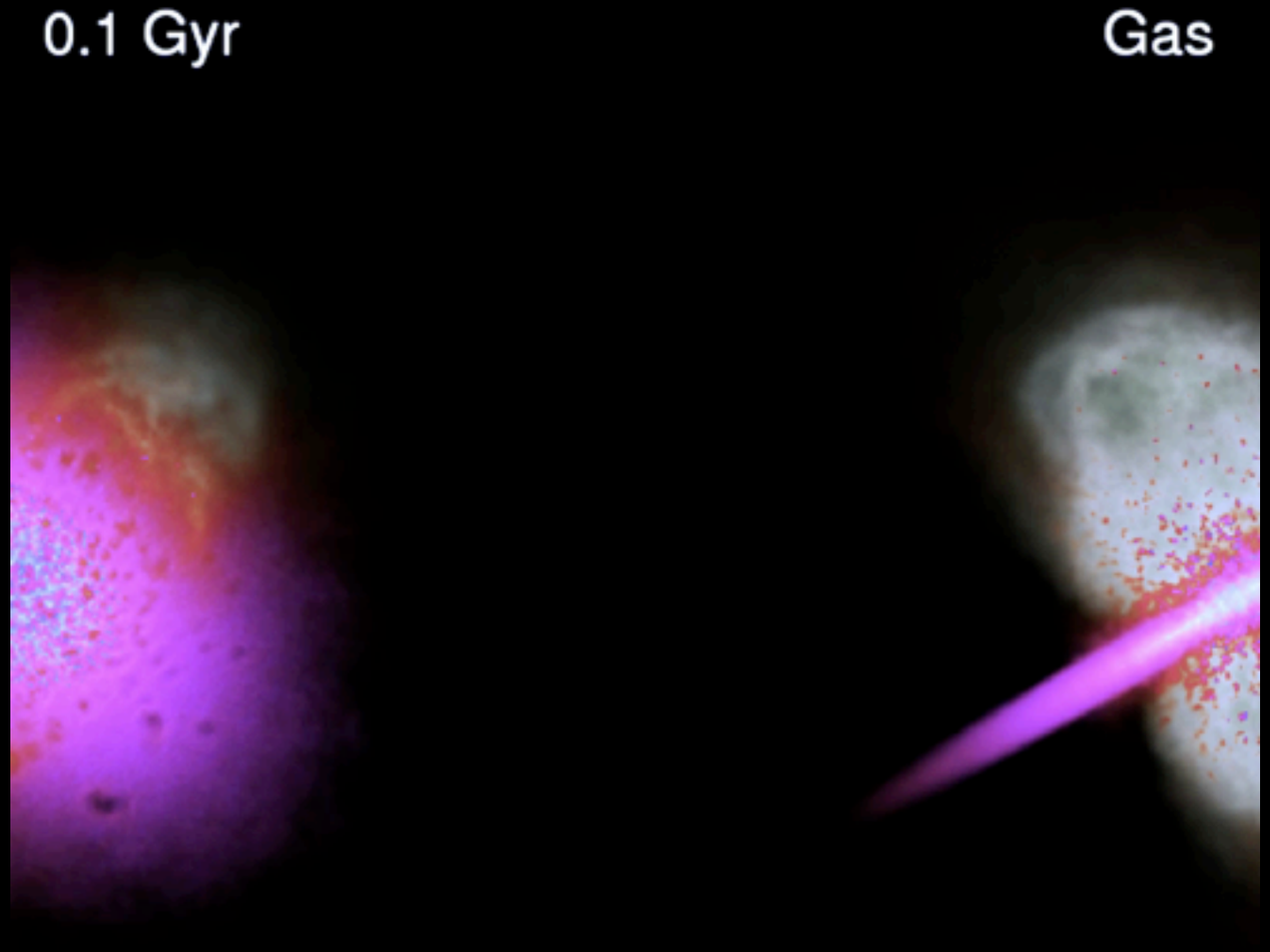
What *Doesn't* Quench Galaxy Formation?

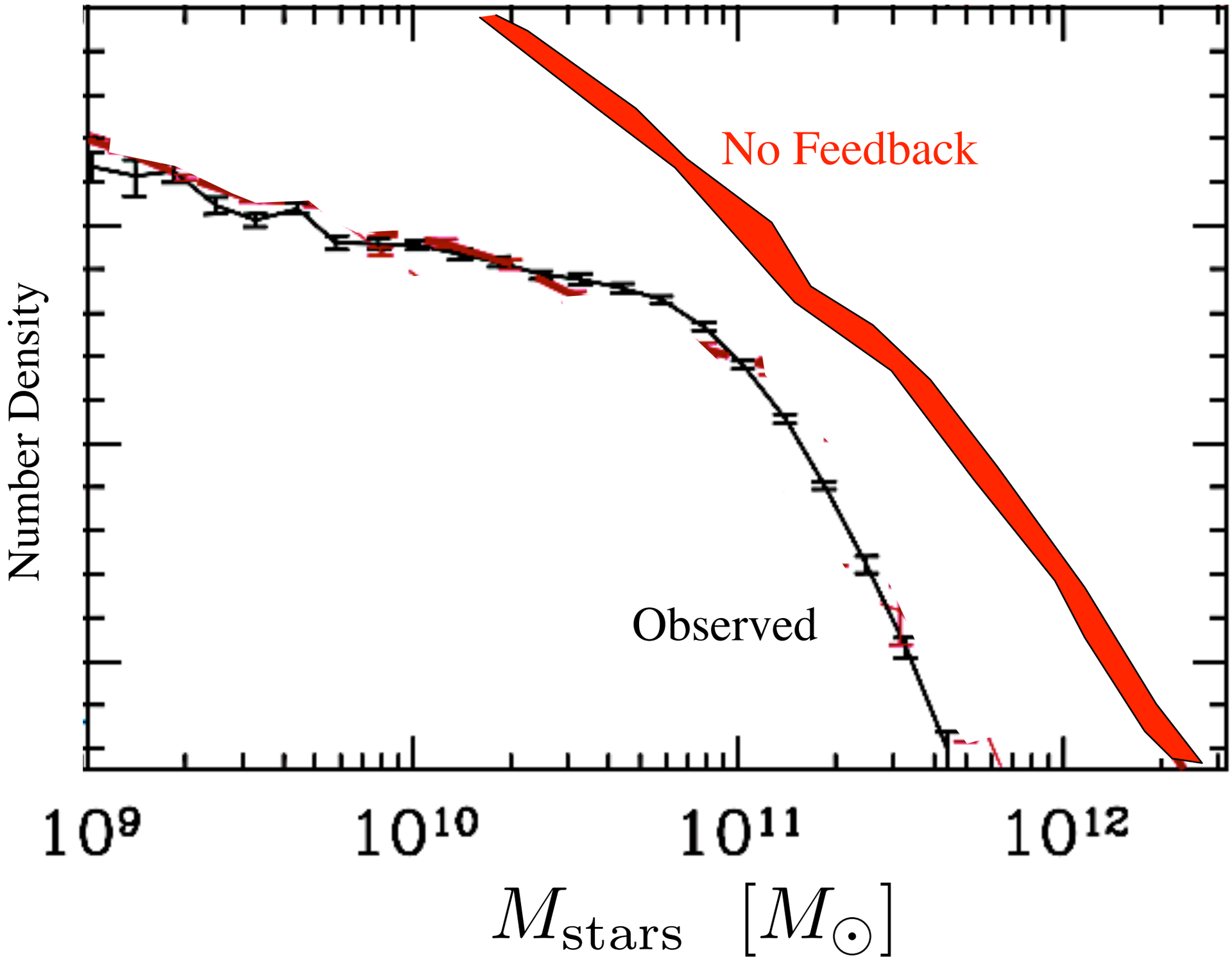


Phil Hopkins

Dusan Keres, Claude Faucher-Giguere, Jose Onorbe, Freeke van de Voort, Sasha Muratov, Xiangcheng Ma, Lena Murchikova, Norm Murray, Eliot Quataert, James Bullock

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Stellar Feedback: How Can We Do Better?

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

- Energy/Mass/Metal Injection:
  - SNe (II & Ia)
  - Stellar Winds (O & AGB)
  - Photoionization (HII) & Photoelectric

- Momentum Flux:
  - Radiation Pressure

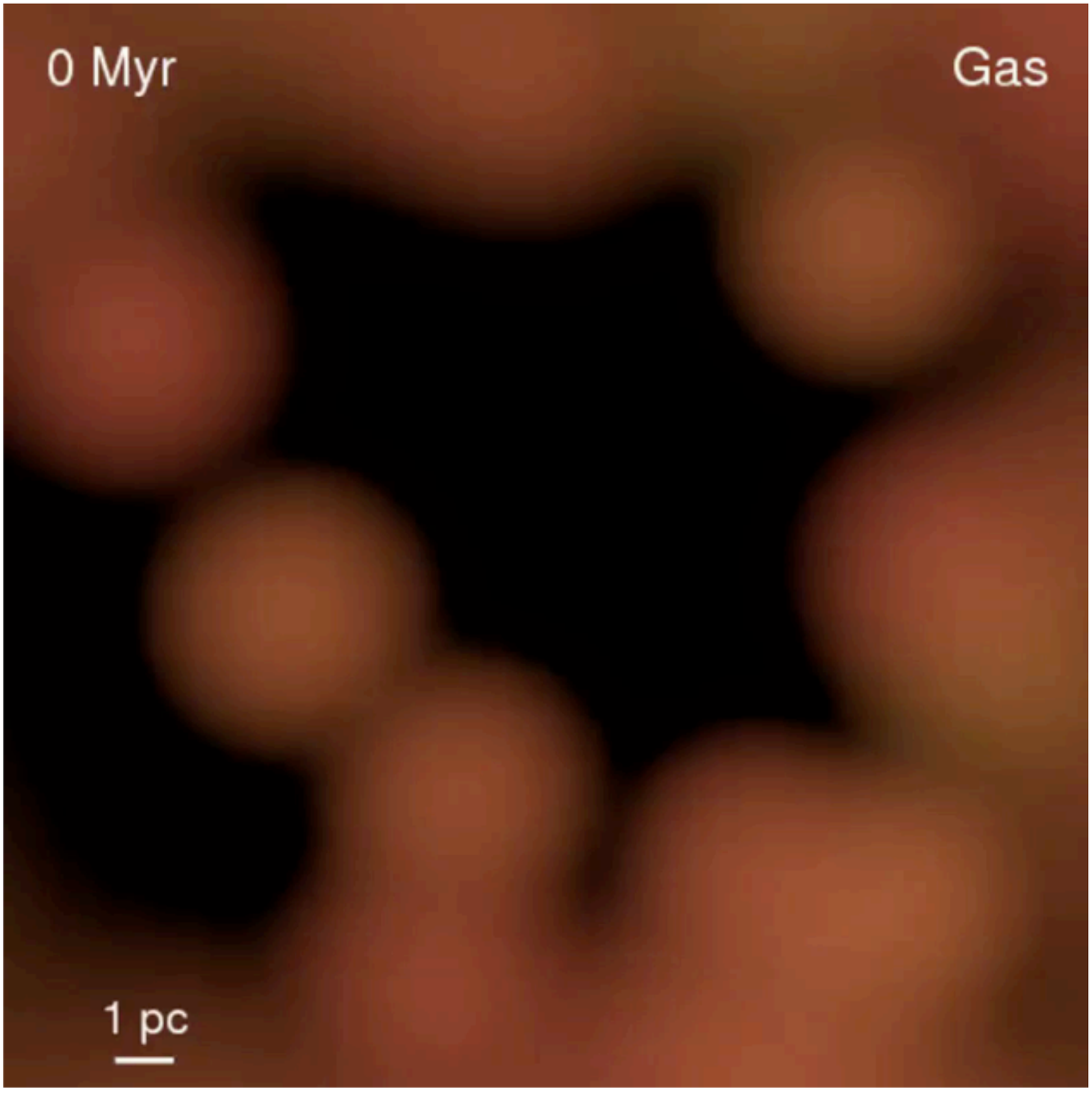
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

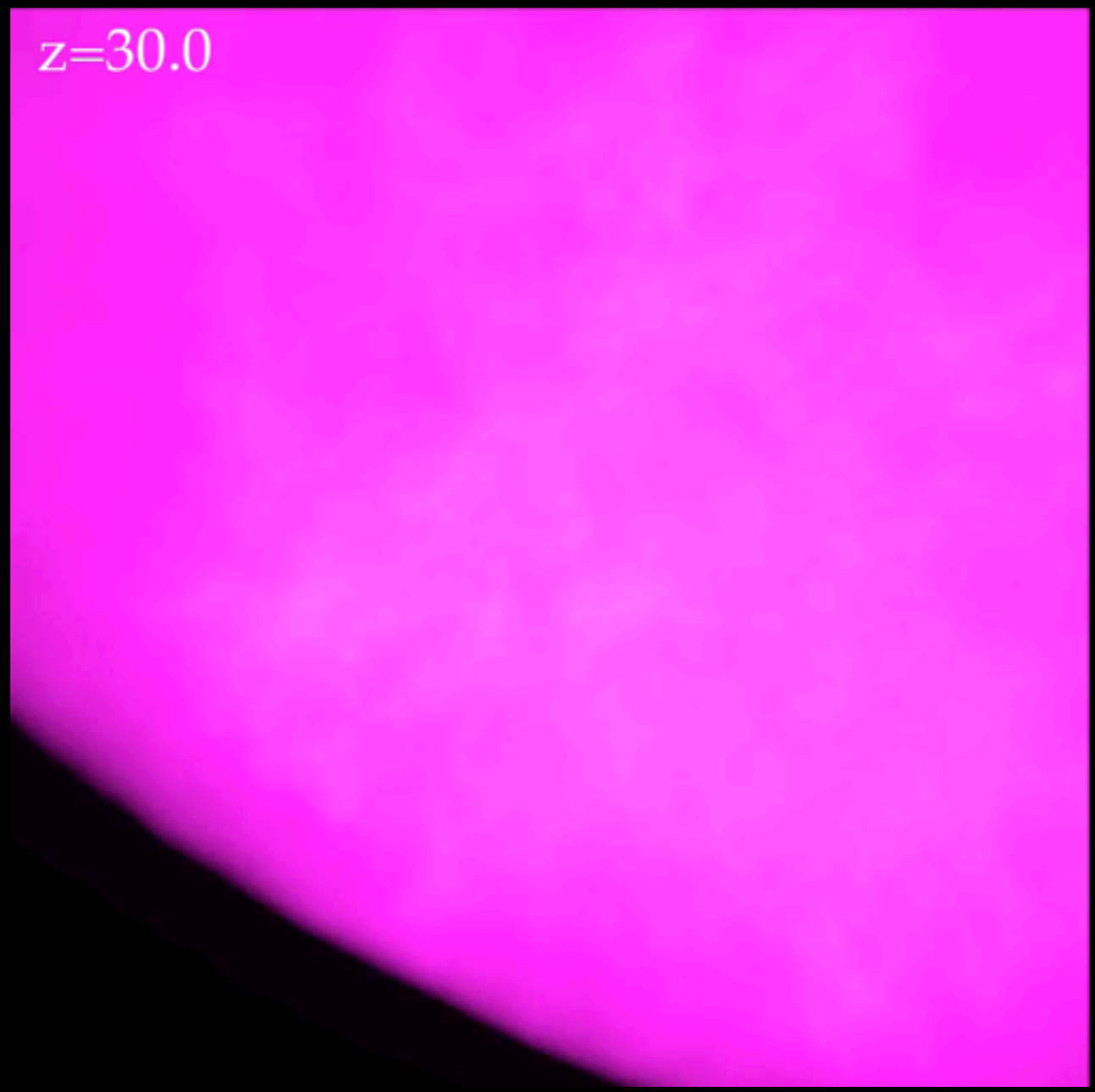
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$



- (also MHD, anisotropic conduction, diffusion)

