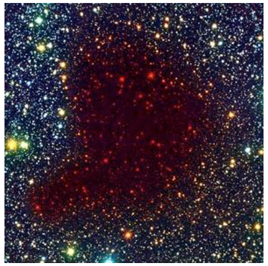
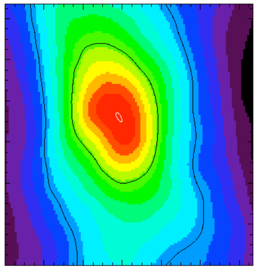
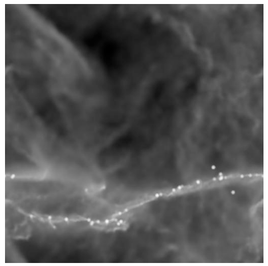
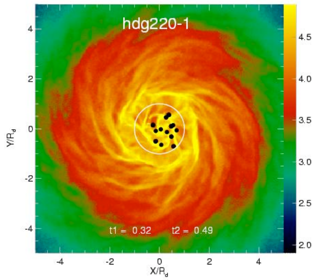
Molecular Cloud Fragmentation and Star Formation

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ARI+ITA+LSW

thanks to ...

- many thanks to the members of the *star formation group* at the *Institute for Theoretical Astrophysics* at the *Center for Astronomy* of *Heidelberg University*

  - Robi Banerjee
  - Paul Clark
  - Christoph Federrath
  - Simon Glover
  - Thomas Greif
  - Susanne Horn
  - Stefan Schmeja
  - Thomas Peters
  - Dominik Schleicher
  - and many guests

agenda

- formation of molecular clouds
  - on galactic scales
  - locally, in convergent flows
  - do molecular clouds loose memory of initial conditions?
- fragmentation of molecular clouds
  - interplay between gravity and turbulence
- star formation
  - initial mass function (models & caveats)
  - some examples
- what‘s next?

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!

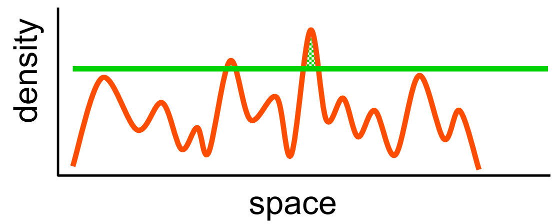
- validity:

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*
  - *gravitational instability*
  - *thermal 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)

predictions

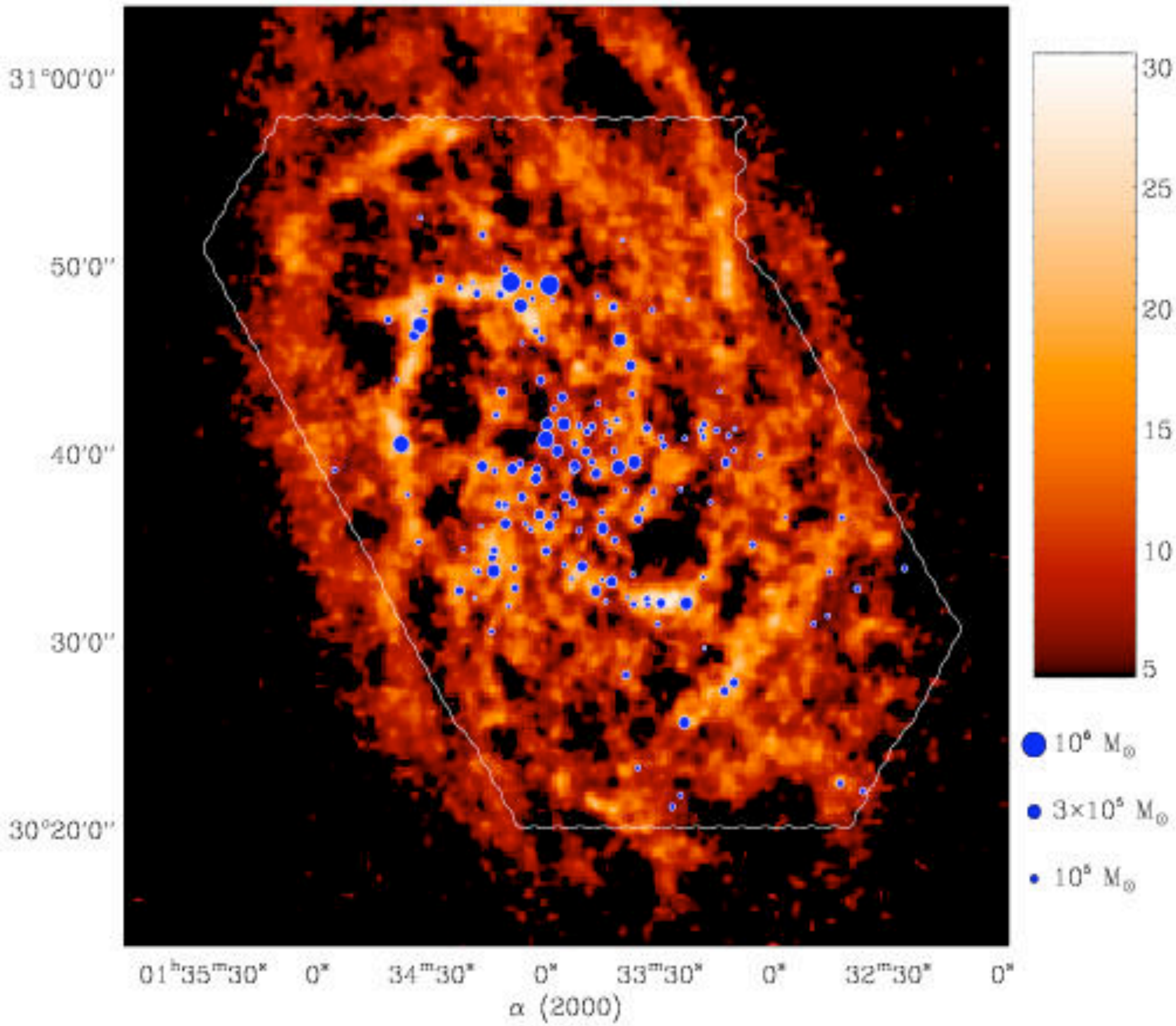
- *star formation on galactic scales*
  - global correlations: Schmidt-law
  - efficiencies, rates, timescales, and long-term evolution: starburst vs. low surface density gal.
  - triggers of star formation on global scales
  - formation of dense cold molecular clouds
    properties of these clouds (structure, turbulence, etc.)
- *star cluster formation within clouds*
  - SF efficiency and timescale
  - properties of young star clusters (structure, kinematics)
  - stellar mass function – IMF
  - multiplicity
  - effects of stellar feedback (jets, outflows, radiation, winds, ...)

galactic scales

molecular cloud formation

- star formation on galactic scales
  → missing link so far:
  formation of molecular clouds
- questions
  - where and when do molecular clouds form?
  - what are their properties?
  - how does that correlation to star formation?
  - global correlations? → Schmidt law

molecular cloud formation

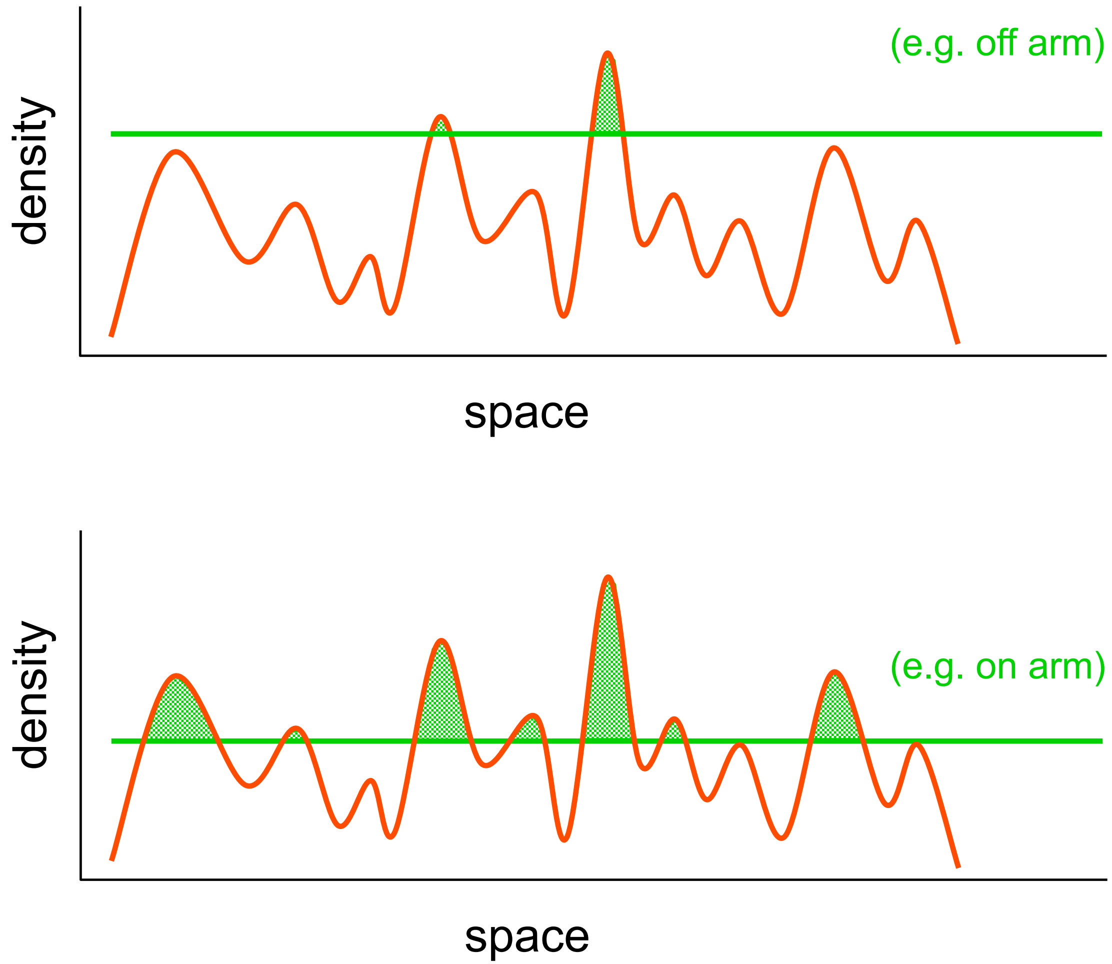


Thesis:

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

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

correlation with large-scale perturbations



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

some fluctuations are *dense* enough to *form H_2* within "*reasonable time*"

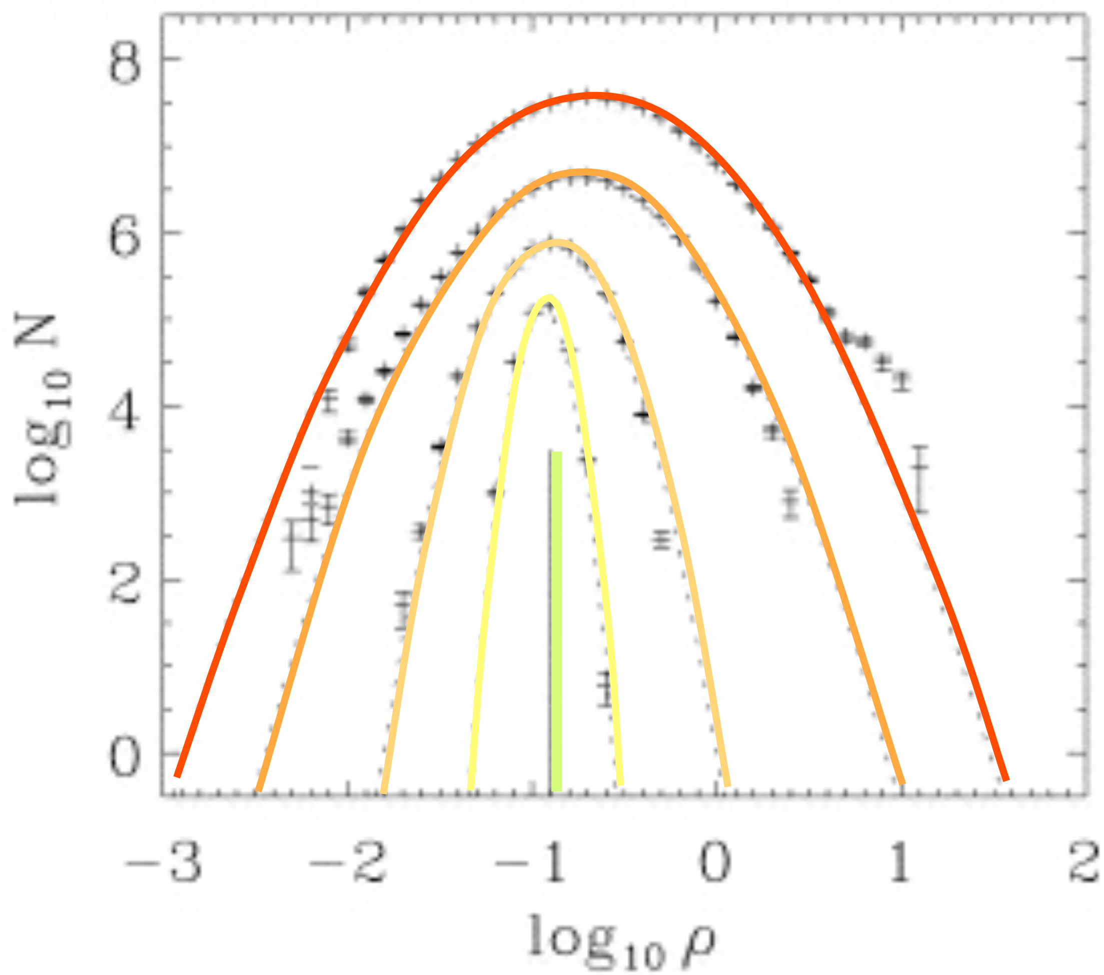
→ *molecular cloud*

(Glover & Mac Low 2007a,b)

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

(e.g. talk by Clare Dobbs)

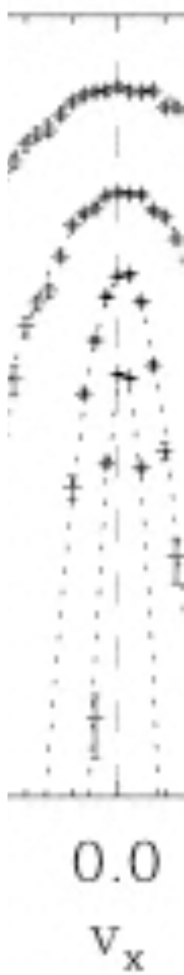
star formation on *global* scales



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

varying rms Mach numbers:

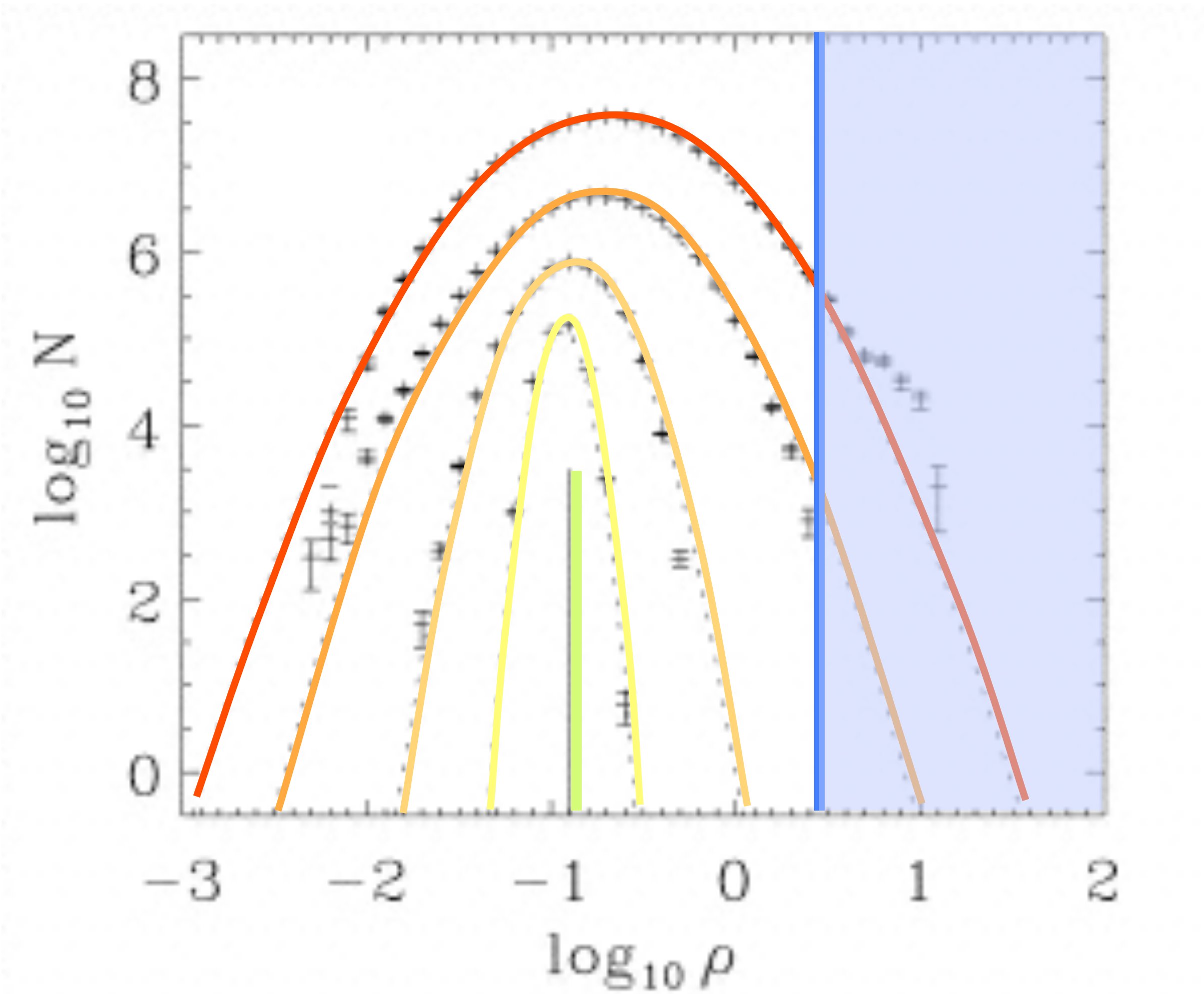
M1 > M2 > M3 > M4 > 0



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

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

star formation on *global* scales



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

(rate from Hollenback, Werner, & Salpeter 1971)

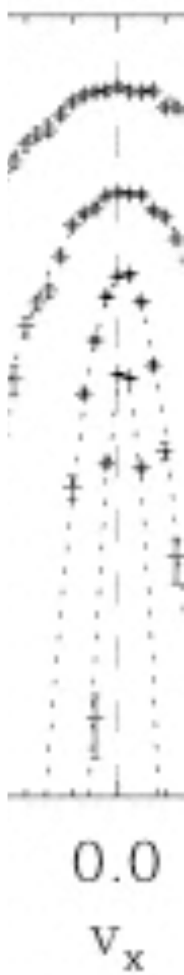
H_2 formation rate:

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

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

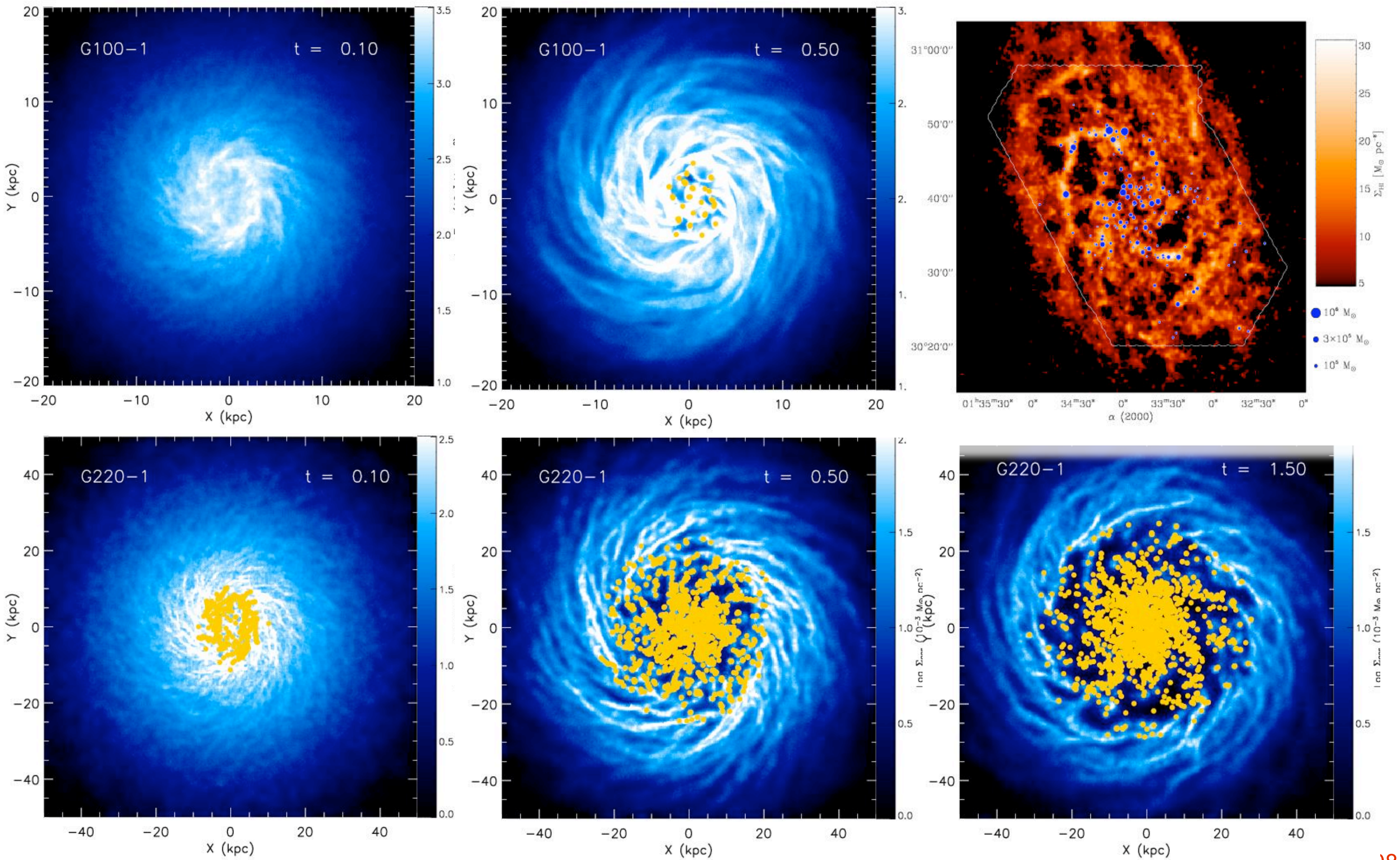
in turbulent gas, the H_2 fraction can become very high on short timescale

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

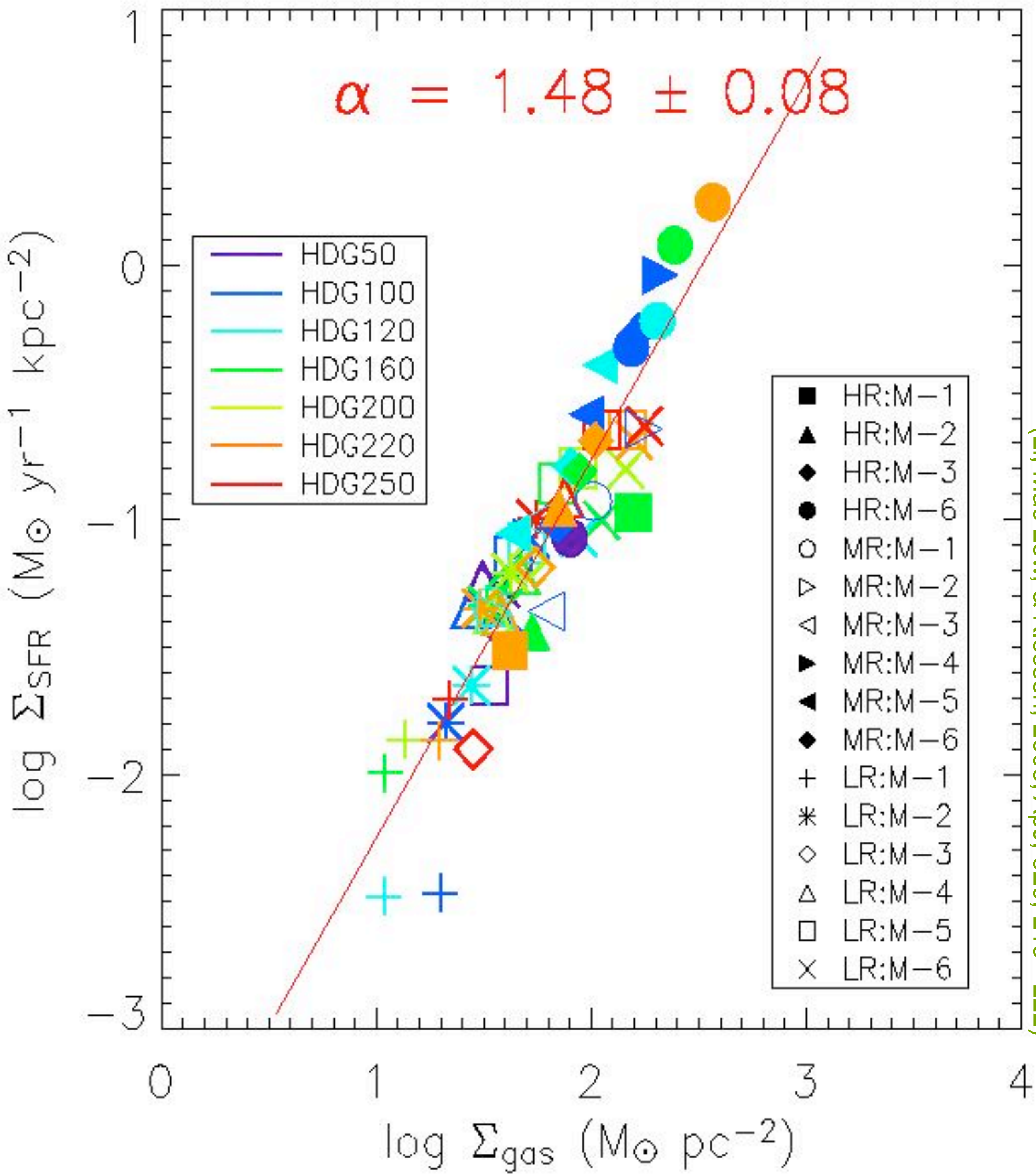


modeling galactic SF

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



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



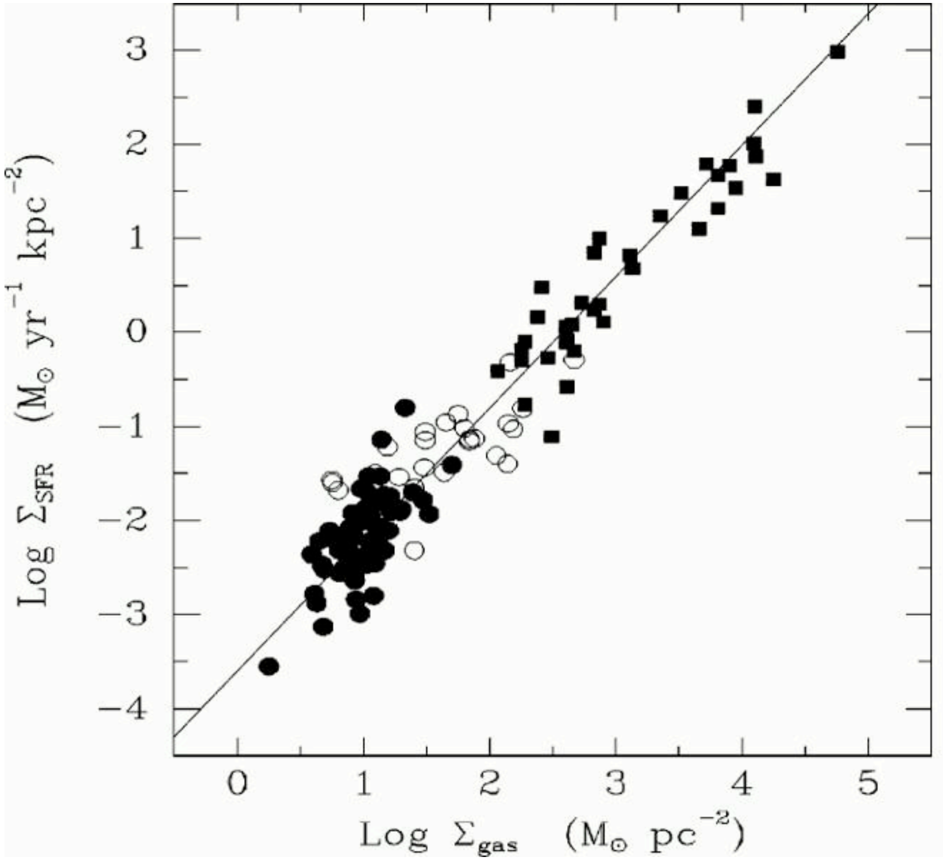
(Li, Mac Low, & Klessen, 2005, ApJ, 620, L19 - L22)

