The effect of photoionising feedback on star formation in colliding clouds

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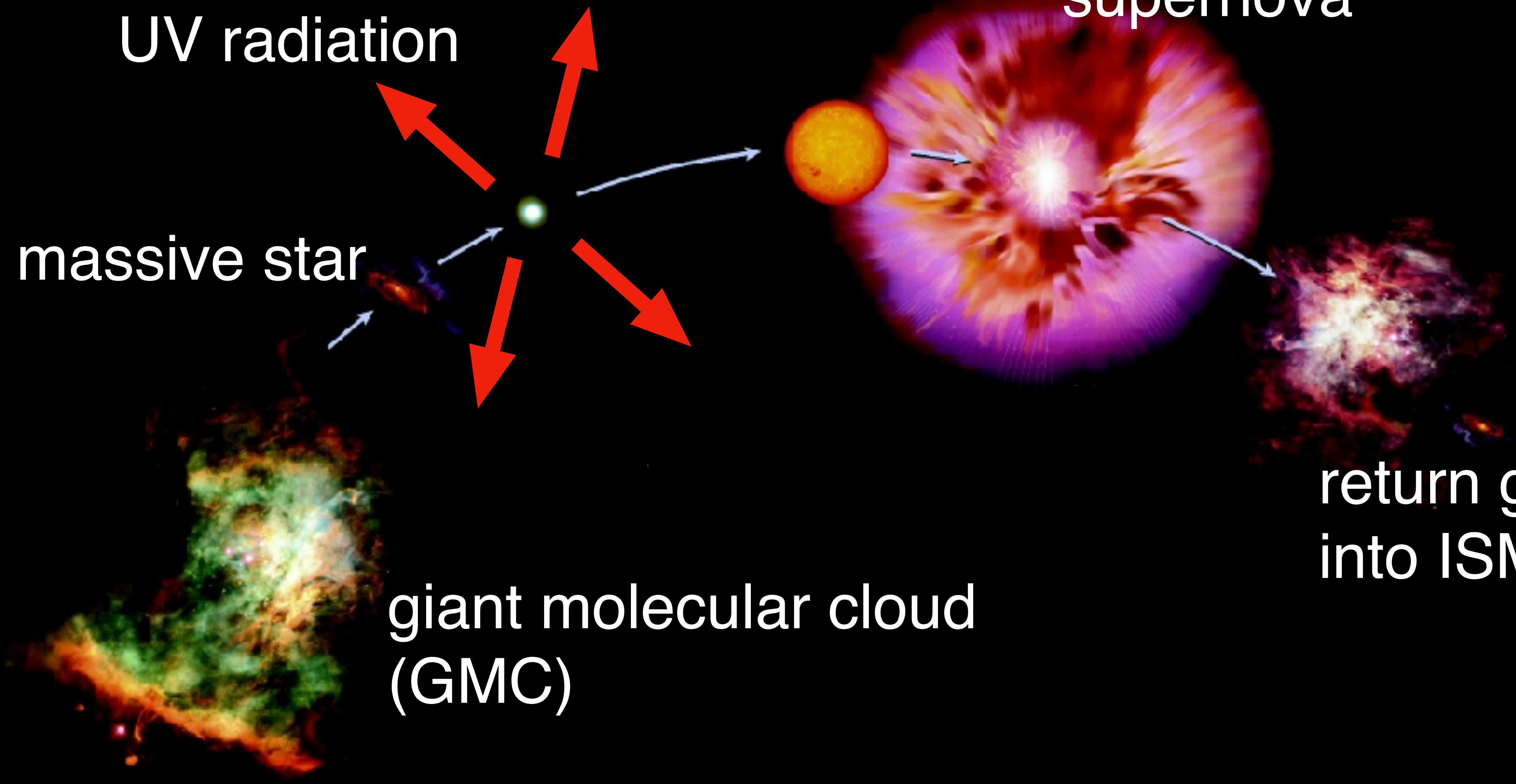
INTRODUCTION

Star formation is important



UV radiation

massive star

supernova

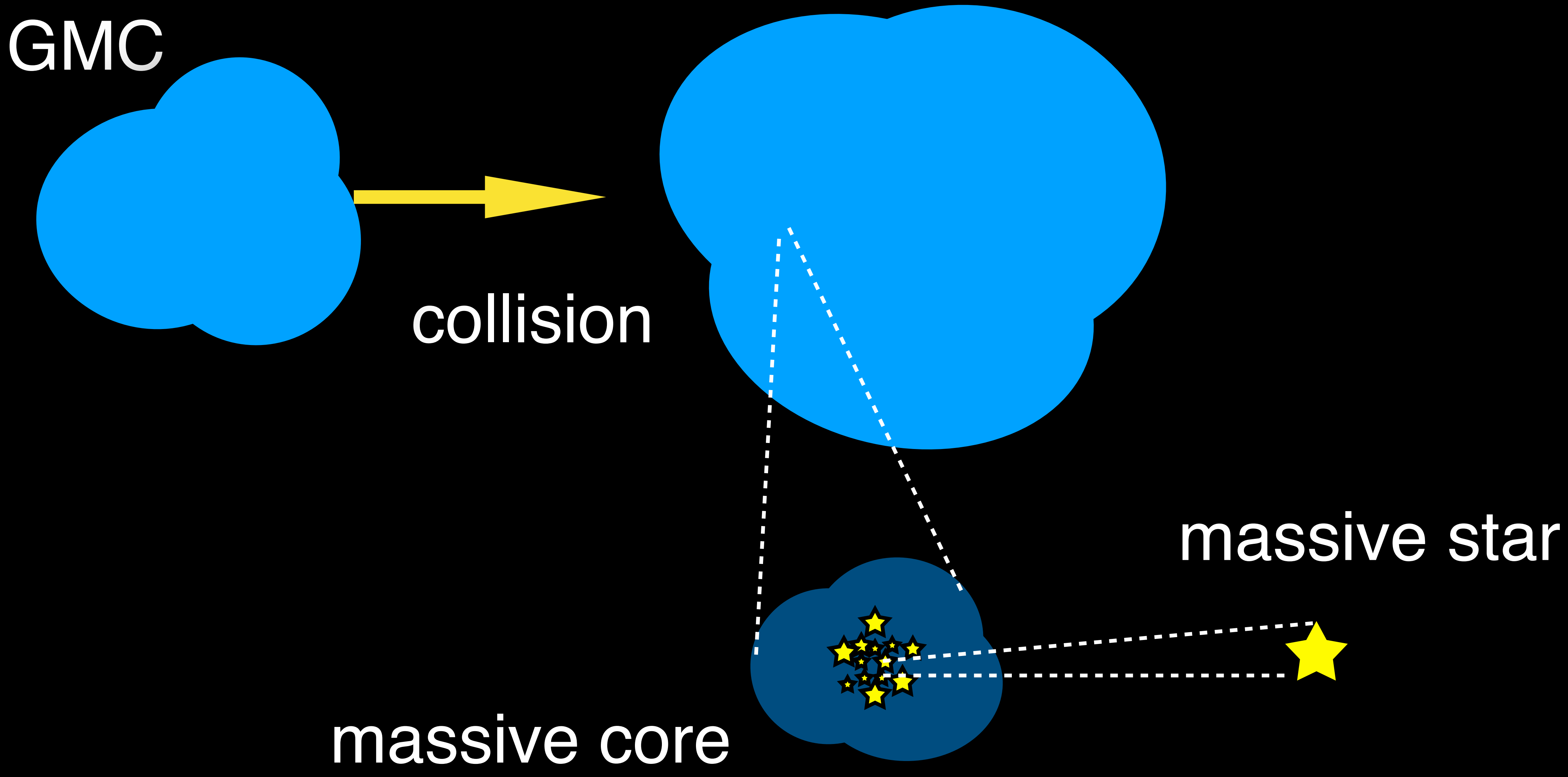
return gas
into ISM

giant molecular cloud
(GMC)

Massive stars have important roles.
-> How do massive stars form?

Cloud-Cloud Collision (CCC) scenario

(Habe+Ohta 1992, Klein+Woods 1998, Anathpindika 2010,
Inoue+Fukui 2013, Takahira+ 2014, Balfour+ 2015, Wu+ 2015,1016)



GMC

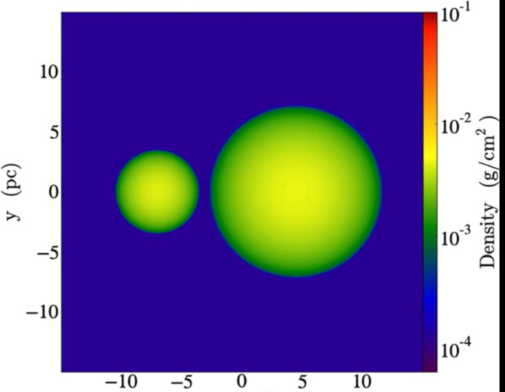
collision

massive star

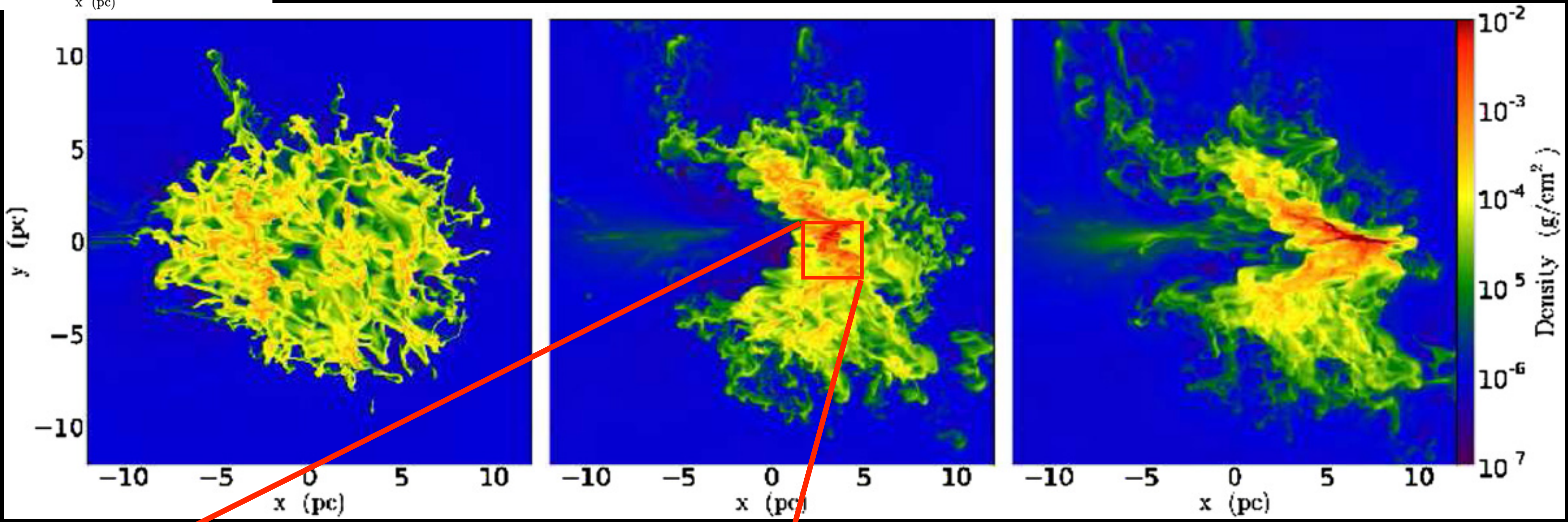
massive core

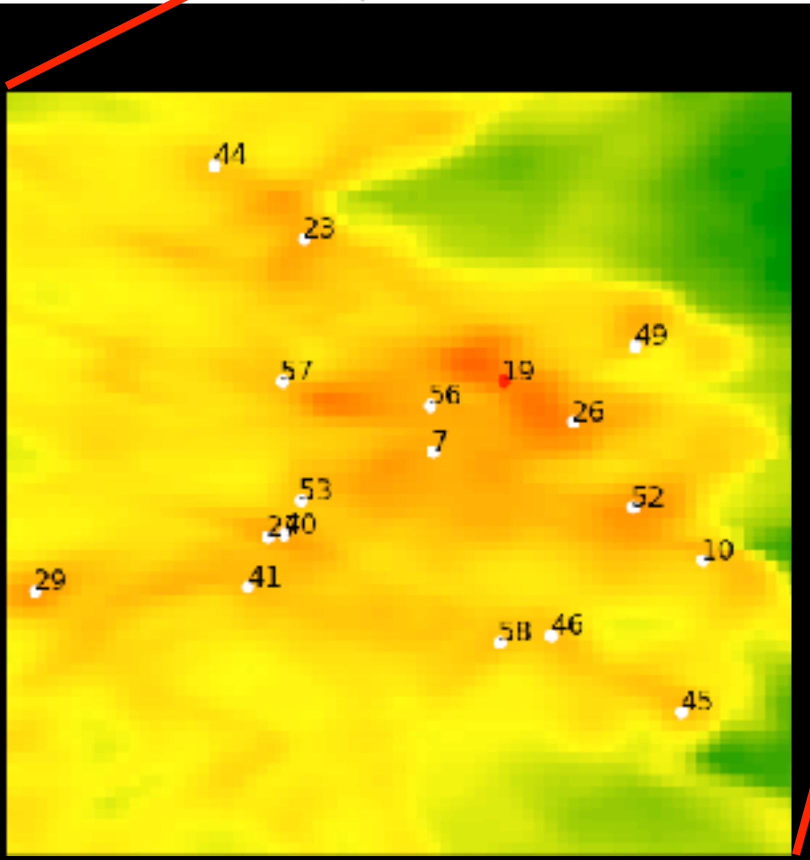
Gas is compressed at the collision interface.
Massive cores will form.

