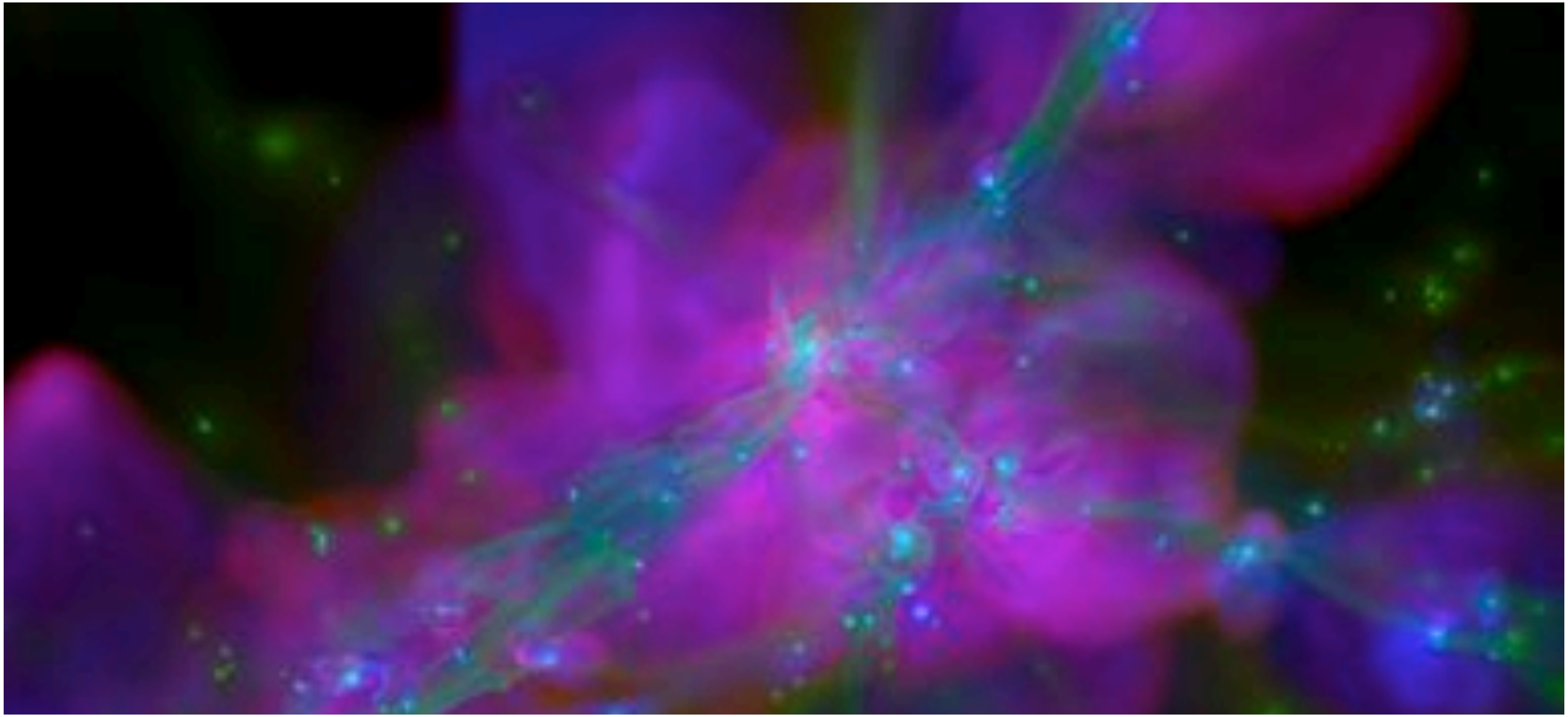
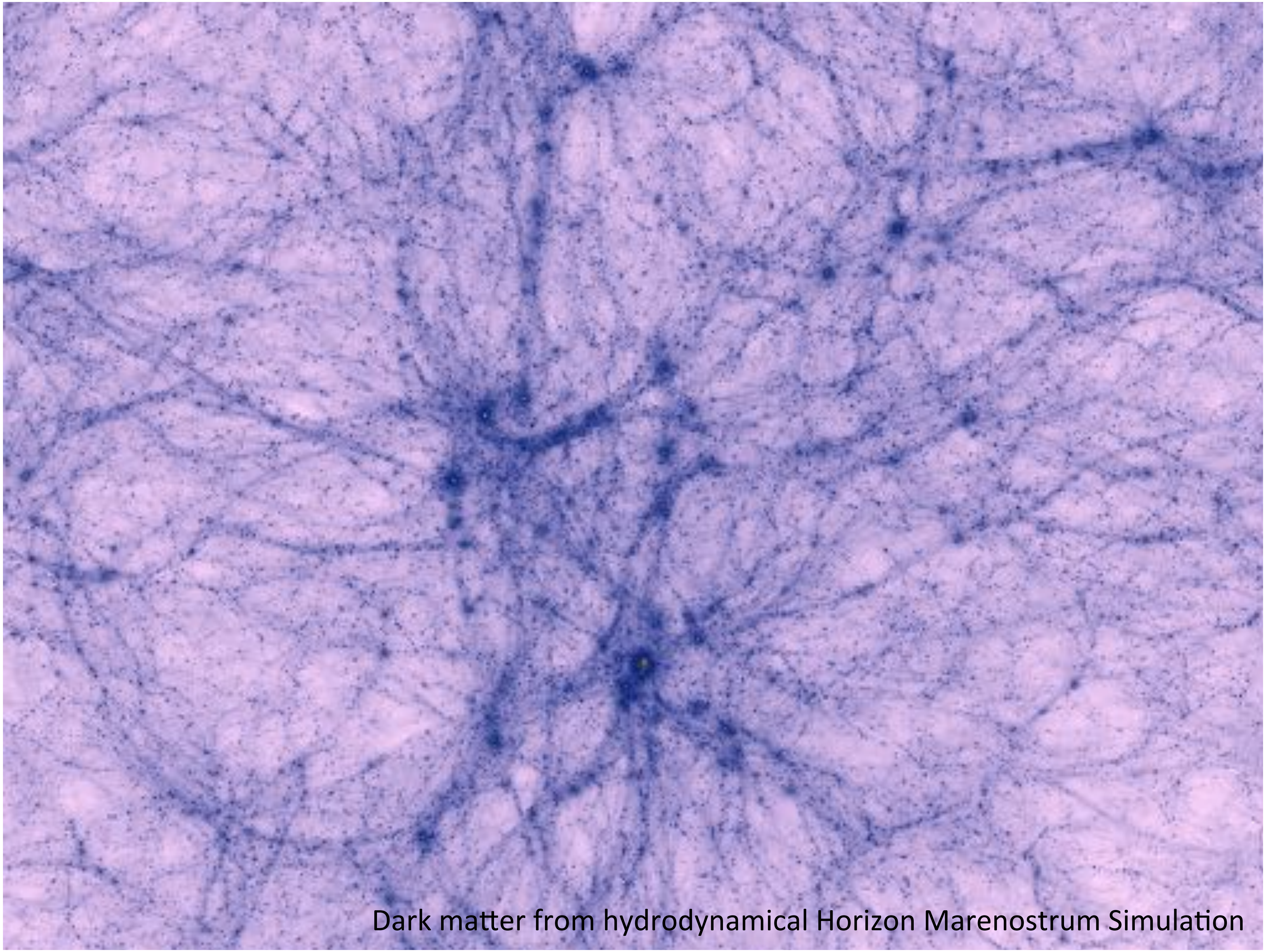


From gas to stars in galaxies

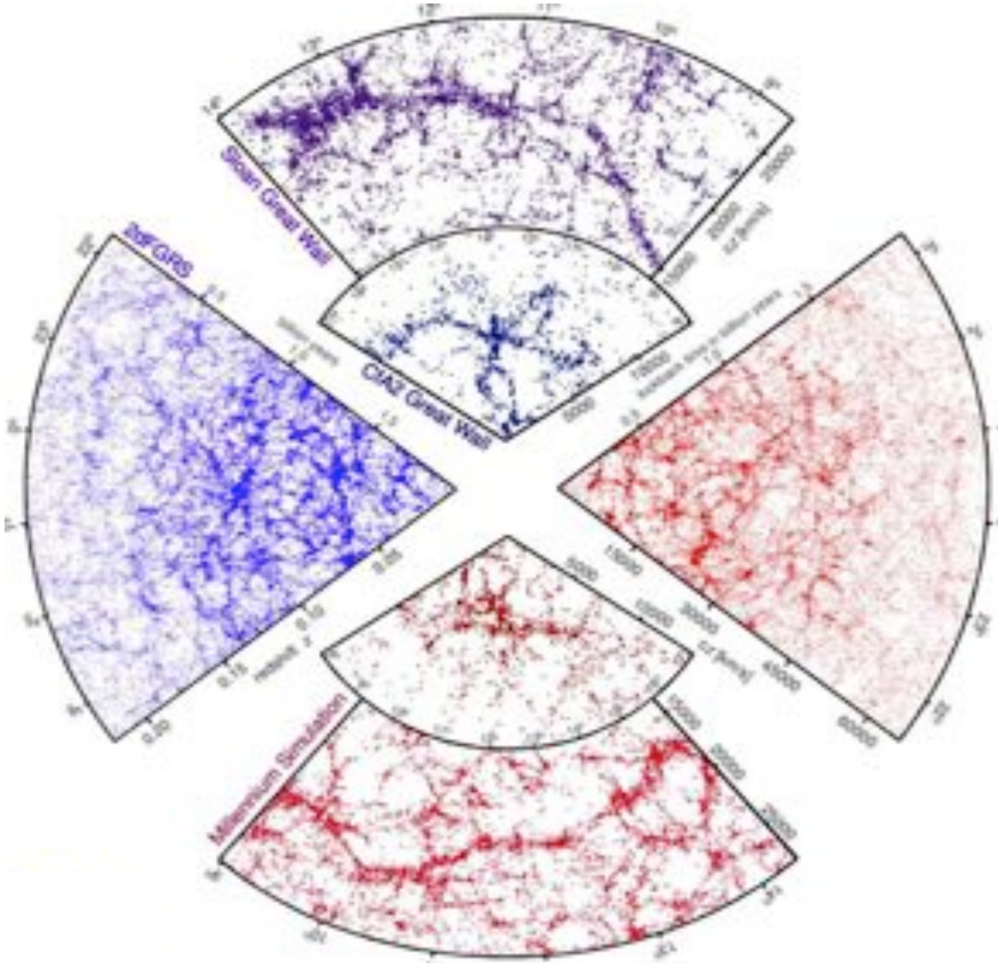
Adrianne Slyz, Julien Devriendt (Oxford)
Taysun Kimm, Renyue Cen (Princeton),
Yohan Dubois (IAP)

DiRAC HORIZONUK


Dark matter from hydrodynamical Horizon Marenostrum Simulation

observations

observations

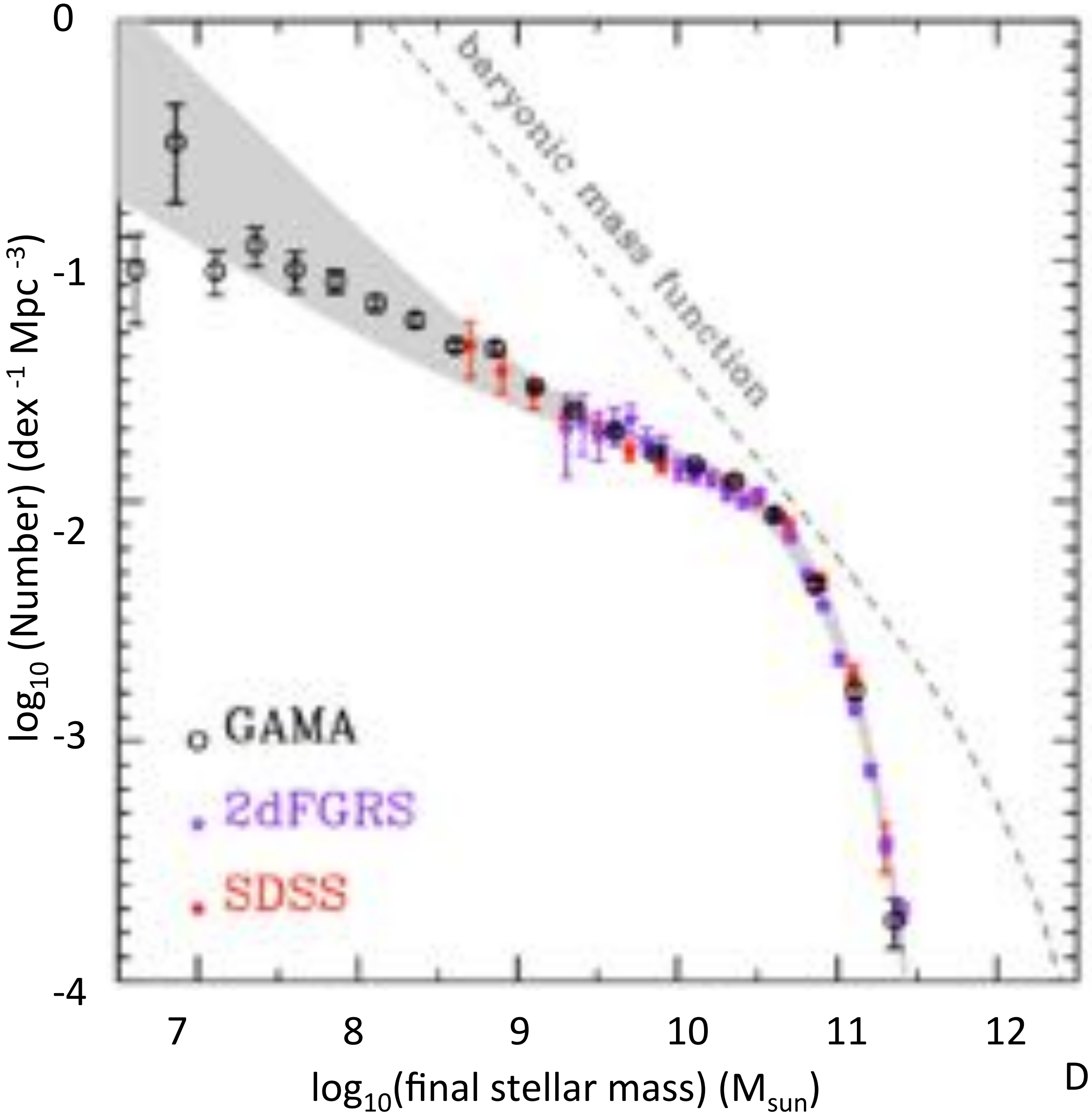


simulations

simulations

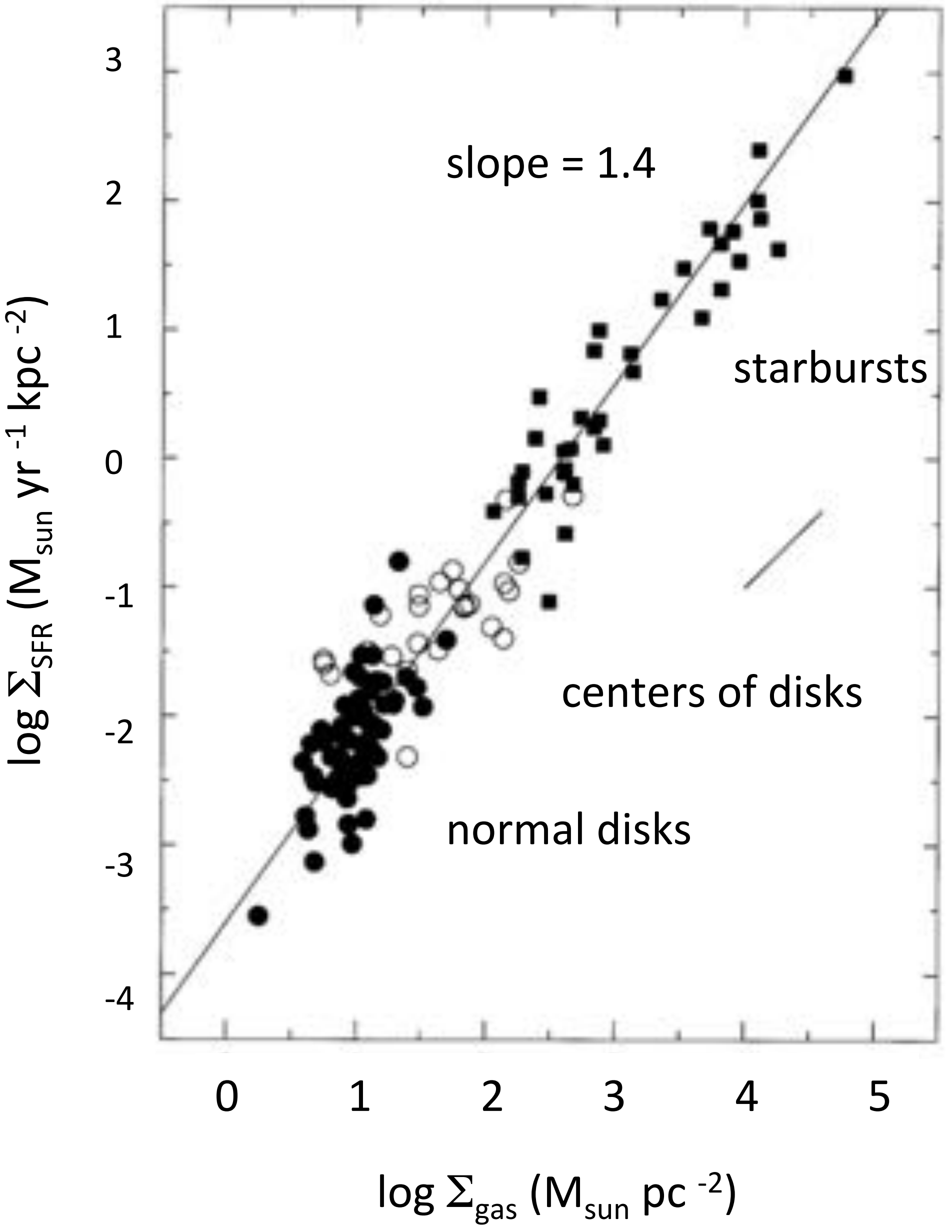
Springel, Frenk, White 2006

Galaxy Stellar Mass Function



Driver et al. 2009

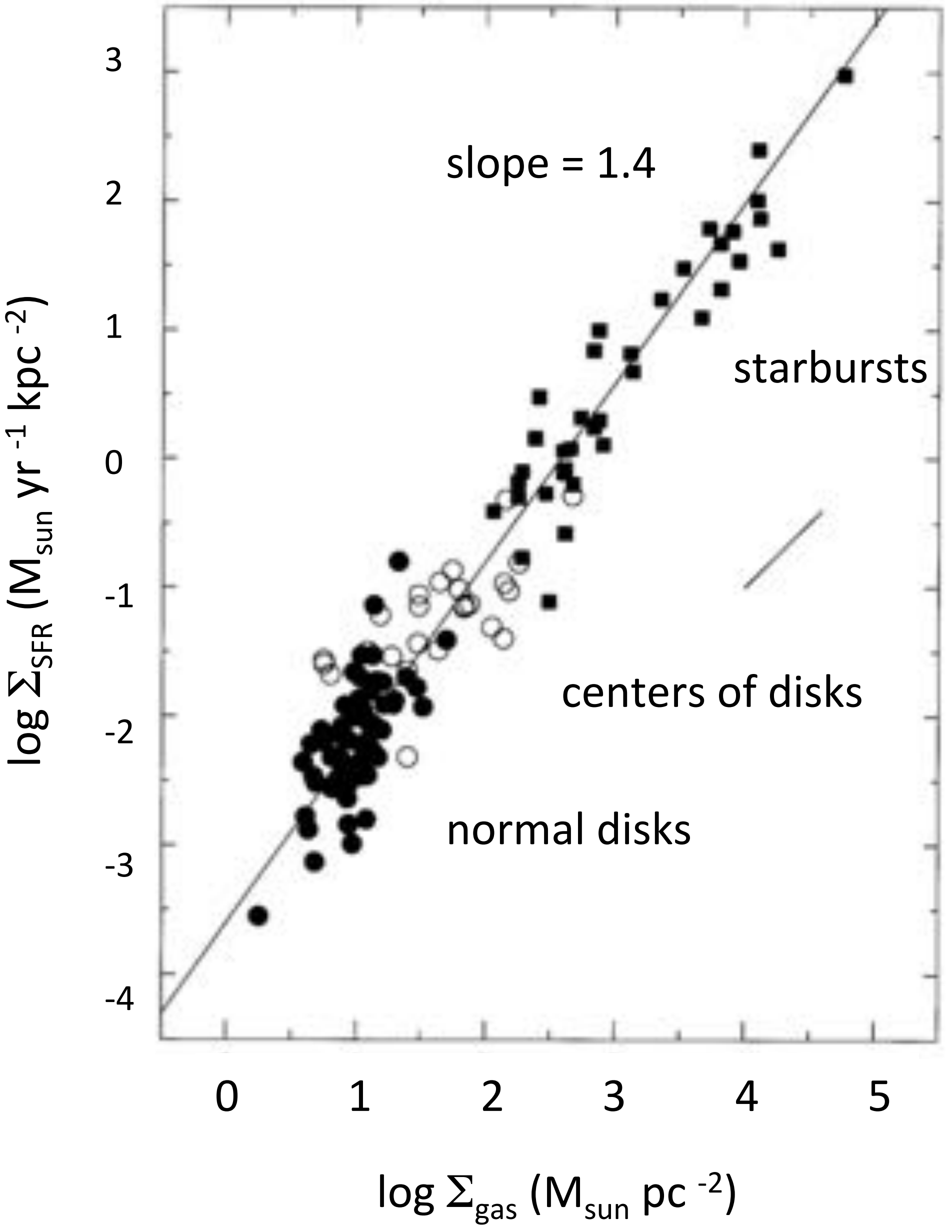
Star formation rate - gas surface density relation



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

Kennicutt 1998

Star formation rate - gas surface density relation



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

Is this simply:

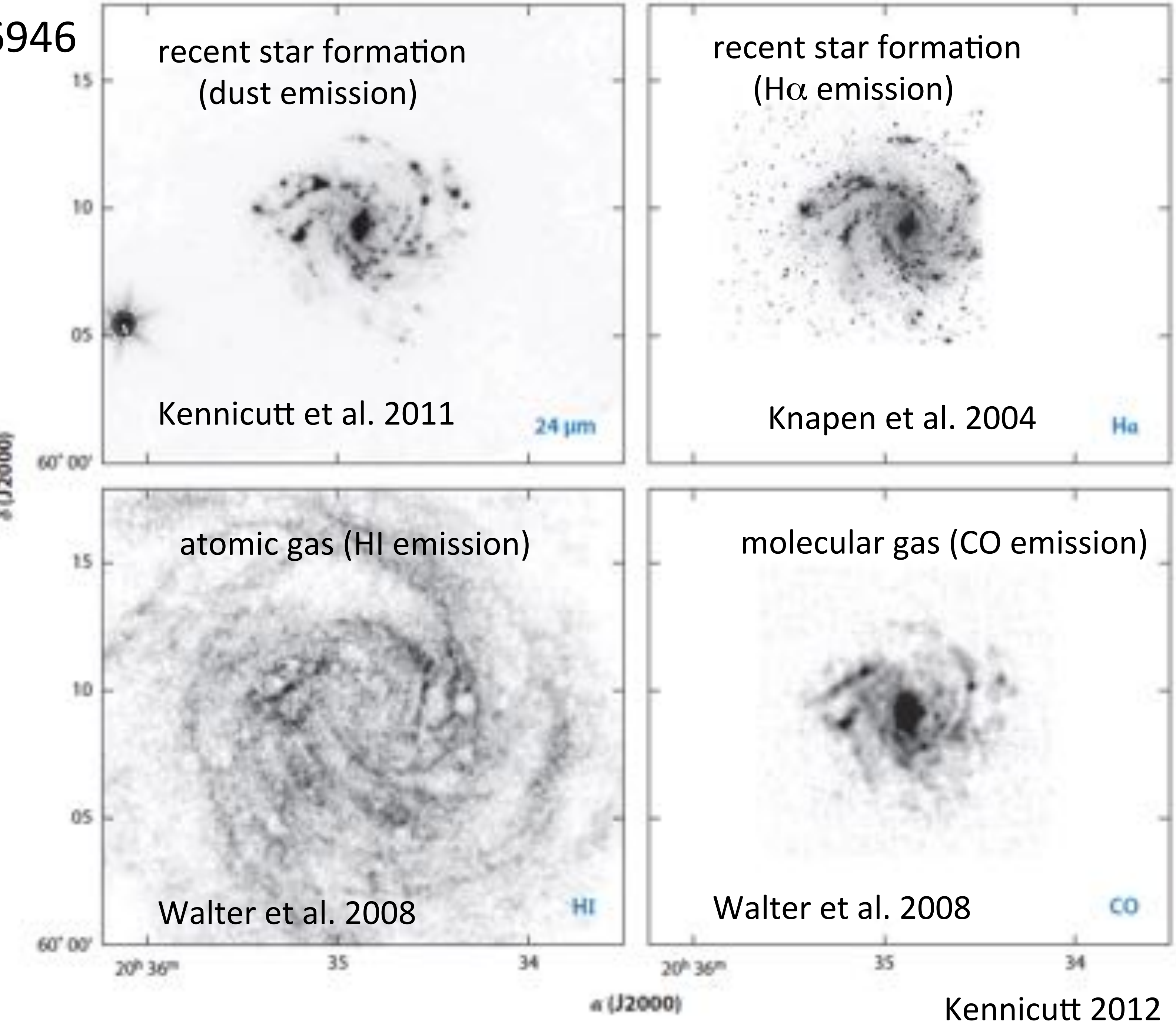
$$\dot{\rho}_* = \frac{\epsilon\ \rho}{t_{ff}} \propto \rho^{3/2}$$

where

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

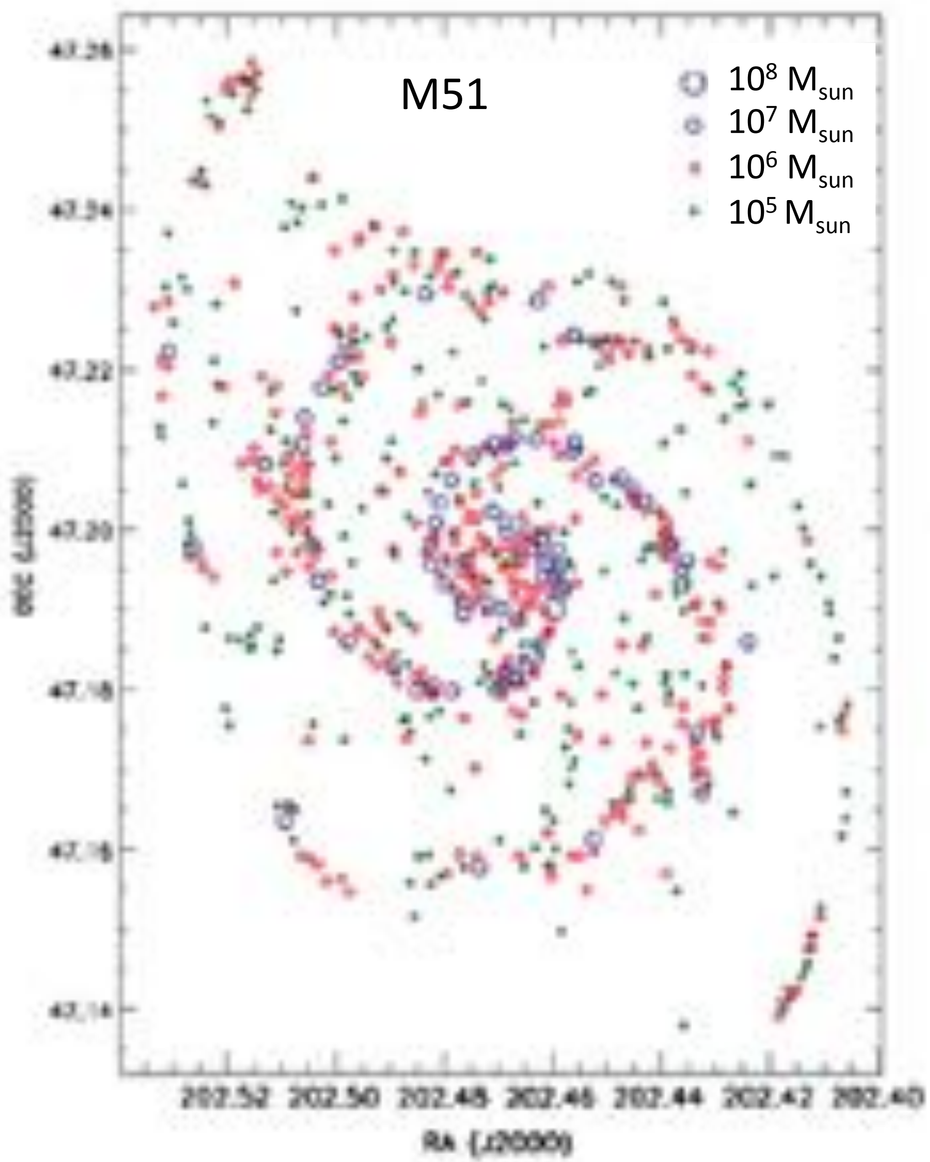
Kennicutt 1998

NGC 6946



Kennicutt 2012

Giant Molecular Cloud Lifetimes

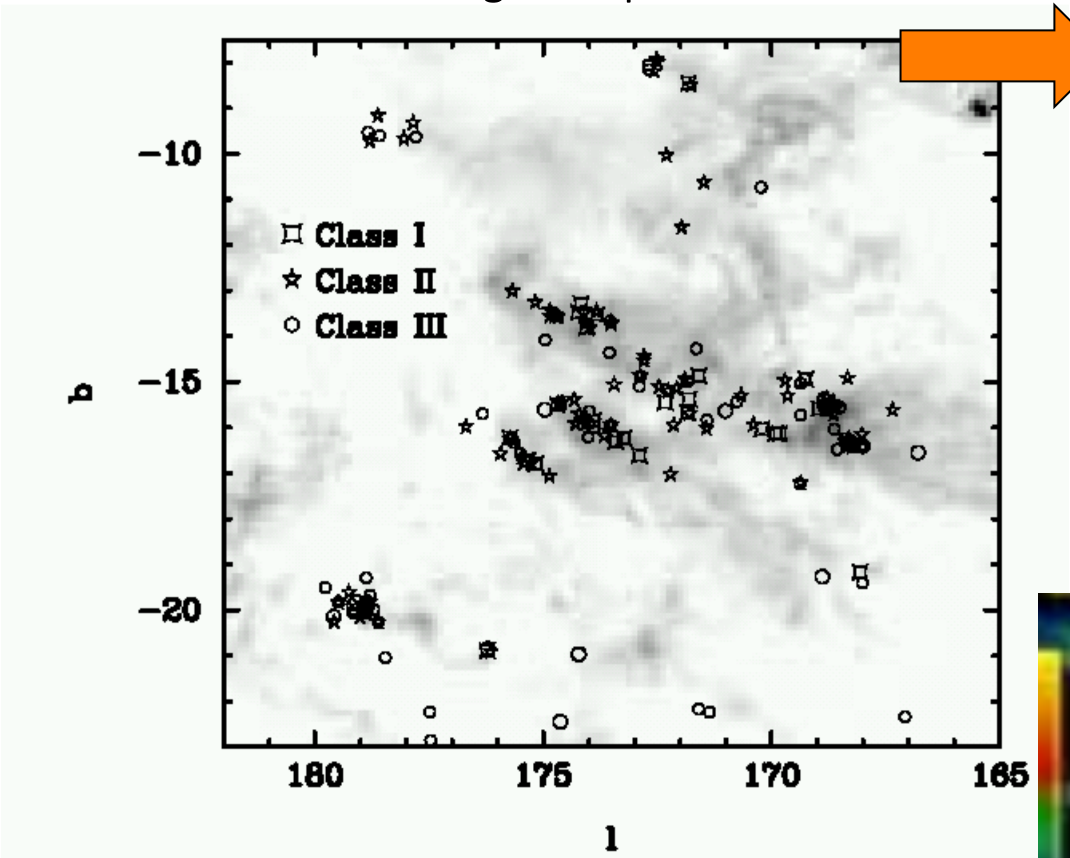


lifetime ~ 100 Myr

Koda et al. 2009

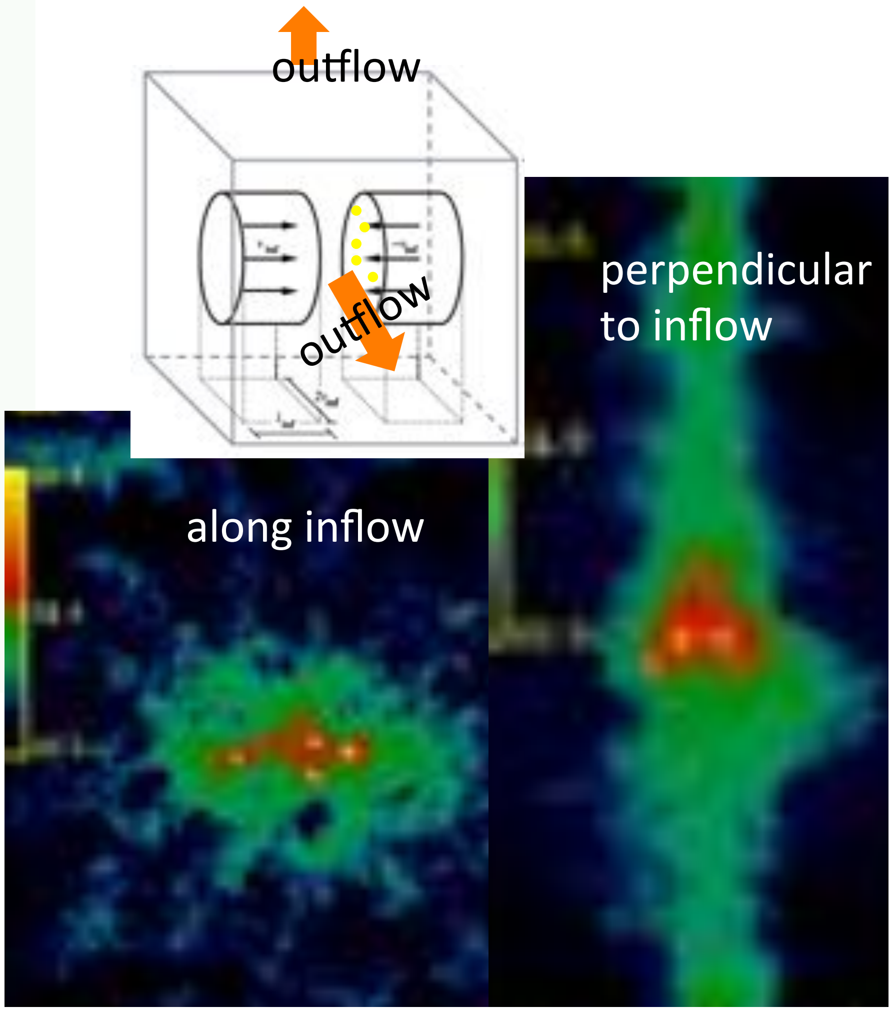
Another estimate of molecular cloud lifetimes…..

Taurus-Auriga complex



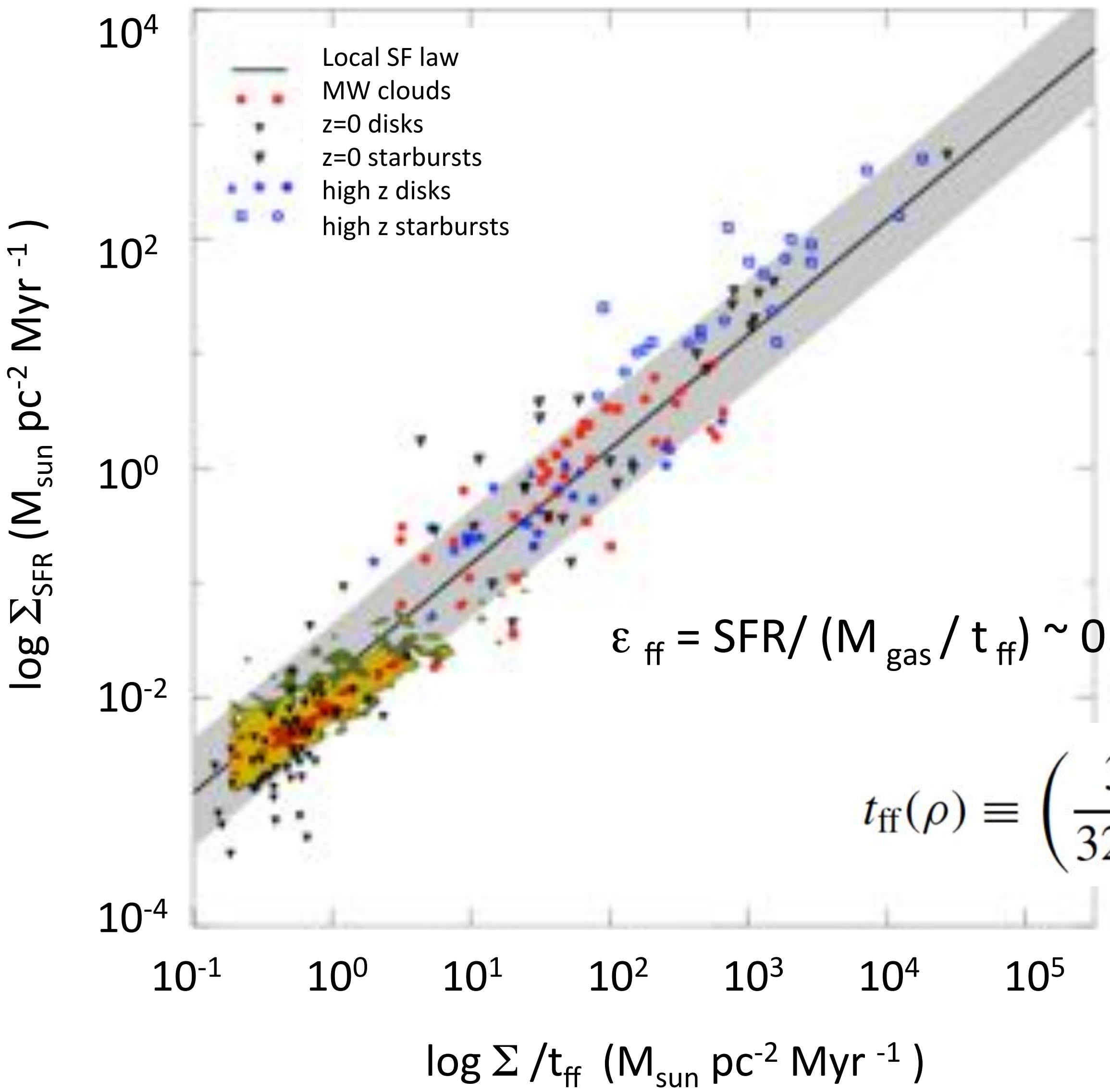
Hartmann, Ballesteros-Paredes,
& Bergin 2001

No stars older than ~5 Myr: rapid star formation? Colliding flows?



Hennebelle & Audit 2007
Heitsch et al.2008,2009
Vazquez-Semadeni et al. 2007, 2012

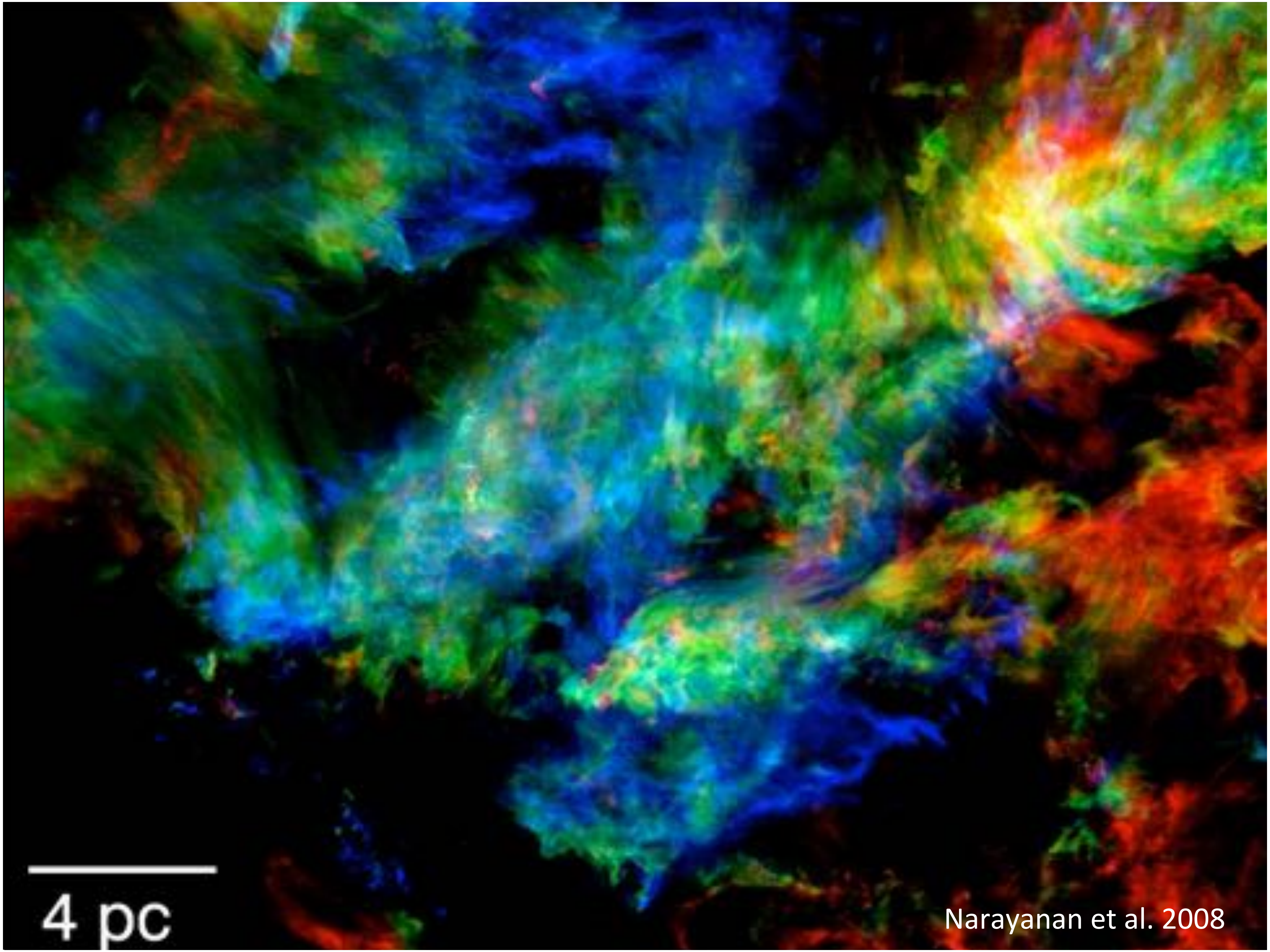
Another look at the star formation - gas surface density relation…..



ε_{ff} = SFR/ (M_{gas} / t_{ff}) ~ 0.015

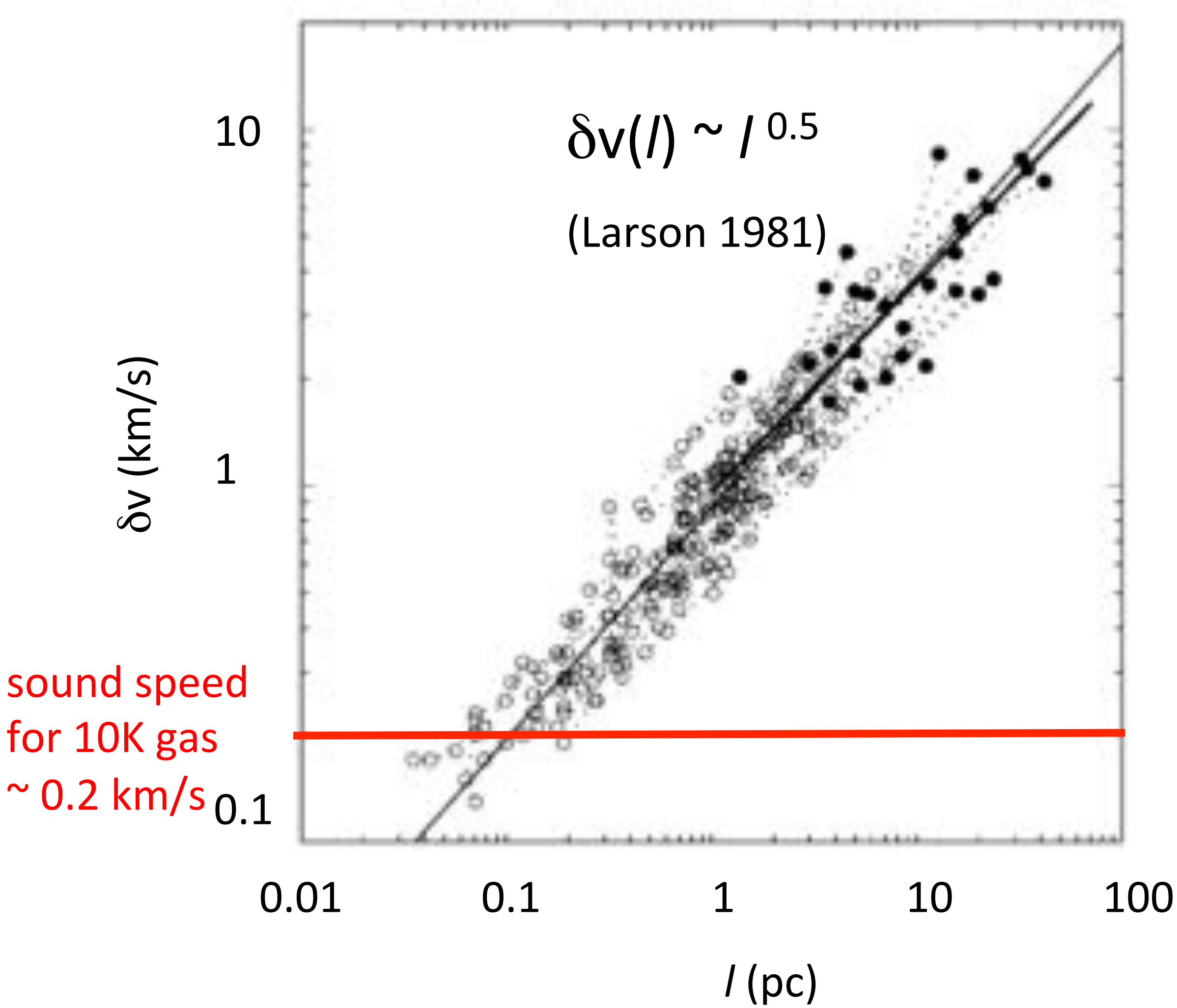
$$t_{\rm ff}(\rho) \equiv \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$ ~ few Myr