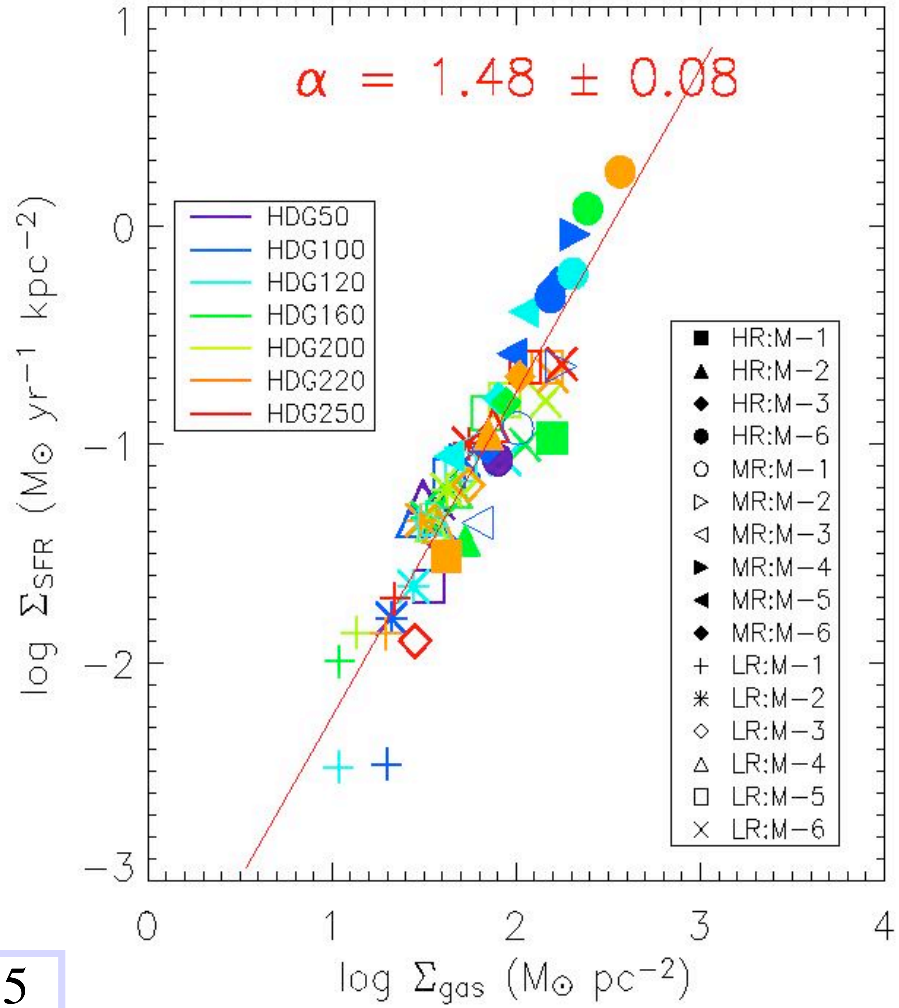
We find correlation between *star formation rate* and *gas surface density:*

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

global Schmidt law

observed Schmidt law

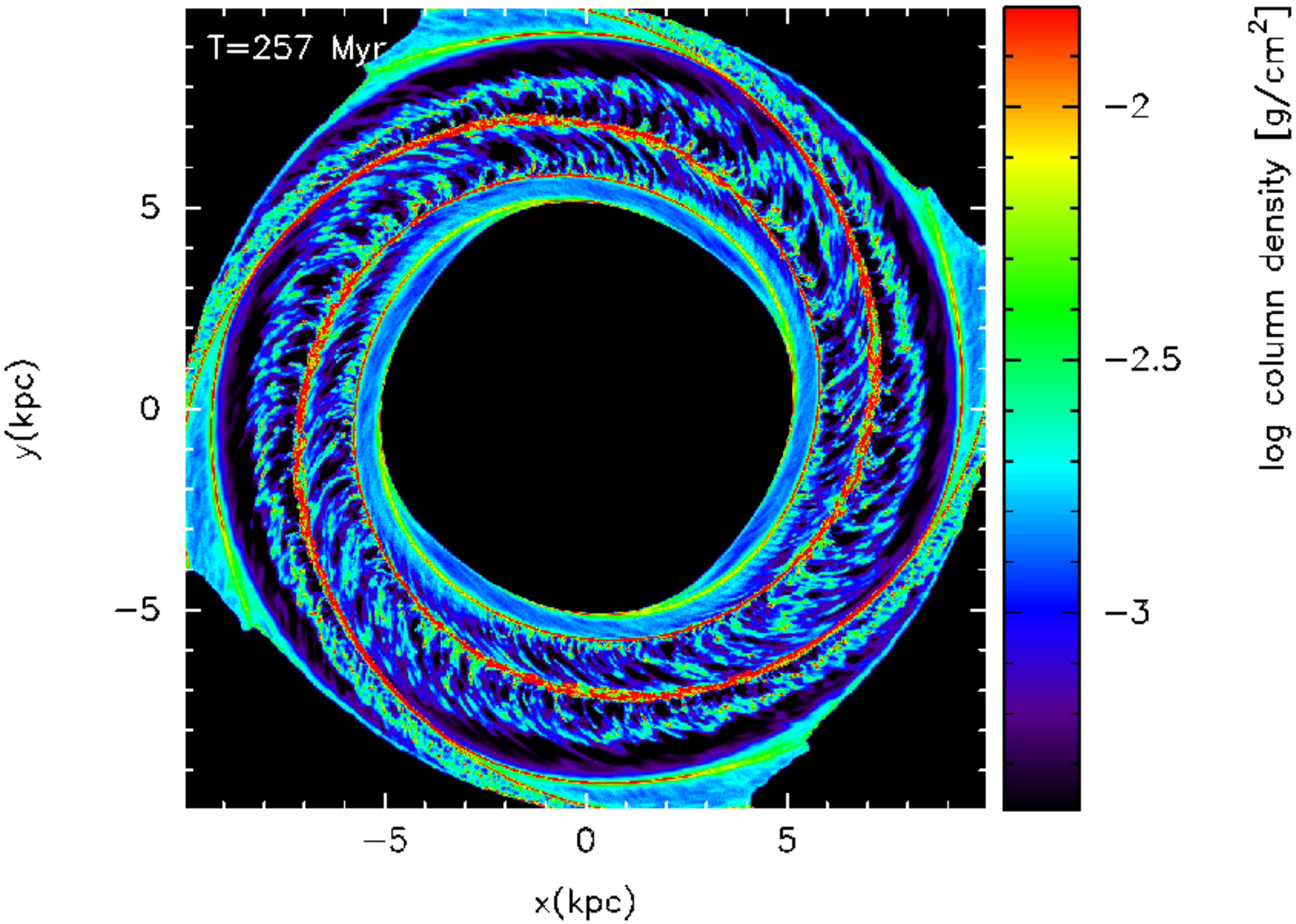




in both cases: $\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{1.5}$

(from Kennicutt 1998)

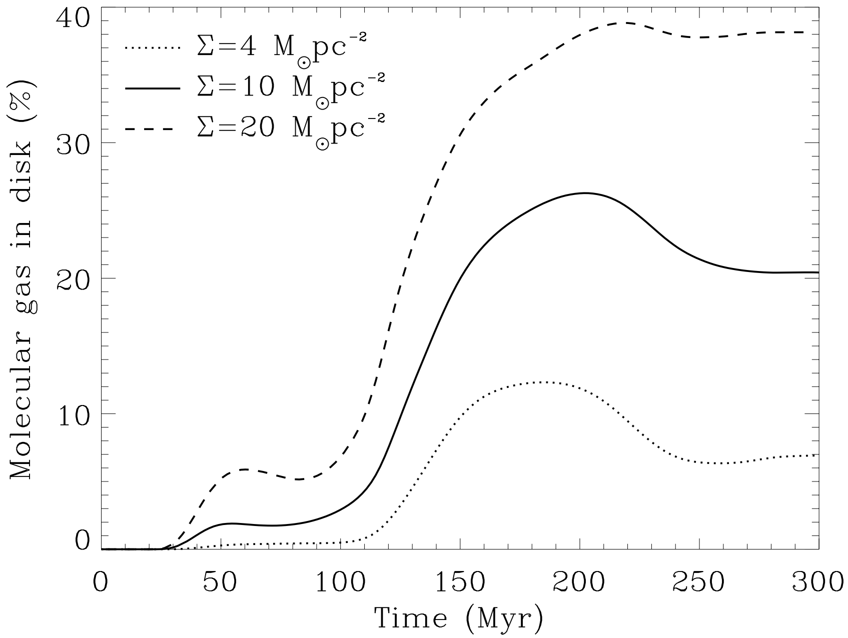
molecular cloud formation



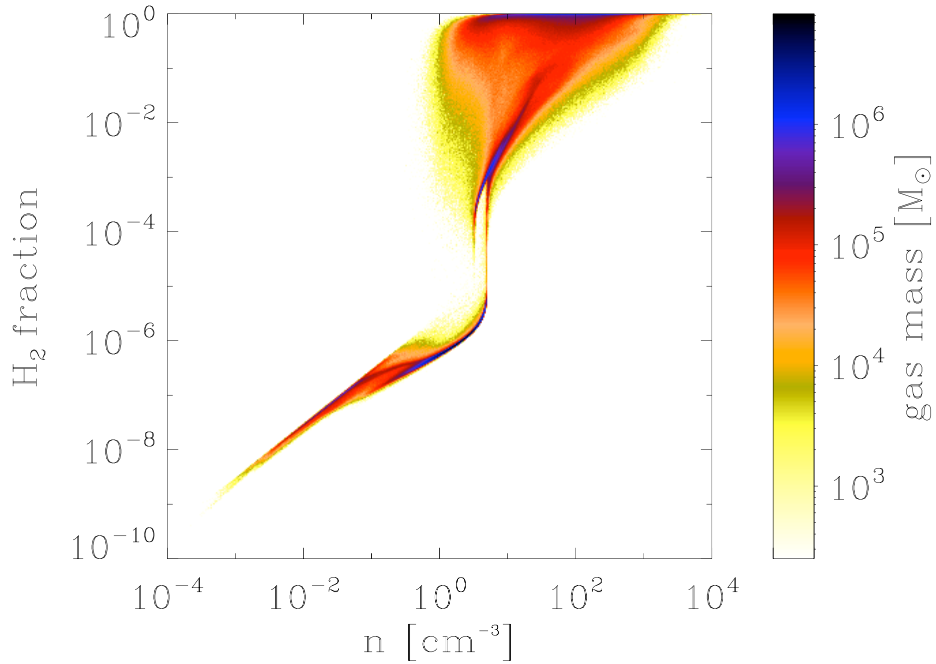
(from Dobbs, Glover, Clark, Klessen 2008)

molecular cloud formation

molecular gas fraction as function of time



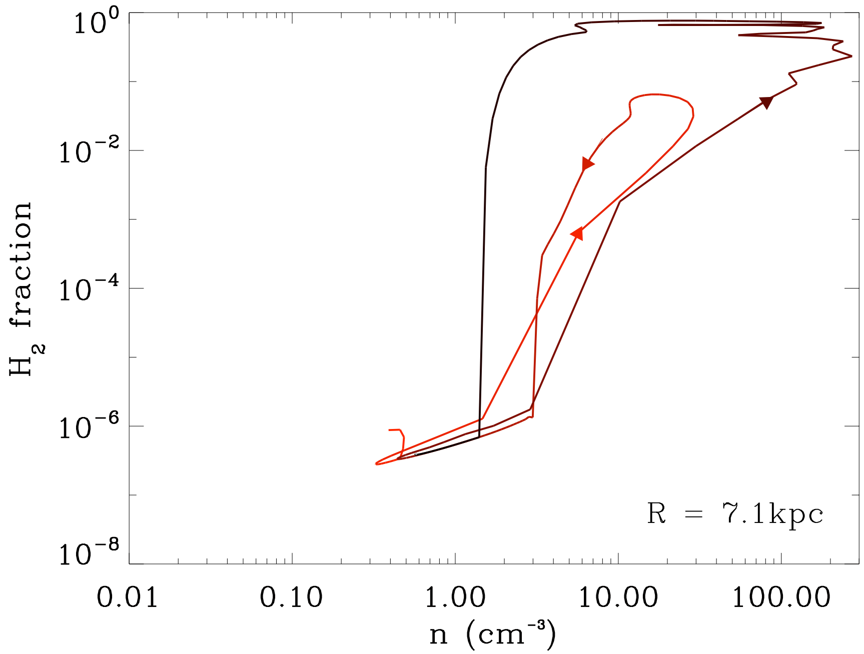
molecular gas fraction as function of density



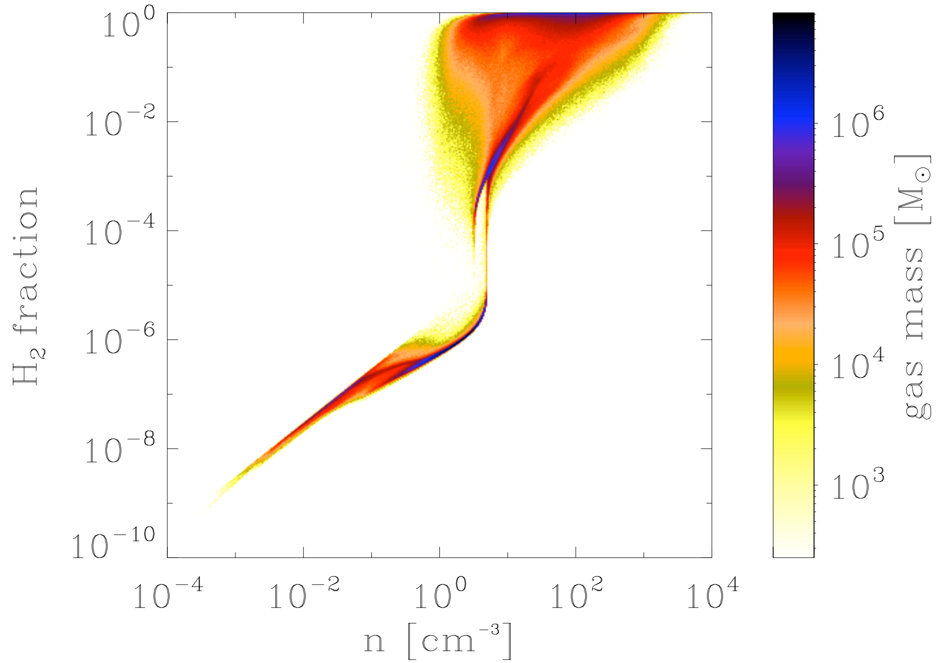
(Dobbs et al. 2008)

molecular cloud formation

molecular gas fraction of fluid element as function of time

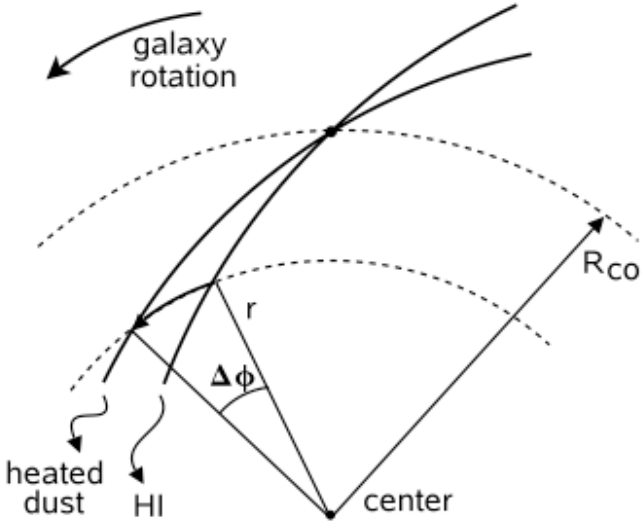


molecular gas fraction as function of density



(Dobbs et al. 2008)

observed timescales



Tamburro et al. (2008)

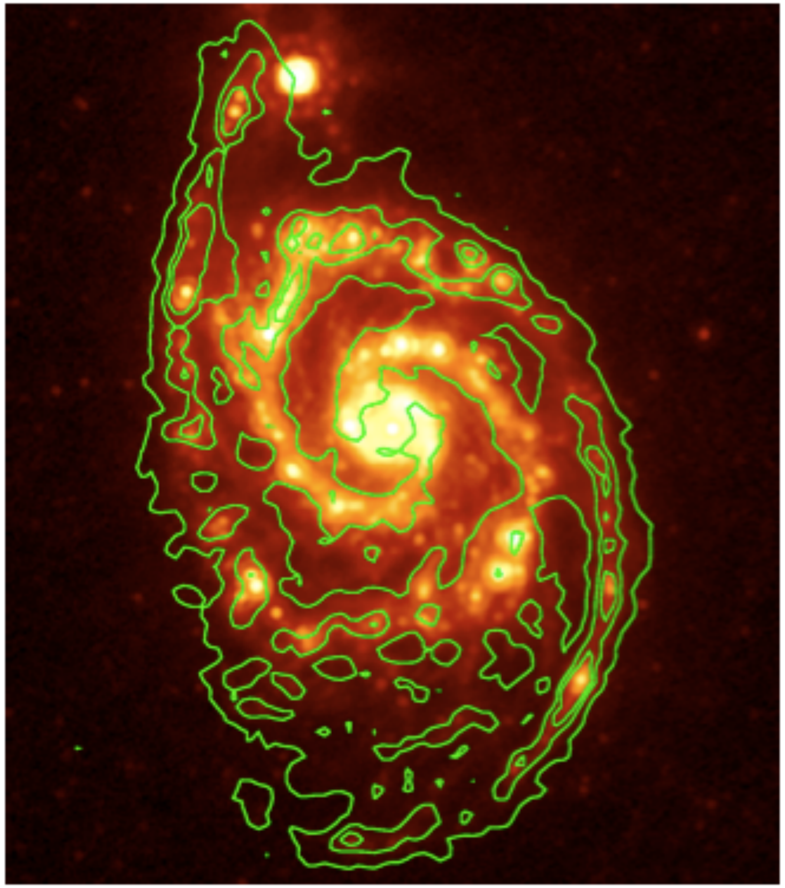
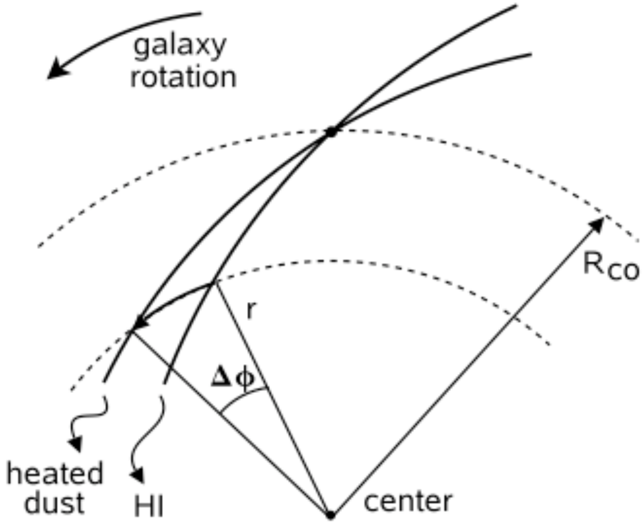


Fig. 1.— NGC 5194: the 24 μm band image is plotted in color scale; the H I emission map is overlayed with green contours.

observed timescales



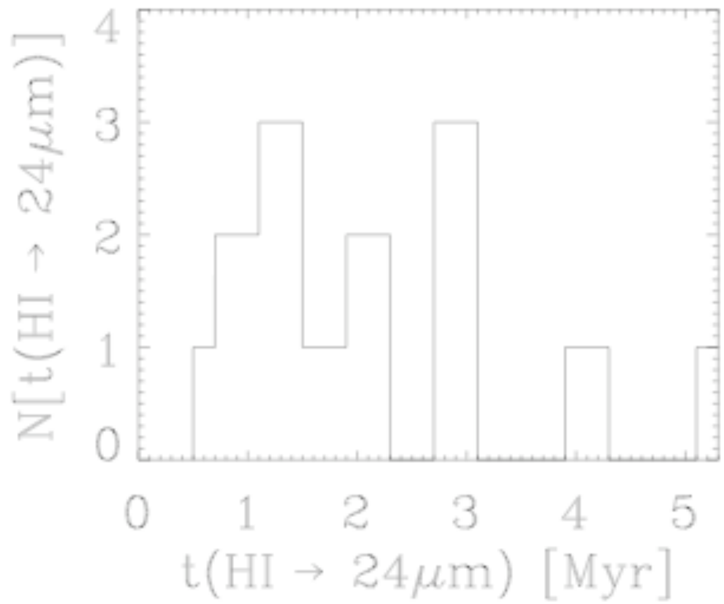


Fig. 5.— Histogram of the time scales $t_{\mathrm{HI} \mapsto 24\,\mu\mathrm{m}}$ derived from the fits in Figure 4 and listed in Table. 2 for the 14 sample galaxies listed in Table. 1. The timescales range between 1 and 4 Myr for almost all galaxies.

Tamburro et al. (2008)

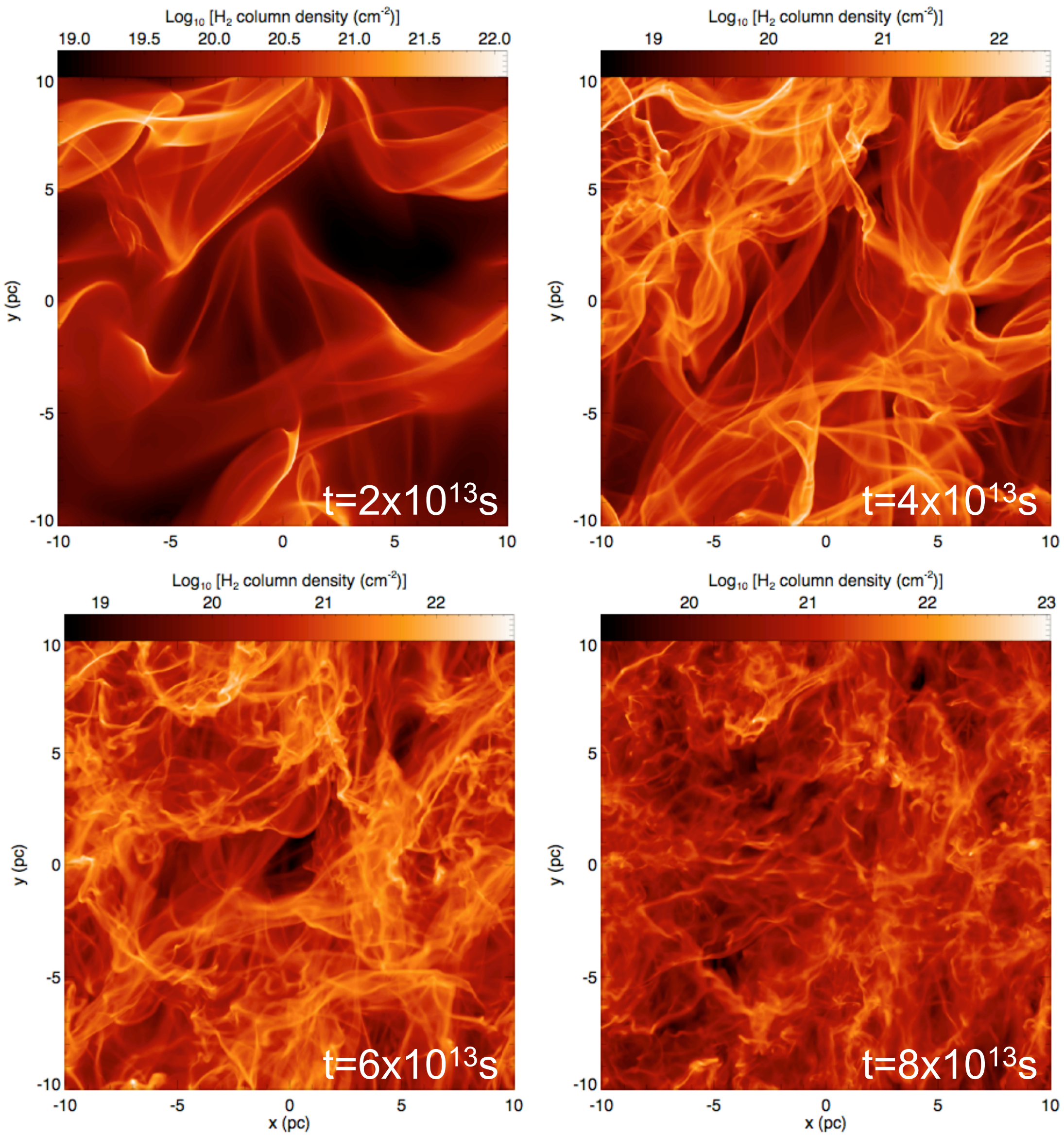
ISM: transition HI to H_2

consistent models of ISM dynamics require to go beyond the simple models!

