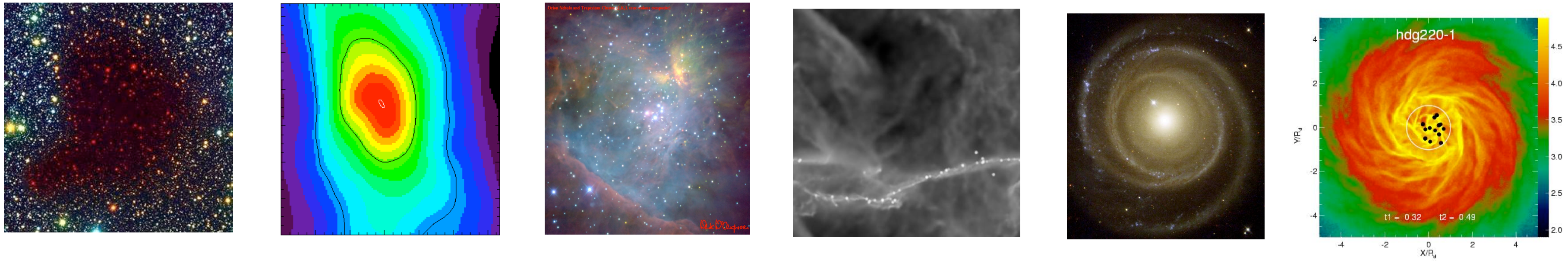
ISM Turbulence and Star Formation



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Collaborators

many thanks to...

- Javier Ballesteros-Paredes (UNAM, Morelia)
- Robi Banerjee (ZAH/ITA)
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- Christoph Federrath (ZAH/ITA)
- Simon Glover (AIP, Potsdam)
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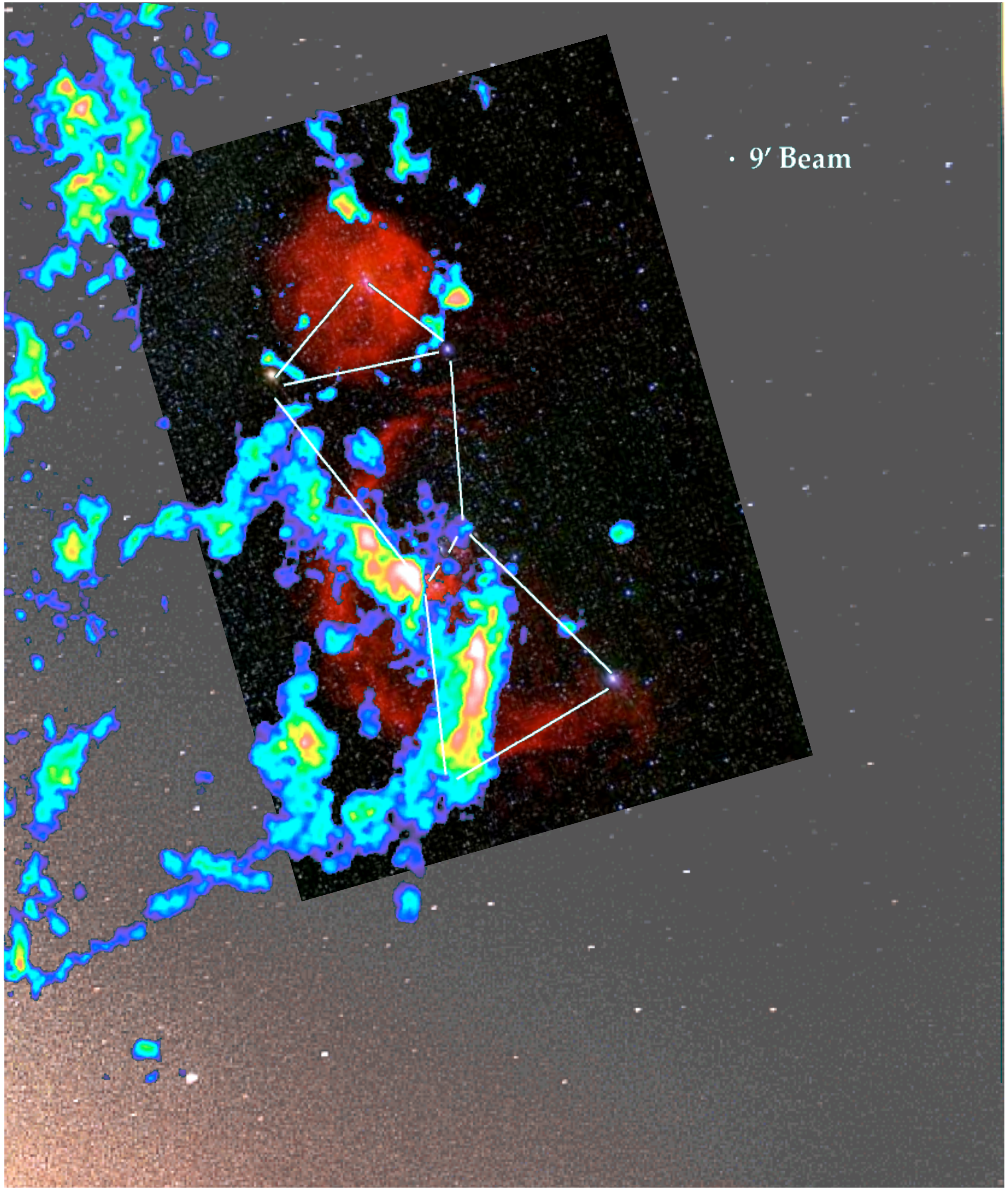
- Mordecai Mac Low (ANMH, New York)
- Marco Spaans (Kapteyn Institute)
- Enrique Vazquez-Semadeni (UNAM, Morelia)

Agenda

- phenomenology
  - Orion
  - Taurus
- interplay between gravity and turbulence
- examples and predictions
  - star cluster formation: dynamics
  - star cluster formation: thermodynamics
    --> stellar initial mass function

phenomenology

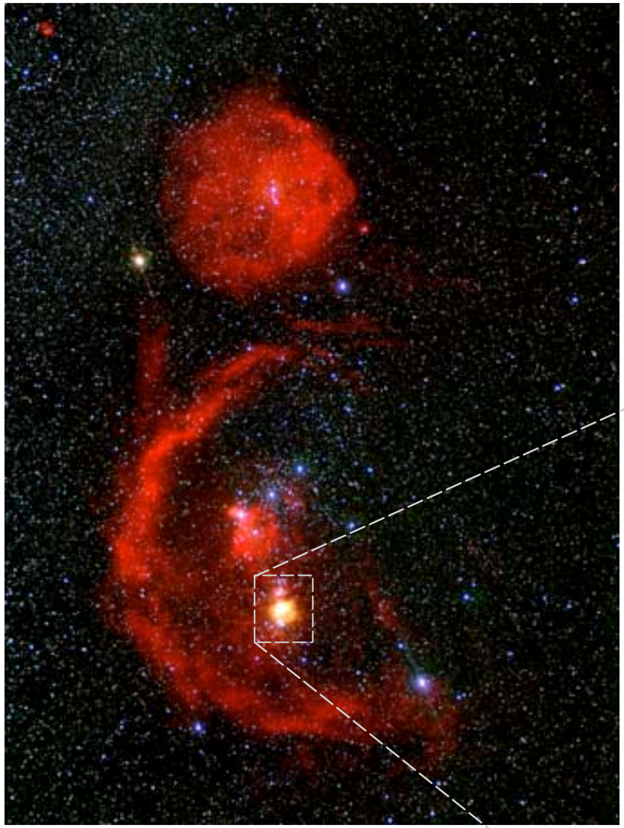


Star formation in Orion

We see

- *Stars* (in visible light)
- Atomic hydrogen (in Hα -- red)
- Molecular hydrogen H_2 (radio emission -- color coded)

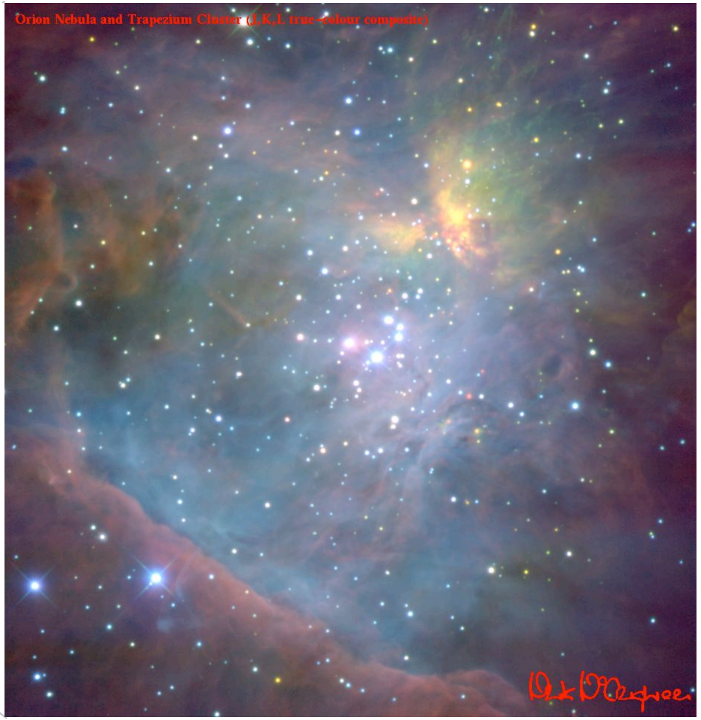
Local star forming region: The Trapezium Cluster in Orion



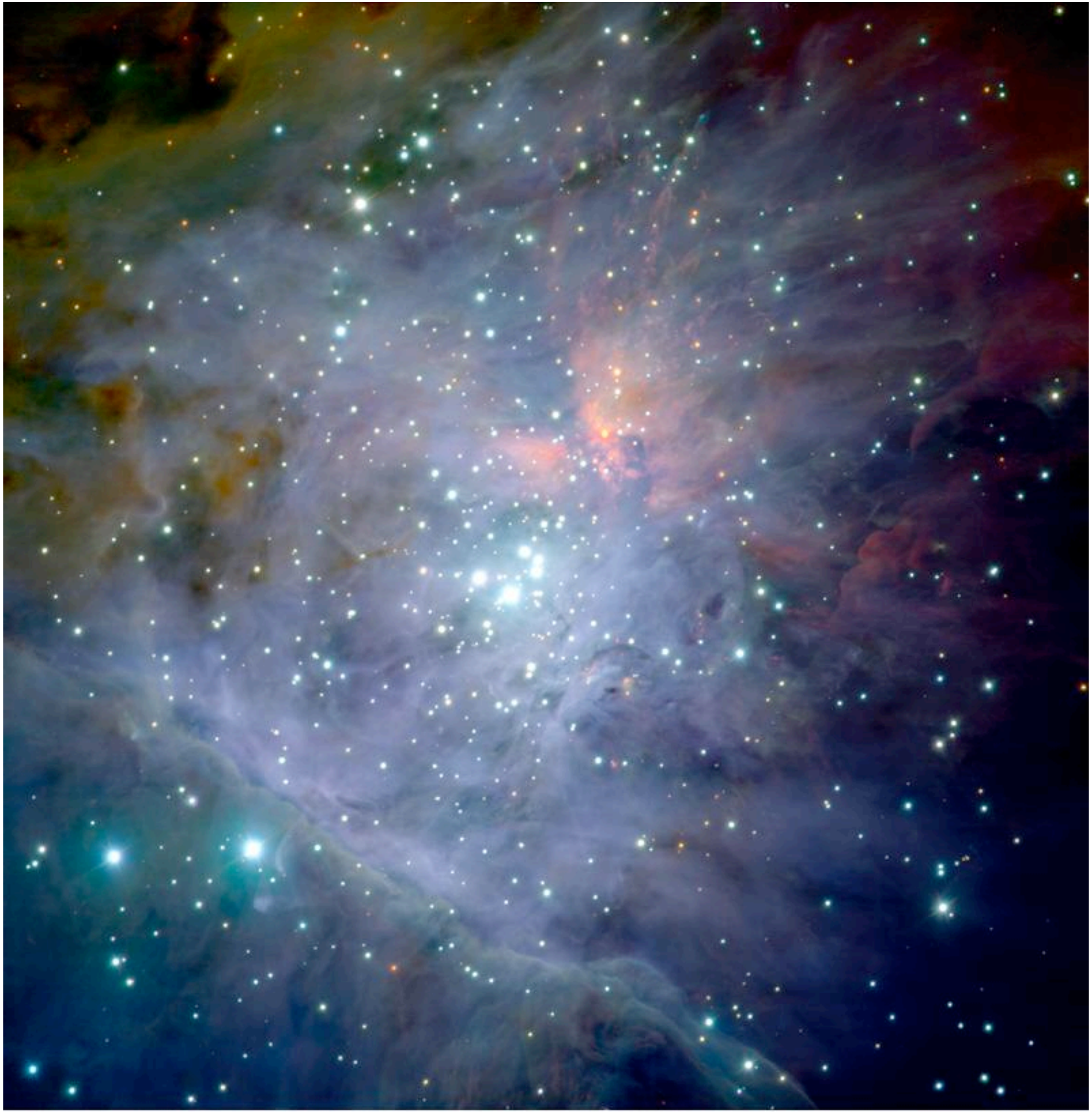
Orion molecular cloud

The Orion molecular cloud is the birth- place of several young embedded star clusters.

The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster



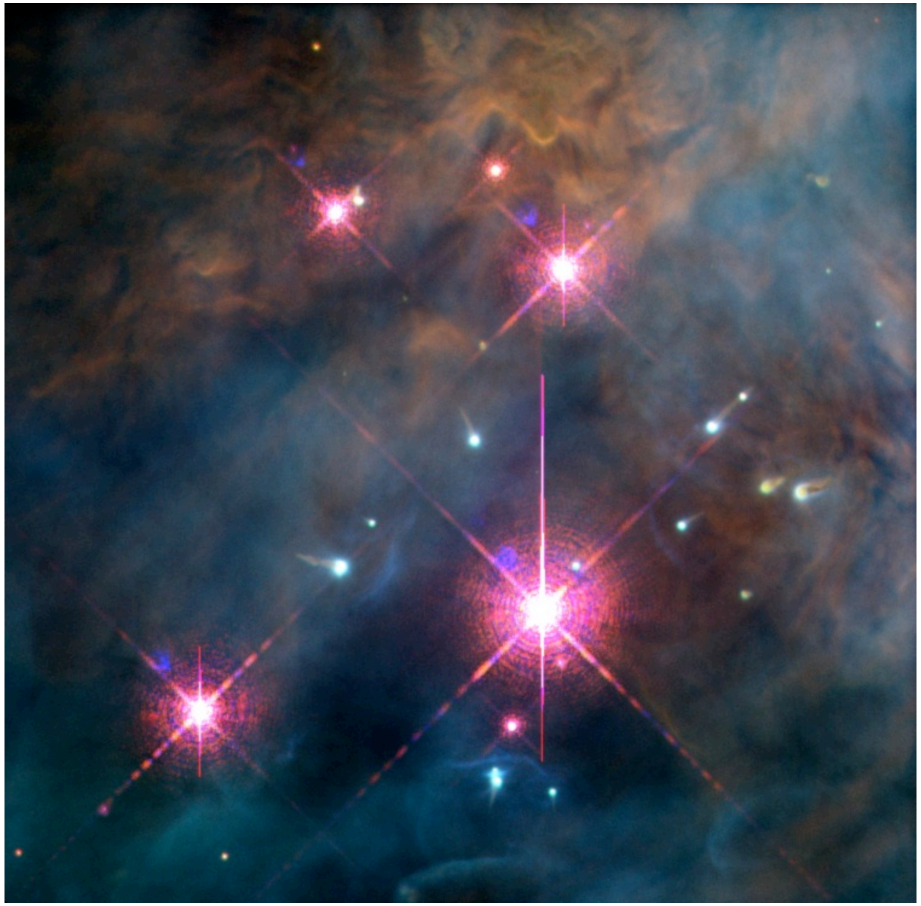
Trapezium Cluster

(detail)

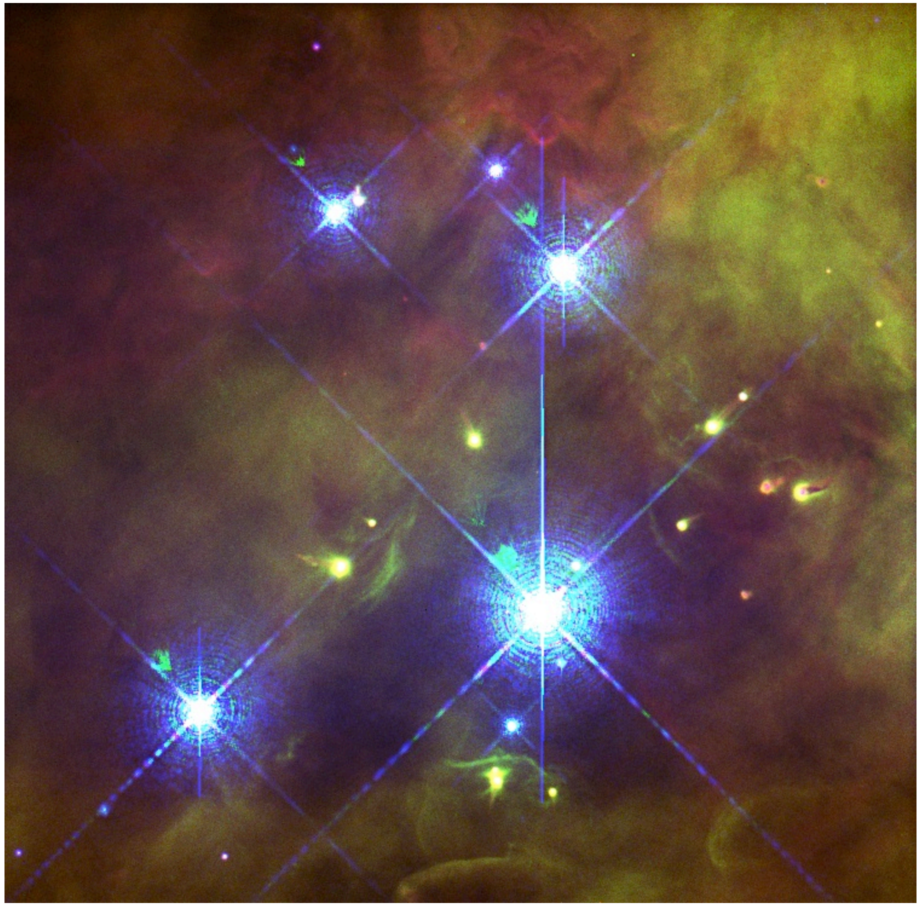
- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

(color composite J,H,K
by M. McCaughrean,
VLT, Paranal, Chile)

Trapezium Cluster: Central Region



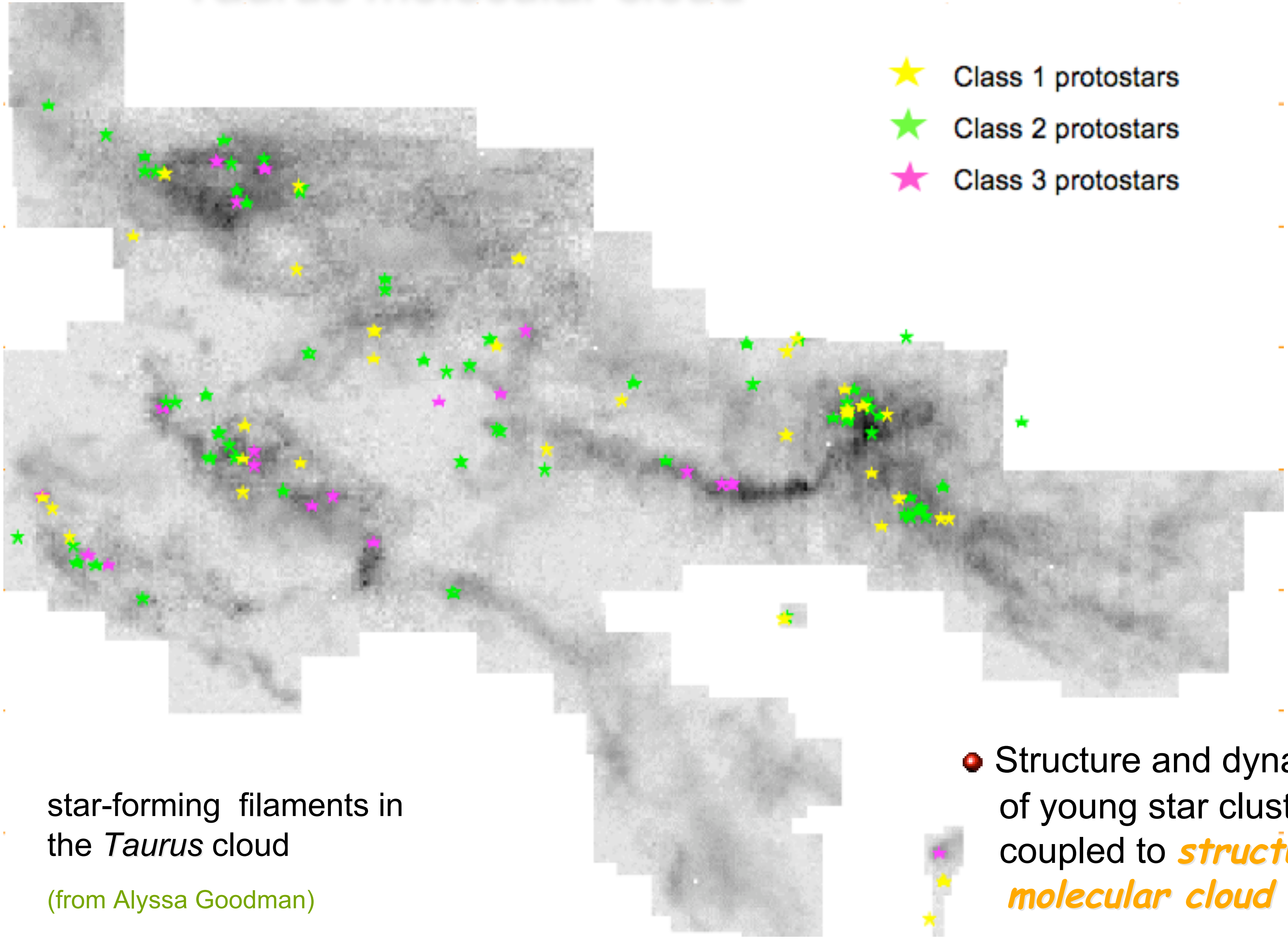
Ionizing radiation from central star
Θ1C Orionis



Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(images: Doug Johnstone et al.)

Taurus molecular cloud



star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

- Structure and dynamics of young star clusters is coupled to ***structure of molecular cloud***

theoretical approach

Gravoturbulent star formation

- Idea:

Star formation is controlled by interplay between gravity and supersonic turbulence!

- Dual role of turbulence:
  - *stability on large scales*
  - *initiating collapse on small scales*

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651;
or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)

Gravoturbulent star formation

- Idea:

Star formation is controlled
by interplay between
gravity and
supersonic turbulence!

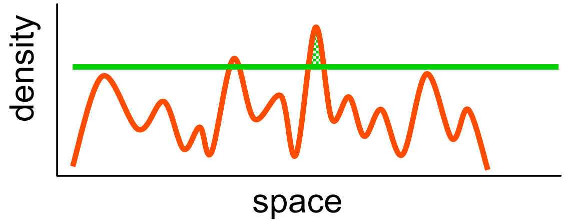
- Validity:

This hold on *all* scales and applies to build-up of stars and star clusters within molecular clouds as well as to the formation of molecular clouds in galactic disk.

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651;
or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)

Gravoturbulent star formation

- interstellar gas is highly *inhomogeneous*



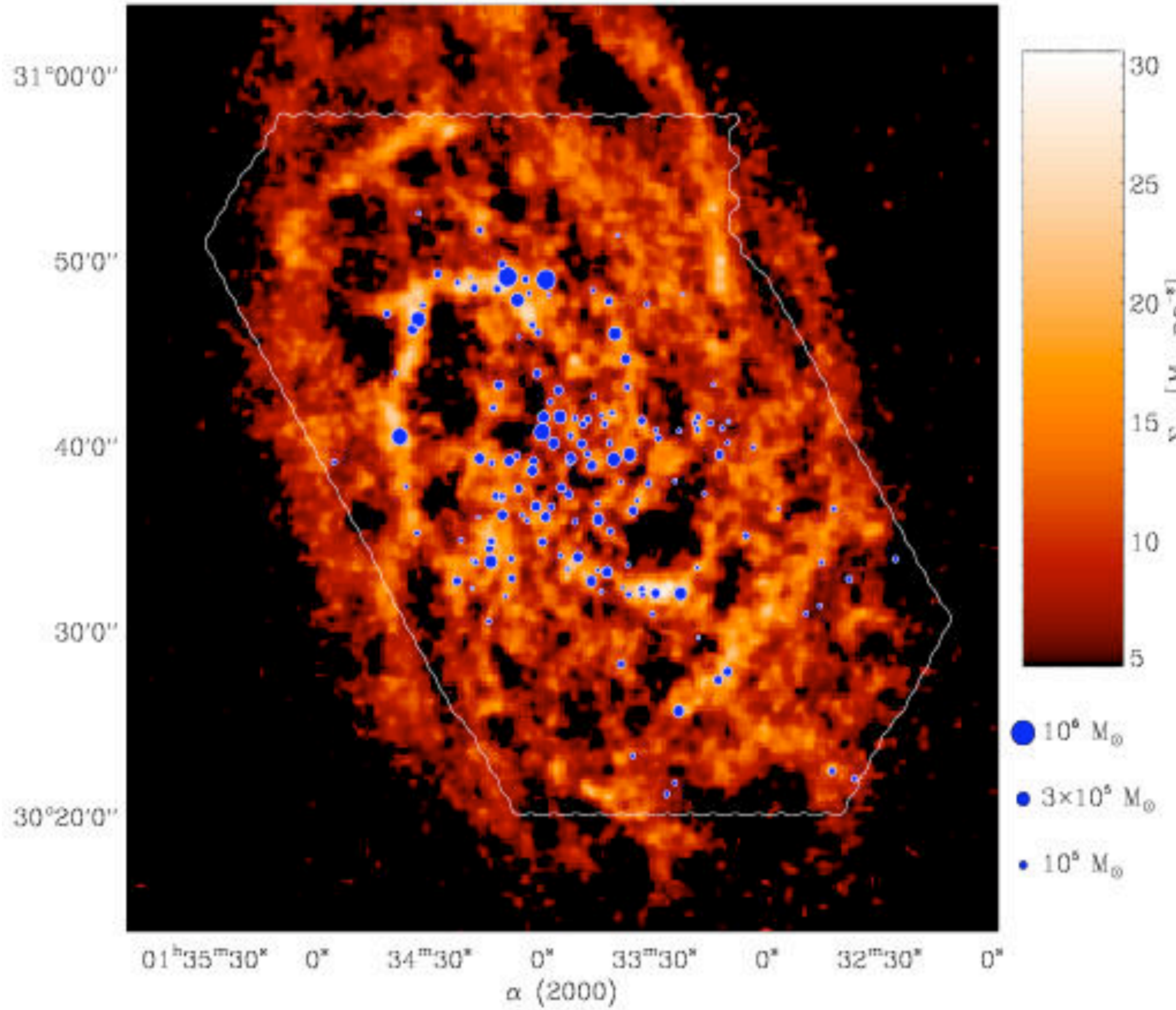
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

→ ***GRAVOTUBULENT FRAGMENTATION***

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

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

molecular cloud formation

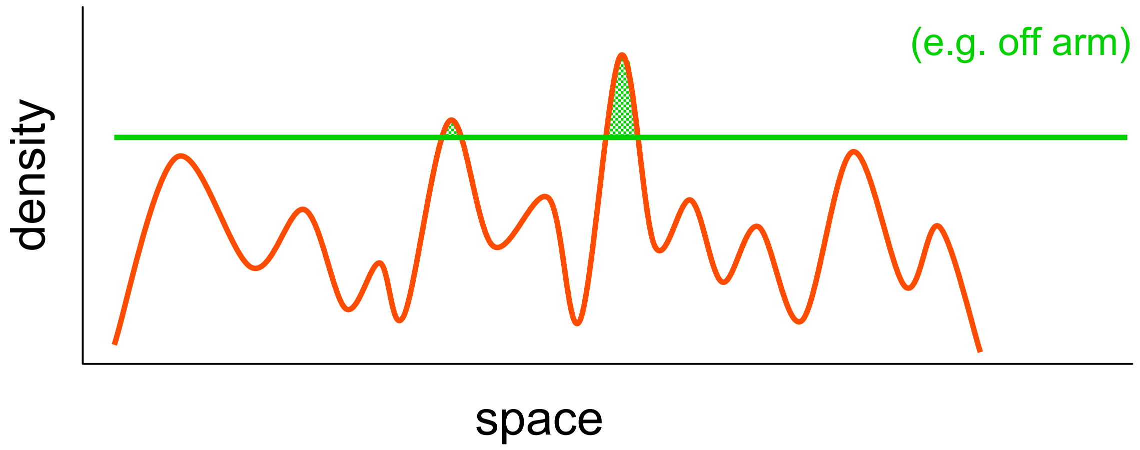


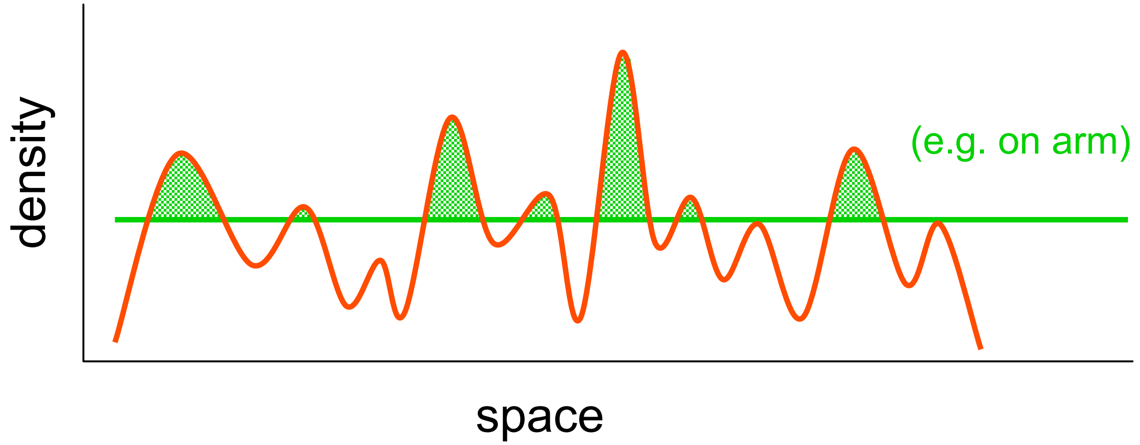
Thesis:

Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations.

