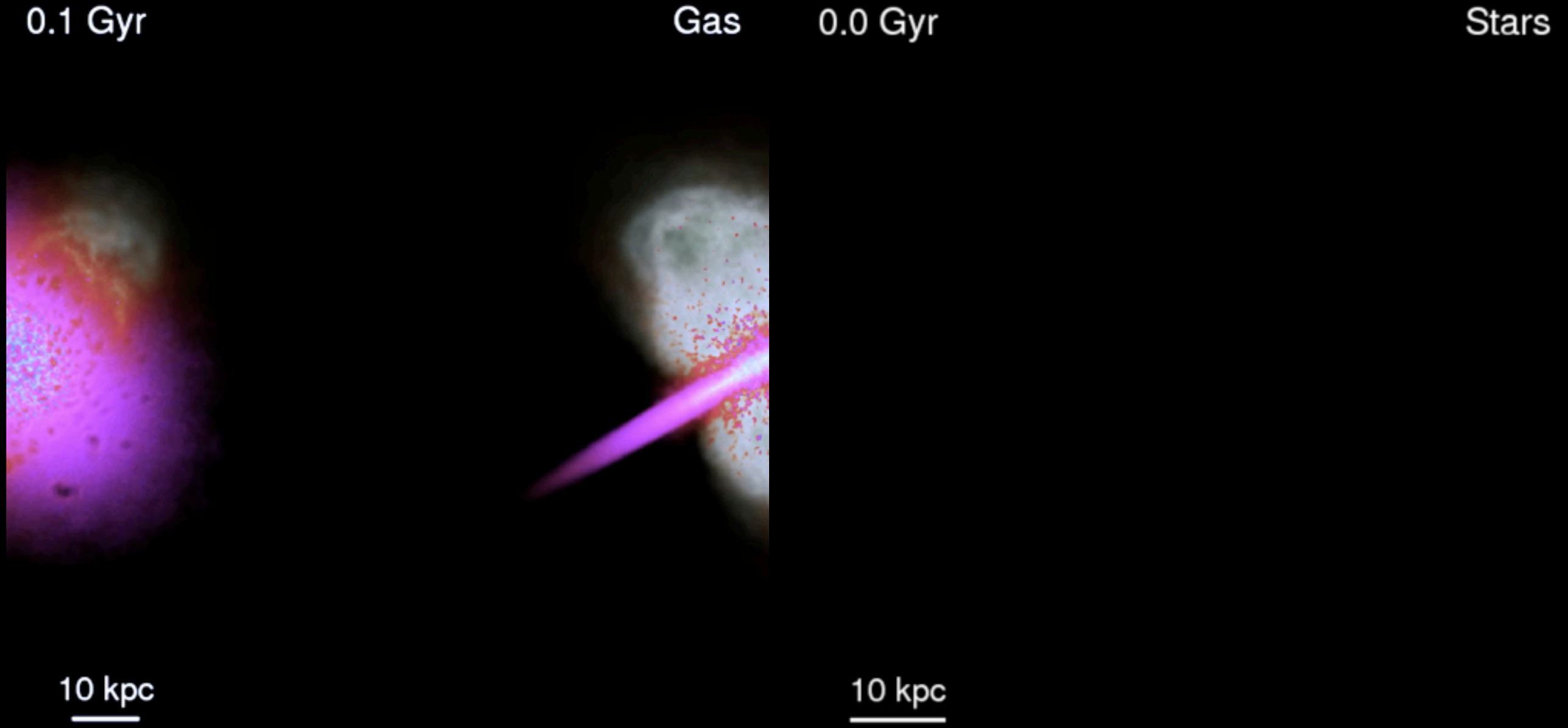
# Galaxies on FIRE: Stellar Feedback & Inefficient Star Formation

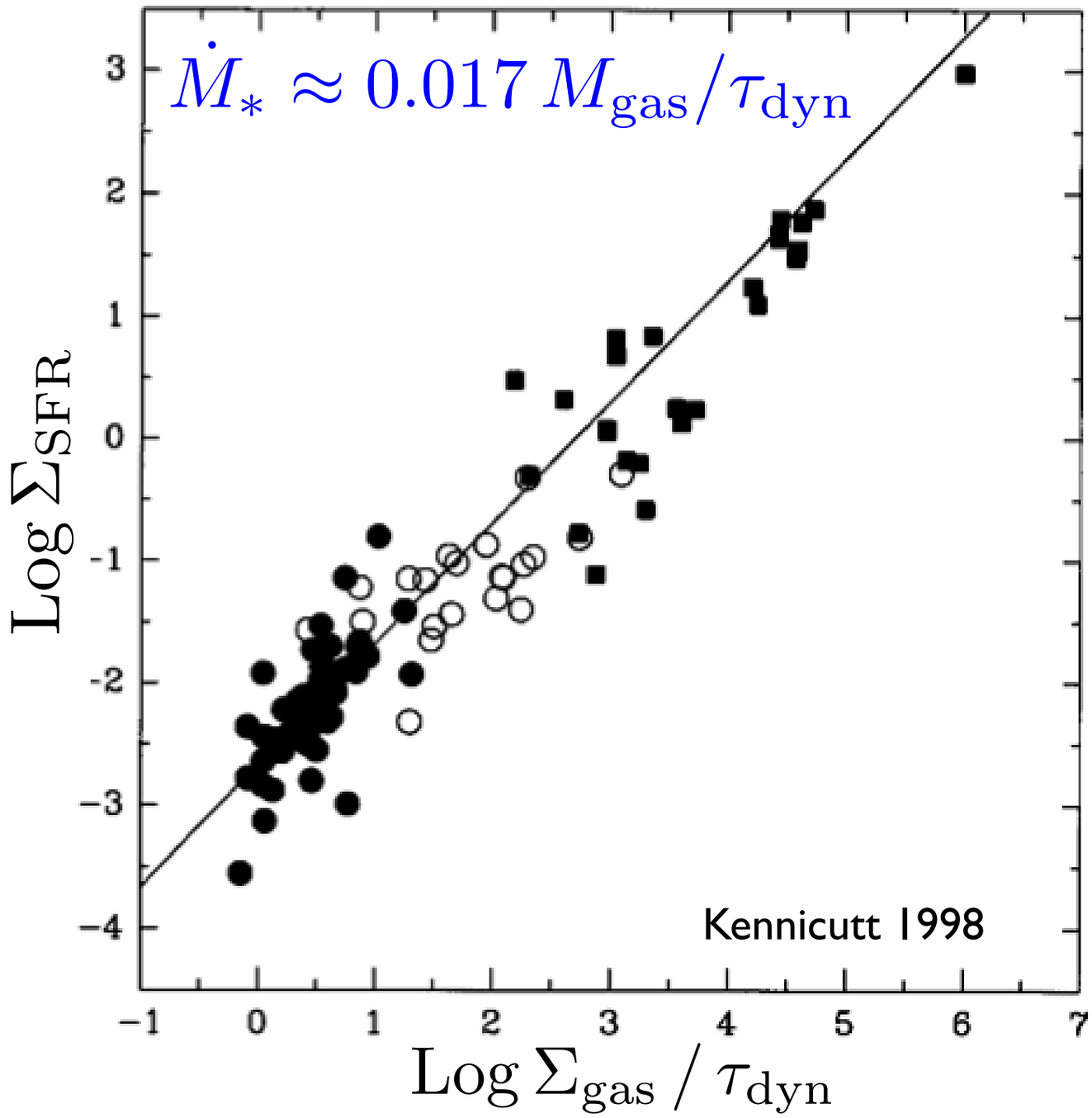



Phil Hopkins

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?



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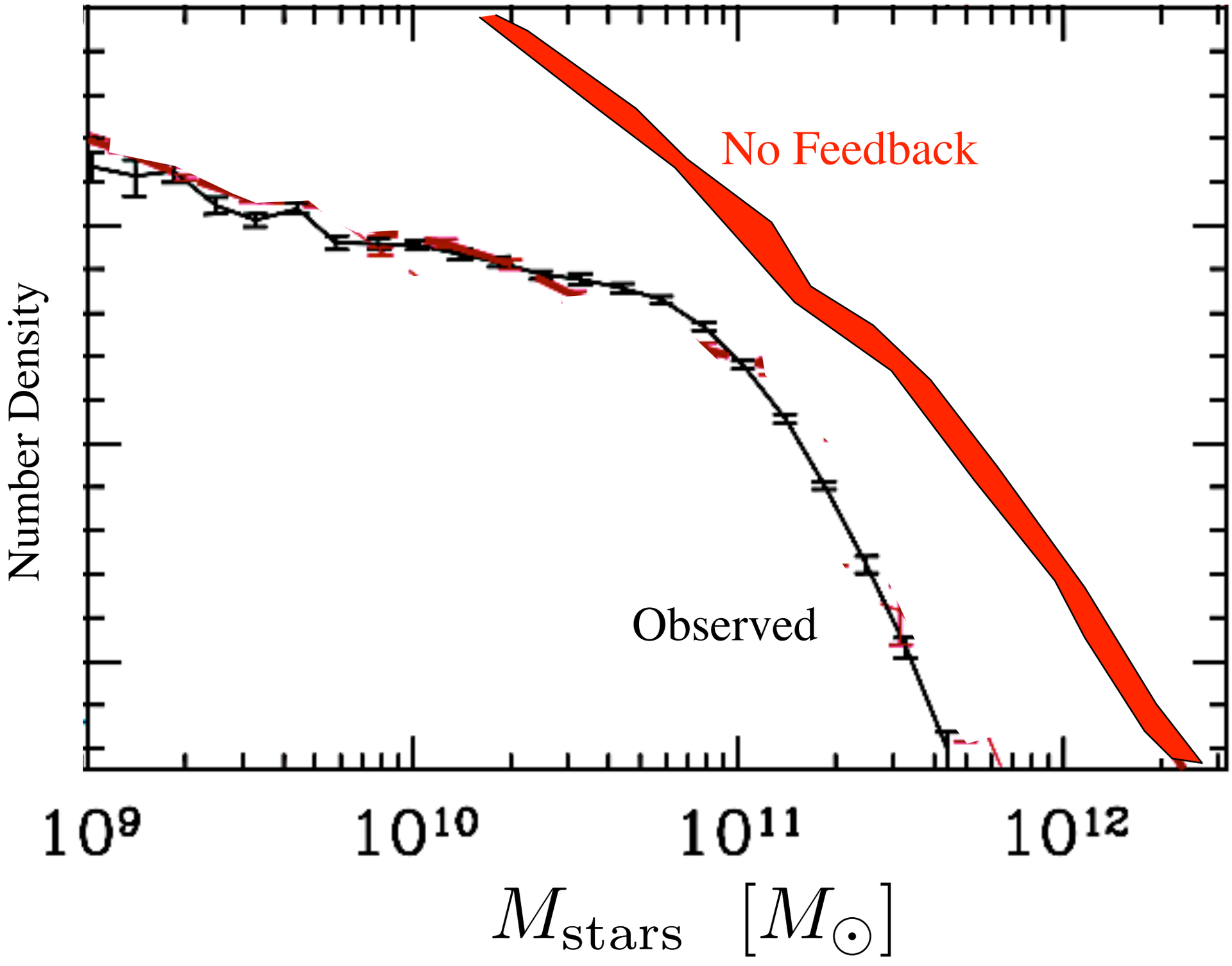


