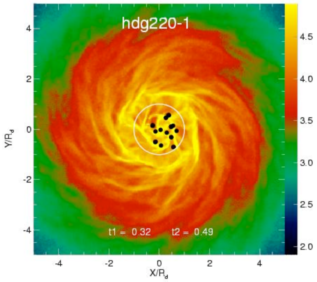
Gravoturbulent Star Formation



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Collaborators

many thanks to...

- Javier Ballesteros-Paredes (UNAM, Morelia)
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- Fabian Heitsch (Uni. München)
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- Doug Lin (UC Santa Cruz)
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- Marco Spaans (Kapteyn Institute)
- Enrique Vazquez-Semadeni (Morelia)
- Hans Zinnecker (AIP, Potsdam)

Overview

1. Concept of gravoturbulent star formation
    a) Excursion to turbulence
    b) Gravoturbulent star formation
2. Numerical approach to star formation
    a) Large-eddy simulations *(LES)* with smoothed particle hydrodynamics *(SPH)*
    b) Transition to stellar-dynamics: introducing *„sink particles“* to represent protostars
    (i.e. to describe *subgrid-scale physics*)
3. Some examples:
    a) Cloud formation in convergent flows
    b) Star formation in filaments
    c) Properties of prestellar cores from gravoturbulent fragmentation
    d) IMF

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)

→ ***What physical processes initiate and control the formation of stars?***

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, or Ballesteros-Paredes et al. 2006, PPV Chapter)

Gravoturbulent star formation

- Idea:

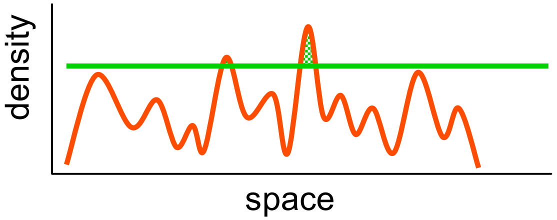
Star formation is controlled
by interplay between
gravity and
supersonic turbulence!

- 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, or Ballesteros-Paredes et al. 2006, PPV Chapter)

Gravoturbulent star formation



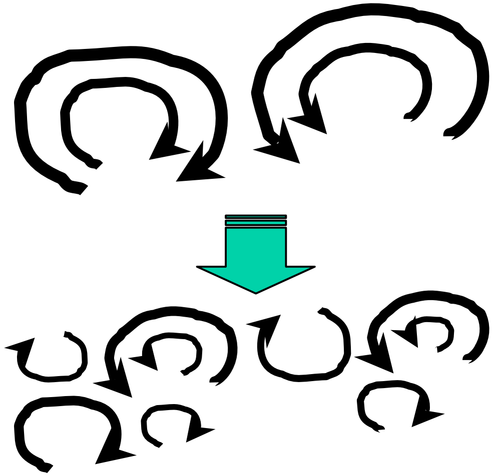
- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows* (for rates see e.g. Glover & Mac Low 2006)
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
  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

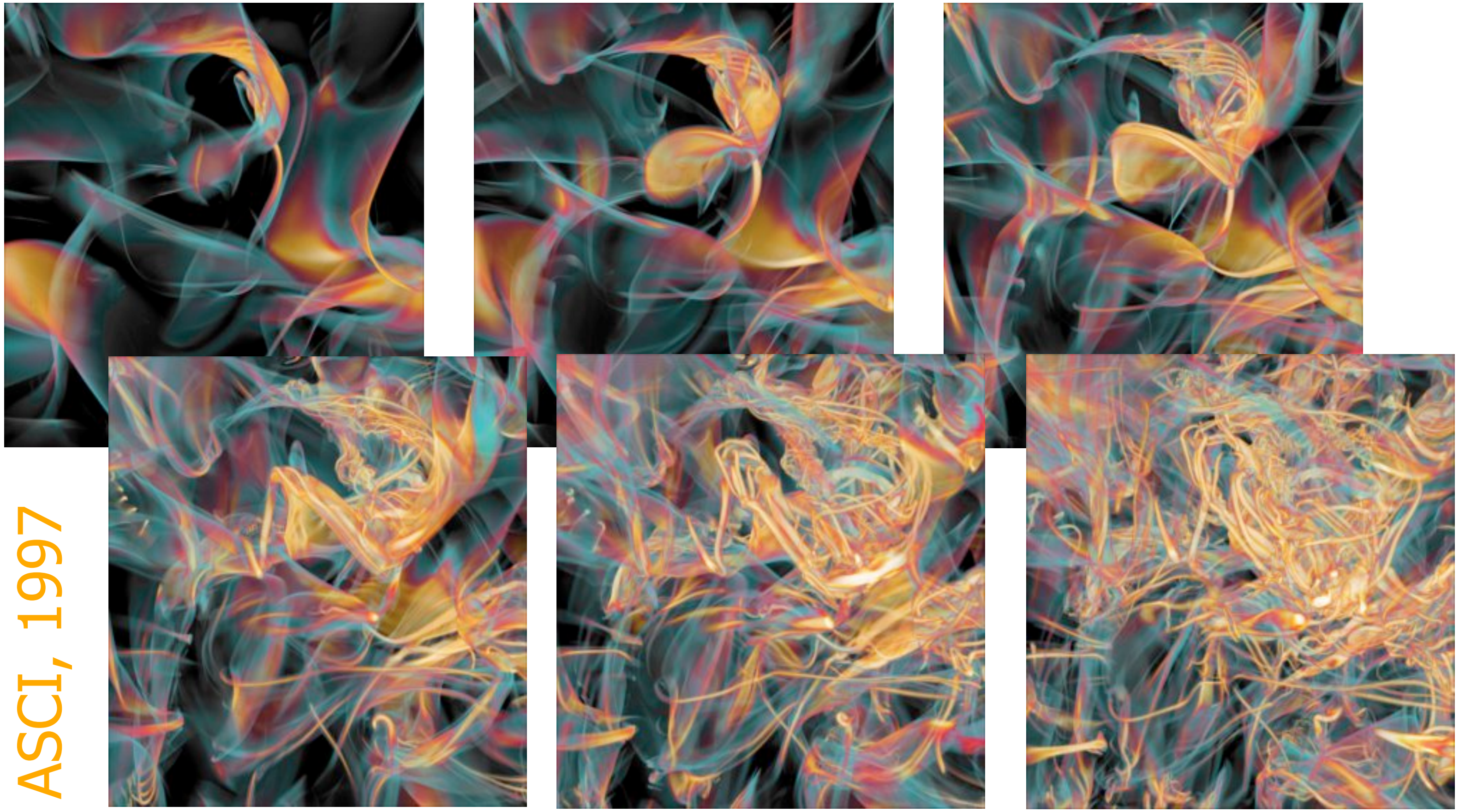
- *vortex streching* --> turbulence is *intrinsically anisotropic*

(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)

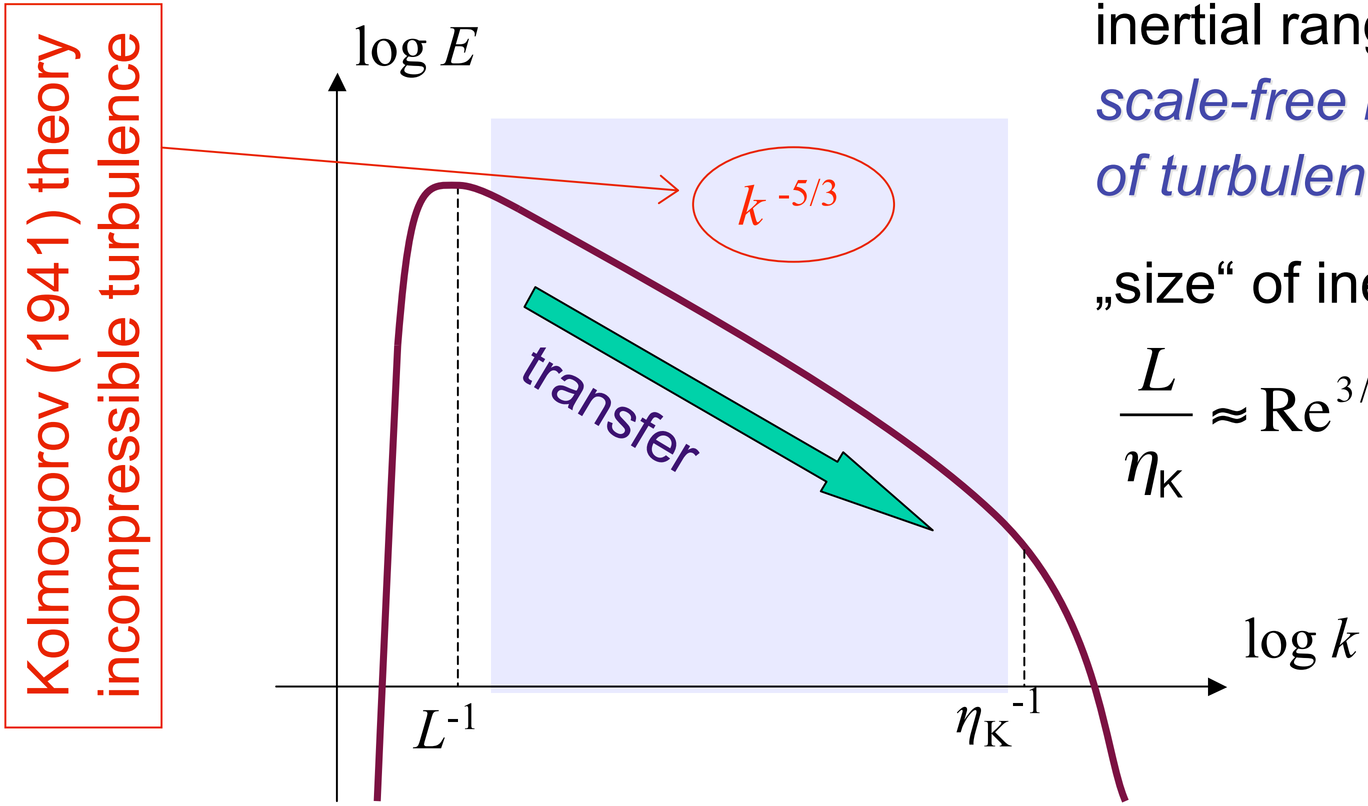
Vortex Formation



Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade



Kolmogorov (1941) theory
incompressible turbulence

inertial range:
scale-free behavior
of turbulence

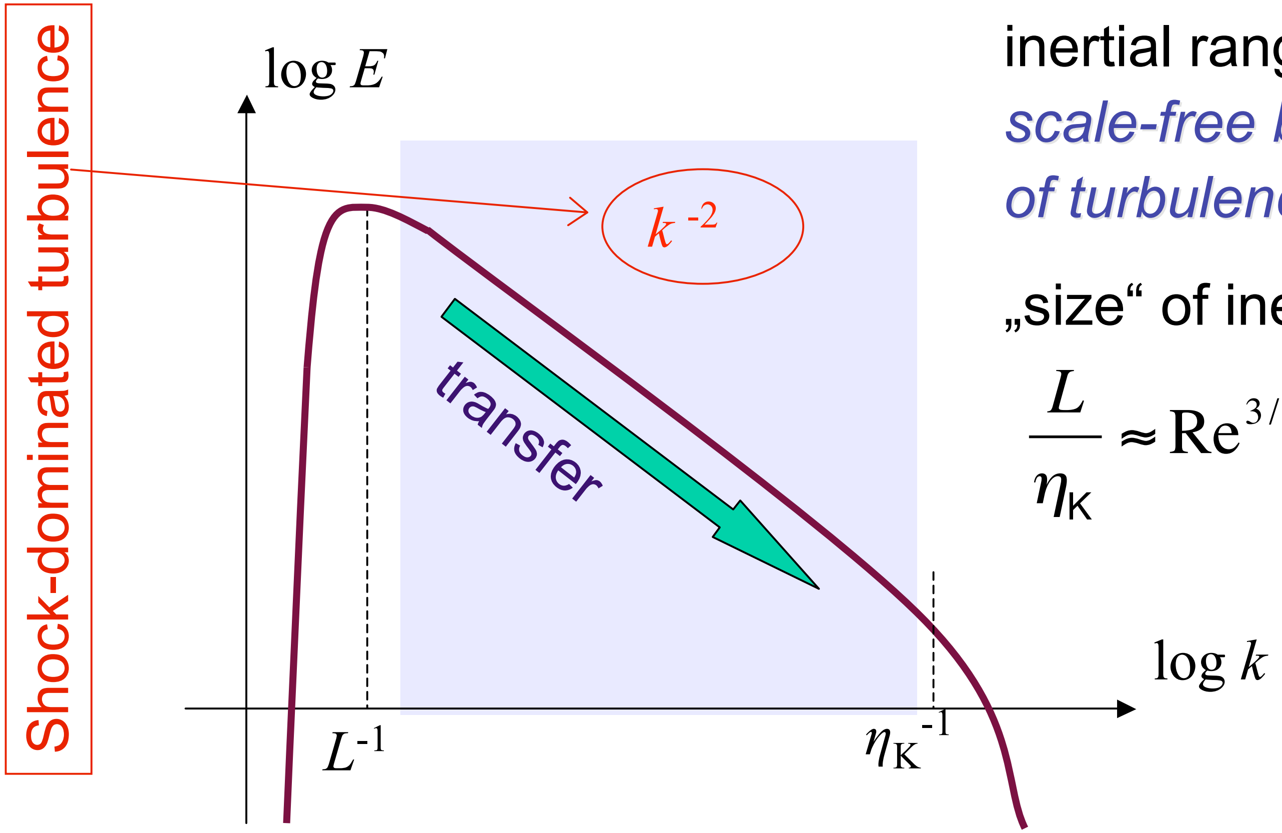
„size" of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:

scale-free behavior of turbulence

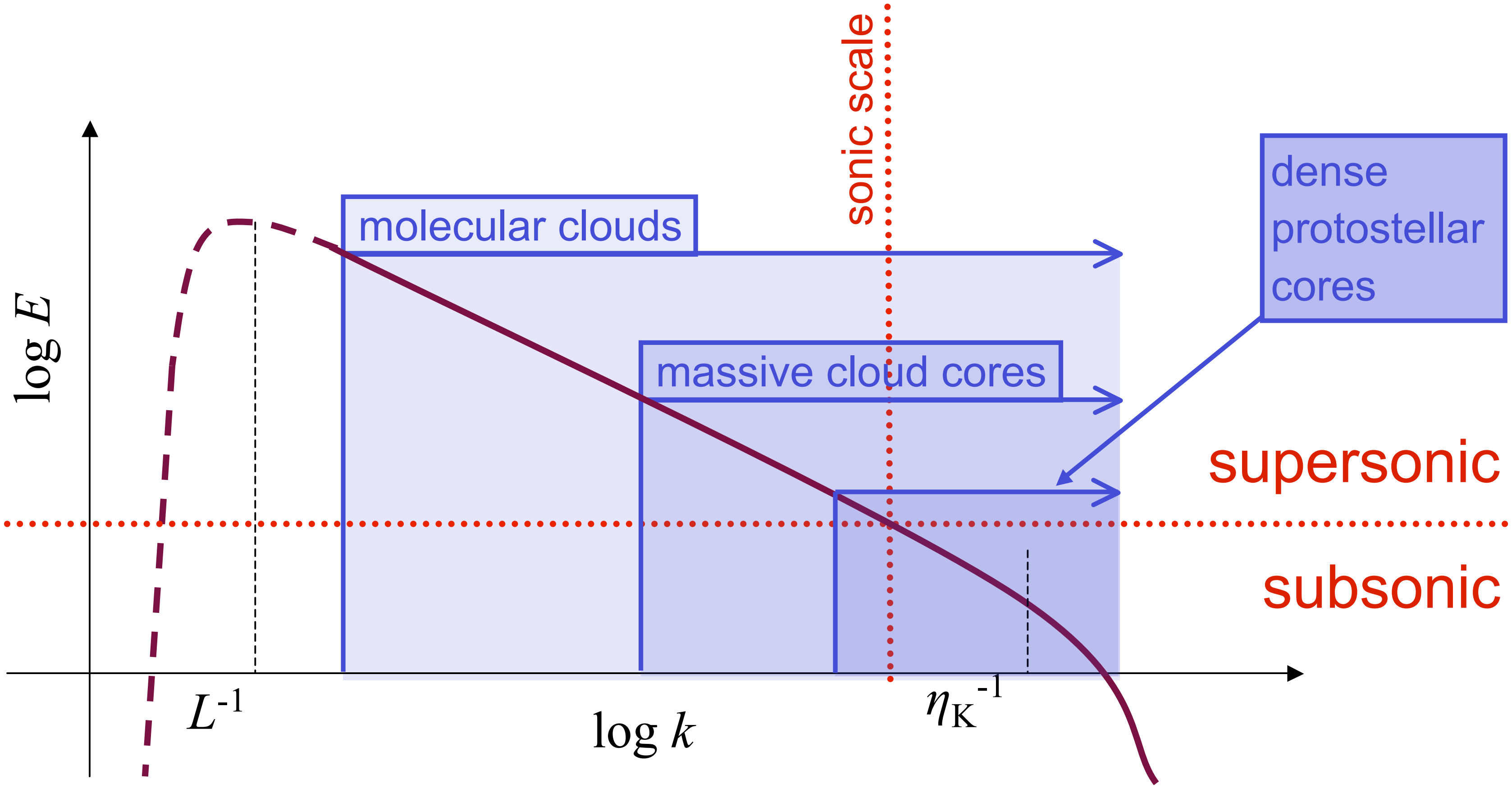
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM

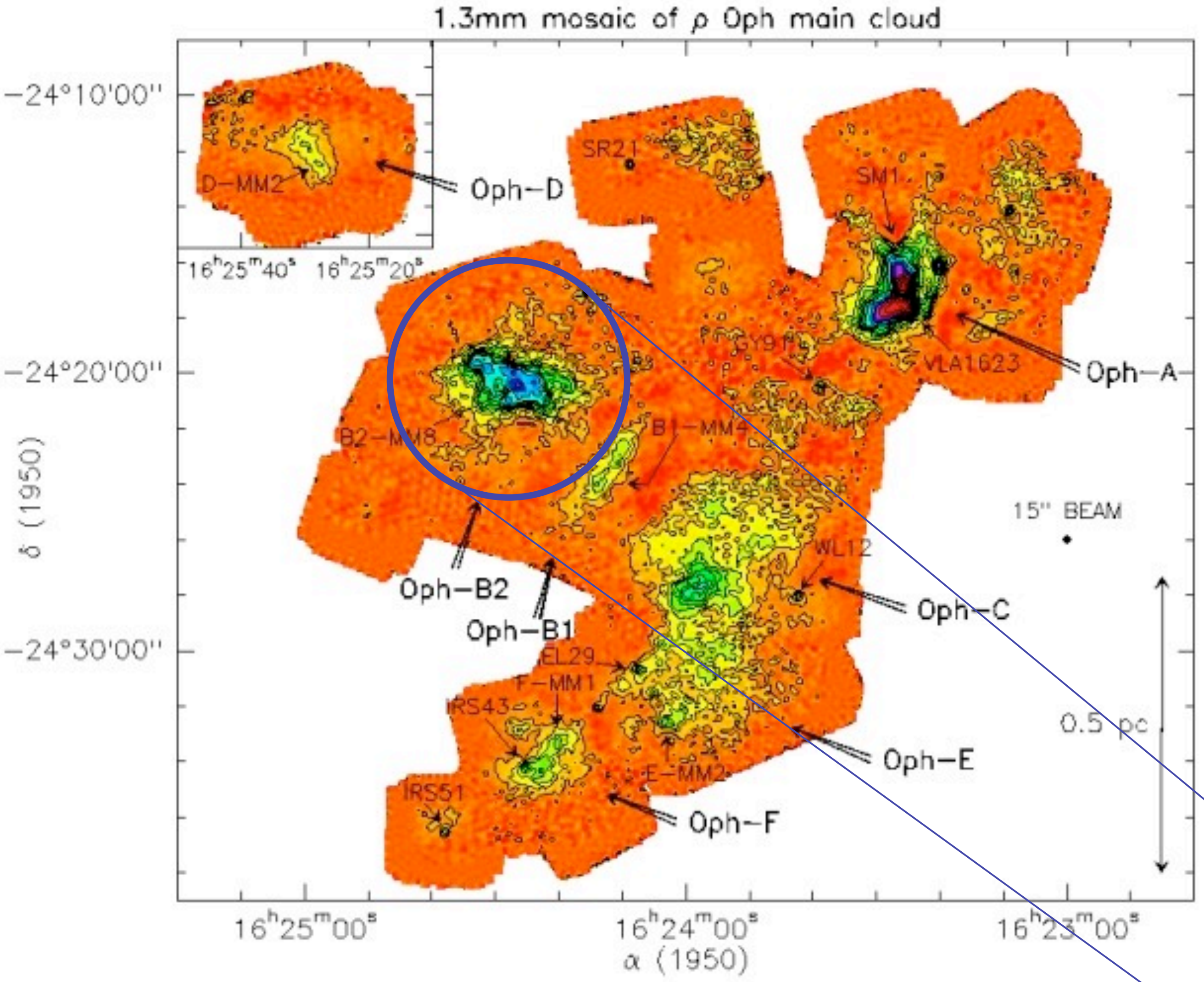


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

$\sigma_{rms} \ll 1$ 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)

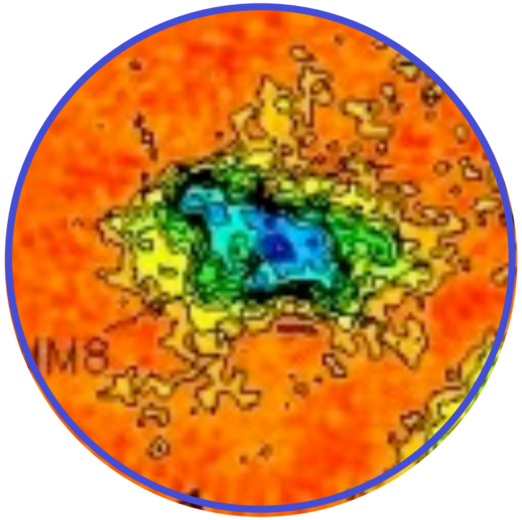
molecular clouds are highly inhomogeneous

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



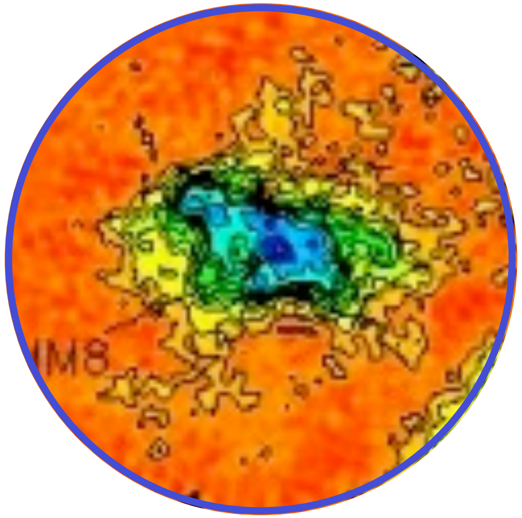
- Does core form single massive star or cluster with mass distribution?

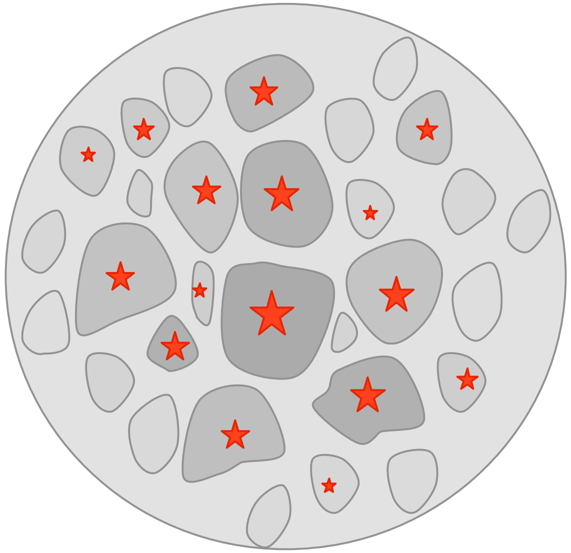
- The Tan & McKee vs. Dobbs et al. question

  or

  micorturbulence vs. *turbulent cascade*

Evolution of cloud cores



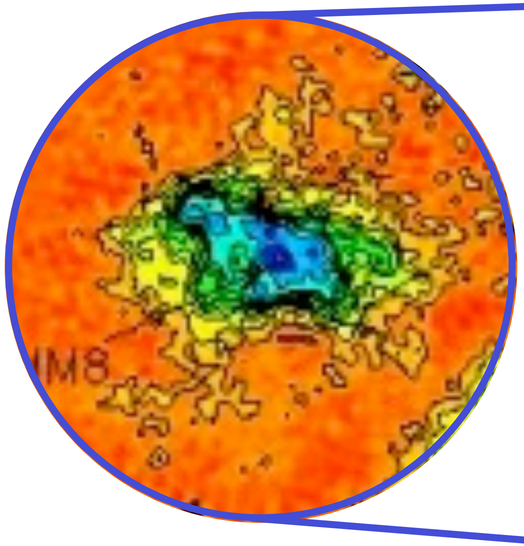


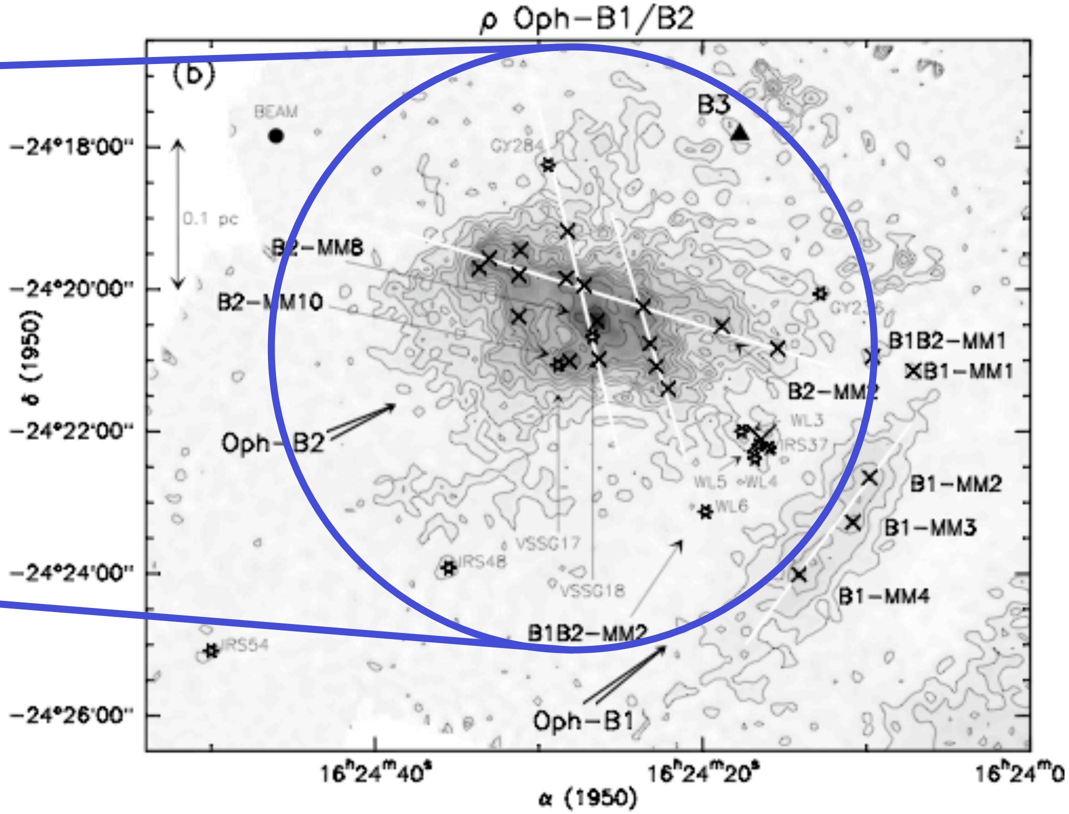
- Does core form single massive star or cluster with mass distribution?

