Star Formation & the Evolution of GMCs in Global Disk Galaxy Simulations

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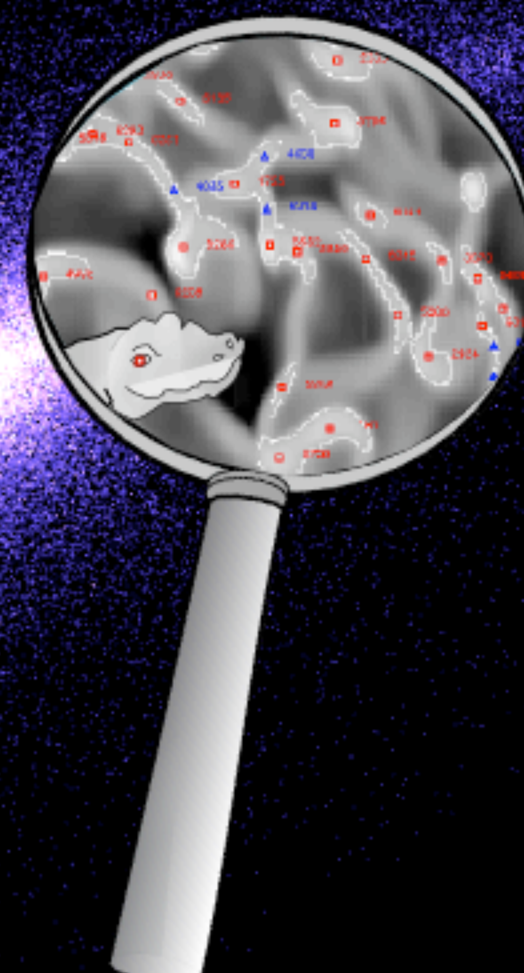
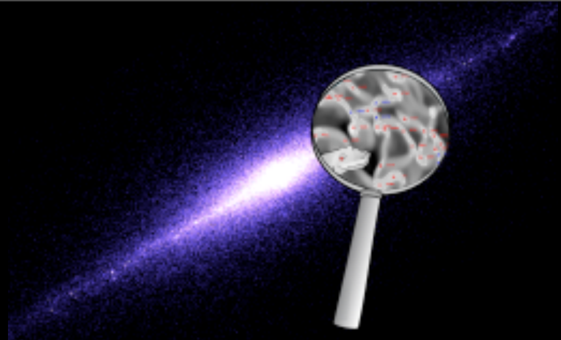
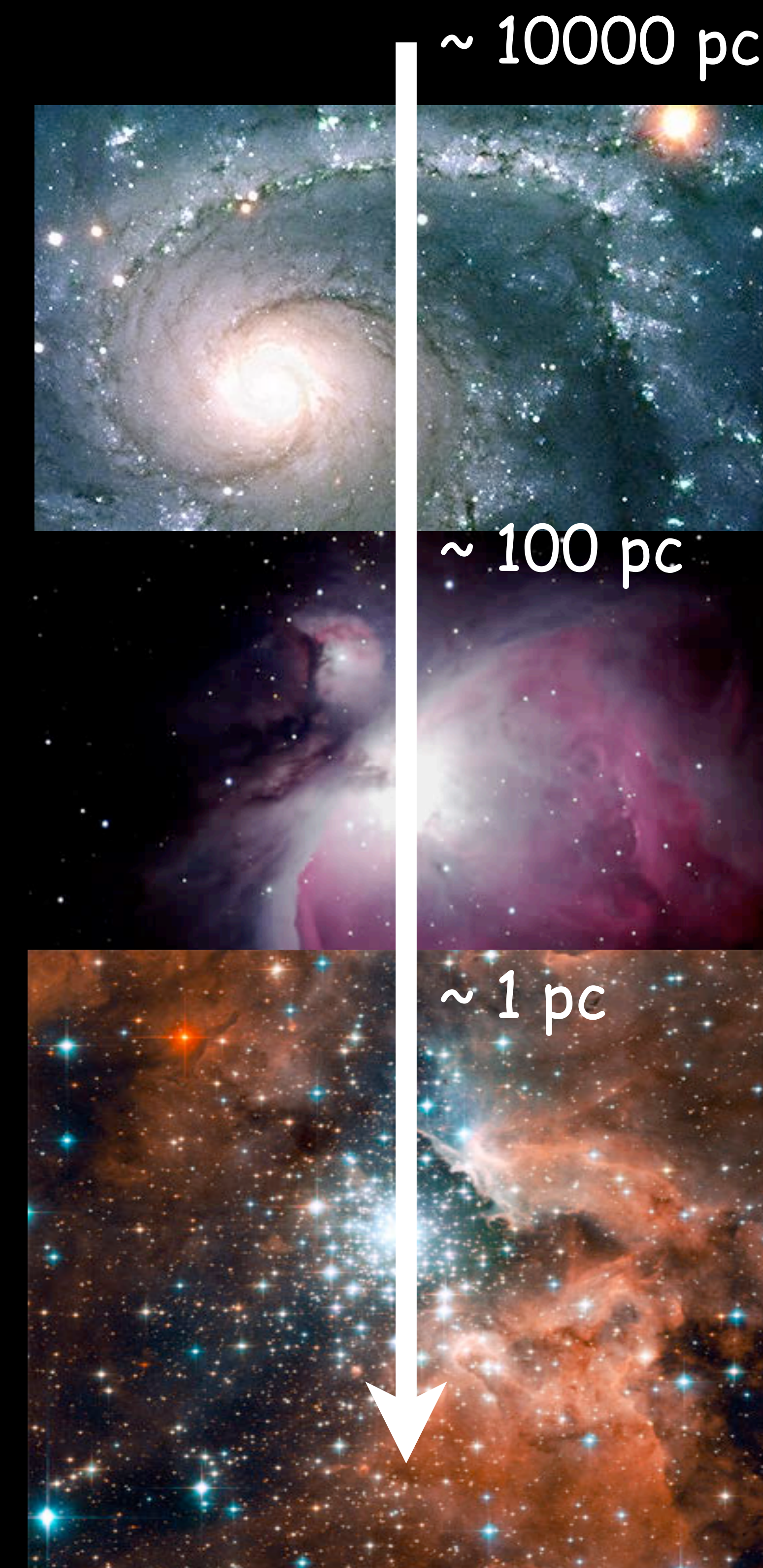




The birth of a star

(A speedy physics overview)

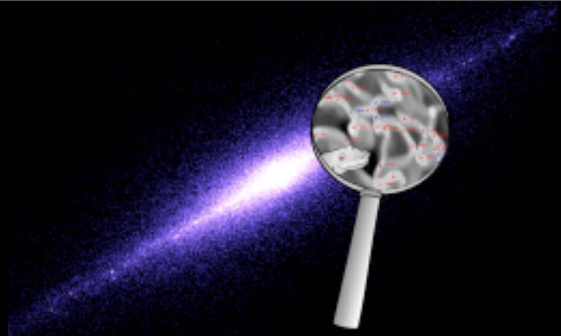


When disk galaxies form, a large fraction of gas settles into rotationally supported disks where the majority of the stellar population is born.

In the disk ISM, most of the cold, dense gas is in GMCs (~ 1/3 of total gas in star forming region).

Inside the GMCs, dense cores collapse to produce star clusters.

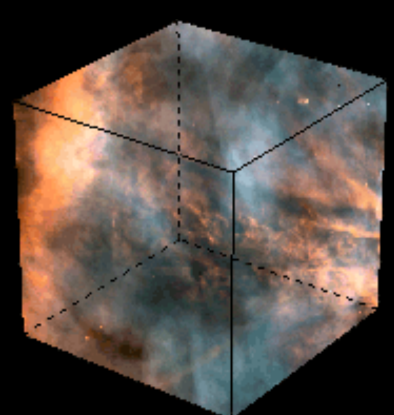
Yet, a detailed understanding star formation completely eludes us -- why?



A question of scale

Local scales : highly complex

Competing forces of gravity, cosmic-ray pressure, magnetic fields & thermal pressure fight for dominance in a turbulent multi-phase interstellar medium.



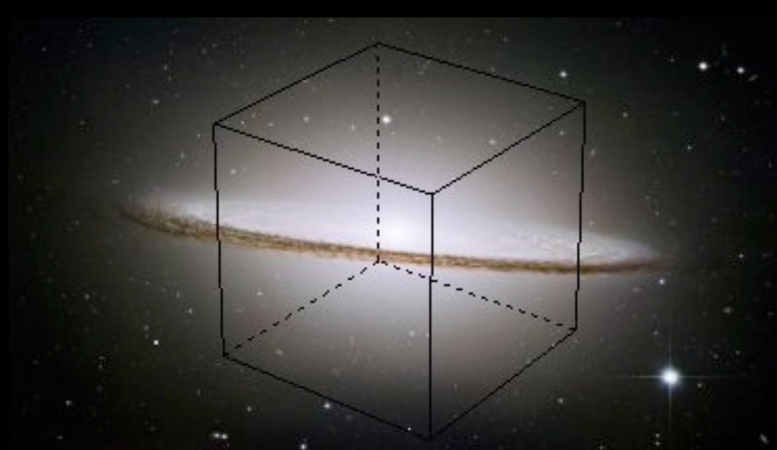
Detailed, but local simulations

$\sim$few parsecs

Global scales : simple relations

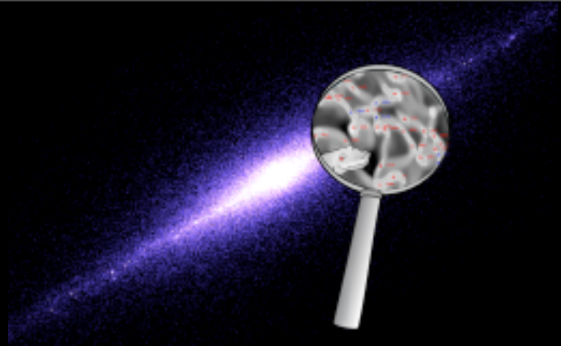
The Kennicutt-Schmidt relation finds that the star formation rate in disk galaxies is proportional to the gas surface density.