(Deul & van der Hulst 1987, Blitz et al. 2004)

correlation with large-scale perturbations





density/temperature fluctuations in warm atomar ISM are caused by *thermal/gravitational instability* and/or *supersonic turbulence*

some fluctuations are *dense* enough to *form H$_2$* within "*reasonable time*"

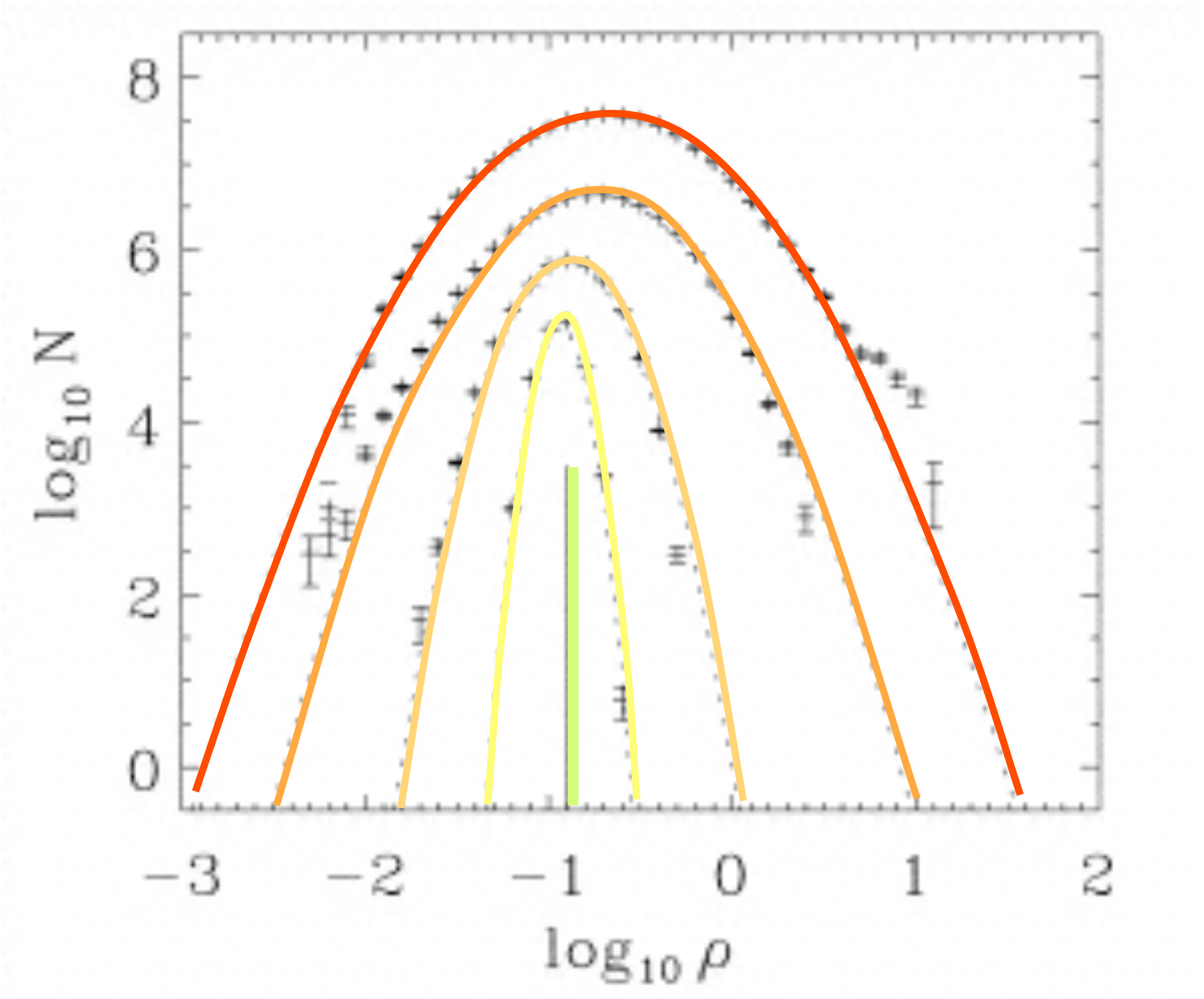
→ *molecular cloud*

(Glover & Mac Low 2007a,b)

external perturbations (i.e. potential changes) *increase* likelihood

(Dobbs & Bonnell 2006, Dobbs et al. 2007)

star formation on *global* scales



probability distribution function of the density (*ρ-pdf)*

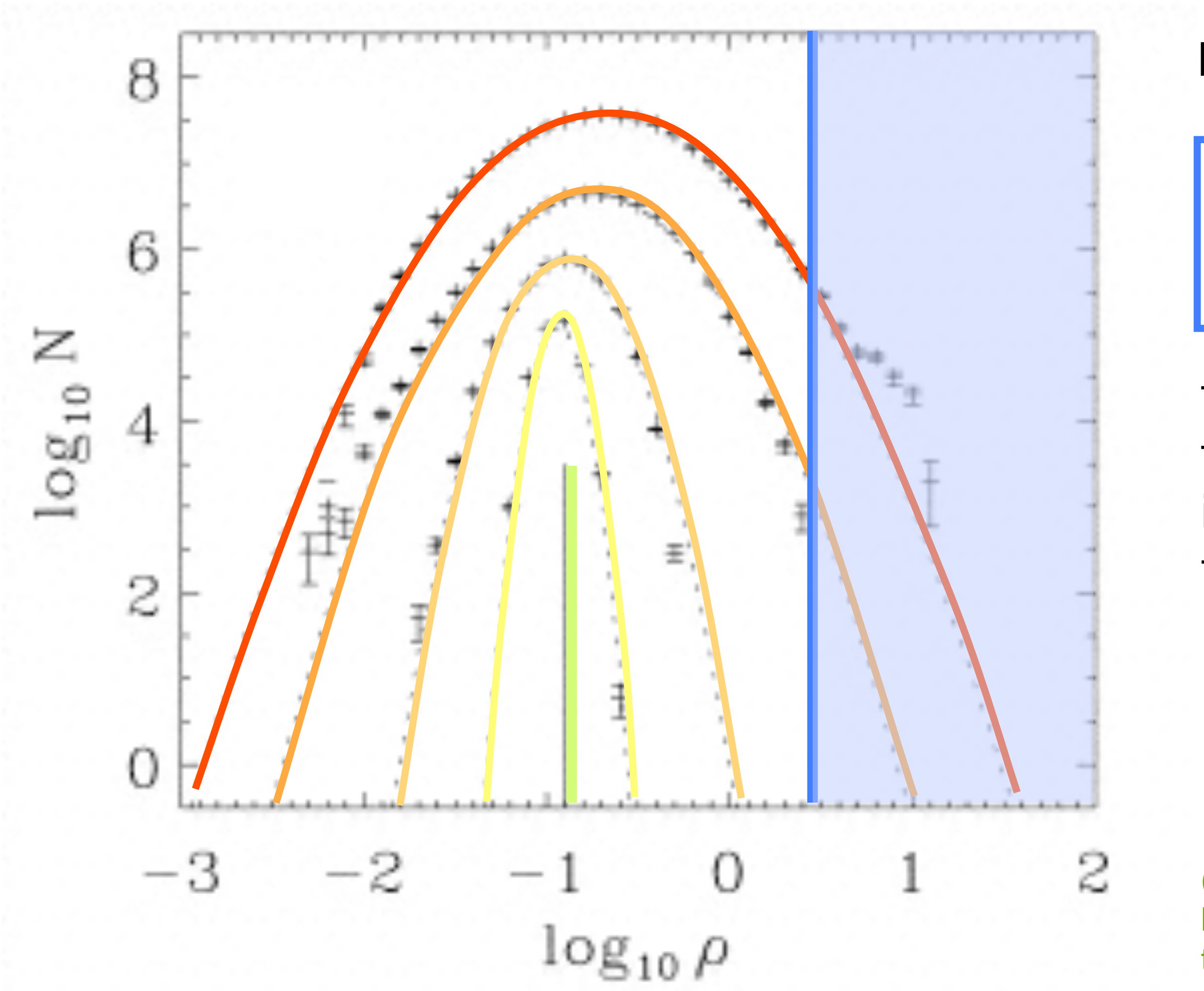
varying rms Mach numbers:

M1 > M2 > M3 > M4 > 0

mass weighted ρ-pdf, each shifted by ΔlogN=1

(from Klessen, 2001; also Gazol et al. 2005, Mac Low et al. 2005)

star formation on *global* scales



mass weighted ρ-pdf, each shifted by ΔlogN=1

(rate from Hollenback, Werner, & Salpeter 1971)

H_2 formation rate:

$$\boxed{\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}}$$

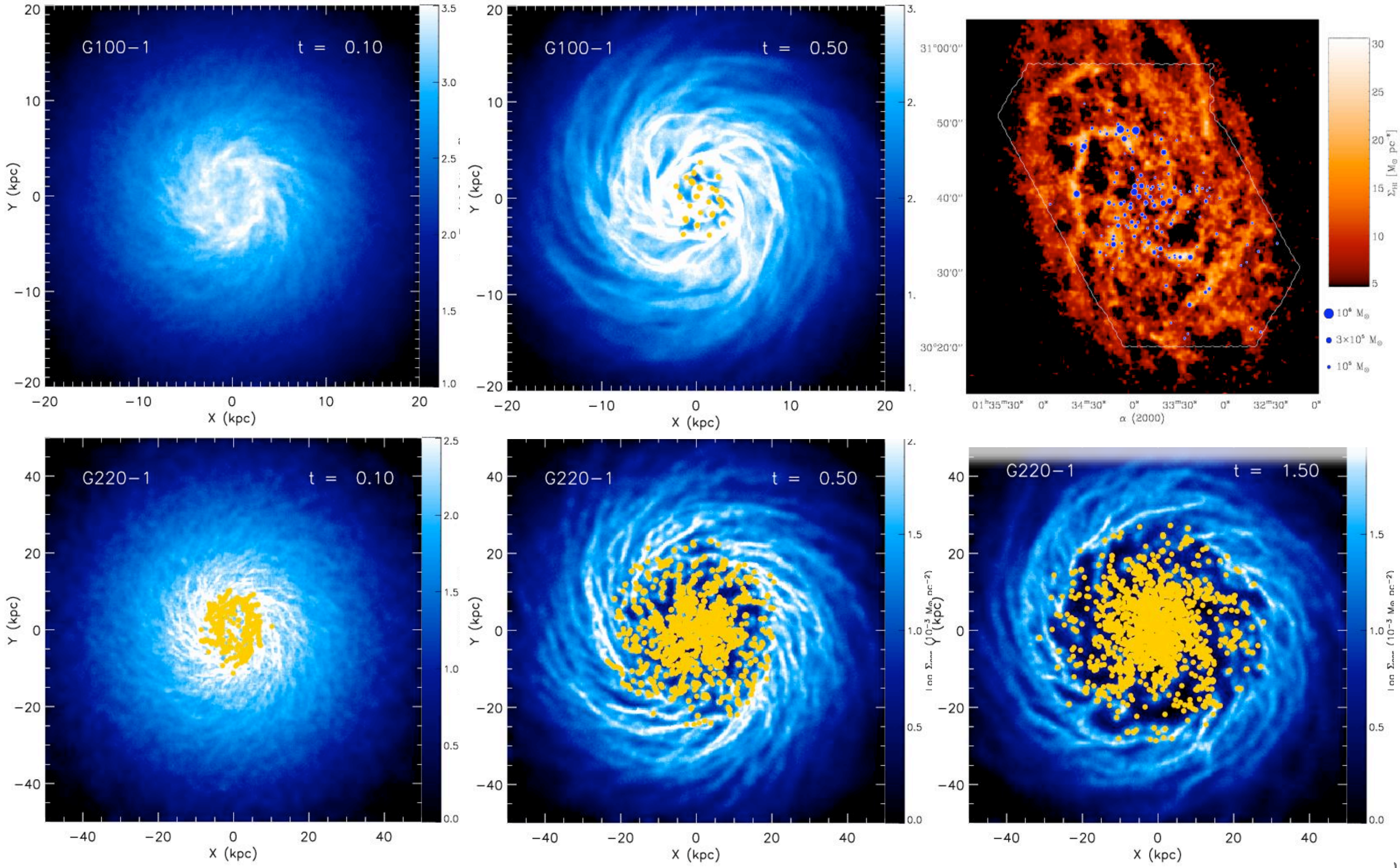
for $n_H \geq 100\ \mathrm{cm}^{-3}$, H_2 forms within 10Myr, this is about the lifetime of typical MC's.

in turbulent gas, the H_2 fraction can become very high on short timescale

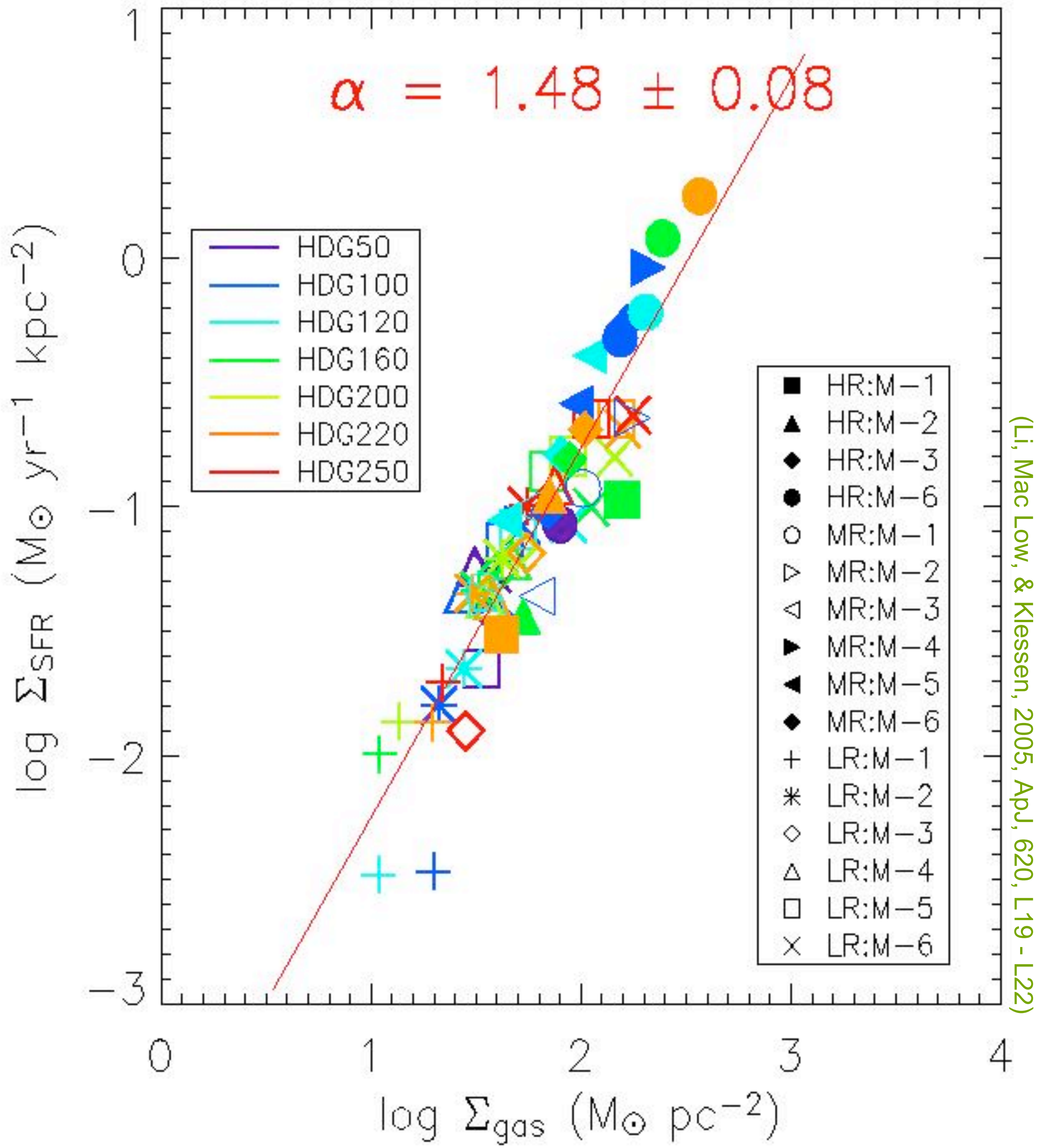
(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

modeling galactic SF

SPH calculations of self-gravitating disks of stars and (isothermal) gas in dark-matter potential, sink particles measure local collapse --> star formation



(Li, Mac Low, & Klessen, 2005, ApJ, 620,L19 - L22)



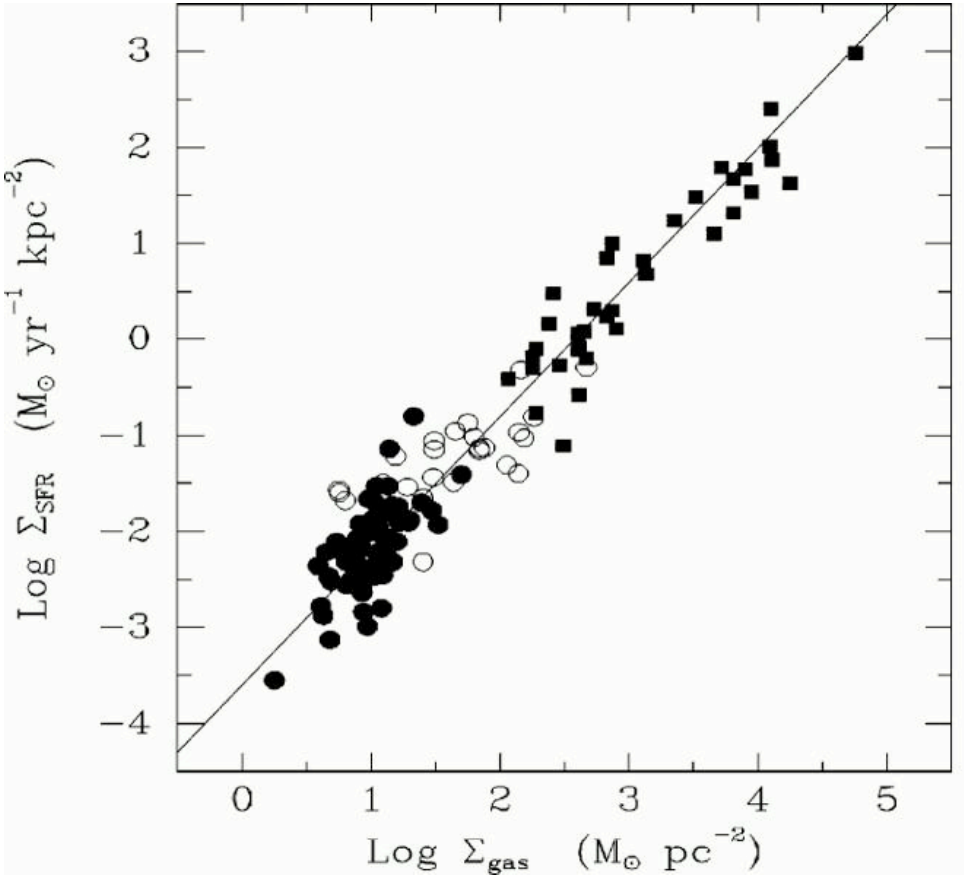
(Li, Mac Low, & Klessen, 2005, ApJ, 620, L19 - L22)

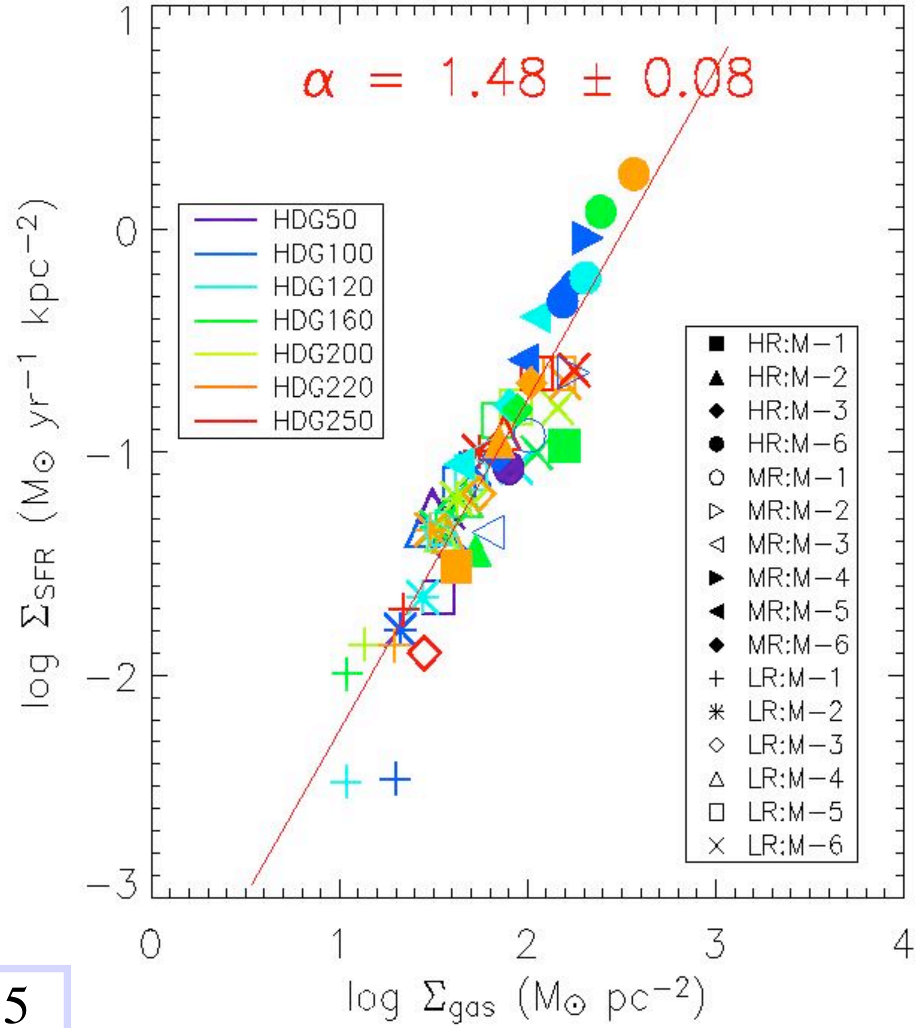
We find correlation between *star formation rate* and *gas surface density:*

