The Impact of Feedback on the ISM

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The ISM and molecular clouds on galaxy scales

- Properties and structure of the ISM

- components of cold, warm, hot ISM
- scale height of the ISM
- distribution and linewidths of HI, CO

- Properties of molecular clouds

- clouds highly structured
- low star formation efficiency
- mass spectra
- retrograde and prograde cloud rotations

The ISM and molecular clouds on galaxy scales

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The ISM and molecular clouds on galaxy scales

- Do we need feedback to match these properties?

- Yes

- Mostly to counteract gravity

Outline

- Properties of molecular clouds and ISM in global simulations
- Cloud formation and dispersal
- Zoom in simulations
- Synthetic CO and HI maps compared with Outer Galaxy

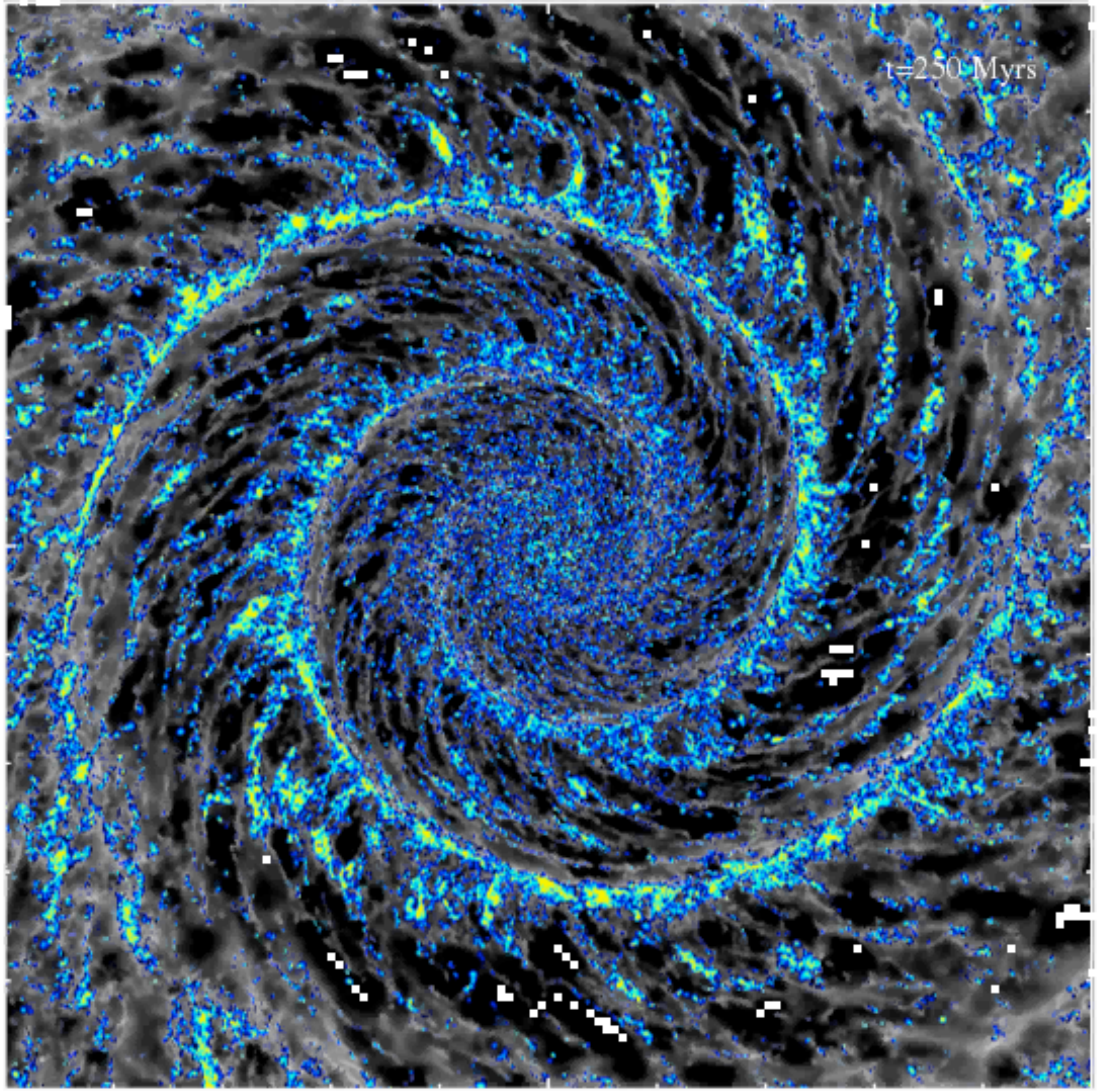
Isolated galaxy simulations

- Logarithmic potential for the stars and dark matter with / without spiral component (m=0,2,4)
- Self gravity of the gas
- Cooling and heating of the ISM (Glover & MacLow 2007)
- H_2 and CO formation
- 1,4,8 million particles Σ=8, 16 $M_\odot pc^{-2}$
- Simple stellar feedback prescription

Isolated galaxy simulations

- Stellar feedback: above densities of 100, 500, 10^4 cm^{-3}, converging flow
- Add kinetic and thermal energy equal to $\frac{\varepsilon\, M(H_2) \times 10^{51}\,\mathrm{ergs}}{160\, M_\odot}$ ε=1%, 5%, 10%, 20%, 40%
- Energy distributed in form of Sedov solution
- Add energy instantaneously, continuously over time, with a delay

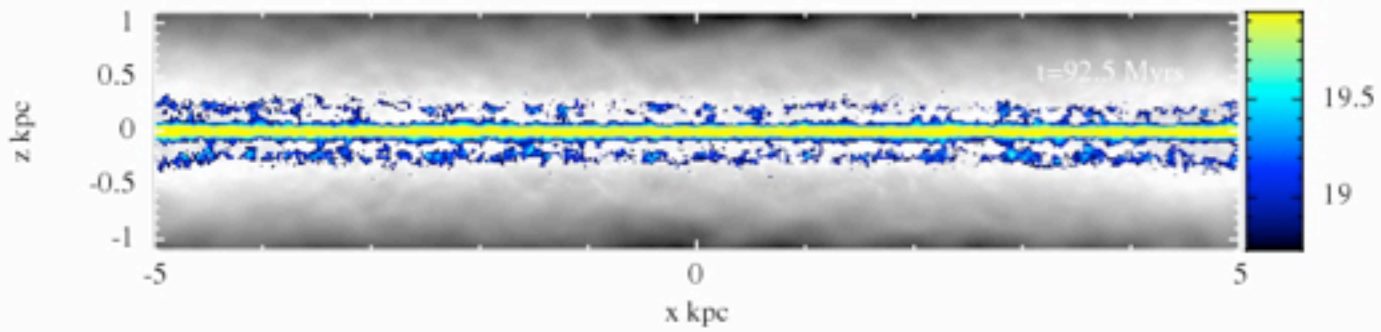
Galaxy simulations



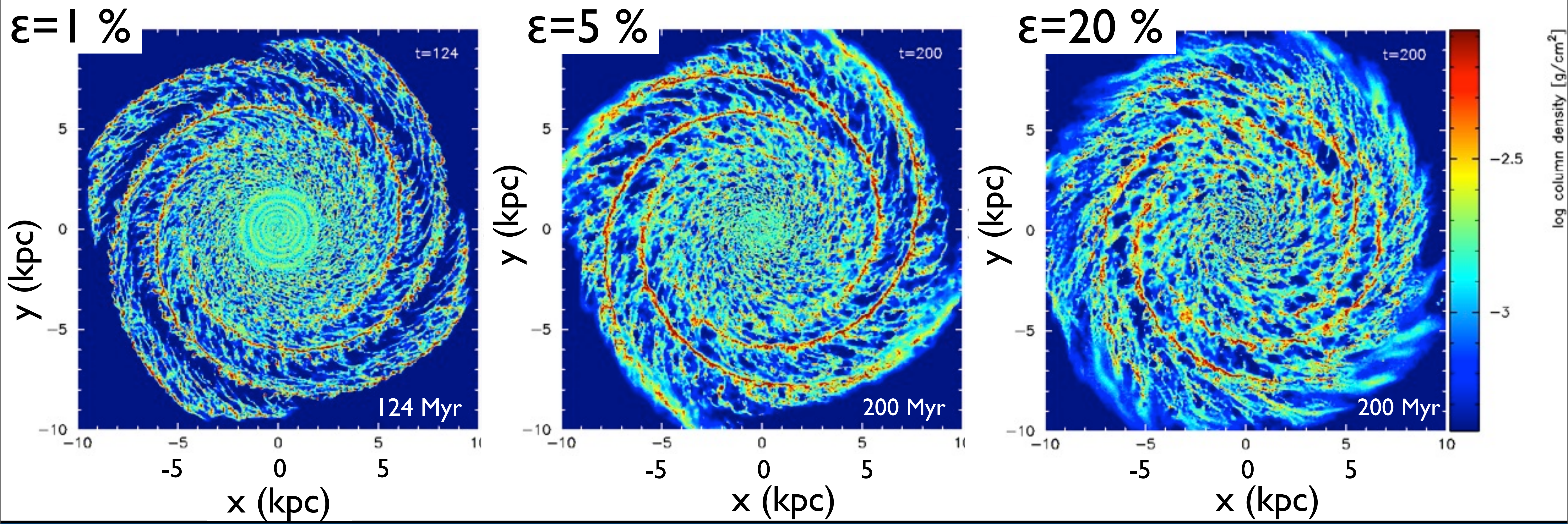
8 million particles

$\Sigma=8\ M_\odot pc^{-2}$

ε=5%



Properties of the disc: Structure

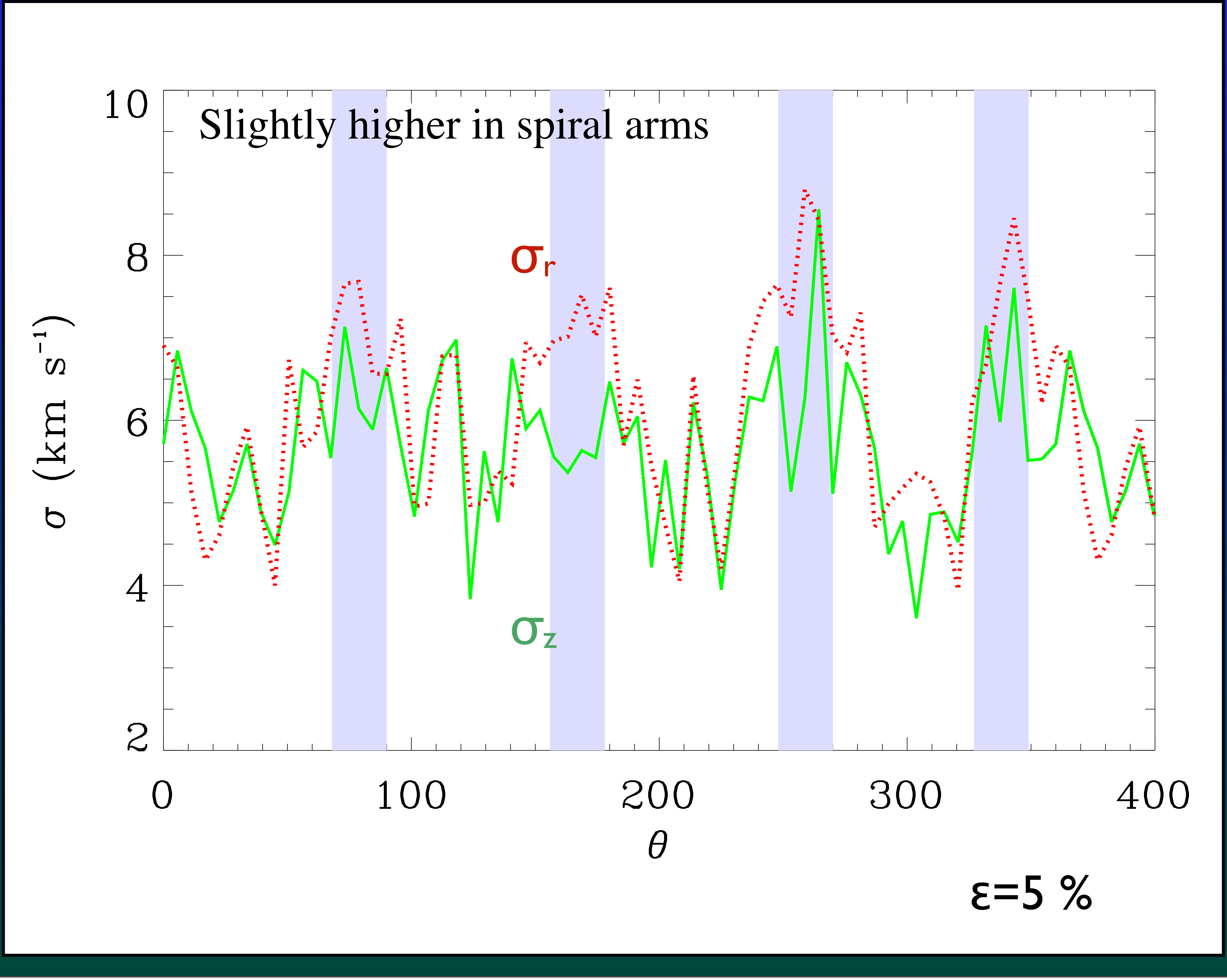


Feedback insufficient to disrupt clouds: no equilibrium state

Clear spiral arms and spurs

Feedback dominates structure

ISM Velocity dispersion

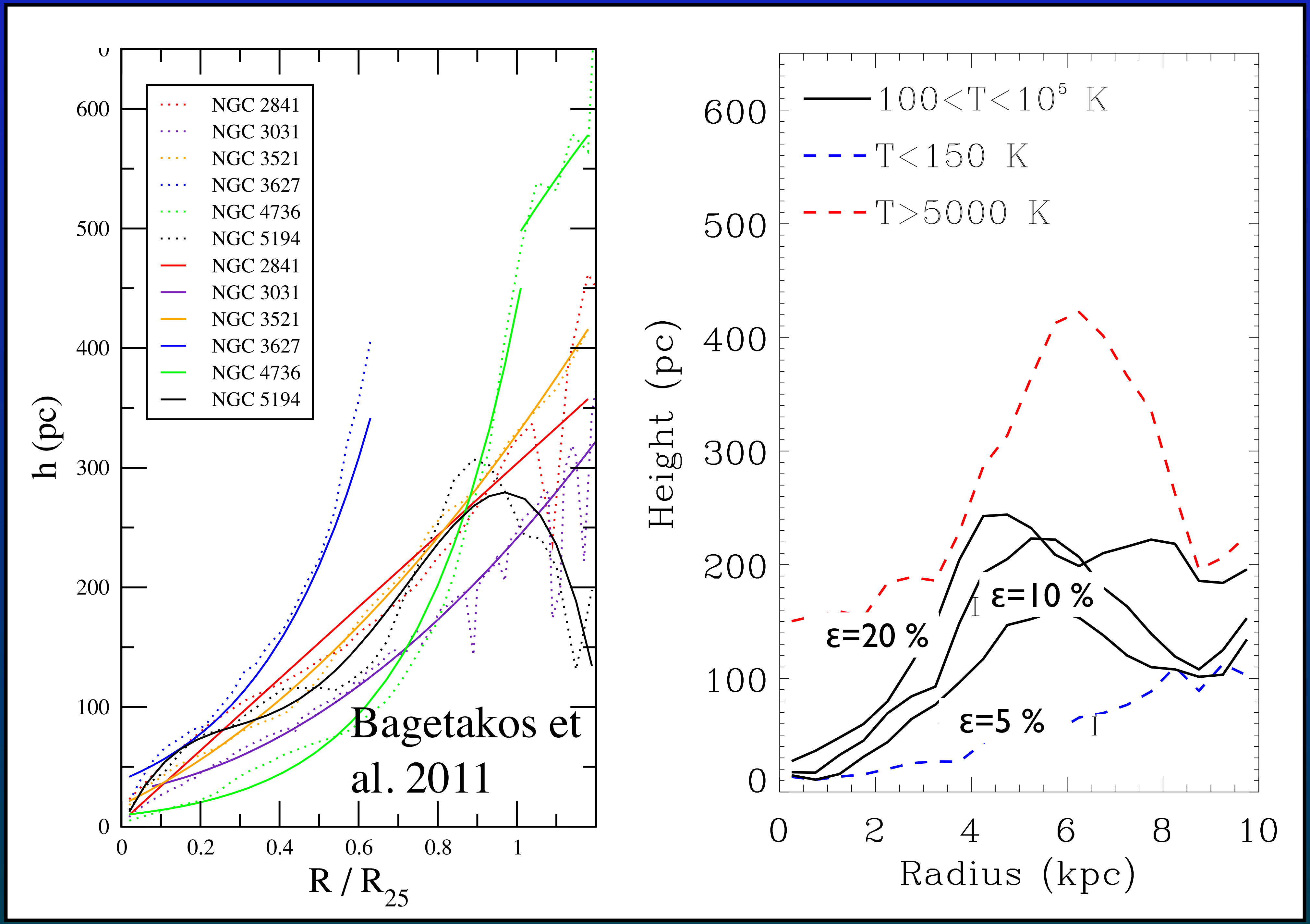


←Velocity dispersion in 500 pc annulus of disc

Below: Typical velocity dispersion in the disc vs feedback (star formation) efficiency

