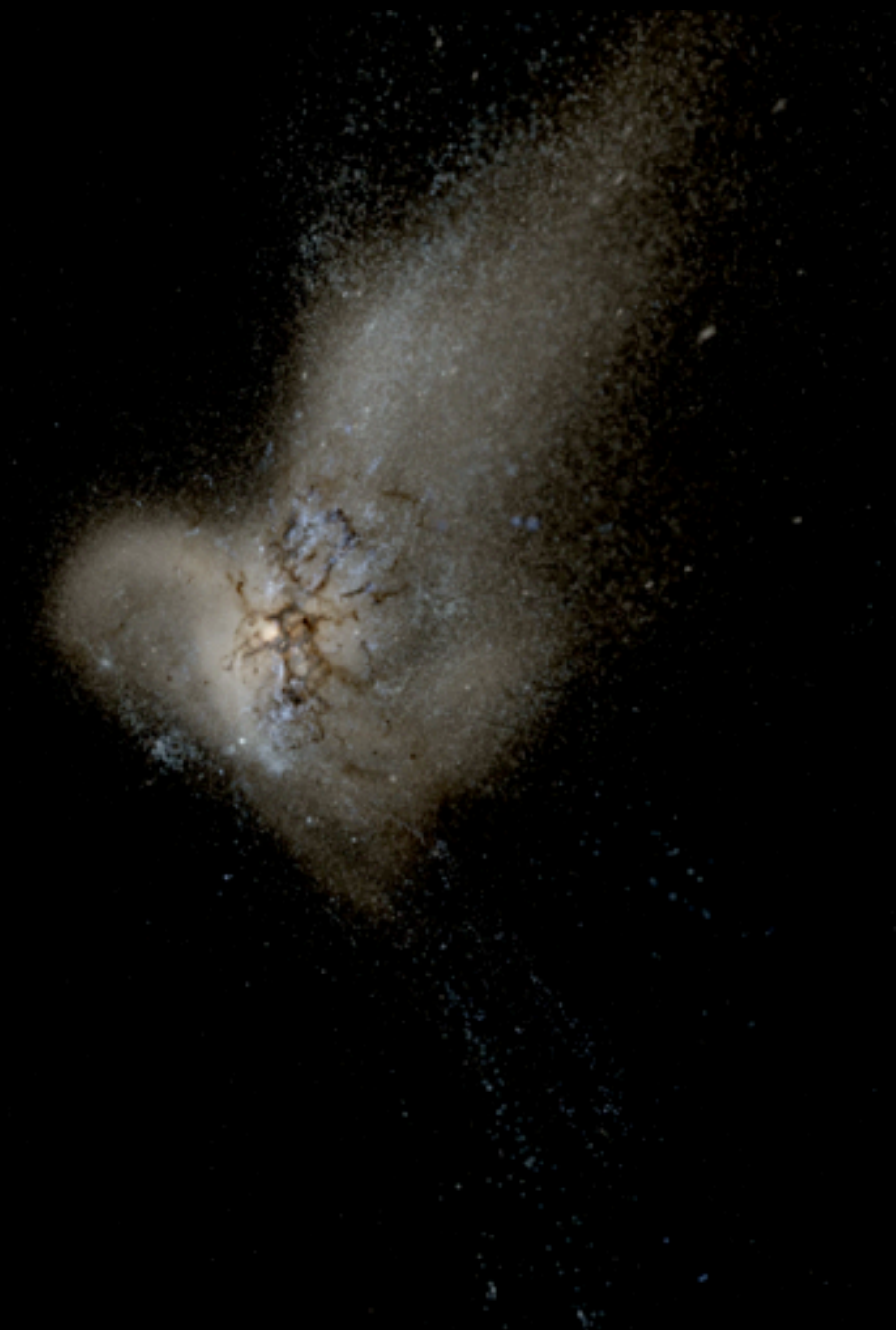
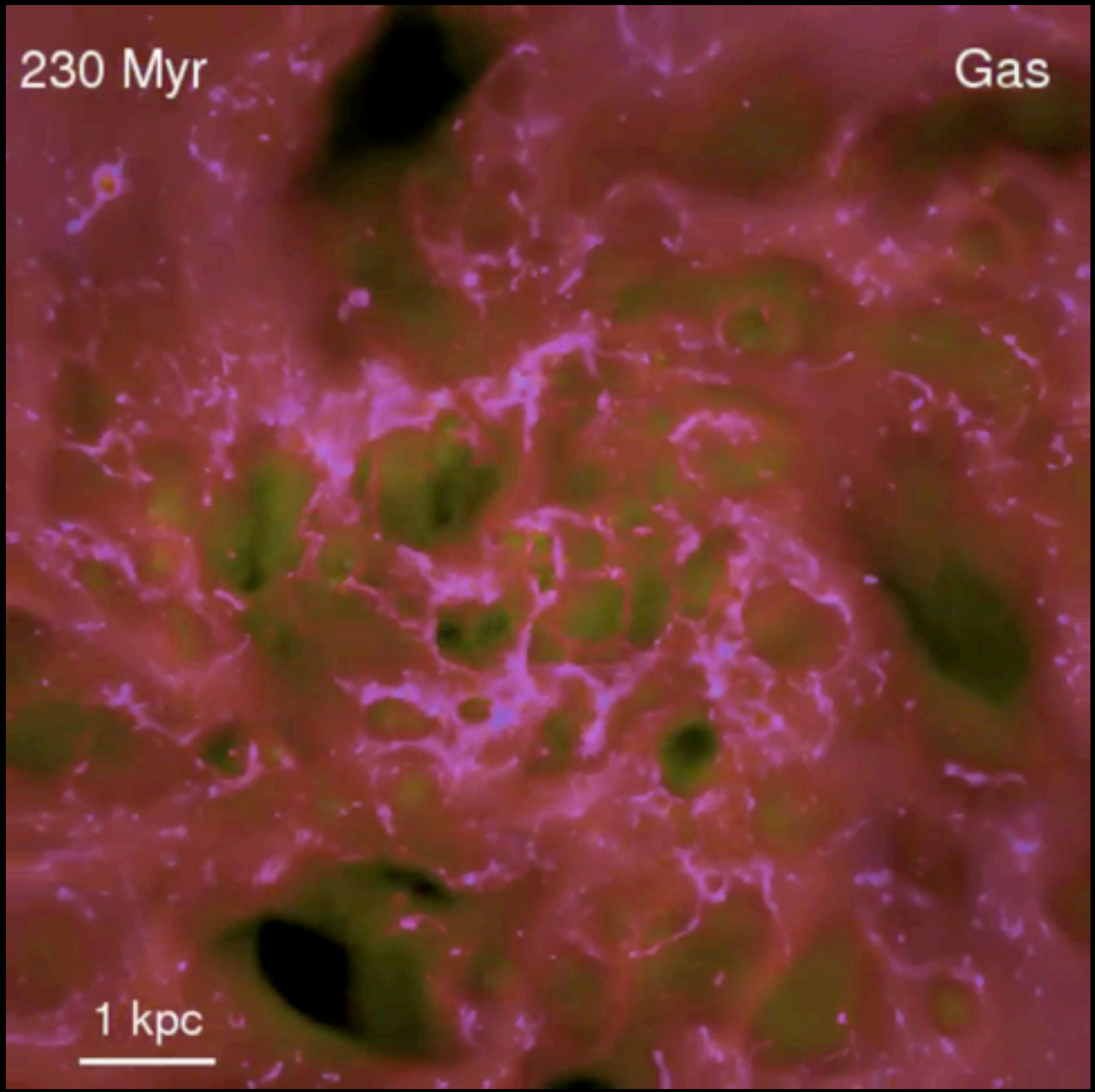
Star Formation is Feedback-Regulated



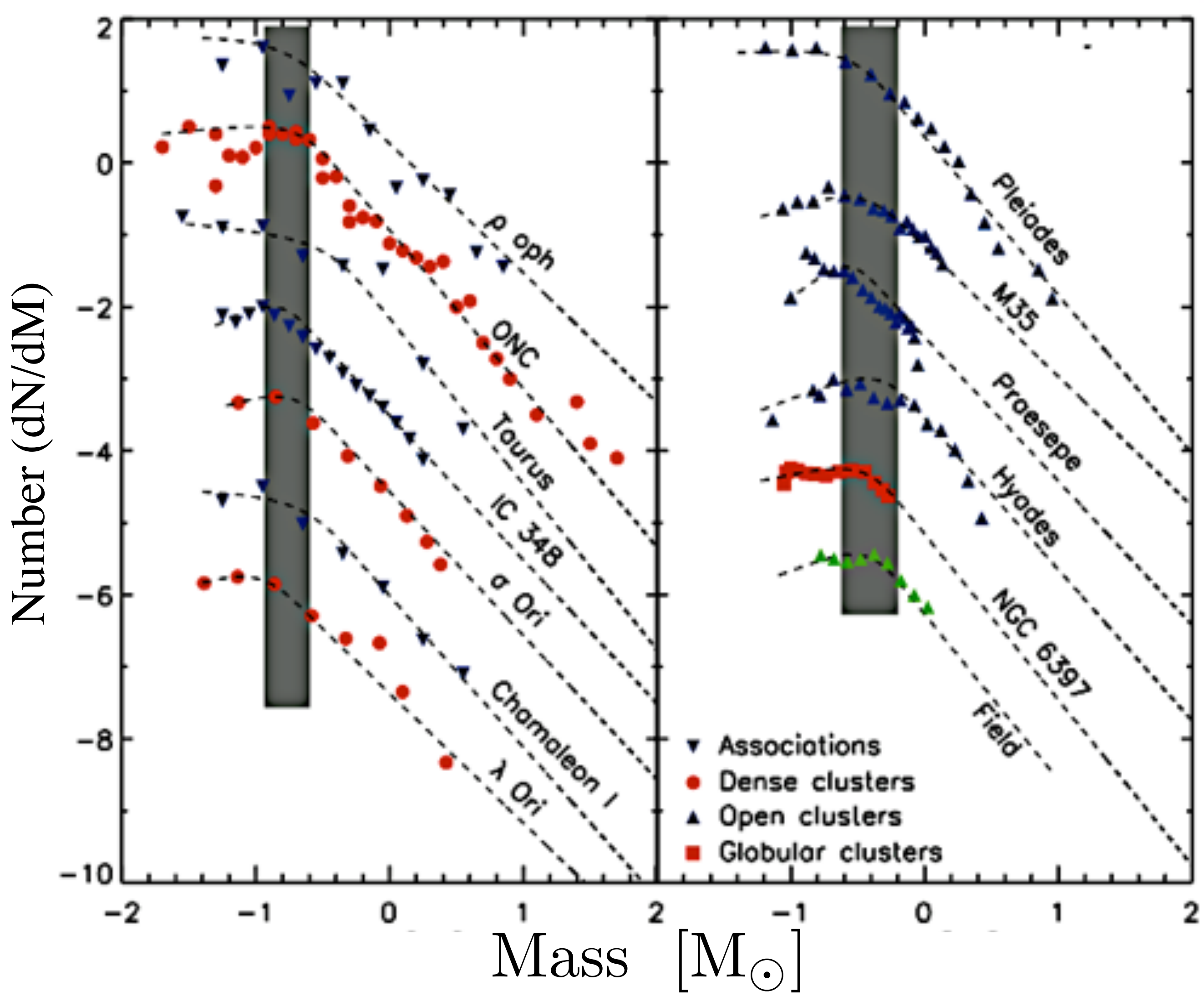


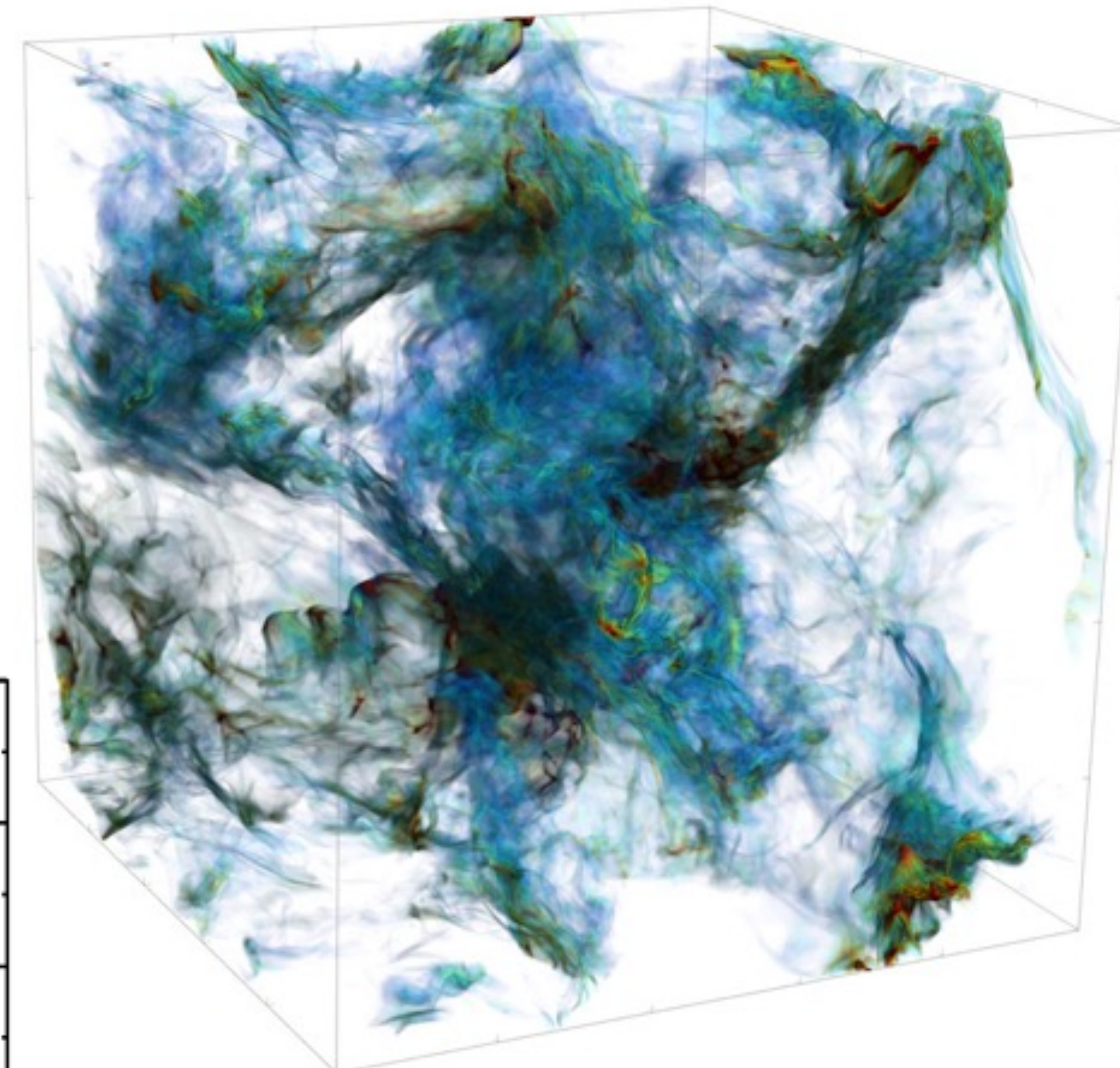
Philip Hopkins

Matt Orr, Mike Grudic, Paul Torrey
Norm Murray, Todd Thompson

We can explain a **lot** with turbulence + gravity

- IMF (mostly)
- Cores
- GMCs
- Voids
- Clustering
- Dark matter halos (really!)