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$$

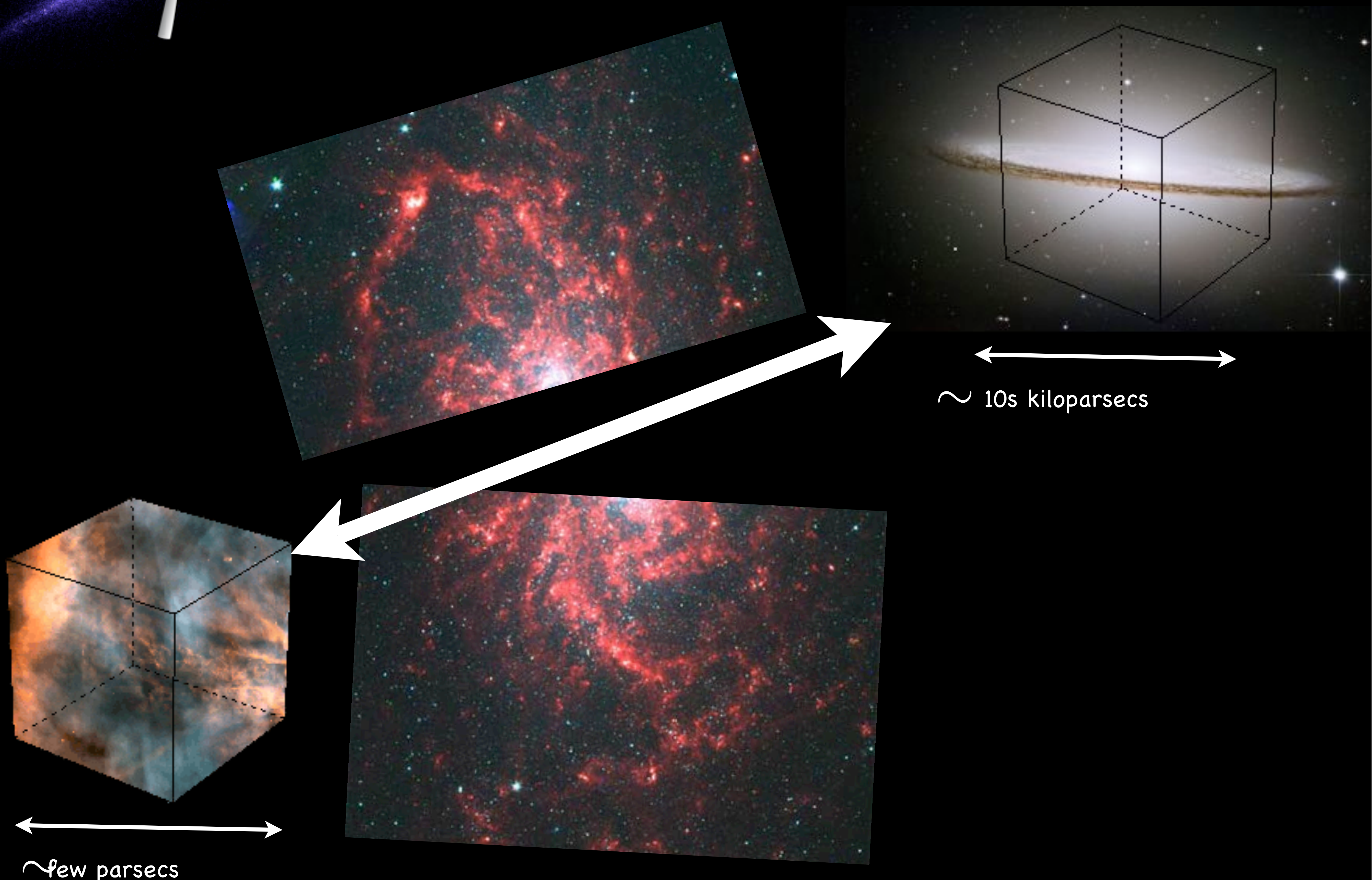


Global, but simple ISM structure

$\sim$ 10s kiloparsecs



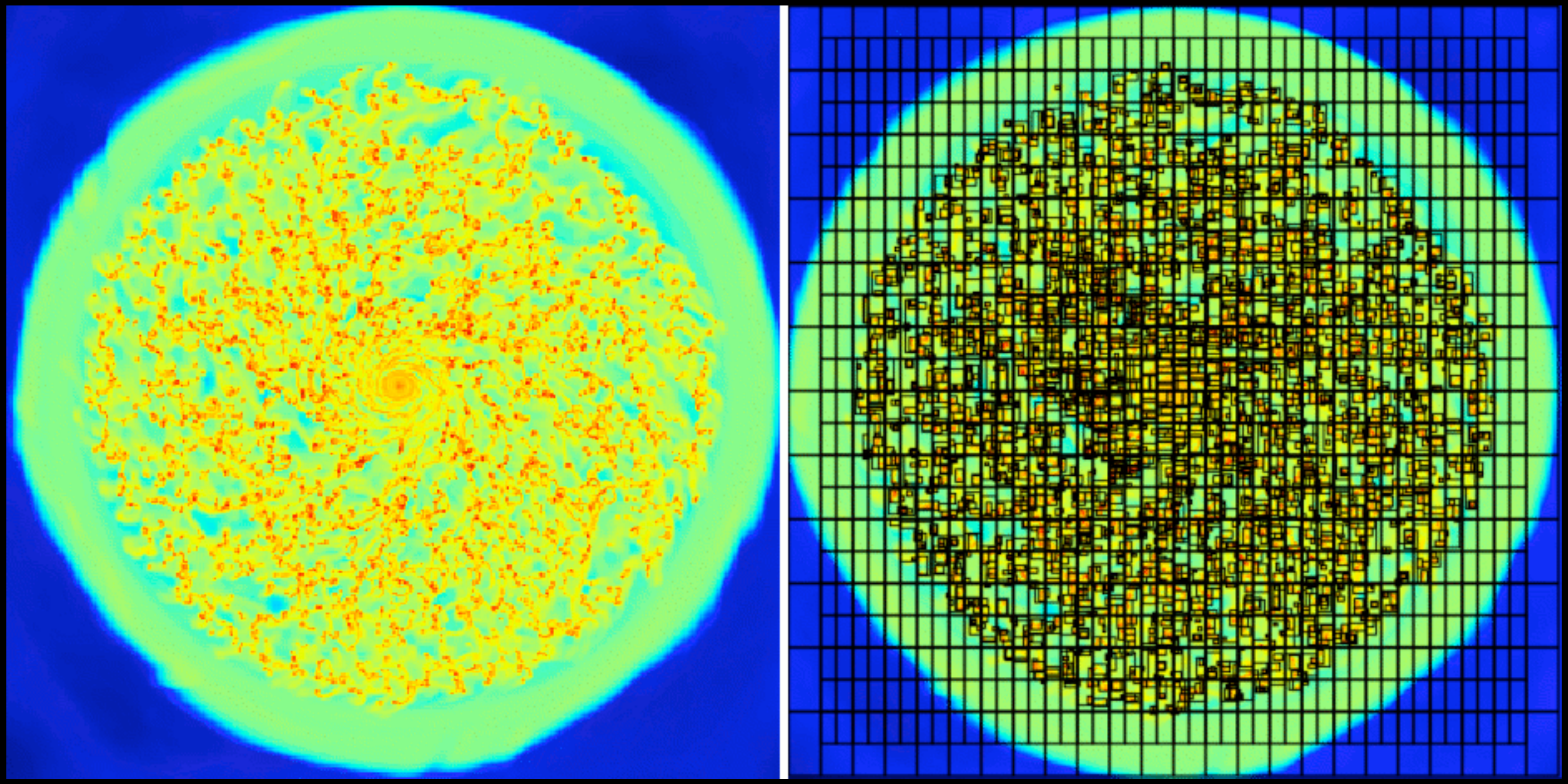
A question of scale

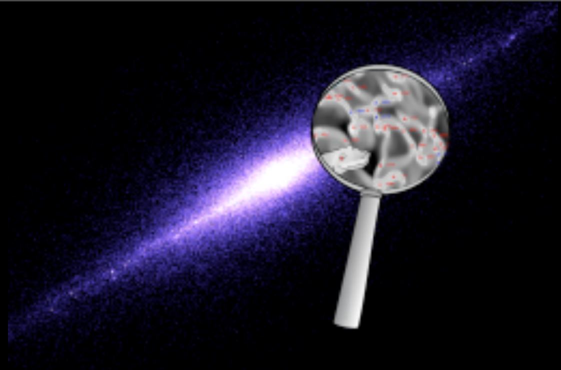


How to Build a Galaxy

Hydrodynamics code, Enzo

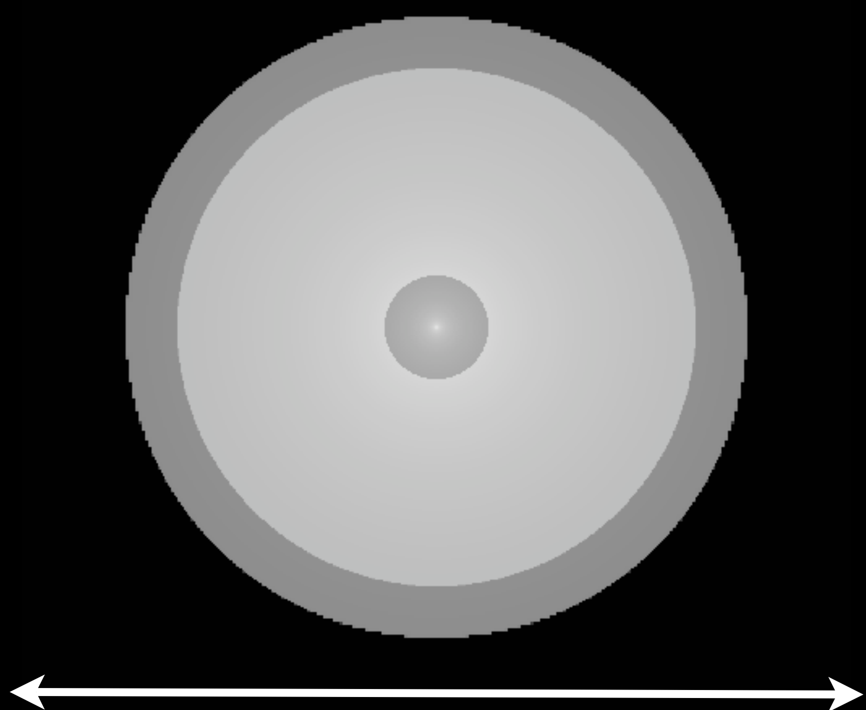
Bryan & Norman, 1997, O'Shea et al., 2004





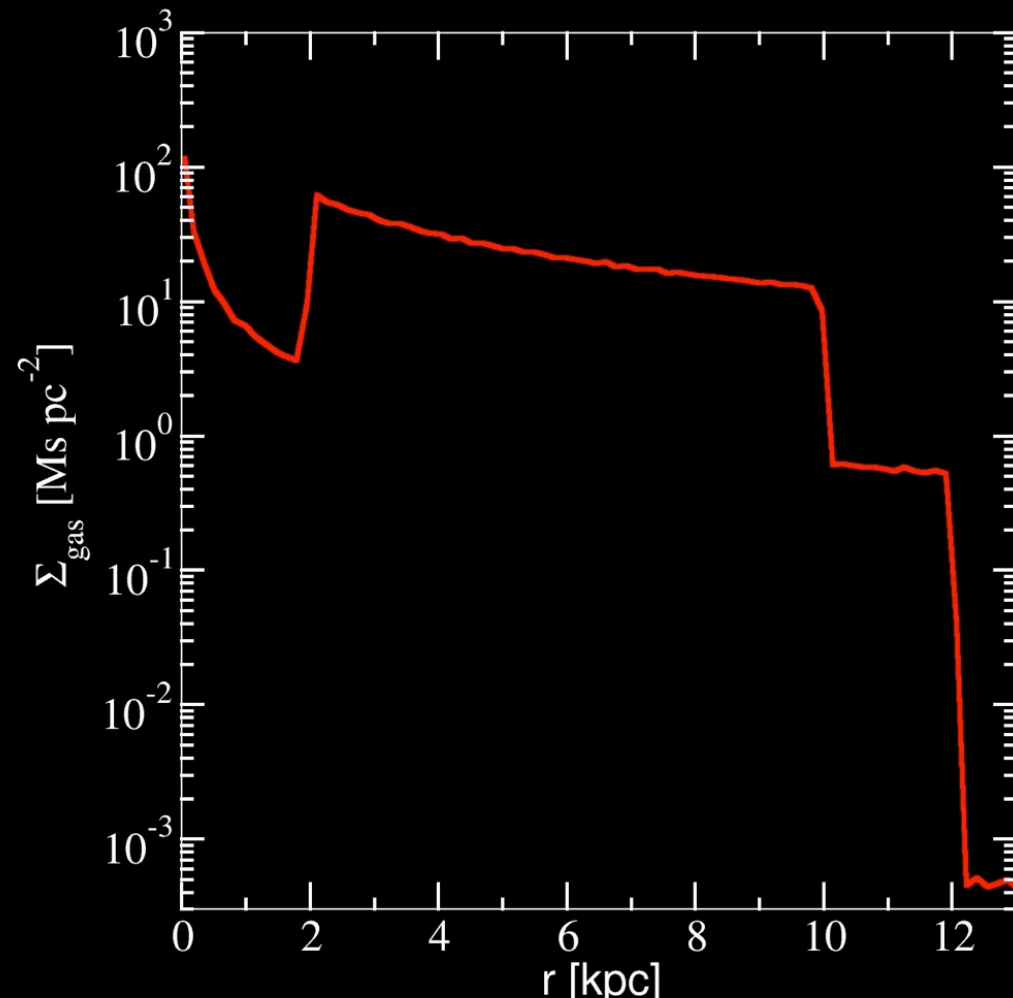
Galactic Properties

Study steady-state evolution;



We concentrate our resolution between 2 - 10 kpc, with the inner and outer regions at lower surface densities.

External galactic potential that represents both stellar and dark matter (flat rotation curve)



Vertical scale height varies based on observations of the HI in the Milky Way.

Galactic Properties

Study Milky Way steady-state evolution;

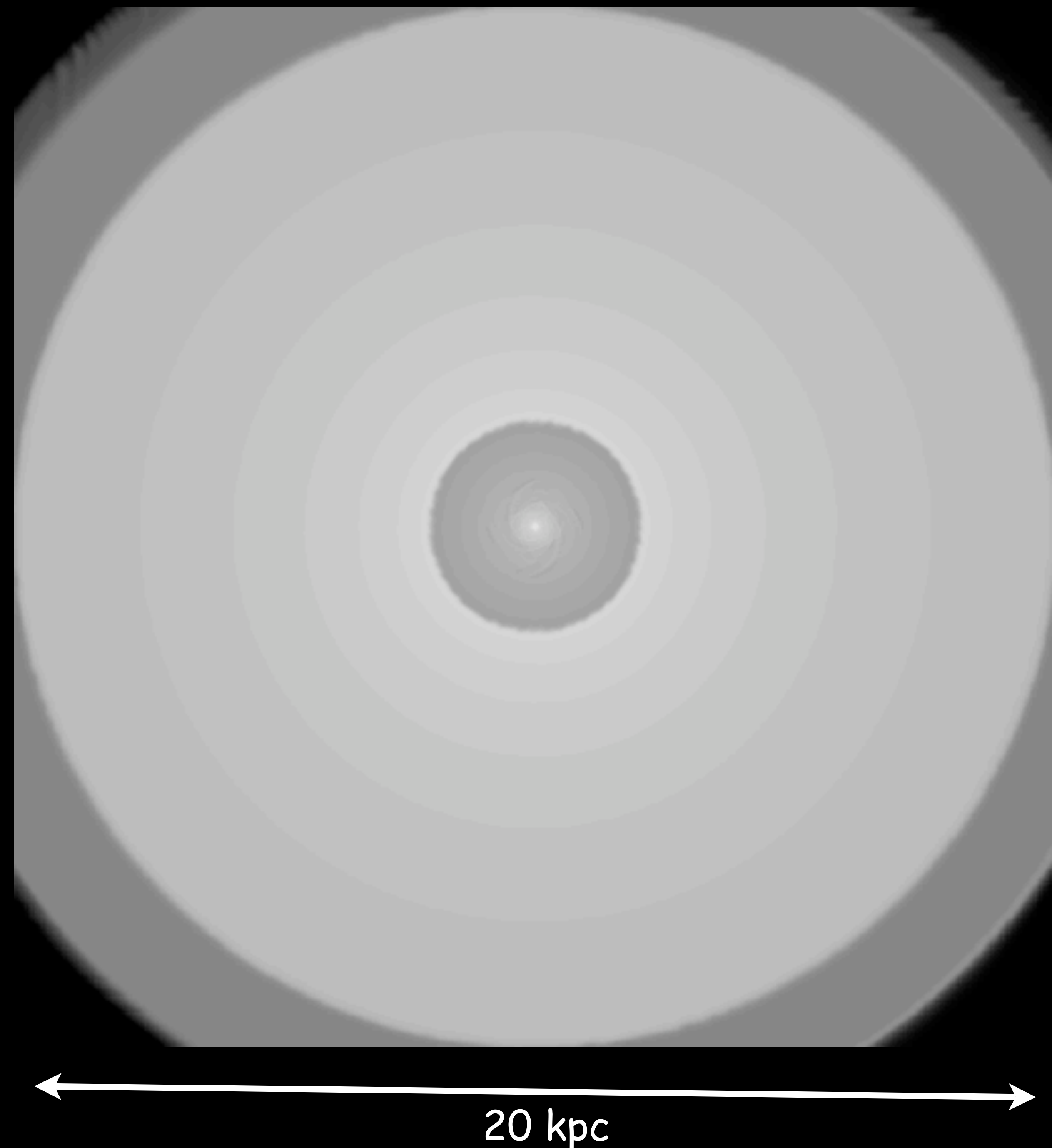
→ External galactic potential that represents both stellar and dark matter (flat rotation curve)

32^3 kpc box, Δx_{min} = 7.8 pc / 15.6 pc

Vertical scale height varies based on observations of the HI in the Milky Way.

Toomre gravitationally unstable region
r = 2.5 - 8.5 kpc : $Q_{Toomre} < 1$

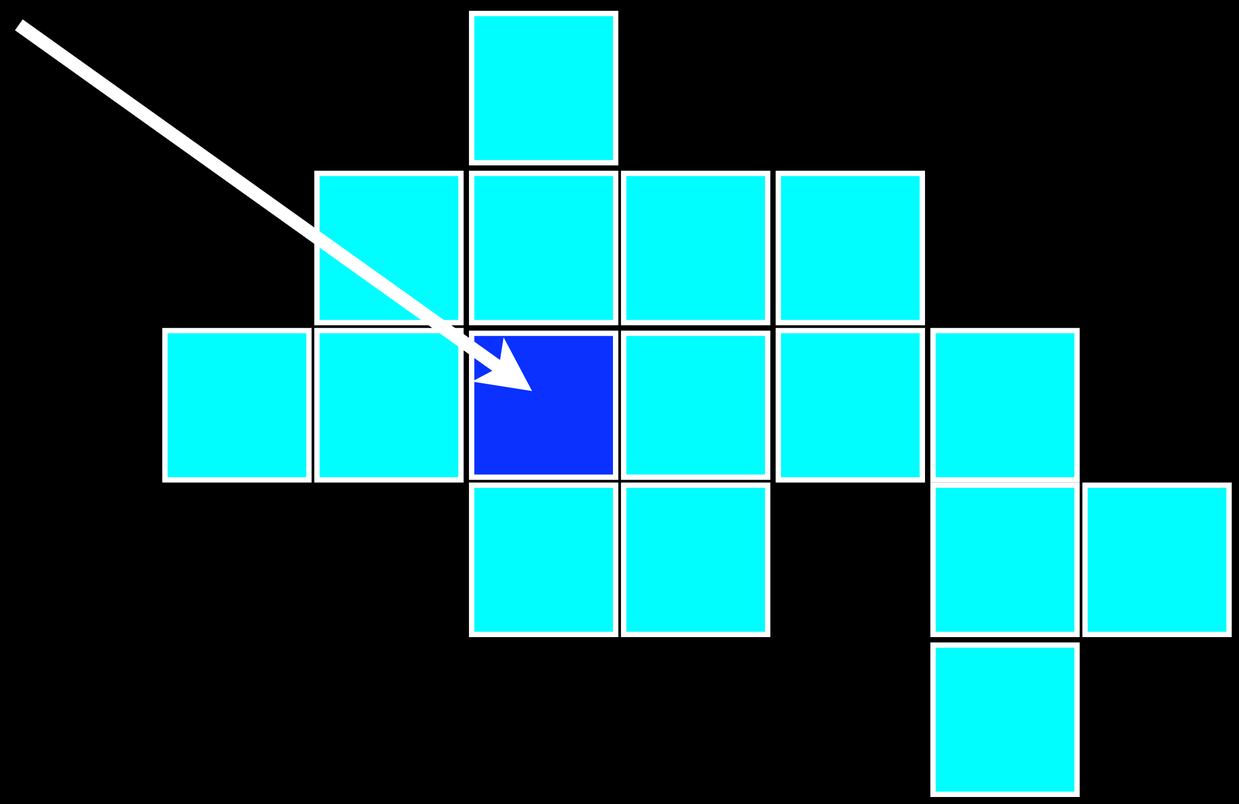
Pure atomic gas with radiative cooling down to 300 K



