Star Formation in Disc Galaxies

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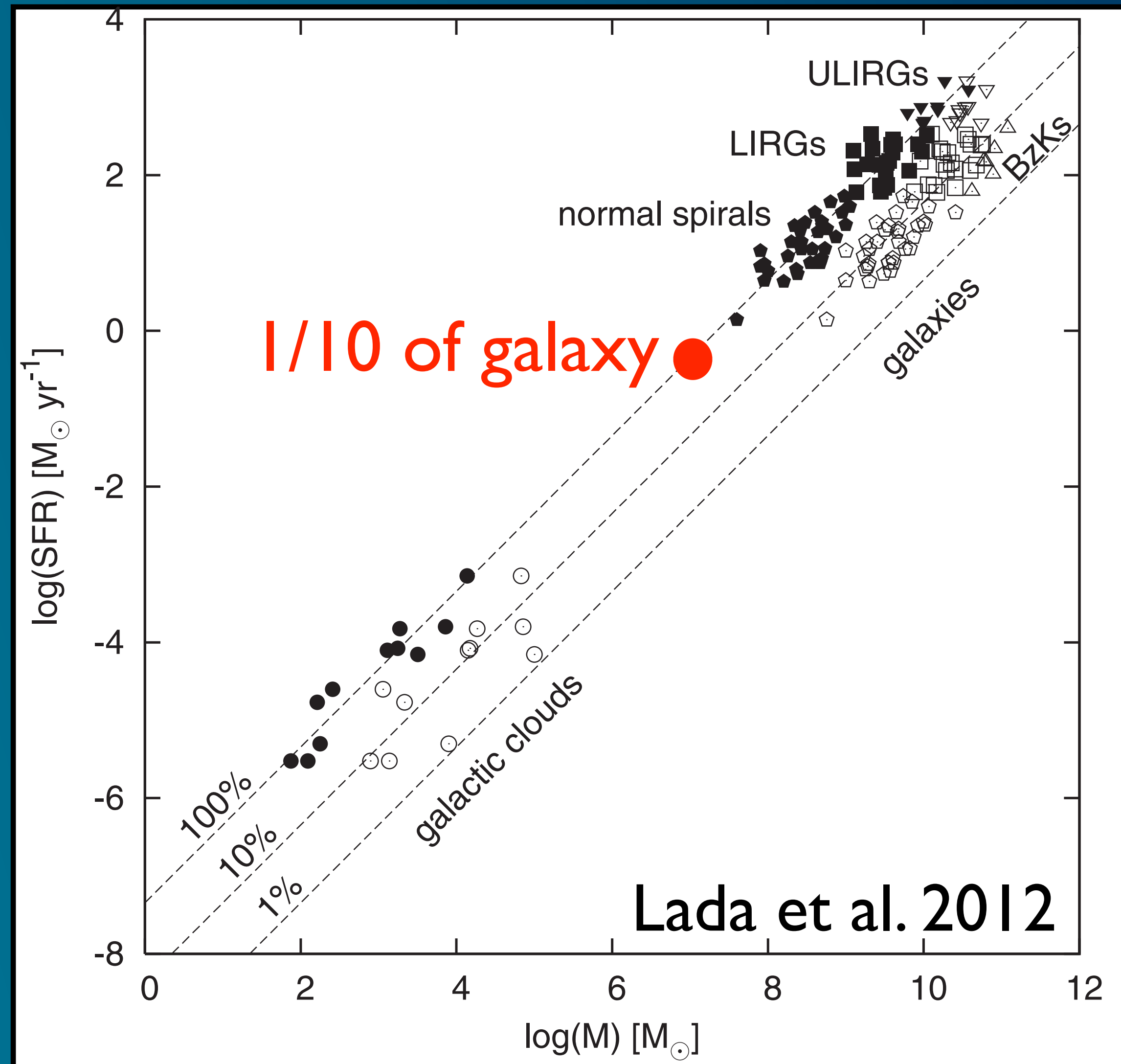
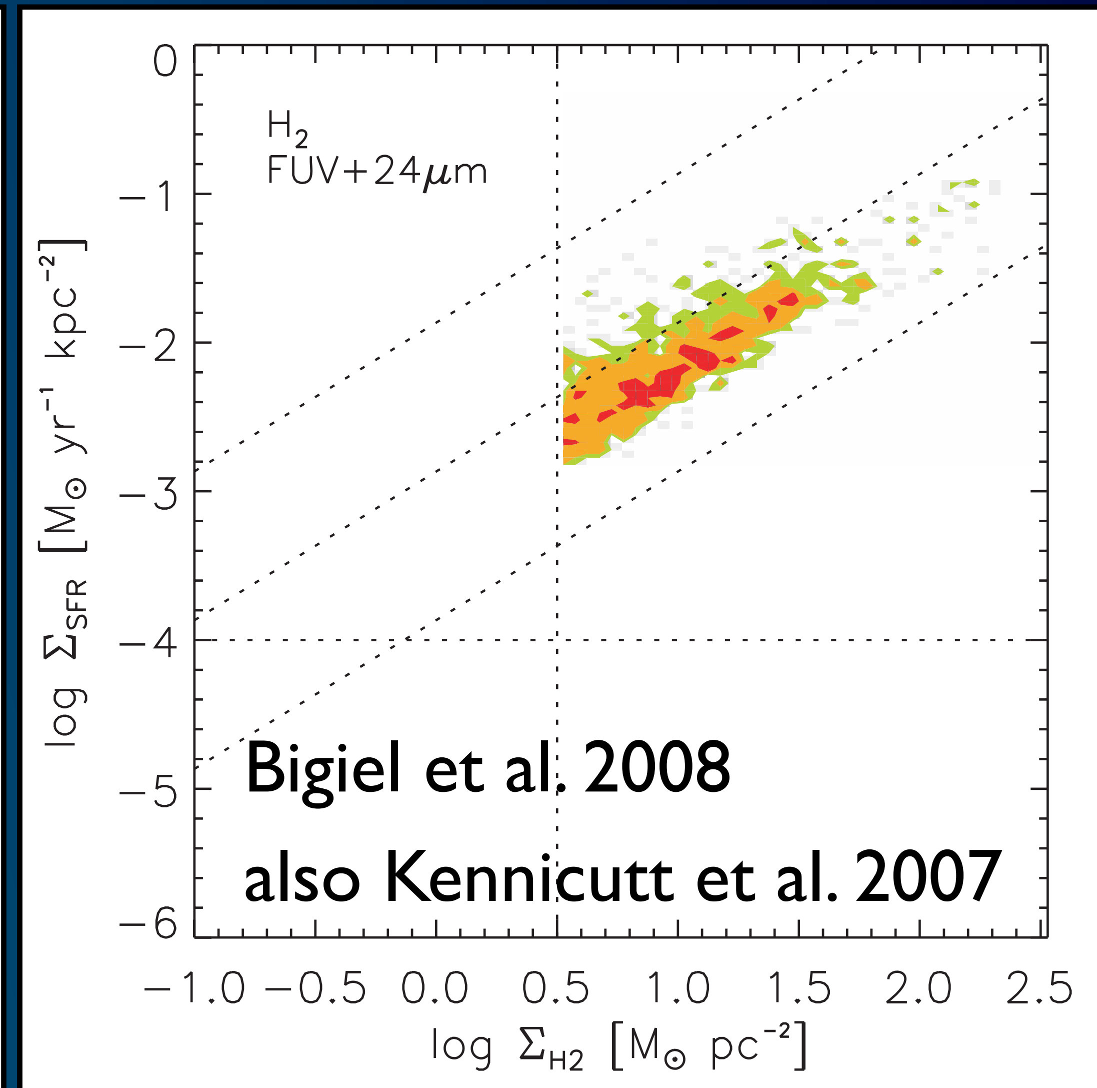




Star formation scales linearly with dense gas

- star formation is additive over galaxy?

- not so simple: Schinnerer, Meidt, Longmore

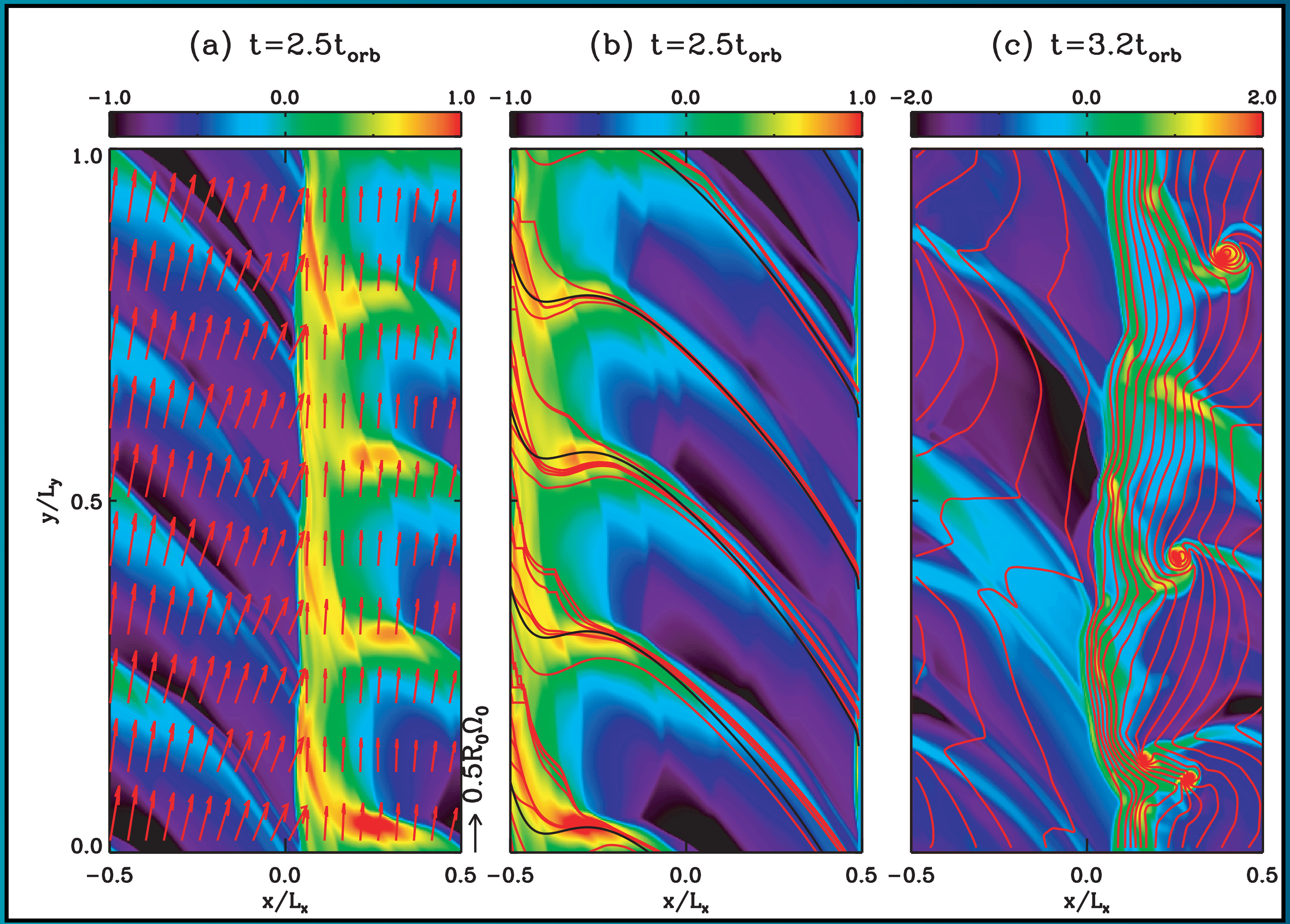
1. What produces dense (CO) gas? 2. What produces dense (10^4 cm^{-3}) gas? 3. What produces stars?

1. Gravitational instabilities

Cowie 1981; Elmegreen 1978, 1982; Elmegreen & Elmegreen 1986; Shetty & Ostriker 2006; Dobbs 2008

Spacing between clouds ~ $$\lambda_{max} = 2c_s^2/G\Sigma,$$

Mass of clouds ~ $$M = \Sigma\left(\frac{\lambda_{max}}{2}\right)^2 = \frac{c_s^4}{G^2\Sigma}$$



Kim & Ostriker 2006

clear in clumpy z~2 galaxies:

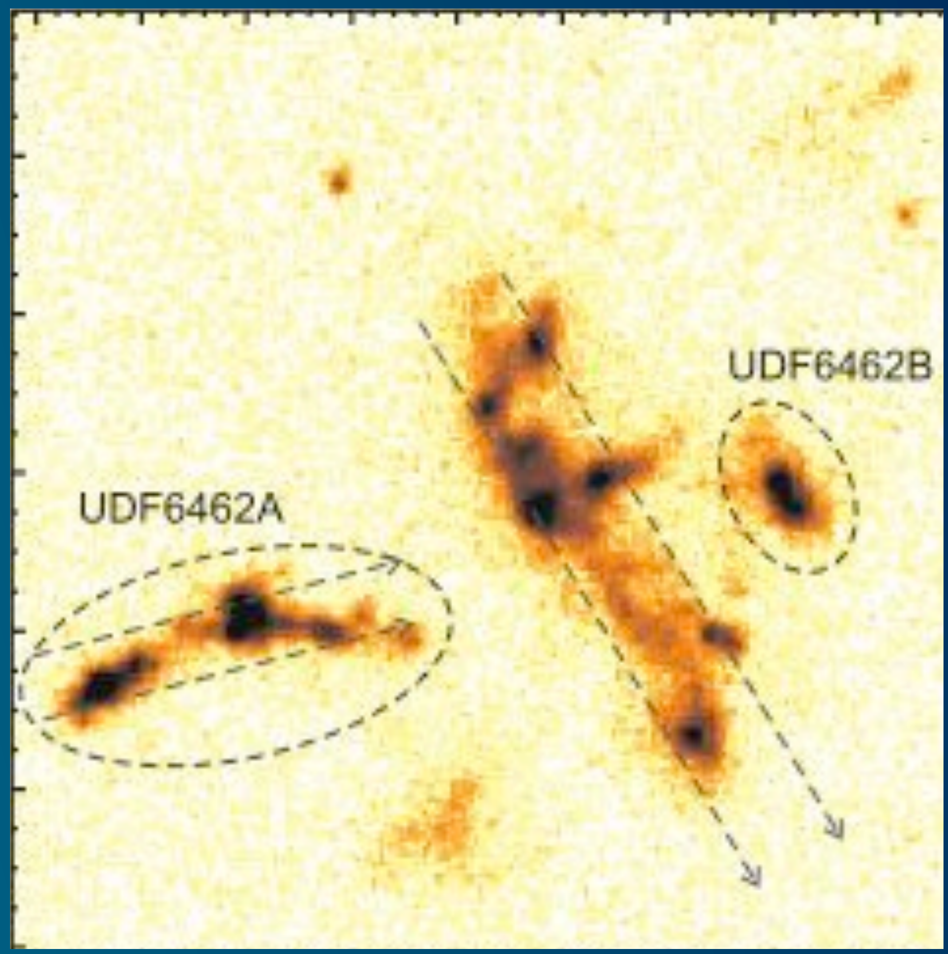
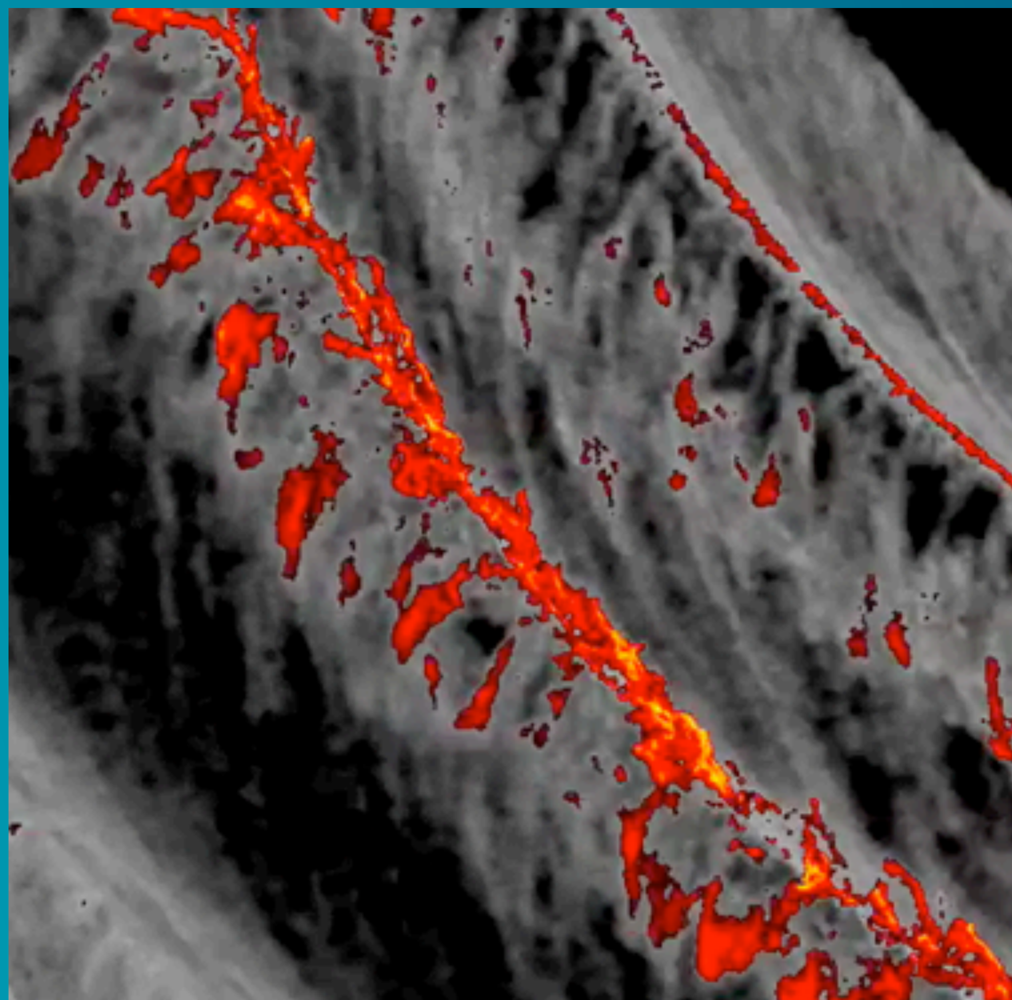


figure from Bournaud, Daddi, & Elmegreen 2008

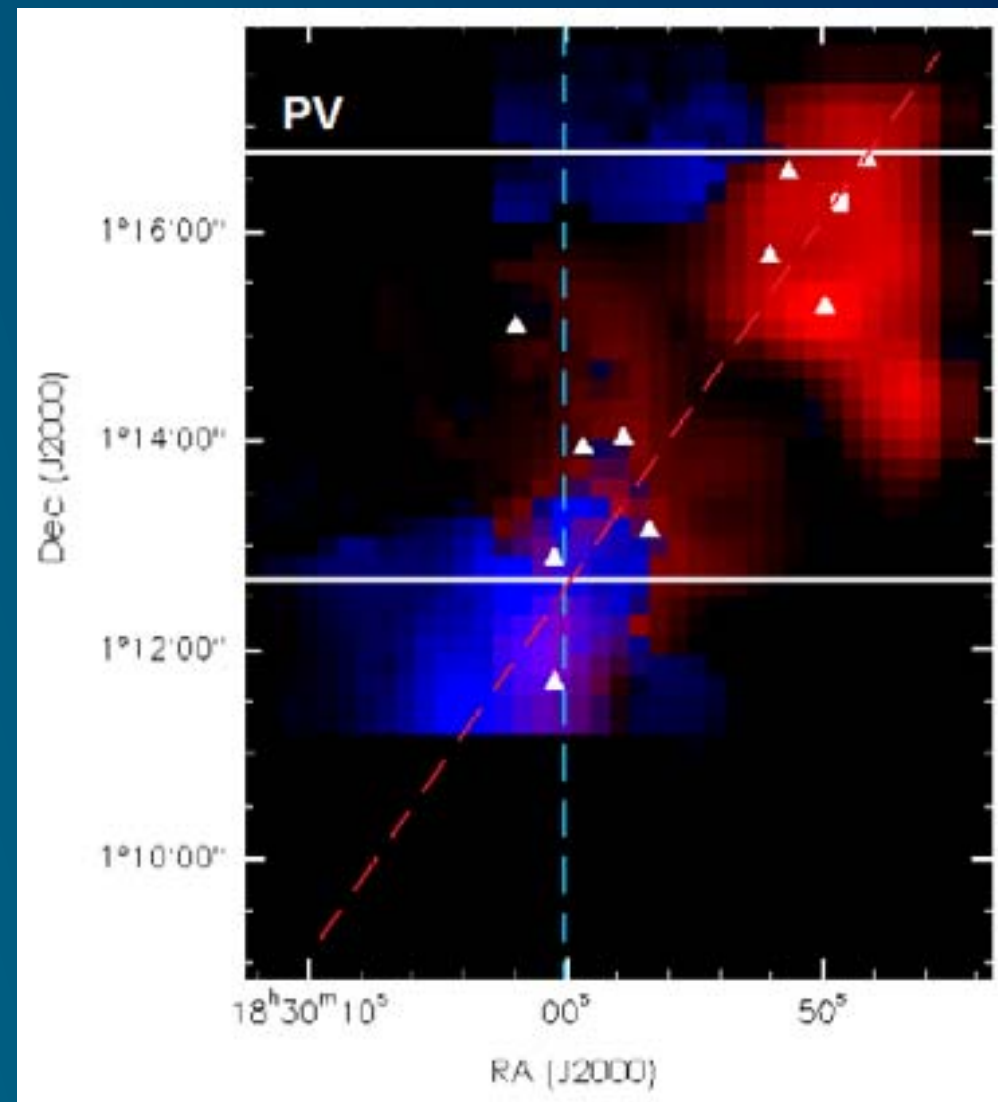
2. Collisions / Coalescence / Agglomeration

