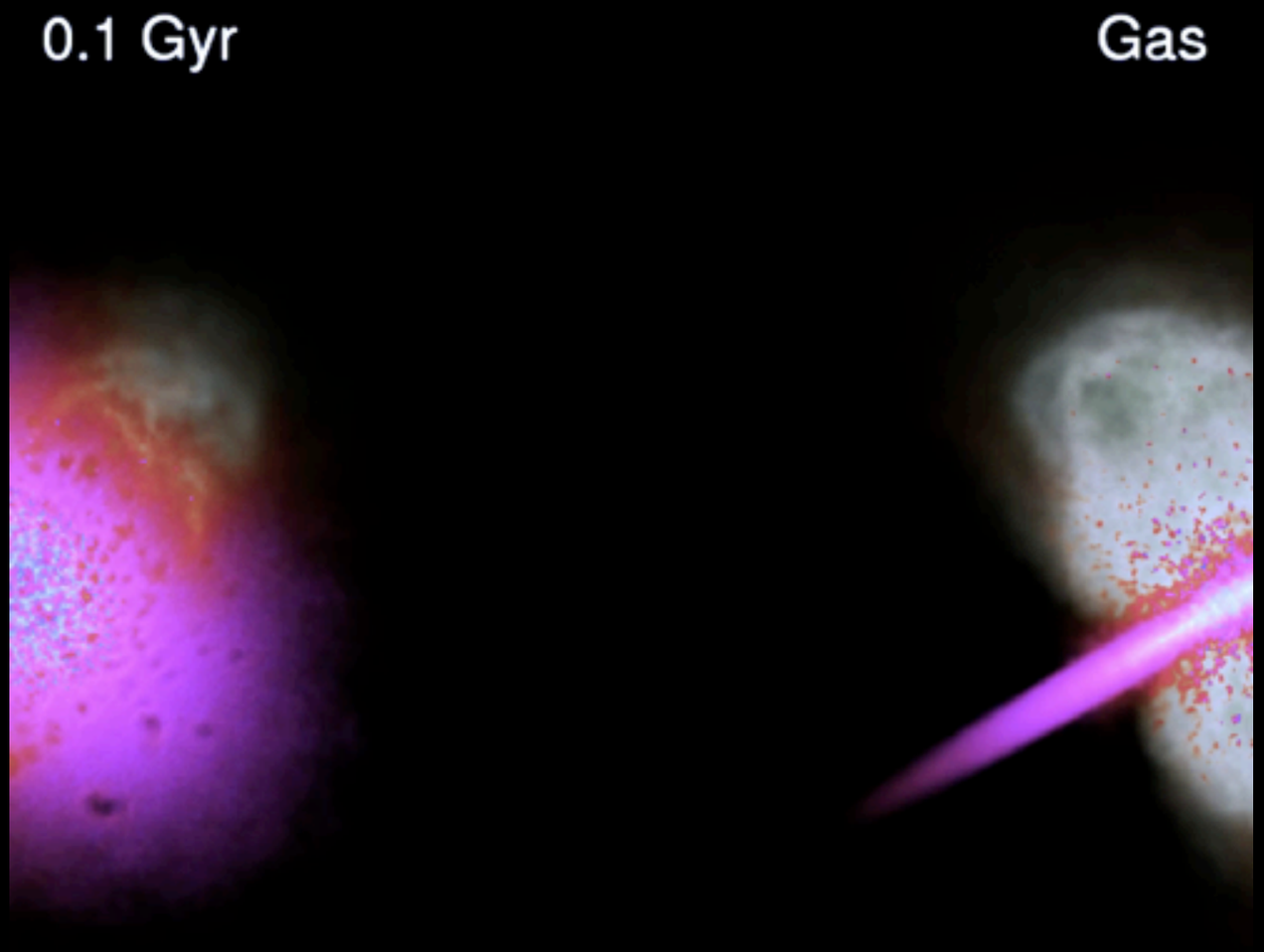
Galaxies on FIRE: Challenges of Adding Physics in Galaxy Formation Models

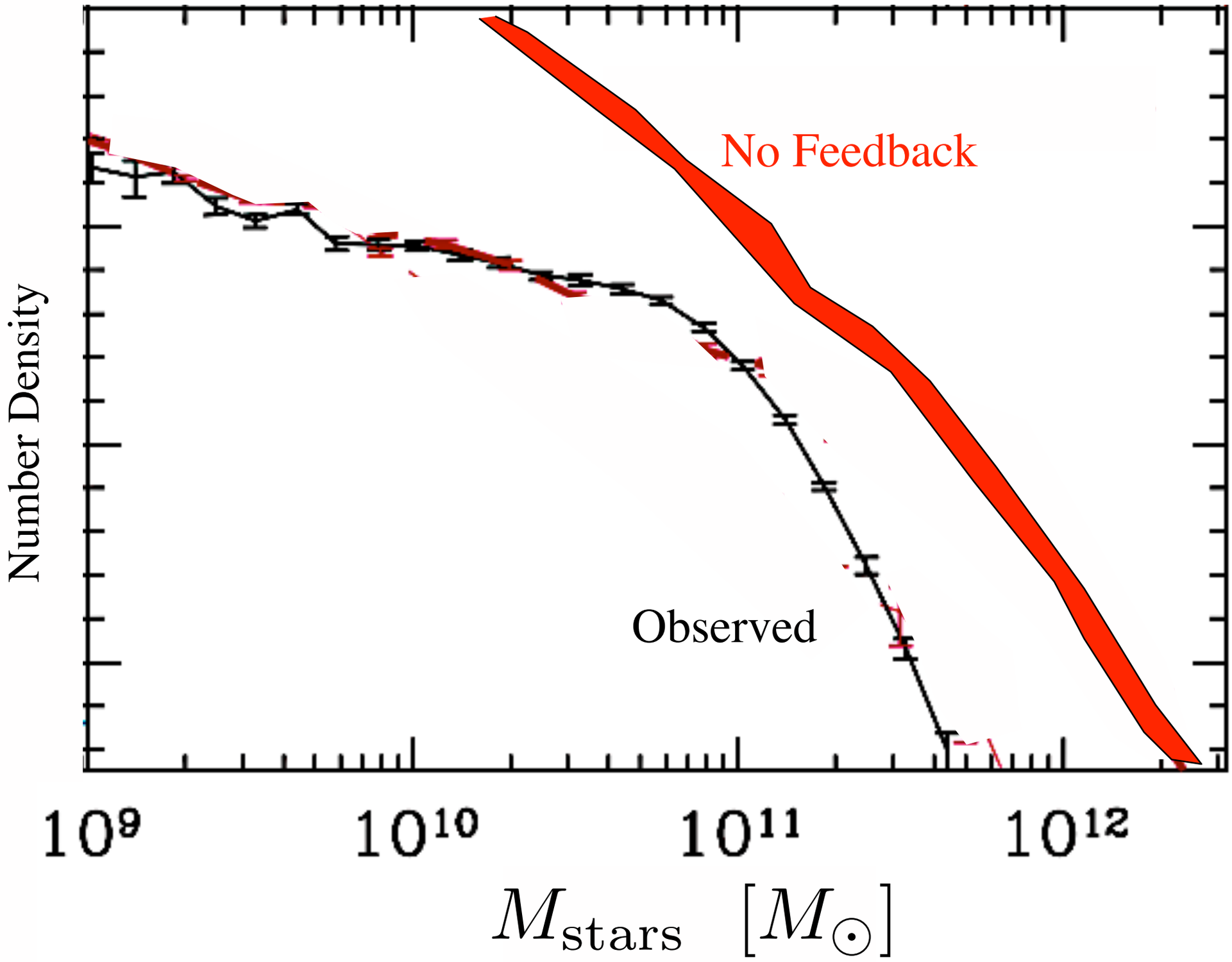


Phil Hopkins

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

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



So What's the Problem?

- Gravity — Good!
- Hydro + Ideal MHD — Yes!
- Chemistry / cooling physics — Not bad
- "Feedback" — Huh?