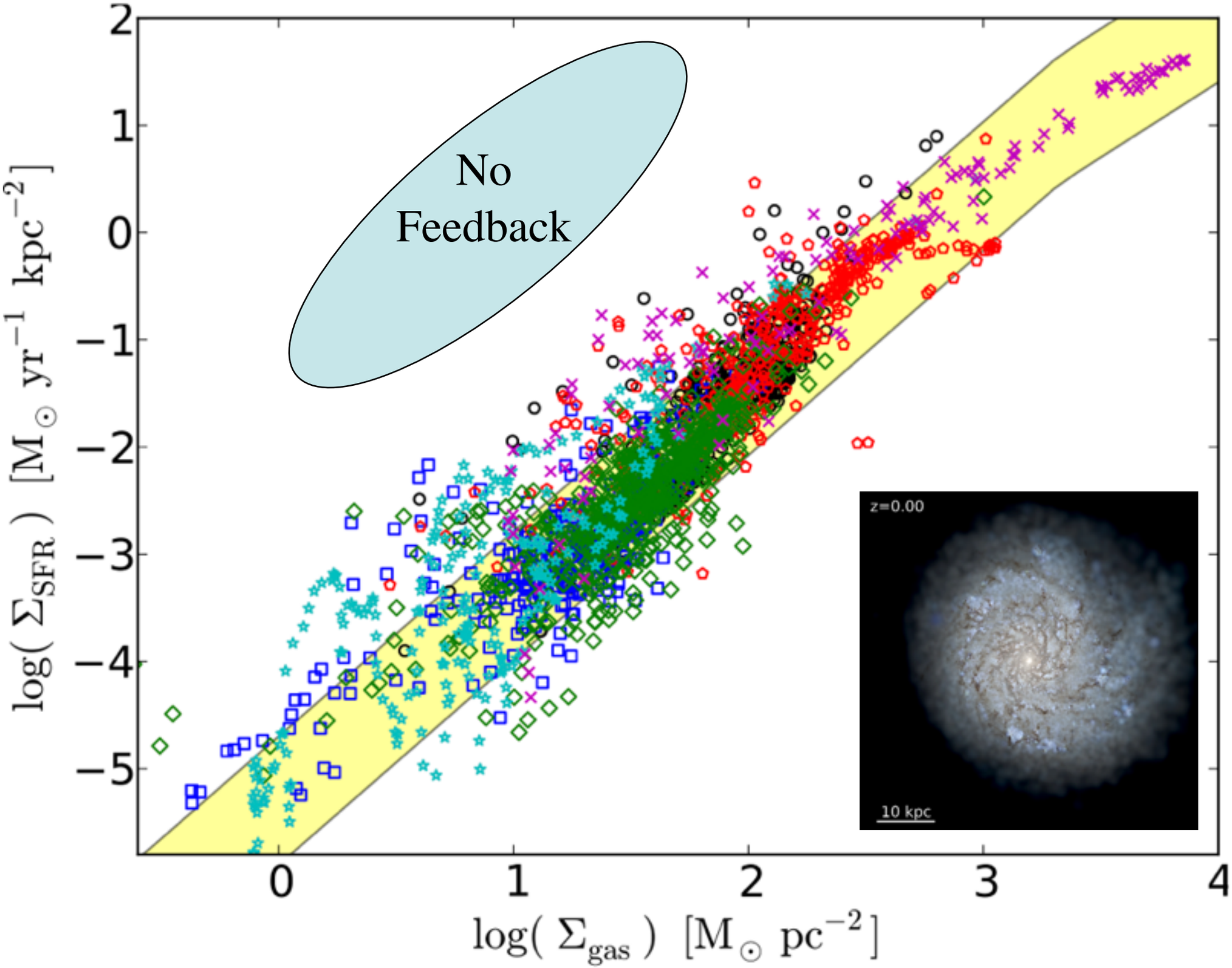
The FIRE Project: Cosmological Simulations at 1-10pc resolution

z=30.0



Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!

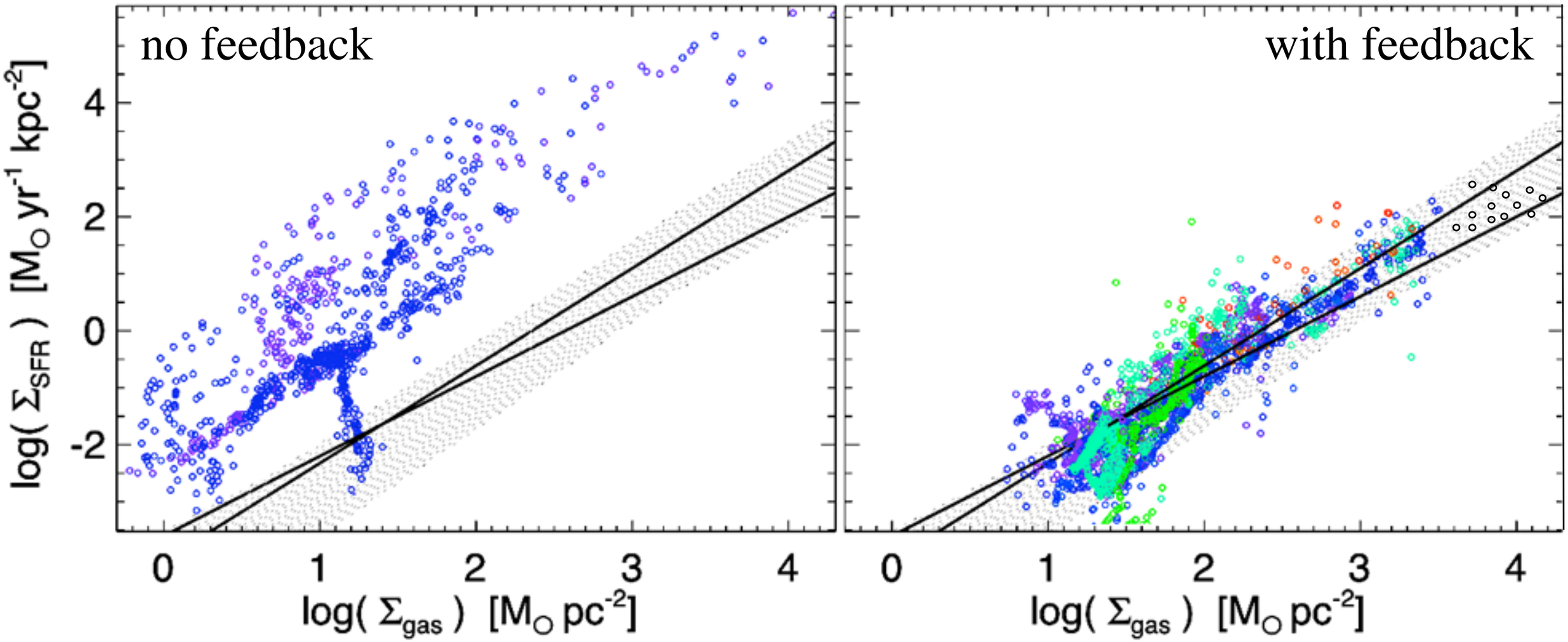


PFH, Keres, et al. (arXiv:1311.2073)

Kennicutt-Schmidt relation emerges naturally

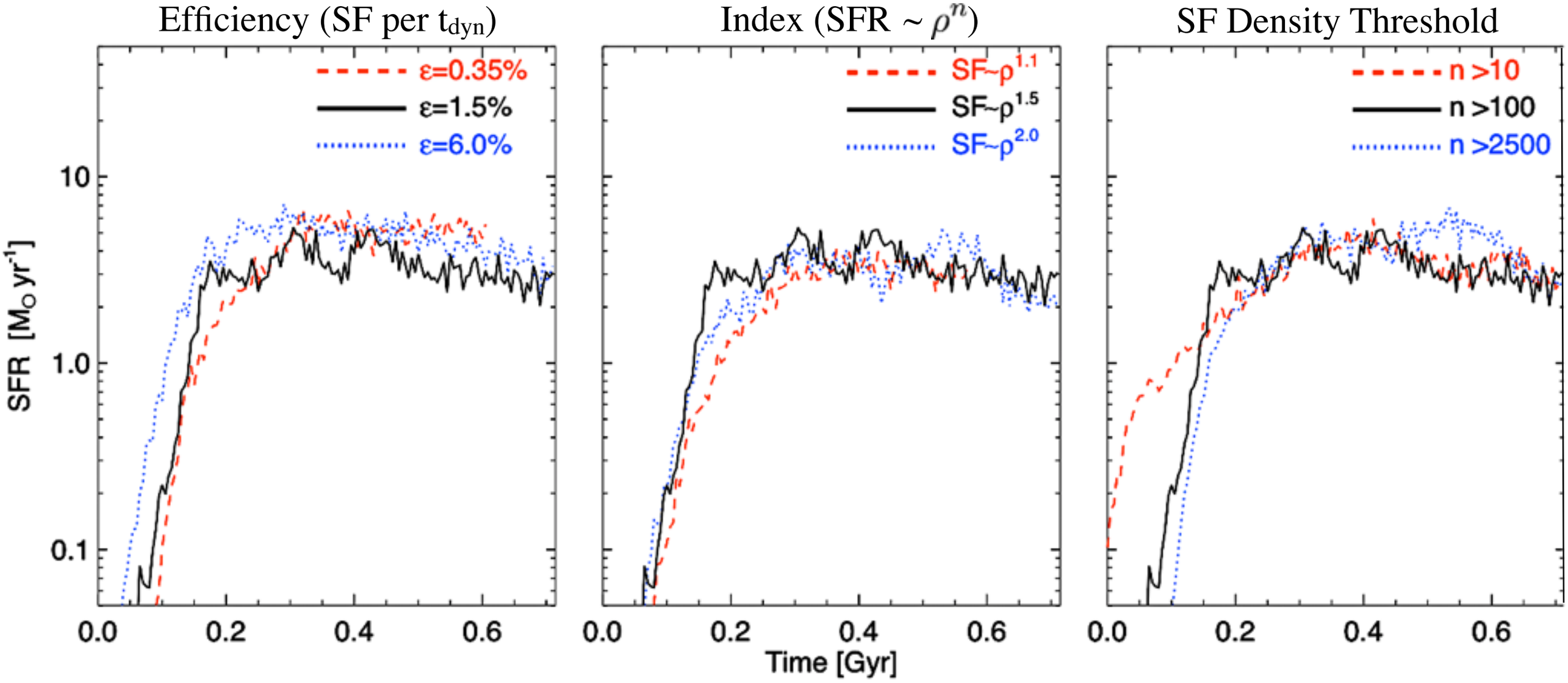
ISOLATED GALAXIES

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



PFH, Quataert, & Murray, 2011a

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



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

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

Inflows & Outflows

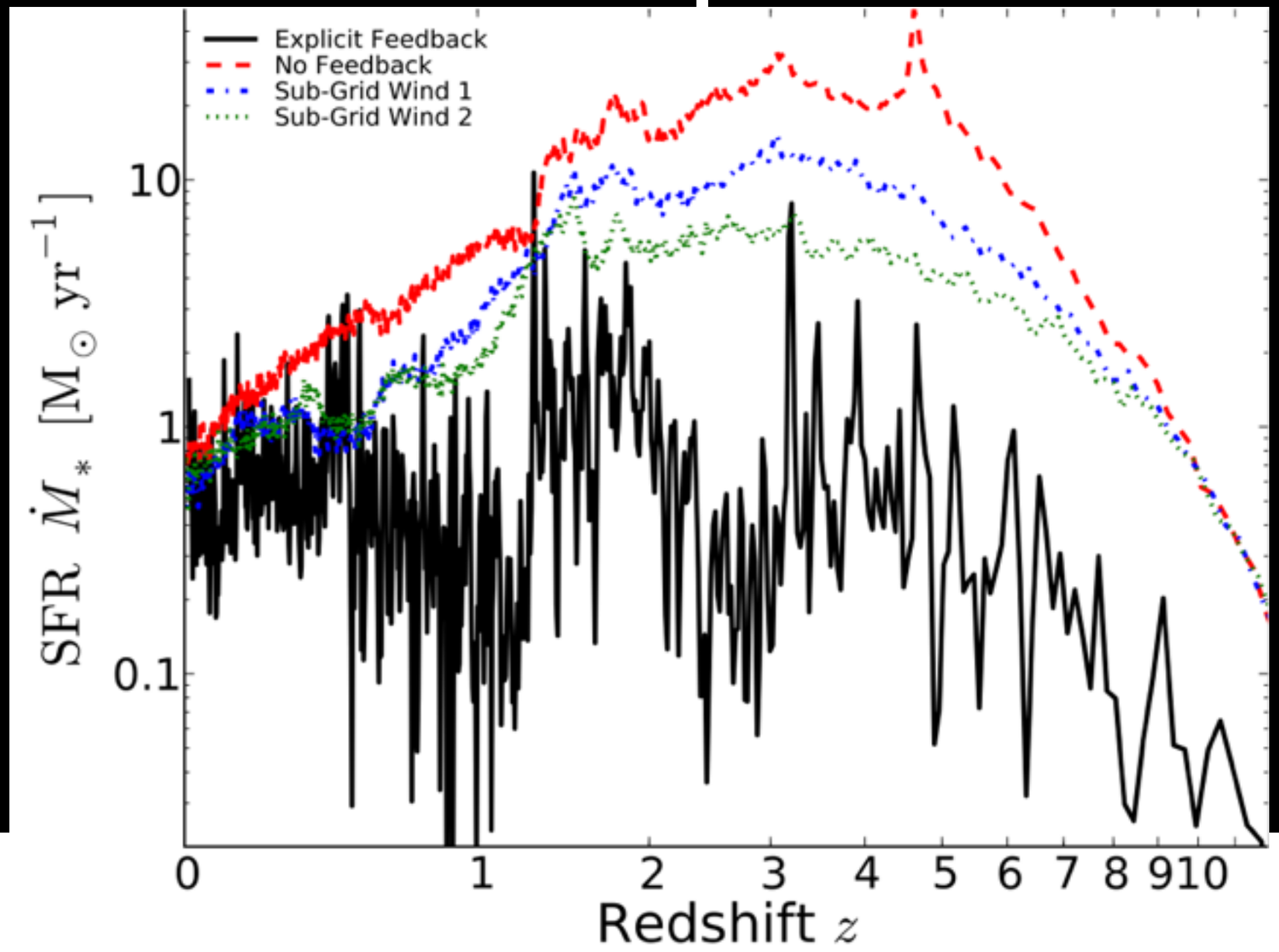
Simplest Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

Proto-MW: Gas Temperature:

"Decoupled Winds" (Sub-Grid)