No star formation, 7.8 pc resolution

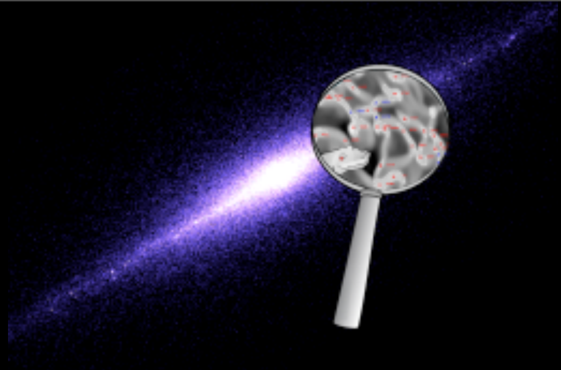
Cloud identification

Find peaks in the gas density field with $n_{HI} > 100cm^{-3}$



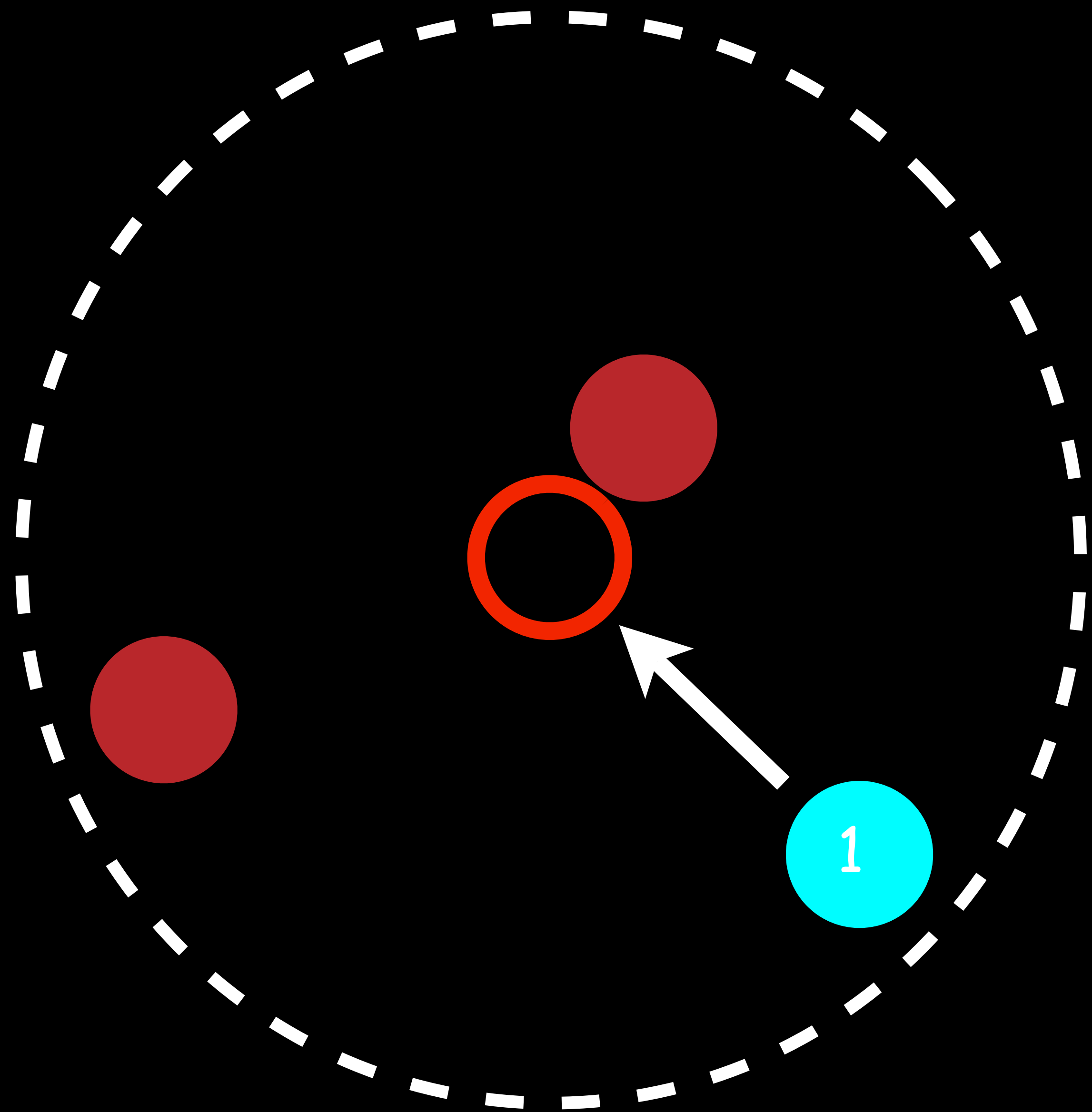
Recursively search peak neighbours for cells also $n_{HI} > 100cm^{-3}$

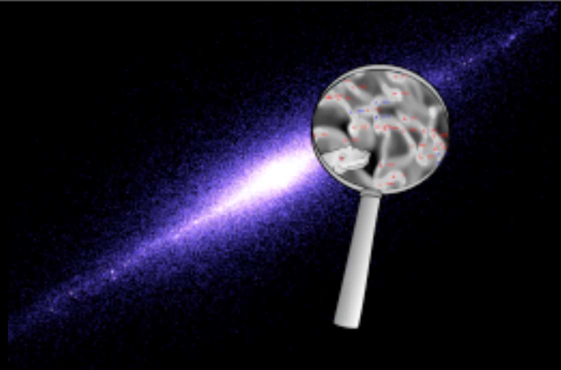
Cloud tracking



Predicted position of each cloud present at t0 is calculated at later time t1.

A volume with radius 4 x cell width is searched for clouds present at t1.





Cloud tracking

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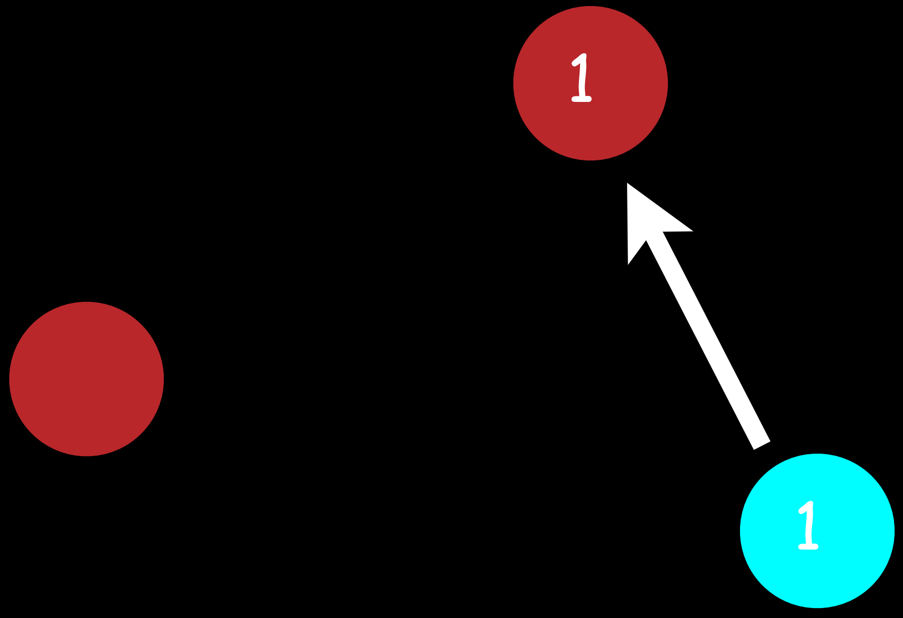
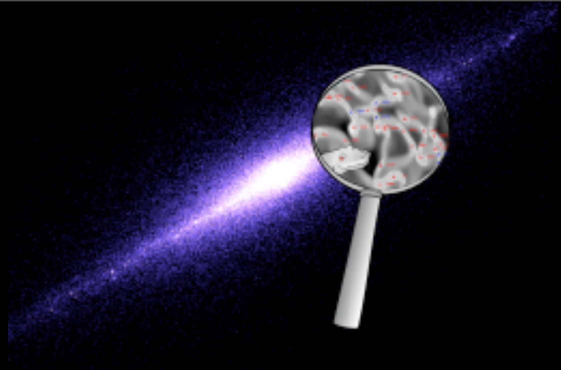
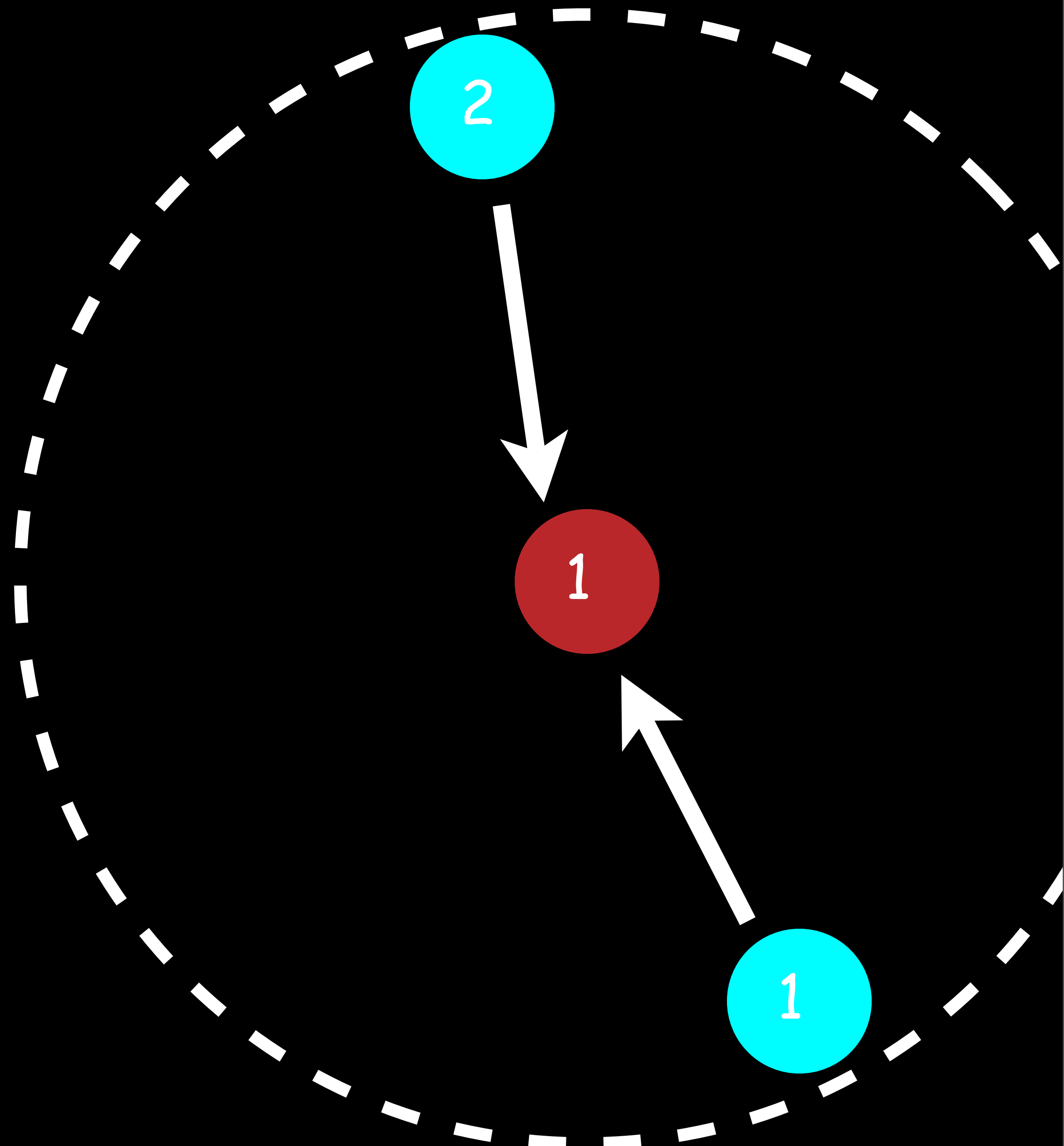
A volume with radius 4 x cell width is searched for clouds present at t1.

Nearest cloud is associated with t0 cloud.





Cloud tracking



Predicted position of each cloud present at t0 is calculated at later time t1.

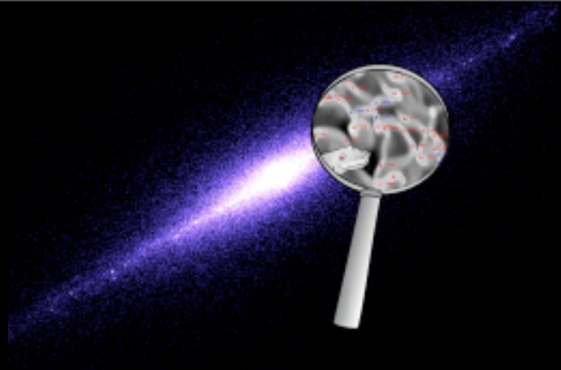
A volume with radius 4 x cell width is searched for clouds present at t1.

Nearest cloud is associated with t0 cloud.

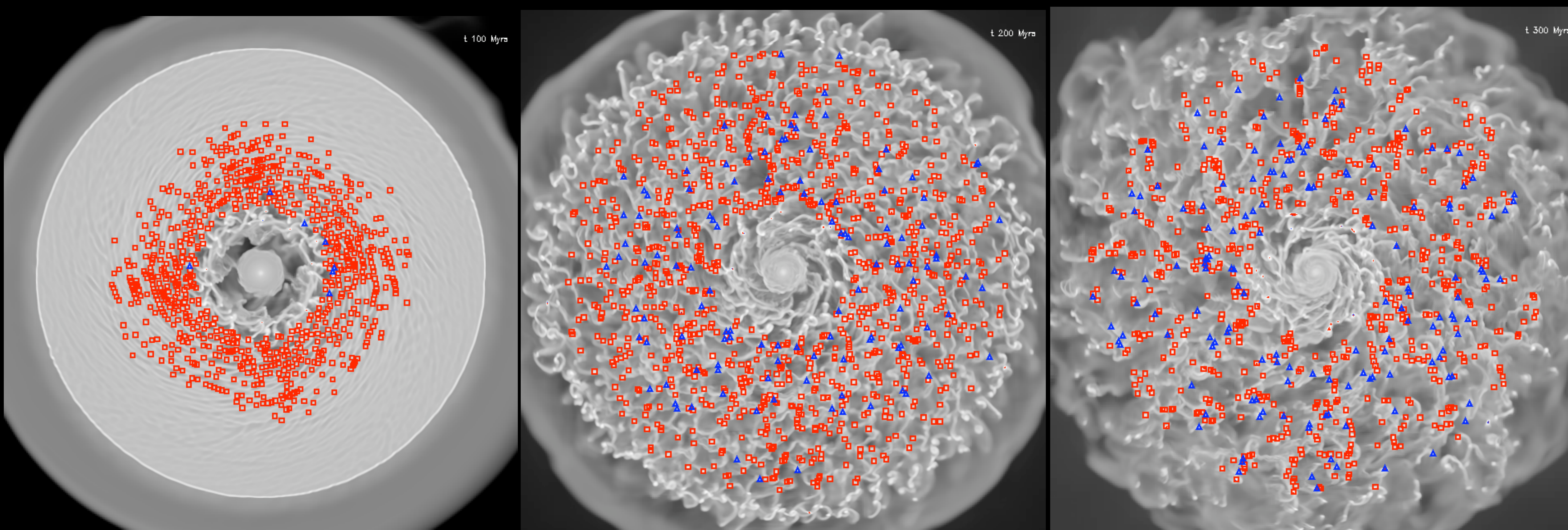
At the end of this process, an area of 2 x average radius of the t1 clouds is searched for unassigned t0 clouds.

Unassigned t0 clouds in this volume are declared as merger events.

