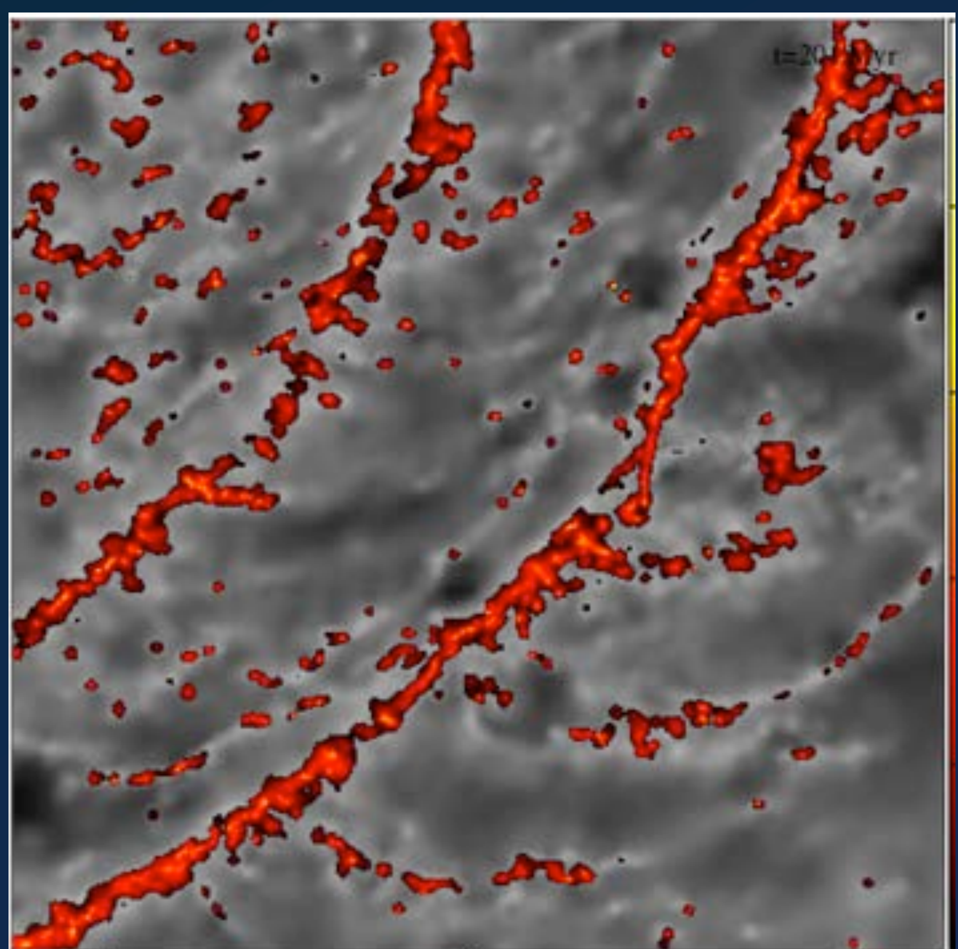
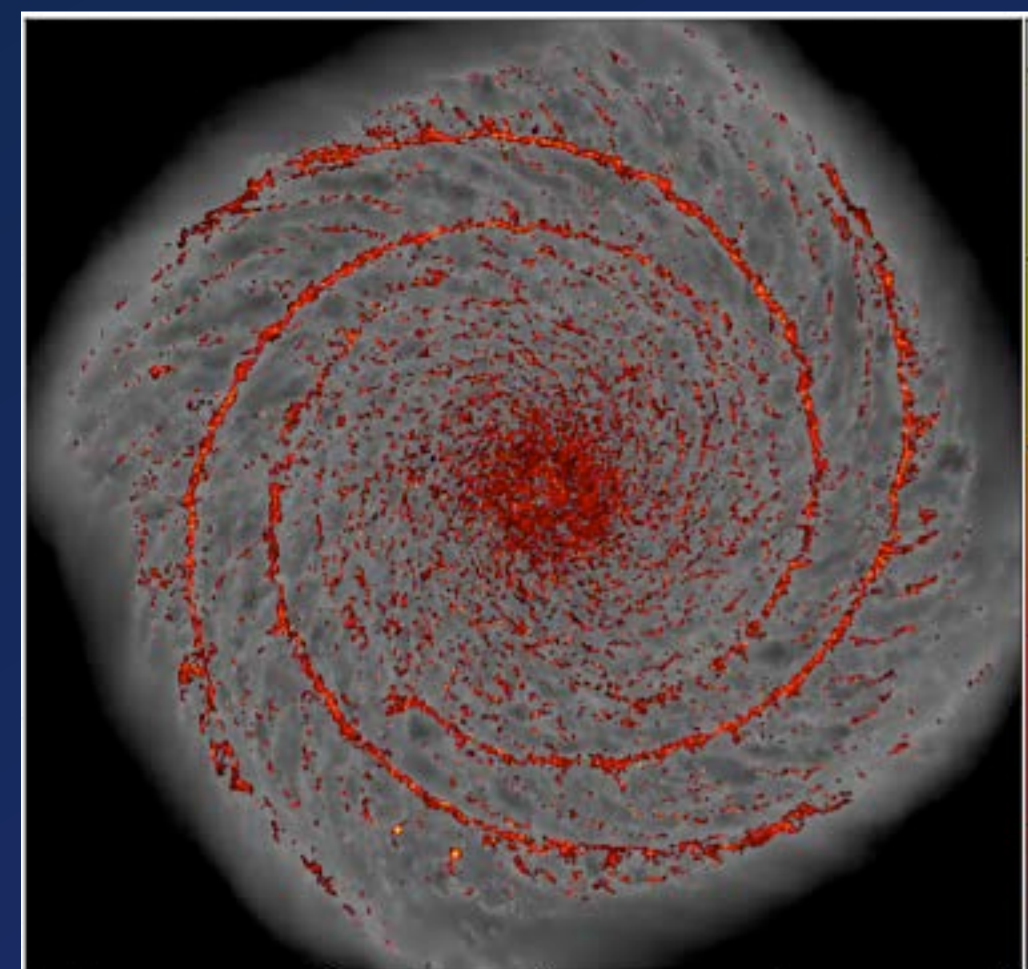
Signatures of Molecular Cloud Formation (II)

Clare Dobbs, MPE and Exeter



Jim Pringle (IoA), Andi Burkert (LMU), Ian Bonnell (St Andrews), Daniel Price (Monash), Simon Glover (ITA)



Key questions

- How do GMCs form?
- What are the properties of GMCs?

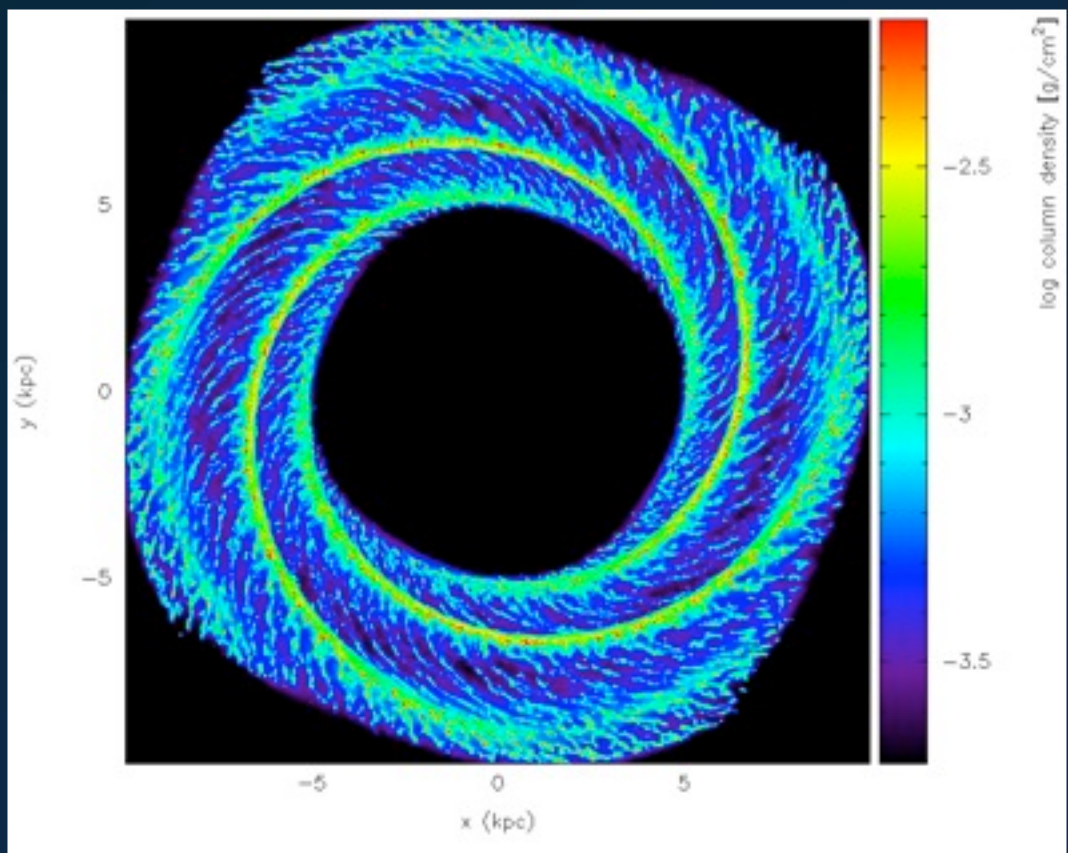
- what are their lifetimes? - how long do they form stars?

- are they dominated by turbulence, magnetic fields, gravity?

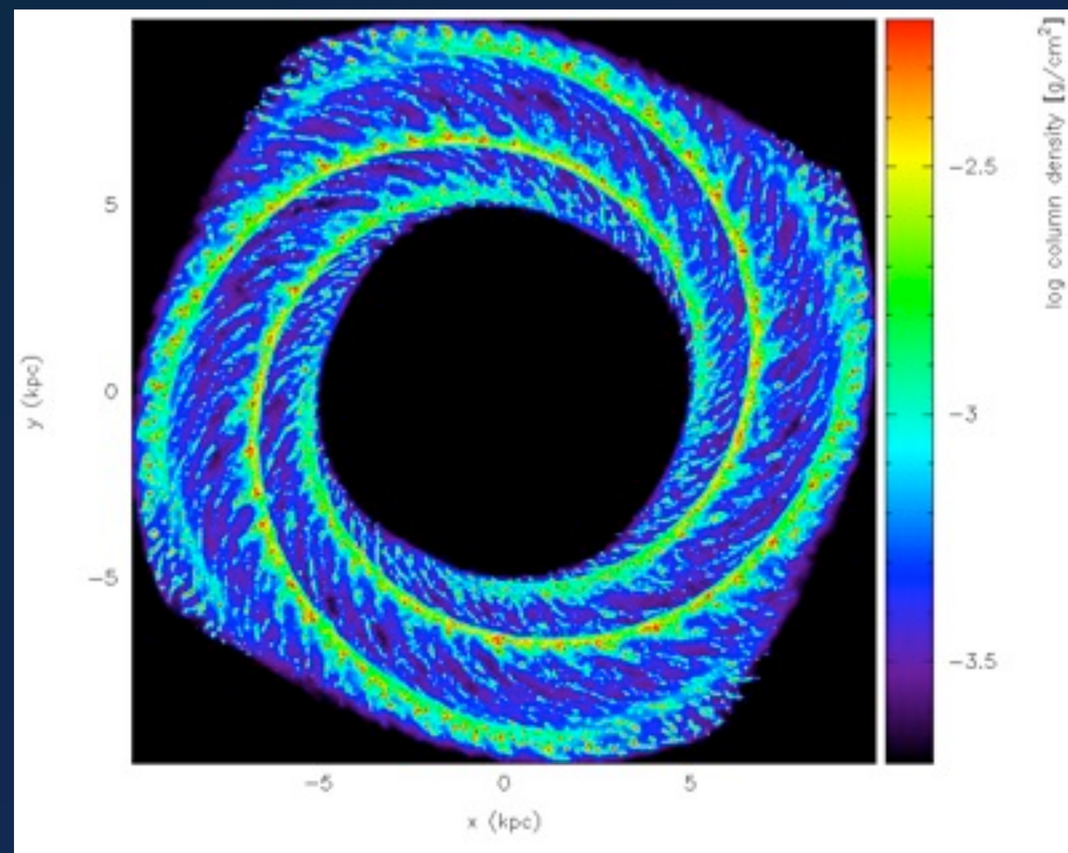
- How are they influenced by stellar feedback?
- Are they formed from atomic or molecular gas?
- Why does such a small fraction of the gas form stars?

Formation of GMCs by Cloud-Cloud Coalescence + Self gravity

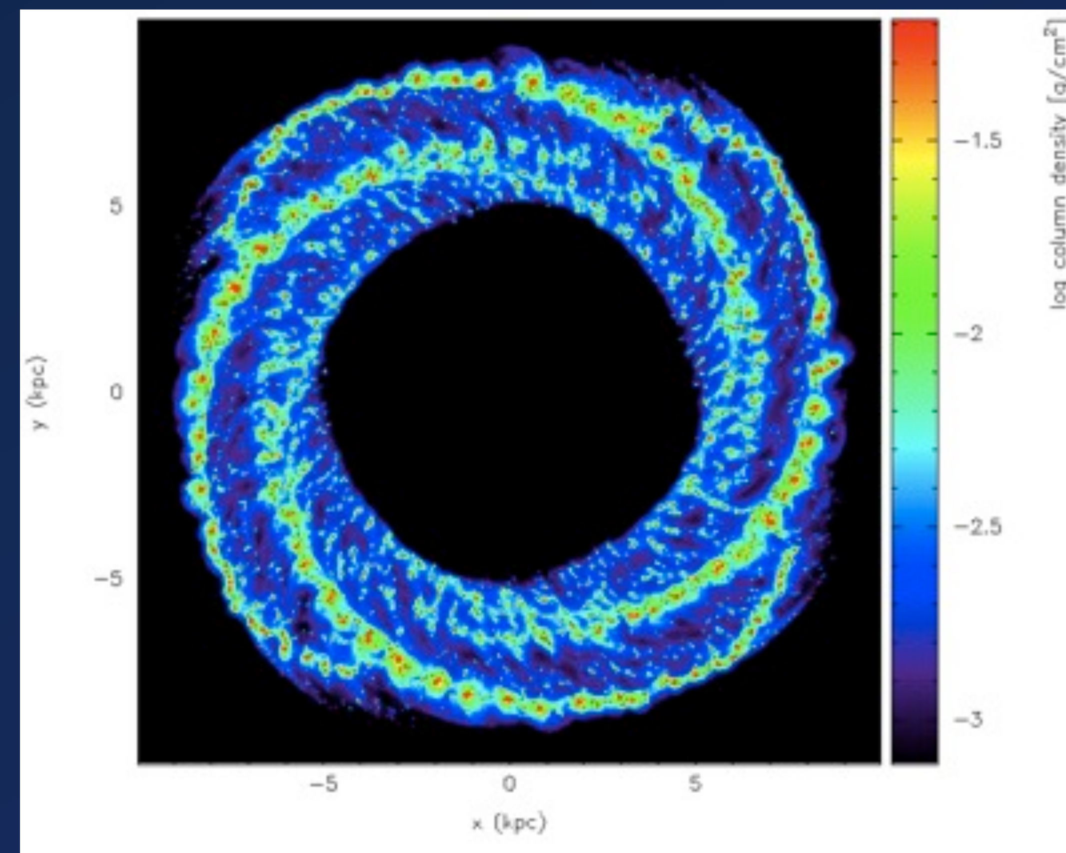
Without self gravity:



With self gravity:



Higher surface density:

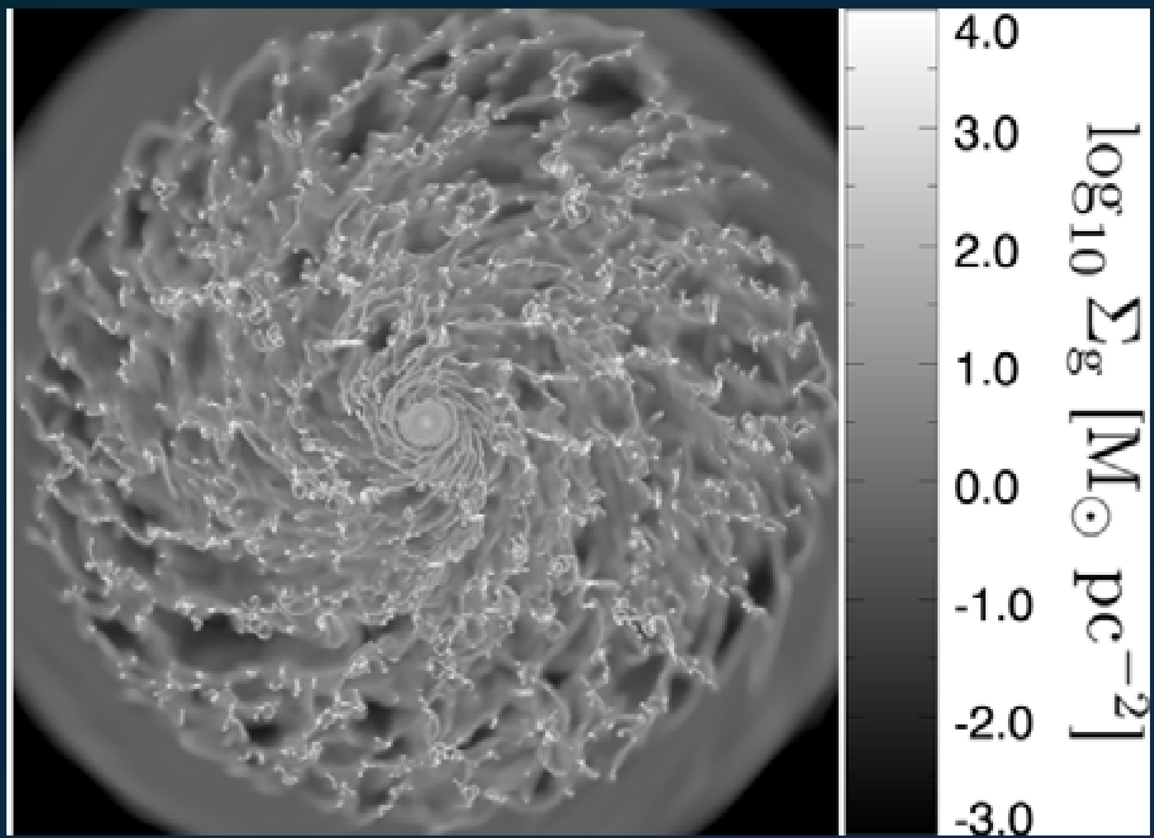


Gas organised into increasingly massive clumps

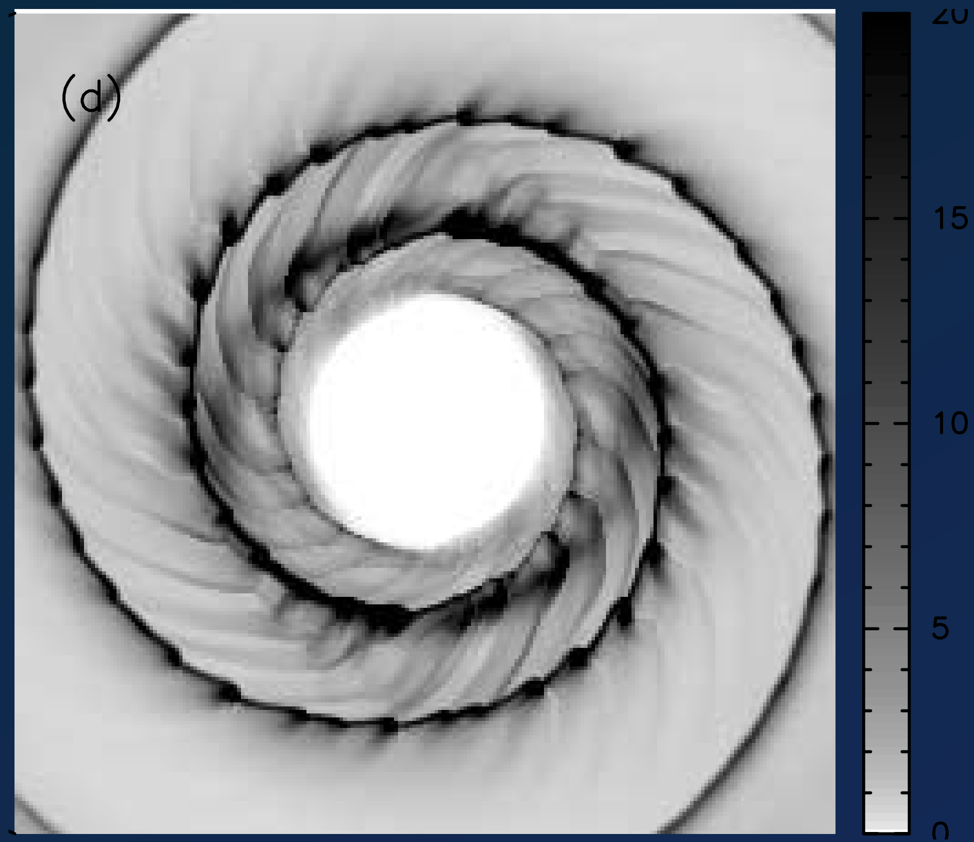
Gas artificially prevented from collapse (by pressure) or simulation stopped when collpase occurs

Dobbs et al. 2006
Dobbs 2008

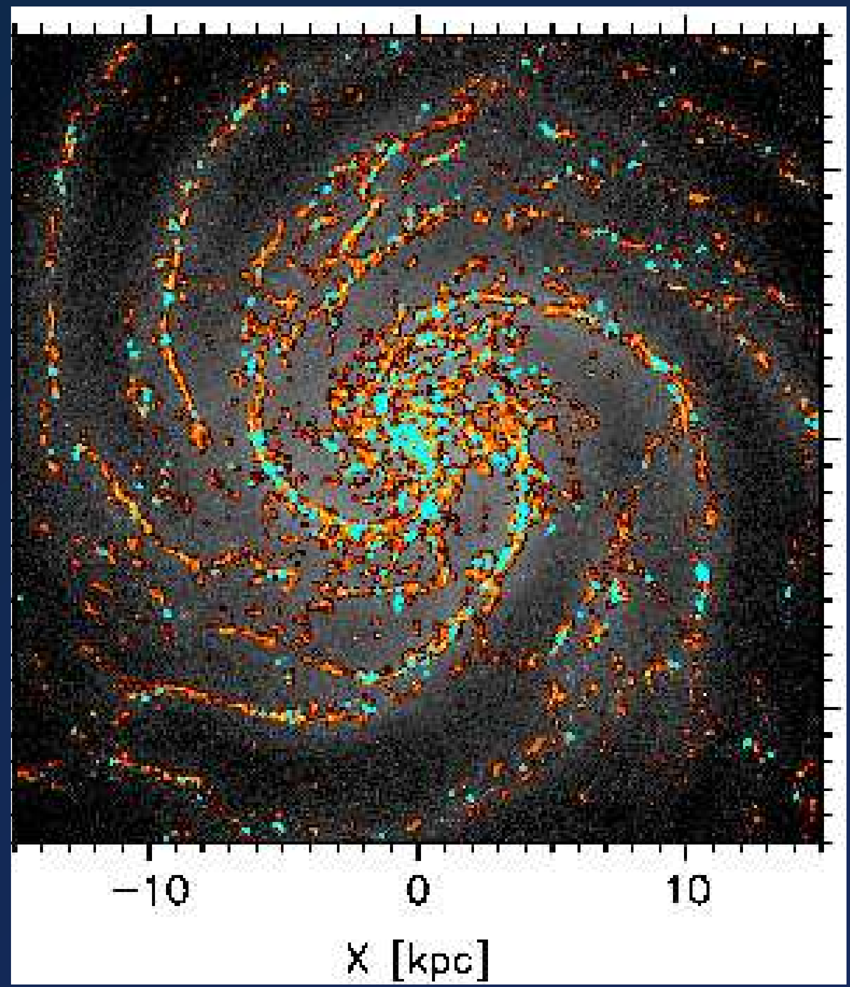
Other numerical work on galaxy scales



Tasker & Tan 2009, Tasker 2011
No spiral potential or stellar arms
No large scale structure, very flocculent
Cloud formation primarily by gravitational instabilities, also cloud-cloud collisions



Shetty & Ostriker 2006
Spiral potential, but isothermal, only 10^4K gas
Cloud formation solely by gravitational instabilities



Wada et al. 2011
Stars and gas produces multi-armed spiral

But have neglected stellar feedback...

Would feedback disrupt smaller clouds before GMCs can form?

Also some problems in the absence of feedback:

- scale height of disc too low (Douglas et al. 2010)
- velocity dispersion only high in spiral arms
- clouds have long (>50 Myr) lifetimes

Details of simulations

- Use Smoothed Particle Hydrodynamics (SPH)
- Particles model gas
- Halo + stellar disc included as external potential

$$\psi = 1/2\, V_0^2 \log (R^2+R_c^2)$$

with 4 armed spiral component (Cox & Gomez 2002)

of form $$\psi_{sp}\,(r,\theta,z,t) = A \cos\left(\frac{n \log(r/r_o)}{\tan i} - (\theta - \Omega_{sp})t\right)$$

where n=4, i=pitch angle, Ω_{sp}=pattern speed of galaxy

Details of simulations

- Thermodynamics of the ISM (Glover & Maclow 2007; Dobbs, Glover, Clark & Klessen 2008)

- H_2 formation (Bergin et al. 2004; Dobbs, Bonnell & Pringle 2006)

- Self gravity (Dobbs 2008)

~1000-5000 $M_\odot$, 10-20 pc resolution

Adding stellar feedback

Stellar (supernovae) feedback: above densities of 100, 1000, 10^4 cm^{-3}

region must be gravitationally boumd, converging flow, div(v)<0

Add kinetic and thermal energy in form of Sedov solution, equal to $\frac{\varepsilon\, M(H_2) \times 10^{51}}{160\, M_\odot}$ ergs ε=0.01,0.05, 0.1, 0.2,0.4

Σ=8, 16, 40 $M_\odot pc^{-2}$

Dobbs, Burkert & Pringle 2011

Four Calculations

All Σ=8 $M_\odot pc^{-2}$

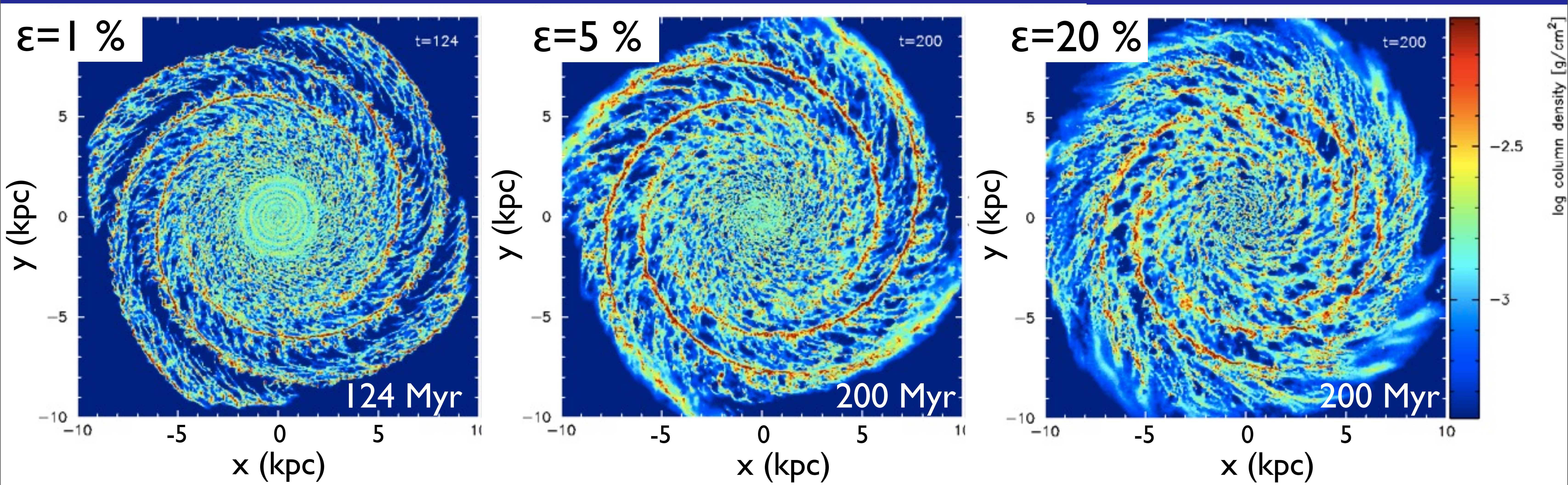
Model	Spiral potential?	ε (%)	Dominant physics
1	Y	1	Self gravity
2	Y	5	Spiral shocks
3	Y	20	Stellar feedback
4	N	5	Self gravity

What are the properties of the ISM and GMCs in these different regimes?

OUTLINE

- Global properties of the disc
- Properties of GMCs
- Evolution of GMCs: what gas do GMCs form from, how do they disperse?

Structure of the disc: different levels of feedback



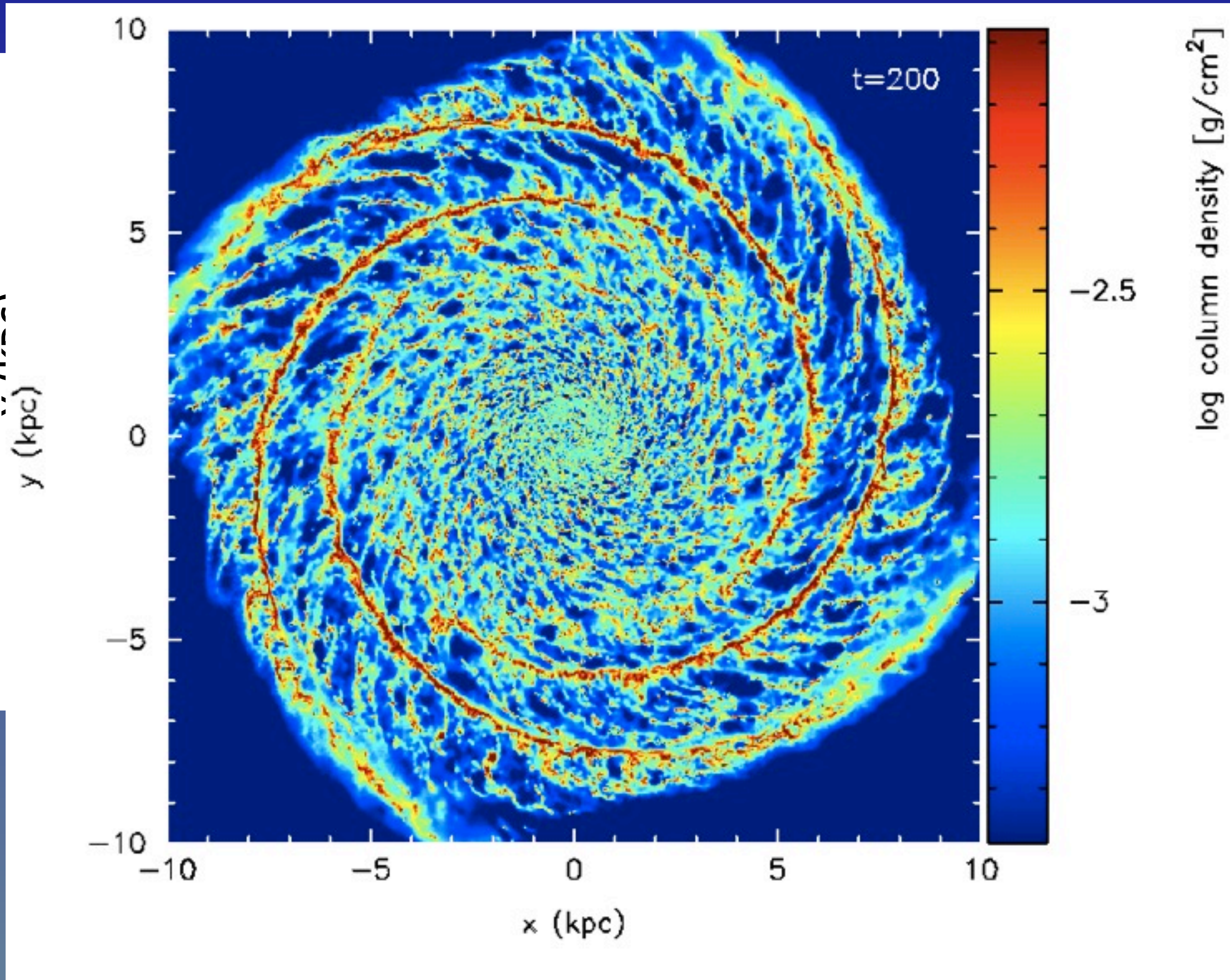
Feedback insufficient to disrupt clouds: no equilibrium state