ε (%)	σ (km/s)
1	2-4
5	4-8
20	8-20

Scale height

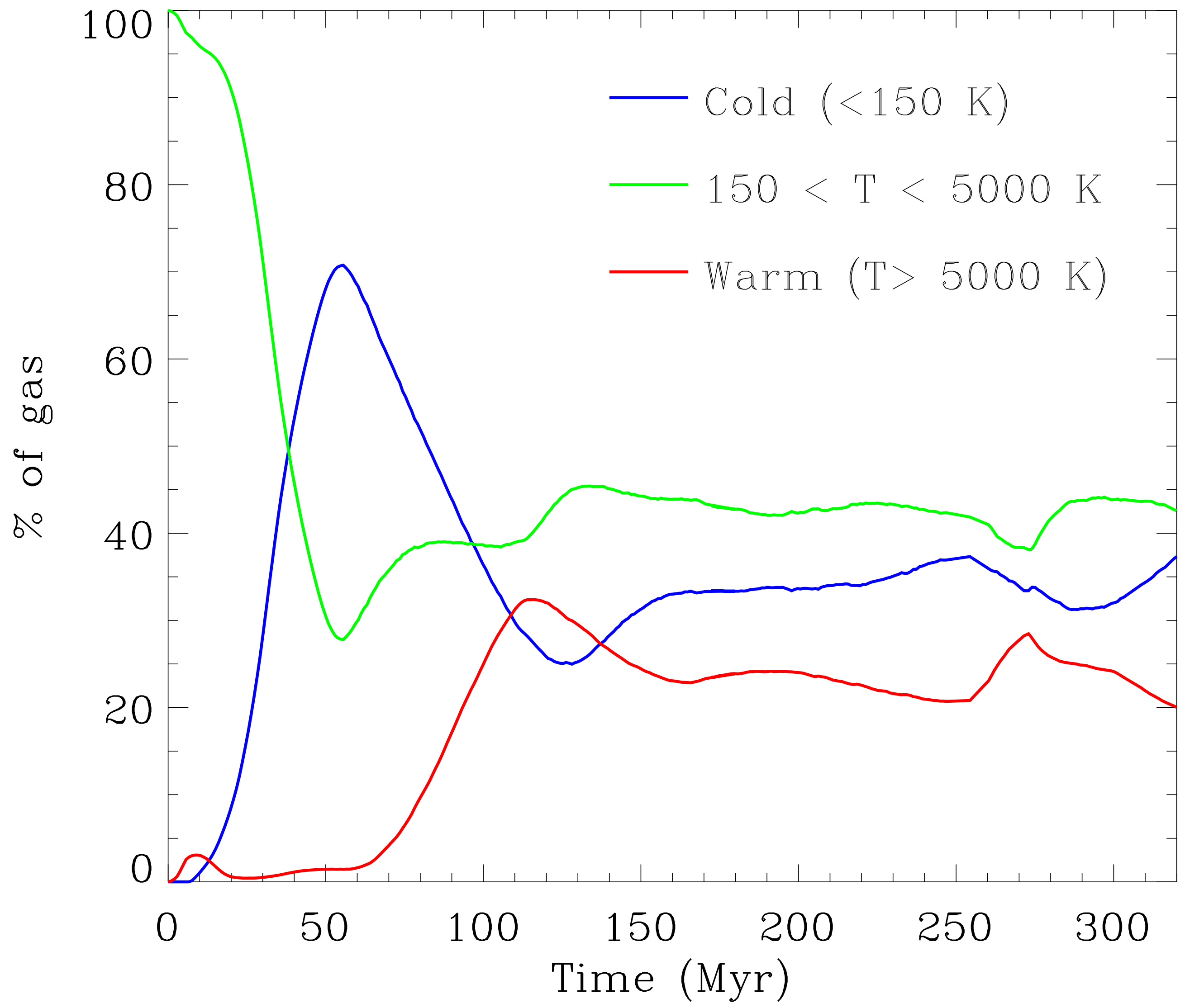


Bagetakos et al. 2011

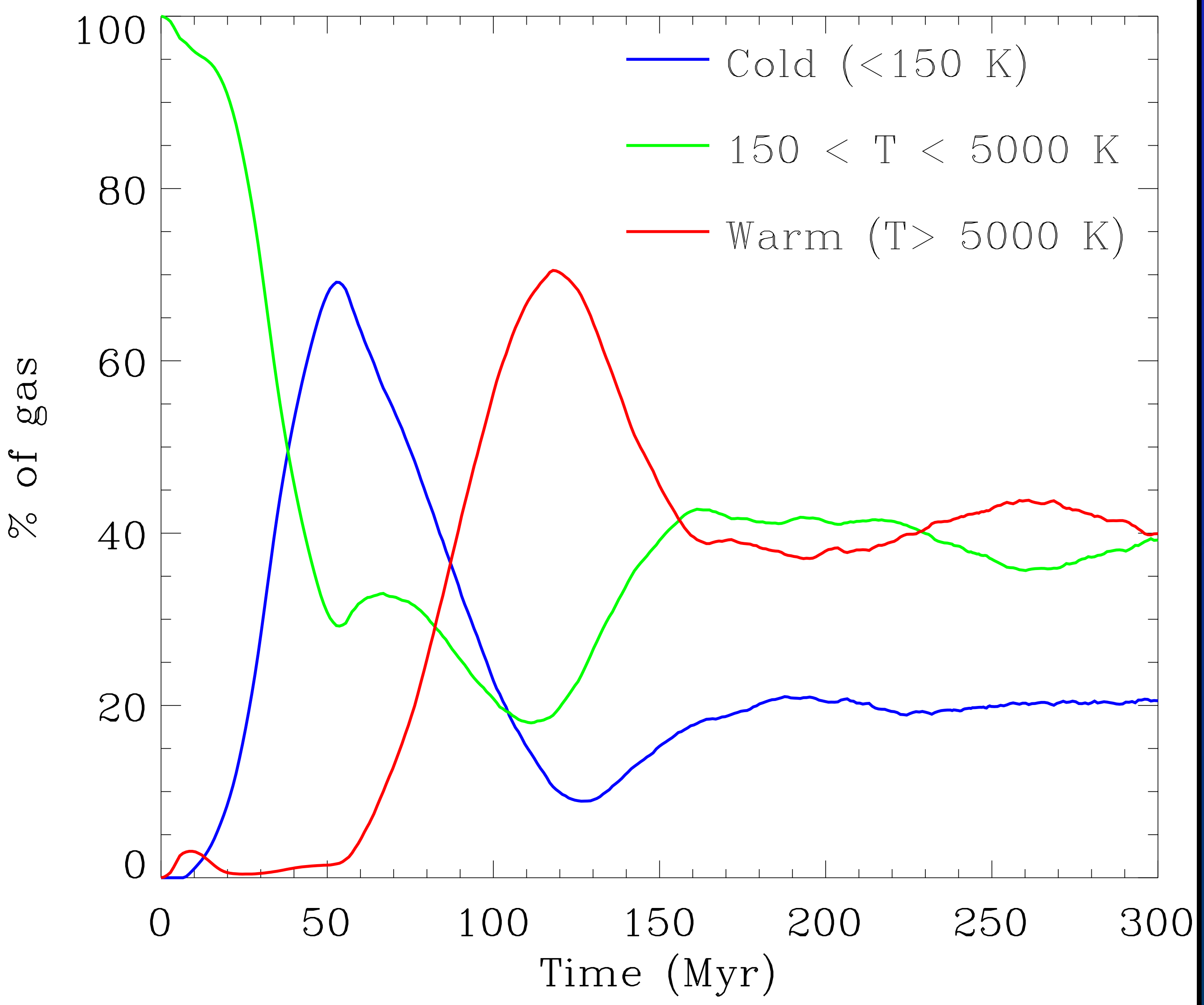
Scale heights qualitatively agree with observations

In simulations, both σ and scale height scale with feedback

Temperature Distribution



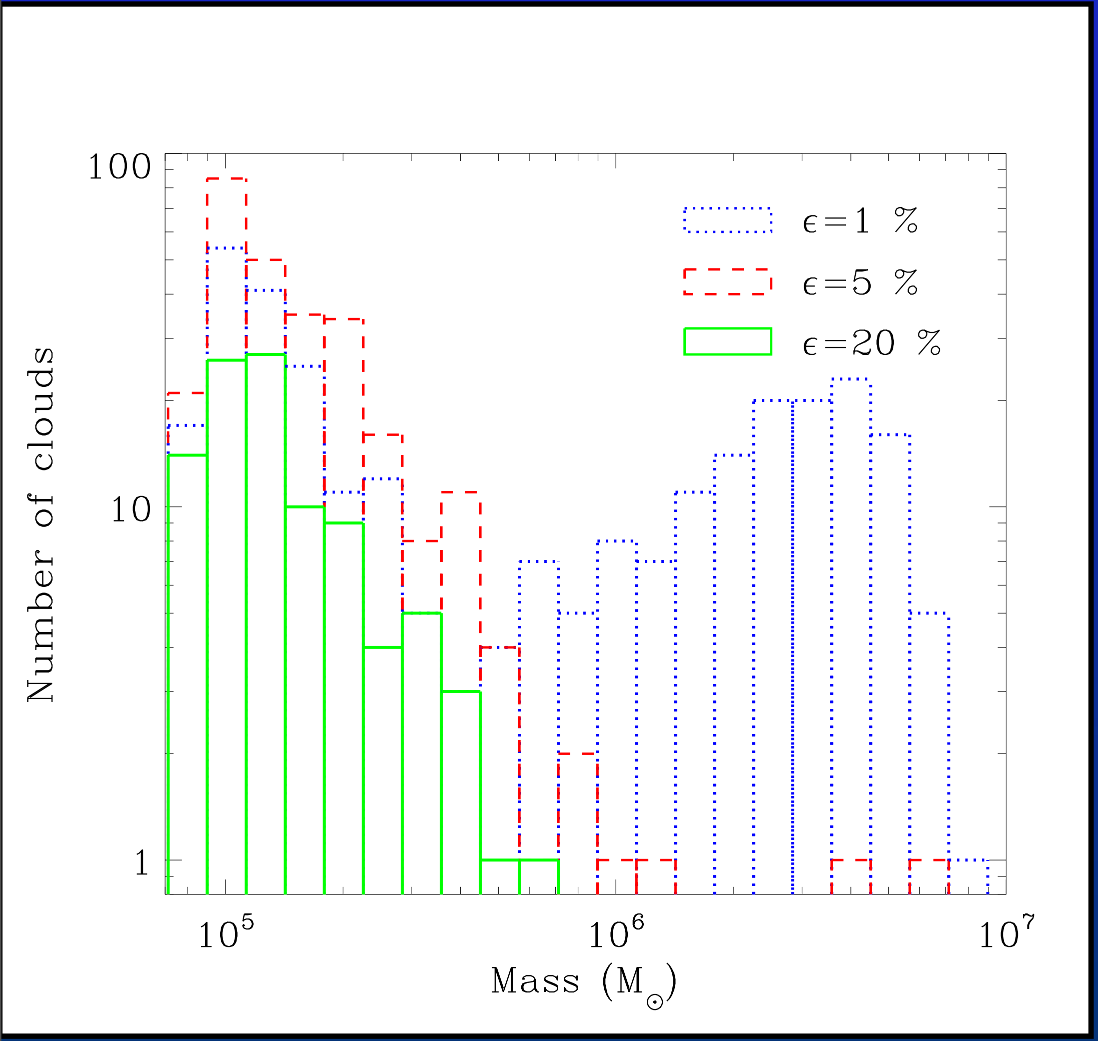
ε=5 % (moderate feedback)



ε=20 % (high feedback)

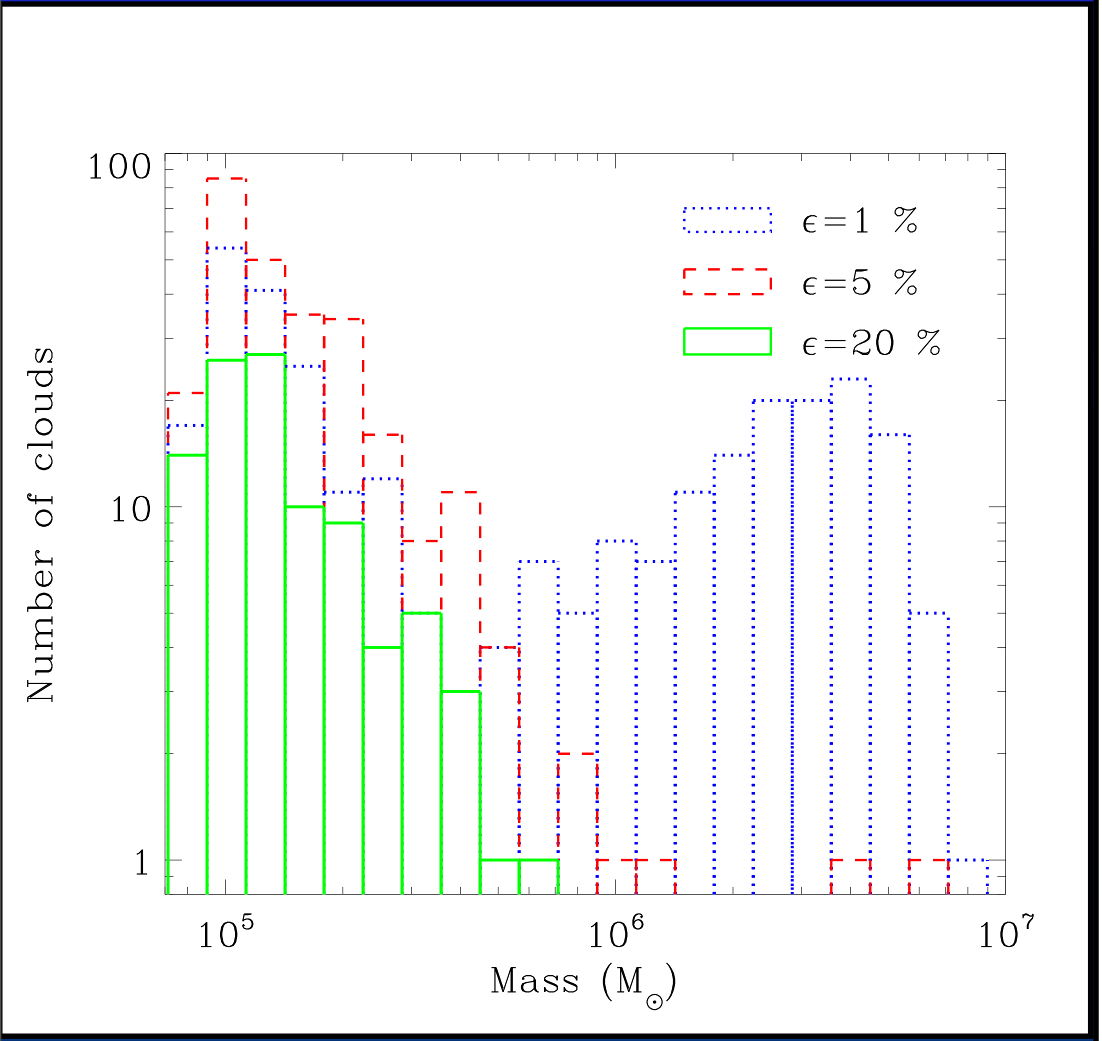
- Hard to generate large amounts of cold gas coupled with high velocity dispersions and scale heights

Properties of clouds



1% feedback gives bimodal distribution

Properties of clouds



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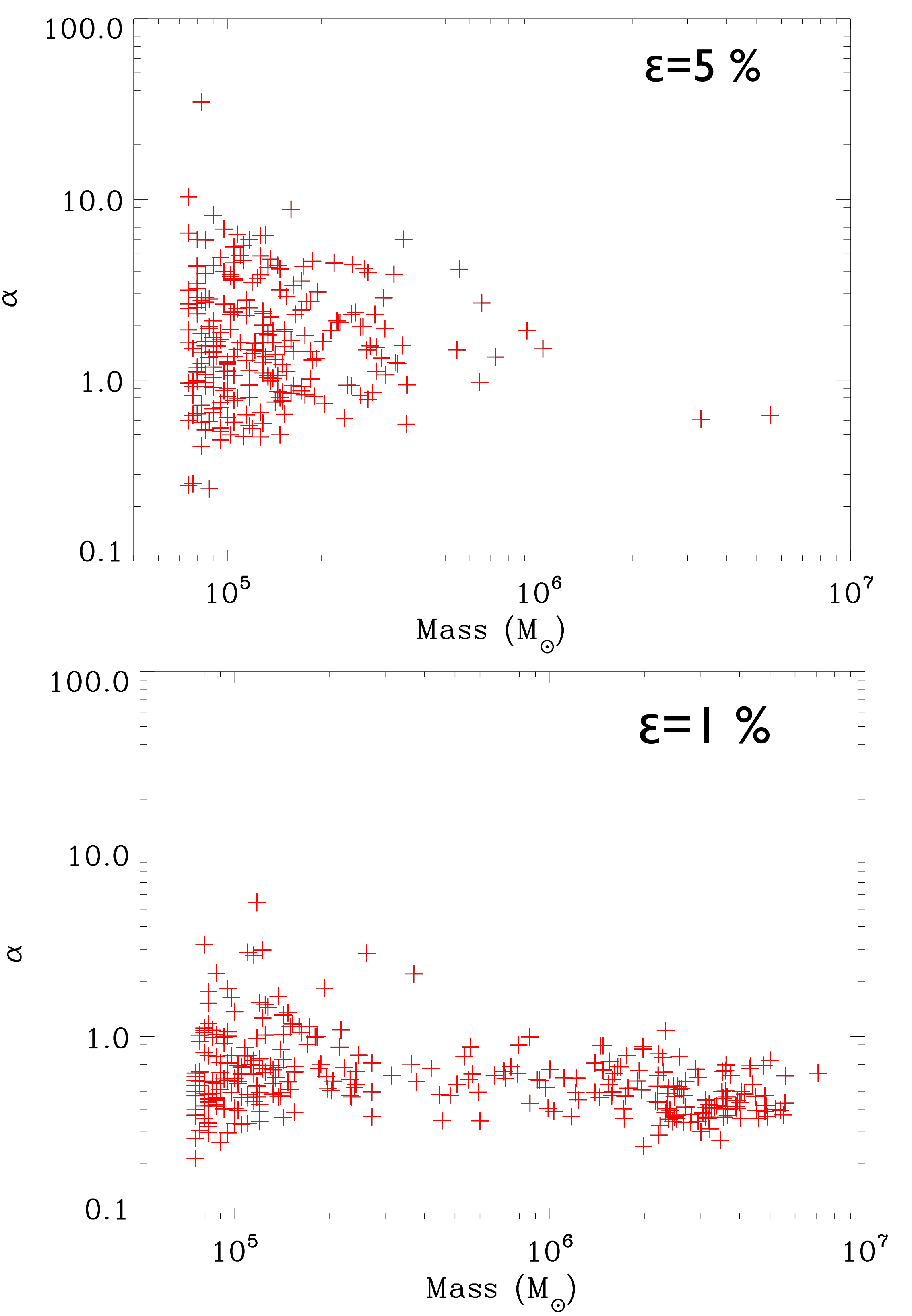
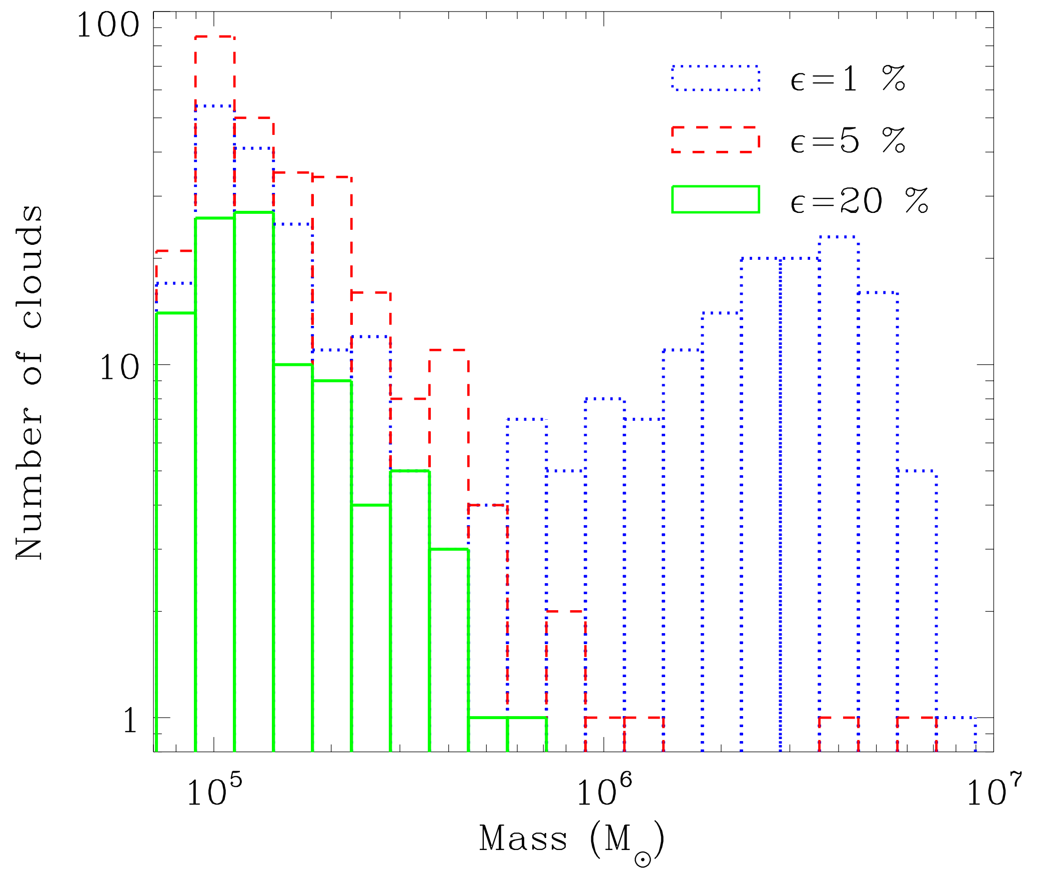