Krumholz et al. 2012, 2013


4 pc
Narayanan et al. 2008

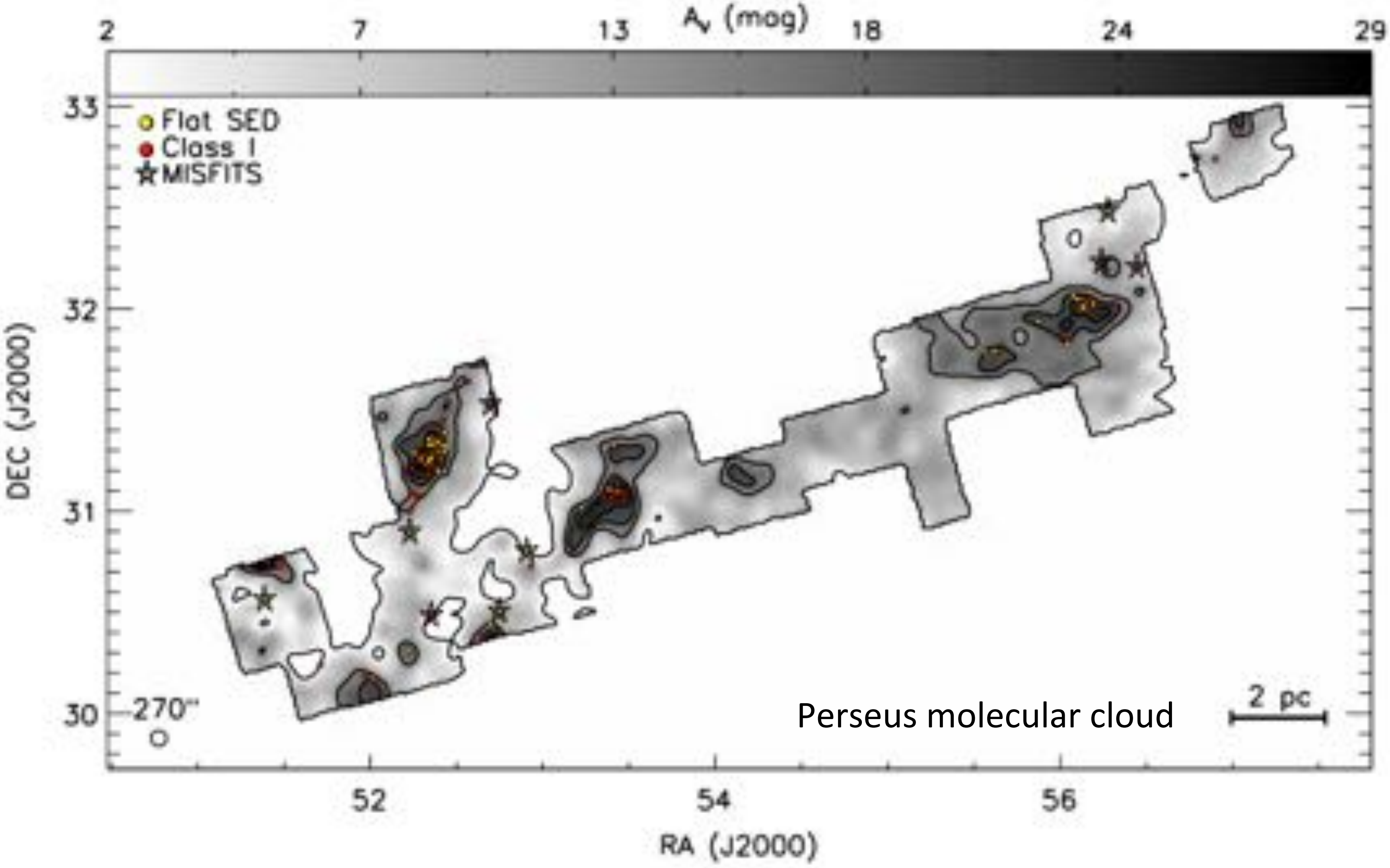
Evidence for compressible, supersonic turbulence

Linewidth-size relation in molecular clouds



Heyer & Brunt 2004

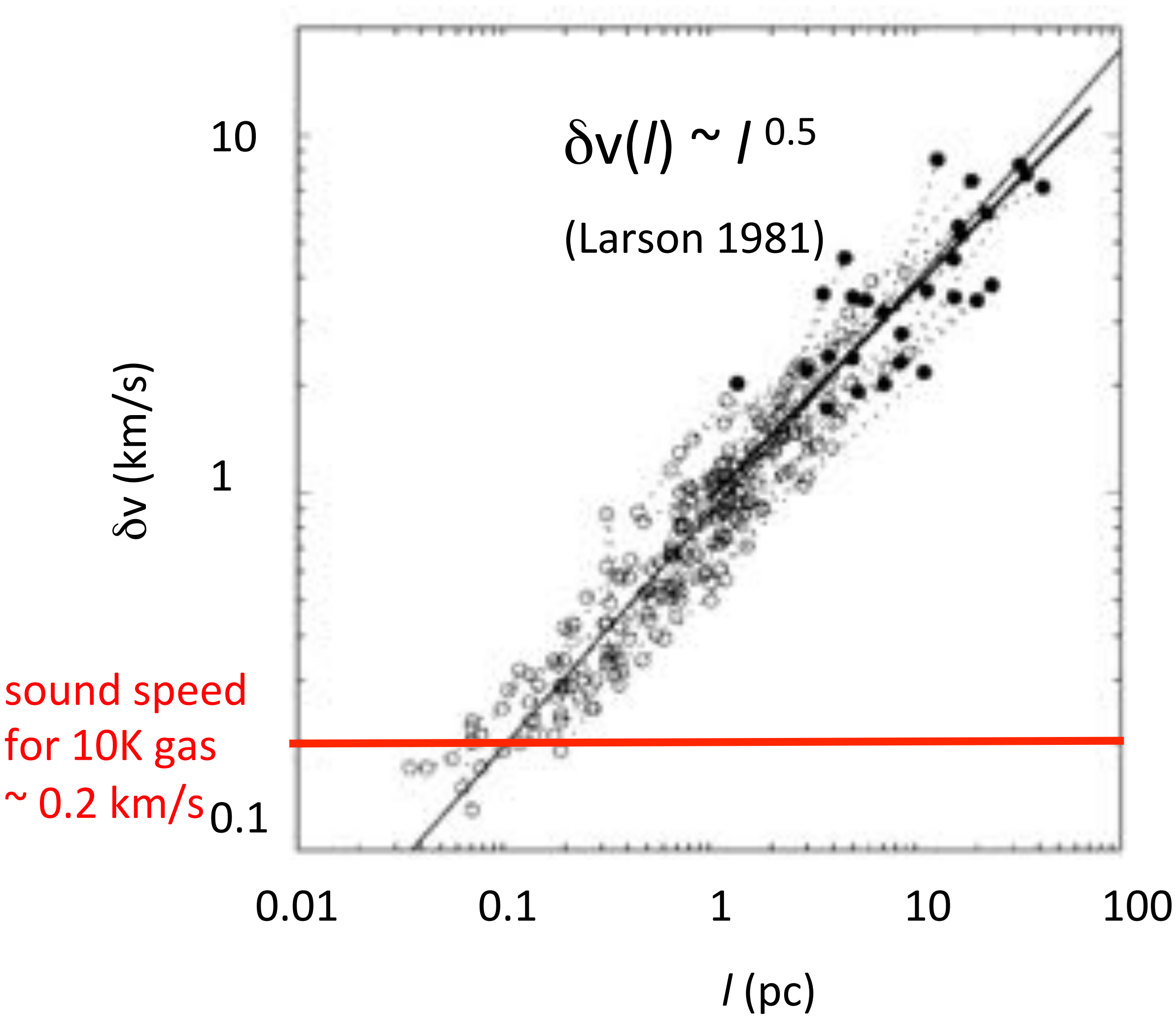
Where do the stars form?



Heiderman et al. 2010

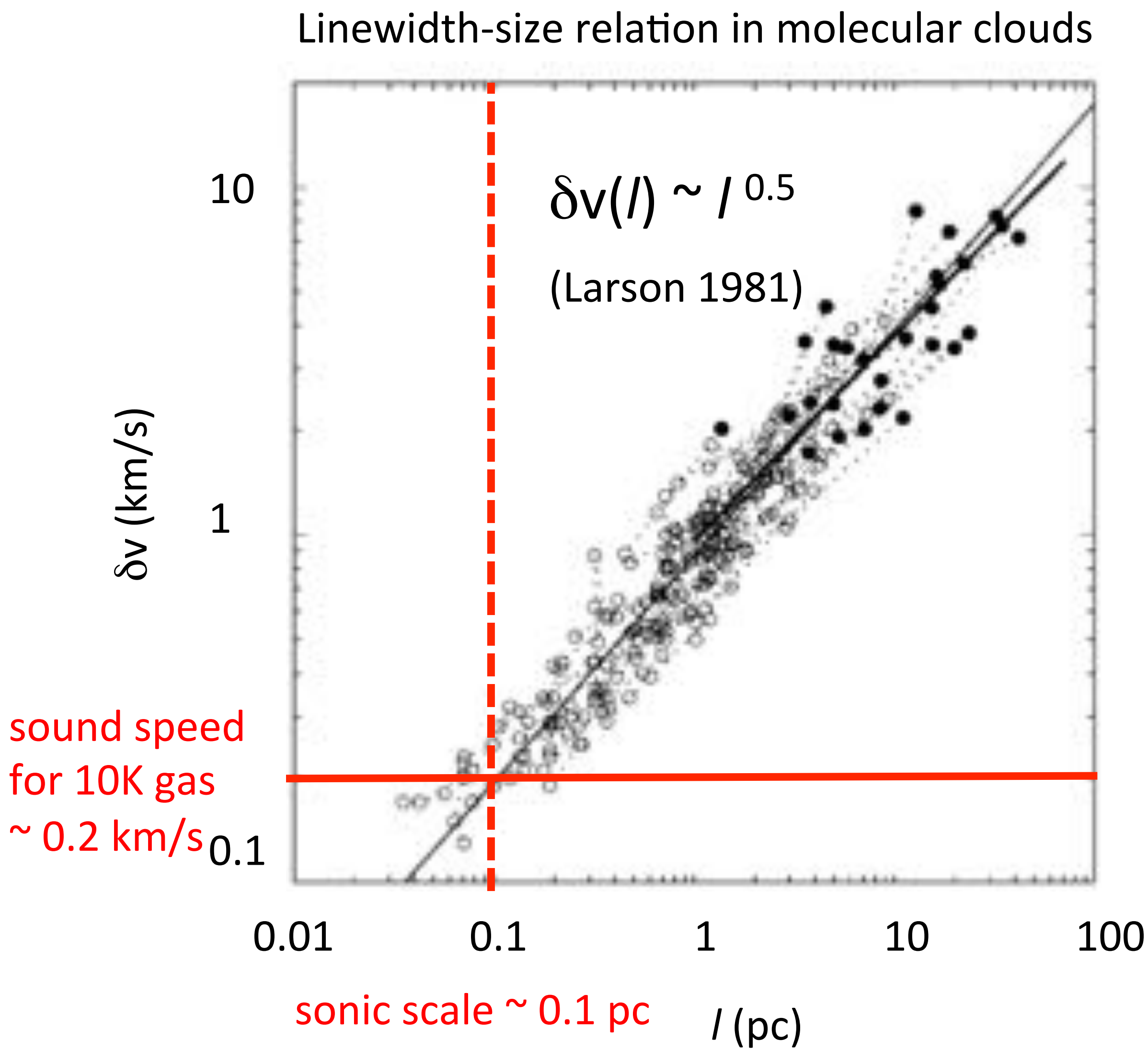
Transition to subsonic turbulence

Linewidth-size relation in molecular clouds



Heyer & Brunt 2004

Transition to subsonic turbulence

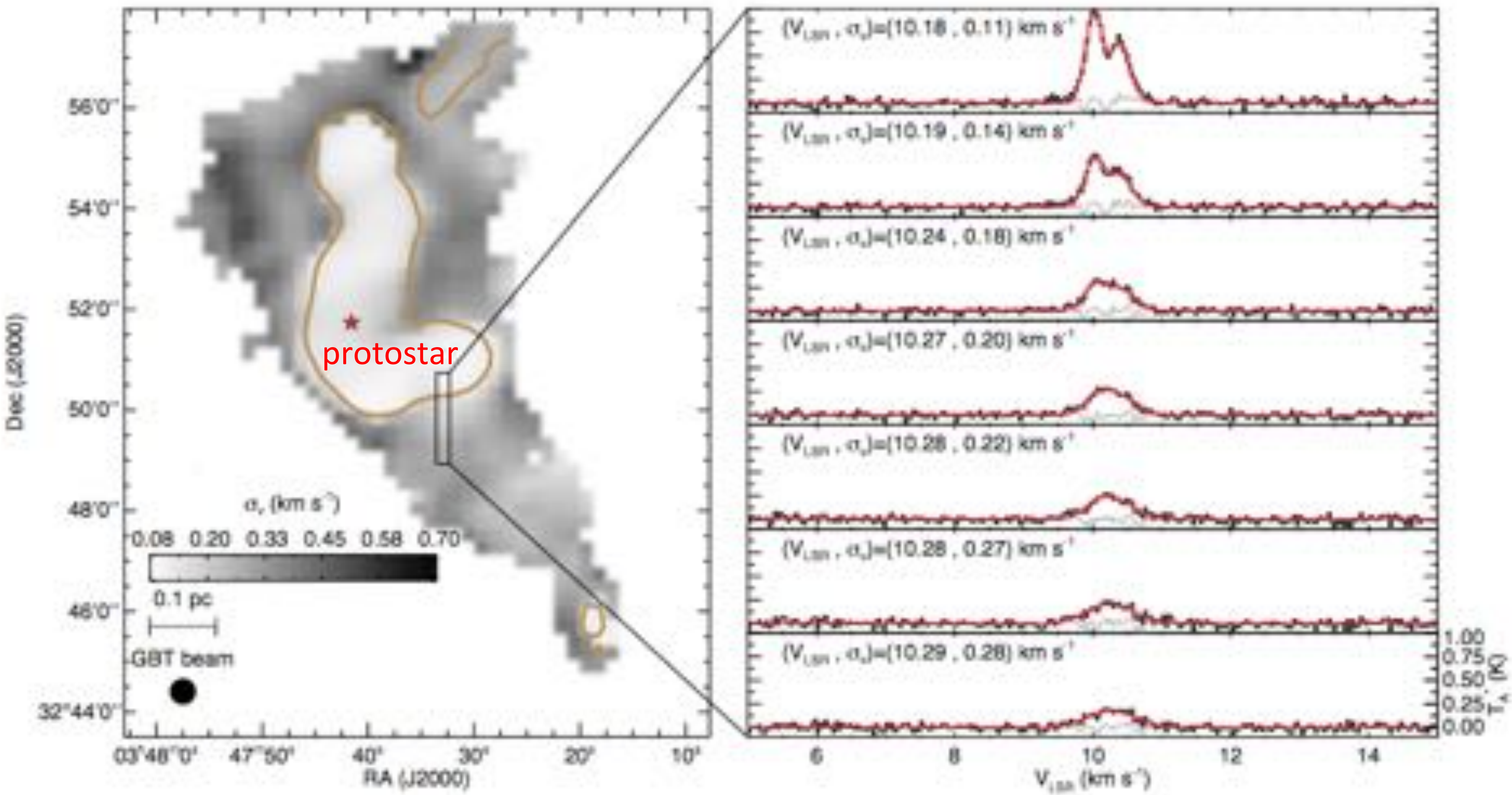


Heyer & Brunt 2004

Transition to coherence: "Islands of calm in a turbulent sea"

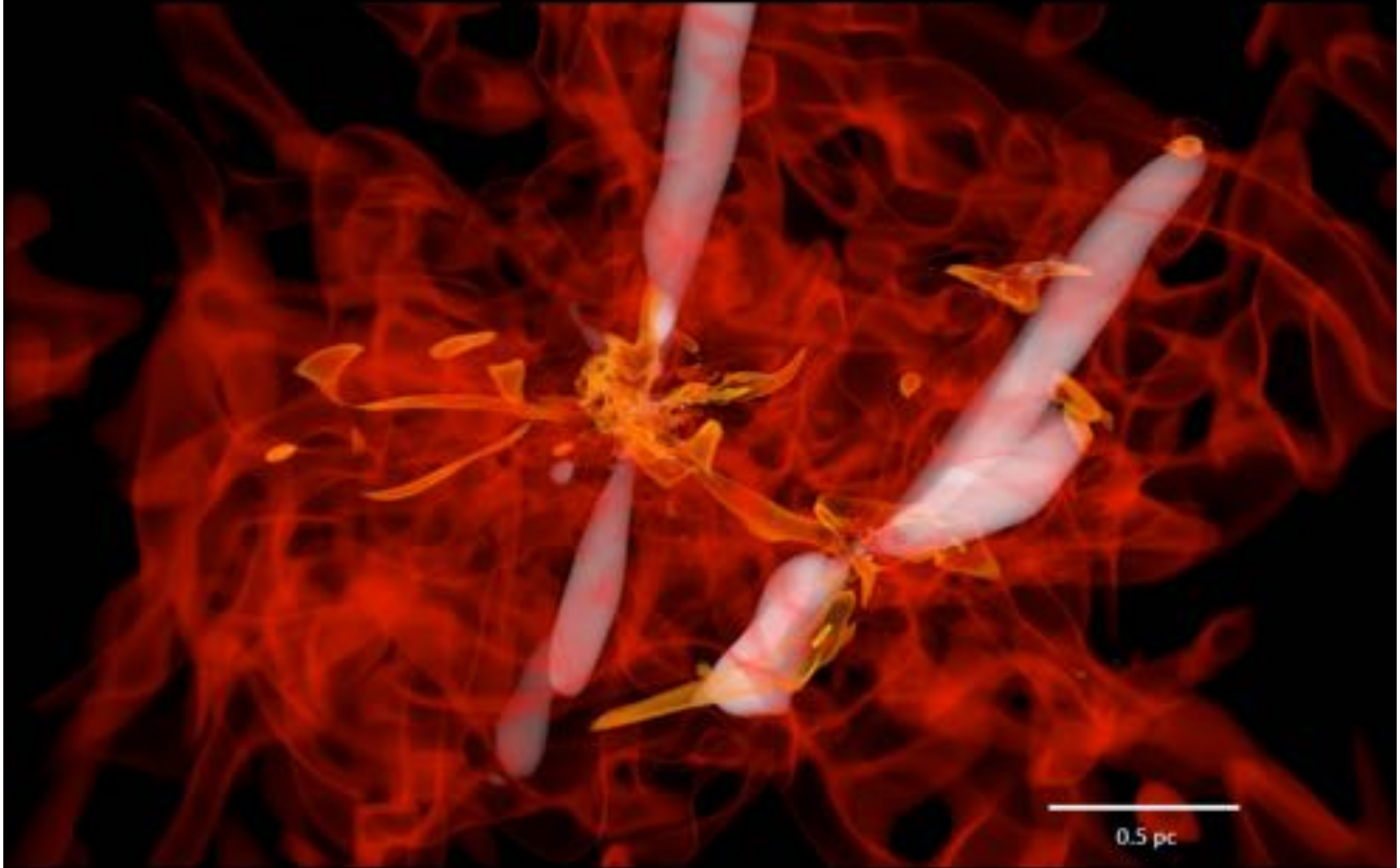
(Goodman et al. 1998, Caselli et al. 2002, see also Arzoumanian et al. 2011)

Perseus B5 map of the NH_3 velocity dispersion



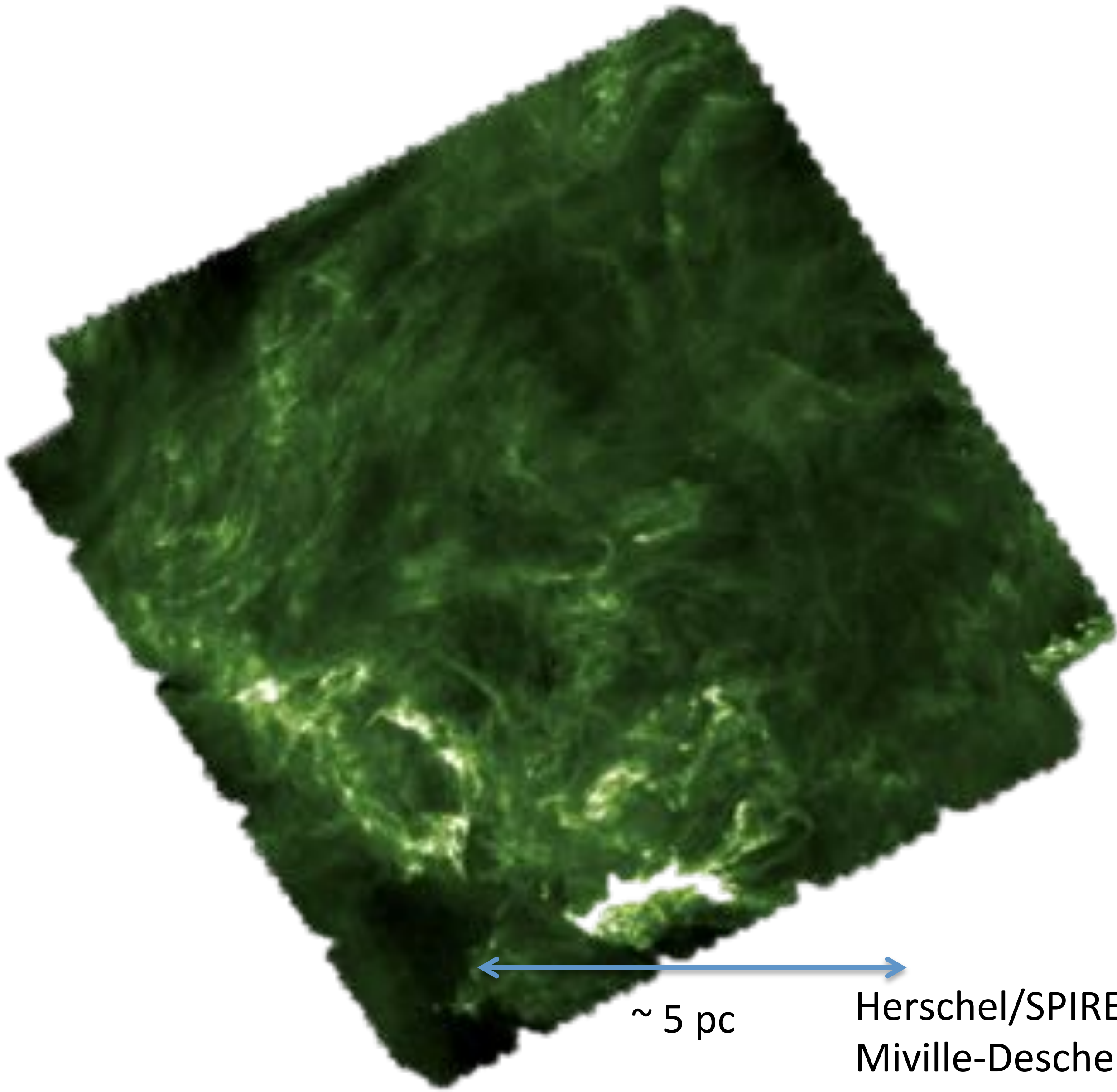
Pineda et al.2010

What drives the turbulence? Internal processes?



