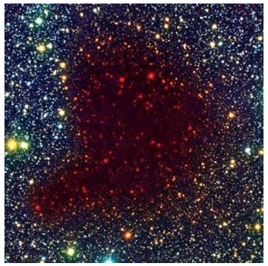
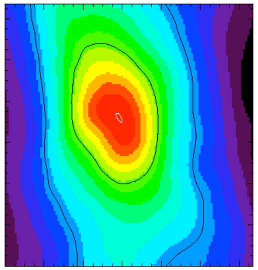
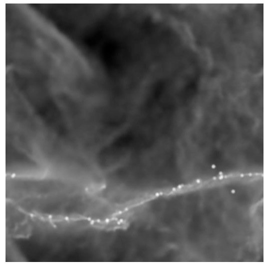
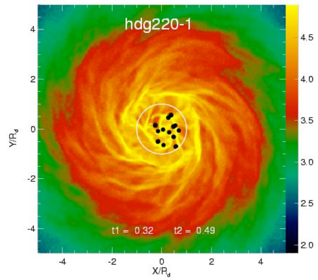
Gravoturbulent Star Formation





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Collaborators

many thanks to...

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- Marco Spaans (Kapteyn Institute)
- Enrique Vazquez-Semadeni (Morelia)
- Hans Zinnecker (AIP, Potsdam)

Structure

Phenomenology and motivation

Historic overview of star formation

The concept of ***gravoturbulent fragmentation*** and ***star formation***.

Applications to star cluster formation

why star formation?

Why study star formation?

STAR FORMATION

cosmology & galaxy formation

- relation between visible and dark matter
- formation of Pop III stars
- properties of high-z universe

planets

- initial conditions for planet formation
- diversity of planetary systems
- habitability (life)

galactic structure & evolution

- stars and star clusters are THE fundamental (visible) building blocks of galaxies
- stars probe galactic structure (e.g. GAIA)
- interrelation between SF and galactic structure

stars

- IMF
- early evolution
- stars as members of culsters

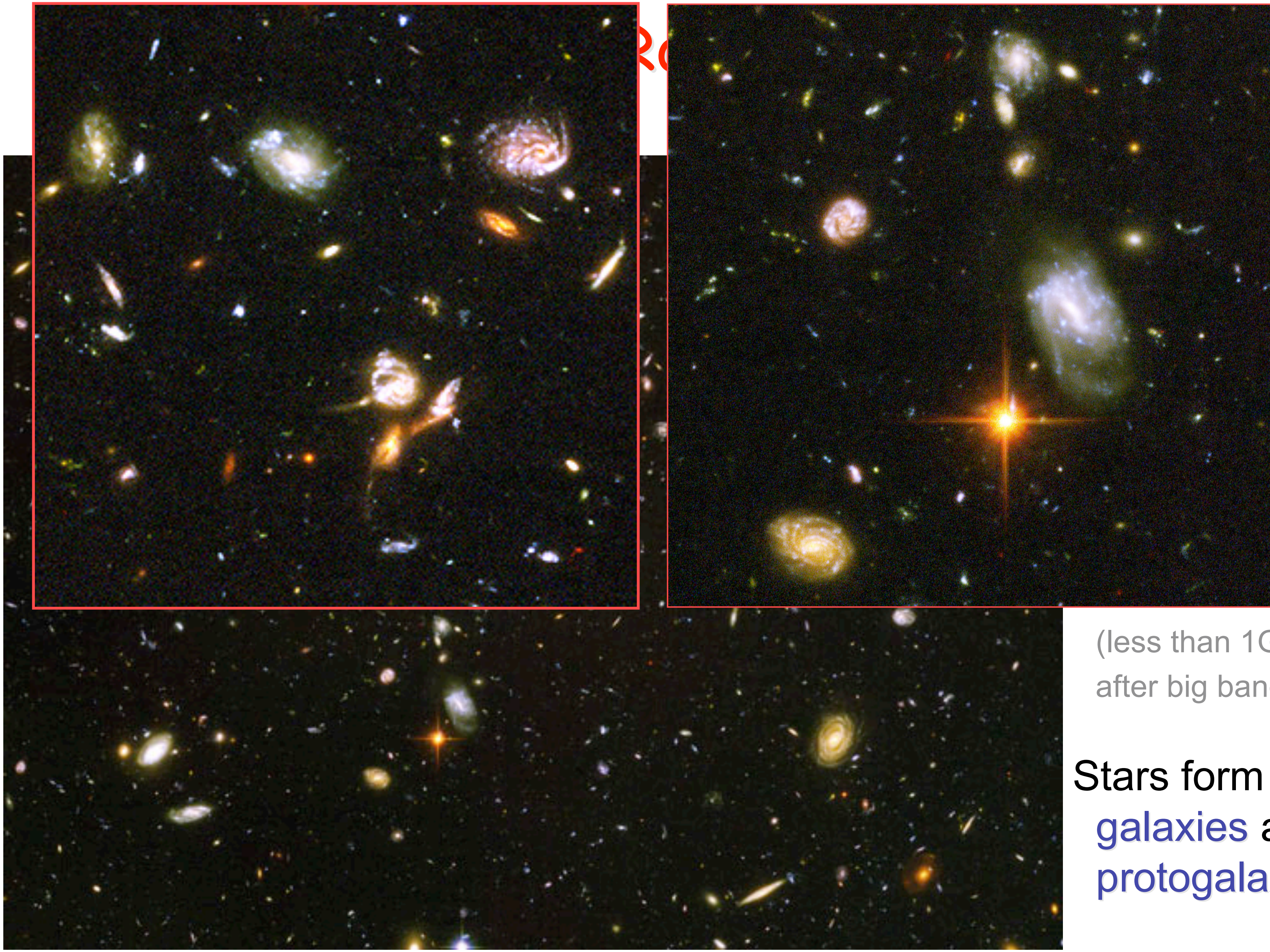
star clusters

- chemical enrichment of galaxies
- probes of SF in the early universe (e.g. globular clusters)
- populate galactic field

ISM

- molecular cloud turbulence
- feedback from star formation
- initial conditions of SF

observations



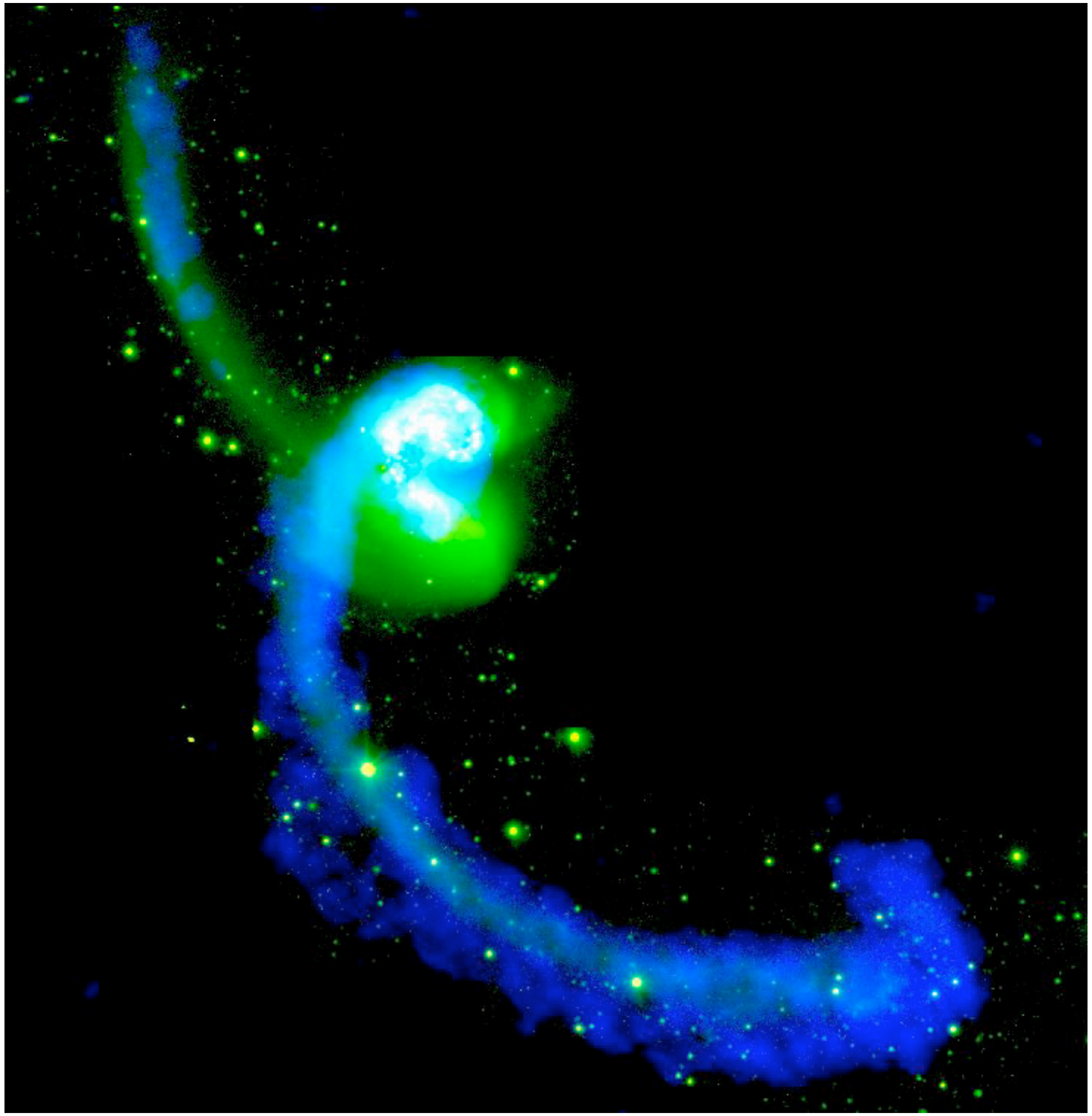
(Hubble Ultra-Deep Field, from HST Web site)

tion
rly

(less than 1Gyr after big bangl)

Stars form in galaxies and protogalaxies

Star formation in interacting galaxies:

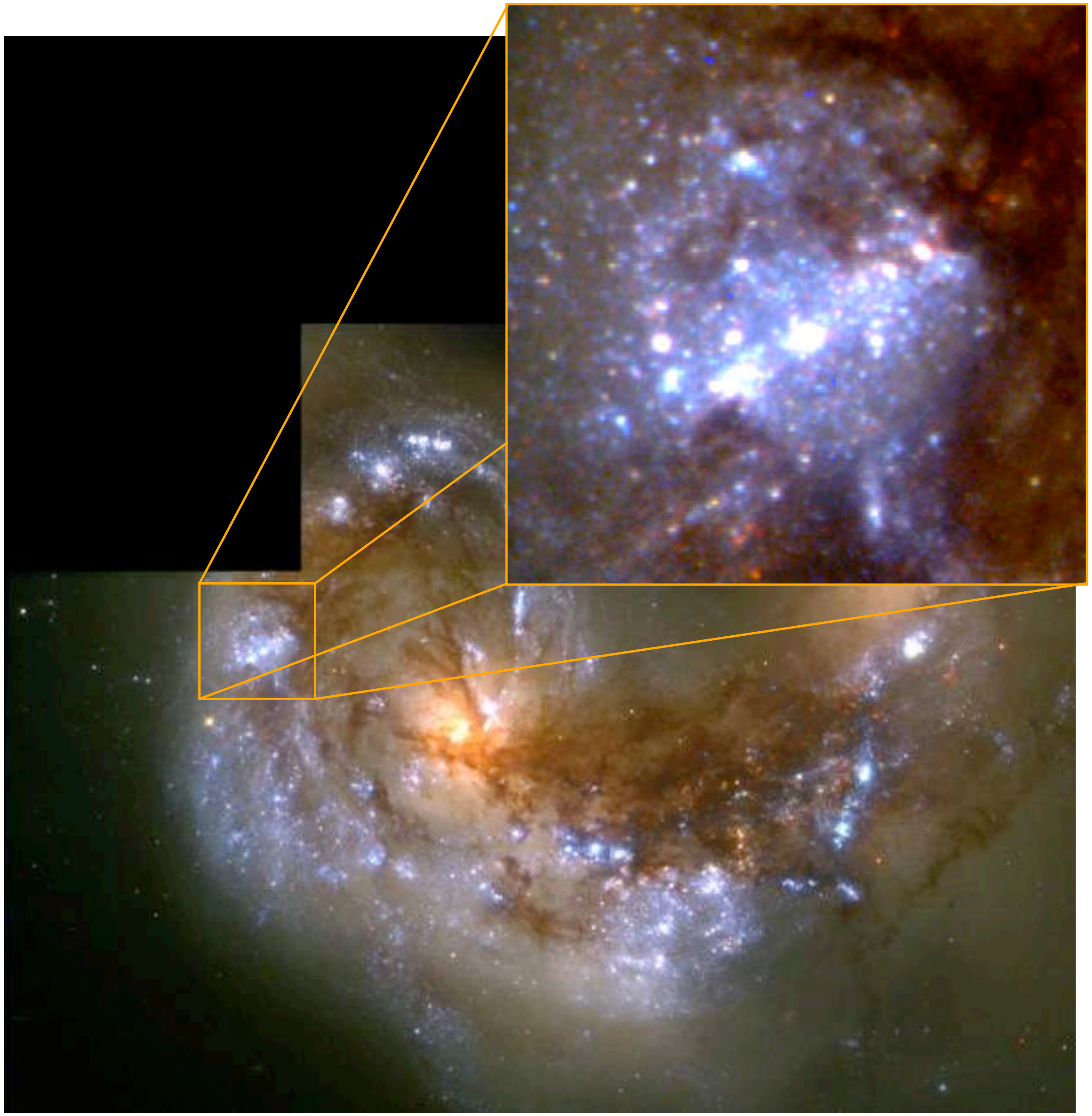


(from the Chandra Webpage)

Antennae galaxy

- *NGC4038/39*
- *distance: 19.2Mpc*
- *vis. Magn: 11.2*
- *optical: white, green*
- *radio: blue*

Star formation in interacting galaxies:



(HST: Whitmore & Schweizer 1997)

Antennae galaxy

- Star formation burst in interacting (merging) galaxies
- Strong perturbation SF in tidal “tales”
- Large-scale gravitational motion determines SF
- Stars form in “knobs” (i.e. superclusters)

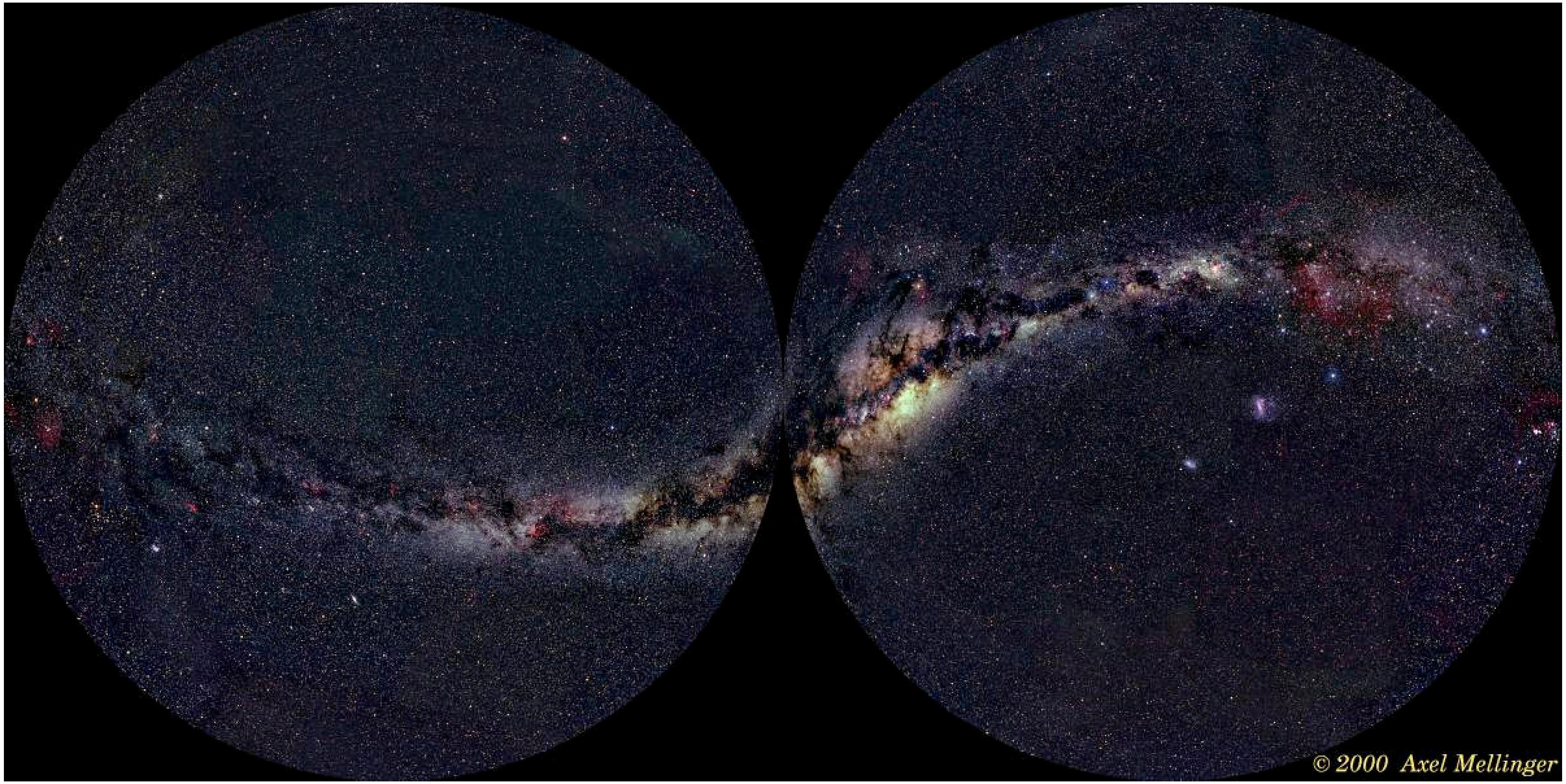
Star formation in "typical" spiral:

(from the Hubble Heritage Team)

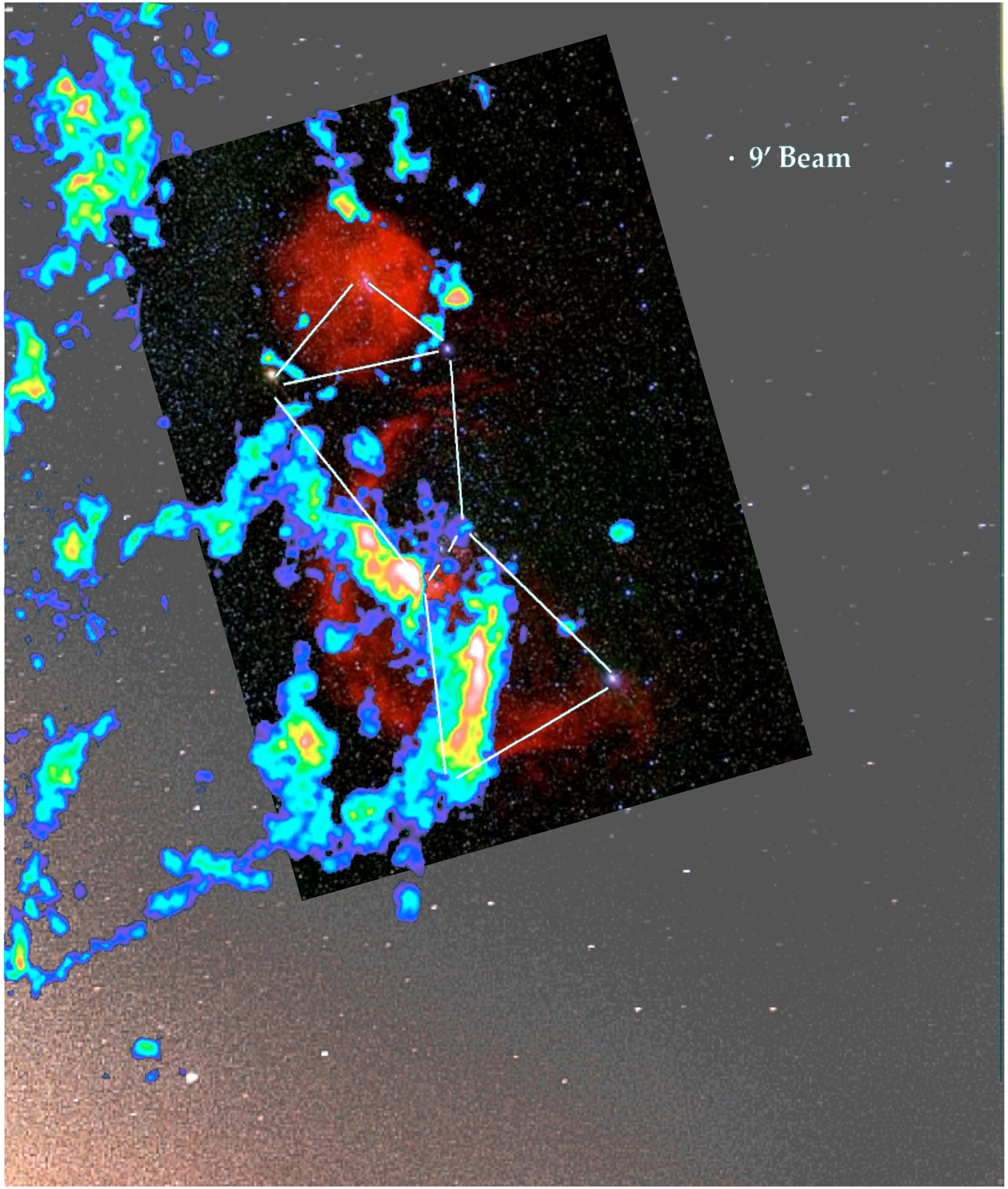
NGC4622

- 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?

Sternentstehung in der Milchstraße



Am Nachthimmel sieht man **Dunkelwolken** und **Sterne**:
Die hellsten Sterne sind *massereich* und daher *jung.*
→ Sternentstehung ist wichtig um beobachtete Struktur der Milchstraße zu verstehen.