unbound clouds with feedback, bound clouds otherwise

Properties of clouds



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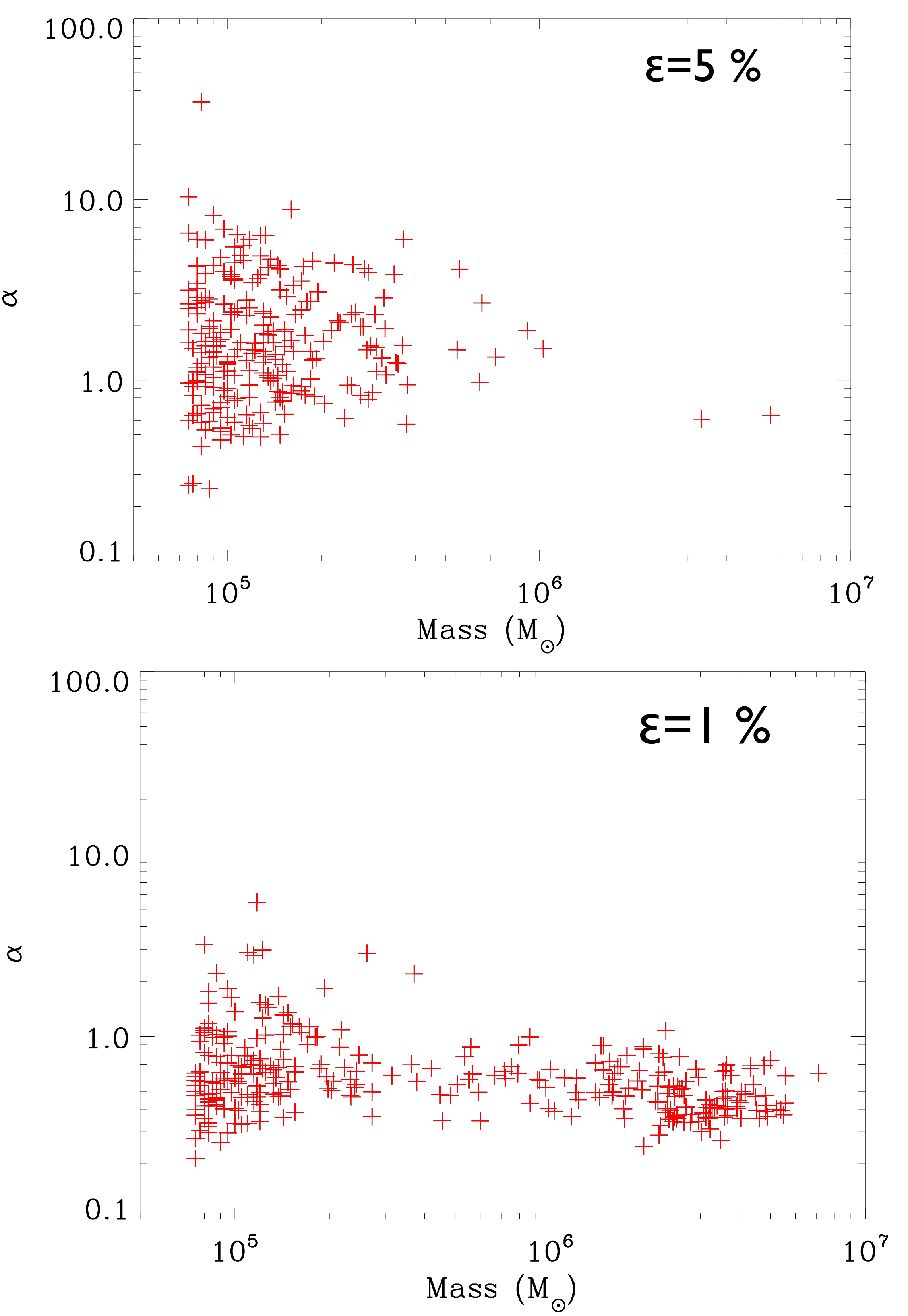

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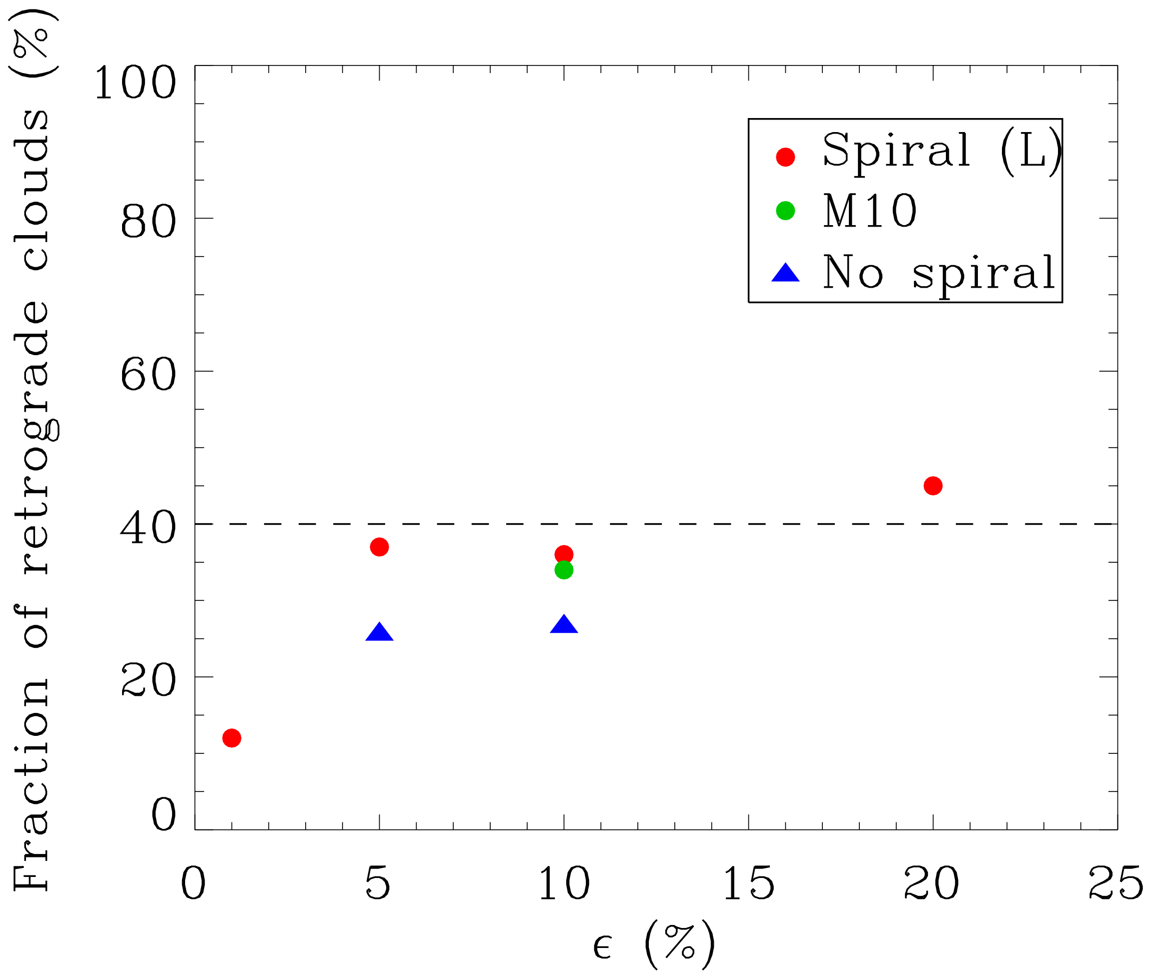
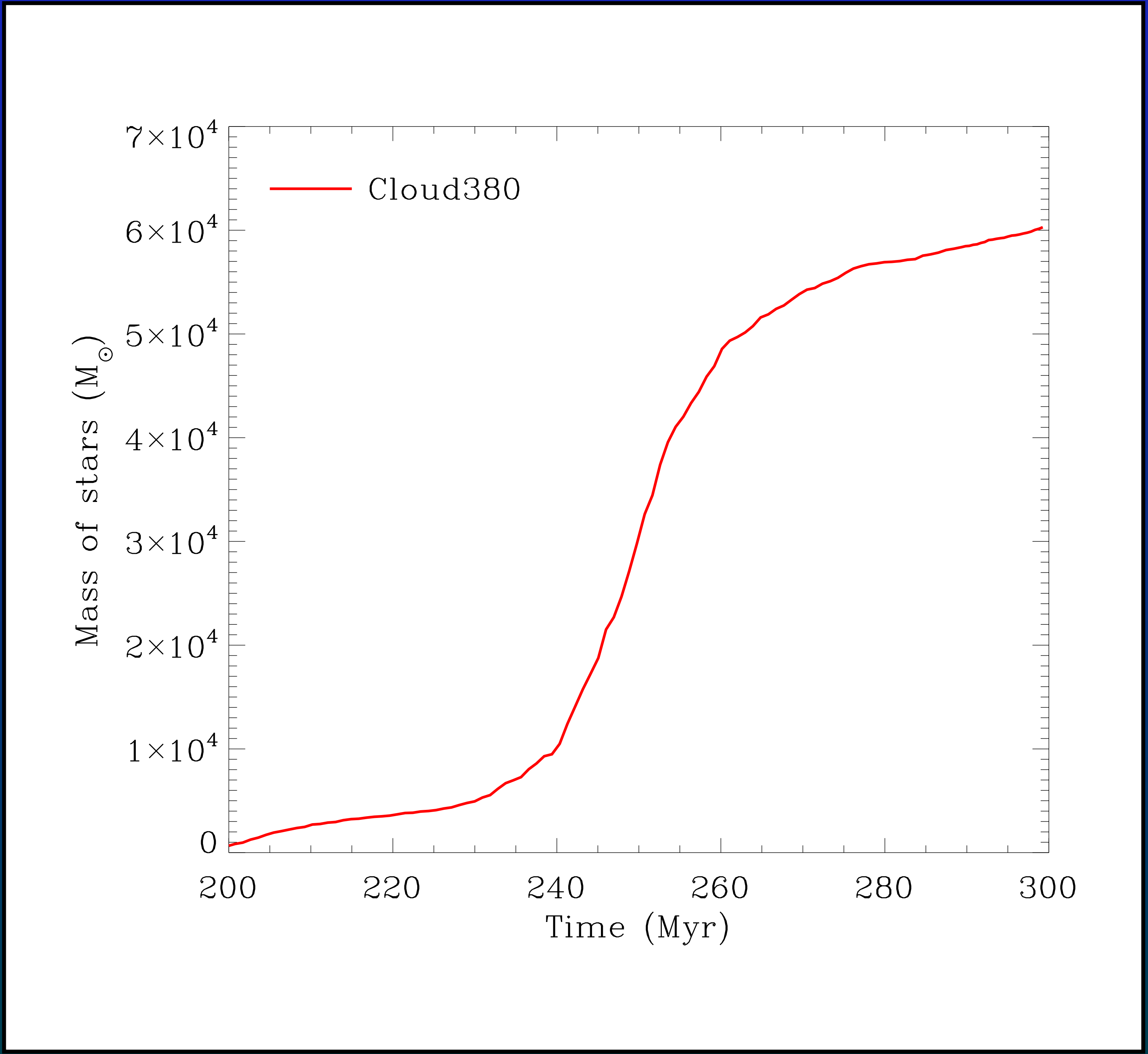


1% feedback: few retrograde clouds, otherwise just less than half retrograde (see also poster by Williamson)

Star Formation Efficiency of Clouds



Individual cloud

Total mass of stars formed~$5\times10^4 M_\odot$

Mass of cloud ~ $2\times10^6 M_\odot$

Efficiency = 2.5%

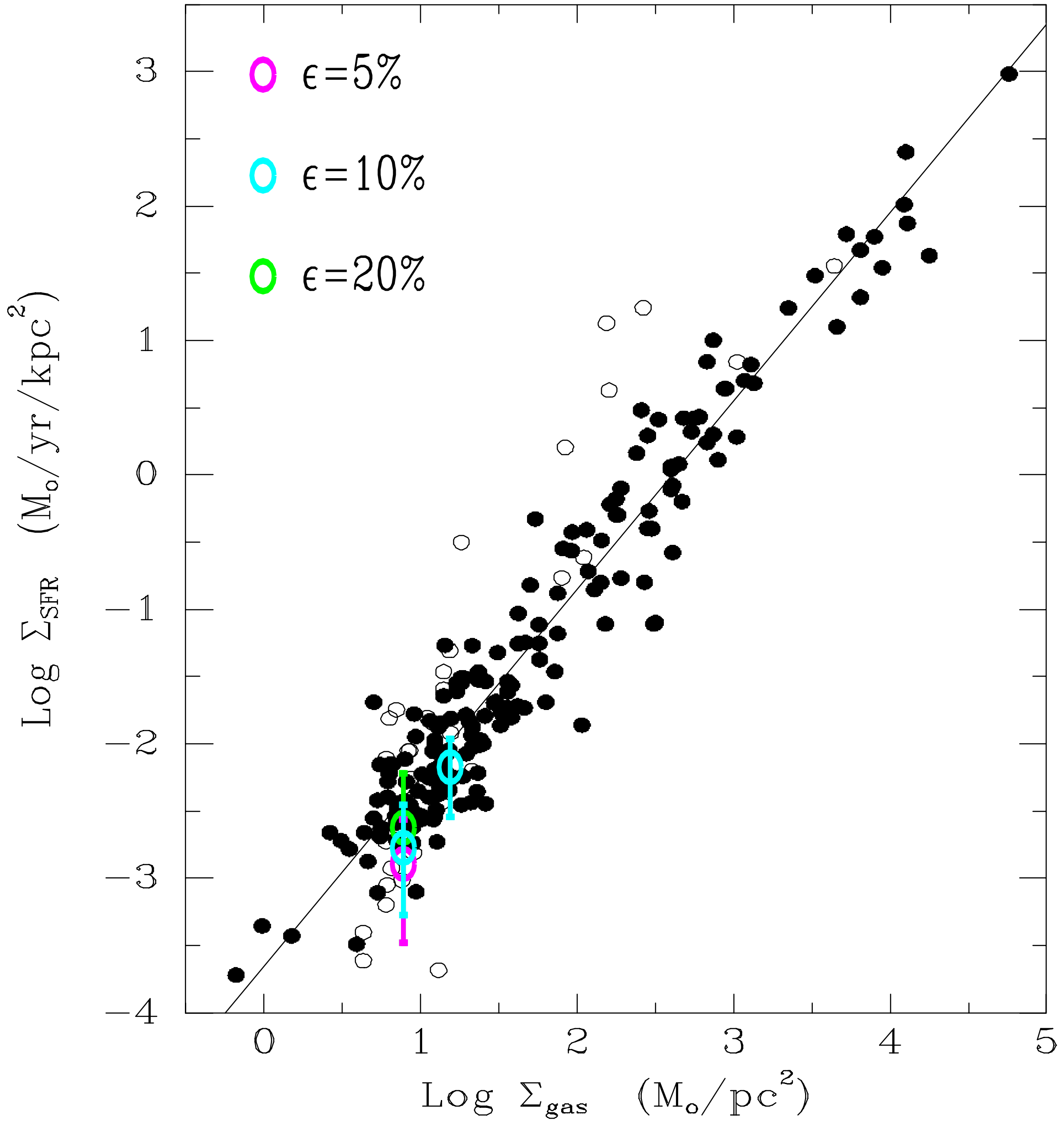
- Generally ~1% of mass of GMCs turned into stars during their lifetime

similar findings by Hopkins et al. 12

most star formation occurs during time cloud is in the spiral arm (and is most massive)