Previous simulations



(Takahira+ 2014)

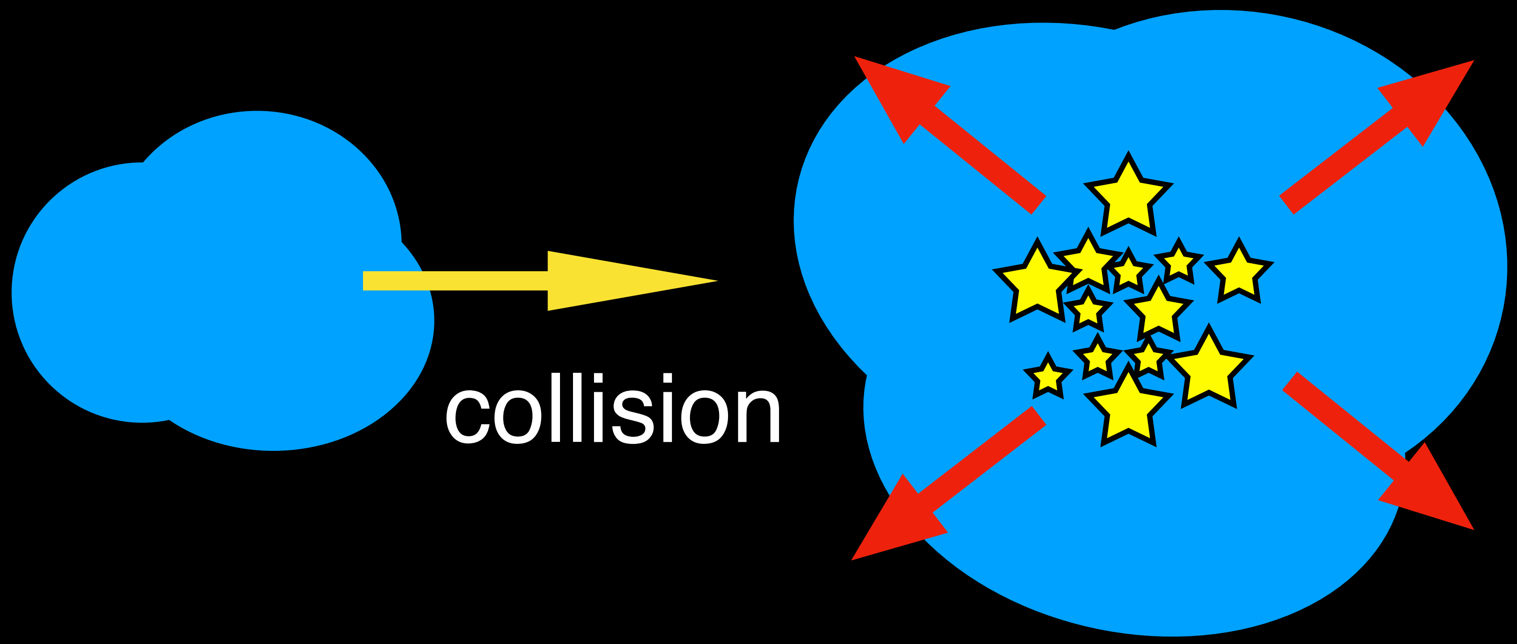




$$M_{J,eff} \propto \frac{(c_s^2 + \sigma_{turb}^2)^{3/2}}{\sqrt{\rho}}$$

Jeans mass increase by turbulence in the shock.

Motivation

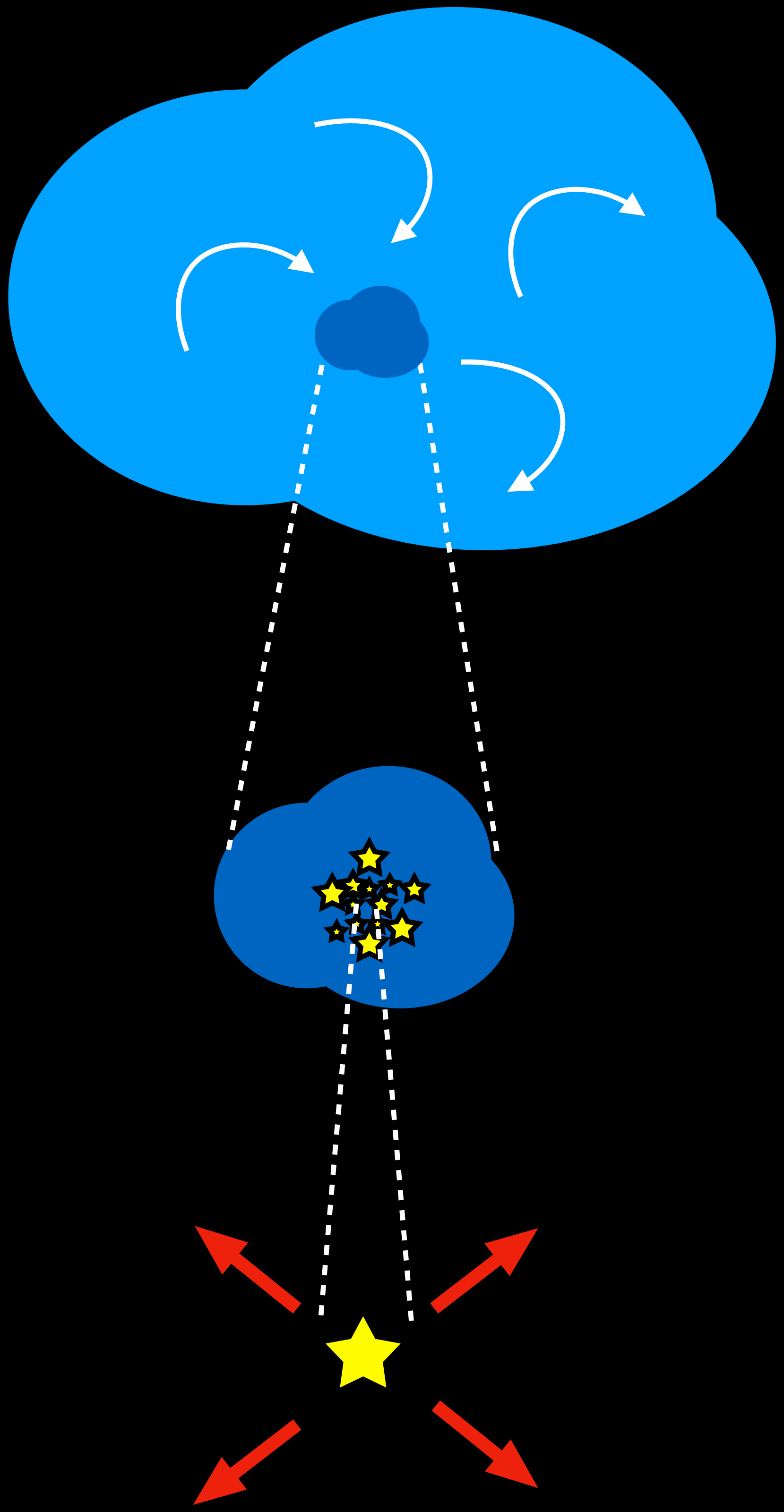


massive star formation

-> What happens to the cloud next?

Massive stars emit larger quantities of UV photons.
The energy will change the physical state of the cloud.
-> (Next) star formation is affected.

Star formation and feedback



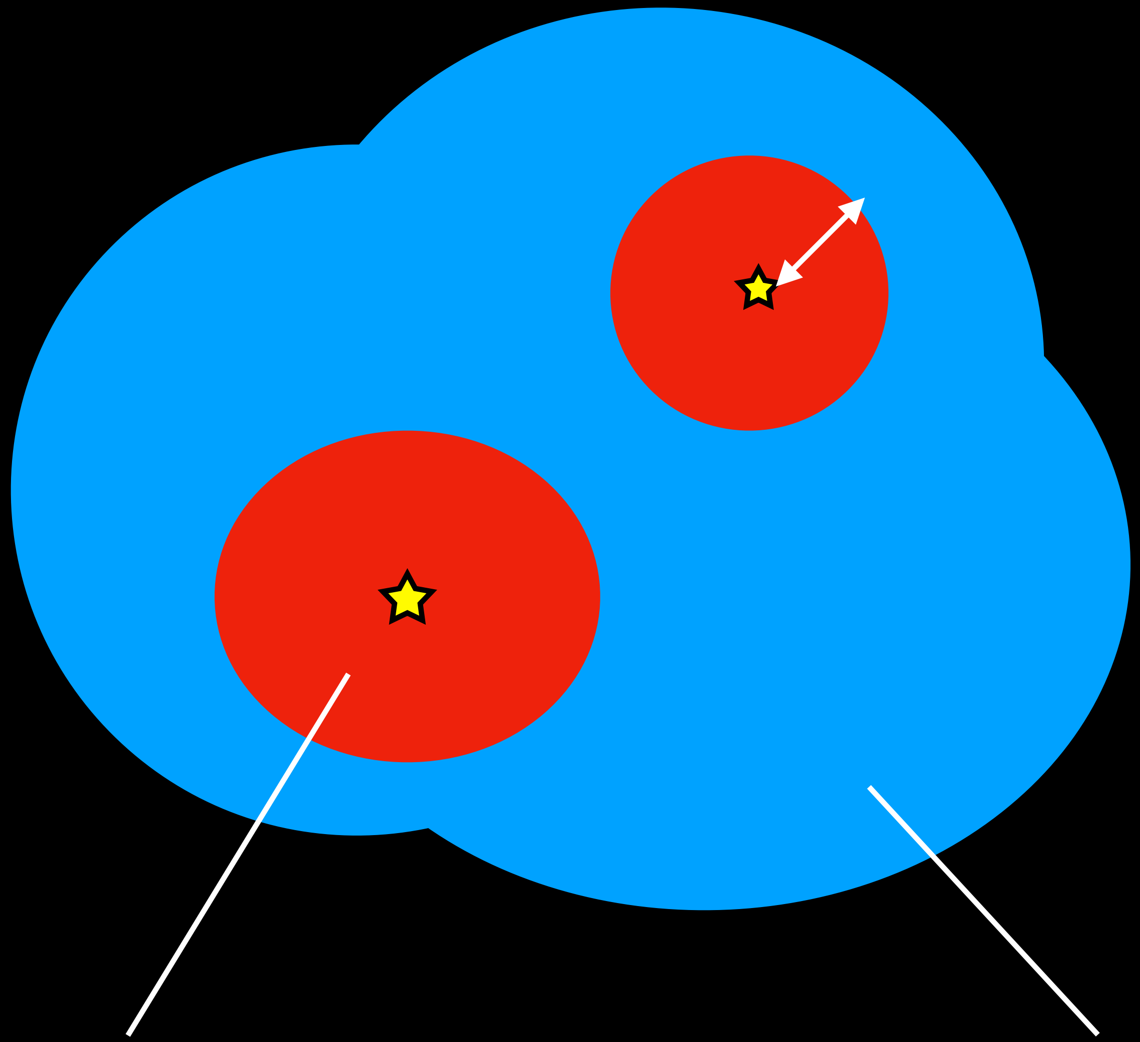
giant molecular cloud (GMC)

Star formation is controlled by the GMC’s state
- self-gravity
- turbulence
- (magnetic fields)

and feedback from other massive stars.

