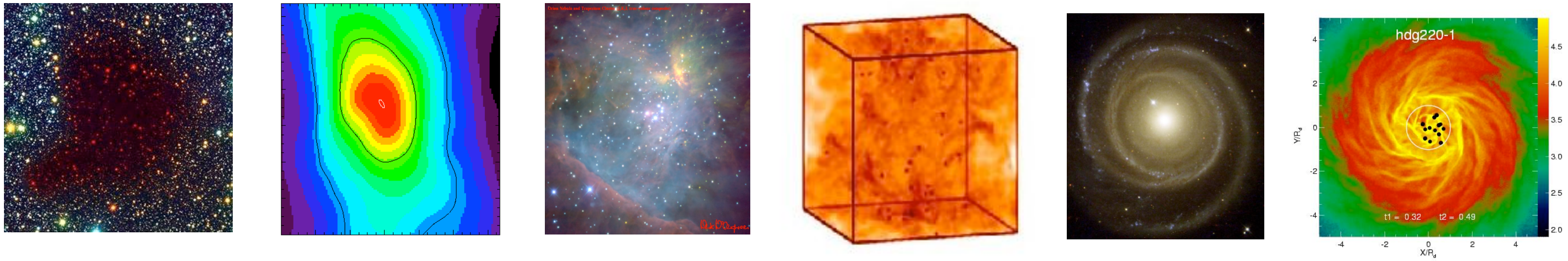
Molecular Cloud Turbulence and Star Formation



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AIP

DFG

Protostars & Planets V: Oct. 24, 2005

Overview

- concept of gravoturbulent star formation
- three „steps“ of star formation:

  1. *formation of molecular clouds in the disk of our galaxy*
      - intermezzo:
        properties of molecular cloud turbulence
  2. *formation of protostellar cores*
  3. *formation of stars: protostellar collapse and the stellar mass spectrum*

- summary

the idea

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

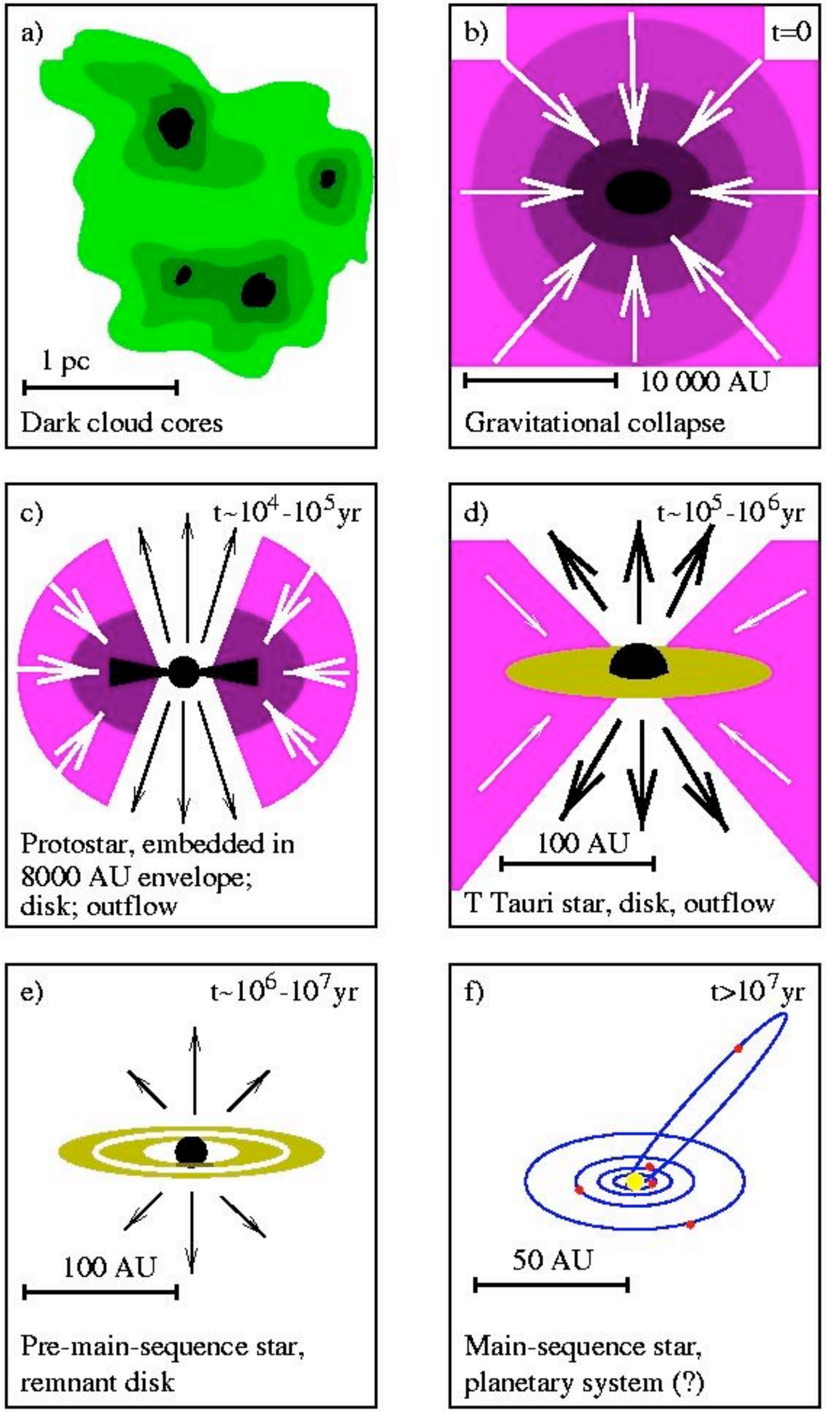
- Idea:

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)



Hogerheijde 1998, after Shu et al. 1987

Competing approaches in SF theory:

quasistatic theories:

magnetically mediated star formation

Shu, Adams, & Lizano (1987, ARAA)

↓

dynamical theories:

turbulent controll of star formation

Larson (2003, Prog. Rep. Phys.)
Mac Low & Klessen (2004, RMP, 76, 125)
Elmegreen & Scalo (2004, ARAA)
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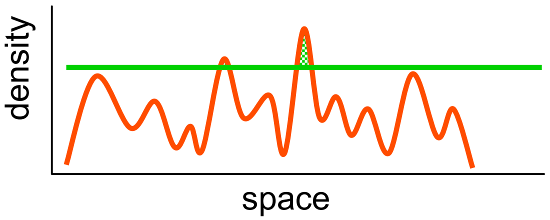
Gravoturbulent star formation



- 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)

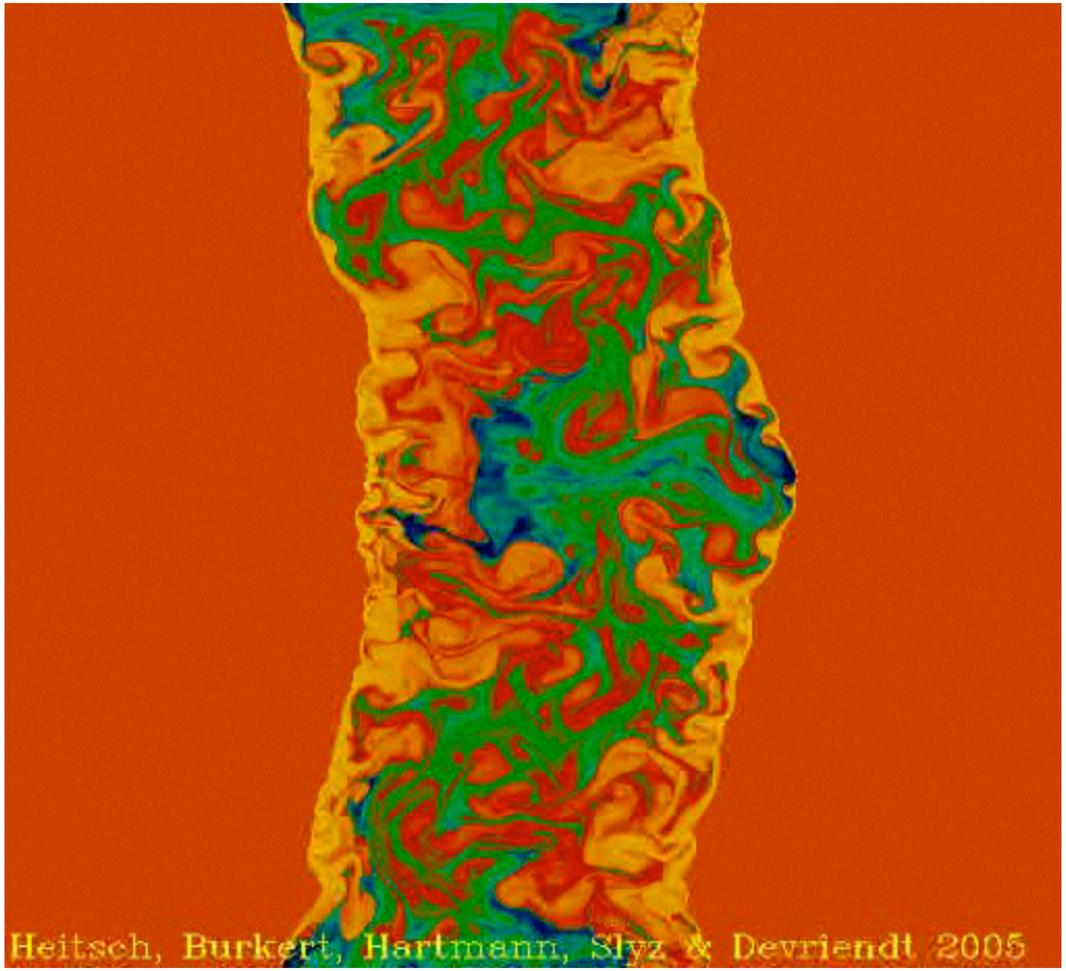
cloud formation

Molecular cloud formation

... in *convergent large-scale flows*

... setting up the *turbulent cascade*

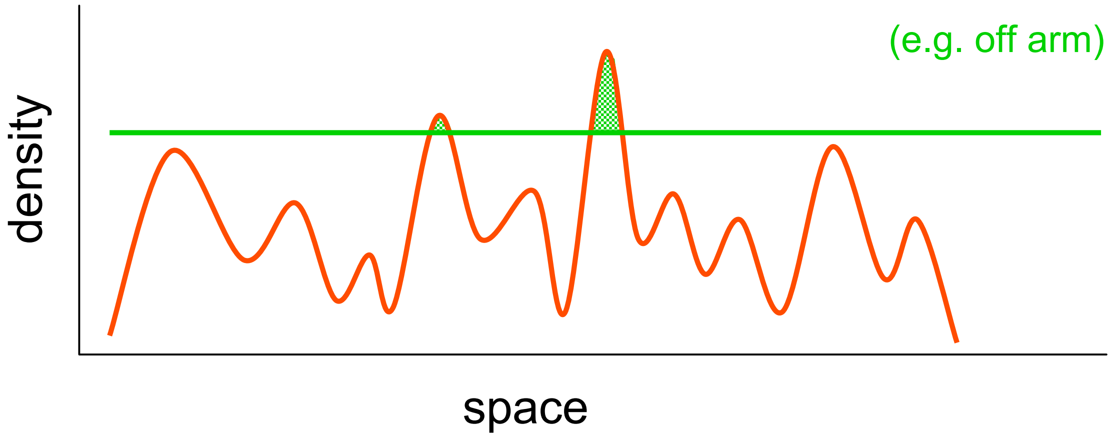
- Mach 3 colliding flow
- Vishniac instability + thermal instability
- compressed sheet *breaks up* and builds up *cold, high-density* „blobs“ of gas
- --> *molecular cloud formation*
- cold cloud motions correspond to supersonic turbulence

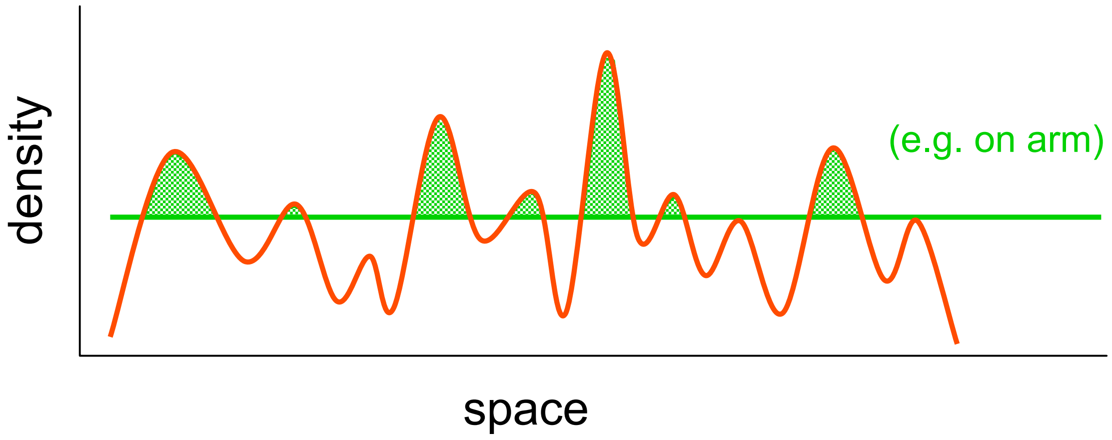


Heitsch, Burkert, Hartmann, Slyz & Devriendt 2005

(e.g. Koyama & Inutsuka 2002, Heitsch et al., 2005, Vazquez-Semadeni et al. 2004; also posters 8577, 8302)

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*"

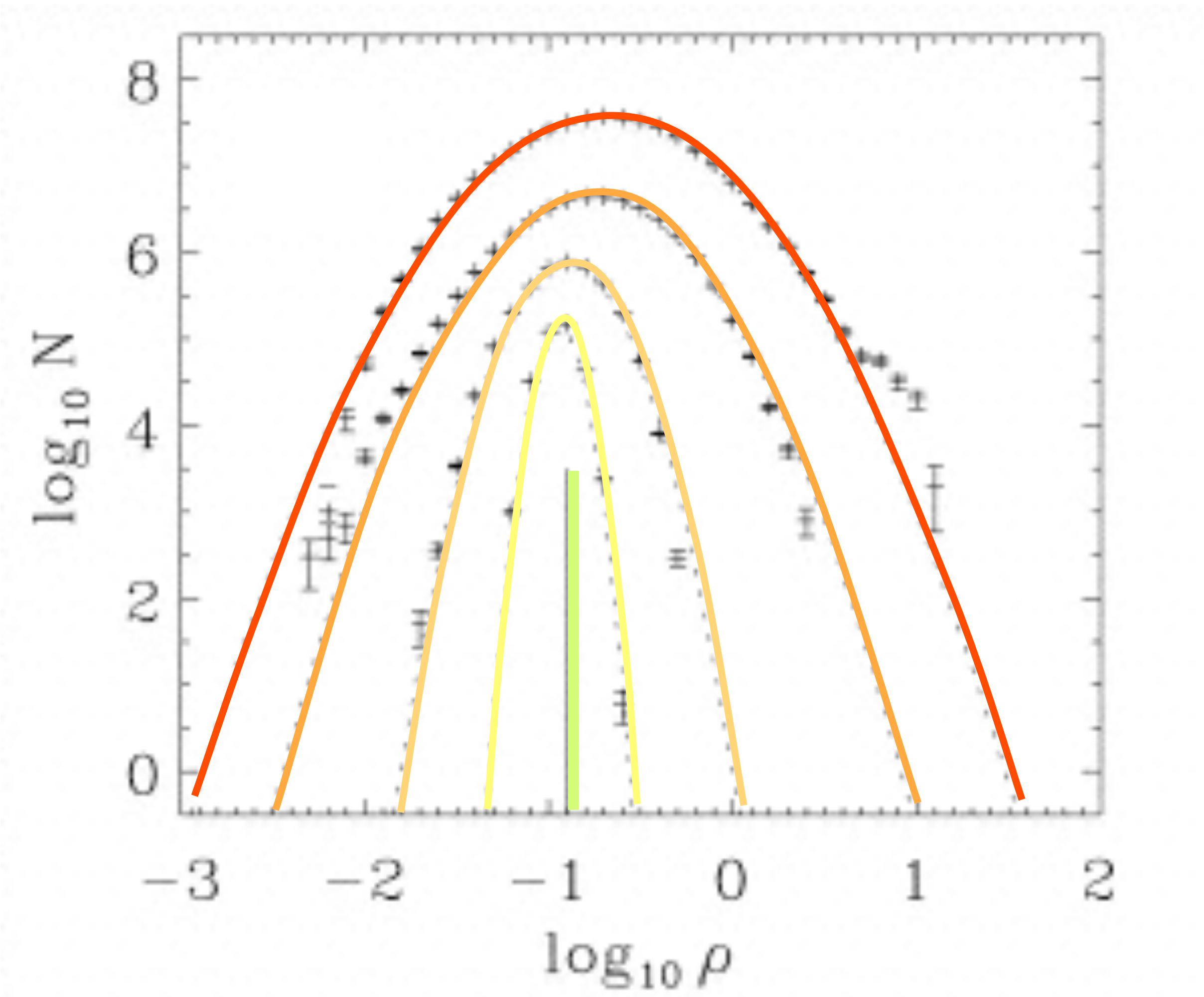
→ *molecular cloud*

(poster 8577: Glover & Mac Low)

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

(poster 8170: Dobbs & Bonnell)