# Feedback is the Key!

## SO WHAT'S THE PROBLEM?

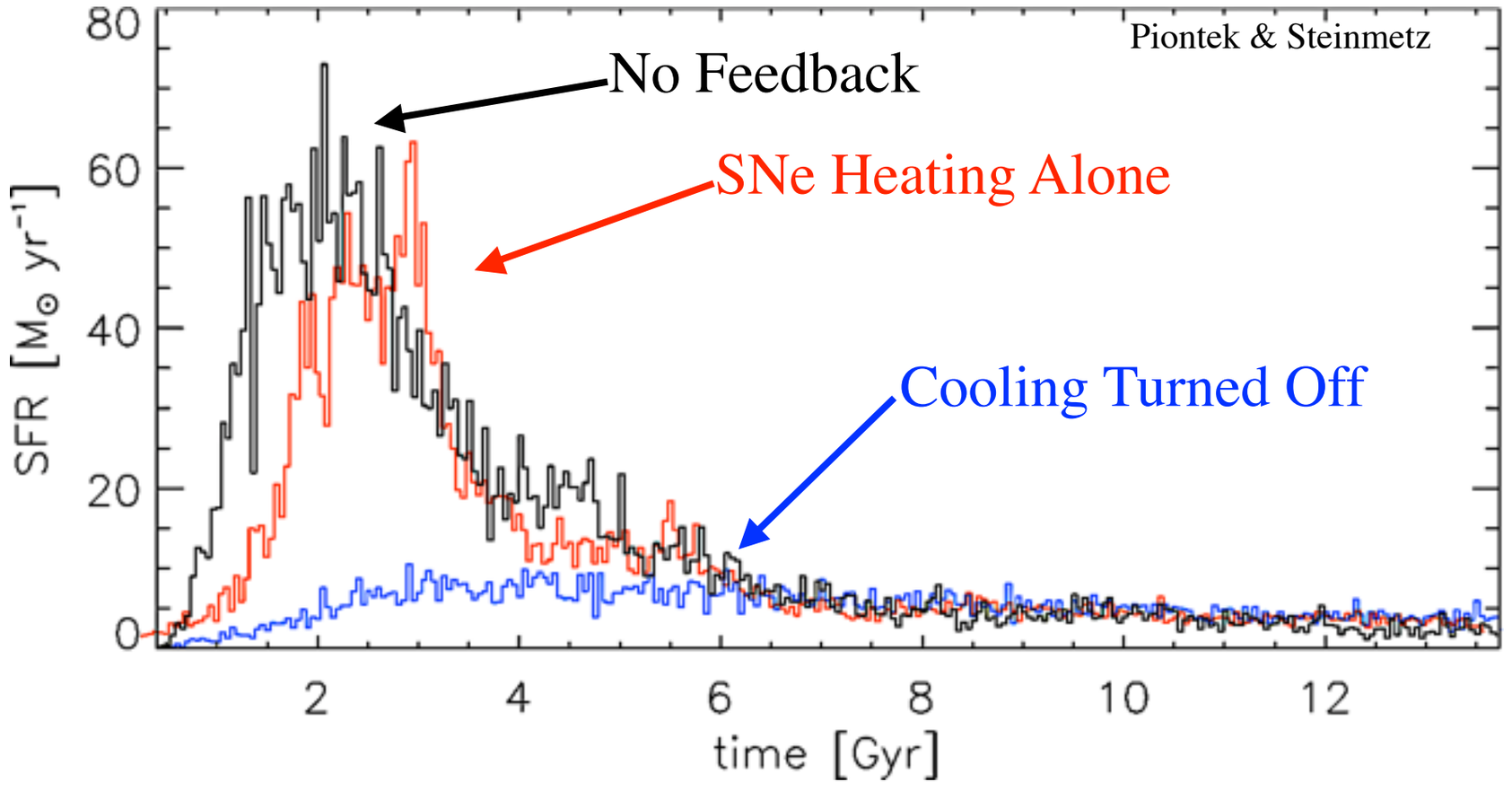
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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?

- 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

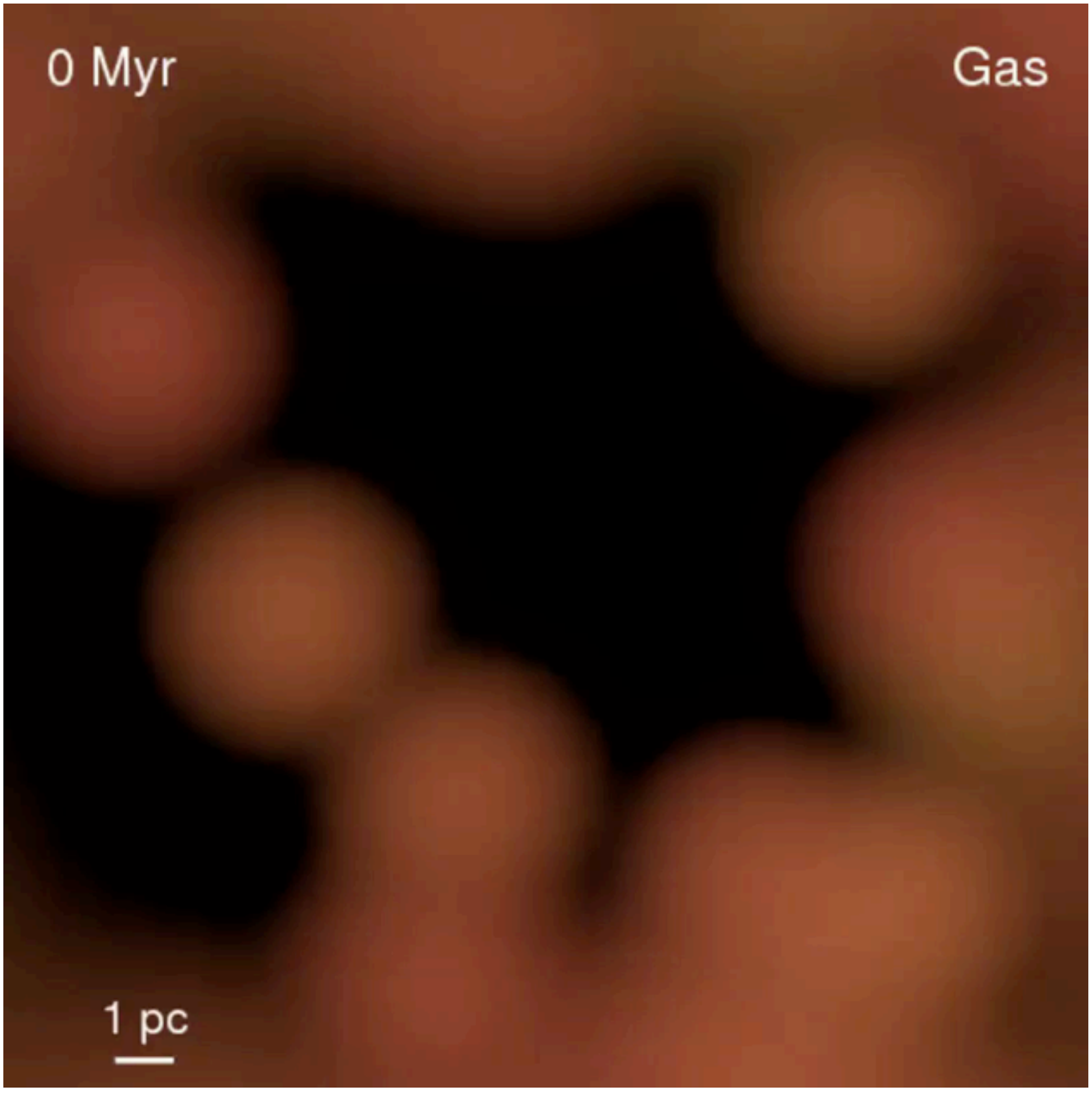
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

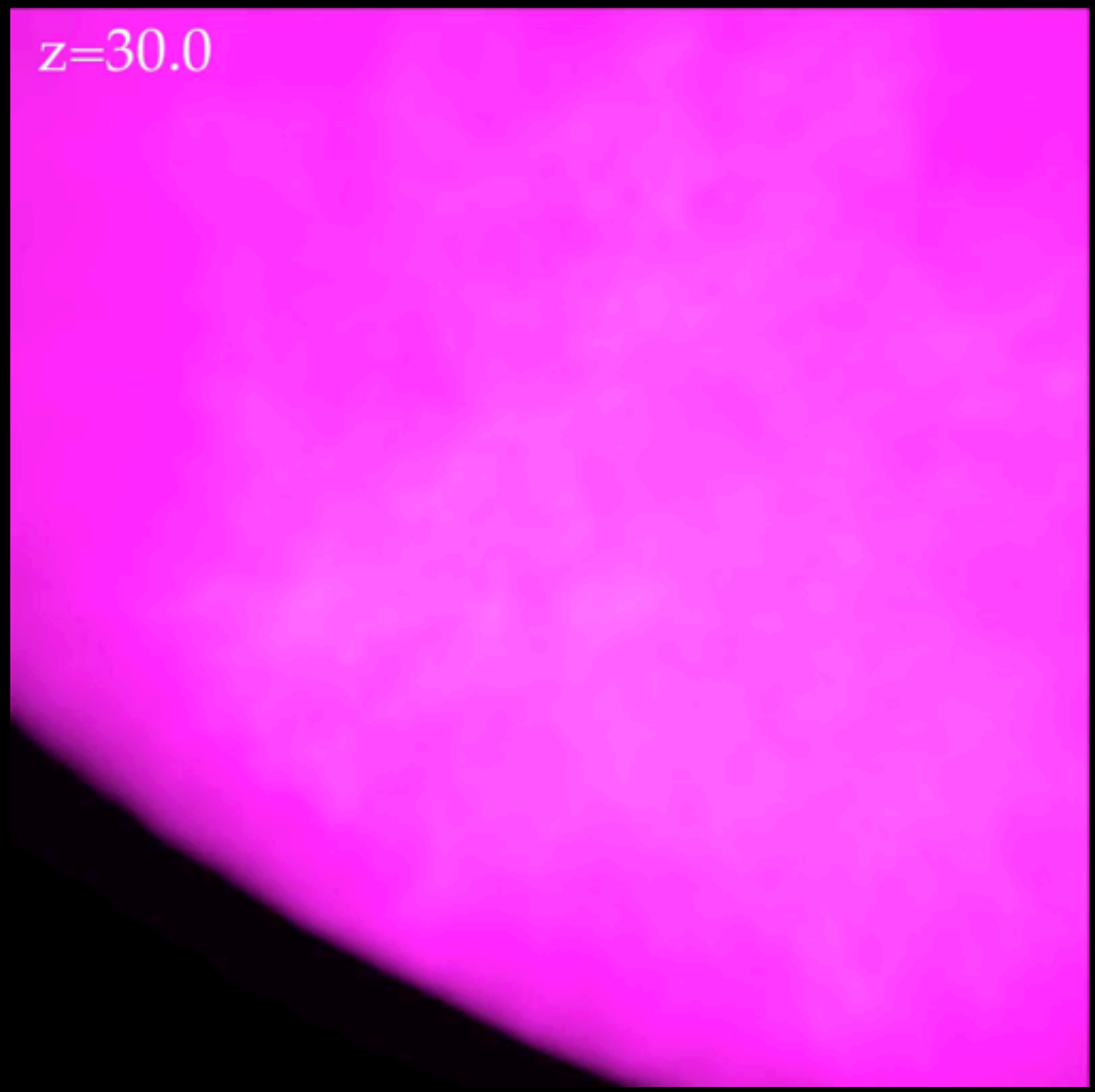
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




- (also MHD, anisotropic conduction, diffusion)

