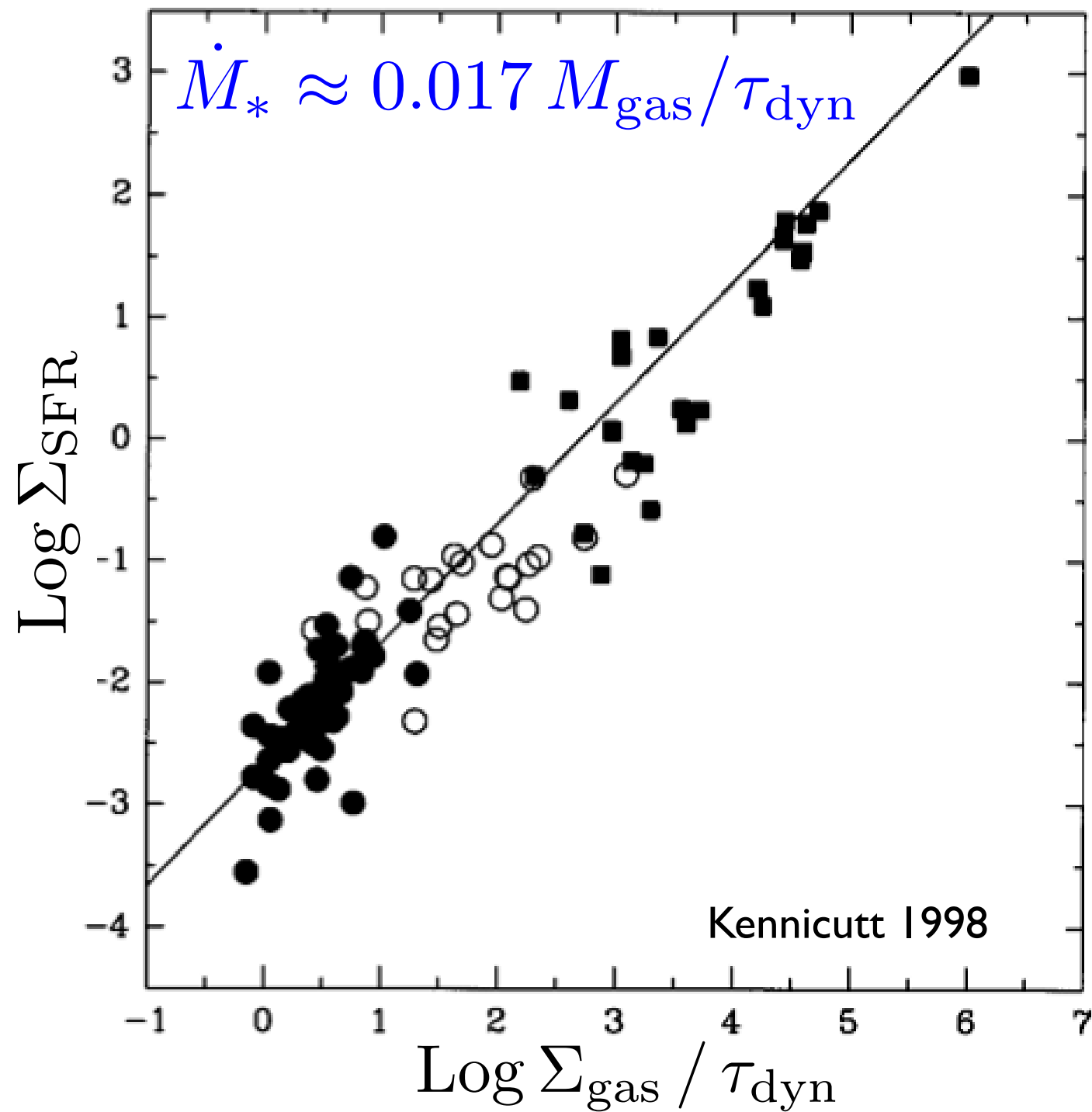


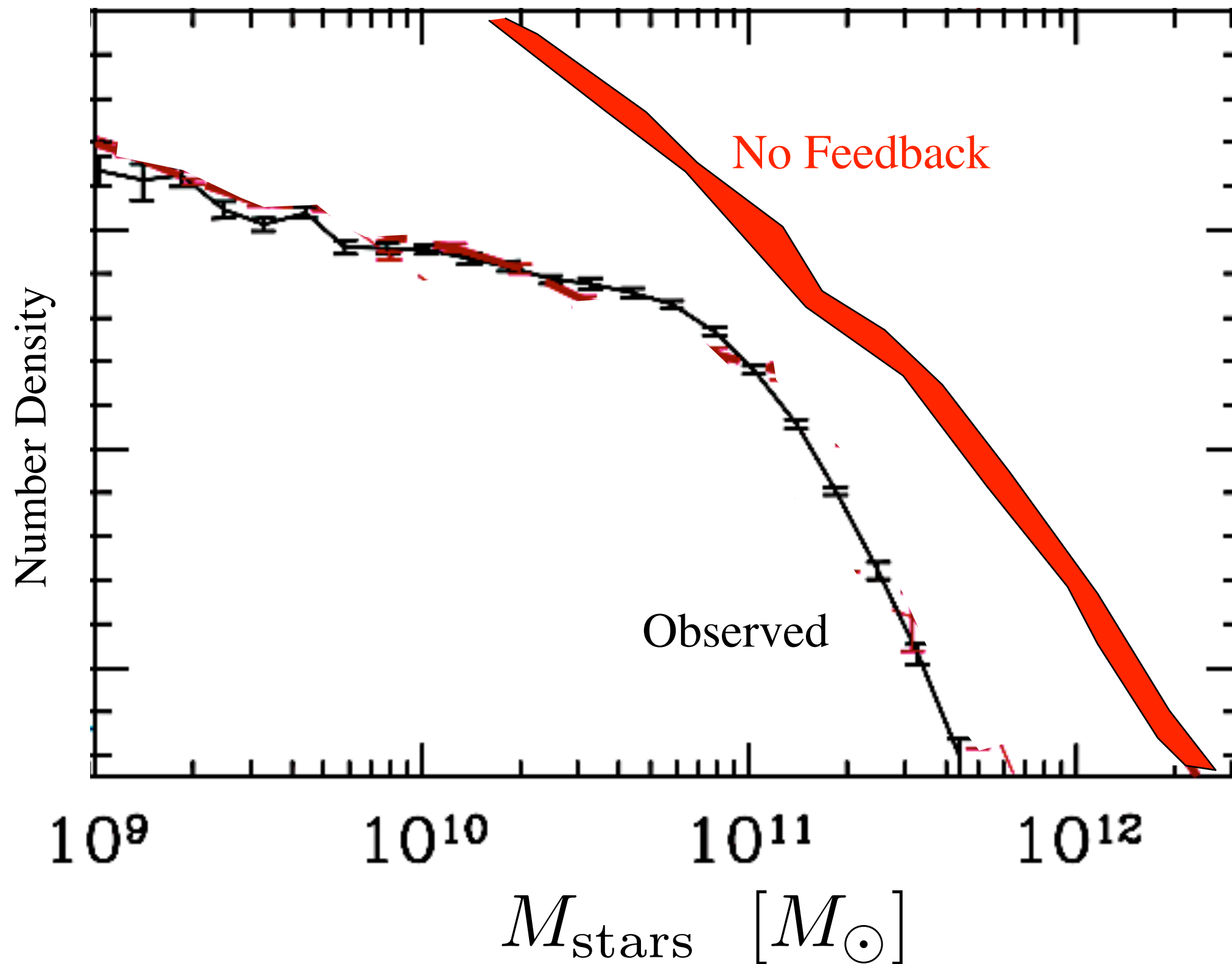
Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Feedback is the Key!

SO WHAT'S THE PROBLEM?

- Standard (in Galaxy Formation):
Couple SNe ($\sim 10^{51}$ erg/SN)
as “heating”/thermal energy

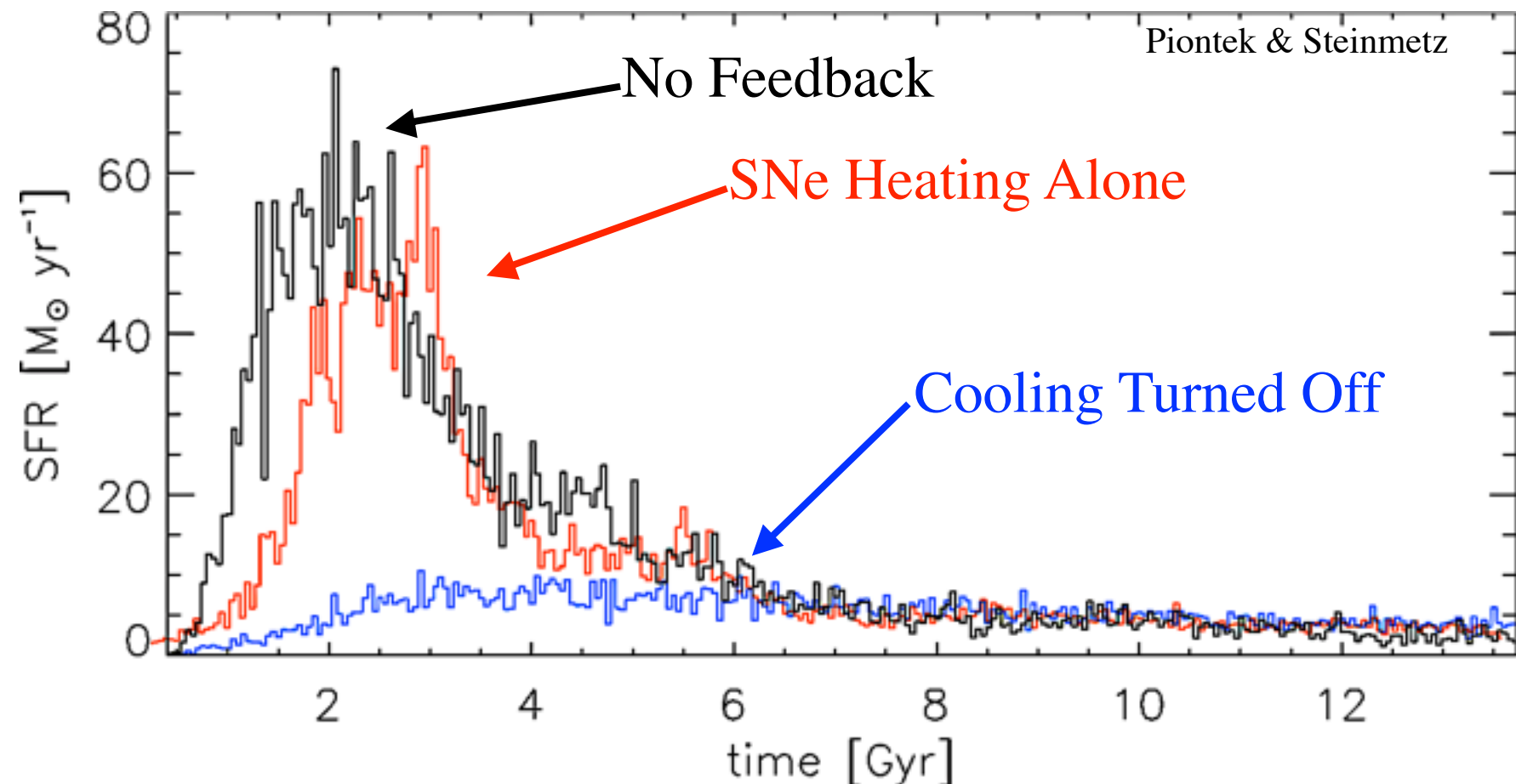
- FAILS:

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

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

- “Cheat”:

- Turn off cooling
- Force wind by hand
(‘kick’ out of galaxy)



Stellar Feedback: How Can We Do Better?

- High-resolution ($\sim 1\text{-}10\text{ pc}$),
molecular/metal cooling ($\sim 10\text{ K}$),
SF at $n_{\text{H}} > 100\text{ cm}^{-3}$

- Energy/Mass/Metal Injection:

- SNe (II & Ia)
- Stellar Winds (O & AGB)
- Photoionization (HII)
& Photoelectric

- Momentum Flux:

- Radiation Pressure

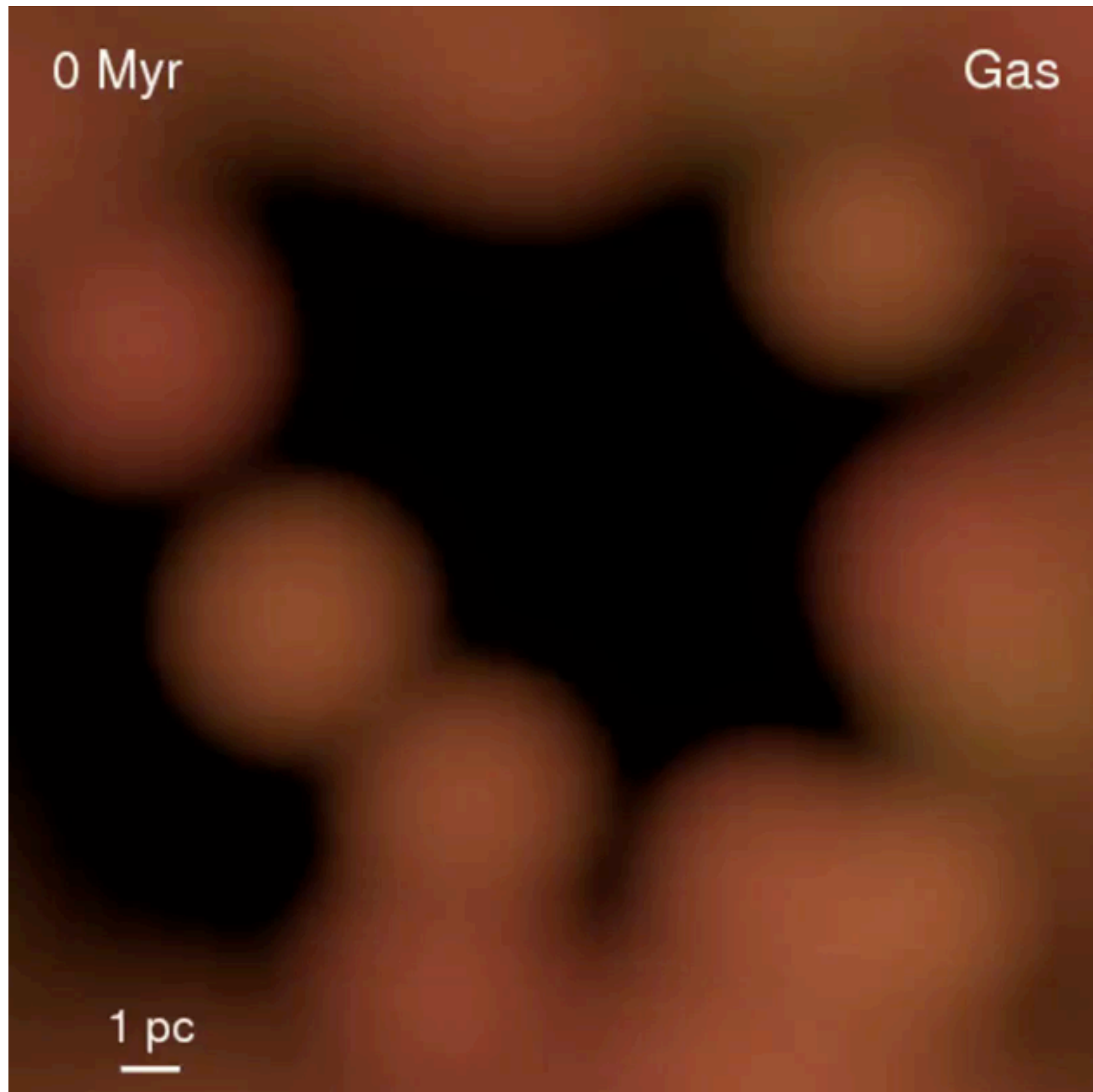
$$\dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}})$$