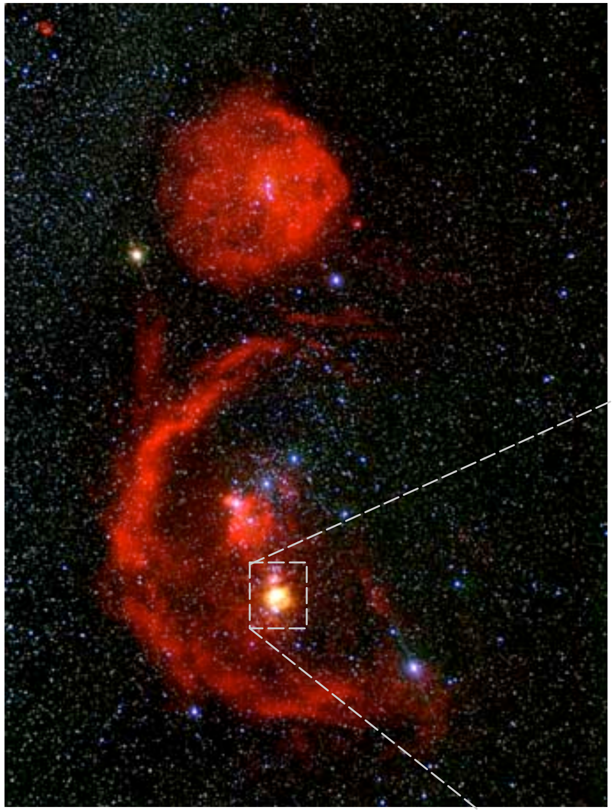


Stern-entstehung in Orion

Wir sehen

- *Sterne* (im sichtbaren Licht)
- Atomaren Wasserstoff (in Hα -- rot)
- Molekularen Wasserstoff H_2 (Radiostrahlung -- farbcodiert)

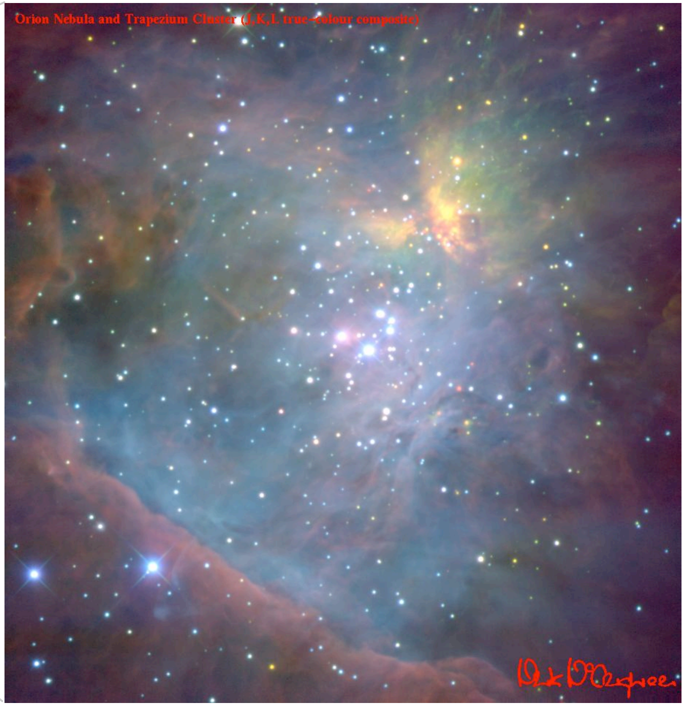
Local star forming region: The Trapezium Cluster in Orion



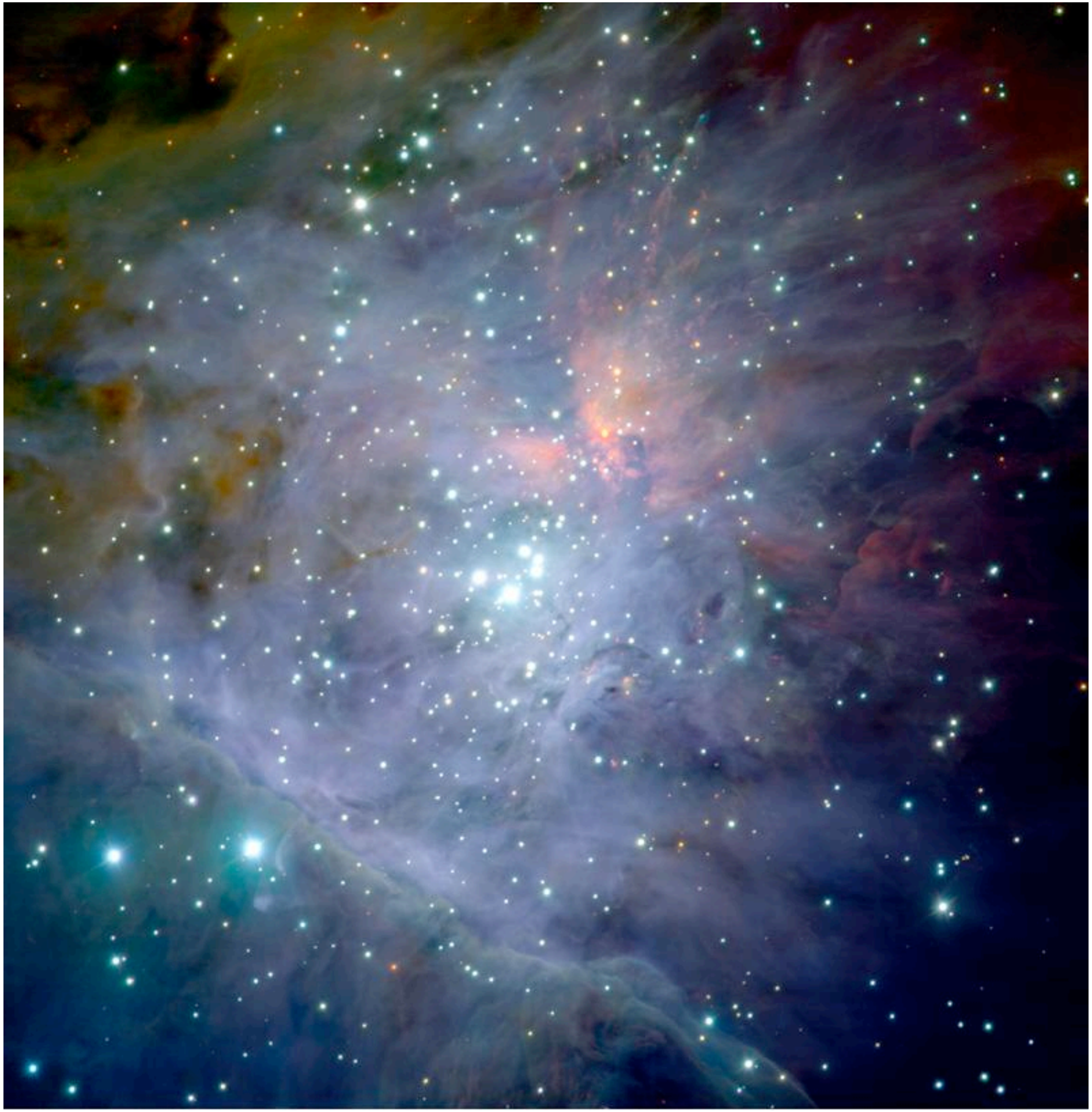
Orion molecular cloud

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

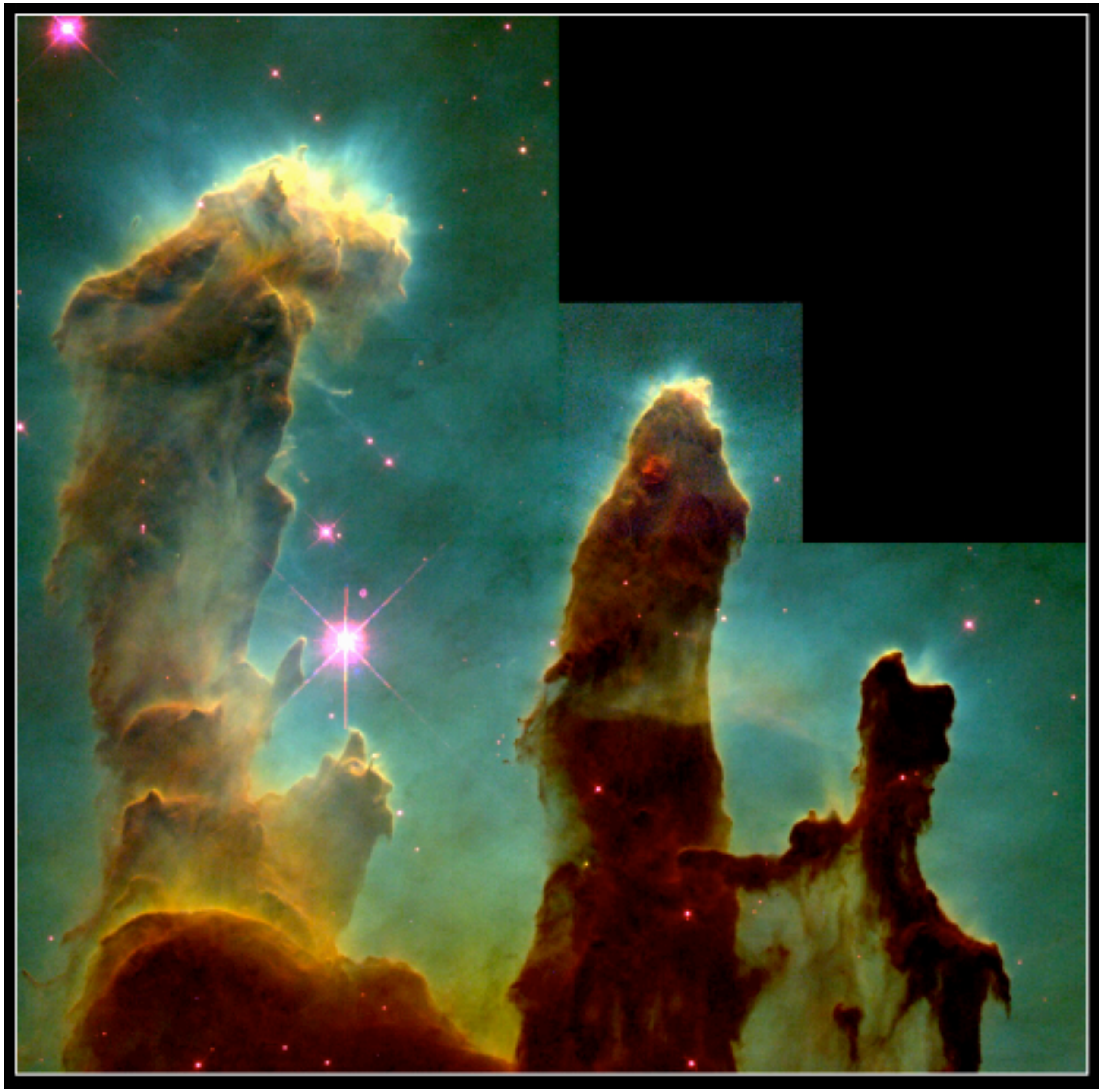


Trapezium Cluster

(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)



HST Aufnahme

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

Infrared observation

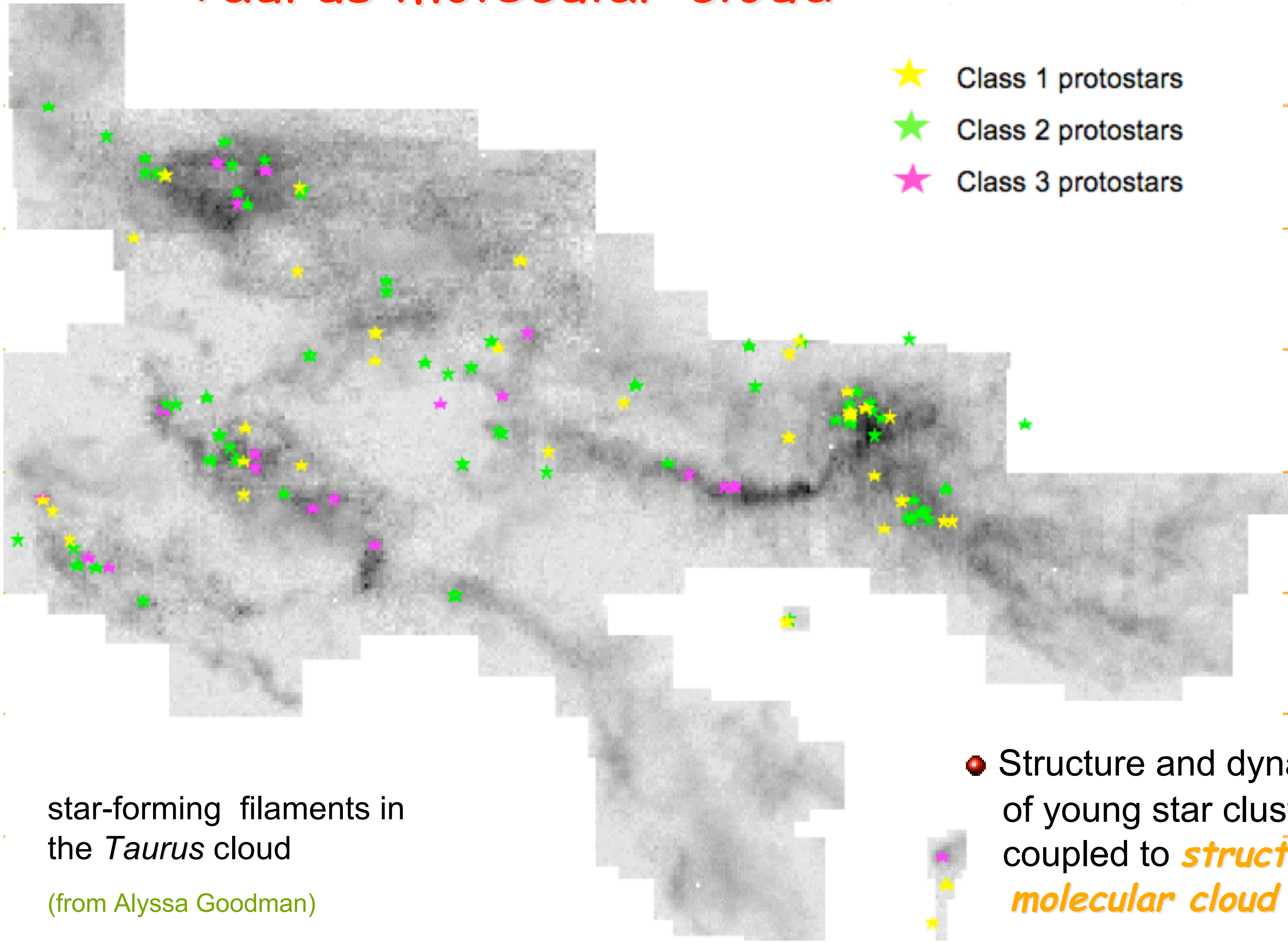
IR observation with ESO-VLT

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

IR observation with ESO-VLT

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

Taurus molecular cloud

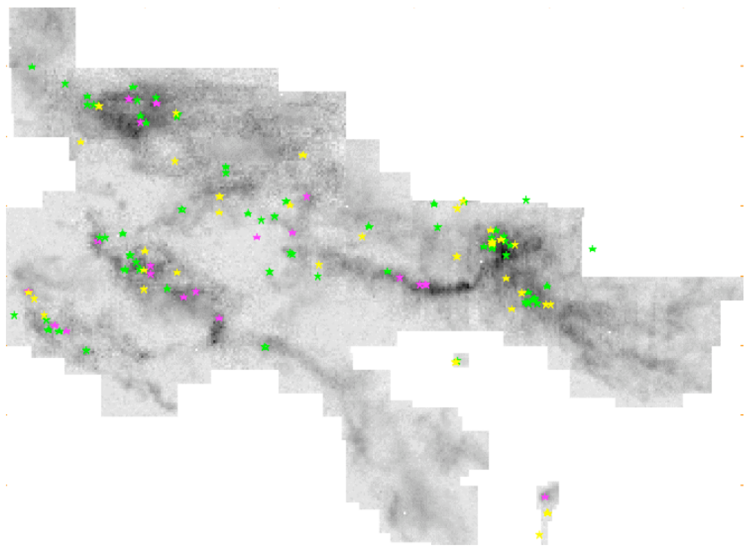


star-forming filaments in the *Taurus* cloud

(from Alyssa Goodman)

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

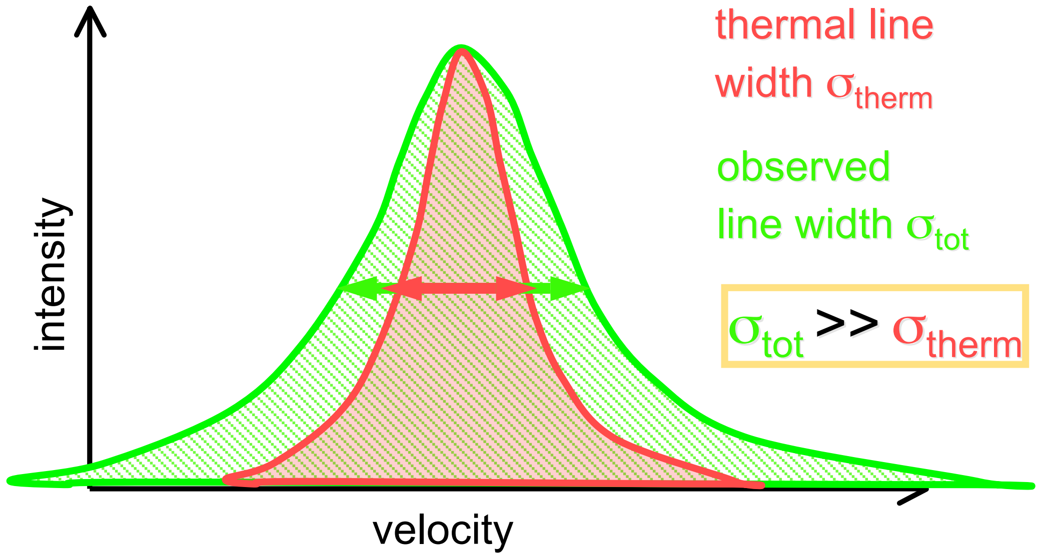
Taurus molecular cloud



Star-forming filaments in *Taurus* cloud
(from Hartmann 2002)

- Strukture and dynamics of ***molekular cloud*** is determined by ***supersonic turbulence***

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



the questions

The star formation process

- *How* do stars form?
- What determines *when* and *where* stars form?
- What *regulates* the process and determines its *efficiency*?
- How do *global* properties of the galaxy influence star formation (a *local* process)?
- Are there different *modes* of SF? (Starburst galaxies vs. *LSBs*, *isolated* SF vs. *clustered* SF)

$\longrightarrow$ ***What physical processes initiate and control the formation of stars?***

historic overview

Early dynamical theory

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\boxed{\omega^2 = c_s^2 k^2 - 4\pi G\rho_0}$$

  - instability when $\omega^2 < 0$
  - minimal mass: $\boxed{M_J = \frac{1}{6}\pi^{-5/2}G^{-3/2}\rho_0^{-1/2}c_s^3 \propto \rho_0^{-1/2}T^{3/2}}$

Sir James Jeans, 1877 - 1946

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

First approach to turbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of **MICROTURBULENCE**
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence

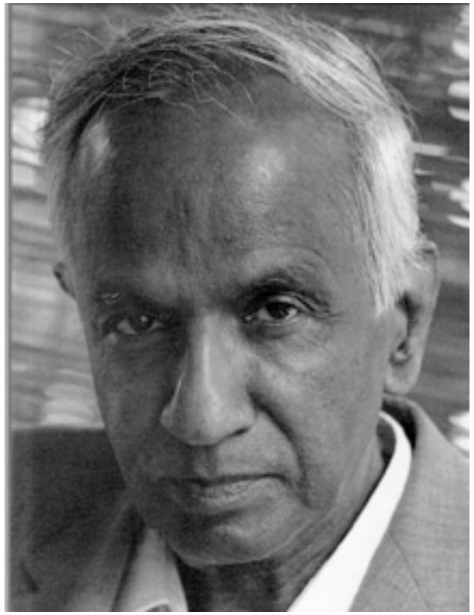
    $\ell_{turb} \ll \ell_{dyn}$

  - then turbulent velocity dispersion contributes to effective soundspeed:

$$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$

  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    (2) supersonic turbulence → usually $\sigma_{rms}^2(k) >> c_s^2$



S. Chandrasekhar, 1910 - 1995

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Properties of IMS turbulence

ISM turbulence is:

- Supersonic (rms velocity dispersion >> sound speed)
- Anisotropic (shocks & magnetic field)
- Driven on large scales (power in mol. clouds always dominated by largest-scale modes)

  Microturbulent approach is NOT valid in ISM

- No closed analytical/statistical formulation known --> necessity for numerical modeling

Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*
  Yet, they do *NOT* form stars at high rate
  and with high efficiency.
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- All throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilitrium entities.
- Molecular clouds are *magnetized.*

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Magnetic star formation

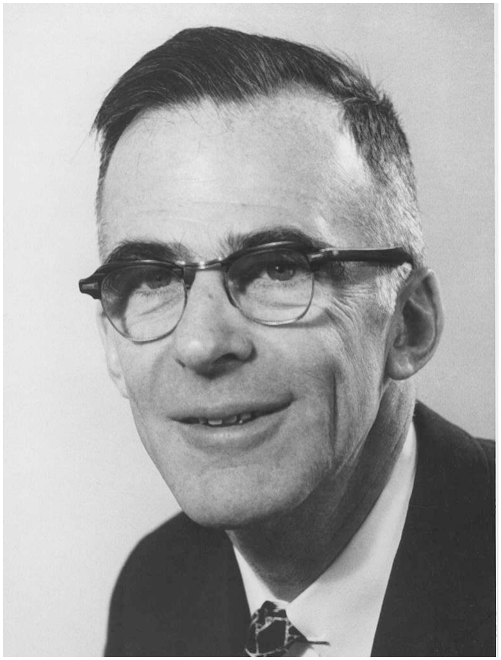
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse***!!!***
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2} \frac{B^3}{G^{3/2}\rho^2}$$

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

  - Ambipolar diffusion can initiate collapse

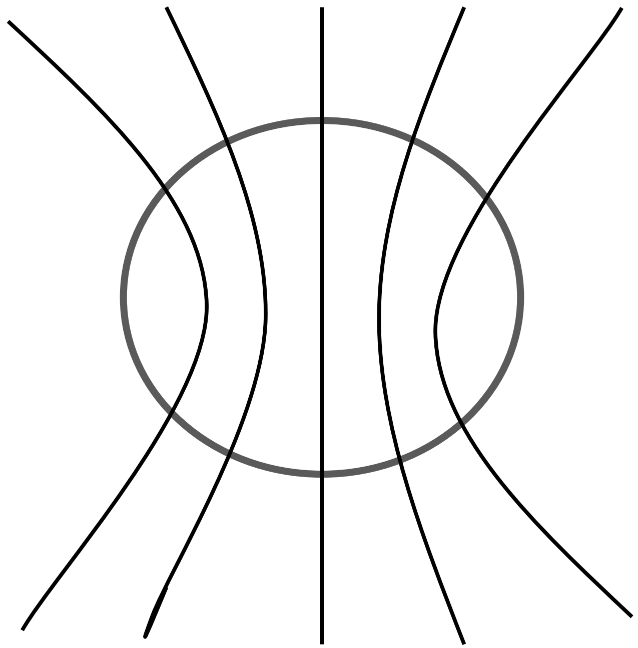


Lyman Spitzer, Jr., 1914 - 1997

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

The "standard theory" of star formation:

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975\ c_s^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars



Problems of magnetic SF

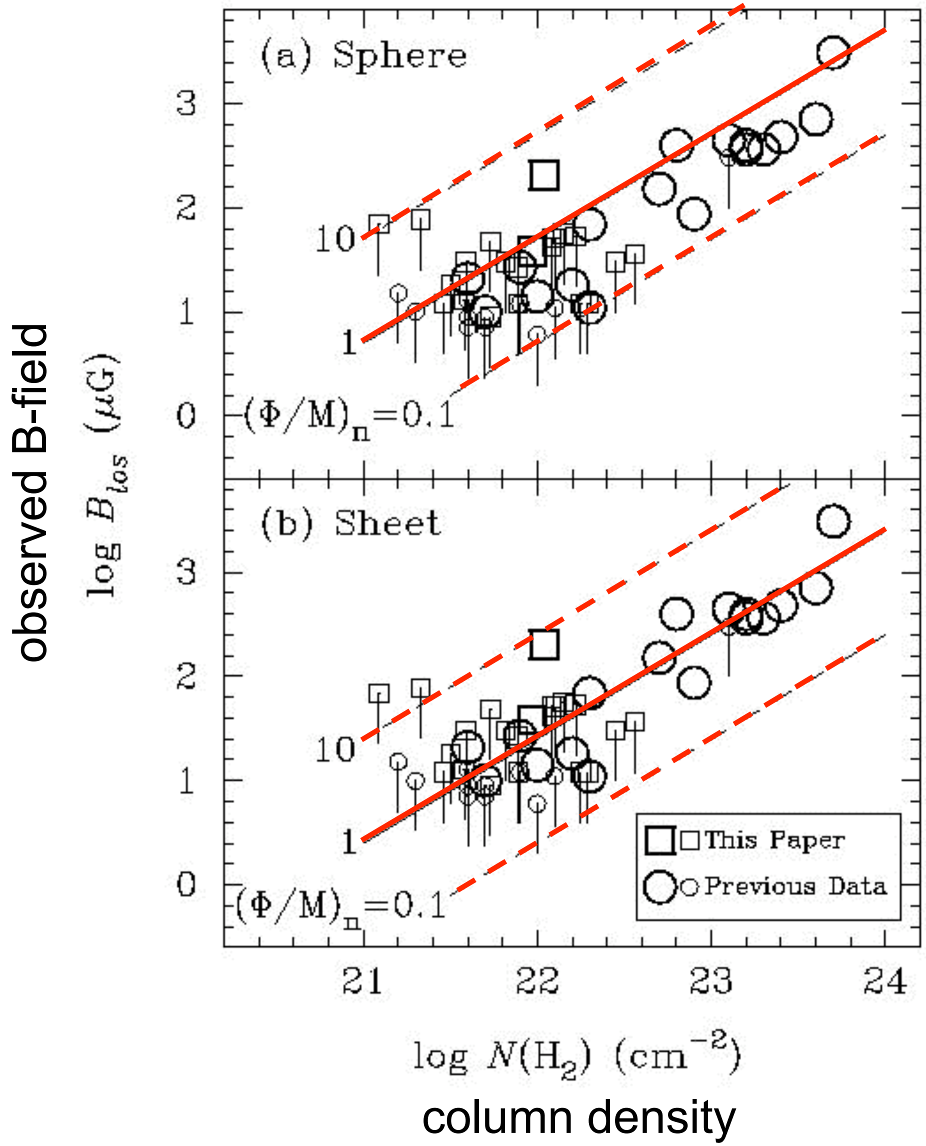
- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence
  (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores
  (Bacman et al. 2000, e.g. Barnard 68 from Alves et al. 2001)
- Strongly time varying dM/dt
  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model
  (Williams & Myers 2000, Myers et al. 2000)