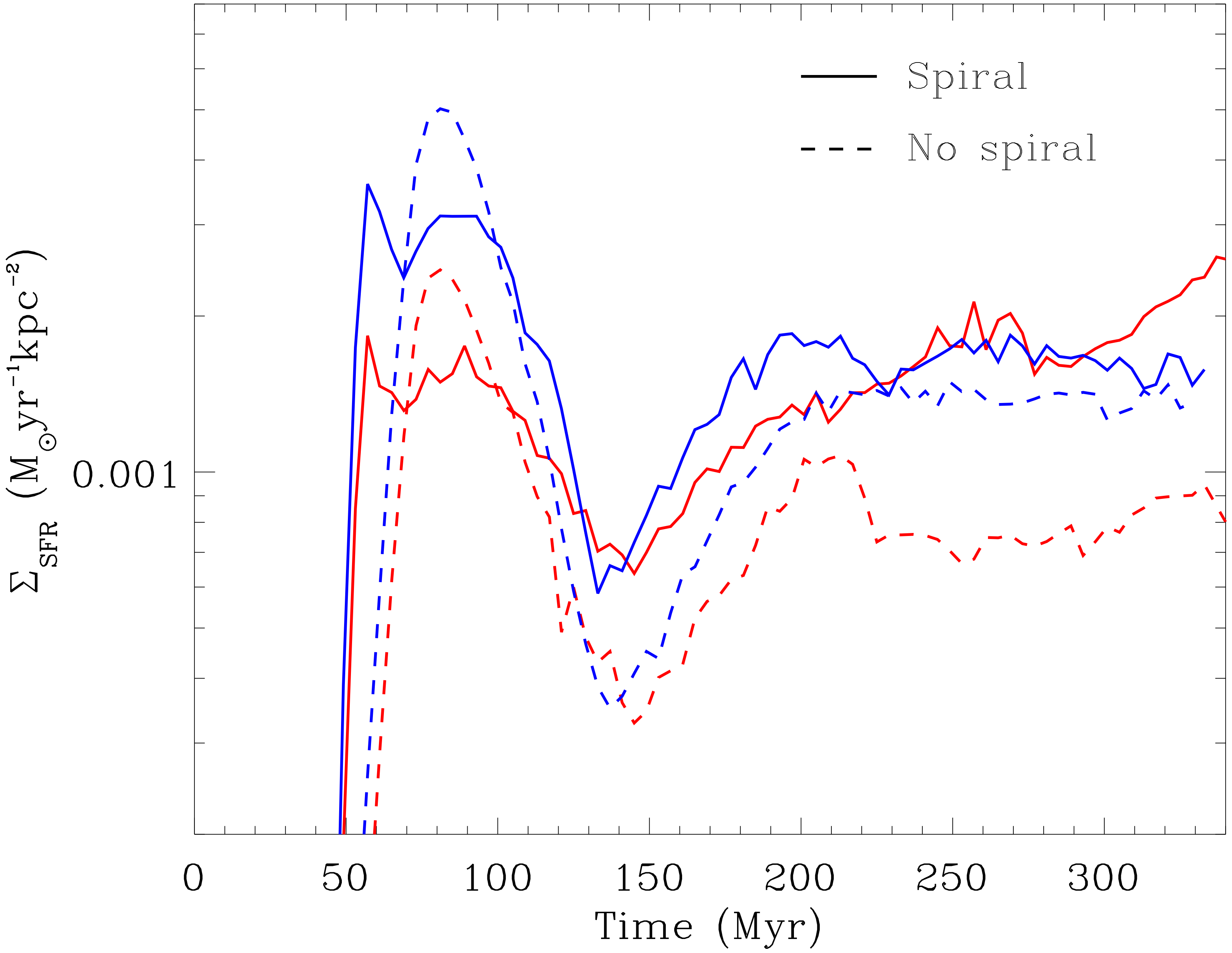
Total Star Formation Rate

Different efficiencies



Background: Kennicutt 2008

Results with / without spiral potential



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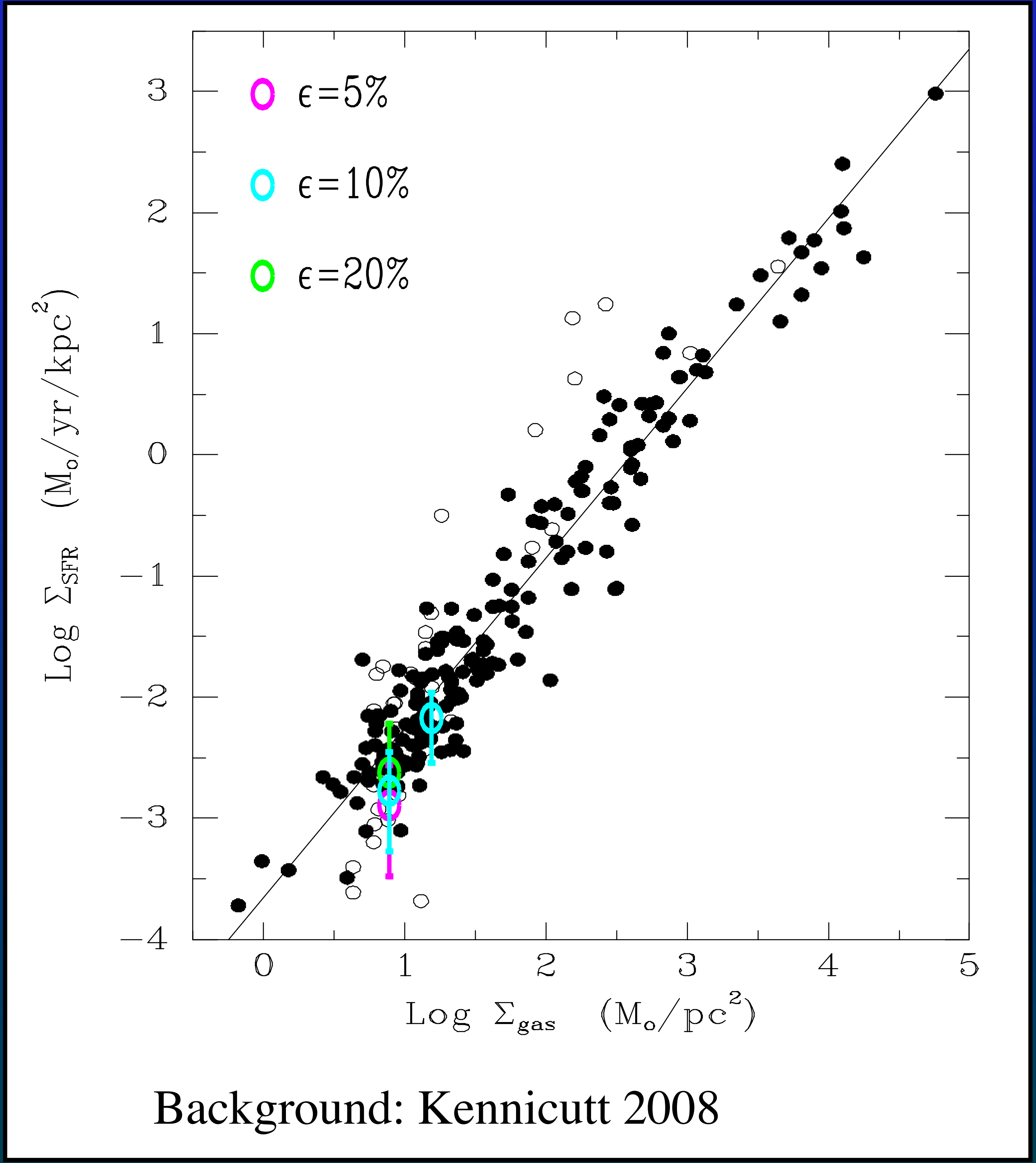

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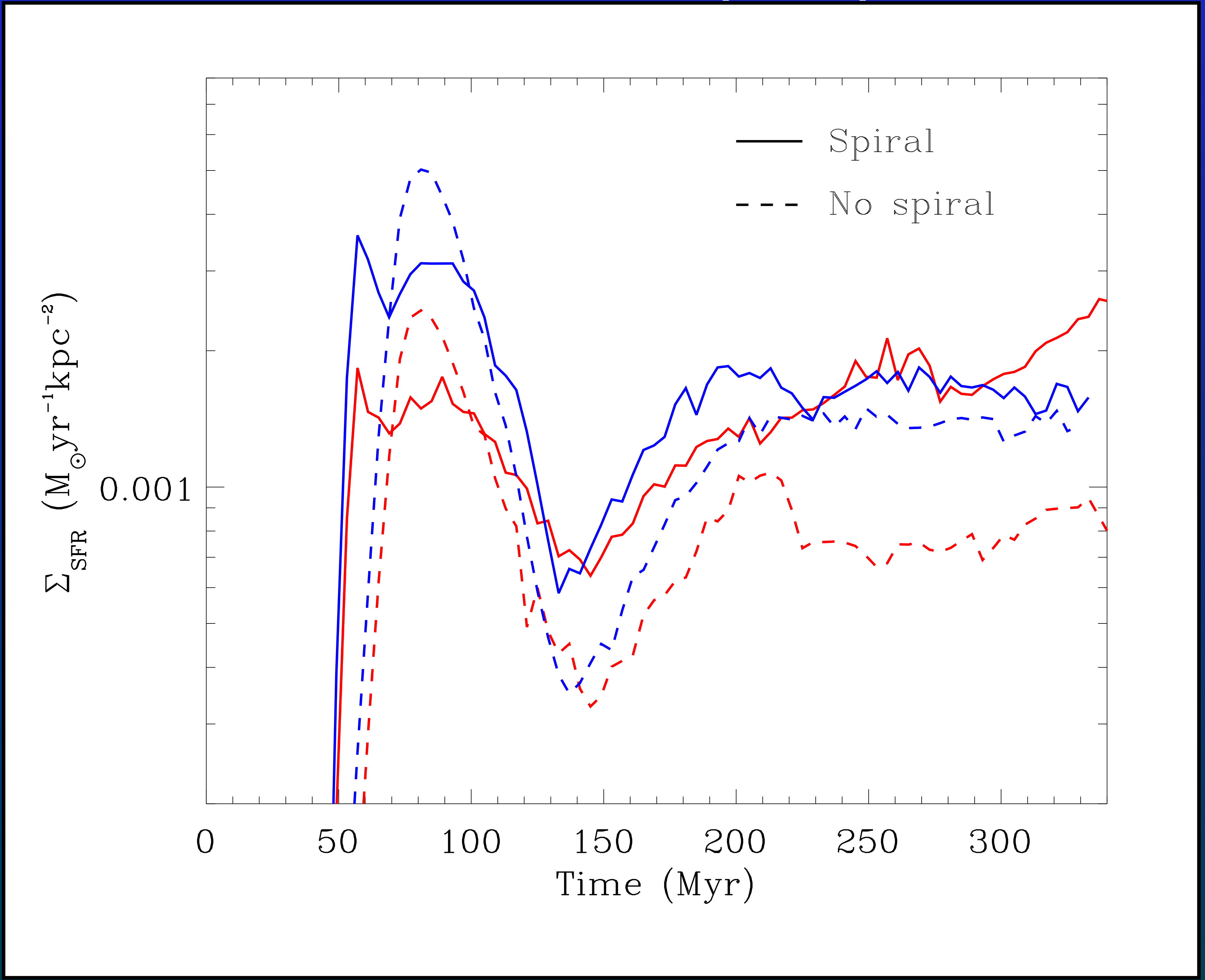
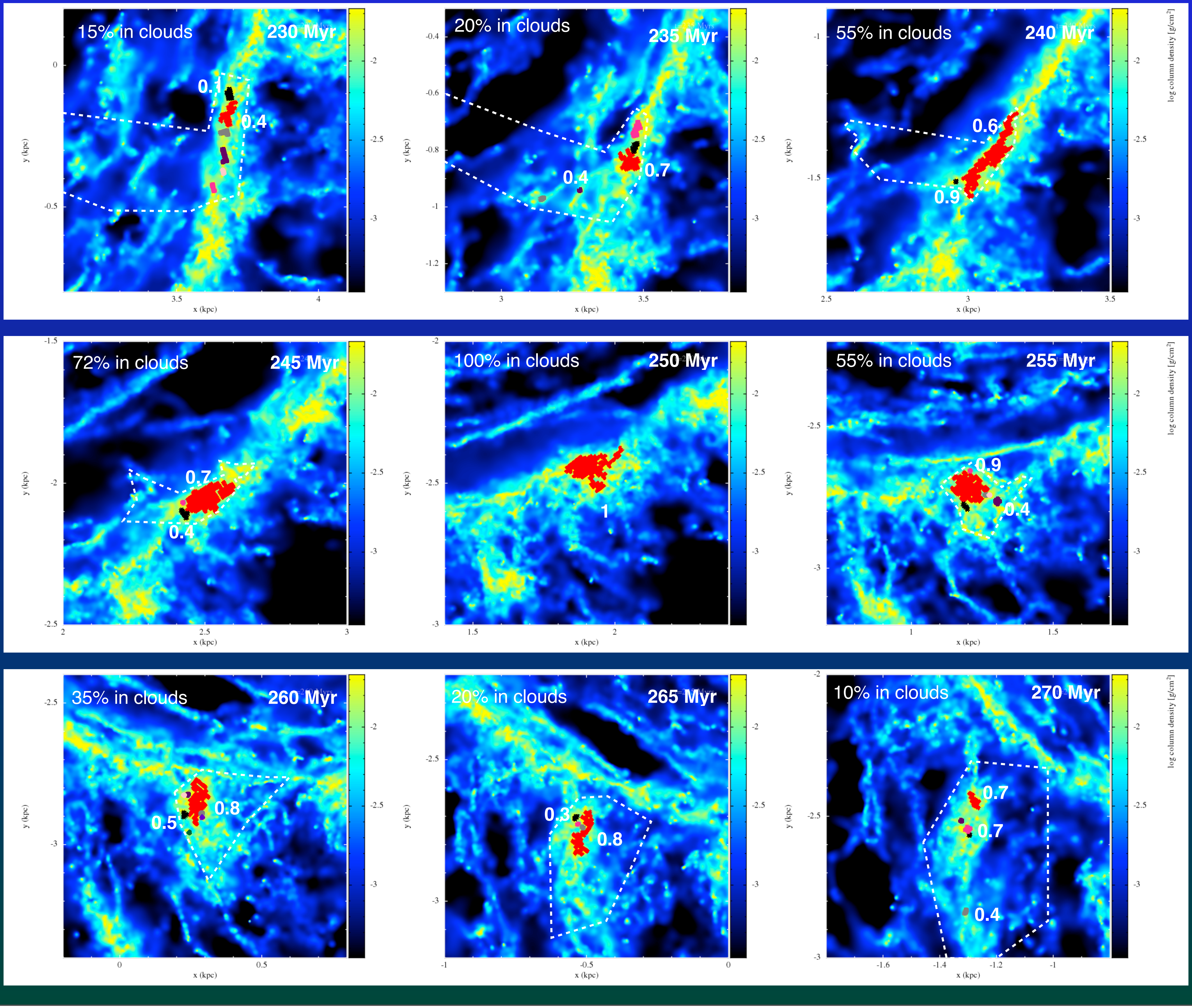


No strong dependency on ε (i.e. self regulating) or spiral structure

How does gas flow when clouds form / disperse?

- How does an individual cloud evolve?
- How important are cloud-cloud collisions?
- How do clouds disperse - feedback, shear?
- Are there signatures in the gas dynamics of what is driving the dynamics?

Detailed evolution of GMC in a rigidly rotating spiral arm



Dobbs & Pringle 13

Cloud-cloud collisions

Consider all $>10^4\ M_\odot$ clouds

Determine which clouds contain particles originating from at least 2 clouds 1 Myr earlier

Frequency of cloud-cloud collisions $\lesssim 10$ Myr in spiral galaxy

agrees with theoretical prediction:

$$\frac{1}{\pi\ r^2\ n_{sp}\ v}$$

using cloud number density in spiral arms $n_{sp} \sim 30\ n_{av}$

But note, may depend on definition (surface density) of cloud

- see also Tasker & Tan 2009

Dobbs et al. 2014, in prep.

Cloud disruption: Feedback or shear?