- SNe

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

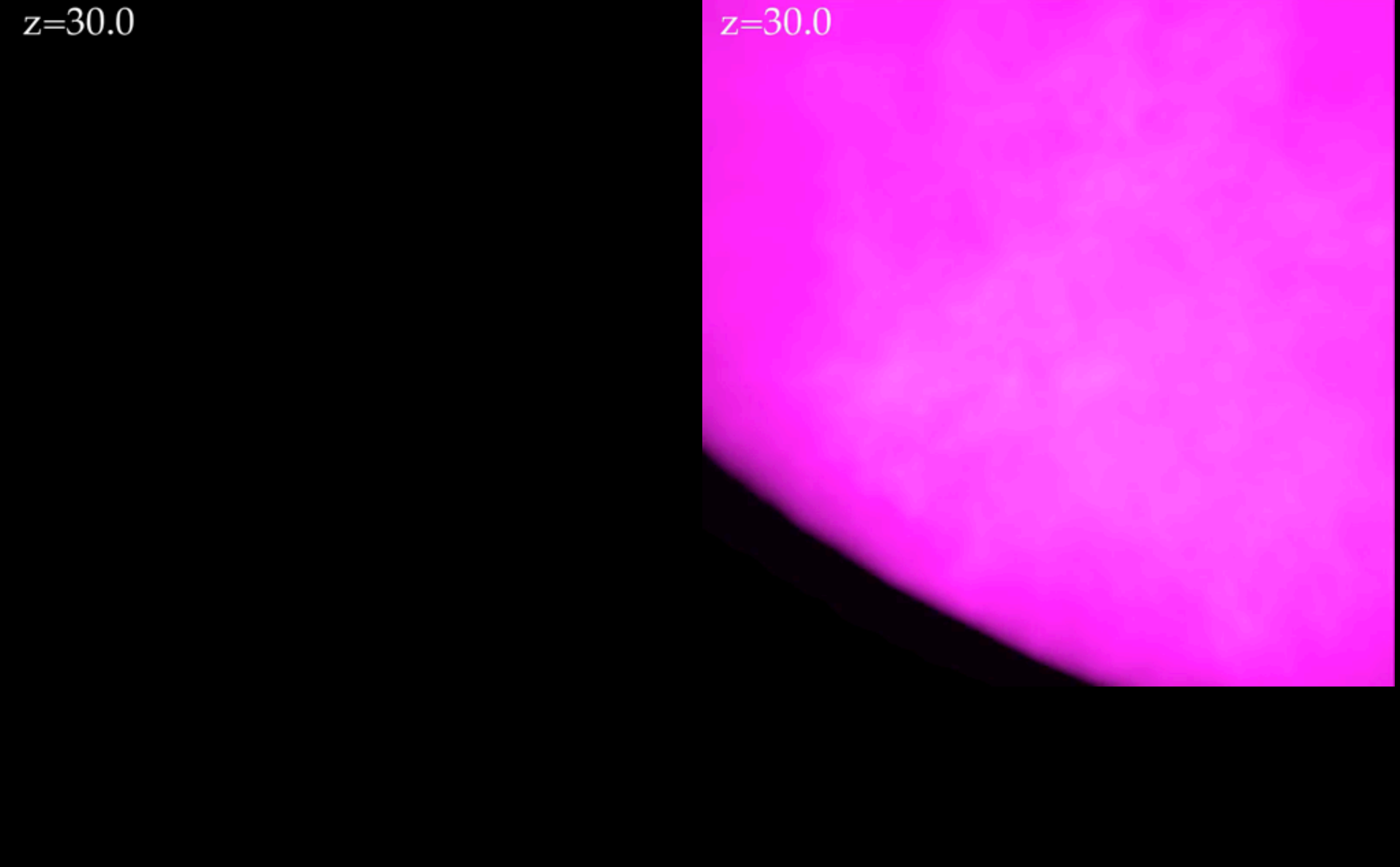
- Stellar Winds

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



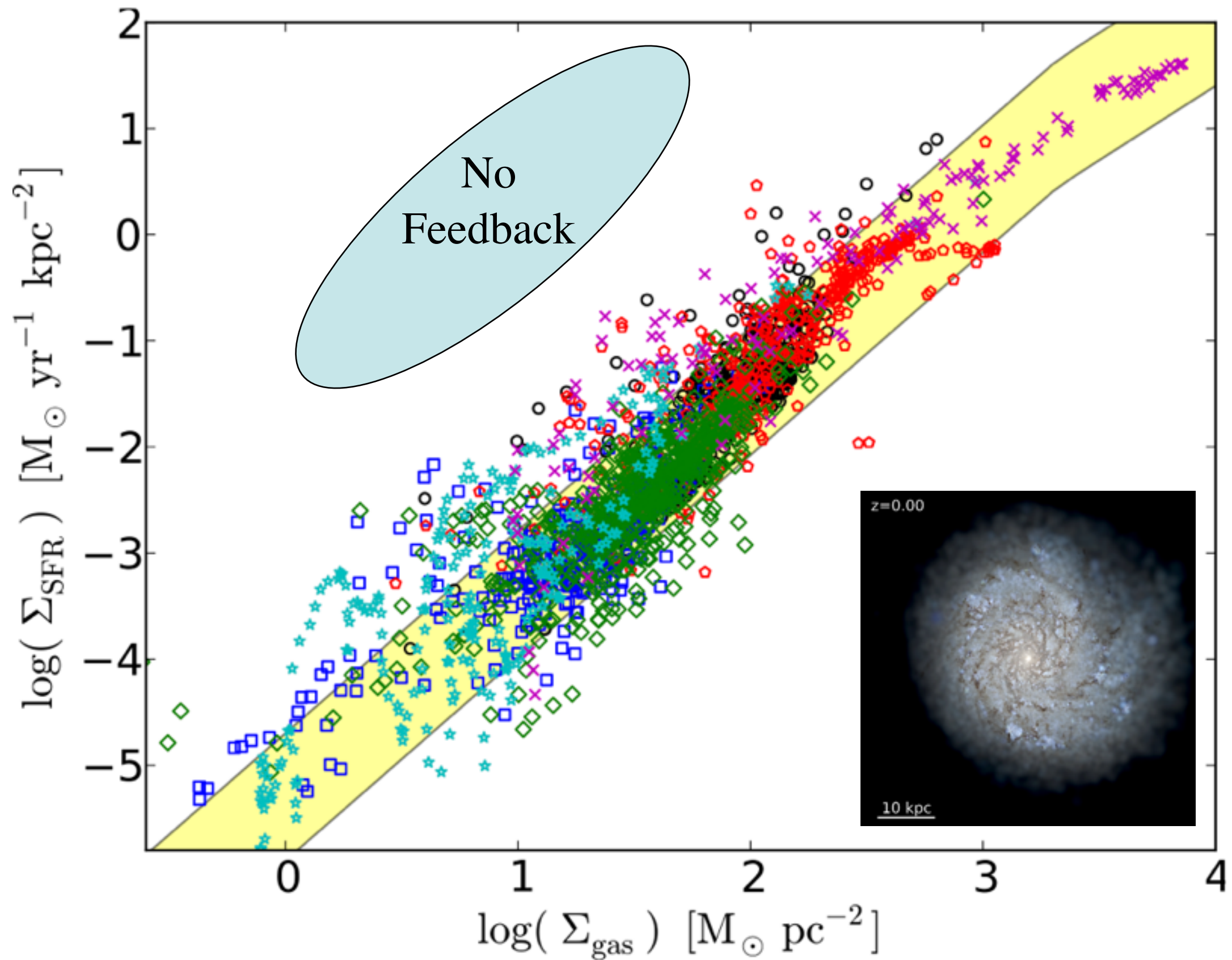
- (also MHD, anisotropic conduction, diffusion)

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



Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!

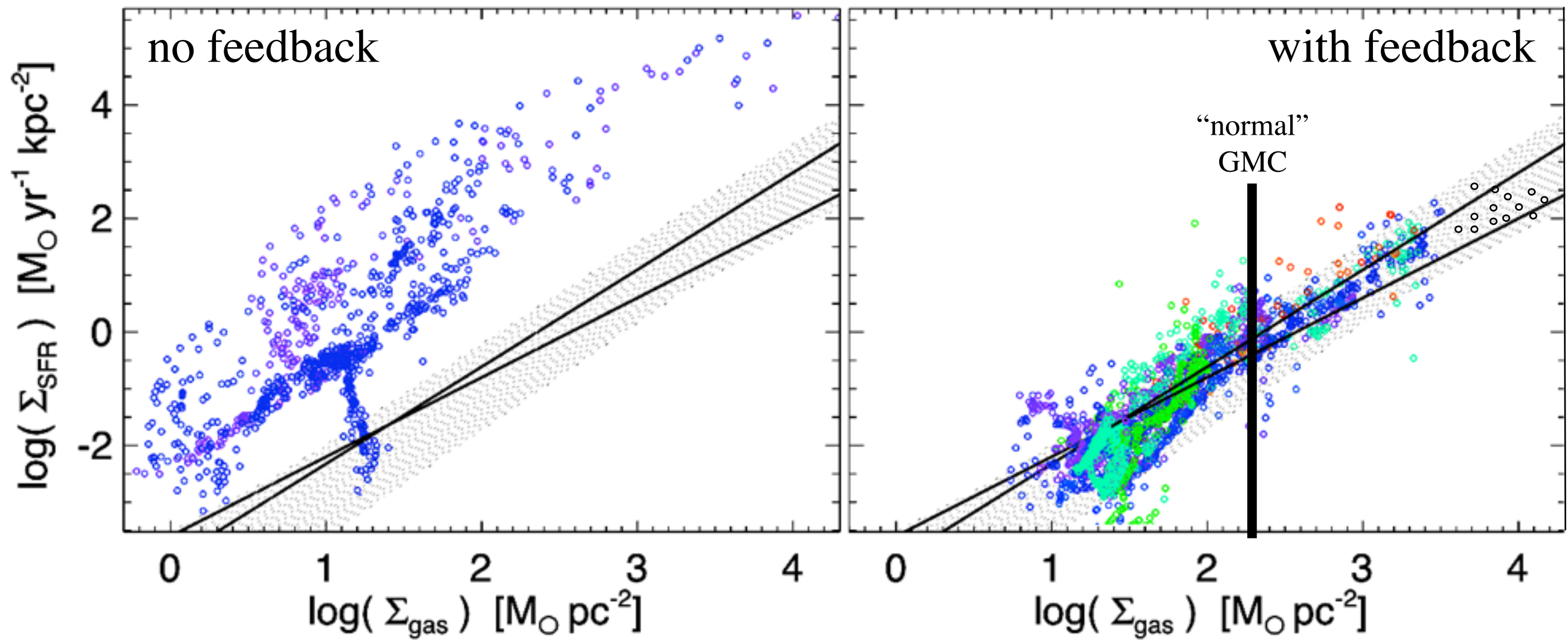


Kennicutt-Schmidt relation emerges naturally

ISOLATED GALAXIES

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

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



- Efficient cooling $\rightarrow$ the gas disk dissipates its support:

$$\dot{P}_{\text{diss}} \sim \frac{M_{\text{gas}} v_{\text{turb}}}{t_{\text{crossing}}} \sim M_{\text{gas}} \sigma_{\text{disk}} \Omega$$

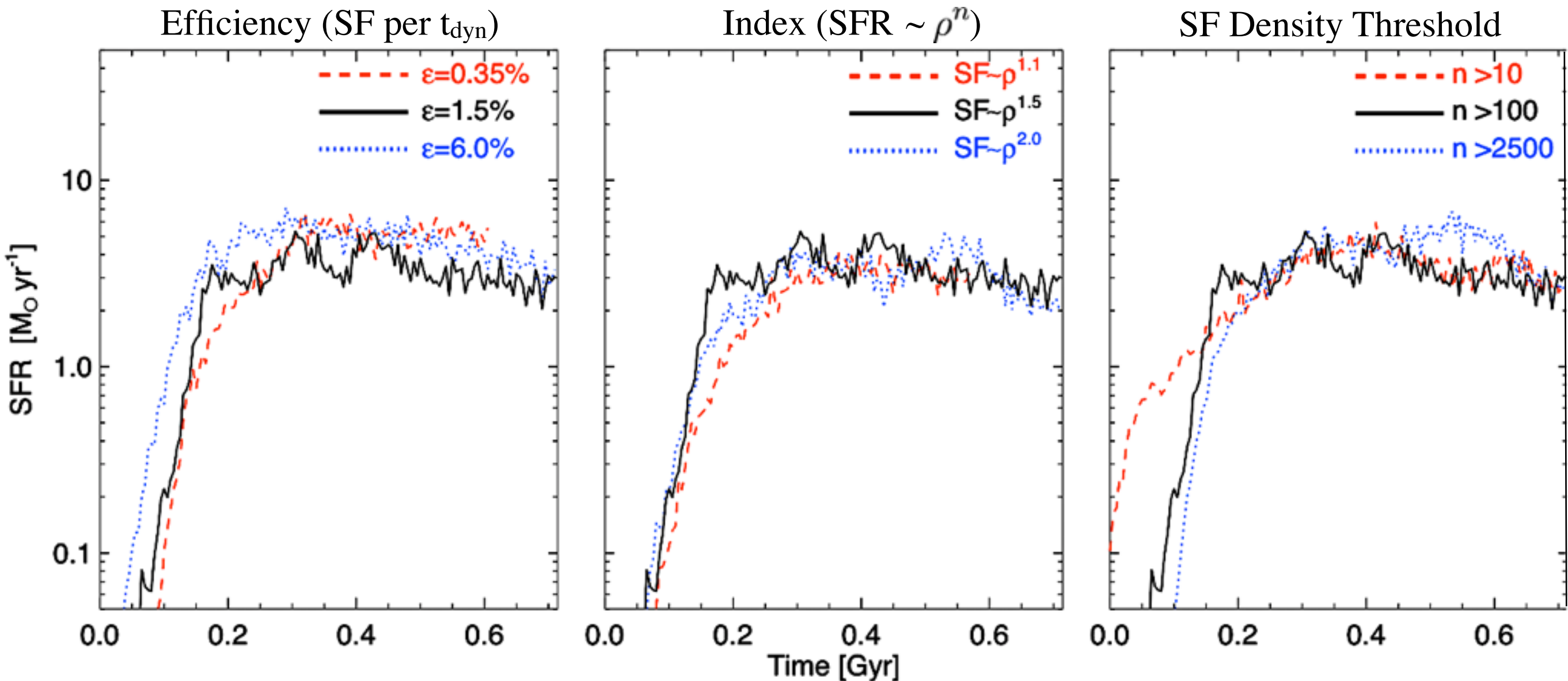
- Collapse stops when momentum input from feedback:

$$\dot{P}_* \sim \dot{P}_{\text{diss}}$$

$$\dot{P}_* \sim \text{few} \times \frac{L}{c} \sim \epsilon_* \dot{M}_* c$$

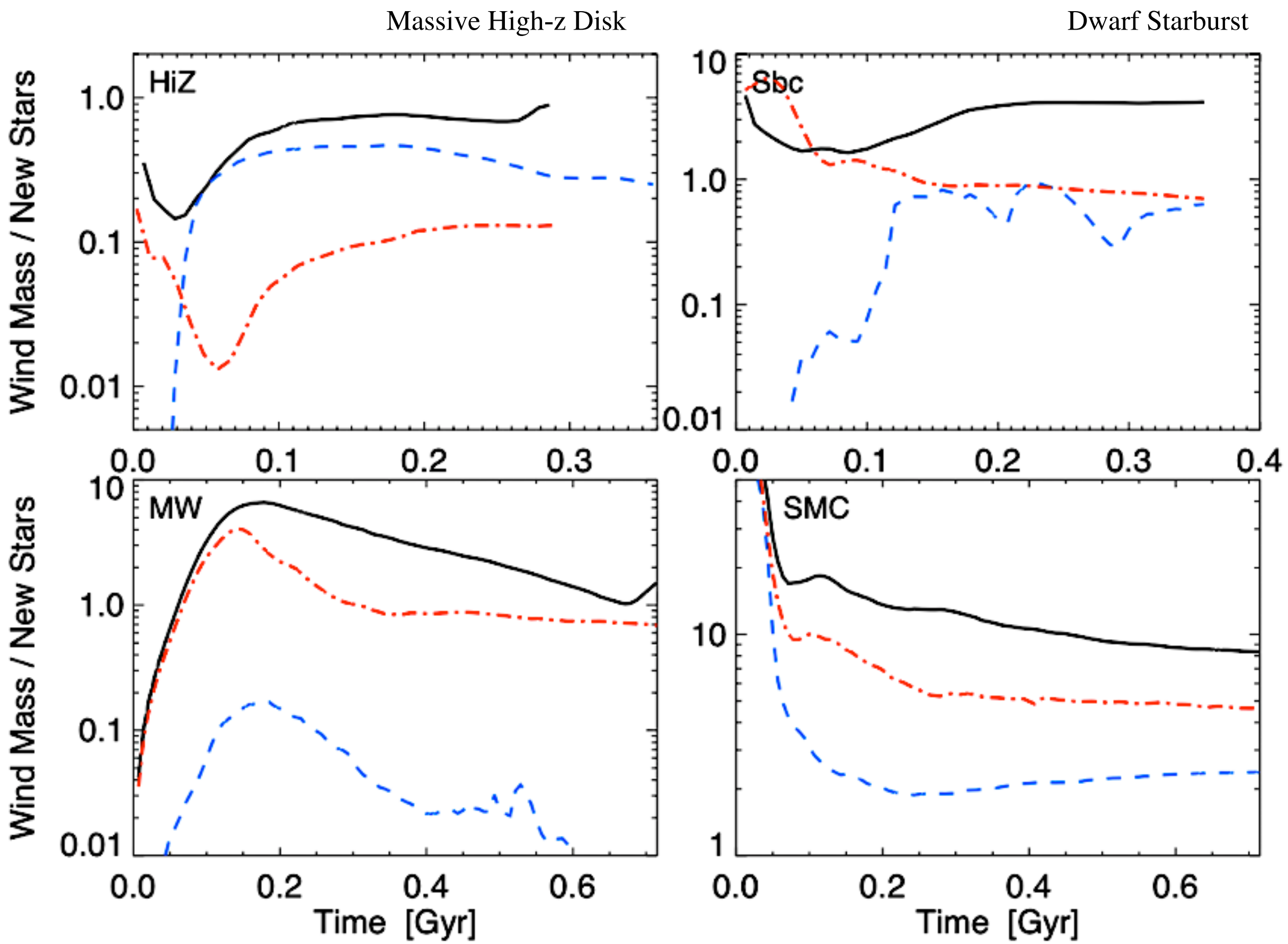
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c} \right) \Sigma_{\text{gas}} \Omega \sim 0.02 \Sigma_{\text{gas}} \Omega$$