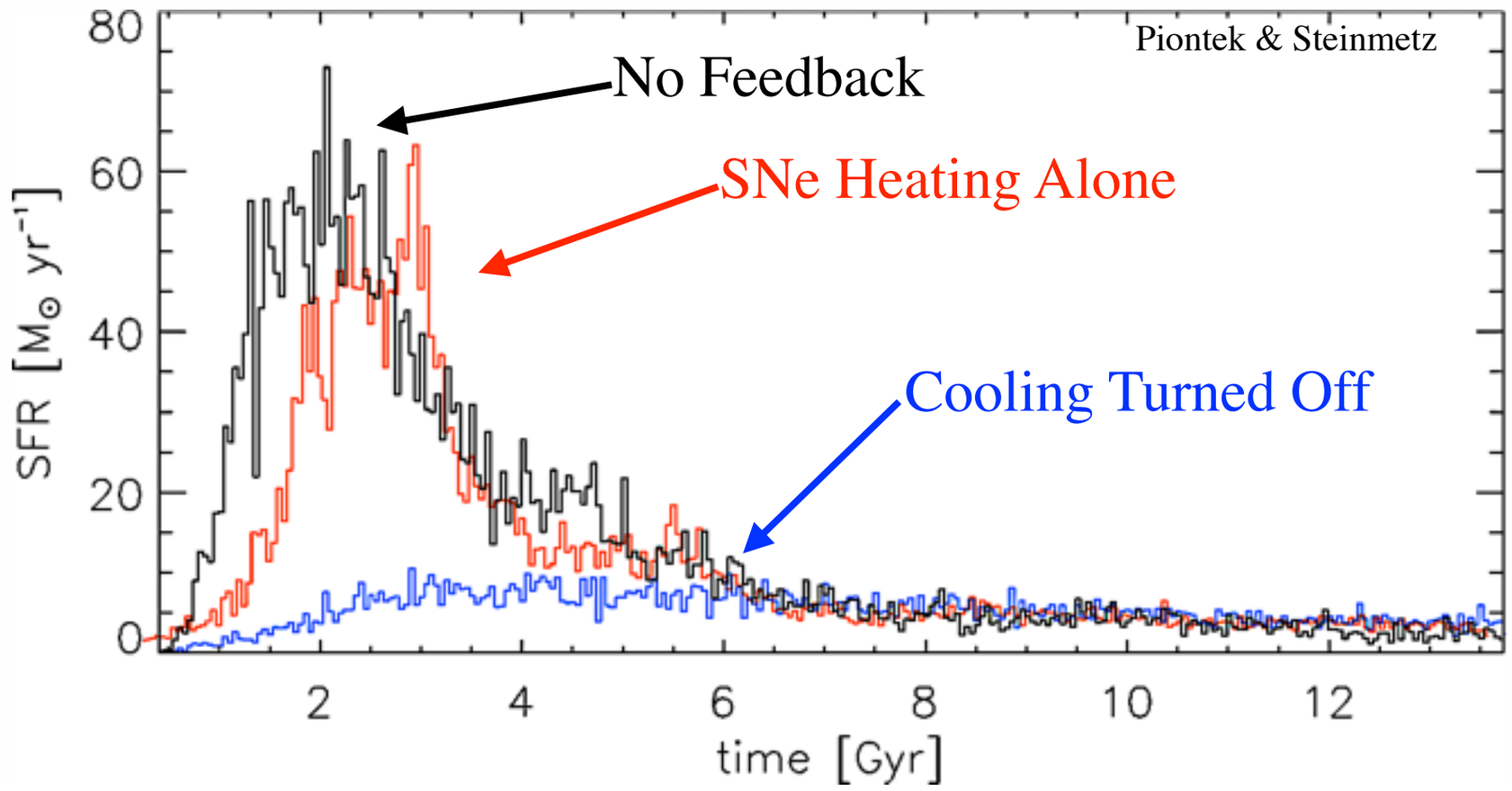
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

...

...

and then "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

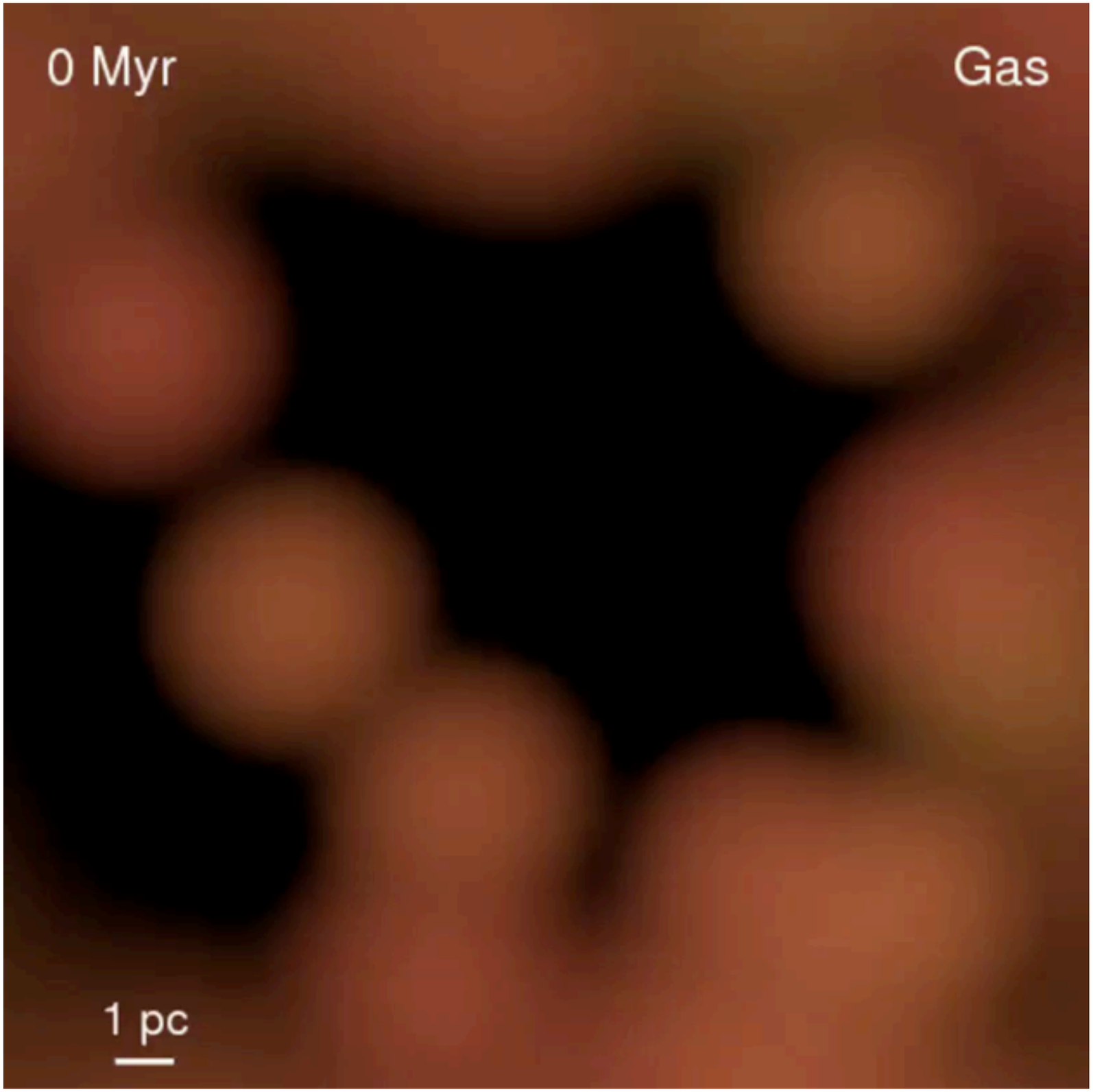
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

  - SNe

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

  - Stellar Winds

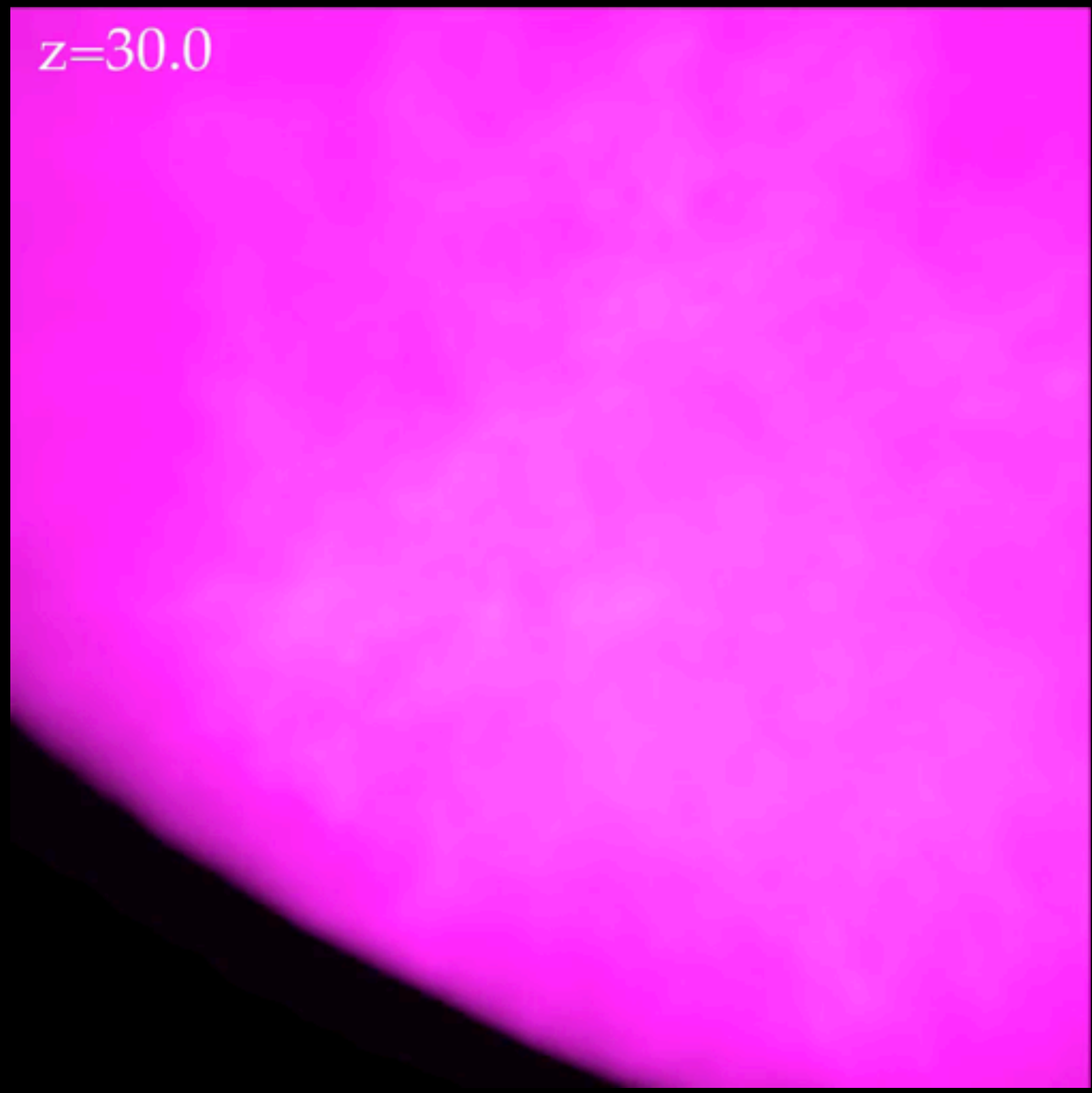
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$



