Turbulence, kinematics & galaxy structure in star formation in dwarfs

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Outline

- Turbulence inhibits star formation, but slowly
- Interplay between turbulence & gravitational instability
- Sources of turbulence: supernovae, radiation pressure, magnetorotational instability
- Gravitational instability in radiatively cooling gas
- Models of dwarf galaxies with feedback-driven turbulence

Turbulence *Prevents* Collapse

- Turbulent motions can be treated as an additional pressure (Chandrasekhar 1951, von Weizsäcker 1951)

$$c_{s,\mathrm{eff}}^2 = c_s^2 + \frac{\langle v^2 \rangle}{3}$$

- Supersonic turbulence increases the mass supported against collapse

$$M_J = \left(\frac{\pi}{G}\right)^{3/2} \rho^{-1/2}\, c_{s,\mathrm{eff}}^3$$

Turbulence *Promotes* Collapse

- Supersonic turbulence drives shock waves that produce density enhancements.
- In isothermal gas, the postshock density increases with the Mach number M as

$$\rho_s = \rho M^2$$

- Supersonic turbulence decreases the mass supported against collapse

$$M_J = \left(\frac{\pi}{G}\right)^{3/2} \rho_s^{-1/2} c_{s,\mathrm{eff}}^3$$

Turbulence *Inhibits* Collapse

$$M_J = \left(\frac{\pi}{G}\right)^{3/2} \rho_s^{-1/2} c_{s,\mathrm{eff}}^3 \propto$$

$$\propto \frac{c_s}{v}\left(c_s^2 + \frac{\langle v^2 \rangle}{3}\right)^{3/2} \sim \quad v^2$$

- Turbulence is intermittent, so uniform pressure does not represent it well.
- On average, increasing velocity increases Jeans mass, but locally, compressions can decrease it

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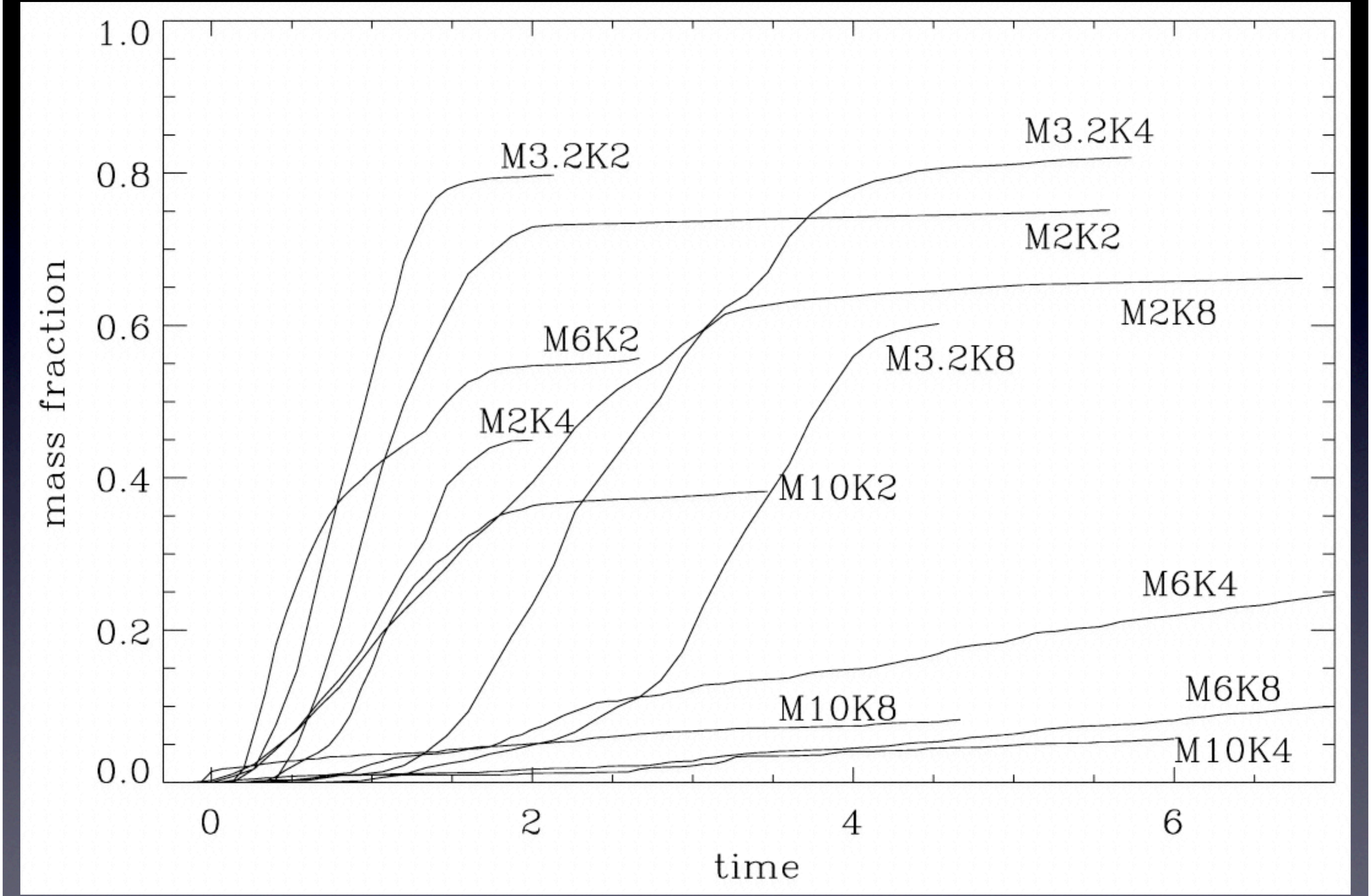
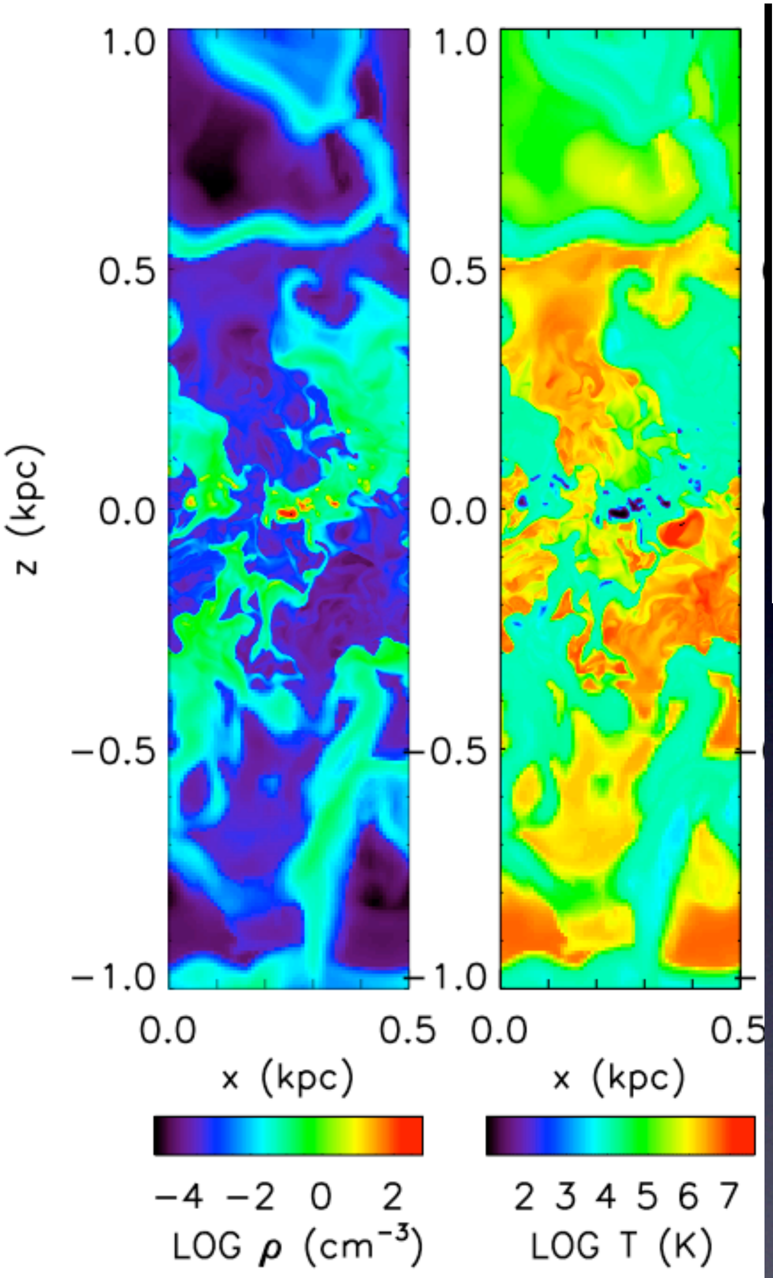
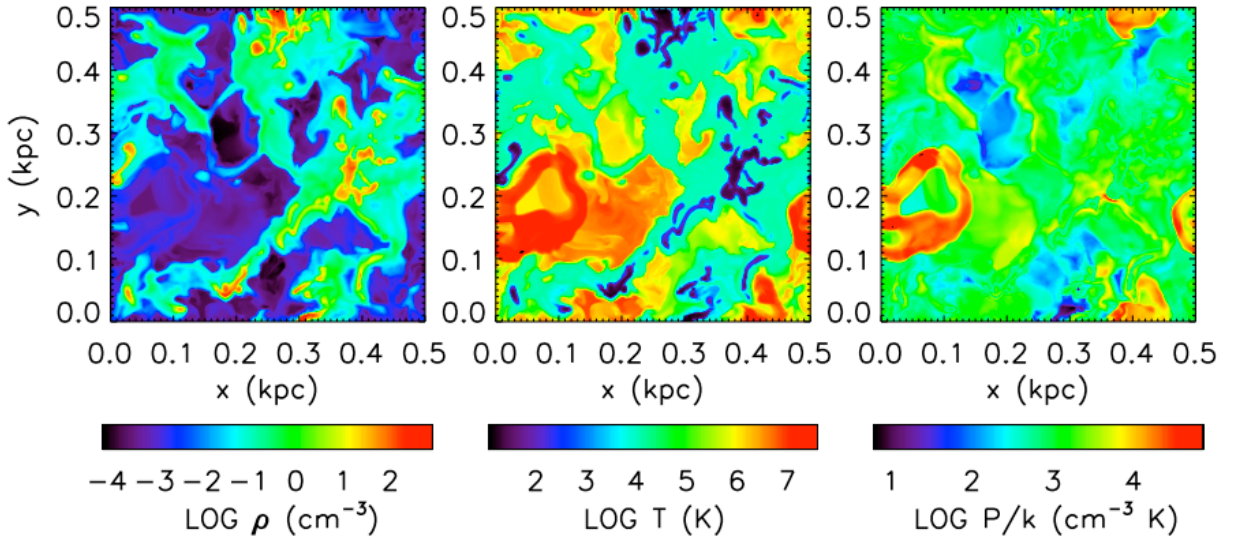
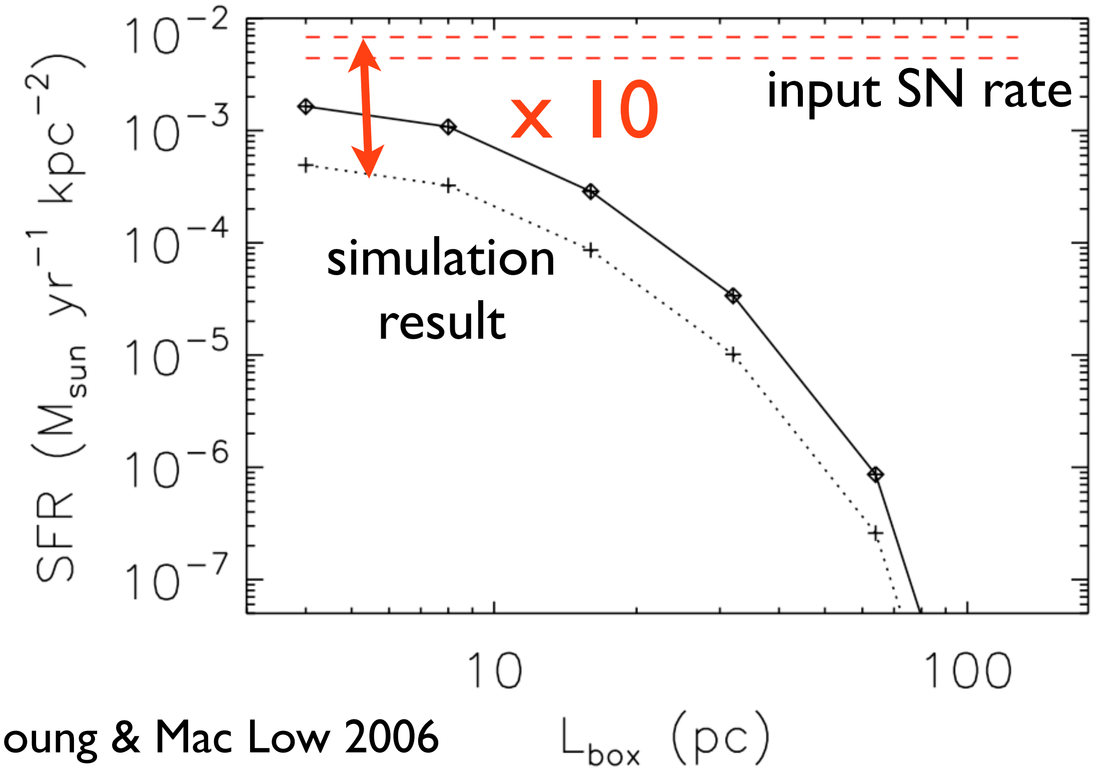
Even strong turbulence allows some collapse



