The impact of turbulent star formation on high-z galaxy properties

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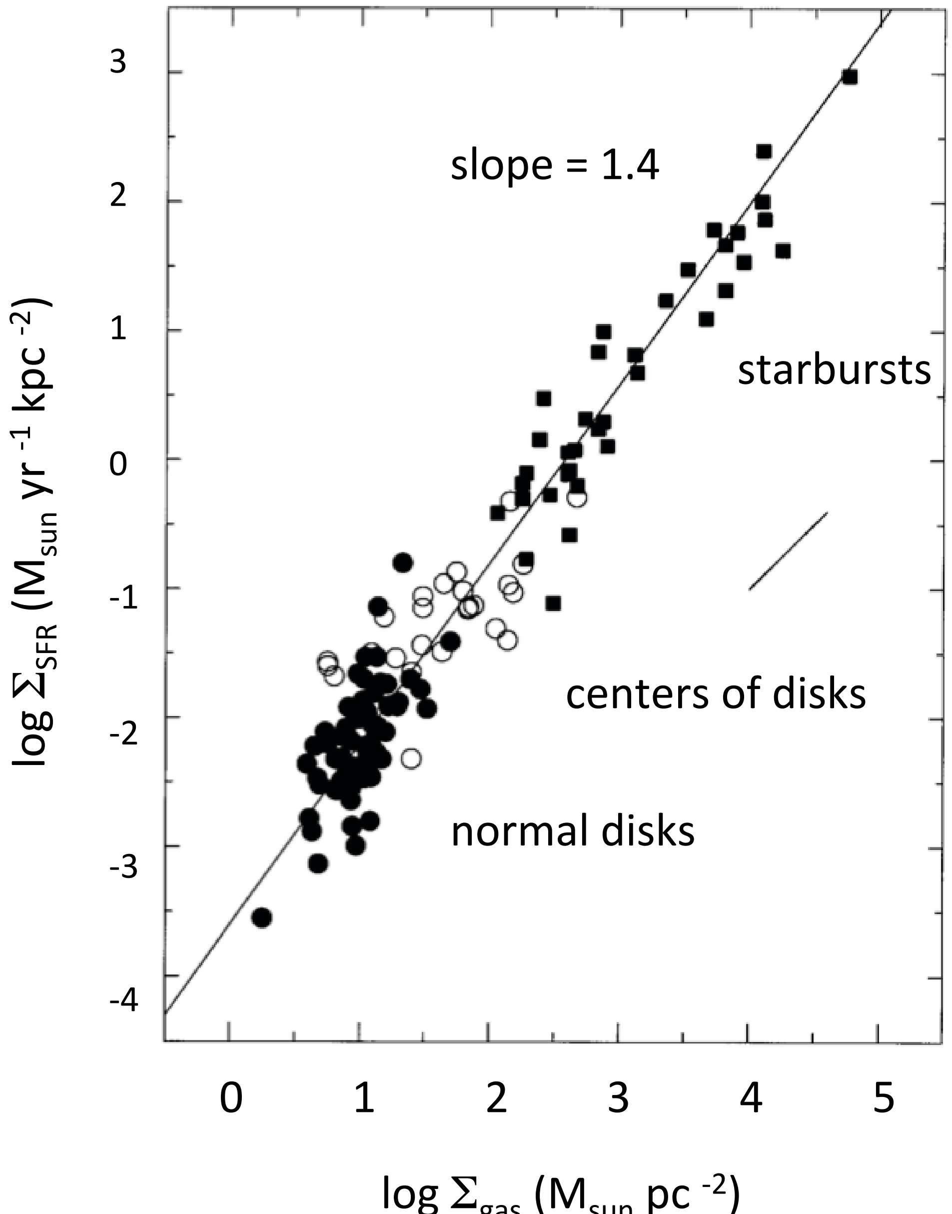
Outlook

- Presentation of the problem
- The case for turbulence
- Modelling efforts
- Results/Impact

How should we form stars in simulations?

-> using the observed star formation-surface gas density relation?



$$\Sigma_{SFR} \sim \Sigma^{1.4}$$

Question: is this simply

$$\dot{\rho}_* = \frac{\epsilon\,\rho}{t_{ff}} \propto \rho^{3/2}$$

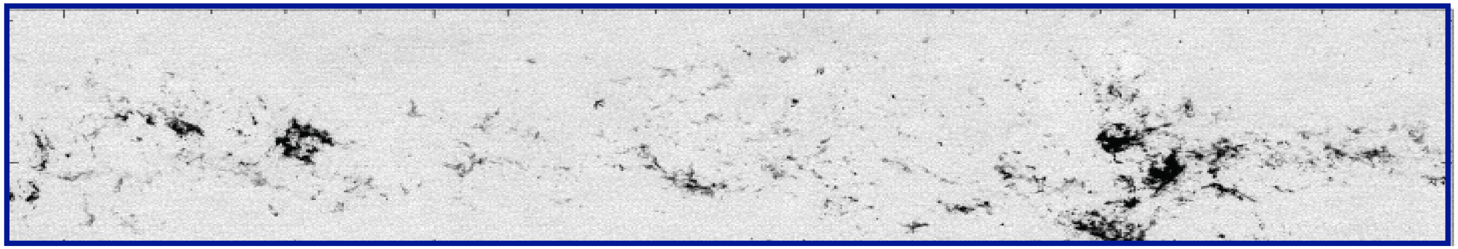
where

$$t_{ff}(\rho) \equiv \left(\frac{3\pi}{32 G\rho}\right)^{1/2}$$?

NB: spatially averaged on kpc scale

Kennicutt 1998

Positive answer: a two parameter implementation



Heyer et al. 1998

(FCRAO CO survey)

if $\rho > \rho_0$ → depends on simulation resolution!

need to at least reach average molecular cloud densities: 50-100 at/cc ??

$$\dot{\rho}_* = \frac{\epsilon\, \rho}{t_{\rm ff}} \propto \rho^{3/2}$$

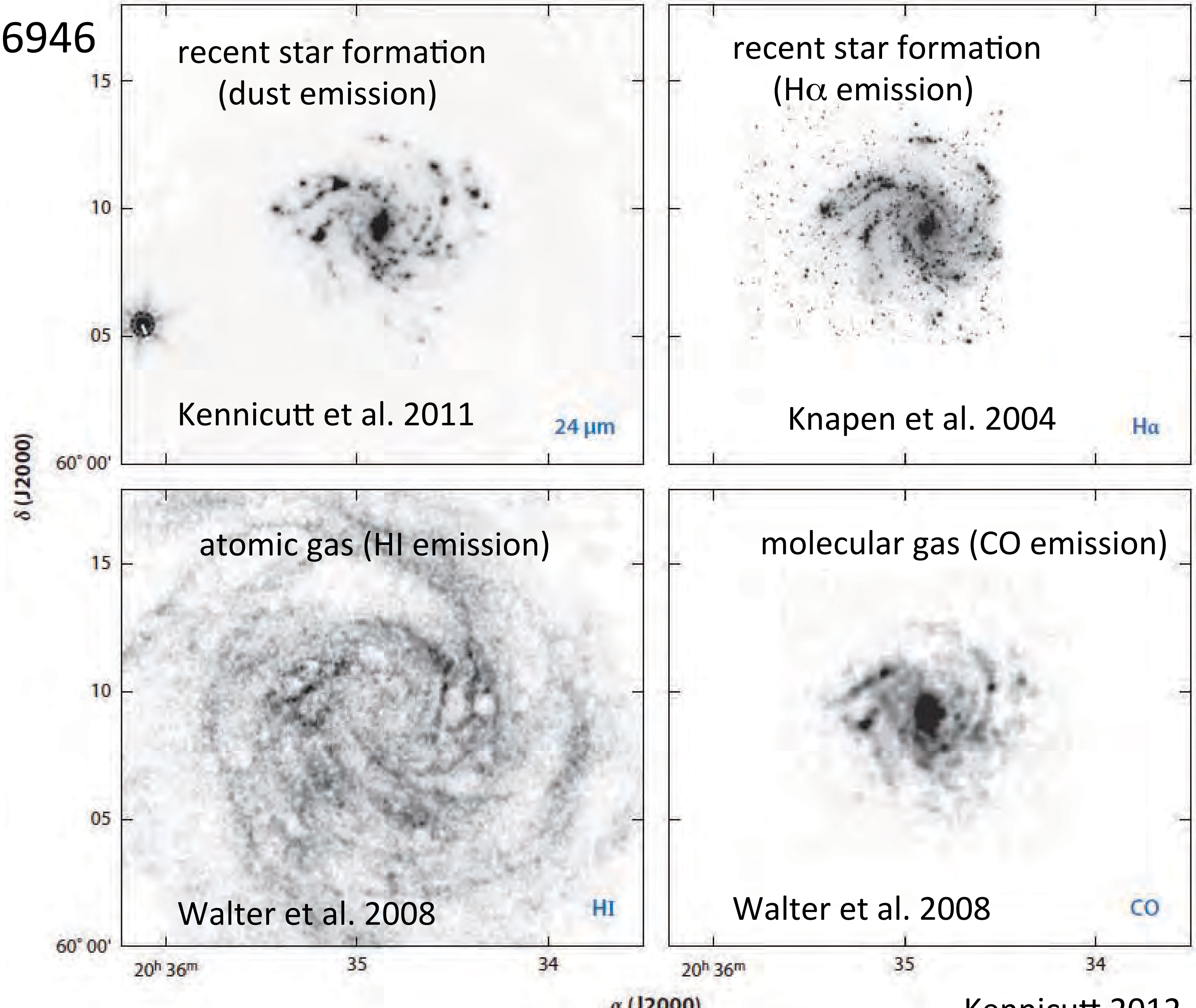
$$t_{\rm ff}(\rho) \equiv \left(\frac{3\pi}{32 G \rho}\right)^{1/2}$$

with $\epsilon = 0.01$

(e.g. Krumholtz & Tan 2005)

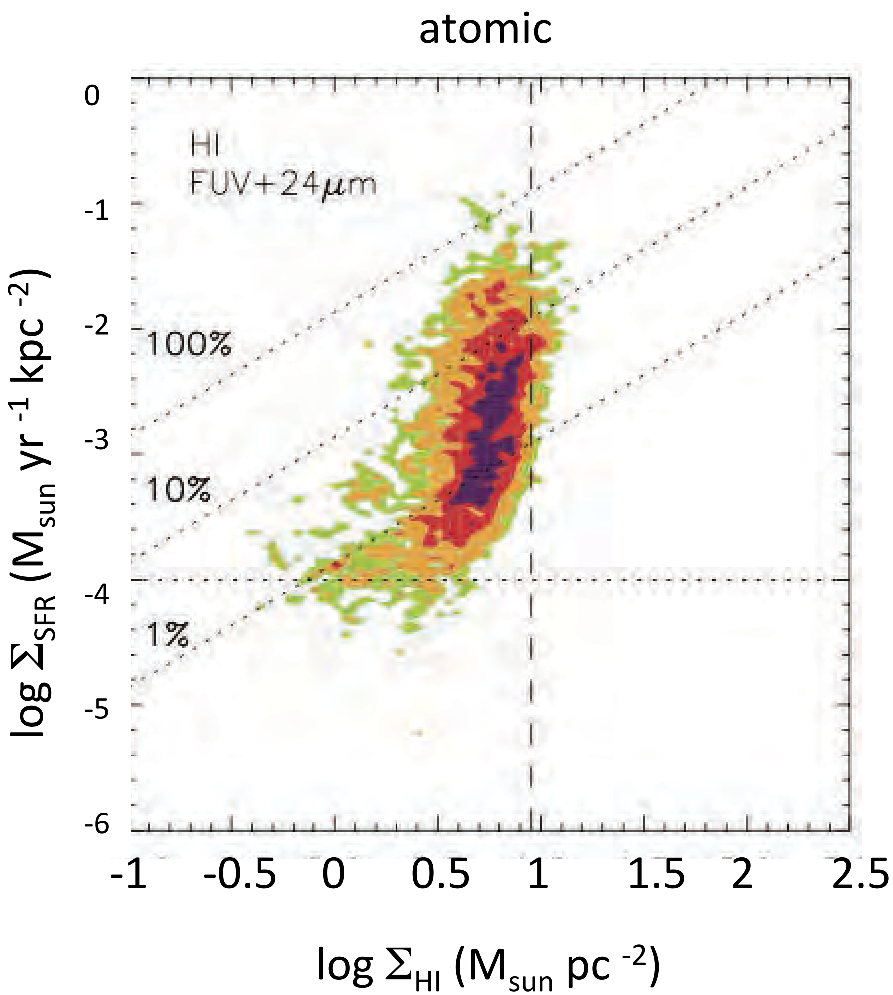
star formation efficiency: Universal parameter? What about prediction?

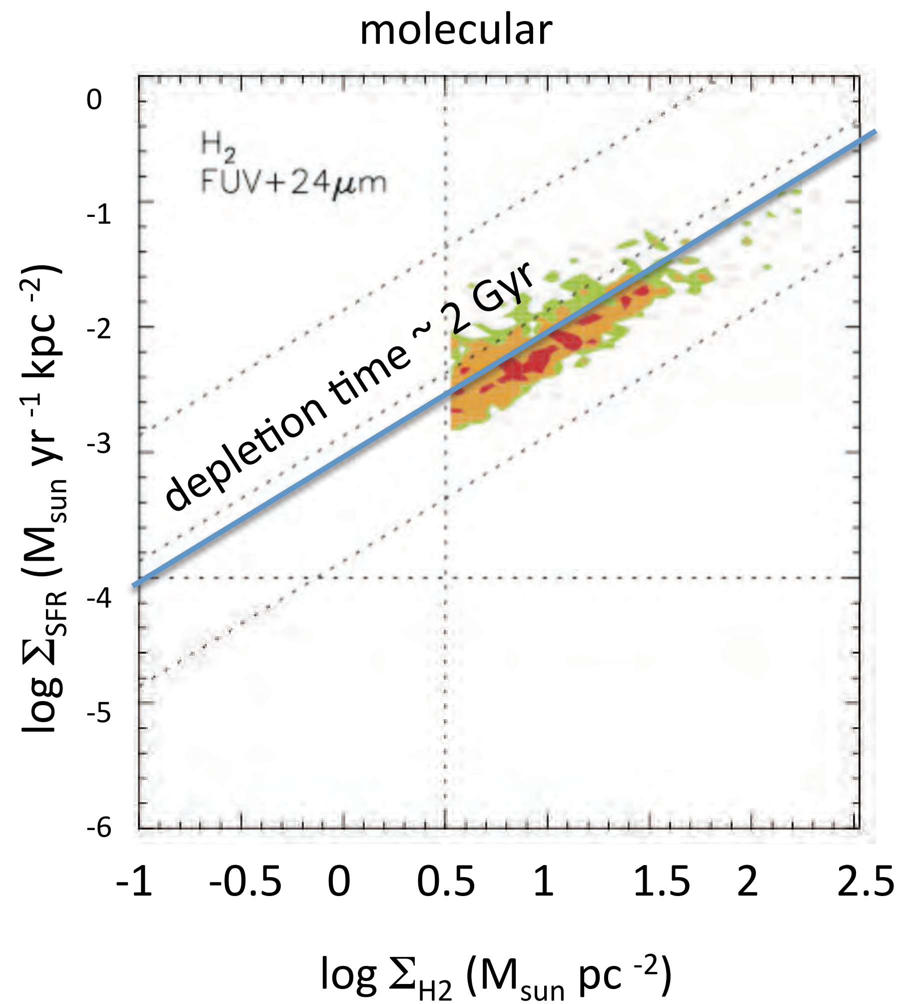
NGC 6946



Kennicutt 2012

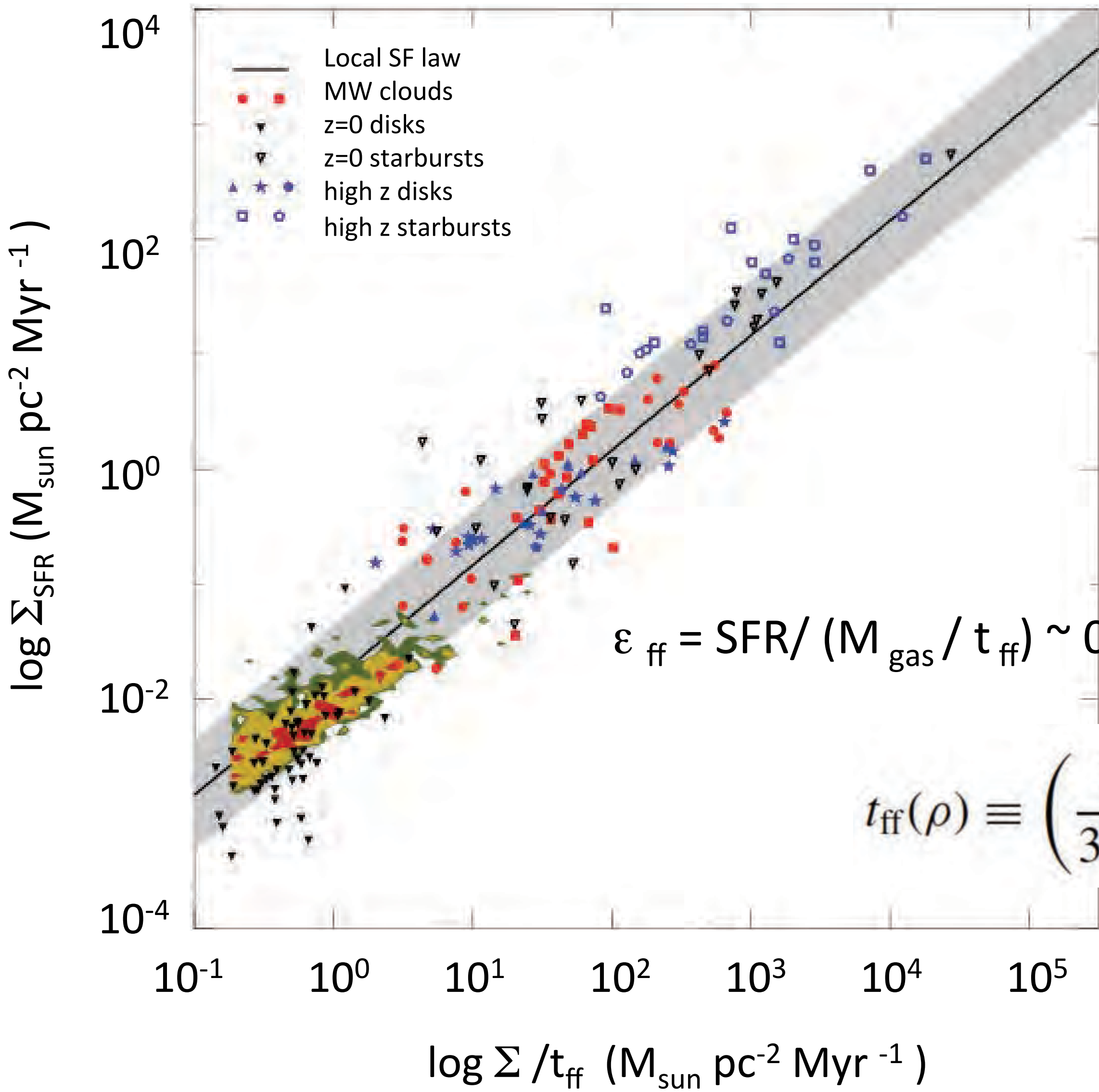
Star formation- surface gas density relations





Bigiel et al. 2008

Clouds on the star formation - gas surface density relation…..



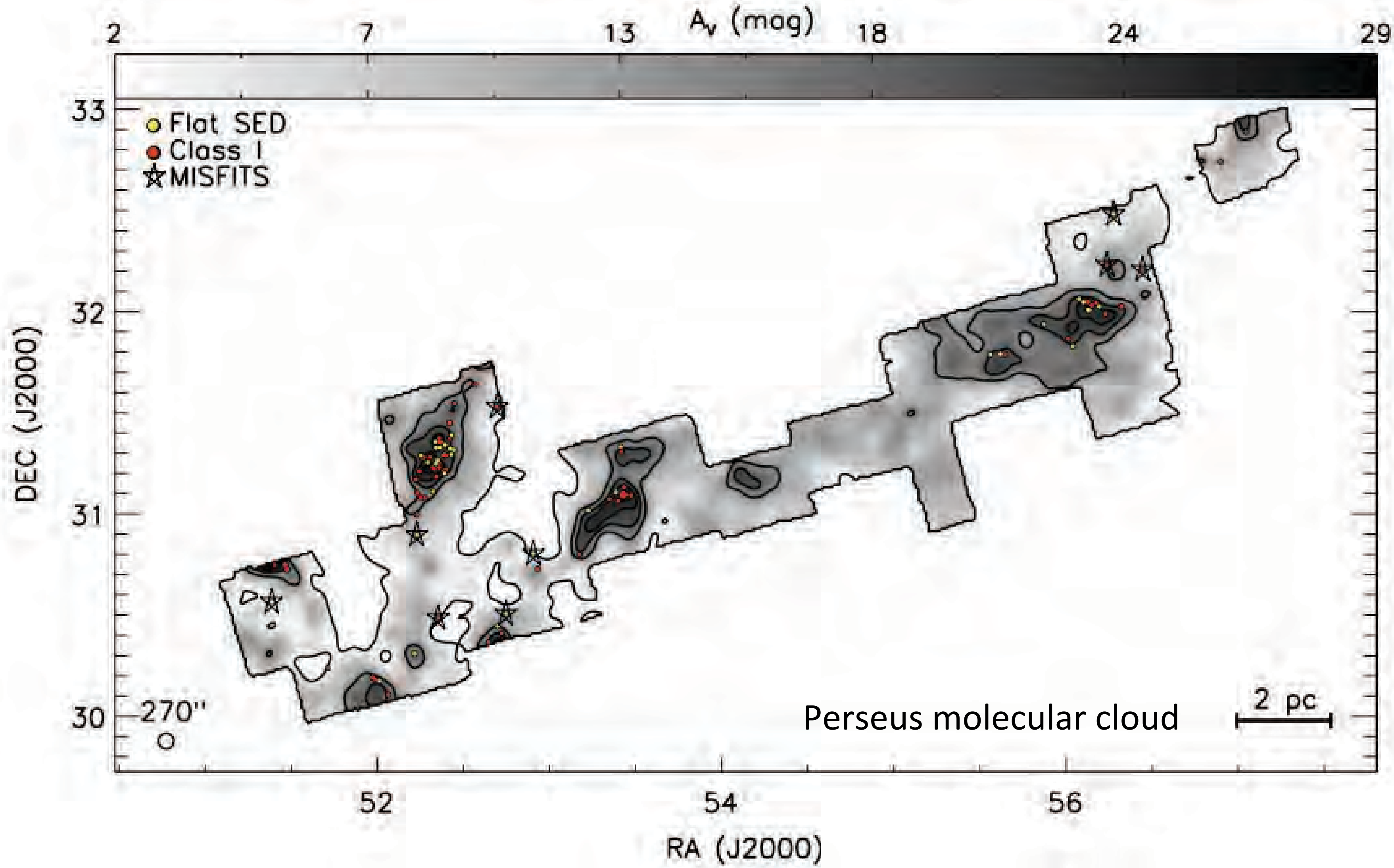
$\varepsilon_{ff} = SFR / (M_{gas} / t_{ff}) \sim 0.015$

$$t_{\rm ff}(\rho) \equiv \left(\frac{3\pi}{32 G \rho}\right)^{1/2} \sim 1\text{-}5 \text{ Myr}$$

NB: Averaged on cloud scales

Krumholz et al. 2012, 2013

Caveat: stars do not form homogeneously in MC!

