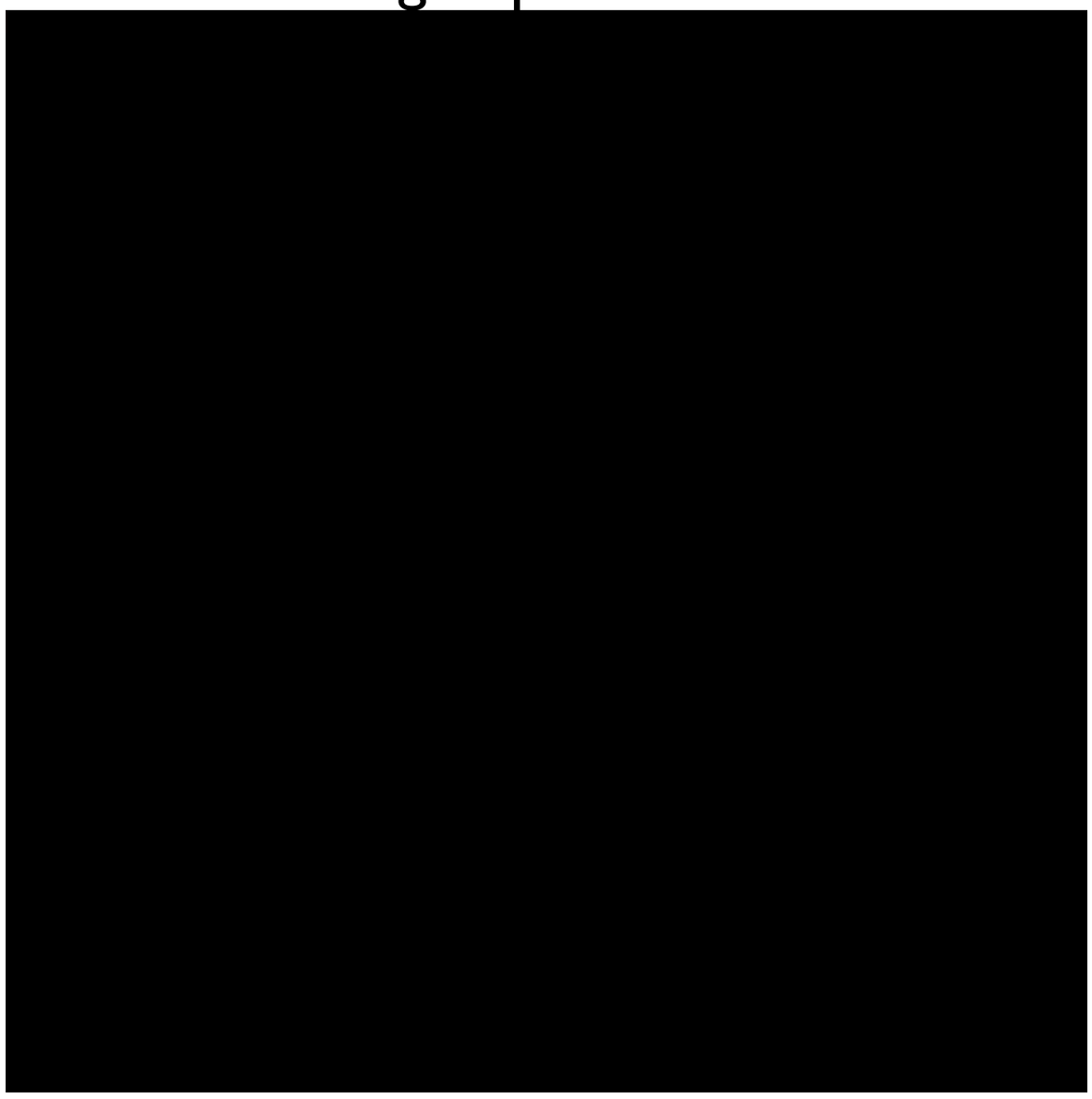
WE NEED TO DO BETTER!

Proto-MW: Gas Temperature:

"Decoupled Winds" (Sub-Grid)



Following Explicit Feedback



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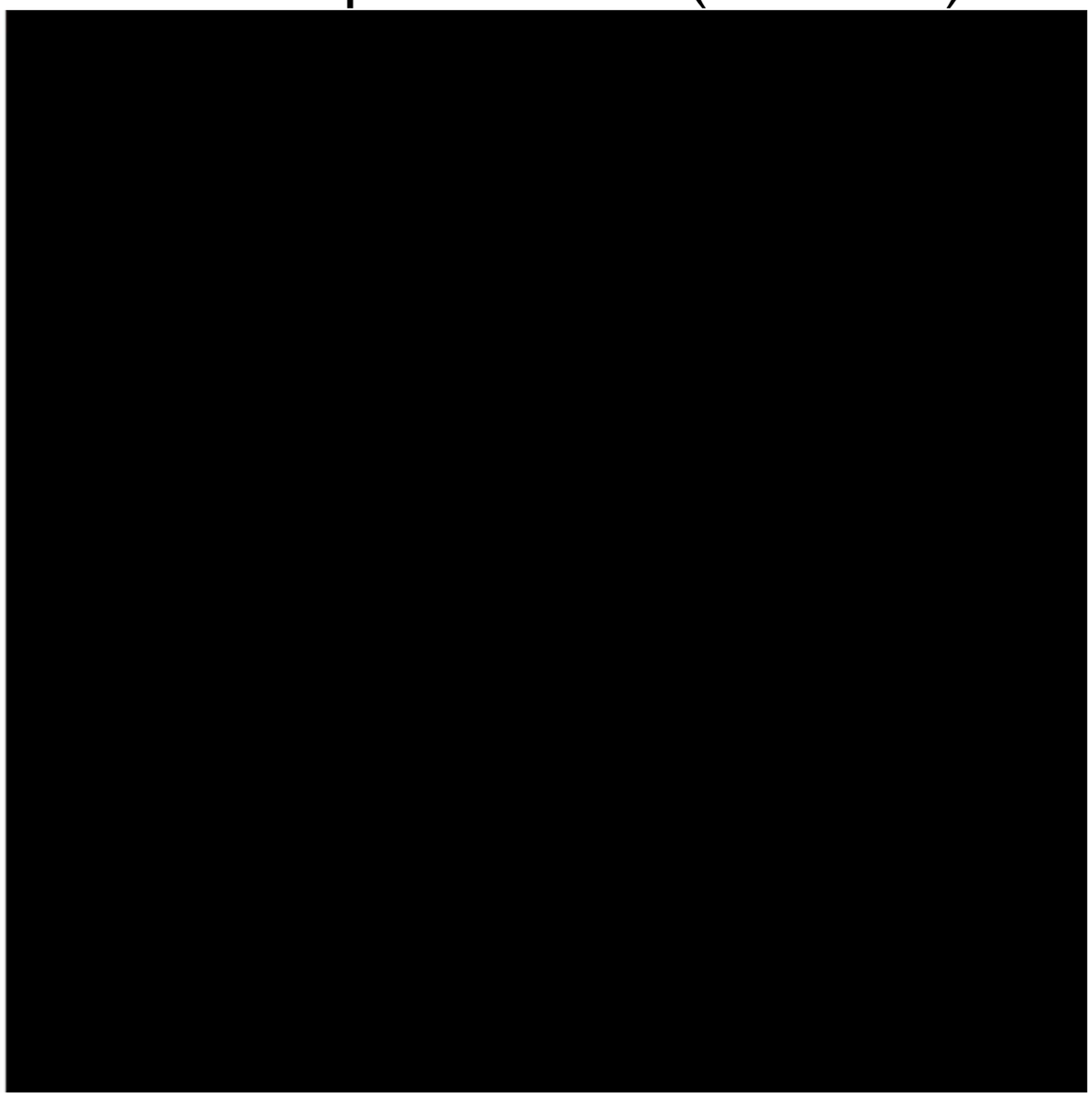

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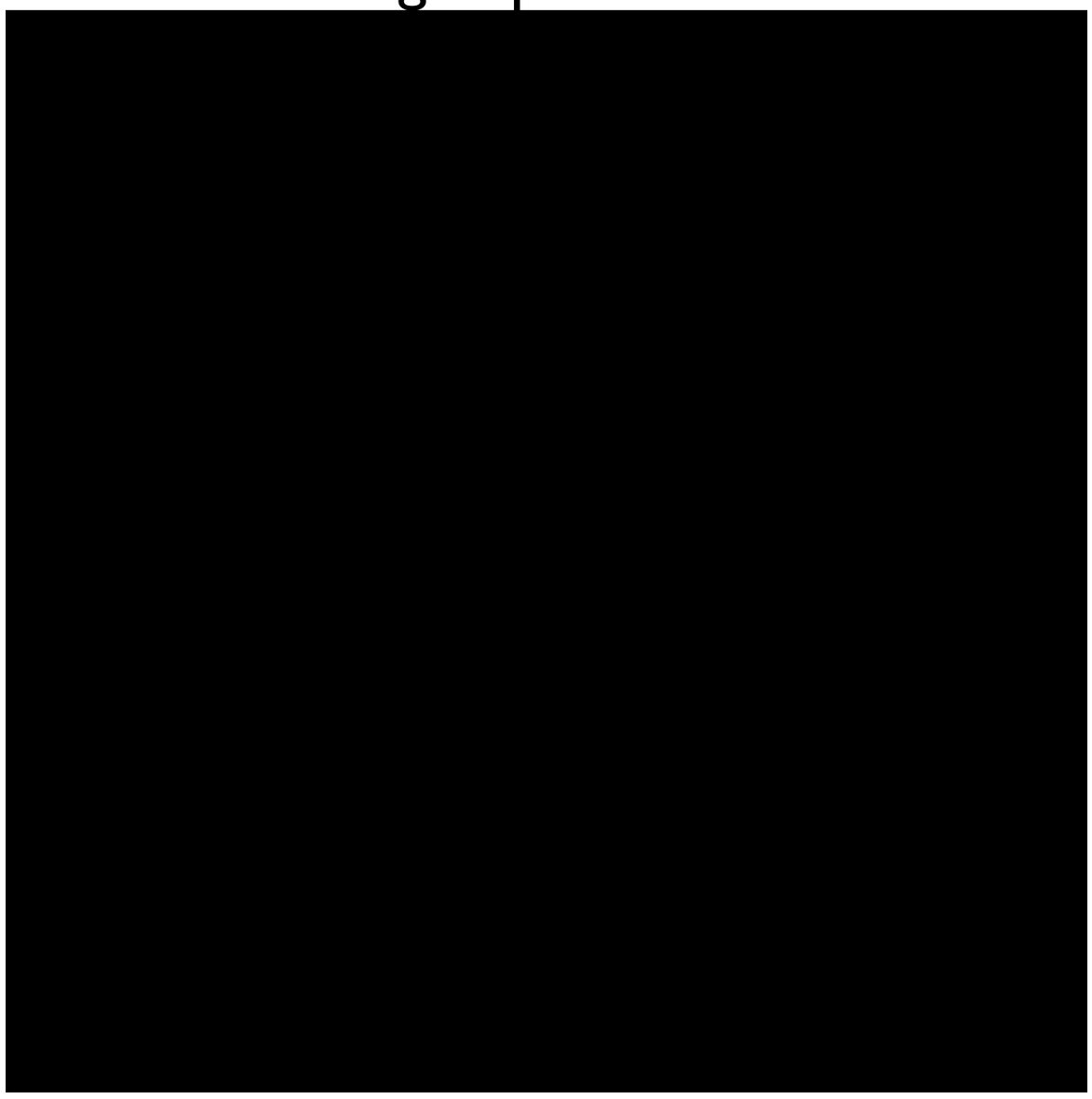

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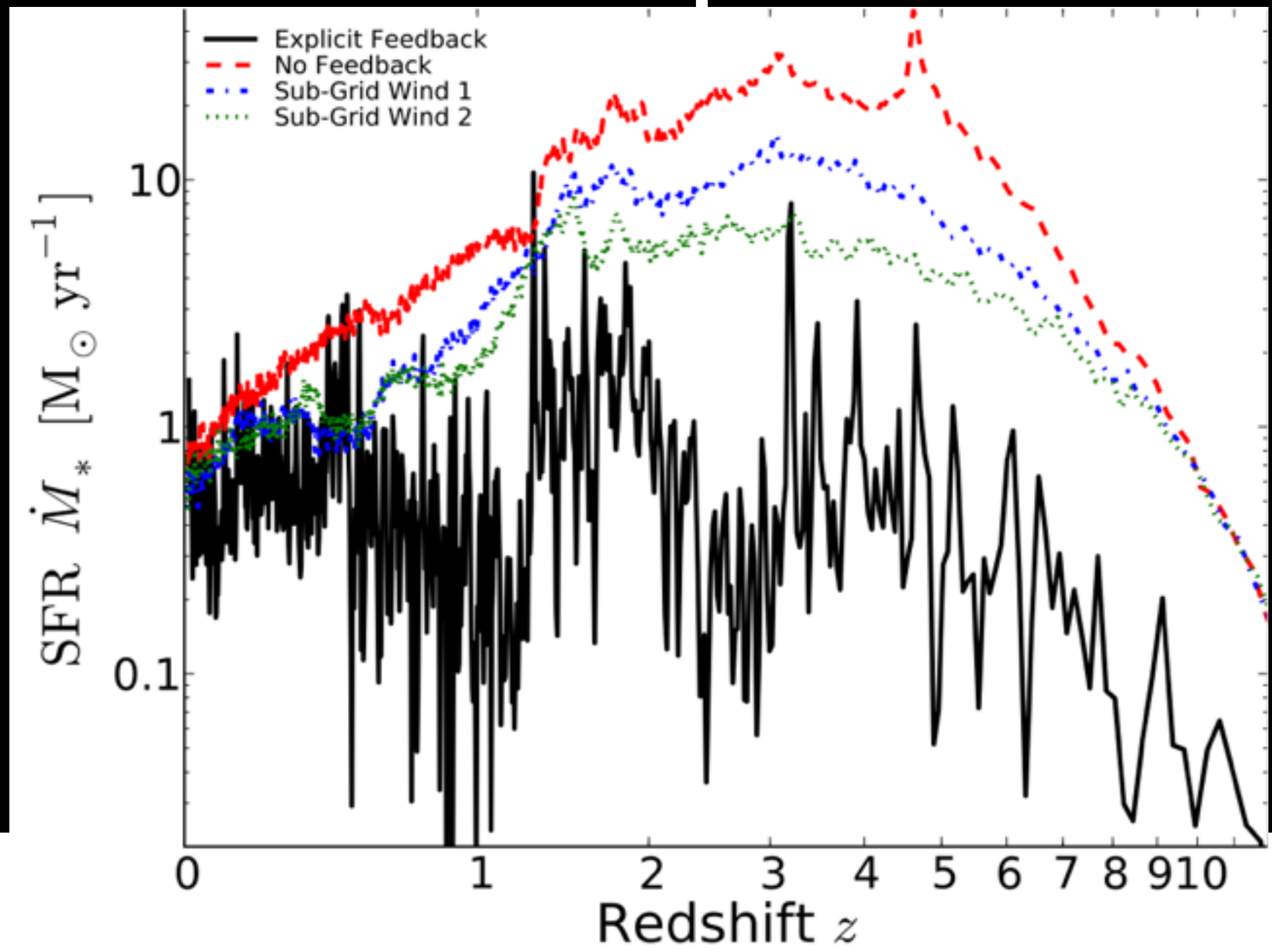
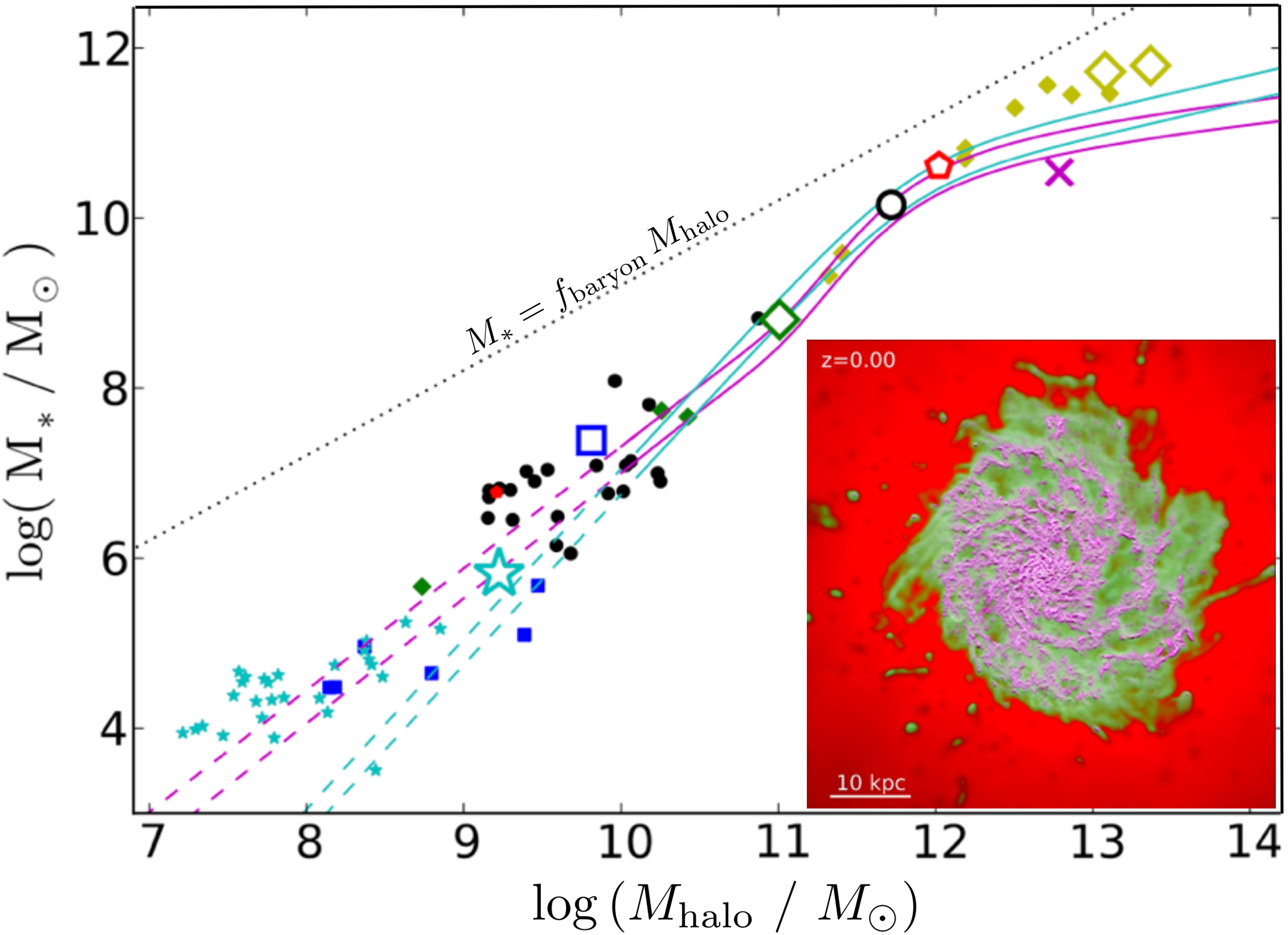


PFH, Keres, et al. (arXiv:1311.2073)

Does Stellar Feedback Explain the Mass Function?

HOW EFFICIENT ARE GALACTIC WINDS?

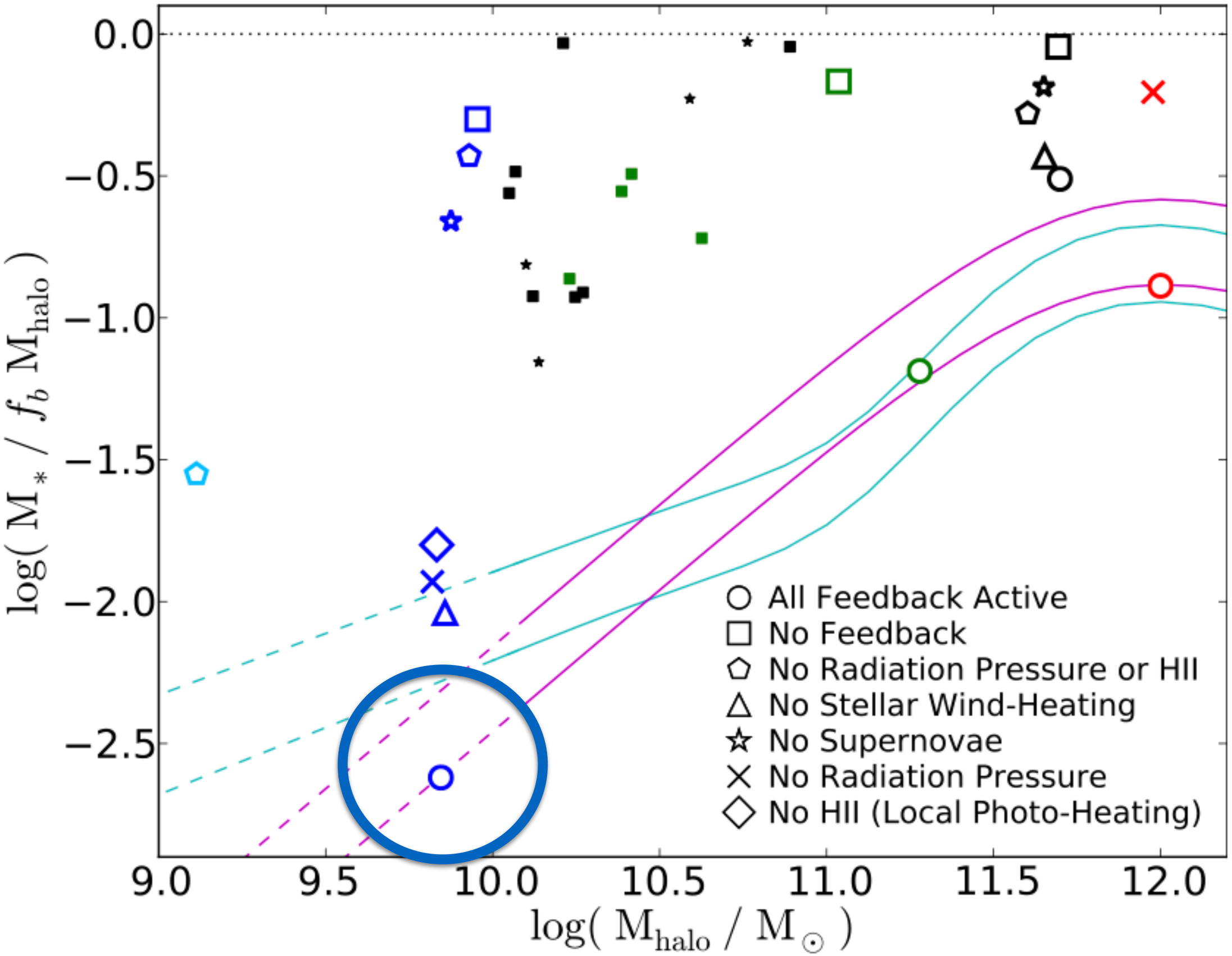
PFH, Keres, et al. (arXiv:1311.2073)



But Feedback *Does* Matter

MULTIPLE FEEDBACK MECHANISMS ARE CRITICAL

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



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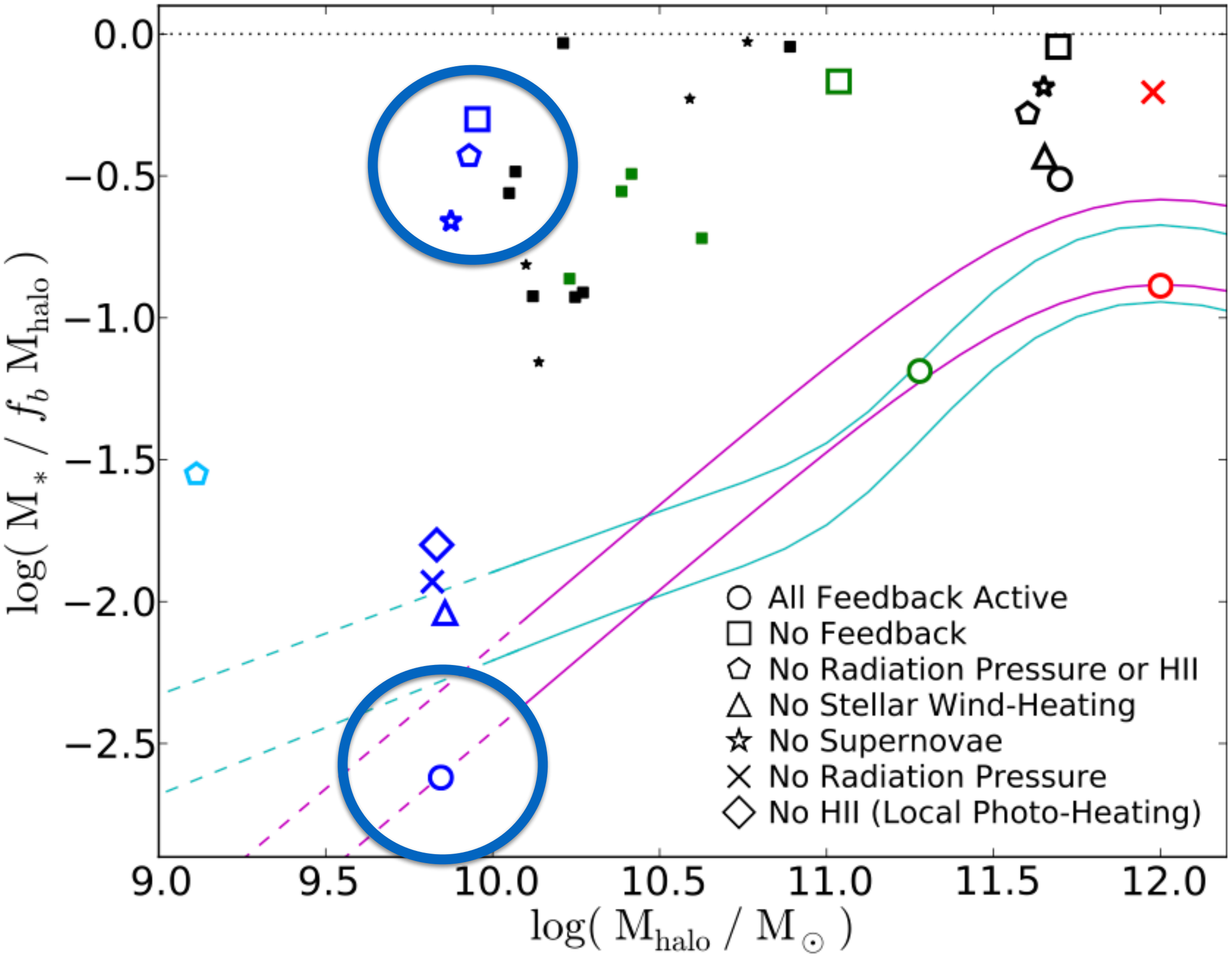
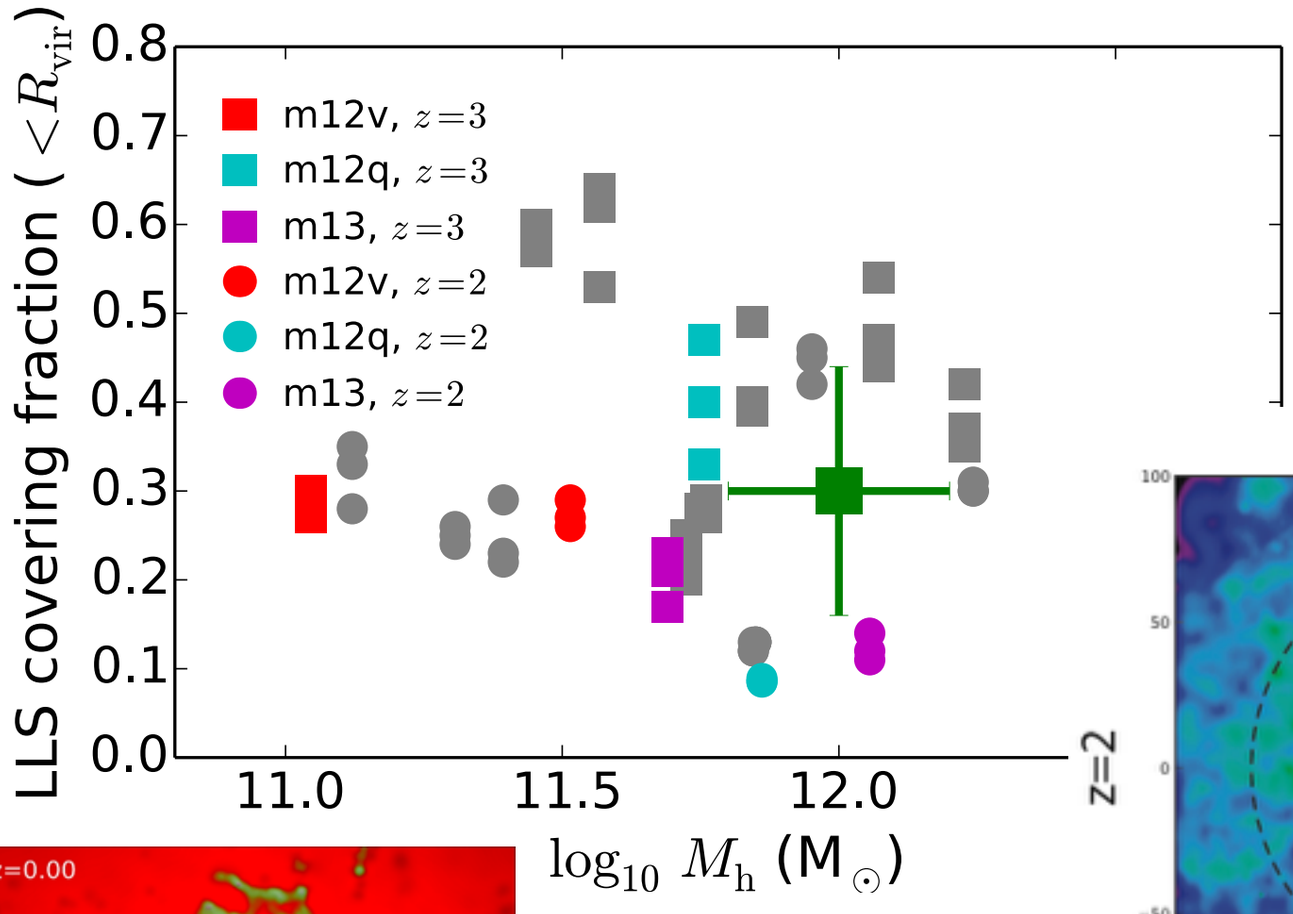
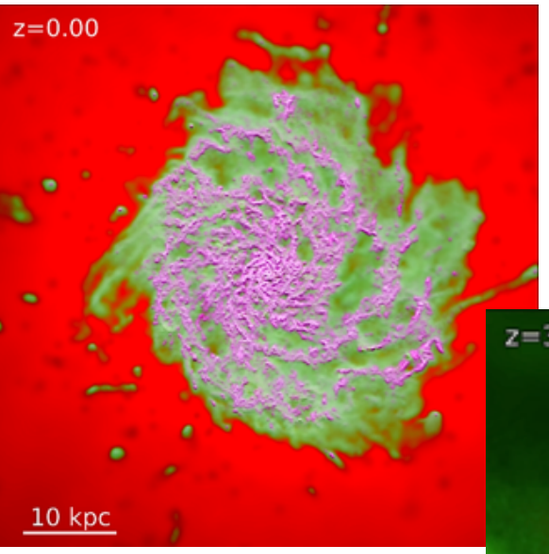