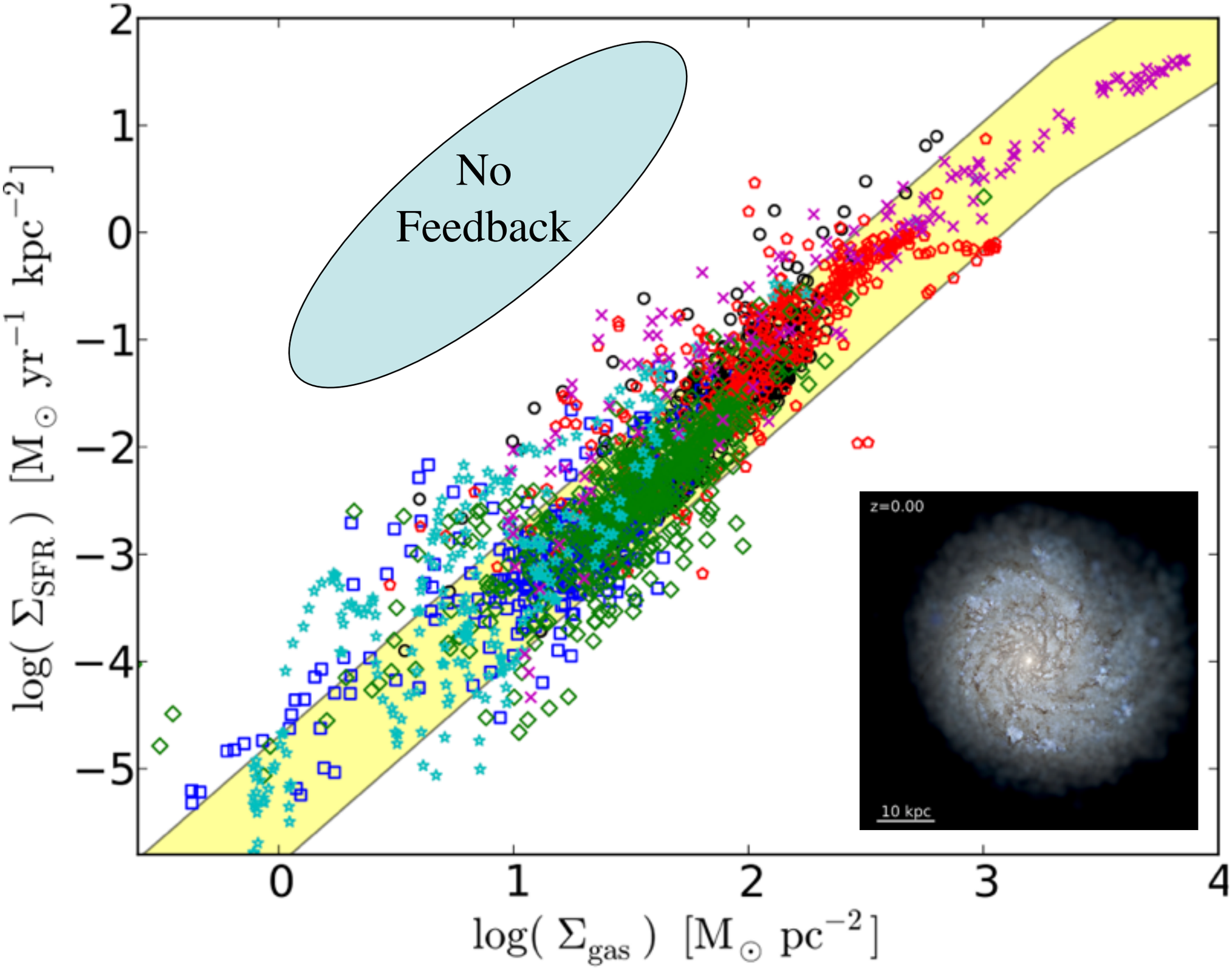
# The FIRE Project: Cosmological Simulations at 1-10pc resolution

z=30.0



# Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!

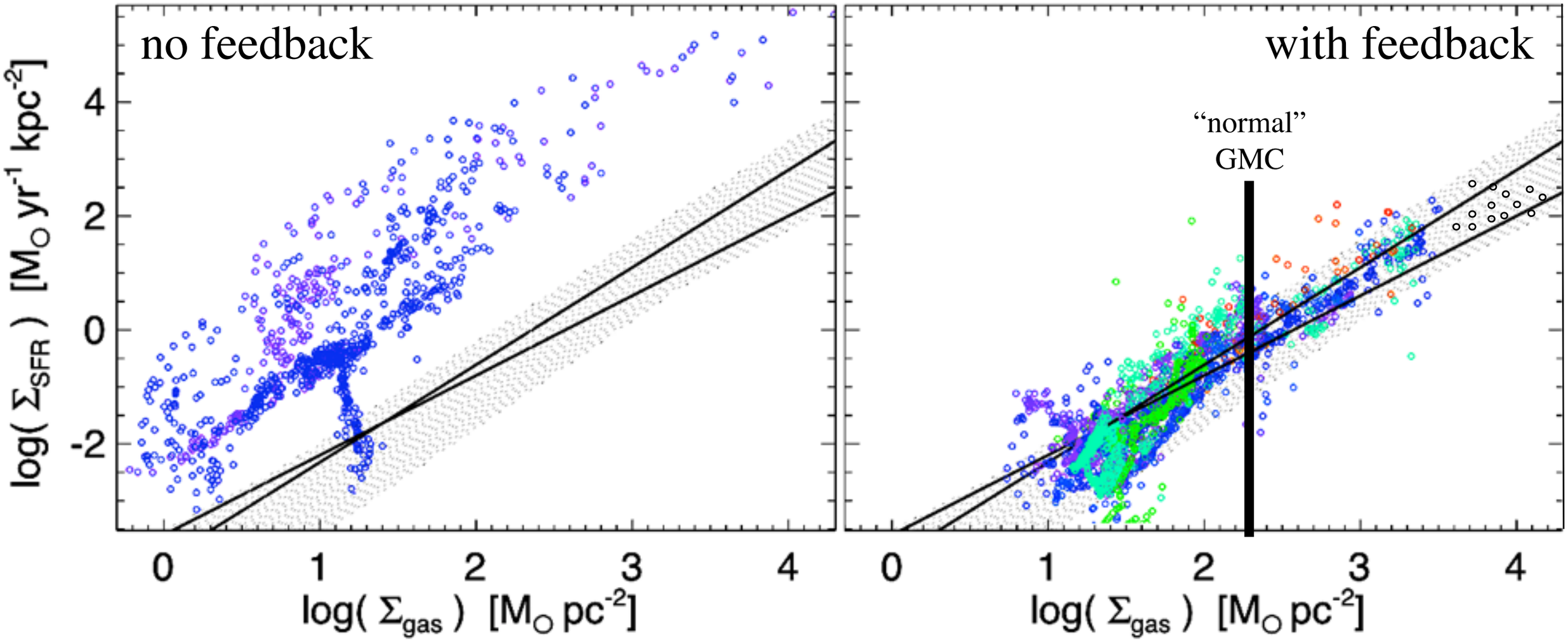



PFH, Keres, et al. (arXiv:1311.2073)

# 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

# Kennicutt-Schmidt relation emerges naturally

Shetty & Ostriker '12
CAFG et al. '13

- Efficient cooling ⟶ the gas disk dissipates its support:

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

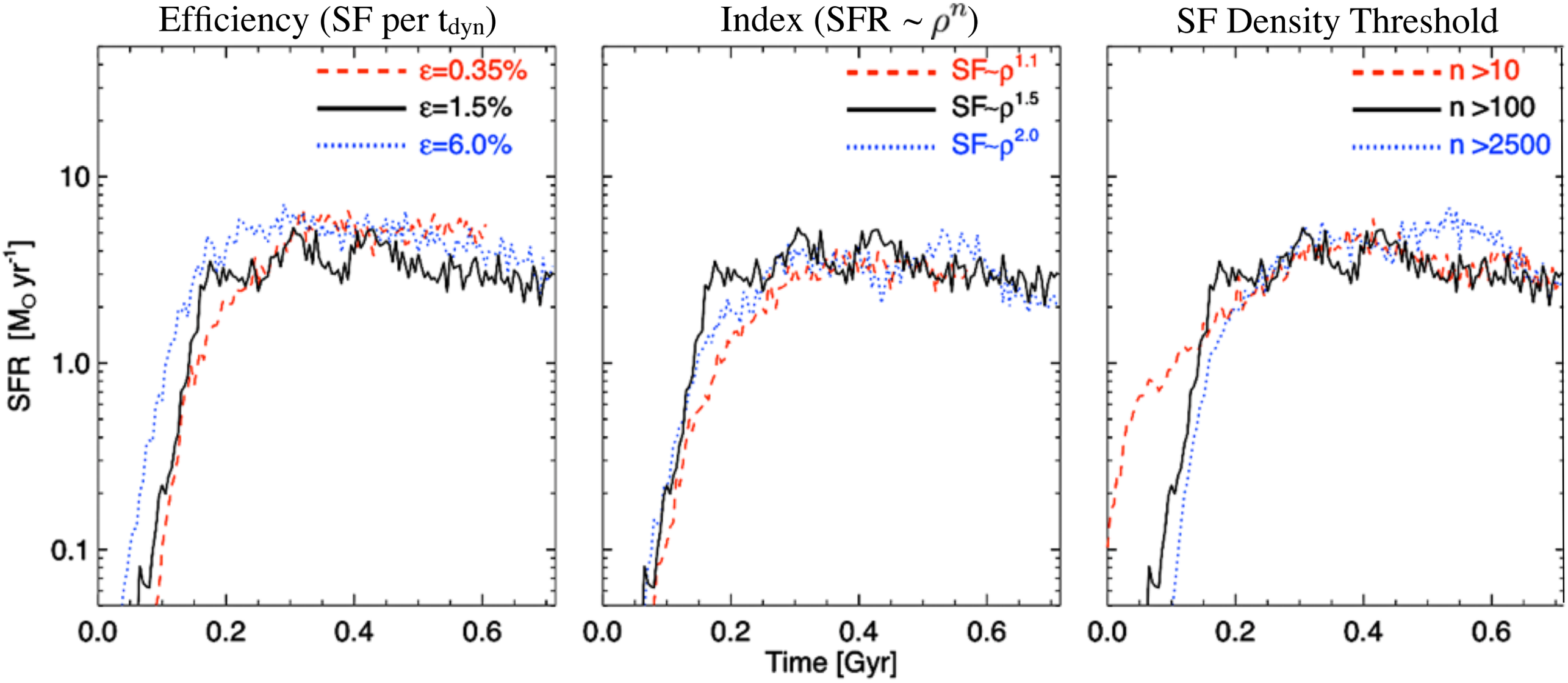
- Collapse stops when momentum input from feedback:

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

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

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

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




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

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

# Inflows & Outflows

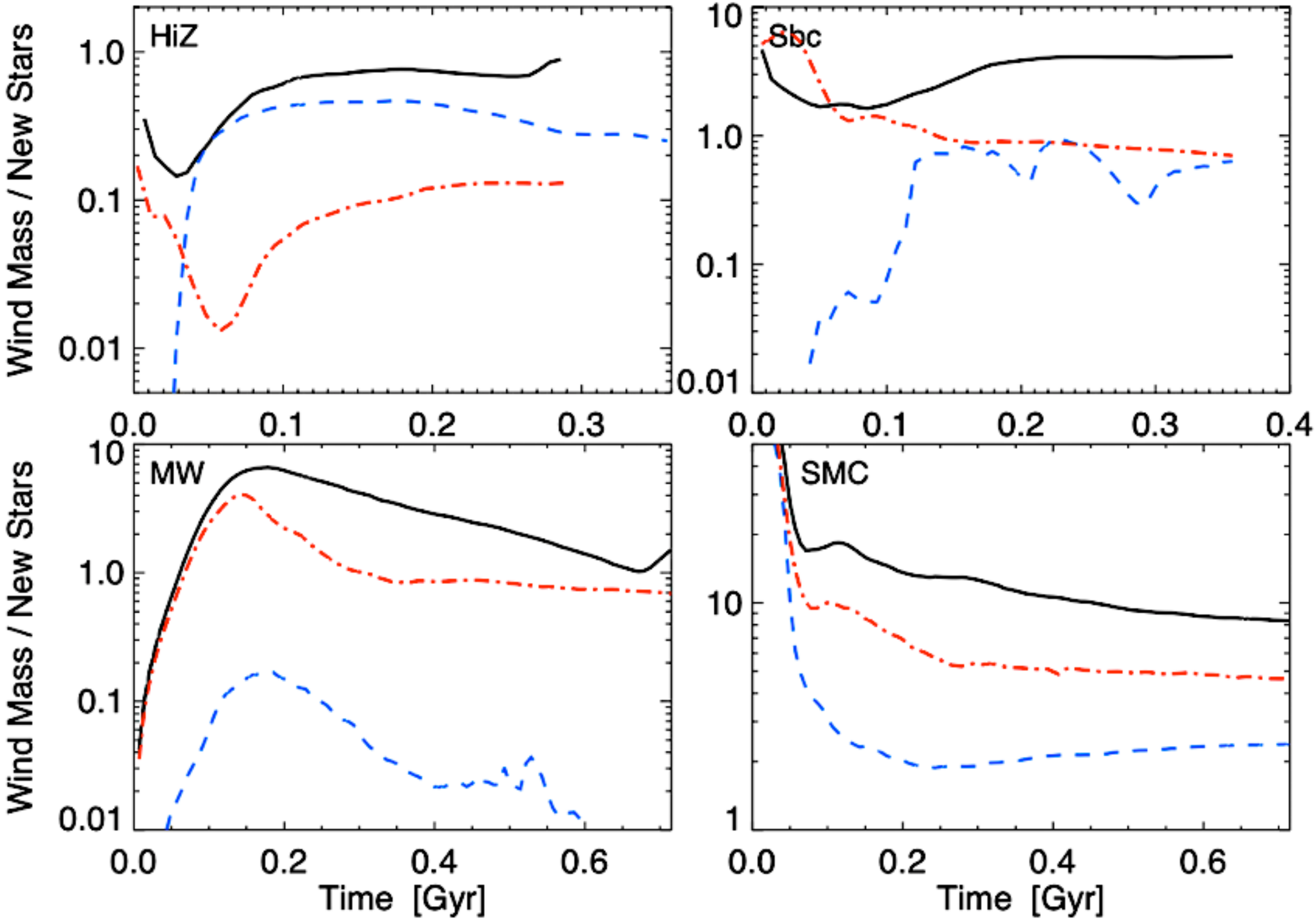
# How Efficient Are Galactic Super-Winds?

## AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c

Massive High-z Disk

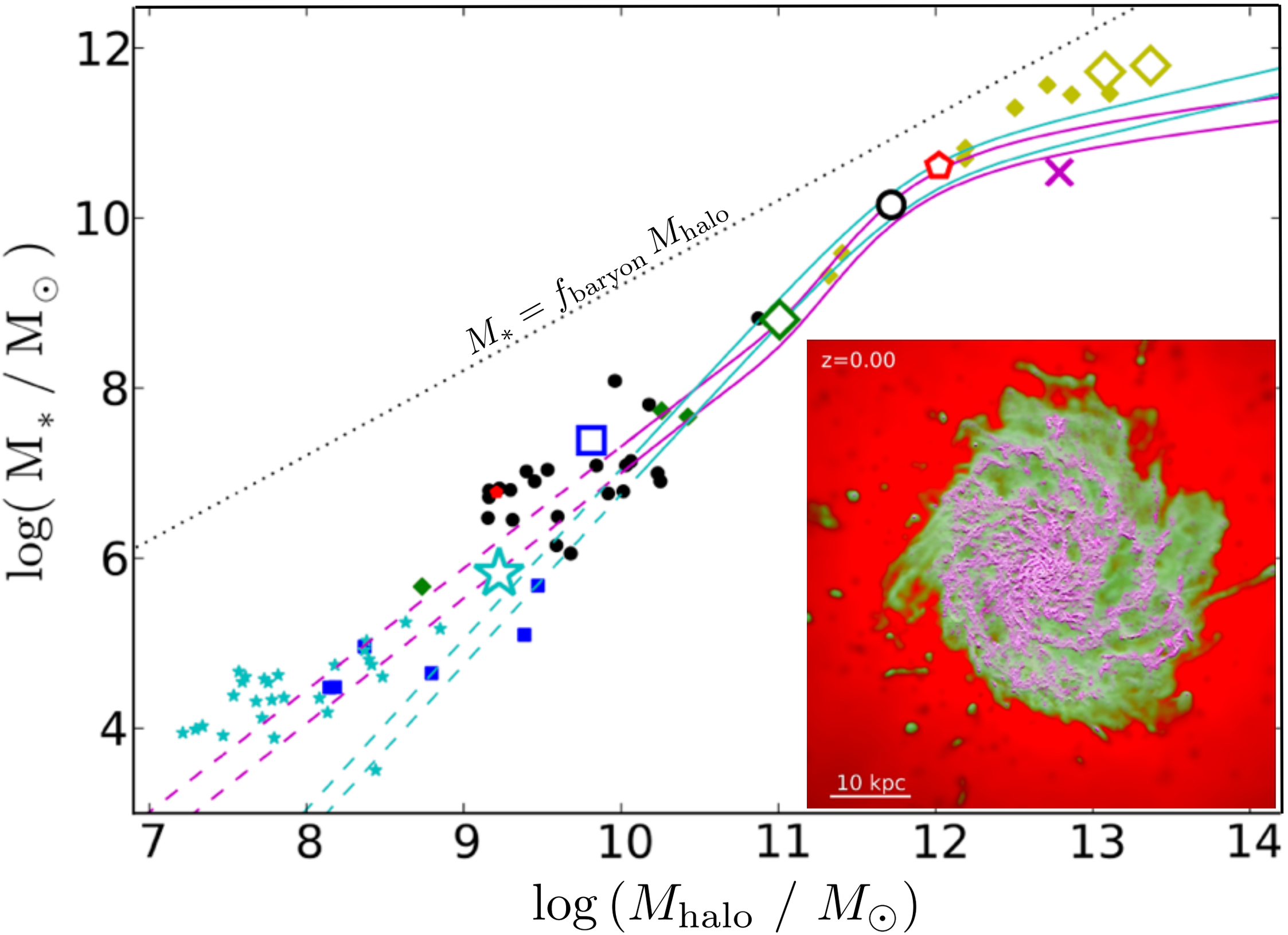
Dwarf Starburst



# Does Stellar Feedback Explain the Mass Function?

## HOW EFFICIENT ARE GALACTIC WINDS?

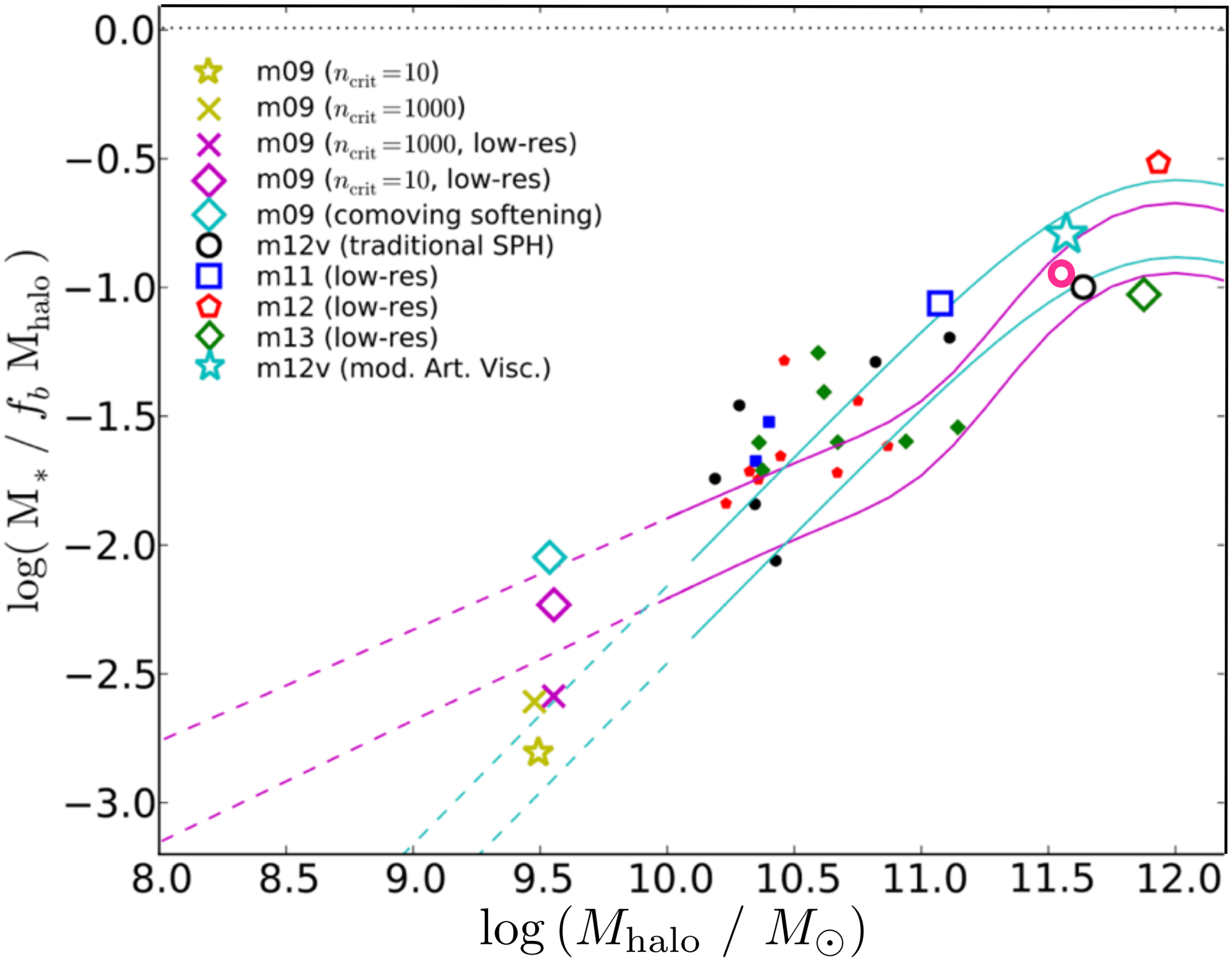
PFH, Keres, et al. (arXiv:1311.2073)