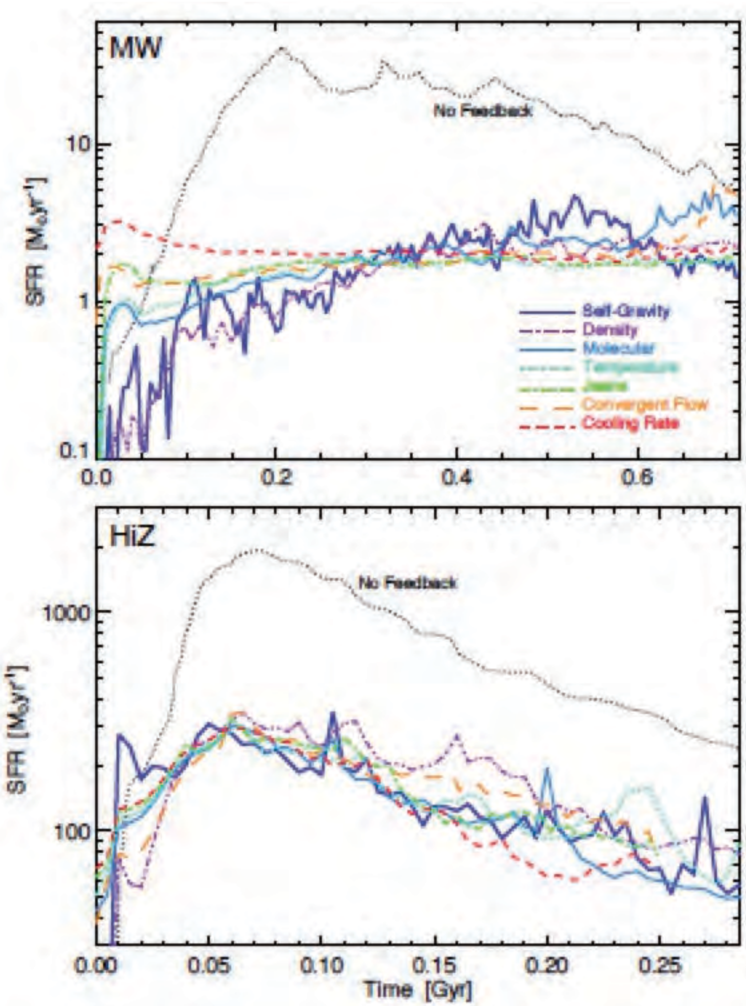


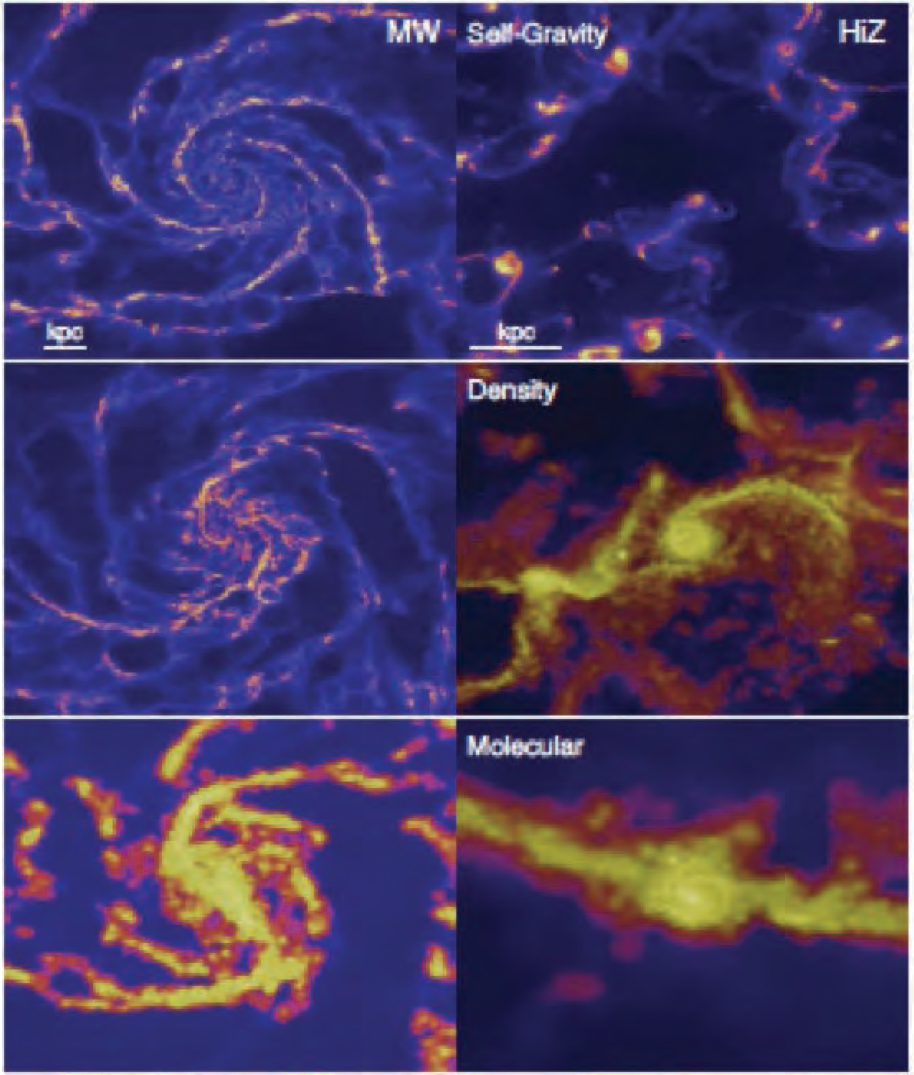
Heiderman et al. 2010

Molecular clouds: necessary but not sufficient?

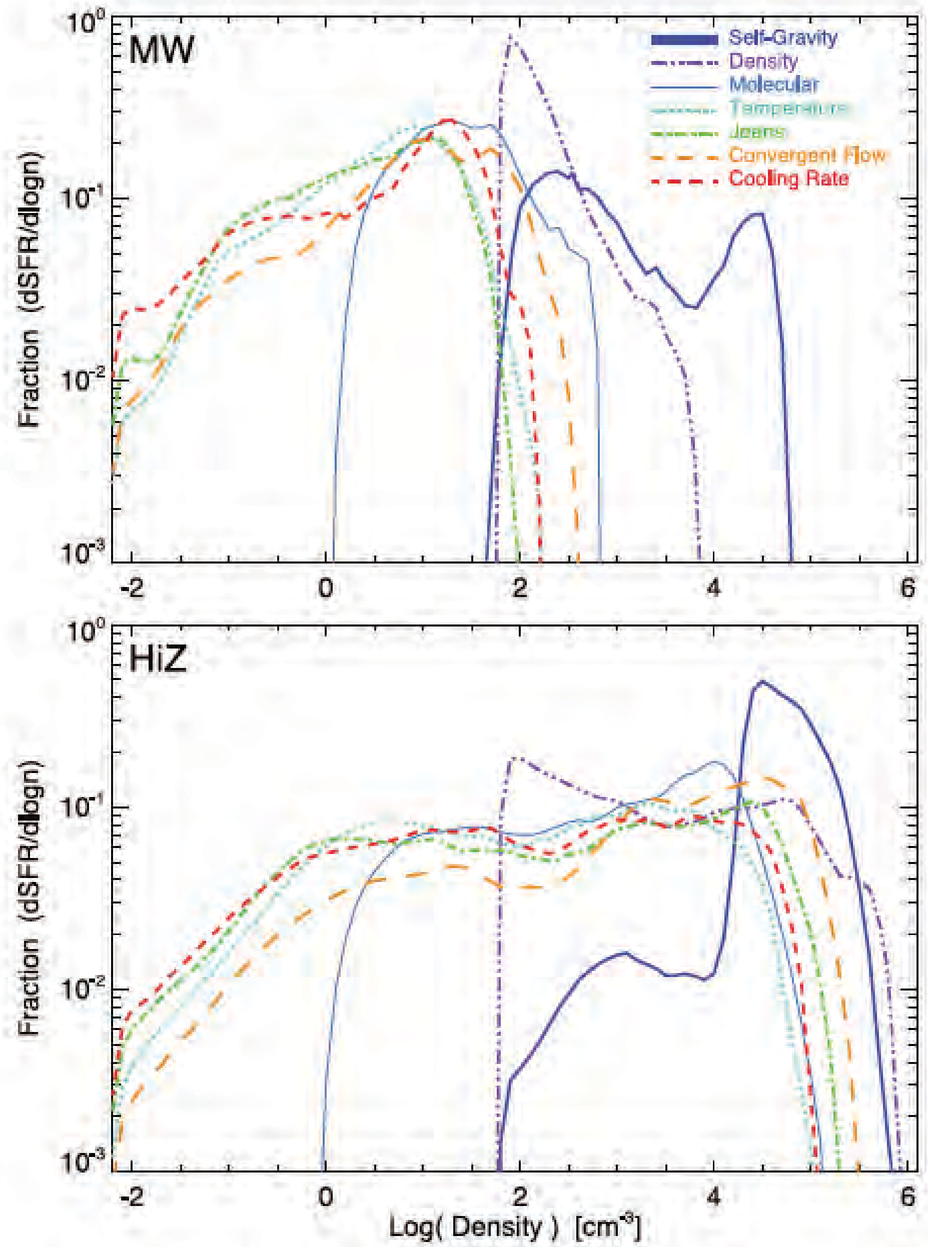
aka low efficiency everywhere vs high efficiency in dense cores only?

Hopkins et al 2013



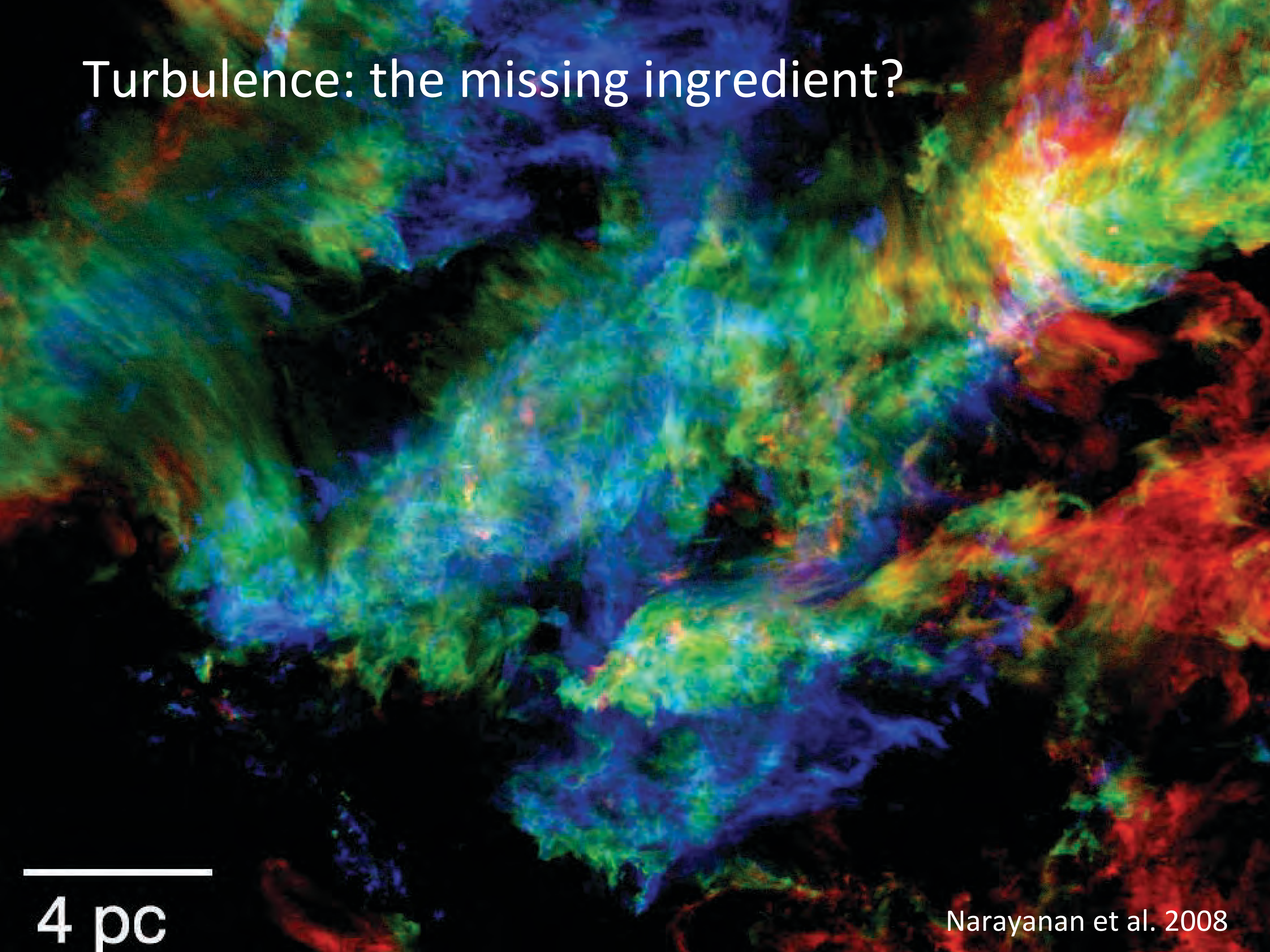


SFR weighted density distribution for different star formation prescriptions



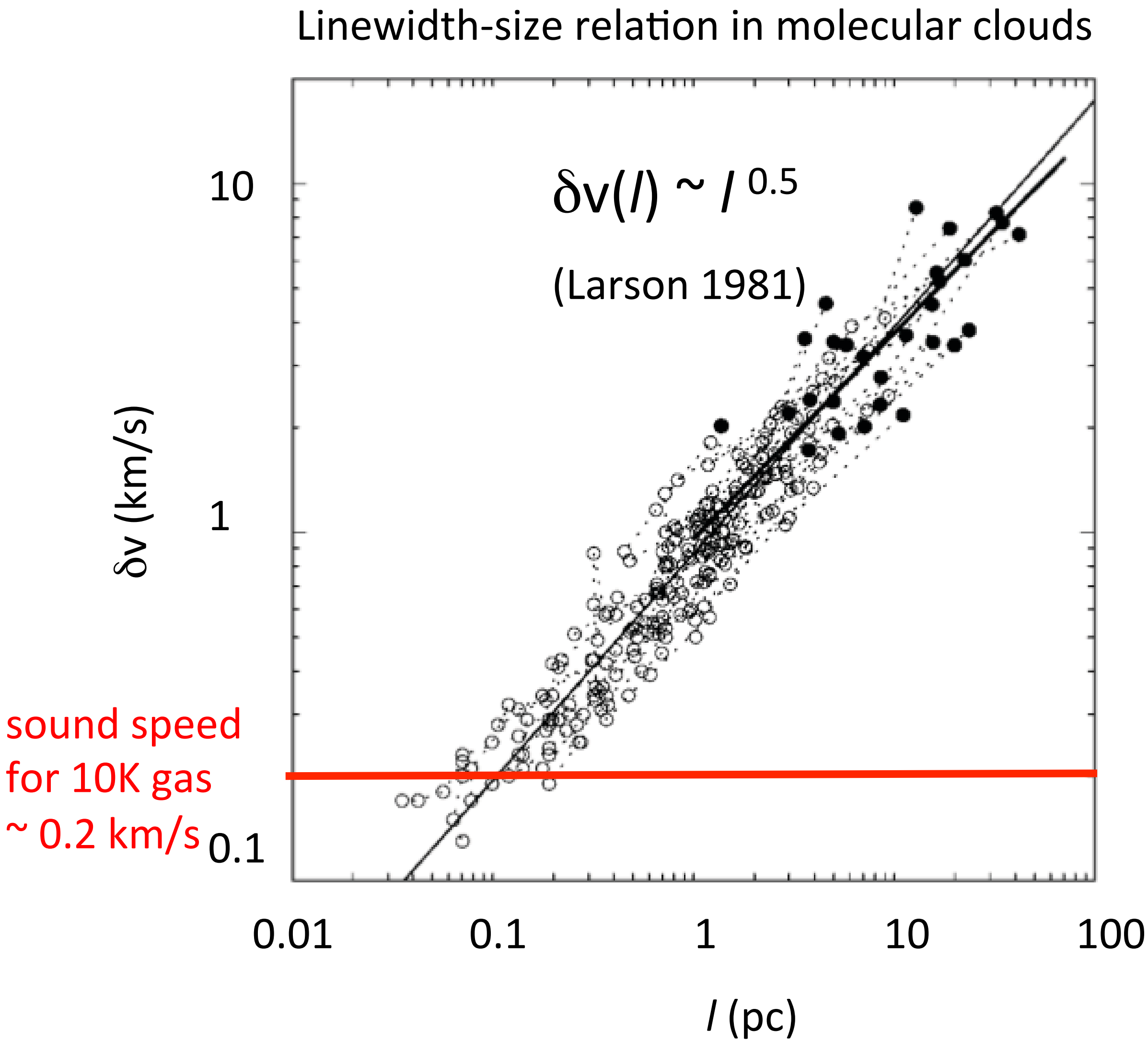
Hopkins et al. 2013

Turbulence: the missing ingredient?



Narayanan et al. 2008

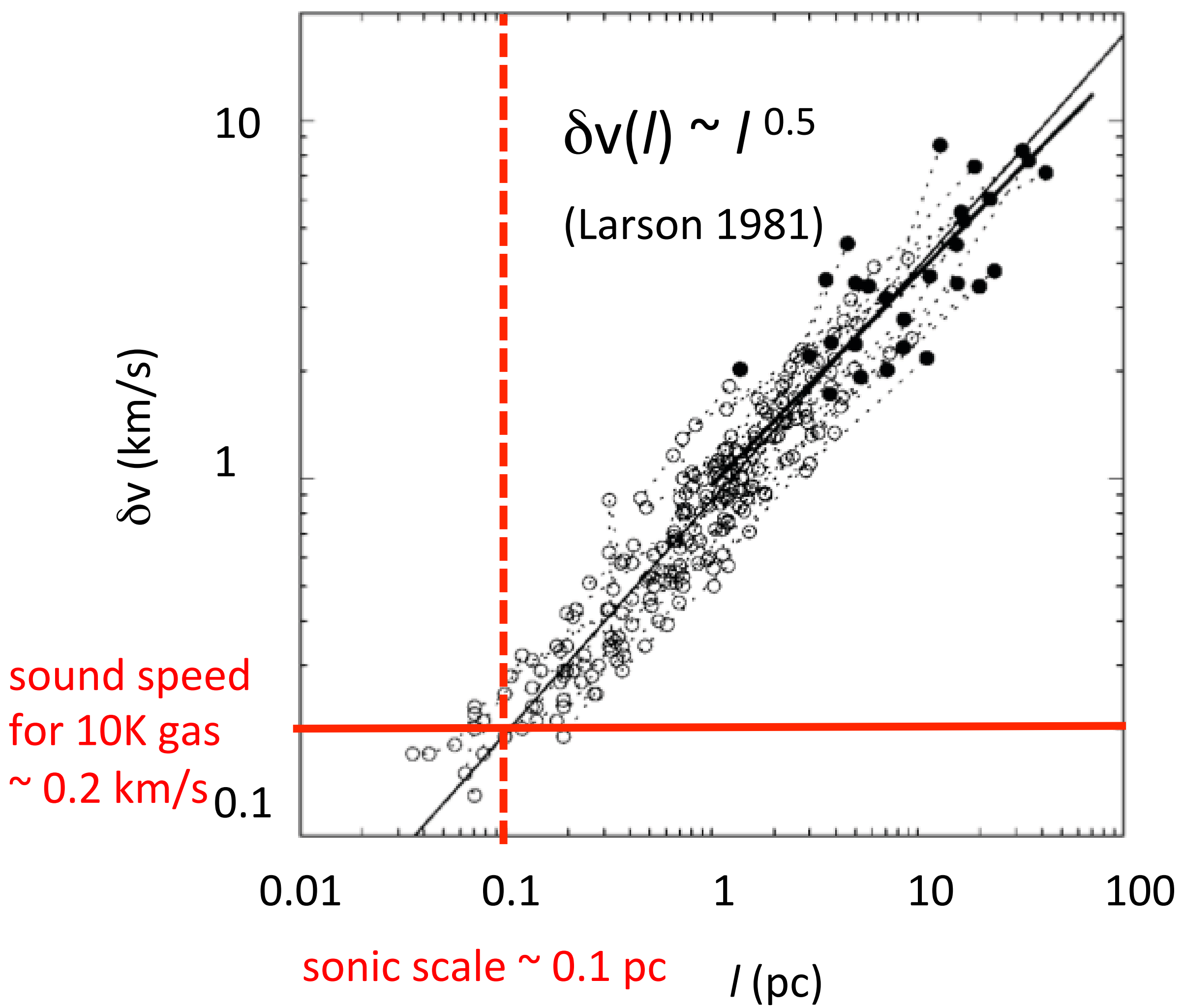
Evidence for compressible, supersonic turbulence