Following Explicit Feedback

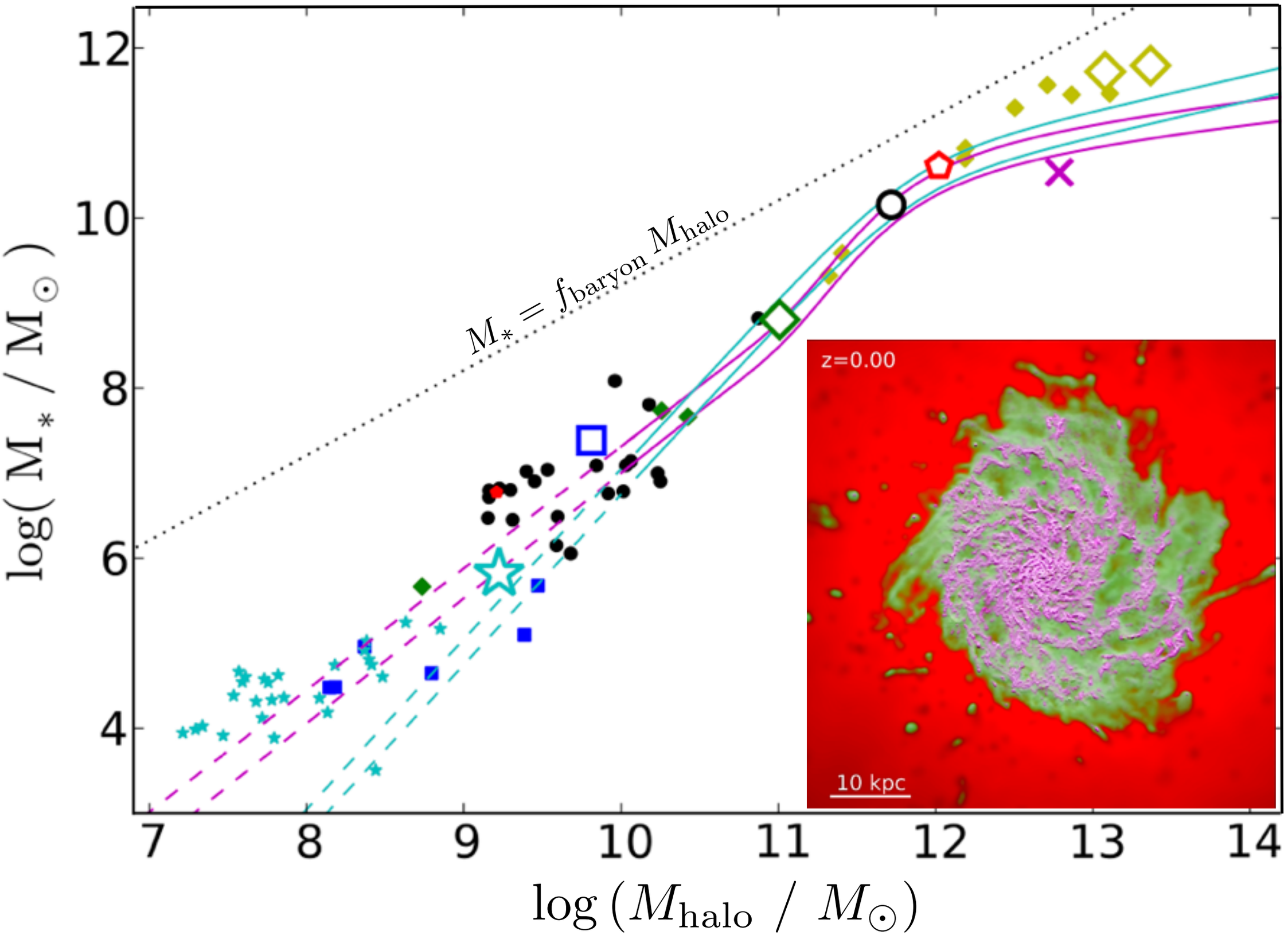


PFH, Keres, et al. (arXiv:1311.2073)

Does Stellar Feedback Explain the Mass Function?

HOW EFFICIENT ARE GALACTIC WINDS?

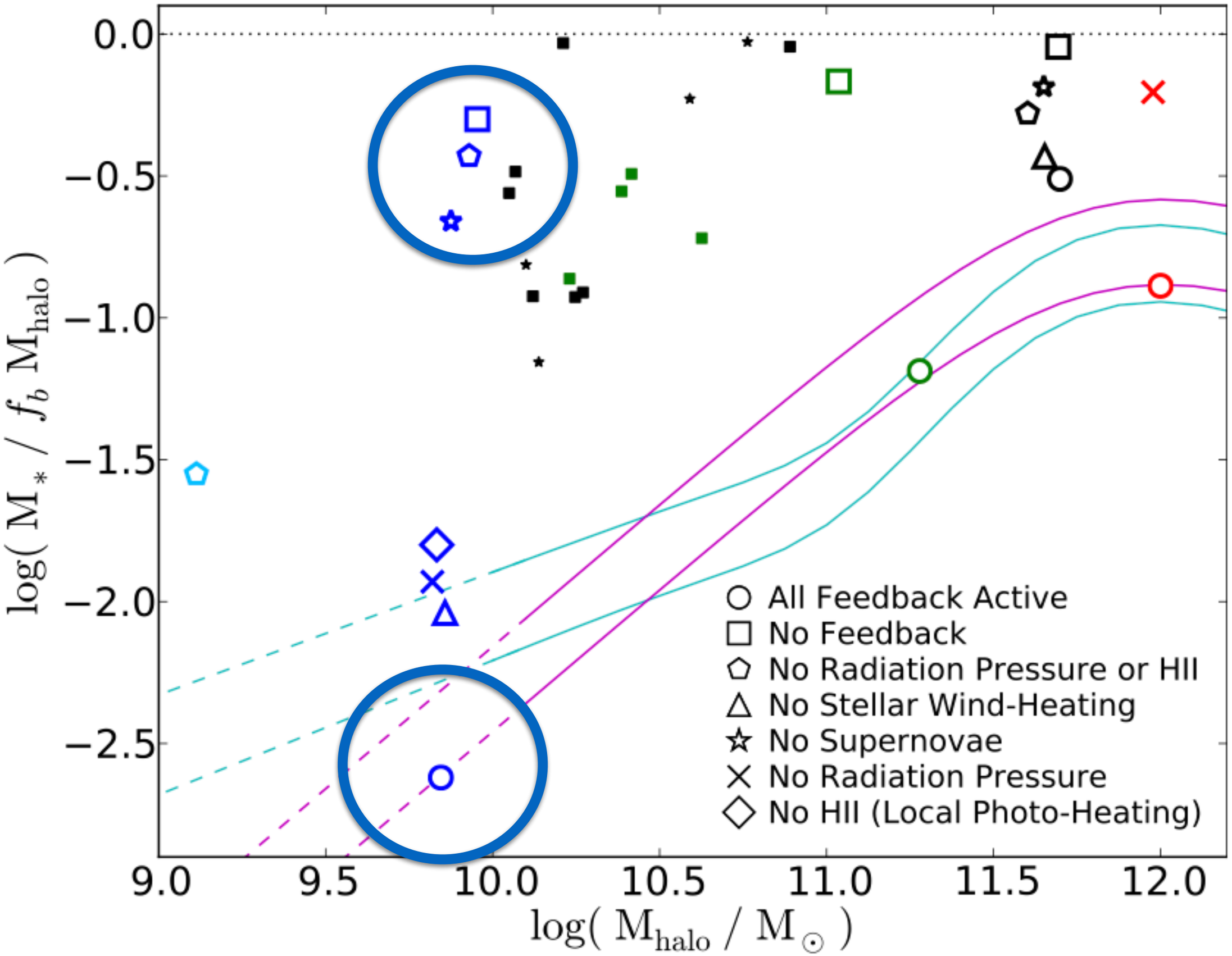
PFH, Keres, et al. (arXiv:1311.2073)



But Feedback *Does* Matter

MULTIPLE FEEDBACK MECHANISMS ARE CRITICAL

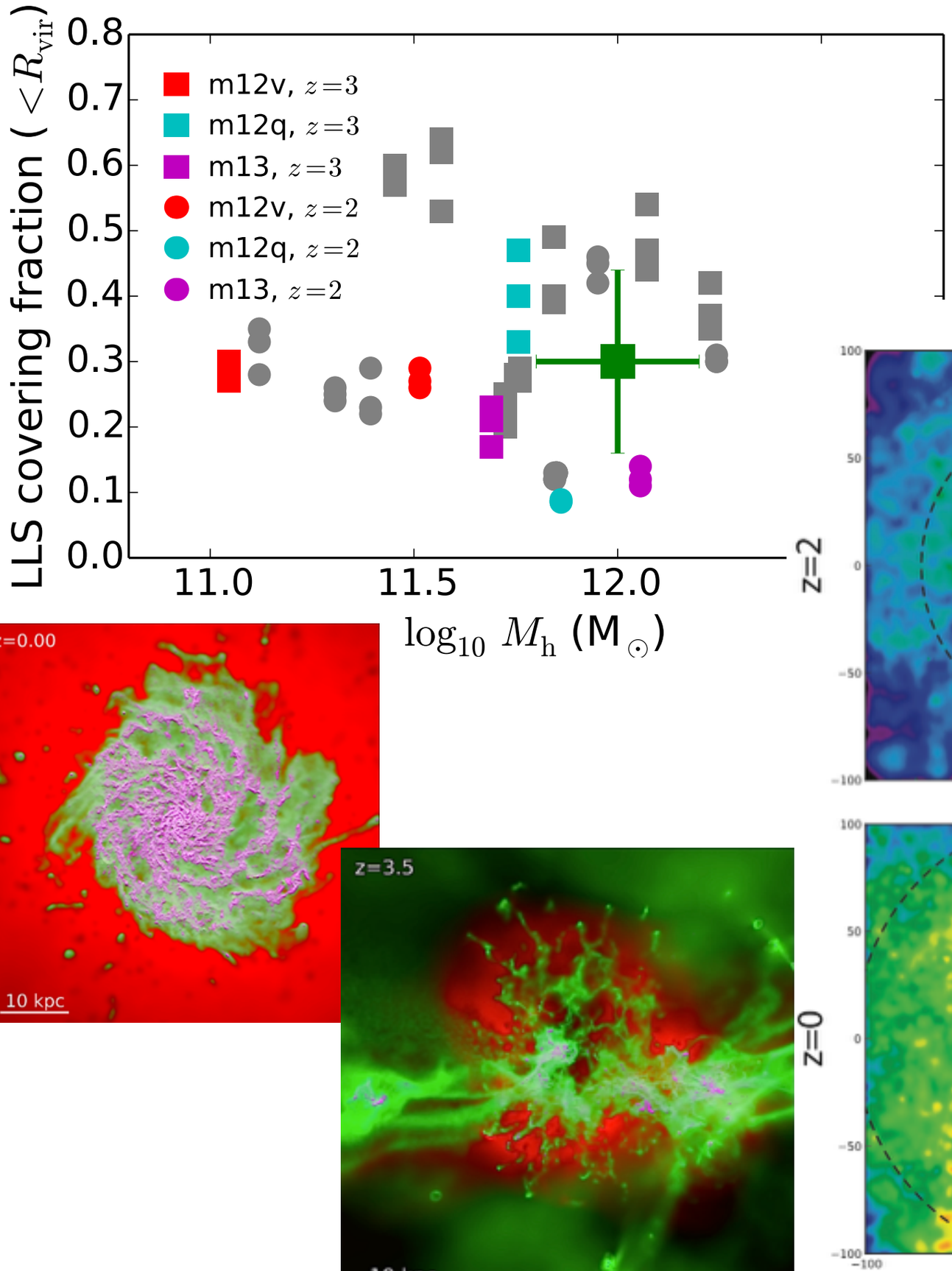
PFH, Keres, et al. (arXiv:1311.2073)

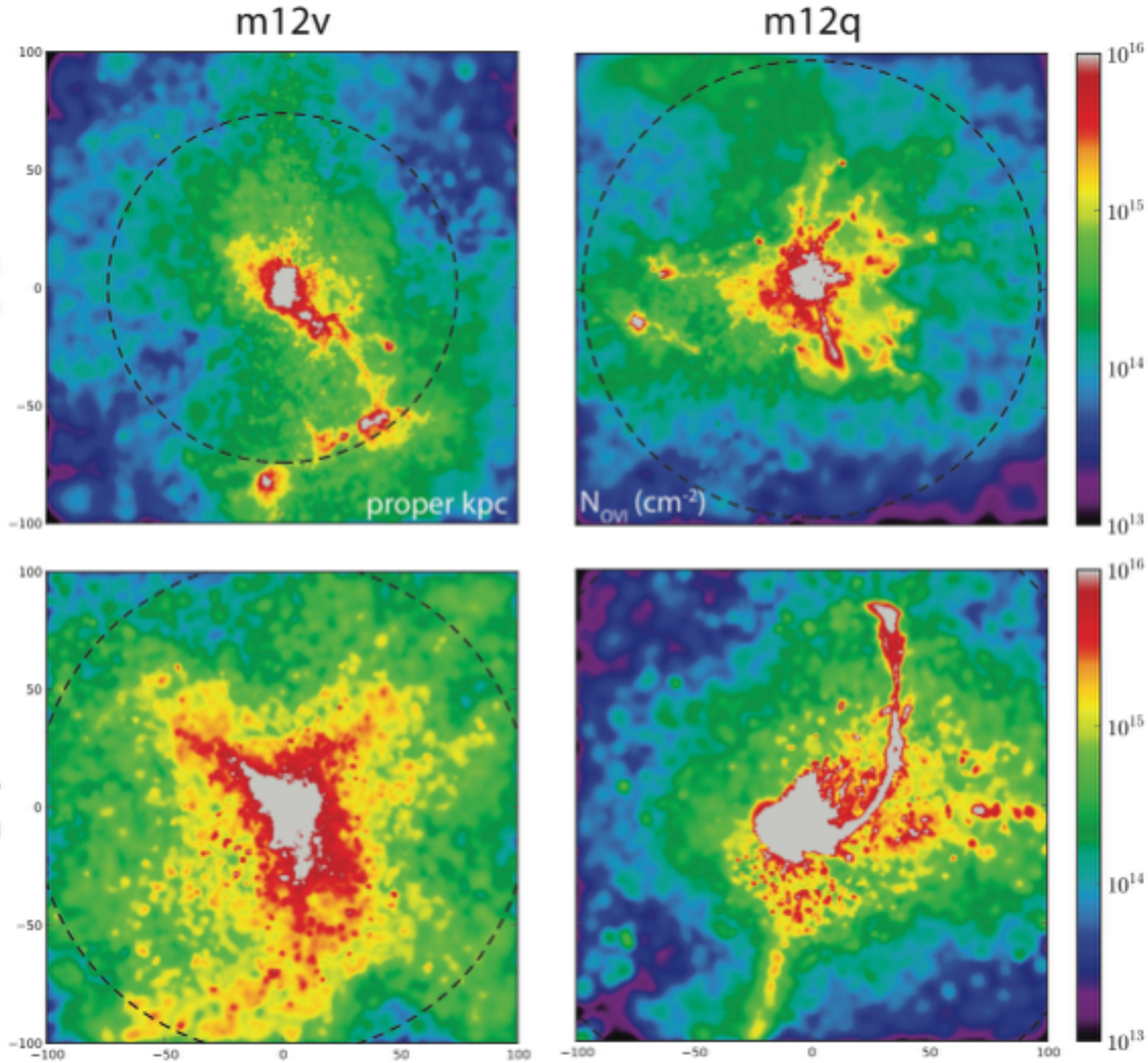


Feedback Determines the Halo Gas Properties

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

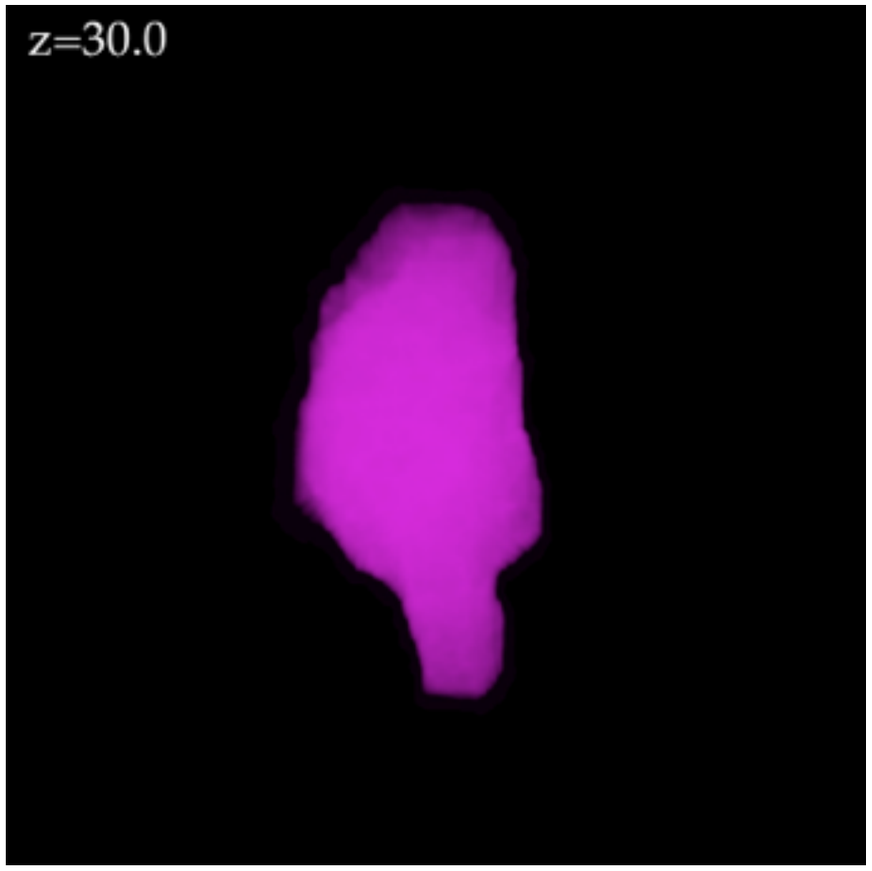
Faucher-Giguere, PFH, et al.