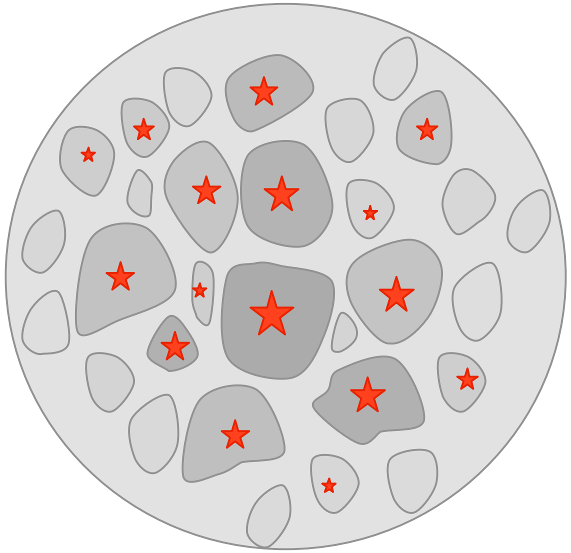
- turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  (microturbulent does *not* work)

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

Evolution of cloud cores



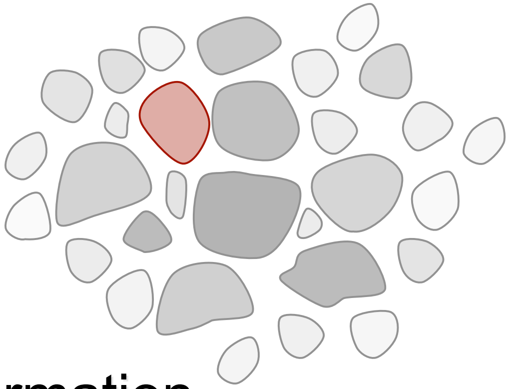




indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores



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

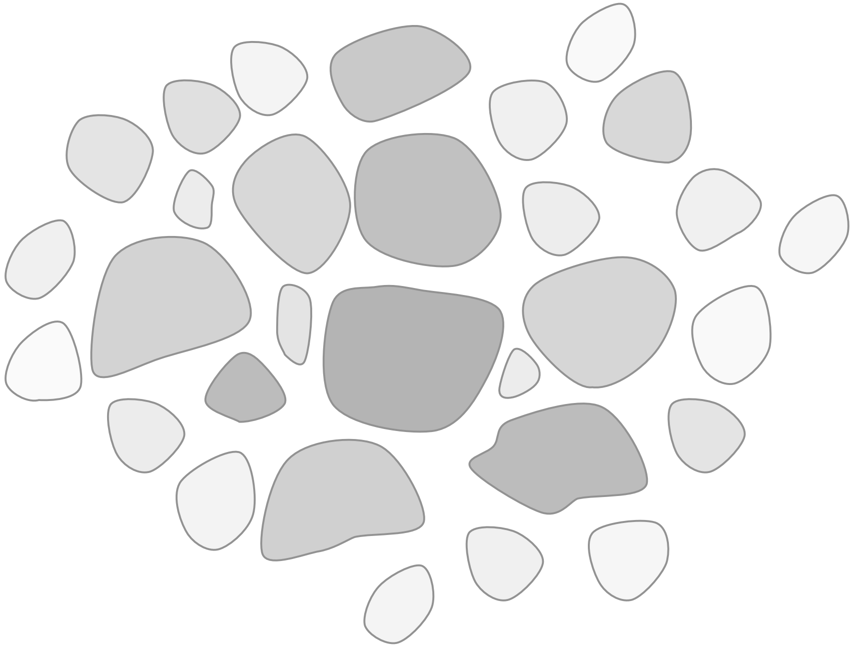
(e.g. Vazquez-Semadeni et al 2005, 2006)

- 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, see also Mouschovias‘ comment yesterday)

Formation and evolution of cores

What happens to distribution of cloud cores?



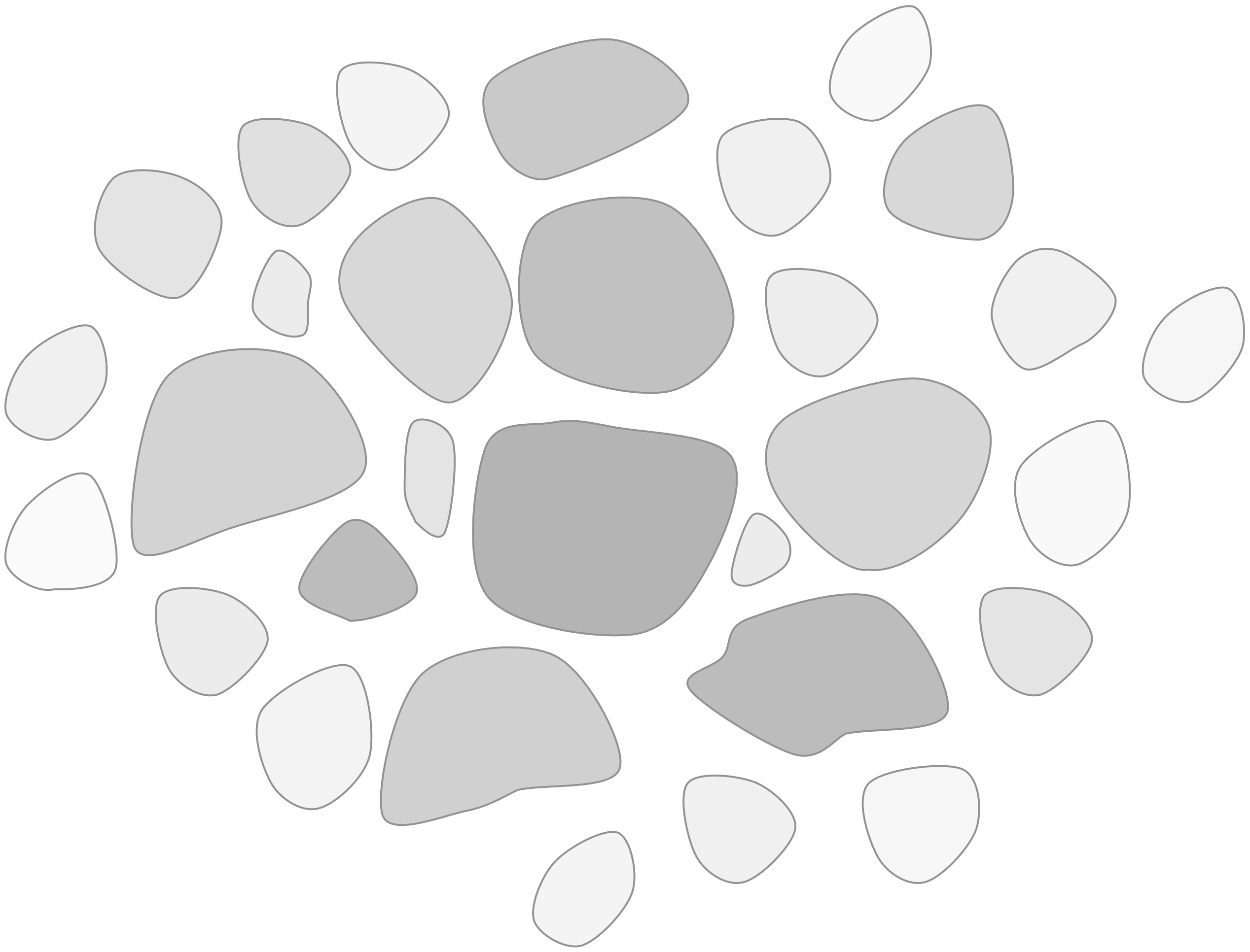
Two exteme cases:

(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*

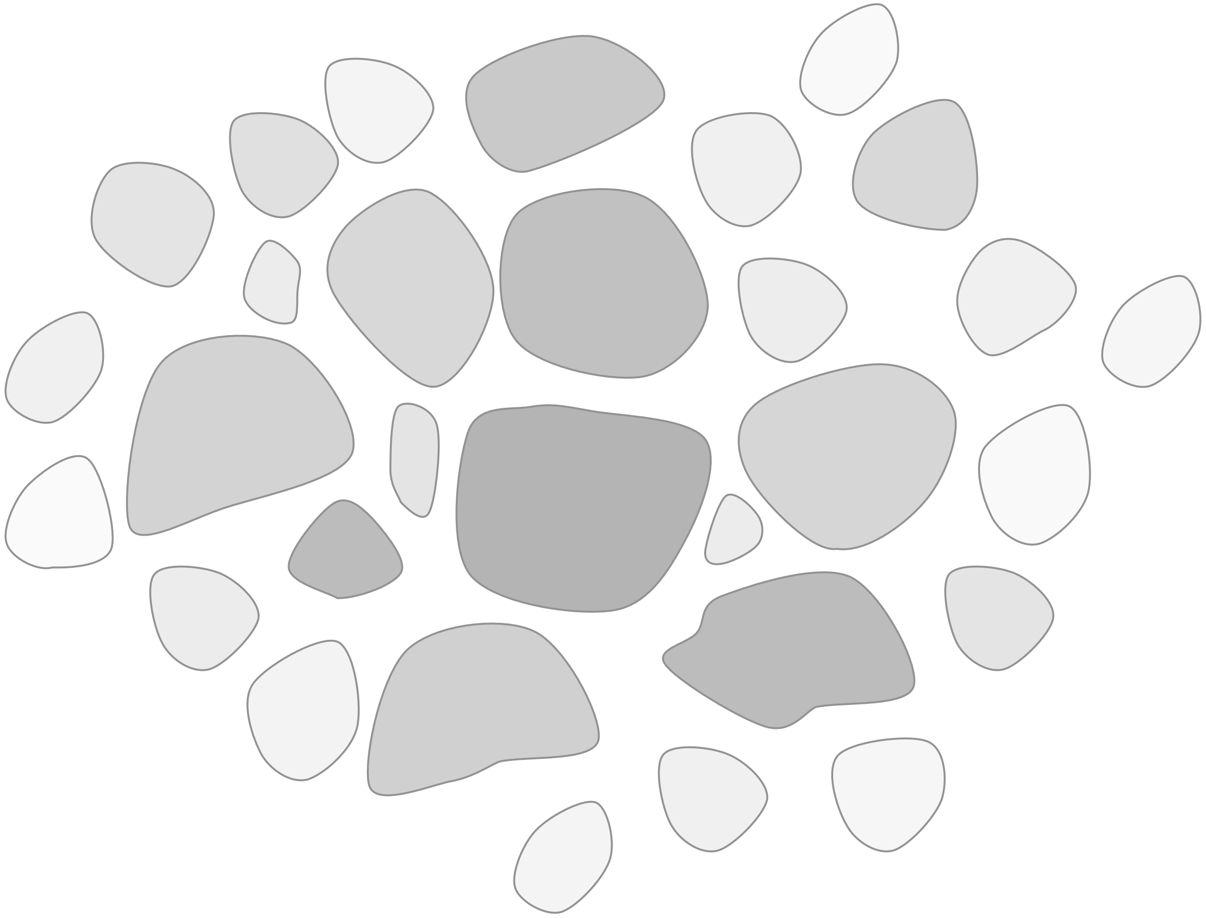
(McKee et al. approach to problem)

(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*

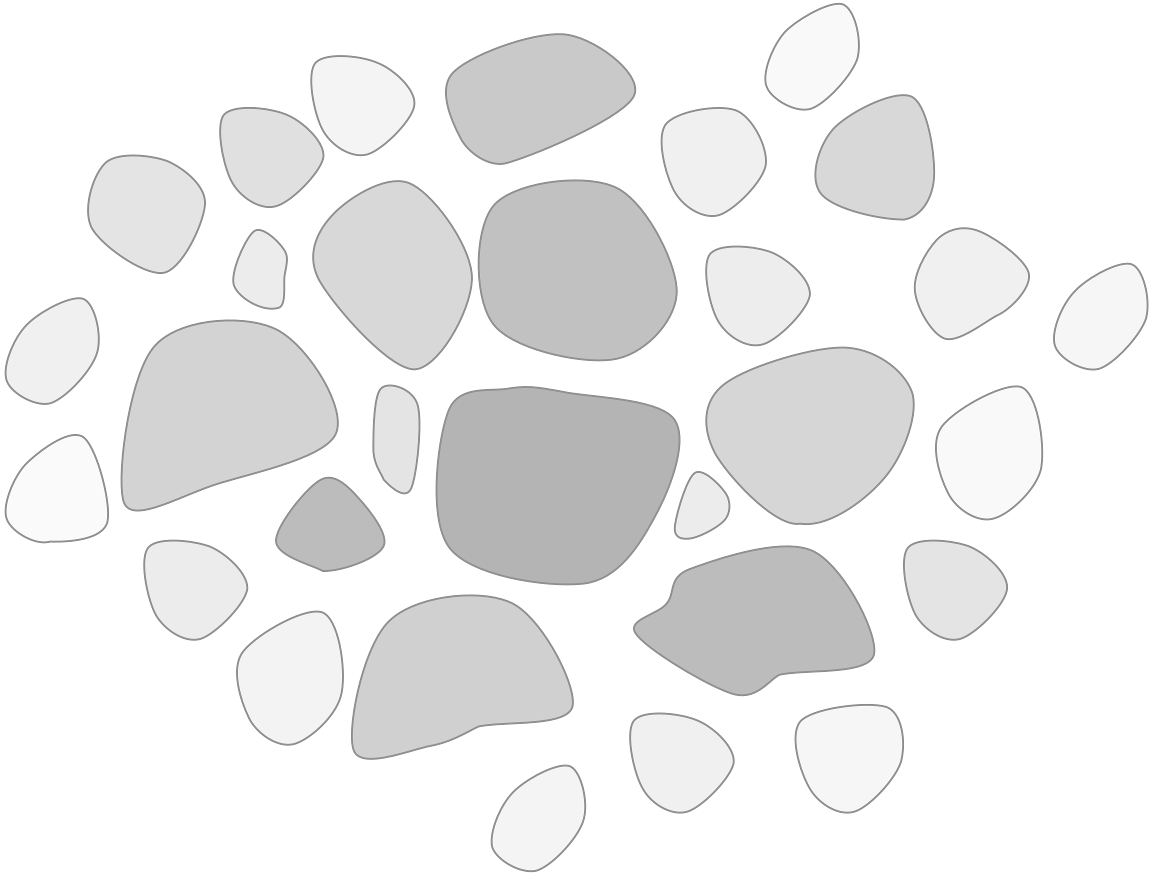
(Bonnell et al. approach)



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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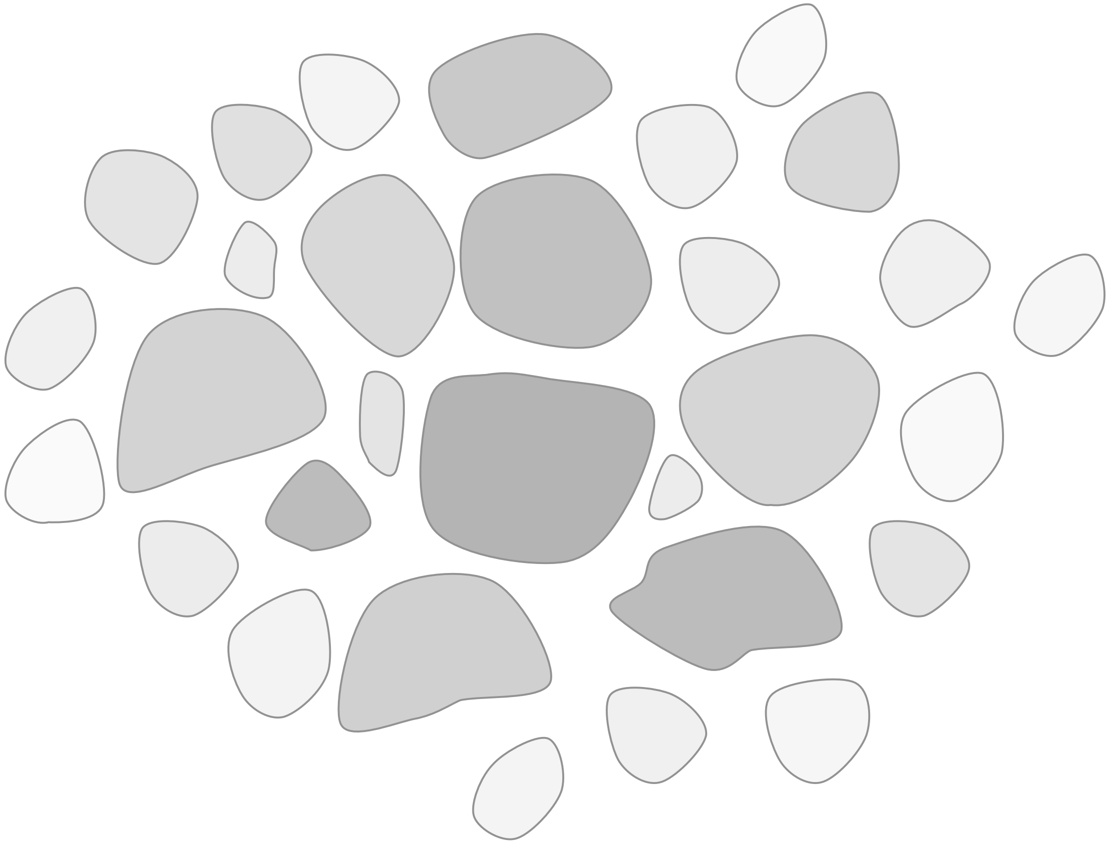
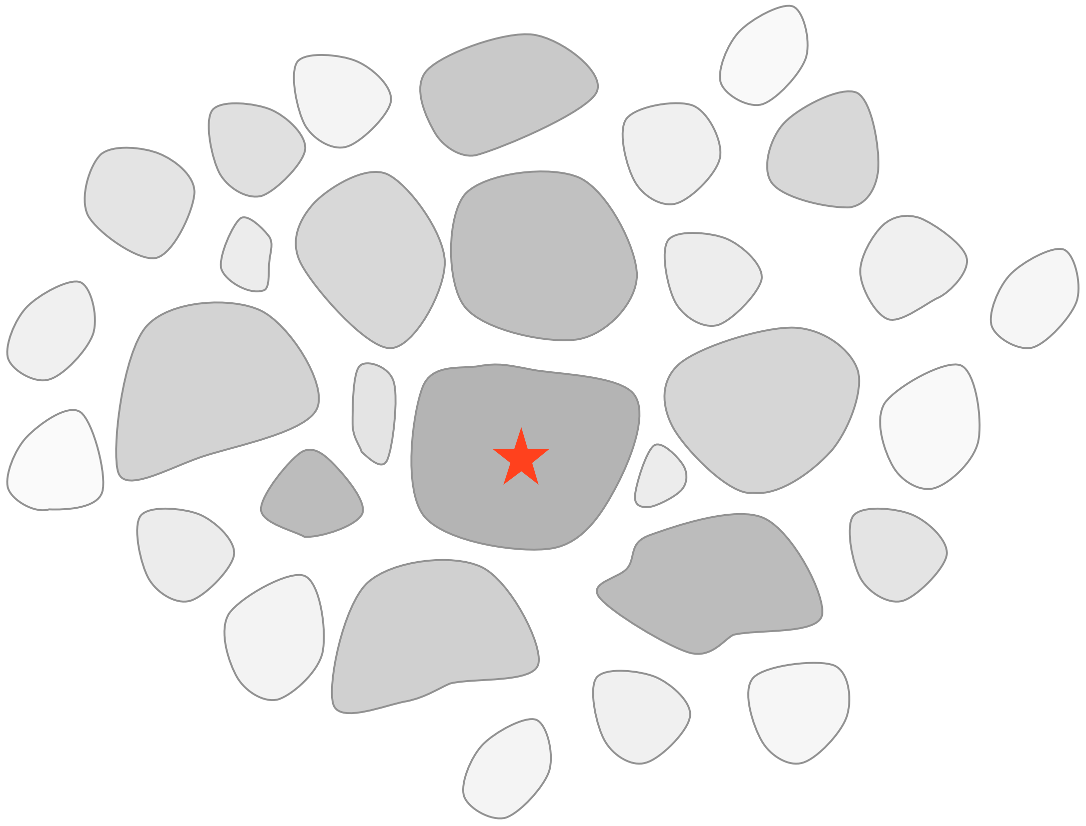


while region contracts, individual clumps collapse to form stars



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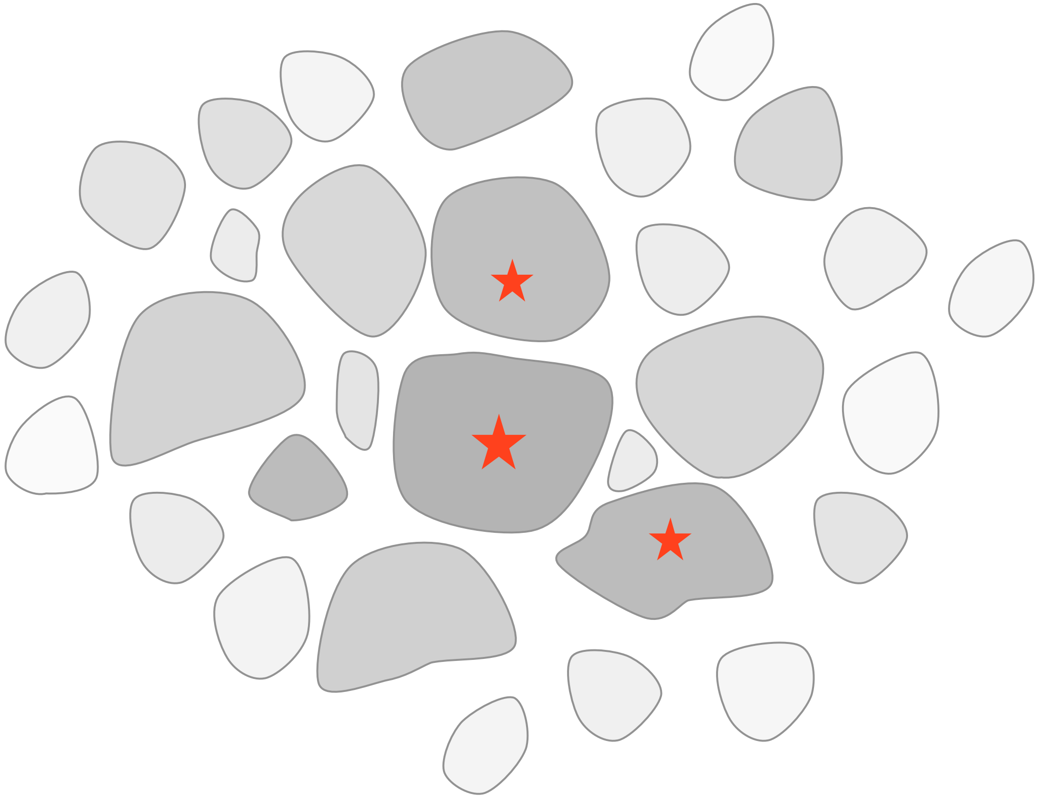
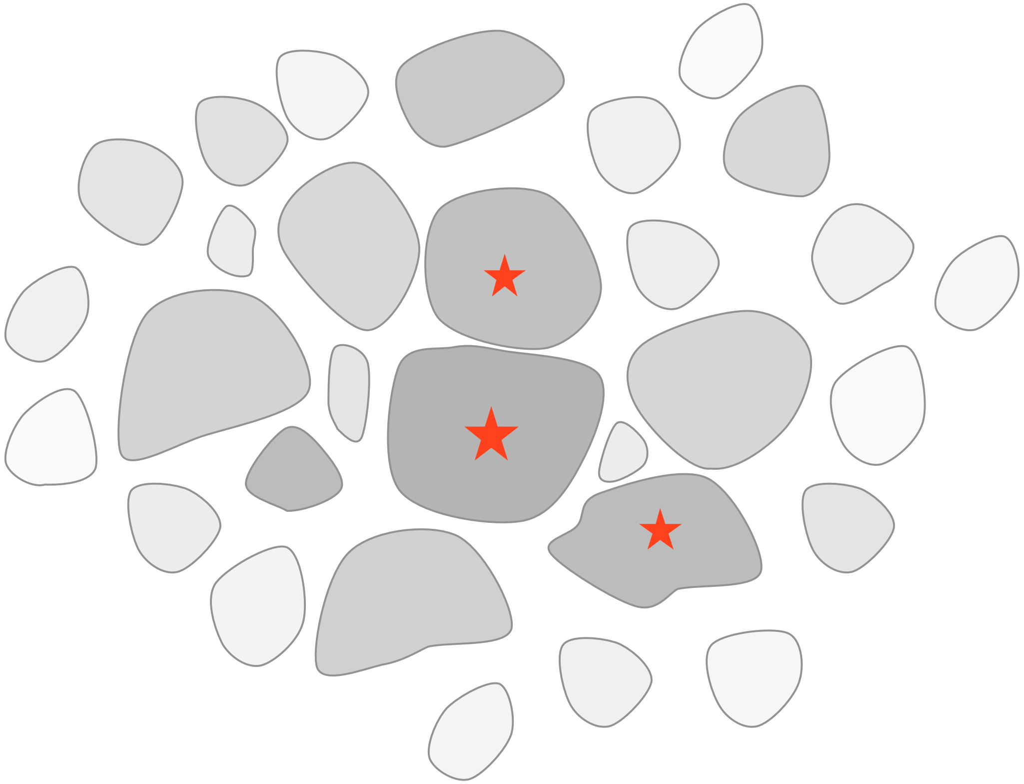
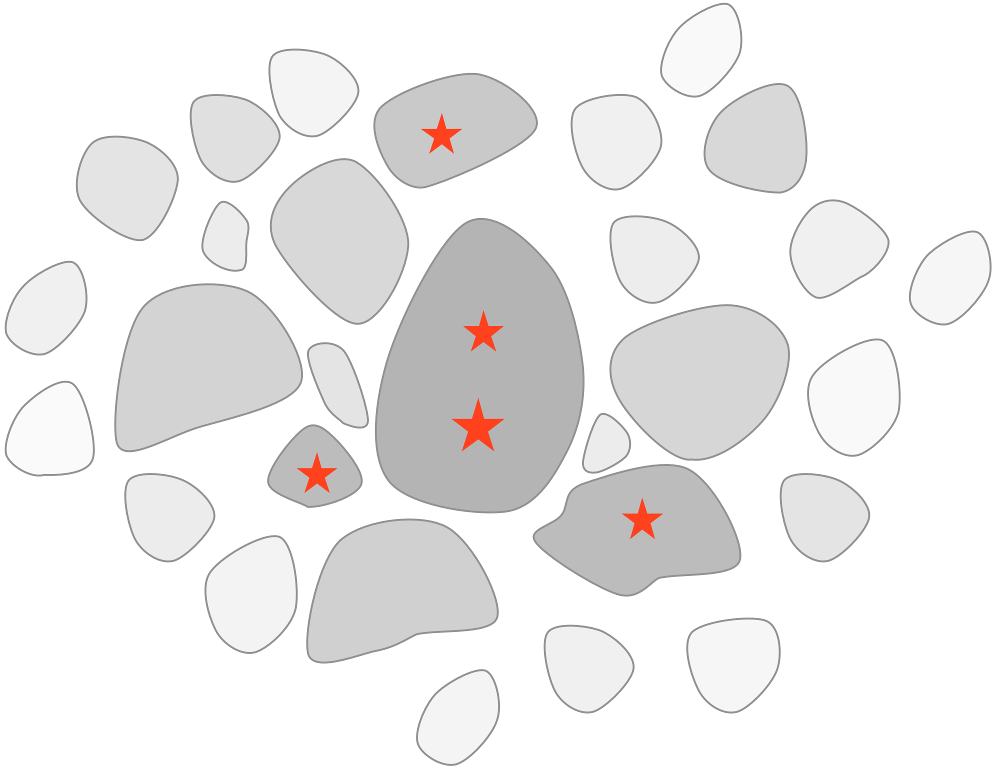