Heyer & Brunt 2004

Transition to subsonic turbulence

Linewidth-size relation in molecular clouds

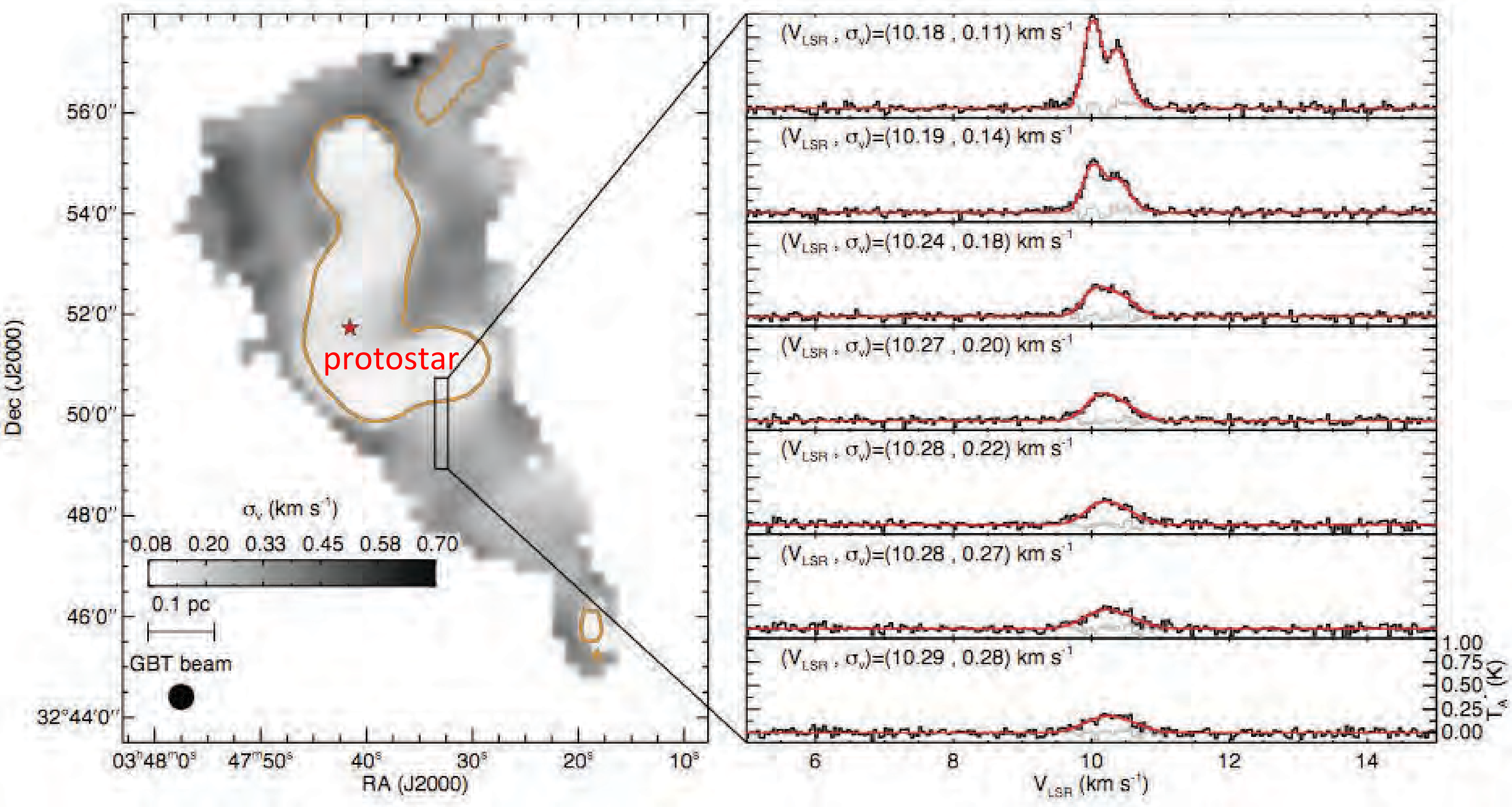


Heyer & Brunt 2004

Transition to coherence: “Islands of calm in a turbulent sea”

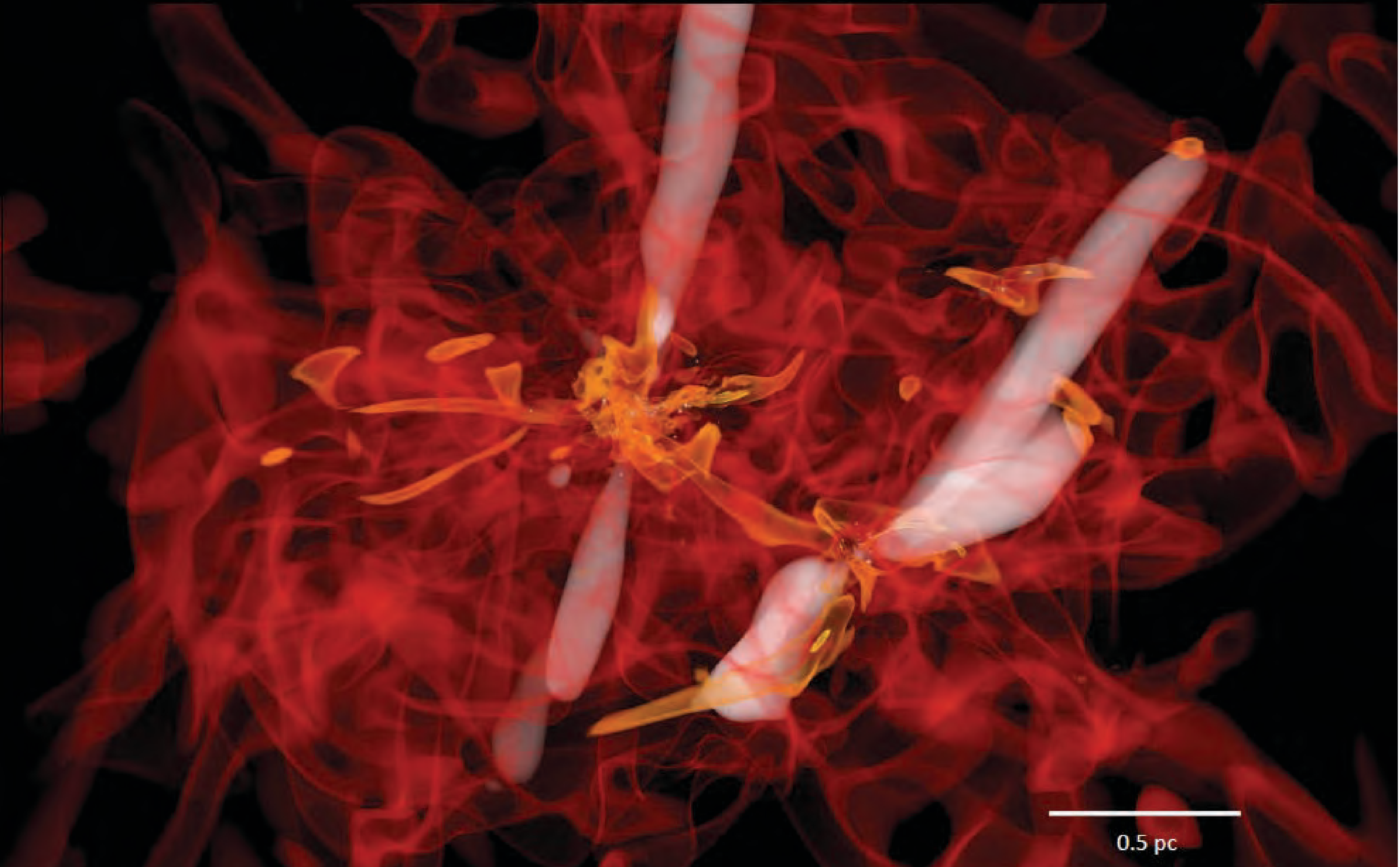
(Goodman et al. 1998, Caselli et al. 2002)

Perseus B5 map of the NH_3 velocity dispersion



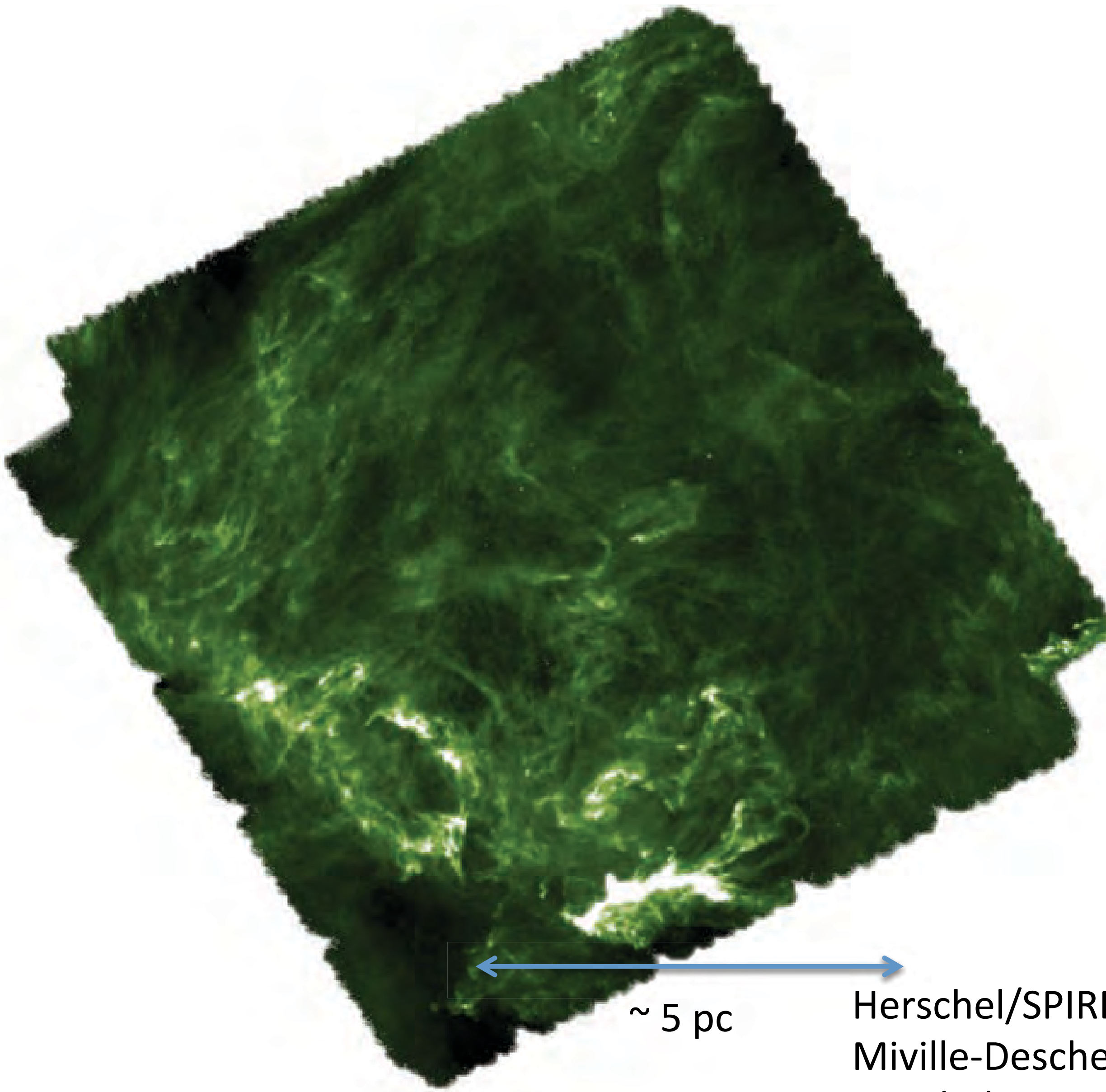
Pineda et al.2010

What drives this turbulence? Internal processes?



Wang et al. (2010, ApJ, 709, 27)

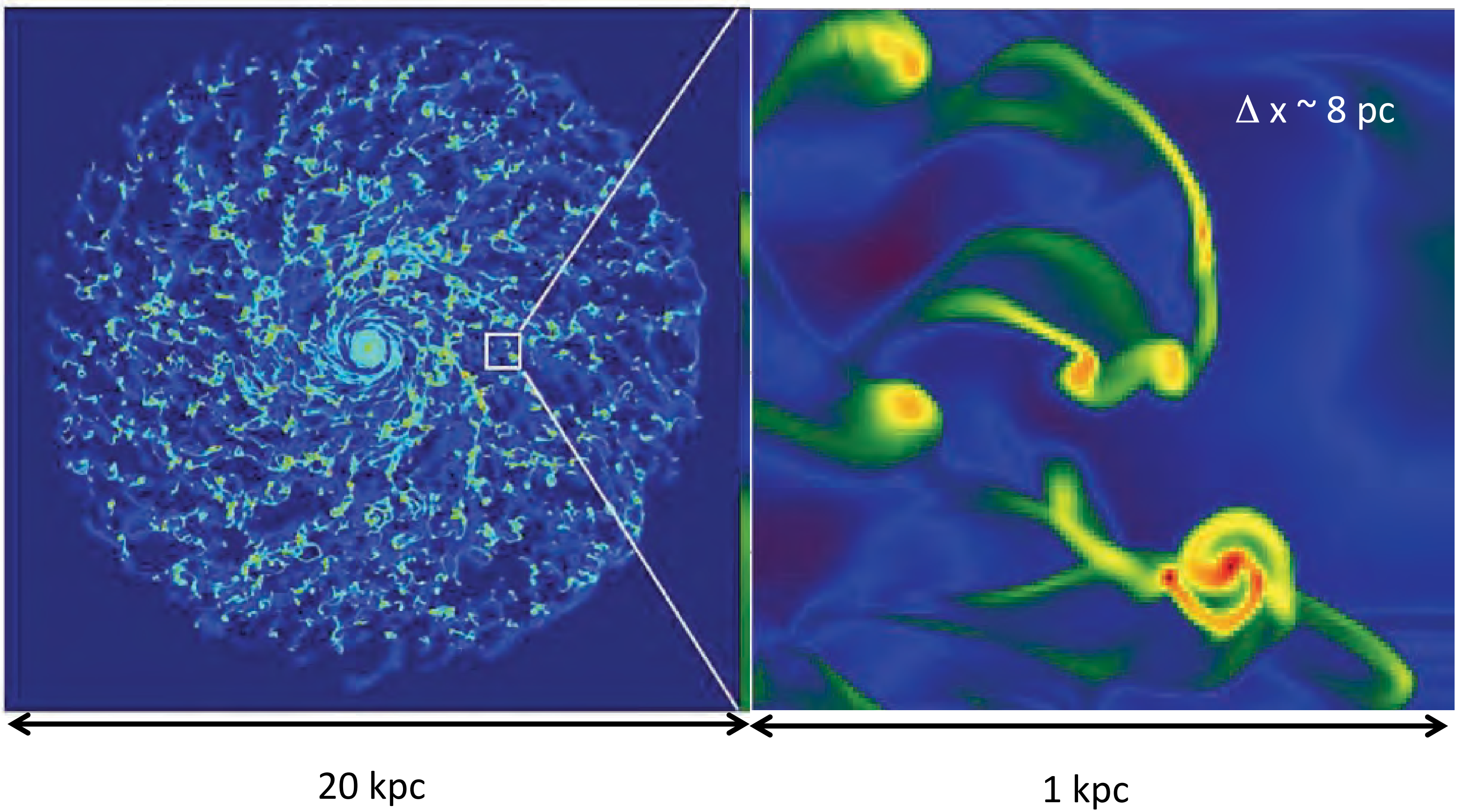
but … Polaris Flare: a non star forming molecular cloud



Herschel/SPIRE 250 μm image
Miville-Deschenes et al. 2010,
Ward-Thompson et al. 2010

Turbulent cascade from large scales: galactic shear & cloud motions

Tasker & Tan 2009, van Loo 2013



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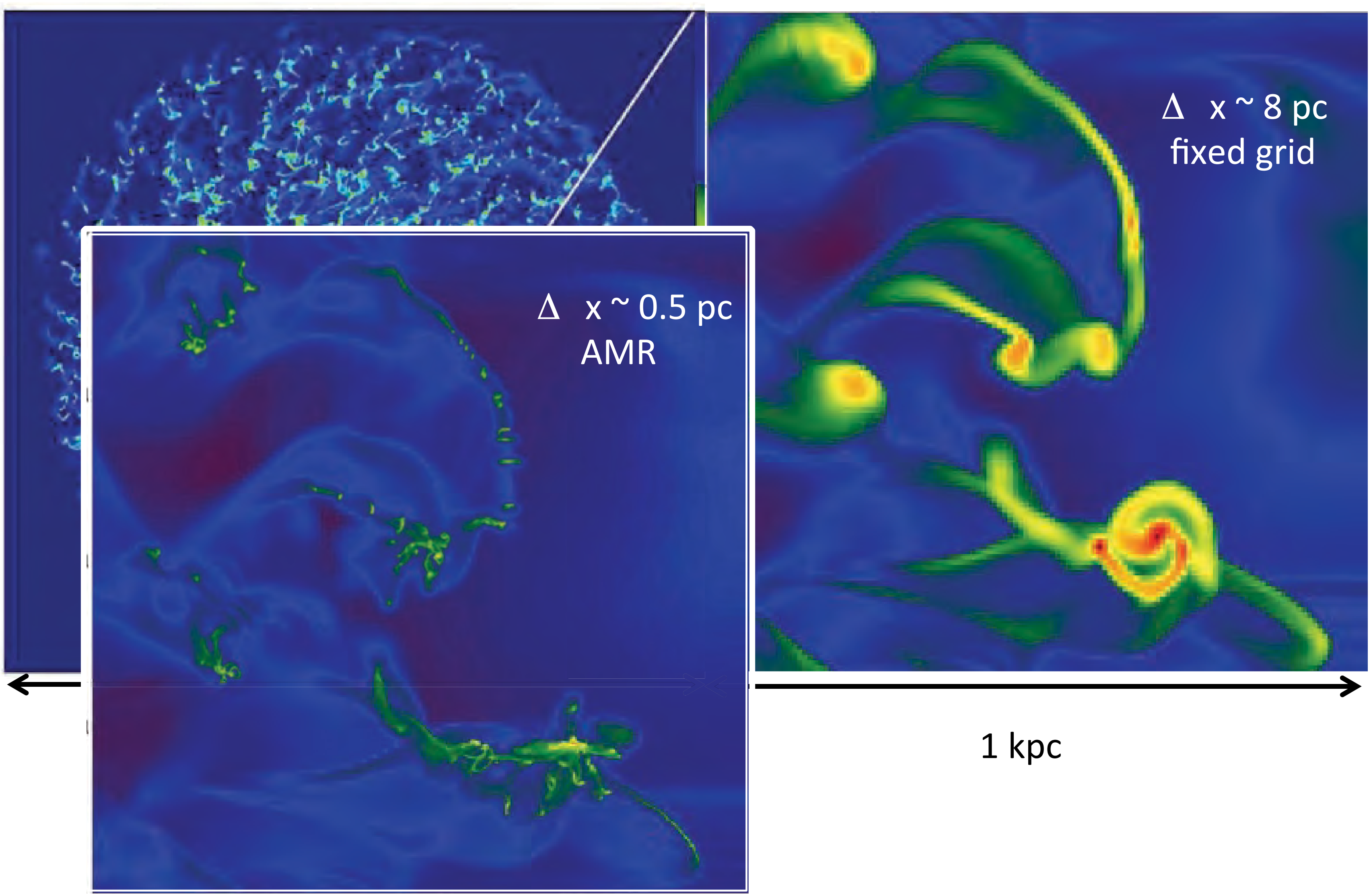
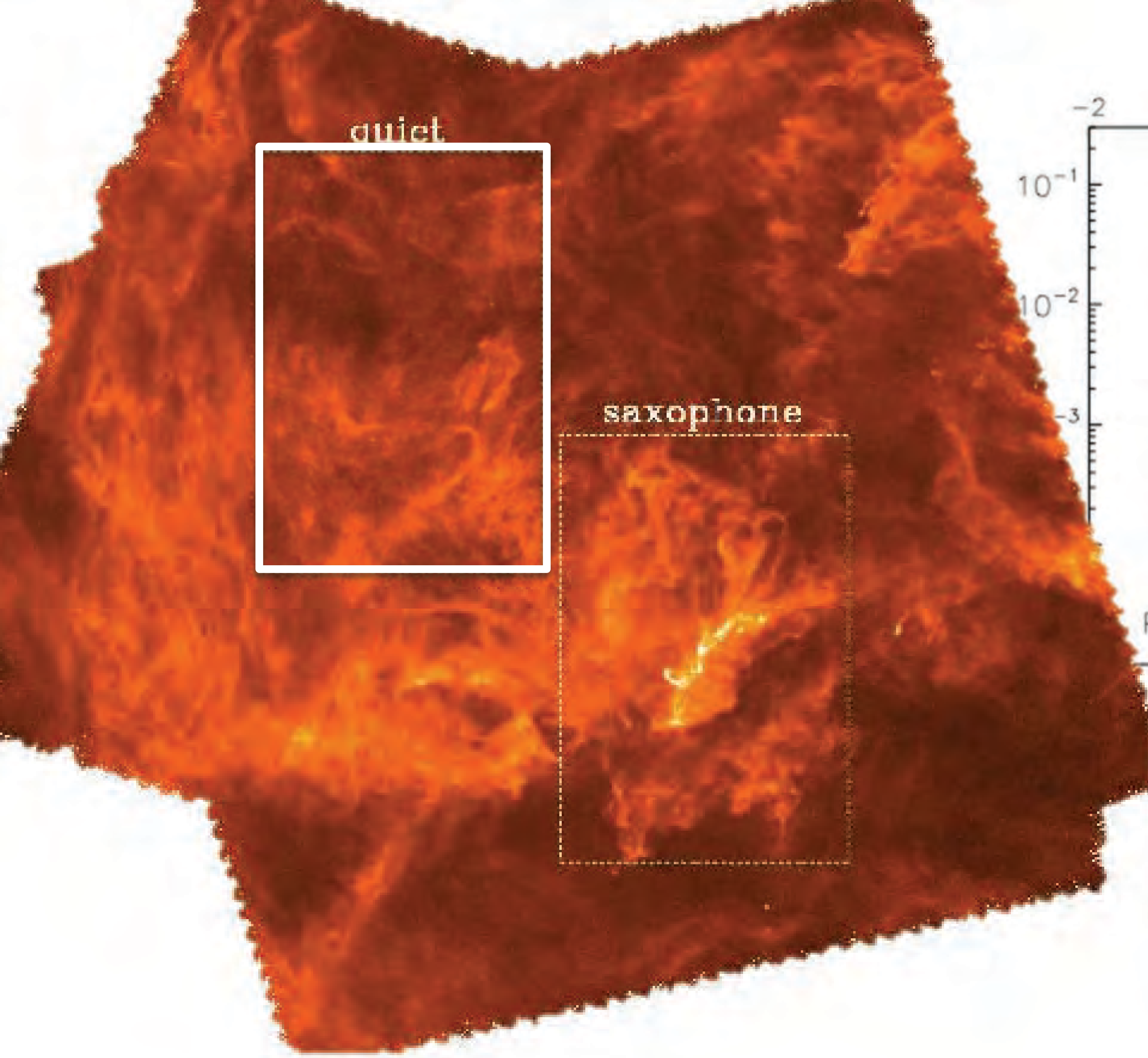
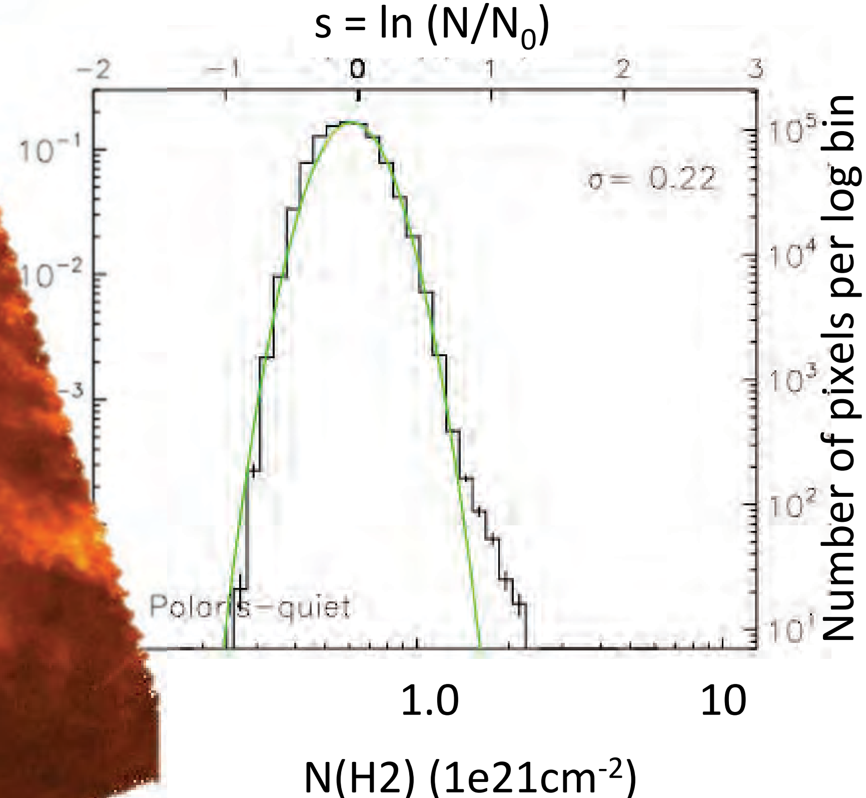
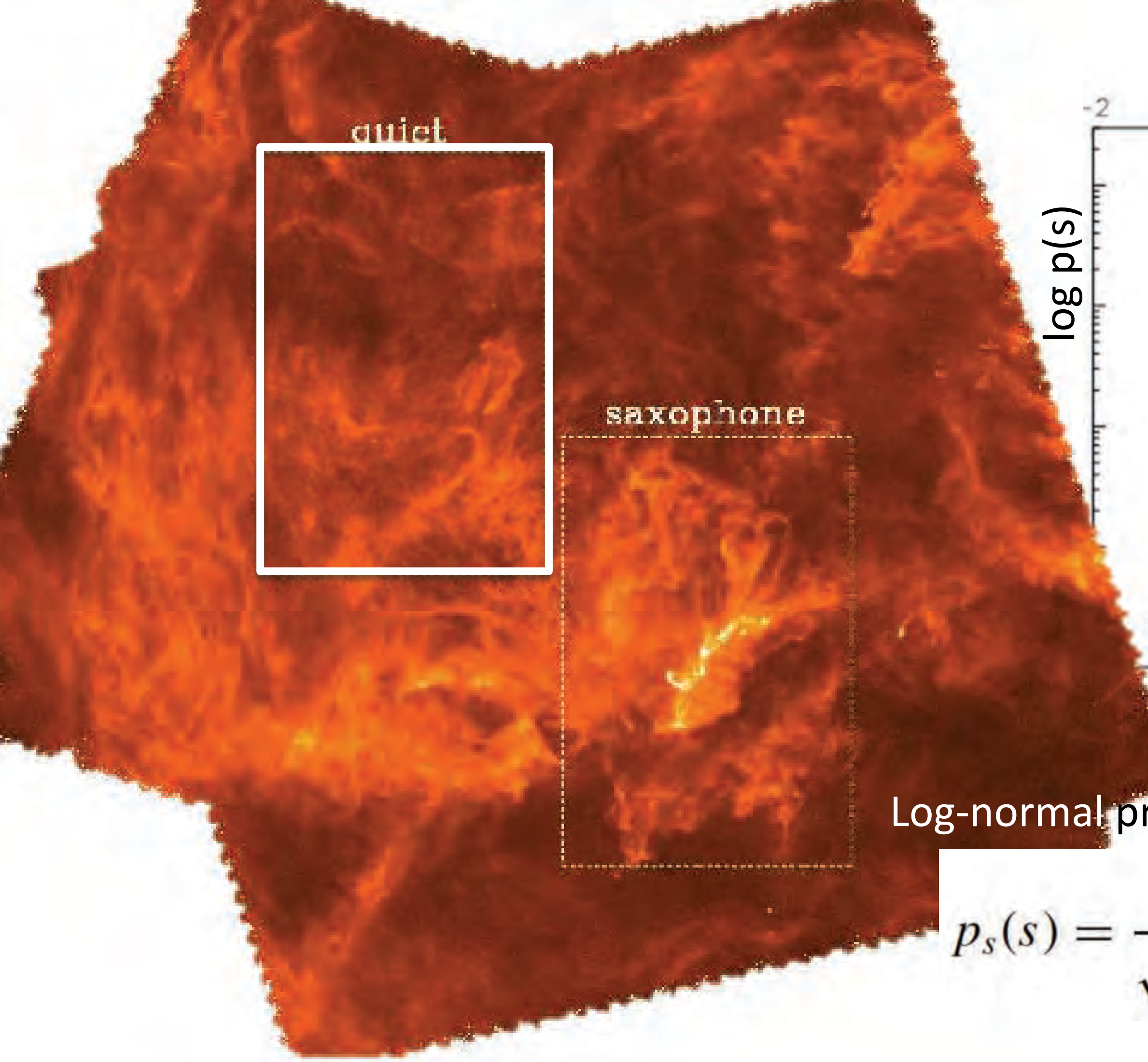


