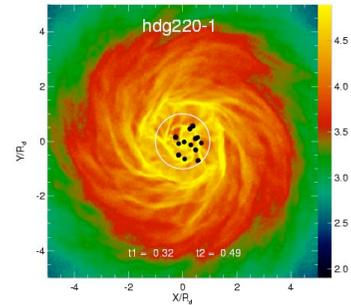
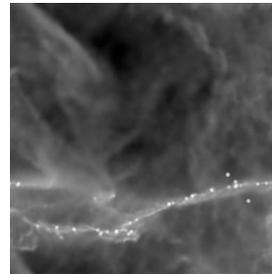
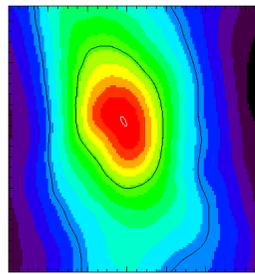
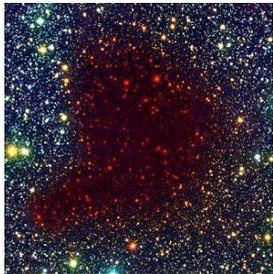


# Star Formation: Stellar Birth Today and in the Early Universe



**Ralf Klessen**



Zentrum für Astronomie der Universität Heidelberg  
Institut für Theoretische Astrophysik



# thanks to ...



... people in the group in Heidelberg:

Robi Banerjee, Simon Glover, Rahul Shetty, Sharanya Sur, Daniel Seifried, Milica Milosavljevic, Florian Mandl, Christian Baczynski, Rowan Smith, Gustavo Dopcke, Jonathan Downing, Jayanta Dutta, Faviola Molina, Christoph Federrath, Erik Bertram, Lukas Konstandin, Paul Clark, Stefan Schmeja, Ingo Berentzen, Thomas Peters, Hsiang-Hsu Wang

... many collaborators abroad!



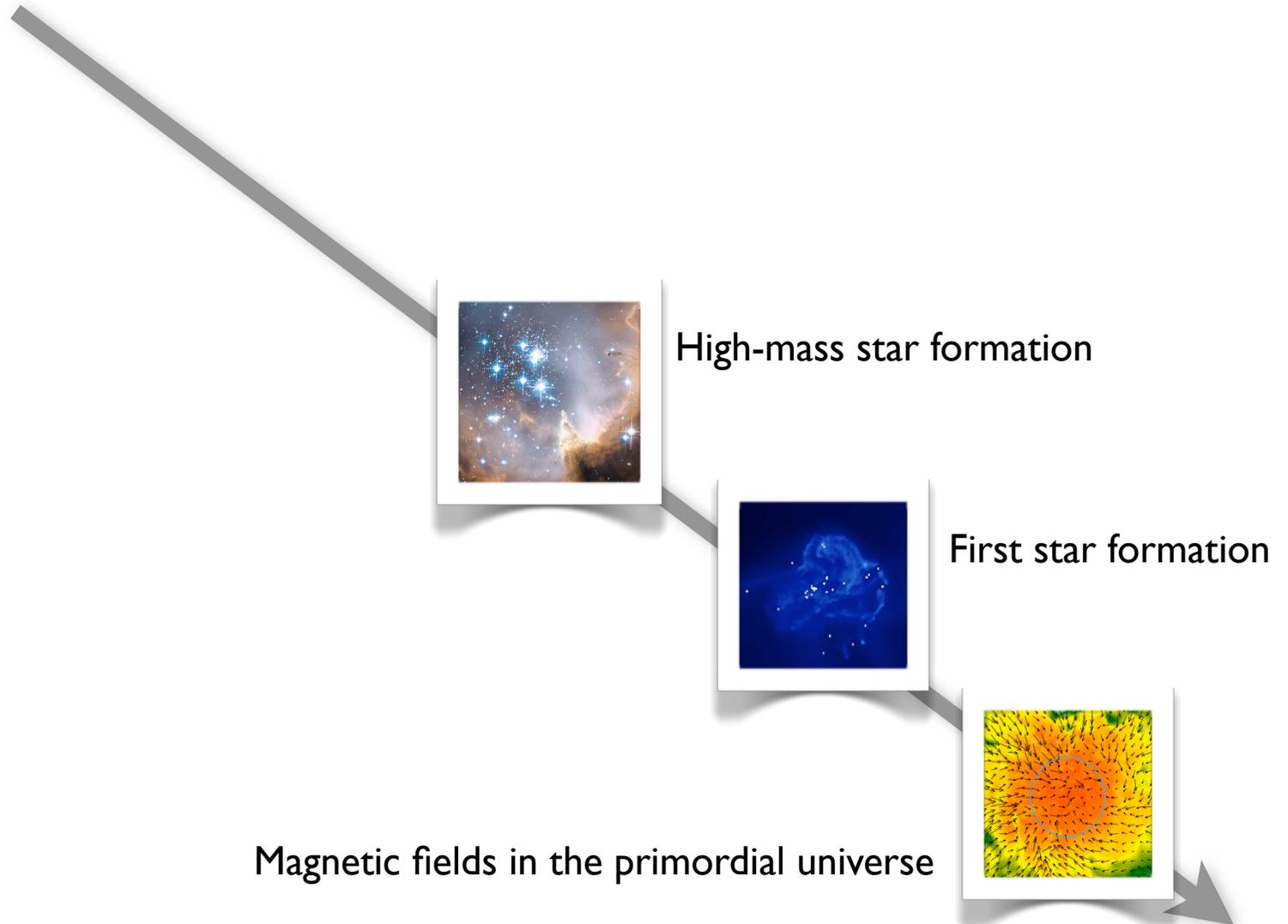
Deutsche  
Forschungsgemeinschaft  
**DFG**



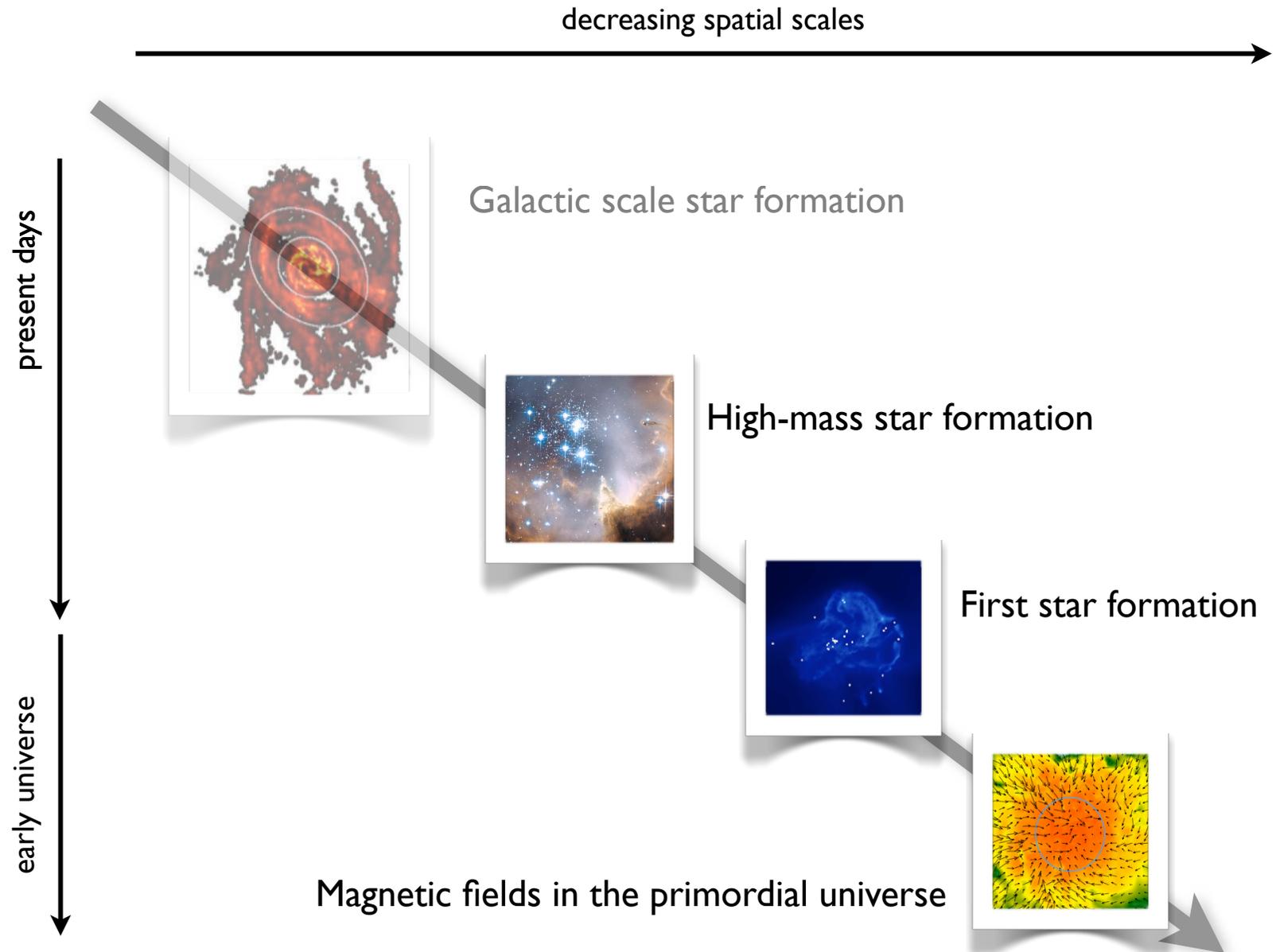
# agenda

- a simple cartoon picture of dynamic star formation theory
- some applications, open issues, and questions

# agenda



# agenda

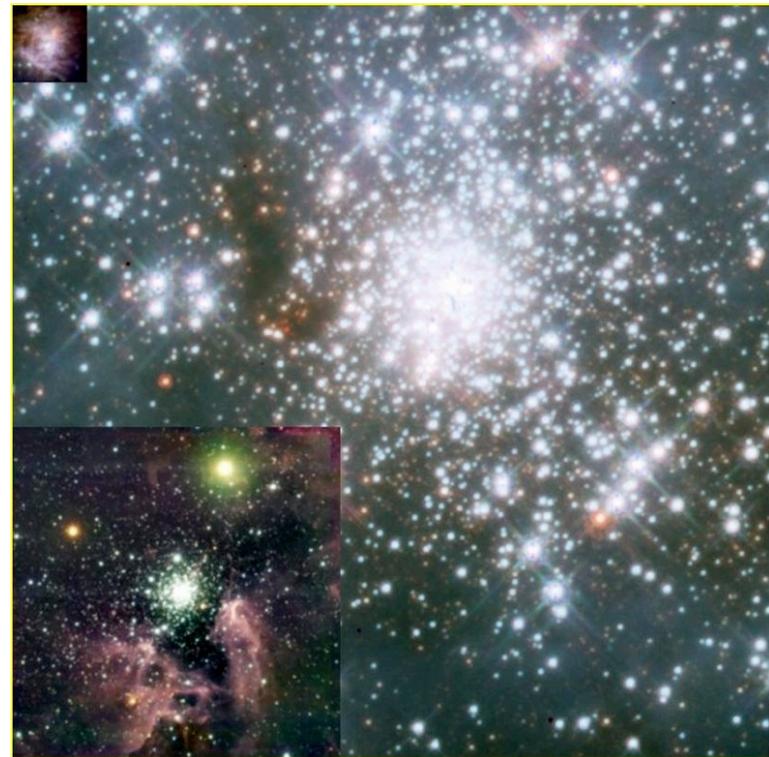
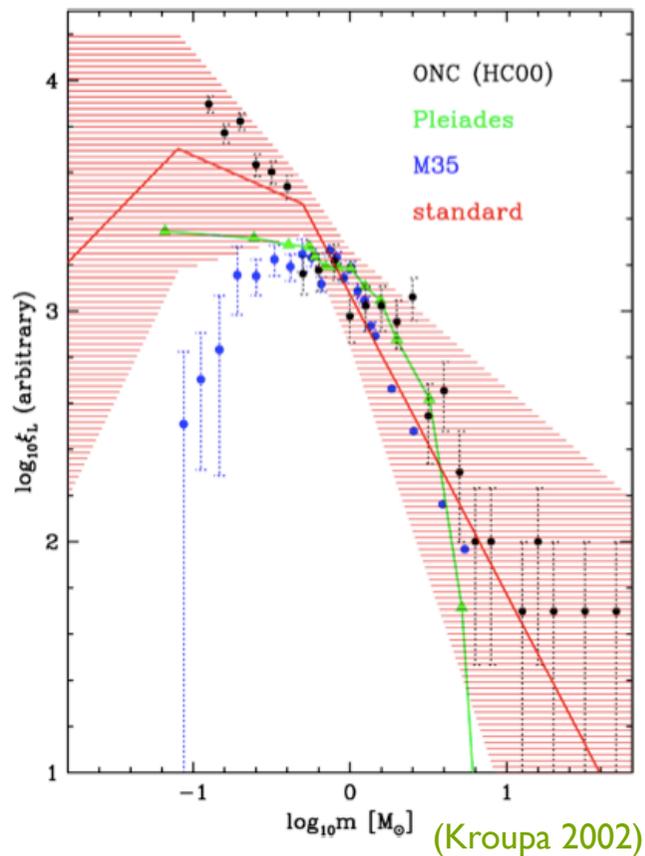




NGC 602 in the LMC: Hubble Heritage Image

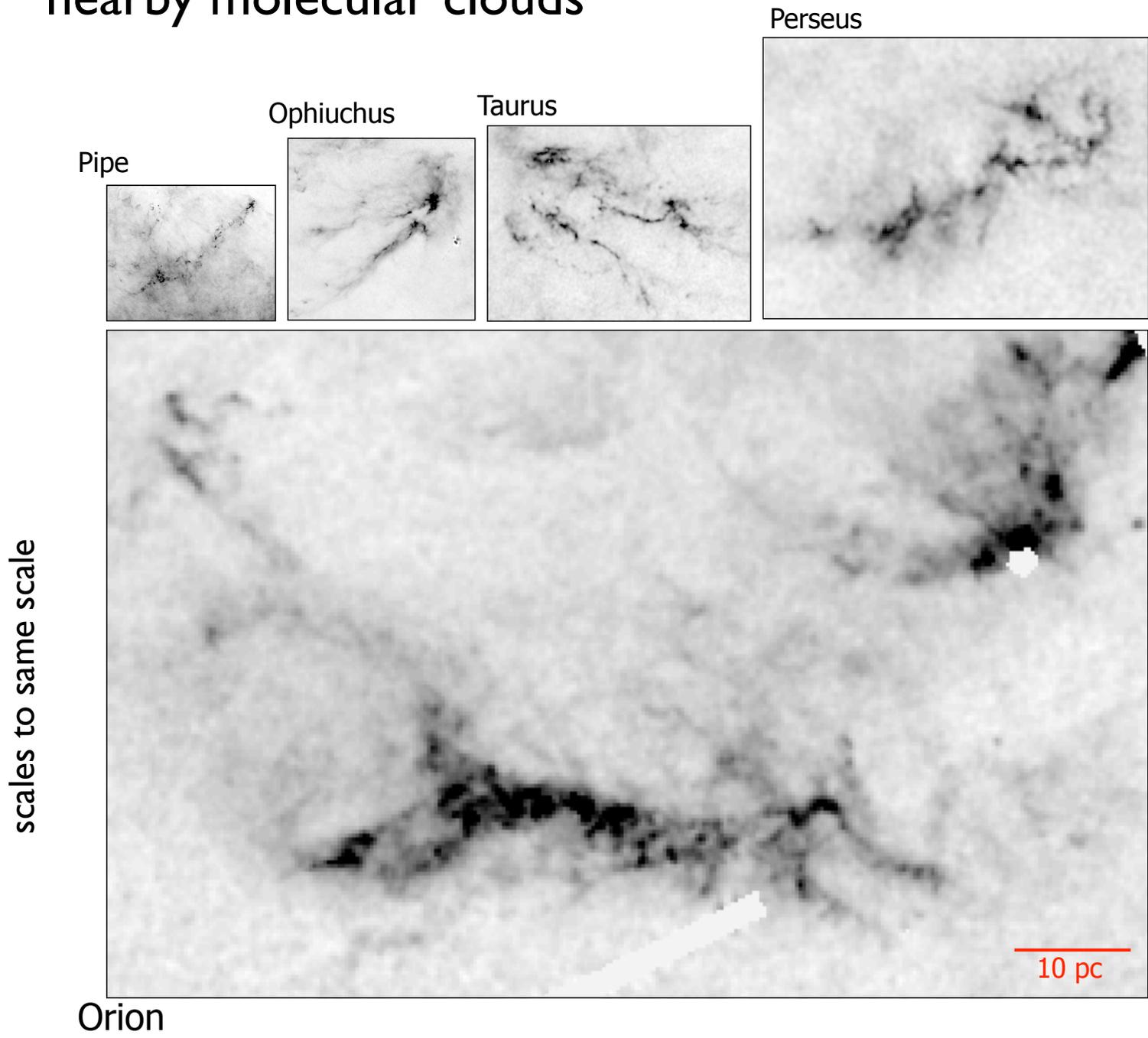
# stellar mass function

stars seem to follow a universal mass function at birth --> IMF



Orion, NGC 3603, 30 Doradus  
(Zinnecker & Yorke 2007)

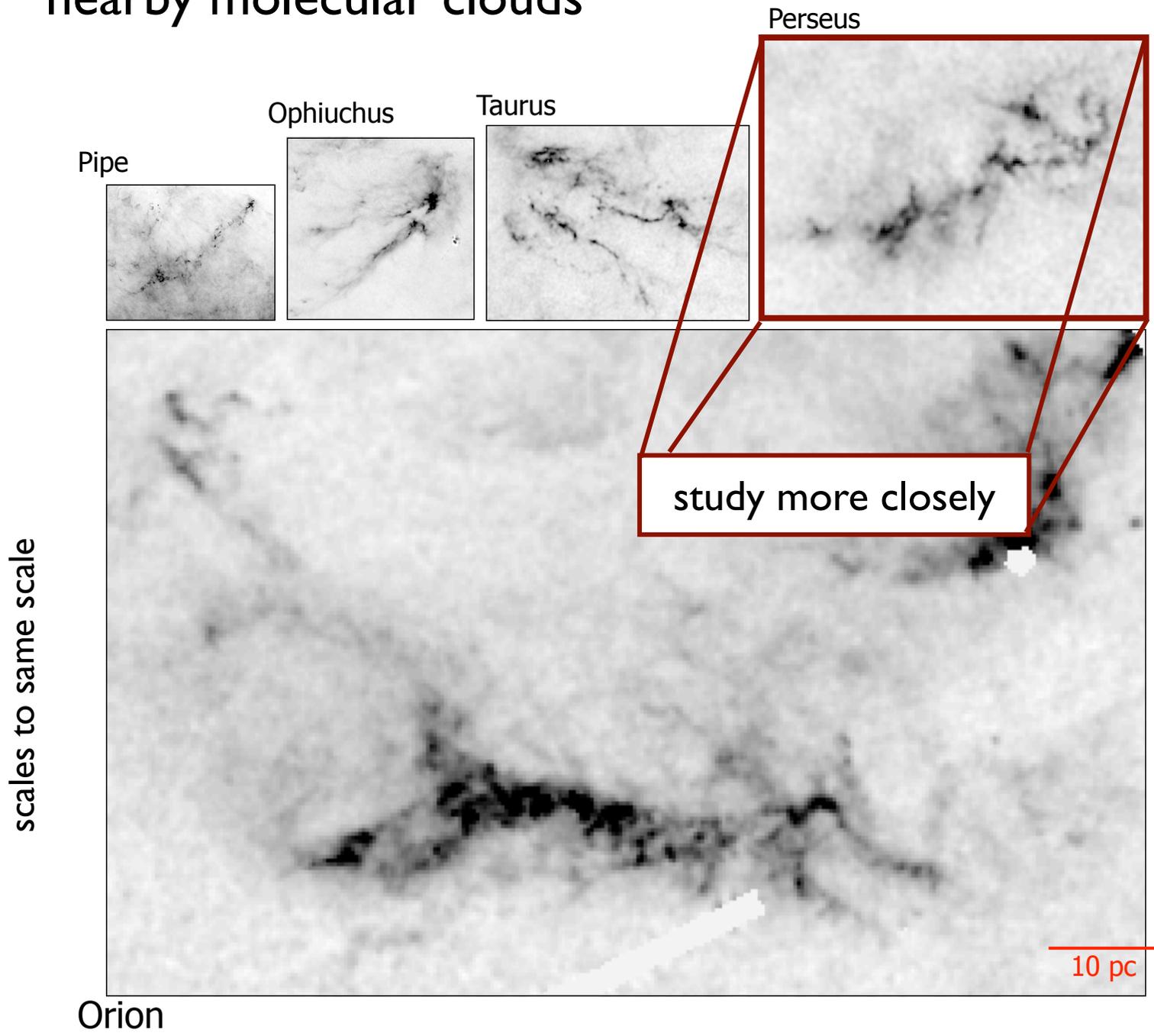
# nearby molecular clouds



scales to same scale

(from A. Goodman)

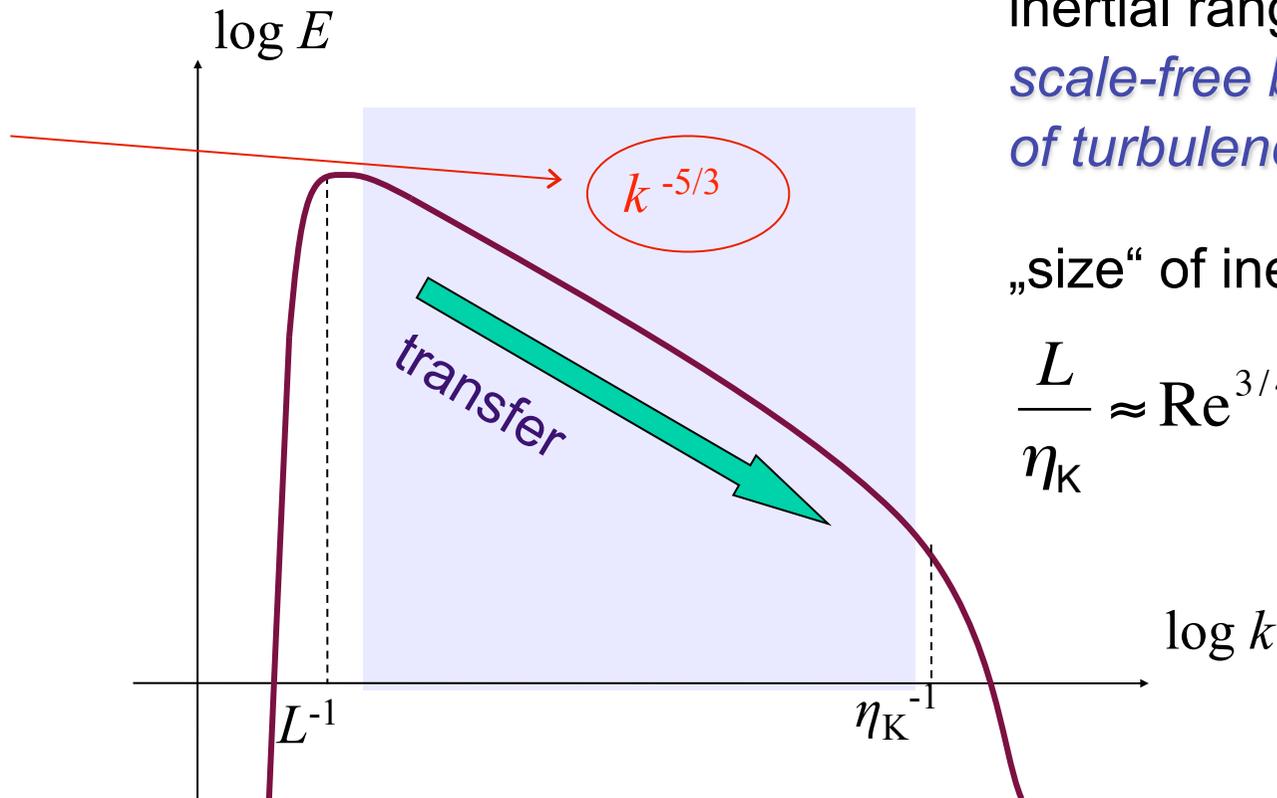
# nearby molecular clouds



(from A. Goodman)