Star formation on *global* scales



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

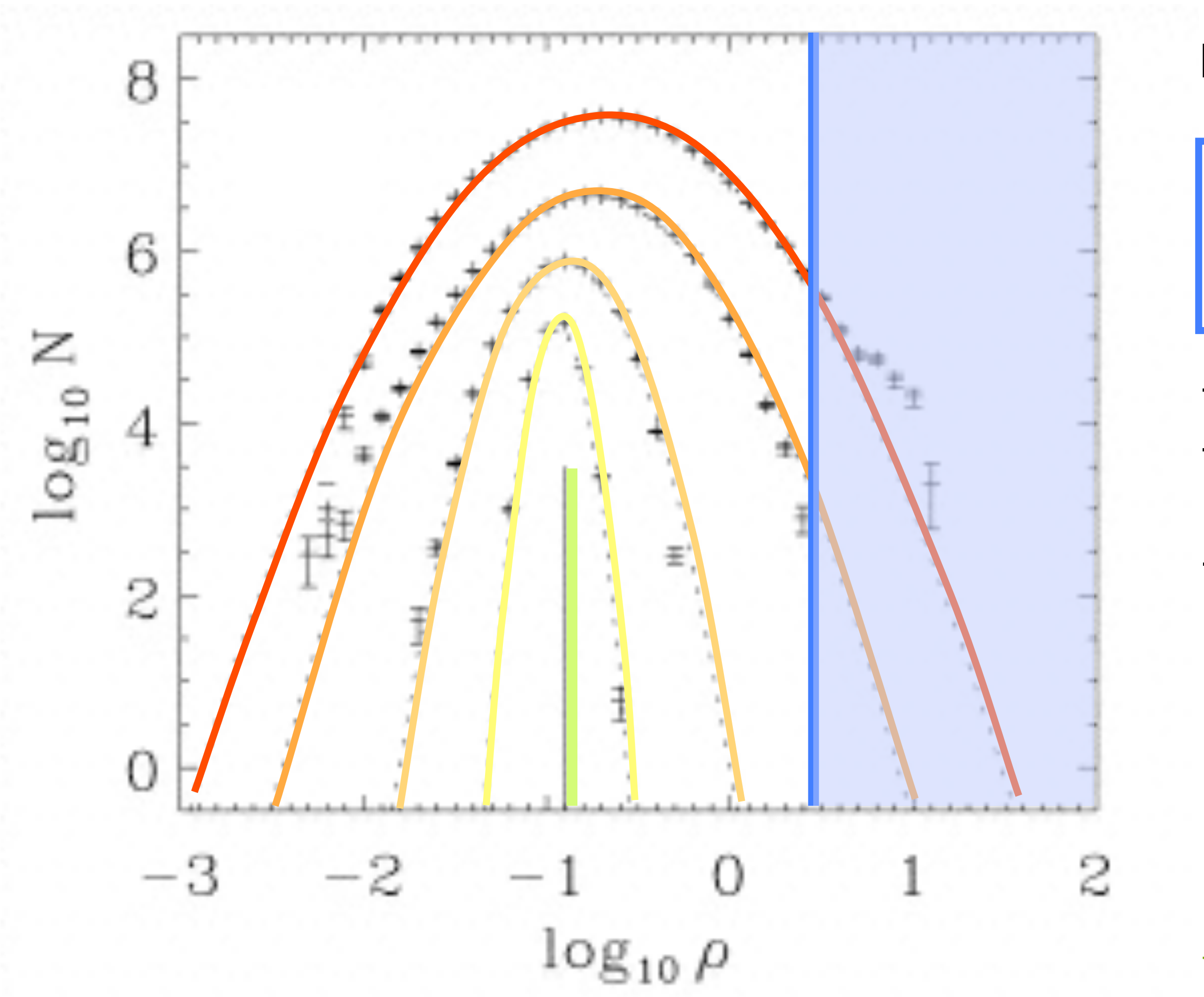
varying rms Mach numbers:

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, see also poster 8577)

H_2 formation rate:

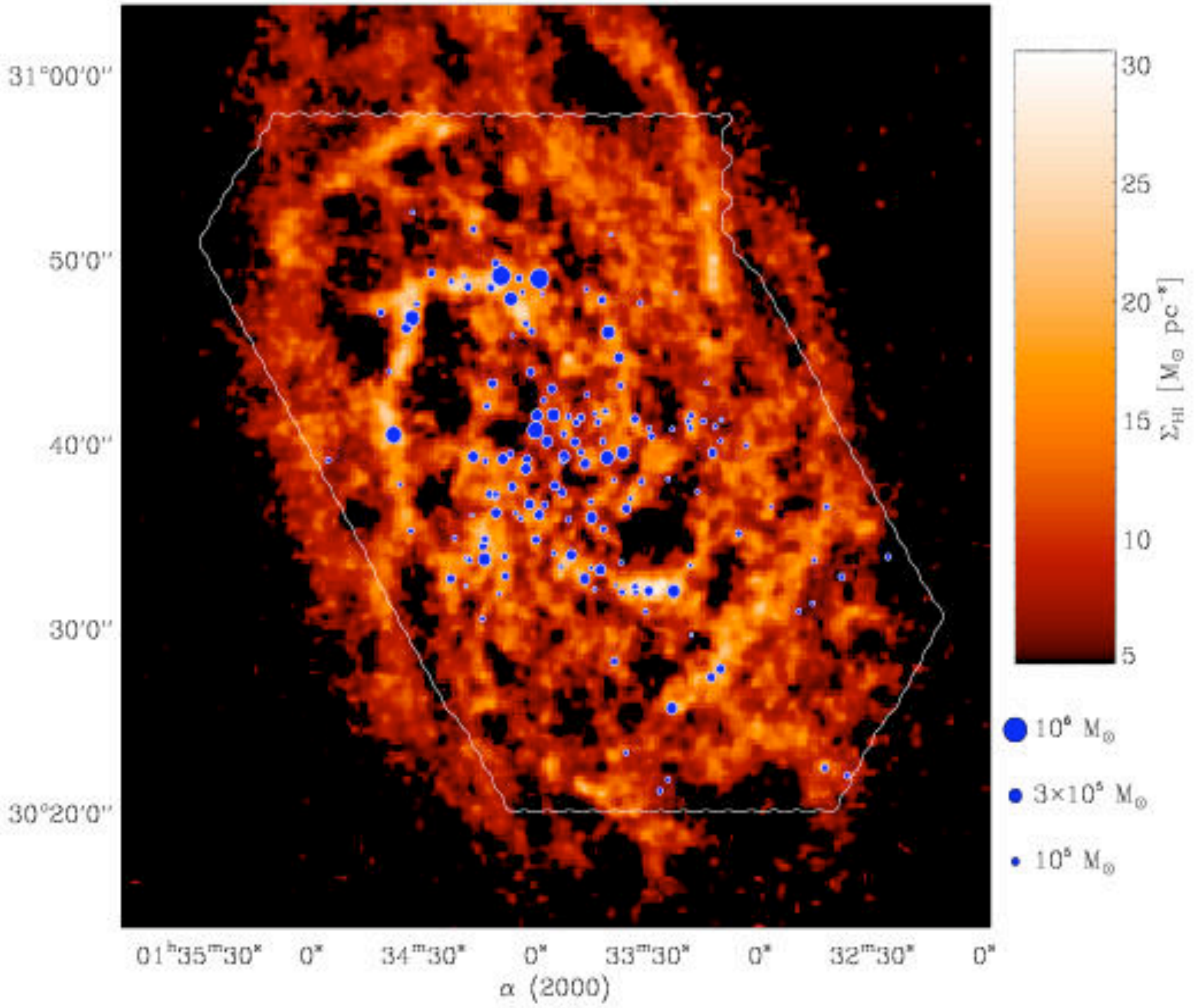
$$\boxed{\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}}$$

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 2005)

Correlation between H_2 and HI



Compare H_2 - HI in M33:

- H_2: BIMA-SONG Survey, see Blitz et al.
- HI: Observations with Westerbork Radio T.

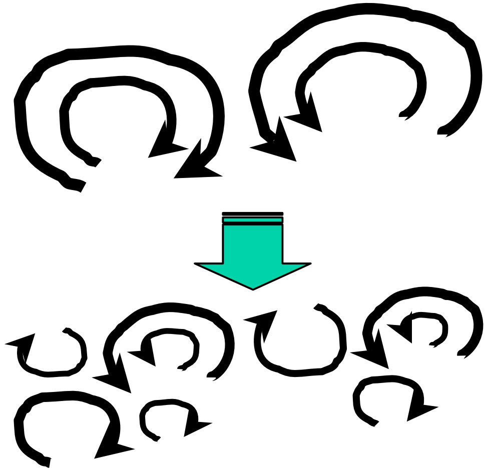
H_2 clouds are seen in regions of high HI density
(in spiral arms and filaments)

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

turbulence

Properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers



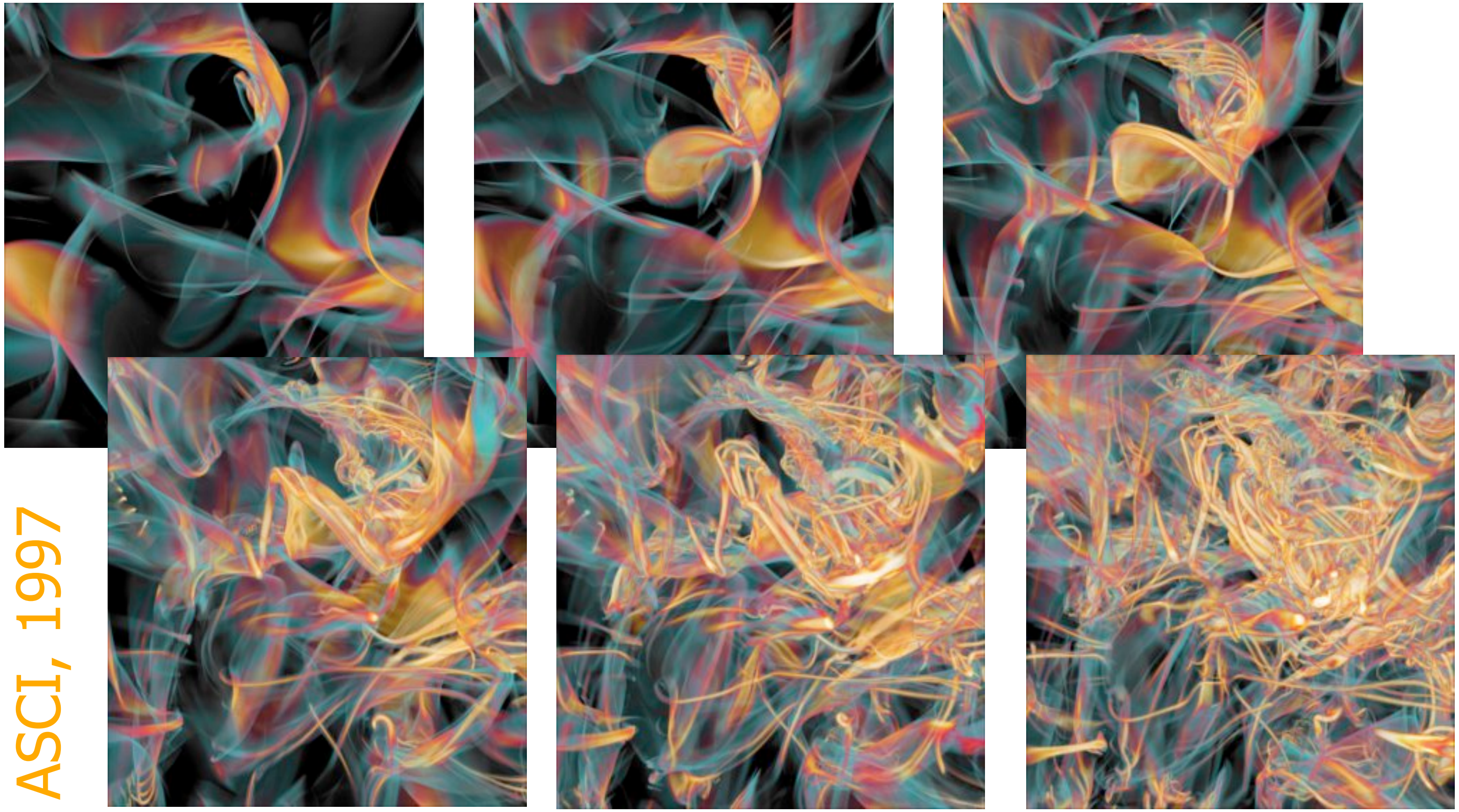
$$\boxed{\mathrm{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}}$$

V= typical velocity on scale L, ν = viscosity, Re > 1000

- *vortex streching* --> turbulence is *intrinsically anisotropic*
  (only on large scales you *may* get homogeneity & isotropy in a statistical sense; see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

  (ISM turbulence: shocks & B-field cause additional inhomogeneity)

Vortex Formation

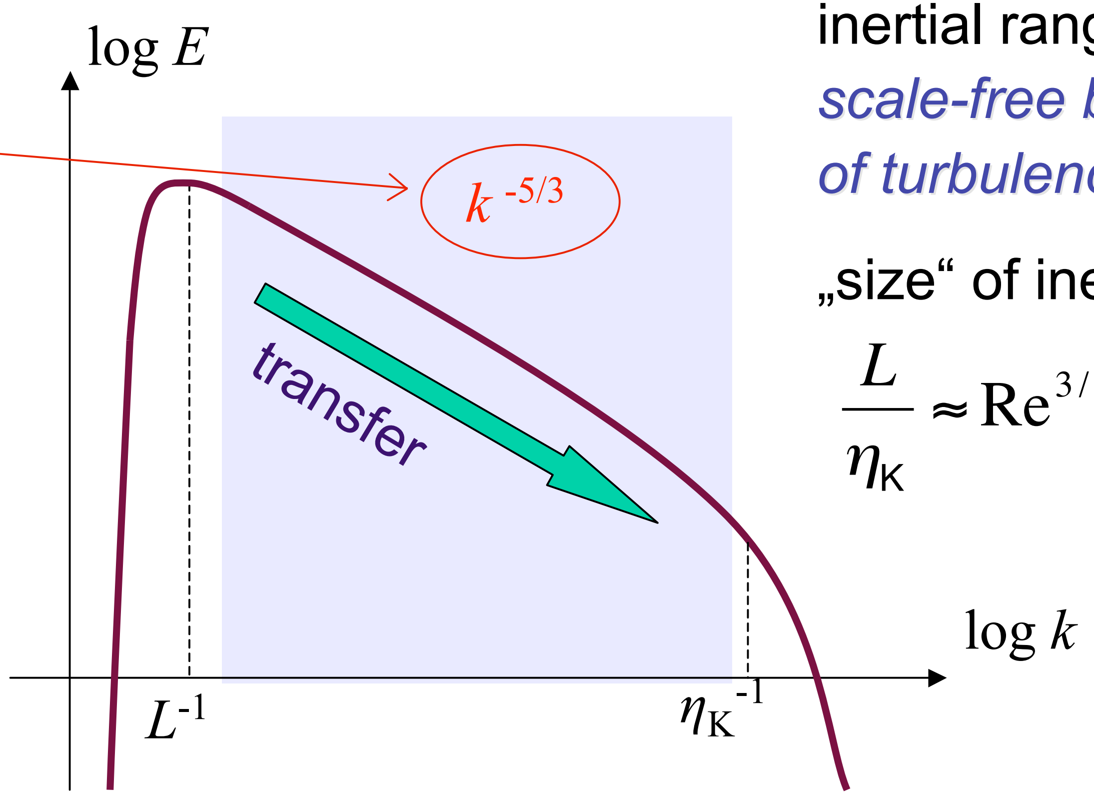


Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:
scale-free behavior of turbulence

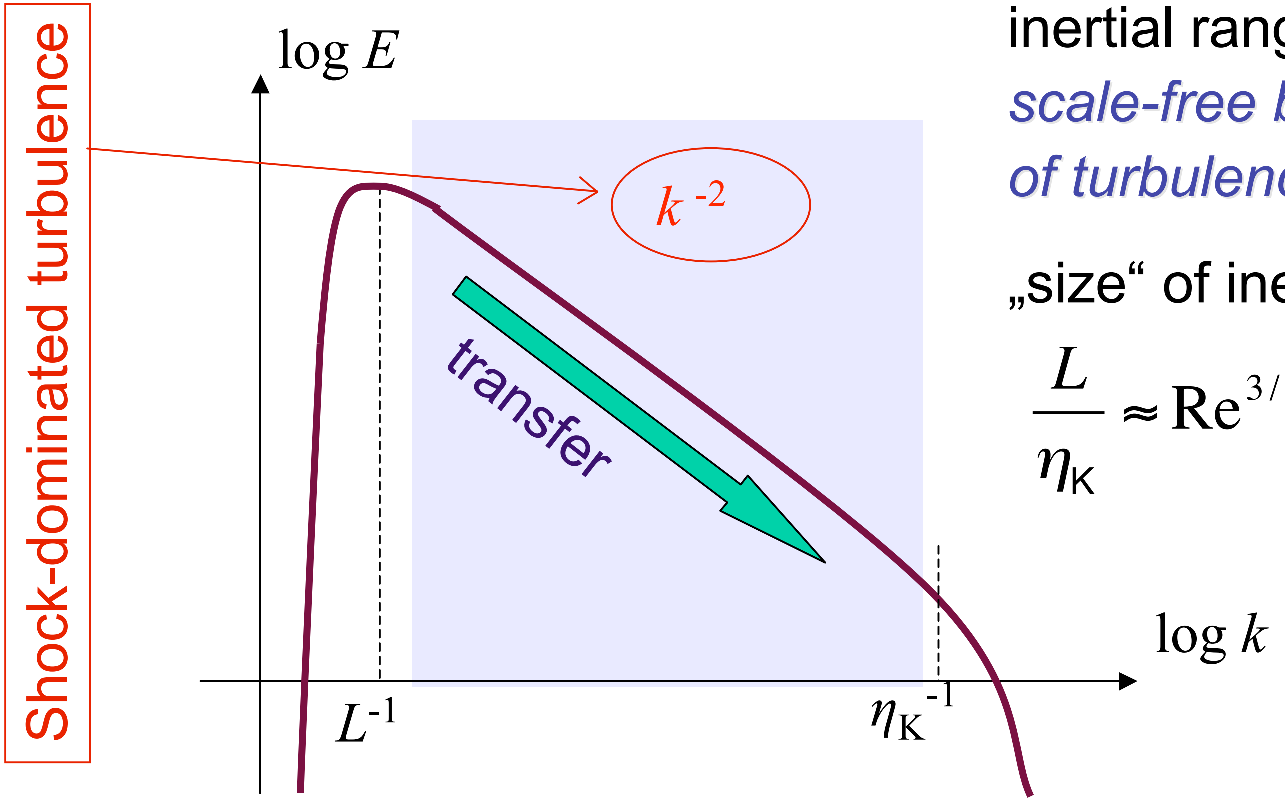
„size" of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