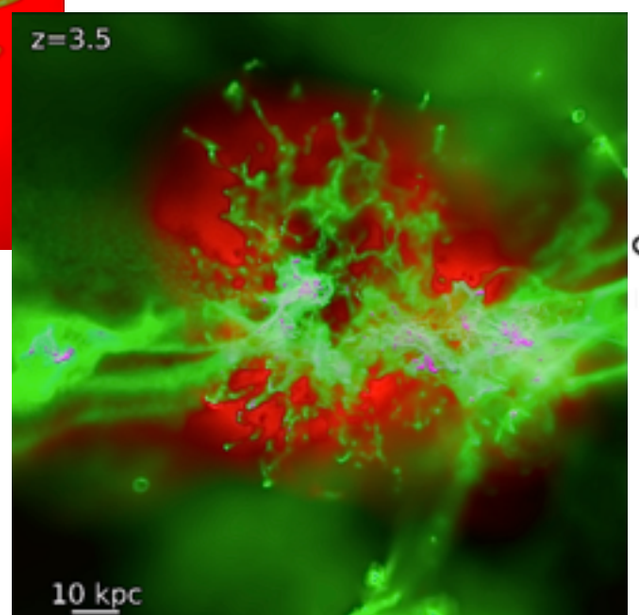
Feedback Determines the Halo Gas Properties

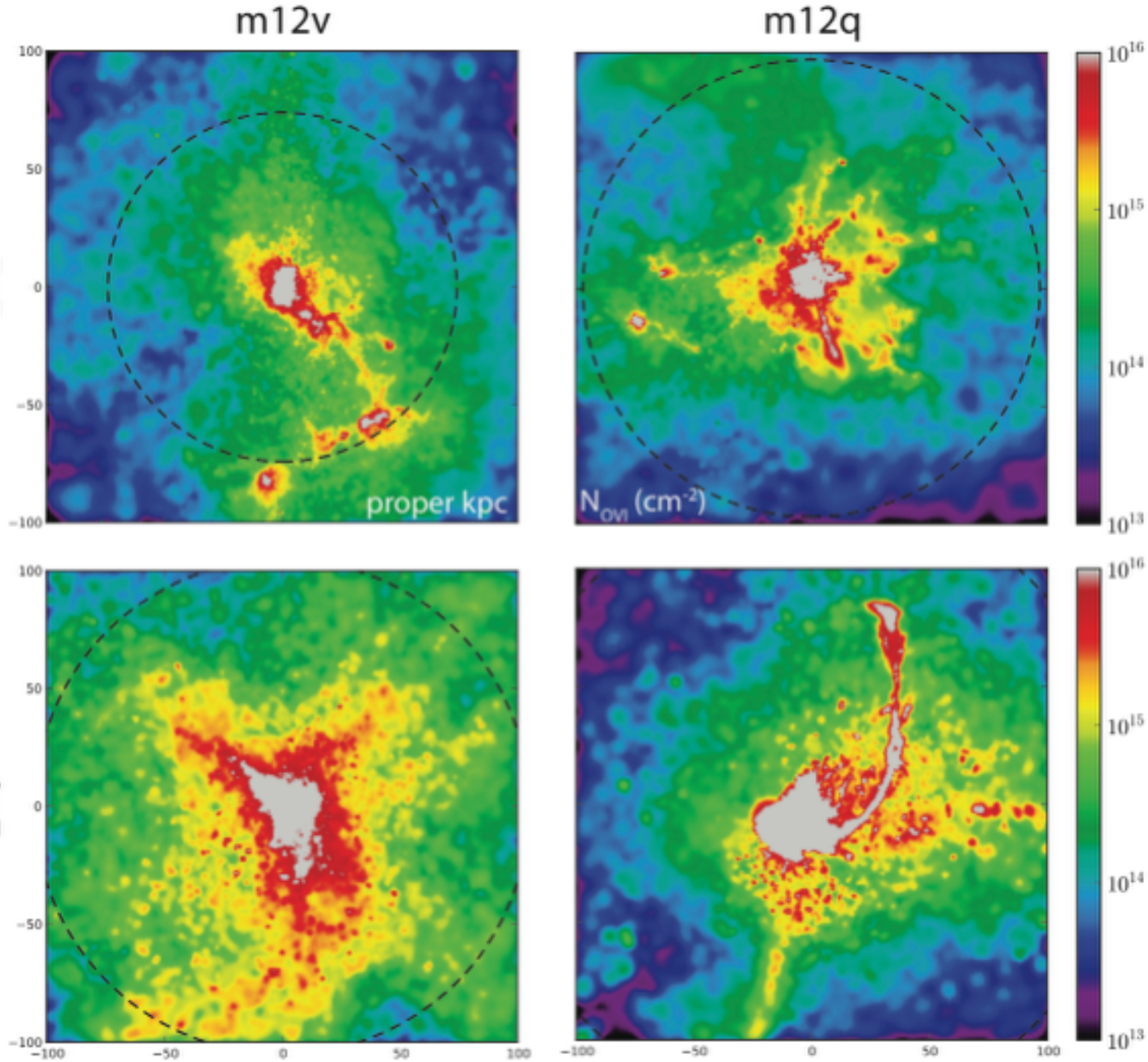
NEED TO PREDICT OUTFLOW MASS, VELOCITY, & GAS *PHASE*

Faucher-Giguere, PFH, et al.



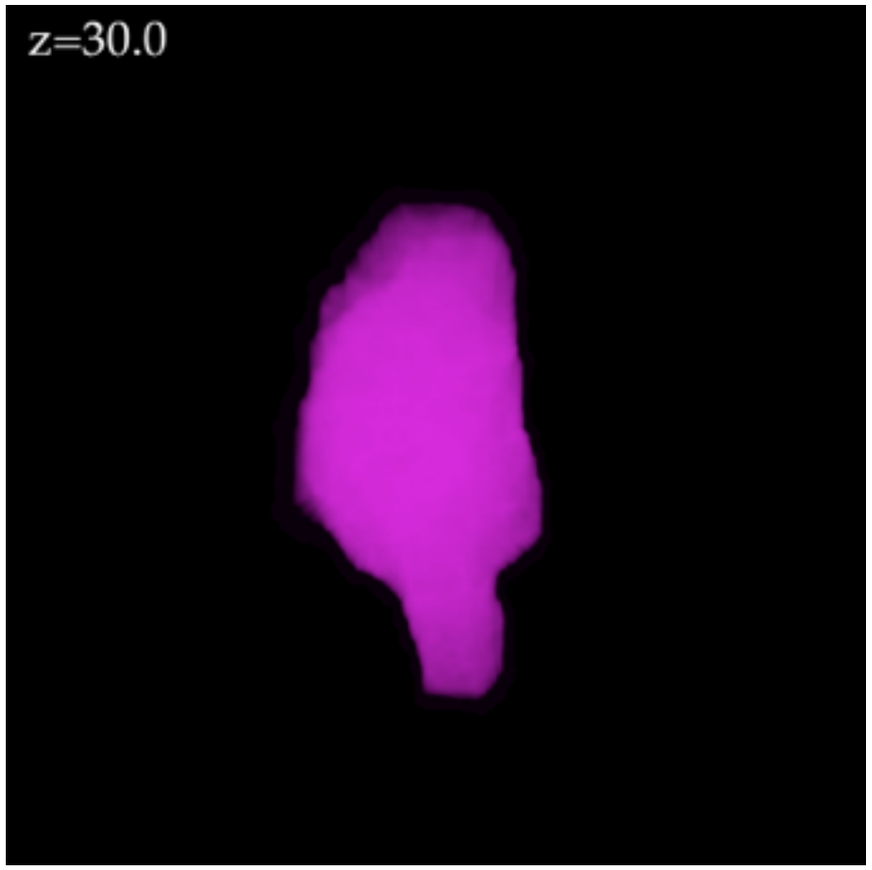






Quenching: Non-AGN Mechanisms *FAIL*

MORE THAN GRAVITY, COOLING, STARS, & MHD



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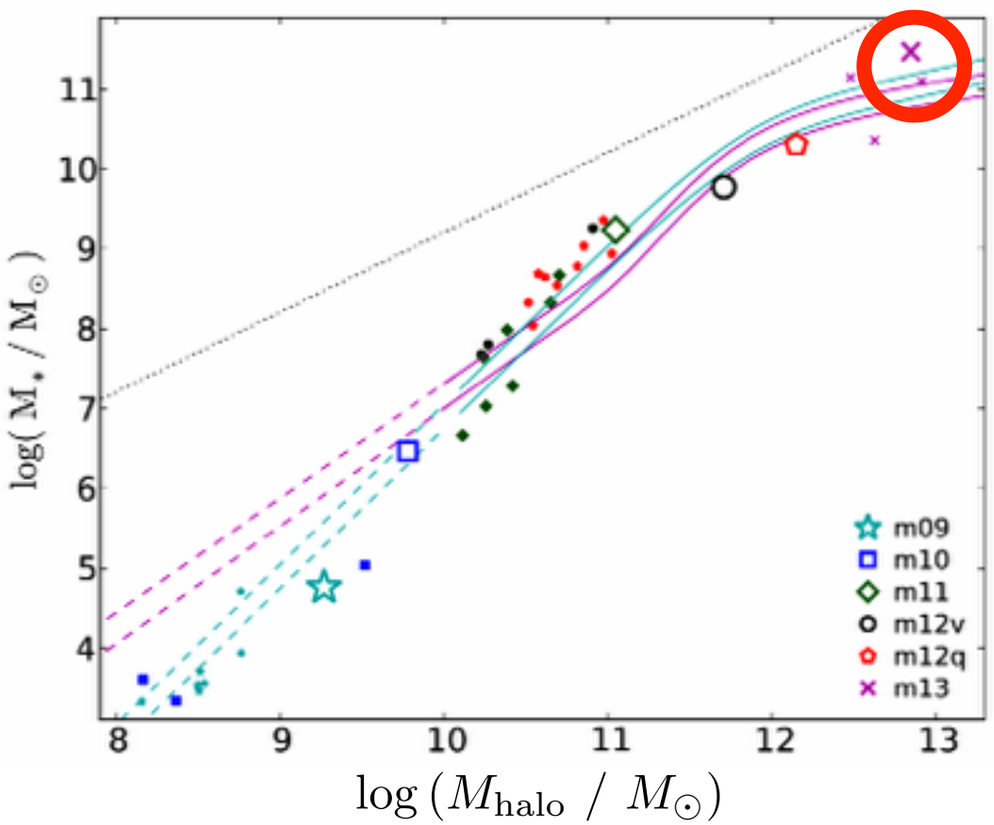

$$M_{\rm halo} \sim 10^{14}\,M_\odot$$

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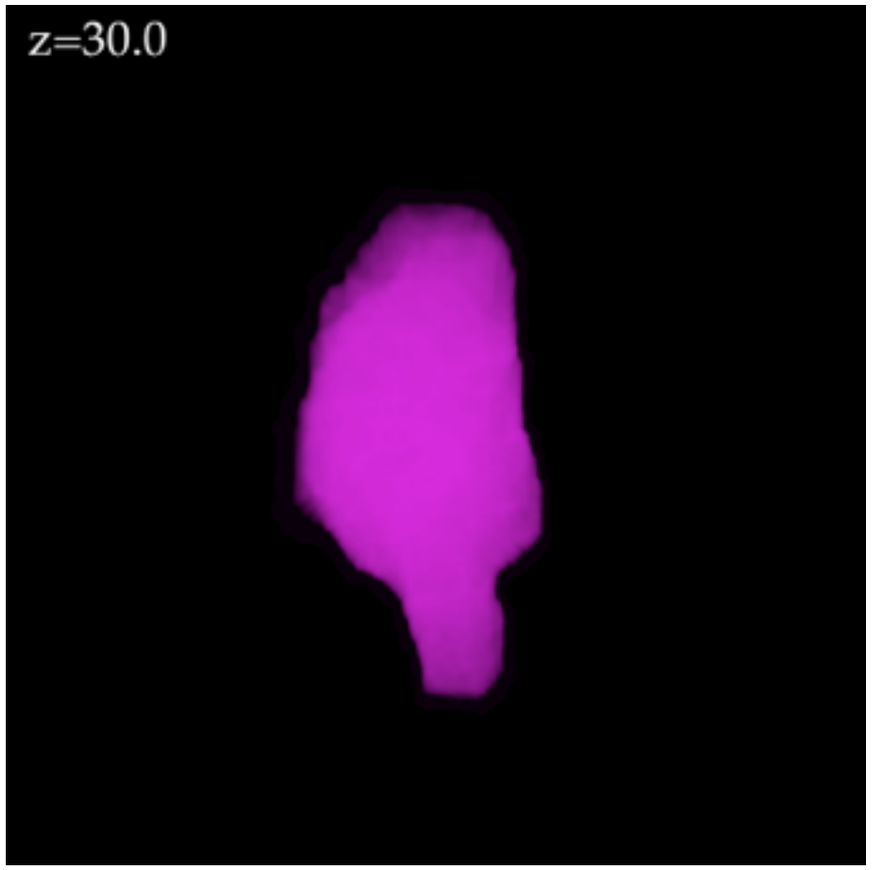

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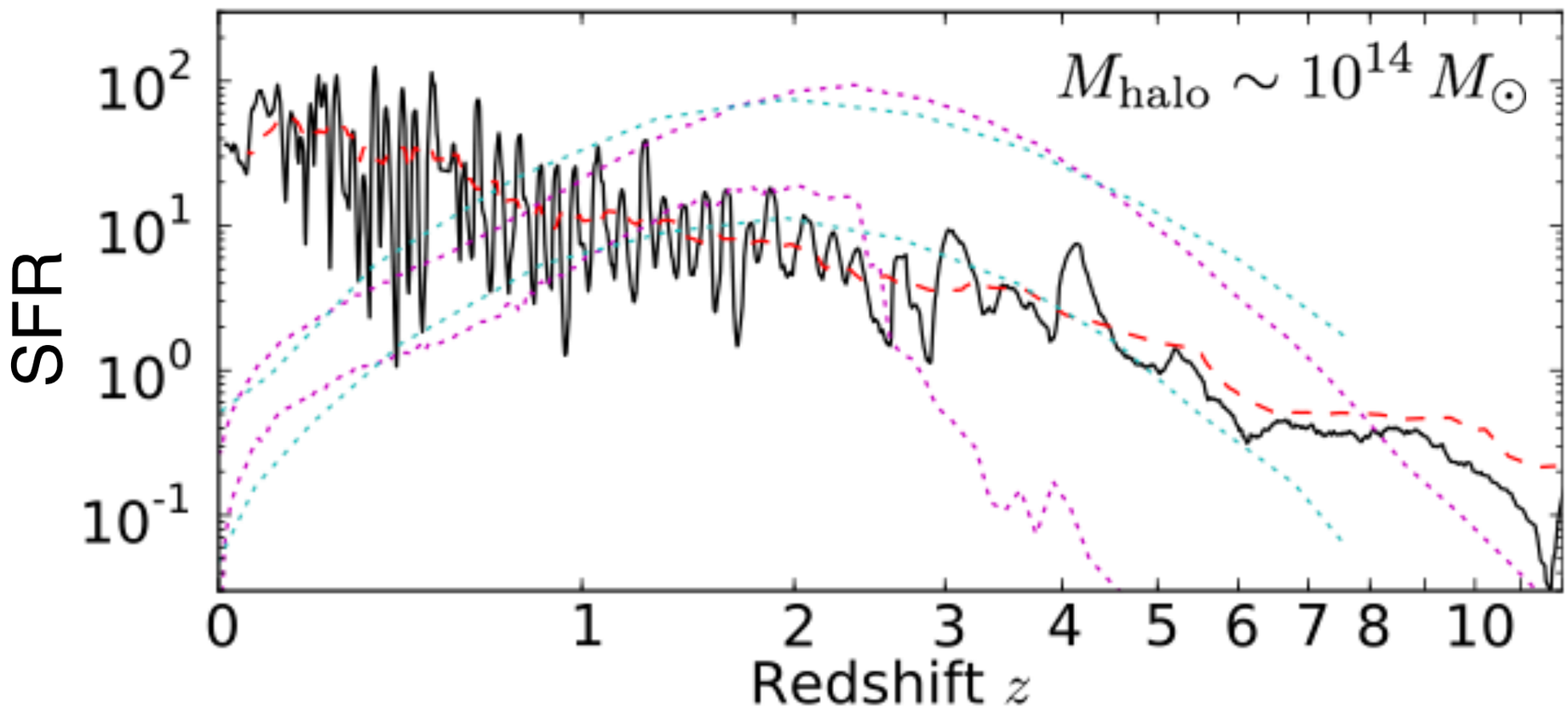

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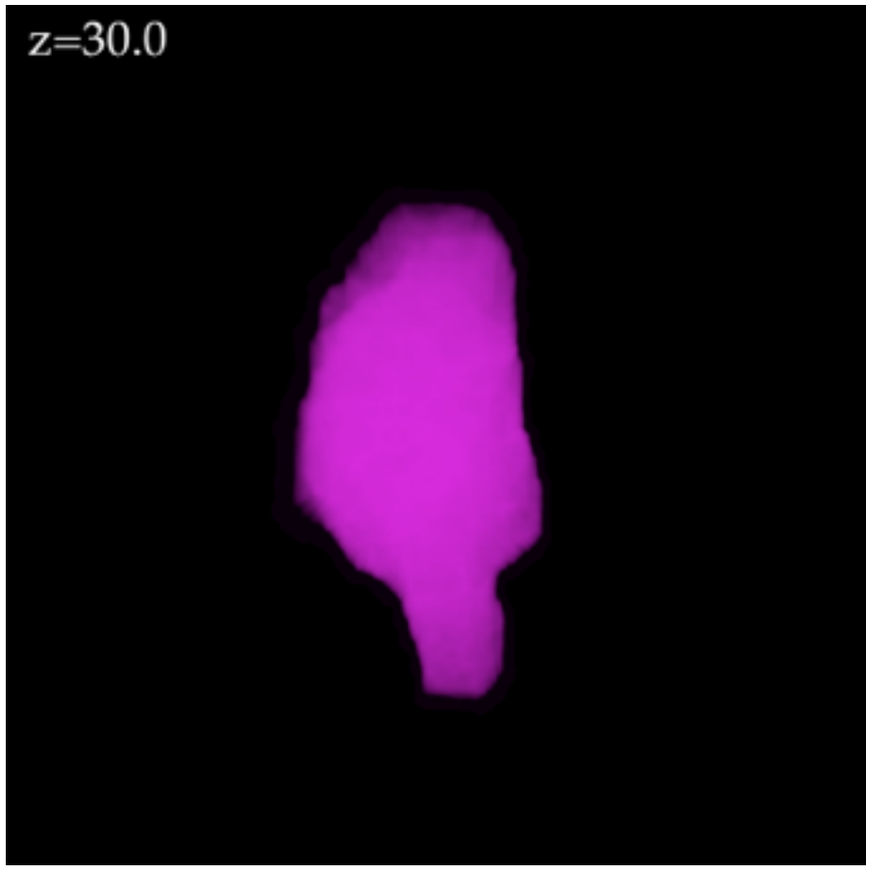

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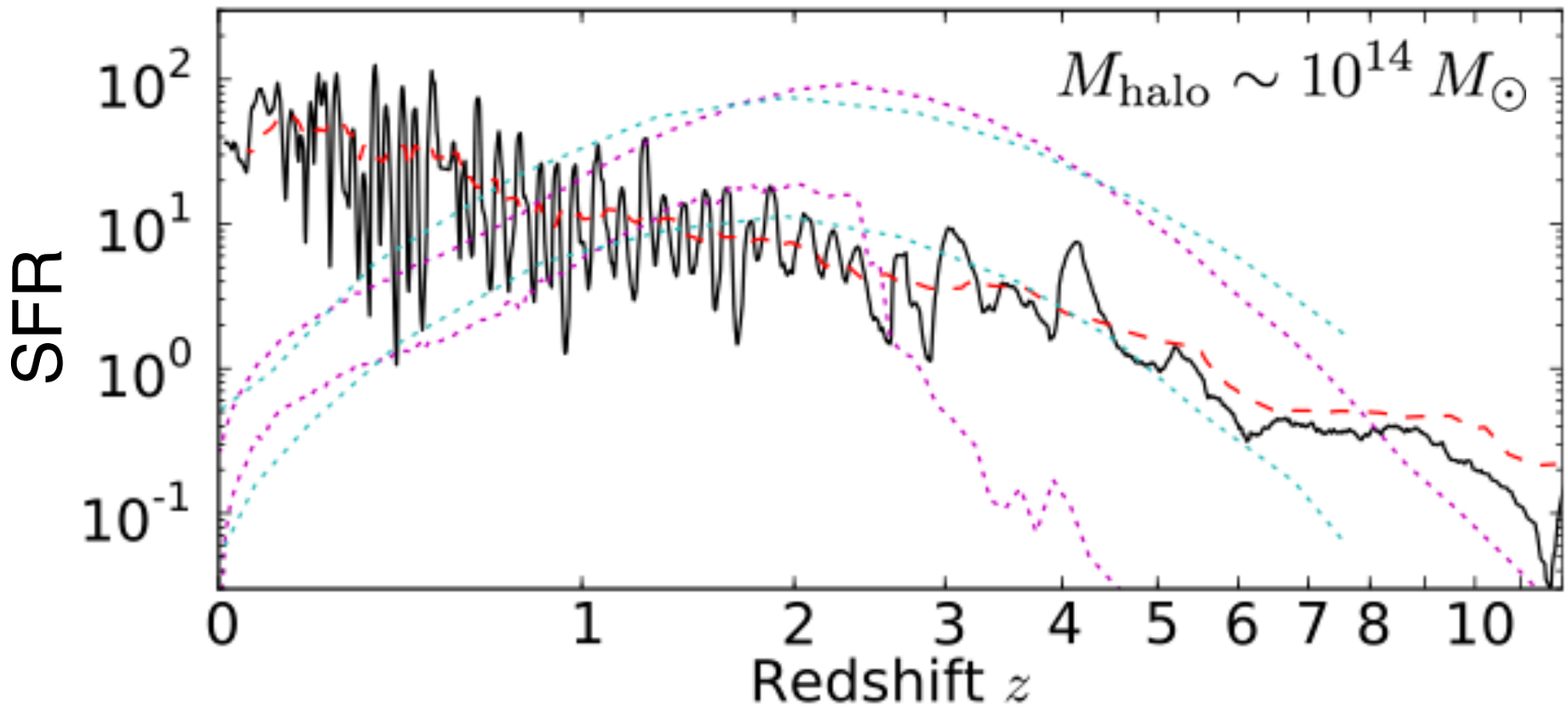

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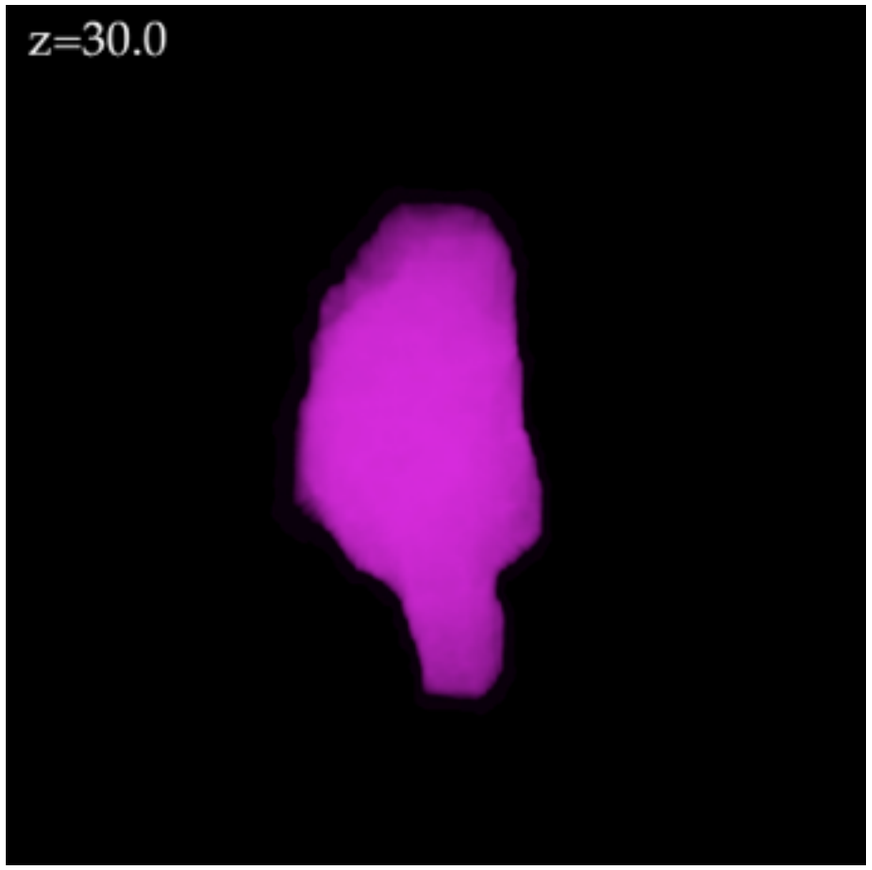

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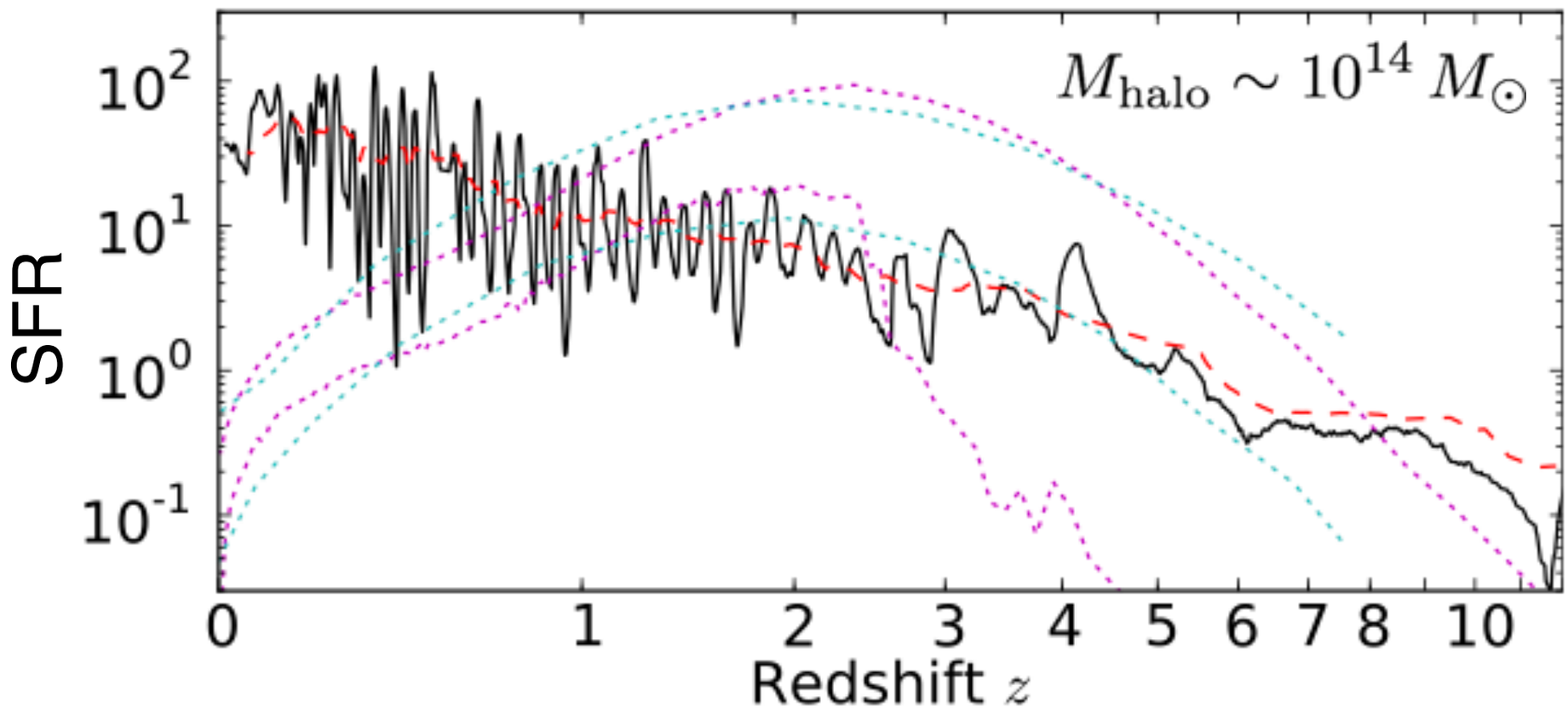

