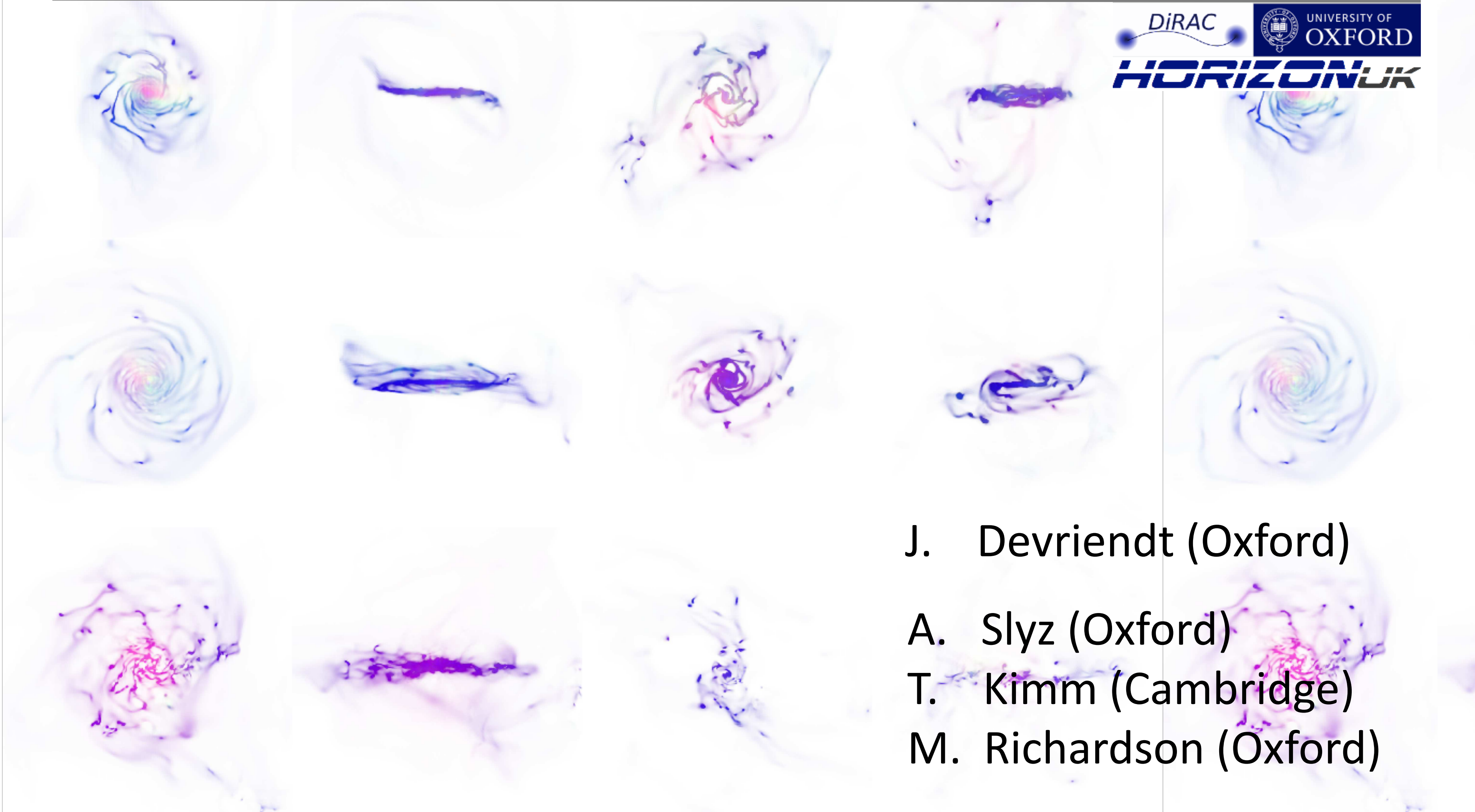
Star formation: how much should we care about its subgrid implementation?



J. Devriendt (Oxford)

A. Slyz (Oxford)

T. Kimm (Cambridge)

M. Richardson (Oxford)

Outlook

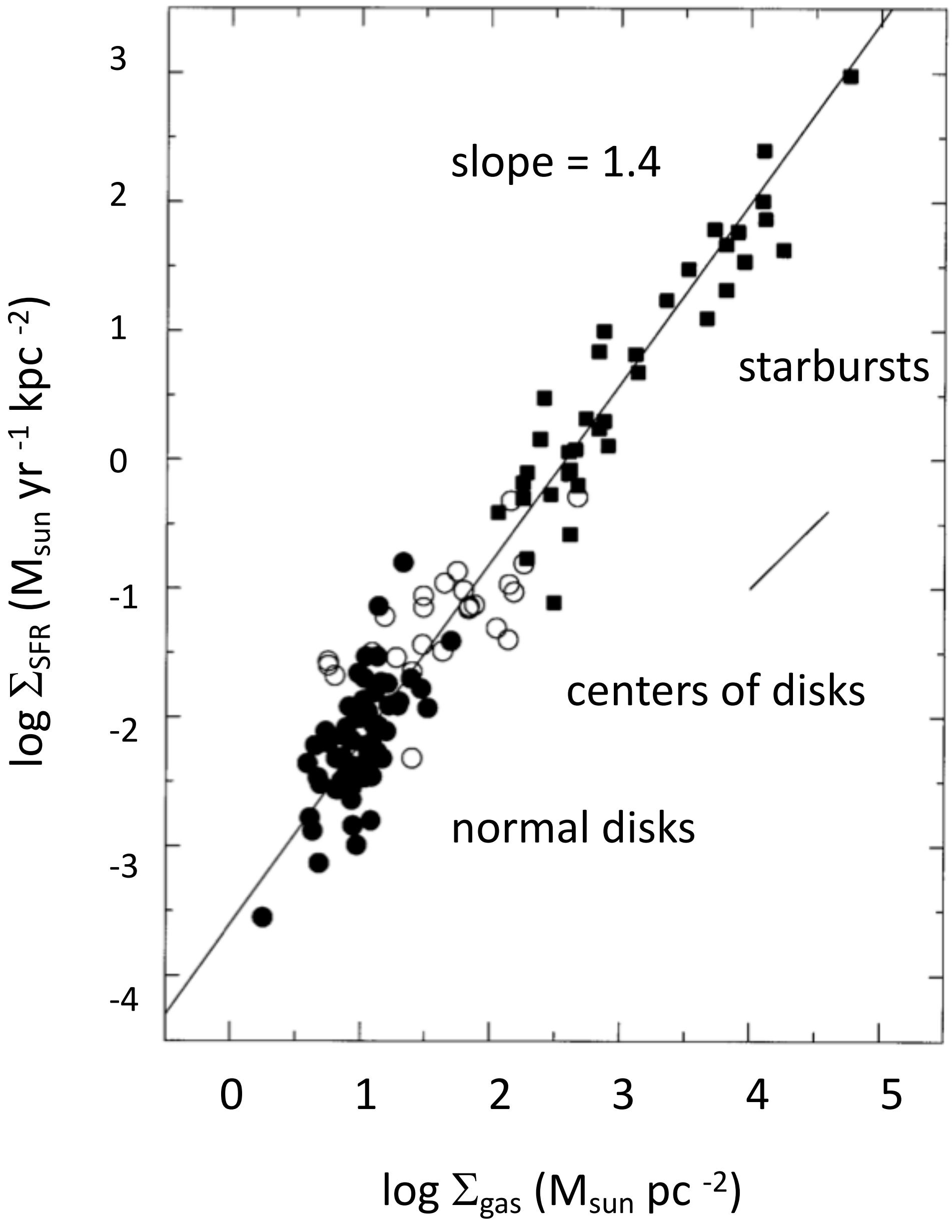
- Presentation of the problem

- A tale of two cities: the case for turbulence

- The devil is in the details: how seemingly small changes in the subgrid model can have significant impact on global galaxy properties …

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

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

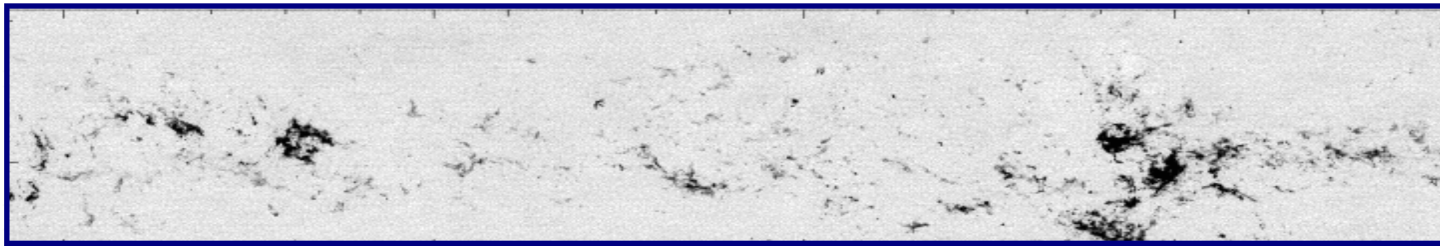
where

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

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 ??

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

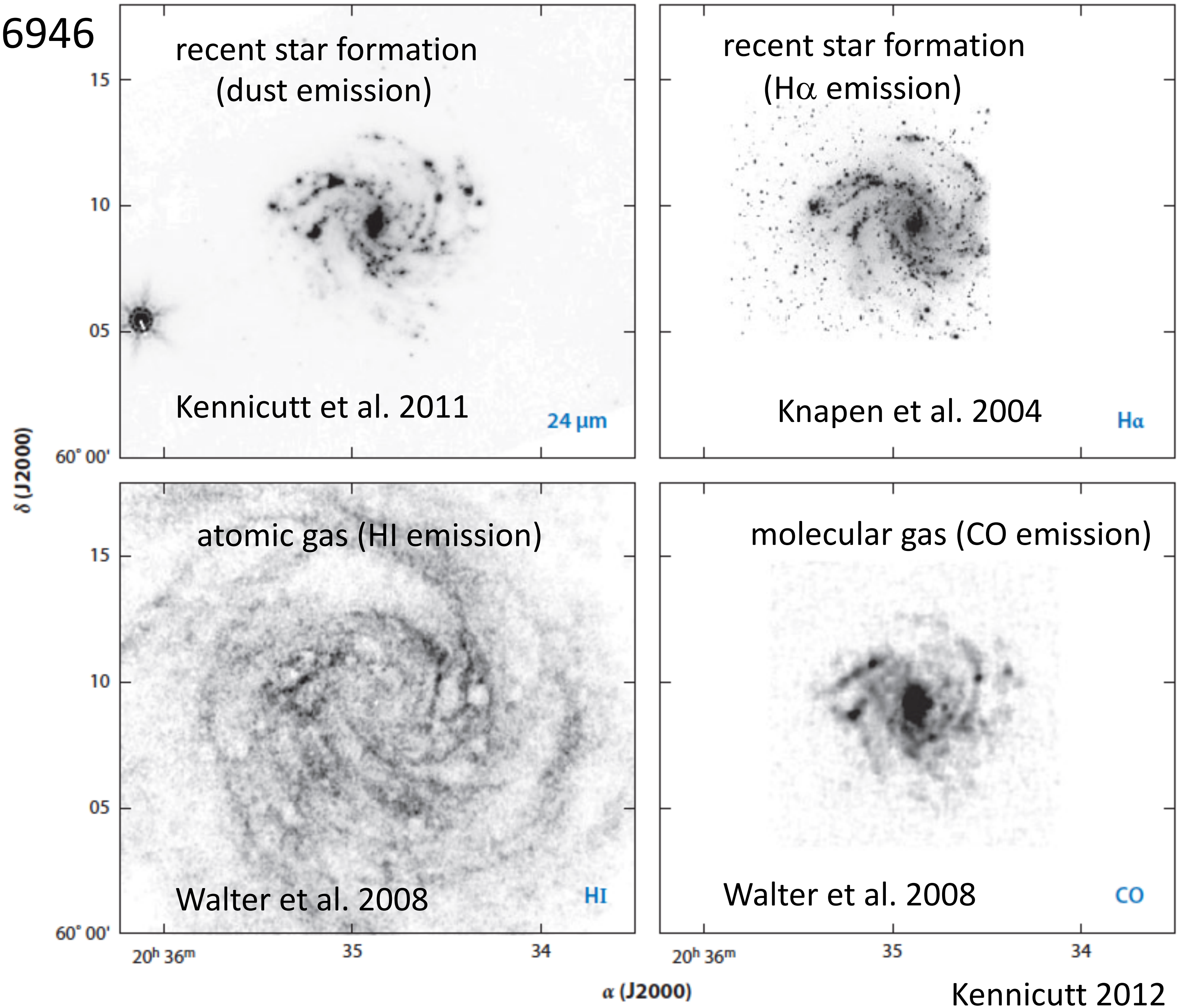
$$t_{\rm ff}(\rho) \equiv \left(\frac{3\pi}{32 G \rho}\right)^{1/2}$$