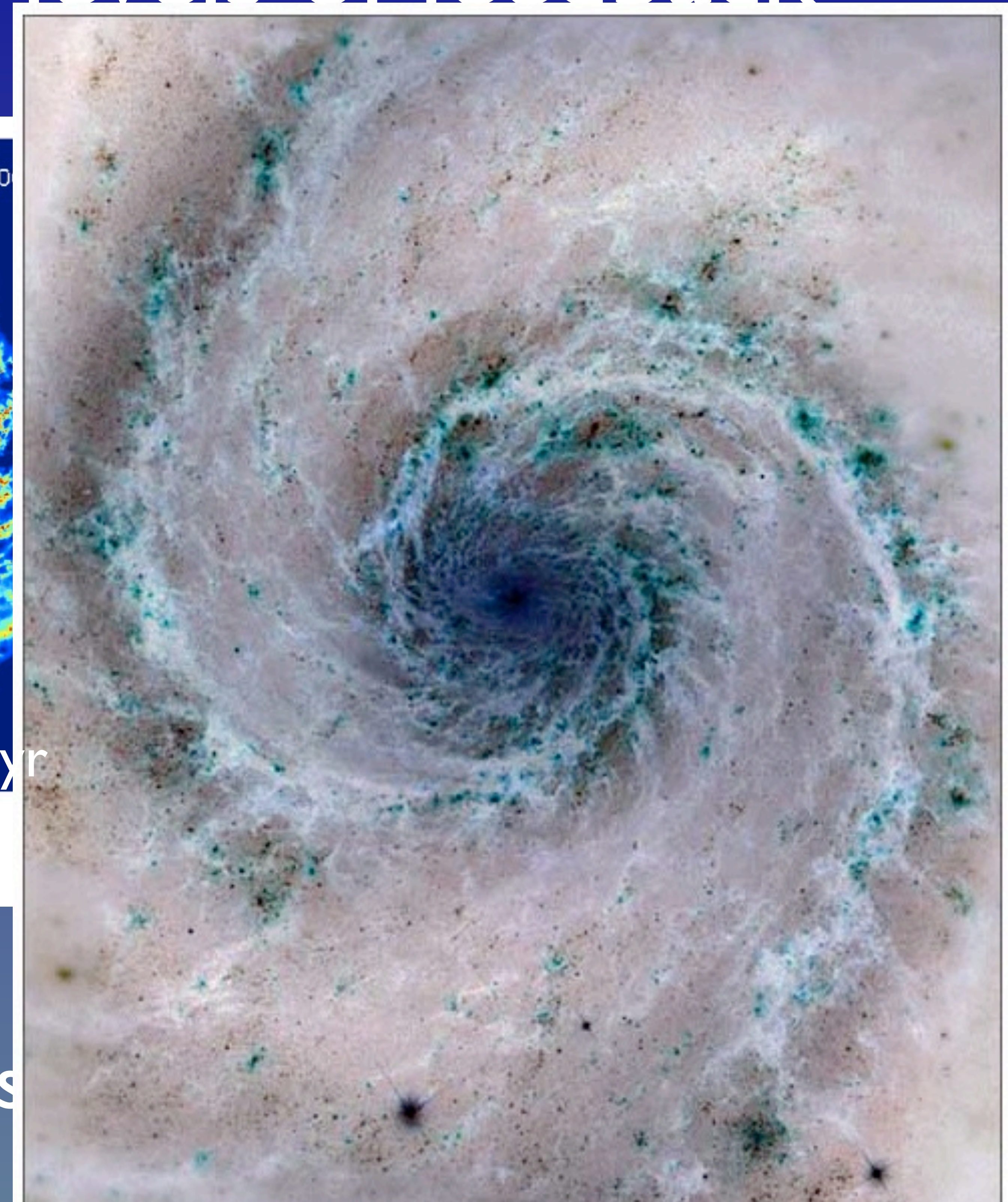
Clear spiral arms and spurs

Feedback dominates structure

Equilibrium: 150-350 Myr

Structure of the disc: different levels of feedback

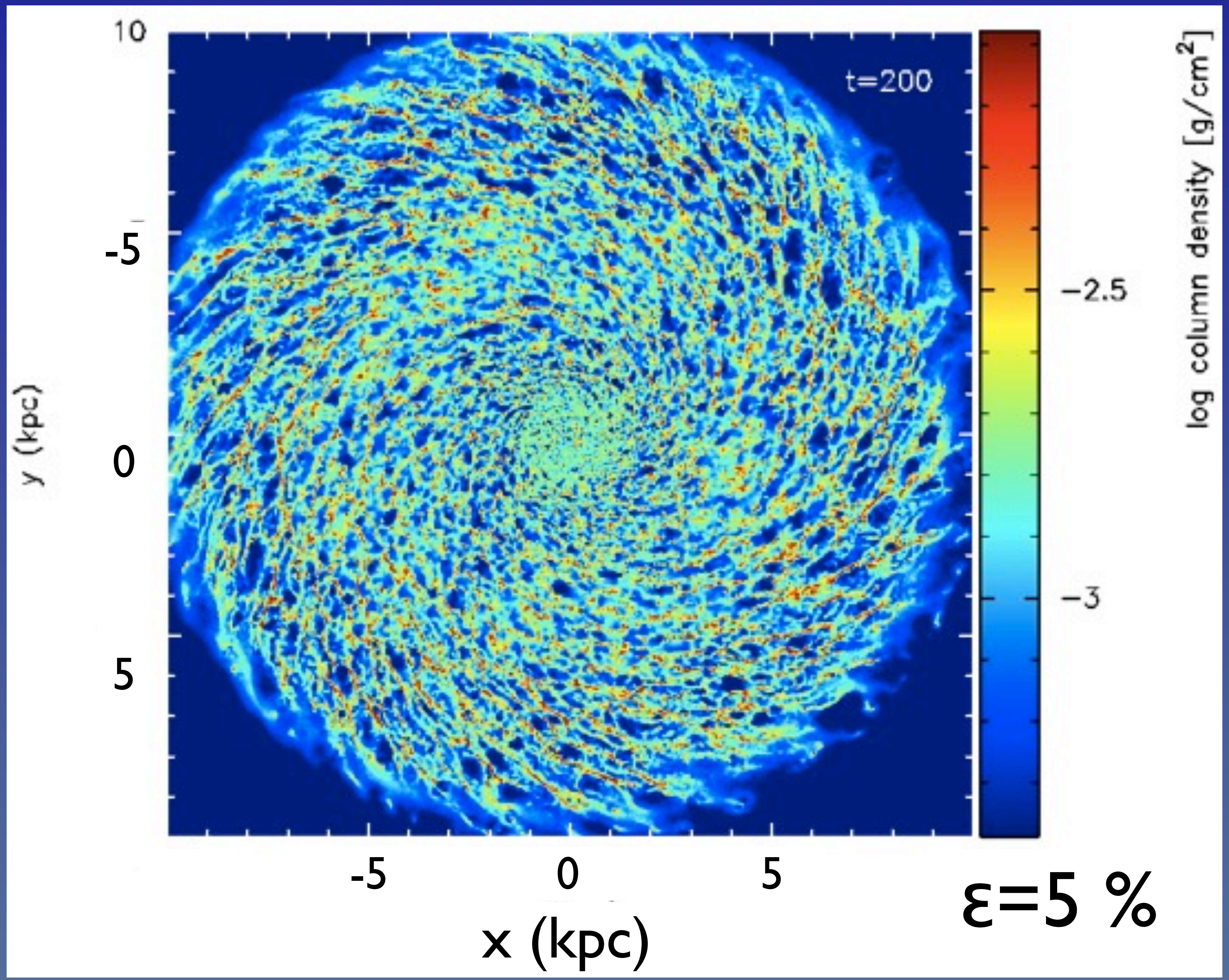


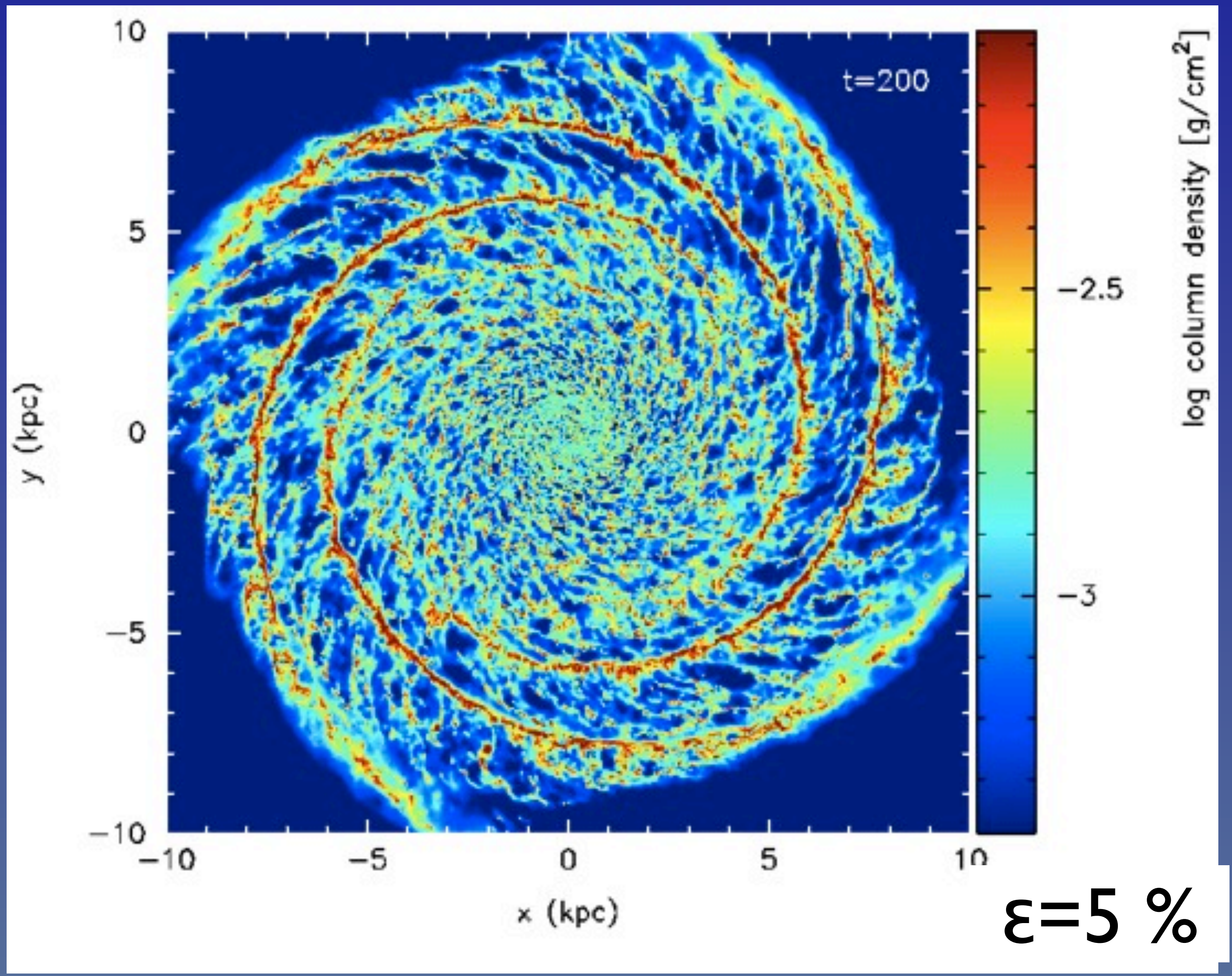


Hubble M51 composite image

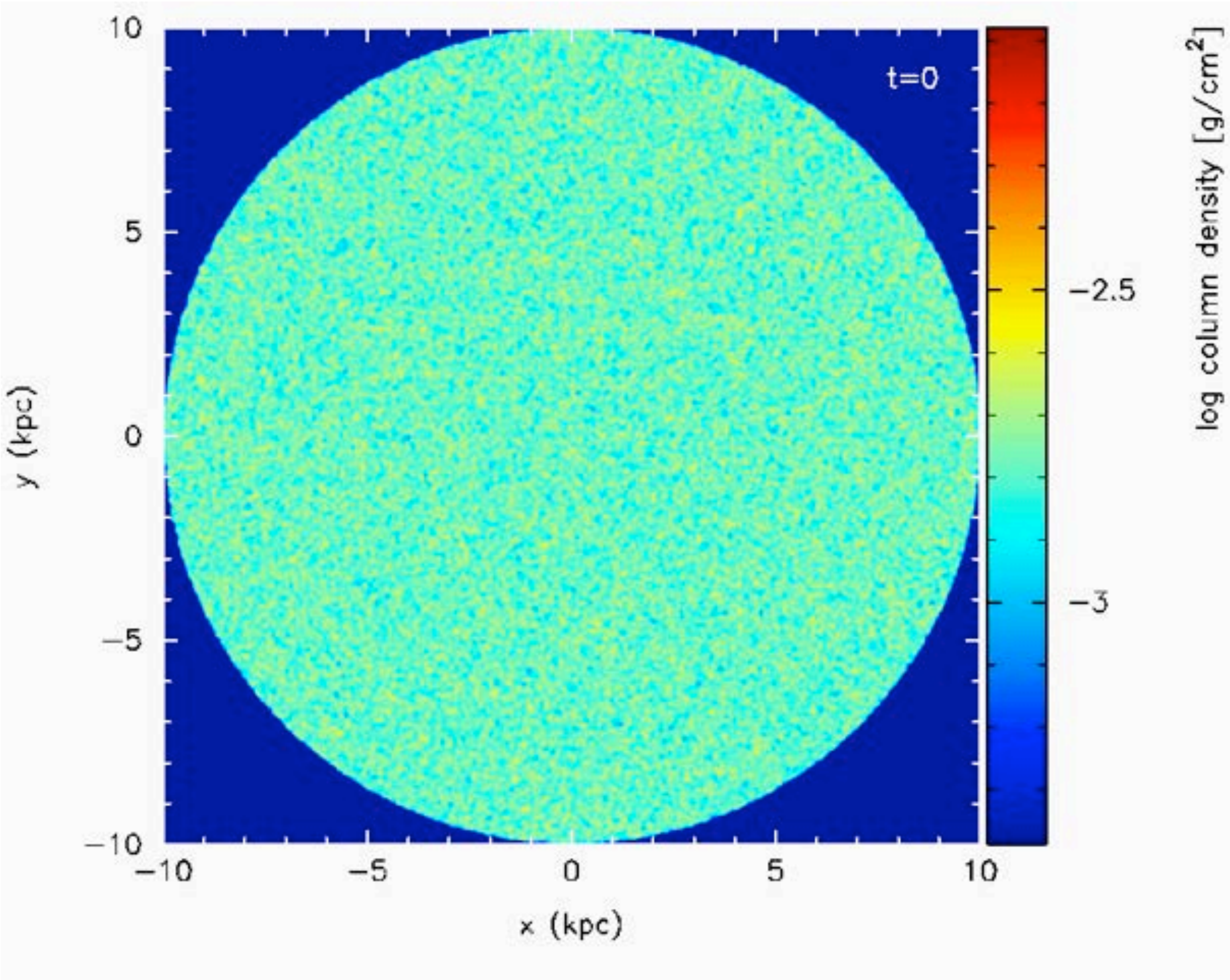
Equilibrium: 150-350 Myr

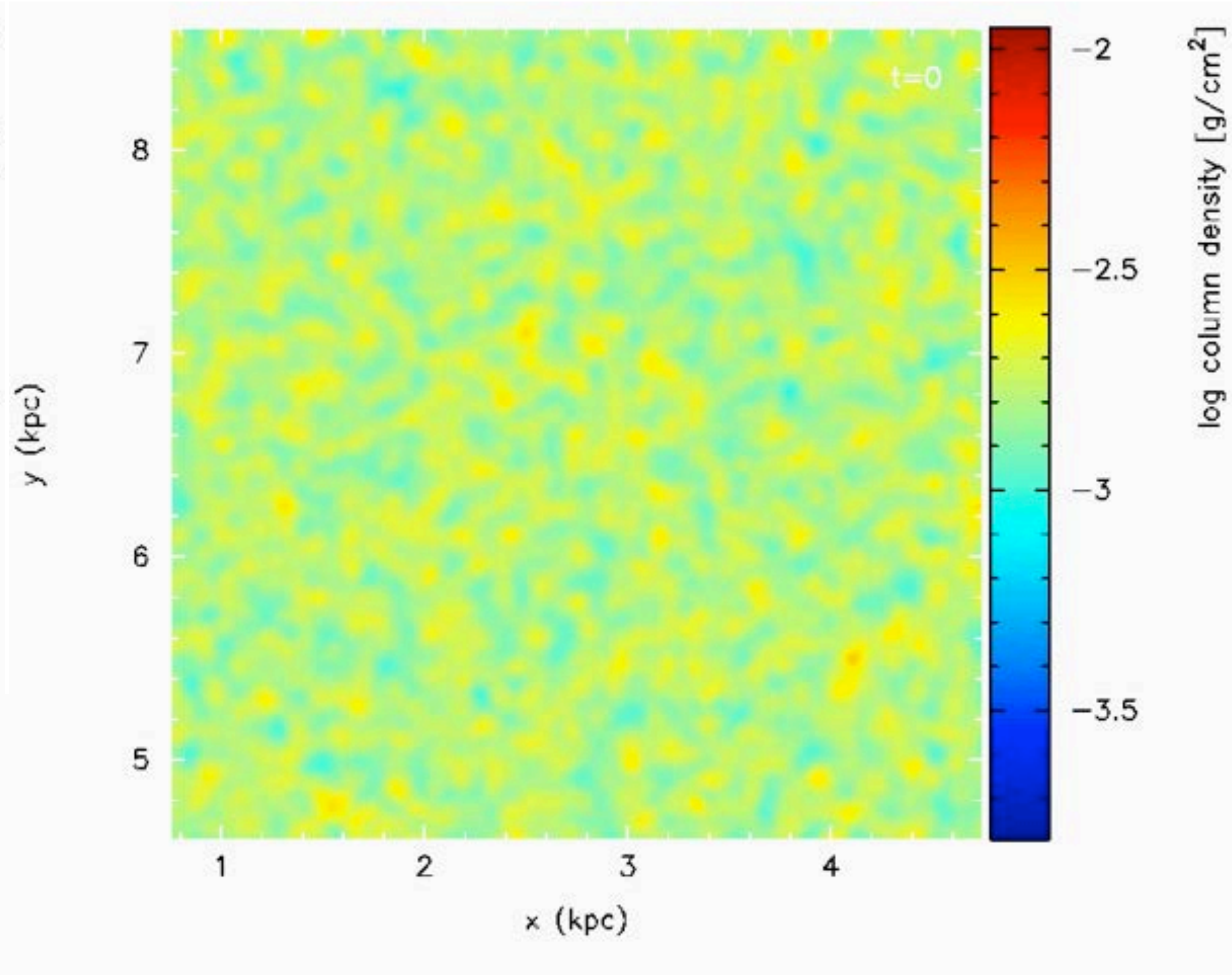
Structure of the disc: spiral vs no spiral potential