- (also MHD, anisotropic conduction, diffusion)

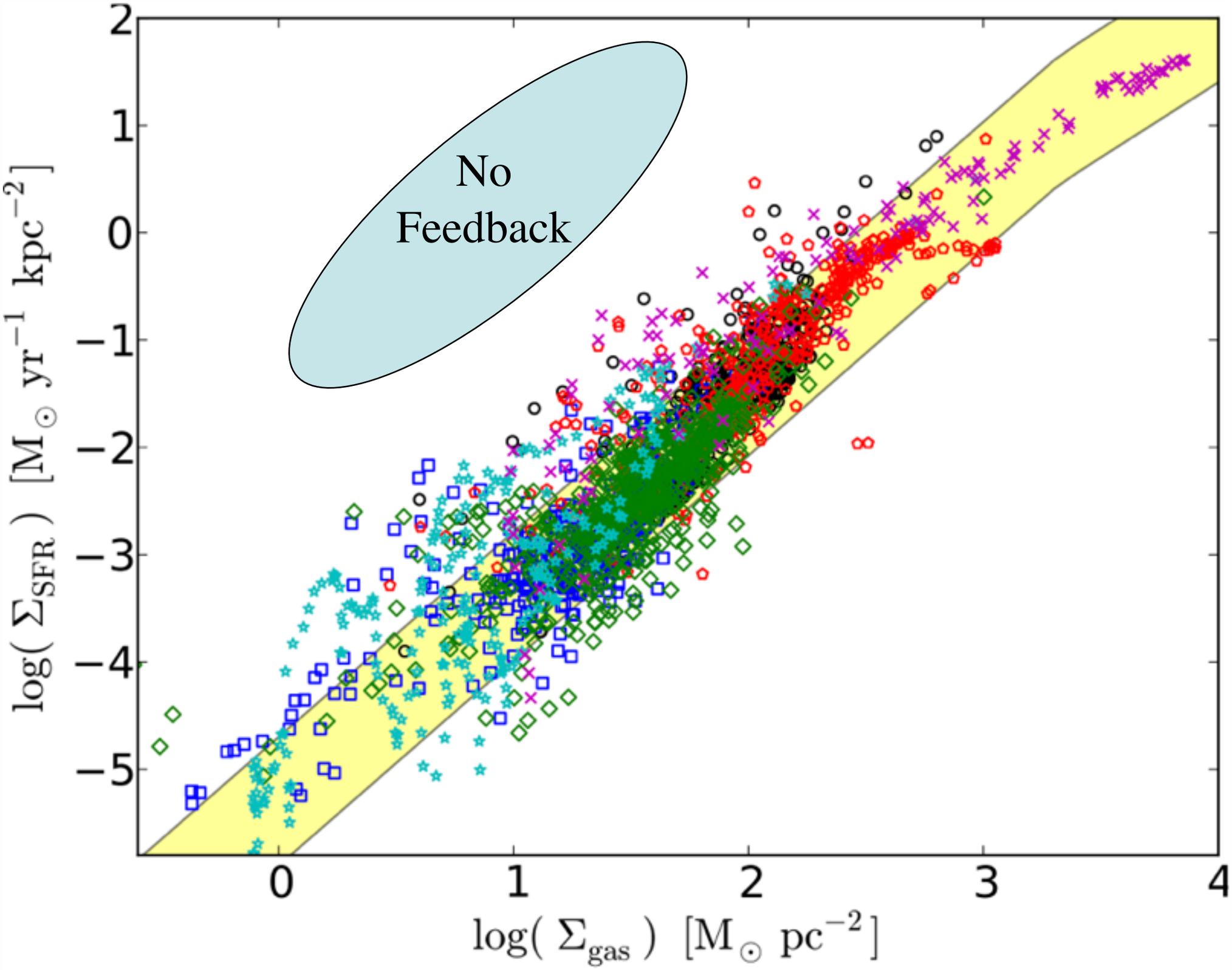
The FIRE Project: Cosmological Simulations at 1-10pc resolution

z=30.0



Cosmological Simulations

NO PARAMETERS ADJUSTED! REALLY!



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

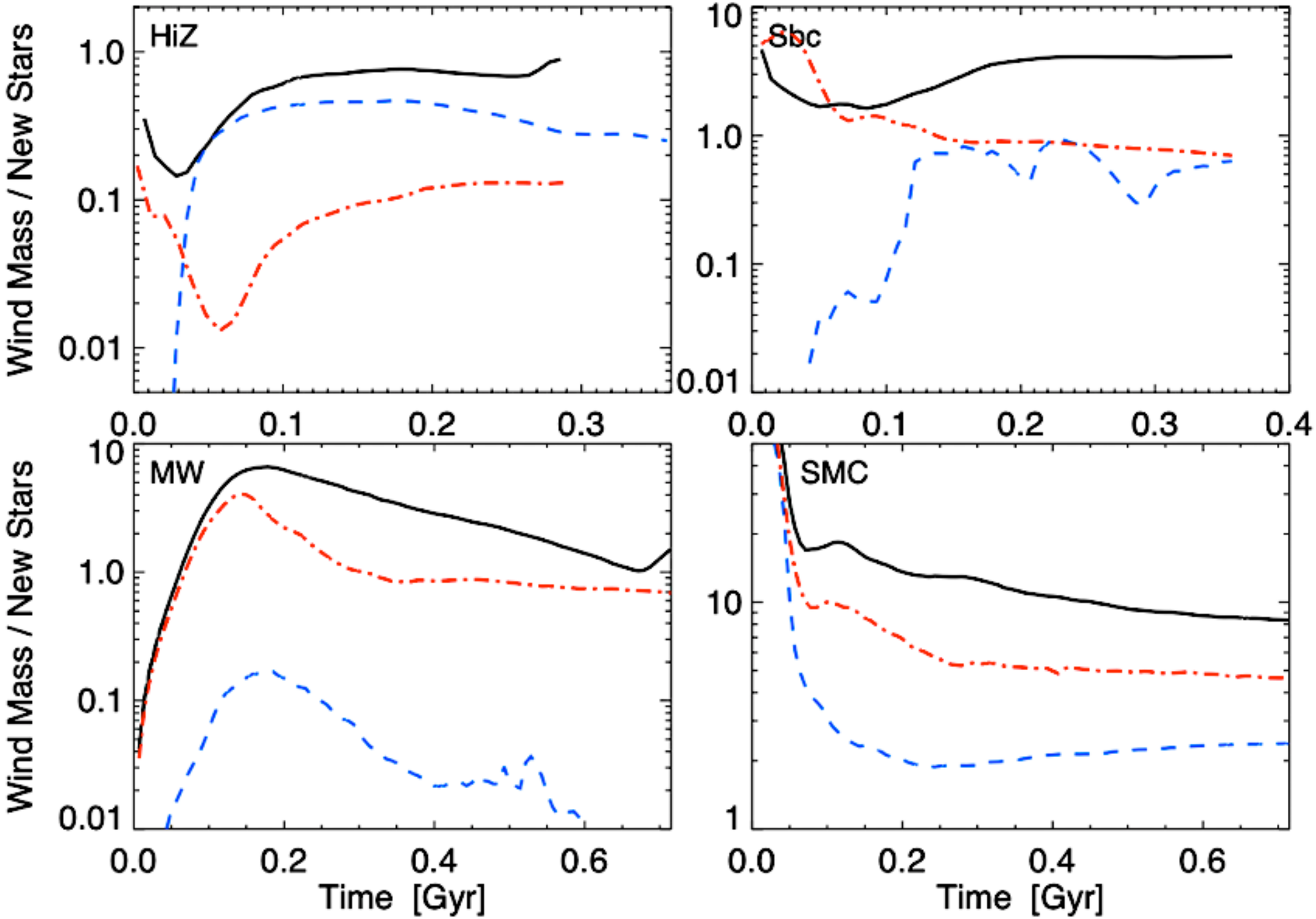
How Do Galactic Super-Winds Form?

AND SHOULD WE BE WORRIED?