- magnetohydrodynamics (account for large-scale dynamics + turbulence)
- time-dependent chemistry (reduced network, focus on few dominant species, e.g. H_2)
- radiation (currently simple assumptions)

H2 forms rapidly in shocks / transient density fluctuations / H2 gets destroyed slowly in low density regions / result: turbulence greatly enhances H2-formation rate

(Glover & Mac Low 2007ab:)



Reduced chemical network

Table 1. The set of chemical reactions that make up our model of non-equilibrium hydrogen chemistry.

Reaction	Reference
1. $H + H + grain \rightarrow H_2 + grain$	Hollenbach & McKee (1979)
2. $H_2 + H \rightarrow 3H$	Mac Low & Shull (1986) (low density), Lepp & Shull (1983) (high density)
3. $H_2 + H_2 \rightarrow 2H + H_2$	Martin, Keogh & Mandy (1998) (low densit; Shapiro & Kang (1987) (high density)
4. $H_2 + \gamma \rightarrow 2H$	See § 2.2.1
5. $H + c.r. \rightarrow H^+ + e$	Liszt (2003)
6. $H + e \rightarrow H^+ + 2e$	Abel *et al.* (1997)
7. $H^+ + e \rightarrow H + \gamma$	Ferland *et al.* (1992)
8. $H^+ + e + grain \rightarrow H + grain$	Weingartner & Draine (2001)

Table 2. Processes included in our thermal model.

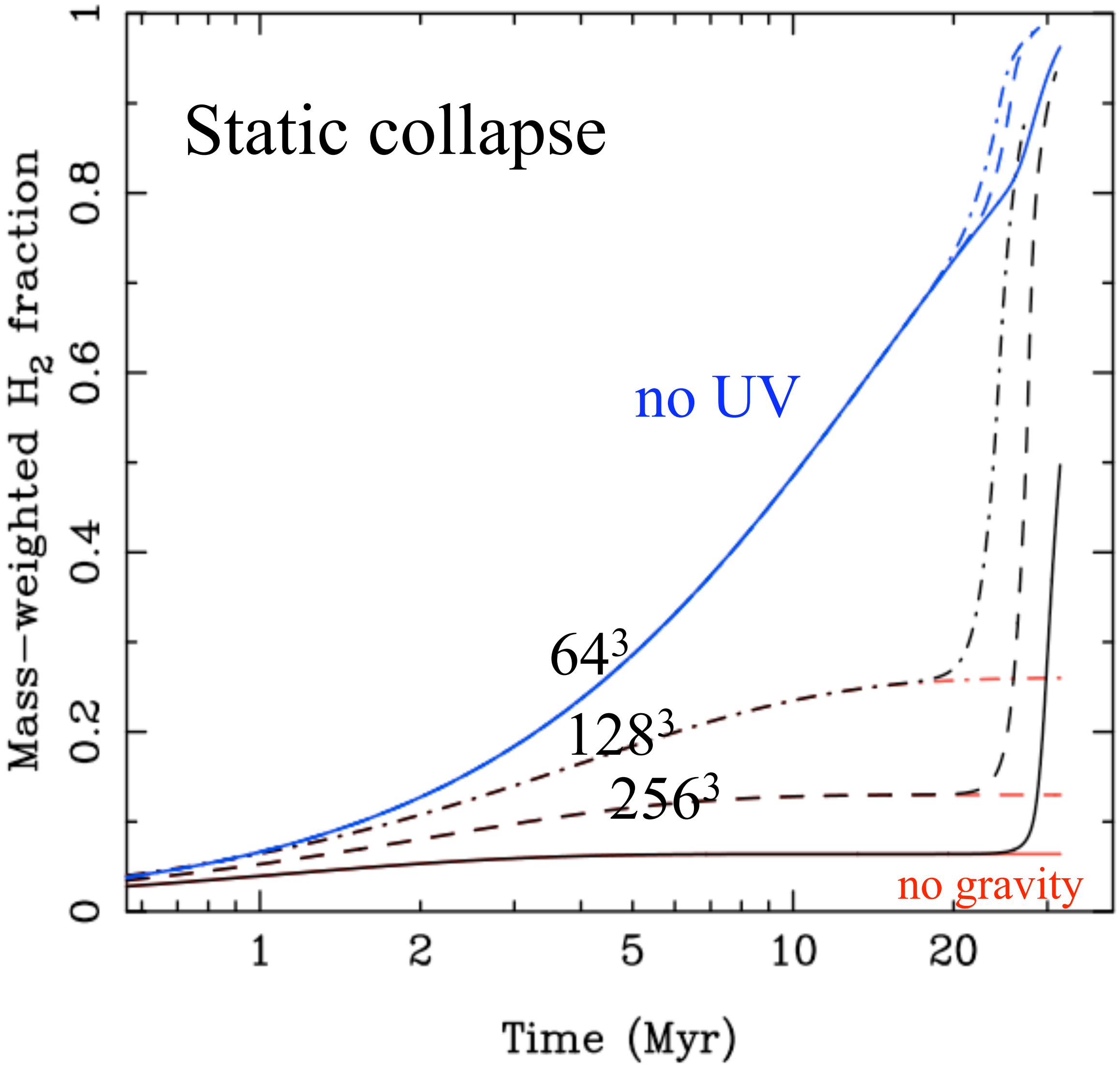
Process	References
Cooling:	
C II fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H_2) – Flower & Launay (1977)
	Collisional rates (H, $T < 2000$ K) – Hollenbach & McKee (1989)
	Collisional rates (H, $T > 2000$ K) – Keenan *et al.* (1986)
	Collisional rates (e^-) – Wilson & Bell (2002)
O I fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H, H_2) – Flower, priv. comm.
	Collisional rates (e^-) – Bell, Berrington & Thomas (1998)
	Collisional rates (H^+) – Pequignot (1990, 1996)
Si II fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H) – Roueff (1990)
	Collisional rates (e^-) – Dufton & Kingston (1991)
H_2 rovibrational lines	Le Bourlot, Pineau des Forêts & Flower (1999)
Gas-grain energy transfer[1]	Hollenbach & McKee (1989)
Recombination on grains	Wolfire *et al.* (2003)
Atomic resonance lines	Sutherland & Dopita (1993)
H collisional ionization	Abel *et al.* (1997)
H_2 collisional dissociation	See Table 1
Heating:	
Photoelectric effect	Bakes & Tielens (1994); Wolfire *et al.* (2003)
H_2 photodissociation	Black & Dalgarno (1977)
UV pumping of H_2	Burton, Hollenbach & Tielens (1990)
H_2 formation on dust grains	Hollenbach & McKee (1989)
Cosmic ray ionization	Goldsmith & Langer (1978)

here: e^-, H^+, H, H_2

in primordial gas we do:

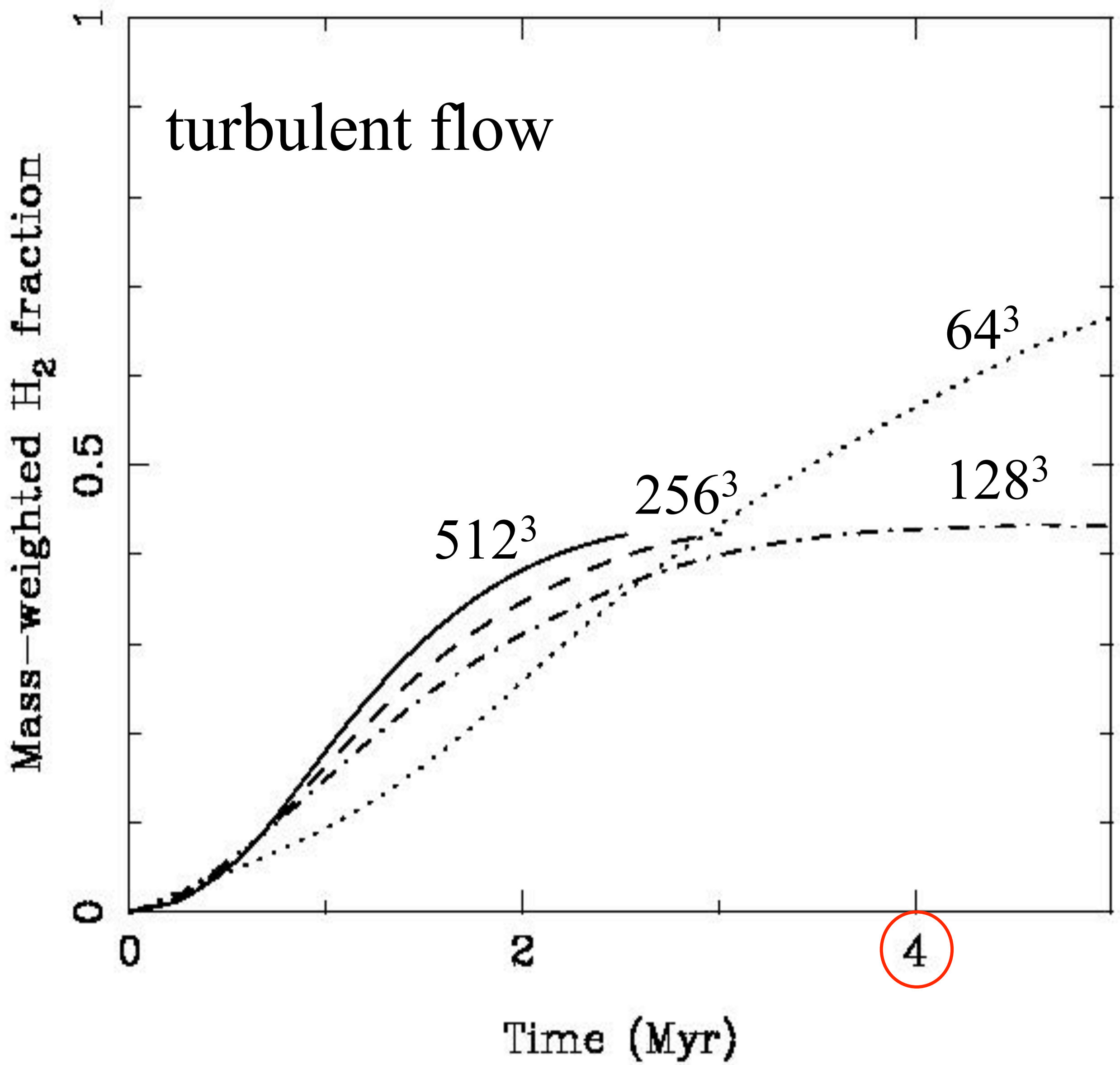
e^-, H^+, H, H^-, H_2^+, H_2, C, C^+, O, O^+

(Glover & Mac Low 2007ab)



L = 40 pc, n_0 = 100 cm-3, B_0 = 5.85 mG, v_{rms} = 0.0

(Glover & Mac Low 2007a)



L = 20 pc, B_0 = 5.85 μG, v_{rms} = 10 km/s

(Glover & Mac Low 2007a)

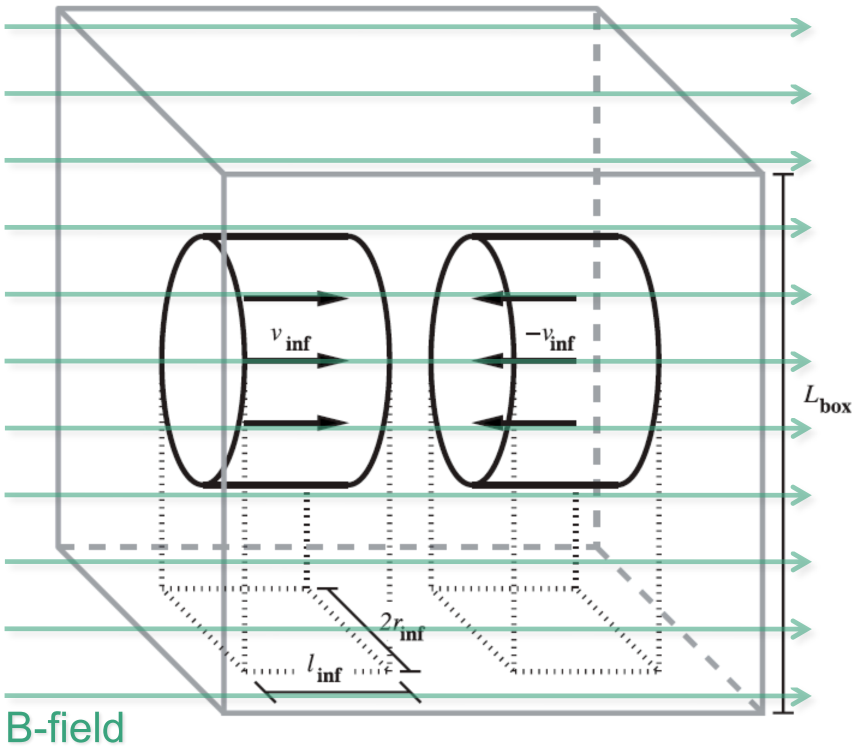
GMC scales

from atomic gas to molecular clouds

- thesis: *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 galaxy
- questions
  - are molecular clouds truly “multi-phase” media?
  - turbulence? dynamical & morphological properties?
  - what is relation to initial & environmental conditions?
  - magnetic field structure? (see special discussion session)

convergent flows: set-up

numerical set-up



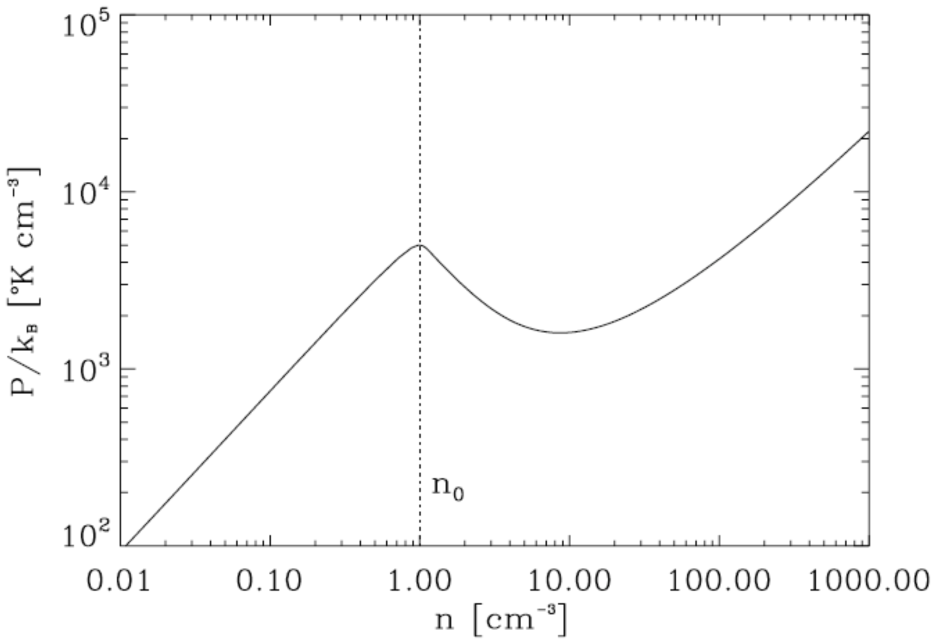
from Vazquez-Semadeni et al. (2007)

- convergent flow studies
  - atomic flows collide
  - cooling curve (soon chemistry)
  - gravity
  - magnetic fields
  - numerics: AMR, BGK, SPH

see studies by Banerjee et al., Heitsch et al., Hennebelle et al., Vazquez-Semadeni et al.

convergent flows: set-up

adopted cooling curve



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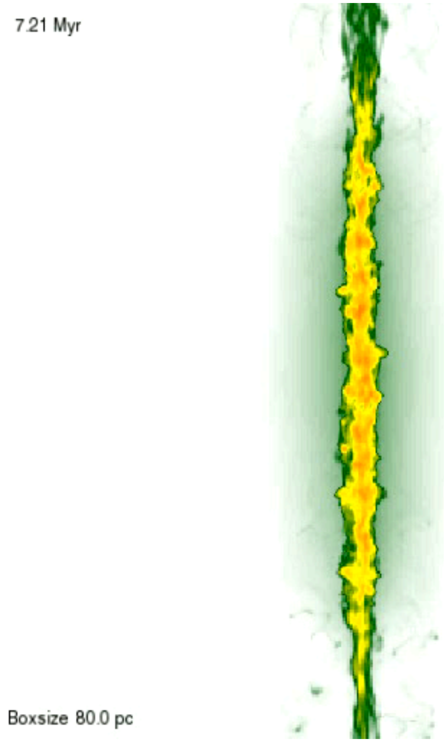
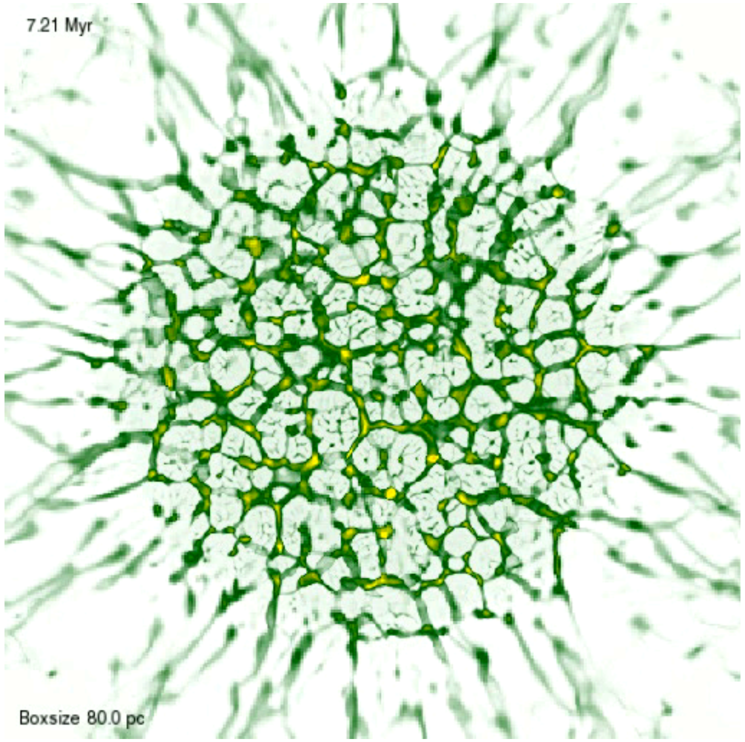
MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:





from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. as well as talk by Fabian Heitsch)

some results: density & B-field

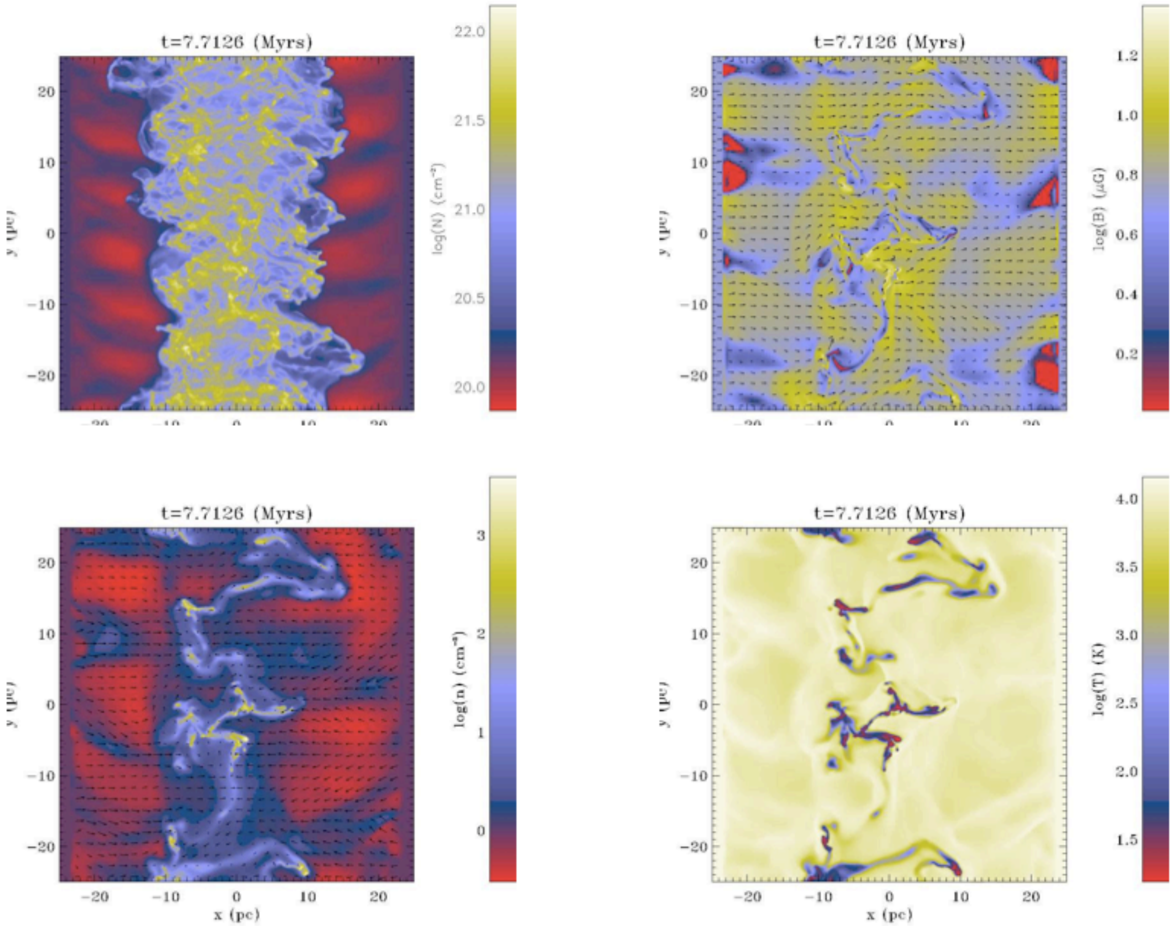
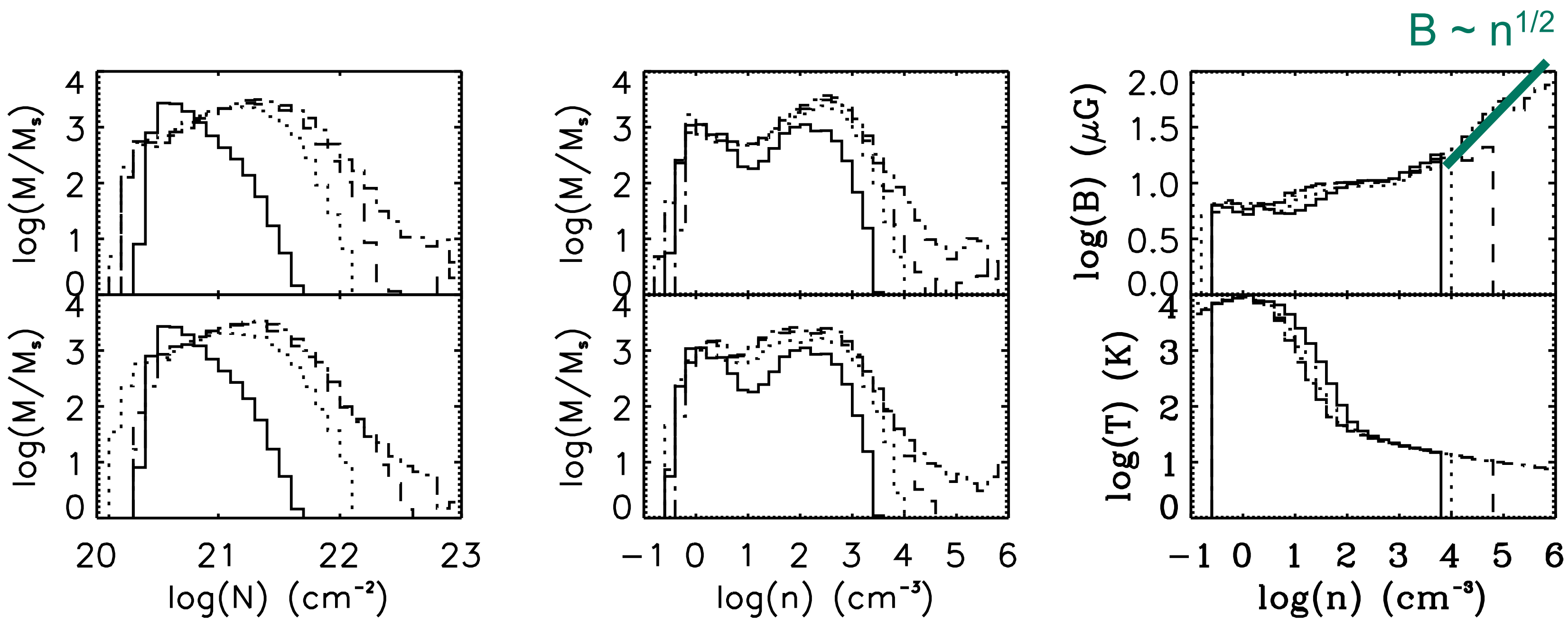


Fig. 2. Top left panel: column density. Top right panel: Magnetic intensity and its xy-components (indicated as arrows) in the $z = 0$ plane. Bottom left panel: density and velocity fields in the $z = 0$ plane. Bottom right panel: temperature in the $z = 0$ plane.