with $\epsilon = 0.01$

(e.g. Krumholtz & Tan 2005)

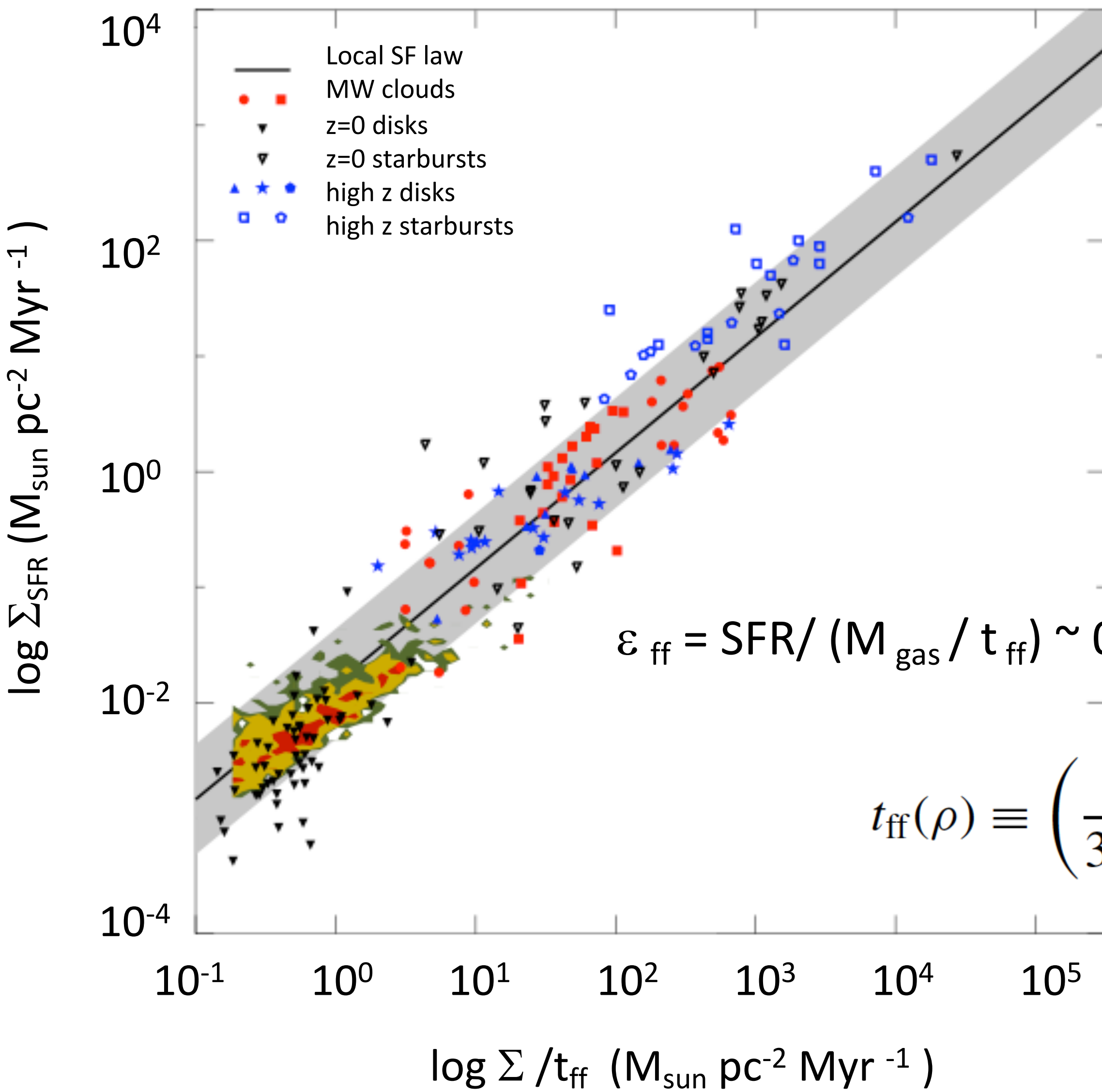
star formation efficiency: Universal parameter? What about prediction?

NGC 6946



Kennicutt 2012

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



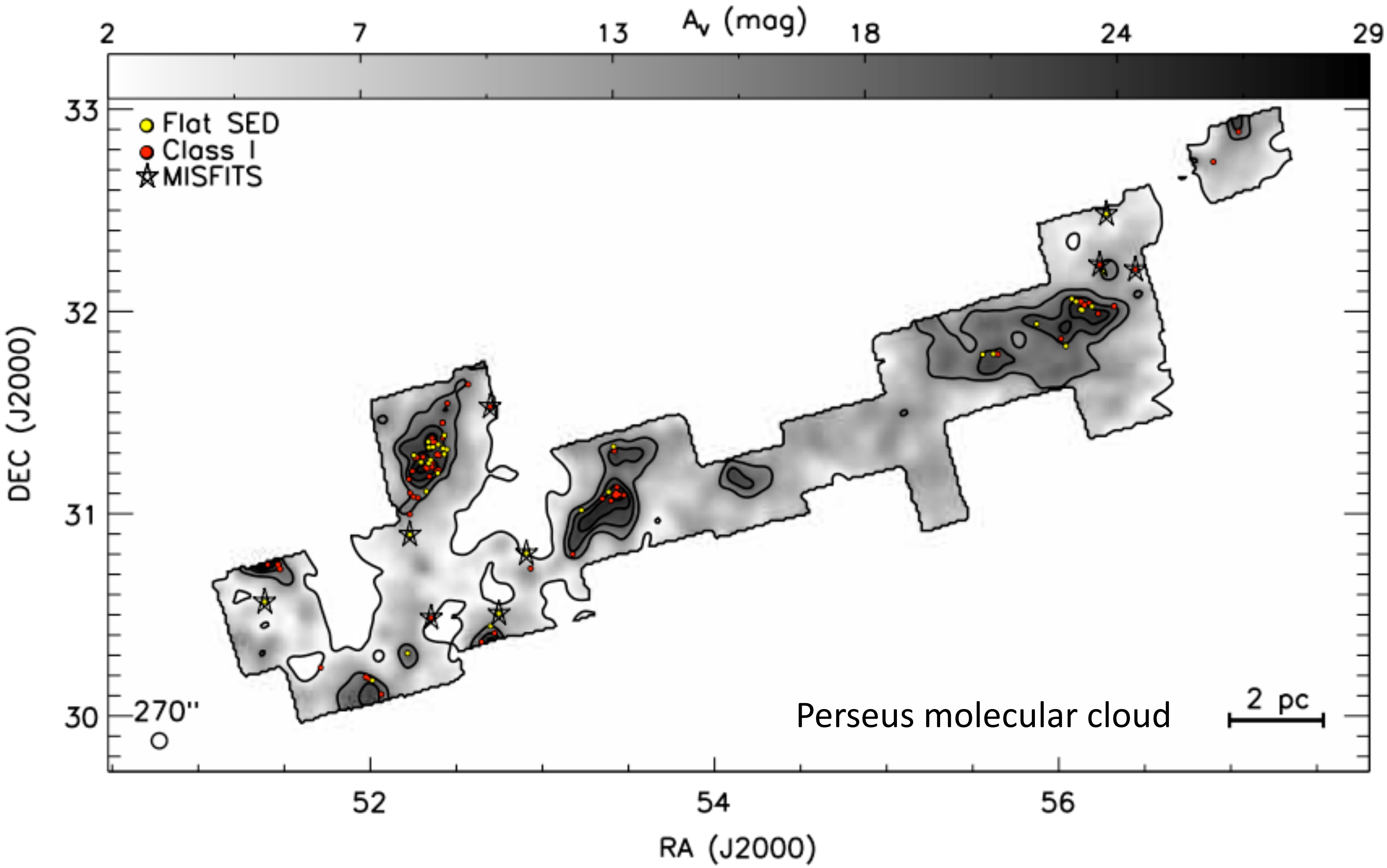
$\varepsilon_{ff} = SFR / (M_{gas} / t_{ff}) \sim 0.015$