individual clumps collapse to form stars

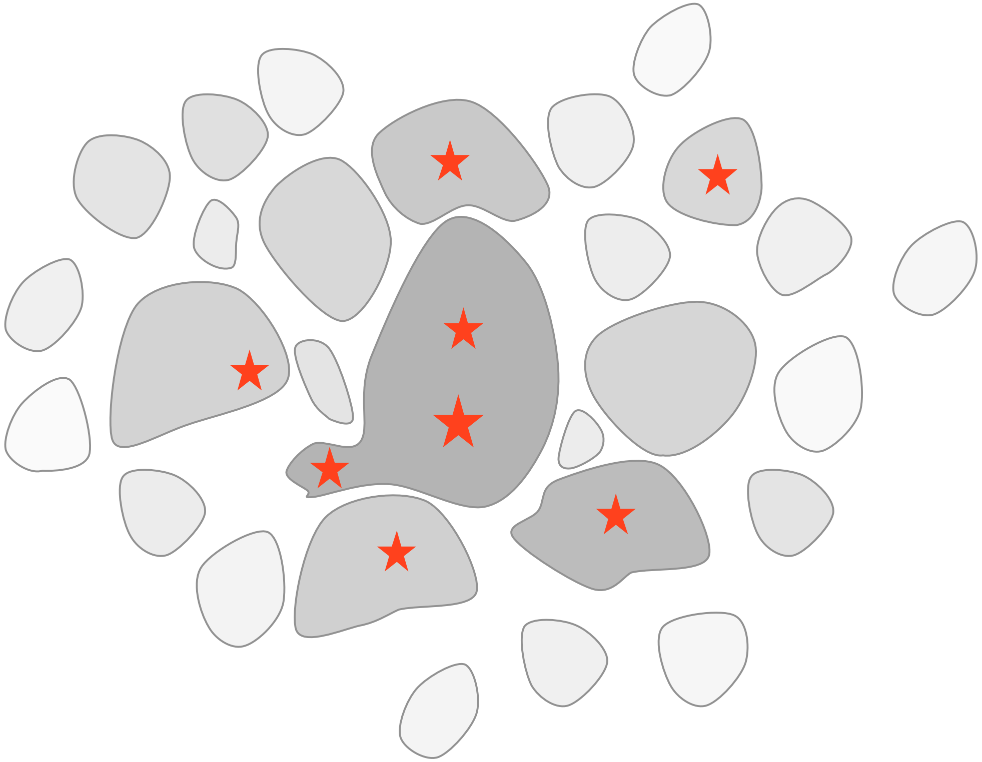


individual clumps collapse to form stars



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

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



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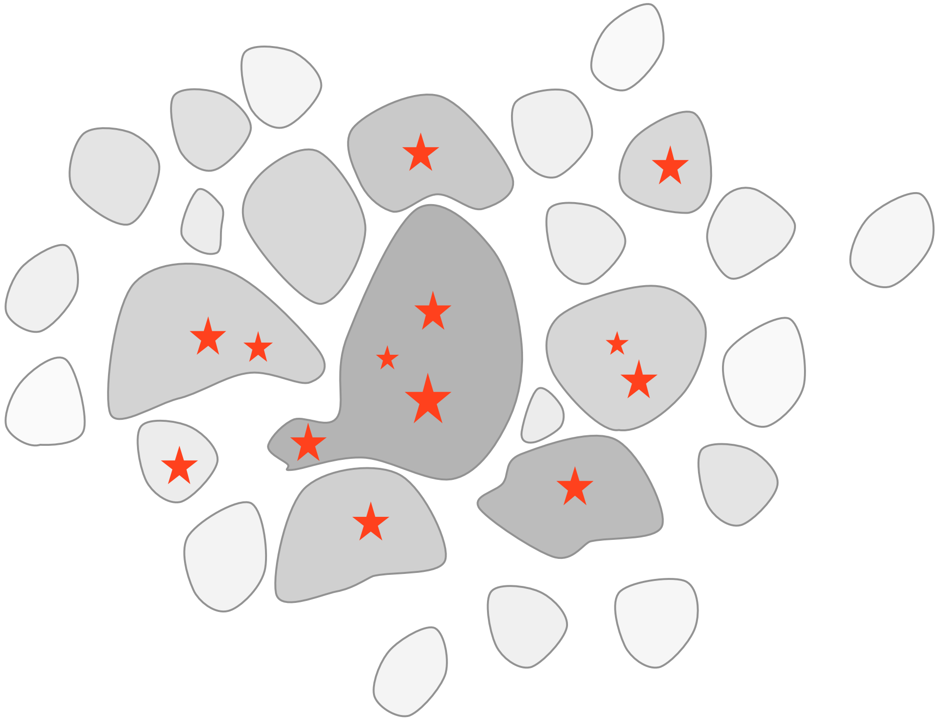

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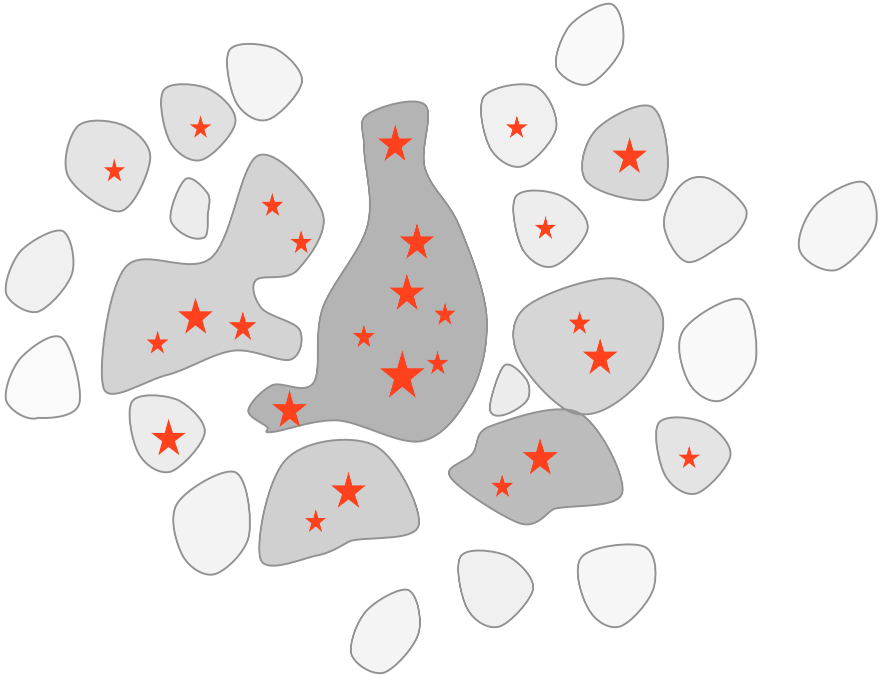
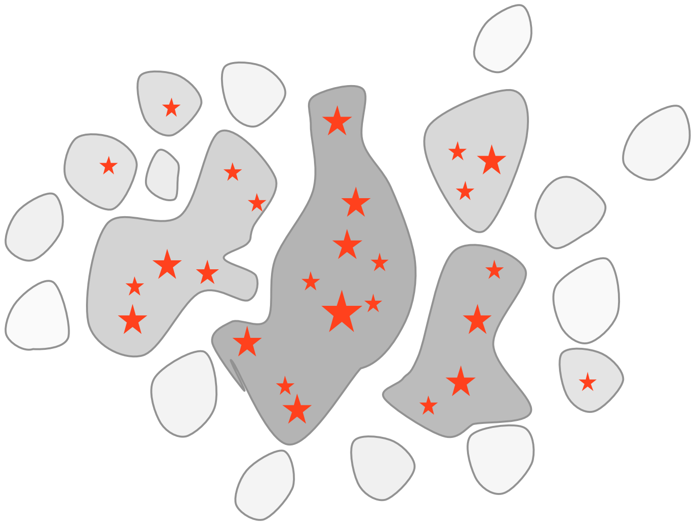


in *dense clusters*, competitive mass growth may become important



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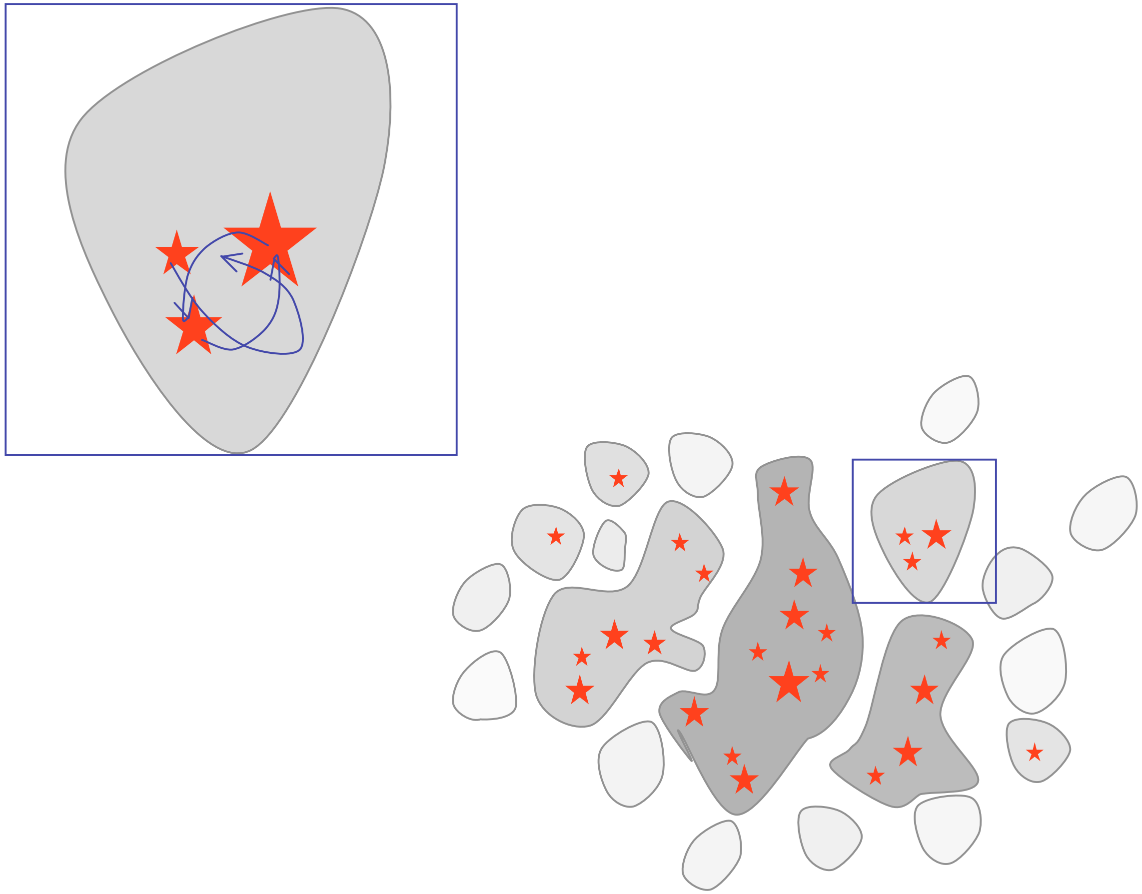
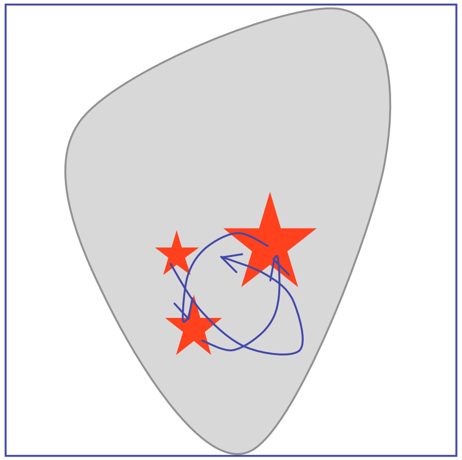
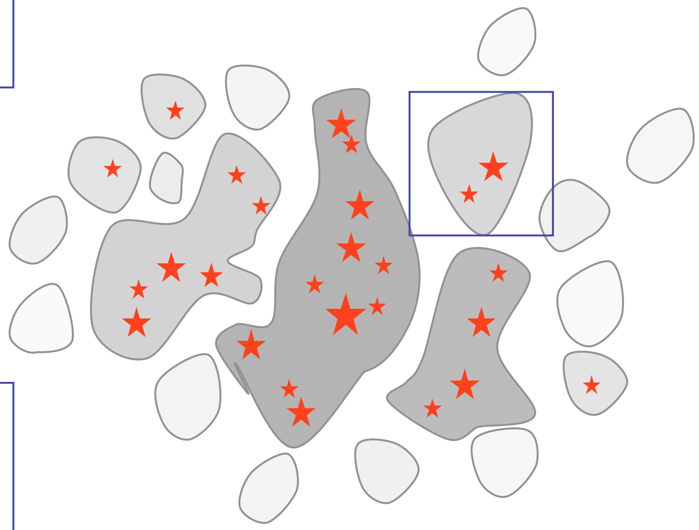
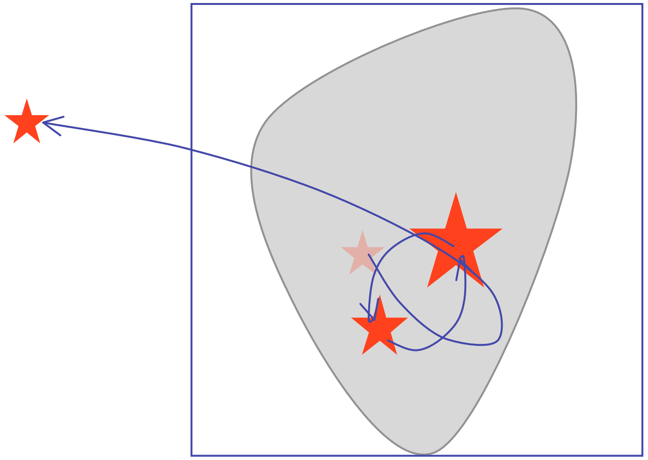


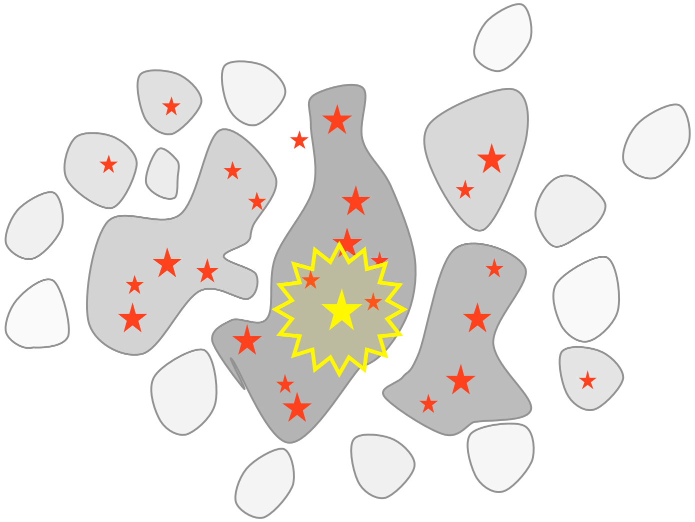
in *dense clusters*, *N*-body effects influence mass growth



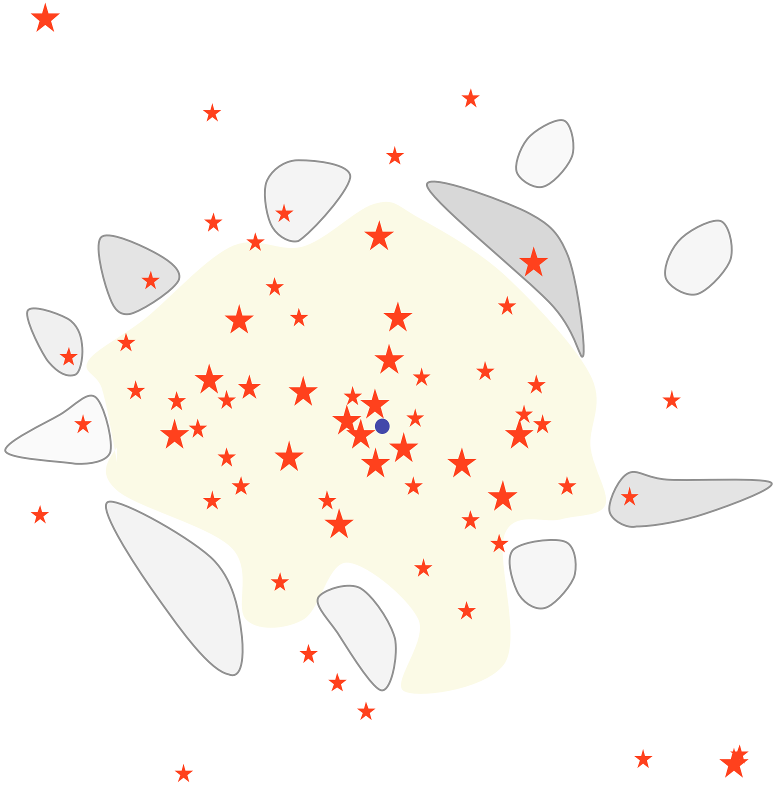




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with HII region

quantitative approach

Goal

- We want to understand the formation of star clusters in turbulent interstellar gas clouds.

--> We want to describe the transition from a hydrodynamic system (the self-gravitating gas cloud) to one that is dominated by (collisional) stellar dynamics (the final star cluster).

- How can we do that?

Numerical approach I

- Problem of star formation is very complex. It involves many scales (10^7 in length, and 10^{20} in density) and many physical processes
  → *NO* analytic solution
  → NUMERICAL APPROACH
- BUT, we need to…
  - solve the MHD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - follow the full turbulent cascade (in the ISM + in stellar interior)
  - include heating and cooling processes (EOS)
  - treat radiation transfer
  - describe energy production by nuclear burning processes

IMPOSSIBLE

Numerical approach II

- Simplify!
  Divide problem into little bits and pieces….
- **GRAVOTURBULENT CLOUD FRAGMENTATION**
- We try to…
  - solve the HD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - include a (humble) approach to supersonic turbulence
  - describe perfect gas (with polytropic EOS)
  - follow collapse: include "sink particles"
    (this will "handle" our subgrid-scale physics)

Large-eddy simulations

- We use ***LES*** to models 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) more complex when processes (chemical reactions, nuclear burning, etc) on subgrid scale determine large-scale dynamics
- Also: stochasticity of the flow ⇒ unpredictable when and where “interesting things” happen
  - occurance of localized collapse
  - location and strength of shock fronts
  - etc.

LES with SPH

- For self-gravitating gases SPH is probably okay …
  - fully Lagrangian (particles are free to move where needed)
  - good resolution in high-density regions (in collapse)
  - particle based --> good for transition from hydrodynamics to stellar dynamics
- BUT:
  - low resolution in low-density region
  - difficult to reach very high levels of refinement (however, particle splitting may be promising path)
  - dissipative and need for artificial viscosity
  - how to handle subgrid scales?

Gravoturbulent SF with SPH

- Comparison between particle-based and grid-based methods: SPH vs. ZEUS

  Klessen, Heitsch, Mac Low (2000)
  Heitsch, Mac Low, Klessen (2001)
  Ossenkopf, Klessen, Heitsch (2001)

- Both methods are complementary…

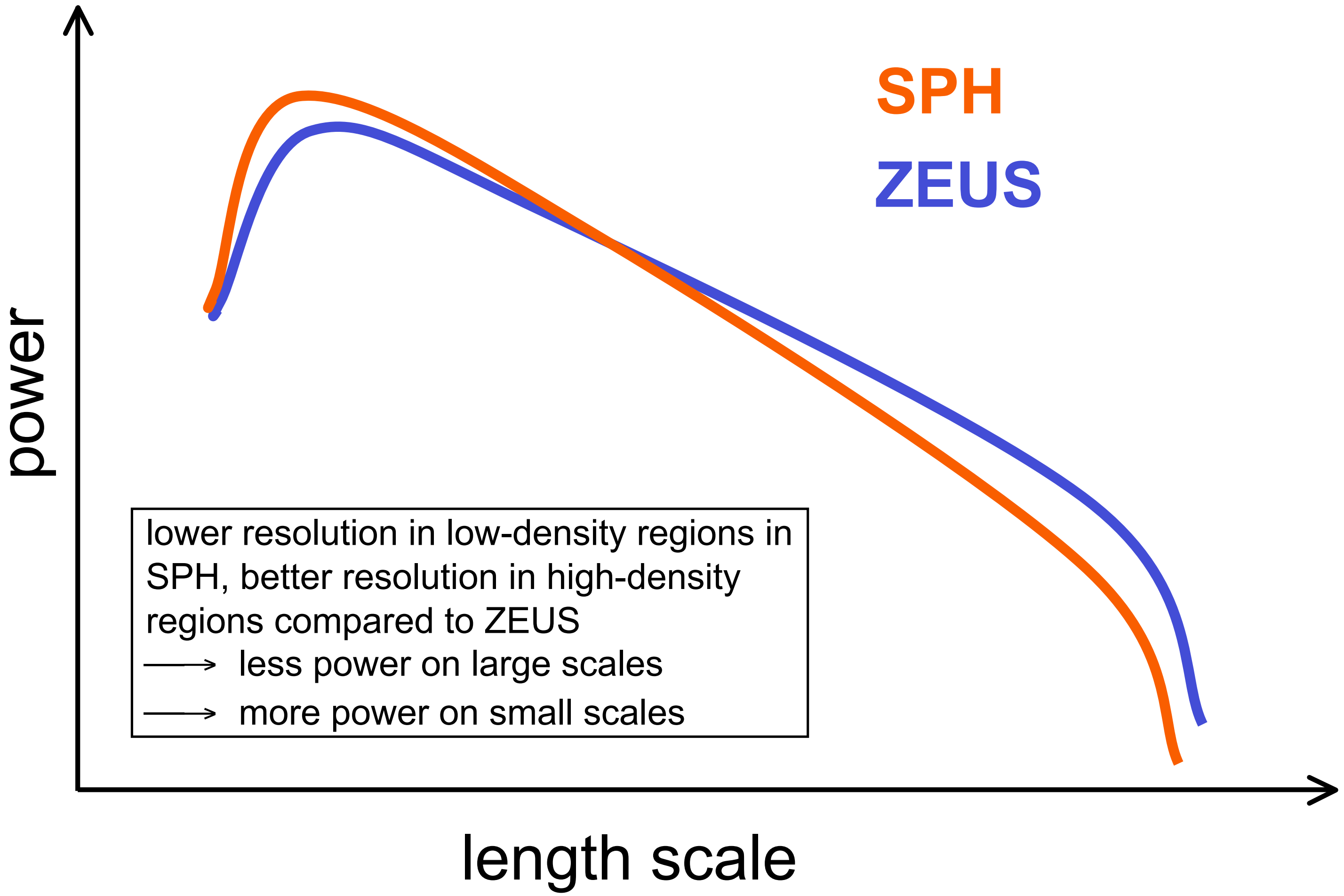
  ⟶ Bracketing reality!

