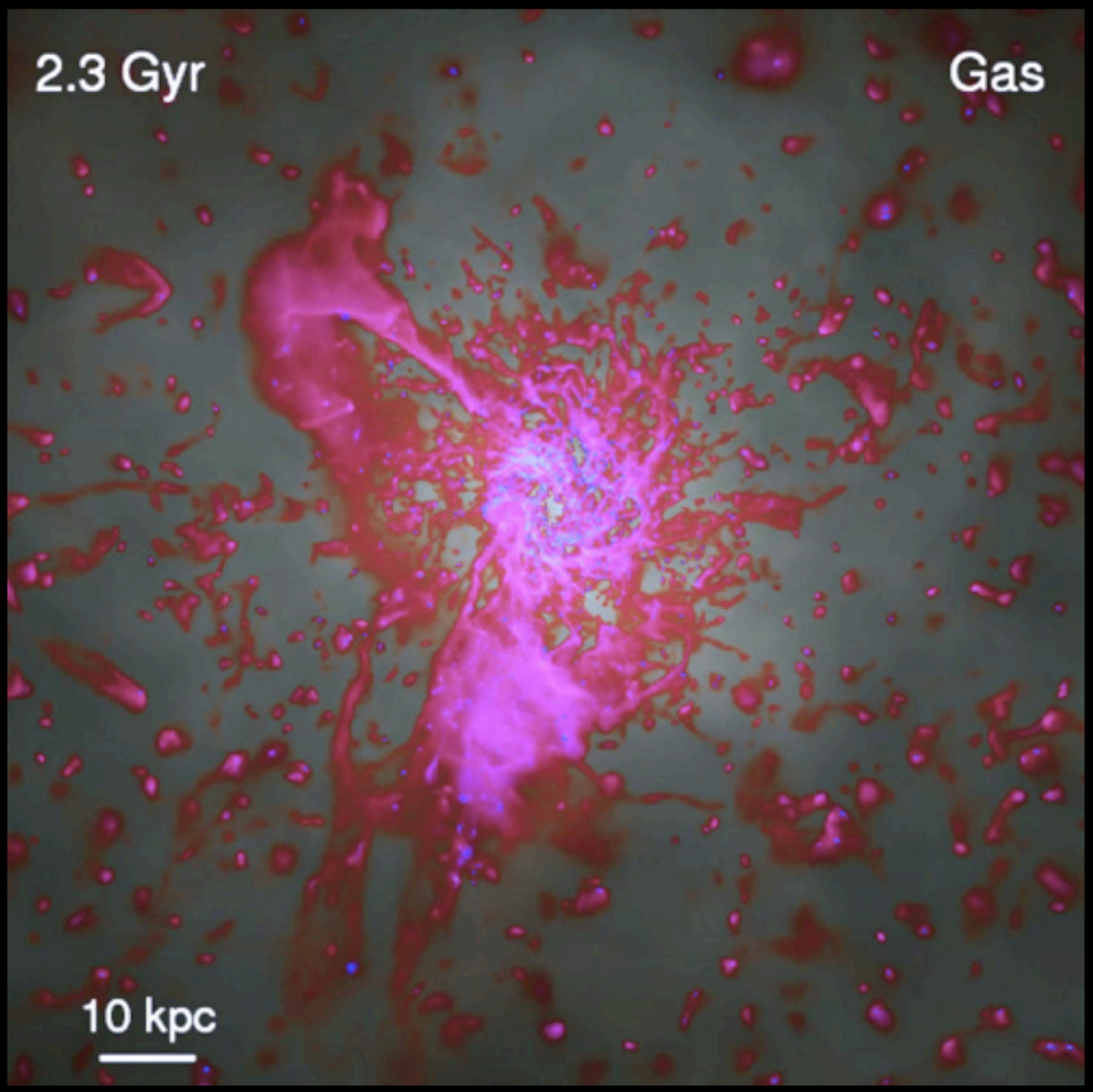
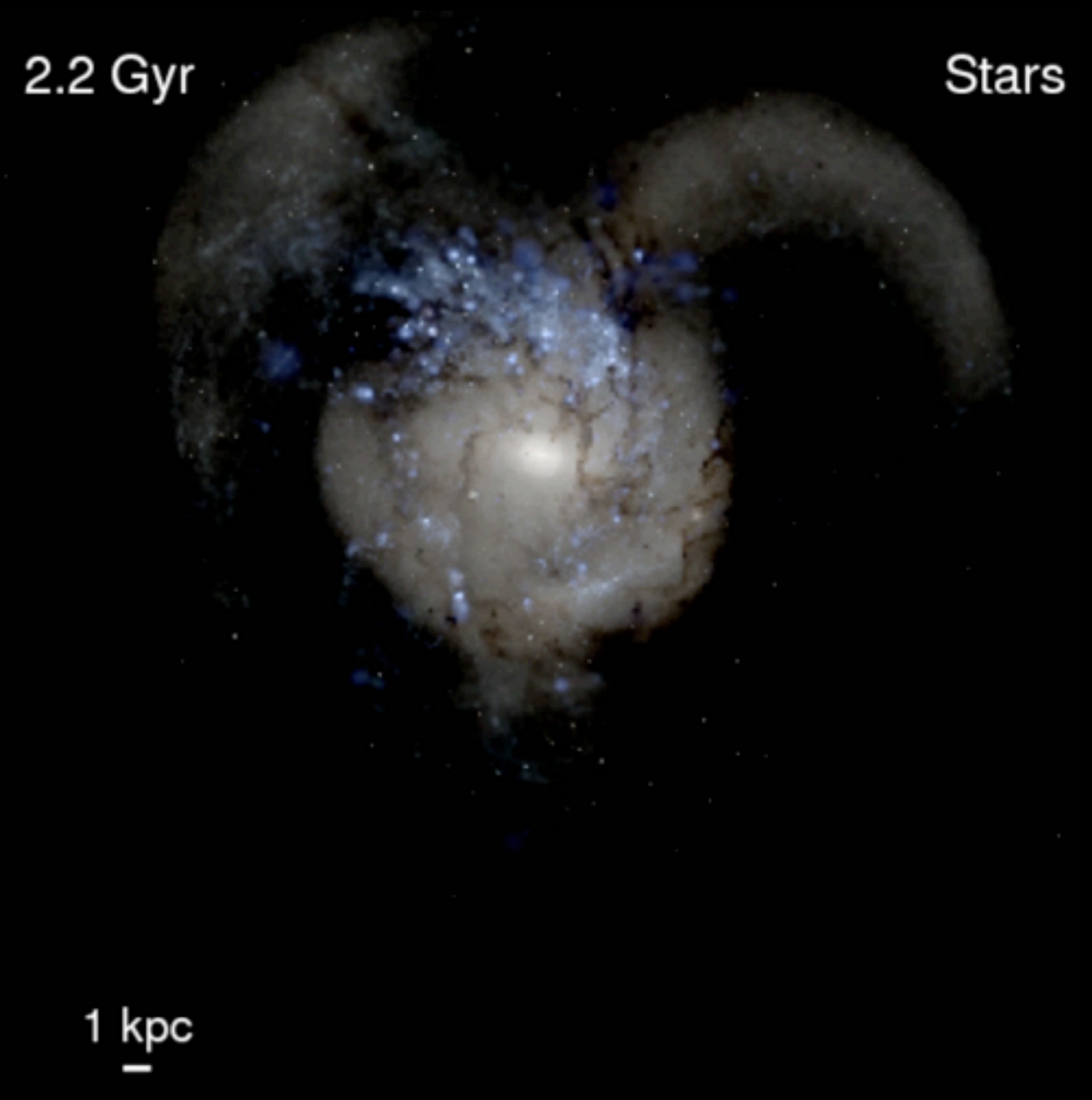
Feedback Regulates Star Formation





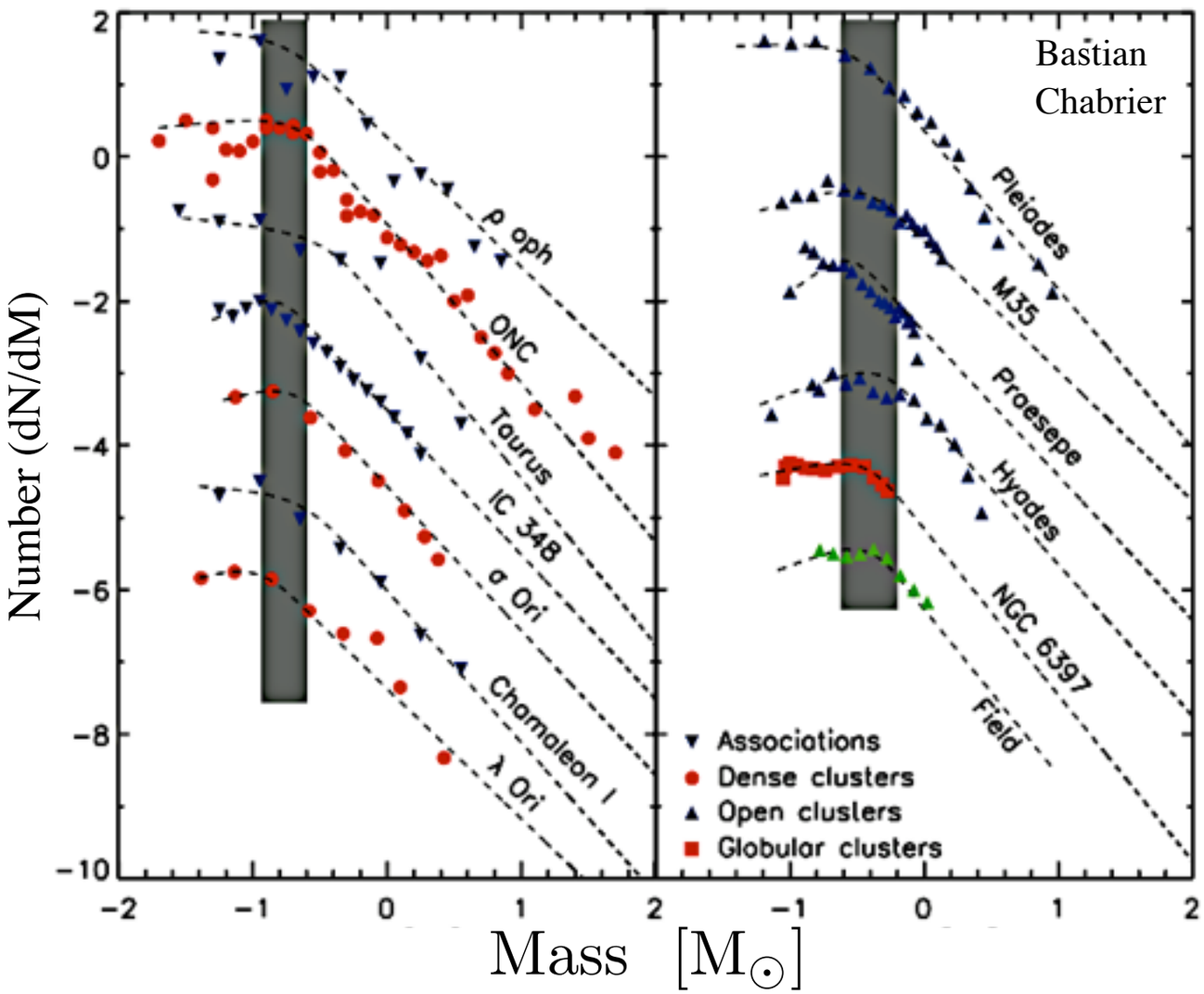
Phil Hopkins

Norm Murray, Eliot Quataert, Chris Hayward, Dusan Keres, Claude Faucher-Giguere, Xiangcheng Ma

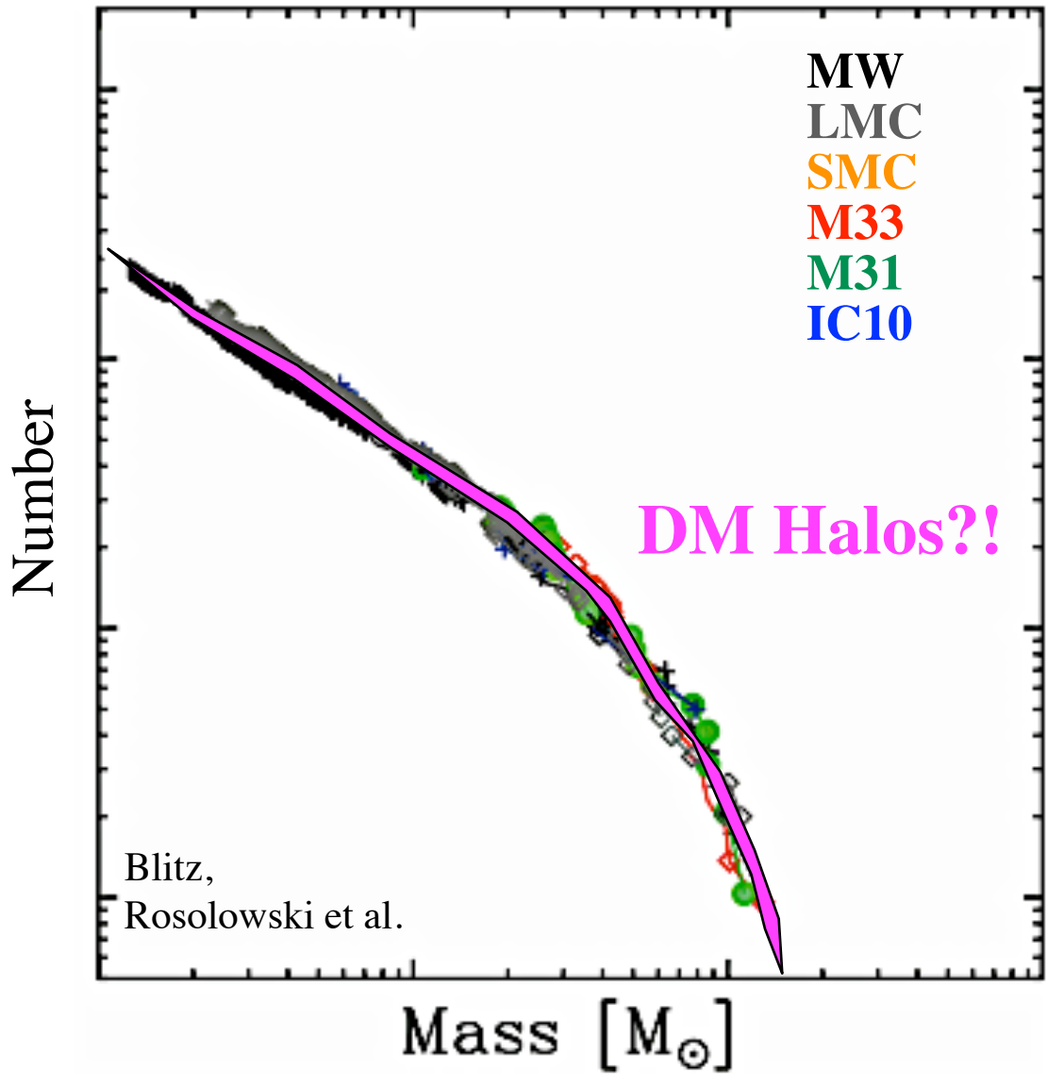
FIRE
Feedback In Realistic Environments

What Does Turbulence Do?