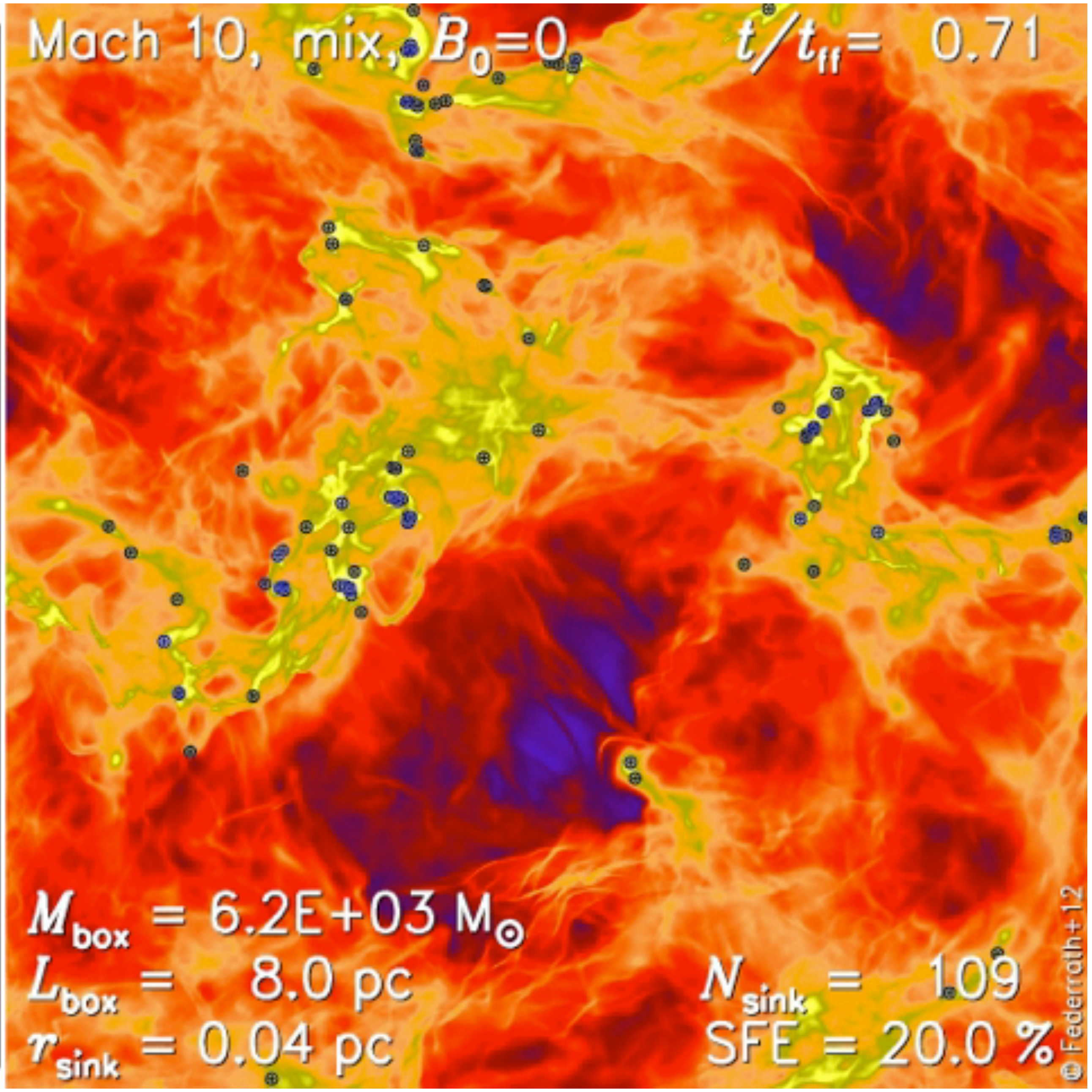


- Wednesday:
  - FM18
  - 5:00pm

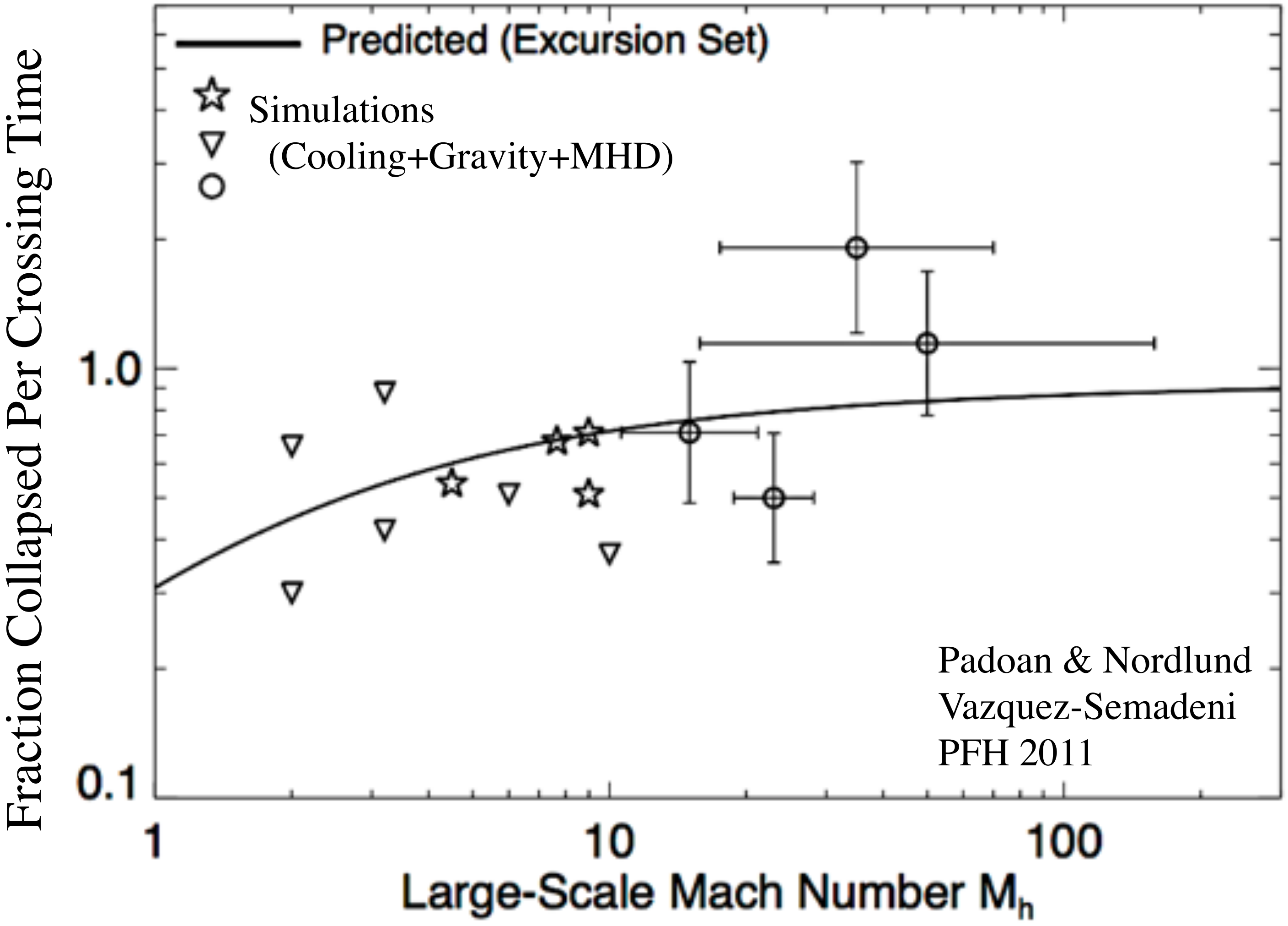
What About Star Formation?

Can’t Regulate it Without Feedback!

TURBULENCE ALONE LEADS TO RUNAWAY COLLAPSE



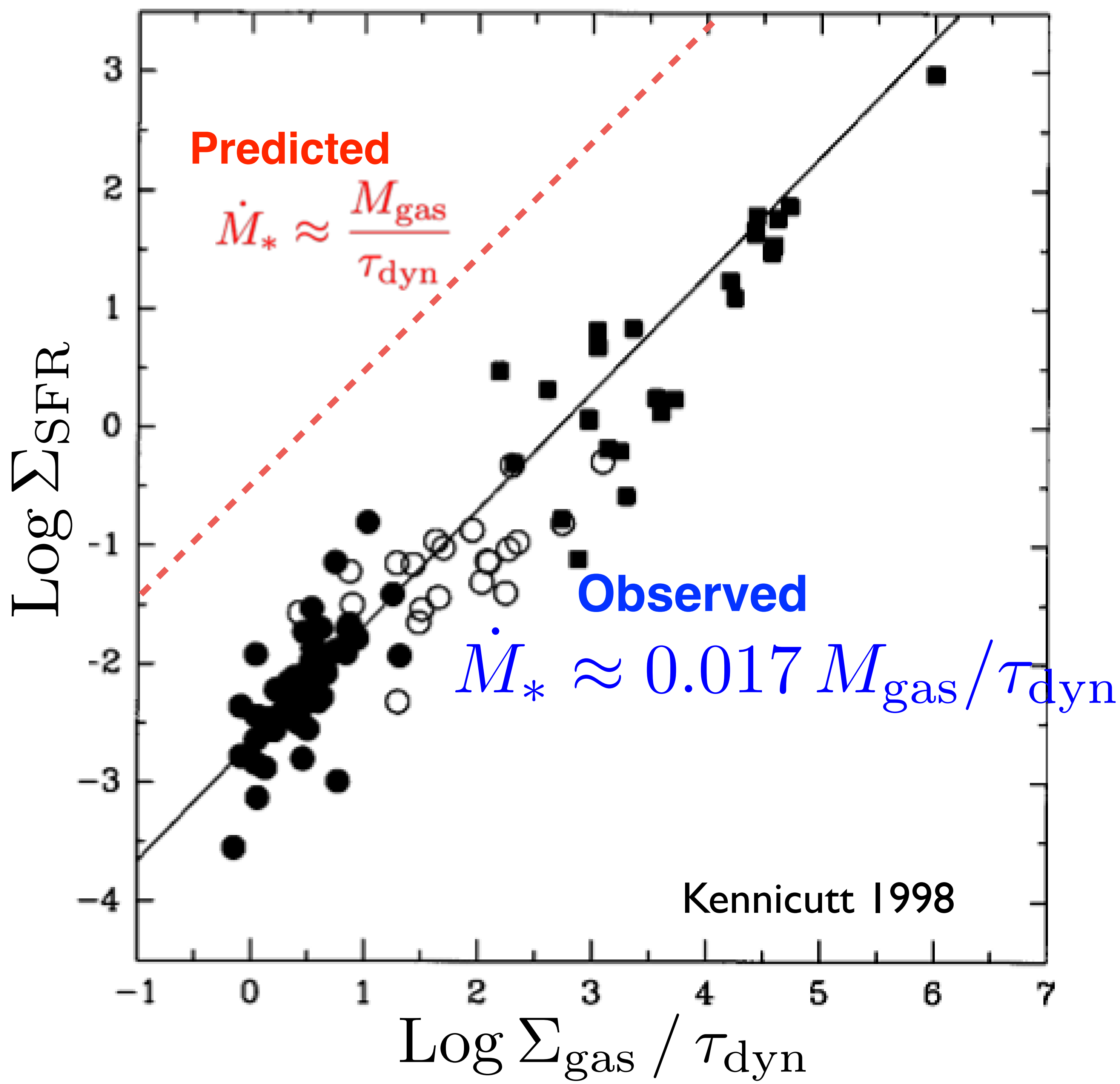
Federrath et al.



Turbulence driven + ALWAYS strong: WAY too many stars form!

Gravity + Hydro + Cooling = Problem Solved?

ANY MODEL FOR KENNICUTT WITHOUT FEEDBACK IS *WRONG*



Elmegreen 77, Larson 81,
& many since

State of the Art Today:

- High-resolution (~1-10 pc), molecular/metal cooling (~10 K), SF at $n_H > 1000$ cm^{-3}
- Energy/Mass/Metal Injection:
  - SNe (II & Ia)
  - Stellar Winds (O & AGB)
  - Photoionization (HII) & Photoelectric
- Momentum Flux:
  - Radiation Pressure