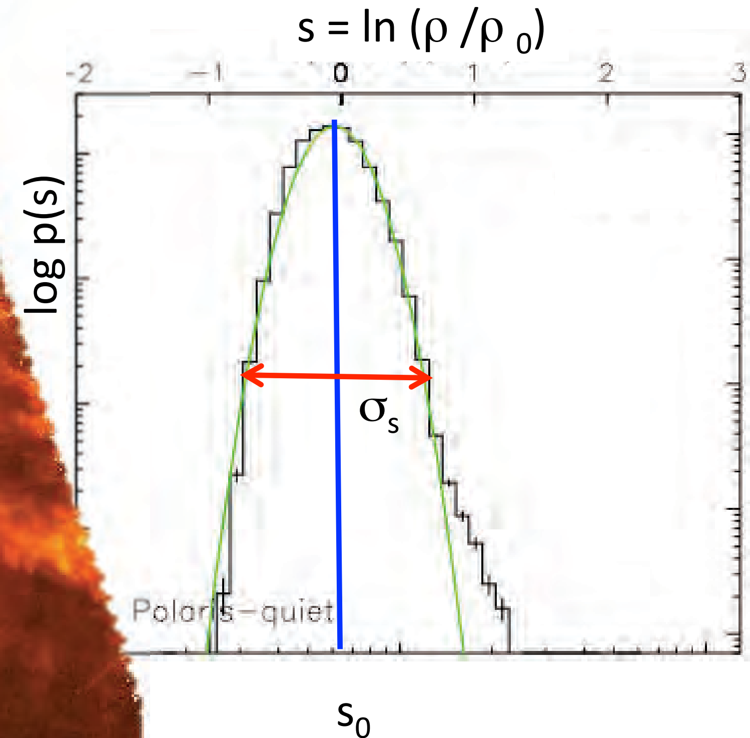




Herschel/SPIRE 250 μm image

Schneider et al. 2013





Log-normal probability density distribution

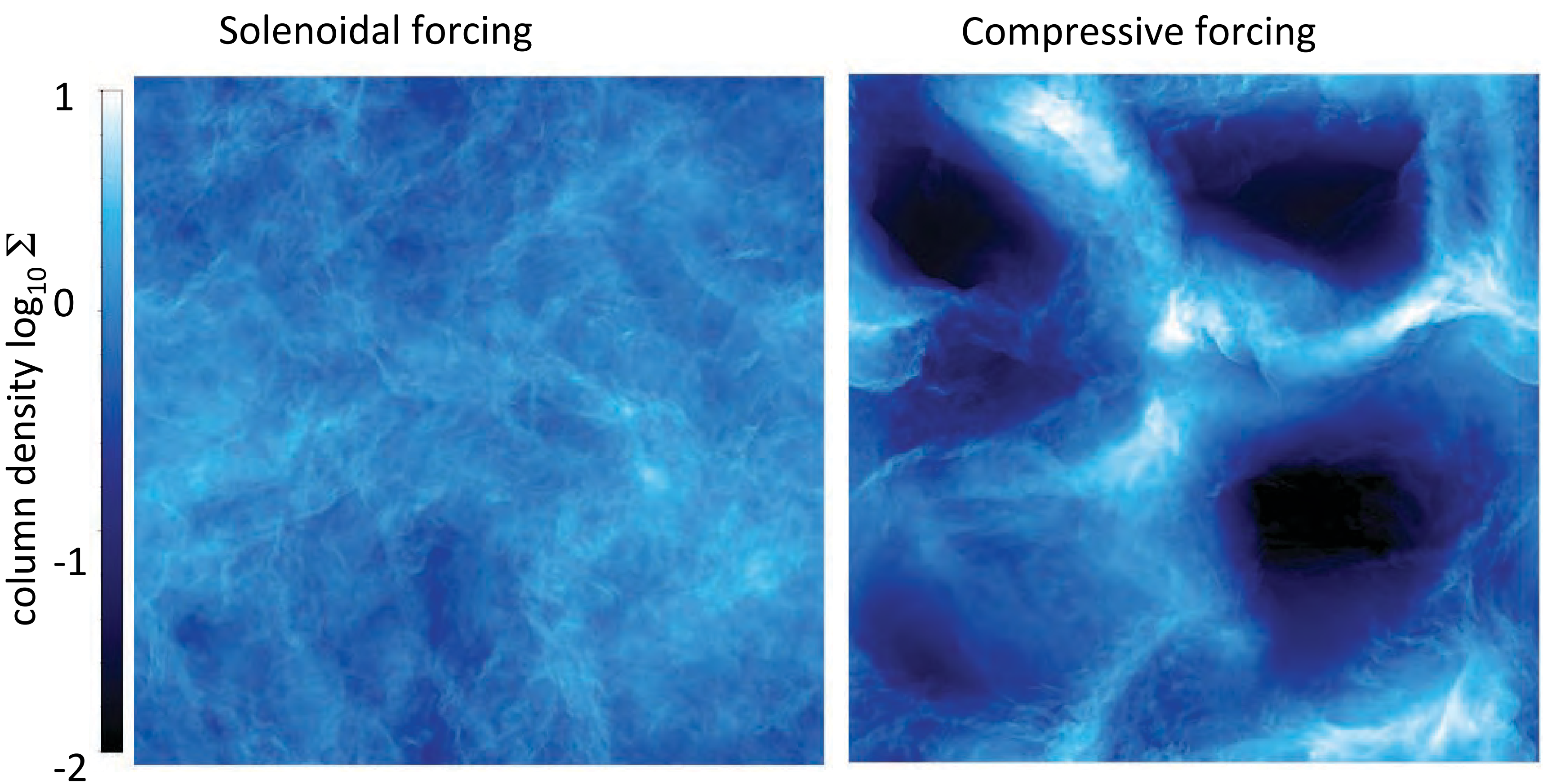
$$p_s(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s - s_0)^2}{2\sigma_s^2}\right)$$

$$s \equiv \ln(\rho/\rho_0) \qquad s_0 = -\frac{1}{2}\sigma_s^2$$

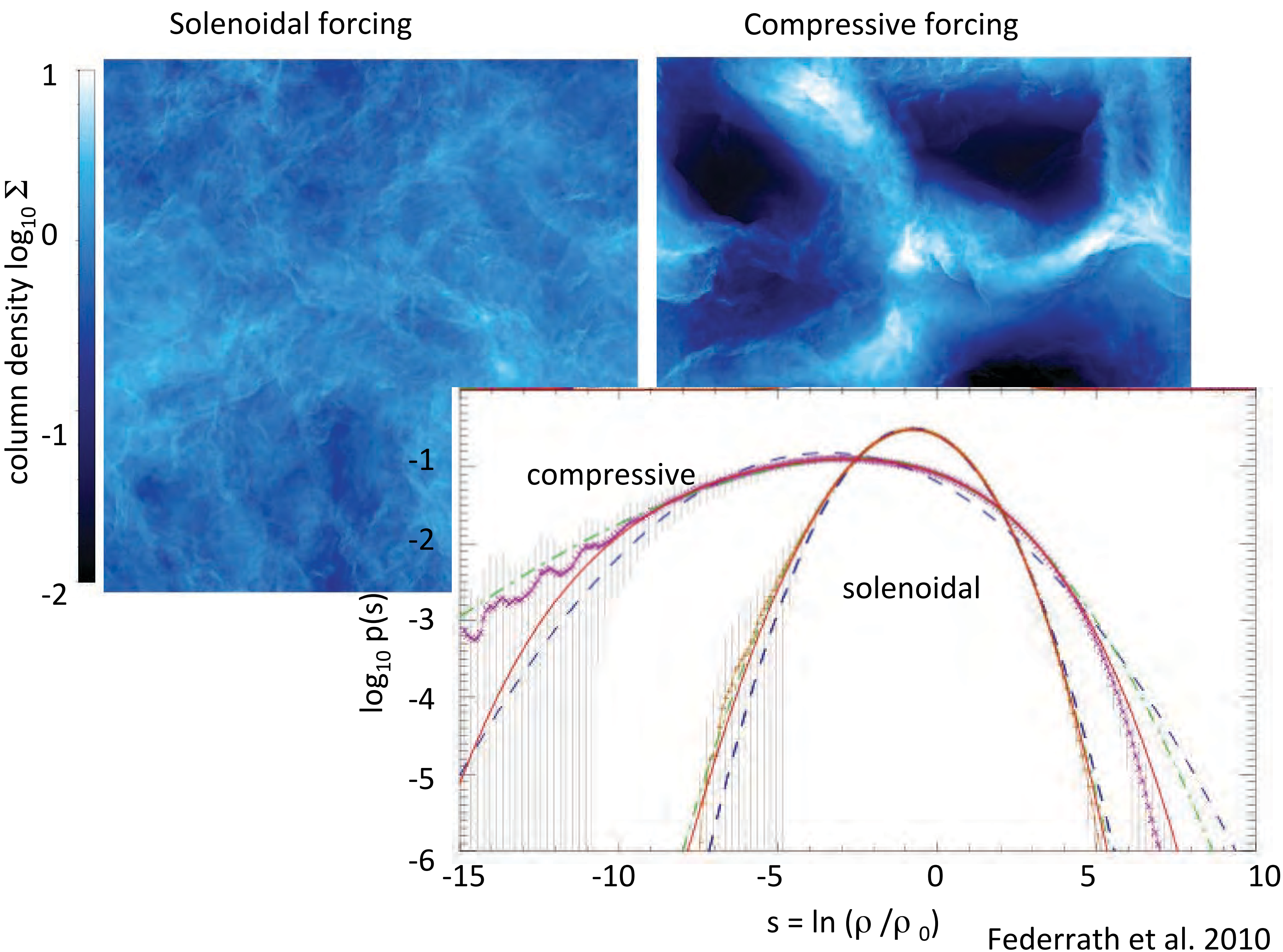
Herschel/SPIRE 250 μm image

Schneider et al. 2013

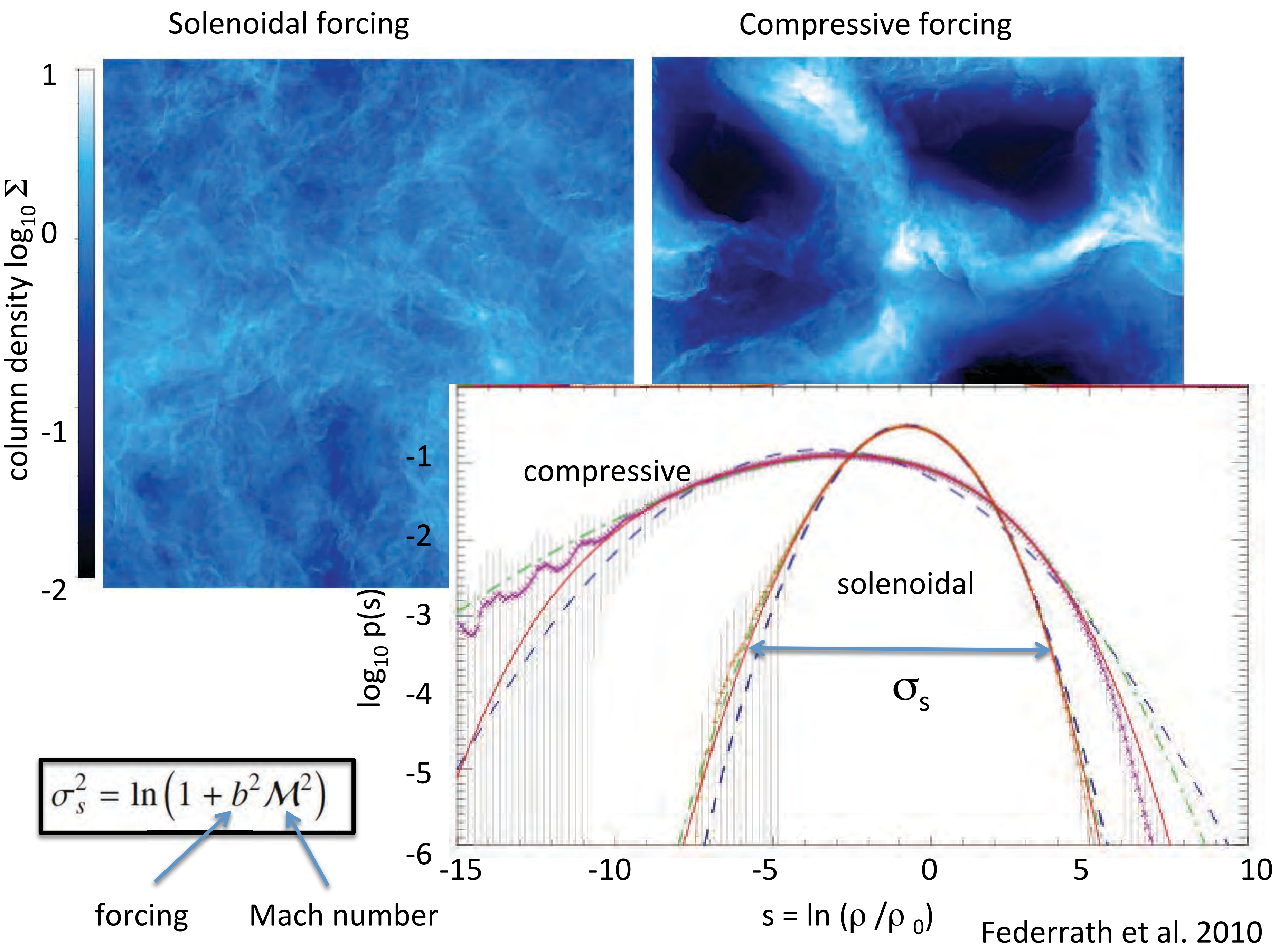
What about σ_s?



Federrath et al. 2010



Solenoidal forcing
Compressive forcing
column density $\log_{10}\Sigma$
1
0
-1
-2
compressive
solenoidal
$\log_{10} p(s)$
-1
-2
-3
-4
-5
-6
-15
-10
-5
0
5
10
$s = \ln(\rho/\rho_0)$
Federrath et al. 2010



Solenoidal forcing
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1
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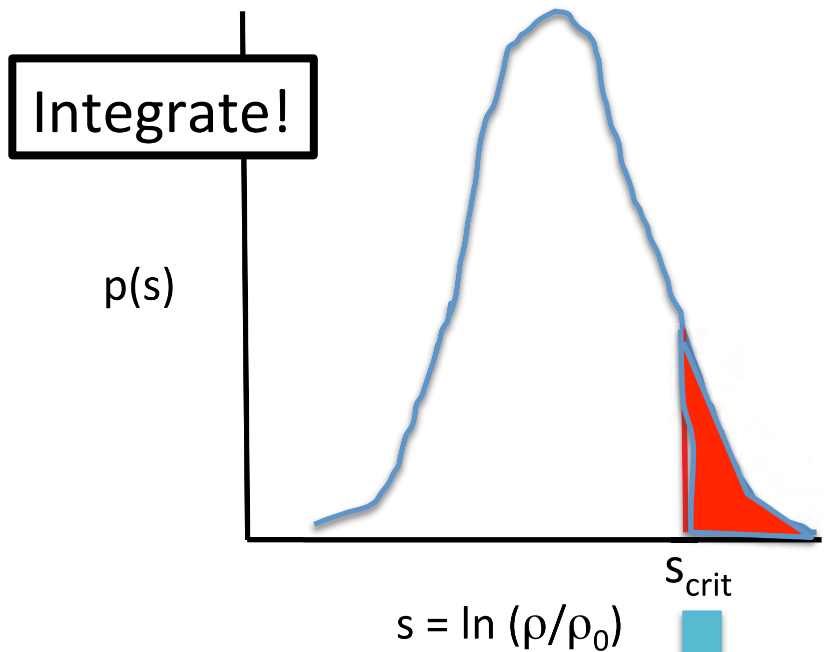
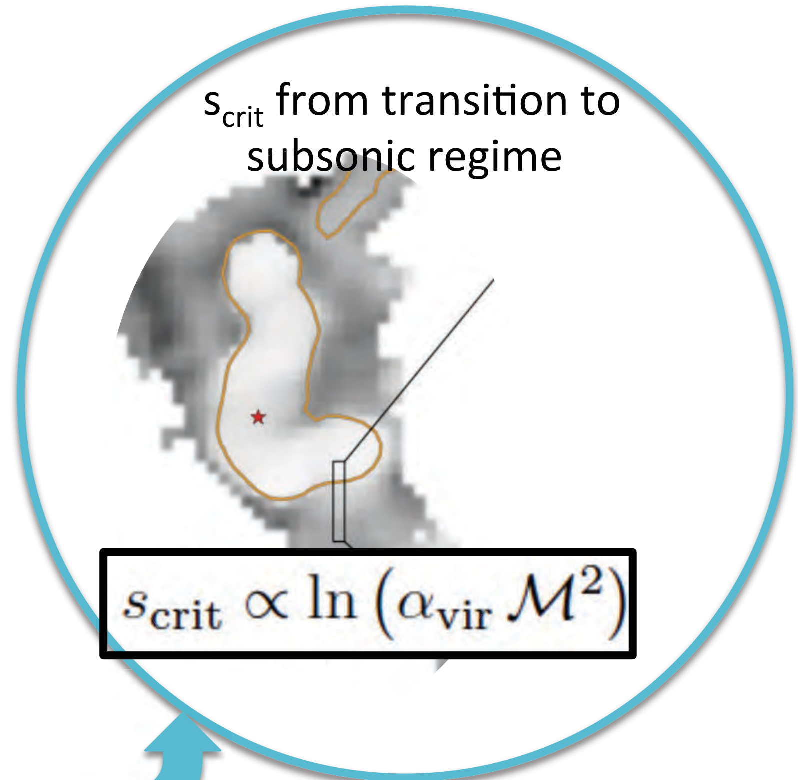
σ_s
$\log_{10} p(s)$
-1
-2
-3
-4
-5
-6
-15
-10
-5
0
5
10
$s = \ln(\rho/\rho_0)$
$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)$
forcing
Mach number
Federrath et al. 2010

Can we use the PDF to derive a star formation efficiency?





