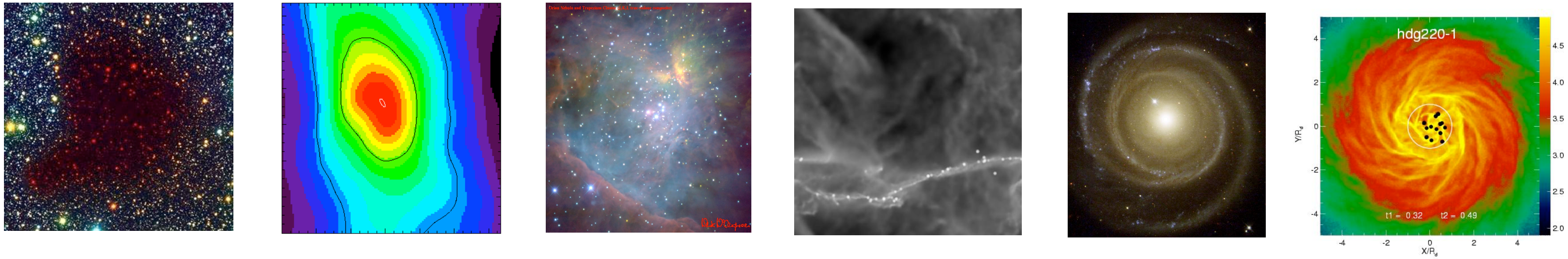
Star Formation in the Turbulent Interstellar Gas



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Research Areas

- planet formation
- star formation
- galaxy formation and dynamics
- galaxy clusters
- gravitatioal lensing
- cosmology

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Agenda

- phenomenology
  - from large to small scales
- interplay between gravity and turbulence
- examples and predictions
  - star cluster formation: dynamics
  - star cluster formation: thermodynamics
    --> stellar initial mass function

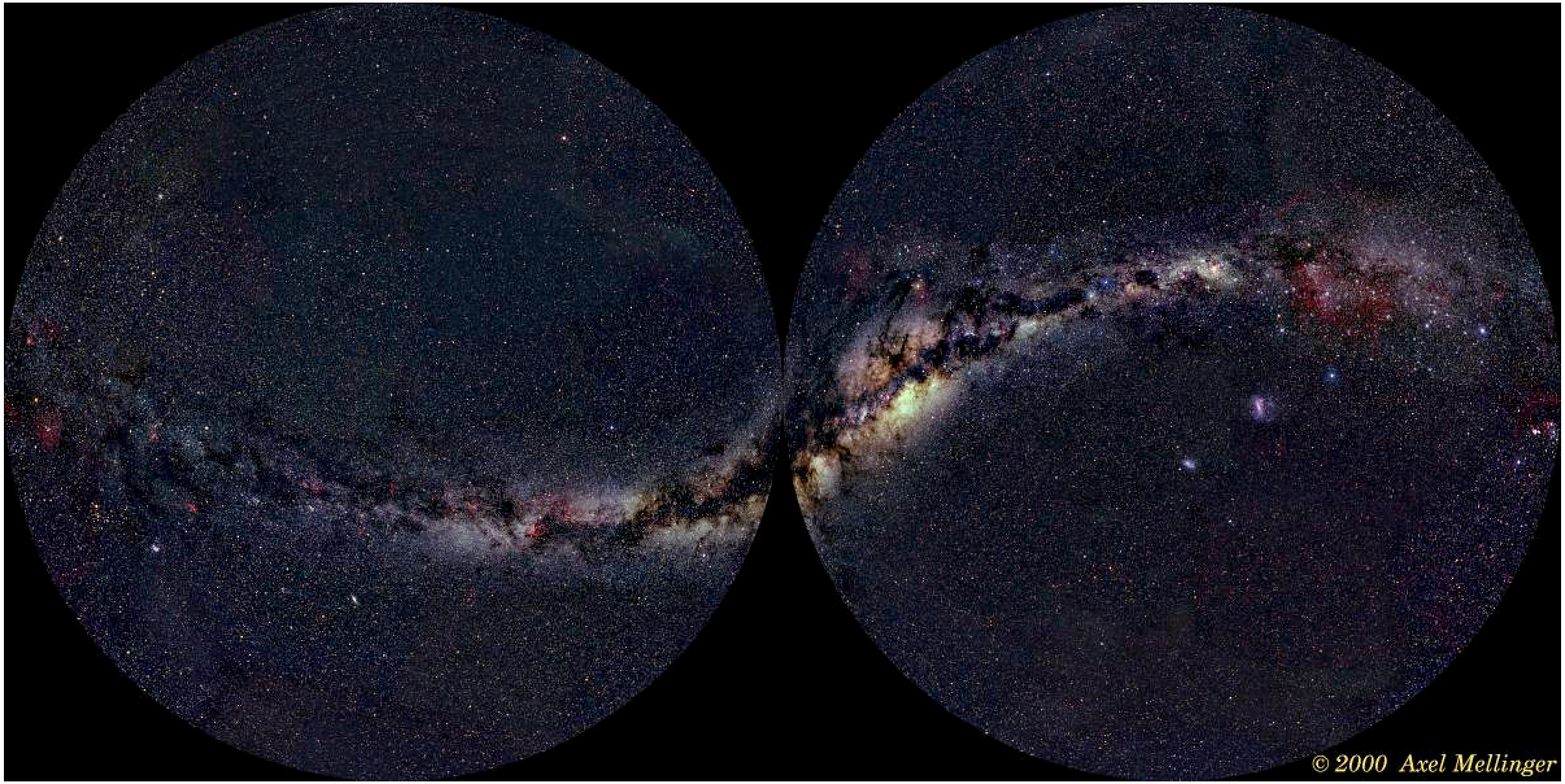
phenomenology

young stars in spiral galaxies

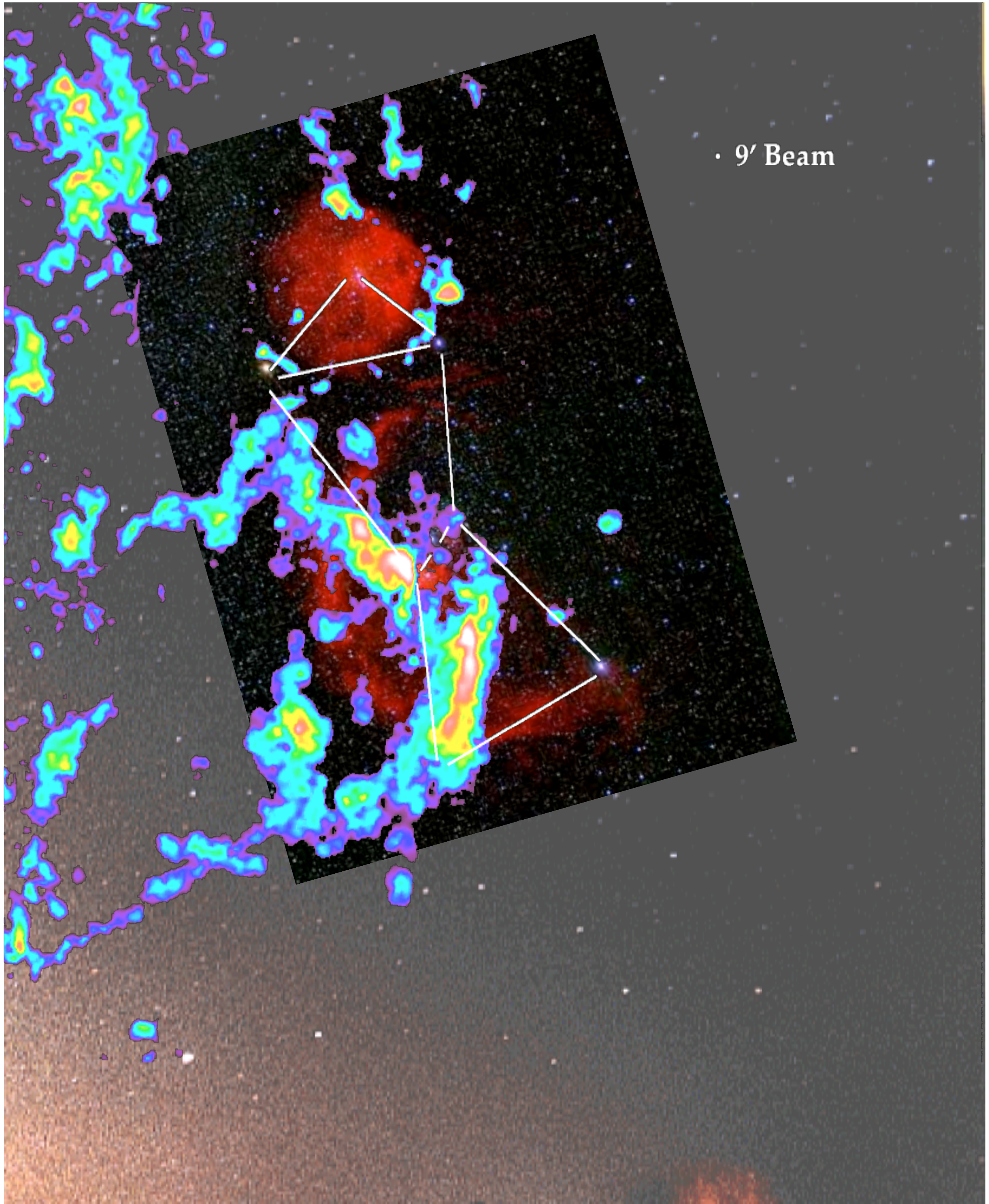
(NGC 4622 from the Hubble Heritage Team)

- Star formation *always* is associated with *clouds of gas and dust*.
- Star formation is essentially a *local phenomenon* (on ~pc scale)
- HOW is star formation is *influenced* by *global* properties of the galaxy?

young stars in the Milky Way



On the night sky, you see ***stars*** and ***dark clouds***:
The brightest stars are massive and therefore young.
→ Star formation is important for understanding the structure of our Galaxy

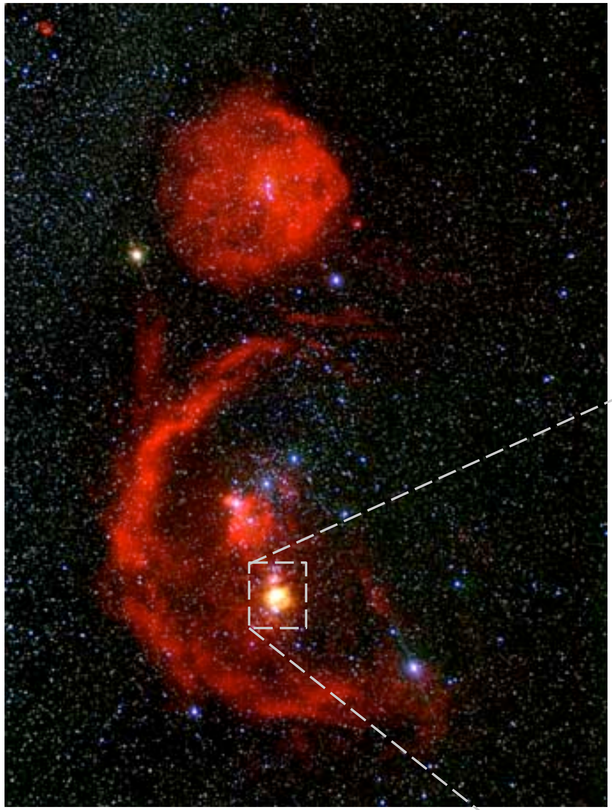


Star formation in Orion

We see

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

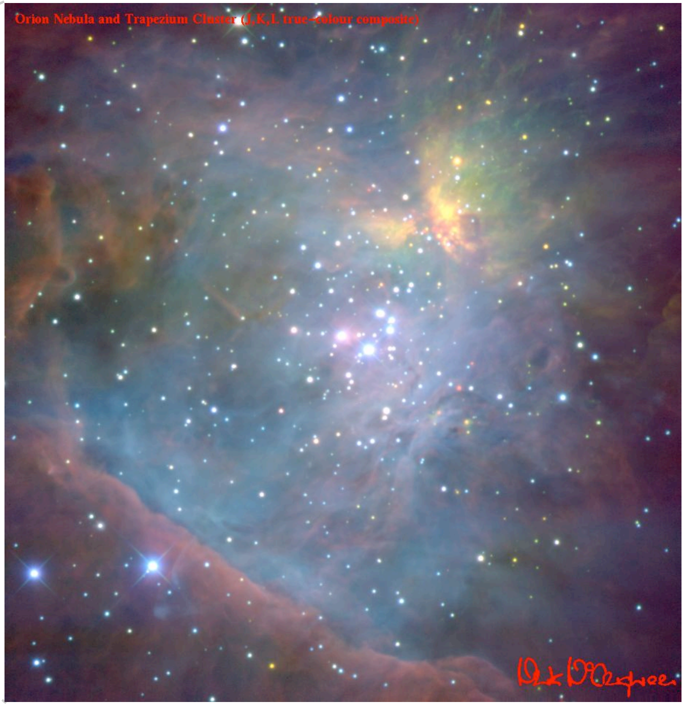
Local star forming region: The Trapezium Cluster in Orion



Orion molecular cloud

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

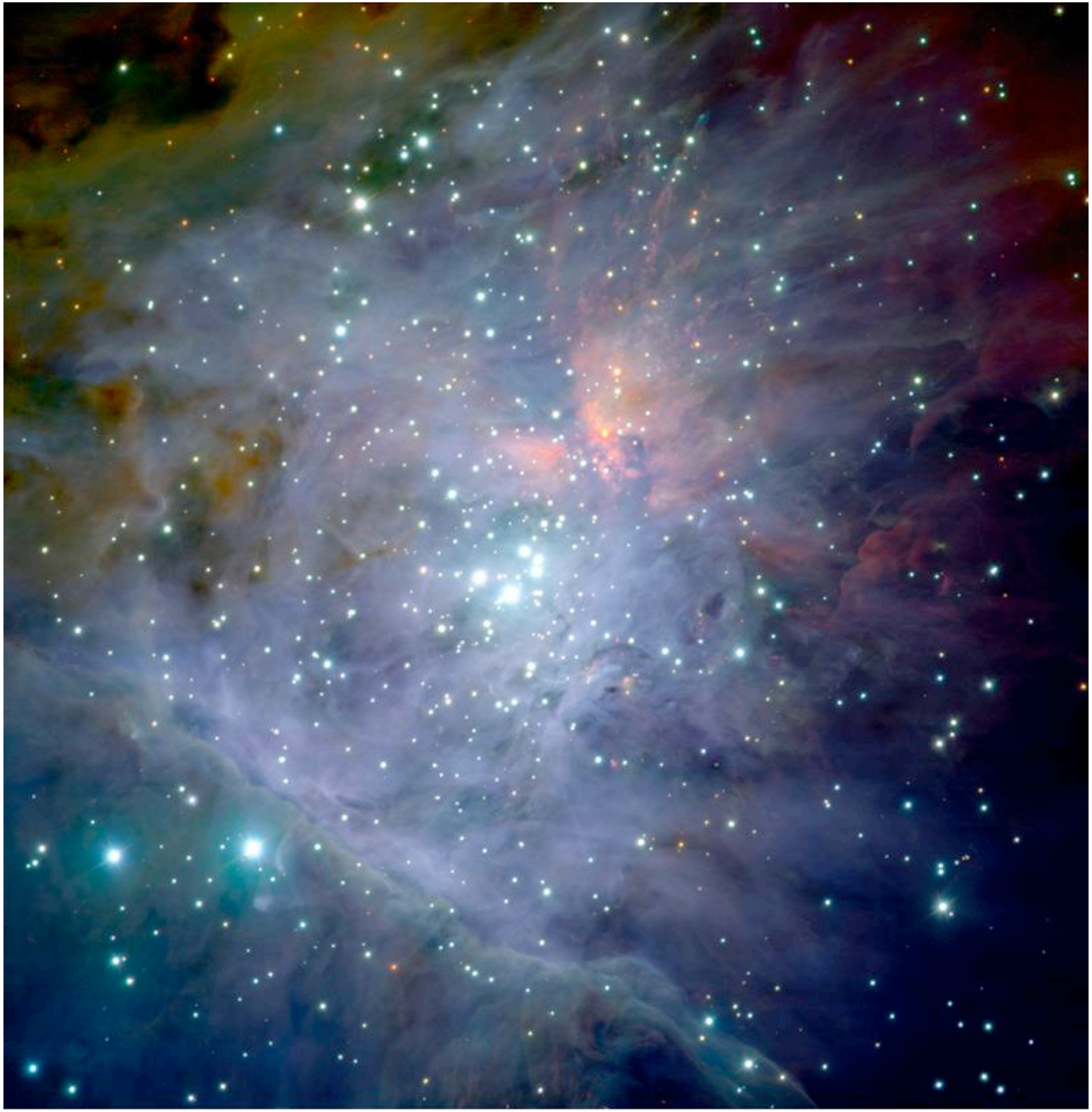
The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster

Trapezium Cluster

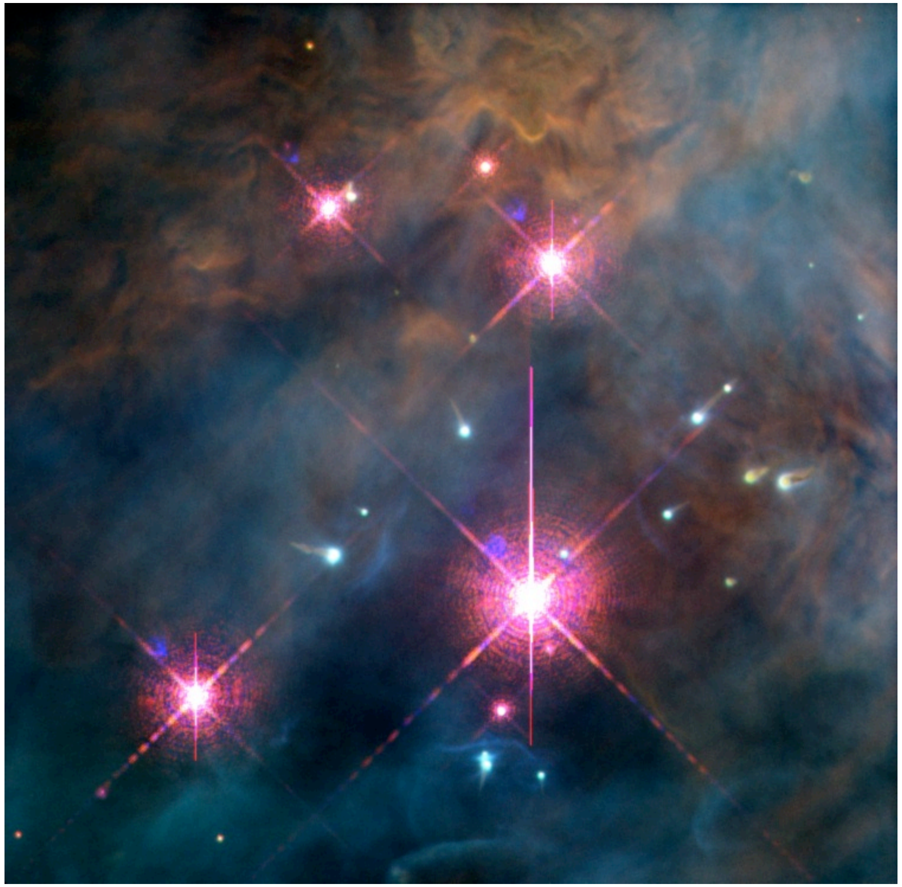
(detail)