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

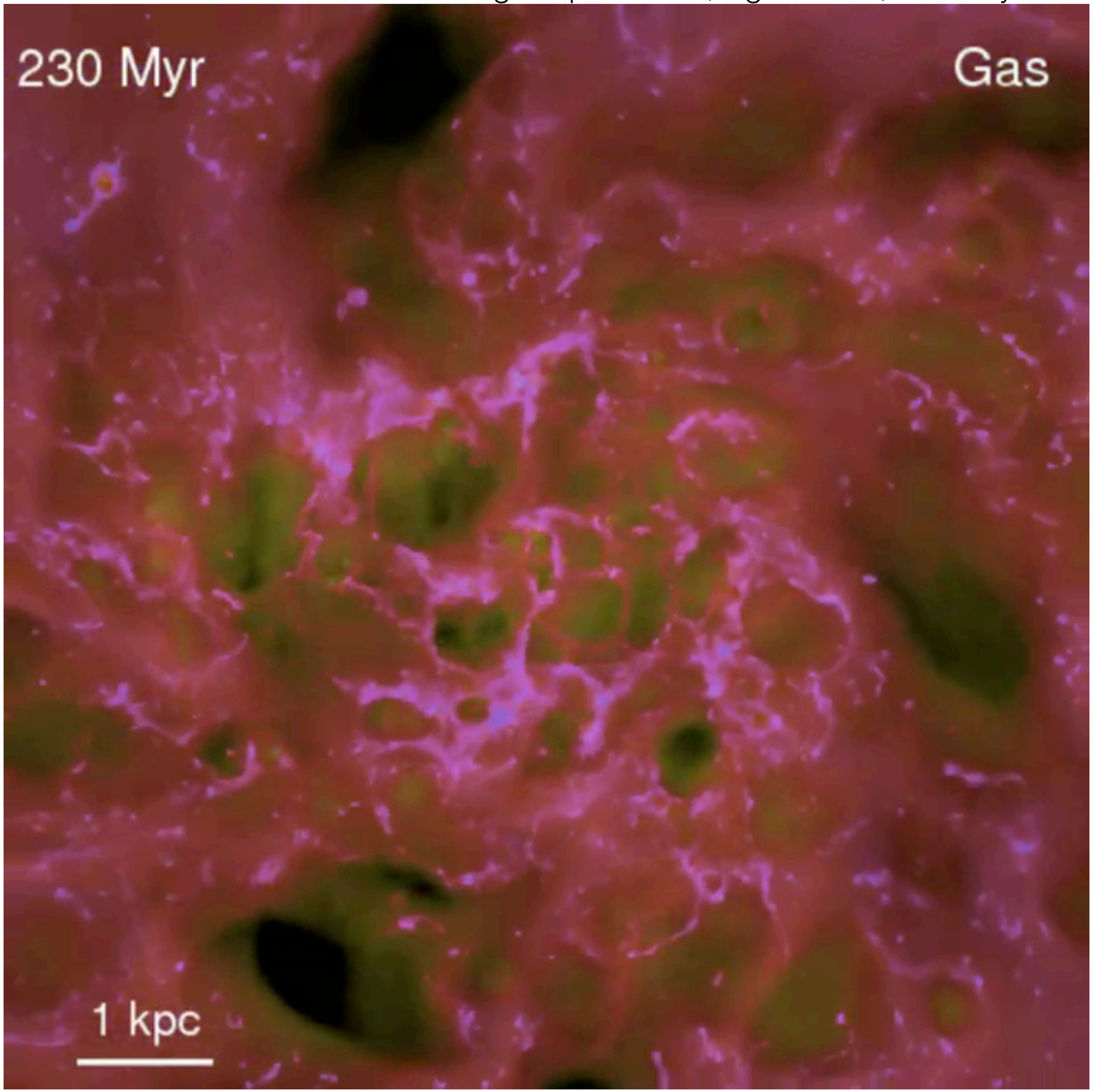
  - SNe

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

  - Stellar Winds

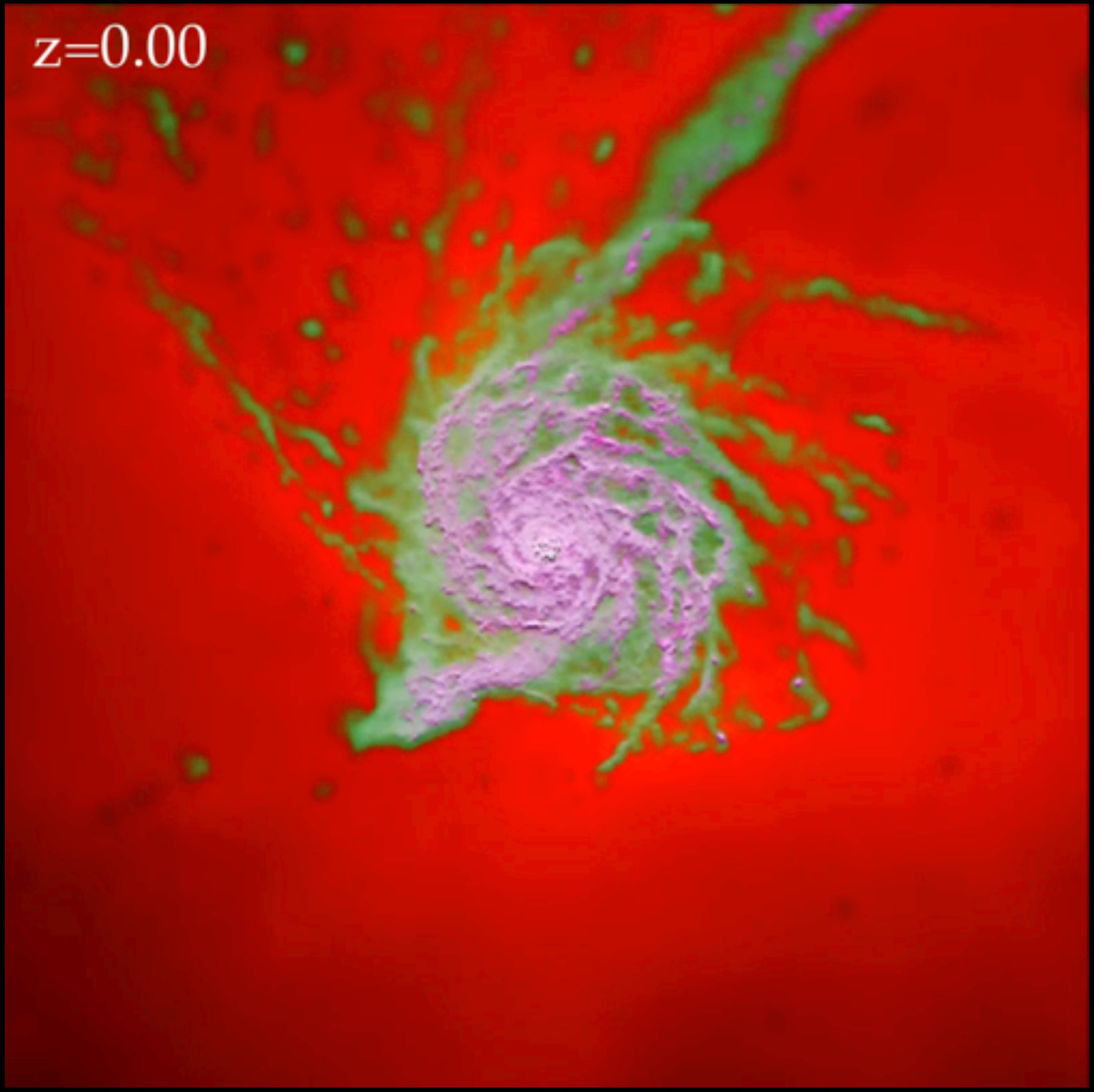
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

e.g. Hopkins+ 10, Agertz+ 13, Wadsley+ 14



- (also MHD, cosmic rays, anisotropic conduction, diffusion)

FIRE project (tomorrow: division J, 10:30 am) (fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

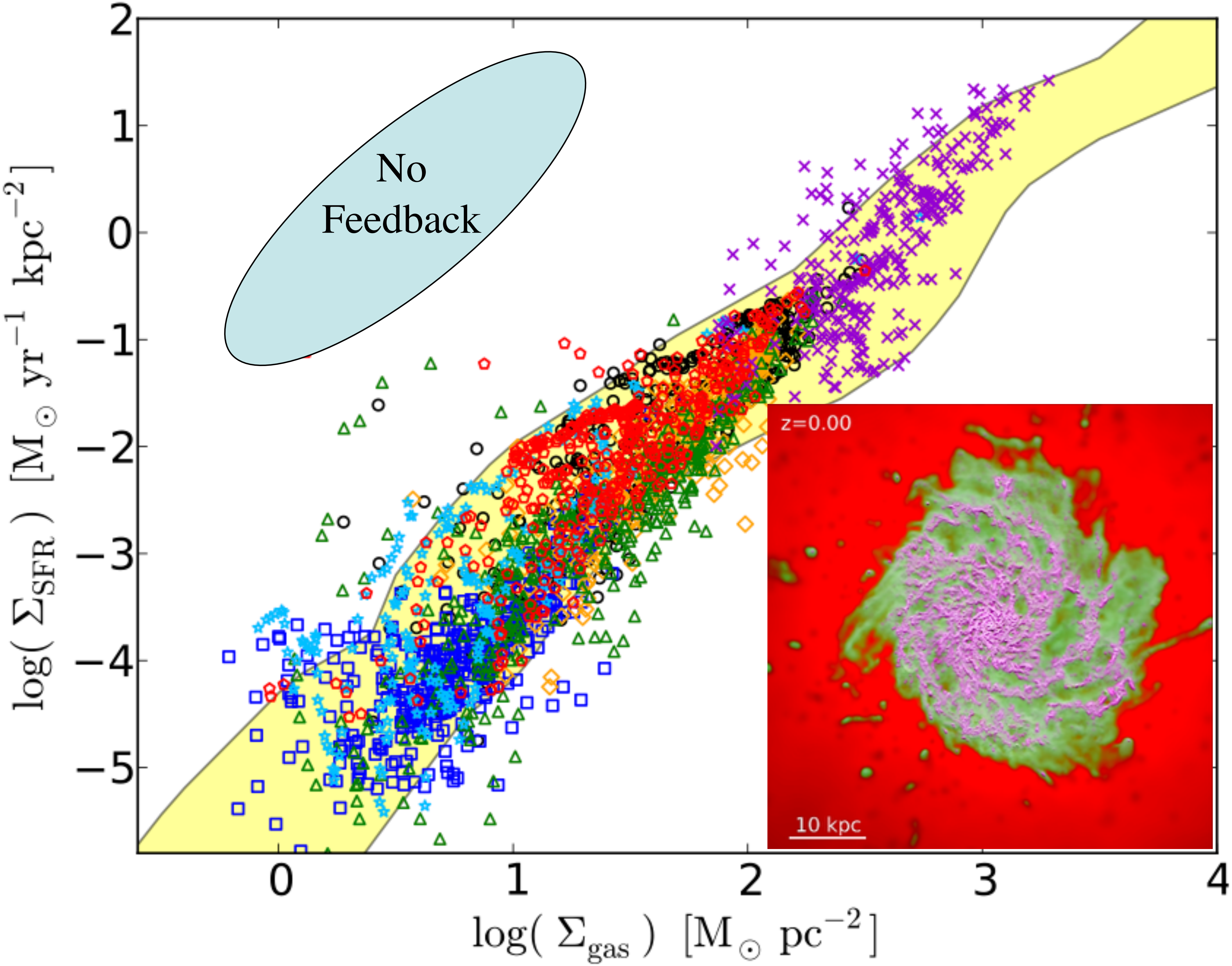
Green: warm (ionized)