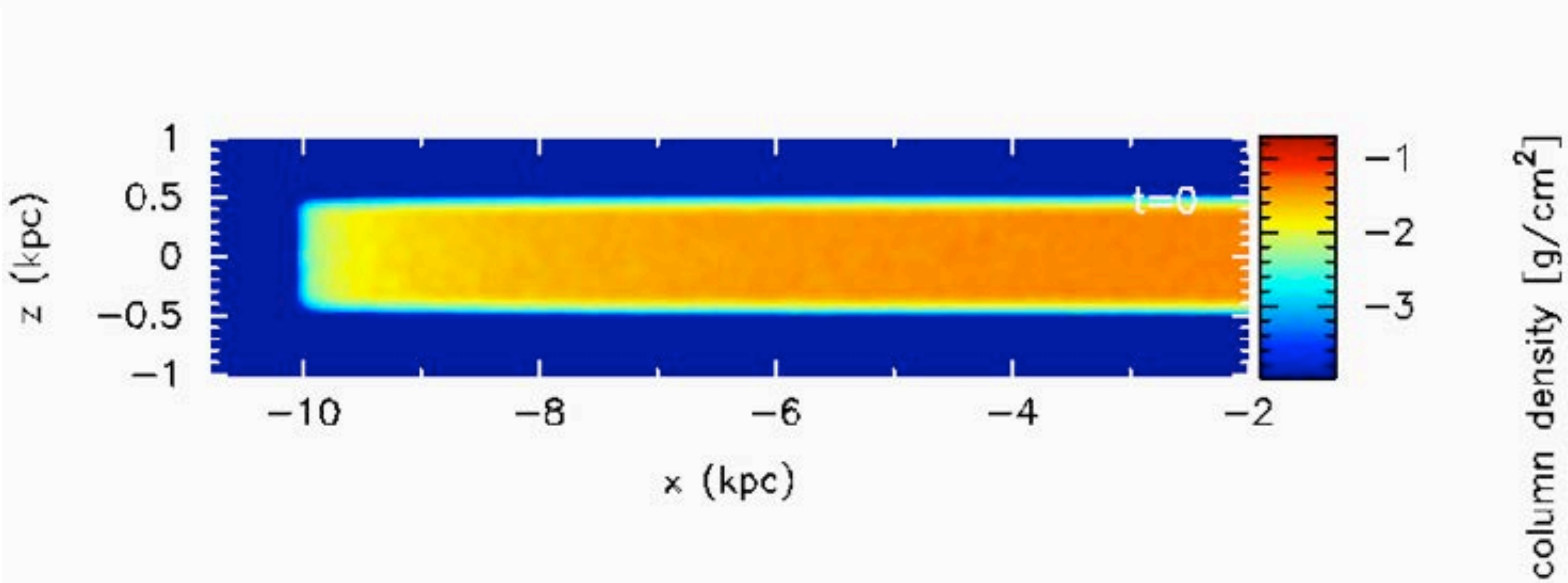




No imposed spiral: structure only on small scales
very flocculent, unlike most observed galaxies
Similar to Tasker & Tan 2009, Wada & Norman1999, 2001,2002



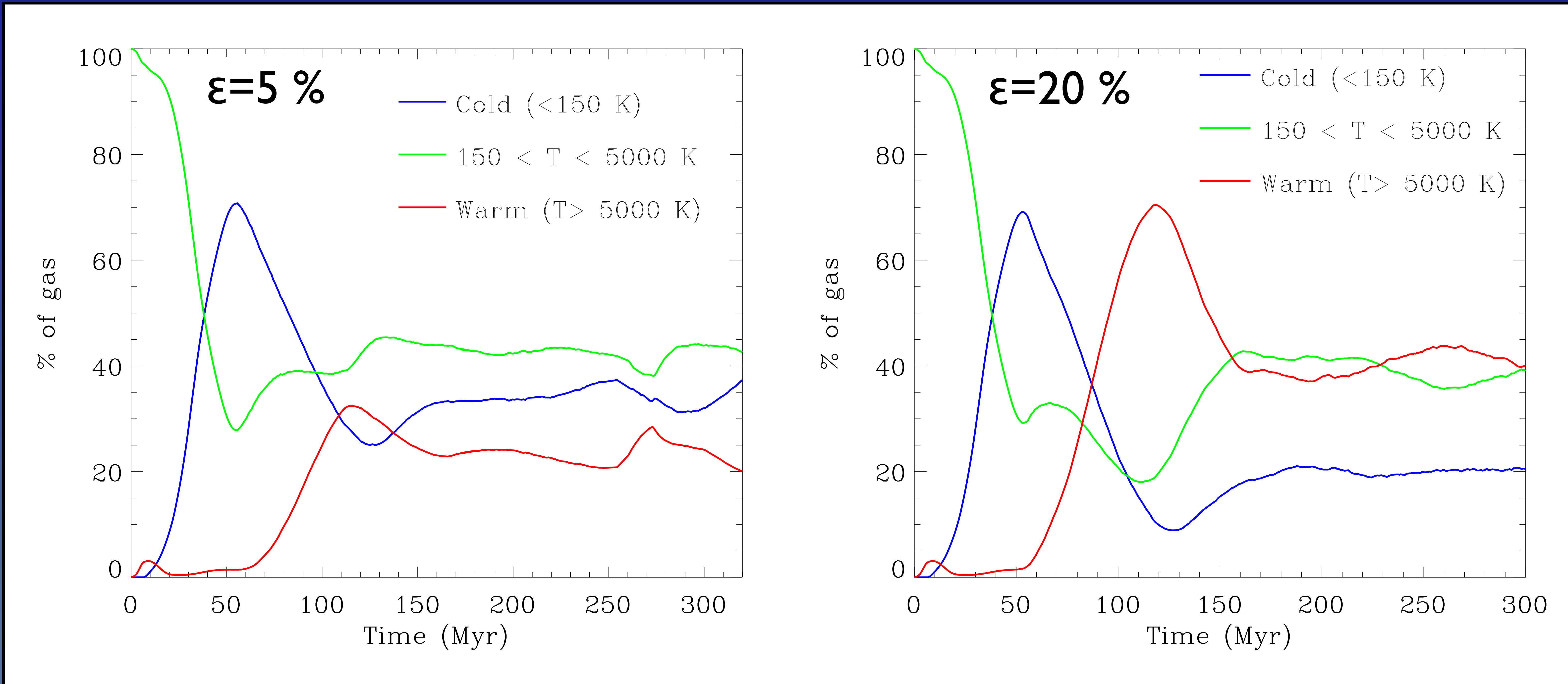




$\varepsilon = 5\ \%$

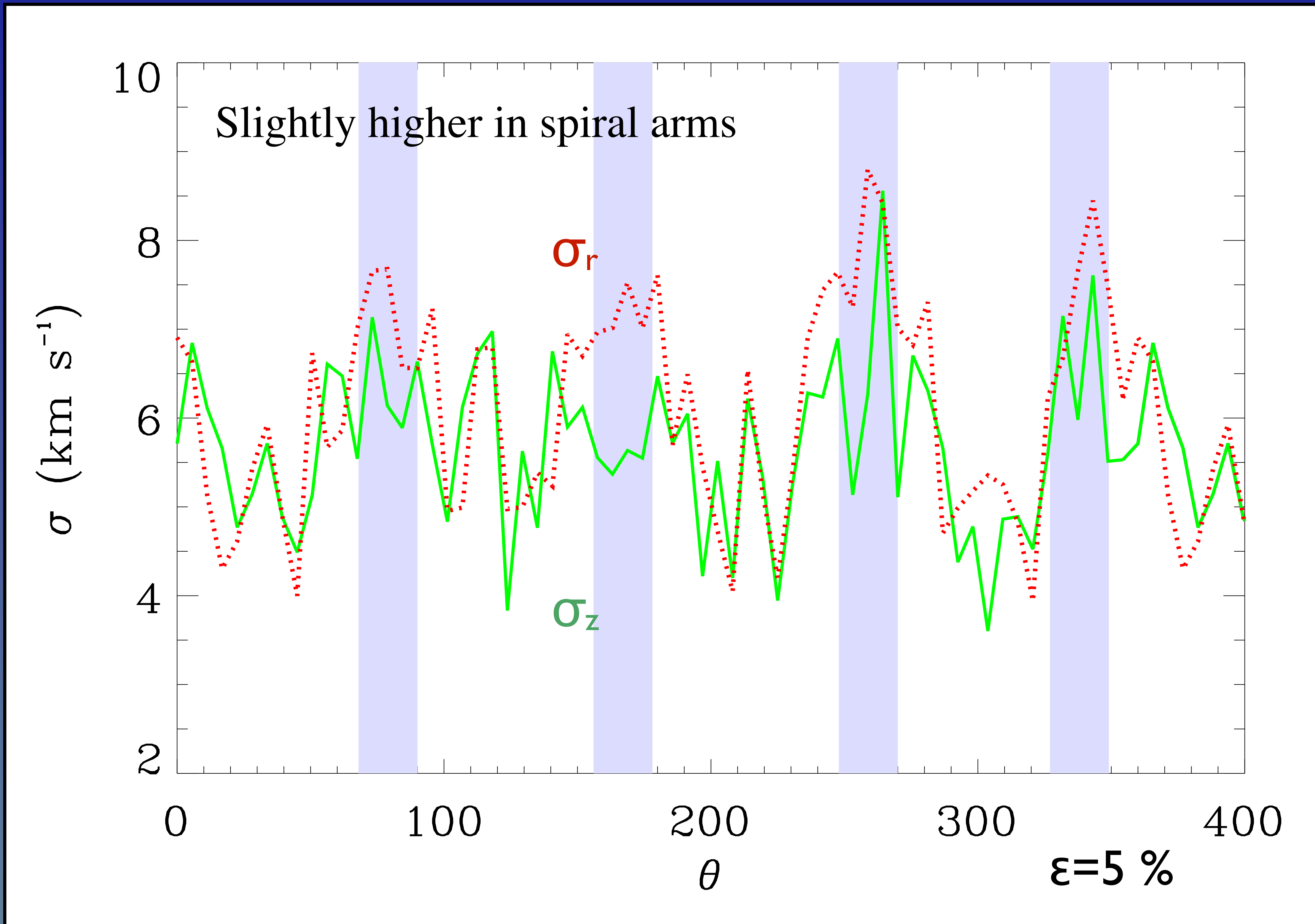
$\Sigma = 8\ M_\odot \mathrm{pc}^{-2}$

Properties of the ISM: phases



With no, or 1 % feedback, 60-70 % of gas is cold
For 5%, one third of the gas lies in cold, unstable, warm phases
With 20 % efficiency feedback, too little gas is cold

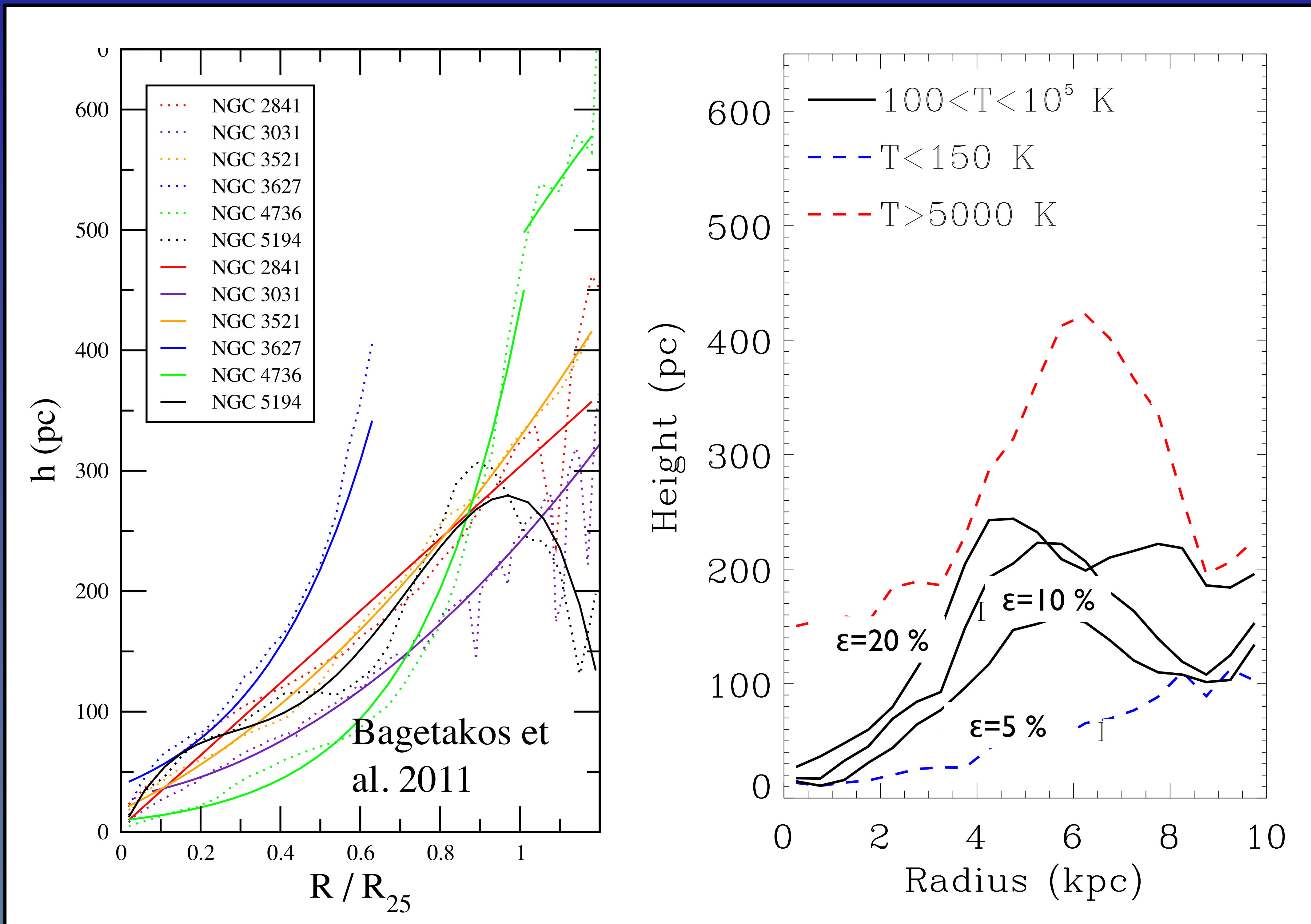
Velocity dispersion



ε (%)	σ (km/s)
1	1-7
5	4-8
20	8-20

- With little or no feedback, σ is too low
- σ fits best for ε=5%
- σ primarily driven by feedback, also spiral shocks

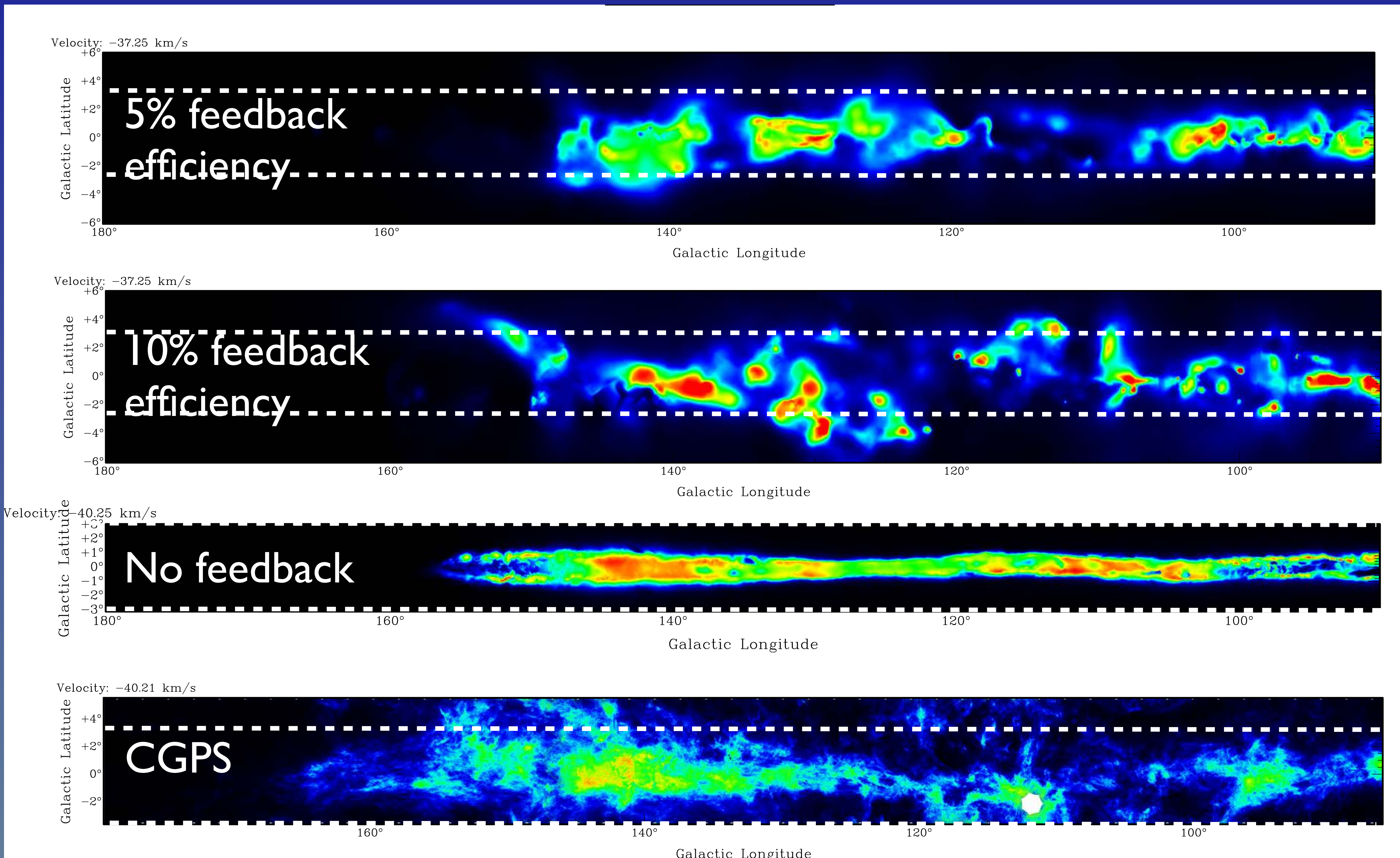
Scale height



Comparison of HI scale height from models with THINGS survey of galaxies (Bagetakos et al. 2011)

again scale height scales with feedback

Scale height - synthetic HI maps



R_{LSR}=8 kpc
l=90-180°

Feedback required to reproduce scale height similar to CGPS (Acreman et al. 2011, submitted) + HISA distribution