PFH, Quataert, & Murray, 2011c

Massive High-z Disk

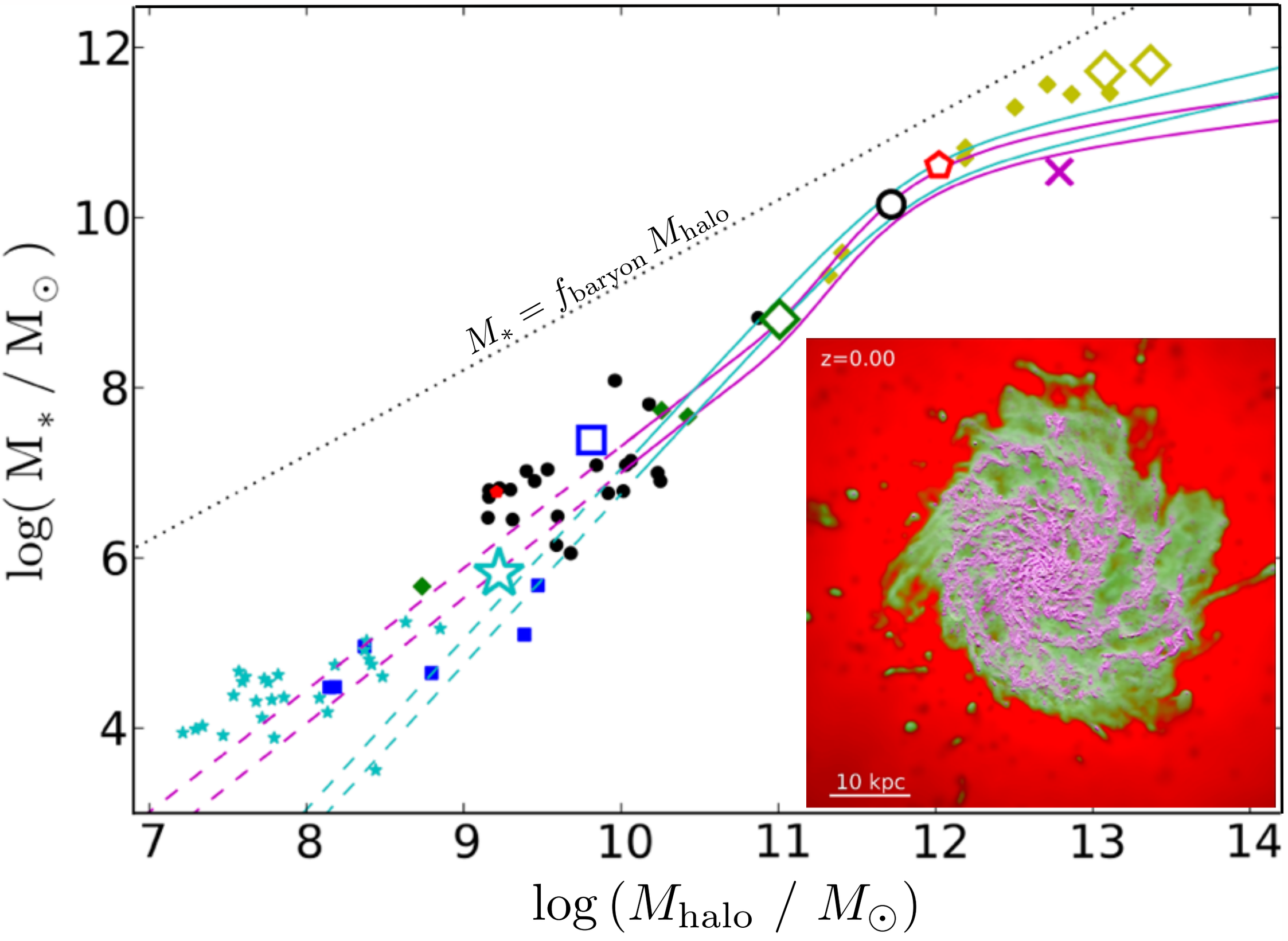
Dwarf Starburst



Does Stellar Feedback Explain the Mass Function?

YES! WE ACTUALLY CAN MAKE PROGRESS!

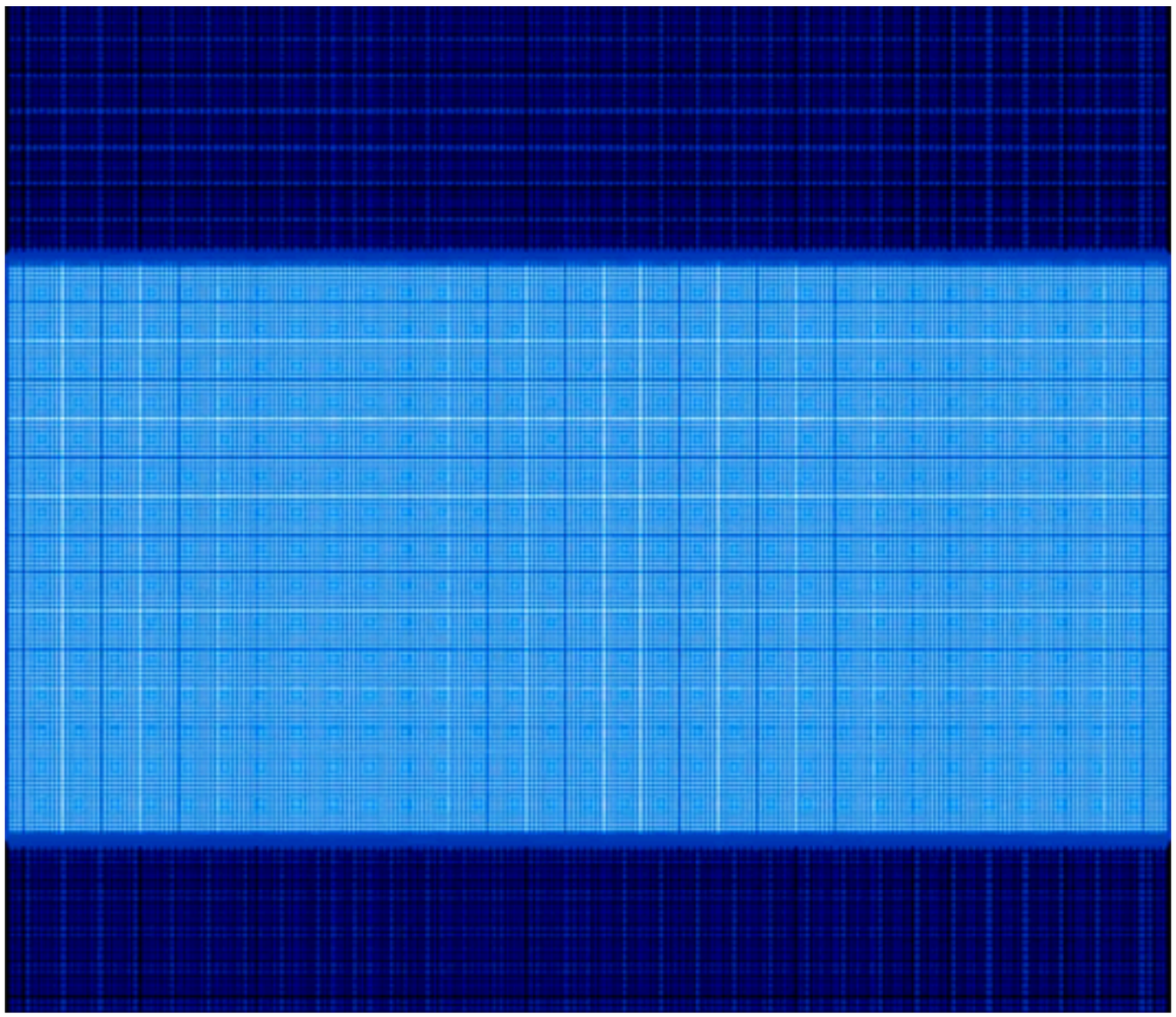
PFH, Keres, et al. (arXiv:1311.2073)