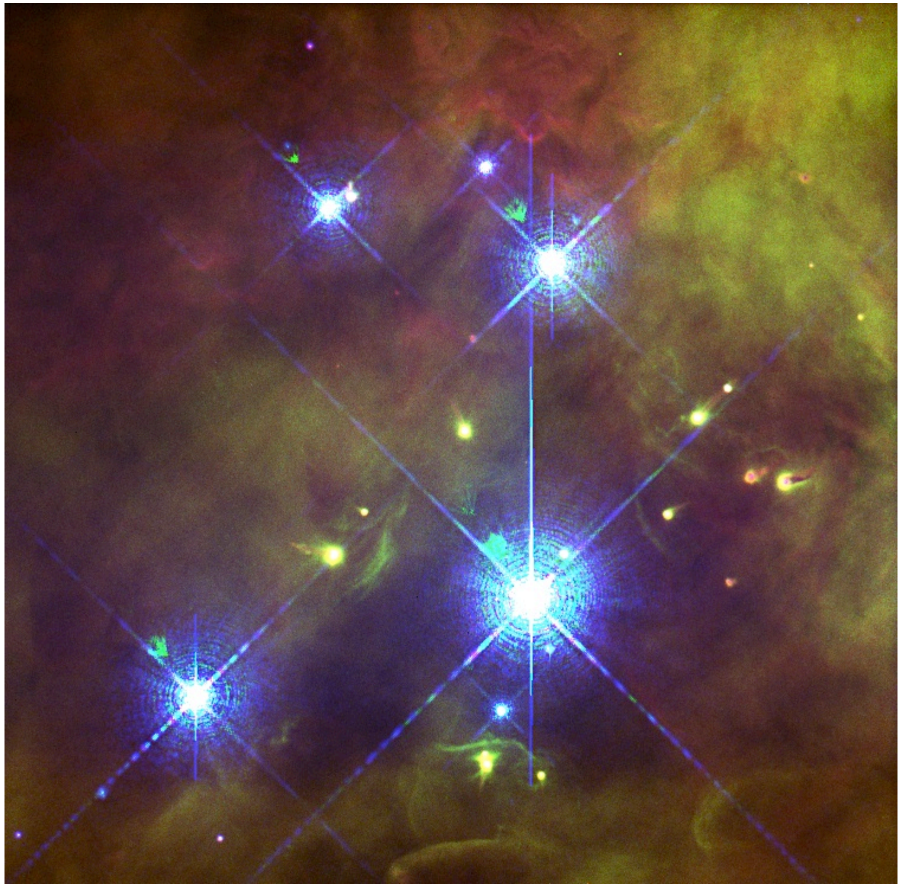
- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

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

Trapezium Cluster: Central Region



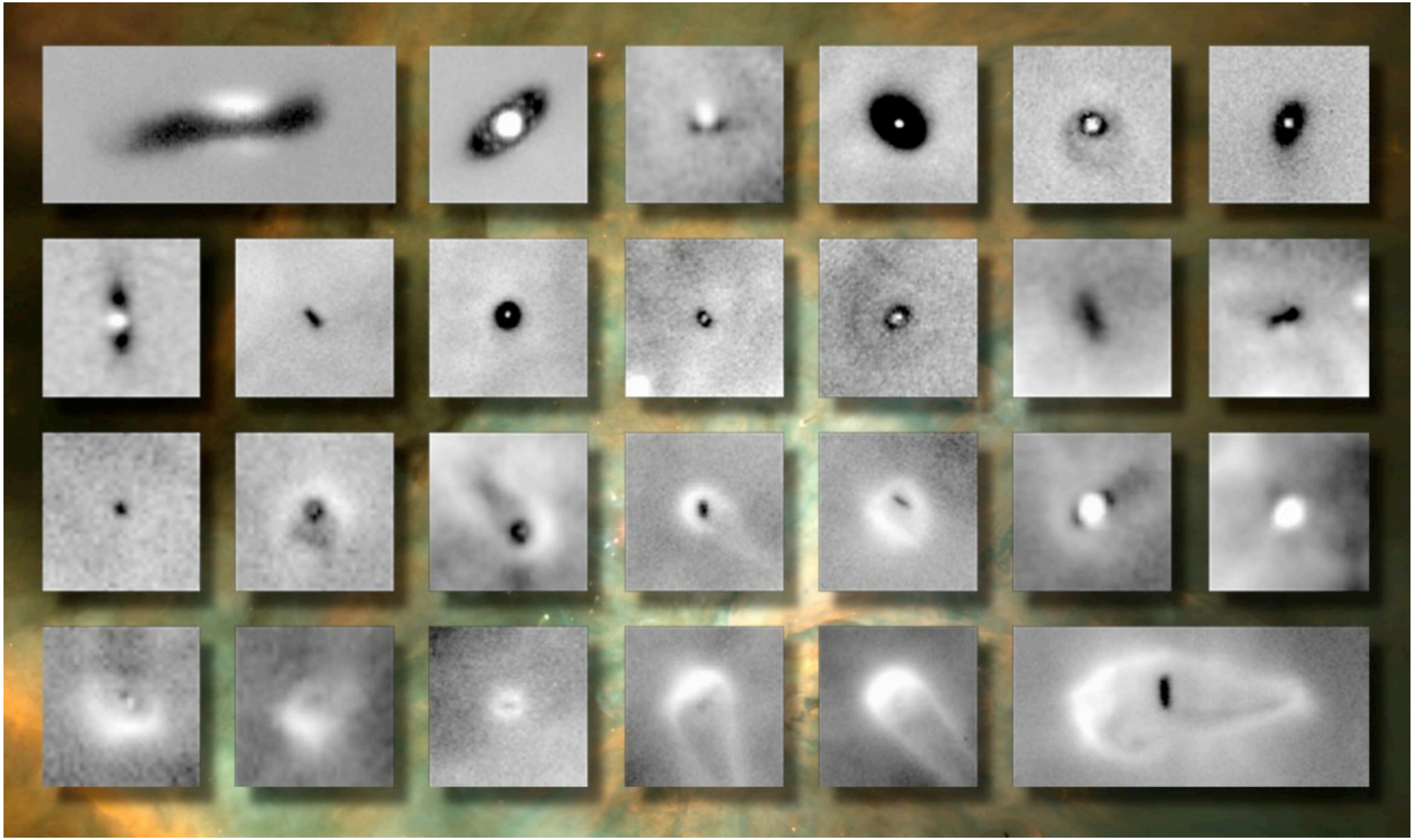
Ionizing radiation from central star **Θ1C Orionis**



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

(images: Doug Johnstone et al.)

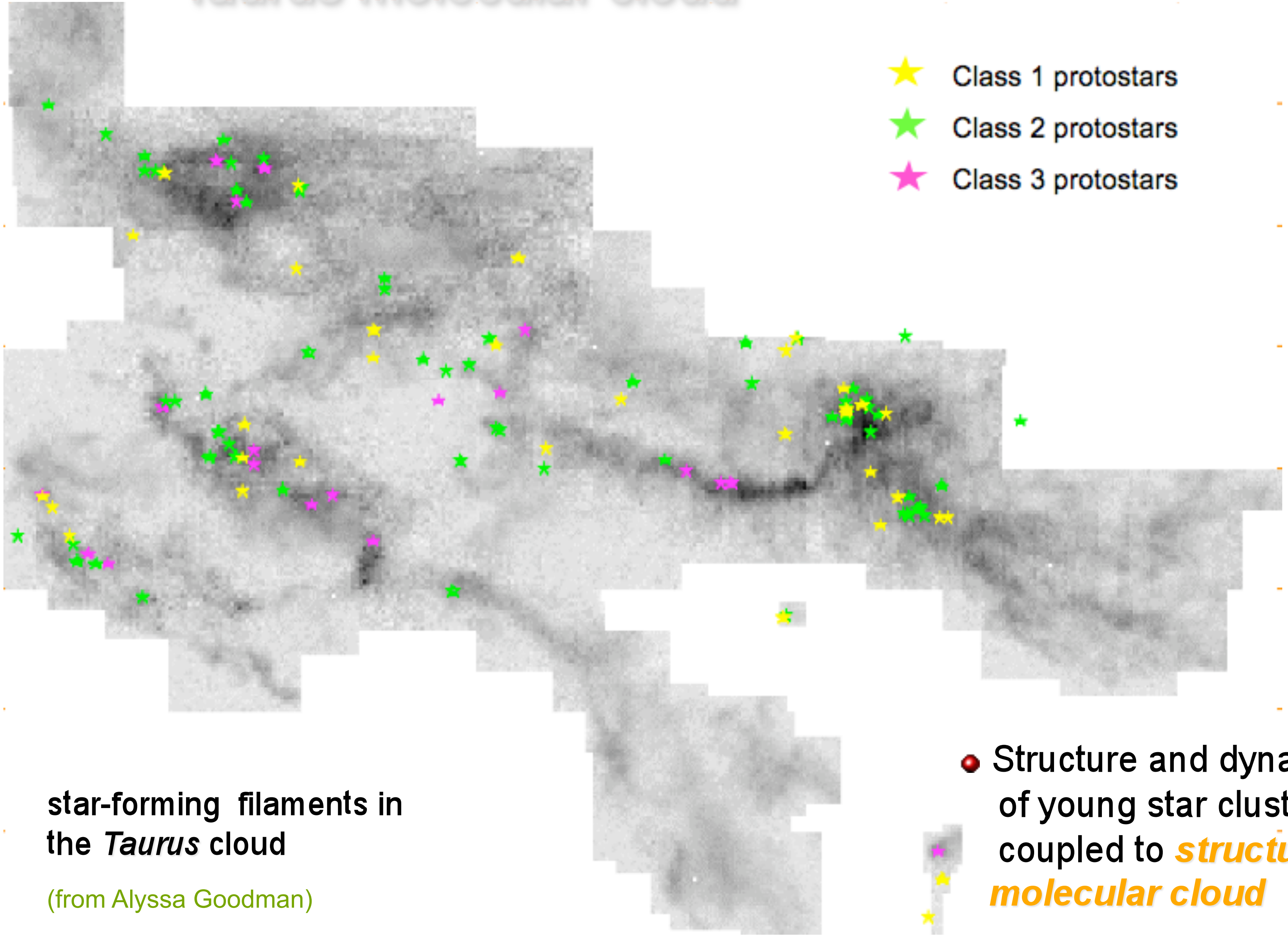
Futher Details: Siluette Disks in Orion



protostellar disks: dark shades in front of the photodissociation region in the background. Each image is 750 AU x 750 AU.

(data: Mark McCaughrean)

Taurus molecular cloud



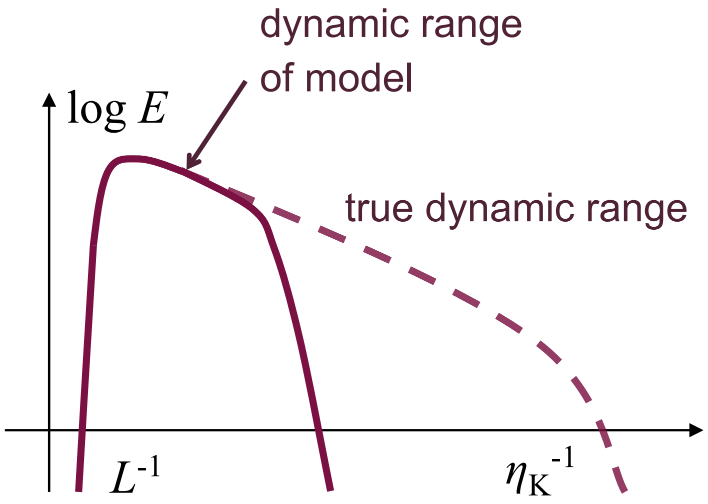
star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

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

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?



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:

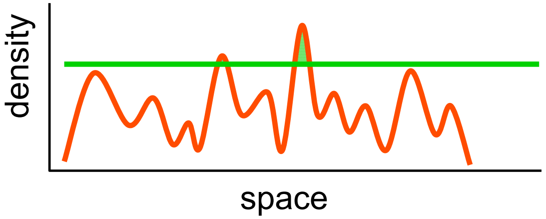
Star formation is controlled by interplay between gravity and supersonic turbulence!

- 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 $\delta\rho/\rho \propto M^2$; 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 → molecular**
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($M \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

→ ***GRAVOTUBULENT FRAGMENTATION***

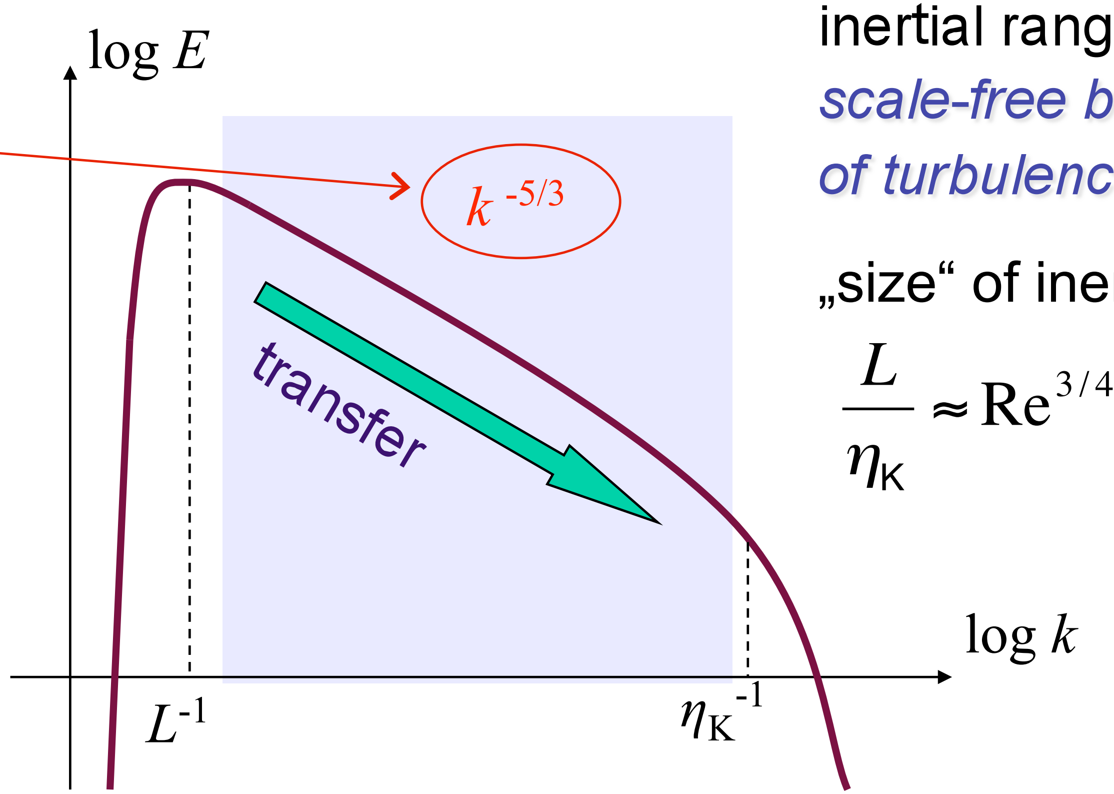
- *turbulent cascade:* local compression *within* a cloud provokes collapse
  → formation of individual *stars* and *star clusters*

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

turbulence

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:

scale-free behavior of turbulence

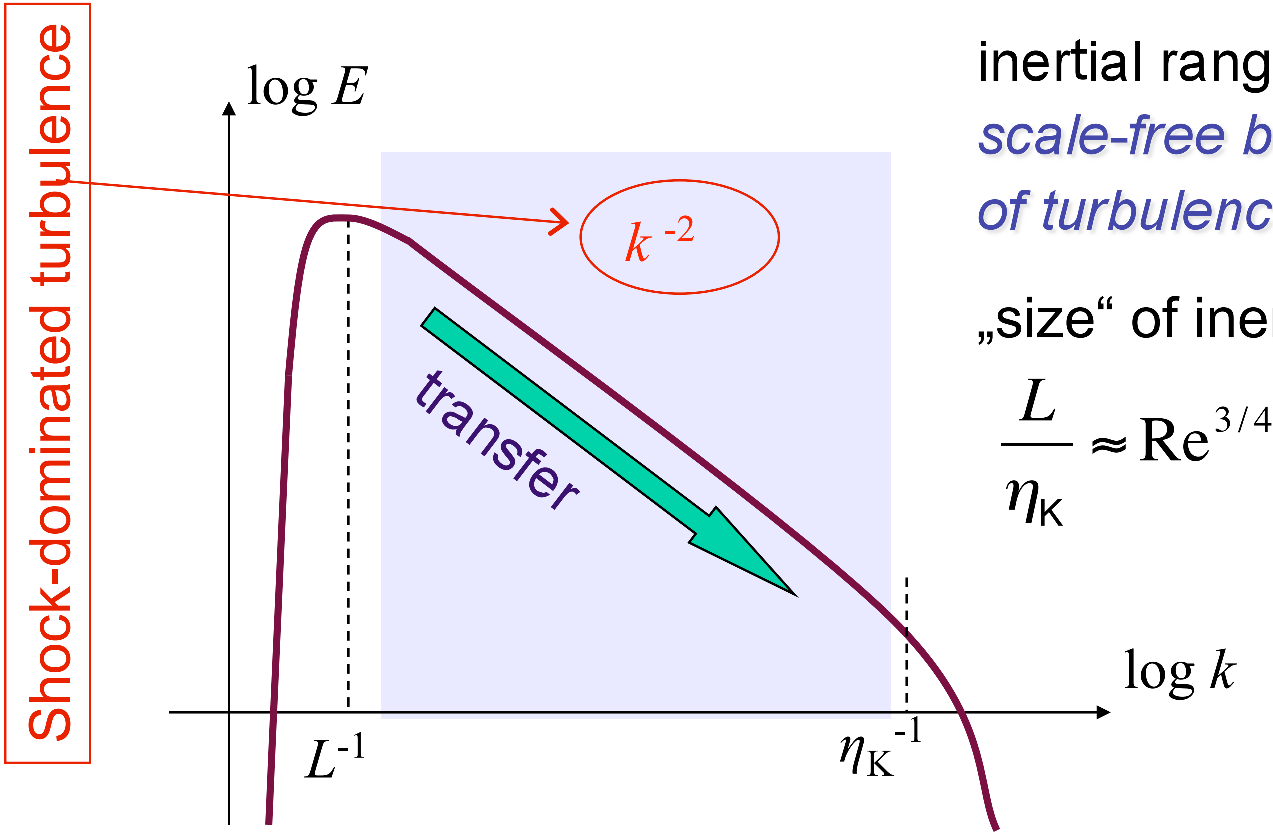
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:

scale-free behavior of turbulence

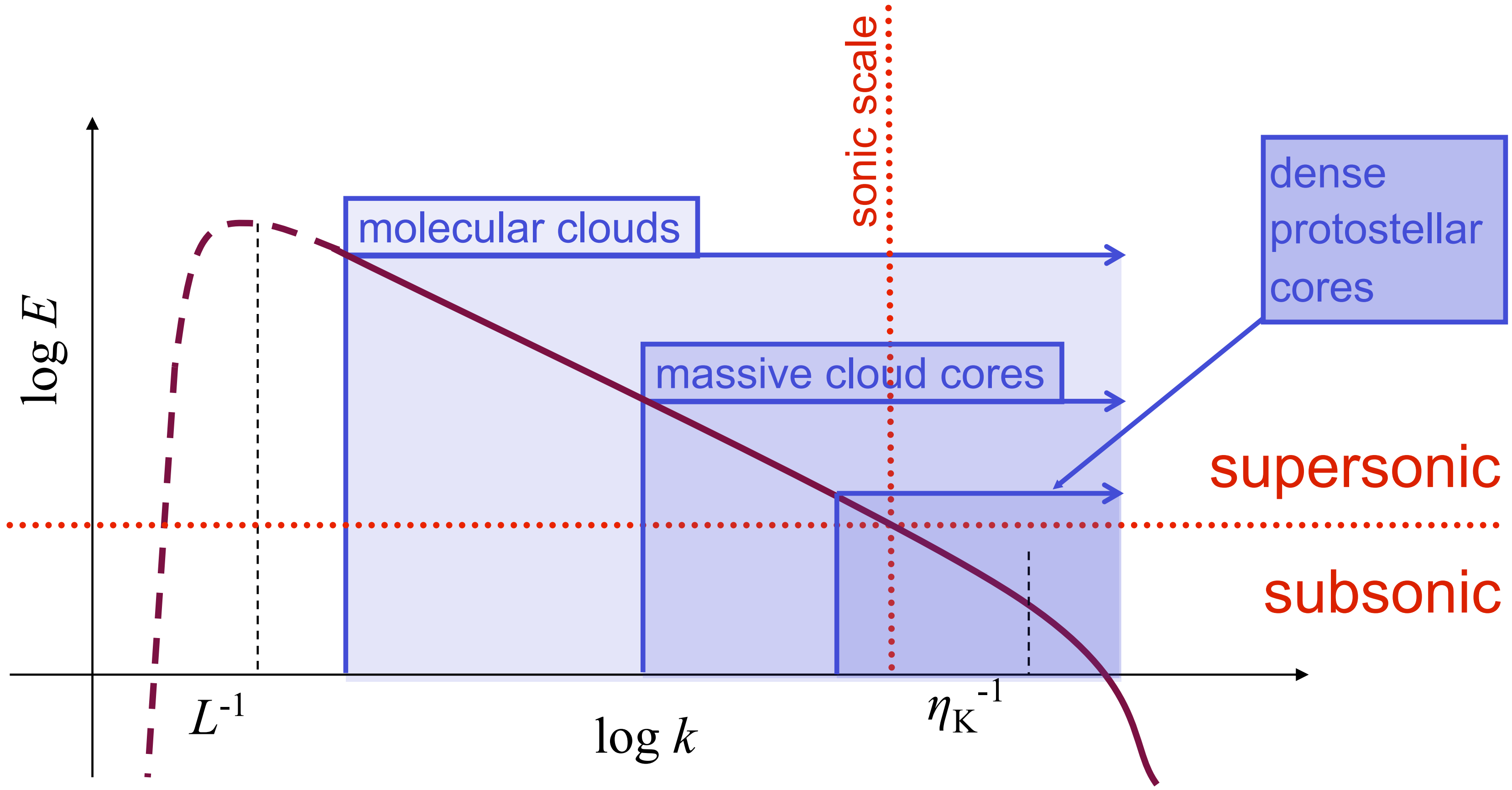
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM

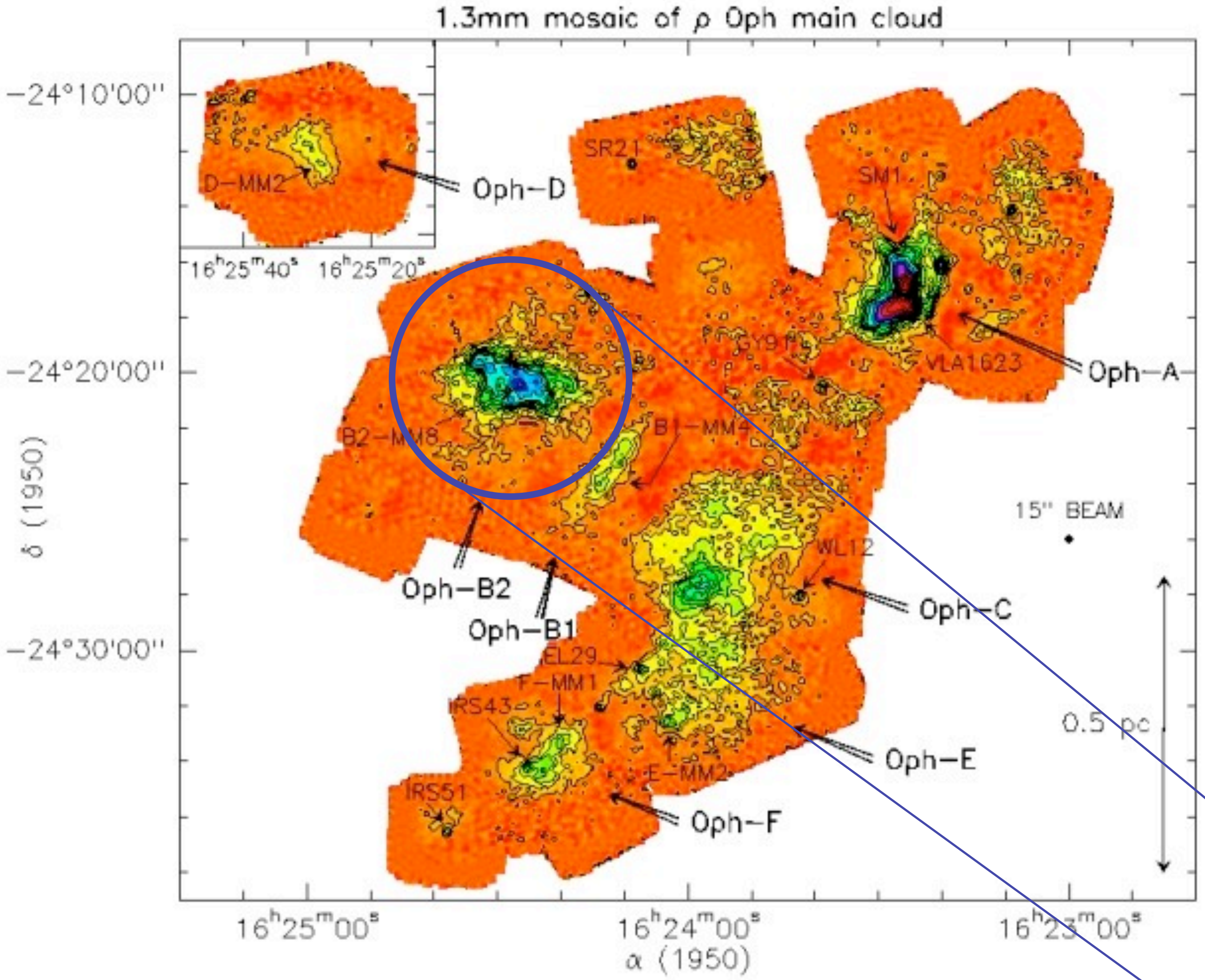


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

σ_{rms} << 1 km/s'sm/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

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

Density structure of MC’s



(Motte, André, & Neri 1998)

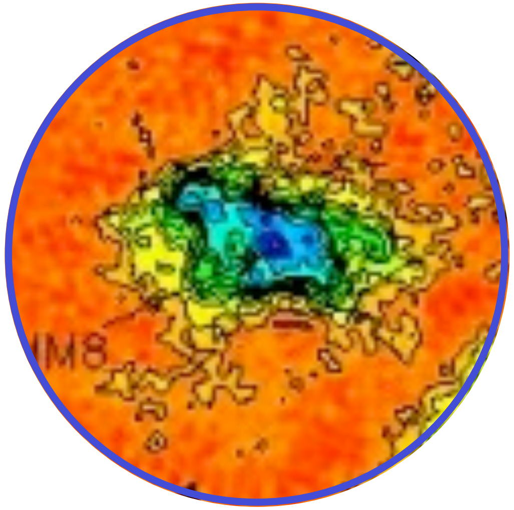
molecular clouds are highly inhomogeneous

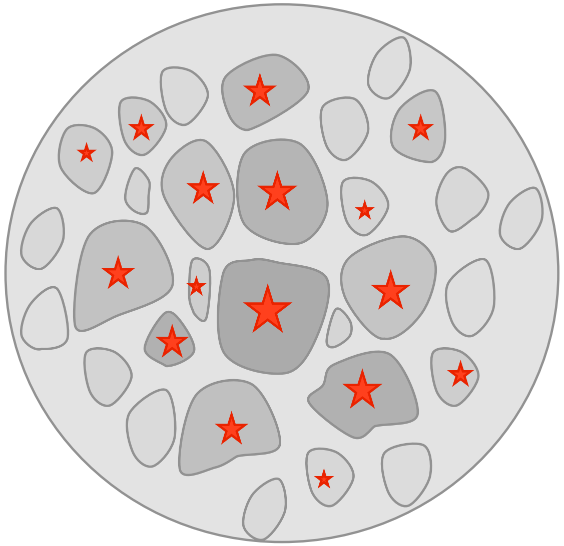
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let‘s focus on a cloud core like this one

Evolution of cloud cores

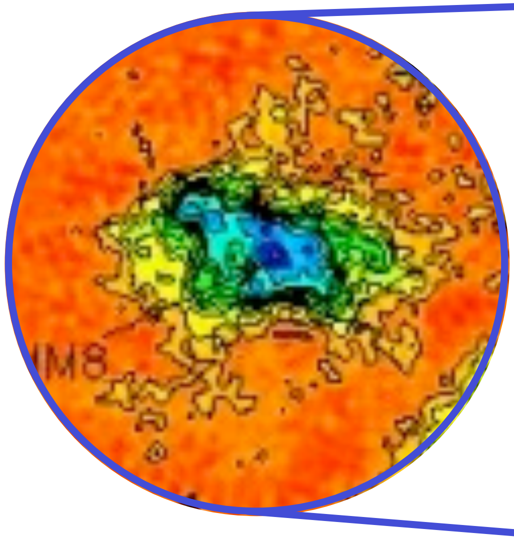


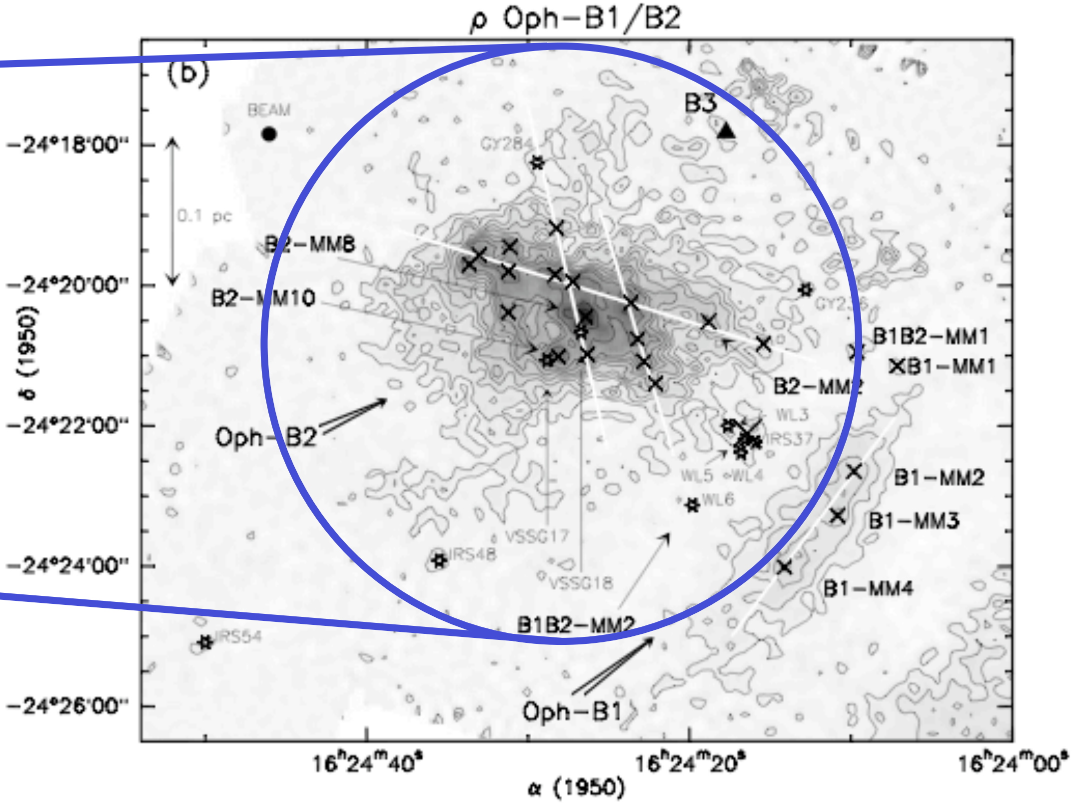


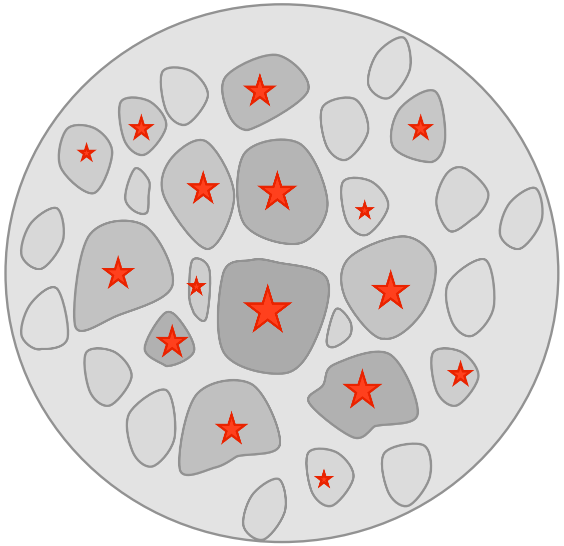
- How does this core evolve?
  Does it form one single massive star
  or cluster with mass distribution?

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



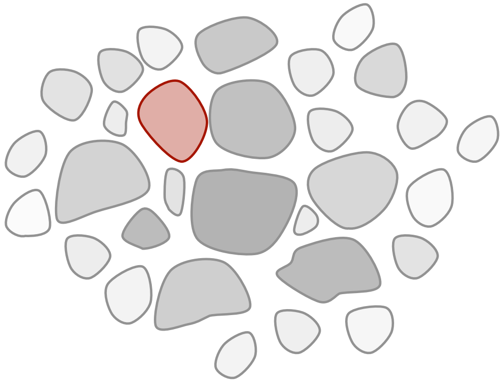




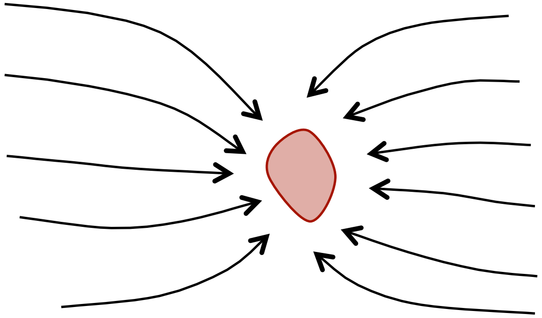
indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

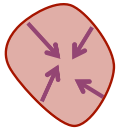
(Motte, André, & Neri 1998)

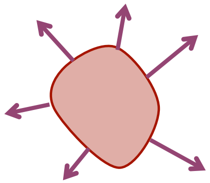
Formation and evolution of cores



- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*







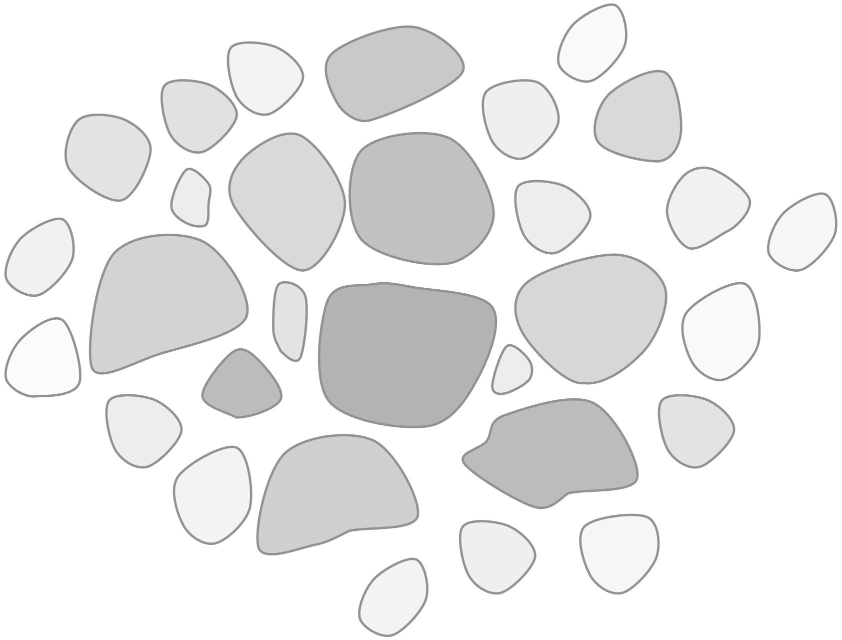
- if $M > M_{crit} \propto \rho^{-1/2} T^{3/2}$: collapse & star formation
- pf $M < M_{crit} \propto \rho^{-1/2} T^{3/2}$: reexpansion after end of external compression