# Weak Numerical Dependence

## "ALGORITHMIC" CHOICES NOT DOMINANT

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



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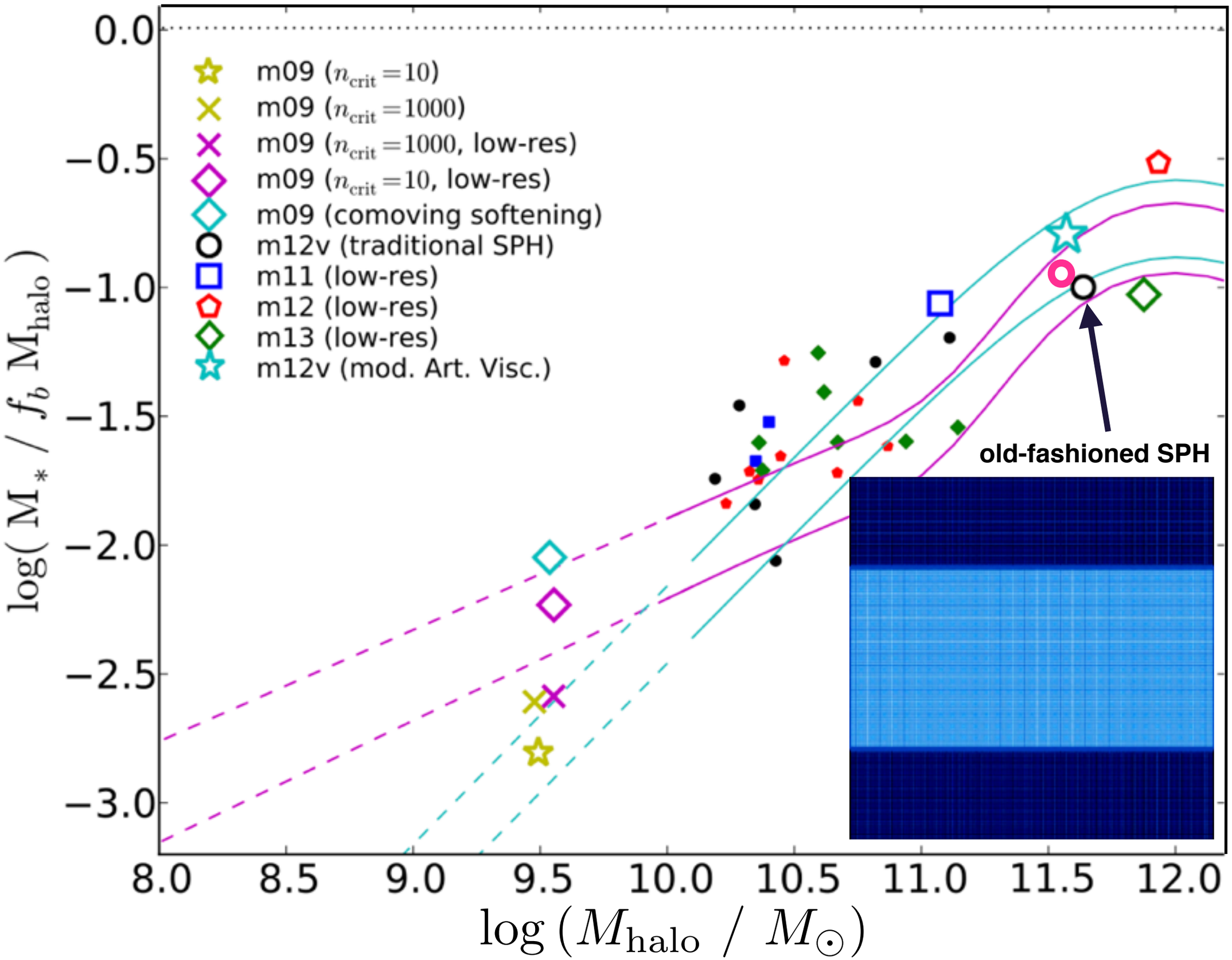

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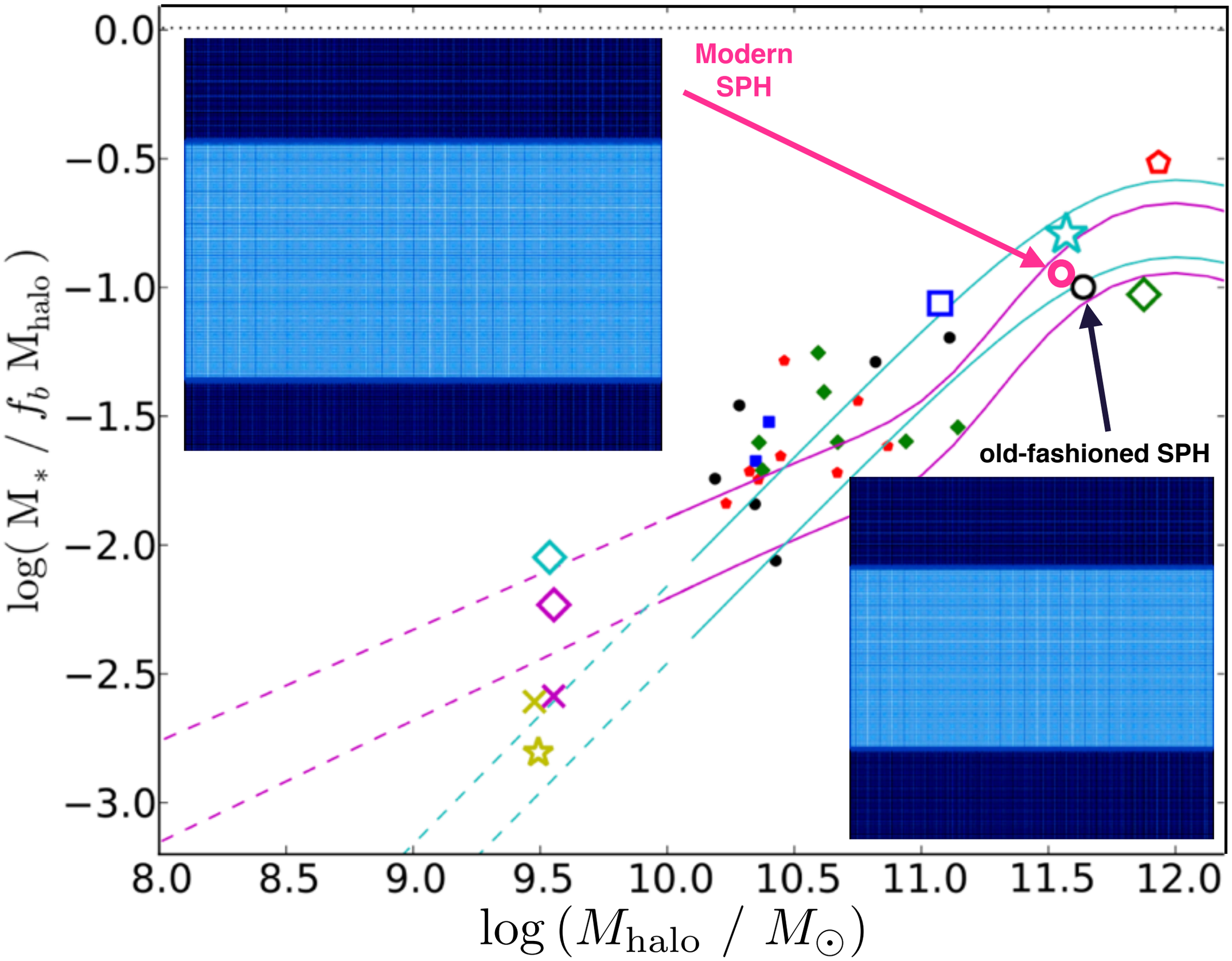
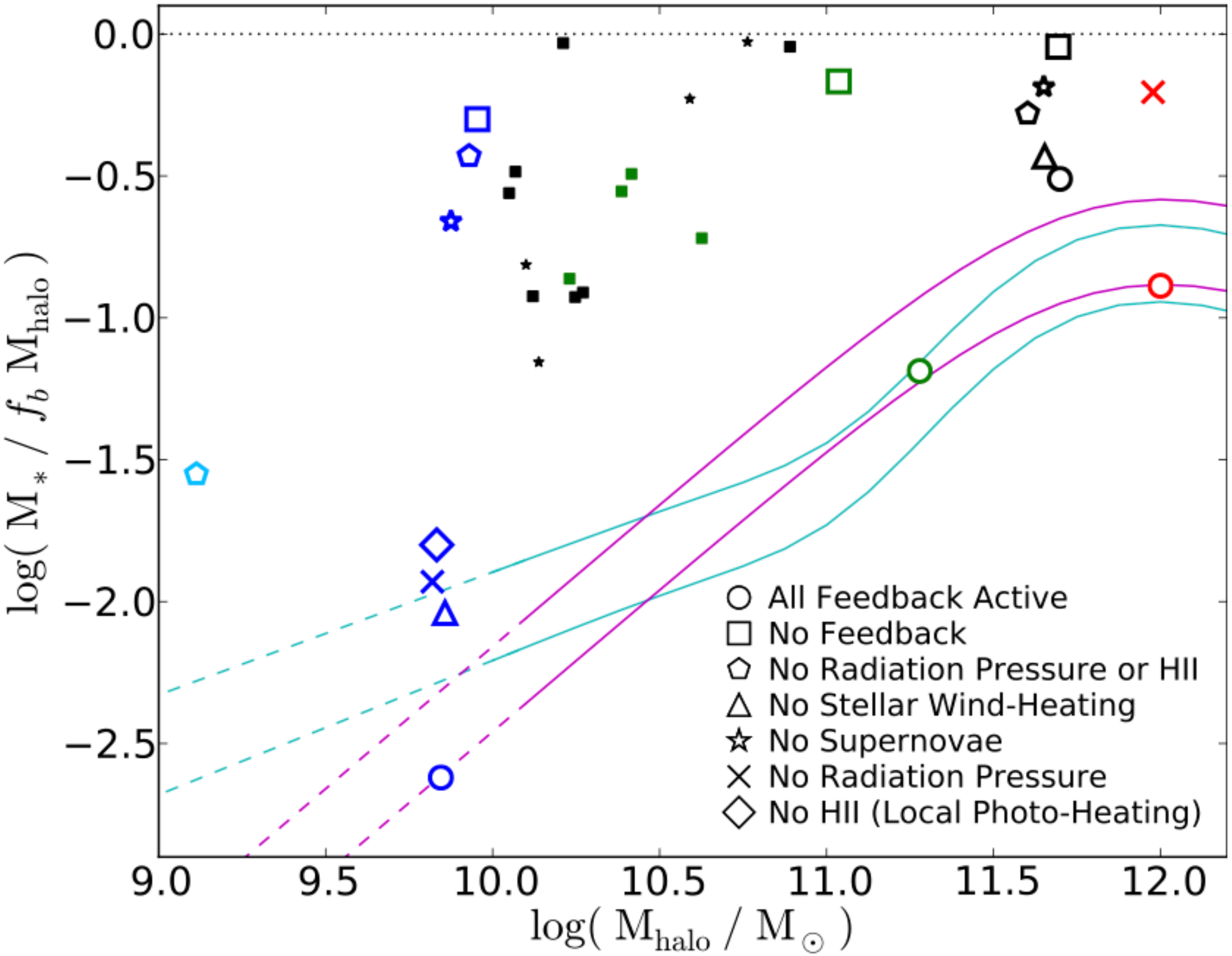