from Hennebelle et al. (2008)

initially B = 5 μG

some results: density & B-field



from Hennebelle et al. (2008)

initially B = 5 μG

some results: growth of cores

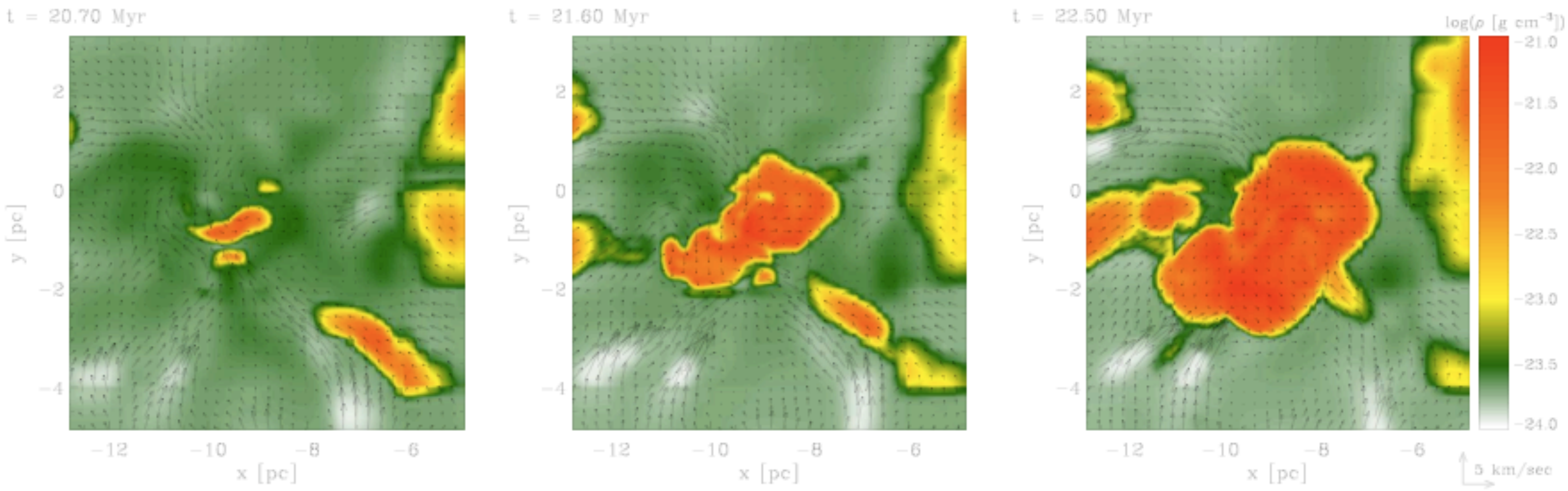
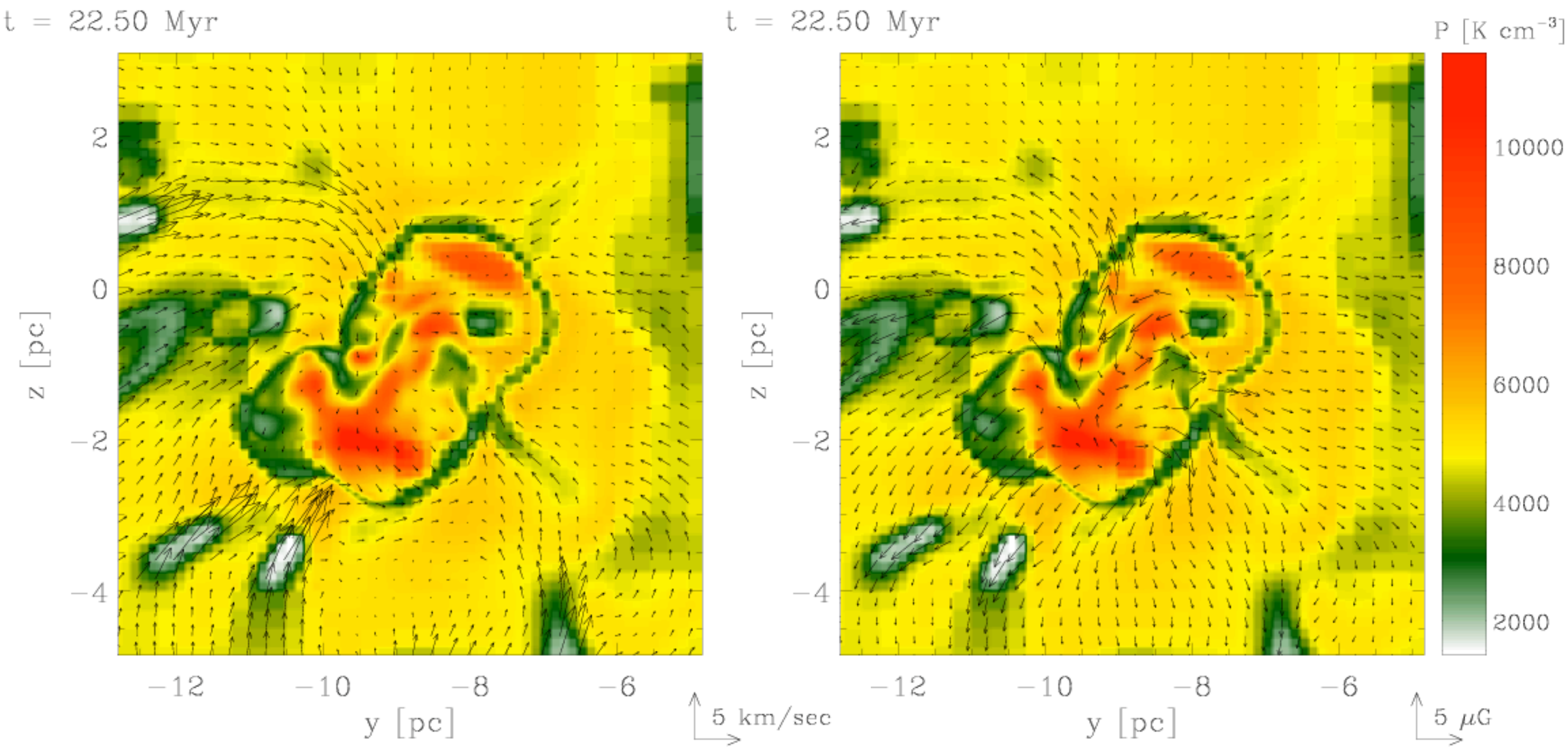


Figure 2. Shows the time evolution of a typical clump which initially develops out of the thermally unstable WNM in shock layers of turbulent flows. A small cold condensate grows by outward propagation of its boundary layer. Coalescence and merging with nearby clumps further increases the size and mass of these clumps. The global gravitational potential of the proto-cloud enhances the merging probability with time. The images show 2D slices of the density (logarithmic colour scale) and the gas velocity (indicated as arrows) in the plane perpendicular to the large scale flows.

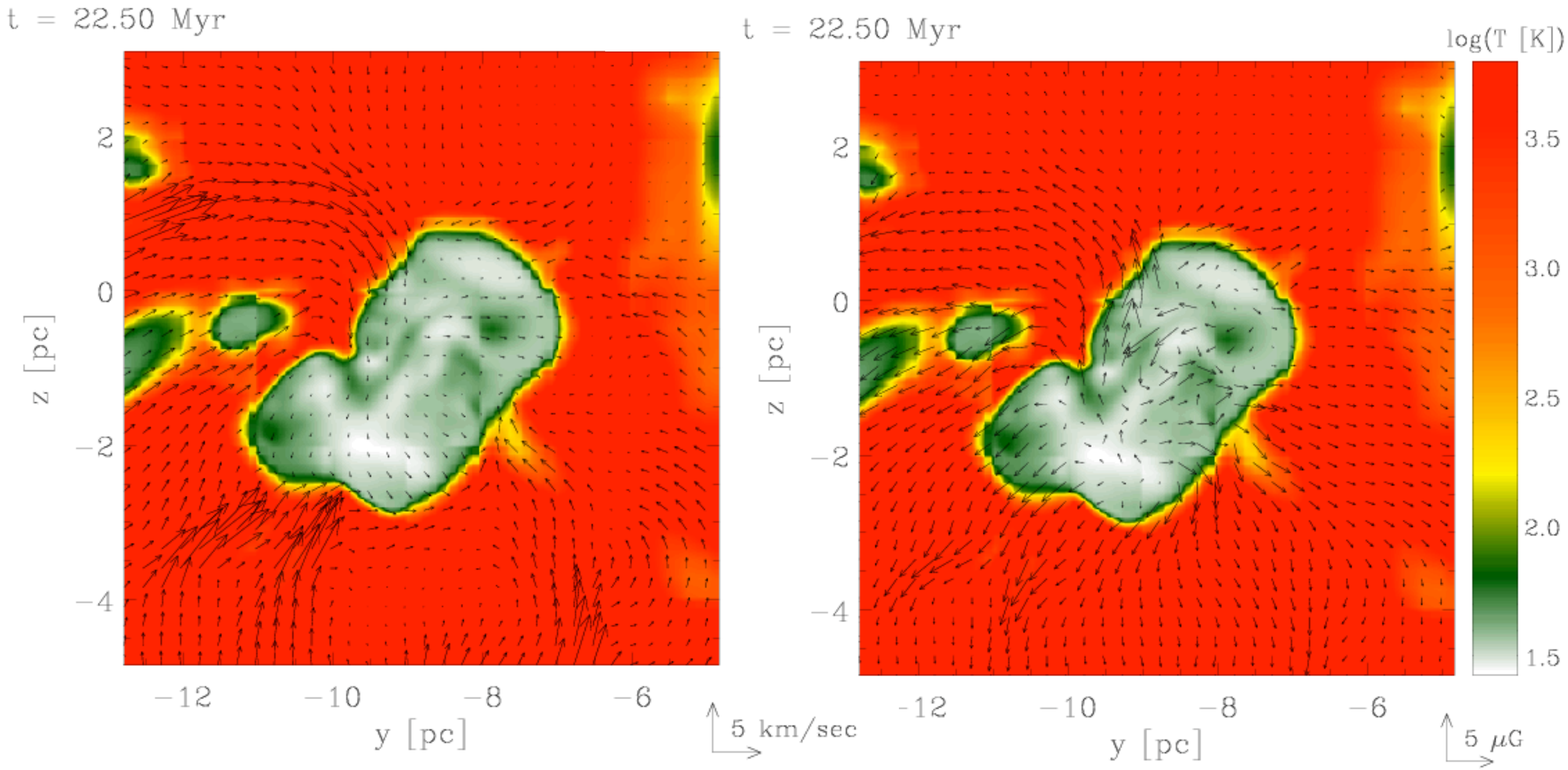
two phases of core growth:
(1) by *outward propagation* of *boundary layer* → Jeans sub-critical phase
(2) *core mergers* → super-Jeans → gravitational collapse & star formation
example: *Pipe nebula* ???

from Banerjee et al. (2008)



relation between flow and magnetic field:
mass flow mostly along field lines

from Banerjee et al. (2008)



relation between flow and magnetic field:
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some results: growth of cores

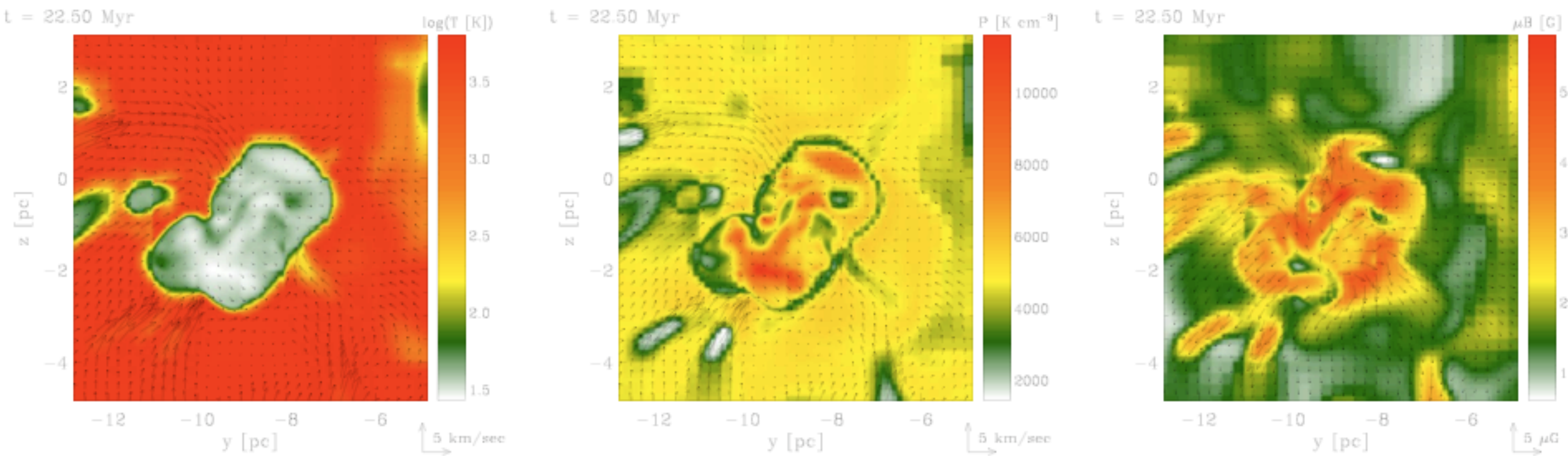


Figure 3. Shows the structure of one typical clump which forms in the thermally unstable WNM gas. The images show 2D slices of the temperature (left, log scale), thermal pressure (middle, linear scale), and magnetic field strength (right, linear scale). The arrows in the temperature and pressure plots indicate the velocity field and, in the right panel, the magnetic stream lines. The cold ($T \sim 30 - 50\,\mathrm{K}$), dense ($n \sim 2 - 5 \times 10^3\,\mathrm{cm}^{-3}$) molecular clump is embedded in the warm atomic gas ($T \sim 5 \times 10^3\,\mathrm{K}$) and has a well defined boundary. Due to the thermal properties of the ISM (see Fig. 2 of Vázquez-Semadeni et al. 2007, for the equilibrium pressure), such clumps are almost in pressure equilibrium with their surrounding. The overdense clumps exert a gravitational force on the low density environment where gas continues to stream into the clump predominately anti-parallel to the magnetic flux lines (see also Fig. 2).

some properties of cores:

(1) cores are in approximate *pressure equilibrium* with surrounding

(2) accretion / mass flow mostly along magnetic field lines

(2) core densities $n \sim 2 - 5 \times 10^3\ cm^{-3}$, core temperature $T \sim 30 - 50\ K$

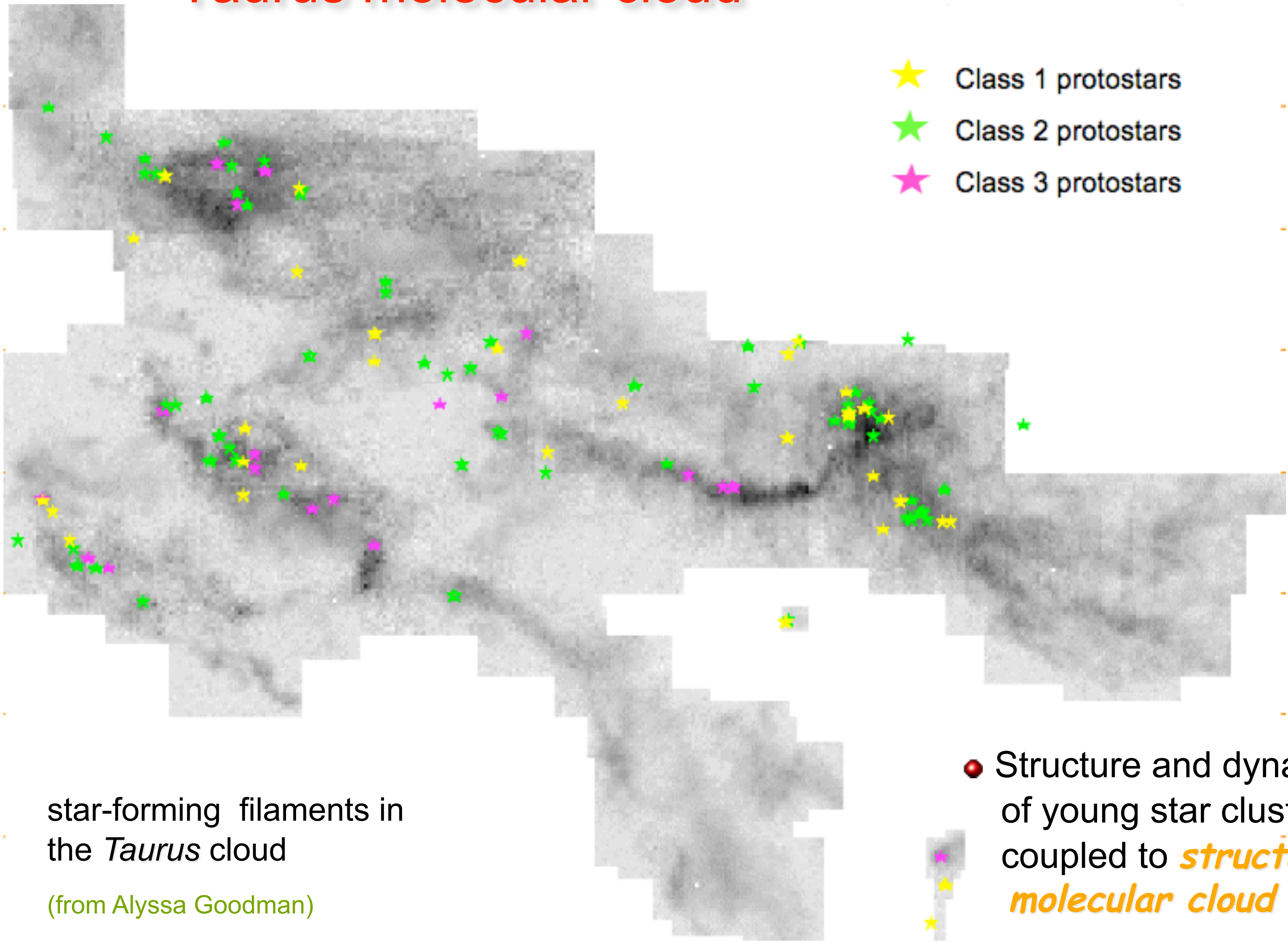
from Banerjee et al. (2008)

cluster scales

fragmentation of molecular clouds

- fragmentation of molecular clouds and relation to stellar birth
- some questions
  - how does the turbulence generated by cloud formation influence cloud fragmentation?
  - how important if turbulence from internal feedback? (is that consistent with observations?)
  - interplay between gravity and turbulence?
    → role of turbulence for star formation

Taurus molecular cloud



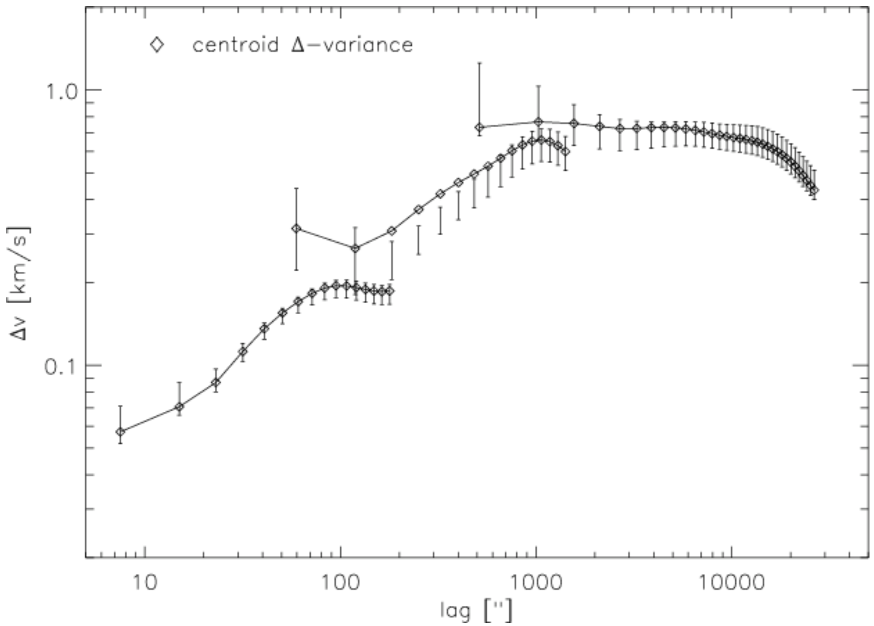
star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

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

turbulence

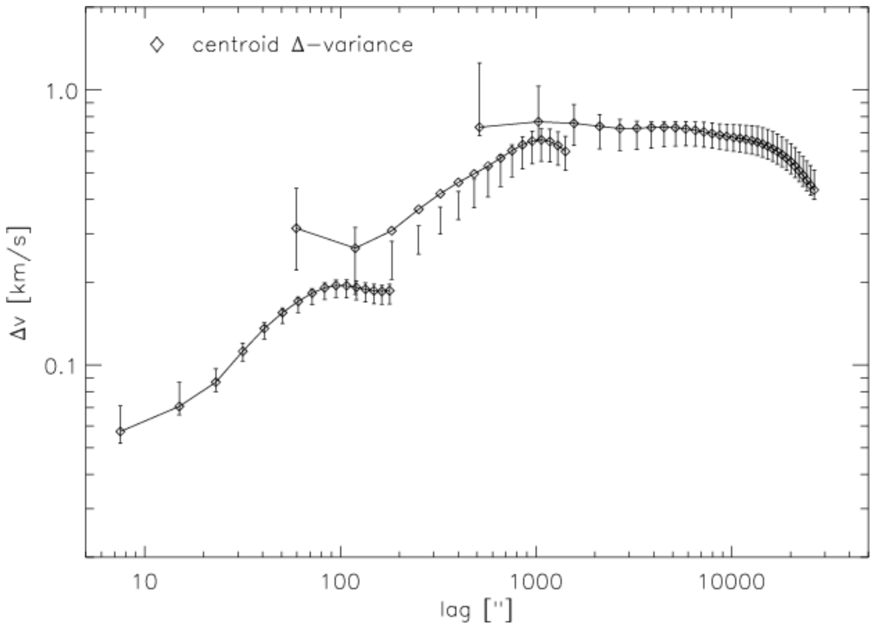
what drives turbulence?



Polaris flare (from Ossenkopf & Mac Low 2002)

- turbulence characteristics
  - molecular cloud turbulence seems to be dominated by large-scale models
  - consistent with external driving
  - convergent flows?
    → the same process that creates the cloud supplies internal turbulence ...
  - alternative mechanisms:
    - gravity (spiral shocks), supernovae, HII regions?
    - internal sources: jets, outflows?

what drives turbulence?

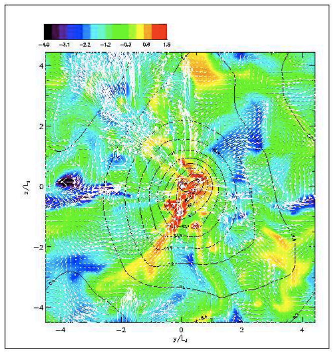


Polaris flare (from Ossenkopf & Mac Low 2002)

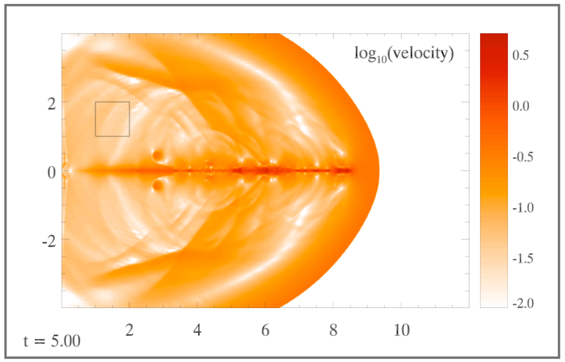
- turbulence characteristics
  - molecular cloud turbulence seems to be dominated by large-scale models
  - consistent with external driving
  - *convergent flows?*
    → the same process that creates the cloud supplies internal turbulence ..
    → caused by
      - *gravity (spiral shocks),* supernovae, HII regions?
  - alternative mechanisms:
      - internal sources: jets, outflows?

what drives turbulence?