Stars
- massive stars emit large energy

Photoionisation feedback



Ionization front

$$R_s = (\frac{3Q_H}{4\pi n_H^2 \alpha_B})^{1/3}$$

$$t_{rec} = \frac{1}{n_H \alpha_B}$$

$$\Gamma_{ph} = k_{ph}(E_{ph} - E_{ph})$$

HII region (ionised gas)
~ 10000 [K]

>>

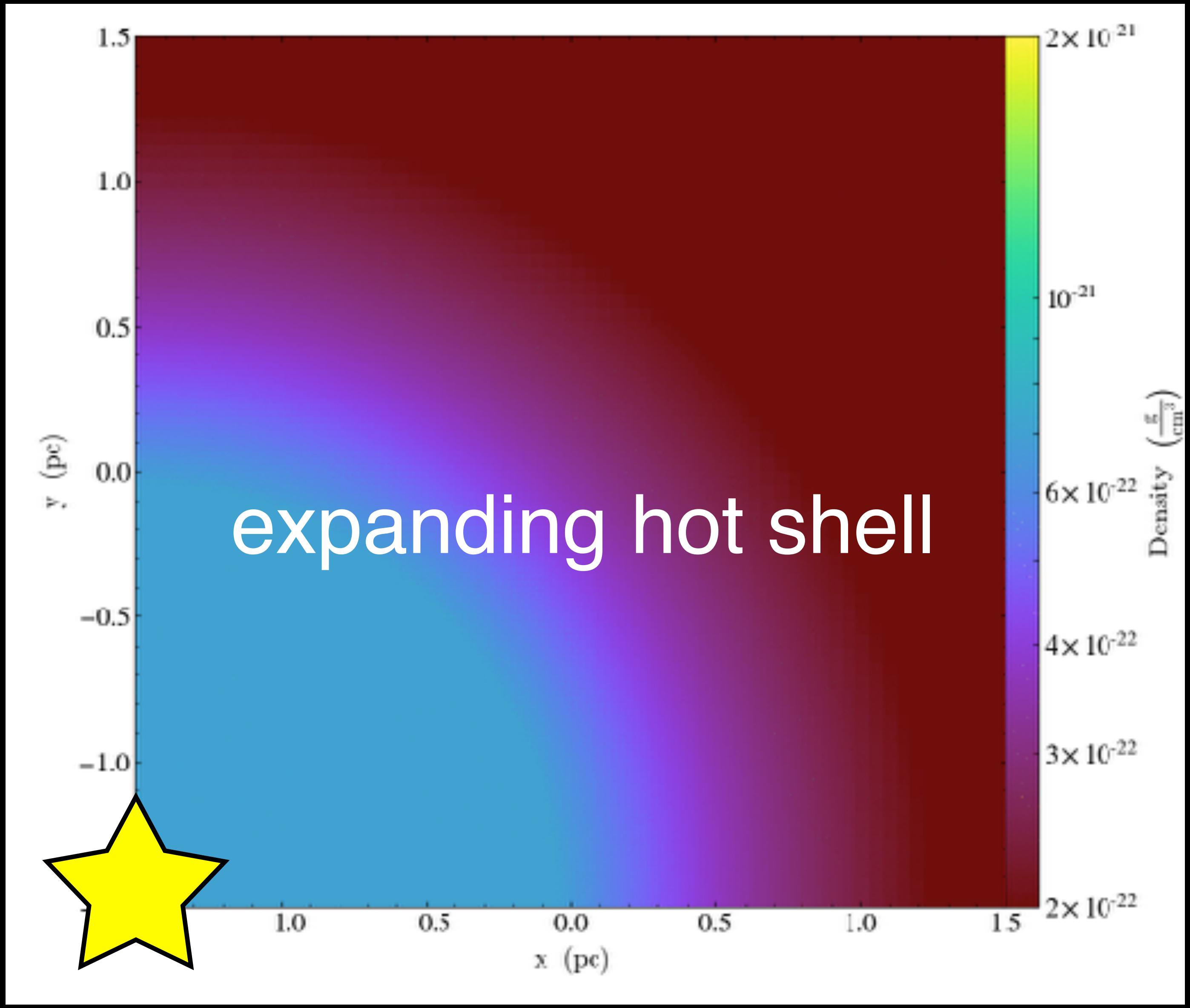
molecular clouds gas
~ 10 [K]

HII regions expand by high pressure.

Photoionisation feedback

(test simulation)

density slice plot



expanding hot shell

massive star

Questions:

enhance star formation?

or

surpress star formation?

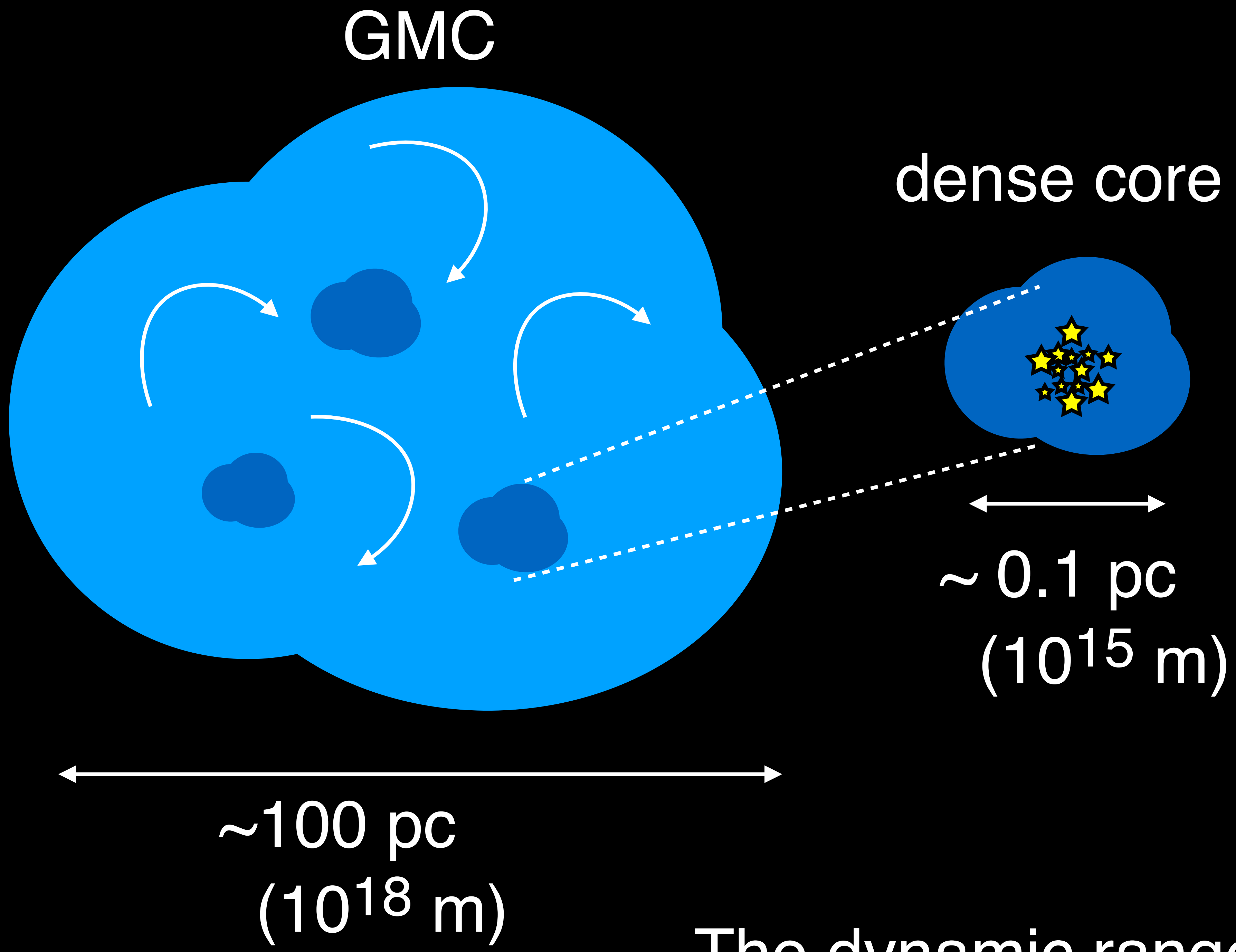
↑

$$M_{J,eff} \propto \frac{(c_s^2 + \sigma_{turb}^2)^{3/2}}{\sqrt{\rho}}$$

↓

NUMERICAL MODEL & METHODS

GMC model



GMC

dense core

~ 0.1 pc
(10^{15} m)

~100 pc
(10^{18} m)

The dynamic range is very large.

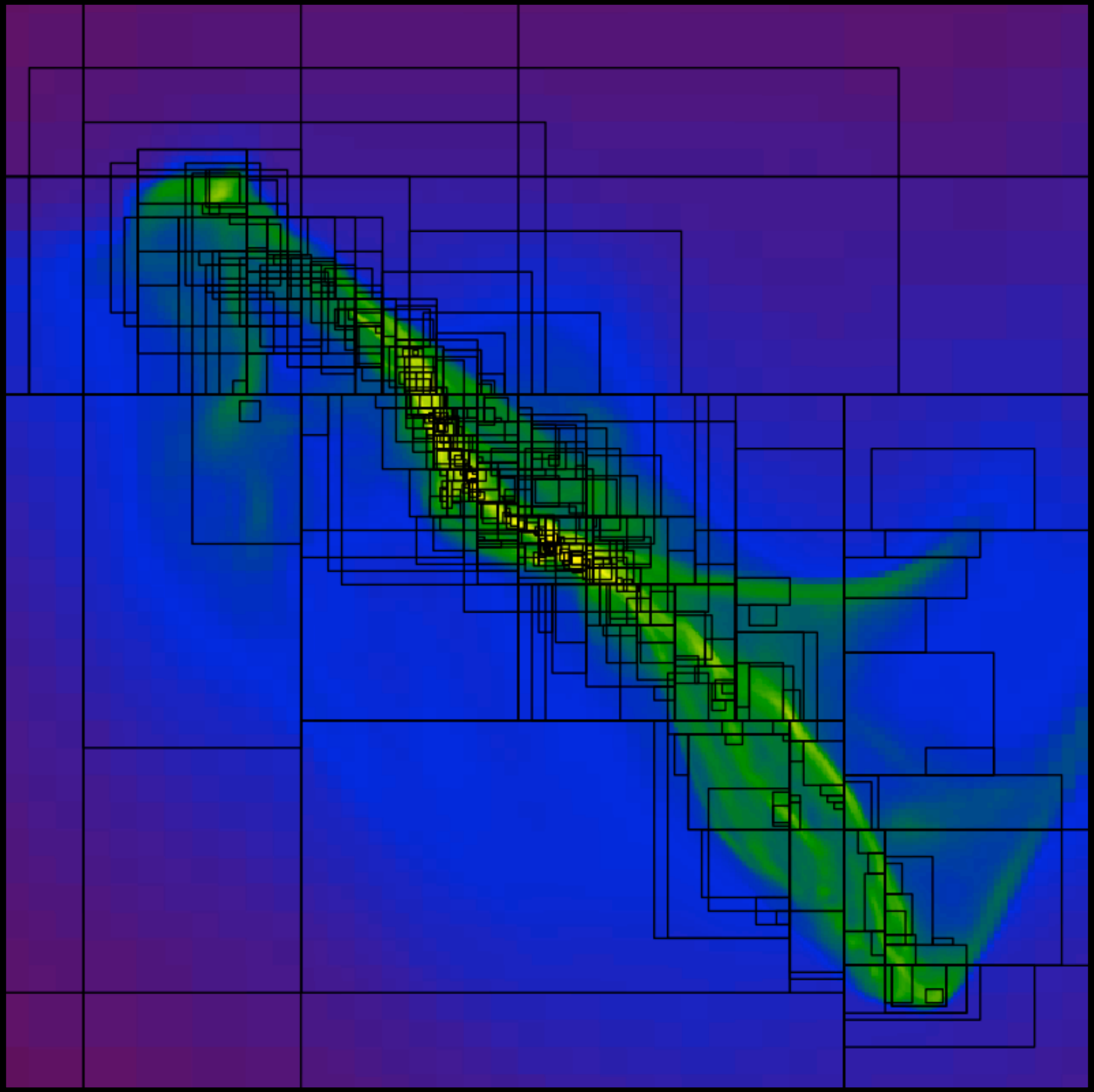
simulation code

Enzo; a 3D AMR code
(Adaptive Mesh Refinement)

(Bryan et al. 2014)

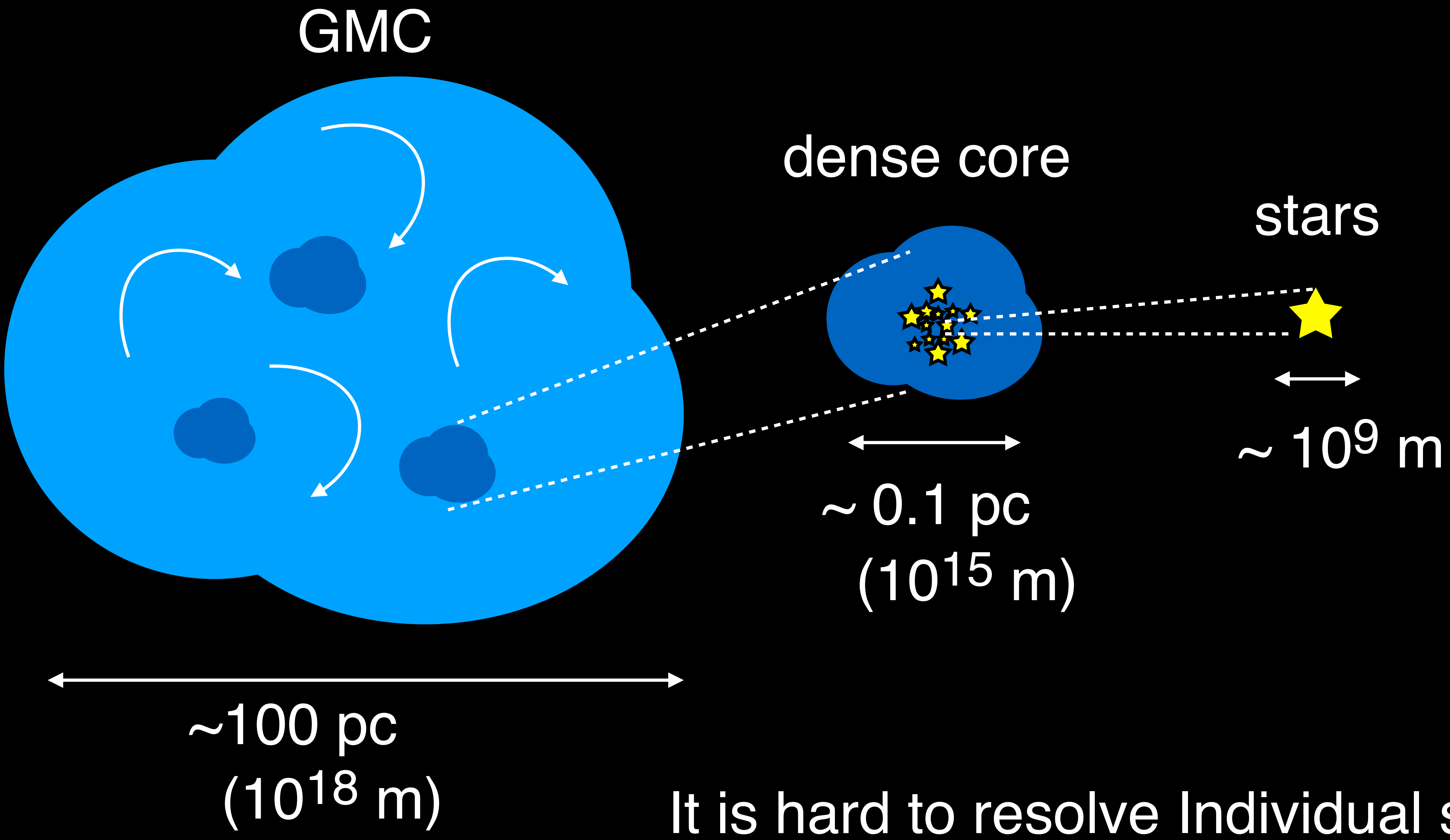
Hydrodynamics is calculated on the meshes.