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



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

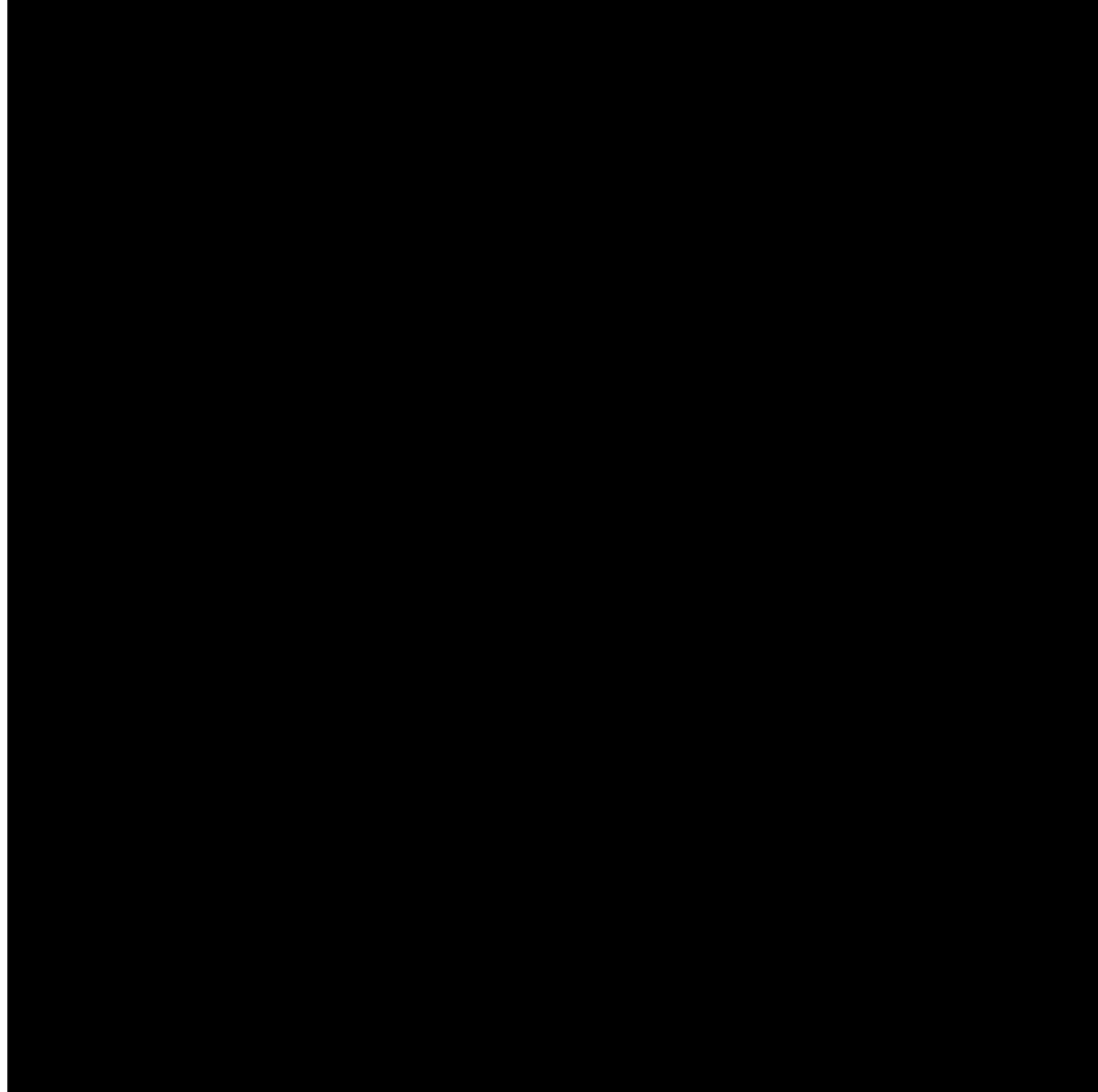
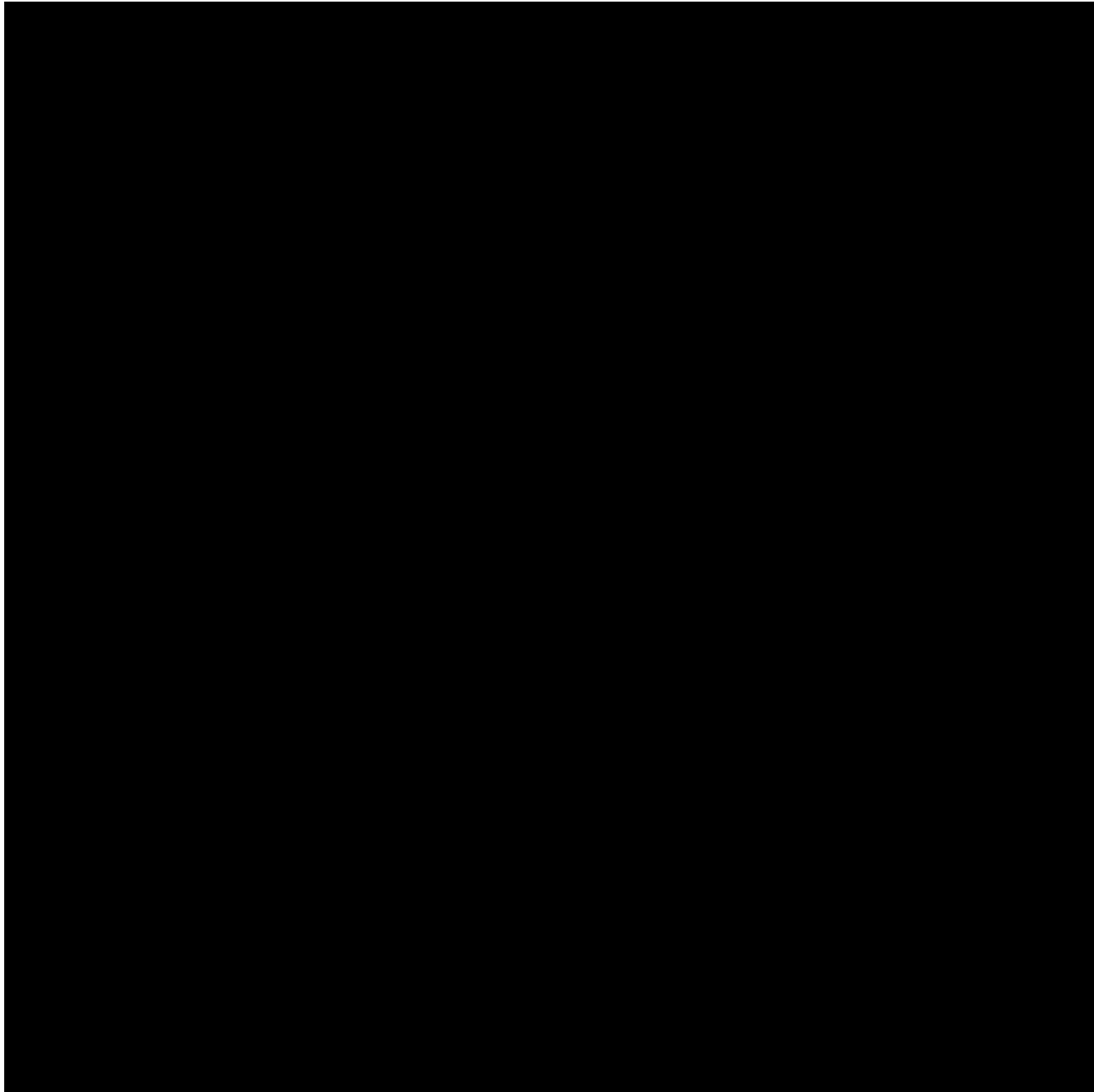
Inflows & Outflows



Proto-MW: Gas Temperature:

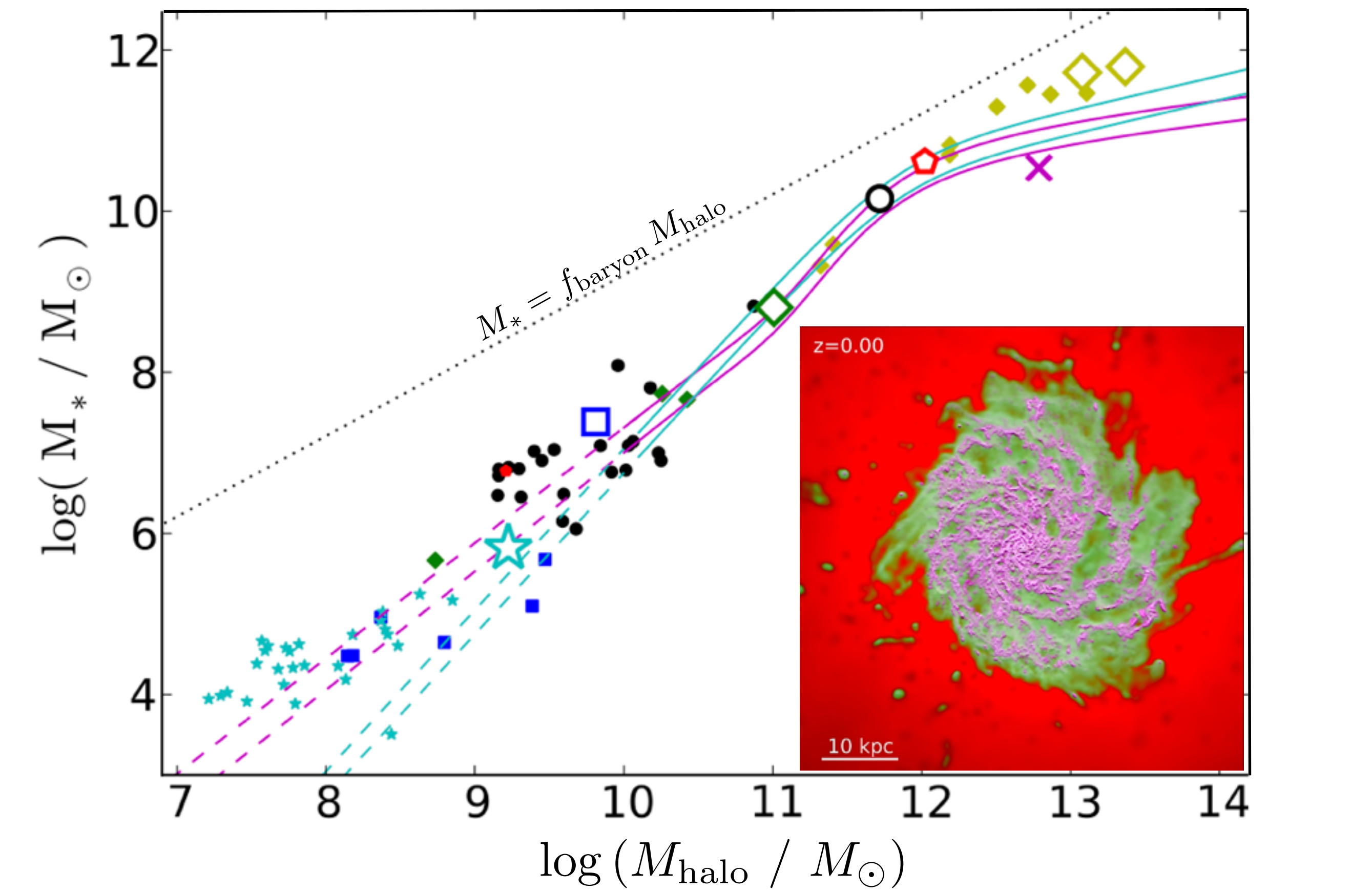
No Feedback

Following Full Feedback

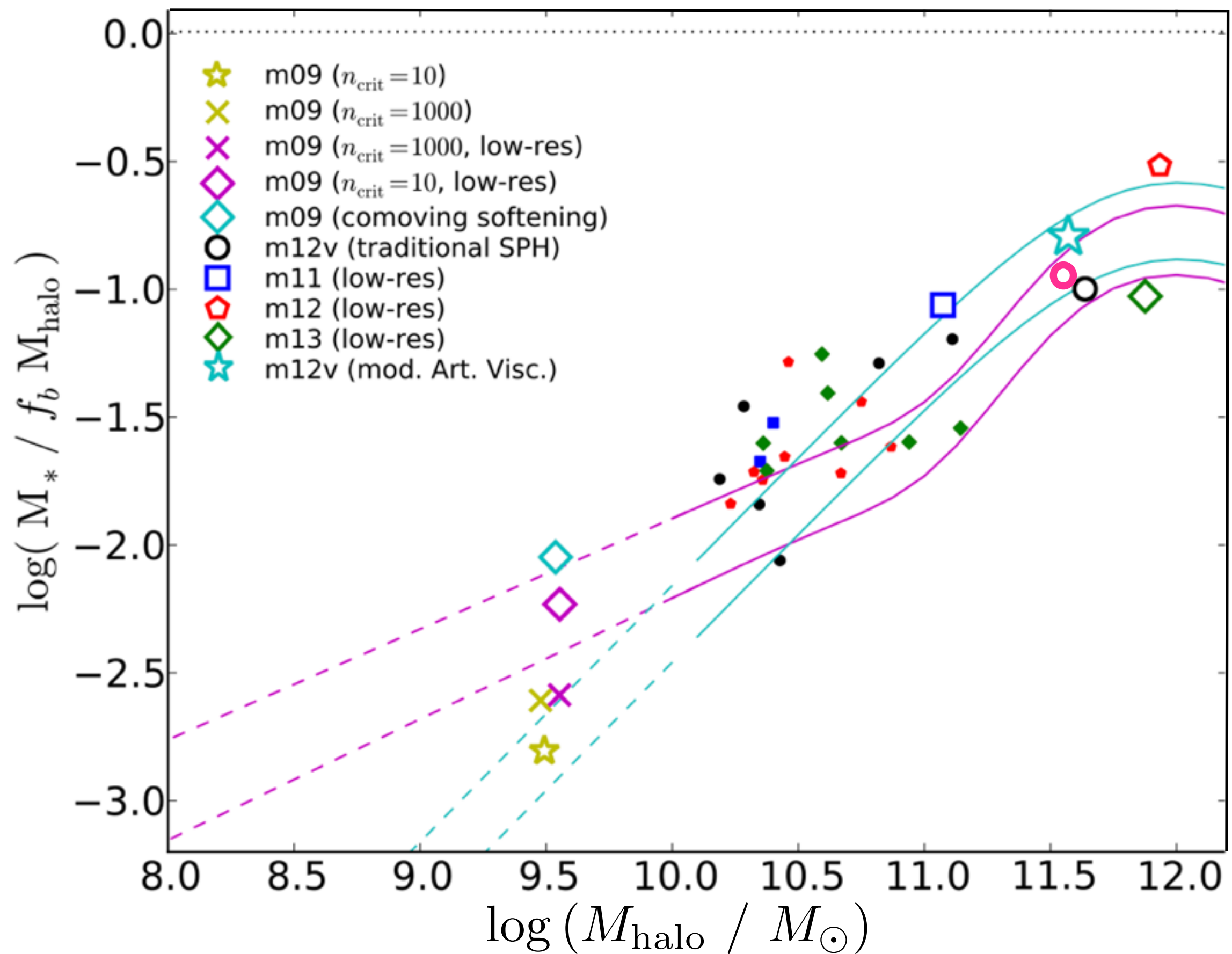


Does Stellar Feedback Explain the Mass Function?
HOW EFFICIENT ARE GALACTIC WINDS?

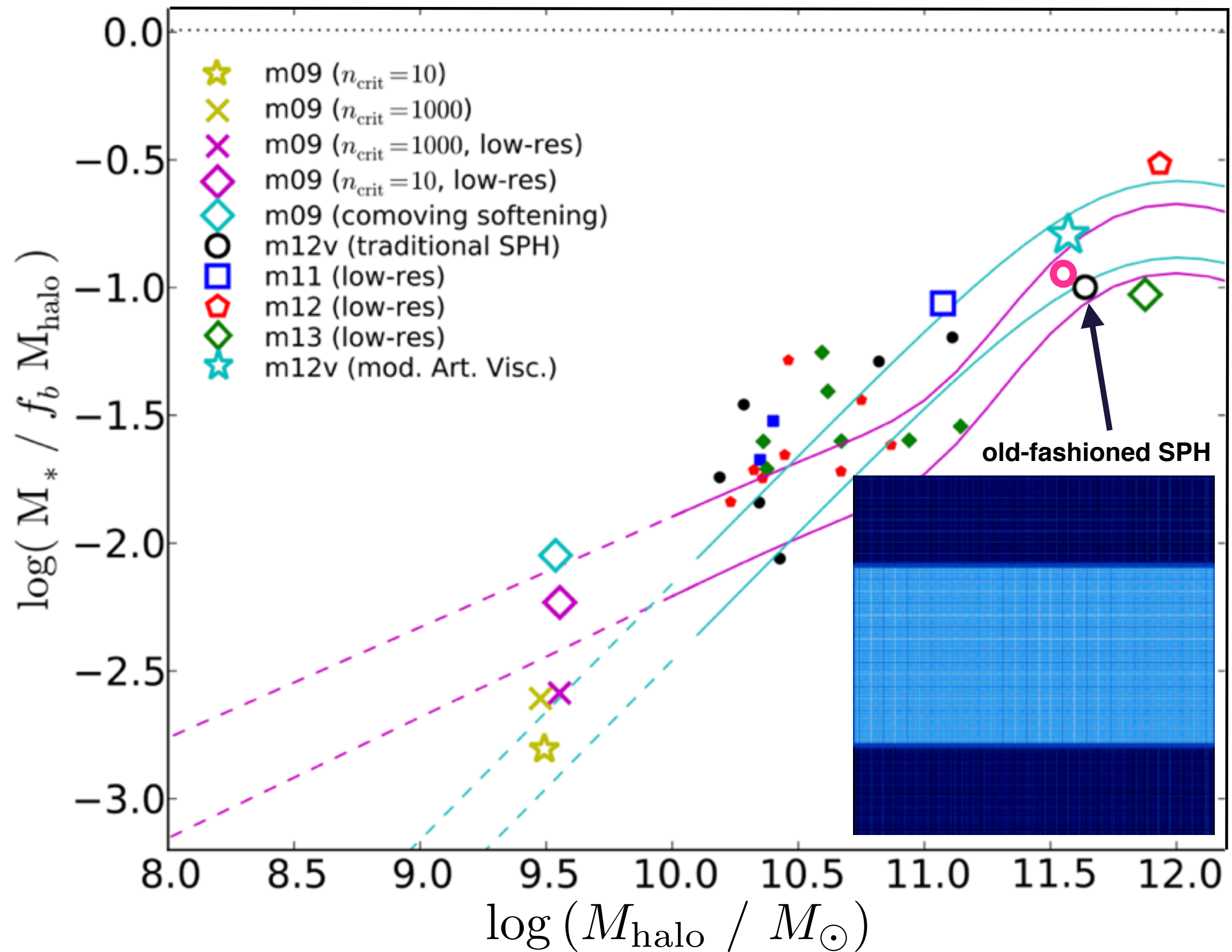
PFH, Keres, et al. (arXiv:1311.2073)