- As a crude estimage:

  SPH is better in high-density regions

  ZEUS is better in low-density regions

SPH vs. ZEUS



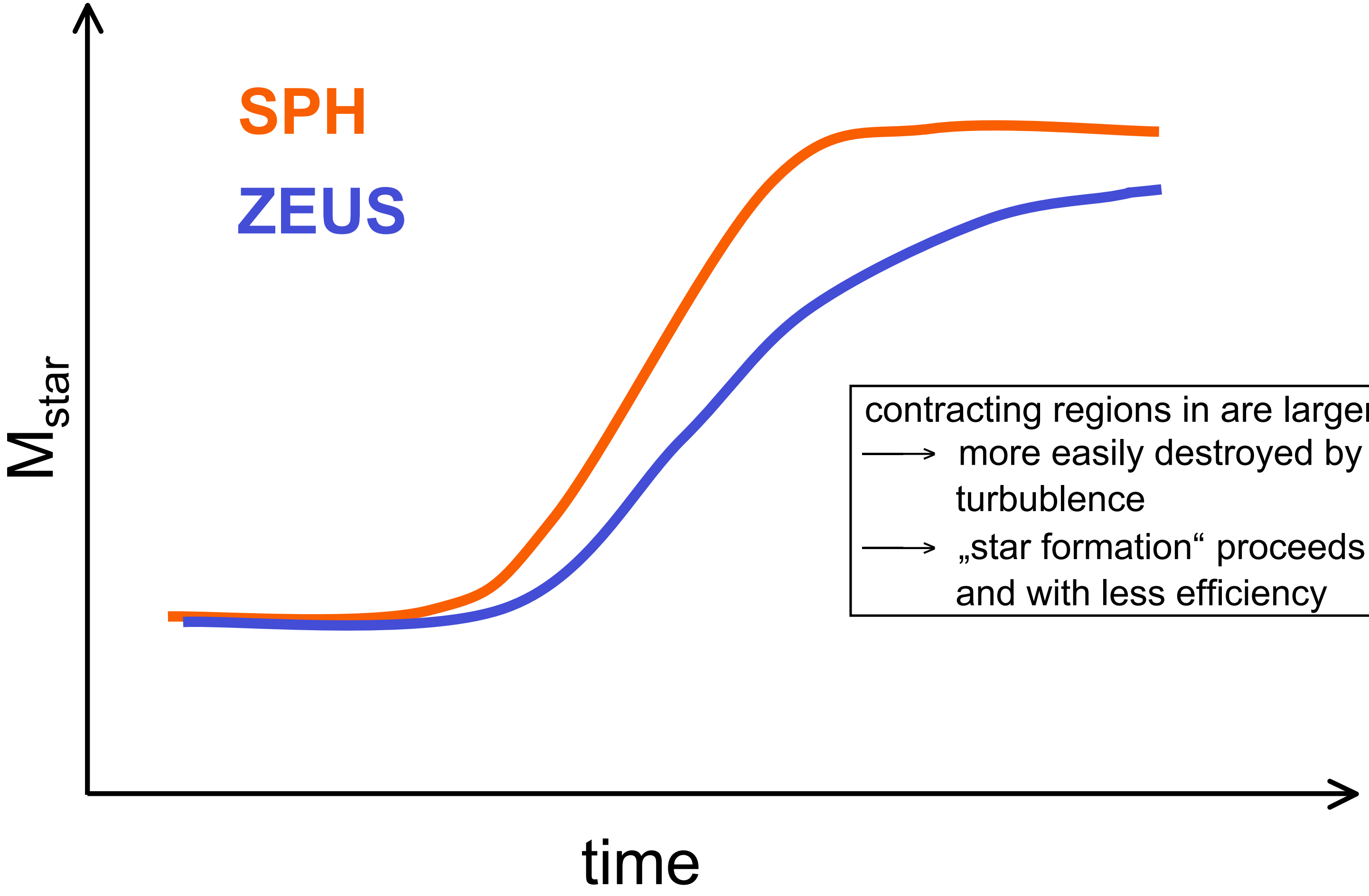
lower resolution in low-density regions in SPH, better resolution in high-density regions compared to ZEUS

⟶ less power on large scales

⟶ more power on small scales

(Ossenkopf, Klessen, Heitsch 2001)

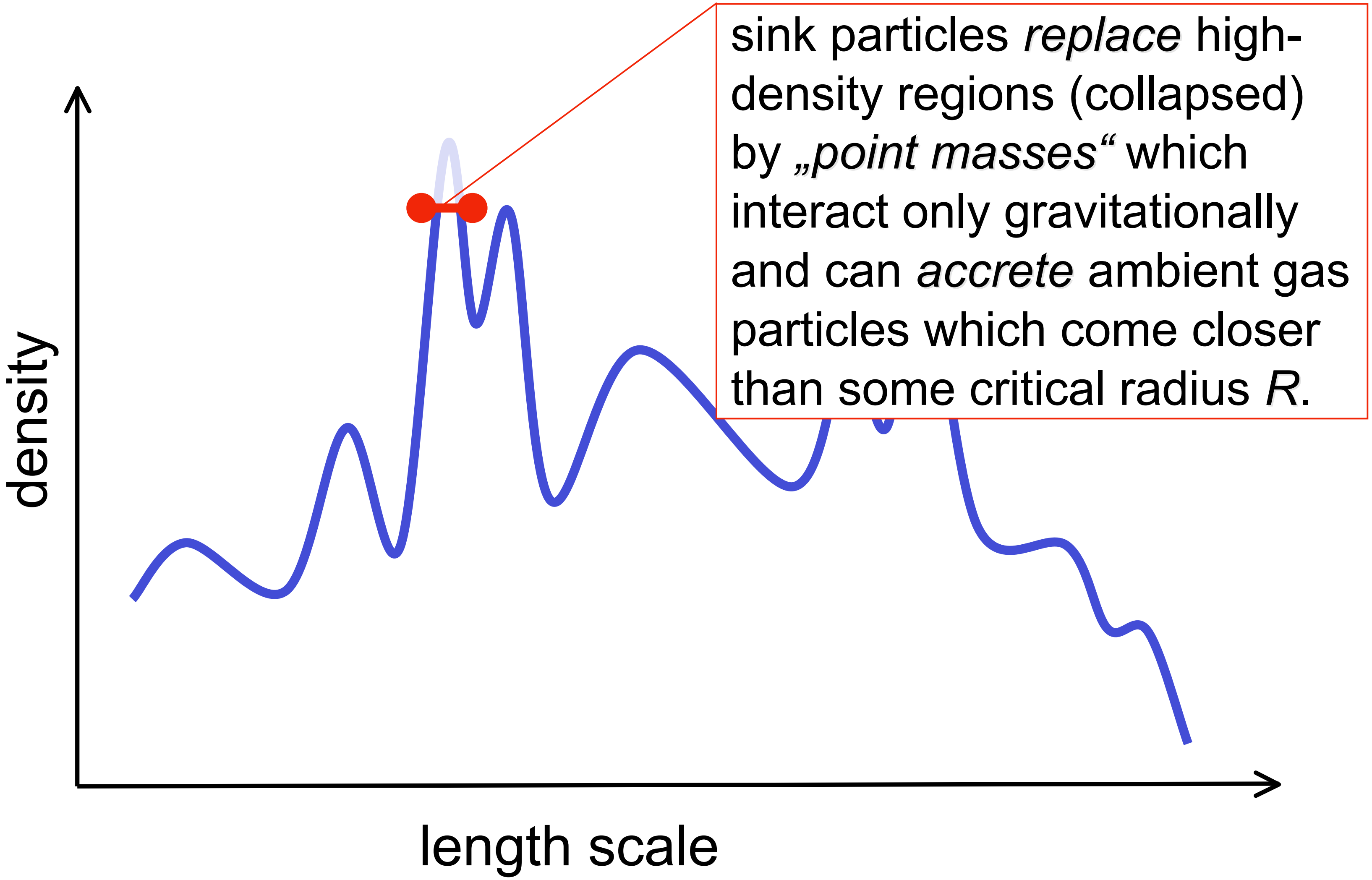
SPH vs. ZEUS



contracting regions in are larger in ZEUS
→ more easily destroyed by ambient turbublence
→ „star formation“ proceeds slower and with less efficiency

(Ossenkopf, Klessen, Heitsch 2001)

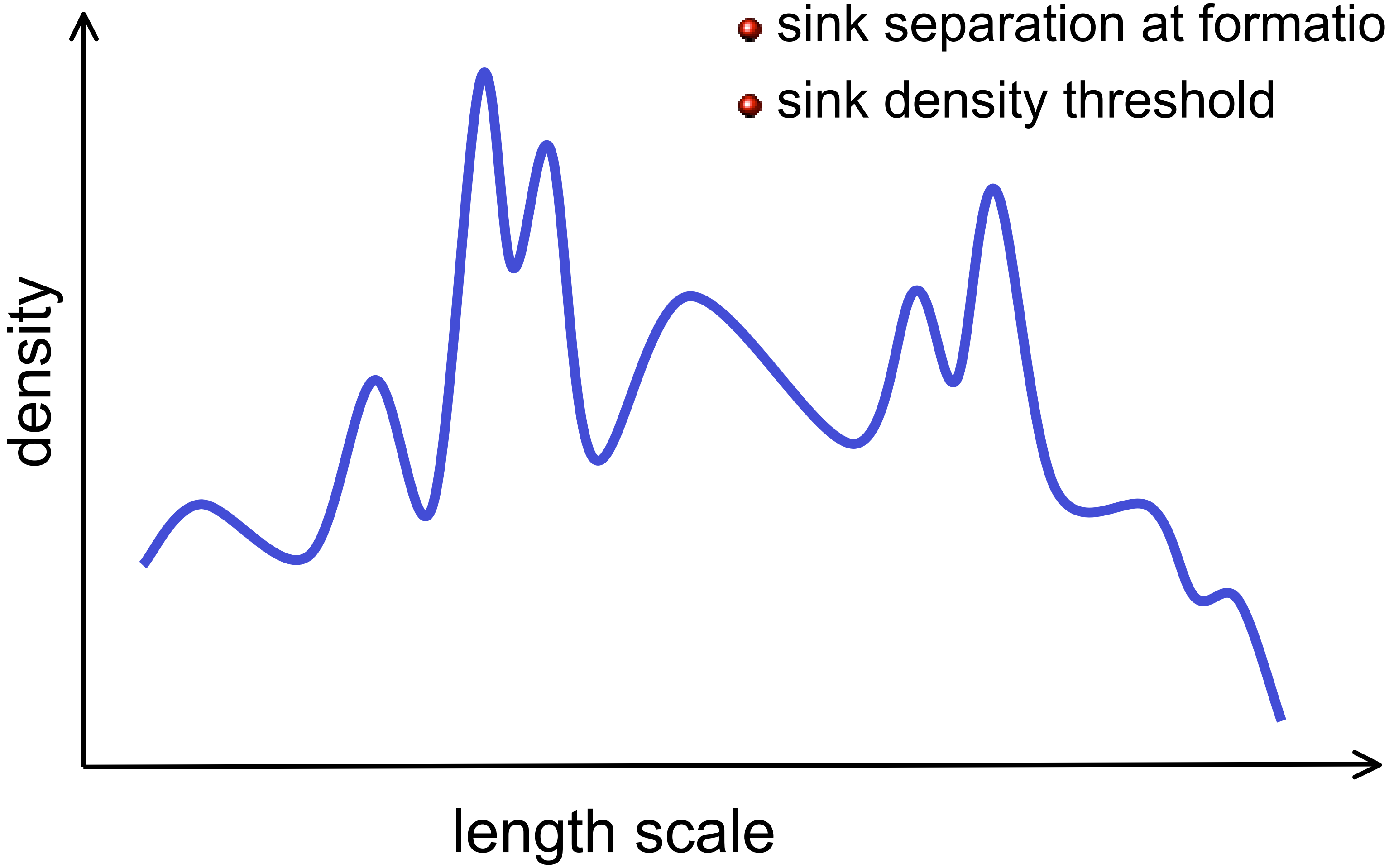
SPH with sink particles I



sink particles *replace* high-density regions (collapsed) by *„point masses“* which interact only gravitationally and can *accrete* ambient gas particles which come closer than some critical radius *R*.

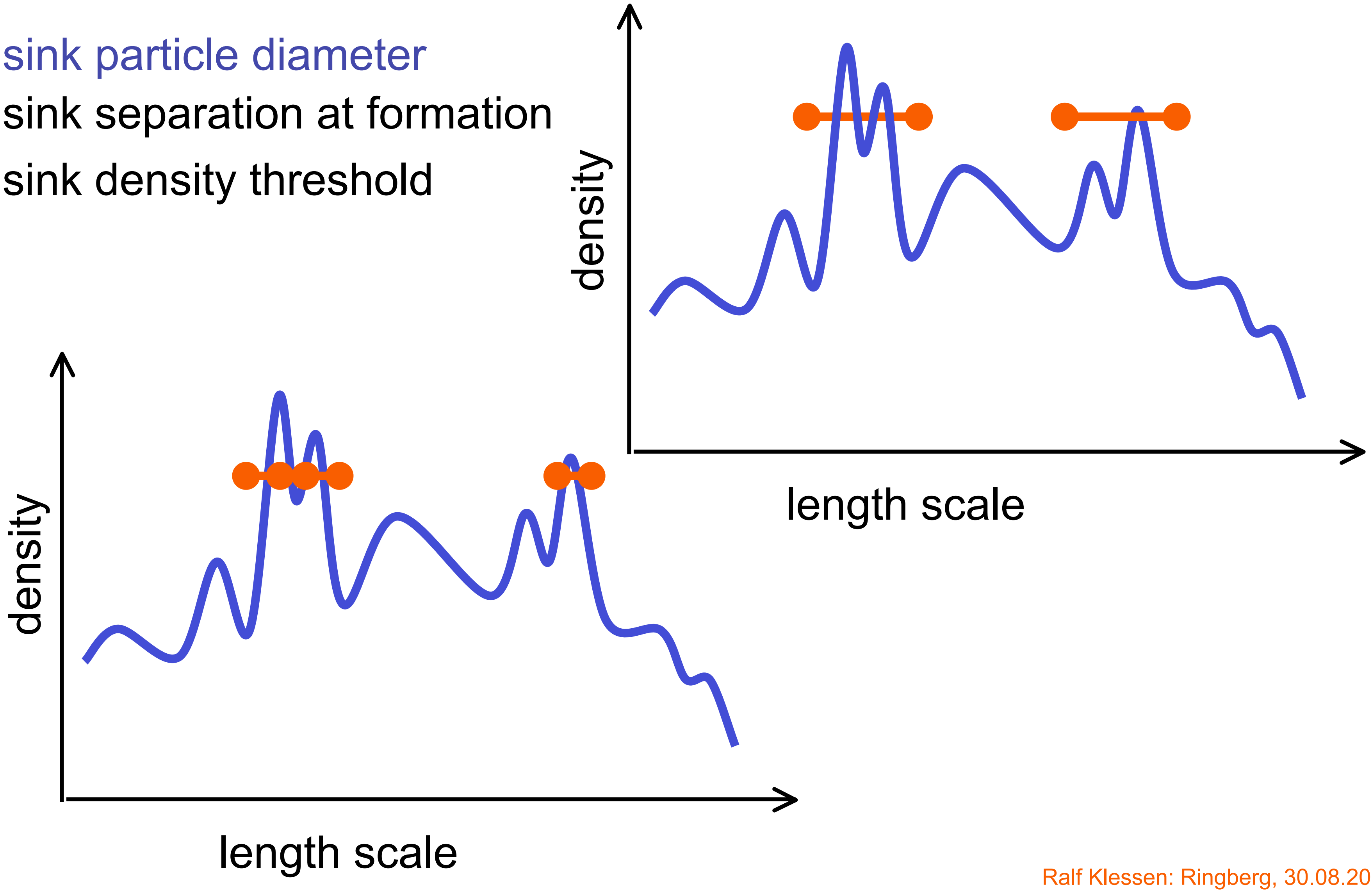
SPH with sink particles I

- sink particle diameter
- sink separation at formation
- sink density threshold



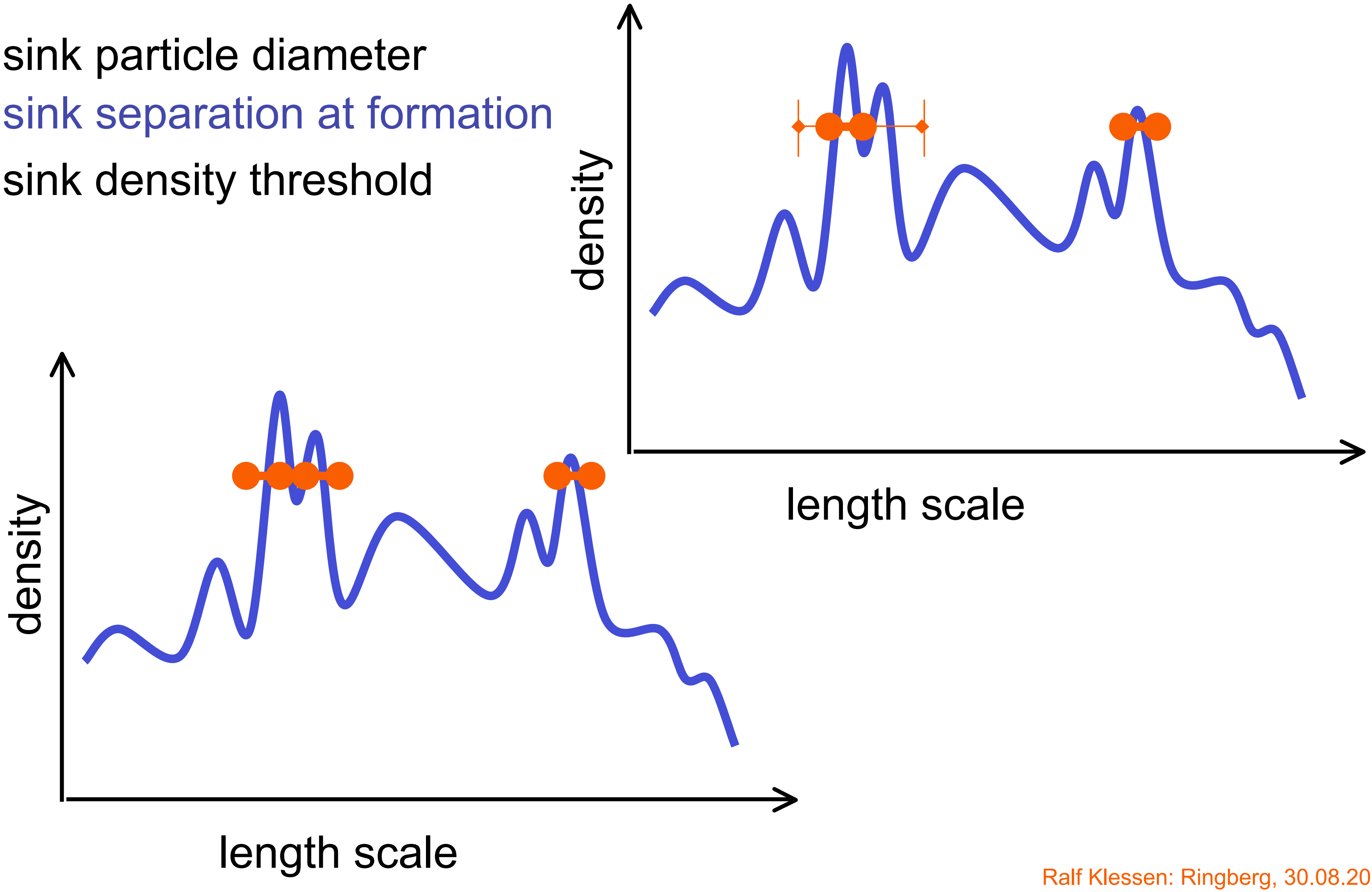
SPH with sink particles II

- sink particle diameter
- sink separation at formation
- sink density threshold



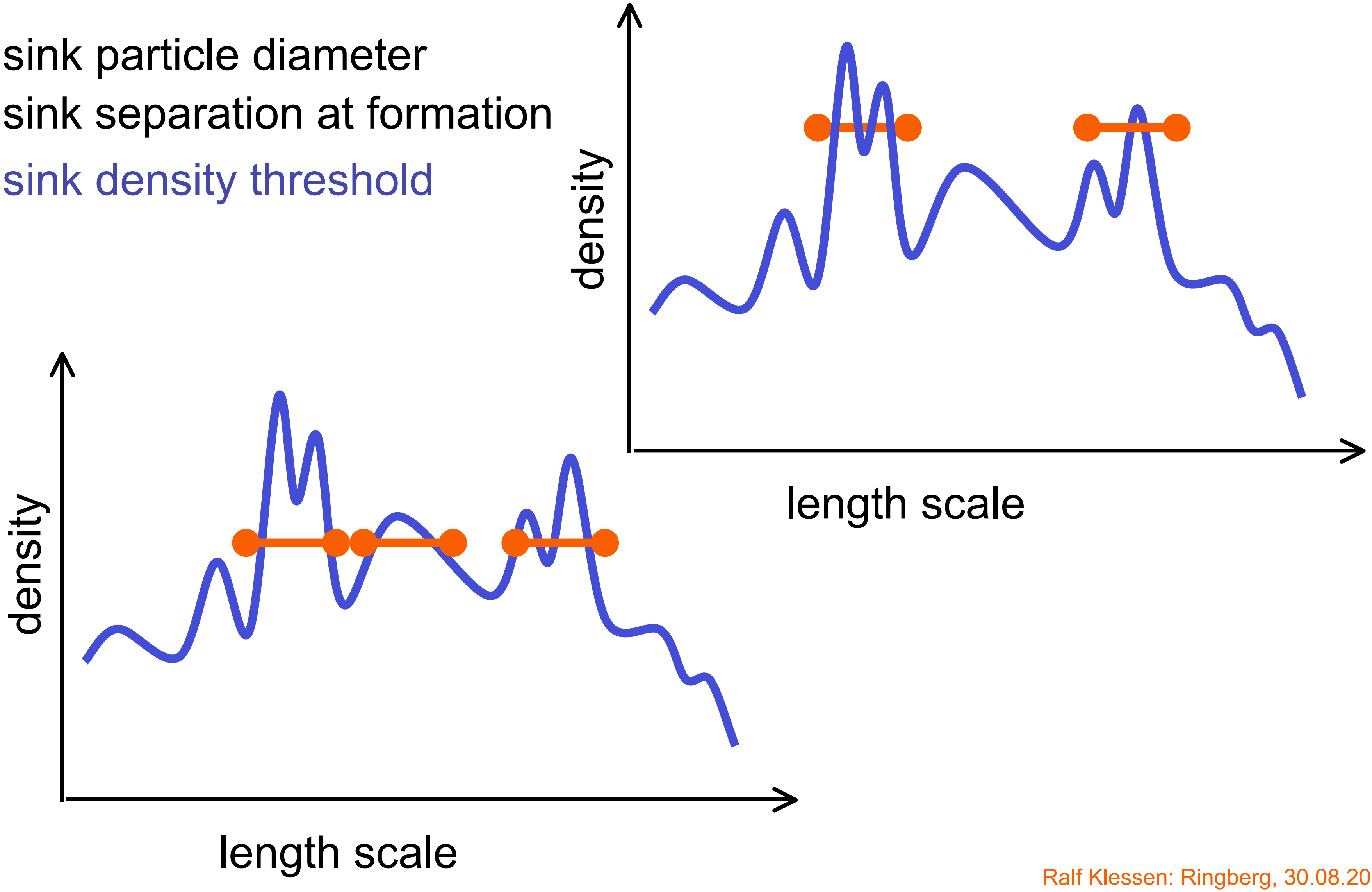
SPH with sink particles III

- sink particle diameter
- sink separation at formation
- sink density threshold



SPH with sink particles IV

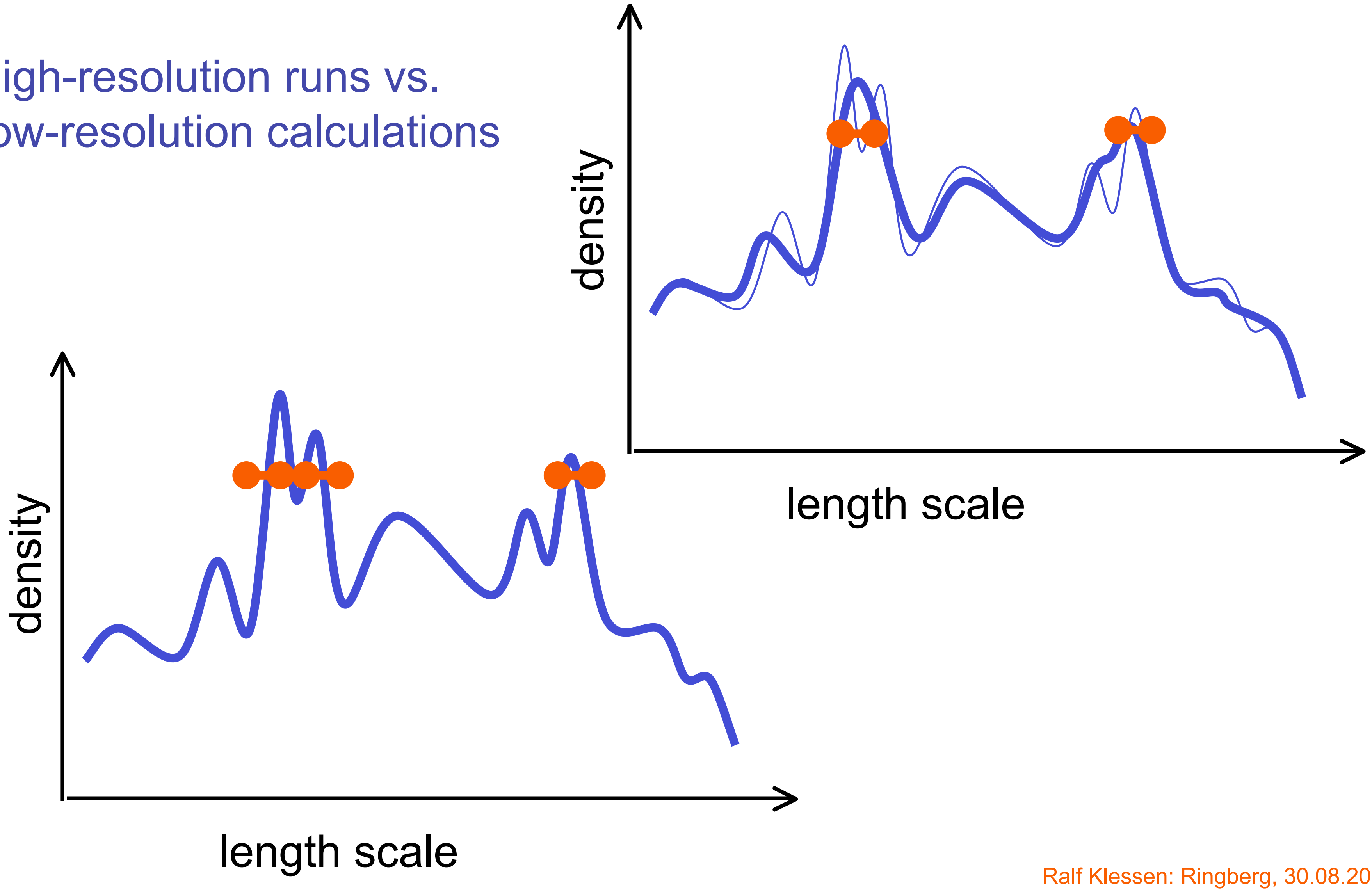
- sink particle diameter
- sink separation at formation
- sink density threshold



Ralf Klessen: Ringberg, 30.08.2006

SPH with sink particles V

high-resolution runs vs.
low-resolution calculations



Some final remarks…

- *GRAVOTURBULENT STAR FORMATION:*
  This dynamic theory can explain and reproduce many features of star-forming regions on small as well as on large galactic scales.