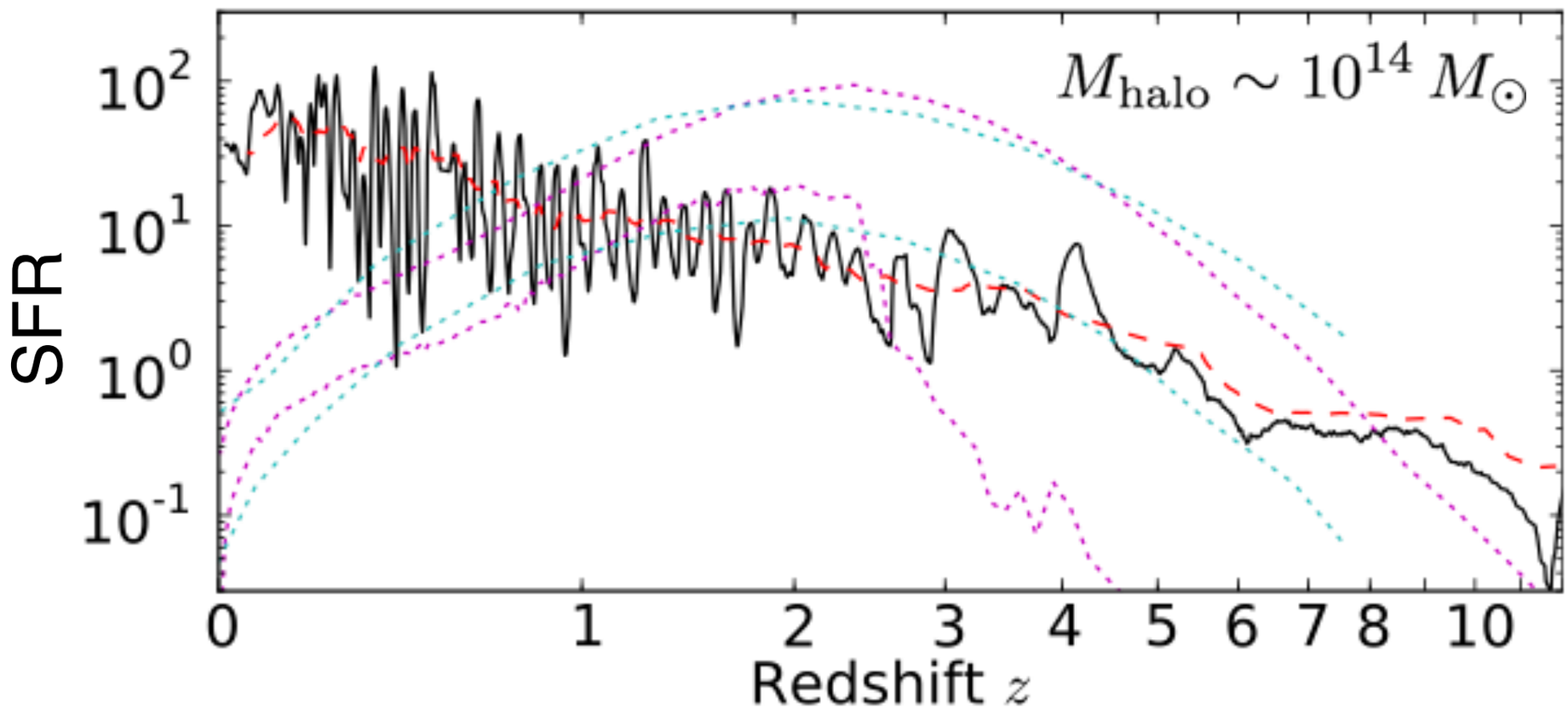


Quenching: Non-AGN Mechanisms *FAIL*

MORE THAN GRAVITY, COOLING, STARS, & MHD

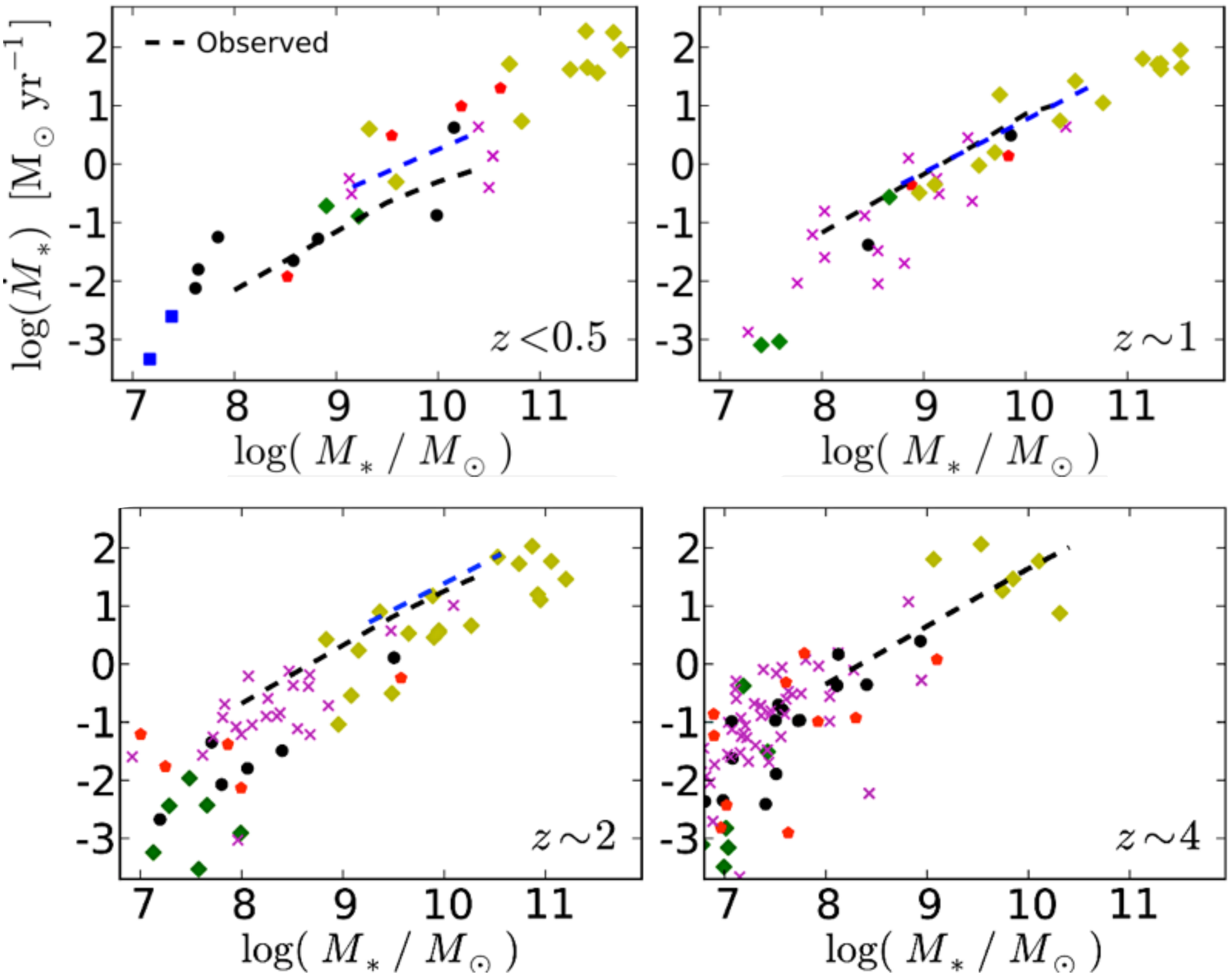


- **Morphology?** (**are** bulge-dominated)
- **Clumps/Gravity?** (resolution ~10^4 M_{sun})
- **MHD/Conduction?** (new runs included)
- **Stars?** (late-time AGB/SNIa included)



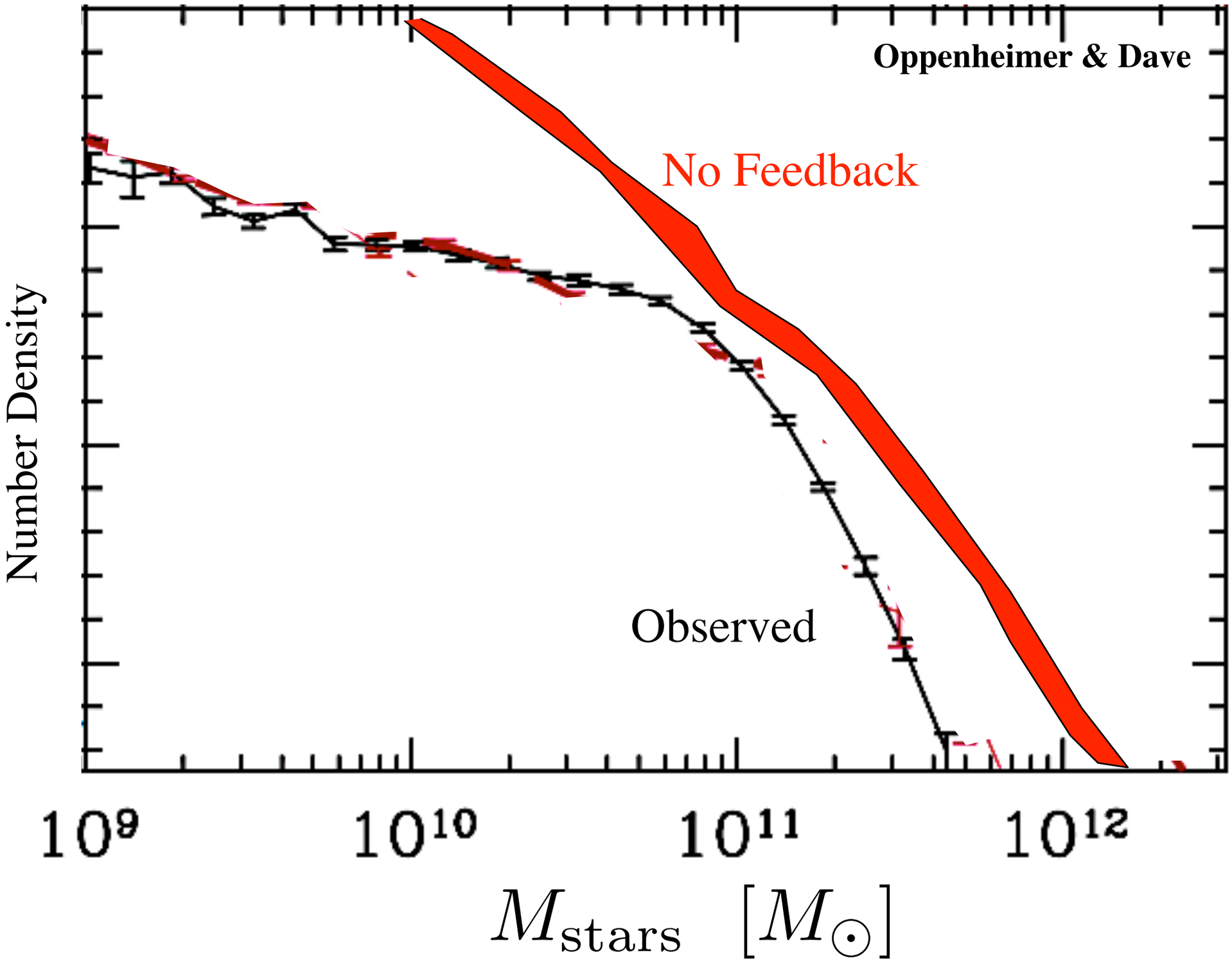
Galaxies Just Keep Plugging Along

NO "QUENCHED" TRACK



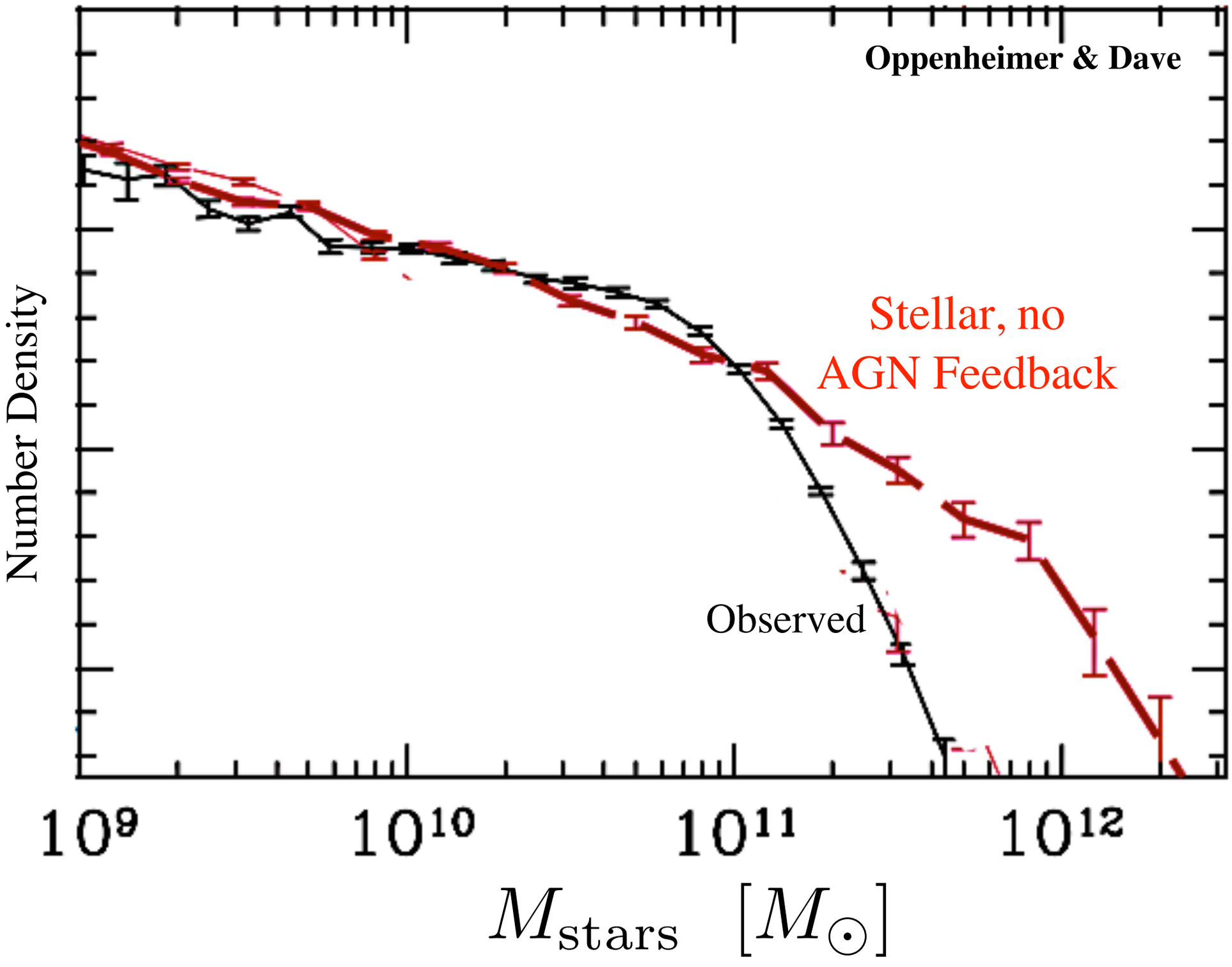
Lesson 1: Don't Trust Models that Don't Do Stars Right