Field & Saslaw 1965, Scoville & Hersch 1979, Casoli & Combes 1982, Kwan & Valdes 1983, 1987, Tomisaka 1984, 1986, Dobbs, Bonnell & Pringle 2006, Dobbs 2008, Tan 2000, Tasker & Tan 2009



section of galactic disc Dobbs, Bonnell & Pringle 2006

separation of features α epicylic radius (shock strength) Dobbs 2008



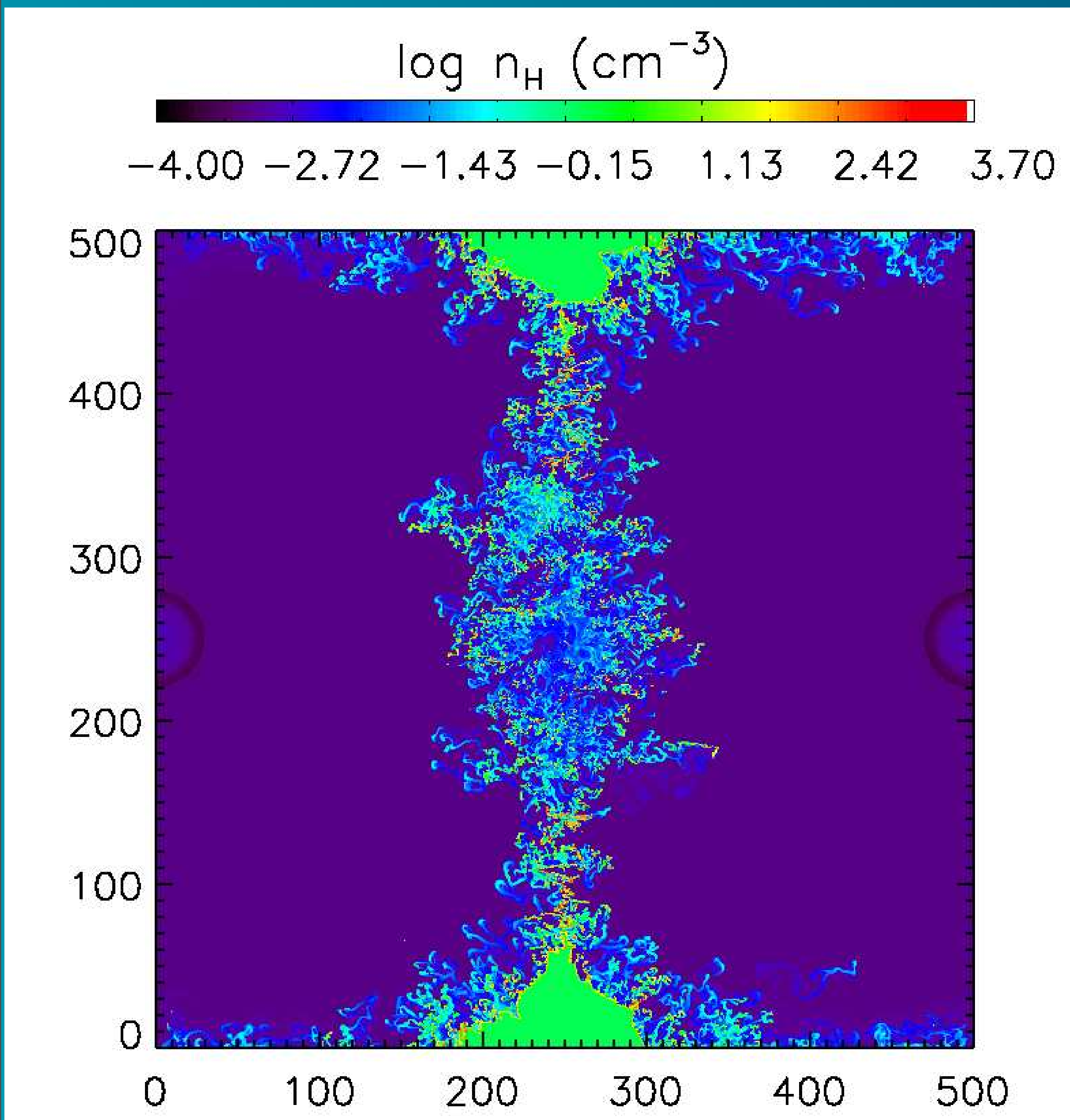
$C^{18}O$ emission in Serpens Duarte Cabral et al. 2011

Evidence in nearby clouds (Greaves & White 1991, Vallee 1995, Schneider et al. 2010, Galvan-Madrid et al. 2010, Nakamura et al. 2012)

3. Colliding flows

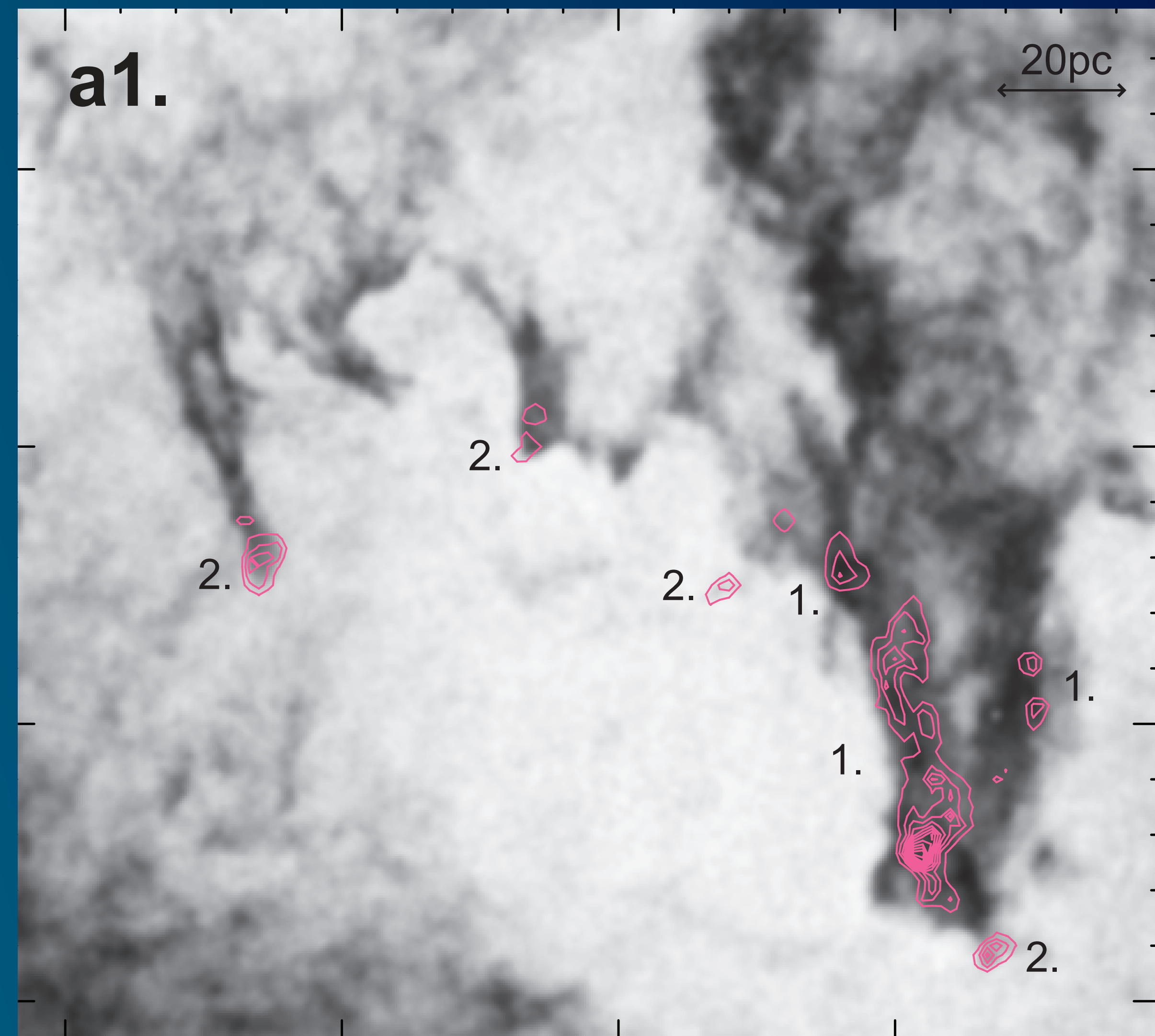
Koyama & Inutsuka 2000, Heitsch et al. 2006, 2008, Vazquez-Semadeni et al. 2006, ...2011, Hennebelle et al. 2008, Banerjee et al. 2009, Inoue & Inutsuka 2008, 2012, Clark & Glover 2012

From Spiral shocks, Supernovae flows



Ntormousi et al. 2011:
2 adjacent supernovae bubbles

also Gaczkowski poster



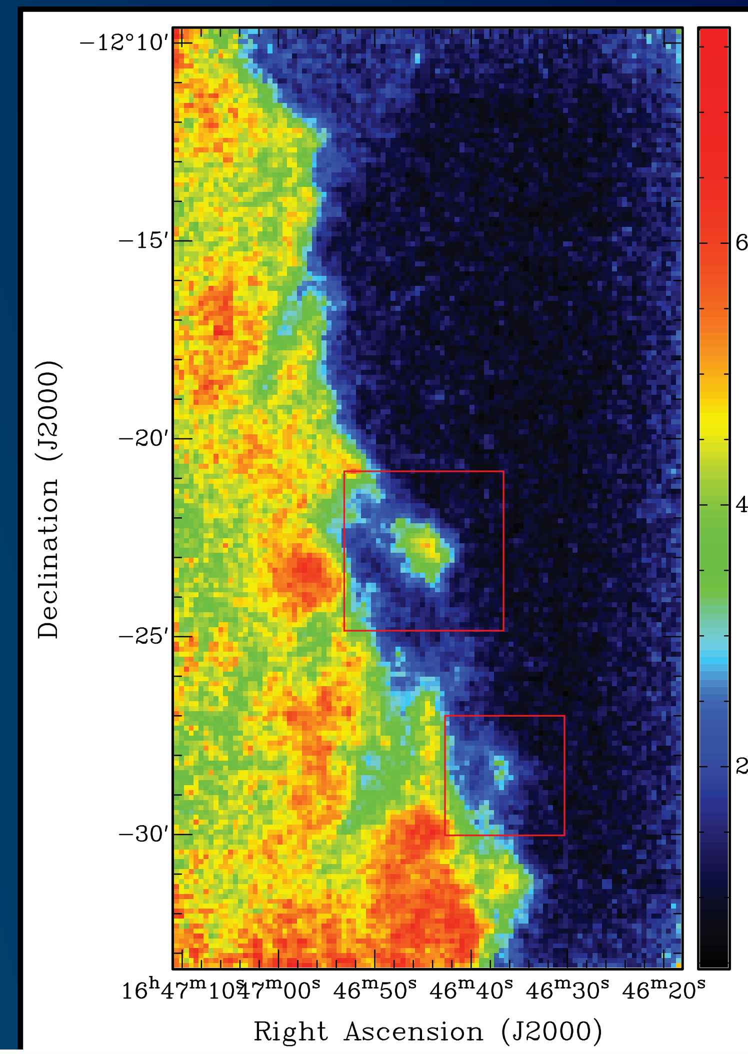
Dawson et al. 2011

CO emission at edges of supershells
LMC: responsible for only few % of clouds (Dawson, et al. in prep)

4. Thermal instabilities

Field et al. 1969, Wolfire 1995, Burkert & Lin 2000, Audit & Hennebelle 2005, Piontek & Ostriker 2005, Koyama & Ostriker 2009, Heitsch et al. 2006, 2011, Tachihara et al. 2012

- very small structures (0.1 pc)



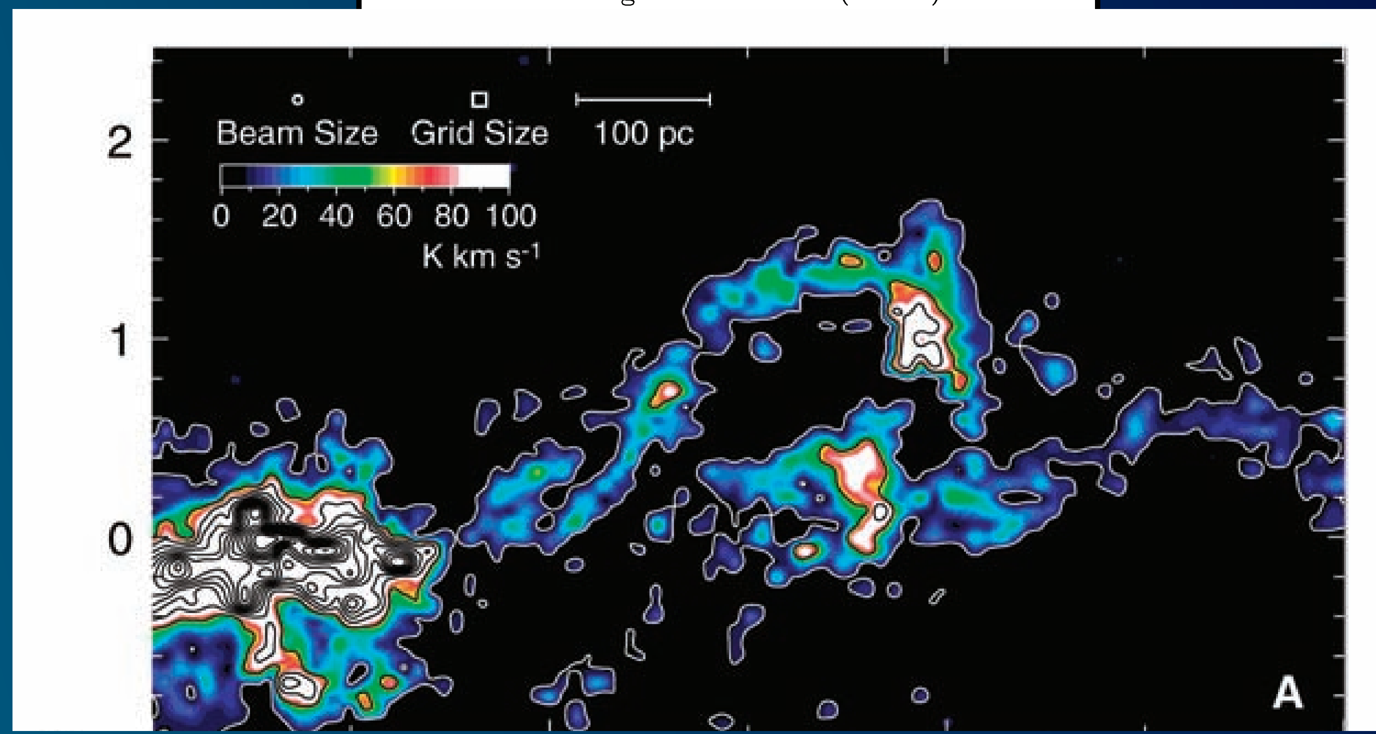
Tachihara et al. 2012

5. Parker instabilities

Mouschovias et al. 1974, 2011, Kosinski & Hanasz 2006, 2007

- Generally gravitational instabilities believed to dominate magnetic

Elmegreen 1982; Kim et al 1998; Kim et al. 2002



magnetic loops in the Galactic centre (Fukui et al. 2006)

Formation of dense clouds

In fact all occur:

- no self gravity - less massive, less coherent clouds
- spiral arms - promote coalescence of gas clouds
- thermal instabilities - lead to dense, small scale structure which coalesces into more massive clouds
- spiral shocks / feedback - lead to 'colliding flows'