Observed B-fields are weak

B versus ***N(H_2)*** from *Zeeman measurements*.
(from Bourke et al. 2001)

→ cloud cores are magnetically supercritical***!!!***

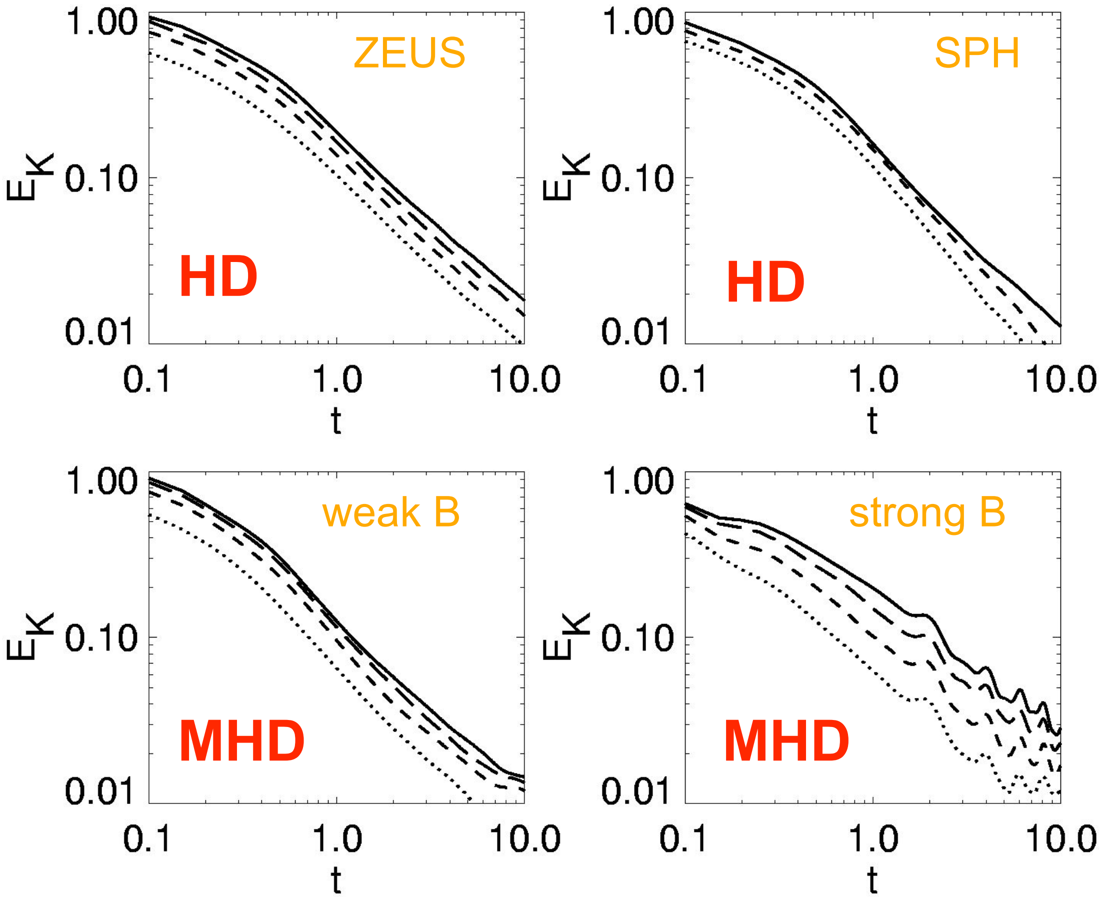
$(\Phi/M)_n > 1$ no collapse
$(\Phi/M)_n < 1$ collapse



Molecular cloud dynamics

- **Timescale problem:** Turbulence *decays* on timescales *comparable to the free-fall time* τ_{ff} ($E \propto t^{-\eta}$ with $\eta \approx 1$).

  (Mac Low et al. 1998,
  Stone et al. 1998,
  Padoan & Nordlund 1999)



(Mac Low, Klessen, Burkert, & Smith, 1998, PRL)

- Magnetic fields (static or wave-like) *cannot* prevent loss of energy.

Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps seem to be chemically young
  (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$)
  (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse
  (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Most stars form as binaries

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:

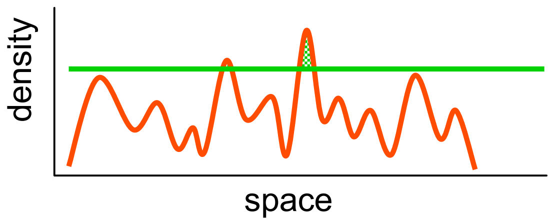
Star formation is controlled by interplay between gravity and supersonic turbulence!

- 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)

Gravoturbulent star formation



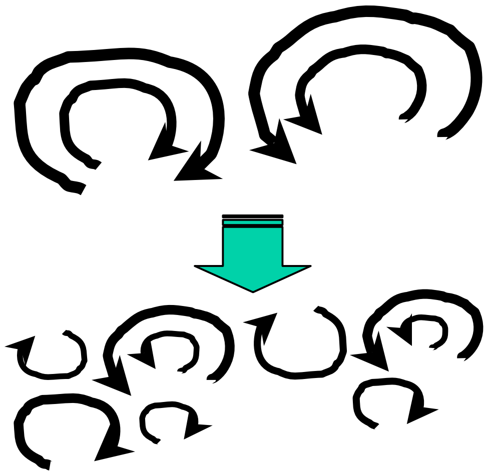
- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation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

turbulence

Properties of turbulence



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

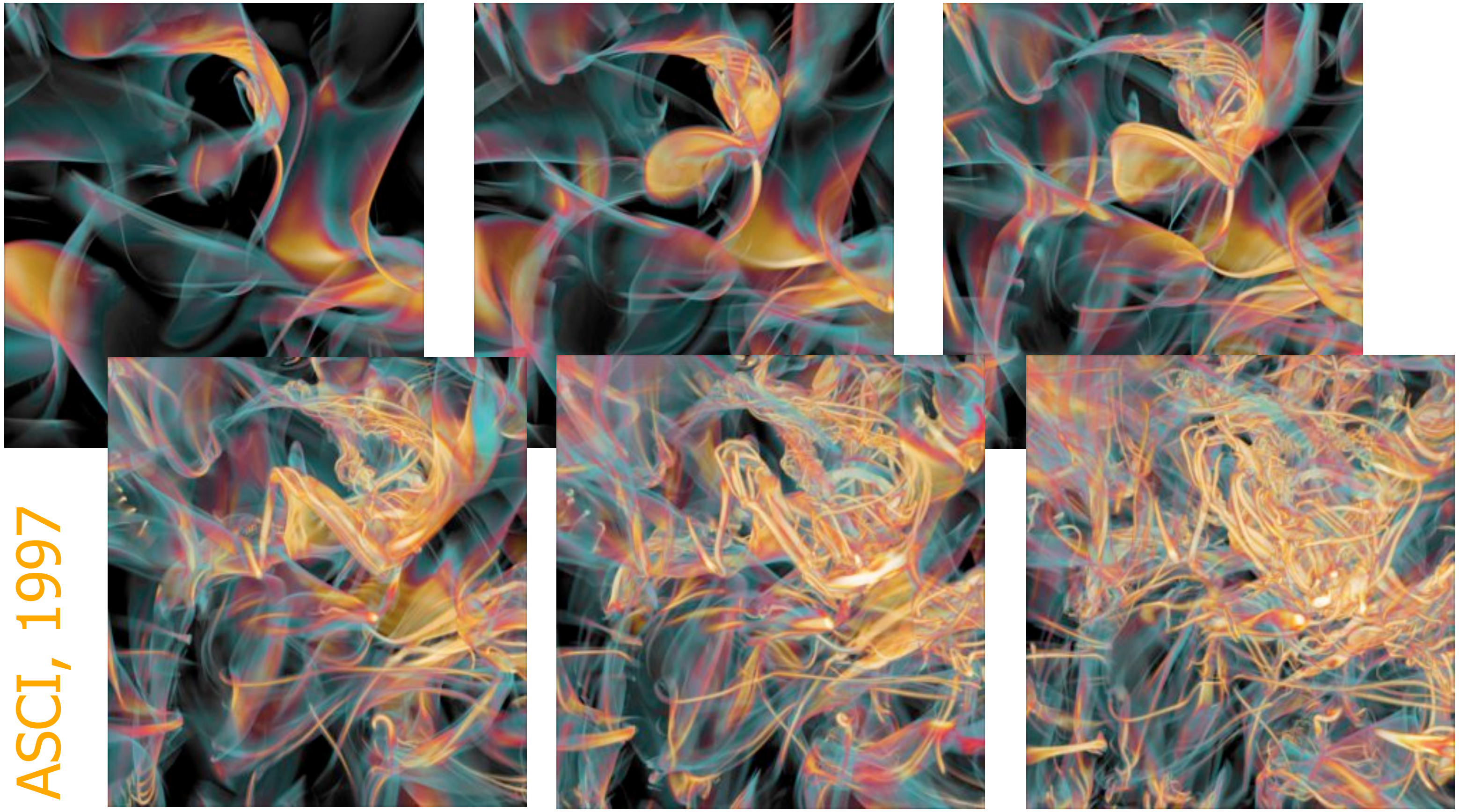
$$\boxed{\mathrm{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}}$$

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)

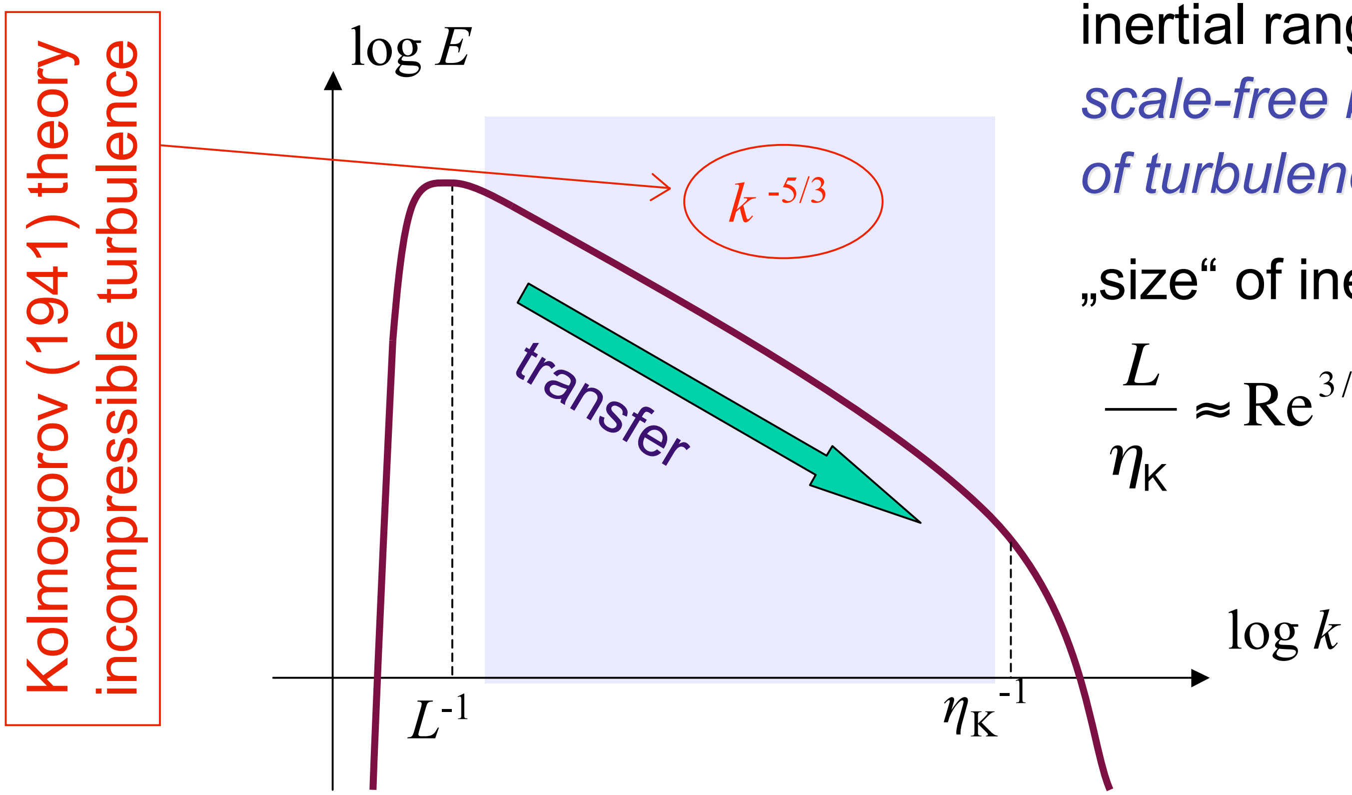
Vortex Formation



Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade



energy
input
scale

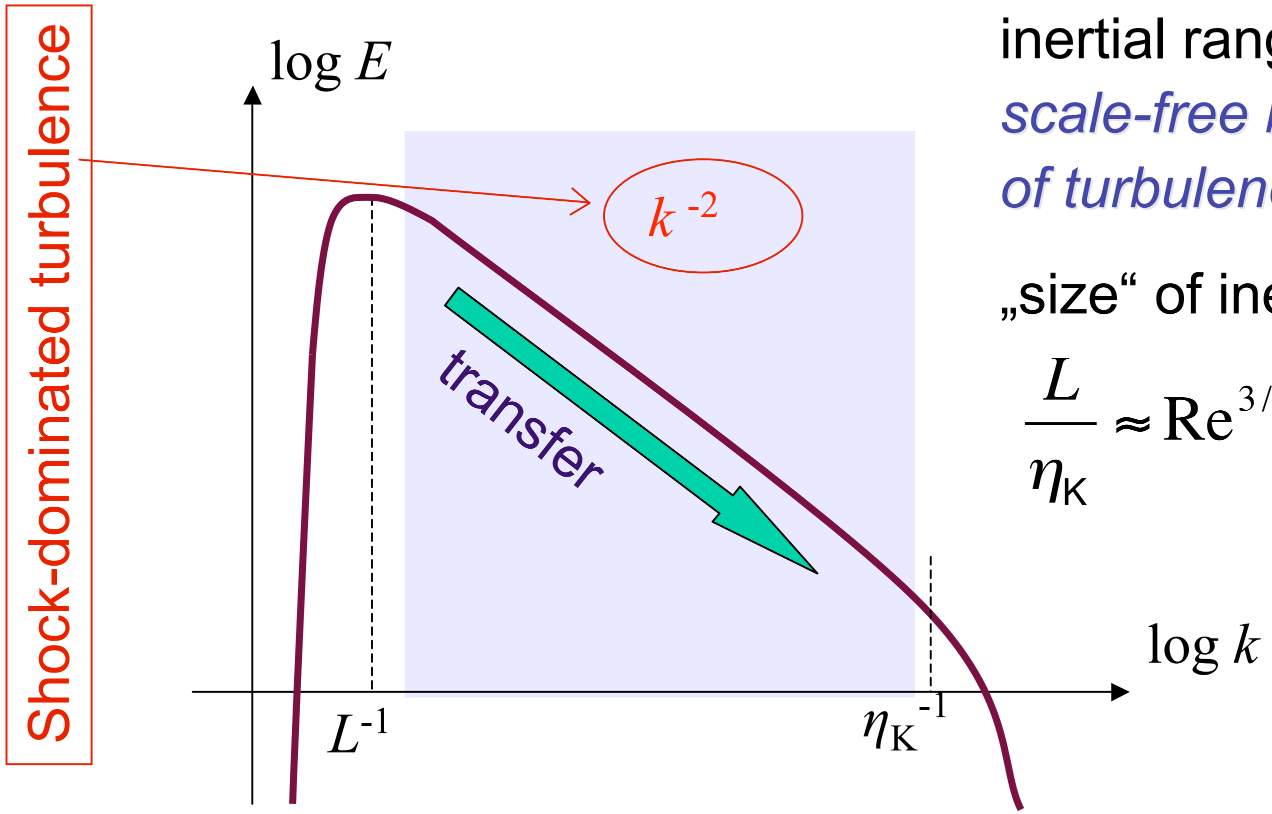
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size" of inertial range:

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

Turbulent cascade



inertial range:
scale-free behavior of turbulence

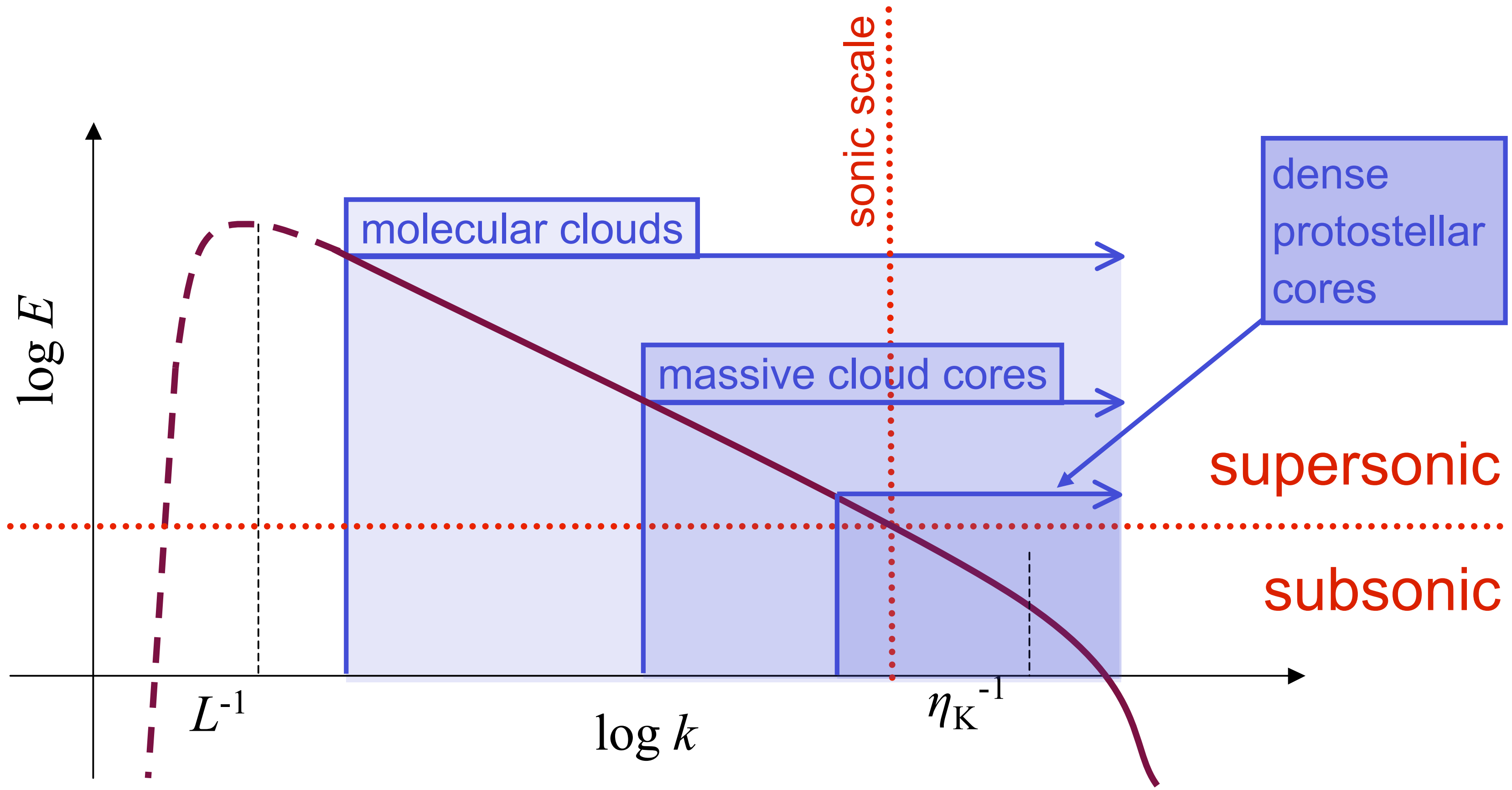
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade in ISM

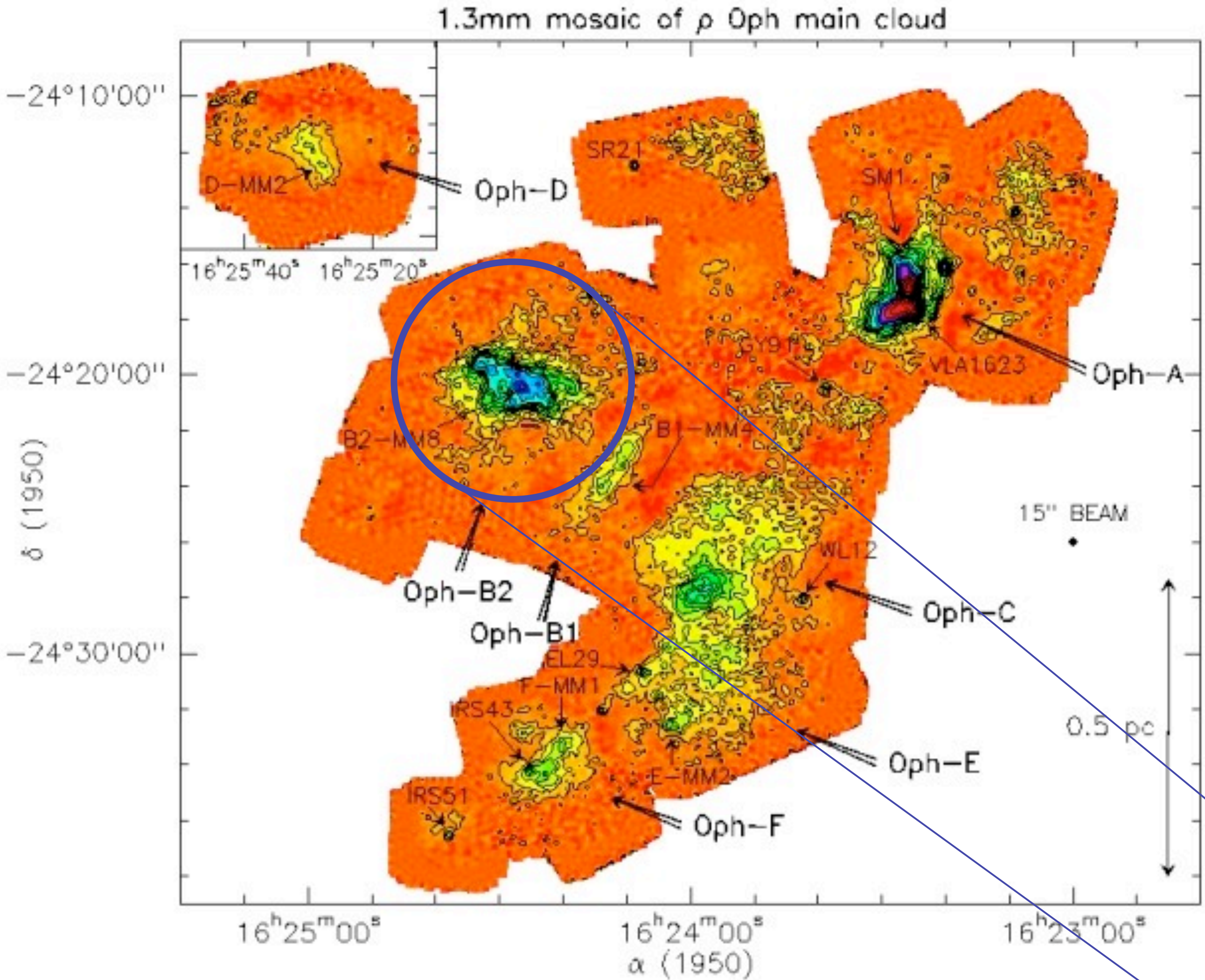


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

Density structure of MC's



(Motte, André, & Neri 1998)