Vázquez-Semadeni, Ballesteros-Paredes, & Klessen 03; see also Klessen, Heitsch, & Mac Low 01







input SN rate

x 10

simulation result

Joung & Mac Low 2006

Flash (Fryxell + 00) models of stratified, SN-driven ISM

Turbulent compression can promote local collapse in stable regions.

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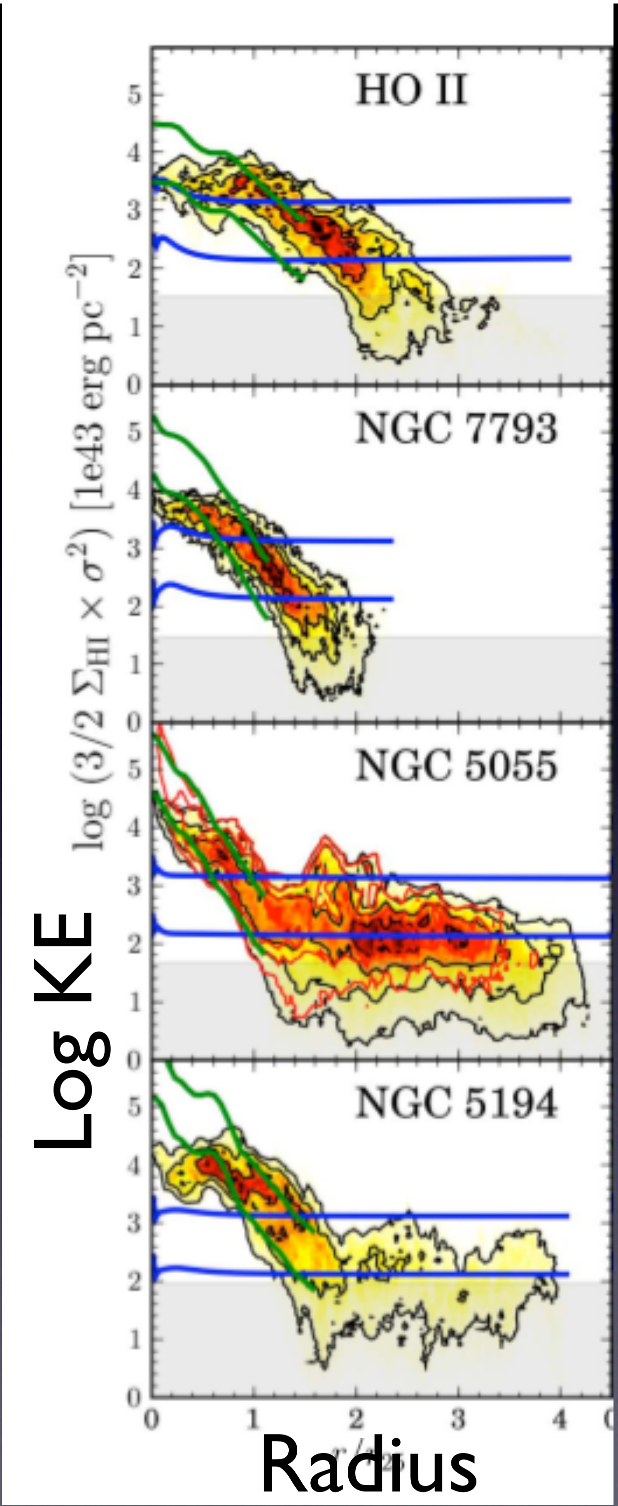
Tamburro, Rix, Leroy, Mac Low + 09



Supernovae, Radiation, or MRI can Resist Gravity

SNR

$$E_k = \eta \times (\epsilon_{\rm SN}\, 10^{51}\ {\rm erg})\tau_D$$

$$\eta = \frac{\rm SFR}{\langle m \rangle} \times f_{*\to {\rm SN}}$$

$$\tau_D \simeq 9.8\ (\lambda_{100}/\sigma_{10})\ {\rm Myr}$$

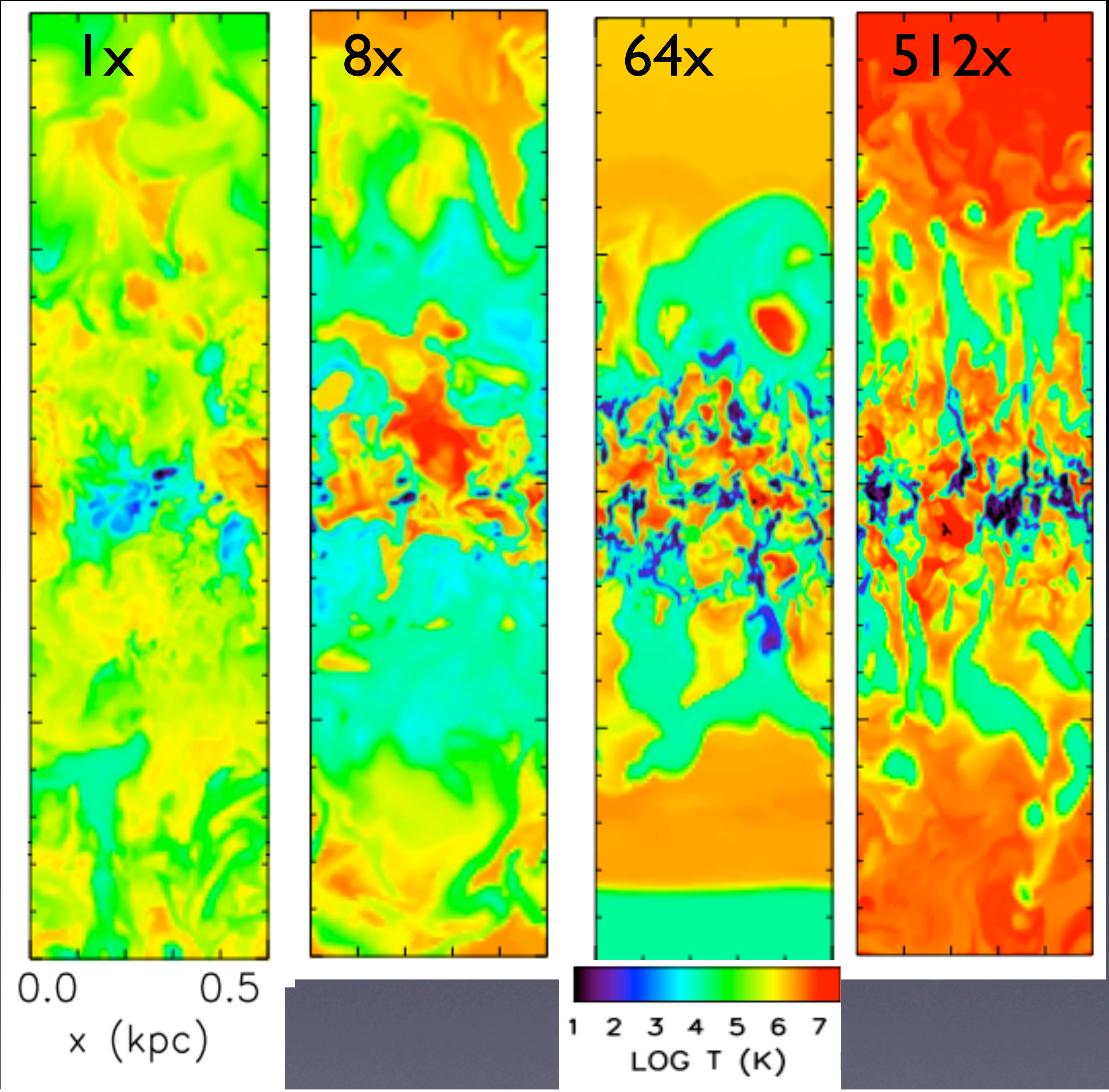
MRI

$$\dot{E}_{\rm MRI} = 3.7 \times 10^{-8}\ {\rm erg\ cm^{-2}\ s^{-1}} \times \left(\frac{h_z}{100\ {\rm pc}}\right)\left(\frac{B}{6\ \mu{\rm G}}\right)^2 \frac{\Omega}{(220\ {\rm Myr})^{-1}}$$

Sellwood & Balbus 99, Mac Low & Klessen 04
see sims by Piontek & Ostriker 04, 05, 07

Elmegreen & Parravano 94 & Schaye 04 argue for UV heating maintaining outer disk KE => no cold phase there. *Testable*!