Numerical simulations

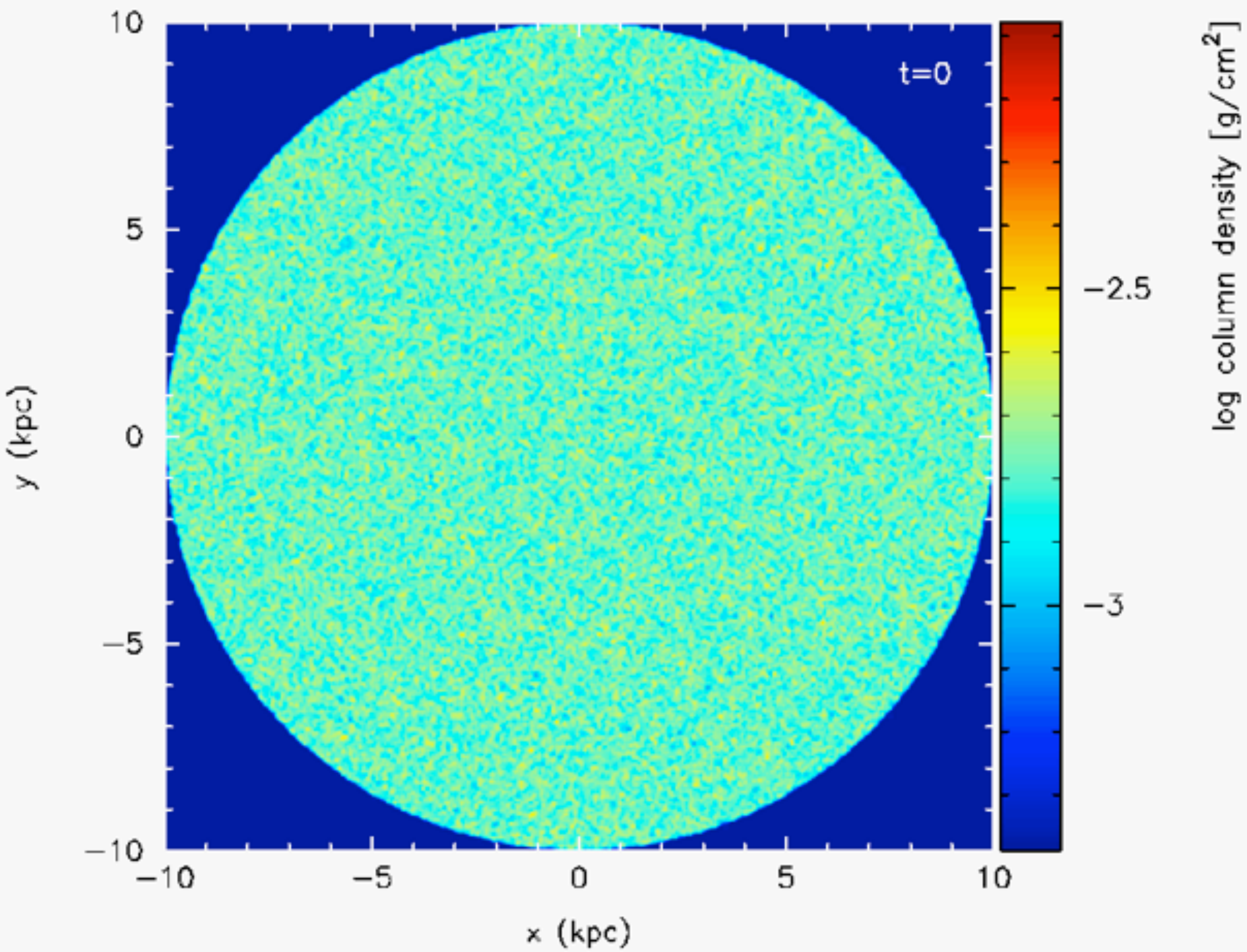
- Potential with 4 armed spiral component (also no spiral, model with stars later)
- Heating and cooling (Glover & Maclow 2006)
- Self gravity
- Stellar feedback

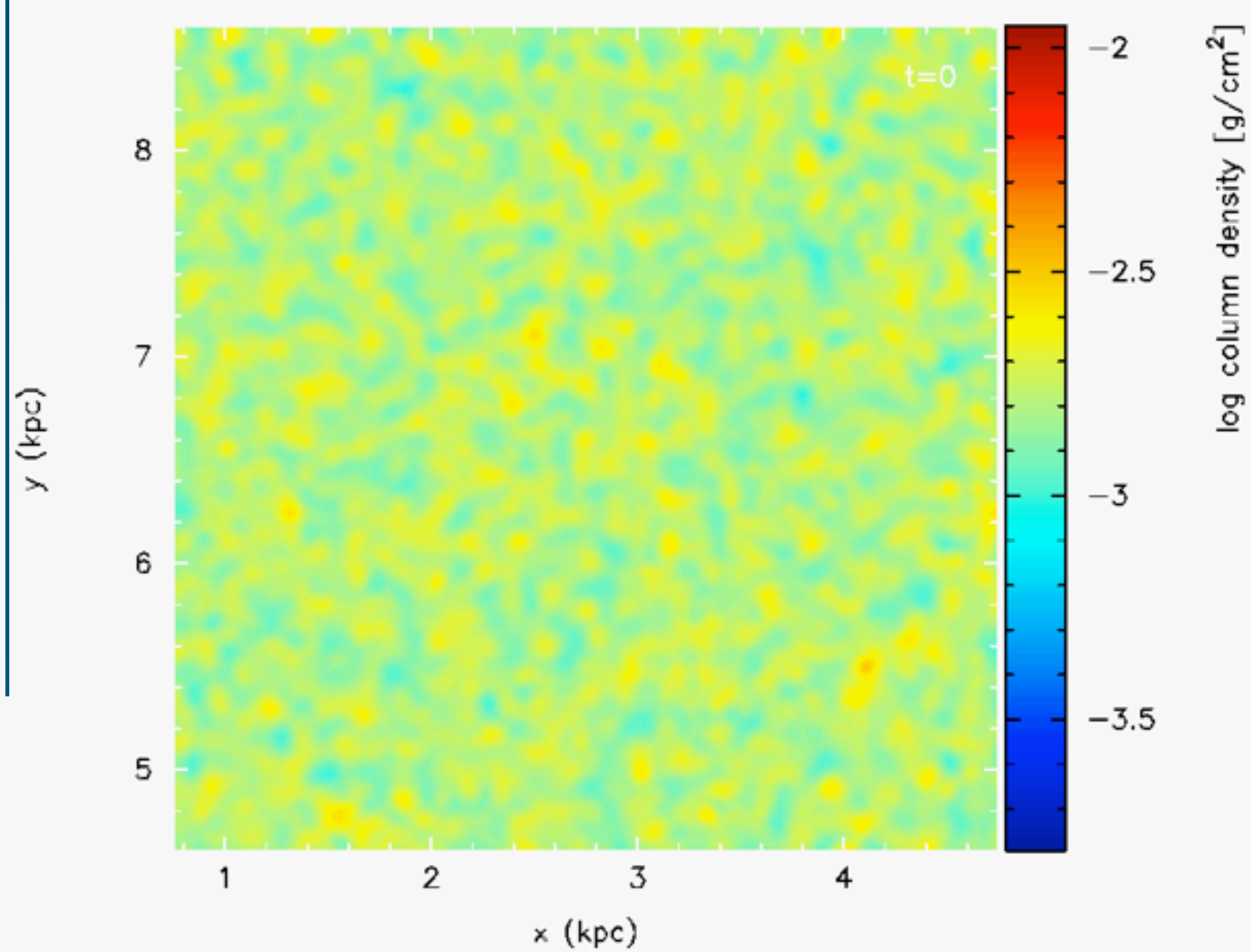
- instantaneous, inserted above a critical density

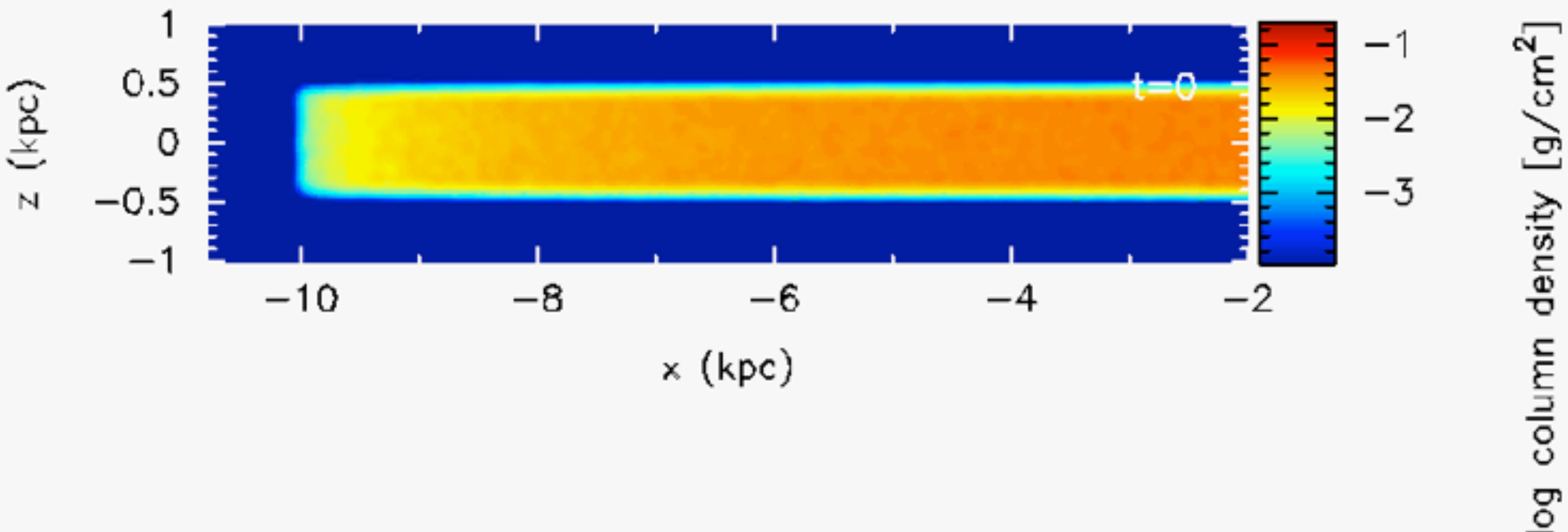
- energy added= $\frac{\varepsilon\, M(H_2) \times 10^{51}}{160\ M_\odot}$ ergs as Sedov solution (thermal + kinetic)

- 1 million particles (8 million later)

Dobbs, Burkert & Pringle 2011





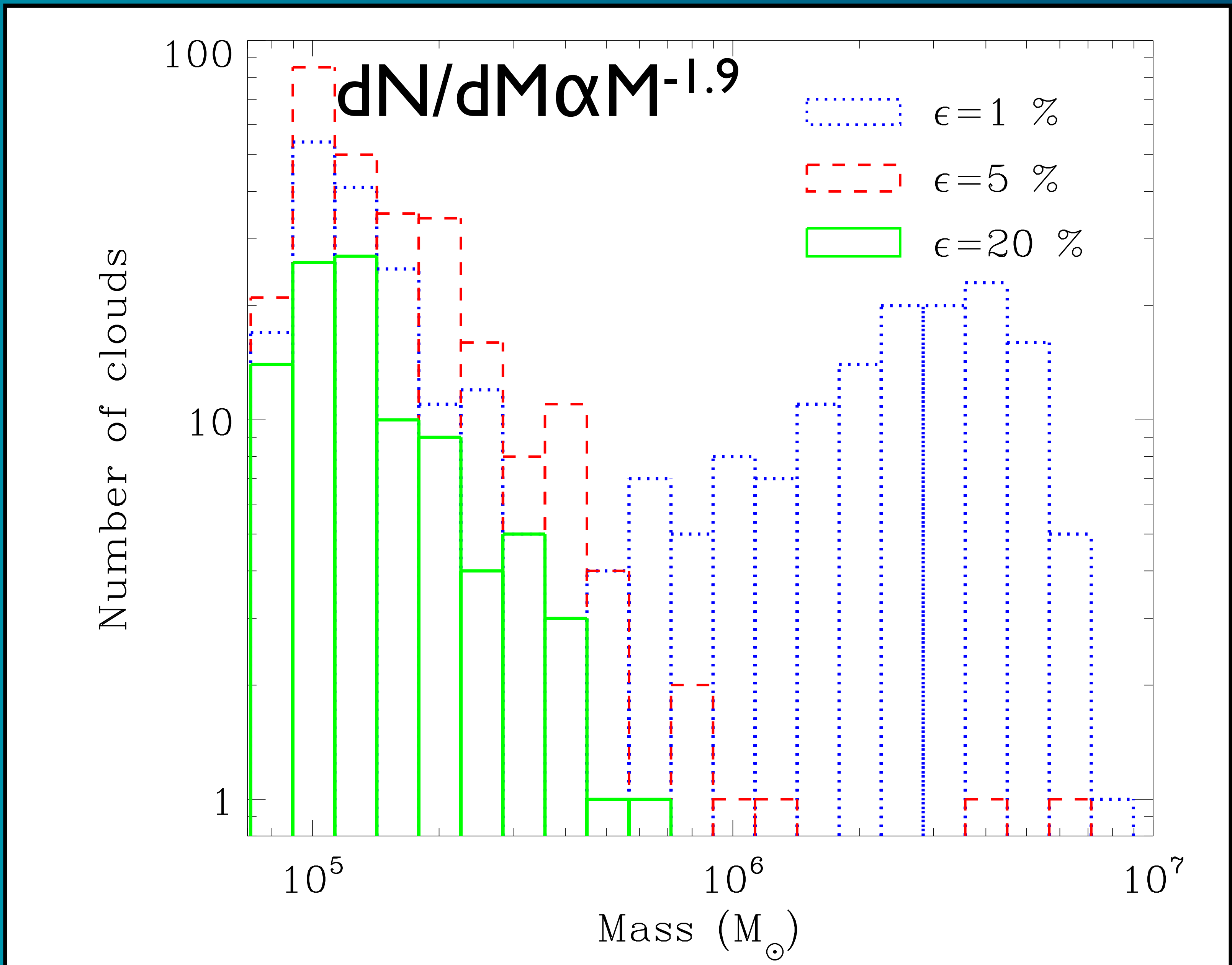


ε=5 %

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

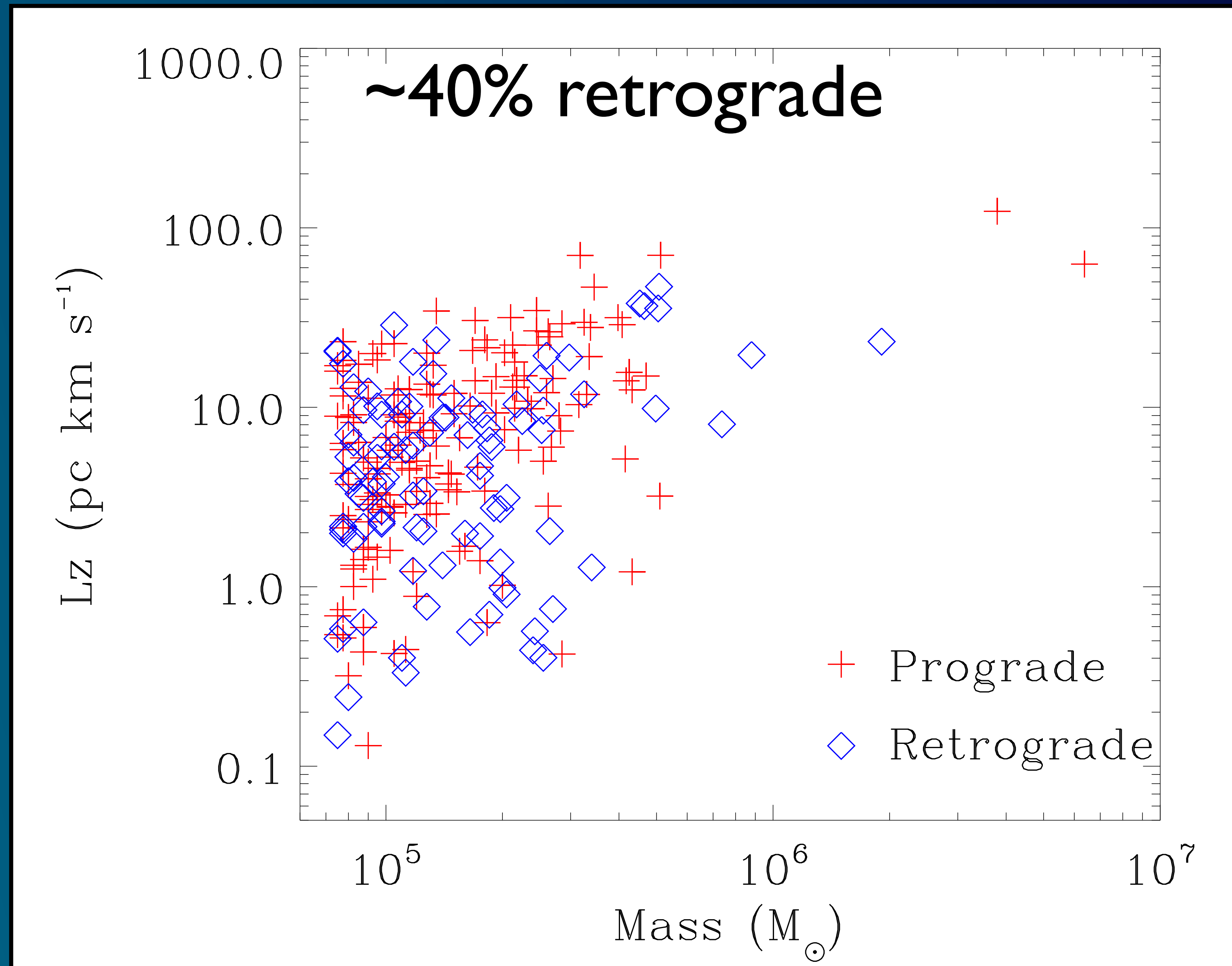
What do cloud properties tell us about cloud formation?