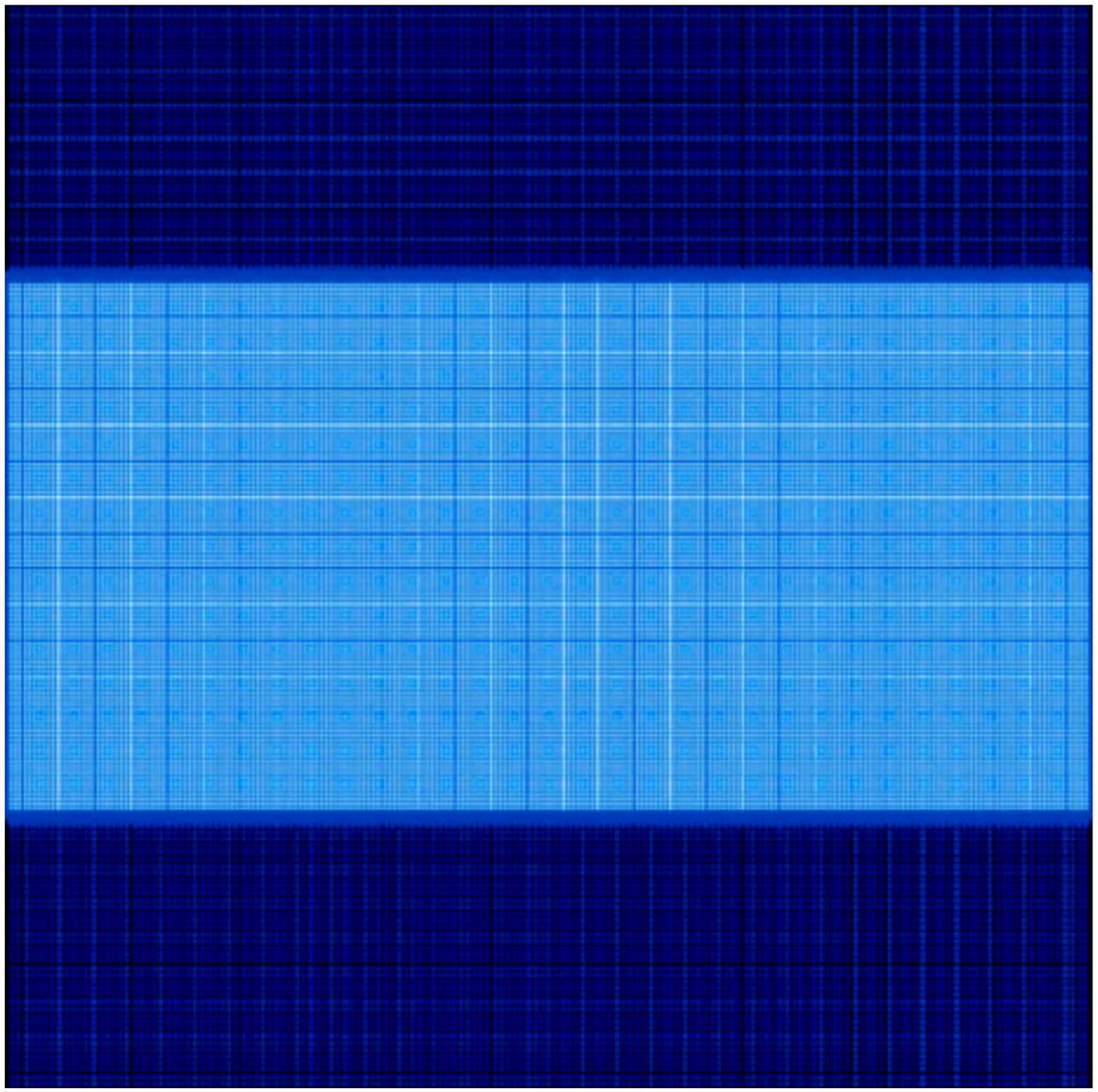
But I Heard (*non-AREPO code here*) Can't Do Anything Right!

Hopkins 2013

CAN WE MODEL MULTI-PHASE FLUIDS?



Pressure-Entropy Formulation
(P-GADGET)

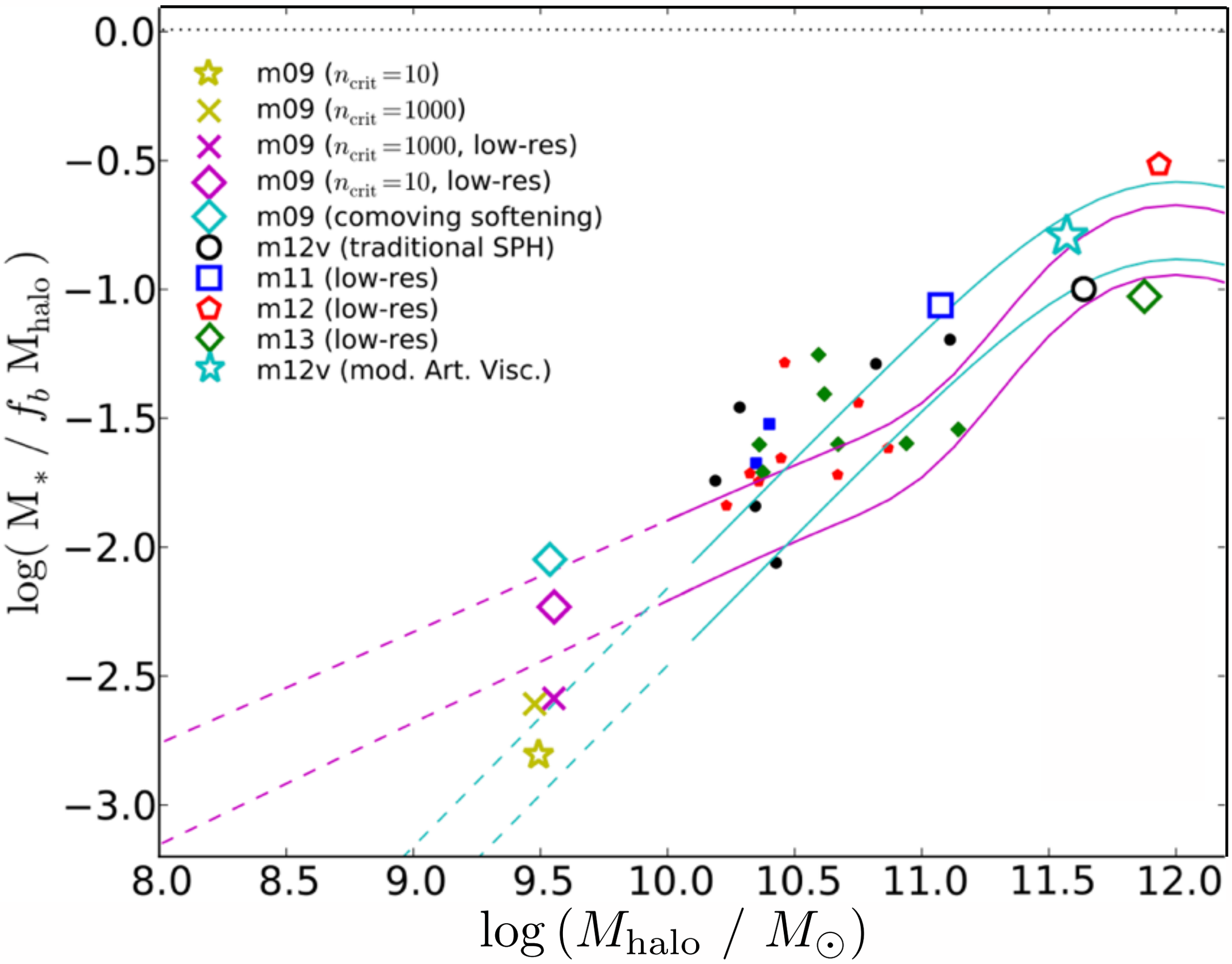


Density Formulation
("Old" GADGET)

Weak Numerical Dependence

"ALGORITHMIC" CHOICES NOT DOMINANT

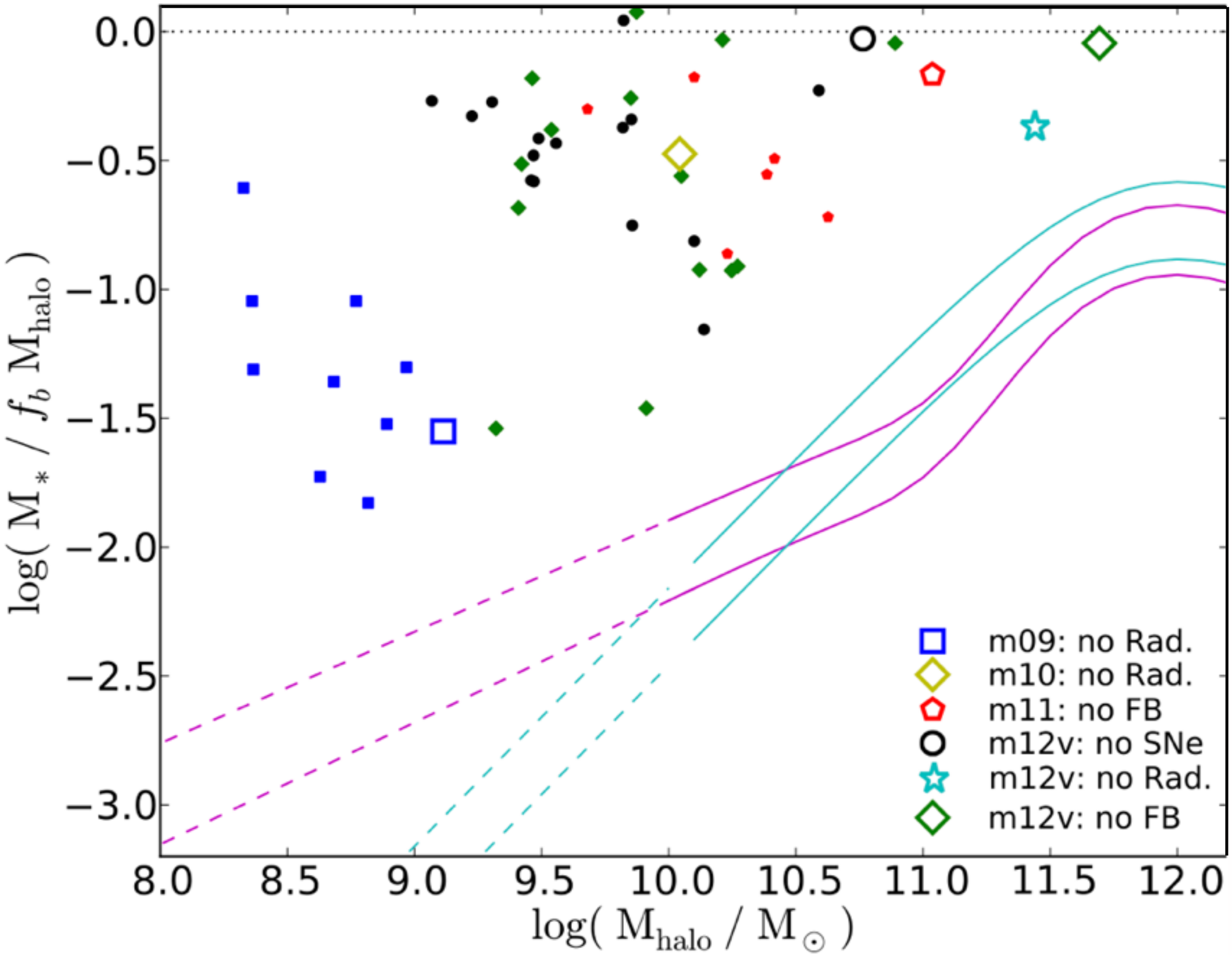
PFH, Keres, et al. (arXiv:1311.2073)