- Some open questions:
  - role of magnetic fields?
  - role of thermodynamic state of the gas?
  - what drives turbulence?
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Some final remarks…

- *NUMERICS:*
  SPH appears able to describe gravoturbulent fragmentation and star formation in molecular clouds.
- Pro:
  - *Lagrangian* character of method.
  - can resolve *large density contrasts*.
  - good for transition from hydro- to stellar dynamics
    --> accreting sink particles describe protostars
- Con:
  - low resolution in low-density regions.
  - difficulties with shock-capturing and treating B-fields.
- Next steps:
  - particle-splitting to locally increase resolution,
  - GPM, XSPH with "physical" viscosity

applications, predictions

Predictions

- *global properties* (statistical properties)
  - molecular cloud build-up
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - 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: molecular cloud formation in colliding flows in the warm neutral medium

example 2: transient structure of turbulent clouds

example 3: quiescent and coherent appearence of molecular cloud cores

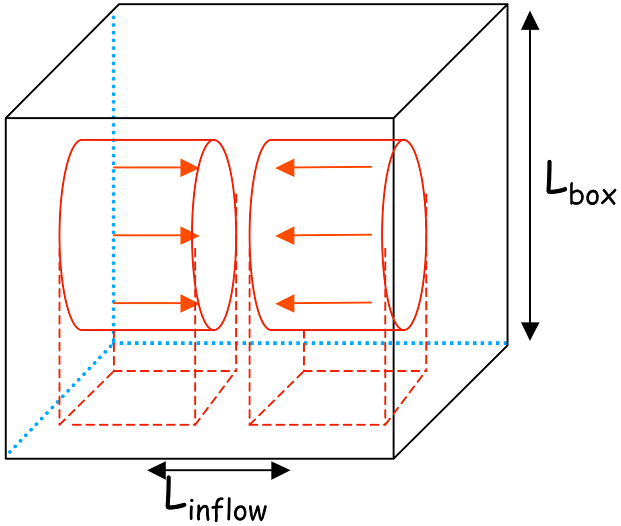
example 4: speculations on the origin of the stellar mass spectrum (IMF)

example 1

MC formation in colliding flows

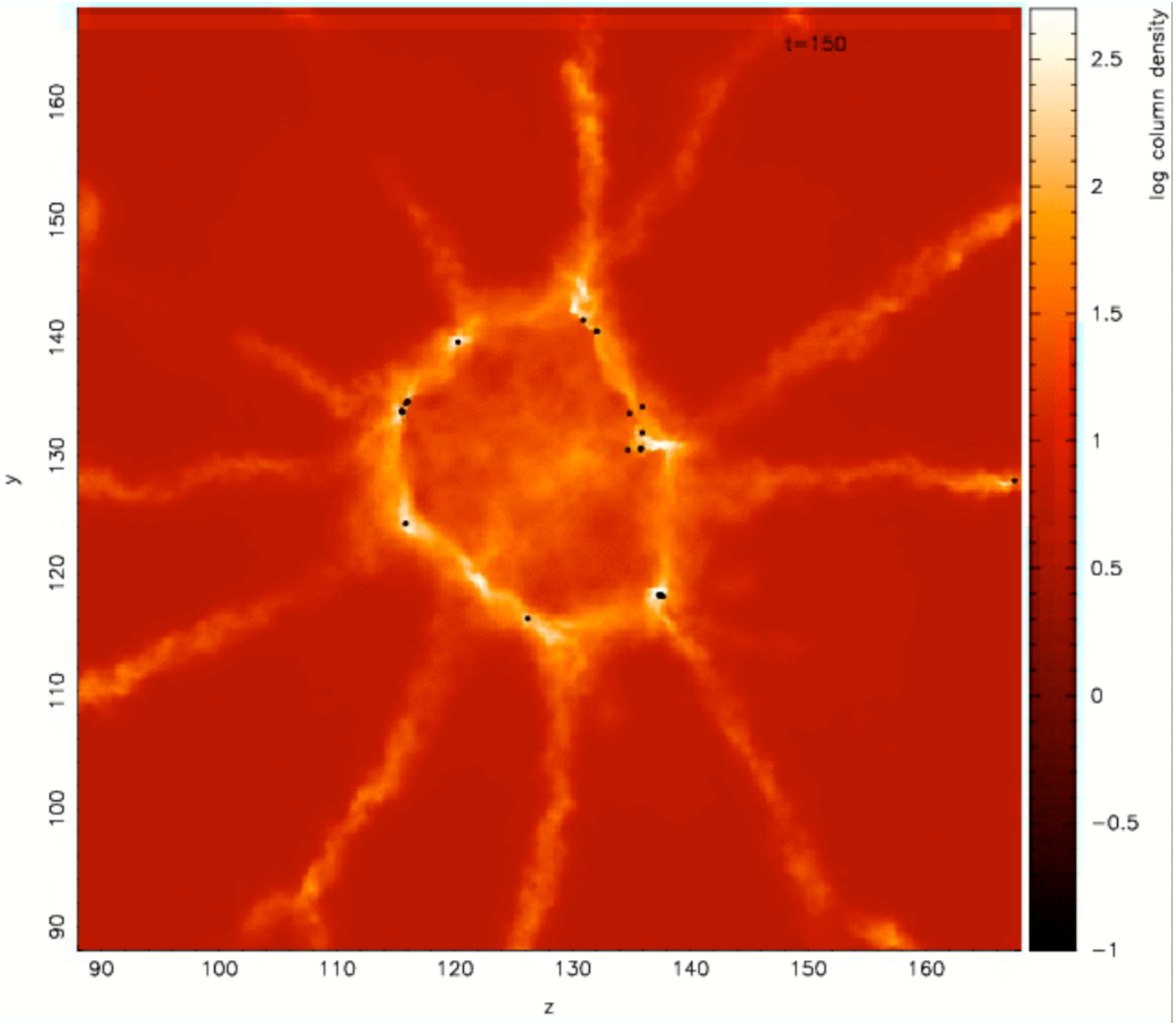
- colliding flow in warm neutral medium
  - SPH code GADGET 3.5 million particles
  - initially: n=1 cm^{-3}, T = 5000K, inflow velosity v = 9.2 km/s (i.e. Mach number M=1.25
  - standard cooling curve to describe thermal evolution of the compressed gas --> cooling instability --> transition to "molecular gas"

Converging inflow setup



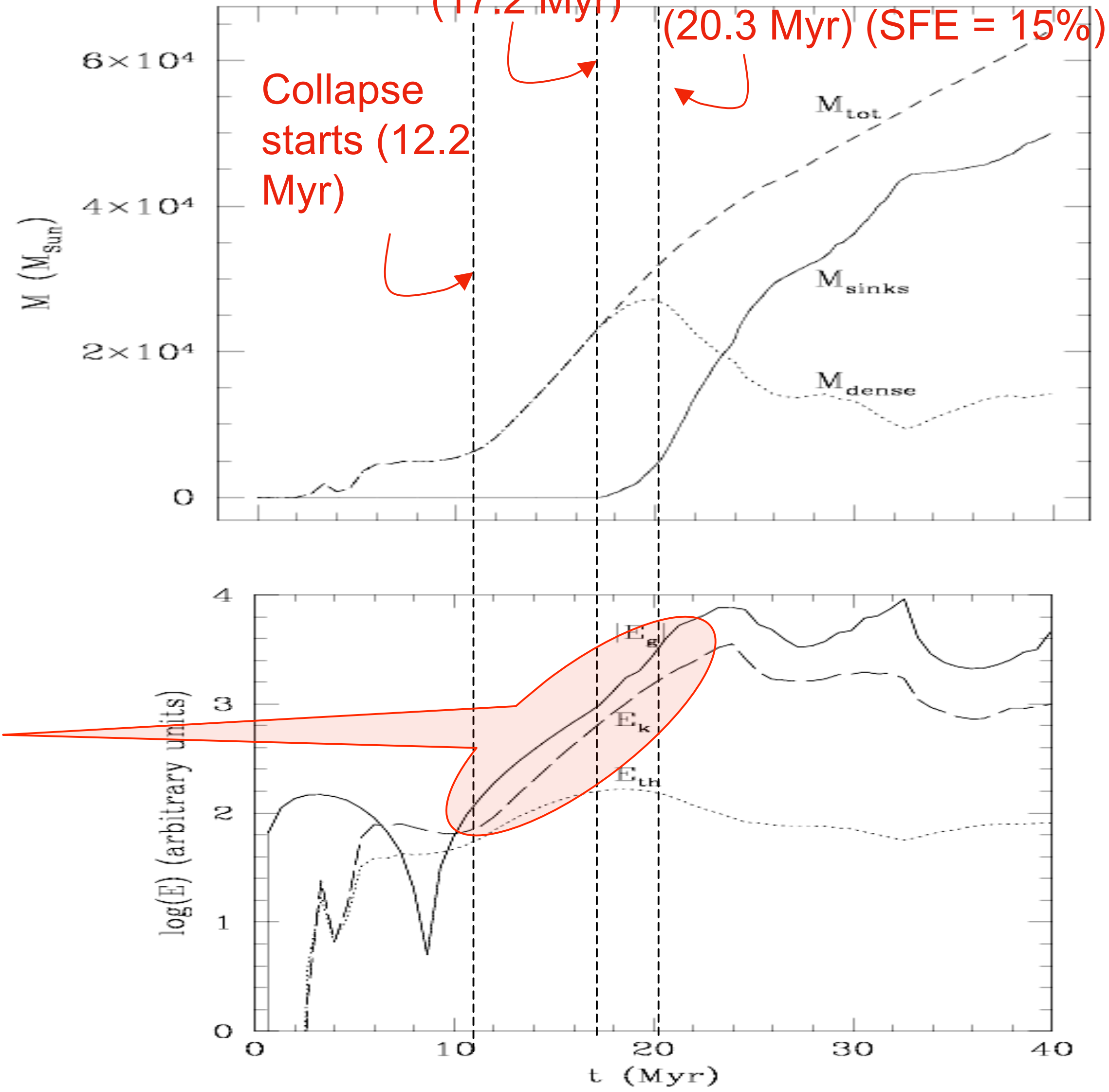
	Run 1	Run 2
L_{box}	128 pc	256 pc
L_{inflow}	48 pc	112 pc
Dt_{inflow}	5.2 Myr	12.2 Myr
M_{inflow}	1.13×10^4 M_{sun}	2.64×10^4 M_{sun}

(Vázquez-Semadeni, Gómez, Jappsen, Ballesteros-Paredes, González & Klessen 2006).



(Vázquez-Semadeni, Gómez, Jappsen, Ballesteros-Paredes, González & Klessen 2006).

Clouds never in virial equilibrium, but in equipartition due to gravitational contraction.



SF starts (17.2 Myr)

SF expected to destroy cloud (20.3 Myr) (SFE = 15%)

Collapse starts (12.2 Myr)

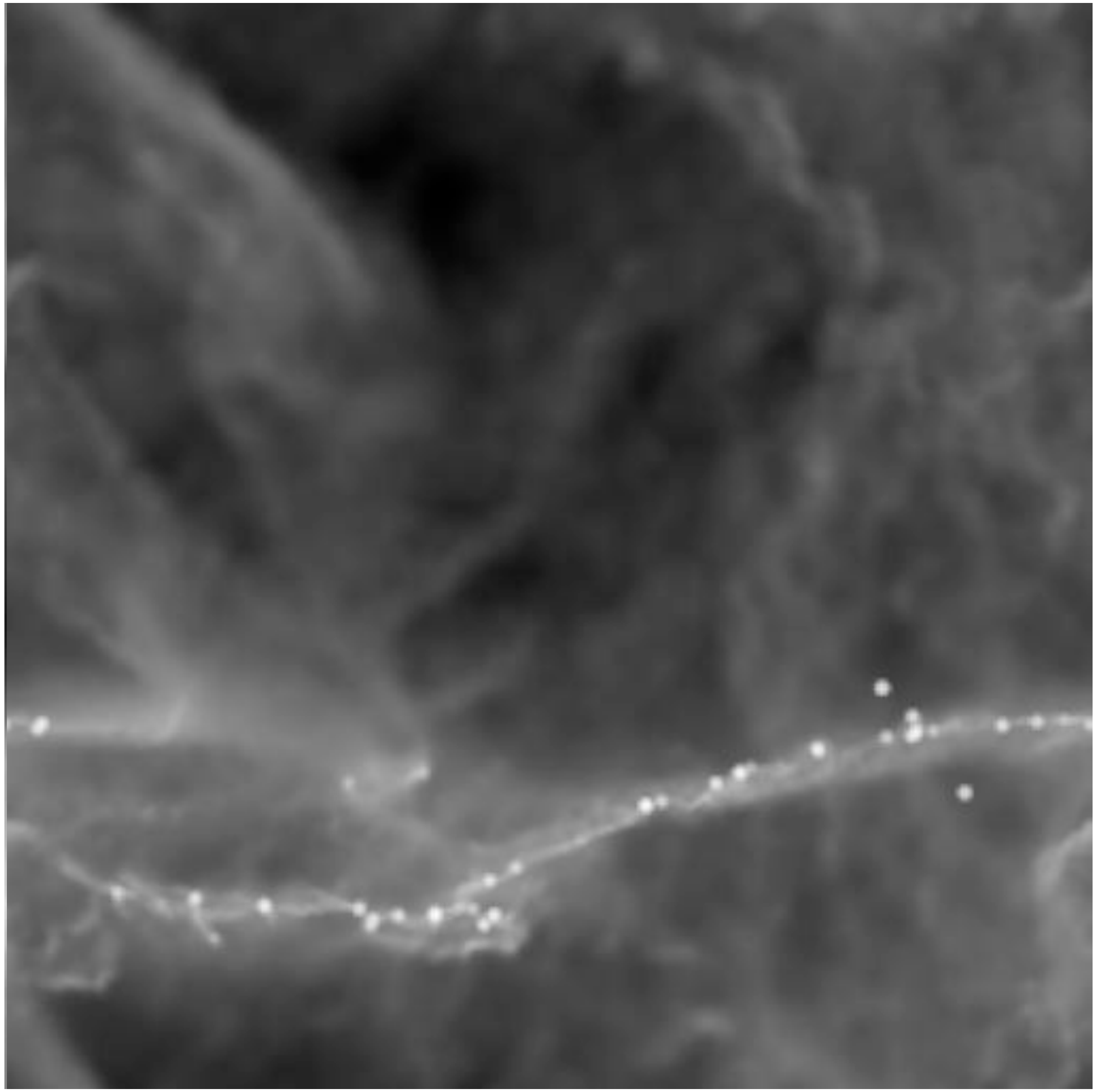
Equipartition:
$|E_g| \sim 2\, E_k$

Run with:
L_{box} = 256 pc,
L_{inf} = 112 pc

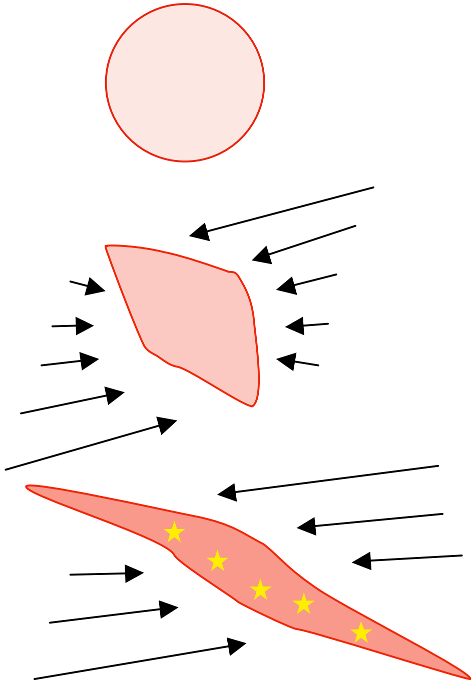
(Vázquez-Semadeni, Gómez, Jappsen, Ballesteros-Paredes, González & Klessen 2006).

example 2

Gravoturbulent fragmentation



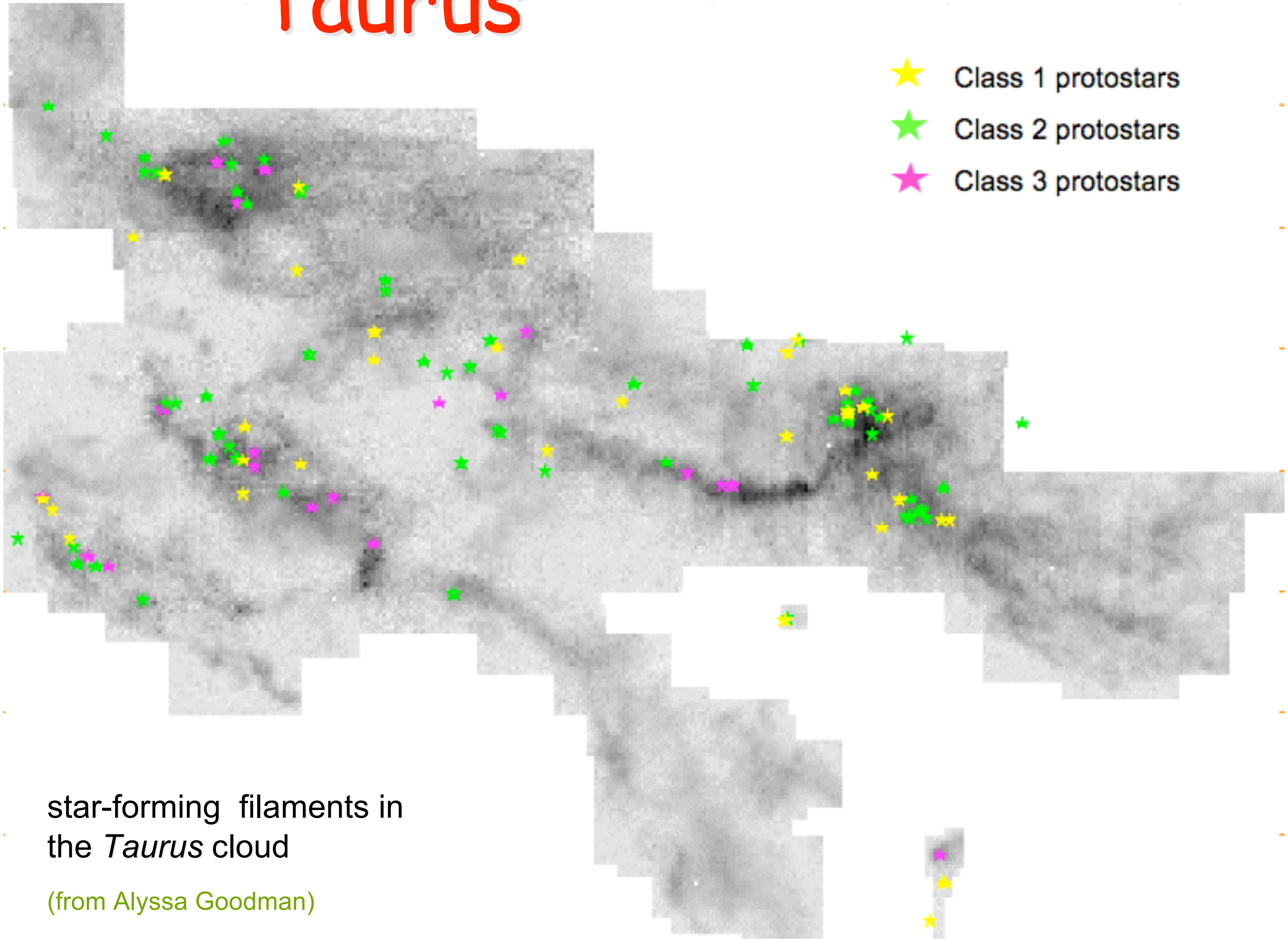
Filament generated by combination of compression and local shear:



"Taurus":

- → density $n(H_2) \approx 10^2\,\mathrm{cm}^{-3}$
- → $L = 6\,\mathrm{pc}$, $M = 5000\,M_\odot$

Taurus



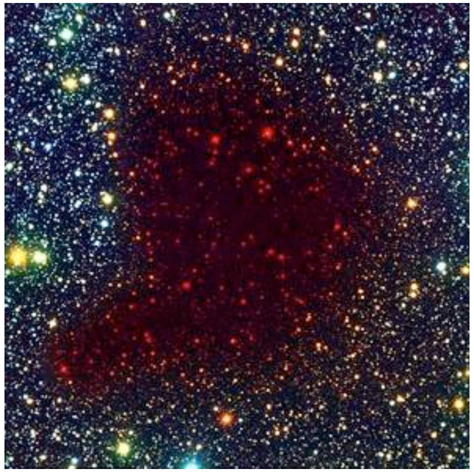
star-forming filaments in the *Taurus* cloud

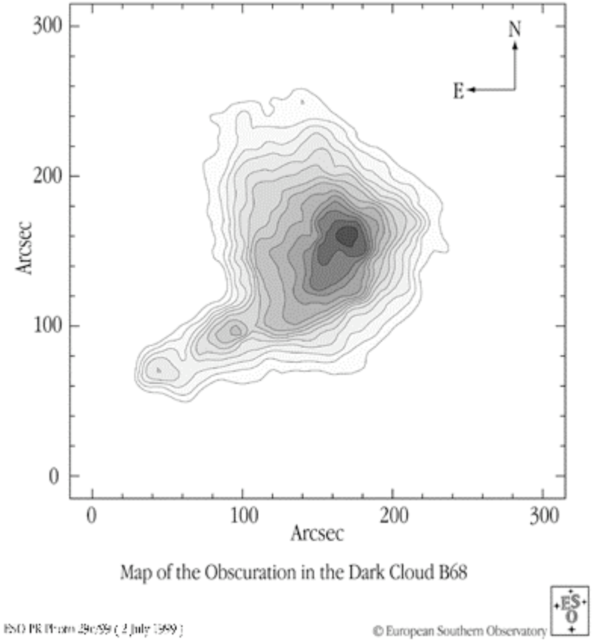
(from Alyssa Goodman)

example 3

BE-type objects from gravoturbulent fragmentation

- One of the best studied examples is the *dark Bok globule* Barnard 68.
- Its radial density profile is well approximated by a *marginally supercritical* Bonnor-Ebert configuration.





Radial density profile of Barnard 68 is fit by a Bonnor-Ebert sphere.