# Turbulent cascade

Kolmogorov (1941) theory  
incompressible turbulence



inertial range:  
*scale-free behavior  
of turbulence*

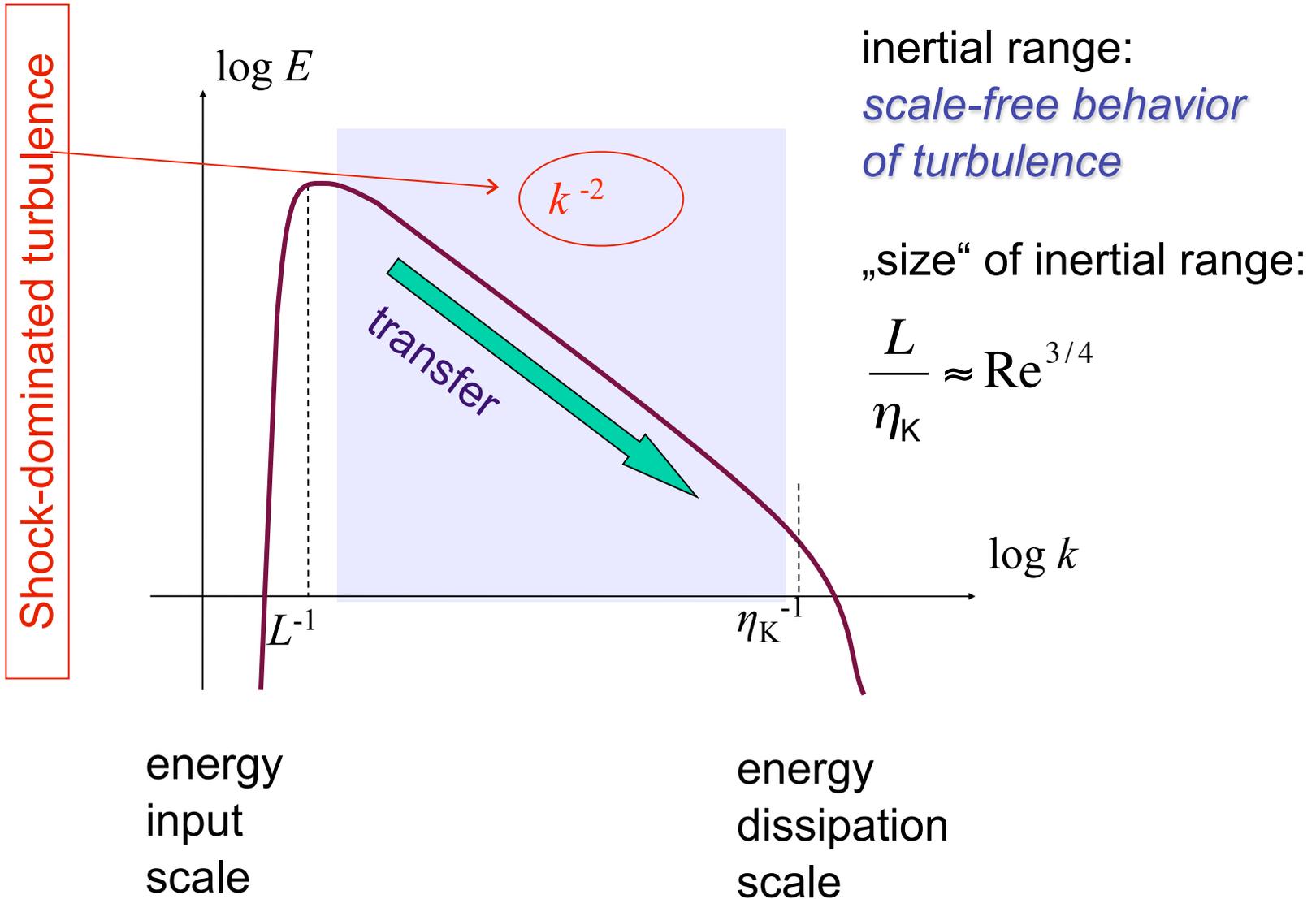
„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \text{Re}^{3/4}$$

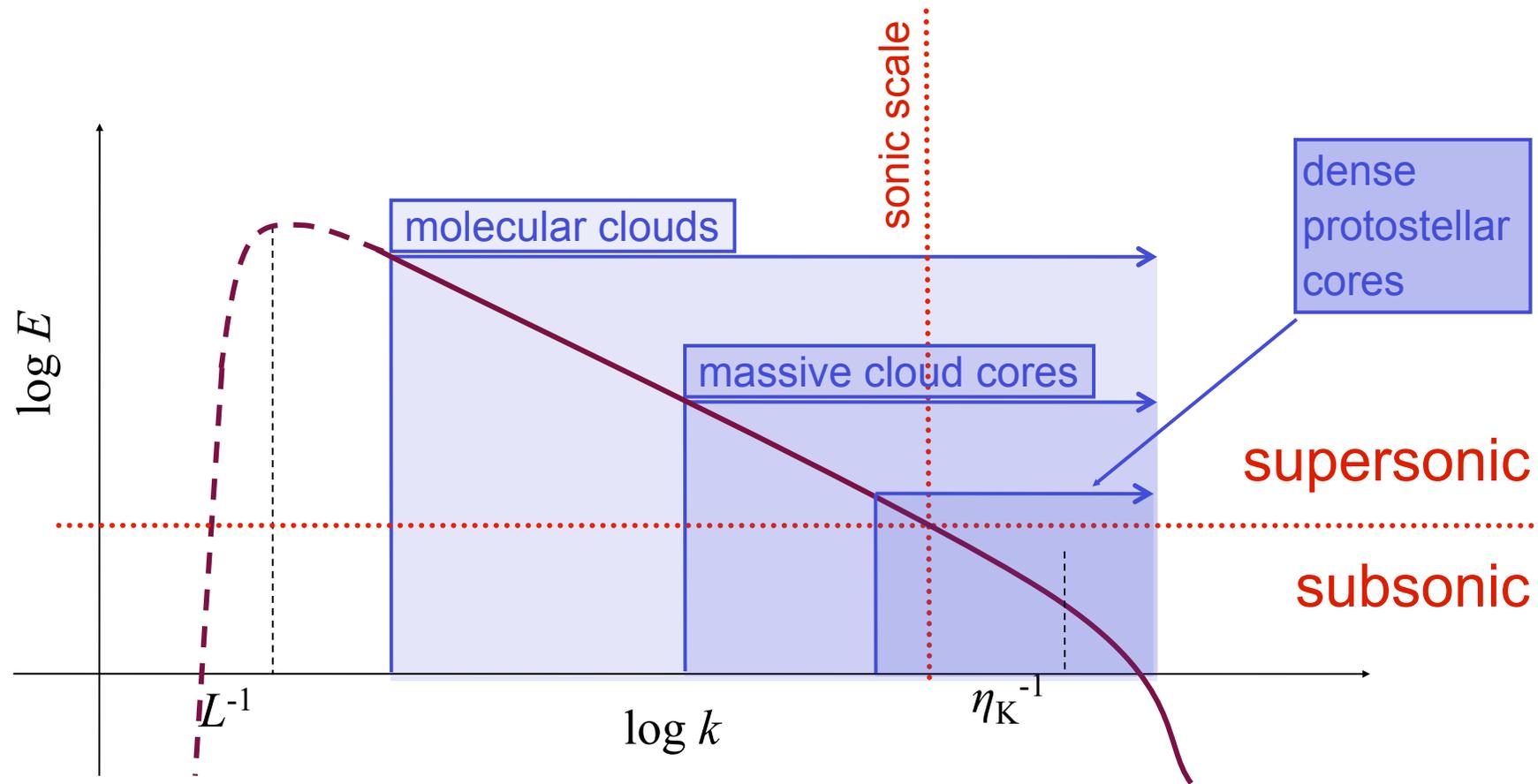
energy  
input  
scale

energy  
dissipation  
scale

# Turbulent cascade



# Turbulent cascade in ISM



energy source & scale  
*NOT known*  
 (supernovae, winds,  
 spiral density waves?)

$$\sigma_{\text{rms}} \ll 1 \text{ km/s}$$

$$M_{\text{rms}} \leq 1$$

$$L \approx 0.1 \text{ pc}$$

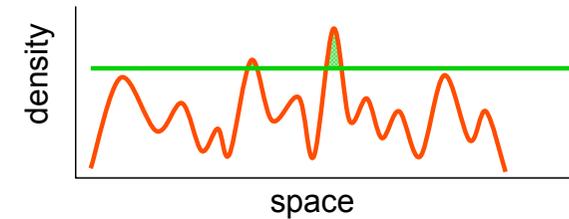
dissipation scale not known  
 (ambipolar diffusion,  
 molecular diffusion?)



# dynamical SF in a nutshell

- interstellar gas is highly *inhomogeneous*

- ◆ *gravitational instability*
- ◆ *thermal instability*
- ◆ *turbulent compression* (in shocks  $\delta\rho/\rho \propto M^2$ ; in atomic gas:  $M \approx 1...3$ )



- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points of convergent large-scale flows*

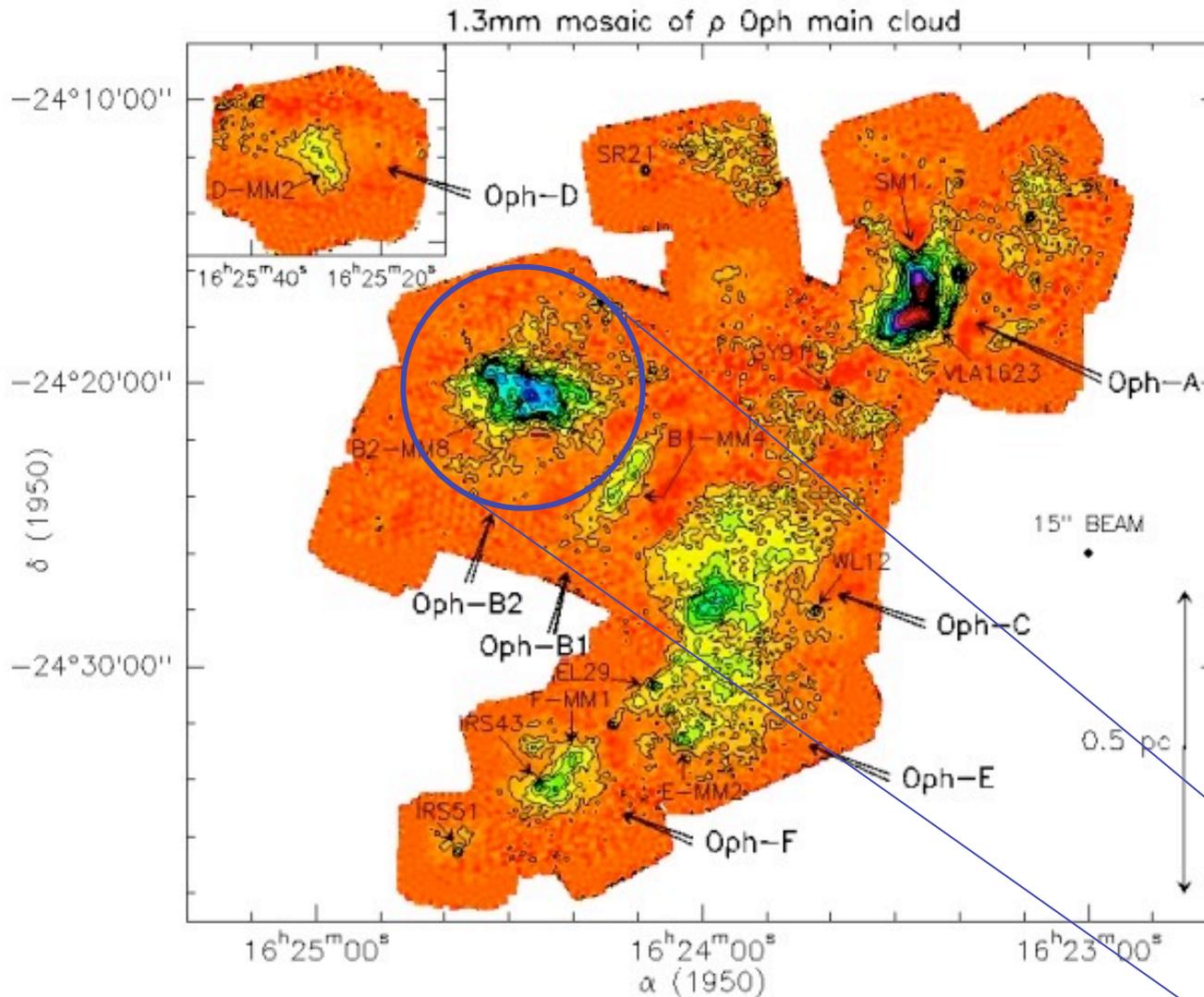
- ◆ chemical *phase transition*: atomic  $\rightarrow$  molecular
- ◆ process is *modulated* by large-scale *dynamics* in the galaxy

- inside *cold clouds*: turbulence is highly supersonic ( $M \approx 1...20$ )  
 $\rightarrow$  *turbulence* creates large density contrast,  
*gravity* selects for collapse

—————→ **GRAVOTUBULENT FRAGMENTATION**

- *turbulent cascade*: local compression *within* a cloud provokes collapse  $\rightarrow$  formation of individual *stars* and *star clusters*

# Density structure of MC's



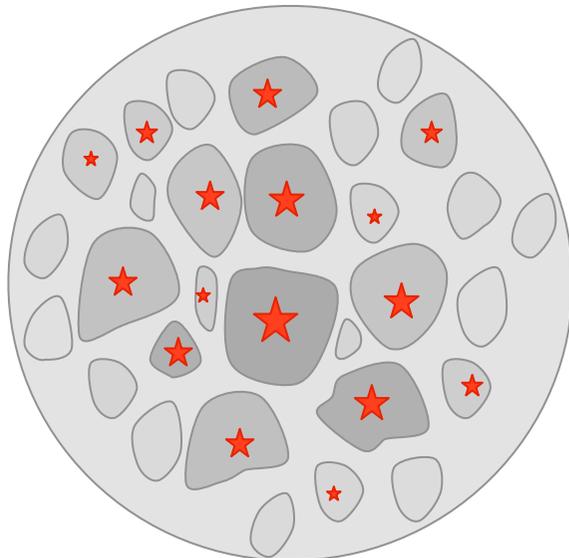
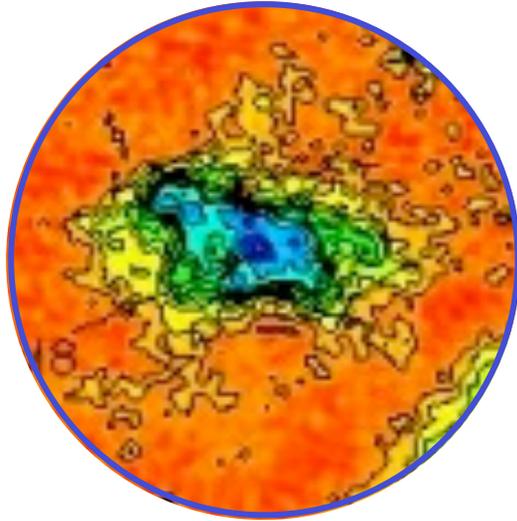
molecular clouds  
are highly  
inhomogeneous

stars form in the  
densest and coldest  
parts of the cloud

$\rho$ -Ophiuchus cloud  
seen in dust  
emission

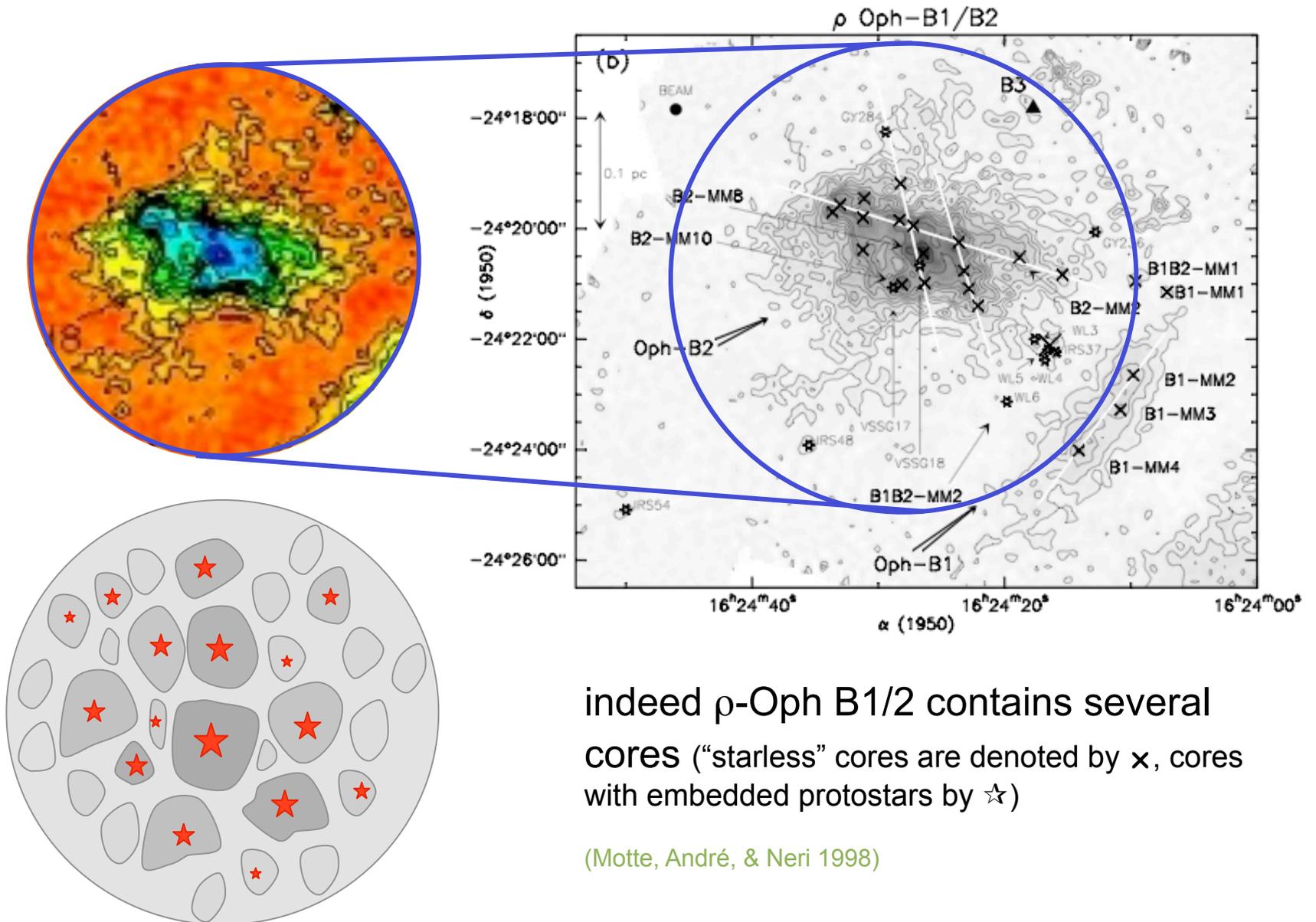
let's focus on  
a cloud core  
like this one

# Evolution of cloud cores



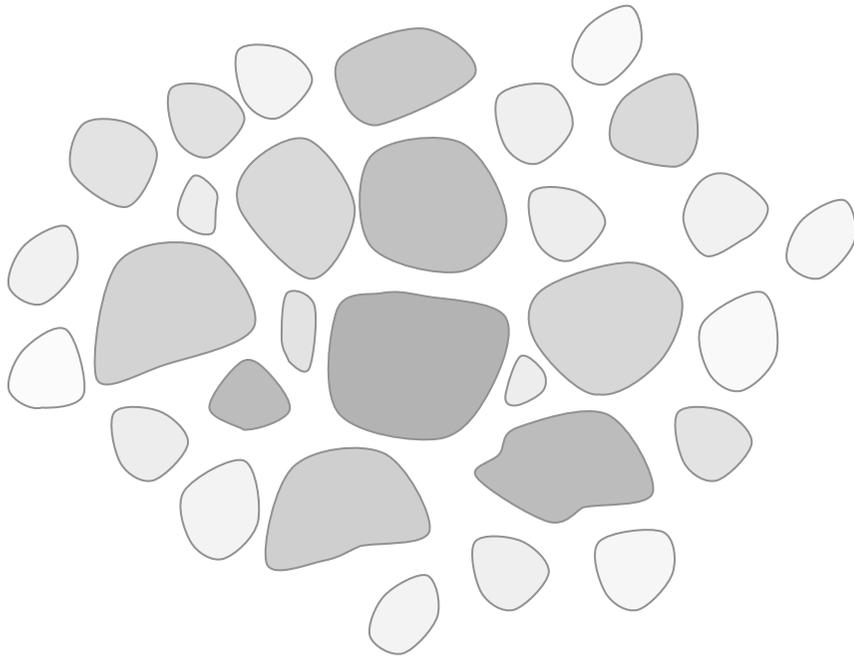
- How does this core evolve?  
Does it form one single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core  
--> NO *scale separation* possible  
--> NO *effective sound speed*
- Turbulence is supersonic!  
--> produces strong density contrasts:  
 $\delta\rho/\rho \approx M^2$   
--> with typical  $M \approx 10$  -->  $\delta\rho/\rho \approx 100!$
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

# Evolution of cloud cores



# Formation and evolution of cores

What happens to distribution of cloud cores?



Two extreme cases:

(1) turbulence dominates energy budget:

$$\alpha = E_{\text{kin}} / |E_{\text{pot}}| > 1$$

--> individual cores do *not* interact

--> *collapse of individual cores*

dominates *stellar mass growth*

--> *loose cluster of low-mass stars*

(2) turbulence decays, i.e. gravity dominates:

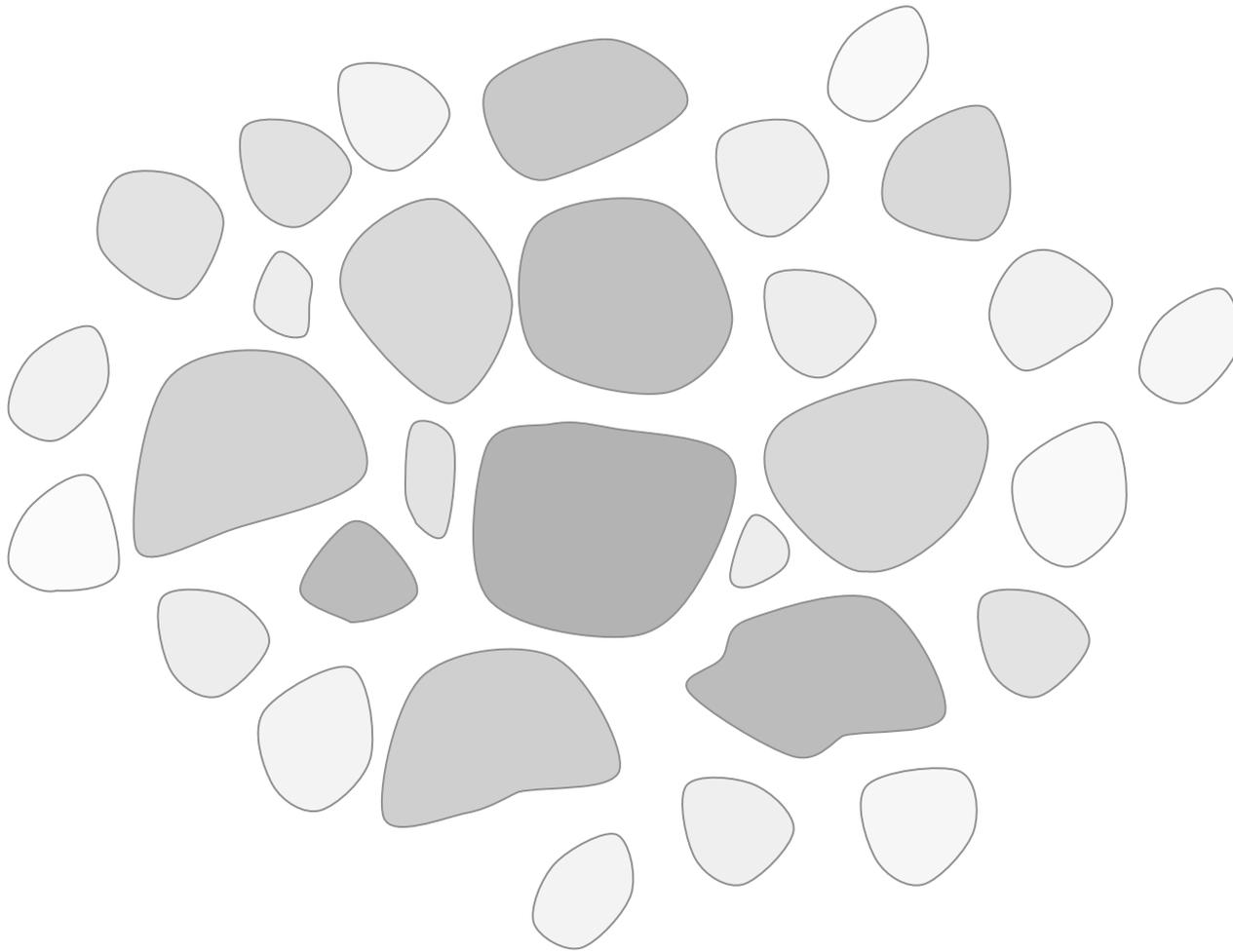
$$\alpha = E_{\text{kin}} / |E_{\text{pot}}| < 1$$