Meshes are added adaptively over regions that require higher resolutions.



(Enzo Workshop)

Star formation model



GMC

dense core

stars

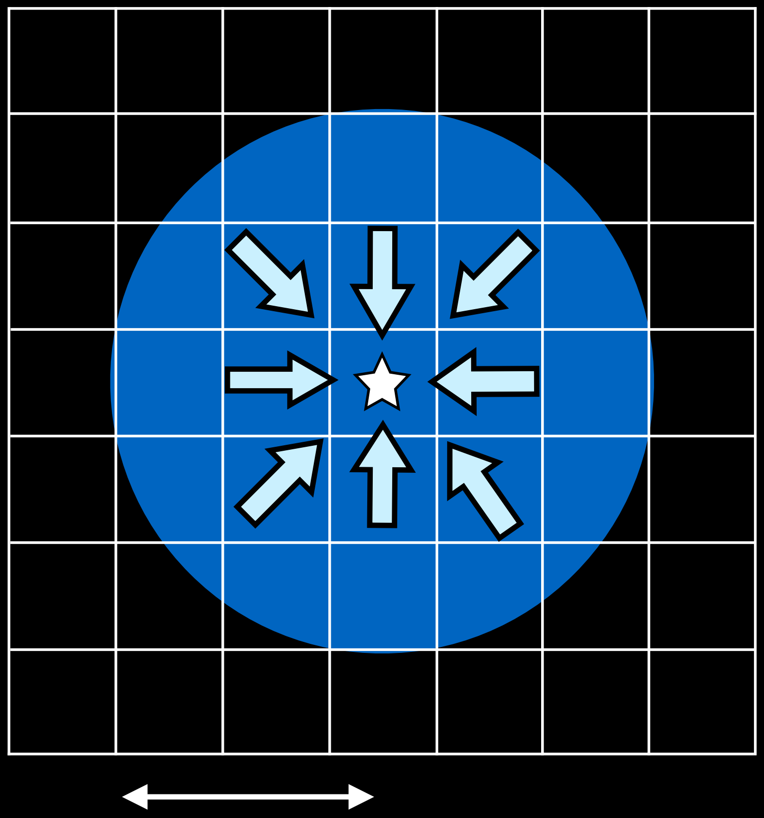
~100 pc
(10^{18} m)

~ 0.1 pc
(10^{15} m)

~ 10^{9} m

It is hard to resolve Individual stars.
-> sink particle model.

Sink particle model



r = 0.07 pc

$$r = \frac{1}{2}\lambda_J$$

$$\lambda_J = 5\Delta \mathrm{x}$$

$$\rho_{crit} = \frac{\pi c_s^2}{G\lambda_J^2}$$

sink formation conditions

(Federrath et al. 2010)

+ the finest level of refinement

+ over density $\rho_{gas} > \rho_{crit}$

+ converging flow

+ gravitational potential minimum

$$\phi_{center} \leq \phi(i,j,k)$$

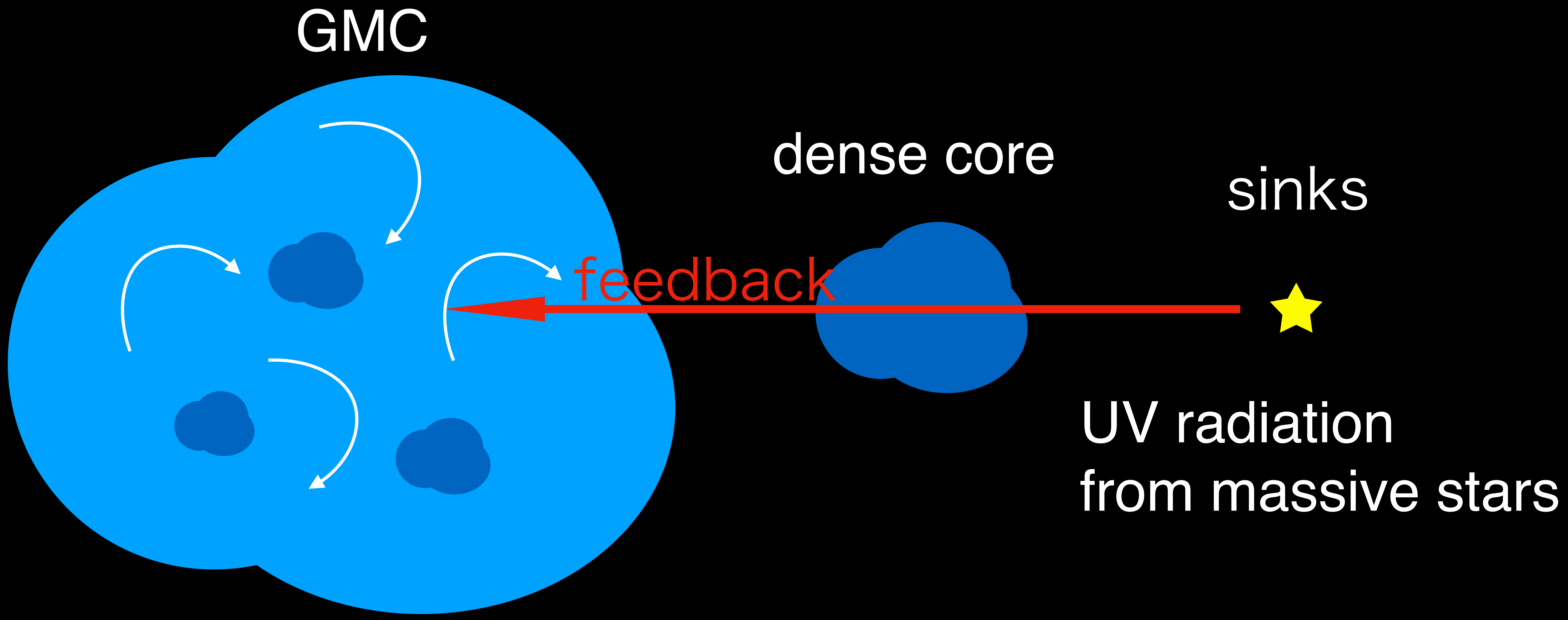
+ Jeans instability check

$$|E_{grav}| > 2\,E_{th}$$

+ bound state check

$$E_{grav} + E_{th} + E_{kin} < 0$$

Feedback model



GMC

dense core

sinks

feedback

UV radiation
from massive stars

Radiation is treated with ray-tracing method.

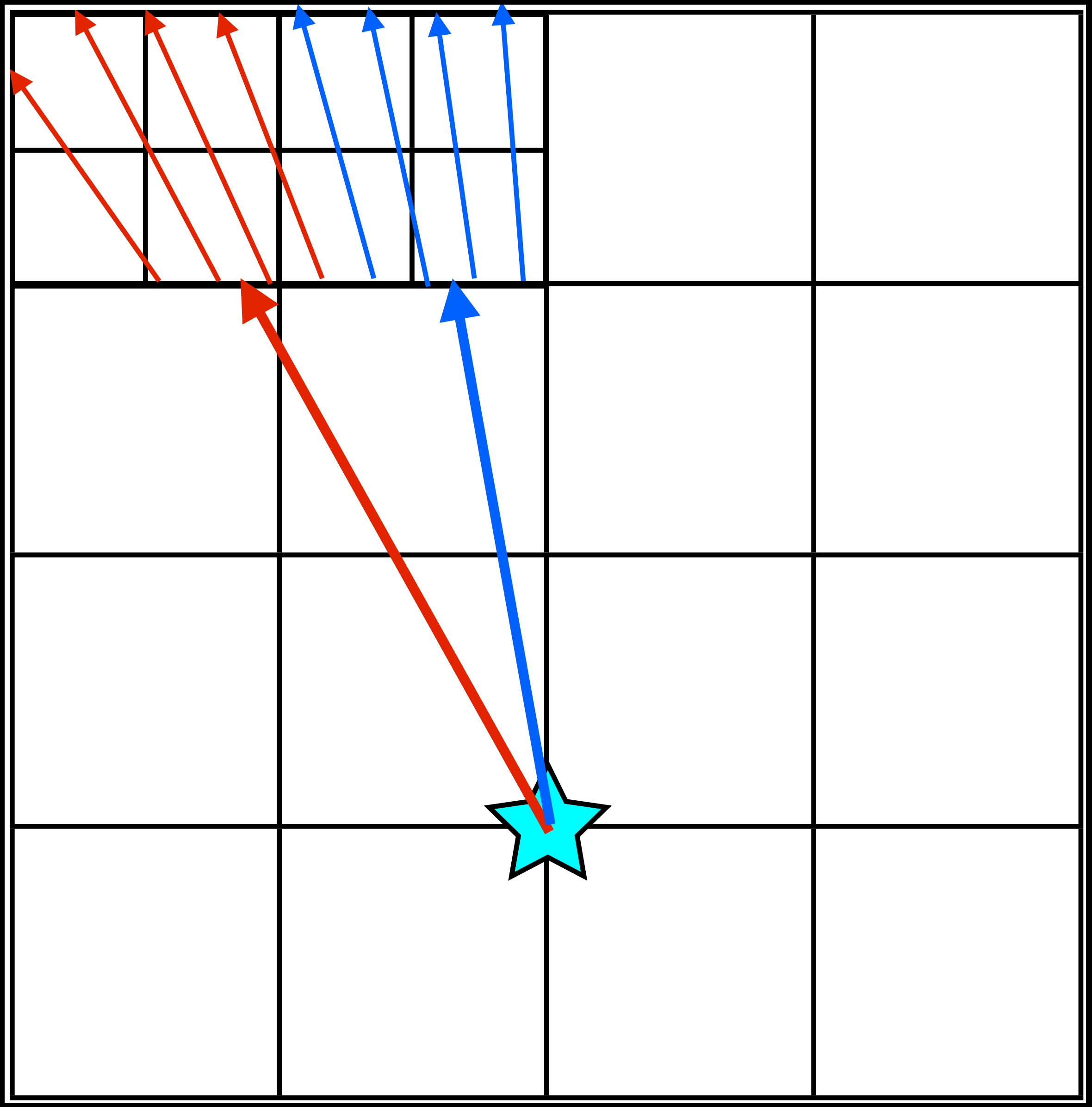
Adaptive ray tracing

(Wise & Abel 2011)

The radiative transfer equation is solved along rays.

Ionisation of hydrogen and the UV heating rate is calculated.