Joung, Mac Low & Bryan 09

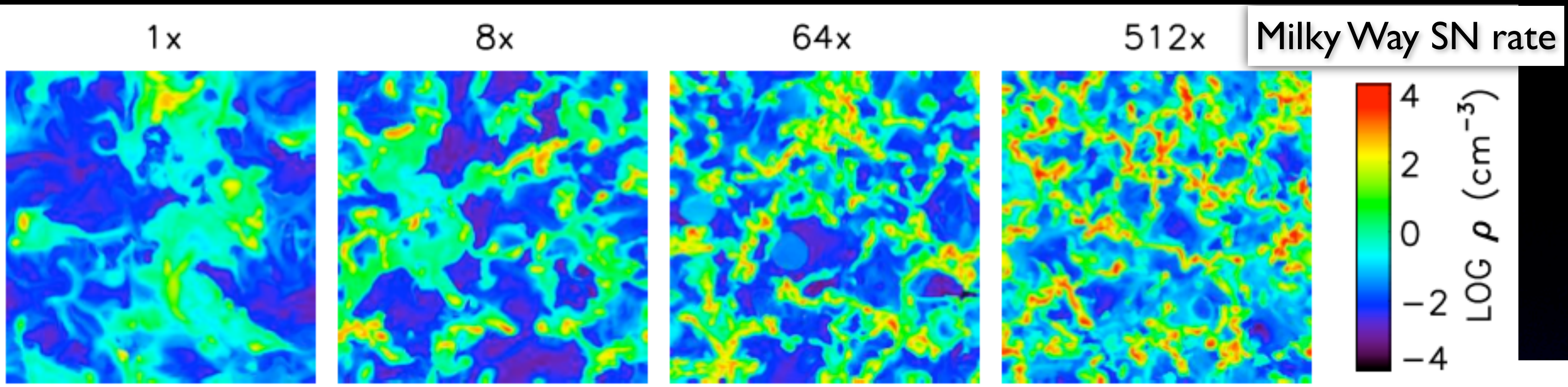


SN/SFR rates in Milky Way units

disk density following Kennicutt-Schmidt Law

$\Delta x = 2$ pc

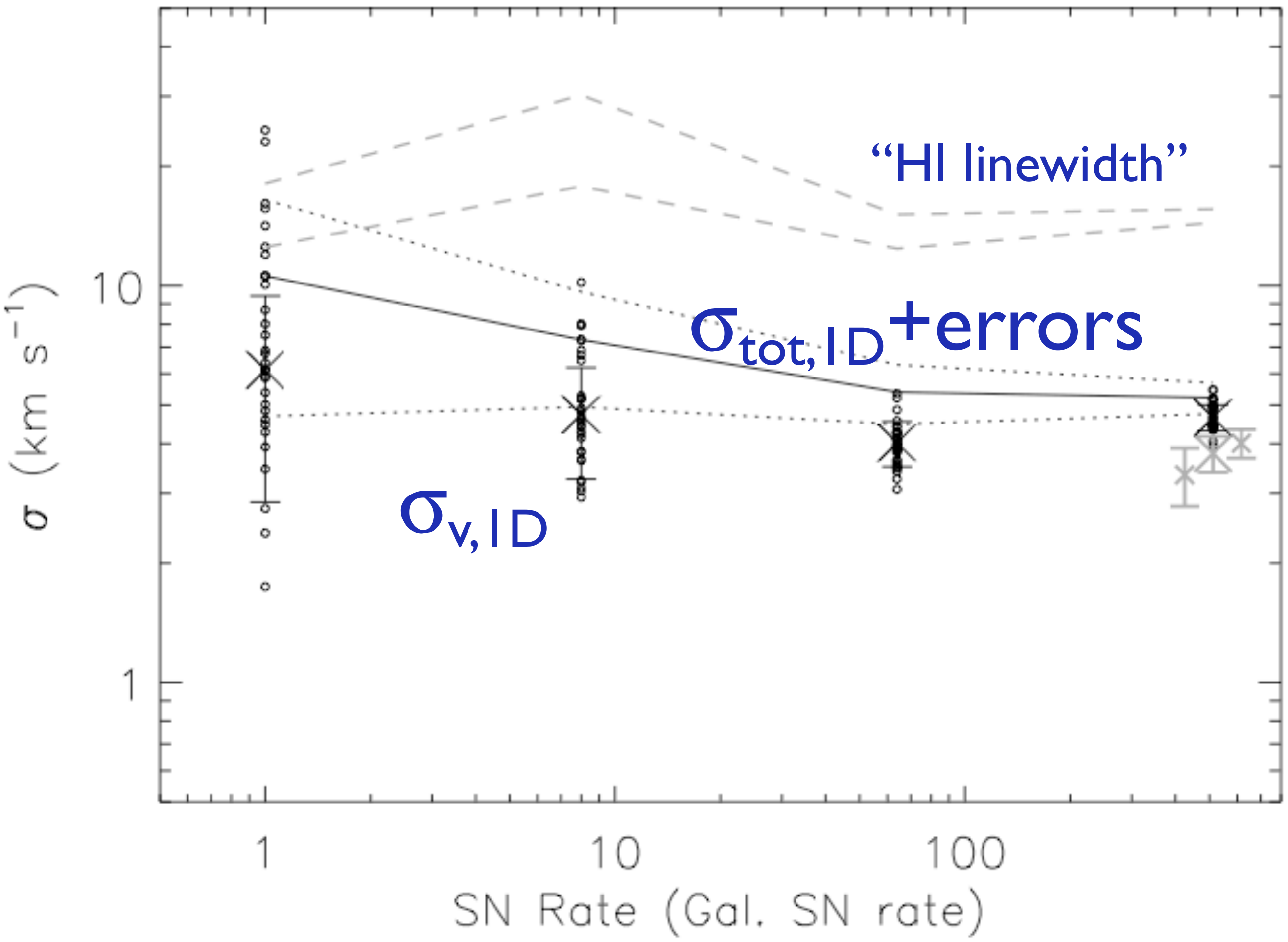
Joung, Mac Low & Bryan 09



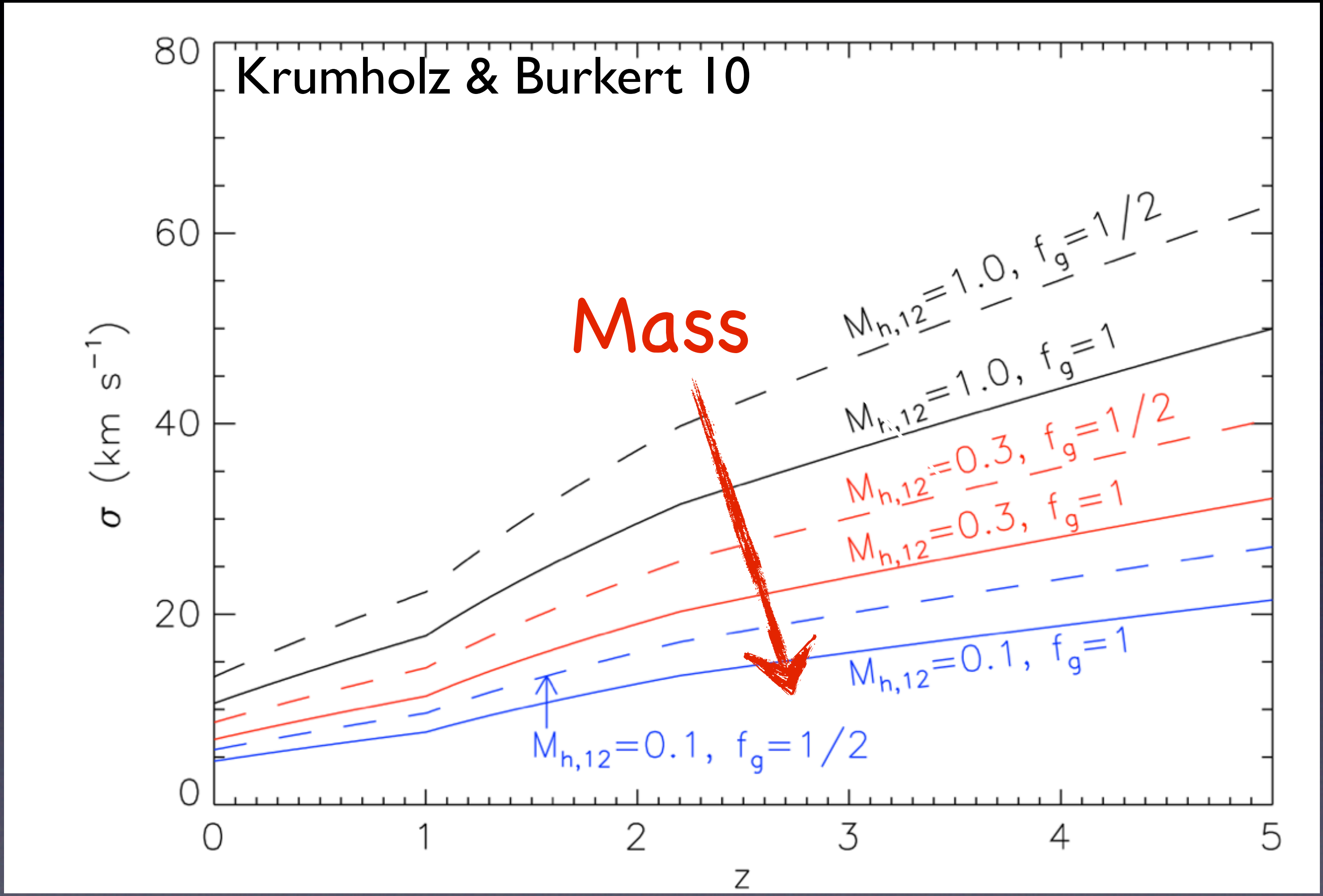
assuming Kennicutt-Schmidt law for gas surface density.