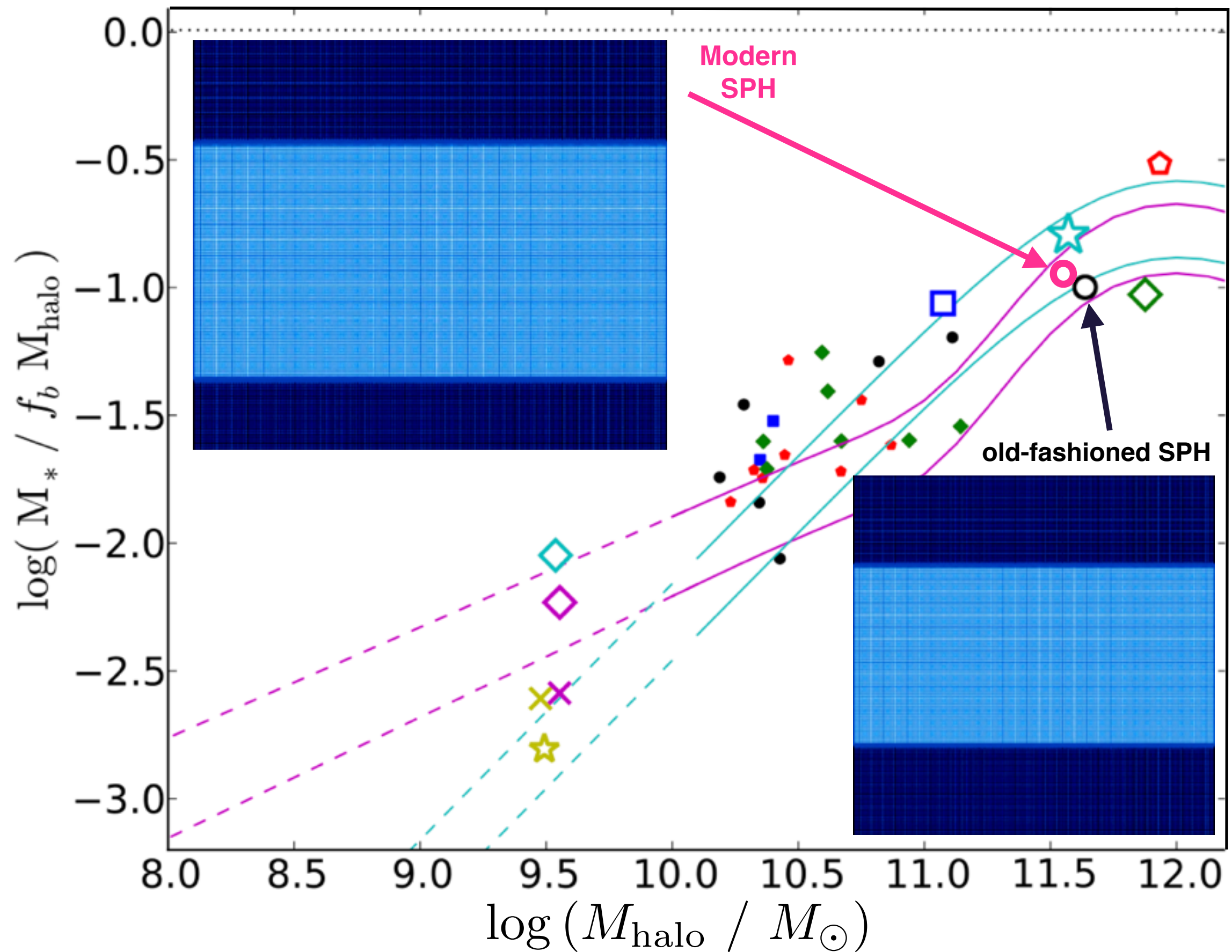
“ALGORITHMIC” CHOICES NOT DOMINANT

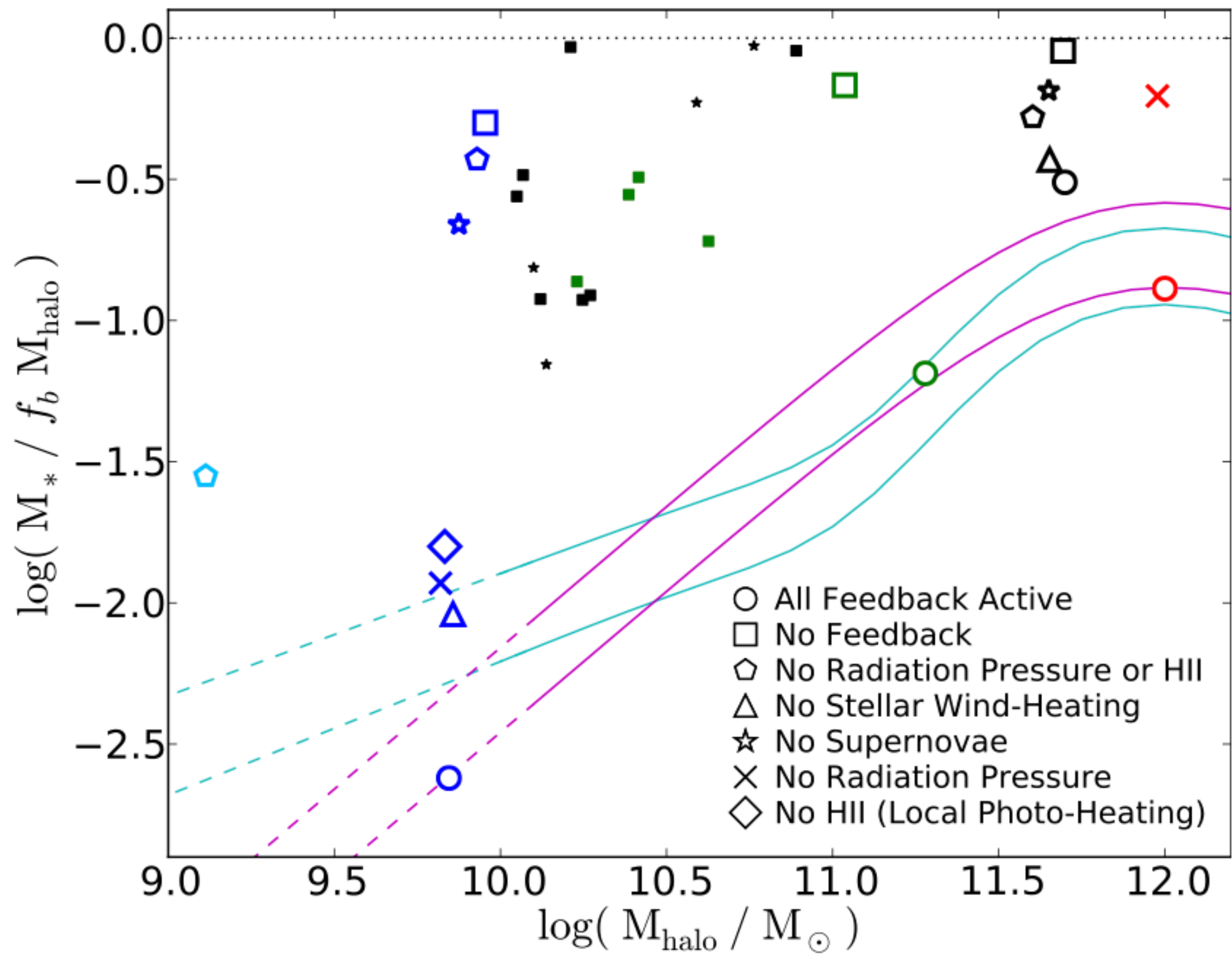


“ALGORITHMIC” CHOICES NOT DOMINANT

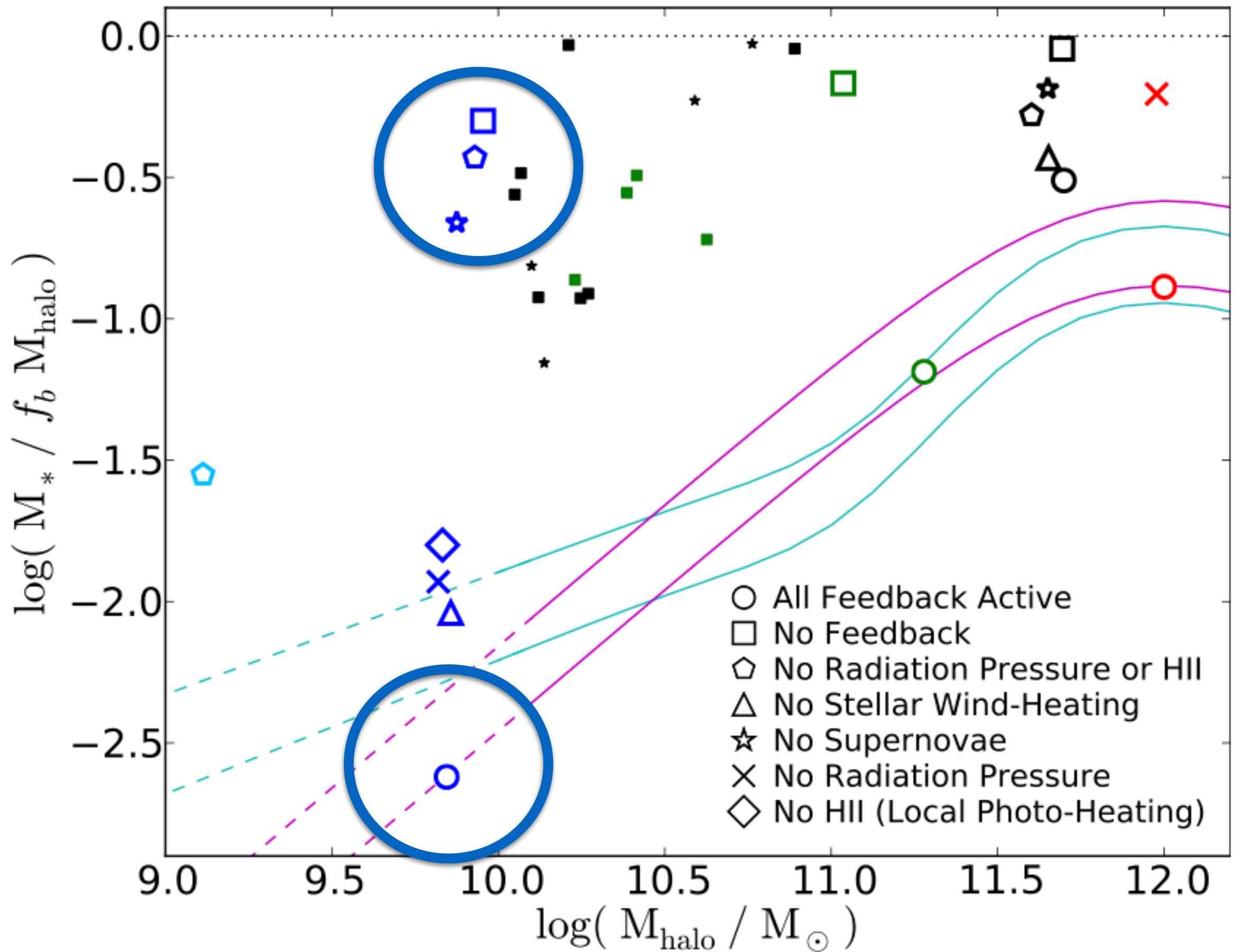


“ALGORITHMIC” CHOICES NOT DOMINANT





MULTIPLE FEEDBACK MECHANISMS ARE CRITICAL

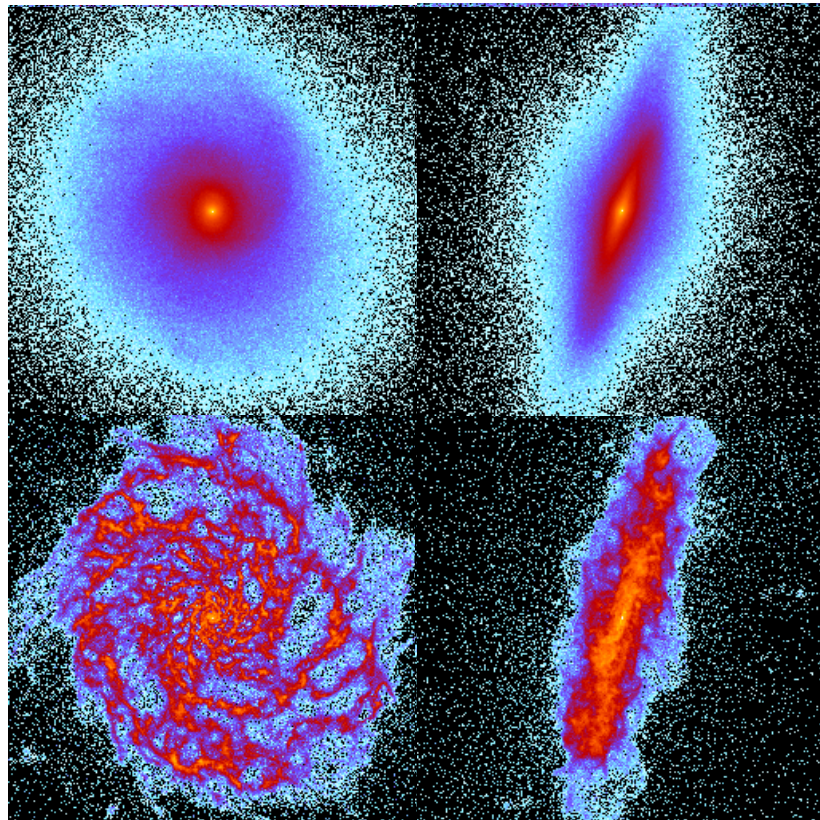


But Feedback *Does* Matter

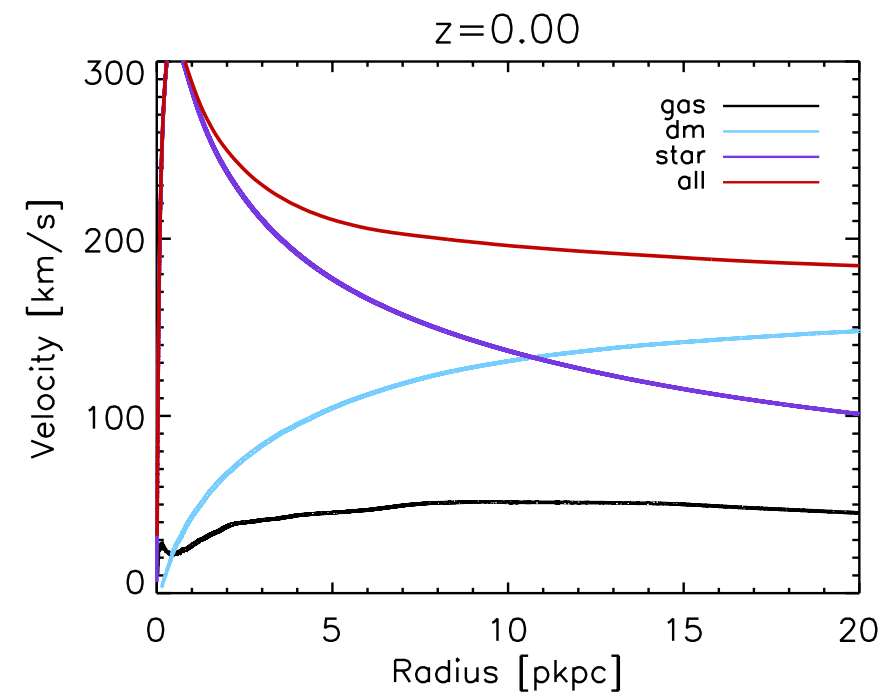
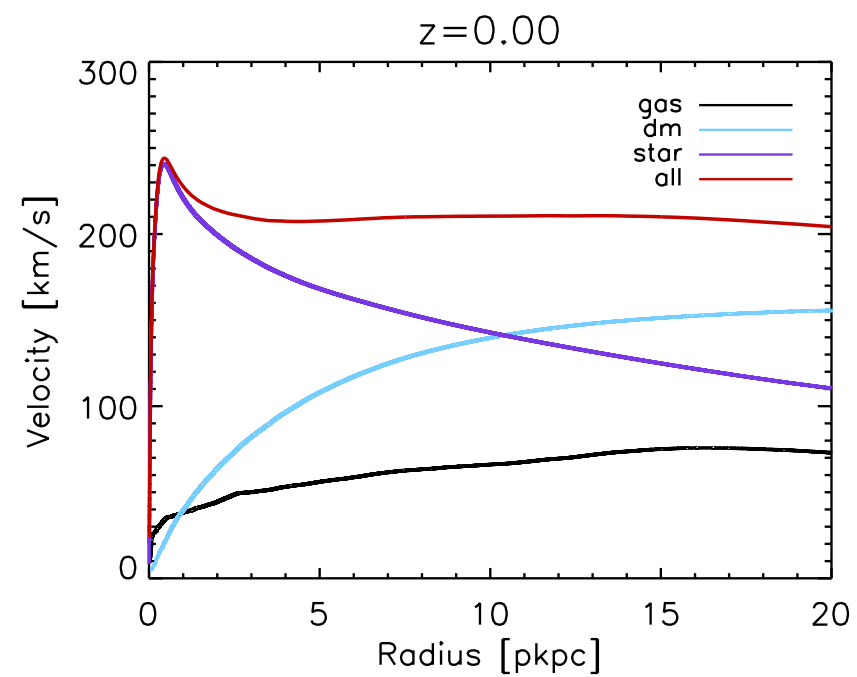
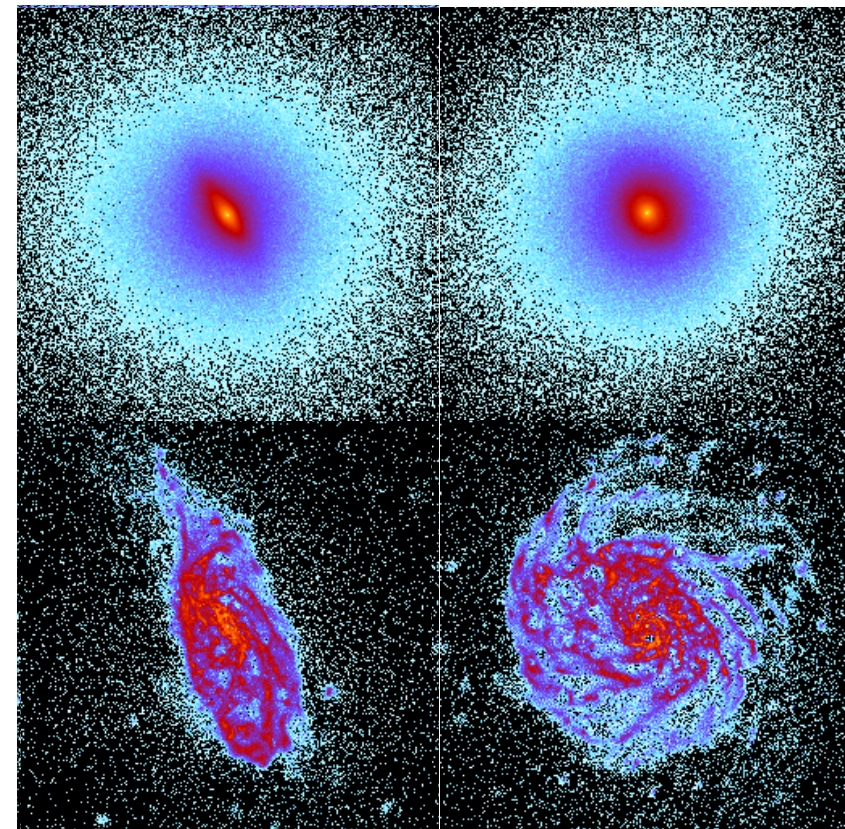
DETAILS & MULTIPLE MECHANISMS IMPORTANT