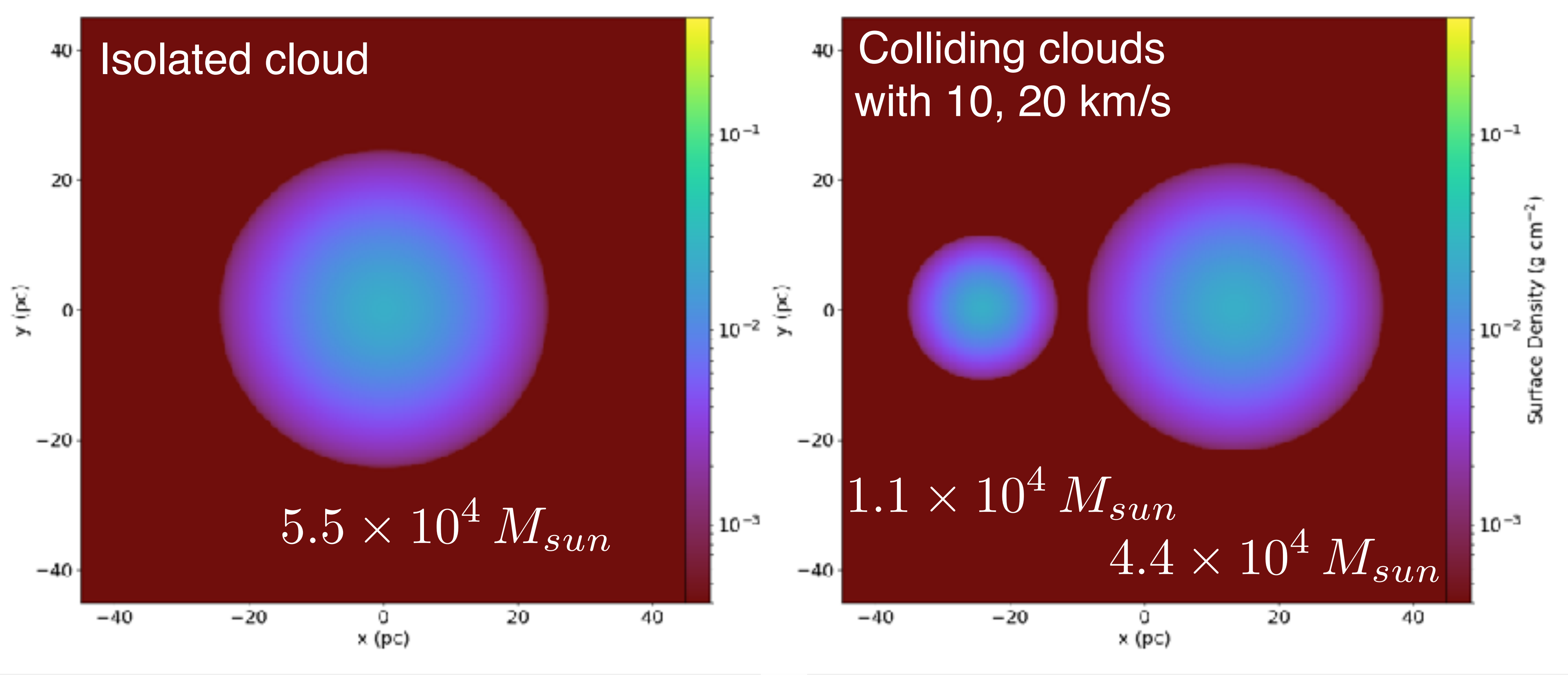
Rays are split into child rays when the solid angle is large compared to the cell face area.



(Enzo Workshop)

Initial conditions

Surface density

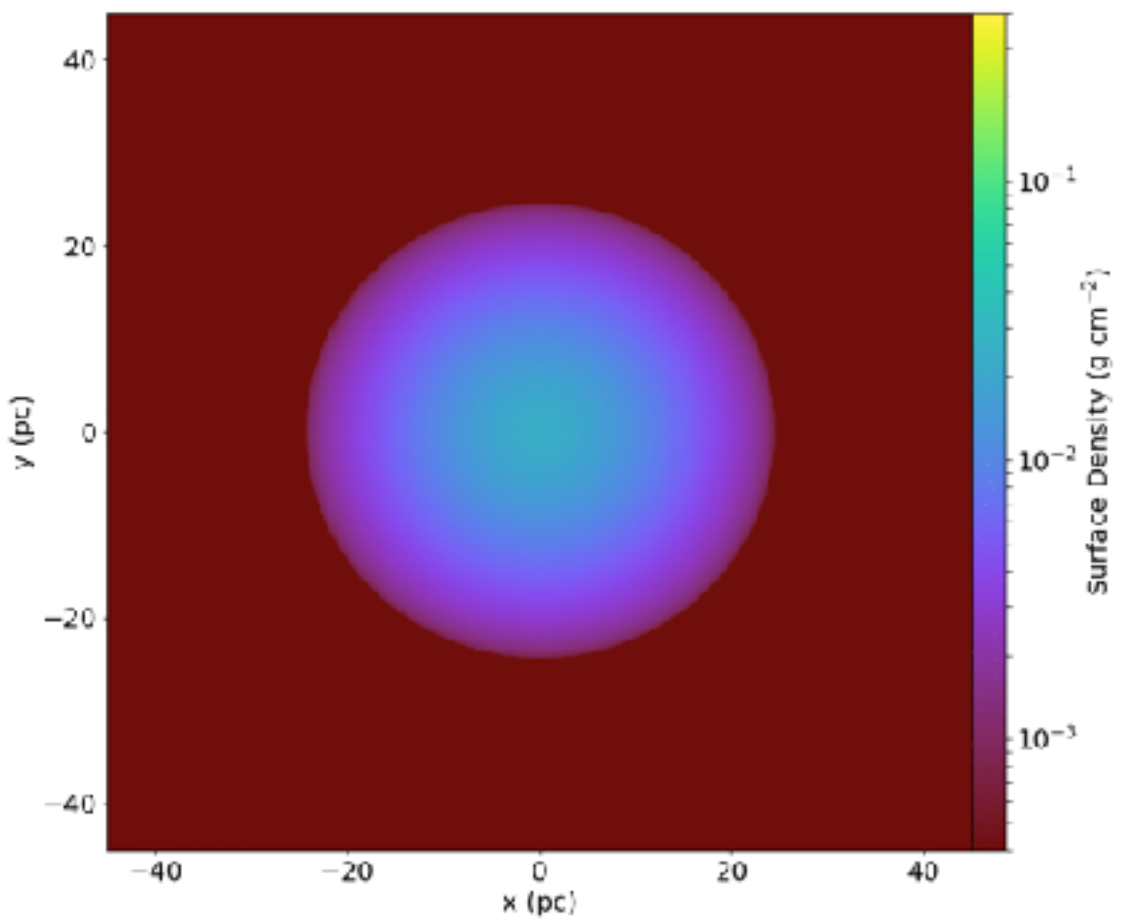


Box size:	90 pc
Maximum refinement level:	5
Resolution:	0.03 pc

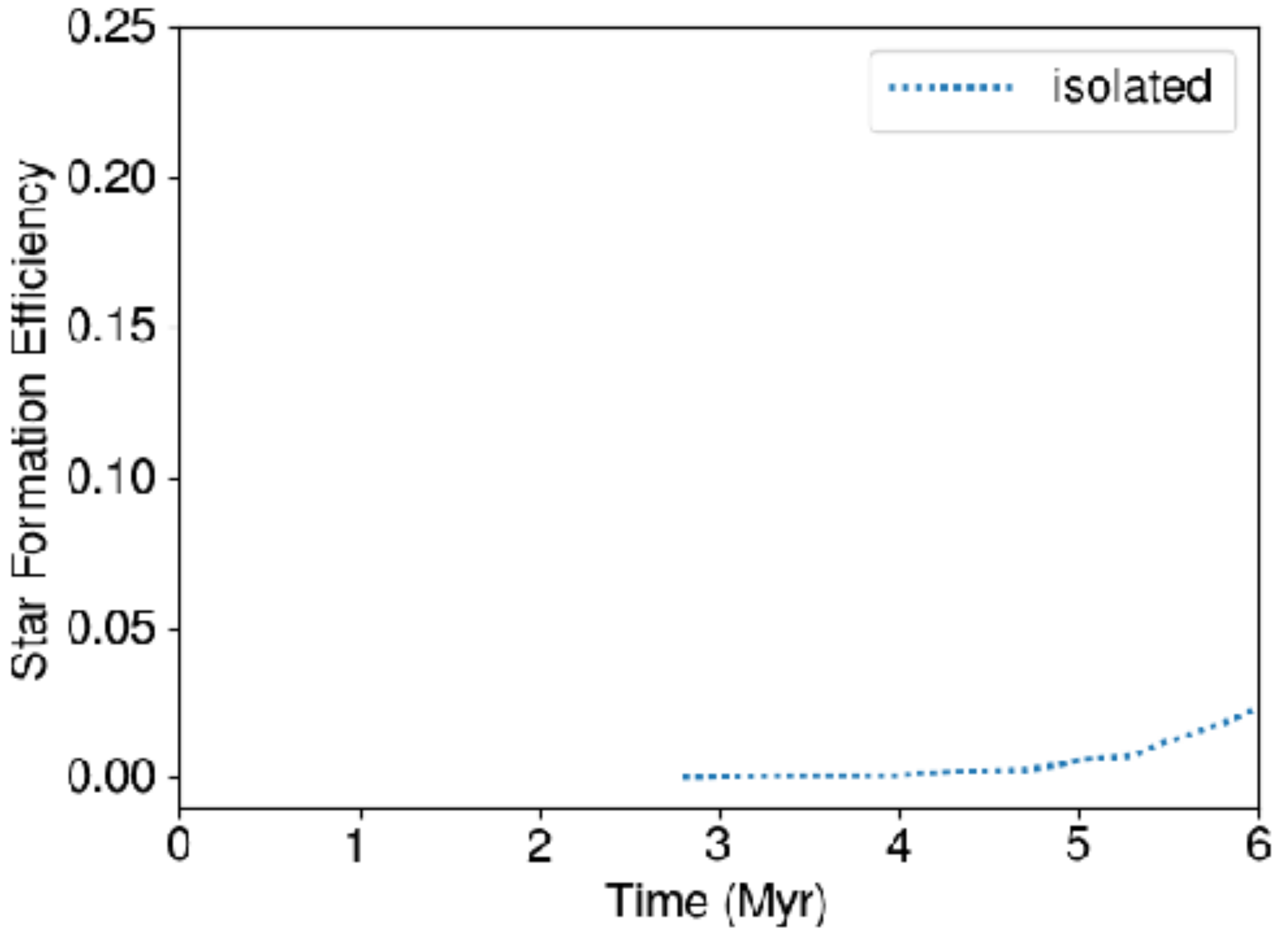
RESULTS

Isolated cloud (NoFeedback)