SMALL GALAXIES BECOME BIG GALAXIES



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

SMALL GALAXIES BECOME BIG GALAXIES

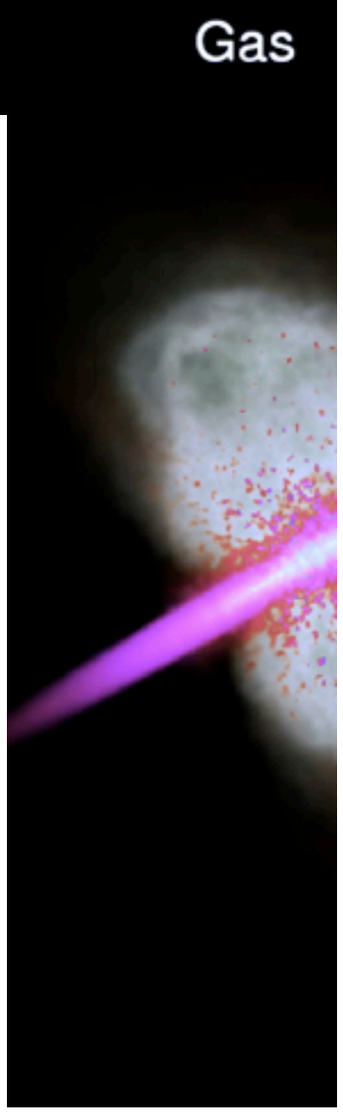


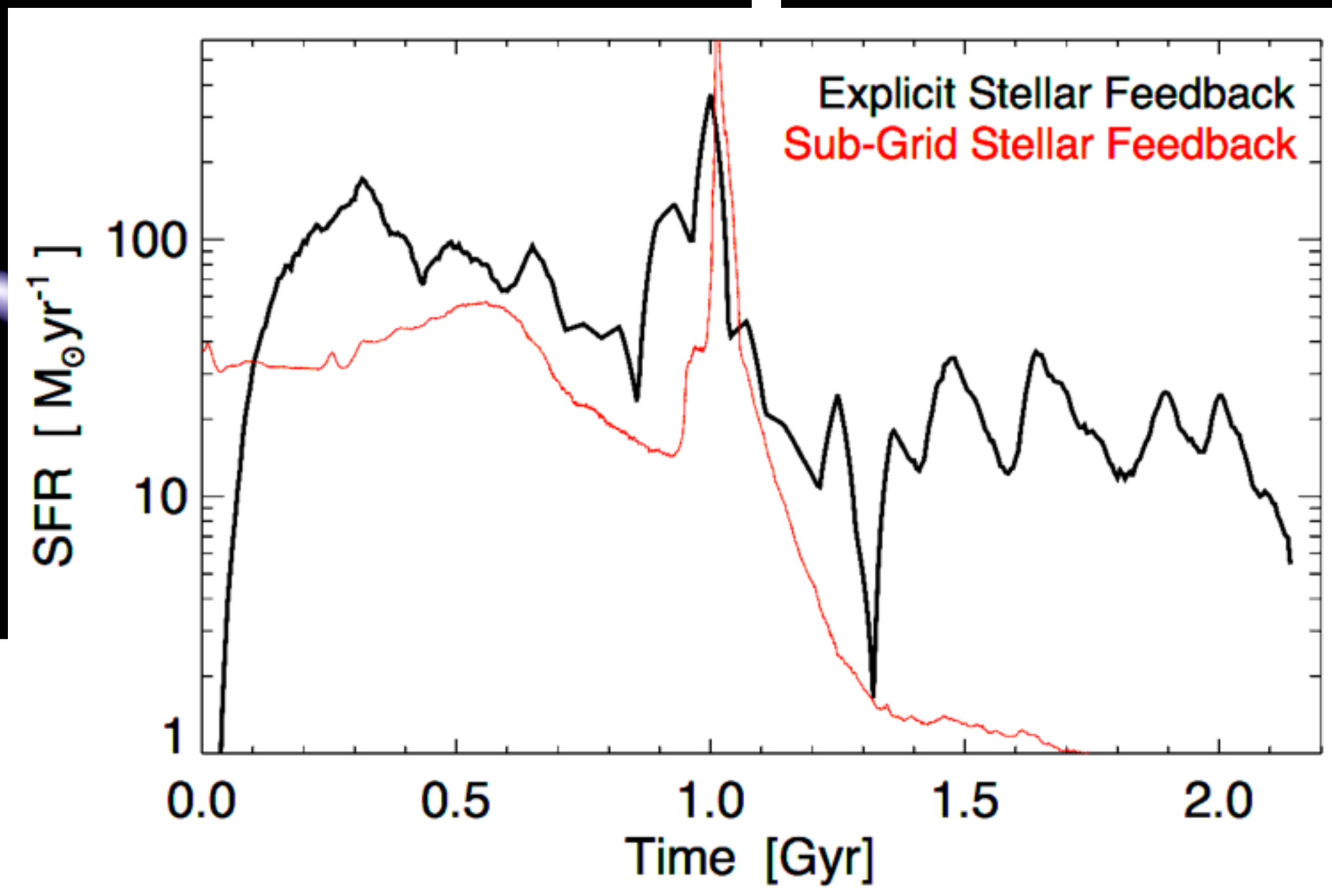
Lesson 1: Don't Trust Models that Don't Do Stars Right

SMALL GALAXIES BECOME BIG GALAXIES

"Decoupled Winds" (Sub-Grid)

Following Explicit Feedback



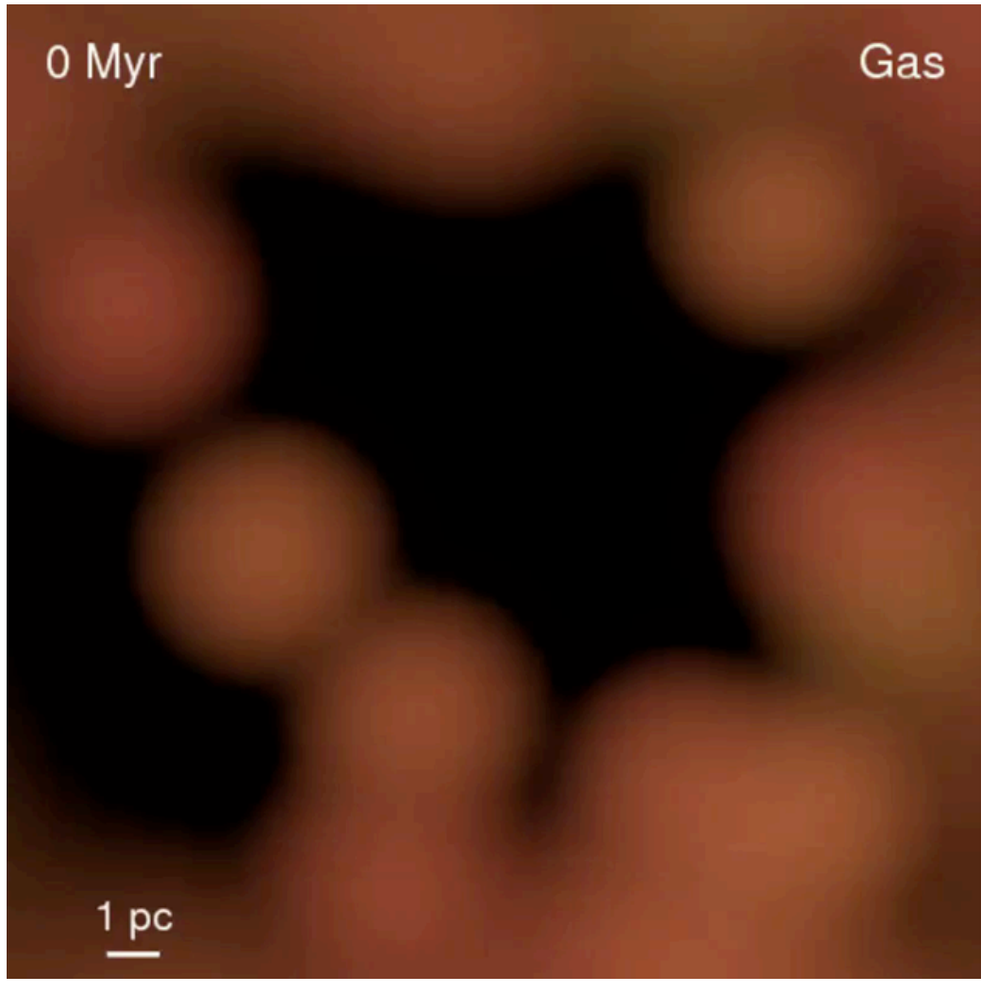


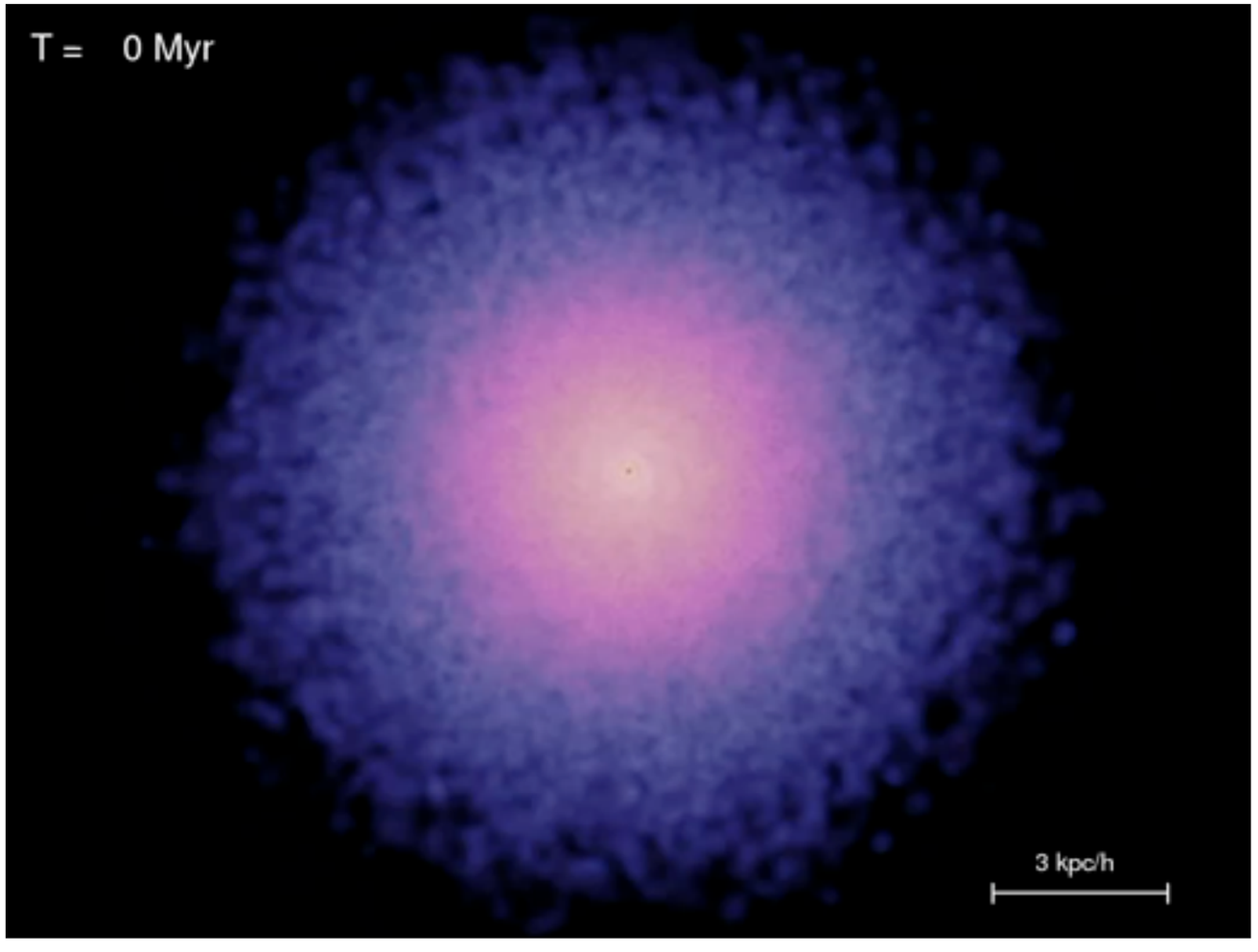
Lesson 2: “Shutting Down” Star Formation in the Disk