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energy
input
scale

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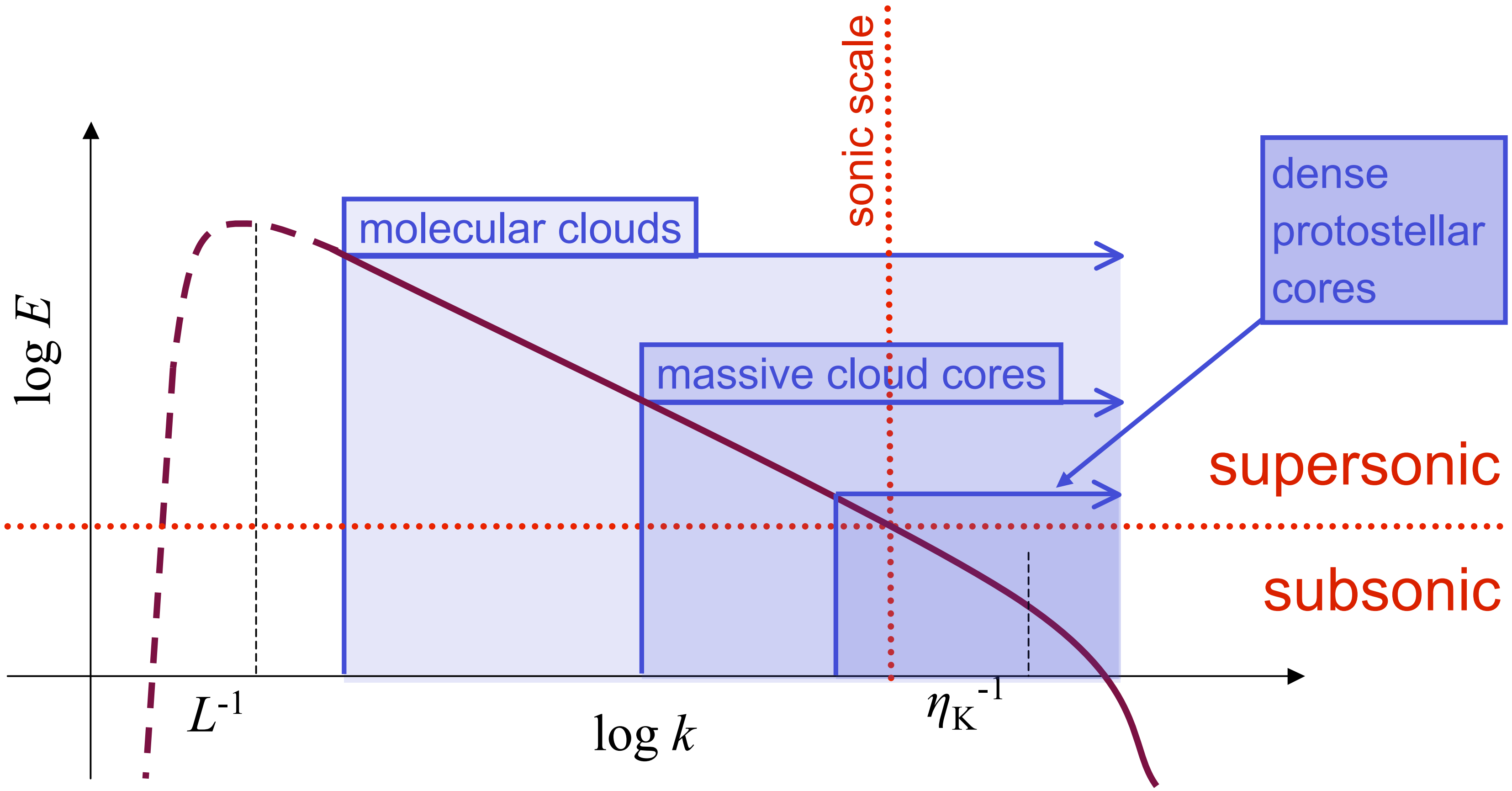
dissipation
scale

Turbulent cascade in ISM

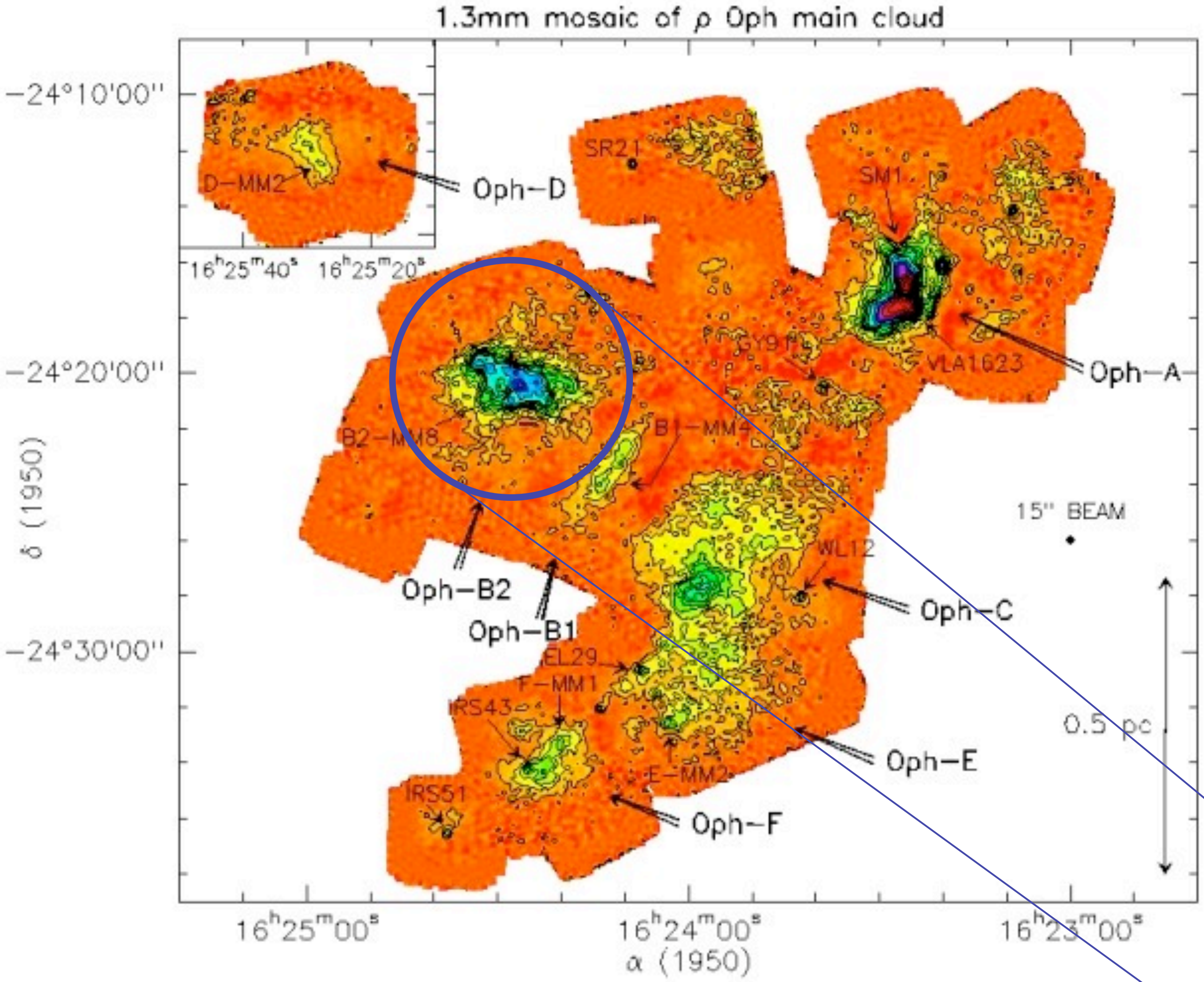


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

$\sigma_{rms} << 1$ km/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)

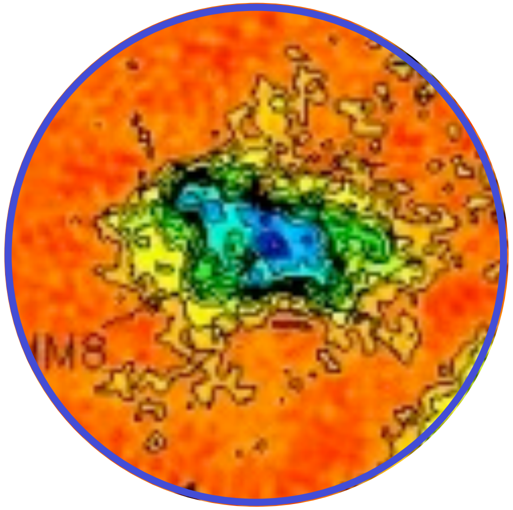
molecular clouds are highly inhomogeneous

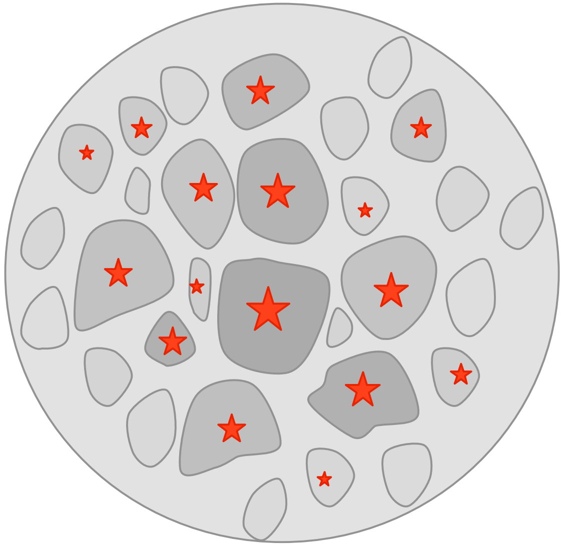
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

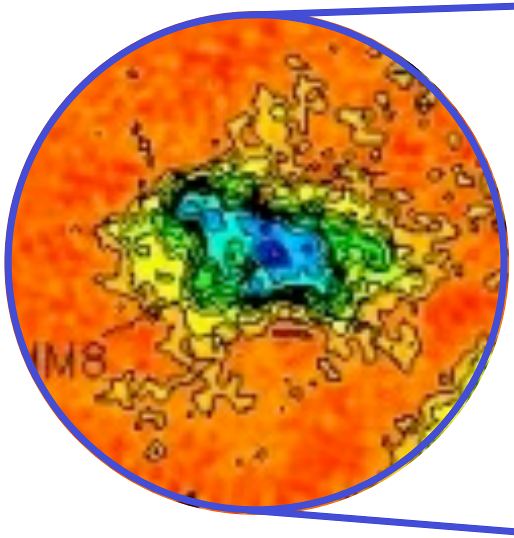


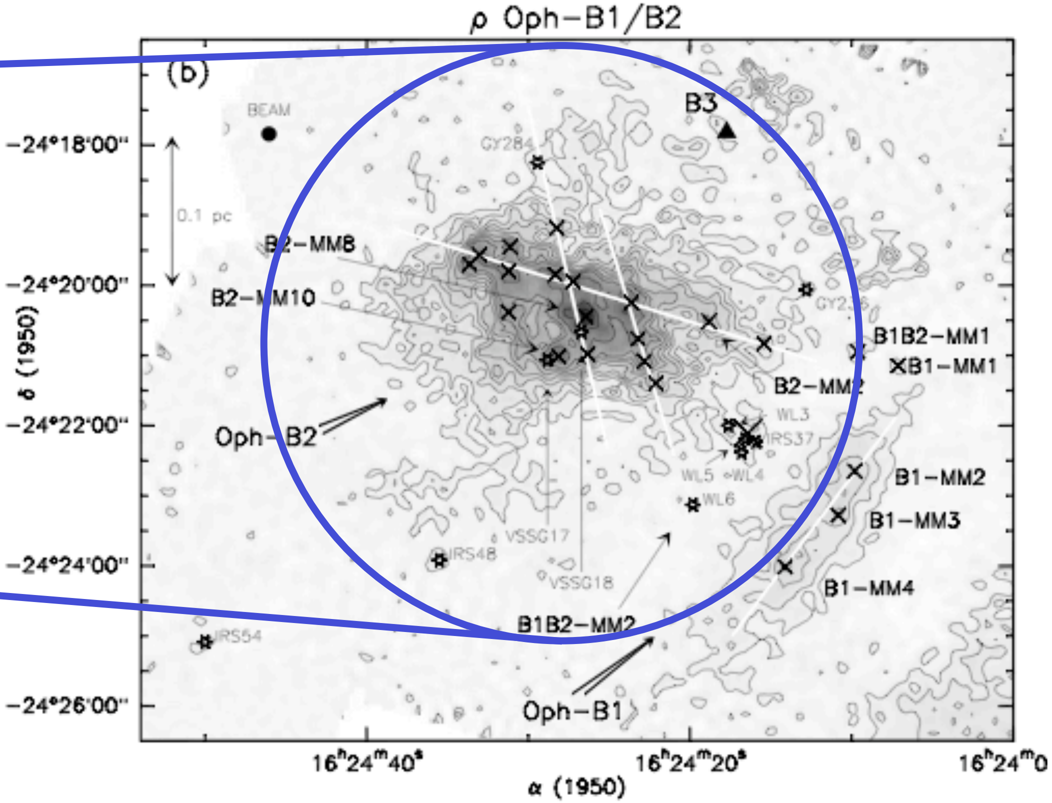


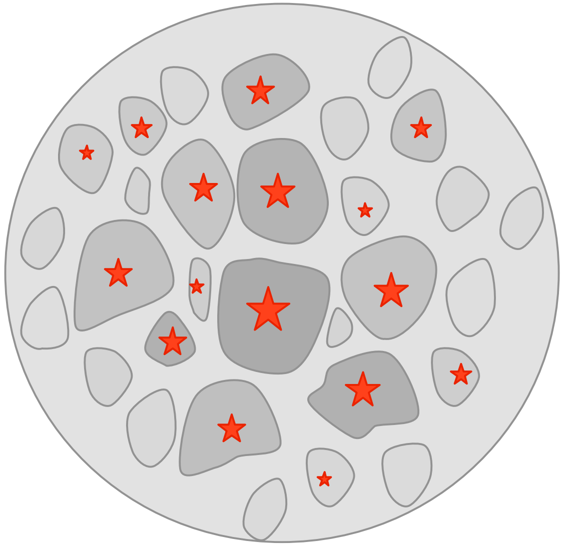
- Does core form single massive star or cluster with mass distribution?

- 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
- --> *core breaks up and forms a cluster of stars*

Evolution of cloud cores



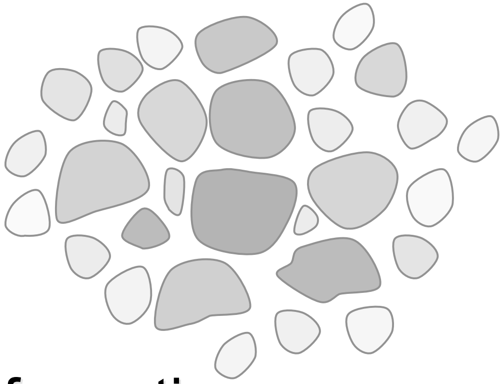




indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores



- protostellar cloud cores form at the *stagnation points* of *convergent turbulent flows*
- if $M > M_{Jeans} \propto \rho^{-1/2}\, T^{3/2}$: collapse and star formation
- if $M < M_{Jeans} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after external compression fades away

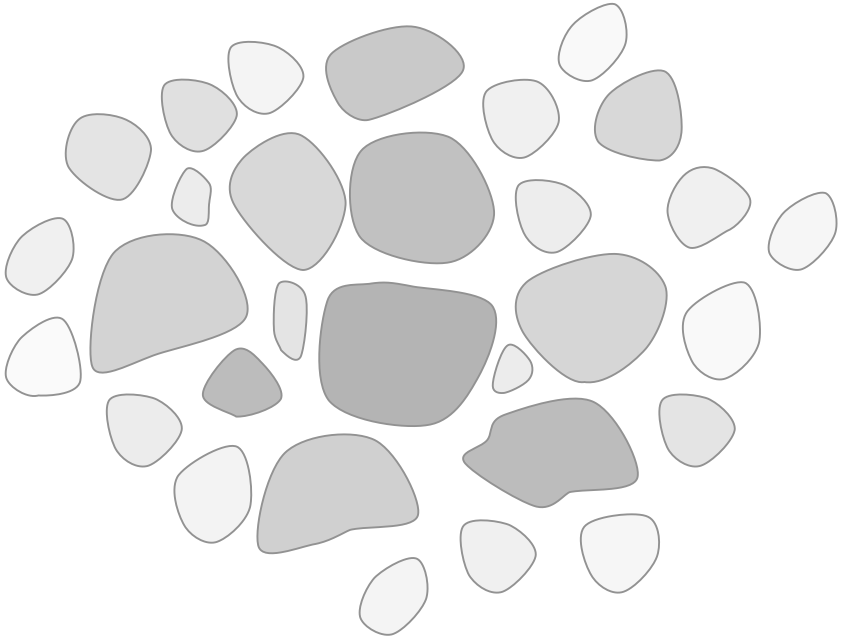
(e.g. Vazquez-Semadeni et al 2005)

- typical timescales: $t \approx 10^4 \ldots 10^5$ yr
- because *turbulent* ambipolar diffusion time is *short*, this time estimate still holds for the presence of magnetic fields, in *magnetically critical cores*

(e.g. Fatuzzo & Adams 2002, Heitsch et al. 2004)

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*

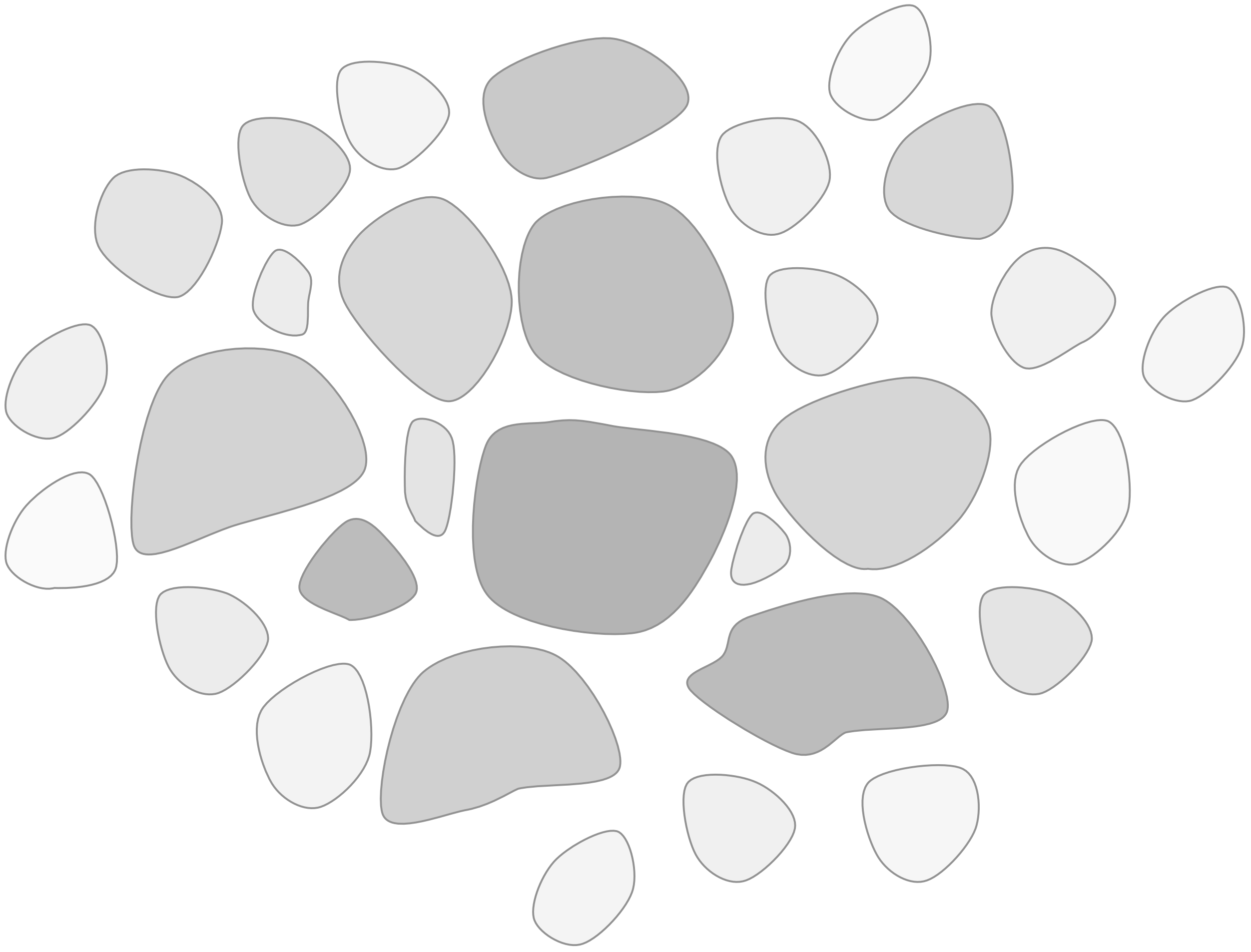
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