(e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

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*

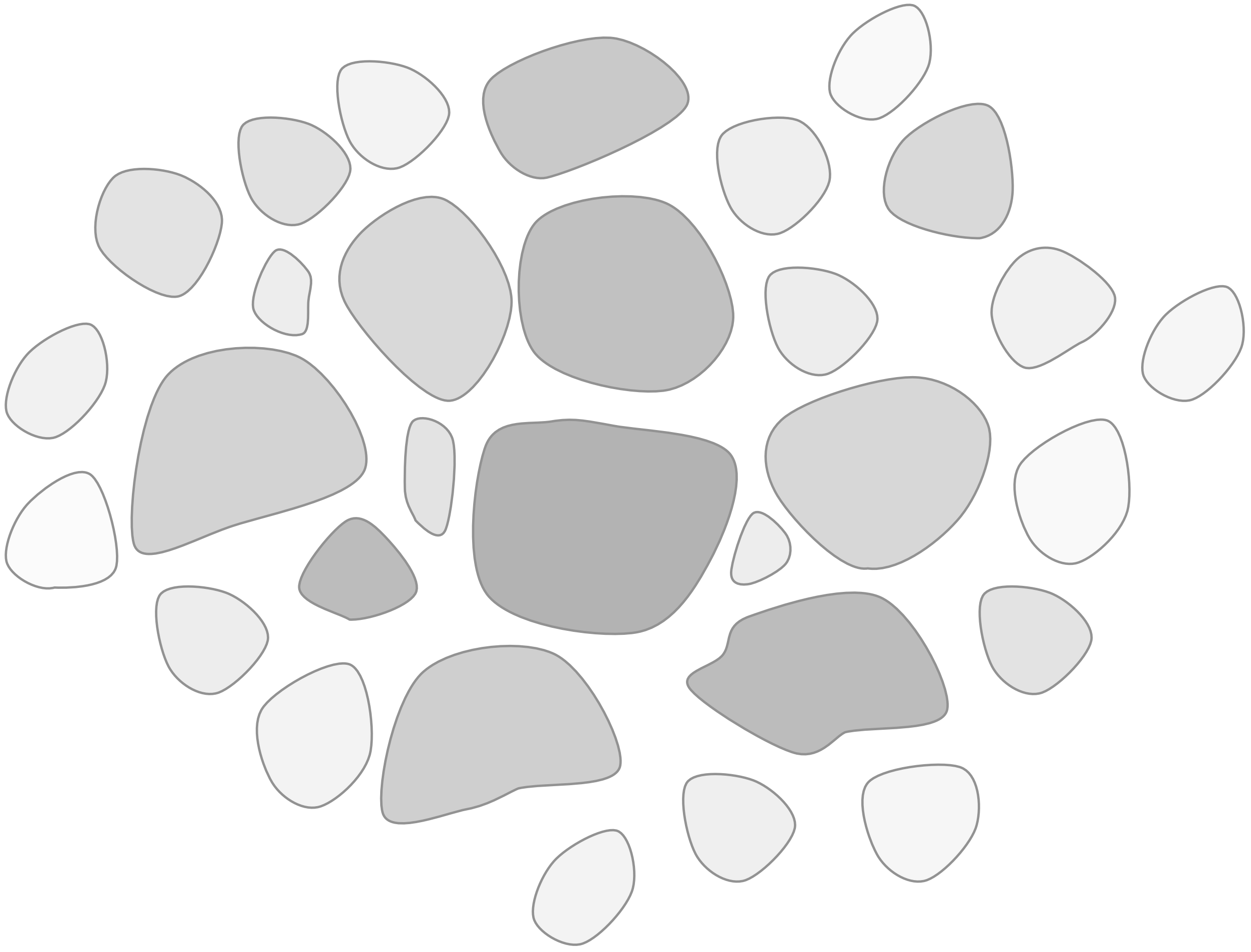
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

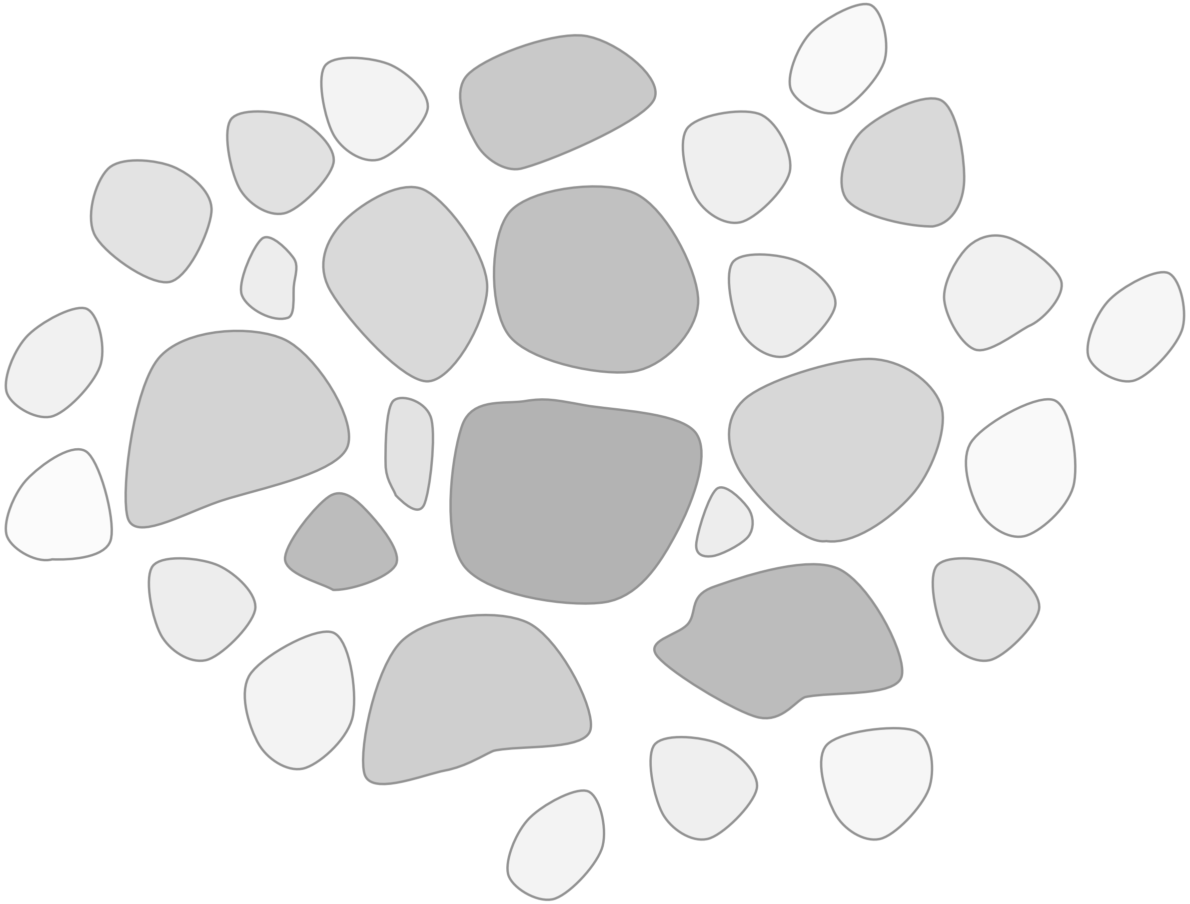
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

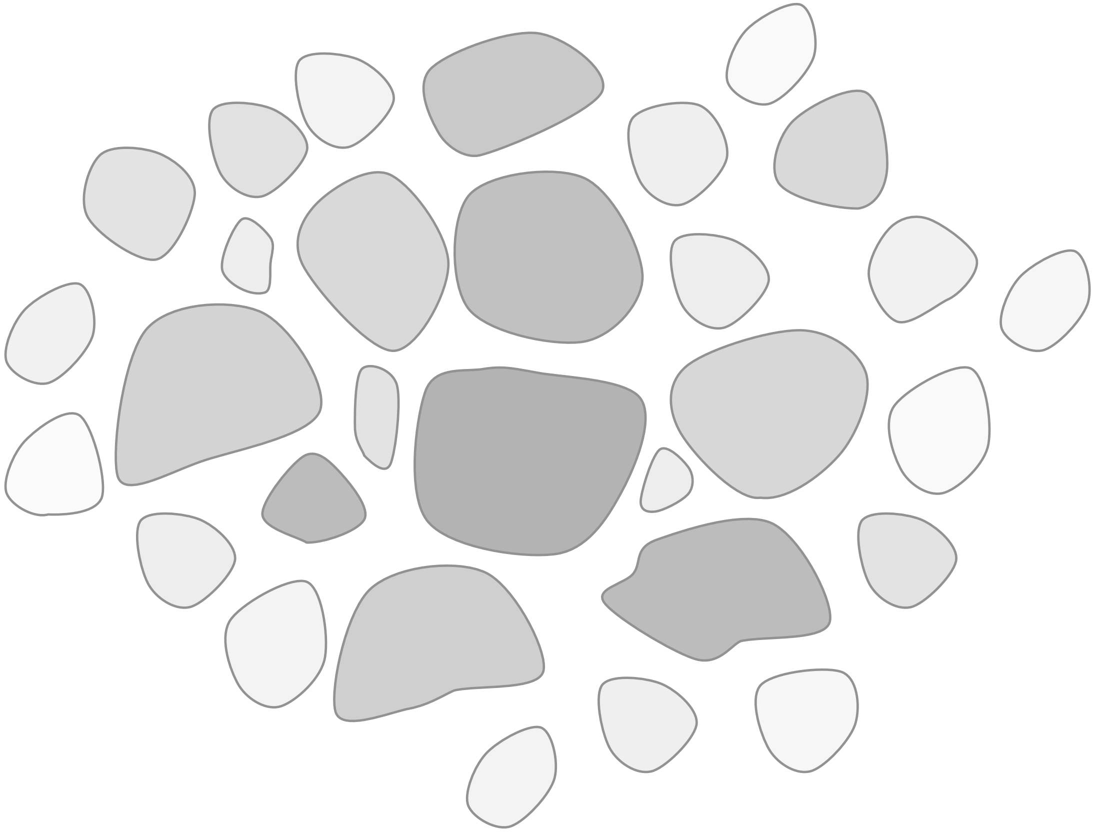
--> *dense cluster with high-mass stars*



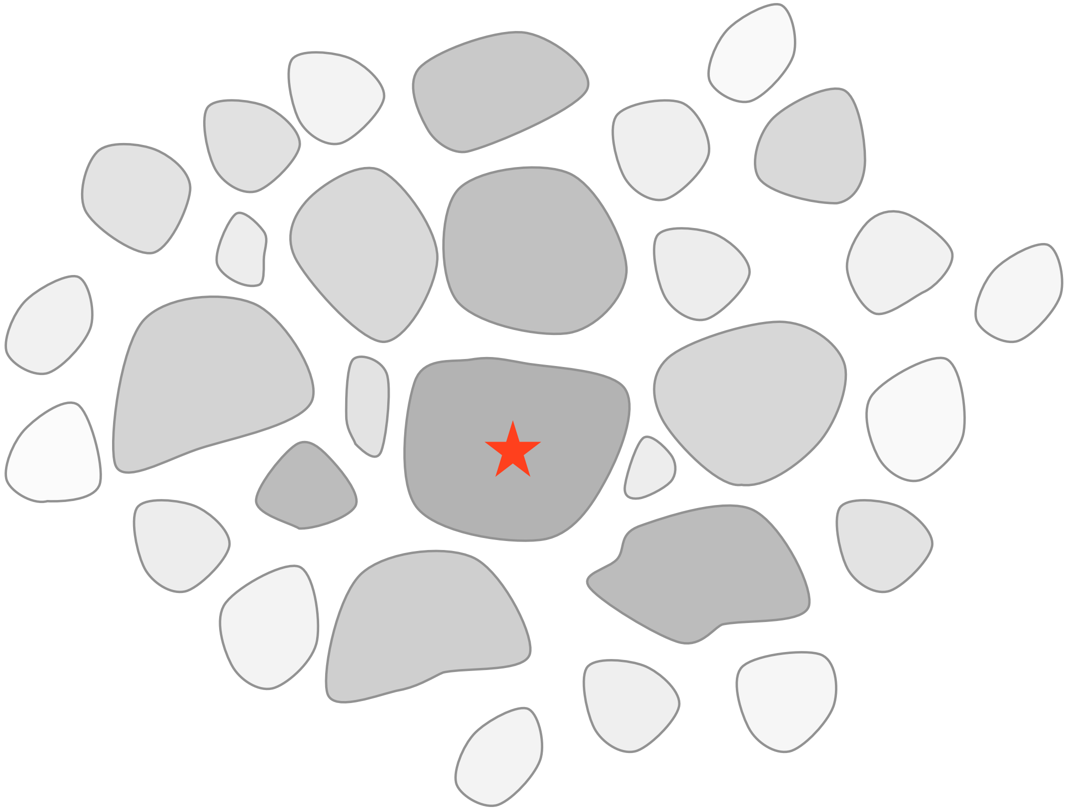
turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



while region contracts, individual clumps collapse to form stars



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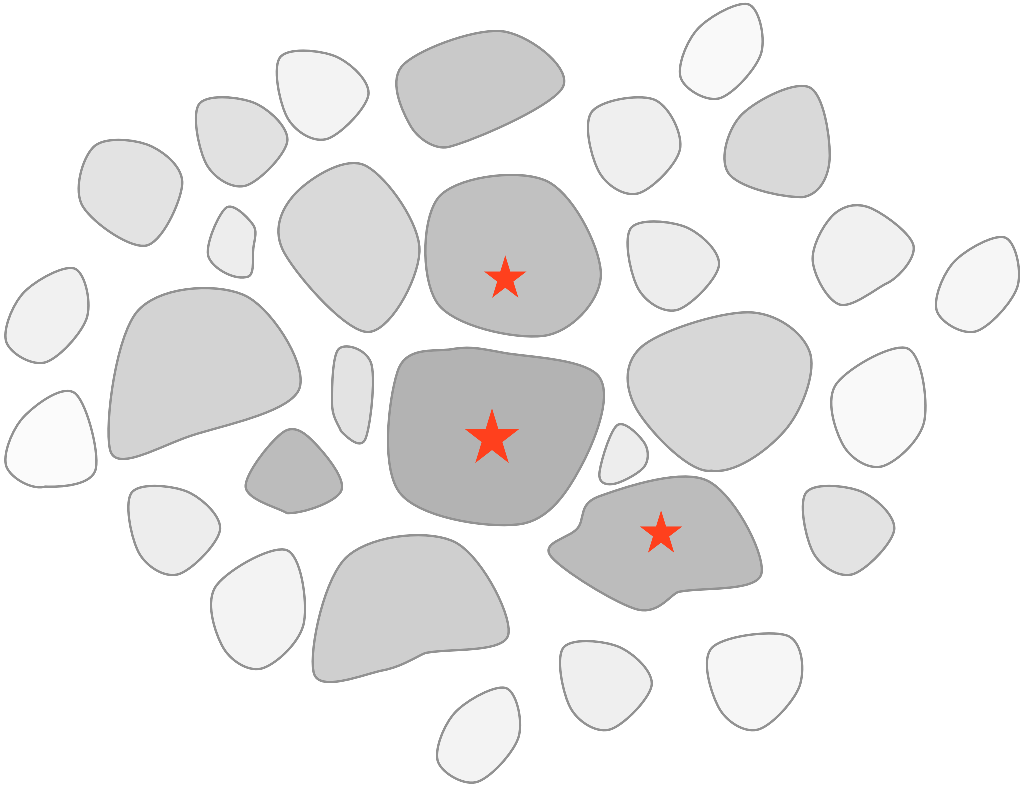
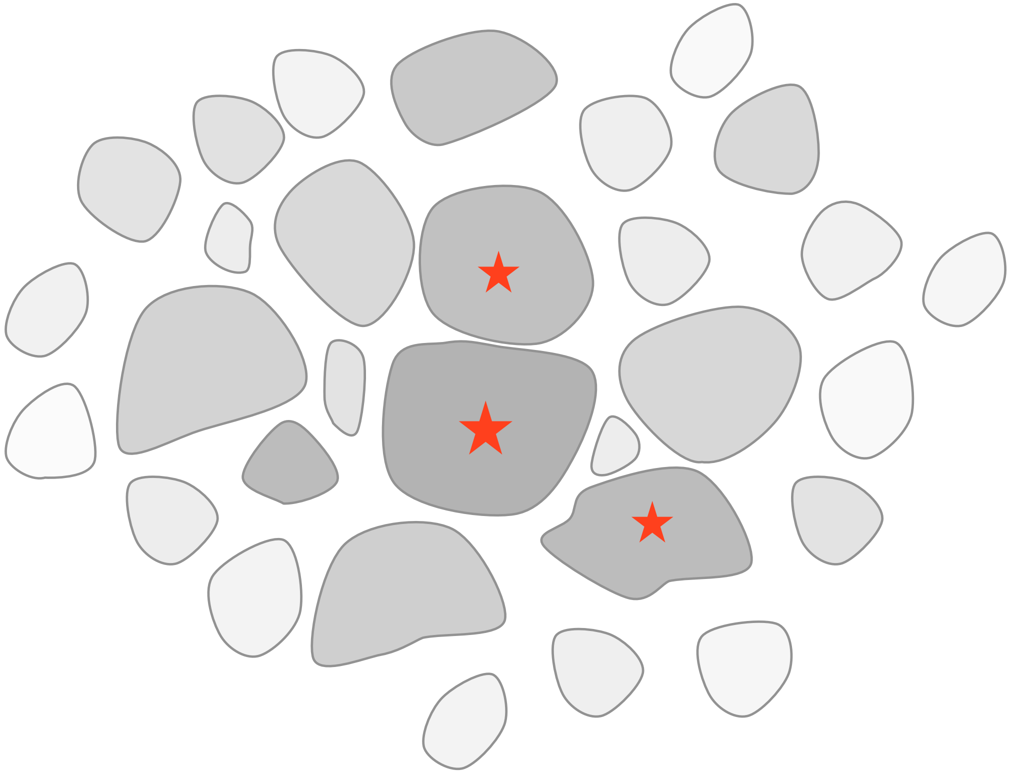
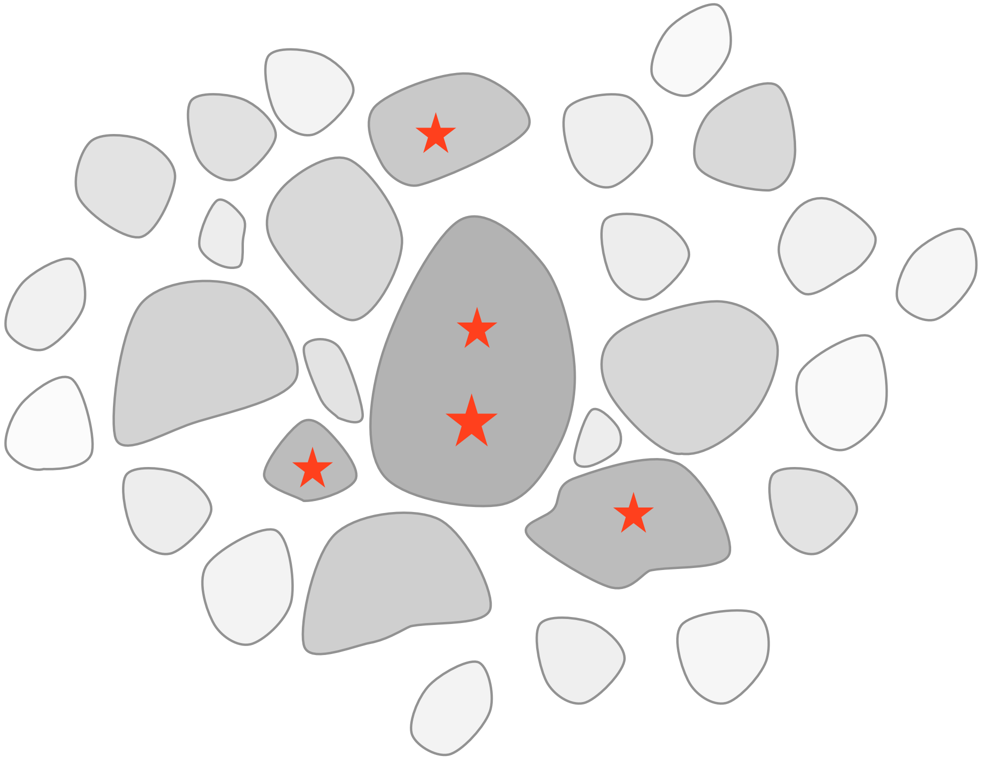