--> *global contraction*

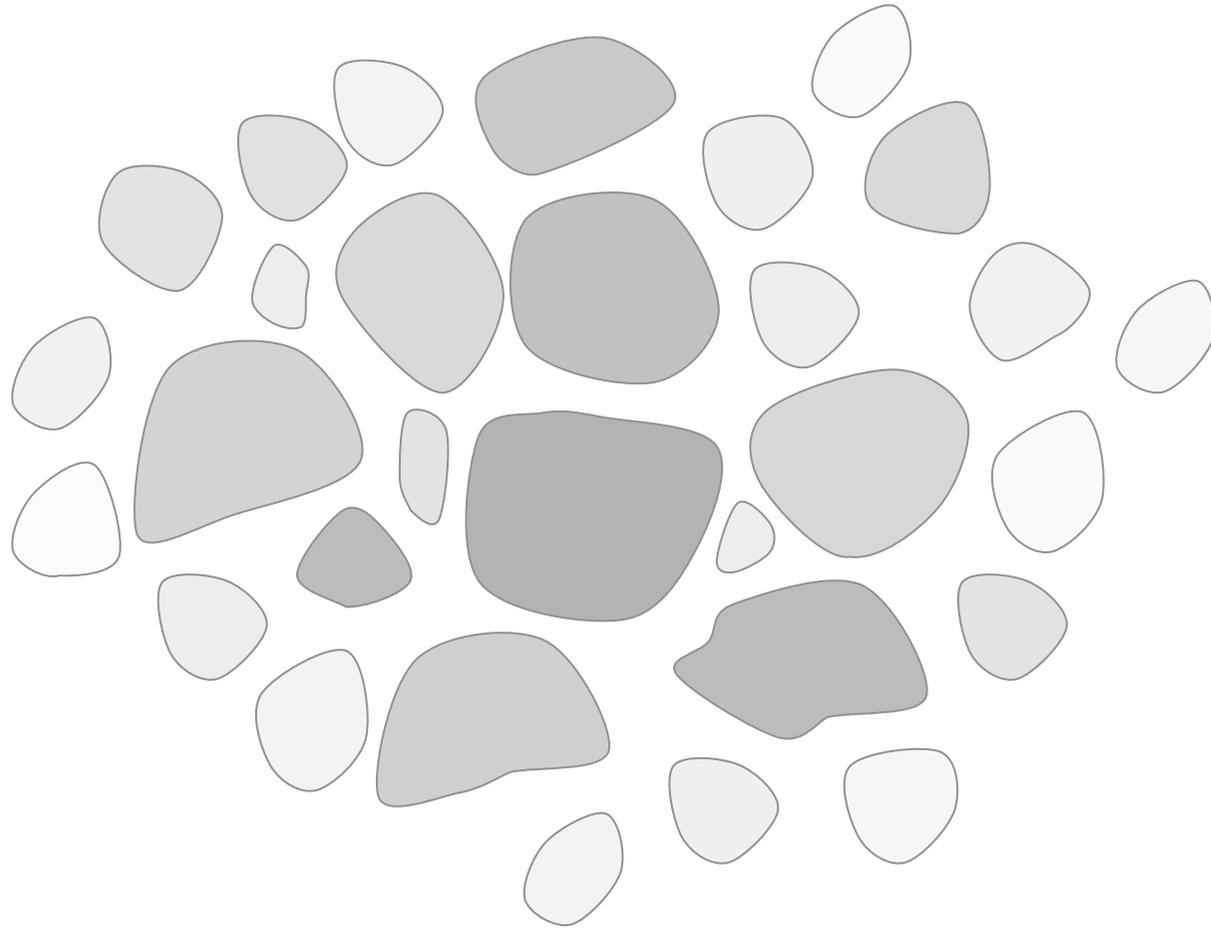
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

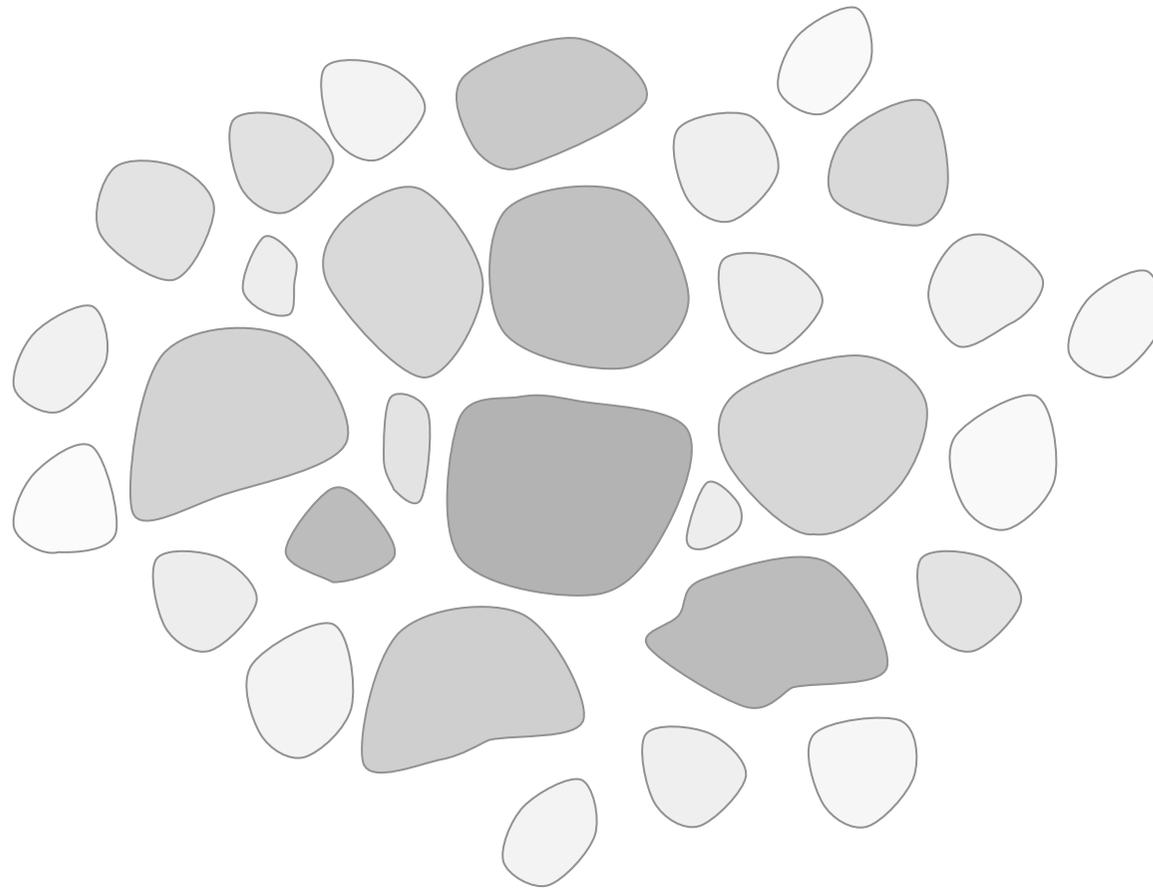
--> *dense cluster with high-mass stars*



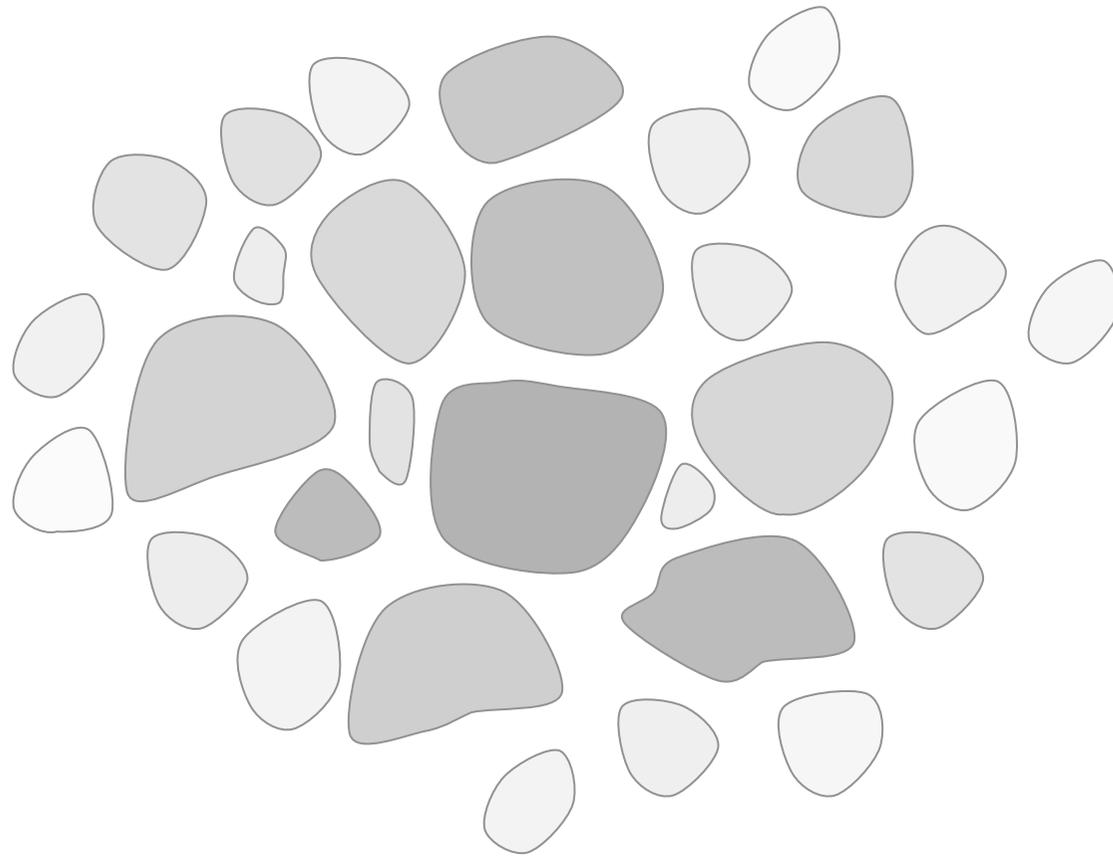
turbulence creates a hierarchy of clumps



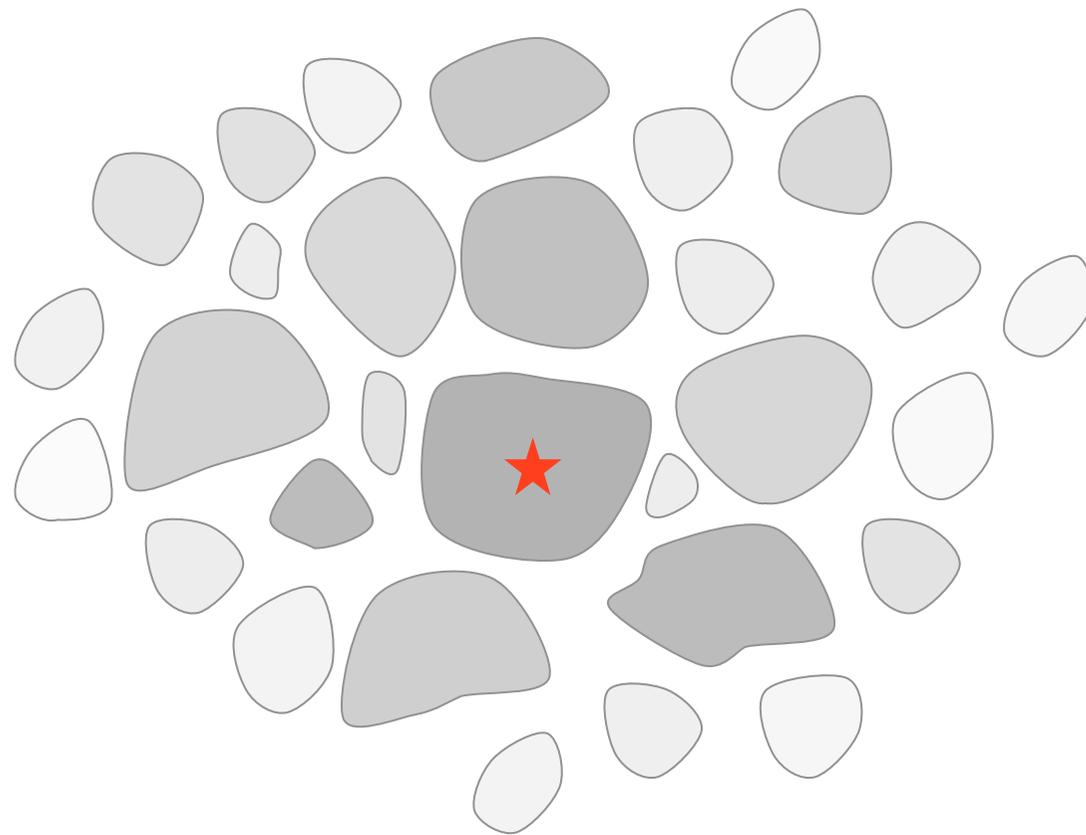
as turbulence decays locally, contraction sets in



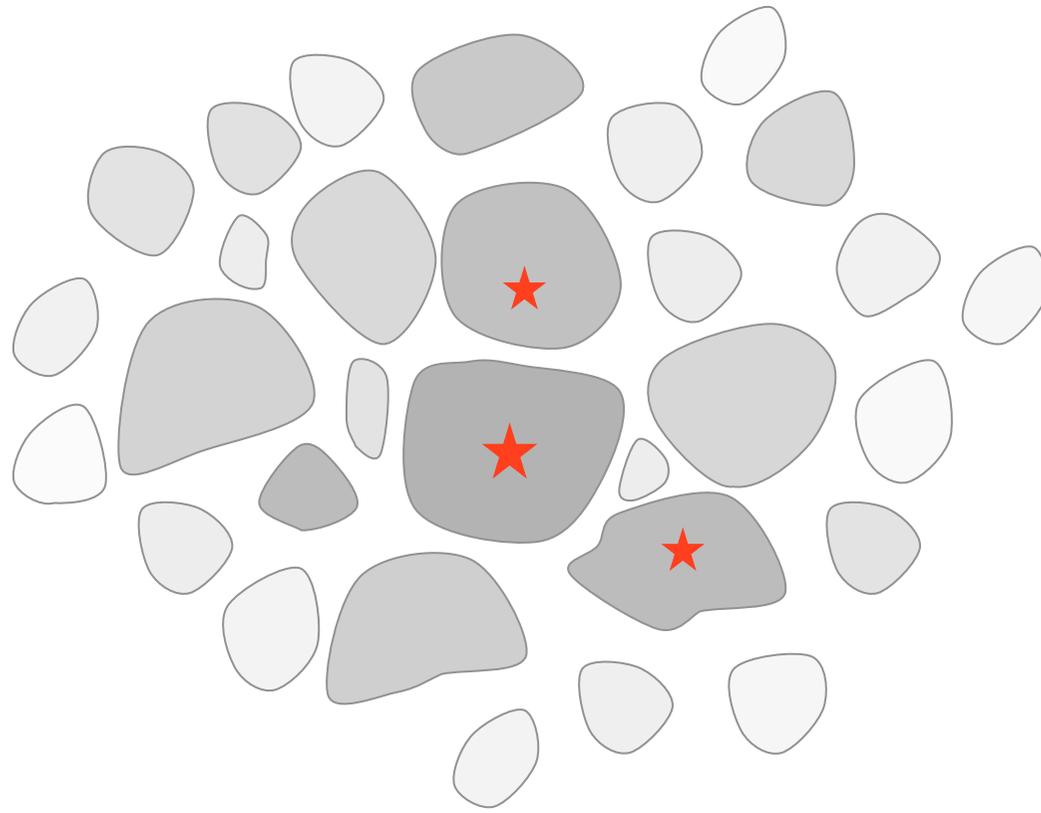
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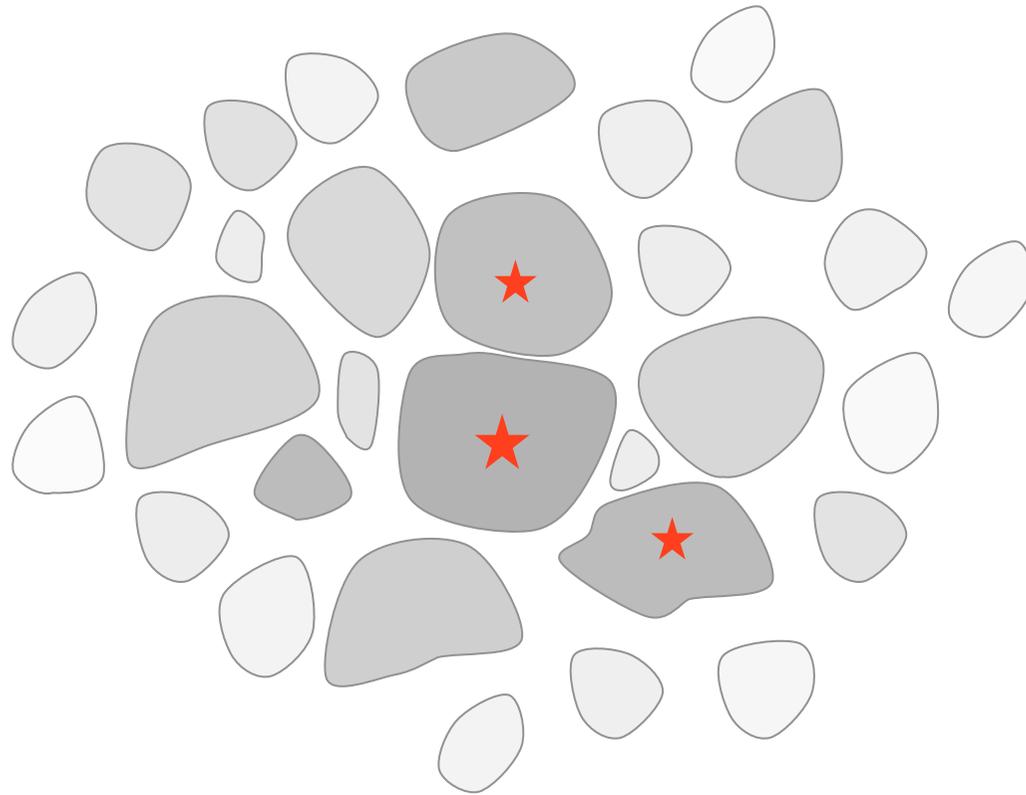
while region contracts, individual clumps collapse to form stars



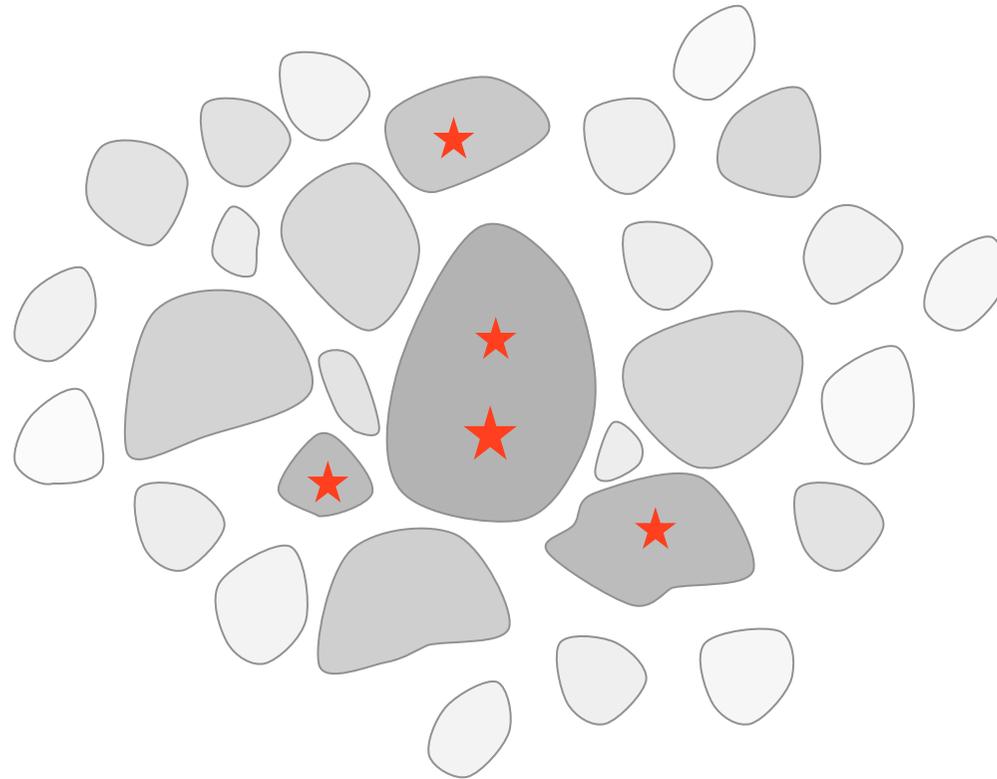
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individual clumps collapse to form stars

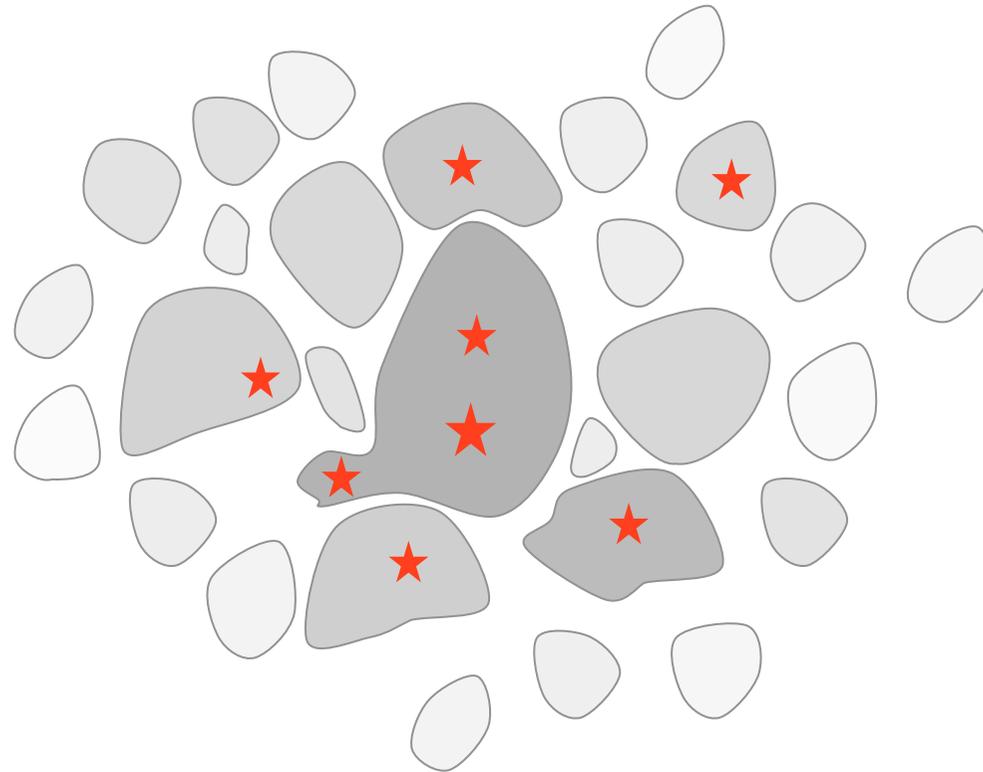


individual clumps collapse to form stars

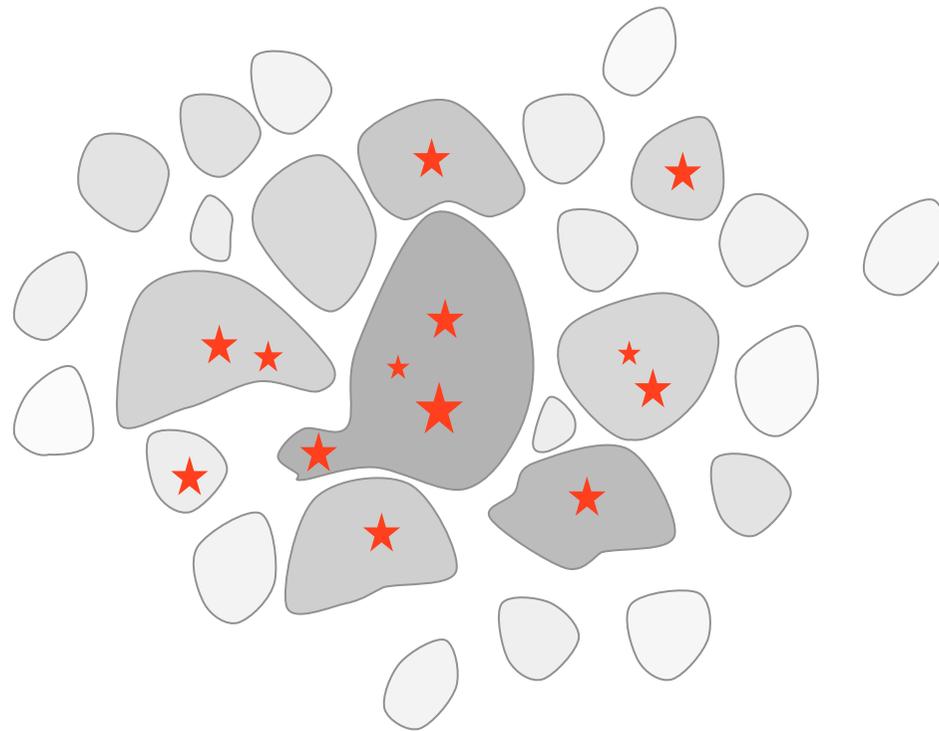


$$\alpha = E_{\text{kin}} / |E_{\text{pot}}| < 1$$

in *dense clusters*, clumps may merge while collapsing  
--> then contain multiple protostars