WHY IT’S HARD

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

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



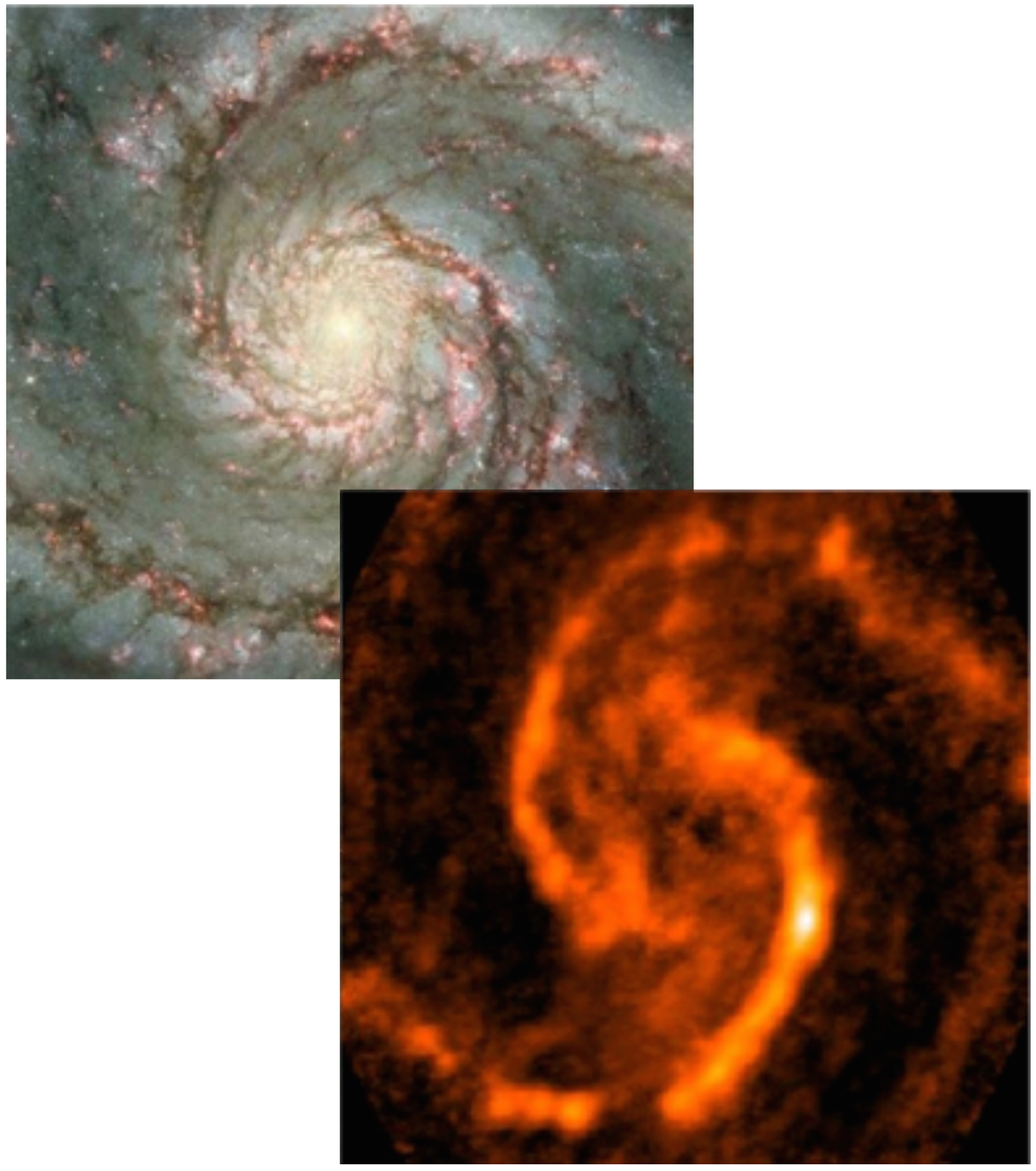


- *Self-Regulated* SF (K-S)
- *Suppressed* SF

“Shutting Down” Star Formation:
GAS DEPLETION NEEDED

$$\Sigma > 10 \left(\frac{Z_\odot}{Z} \right) \frac{M_\odot}{\mathrm{pc}^2}$$

$$Q_{\mathrm{therm}} \sim 0.1 \frac{\Omega_{\mathrm{MW}}}{\Sigma_{10}}$$



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

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

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

"Shutting Down" Star Formation:
GAS DEPLETION NEEDED

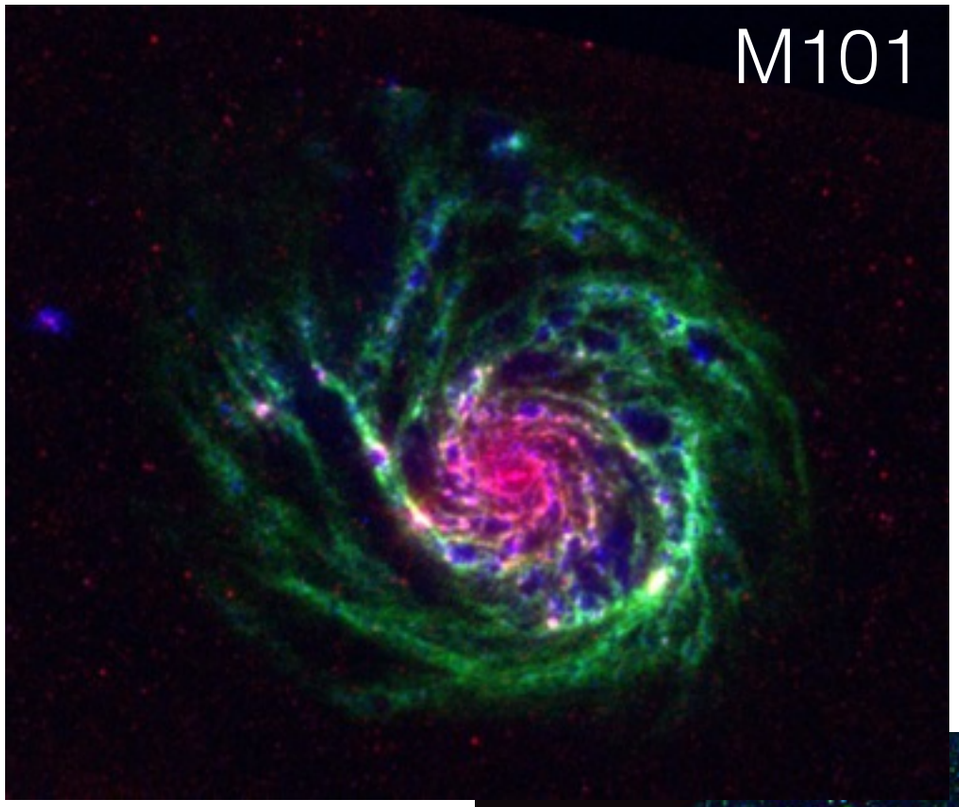
$$\Sigma < 10 \left(\frac{Z_\odot}{Z}\right) \frac{M_\odot}{\mathrm{pc}^2}$$

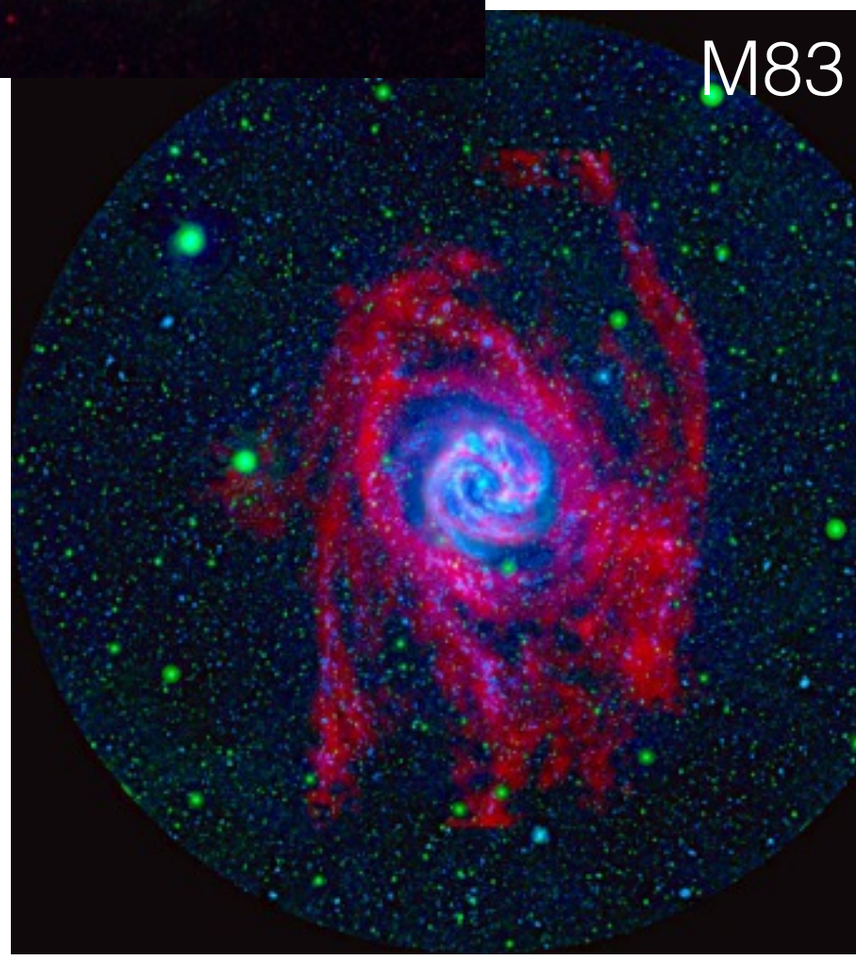
can't self shield (T~10^4 K):

$$Q_{\mathrm{therm}} \sim 3 \frac{\Omega_{\mathrm{MW}}}{\Sigma_{10}}$$

$$M_{\mathrm{gas}} < 10^9\, M_\odot \left(\frac{Z_\odot}{Z}\right) \left(\frac{M_{\mathrm{halo}}}{10^{12}\, M_\odot}\right)^{2/3}$$

$$\dot{M}_{\mathrm{cool}} < 0.1 \frac{M_\odot}{\mathrm{yr}} \left(\frac{Z_\odot}{Z}\right) \left(\frac{M_{\mathrm{halo}}}{10^{12}\, M_\odot}\right)^{2/3}$$





Can "Morphology" Do It?

Morphological/'Toomre'/Dynamical Quenching (Martig, Dekel,+)

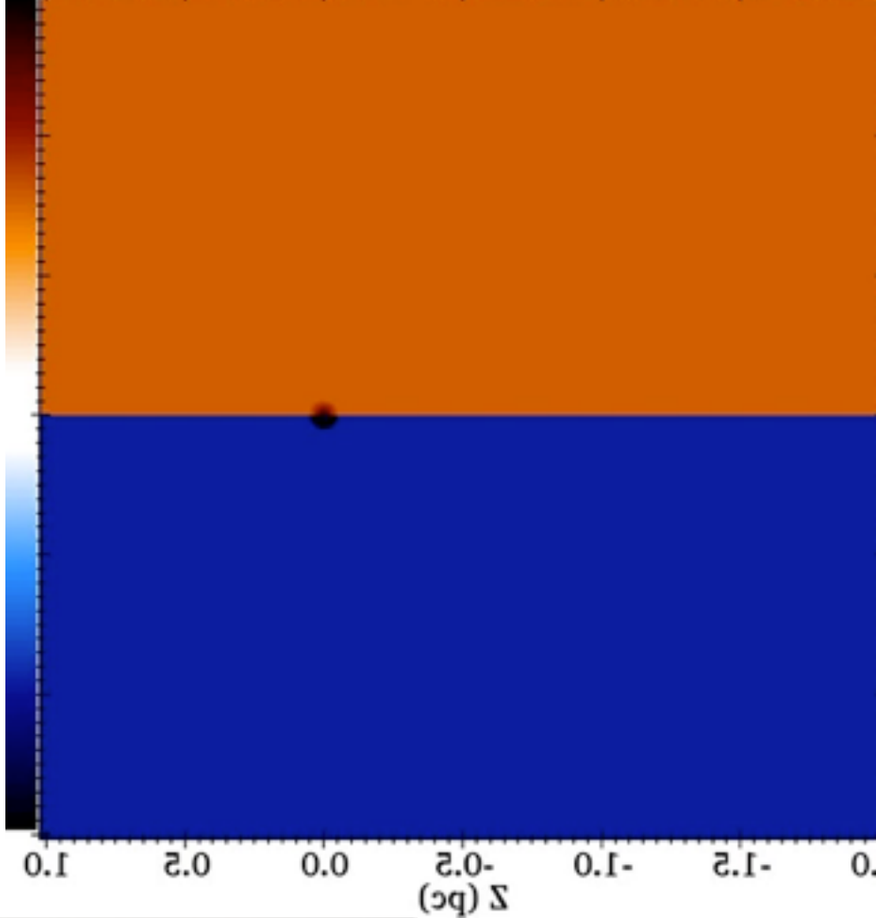
$$\text{Disk} \rightarrow \text{Bulge} \neq \text{Quenching}$$

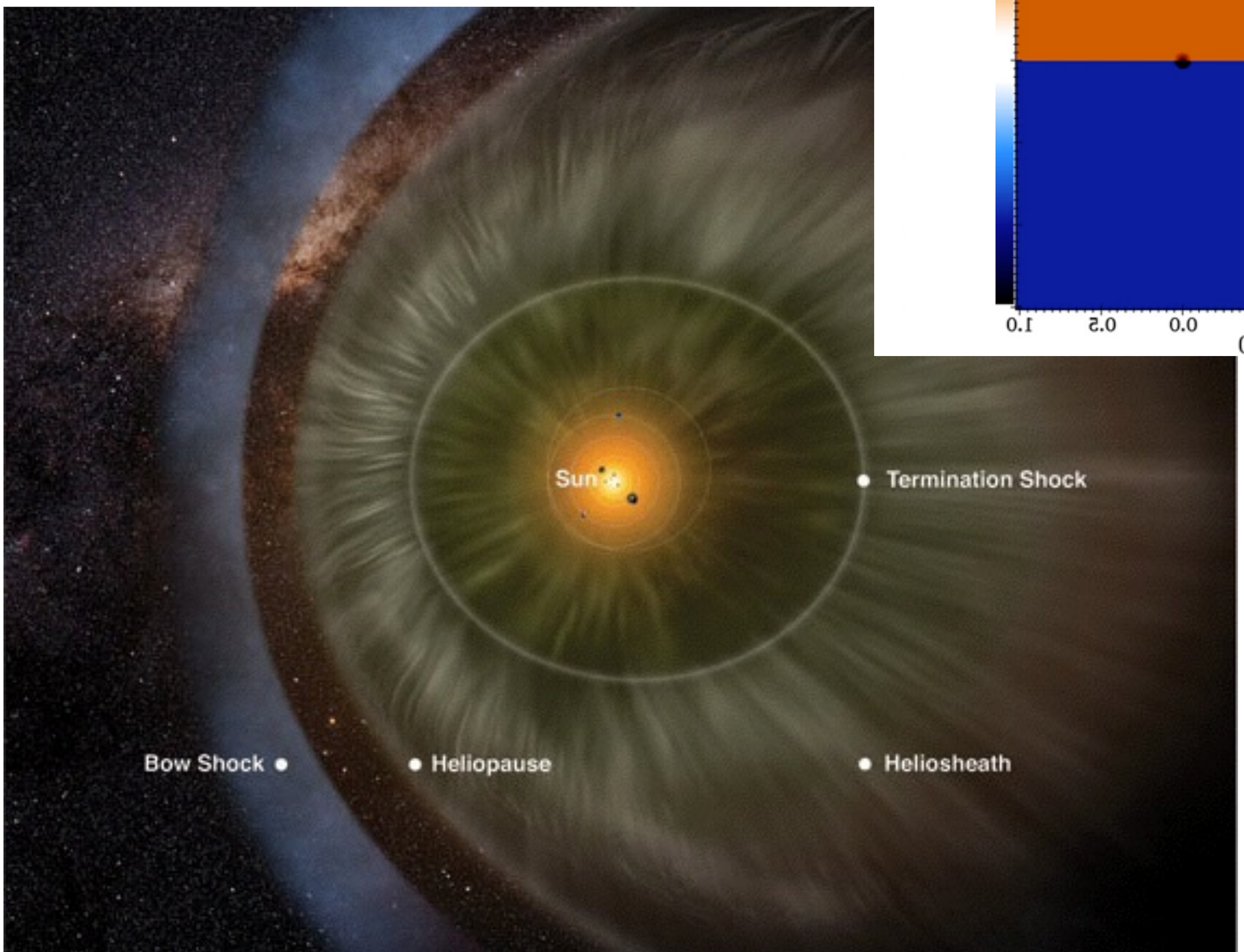
$$\text{Mass} \rightarrow \text{center} \neq \text{Quenching}$$

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

Can Stars Do It?

SNIa, AGB (Conroy+, Ostriker, Novak)





Can Stars Do It?