But Feedback *Does* Matter

WE'RE PHYSICS-LIMITED

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



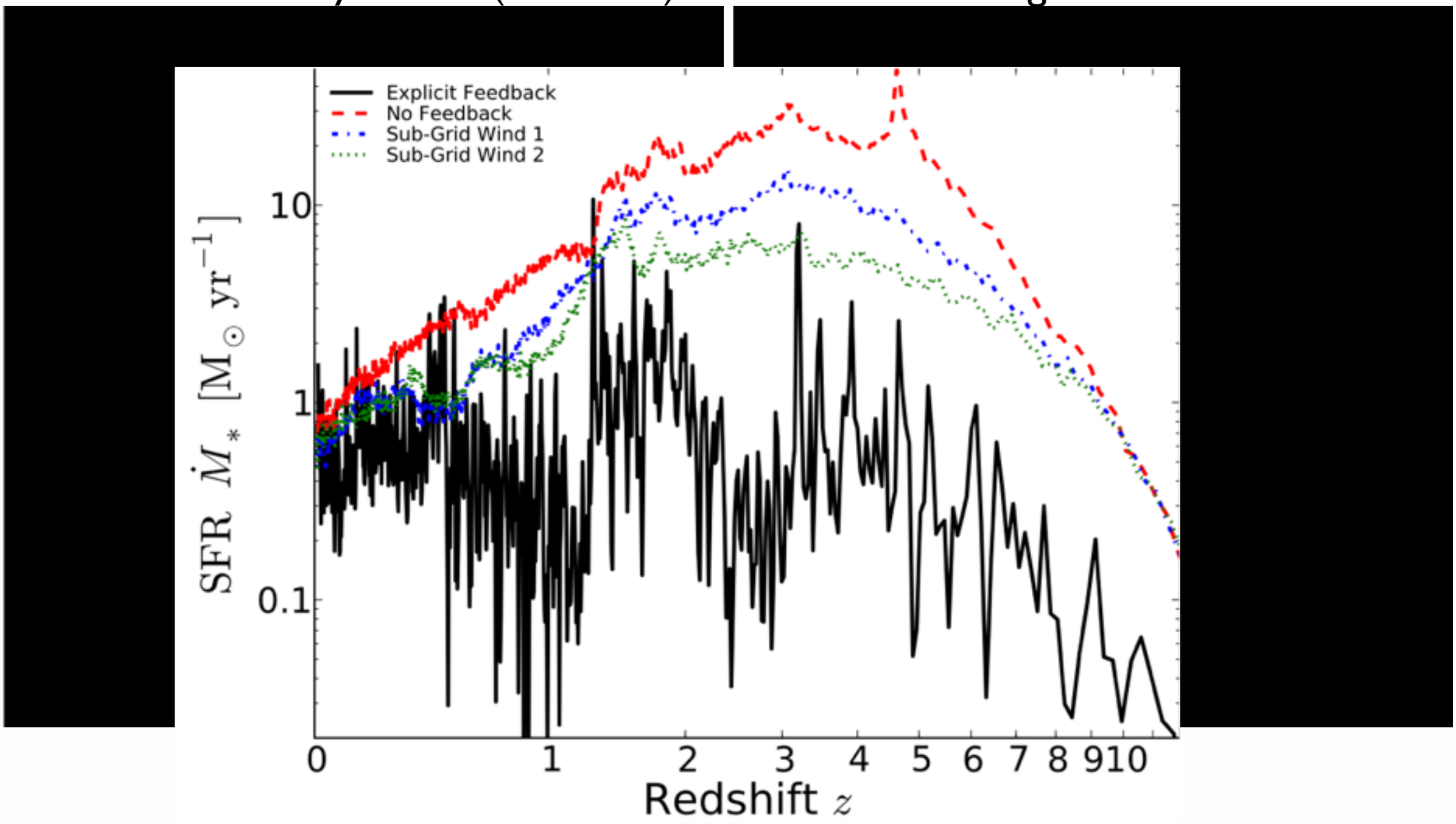
Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

Following Full Feedback

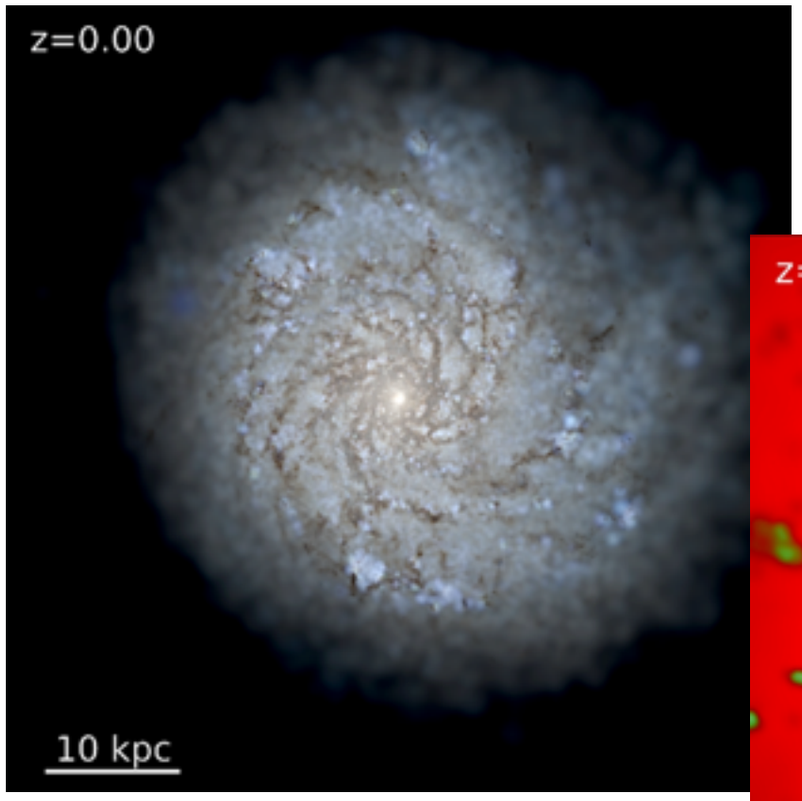


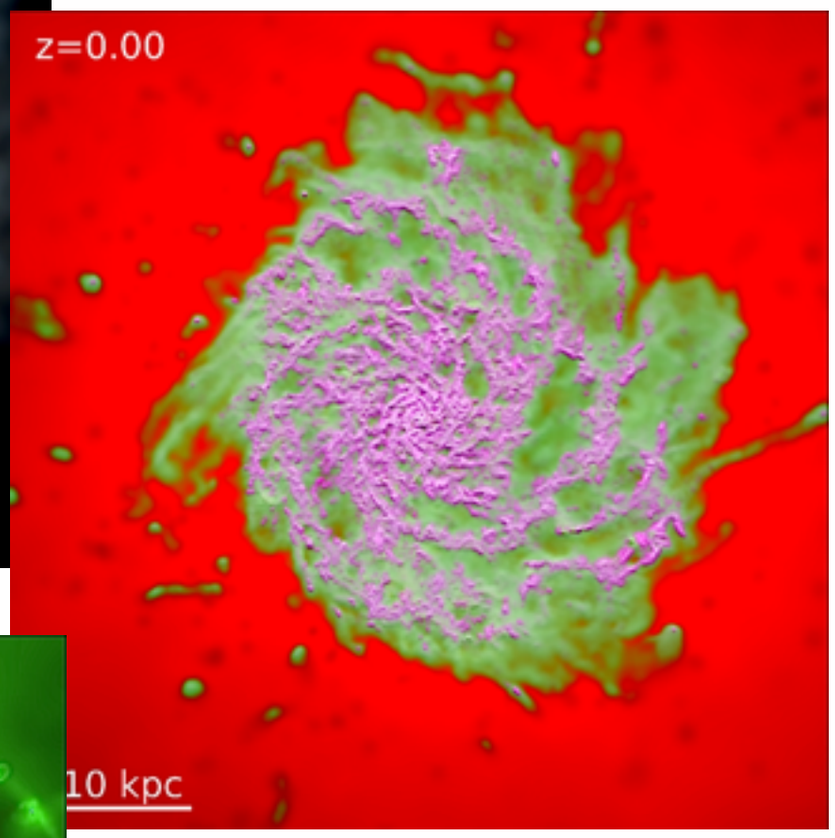
PFH, Keres, et al. (arXiv:1311.2073)