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

global Schmidt law

observed Schmidt law



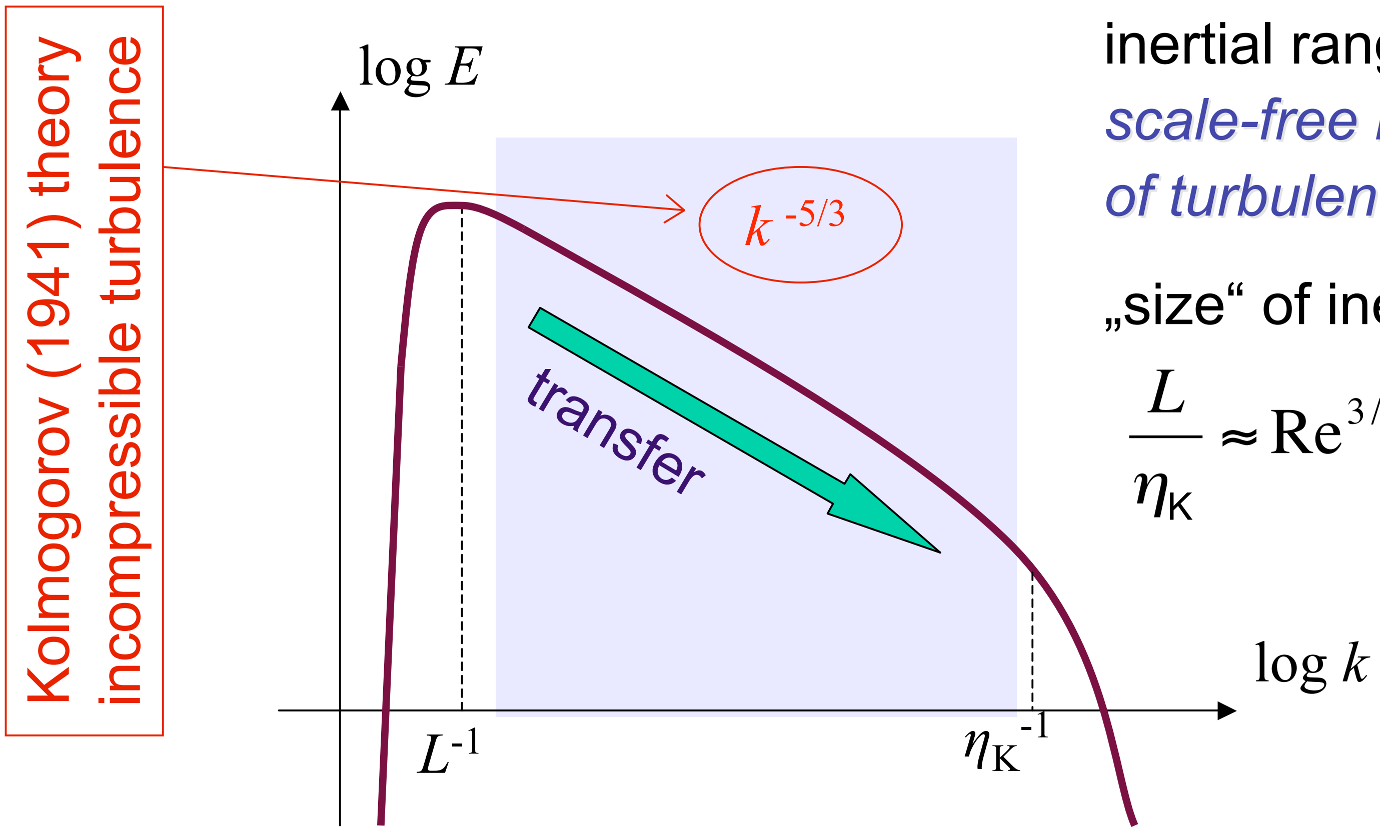


in both cases: $\boxed{\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}}$

(from Kennicutt 1998)

turbulence

Turbulent cascade



Kolmogorov (1941) theory
incompressible turbulence

inertial range:
scale-free behavior of turbulence

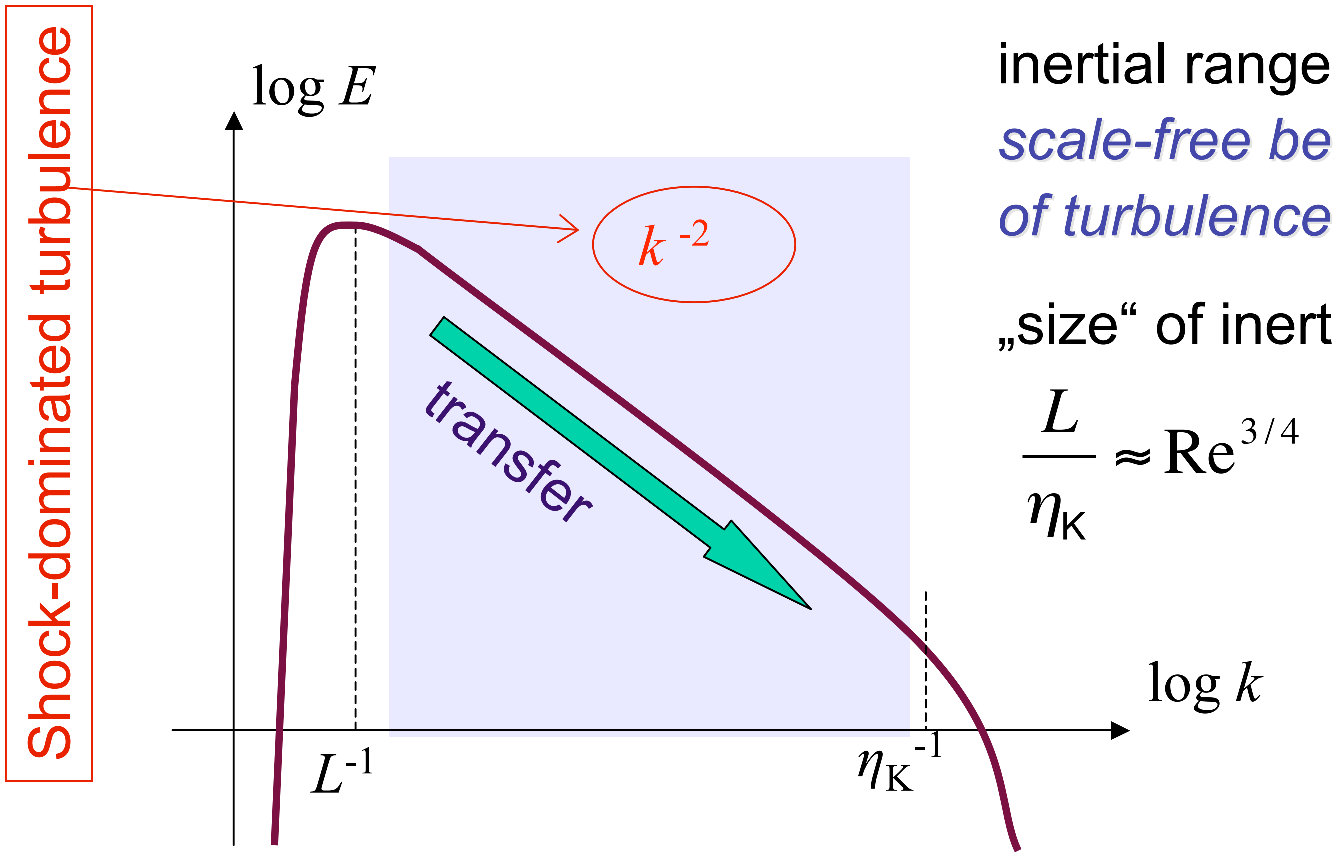
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:
scale-free behavior of turbulence

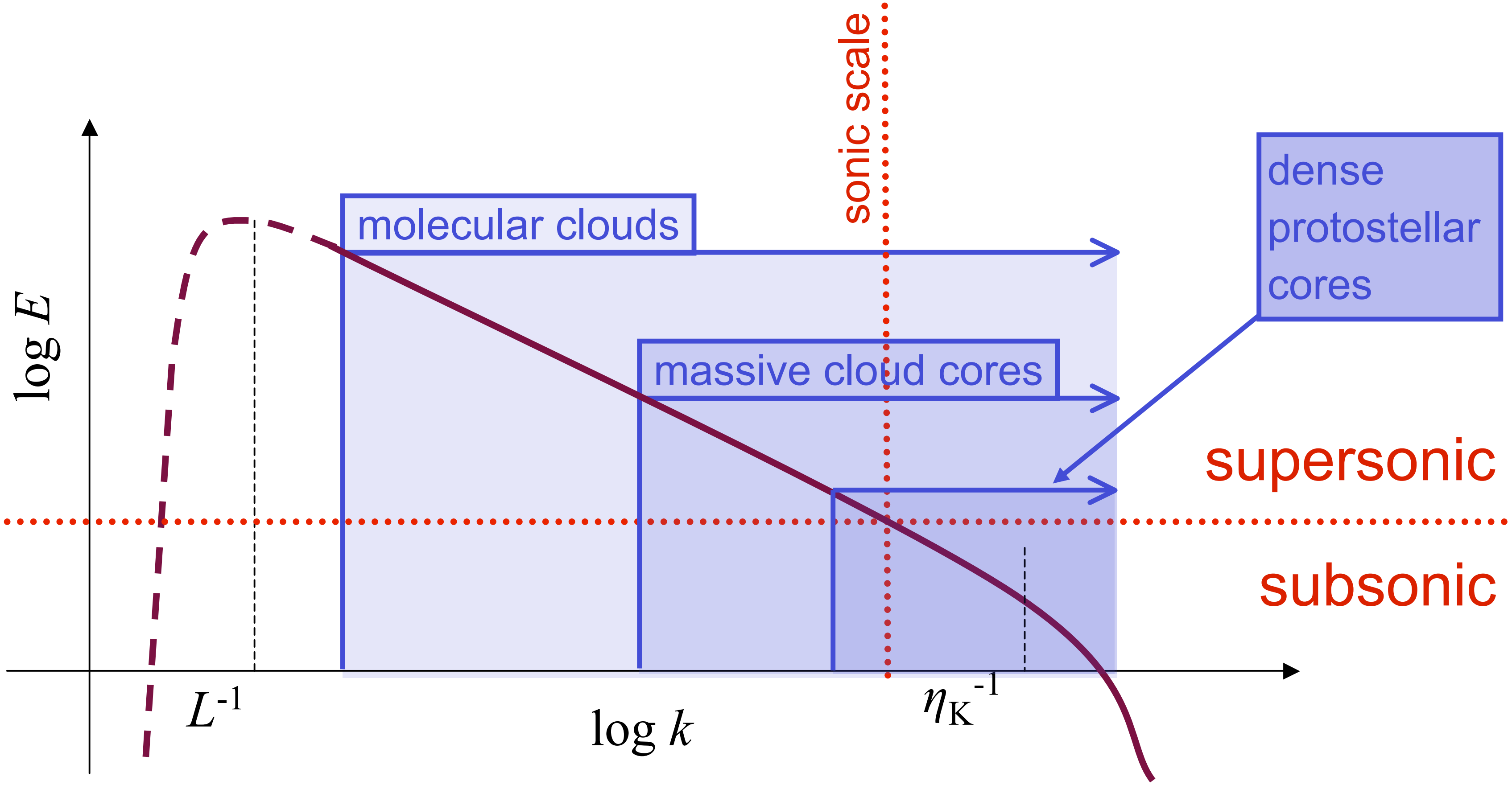
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM



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

$\sigma_{rms} << 1$ km/s
$\mathcal{M}_{rms} \leq 1$
$L \approx 0.1$ pc

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

Modeling supersonic turbulence

Gravoturbulent fragmentation of turbulent self-gravitating clouds

xy projection

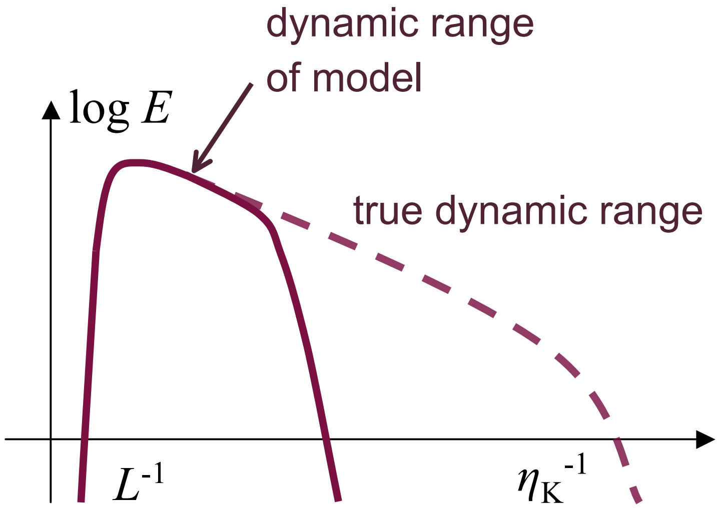
xz projection

yz projection

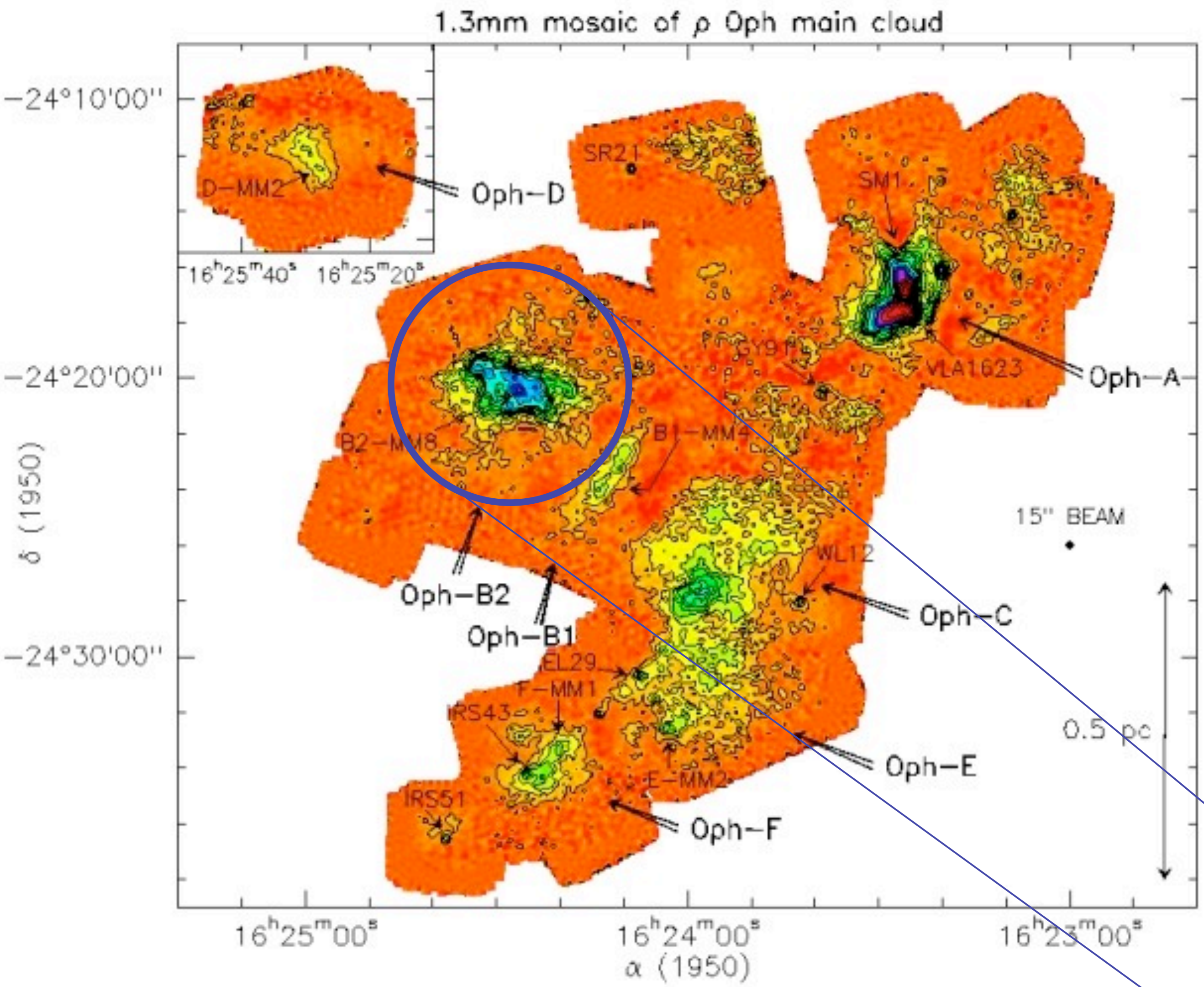
PROBLEM: all current numerical models have *small* Reynolds numbers (10^2-10^3 instead of 10^7-10^{10}) --> modeling crude oil instead of ISM turbulence

Large-eddy simulations

- We use ***LES*** to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: Re = LV/ν ***(*Re_{nature} *>>* Re_{model}*)***
  - dynamic range much smaller than true physical one
  - need *subgrid model* (in our case simple: only dissipation)
  - but what to do for more complex when processes on subgrid scale determine large-scale dynamics
    (chemical reactions, nuclear burning, etc)
  - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?



Density structure of MC's



(Motte, André, & Neri 1998)

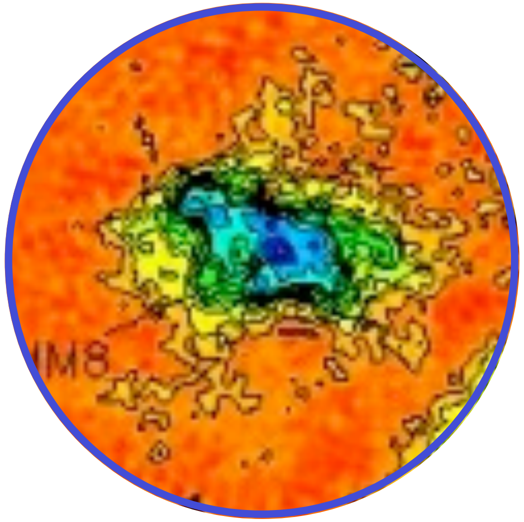
molecular clouds are highly inhomogeneous

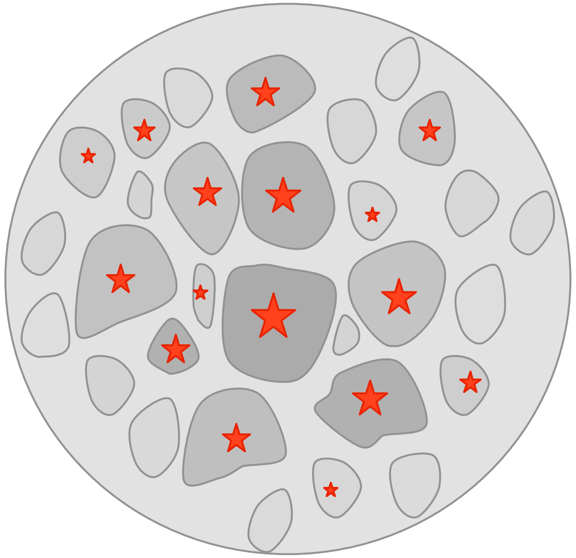
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

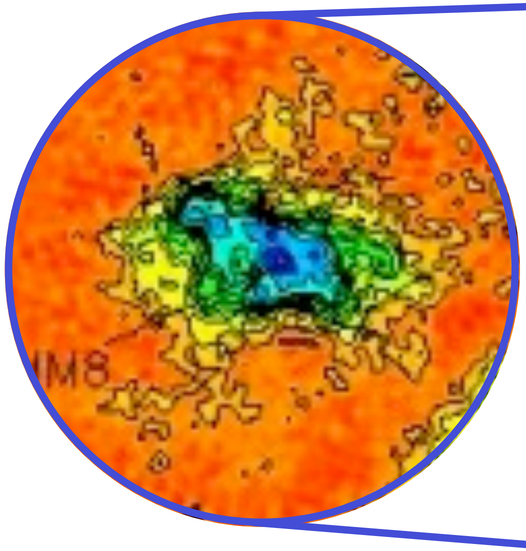


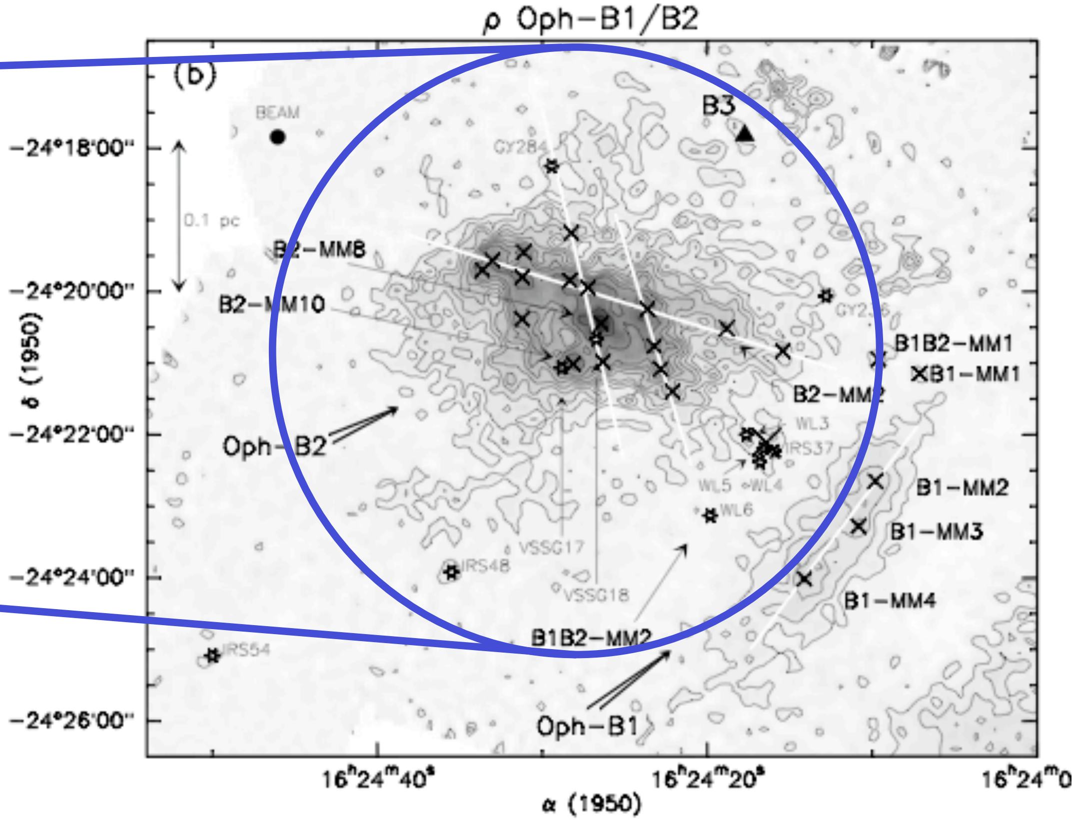


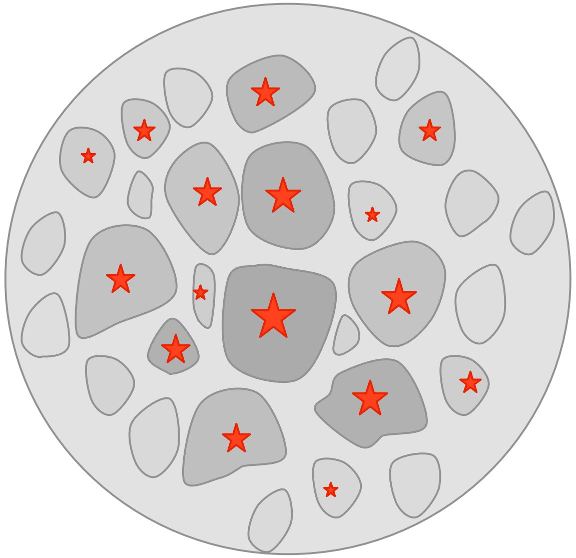
- How does this core evolve?
  Does it form one single massive star
  or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!
- 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





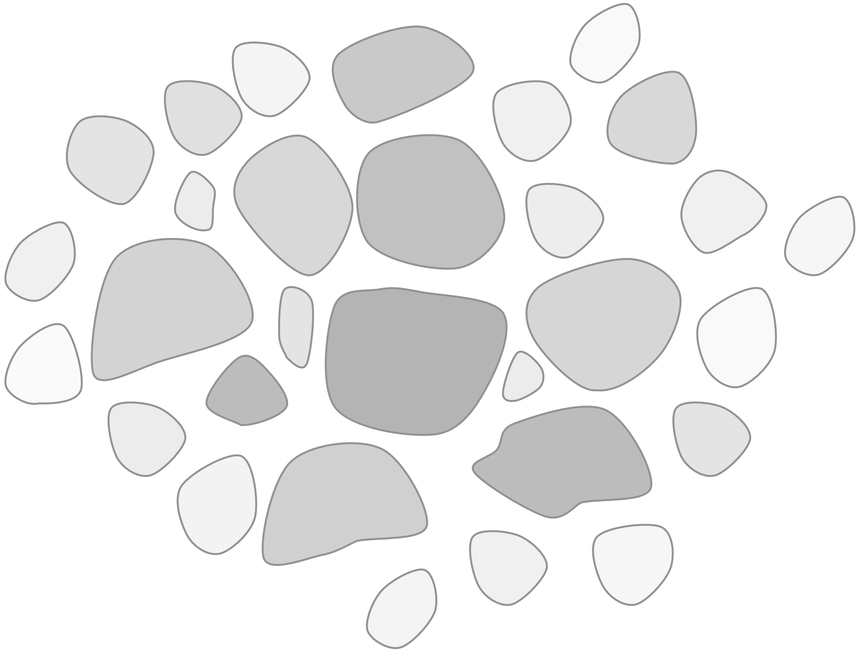


indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

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

--> individual cores do *not* interact

--> *collapse* of *individual* cores dominates *stellar mass growth*

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

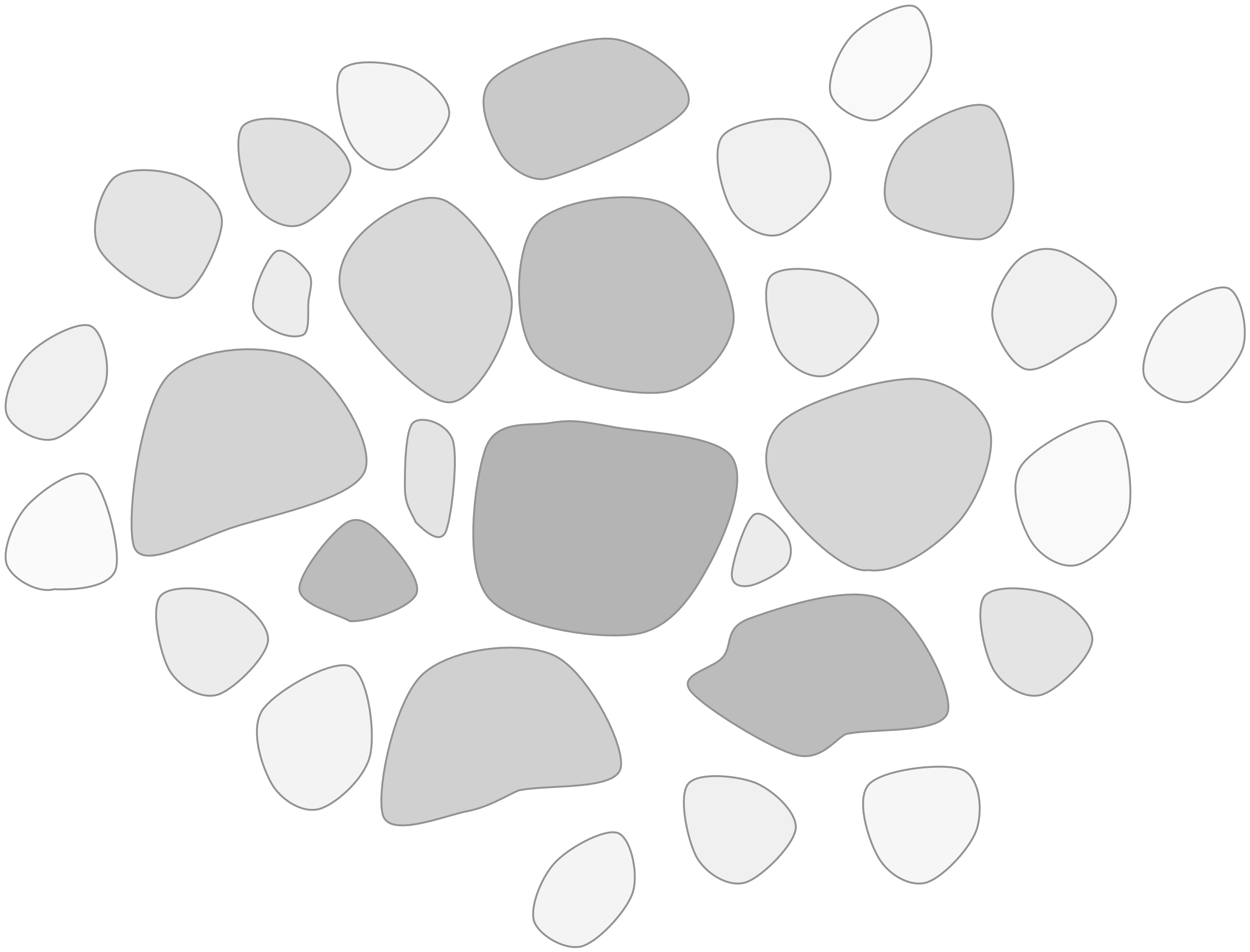
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