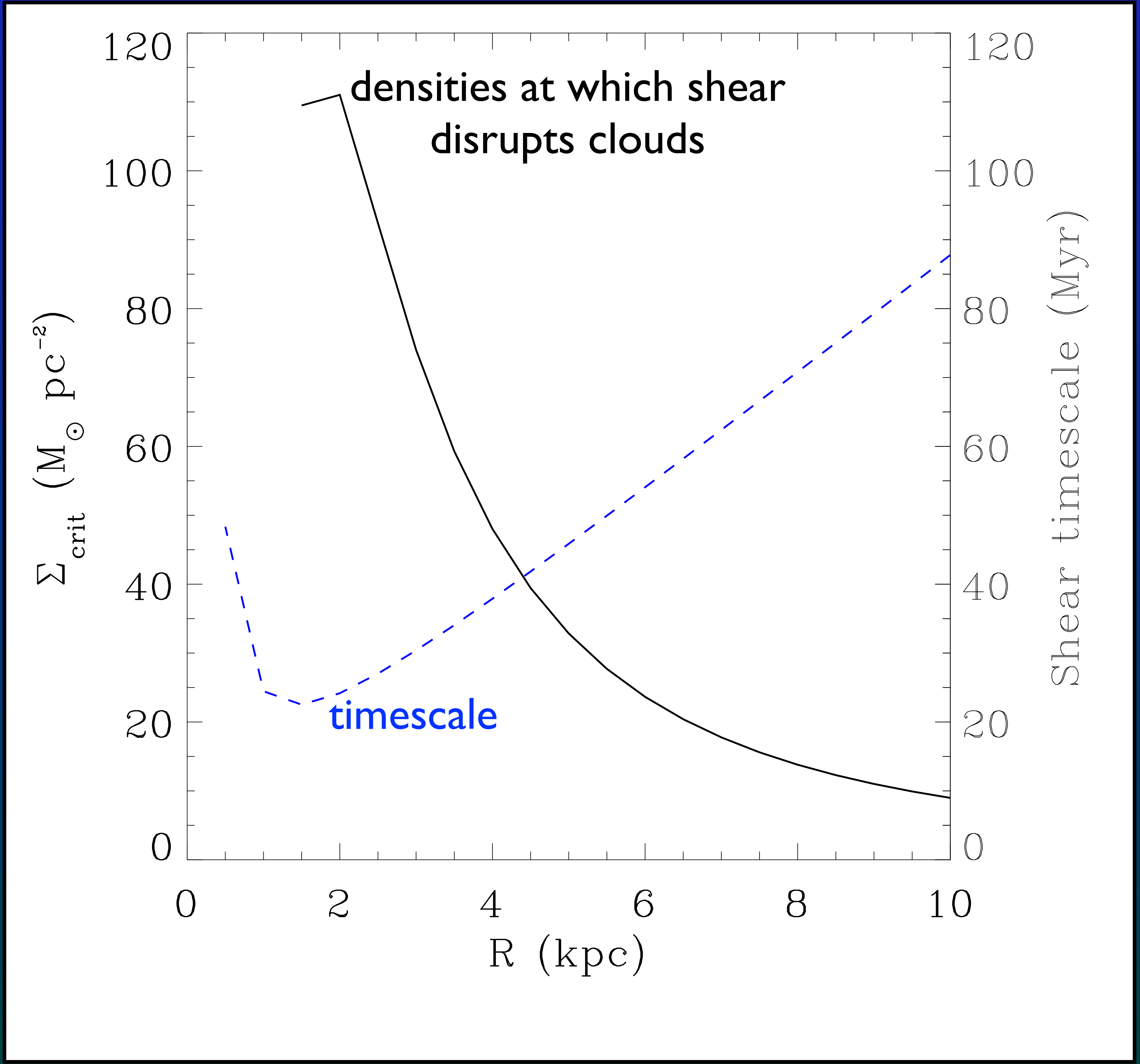
Can calculate Σ where shear becomes important

$$r_{\text{cloud}} \frac{dF}{dr} = \Sigma_{\text{crit}} G \quad (r_{\text{cloud}}=50\text{pc})$$

timescale~A^{-1}

shear acts over lifetime of cloud, and fairly large scales

feedback likely more important for smaller clouds, bound clouds, and bound clumps



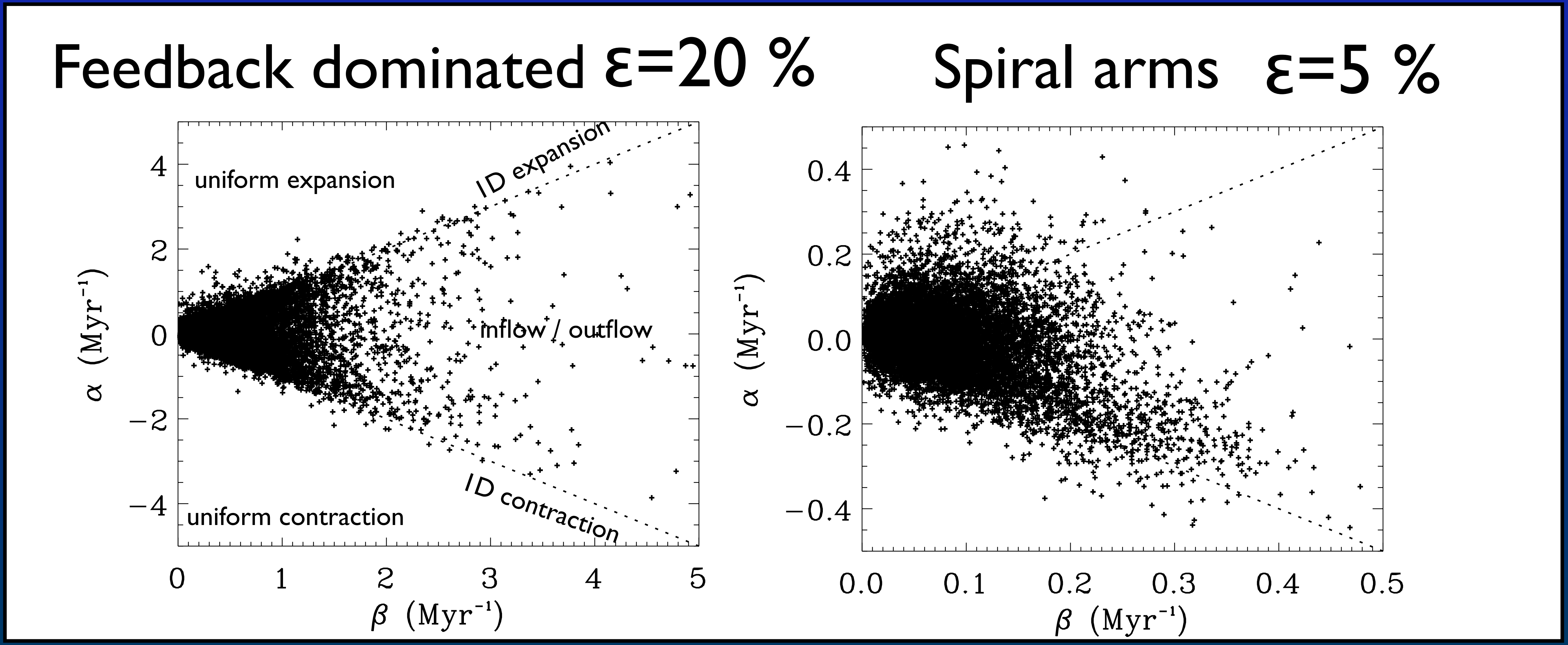
shear also low at large R

Dobbs & Pringle 13

Overall gas dynamics

λ_1, λ_2 eigenvalues of rate of strain tensor

$\alpha=\lambda_1+\lambda_2$ (divergence) $\beta=\lambda_1-\lambda_2$


Feedback dominated ε=20 %

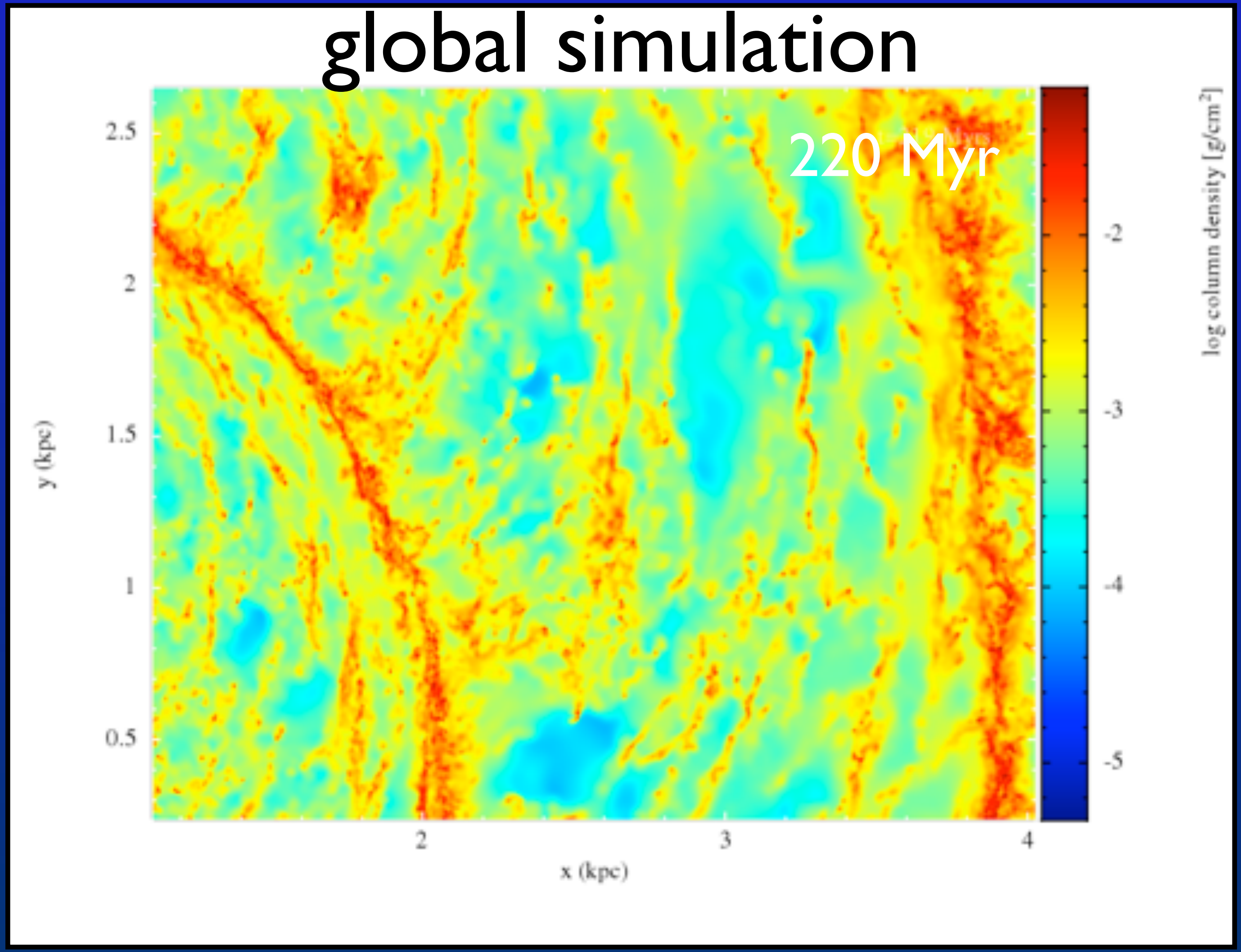
Spiral arms ε=5 %

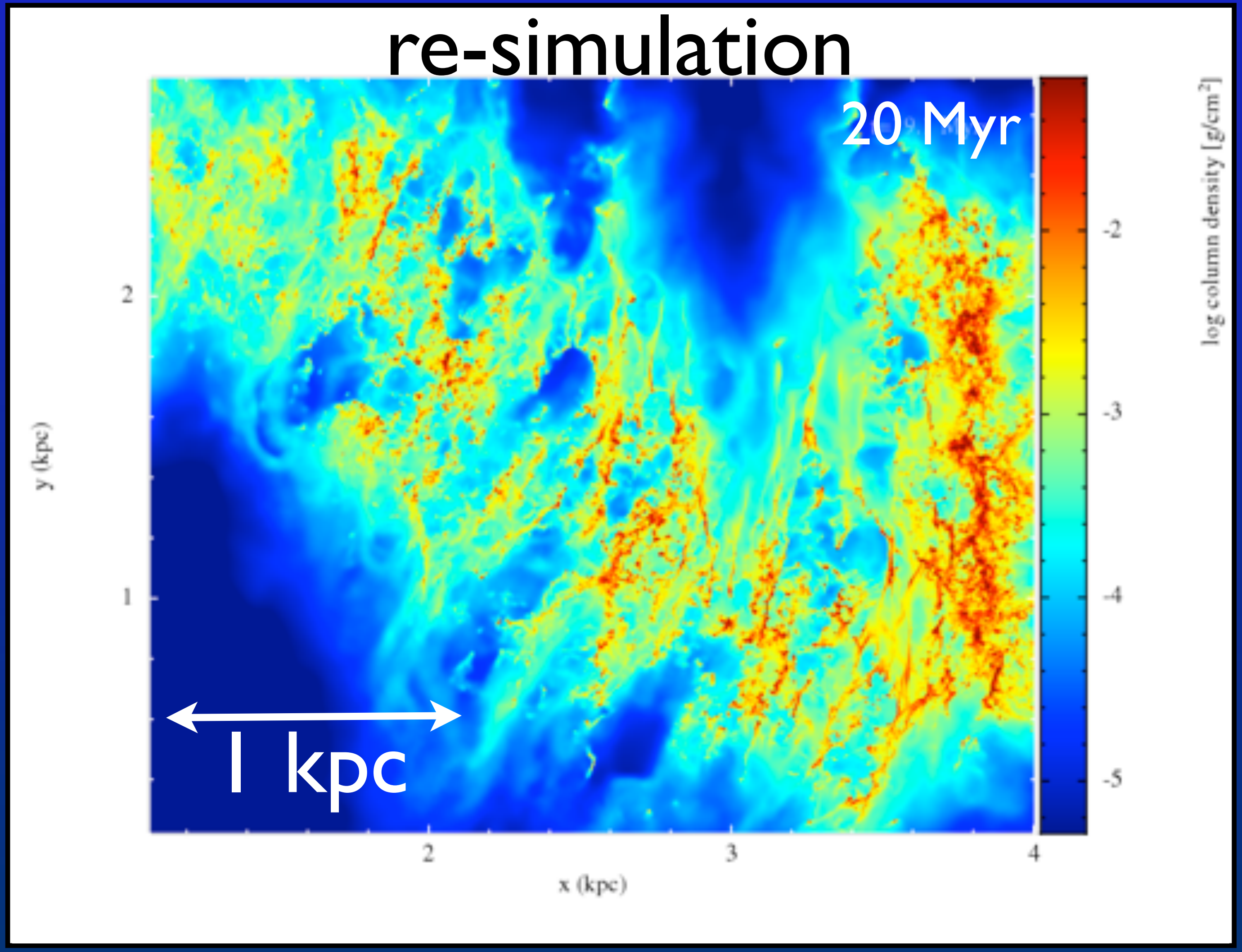
Dobbs, Pringle & Burkert 12

flows acting on much faster timescales in feedback regime

converging flows in spiral arms apparent in lower feedback case

What about higher resolution?


global simulation


re-simulation

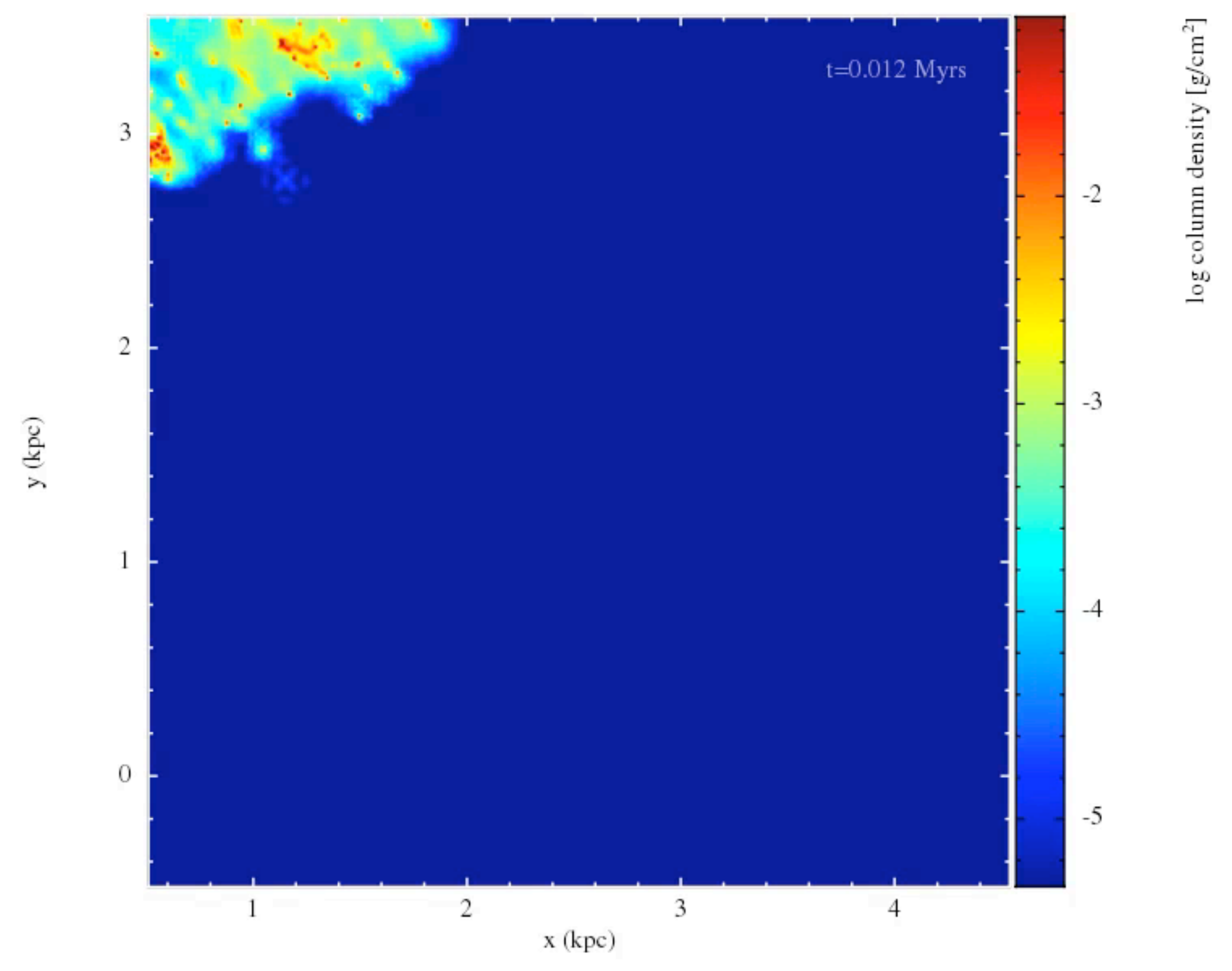
Re-simulations of section of spiral arm with mass per particle of 3.85 $M_\odot$