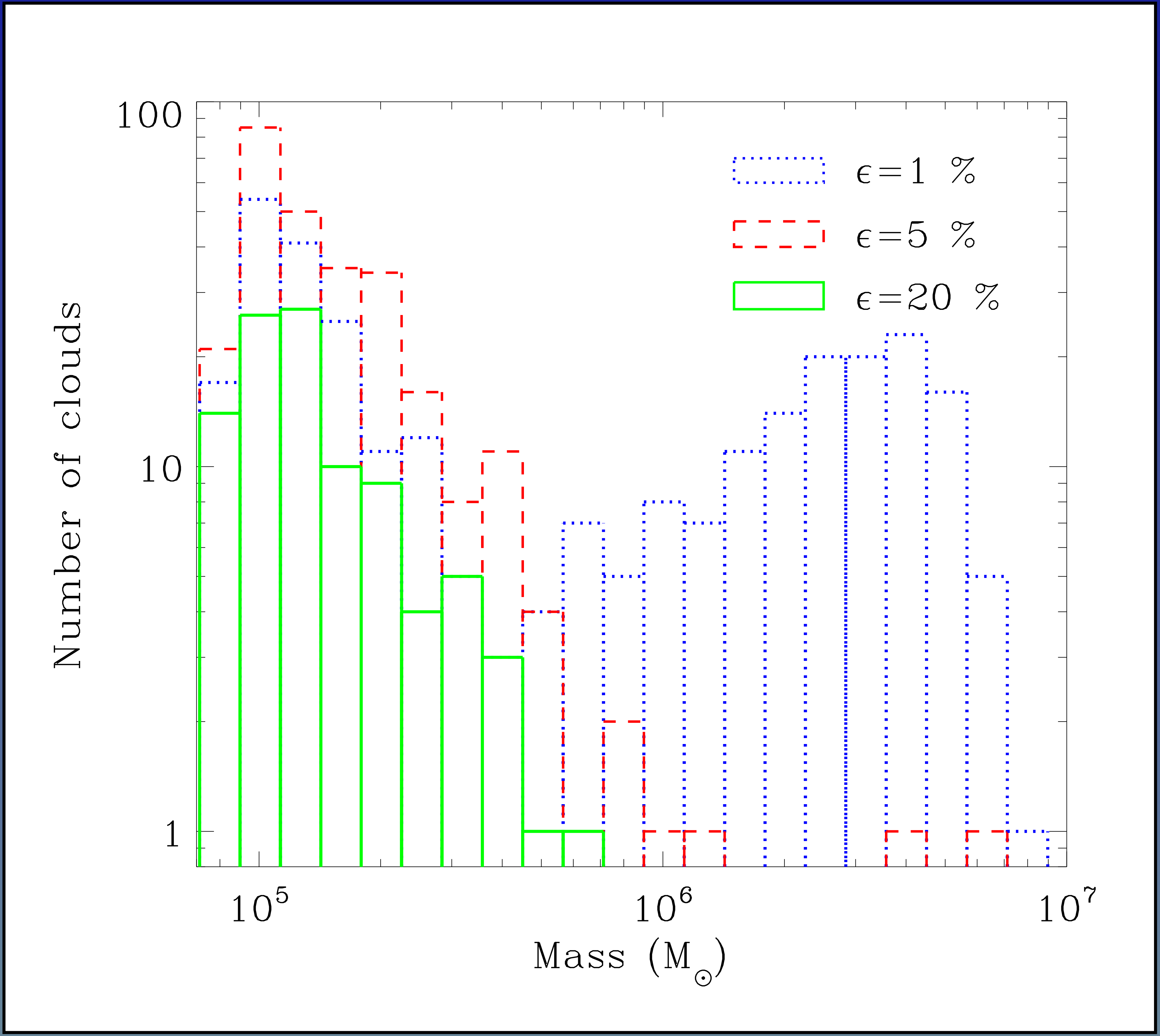
Conclusions - global properties

- Velocity dispersion and scale height only matched when feedback is included
- Best fit for all properties (structure, thermal, distribution, σ, scale height) when there is a moderate (5 %) level of feedback

Properties of GMCs

- Cloud mass spectra
- Virial parameters
- Cloud rotations
- Aspect ratio

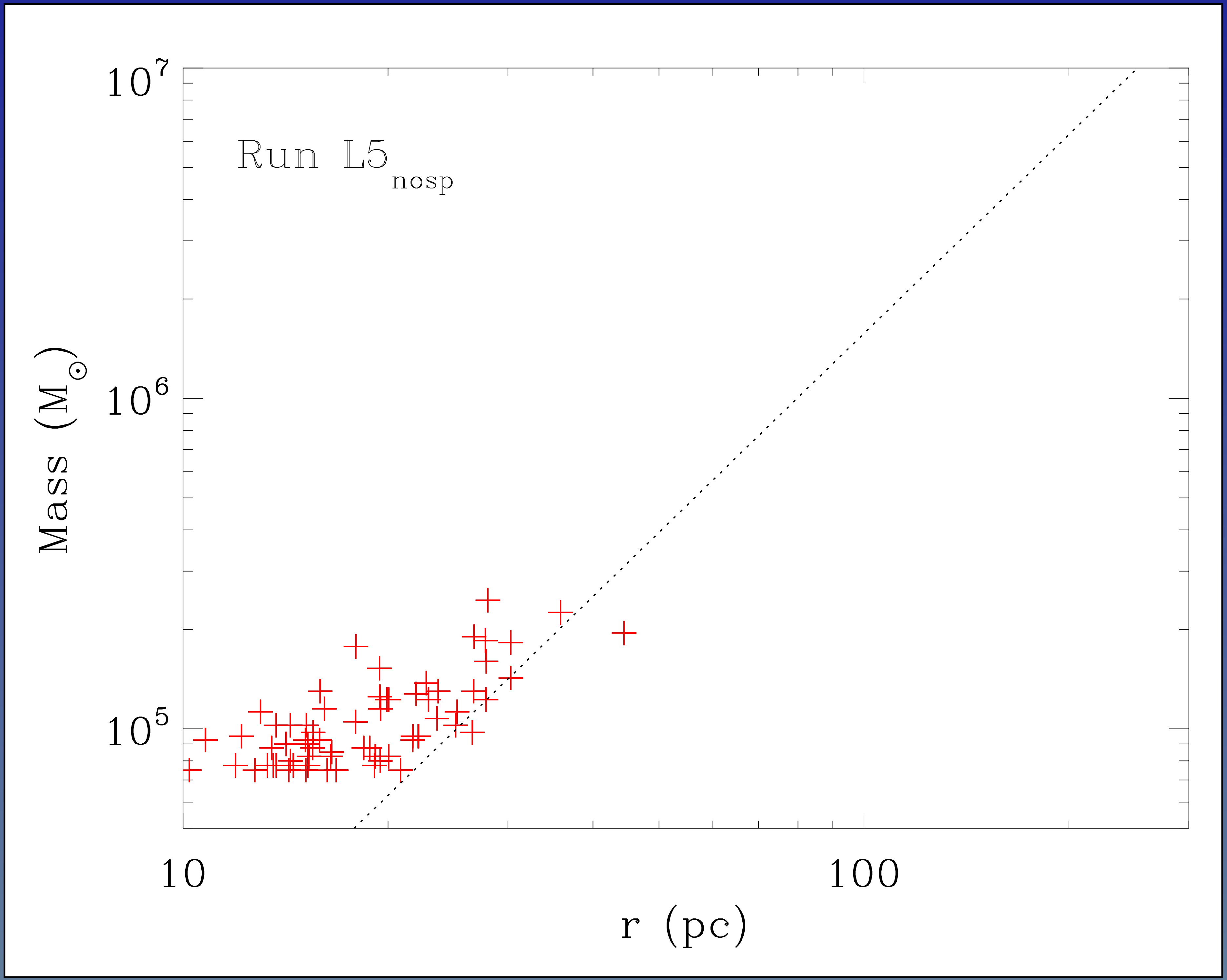
Properties of GMCs: Mass function



Spectra roughly match observations with 5% feedback

1% Feedback is insufficient to disrupt clouds - end up with large population of massive clouds

Properties of GMCs: Masses

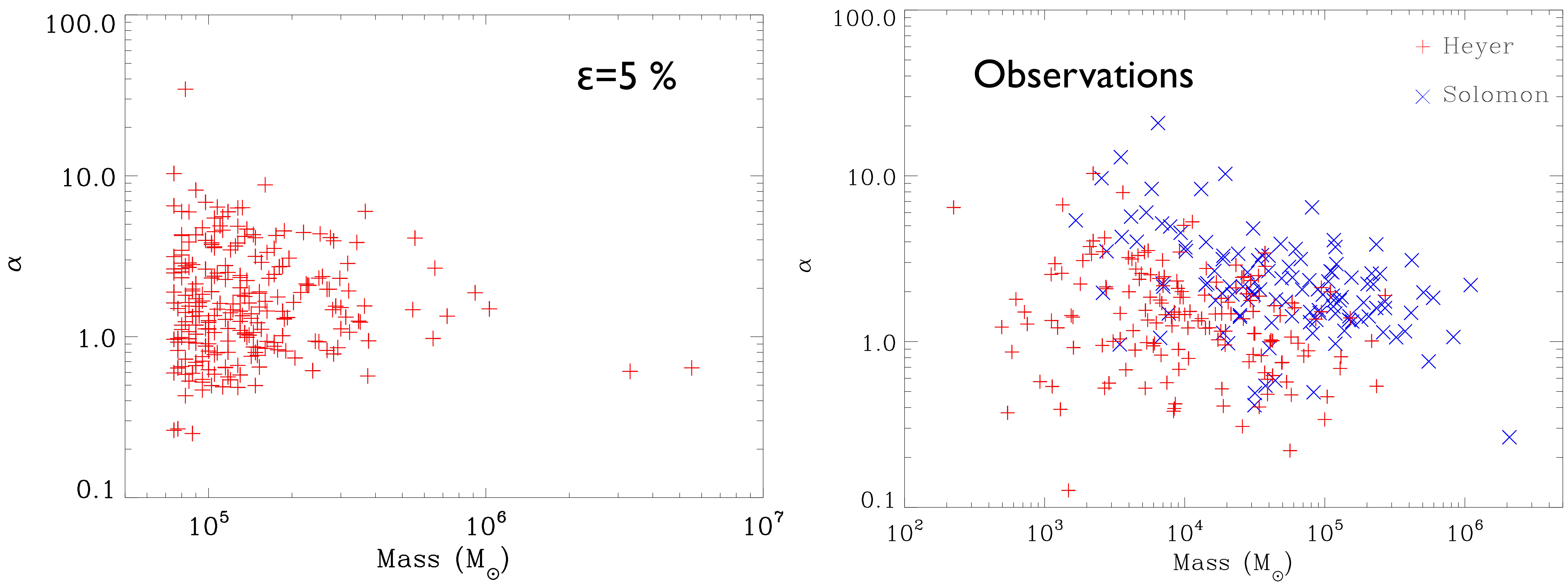


No spiral potential: no massive clouds

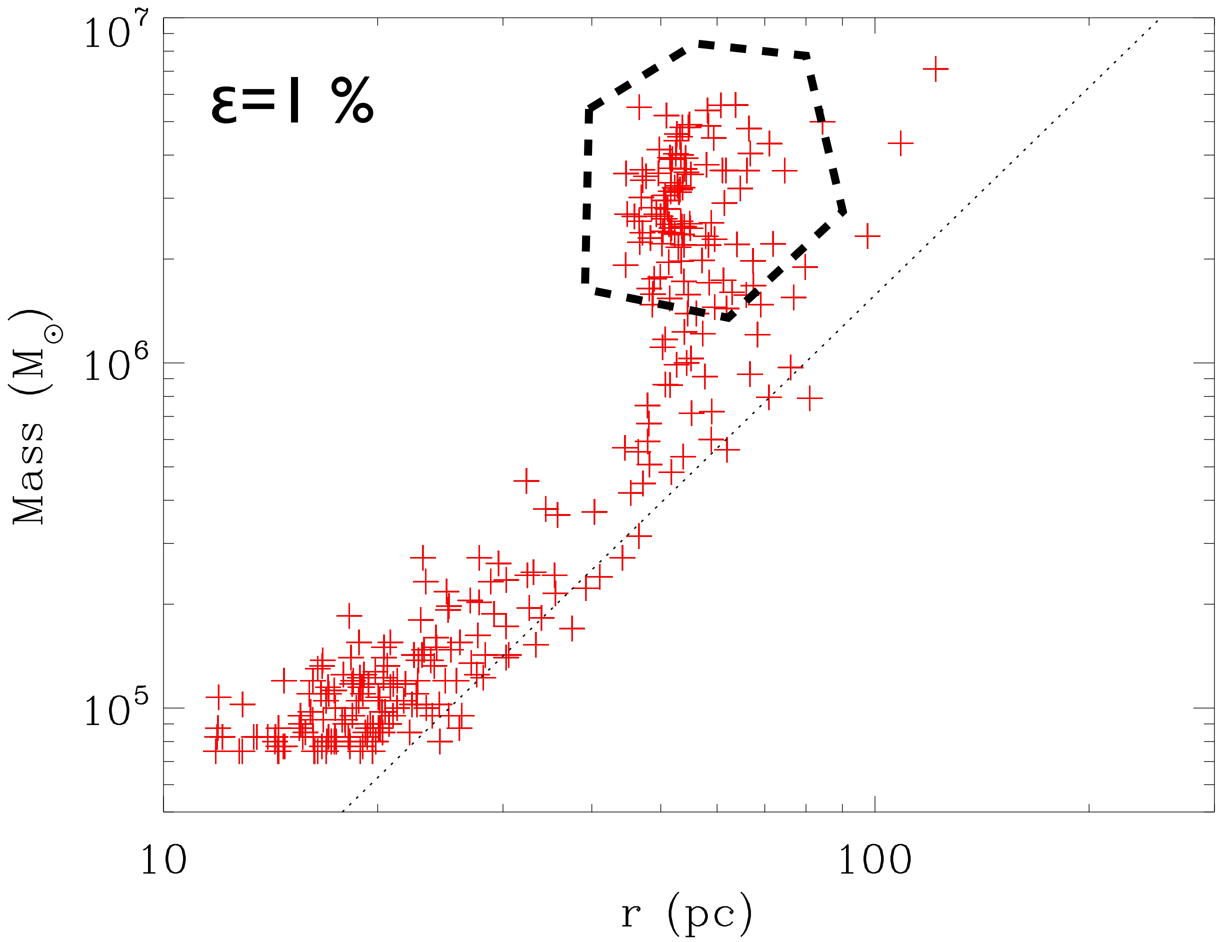
Virial parameters of GMCs

$$\alpha \sim \frac{5\sigma^2 R}{3GM}$$

MOST CLOUDS ARE UNBOUND!