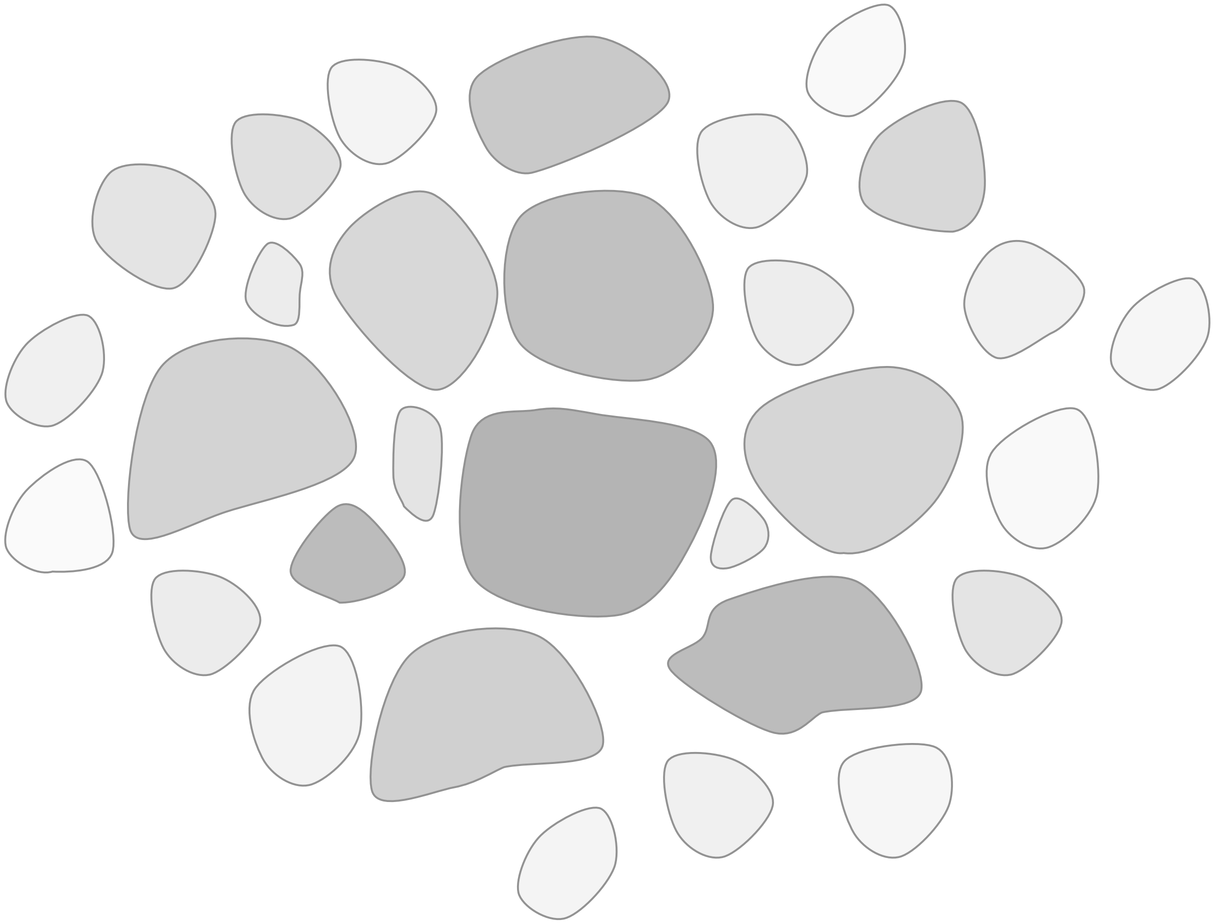
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

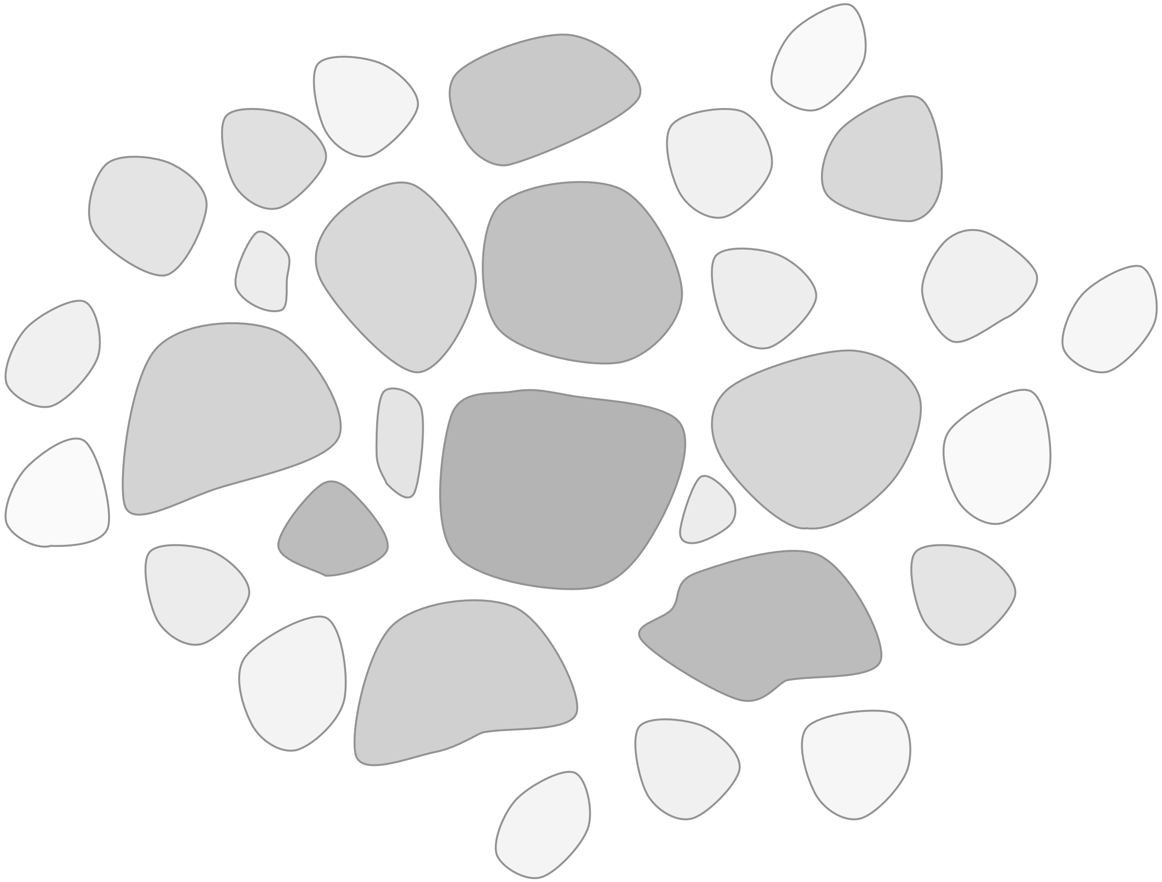
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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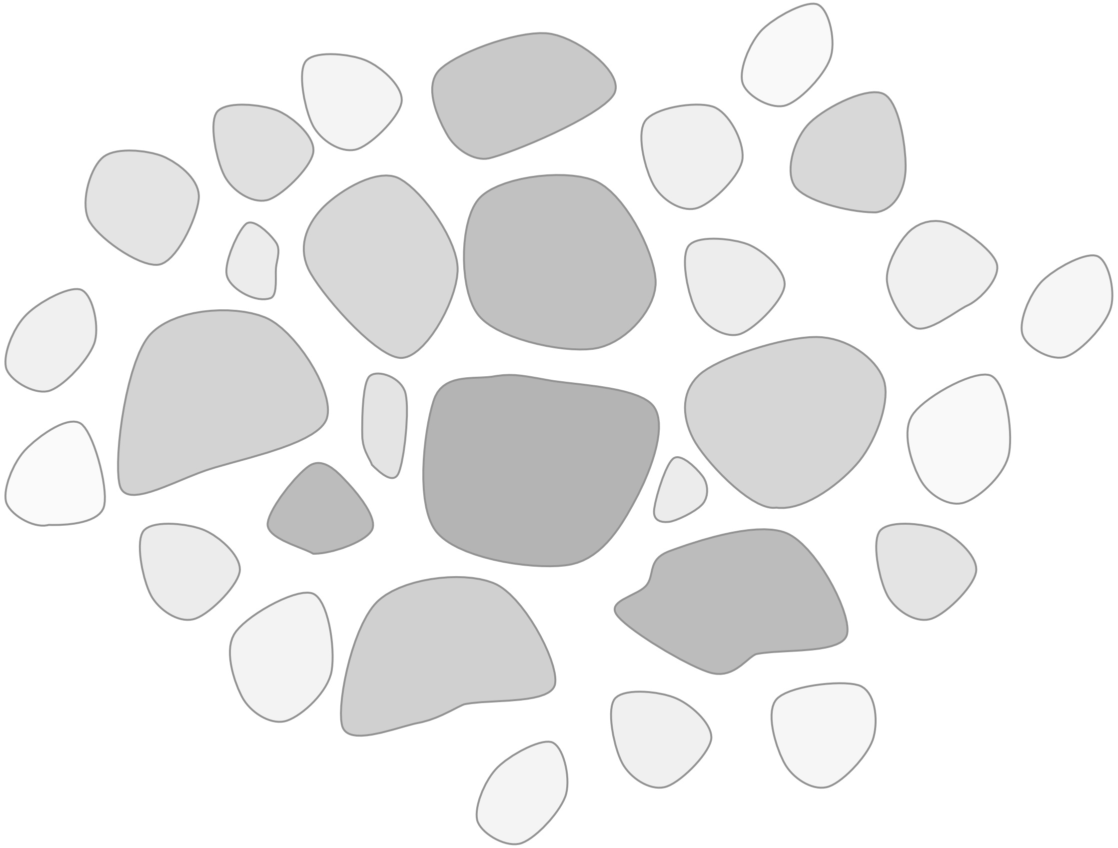
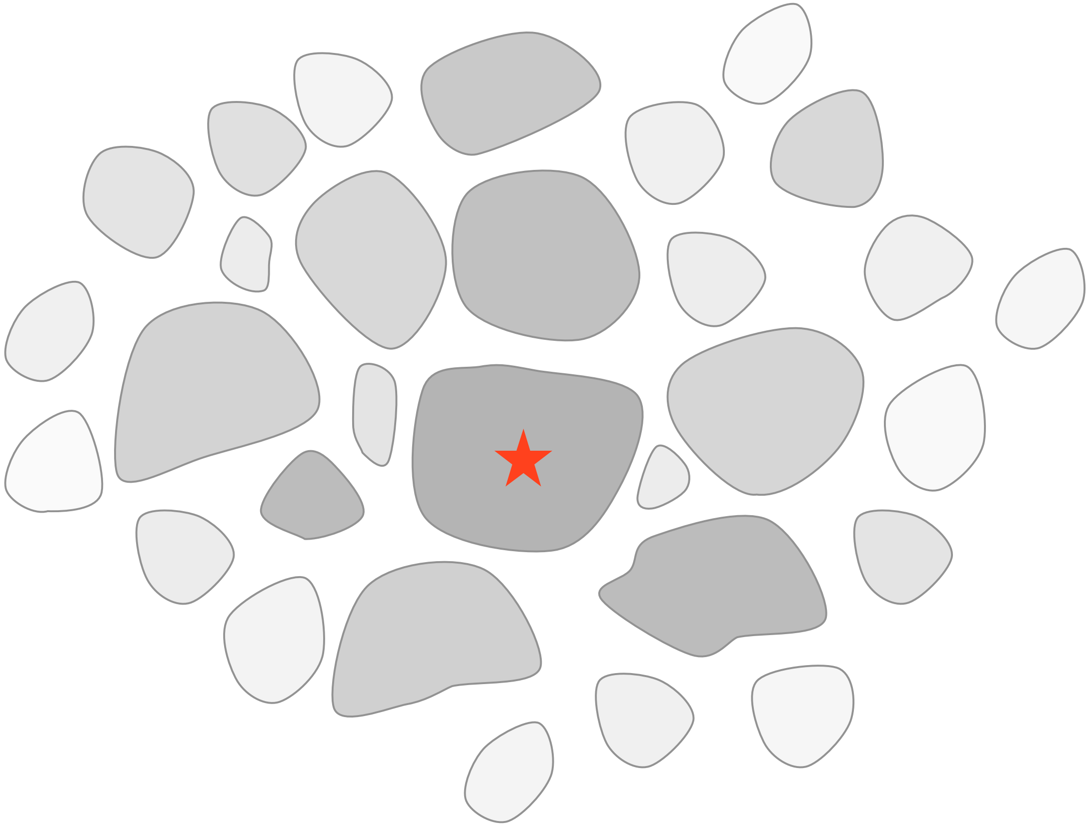


while region contracts, individual clumps collapse to form stars



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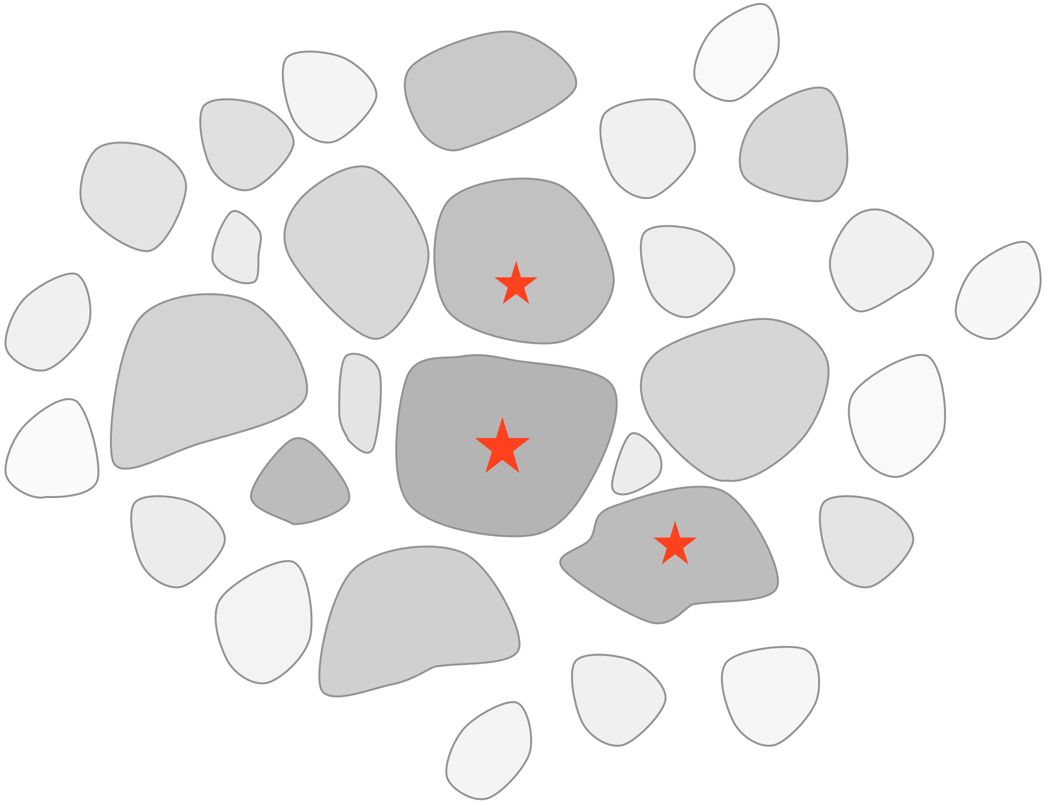
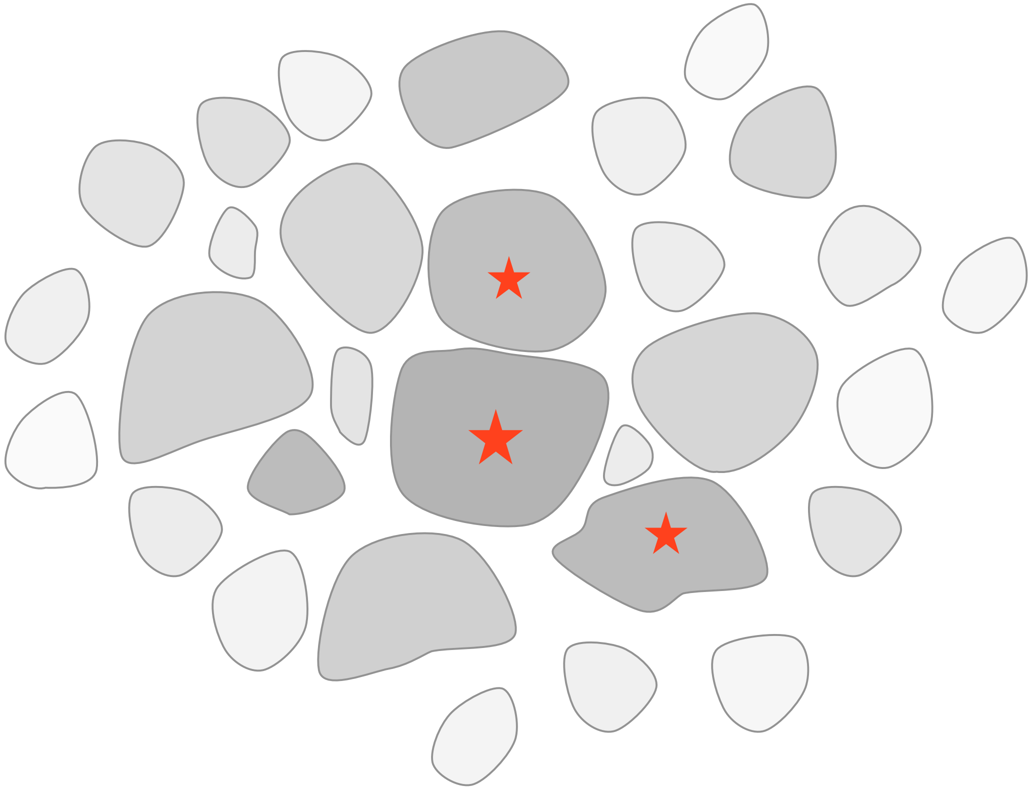


individual clumps collapse to form stars



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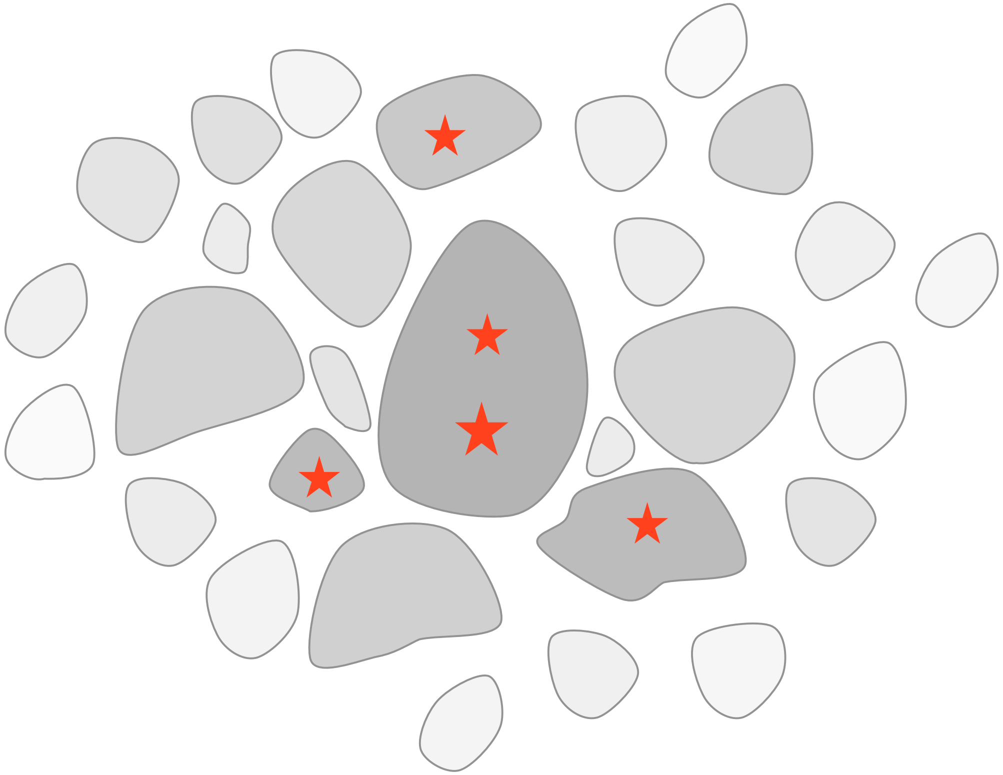
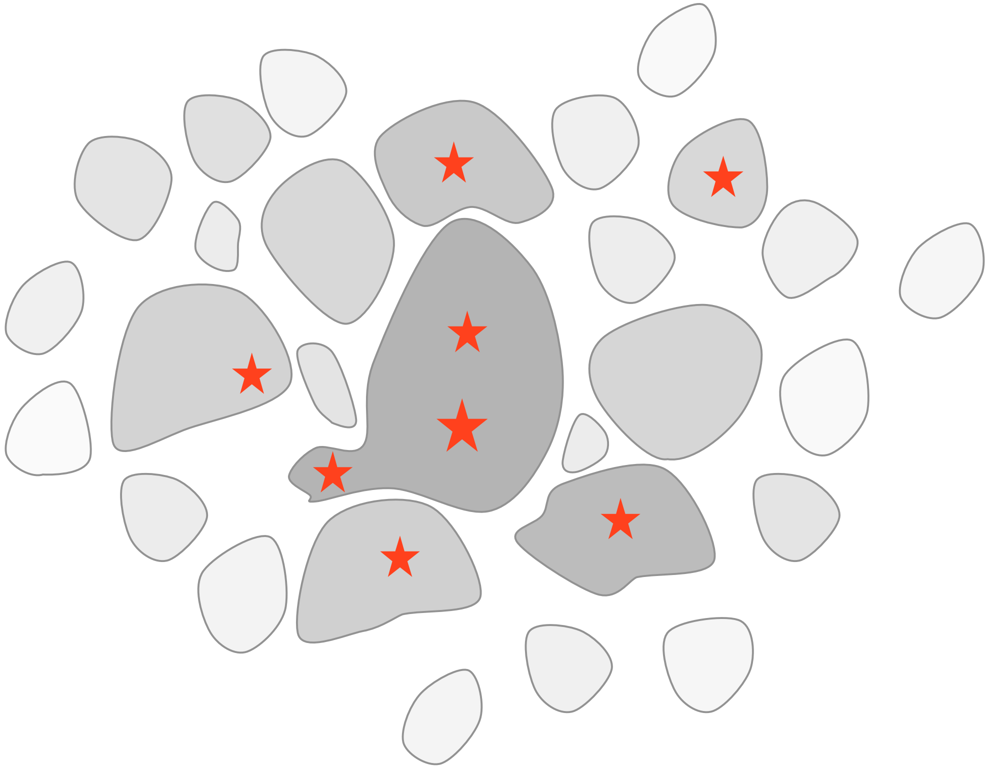


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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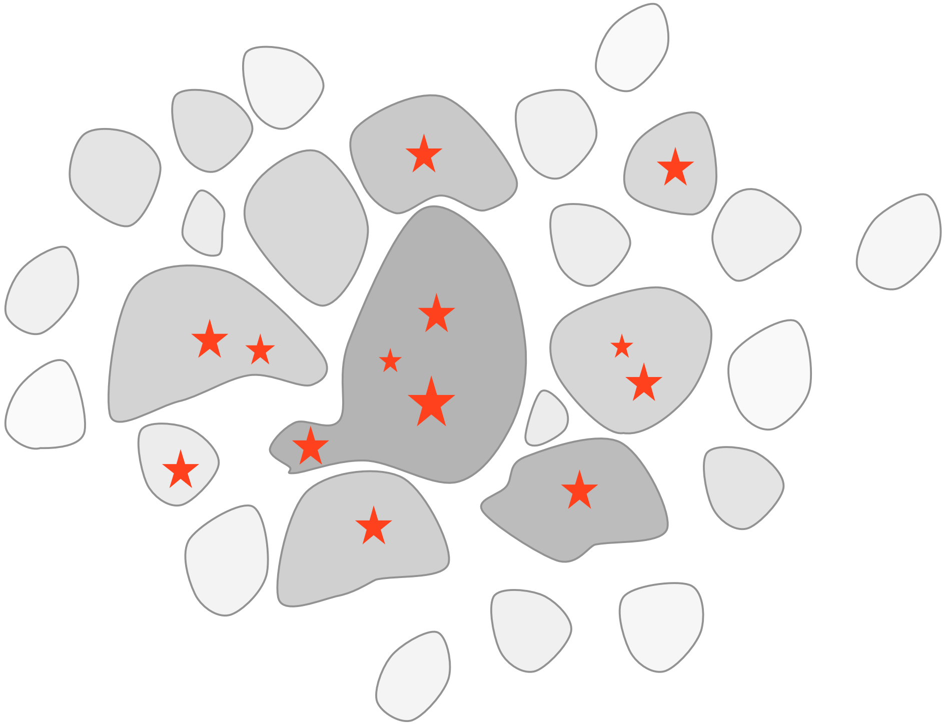