Stars & Pre-Stellar Gas Cores:



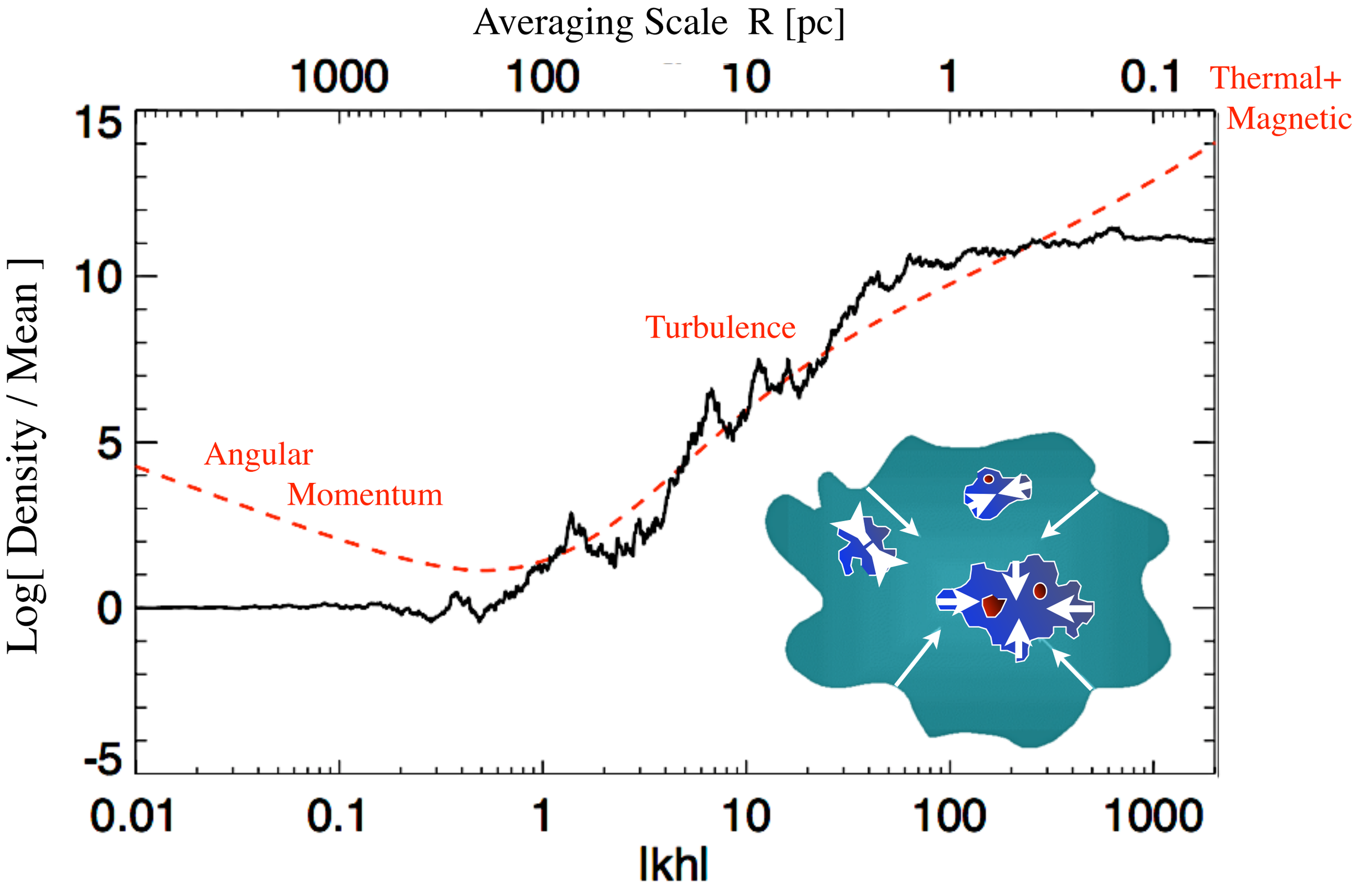
Giant Molecular Clouds:



Turbulent Fragmentation: From GMCs to Stars

PFH 2011

JUST COUNTING "CLOUDS IN CLOUDS"

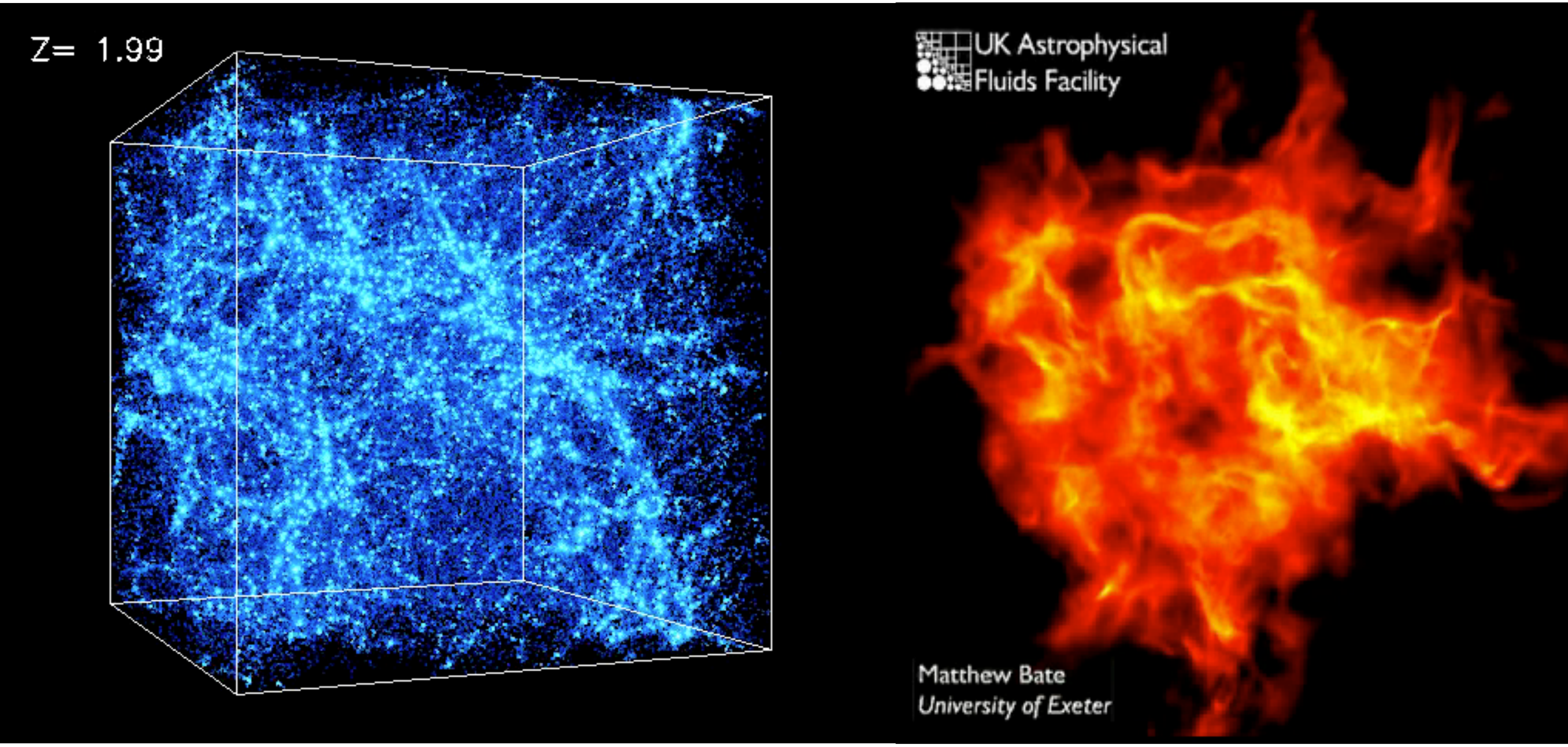


Turbulent Fragmentation: From GMCs to Stars

JUST COUNTING "CLOUDS IN CLOUDS"

STRUCTURE FORMATION

STAR FORMATION

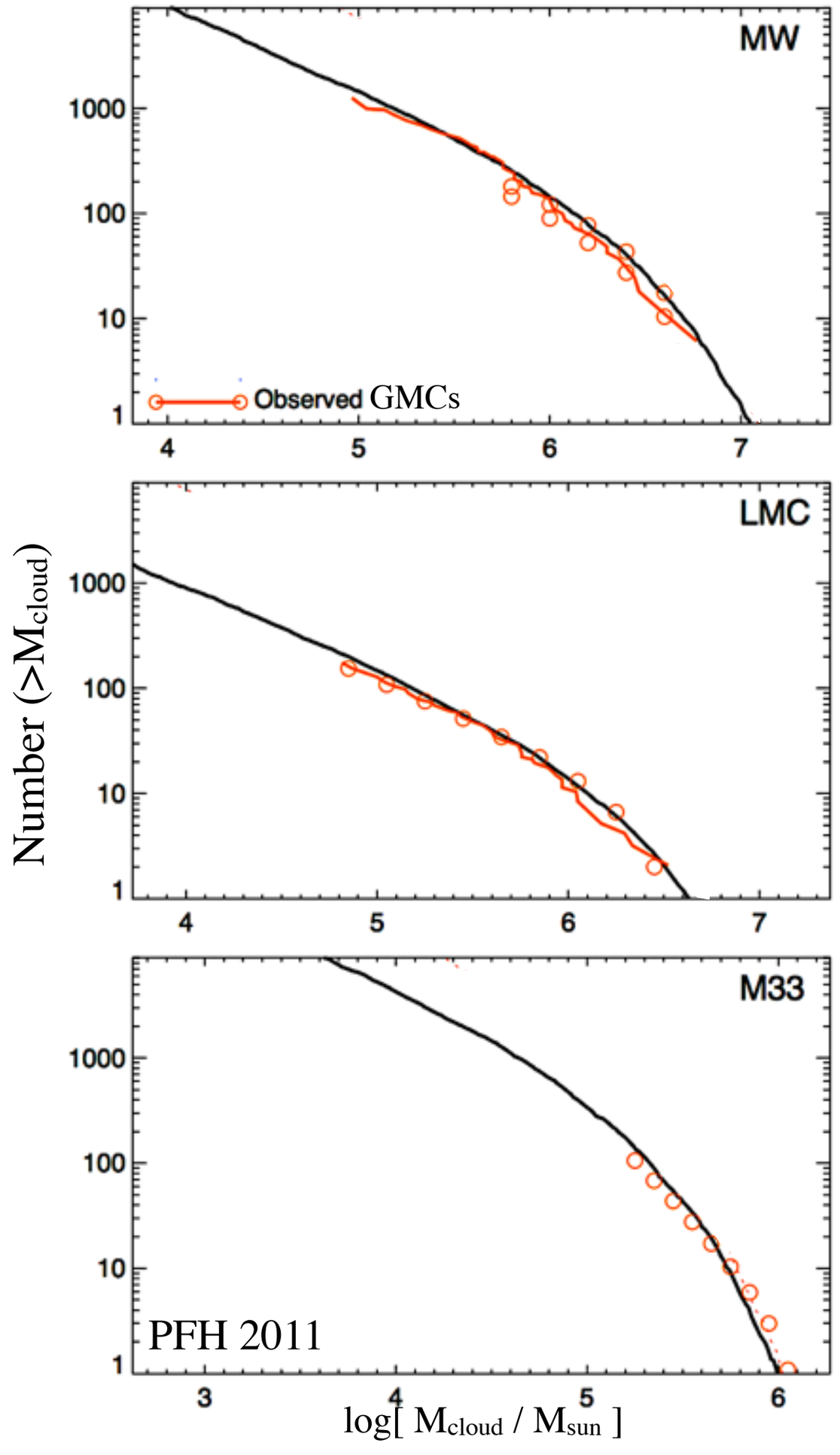


The “First Crossing” Mass Function

VS GIANT MOLECULAR CLOUDS

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha}\, e^{-(M/M_J)^{\beta}}$$