- Select region of gas in global simulation
- Trace back gas by 50Myr
- Split particles

compare with Bonnell et al. 2013, van Loo et al. 2013

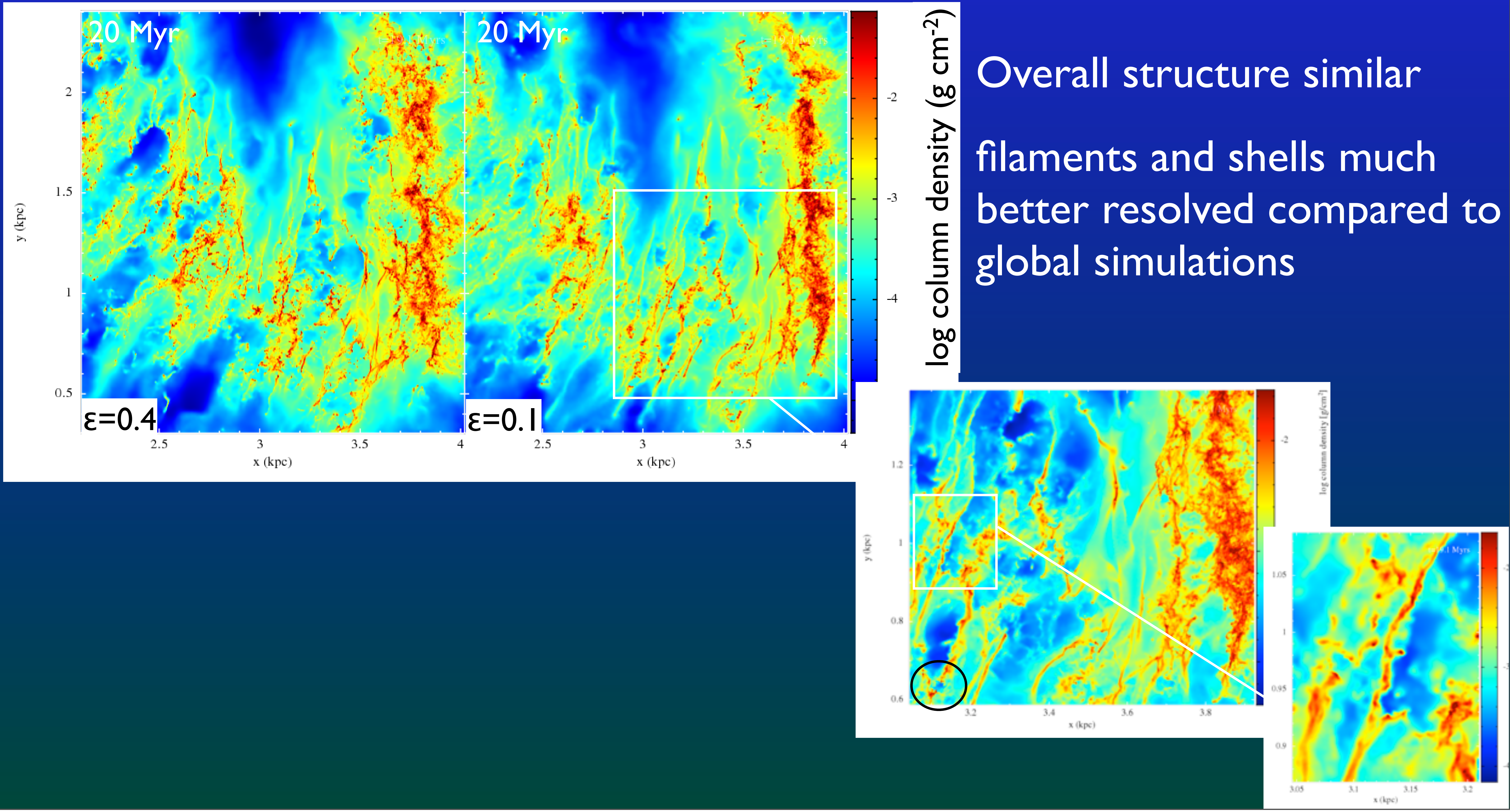
Dobbs et al., in prep.

What about higher resolution?



Dobbs et al., in prep.

Different feedback at higher resolution



Overall structure similar

filaments and shells much better resolved compared to global simulations

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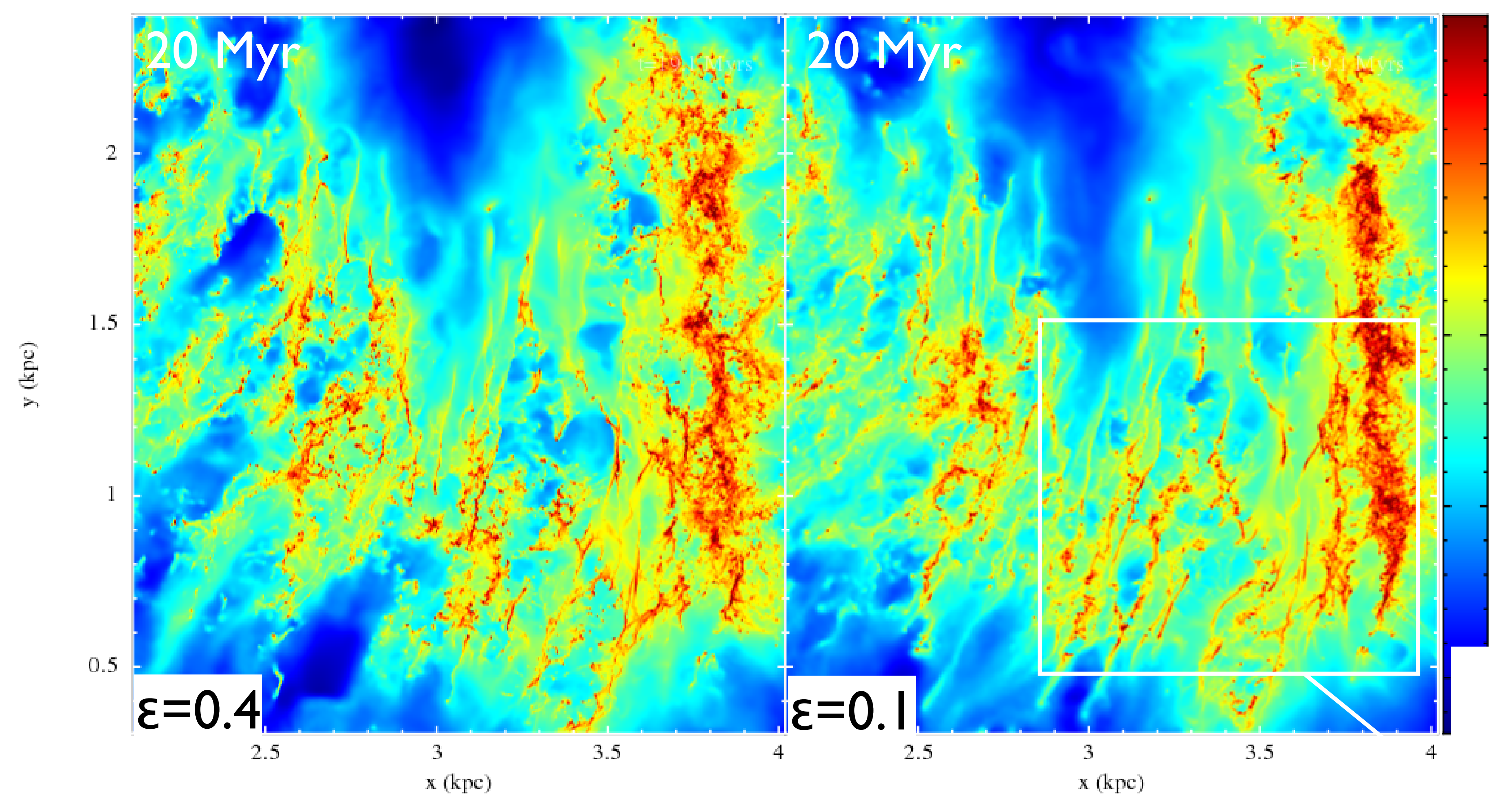

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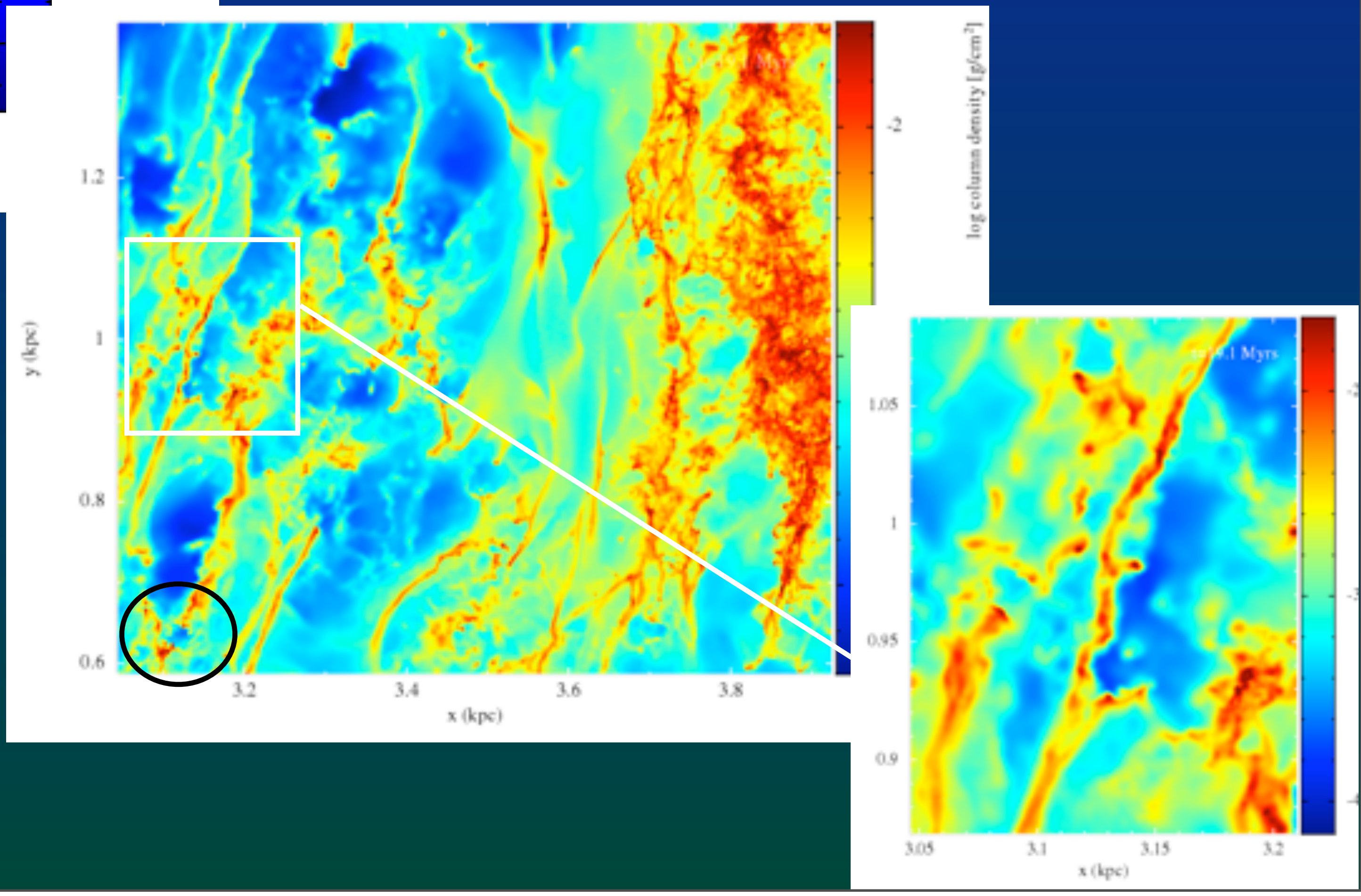
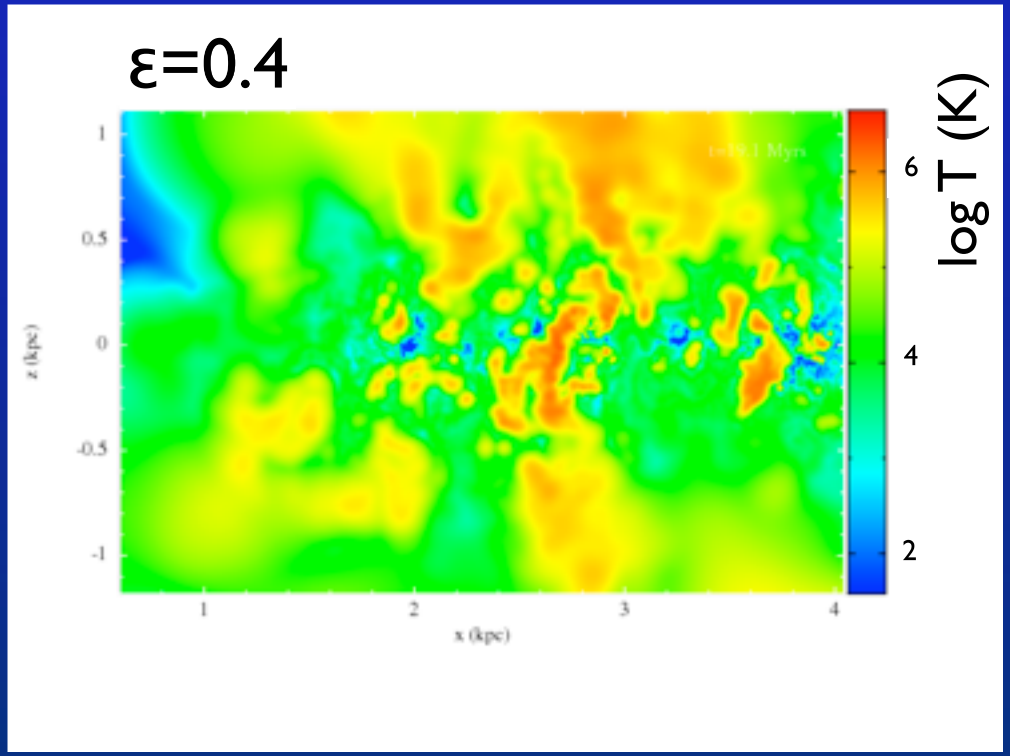
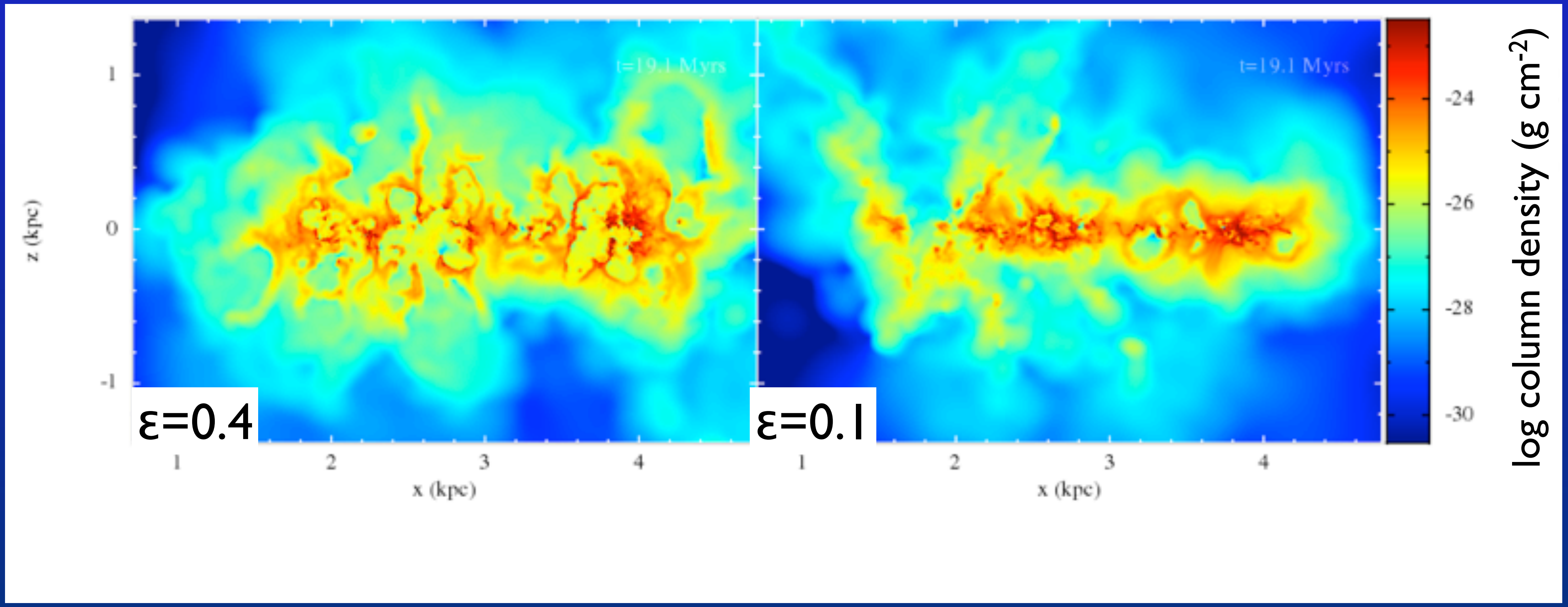


Little difference with different feedback, including adding feedback over time, stochastic implementation