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

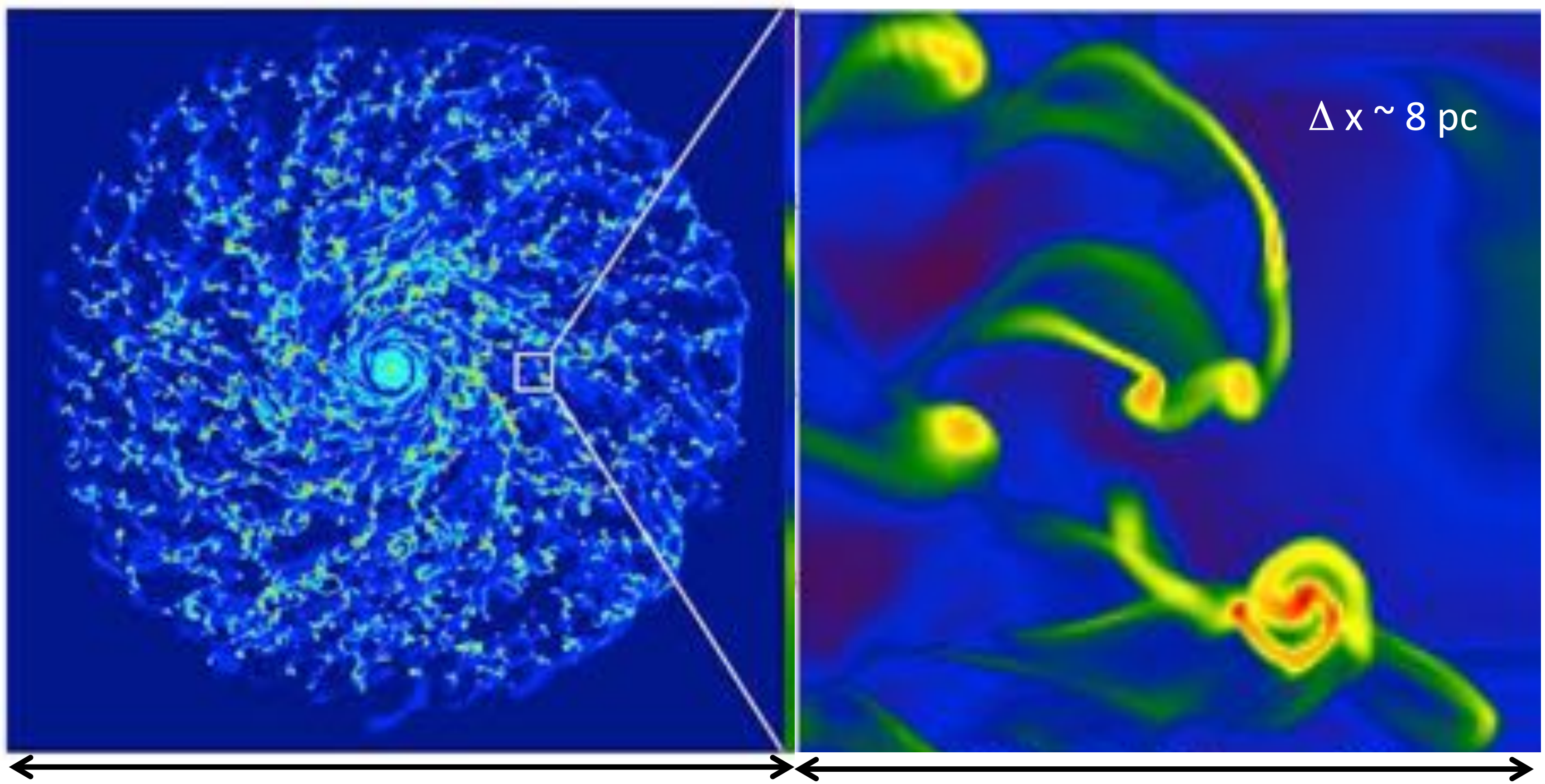
Polaris Flare: non star forming molecular cloud



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

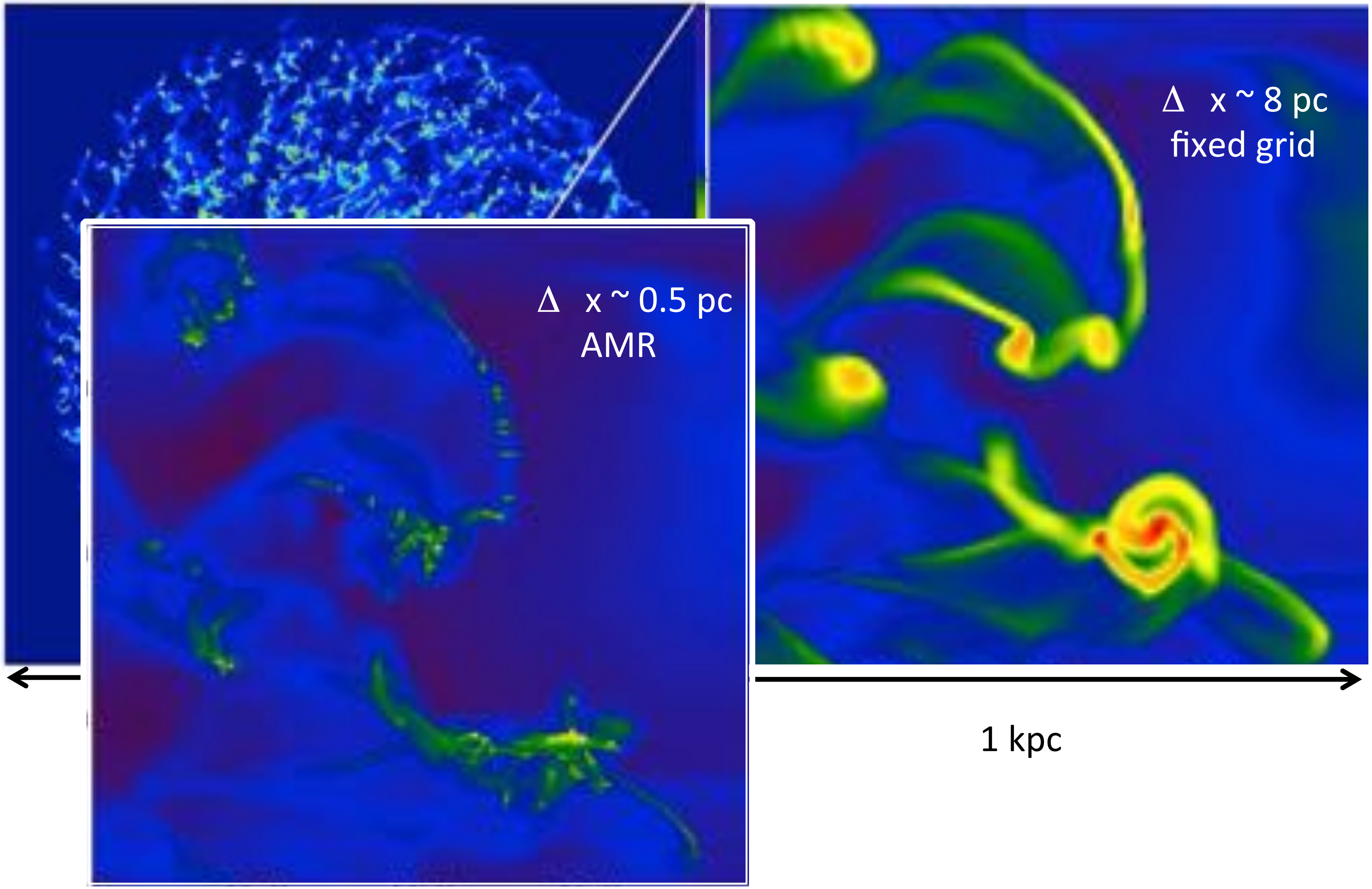


20 kpc

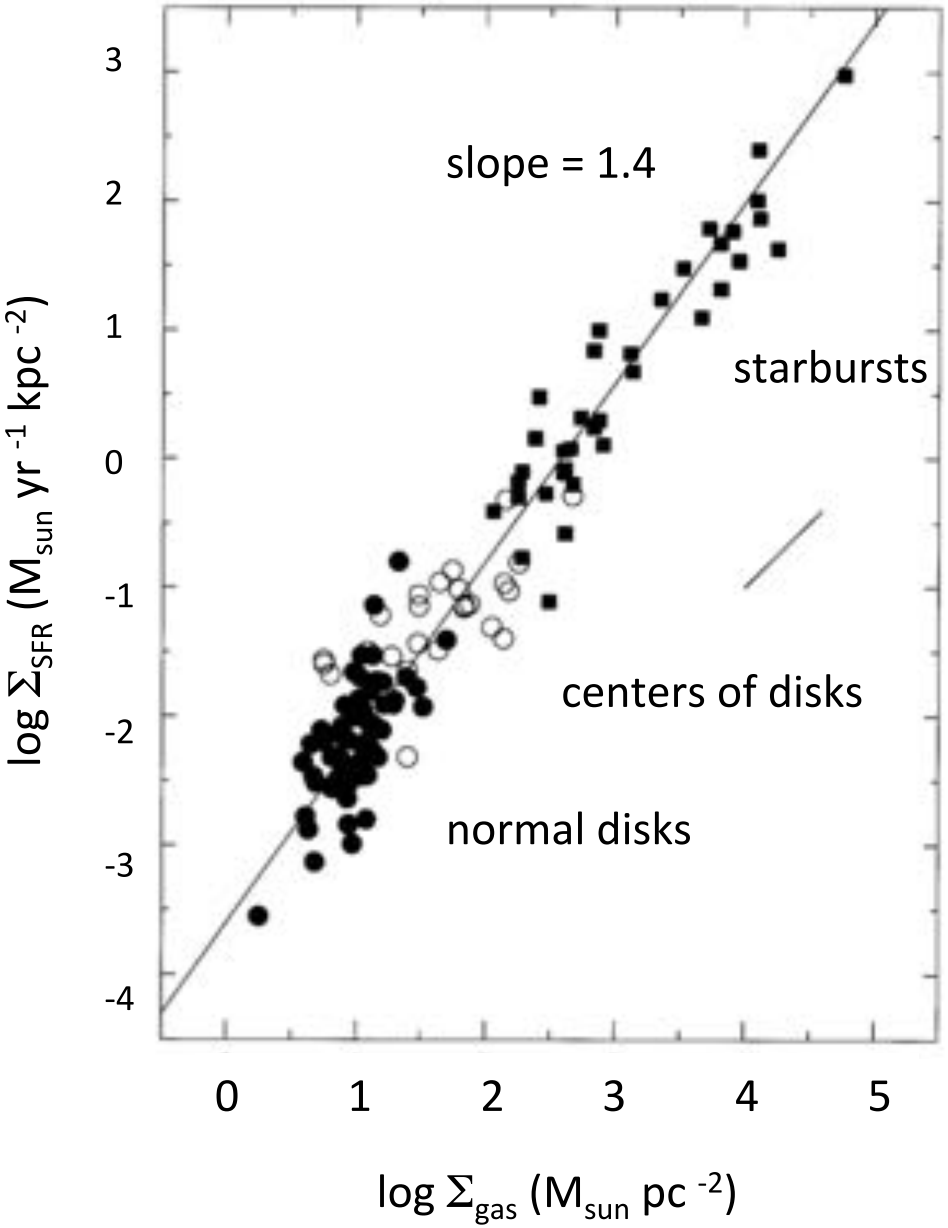
1 kpc

Turbulent cascade from large scales:
galactic shear & cloud motions

Tasker & Tan 2009, van Loo 2013



How should we form stars in the simulations?



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

Is this simply:

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

where

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

Kennicutt 1998

How should we form stars in the simulations?

Heyer et al. 1998

(FCRAO CO survey)

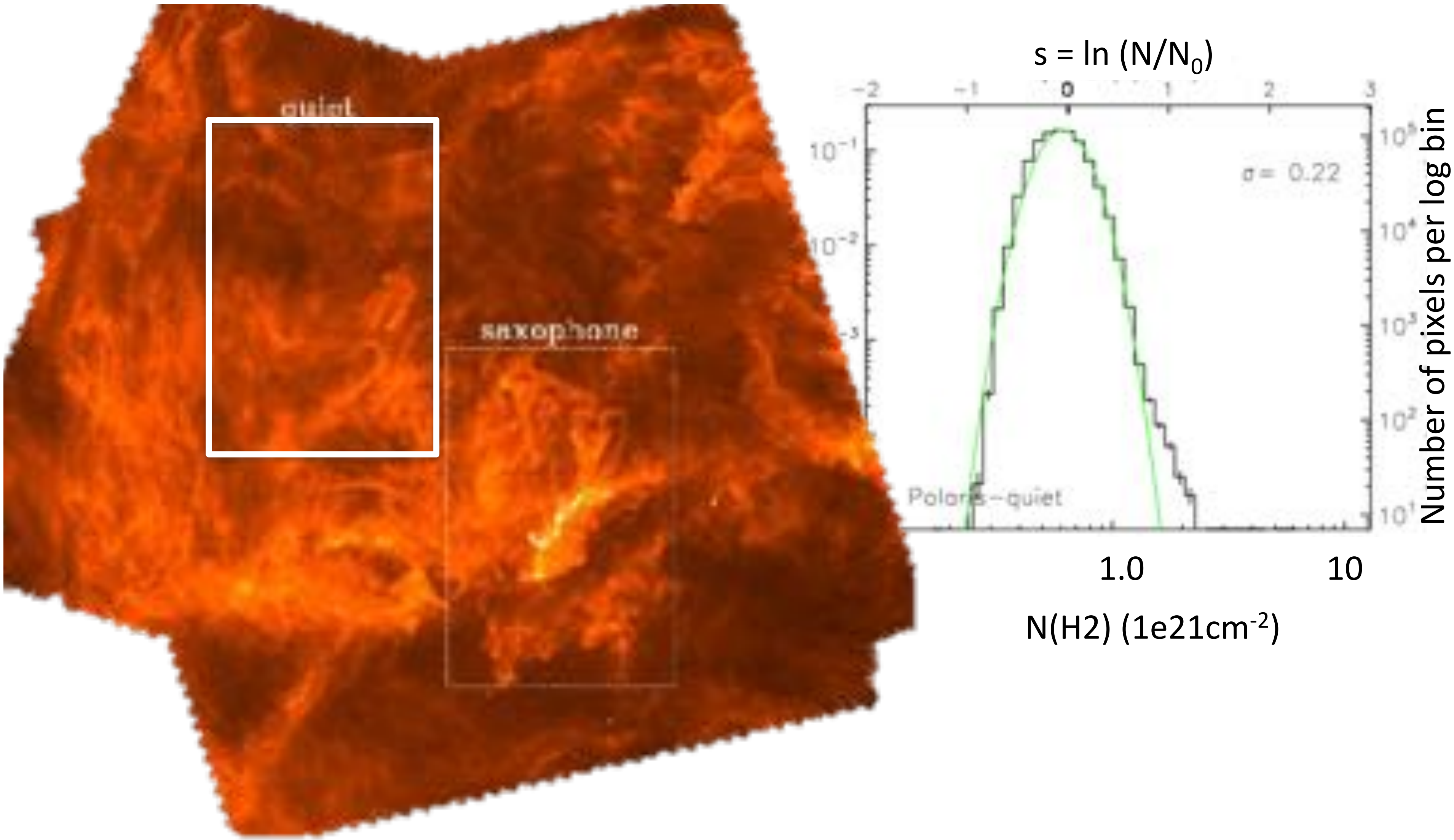
if $\rho > \rho_0$

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

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

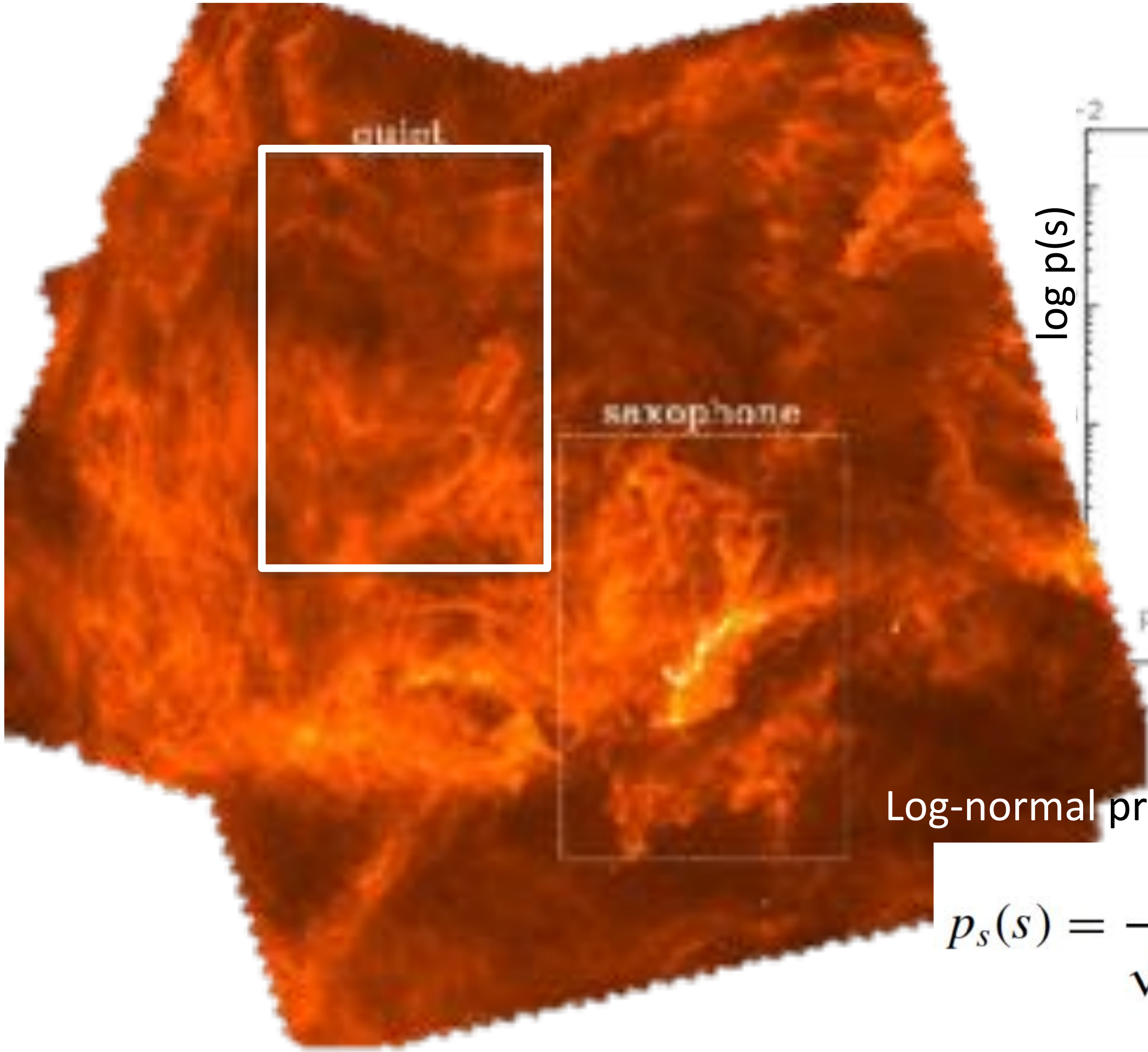
with ϵ = 0.01

star formation efficiency



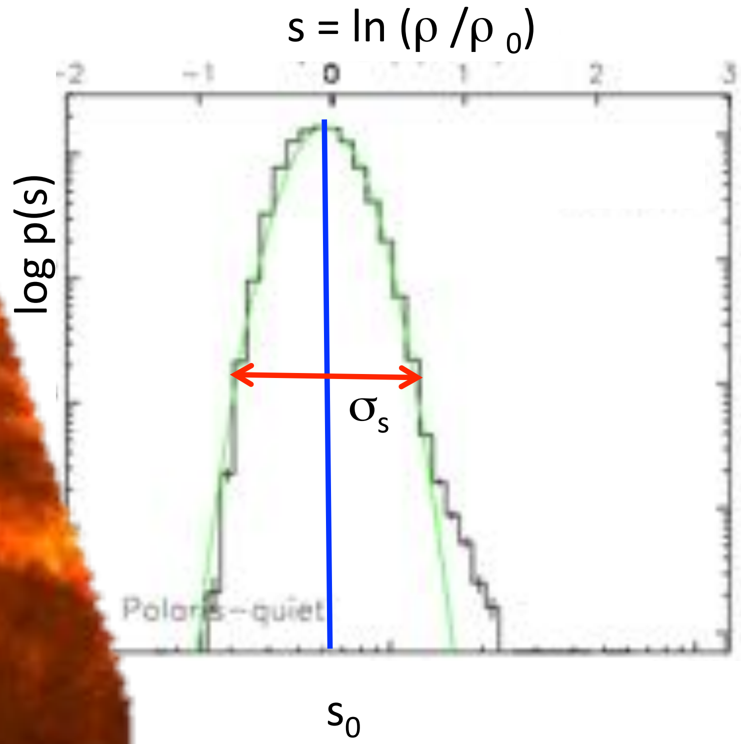
Herschel/SPIRE 250 μm image

Schneider et al. 2013



Herschel/SPIRE 250 μm image

Schneider et al. 2013

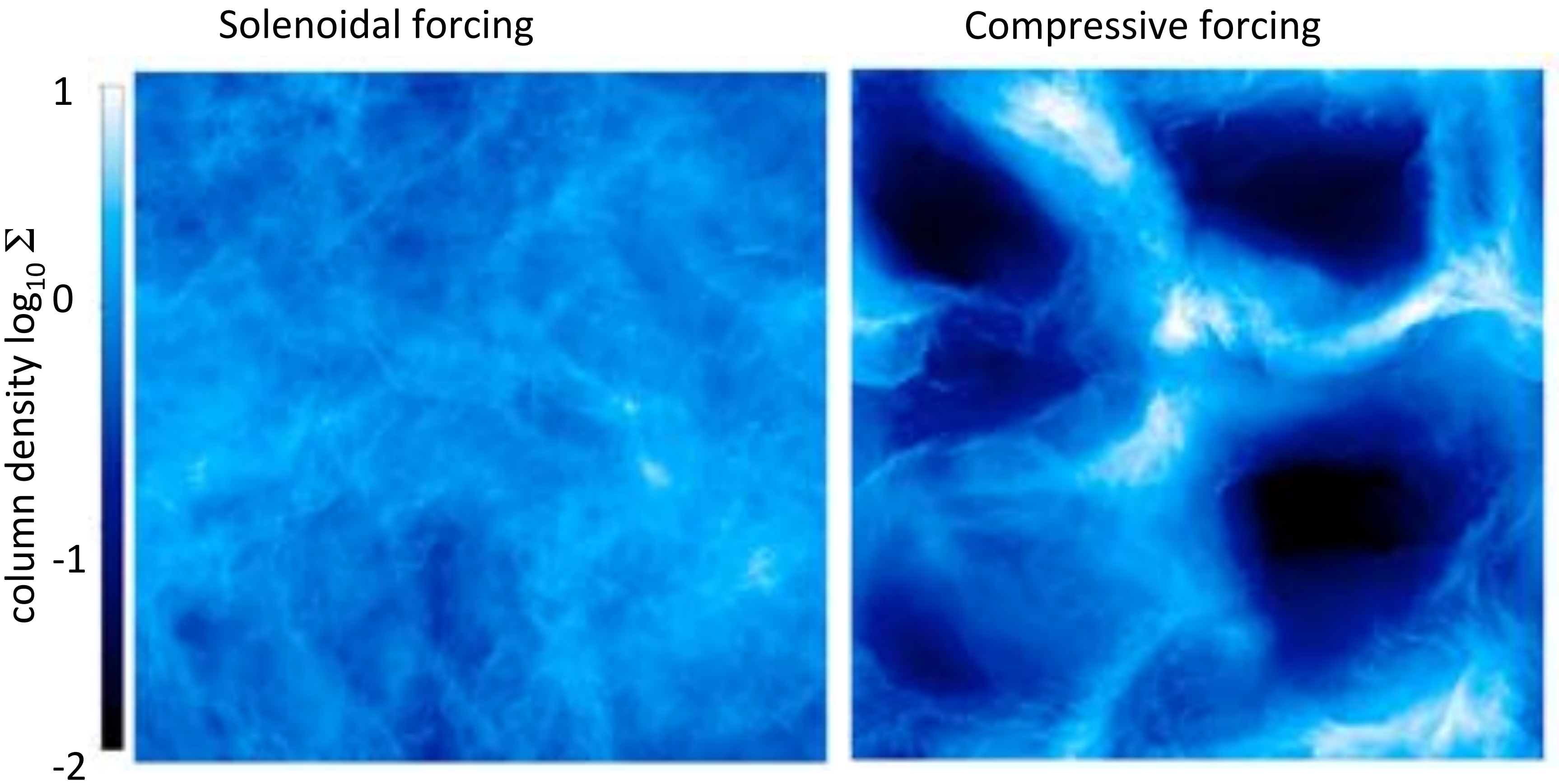


Log-normal probability density distribution (PDF)