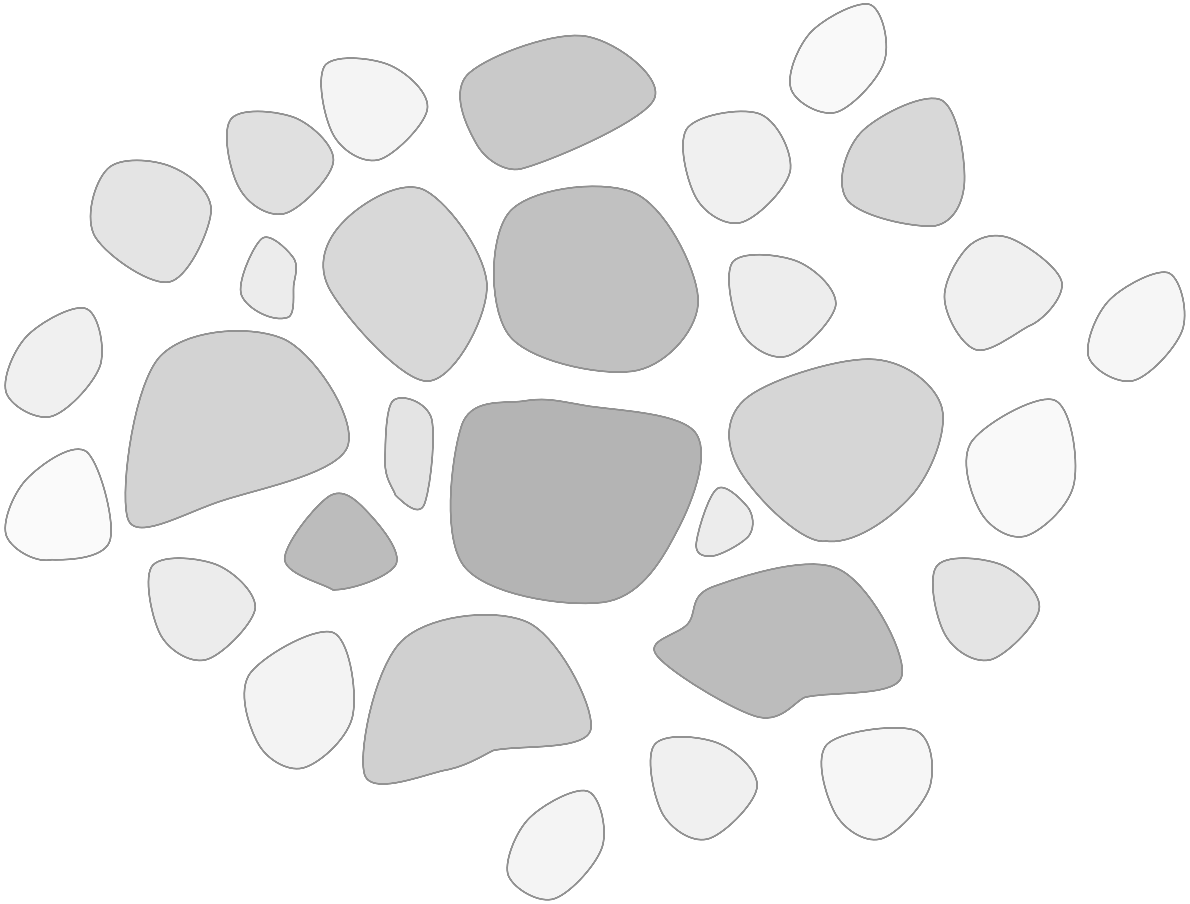
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

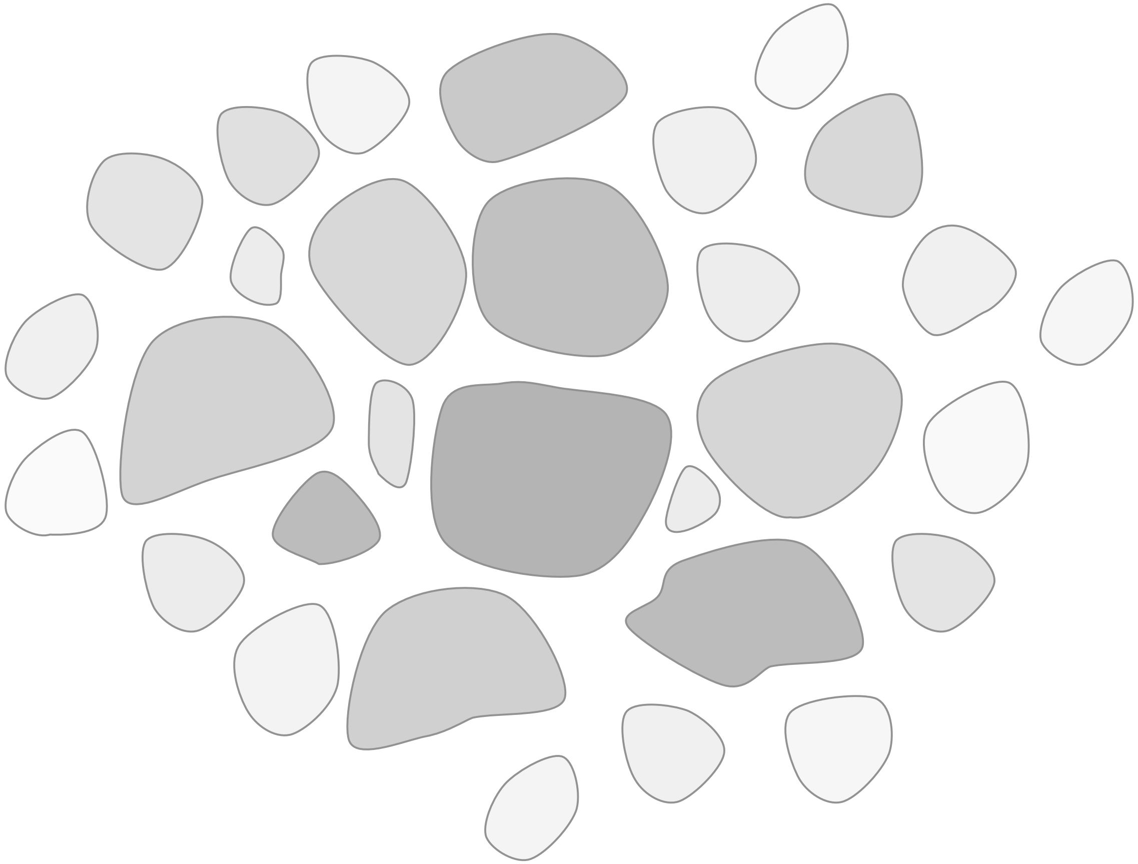
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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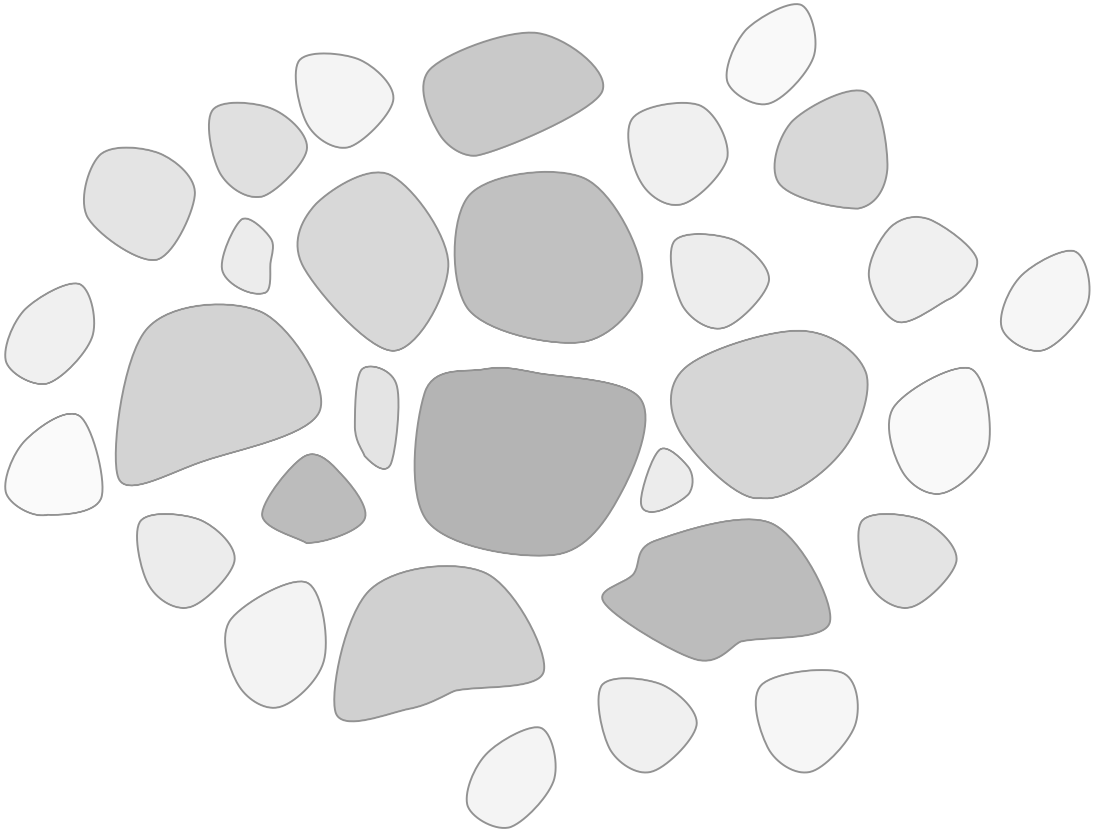
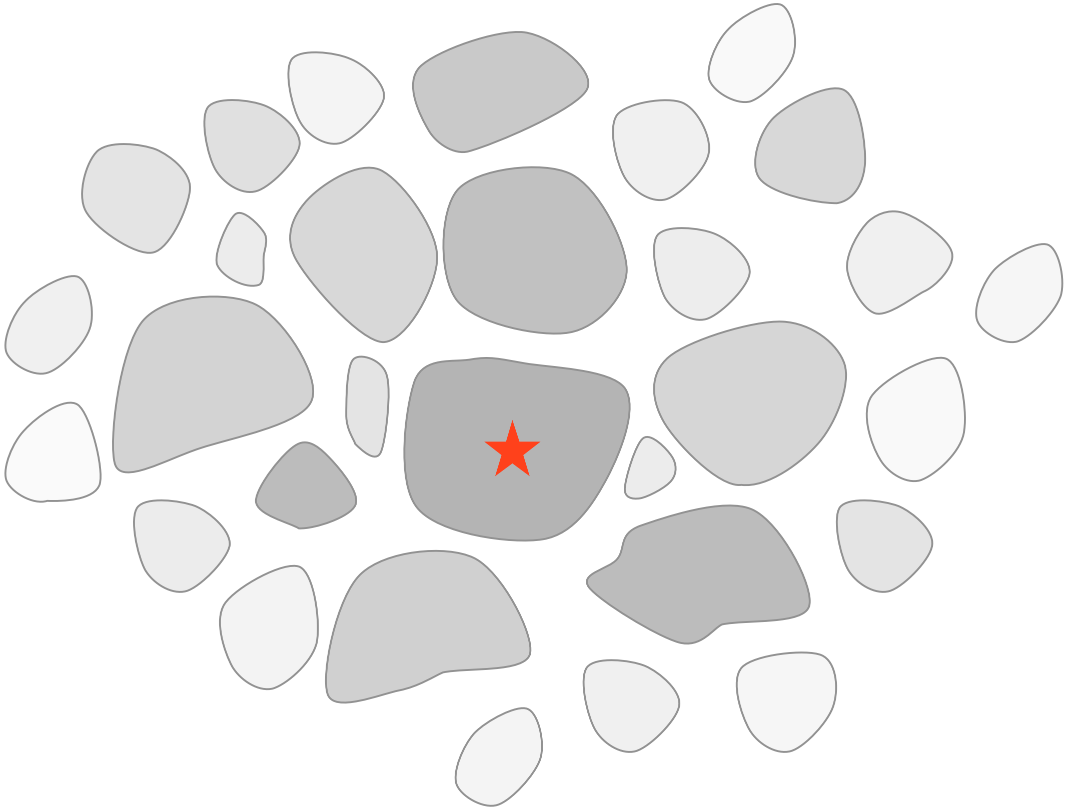


while region contracts, individual clumps collapse to form stars



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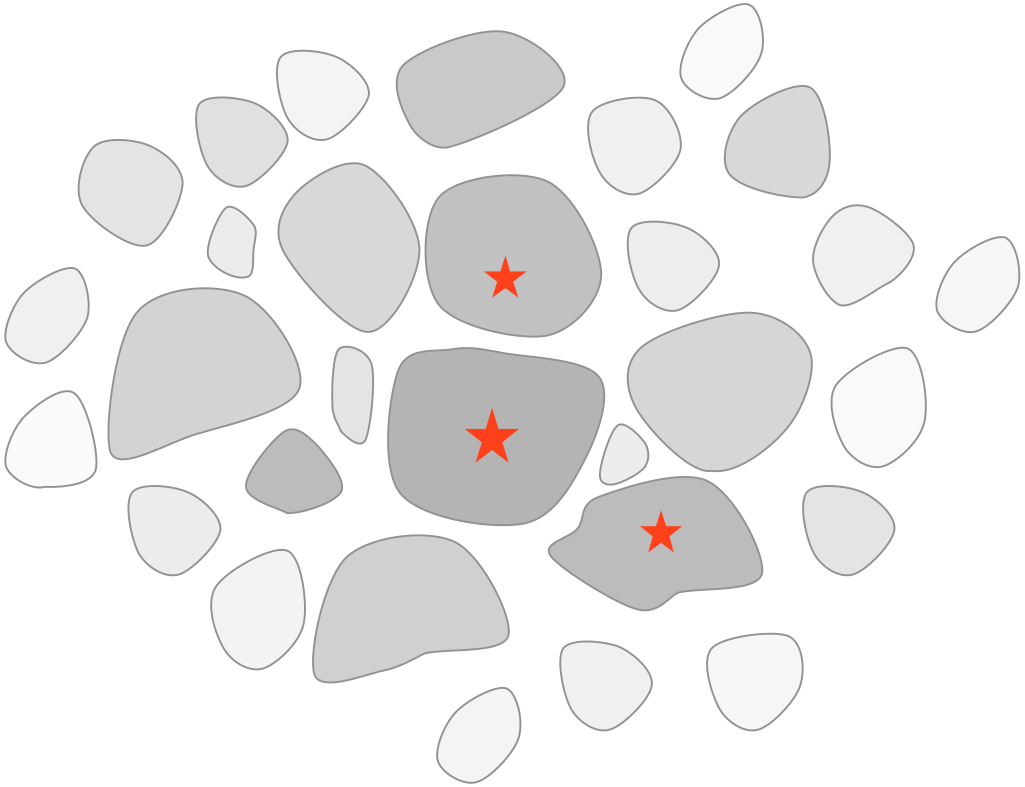
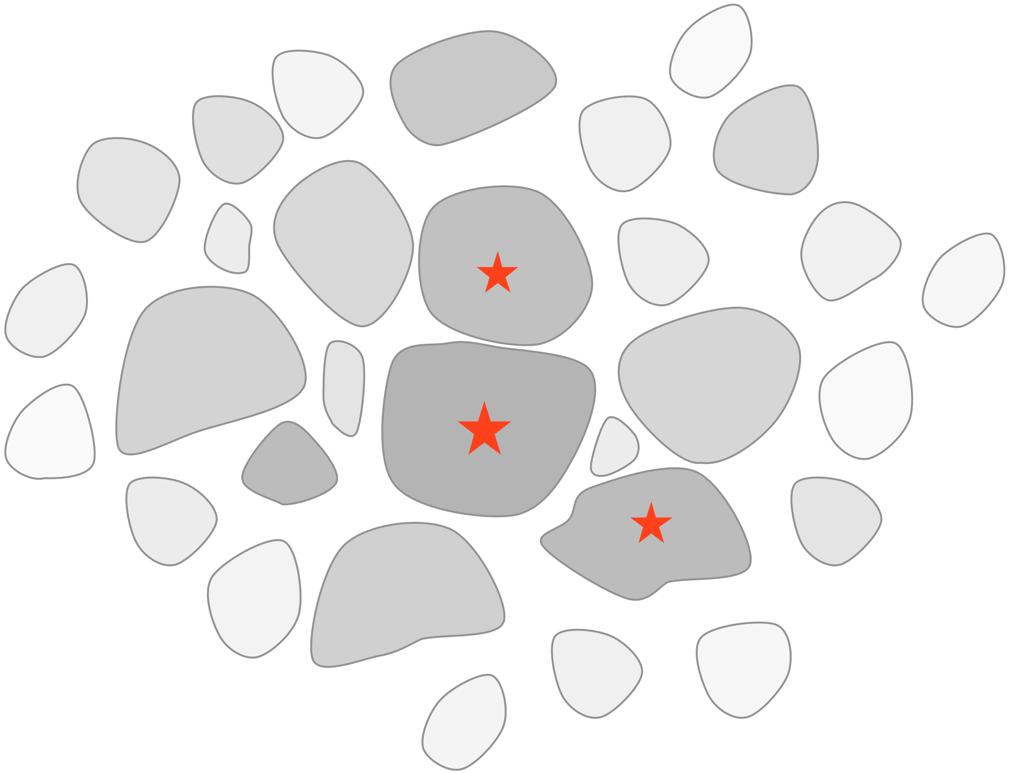