van de Voort et al., in prep

standard



no multiple-scattering



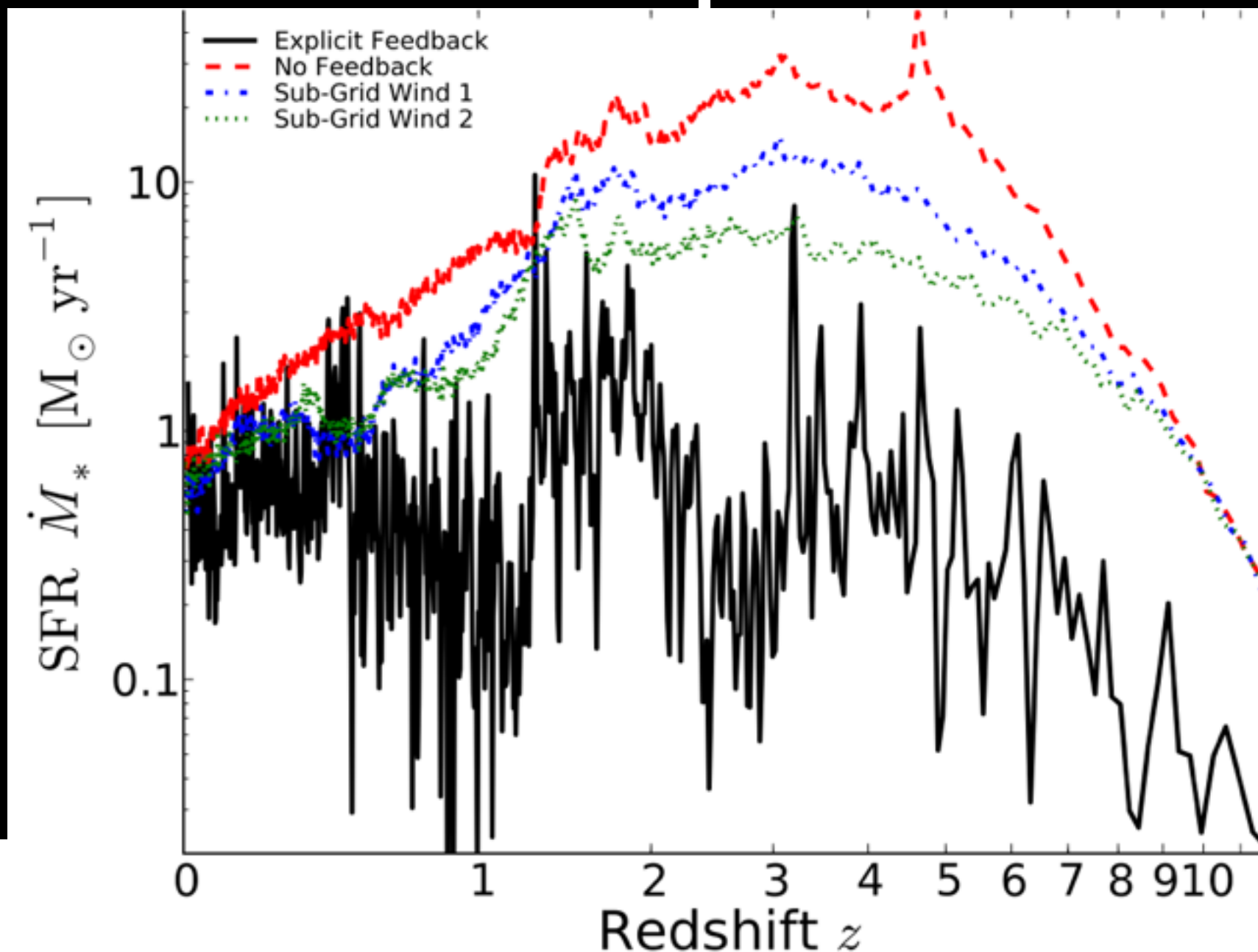
Simplest Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

Proto-MW: Gas Temperature:

“Decoupled Winds” (Sub-Grid)

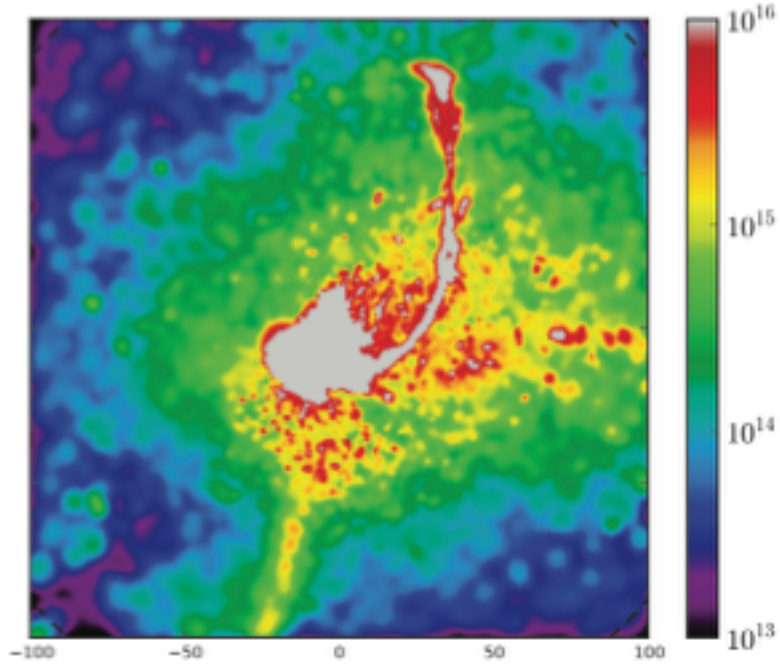
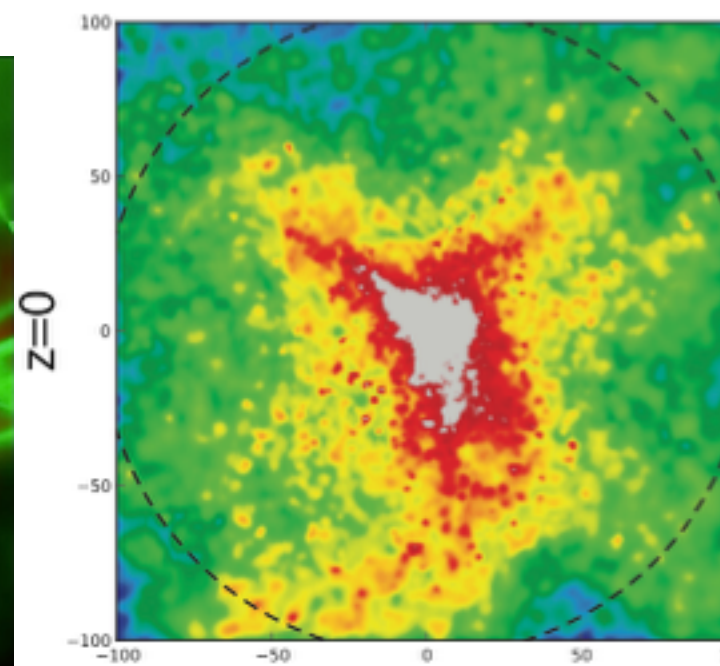
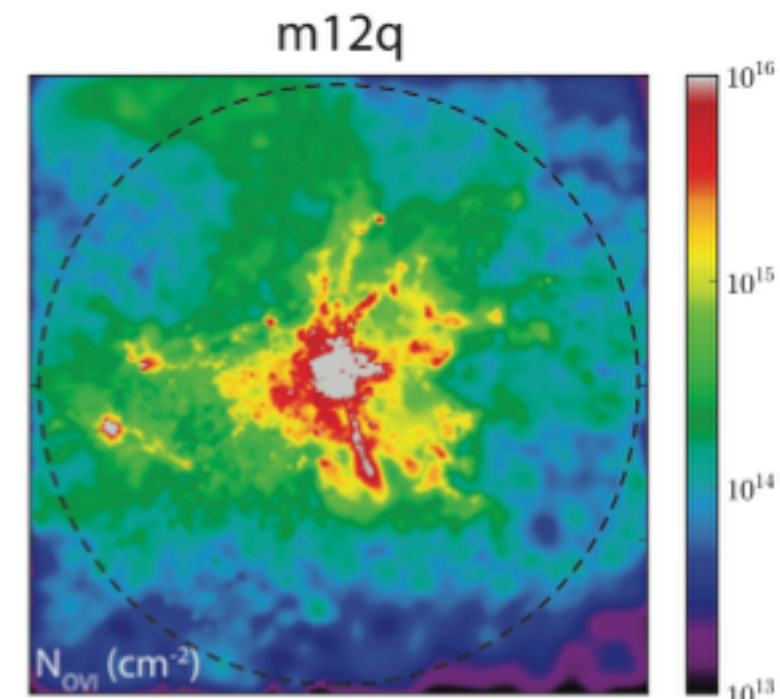
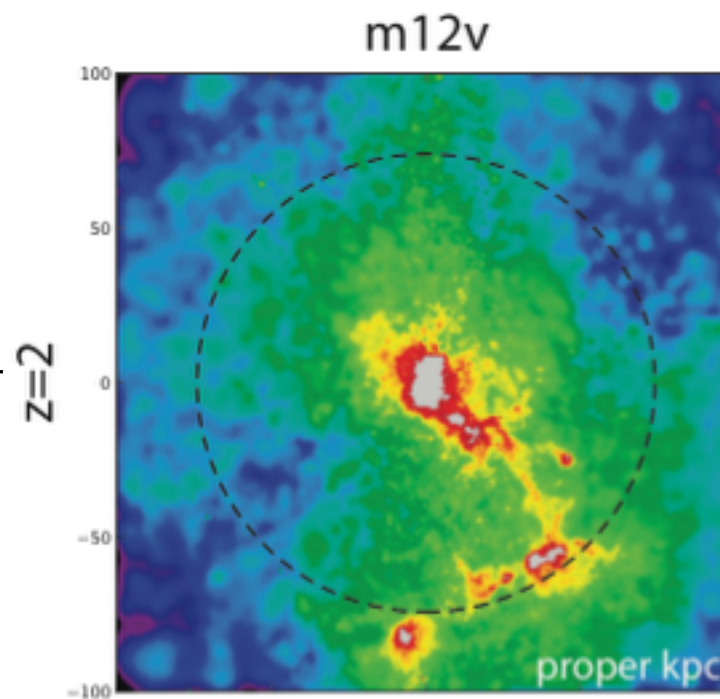
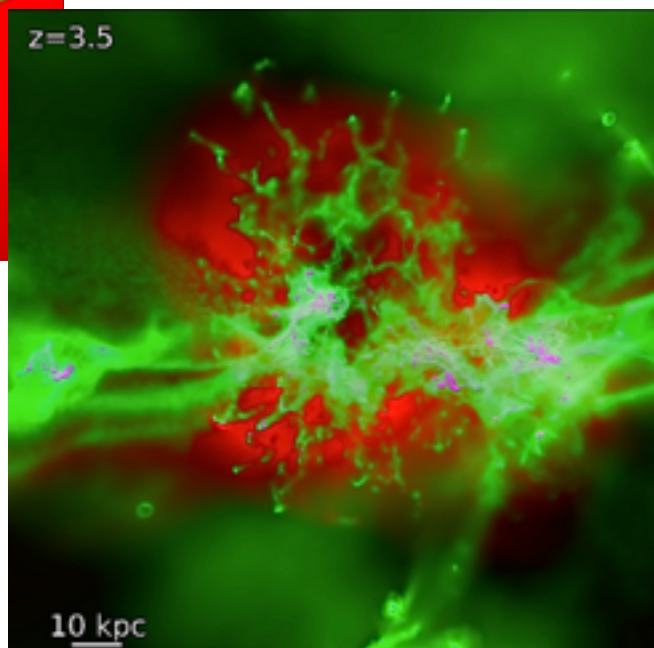
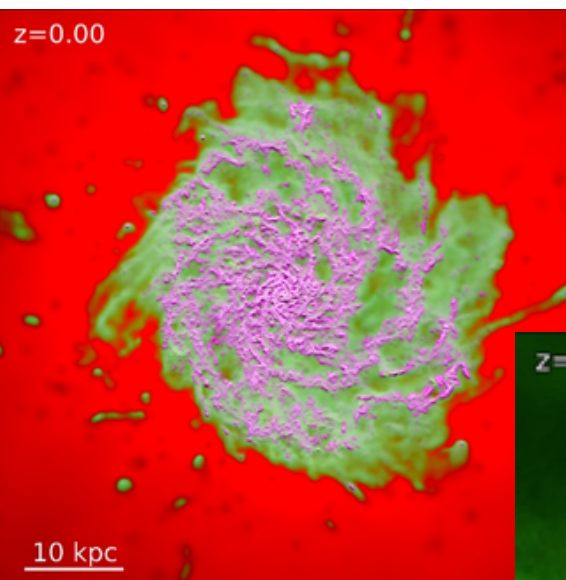
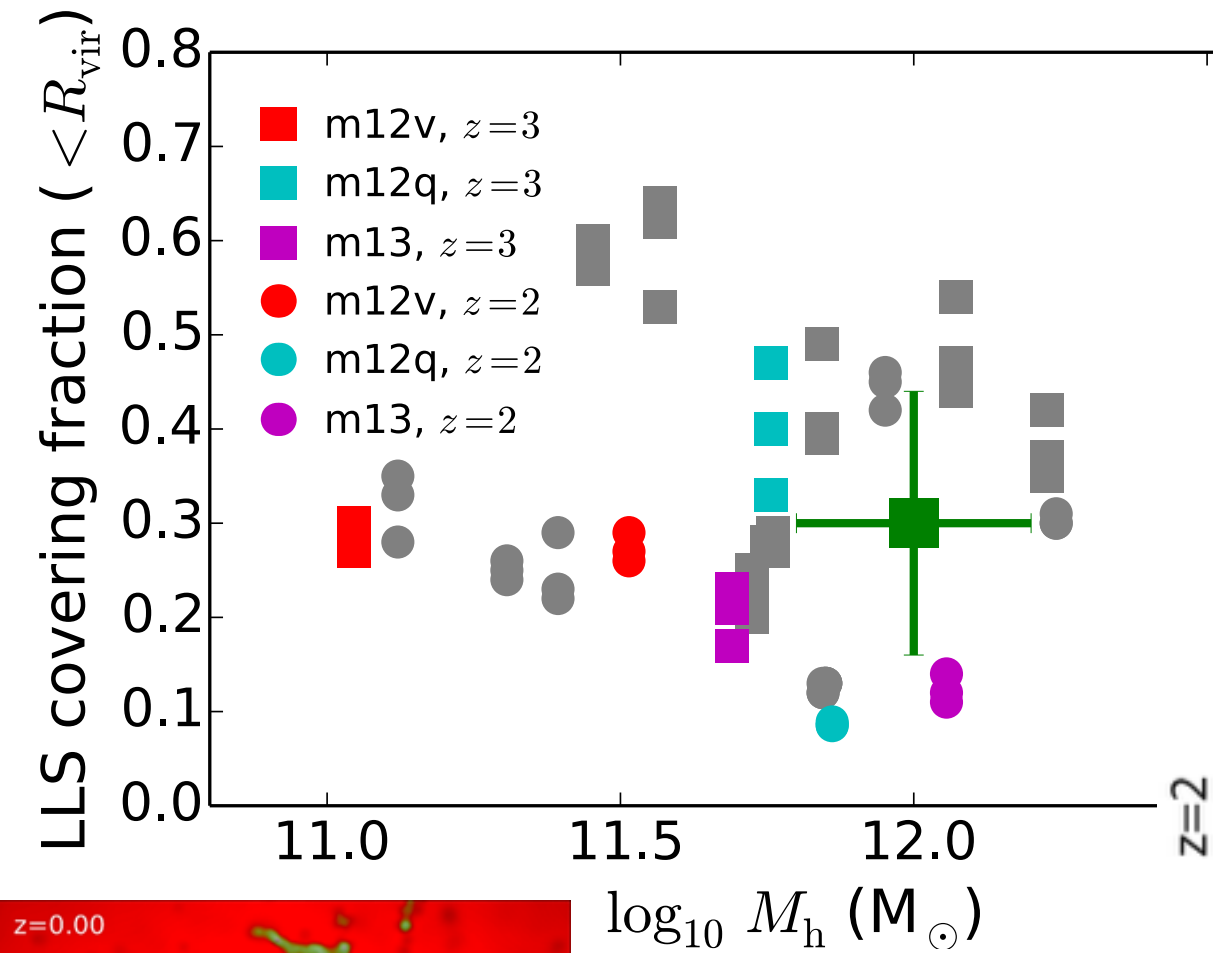
Following Explicit Feedback