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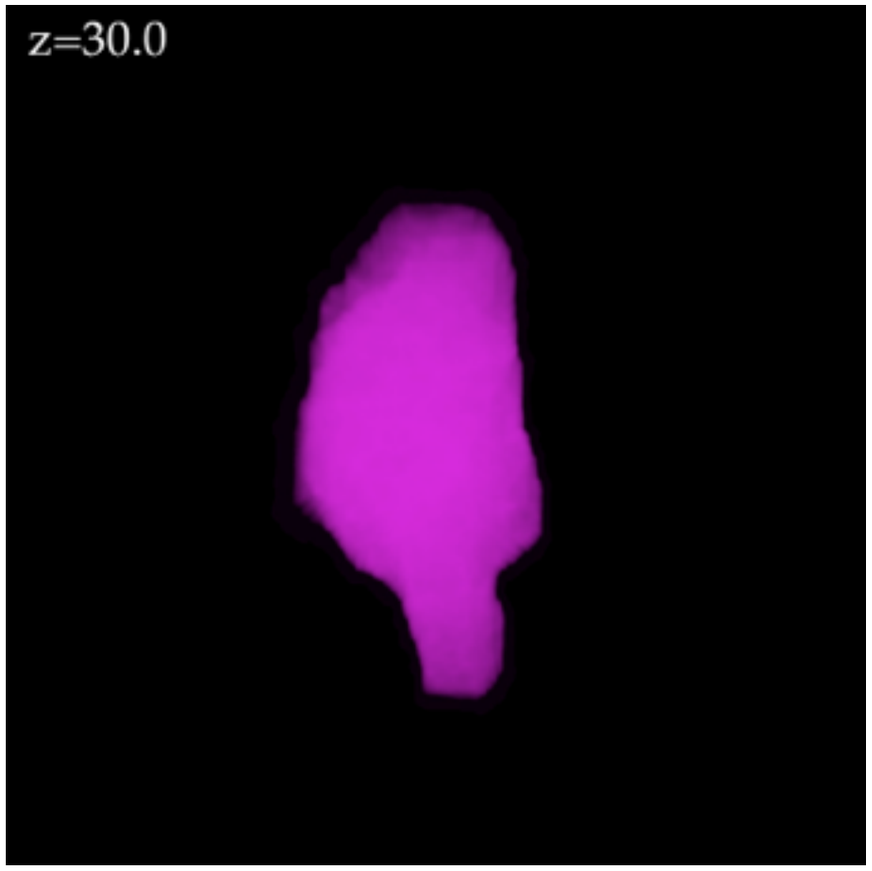

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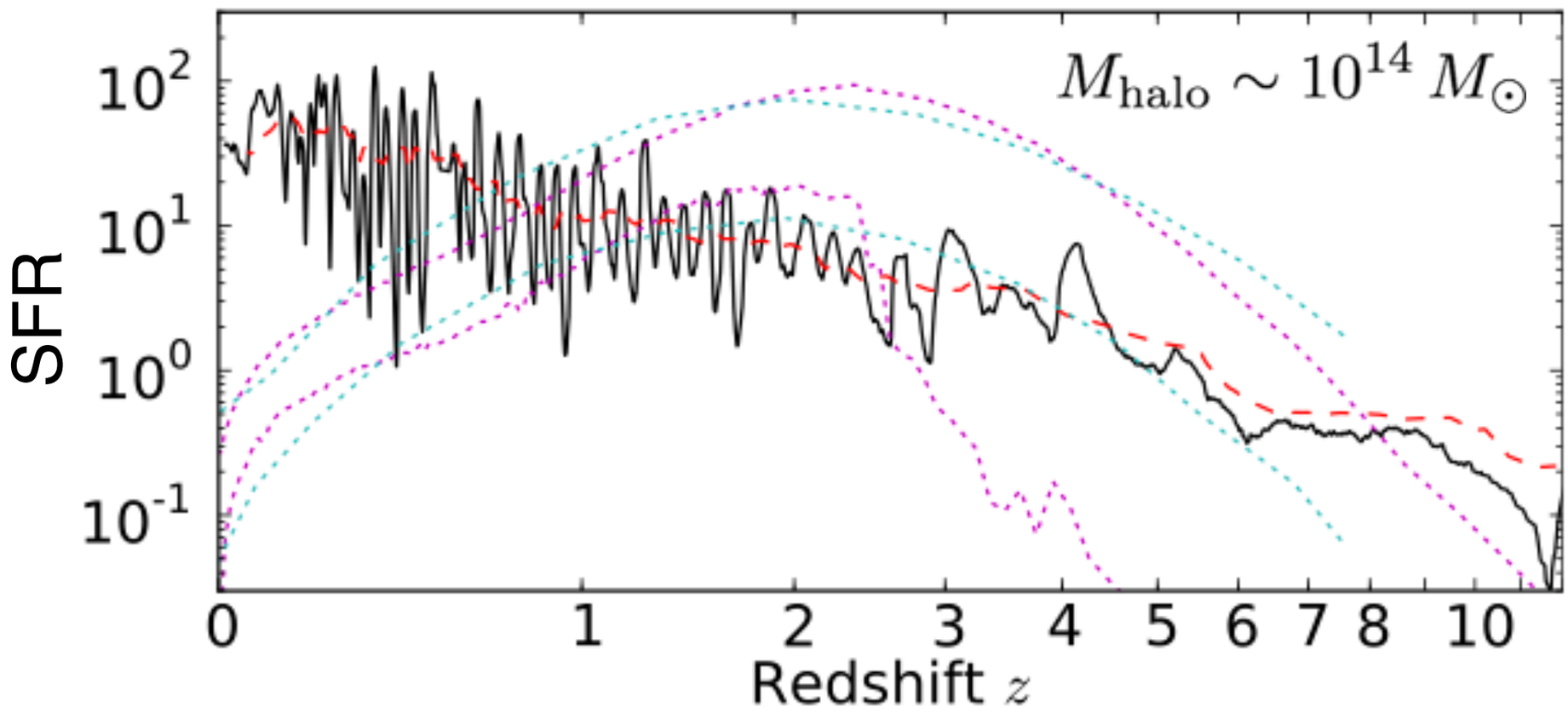
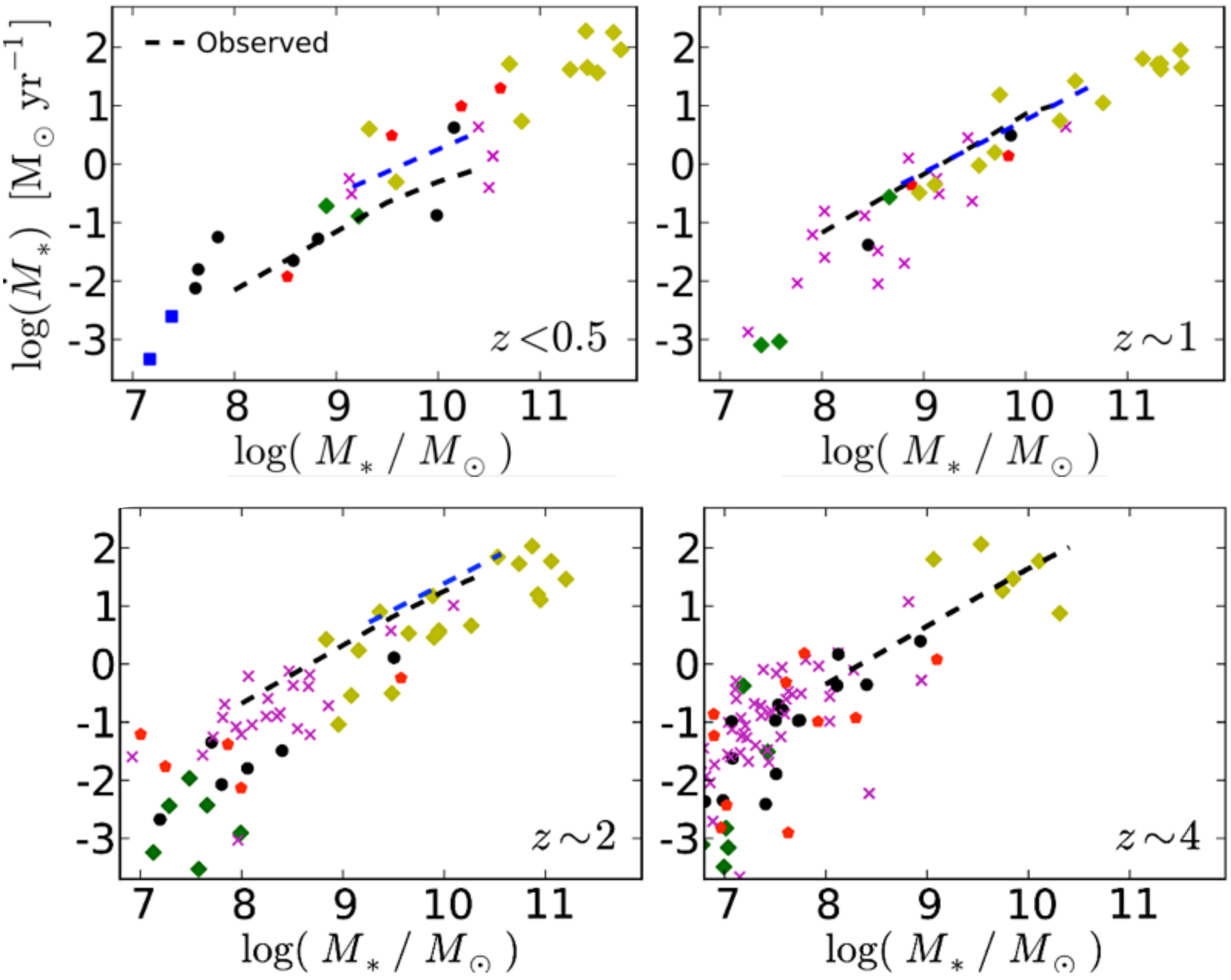
- **MHD/Conduction?** (new runs included)
- **Stars?** (late-time AGB/SNIa included)



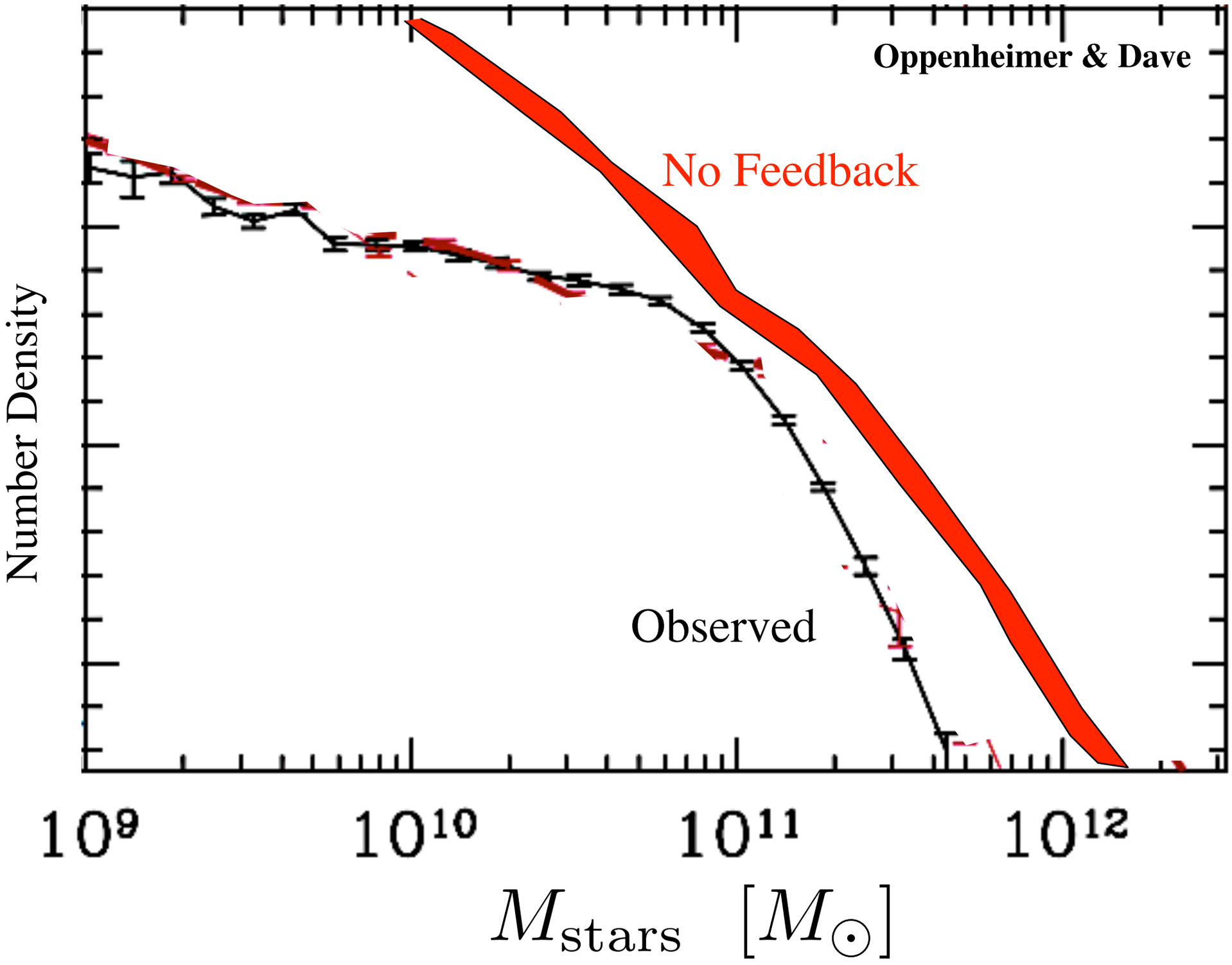
Galaxies Just Keep Plugging Along

NO "QUENCHED" TRACK



Lesson 1: Don't Trust Models that Don't Do Stars Right

SMALL GALAXIES BECOME BIG GALAXIES



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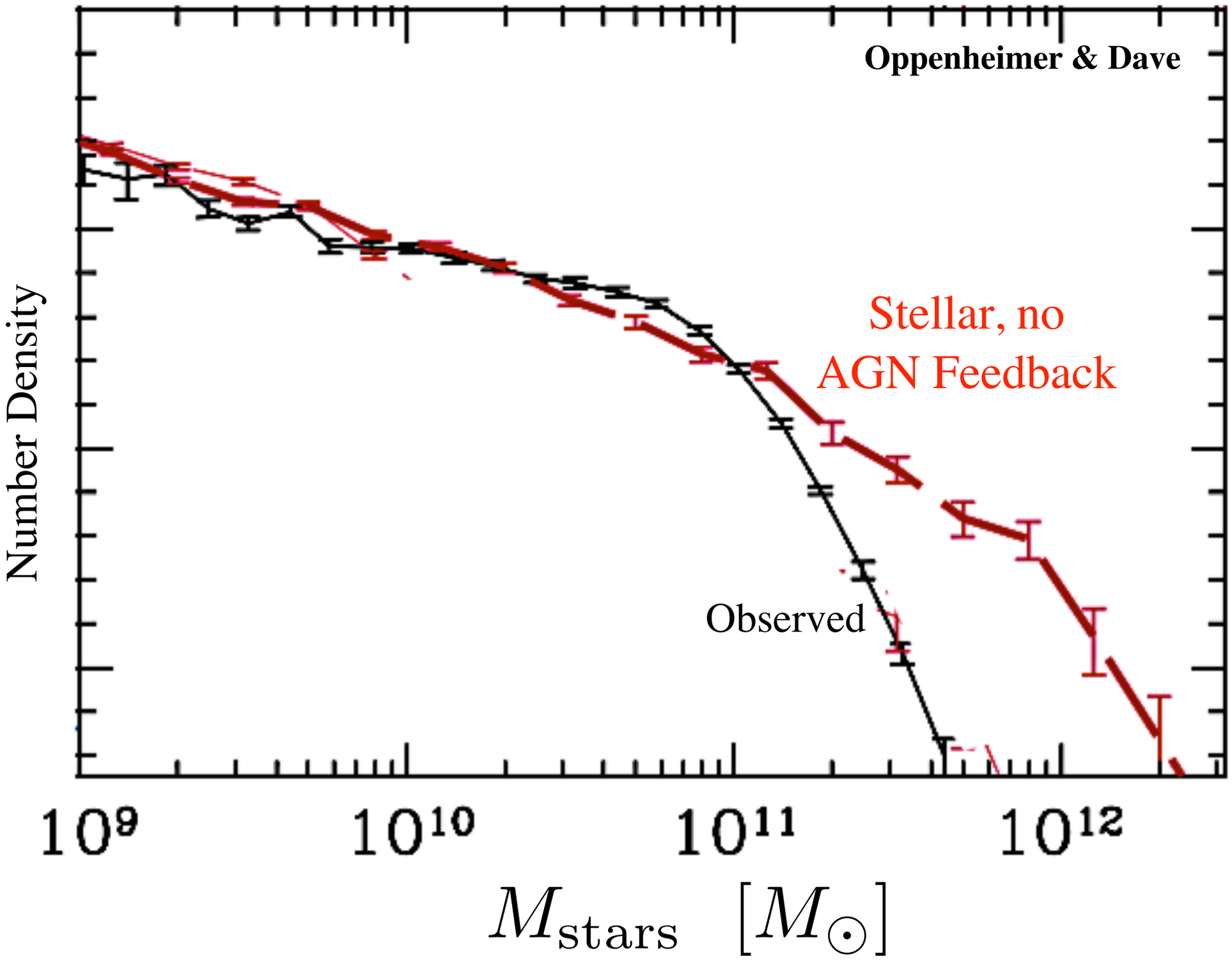

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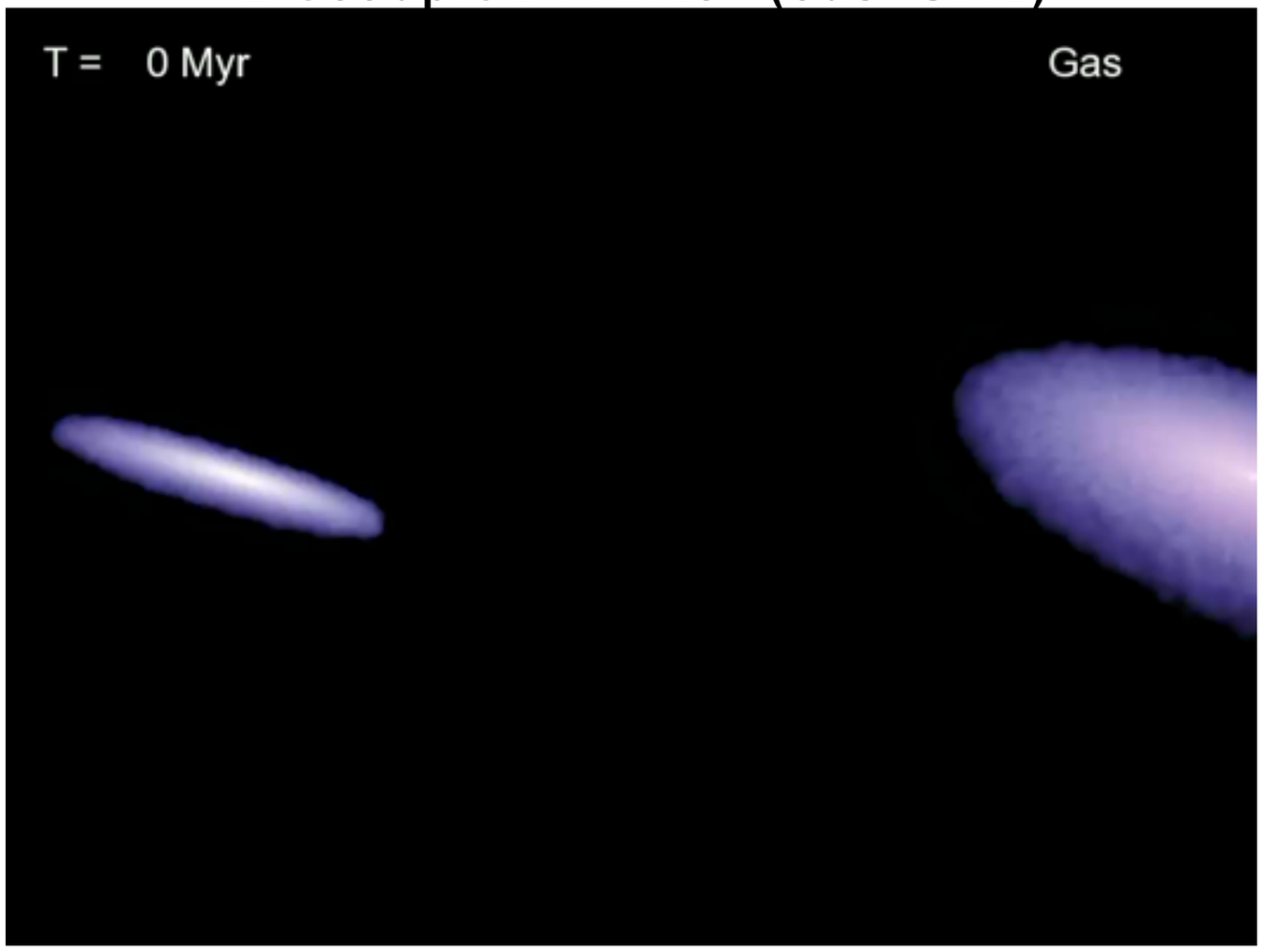
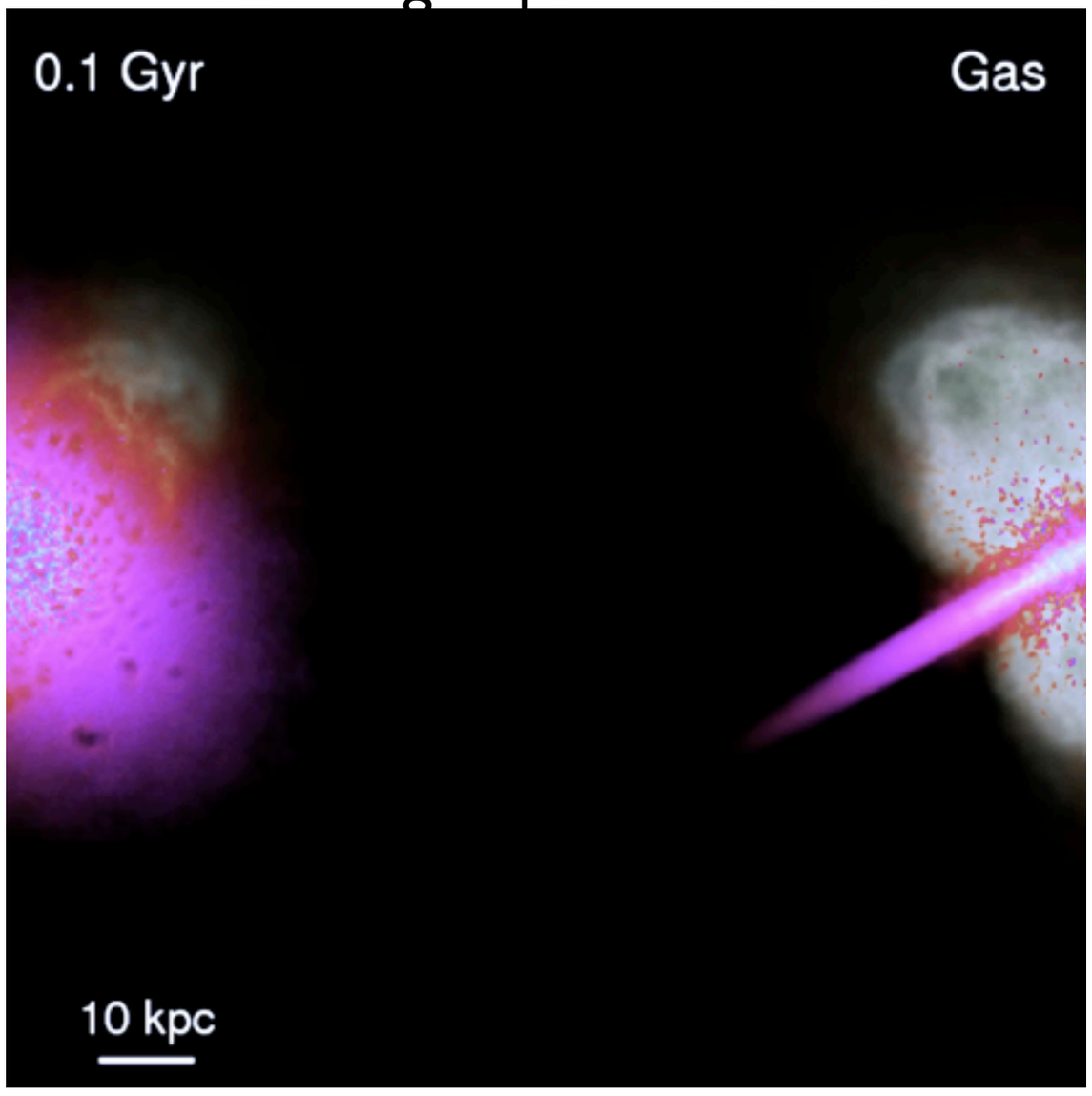
"Decoupled Winds" (Sub-Grid)



Following Explicit Feedback



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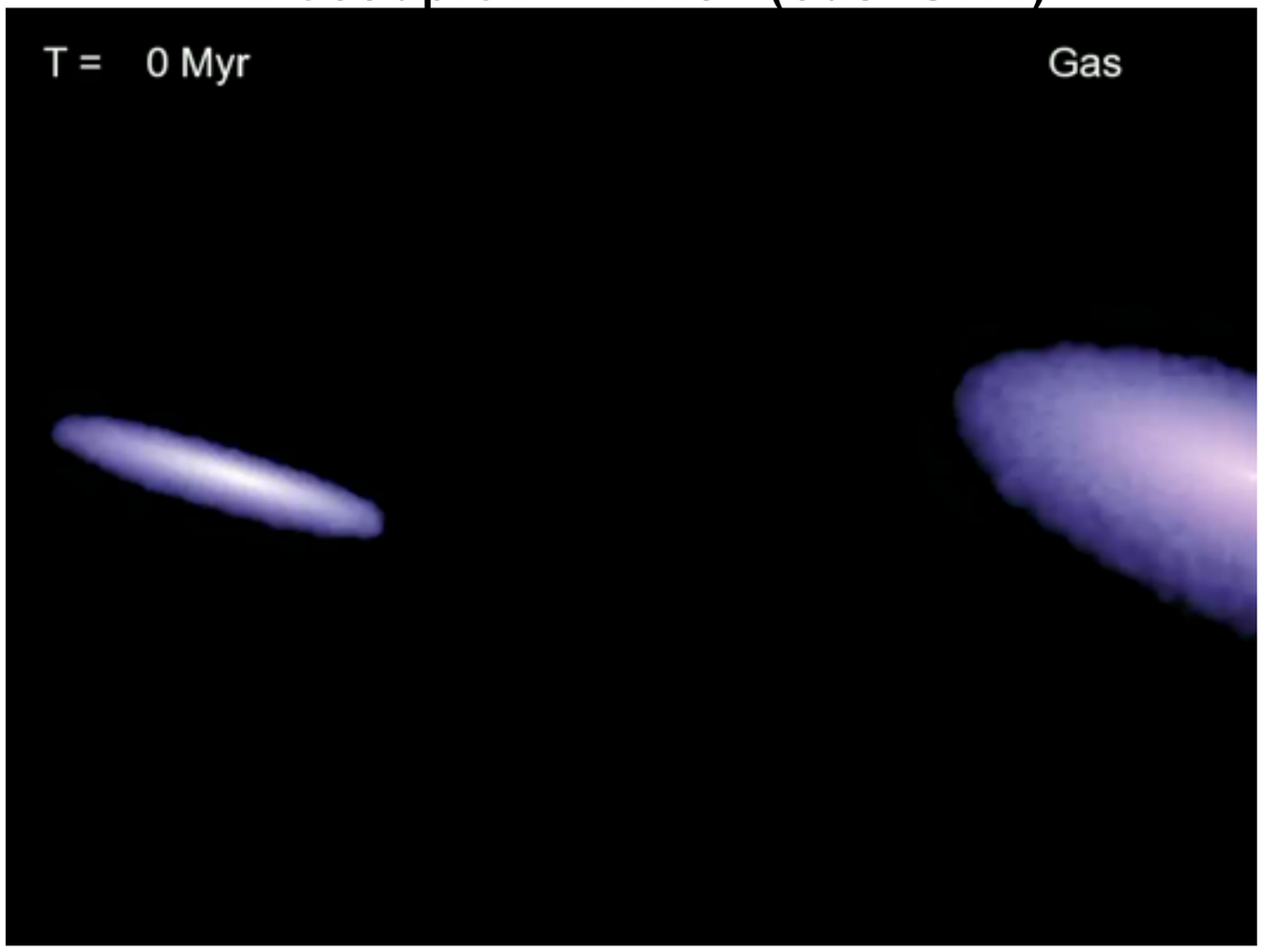