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

NB: Averaged on cloud scales

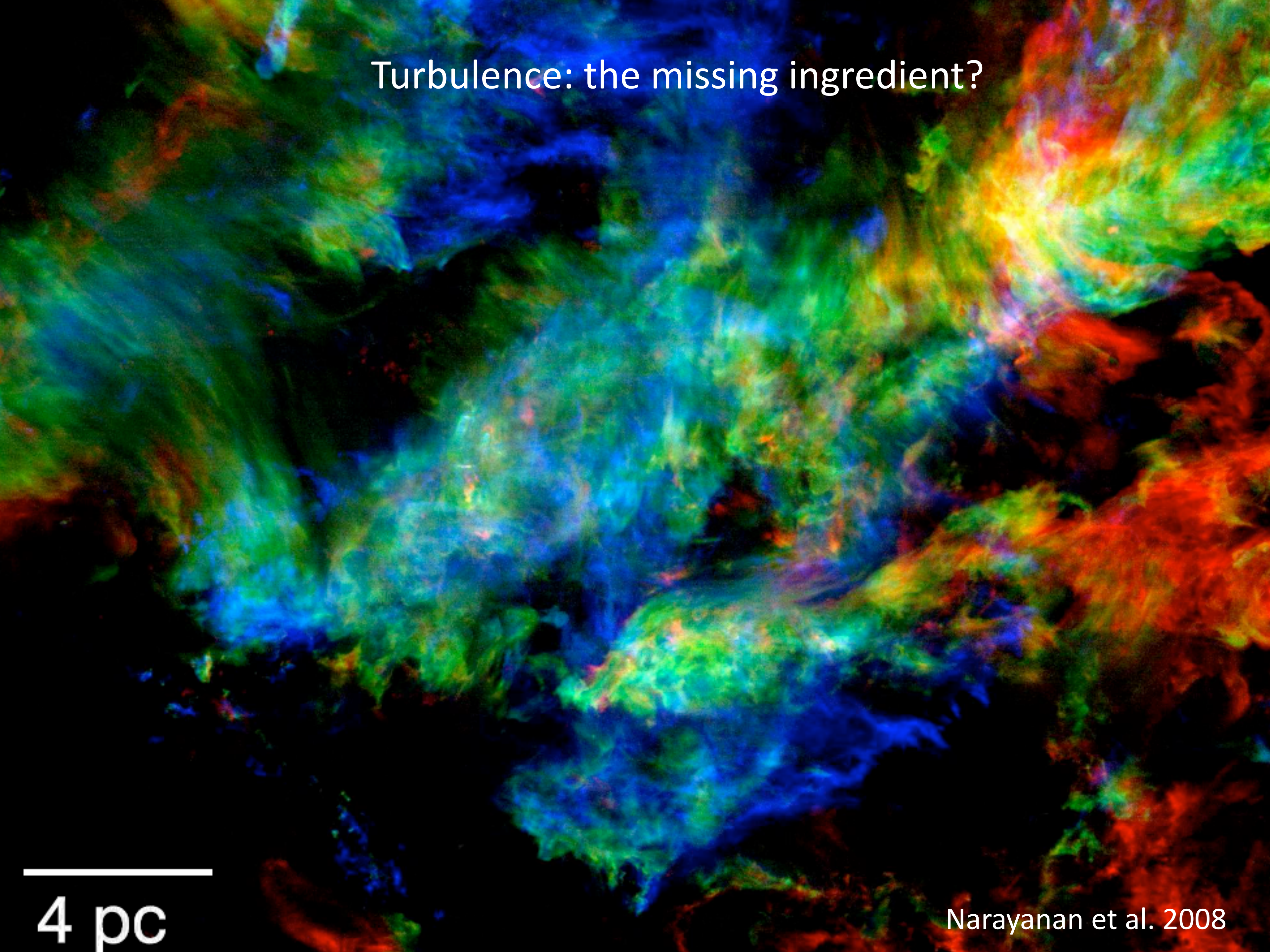
Krumholz et al. 2012, 2013

Caveat: stars do not form homogeneously in MC!



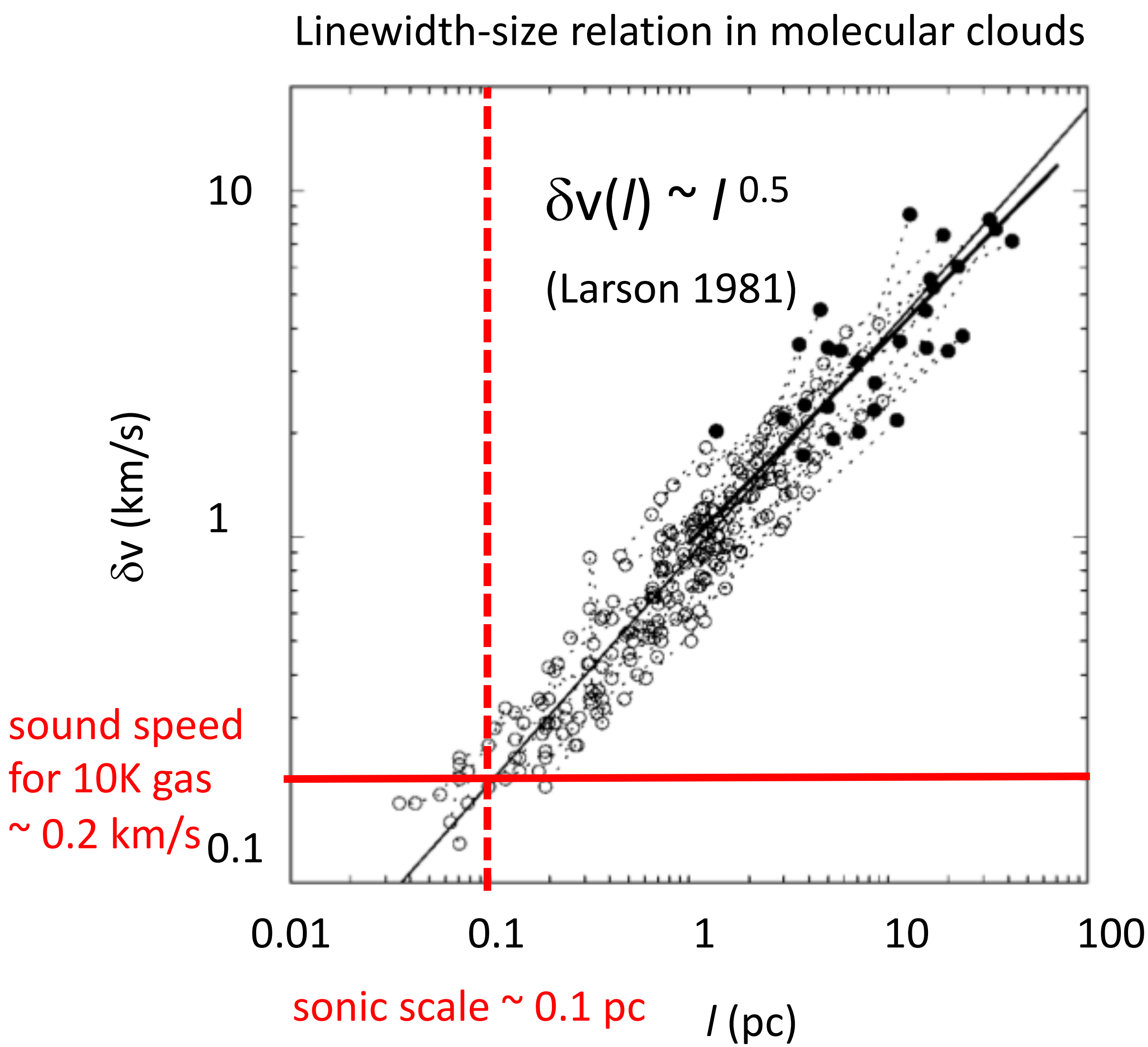
Heiderman et al. 2010

Turbulence: the missing ingredient?



Narayanan et al. 2008

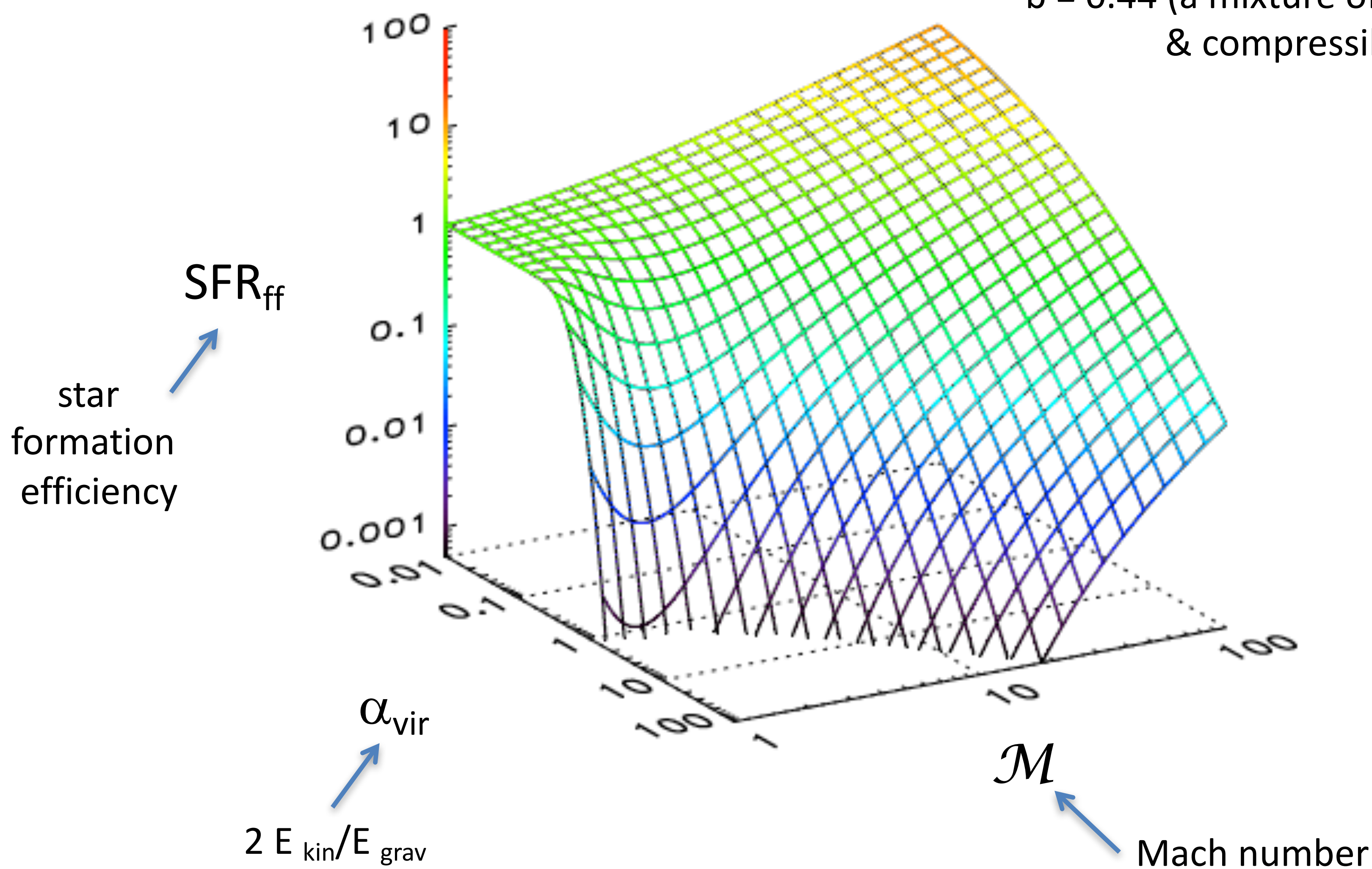
Evidence for supersonic compressible turbulence