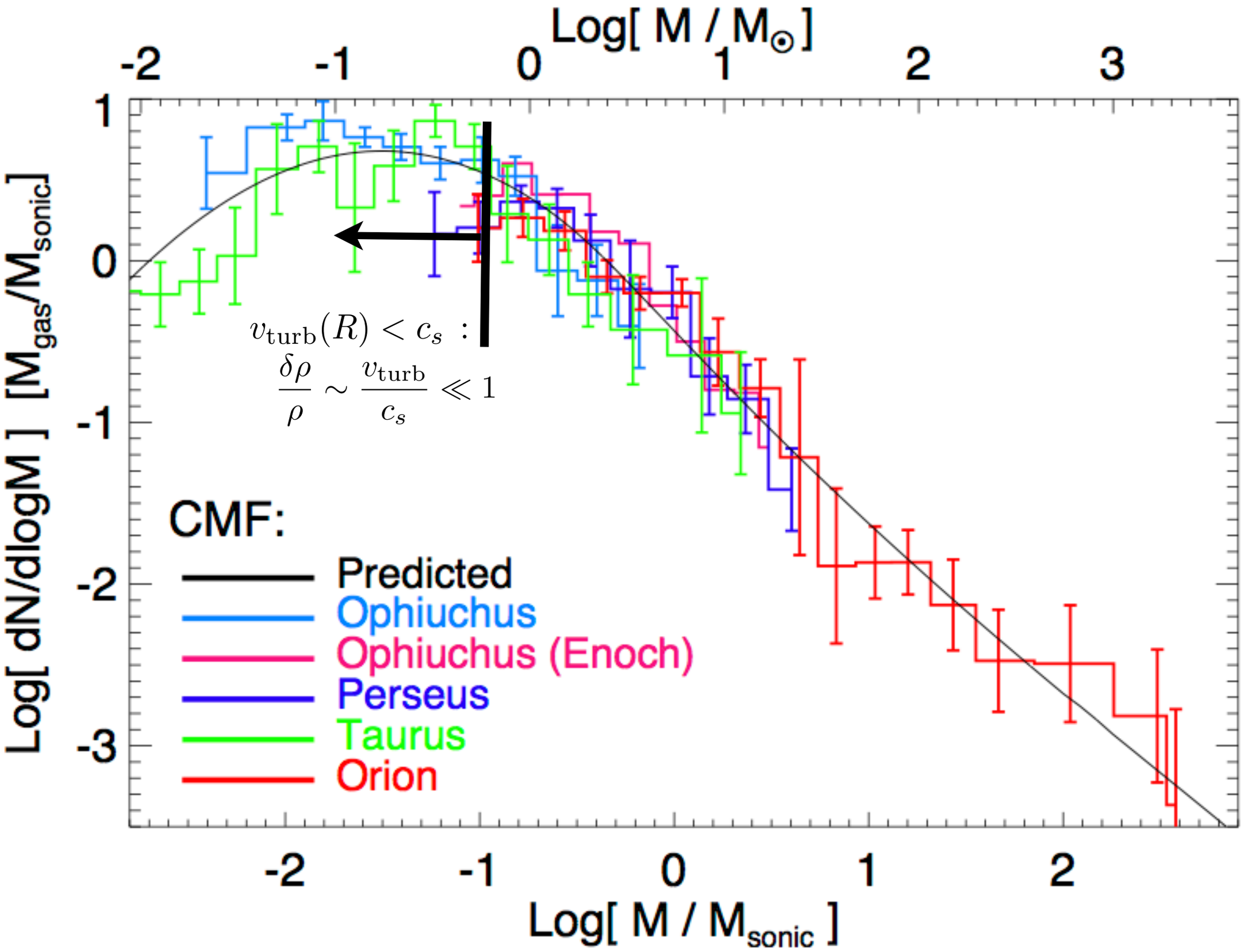
$$\alpha \approx 2 - \epsilon(M)$$



The "Last Crossing" Mass Function

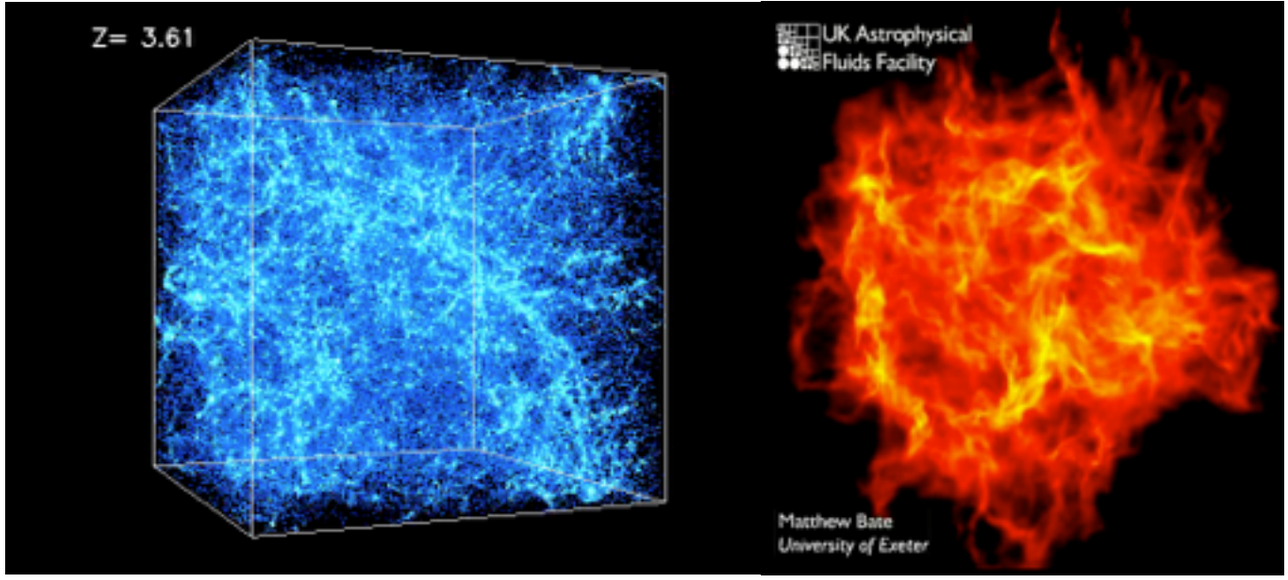
VS PROTOSTELLAR CORES

(Hennebelle & Chabrier, Padoan & Nordlund, PFH 2012)

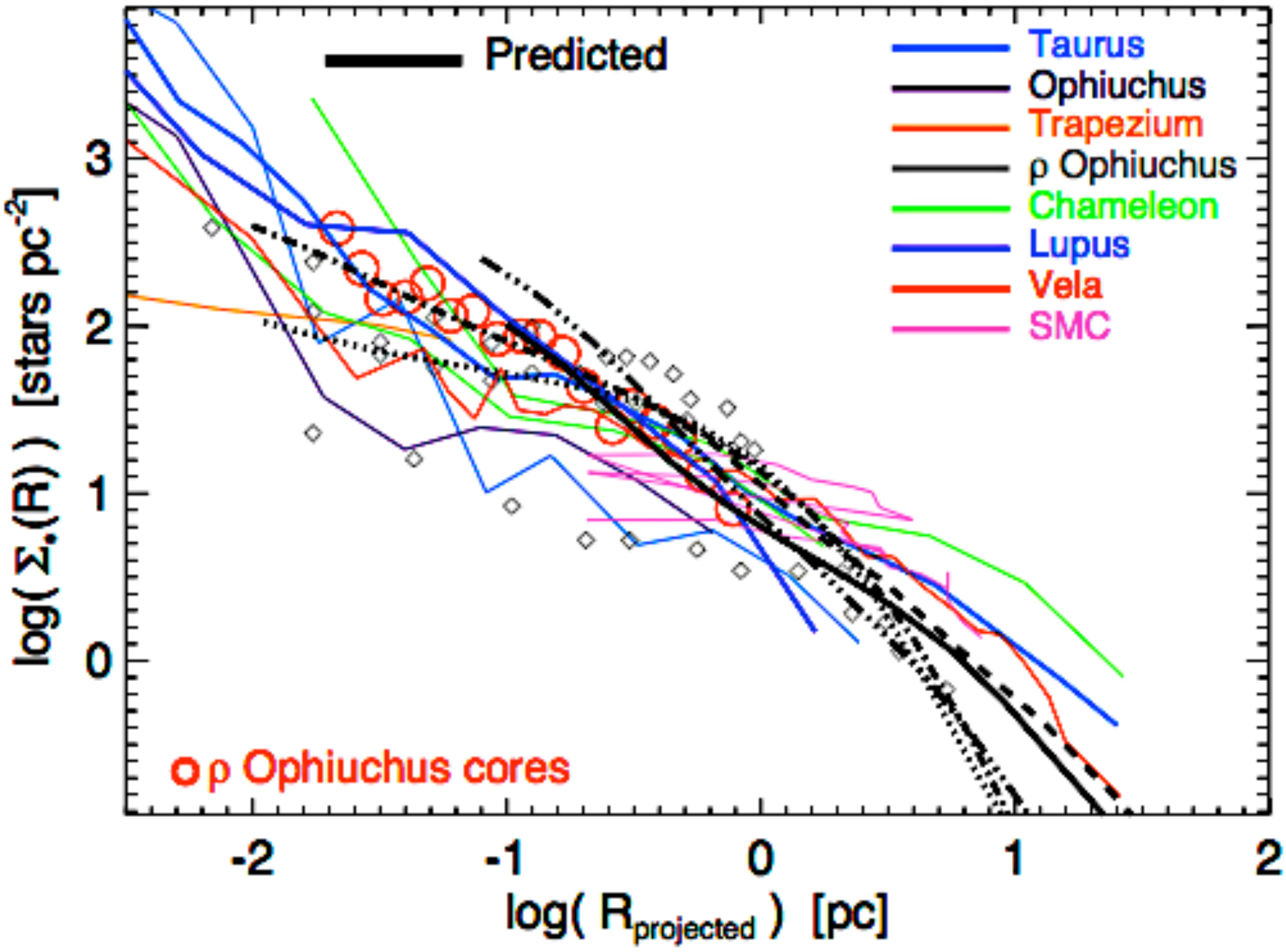


Clustering of Stars/Cores

CLUSTERING IS *INEVITABLE*



PFH 2012

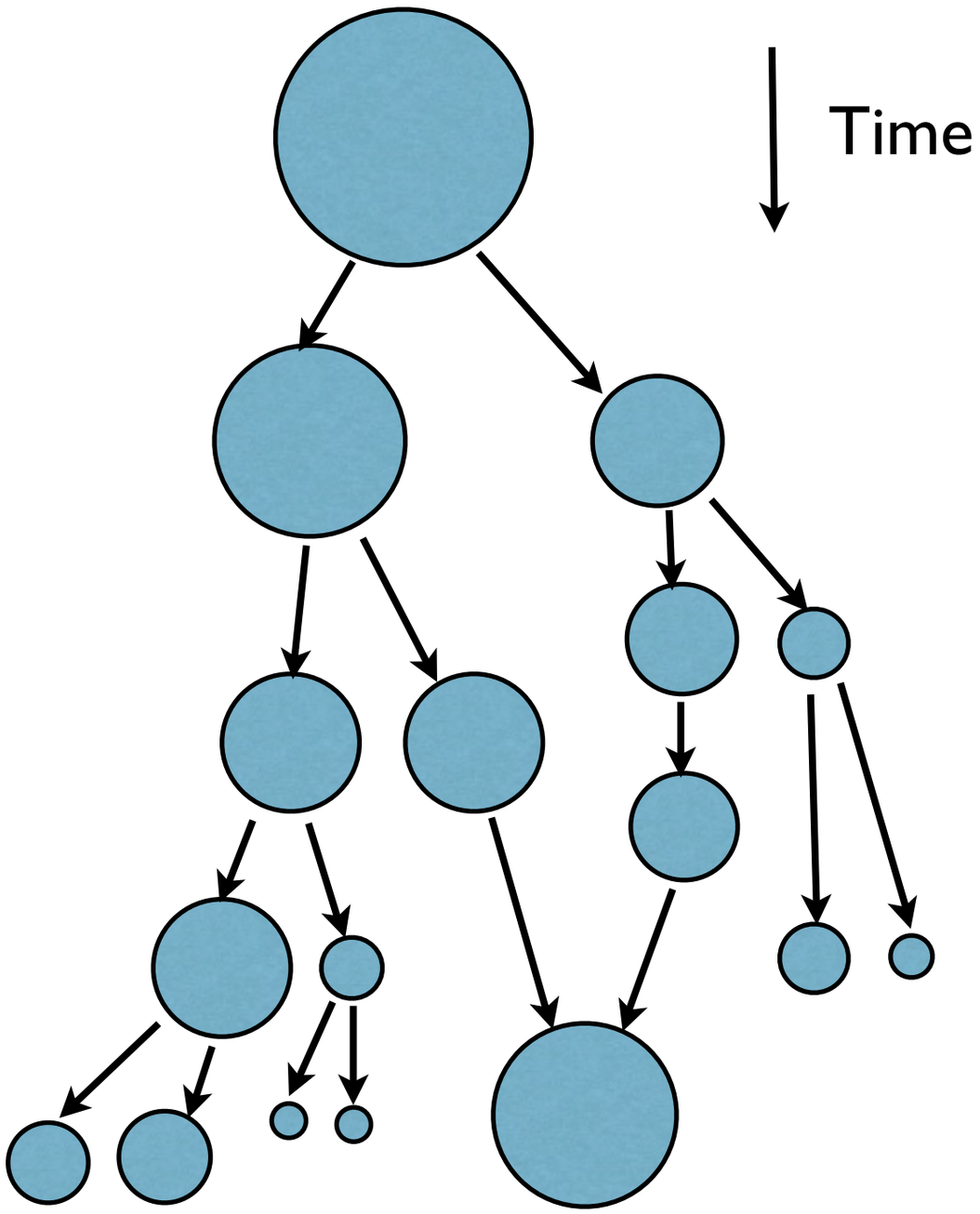


From Cores to Stars

D. Gusjenov

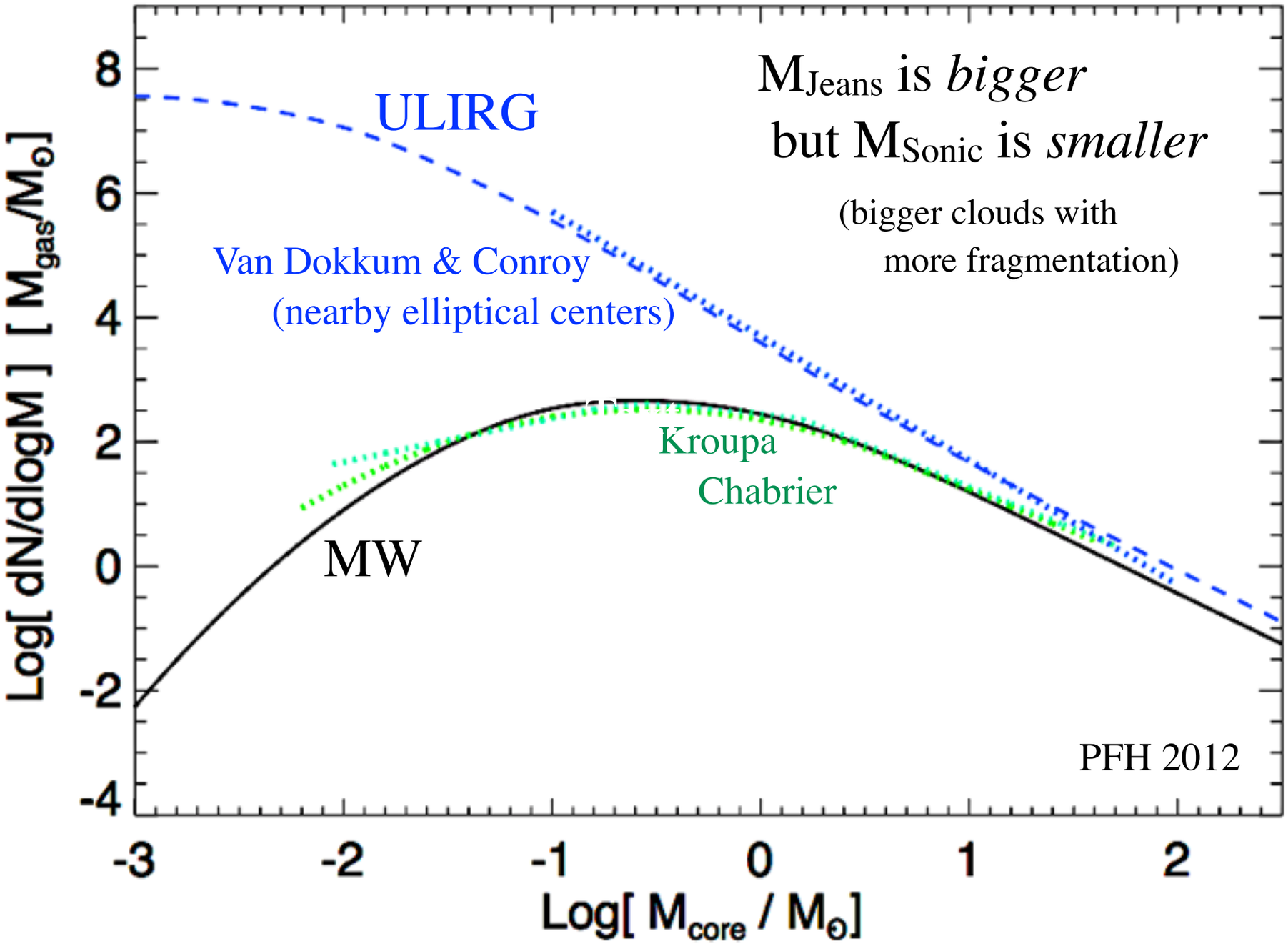
YOU *CAN* TAKE TURBULENT FRAGMENTATION TO THE IMF

"Fragmentation Tree":



What About Starbursts (Extreme Environments)?