Krumholtz & McKee 2005

star formation = efficiency

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s)\,\mathrm{d}s$$

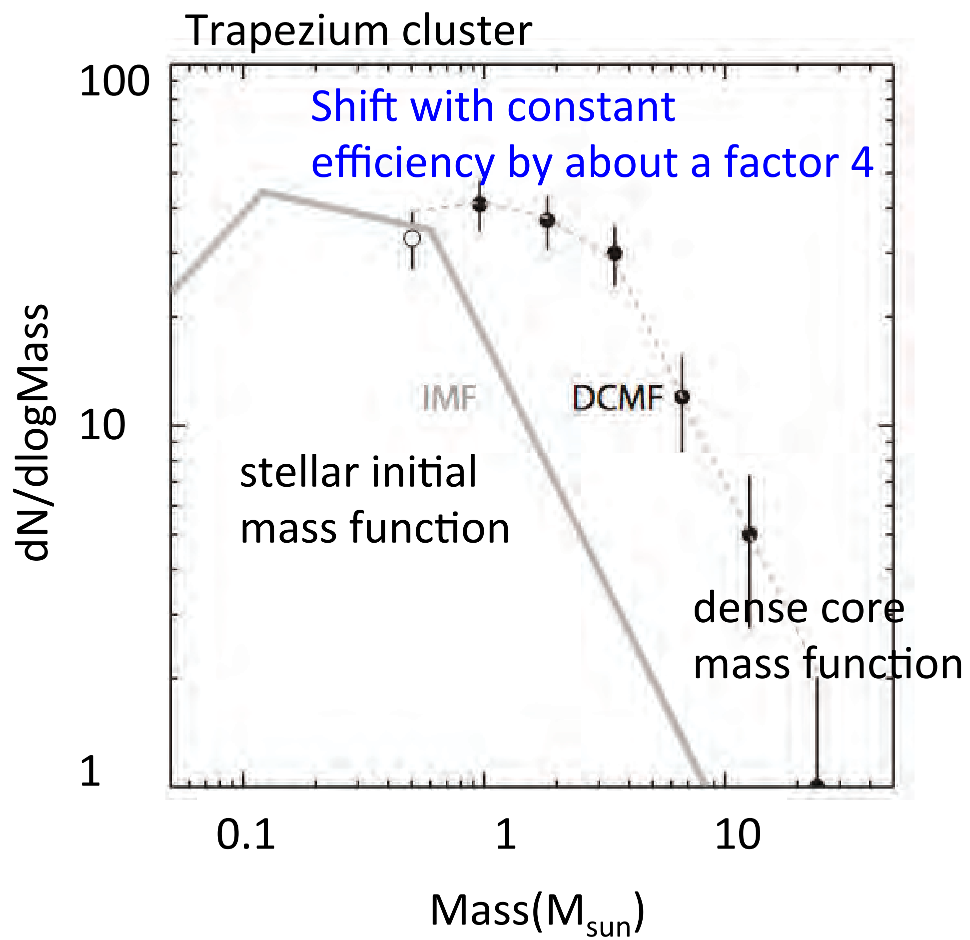
$$\mathrm{SFR}_{\mathrm{ff}} = \mathrm{SFR}_{\mathrm{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}\right)$$

$2\ E_{kin}/E_{grav}$ forcing Mach number

Federrath & Klessen 2012

Dust under the carpet: the core-to-star efficiency

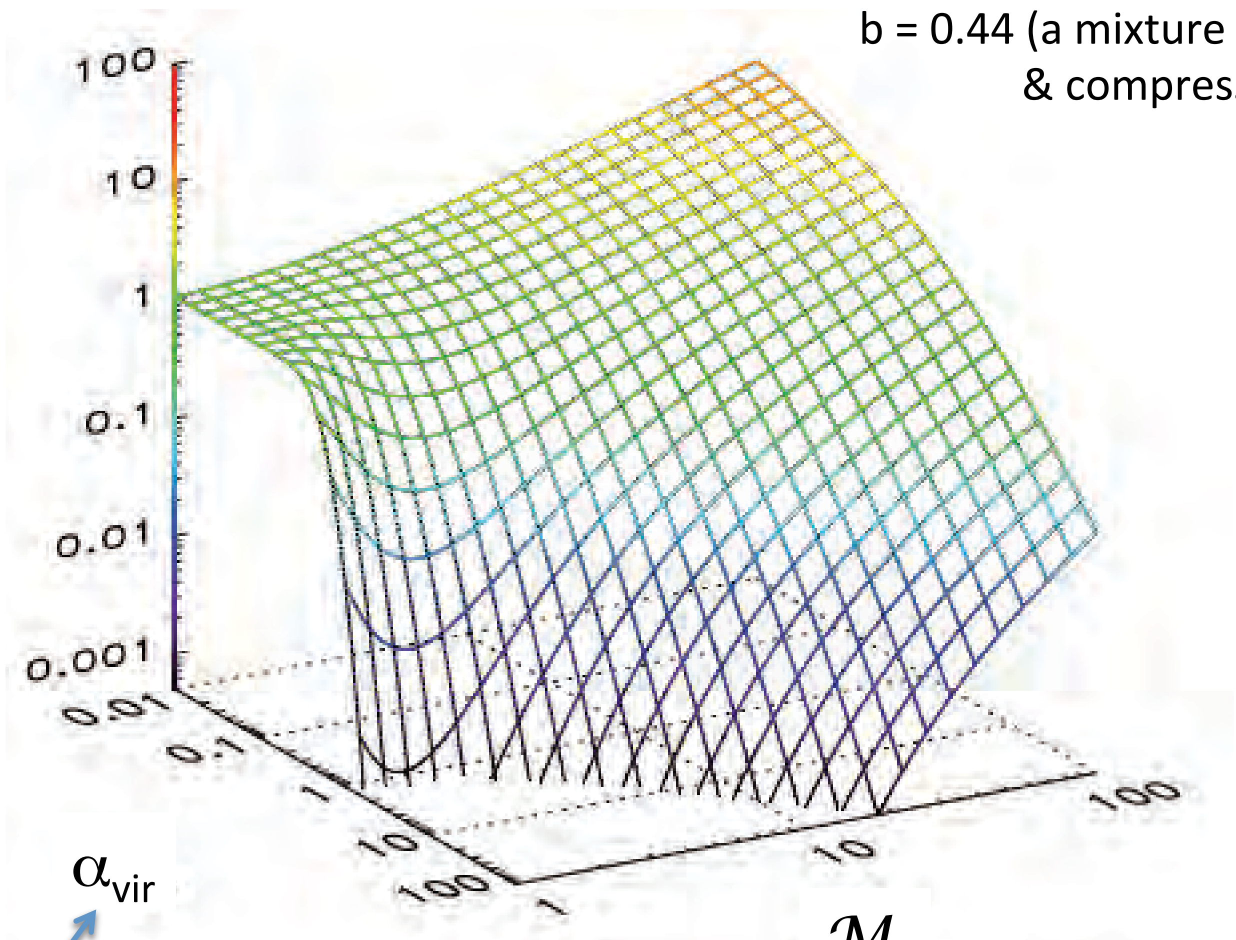
$$\mathrm{SFR_{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s)\, \mathrm{d}s$$



Alves et al. 2007

Dependence of star formation efficiency on dynamic properties of gas

b = 0.44 (a mixture of solenoidal & compressible modes)



SFR$_{ff}$

star formation efficiency

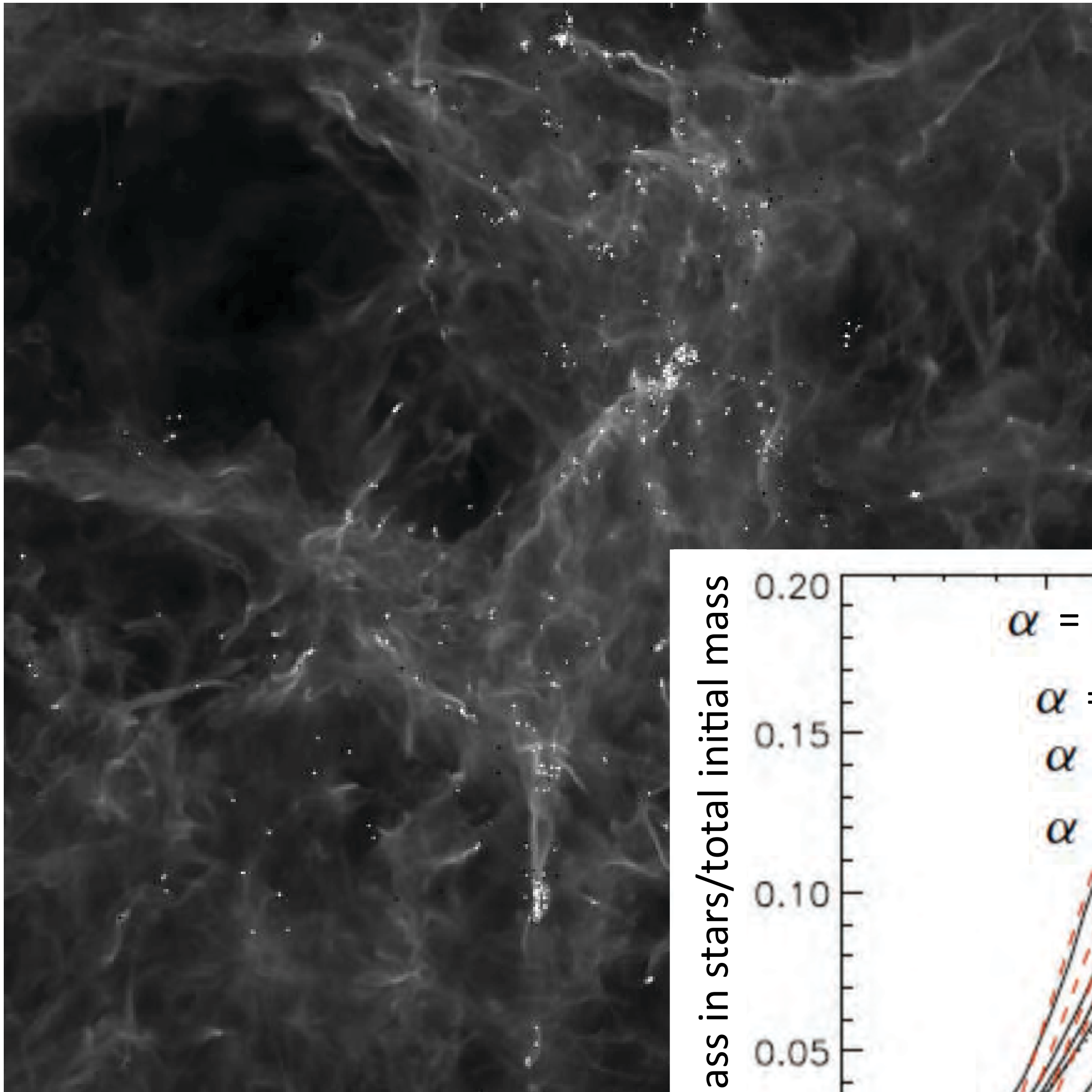
α_{vir}

2 E $_{kin}$/E $_{grav}$

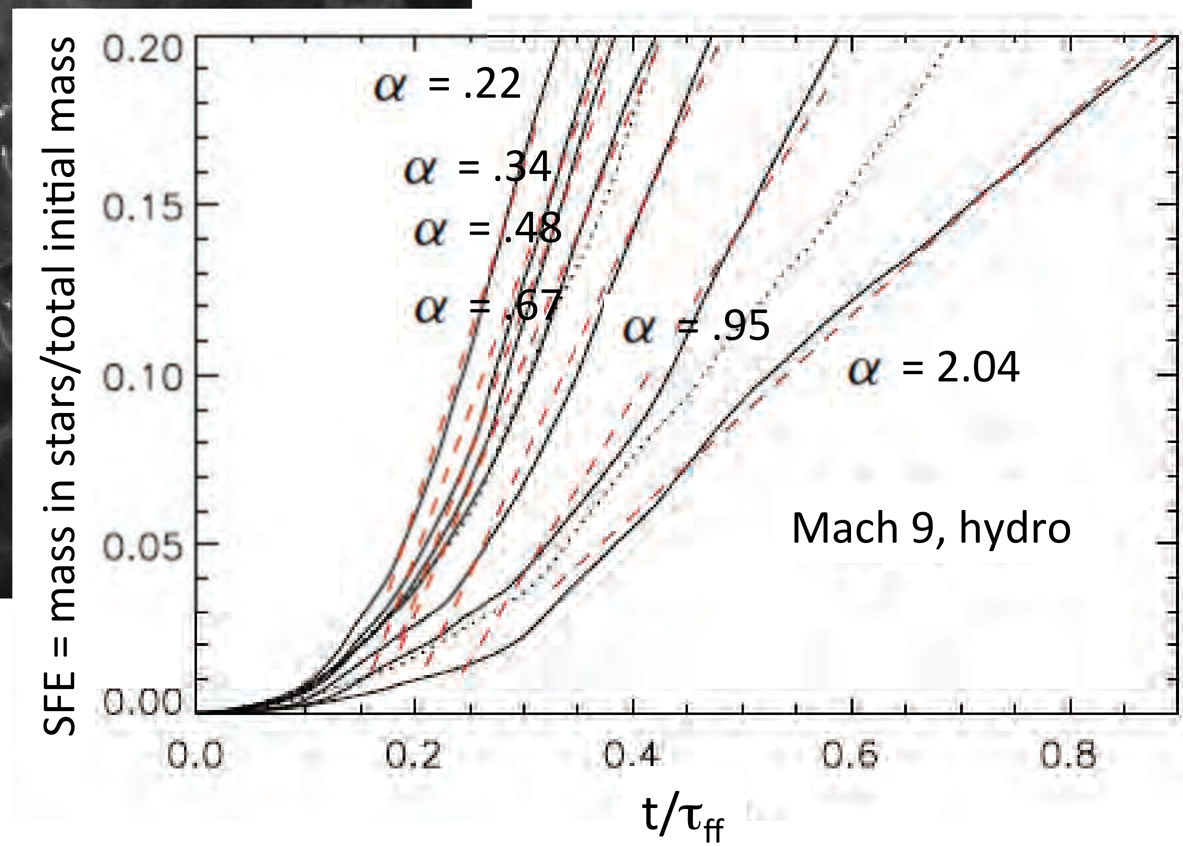
$\mathcal{M}$

Mach number

Federrath & Klessen 2012

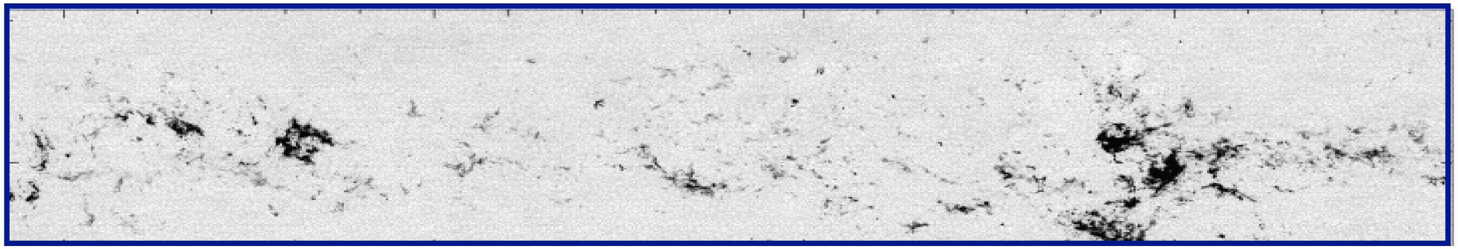


Excellent description of star formation rate in high resolution driven supersonic turbulence simulations (reduced chi squared of order unity)



Padoan & Nordlund 2011

How should we form stars in simulations?



if $\sigma_{\rm eff}^2 + c_s^2 < \beta\, G\, M$

Hopkins, Narayanan, Murray 2013

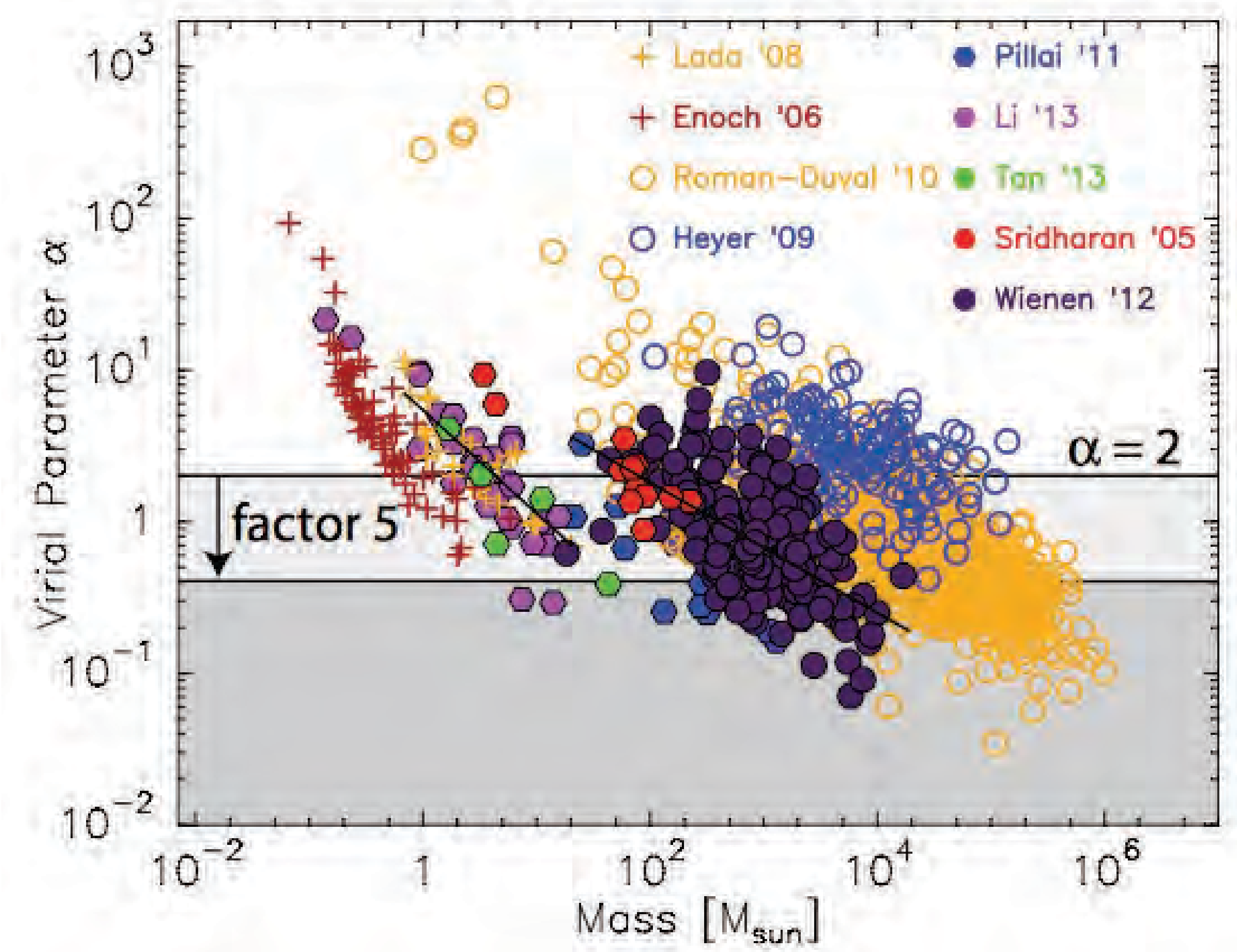
No more resolution-dependent density threshold!