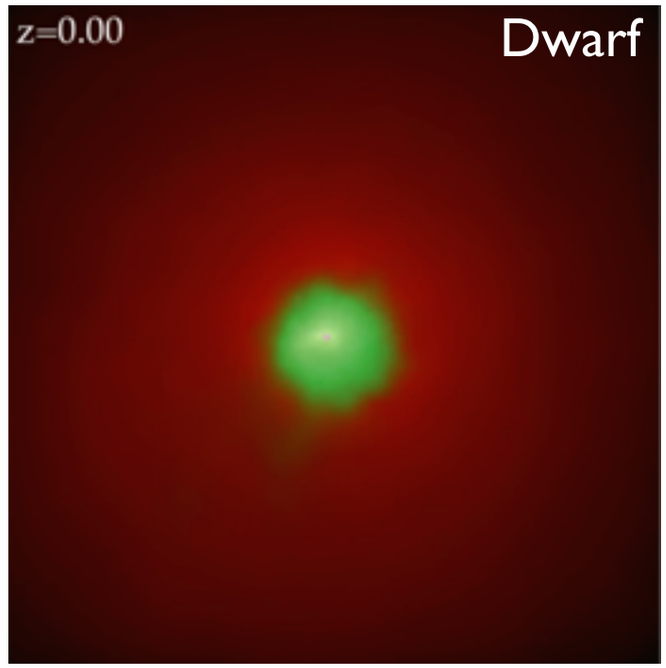
Sub-Grid Is Not Enough

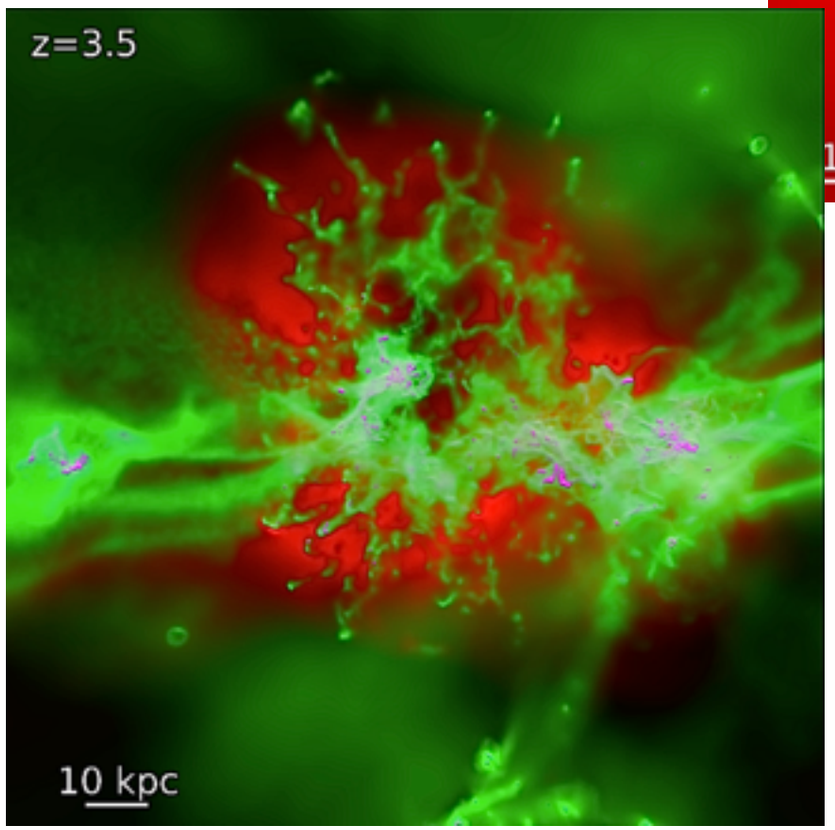
RICH DATA SETS NEED RICH MODELS!

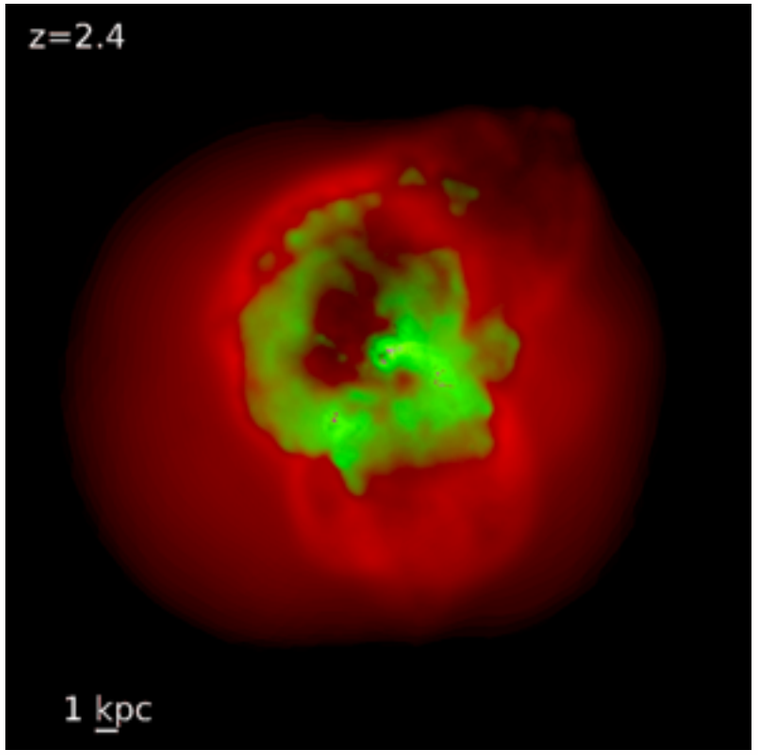
Getting feedback right is even ***more*** important at high-z