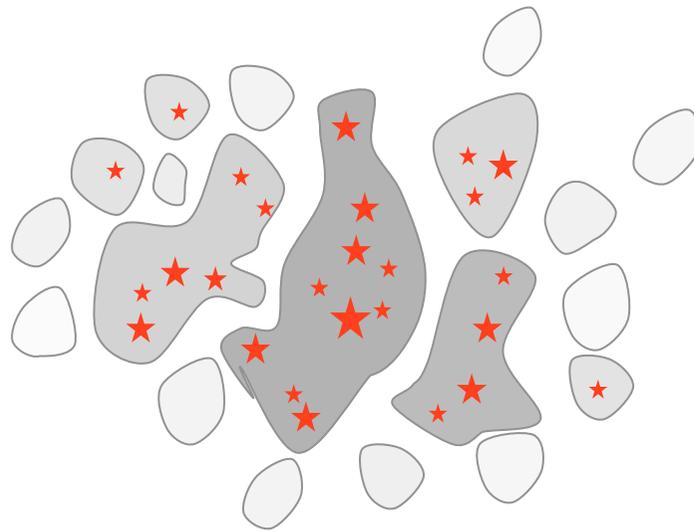
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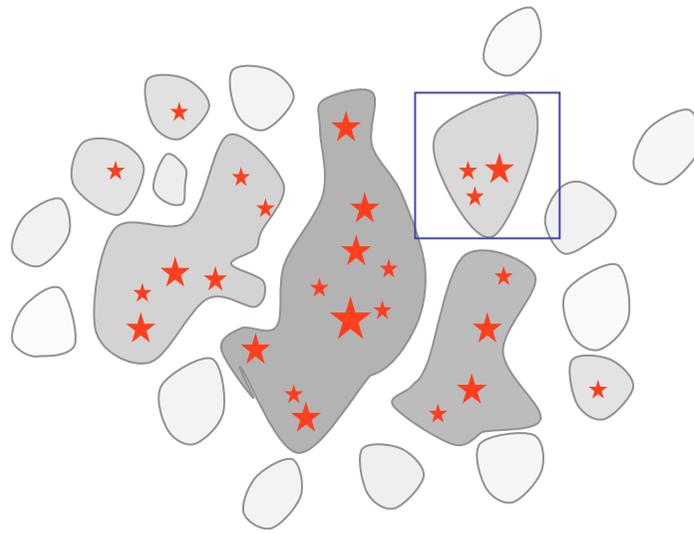
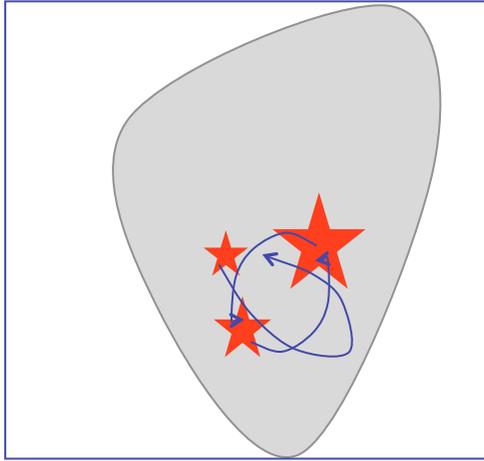
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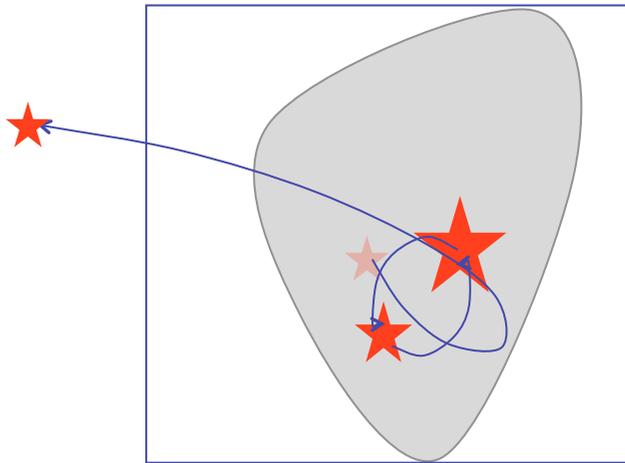
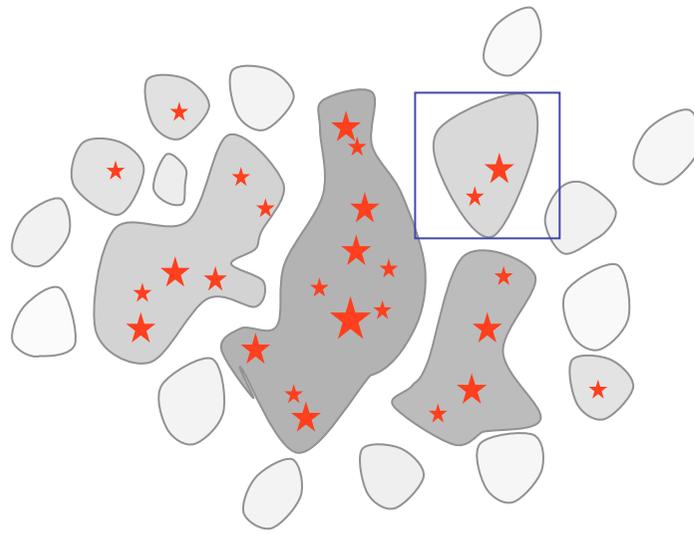
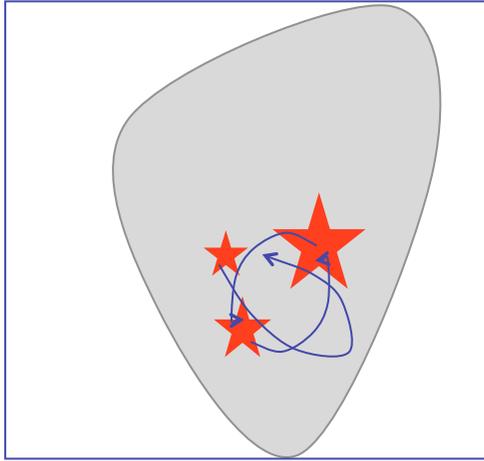
in *dense clusters*, competitive mass growth becomes important



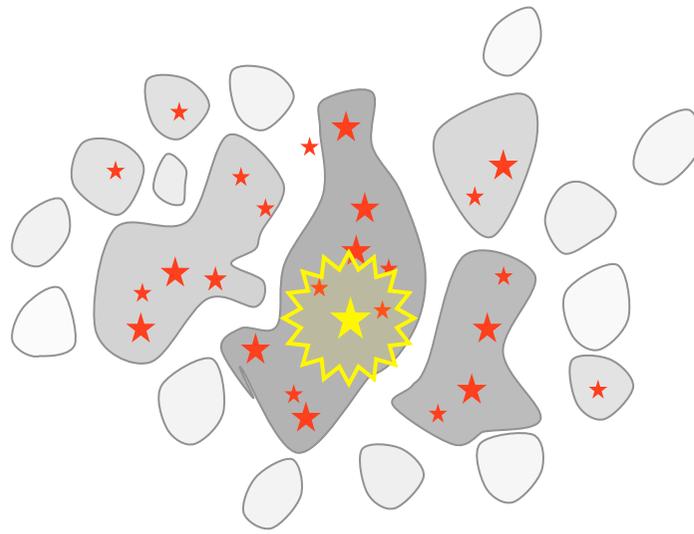
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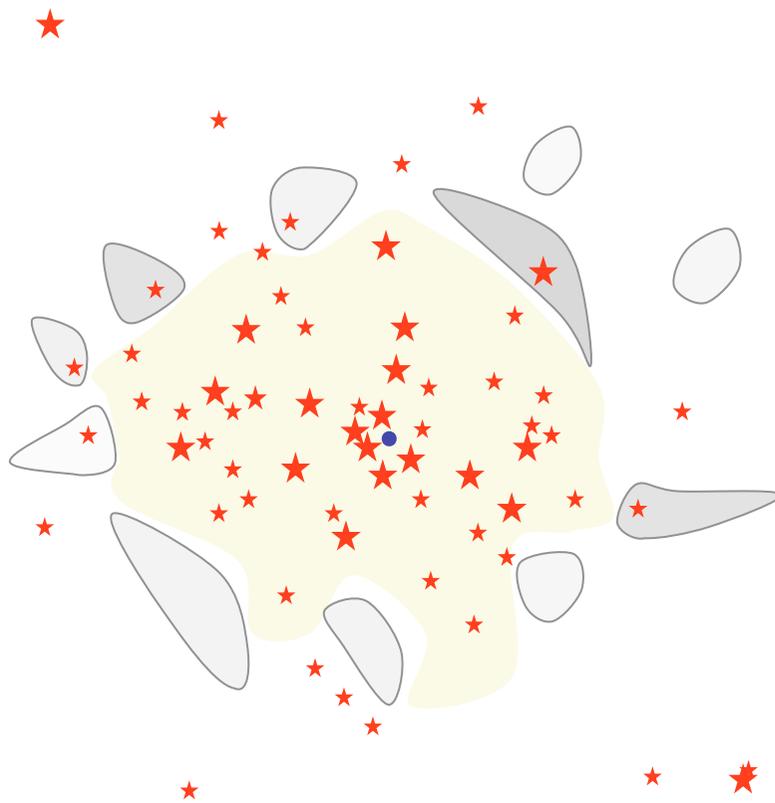
in *dense clusters*,  $N$ -body effects influence mass growth



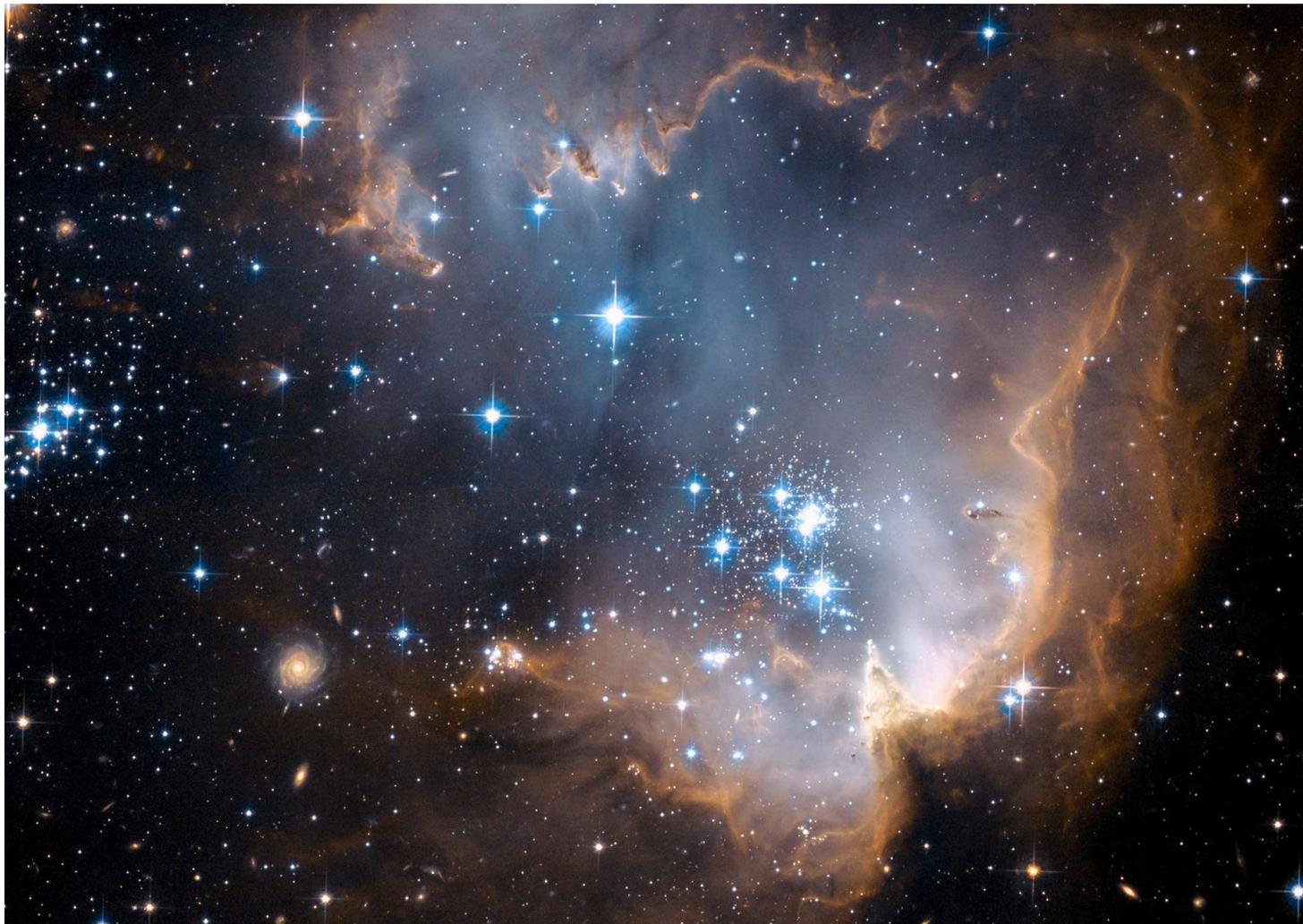
low-mass objects may  
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with H<sub>II</sub> region

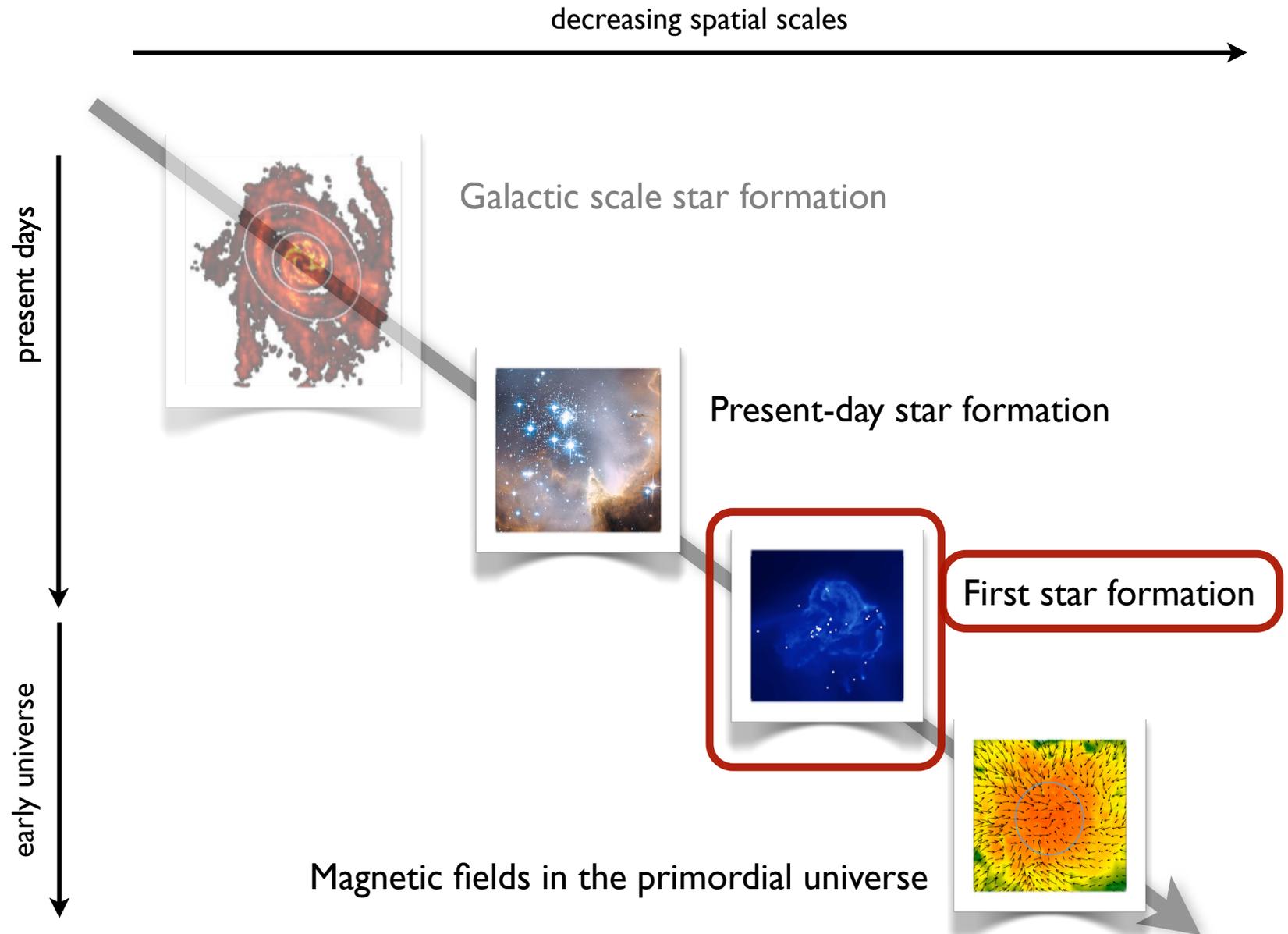


NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with H<sub>II</sub> region

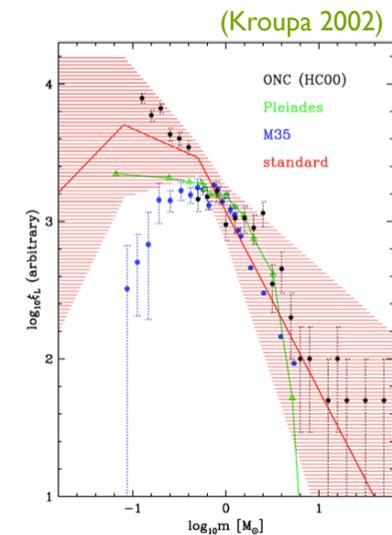


# agenda



# stellar masses

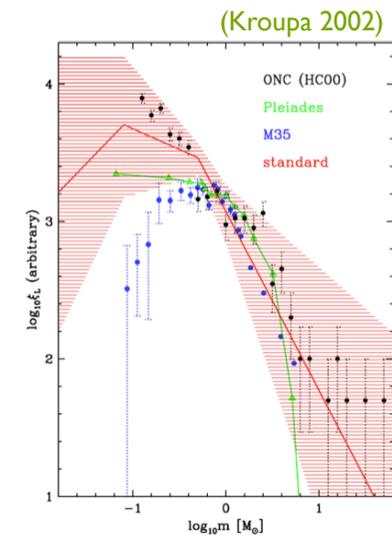
- distribution of stellar masses depends on
  - turbulent initial conditions
    - > mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    - > accretion and  $N$ -body effects
  - thermodynamic properties of gas
    - > balance between heating and cooling
    - > EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    - ionizing radiation, bipolar outflows, winds, SN



# stellar masses

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# example: model of Orion cloud

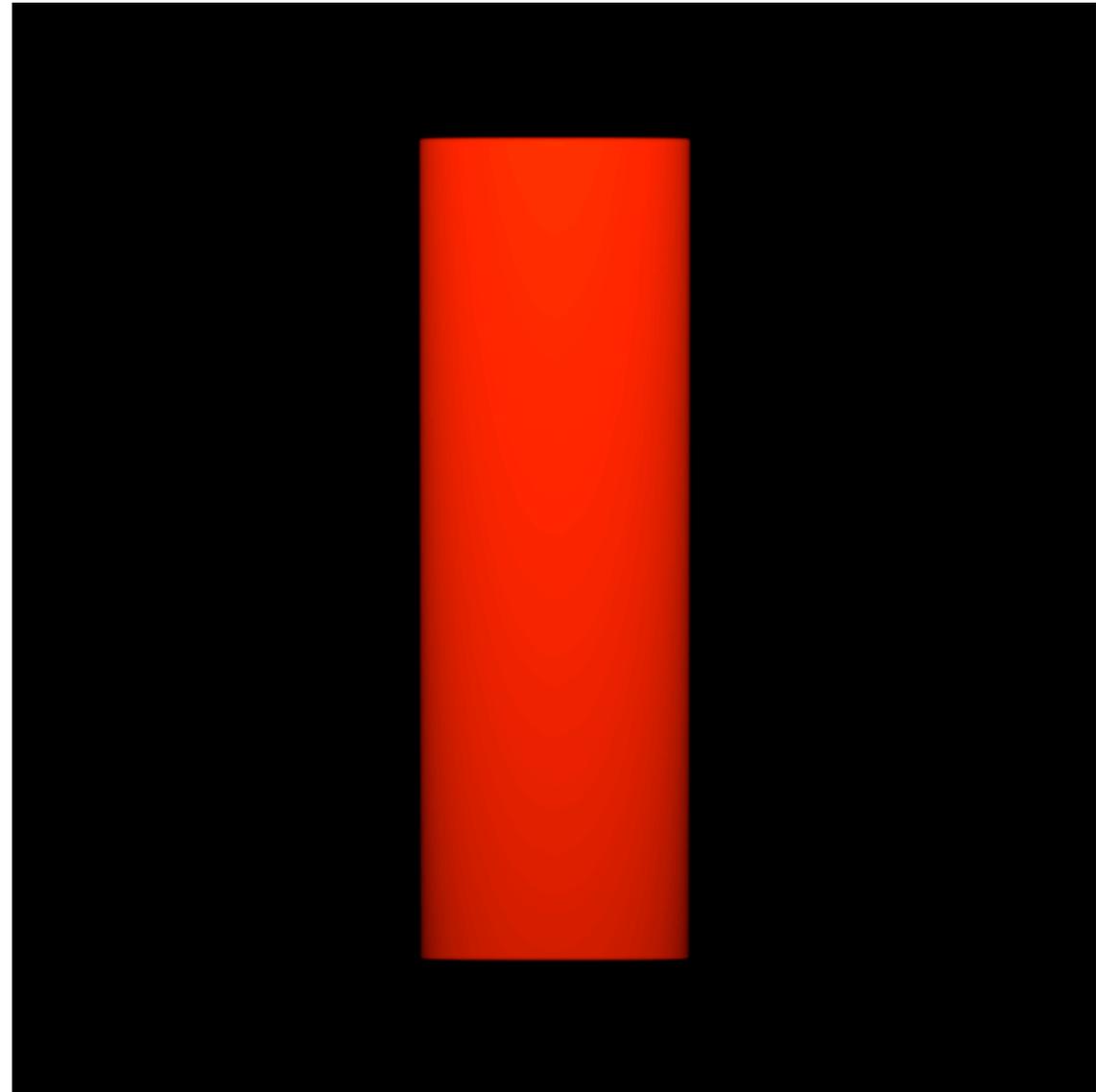
„model“ of Orion cloud:  
15.000.000 SPH particles,  
 $10^4 M_{\text{sun}}$  in 10 pc, mass resolution  
 $0,02 M_{\text{sun}}$ , forms  $\sim 2.500$   
„stars“ (sink particles)

isothermal EOS, top bound, bottom  
unbound

has clustered as well as distributed  
„star“ formation

efficiency varies from 1% to 20%

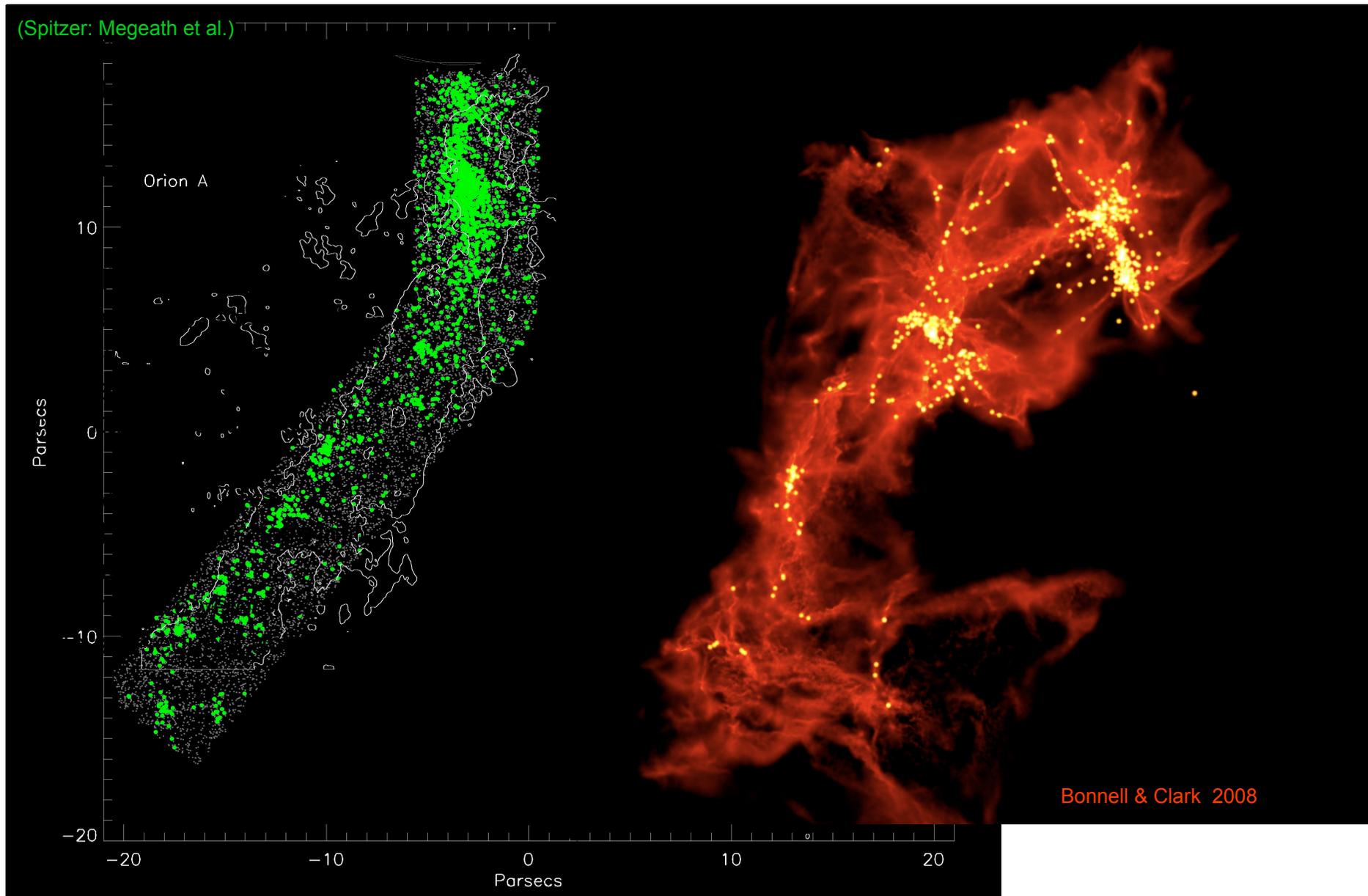
develops full IMF  
(distribution of sink particle masses)