Self-gravity criterion (beta ~ 1) equiv to “turbulent” Jeans length to pick the locii of star formation → no need to add (numerical) pressure support

$$\dot{\rho}_* = \frac{\epsilon\, \rho}{t_{\rm ff}}$$

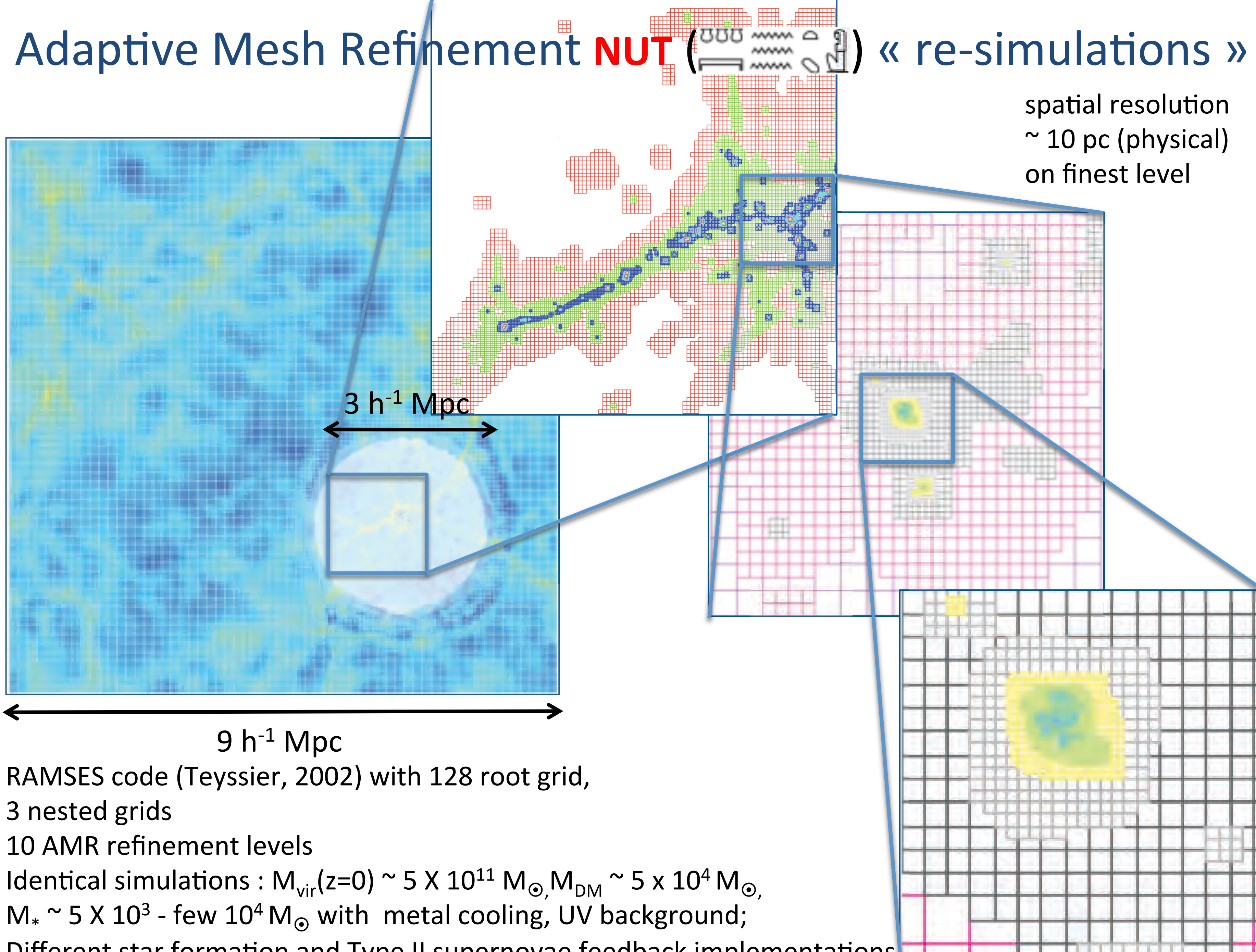
with ϵ = $\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\rm vir}, b, \mathcal{M})$ Federrath & Klessen 2012

How wrong is it? What values for the virial parameter?



Kauffmann et al. 2013

Adaptive Mesh Refinement **NUT** ( ) « re-simulations » …

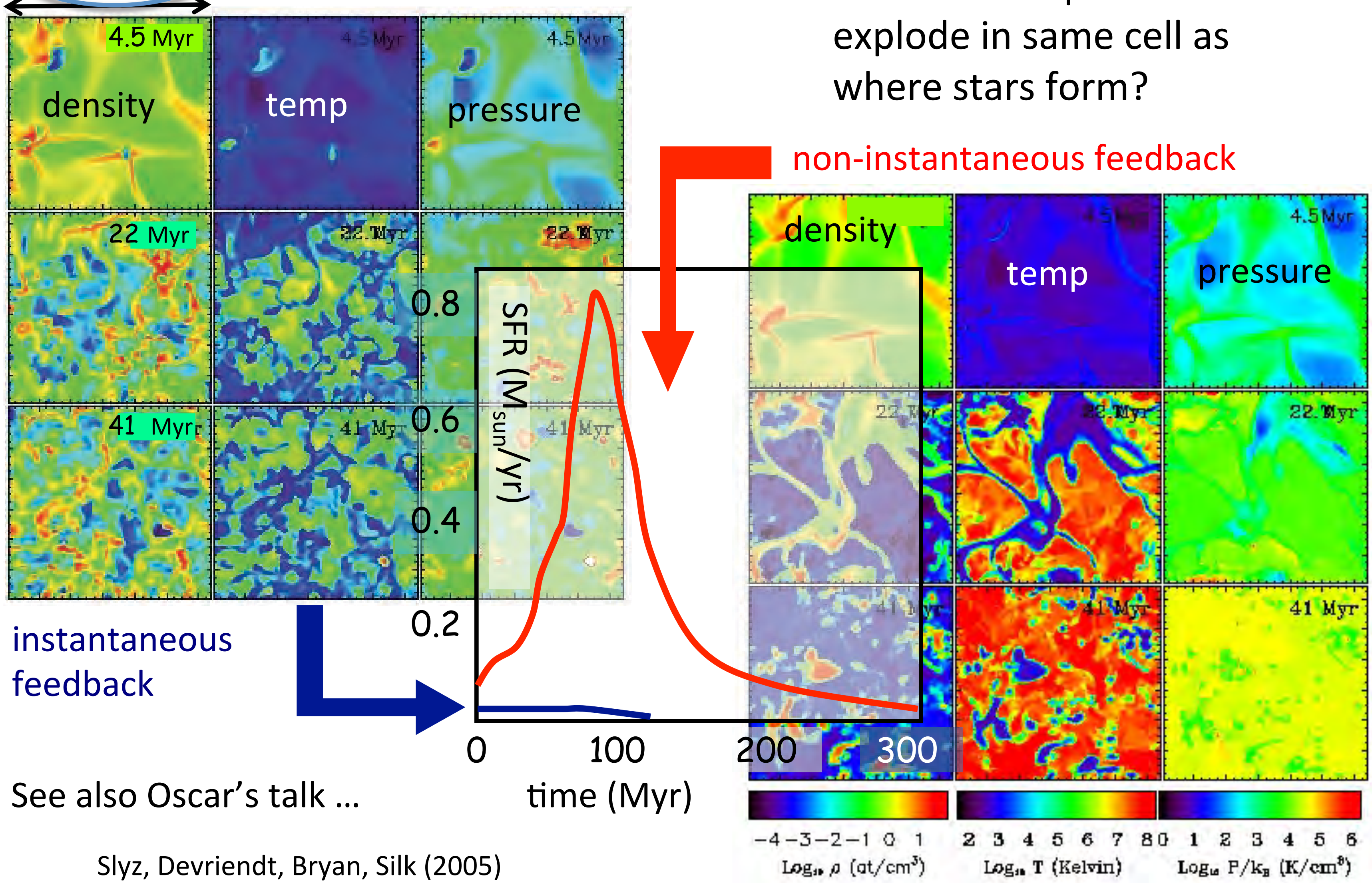


RAMSES code (Teyssier, 2002) with 128 root grid,
3 nested grids
10 AMR refinement levels
Identical simulations : $M_{vir}(z=0) \sim 5 \times 10^{11}\, M_\odot$, $M_{DM} \sim 5 \times 10^4\, M_\odot$,
$M_* \sim 5 \times 10^3$ - few $10^4\, M_\odot$ with metal cooling, UV background;
Different star formation and Type II supernovae feedback implementations

What about (SN) feedback ? → linked to SF

1 kpc → Typical res of cosmo sims!

What if let supernovave explode in same cell as where stars form?



See also Oscar's talk …

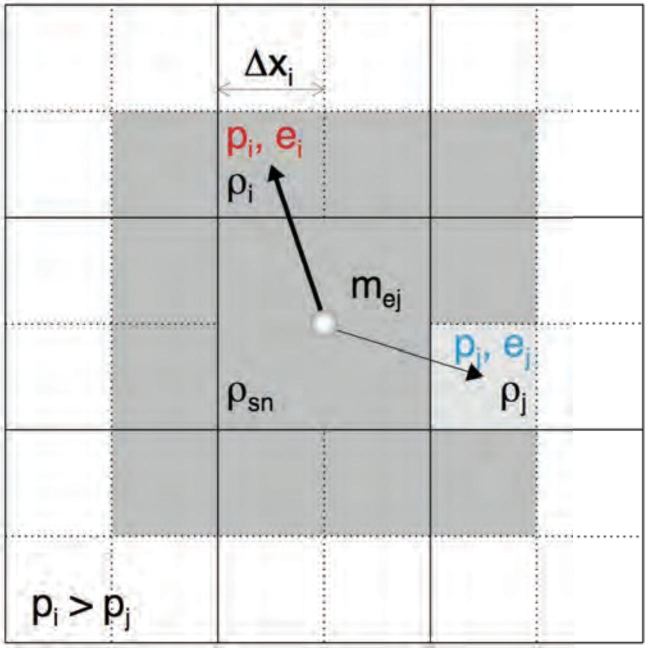
Slyz, Devriendt, Bryan, Silk (2005)

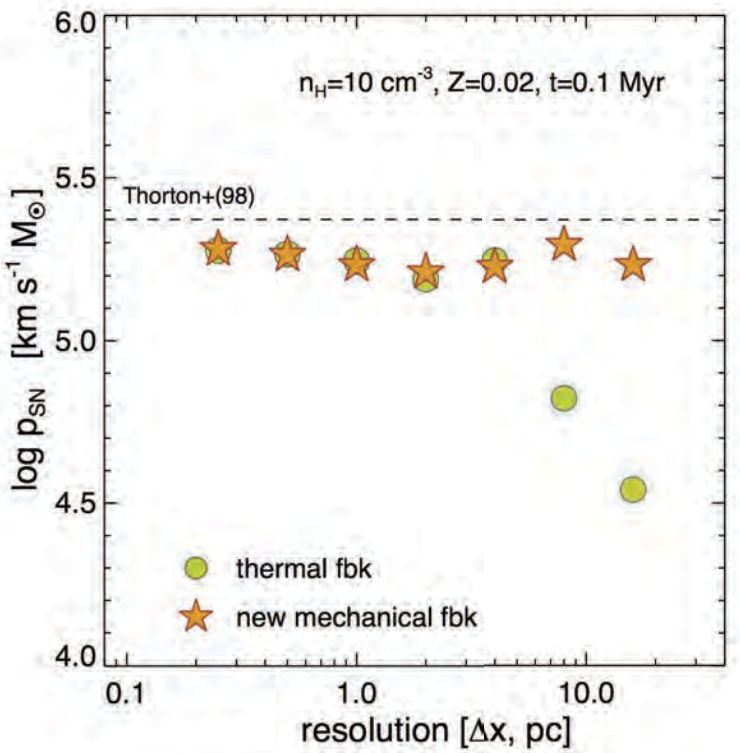
Supernovae Feedback implementation in this talk

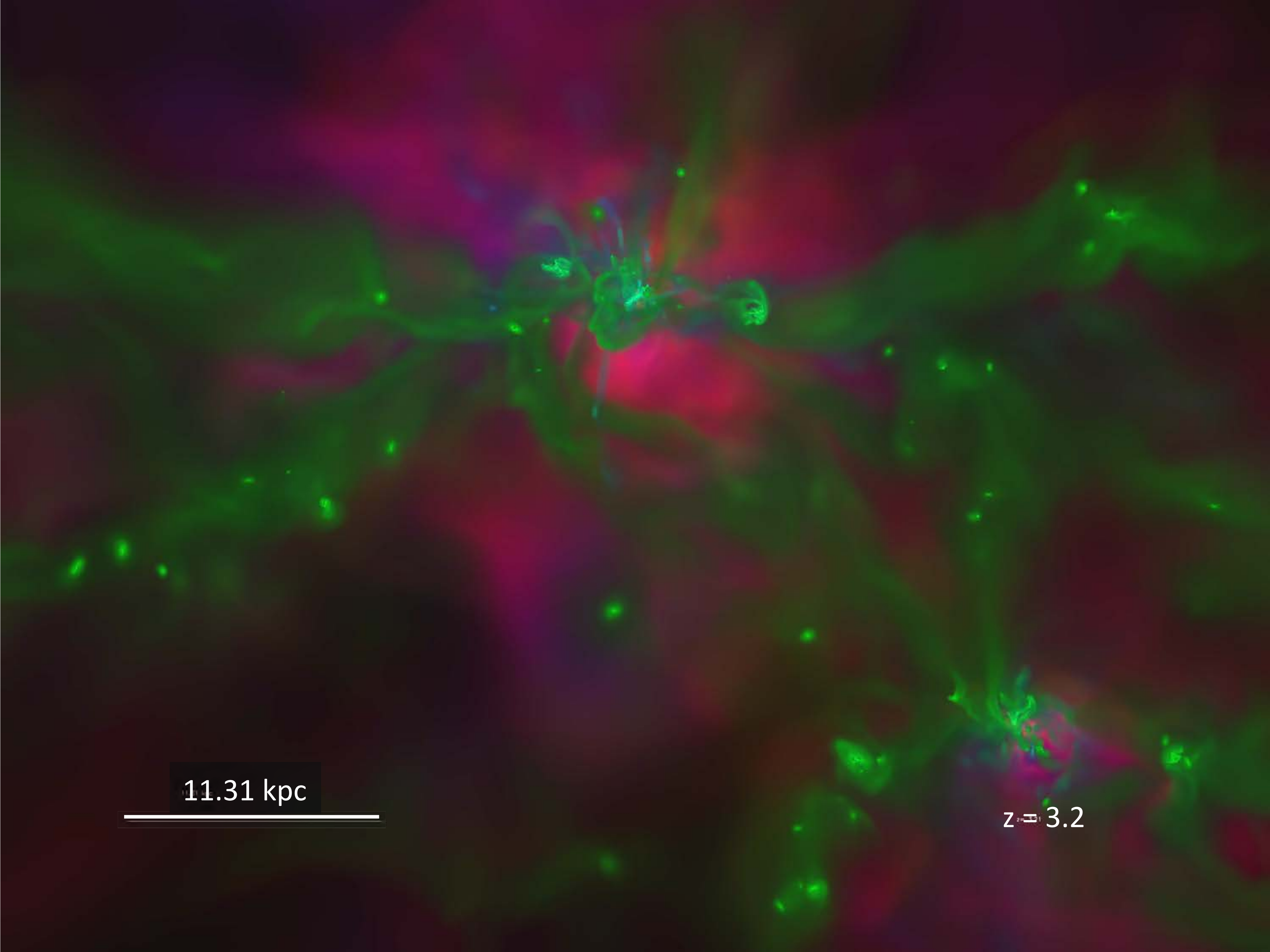
If energy conserving phase is captured
→ Sedov solution a la Dubois & Teyssier 2008

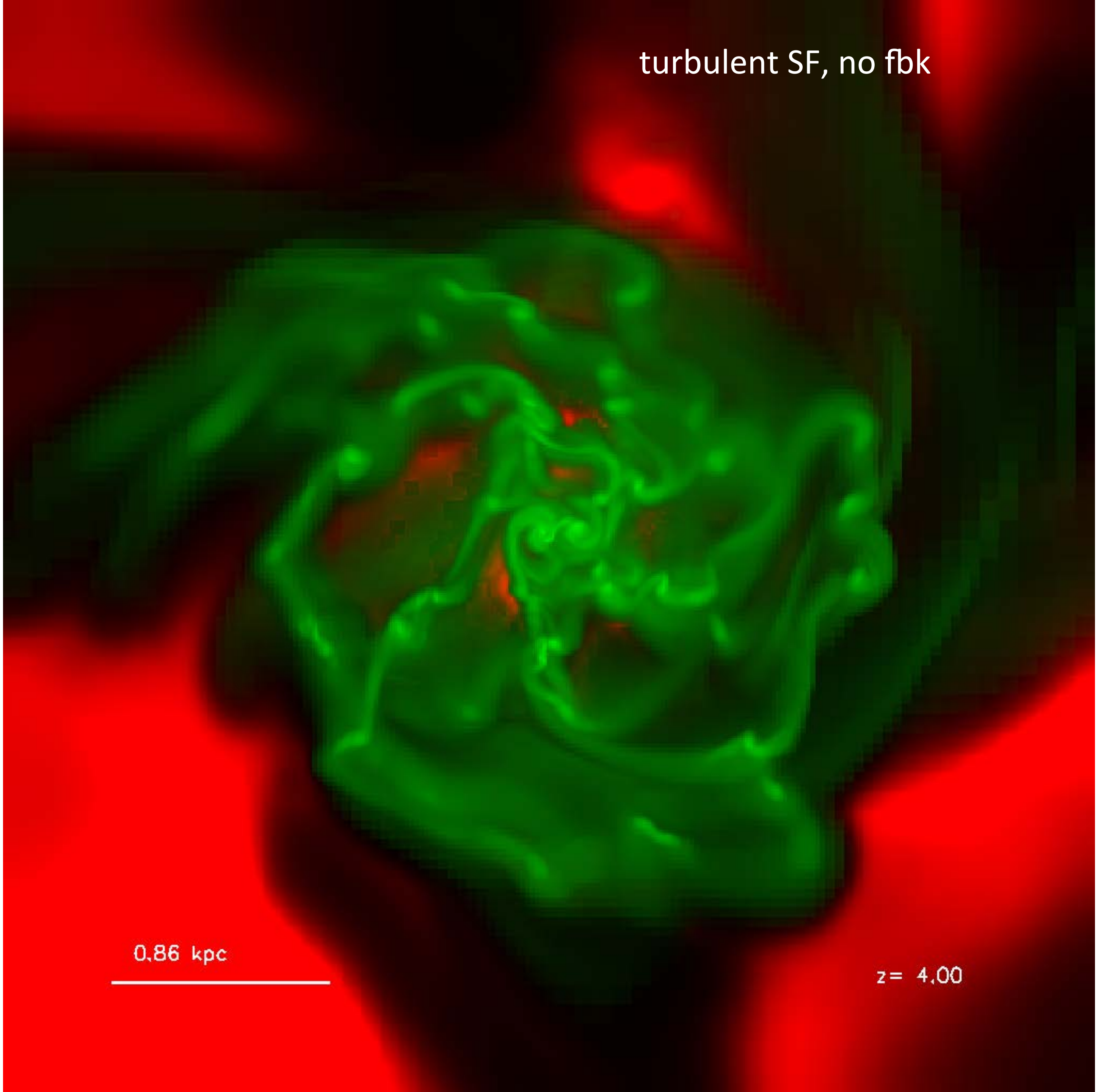
If only momentum conserving phase is captured
→ Kimm & Cen 2014

→ Simple 10 Myr time delay in both cases
as in 2005 paper

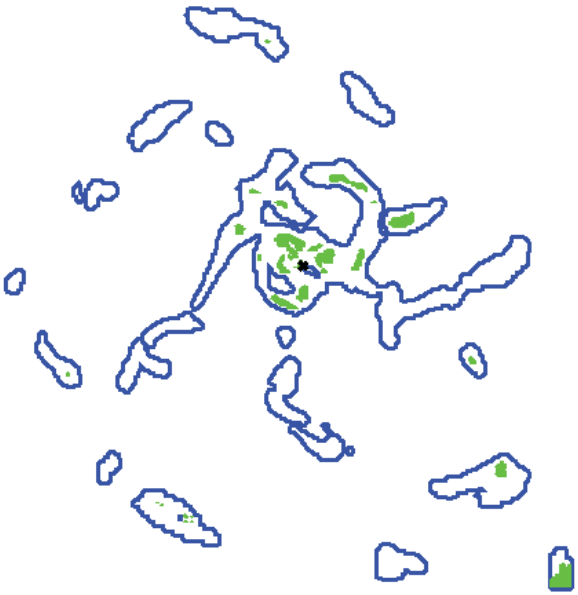





11.31 kpc
z = 3.2



Devriendt, Slyz, Kimm (in prep)



Blue contours: isodensity at 100 at/cm^3
Green : gravitationally unstable regions