# But Feedback *Does* Matter

## *MULTIPLE* FEEDBACK MECHANISMS ARE CRITICAL

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



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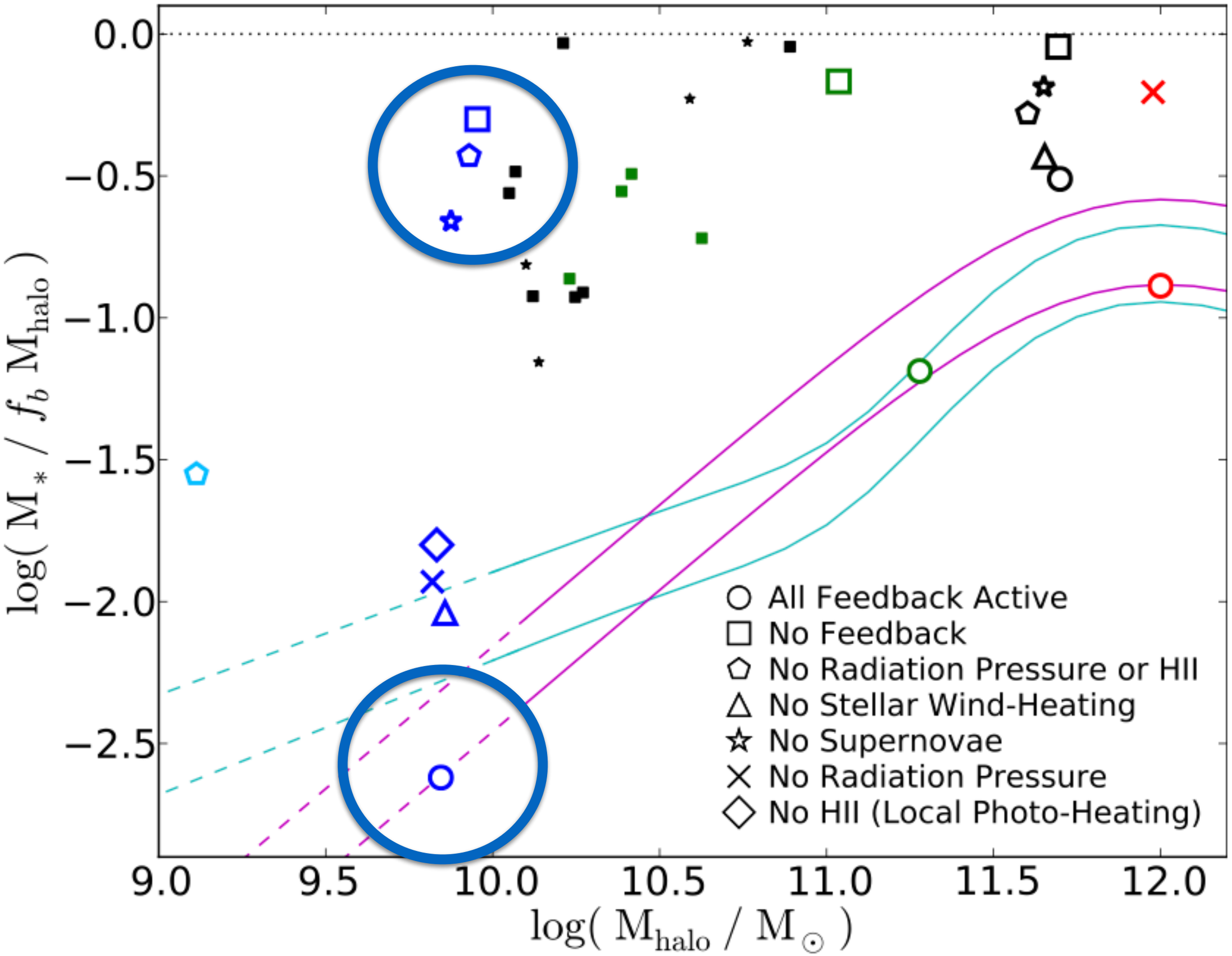
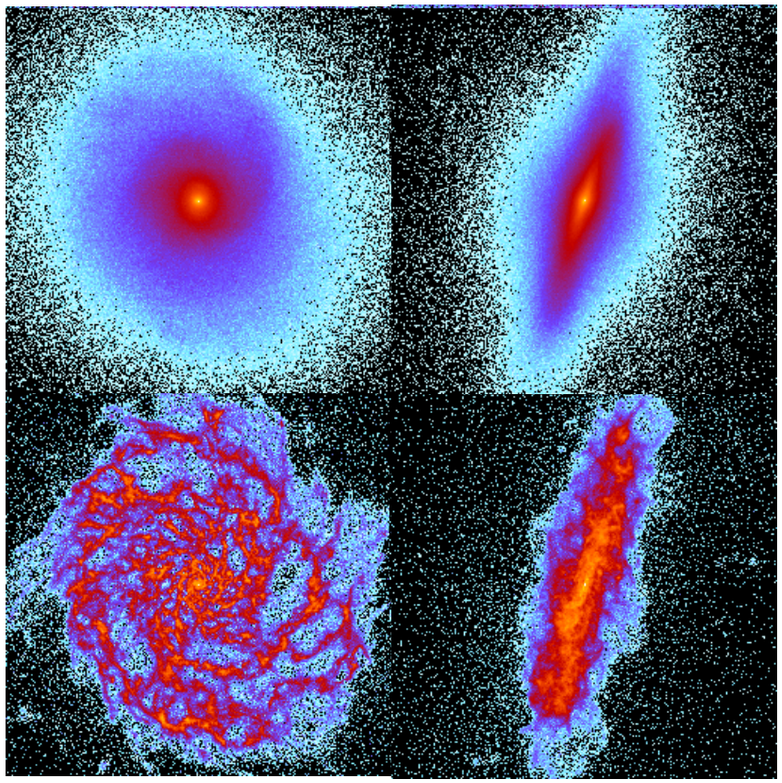