ISM in the vertical direction

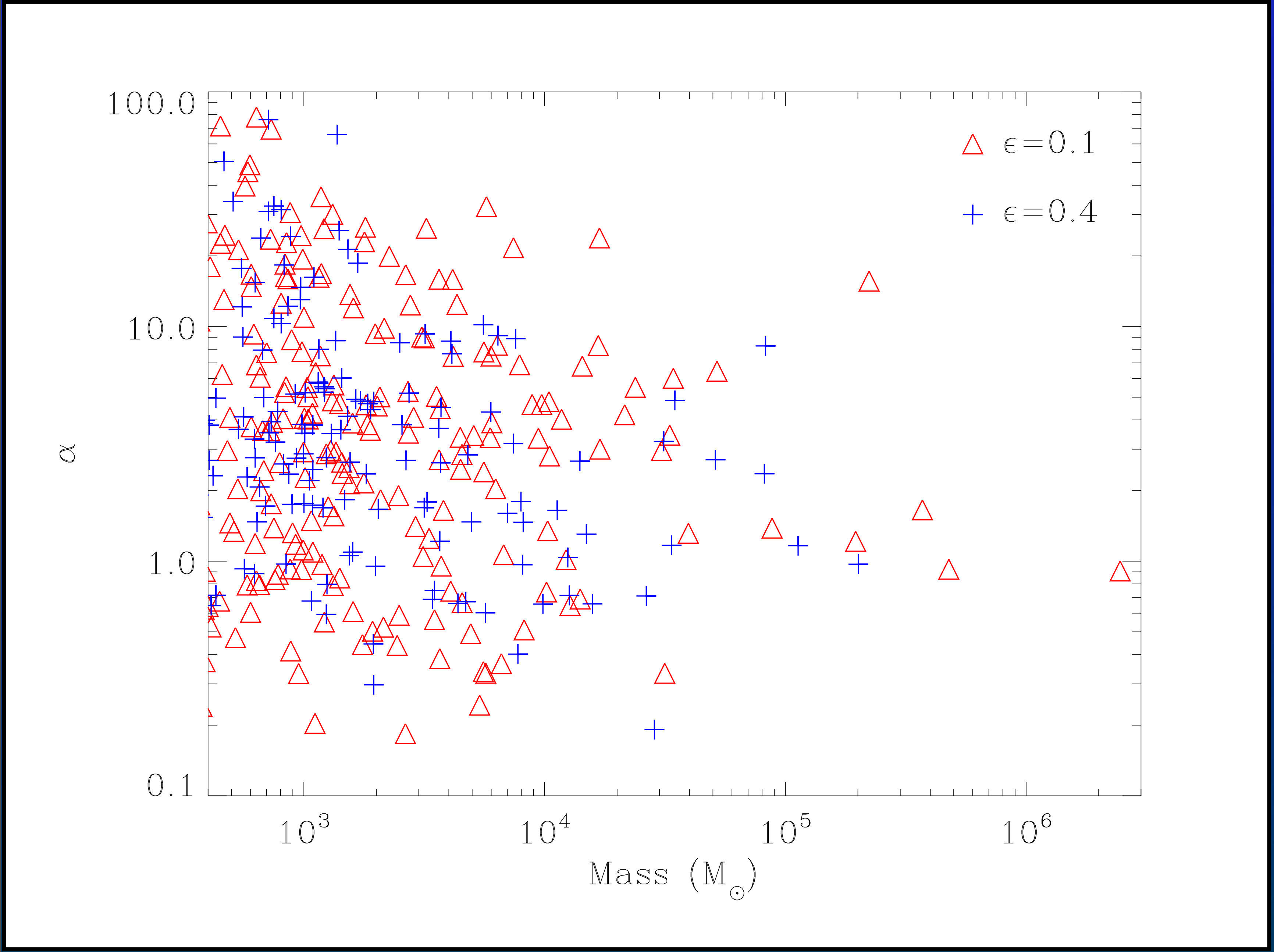


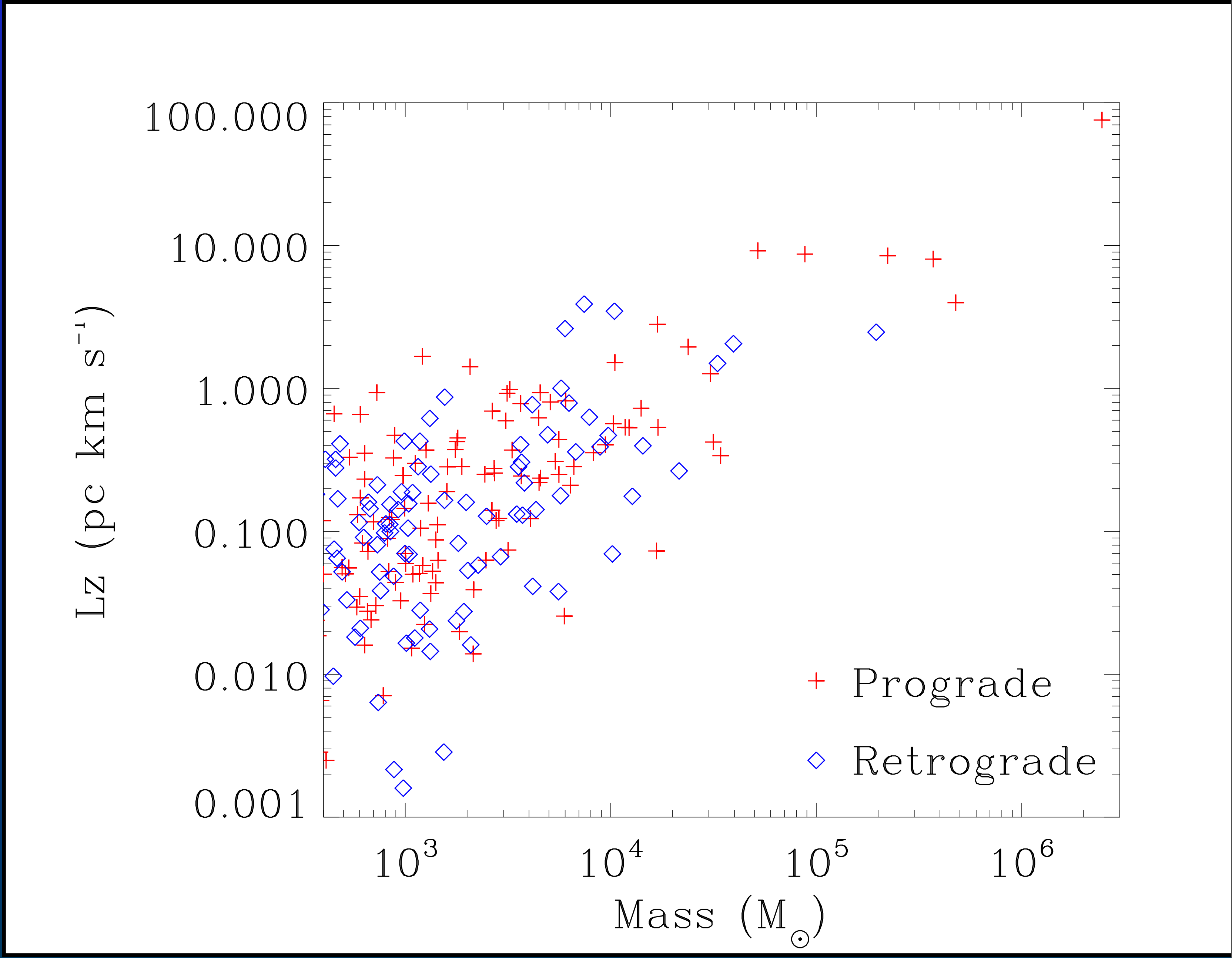


Feedback has a larger impact on vertical distribution, and amount of very hot gas

Otherwise ISM (and star formation) still largely reflect initial conditions

Cloud properties at higher resolution



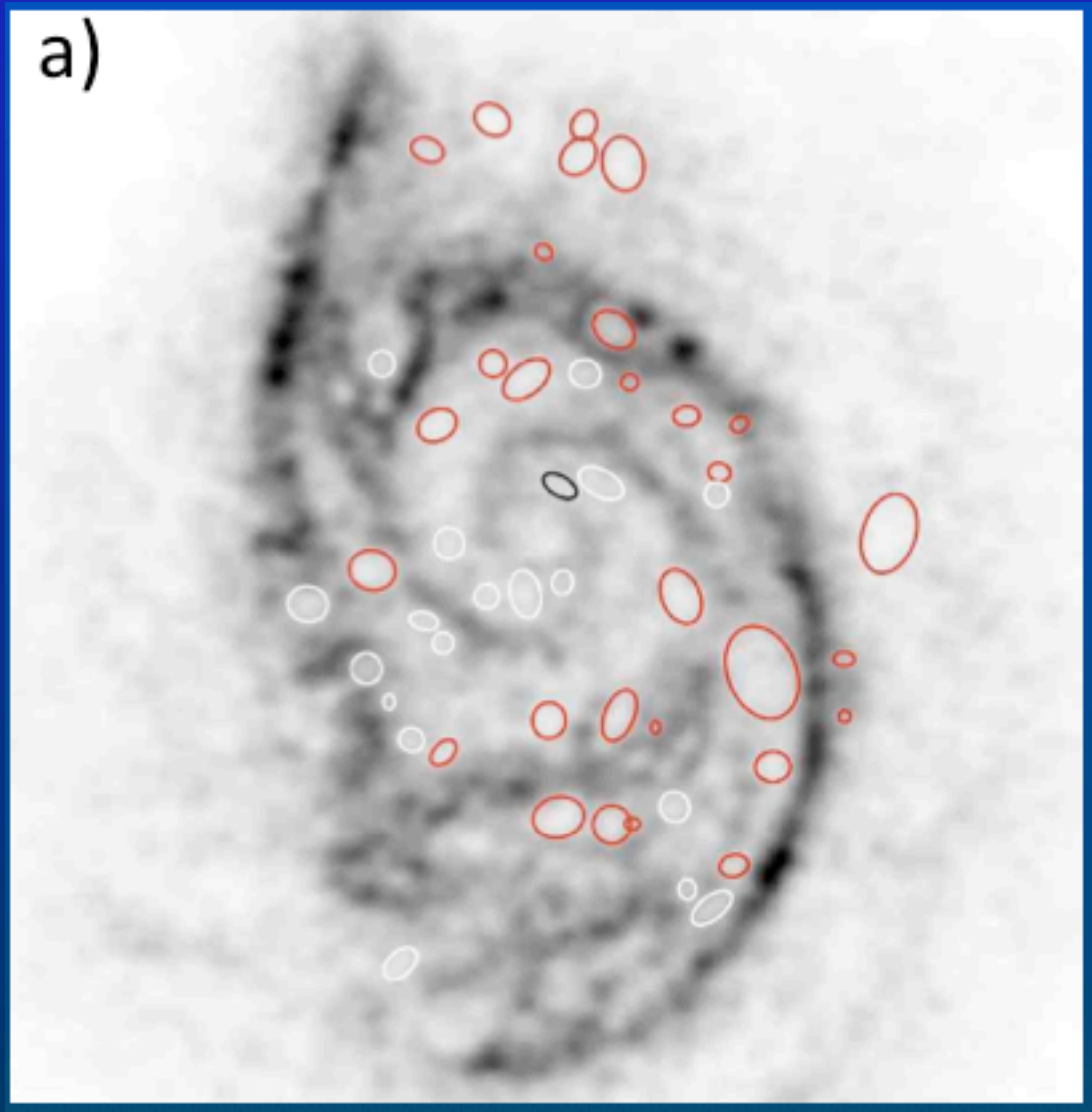


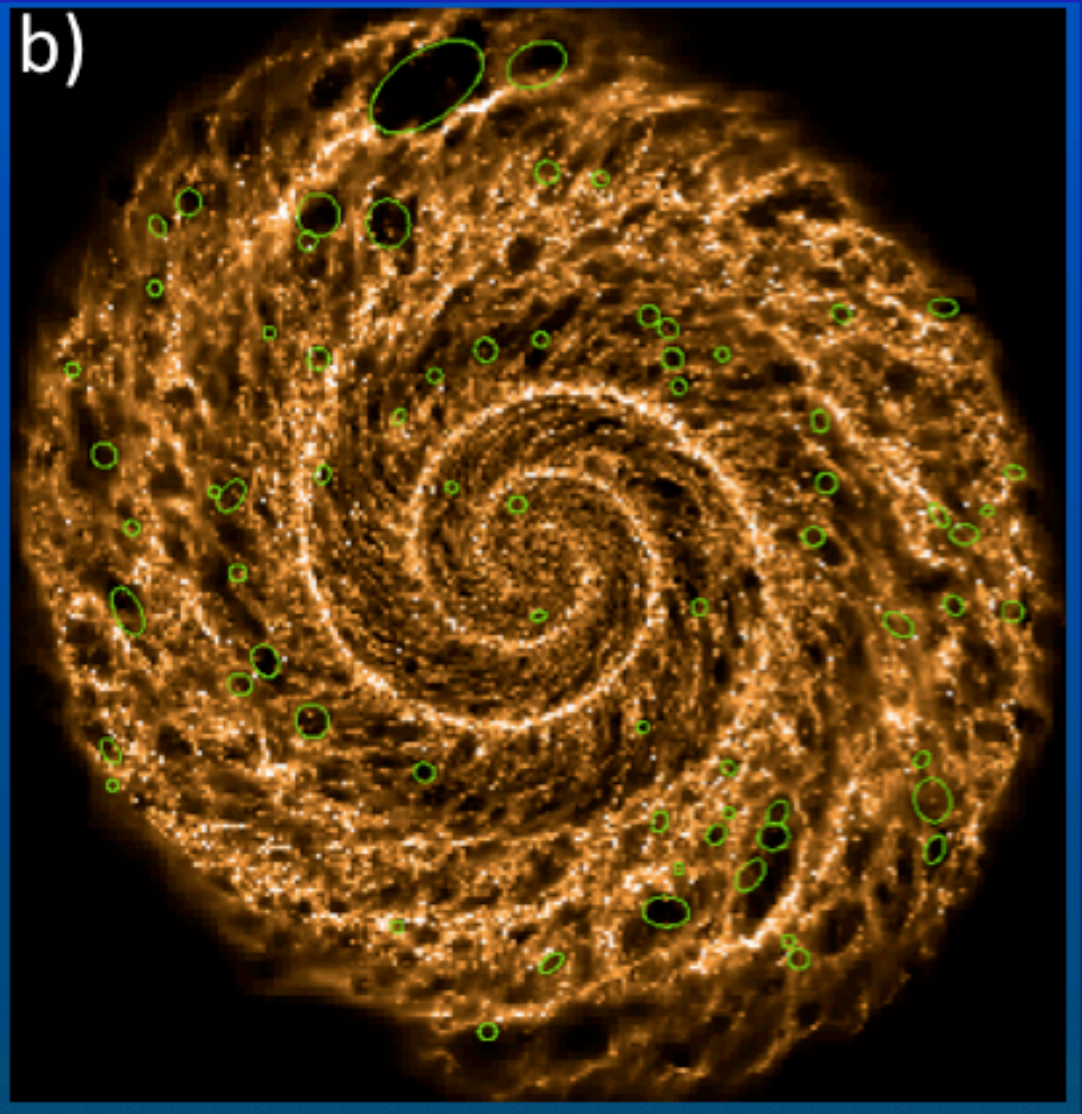
virial parameters

angular momenta - fraction of retrograde clouds =46%

cloud properties (+mass spectrum) very similar to global simulation (Dobbs & Pringle 2013)

Comparisons with HI observations: Distribution of ‘holes’