individual clumps collapse to form stars



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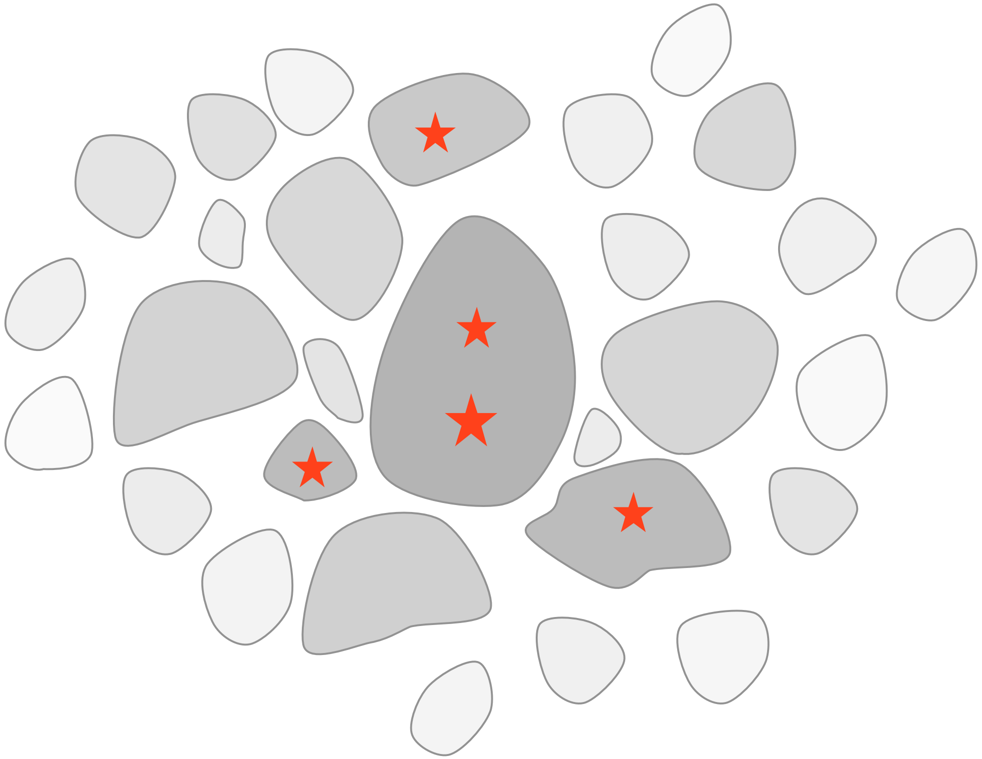
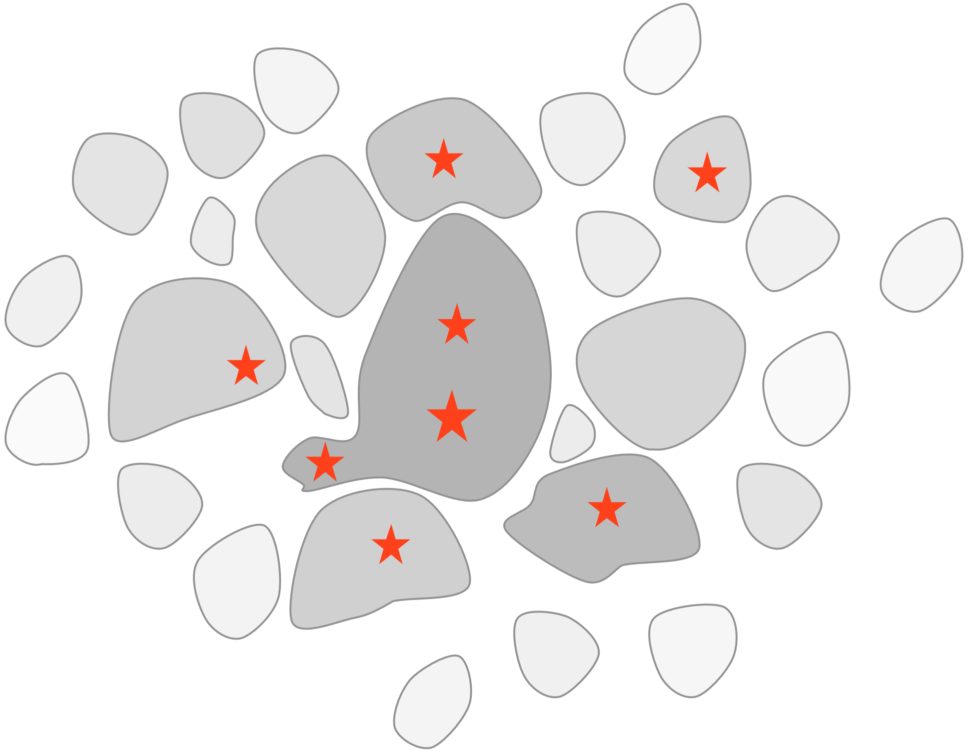


in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars

Ralf Klessen: PPV, Oct. 24, 2005



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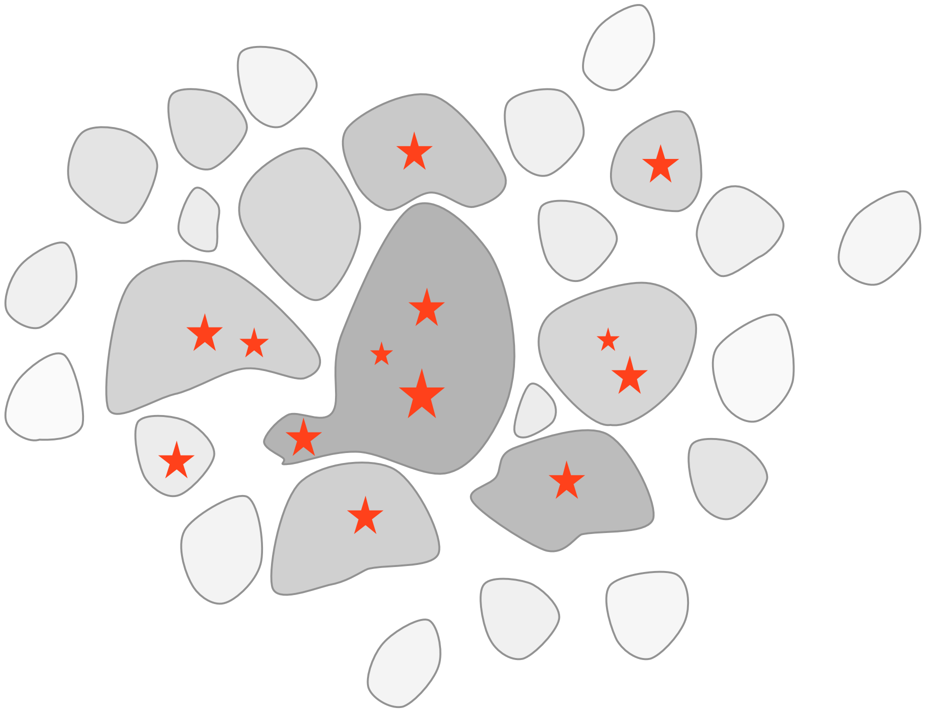

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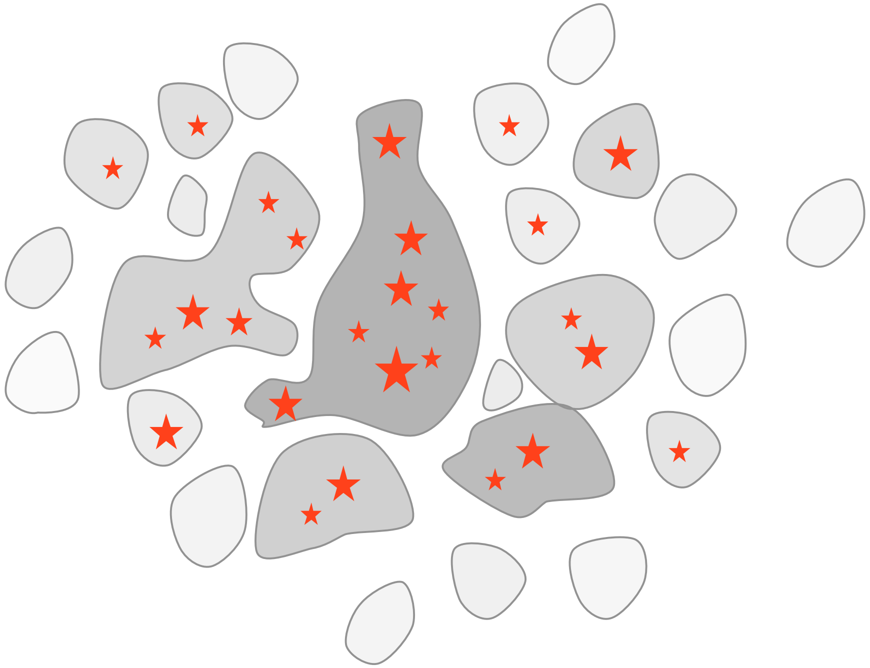
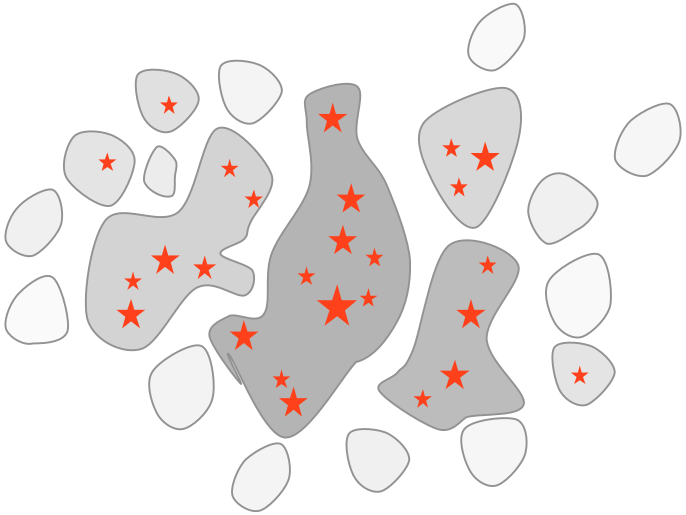


in *dense clusters*, competitive mass growth becomes important



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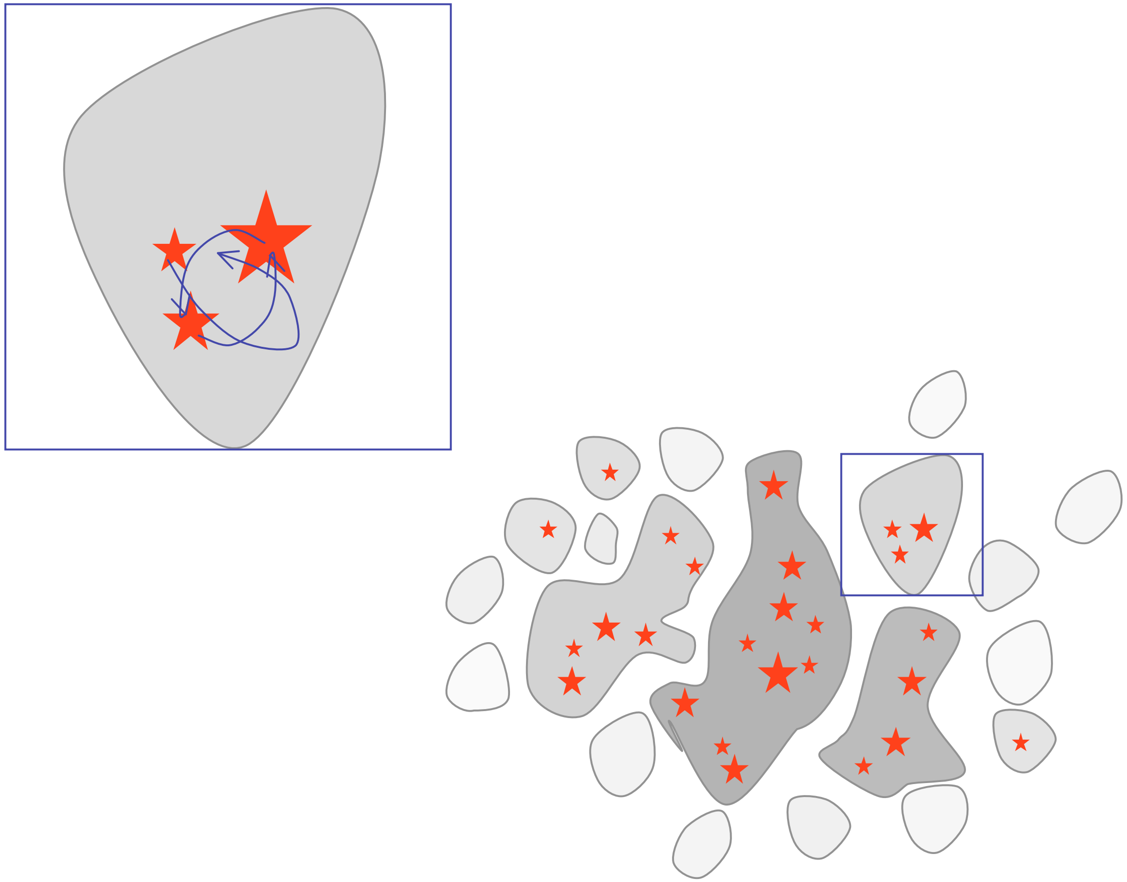
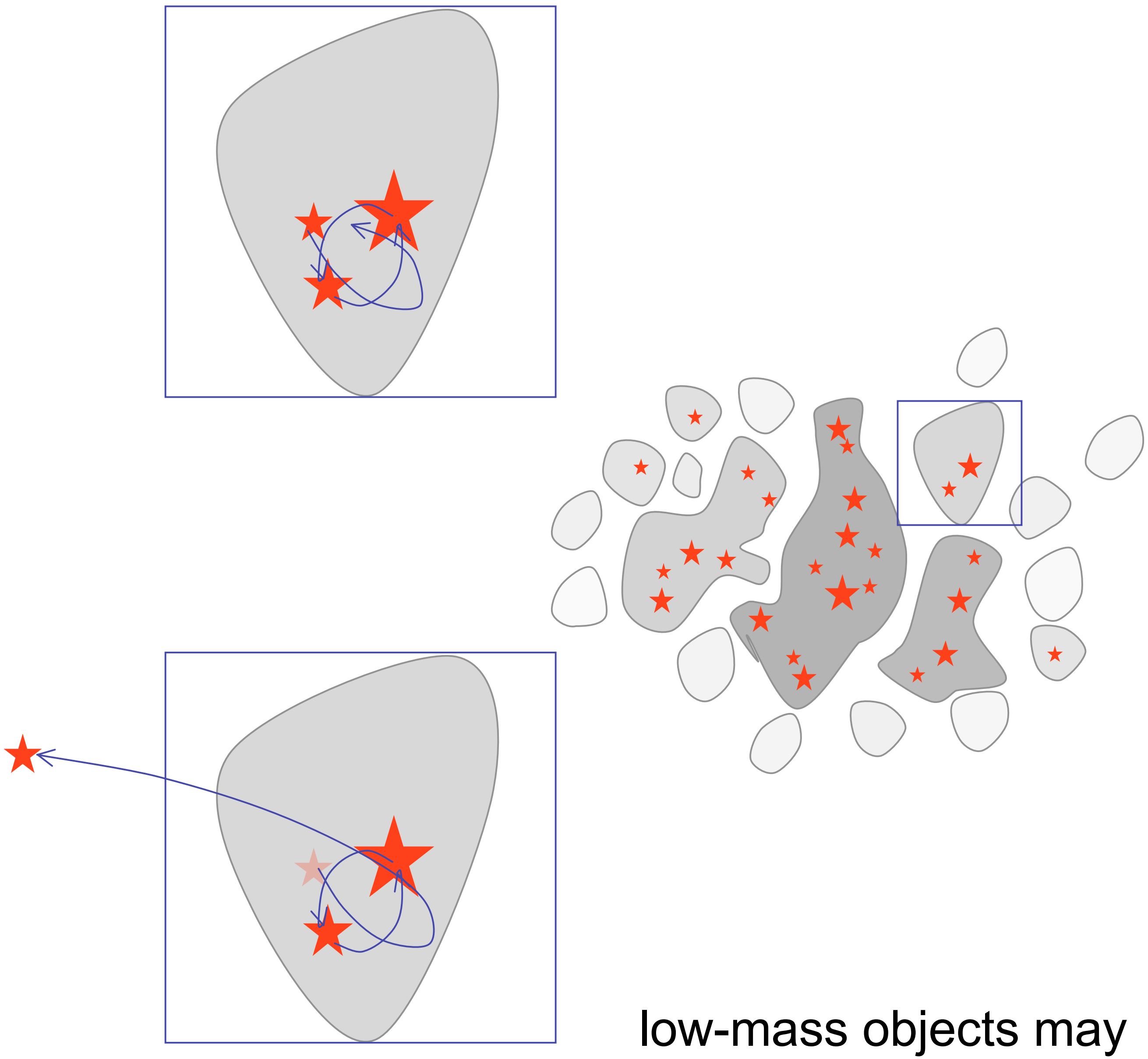
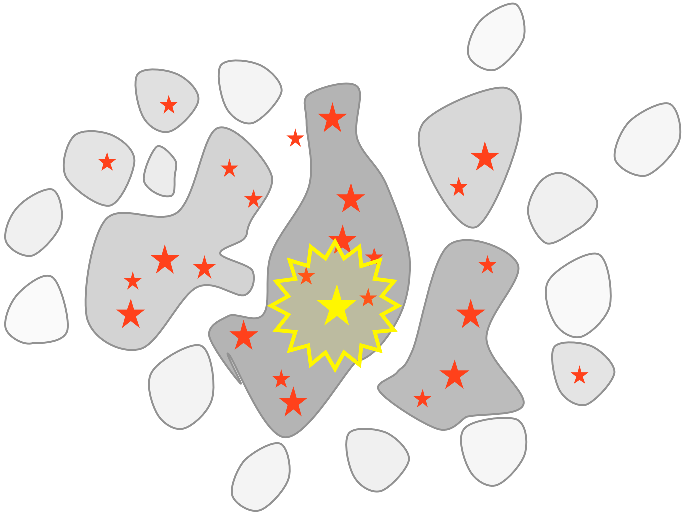