- some words on internal sources
  - molecular cloud turbulence seems to be dominated by large-scale models
  - jets / outflow can only work after onset of star formation
    → what about turbulence in non-star forming parts of clouds, or during initial phases?
- there is debate on effectiveness of internal sources for driving supersonic turbulence
  (Li & Nakamura vs. Banerjee, Klessen, Fendt)



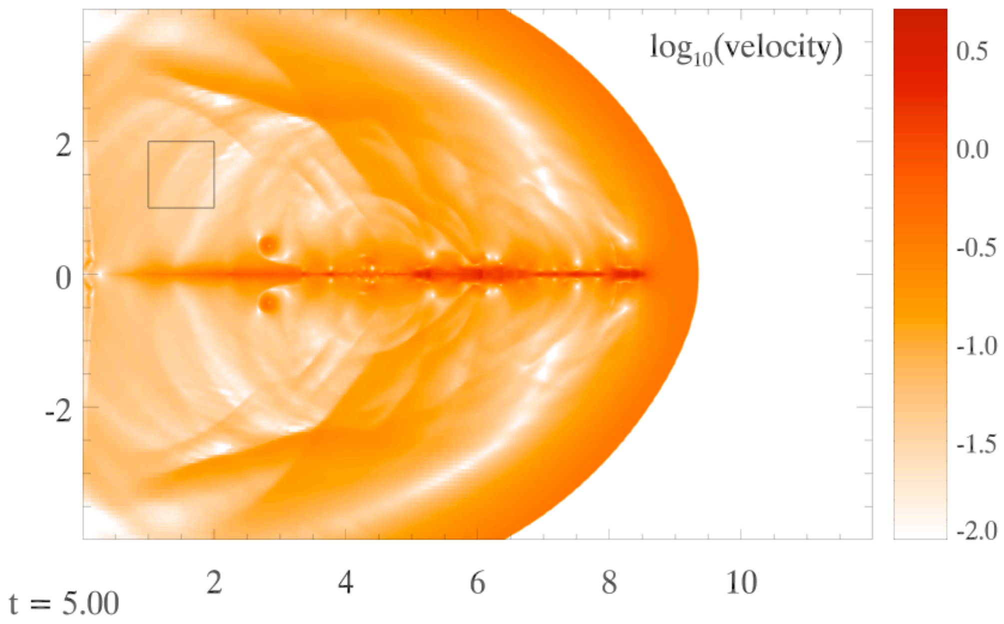
(Nakamura & Li 2007)

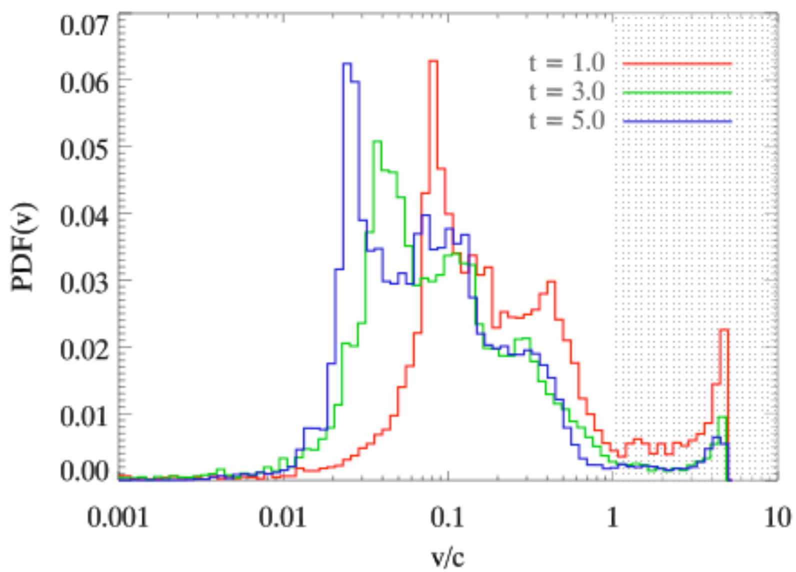


(Banerjee, Klessen, Fendt 2008)

local feedback

- individual jets cannot drive supersonic turbulence in a space-filling way → need additional physics

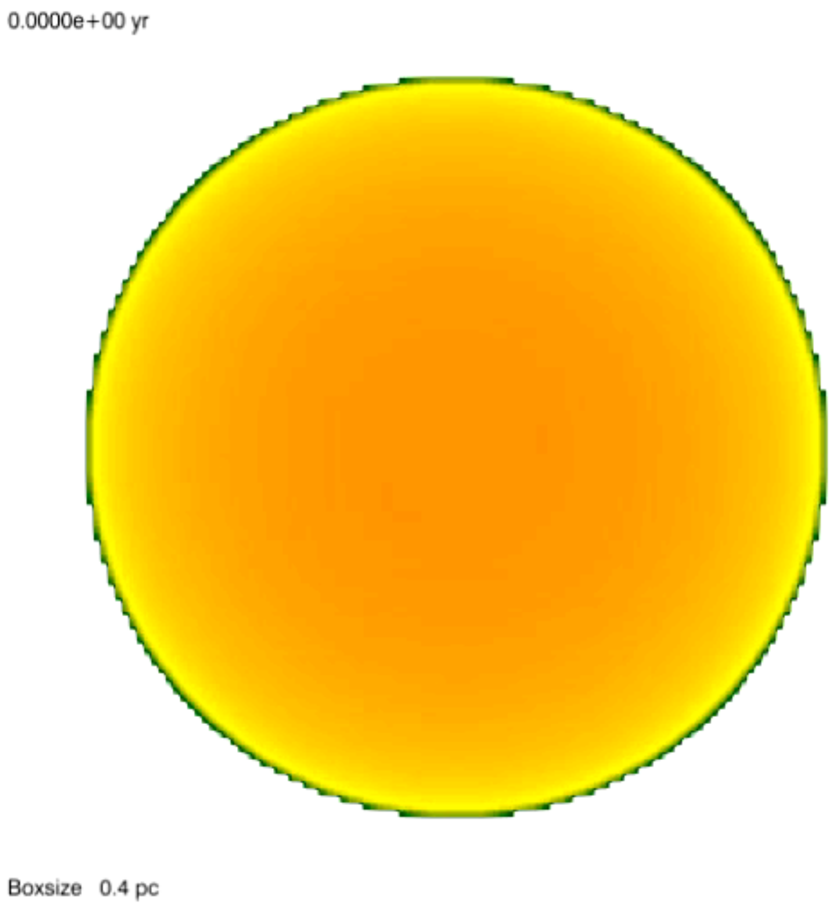




Banerjee, Klessen, & Fendt (2008)

cluster forming cloud with jets

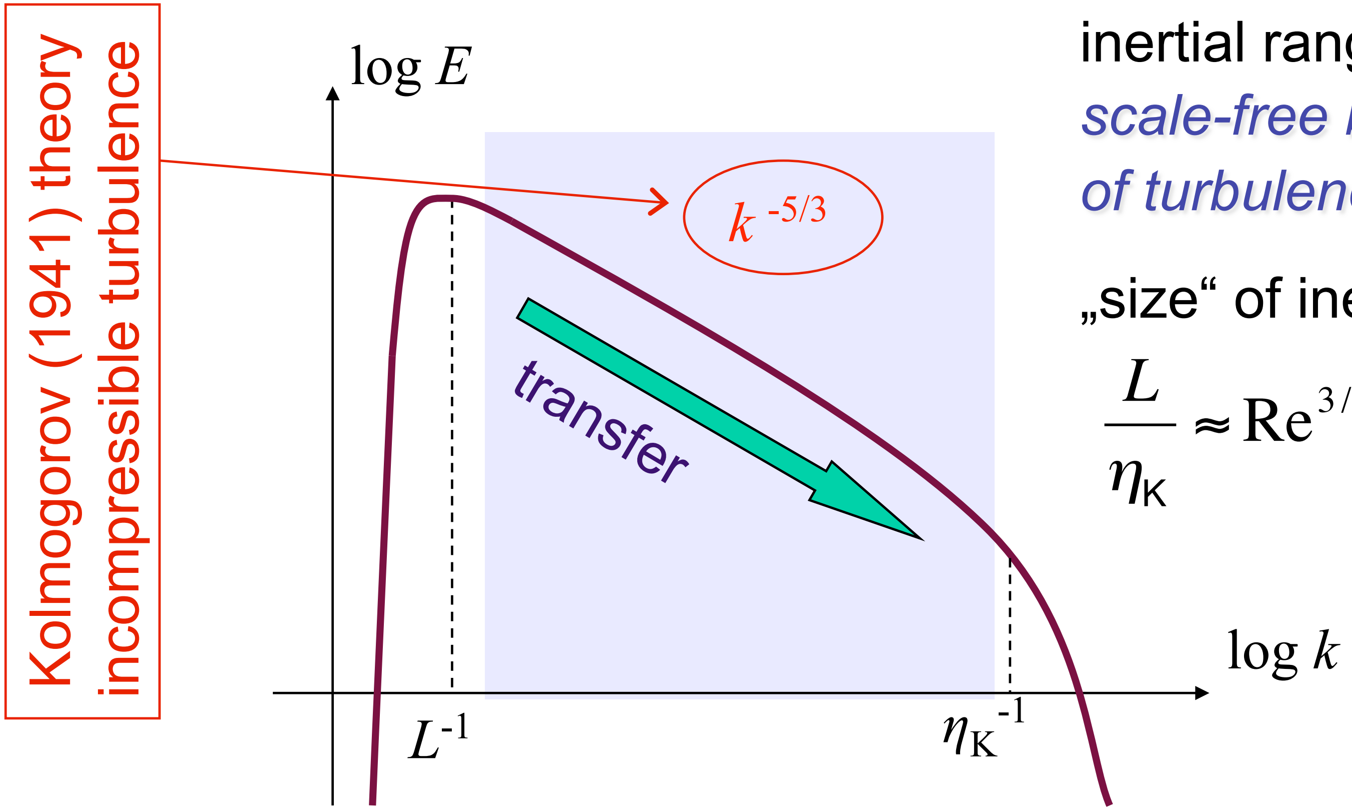
- jets from cluster with self-gravity
  with AMR code
  FLASH



Banerjee et al. (very preliminary study)

turbulence

Turbulent cascade



inertial range:
scale-free behavior of turbulence

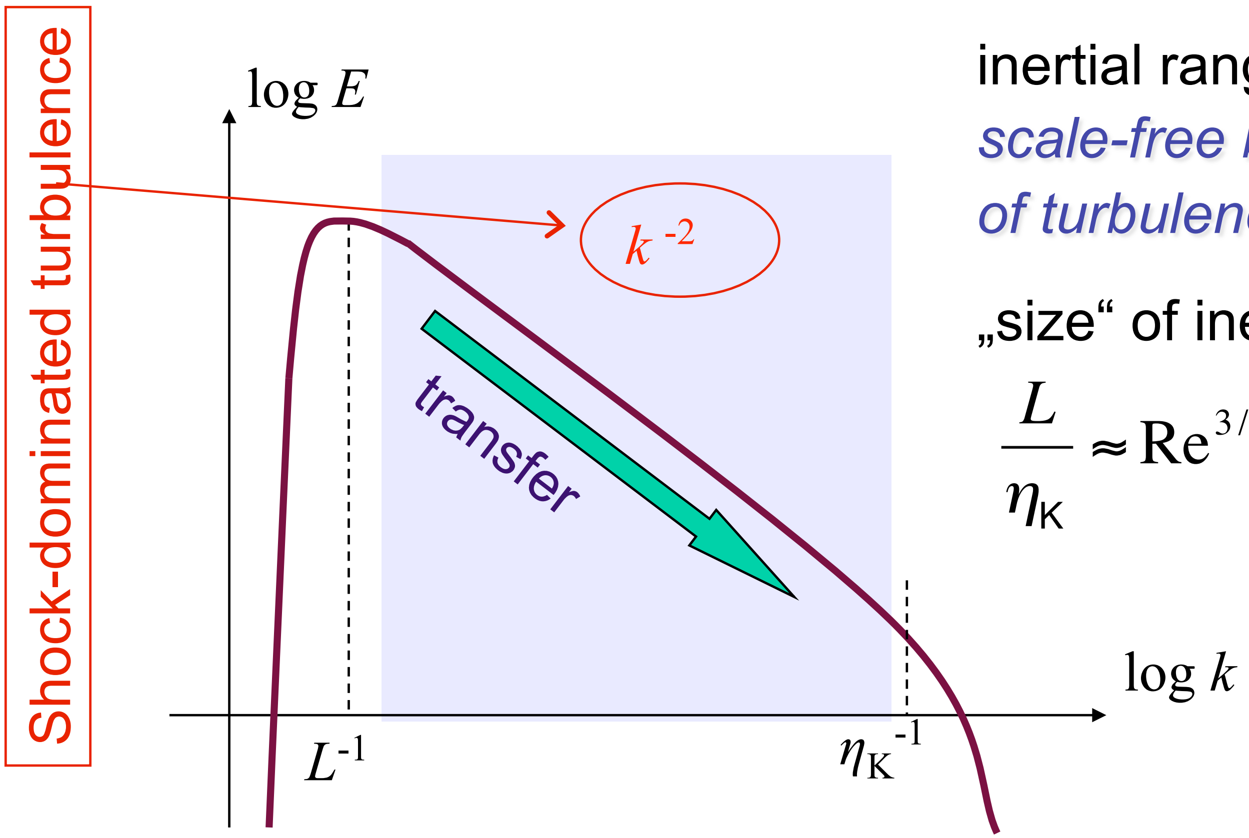
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade



inertial range:

scale-free behavior of turbulence

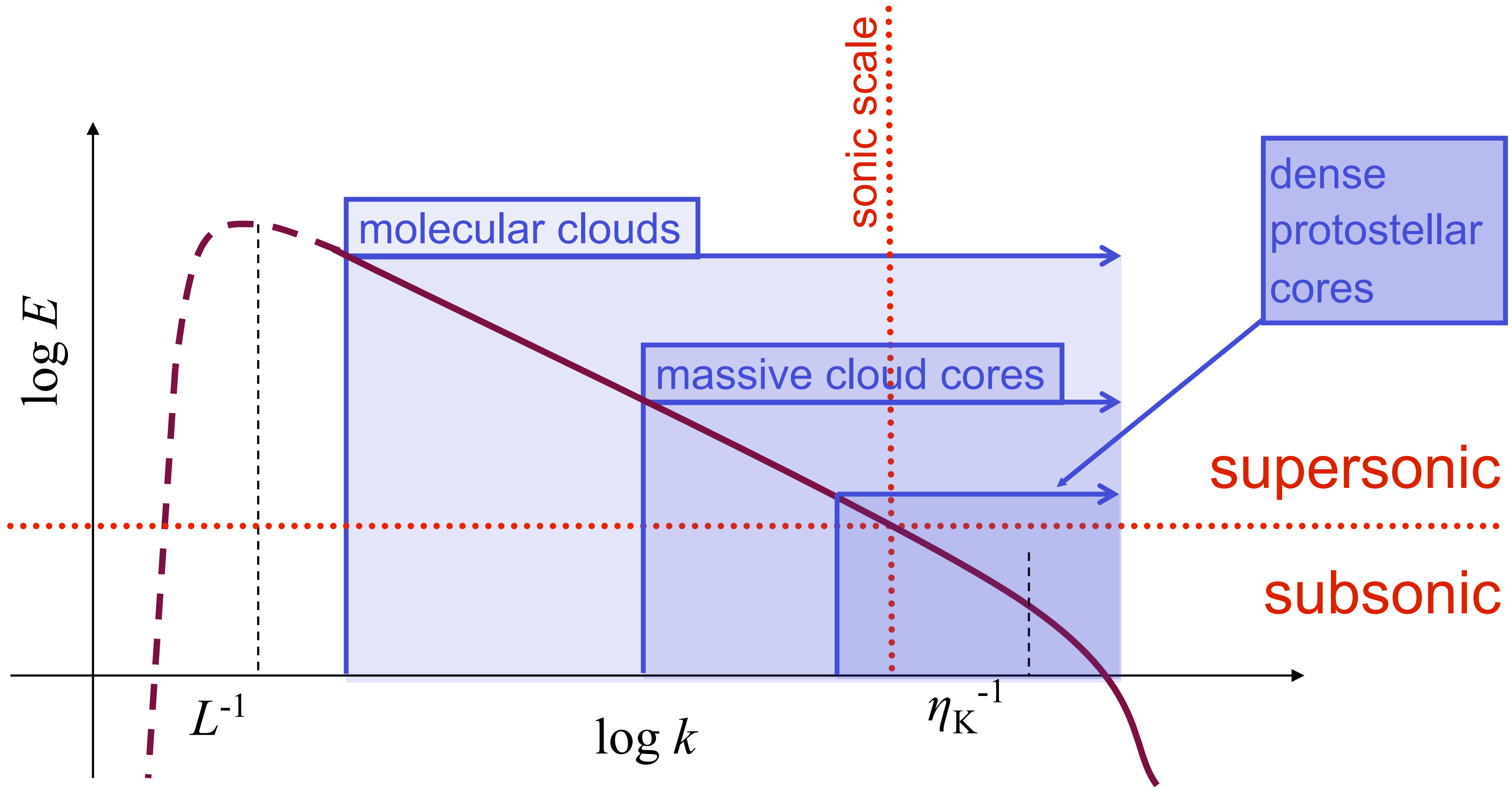
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade in ISM

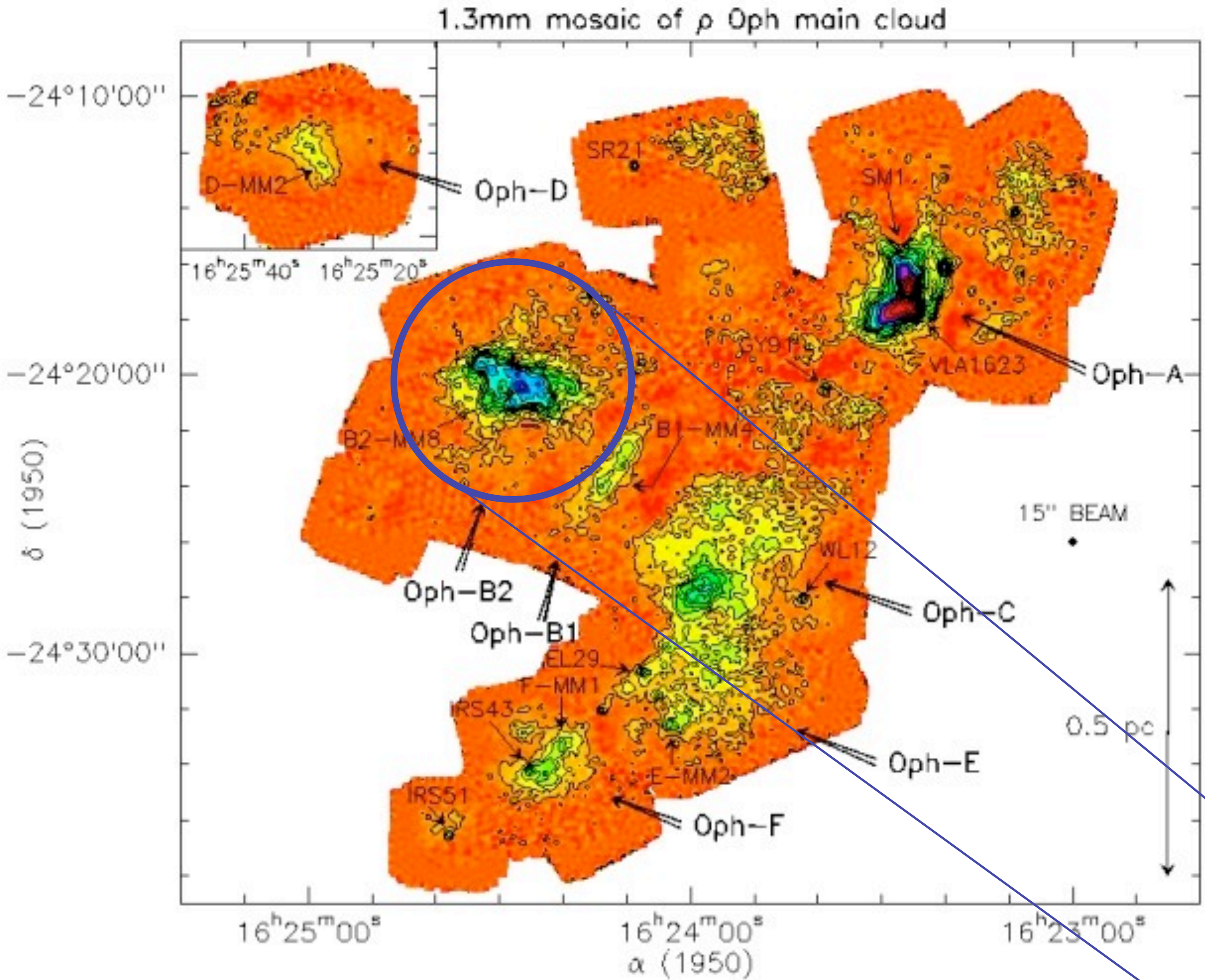


energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

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

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

Density structure of MC's



(Motte, André, & Neri 1998)

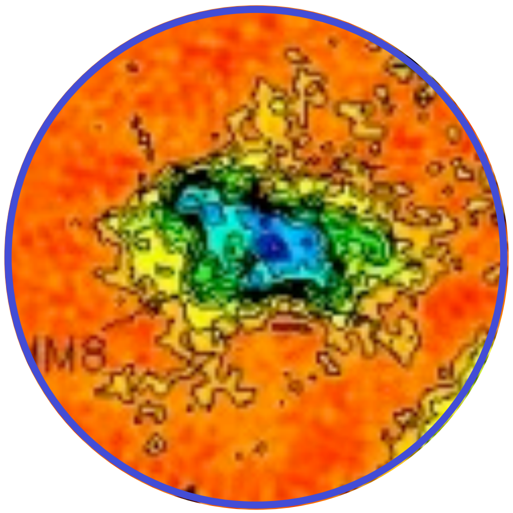
molecular clouds are highly inhomogeneous

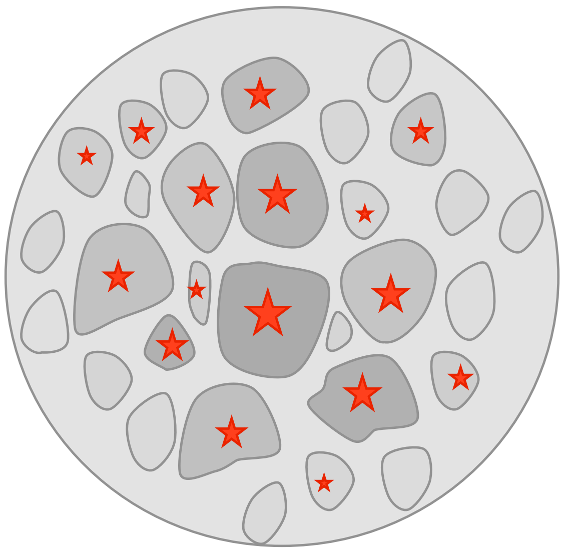
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

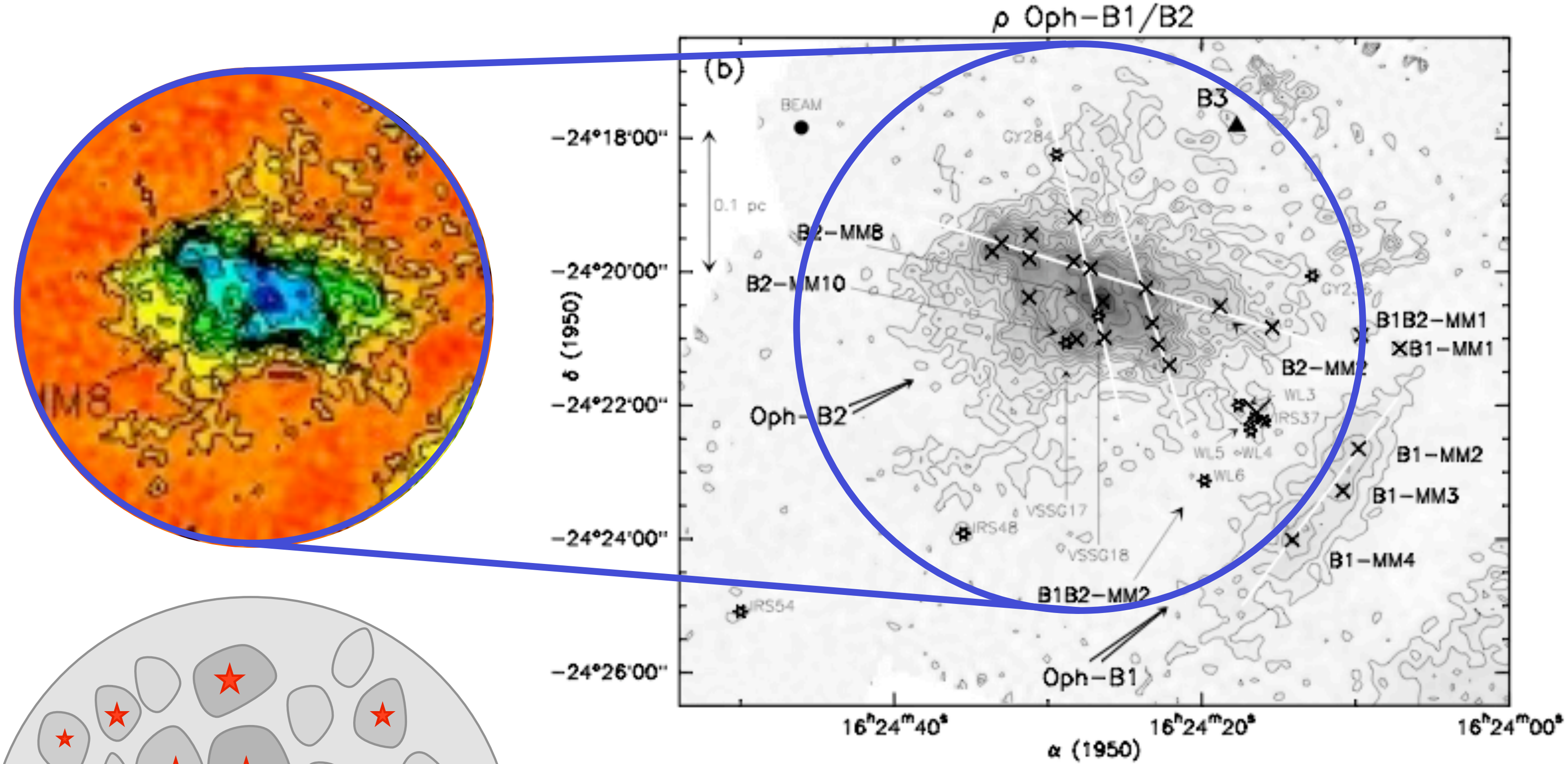
Evolution of cloud cores

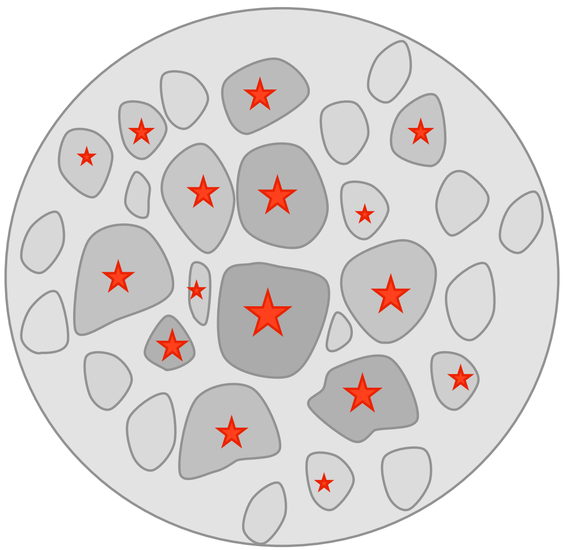




- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores

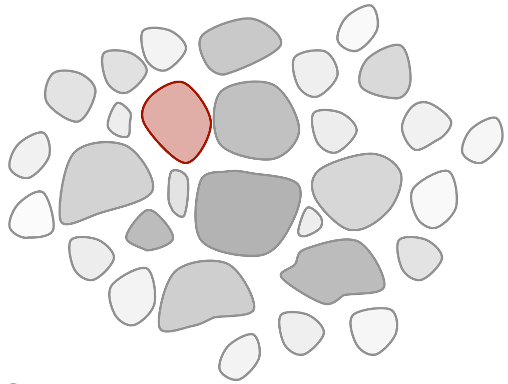




indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores



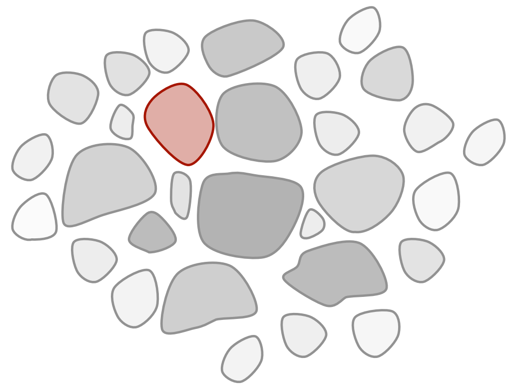
- protostellar cloud cores form at the *stagnation points* of *convergent turbulent flows*
- if $M > M_{Jeans} \propto \rho^{-1/2}\, T^{3/2}$: collapse and star formation
- if $M < M_{Jeans} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after external compression fades away