(Bonnell & Clark 2008)



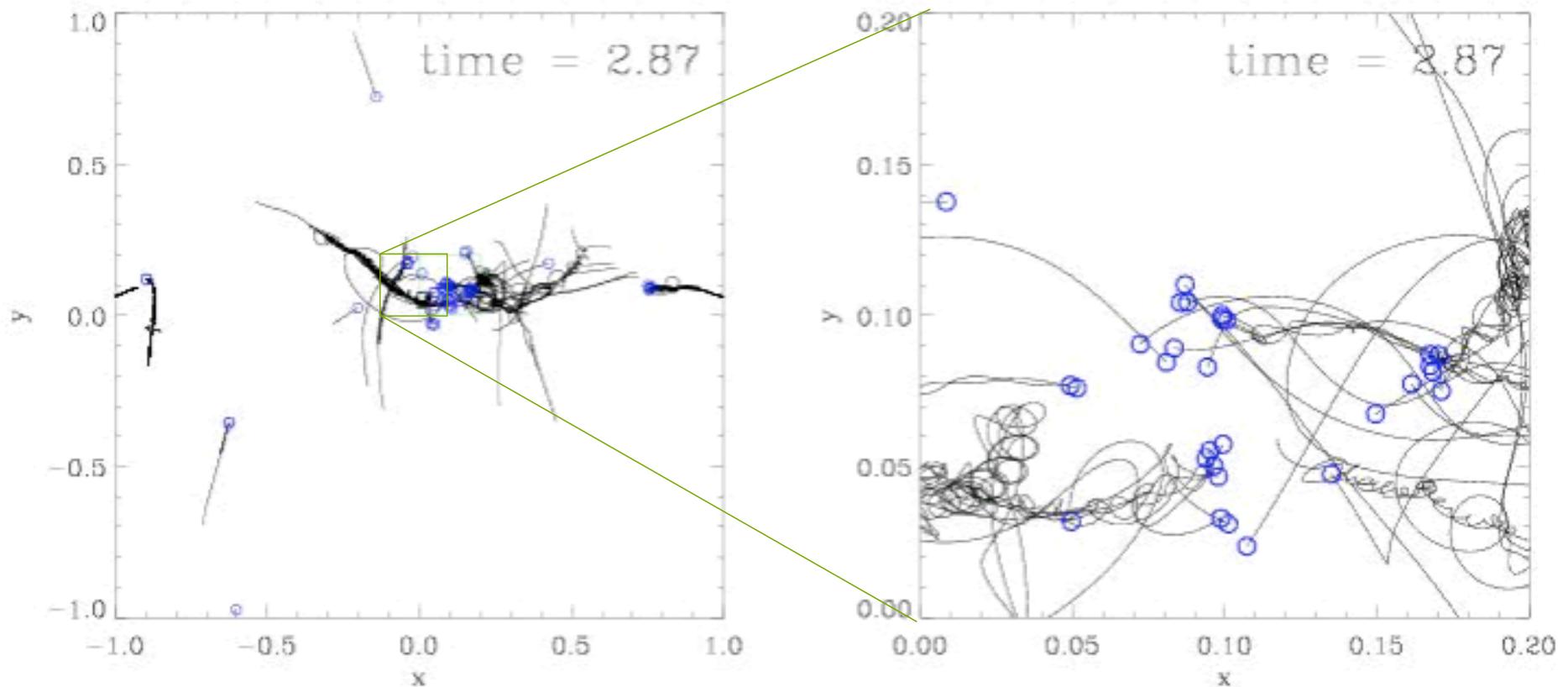
# example: model of Orion cloud





# Dynamics of nascent star cluster

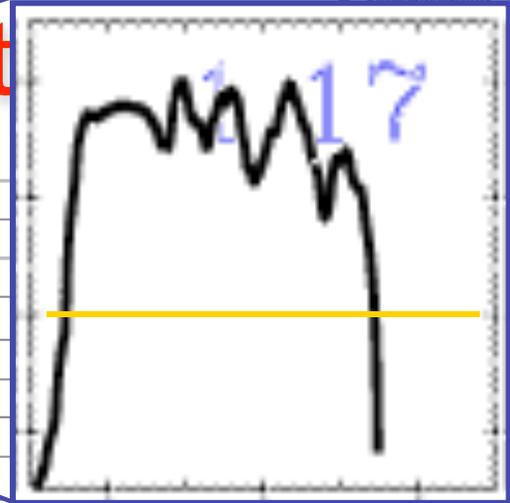
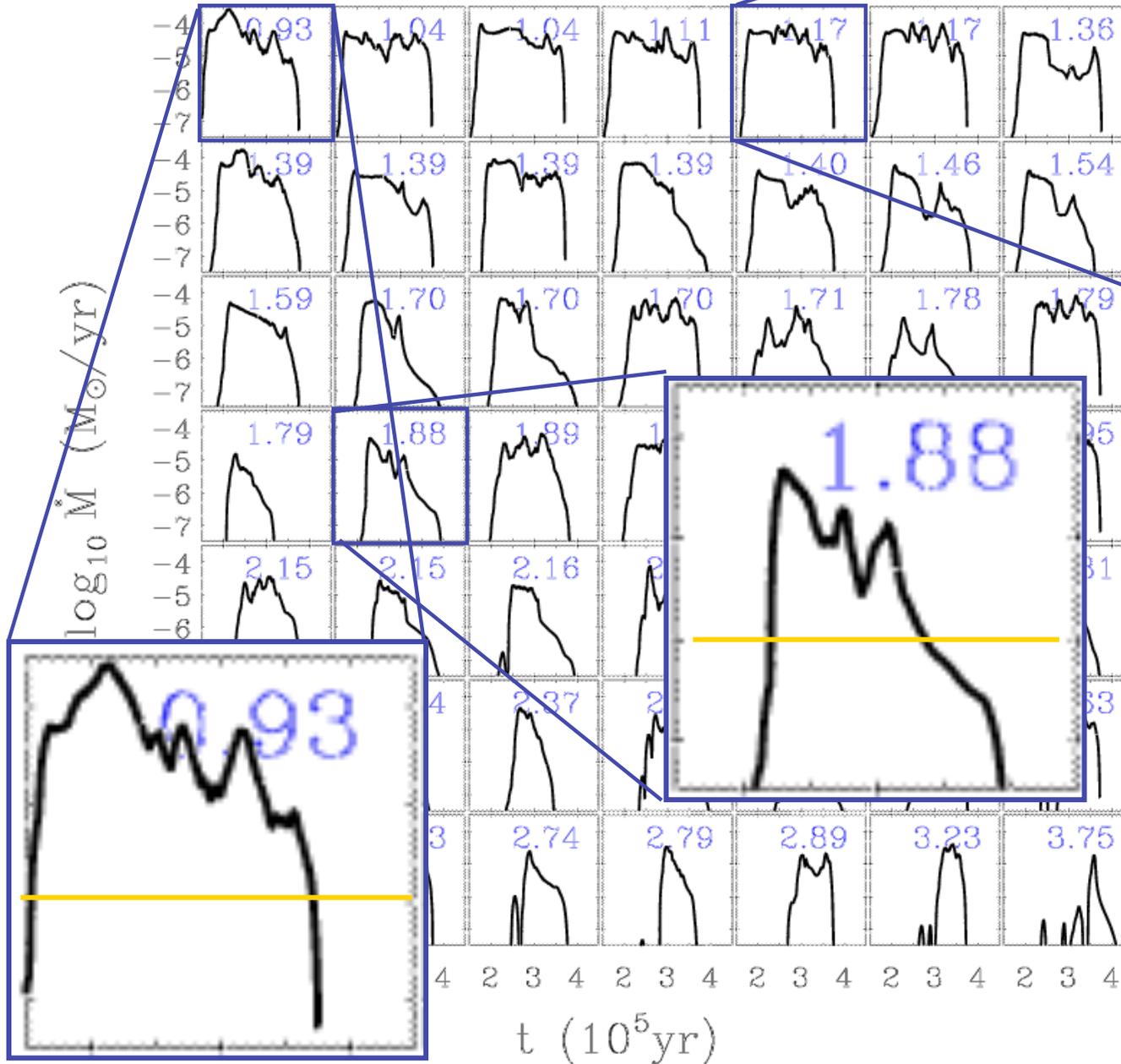
in dense clusters protostellar interaction may become important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation  
(from Klessen & Burkert 2000, ApJS, 128, 287)



# accretion rates in clust

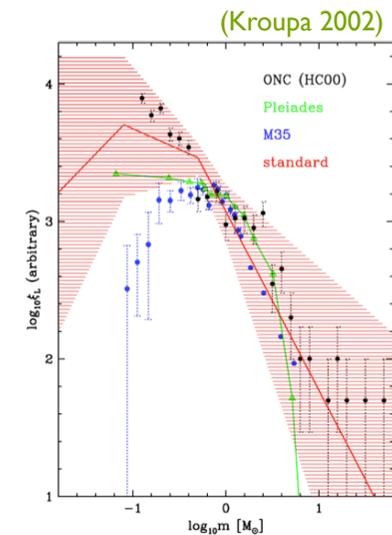


Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

# stellar masses

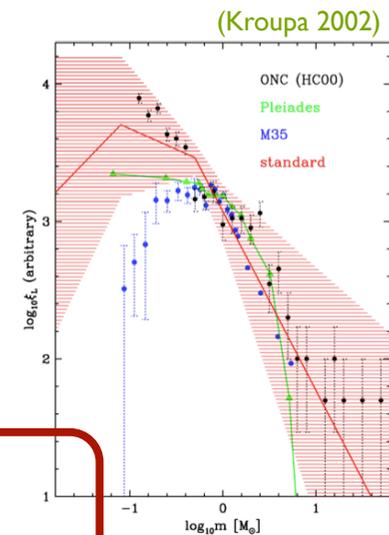
- distribution of stellar masses depends on
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# stellar masses

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application to first star formation



# thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

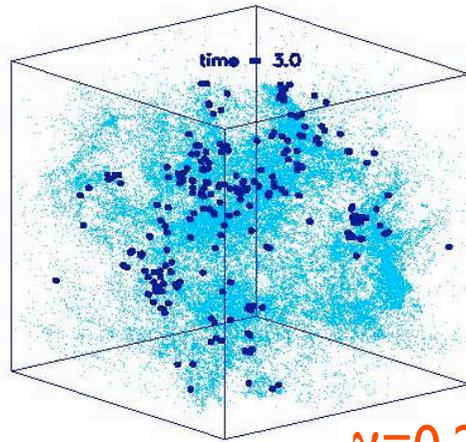
polytropic EOS:  $p \propto \rho^\gamma$

$\gamma < 1$ : dense cluster of low-mass stars

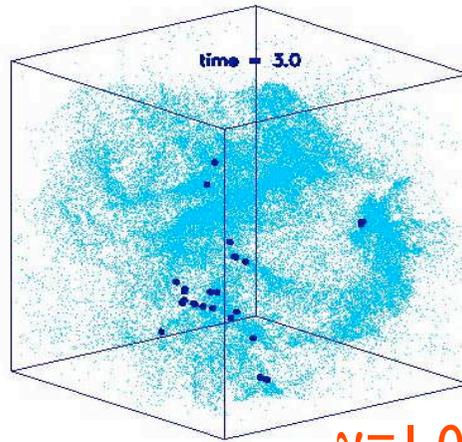
$\gamma > 1$ : isolated high-mass stars

(see Li et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)

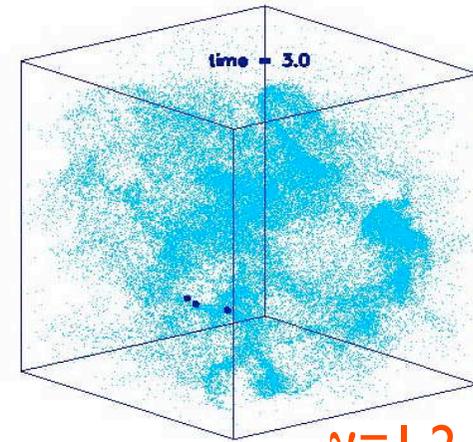
# dependency on EOS



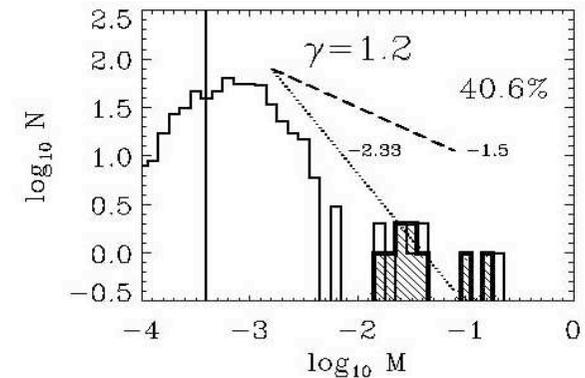
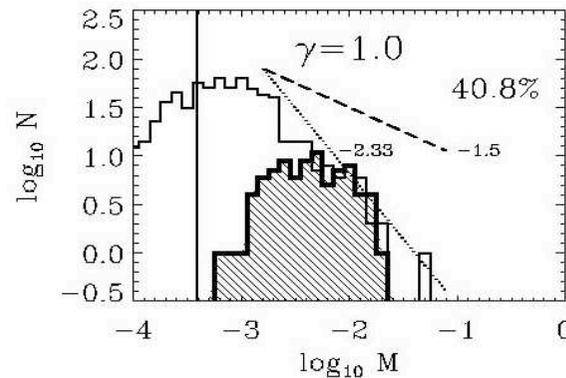
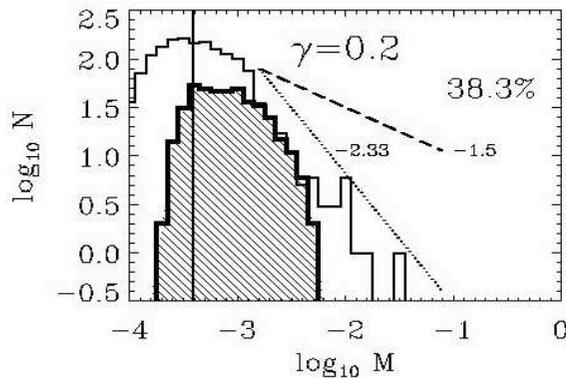
$\gamma = 0.2$



$\gamma = 1.0$



$\gamma = 1.2$

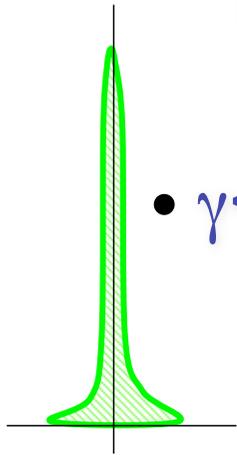


for  $\gamma < 1$  fragmentation is enhanced  $\rightarrow$  *cluster of low-mass stars*  
for  $\gamma > 1$  it is suppressed  $\rightarrow$  formation of *isolated massive stars*

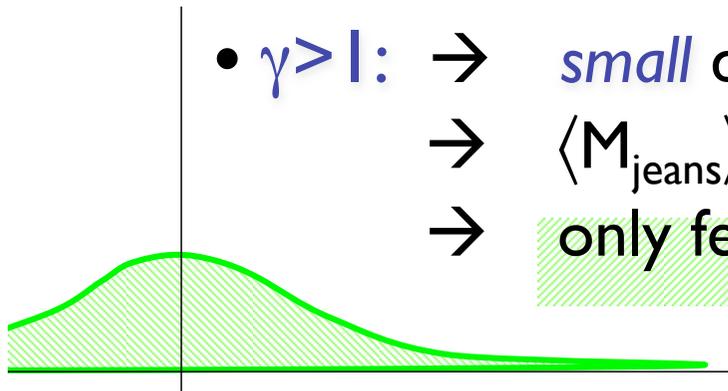
# how does that work?

$$(1) \mathbf{p} \propto \rho^\gamma \rightarrow \rho \propto \mathbf{p}^{1/\gamma}$$

$$(2) \mathbf{M}_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$$

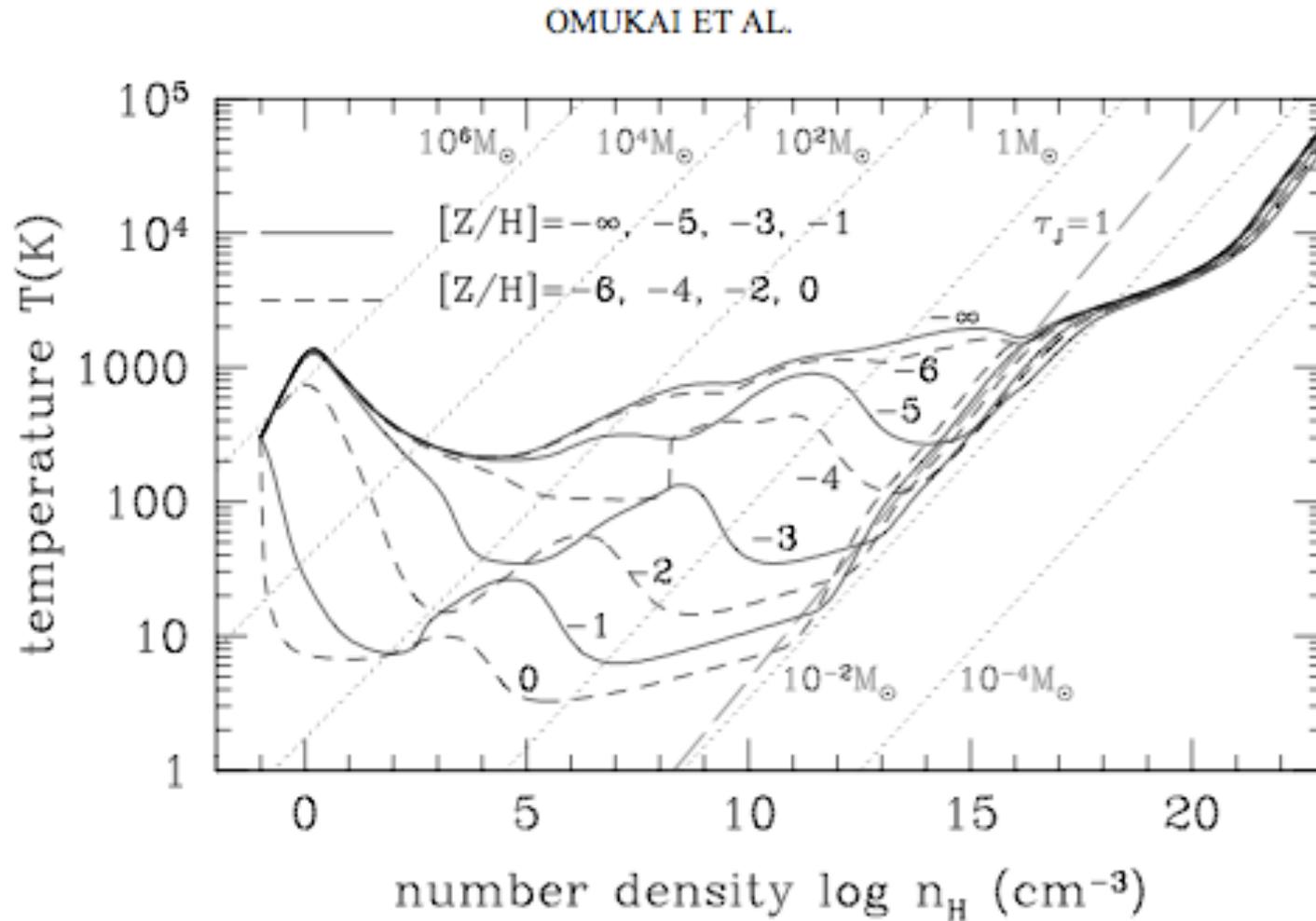


- $\gamma < 1$ :  $\rightarrow$  *large* density excursion for given pressure
  - $\rightarrow$   $\langle M_{\text{jeans}} \rangle$  becomes small
  - $\rightarrow$  number of fluctuations with  $M > M_{\text{jeans}}$  is large



- $\gamma > 1$ :  $\rightarrow$  *small* density excursion for given pressure
  - $\rightarrow$   $\langle M_{\text{jeans}} \rangle$  is large
  - $\rightarrow$  only few and massive clumps exceed  $M_{\text{jeans}}$

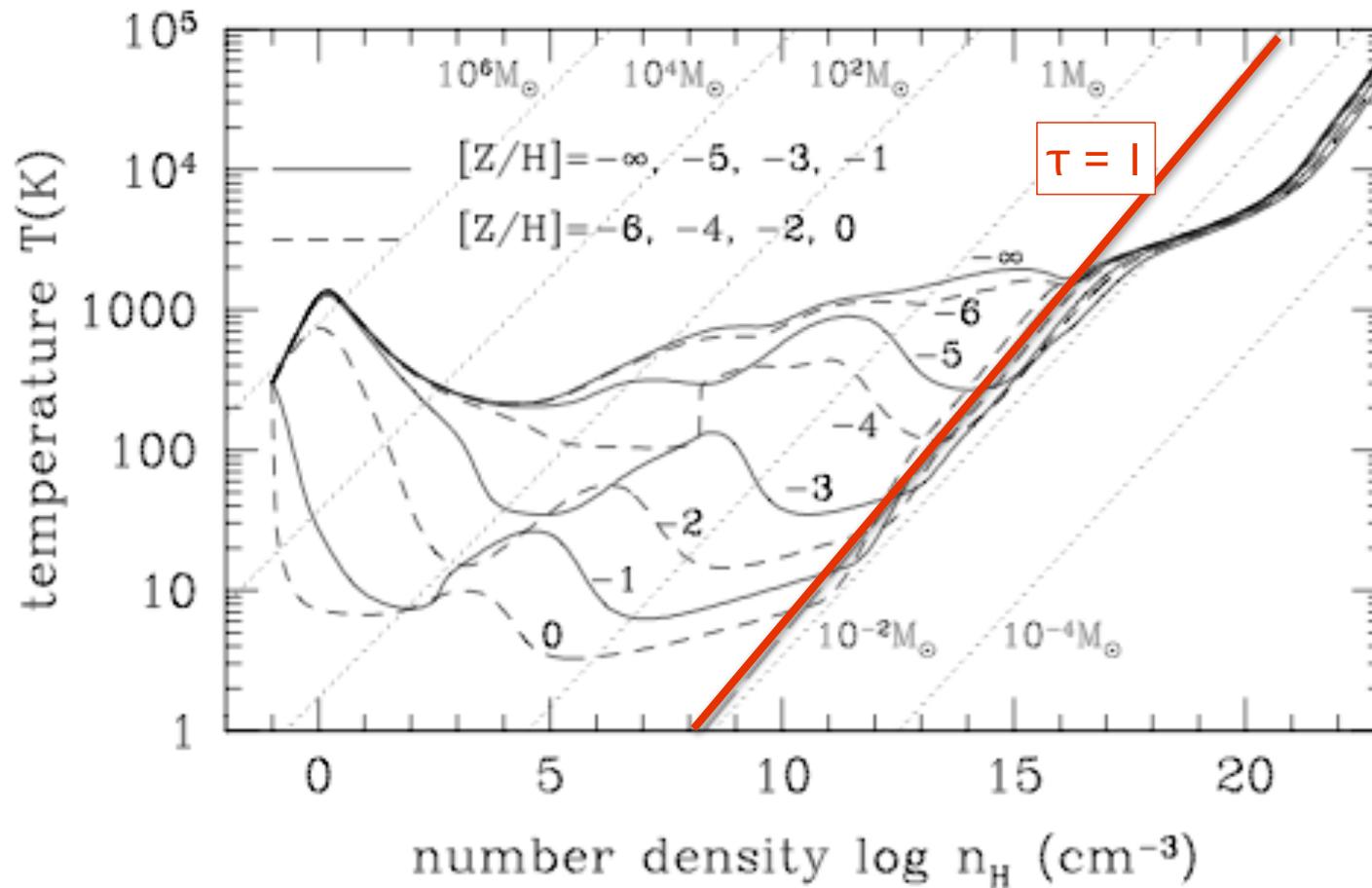
# EOS as function of metallicity



(Omukai et al. 2005)