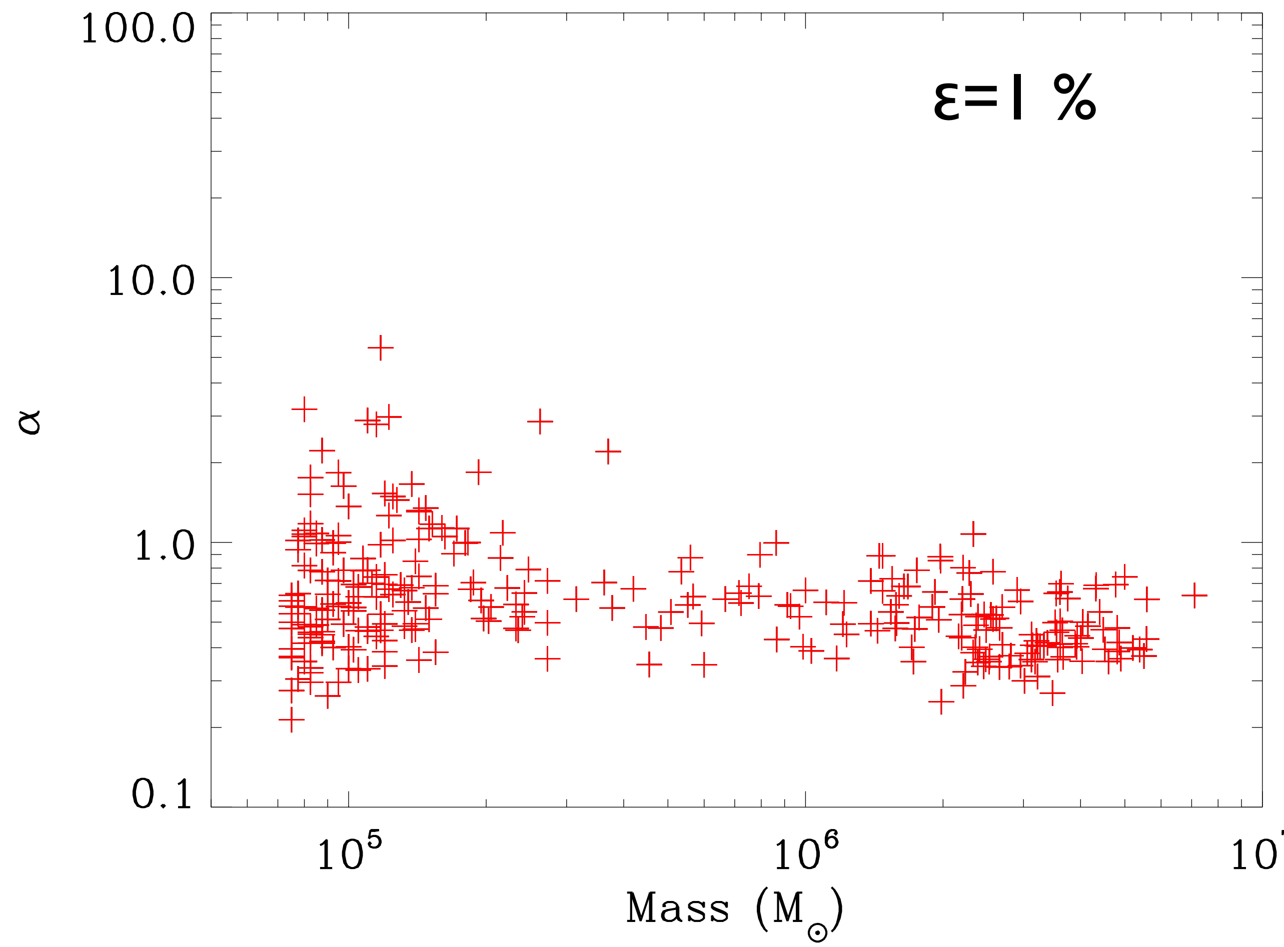


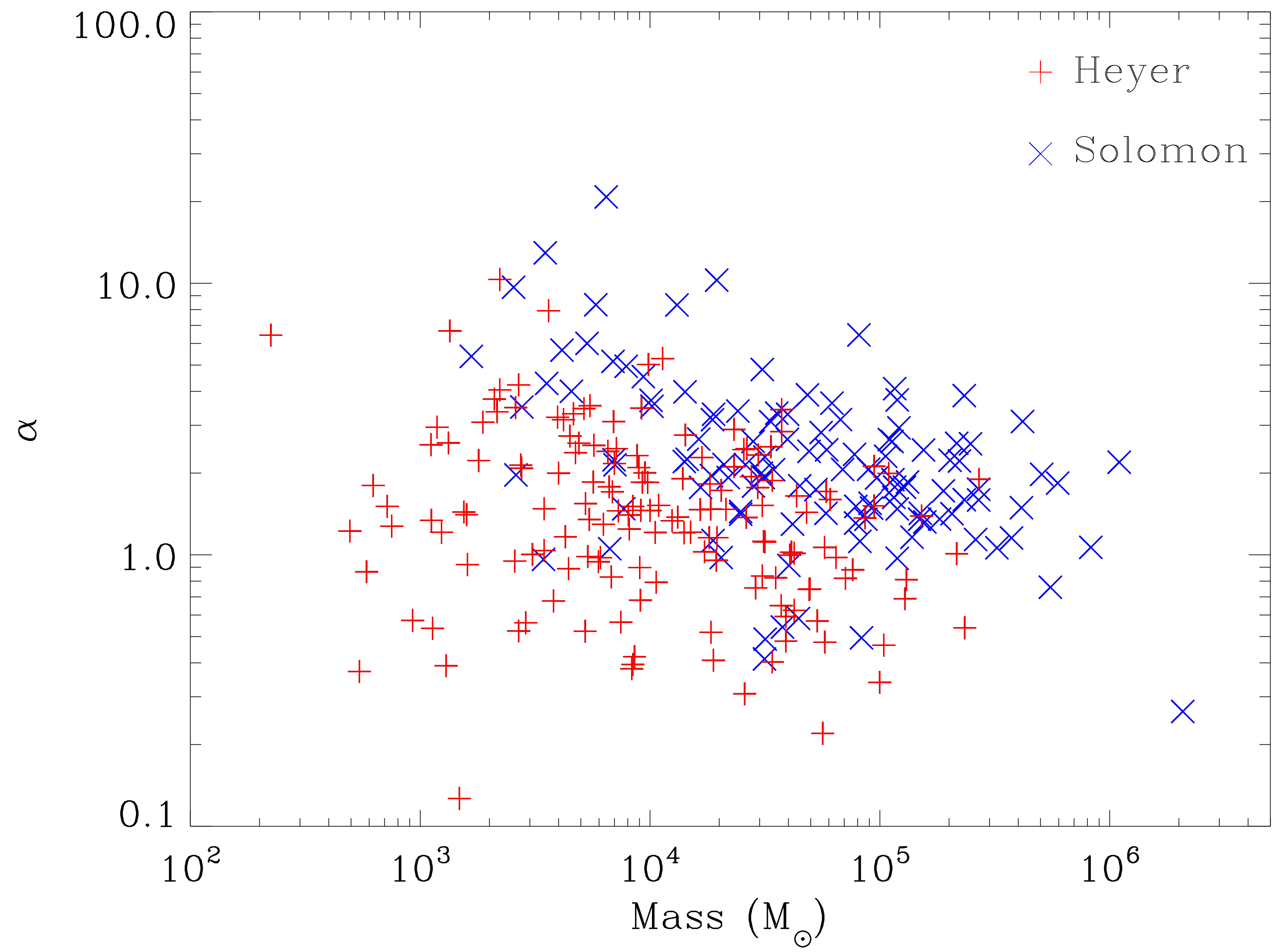
Virial parameters of GMCs



With only 1% efficiency, clouds more bound compared to observations

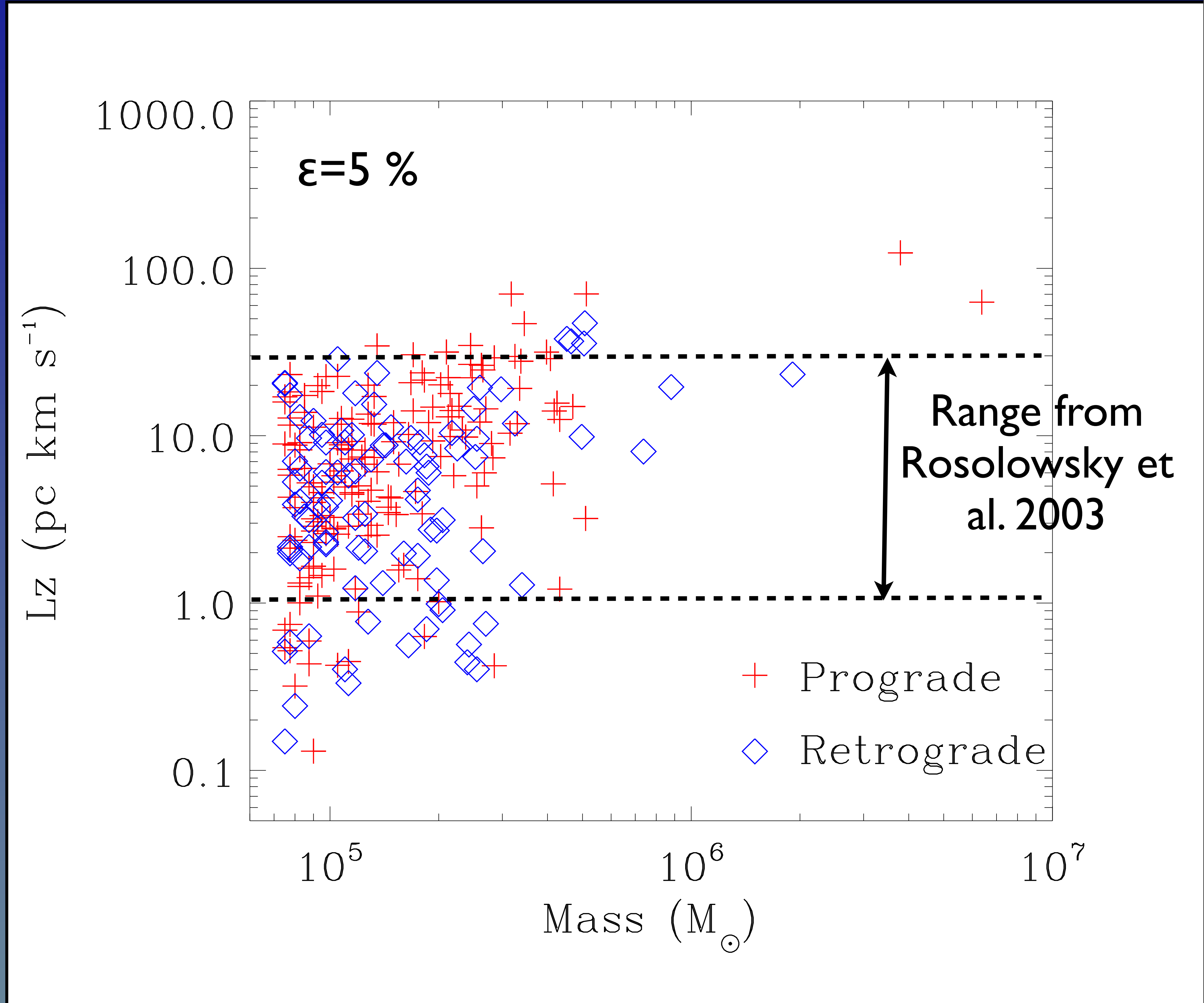
Clouds no longer exhibit constant surface densities





Cloud rotation

For 5% feedback, 40% of clouds exhibit retrograde rotation

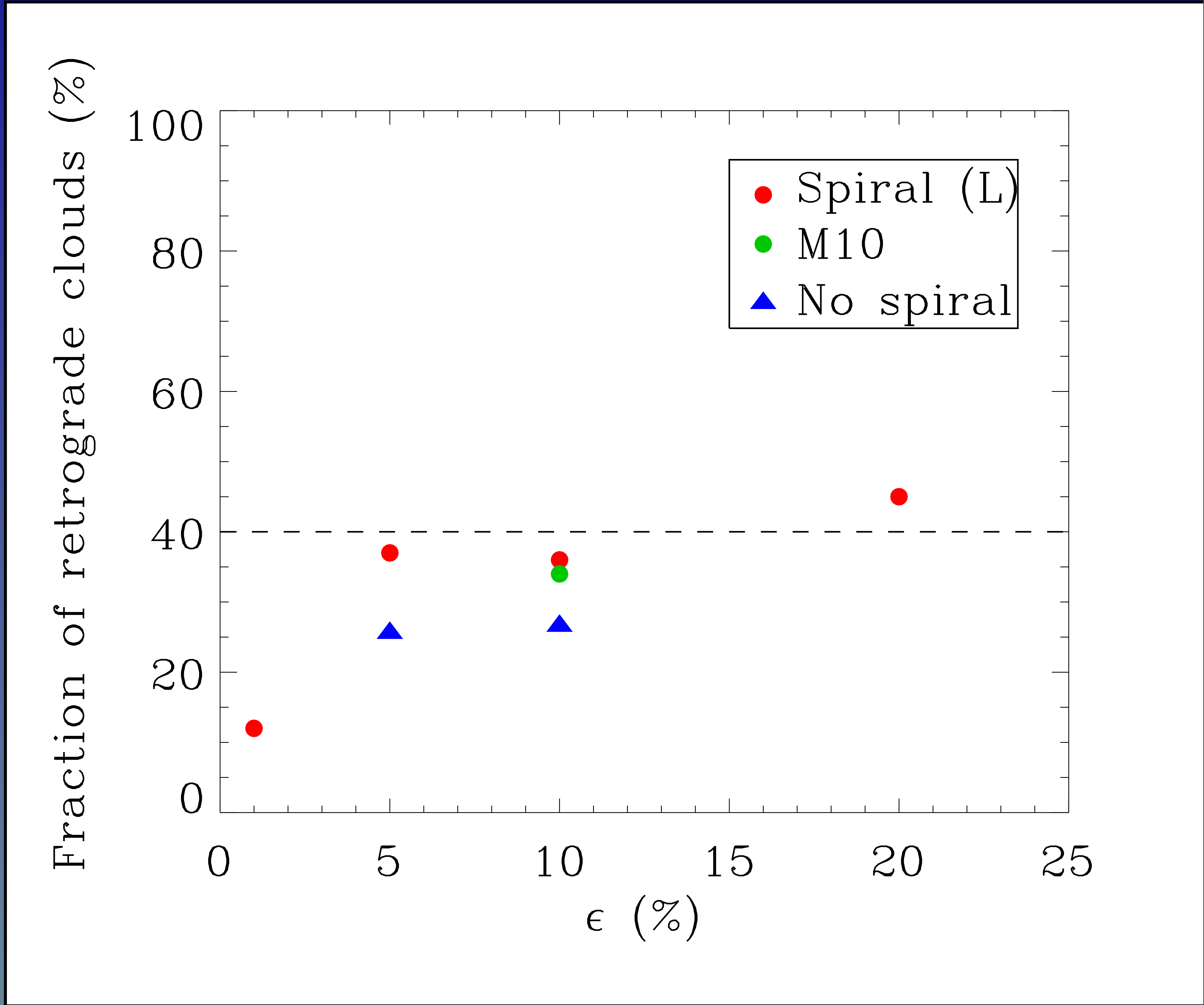


Cloud rotation

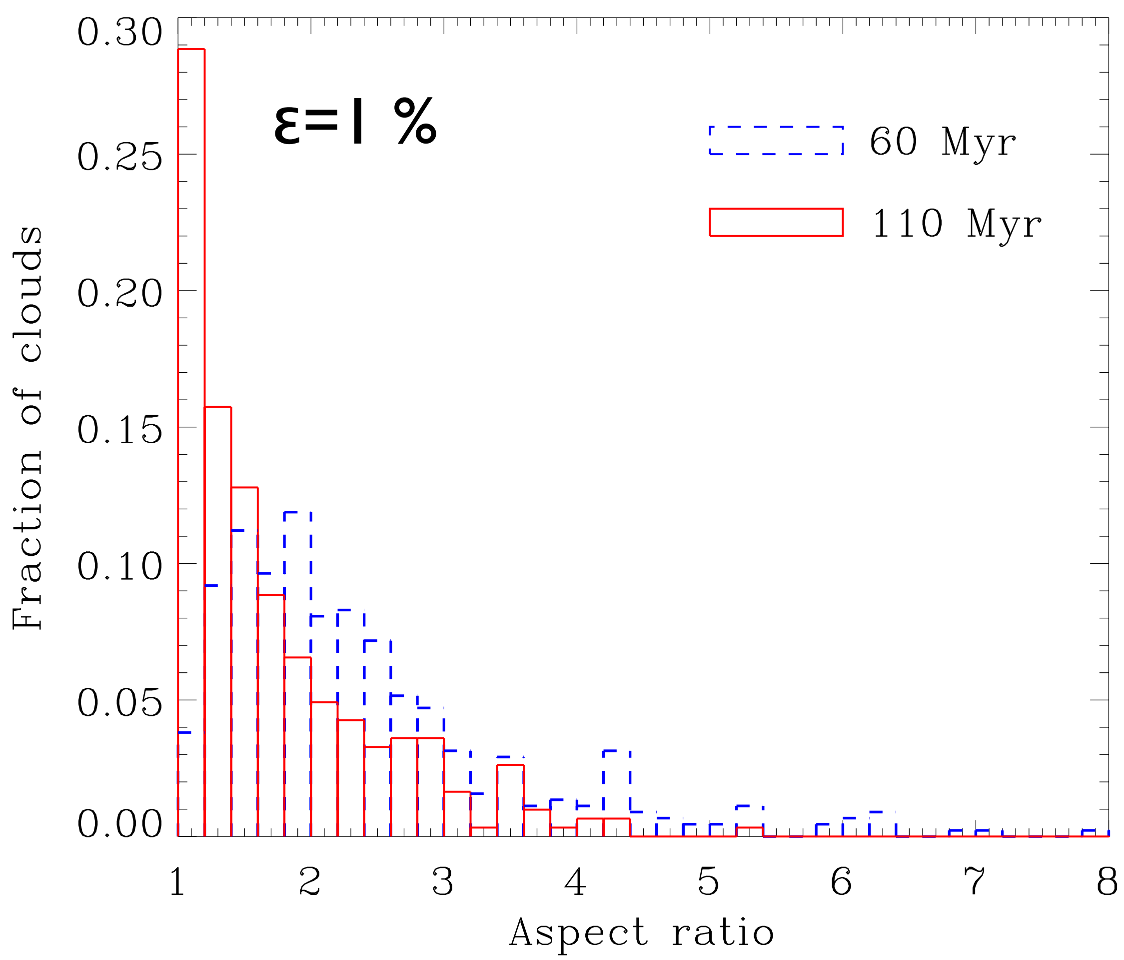
For 5% feedback, 40% of clouds exhibit retrograde rotation