(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



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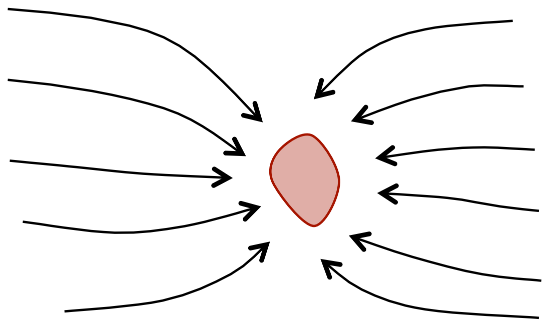
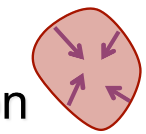
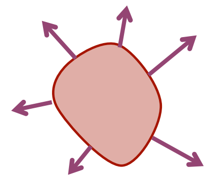


- if $M > M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: collapse & star formation



- pf $M < M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after end of external compression

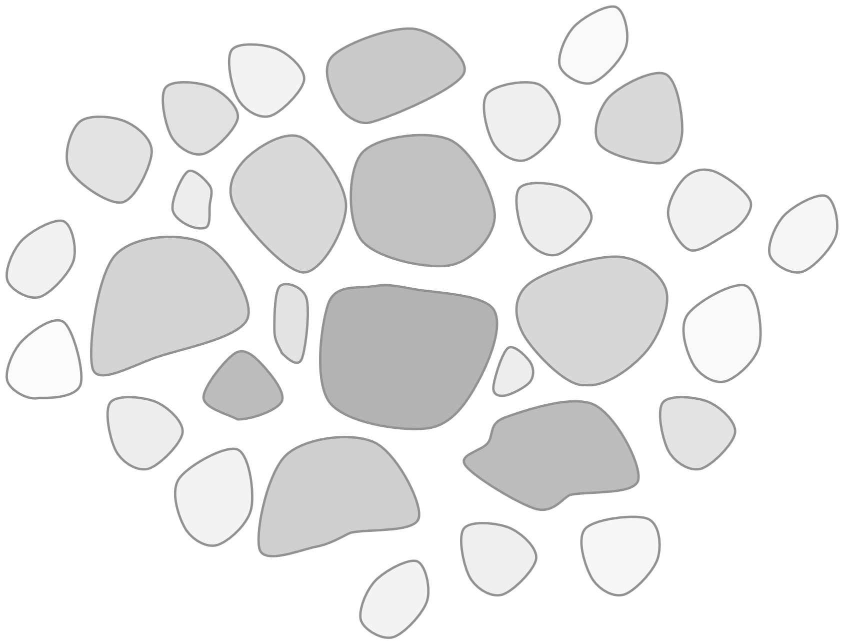


(e.g. Vazquez-Semadeni et al 2005)

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

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

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

--> individual cores do *not* interact

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

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

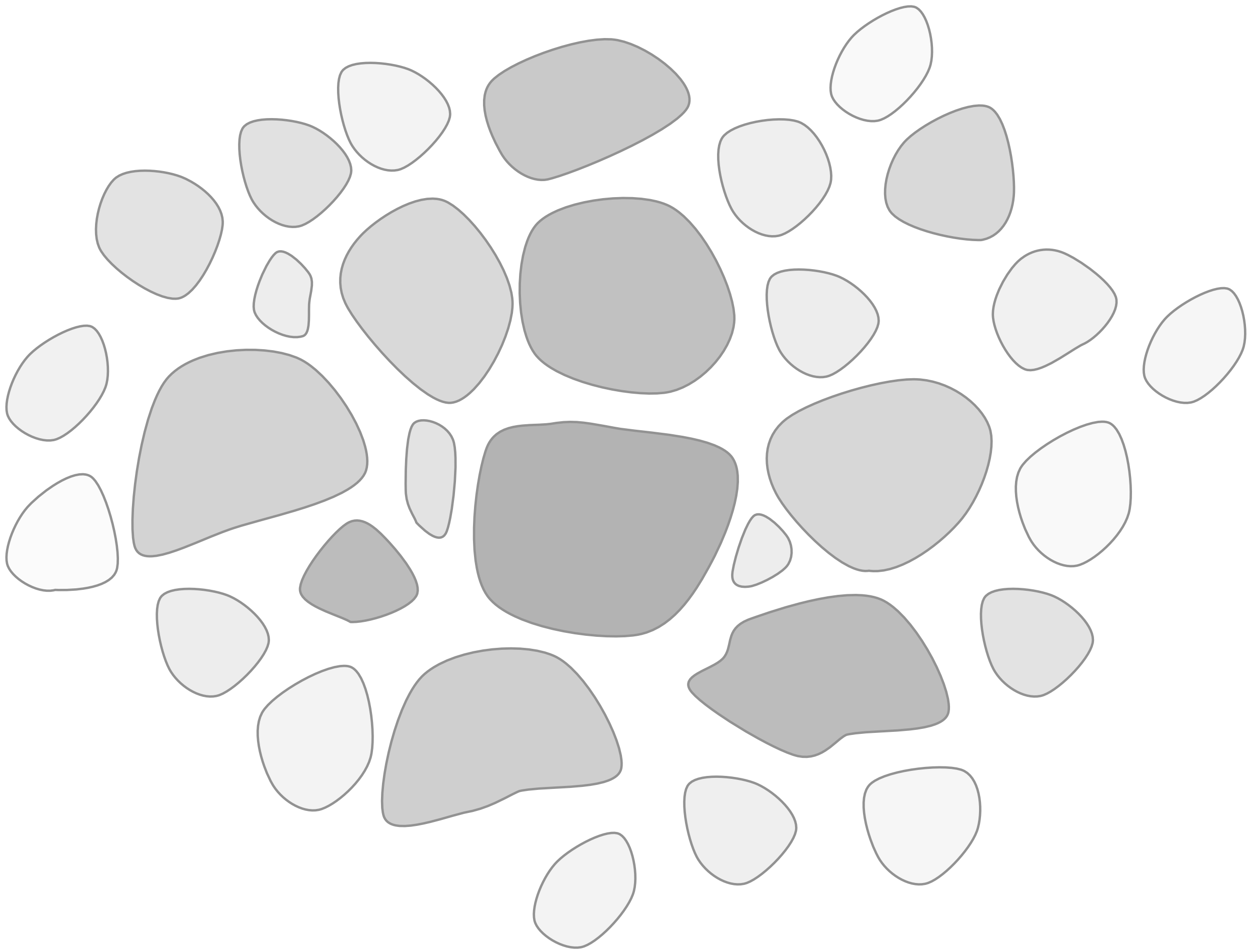
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

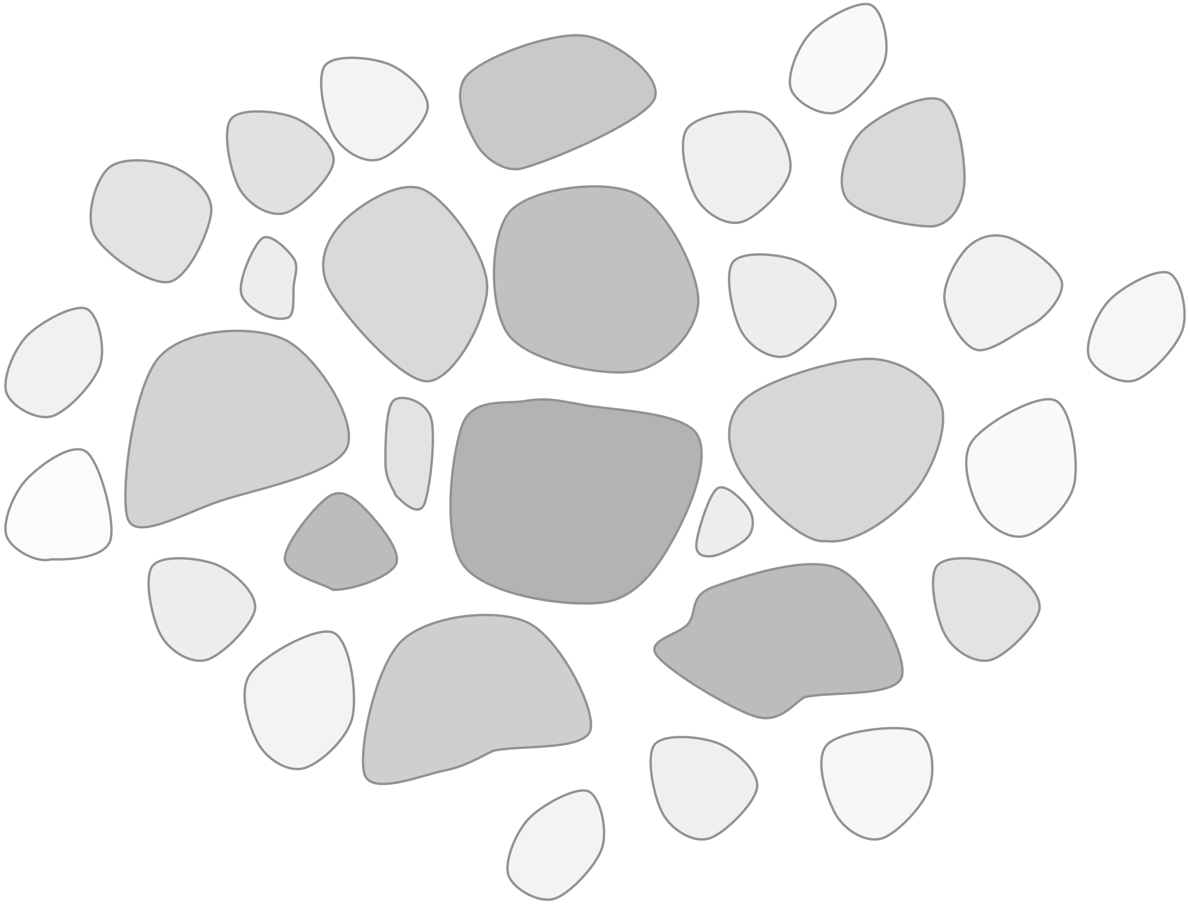
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

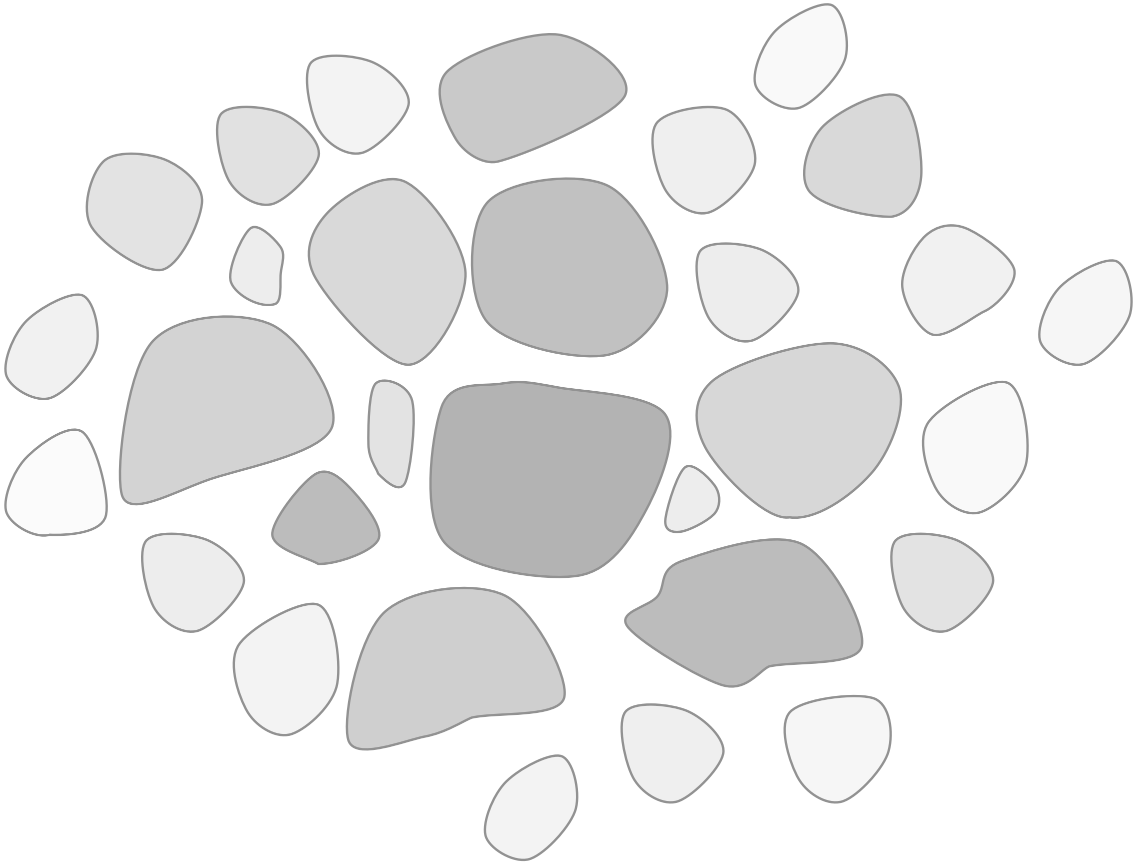
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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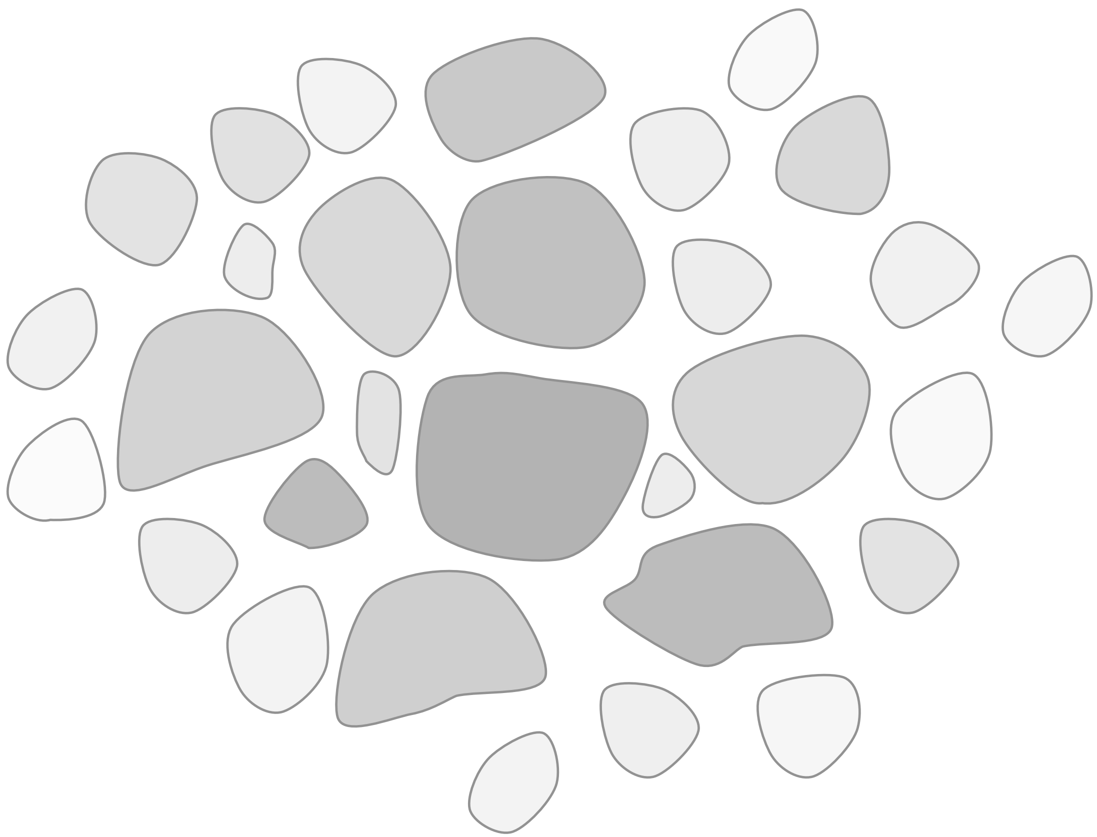
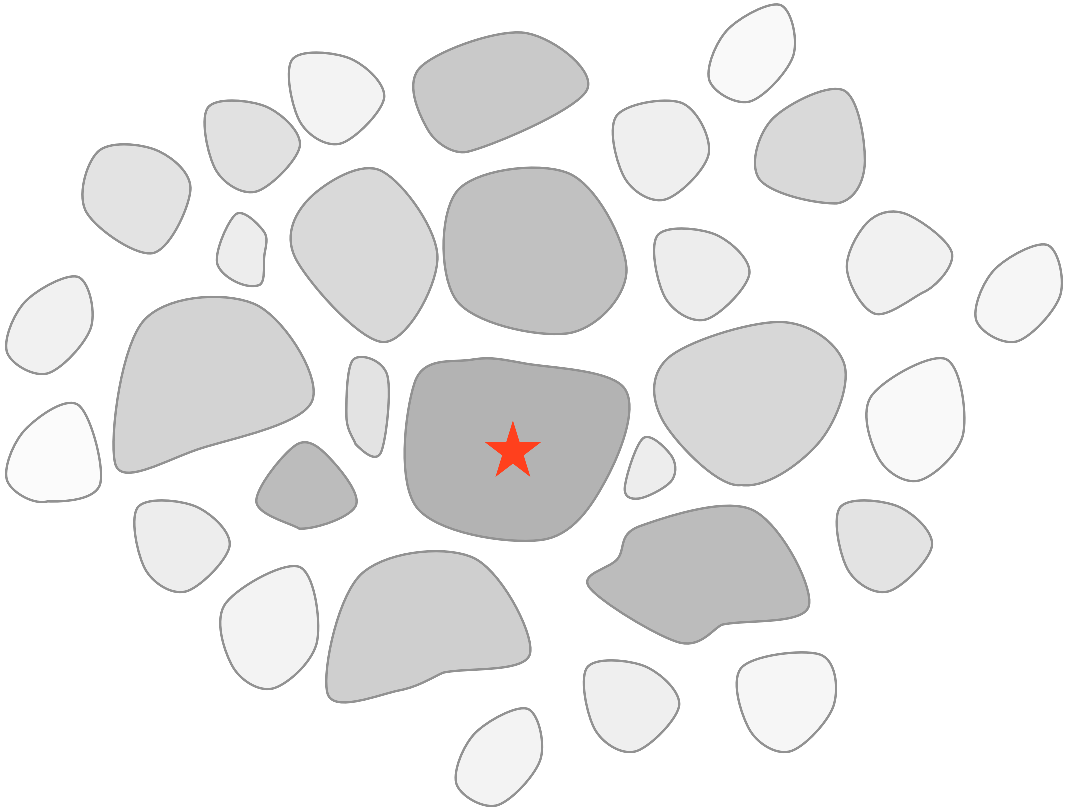


while region contracts, individual clumps collapse to form stars



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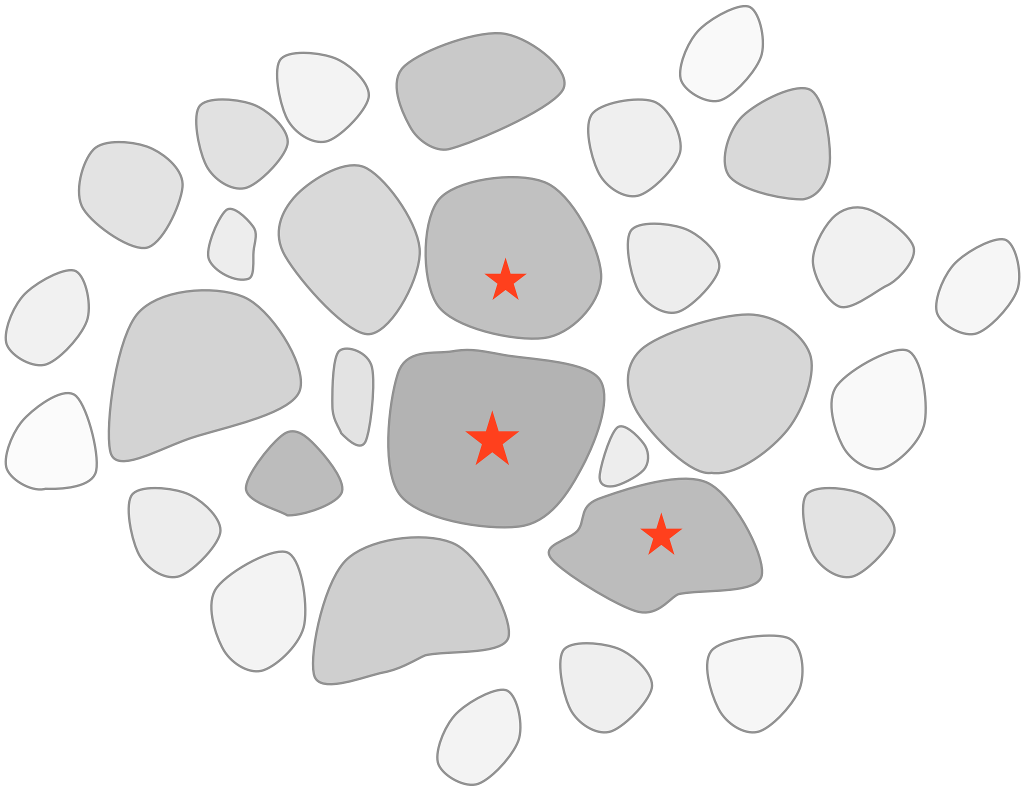

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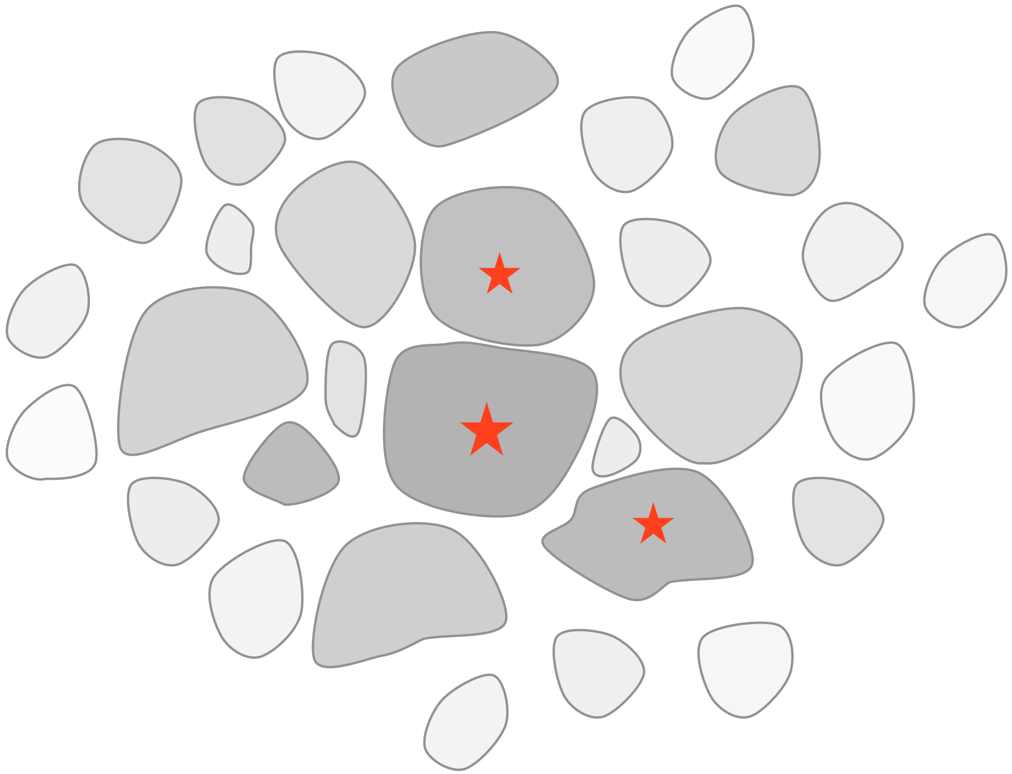

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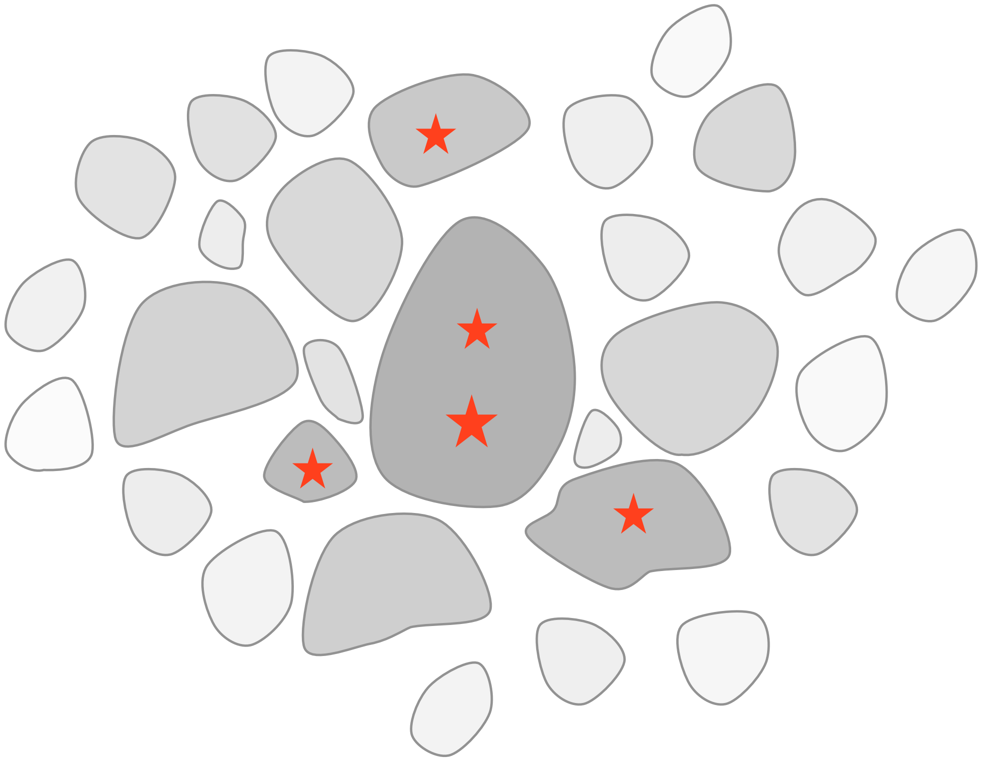
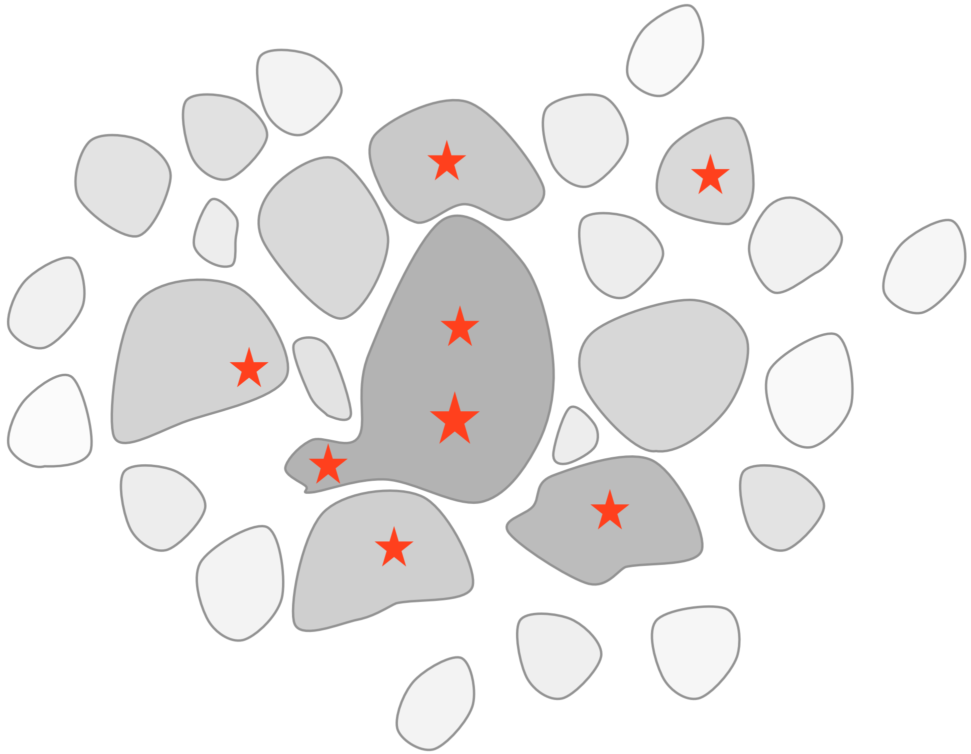