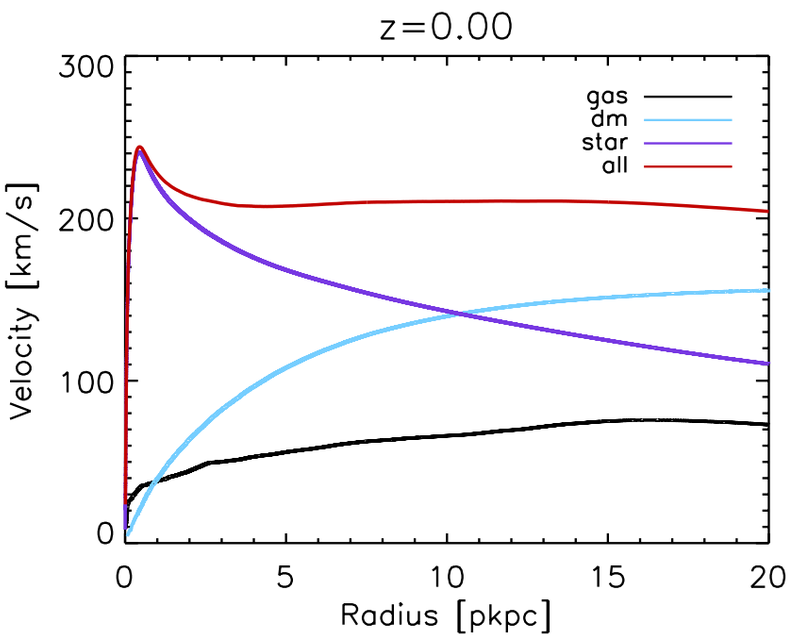
# But Feedback *Does* Matter

## DETAILS & MULTIPLE MECHANISMS IMPORTANT

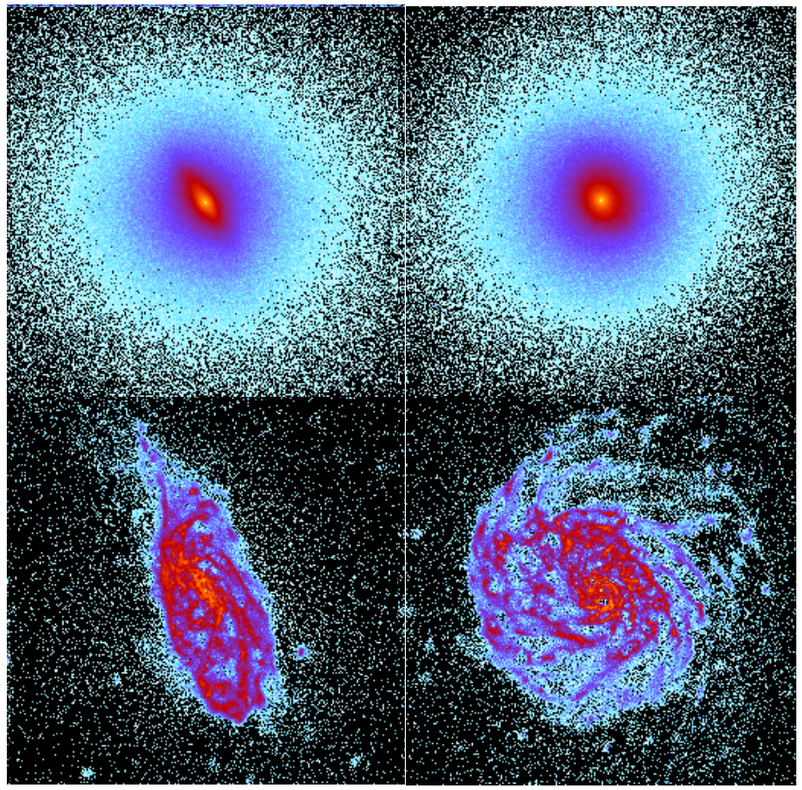
van de Voort et al., in prep

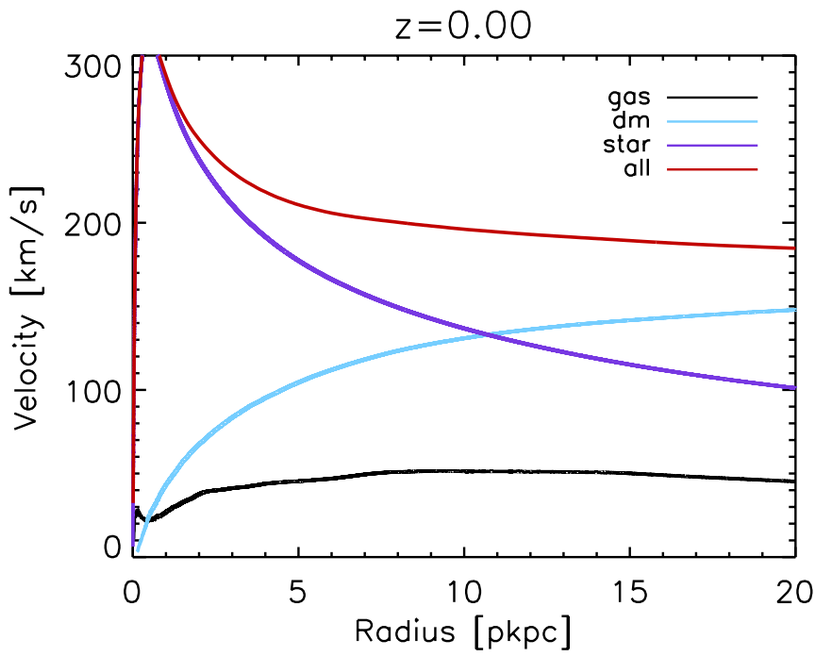
standard






no multiple-scattering





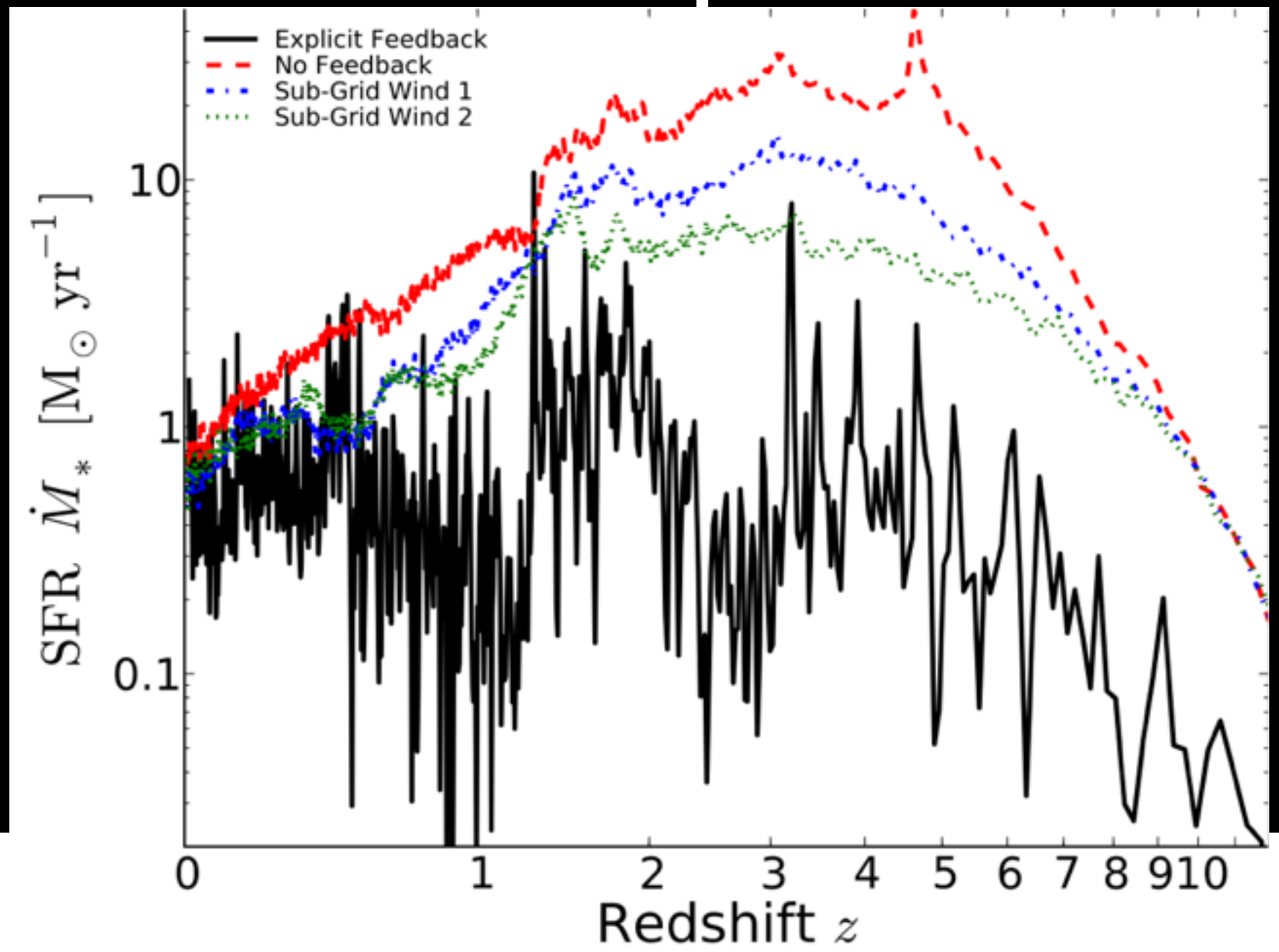
# Simplest Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

## Proto-MW: Gas Temperature:

"Decoupled Winds" (Sub-Grid)

Following Explicit Feedback

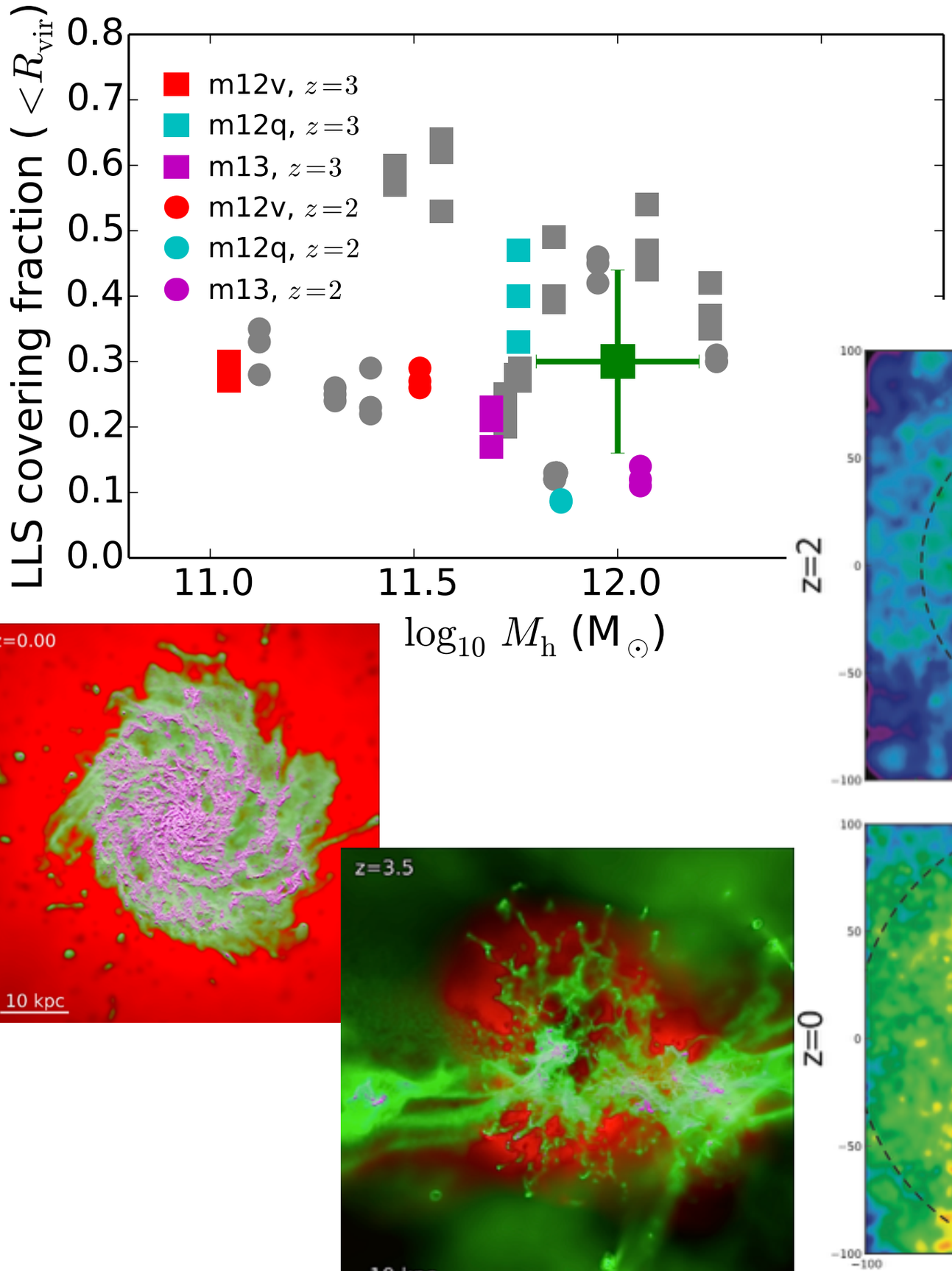



PFH, Keres, et al. (arXiv:1311.2073)

# Feedback Determines the Halo Gas Properties

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

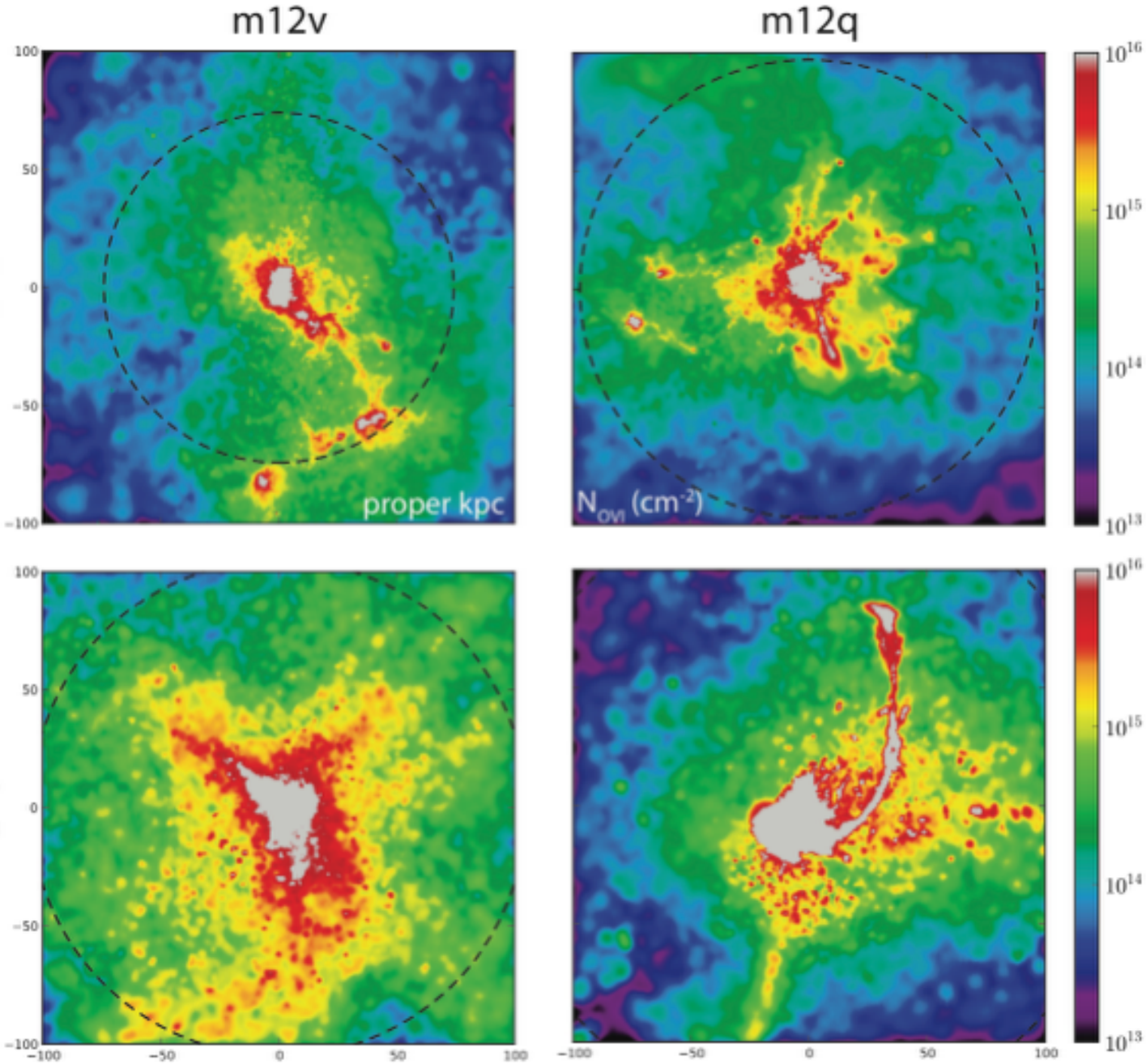
Faucher-Giguere, PFH, et al.