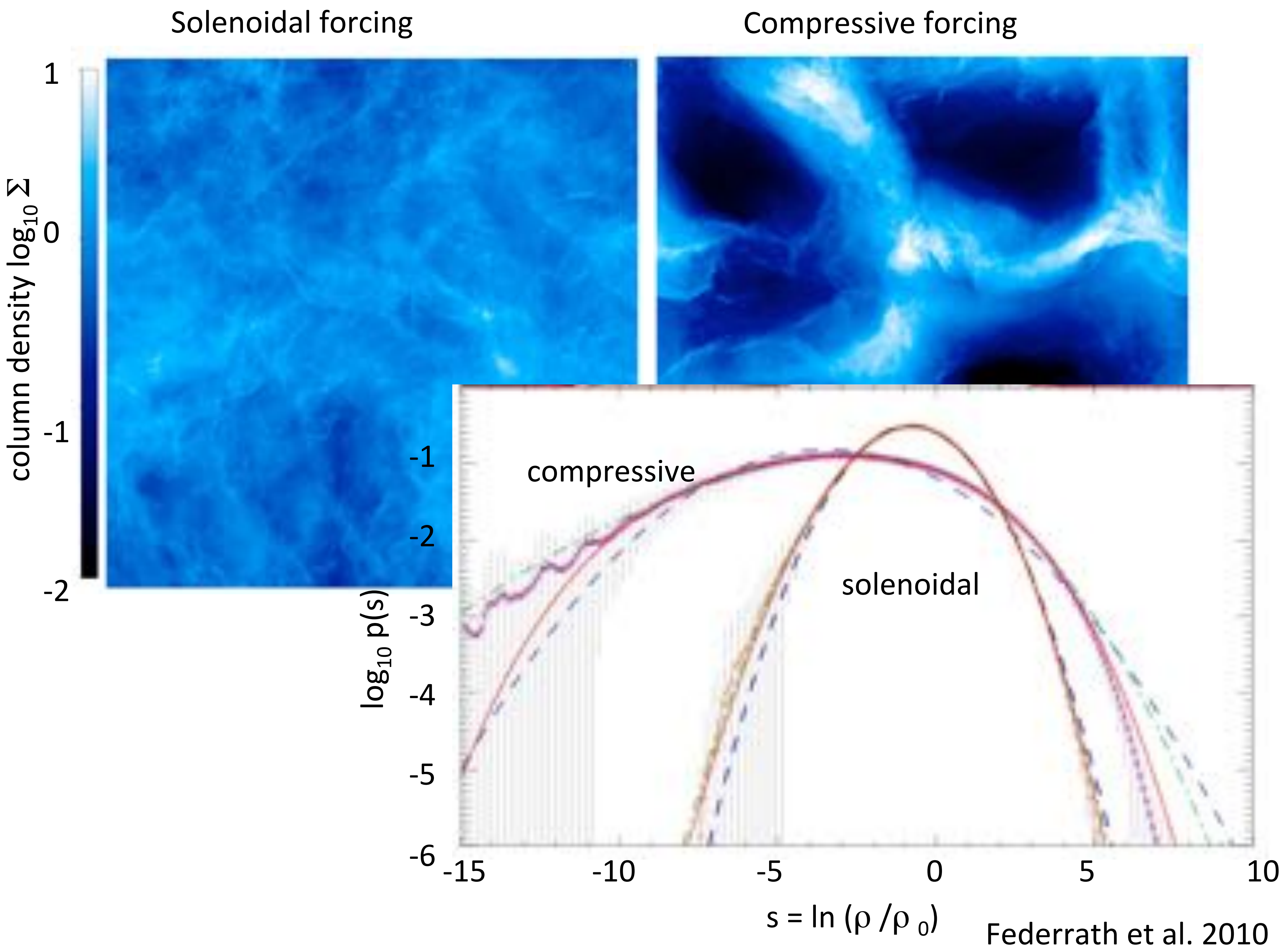
$$p_s(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s - s_0)^2}{2\sigma_s^2}\right)$$

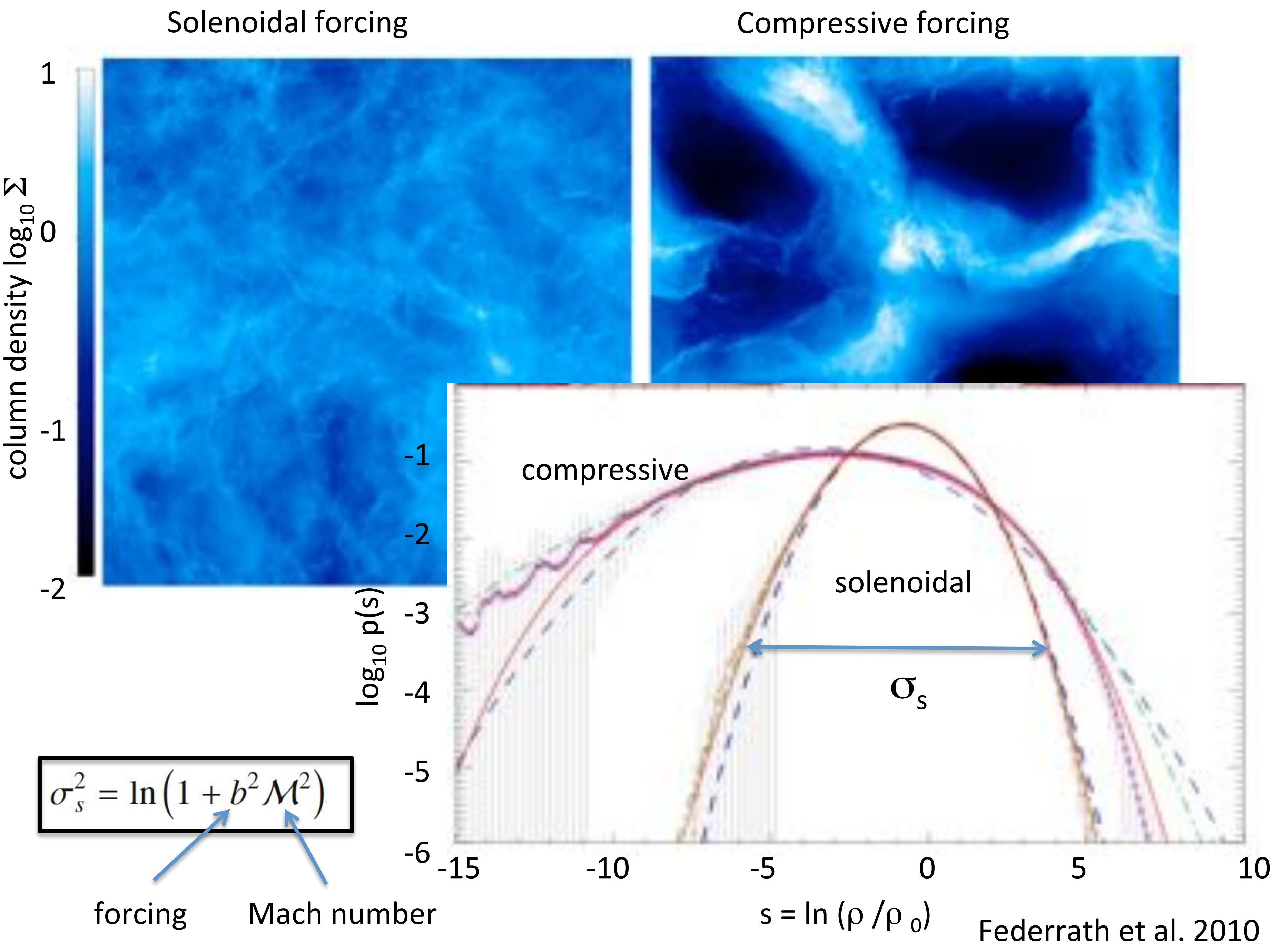
$$s \equiv \ln(\rho/\rho_0) \qquad s_0 = -\frac{1}{2}\sigma_s^2$$

What about σ_s?

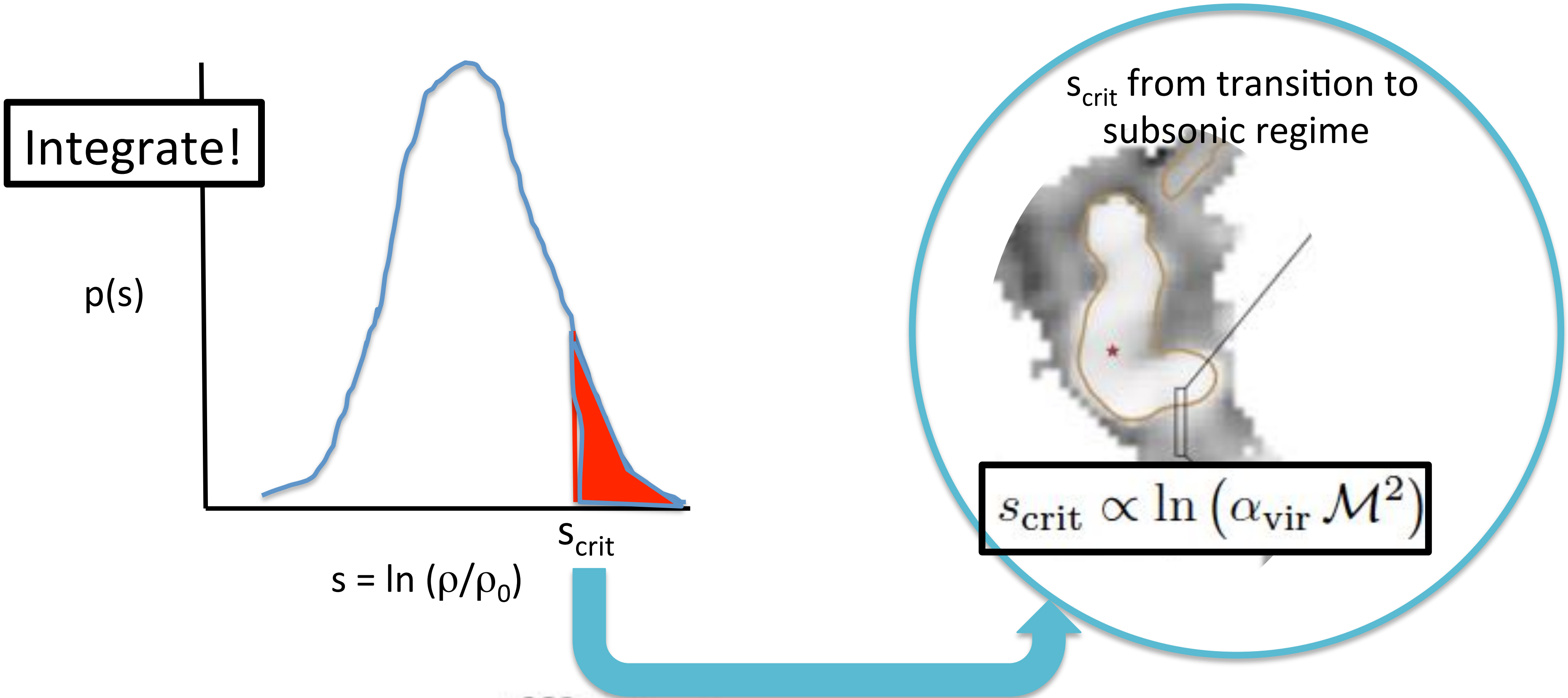


Federrath et al. 2010


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
Compressive forcing
column density $\log_{10} \Sigma$
1
0
-1
-2
compressive
solenoidal
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?



star formation efficiency per free fall time =

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

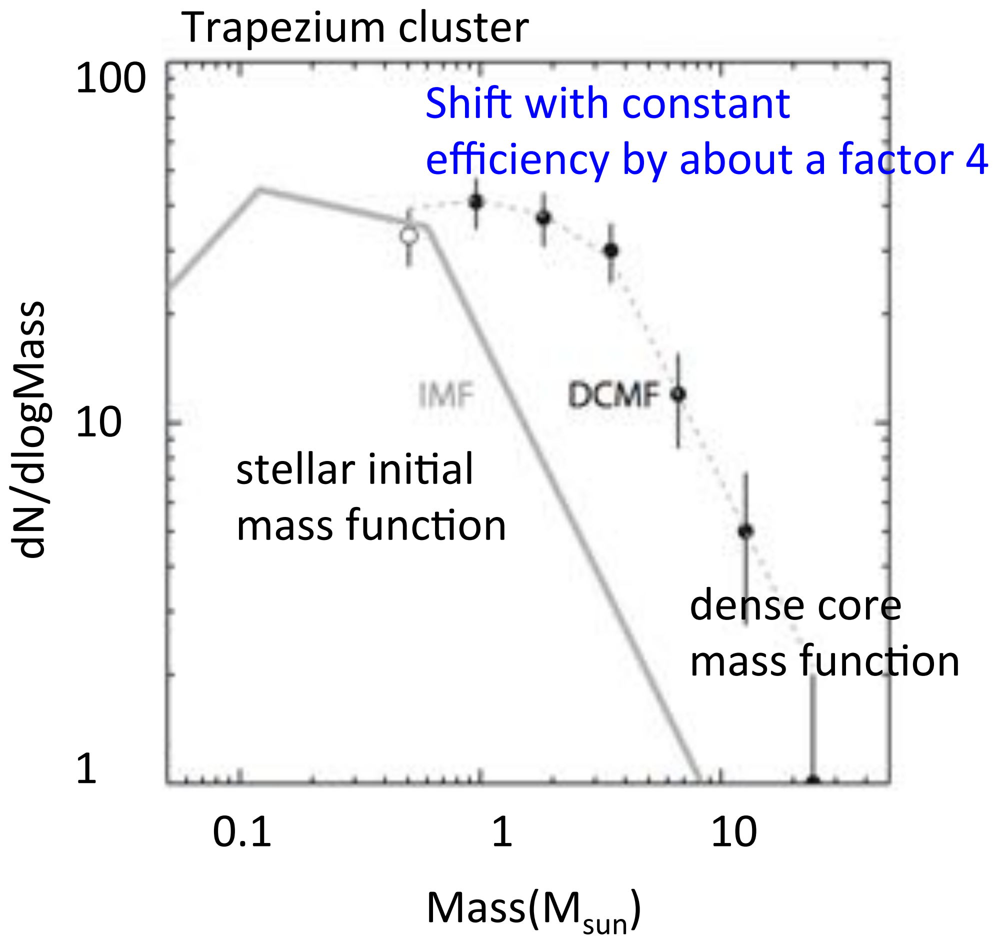
$$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\left(\alpha_{\rm vir}, b, \mathcal{M}\right)$$

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

Federrath & Klessen 2012

Dust under the carpet: the core to star efficiency

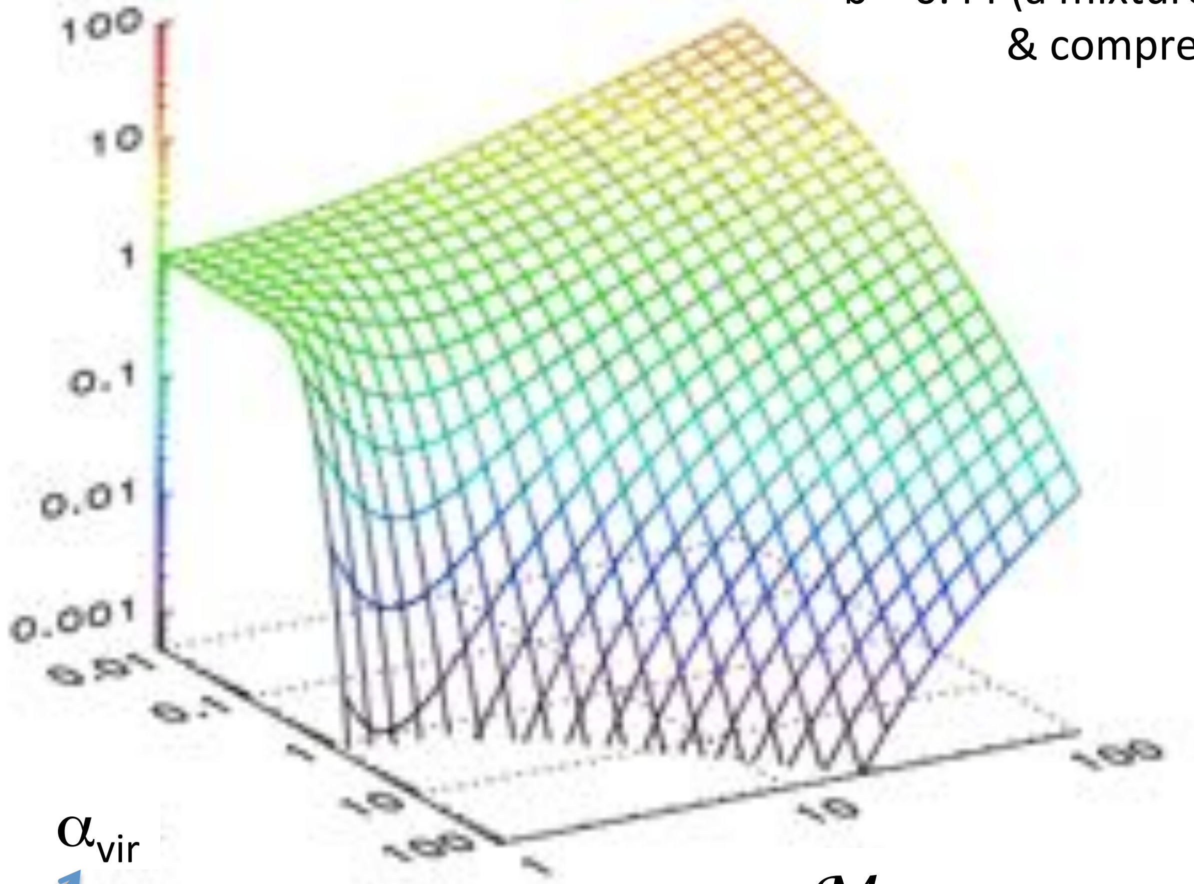
$$\mathrm{SFR_{ff}} = \epsilon \int_{s_\mathrm{crit}}^{\infty} \frac{t_\mathrm{ff}(\rho_0)}{t_\mathrm{ff}(\rho)} \frac{\rho}{\rho_0} p(s)\, \mathrm{d}s$$



Alves et al. 2007

Dependence of star formation efficiency on dynamic properties of gas

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

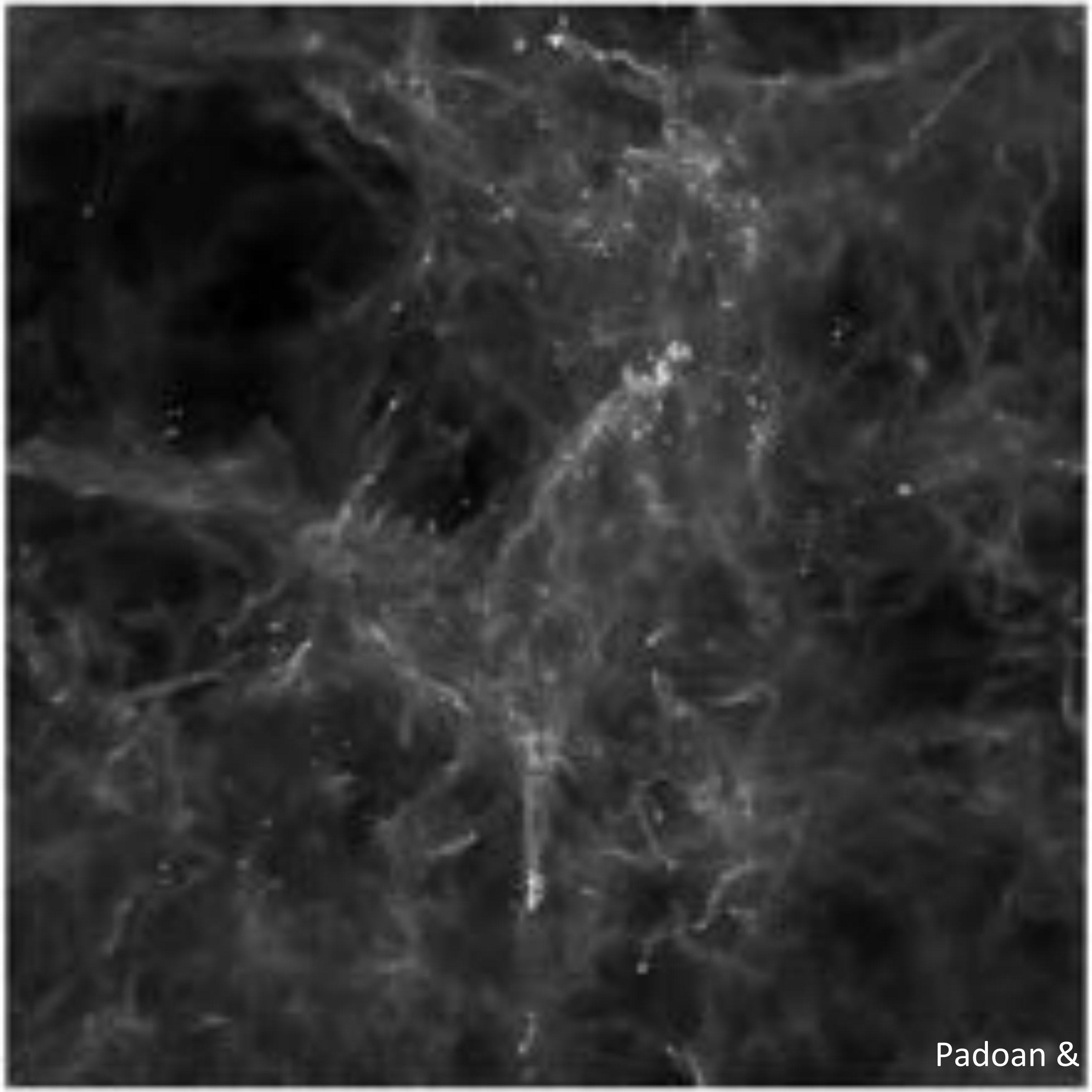


SFR_{ff} ← star formation efficiency per free fall time

α_{vir} ← $2\ E_{kin}/E_{grav}$

$\mathcal{M}$ ← Mach number

Federrath & Klessen 2012



Padoan & Nordlund 2011

How should we form stars in the simulations?