SN feedback drives rather *constant* (not high) H I velocity dispersions.

cf. Monaco 04a
Ceverino & Klypin 09



Gravitational instability in accreting disks can drive high velocity dispersions at high z



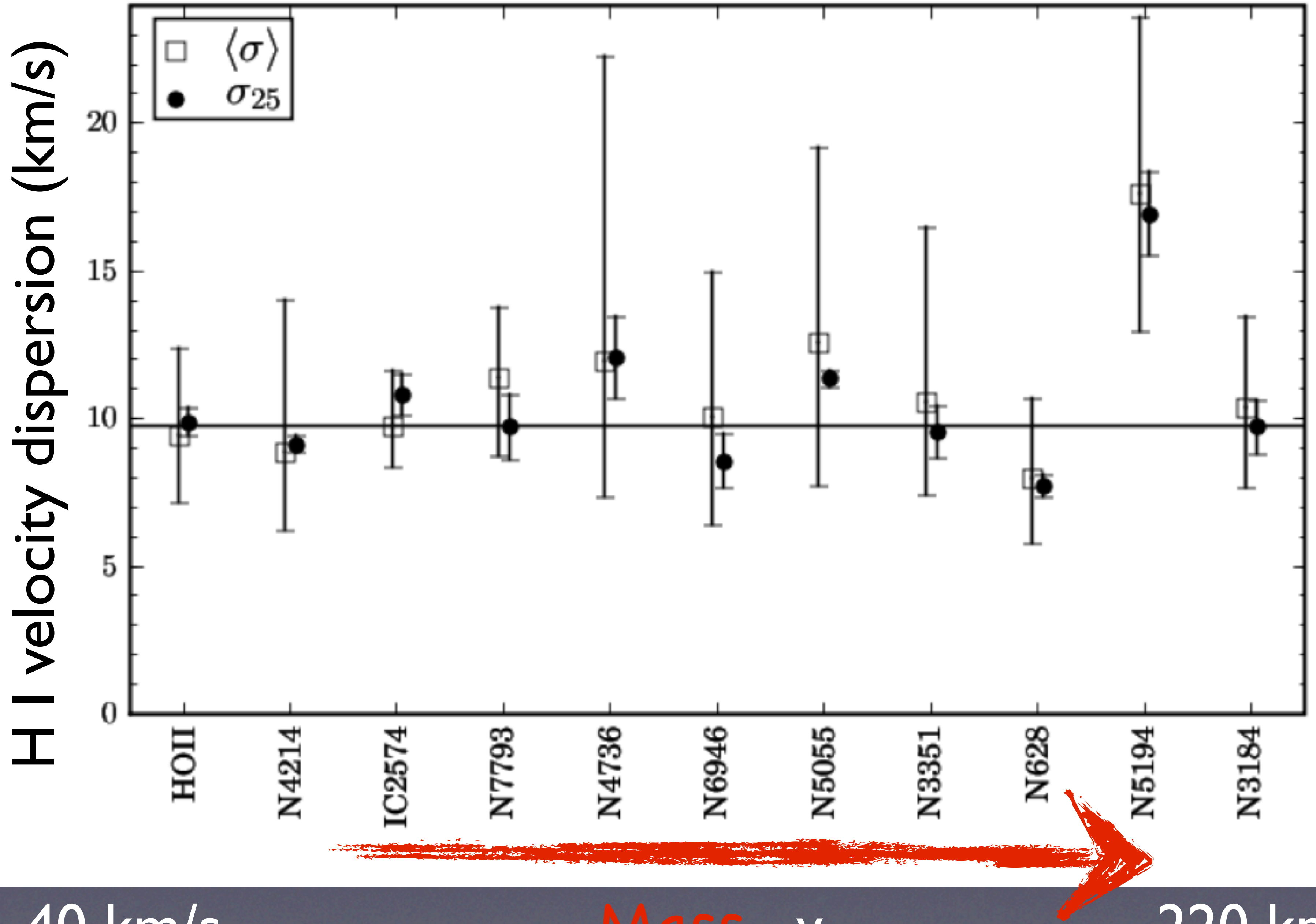
Assume Q = 1 and radiative cooling a function of crossing time

predicts mass dependent velocity dispersion at high-z

Also see numerical models by Kim & Ostriker 07, Agertz +09

not evident at $z = 0$

Tamburro, Rix, Leroy, Mac Low + 09

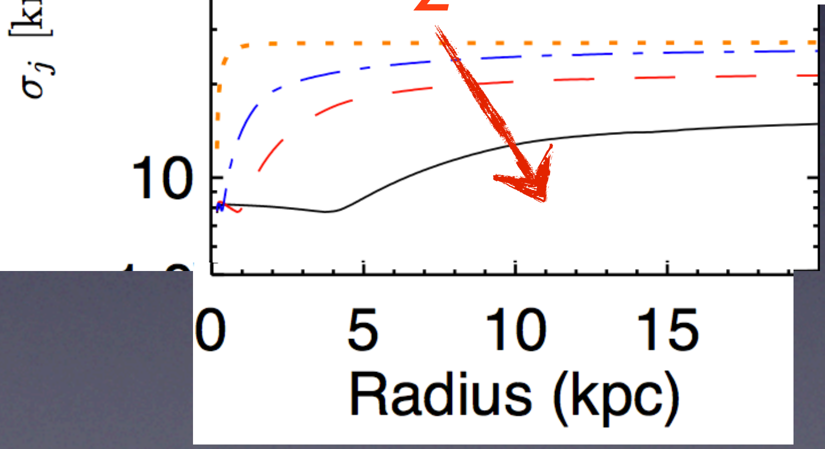


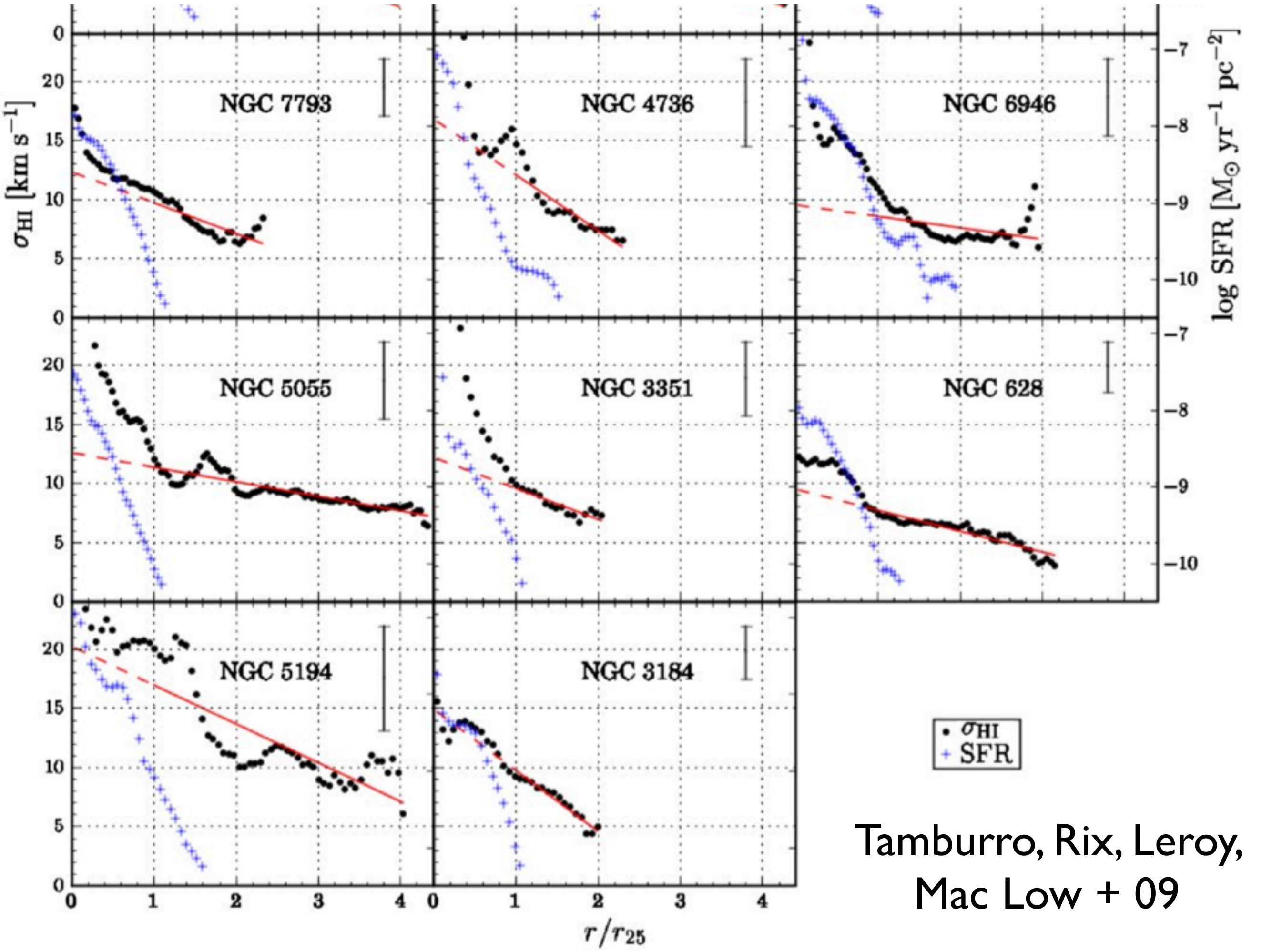
40 km/s

Mass v_{rot}

220 km/s

Time dependent model by Forbes, Krumholz, Burkert 12





Tamburro, Rix, Leroy, Mac Low + 09

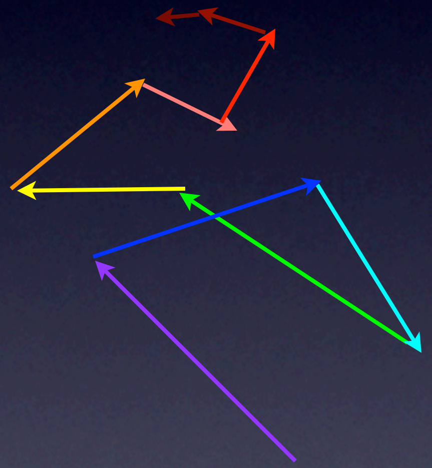
radial profiles determined by other mechanisms at z = 0

How effective is radiative driving?