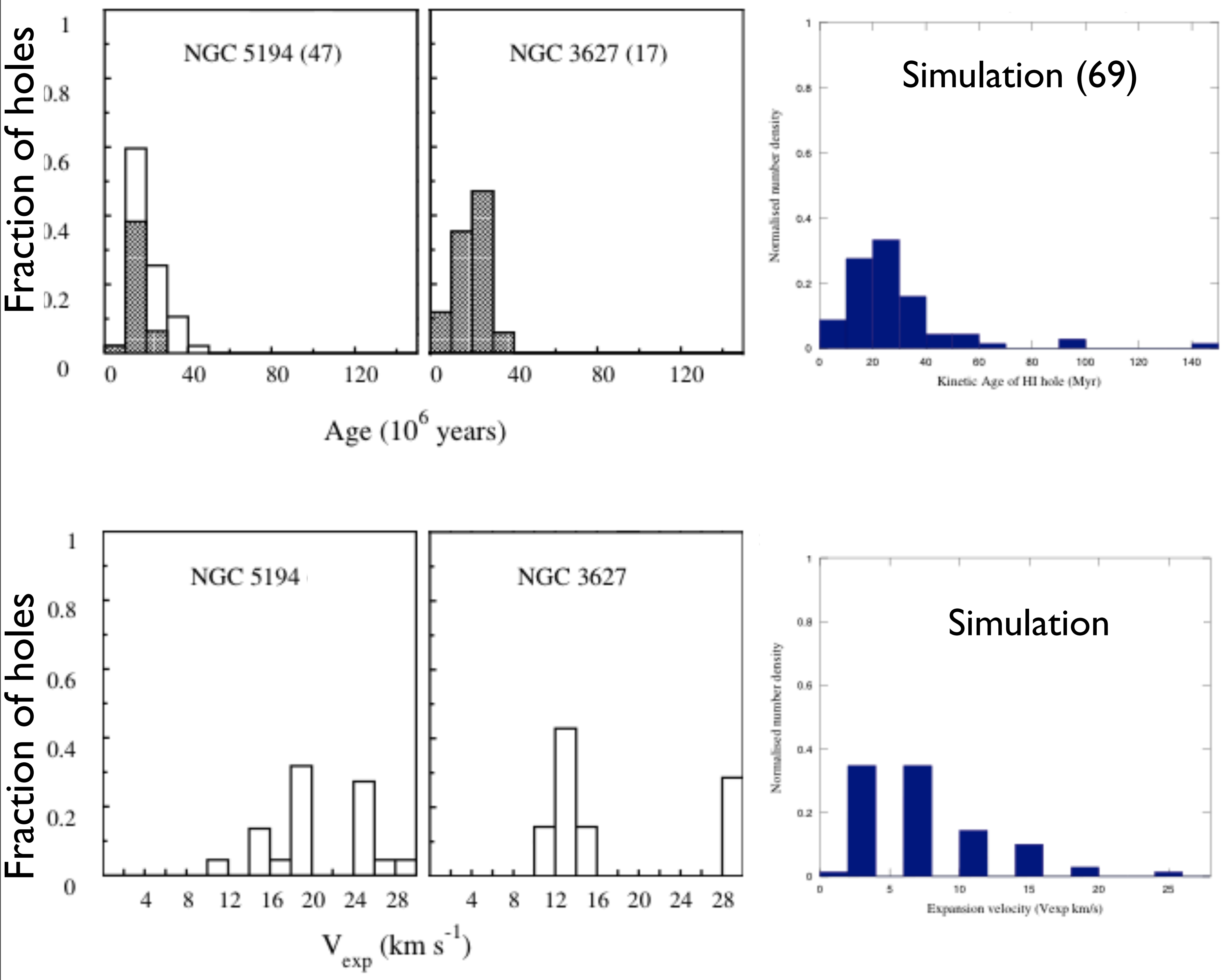


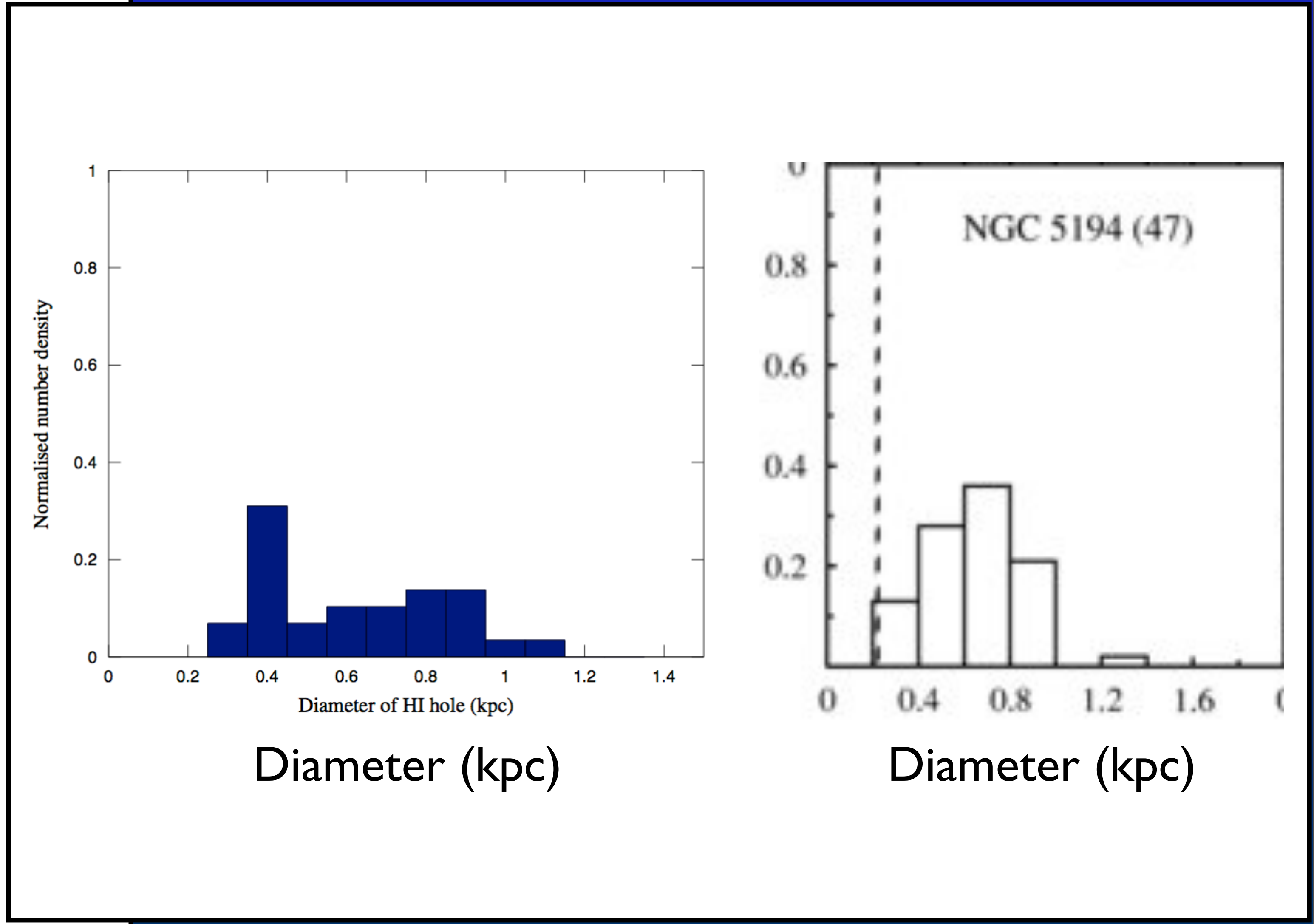
Compare holes in different simulations and observations, identified by different people, and with Bagetakos et al. 2011
Check with KS test

THINGS data: M51
Bagetakos et al. 2011

Simulated m=2 galaxy in HI (Dobbs & Pringle 2013)

Distribution of 'hole' parameters





- Observations and simulations find similar distributions of hole radii, age, location, aspect ratio (most ~1). Some difference in expansion velocity

Distribution of ‘holes’

- Some holes in simulations certainly due to feedback, smaller holes may not be
- KS test does not reveal difference in distribution of hole size in simulations and observations
- Also tested simulated galaxies at different inclinations, and resolutions
- KS test finds hole properties unreliable at i) high inclination (>60°) and ii) low resolution (≲THINGS data)

Synthetic CO maps

H_2 added according to Bergin et al. 2004:

$$\frac{\partial n(H_2)}{\partial t} = R_g n_{HI}\, n_{H2} T^{0.5} - (\text{Ç}_c + \text{Ç}_{phot}(n_{H2}))n_{H2}$$

Dobbs et al. 2006

CO added according to Nelson & Langer 1997:

$$\frac{\partial n(CO)}{\partial t} = k_0\, n_{H2}\, n(C^+)\beta - \text{Ç}_{CO}(n_{....})\, n(CO)$$

Pettitt et al., 2014, submitted
Duarte-Cabral et al. 2014, in prep.

Apply radiative transfer code (TORUS, Harries 2003) to generate synthetic maps

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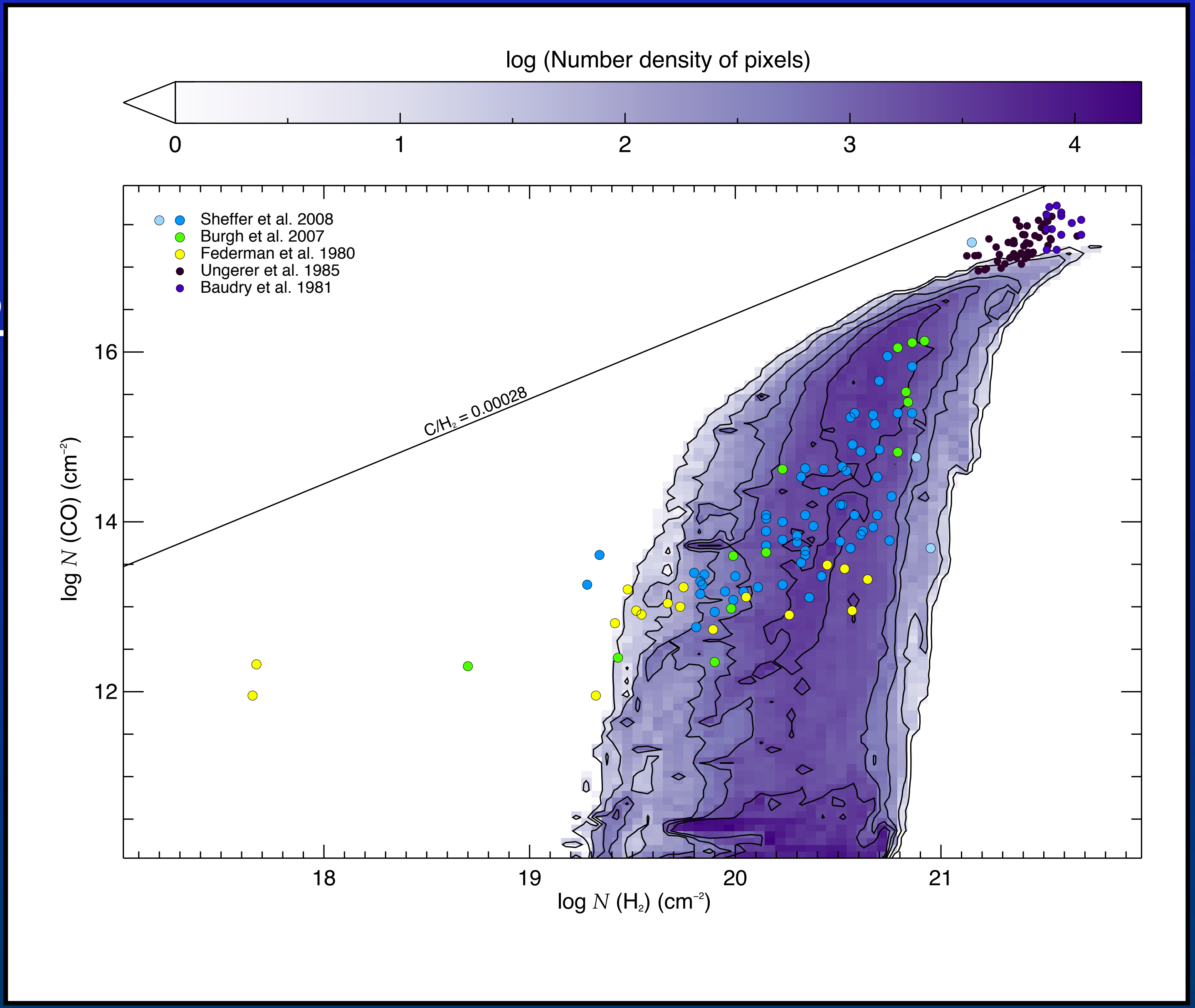
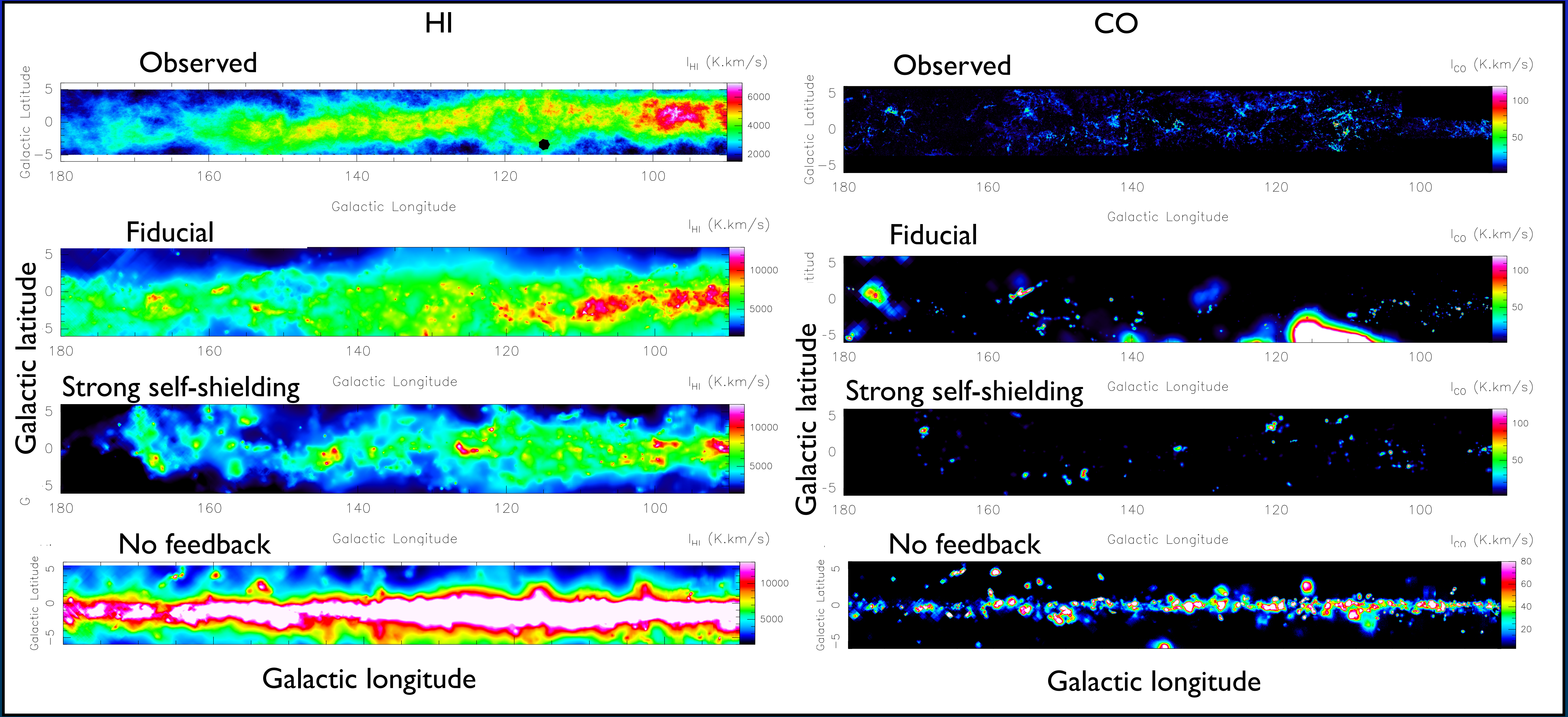


Comparison with observations (FUSE)

Apply radiative transfer code (TORUS, Harries 2003) to generate synthetic maps

Synthetic CO maps (2nd quadrant)



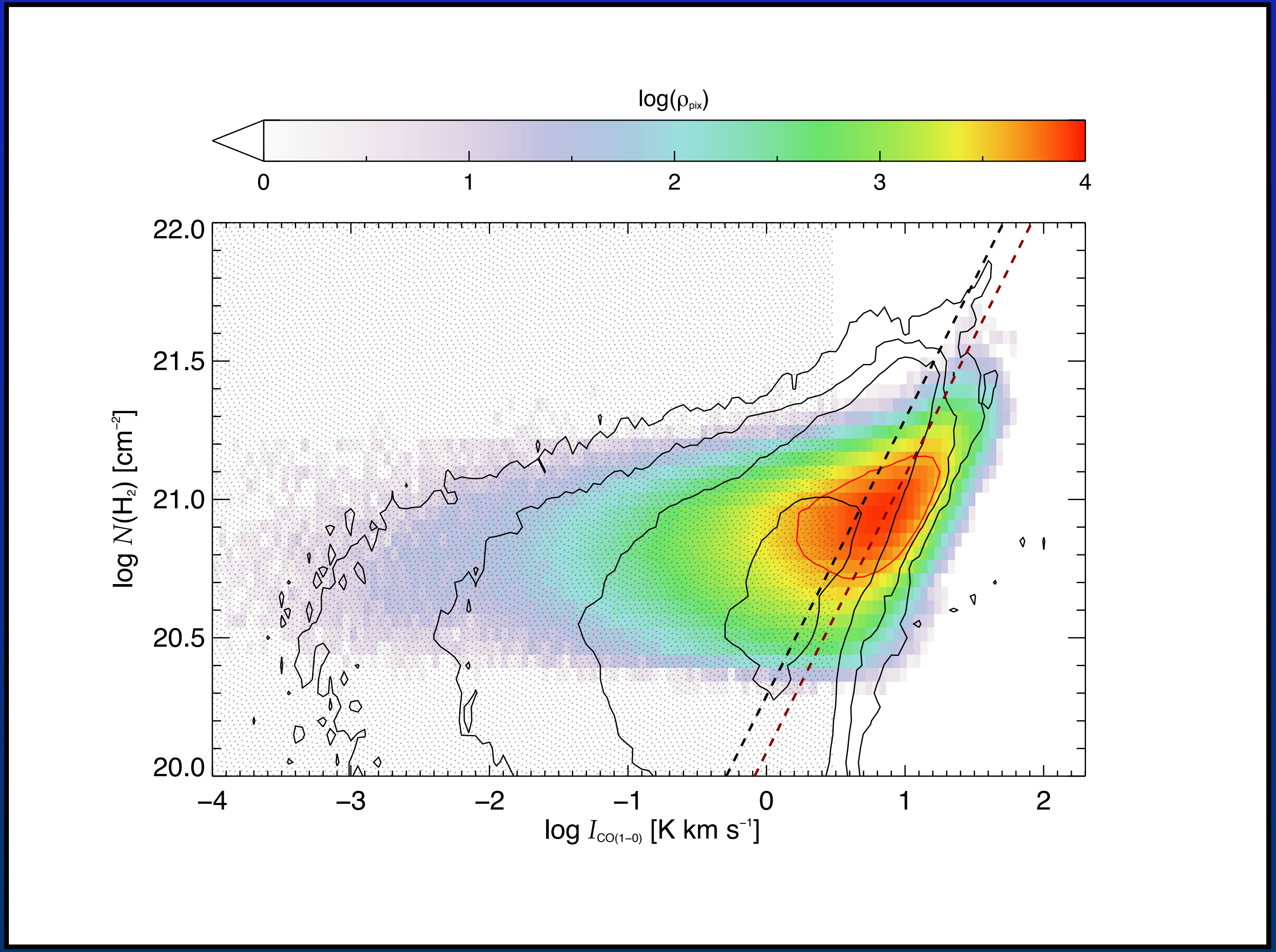
Acreman et al. 2012, Duarte-Cabral et al., in prep.

Total amount of molecular gas~10-60%

Little difference to results with different chemistry

Greatest difference with / without feedback, to a lesser extent Σ

X factor



Distribution of H_2 column density versus CO intensity

median $X_{CO}=1.9\times10^{20}\mathrm{cm}^{-2}\mathrm{K\ km\ s}^{-1}$

very close to observations

but some scatter in models $X_{CO}=1\text{-}3\ \mathrm{cm}^{-2}\mathrm{K\ km\ s}^{-1}$, more than observations (see also Smith et al. 2014, Shetty et al. 2011)

Conclusions

- From global simulations, 3 outcomes:

- no / too little feedback: population of strongly bound, infinitely long-lived spherical clouds

- moderate feedback: clouds and ISM exhibit characteristics comparable to those observed

- too much feedback: spiral structure disrupted

- Feedback and shear important for cloud dispersal
- Zoom in simulations seem to confirm results of global simulations
- Starting to characterise ISM with CO and HI maps