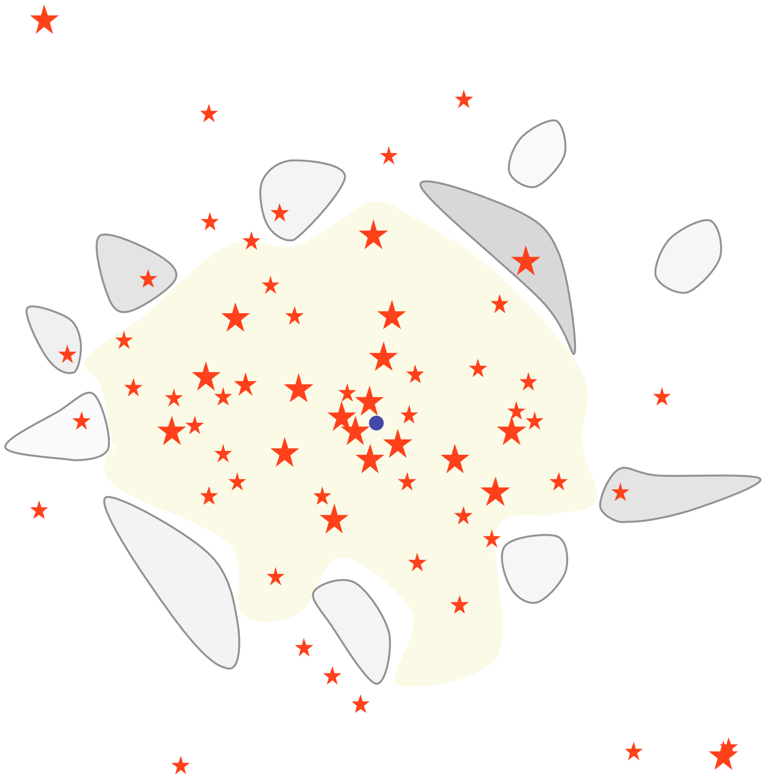
in *dense clusters*, *N*-body effects influence mass growth



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: transient structure of turbulent clouds

example 2: quiescent and coherent appearence of molecular cloud cores

example 3: speculations on the origin of the stellar mass spectrum (IMF)

example 1

Transient cloud structure

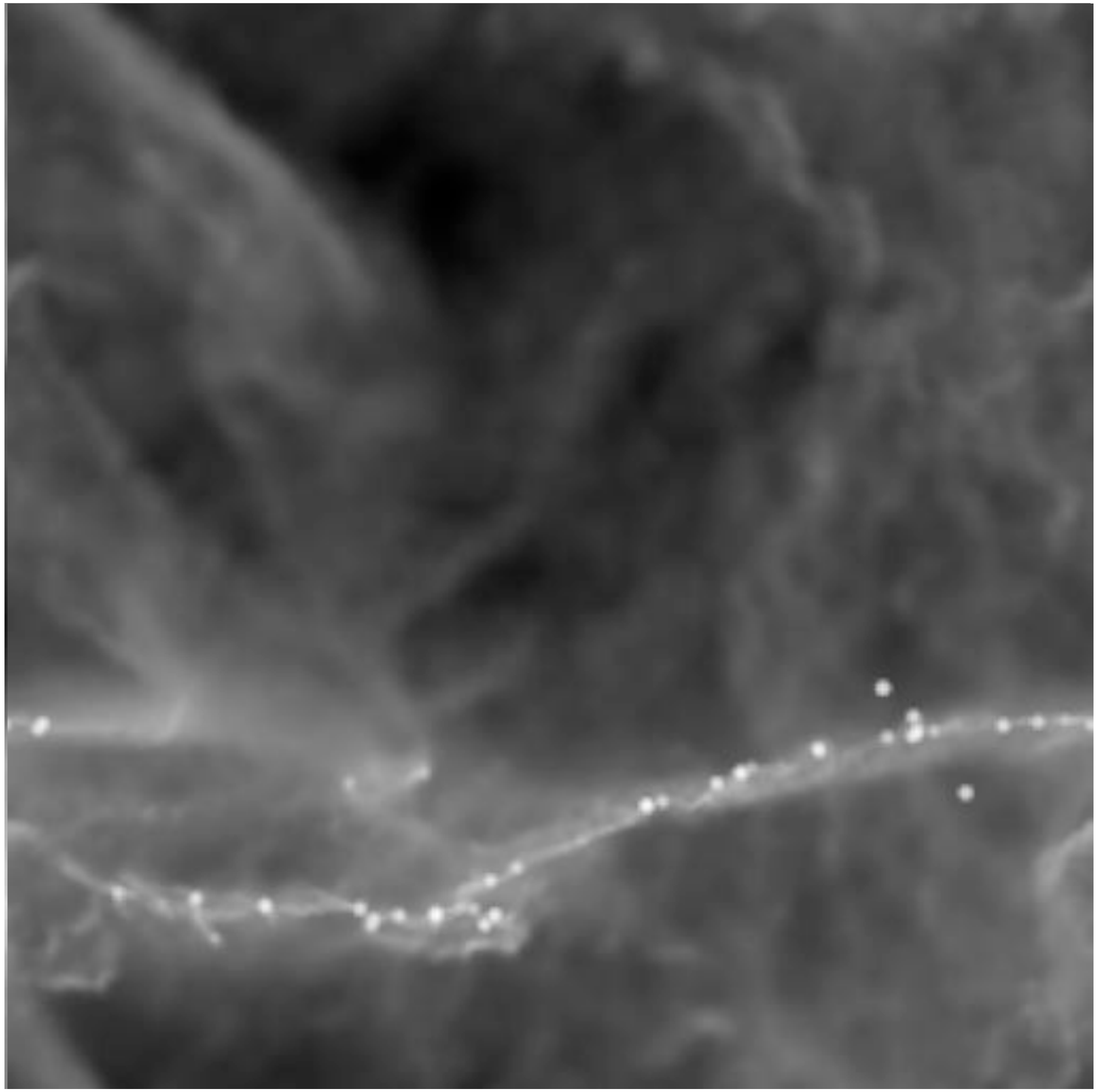
Gravoturbulent fragmentation of turbulent self-gravitating clouds

xy projection *xz projection* *yz projection*

- SPH model with 1.6×10^6 particles
- large-scale driven turbulence

- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling: “Taurus”

Gravoturbulent fragmentation



Gravoturbulent fragmentation in molecular clouds:

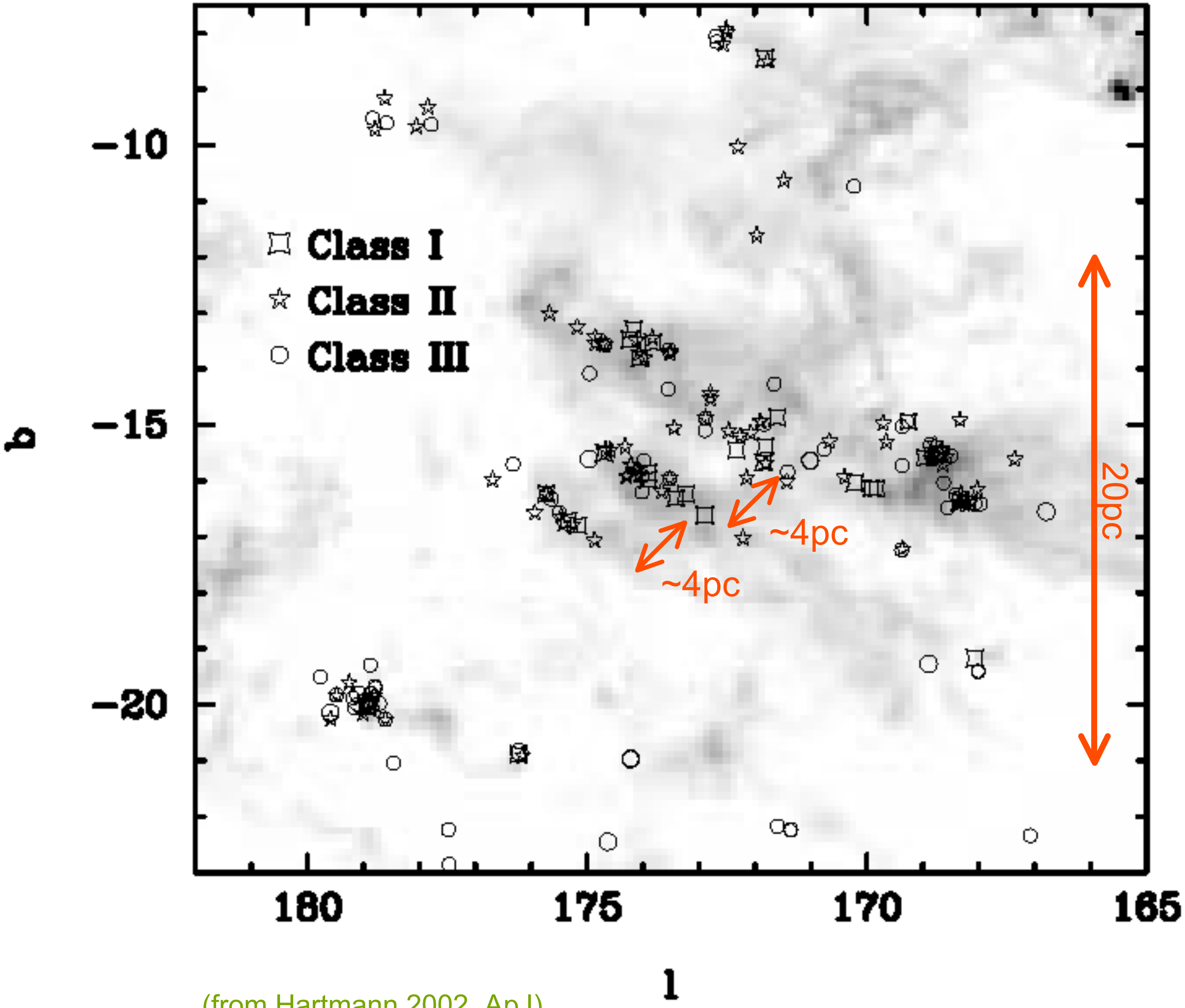
- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"Taurus":

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

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

Taurus cloud



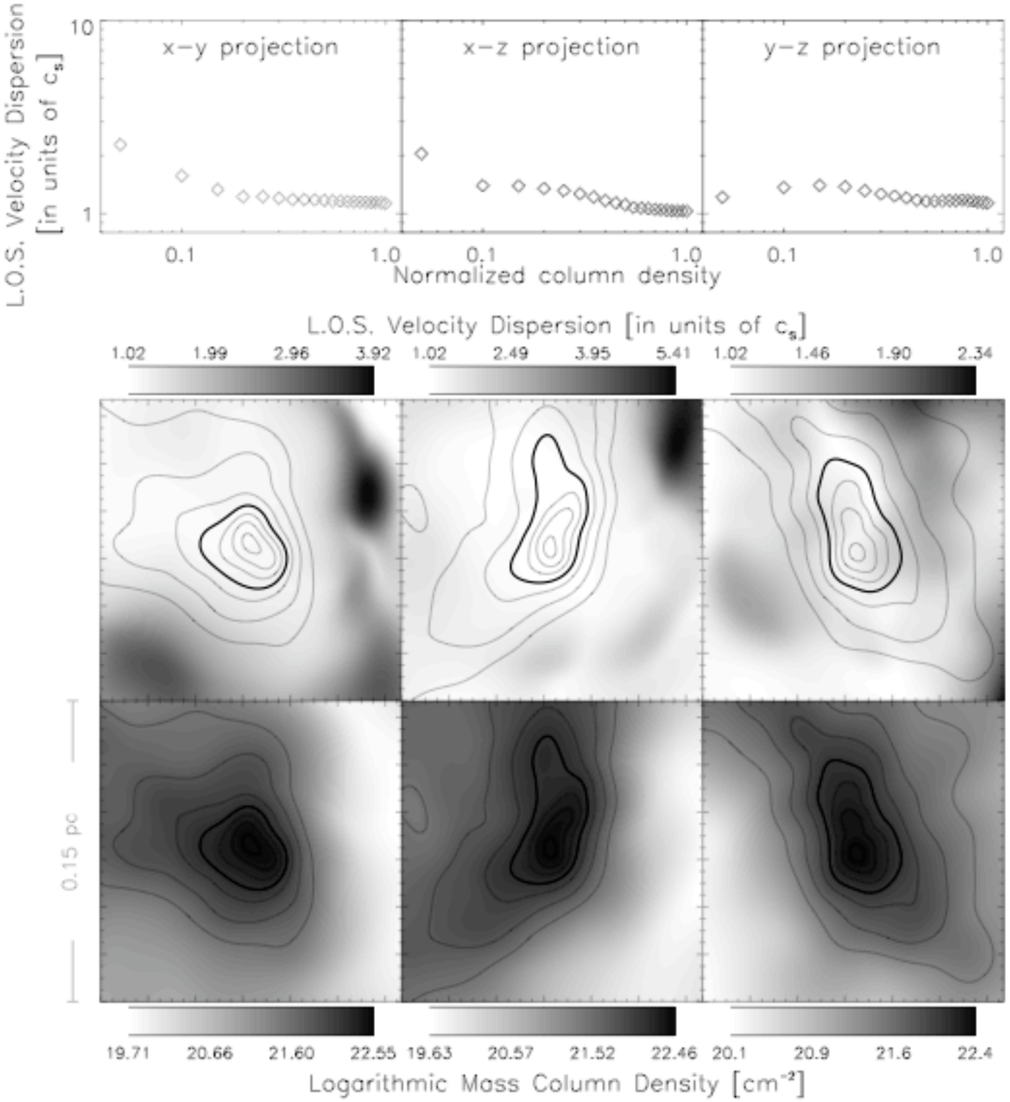
(from Hartmann 2002, ApJ)

Star-forming filaments in the *Taurus* molecular cloud

example 2

Quiescent & coherent cores

(from Klessen et al. 2005, ApJ, 620, 768 - 794; also poster 8415)



correlation between linewidth and column density

(e.g. Goodman et al. 1998;
Barranco & Goodman 1998
Caselli et al. 2002; Tafalla et al. 2004)

map of linewidth
(contours column density)

column density map
(contours column density)

Quiescent & coherent cores

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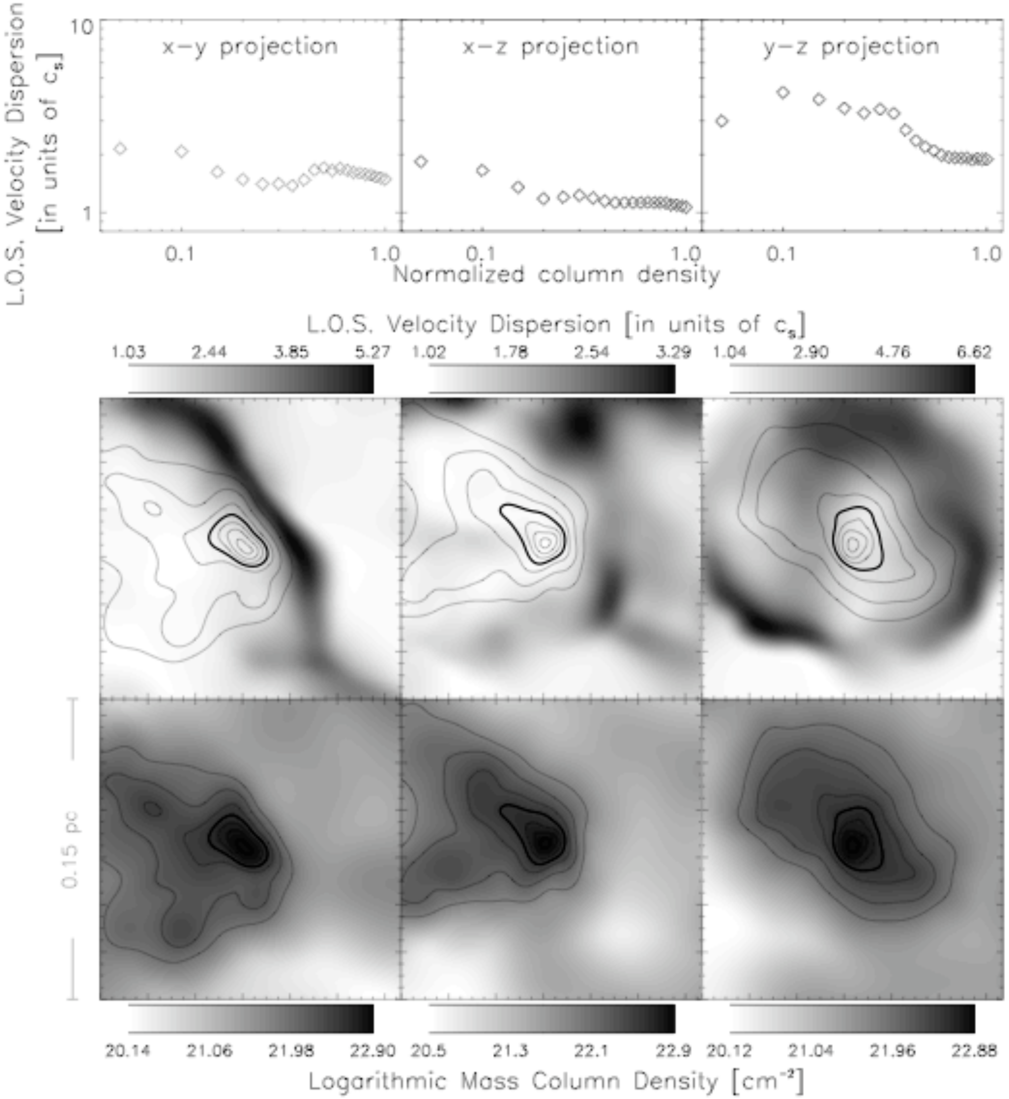