Heyer et al. 1998

(FCRAO CO survey)

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

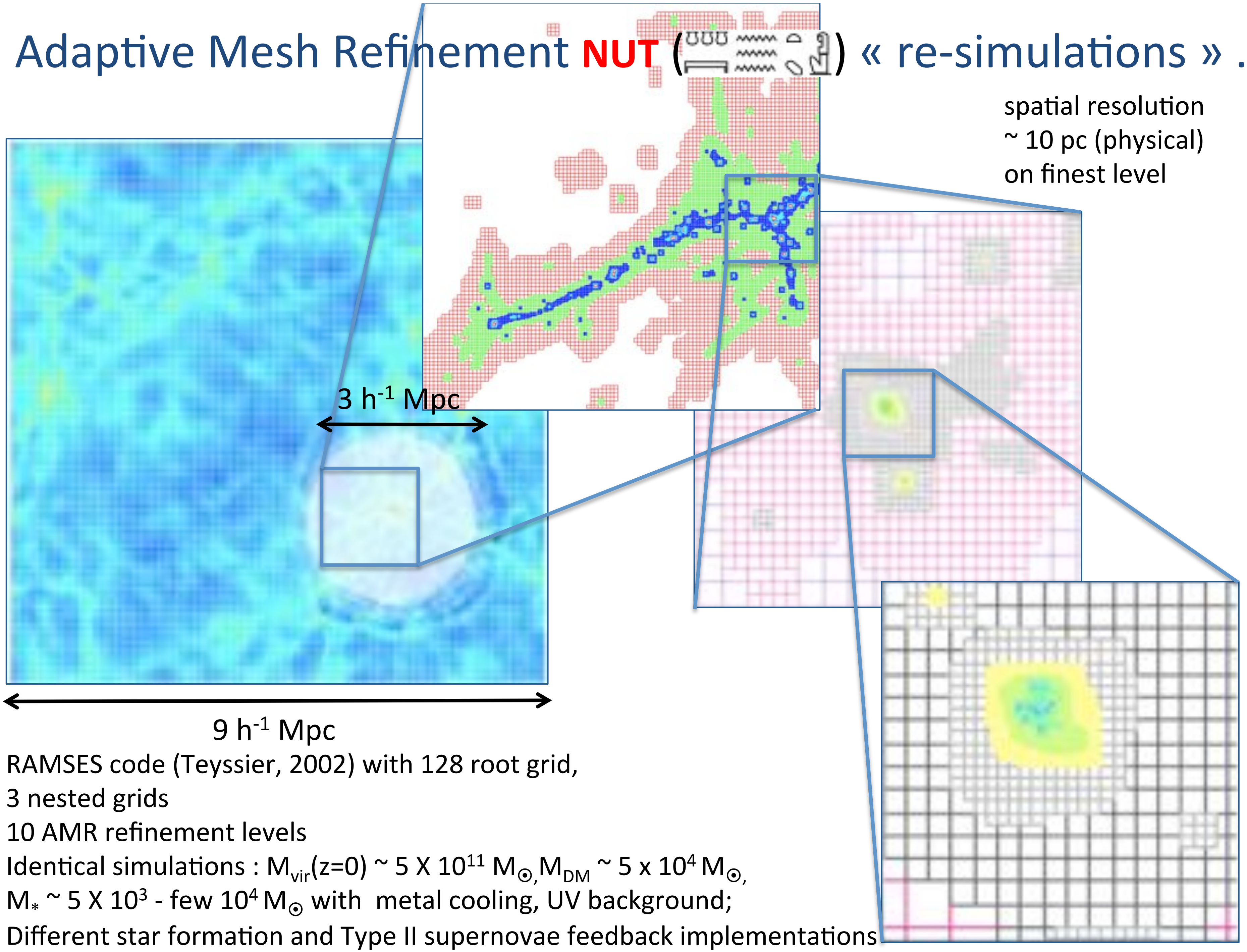
Hopkins, Narayanan, Murray 2013

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

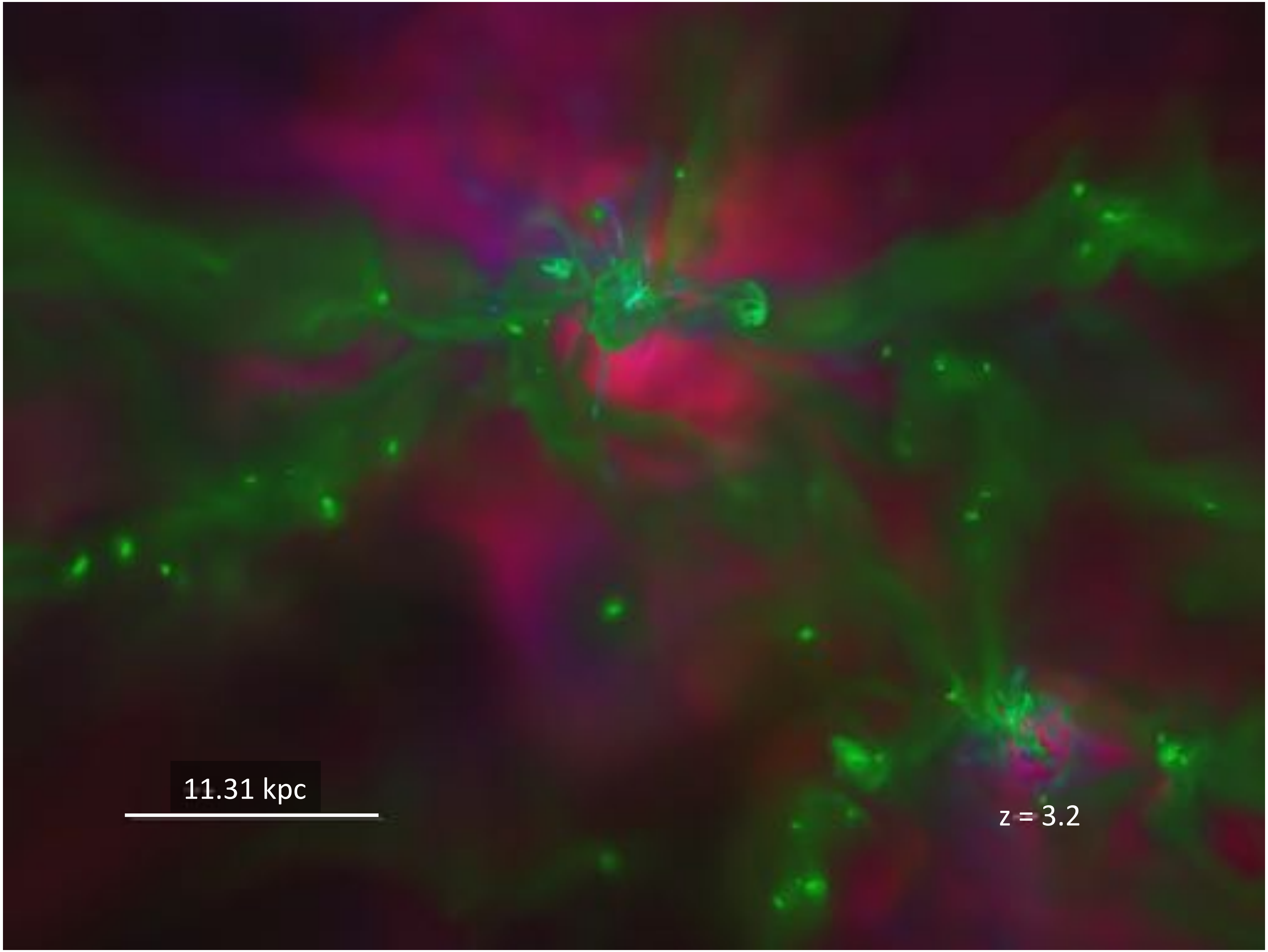
with ϵ = $\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\rm vir}, b, \mathcal{M})$

Federrath & Klessen 2012

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


11.31 kpc
z = 3.2

Simulations

1. density threshold star formation, no SN feedback

2. “ , energy conserving SN fbk (Dubois & Teyssier 2008)

3. “ , momentum conserving SN fbk (Kimm & Cen 2014)

4. turbulent star formation, no SN feedback

5. “ , energy conserving SN fbk

6. “ , momentum conserving SN fbk

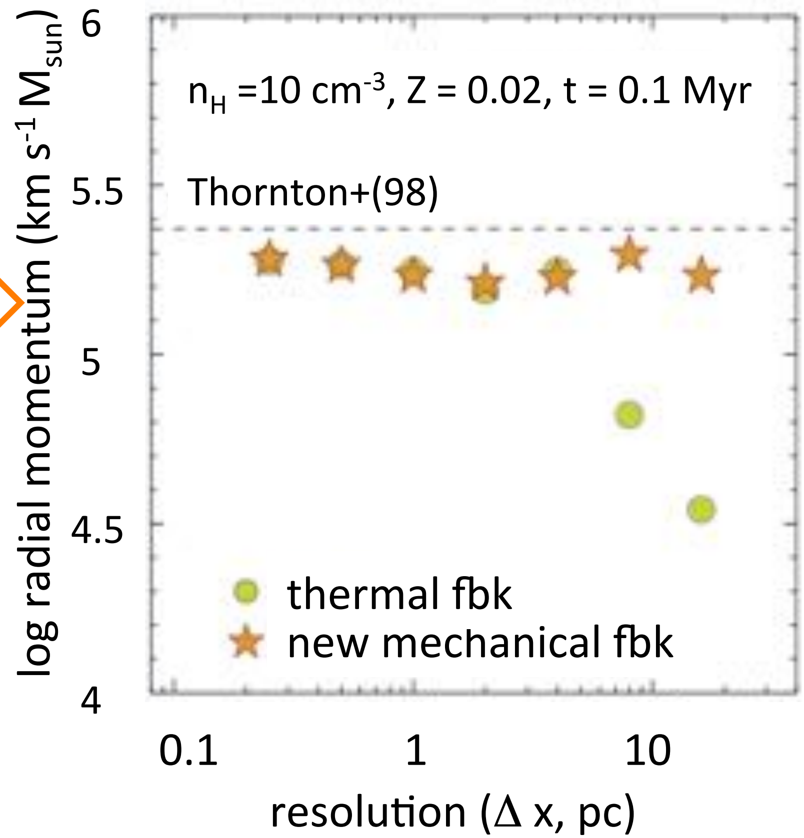
Supernovae Feedback

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

Momentum transfer from single SN in uniform medium



Simulations

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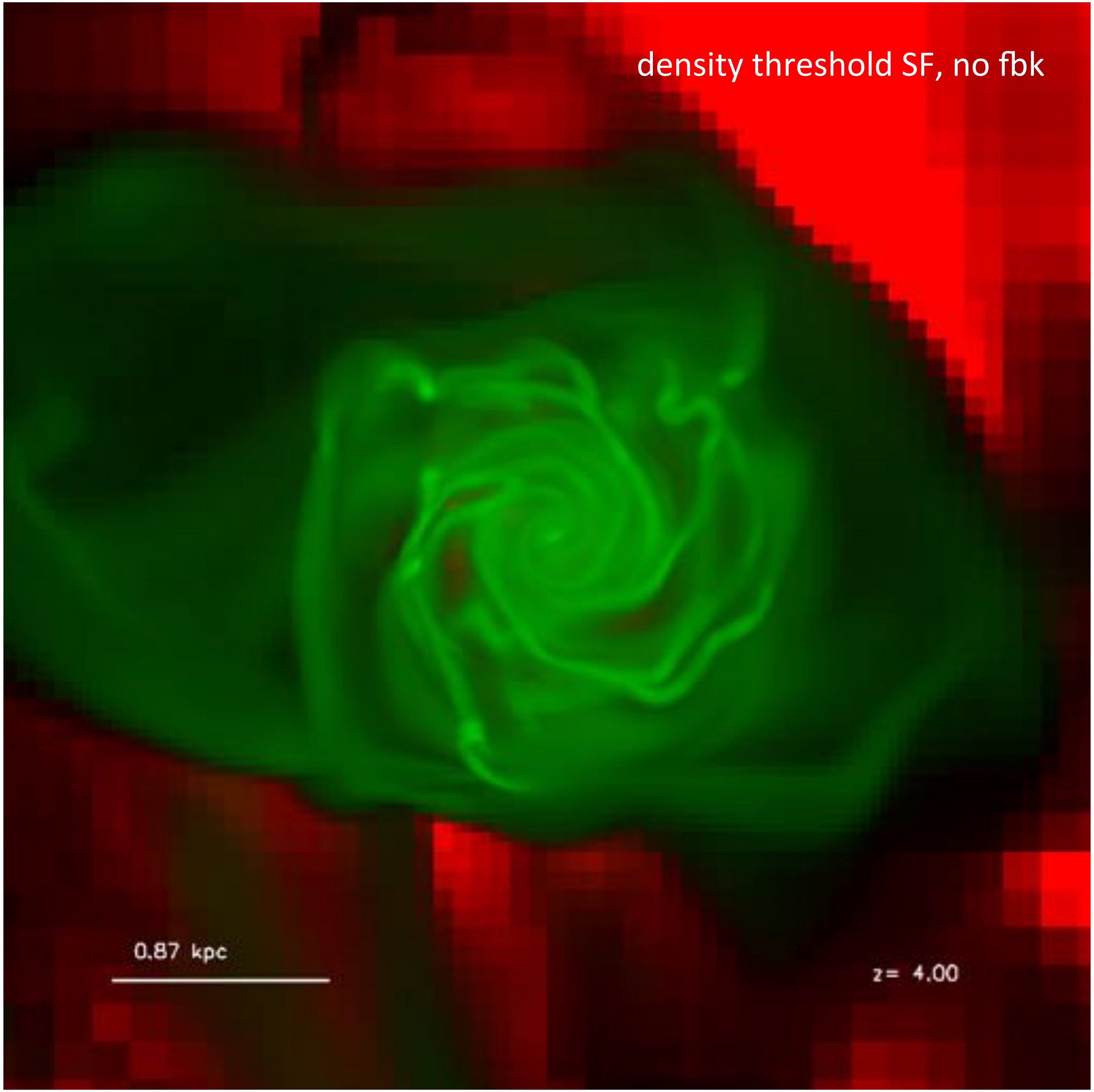
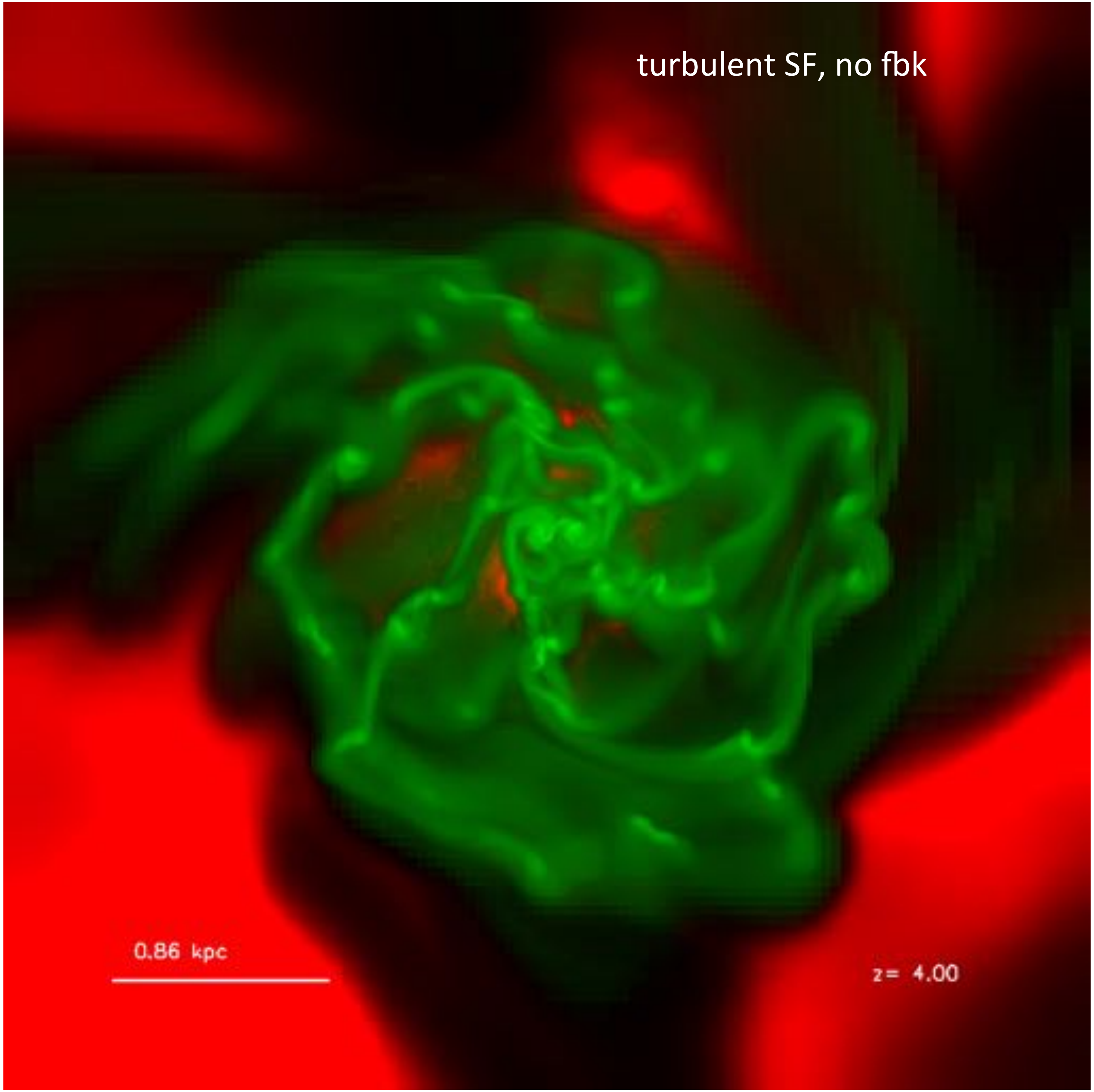
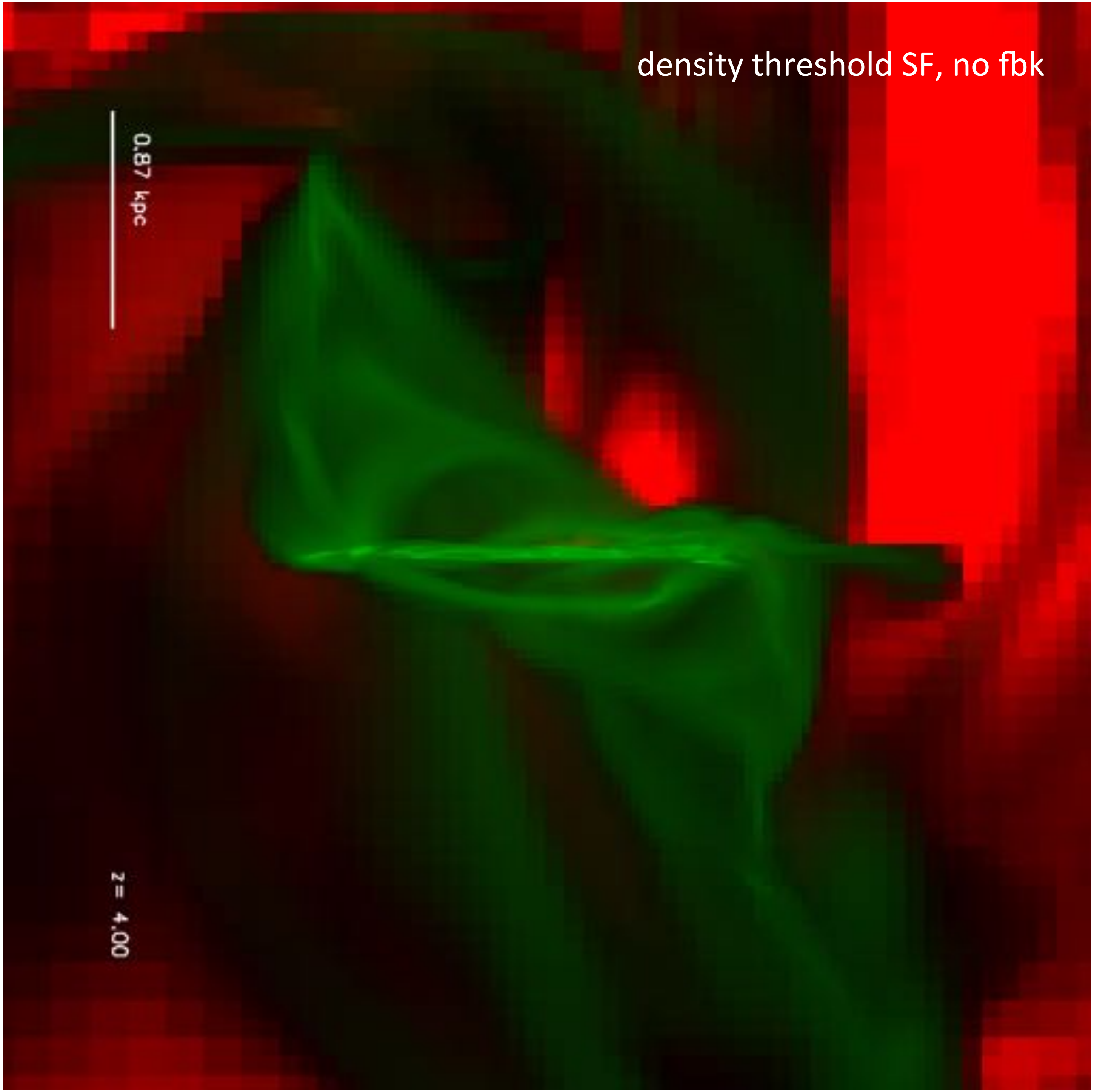


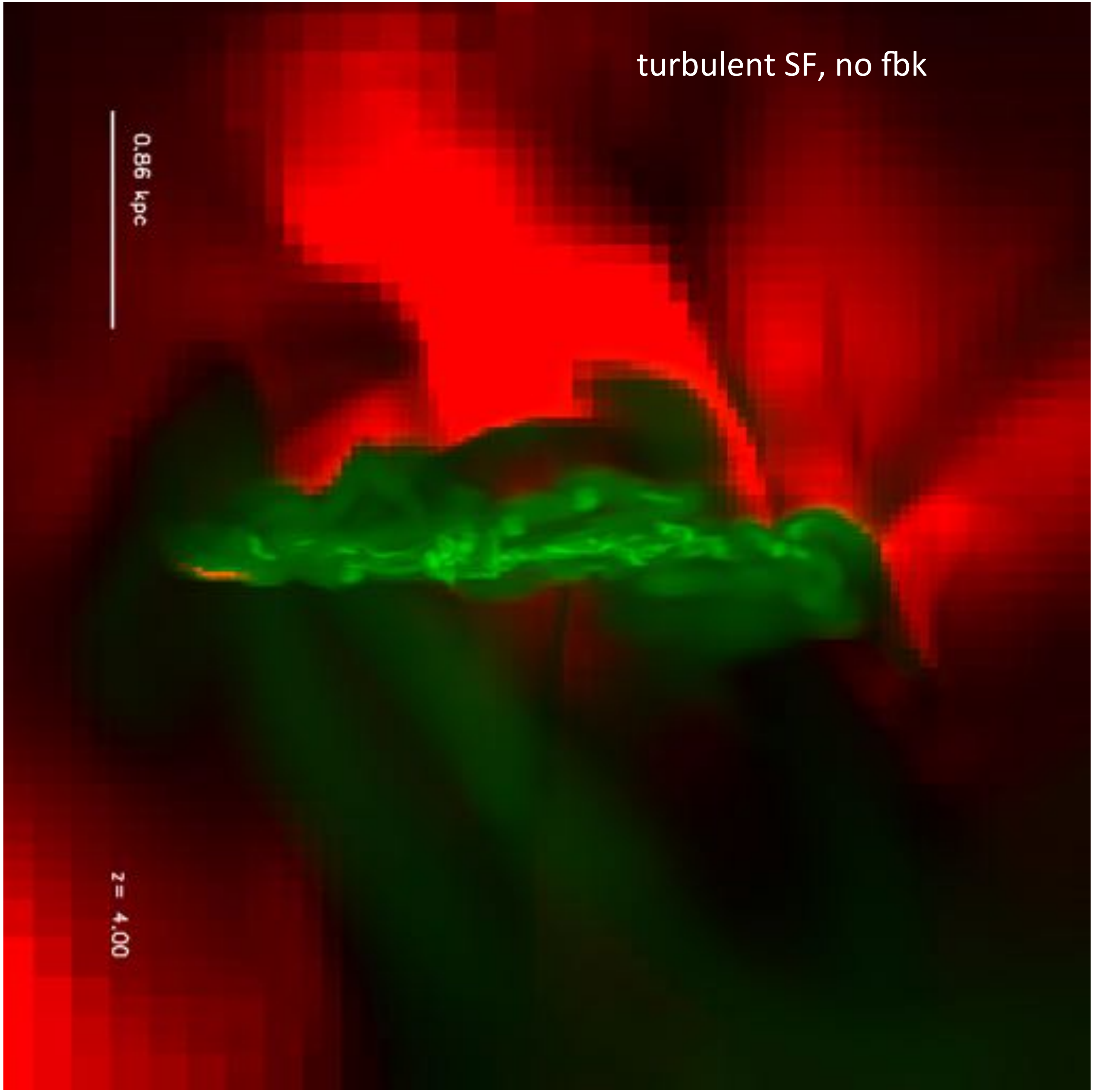
Devriendt, Slyz, Kimm (in prep)