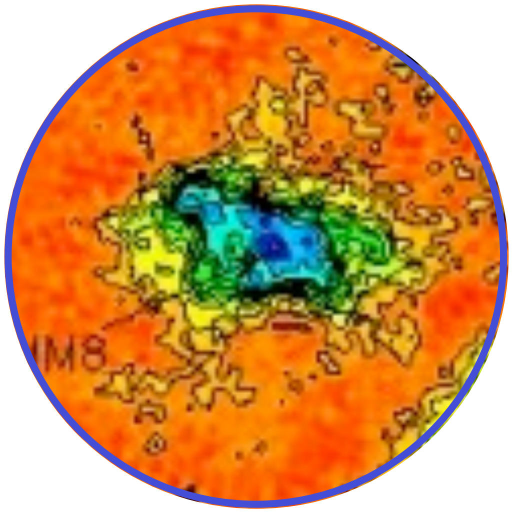
molecular clouds are highly inhomogeneous

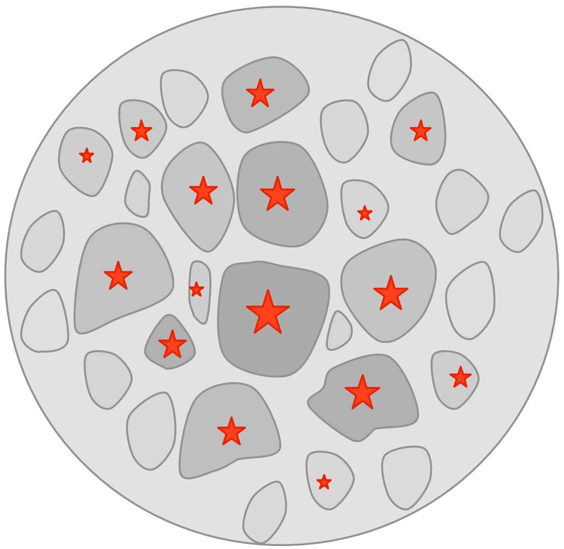
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

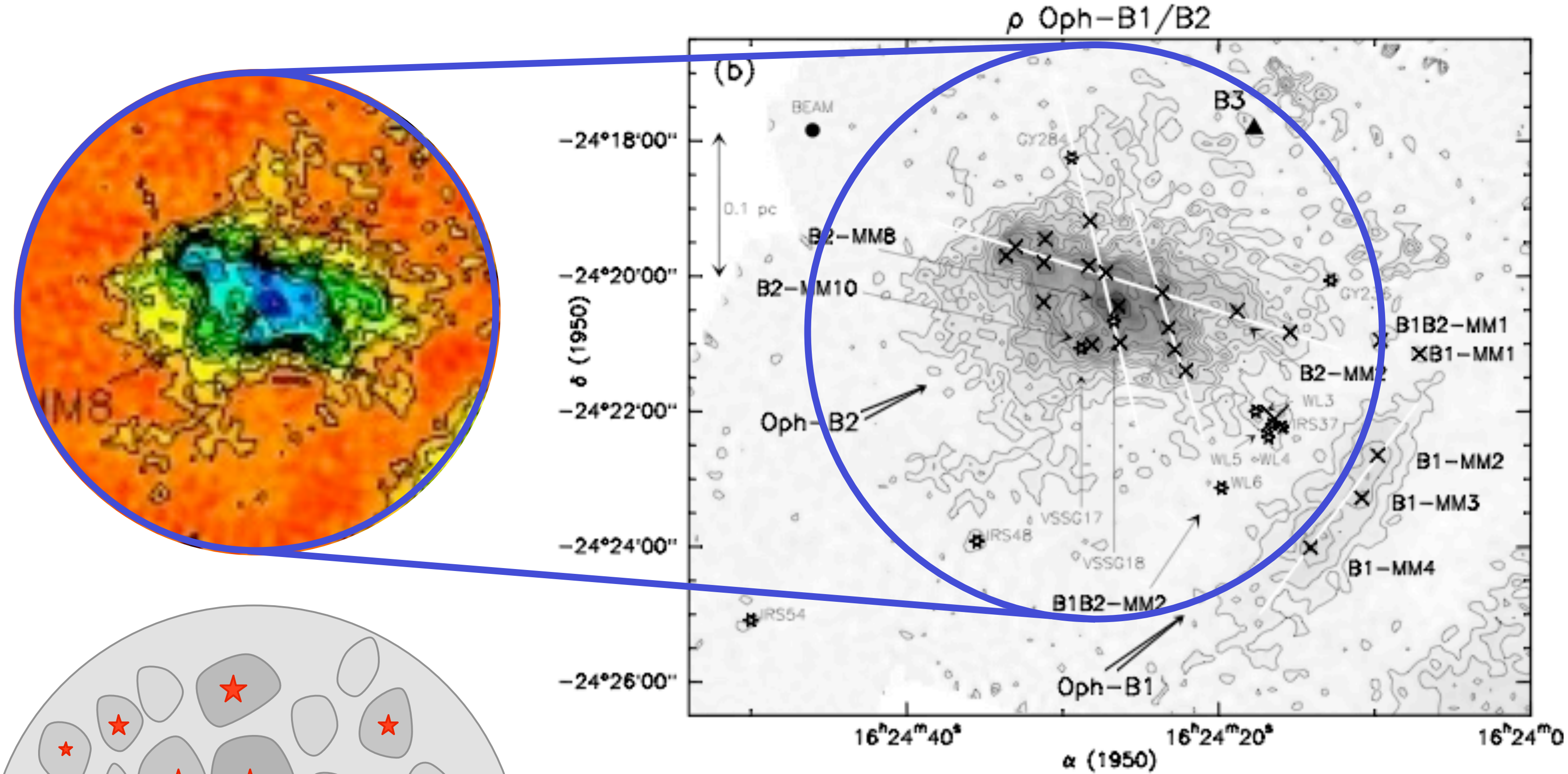
Evolution of cloud cores

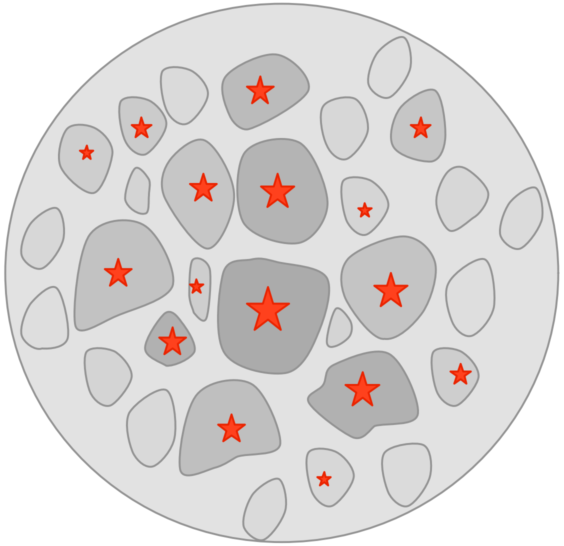




- Does core form single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> 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

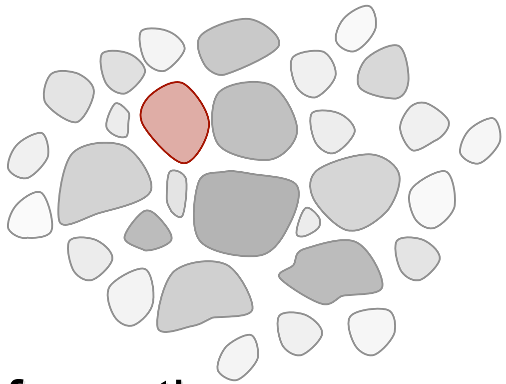




indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(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

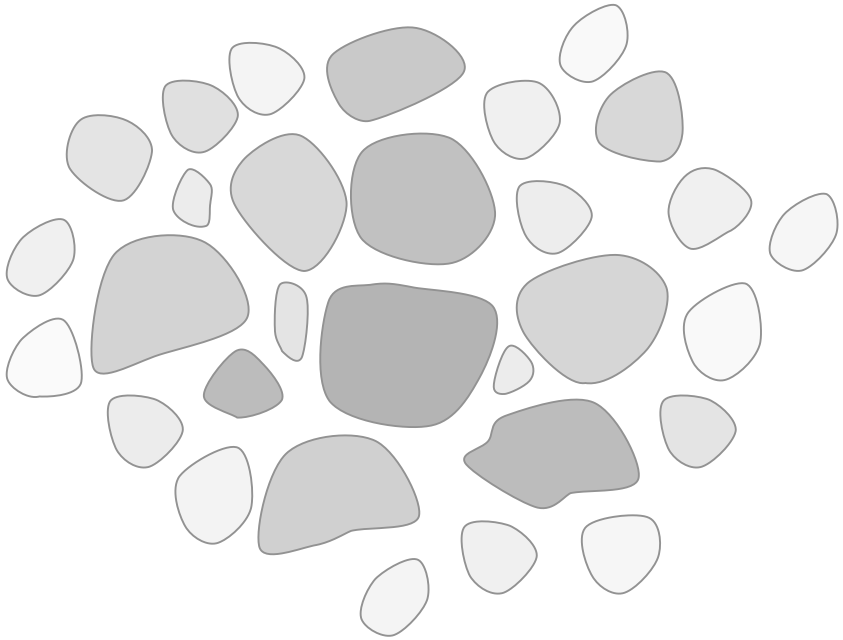
  (e.g. Vazquez-Semadeni et al 2005)

- 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

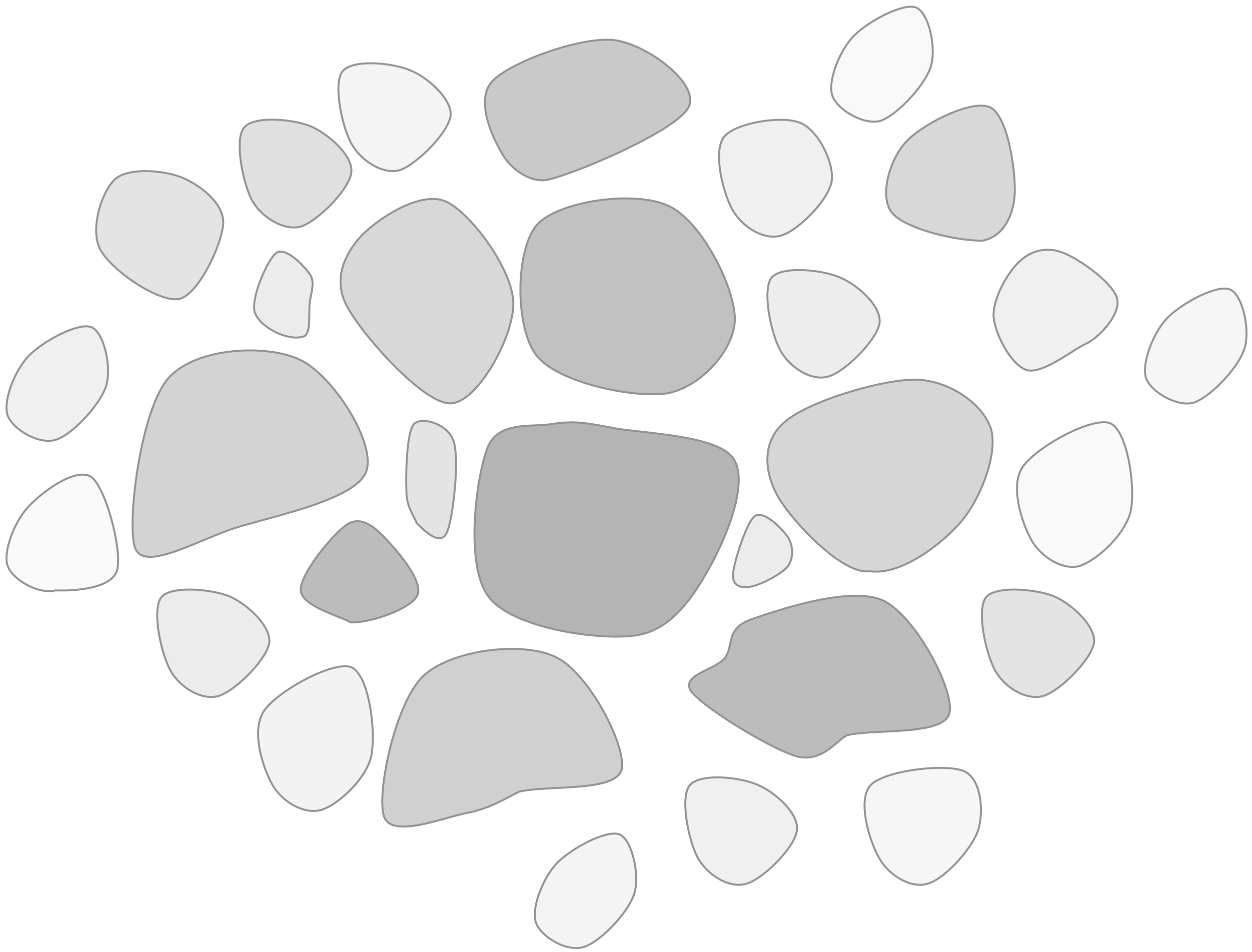
What happens to distribution of cloud cores?



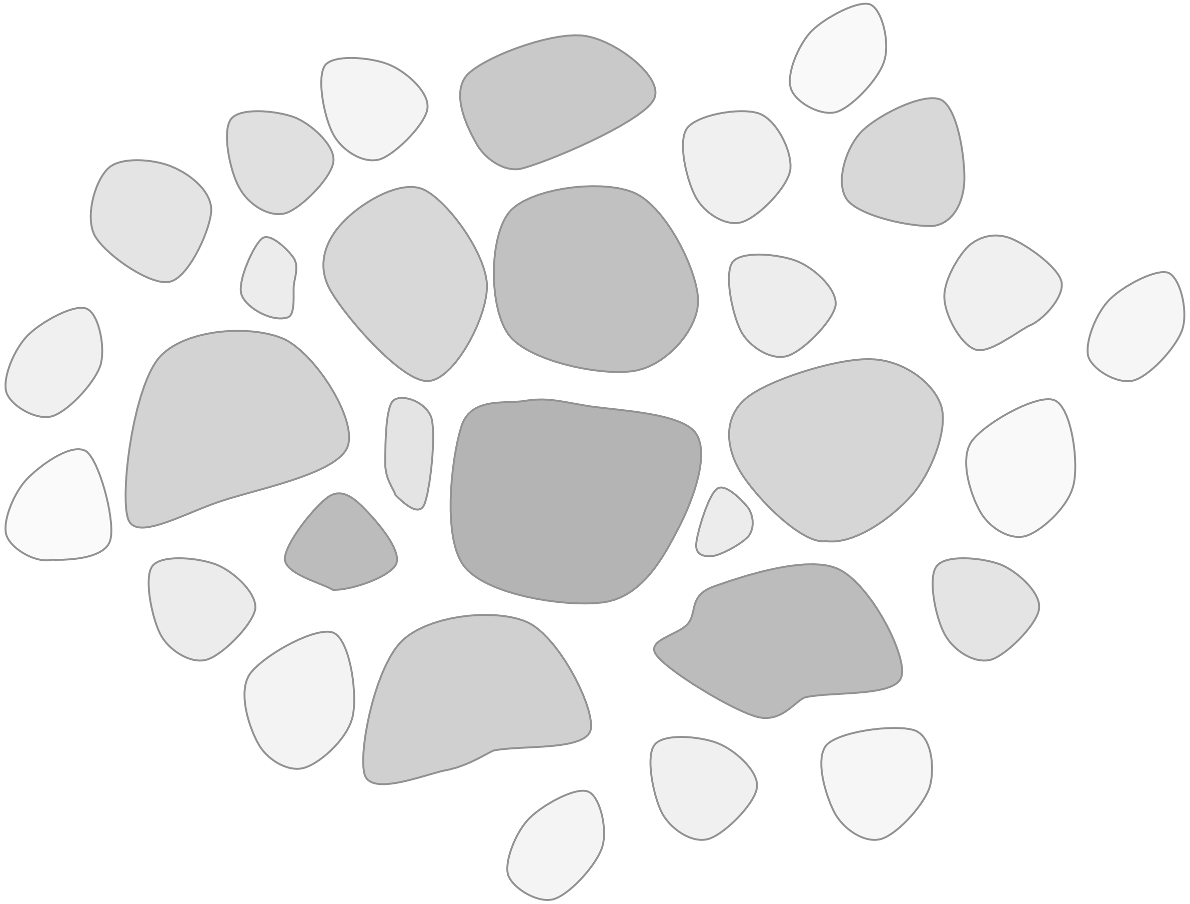
Two exteme cases:

(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*

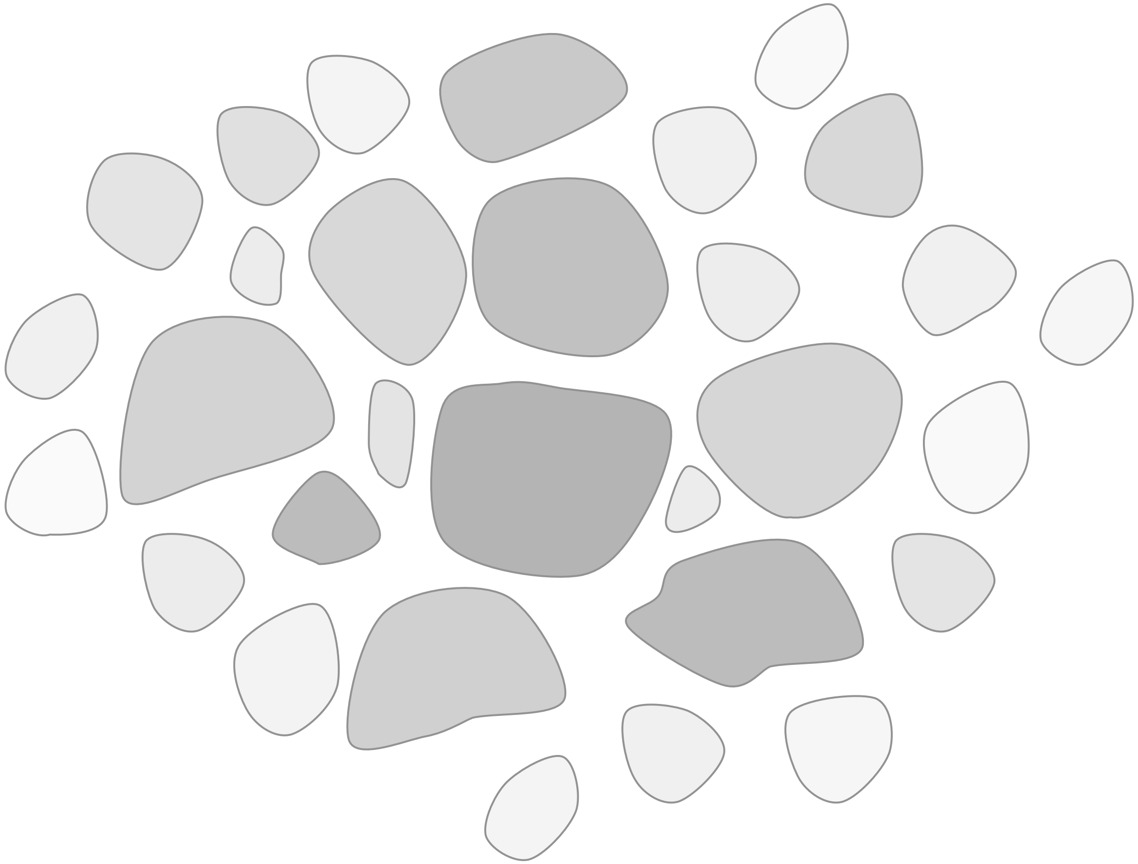
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
--> *global contraction*
--> core do *interact* while collapsing
--> *competition* influences *mass growth*
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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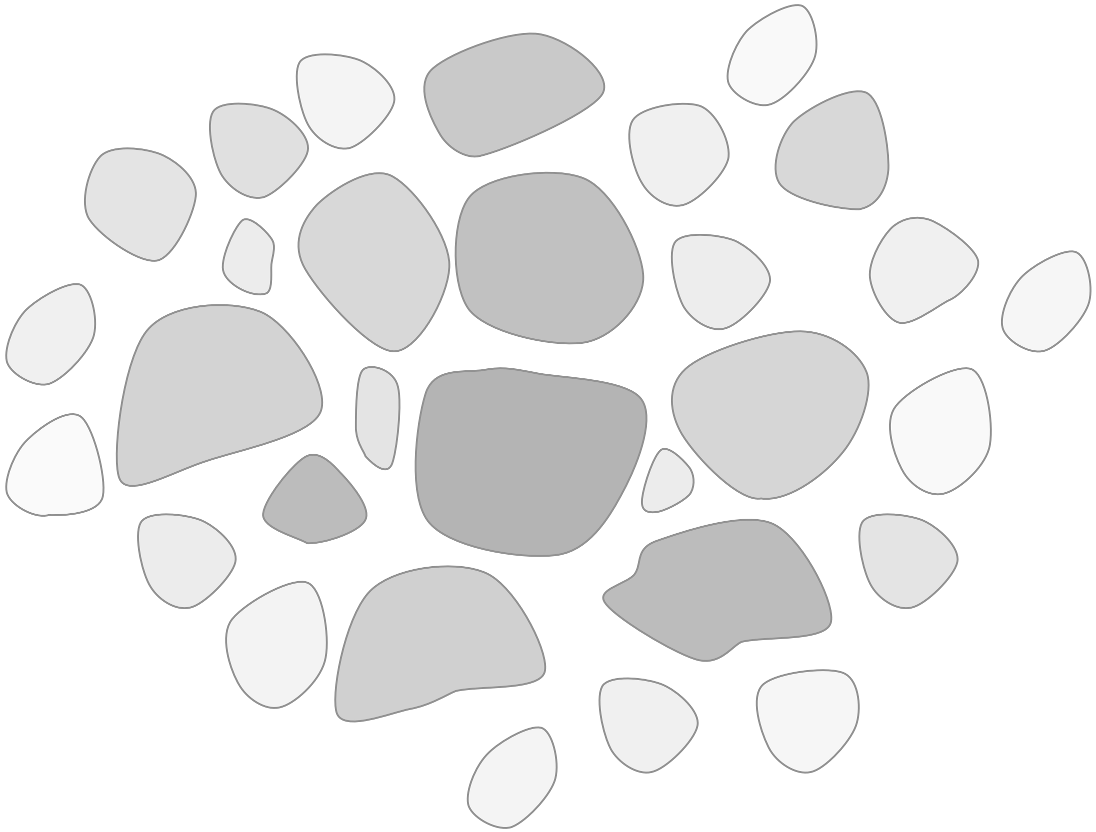
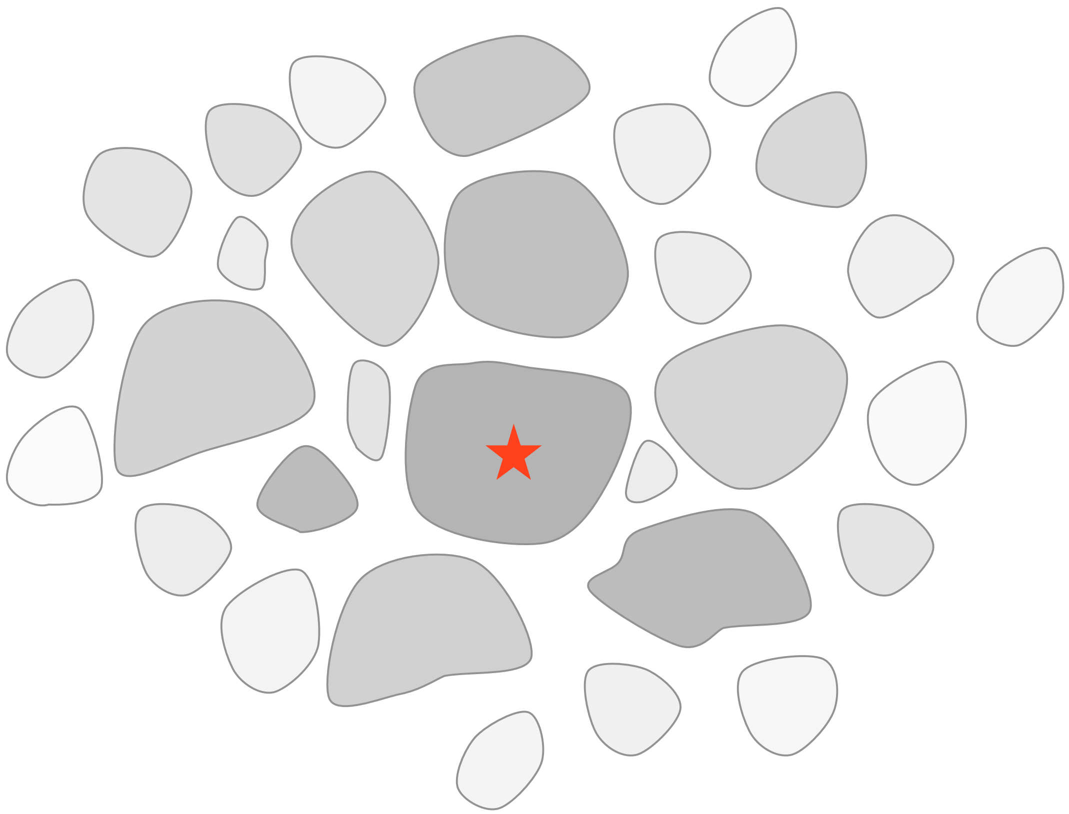
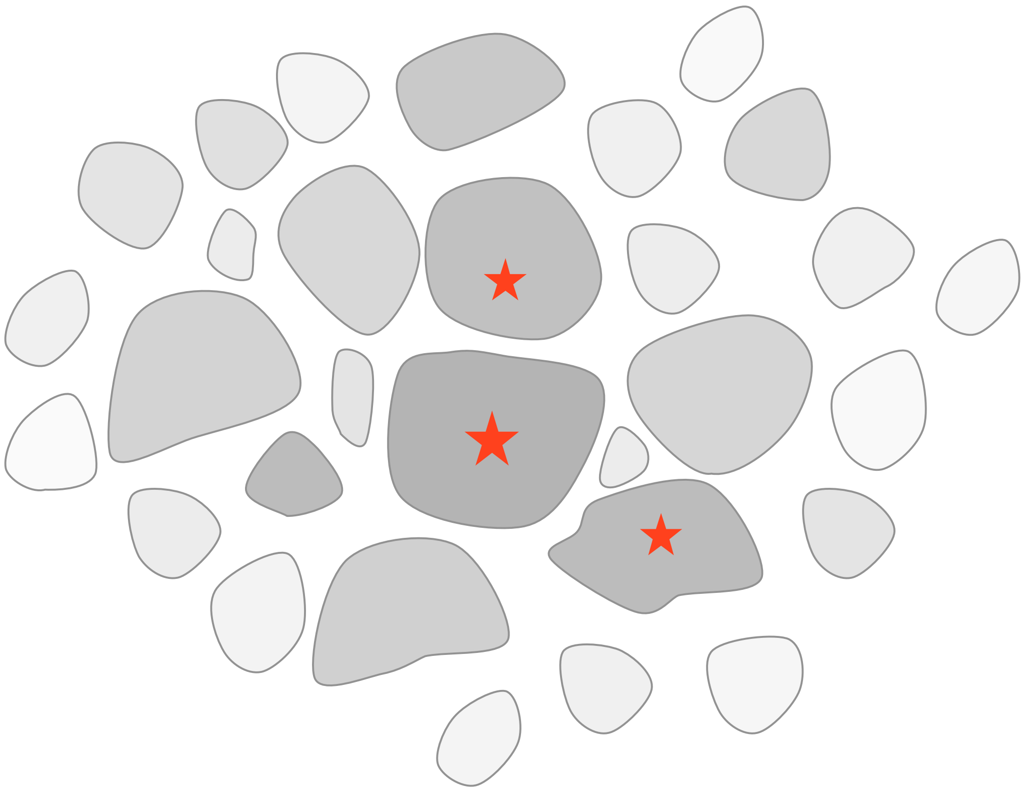