individual clumps collapse to form stars



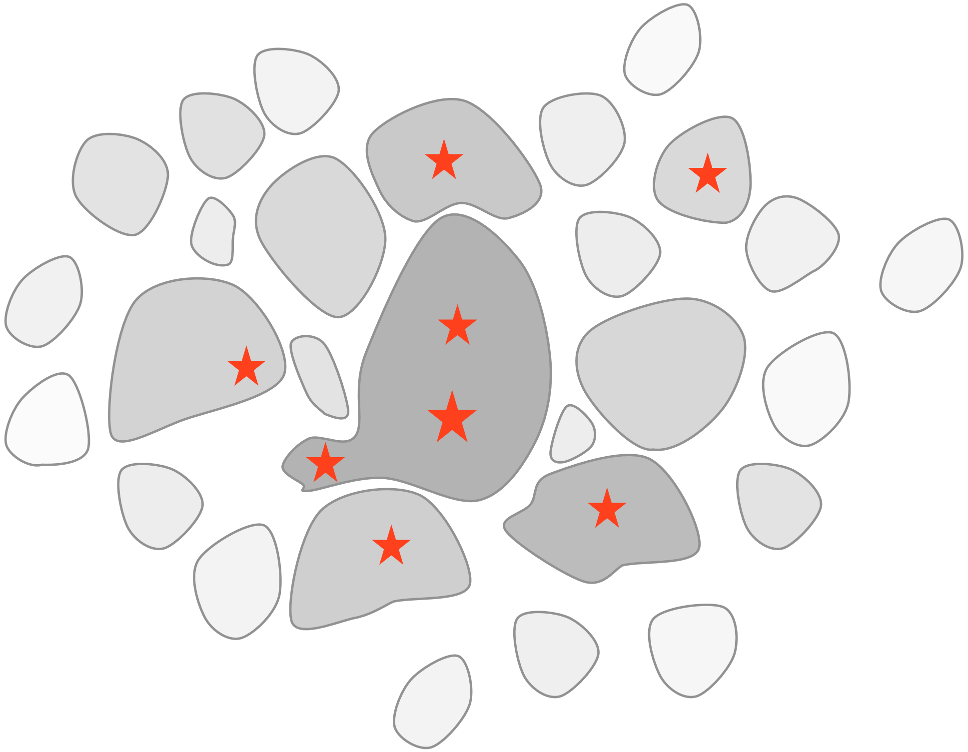
individual clumps collapse to form stars

Ralf Klessen: Nanjing, 31.03.2008



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

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



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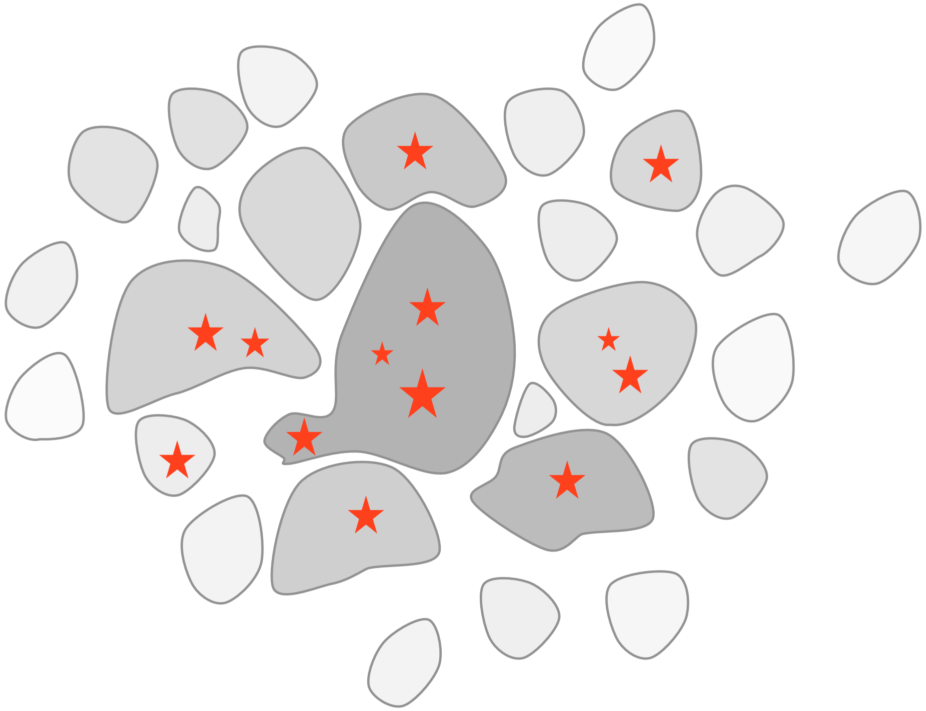

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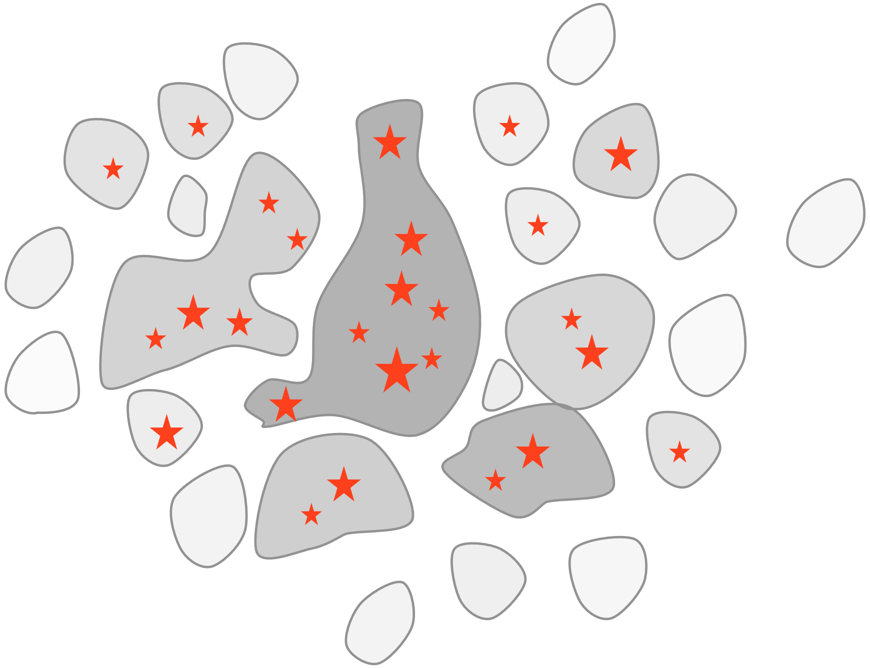
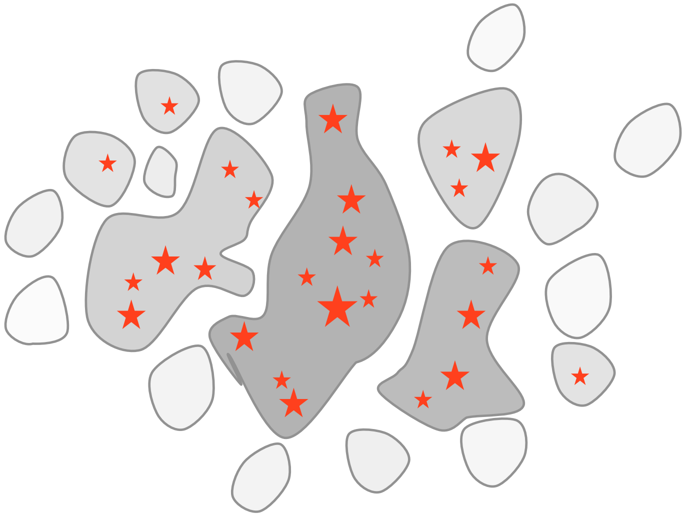


in *dense clusters*, competitive mass growth becomes important



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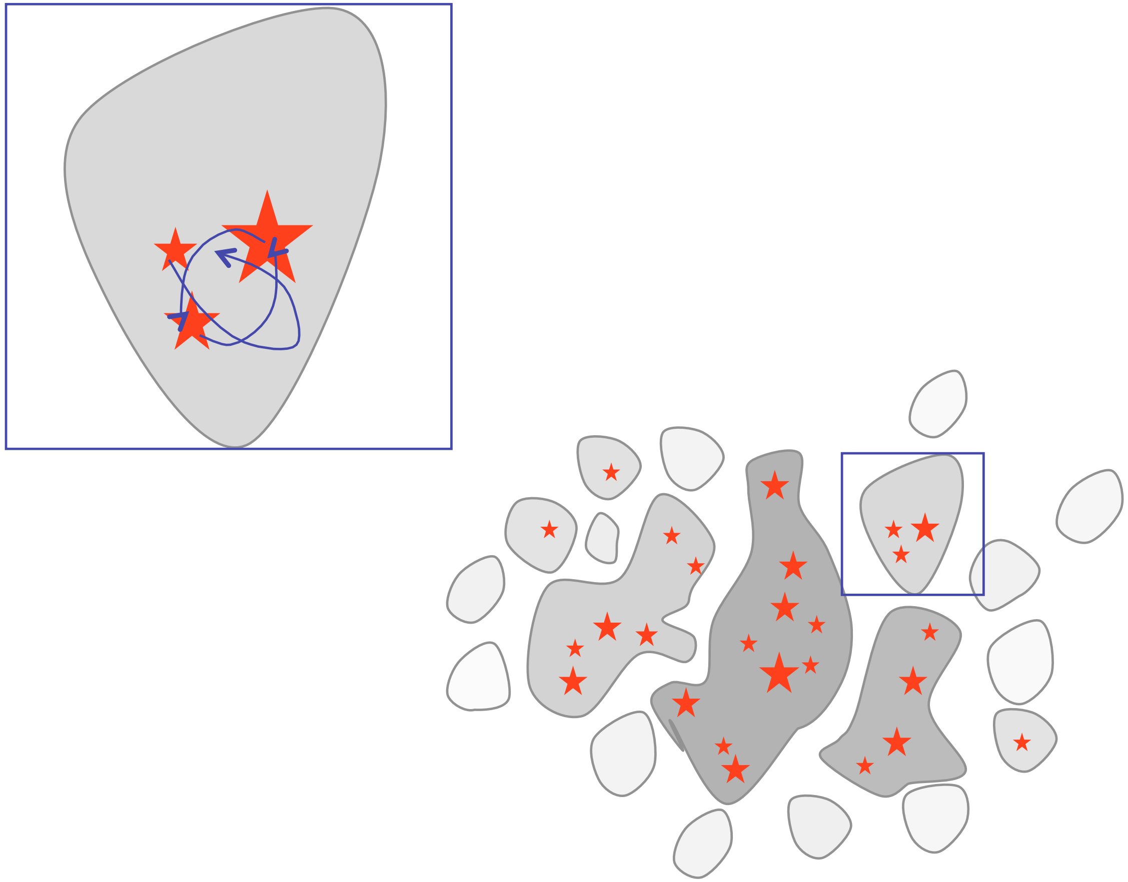
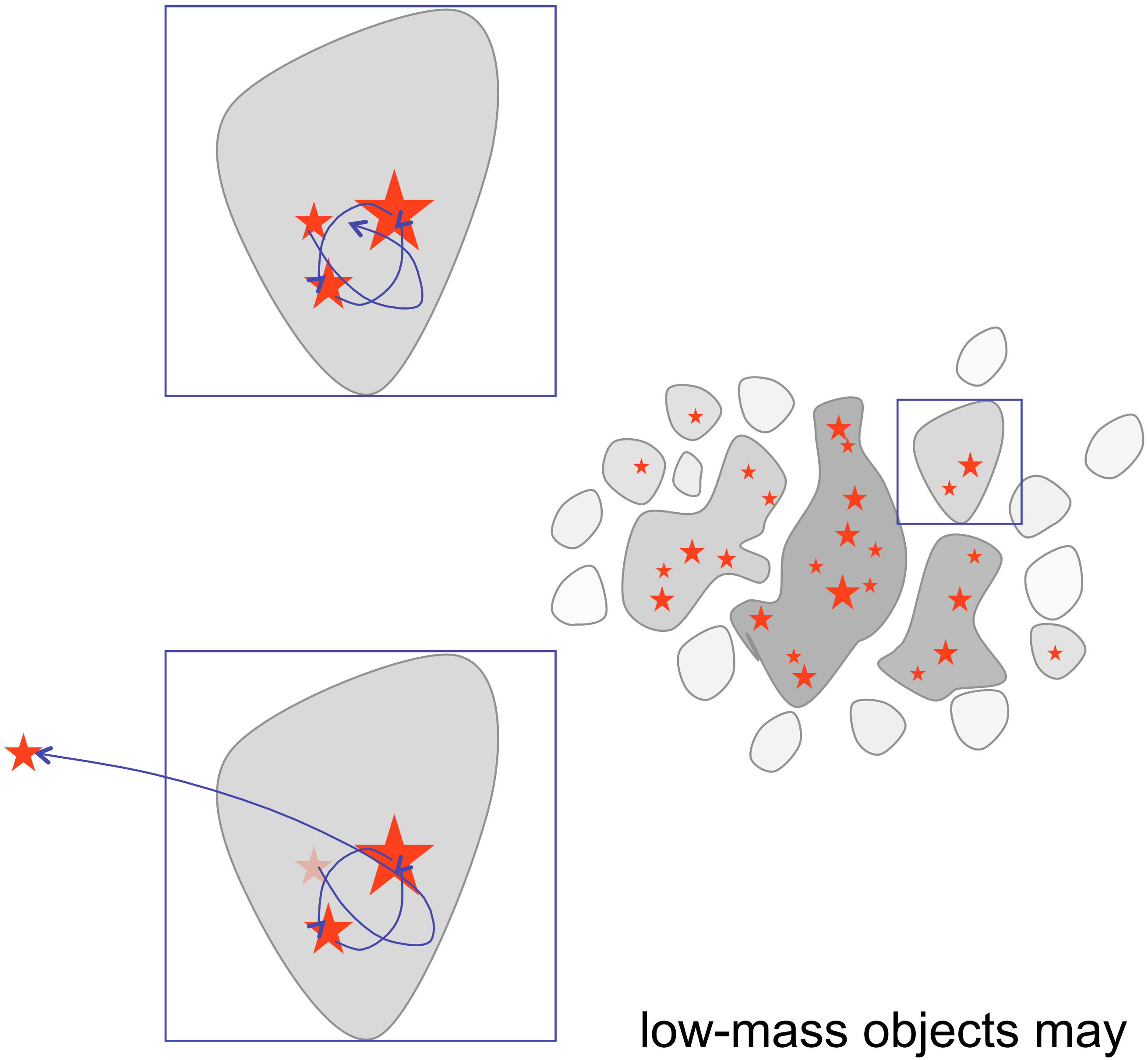
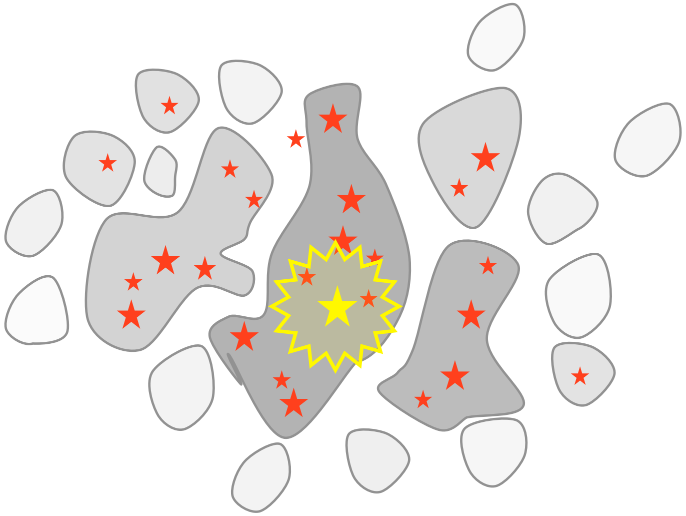


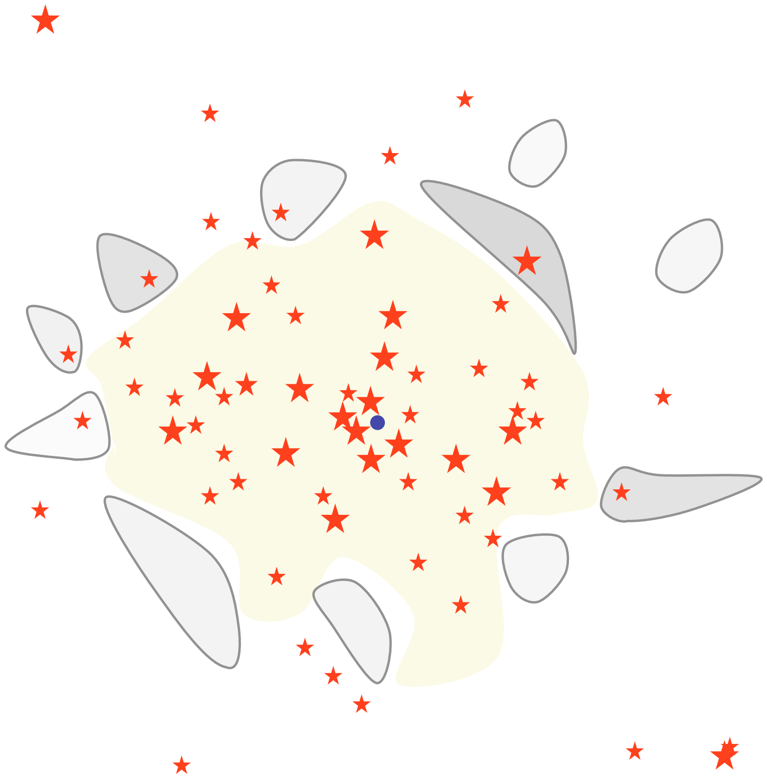
in *dense clusters*, *N*-body effects influence mass growth