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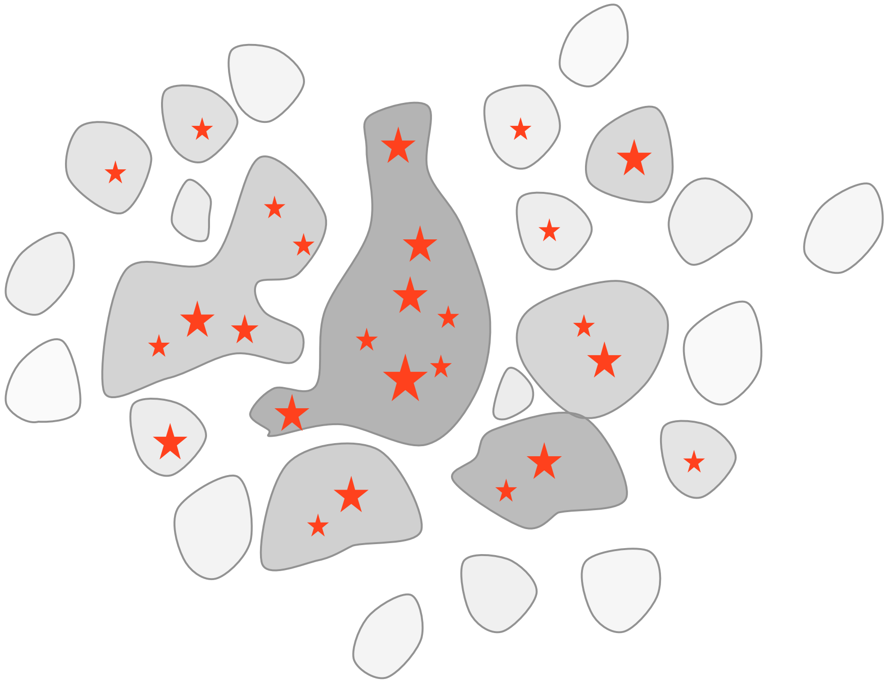
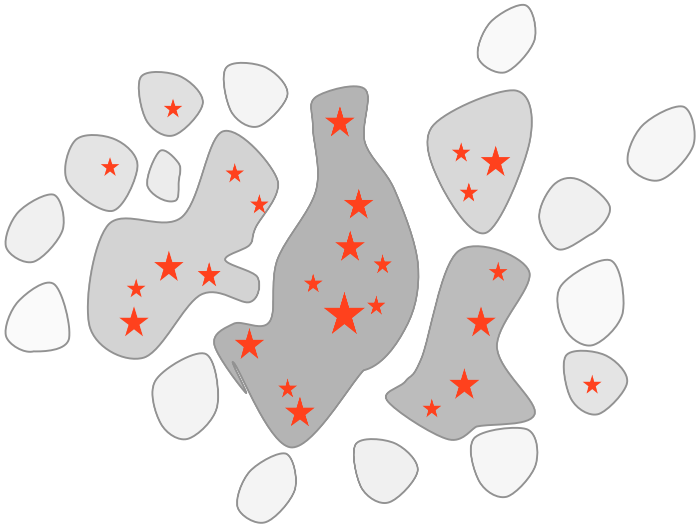


in *dense clusters*, competitive mass growth becomes important



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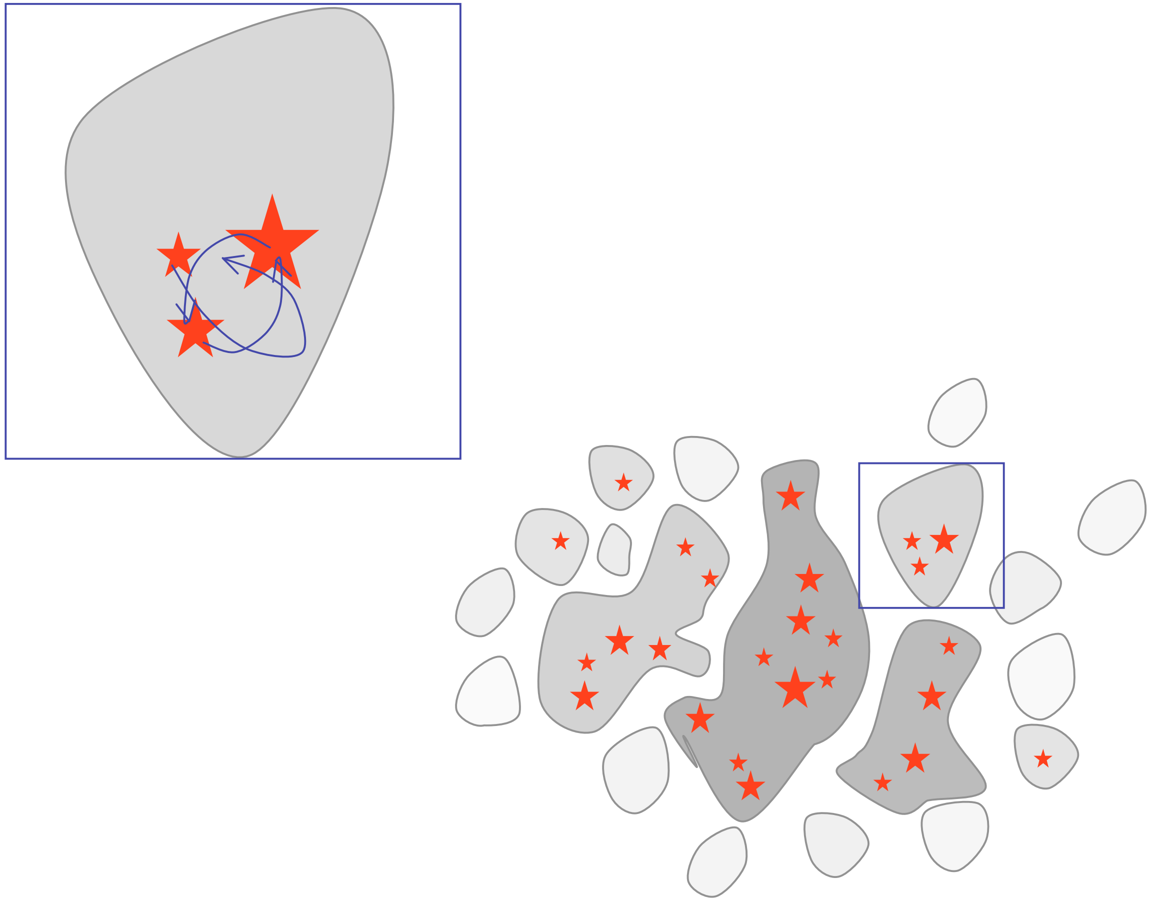
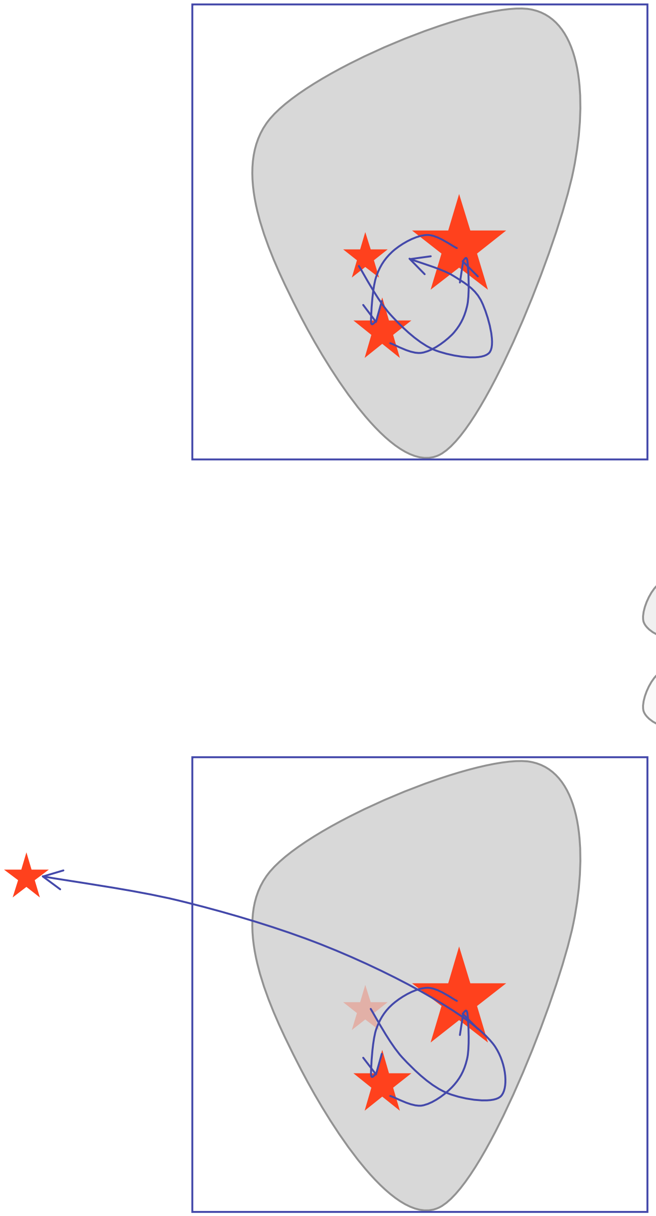
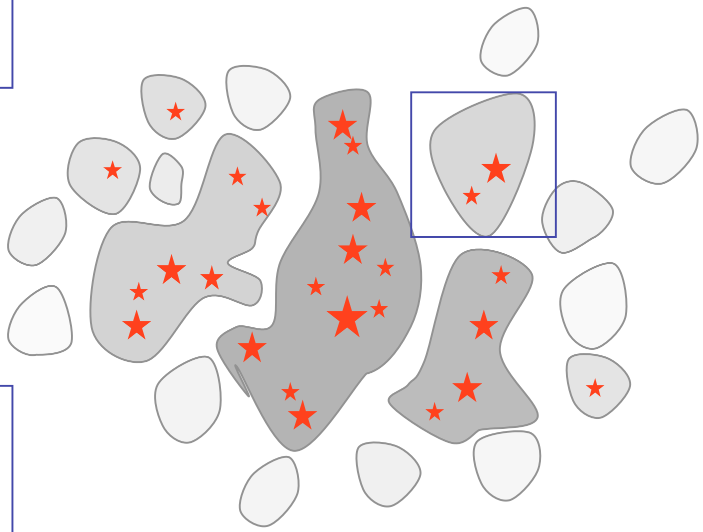
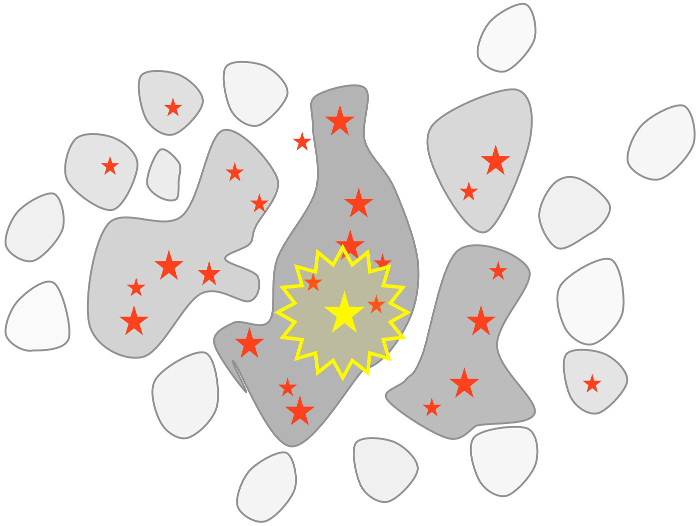


in *dense clusters*, *N*-body effects influence mass growth

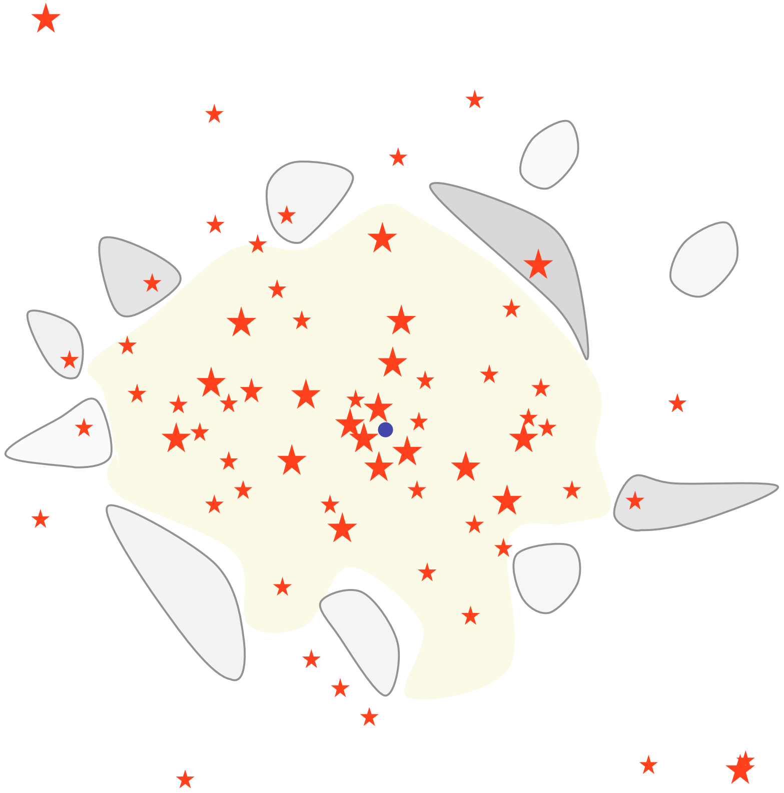




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with HII region

predictions

Predictions

- *global properties* (statistical properties)
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)
  - properties of individual clumps (e.g. shape, radial profile, lifetimes)
  - accretion history of individual protostars (dM/dt vs. t, j vs. t)
  - binary (proto)stars (eccentricity, mass ratio, etc.)
  - SED's of individual protostars
  - dynamic PMS tracks: T_{bol}-L_{bol} evolution

Examples and predictions

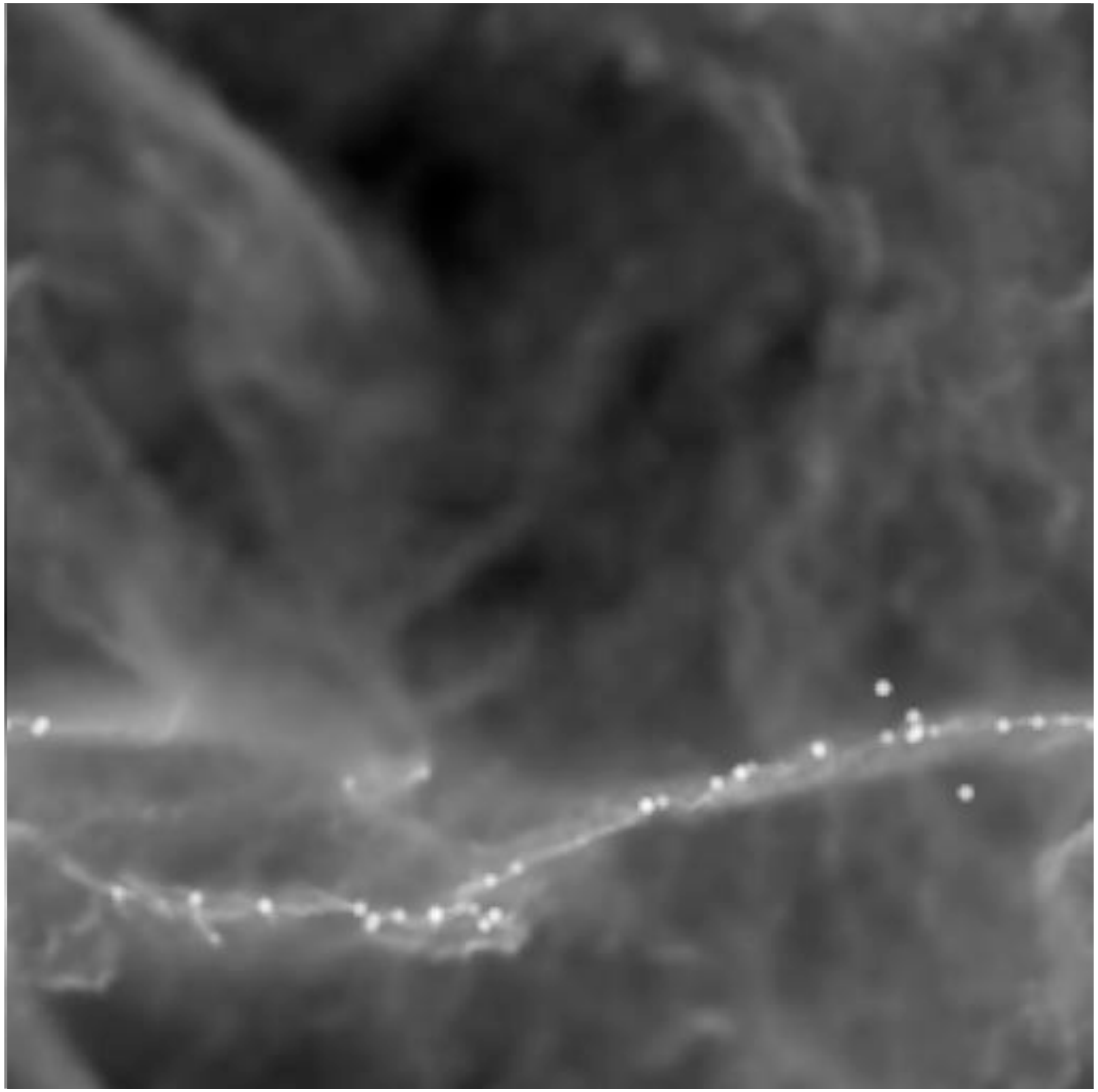
example 1: star cluster formation: *dynamics*

example 2: star cluster formation: *thermodynamics*
--> speculations on the origin of the stellar mass spectrum (IMF)

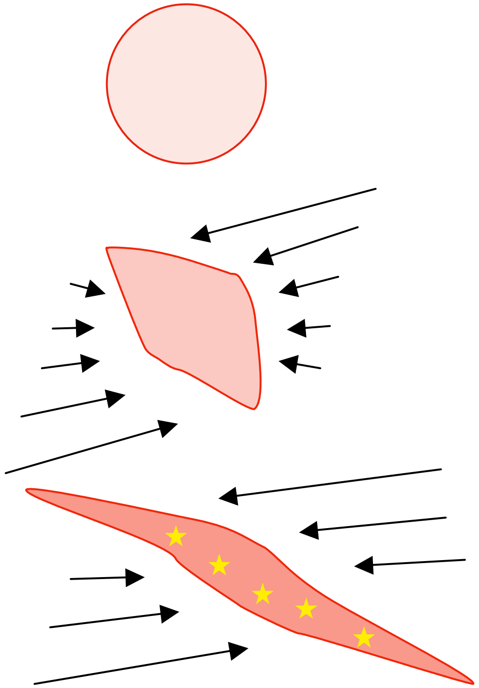
- solar neighborhood
- starburst regions
- transition from Pop III to Pop II.5

example 1

Gravoturbulent fragmentation



Filament generated by combination of compression and local shear:

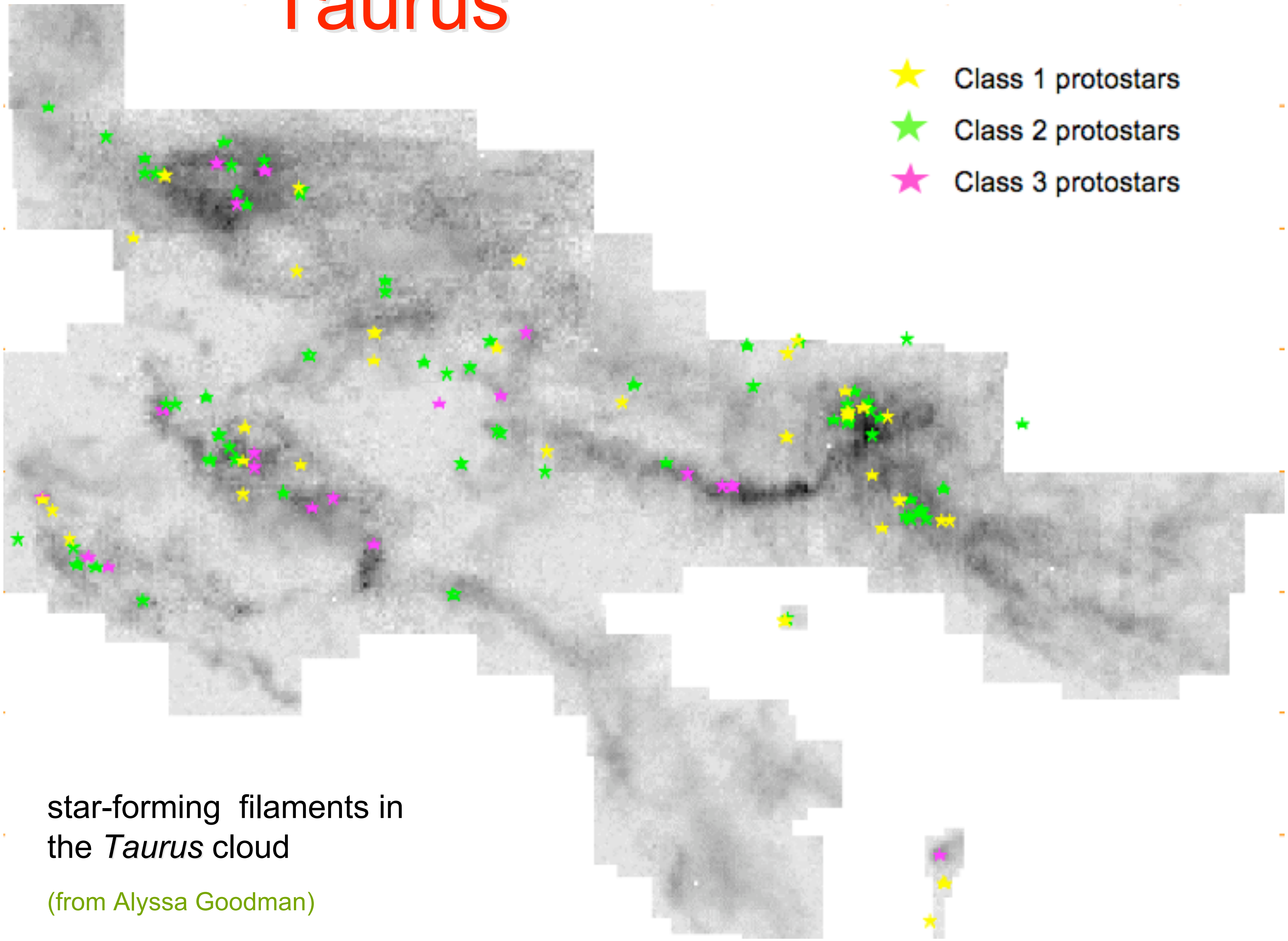


"Taurus":

→ density $n(H_2) \approx 10^2\,\mathrm{cm}^{-3}$

→ $L = 6\,\mathrm{pc}$, $M = 5000\,M_\odot$

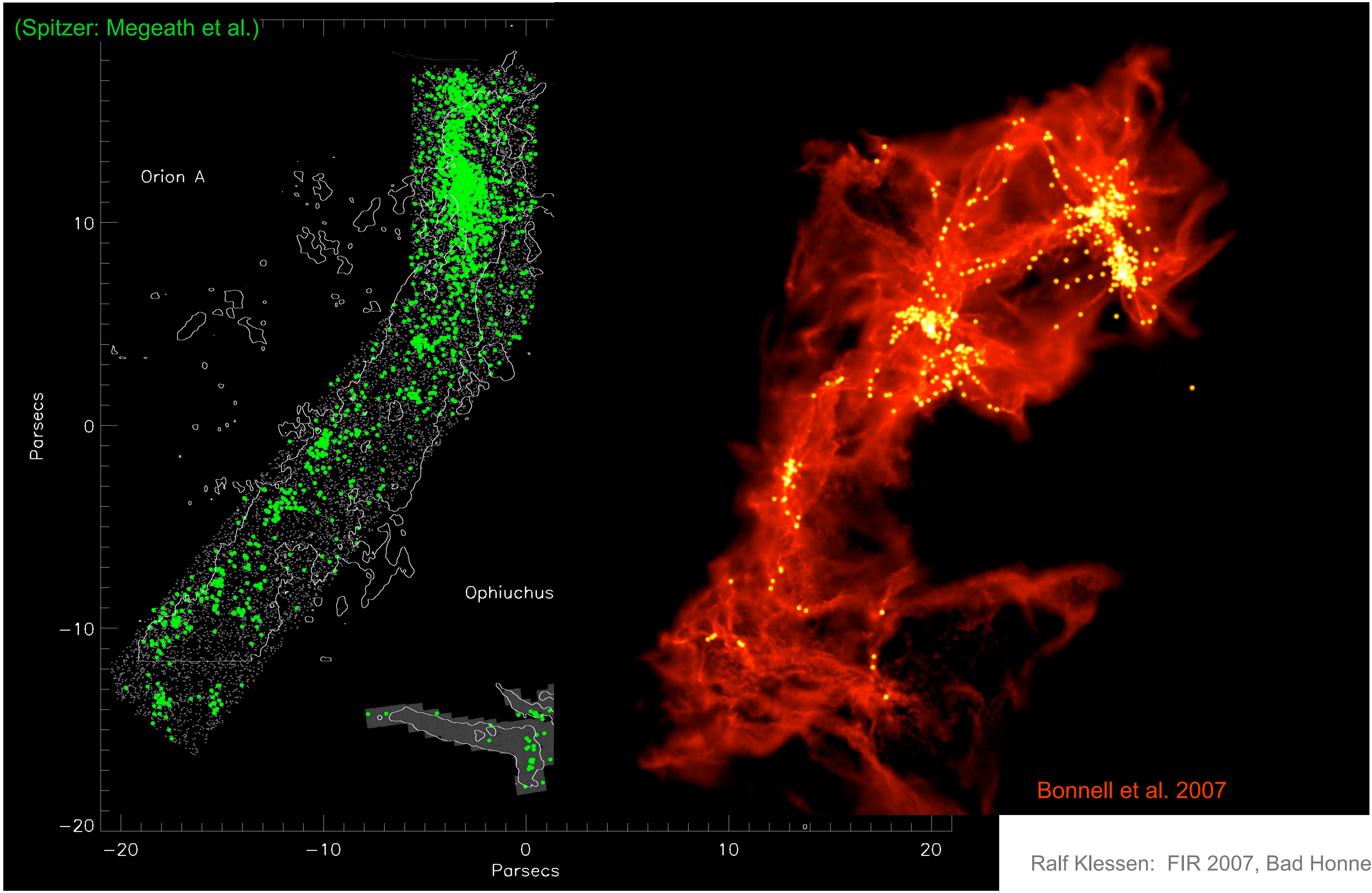
Taurus



star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

Example: modeling Orion cloud

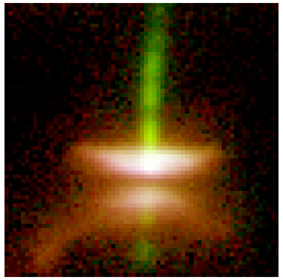


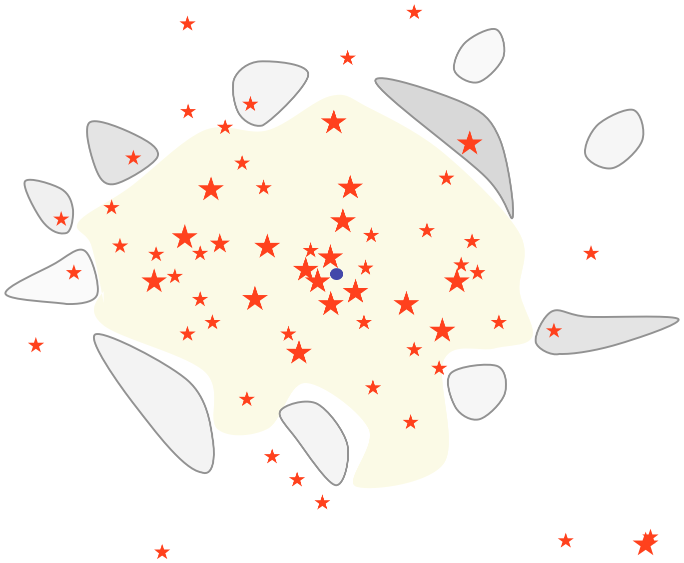
(Spitzer: Megeath et al.)