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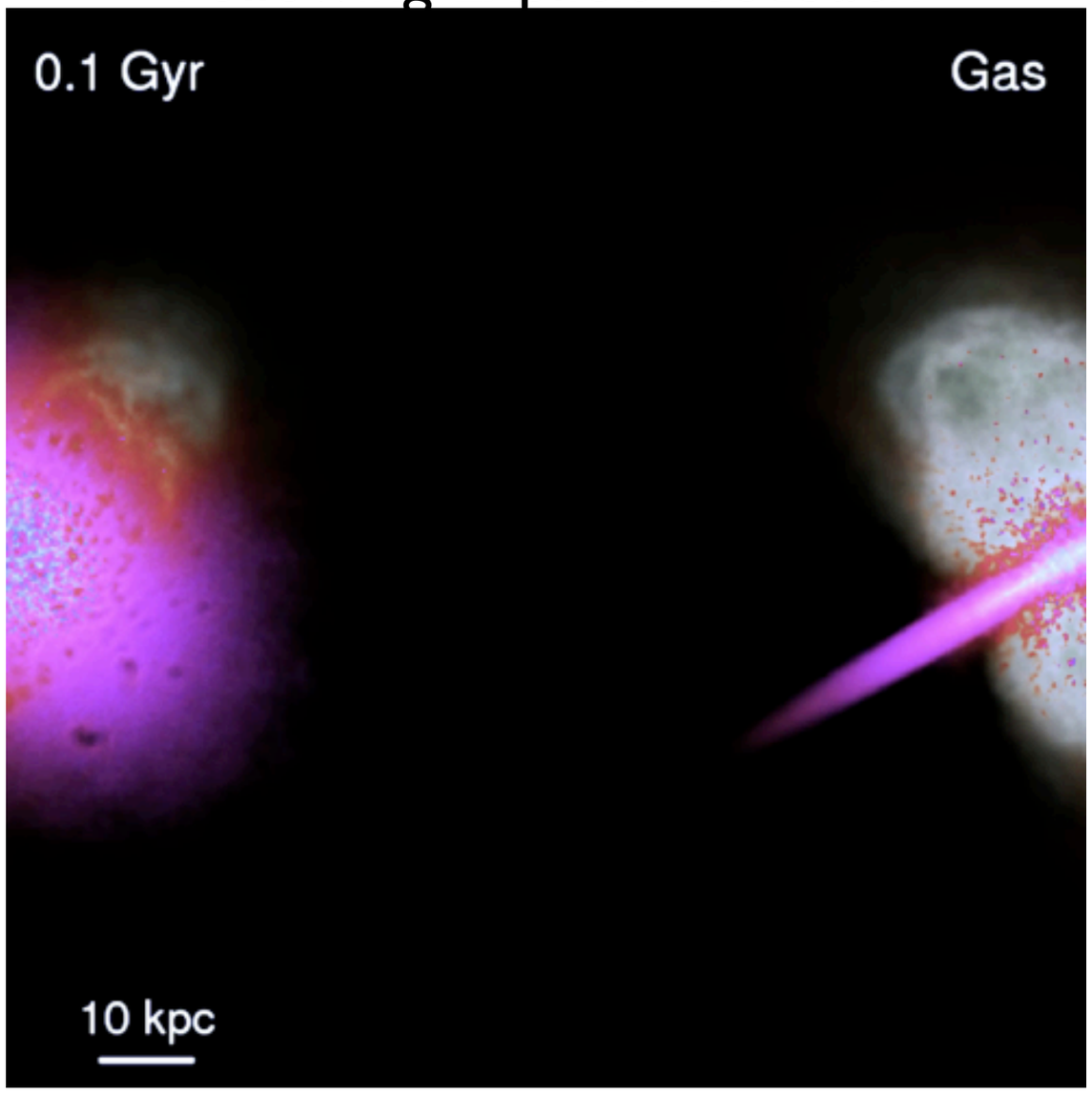

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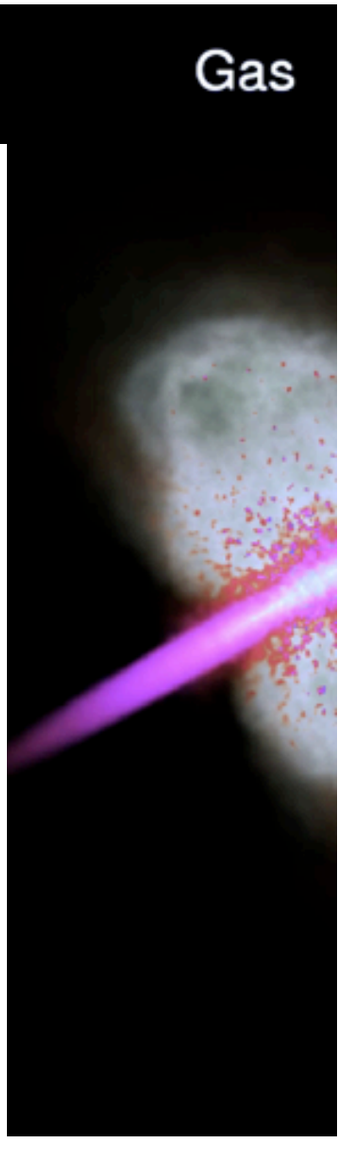
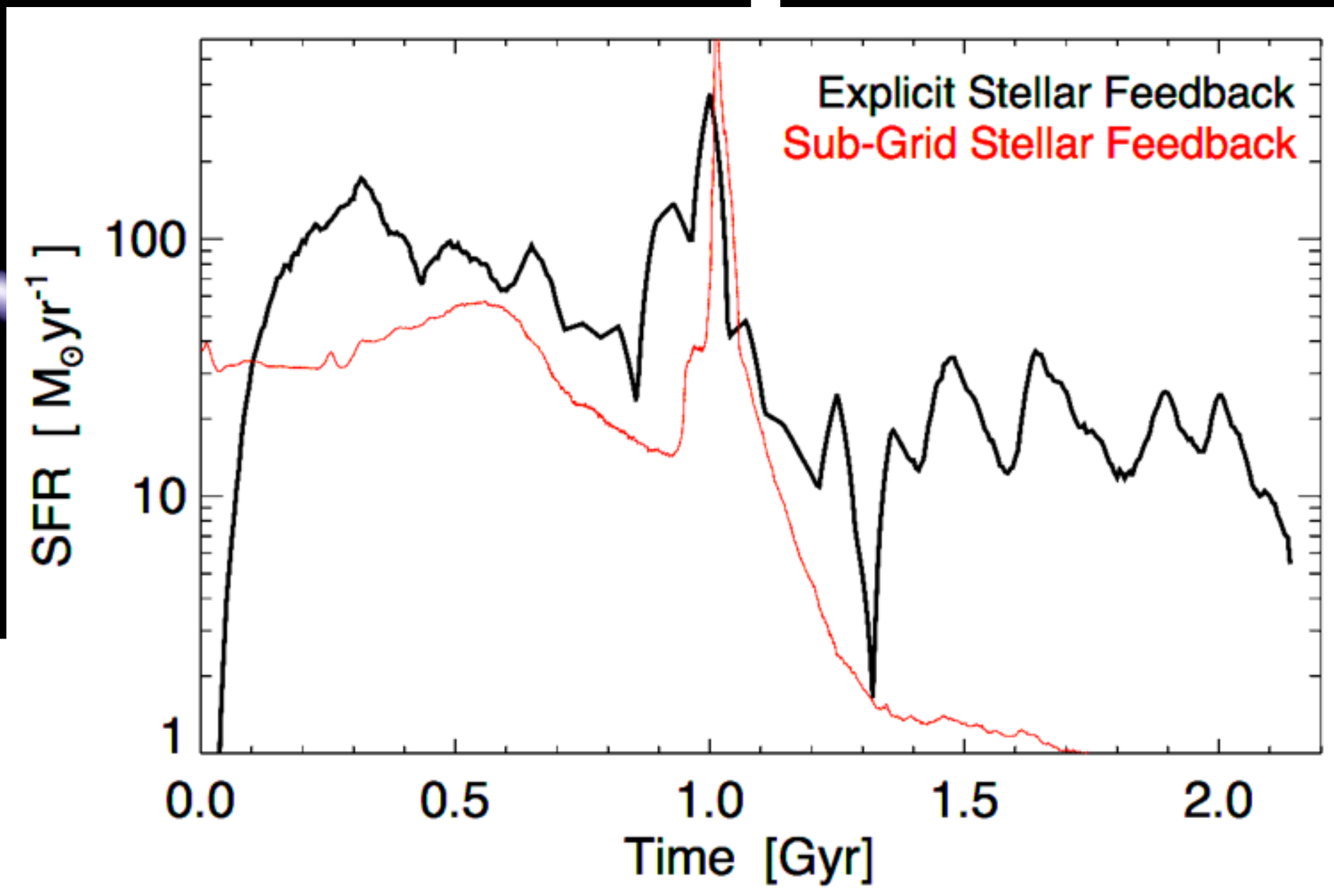


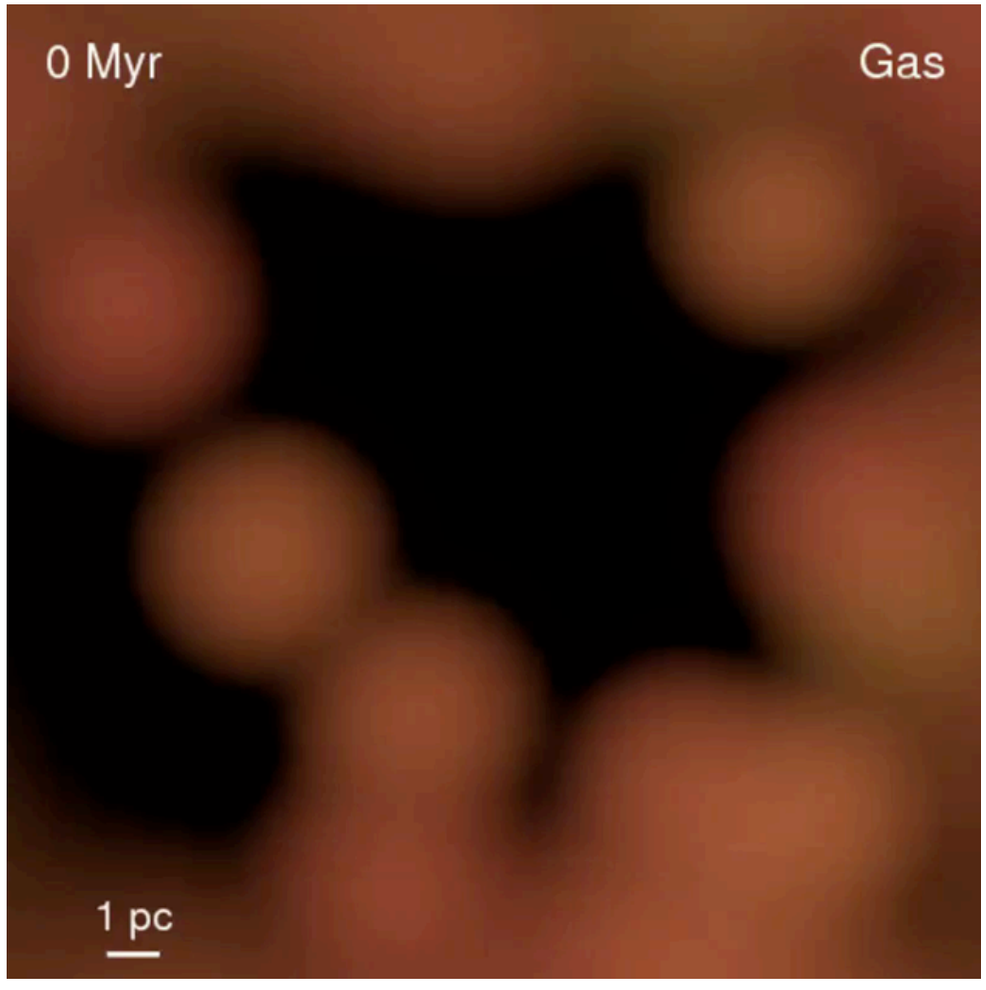


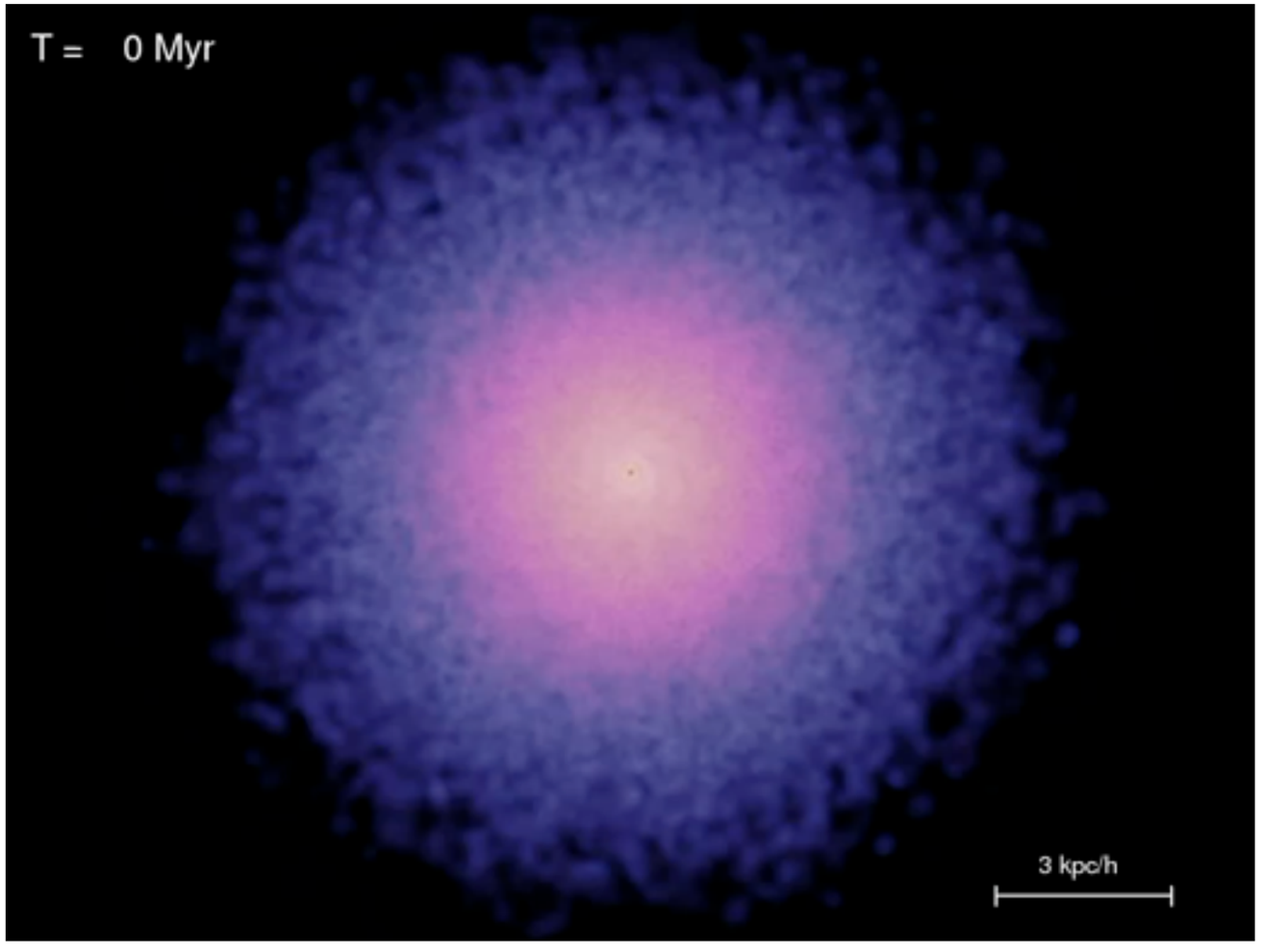
Lesson 2: “Shutting Down” Star Formation in the Disk

WHY IT’S HARD

$$Q_{\rm turb} = \frac{\sigma_{\rm turb}\,\kappa}{\pi\,G\,\Sigma} > 1$$

$$Q_{\rm therm} = \frac{c_s\,\kappa}{\pi\,G\,\Sigma} > 1$$





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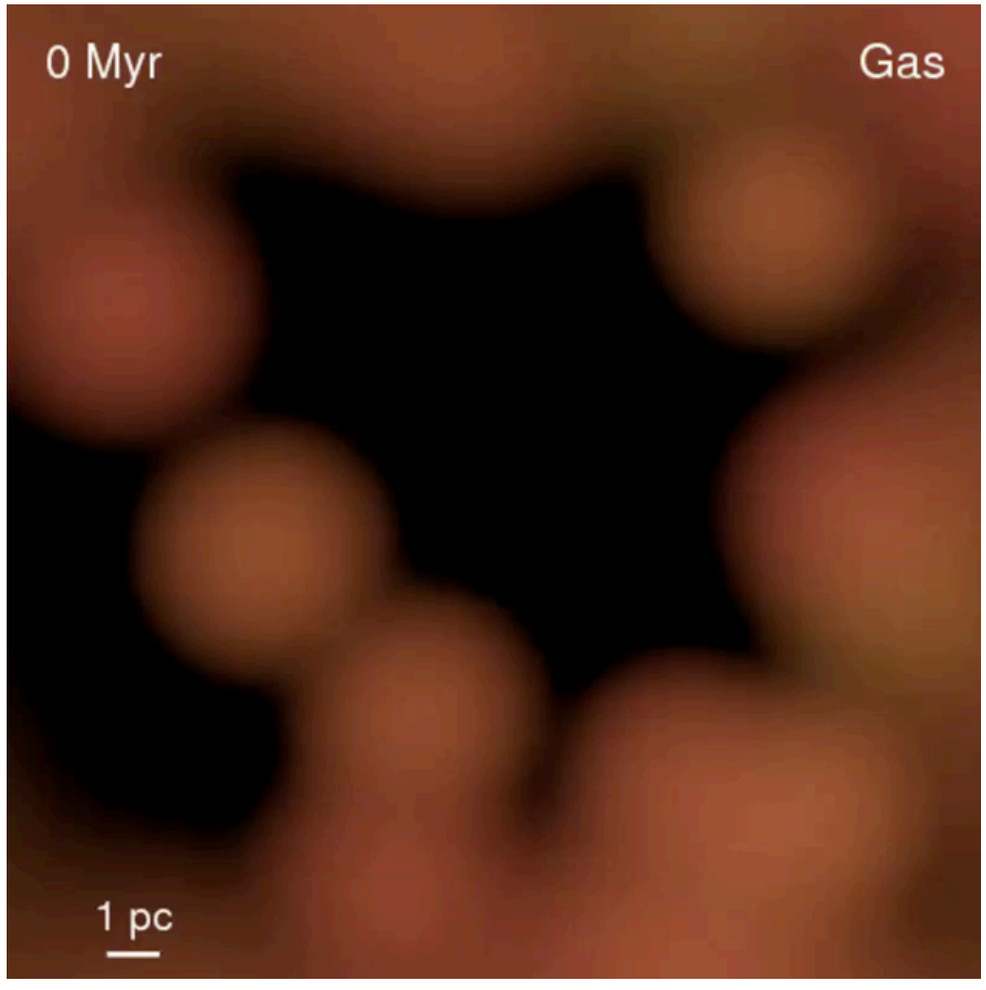

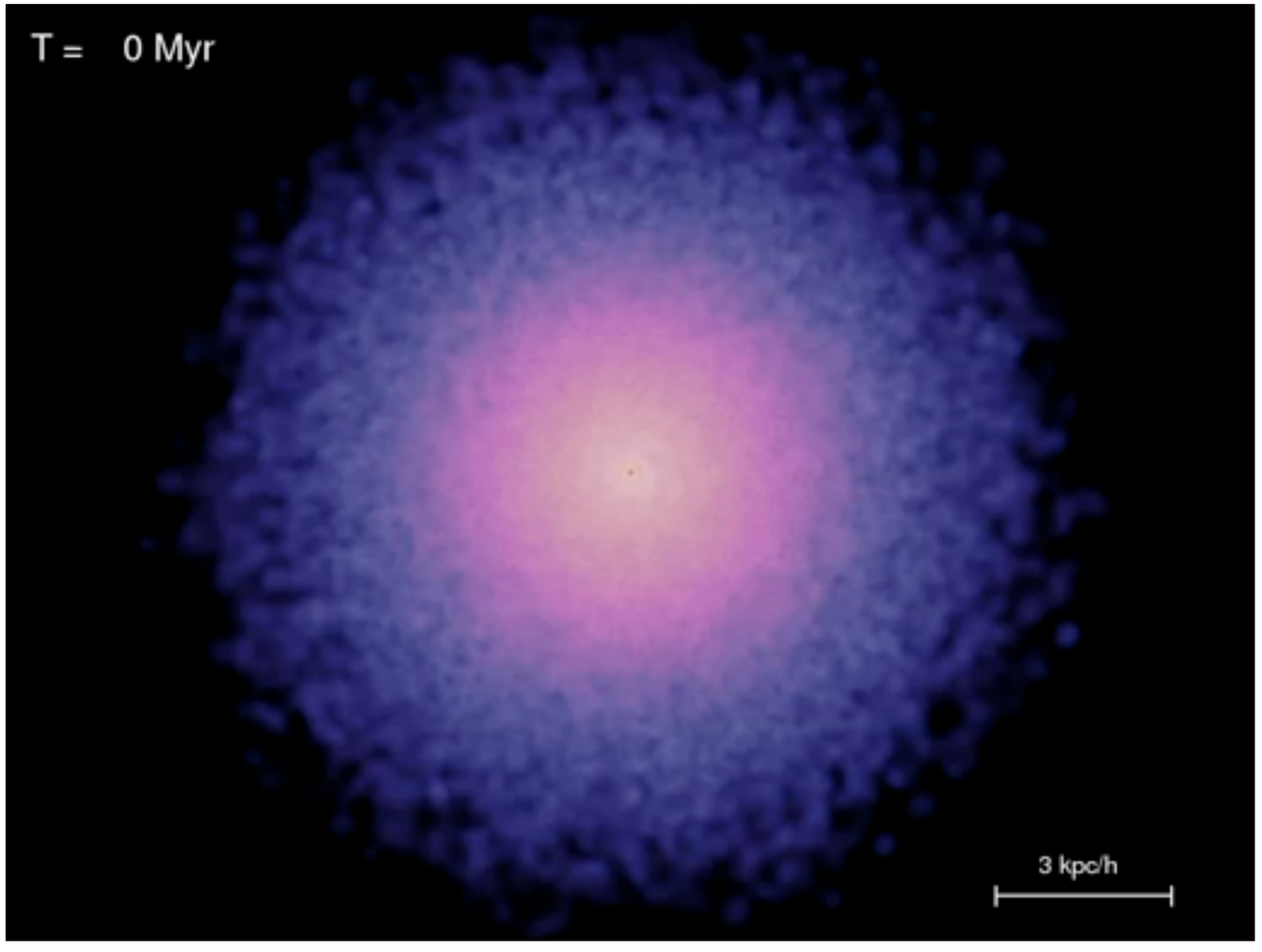

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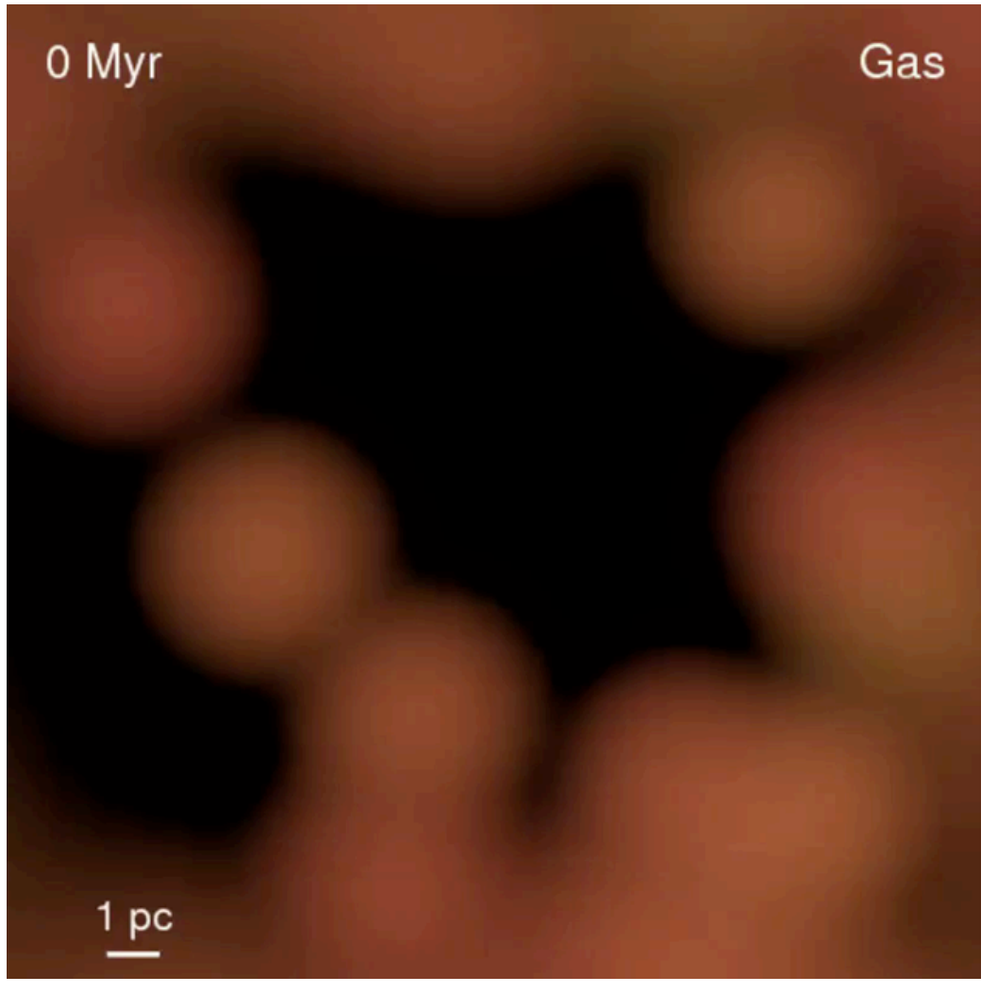