$$L/c \quad < \quad \tau_{IR} L/c \quad < \quad L/v$$

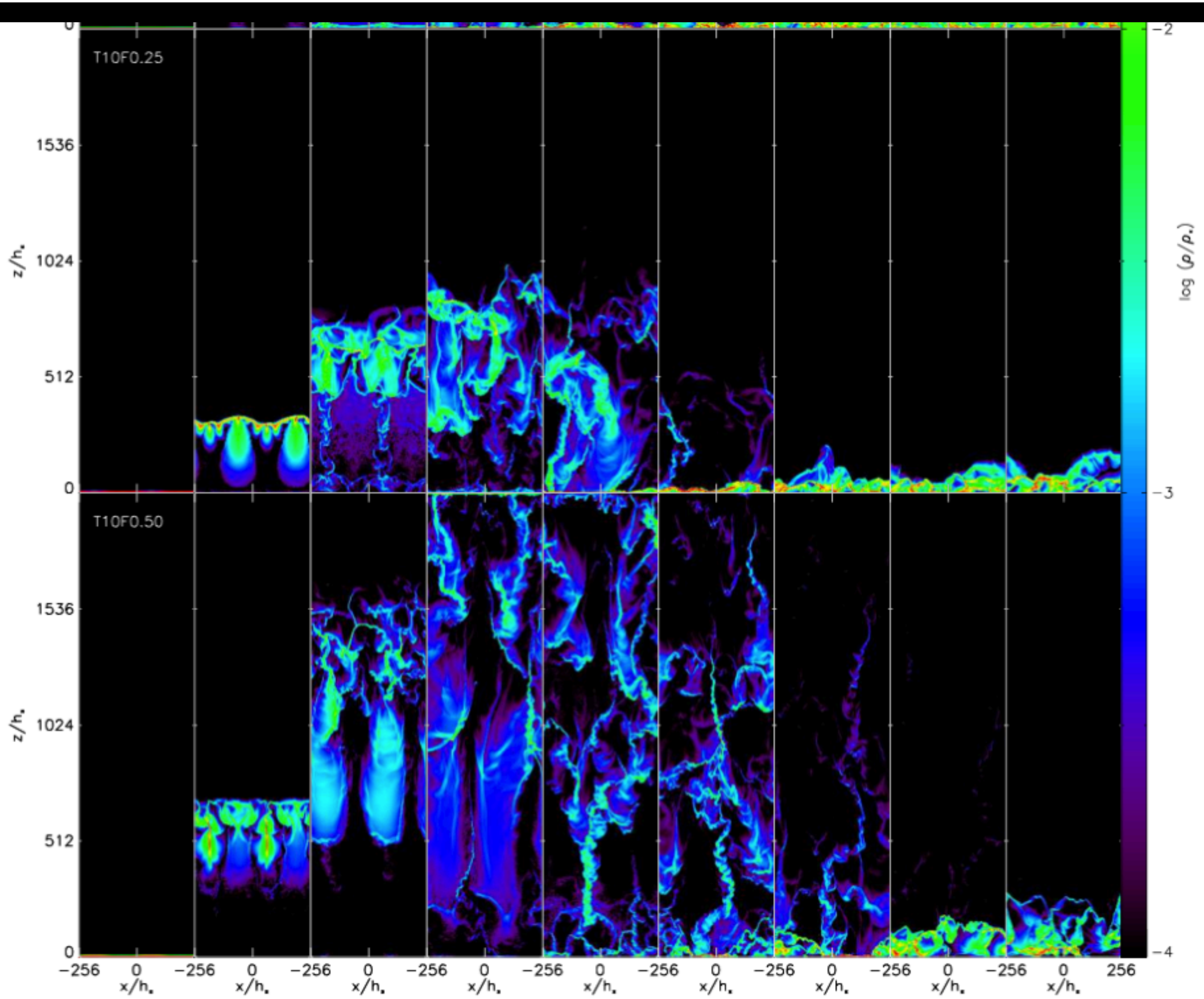
"Momentum-driven"
Krumholz & Matzner 09
Fall + 10

Thompson + 05
Murray + 10
Andrews & Thompson 11
Hopkins + 11 b



"Energy-driven"

Krumholz & Thompson 12



Krumholz & Thompson 12

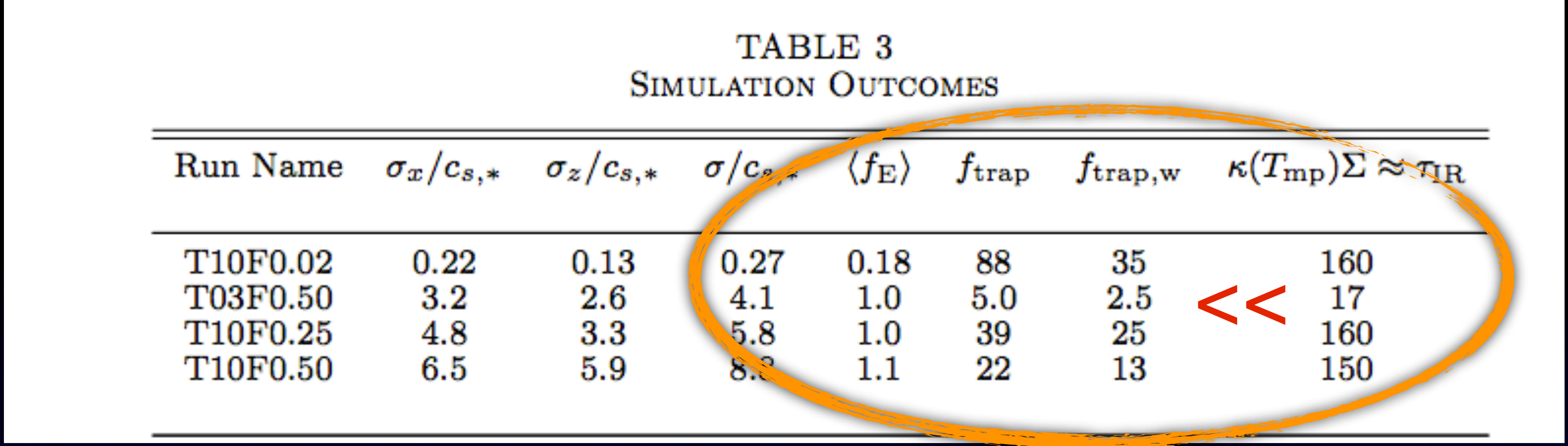


TABLE 3
SIMULATION OUTCOMES

Run Name	$\sigma_x/c_{s,*}$	$\sigma_z/c_{s,*}$	$\sigma/c_{s,*}$	$\langle f_E \rangle$	f_{trap}	$f_{trap,w}$	$\kappa(T_{mp})\Sigma \approx \tau_{IR}$
T10F0.02	0.22	0.13	0.27	0.18	88	35	160
T03F0.50	3.2	2.6	4.1	1.0	5.0	2.5	<< 17
T10F0.25	4.8	3.3	5.8	1.0	39	25	160
T10F0.50	6.5	5.9	8.[illegible]	1.1	22	13	150

So assumption of $\tau_{IR} L/c$ far too high, but L/c too low.

Krumholz & Thompson 12

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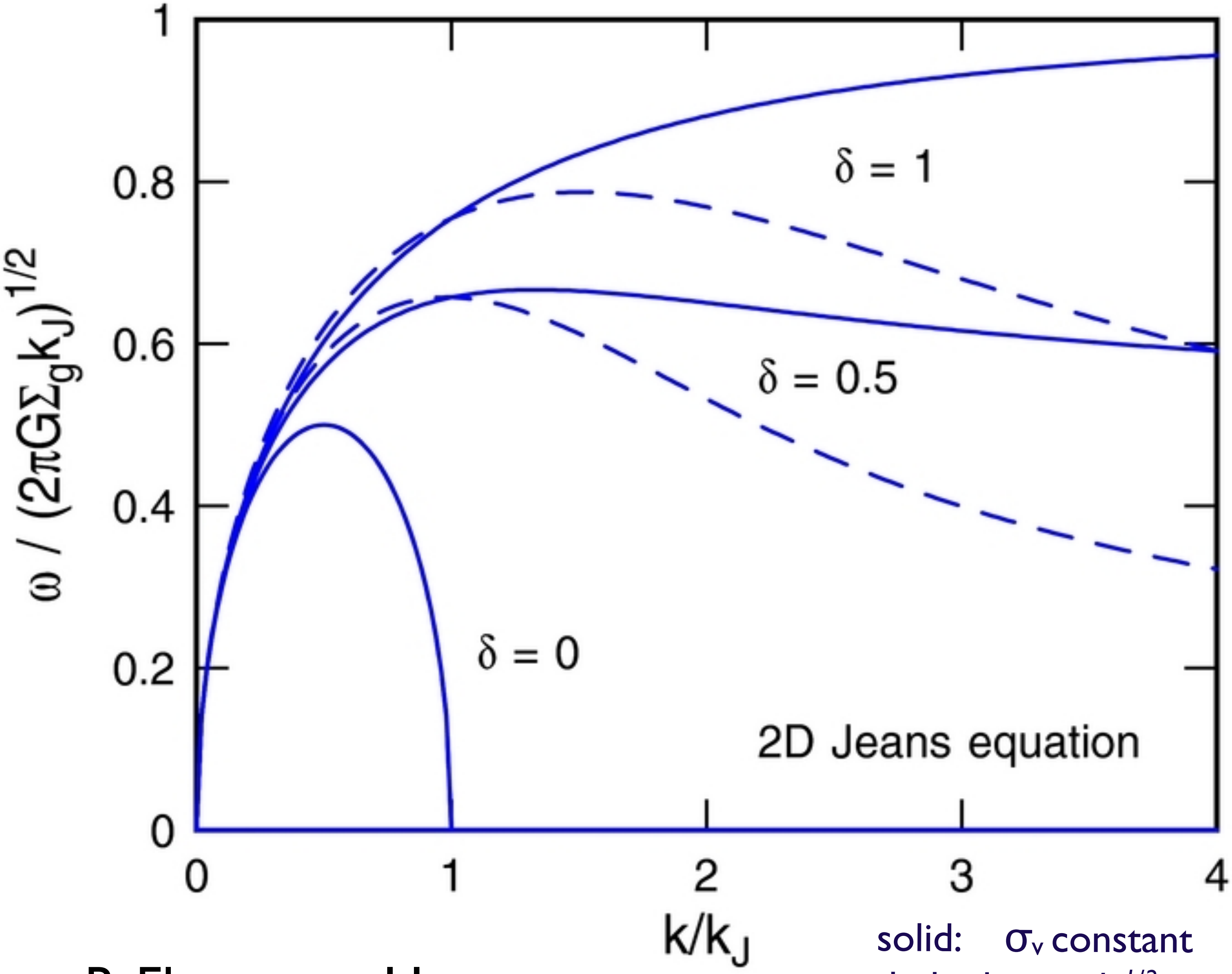
Turbulent dissipation drives arbitrarily high-wavenumber gravitational instability



solid: σ_v constant
dashed: $\sigma_v \propto k^{-1/2}$

B. Elmegreen 11

$$\delta = \frac{t_{\rm cross}}{t_{\rm diss}}$$

also for stars & gas together.
(cf. Rafikov 01)

finite disk thickness stabilizes at large *k*

Gravity Competes with Feedback & MRI

- Gravitational or accretional driving must be supplemented by other energy sources at $z = 0$.
- Otherwise simulations and analytic models without stellar feedback would be sufficient to reproduce observed galaxies.
- Modern galaxies seem to be shaped by the contest between gravity on the one hand and stellar feedback and magnetorotational instability on the other.