$\alpha=E_{kin}/|E_{pot}| < 1$

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



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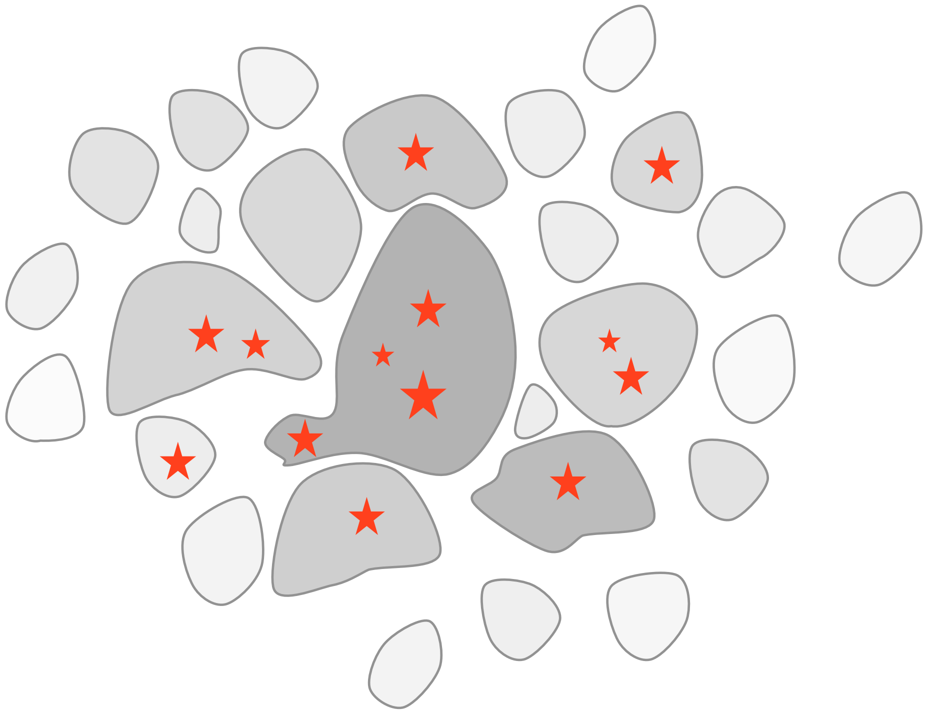

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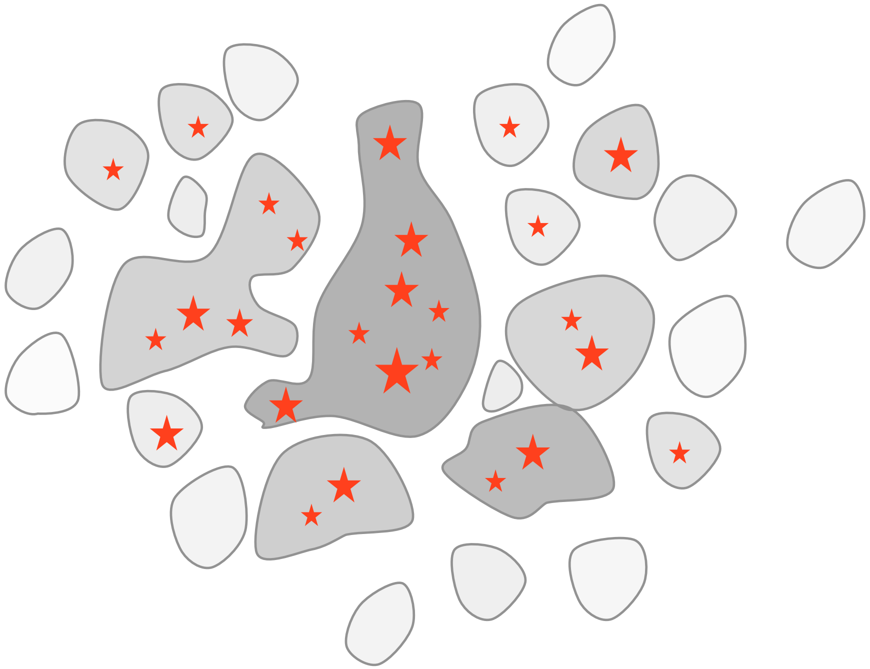
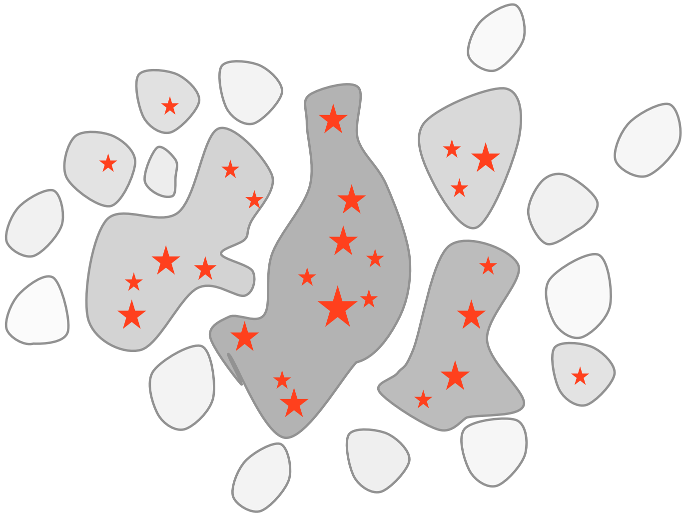


in *dense clusters*, competitive mass growth becomes important



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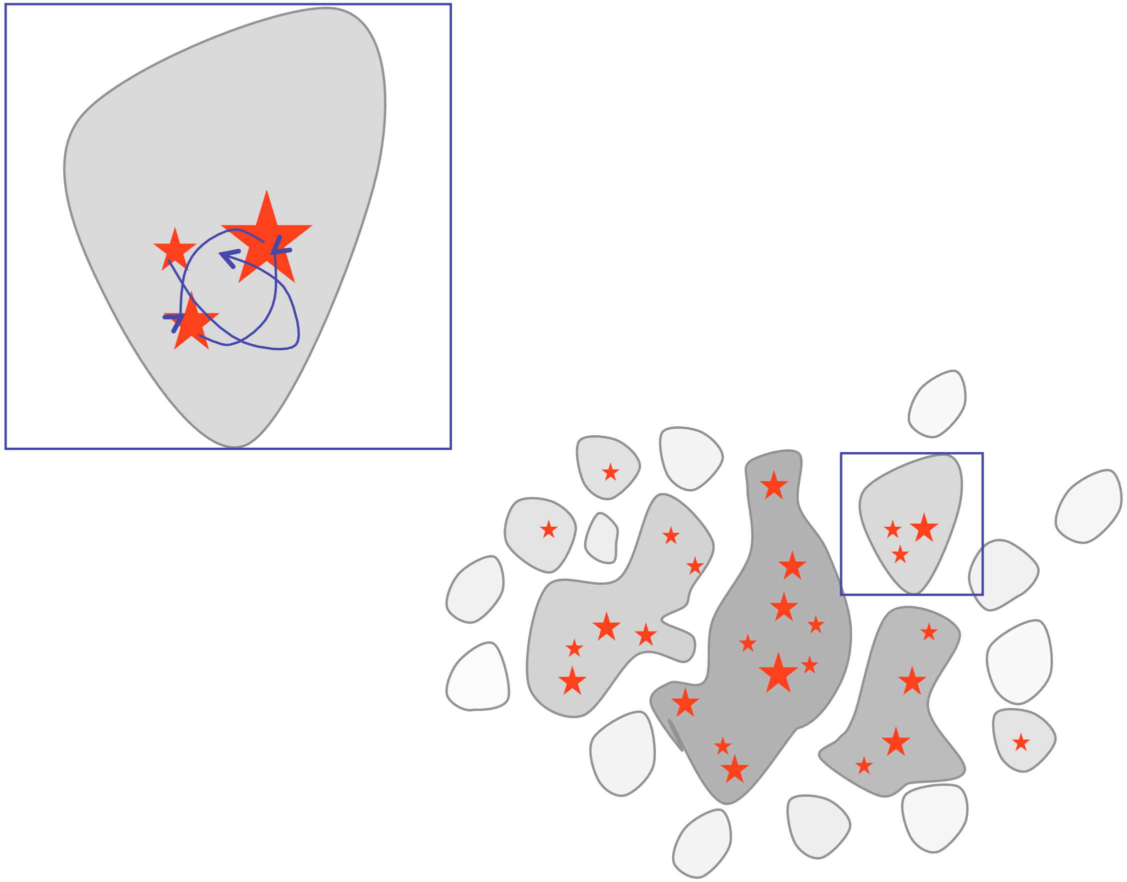
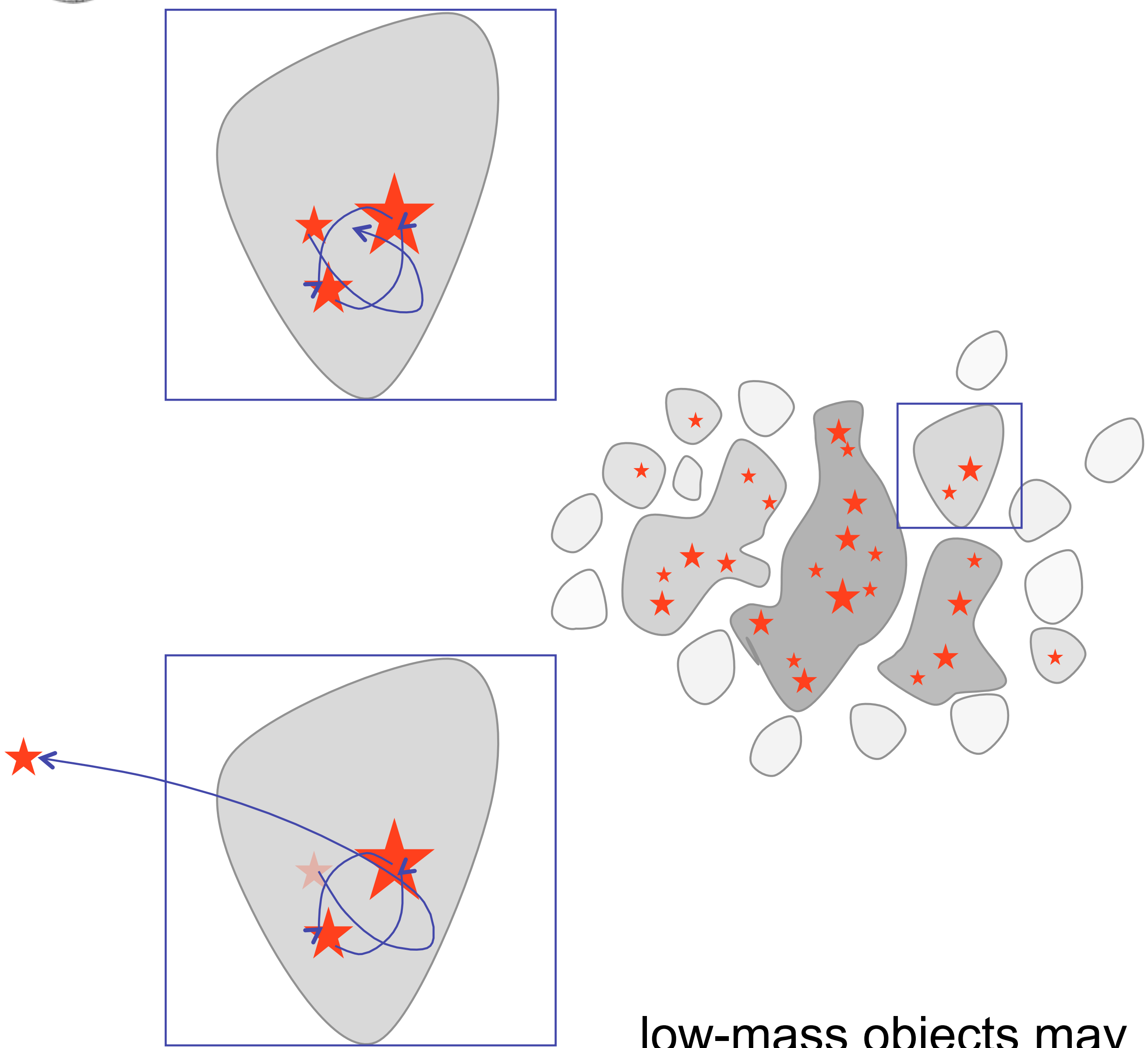
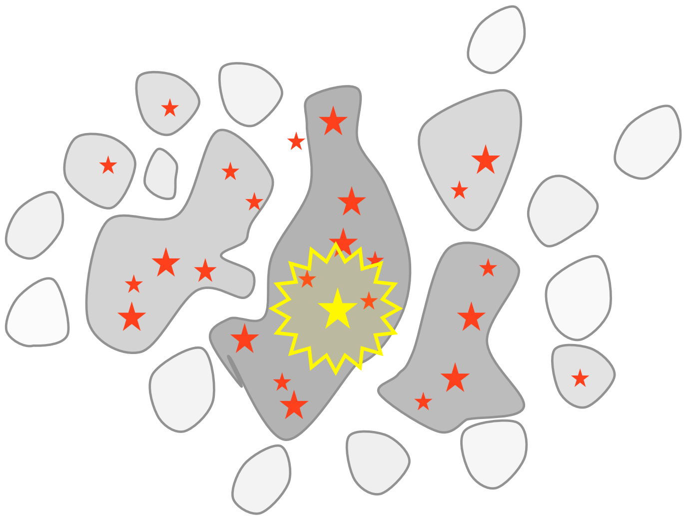


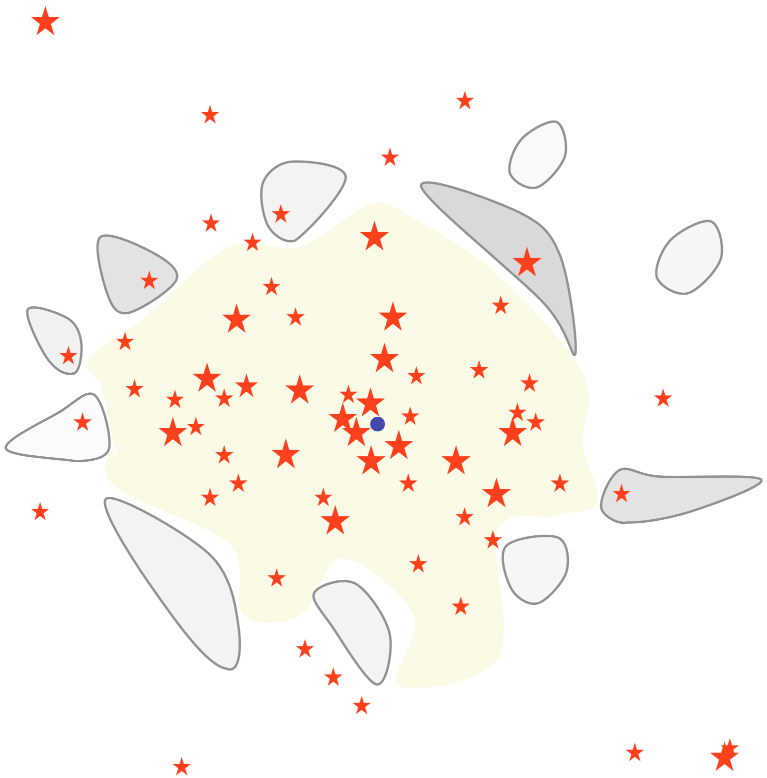
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region

initial mass function

initial mass function

- what is the relation between molecular cloud fragmentation and the distribution of stars?
- important quantity: *IMF*
- BUT: “everyone” gets the right IMF
  → better look for secondary indicators
  - *stellar multiplicity* (see focus group lead by H. Zinnecker)
  - protostellar *spin* (including disk)
  - *spatial distribution* + *kinematics* in young clusters
  - *magnetic field strength* and *orientation*
    (see focus group lead by R. Crutcher)

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)

IMF

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  - *turbulent initial conditions*
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compressive vs. rotational driving

- statistical characteristics of turbulence depend strongly on „type“ of driving
- example: dilatational vs. solenoidal driving
- question: what drives ISM turbulence on different scales?

dilatational vs. solenoidal

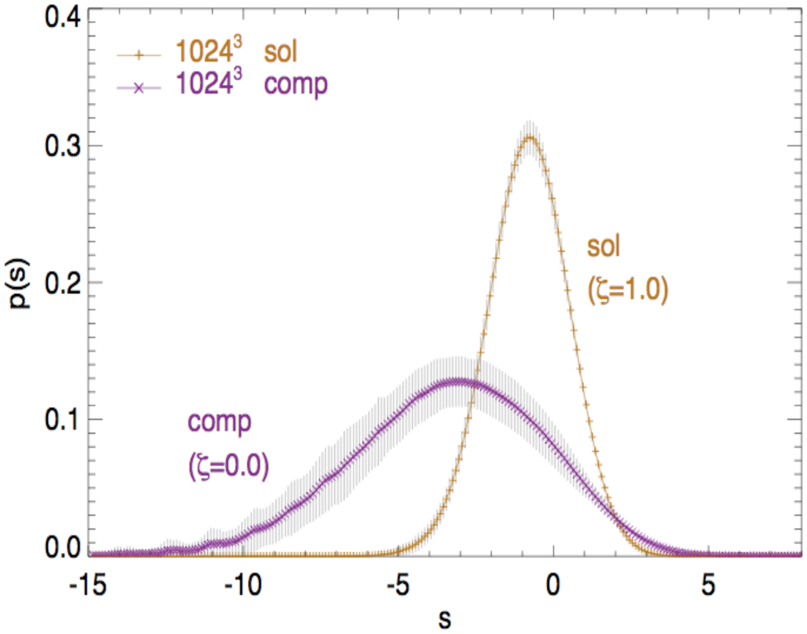

FIG. 2.— Volume-weighted density PDFs $p_s(s)$ in linear scaling where $s = \ln(\rho/\rho_0)$. The PDF obtained by compressive forcing (comp, $\zeta = 0.0$) is much broader compared to the solenoidal one (sol, $\zeta = 1.0$) at the same rms Mach number. The peak is shifted due to mass conservation (Vázquez-Semadeni 1994). Gray error bars indicate 1-sigma temporal fluctuations of the PDF. A sample of $\sim 10^{11}$ datapoints contribute to each PDF.

Federrath, Klessen, Schmidt (2008a)

- density pdf depends on "dimensionality" of driving
  - relation between width of pdf and Mach number

$$\sigma_\rho/\rho_0 = b\mathcal{M}$$

  - with b depending on ζ via

$$b = 1 + \left[\frac{1}{D} - 1\right]\zeta = \begin{cases} 1 - \frac{2}{3}\zeta & \text{, for } D = 3 \\ 1 - \frac{1}{2}\zeta & \text{, for } D = 2 \\ 1 & \text{, for } D = 1 \end{cases}$$

  - with ζ being the ratio of dilatational vs. solenoidal modes:

$$\mathcal{P}_{ij}^{\zeta} = \zeta\mathcal{P}_{ij}^{\perp} + (1-\zeta)\mathcal{P}_{ij}^{||} = \zeta\delta_{ij} + (1-2\zeta)\frac{k_i k_j}{|k|^2}$$

dilatational vs. solenoidal

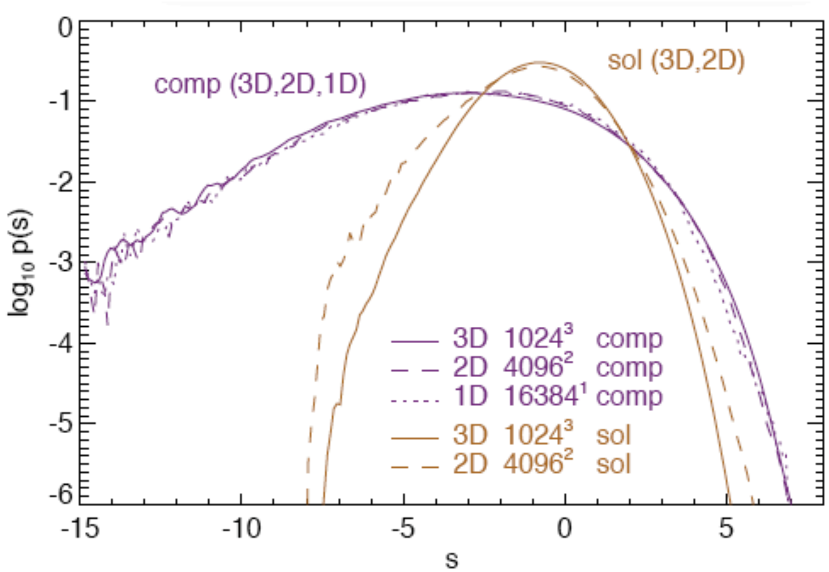

FIG. 3.— Volume-weighted density PDFs $p(s)$ obtained from 3D, 2D and 1D simulations with compressive forcing and from 3D and 2D simulations using solenoidal forcing. Note that in 1D, only compressive forcing is possible as in the study by Passot & Vázquez-Semadeni (1998). As suggested by eq. (5), compressive forcing yields almost identical density PDFs in 1D, 2D and 3D with $b \sim 1$, whereas solenoidal forcing leads to a density PDF with $b \sim 1/2$ in 2D and with $b \sim 1/3$ in 3D.

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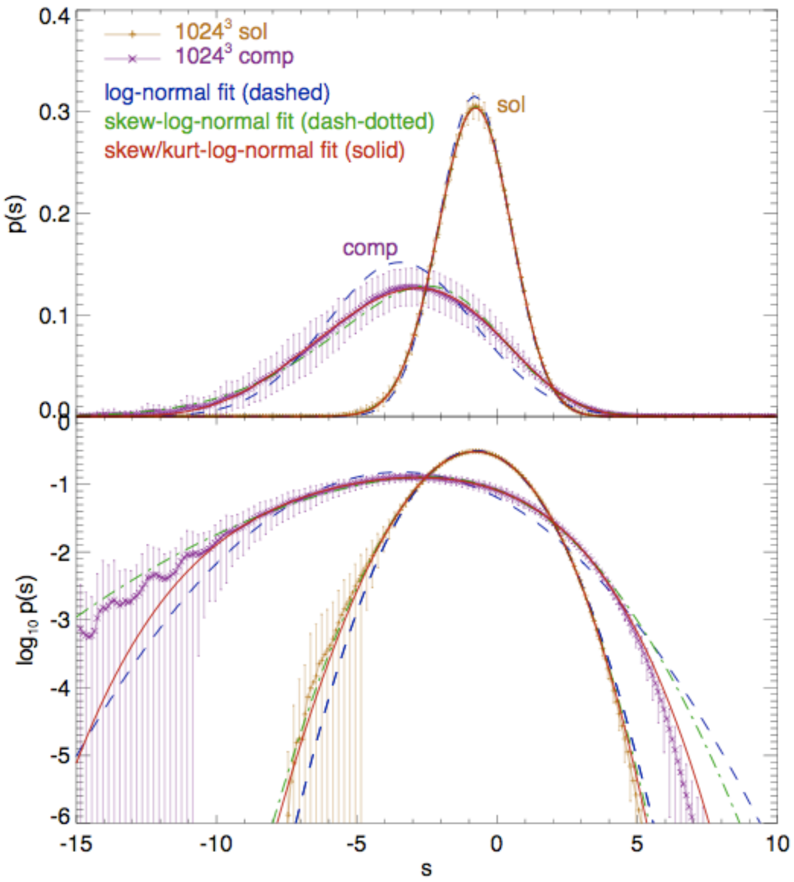
dilatational vs. solenoidal

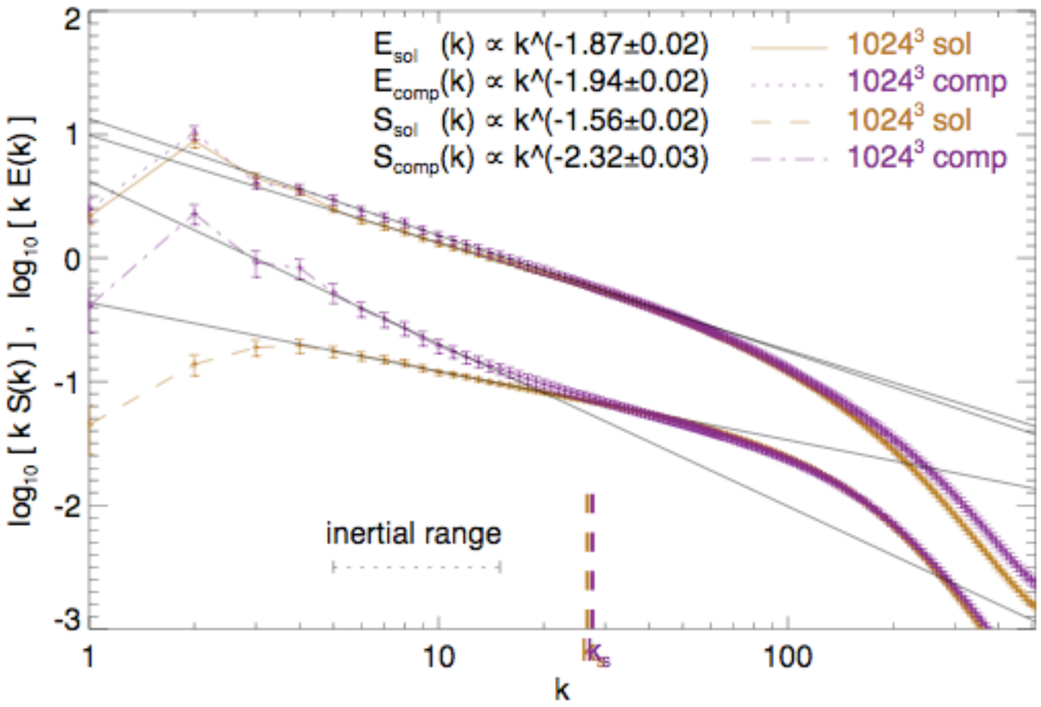


good fit needs 3rd and 4th moment of distribution!