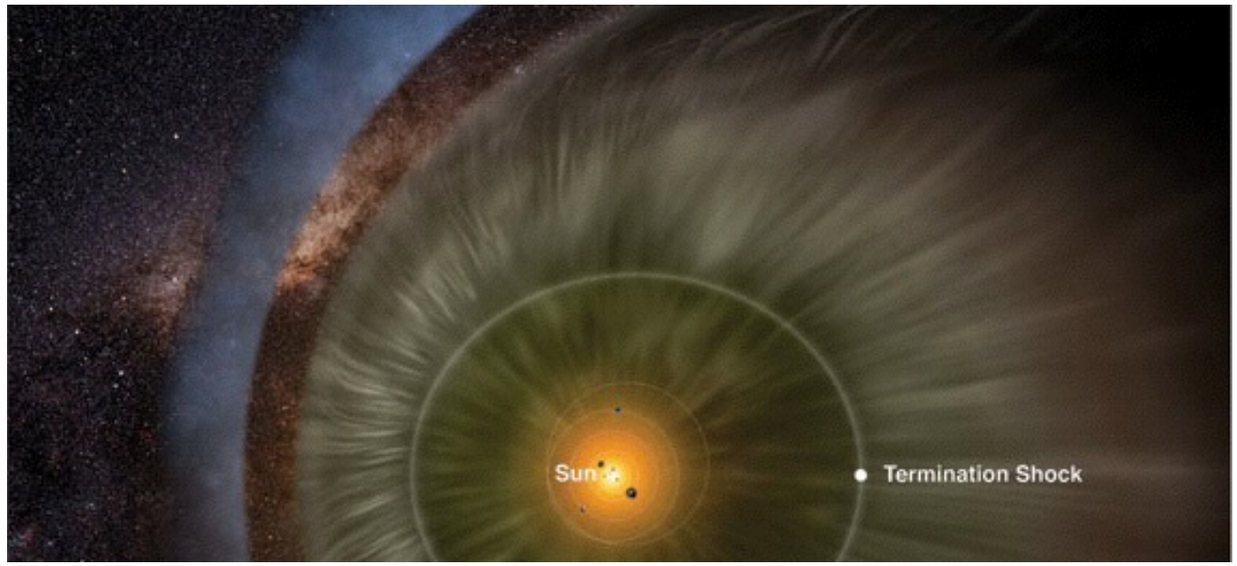
SNIa, AGB (Conroy+, Ostriker, Novak)

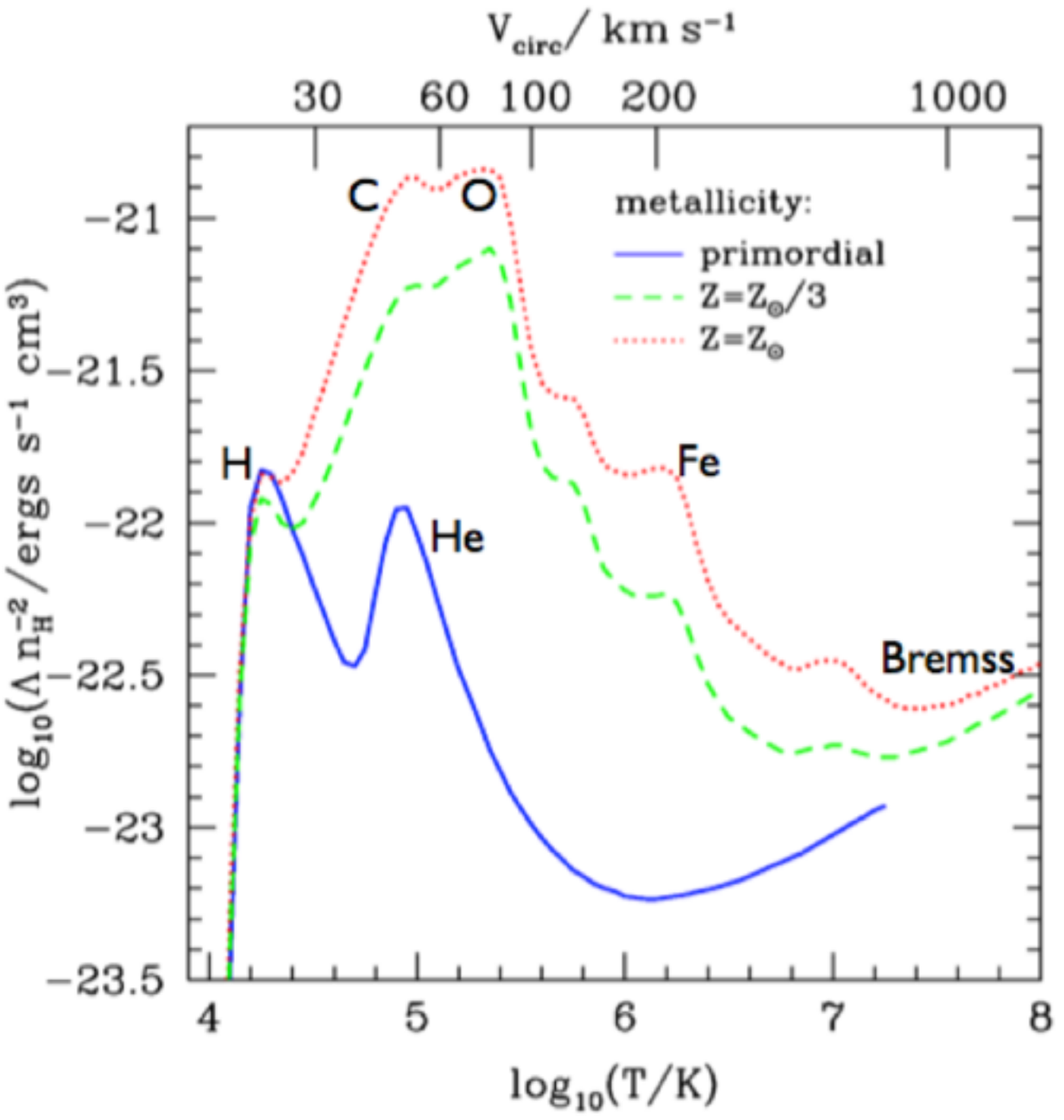
$$f_{\rm late}\, M_*\, \delta v^2_{\rm wind} \sim M_{\rm gas}\, T_{\rm max}$$

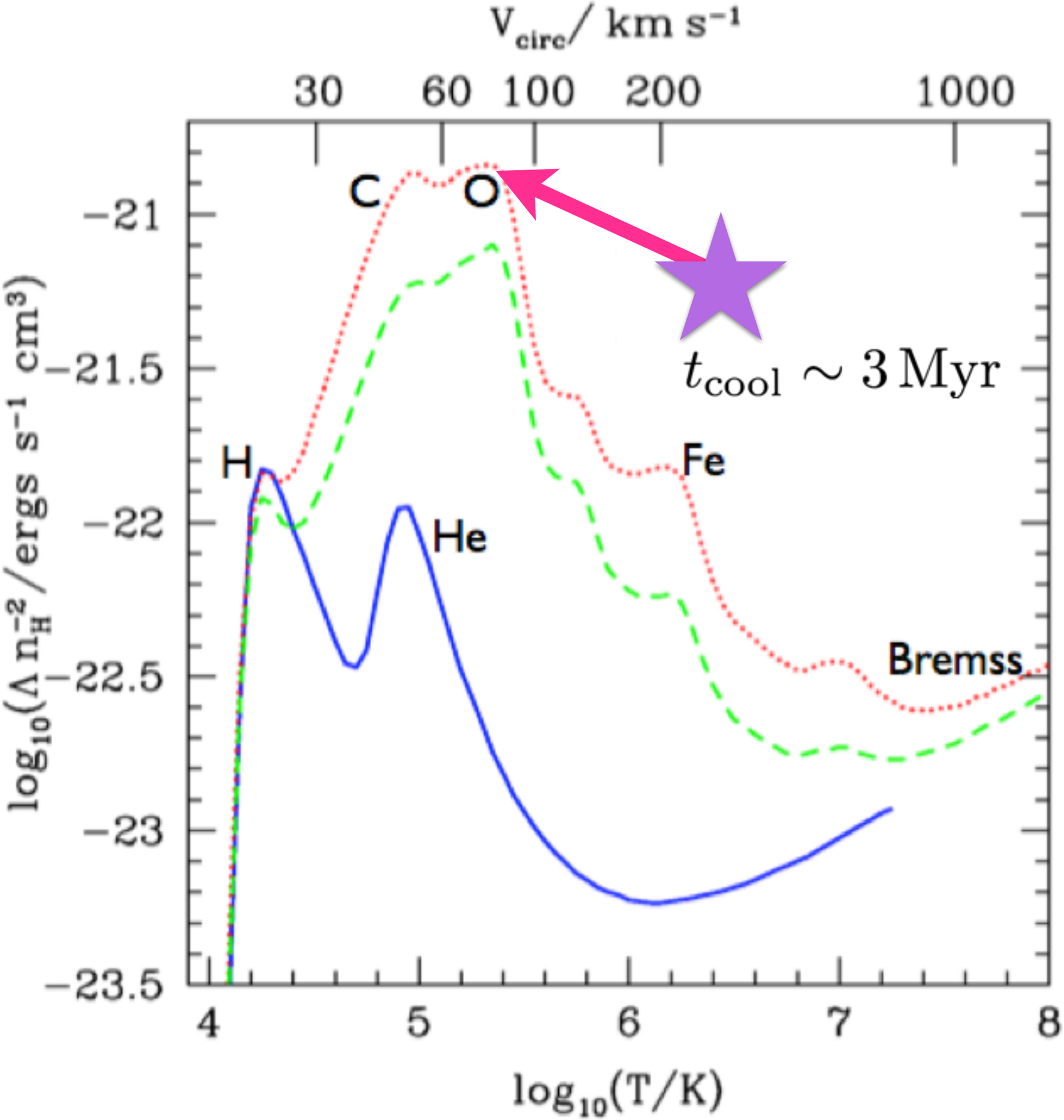
$$M_{\rm gas}(\sim T_{\rm vir}) \ll M_*$$

$$Z_{\rm AGB} \gtrsim 3 - 5\, Z_\odot$$

$$Z_{\rm SNIa} \sim 10 - 300\, Z_\odot$$

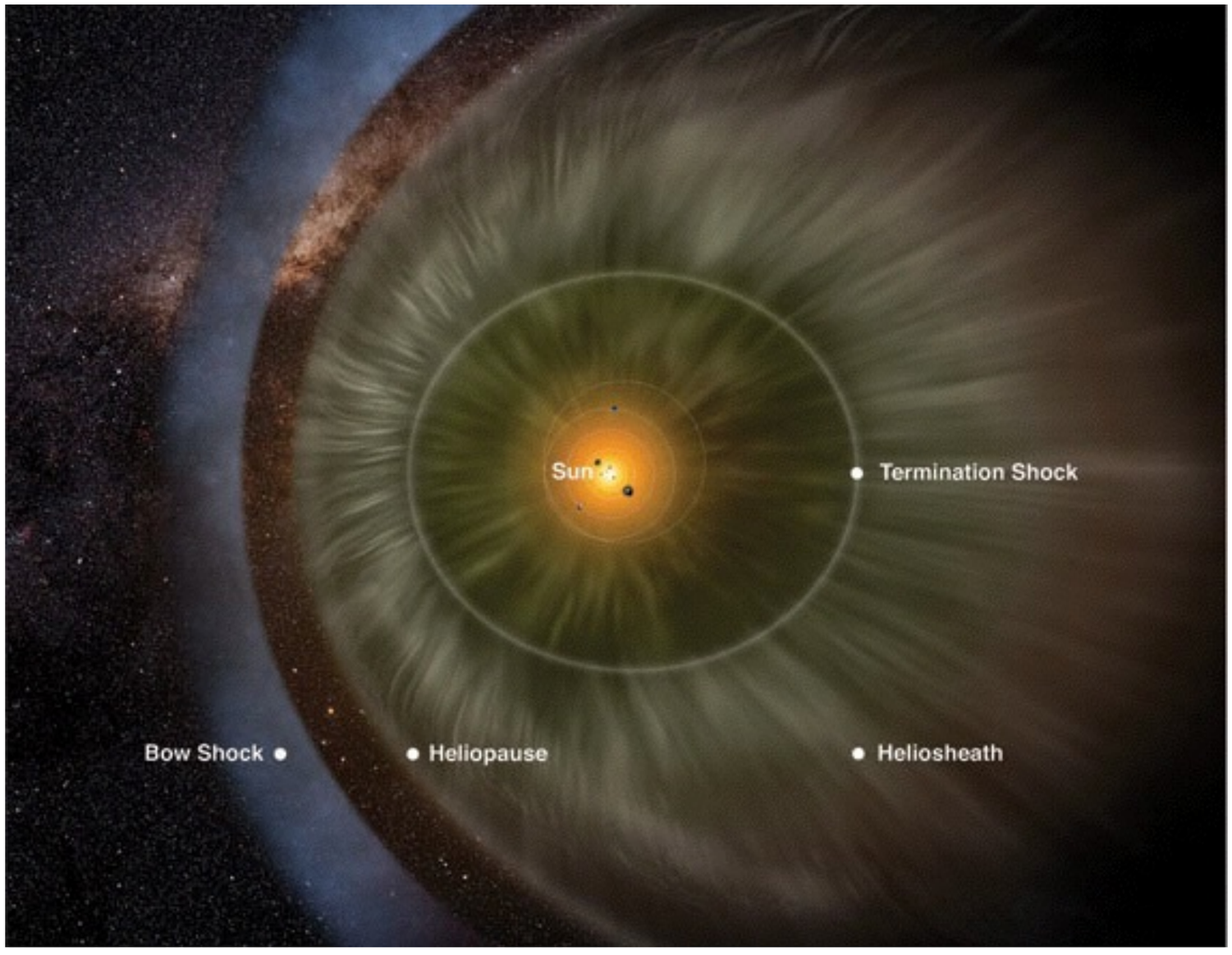





V_{circ}/ km s^{-1}
30
60
100
200
1000
C
O
H
He
Fe
Bremss
$t_{cool} \sim 3\,\mathrm{Myr}$
−21
−21.5
−22
−22.5
−23
−23.5
$\log_{10}(\Lambda\, n_H^{-2}$ /ergs s^{-1} cm^3)
4
5
6
7
8
$\log_{10}$(T/K)

Can Stars Do It?

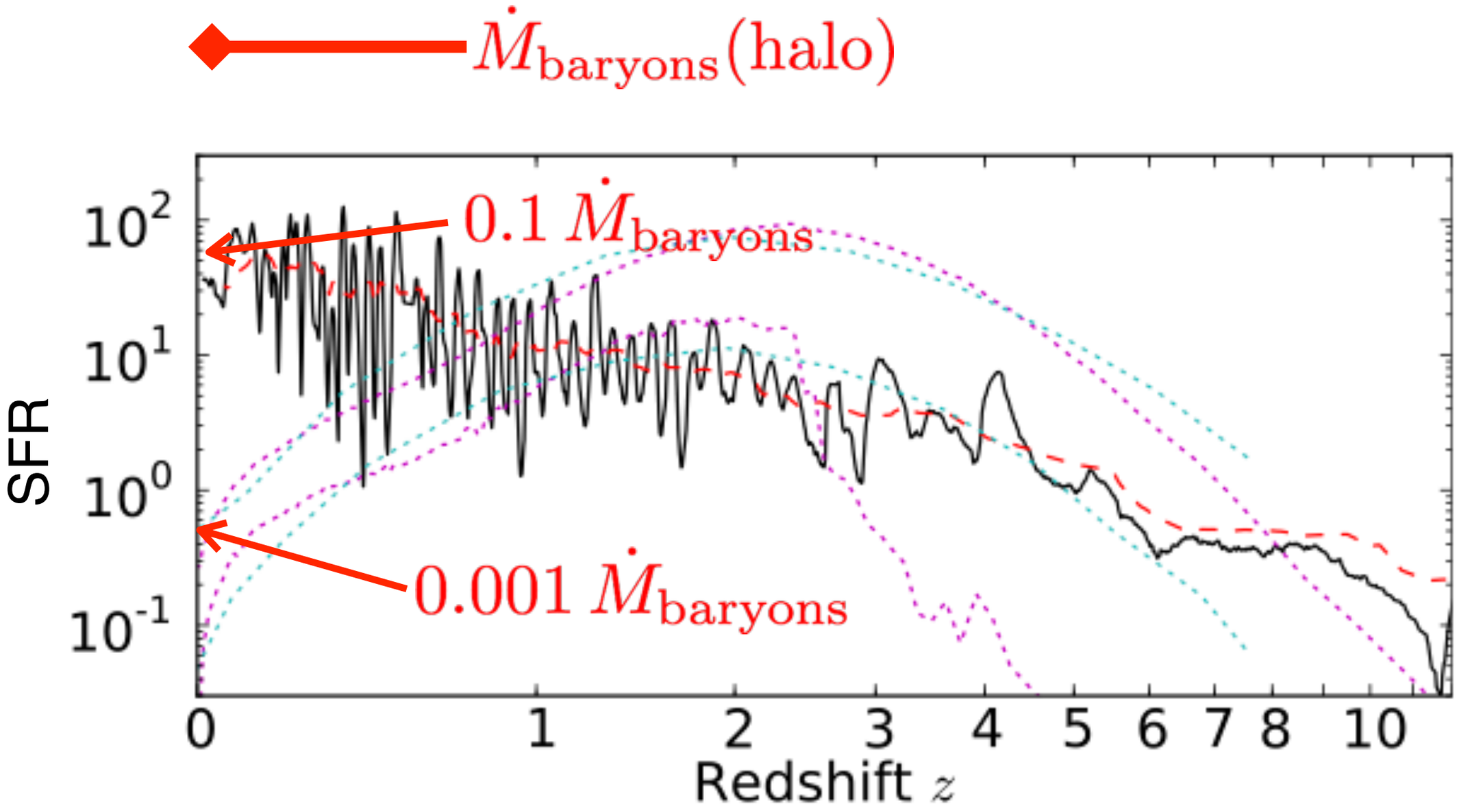
SNIa, AGB (Conroy+, Ostriker, Novak)



NO

Can Gravitational Heating Do It?