Surface Density



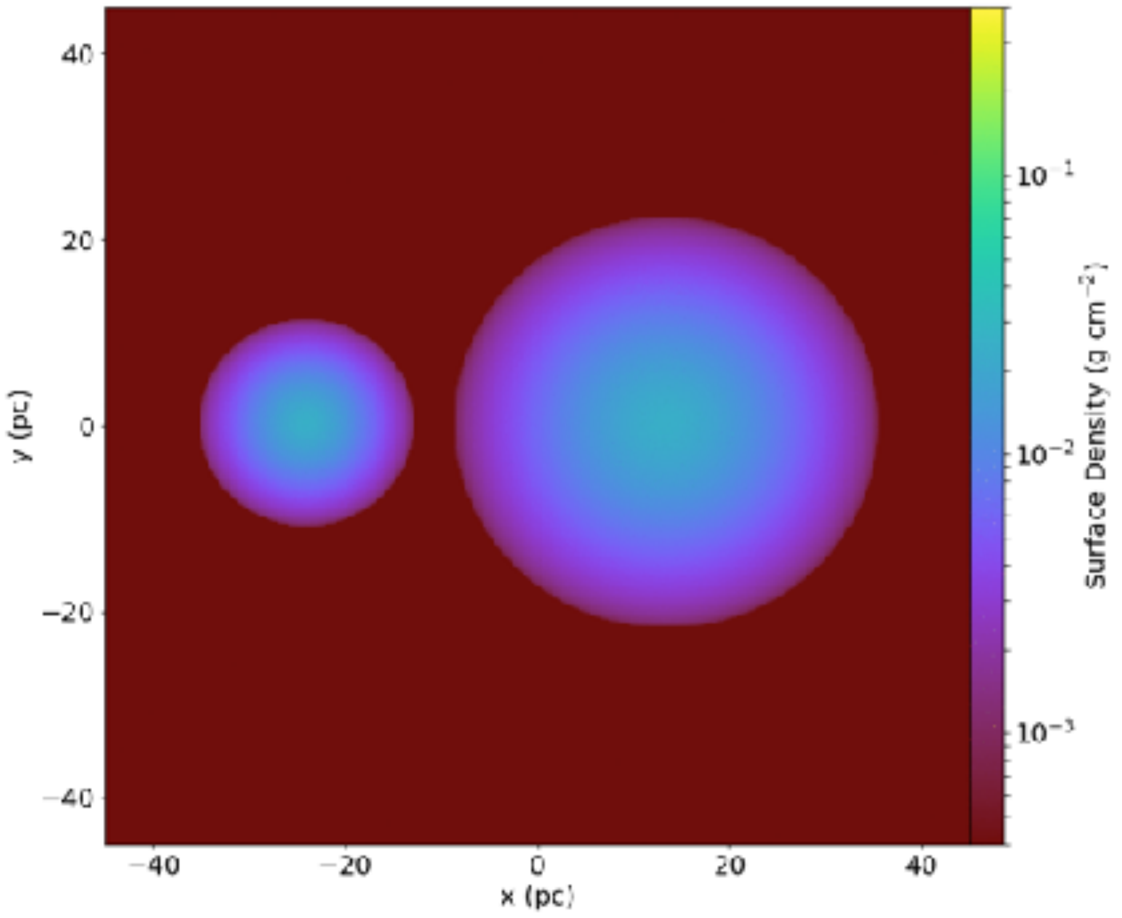
SFE v.s. Time



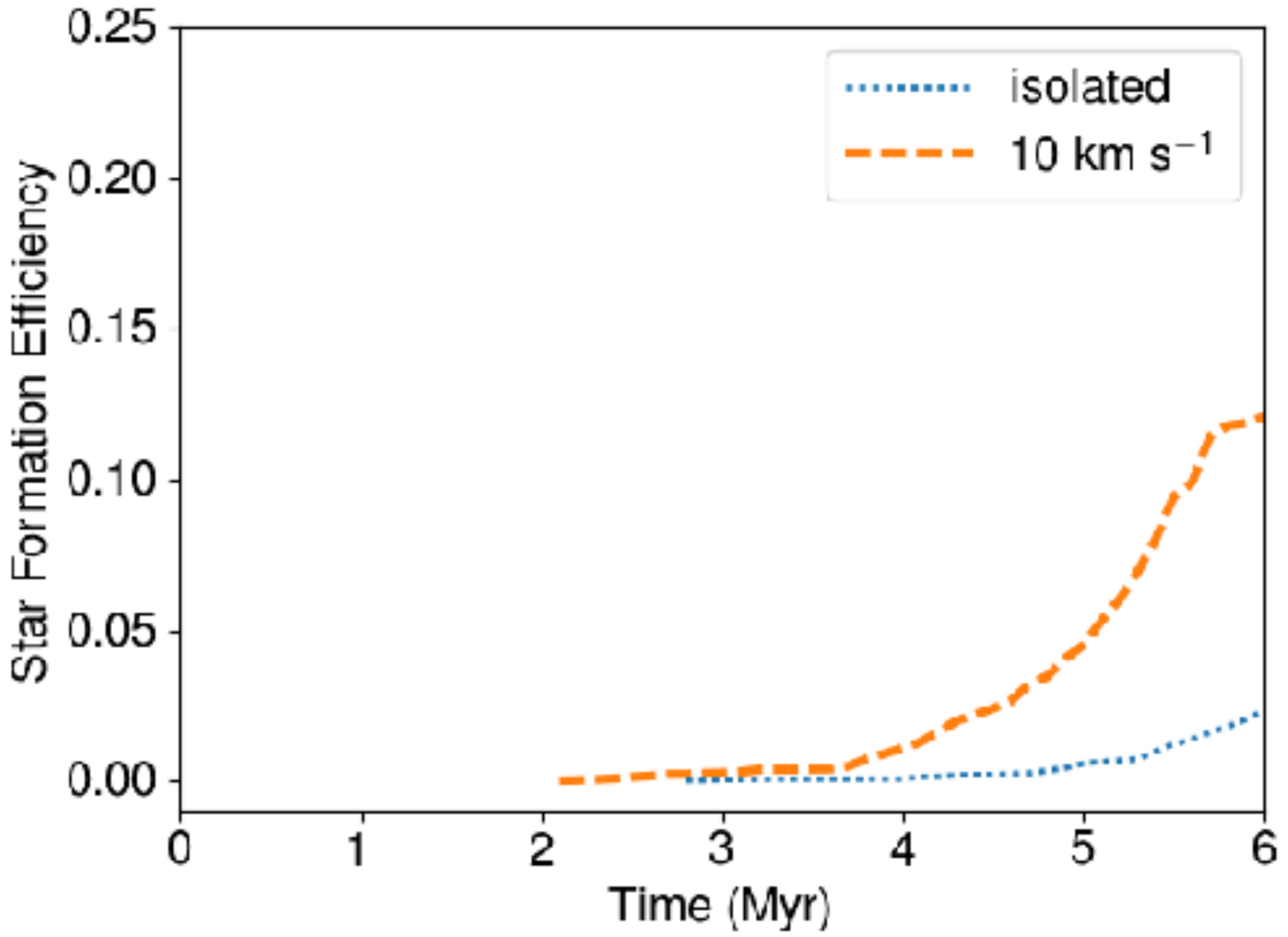
Turbulence decays and the cloud begins to collapse.
The SFE reaches ~ 2% at 6 Myr.

Colliding cloud at 10 km/s (NoFeedback)

Surface Density



SFE v.s. Time

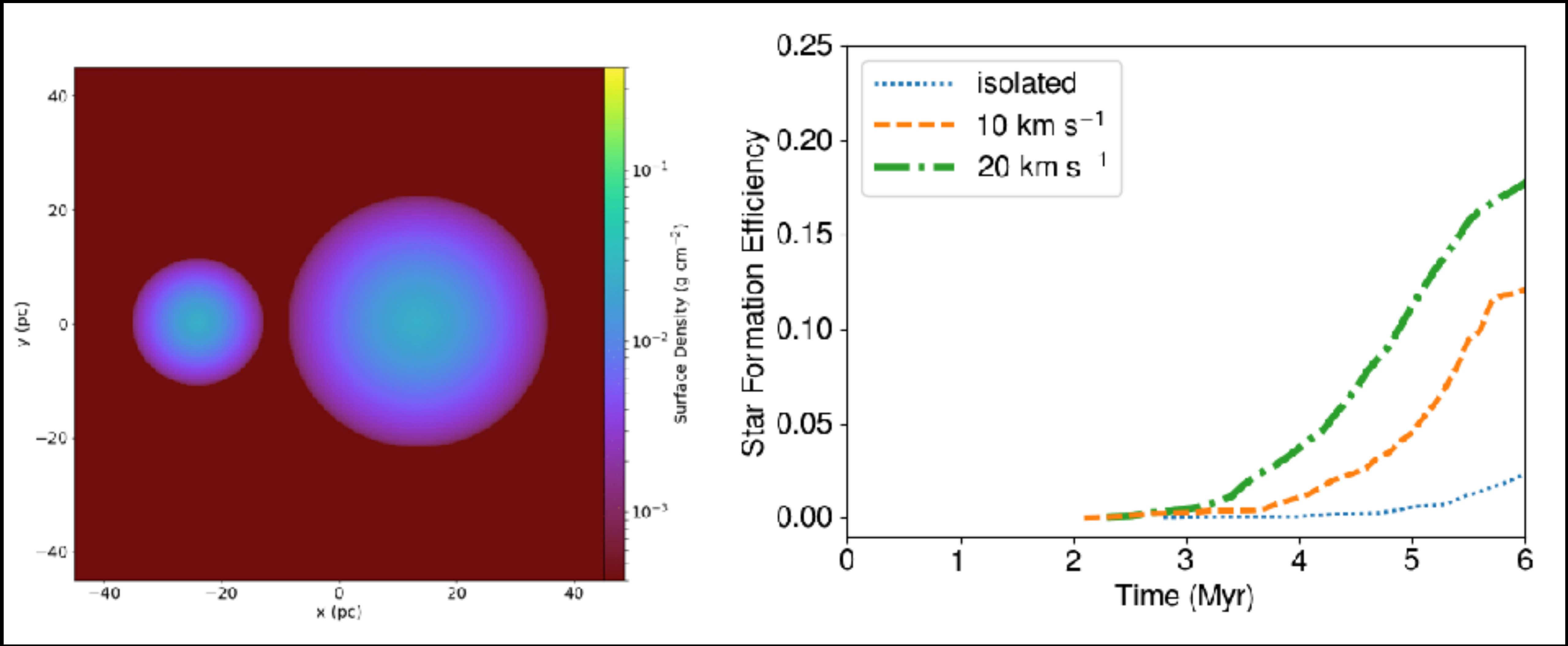


The colliding clouds begin star formation earlier.
The SFE reaches 12 % at 6 Myr.

Colliding cloud at 20 km/s (NoFeedback)

Surface Density

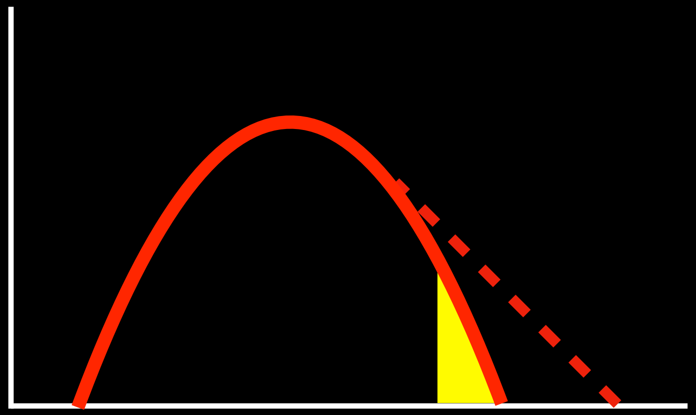
SFE v.s. Time



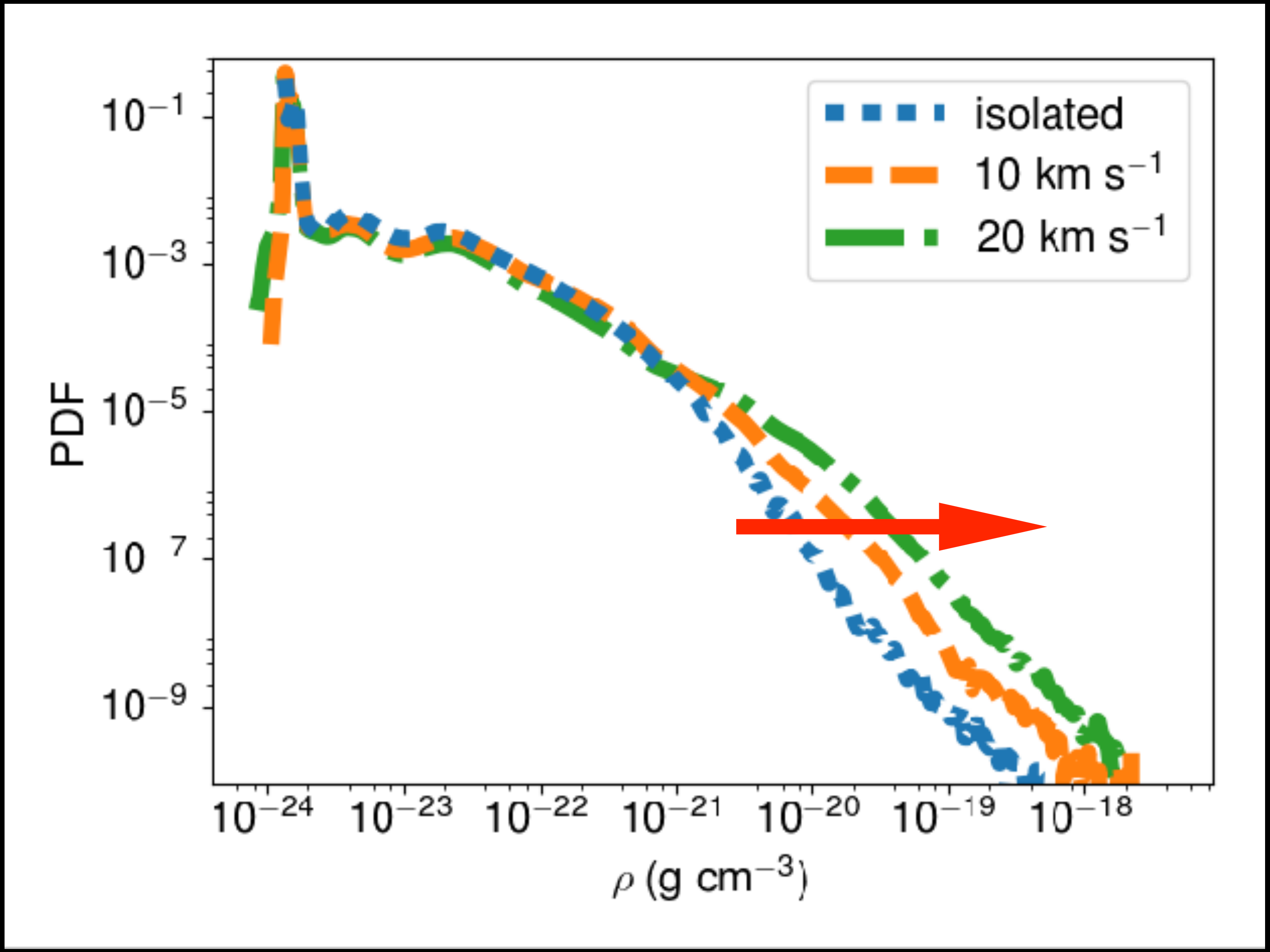
The faster collision produces stars more rapidly.
The SFE reaches 17 % at 6 Myr.