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)

example 1

Example: model of Orion cloud

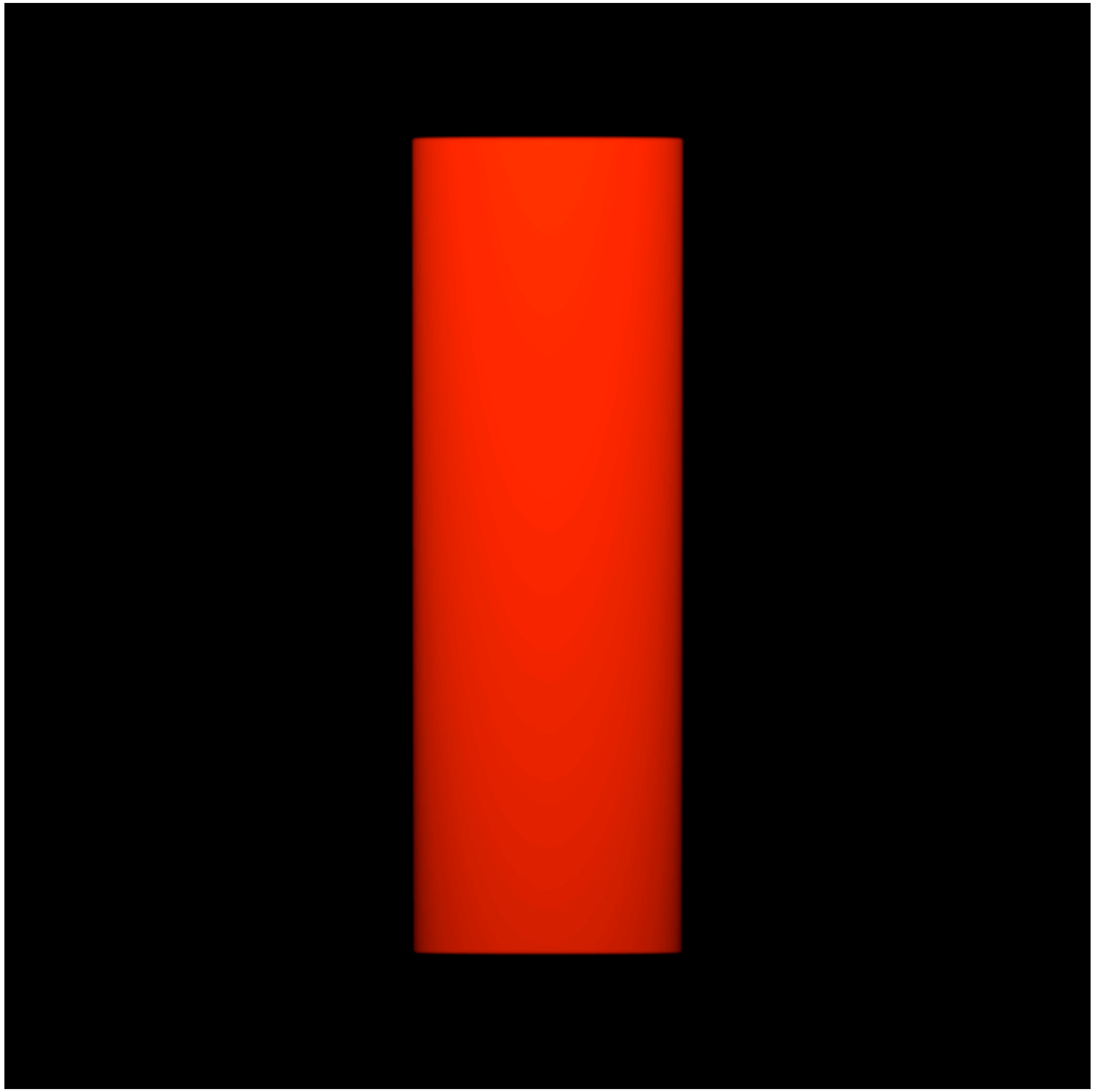
„model“ of Orion cloud: 15.000.000 SPH particles, 10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

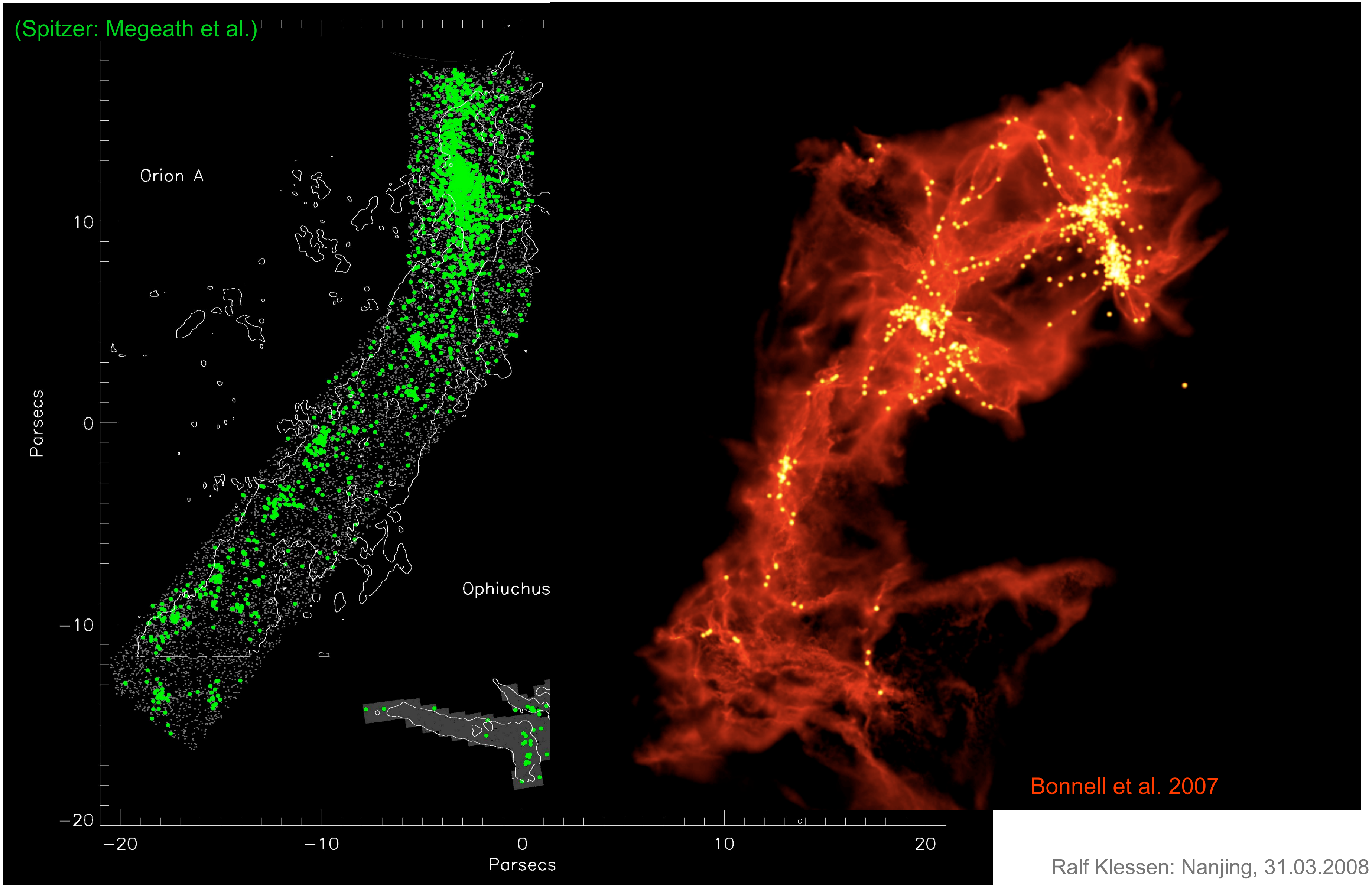
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



(Bonnell et al. 2007)

Example: model of Orion cloud

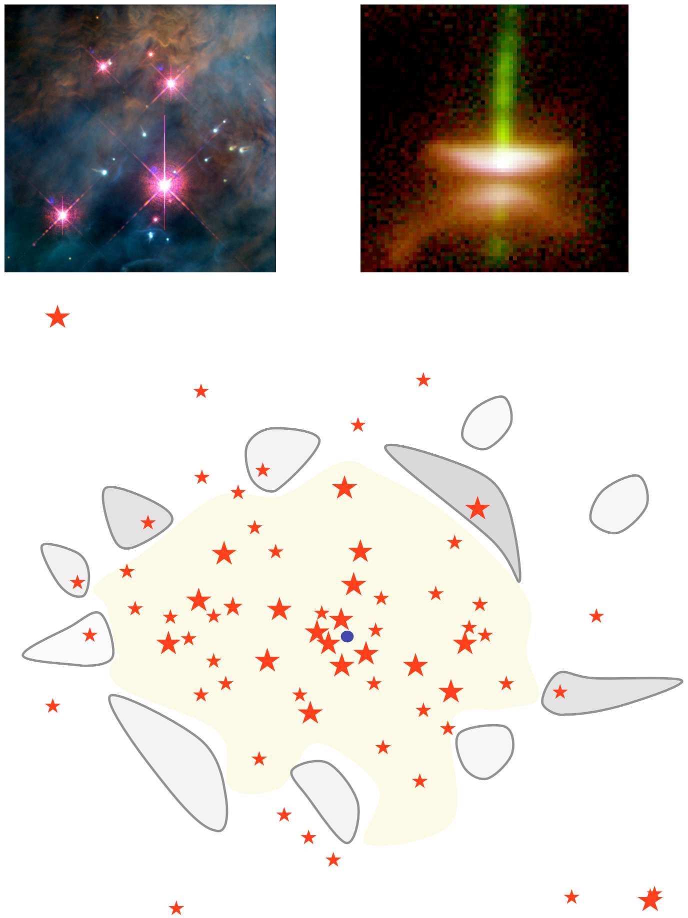


(Spitzer: Megeath et al.)

Bonnell et al. 2007

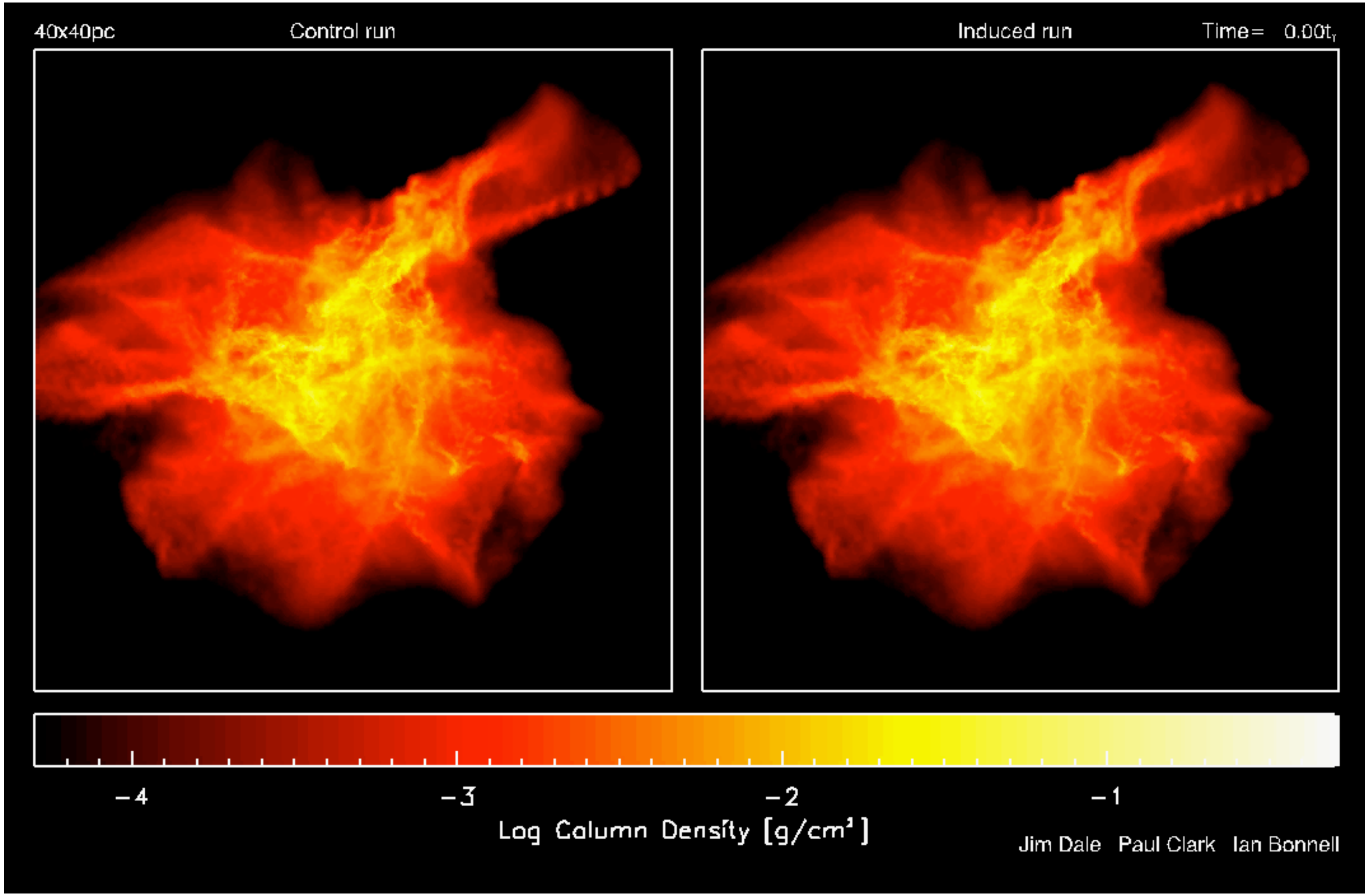
Models of star cluster formation

- dynamics:
  basic properties are probably okay
- BUT: no feedback
  (outflows, radiation, etc.)
- *how much detail are we missing?*
  - how does that change properties like *IMF*, *boundedness*, *efficiency*?



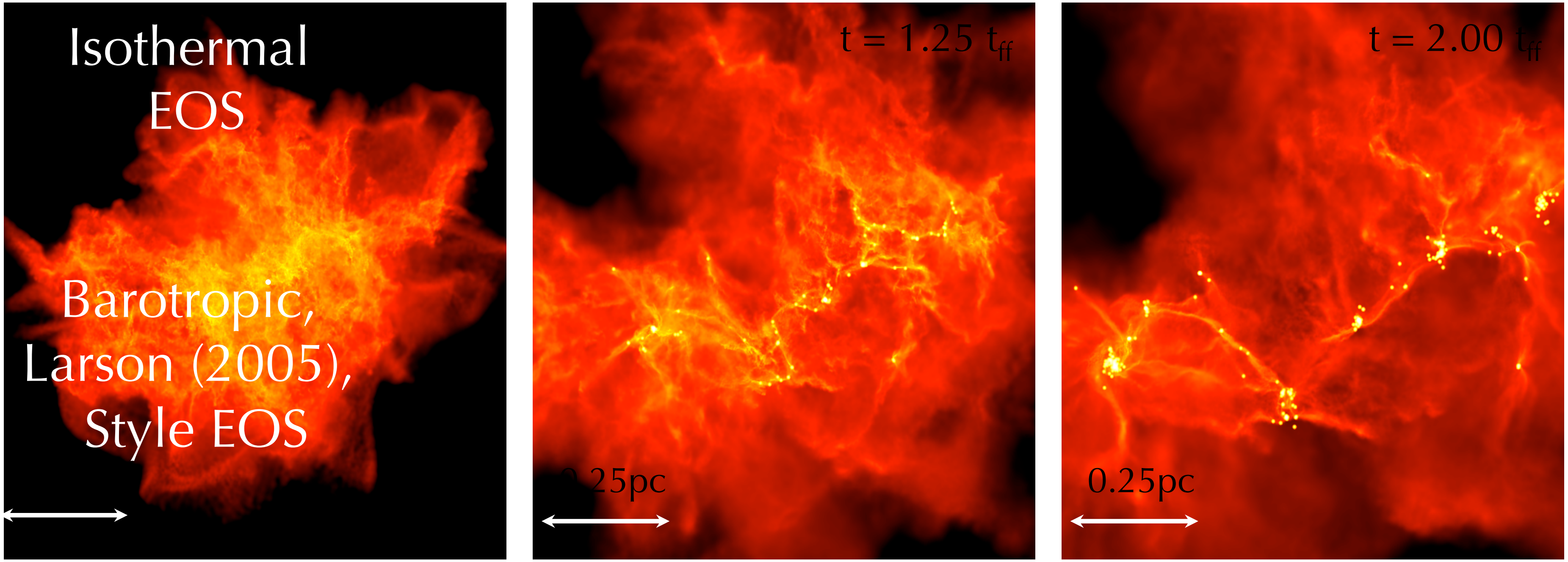
Model with ionizing feedback

SPH with radiation feedback: first calculations of star-cluster formation with ionization



Unbound clouds

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



No global collapse:

local t_{ff} < global interaction time-scale

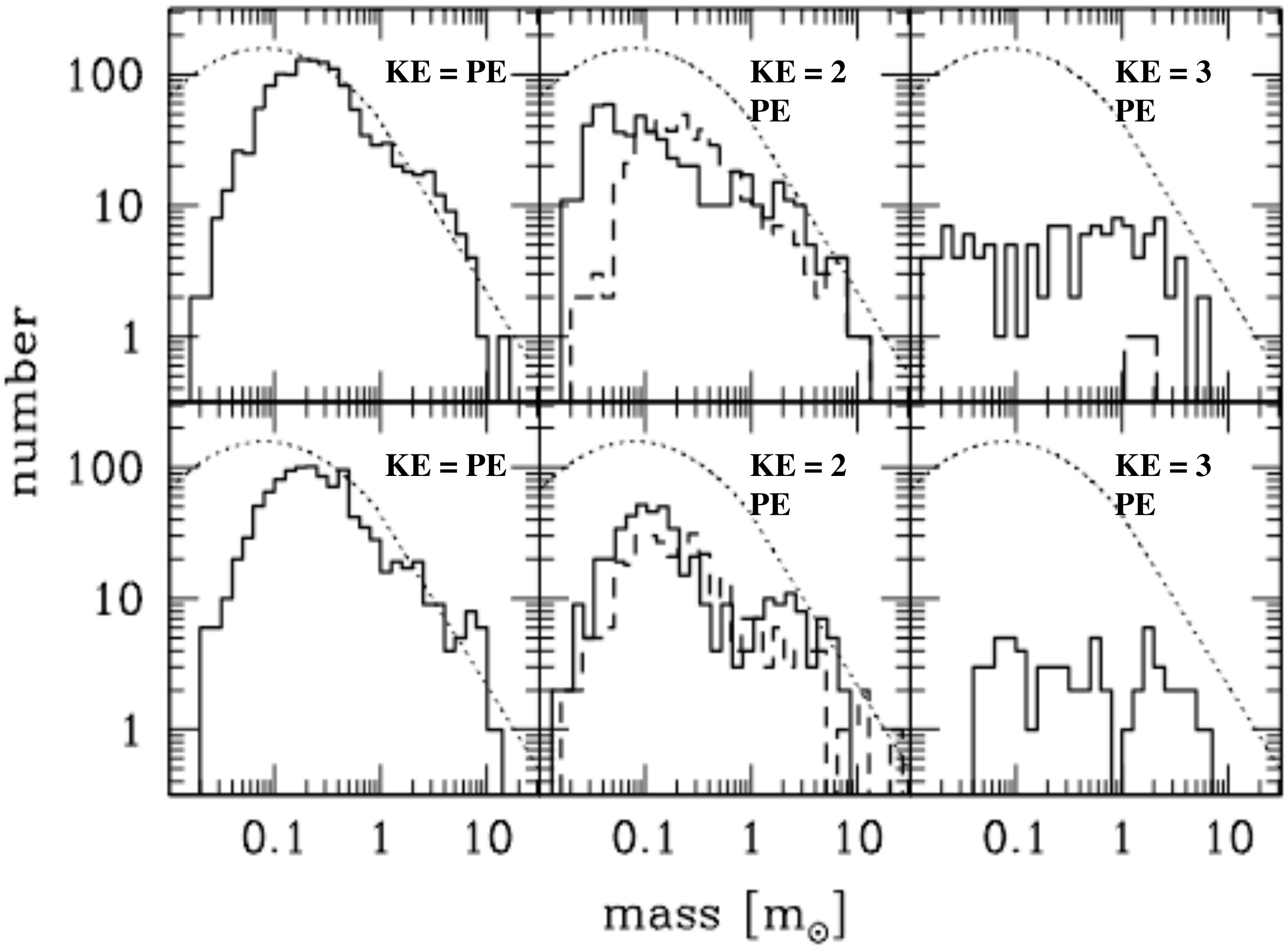
$t_{ff} \sim 2 \times 10^5$ years

Clark, Bonnell & Klessen (2007)