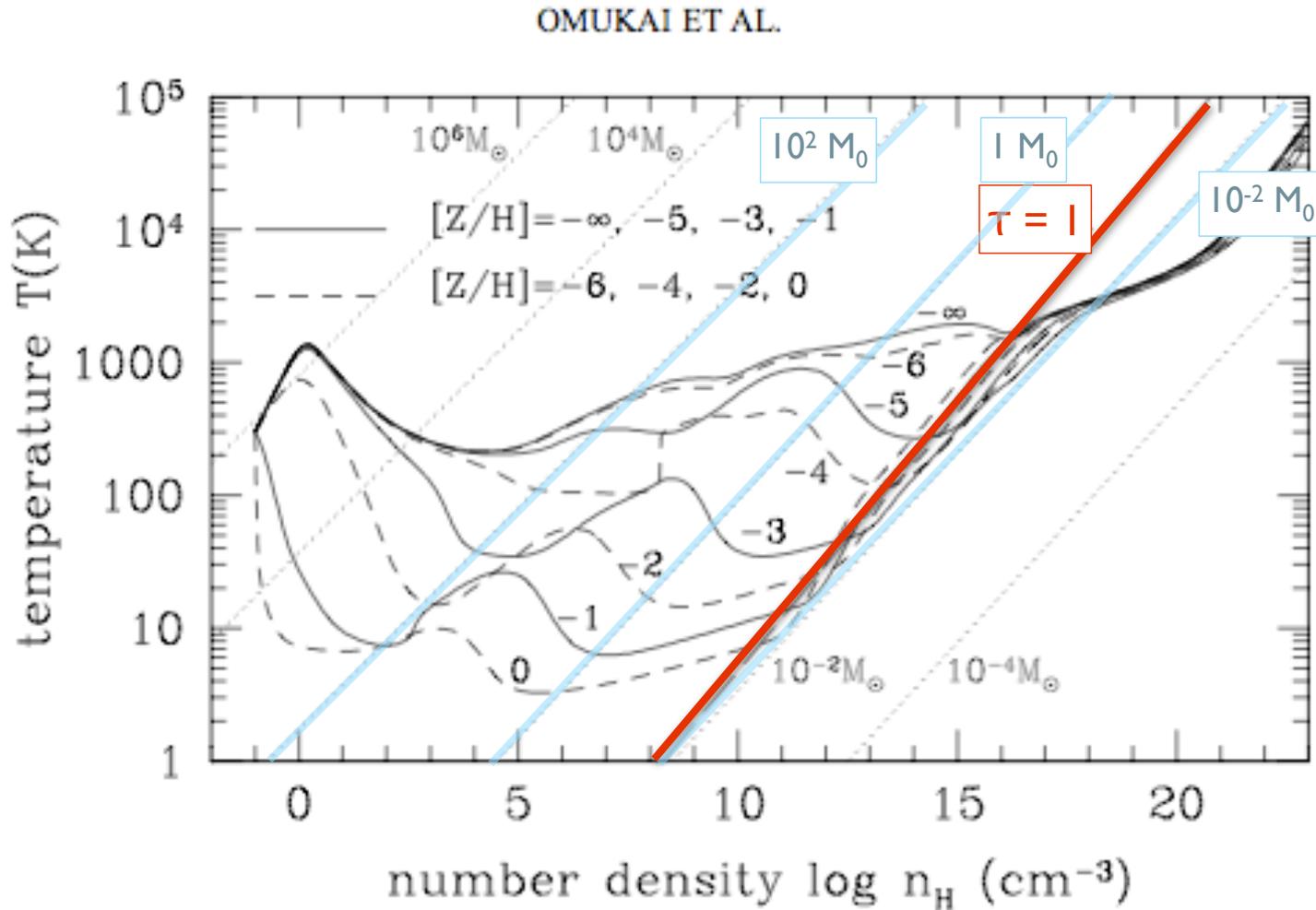
# EOS as function of metallicity

OMUKAI ET AL.



(Omukai et al. 2005)

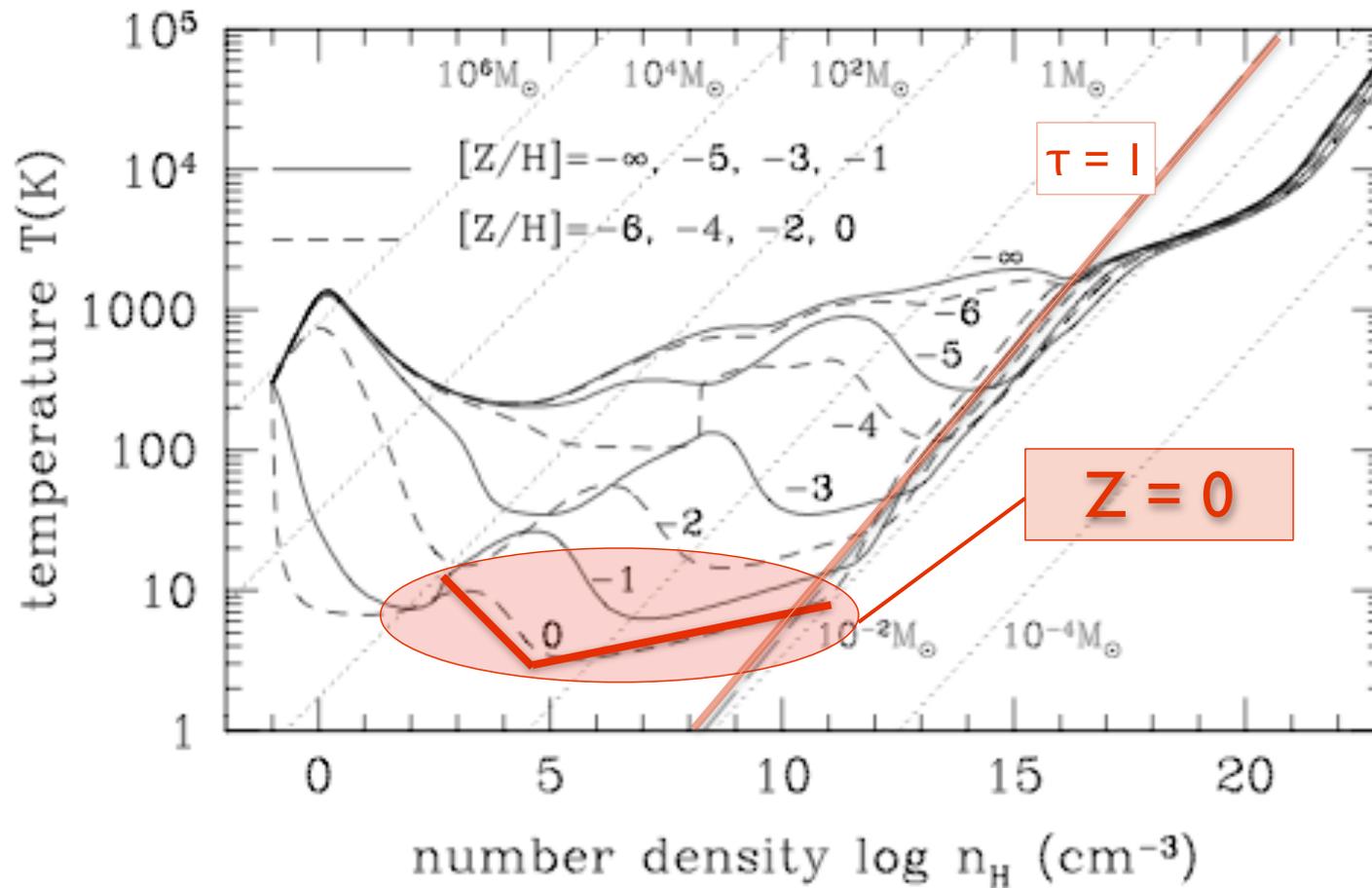
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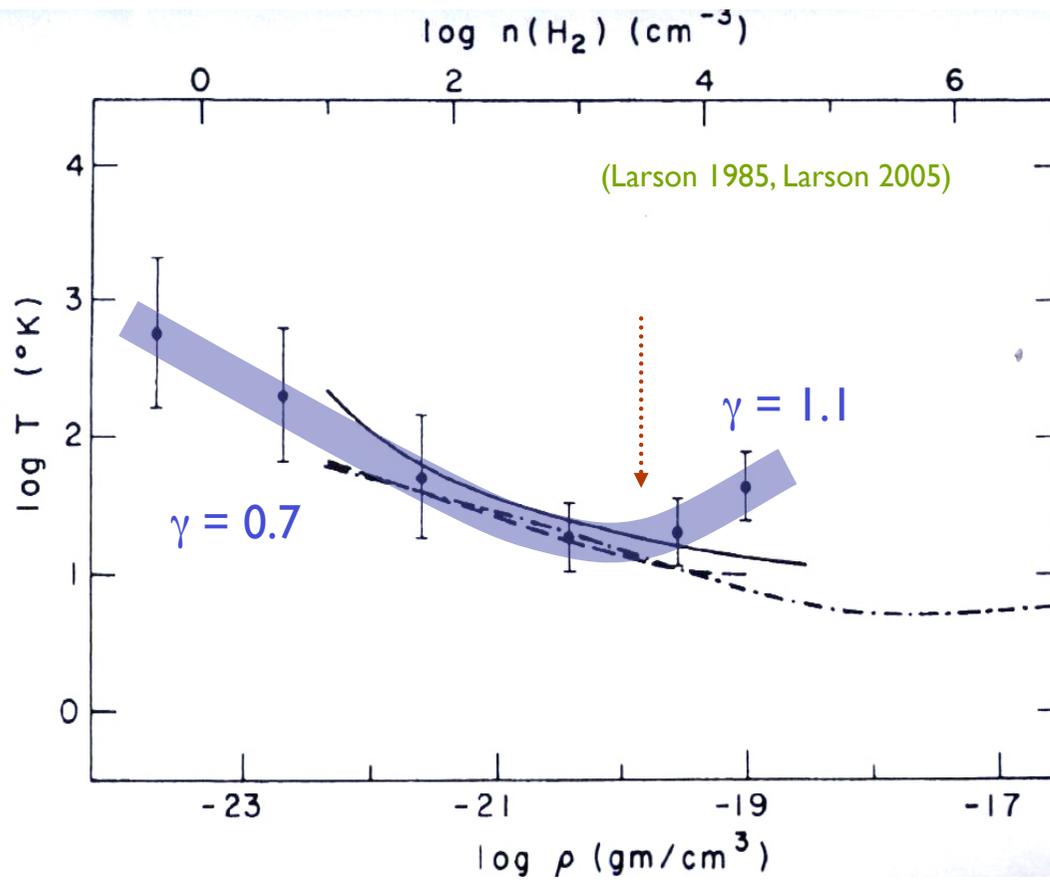
# present-day star formation

OMUKAI ET AL.



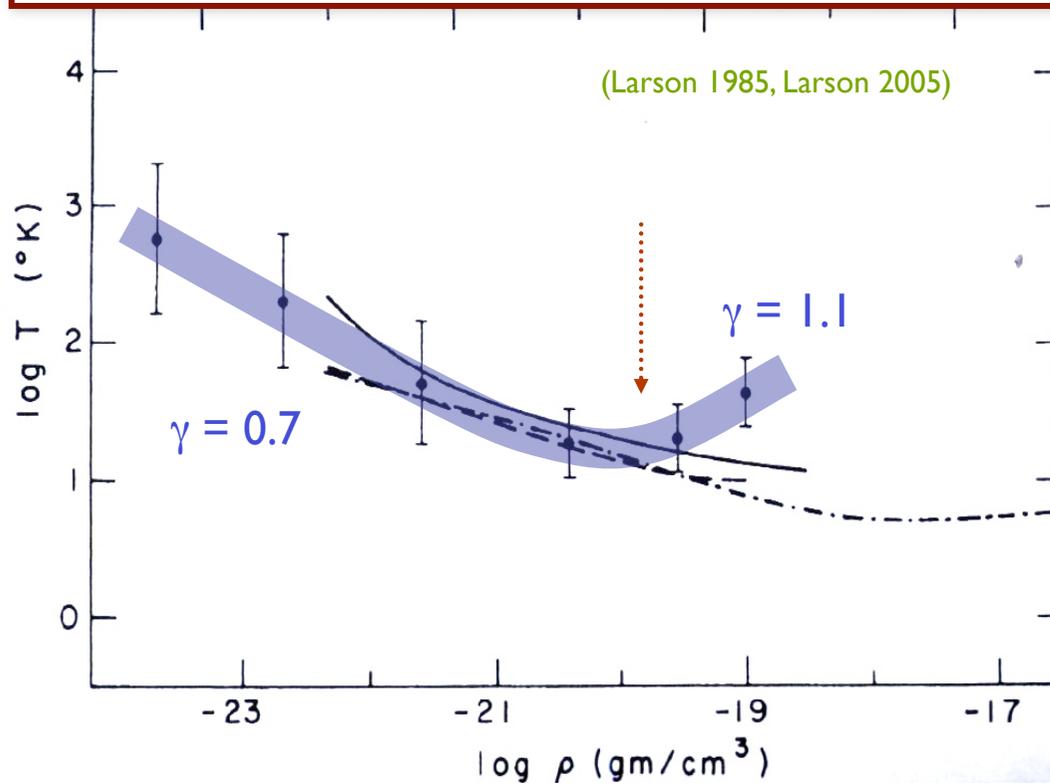
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

# present-day star formation

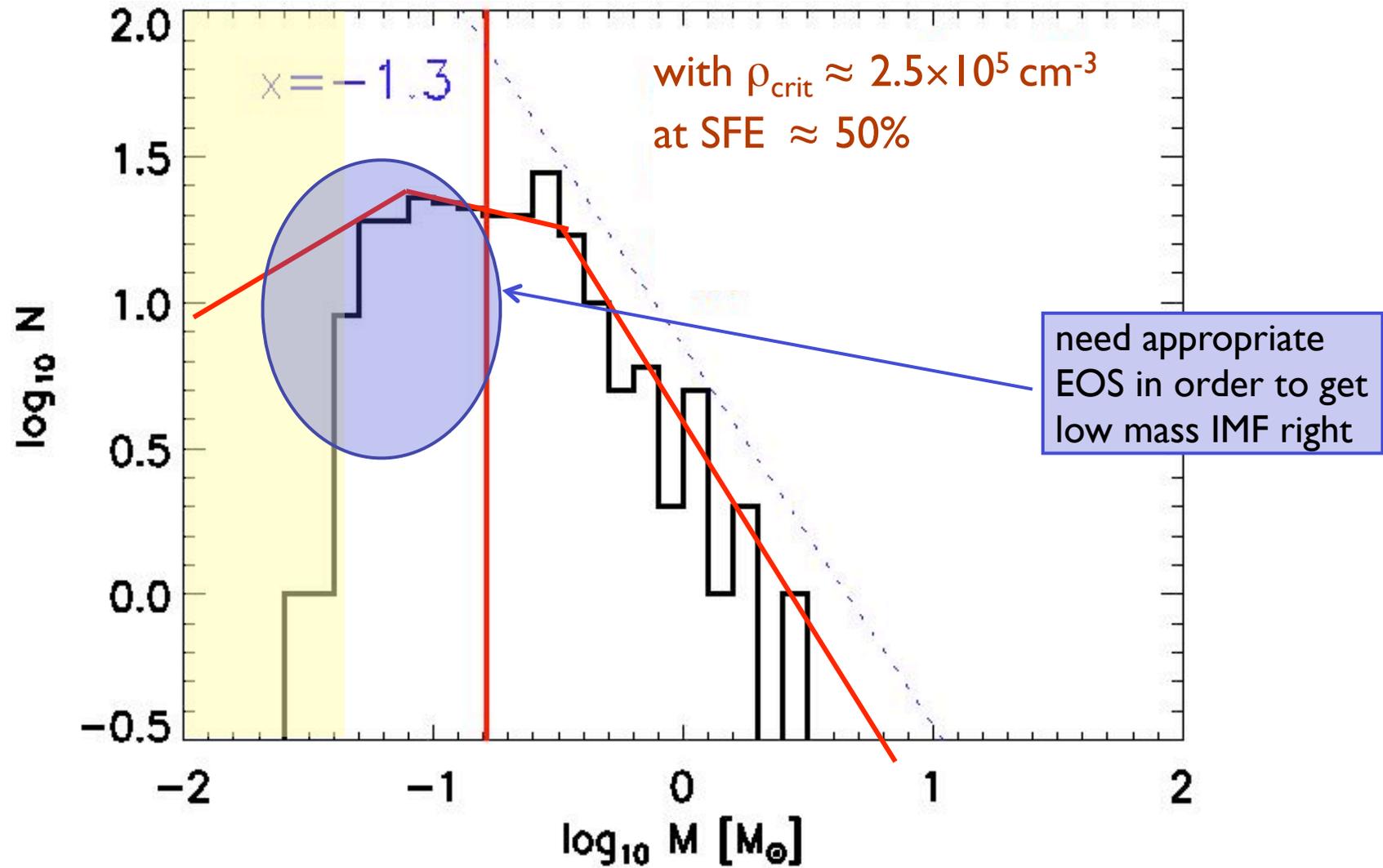


# present-day star formation

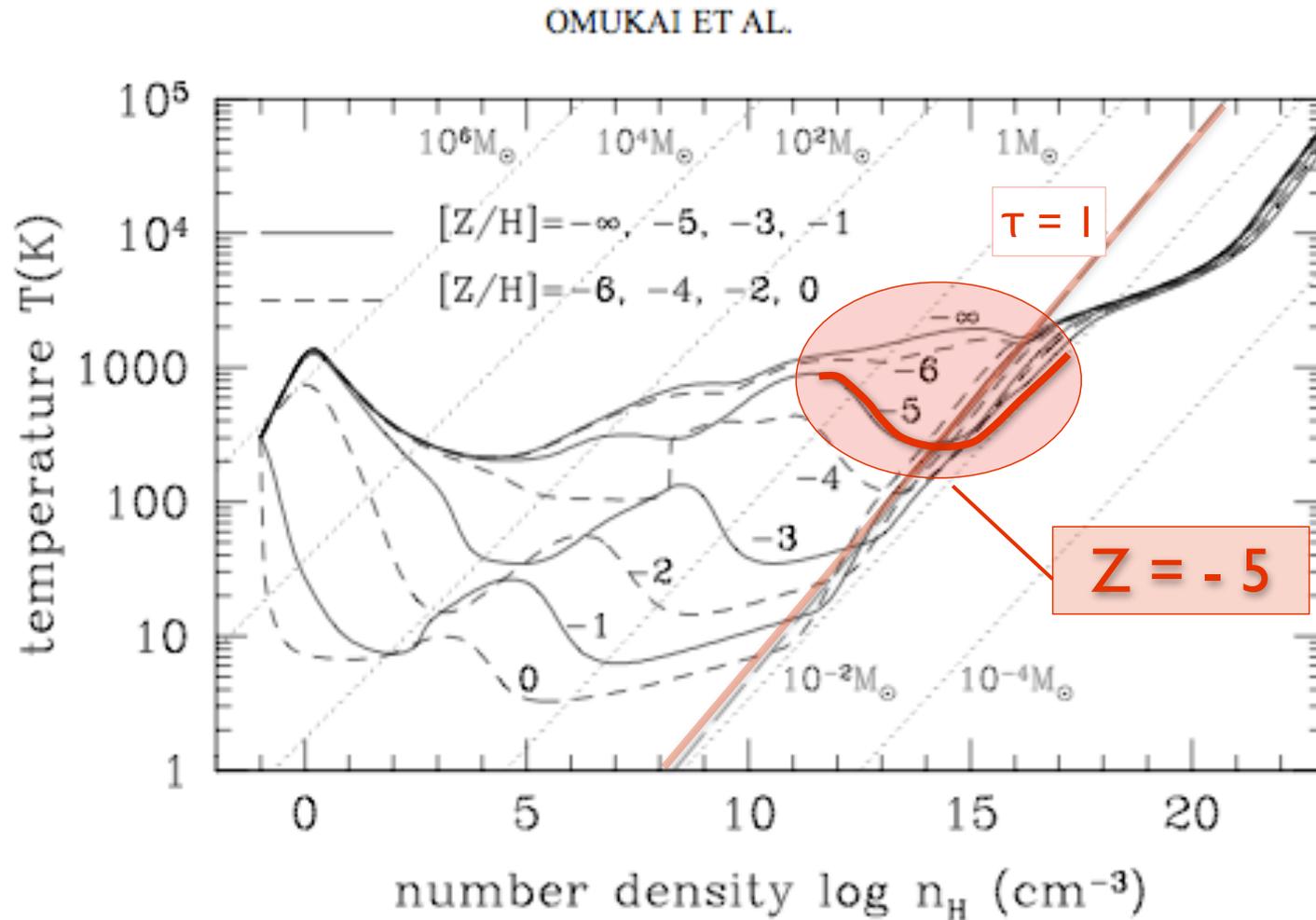
This kink in EOS is very insensitive to environmental conditions such as ambient radiation field  
--> reason for universal form of the IMF? (Elmegreen et al. 2008)



# IMF in nearby molecular clouds



# transition: Pop III to Pop II.5



(Omukai et al. 2005)

# transition: Pop III to Pop II.5

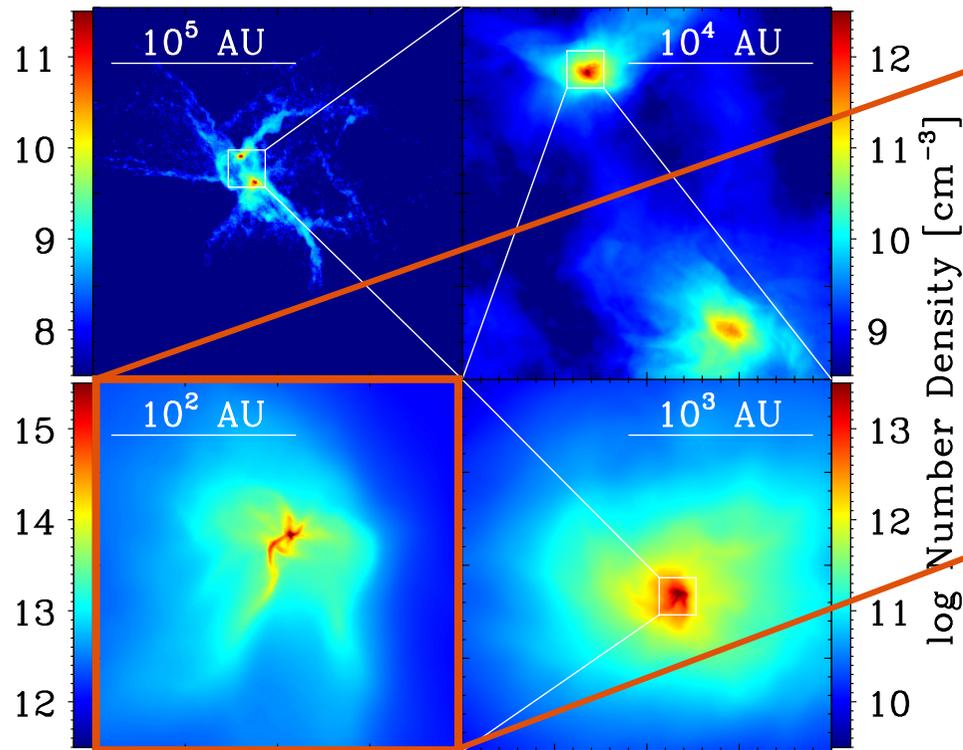


FIG. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

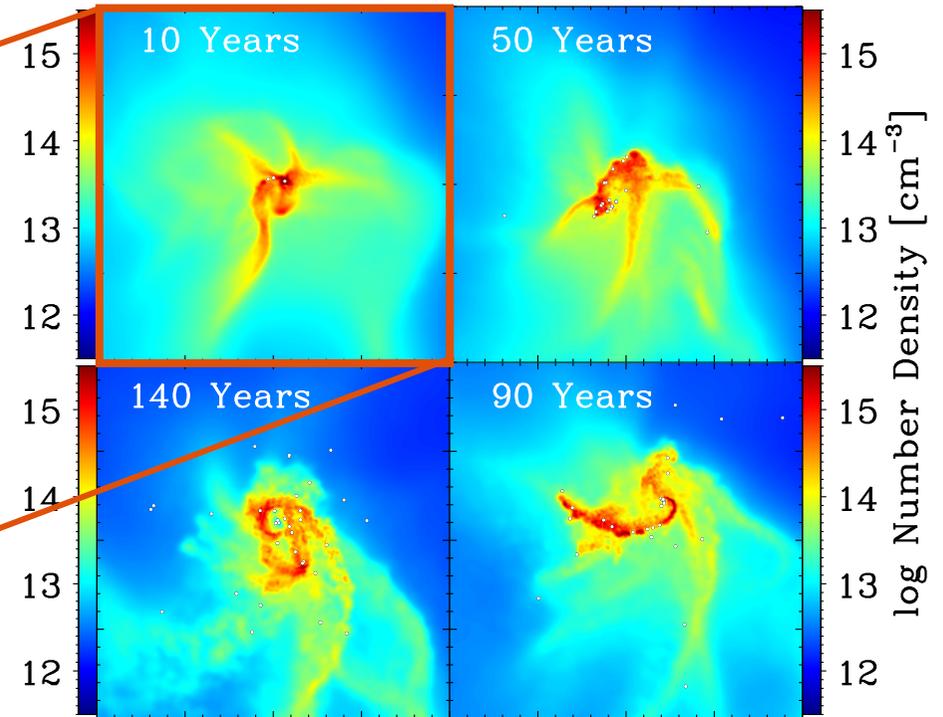


FIG. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and  $Z = 10^{-4}Z_{\odot}$ . The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