Mass spectrum



dependent on feedback

Rotation



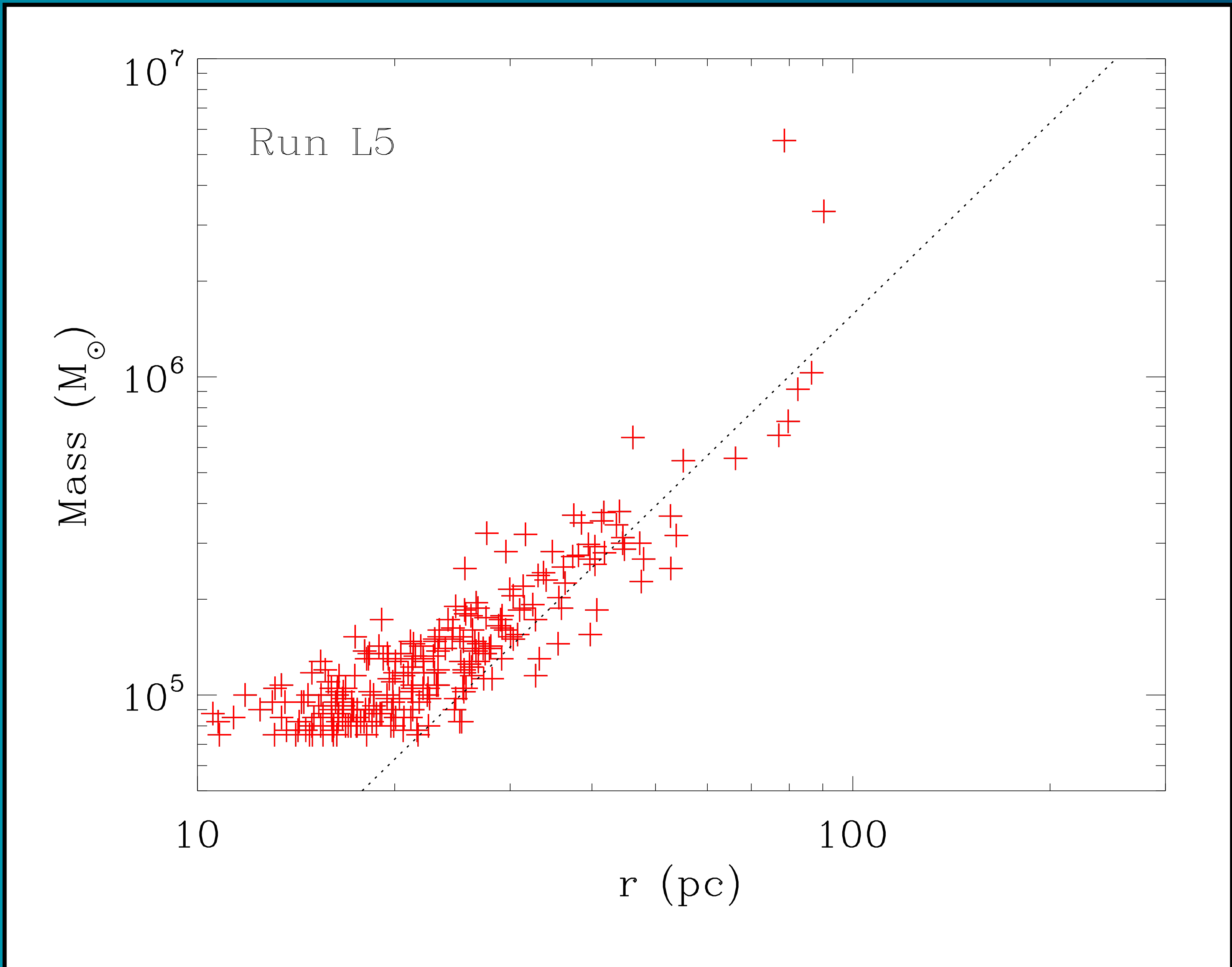
cloud-cloud interactions important

Dobbs, Burkert & Pringle 2011

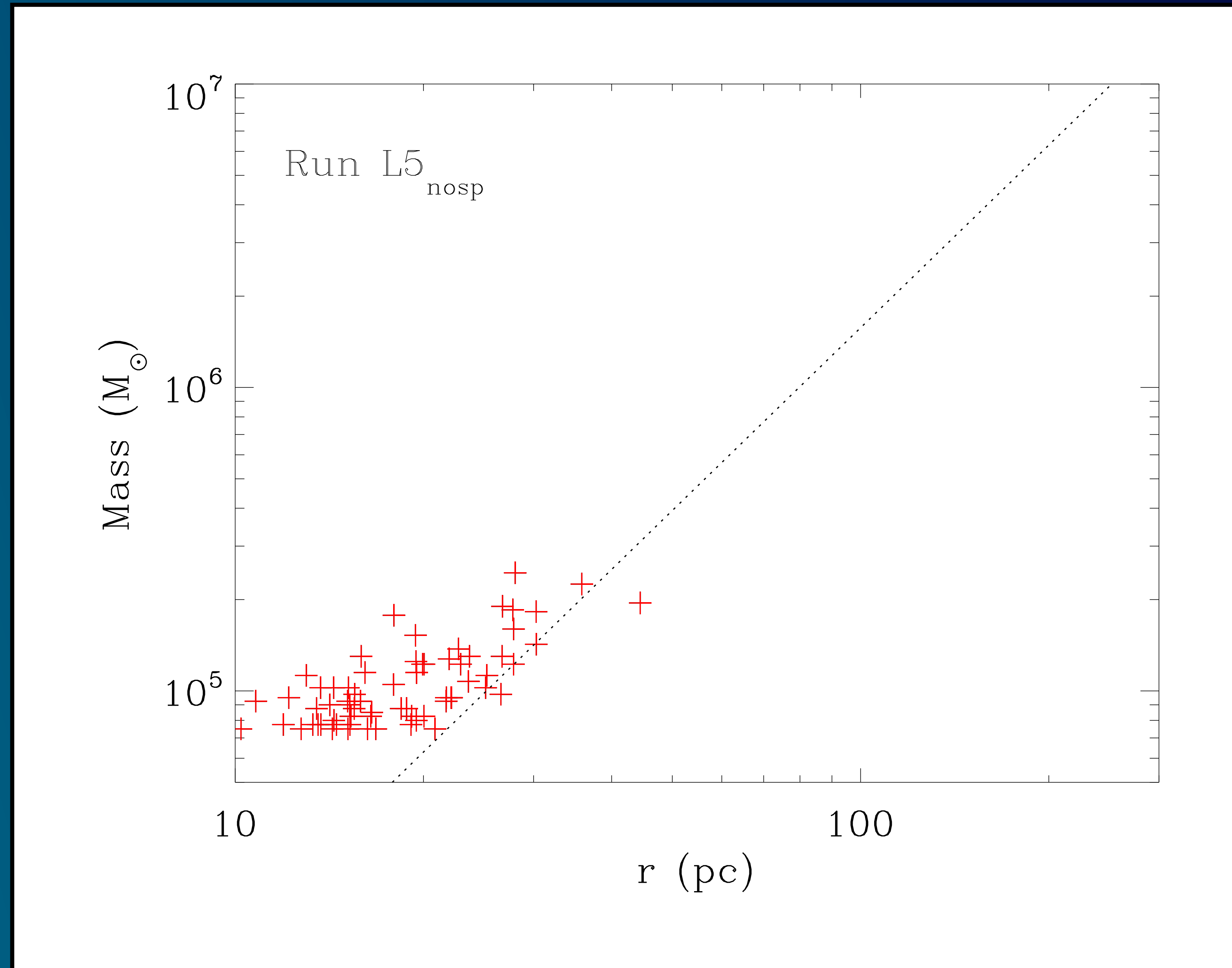
(see also Tasker & Tan 2009, Tasker 2011, Hopkins 2012, Khoperskov, Fujimoto posters)

What do cloud properties tell us about cloud formation?

With spiral potential



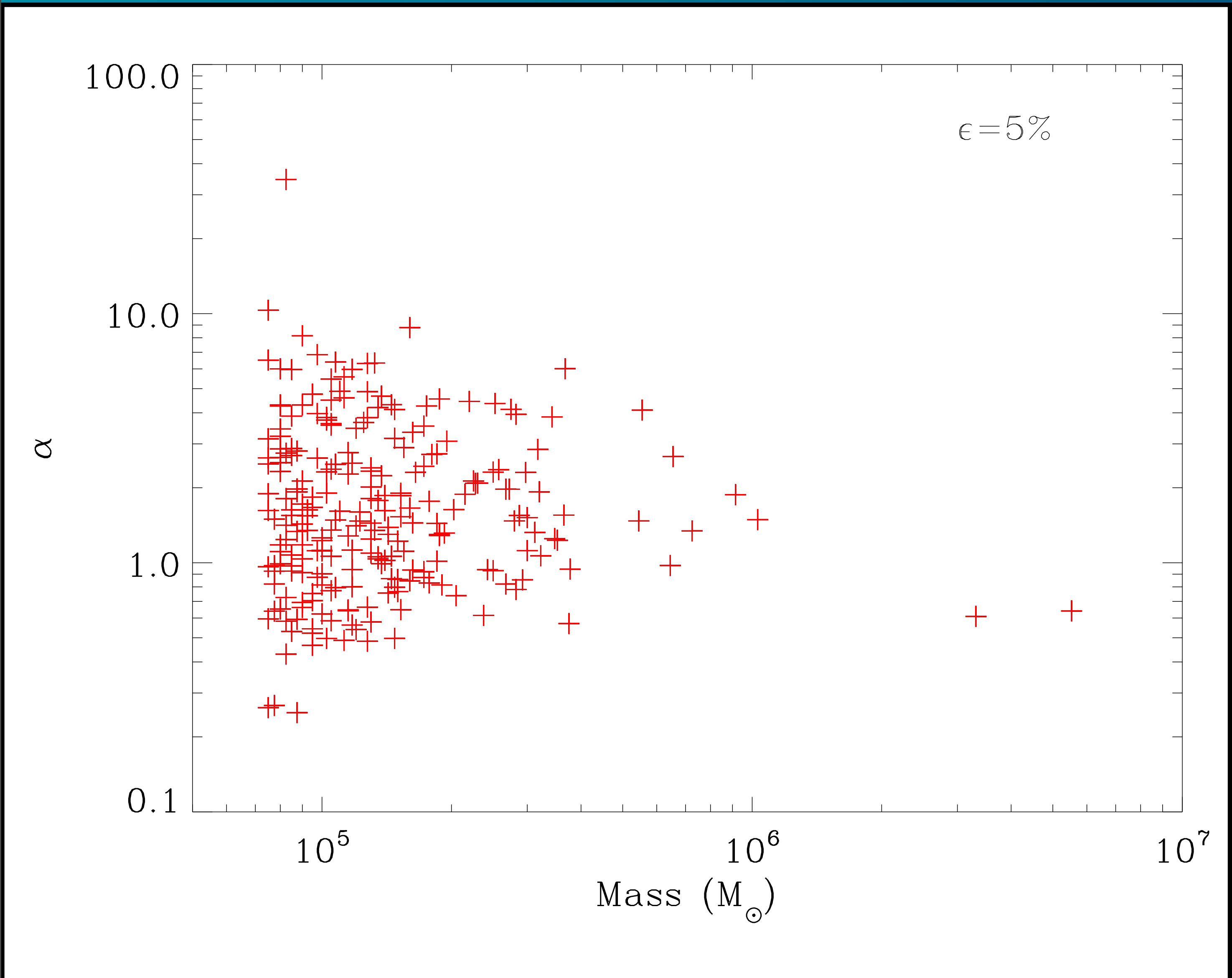
No spiral potential



more massive clouds formed by coalescence in spiral arms

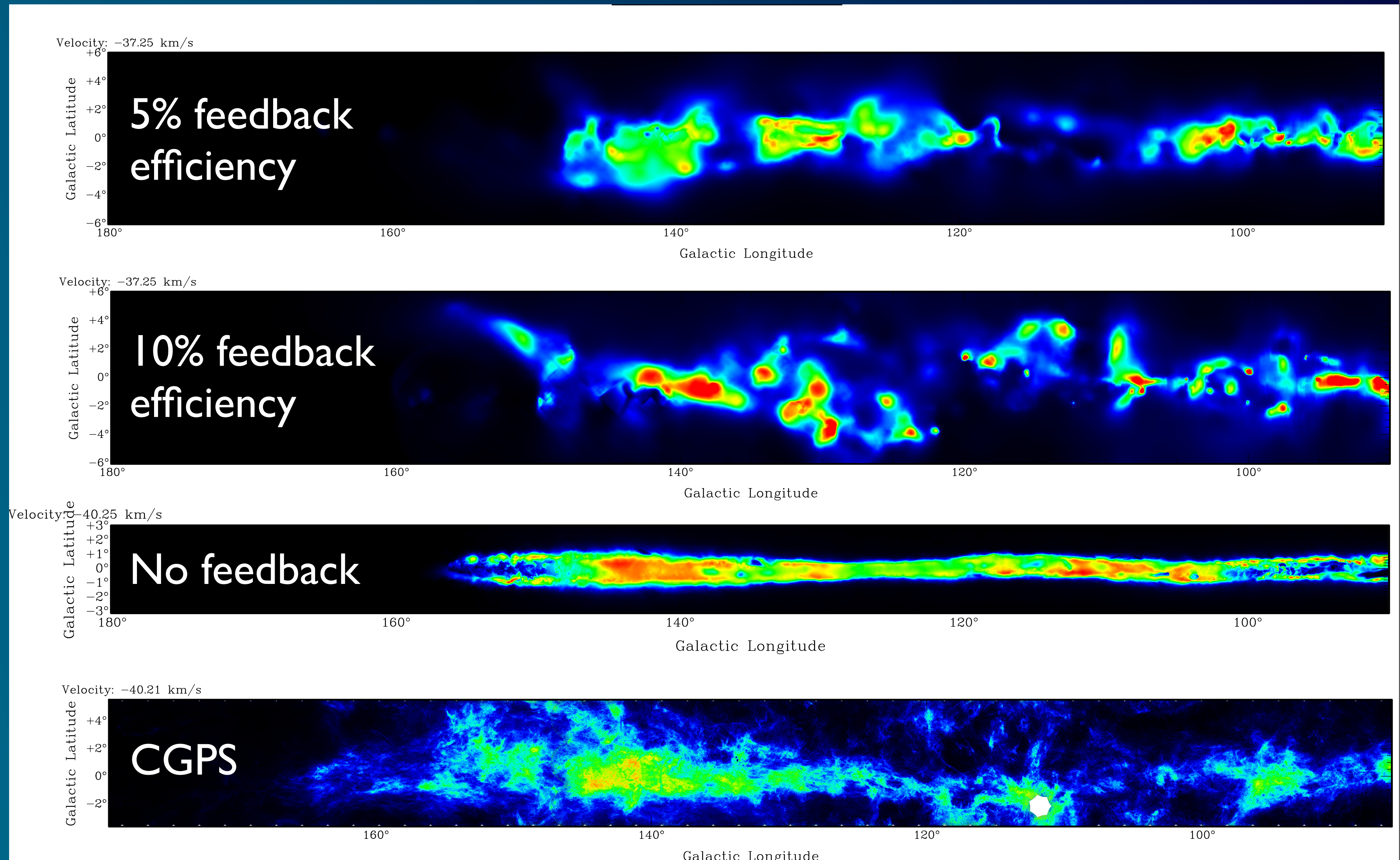
What do cloud properties tell us about cloud formation?

Virial parameter



Bound *and* unbound clouds (Dobbs et al. 2011): gravity not dominant in many clouds

Scale height in disc

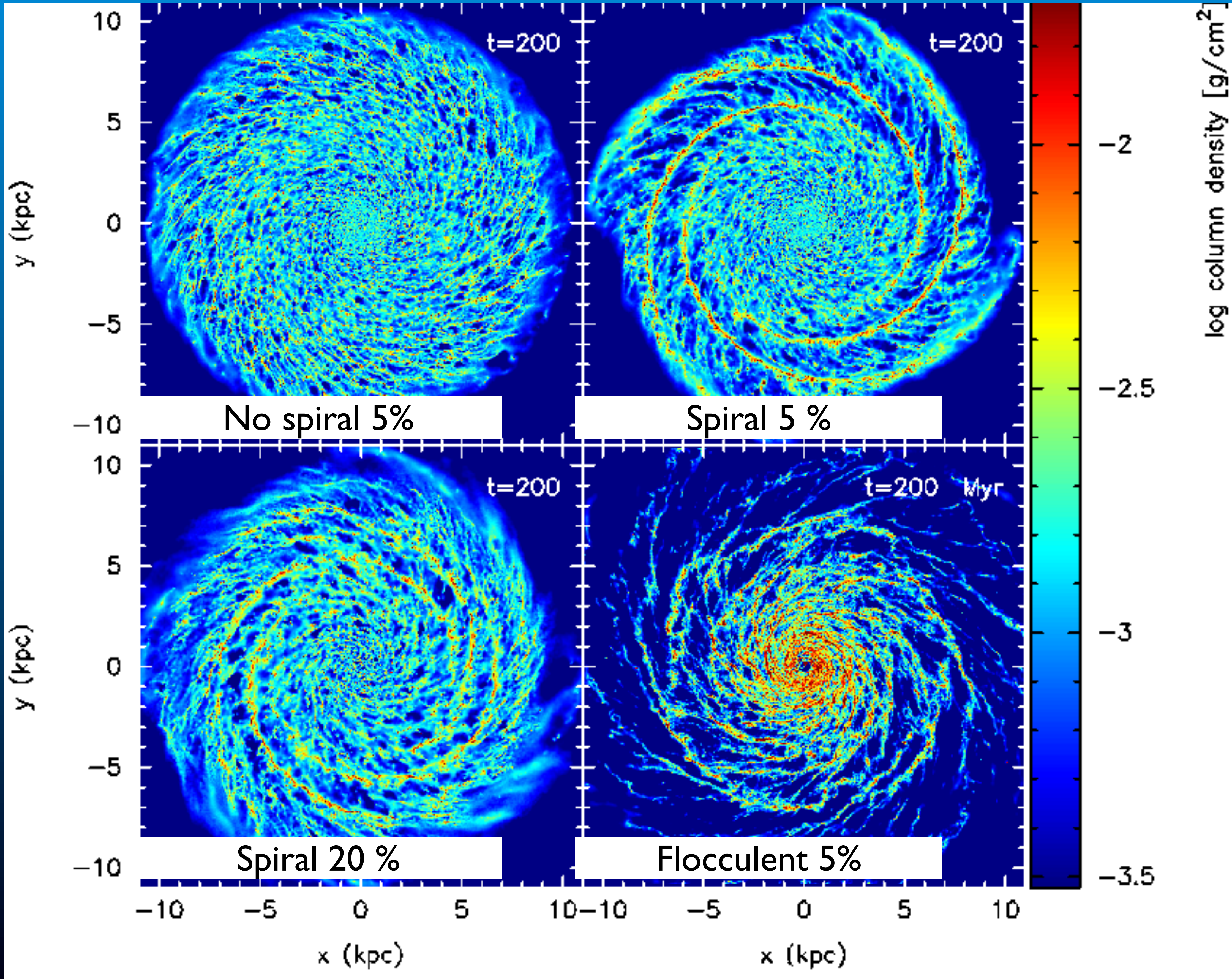


Feedback required to reproduce scale height (Acreman et al. 2012)

What do velocity flows in galaxies tell us about cloud formation?

Dobbs, Pringle & Burkert 2012

Gas flows in galaxies - 4 examples

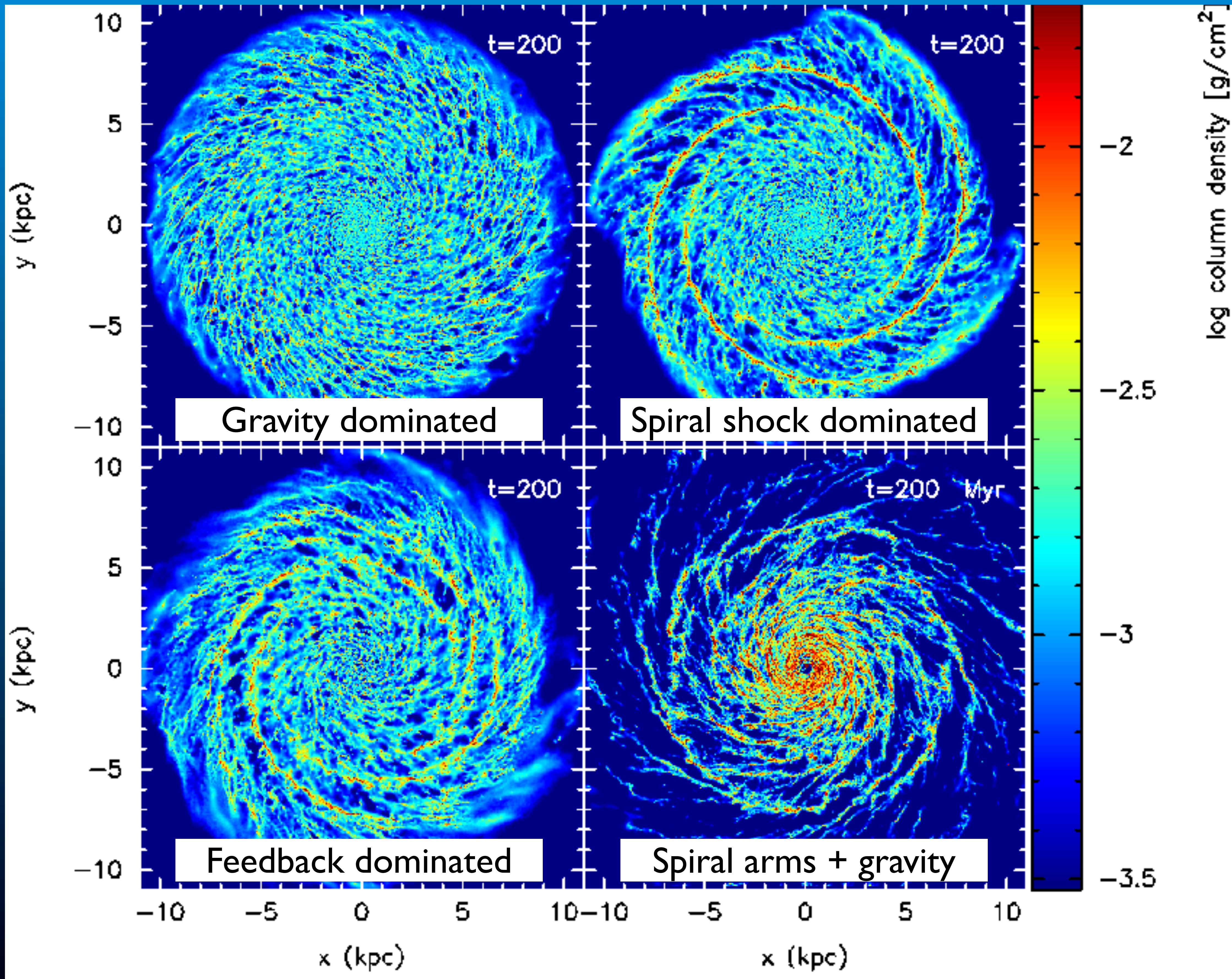


5, 20% indicates level of feedback in the simulation

'Flocculent' spiral contains star particles rather than potential

1 million gas particles

Gas flows in galaxies - 4 examples



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'Flocculent' spiral contains star particles rather than potential

1 million gas particles

What are the signatures of cloud formation?