(Alves, Lada, & Lada 2001)

BE-type objects from gravoturbulent fragmentation

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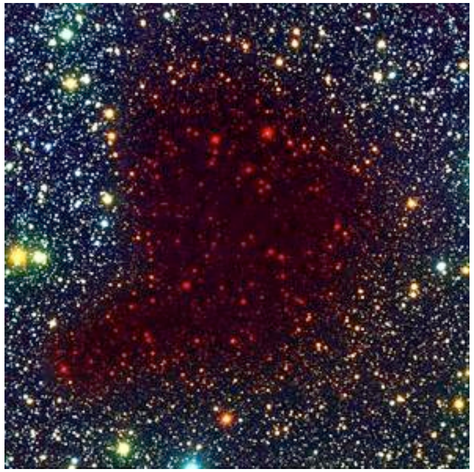

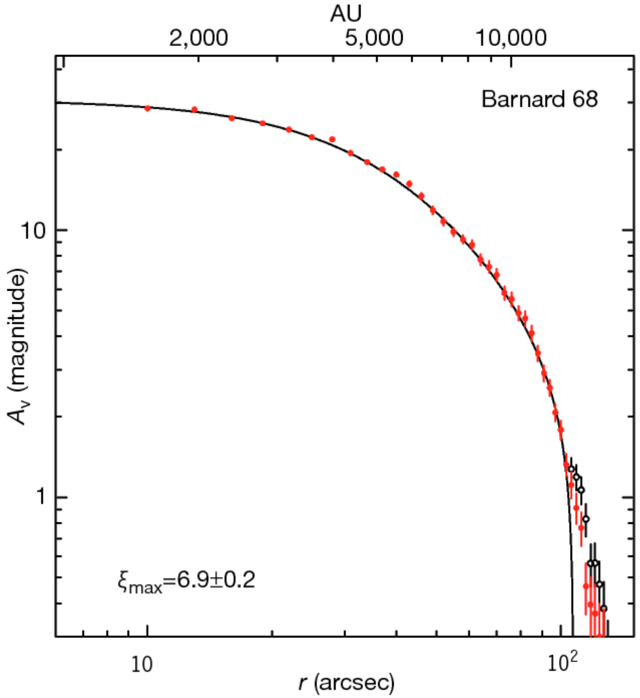

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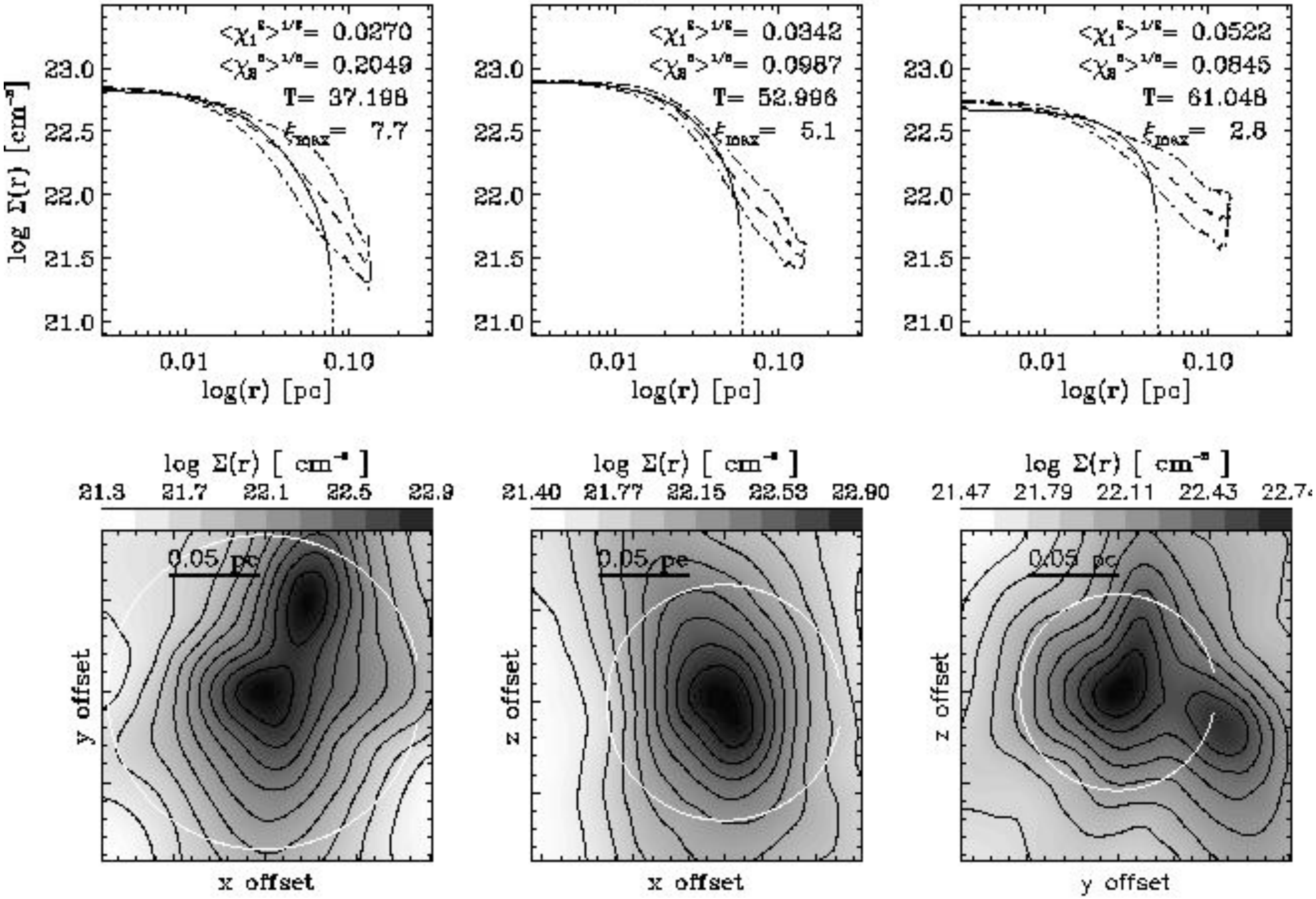
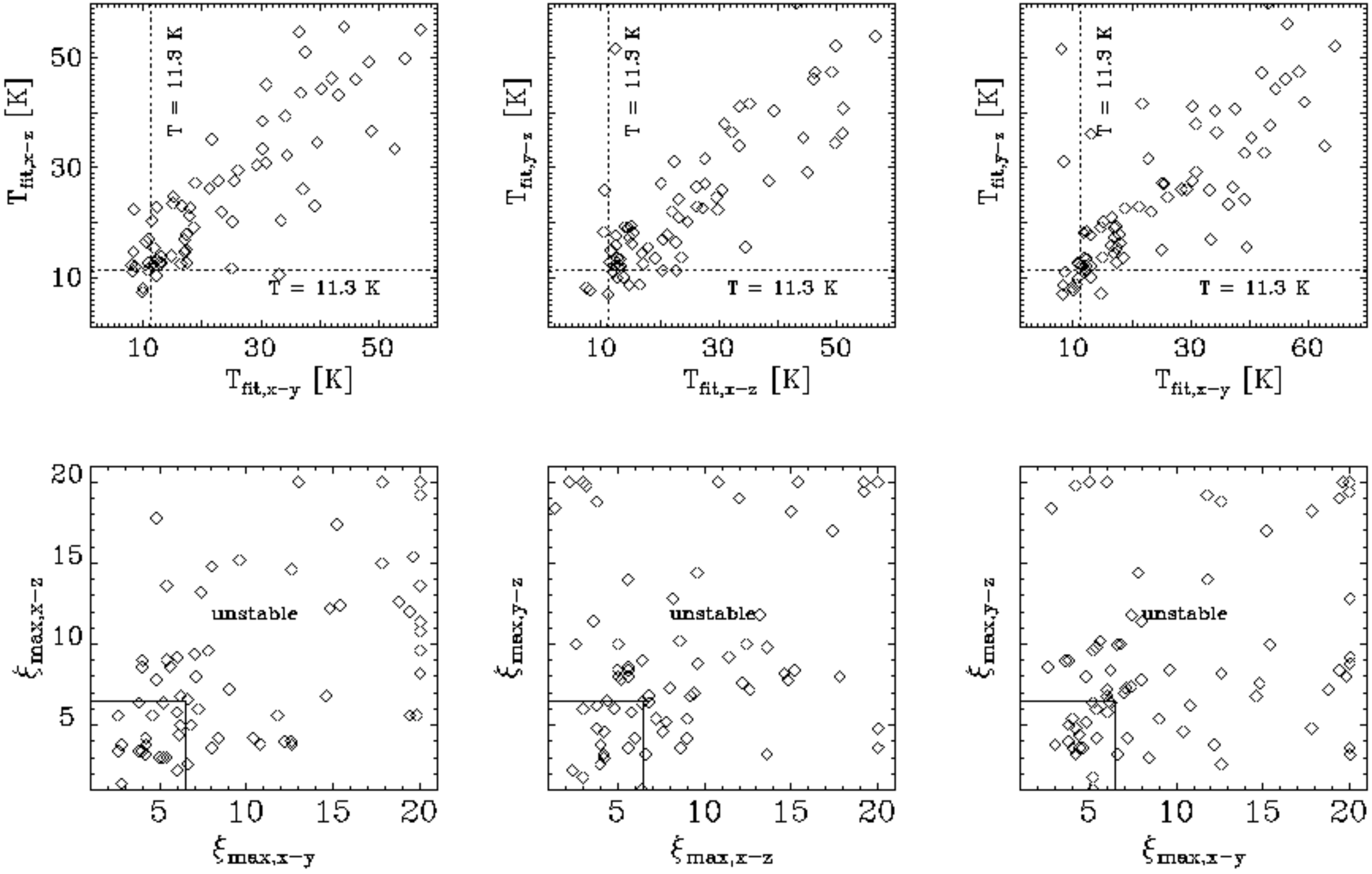
(Alves, Lada, & Lada 2001)

GC clump 04 time t_0



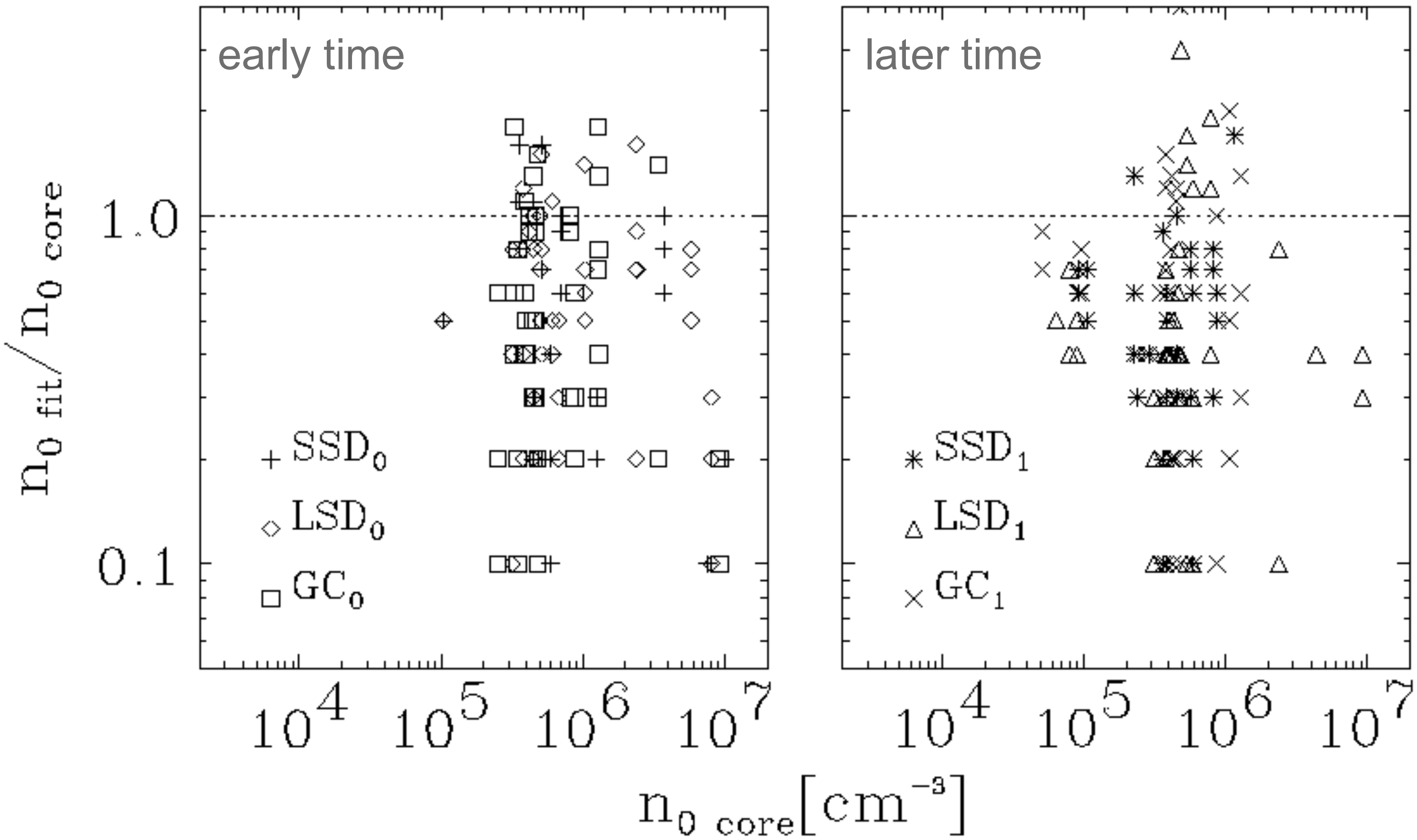
126 cores analyzed in 3 projections: 63% good BE fit

effects of projection



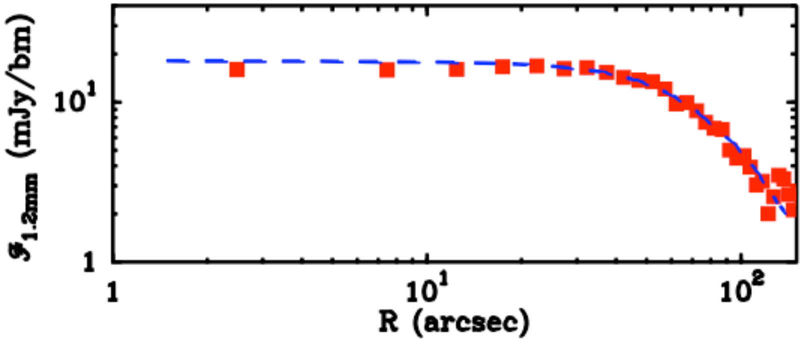
126 cores analyzed in 3 projections: 63% good BE fit

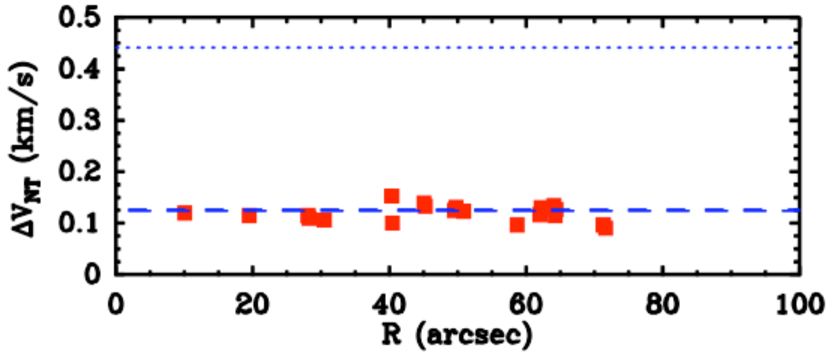
comparison between real central density and BE-fit density



Quiescent & coherent cores

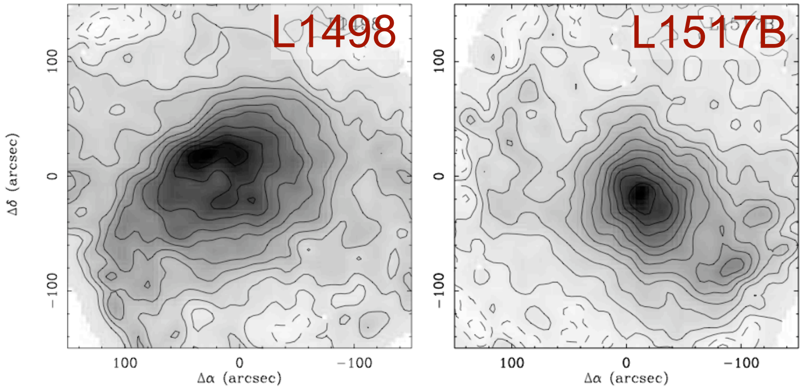
- some small cores have very small linewidth!
- is this consistent with gravo-turbulent star formation?





map of linewidth

(contours column density)

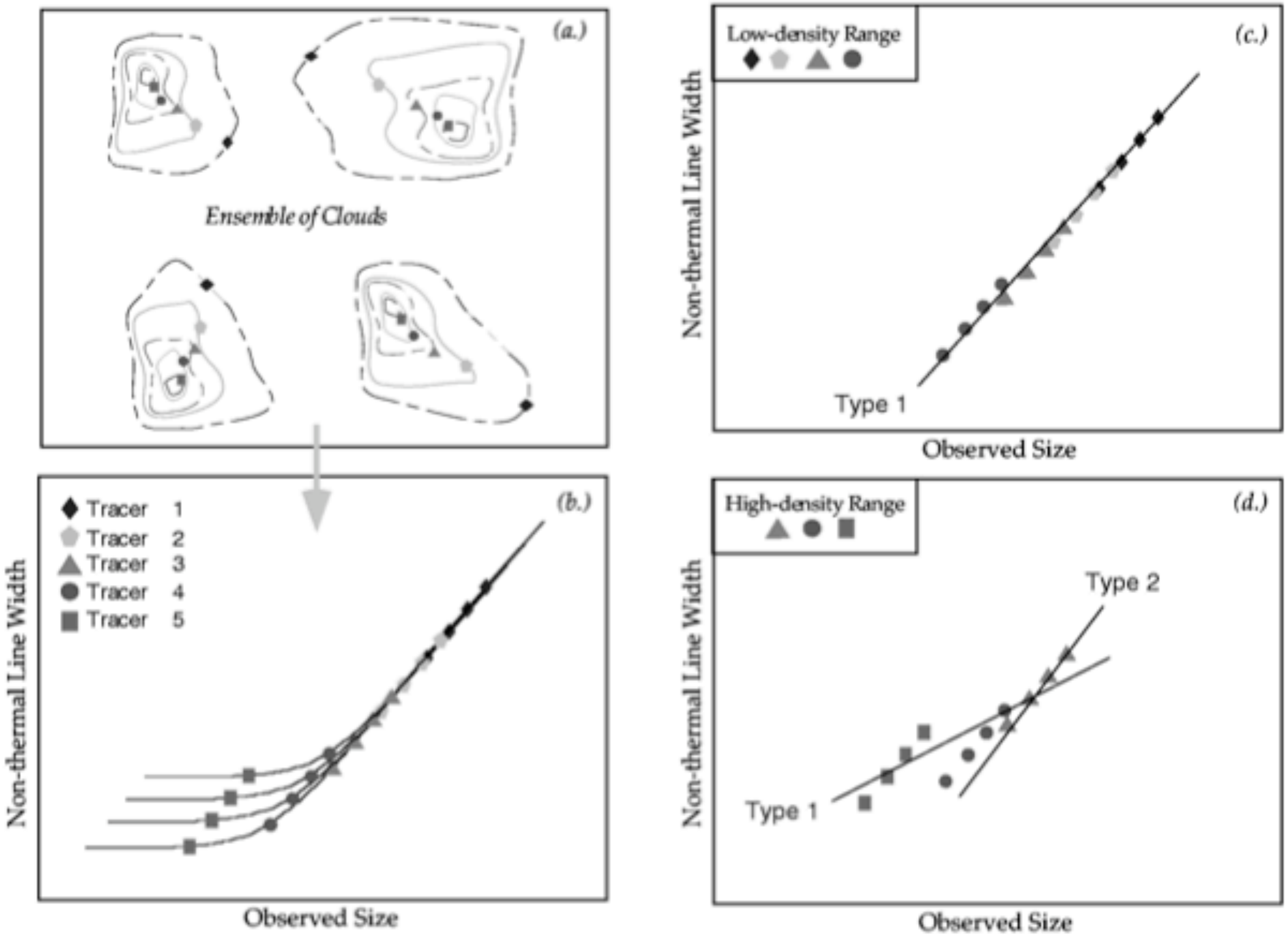


column density map

(contours column density)

(Tafalla et al. 2004)

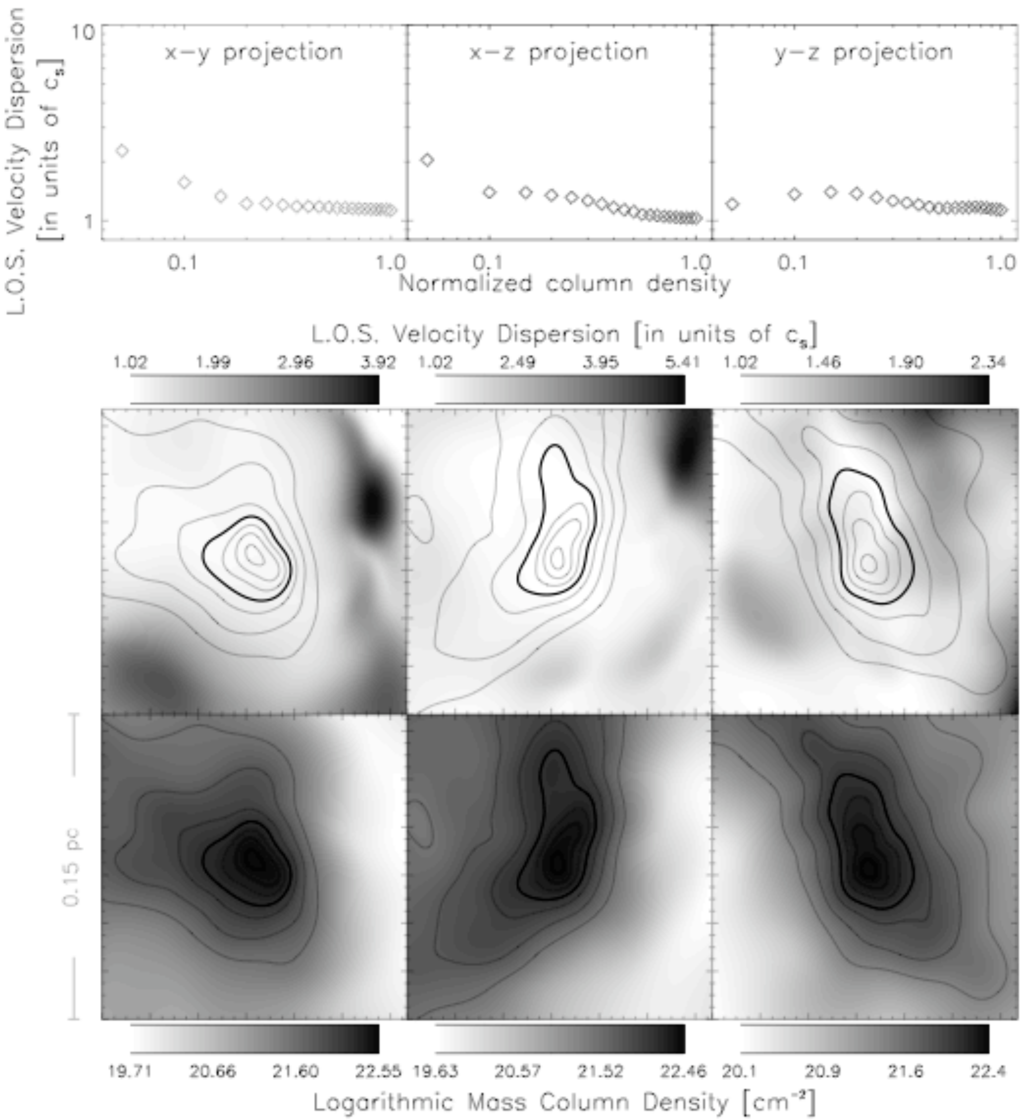
Quiescent & coherent cores


MULTIPLE CLOUDS OBSERVED IN MULTIPLE TRACERS

(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)

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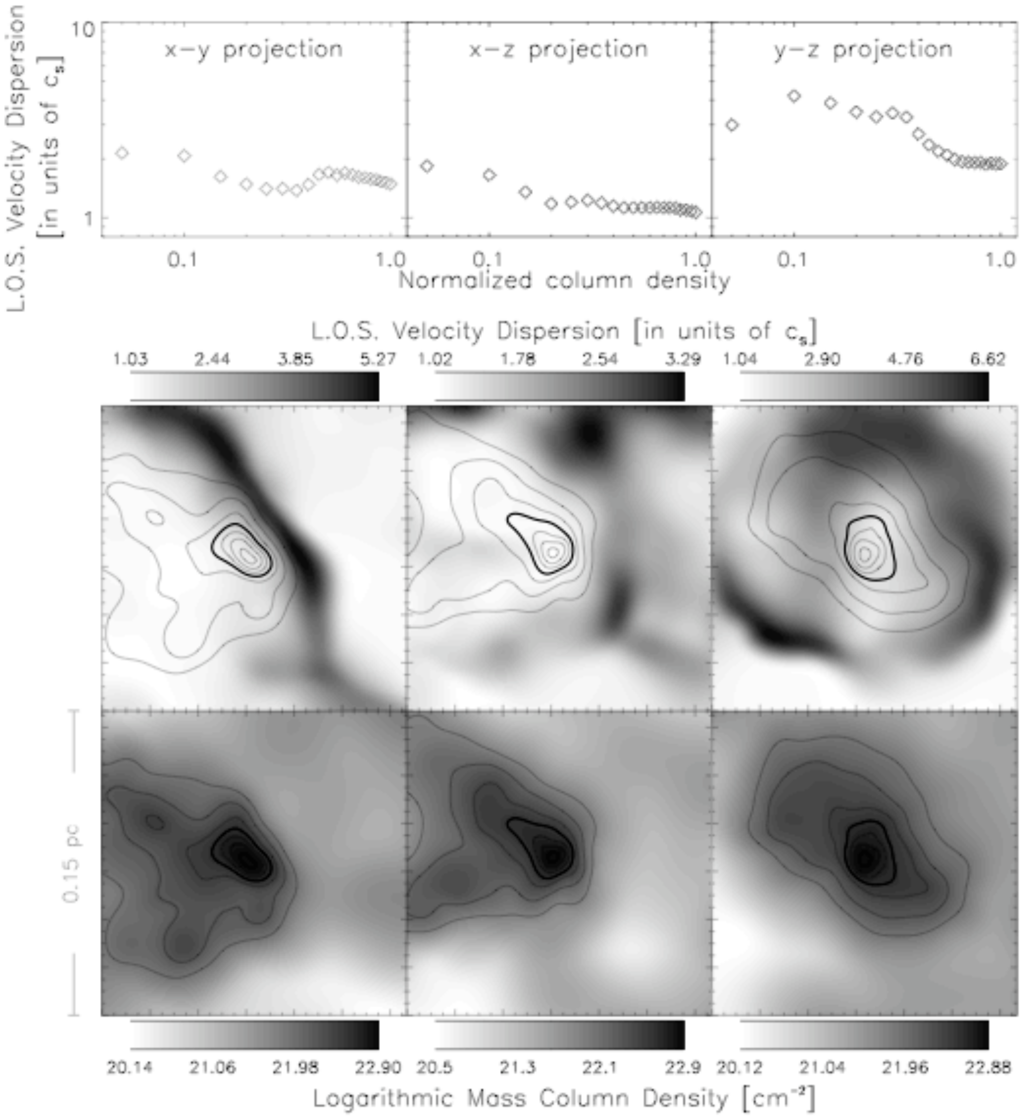

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(e.g. Goodman et al. 1998;
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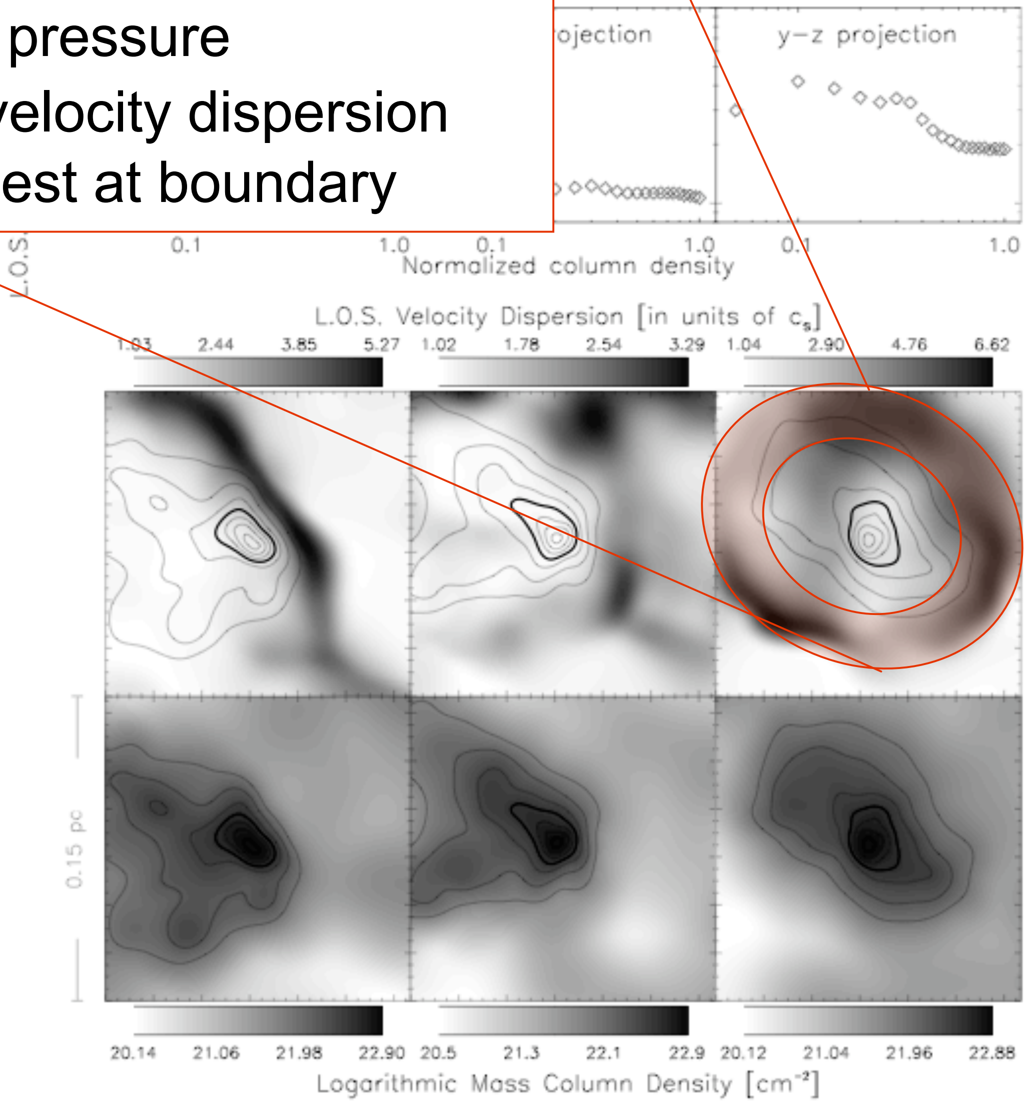
map of linewidth
(contours column density)