Bonnell et al. 2007

Current status of numerical models

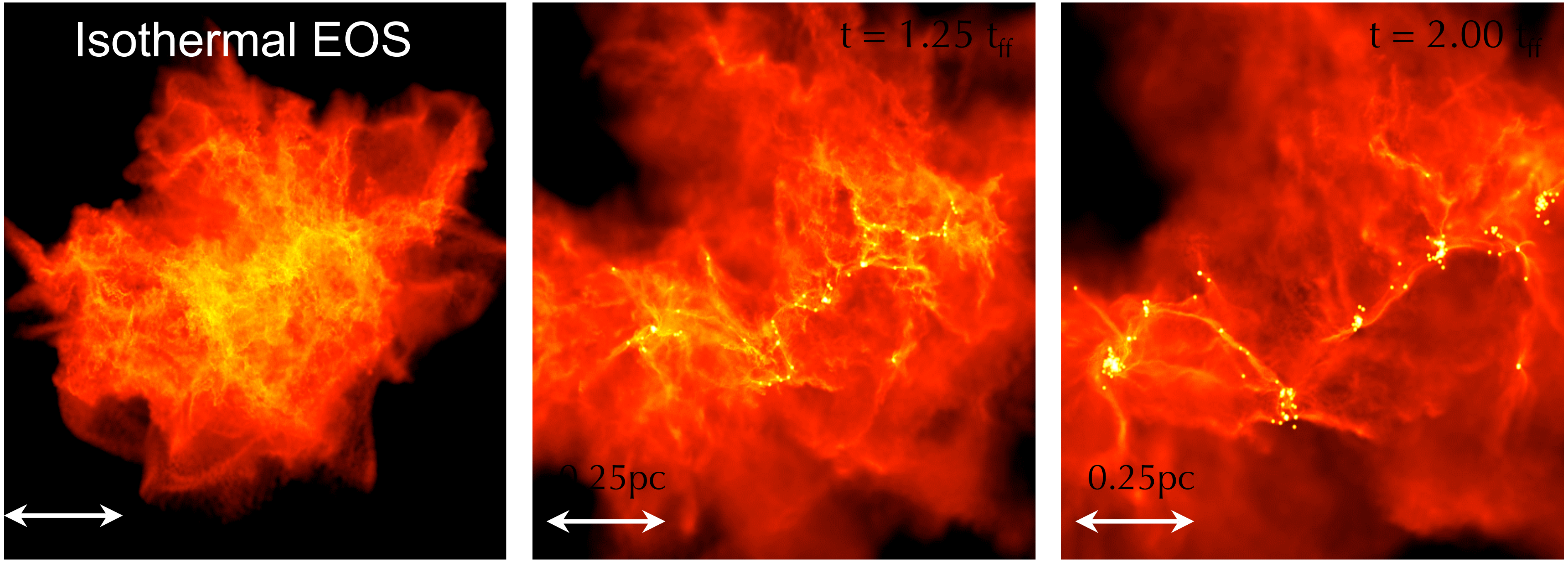
- basic properties: prob. okay
- BUT:
    - no feedback
      (outflows, heating, ionizing radiation, etc.)★
    - no chemistry and radiation
    - often no B-fields
    - initial / boundary conditions
- *how important is missing physics? (IMF, efficiency, timescales)*





Models of unbound clouds: dynamics

KE = 2 x PE (initially), 1000 solar masses, 0.5pc



No global collapse:

local t_{ff} < global interaction time-scale

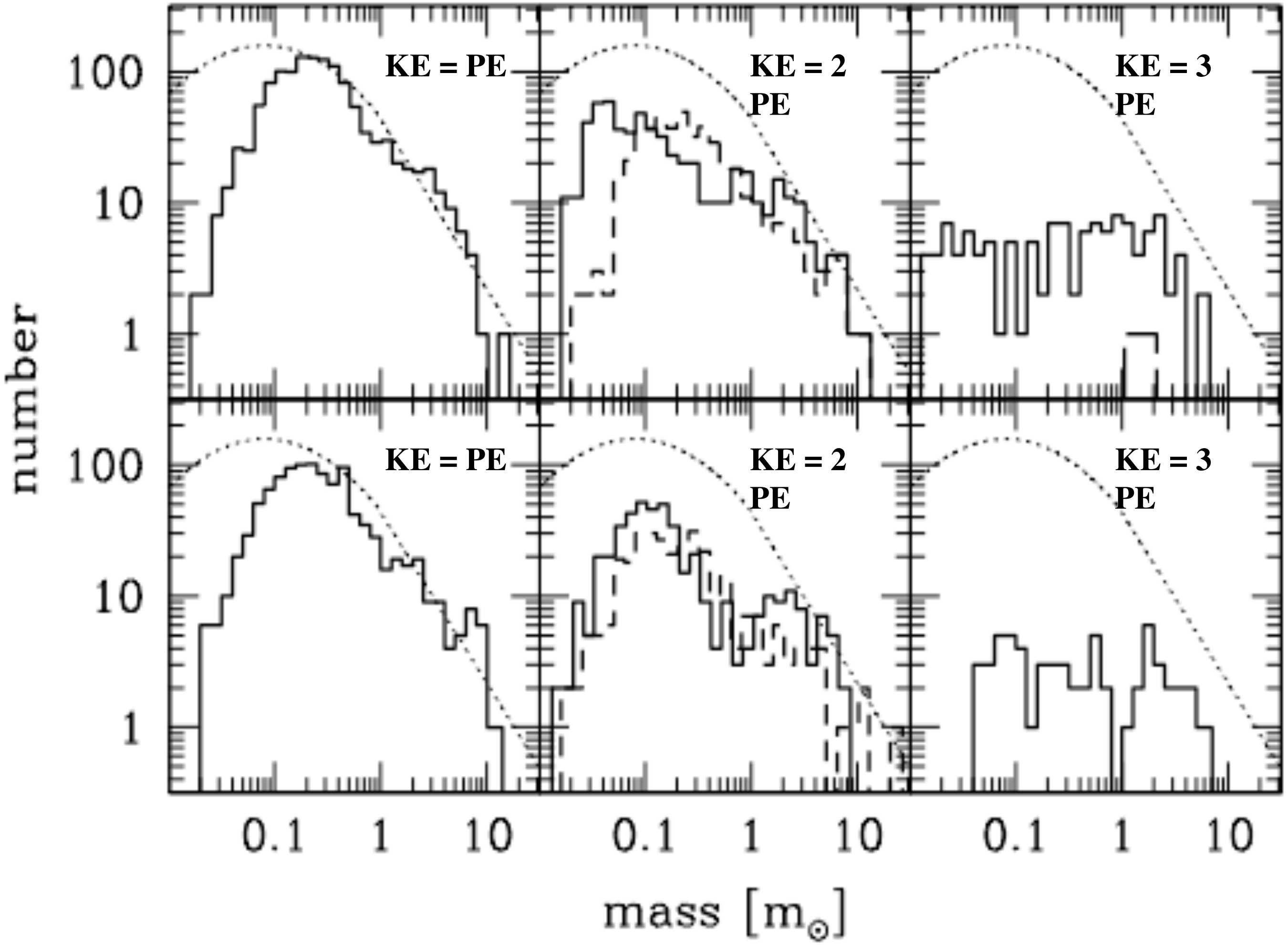
$t_{ff} \sim 2 \times 10^5$ years

Clark, Bonnell & Klessen (2007)

Models of unbound clouds: IMF

Isothermal
EOS

Barotropic,
Larson
(2005), Style
EOS



Clark, Bonnell & Klessen (2007)

example 2

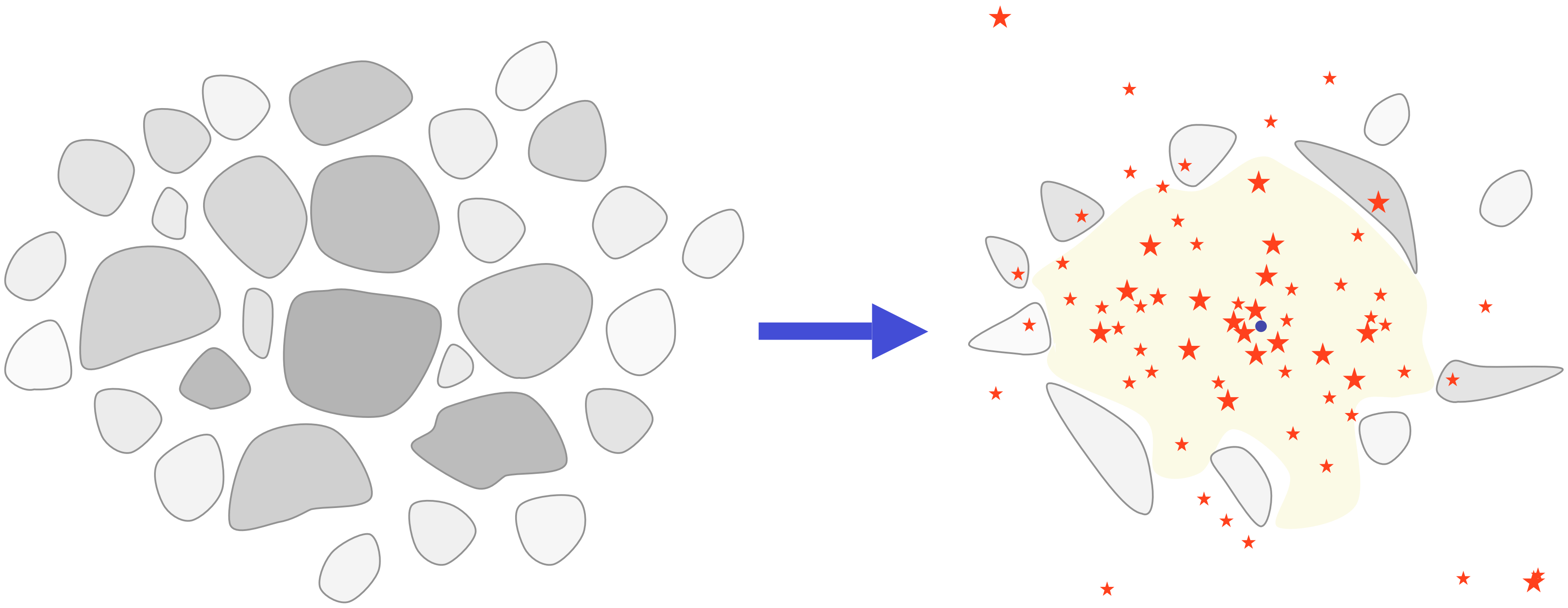
IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive 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

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

Star cluster formation

Most stars form in clusters → *star formation = cluster formation*



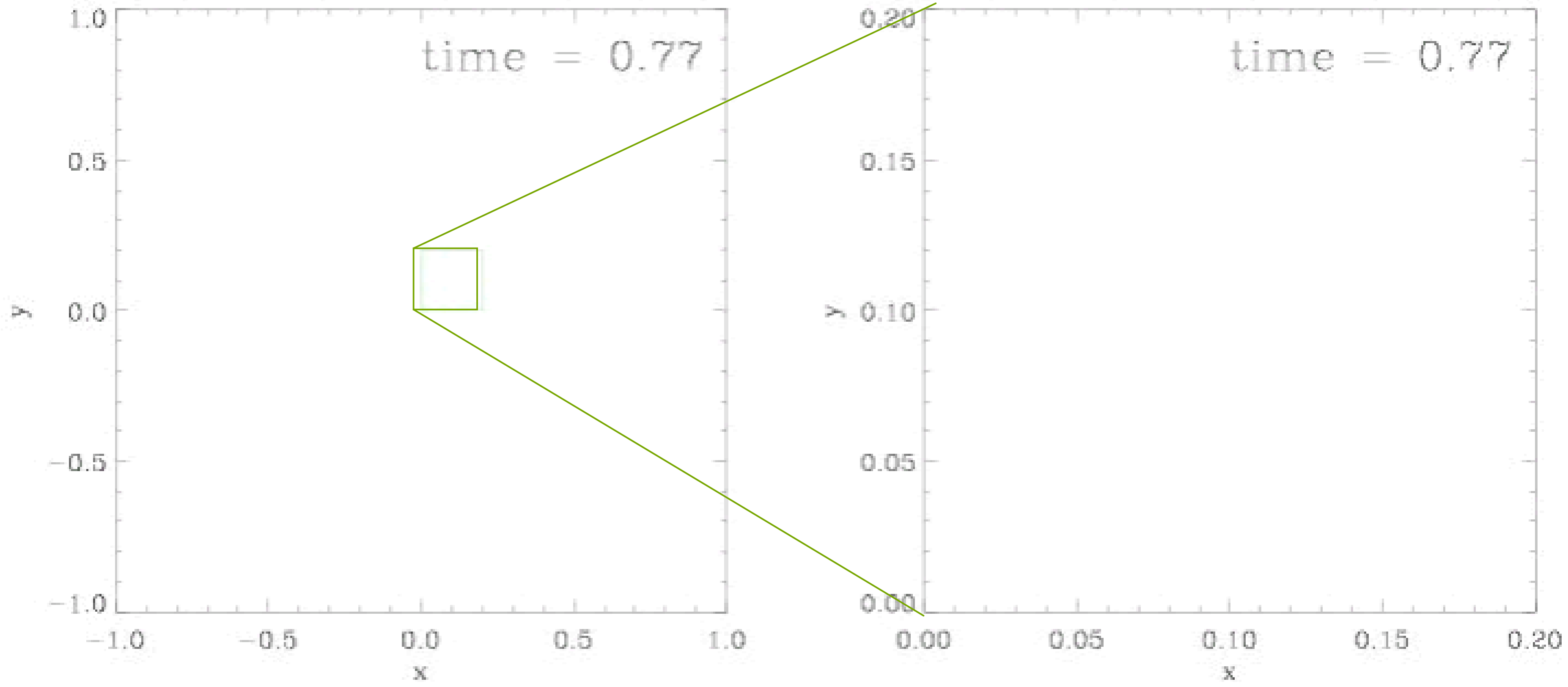
How to get from cloud cores to star clusters?

How do the stars acquire mass?

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

Dynamics of nascent star cluster

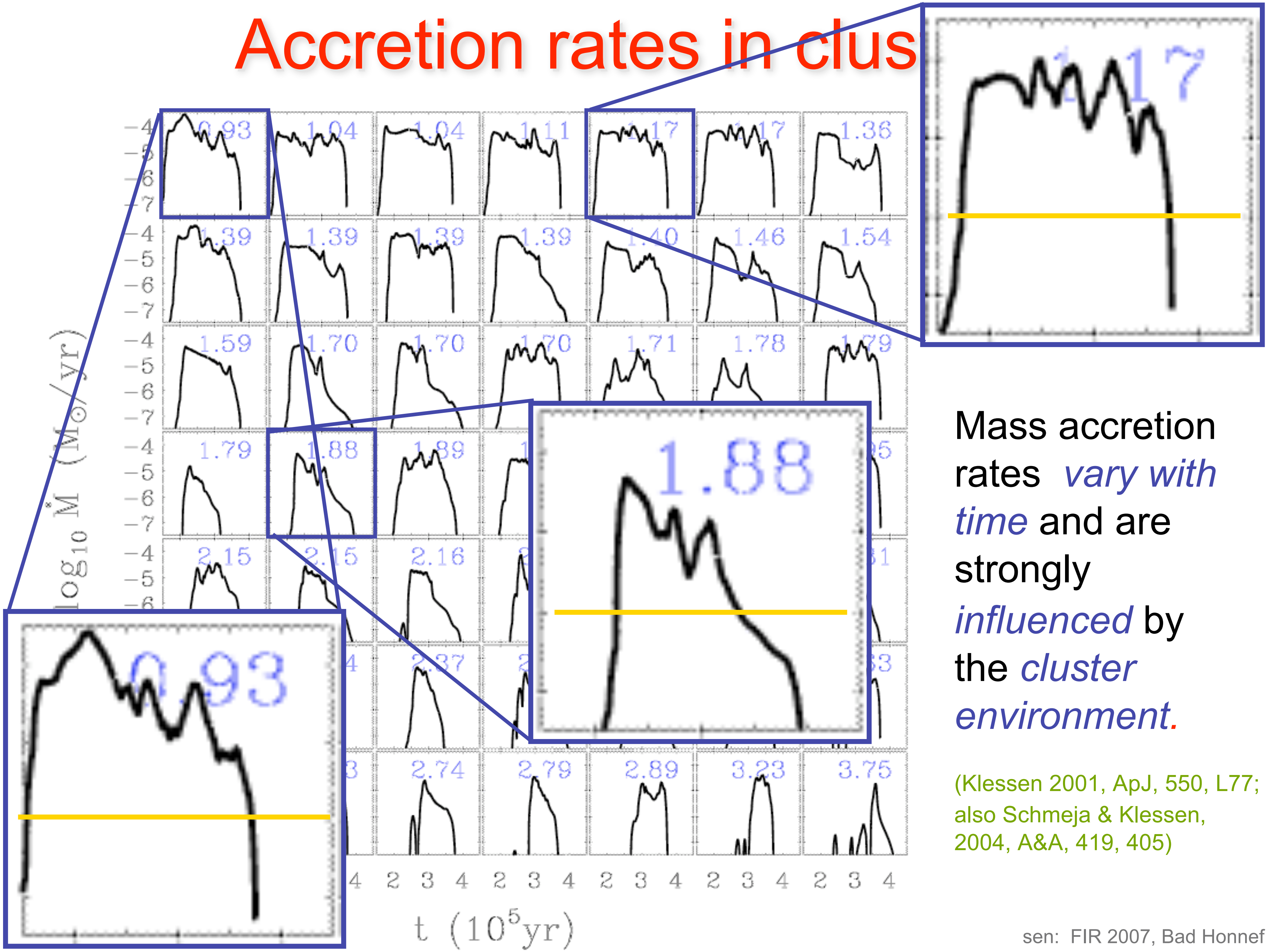
in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

(from Klessen & Burkert 2000, ApJS, 128, 287)

Accretion rates in clus



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)

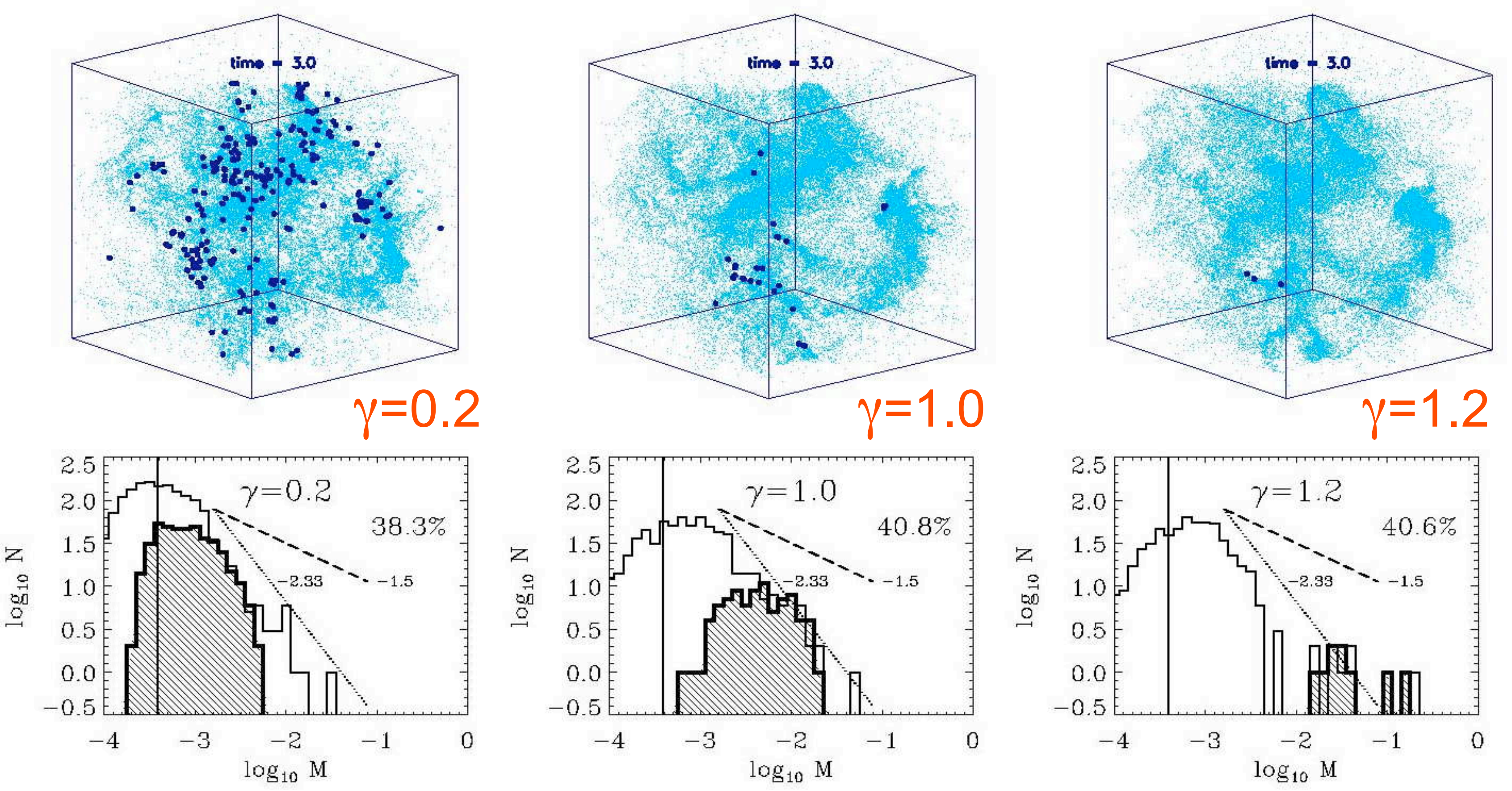
Dependency on EOS

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

Dependency on EOS



γ=0.2 γ=1.0 γ=1.2

for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

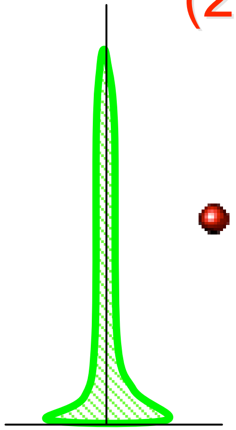
for γ>1 it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

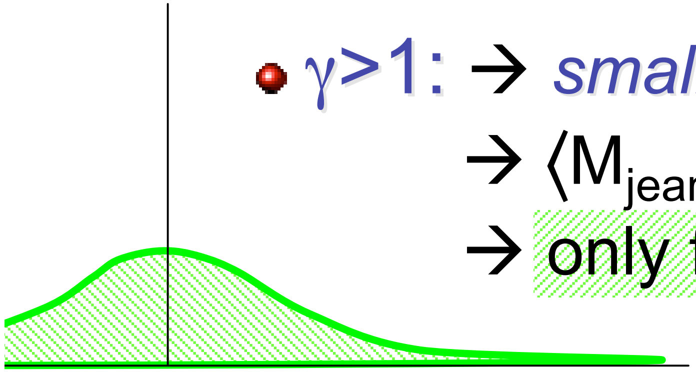
How does that work?

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

(2) $\mathbf{M_{jeans} \propto \gamma^{3/2}\,\rho^{(3\gamma-4)/2}}$



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

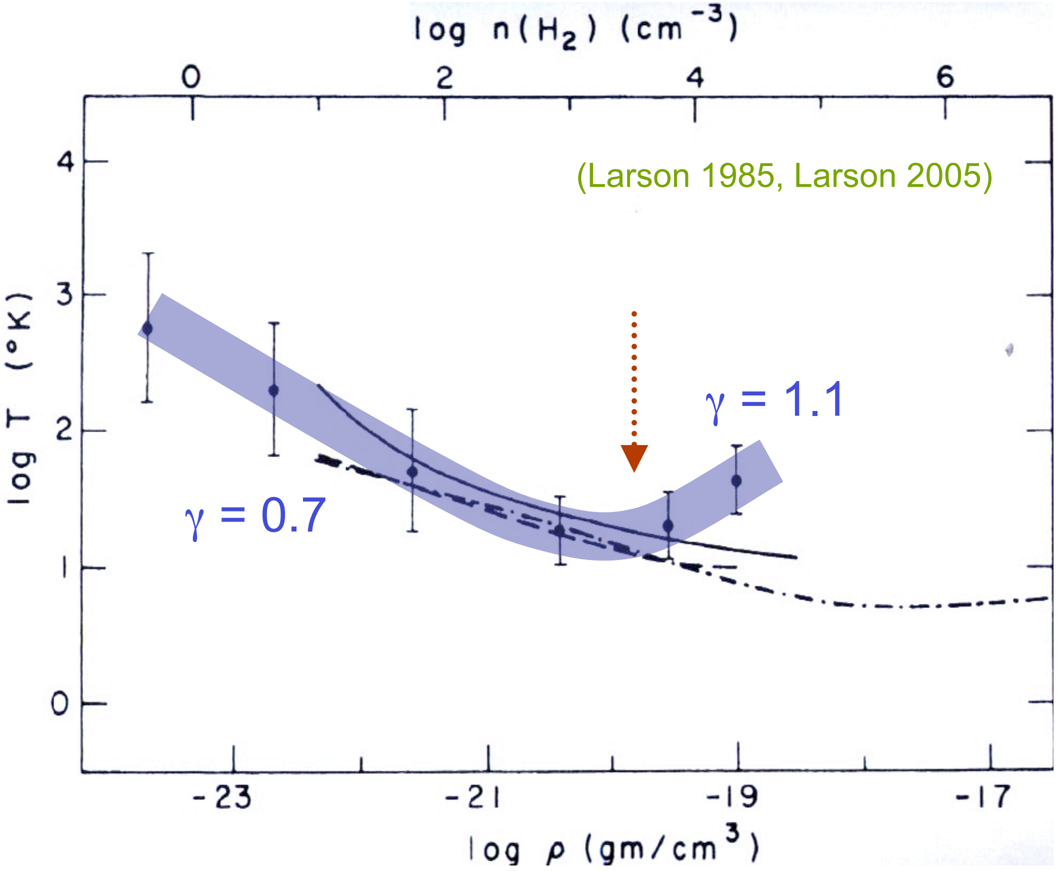


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans}\rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ↑ ⟹ T ↓

above 10^{-18} gcm^{-3}: ρ ↑ ⟹ T ↑



(Larson 1985, Larson 2005)

$P \propto \rho^{\gamma}$

$P \propto \rho T$

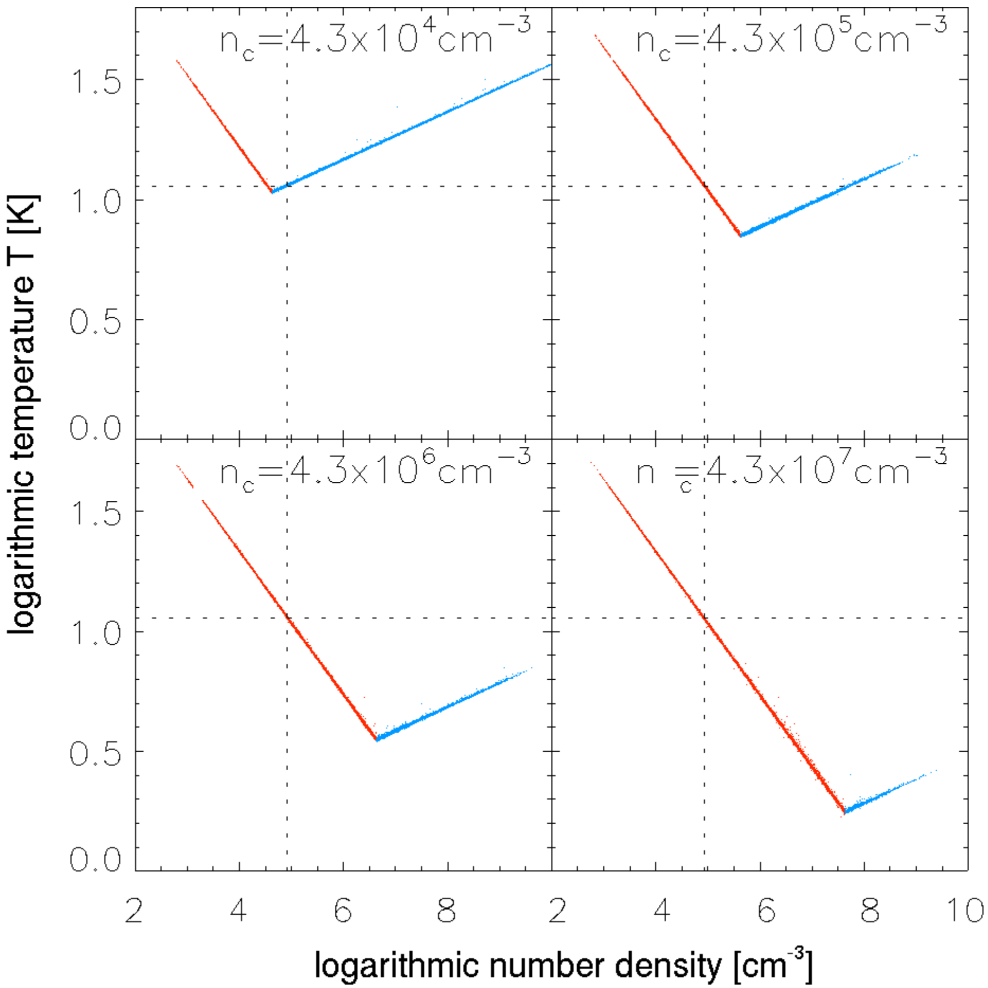
$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