BOTTOM-HEAVY: TURBULENCE WINS!

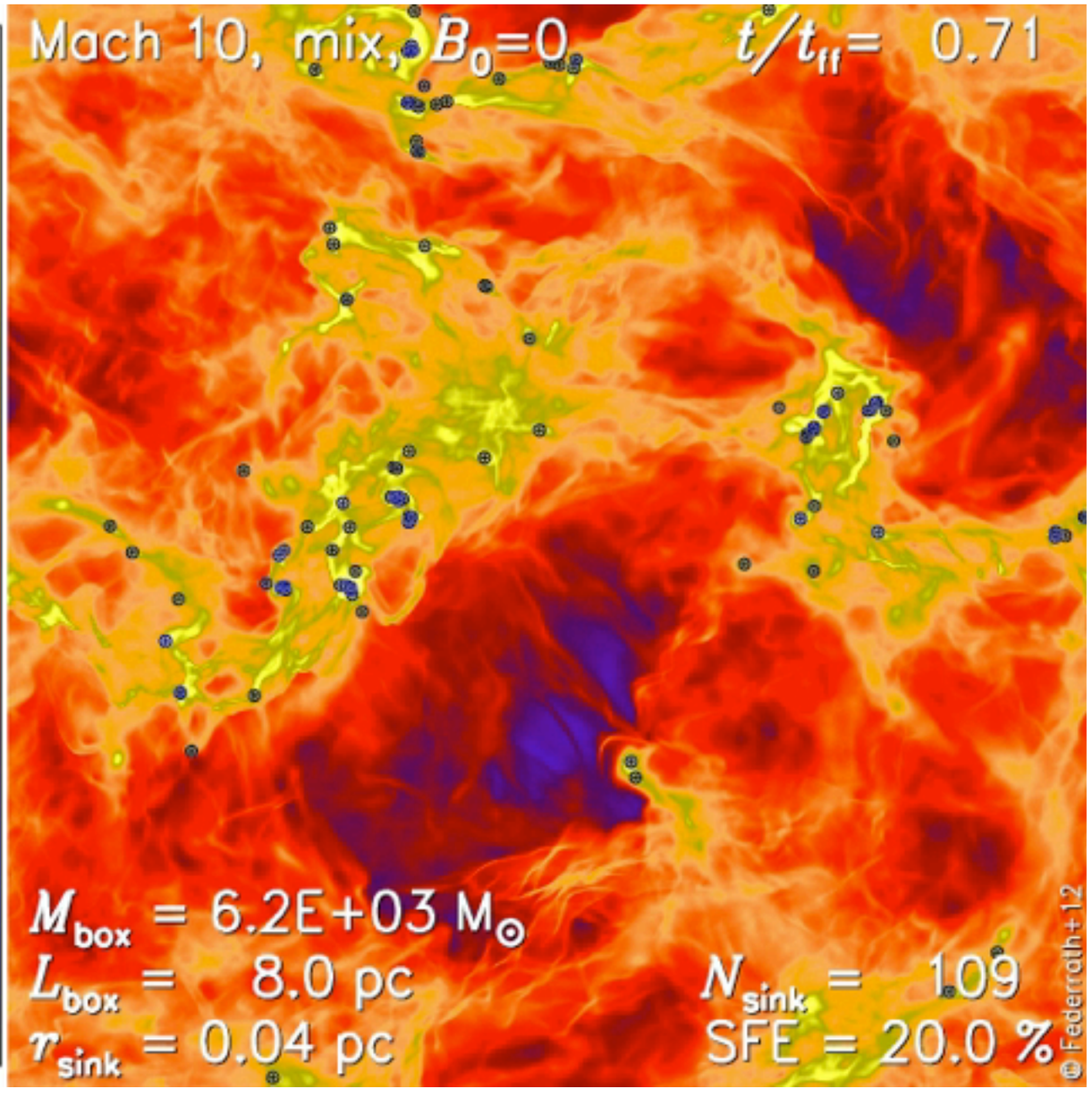


(see Giles's talk,
recent HC 2014 work)

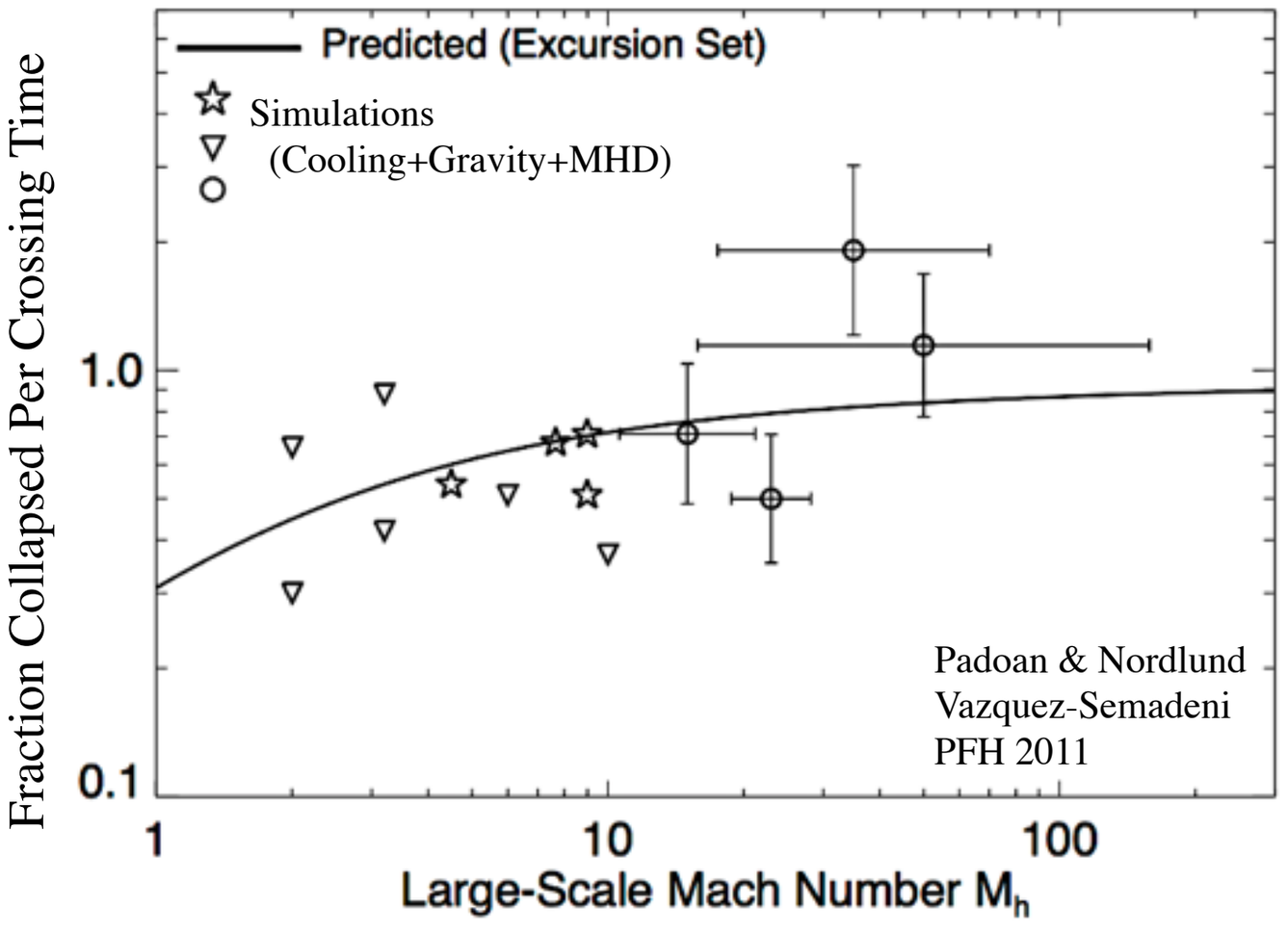
Is Star Formation Self-Regulating?

Not Without Feedback!

TURBULENT FRAGMENTATION LEADS TO RUNAWAY COLLAPSE (ALSO, WHAT DRIVES THE TURBULENCE?)



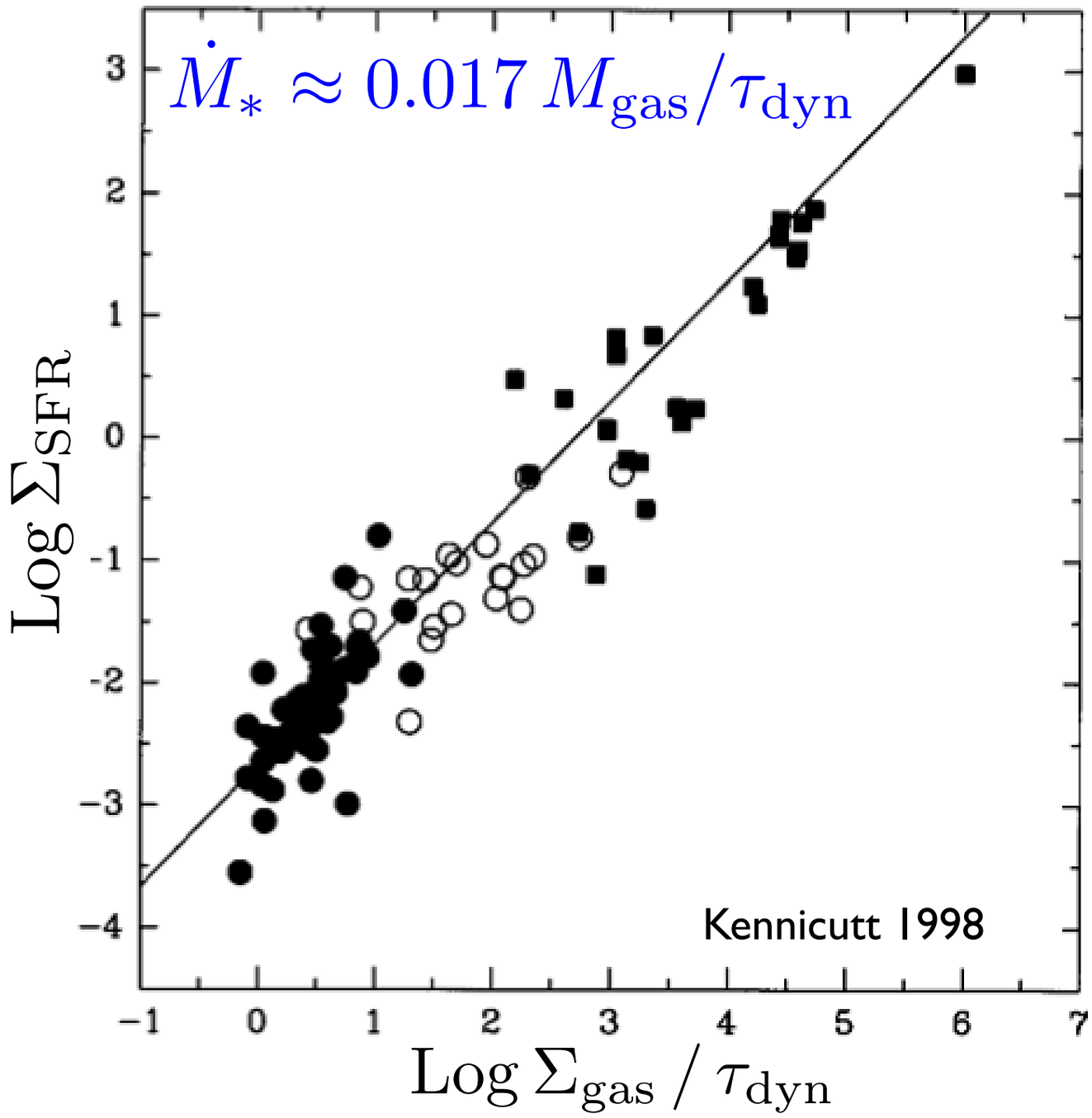
Federrath et al.



(see Paulo's talk)

But Star Formation is Slow!