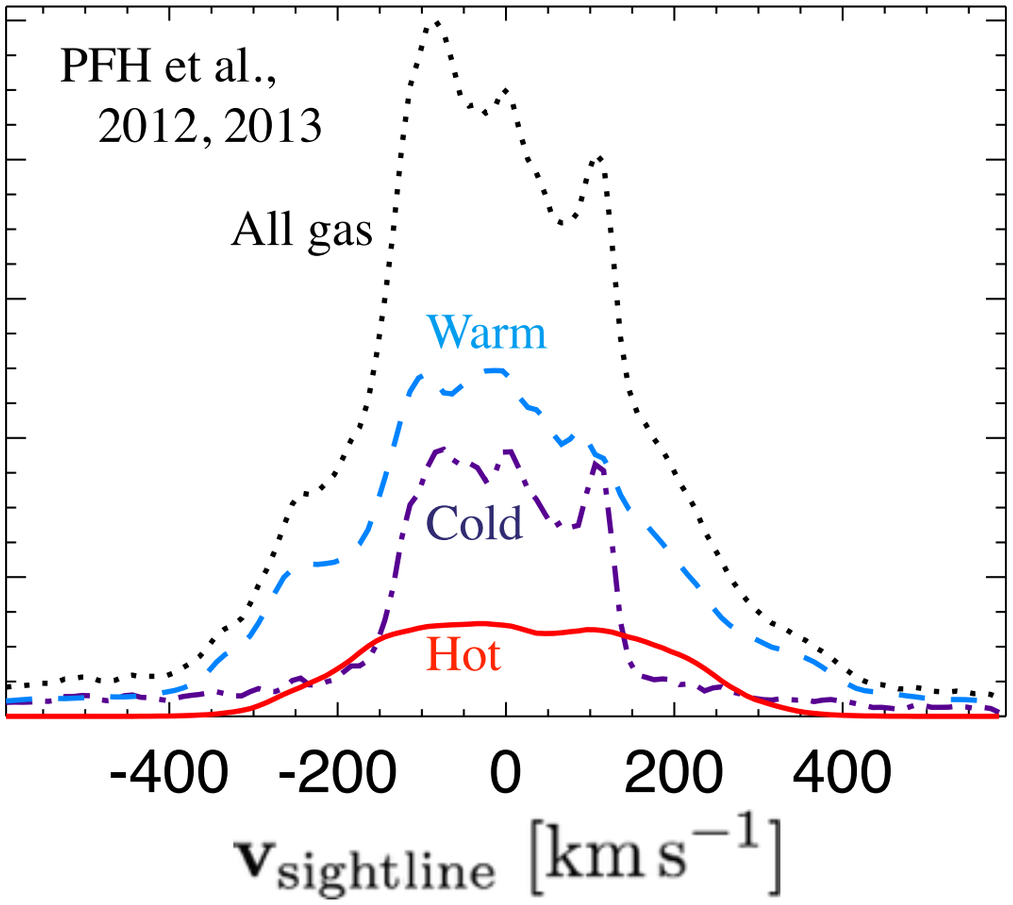


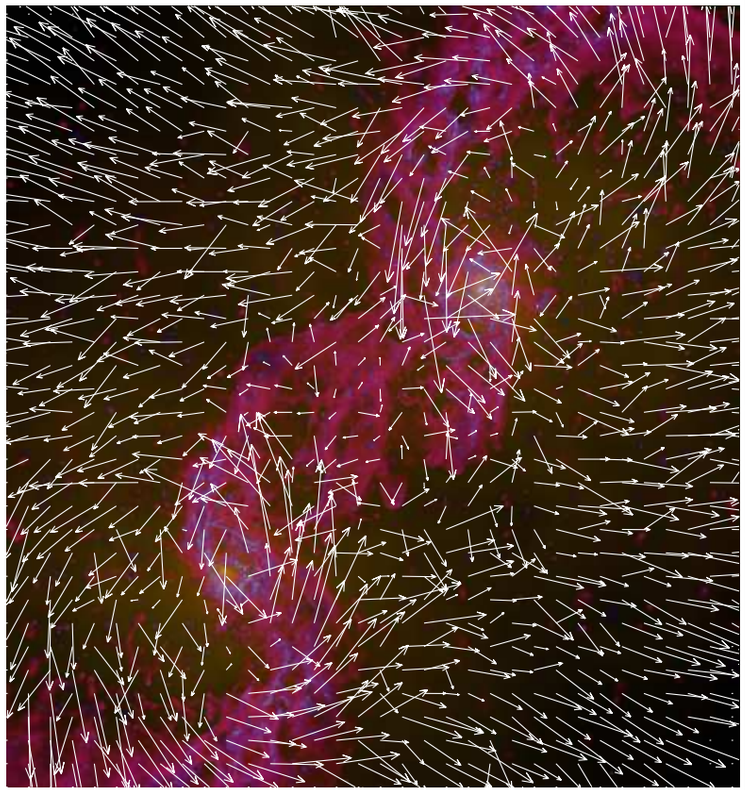


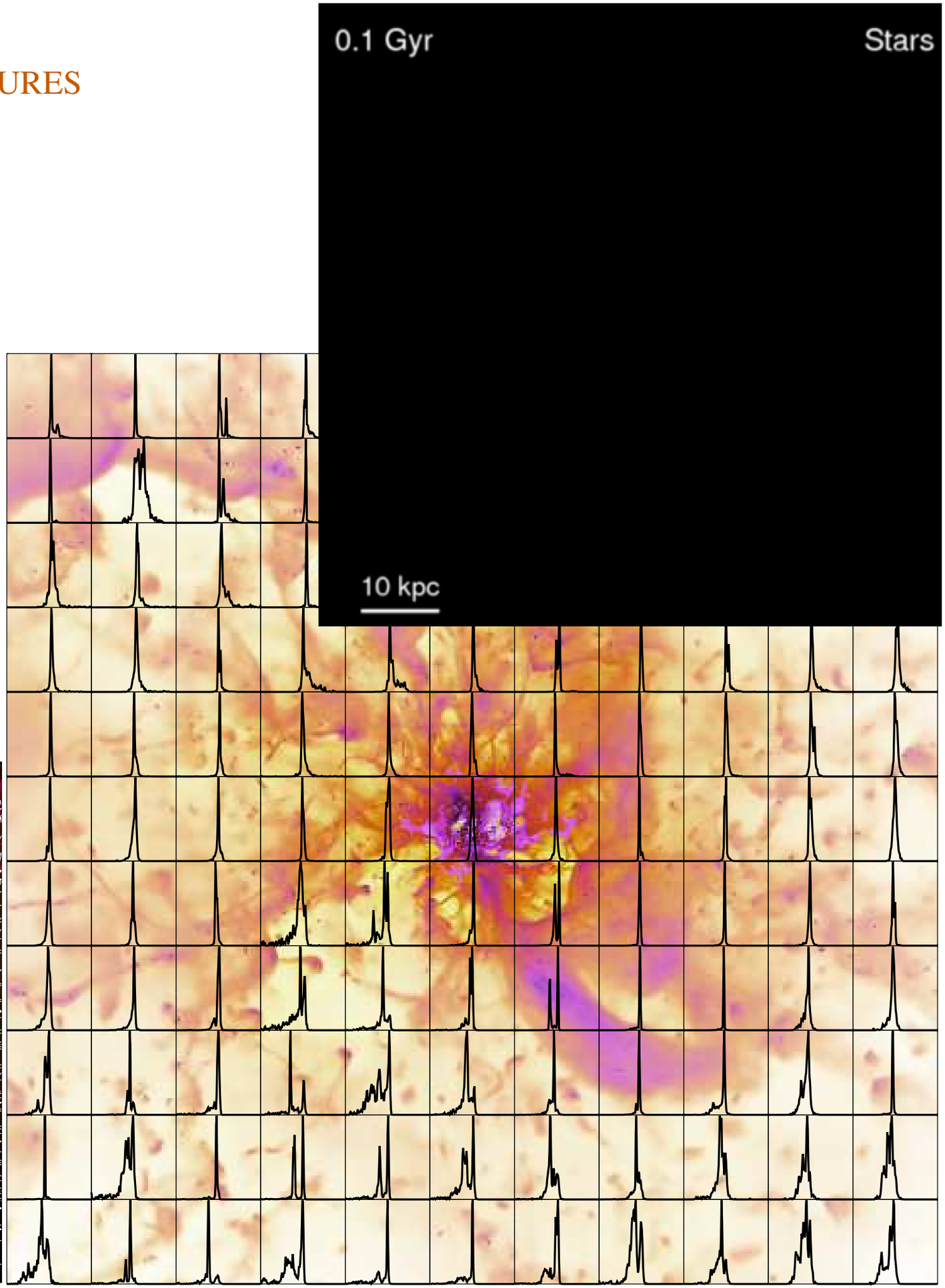



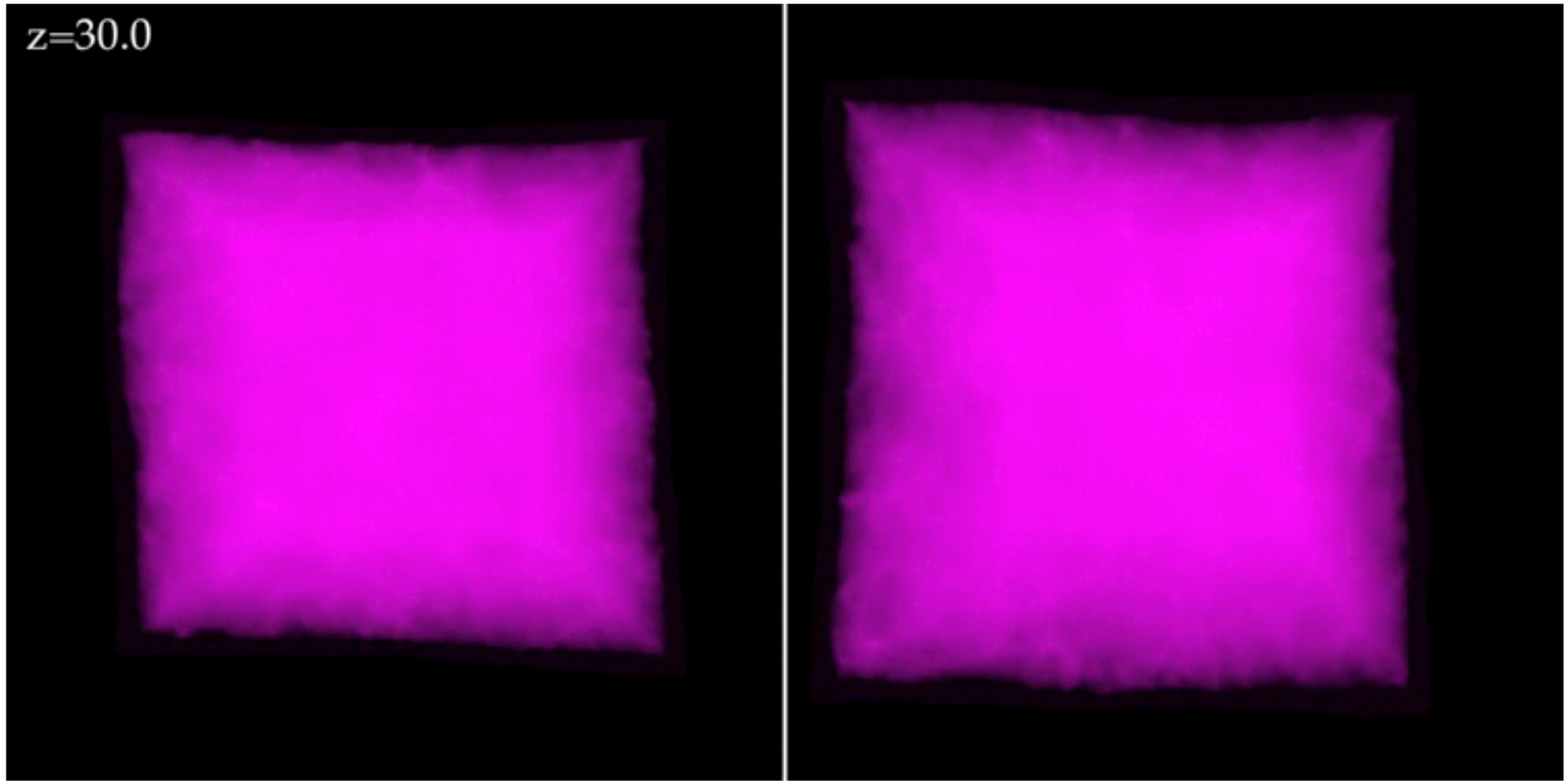
# Kinematics of Stars & Gas

## DIFFERENT MECHANISMS = DIFFERENT SIGNATURES








- **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-$\rho$: rad. pressure & photo-heating
  - Low-$\rho$: 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"