Take Cauchy strain tensor: $$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

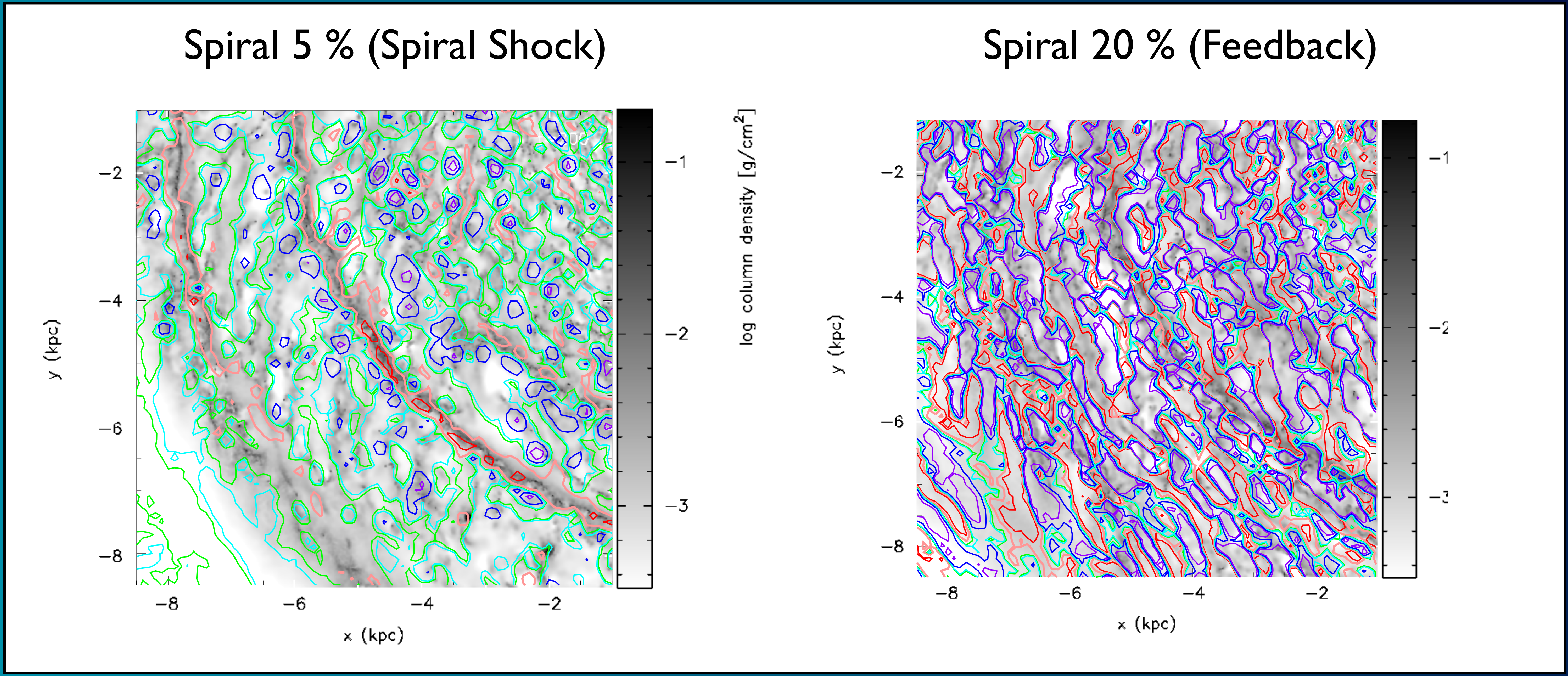
Evaluate eigenvalues, λ_1, λ_2

Then use $\alpha = \lambda_1 + \lambda_2$ (divergence), $\beta = |\lambda_1 - \lambda_2|$ (‘measure of asymmetry’)

α shows convergence, $\alpha\beta$ plane indicates nature of flows

(2D gas flows, neglect vertical dimension)

What are the signatures of cloud formation?



Maps of divergence (α)

Contours from grid of 100 pc resolution

Red - converging on 4 Myr
Orange - converging on 10 Myr

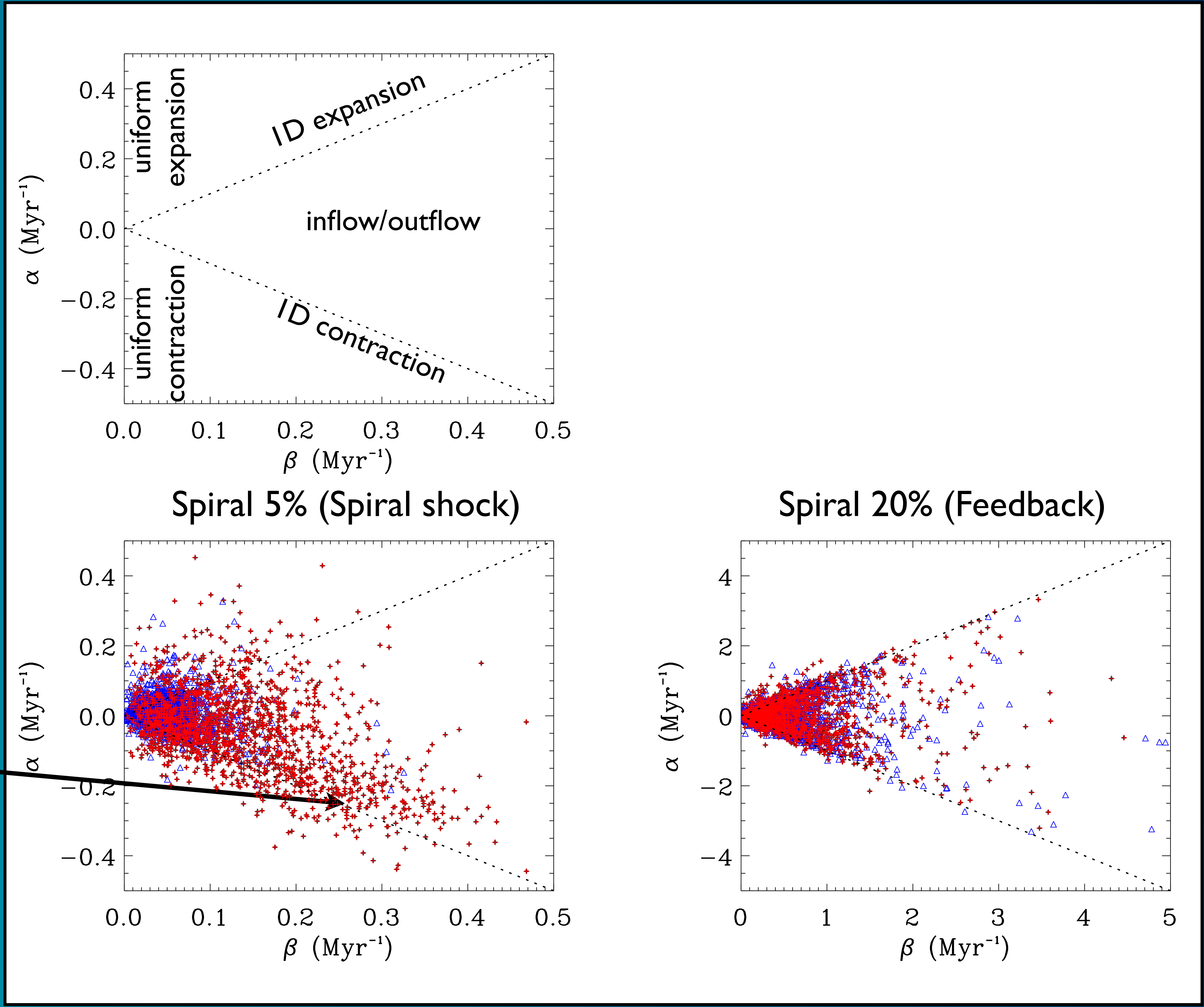
Purple - diverging on 4 Myr
Blue - diverging on 10 Myr

What are the signatures of cloud formation?

Red=dense

Blue=low density

1D Converging flows (dense gas)



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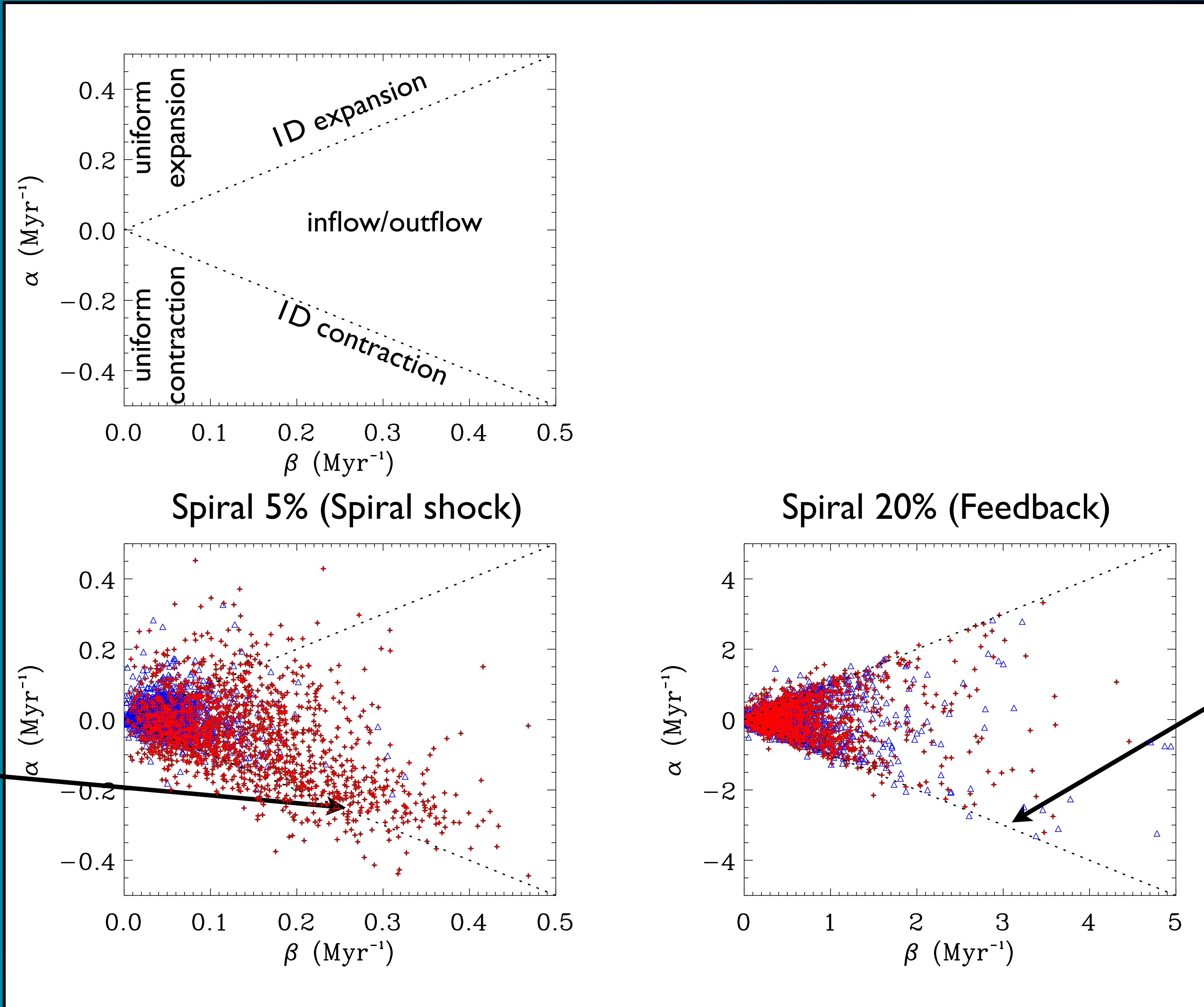


Gas converges / diverges on short timescales (< 1 Myr)

Gas gathered together independently of density

What are the signatures of cloud formation?

For other cases see paper!

What gas do GMCs form from?
and
How long do they take to disperse?

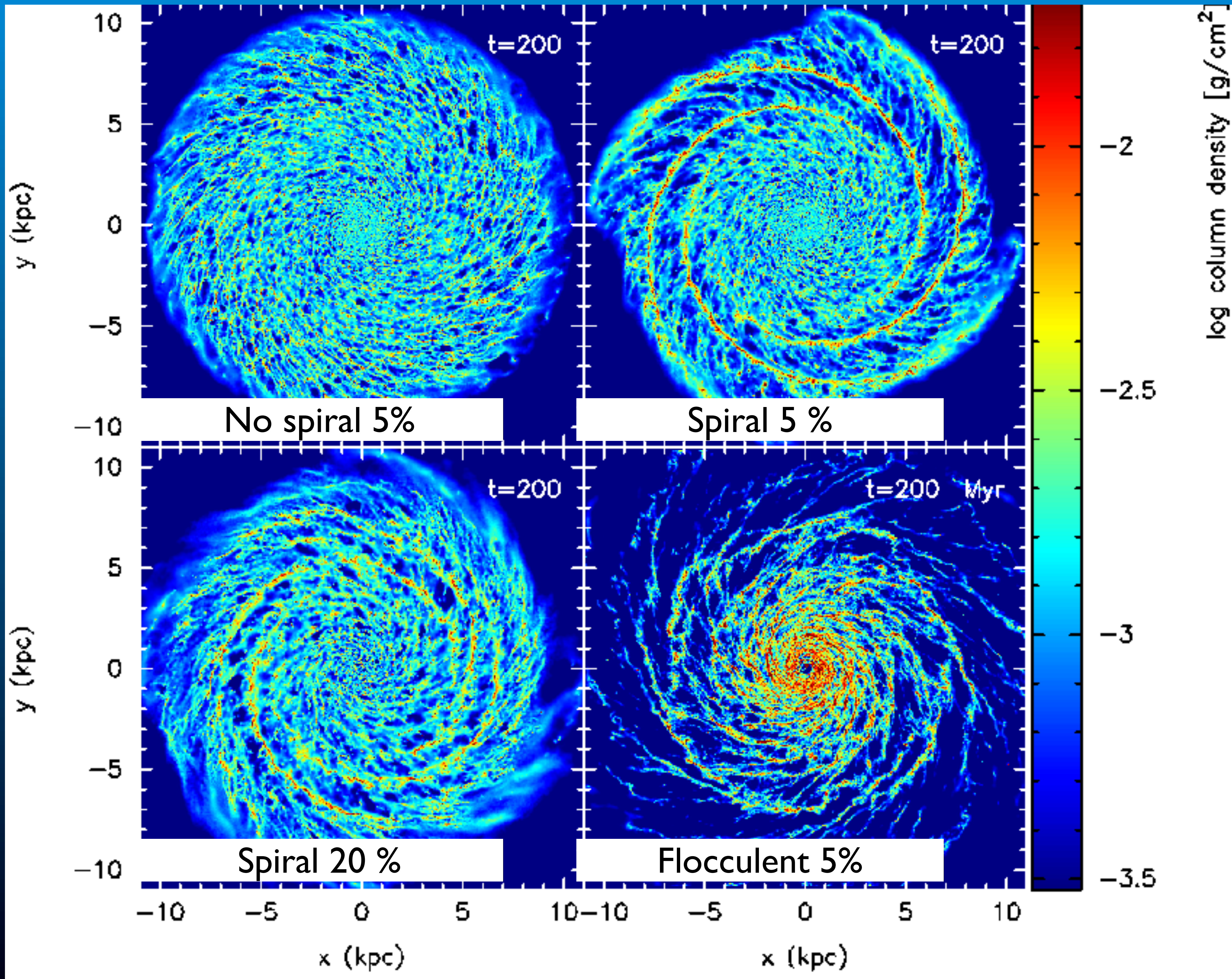
Use SPH to trace gas in GMCs to earlier and later times

density distribution?

density distribution?

Dobbs, Pringle & Burkert 2012

Gas flows in galaxies - 4 examples



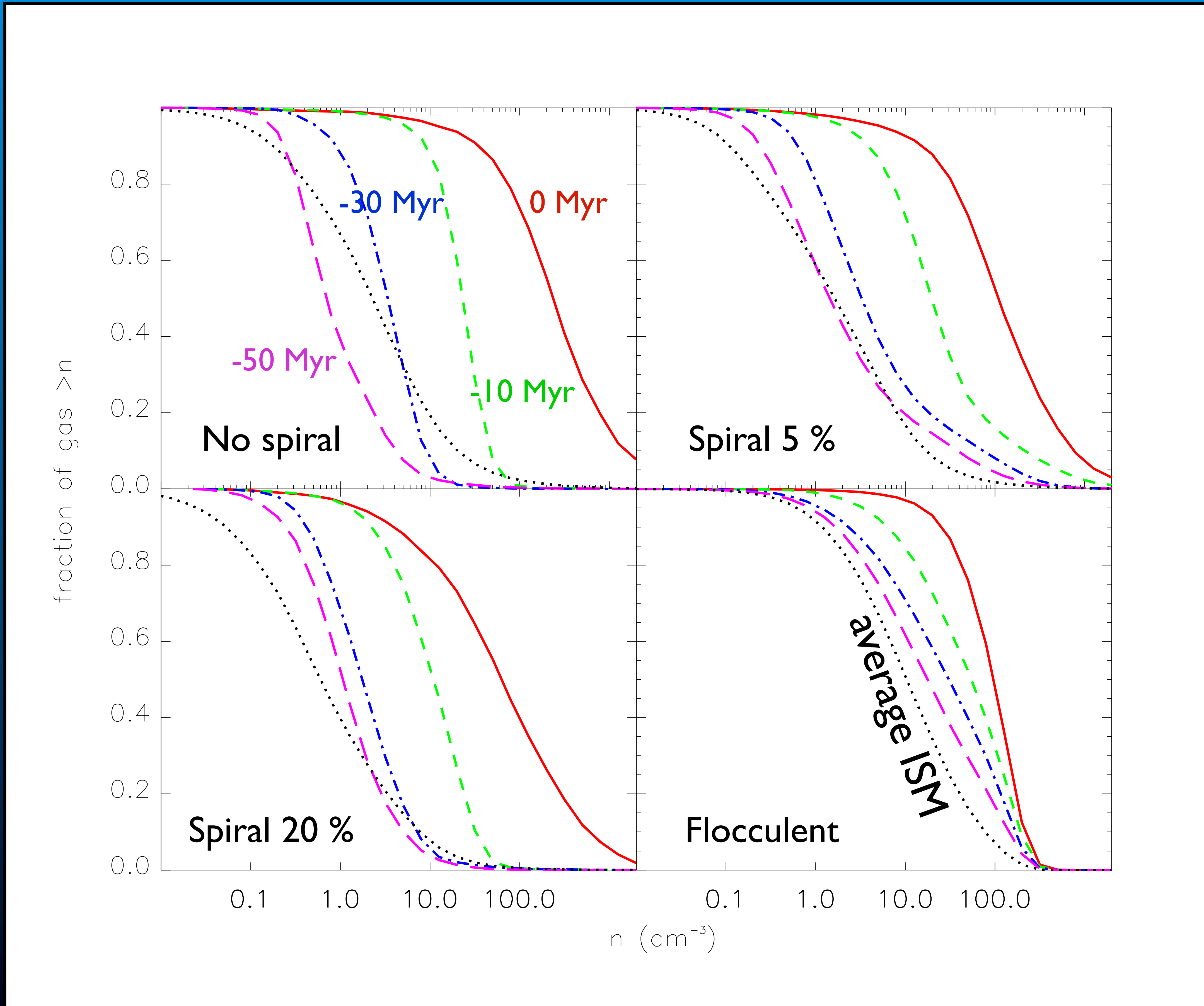
5, 20% indicates level of feedback in the simulation

'Flocculent' spiral contains star particles rather than potential

1 million gas particles

What gas goes in to GMCs?