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Galactic Scales: 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

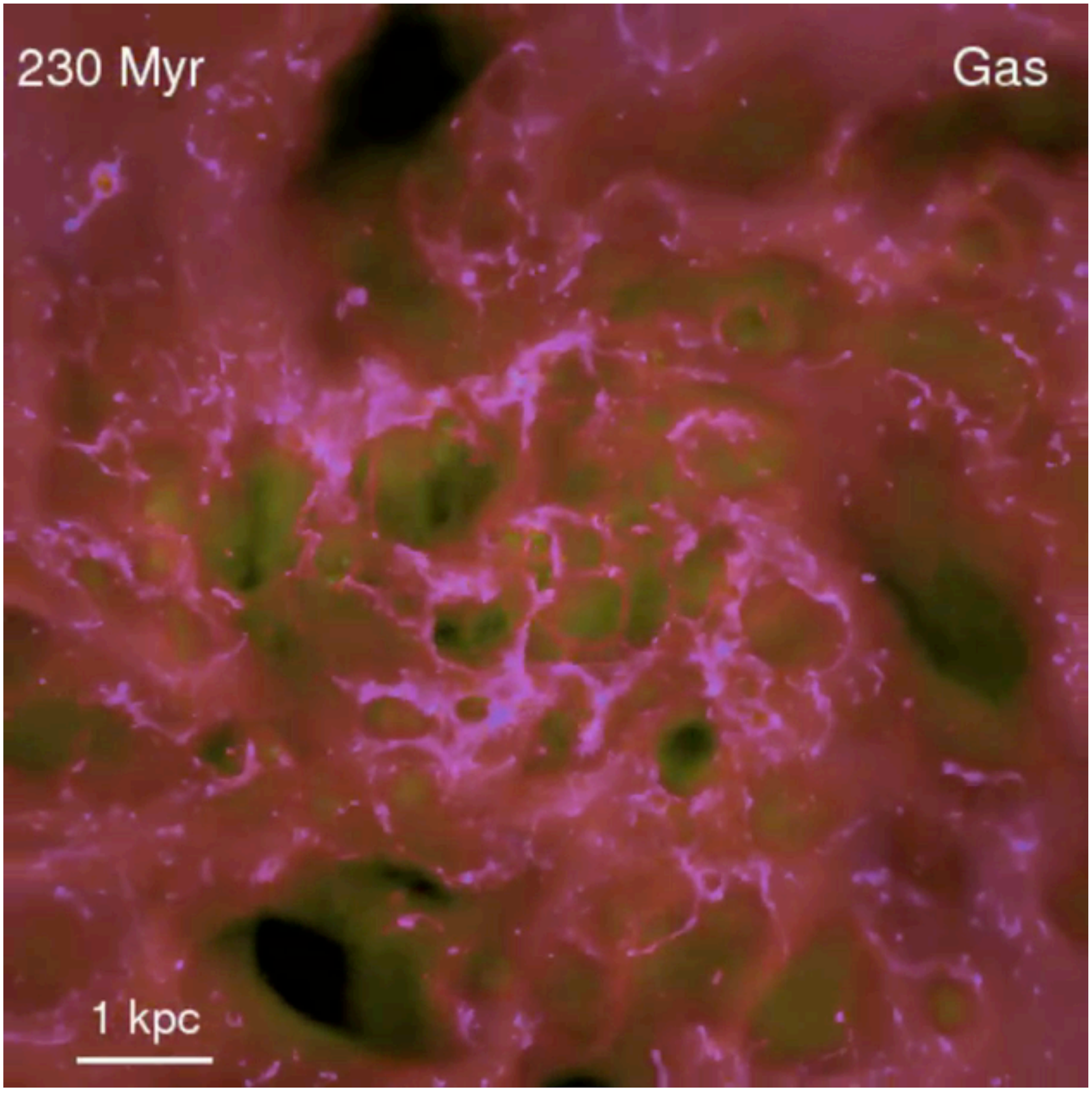
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

  - SNe

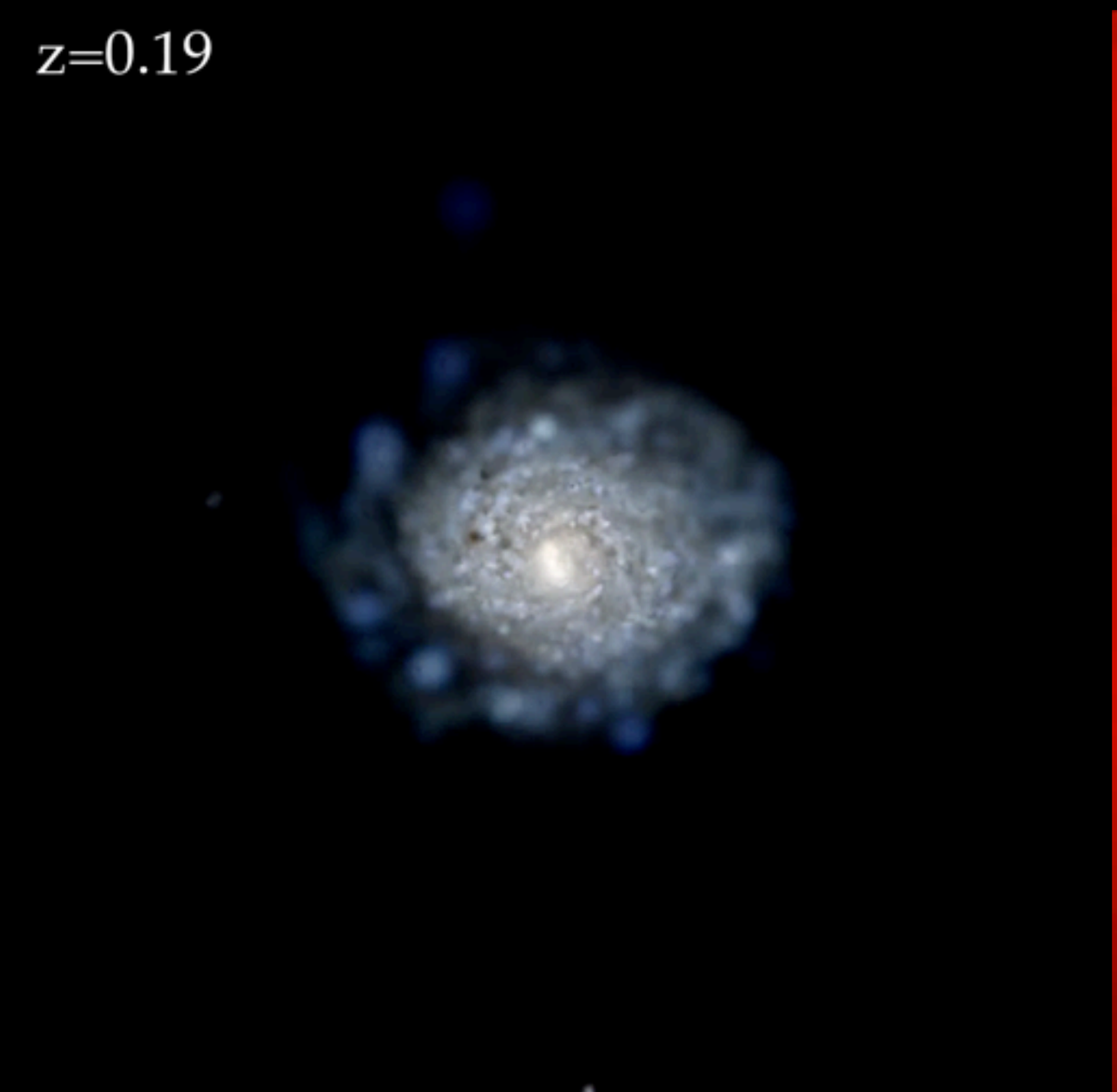
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

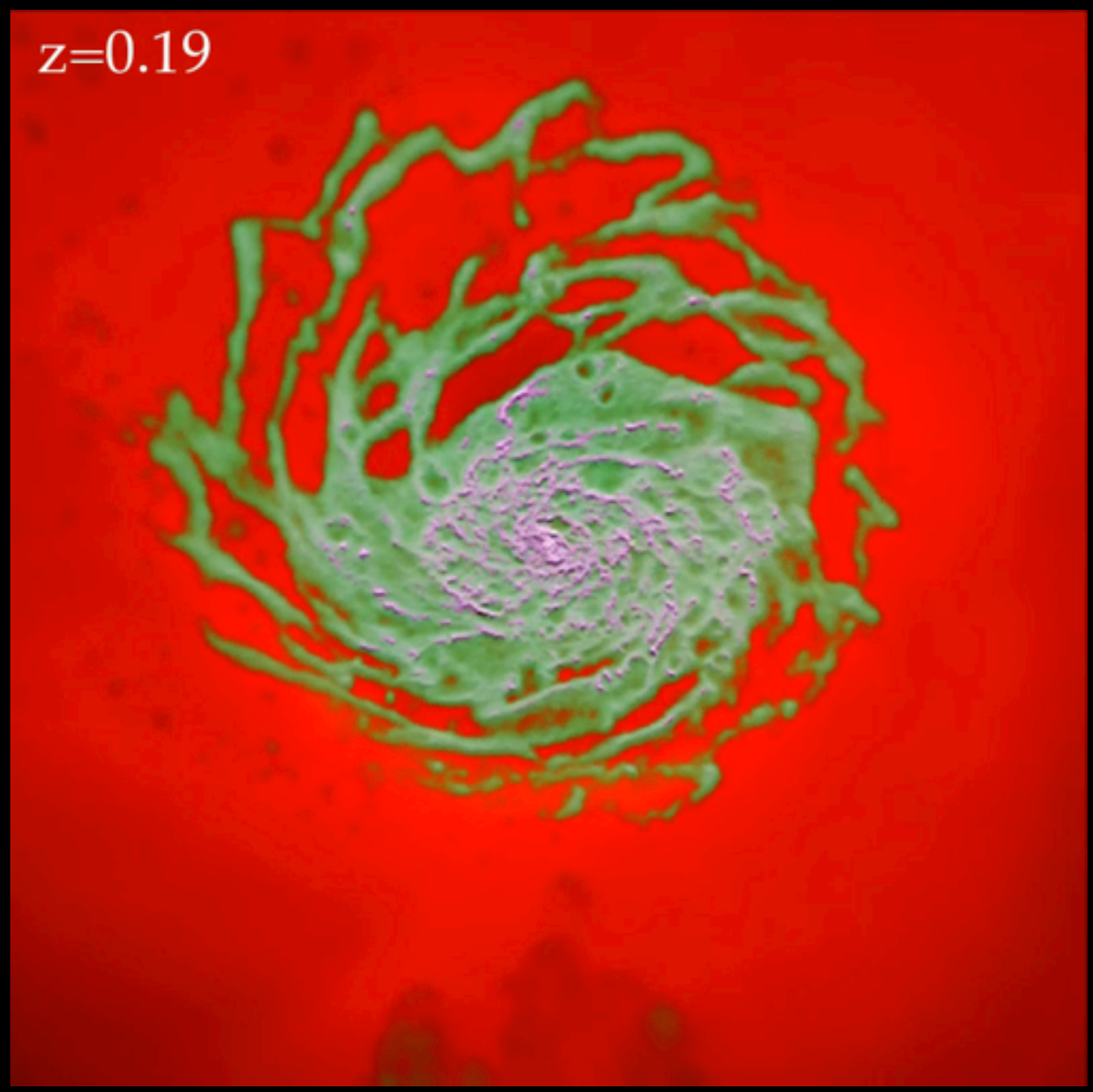
  - Stellar Winds

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



- (also MHD, anisotropic conduction, diffusion)





Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

Gas: Magenta: cold $(< 10^4\,K)$

Green: warm (ionized)

Red: hot $(> 10^6\,K)$

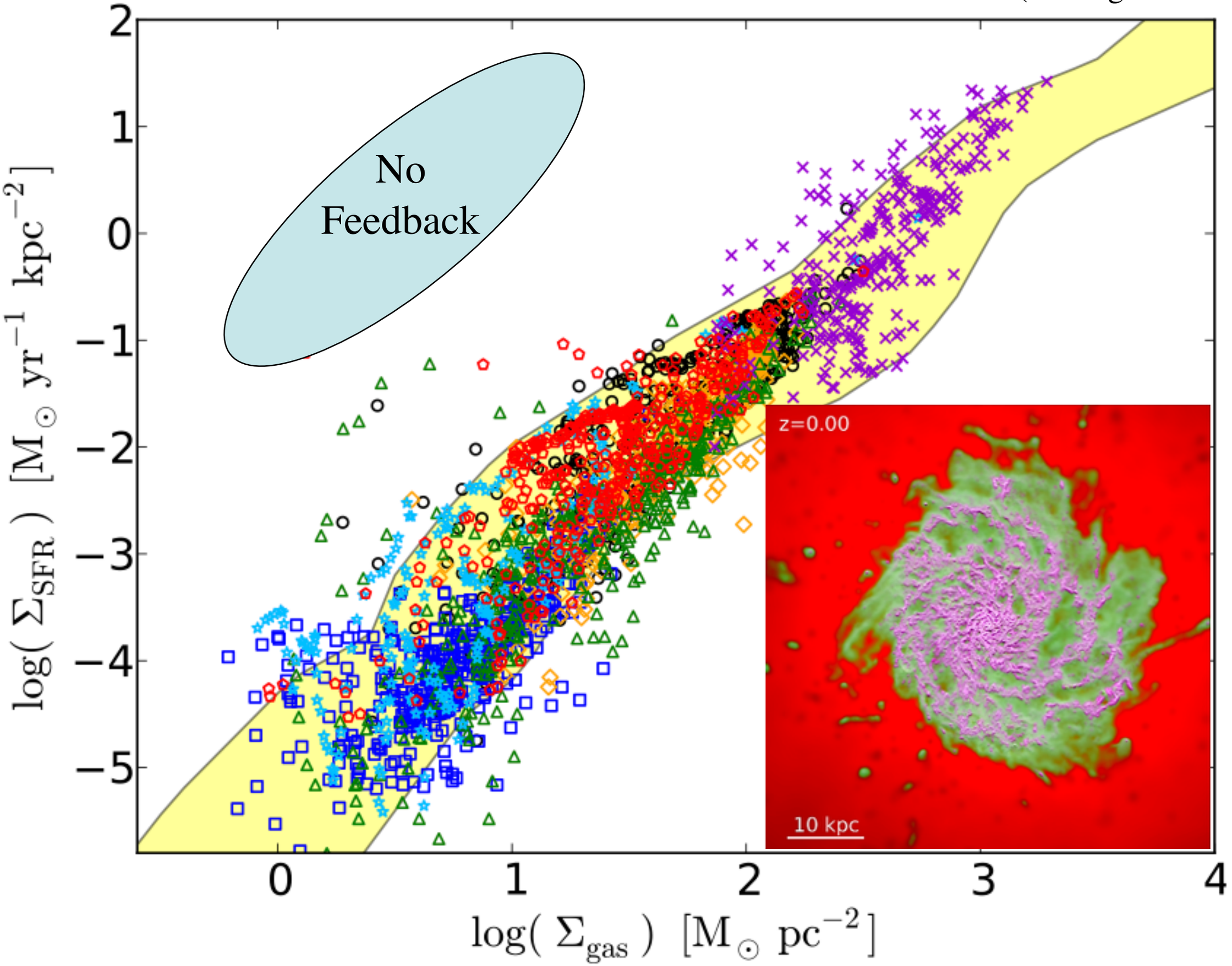
Is Star Formation Self-Regulating?