IMPORTANT, BUT … **NO**

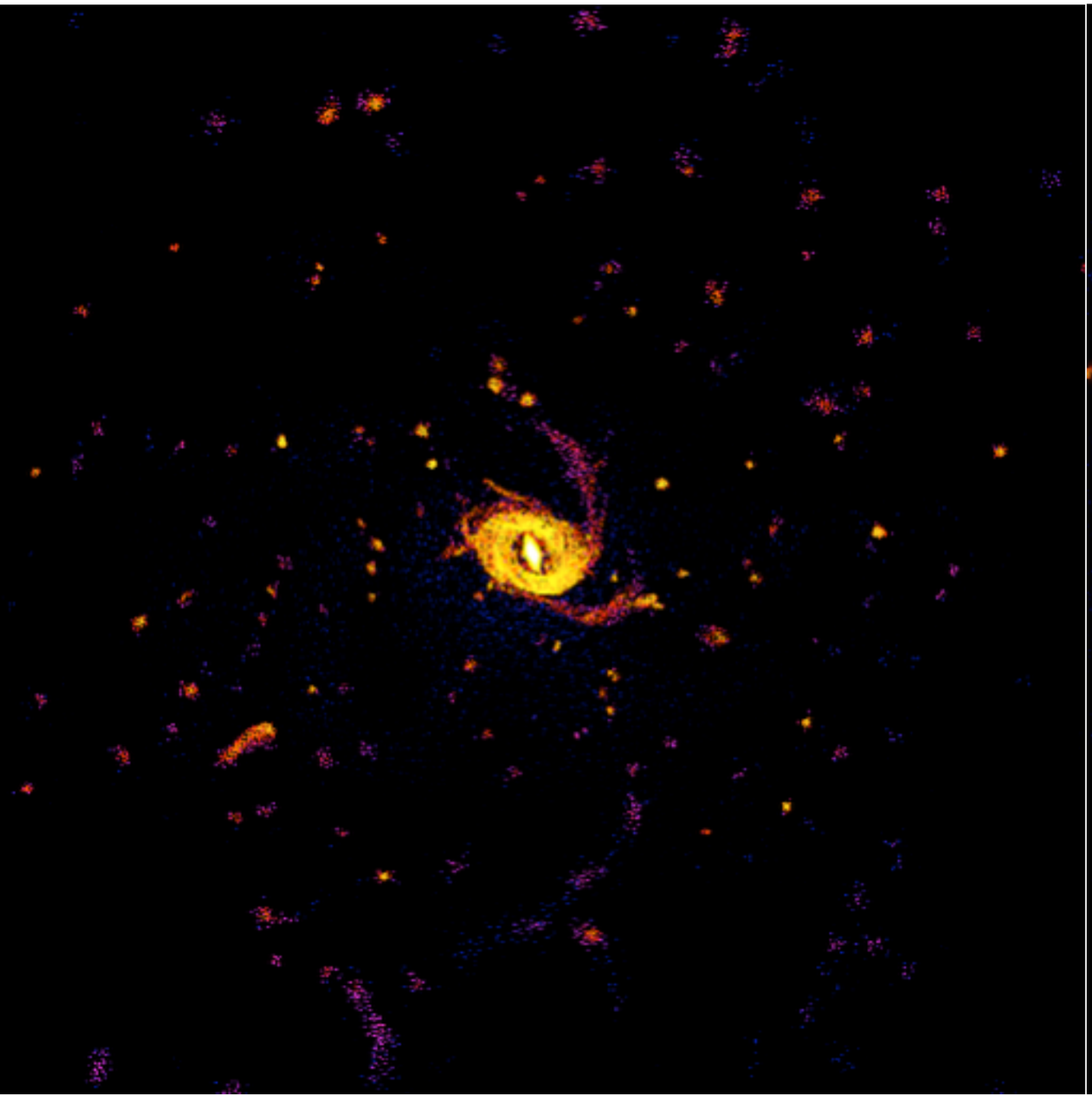


Virial shock-heating, stirring by clumps/substructure keeps 90% of gas hot

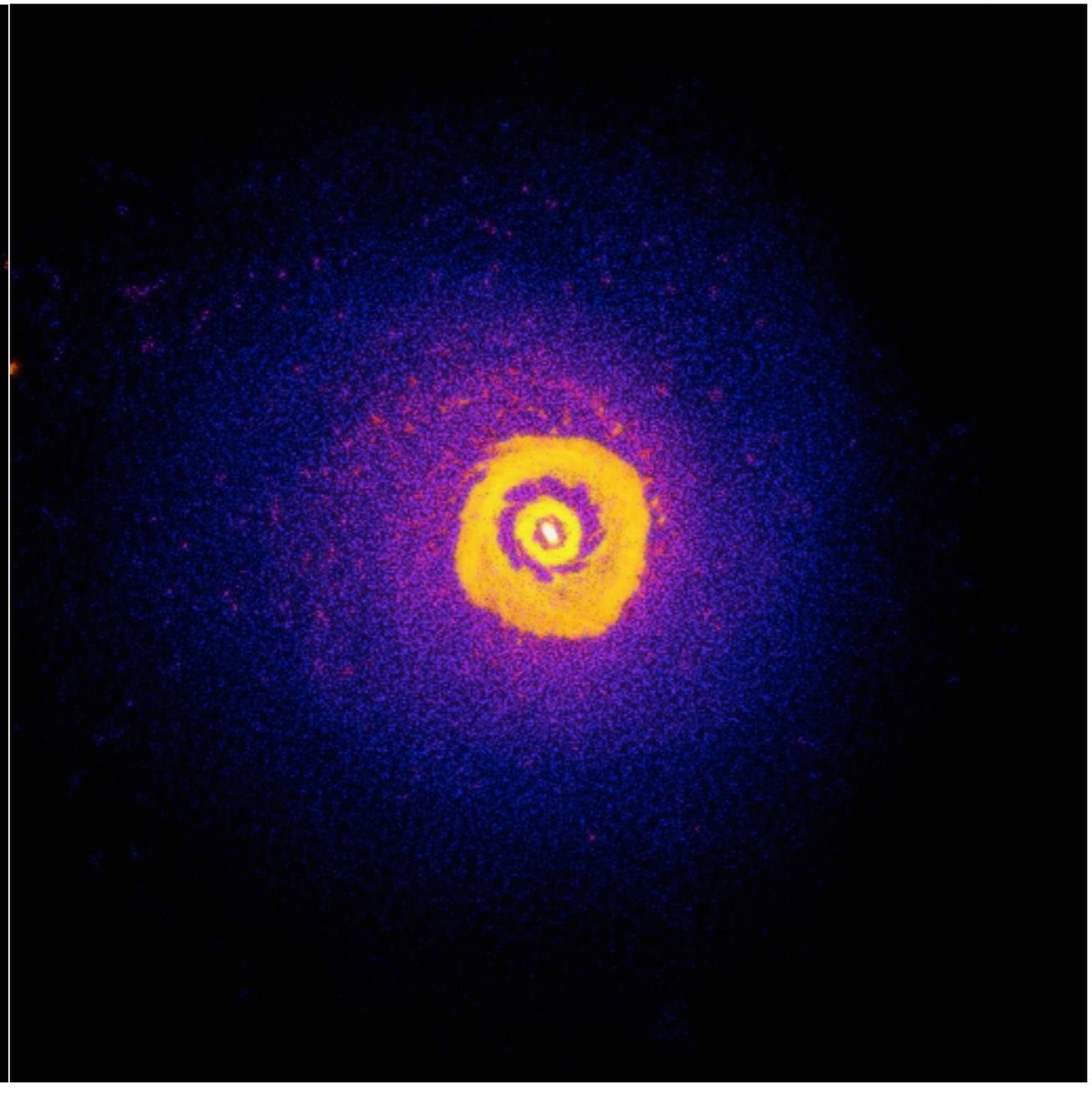
Gravitational Heating

NOT AS MANY CLUMPS THESE DAYS!

Keres et al., in prep



Density Formulation
("Old" GADGET)

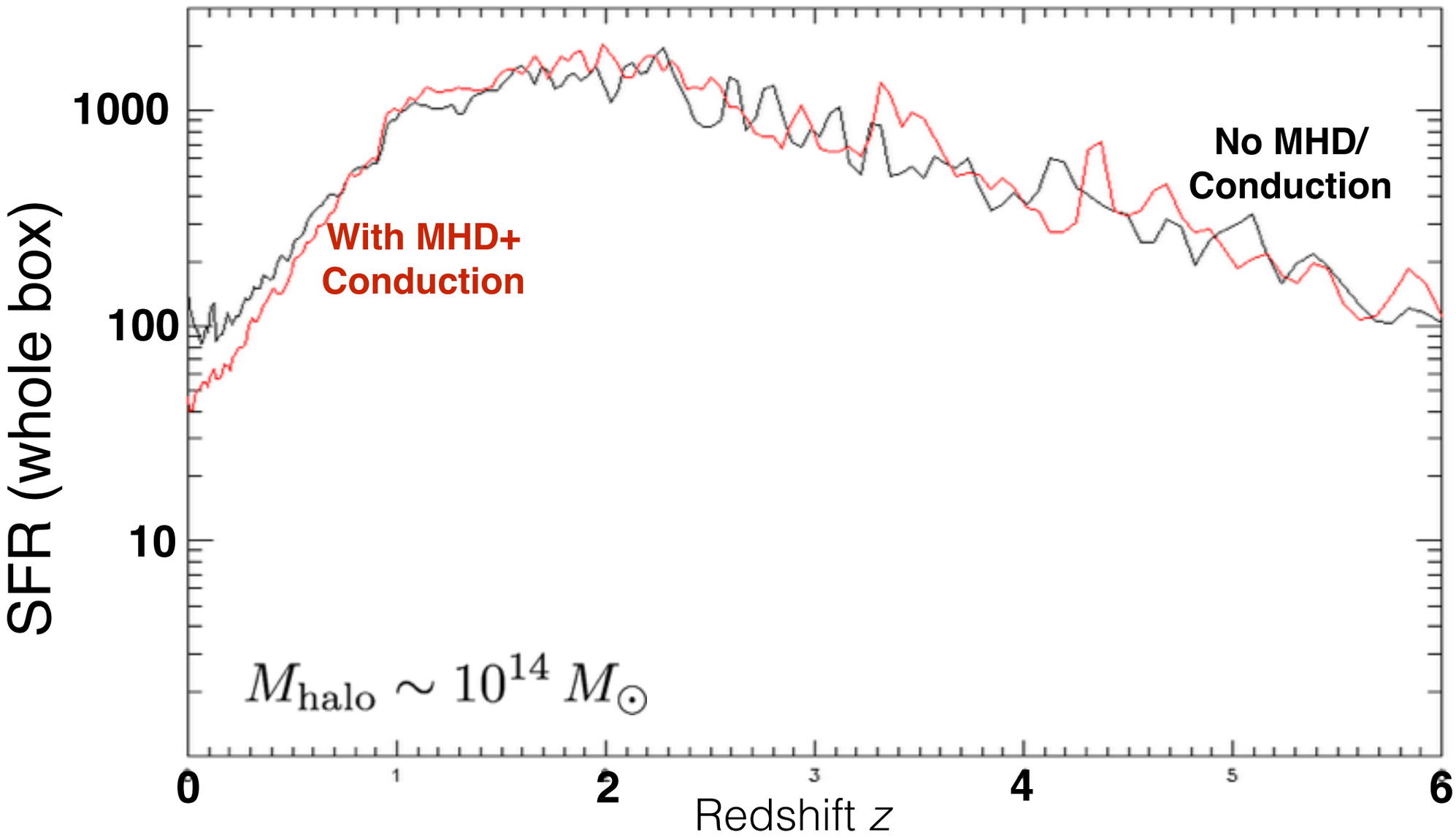


Pressure-Entropy Formulation
(P-GADGET)

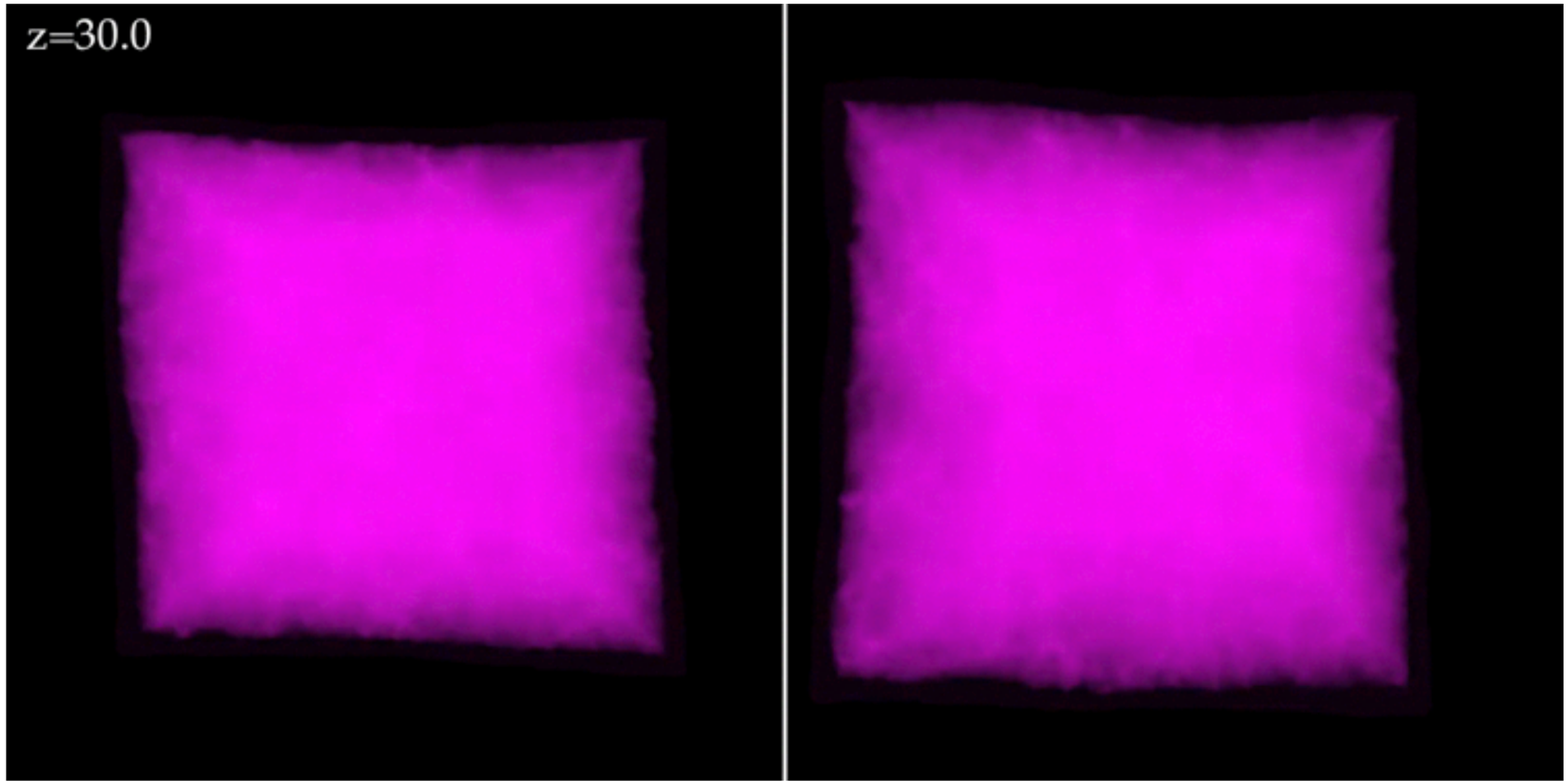
Not enough clumps, & existing ones are too metal-rich (join the cooling flow)

Can MHD & Conduction Do It?

NO



- 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.