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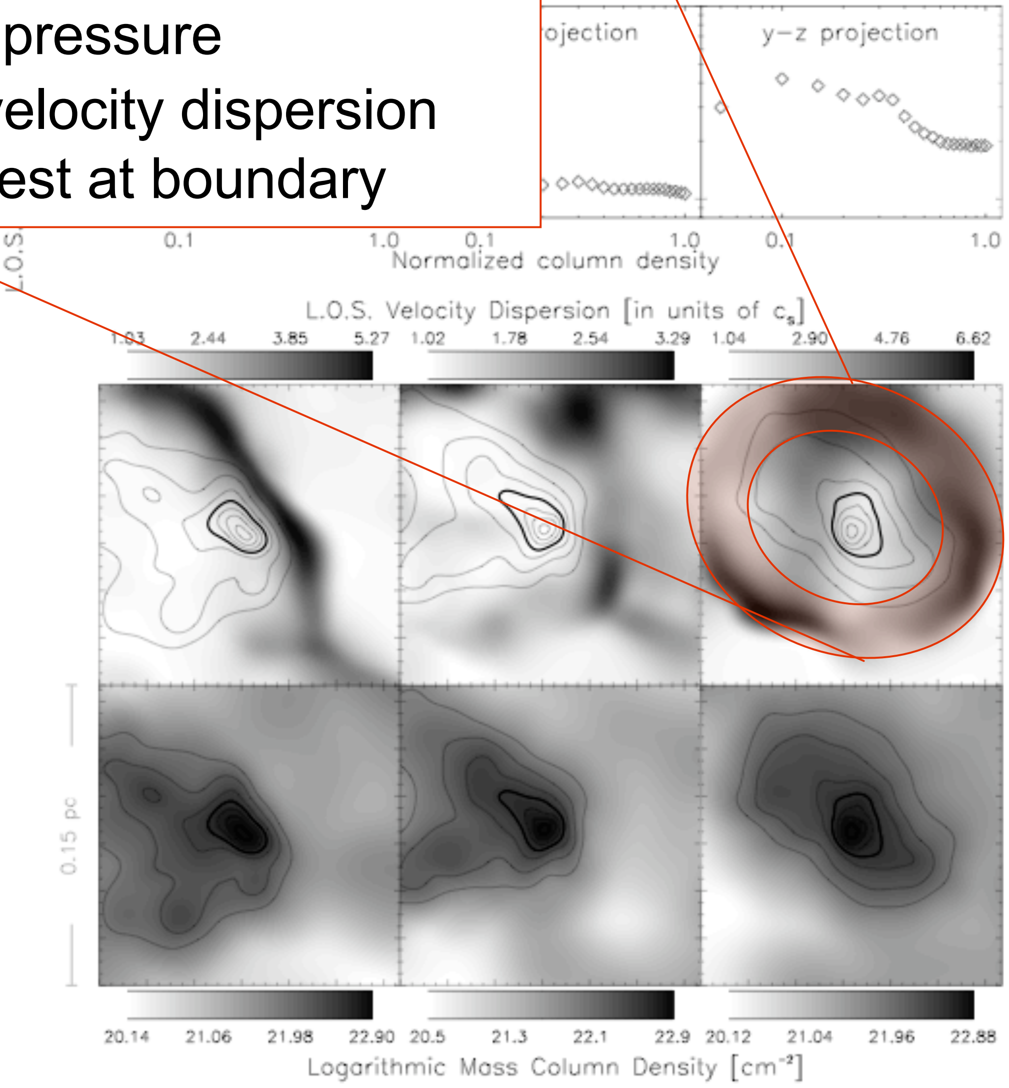
column density map (contours column density)

t & coherent cores

cores form at stagnation points of convergent large-scale flows

--> often are bounded by ram pressure

--> velocity dispersion highest at boundary



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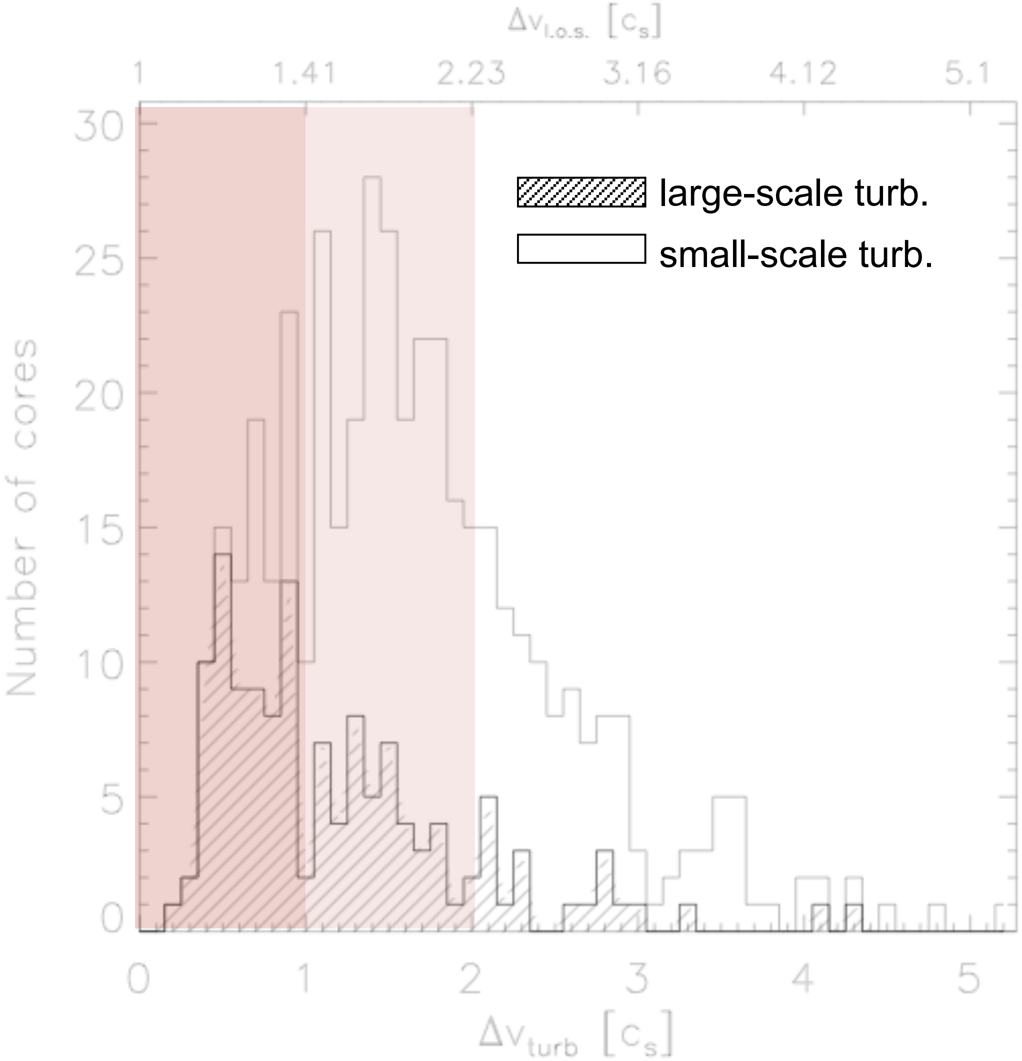
(contours column density)

Quiescent & coherent cores



(from Klessen et al. 2005, ApJ, 620, 768 - 794; also poster 8415)

Statistics:

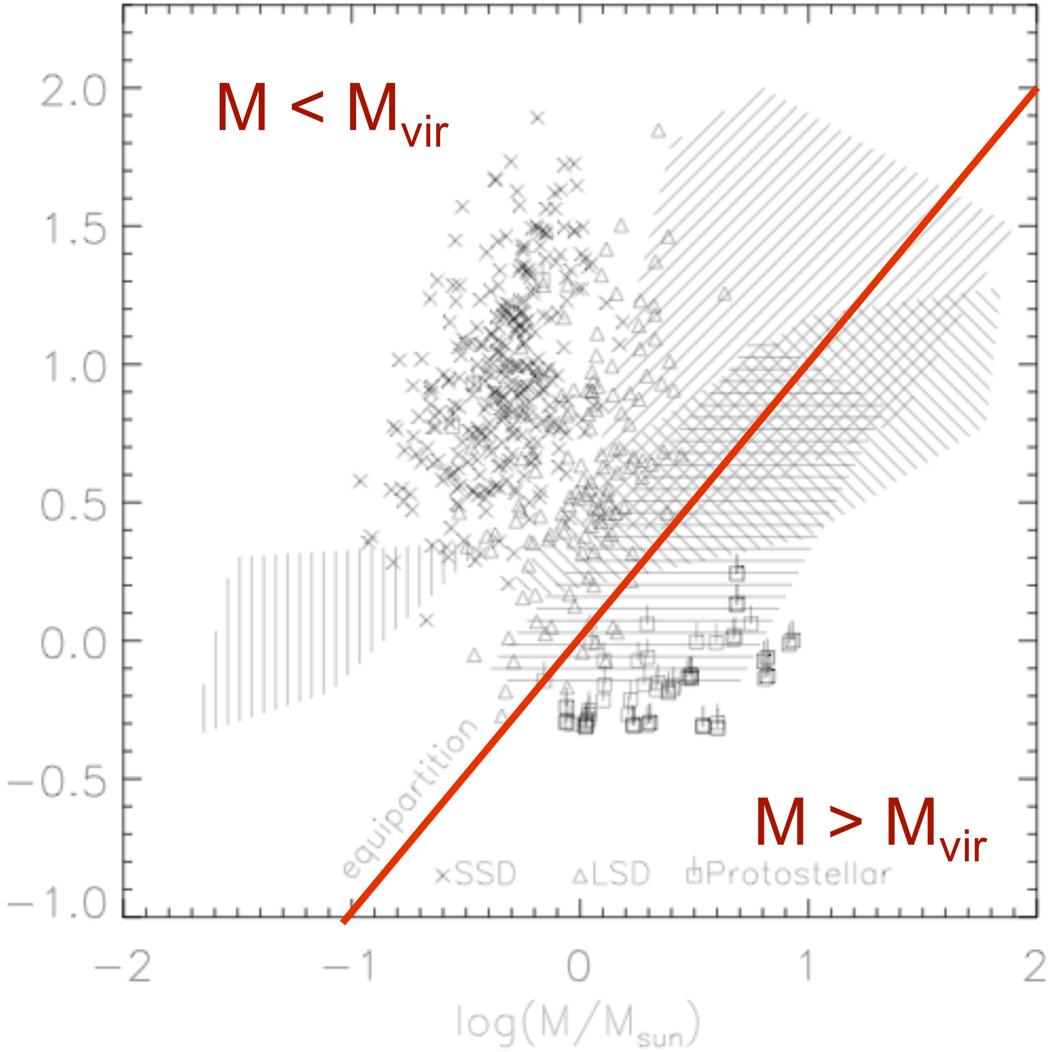
23% of our cores are *quiescent* (i.e. with $\sigma_{rms} \leq c_s$)

48% of our cores are *transonic* (i.e. with $c_s \leq \sigma_{rms} \leq 2c_s$)

half of our cores are *coherent* (i.e. with σ_{rms} independent of N)

Quiescent & coherent cores

(from Klessen et al. 2005, ApJ, 620, 768 - 794; also poster 8415)



Statistics:

most cores have masses smaller than M_{vir} (should reexpand once external compresseion fades)

some core have more mass than M_{vir} (should collapse) (indeed all cores with protostars have $M>M_{vir}$)

example 3

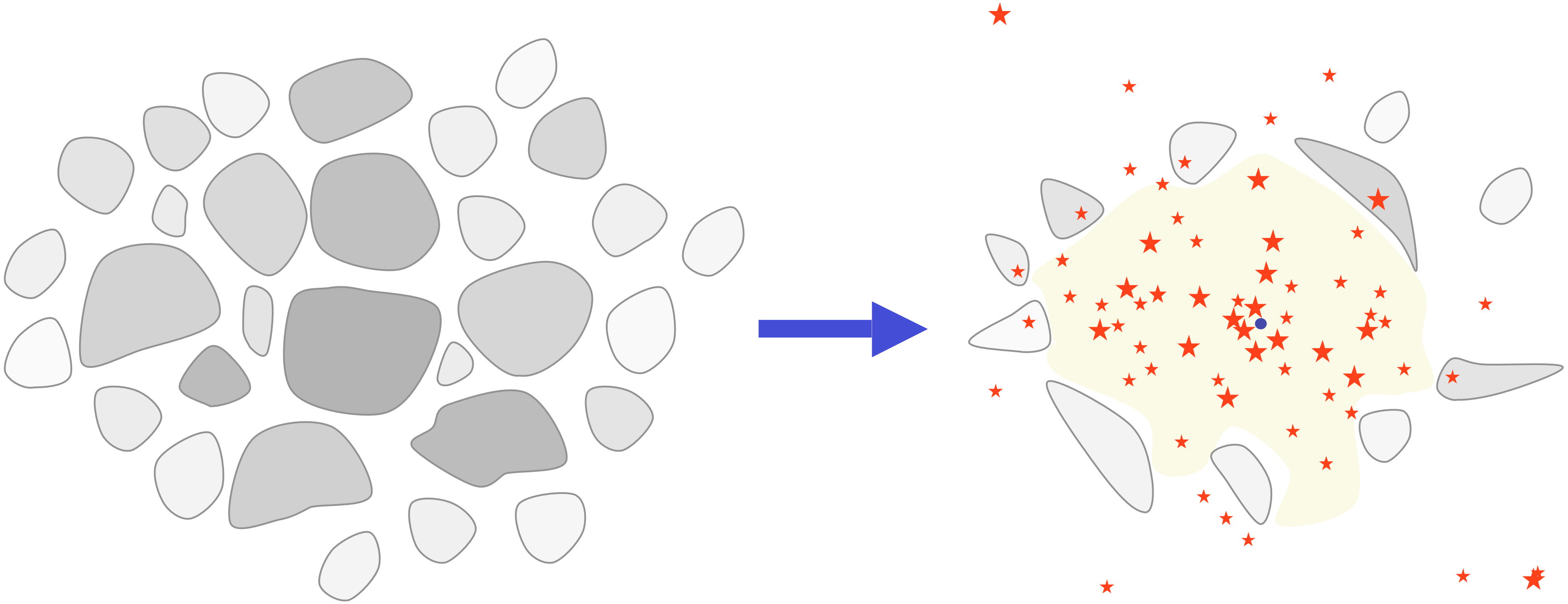
IMF

- 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*



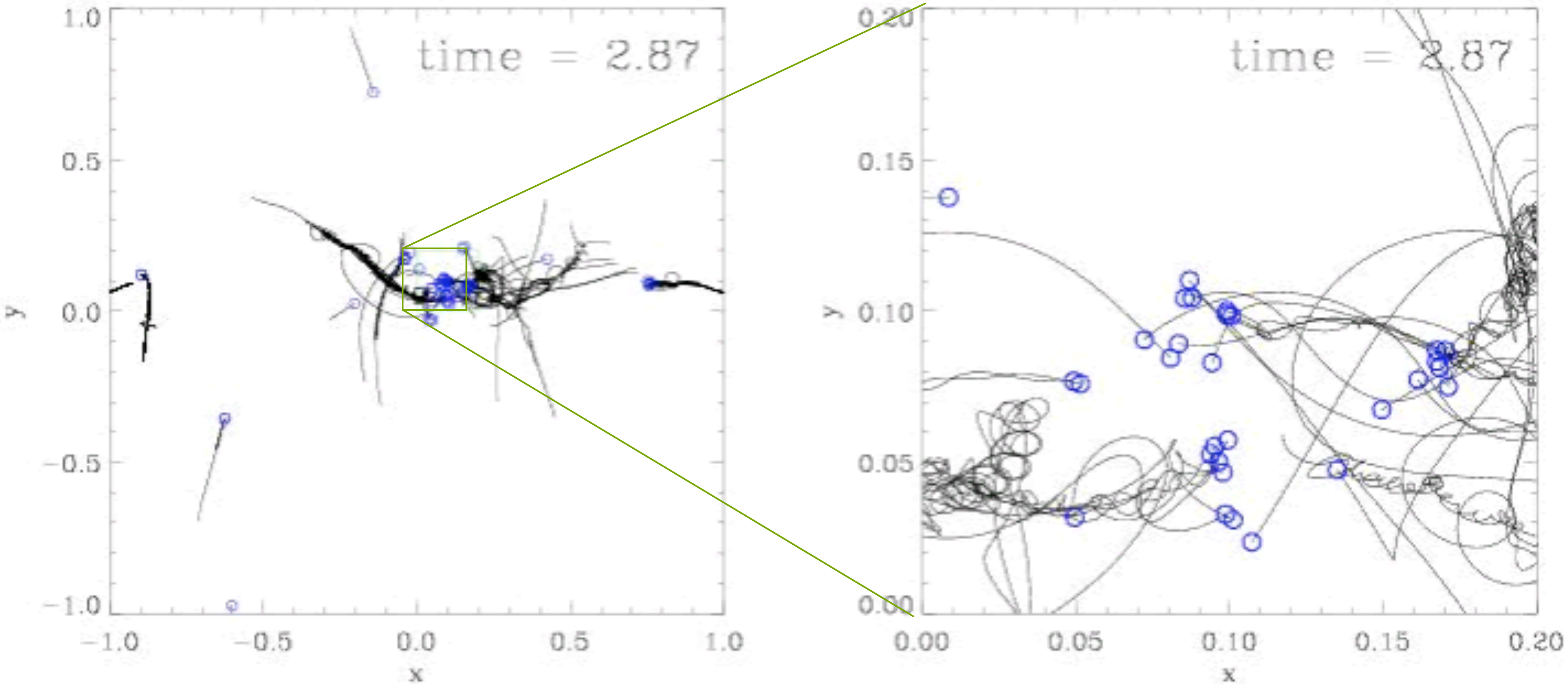
How to get from cloud cores to star clusters?