The Kennicutt Law Emerges

INDEPENDENT OF SMALL-SCALE SF LAW

PFH et al. (arXiv:1311.2073)

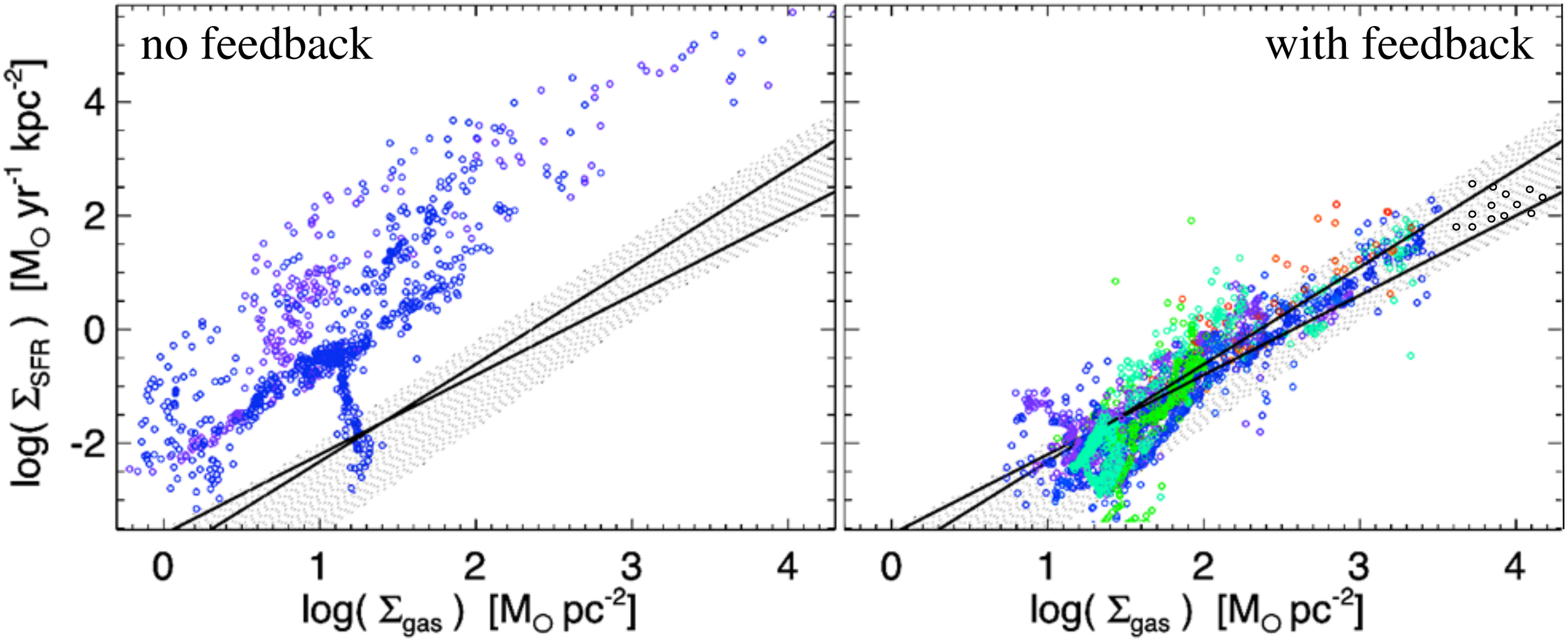
(also Agertz+ 1404.2613)



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:

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

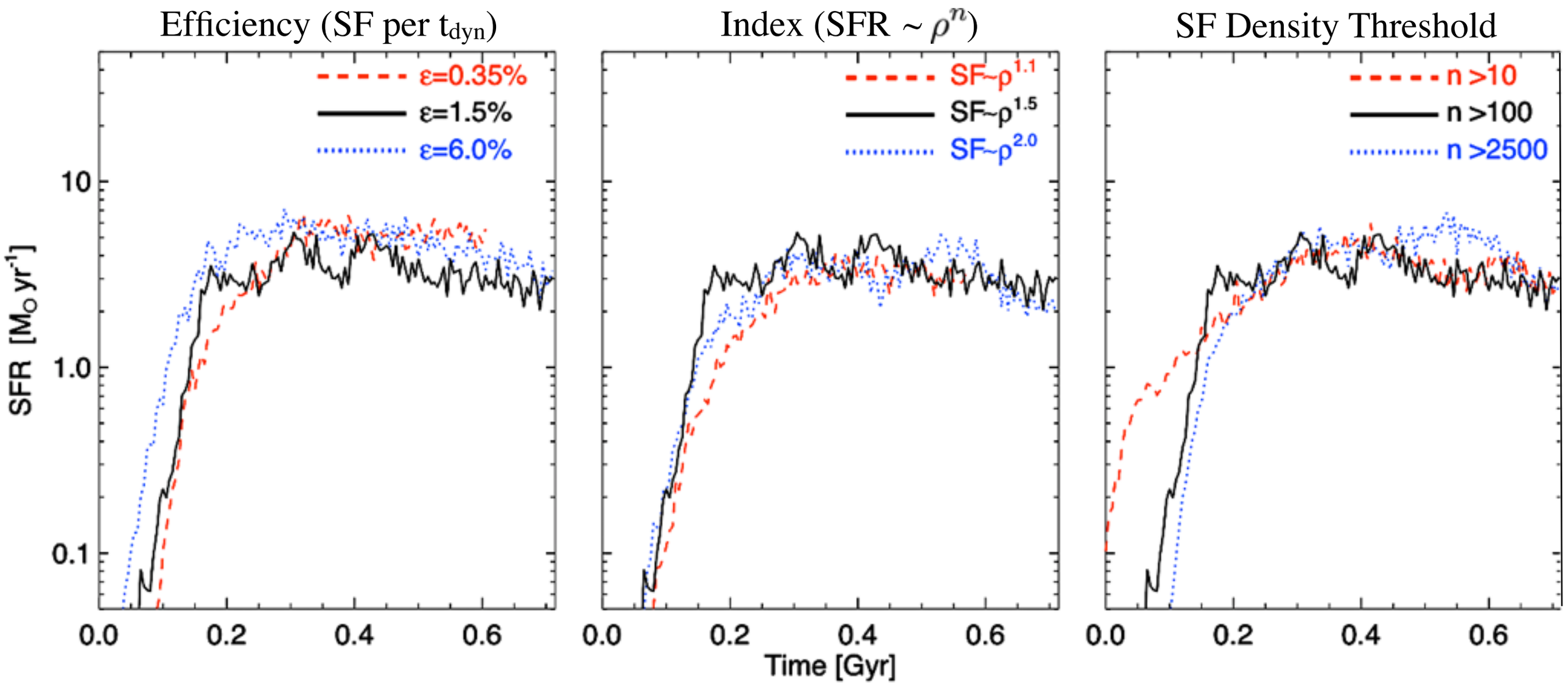
- Collapse stops when momentum input from feedback:

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

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

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

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

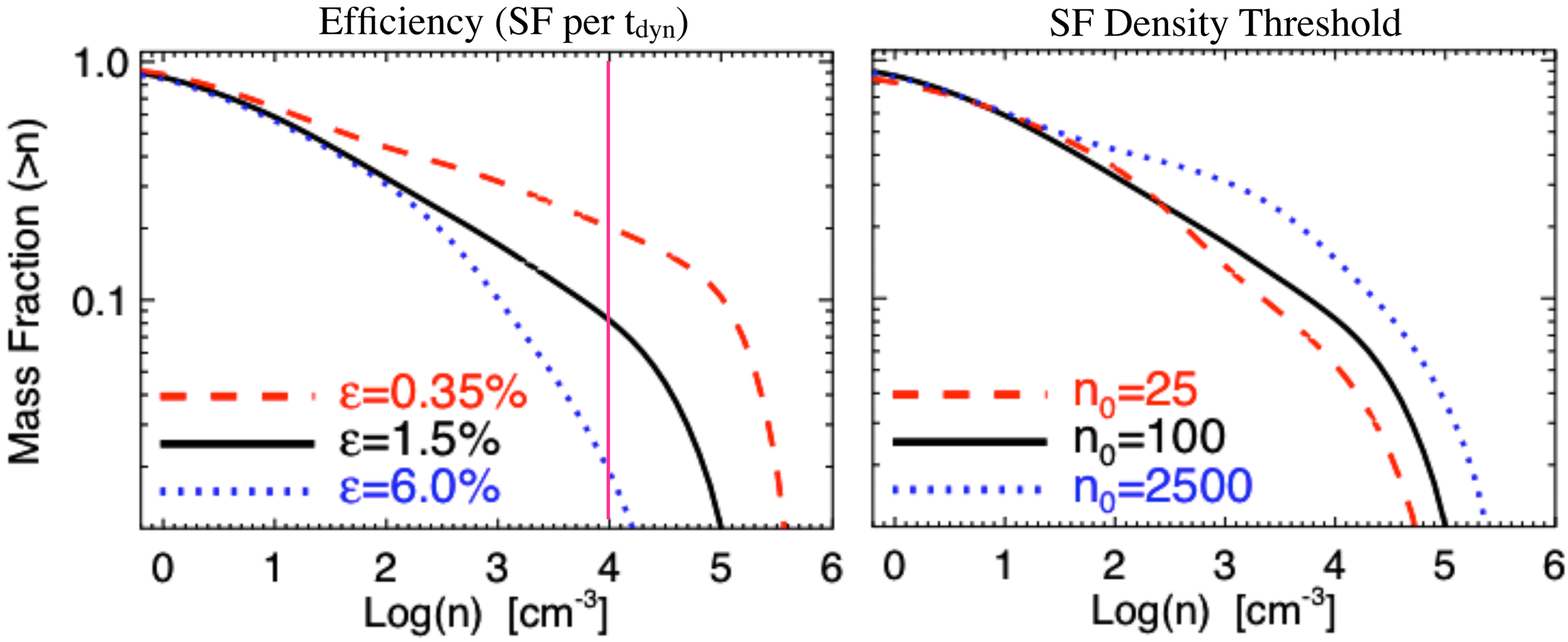


- Set by feedback (SFR) needed to maintain marginal stability

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

How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS



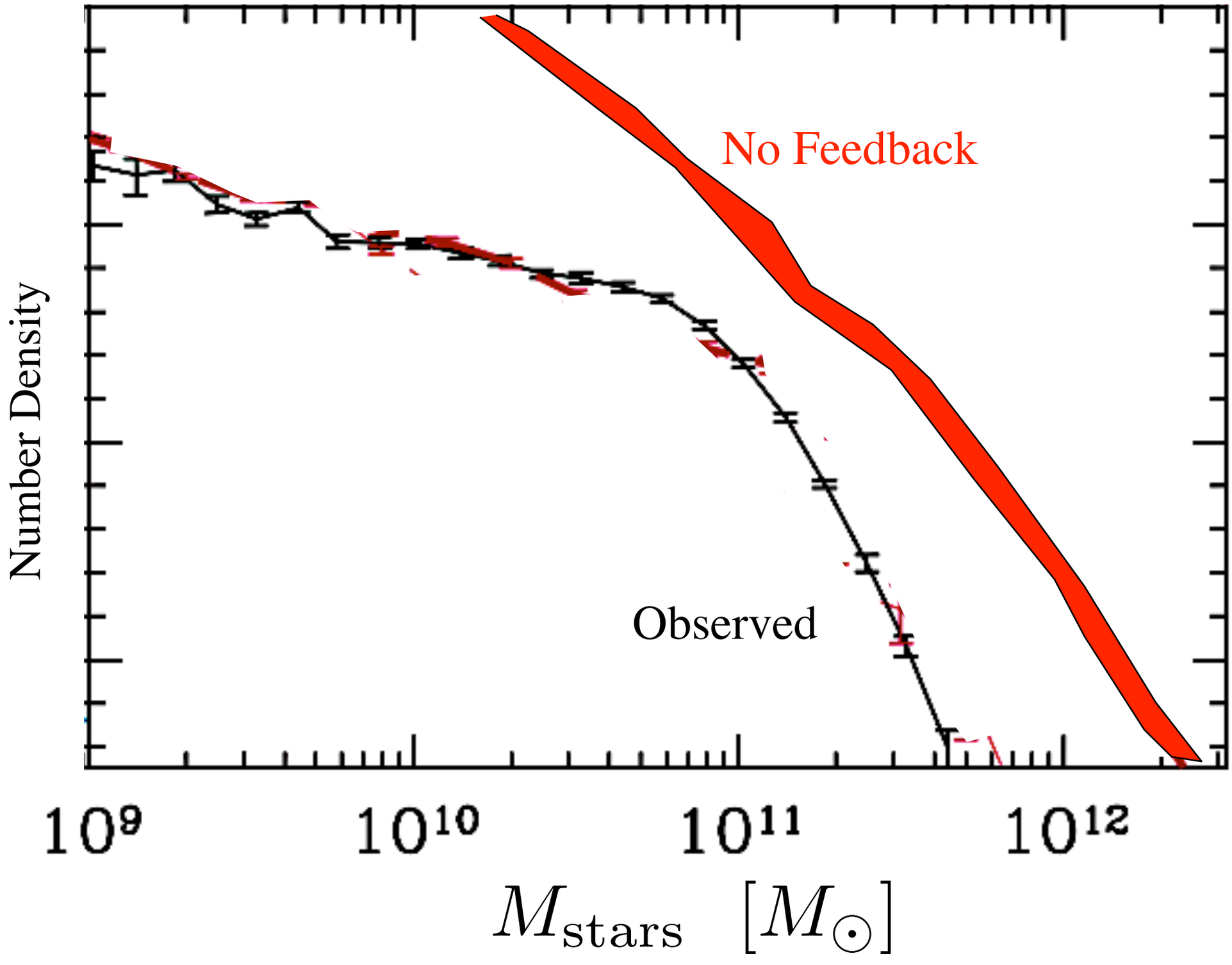
- Pile up more dense gas until the SFR "needed" is obtained!

Hopkins, Quataert, & Murray 2011

Are We Done?

No! Star Formation is Inefficient In the Integral

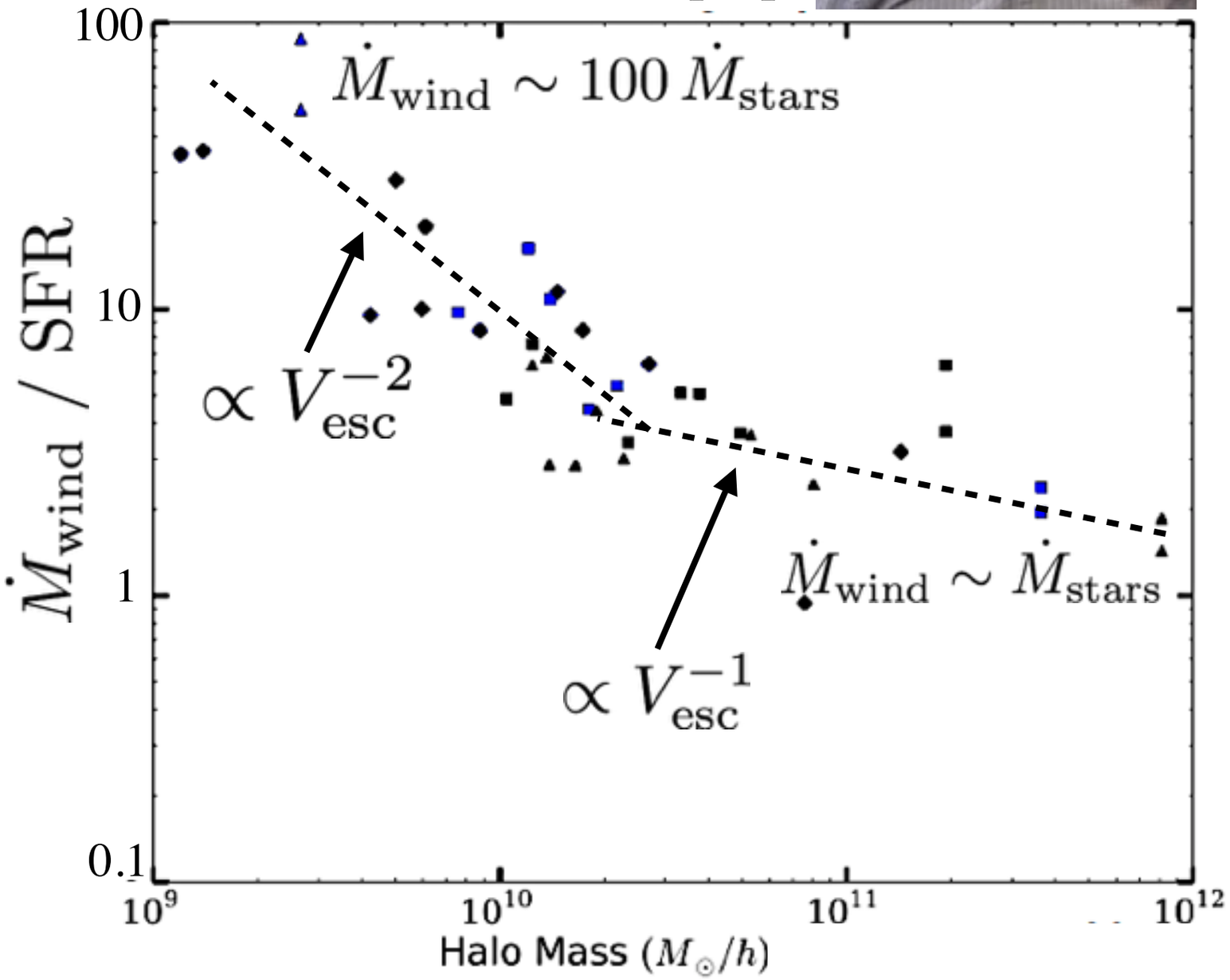
Q: WHAT KEEPS GAS OUT OF GALAXIES?