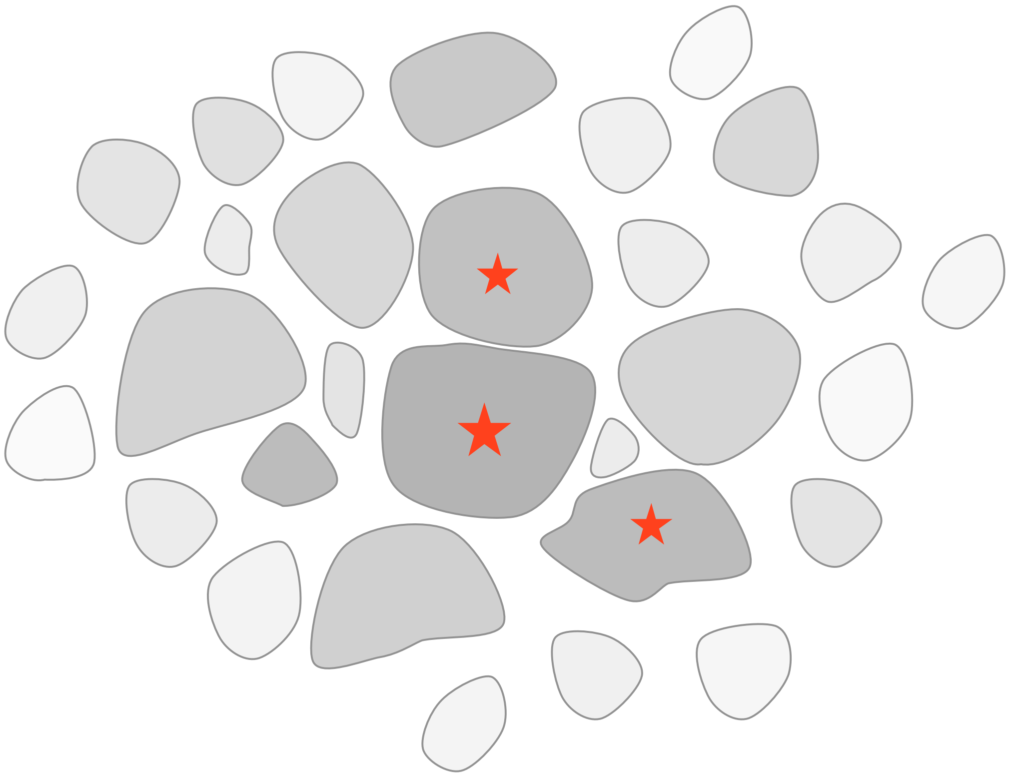
while region contracts, individual clumps collapse to form stars



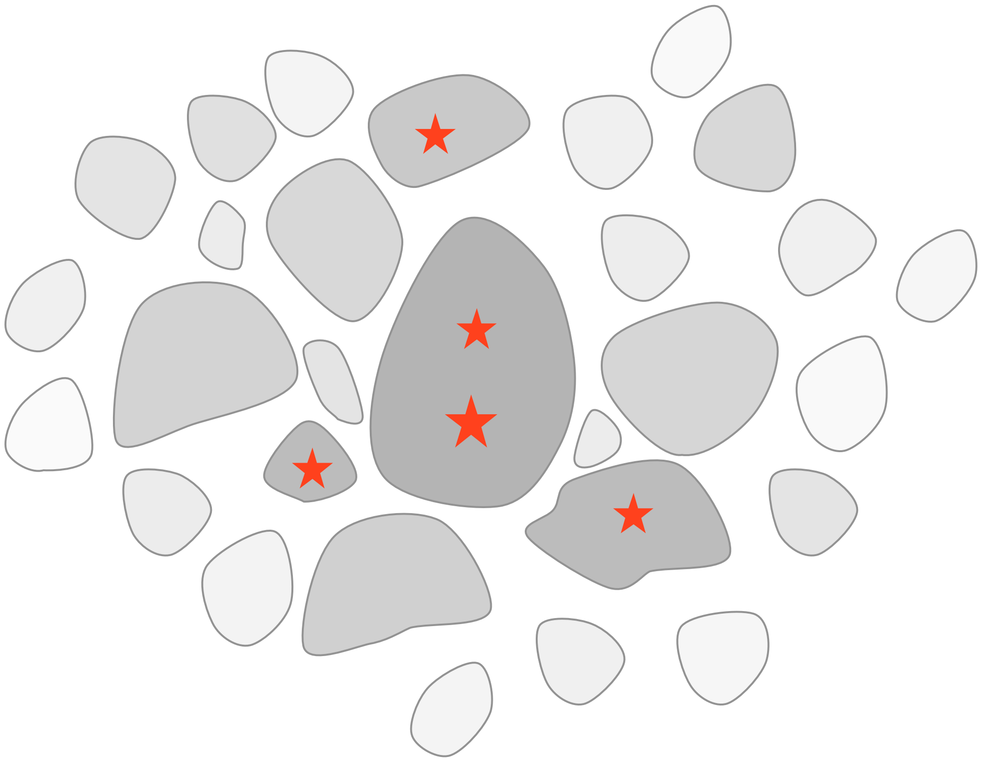
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

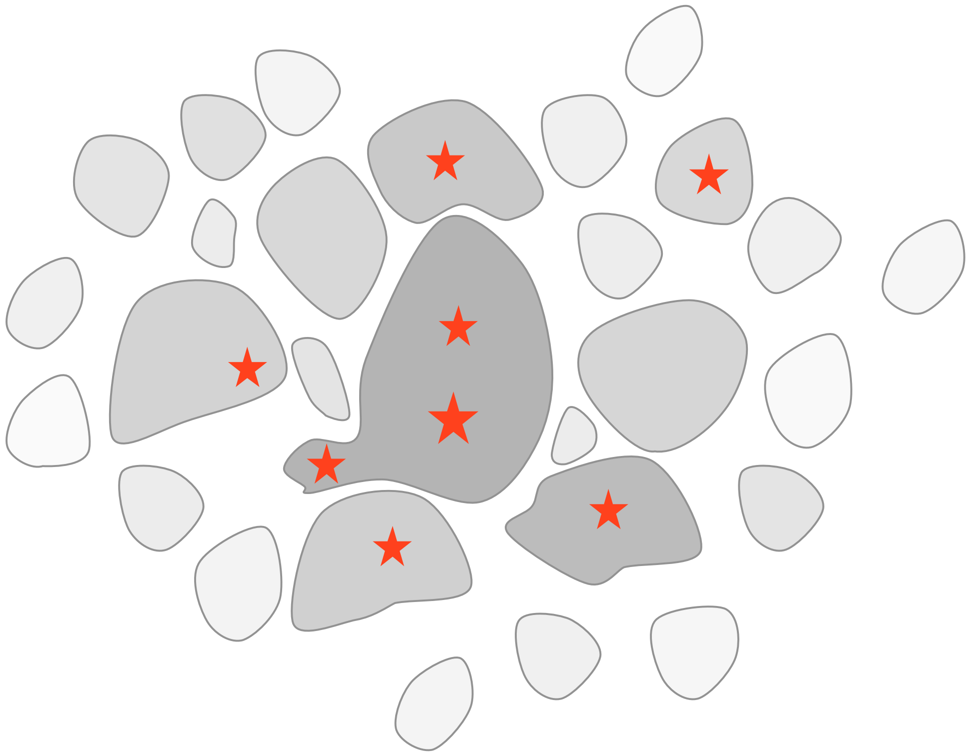


individual clumps collapse to form stars



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

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



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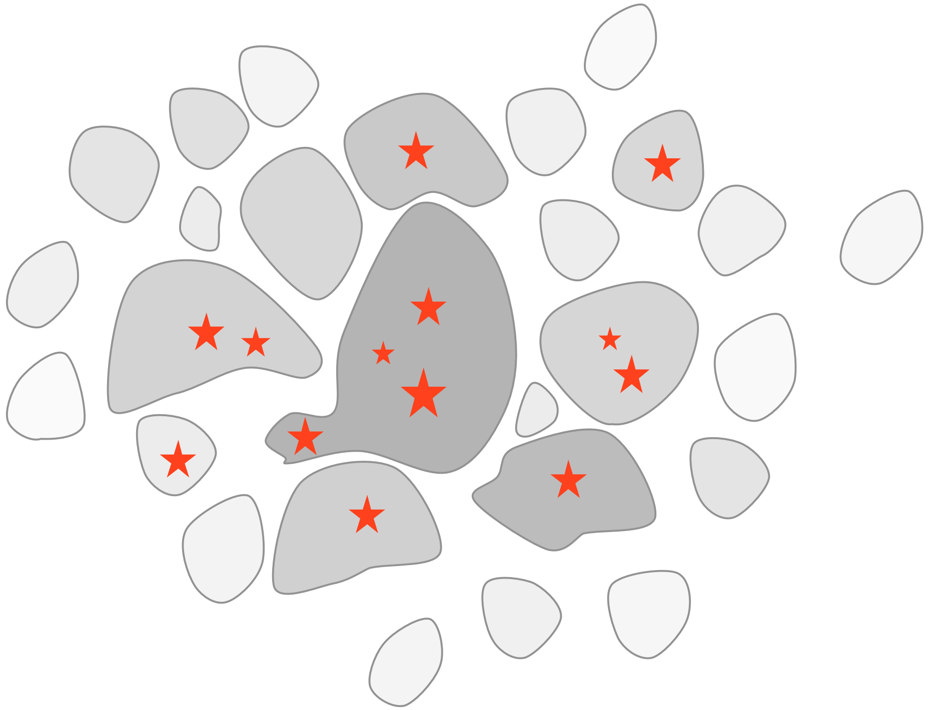

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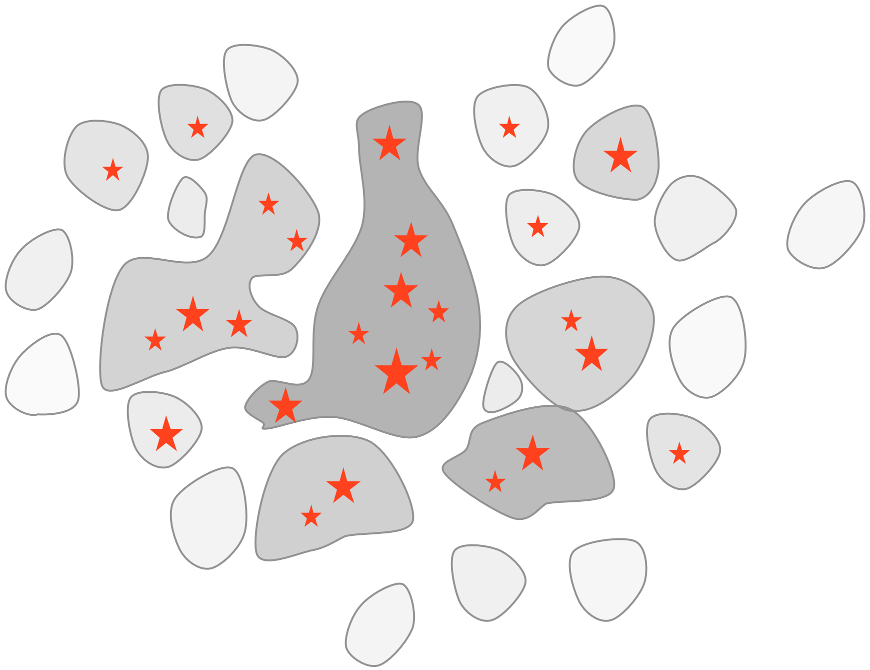
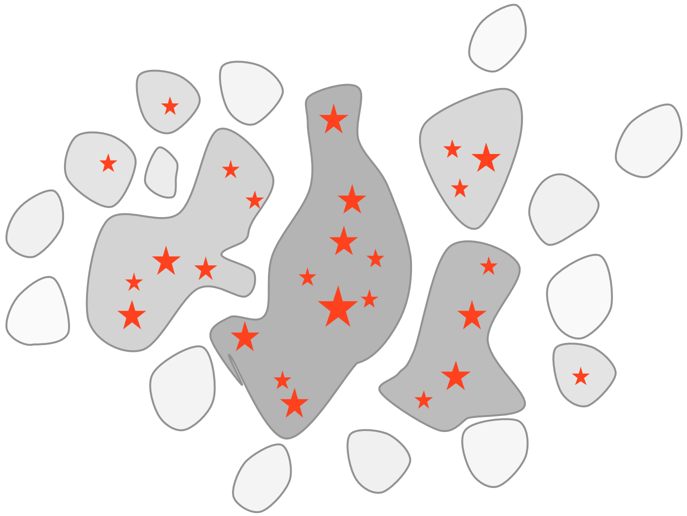


in *dense clusters*, competitive mass growth becomes important



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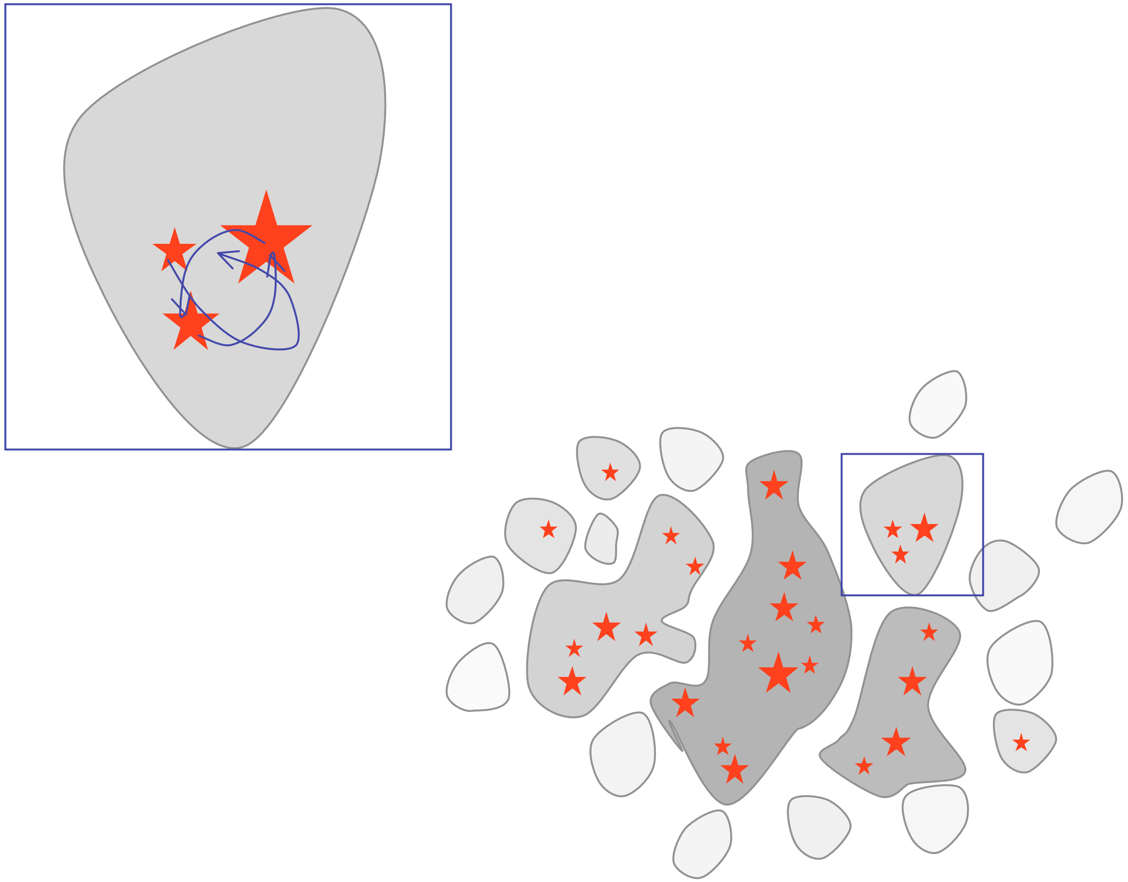
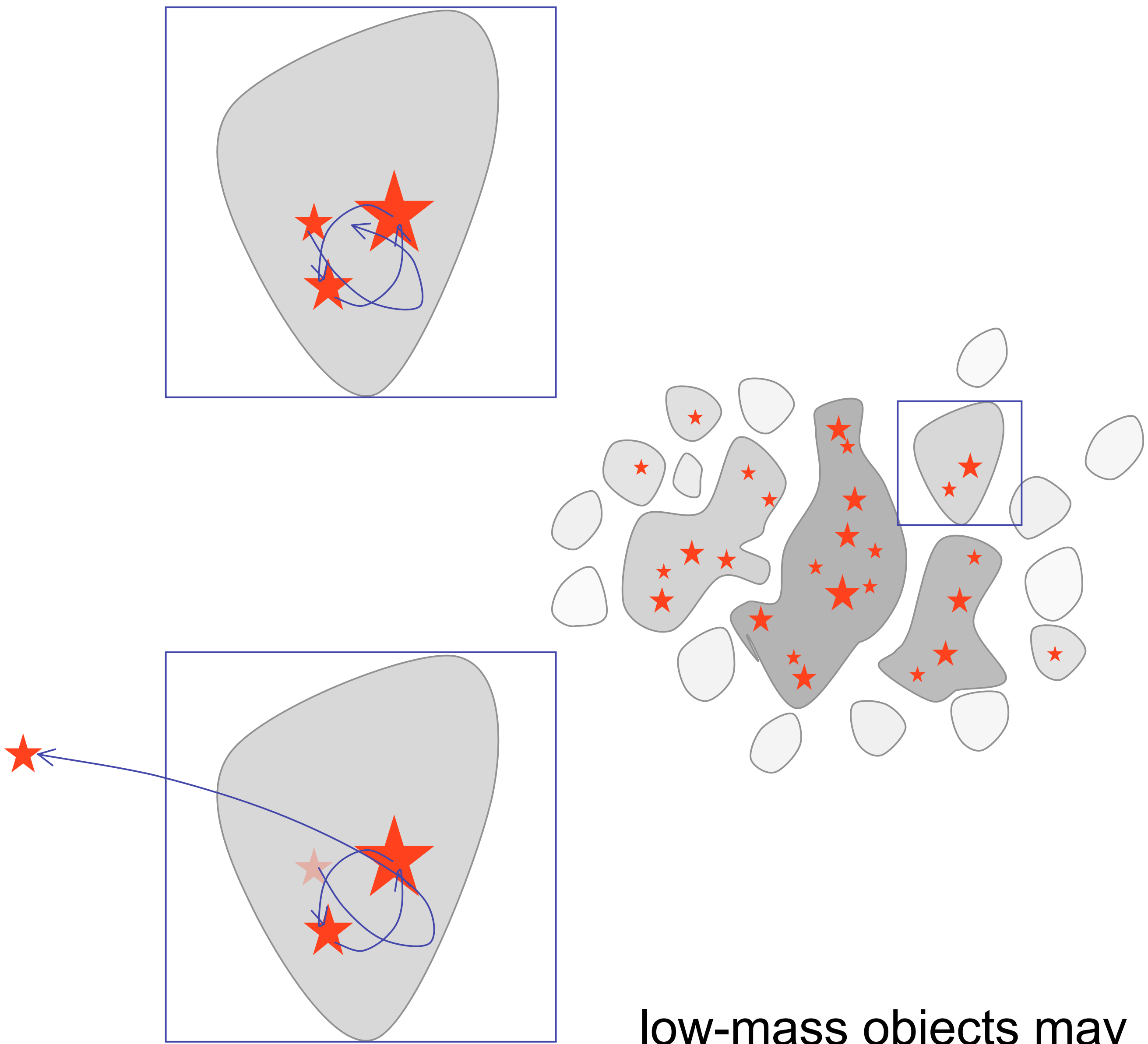
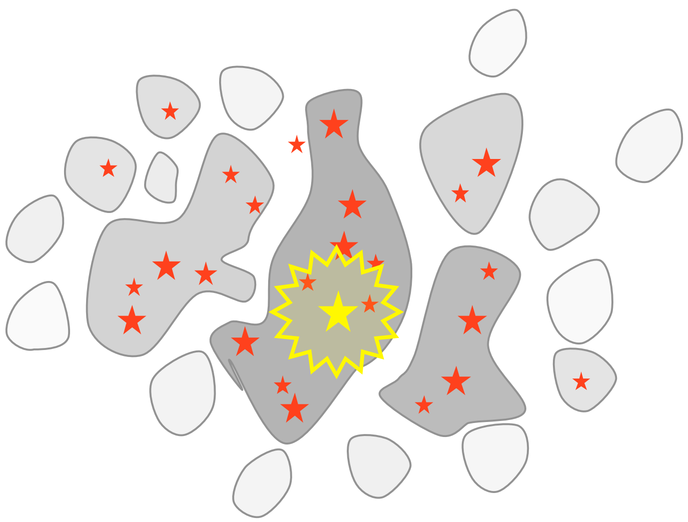