Cloud tracking



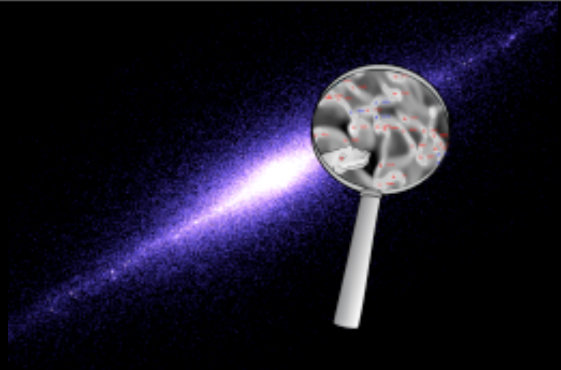
100 Myrs   200 Myrs   300 Myrs



20 kpc

Prograde clouds (rotate in same direction as the galaxy)

Retrograde clouds (rotate in opposite sense to the galaxy)



Star formation and feedback

Star formation:

Density threshold $n_{HI} > 100cm^{-3}$

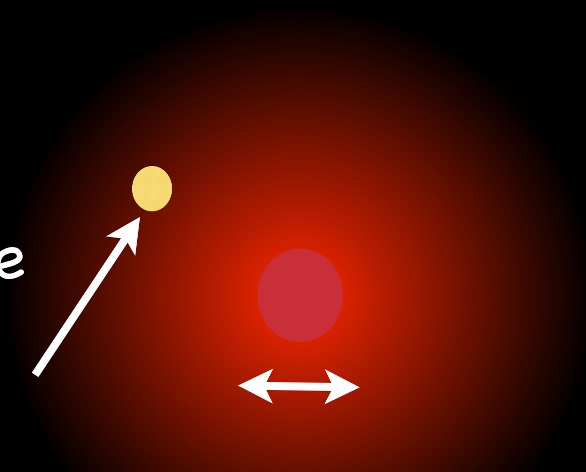
Efficiency / free-fall time $\varepsilon = 0.02$

Photoelectric heating from dust grains:

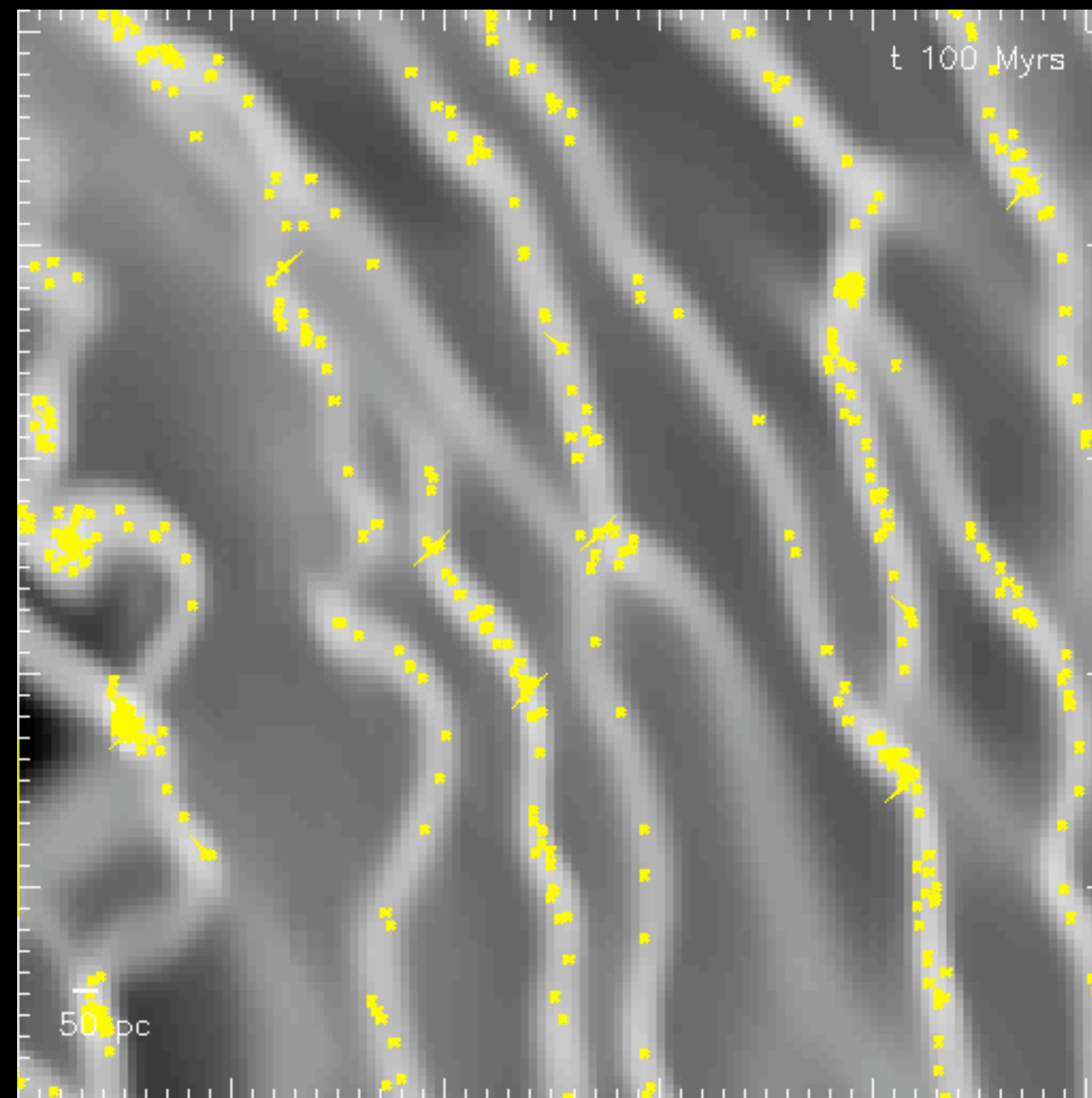
Radial profile from Wolfire, 2003.

$\propto e^{-(R-R_0)/H_R}$

Local FUV at 8 kpc
1.7 G0 ergs s-1 cm-2
(G0 = Habing estimate
for local ISM value),
in agreement with
Draine



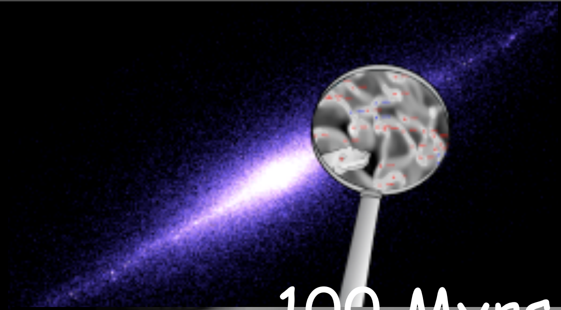
Constant for R < 4 kpc



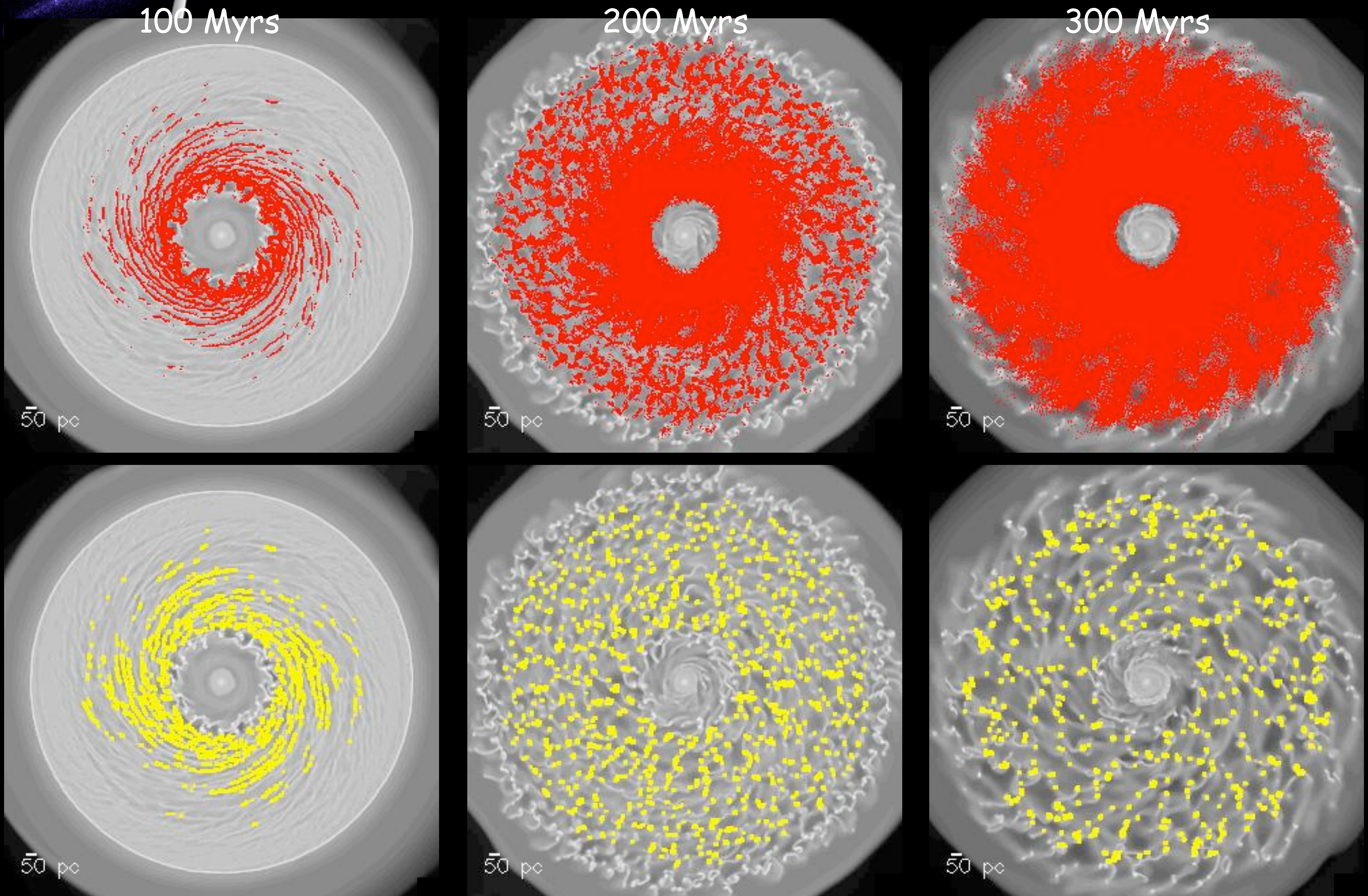
On movie: young star particles < 1 Myr

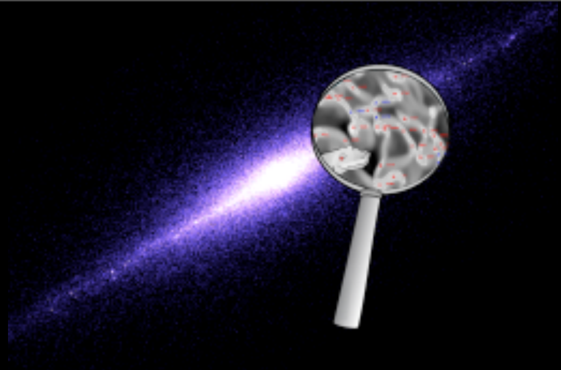
15.6 pc resolution

NO SNe FEEDBACK!