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

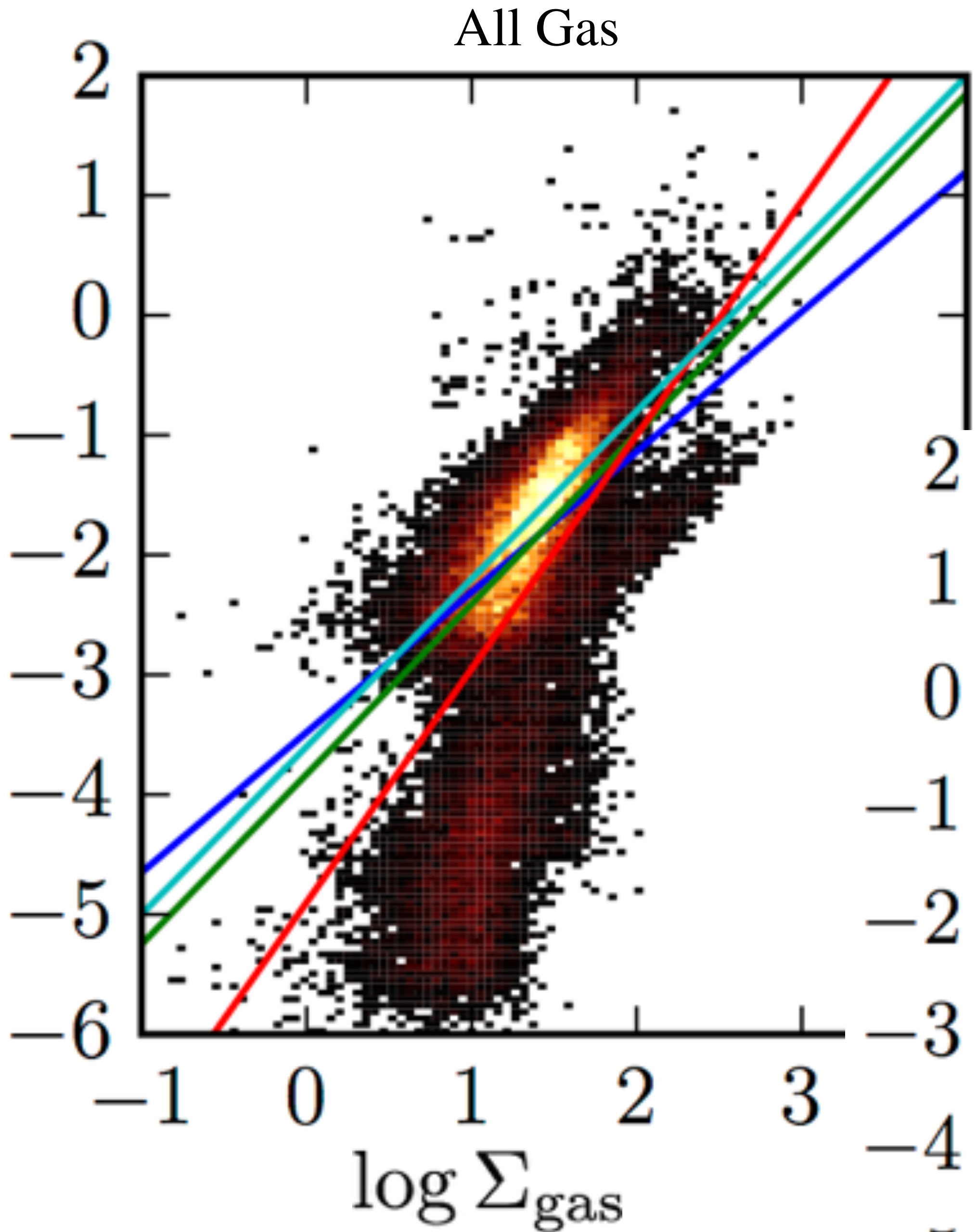
The Kennicutt Law Emerges

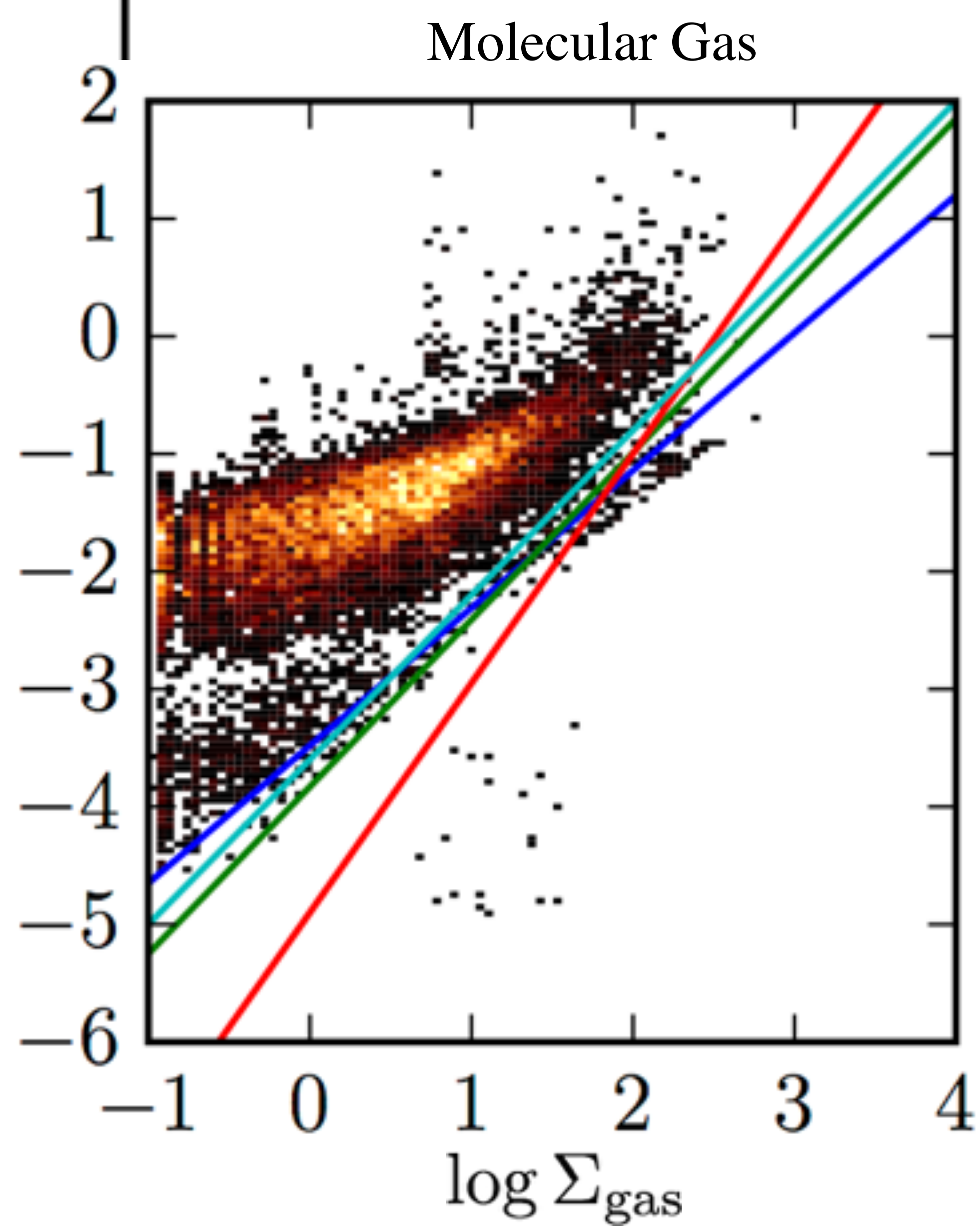
WITH FEEDBACK

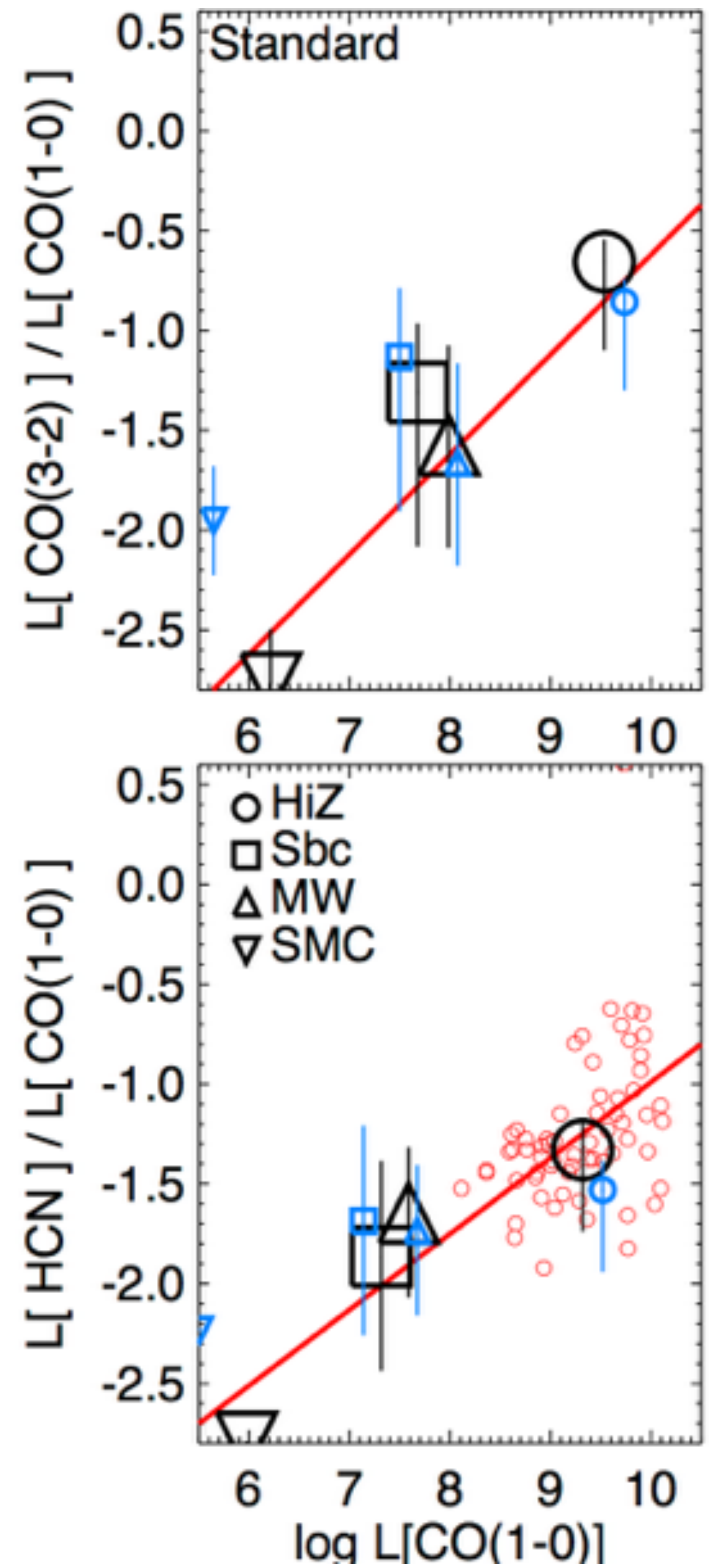
Hopkins+ 11,14; Agertz+14;
Shetty & Ostriker 12



The KS Law: It's Feedback.

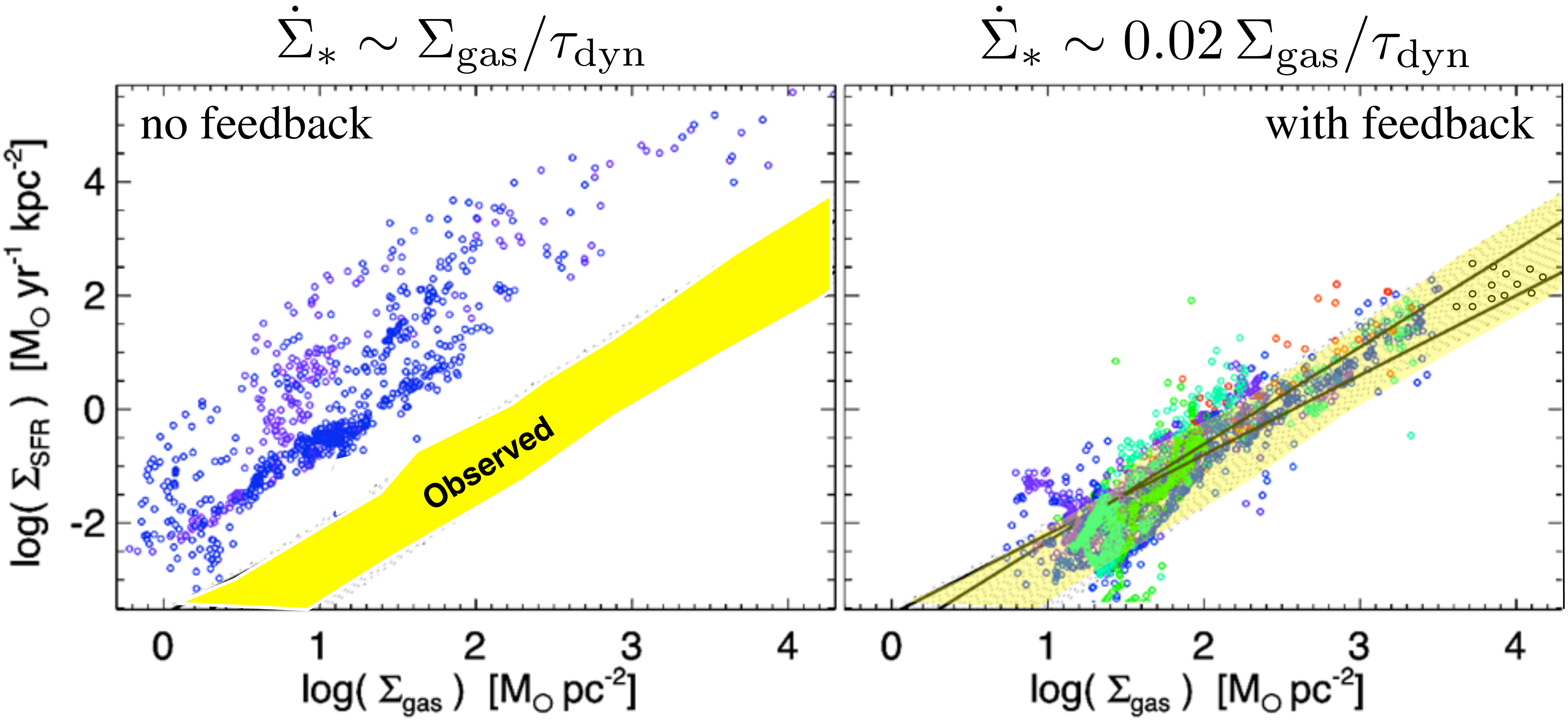






Matt Orr: more in prep

The KS Law: It’s Feedback.



PFH, Quataert, & Murray, 2011a

The KS Law: It's Feedback.

Shetty & Ostriker '12
CAFG et al. '13

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

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

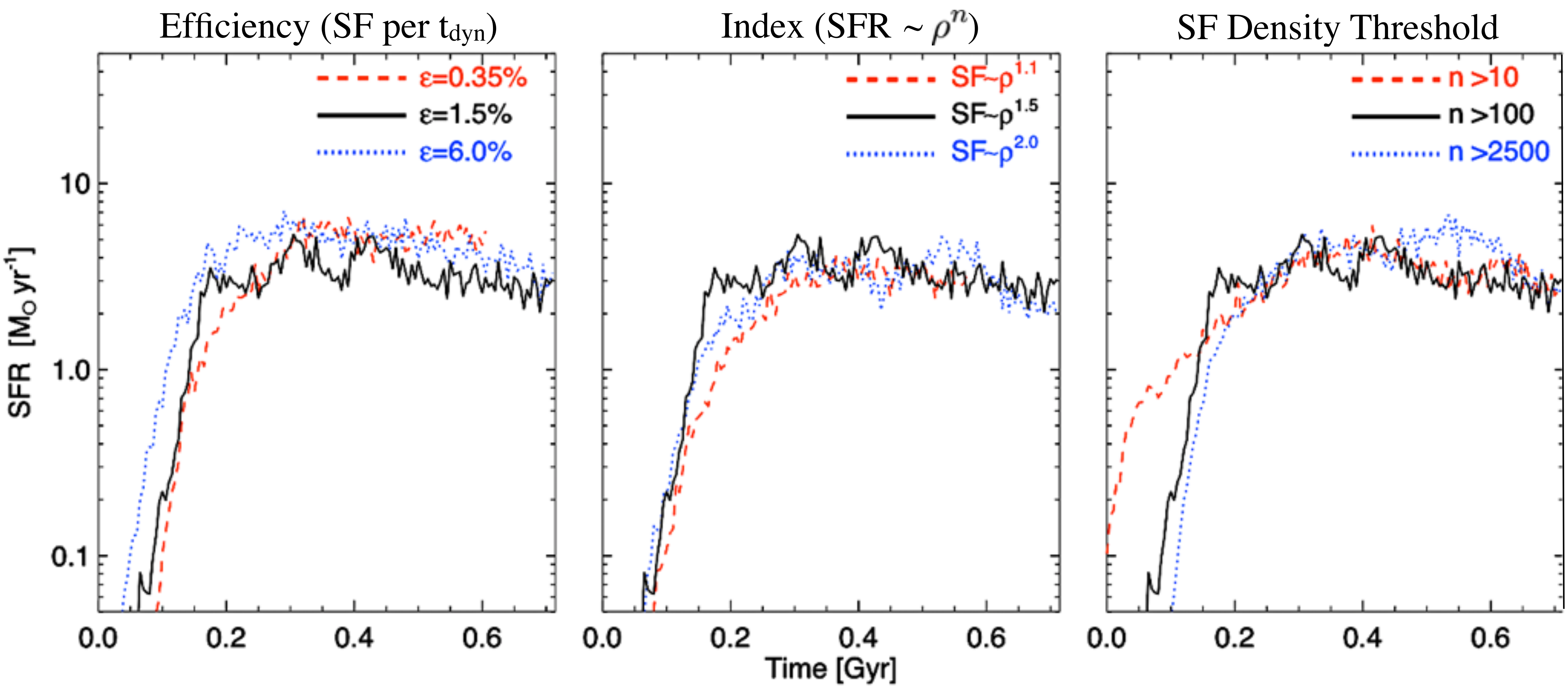
- Collapse stops when momentum input from feedback:

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

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

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

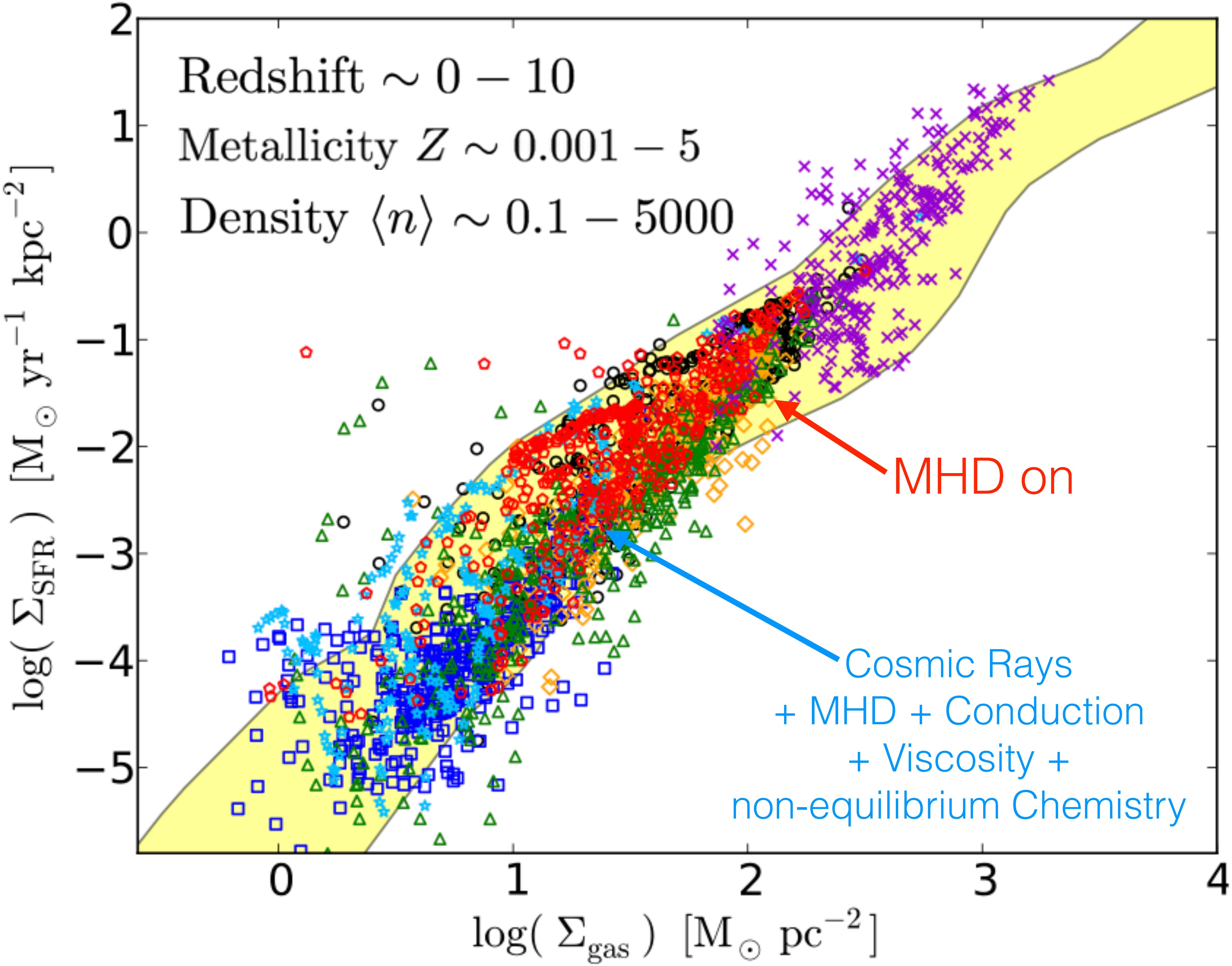
(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!



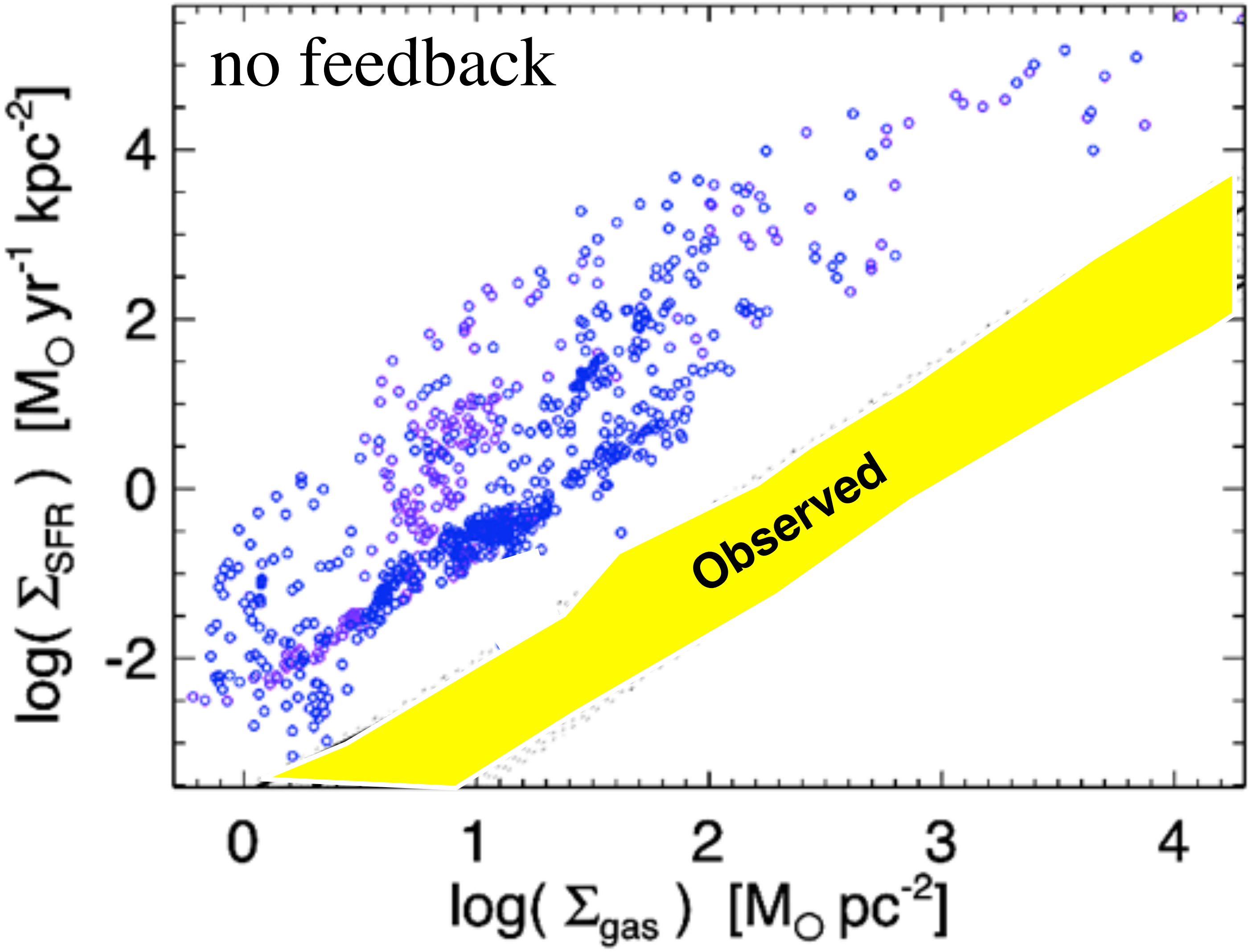
- Set by feedback (SFR) needed to maintain marginal stability

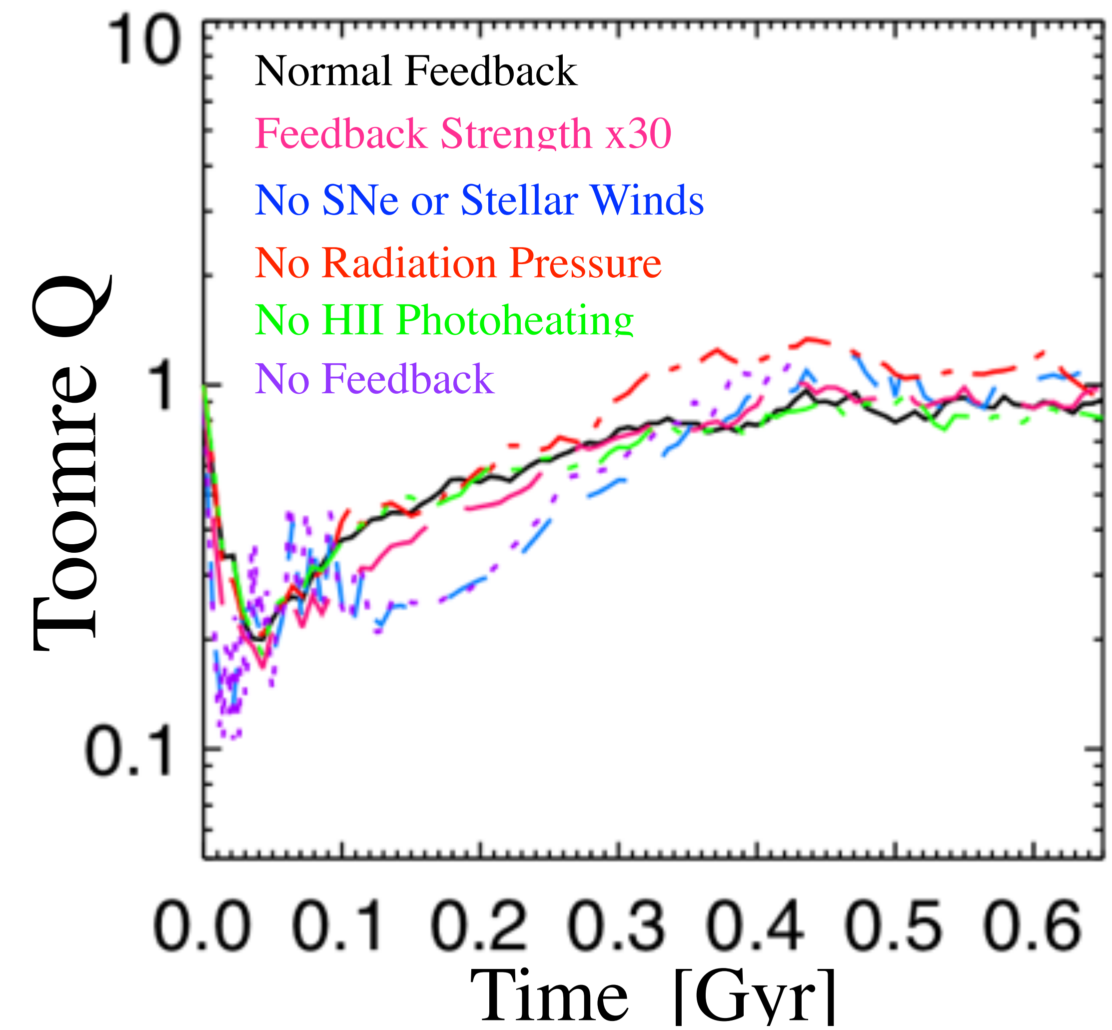
Hopkins, Quataert, & Murray 2011
also Saitoh+ 2008, Agertz+ 14

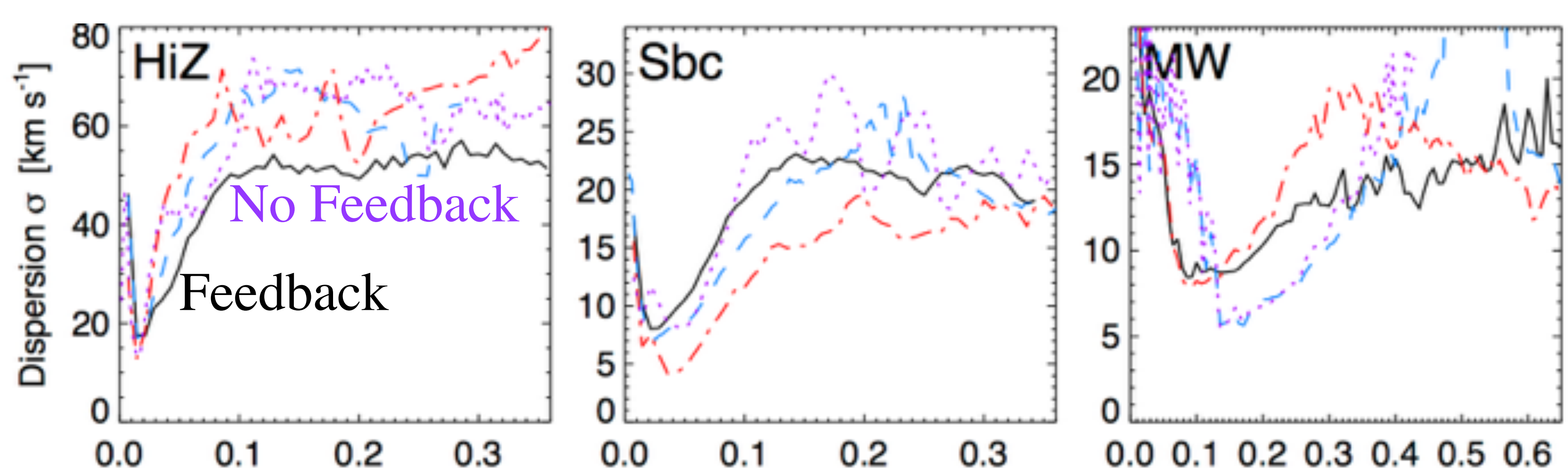
The KS Law: It's Feedback.