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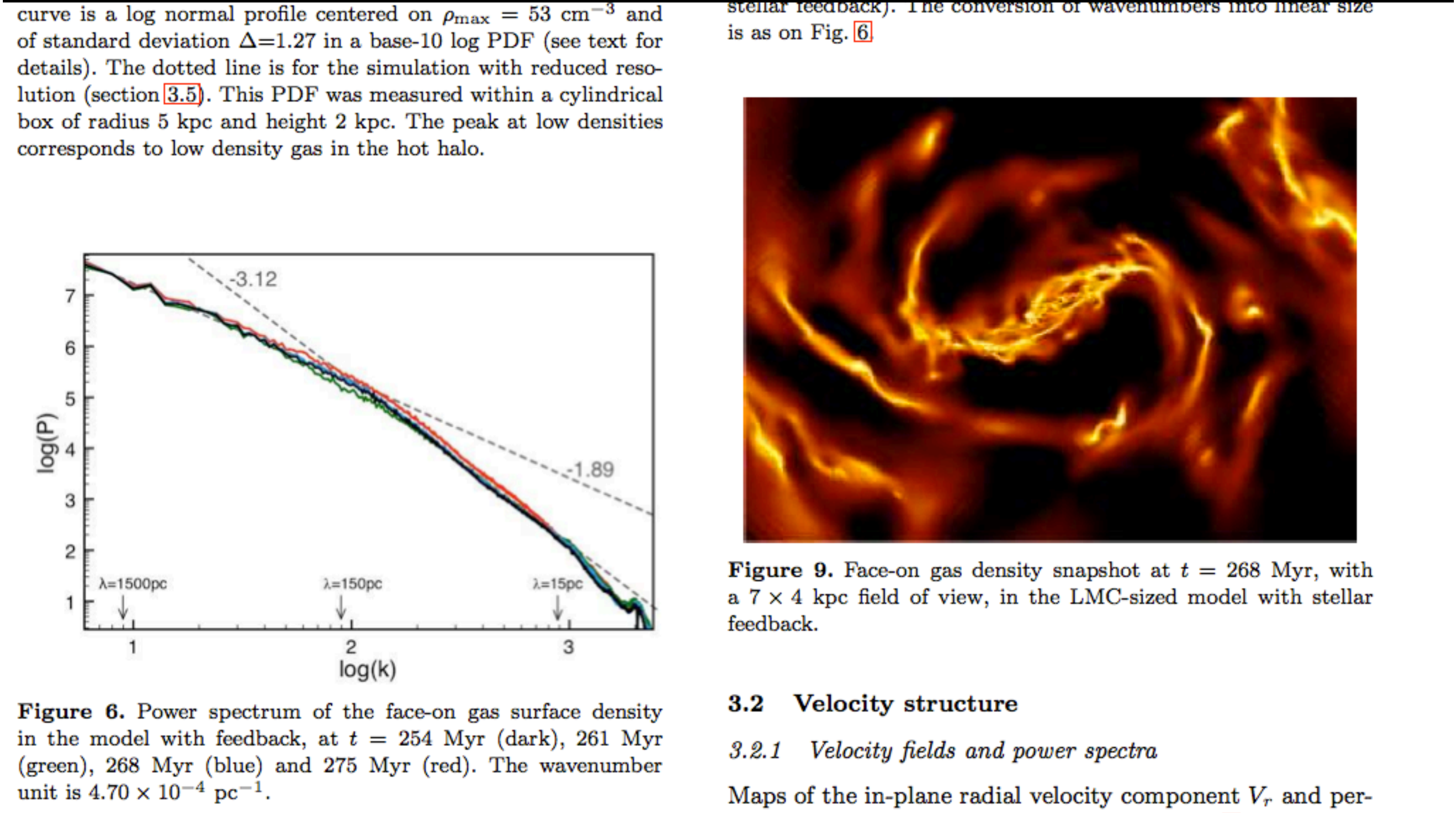


curve is a log normal profile centered on $\rho_{\max} = 53$ cm^{-3} and of standard deviation Δ=1.27 in a base-10 log PDF (see text for details). The dotted line is for the simulation with reduced resolution (section 3.5). This PDF was measured within a cylindrical box of radius 5 kpc and height 2 kpc. The peak at low densities corresponds to low density gas in the hot halo.

Figure 6. Power spectrum of the face-on gas surface density in the model with feedback, at t = 254 Myr (dark), 261 Myr (green), 268 Myr (blue) and 275 Myr (red). The wavenumber unit is 4.70×10^{-4} pc^{-1}.

stellar feedback). The conversion of wavenumbers into linear size is as on Fig. 6.

Figure 9. Face-on gas density snapshot at t = 268 Myr, with a 7 × 4 kpc field of view, in the LMC-sized model with stellar feedback.

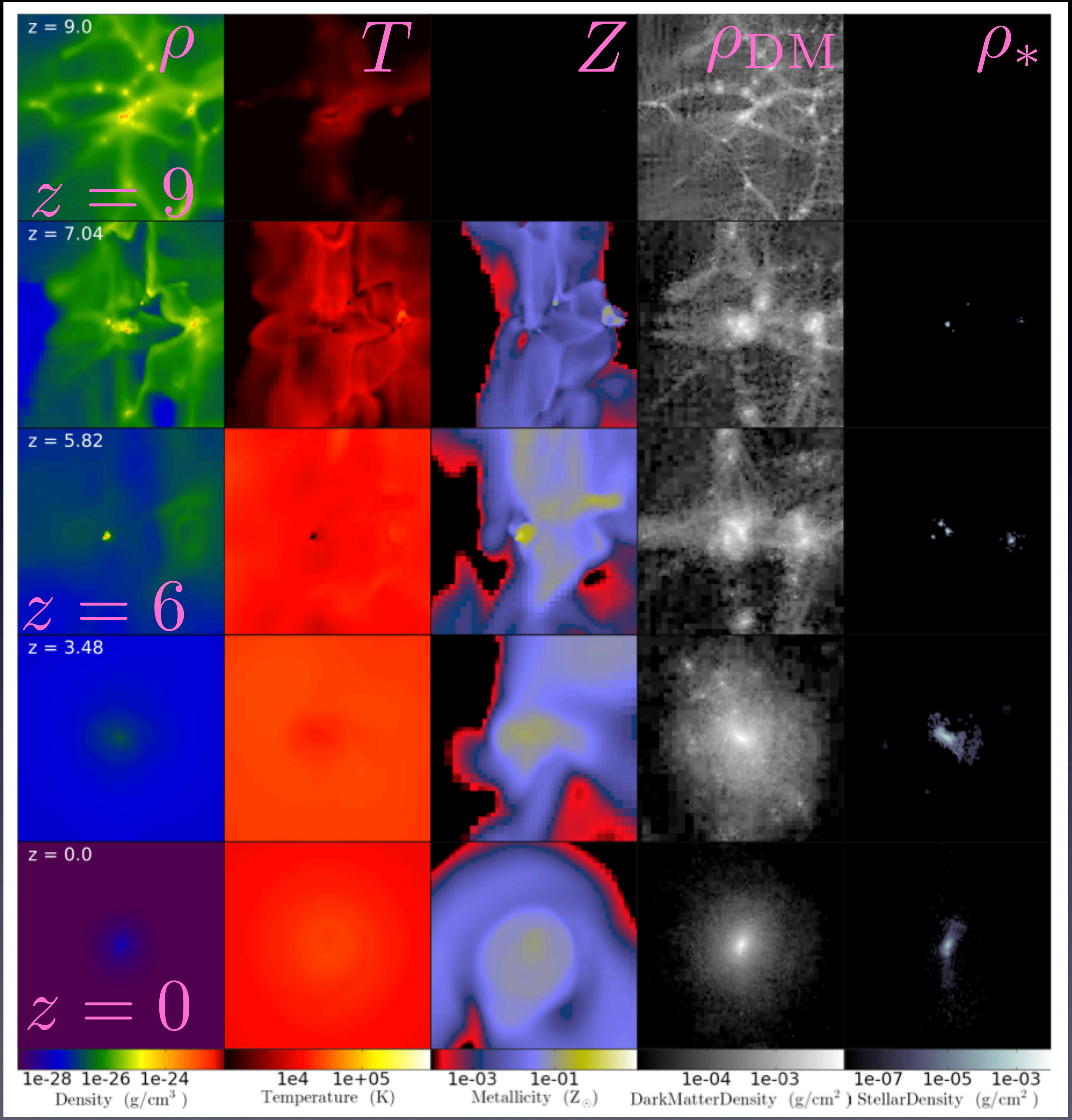
3.2 Velocity structure

3.2.1 Velocity fields and power spectra

Maps of the in-plane radial velocity component V_r and per-

Bournaud + 10

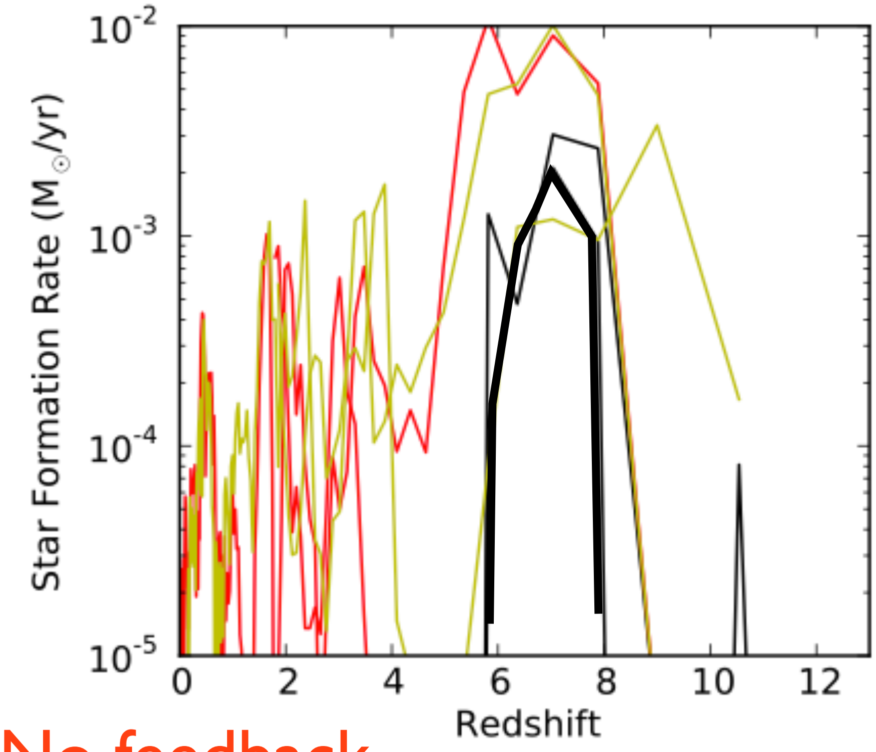
High resolution models of an isolated dwarf