Gas which forms GMCs is atypical <u>30 Myr</u> beforehand (overdense)

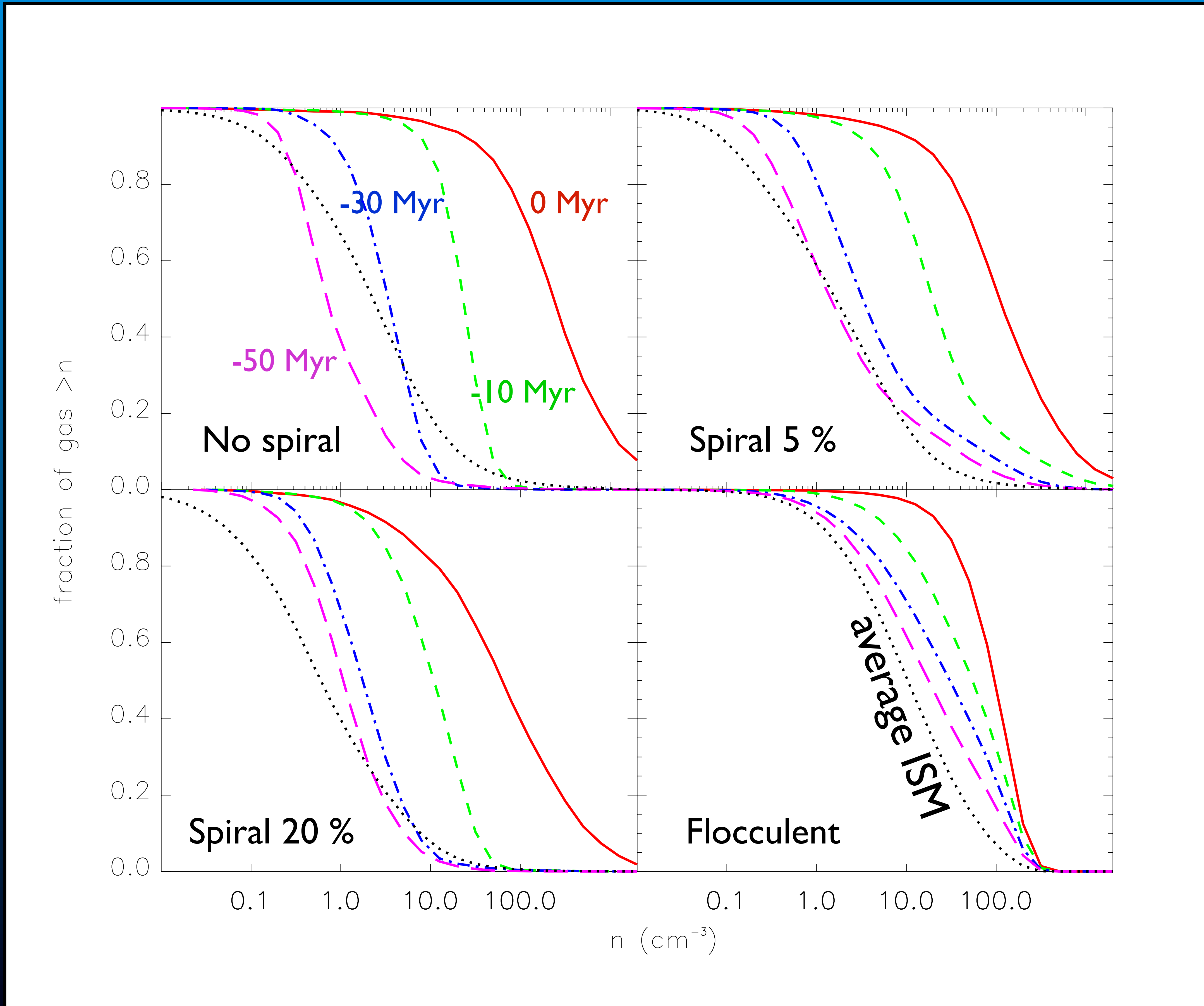


What gas goes in to GMCs?

Gas which forms GMCs is atypical <u>30 Myr</u> beforehand (overdense)

No spiral - sudden phase change

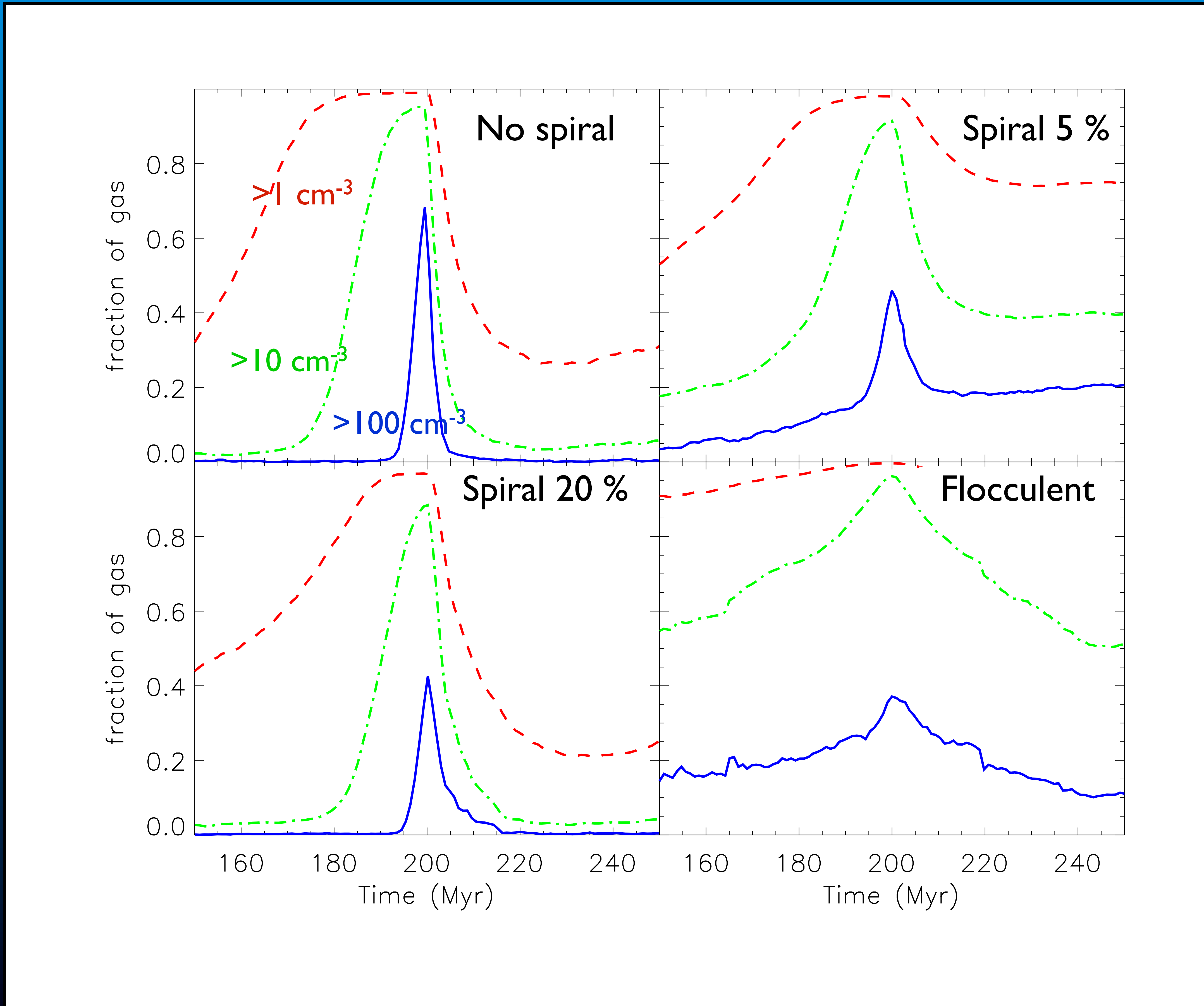
Spiral 5% - gradually more gas becomes dense (molecular)



When is gas in GMCs?

Very dense gas occurs 5-10 Myr around star formation

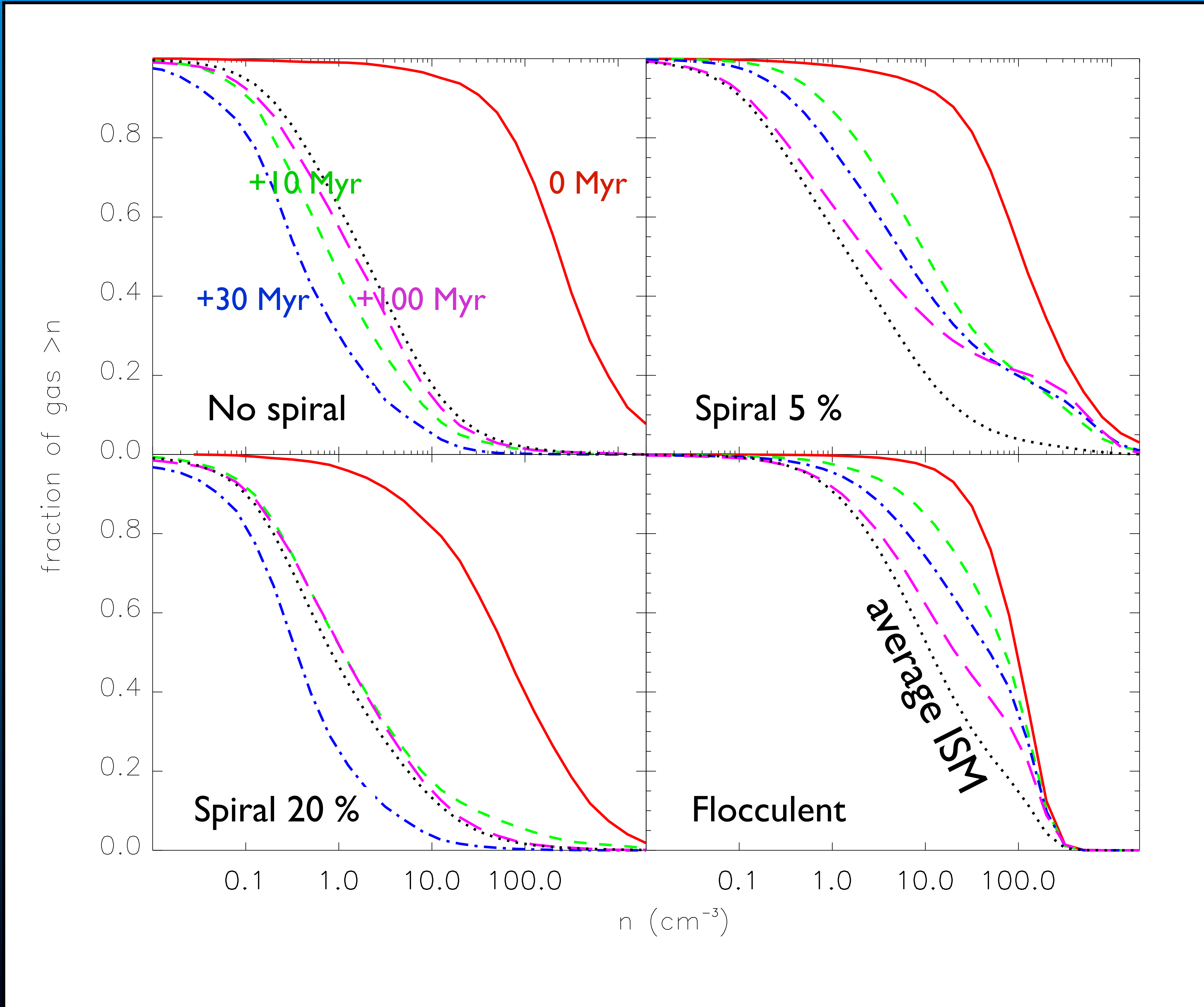
Moderately dense gas exists for much longer



What happens to gas which was in GMCs?

Gas also takes a long time (50 Myr to return to typical ISM)

For spiral 5% and flocculent models, gas is not completely recycled!