Mass functions

Isothermal EOS

Barotropic, Larson (2005), Style EOS



Clark, Bonnell & Klessen (2007)

example 2

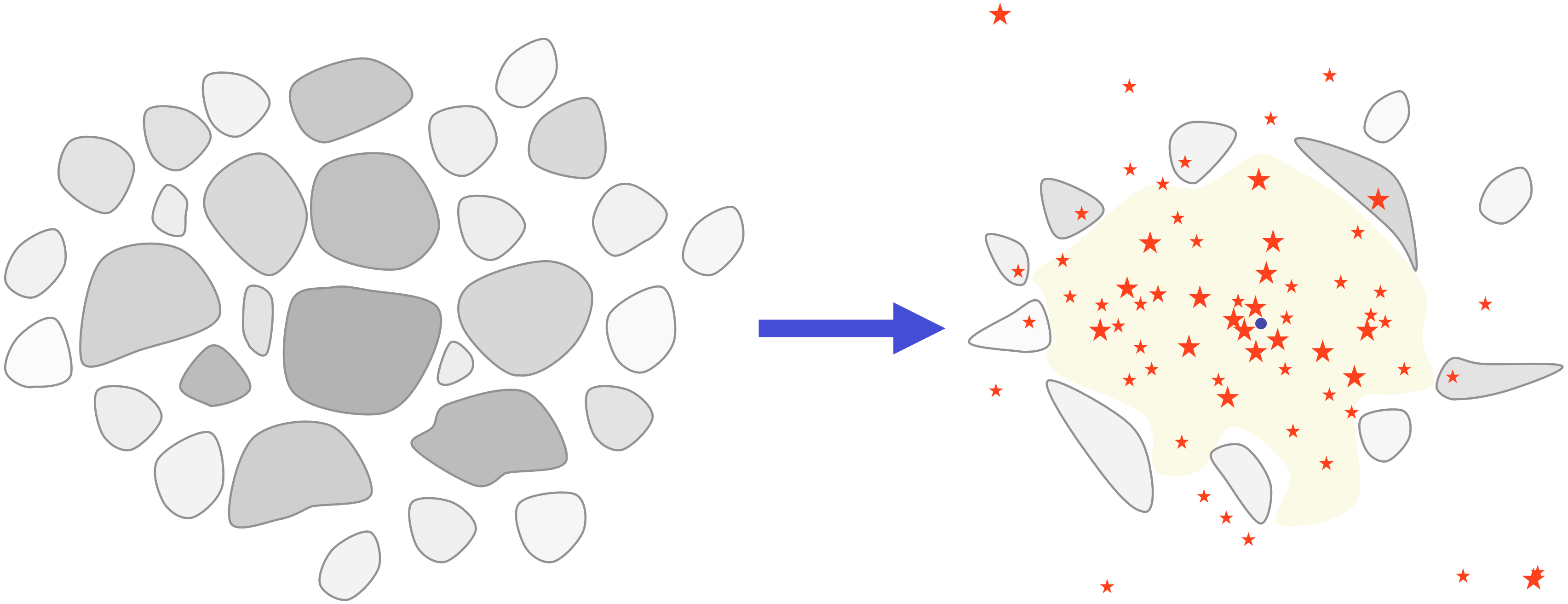
IMF

- 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*



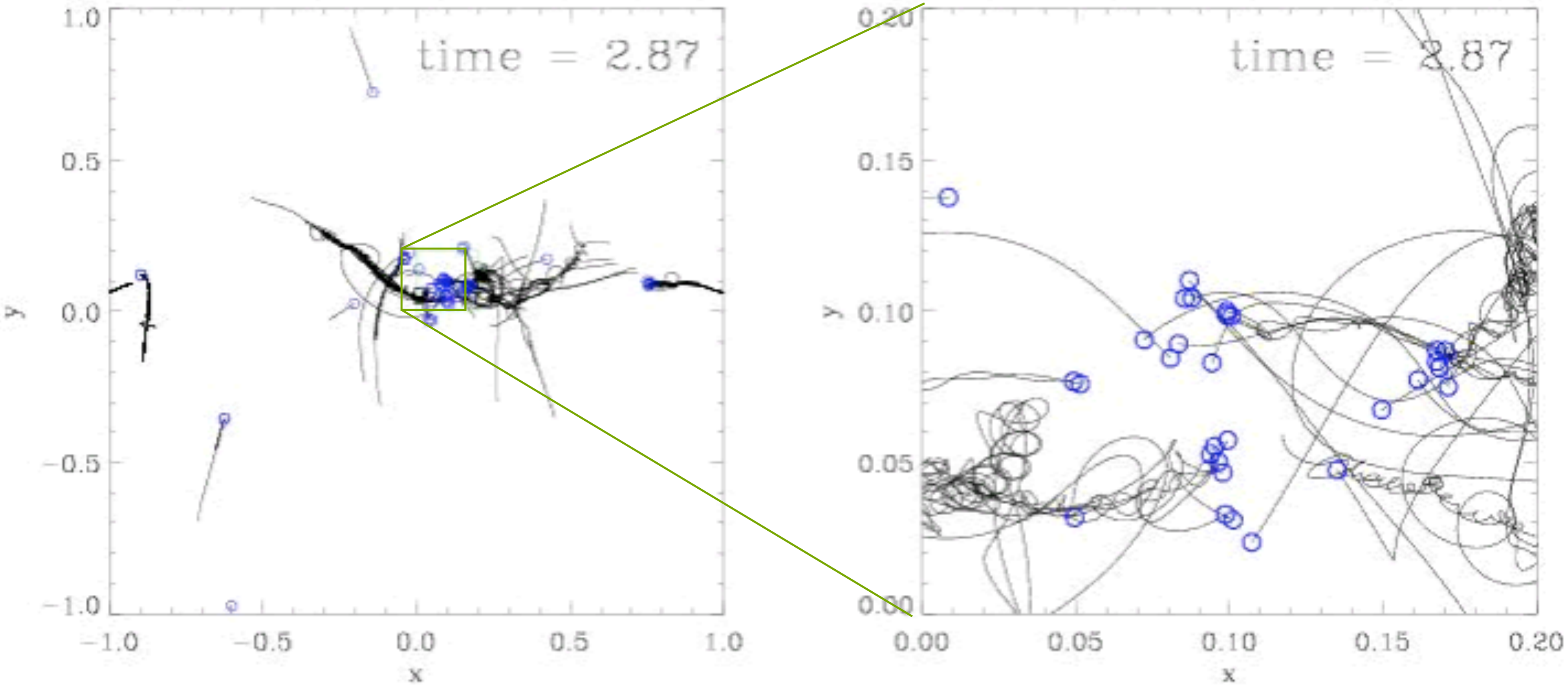
How to get from cloud cores to star clusters?

How do the stars acquire mass?

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

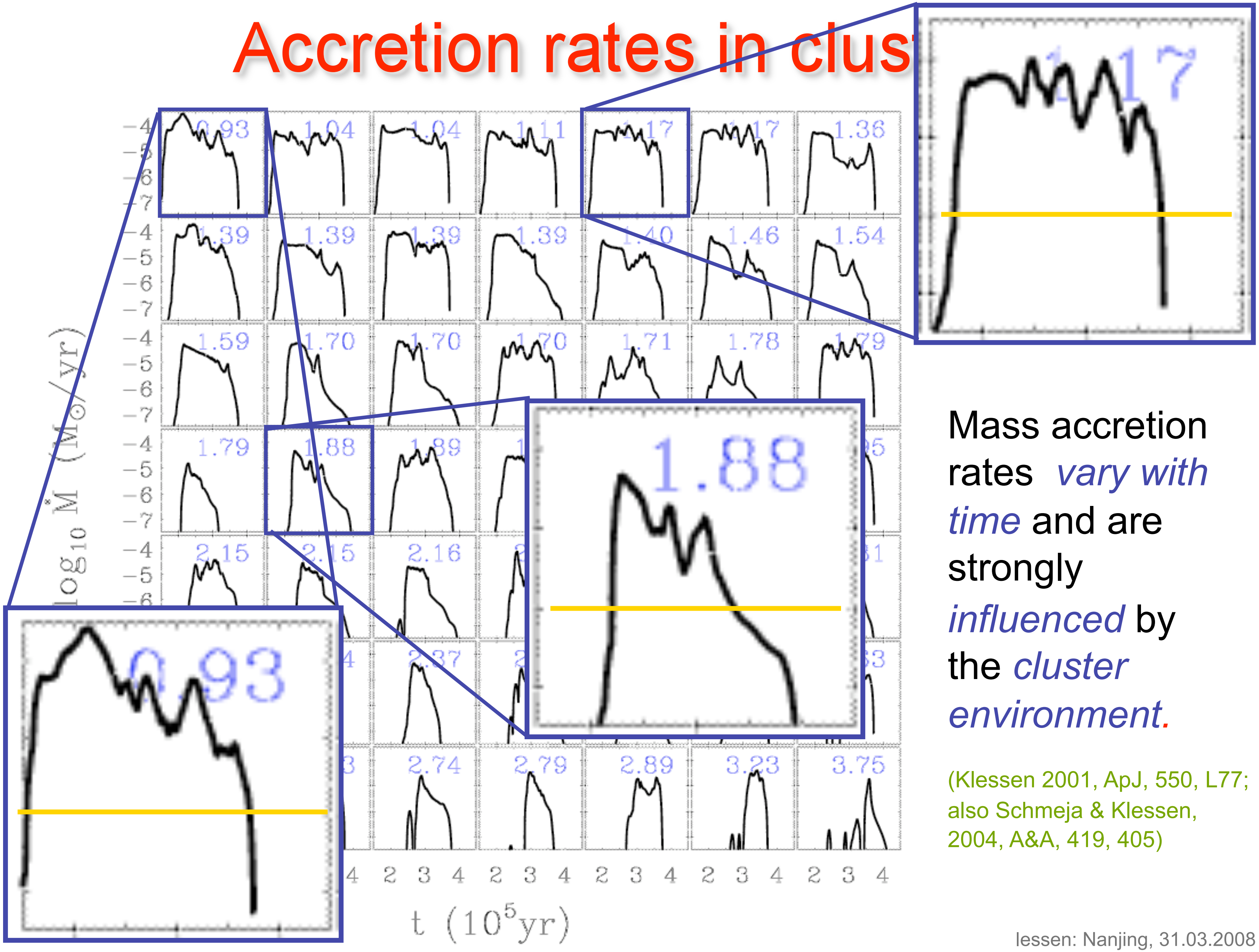
Star cluster formation

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



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)

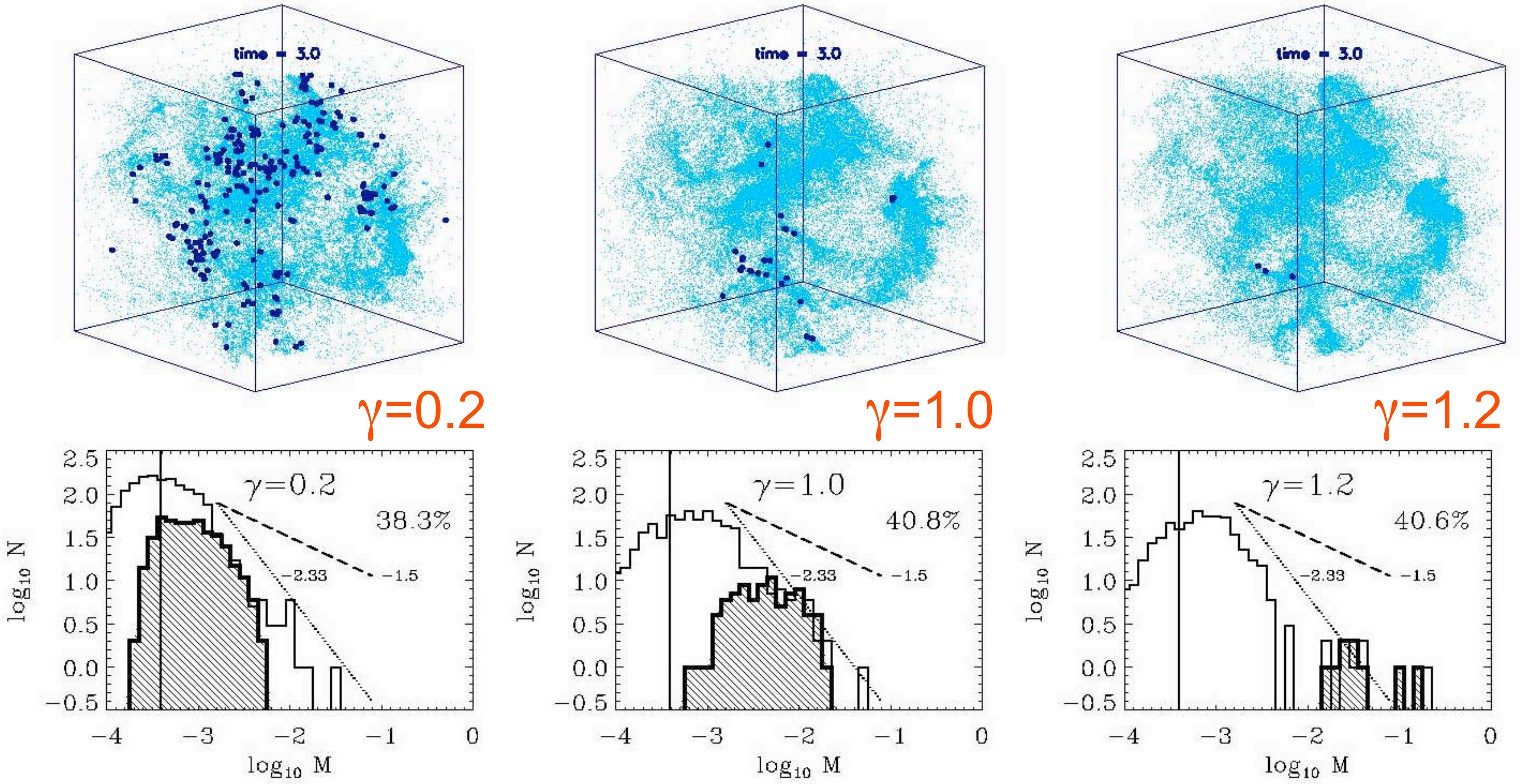
Dependency on EOS

- 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



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

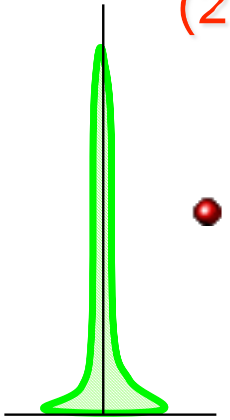
for γ>1 it is suppressed → formation of *isolated massive stars*

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

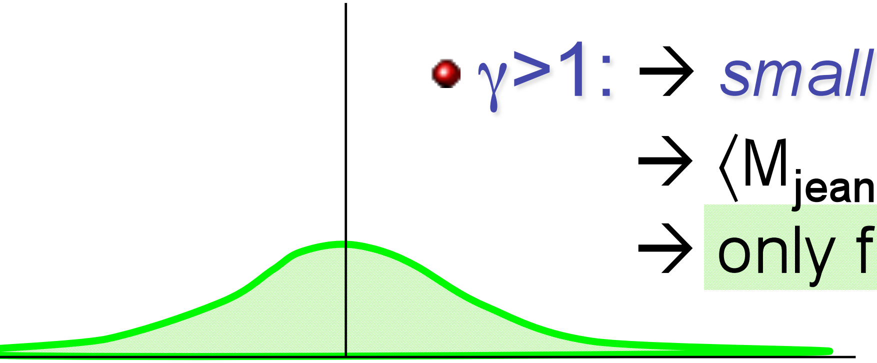
How does that work?