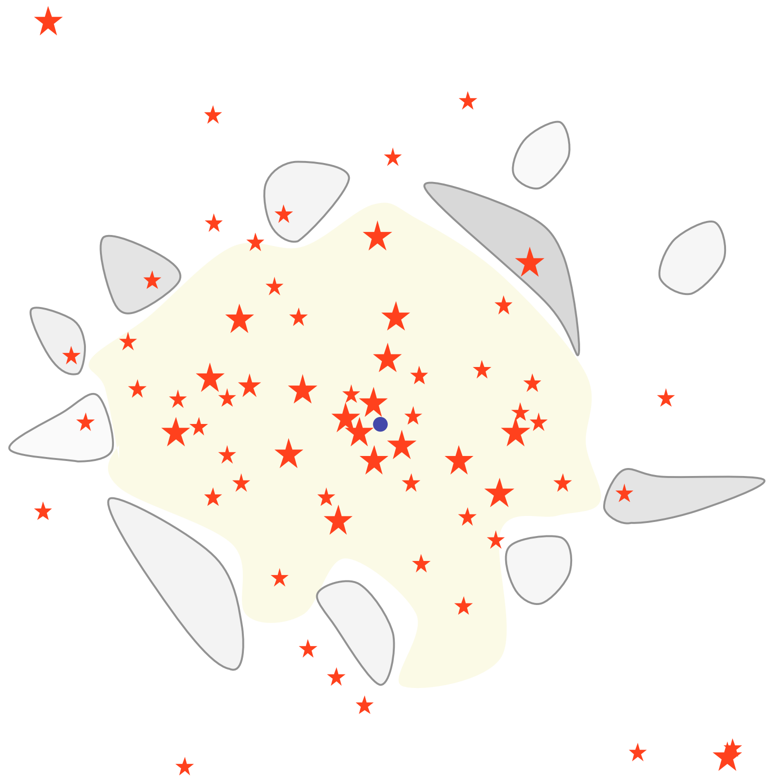
in *dense clusters*, *N*-body effects influence mass growth



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: 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

Transcient cloud structure

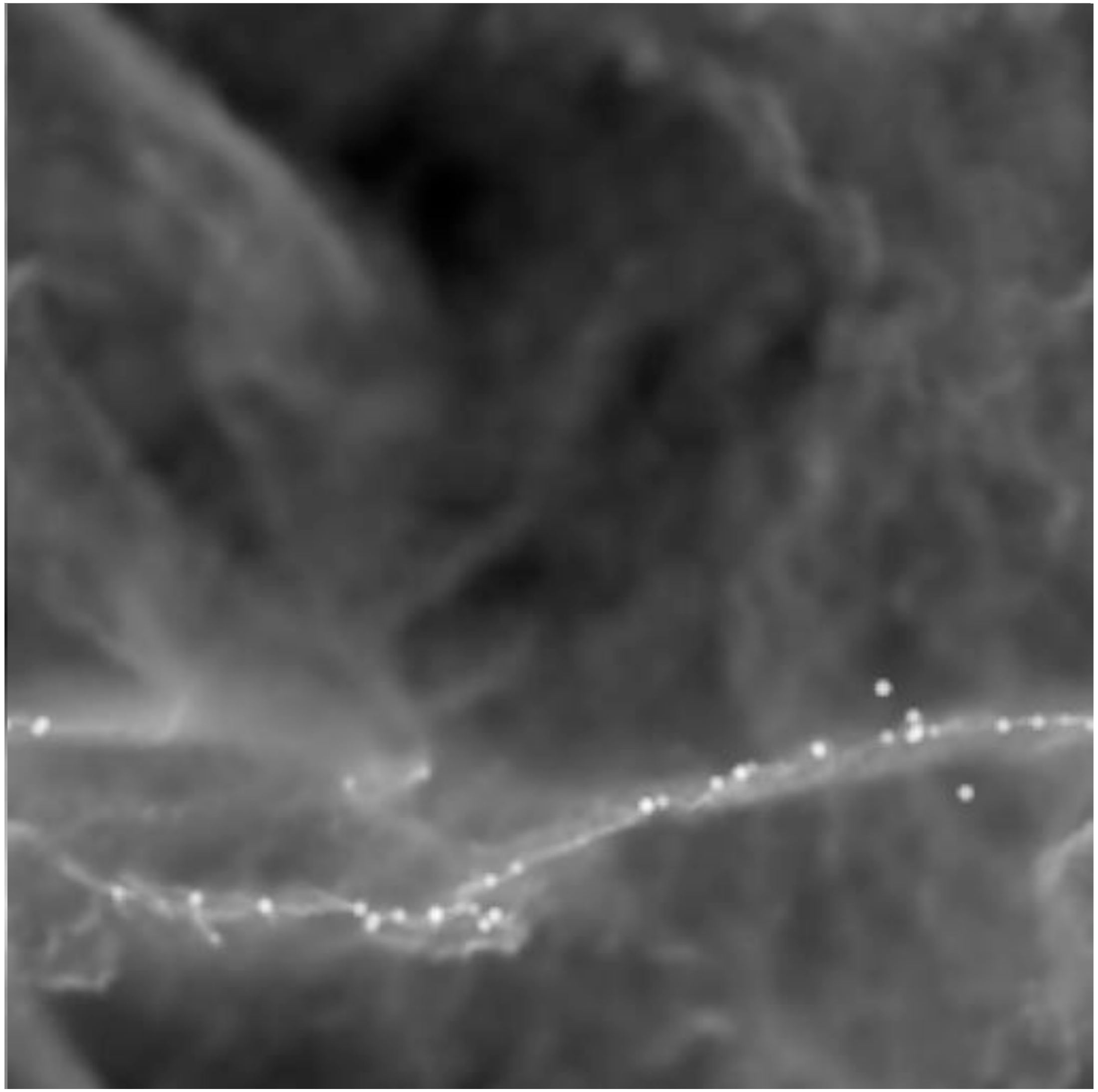
Gravoturbulent fragmentation of turbulent self-gravitating clouds

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:

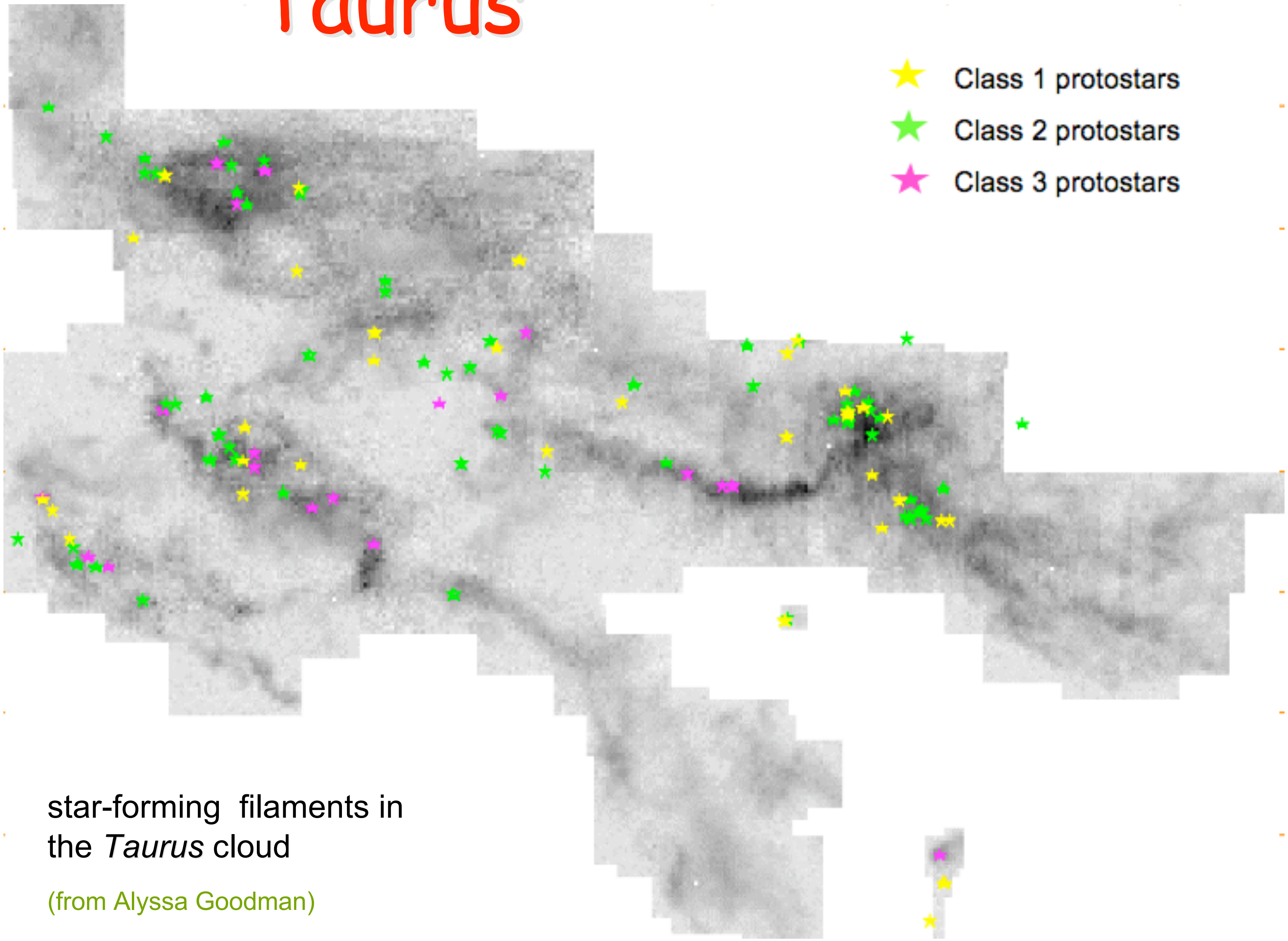
- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"Taurus":

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

→ $L = 6\,pc$, $M = 5000\,M_\odot$

Taurus

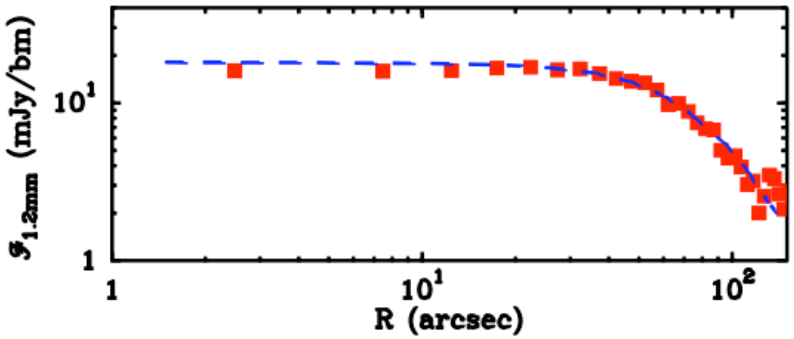


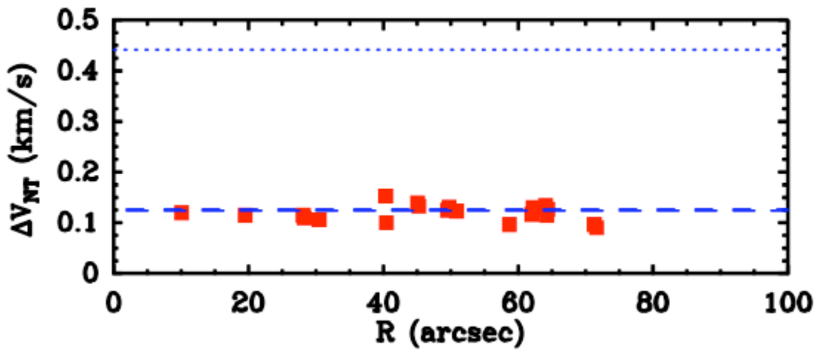
star-forming filaments in the *Taurus* cloud

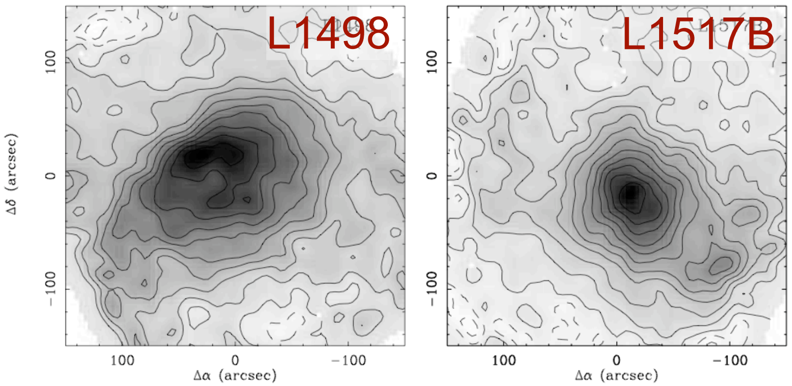
(from Alyssa Goodman)

example 2

Quiescent & coherent cores







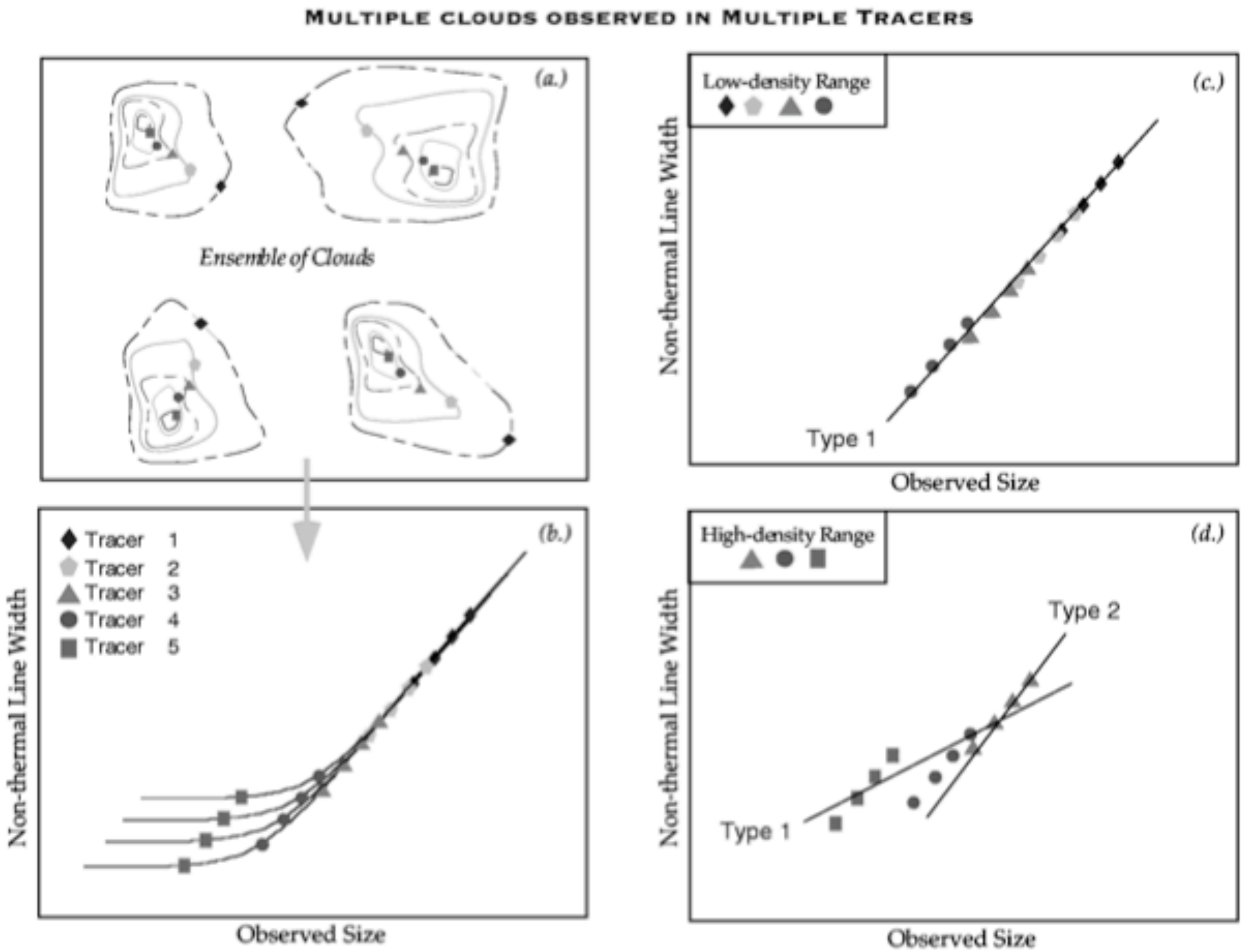
(Tafalla et al. 2004)

- some small cores have very small linewidth!
- is this consistent with gravo-turbulent star formation?

map of linewidth
(contours column density)

column density map
(contours column density)

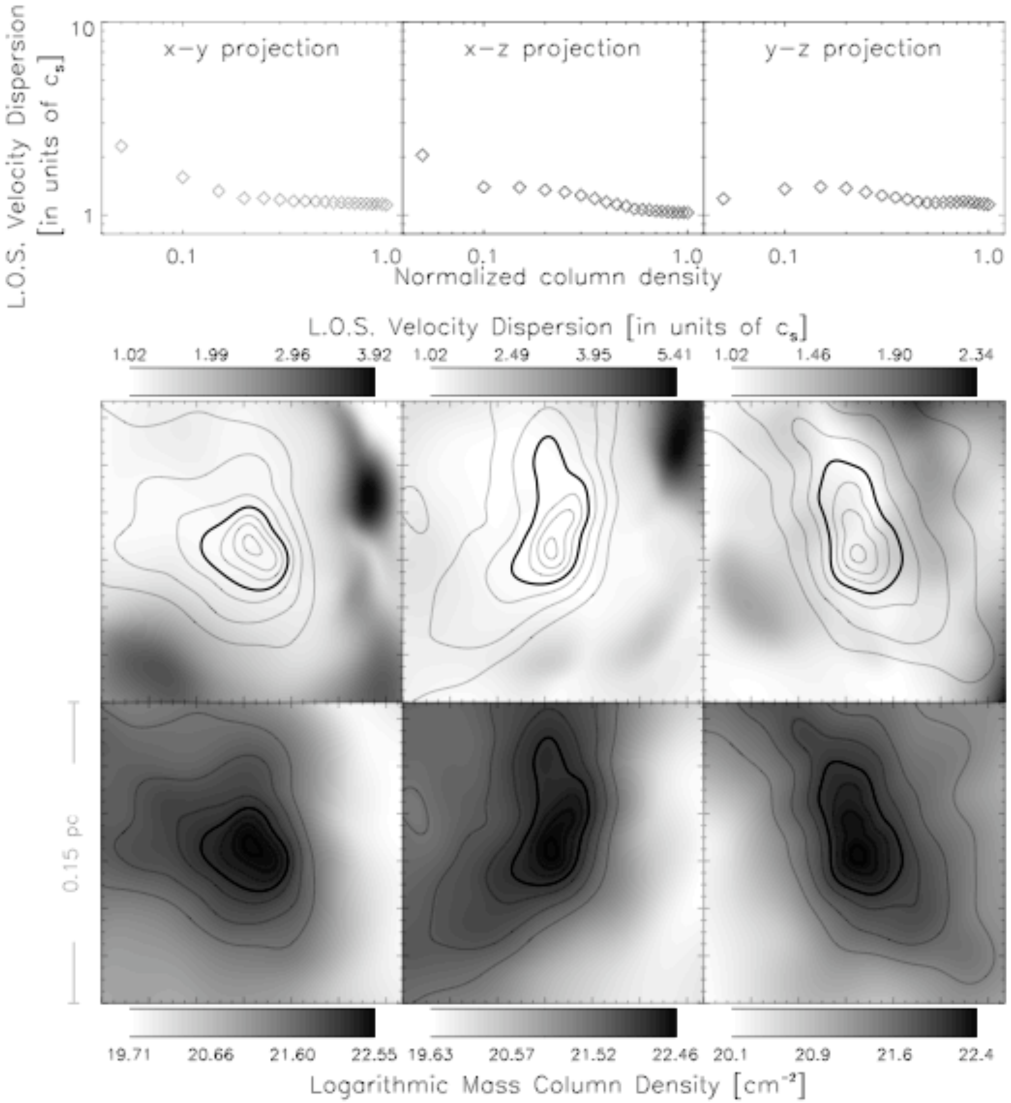
Quiescent & coherent cores



(Goodman et al. 1998)

Quiescent & coherent cores

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



correlation between linewidth and column density

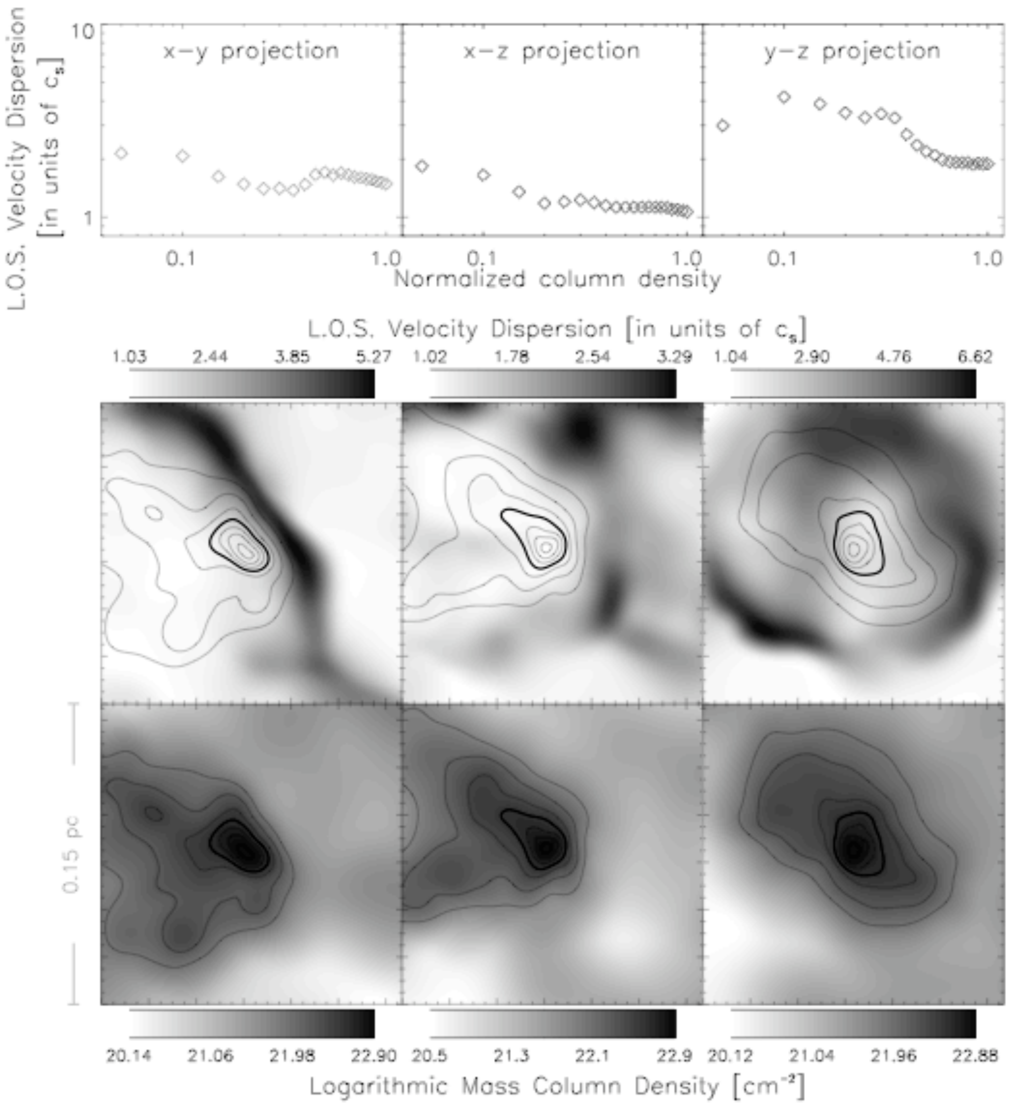
(e.g. Goodman et al. 1998; Barranco & Goodman 1998 Caselli et al. 2002; Tafalla et al. 2004)

map of linewidth (contours column density)

column density map (contours column density)