fewer clouds retrograde for case without spiral potential

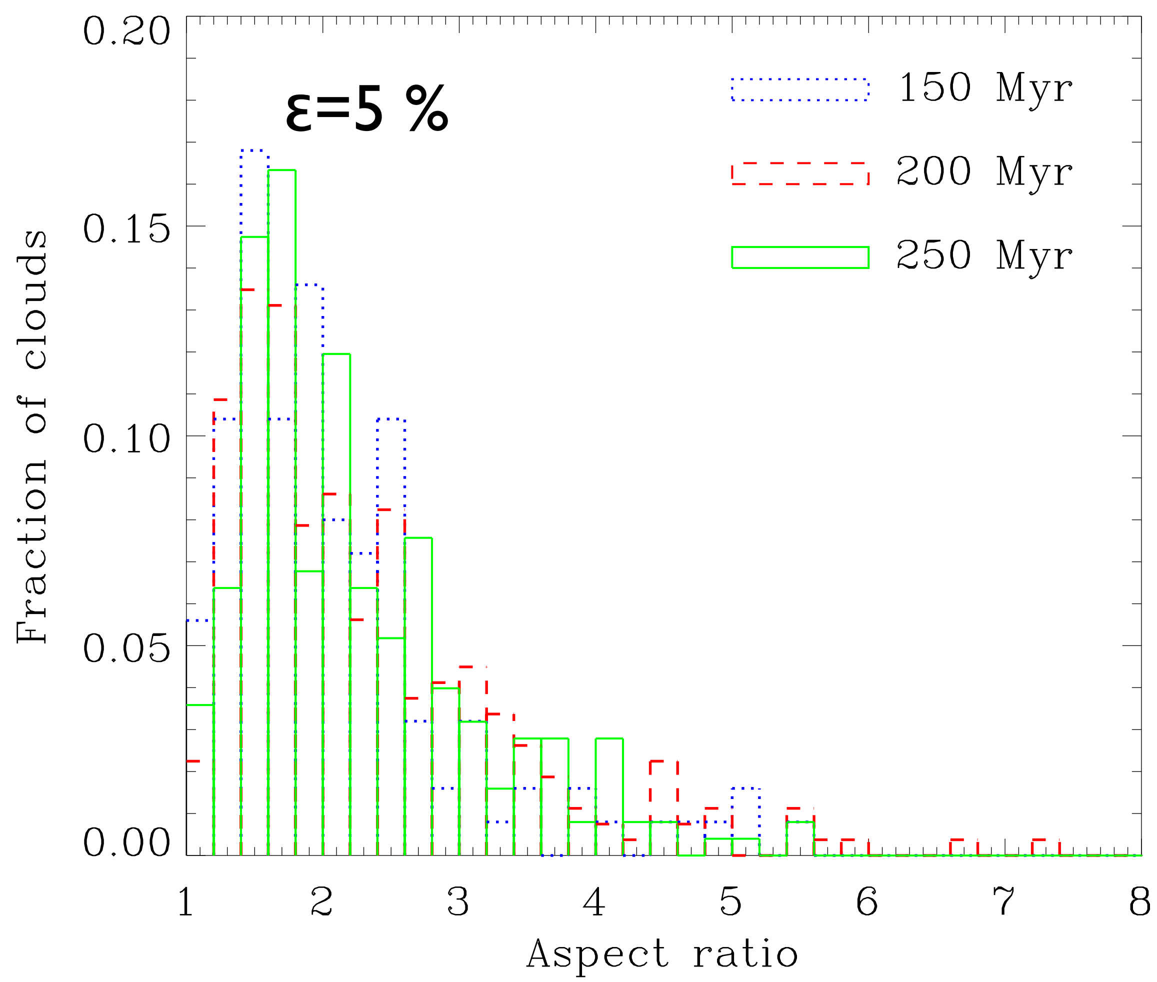
only few % retrograde for 1% efficiency calculation



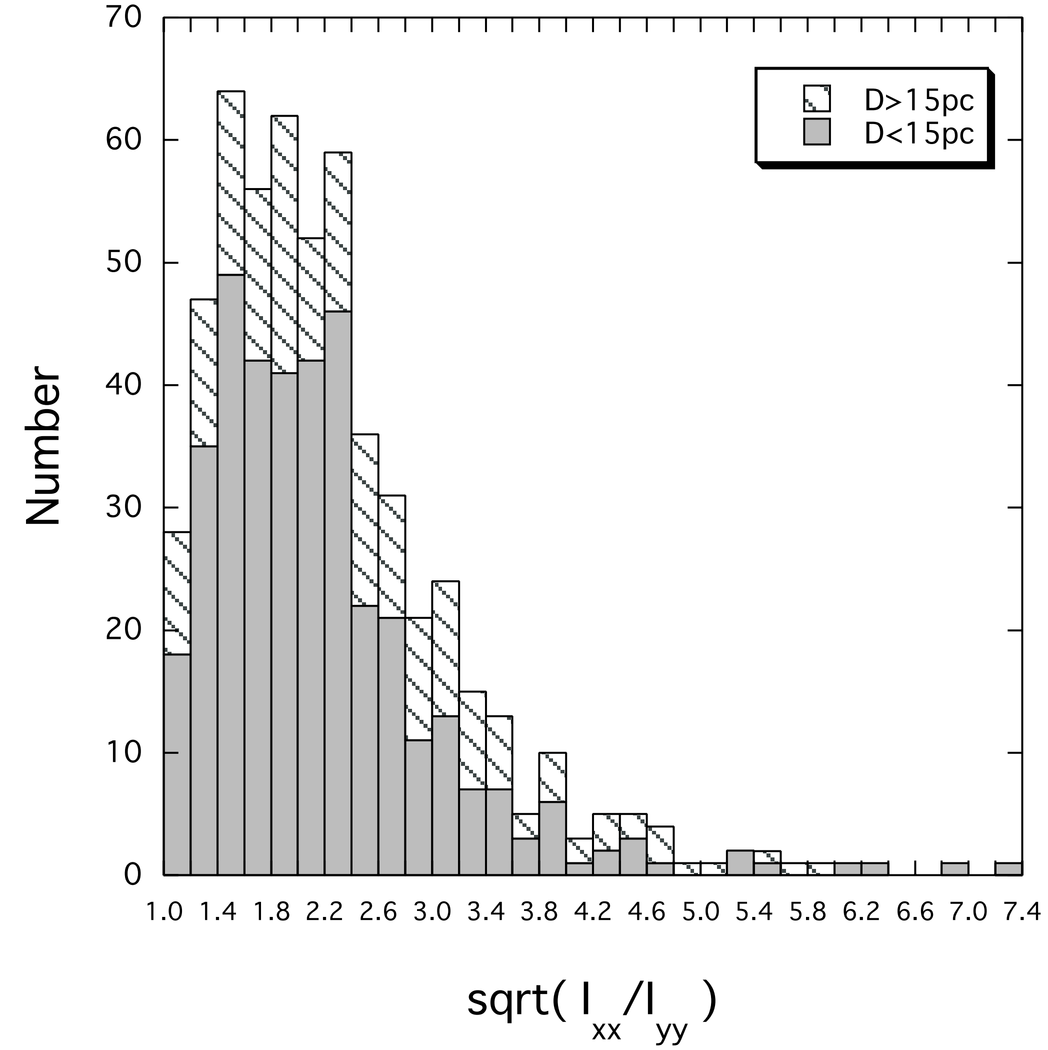
Aspect ratios of molecular clouds



Gravitationally dominated: clouds are predominantly spheres



Dynamically driven: more clouds are elongated



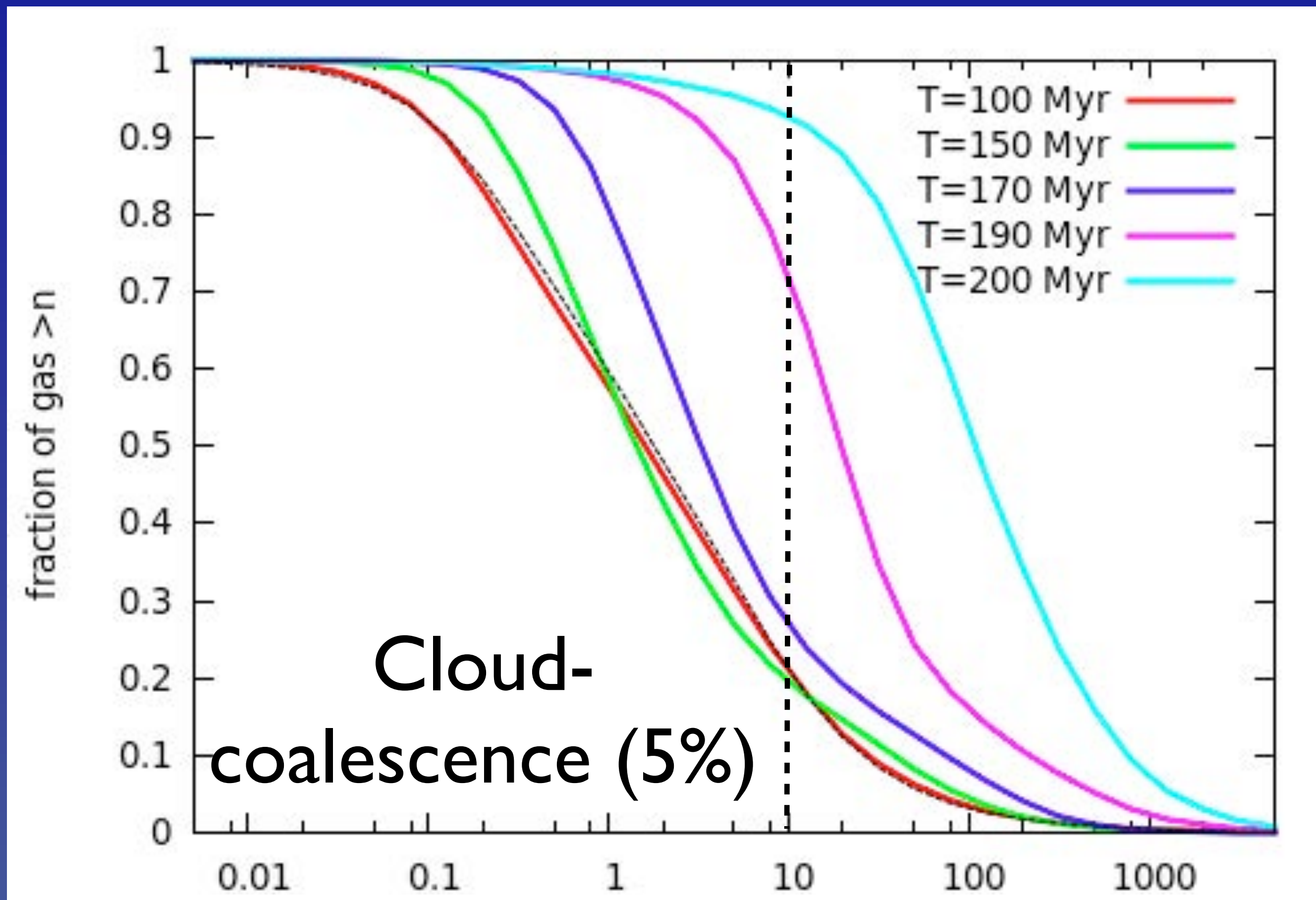
Milky Way clouds (Koda et al. 2006)

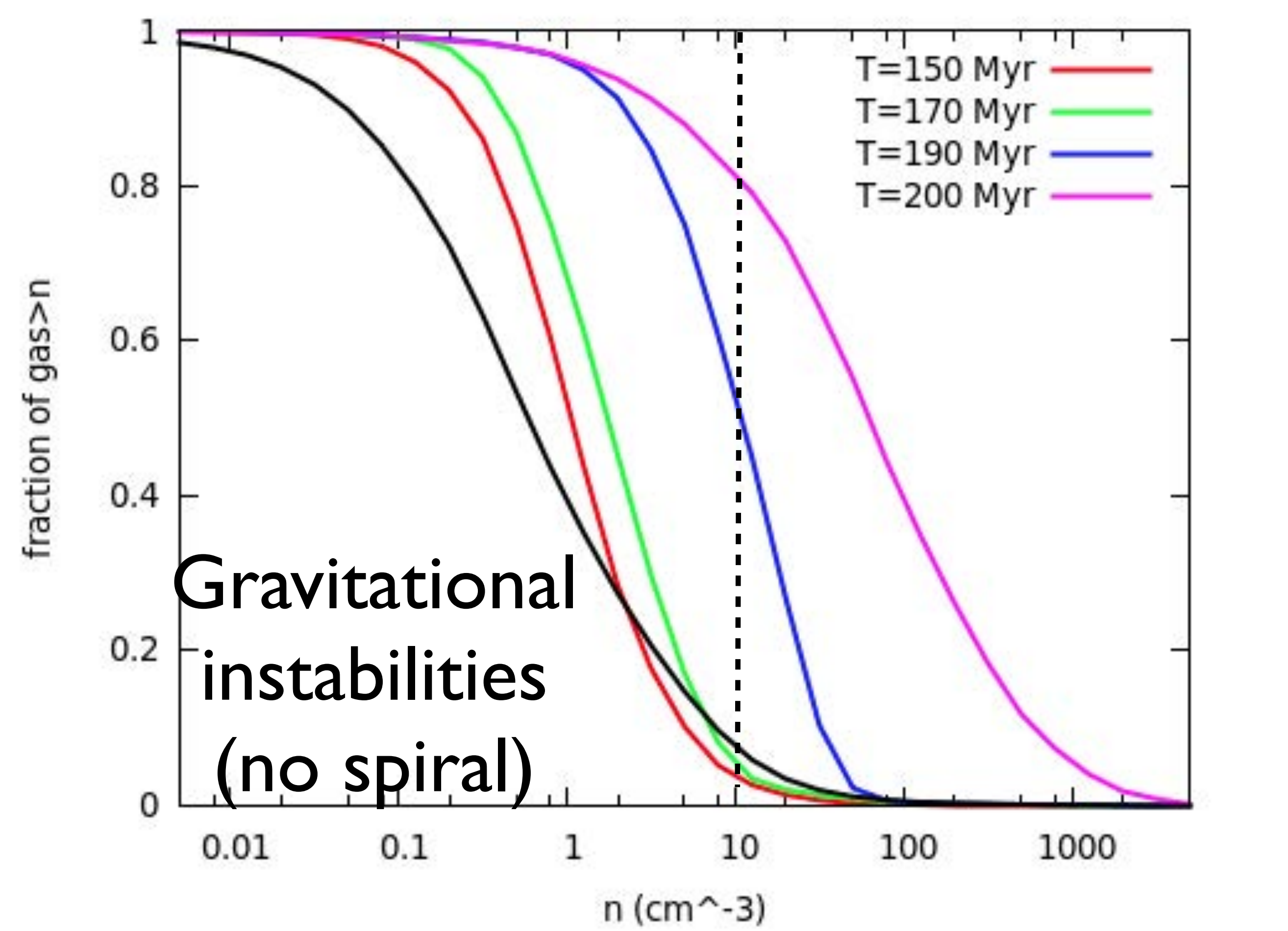
Again, 5% case fits well, 1% is wrong

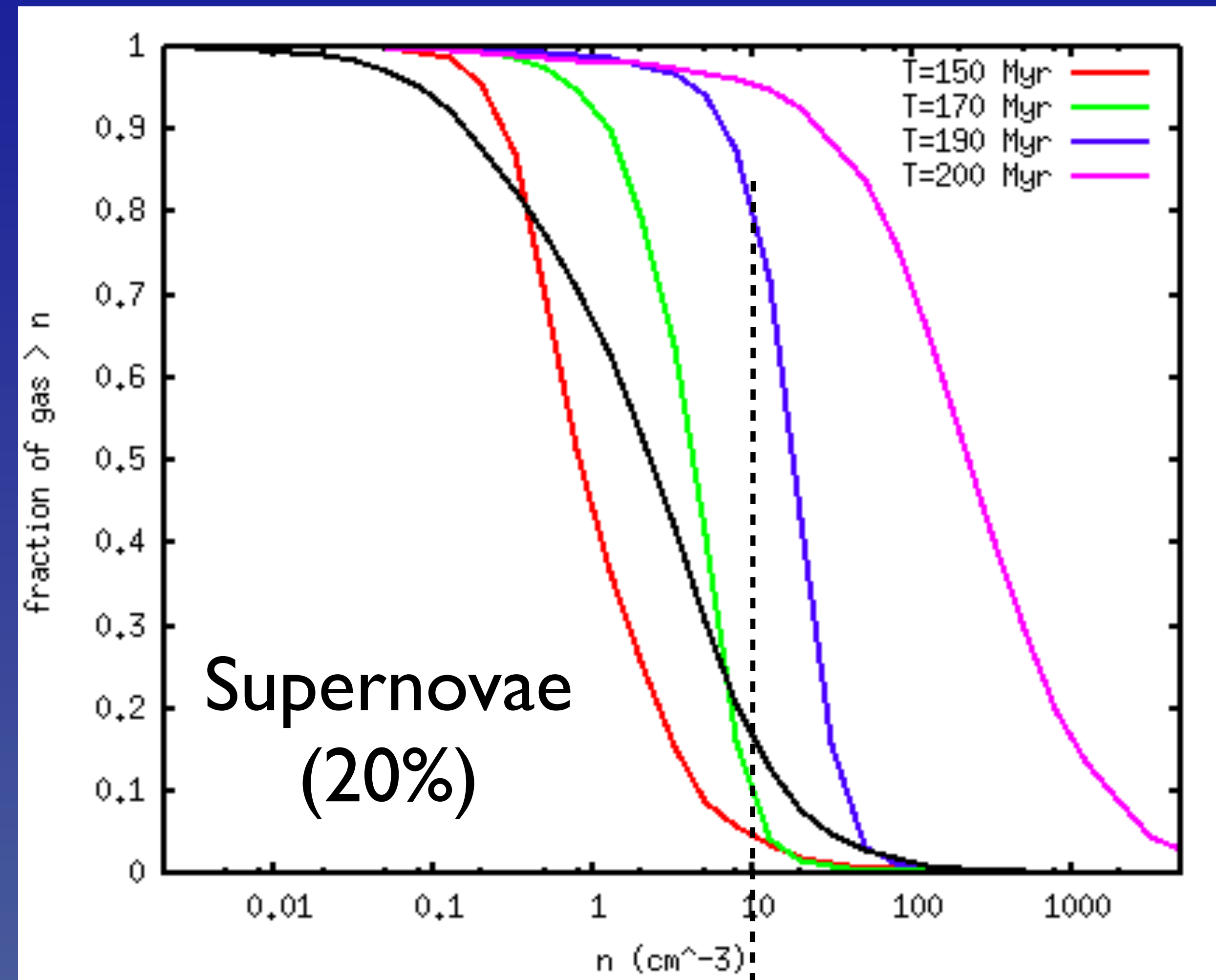
Conclusions - GMC properties

- Properties of GMCs all disagree with observations when there is minimal feedback (and GMCs are strongly dominated by self gravity)
- Some feedback necessary to disperse the clouds and prevent them becoming too strongly bound
- Imposed spiral structure produces more massive clouds
- Cloud collisions increase the fraction of retrograde-rotating clouds

GMC formation - what gas forms GMCs?