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



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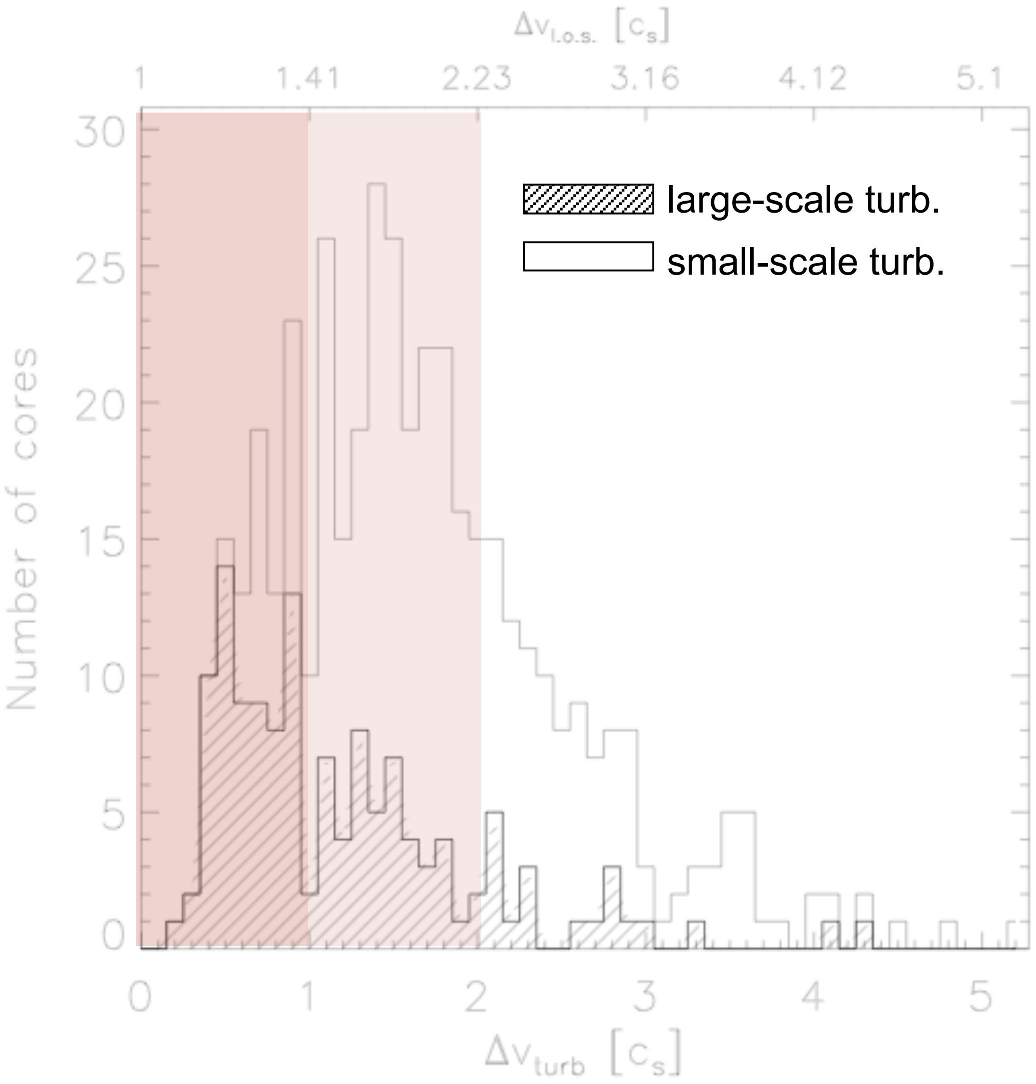


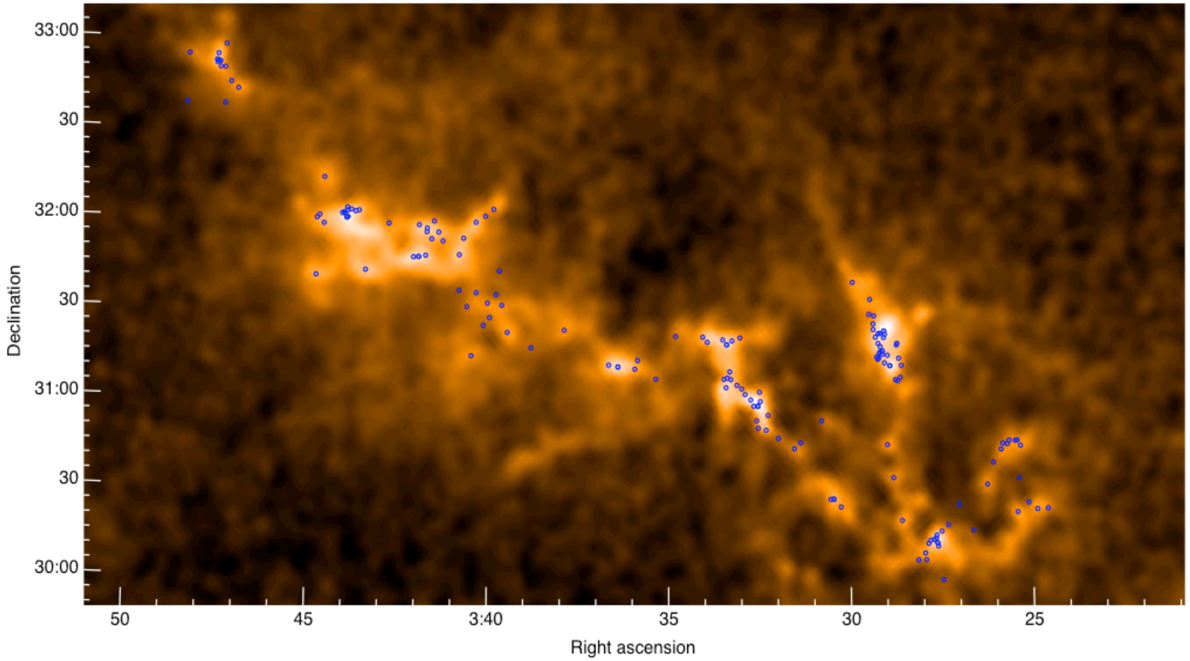
(from Klessen et al. 2005, ApJ, 620, 768 - 794; also poster 8415)

Statistics:

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

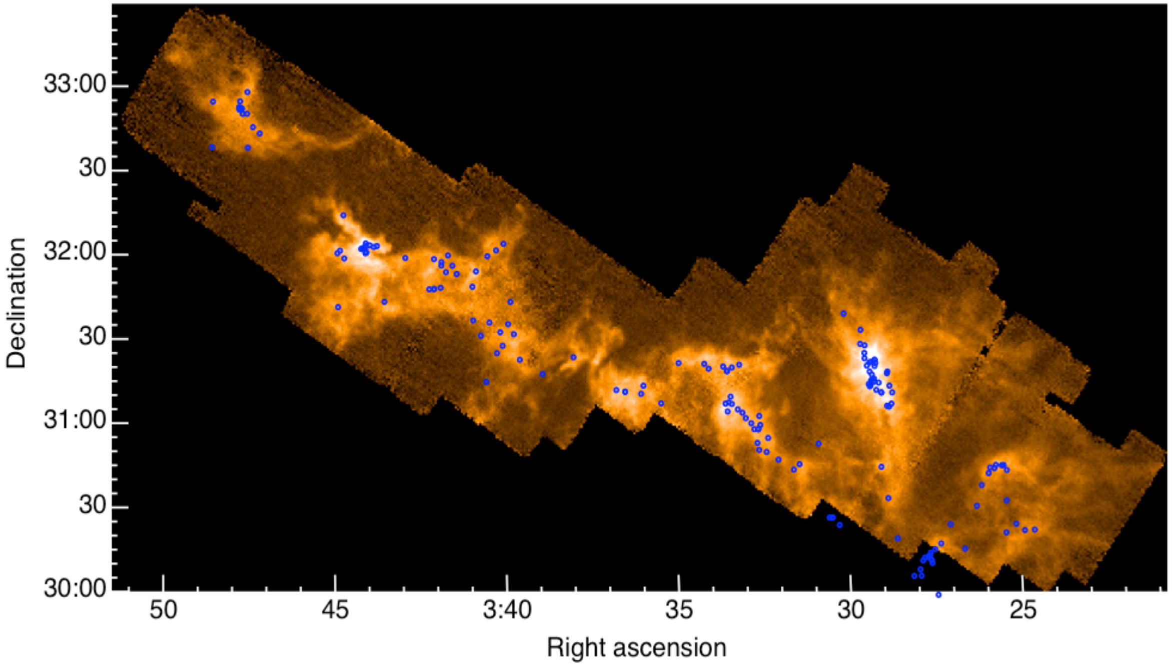
48% of our cores are *transonic* (i.e. with $c_s \leq \sigma_{rms} \leq 2c_s$)

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



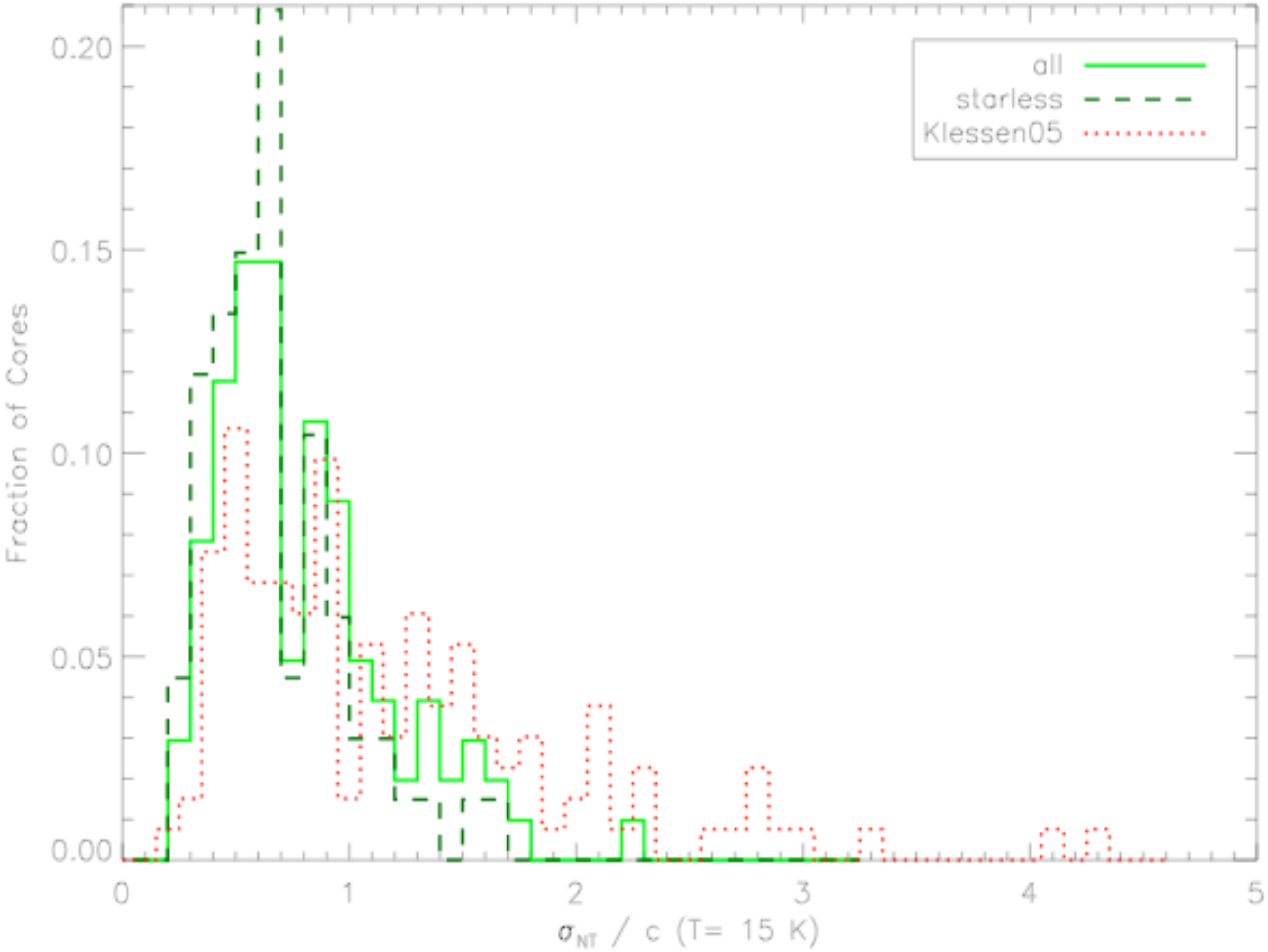
IRAM Observations

- N_2H^+ and $C^{18}O$
- 15 arcsecond res.
  - ~3000 AU
- N_2H^+ dense gas tracer
  - Most SCUBA
  - Few extinction!



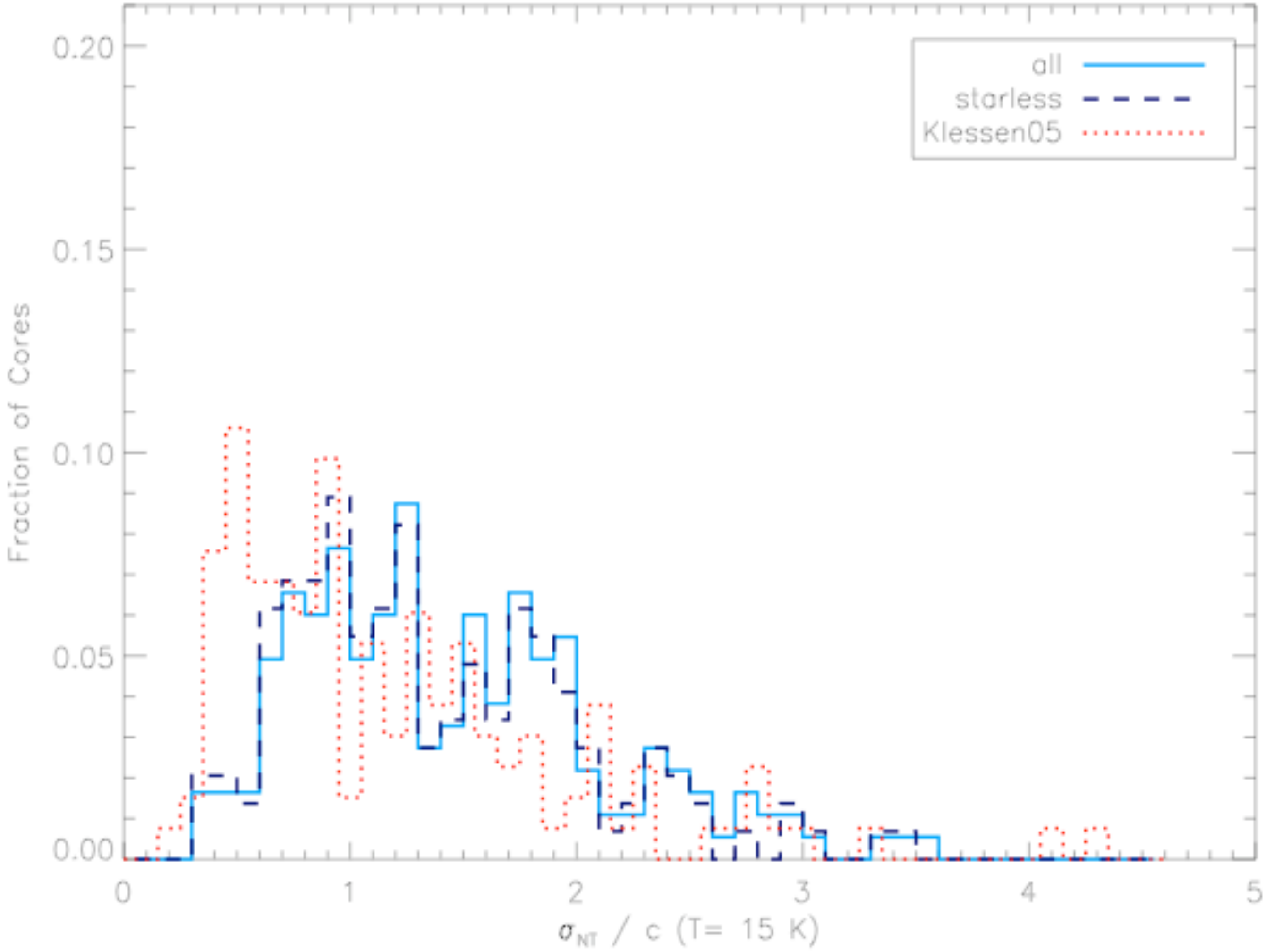
(Doug Johnstone’s talk)

N_2H^+ linewidths of cores mostly thermal!



(Doug Johnstone’s talk)

C^{18}0 linewidths of cores larger non-thermal component.



(Doug Johnstone's talk)

example 4

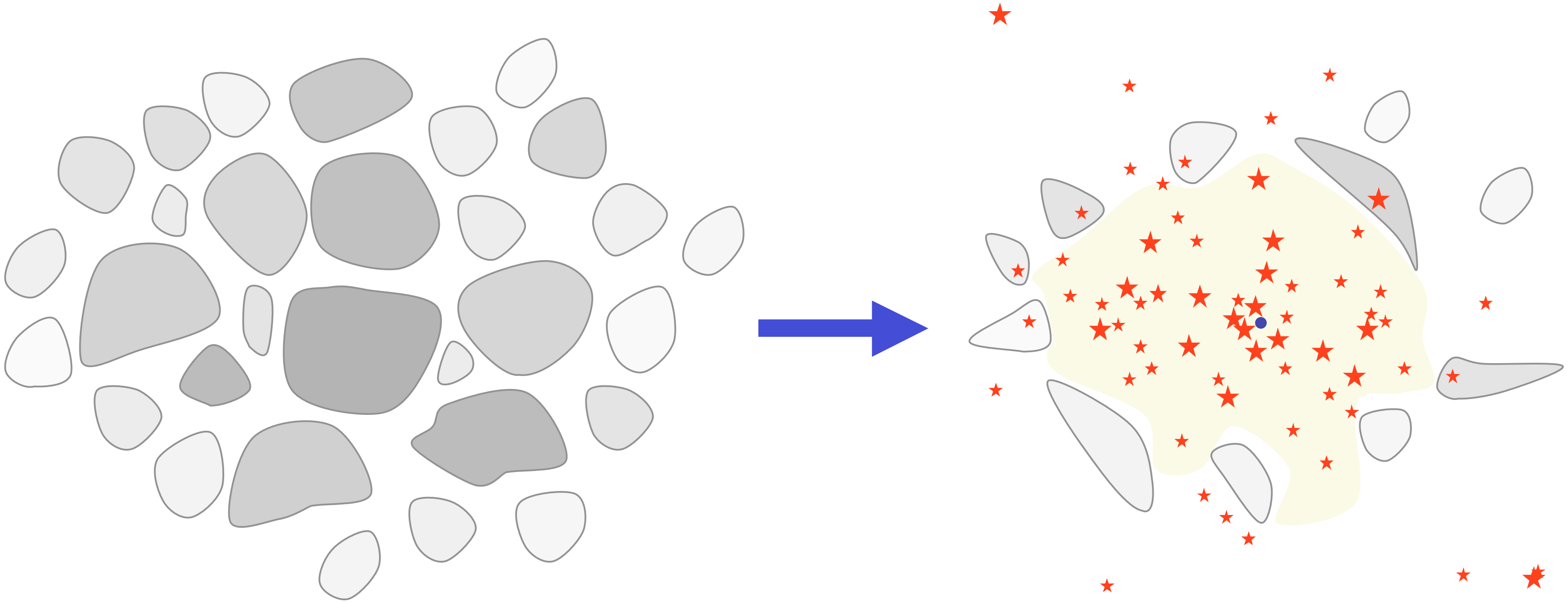
IMF

- 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*



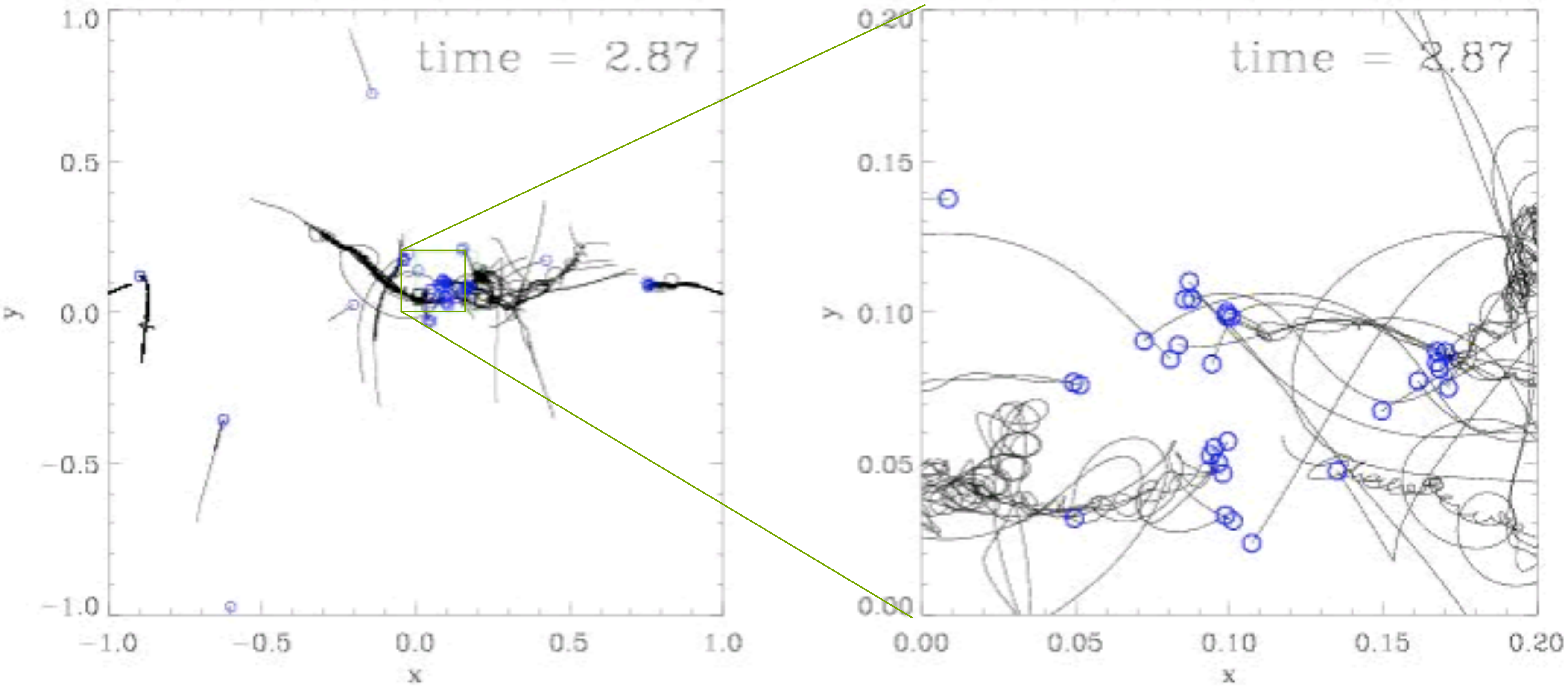
How to get from cloud cores to star clusters?

How do the stars acquire mass?