Probability Distribution Function (PDF) of density

turbulence
-> log-normal PDF



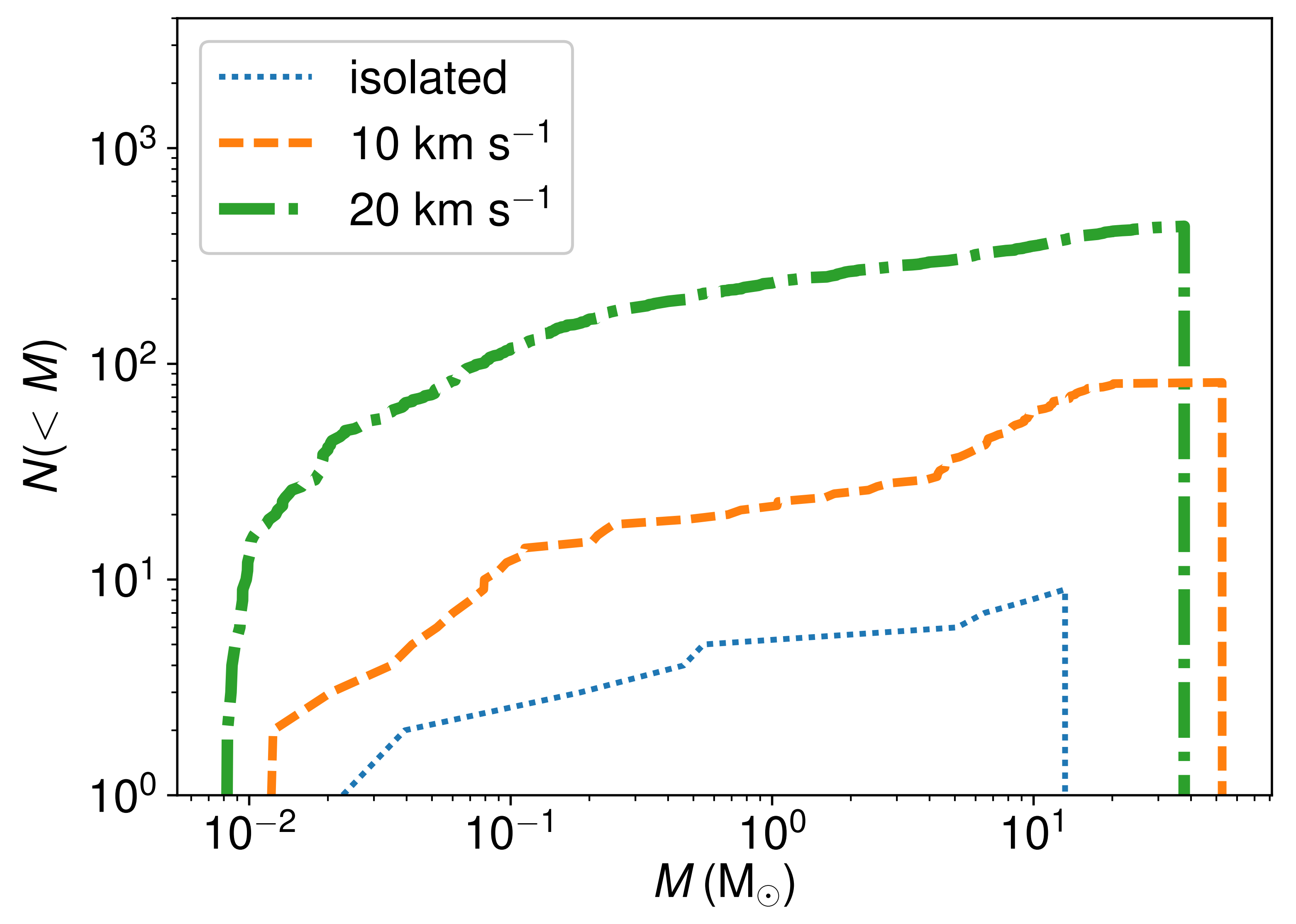
collapse -> tail



Gas is compressed by collision.

Collision effect on star formation

cumulative mass function



more small & massive sinks

$$M_{J,eff} \propto \frac{(c_s^2 + \sigma_{turb}^2)^{3/2}}{\boxed{\sqrt{\rho}}}$$

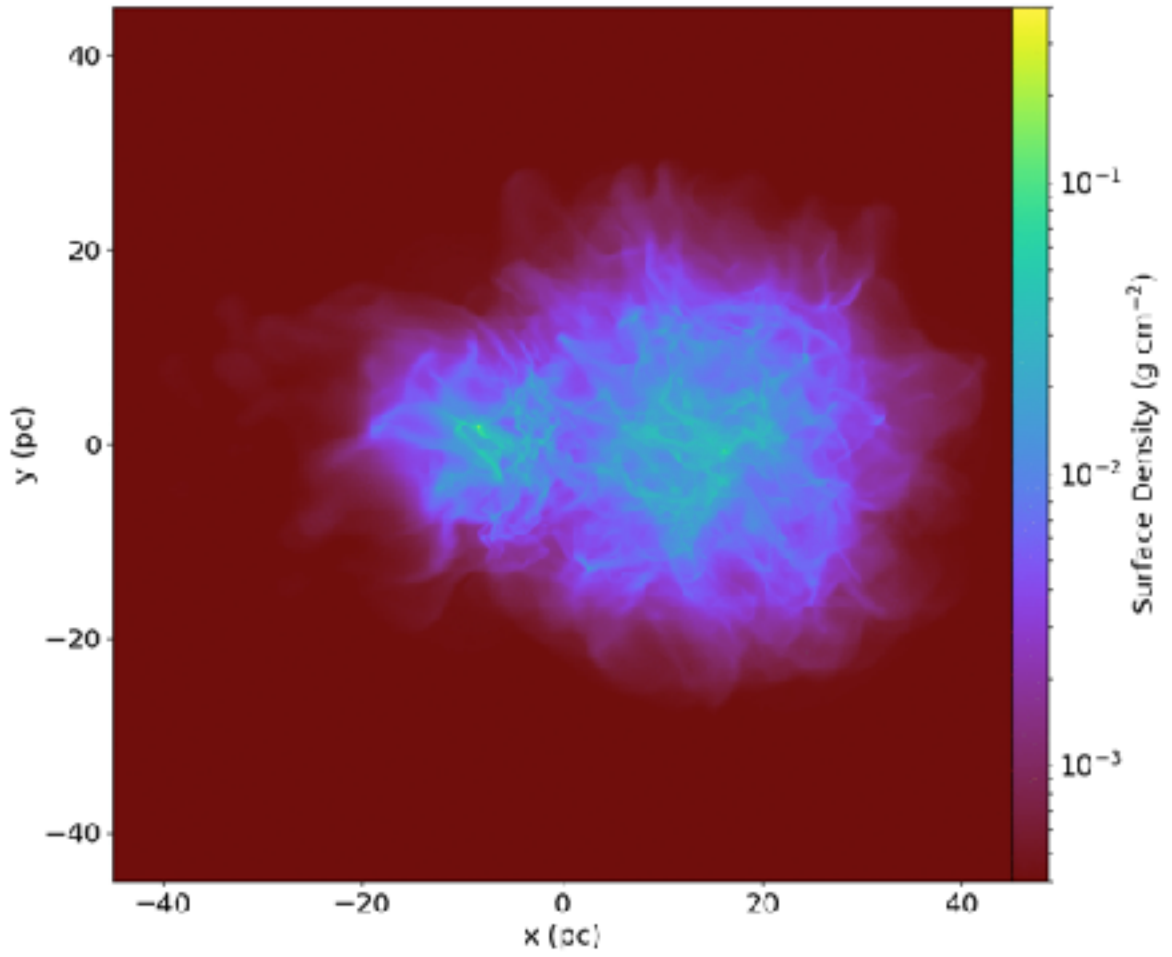
fragment into small species

$$M_{J,eff} \propto \frac{(c_s^2 + \boxed{\sigma_{turb}^2})^{3/2}}{\sqrt{\rho}}$$

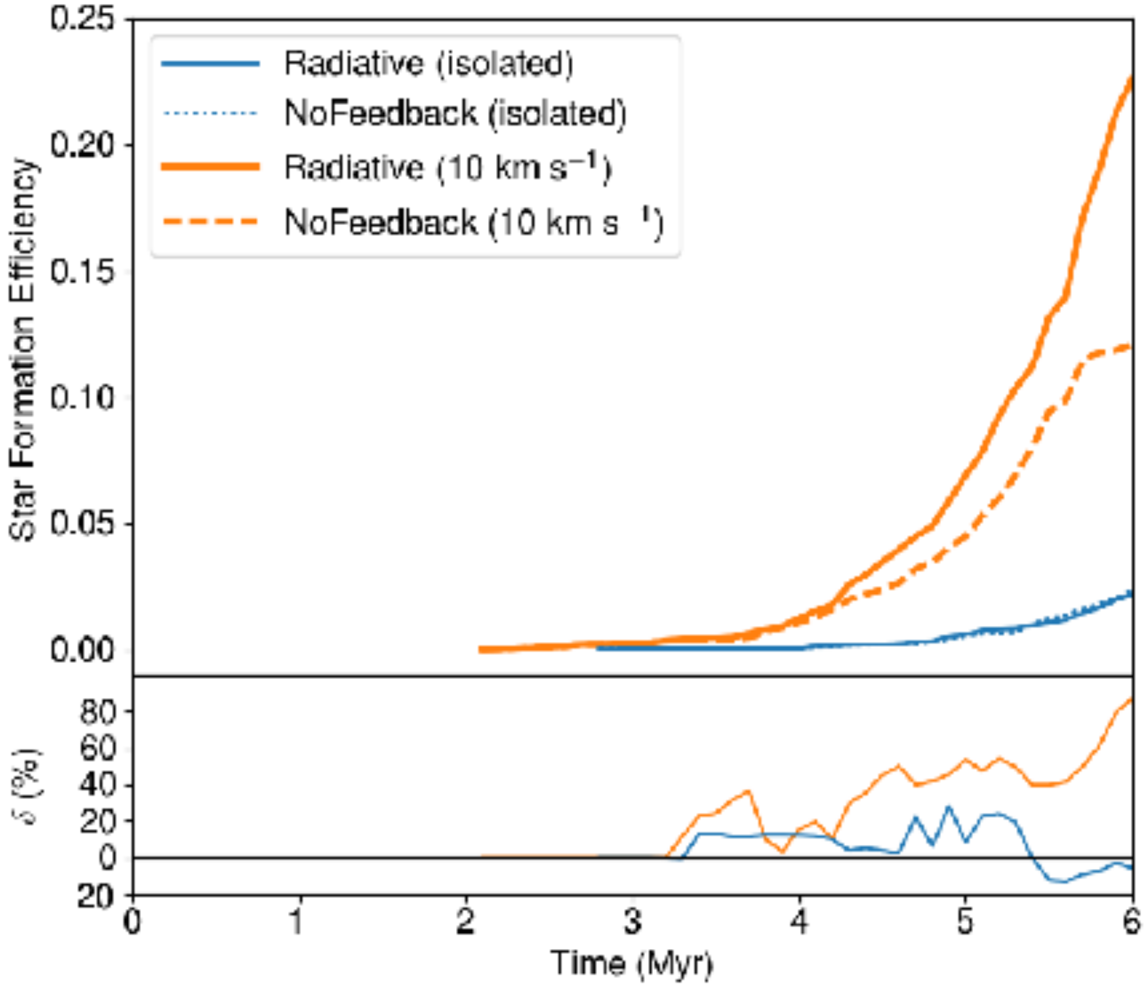
more massive sinks

Feedback effect on star formation (colliding cloud)