Feedback Determines the Halo Gas Properties

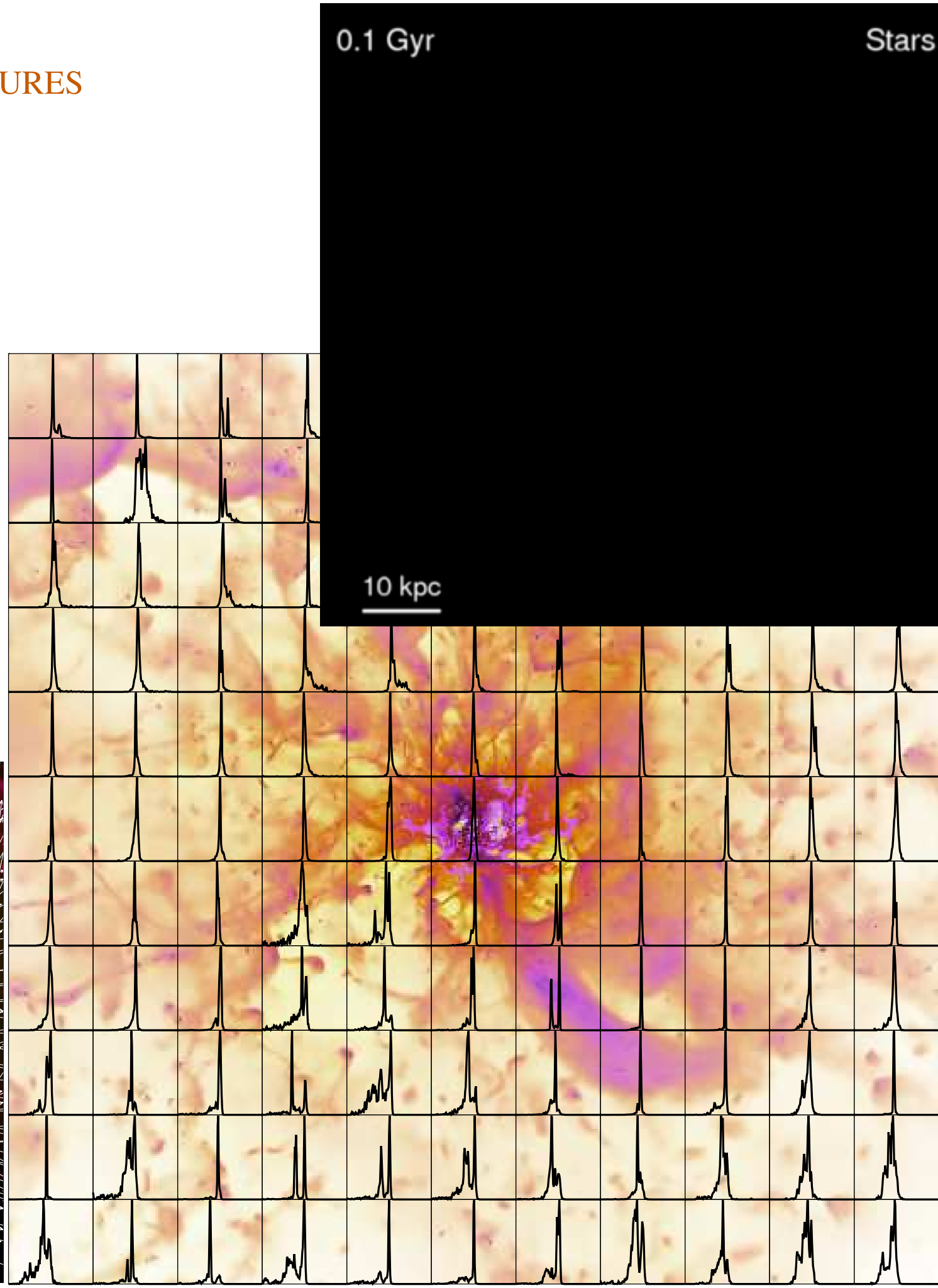
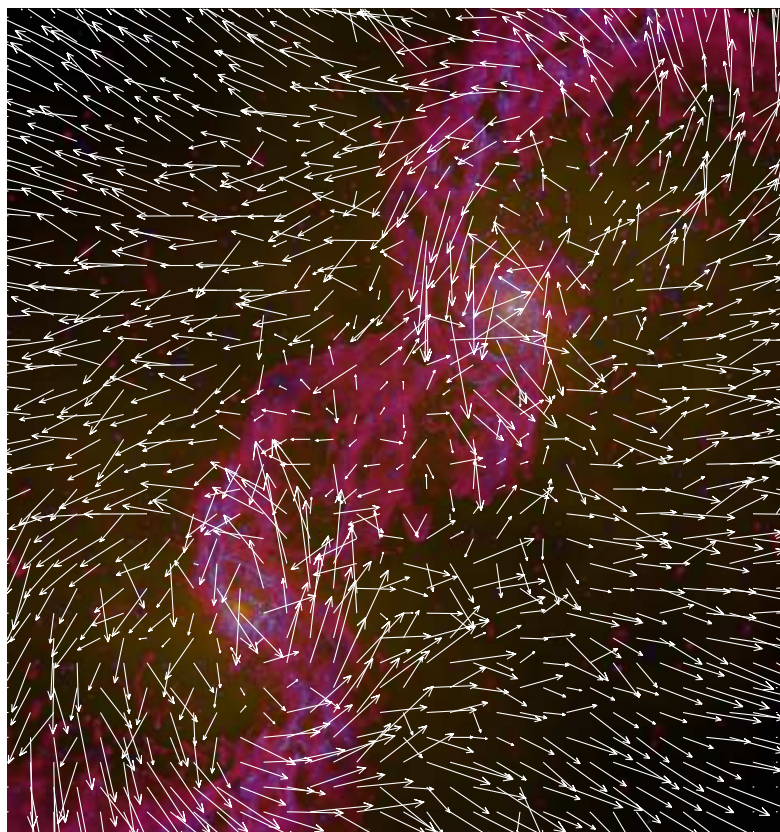
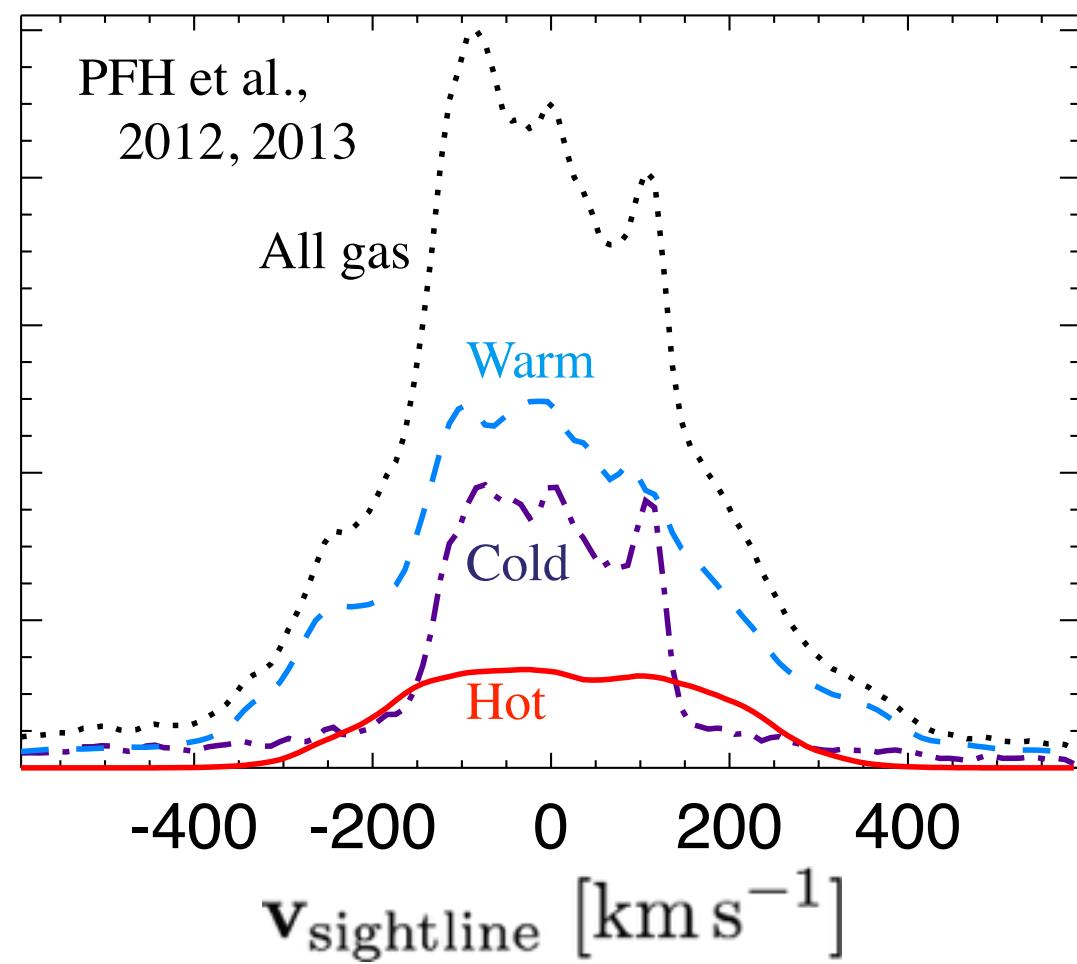
NEED TO PREDICT OUTFLOW MASS, VELOCITY, & GAS *PHASE*

Faucher-Giguere, PFH, et al.



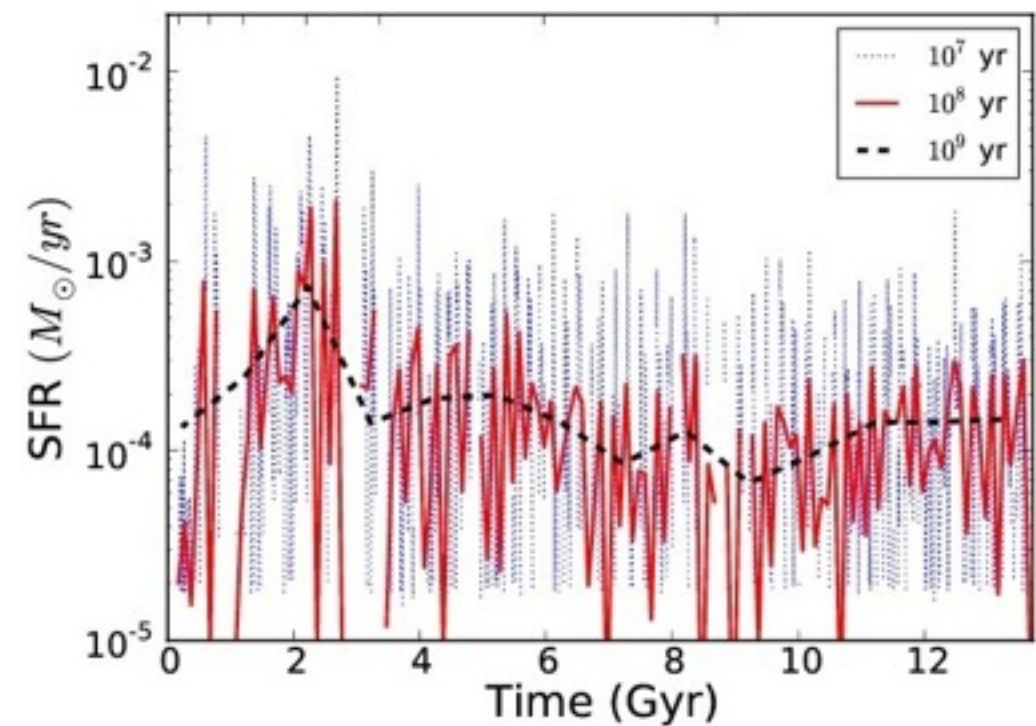
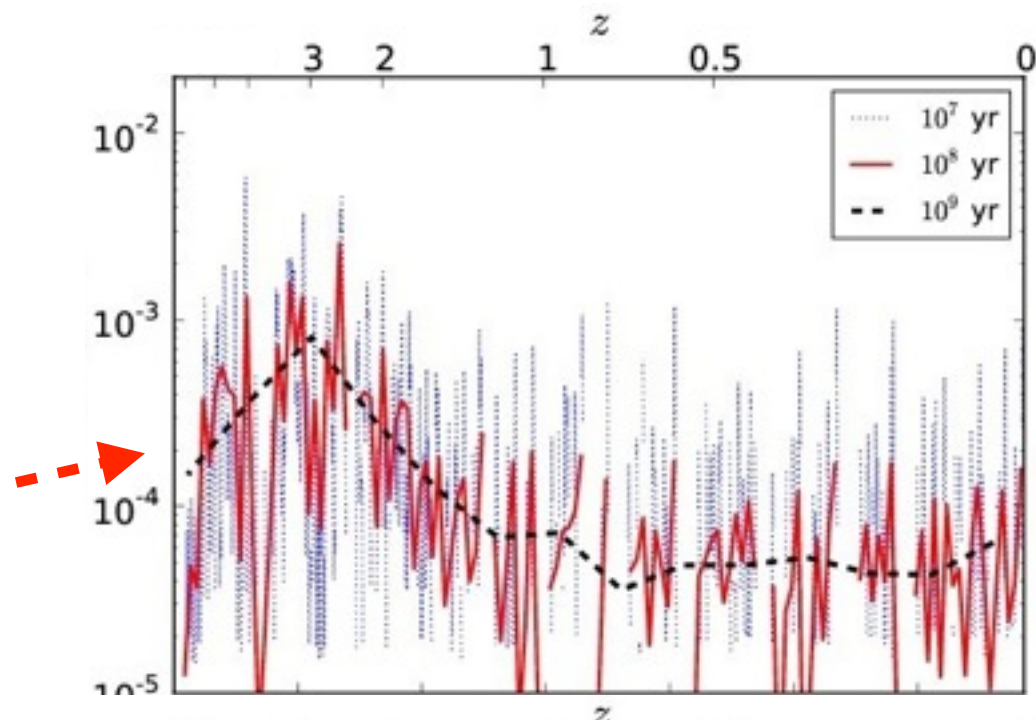
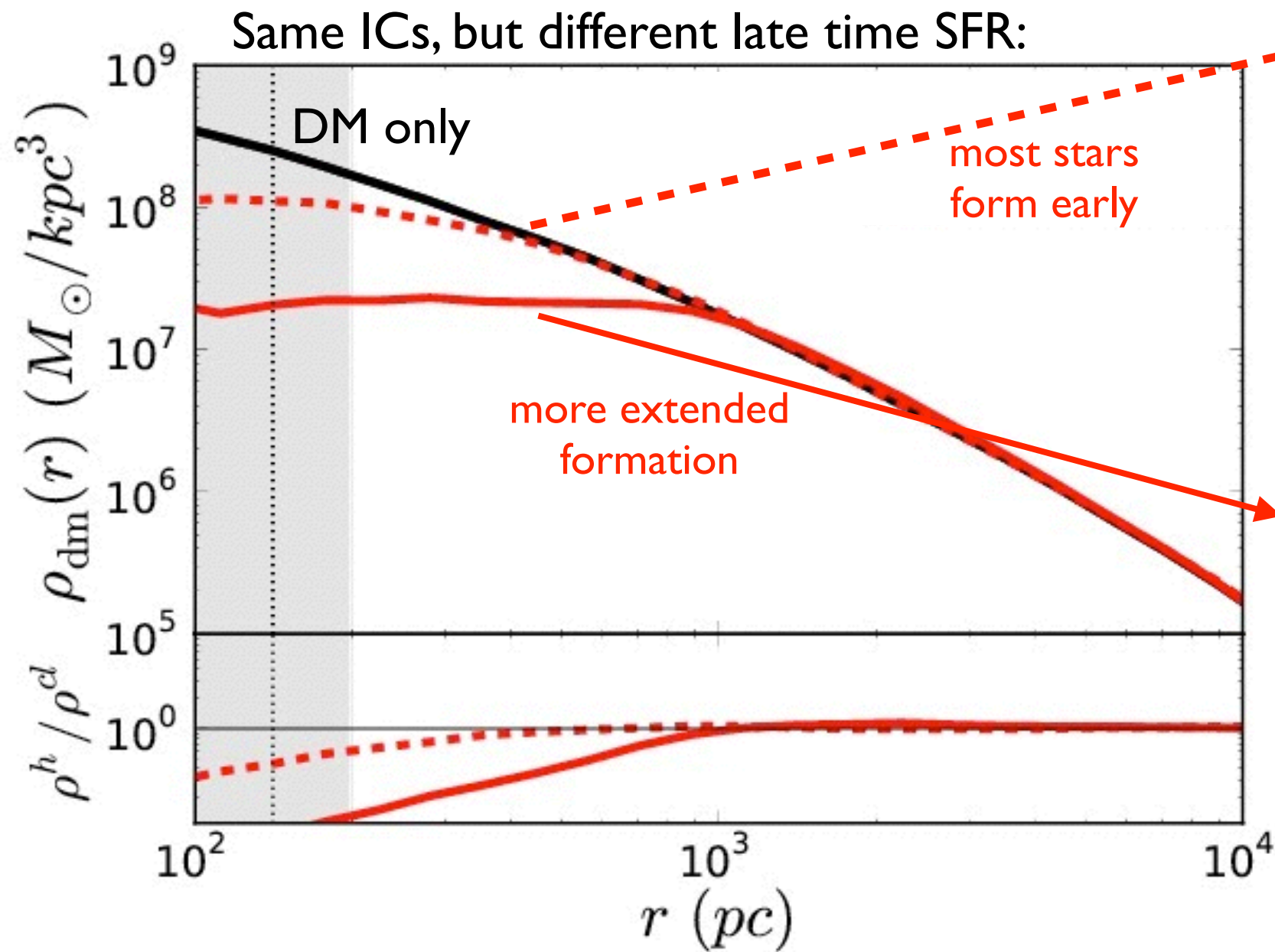
Kinematics of Stars & Gas

DIFFERENT MECHANISMS = DIFFERENT SIGNATURES



Cusp or Core?