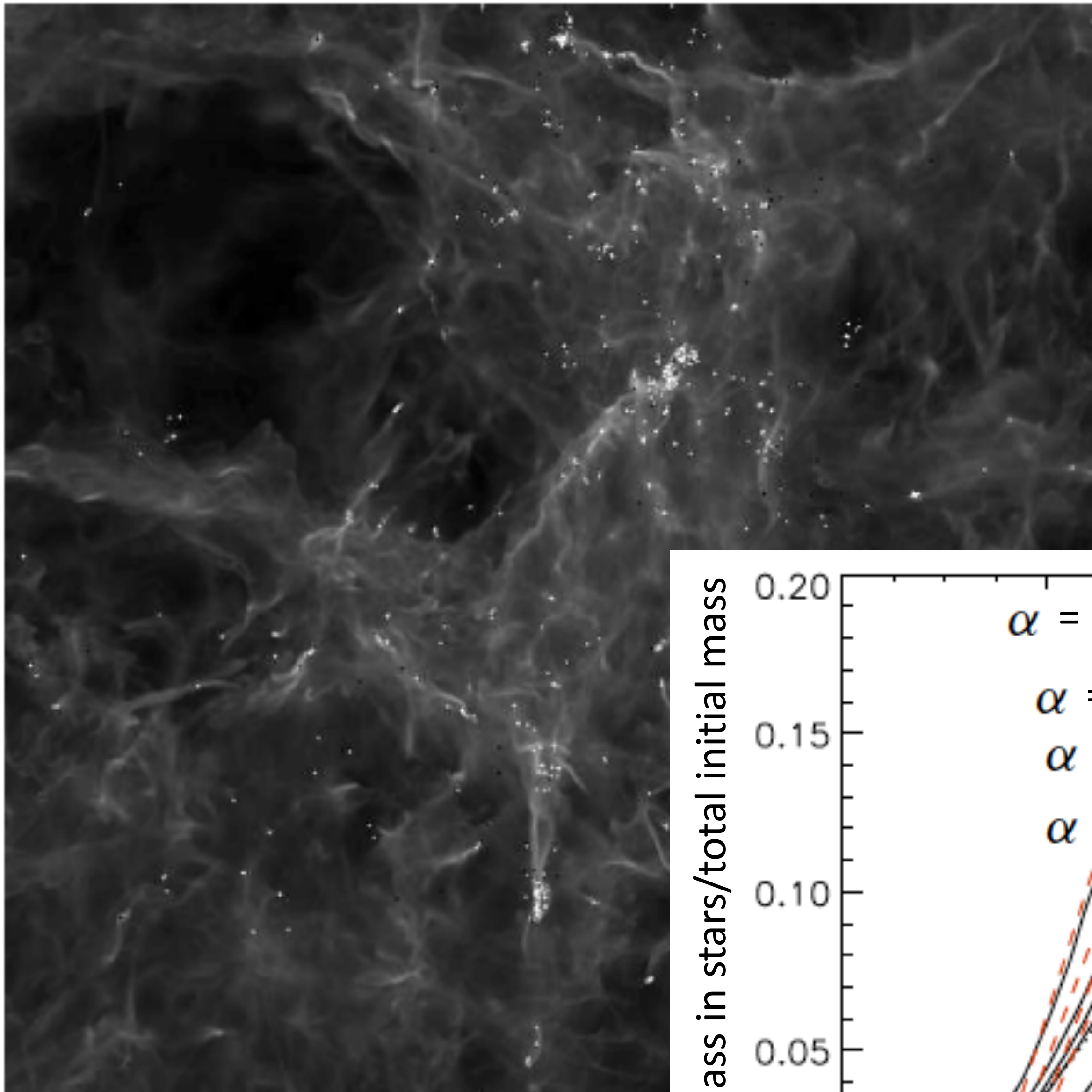
Heyer & Brunt 2004

→ Build a model where star formation efficiency depends explicitly on dynamic properties of gas

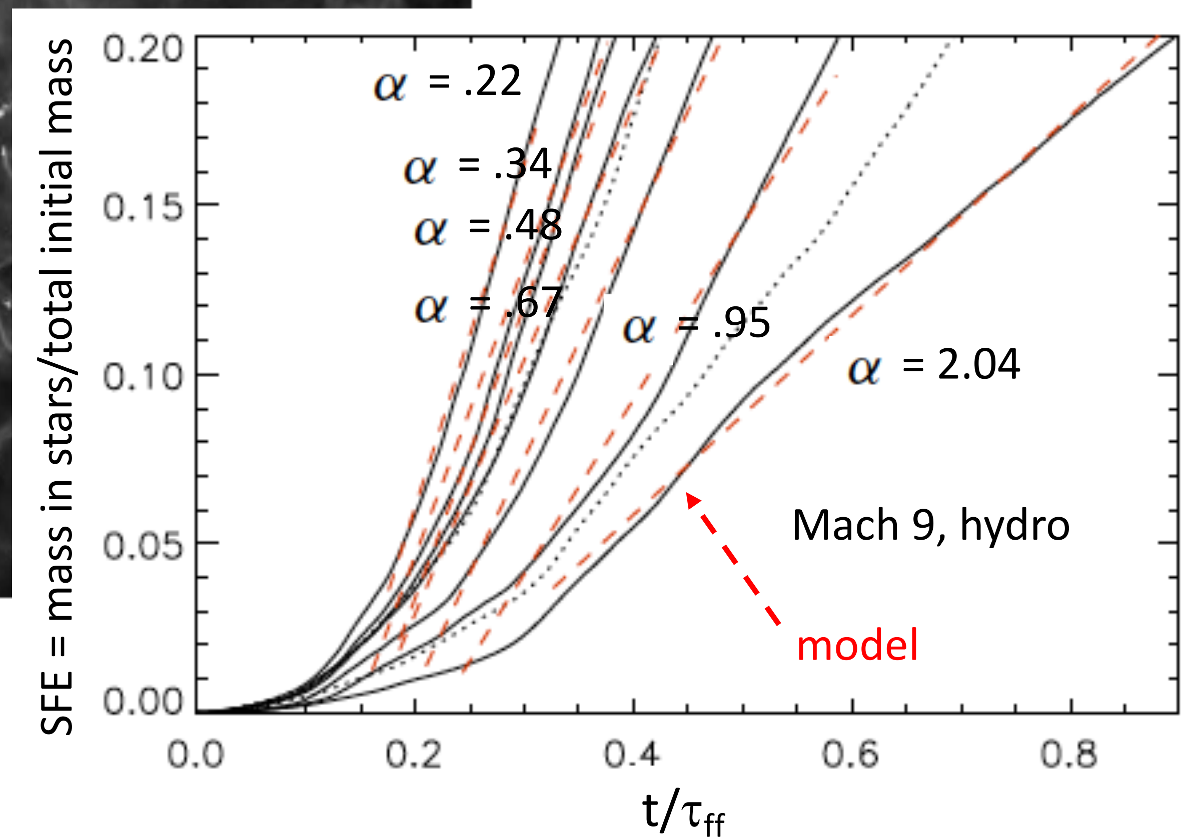
b = 0.44 (a mixture of solenoidal & compressible modes)



Federrath & Klessen 2012, Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011

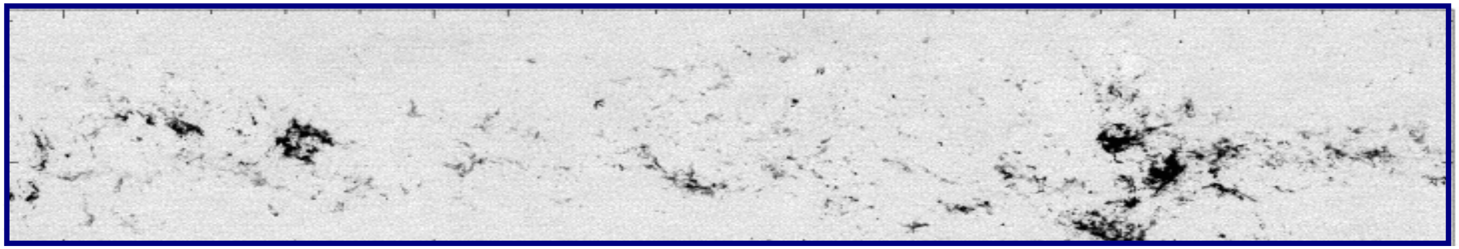


Excellent description of star formation rate in high resolution driven supersonic turbulence simulations (reduced chi squared of order unity)



Padoan & Nordlund 2011

How should we form stars in simulations?



Heyer et al. 1998

(FCRAO CO survey)

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

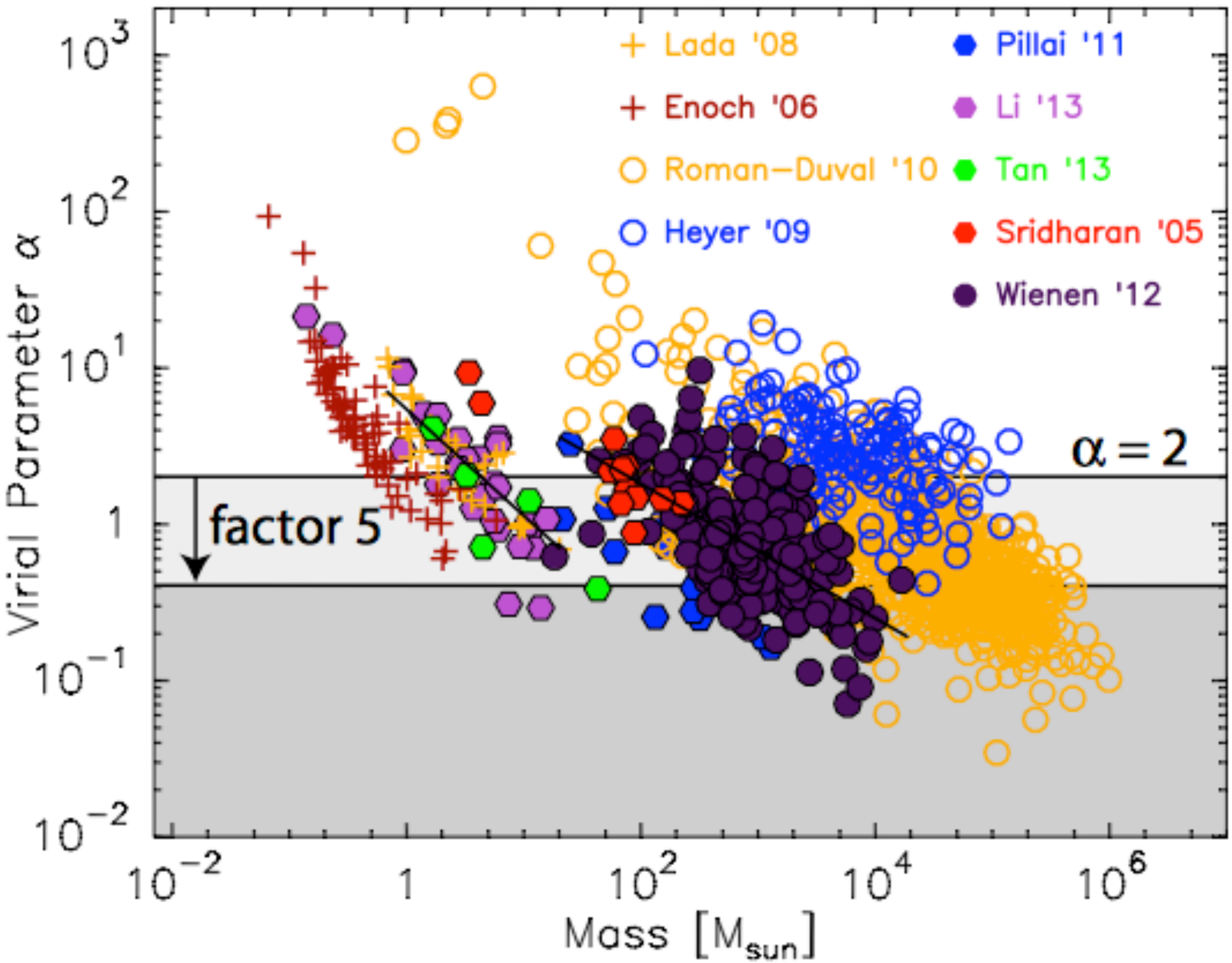
$$\dot{\rho}_* = \frac{\epsilon\, \rho}{t_{\rm ff}}$$