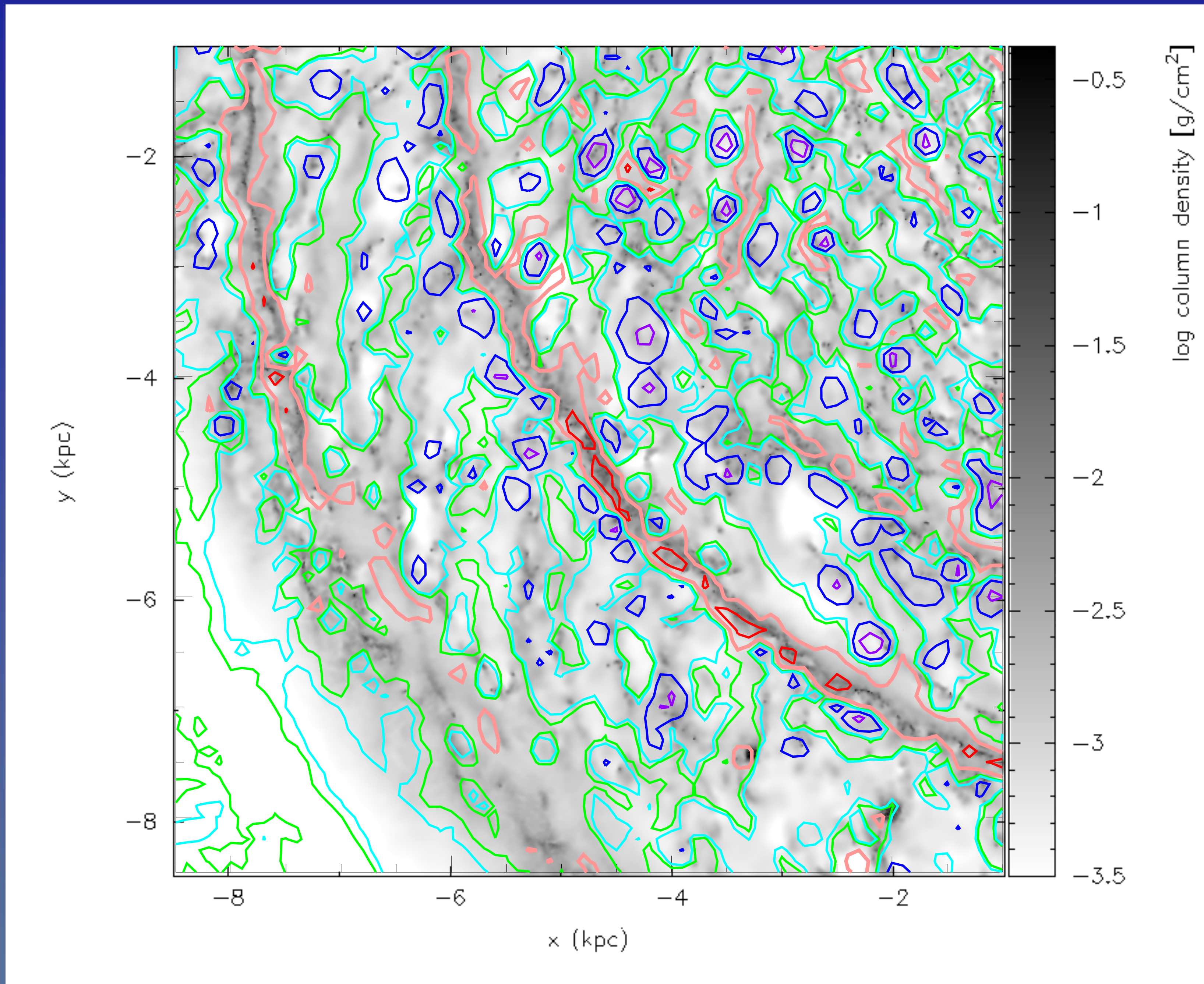


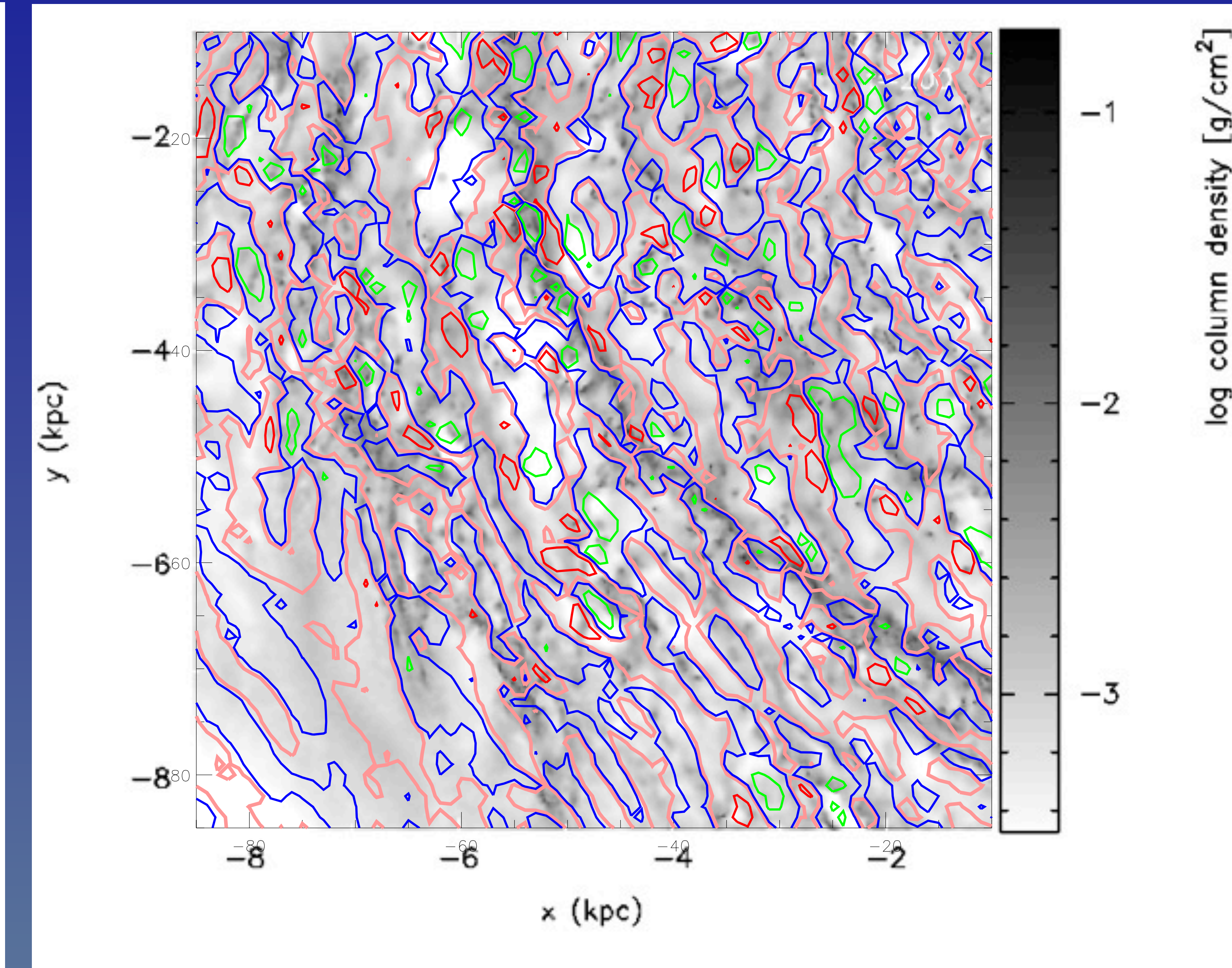




- Cloud-coalescence: clouds formed from mixture of low and high density gas
- Gravitational instabilities/ supernovae : a transition from atomic to molecular gas

What about converging flows?

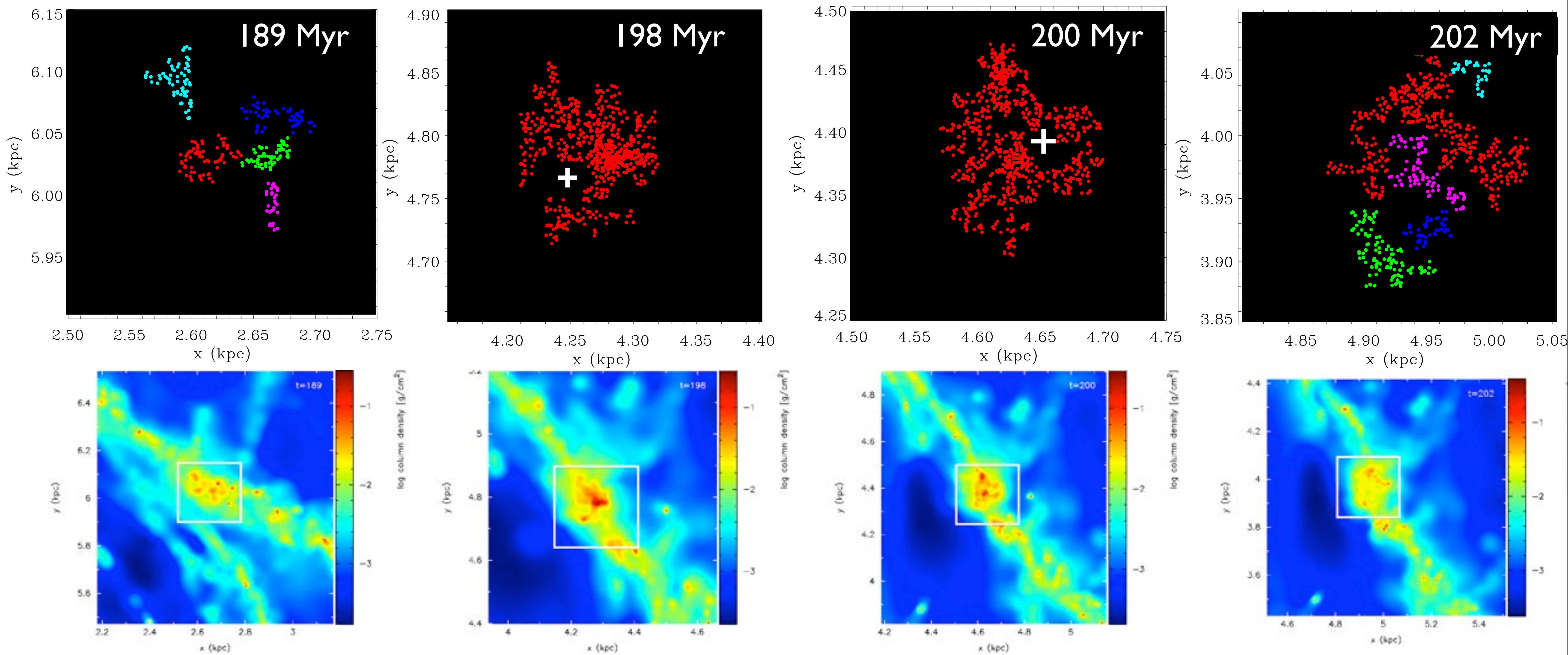




ε=5% red=converge in 4 Myr
violet=diverge in 4 Myr

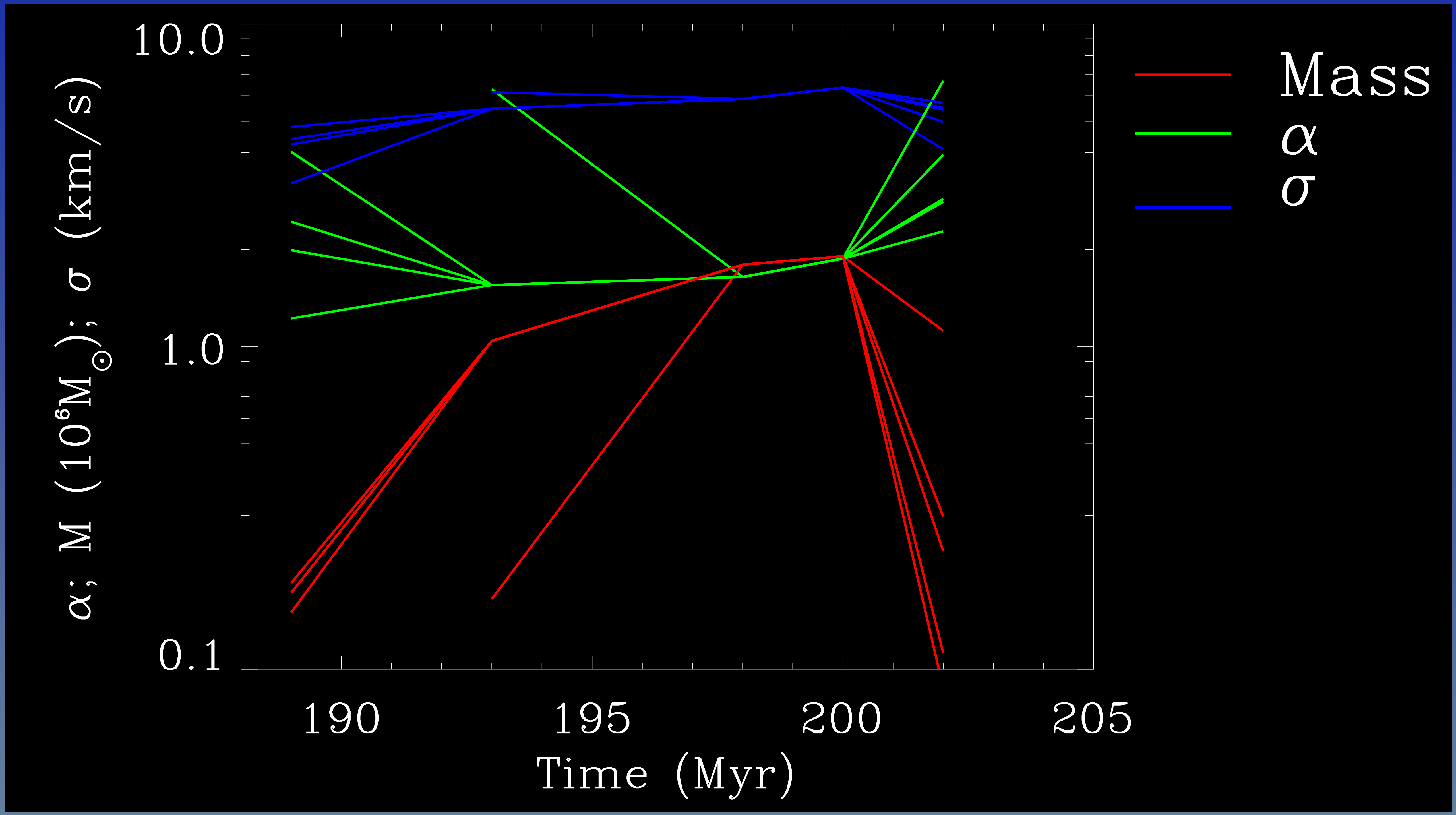
ε=20% red=converge in 1 Myr
green=diverge in 1 Myr

Individual clouds (5% case)



Dobbs, Burkert & Pringle 2011

Individual clouds



- cloud disrupted by feedback on timescales of 10-20 Myr
- clouds stay unbound/ marginally bound

Conclusions / Future Work

- GMCs likely formed by a combination of cloud coalescence, and self gravity
- With 5% efficiency feedback we can reproduce reasonably well:

- the properties of the ISM

- large scale structure

- properties of GMCs

- Minimal feedback: properties of GMCs do not match observations
- Future simulations:

- use higher resolution, test delay - consistently model spiral structure

- use radiative transfer models to obtain CO emission, and to use same techniques as observers to consistently compare GMC properties