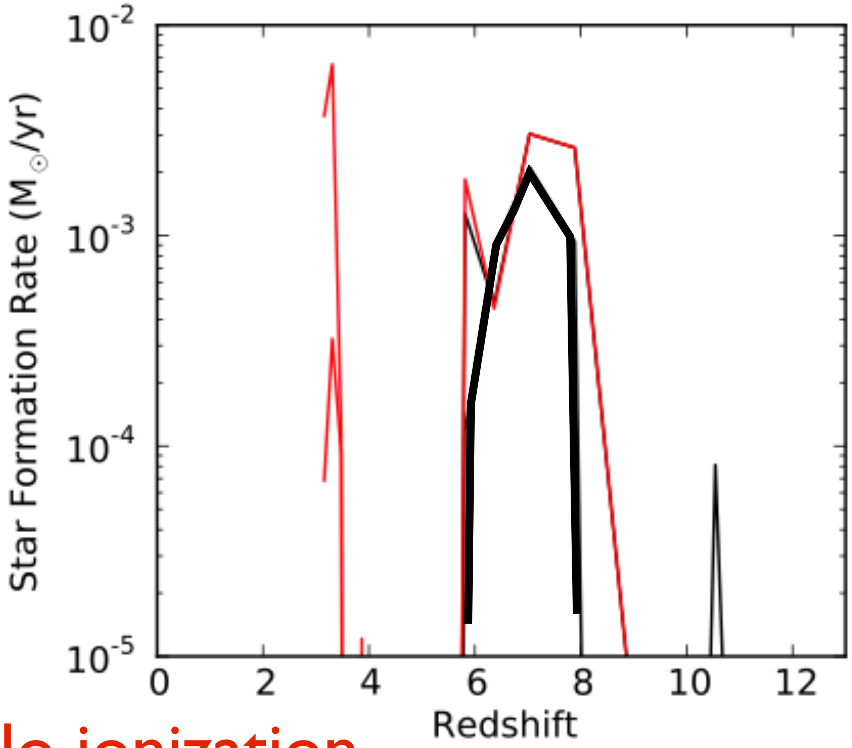
numerical resolution:
10.8 pc comoving
(1 pc at z = *10*)

Simpson, Bryan, Johnston, Smith, Mac Low + 12, in prep

SNe + background ionization needed to get SF history consistently

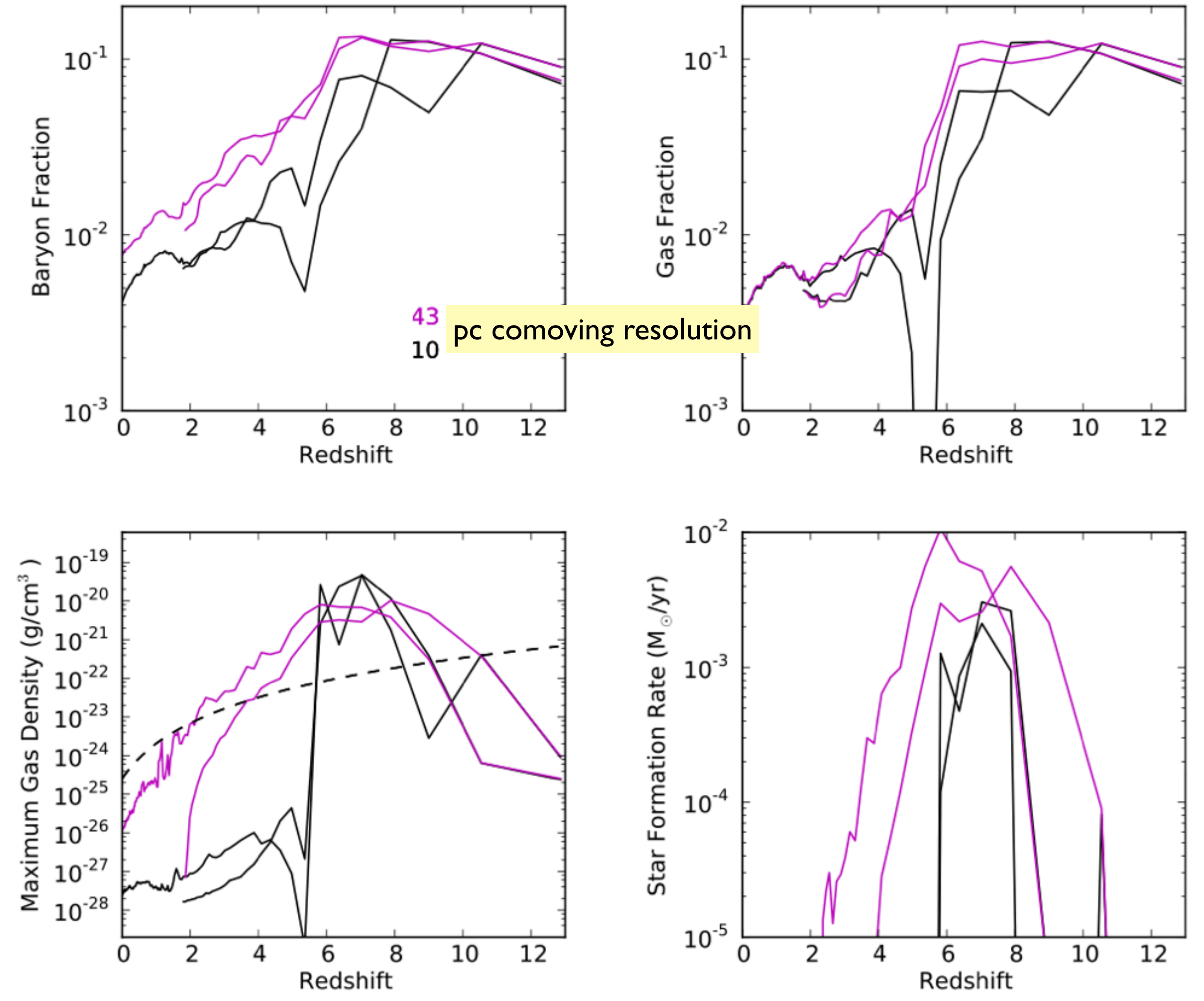


No feedback



No ionization

Simpson, Bryan, Johnston, Smith,
Mac Low + 12, in prep

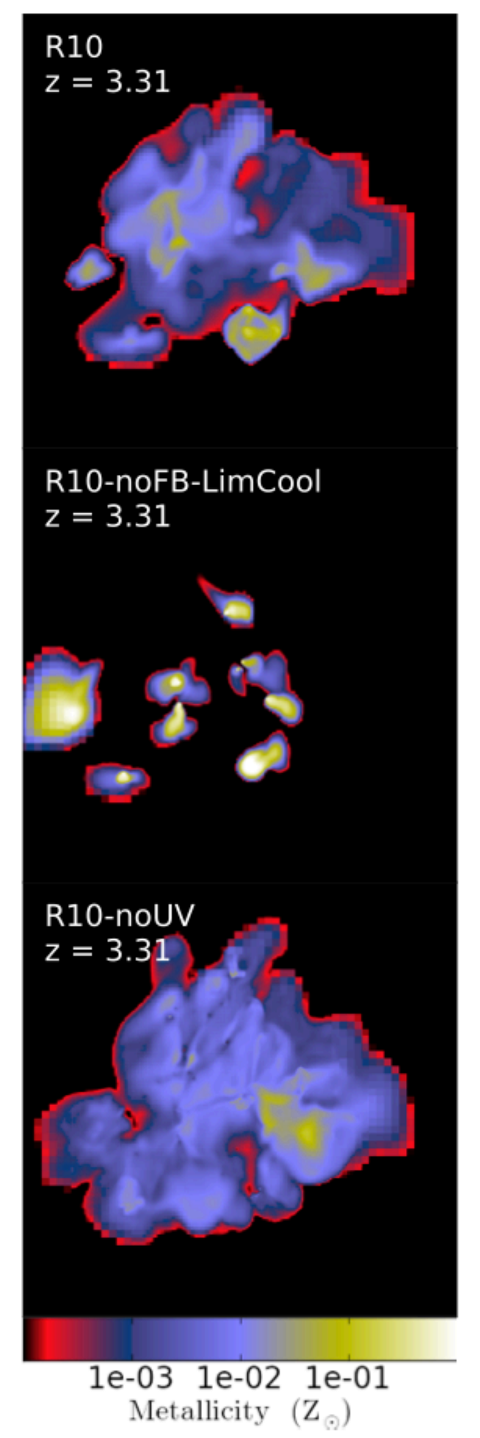


cf.
Sawala + 10,
Sawala + 11,
Governato + 12
all with ~40 pc resolution

(all have feedback tuned to their lower resolution)

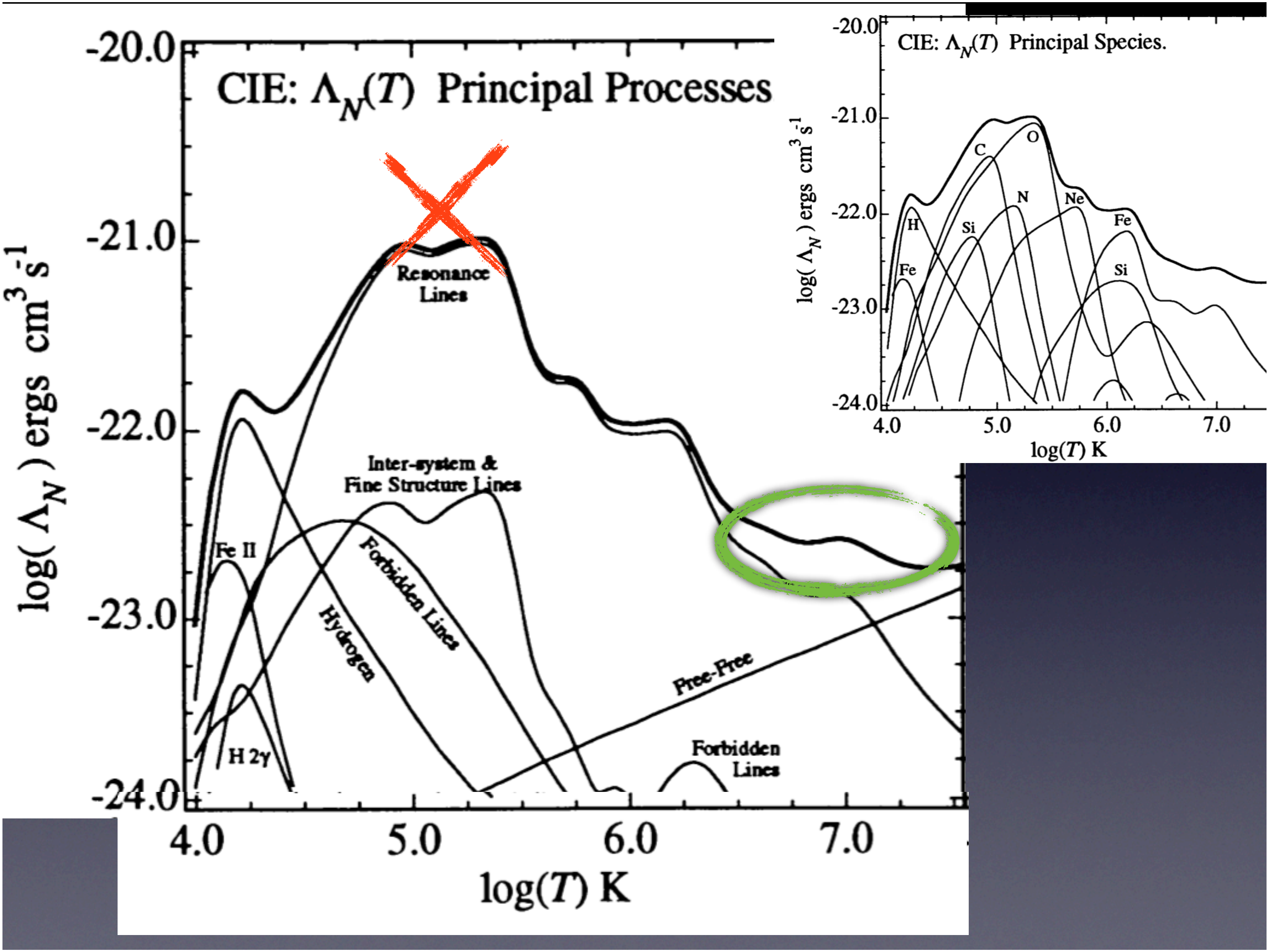
Simpson, Bryan, Johnston, Smith, Mac Low, + 12, in prep