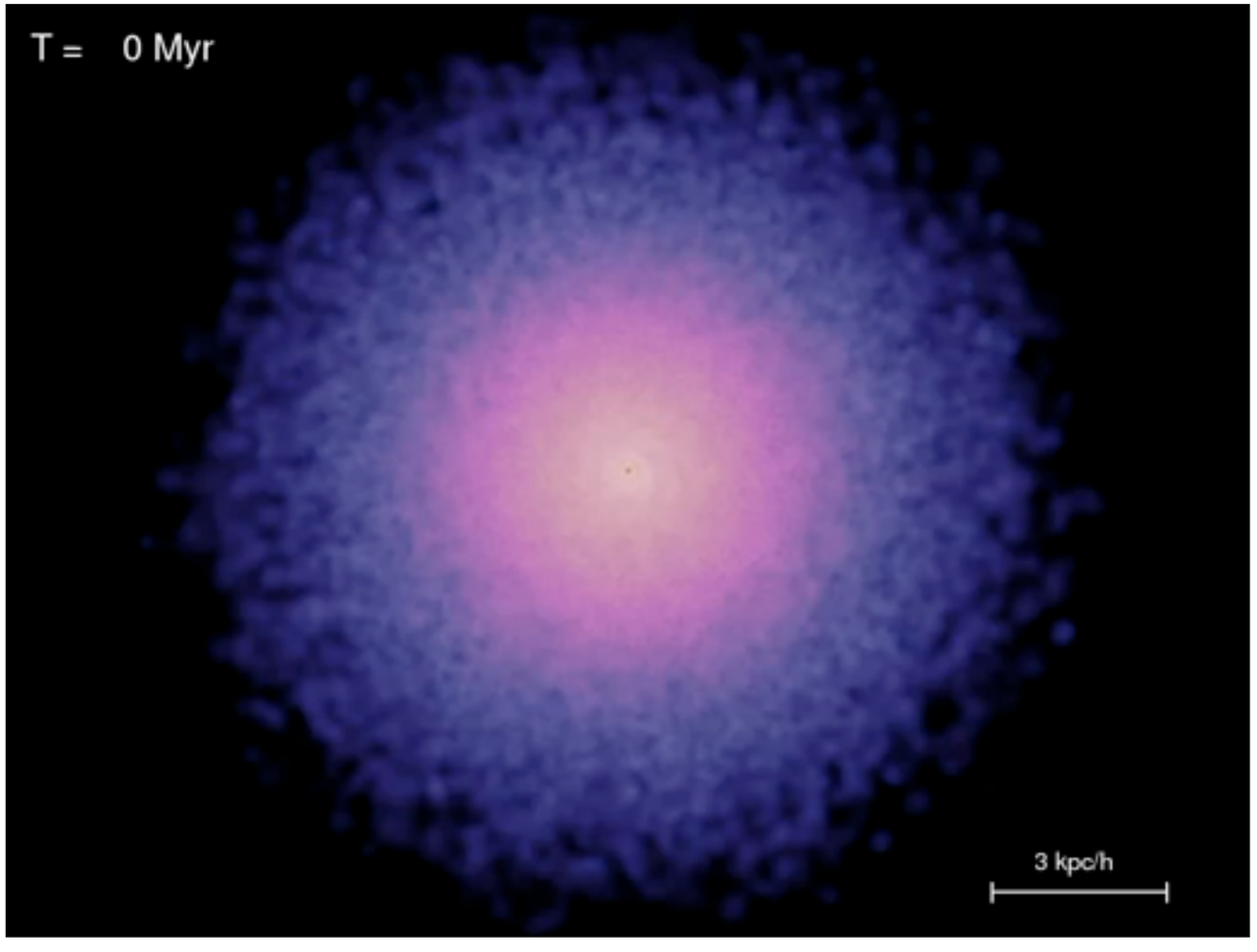

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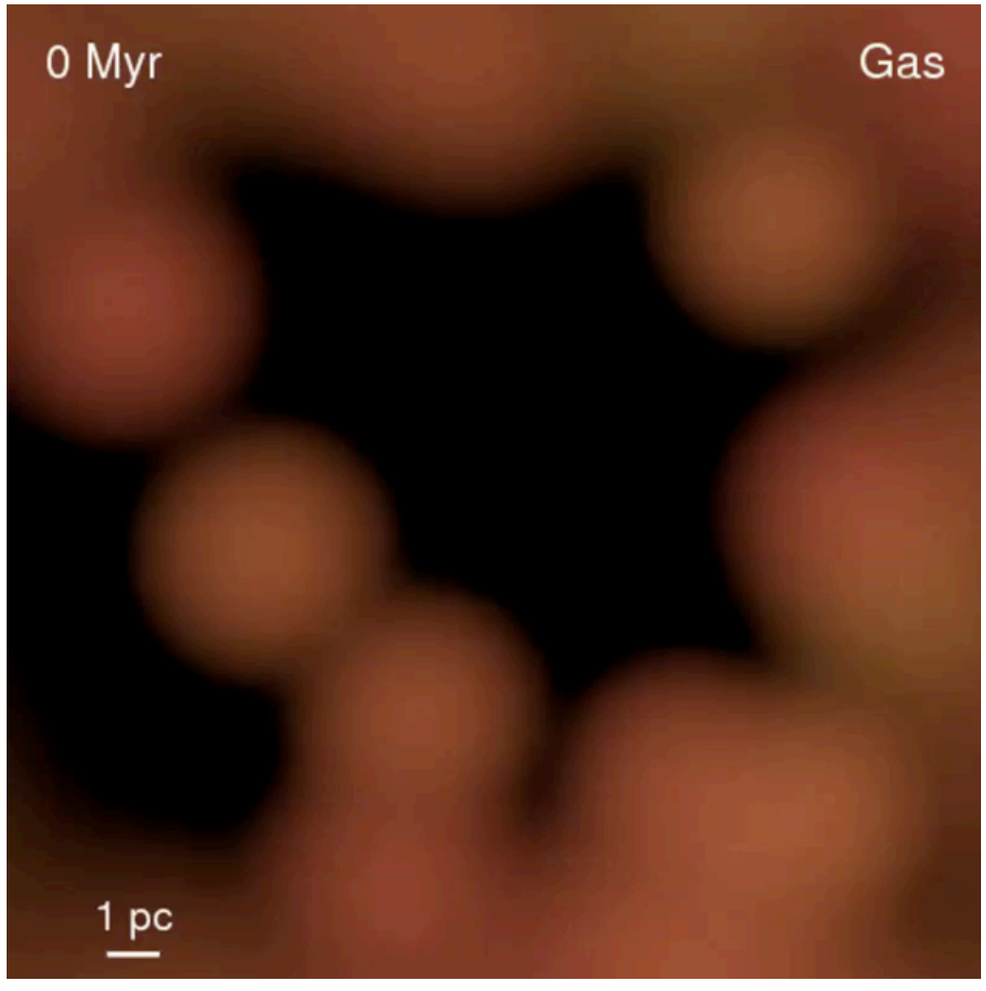

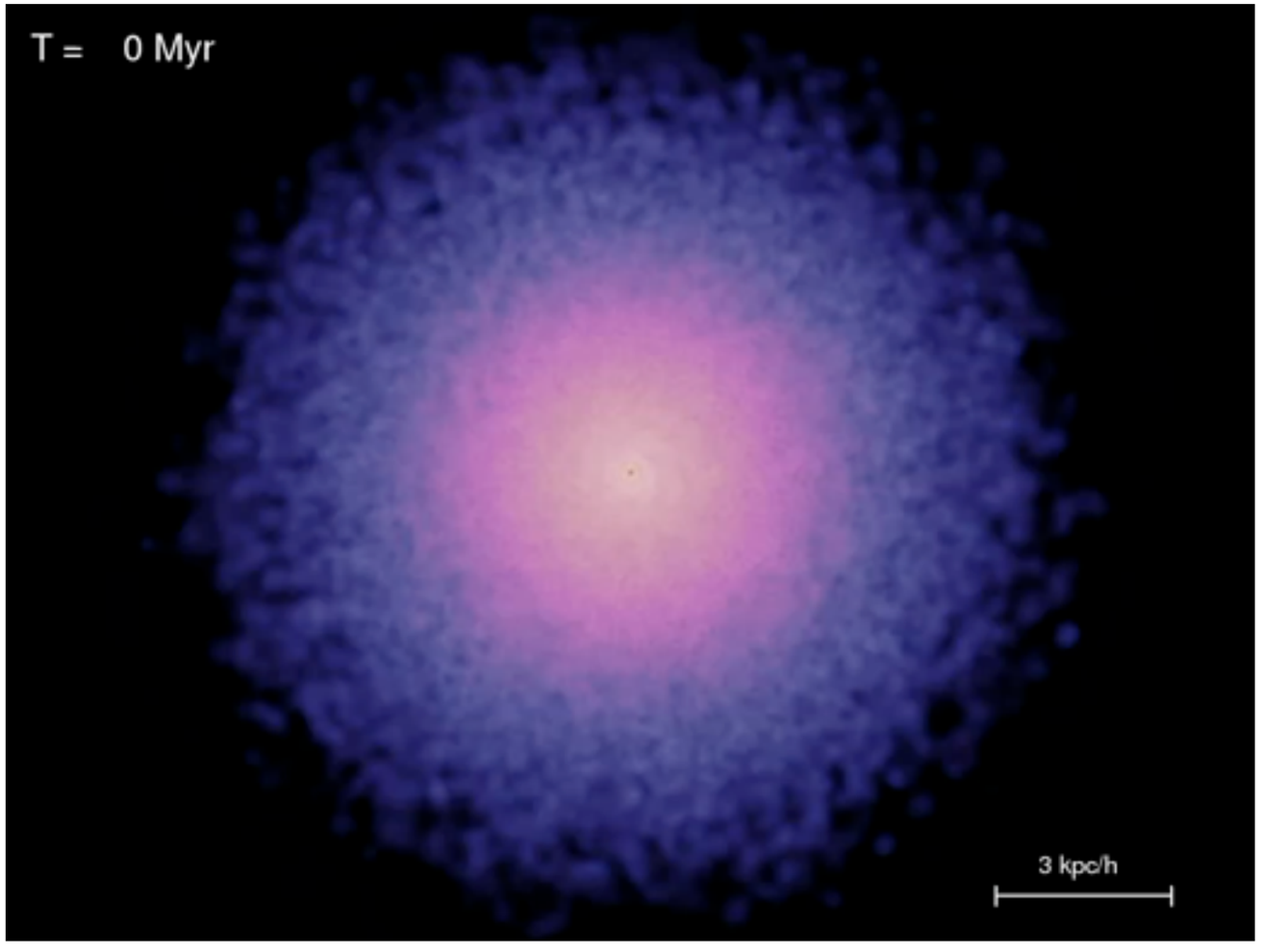

- *Self-Regulated* SF (K-S)
- *Suppressed* SF

“Shutting Down” Star Formation:

GAS DEPLETION NEEDED

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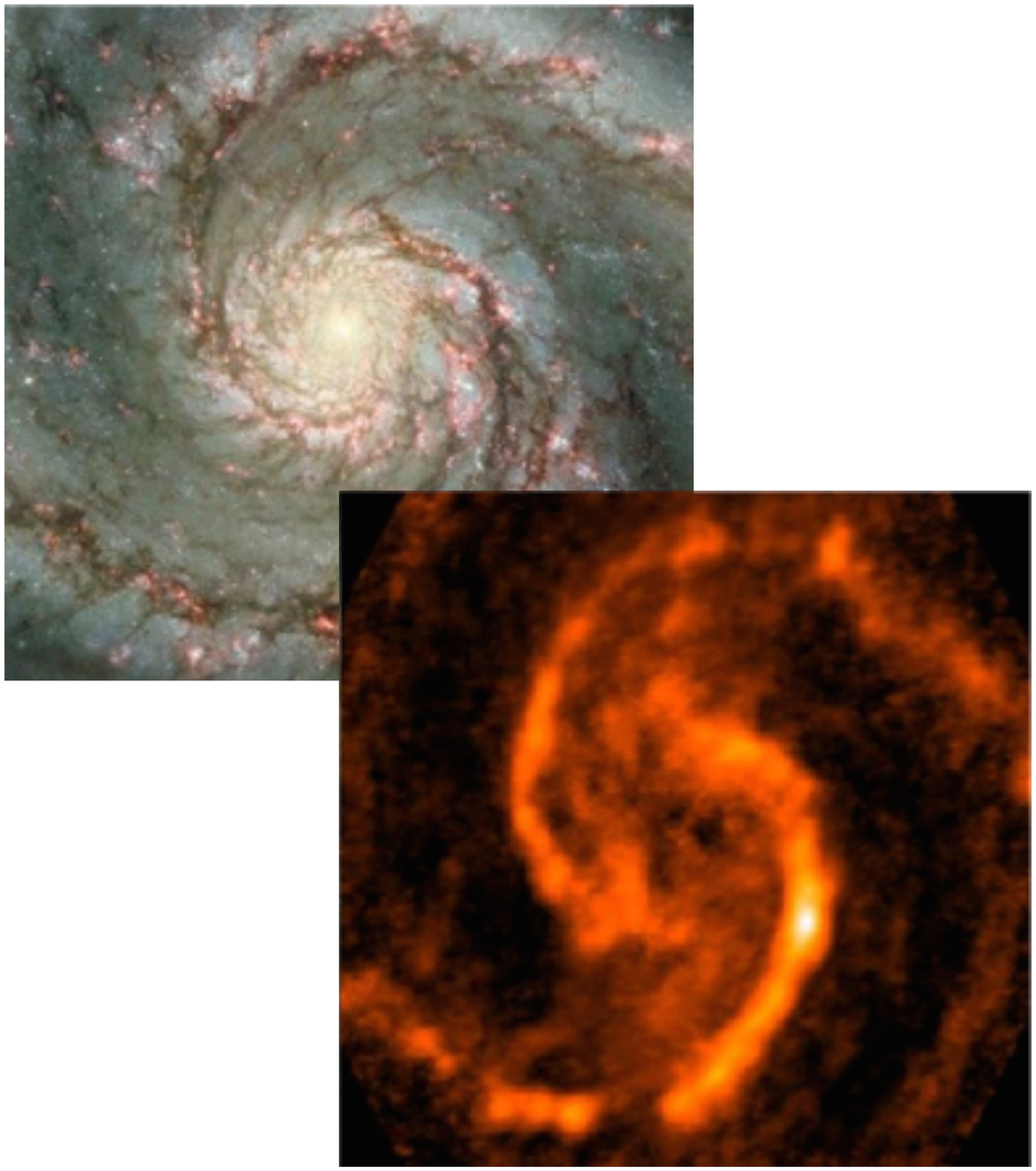

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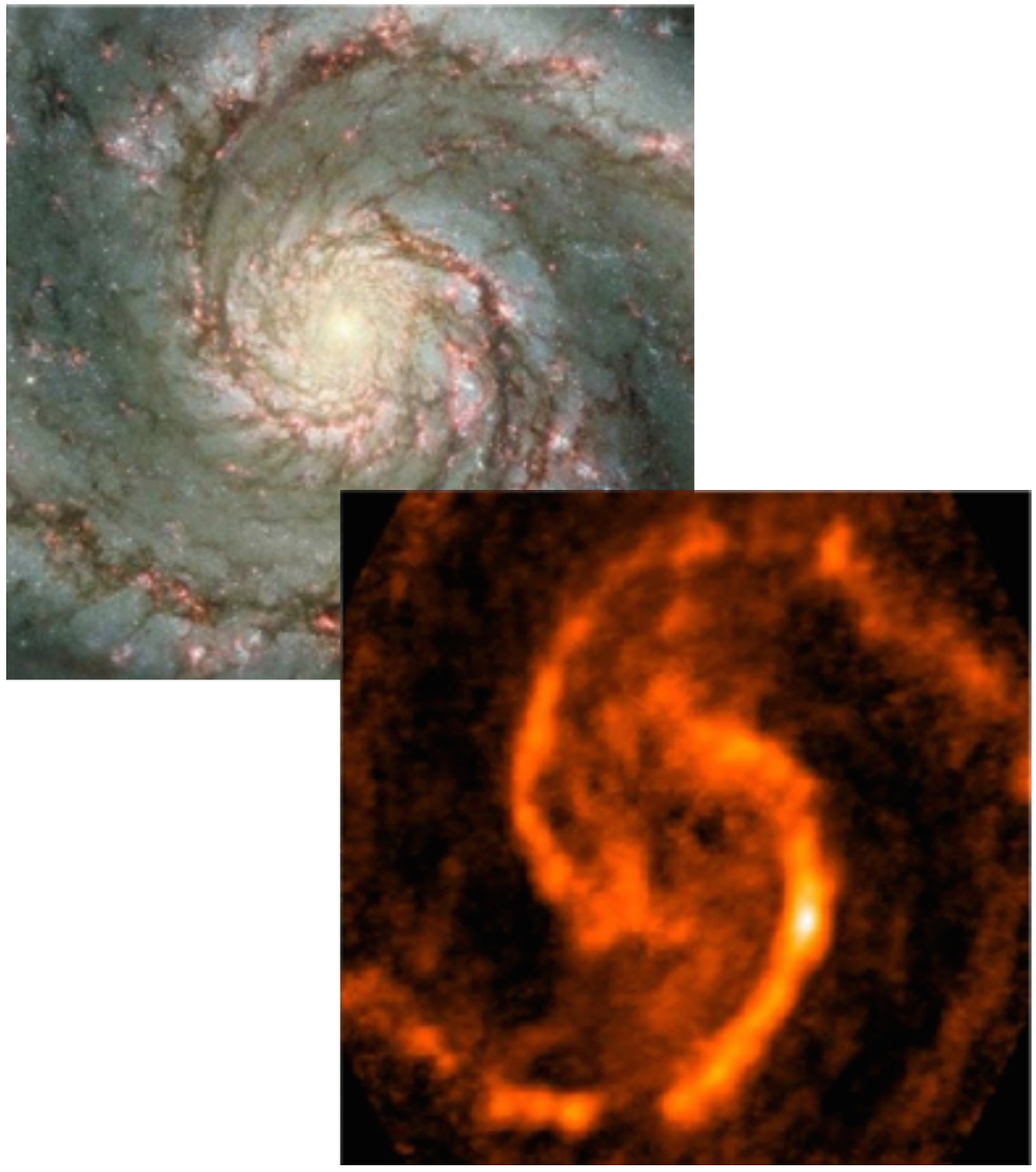
ok, let’s raise $\Omega \sim \sqrt{\frac{G\,M}{R^3}}$



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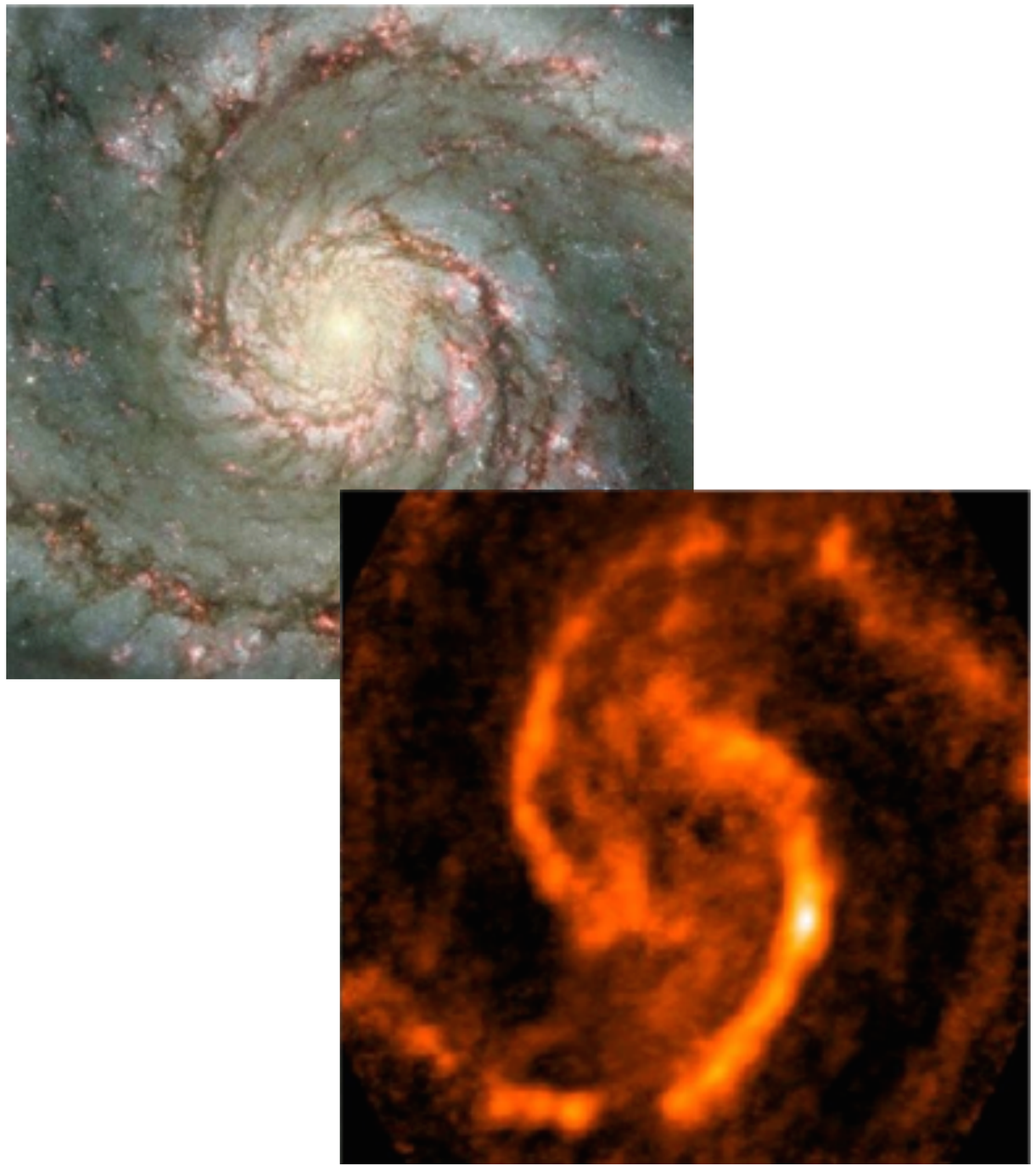

ok, let’s raise $\Omega \sim \sqrt{\frac{G\,M}{R^3}}$

$$M \gg 10^{13}\, M_\odot \; (R \sim 8\,\mathrm{kpc})$$

$$M \gg 10^{14}\, M_\odot \; (R \sim 1\,\mathrm{kpc})$$

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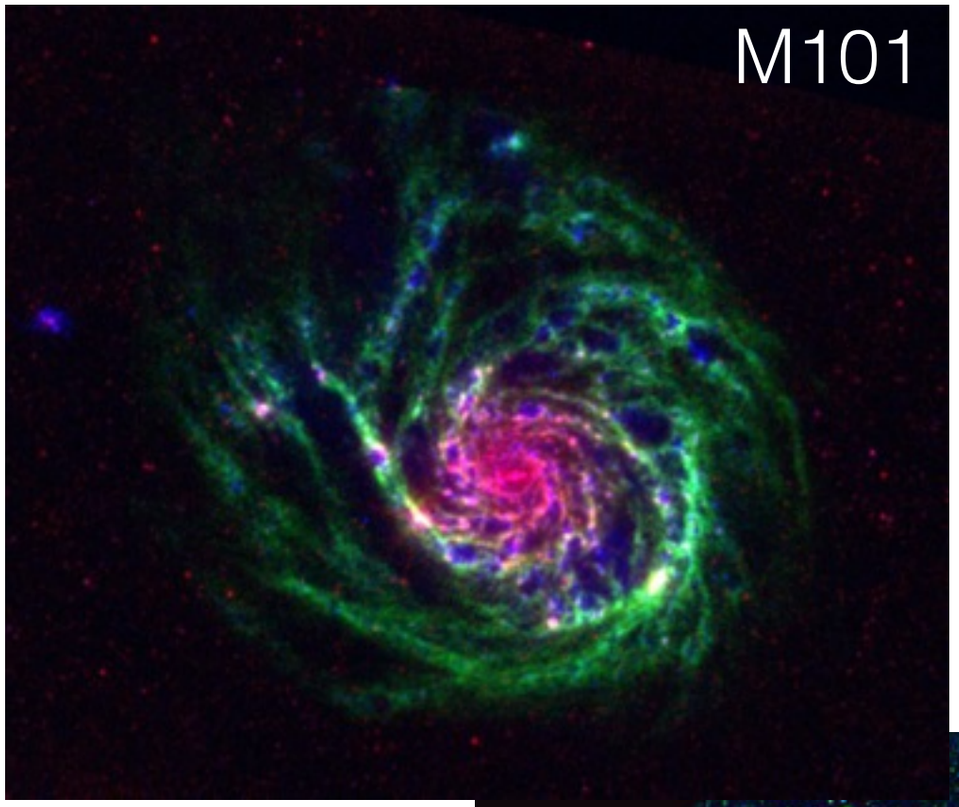

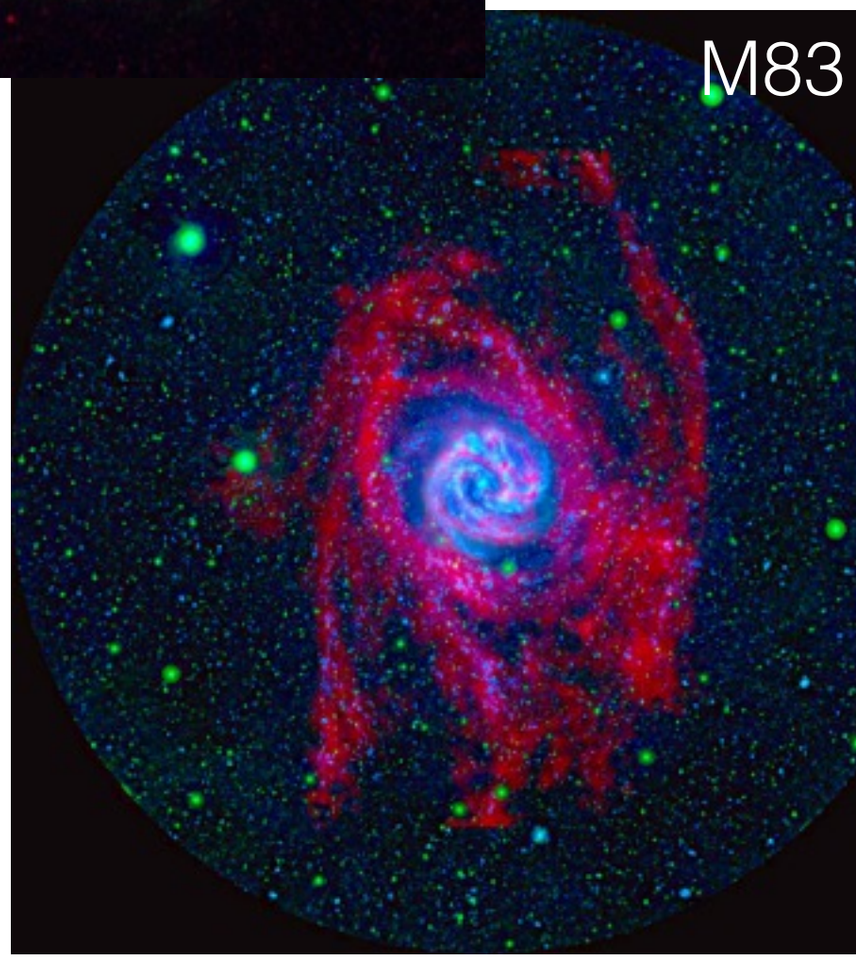

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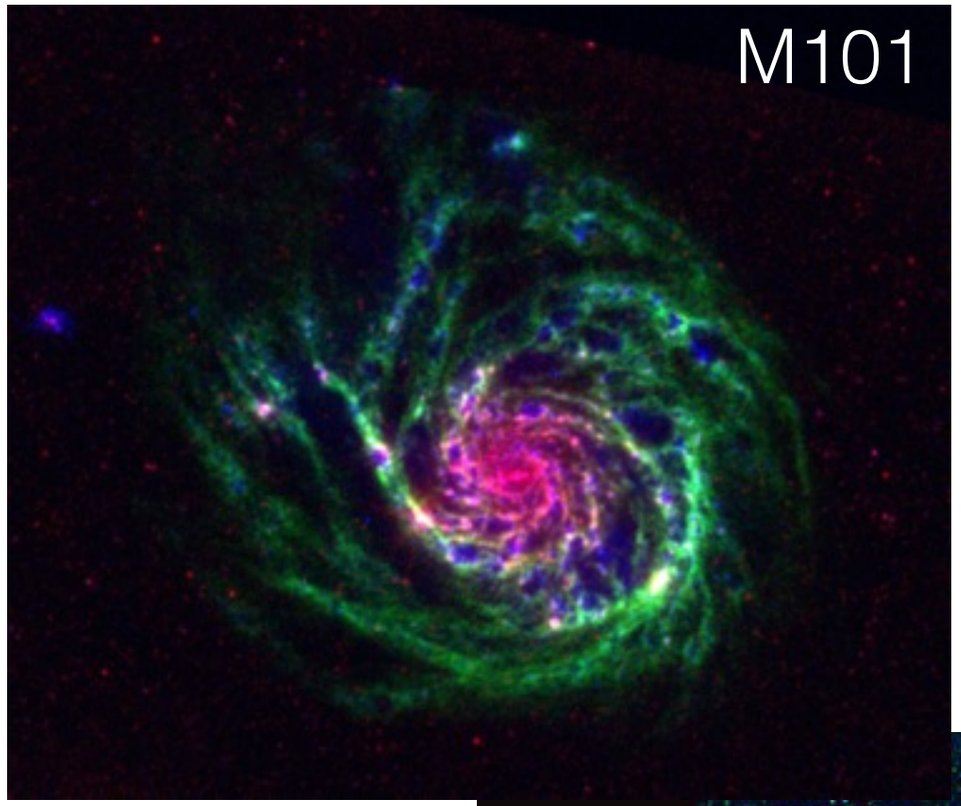

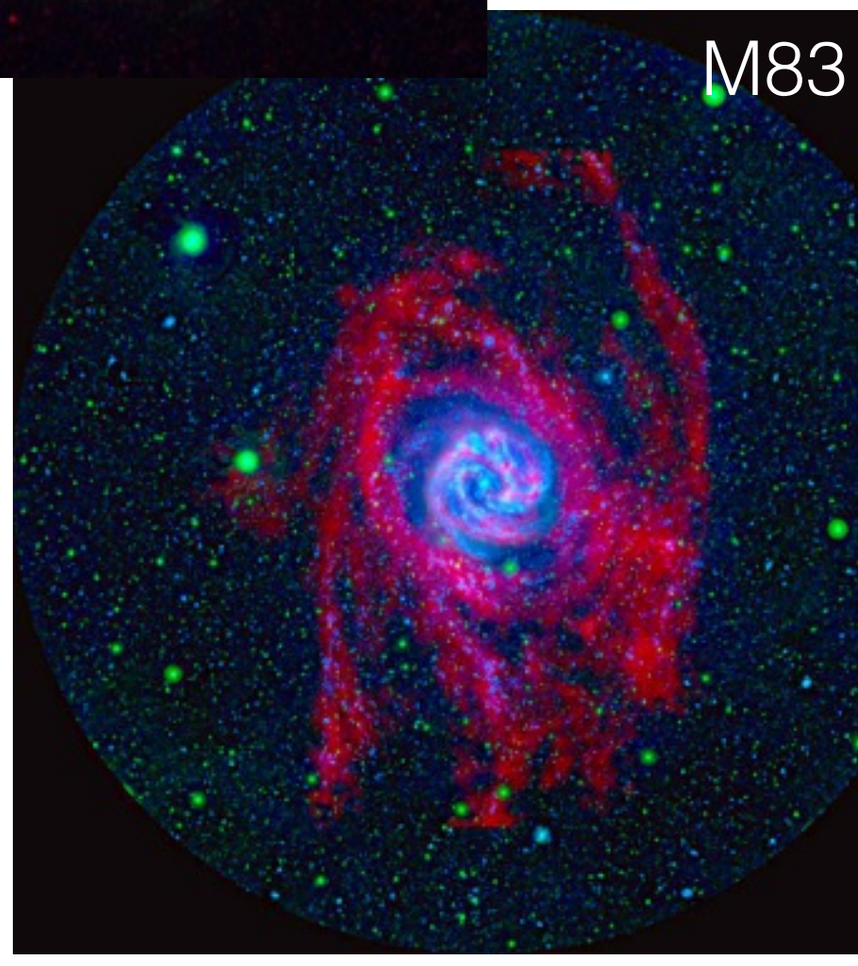

Can “Morphology” Do It?