# transition: Pop III to Pop II.5

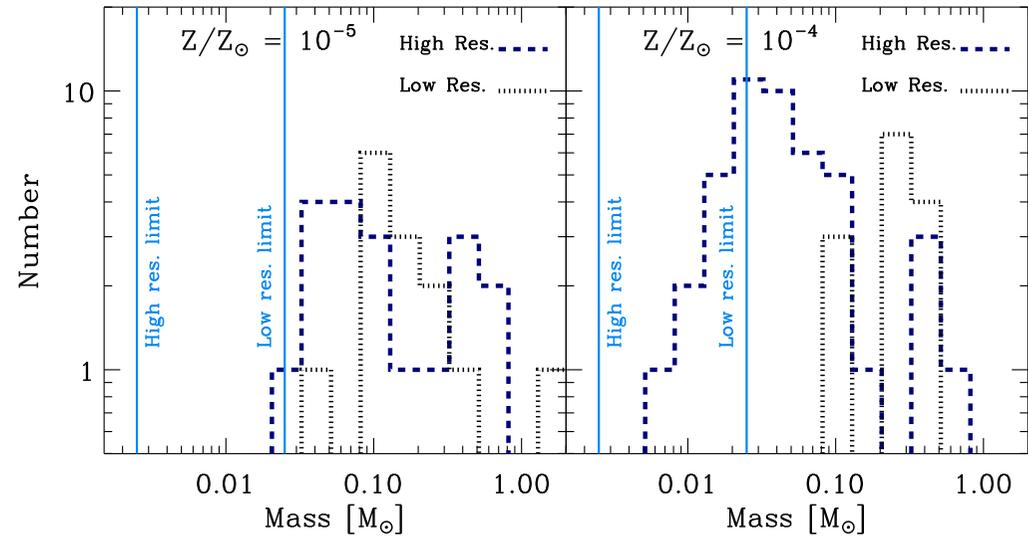
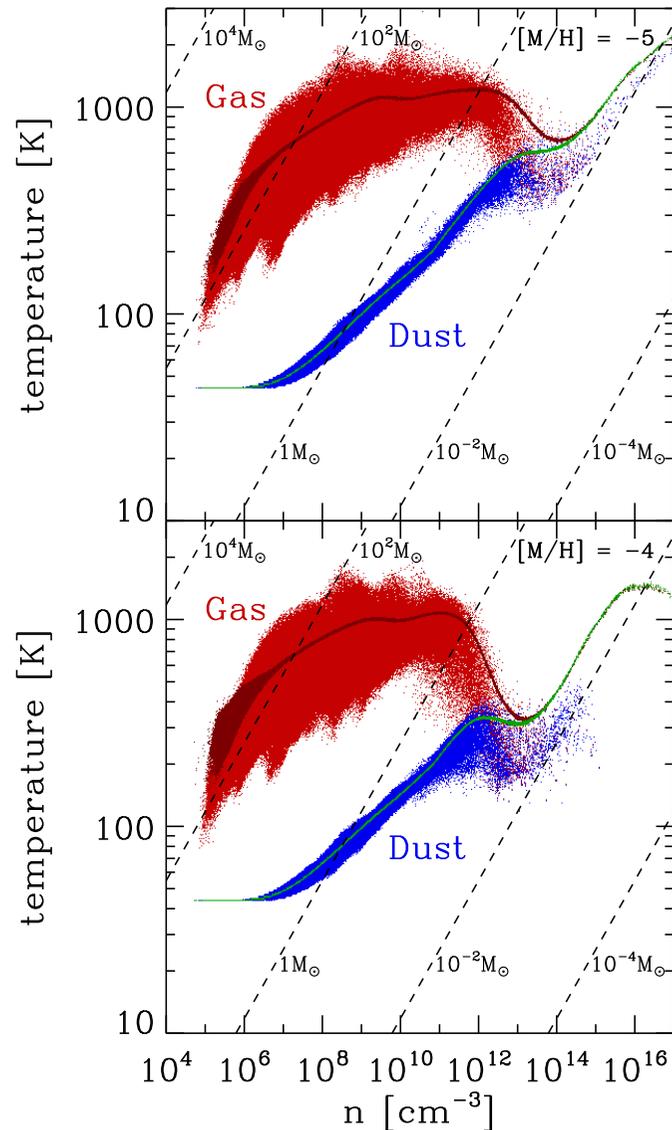
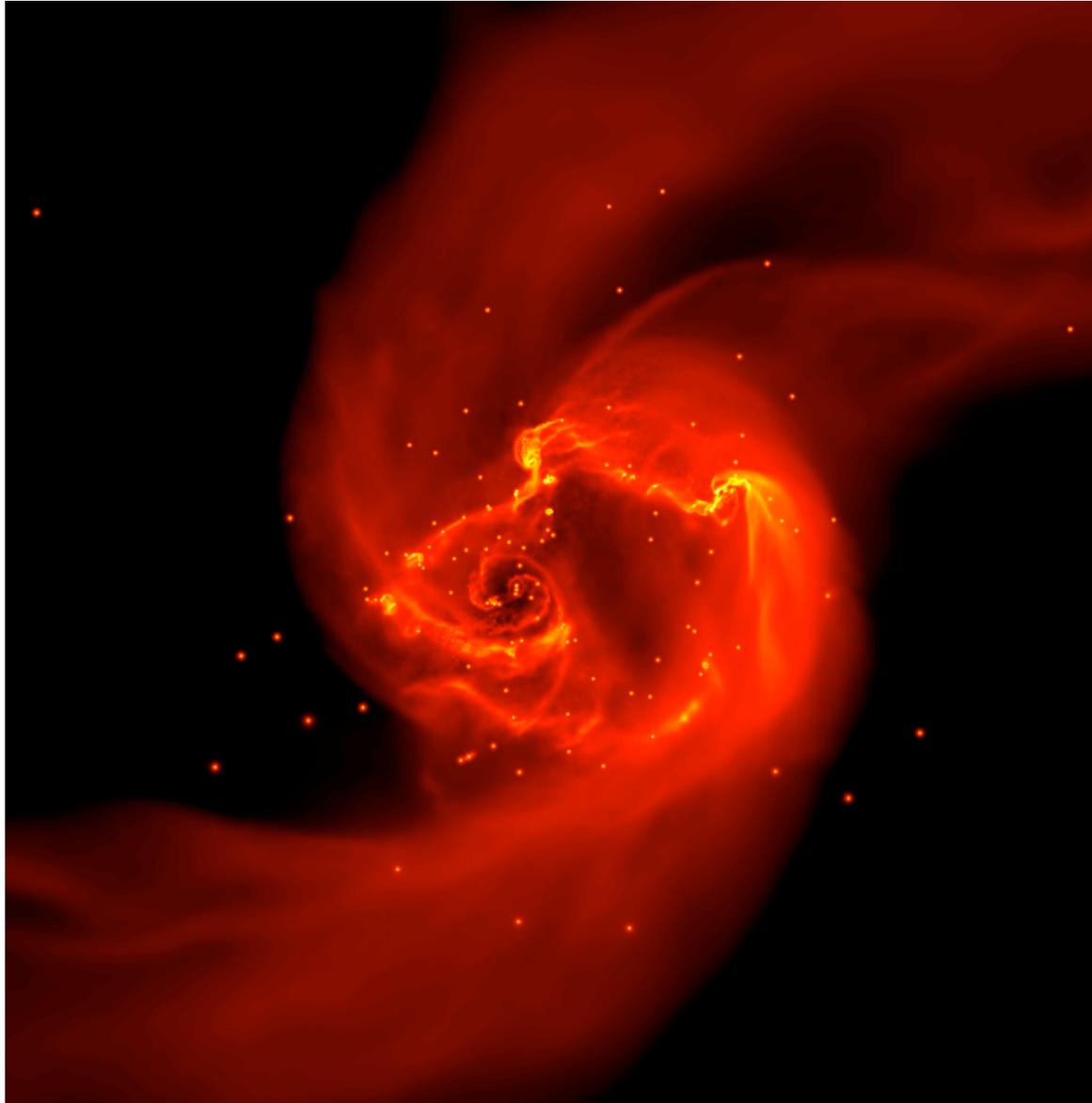


FIG. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas couple and the compressional heating starts to dominate over the dust cooling. At the time shown, around  $5 M_\odot$  of gas had been accreted by the sink particles in each simulation.

red / blue: turbulence and rotation  
 dark red / green: simple collapse

# dust induced fragmentation at $Z=10^{-5}$

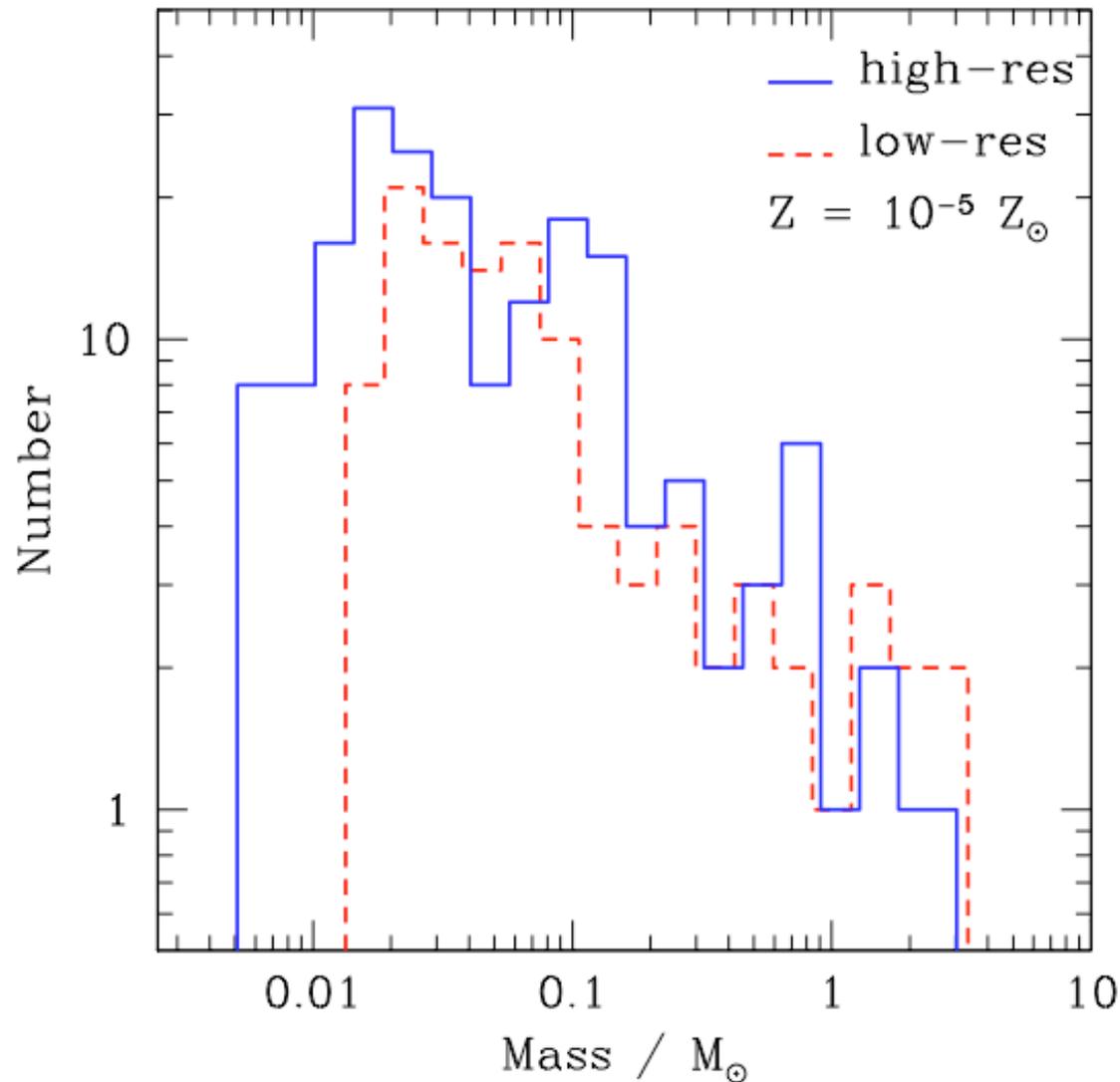


dense cluster of low-mass  
protostars builds up:

- mass spectrum  
peaks *below*  $1 M_{sun}$
- cluster VERY dense  
 $n_{stars} = 2.5 \times 10^9 pc^{-3}$
- fragmentation  
at density  
 $n_{gas} = 10^{12} - 10^{13} cm^{-3}$

(Clark et al. 2008, ApJ 672, 757)

# dust induced fragmentation at $Z=10^{-5}$



dense cluster of low-mass protostars builds up:

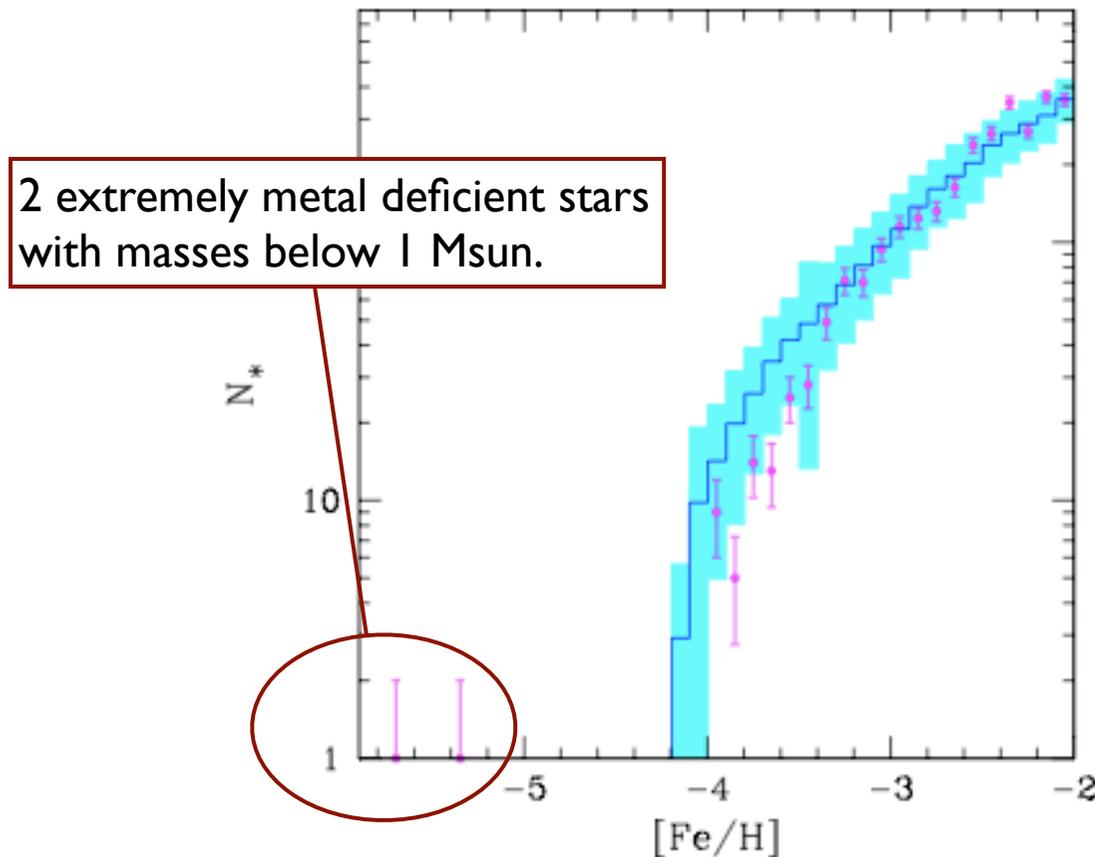
- mass spectrum peaks below  $1 M_{\text{sun}}$
- cluster VERY dense  
 $n_{\text{stars}} = 2.5 \times 10^9 \text{ pc}^{-3}$

- *predictions:*

- \* low-mass stars with  $[\text{Fe}/\text{H}] \sim 10^{-5}$
- \* high binary fraction

(Clark et al. 2008)

# dust induced fragmentation at $Z=10^{-5}$



(plot from Salvadori et al. 2006, data from Frebel et al. 2005)

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1  $M_{\text{sun}}$
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 $n_{\text{stars}} = 2.5 \times 10^9 \text{ pc}^{-3}$

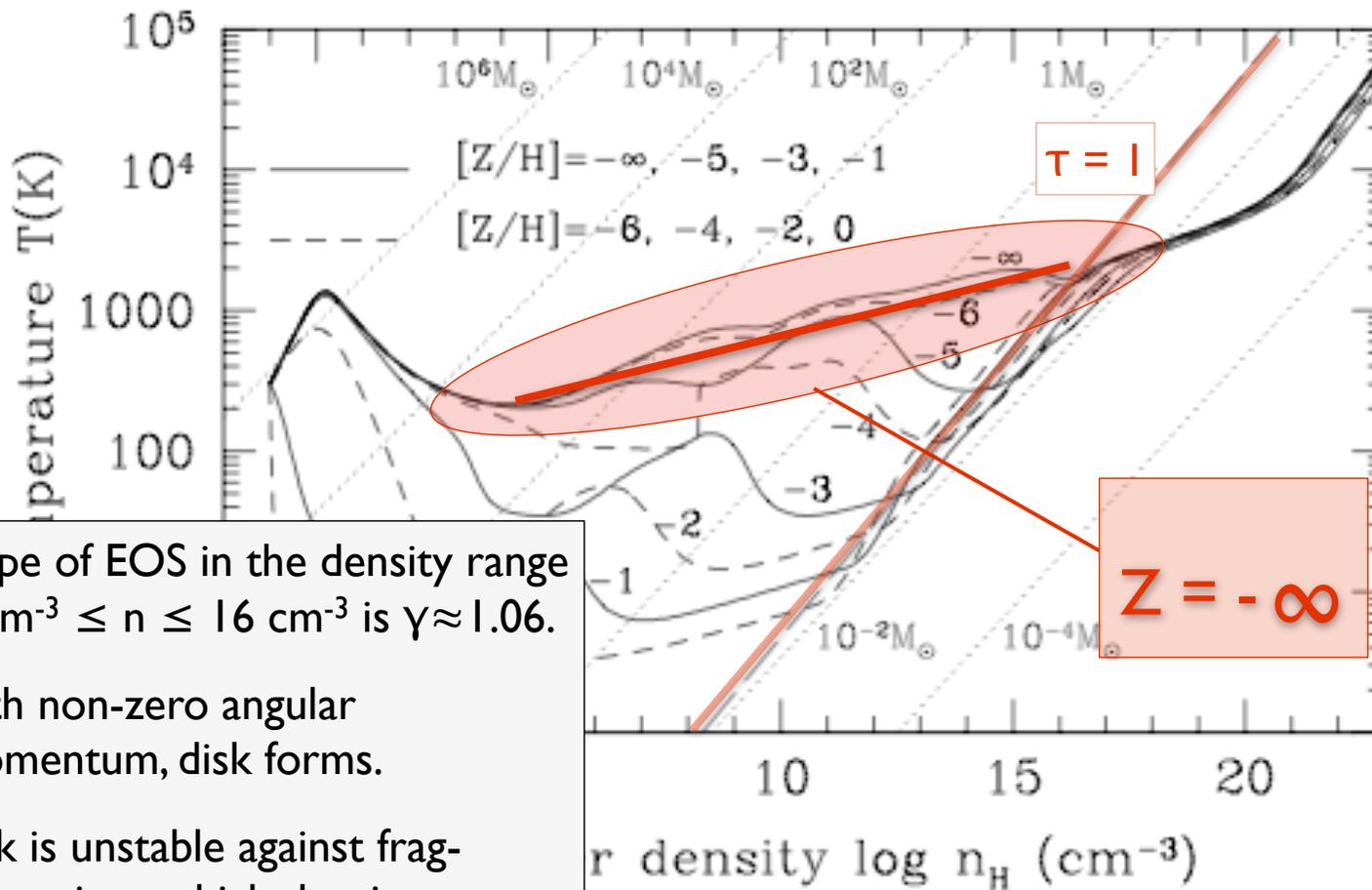
- *predictions:*

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(Clark et al. 2008)

# metal-free star formation

OMUKAI ET AL.

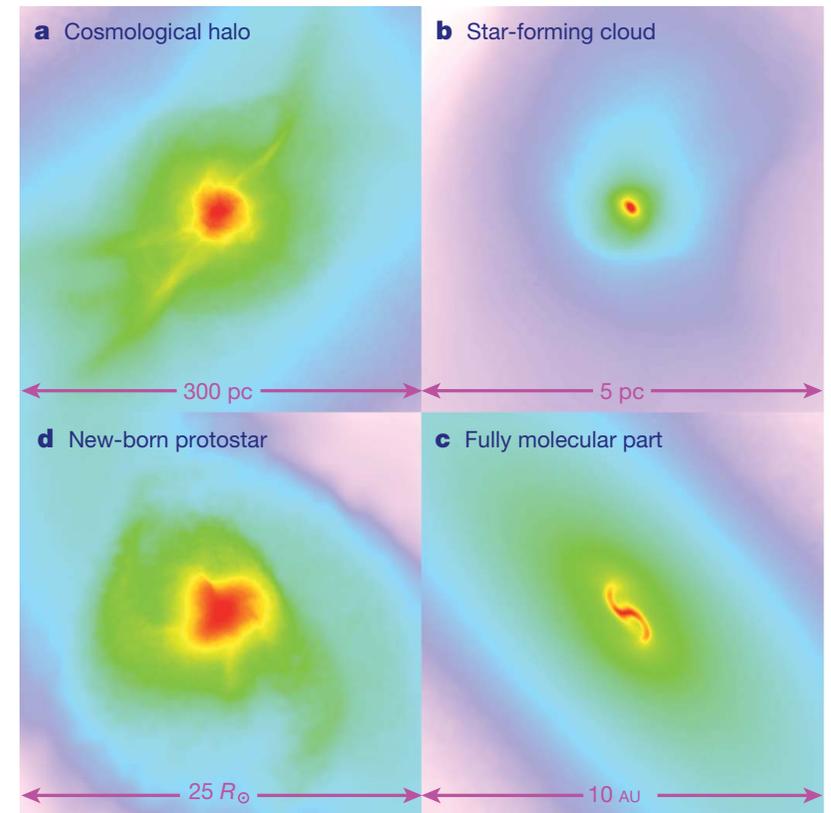


- slope of EOS in the density range  $5 \text{ cm}^{-3} \leq n \leq 16 \text{ cm}^{-3}$  is  $\gamma \approx 1.06$ .
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005)

# metal-free star formation

- most current numerical simulations of Pop III star formation predict very massive objects (e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)
- similar for theoretical models (e.g. Tan & McKee 2004)
- there are some first hints of fragmentation, however (Turk et al. 2009, Stacy et al. 2010)



**Figure 1 | Projected gas distribution around a primordial protostar.** Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming cloud; **c**, the central part of the fully molecular core; and **d**, the final protostar. Reproduced by permission of the AAAS (from ref. 20).