Quiescent & coherent cores

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



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

map of linewidth

(contours column density)

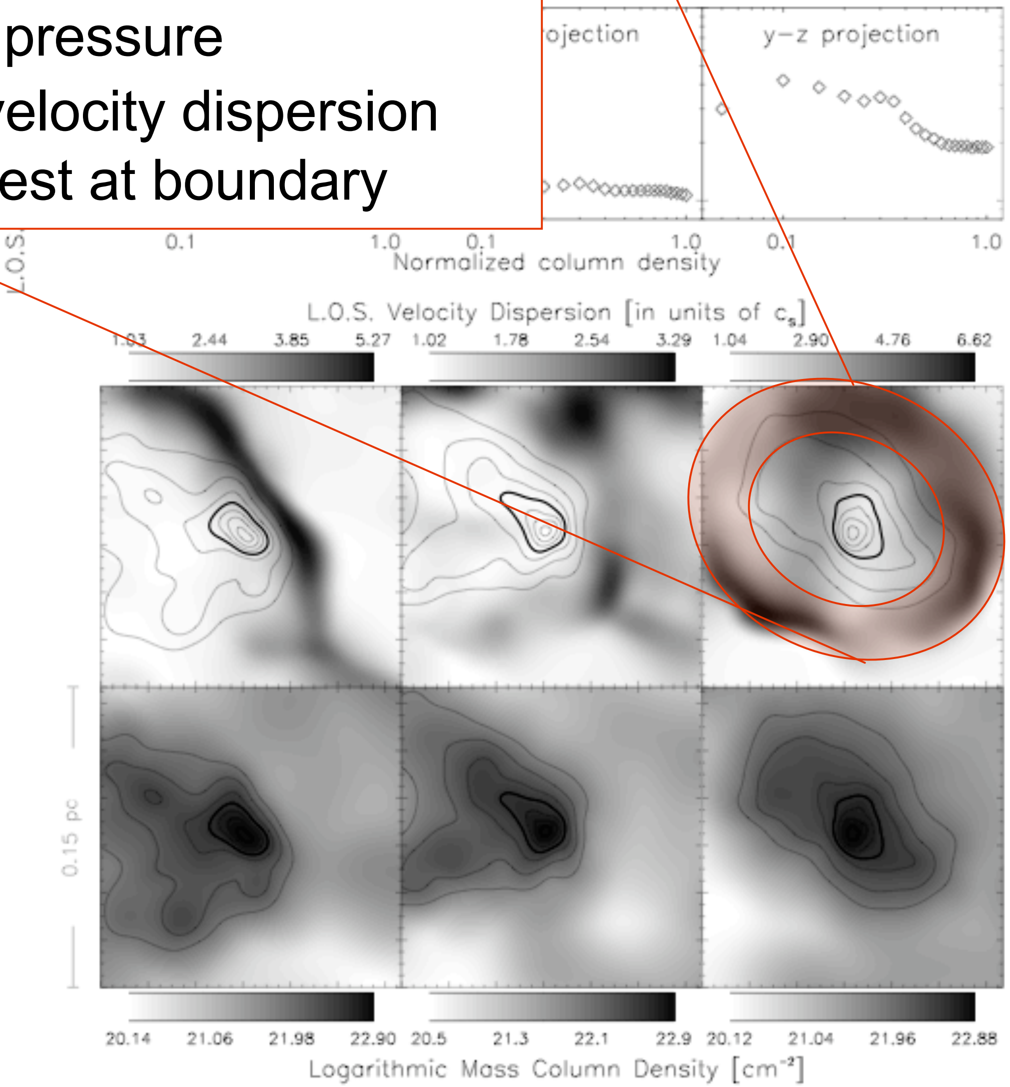
column density map

(contours column density)

cores form at stagnation points of convergent large-scale flows
--> often are bounded by ram pressure
--> velocity dispersion highest at boundary

t & coherent cores

(from Klessen et al. 2005, ApJ, 620, 768 - 794; also p



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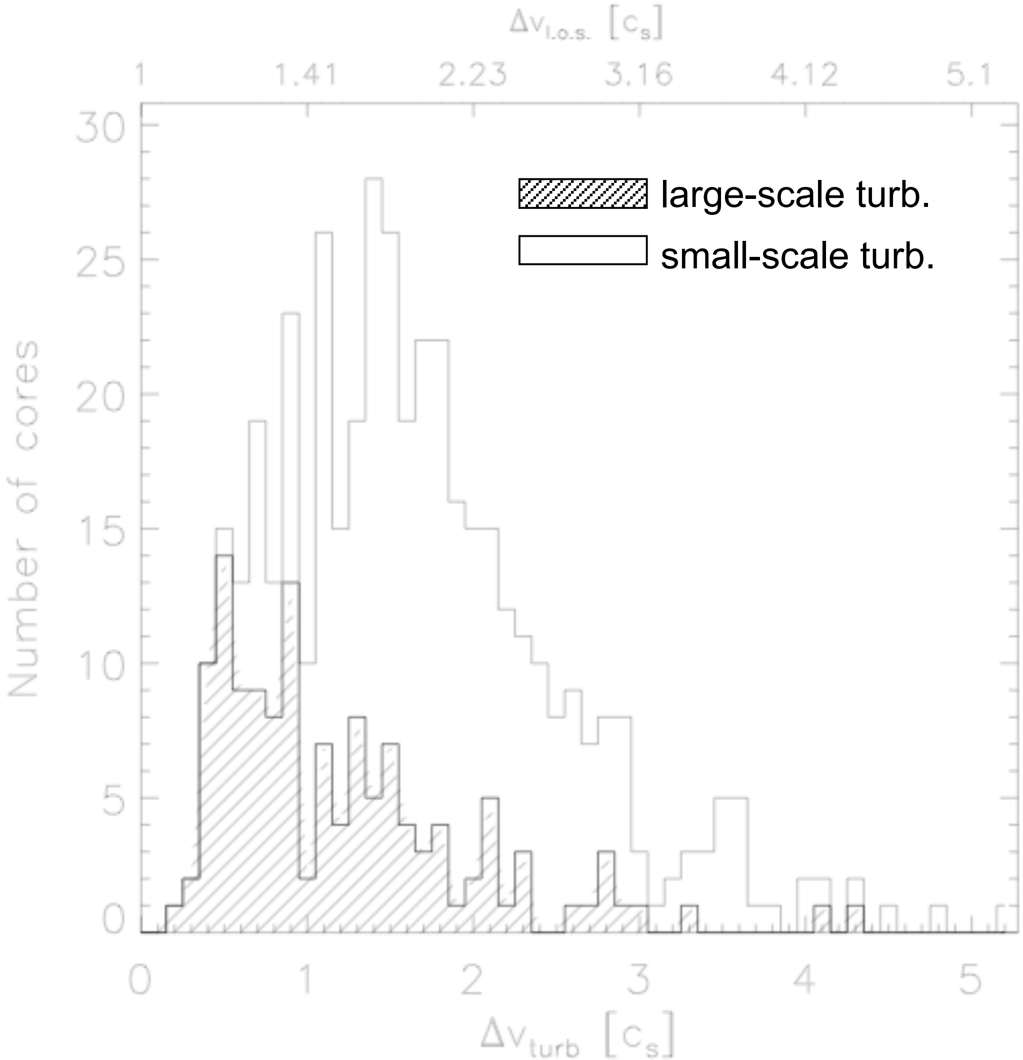
Quiescent & coherent cores

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



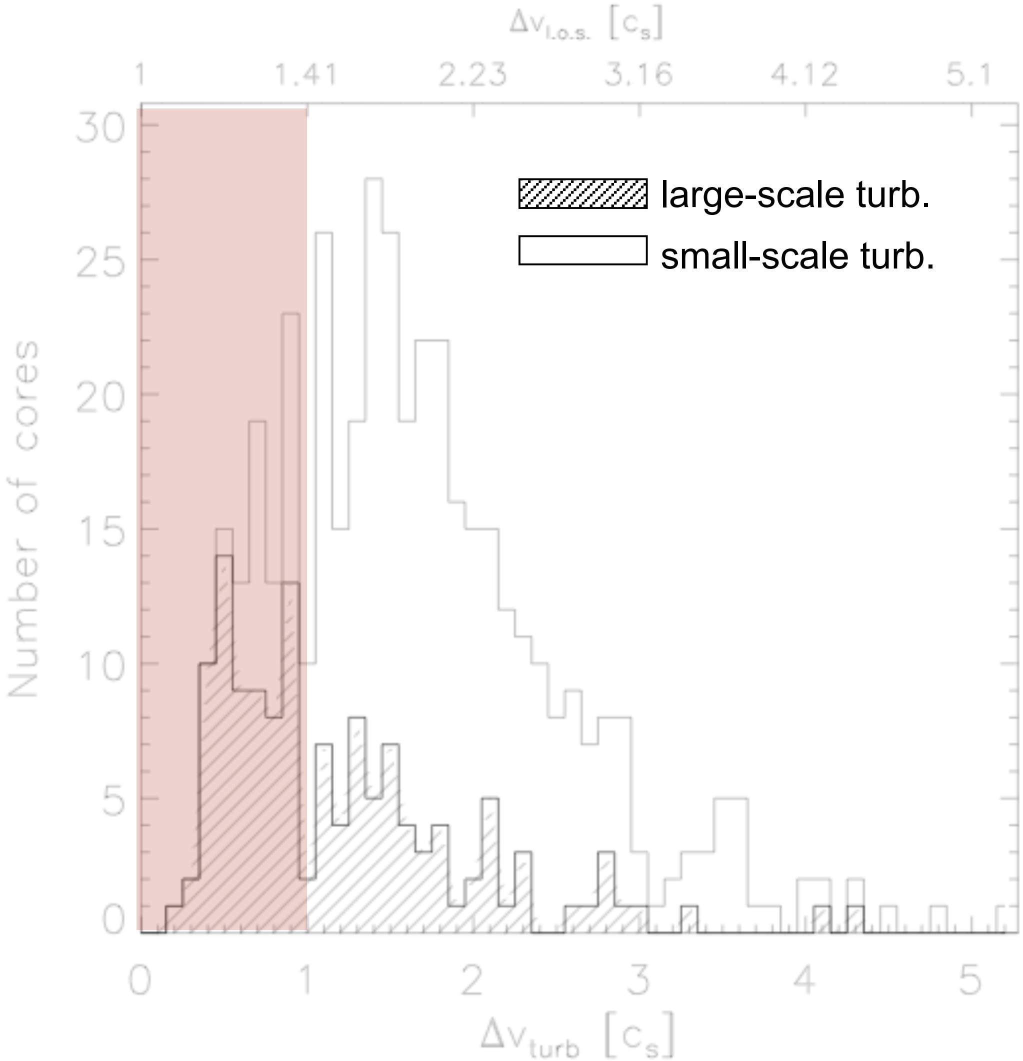
Statistics:

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



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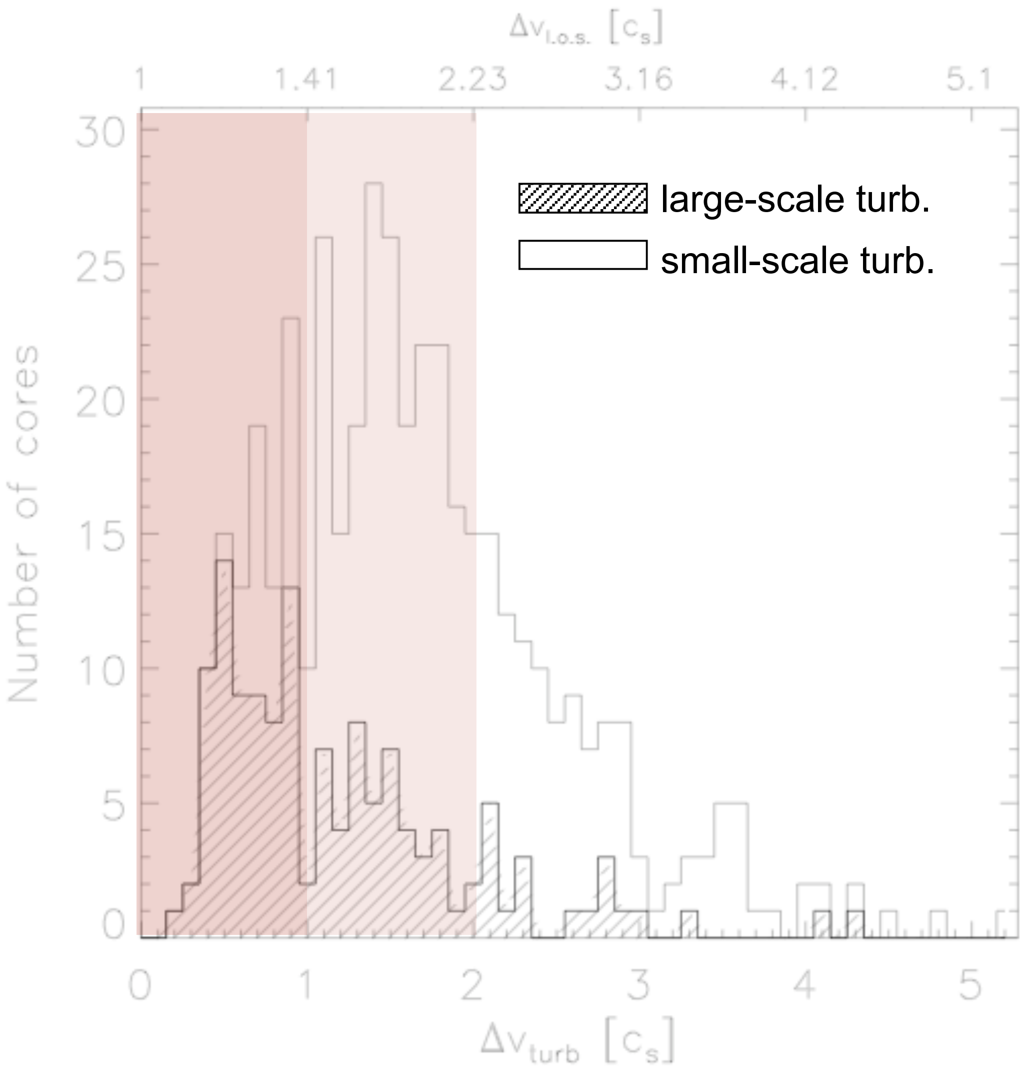
Quiescent & coherent cores



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

example 3

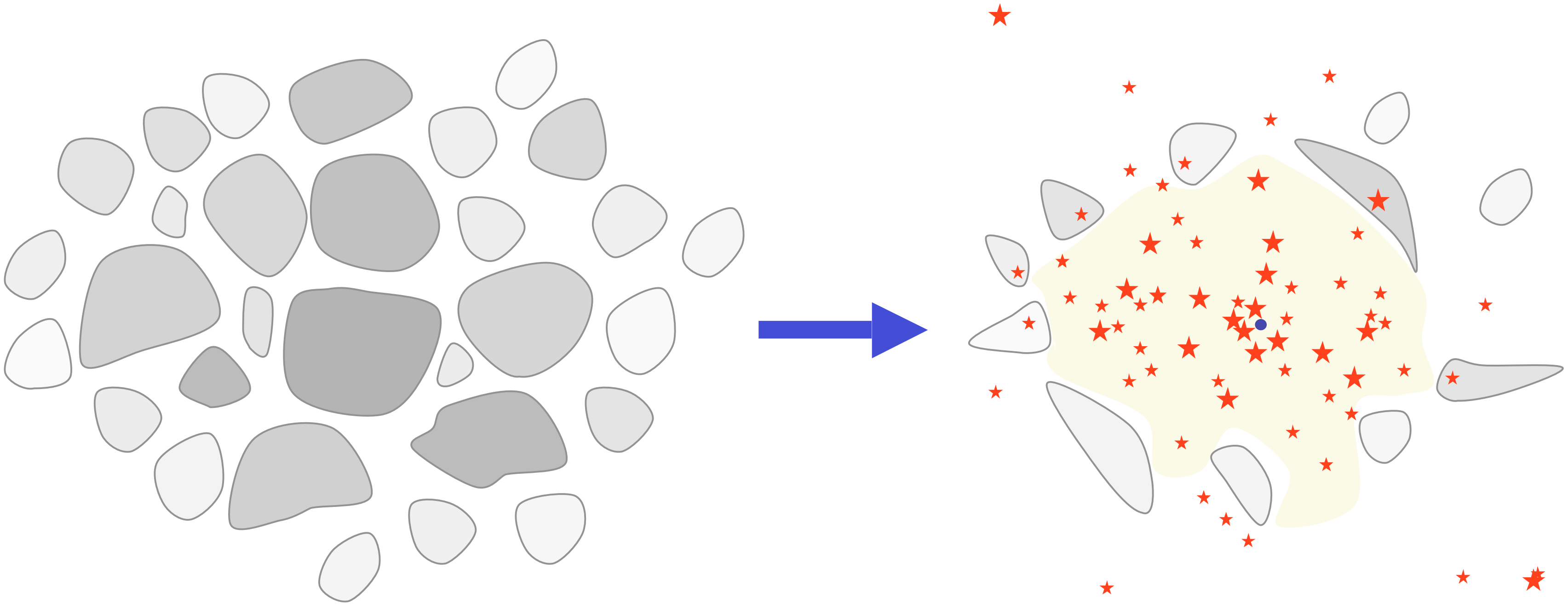
IMF

- 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*



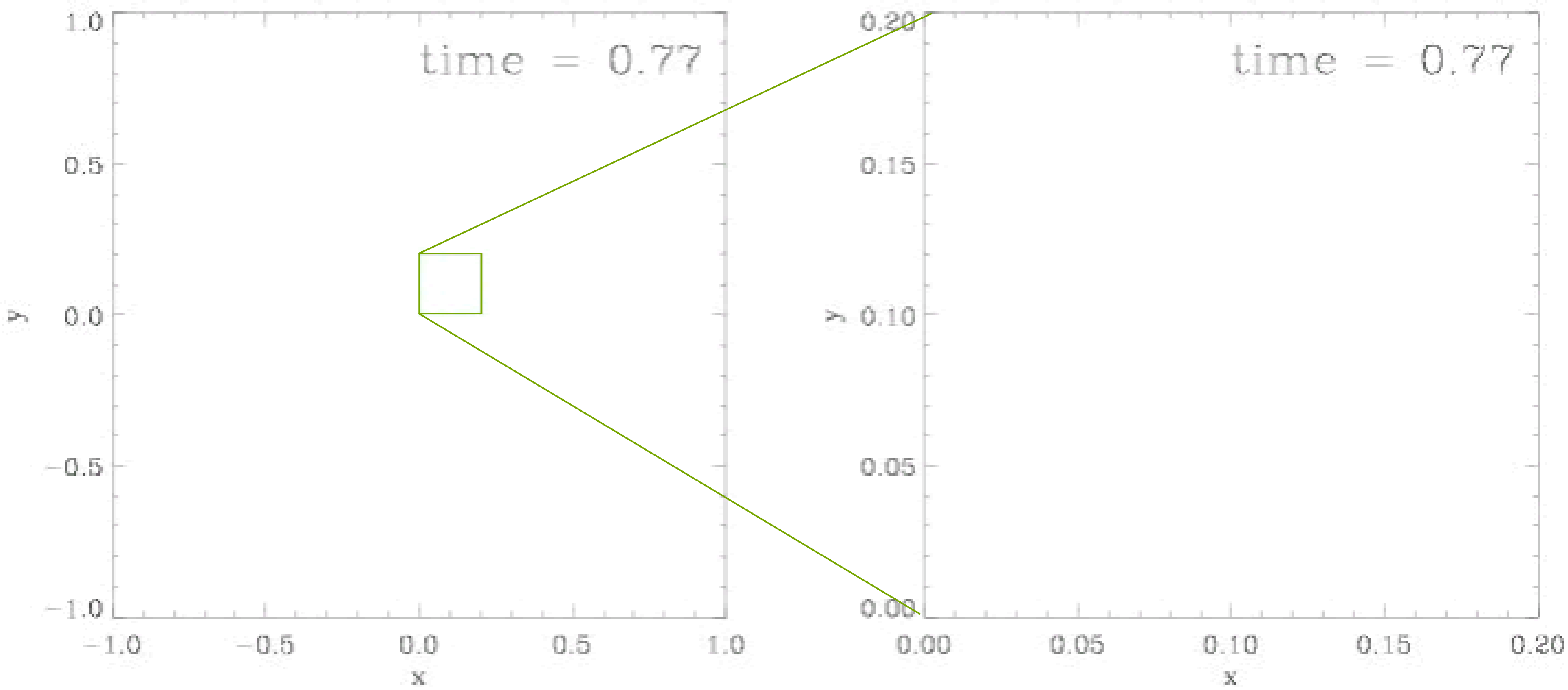
How to get from cloud cores to star clusters?

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

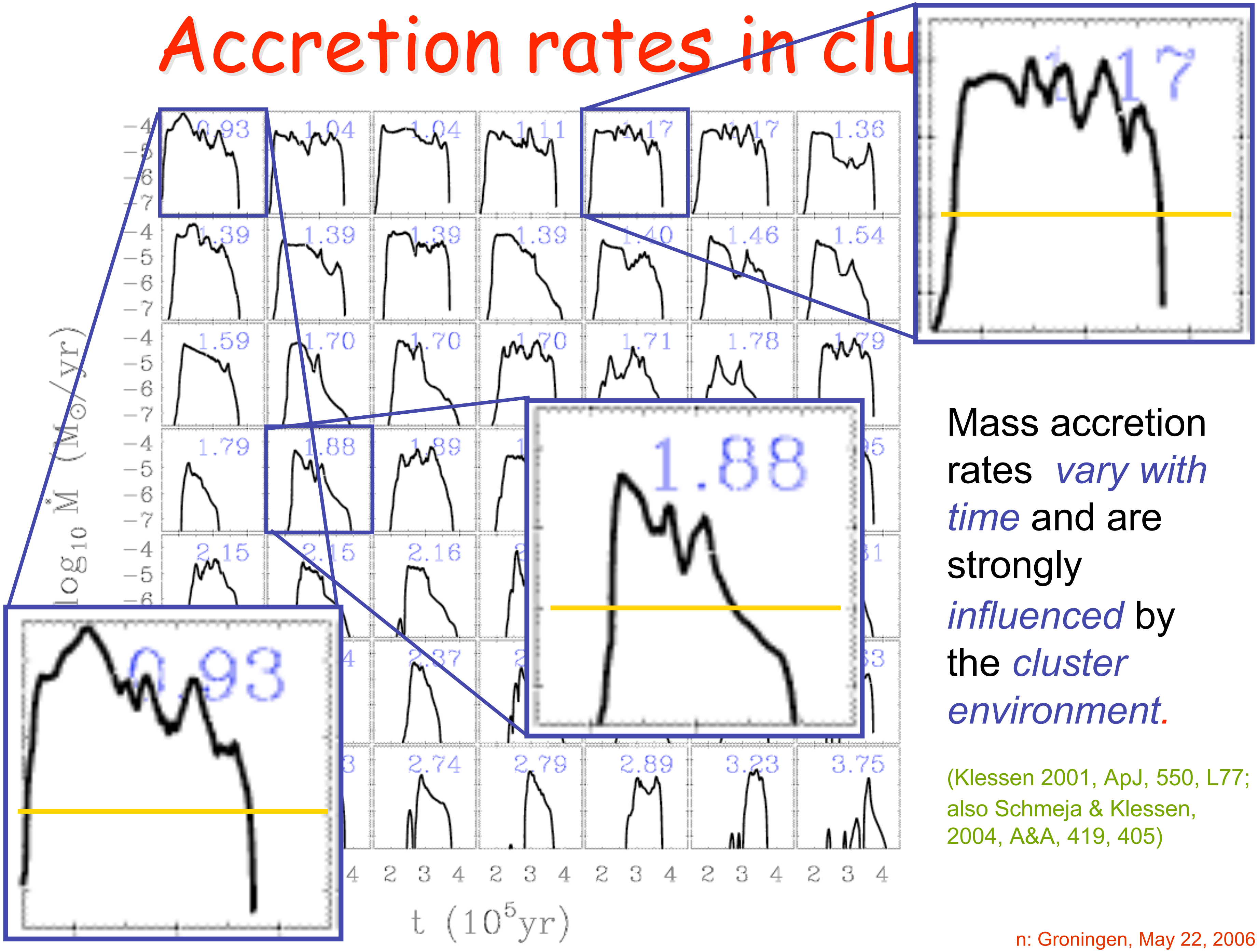
in dense clusters protostellar interaction may be come important!