Morphological/‘Toomre’/Dynamical Quenching (Martig, Dekel,+)

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$$\begin{matrix} \text{Gas Depletion} \\ + \\ \text{Suppressed Cooling} \end{matrix} = \text{Quenching}$$

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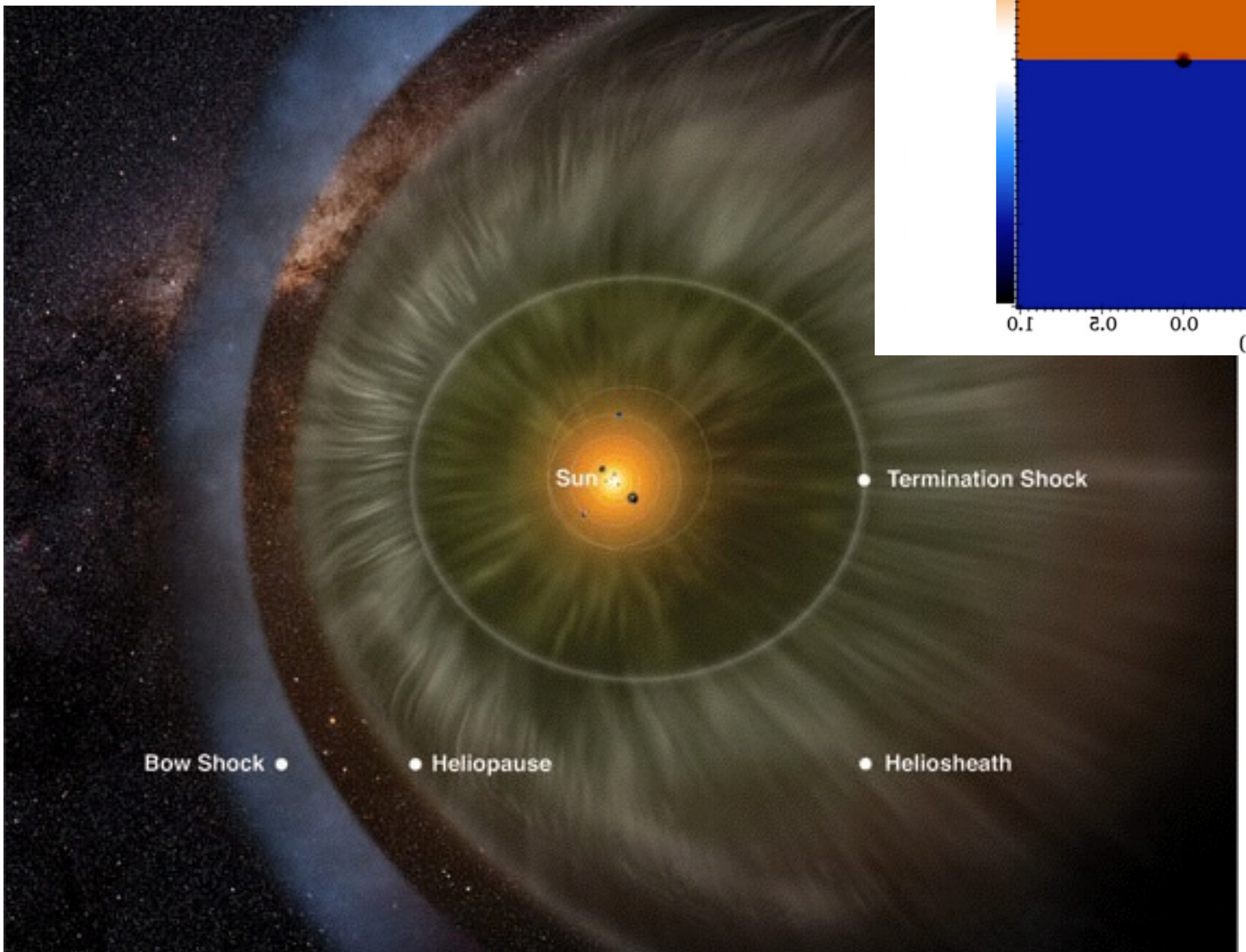

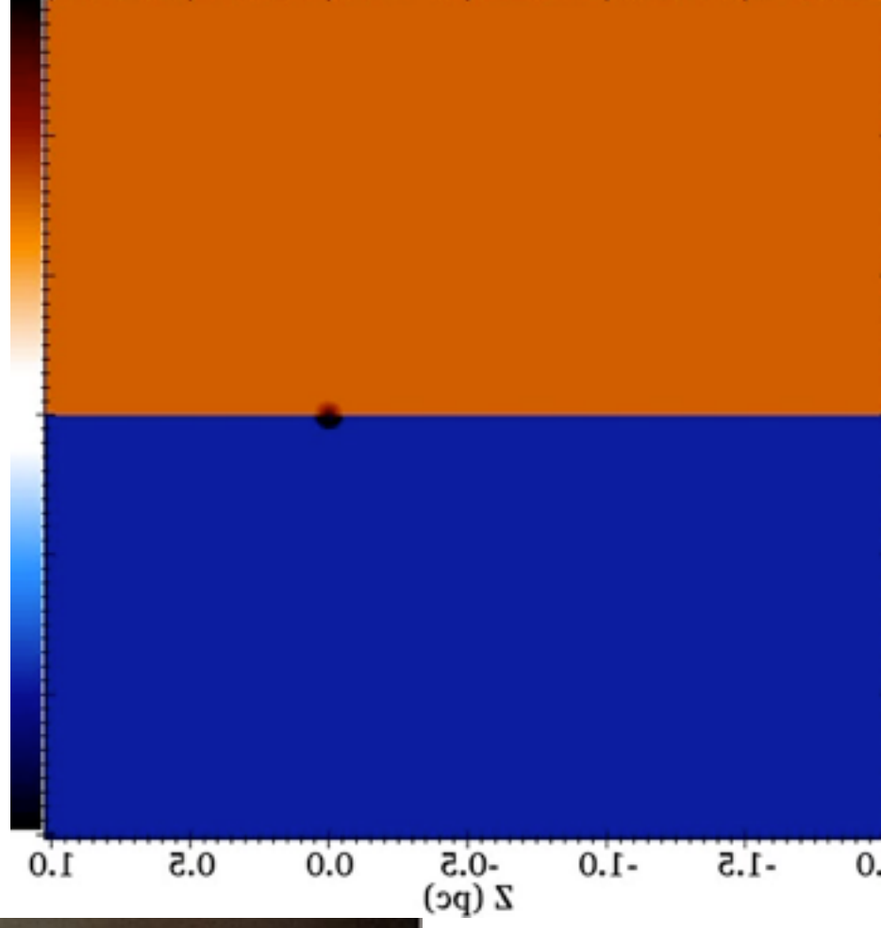

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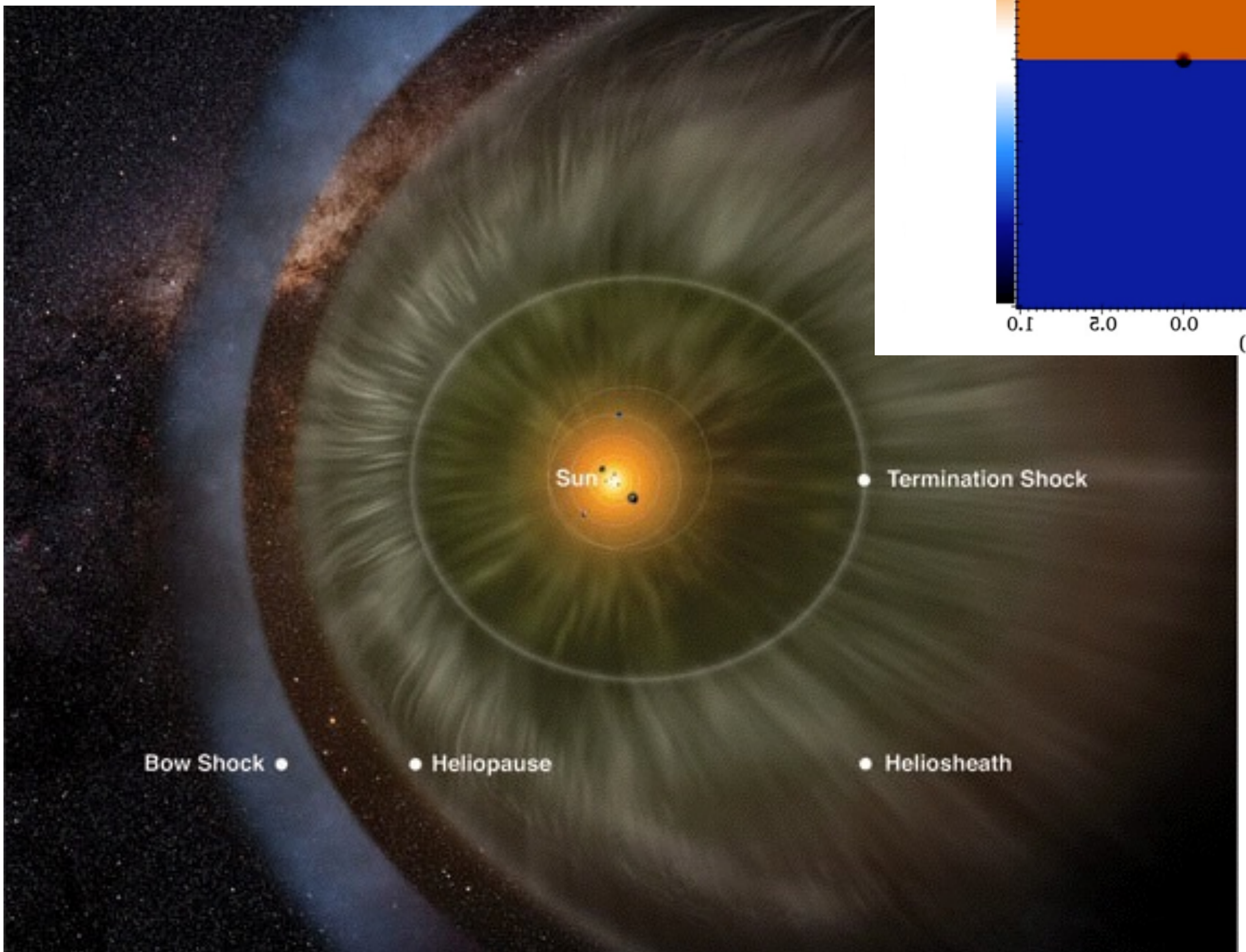

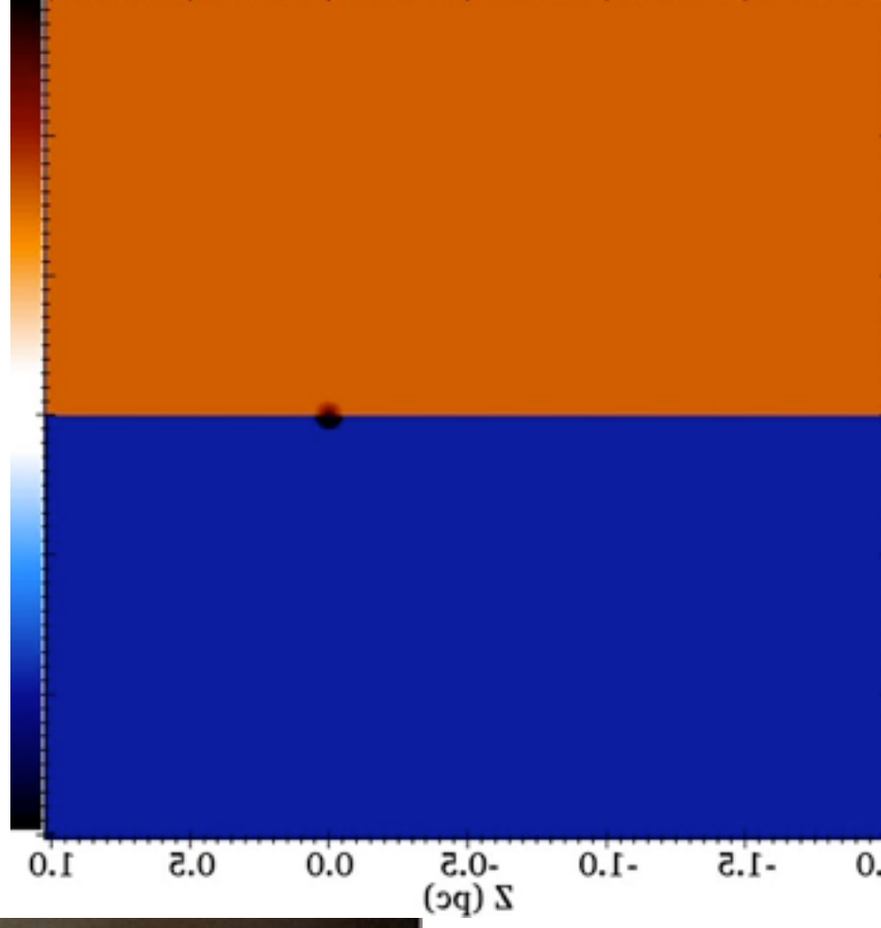

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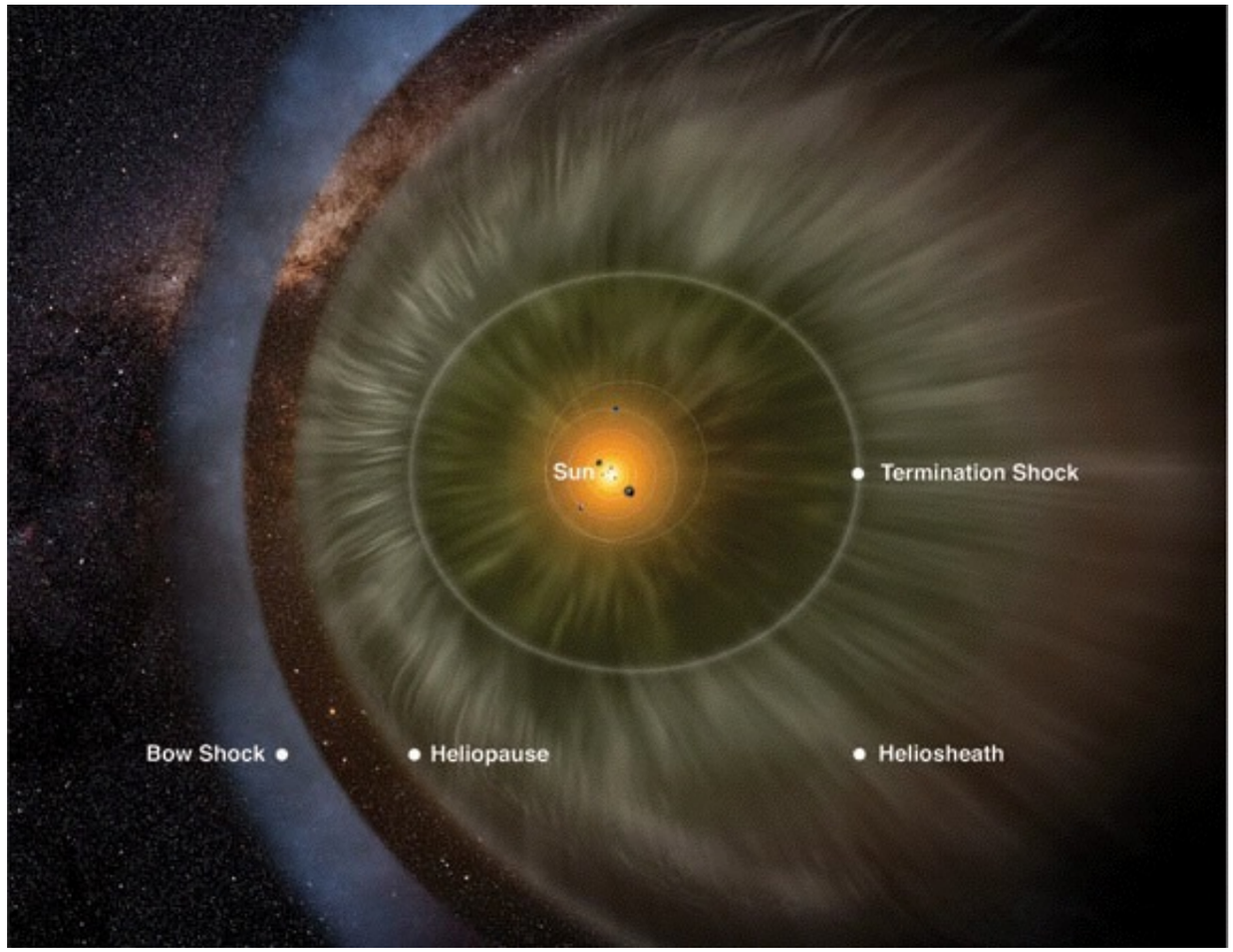

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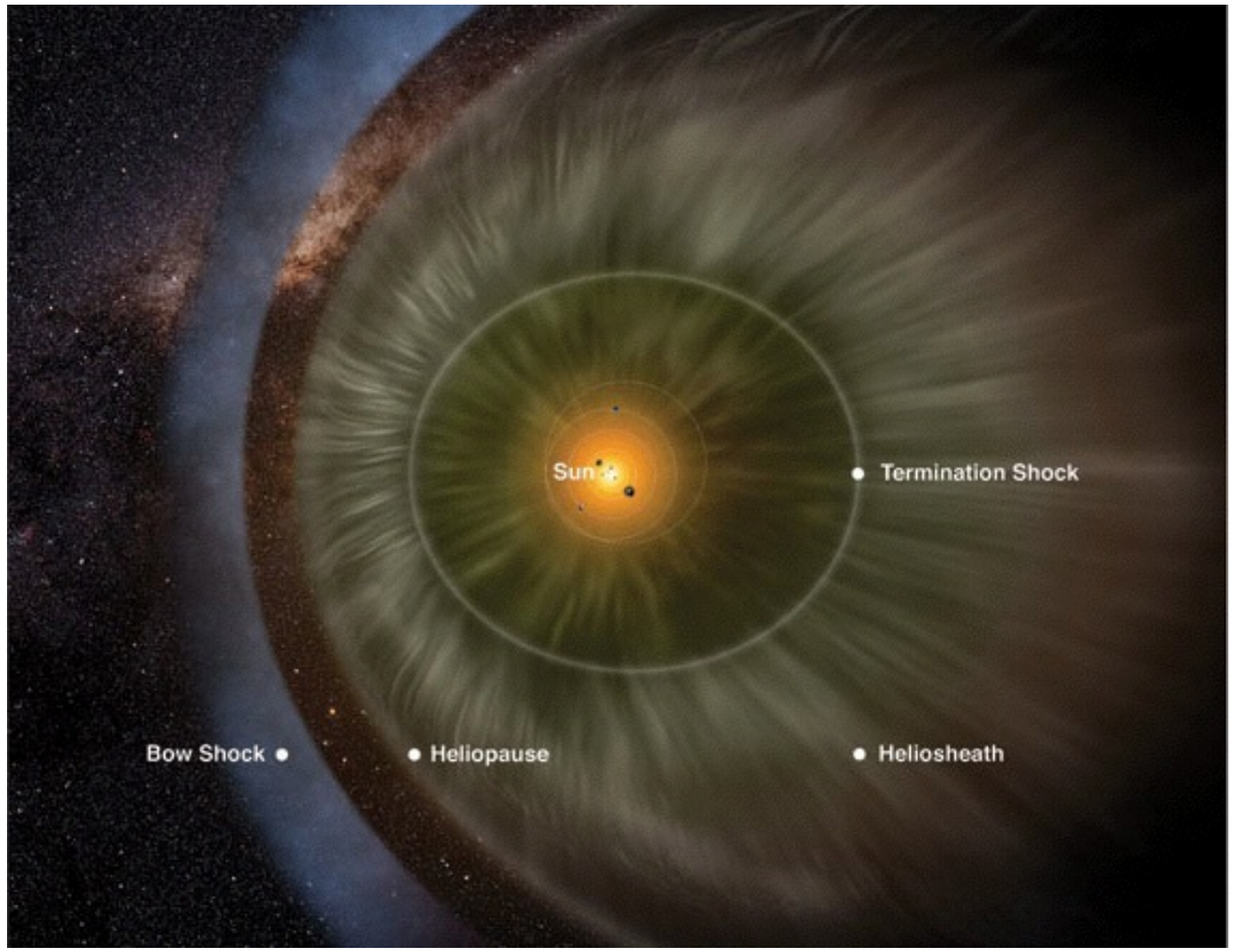

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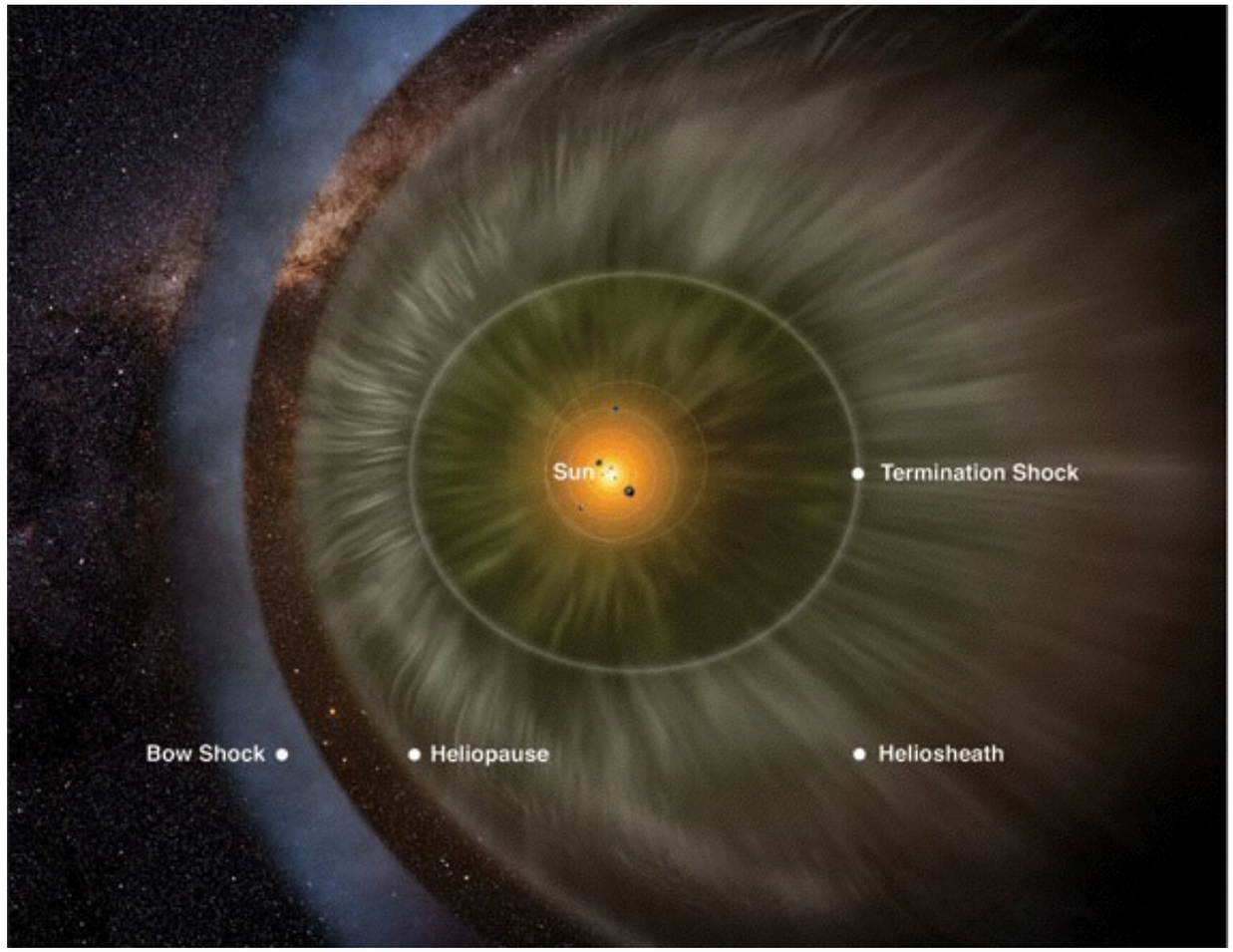

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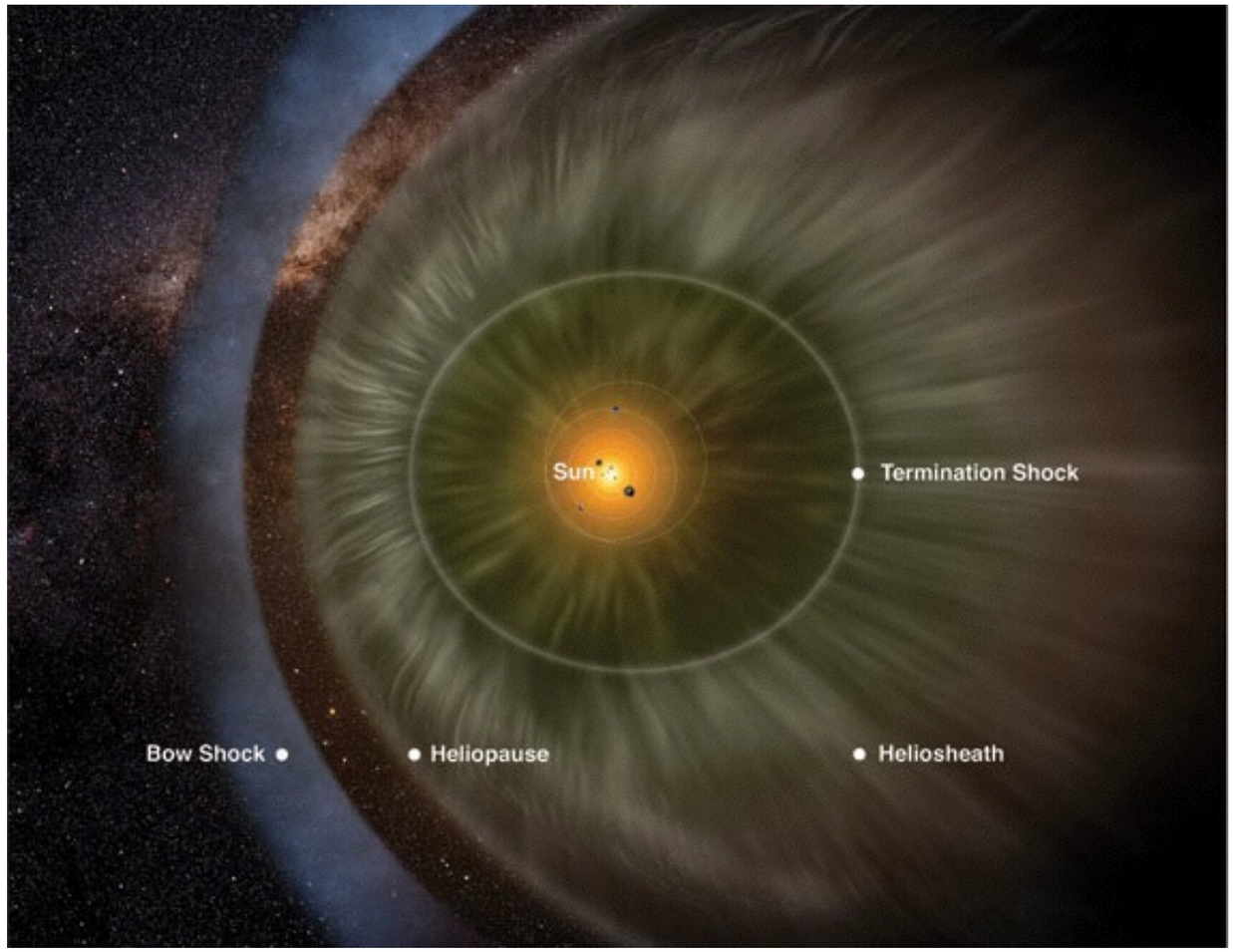