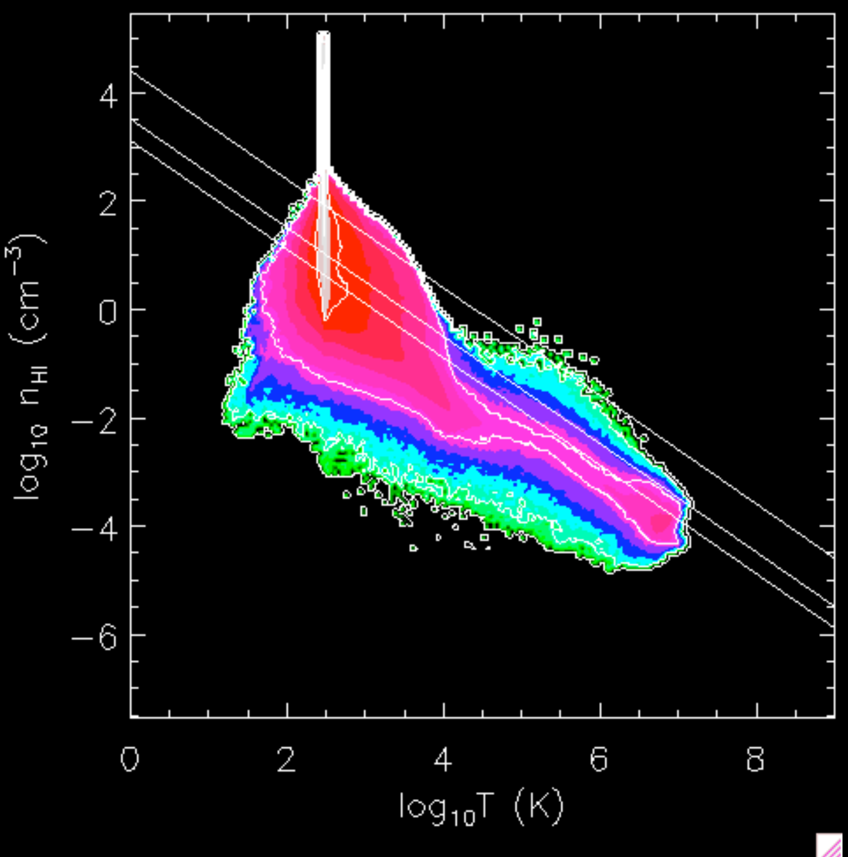
Star formation and feedback



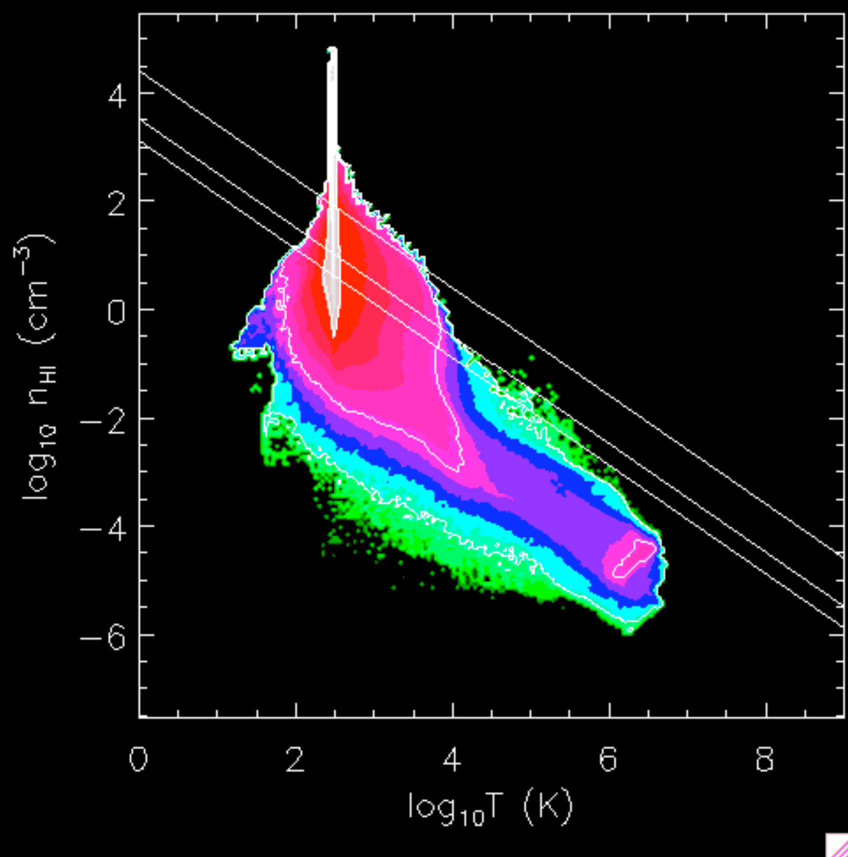


ISM structure

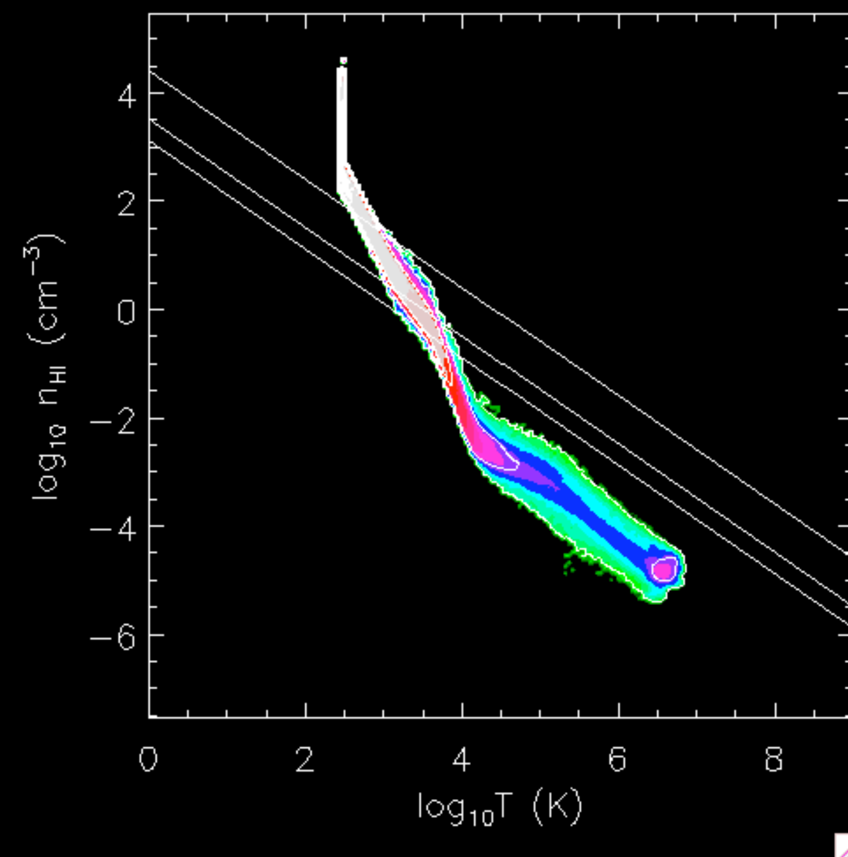
t = 250 Myrs



No star formation



Star formation

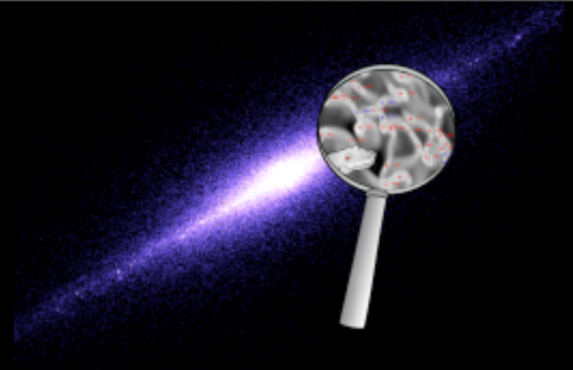


Star formation and photoelectric heating

Mass weighted contour plots

Star formation reduces mass of cold dense gas, while further heating reduces cold gas present at lower densities.

ISM structure



Mass weighted PDFs

No SF:

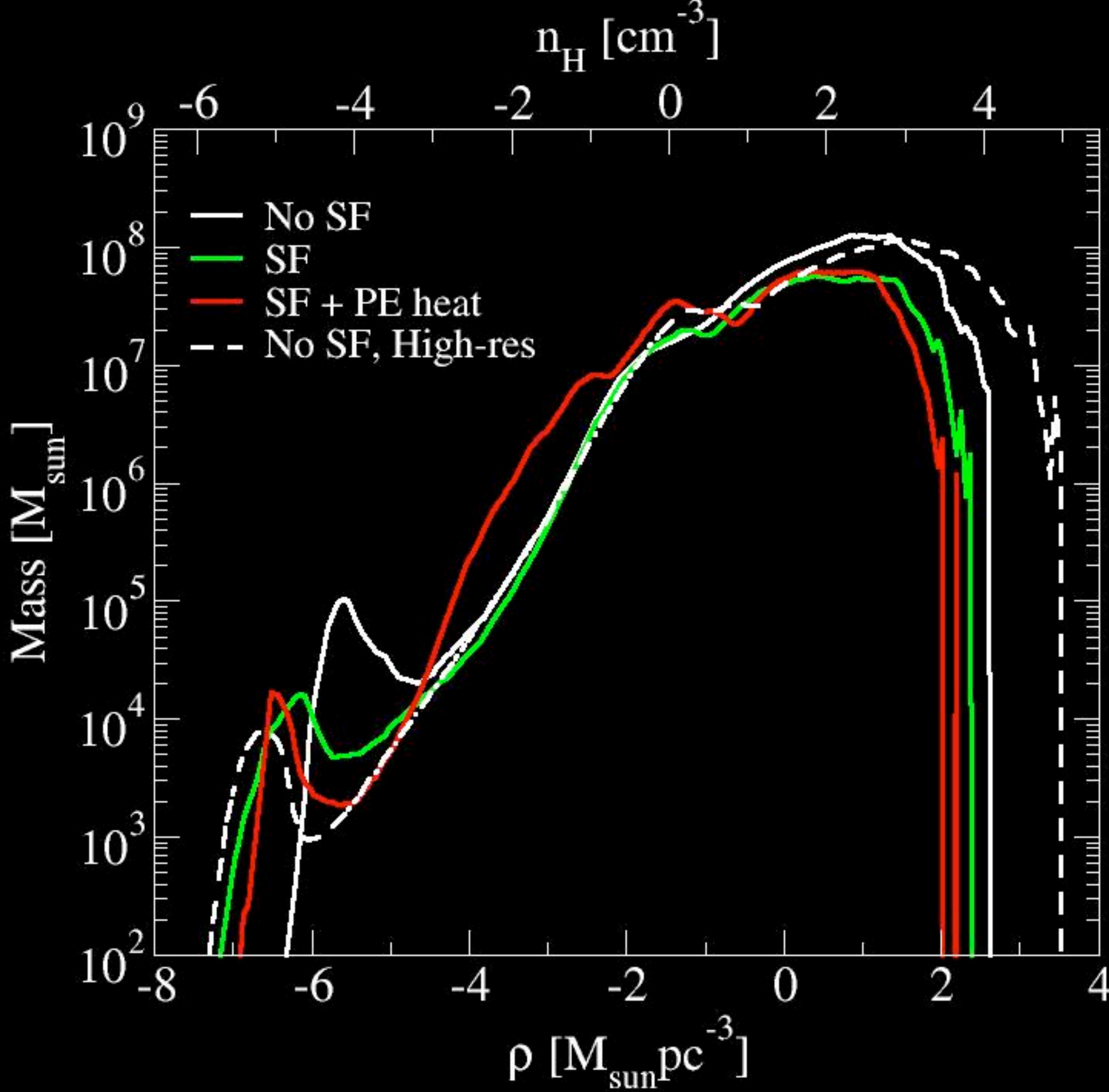
Fraction of gas in clouds: 0.6

SF:

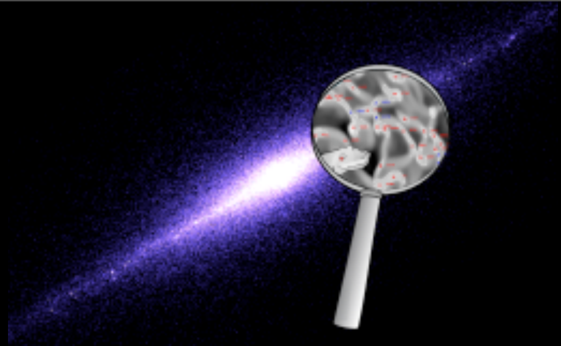
Fraction of gas in clouds: 0.45

SF + PE heating:

Fraction of gas in clouds: 0.36



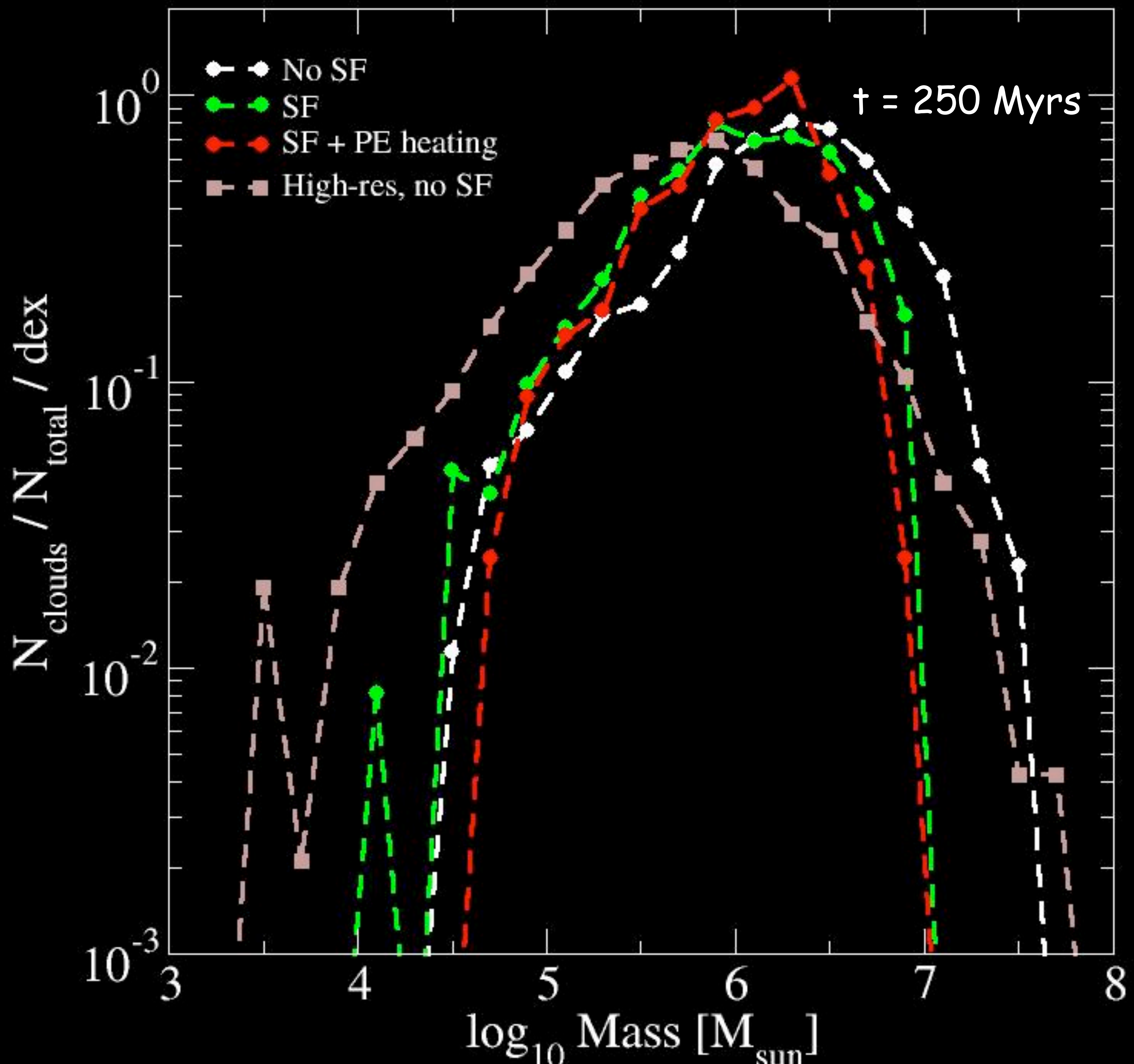
Cloud properties : mass

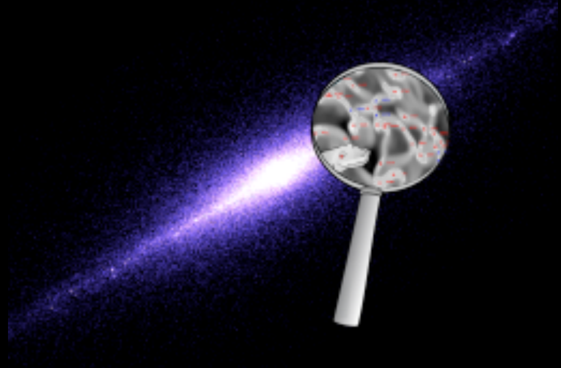


Without SF, there is little to stop clouds gaining in mass.

Collisions and agglomerations result in a high mass tail.

Star formation removes gas from the clouds, reducing their maximum size.





Cloud properties : mass

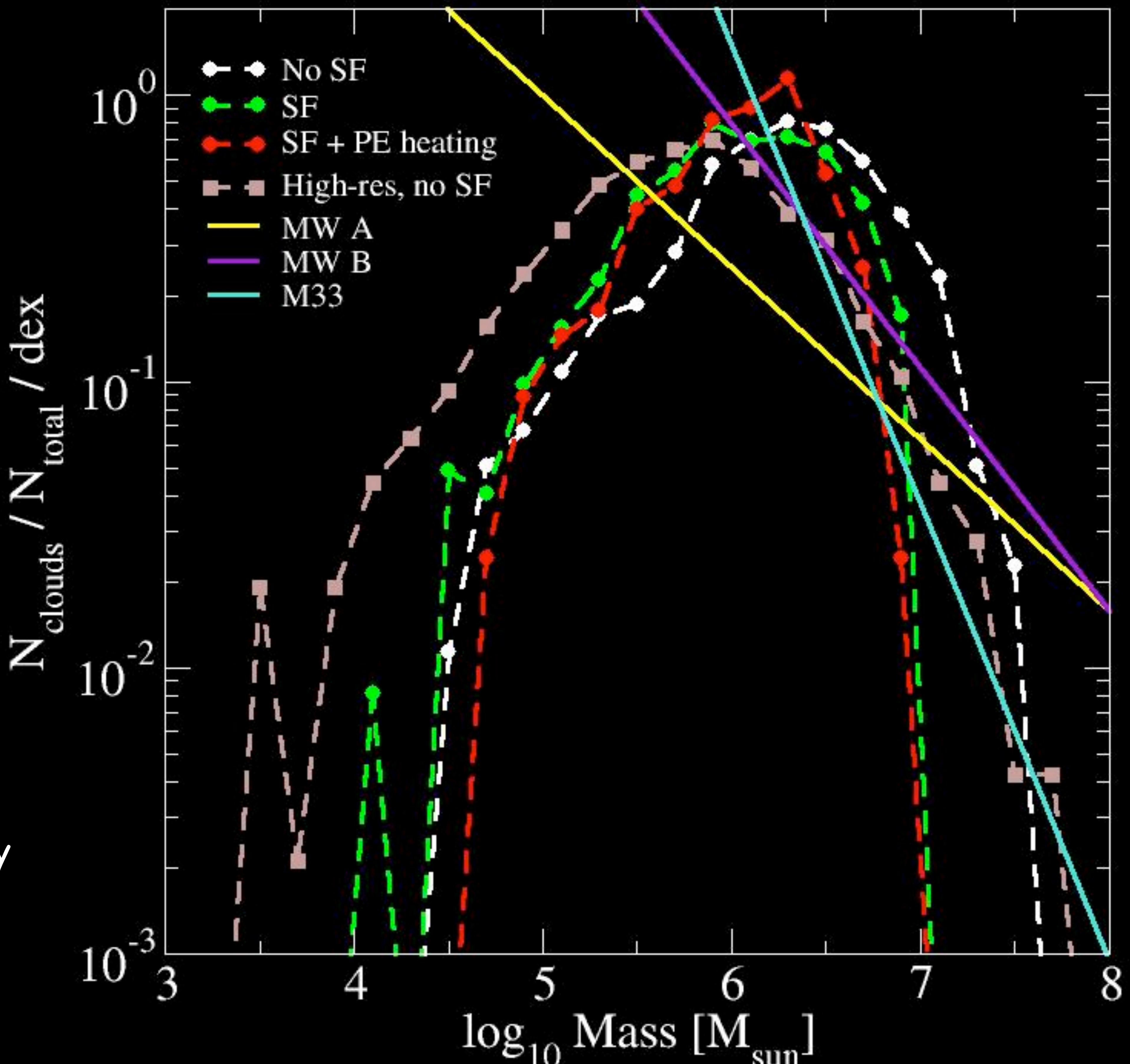
The mass function of GMCs in the Milky Way and M33 fits a power law (Rosolowky et al. 2003):

$$\frac{dN}{dM} \propto M^{\alpha}$$

Where α = -1.6 for Milky way (scaled distribution)