Simulations

1. density threshold star formation, no SN feedback

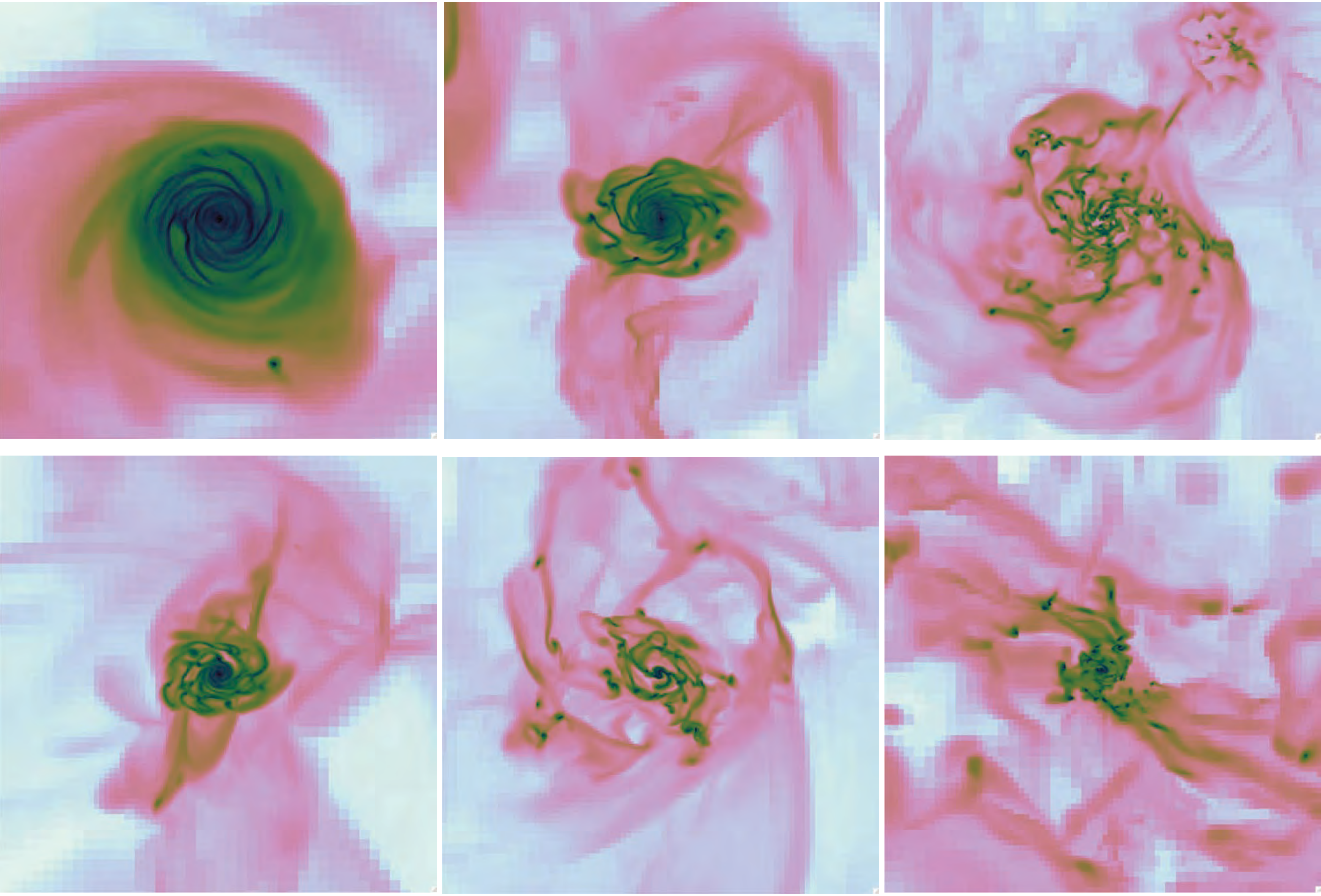
2. " , energy conserving SN fbk

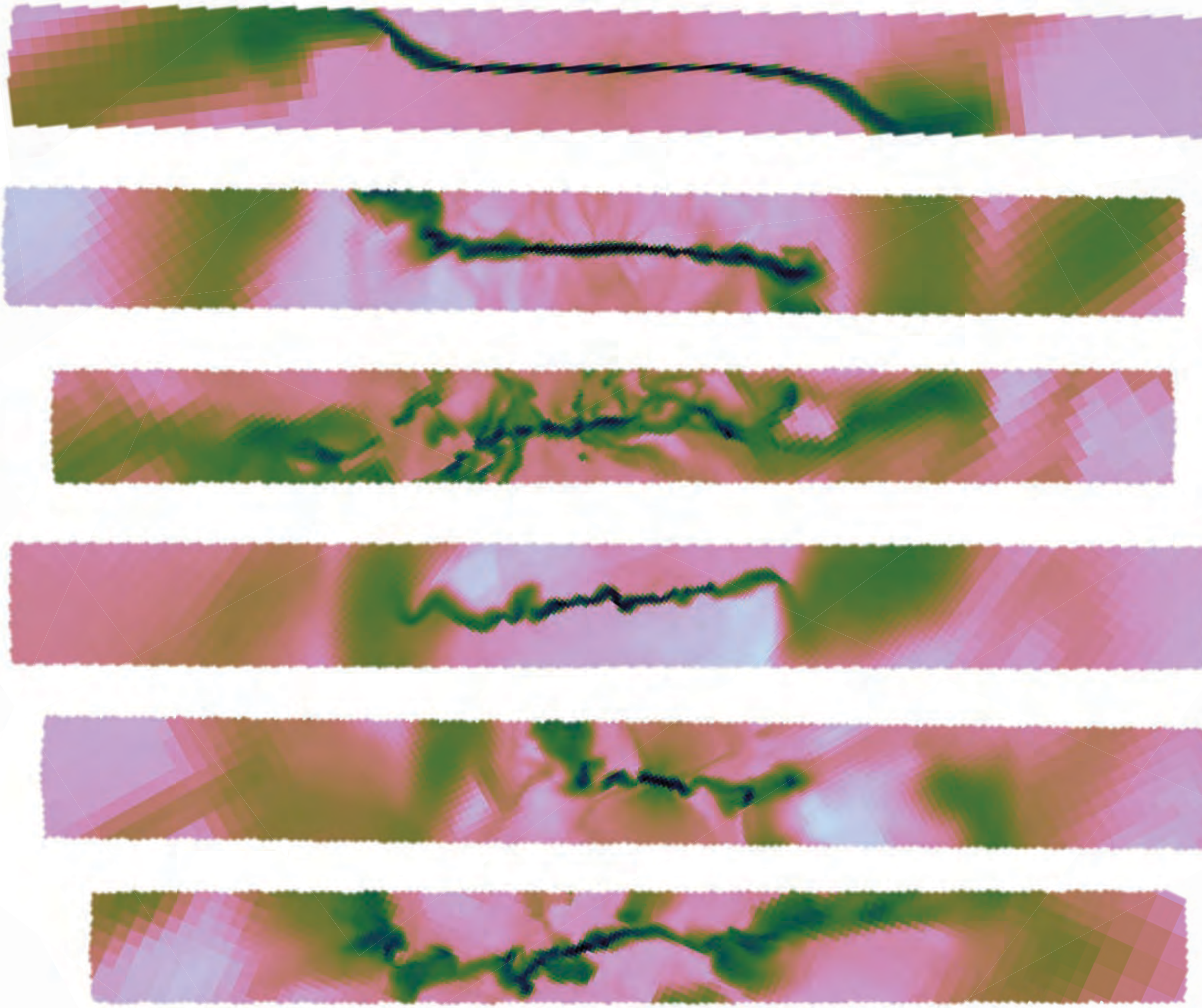
3. " , momentum conserving SN fbk

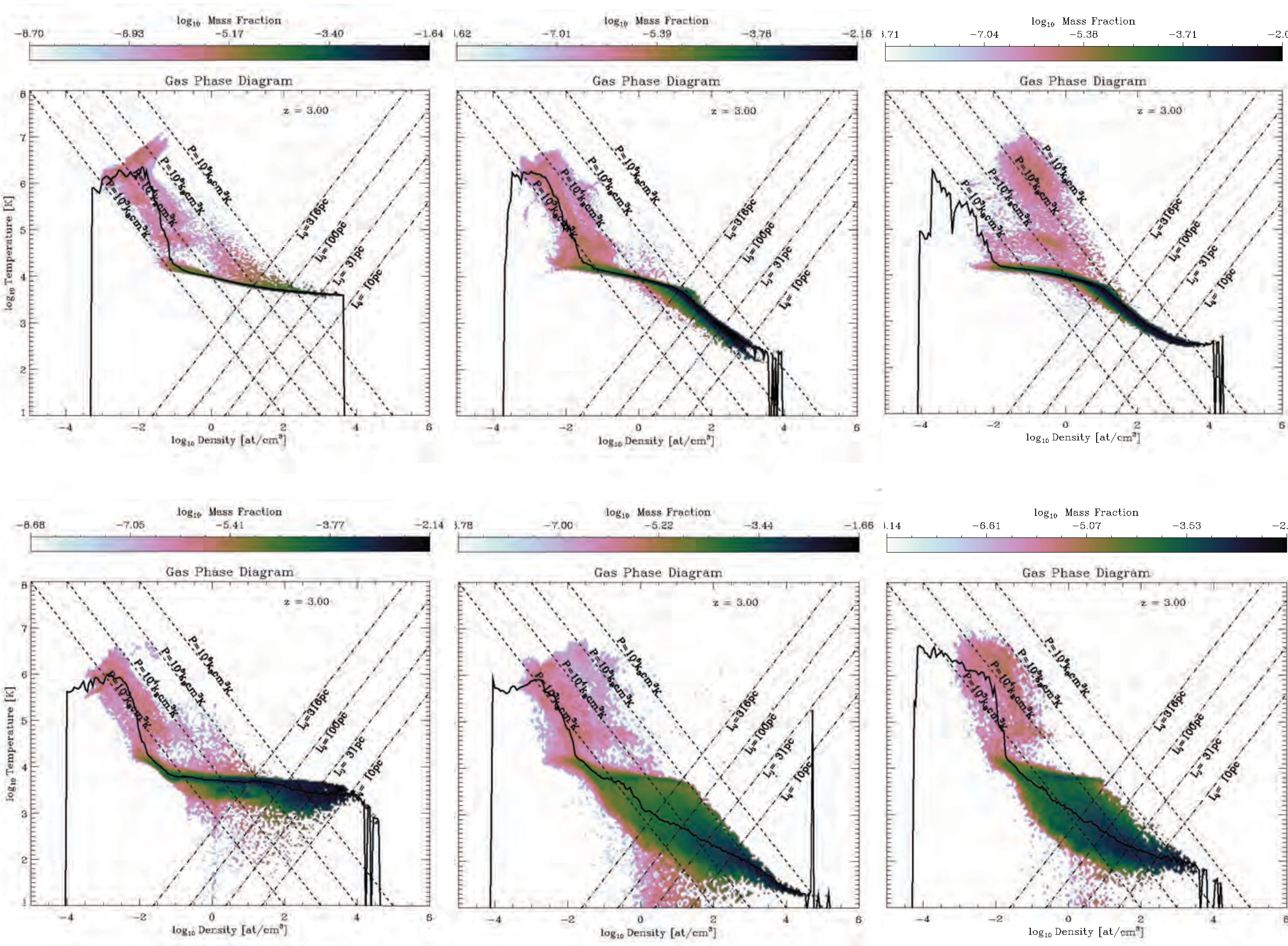
4. turbulent star formation, no SN feedback

5. " , energy conserving SN fbk

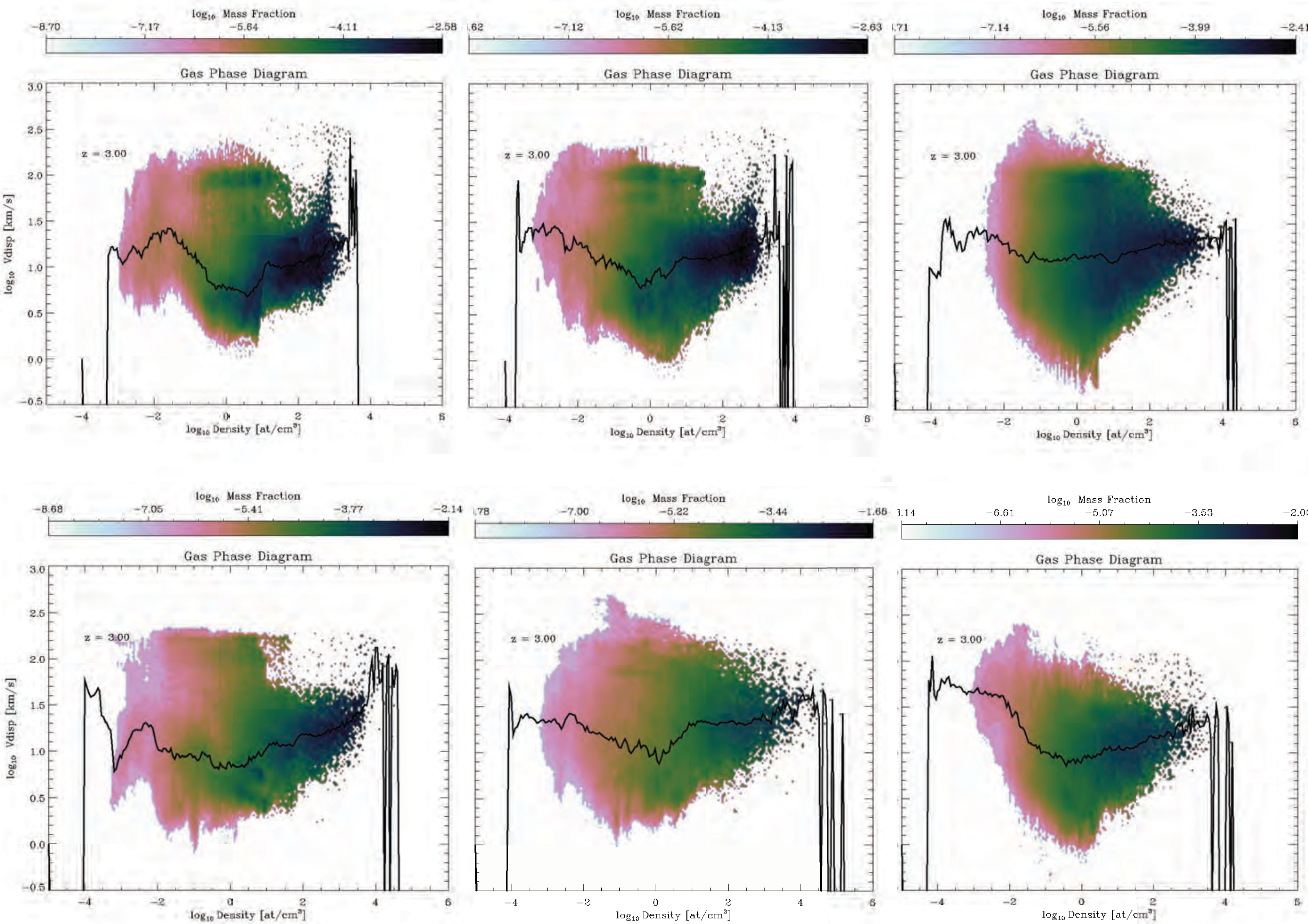
6. " , momentum conserving SN fbk



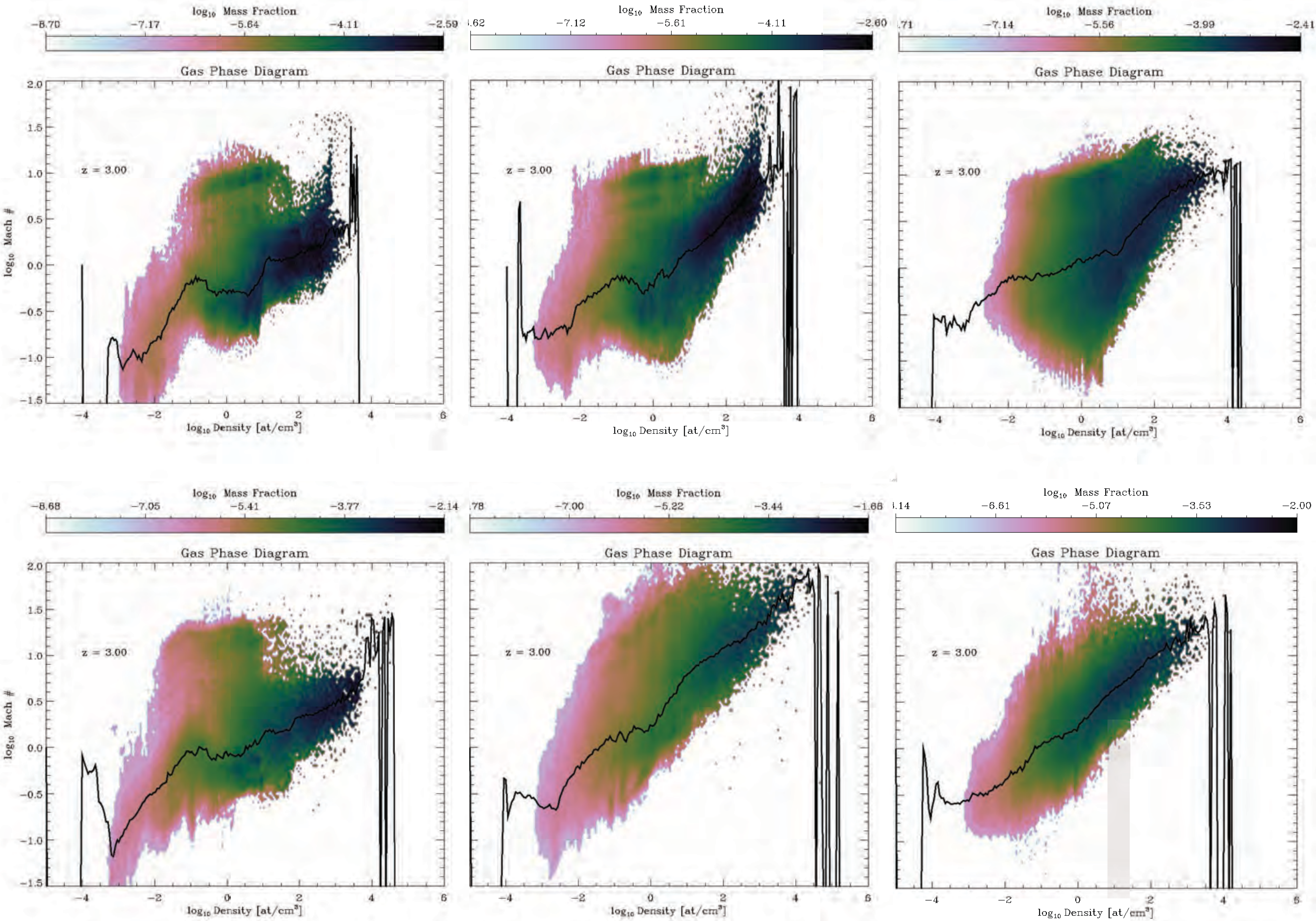




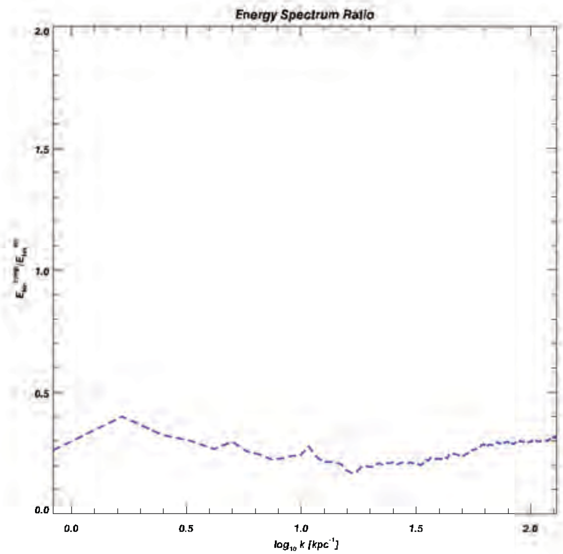
log10 Mass Fraction
-8.70 -6.93 -5.17 -3.40 -1.64
-7.01 -5.39 -3.78 -2.16
-7.04 -5.38 -3.71 -2.05
-8.68 -7.05 -5.41 -3.77 -2.14
-7.00 -5.22 -3.44 -1.66
-6.61 -5.07 -3.53 -2.00
Gas Phase Diagram
z = 3.00
log10 Temperature [K]
log10 Density [at/cm3]
P=10^3 kB cm^-3 K
P=10^4 kB cm^-3 K
P=10^5 kB cm^-3 K
P=10^6 kB cm^-3 K
LJ=316pc
LJ=100pc
LJ=31pc
LJ=10pc

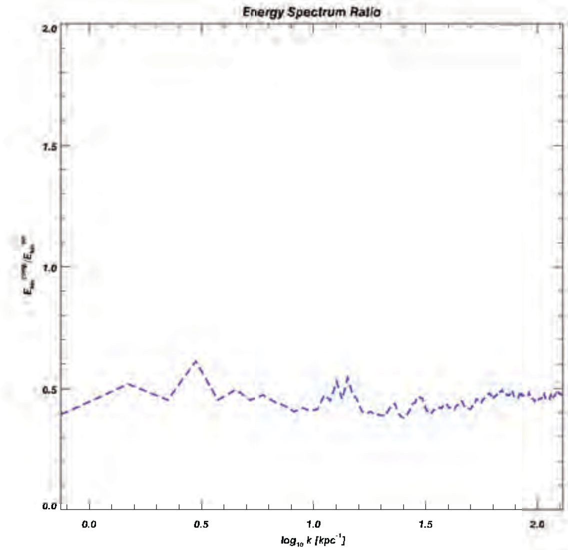


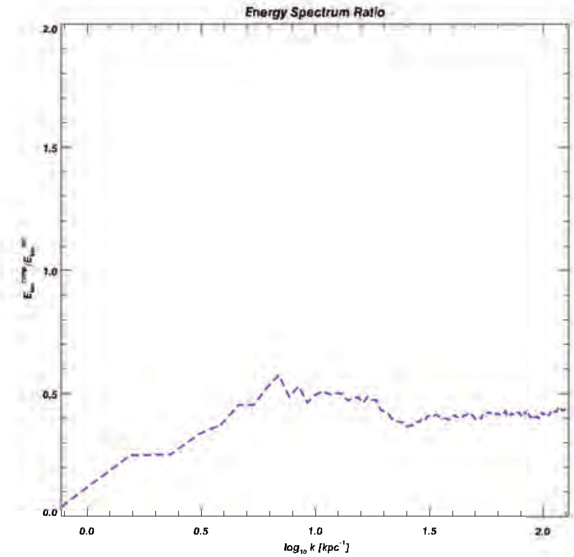
log10 Mass Fraction
−8.70 −7.17 −5.64 −4.11 −2.58
Gas Phase Diagram
z = 3.00
log10 Vdisp [km/s]
log10 Density [at/cm³]
log10 Mass Fraction
.62 −7.12 −5.62 −4.13 −2.63
Gas Phase Diagram
z = 3.00
log10 Density [at/cm³]
log10 Mass Fraction
.71 −7.14 −5.56 −3.99 −2.41
Gas Phase Diagram
z = 3.00
log10 Density [at/cm³]
log10 Mass Fraction
−8.68 −7.05 −5.41 −3.77 −2.14
Gas Phase Diagram
z = 3.00
log10 Vdisp [km/s]
log10 Density [at/cm³]
log10 Mass Fraction
.78 −7.00 −5.22 −3.44 −1.66
Gas Phase Diagram
z = 3.00
log10 Density [at/cm³]
log10 Mass Fraction
3.14 −6.61 −5.07 −3.53 −2.00
Gas Phase Diagram
z = 3.00
log10 Density [at/cm³]

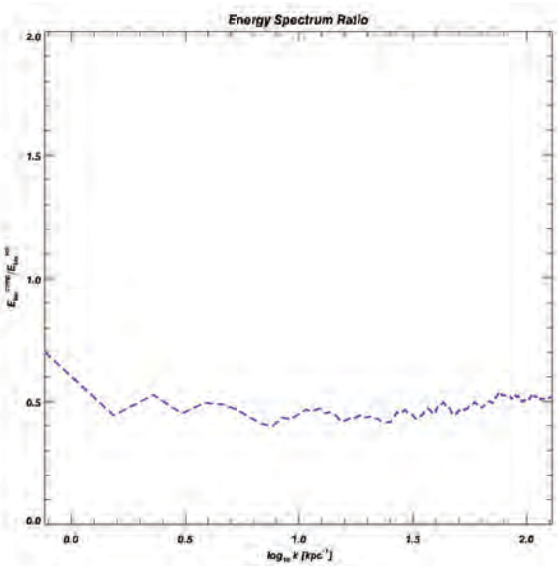

log10 Mass Fraction
−8.70 −7.17 −5.64 −4.11 −2.59
Gas Phase Diagram
z = 3.00
log10 Mach #
log10 Density [at/cm3]
log10 Mass Fraction
.62 −7.12 −5.61 −4.11 −2.60
Gas Phase Diagram
z = 3.00
log10 Density [at/cm3]
log10 Mass Fraction
.71 −7.14 −5.56 −3.99 −2.41
Gas Phase Diagram
z = 3.00
log10 Density [at/cm3]
log10 Mass Fraction
−8.68 −7.05 −5.41 −3.77 −2.14
Gas Phase Diagram
z = 3.00
log10 Mach #
log10 Density [at/cm3]
log10 Mass Fraction
.78 −7.00 −5.22 −3.44 −1.66
Gas Phase Diagram
z = 3.00
log10 Density [at/cm3]
log10 Mass Fraction
.14 −6.61 −5.07 −3.53 −2.00
Gas Phase Diagram
z = 3.00
log10 Density [at/cm3]