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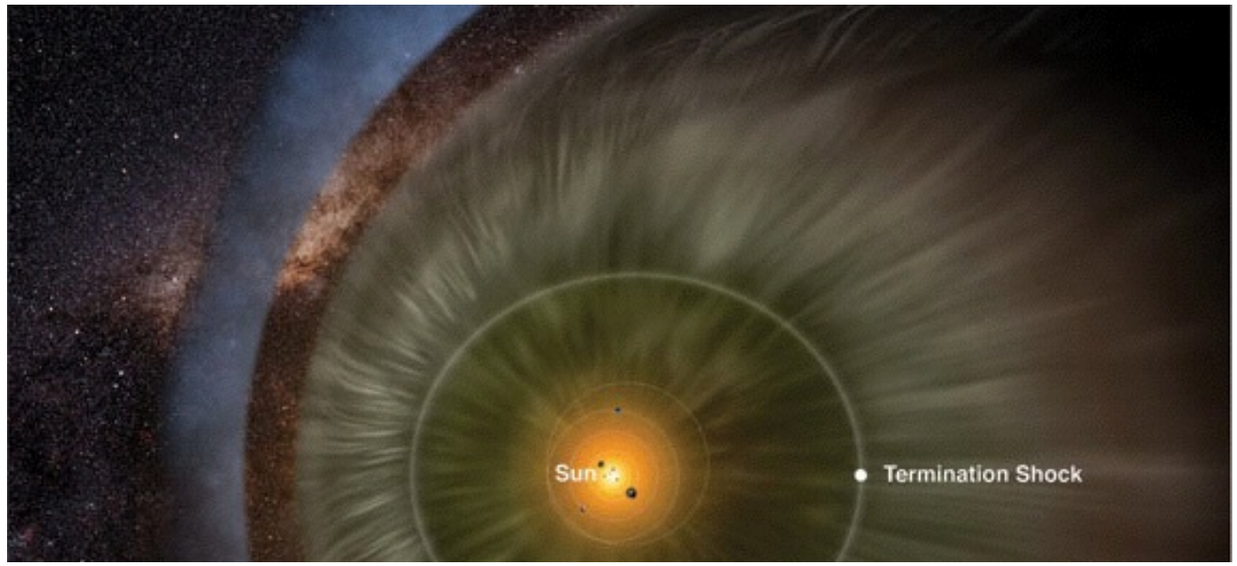
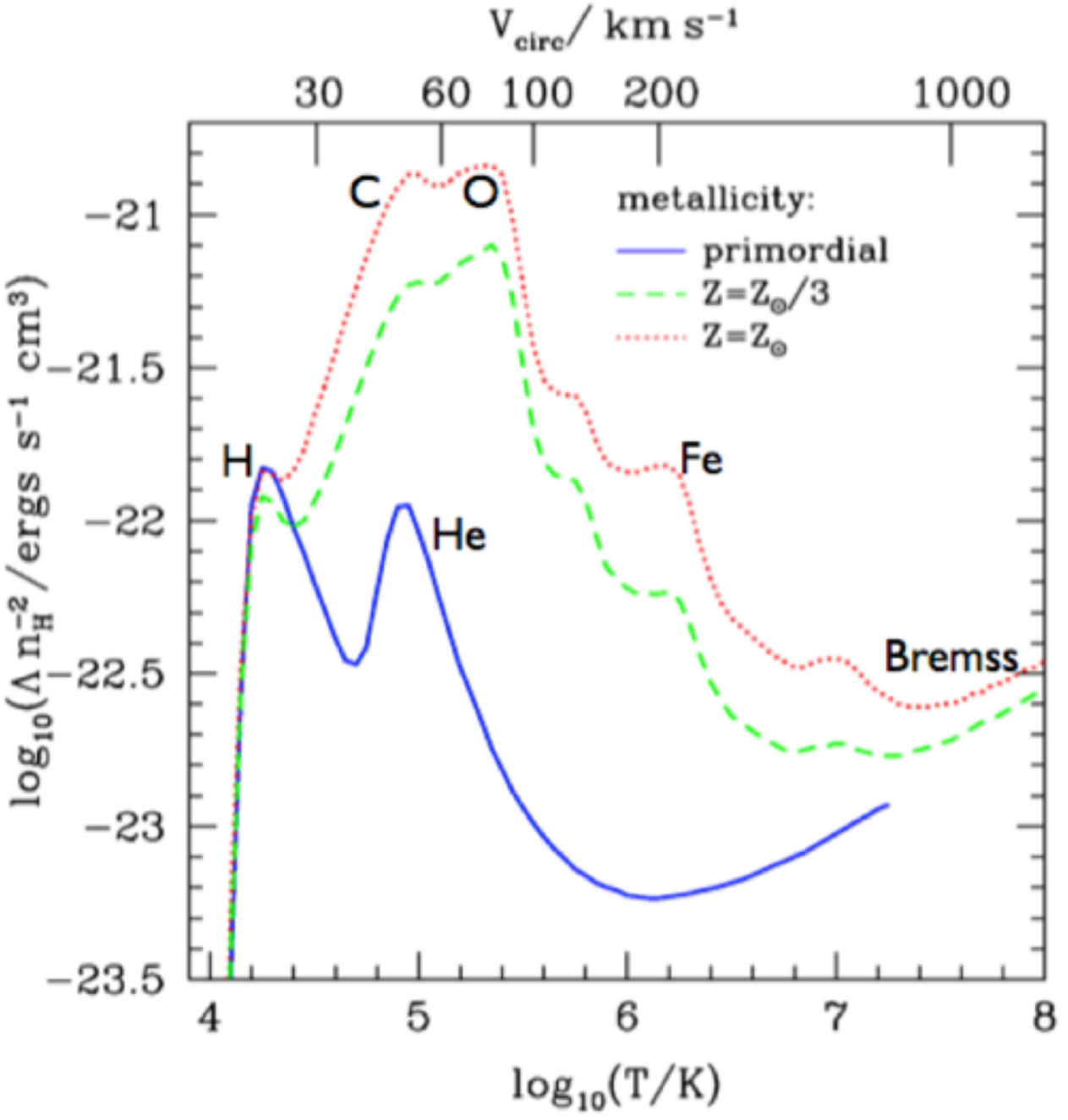
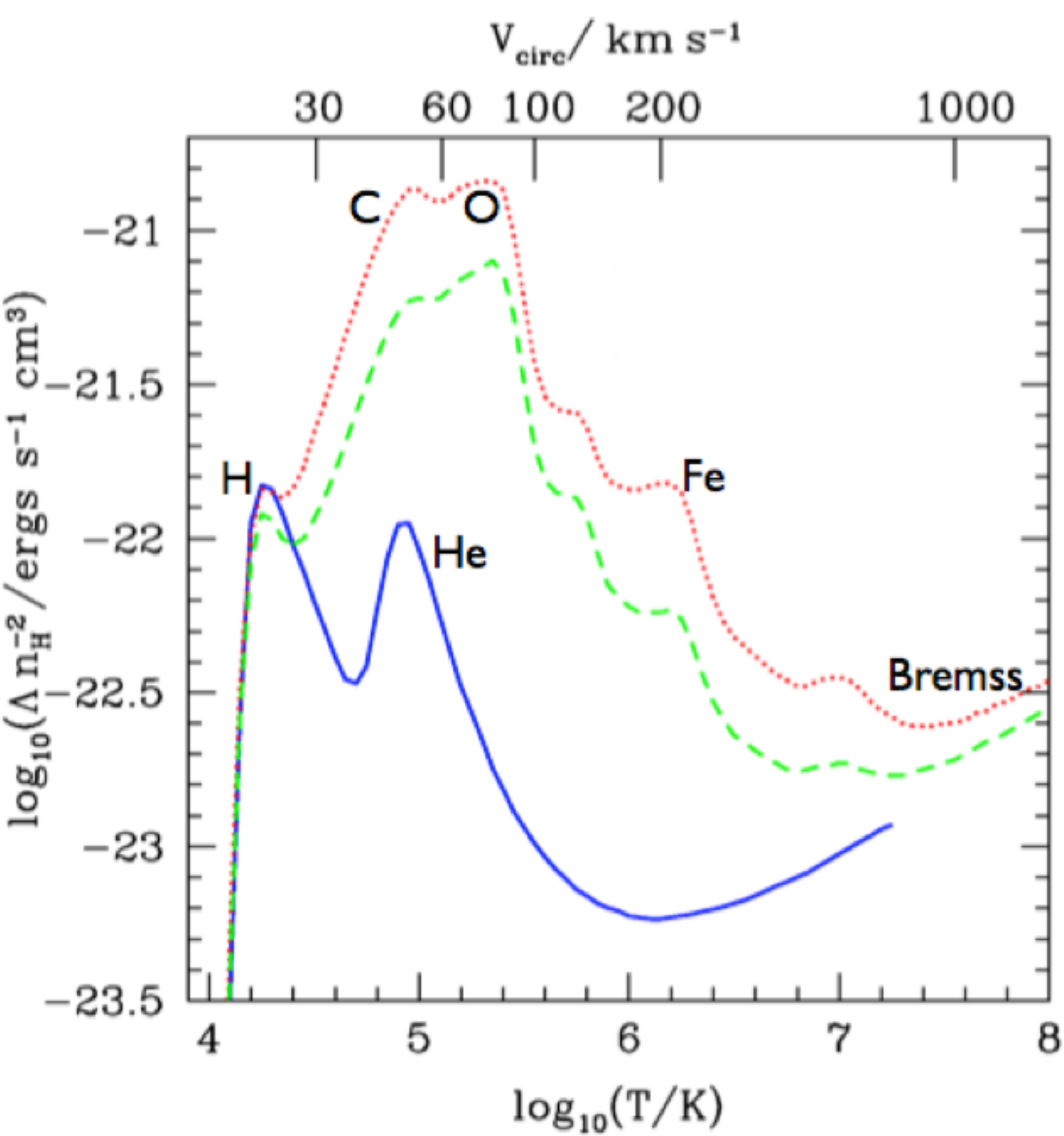
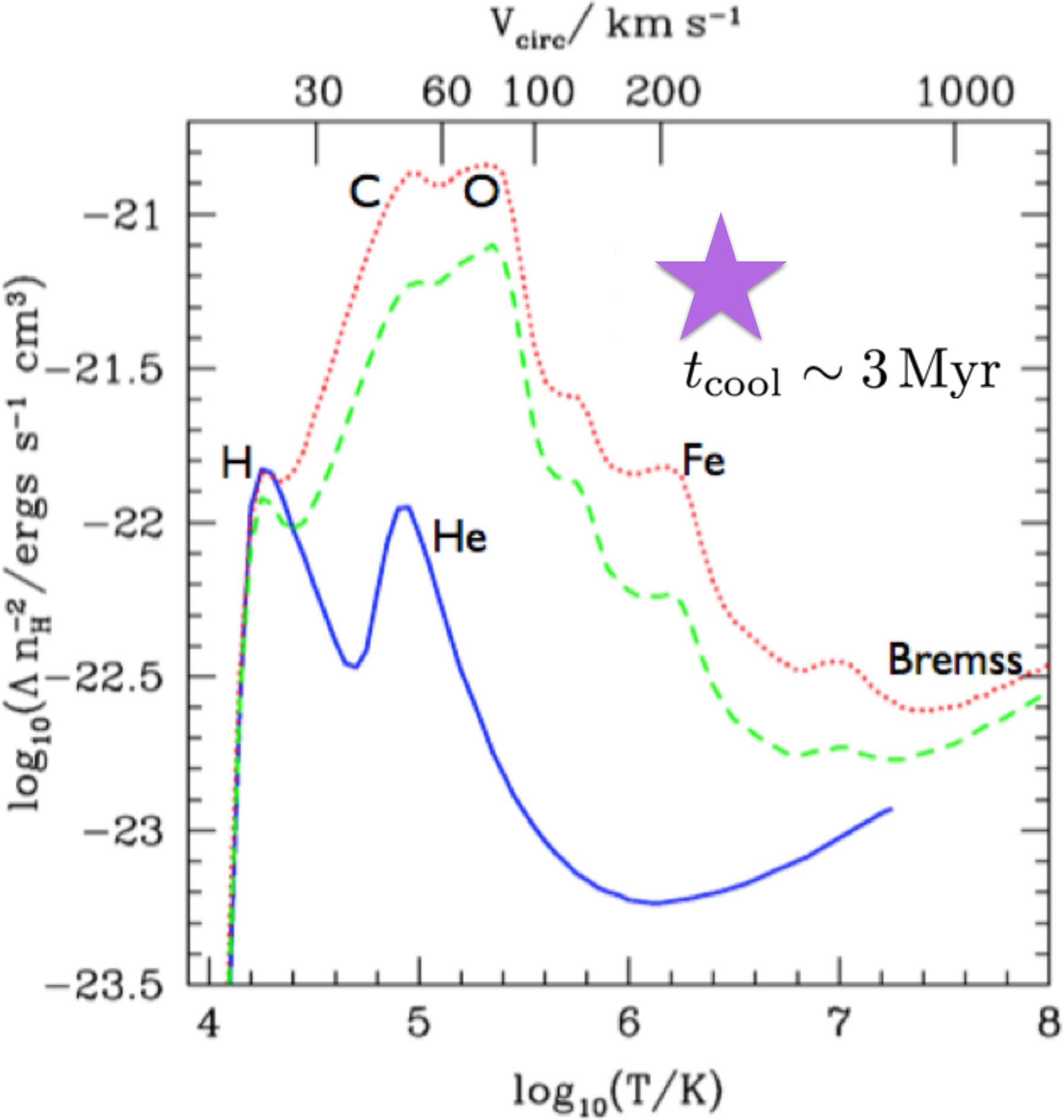





V_circ / km s^-1
30
60
100
200
1000
C
O
Fe
H
He
Bremss
−21
−21.5
−22
−22.5
−23
−23.5
log10(Λ nH^-2 / ergs s^-1 cm^3)
4
5
6
7
8
log10(T/K)


V_{circ}/ km s^{-1}
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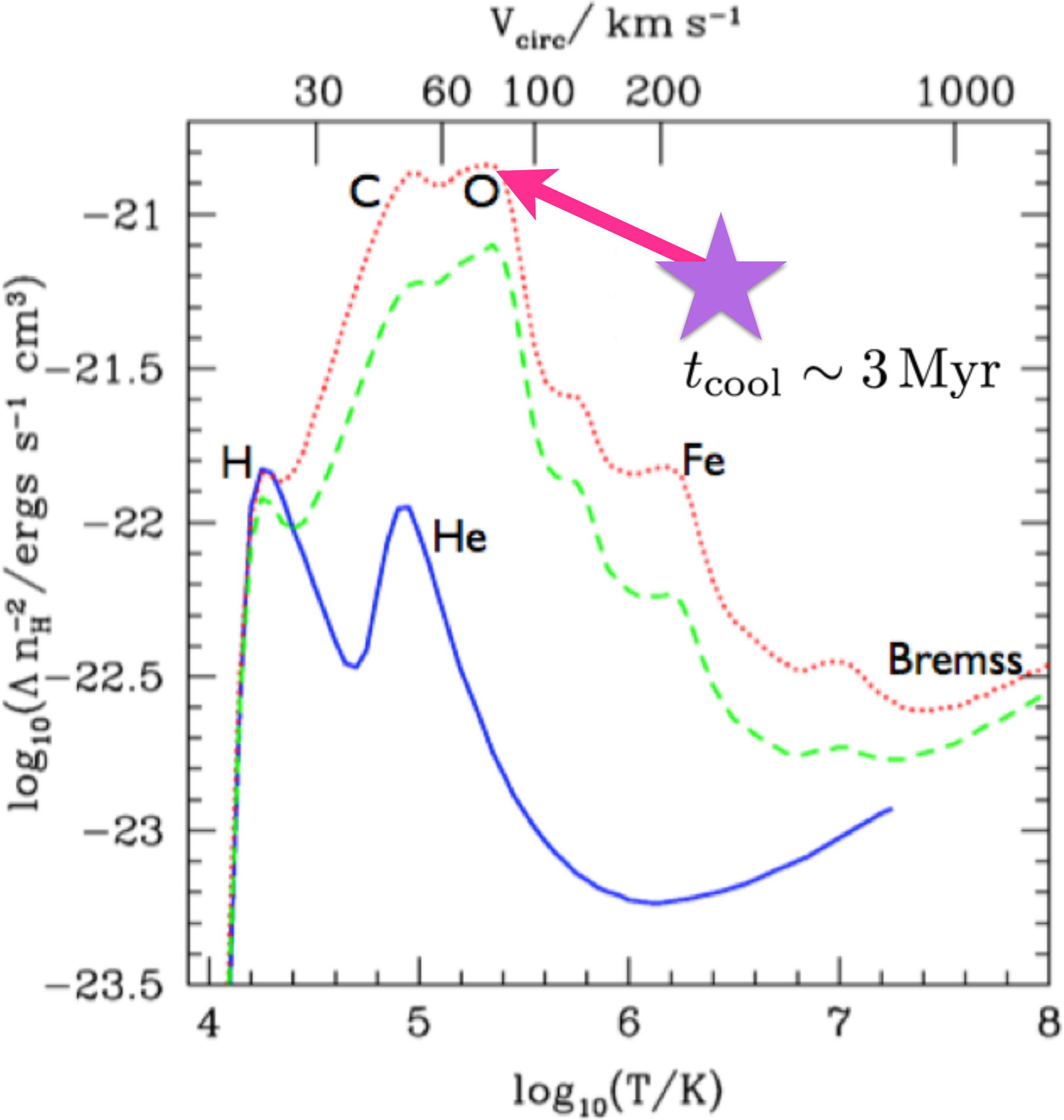
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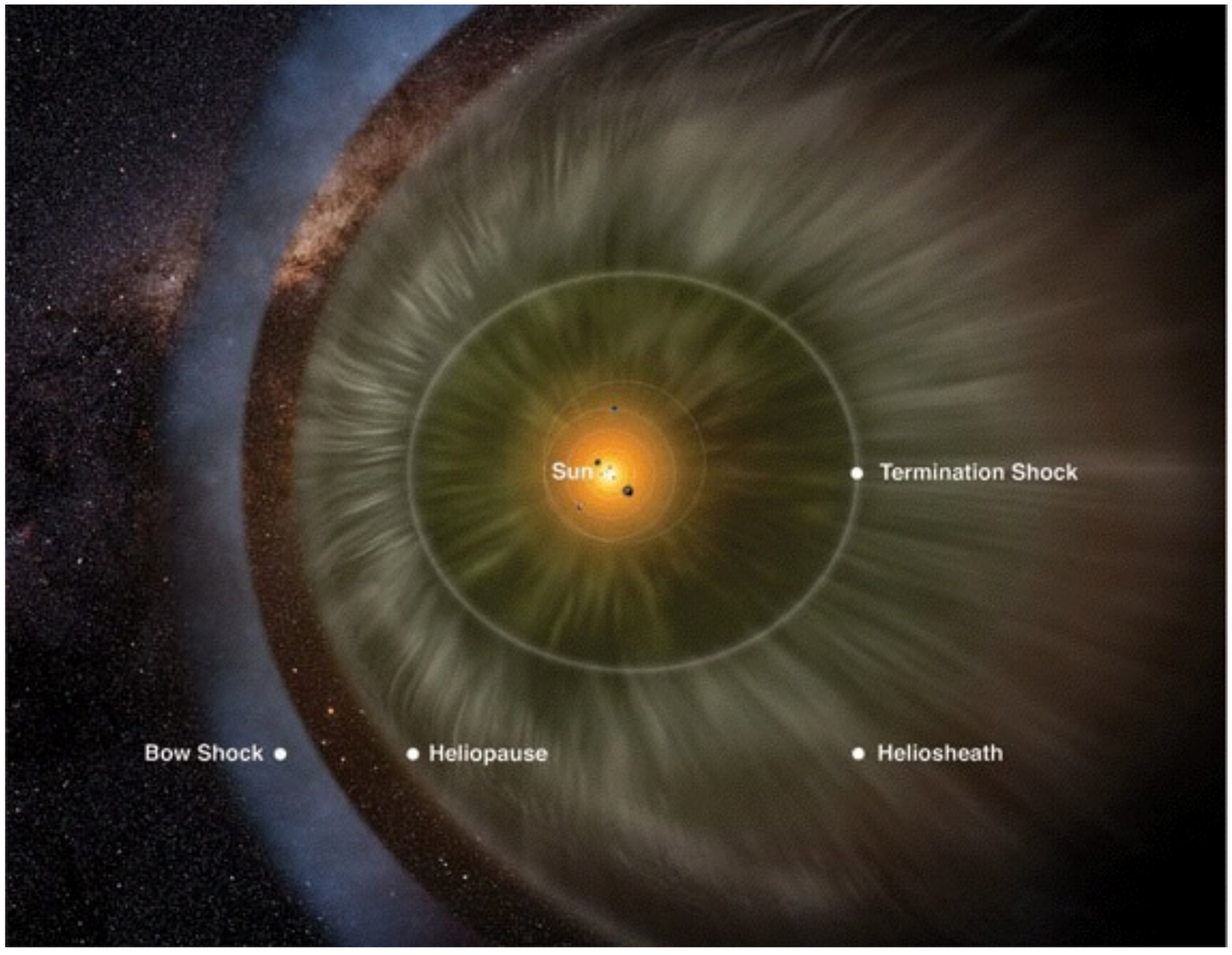

NO

Can Gravitational Heating Do It?

IMPORTANT, BUT … **NO**

Virial shock-heating, stirring by clumps/substructure keeps 90% of gas hot

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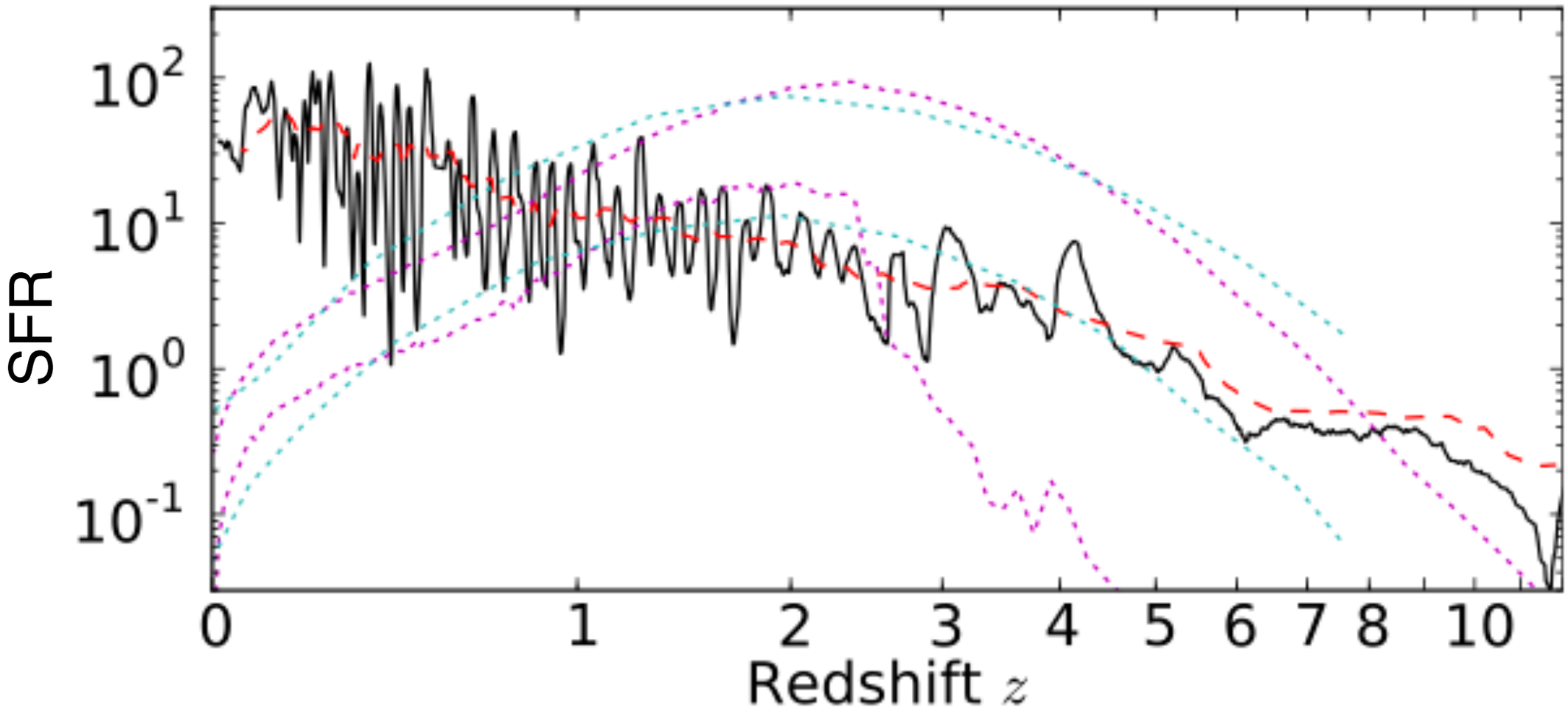

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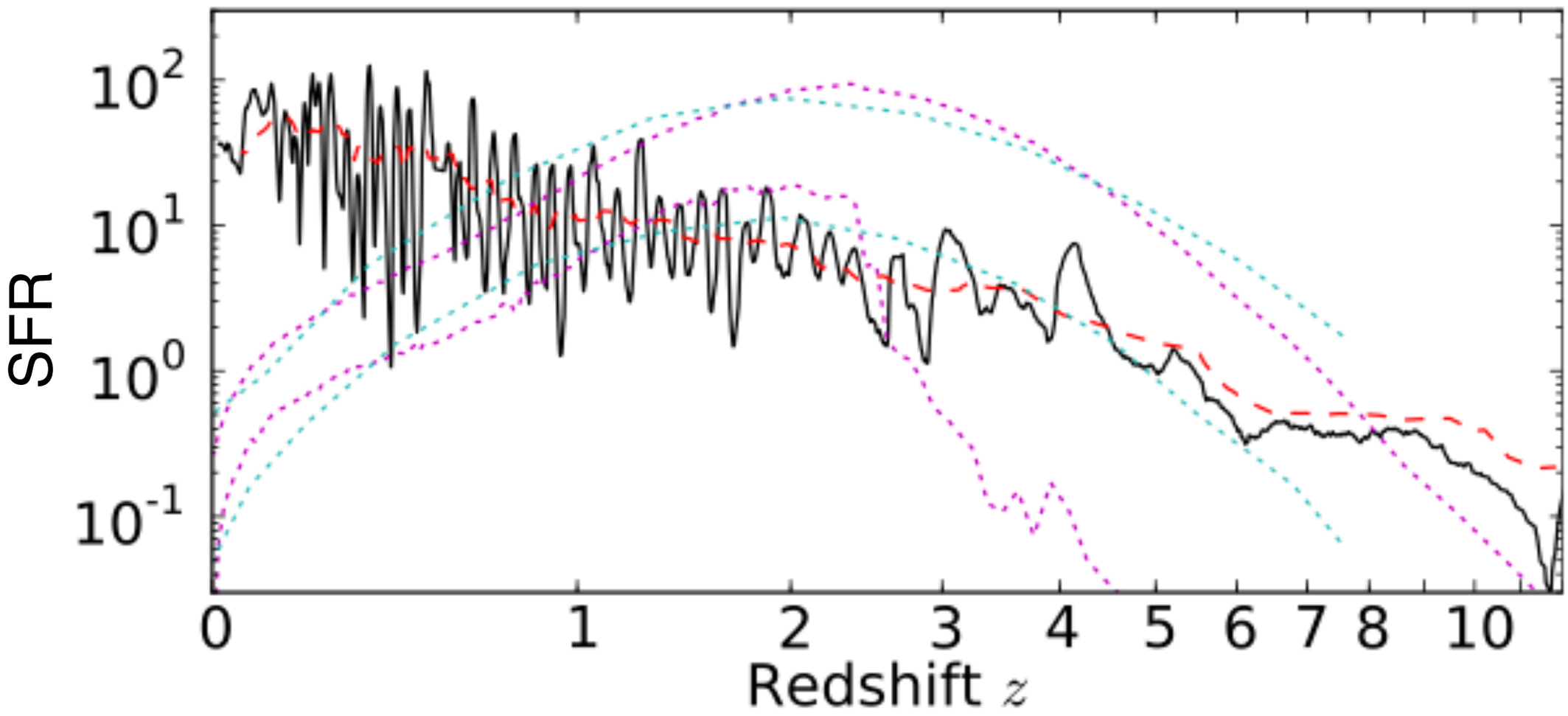
$\dot{M}_{\rm baryons}({\rm halo})$