Evolution of a $2 \times 10^6 M_\odot$ GMC

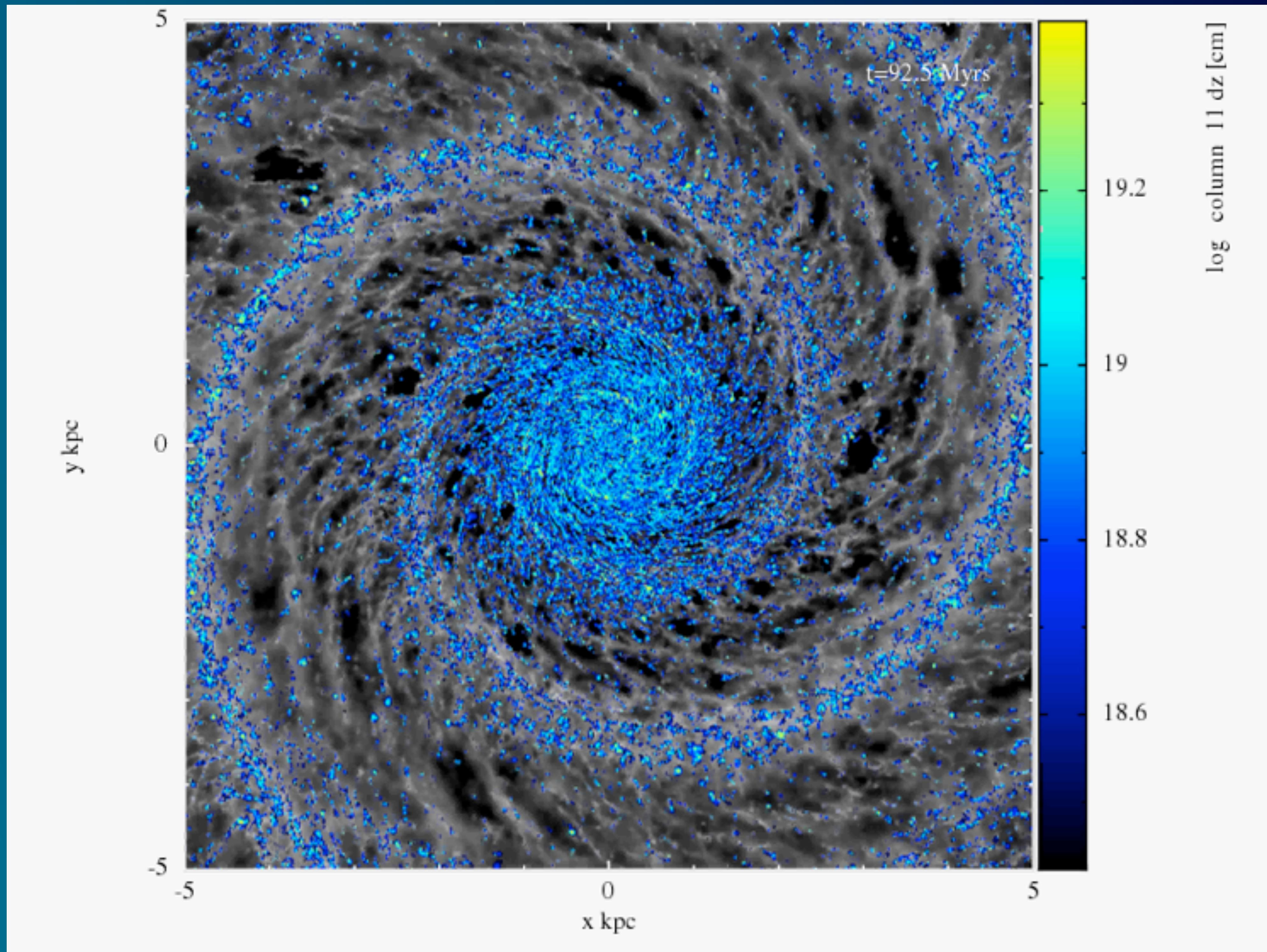
8 million particles

Cooling / heating

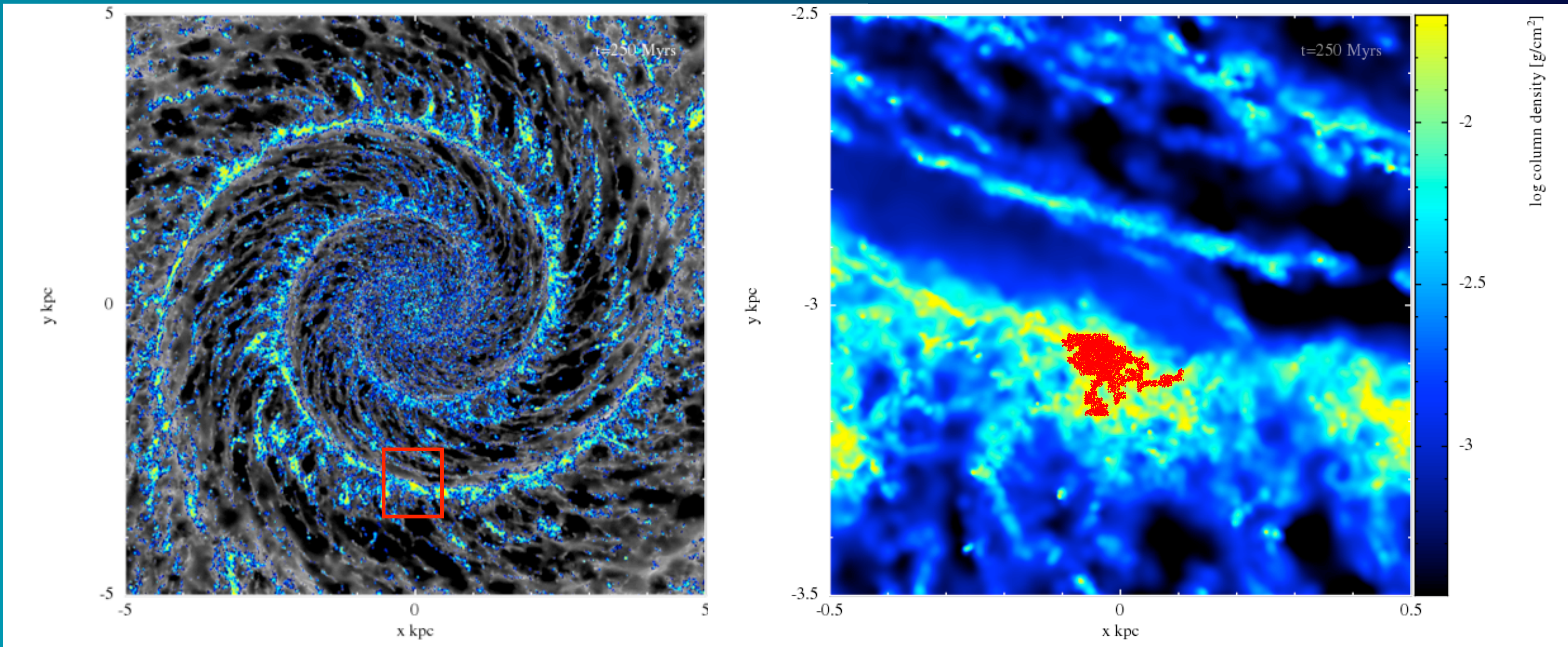
Self gravity

n=2 spiral potential

Supernovae feedback

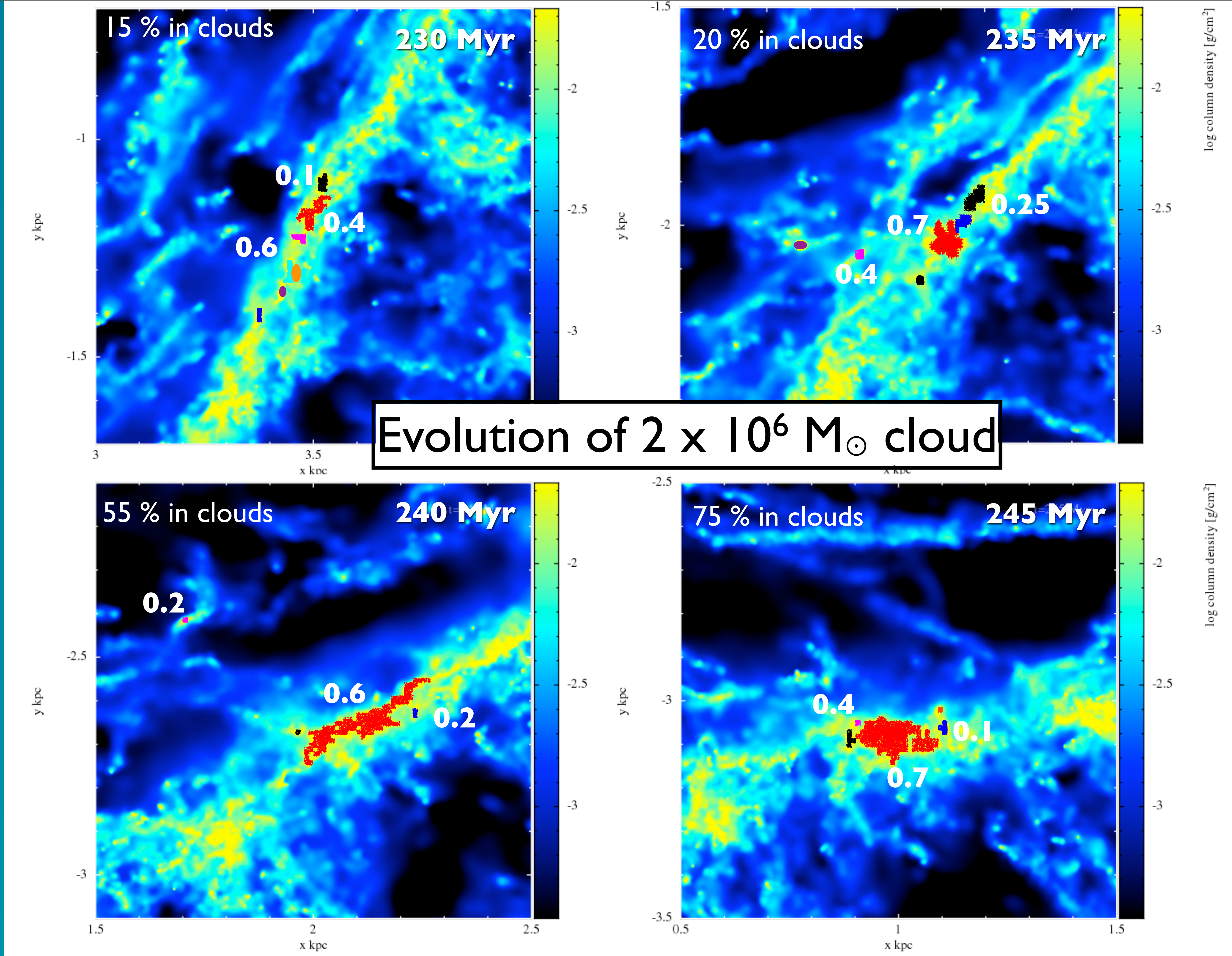


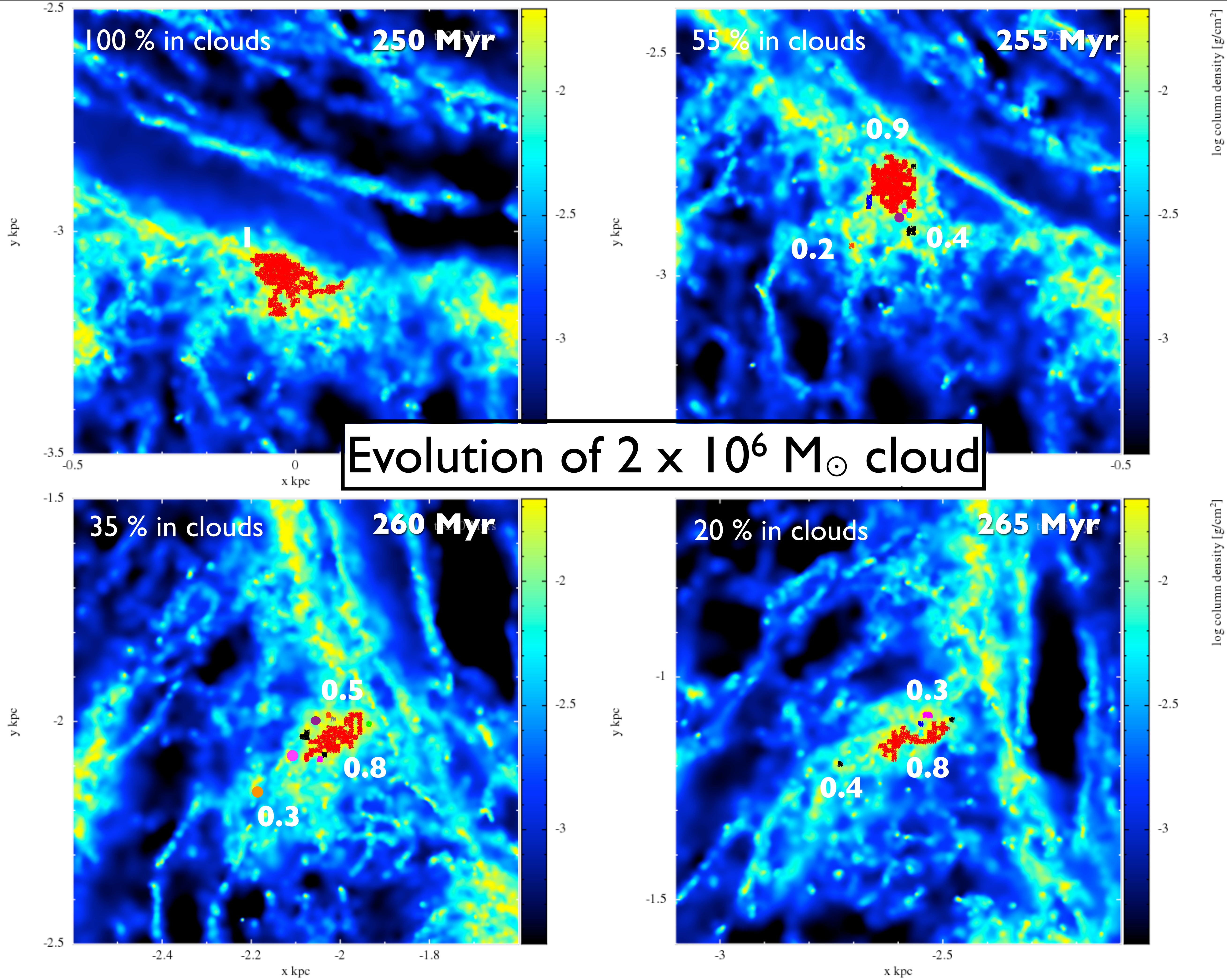
Evolution of individual cloud



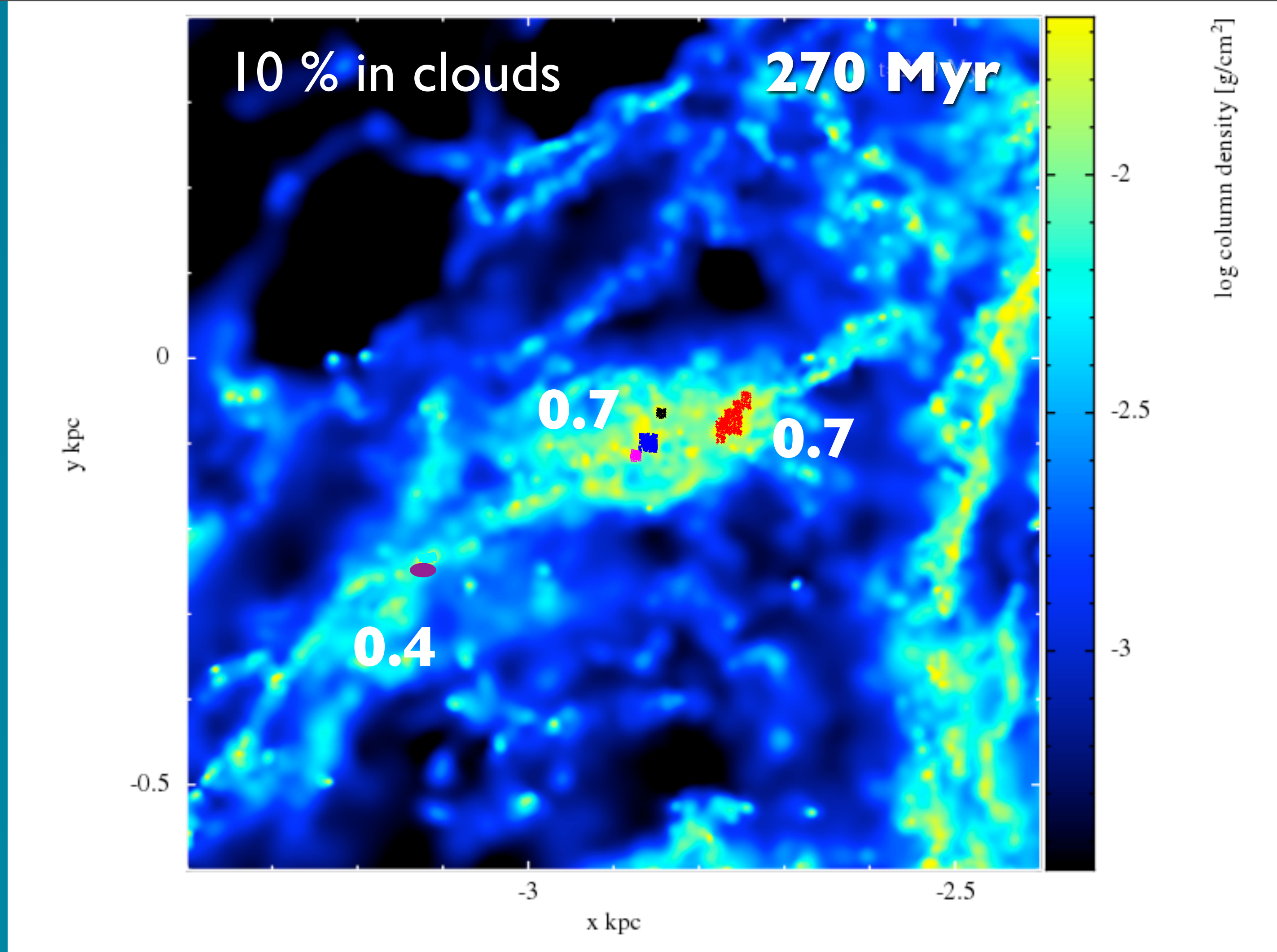
6400 particles

Evolution of 2 x 10^6 $M_\odot$ cloud



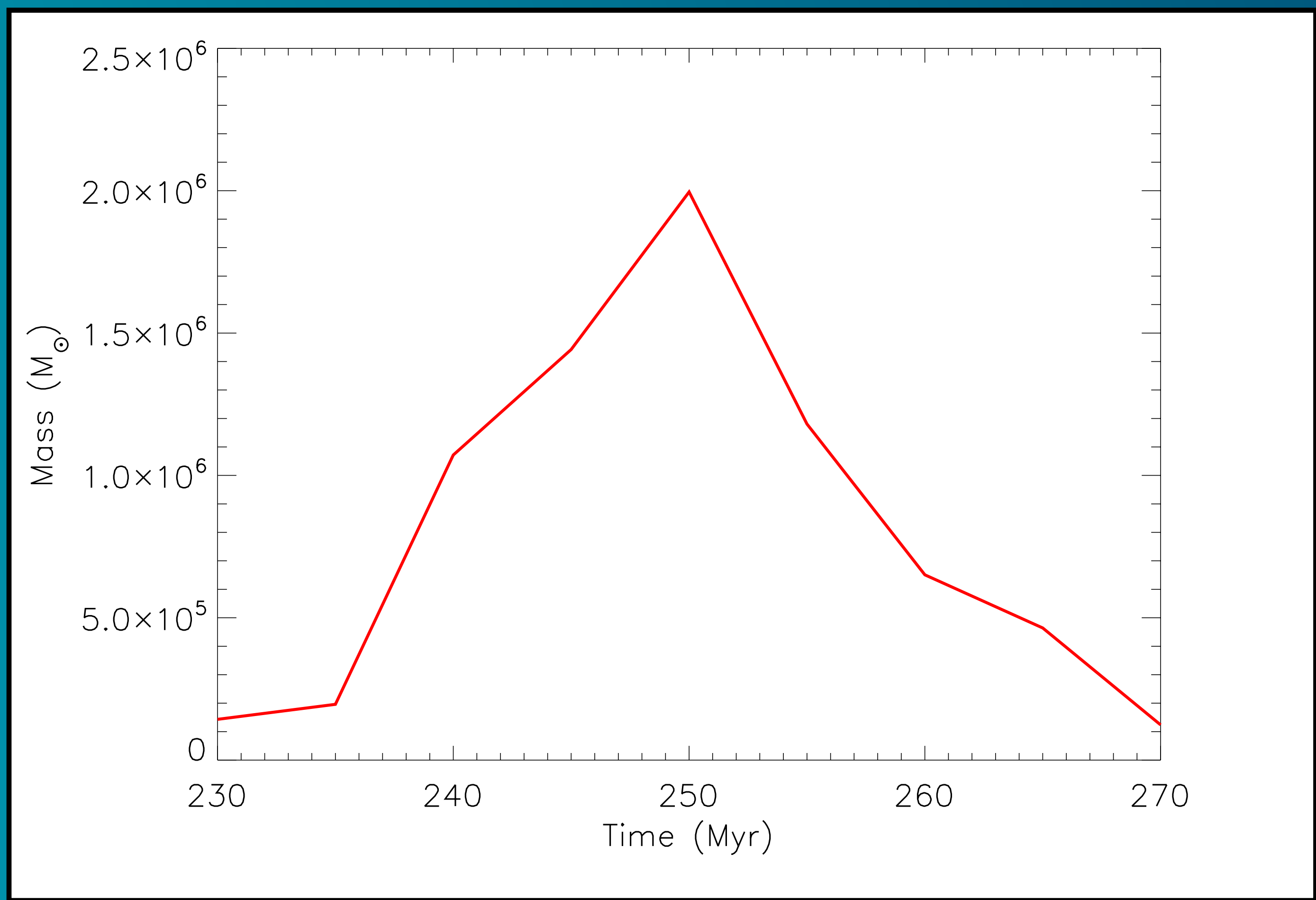


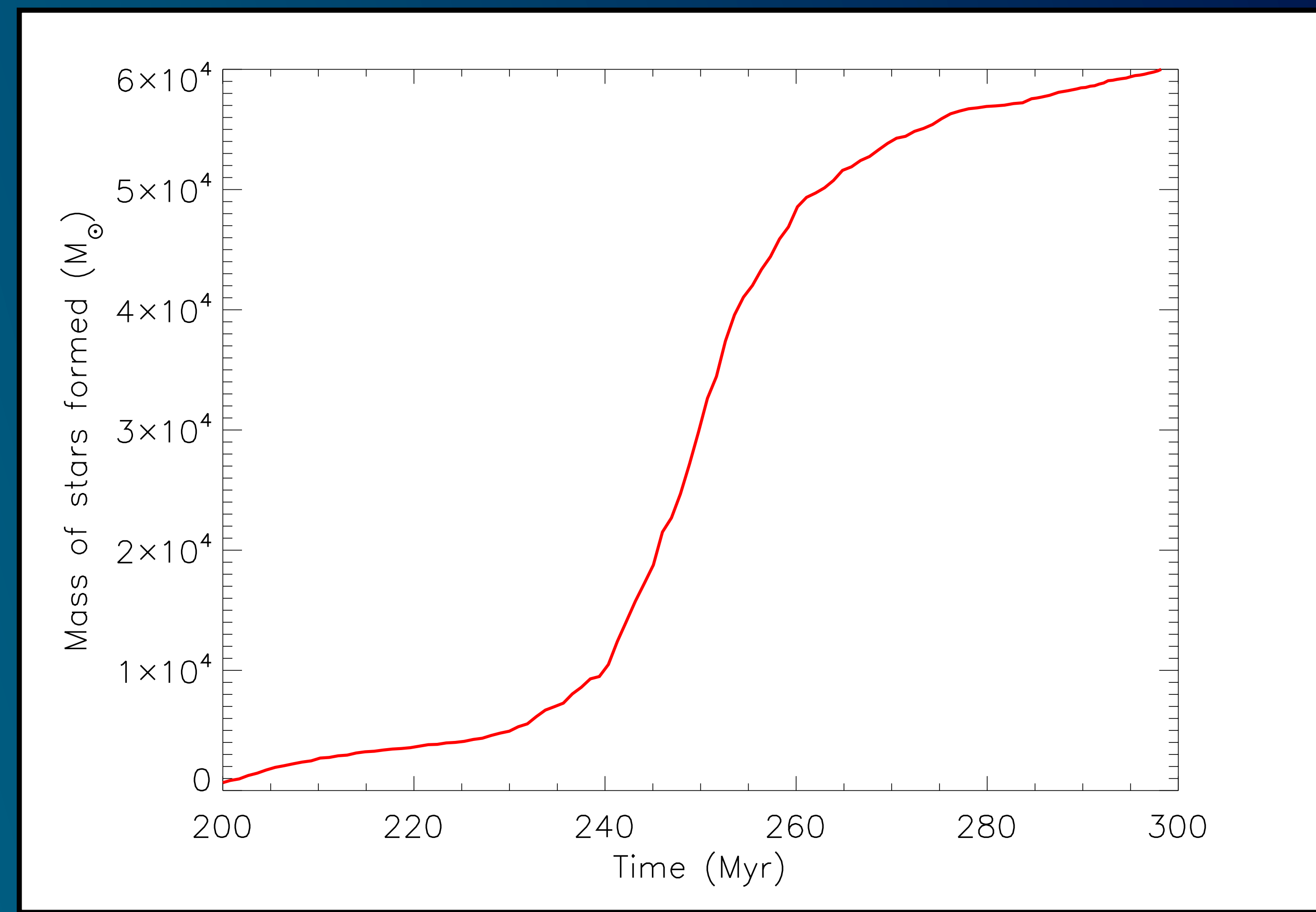
Evolution of 2 x 10^6 $M_\odot$ cloud


10 % in clouds
270 Myr
0.7
0.7
0.4
0
-0.5
y kpc
-3
-2.5
x kpc
-2
-2.5
-3
log column density [g/cm^2]