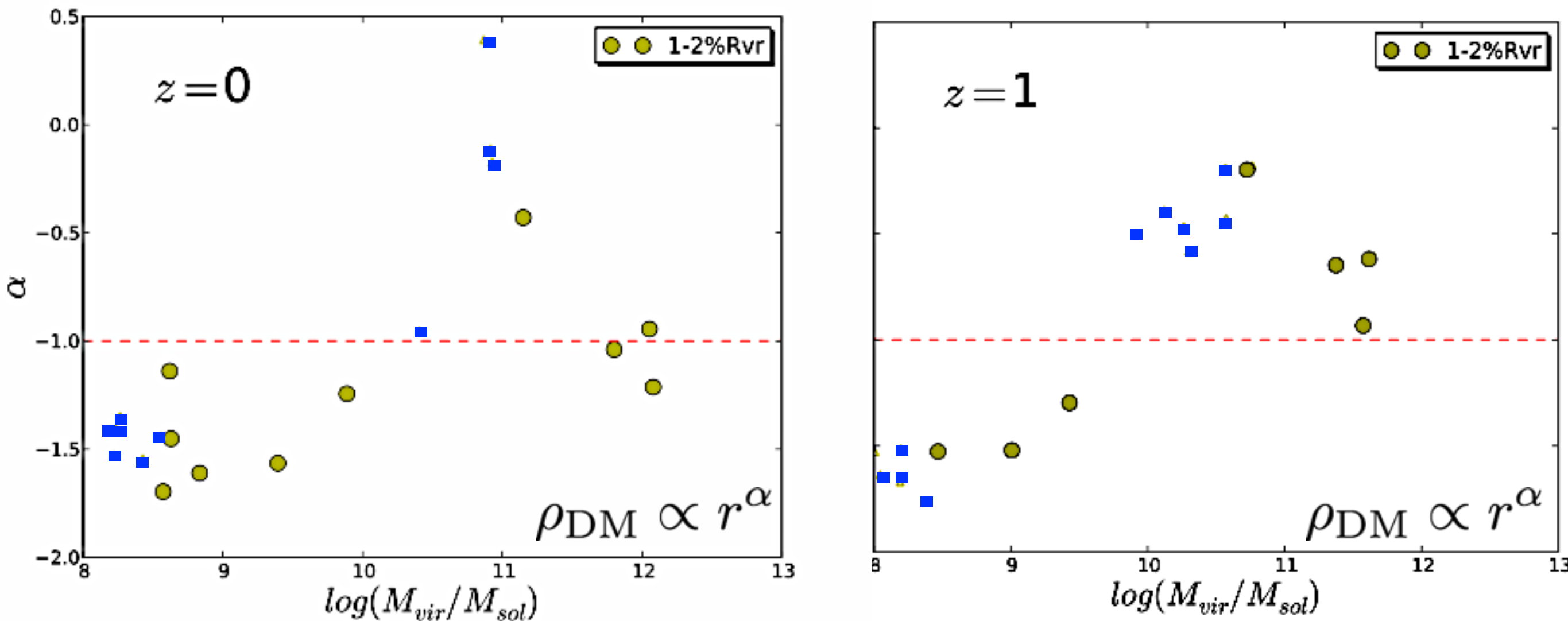
OUTCOME IS SENSITIVE TO STAR FORMATION HISTORY



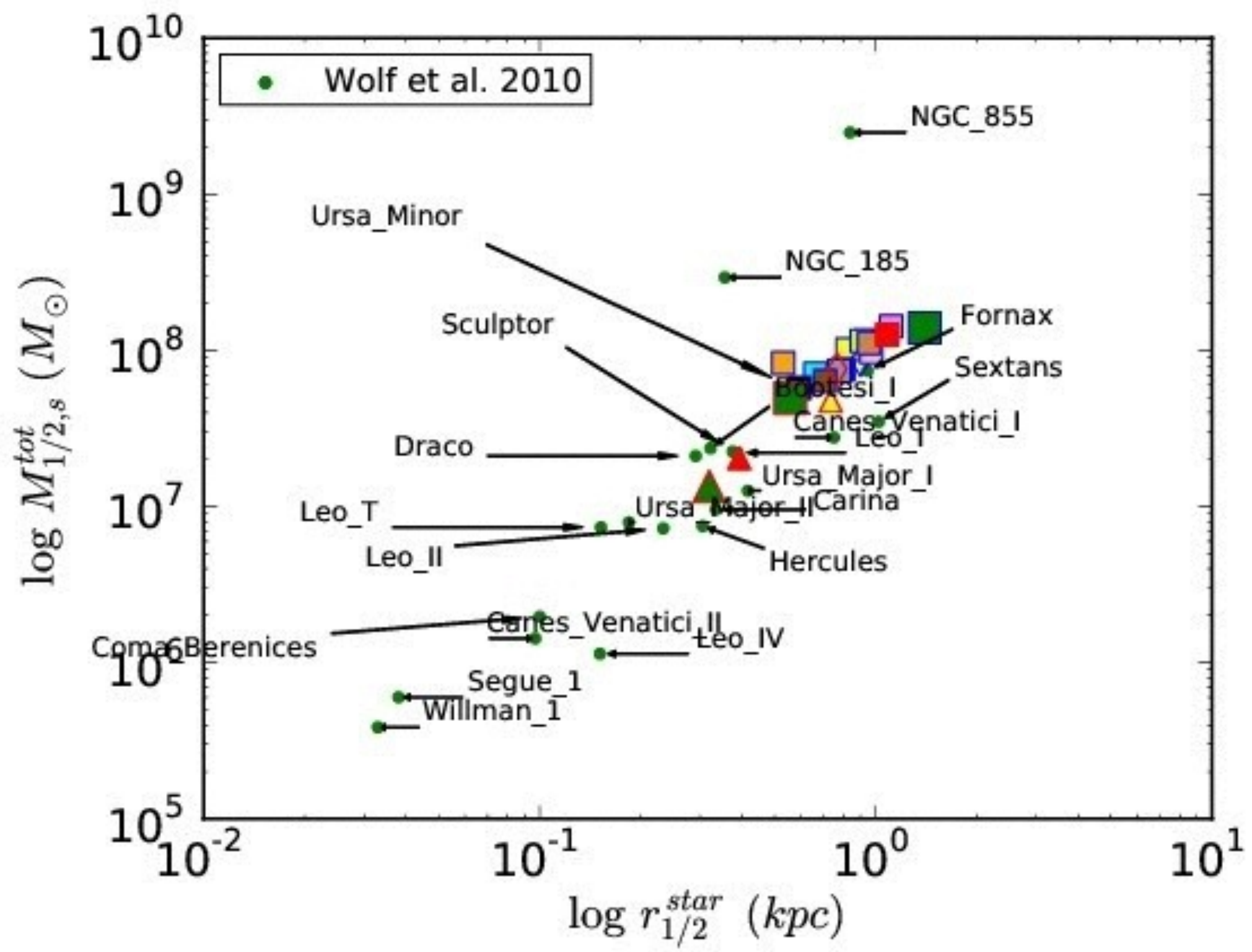
Cusp or core?

Overall in FIRE, cores form only in a limited range of halo masses:
 $\sim 10^{10} - 10^{11} M_{\text{sun}}$ (halos hosting galaxies with $M_* \sim 10^6 - 10^9 M_{\text{sun}}$).

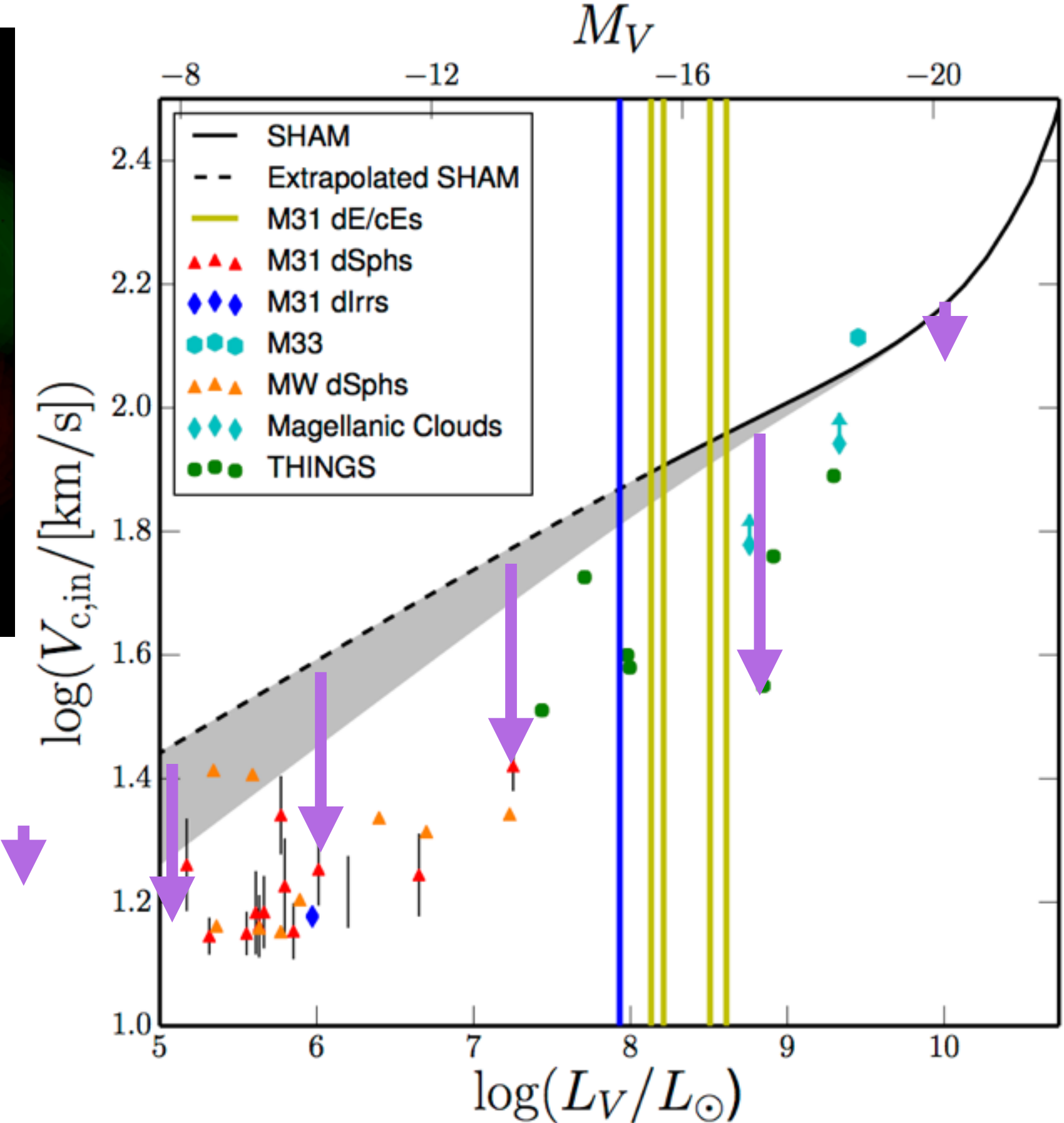
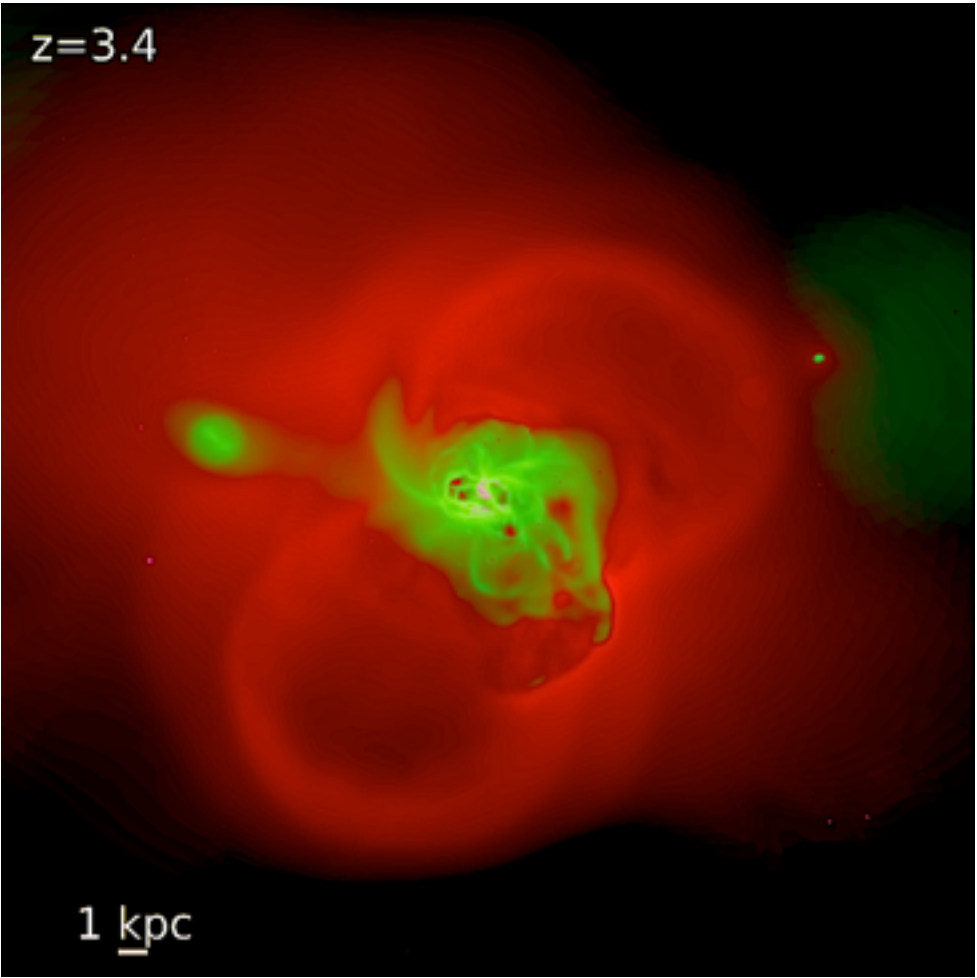
$\sim$ MW mass halos are also affected: very little or no adiabatic contraction!



Dwarf Galaxies, Cusps, & “Too Big to Fail”
RESOLVED FEEDBACK MATTERS

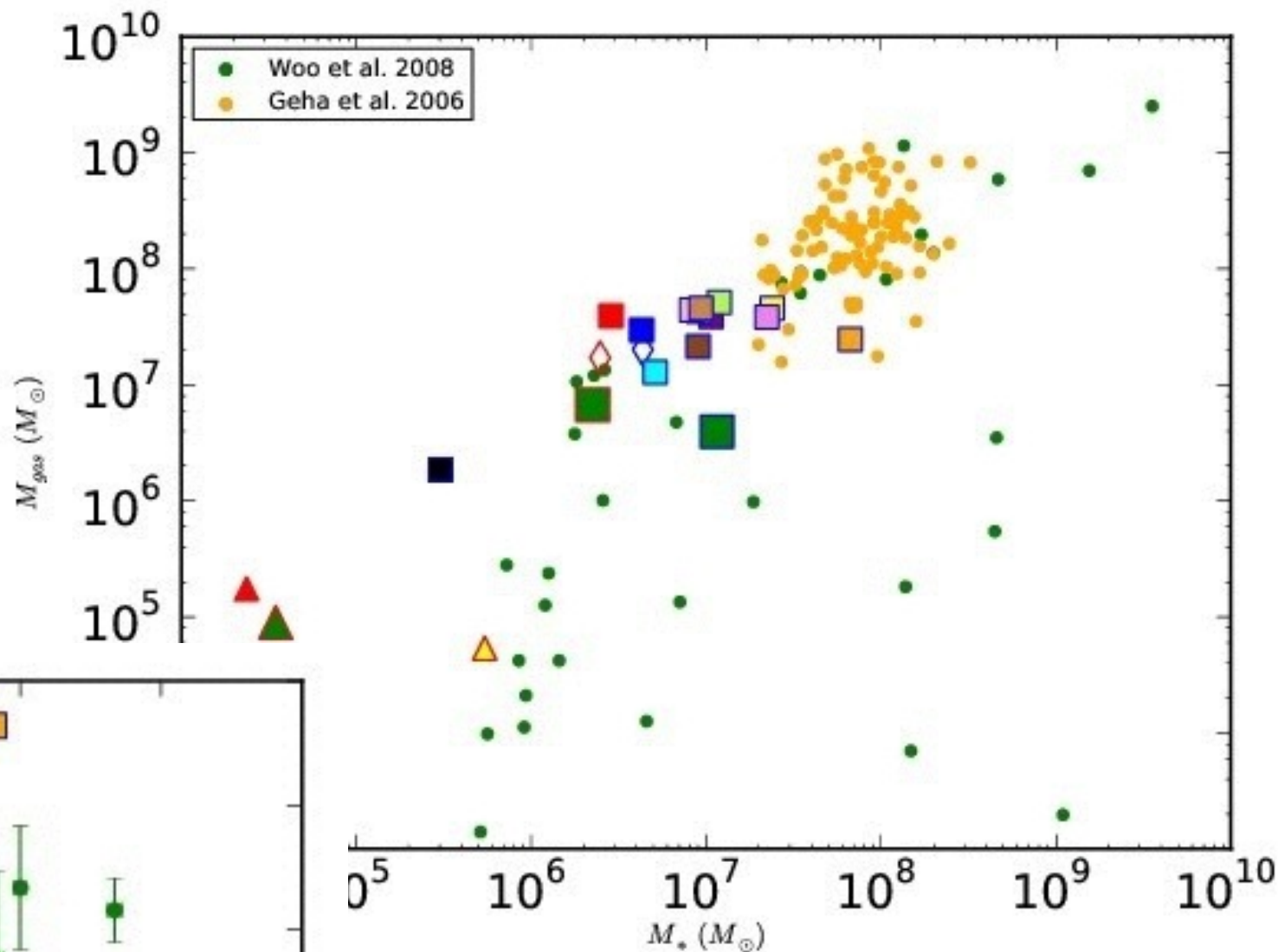
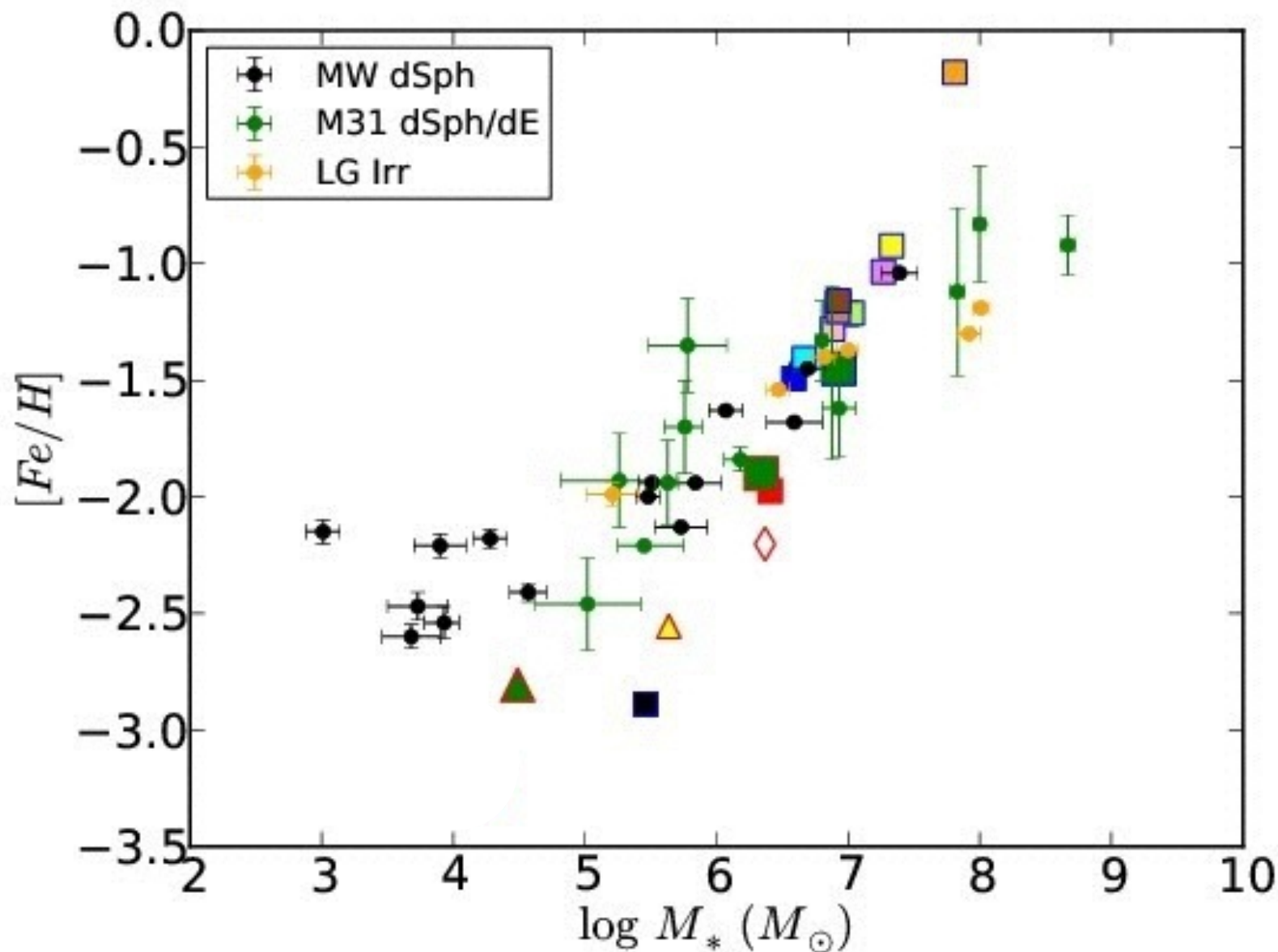