Feedback doesn't *just* "drive turbulence"



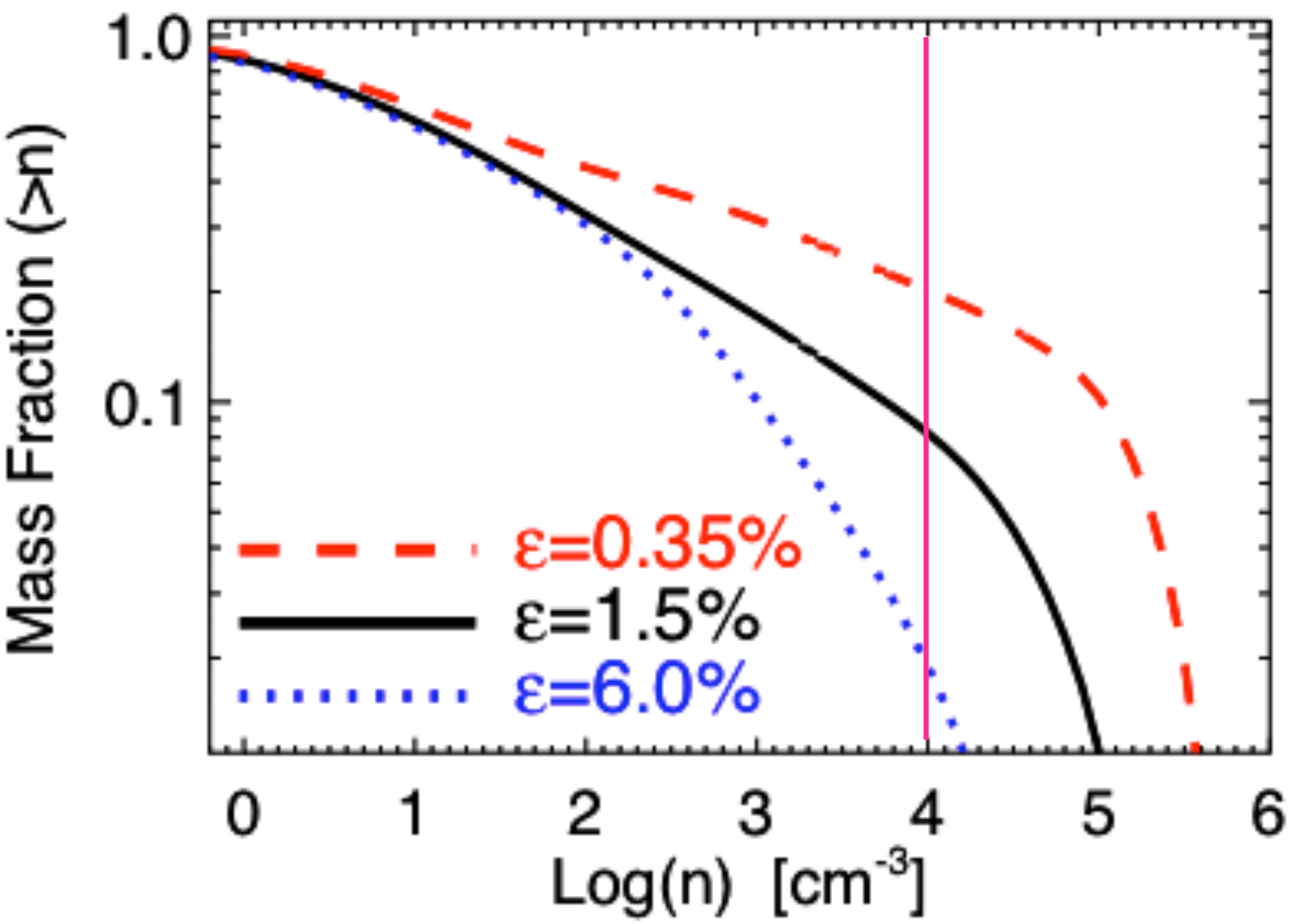


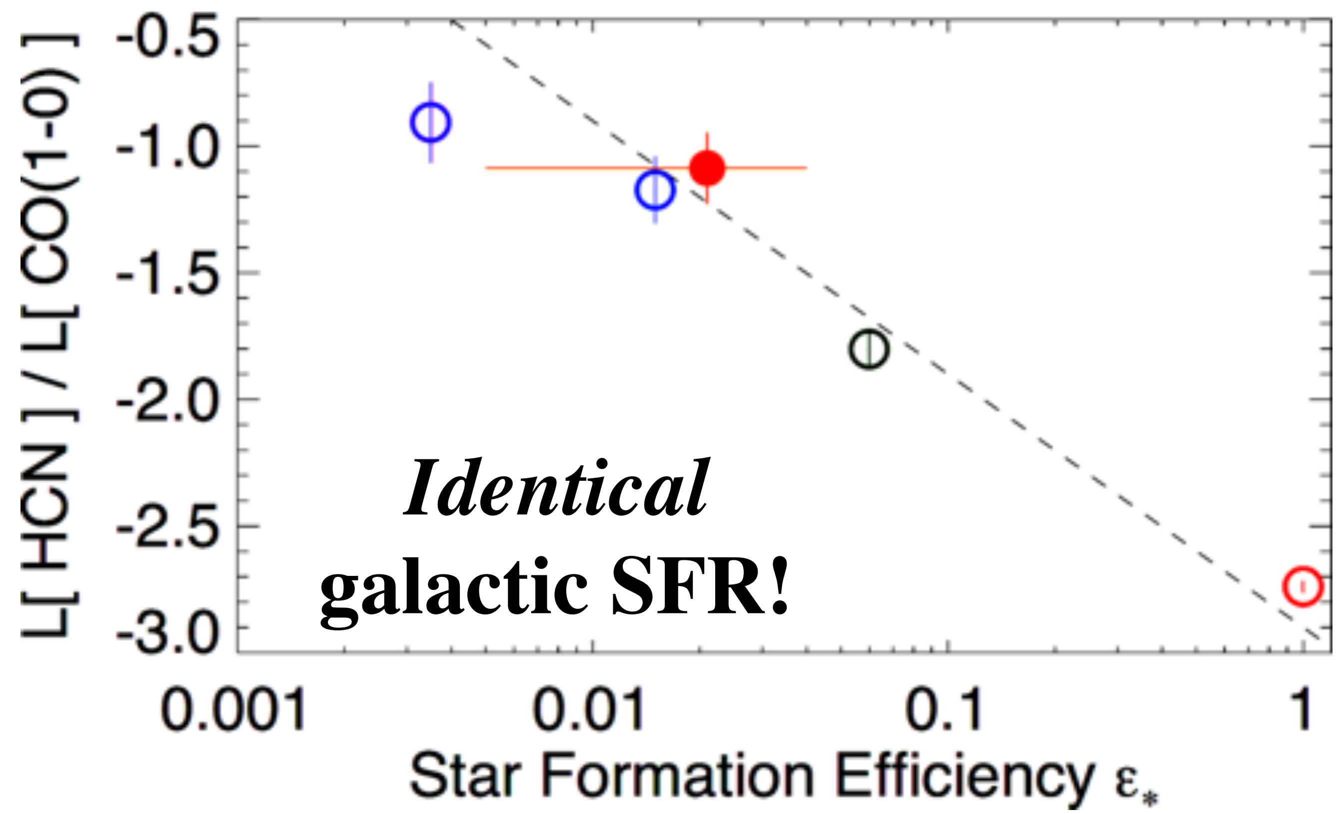


Don’t “Stars Form in Dense Gas”?

SELF-ADJUSTS TO MATCH THE “NEEDED” LEVEL

Efficiency (SF per t_{dyn})
in *dense* (>1e4) gas





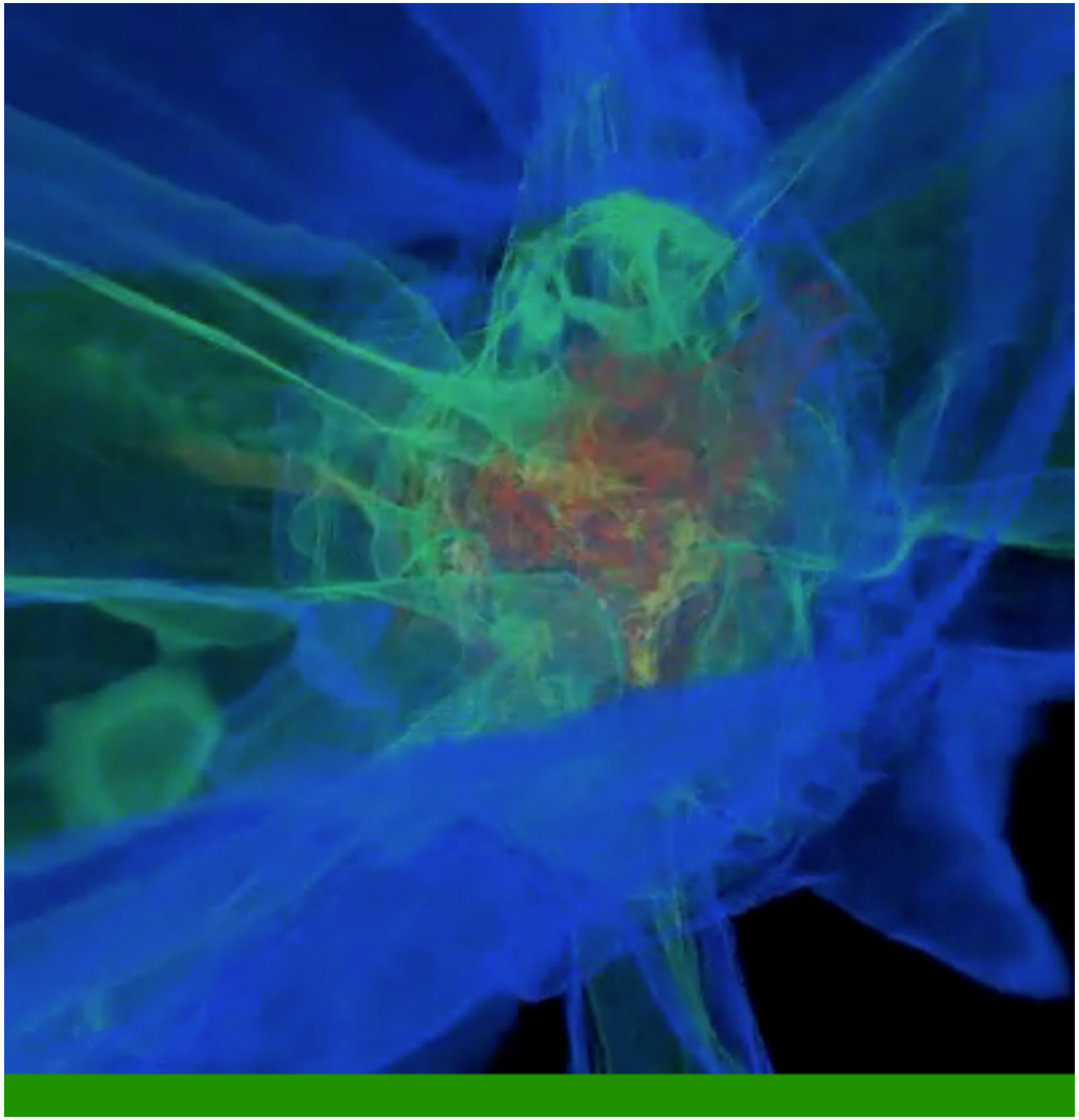
- Pile up more dense gas until the SFR “needed” is obtained!

Hopkins, Quataert, & Murray 2011

When does my argument fail?

Where does this argument fail?

LOWEST METALLICITIES



First stars (e.g. Abel et al.):

$$t_{\rm cool} \propto Z^{-1}$$

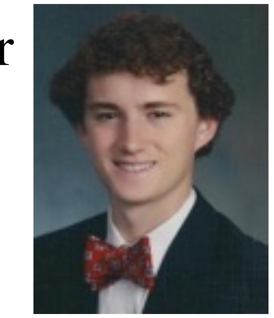
$$t_{\rm cool} \gg t_{\rm dyn}:$$

$$\frac{Z}{Z_\odot} \lesssim 10^{-4}\,\frac{(T/100\,{\rm K})}{(n/100\,{\rm cm^{-3}})^{1/2}}$$

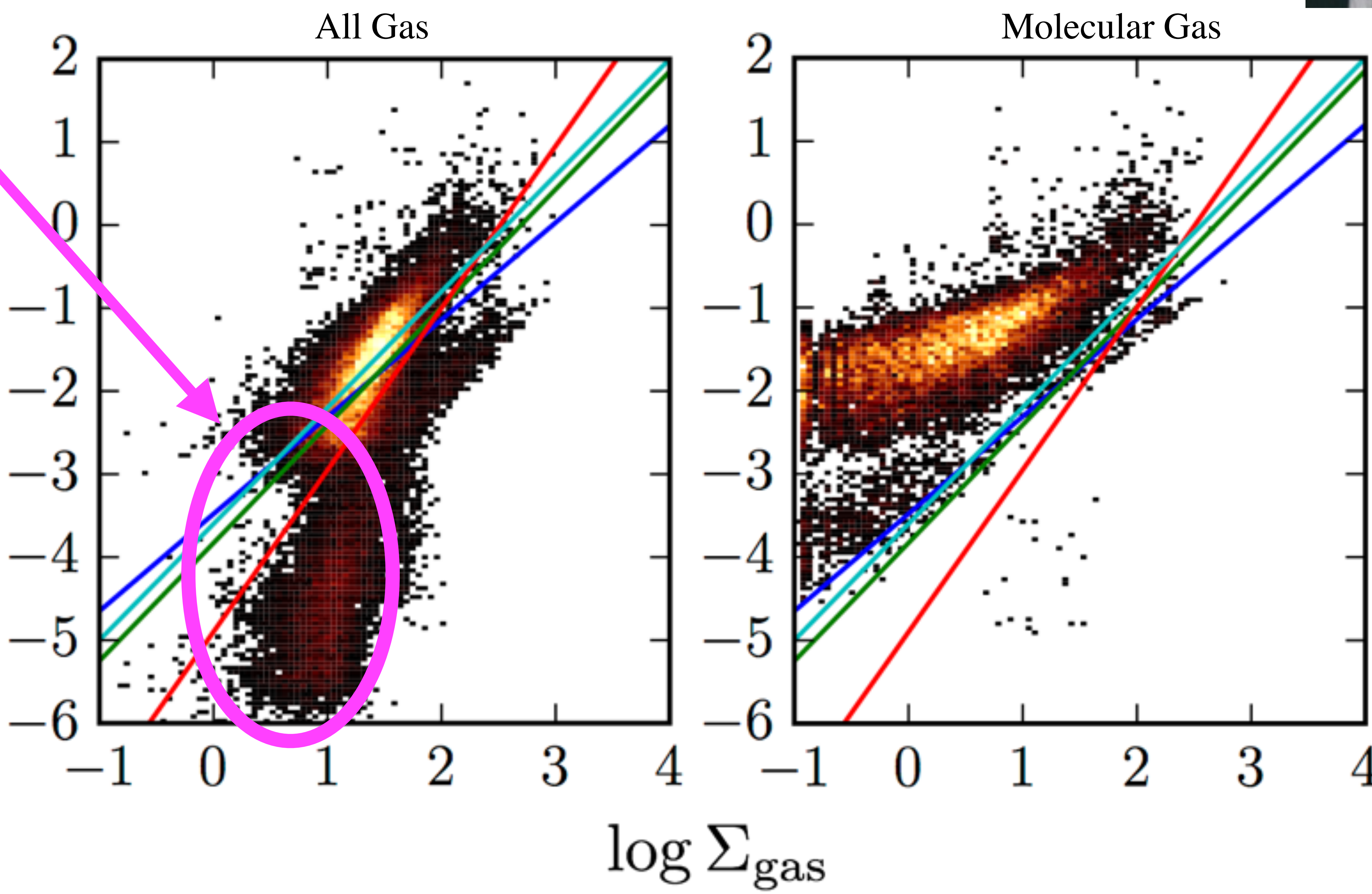
Where does this argument fail?

LOW DENSITIES: THE "THRESHOLD" (?)

Matt Orr



No shielding
=
can't cool



STILL FEEDBACK:

$$\Gamma_{\rm photo-heat} \sim \Lambda_{\rm cool} \;\rightarrow\; \Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{2+}$$

(Ostriker & McKee 2010)

Where does this argument fail?