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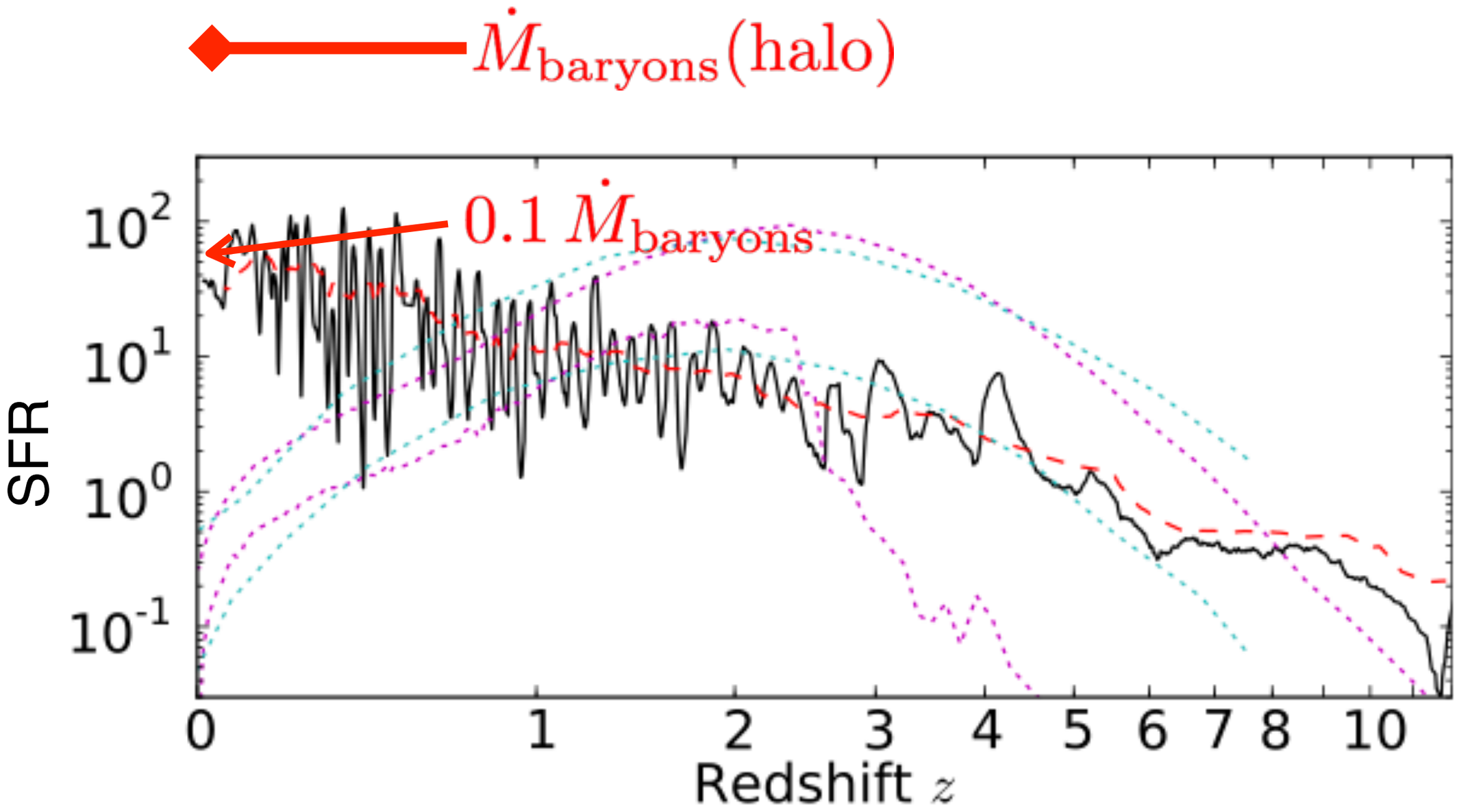

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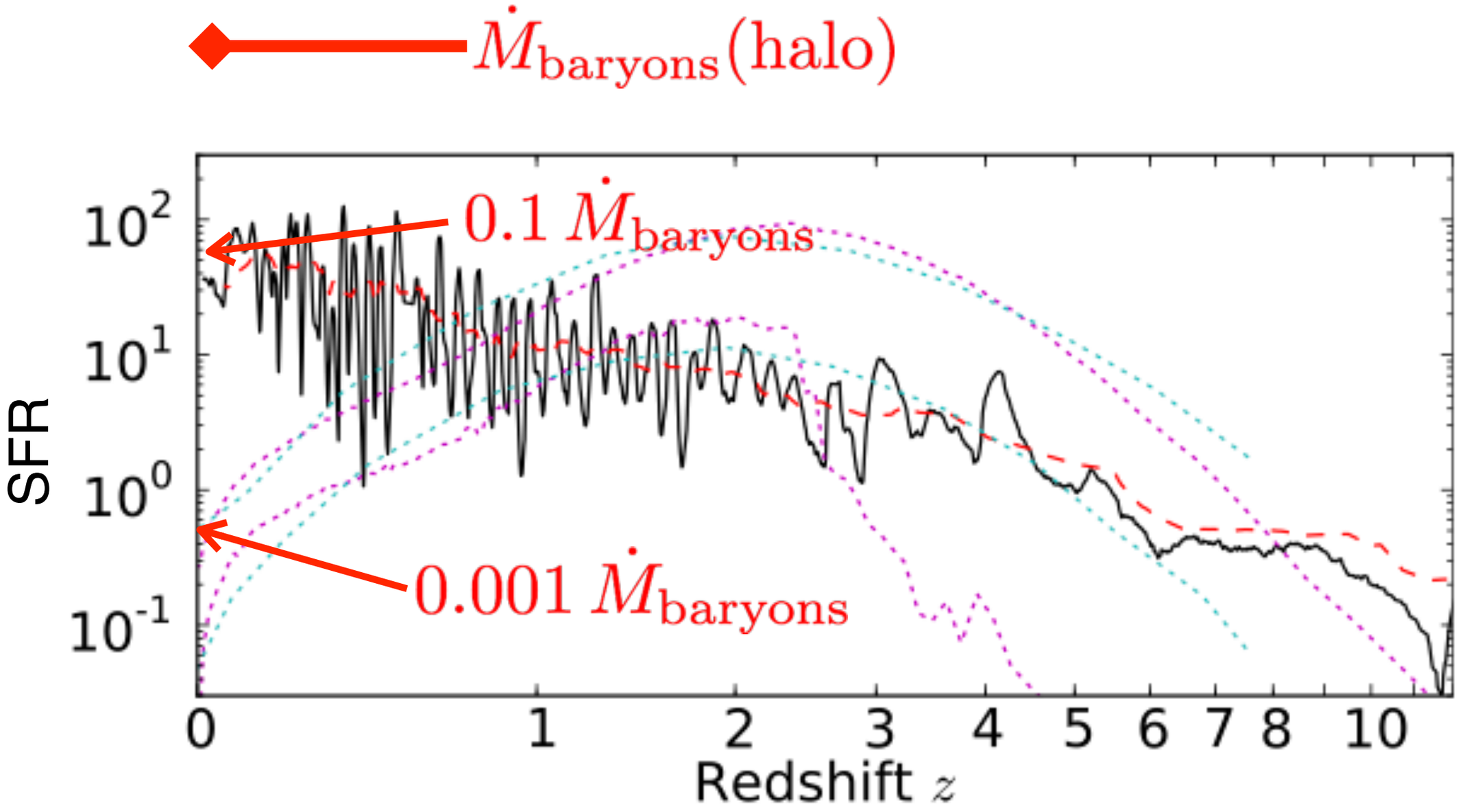

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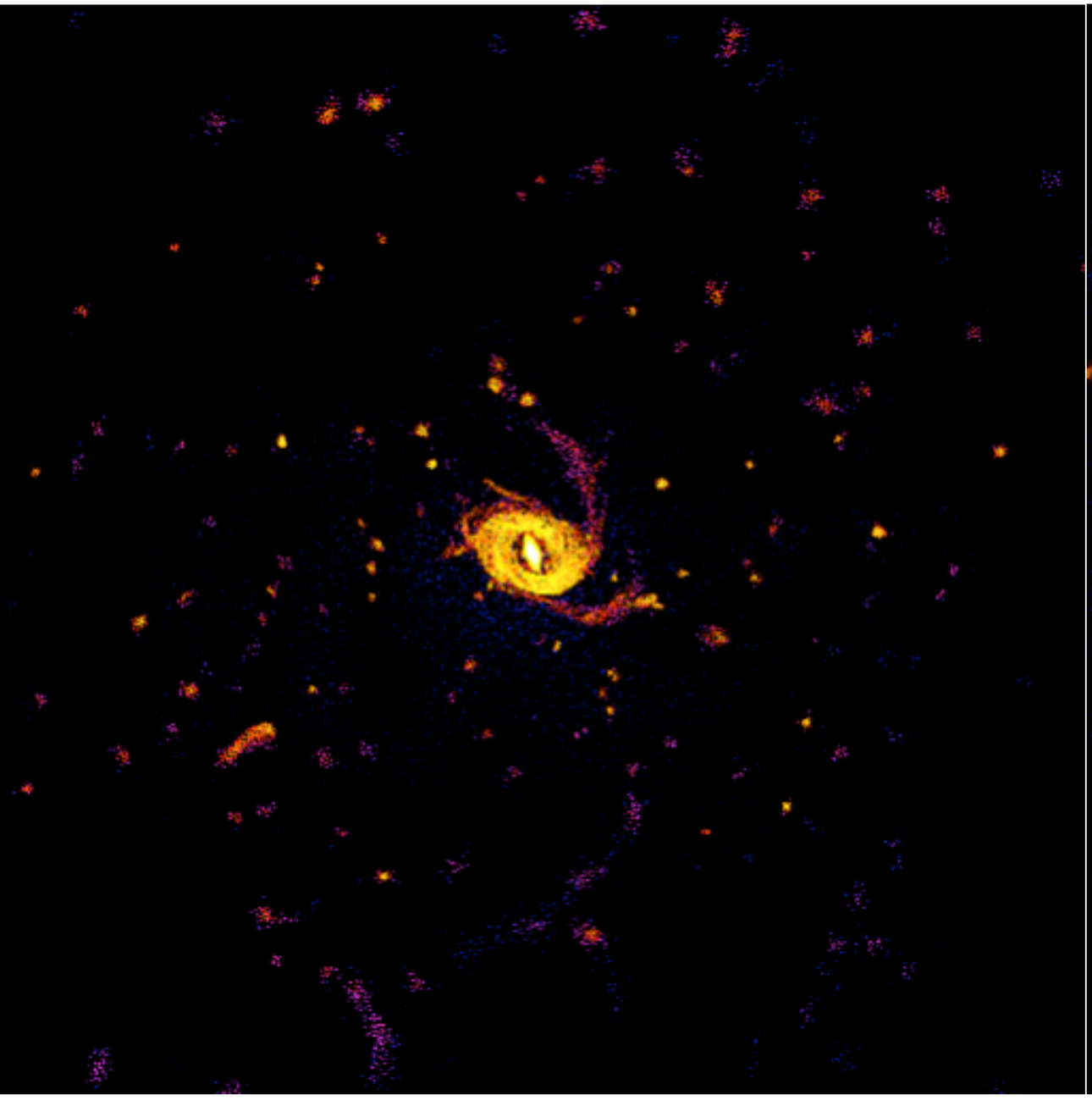
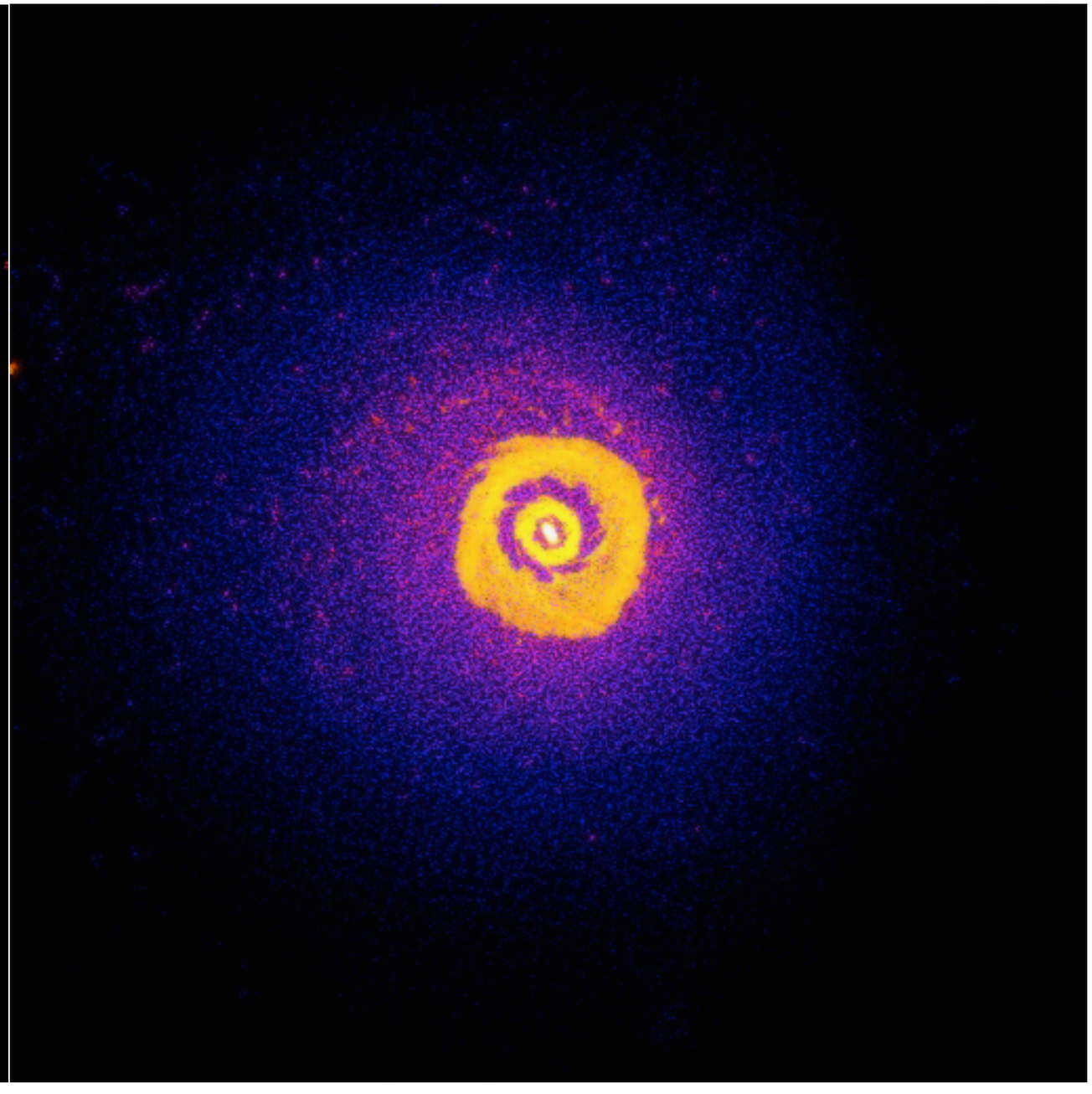
Gravitational Heating

NOT AS MANY CLUMPS THESE DAYS!

Keres et al., in prep



Density Formulation
("Old" GADGET)

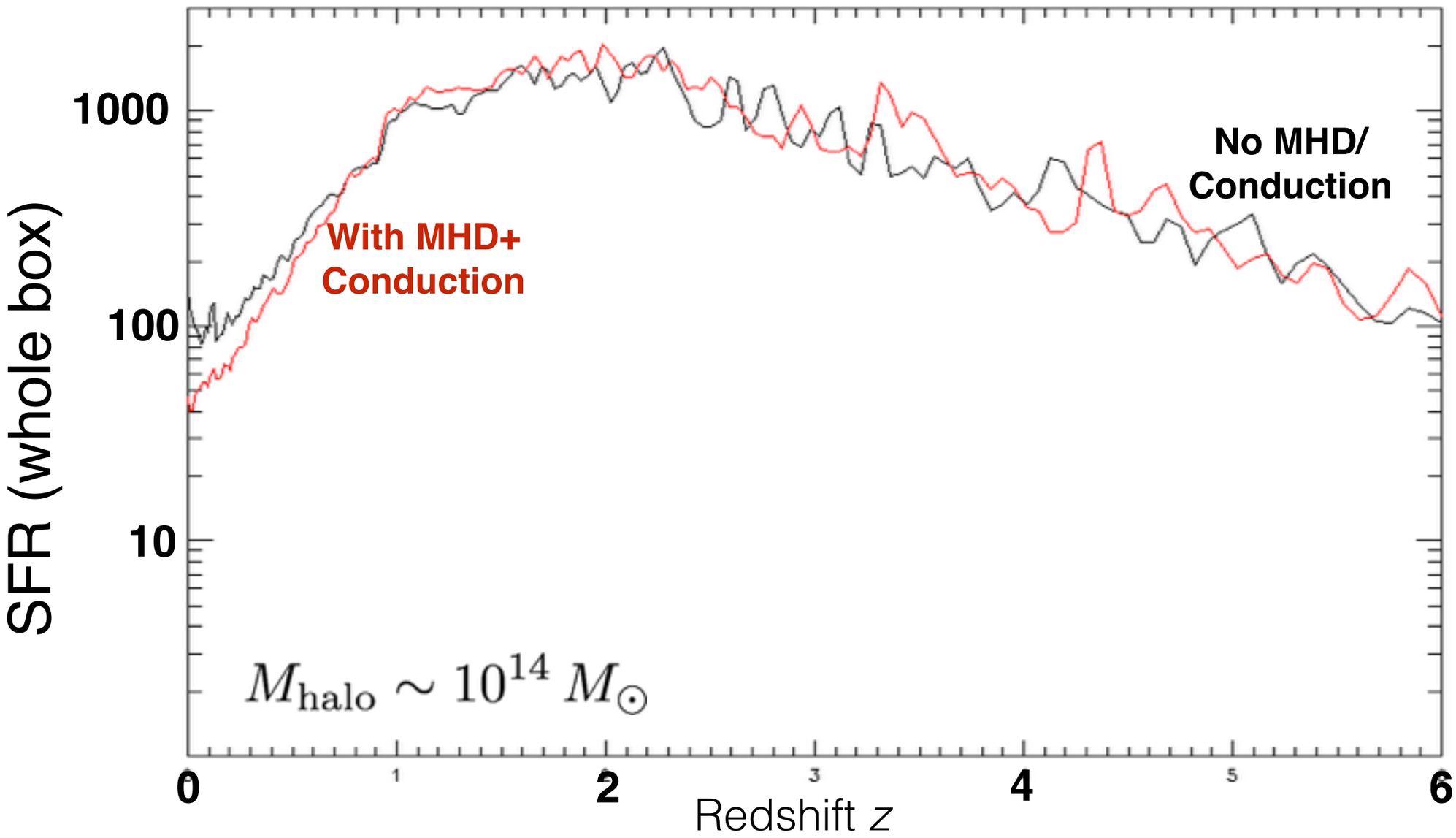


Pressure-Entropy Formulation
(P-GADGET)

Not enough clumps, & existing ones are too metal-rich (join the cooling flow)

Can MHD & Conduction Do It?

NO



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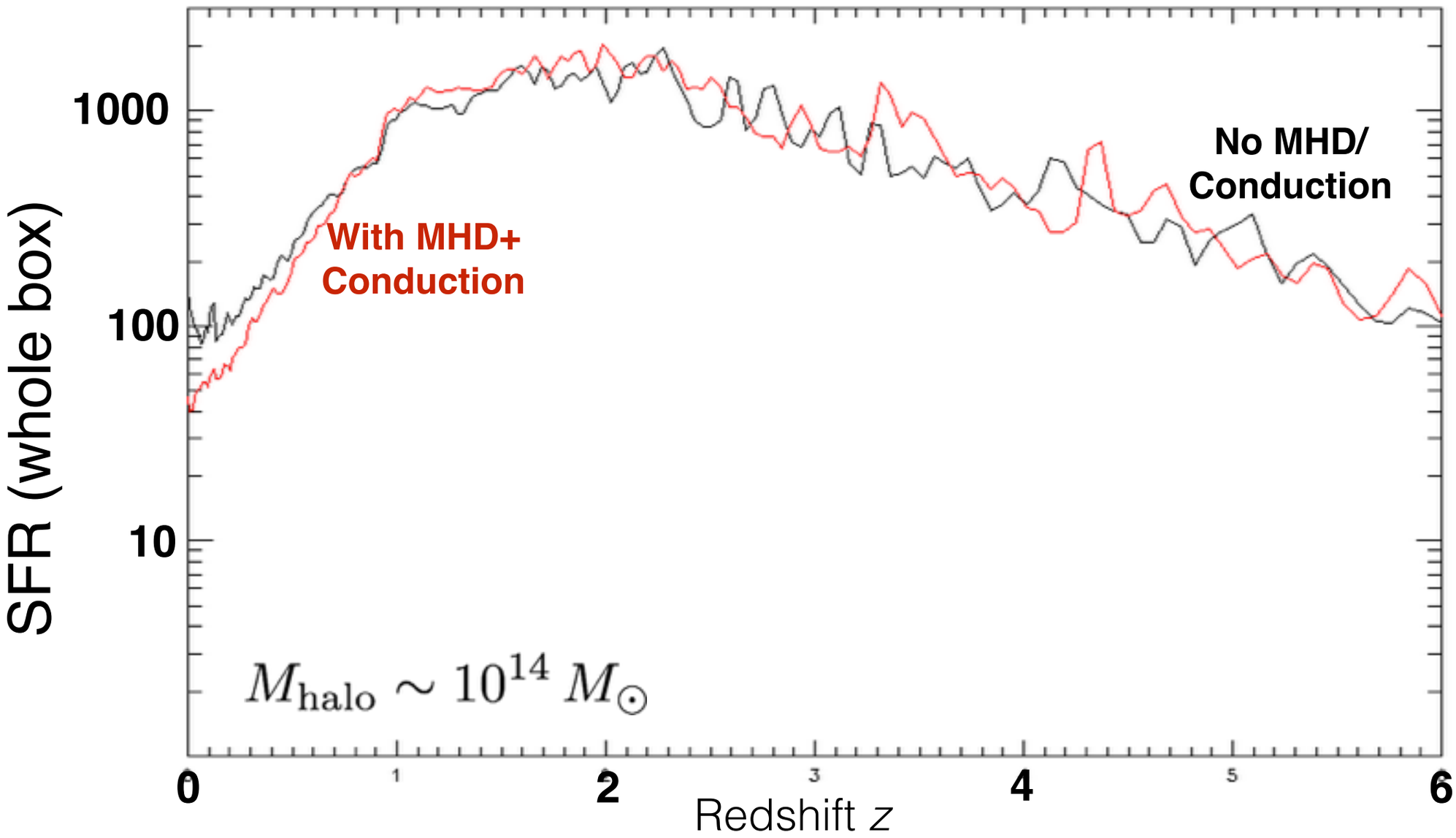
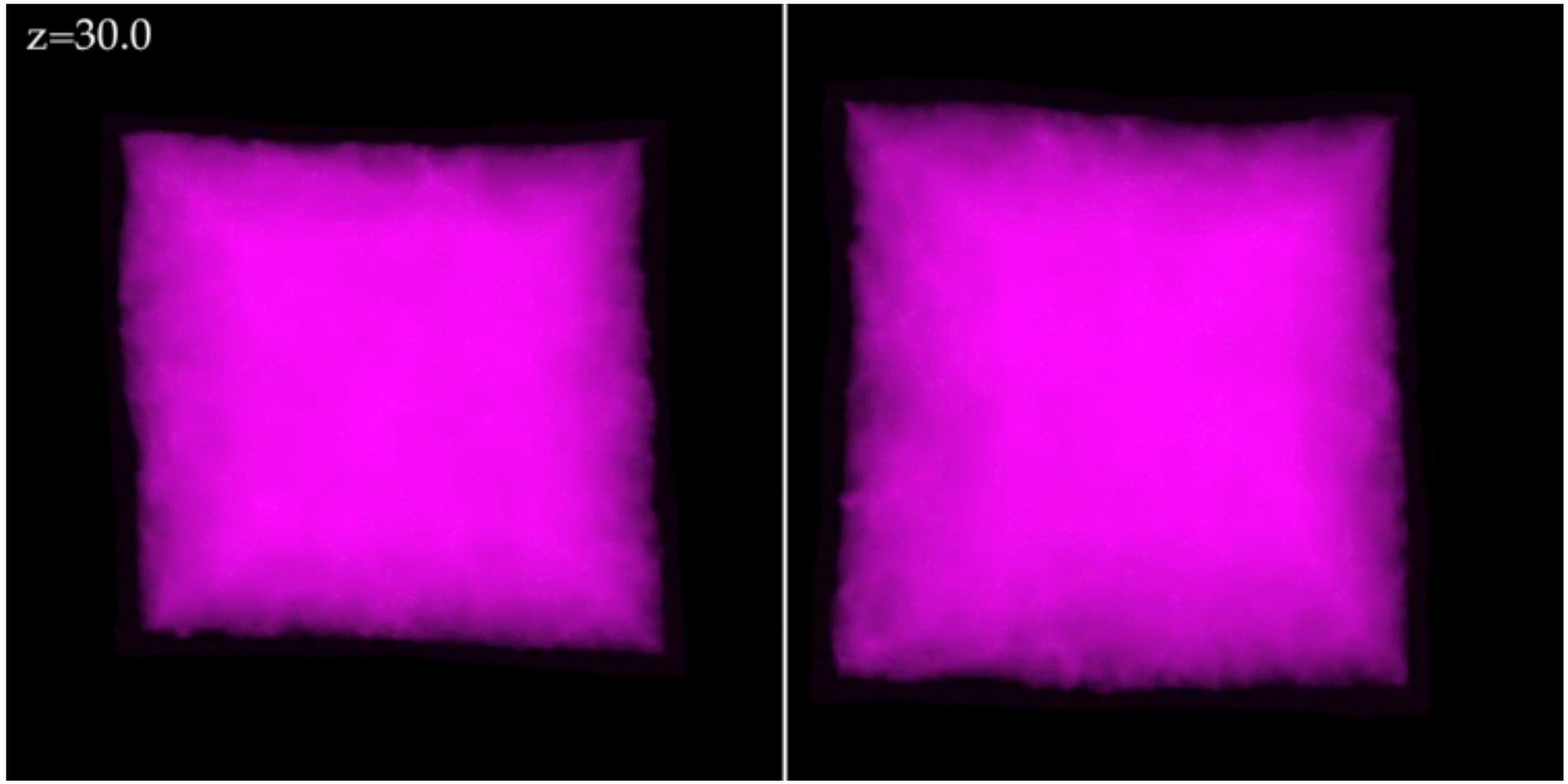
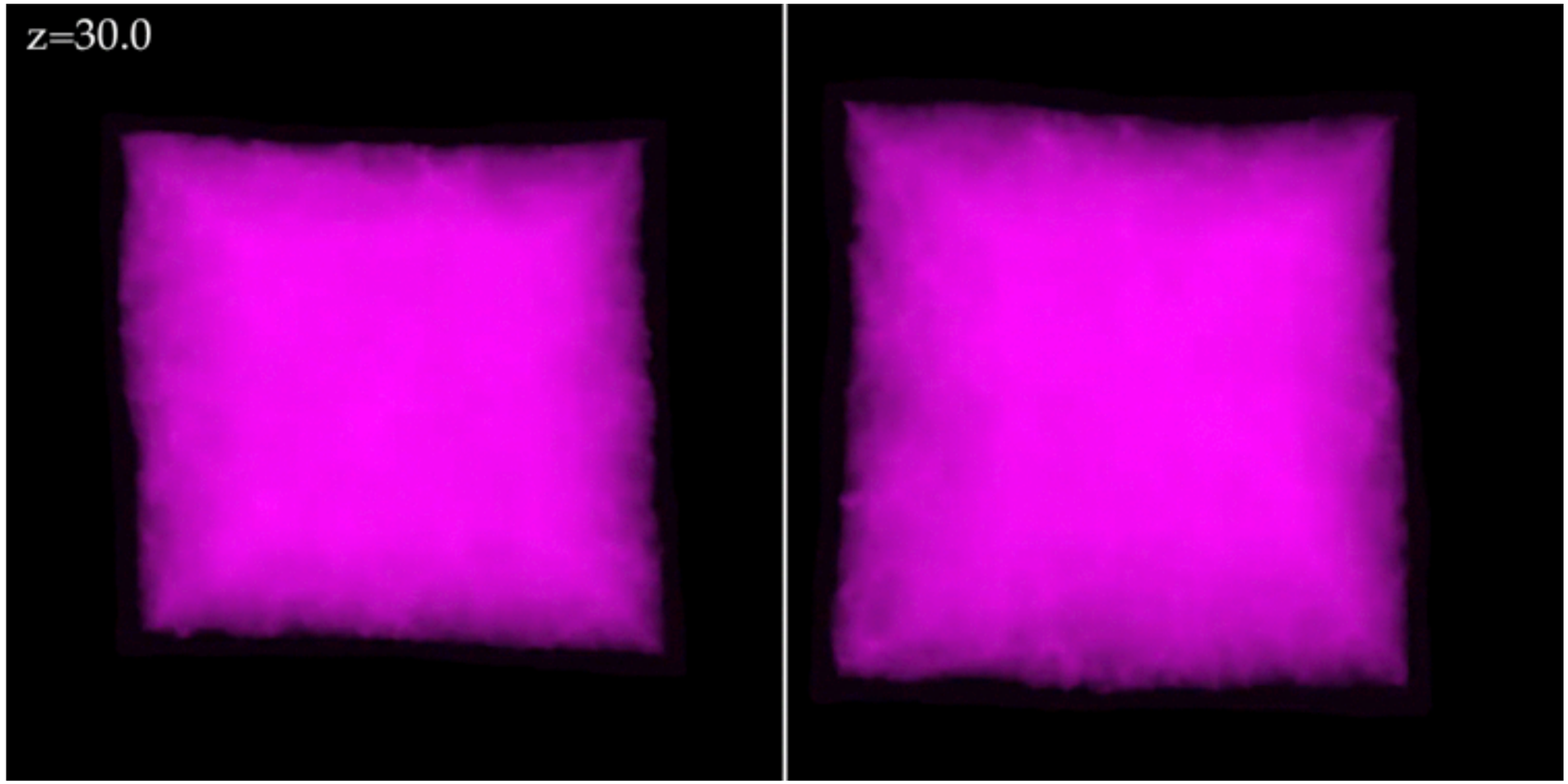


- Conduction doesn't save us:
  - Magnetic Instabilities (HBI; Quataert '08)
  - Inefficient in halos < 10^{14} M_{SUN}



- **Star formation is Feedback-Regulated**: *independent* of small-scale SF
  - Enough stars to offset gravity = Kennicutt relation, winds, sub-MW galaxies
- **Something else** needed to "quench"
  - Deplete disks (< 10 M_{sun}/pc^2) & ***Prevent Cooling***
  - Need to get stars+ISM right
- **Old Stars**: Not enough energy, and too many metals!
- **Conduction**: Not efficient at low-mass halos, suppressed by MHD instabilities
- **Morphology Alone**: Can't stop cooling! (in the disk or from the halo)
- **Gravitational Heating**: Not enough. Too few clumps, too far out, too many metals.



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