Can also add B field (Sergio Martin's talk)

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

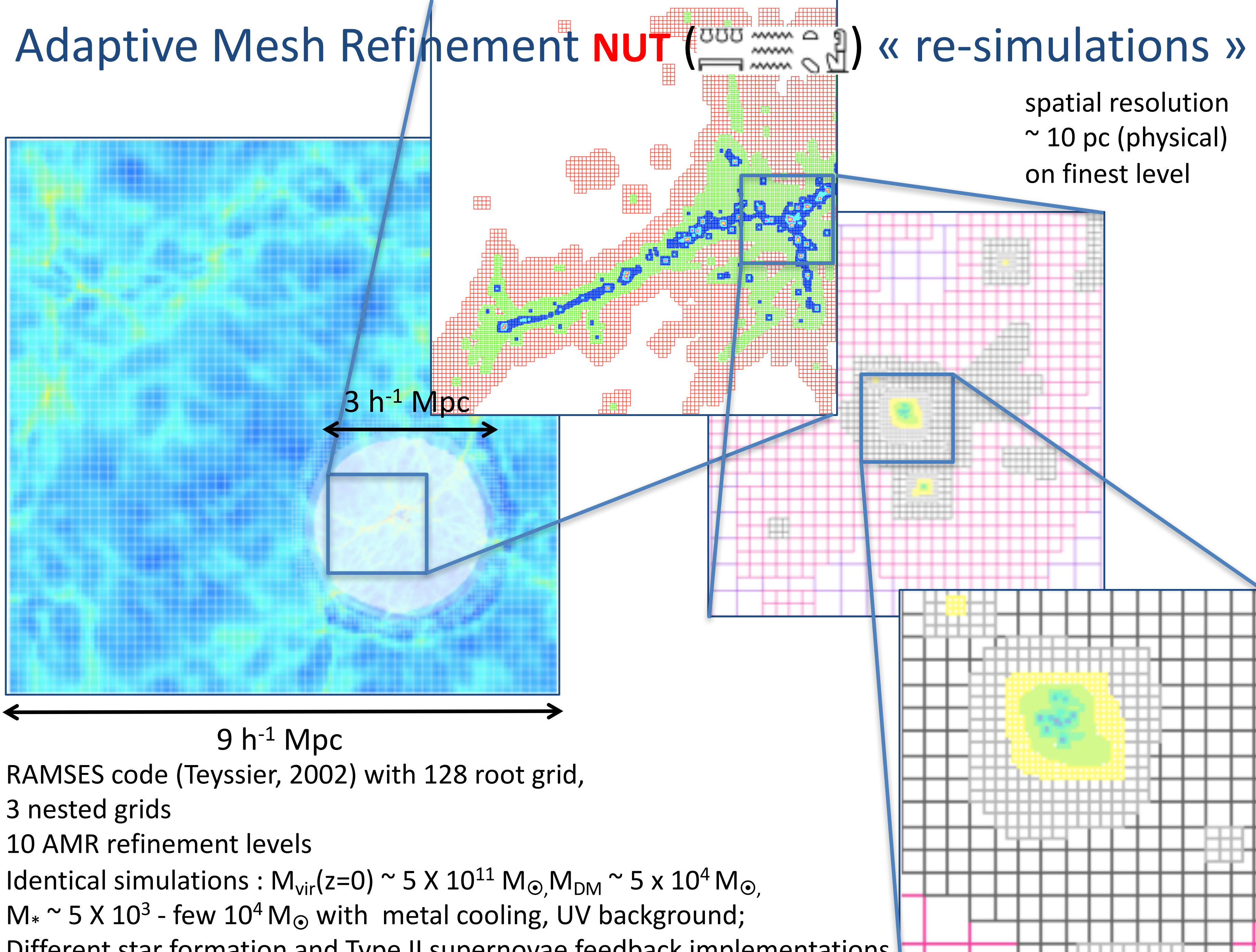
How wrong is self-gravity assumption?

What values for the virial parameter?

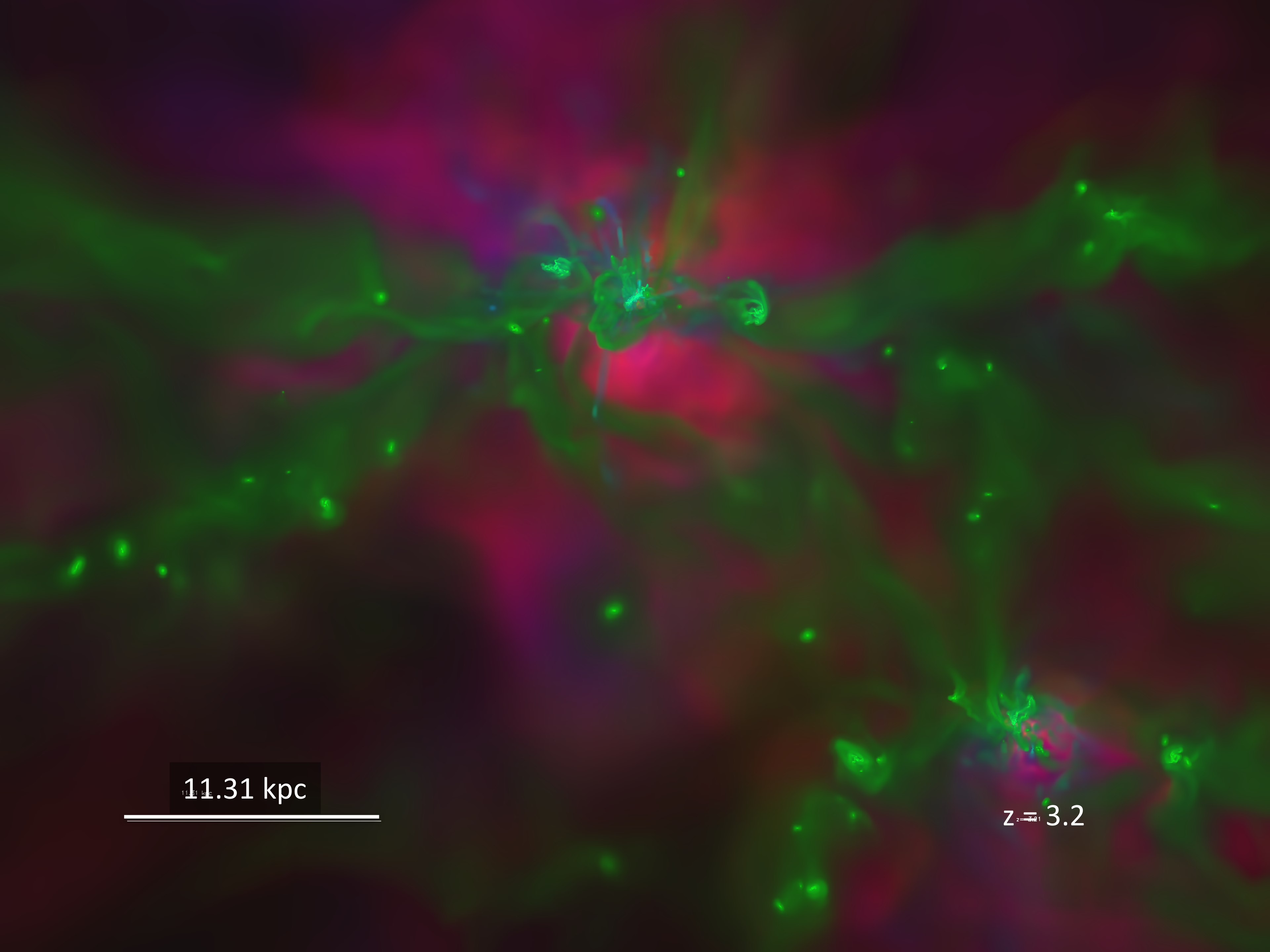


Kauffmann et al. 2013

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


11.31 kpc
z = 3.2

Snapshot of the difference between SF models in a slice

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

Simulations & Results

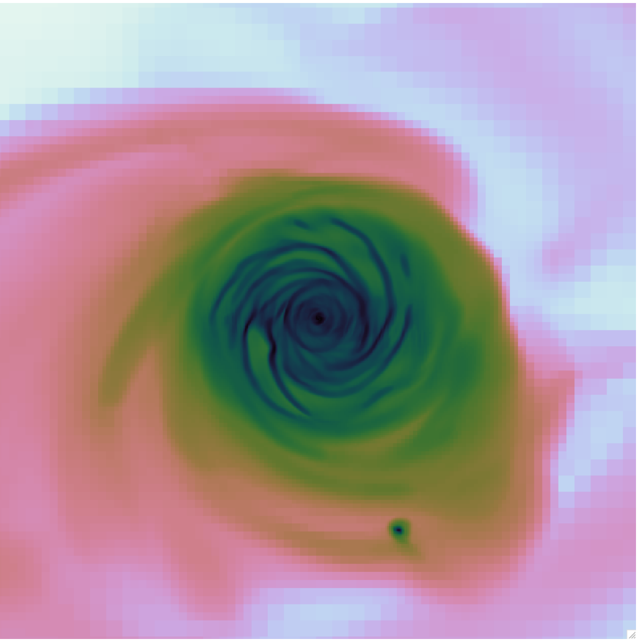
1. density threshold star formation, no SN feedback (SF1)

(2. “ , momentum conserving SN fbk)

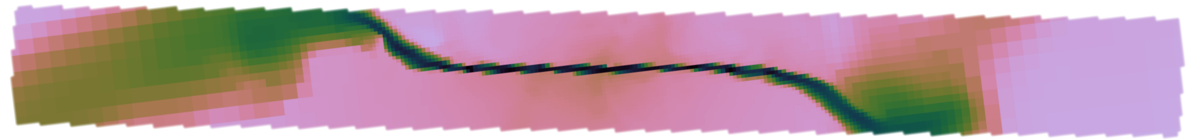
3. turbulent star formation, no SN feedback (SF2)

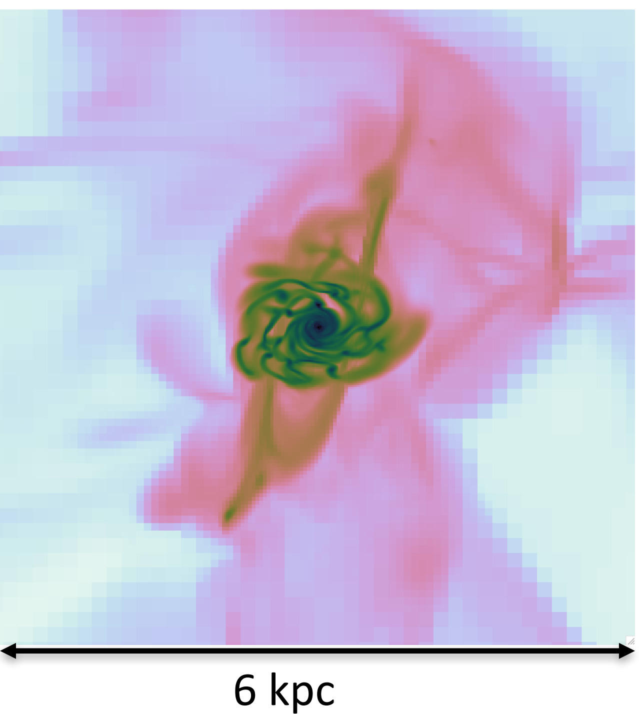
(4. “ , momentum conserving SN fbk)

How does the galaxy ISM look like?