HIGHEST DENSITIES

Supernovae
+ Winds
+ Radiation Pressure
(+ Jets + Photo-heating
+ Cosmic-rays)

$$\text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (\ldots)\, M_*$$

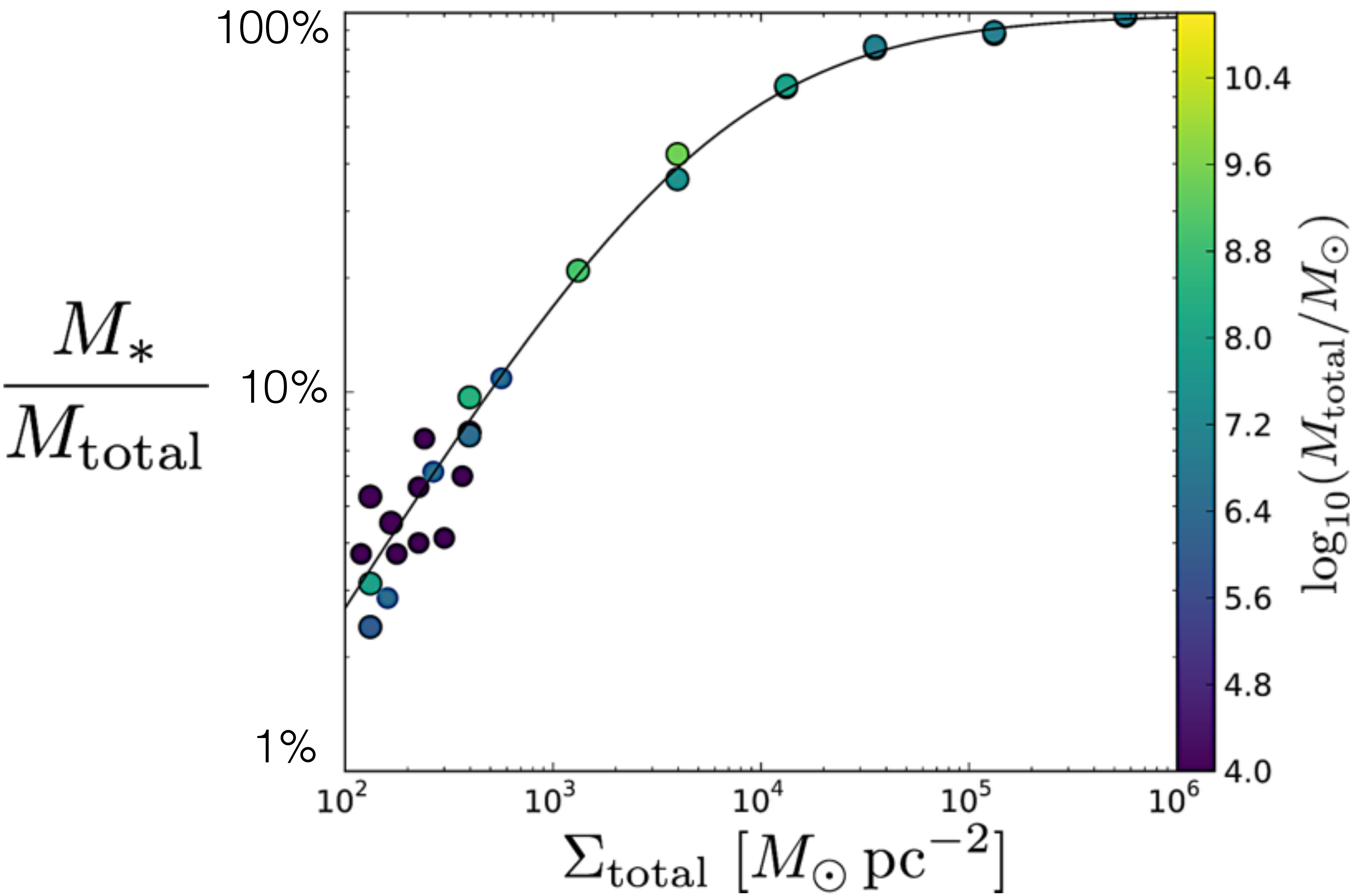
$$\text{Gravity} \sim \frac{G\, M_{\rm tot}\, M_{\rm gas}}{R^2} \propto M_{\rm tot}\, \Sigma_{\rm gas}$$

$$\rightarrow \frac{M_*}{M_{\rm tot}} \sim \frac{\Sigma}{({\rm few})\, 10^4\, M_{\odot}\, {\rm pc}^{-2}}$$

see Matzner '08,10

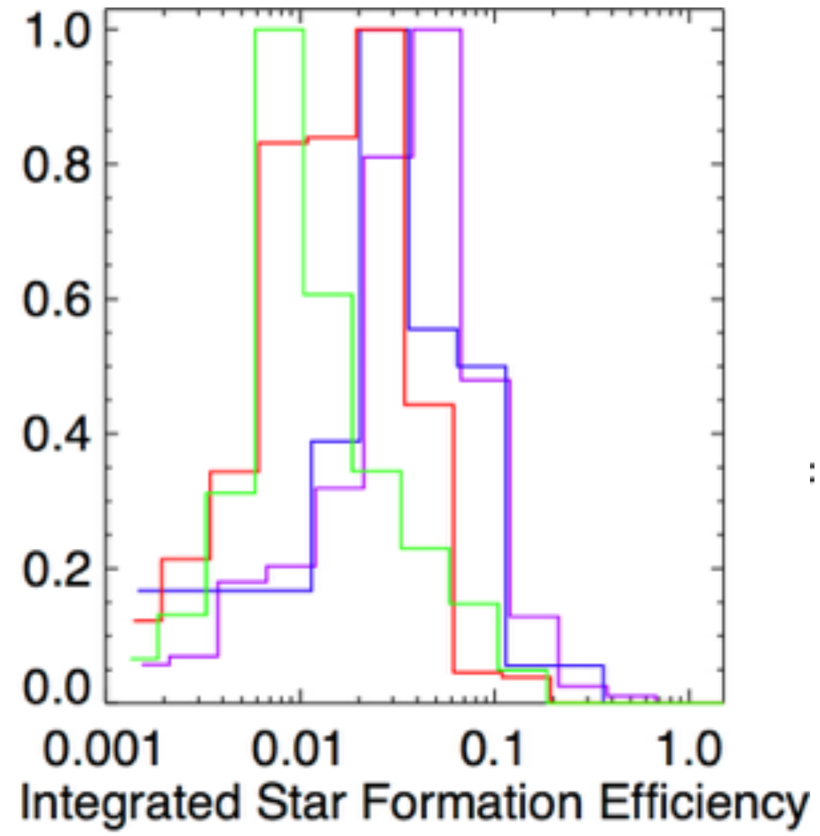
Where does this argument fail?
HIGHEST DENSITIES

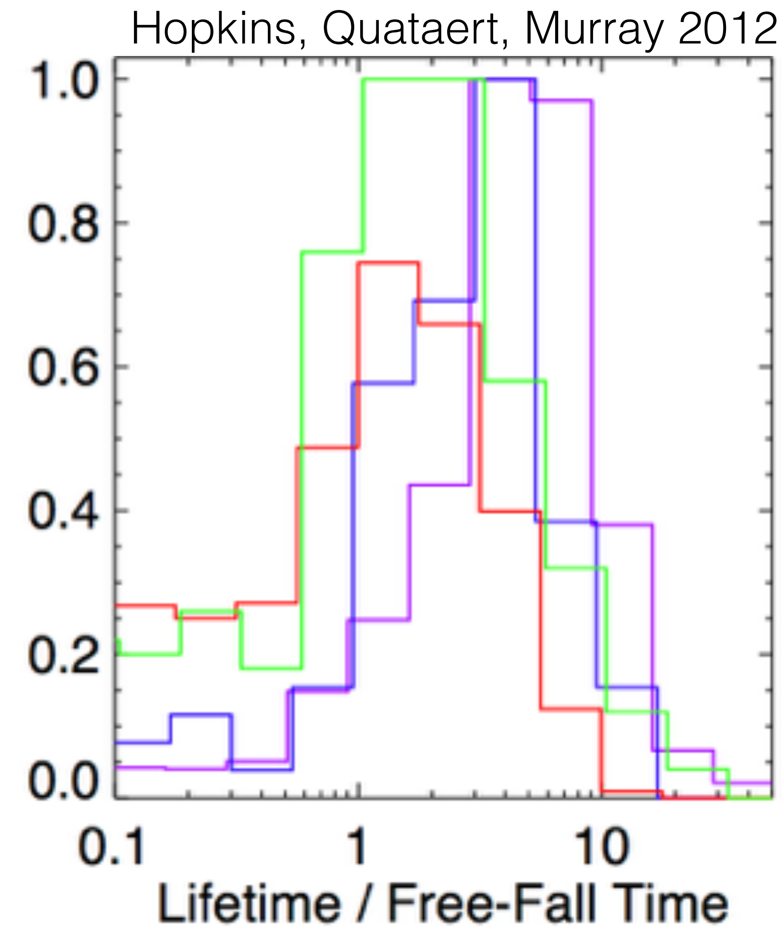
Mike Grudic
(in prep)

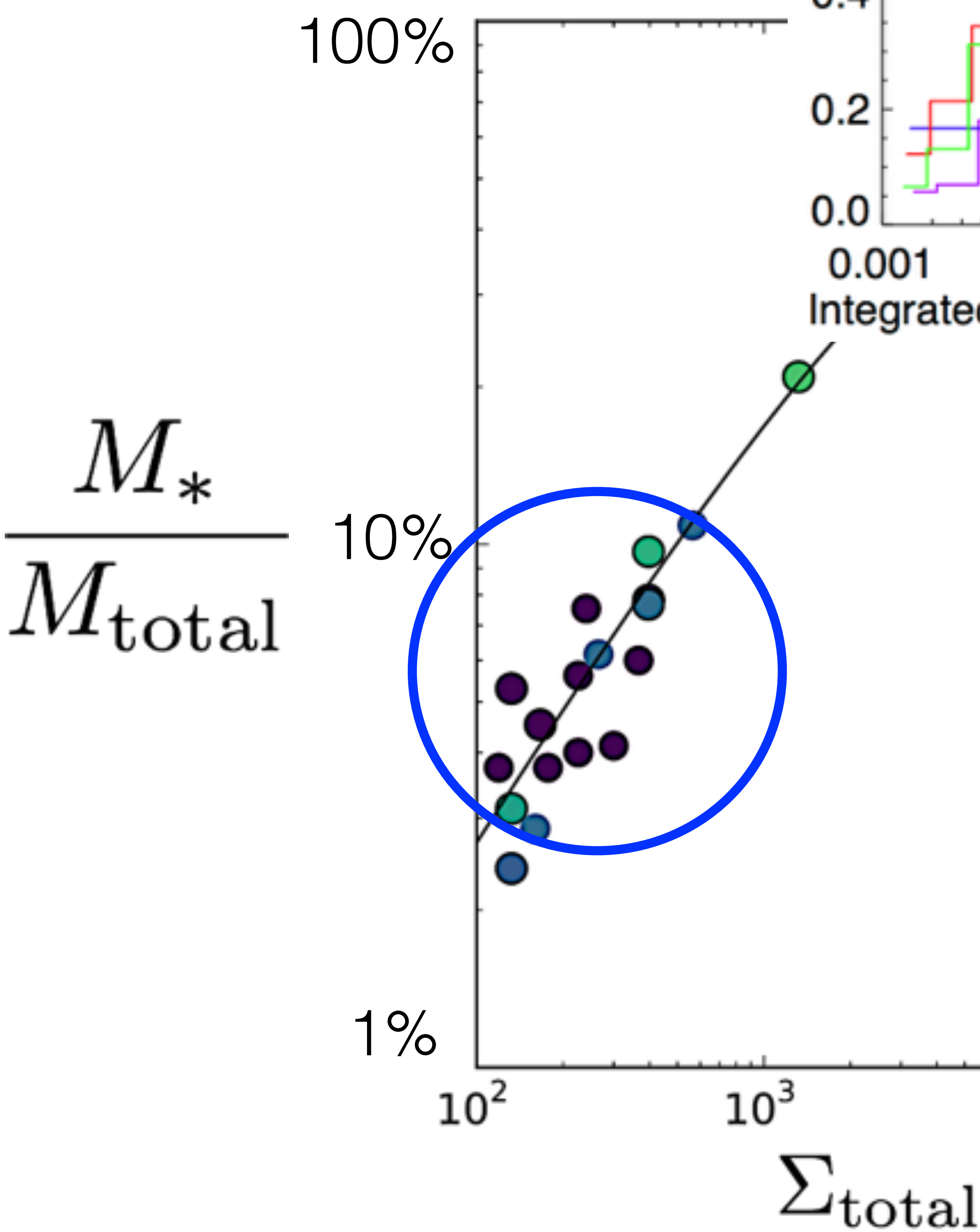


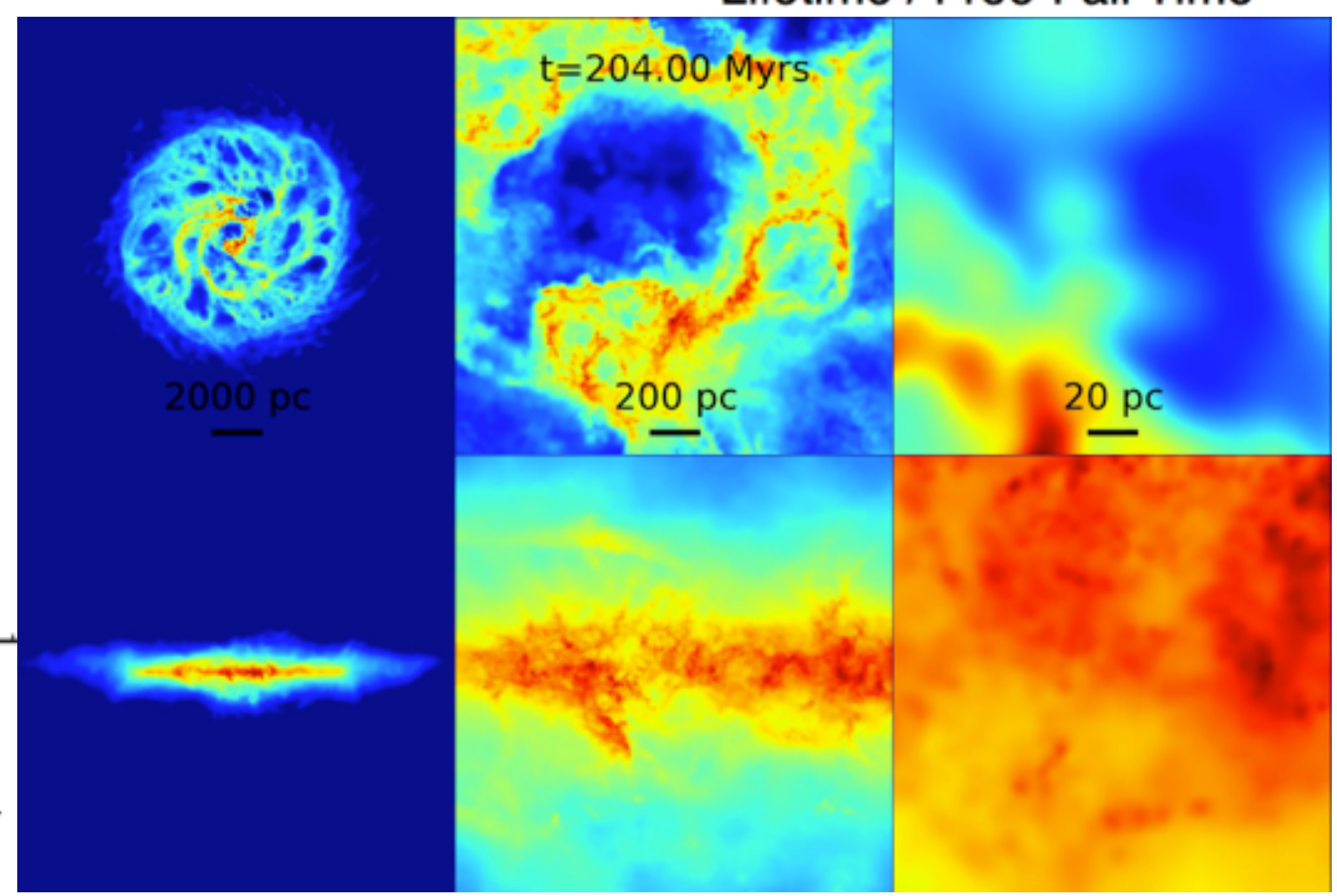
Where does this argument fail?