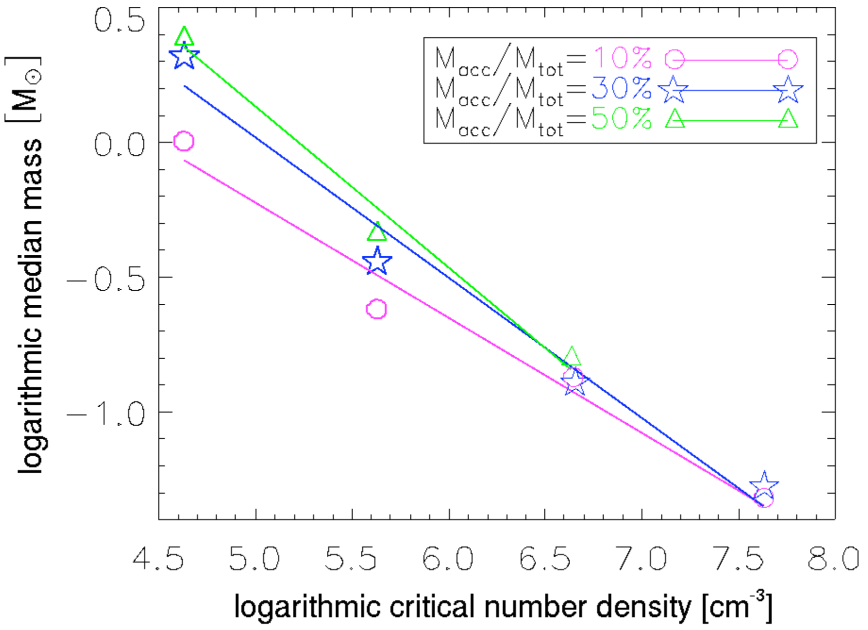
$$\boxed{T \sim \rho^{\gamma-1}}$$

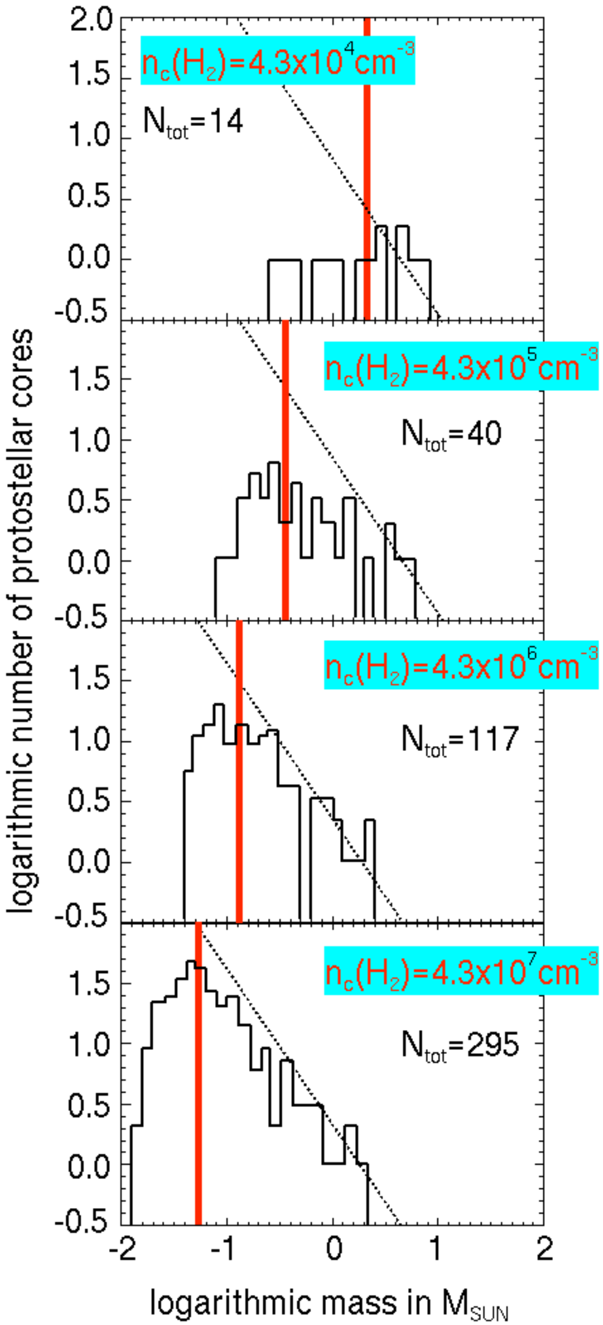


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

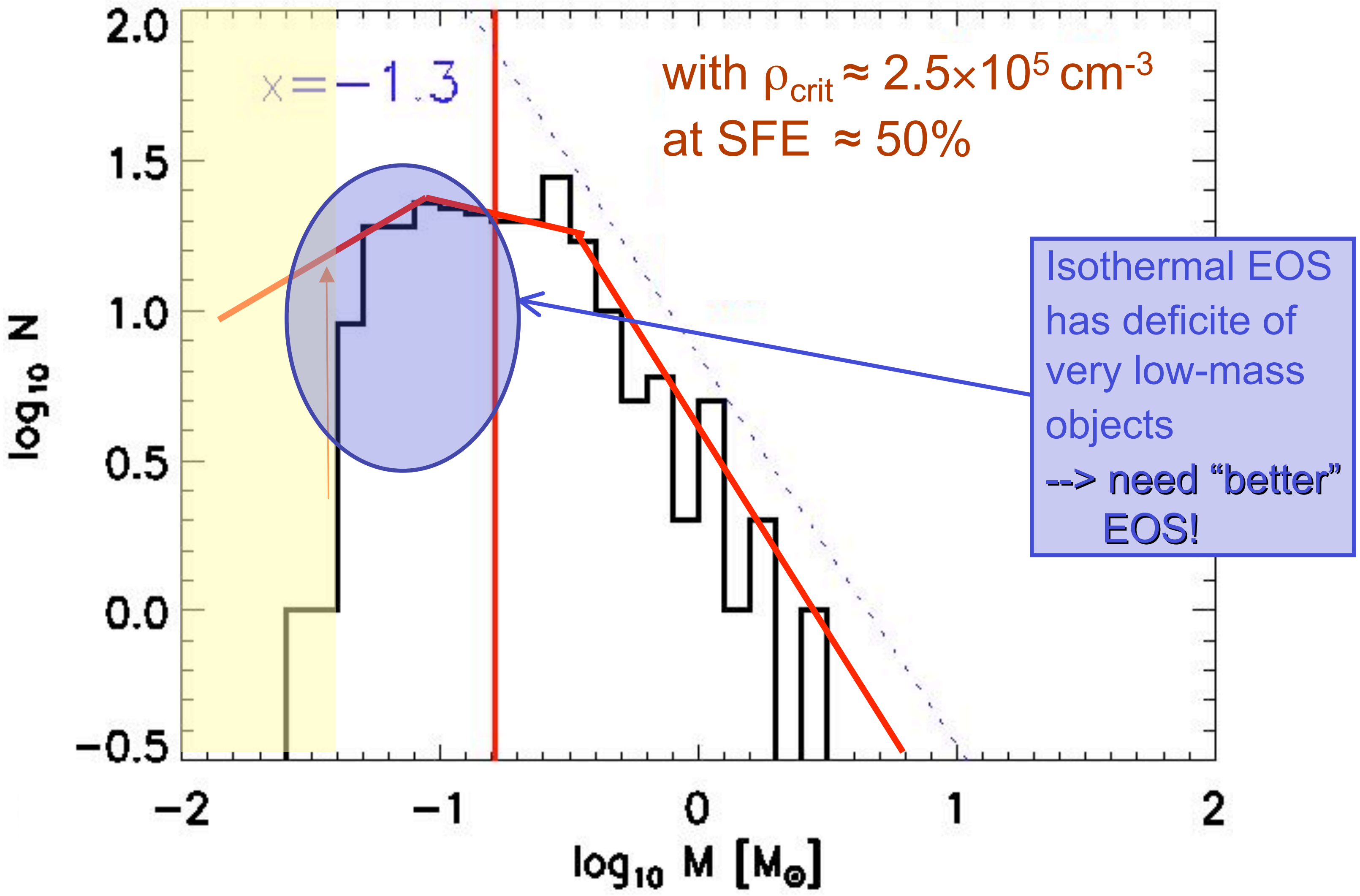
critical density ⬆ ⇨ median mass ⬇





(Jappsen et al. 2005)

IMF in nearby molecular clouds



with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}
at SFE ≈ 50%

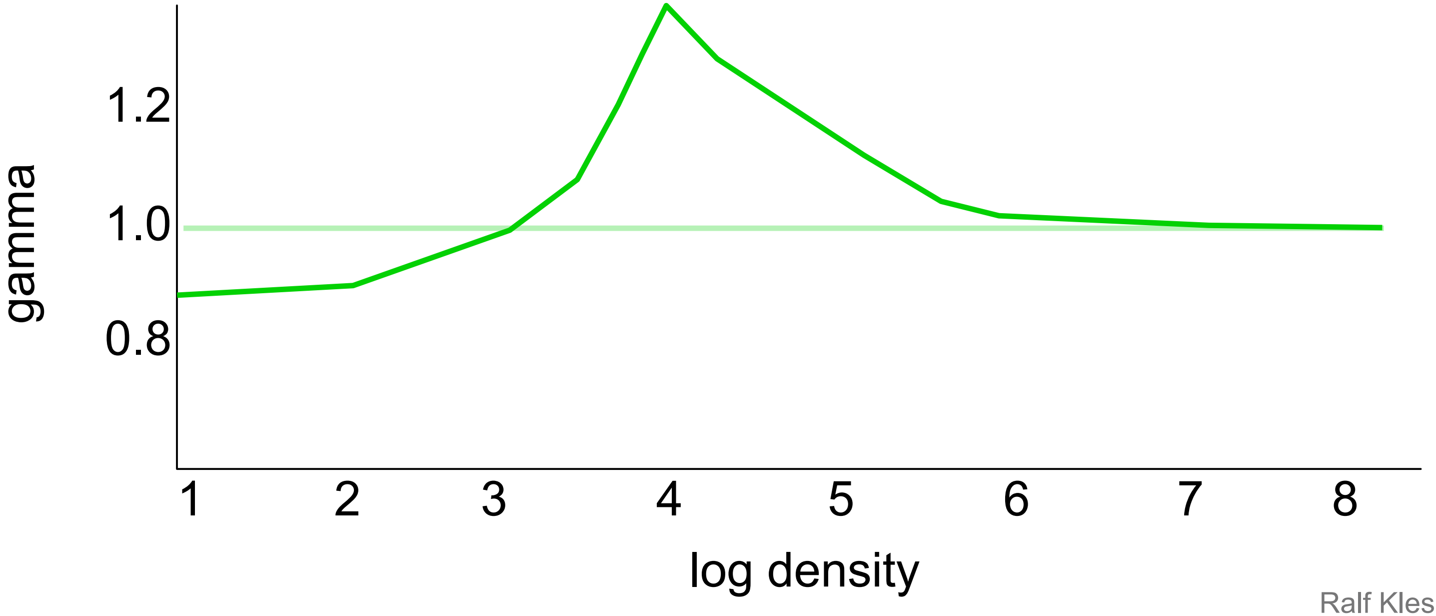
Isothermal EOS has deficite of very low-mass objects

--> need “better” EOS!

(Jappsen et al. 2005, A&A, 435, 611)c

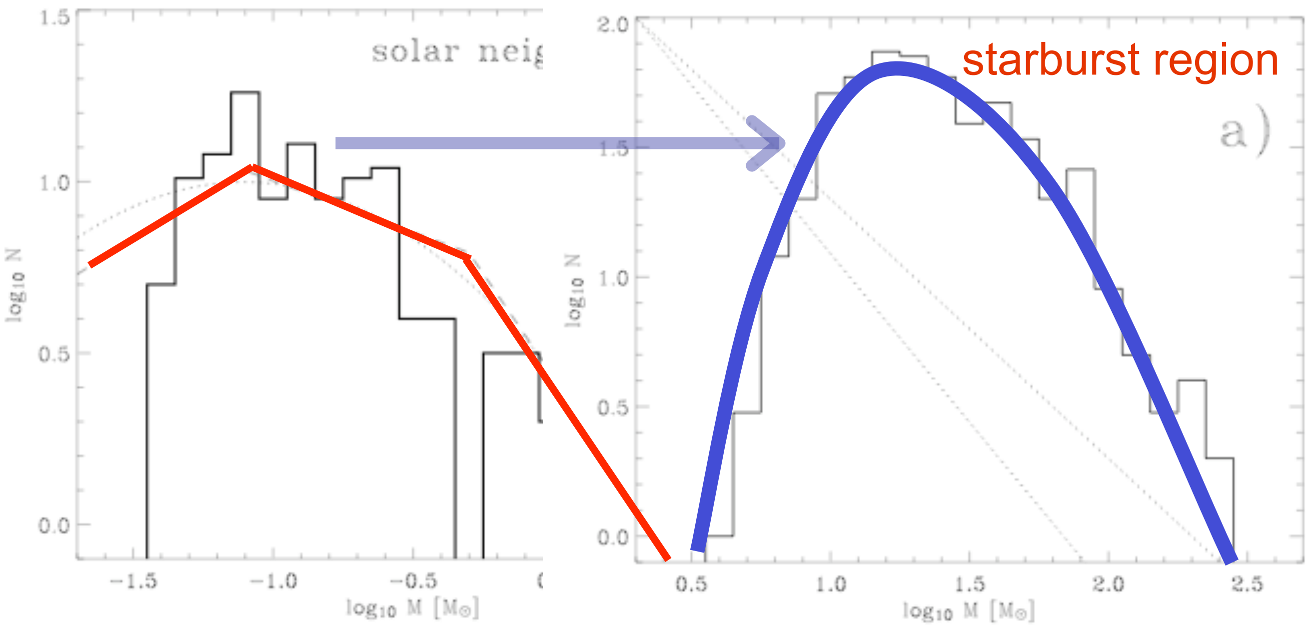
IMF in starburst galaxies

- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
  (see Spaans & Silk 2005)

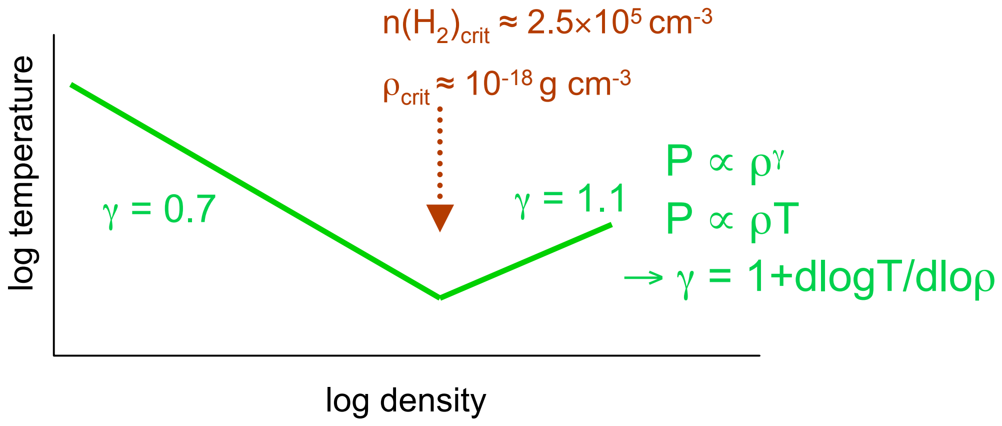


IMF in starburst galaxies

- Starburst EOS --> top-heavy IMF
  (Klessen, Spaans, Jappsen, 2007)



fragmentation depends on EOS



$n(H_2)_{crit} \approx 2.5\times10^{5}\ cm^{-3}$

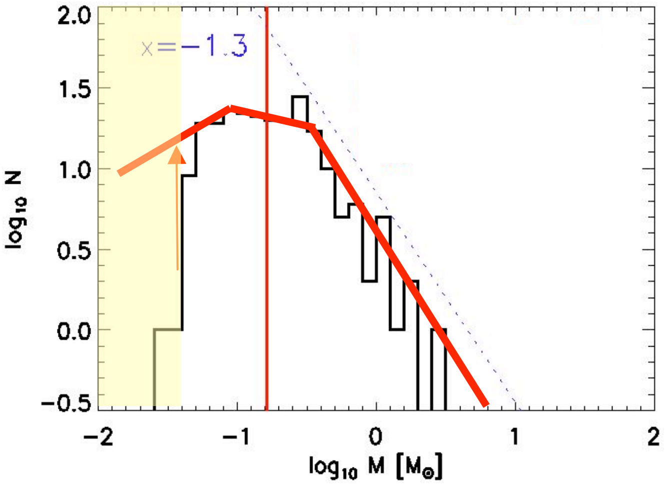
$\rho_{crit} \approx 10^{-18}\ g\ cm^{-3}$

$P \propto \rho^{\gamma}$

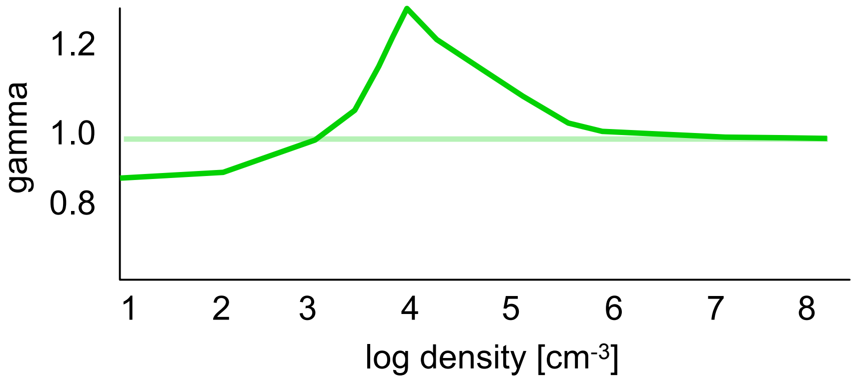
$P \propto \rho T$

$\rightarrow \gamma = 1 + d\log T / d\log\rho$

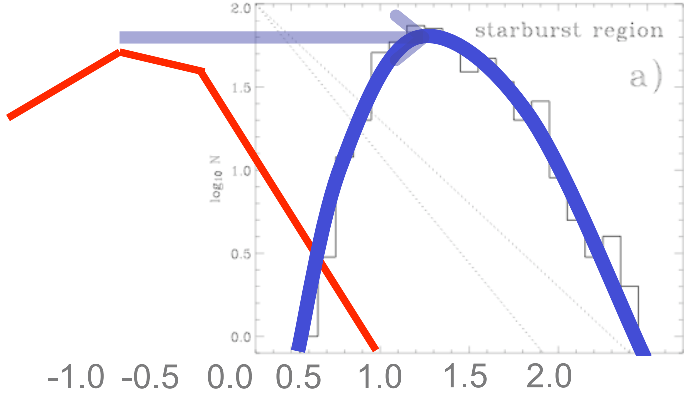
(Larson 2005)



(Jappsen et al. 2005)

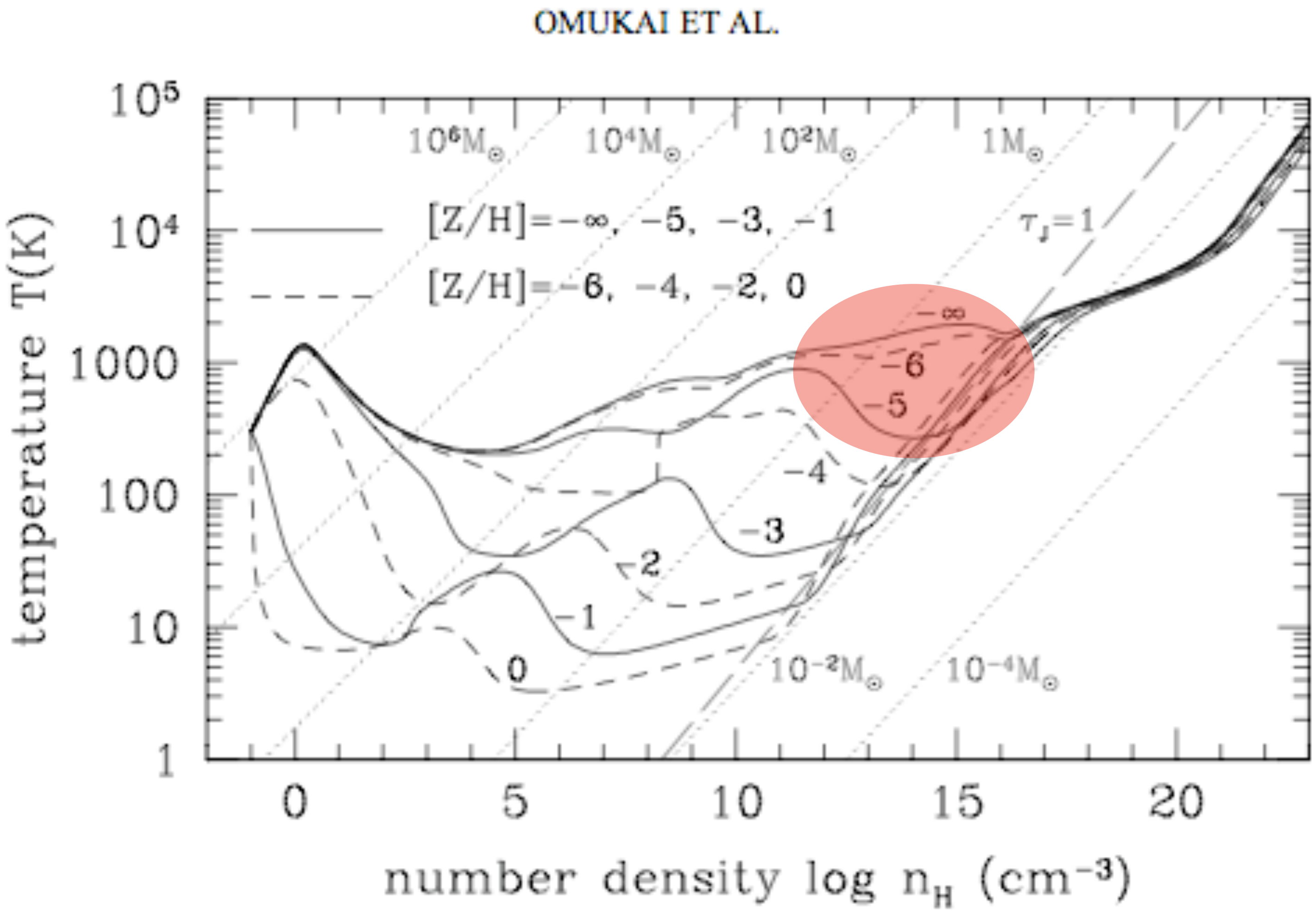


(Spaans & Silk 2005)



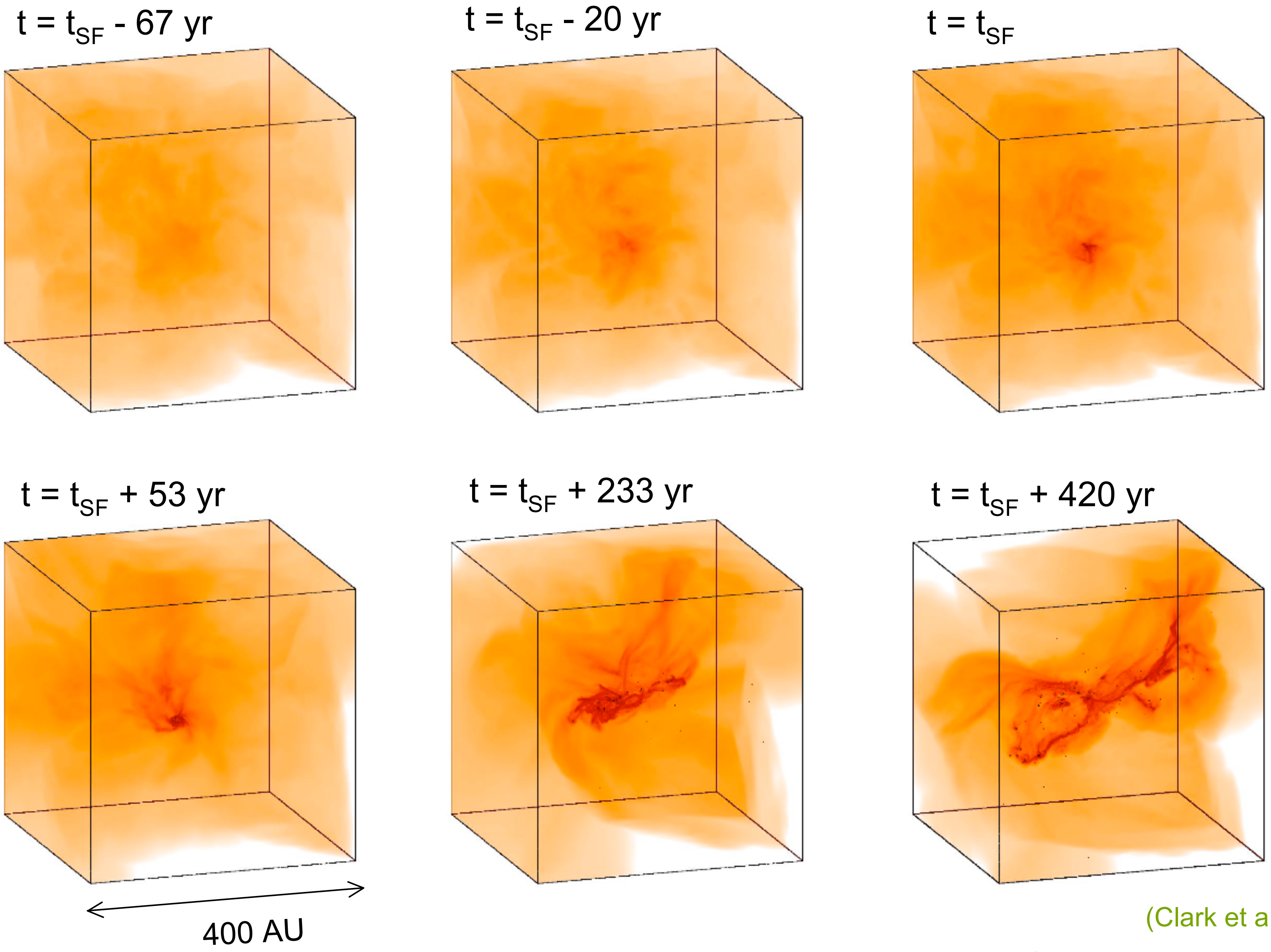
(Klessen et al. 2007)

transition: Pop III to Pop II.5



(Omukai et al. 2005)