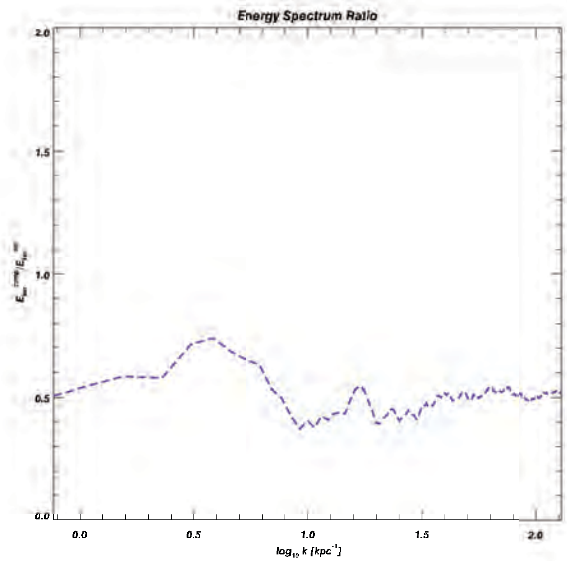
Measure of the mix between compressible and solenoidal energy

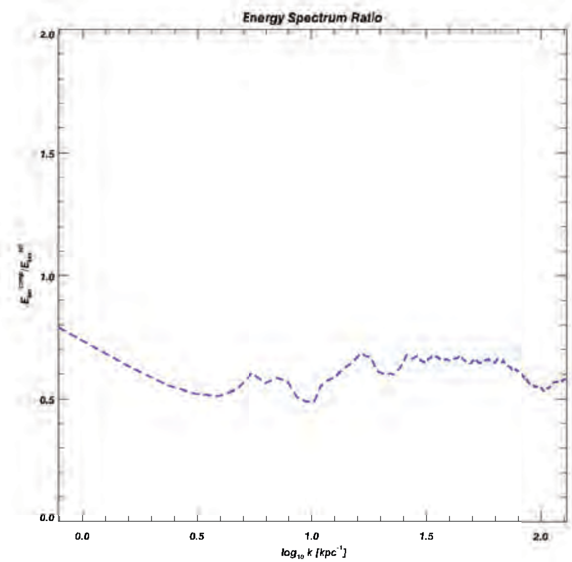




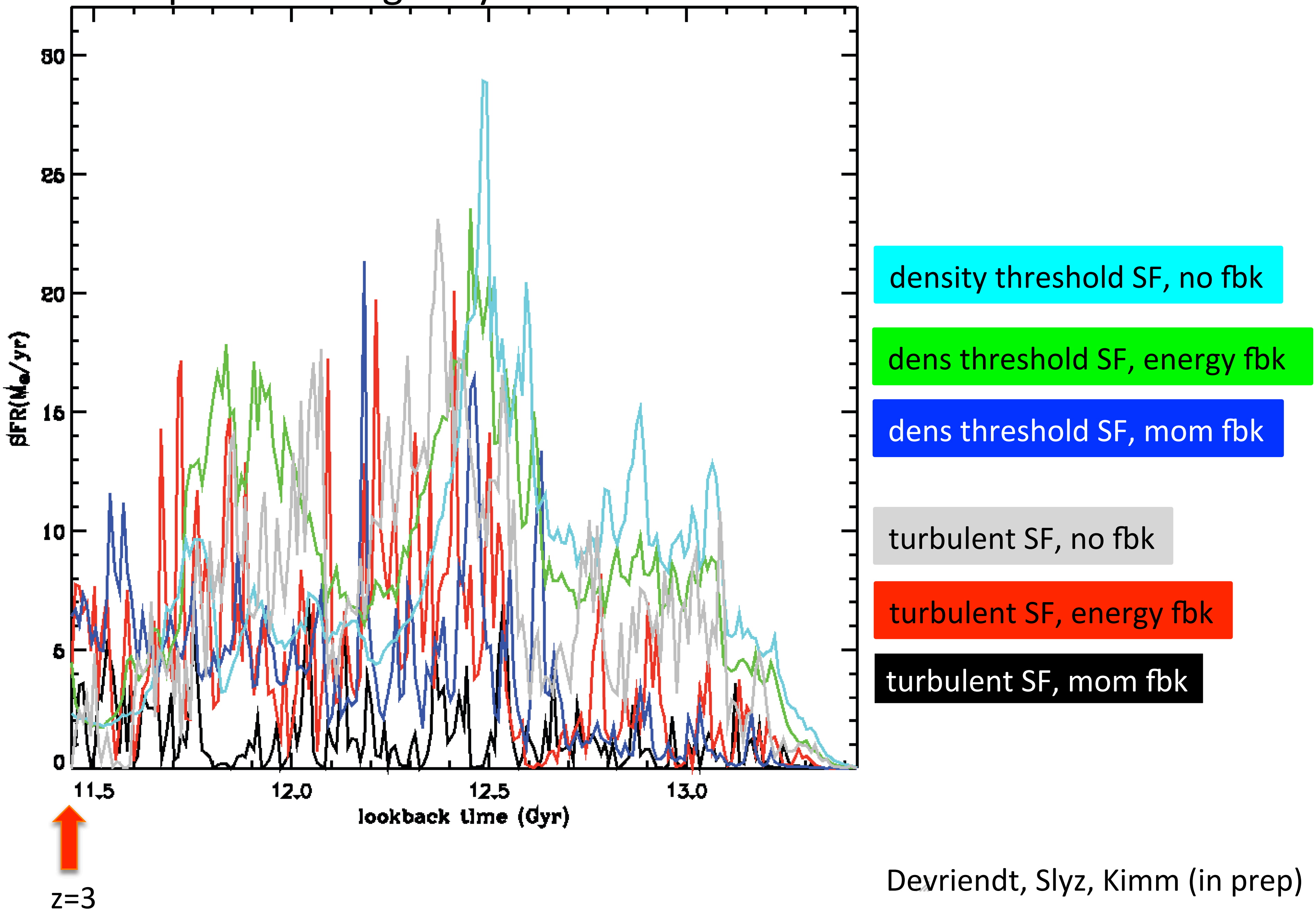








Impact on the galaxy star formation rate



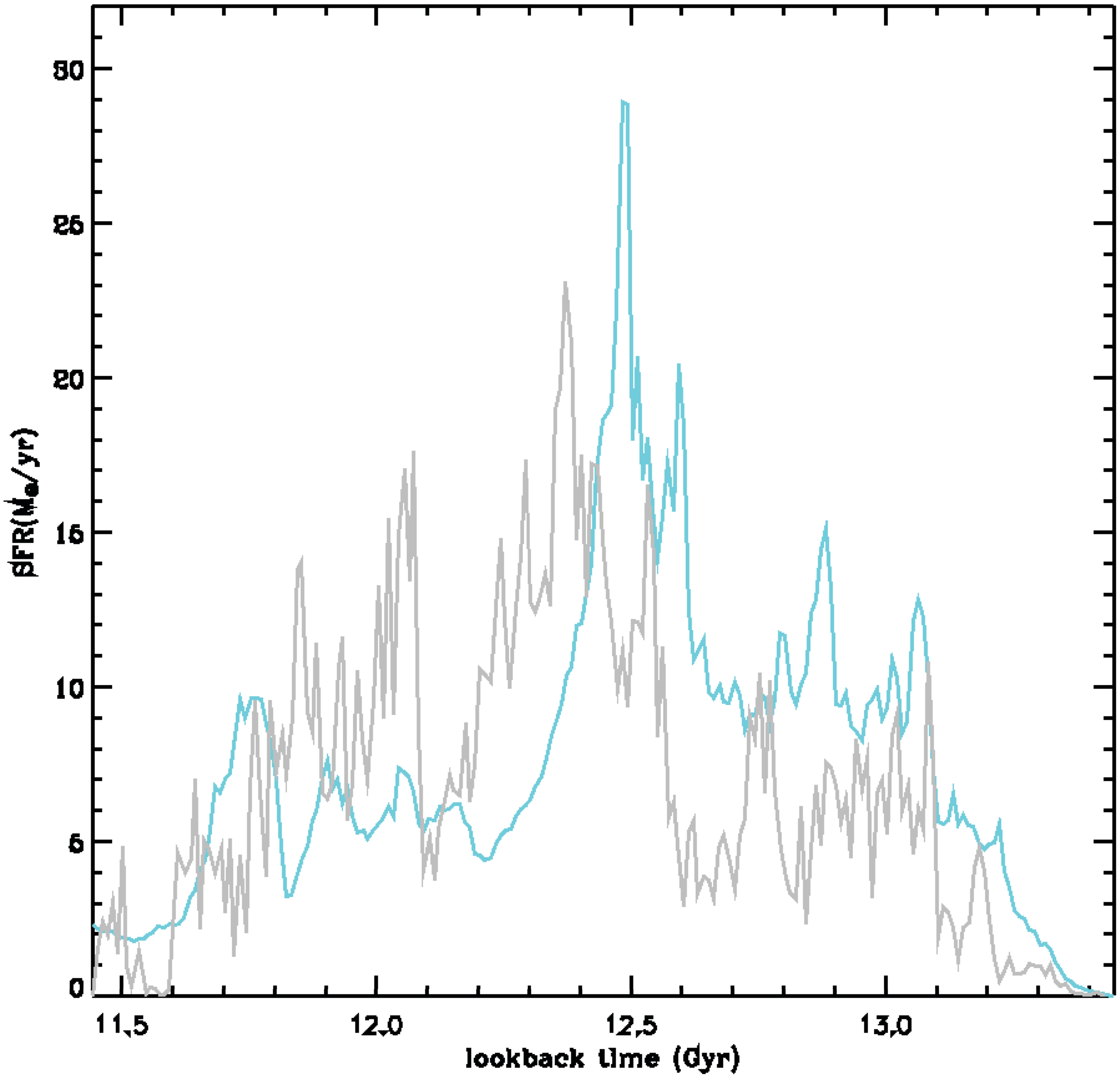
Devriendt, Slyz, Kimm (in prep)

No feedback runs

Stellar mass @ z=3

$1.5\ 10^{10}\ M_{sun}$

$1.3\ 10^{10}\ M_{sun}$

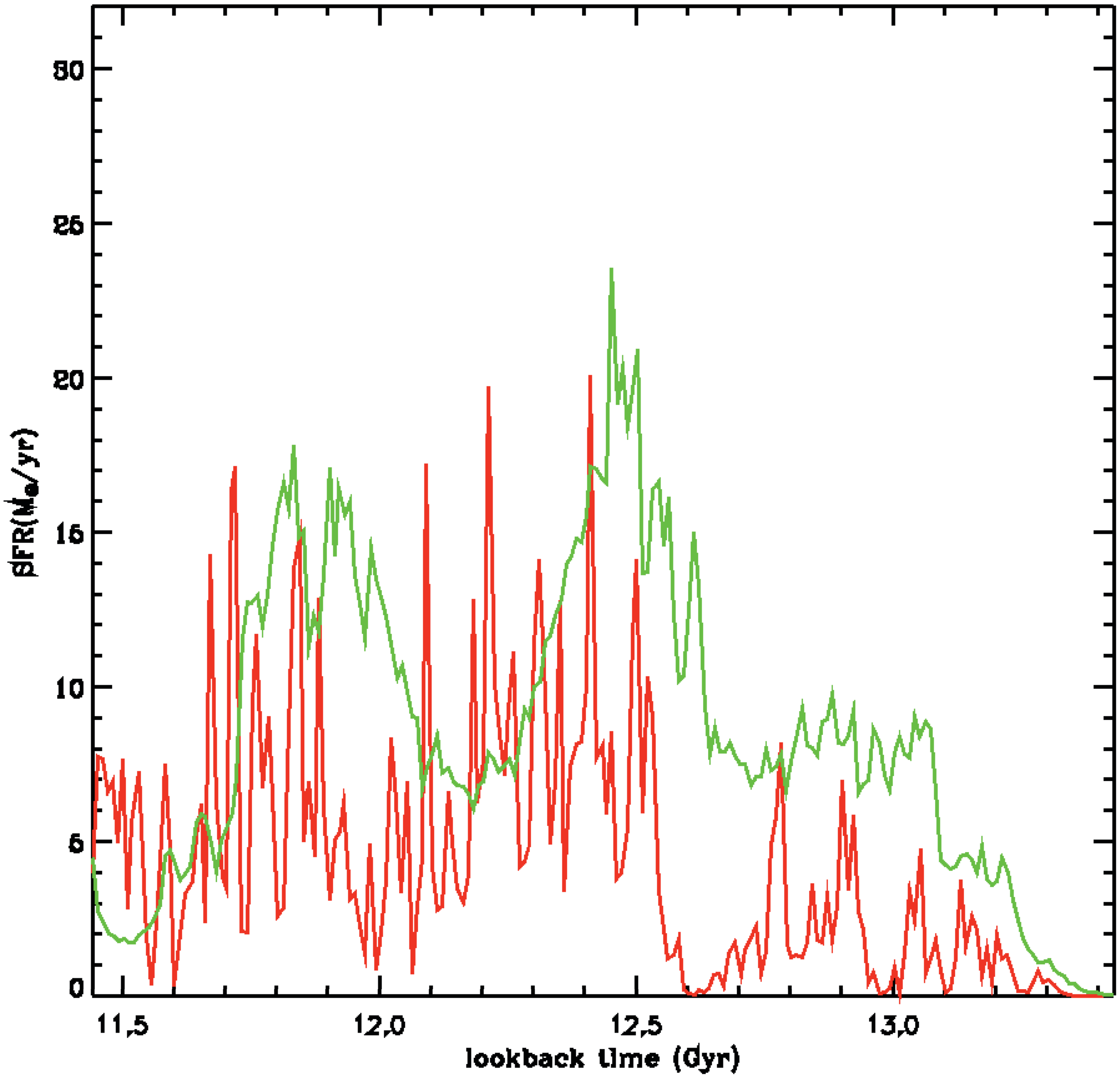


Energy feedback runs

Stellar mass @ z=3

1.4 10^{10} M_{sun}

8.5 10^{9} M_{sun}

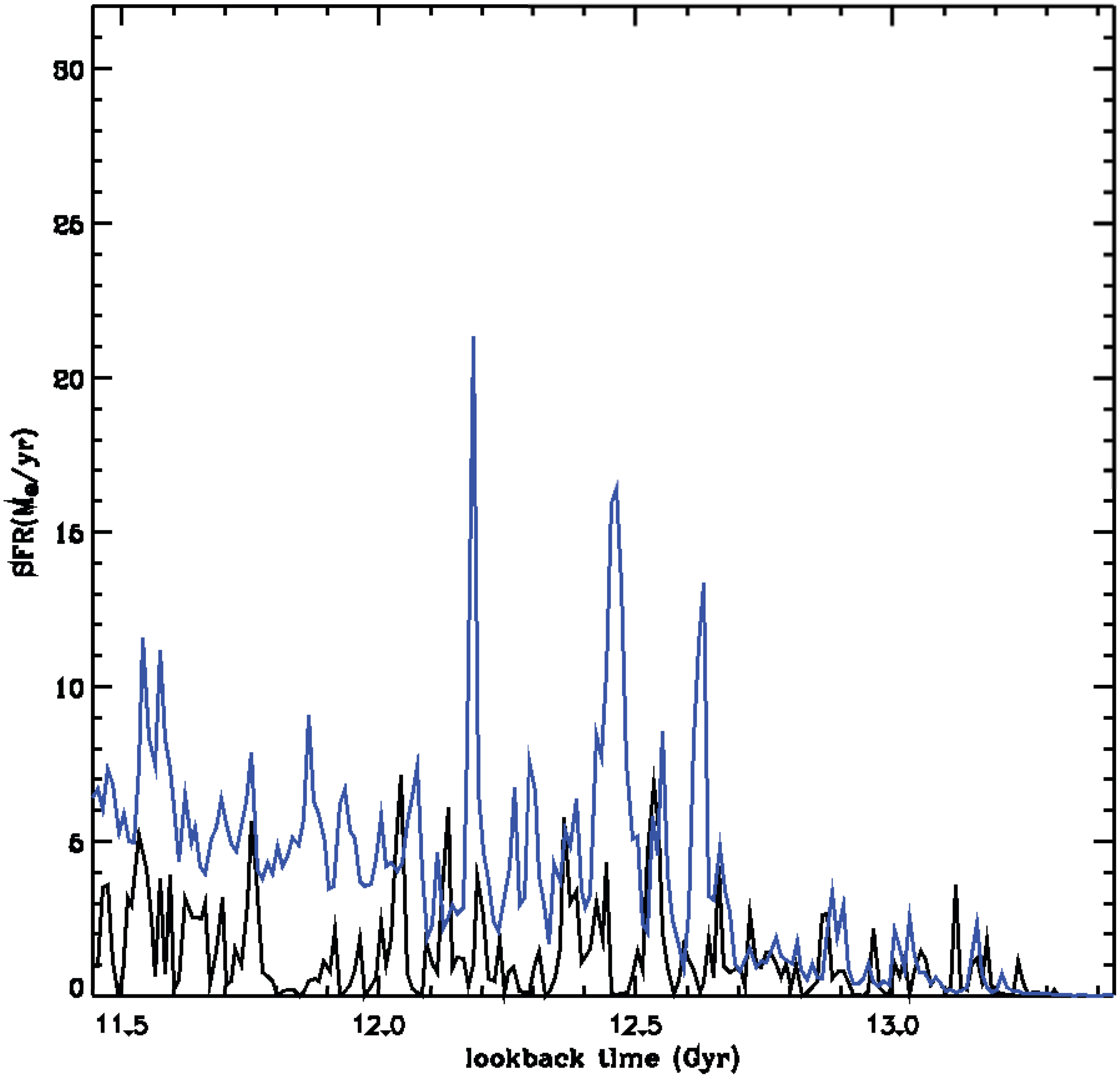


Momentum feedback runs

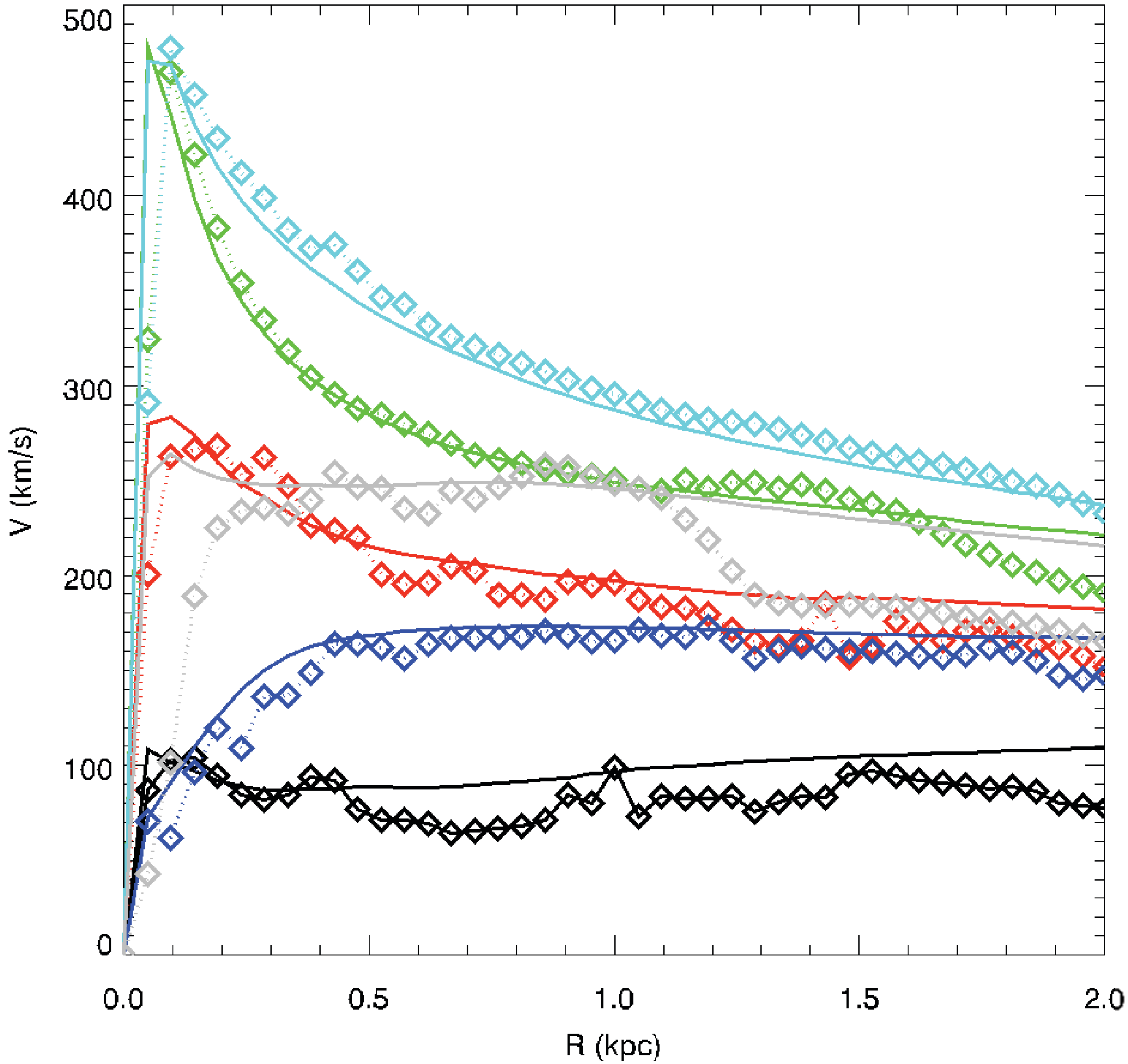
Stellar mass
@ z=3

$7.5\ 10^9\ M_{sun}$

$2.5\ 10^9\ M_{sun}$



Impact on galaxy rotation curves



Conclusions

Good news is that we have (finally) entered an era where numerical resolution allows us to (partially) resolve the turbulent ISM in cosmological zoom simulations of galaxies (scale height of the disc)

Bad news is we need to revisit sub-grid models to take advantage of it, and in particular the way we form stars in these simulations

Turbulence driven star formation alone has potentially non trivial consequences for the dynamics of the central region of galaxies (e.g. important suppression of the peak of the rotation curve)

When coupled to feedback, such changes can become dramatic, with up to a factor 3 suppression of the stellar mass when a simple SN momentum injection model is considered