HIGHEST DENSITIES





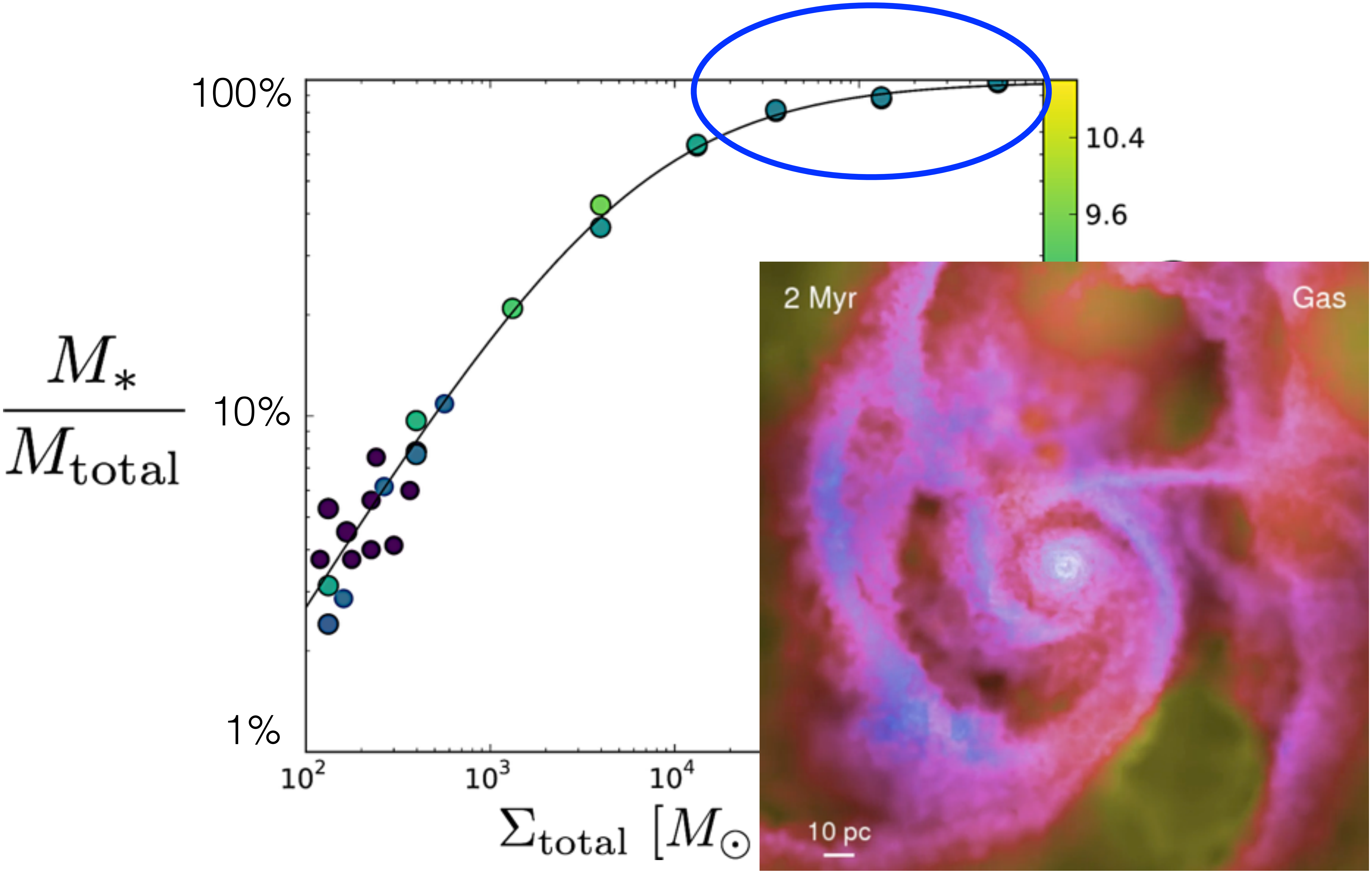




Where does this argument fail?

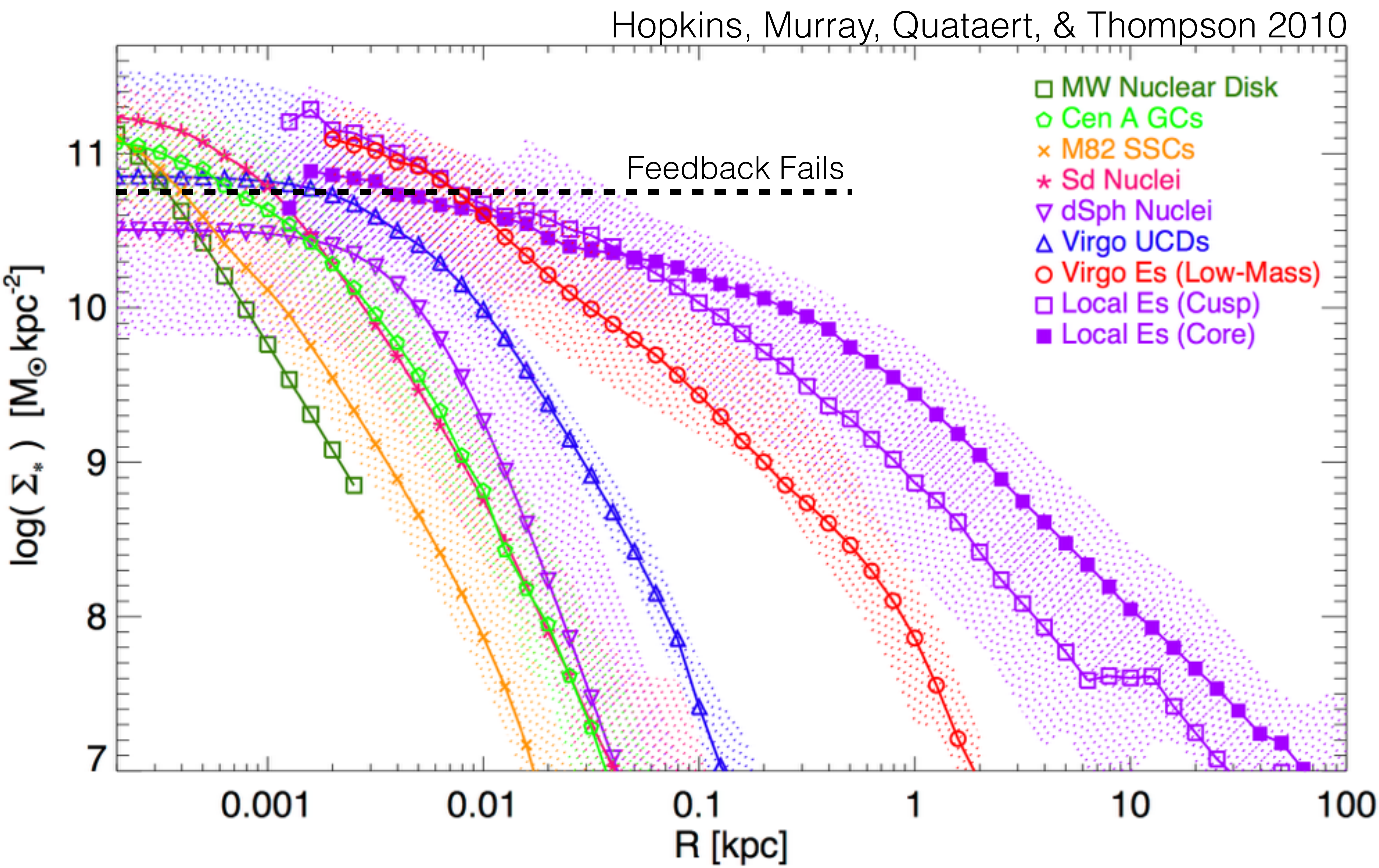
HIGHEST DENSITIES

Mike Grudic
(in prep)



Where does Feedback *Fail*?

HIGHEST DENSITIES: THE SMOKING GUN



Where does Feedback *Fail*?

HIGHEST DENSITIES: THE SMOKING GUN

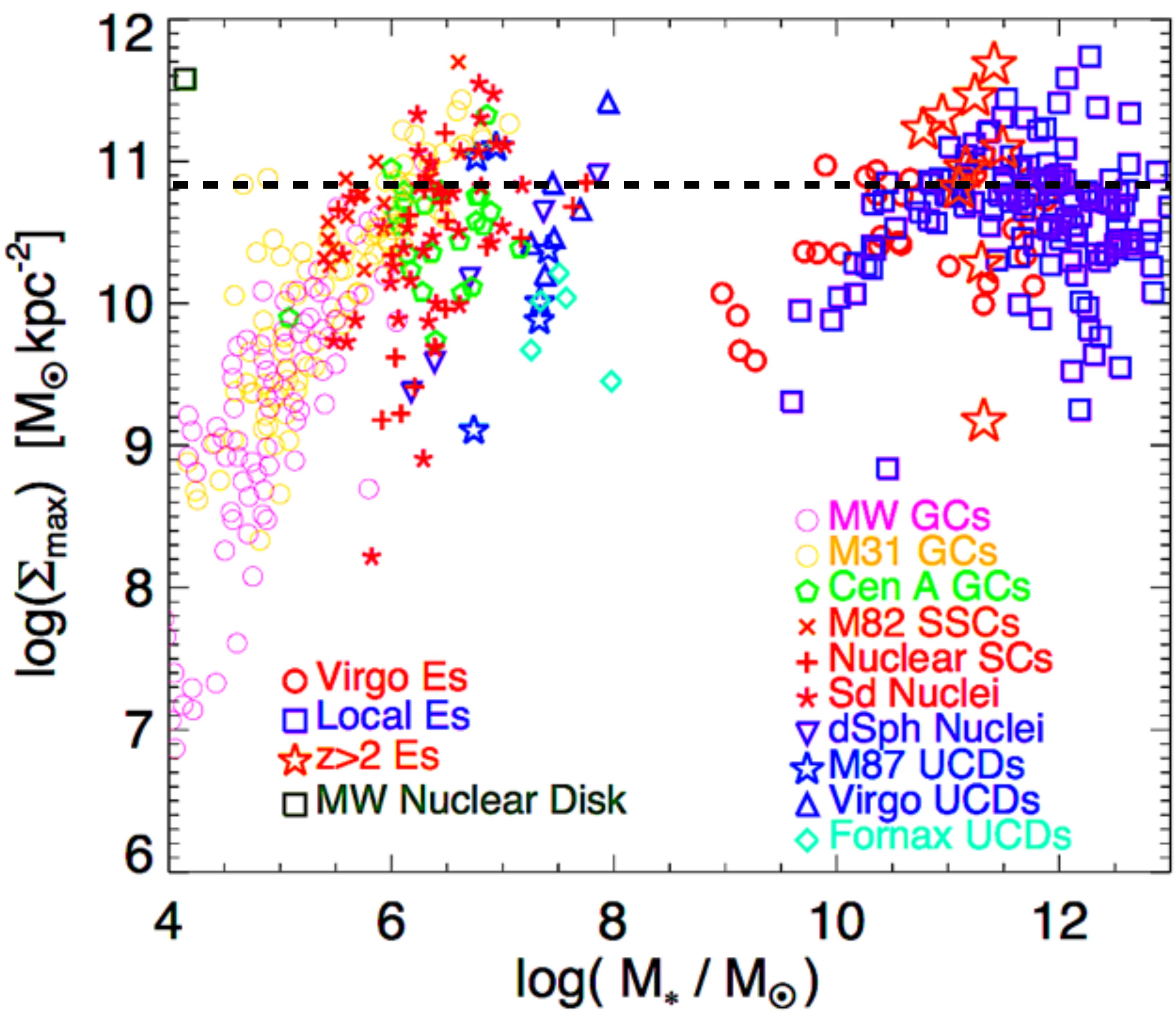
$R_{\rm eff} \sim 0.1 - 10^4\,{\rm pc}$

$M_* \sim 10^4 - 10^{12}\,M_\odot$

$\rho \sim 1 - 10^5\,\frac{M_\odot}{{\rm pc}^3}$

$Z \sim 0.01 - 5\,Z_\odot$

${\rm Redshift}_{\rm form} \sim 0 - 6$



Hopkins, Murray, Quataert, & Thompson 2010

Summary

STAR FORMATION IS FEEDBACK-REGULATED

- Turbulence alone Fails (see my other talk for what it *can* do)

- **Star formation is Feedback-Regulated:**
  - KS law = feedback balancing gravity
  - *Independent* of small-scale star formation physics
  - *Independent* of non-feedback microphysics (MHD, conduction, chemistry, etc)

- Dense gas self-regulates:
  - Need to produce same feedback (SFR):
    dense gas tracers measure how fast *dense* gas turns into stars

- Thresholds:
  - Low surface-density? *Just different feedback*
  - Low metallicity? $Z < 0.0001$ solar

- **Failure of Feedback = Universal Maximum Surface Density:**
  - Surface densities > $10^5\ M_{sun}/pc^2$: can't self-regulate
  - Globulars, super star-clusters, dwarf nuclei, bulges, ellipticals, high-z galaxies, & nuclear disks
    - *All* obey the same "surface density limit"