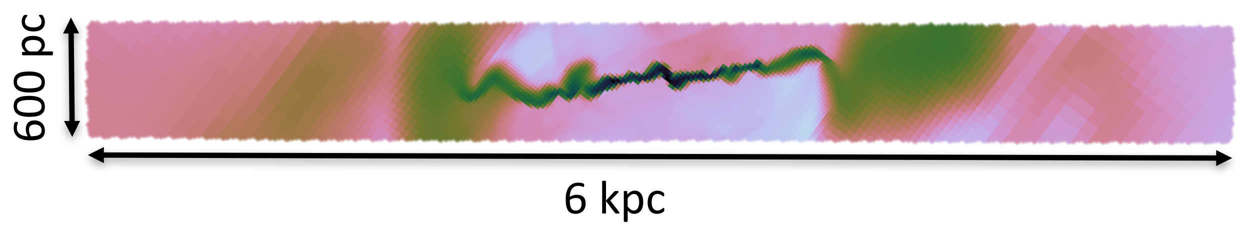


SF1 gas density: Face-on & Edge-on @ z=3

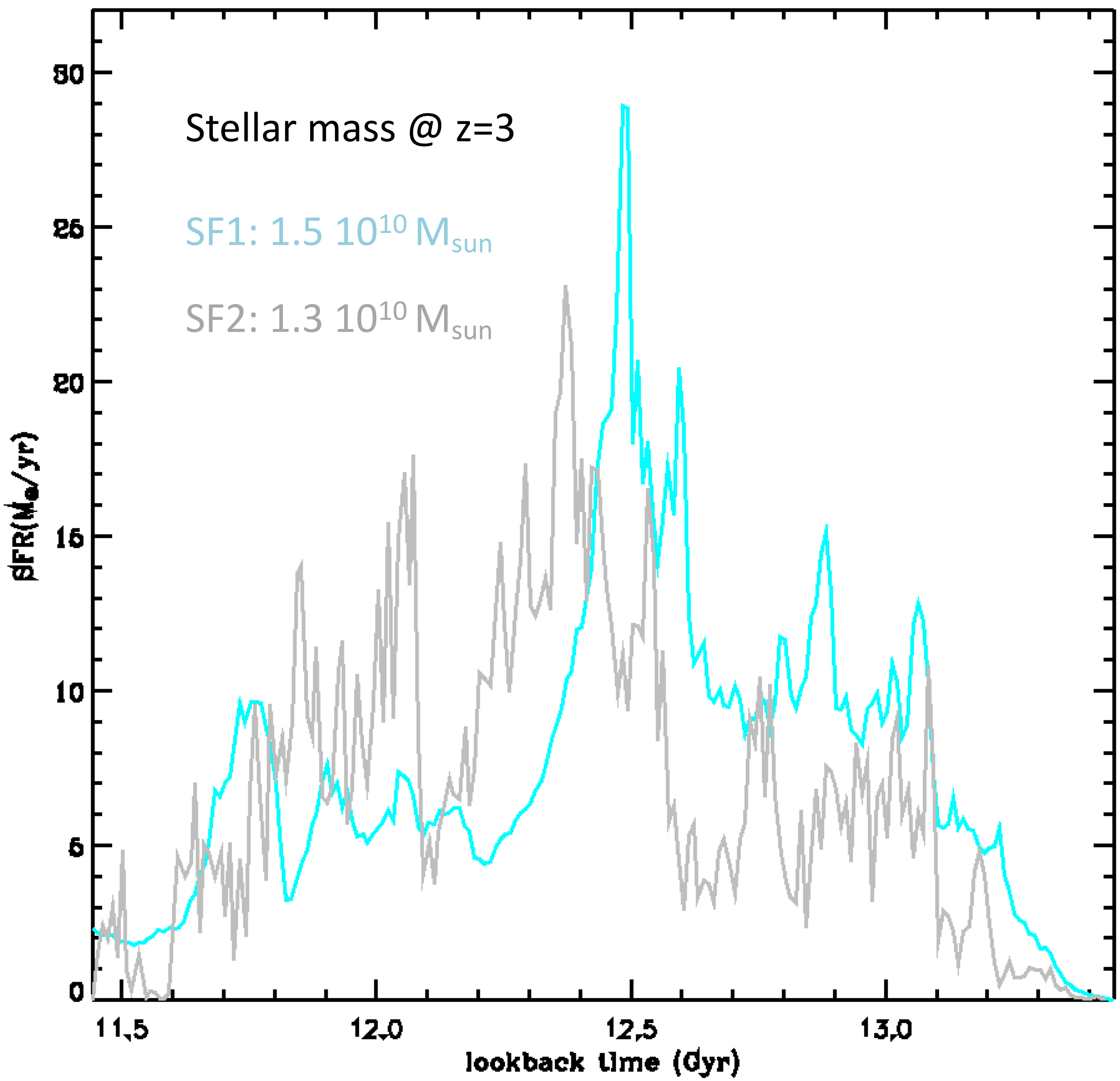




SF2 gas density: Face-on & Edge-on @ z=3

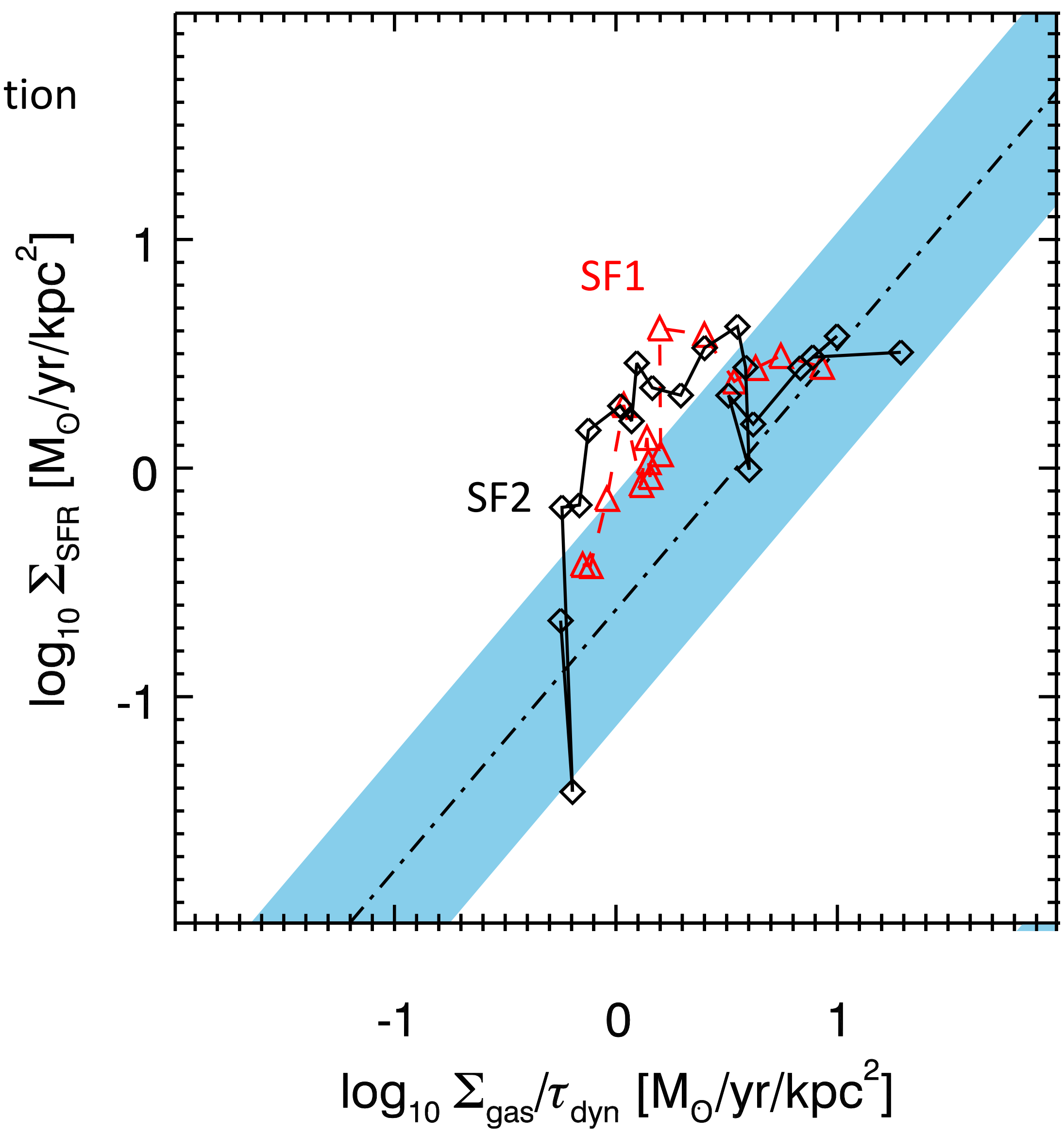


SF1 & SF2 have similar star formation rate histories

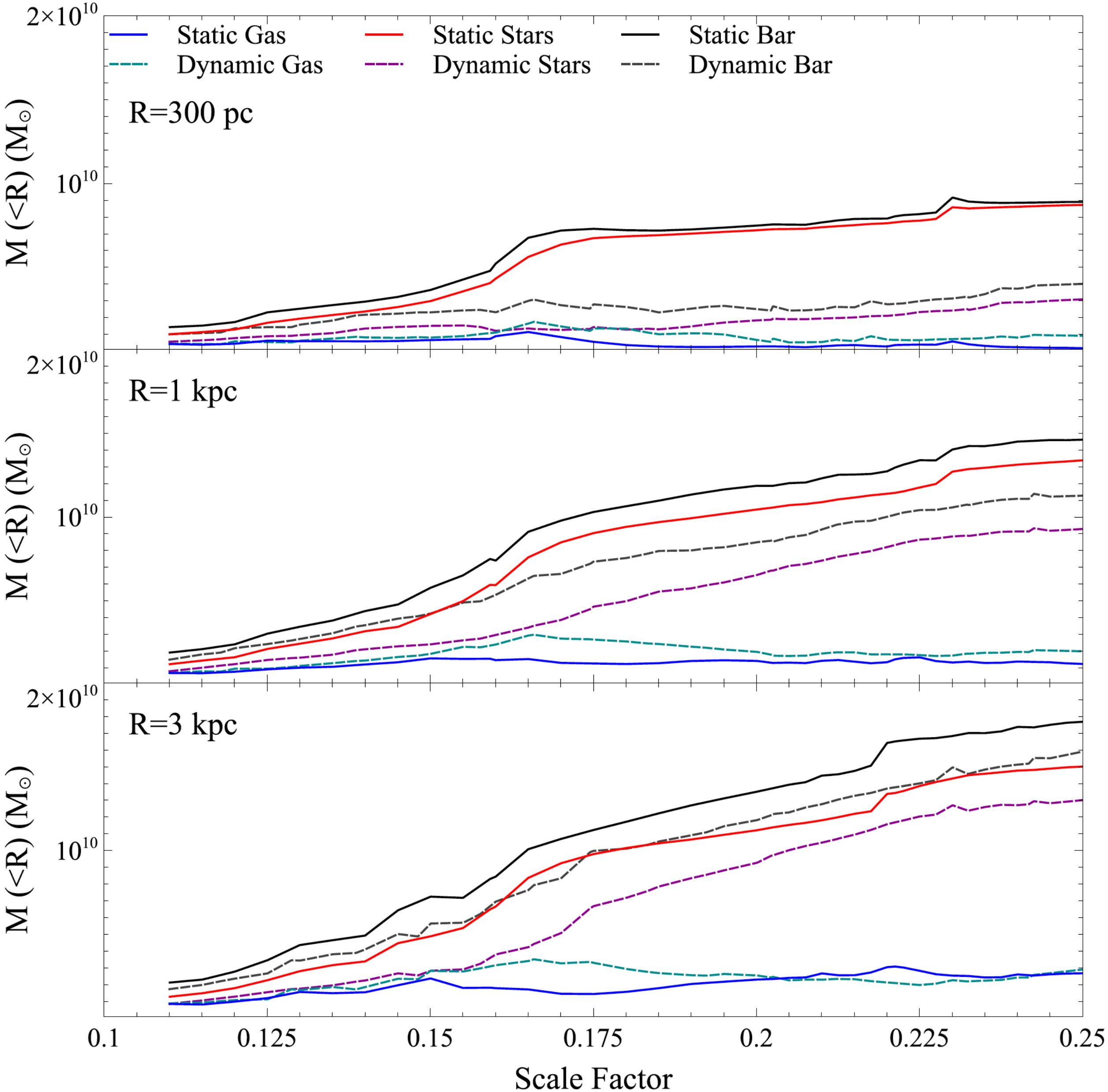


Both runs occupy similar locii on the Kennicutt-Schmidt law

Time evolution