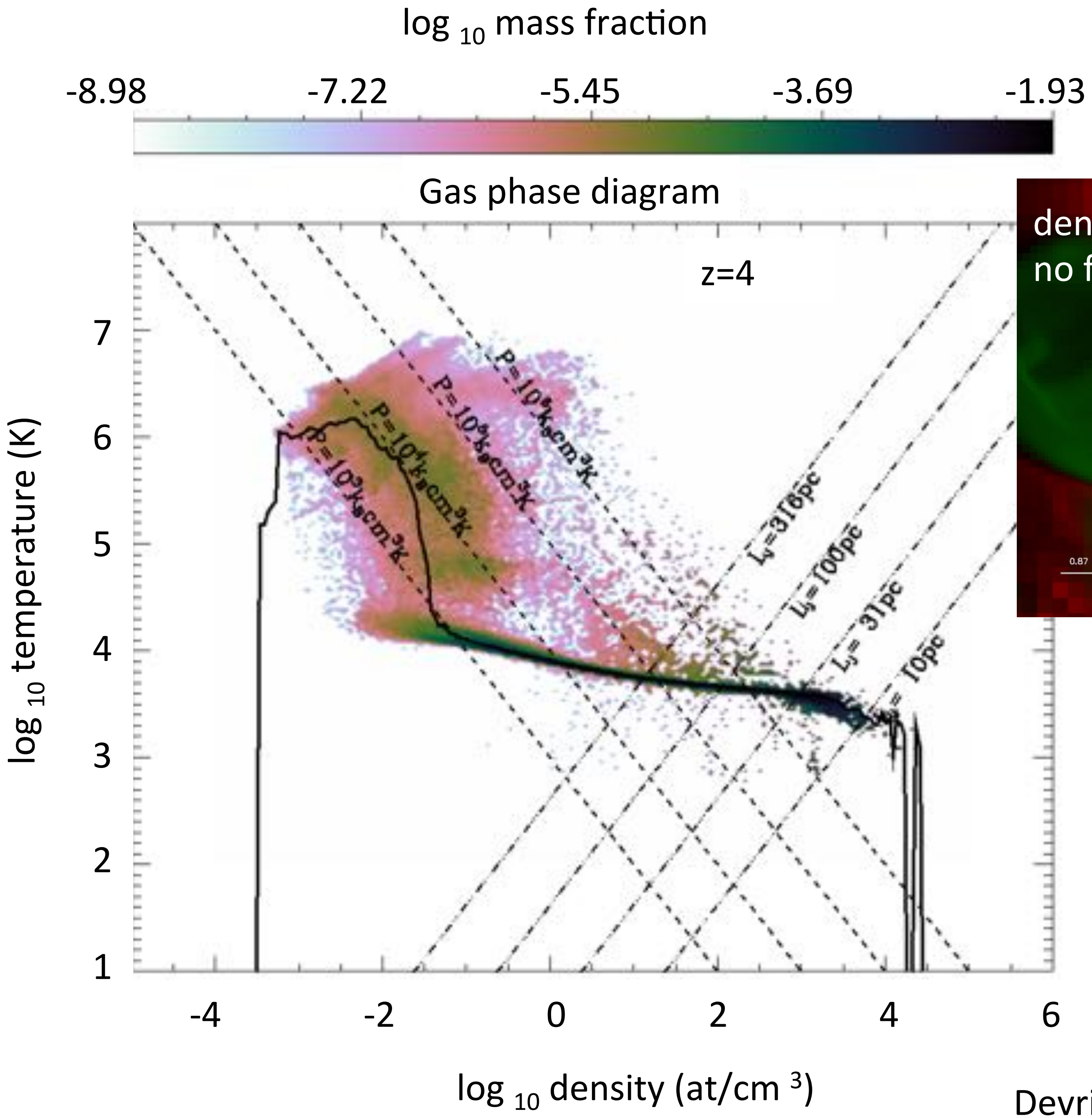
Devriendt, Slyz, Kimm (in prep)

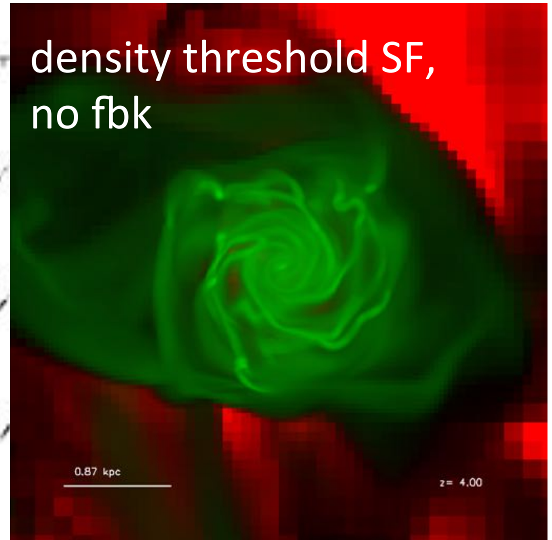


Devriendt, Slyz, Kimm (in prep)

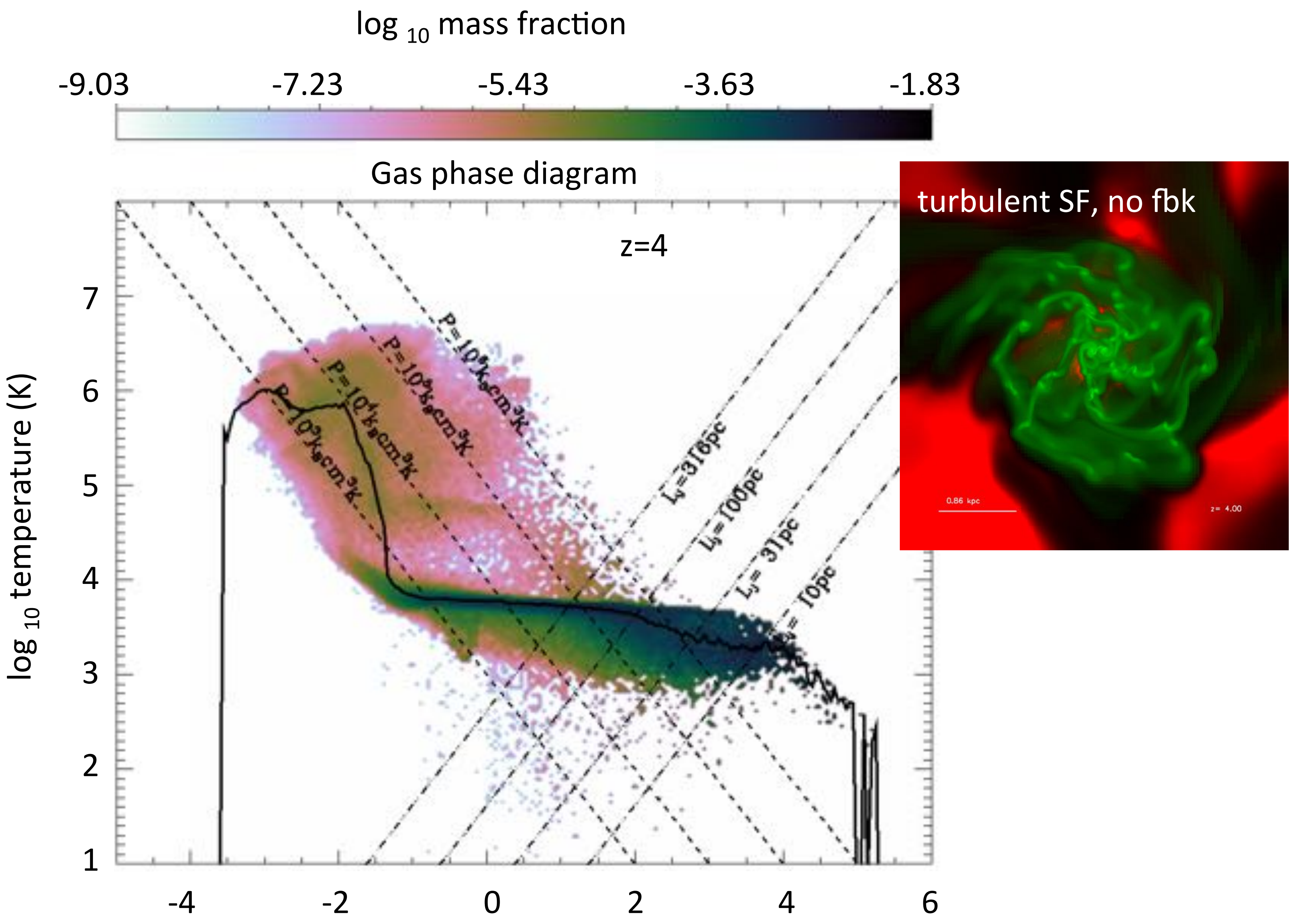


Devriendt, Slyz, Kimm (in prep)



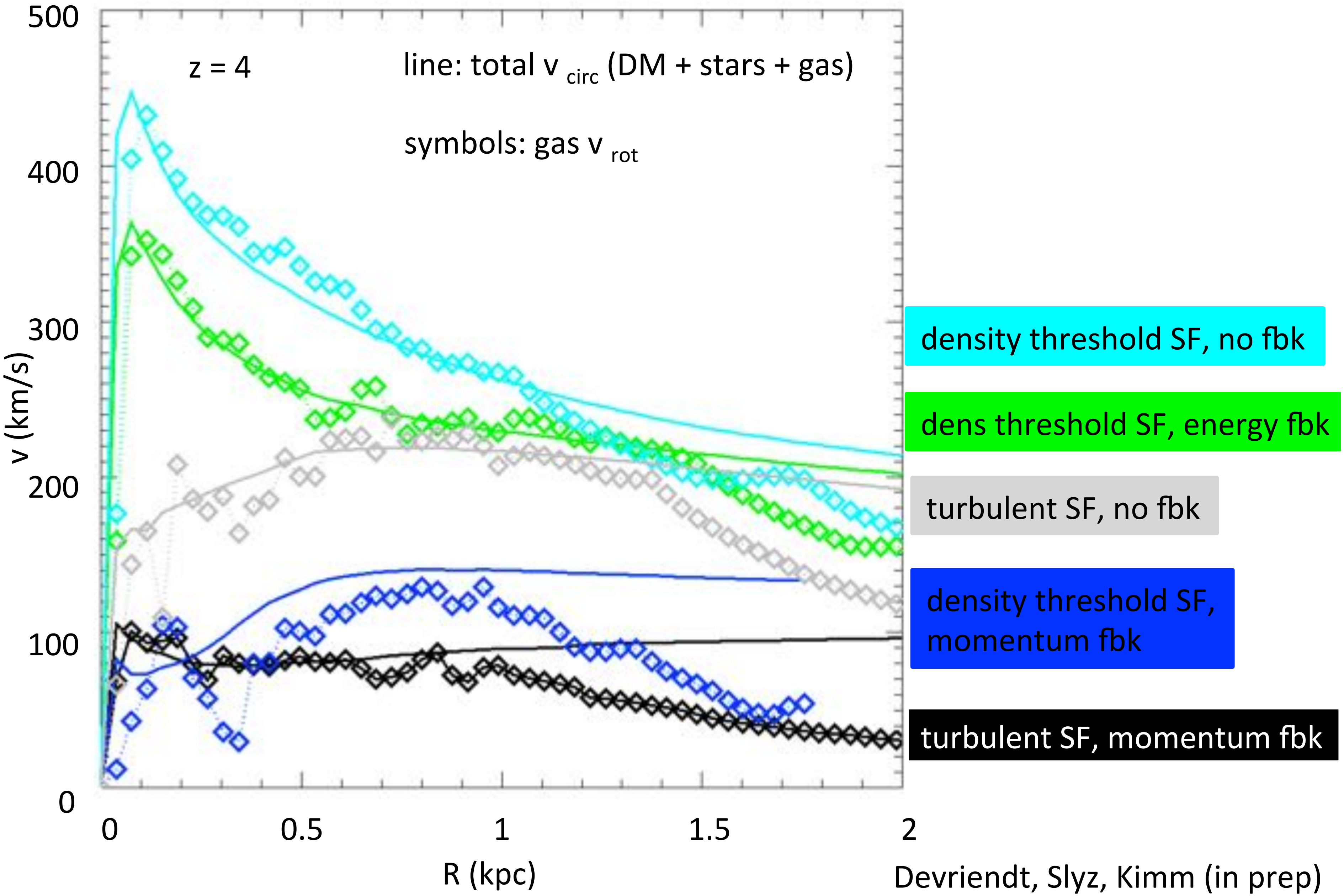


Devriendt, Slyz, Kimm (in prep)



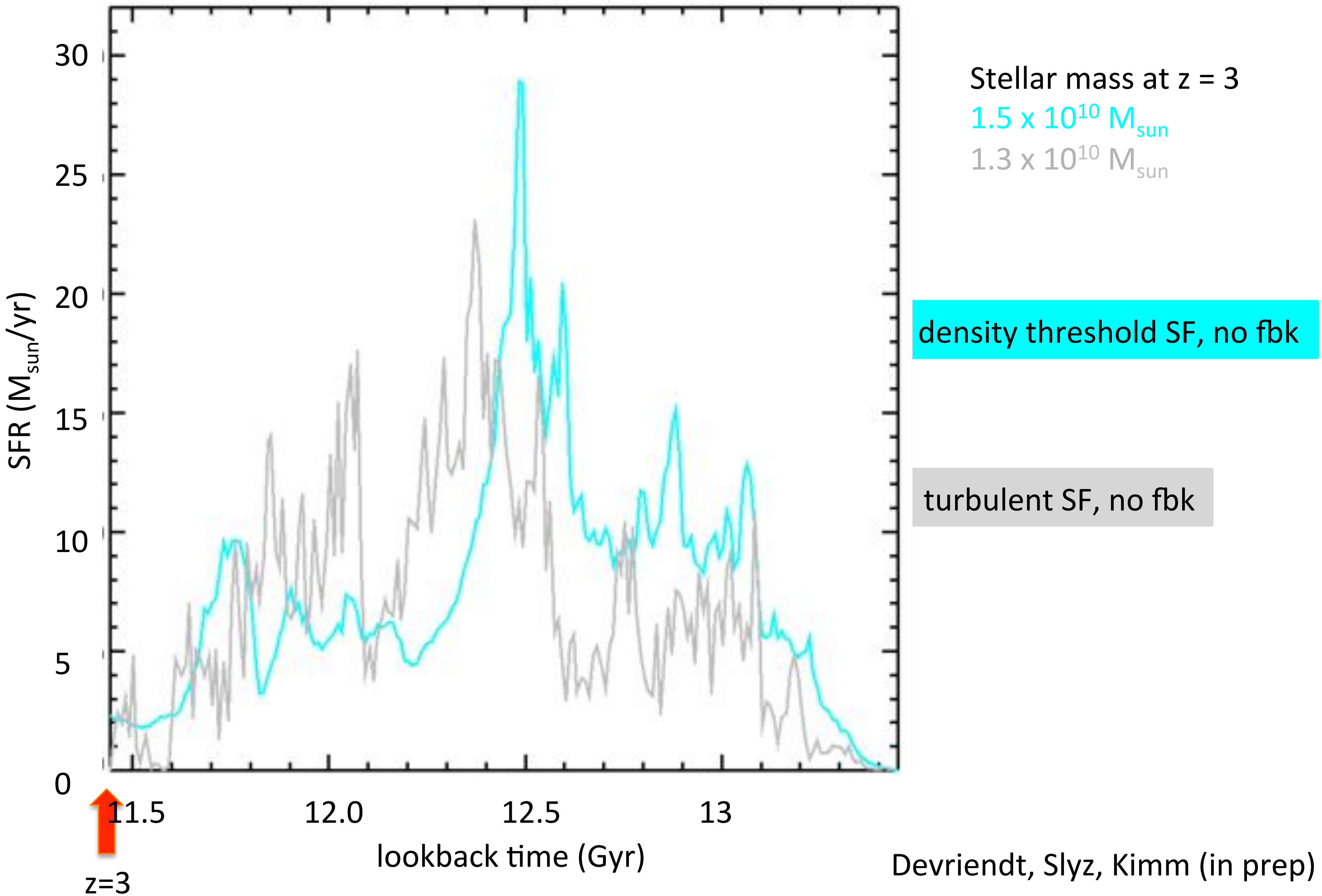
Devriendt, Slyz, Kimm (in prep)

Rotation curves

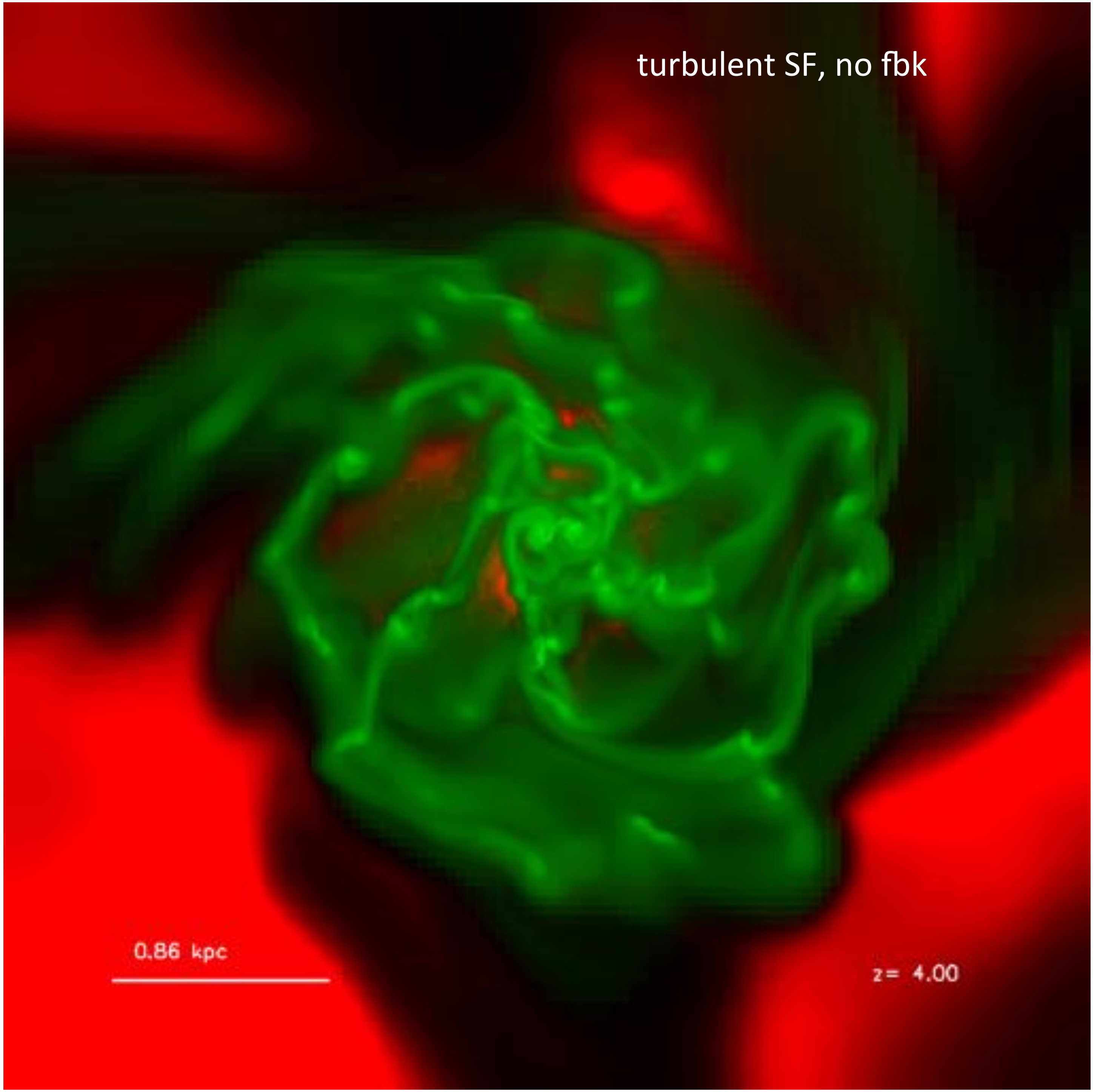


Devriendt, Slyz, Kimm (in prep)

Star formation rates: no feedback runs



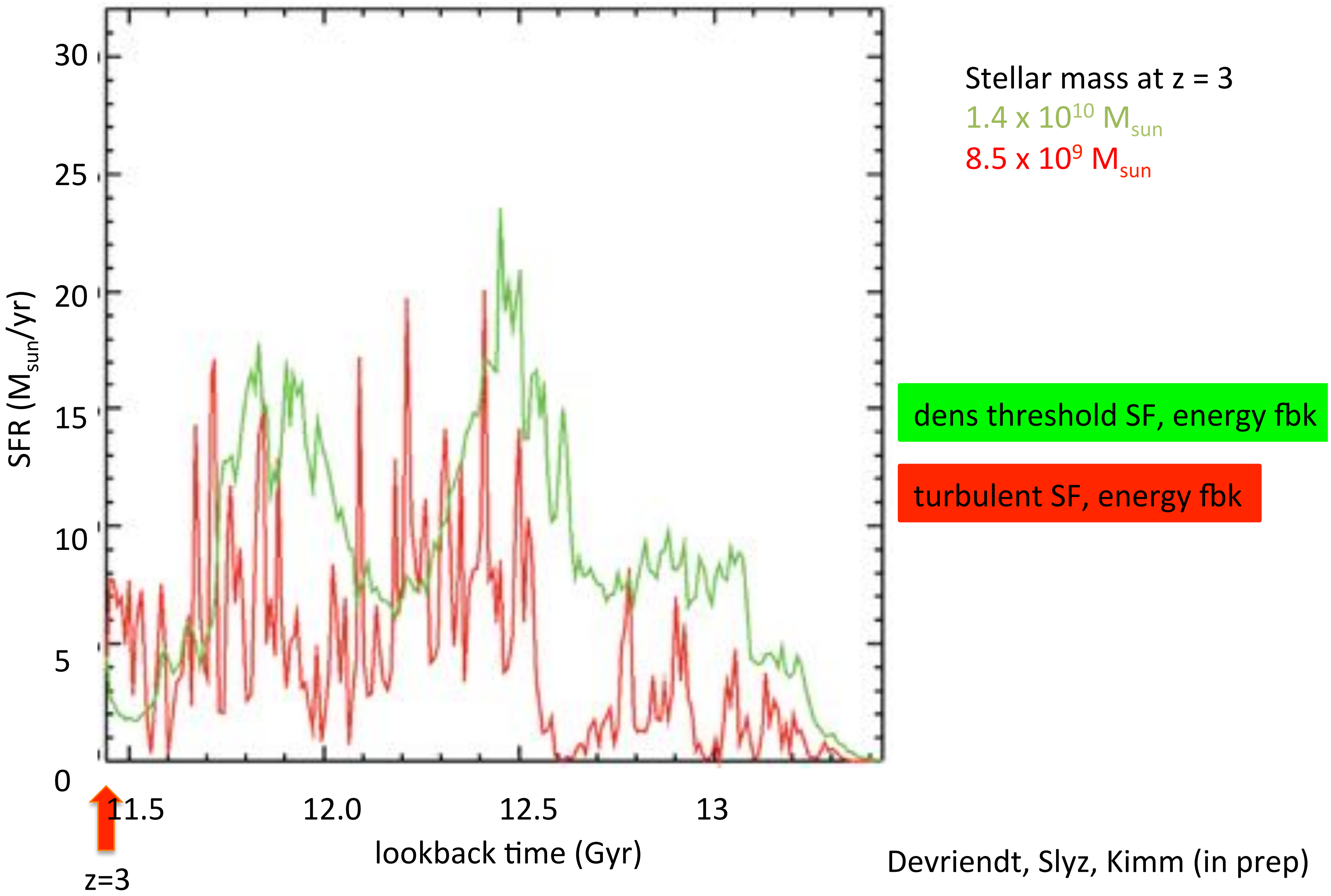
Devriendt, Slyz, Kimm (in prep)



Devriendt, Slyz, Kimm (in prep)