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

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

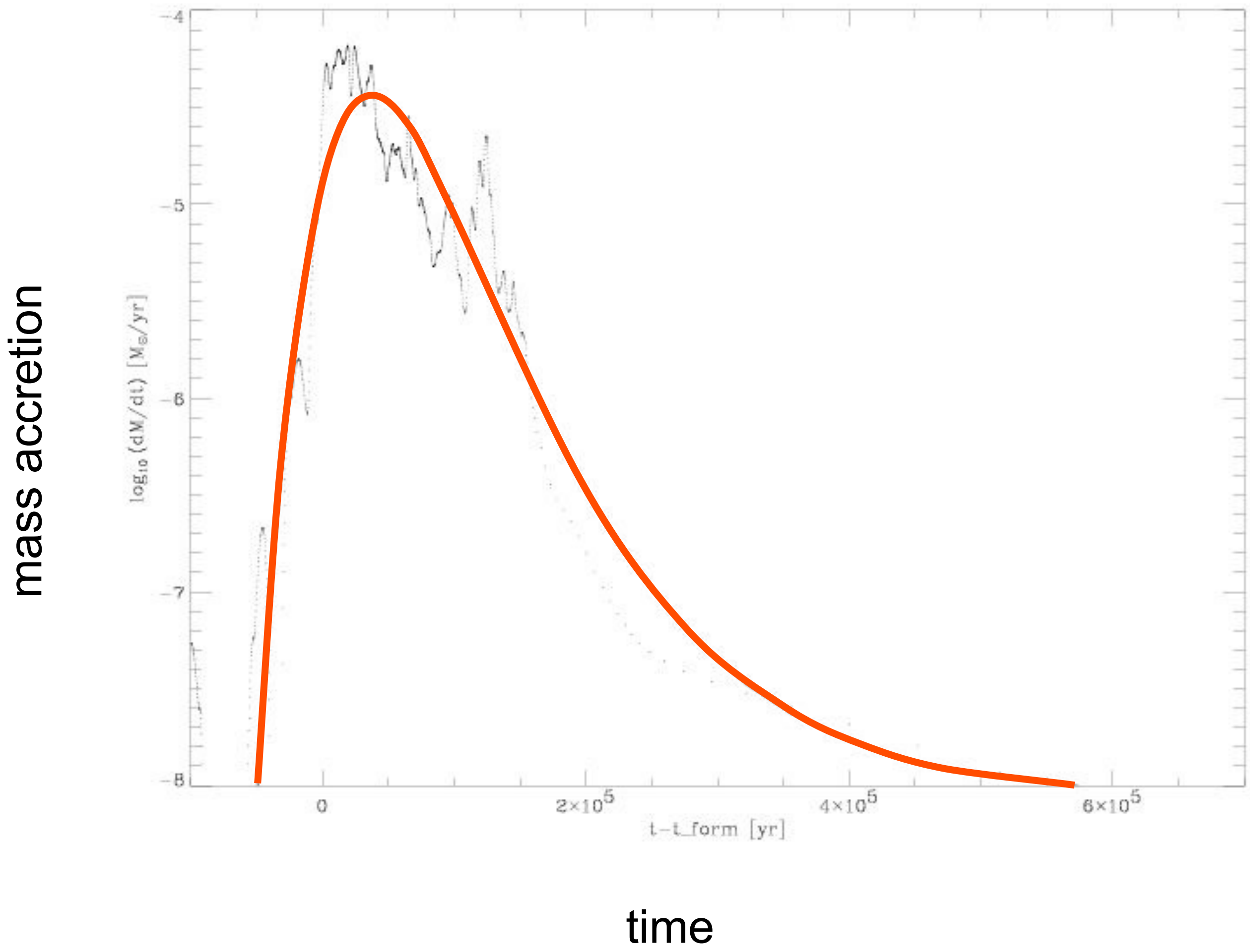
Accretion rates in clu



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)

"Empirical" mass accretion law



Simple analytic formula for individual mass accretion rates: $\boxed{dM/dt = At \cdot \exp(-t/\tau)}$

(Schmeja & Klessen, 2004 -- A&A, 419, 405 - 417)

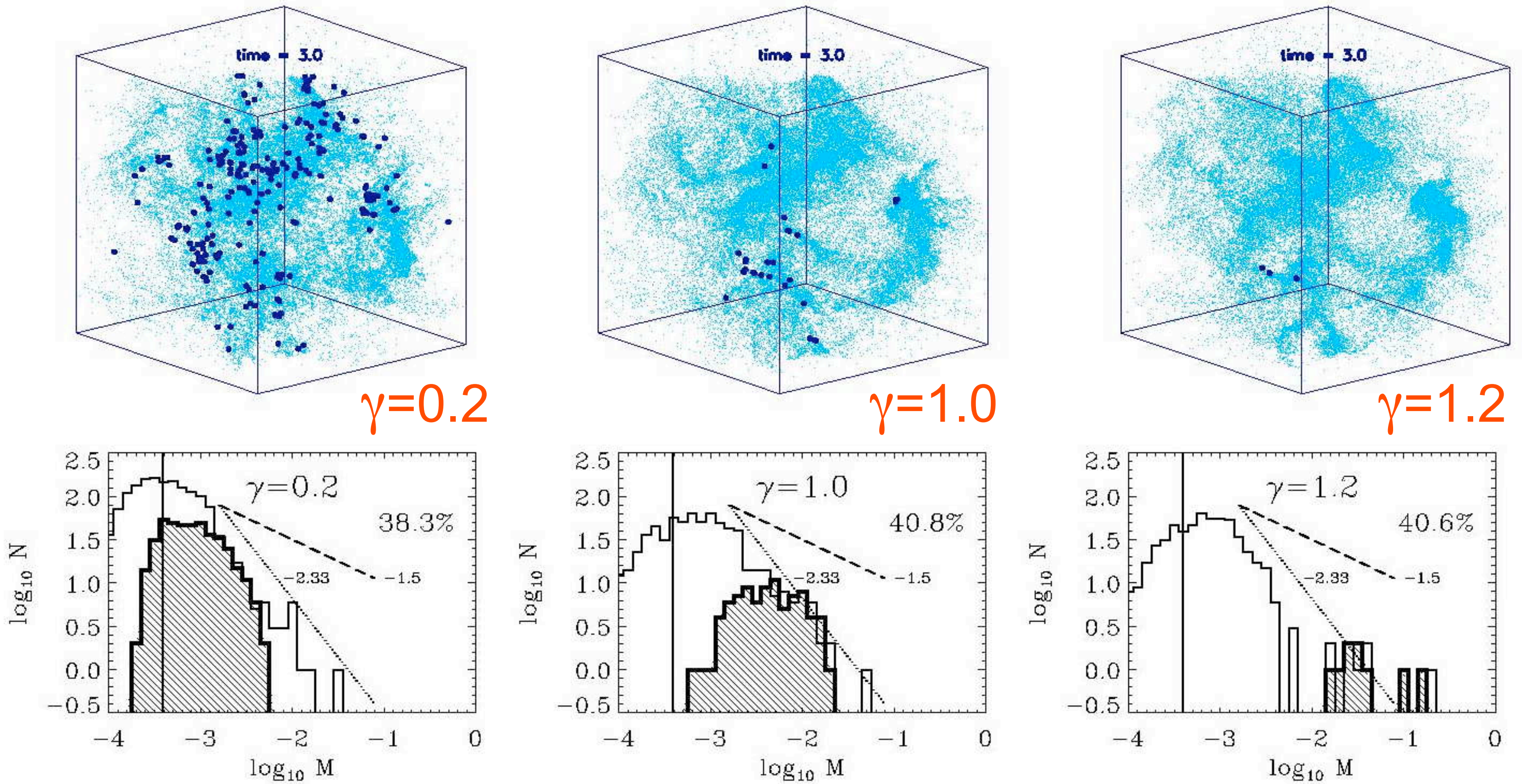
Dependency on EOS

- 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



for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*

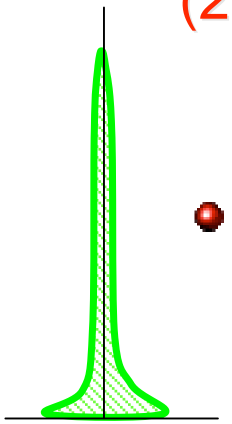
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

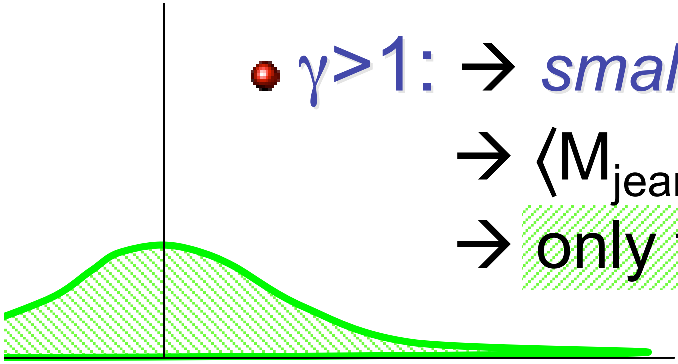
How does that work?

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

(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}

Implications

- 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; 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

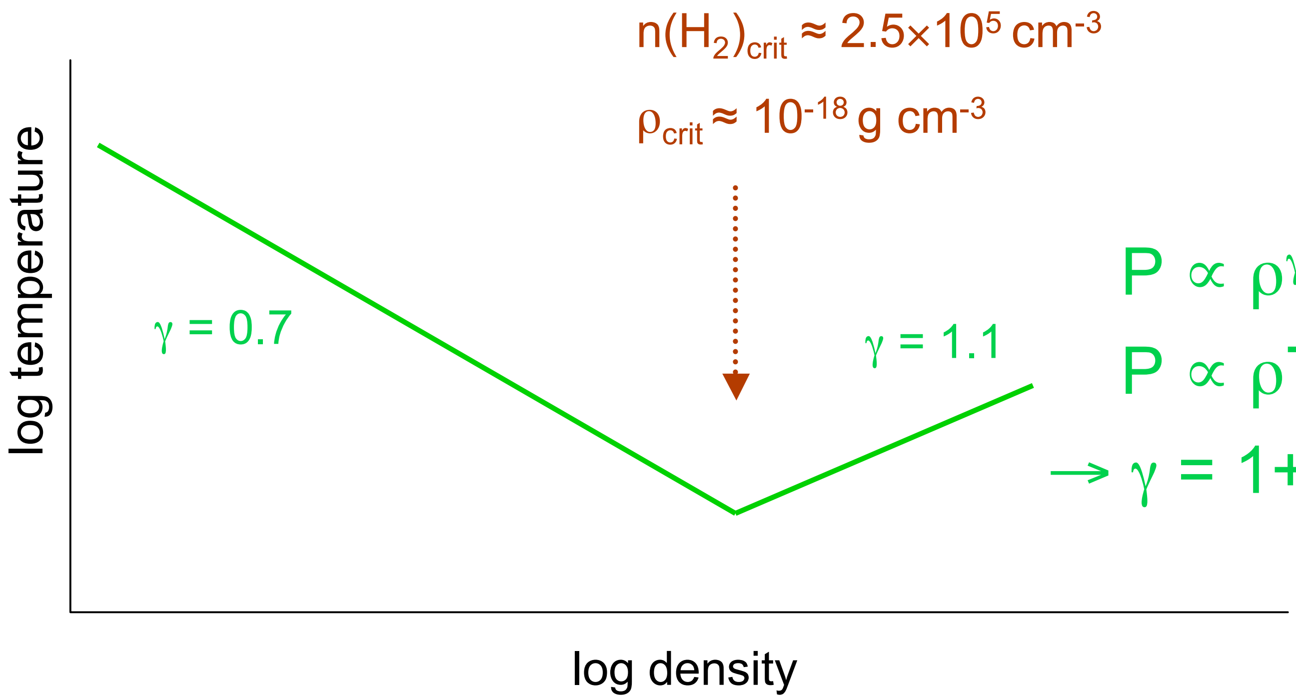
  (Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2005)

- 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*



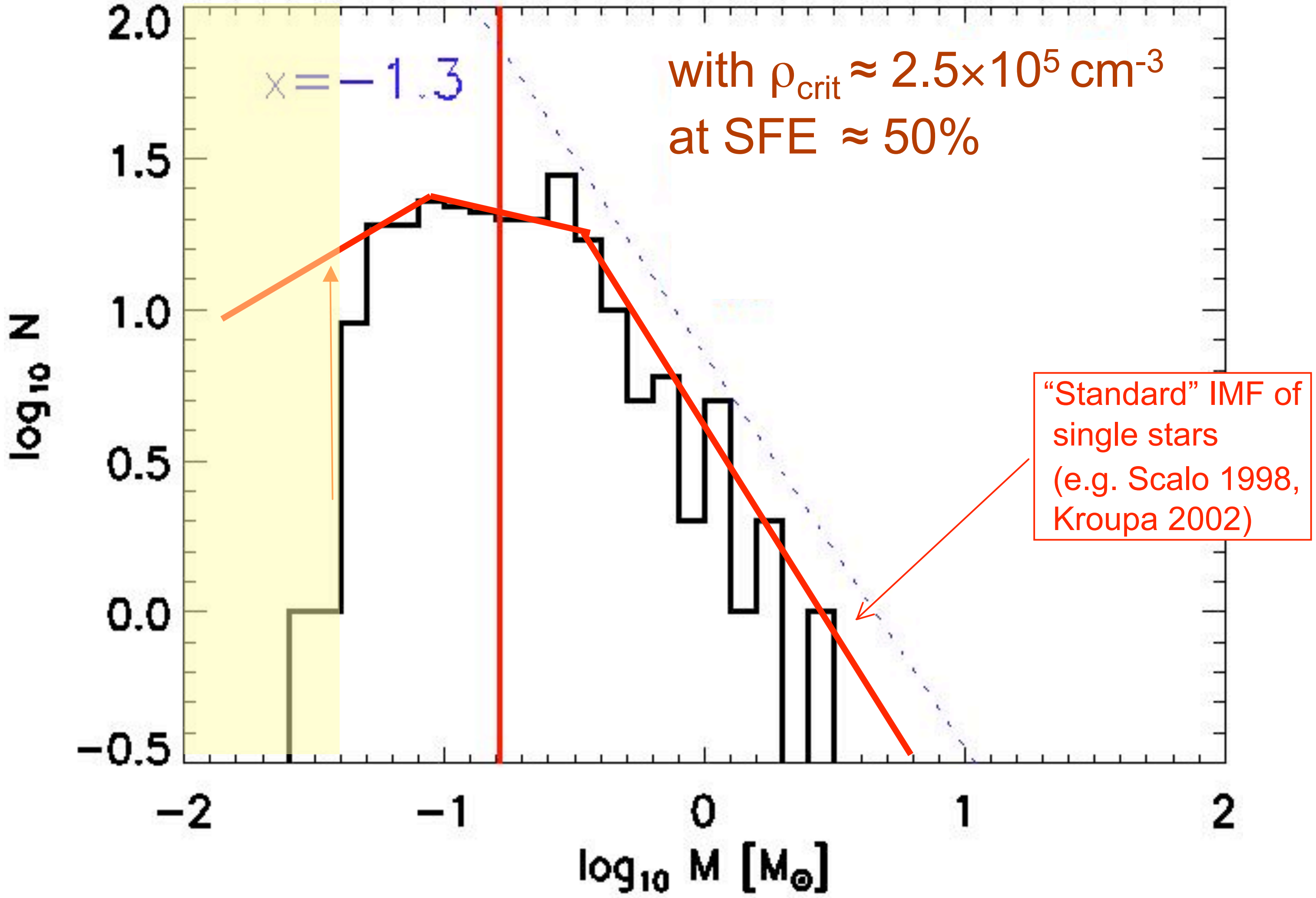
$P \propto \rho^\gamma$

$P \propto \rho T$

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

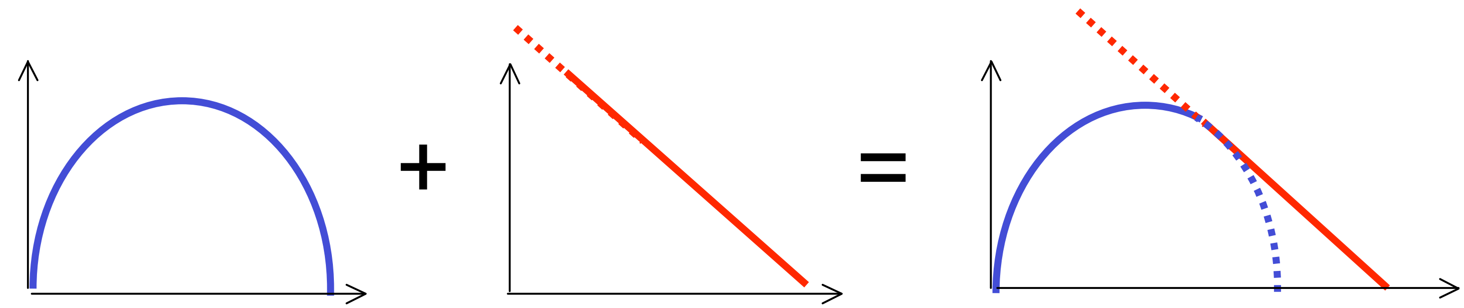
(Larson 2005; Jappsen et al. 2005, A&A, 435, 611)

IMF in nearby molecular clouds



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

Plausibility argument for shape



- Supersonic turbulence is scale free process

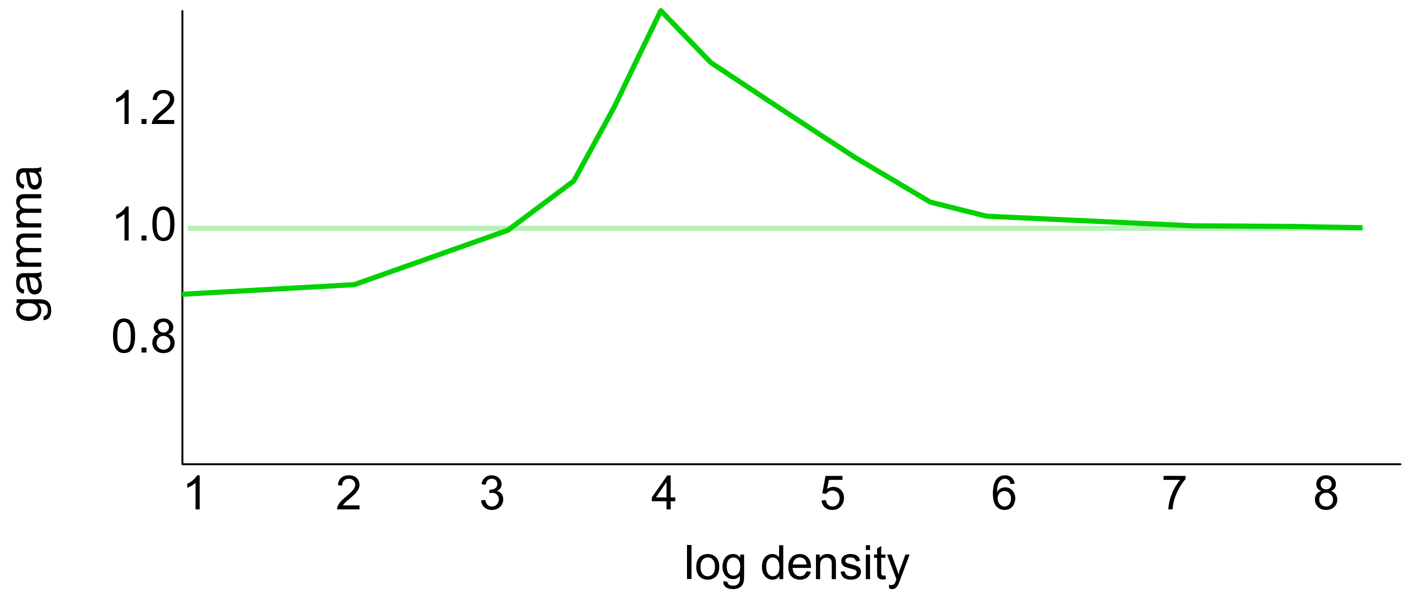
  → *POWER LAW BEHAVIOR*

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

  → *GAUSSIAN DISTRIBUTION*

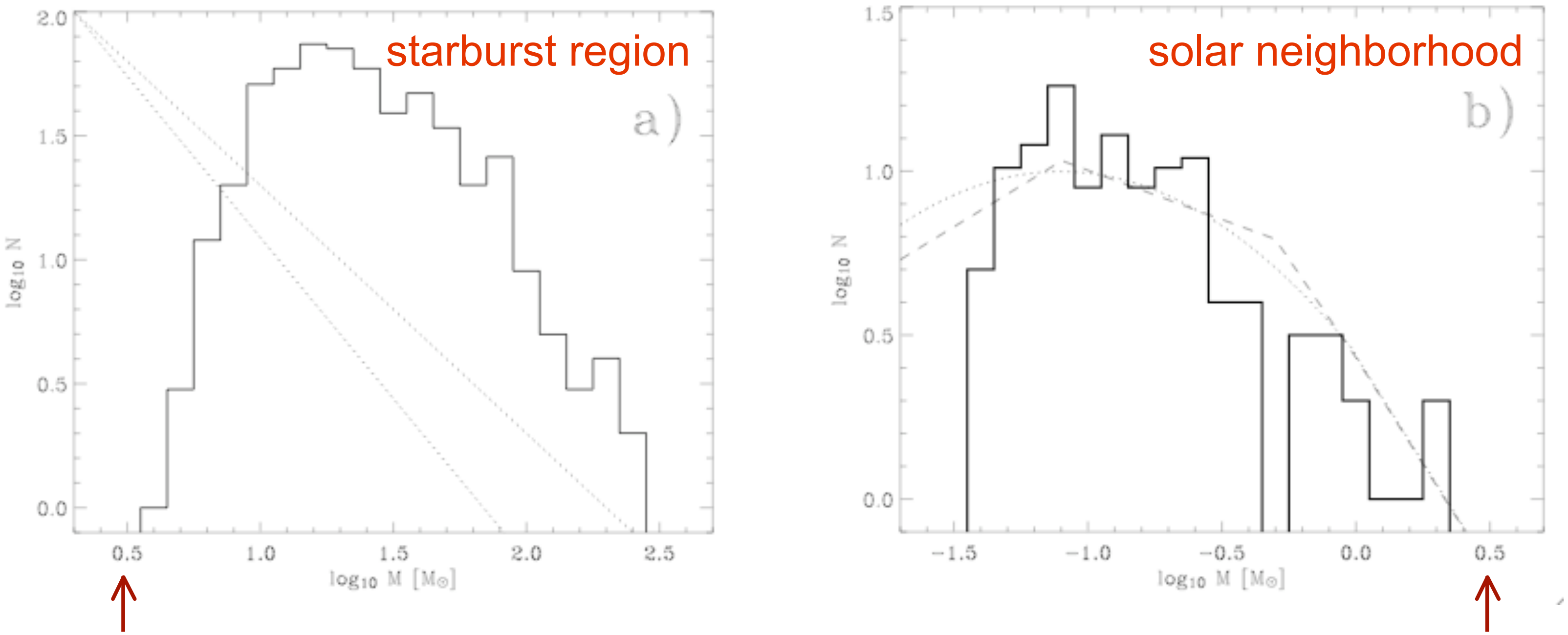
IMF in starburst galaxies

- 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

- Different EOS --> different IMF
  (see Klessen, Spaans, Jappsen, in prep.)



note the different mass scale...

Summary

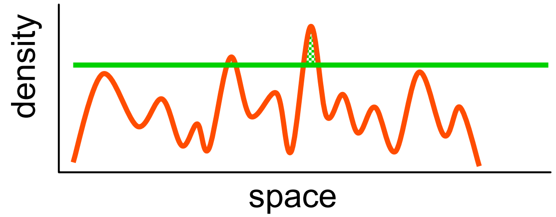
Summary

- 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*)

(Larson 2003, PRP; Mac Low & Klessen 2004, RMP, 76, 125-194, Ballesteros-Paresed et al. PPV)

Summary



- 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)

Thanks!