Lifetime of 2×10^6 $M_\odot$ GMC

- What is 'lifetime'?
- No obvious definition





Most gas in a cloud which is also in chosen 250 Myr cloud

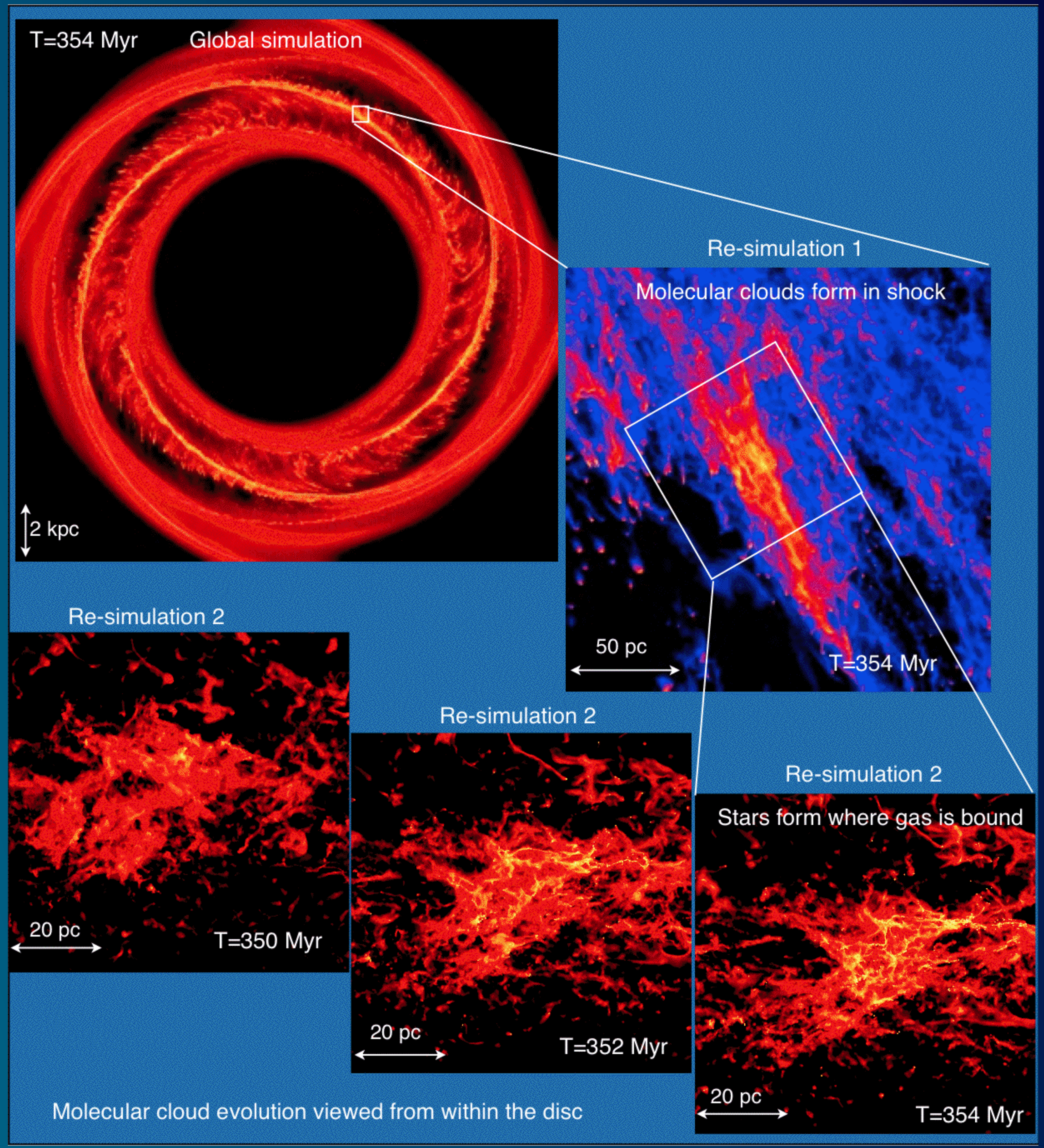
Lifetime~20 Myr?

Total mass of stars formed~$5 \times 10^4 M_\odot$

Efficiency (stars formed / cloud mass) = 2.5%

What about star formation?

Star formation from galactic scales:

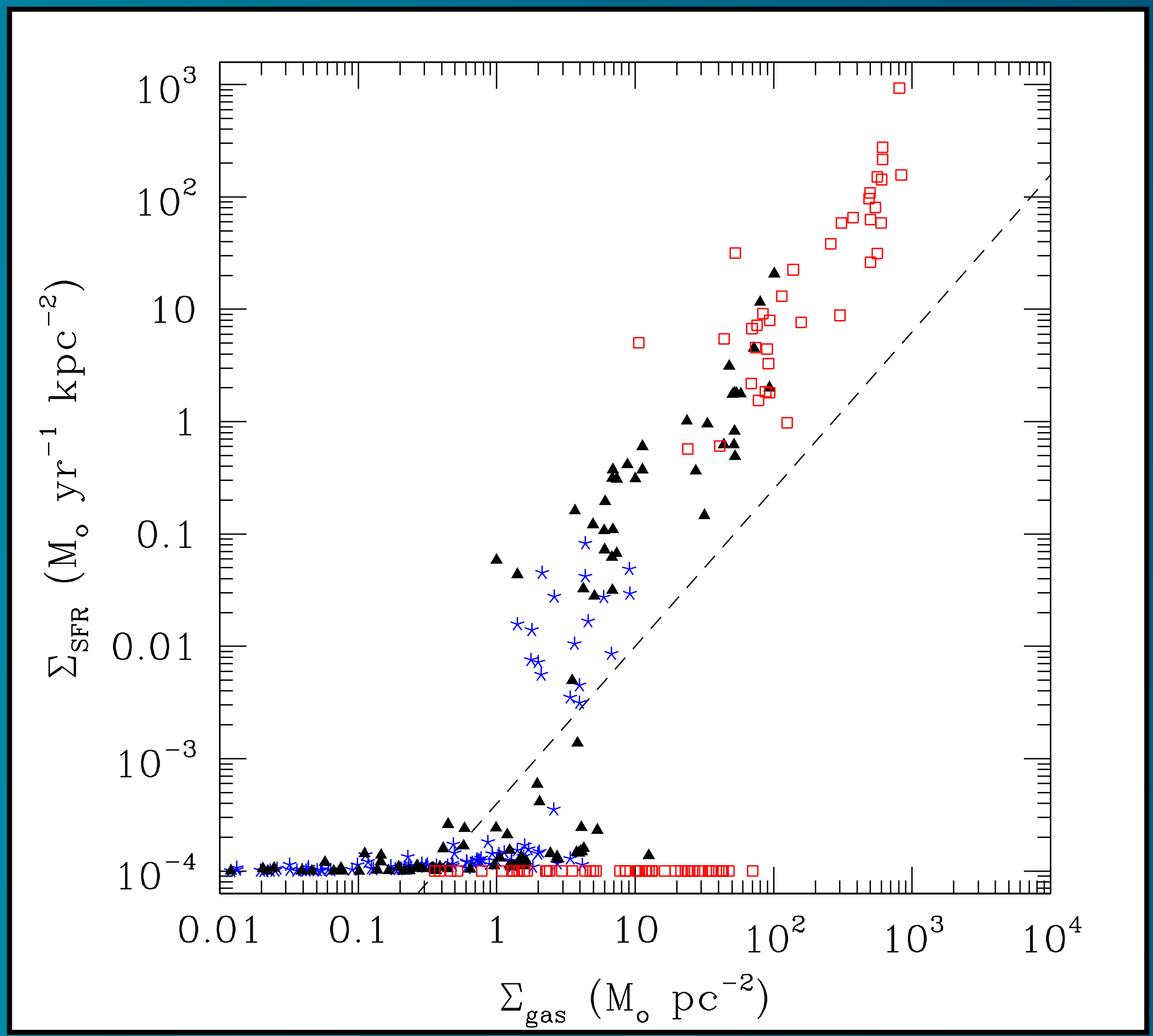


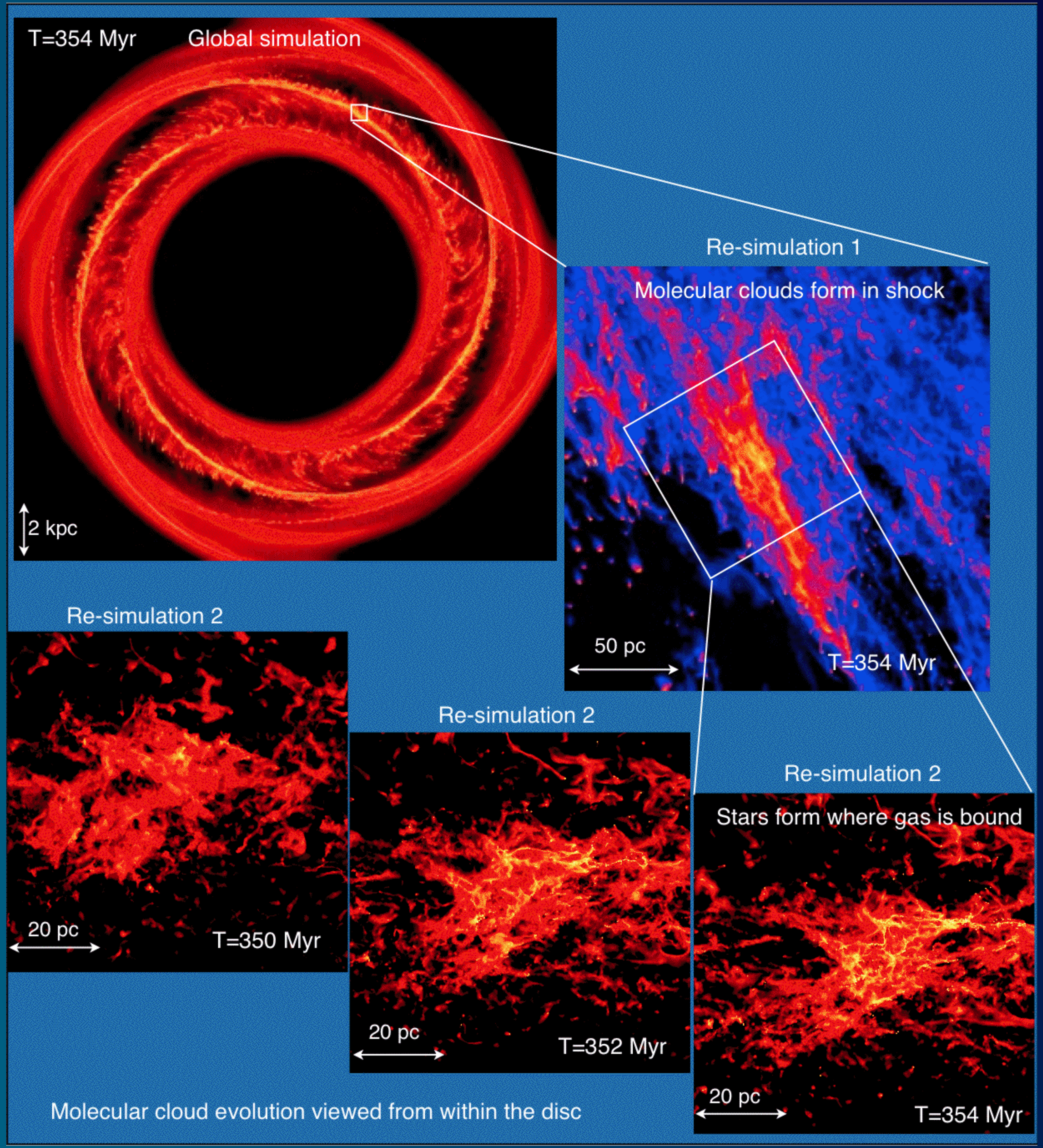
What about star formation?

Star formation from galactic scales:

- reproduce ~ linear relation
- but star formation too efficient

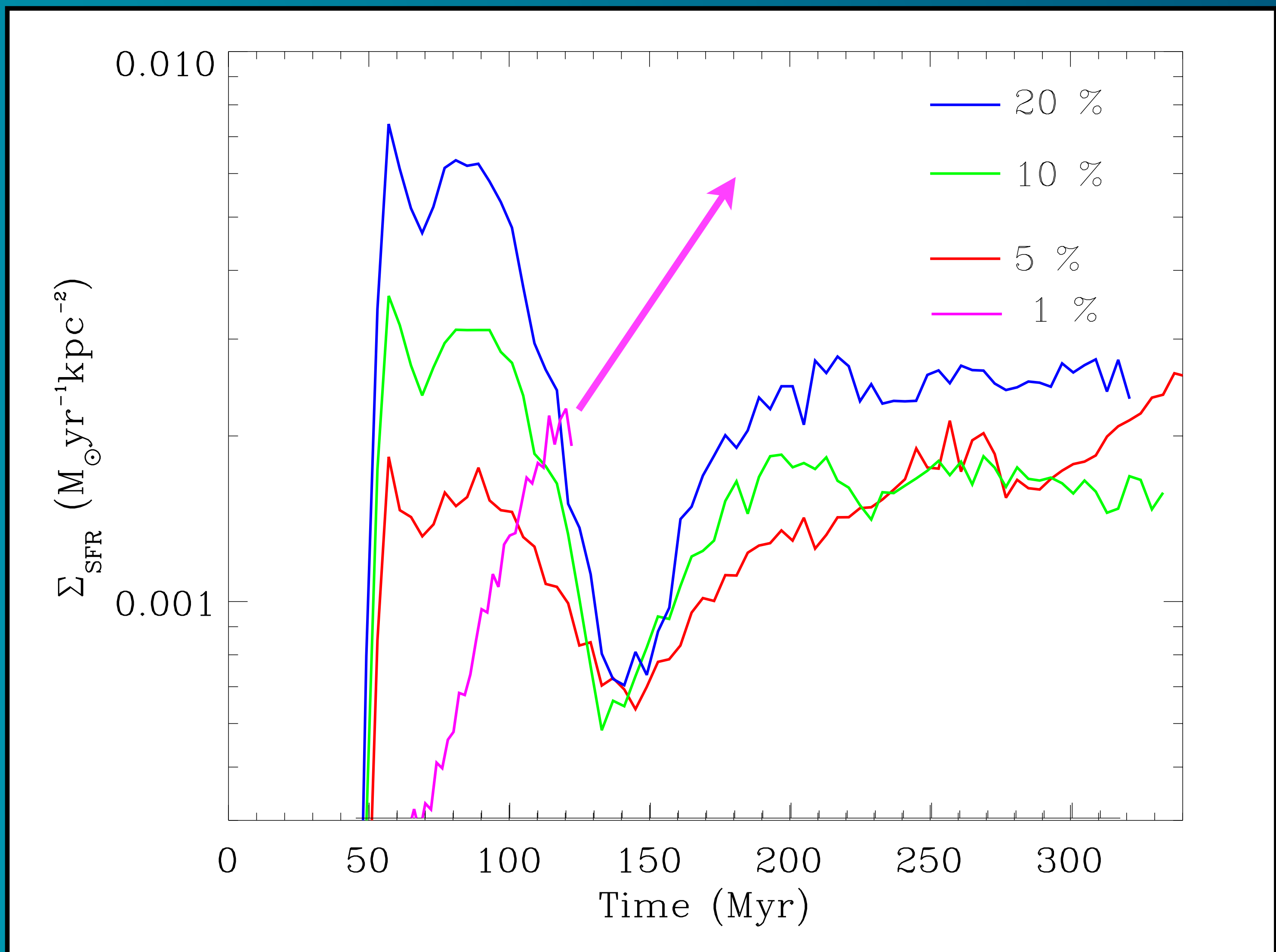
Bonnell et al., in prep.





What reduces star formation efficiency?

Feedback

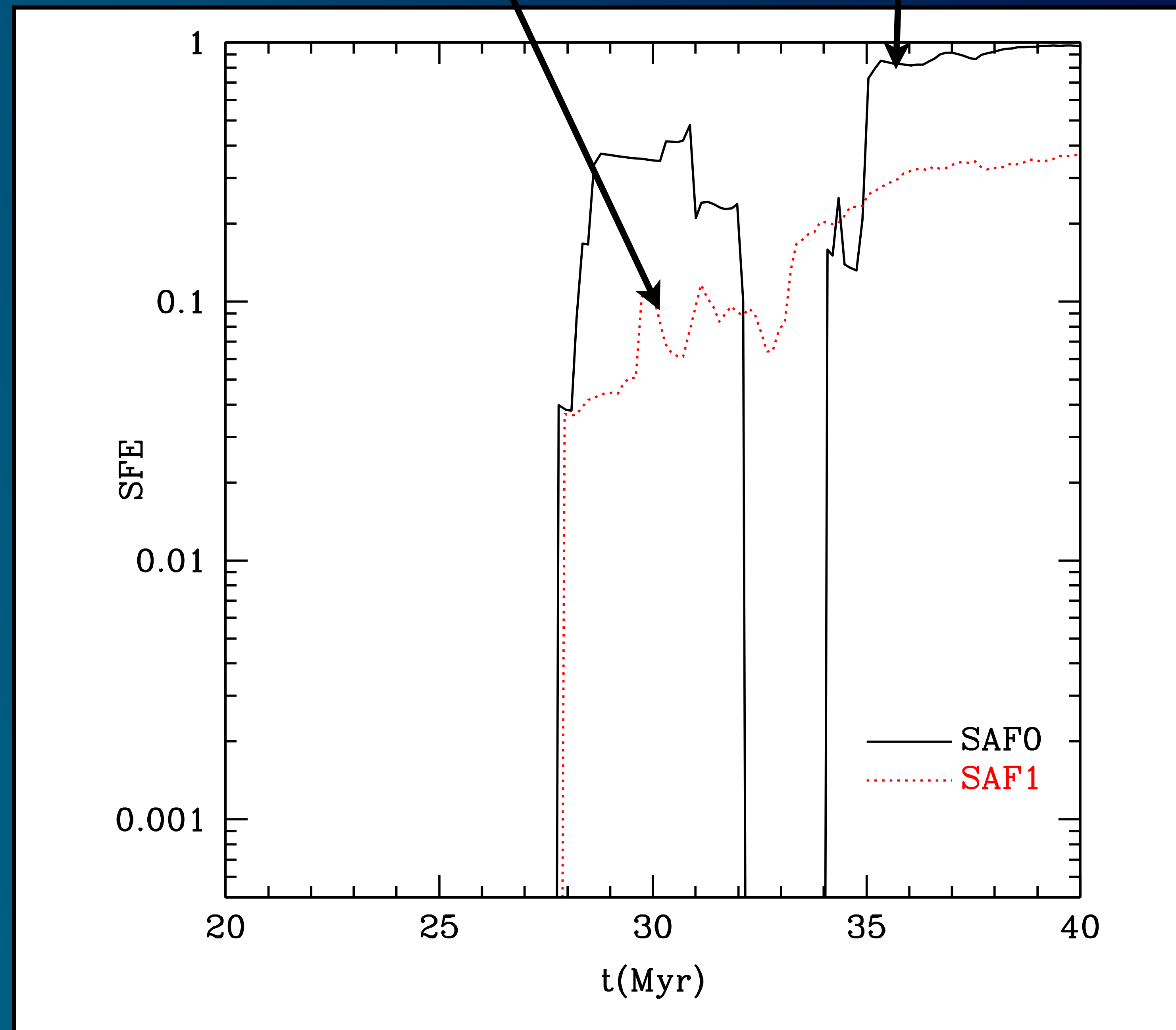


Dobbs, Pringle & Burkert 2011

see also Hopkins talk, Agertz poster

feedback

no feedback



Vazquez-Semadeni et al. 2010

Conclusions

Formation of dense clouds complex:

• observational and theoretical evidence for a variety of processes - cloud coalescence, self gravity, thermal instabilities, supernovae flows

• cloud properties in good agreement with observations

• cloud formation mechanisms can be distinguished by velocity flows

• evolution of individual GMC very complex, involving clouds merging, splitting apart, accreting gas

- cloud lifetimes difficult to determine

• star formation too efficient - but both feedback and magnetic fields shown to reduce amount of star formation