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

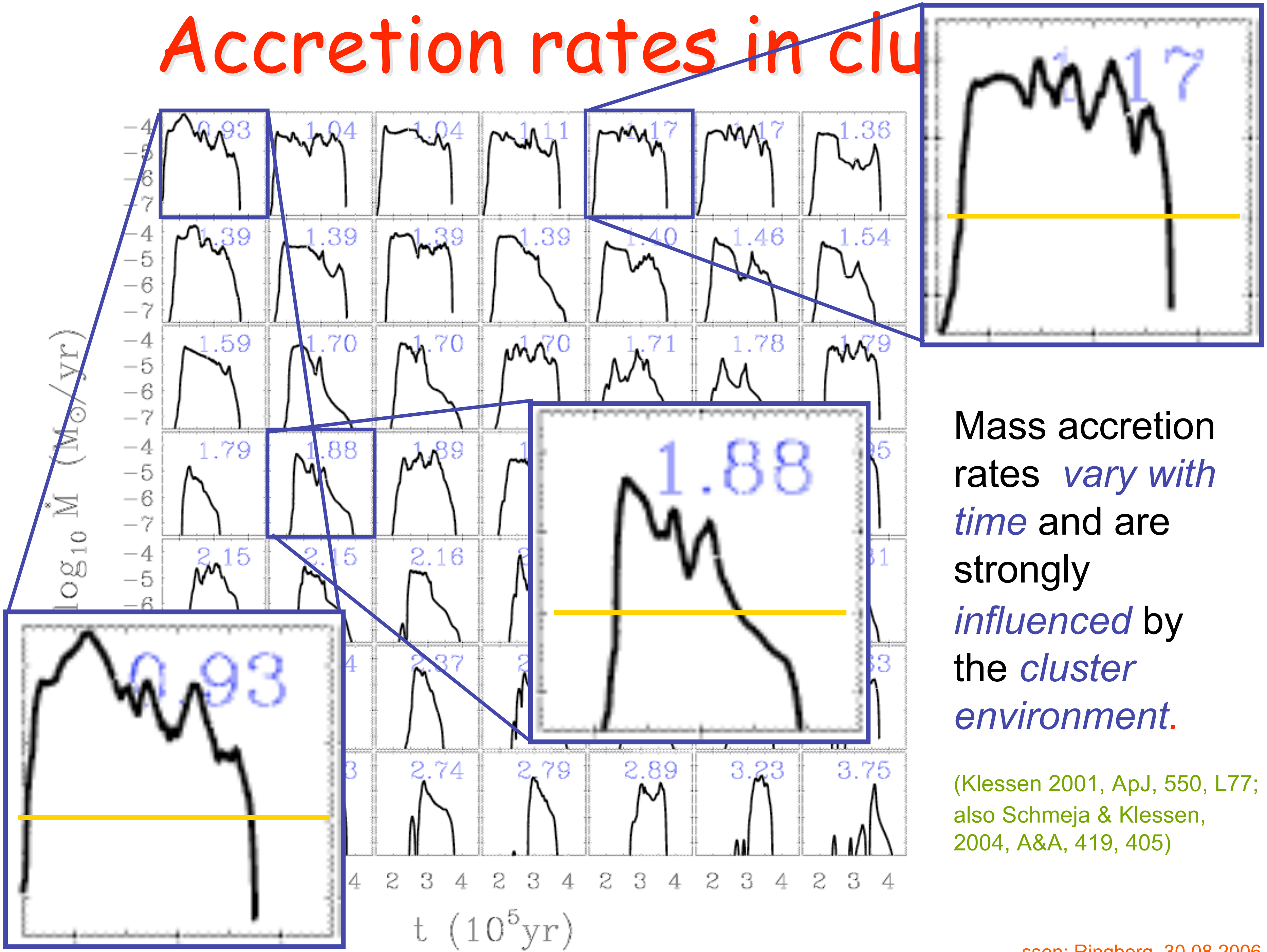
Star cluster formation

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)

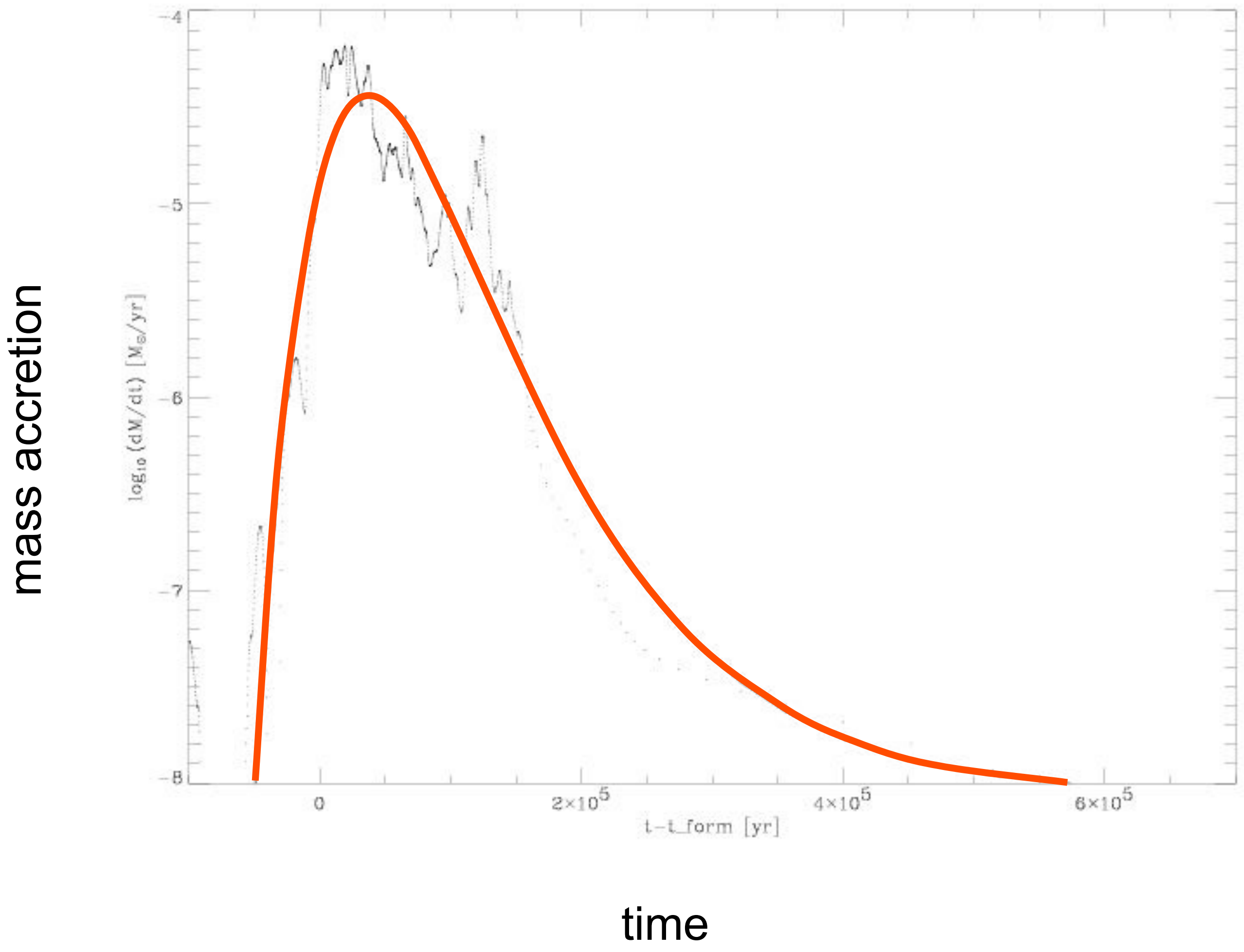
Accretion rates in clu



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)

“Empirical” mass accretion law



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

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

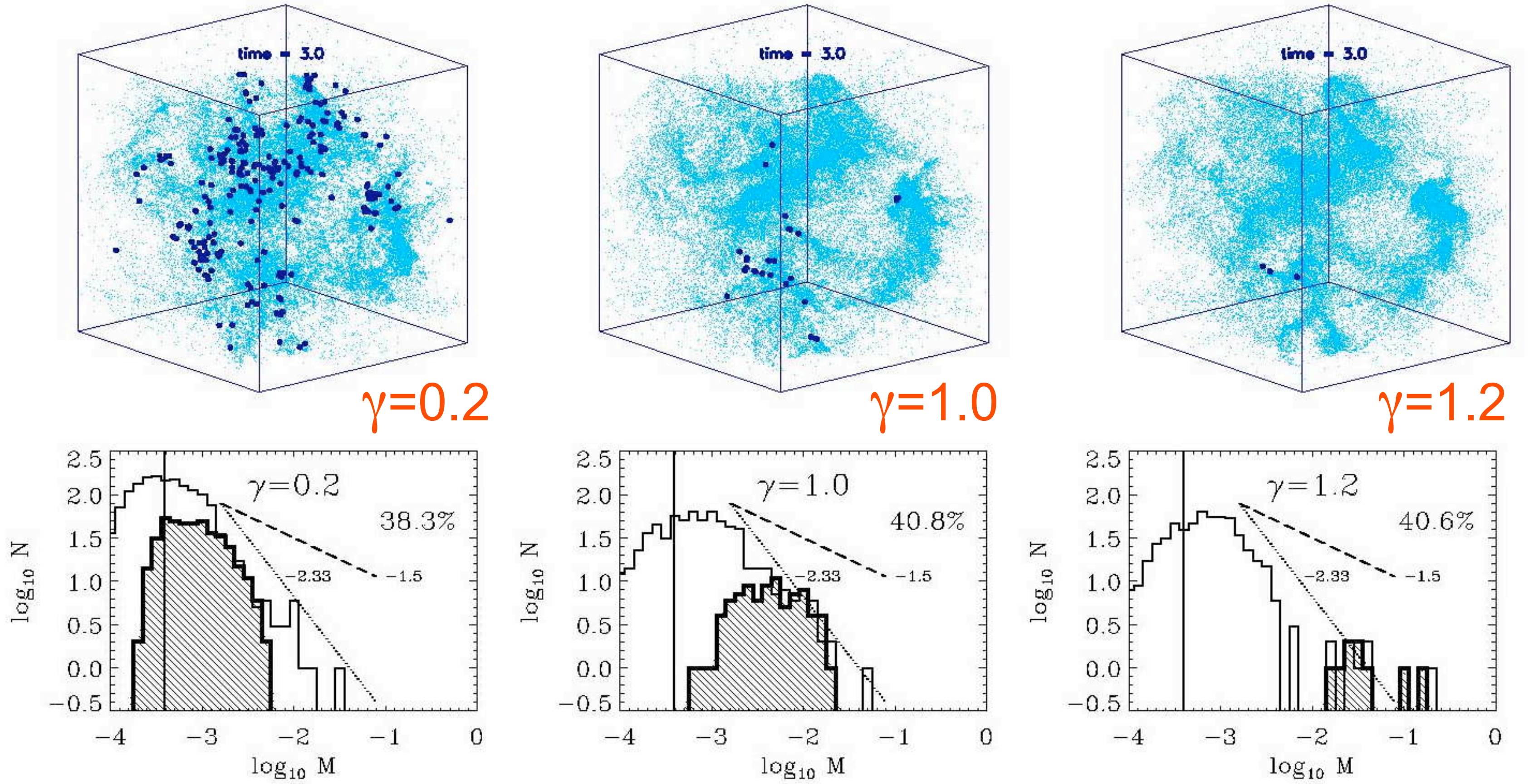
Dependency on EOS

- 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*

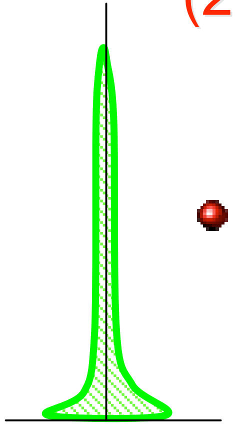
for γ>1 it is suppressed → formation of *isolated massive stars*

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

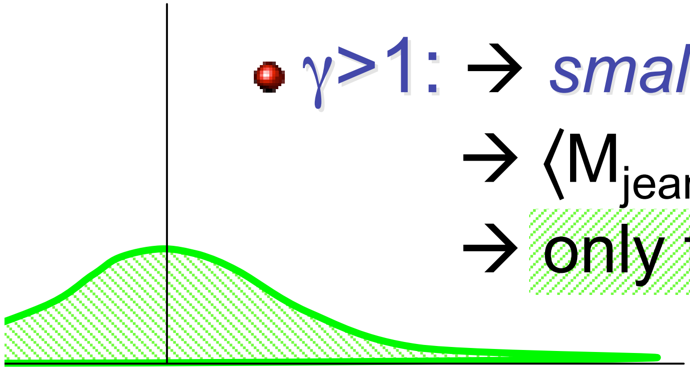
How does that work?

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

(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

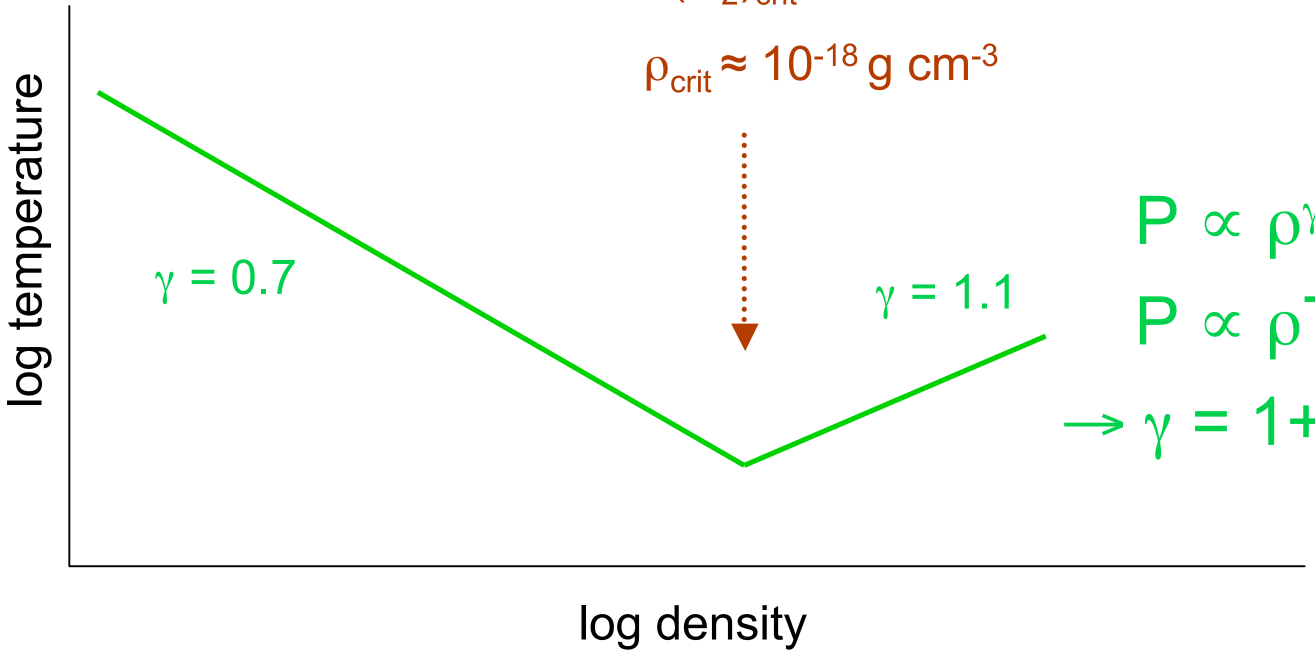
(Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2005)

- 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*



$n(H_2)_{crit} \approx 2.5 \times 10^5\ \mathrm{cm}^{-3}$

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

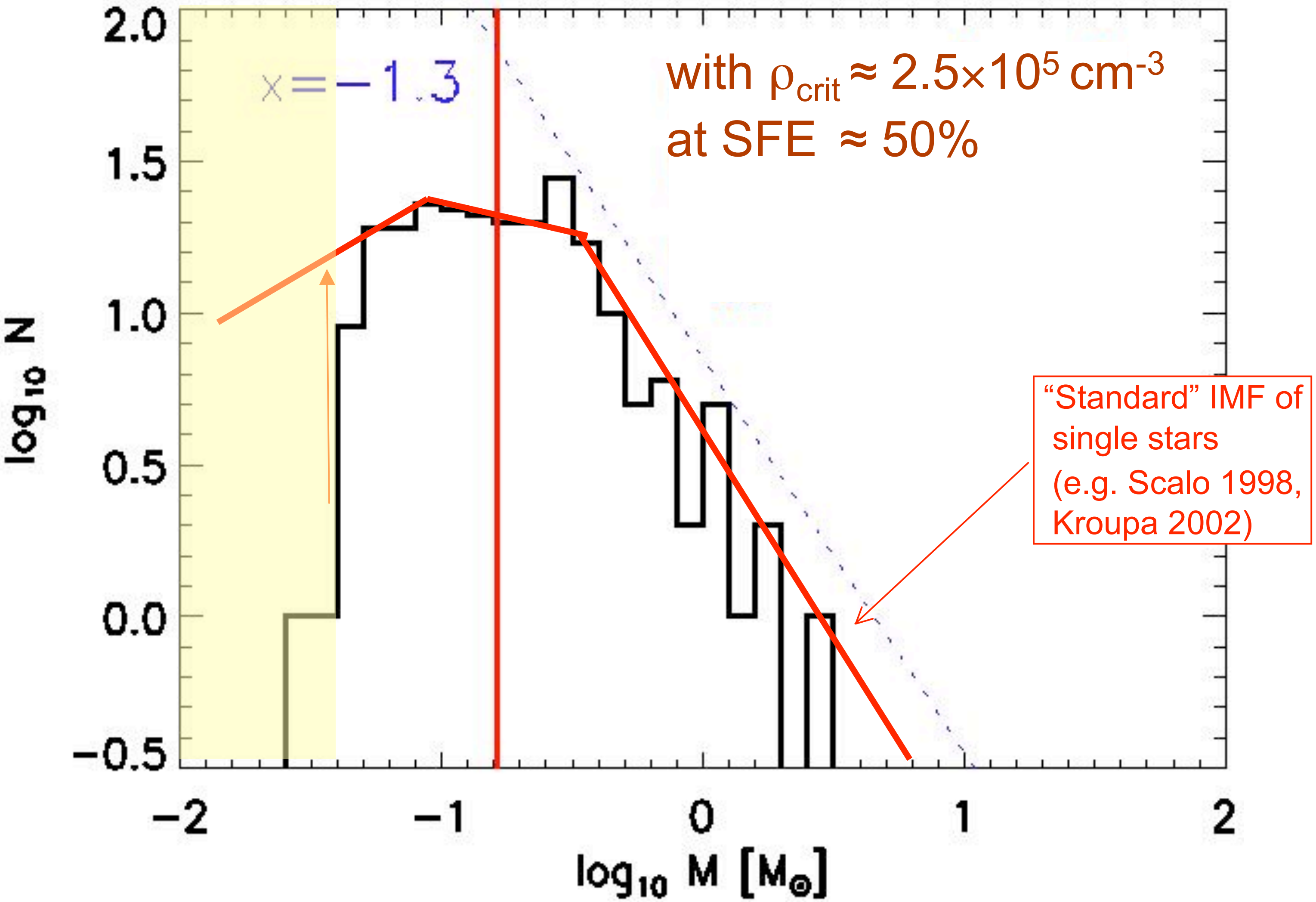
$P \propto \rho^\gamma$

$P \propto \rho T$

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

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

IMF in nearby molecular clouds



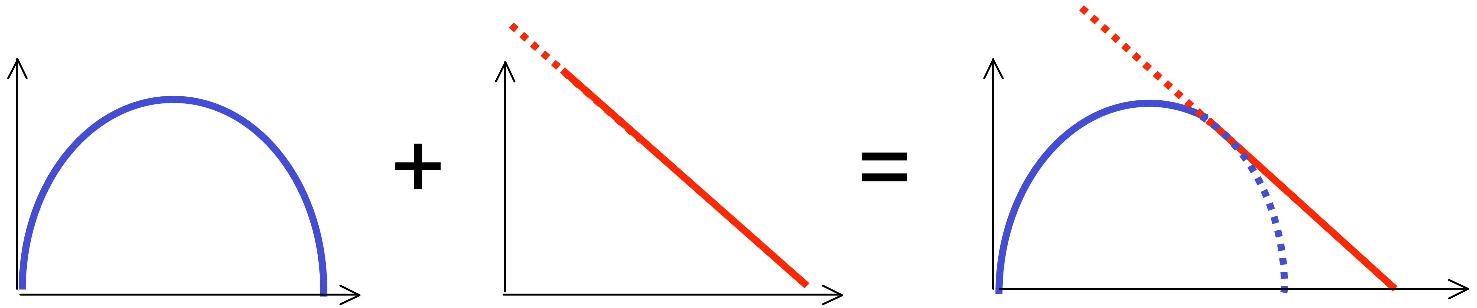
with $\rho_{crit} \approx 2.5 \times 10^5$ cm^{-3}

at SFE ≈ 50%

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

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

Plausibility argument for shape



- Supersonic turbulence is scale free process

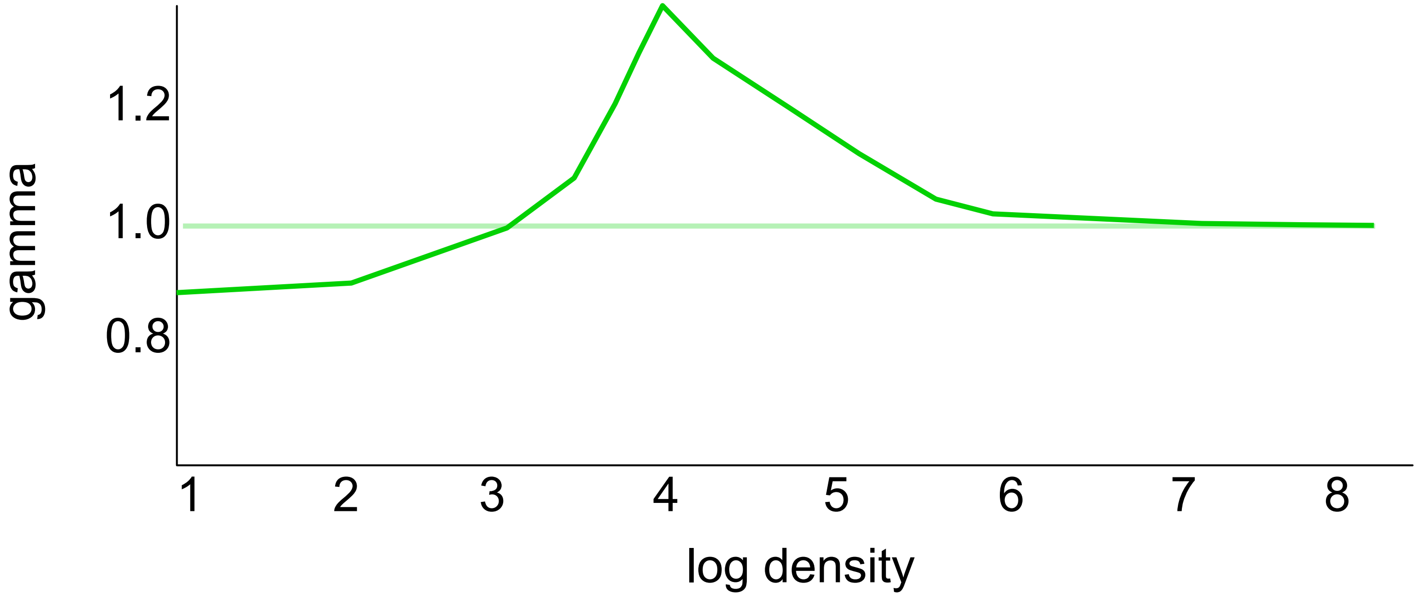
  → *POWER LAW BEHAVIOR*

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

  → *GAUSSIAN DISTRIBUTION*

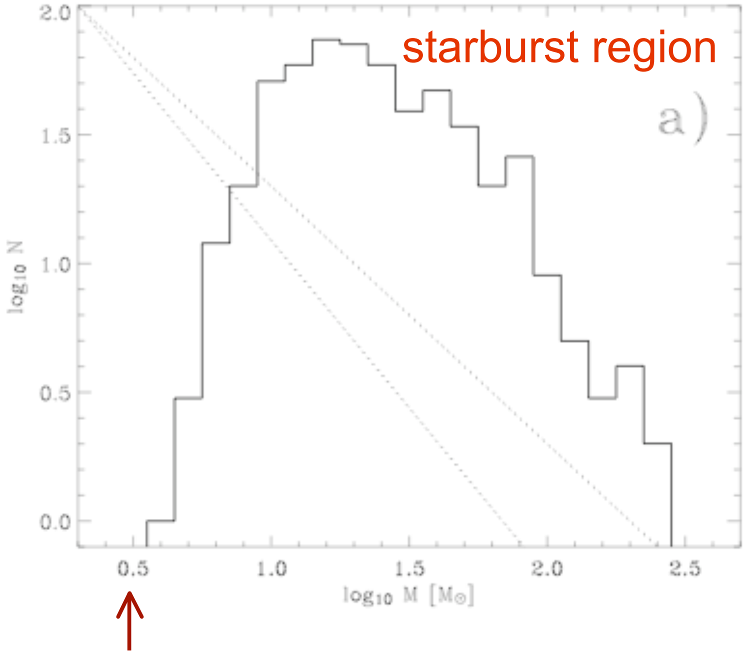
IMF in starburst galaxies

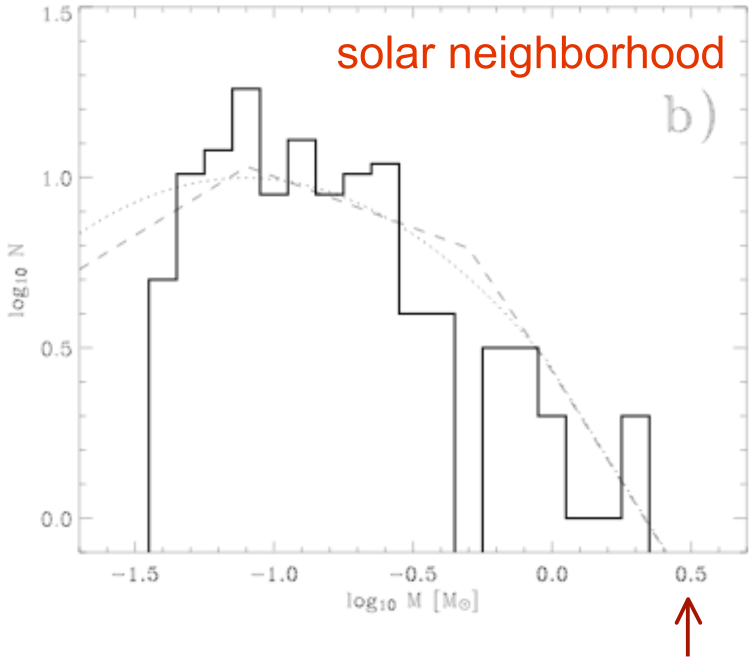
- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
  (see Spaans & Silk 2005)



IMF in starburst galaxies

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

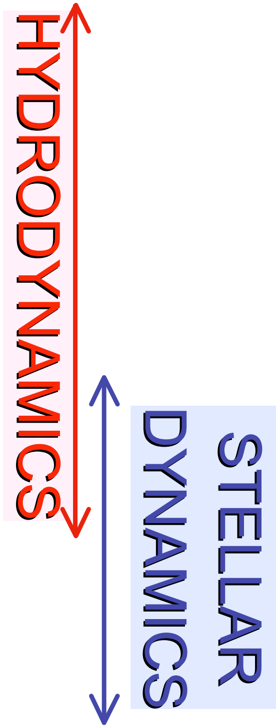




note the different mass scale...

IMF: Summary

- To get the stellar mass function (IMF) we need to:
  - describe supersonic turbulence (LES)
  - include self-gravity
  - model thermodynamic balance of the gas (heating, cooling, time-dependent chemistry, EOS)
  - follow formation of compact collapsed cores (transition from hydro to stellar dynamcis)
  - treat stellar dynamical processes (protostellar collisions, ejection by close encounters)



HYDRODYNAMICS

STELLAR DYNAMICS

Some final remarks…

- *GRAVOTURBULENT STAR FORMATION:*
  This dynamic theory can explain and reproduce many features of star-forming regions on small as well as on large galactic scales.

- Some open questions:
  - role of magnetic fields?
  - role of thermodynamic state of the gas?
  - what drives turbulence?
  - how are small scales (local molecular clouds) connected to large-scale dynamics?
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Some final remarks…

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  SPH appears able to describe gravoturbulent fragmentation and star formation in molecular clouds.
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