Dwarf Galaxies, Cusps, & “Too Big to Fail”
RESOLVED FEEDBACK MATTERS



Mass-Metallicity Relation & Gas Fractions Sensitive to Feedback

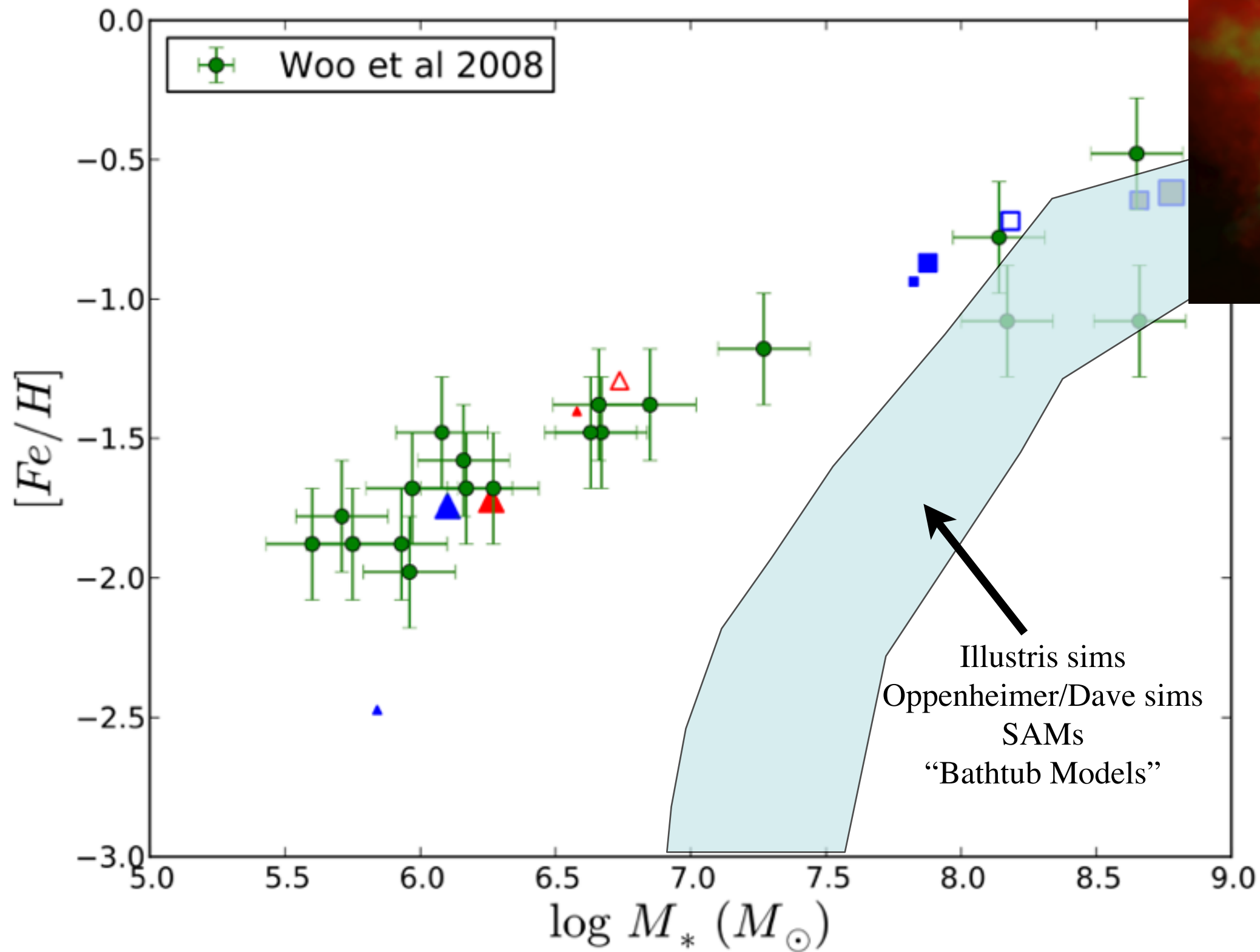
DETAILS MATTER



L. Murchikova et al.,
in preparation

But, Mass-Metallicity Relation is Sensitive to Feedback

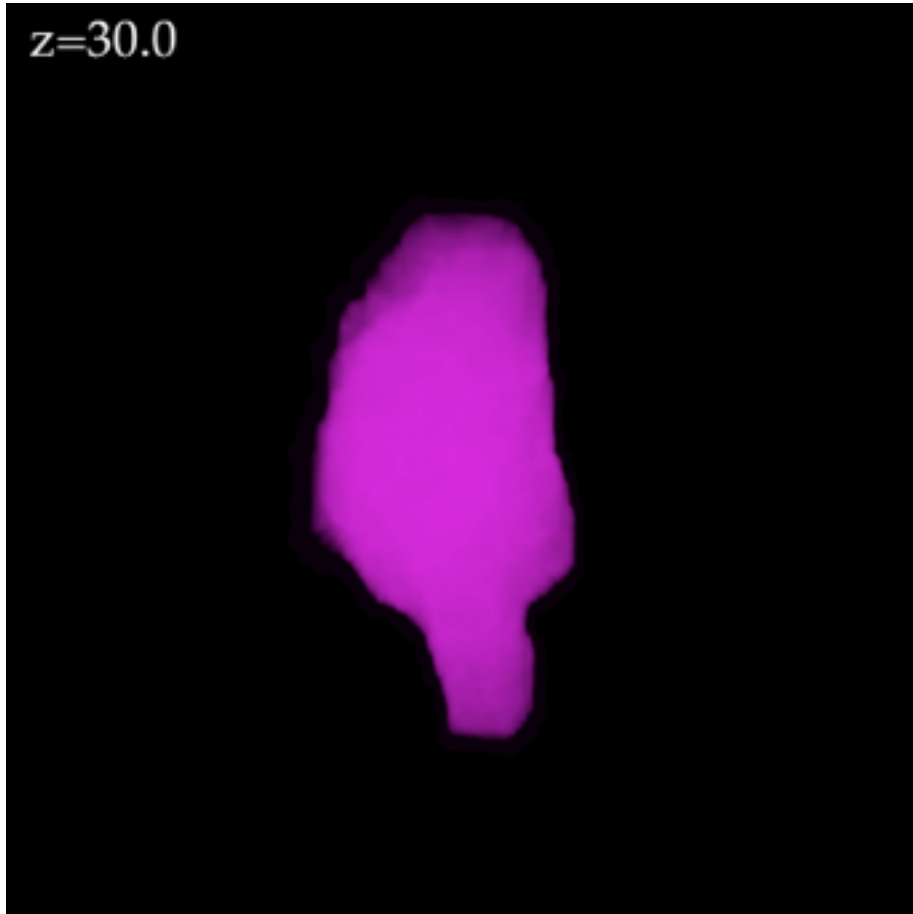
DETAILS MATTER



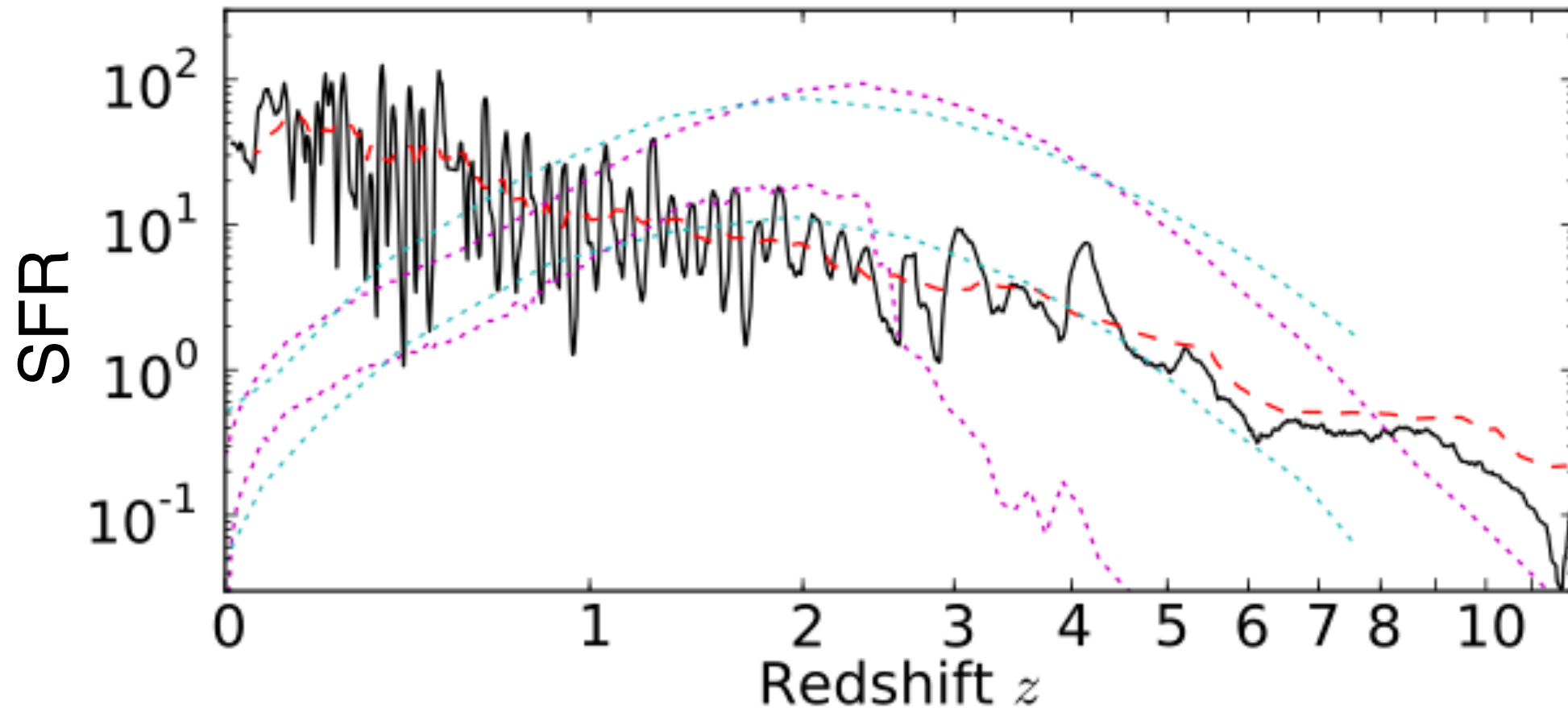
- Outflows suppress “new” infall of pristine material
- Metal-rich gas preferentially re-accretes in fountains

Quenching: Non-AGN Mechanisms *FAIL*

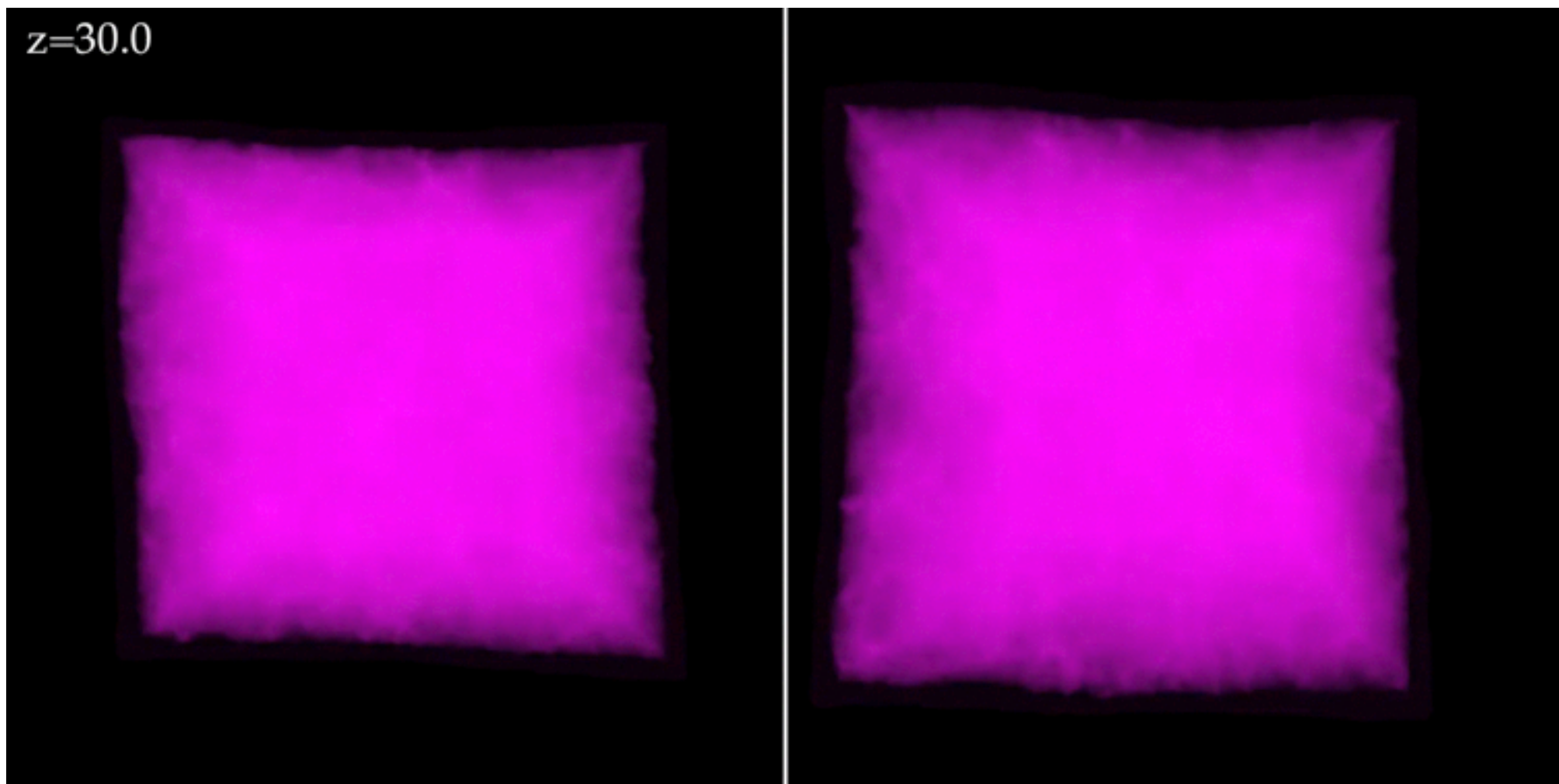
MORE THAN GRAVITY, COOLING, STARS, & MHD



- **NO** “Morphological Quenching” (Martig+)
 - Morphology $\neq$ cooling
- **NO** “Clump/Halo/Gravitational Quenching” (Dekel & Birnboim)
 - Not enough clumps, and they sink (cool!)
- **NO** “AGB Wind” Quenching (Conroy+):
 - Too concentrated, rapidly cooling



$z=30.0$



- **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
 - **Resolved feedback $\neq$ sub-grid feedback!**
 - Mass-metallicity, SFHs, morphology *not the same*
- **Something else** needed to “quench”