Surface Density



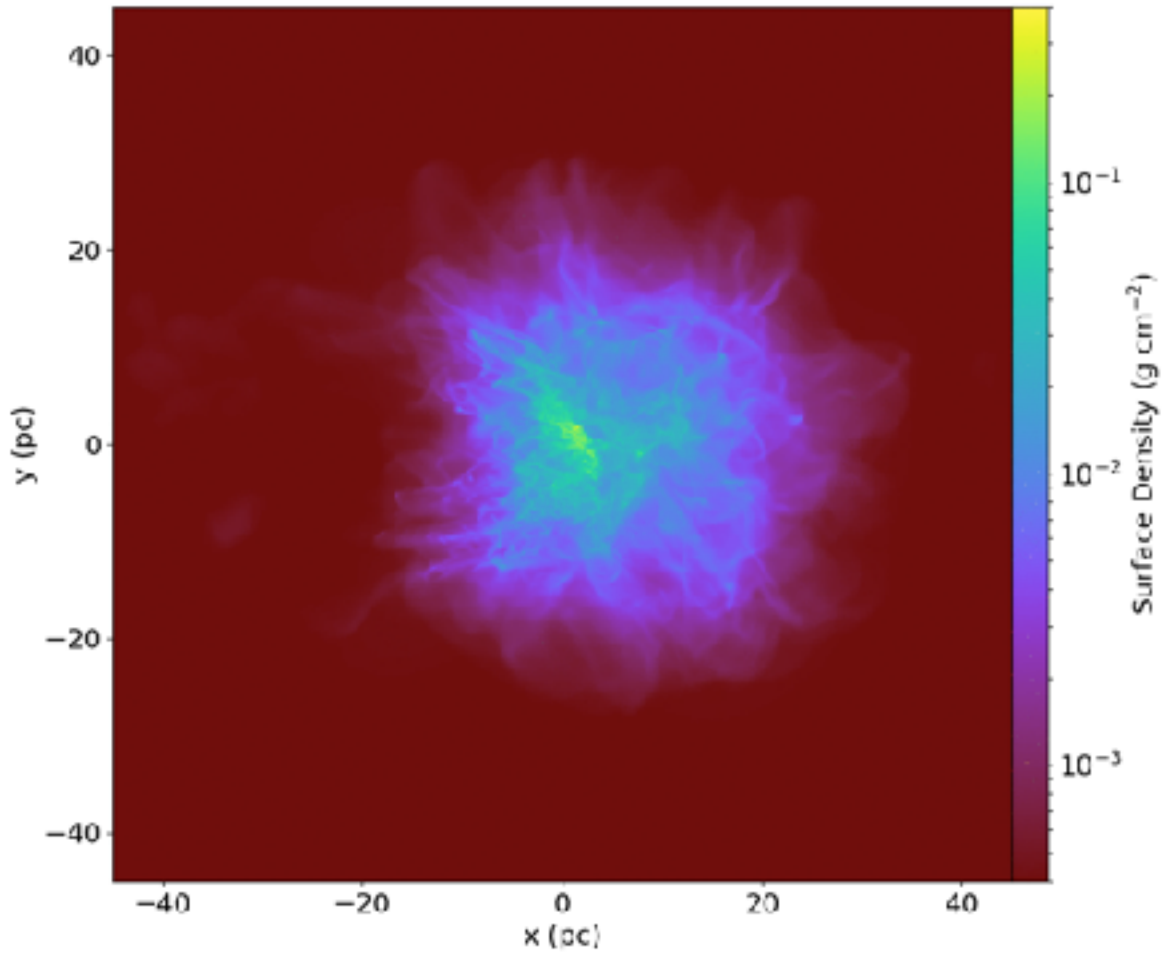
SFE v.s. Time



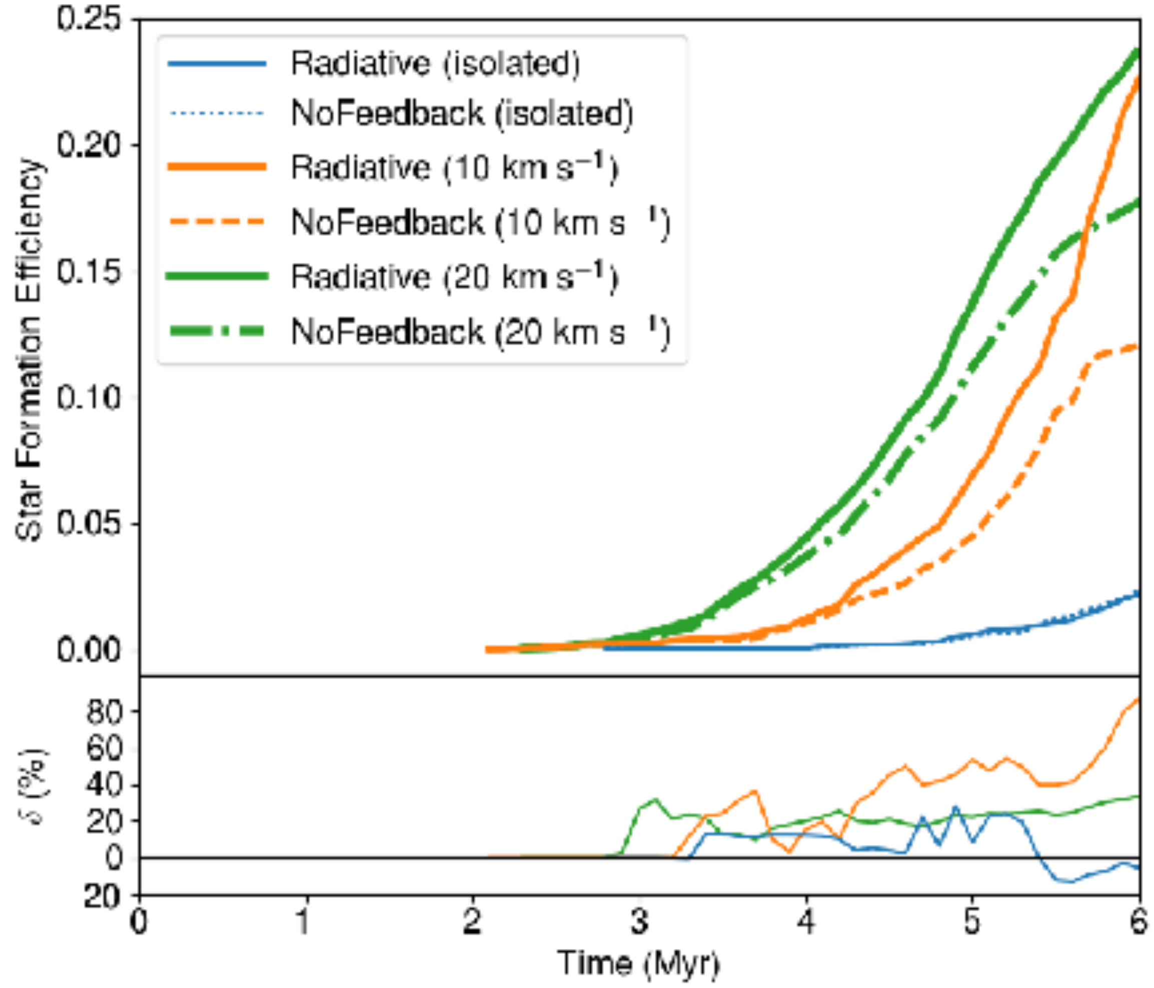
The effect is positive in the colliding clouds.
The SFE reaches 23 % at 6 Myr.

Feedback effect on star formation (colliding cloud)

Surface Density



SFE v.s. Time



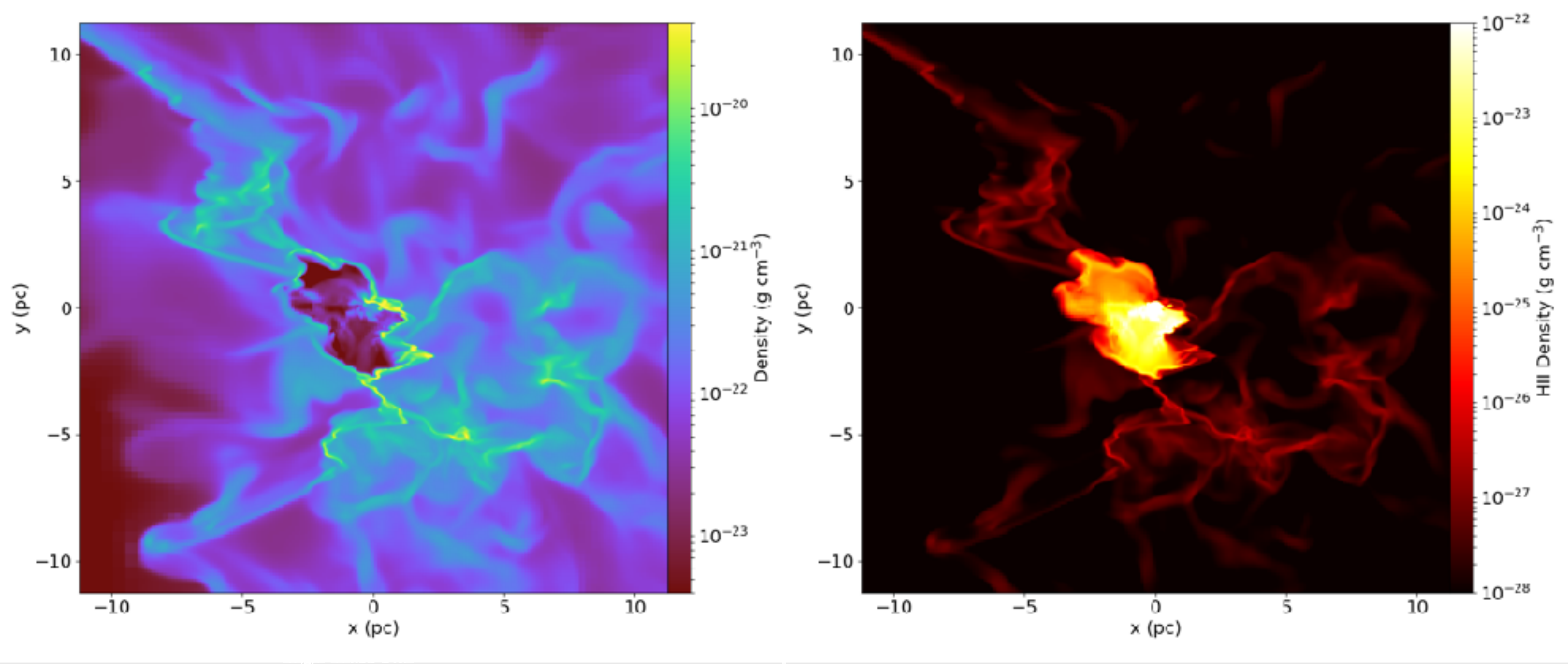
The effect is positive in the colliding clouds.
The SFE reaches 24 % at 6 Myr.

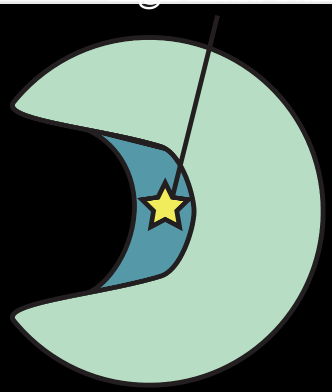
DISCUSSION

Why feedback is positive ?

Density slice

HII Density slice

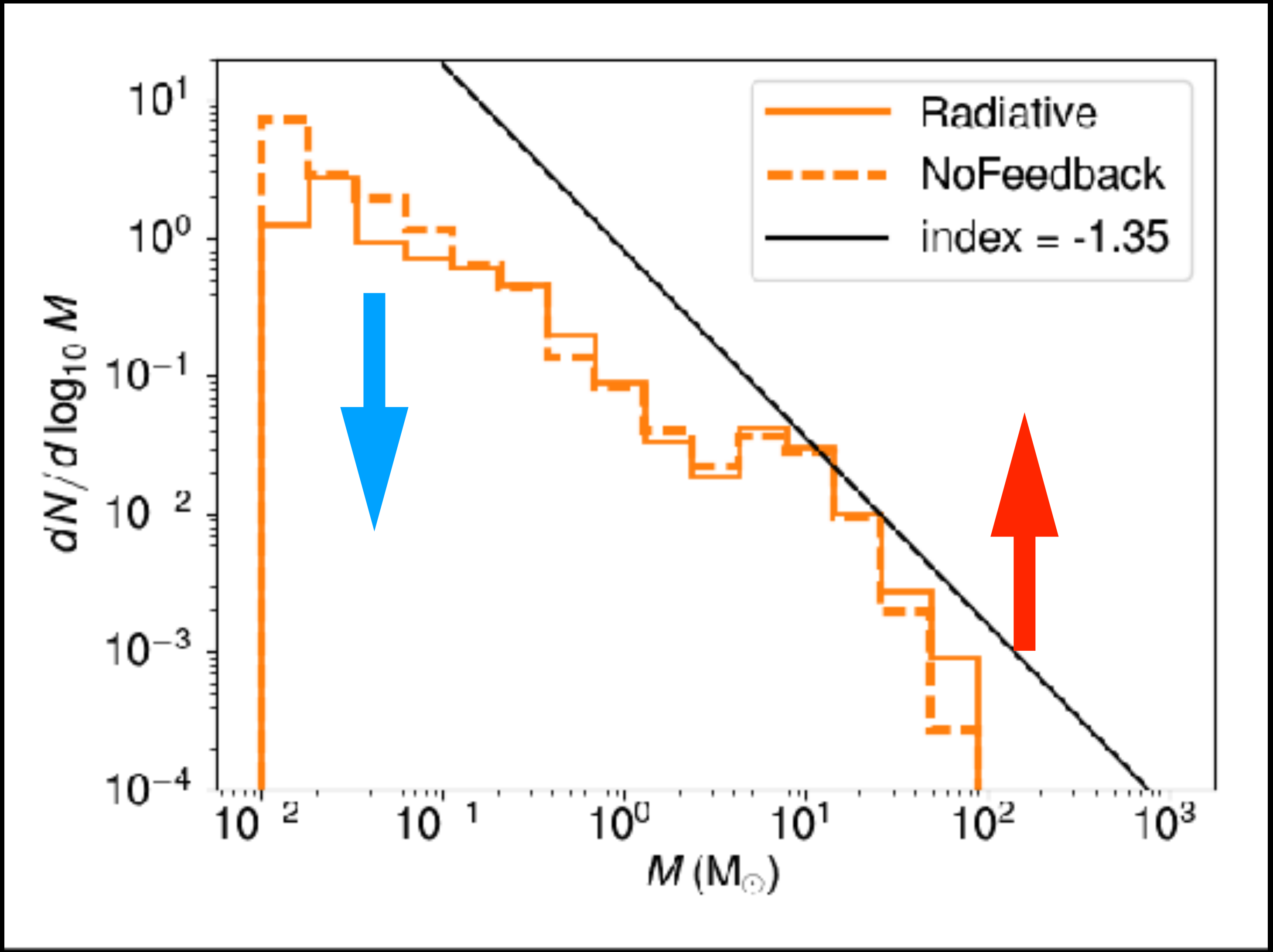




HII regions formed in the interface.

Why feedback is positive ?

mass function



less small sinks & more massive sinks

-> fragmentation is suppressed

CONCLUSIONS

We made numerical simulations to study star formation in colliding cloud considering feedback.

The colliding clouds promote star formation efficiency by a factor of 10 higher than the isolated cloud.

The photoionising feedback increases the SFE in the colliding clouds.

-> feedback is positive in colliding clouds!