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

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



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

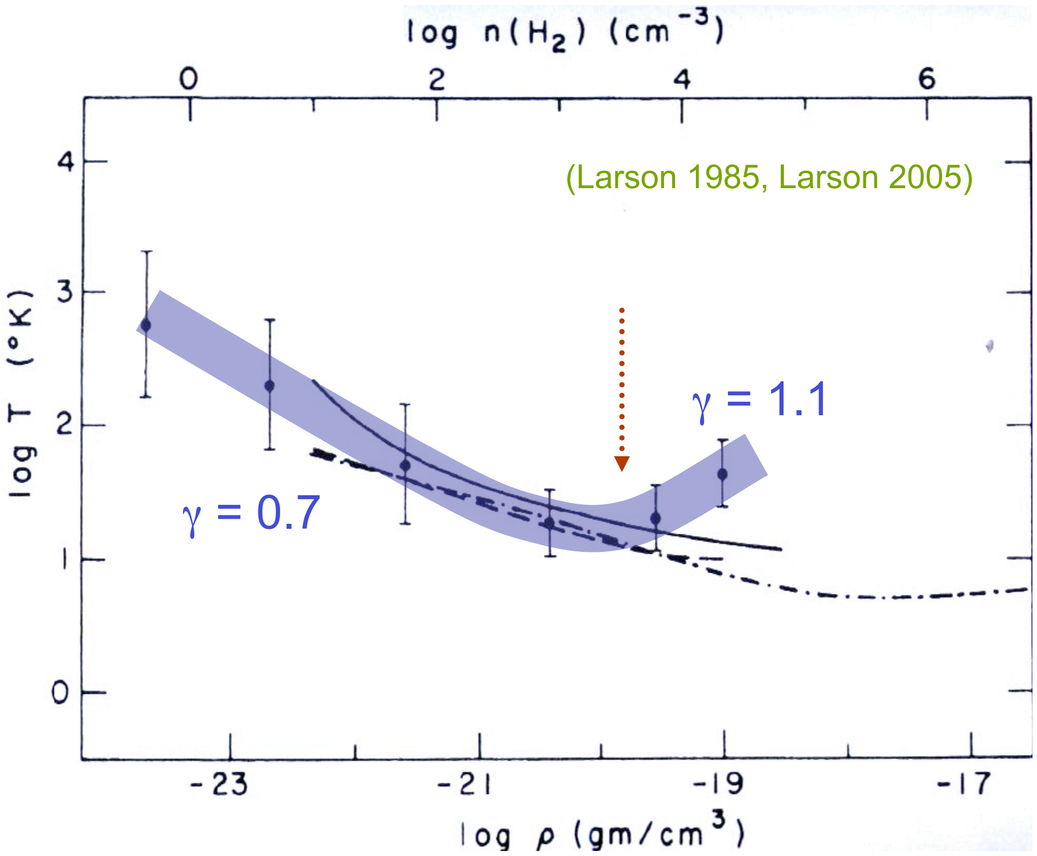


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬆



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

$P \propto \rho T$

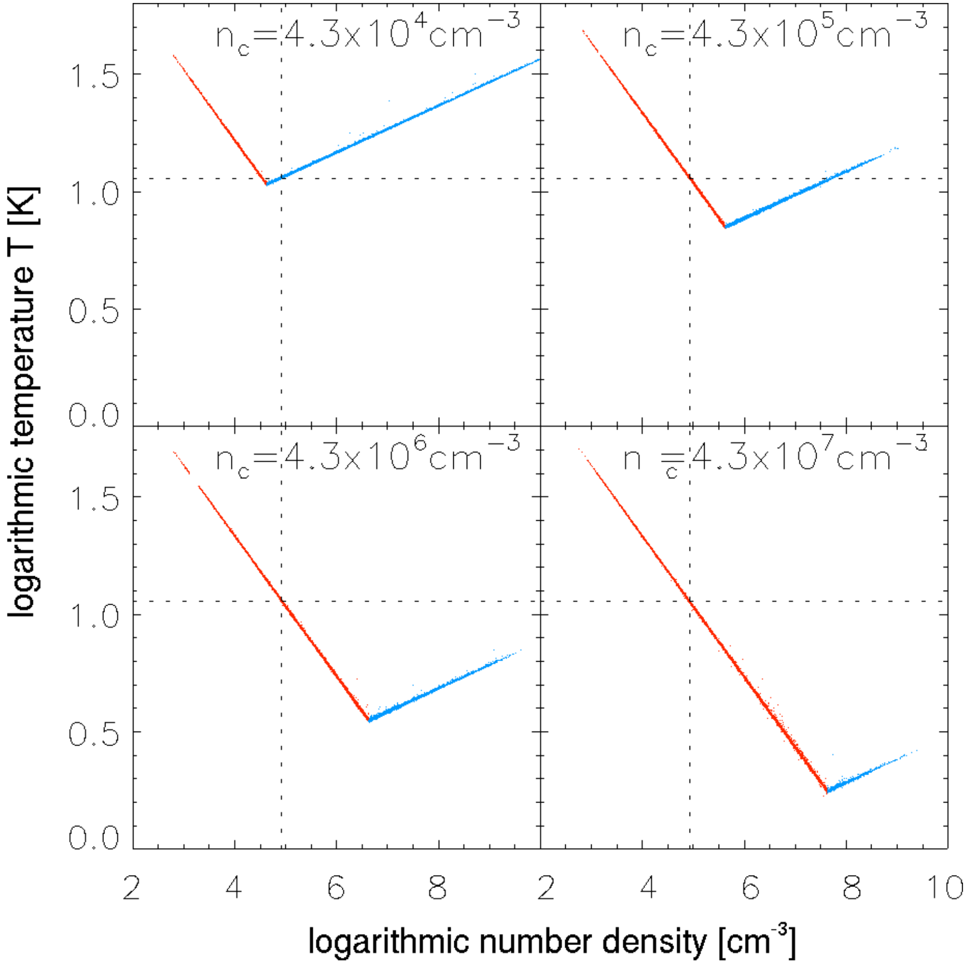
$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

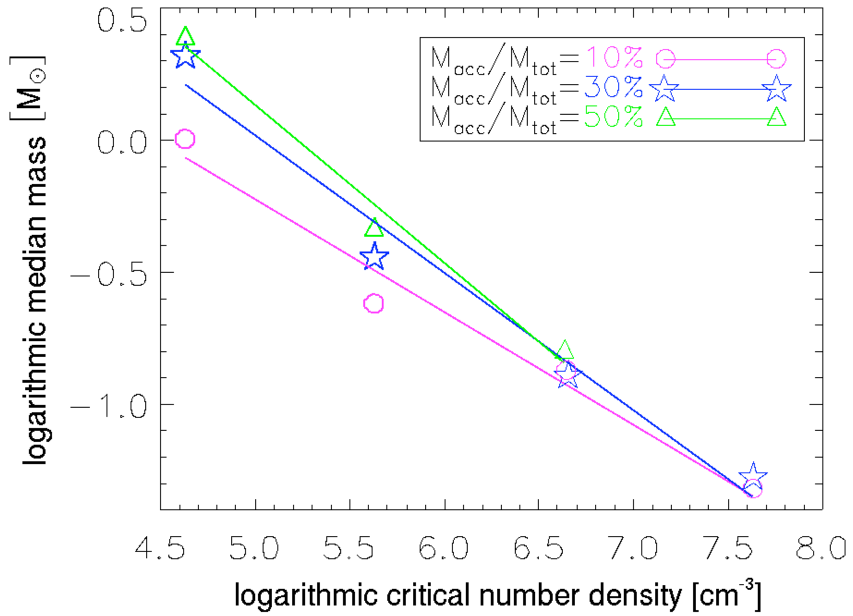
$$\boxed{T \sim \rho^{\gamma-1}}$$

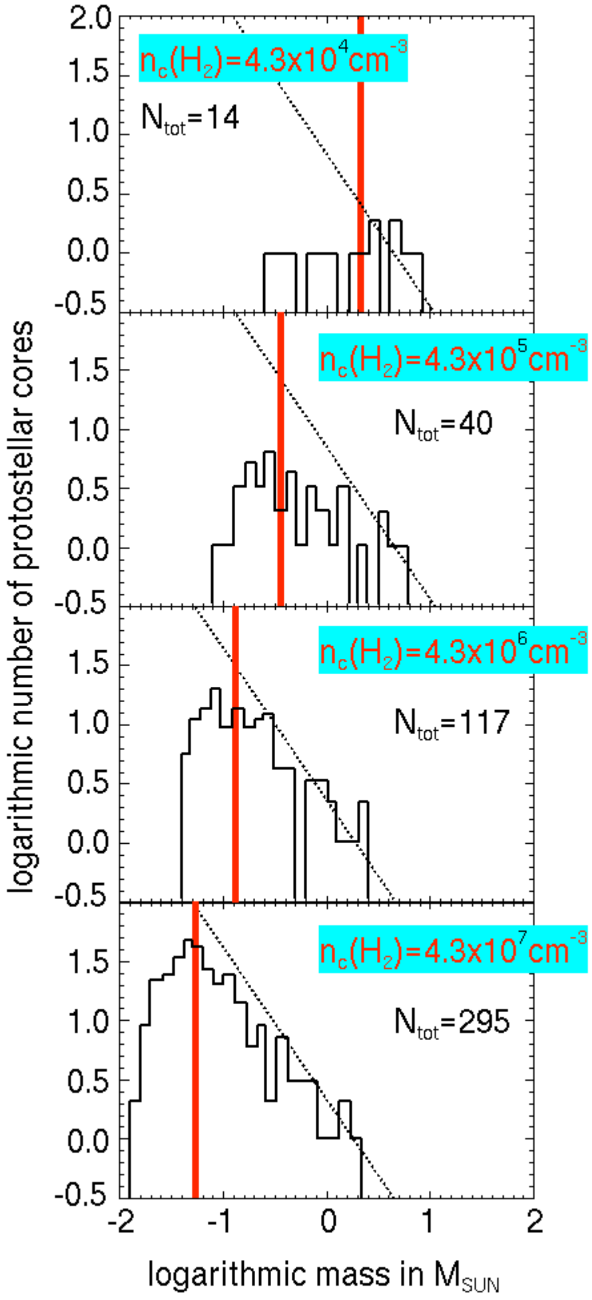


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

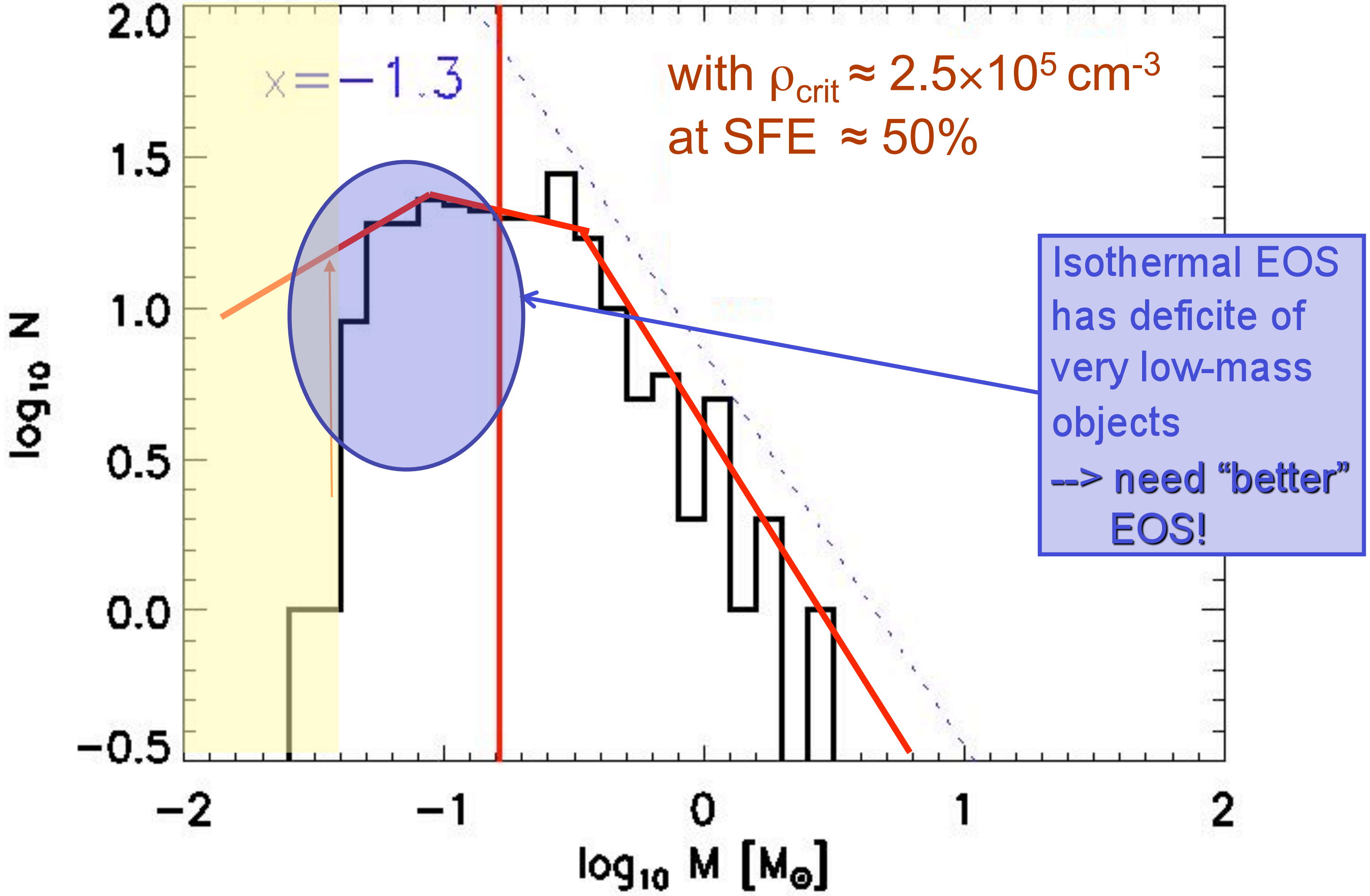
critical density ↑ ⇨ median mass ↓





(Jappsen et al. 2005)

IMF in nearby molecular clouds

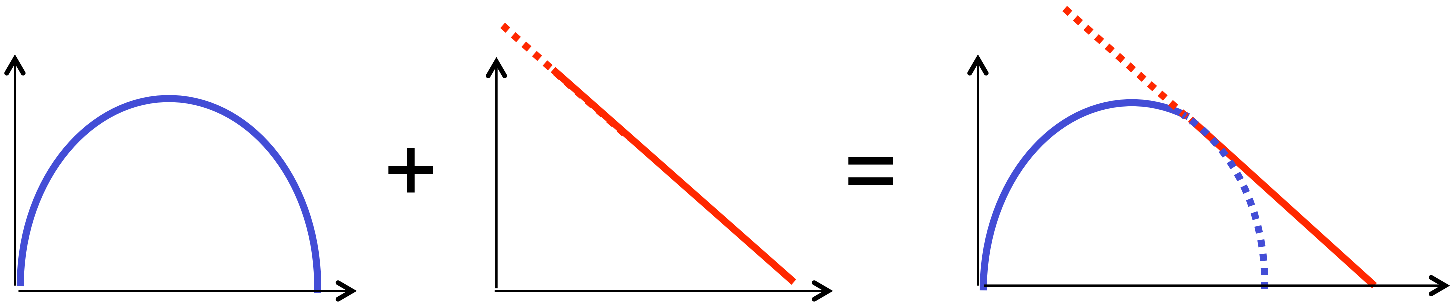


with $\rho_{crit} \approx 2.5\times10^{5}$ cm^{-3}
at SFE ≈ 50%

Isothermal EOS has deficite of very low-mass objects
--> need “better” EOS!

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

Plausibility argument for shape



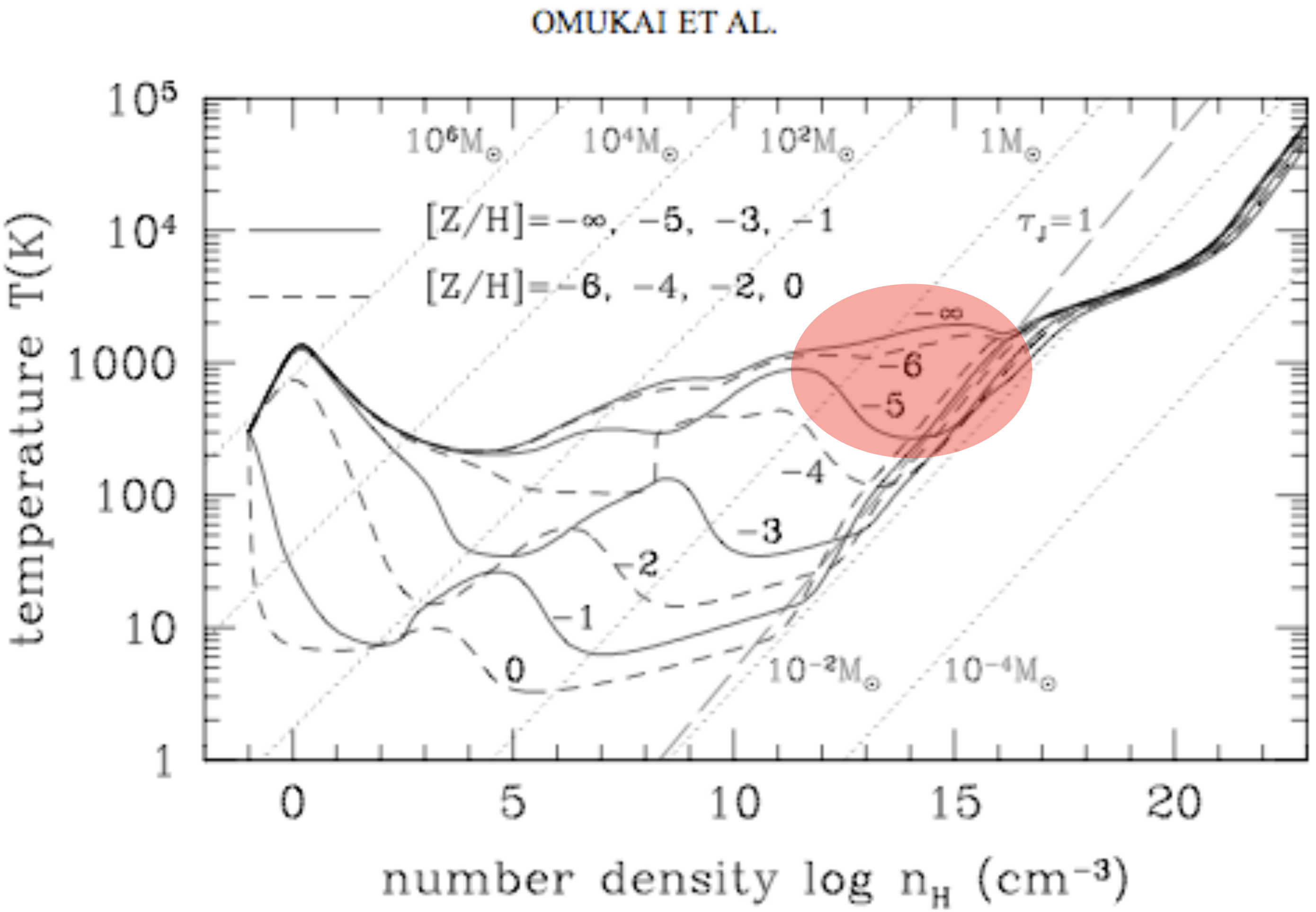
- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*

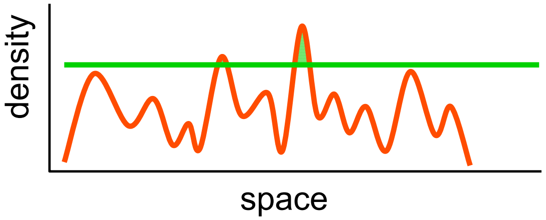
transition: Pop III to Pop II.5



(Omukai et al. 2005)

Summary

Summary I



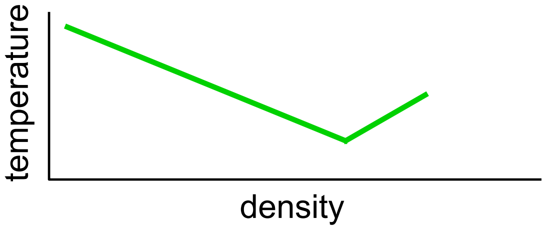
- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto M^2$; in atomic gas: $M \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent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