Cumulative mass profiles evolution



Stellar mass @ z=3

SF1: 0.9 10^{10} M_{sun}

SF2: 0.3 10^{10} M_{sun}

Stellar mass @ z=3

SF1: 1.3 10^{10} M_{sun}

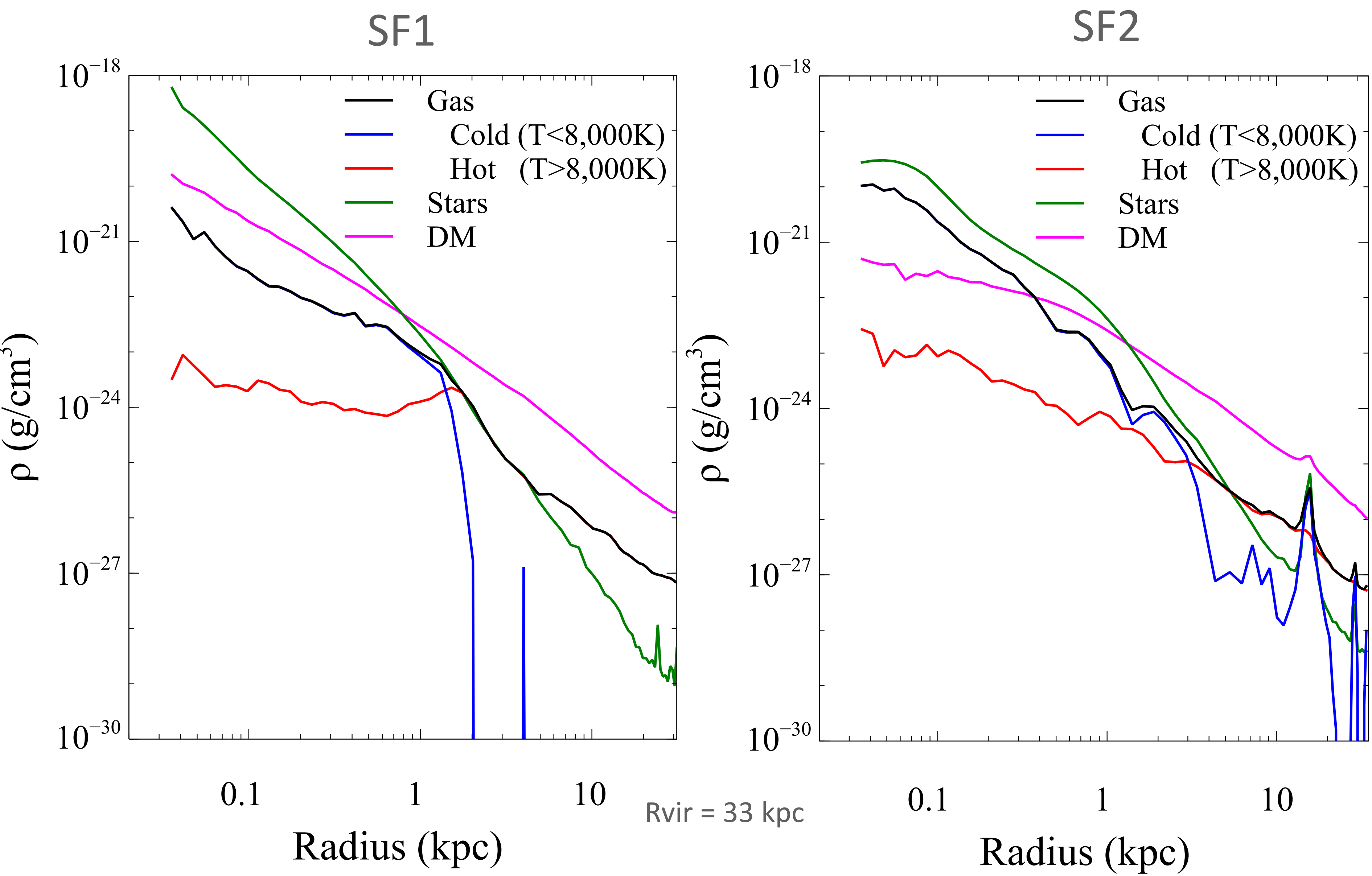
SF2: 0.9 10^{10} M_{sun}

Stellar mass @ z=3

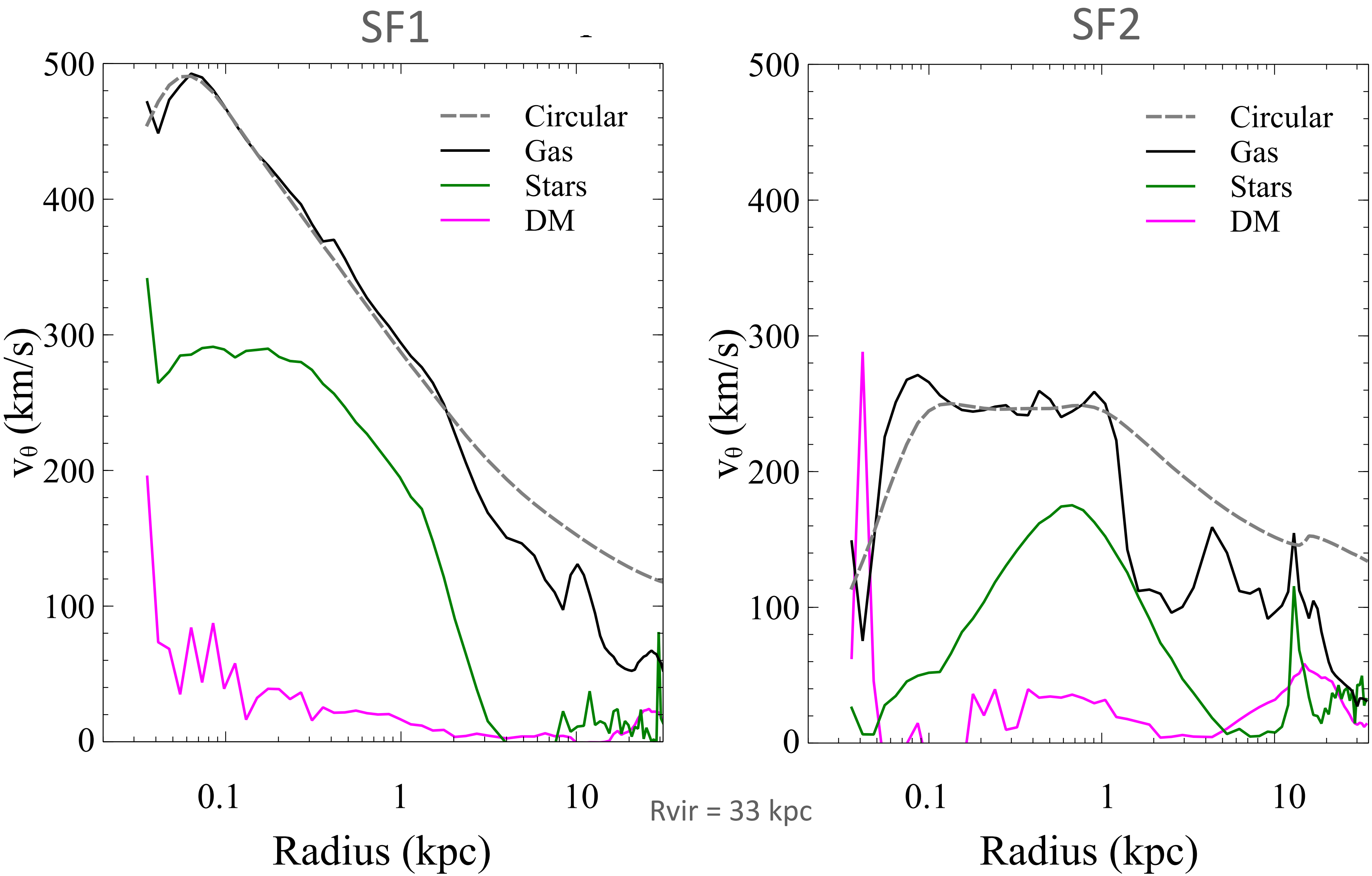
SF1: 1.5 10^{10} M_{sun}

SF2: 1.3 10^{10} M_{sun}

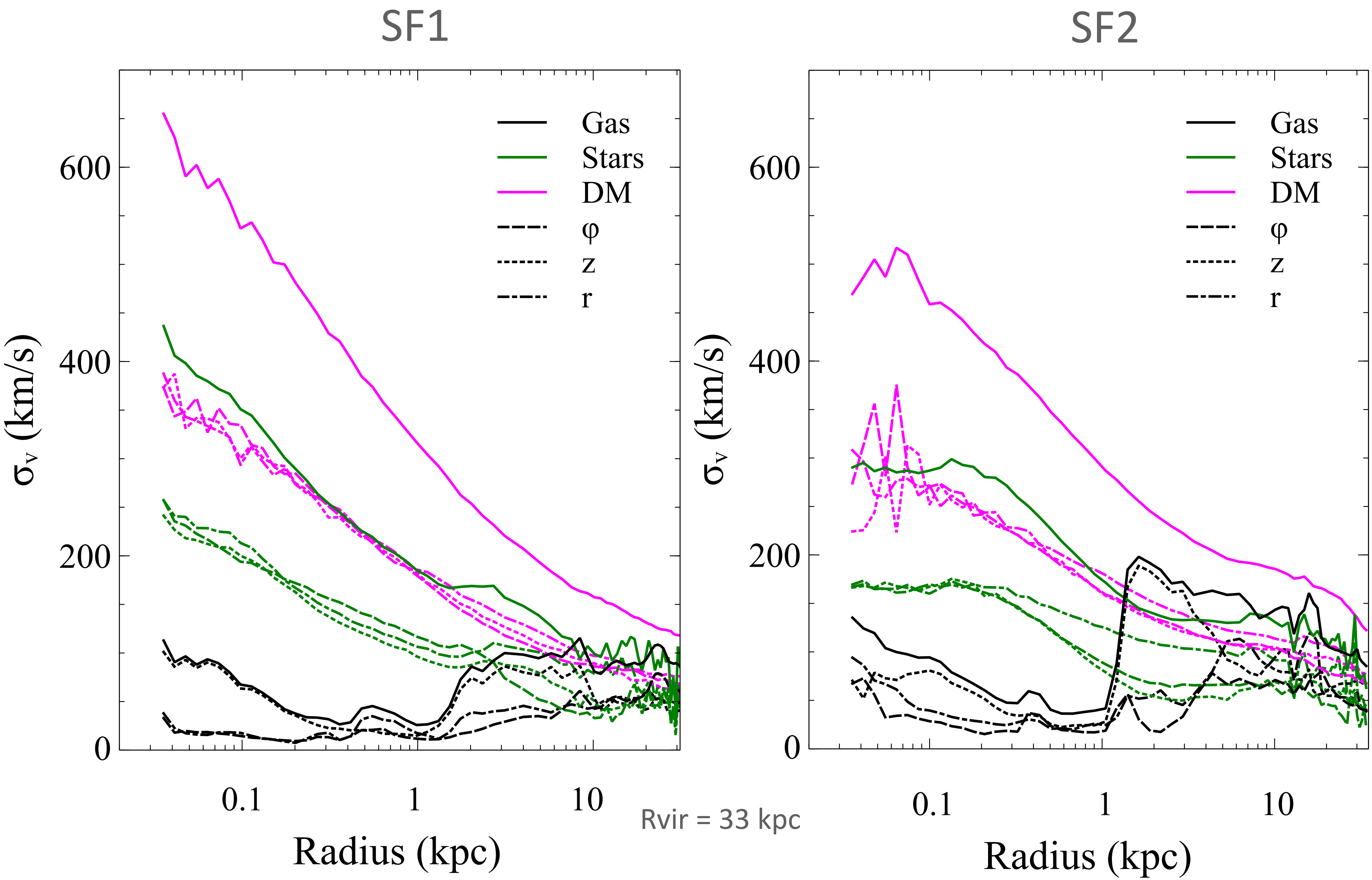
Galaxy density profiles @ z=3