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

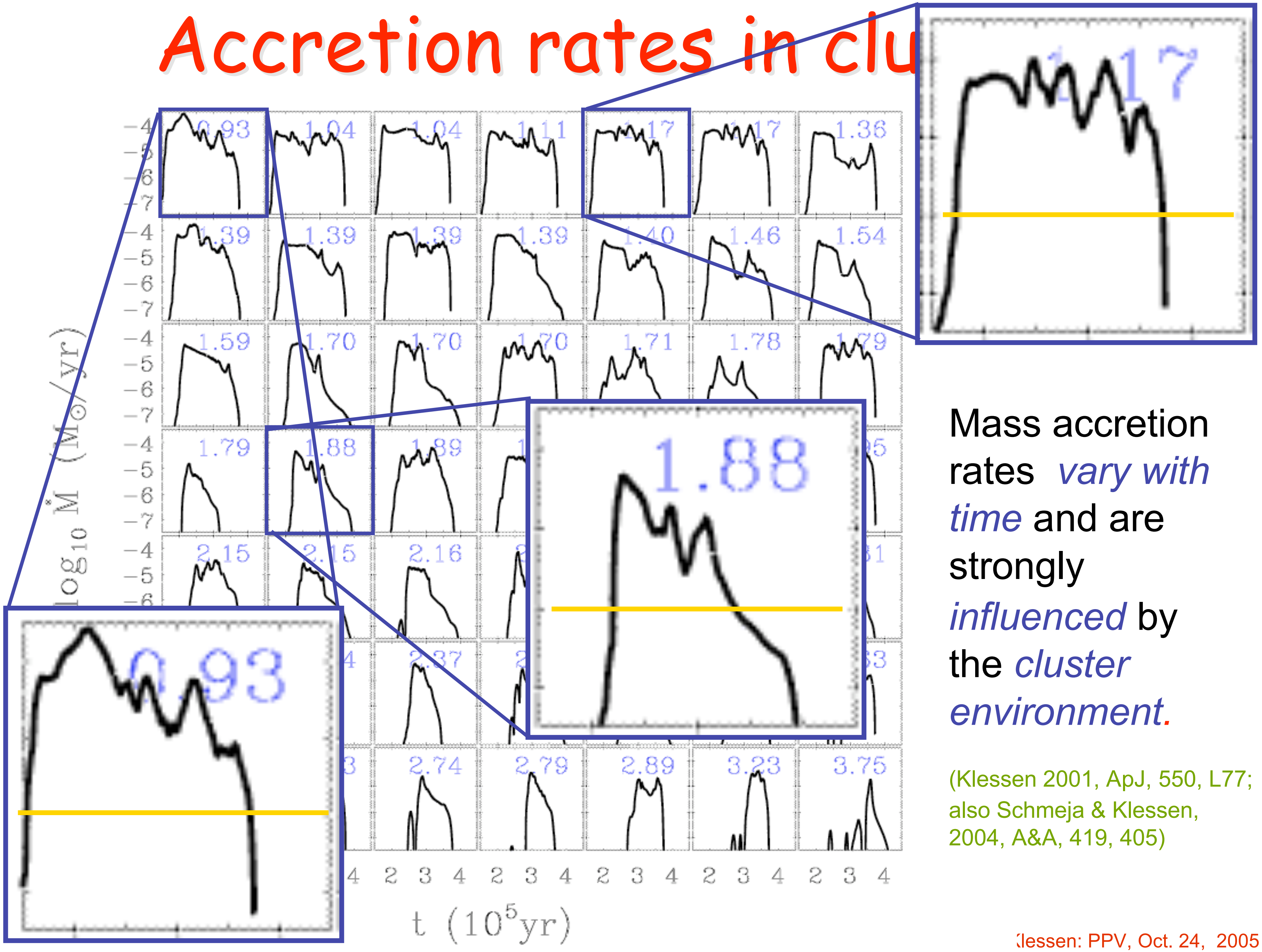
Most stars form in clusters → *star formation = cluster formation*



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

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

Accretion rates in clu



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)

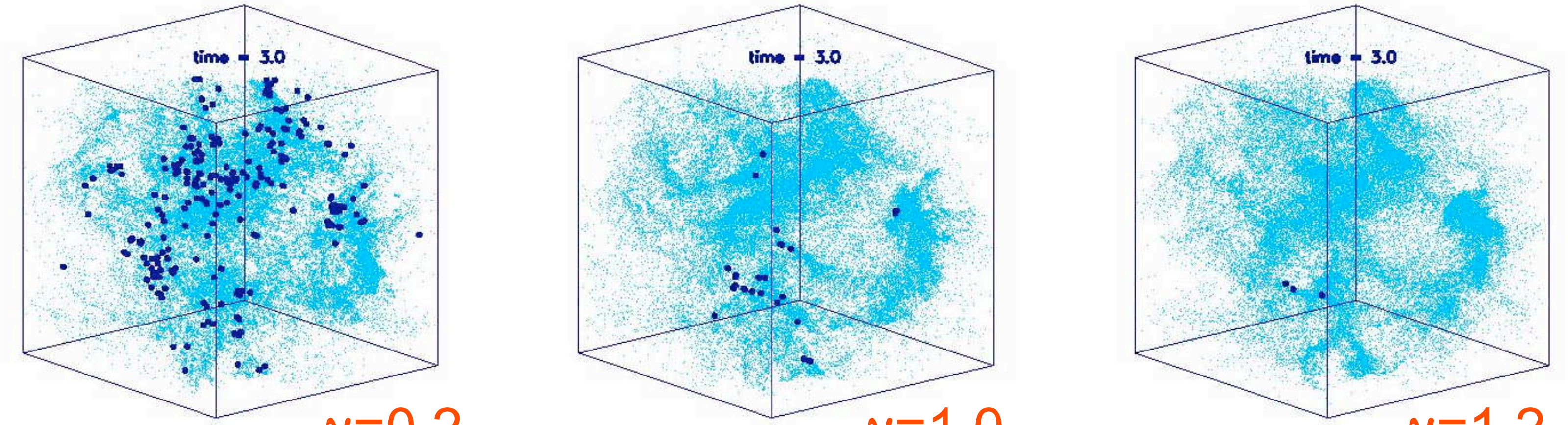
Dependency on EOS

- degree of fragmentation depends on *EOS!*

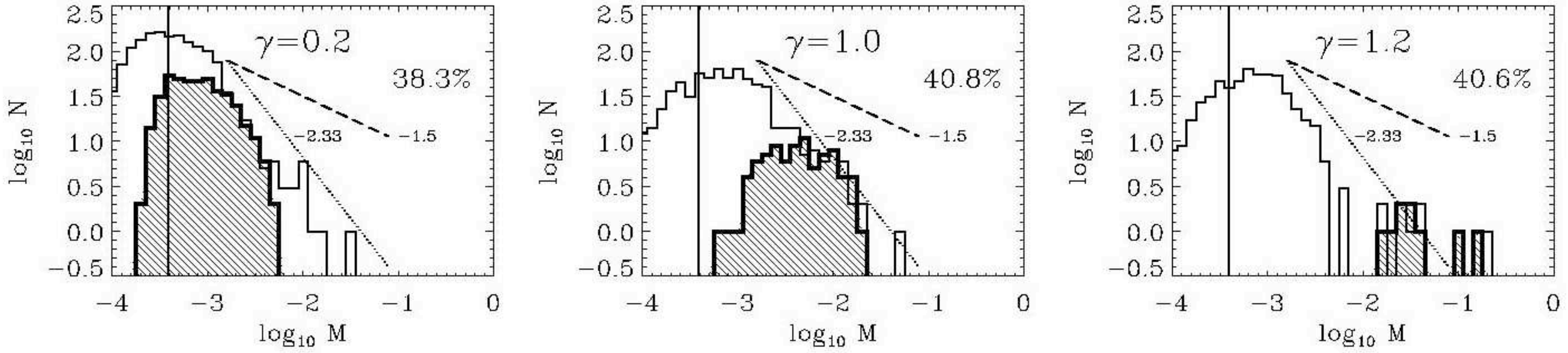
- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(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*

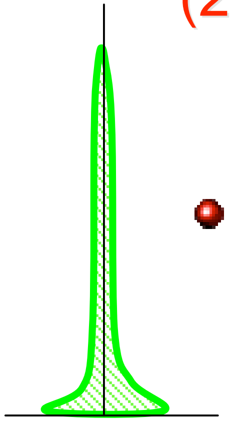
for γ>1 it is suppressed → formation of *isolated massive stars*

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

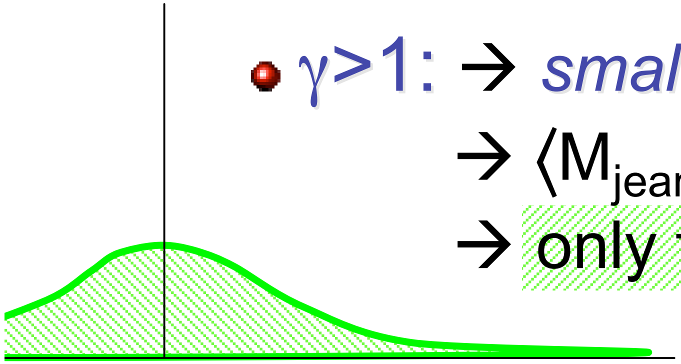
How does that work?

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

(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}

Implications

- 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; Kawachi & Hanawa 1998; Larson 2003; also Jappsen, Klessen, Larson, Li, Mac Low, 2005, 435, 611)

- implications for extreme environmental conditions
  - expect Pop III stars to be massive and form in isolation
  - expect IMF variations in warm & dusty starburst regions

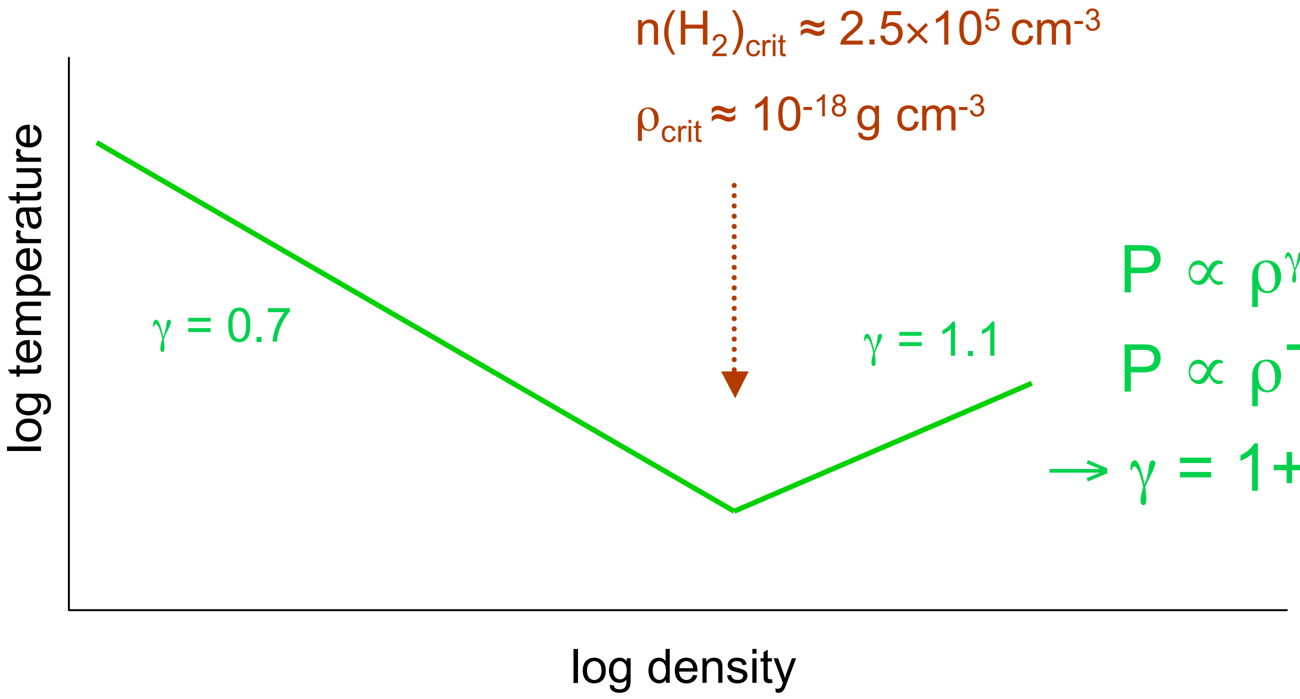
(Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2005)

- Observational findings: isolated O stars in LMC (and M51)?

(Lamers et al. 2002, Massey 2002; see however, de Witt et al. 2005 for Galaxy)

More realistic EOS

- But EOS depends on *chemical state*, on *balance* between *heating* and *cooling*



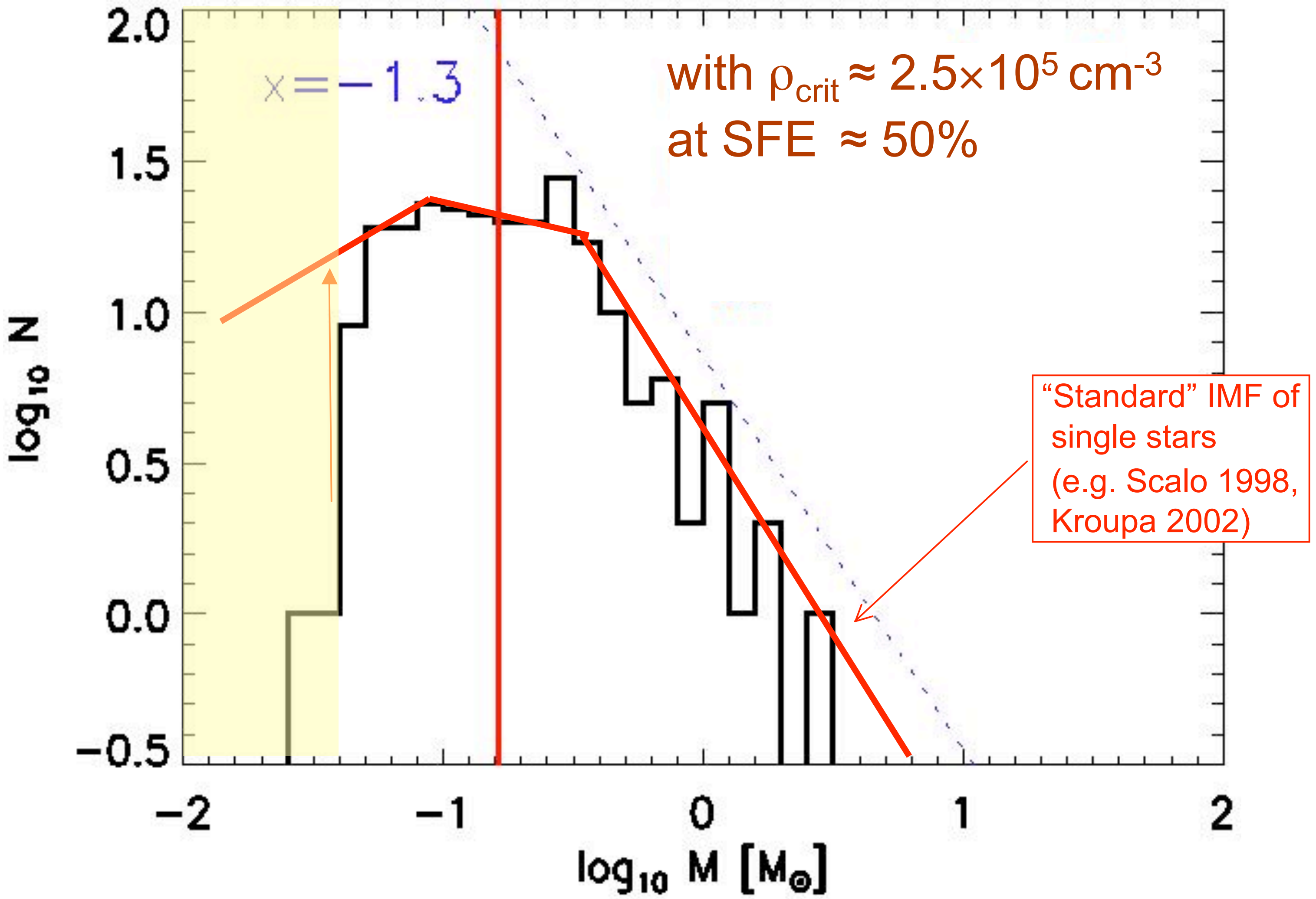
$P \propto \rho^\gamma$

$P \propto \rho T$

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

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

IMF in nearby molecular clouds



with $\rho_{crit} \approx 2.5 \times 10^5$ cm^{-3}
at SFE ≈ 50%

“Standard” IMF of single stars (e.g. Scalo 1998, Kroupa 2002)

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

Summary

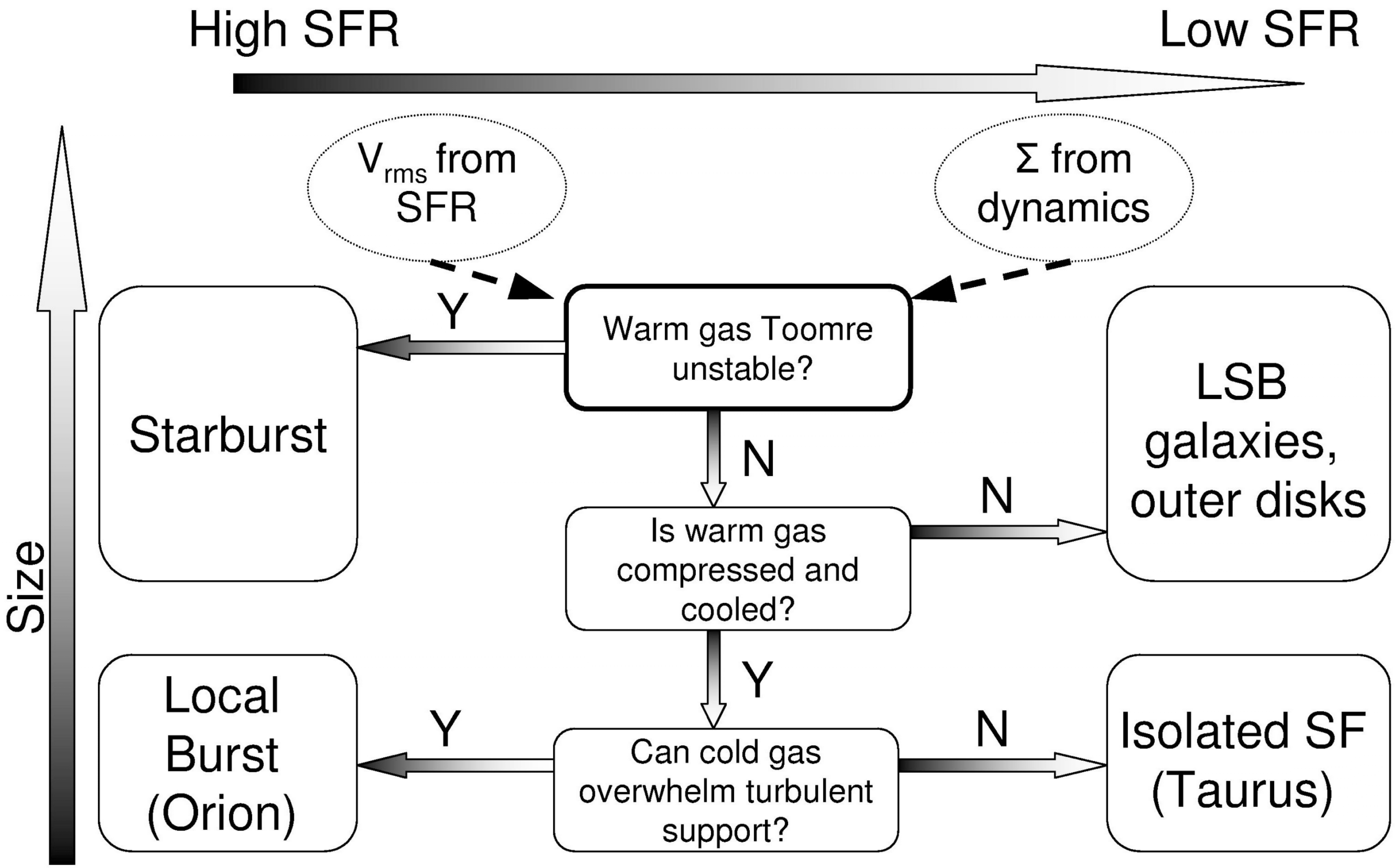
Summary

- interstellar gas is highly inhomogeneous
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \approx \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* form rapidly in high-density regions
  - 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 structure, *gravity* selects for collapse

  ——→ ***GRAVOTUBULENT FRAGMENTATION***
- *turbulent cascade:* local compression *within* a cloud provokes collapse
- individual *stars* and *star clusters* form through *sequence* of highly *stochastic* events:
  - *collapse* of cloud cores in turbulent cloud (cores change during collapse)
  - plus mutual *interaction* during collapse (importance depends on ratio of potential energy to turbulent energy) (buzz word: *competitive accretion*)

Thanks!

SF Flow Chart



High SFR

Low SFR

Size

V_{rms} from SFR

Σ from dynamics

Warm gas Toomre unstable?

Y

Starburst

N

Is warm gas compressed and cooled?

N

LSB galaxies, outer disks

Y

Can cold gas overwhelm turbulent support?

Y

Local Burst (Orion)

N

Isolated SF (Taurus)

(from Mc Low & Klessen, 2004, Rev. Mod. Phys., 76, 125 - 194)