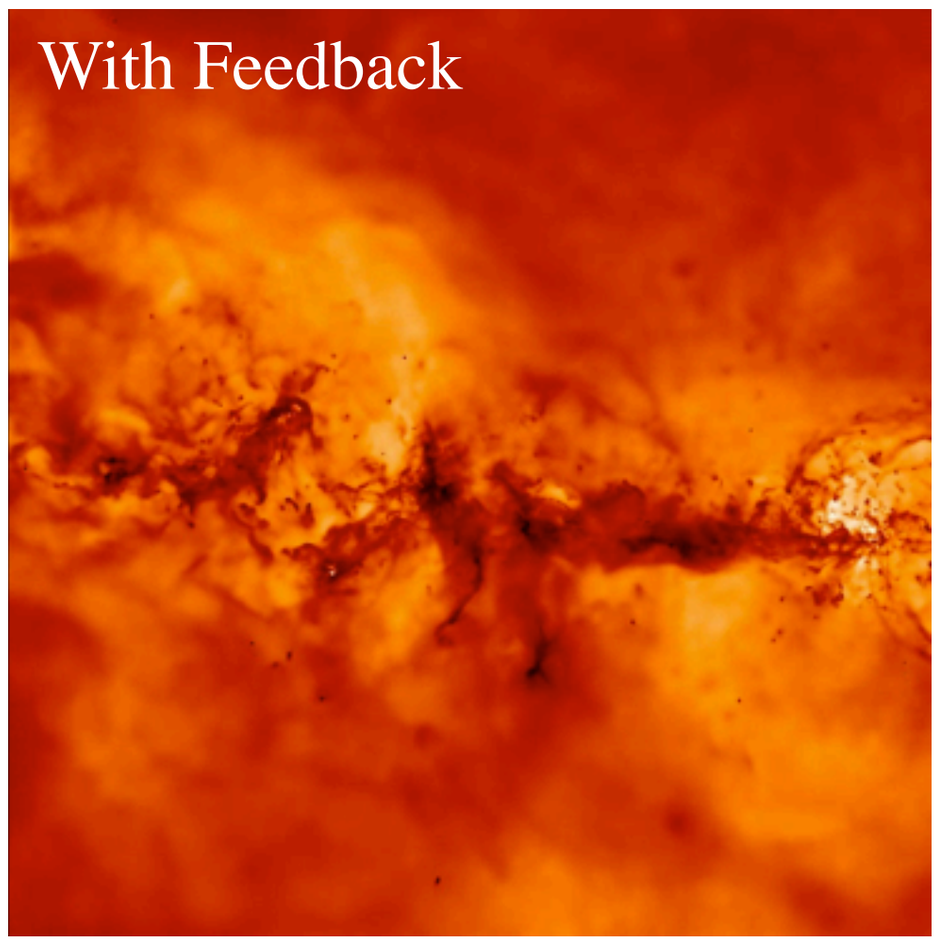


How Efficient Are Galactic Super-Winds?

WHAT MECHANISMS DRIVE THEM?

S. Muratov et al., in prep

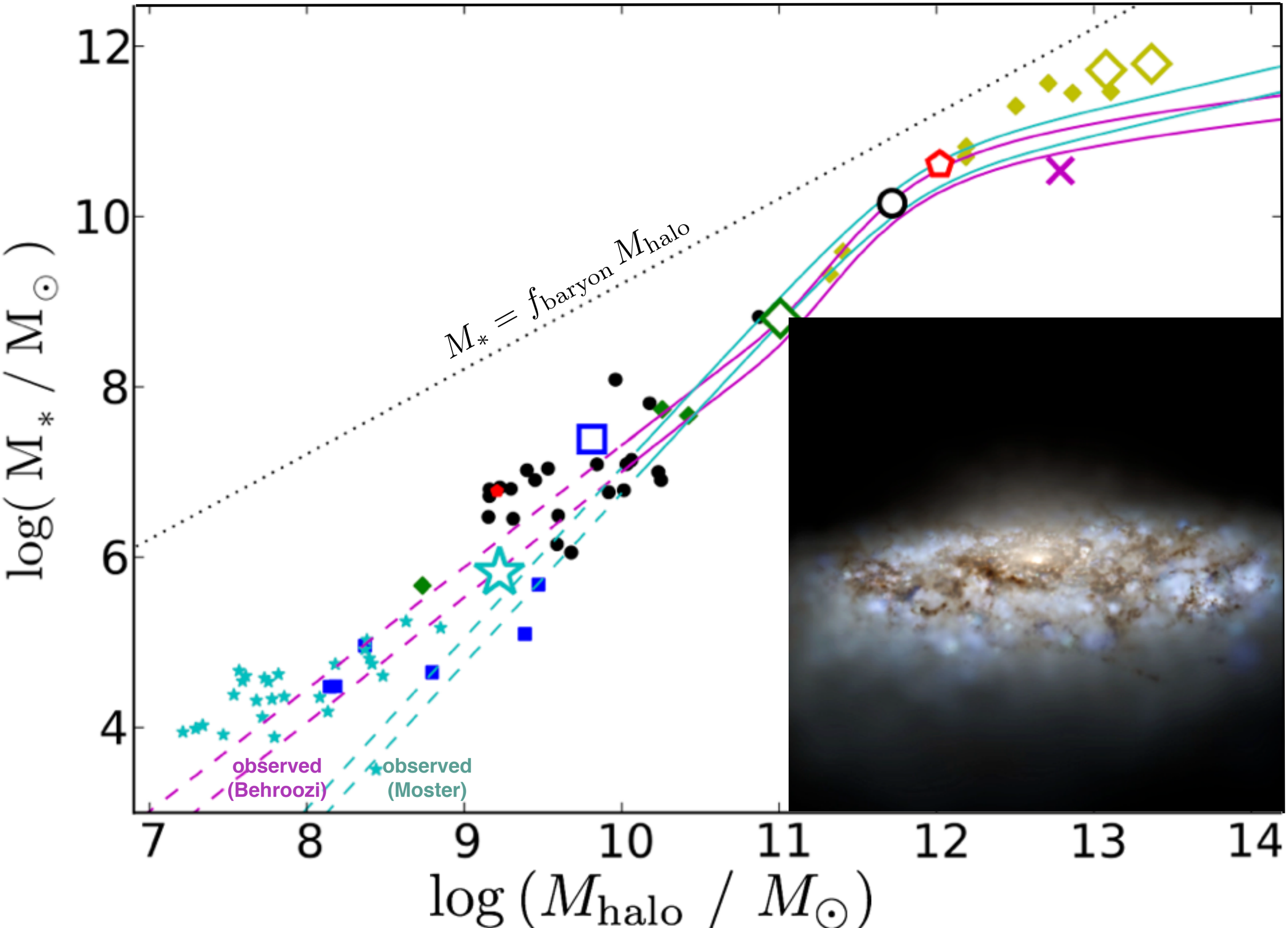




Does Stellar Feedback Explain the Mass Function?

PFH et al. (arXiv:1311.2073)

HOW EFFICIENT ARE GALACTIC WINDS?



Sub-Grid Is Not Enough

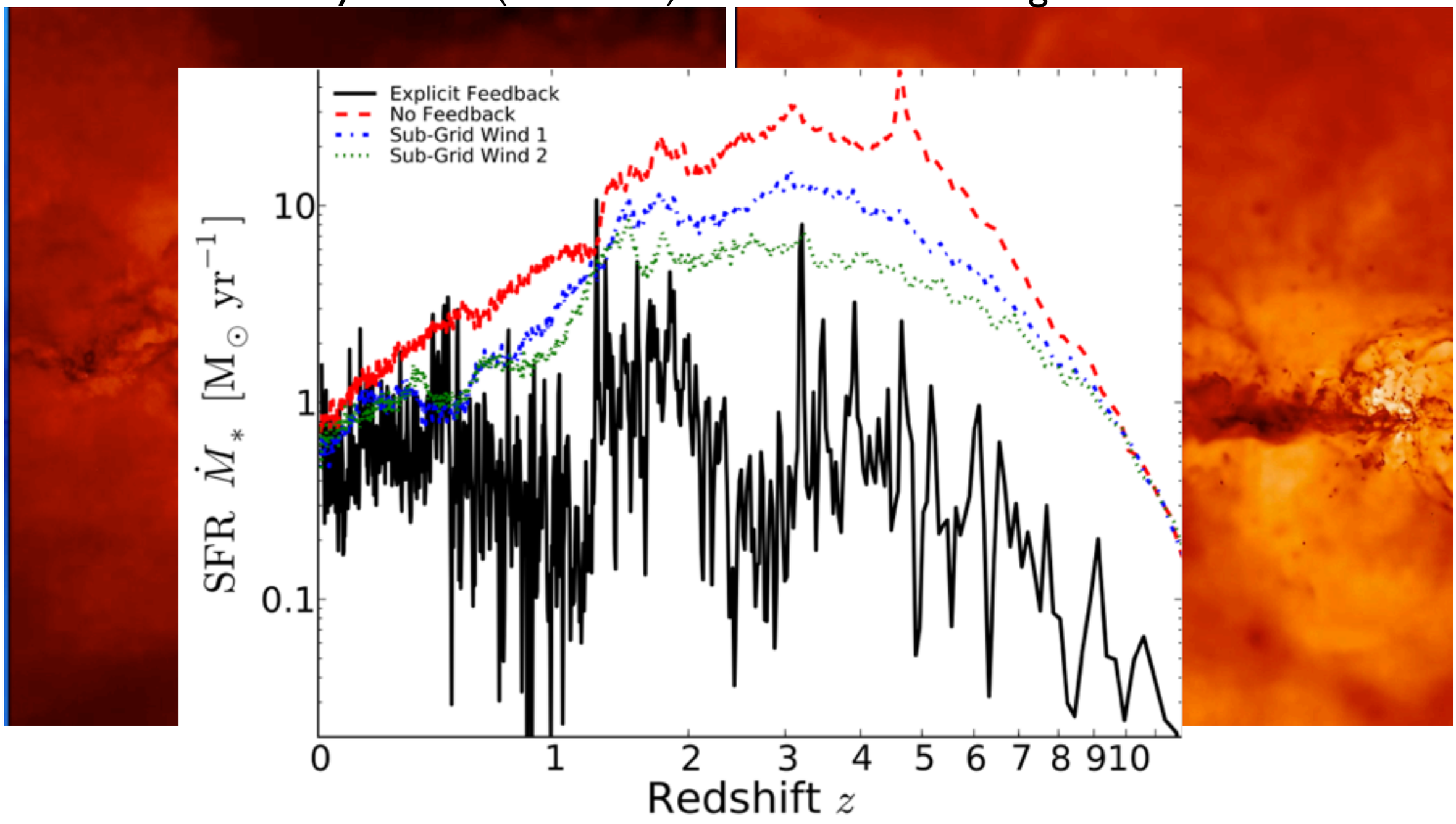
PHASE STRUCTURE AND RECYCLING OF OUTFLOWS MUST BE CAPTURED!