Galaxy rotation curves @ z=3

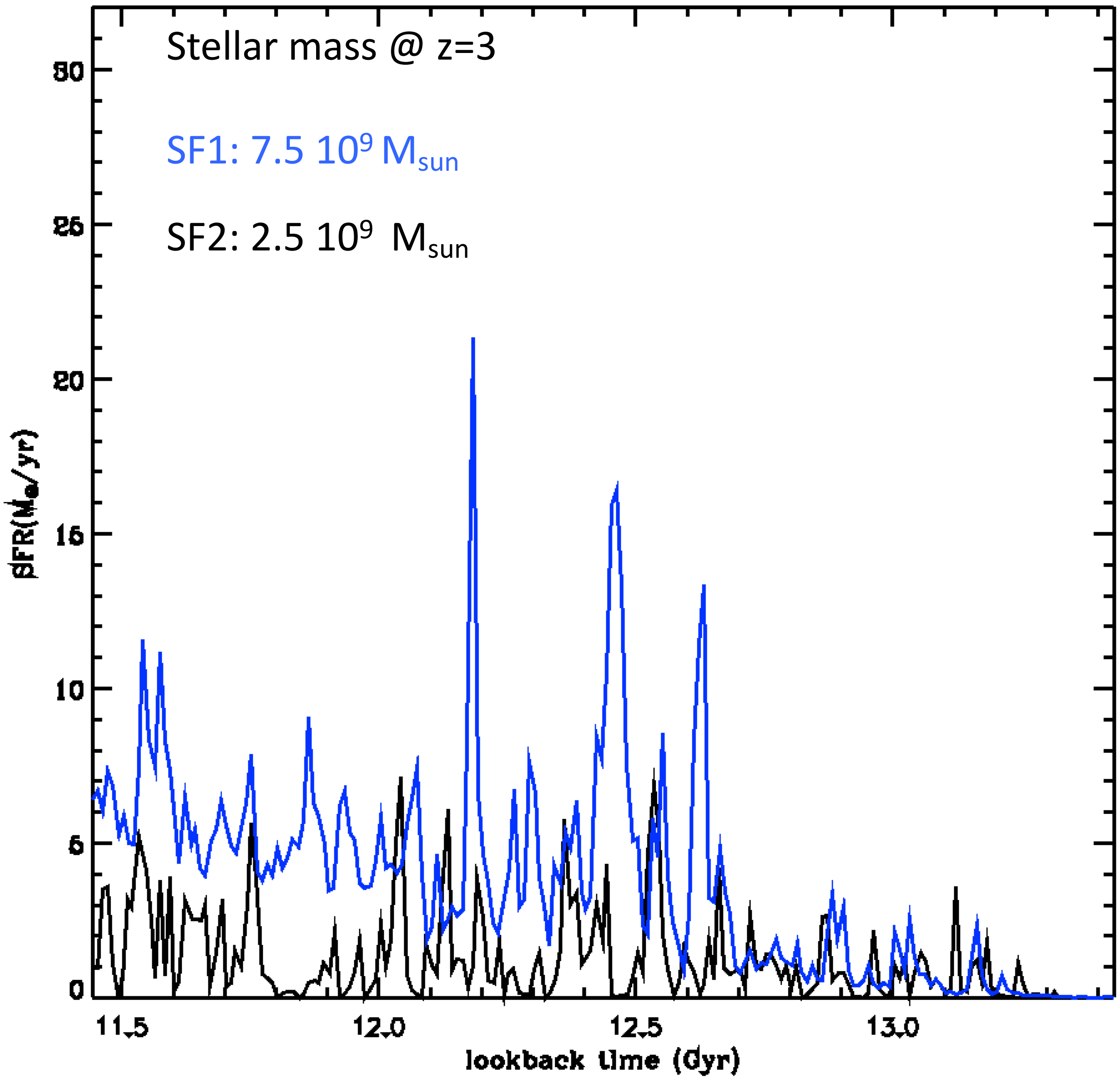


Galaxy velocity dispersions @ z=3

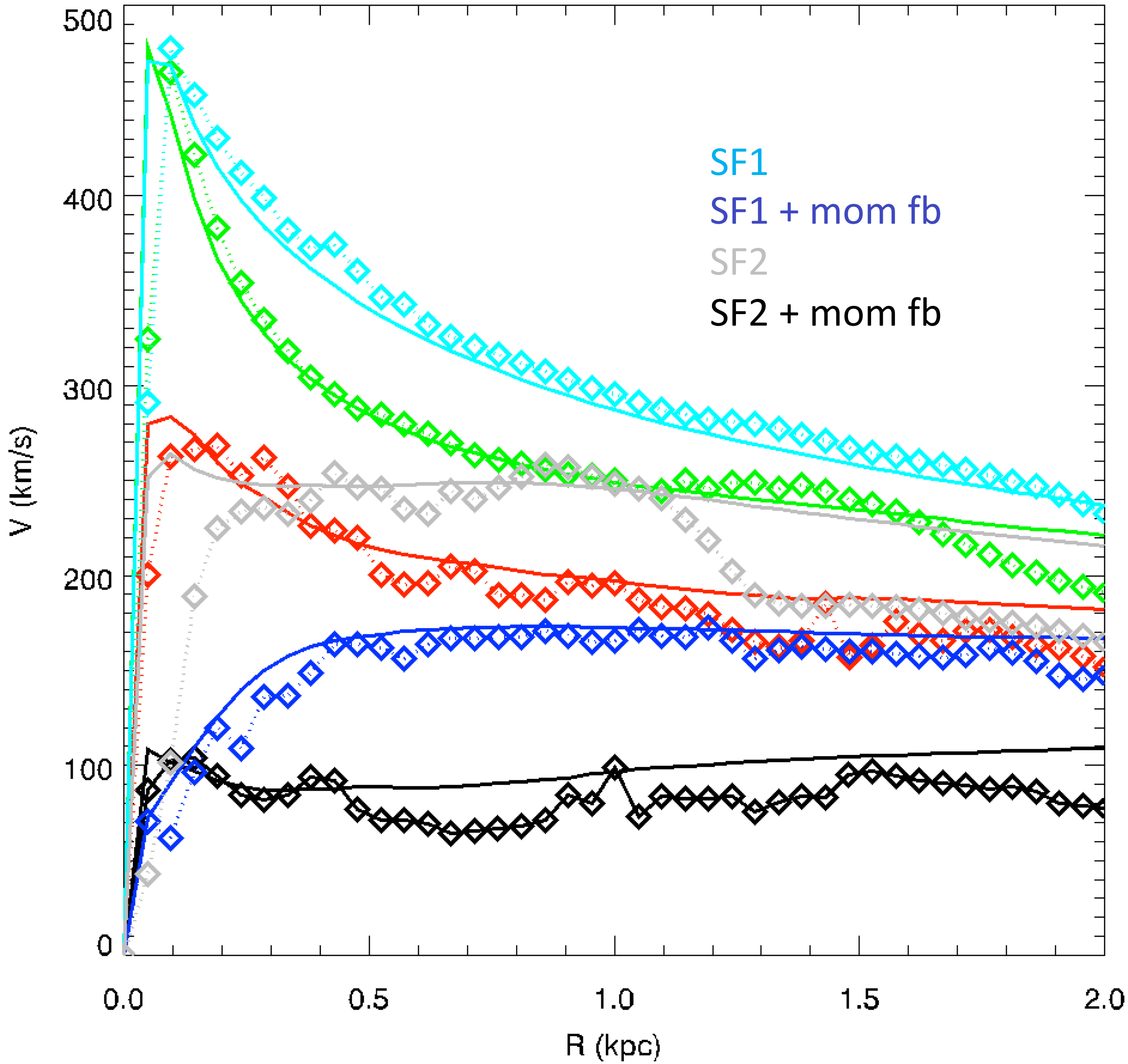


Rvir = 33 kpc

What if we add same (momentum) stellar feedback to SF1 & SF2?



Impact of SF + Feedback on galaxy rotation curves @ z=3



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 stellar 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