α = -1.8 for Milky Way (more low mass clouds)

α = -2.6 for M33

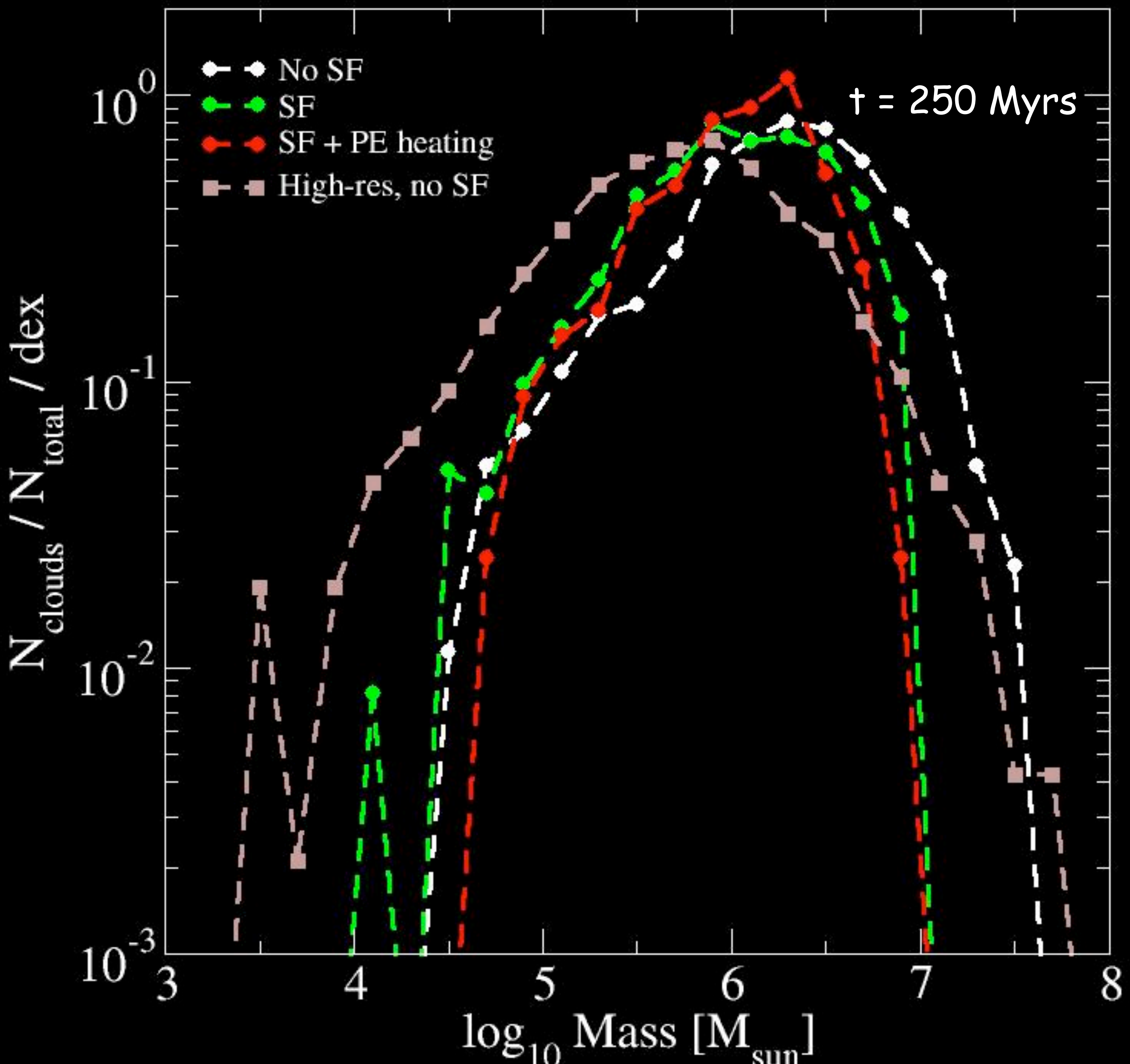


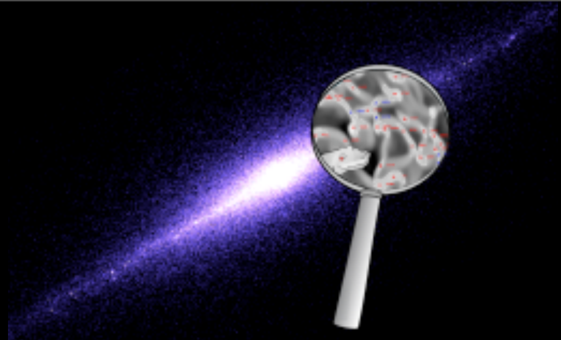
Cloud properties : mass

Observed clouds (including atomic envelopes) have max masses < $1.2 \times 10^7 M_\odot$

(Williams & McKee, 1997)

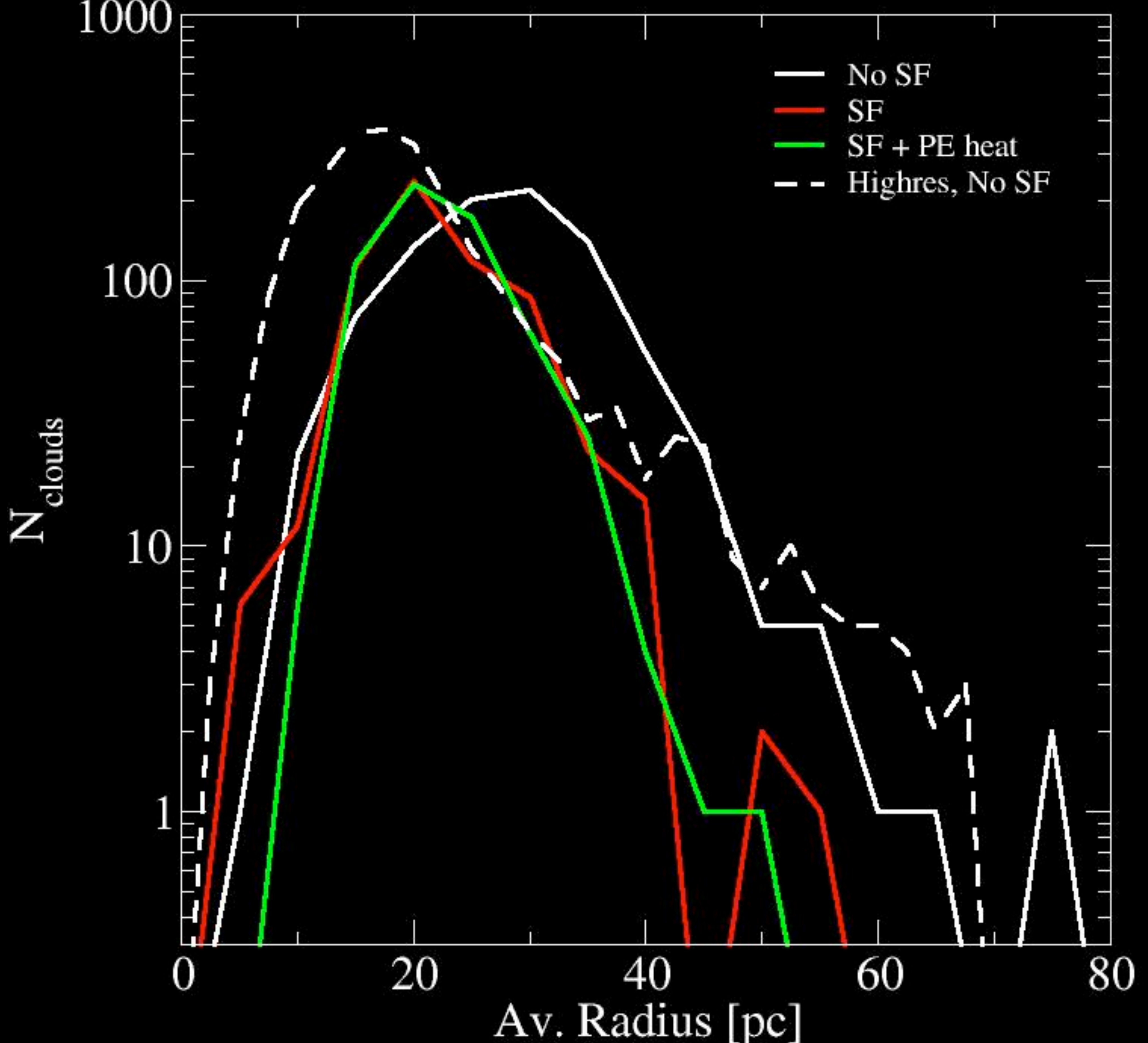
This is in good agreement with the runs that include SF, despite the lack of SNe feedback.

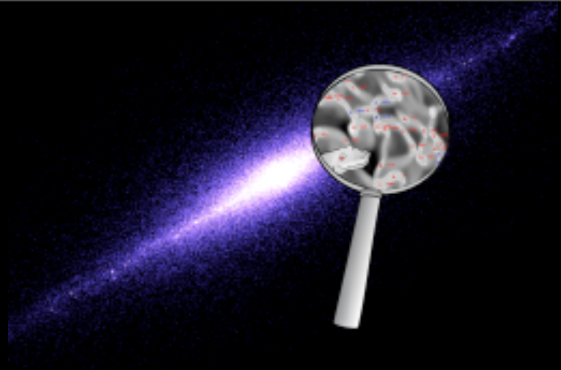




Cloud properties : radii

Likewise, star formation removes gas from the clouds, preventing the formation of very large clouds.





Are the clouds gravitationally bound?

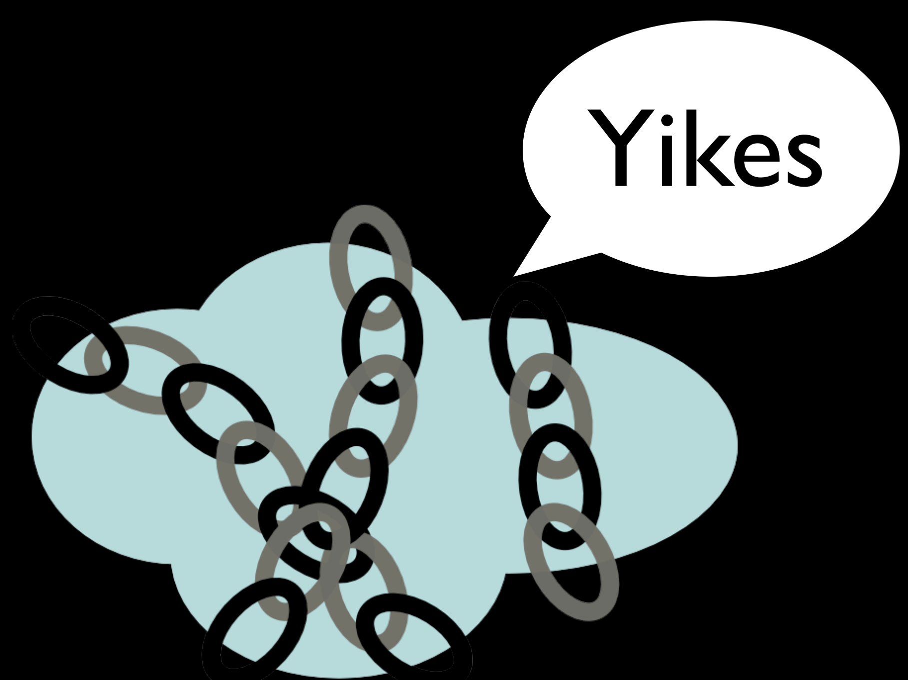
Assuming a cloud survives for longer that tff (free-fall time), then it is gravitationally bound if:

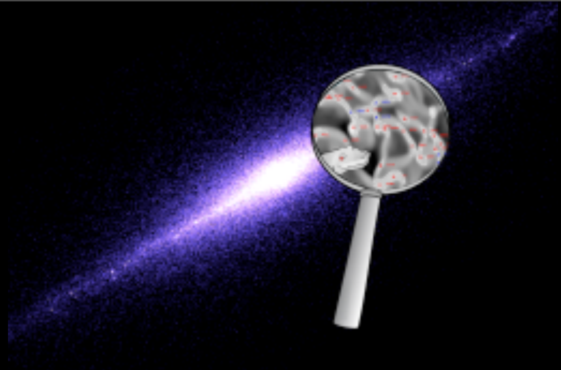
$$\alpha_{vir} \equiv \frac{5\sigma_{g,c}^2 R_{c,A}}{GM_c} < 1$$

dimensionless virial parameter
(Bertoldi & McKee, 1992)