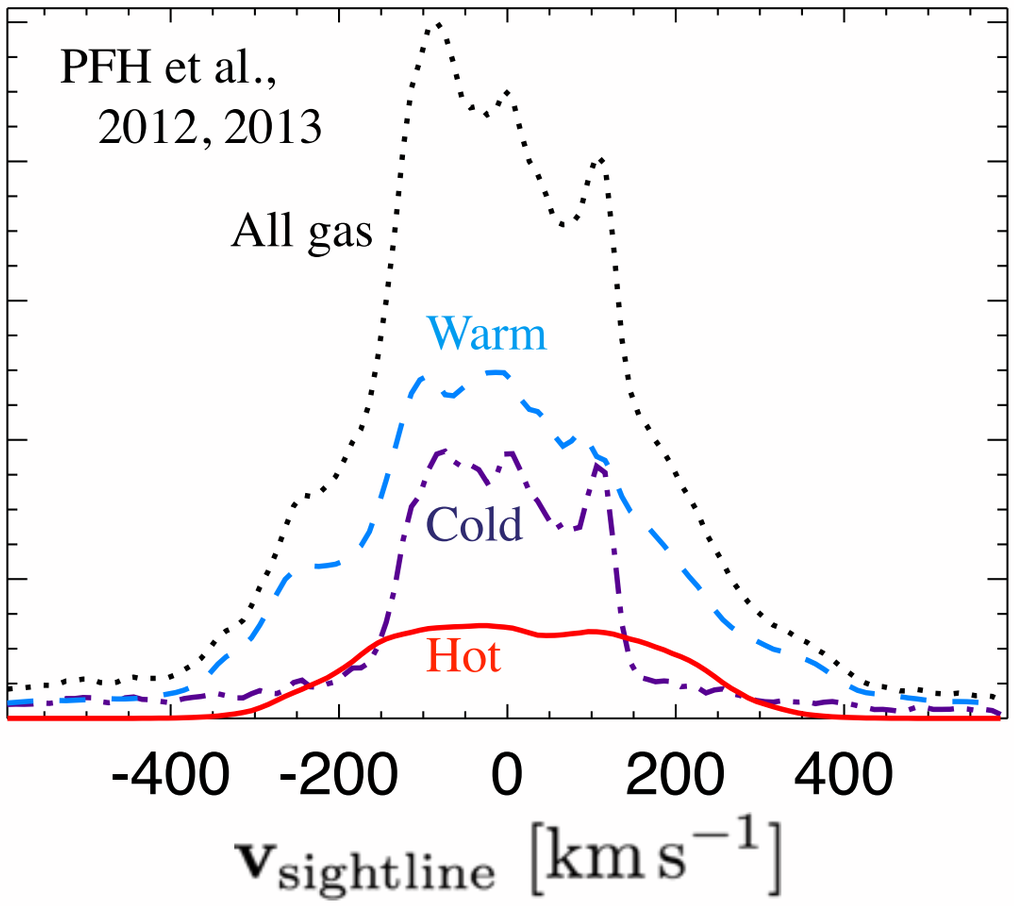


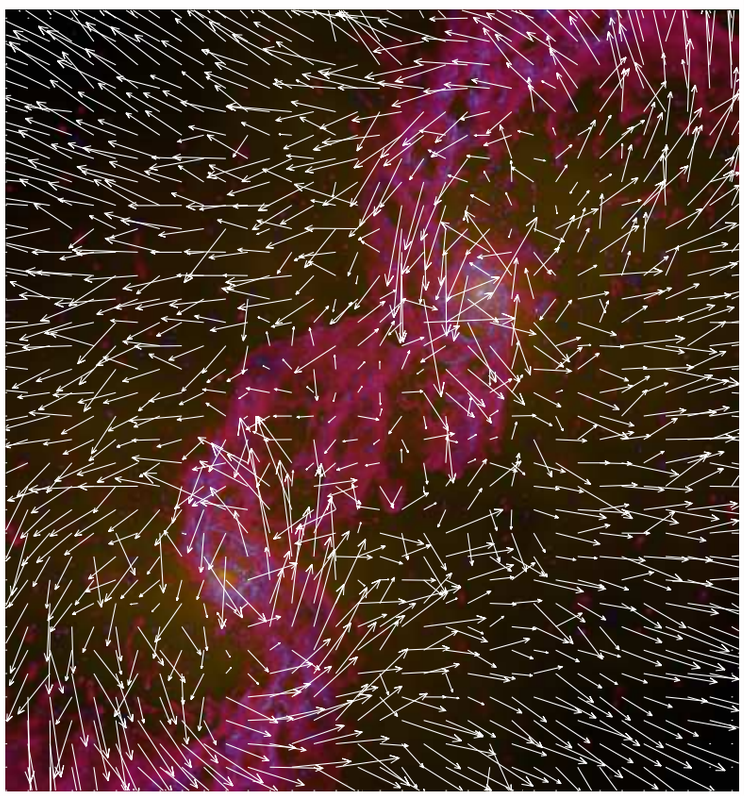


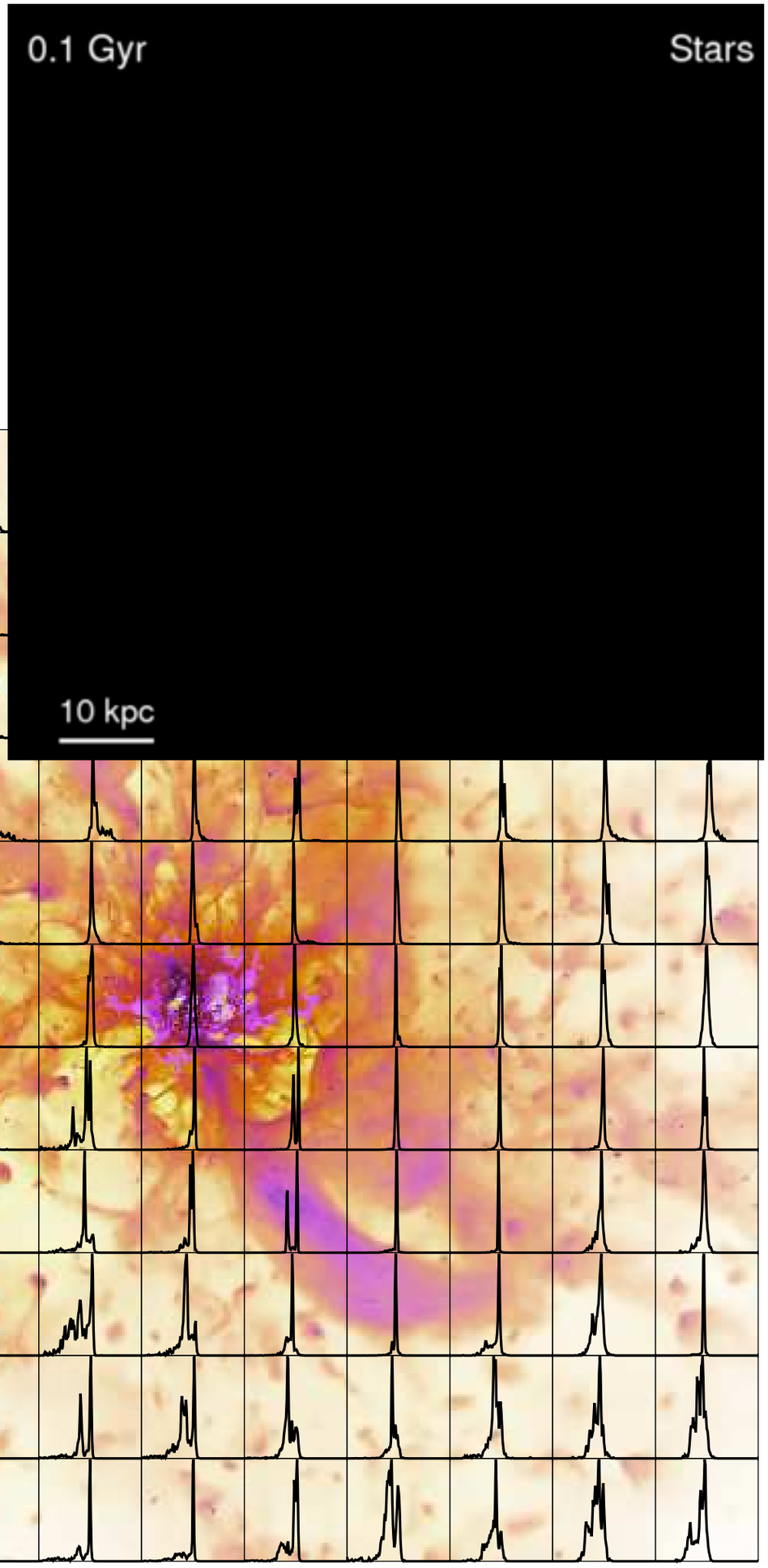
Faucher-Giguere, PFH, et al.

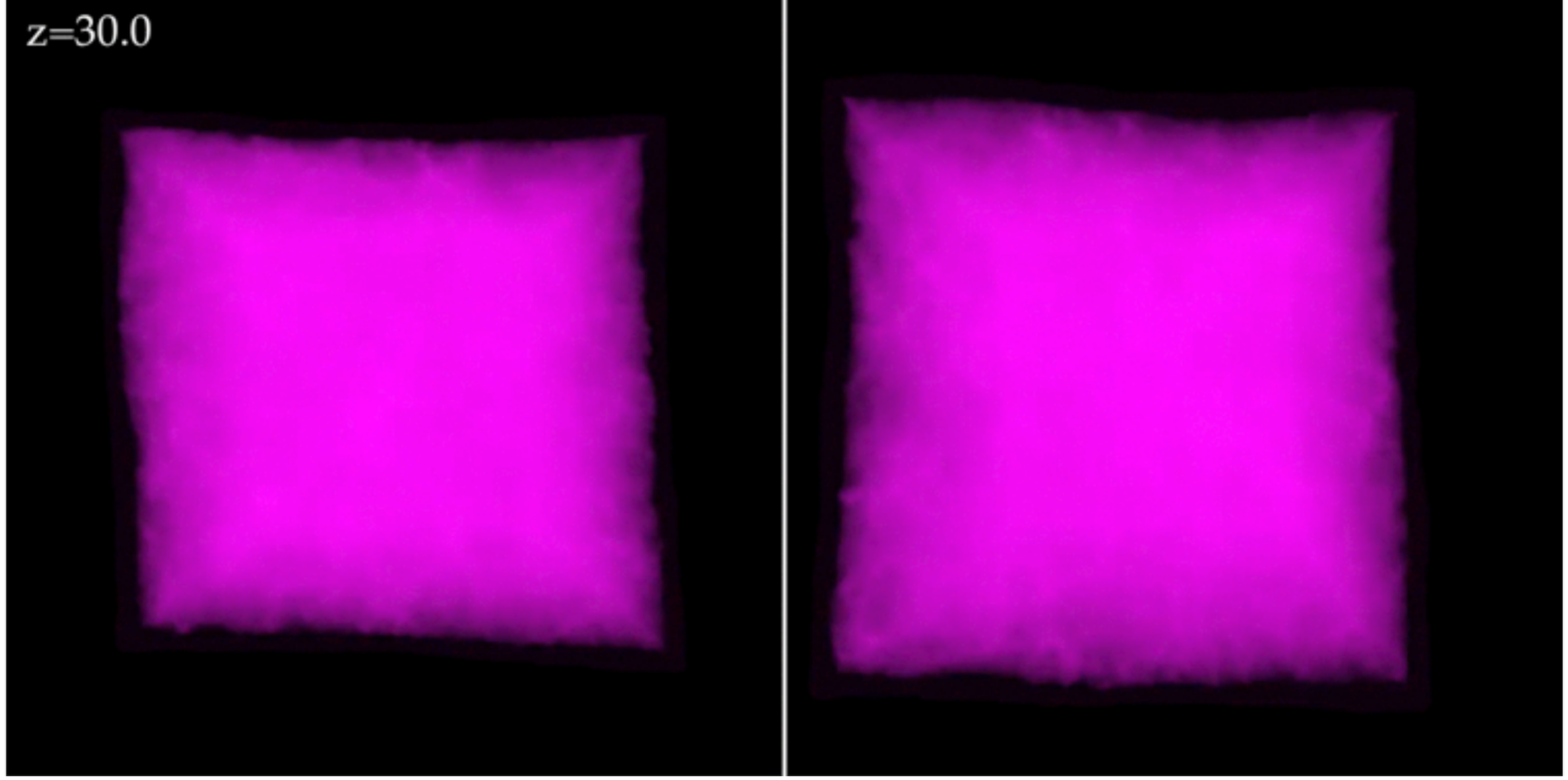
Kinematics of Stars & Gas

DIFFERENT MECHANISMS = DIFFERENT SIGNATURES









- **Challenges:**
- Dynamic Range: inherently resists parallelization
- *Looooooooong* integrations: need an exceptionally stable method
- Feedback = strong coupling between small & large scales (mass, time, space)
- Radiation: *no* good method for all regimes we care about
  (optically thin & thick, line & continuum, point sources & diffuse emission)
- Unknown physics!
  AGN feedback? Cosmic Rays?