(Yoshida et al. 2008, *Science*, 321, 669)

# SPH study: face on look at accretion disk

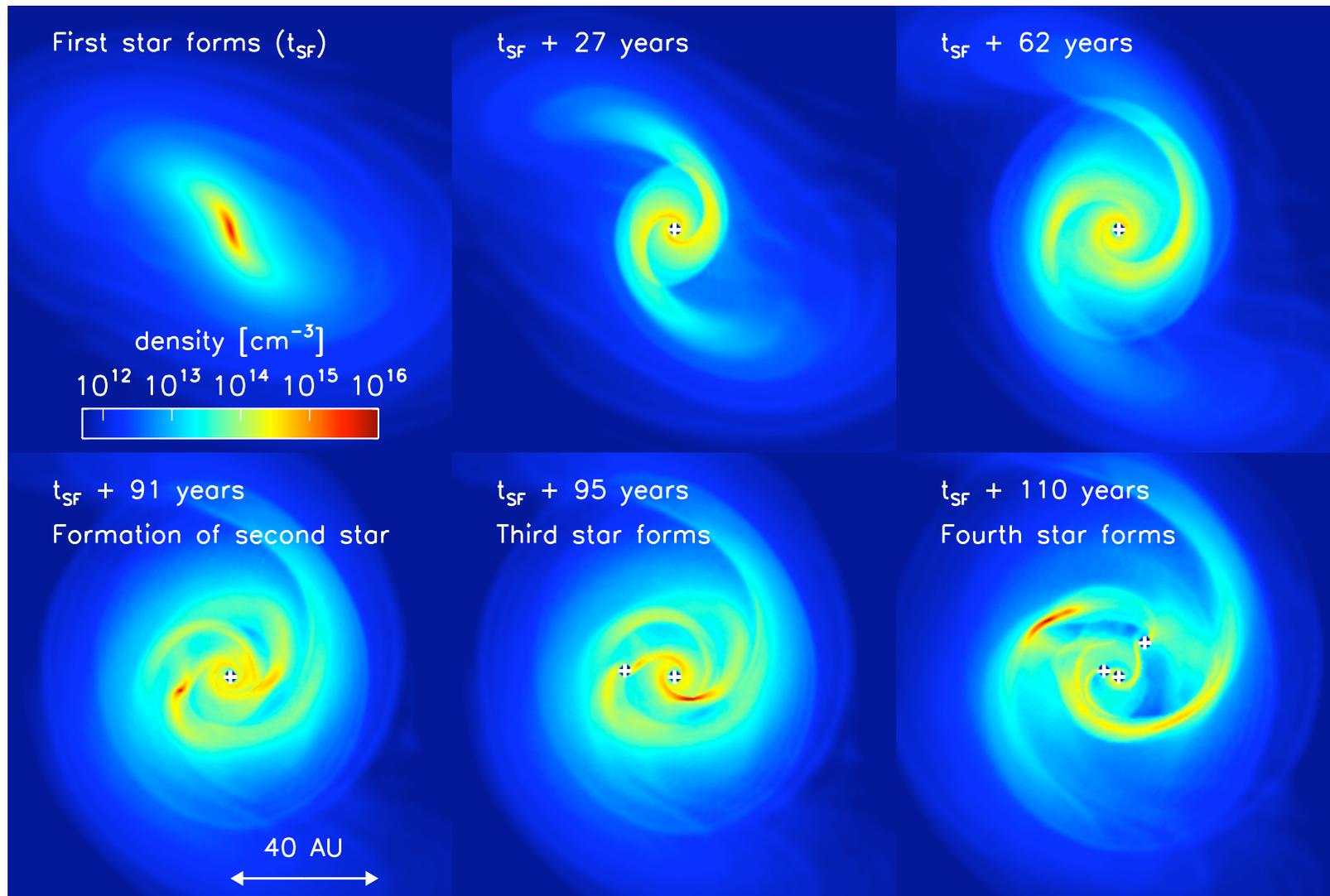


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.

# SPH study: some disk parameters

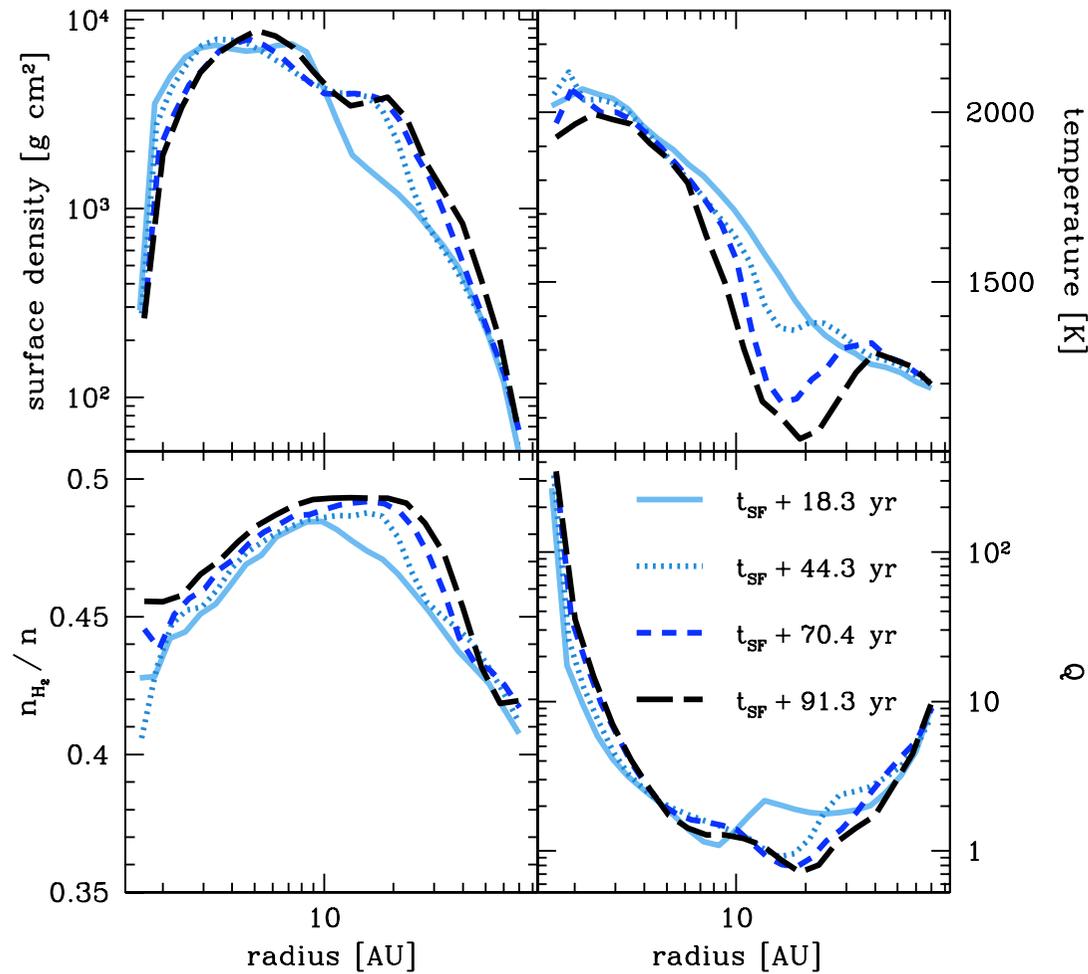


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter,  $Q = c_s \kappa / \pi G \Sigma$ , where  $c_s$  is the sound speed and  $\kappa$  is the epicyclic frequency. Because our disk is Keplerian, we adopted the standard simplification, and replaced  $\kappa$  with the orbital frequency. The molecular fraction is defined as the number density of hydrogen molecules ( $n_{\text{H}_2}$ ), divided by the number density of hydrogen nuclei ( $n$ ), such that fully molecular gas has a value of 0.5

# SPH study: mass accretion onto disk and onto protostars

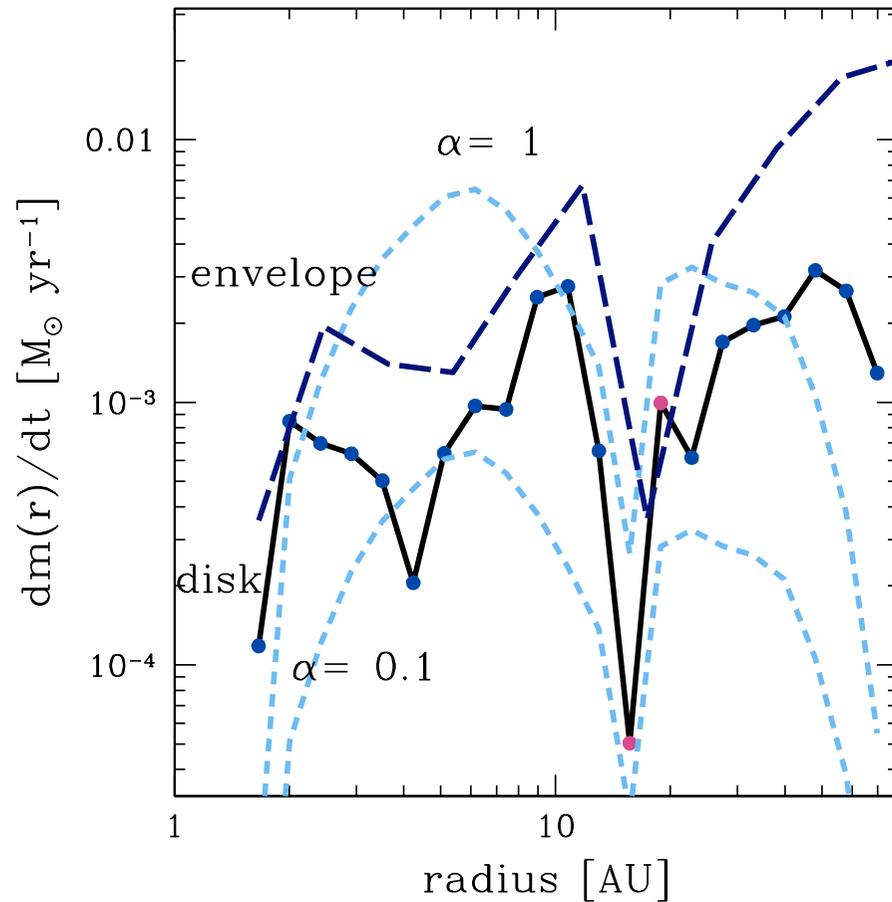


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure of the material flowing through *and onto* the disk at each radius. Both are shown at the onset of disk fragmentation. In the case of the disk accretion we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink (further details can be found in Section 6 of the online material). The light blue dashed lines show the accretion rates expected from an ‘alpha’ (thin) disk model, where  $\dot{M}(r) = 3\pi\alpha c_s(r)\Sigma(r)H(r)$ , with two global values of alpha and where  $c_s(r)$ ,  $\Sigma(r)$ , and  $H(r)$  are (respectively) the sound speed, surface density and disk thickness at radius  $r$ .

# SPH study: comparison of all relevant heating and cooling processes

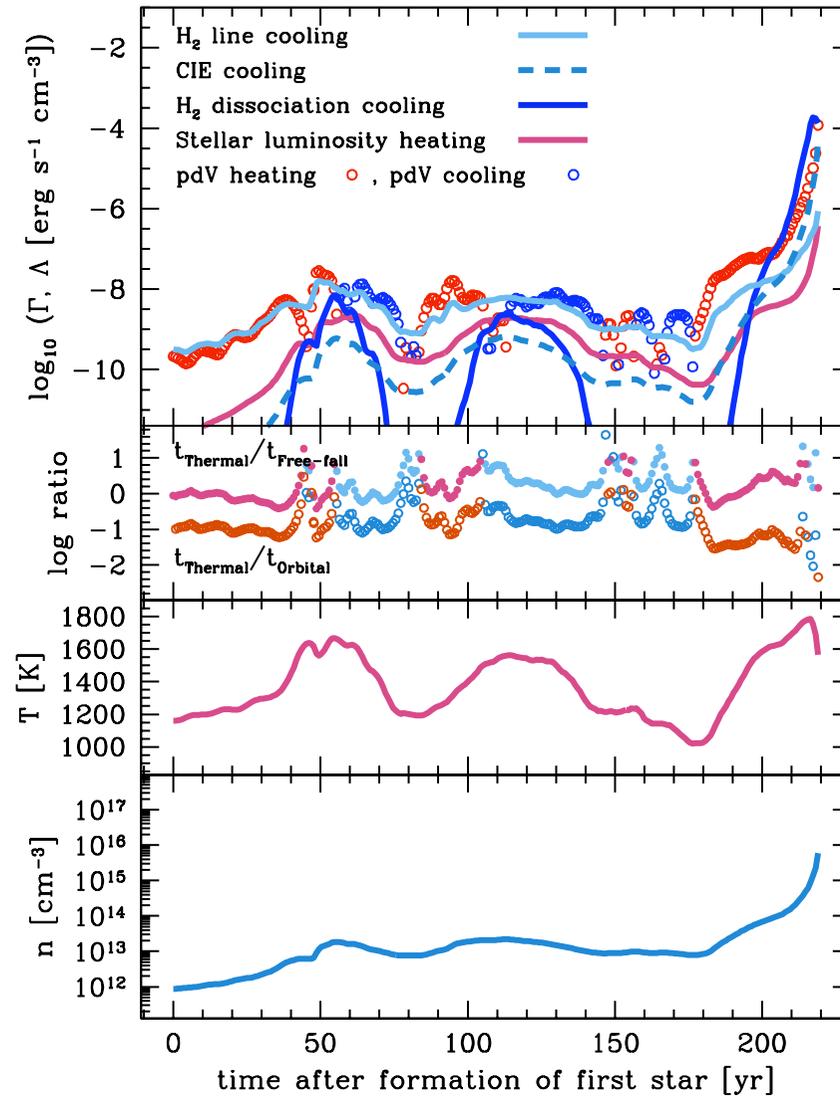
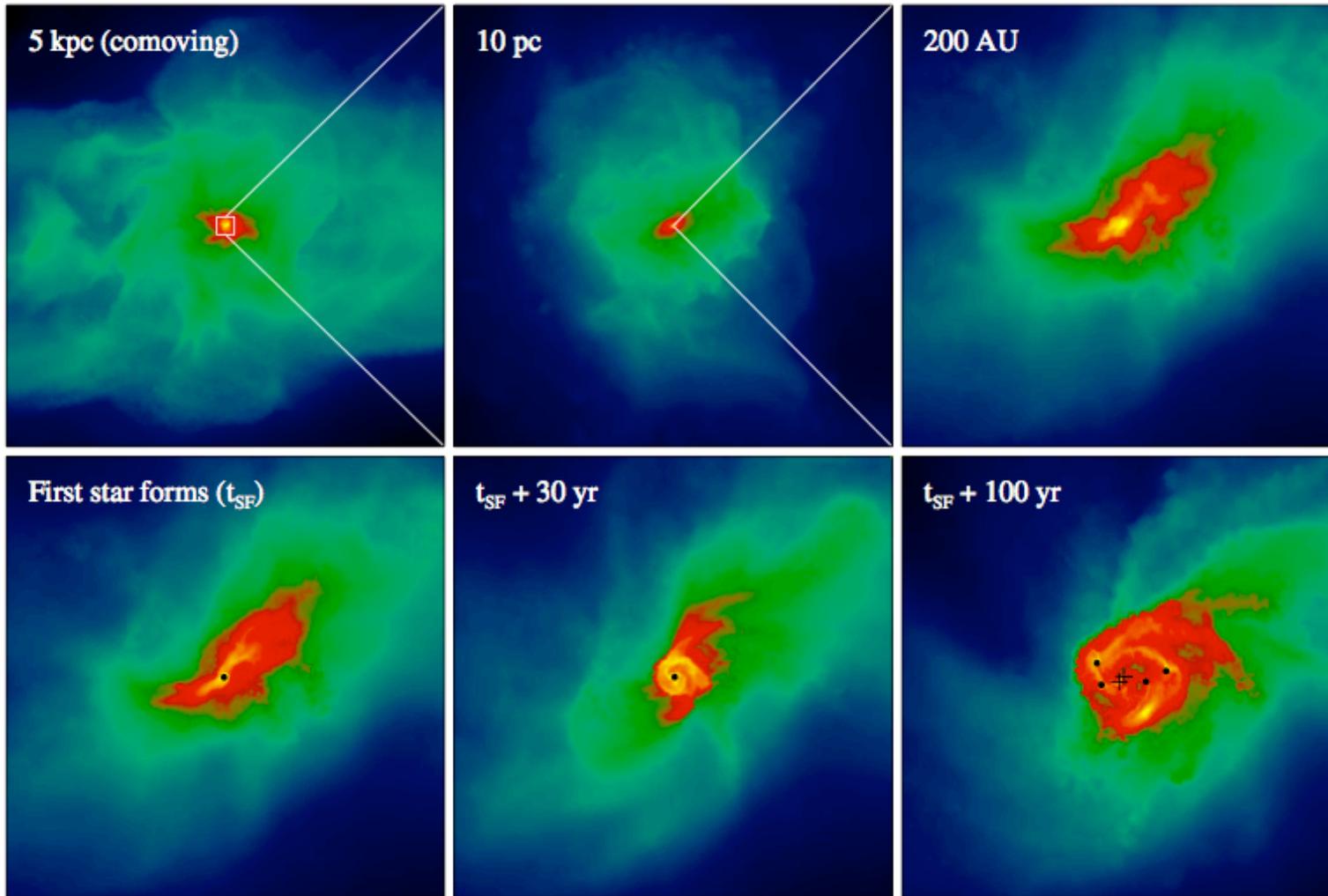
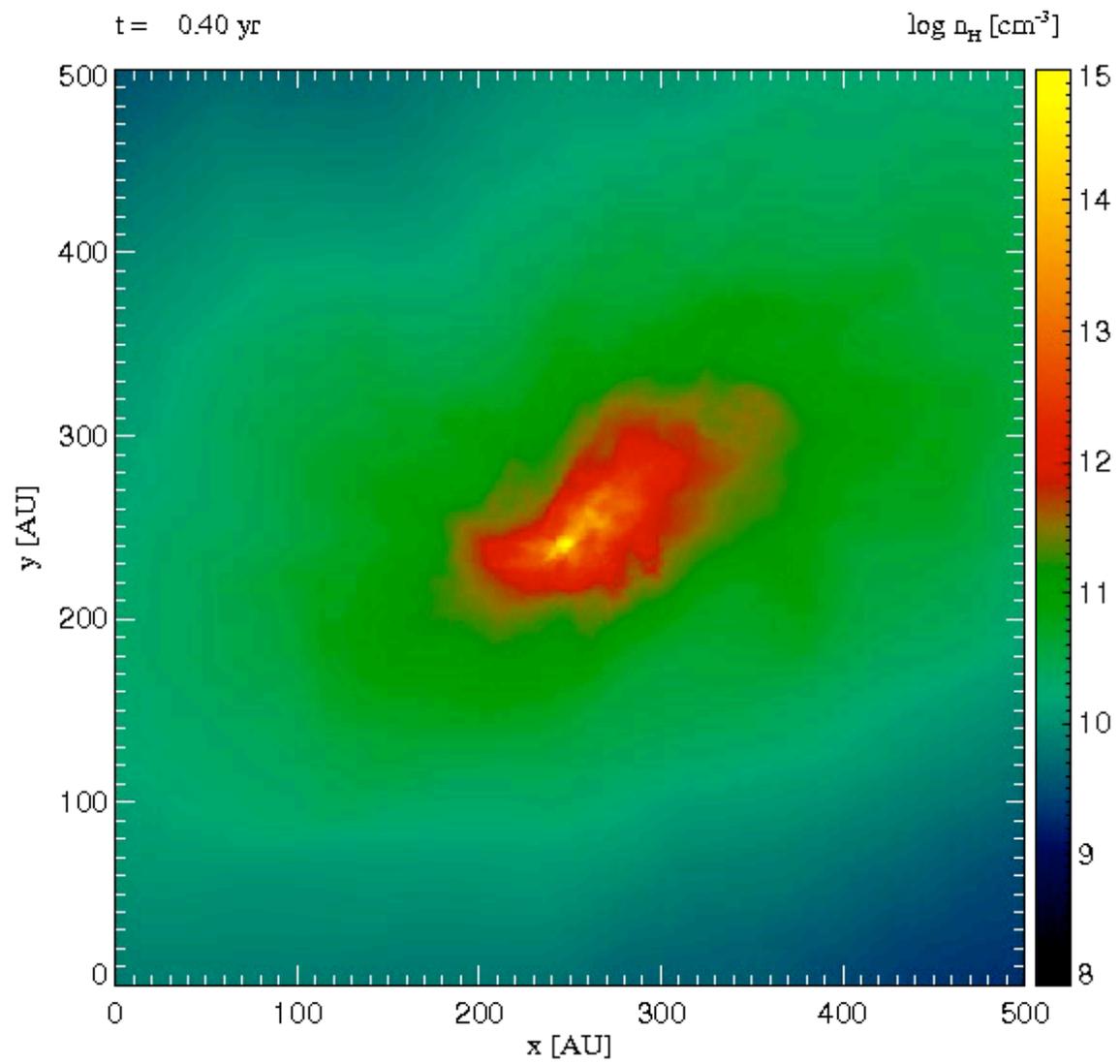


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale,  $t_{\text{thermal}}$ , to the free-fall timescale,  $t_{\text{ff}}$ , for the gas that forms the second sink particle. Periods when the gas is cooling are indicated in blue, while periods when the gas is heating are indicated in red. Lower line: ratio of  $t_{\text{thermal}}$  to the orbital timescale,  $t_{\text{orbital}}$ , for the same set of SPH particles (c) Temperature evolution of the gas that forms the second sink (d) Density evolution of the gas that forms the second sink

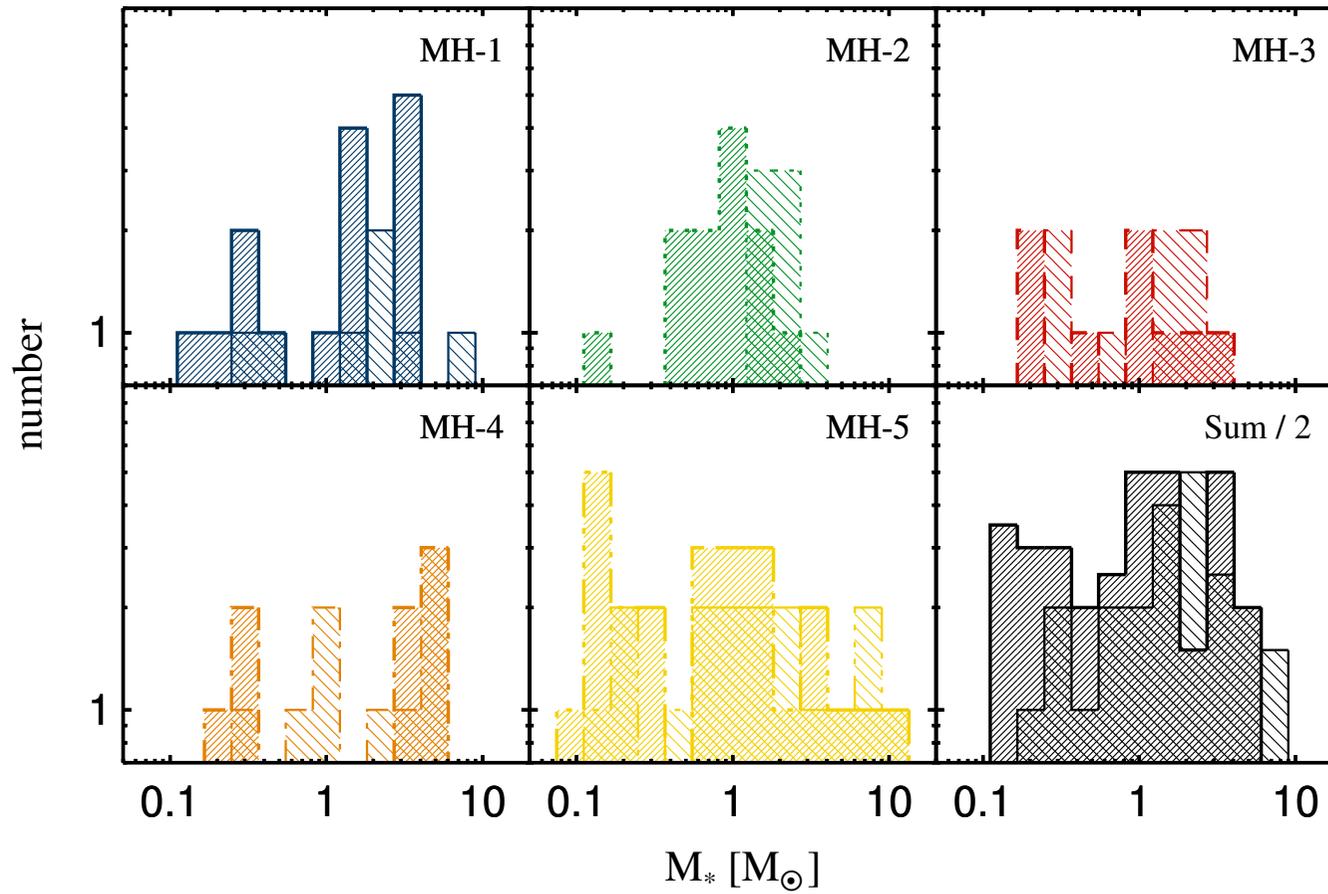
## Arepo study: surface density at different times



one out of five halos



# Arepo study: mass spectrum of fragments



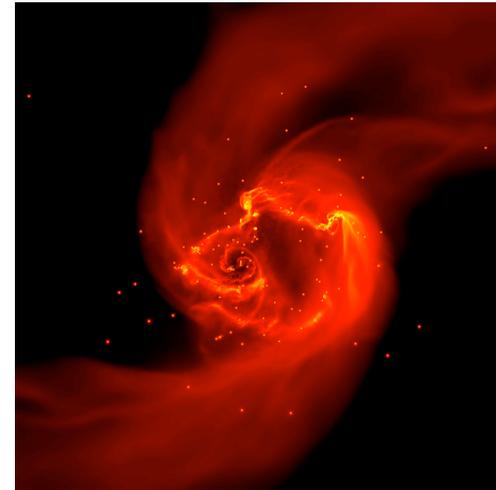
# primordial star formation

- just like in present-day SF, we expect

- *turbulence*
- *thermodynamics*
- *feedback*
- *magnetic fields*

to influence Pop III/II star formation.

- masses of Pop III stars still *uncertain* (surprises from new generation of high-resolution calculations that go beyond first collapse)
- disks unstable: Pop III stars should be *binaries* or *part of small clusters*
- effects of feedback less important than in present-day SF



# questions

- is claim of Pop III stars with  $M \sim 0.5 M_{\odot}$  really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback
- how would we find them?
  - spectral features
- where should we look?
- what about magnetic fields?