$\sigma_{g,c}$ = 1D velocity dispersion

$R_{c,A}$ = ((projected cloud area)/pi)^1/3

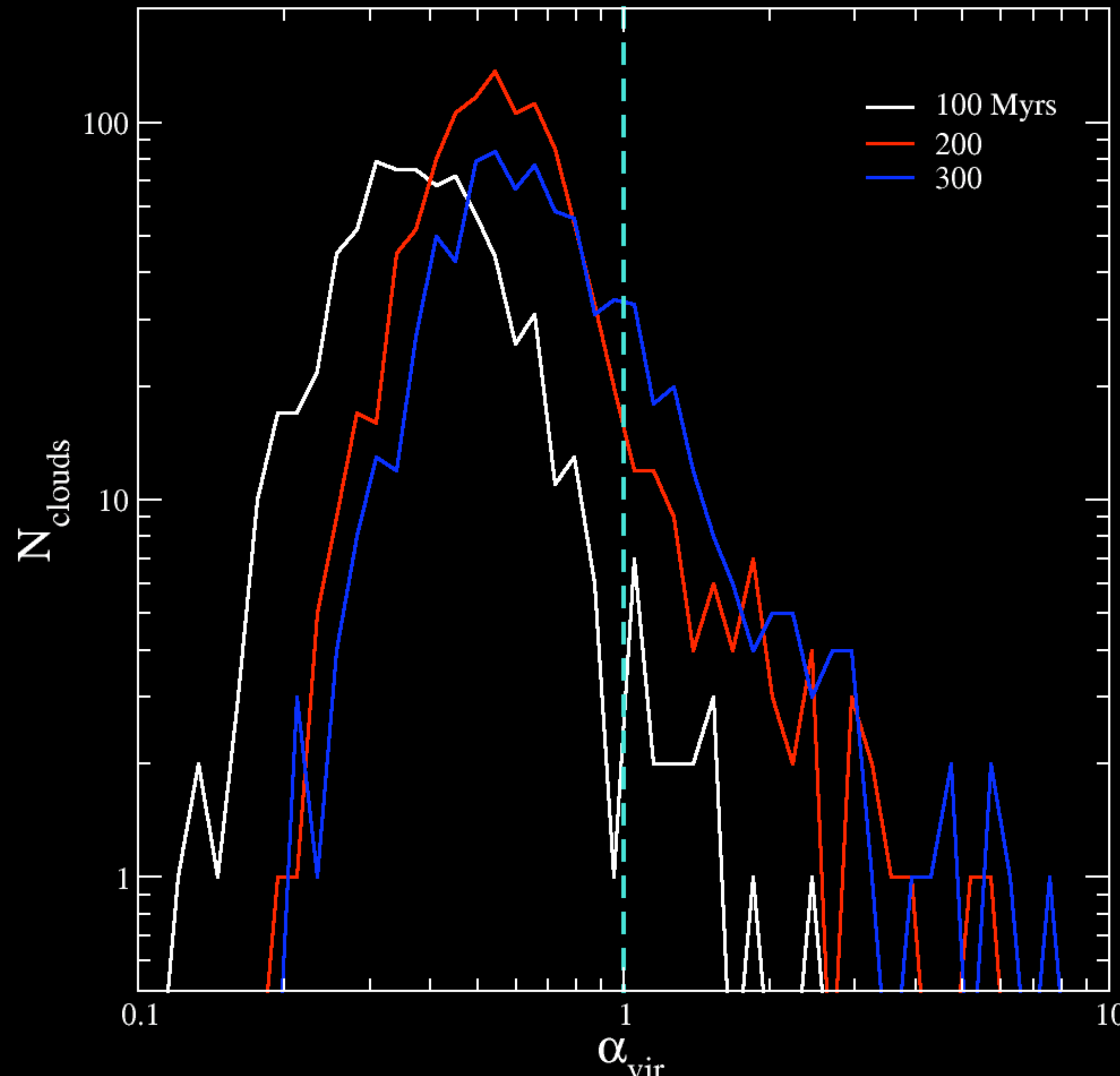


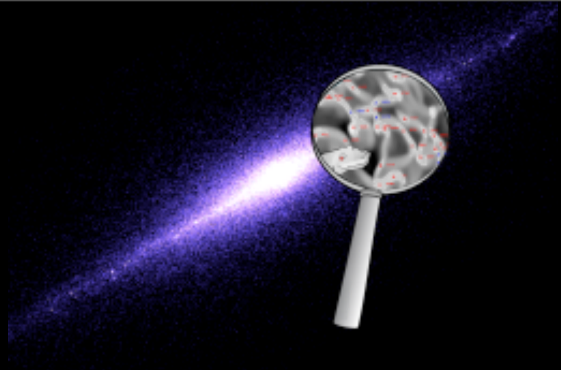


Are the clouds gravitationally bound?

High resolution (7.8pc), no SF run.

Clouds are largely bound, but weakly so

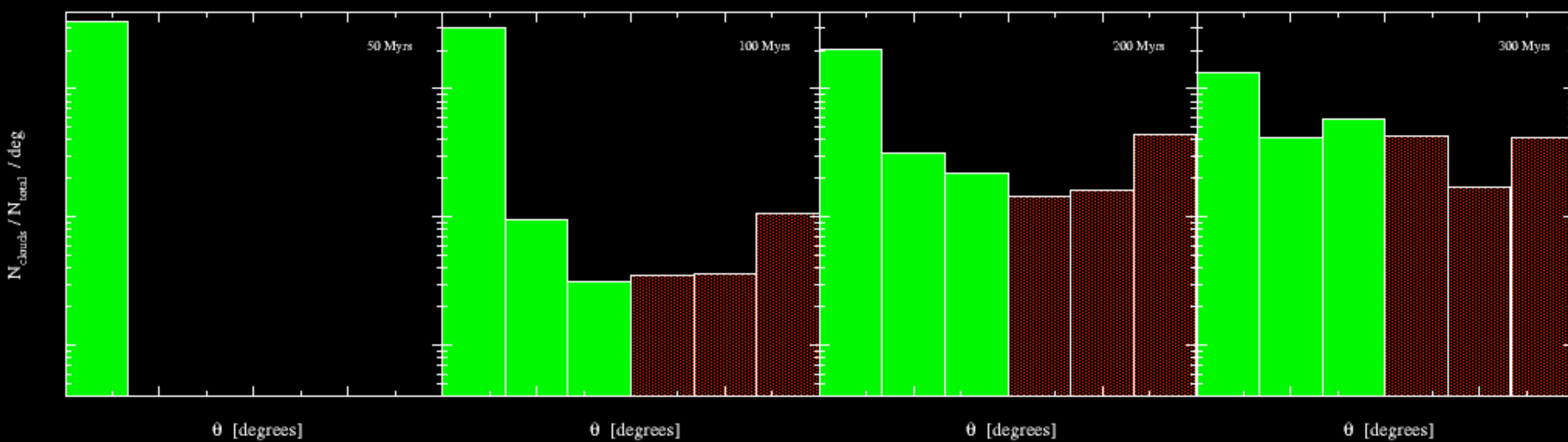




Cloud rotation

High resolution (7.8pc), no SF run.

50 Myrs 100 Myrs 200 Myrs 300 Myrs

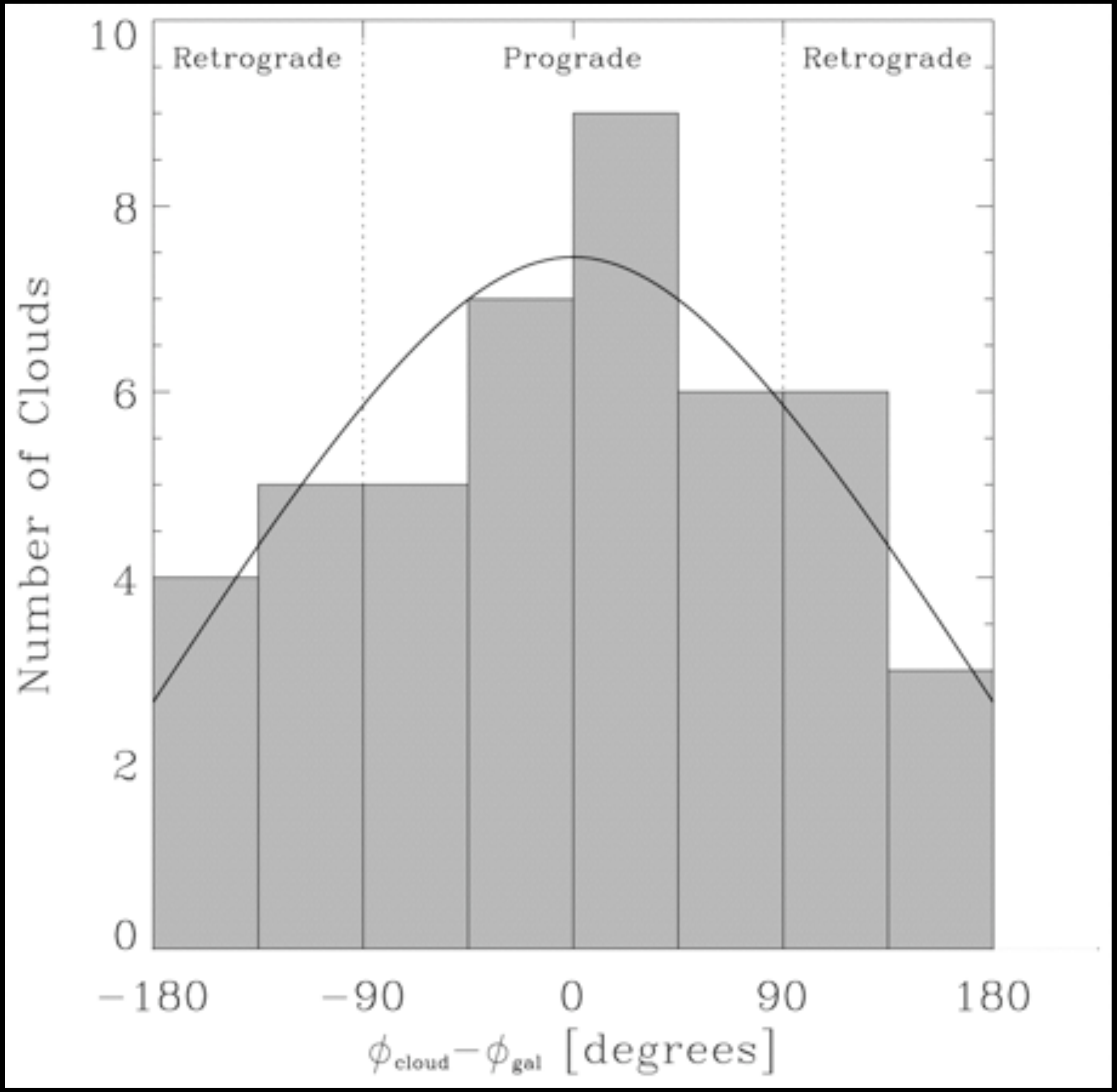


At early simulation times, all clouds are prograde (rotating in the same sense as the galaxy)

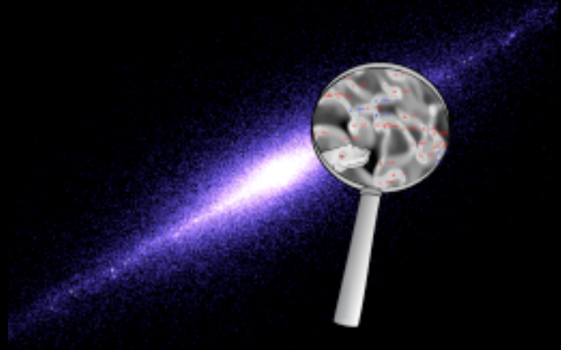
As the simulation evolves, cloud distribution is a mix of pro- and retro- grade rotation, with ~ 30 % being retrograde by 300 Myrs.

Cloud rotation

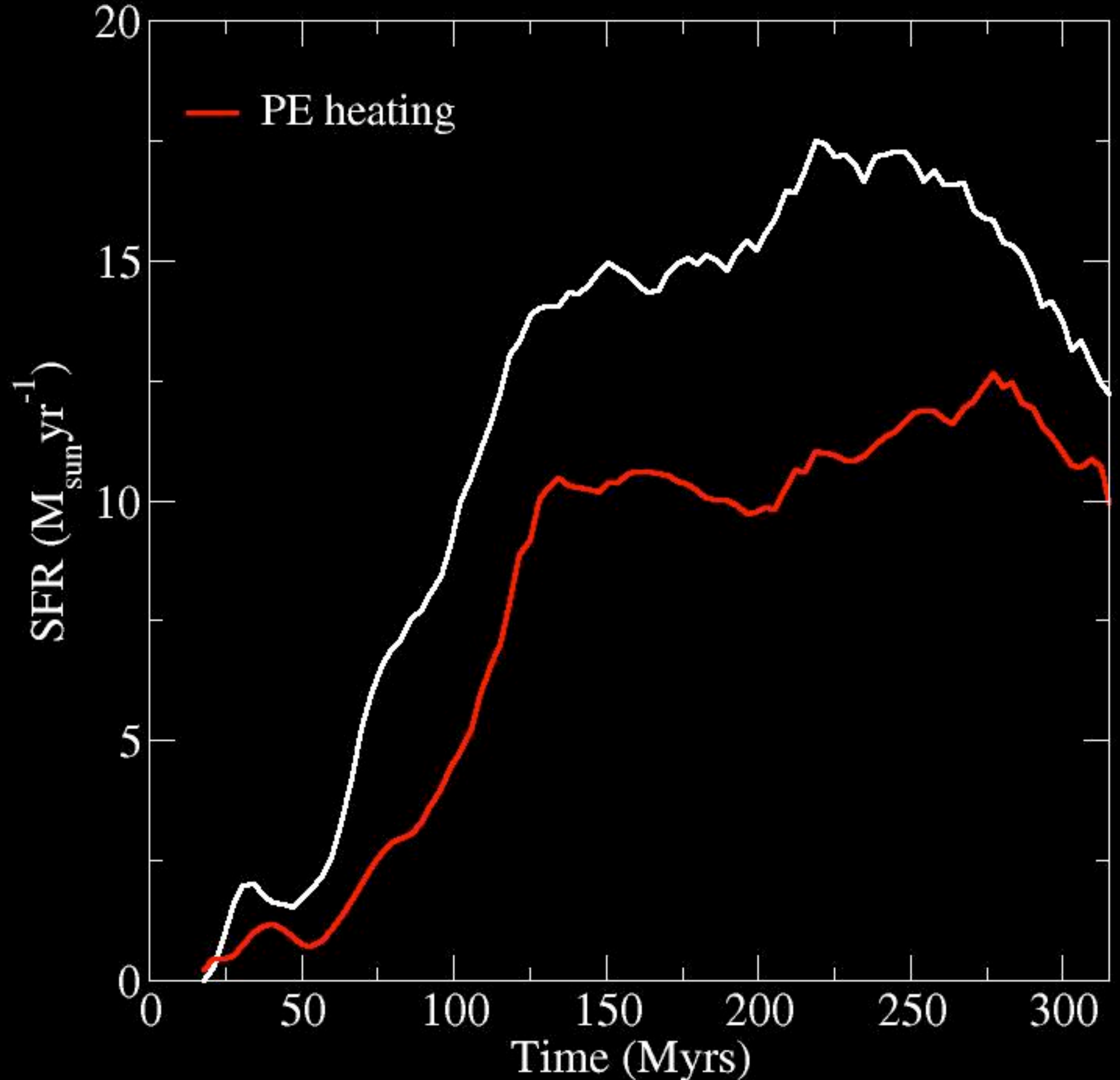
Current observations show a relatively even spread of prograde and retrograde clouds, with ~ 40 % of clouds observed to be retrograde in M33

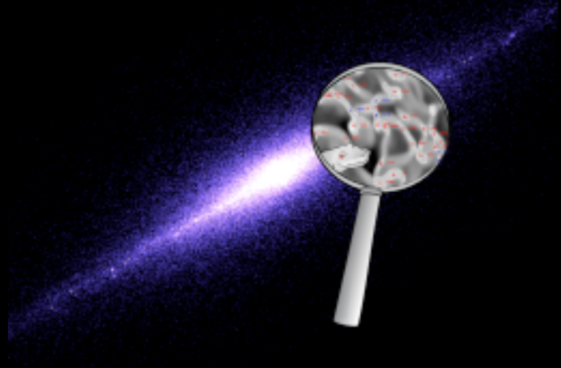


Rosolowsky et al, 2003 measured 45 GMCs in M33, with a resolution of 20 pc.