Metallicity depends on supernova feedback

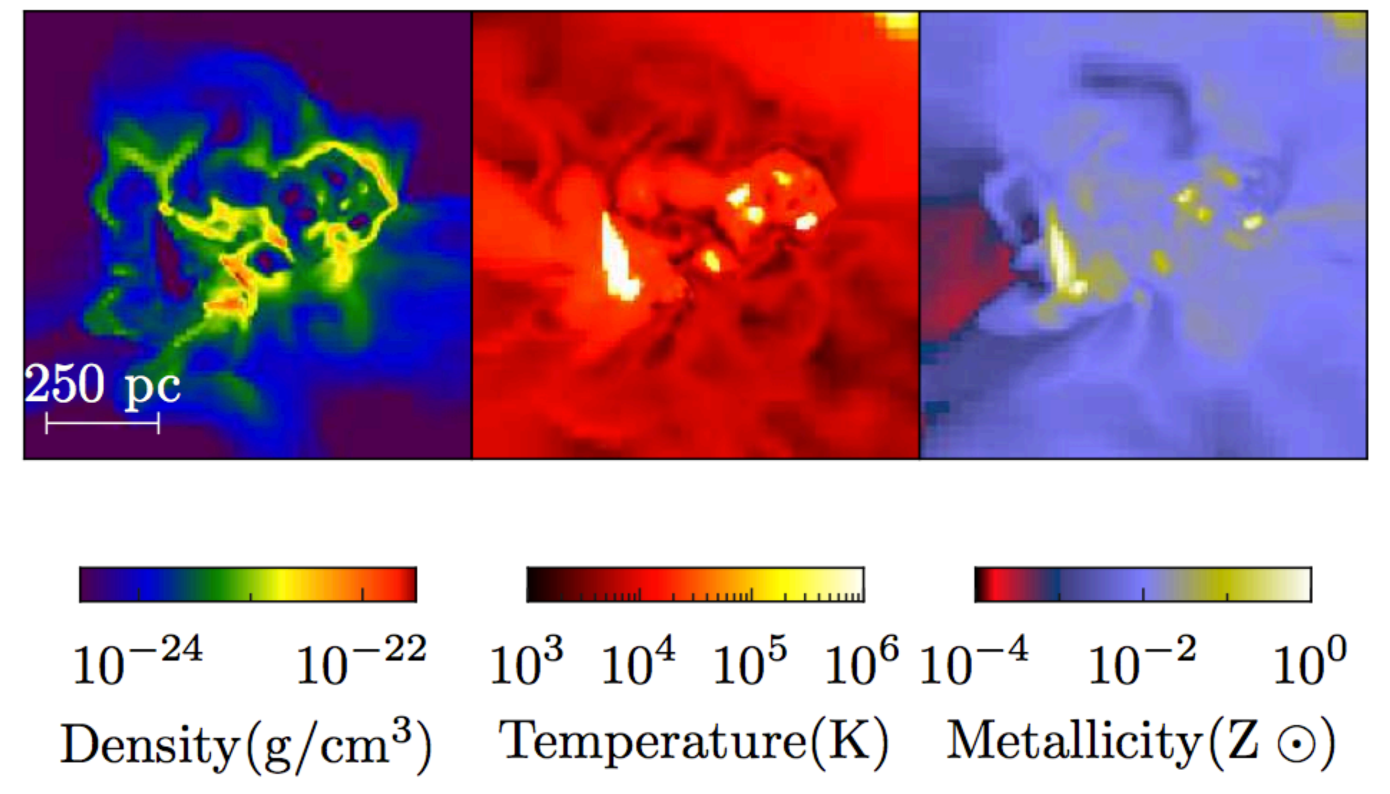


Simpson, Bryan, Johnston, Smith, Mac Low, Sharma, Tumlinson 12, in prep

- Model metallicities above 0.1 suggest insufficiently energetic SN feedback
- Continuous energy input from clusters heats gas insufficiently.
- SN by SN injection likely necessary (eg Joung + 06, 09)
- local ionization and even radiation pressure feedback could also play a major role by reducing peak densities: would also extend SF

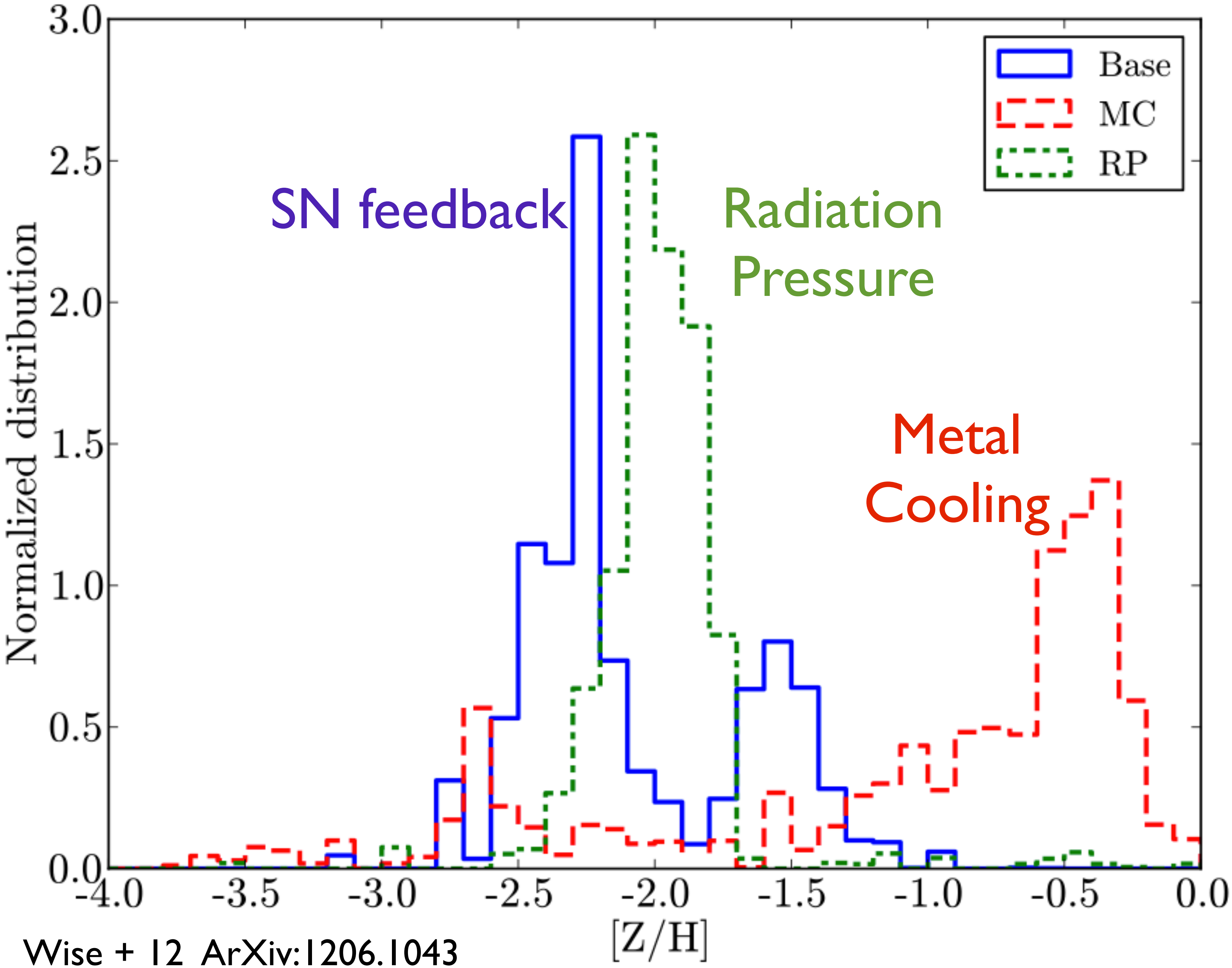


CIE: $\Lambda_N(T)$ Principal Processes
$\log(\Lambda_N)$ ergs $cm^3 s^{-1}$
$\log(T)$ K
-20.0
-21.0
-22.0
-23.0
-24.0
4.0
5.0
6.0
7.0
Resonance Lines
Inter-system & Fine Structure Lines
Fe II
H 2γ
Hydrogen
Forbidden Lines
Free-Free
Forbidden Lines
CIE: $\Lambda_N(T)$ Principal Species.
$\log(\Lambda_N)$ ergs $cm^3 s^{-1}$
$\log(T)$ K
-20.0
-21.0
-22.0
-23.0
-24.0
4.0
5.0
6.0
7.0
H
Fe
C
O
Si
N
Ne
Fe
Si



Wise + 12

17 < *z* < 8
1 comoving pc res'n
radiation pressure acting with *L*/*c*



Wise + 12 ArXiv:1206.1043

Summary

- Turbulence inhibits star formation, but doesn't prevent it
  - Turbulent compression promotes local collapse in stable regions.
- Sources of turbulence: supernovae, magnetorotational instability consistent with observations at z = 0
  - Accretion likely important at high z, but does not predict observed z = 0 velocity dispersions
- Gravitational instability in quickly radiatively cooling gas only cuts off due to finite disk effects
- Models of dwarf galaxies with feedback-driven turbulence are getting close to explaining SF & metallicity histories.
- Low-z dwarfs likely differ fundamentally from high-z because of importance of accretion at high-z