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



$t = t_{SF} - 67$ yr

$t = t_{SF} - 20$ yr

$t = t_{SF}$

$t = t_{SF} + 53$ yr

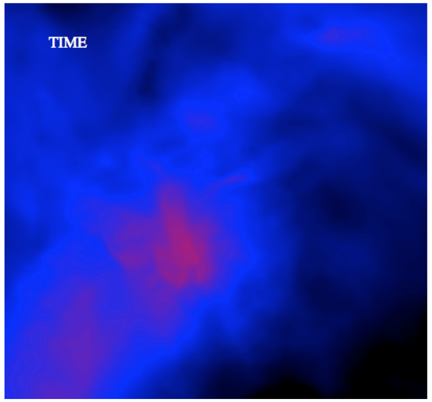
$t = t_{SF} + 233$ yr

$t = t_{SF} + 420$ yr

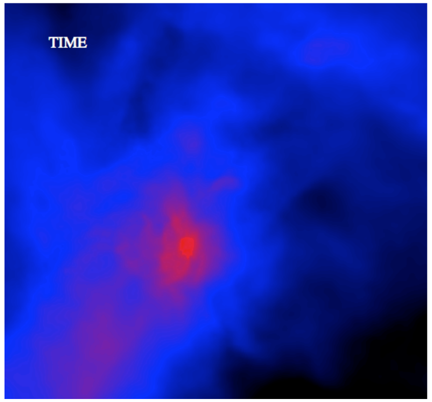
(Clark et al. 2007)

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

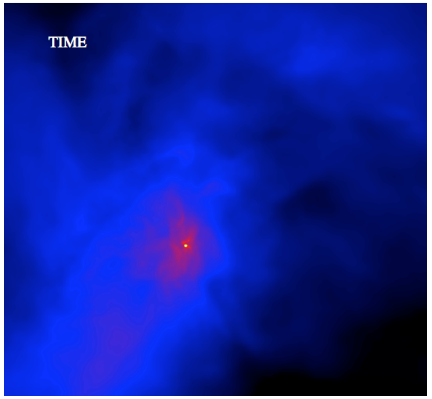
$t = t_{SF} - 67$ yr



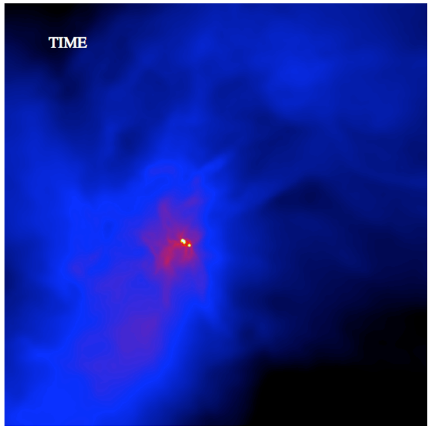
$t = t_{SF} - 20$ yr



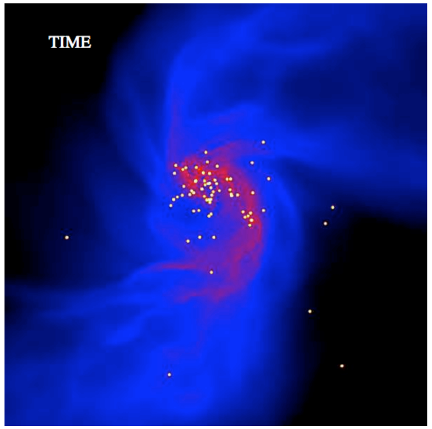
$t = t_{SF}$



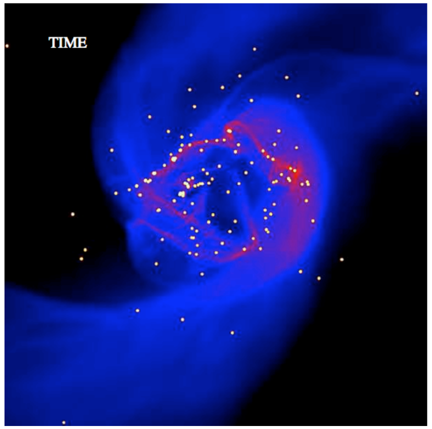
$t = t_{SF} + 53$ yr



$t = t_{SF} + 233$ yr



$t = t_{SF} + 420$ yr



(Clark et al. 2007)

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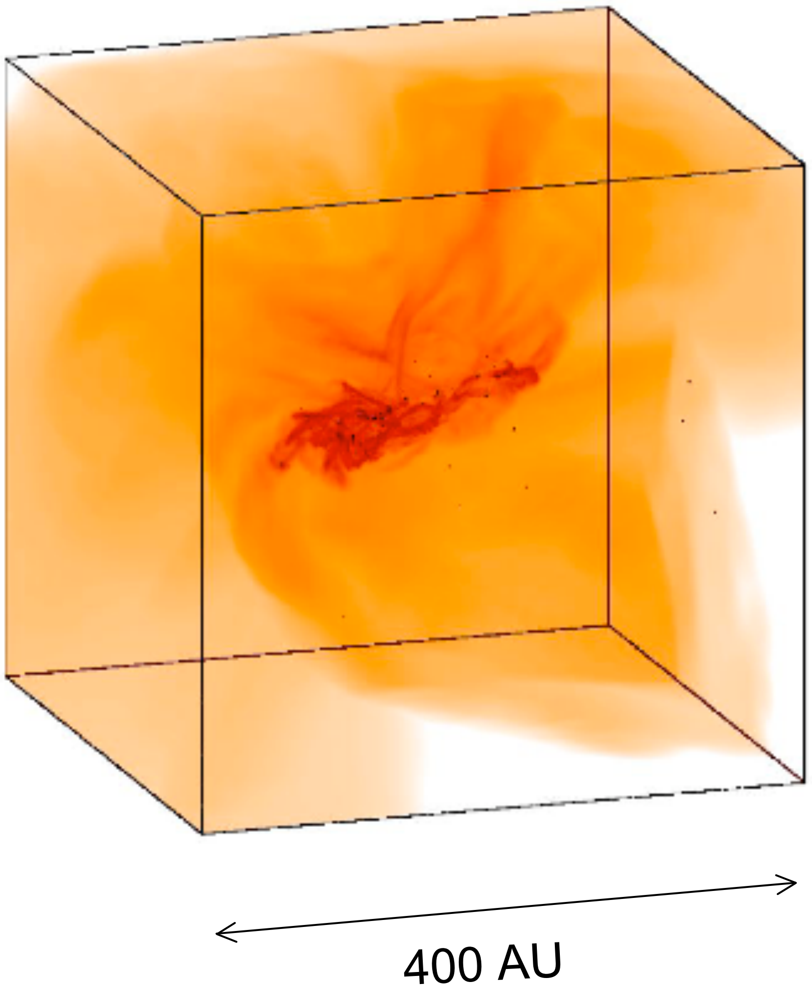


dense cluster of low-mass protostars builds up:

- 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. 2007)

cluster build-up

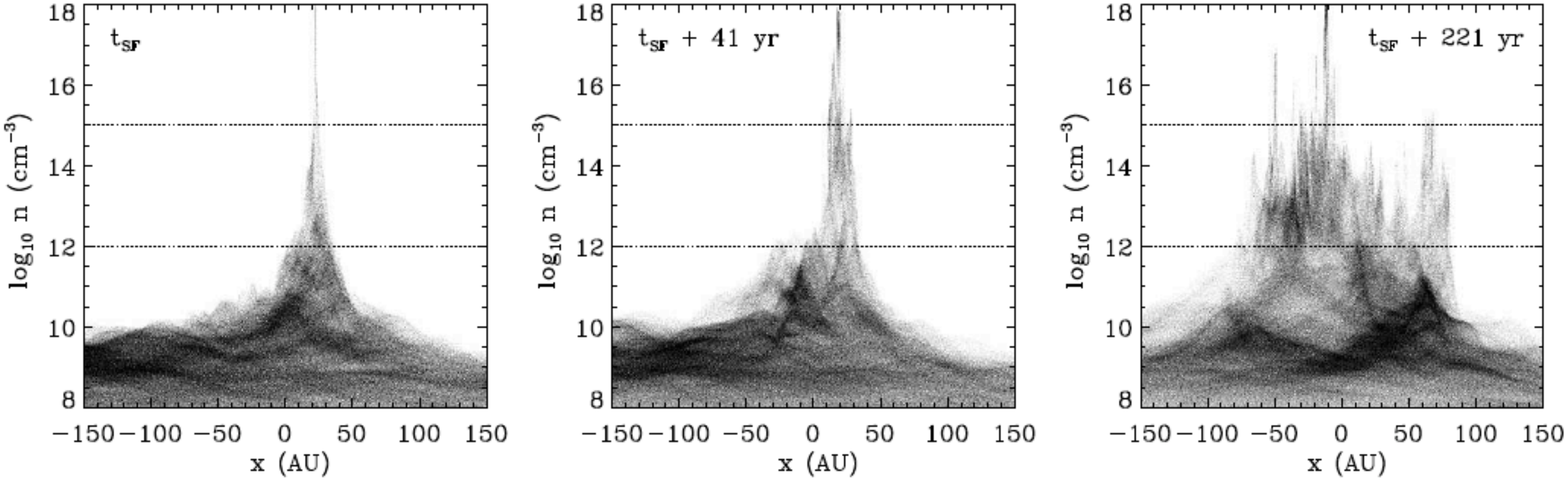
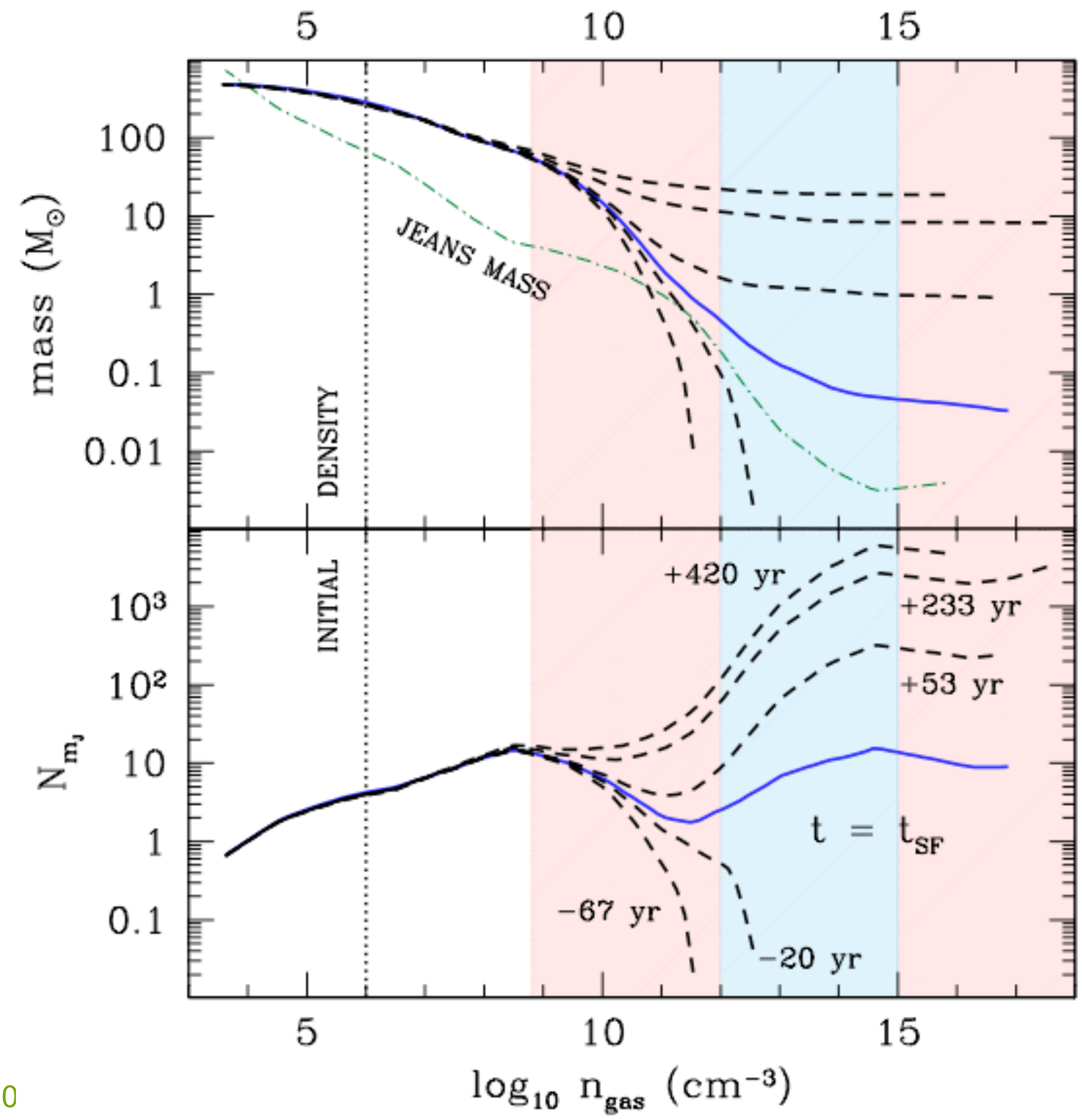


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_\odot$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We show here results at three different output times, ranging from the time that the first star forms (t_{sf}) to 221 years afterwards. The densities lying between the two horizontal dashed lines denote the range over which dust cooling lowers the gas temperature.

(Clark et al. 2007)

cluster build-up



🟥

$\gamma > 1$
(heating)

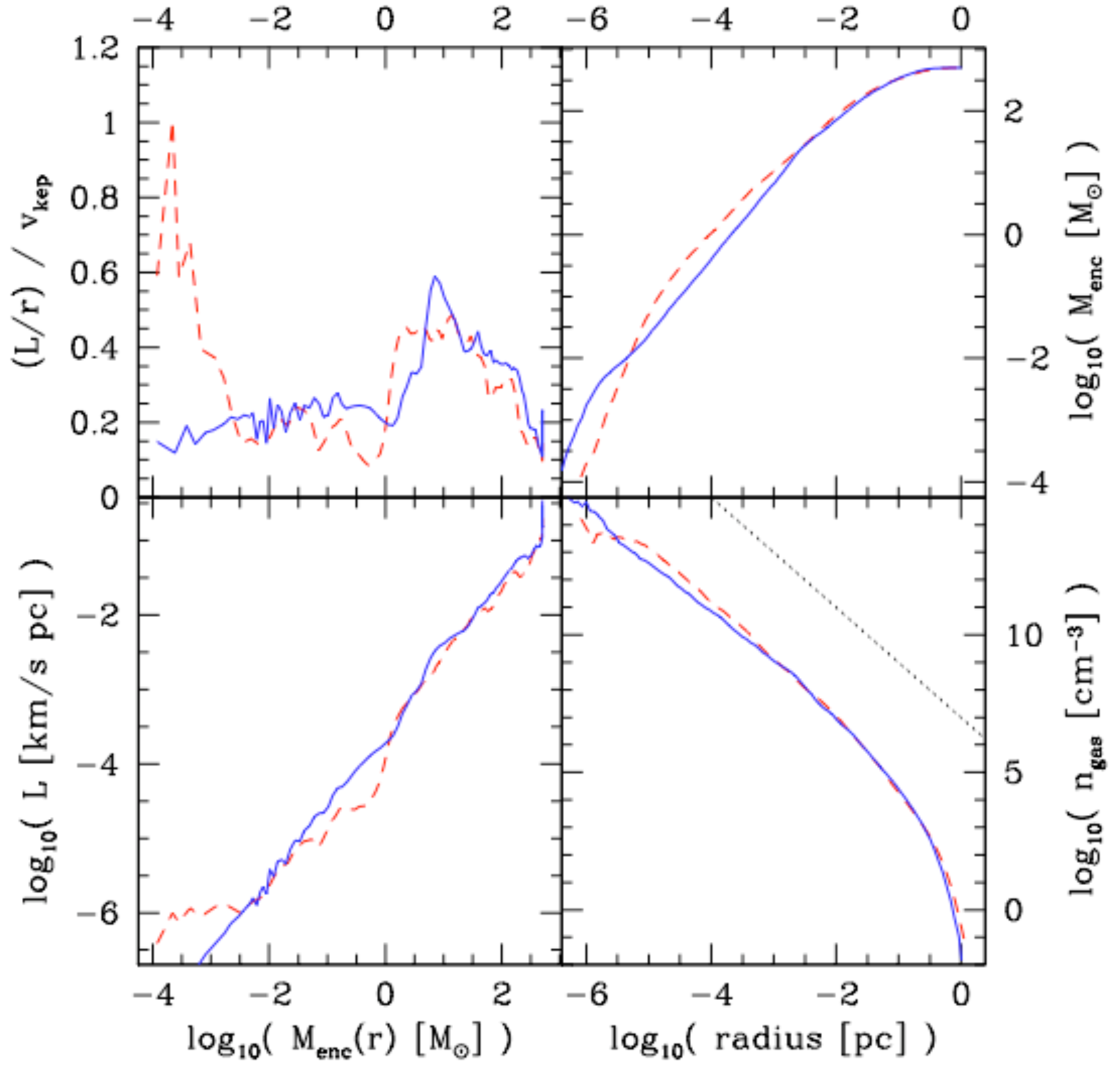
🟦

$\gamma < 1$
(cooling)

(Clark et al. 20

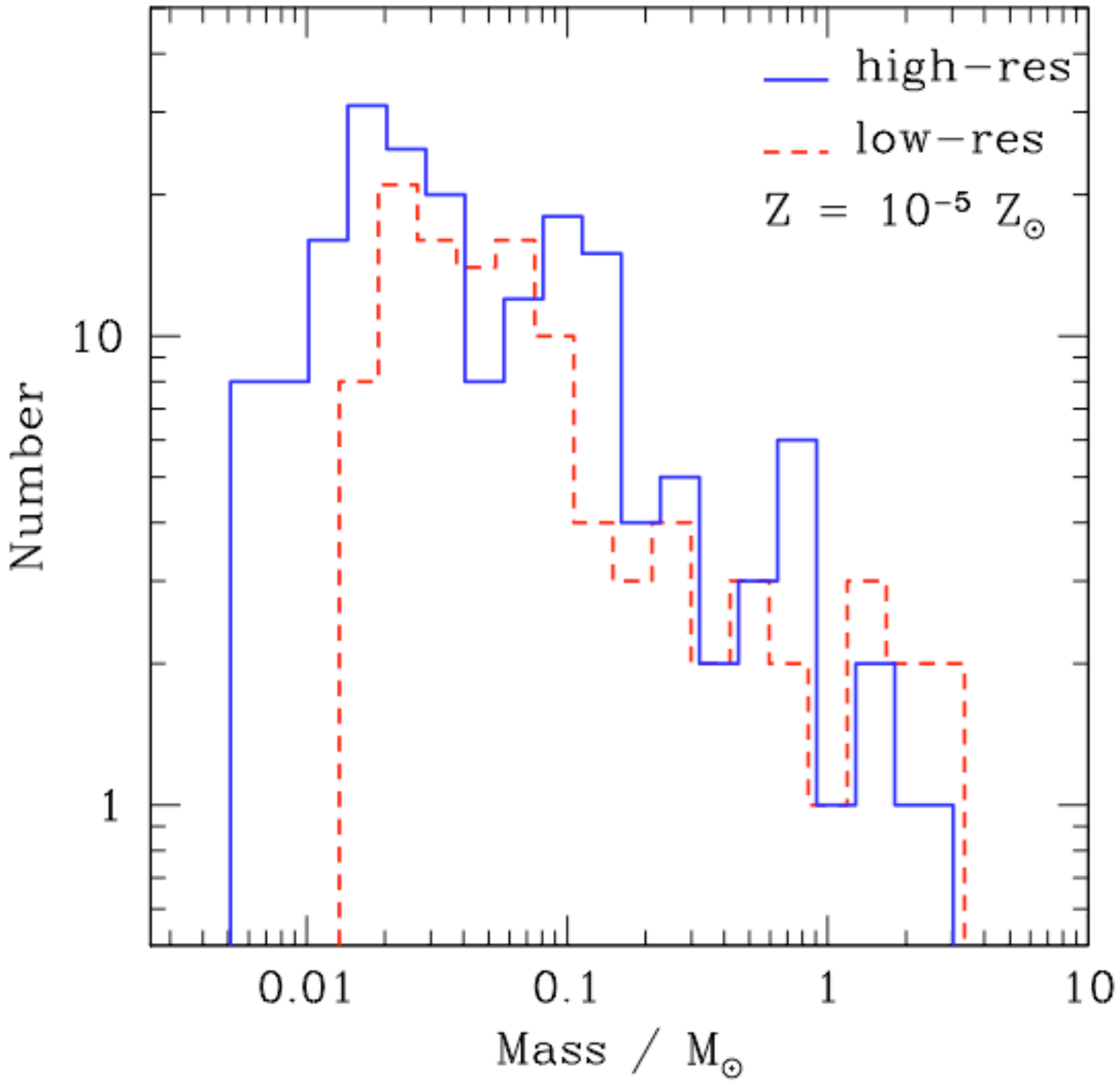
gas properties

gas properties at time when first star forms



(Clark et al. 2007)

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



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(Clark et al. 2007)

comparison for different Z

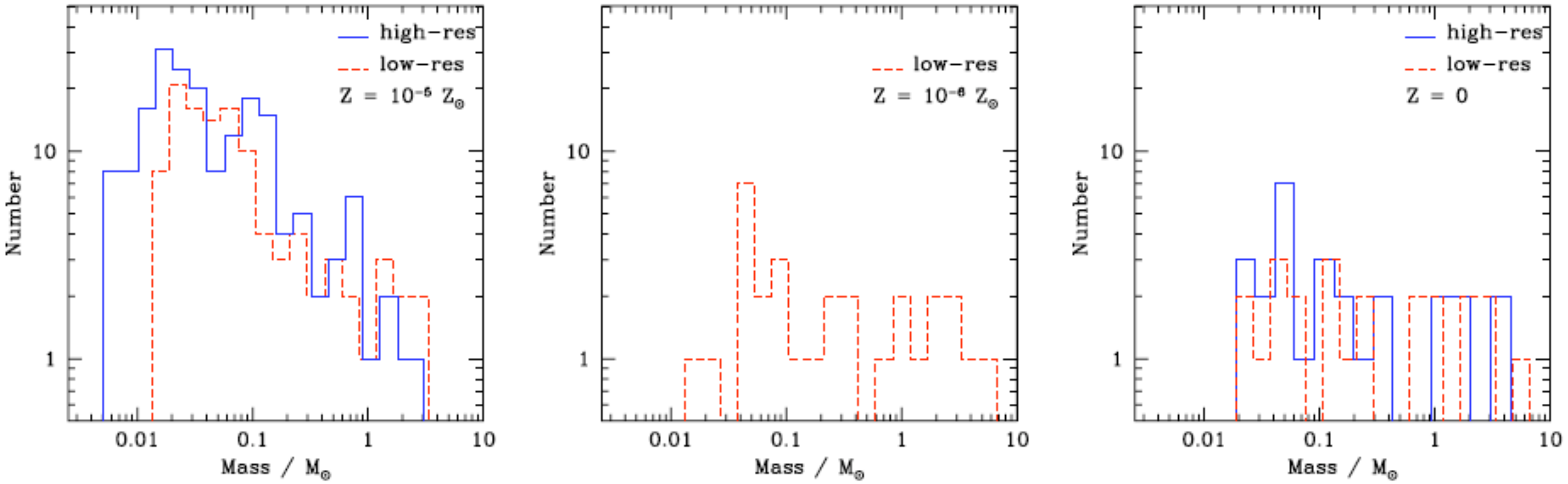


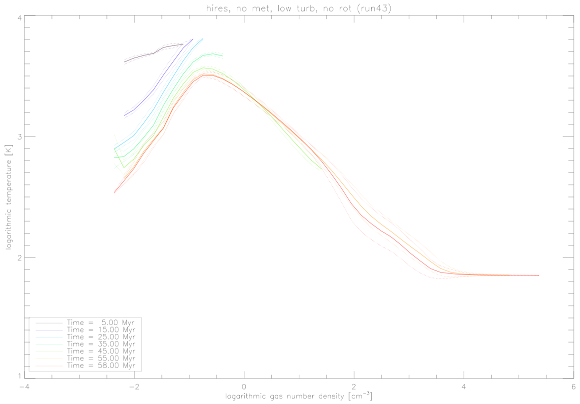
FIG. 4.— Mass functions resulting from simulations with metallicities $Z = 10^{-5}\ Z_\odot$ (left-hand panel), $Z = 10^{-6}\ Z_\odot$ (center panel), and $Z = 0$ (right-hand panel). The plots refer to the point in each simulation at which 19 $M_\odot$ of material has been accreted (which occurs at a slightly different time in each simulation). The mass resolutions are 0.002 $M_\odot$ and 0.025 $M_\odot$ for the high and low resolution simulations, respectively. Note the similarity between the results of the low-resolution and high-resolution simulations. The onset of dust-cooling in the $Z = 10^{-5}\ Z_\odot$ cloud results in a stellar cluster which has a mass function similar to that for present day stars, in that the majority of the mass resides in the lower-mass objects. This contrasts with the $Z = 10^{-6}\ Z_\odot$ and primordial clouds, in which the bulk of the cluster mass is in high-mass stars.

even zero-metallicity case fragments
(although much more weakly)

(Clark et al. 2007)

Simple EOS vs. radiation transfer

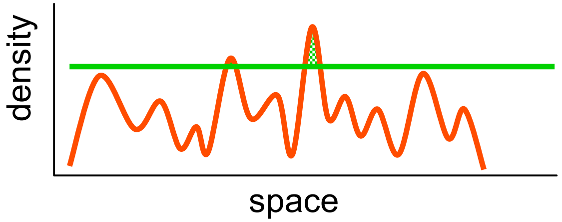
- how good is EOS approach?
  - time to reach chemical and thermal equilibrium shorter than dynamical time?
  - how does EOS depend on dynamics? (e.g. 1D collapse with large-gradient approx. versus complex 3D turbulent flows)



- how important is heating from stars?
  - accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)
- how can we model that best?
  - full radiation transfer vs. approximate schemes

Summary

Summary I



- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates density contrast, *gravity* selects for collapse

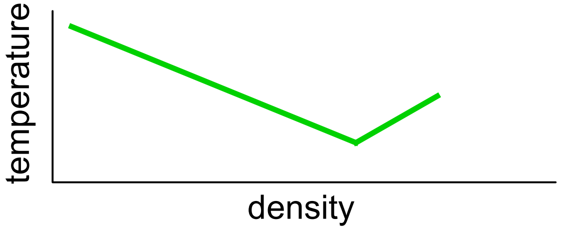
→ ***GRAVOTUBULENT FRAGMENTATION***

- *turbulent cascade:* local compression *within* a cloud provokes collapse → formation of individual *stars* and *star clusters*
- *star cluster:* gravity dominates in large region (--> competitive accretion)

(e.g. Mac Low & Klessen, 2004, Ballesteros-Paredes et al. 2006, McKee & Ostriker 2007)

Summary II

- *thermodynamic response* (EOS) determines fragmentation behavior
  - characteristic stellar mass from fundamental atomic and molecular parameters
    --> explanation for quasi-universal IMF?



- *stellar feedback* is important
  - accretion heating may reduce degree of fragmentation
  - ionizing radiation will set efficiency of star formation
- *CAVEATS:*
  - star formation is *multi-scale, multi-physics* problem --> VERY difficult to model
  - in simulations: very small turbulent inertial range (Re < 1000)
  - can we use EOS to describe thermodynamics of gas, or do we need time-dependent chemical network and radiative transport?
  - stellar feedback requires (at least approximative) radiative transport, most numerical calculations so far have neglected that aspect

(e.g. Mac Low & Klessen, 2004, Ballesteros-Paredes et al. 2006, McKee & Ostriker 2007)

Thanks!