Star formation and feedback





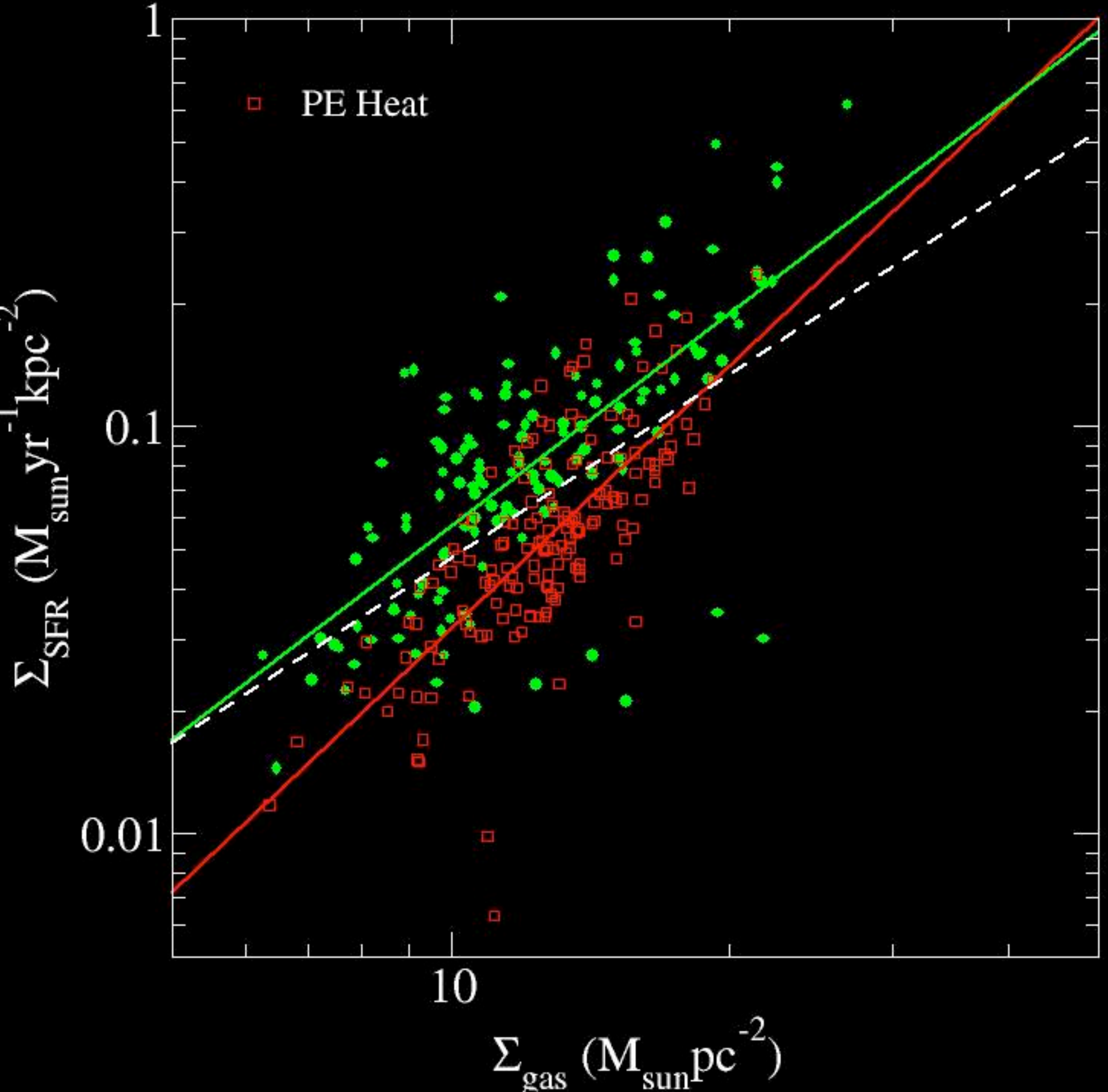
Star formation and feedback

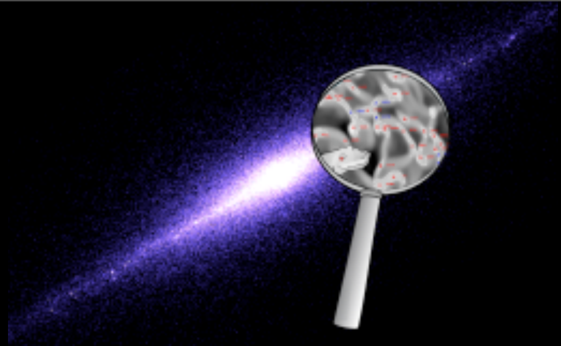
Radially averaged local Schmidt law

Best fit gradient:

SF: 1.7

SF + PE heat: 2.1





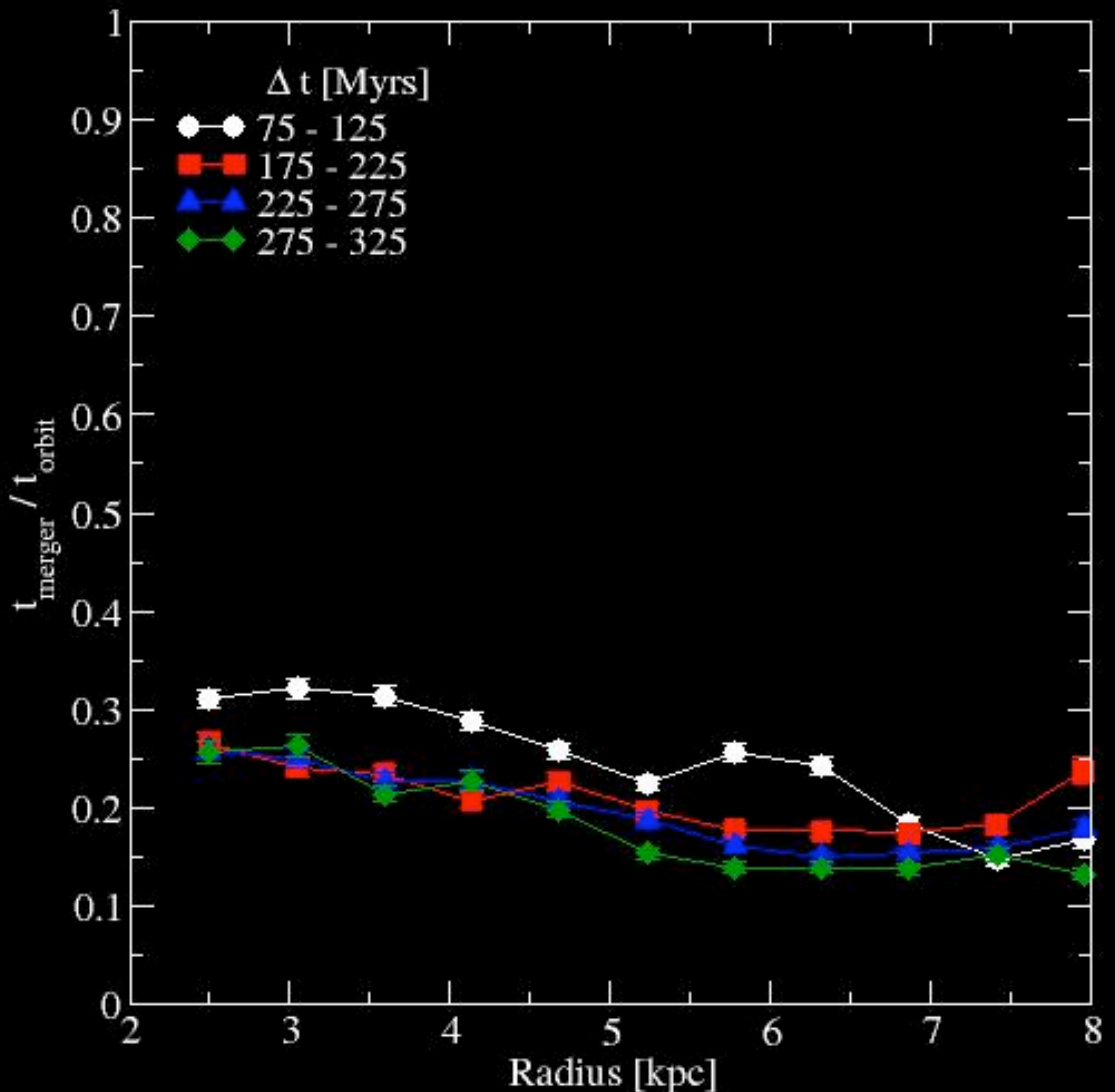
Cloud collision rate

Cloud collisions may also act as a trigger for star formation.

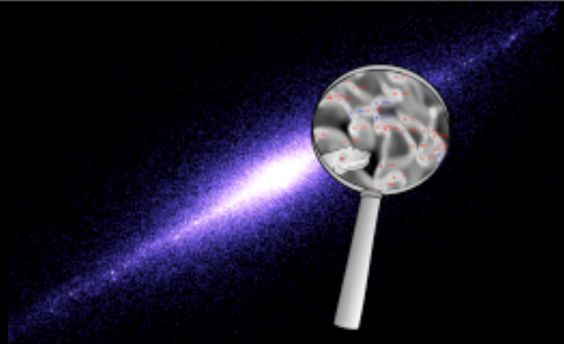
Tan (2000) showed that is the average cloud collision time is a fraction of the orbital period, and these events trigger star formation, then this can produce the observed Kennicutt-Schmidt relation.

Merger rate ~ 0.15 - 0.3 over most of the simulation

This is easily within many of the lifetime estimates for GMCs, suggesting cloud collisions could be a determining factor in disk SF.



No SF run, resolution 7.8 pc

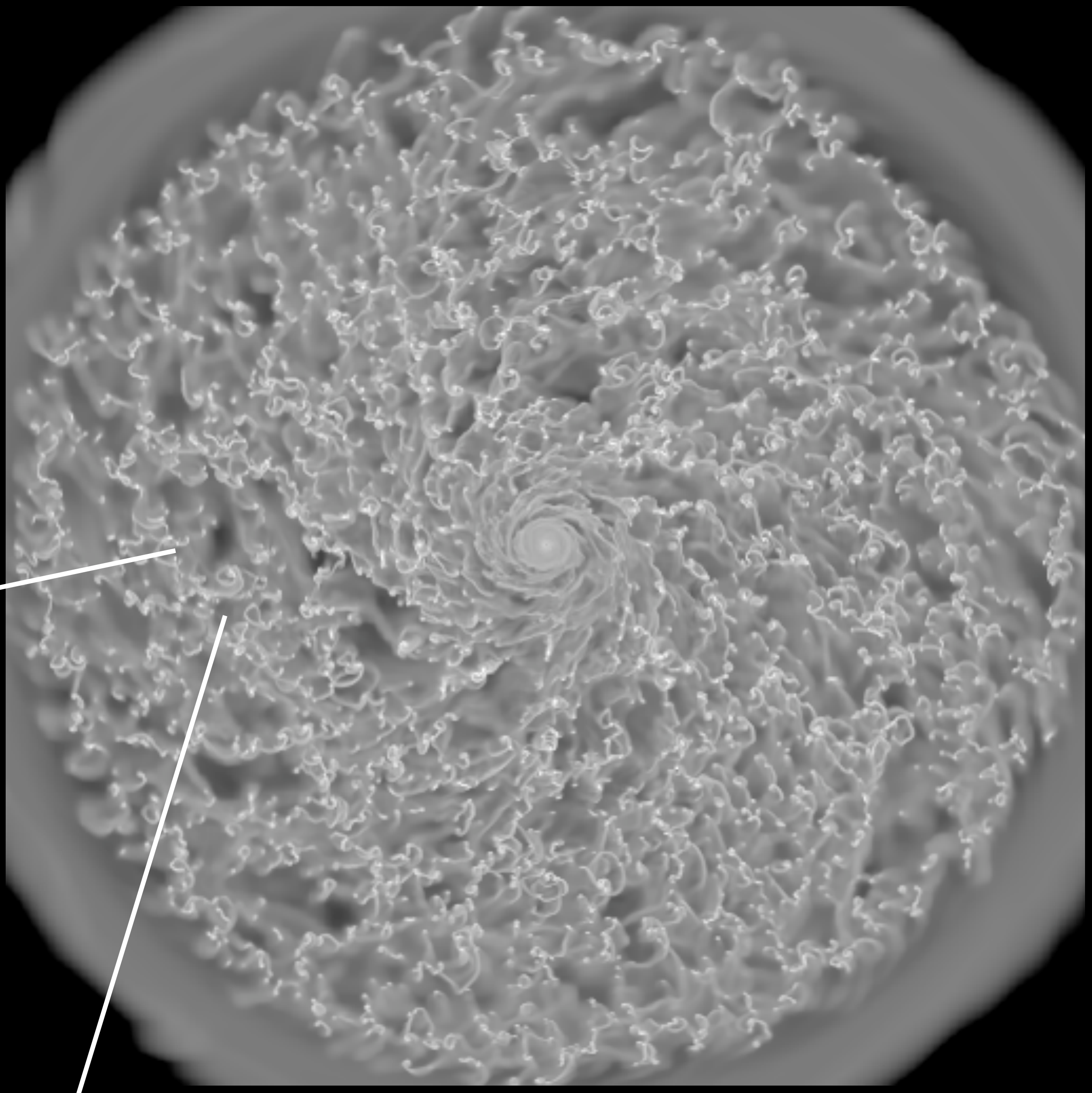


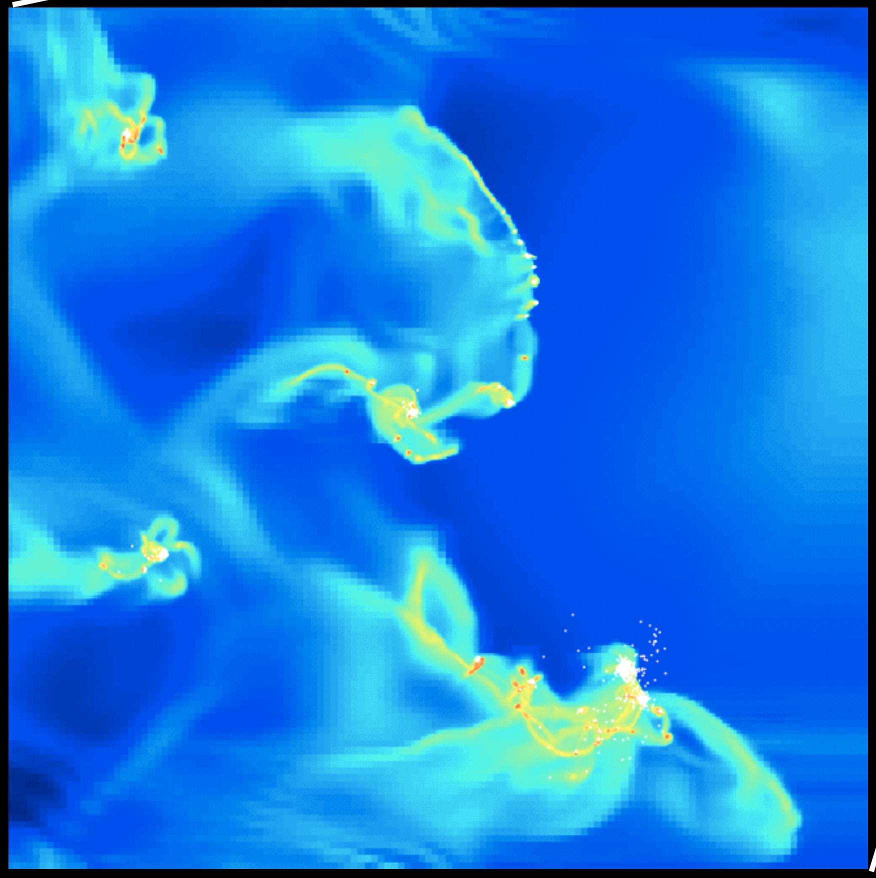
Still subgrid?

Local box simulation

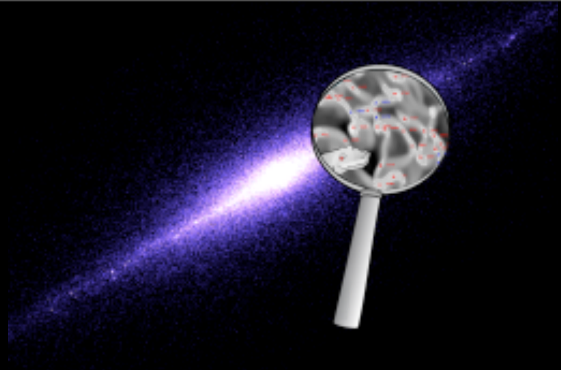
Initial conditions from 1 kpc patch of global simulation

Resolve down to sub-parsec scales





Mike Butler's simulation



Conclusions

- We modeled a Milky Way-type galaxy at 10s-parsec resolution in 3D with a fully multiphase ISM, including star formation and feedback from photoelectric heating.
- We identified and tracked GMCs through the galactic disk
- Cloud masses and radii are in good agreement with observed galaxies
- Cloud merger rate is a fraction of the orbital period, suggesting that such interactions could be the determining factor in star formation rates.
- This was all in the absence of feedback from SNe
- Higher resolution local simulations can compare the accuracy of our subgrid star formation models