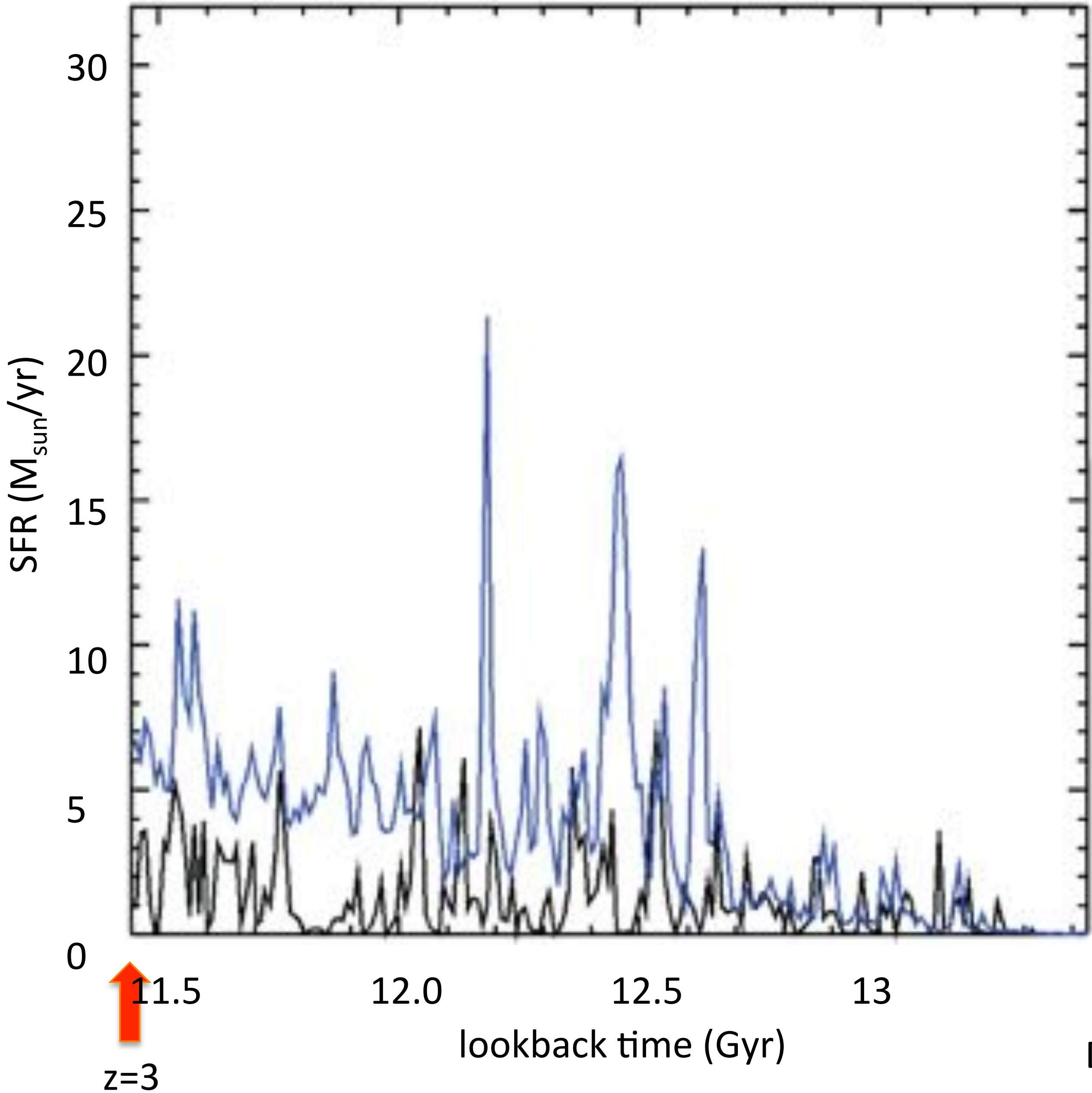
Blue contours: isodensity at 400 at/cm^3
Green : gravitationally unstable regions

Star formation rates: energy feedback runs



Devriendt, Slyz, Kimm (in prep)

Star formation rates: momentum feedback runs



Stellar mass at z = 3

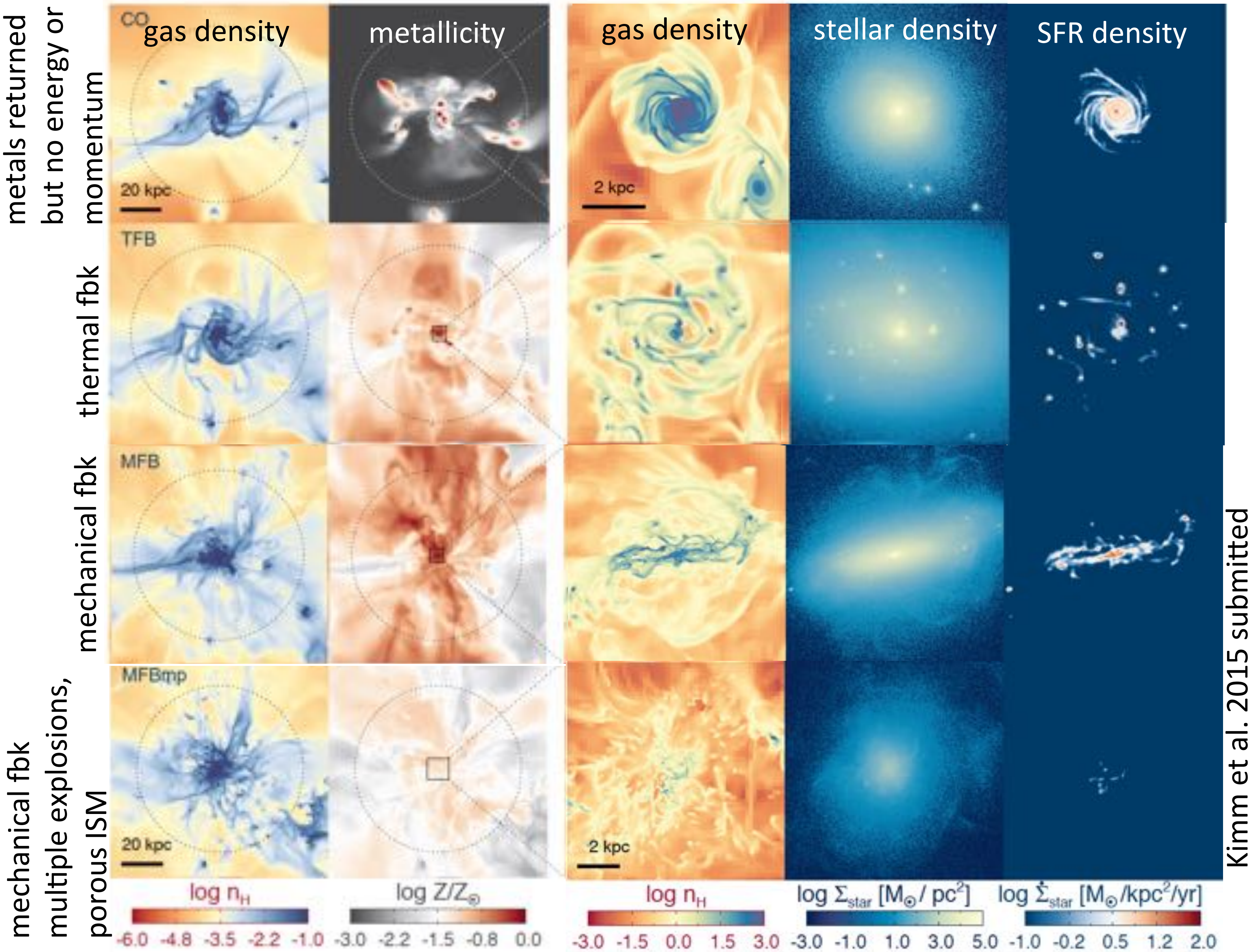
7.5×10^9 M_{sun}

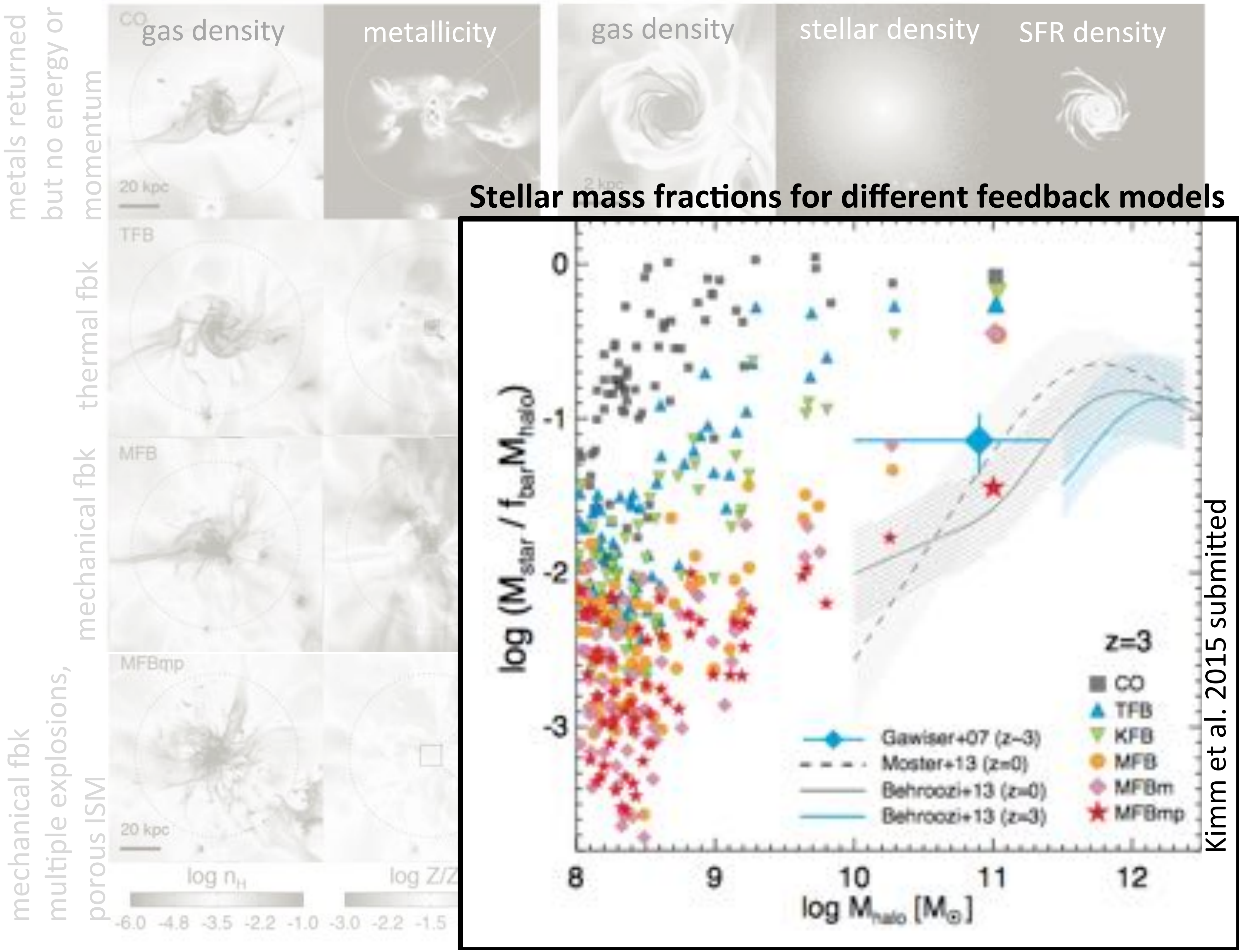
1.5×10^9 M_{sun}

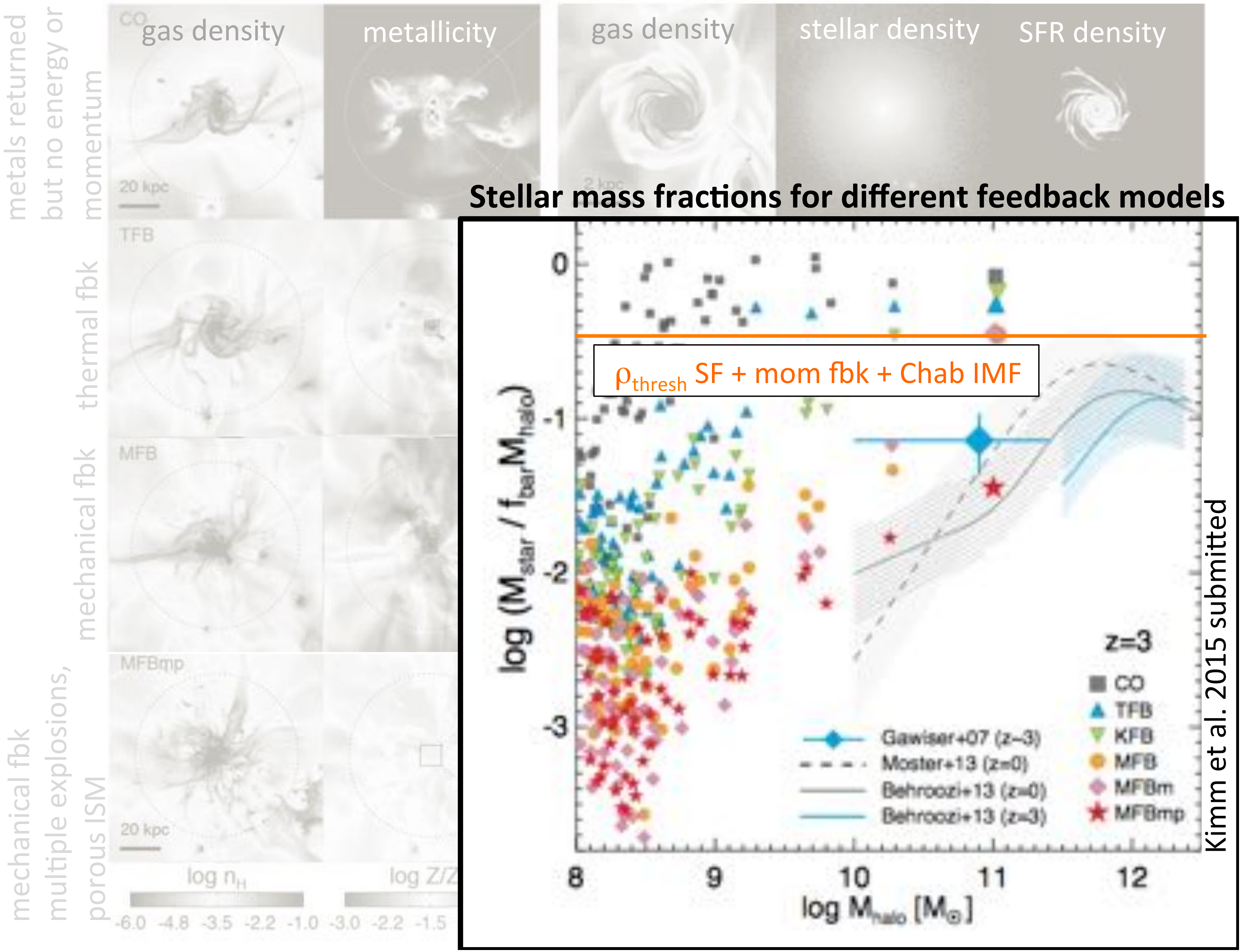
density threshold SF, momentum fbk

turbulent SF, momentum fbk

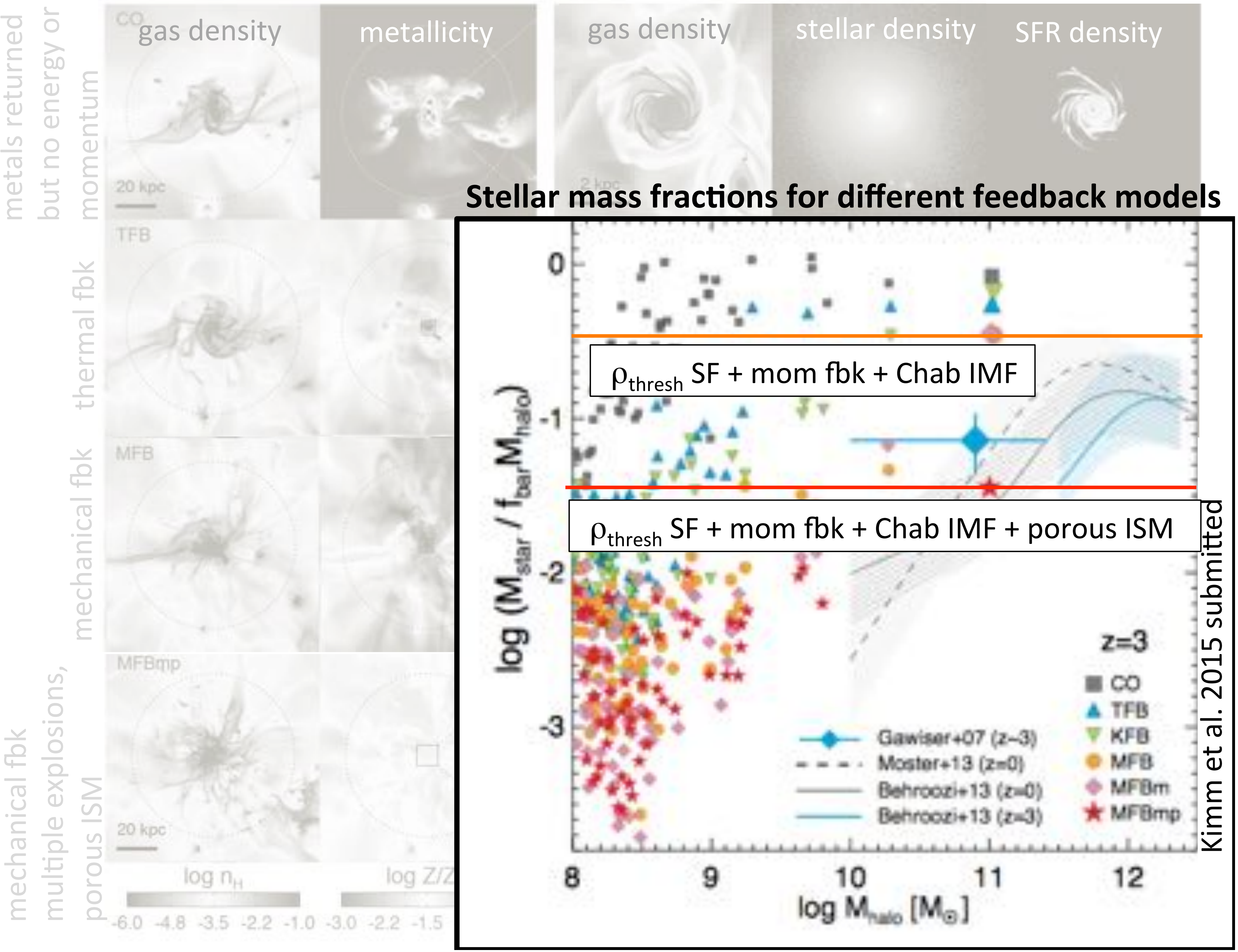
Devriendt, Slyz, Kimm (in prep)


gas density
metallicity
gas density
stellar density
SFR density
metals returned but no energy or momentum
thermal fbk
mechanical fbk
mechanical fbk multiple explosions, porous ISM
CO
TFB
MFB
MFBmp
20 kpc
2 kpc
log n_H
log $Z/Z_\odot$
log Σ_{star} [$M_\odot$/ pc^2]
log $\dot{\Sigma}_{star}$ [$M_\odot$/kpc^2/yr]
-6.0 -4.8 -3.5 -2.2 -1.0
-3.0 -2.2 -1.5 -0.8 0.0
-3.0 -1.5 0.0 1.5 3.0
-3.0 -1.0 1.0 3.0 5.0
-1.0 -0.2 0.5 1.2 2.0
Kimm et al. 2015 submitted


Stellar mass fractions for different feedback models
metals returned but no energy or momentum
thermal fbk
mechanical fbk
mechanical fbk multiple explosions, porous ISM
CO
TFB
MFB
MFBmp
gas density
metallicity
gas density
stellar density
SFR density
20 kpc
2 kpc
log n_H
log Z/Z
-6.0 -4.8 -3.5 -2.2 -1.0
-3.0 -2.2 -1.5
log (M_{star} / $f_{bar}M_{halo}$)
log M_{halo} [$M_\odot$]
z=3
Gawiser+07 (z~3)
Moster+13 (z=0)
Behroozi+13 (z=0)
Behroozi+13 (z=3)
CO
TFB
KFB
MFB
MFBm
MFBmp
Kimm et al. 2015 submitted



Stellar mass fractions for different feedback models
metals returned but no energy or momentum
thermal fbk
mechanical fbk
mechanical fbk multiple explosions, porous ISM
CO
gas density
metallicity
gas density
stellar density
SFR density
20 kpc
2 kpc
TFB
MFB
MFBmp
20 kpc
log n_H
-6.0 -4.8 -3.5 -2.2 -1.0
log Z/Z
-3.0 -2.2 -1.5
ρ_thresh SF + mom fbk + Chab IMF
log (M_star / f_bar M_halo)
0
-1
-2
-3
8
9
10
11
12
log M_halo [M_⊙]
z=3
CO
TFB
KFB
MFB
MFBm
MFBmp
Gawiser+07 (z~3)
Moster+13 (z=0)
Behroozi+13 (z=0)
Behroozi+13 (z=3)
Kimm et al. 2015 submitted



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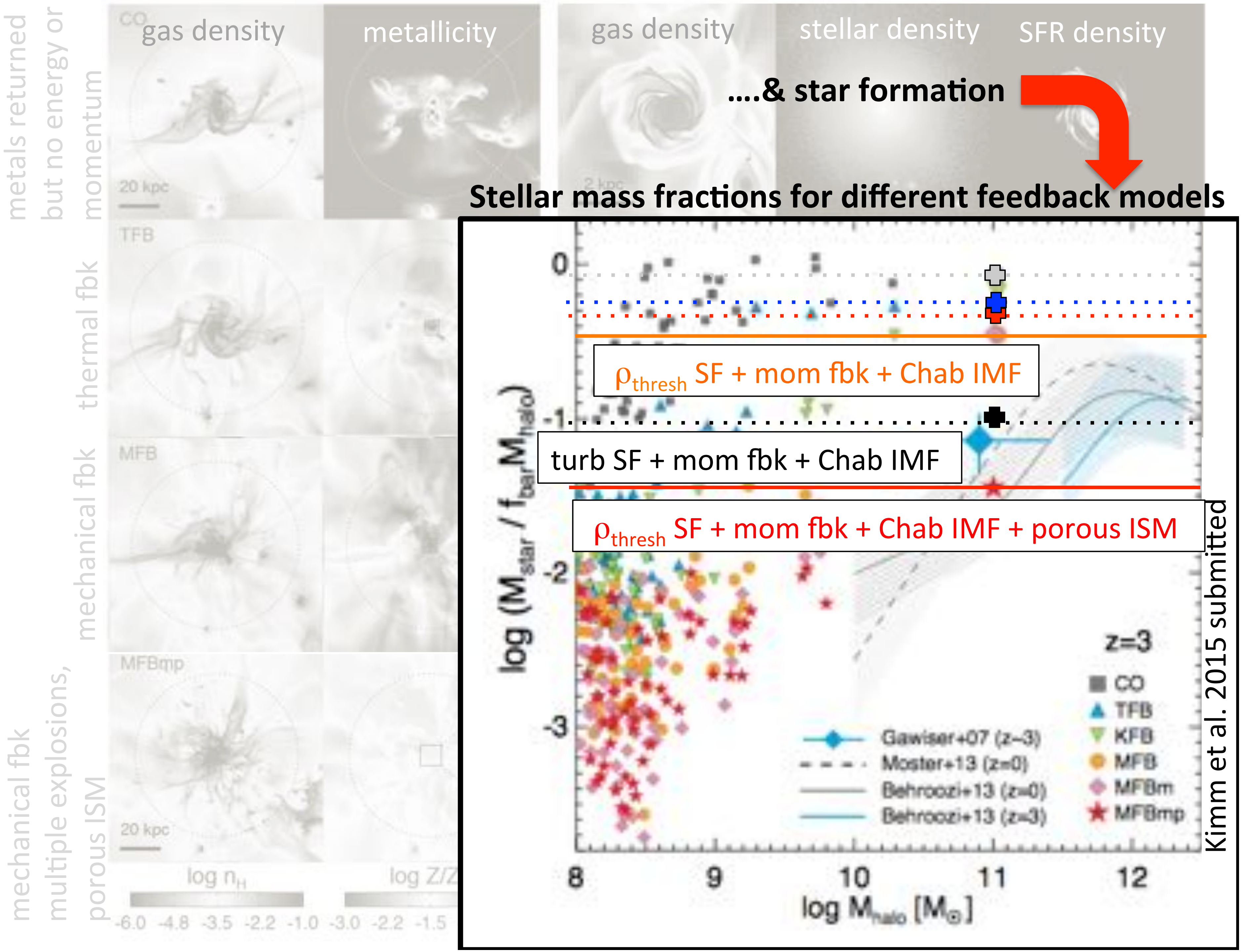

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20 kpc
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....& star formation
Stellar mass fractions for different feedback models
ρ_{thresh} SF + mom fbk + Chab IMF
turb SF + mom fbk + Chab IMF
ρ_{thresh} SF + mom fbk + Chab IMF + porous ISM
$\log (M_{star} / f_{bar} M_{halo})$
$\log M_{halo}$ [$M_\odot$]
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Take home message:

We have 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).

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 10 suppression of the stellar mass when a simple SN momentum injection model is considered