S. Muratov
(stay tuned)

Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

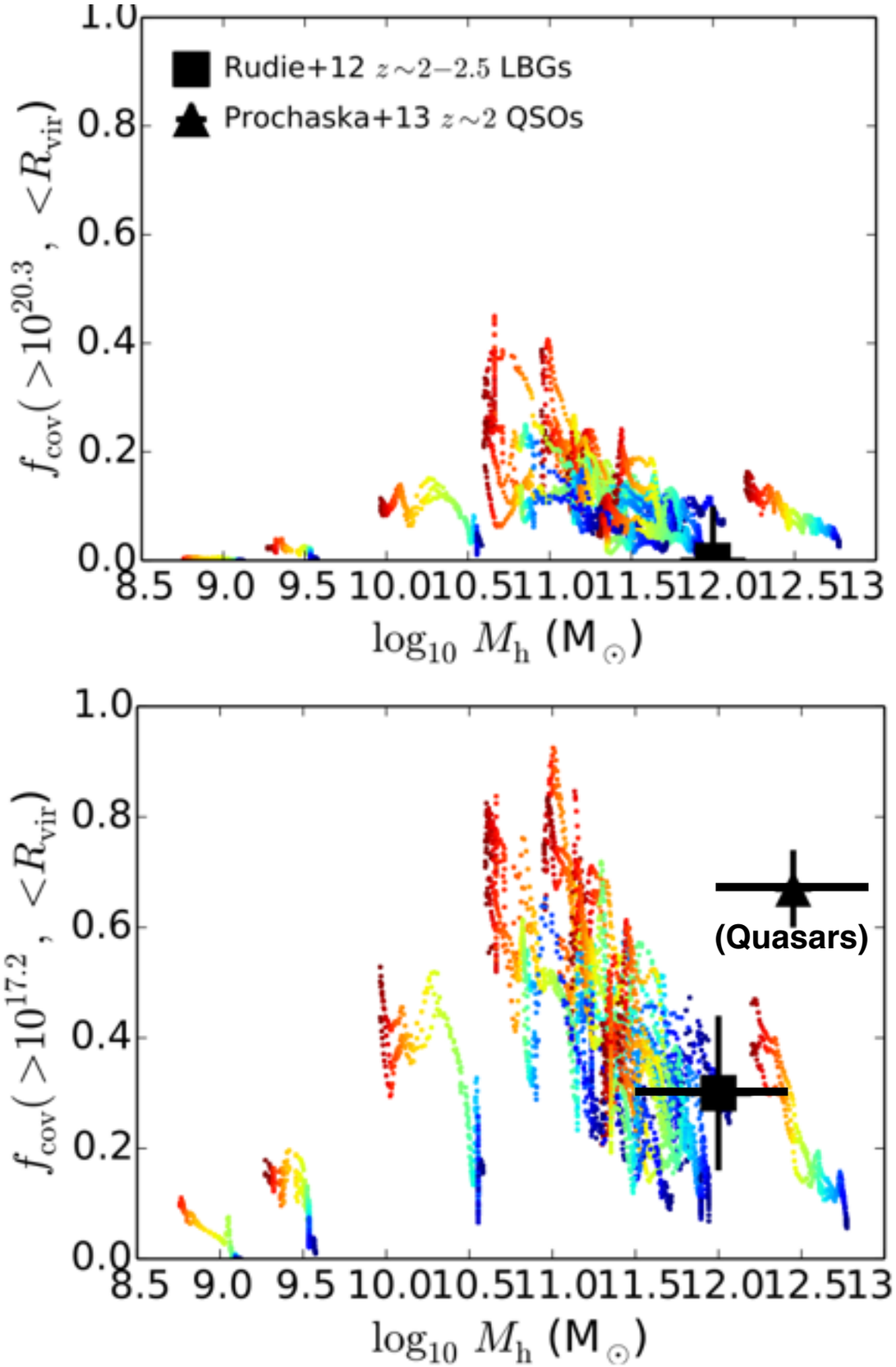
Following Full Feedback

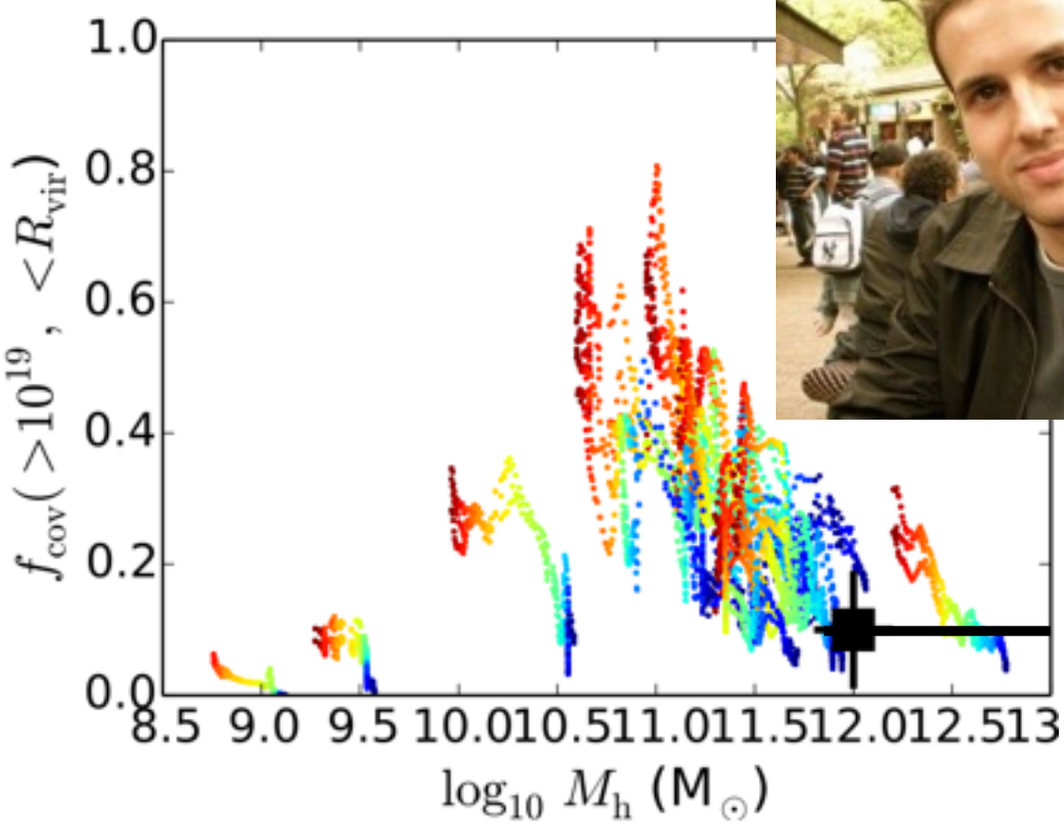


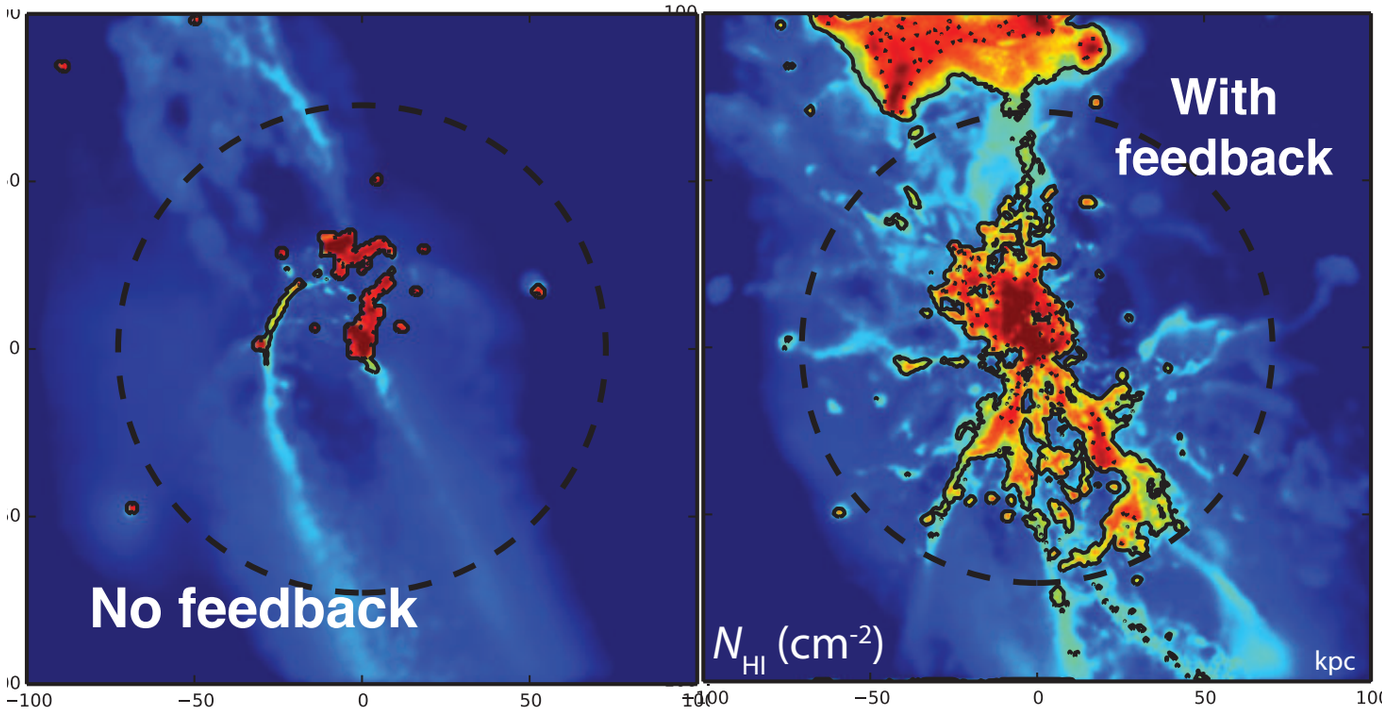
Feedback Determines the Halo Gas Properties

ABSORBERS FALL OUT NATURALLY (EXCEPT QUASARS)

Faucher-Giguere, arXiv:1409.1919



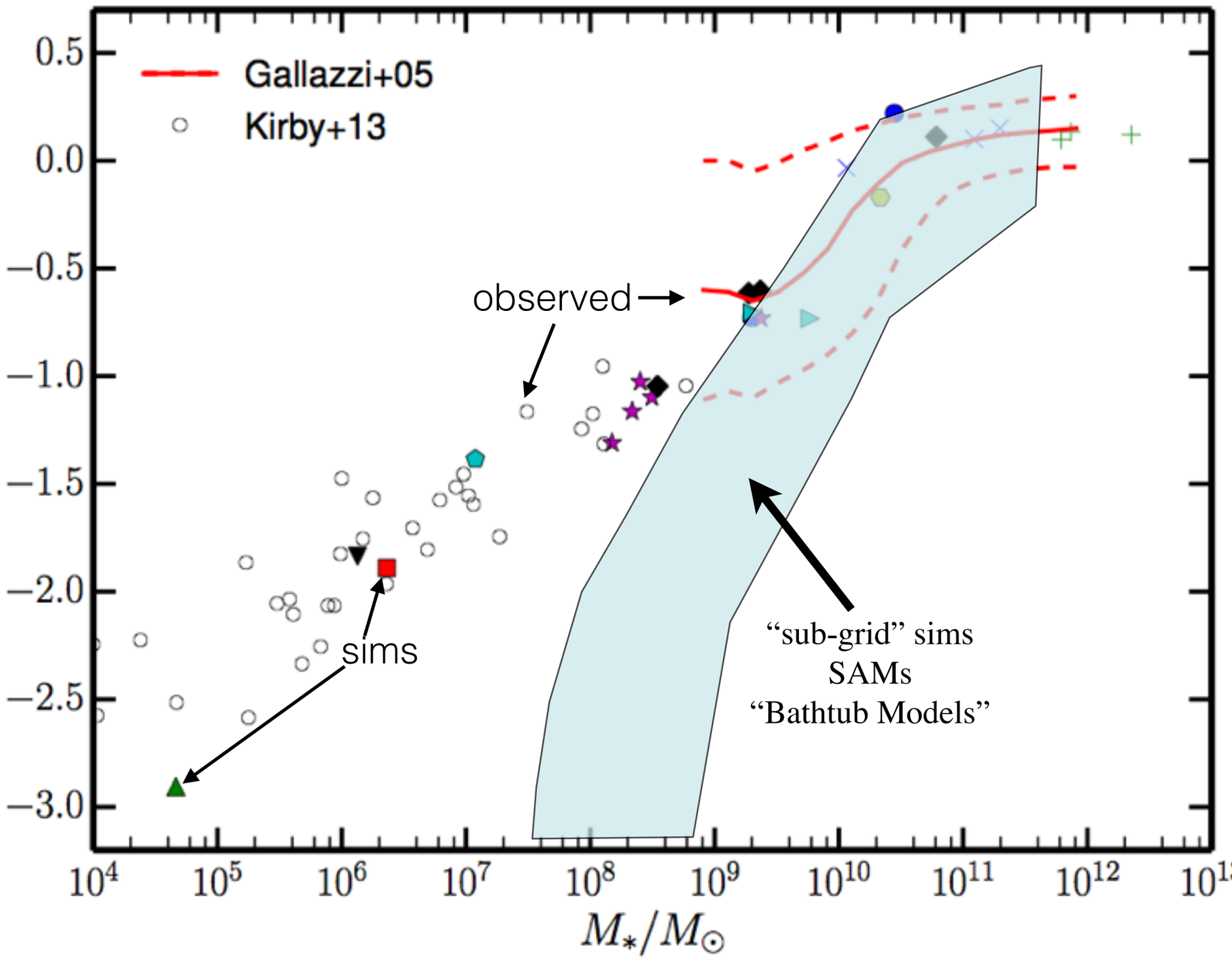




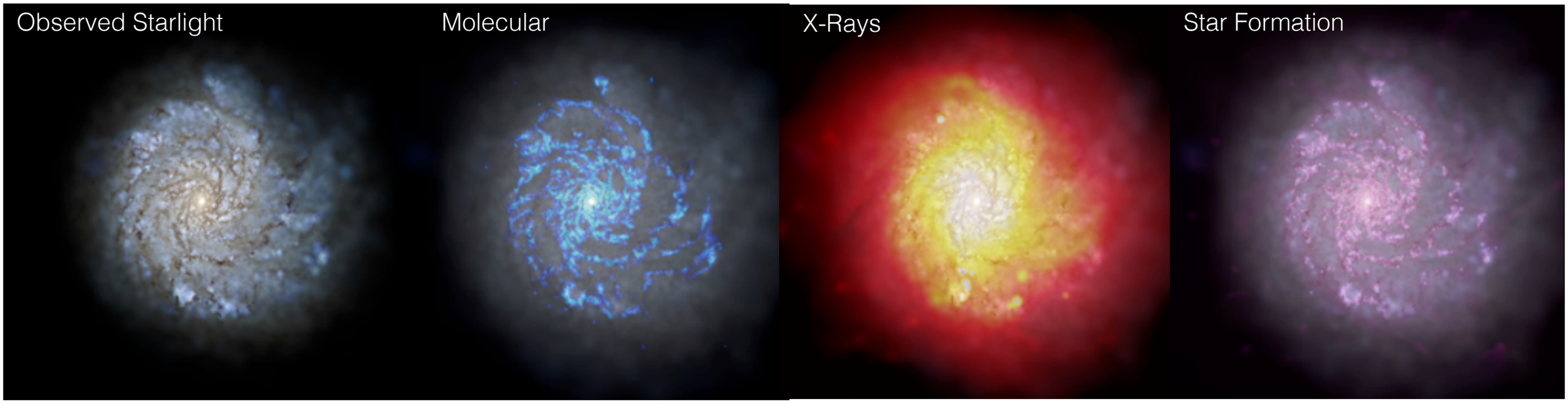
Dwarf Metallicities: Revealing Feedback

DEPENDS ON DETAILS OF INFLOW-OUTFLOW INTERACTIONS

Xiancheng Ma



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



- "Turbulent Fragmentation" at all scales:
  - **GMCs:** universal mass function (power-law 1.x + cutoff at Toomre)
  - **Larson's Laws:** trace the turbulence
  - **Cores:** universal slope 2.x, turnover at sonic scale
  - **IMF:** fragmentation from cores: Salpeter slope & weak dependence of Mpeak
  - **Stellar Clustering:** ~0.1pc - kpc, follows *directly* from turbulent fluctuations
- **Star formation is Feedback-Regulated**:
  - KS law is *independent* of small-scale SF physics!
  - SF is not "slow because of turbulence": is slow because feedback unbinds gas!
- Cosmologically:
  - **Winds** determine **IGM enrichment, temperature, & subsequent inflow**
  - **Resolved feedback ≠ sub-grid feedback**!
    - Mass-metallicity, SFHs, morphology *not the same*