Federrath, Klessen, Schmidt (2008b)

- density pdf depends on "dimensionality" of driving
  → is that a problem for the Krumholz & McKee model of the SF efficiency?
- density pdf of compressive driving is *NOT log-normal*
  → is that a problem for the Padoan & Nordlund IMF model?
- most "physical" sources should be *compressive* (convergent flows from spiral shocks or SN)

dilatational vs. solenoidal



compensated density spectrum kS(k) shows clear break at sonic scale. below that shock compression no longer is important in shaping the power spectrum ...

- density power spectrum differs between dilatational and solenoidal driving!

  → dilatational driving leads to break at sonic scale!

- can we use that to determine driving sources from observations ?

Federrath, Klessen, Schmidt (2008b)

IMF

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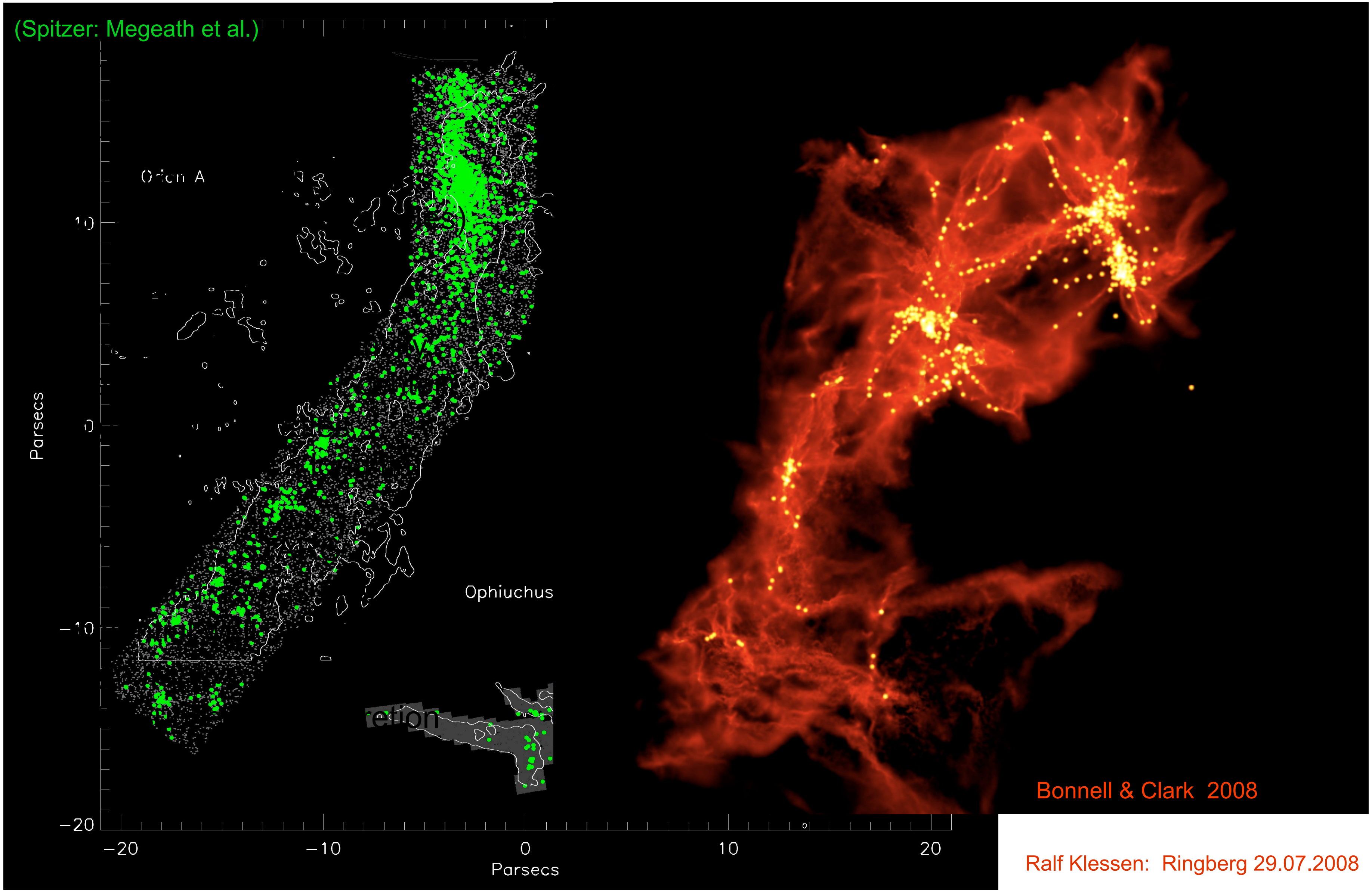
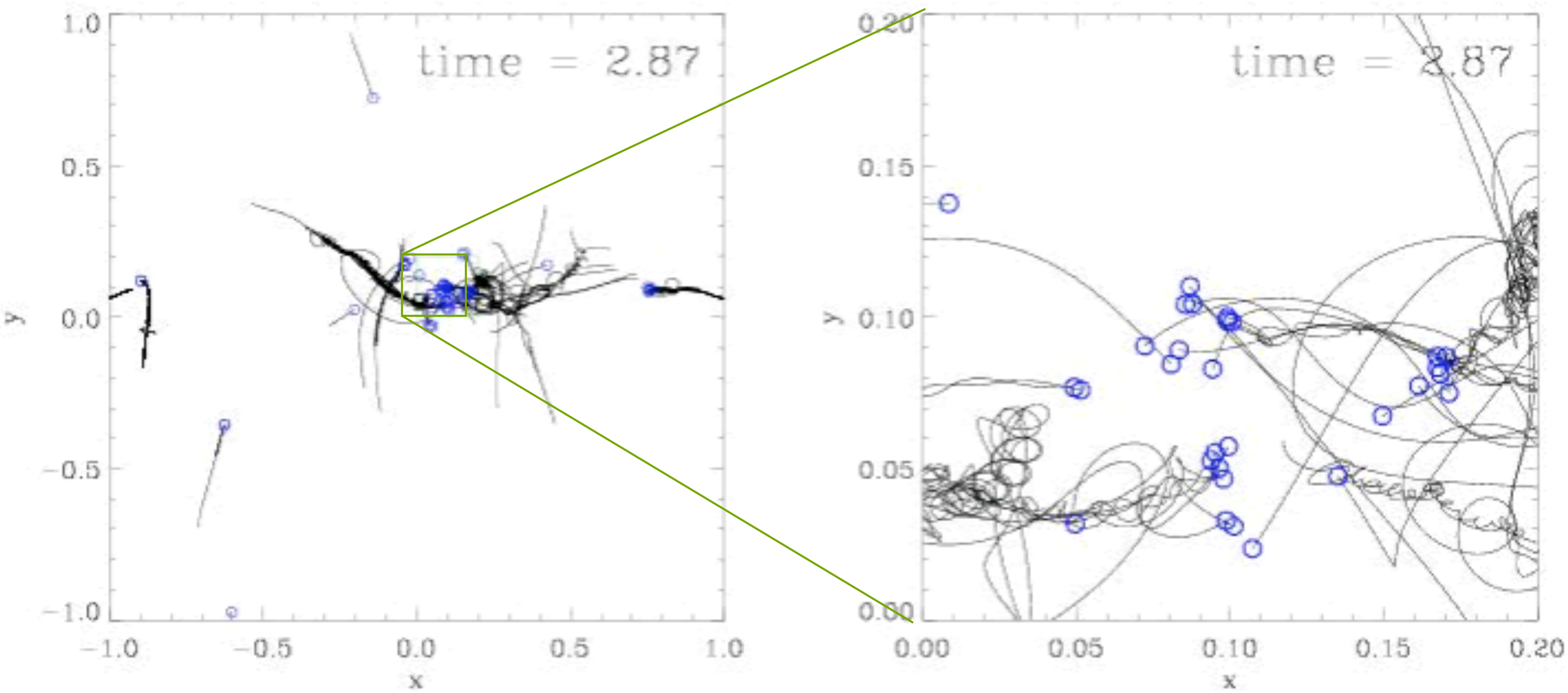
example: model of Orion cloud



Dynamics of nascent star cluster

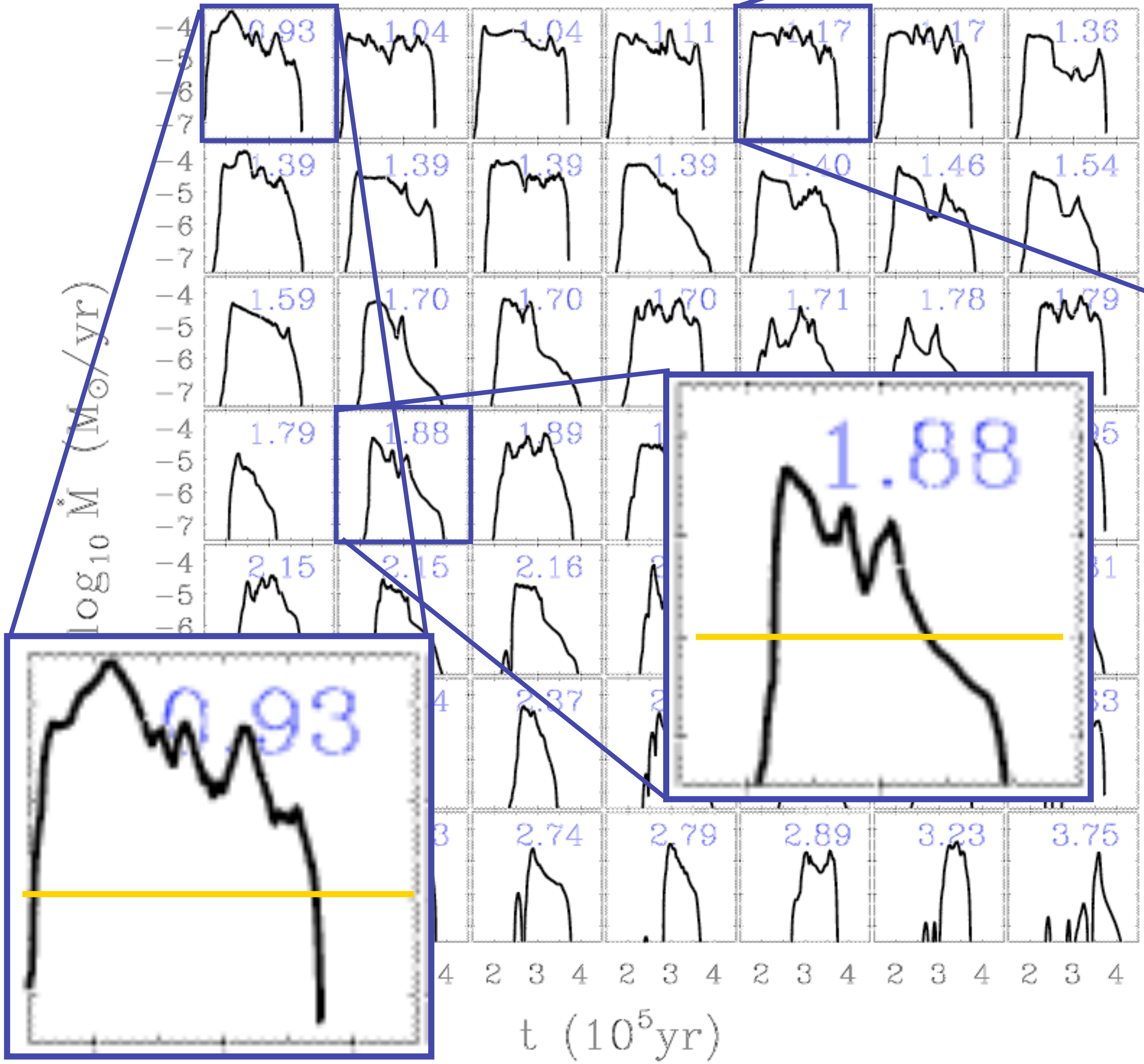
in dense clusters protostellar interaction may be come important!

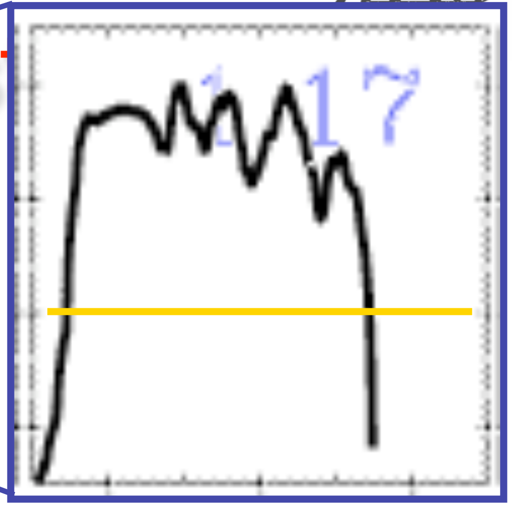


Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

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

accretion rates in clus





Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

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)

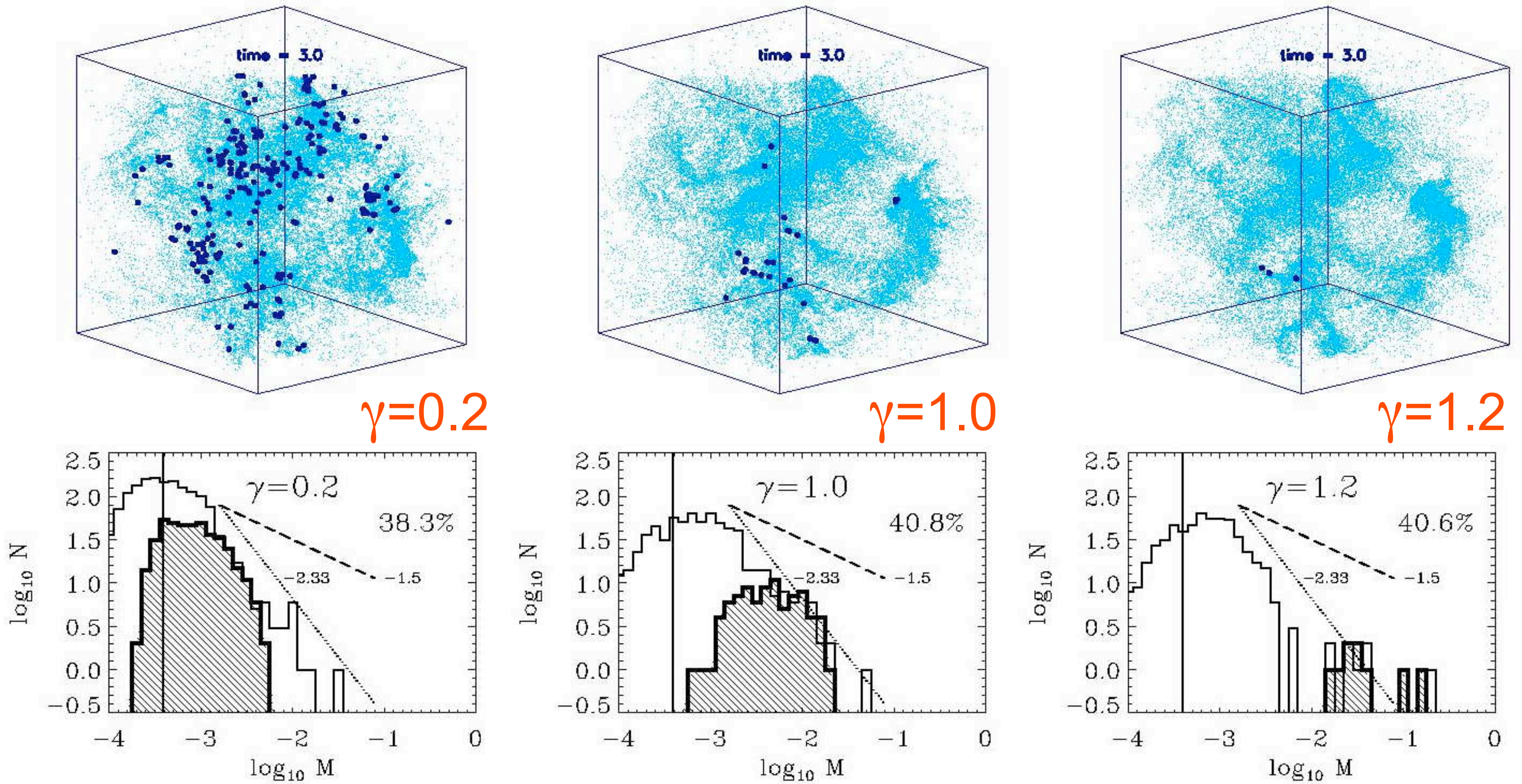
dependency on EOS

- 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*

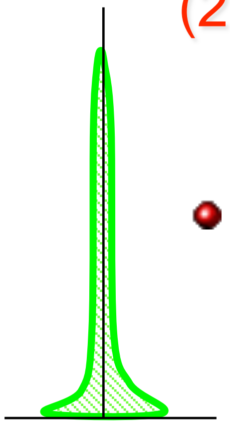
for γ>1 it is suppressed → formation of *isolated massive stars*

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

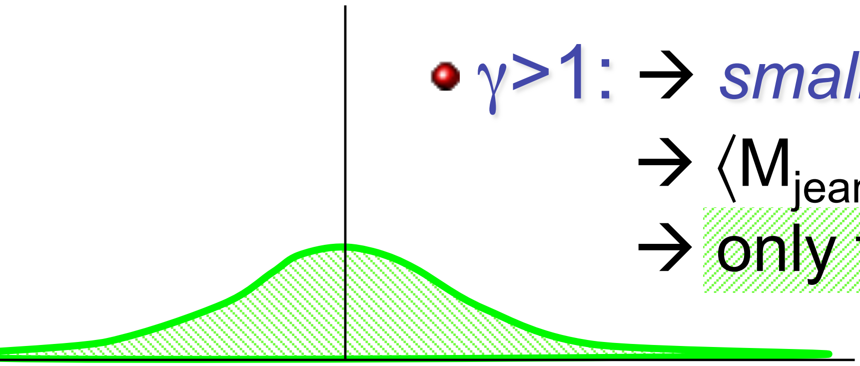
how does that work?

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

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



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

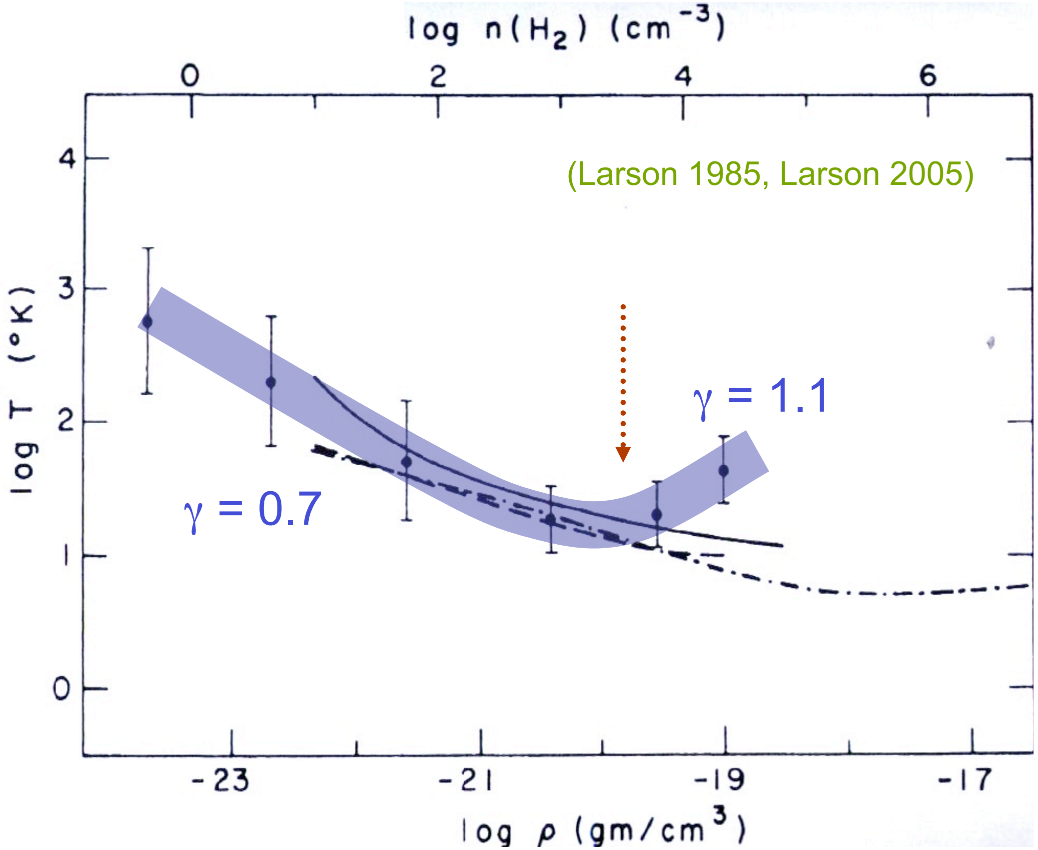


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬆



$P \propto \rho^\gamma$

$P \propto \rho T$

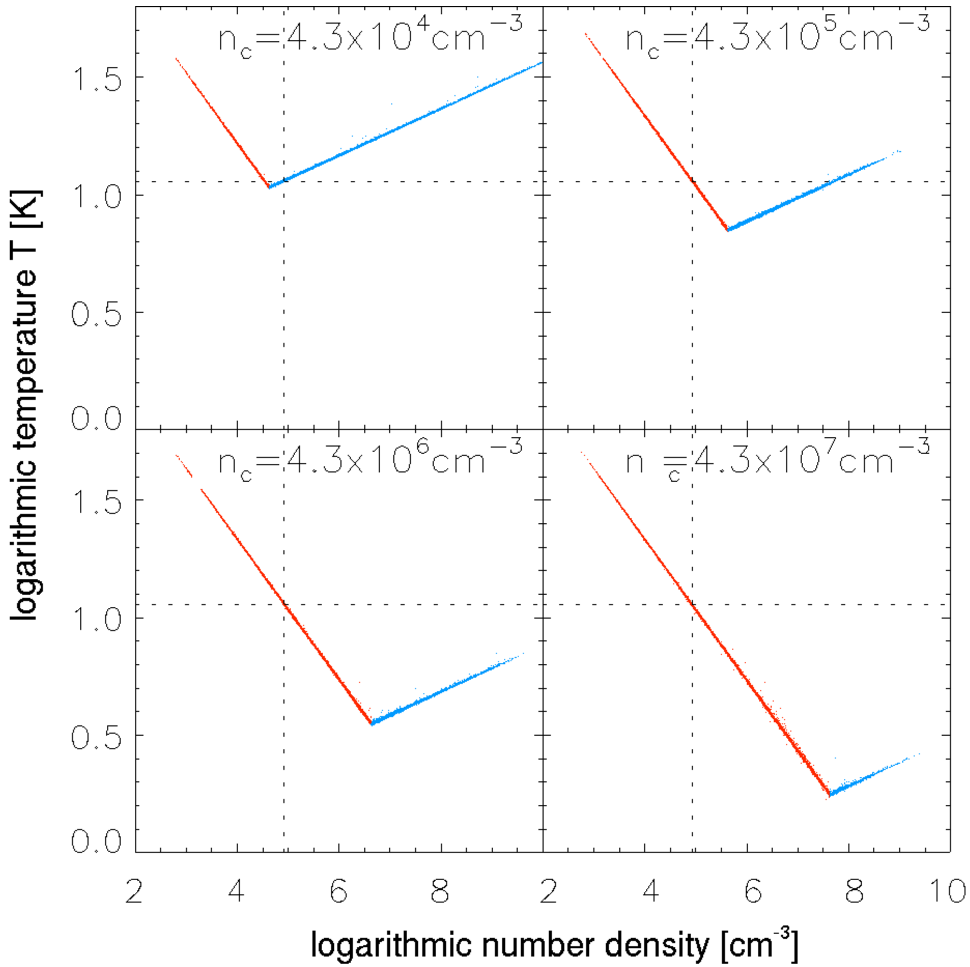
$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

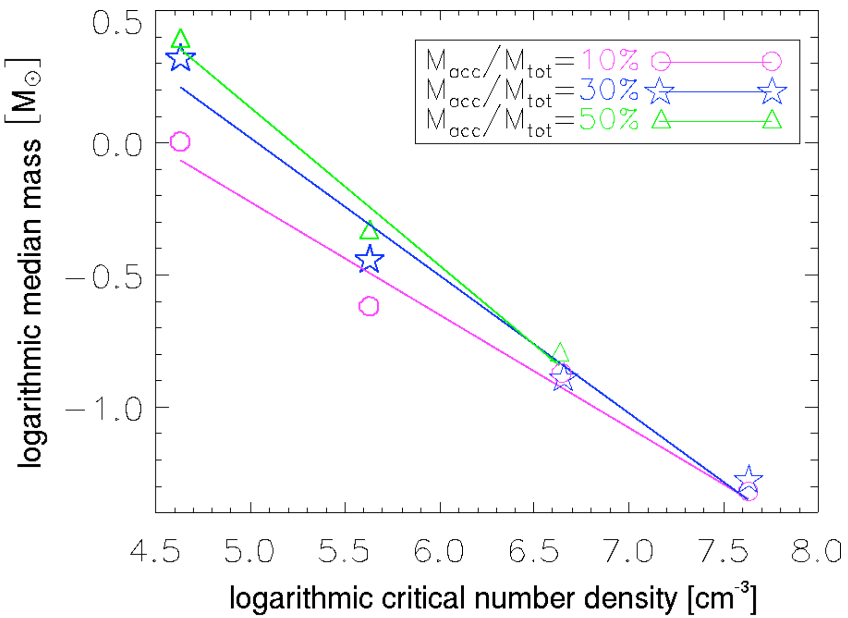
$T \sim \rho^{\gamma-1}$

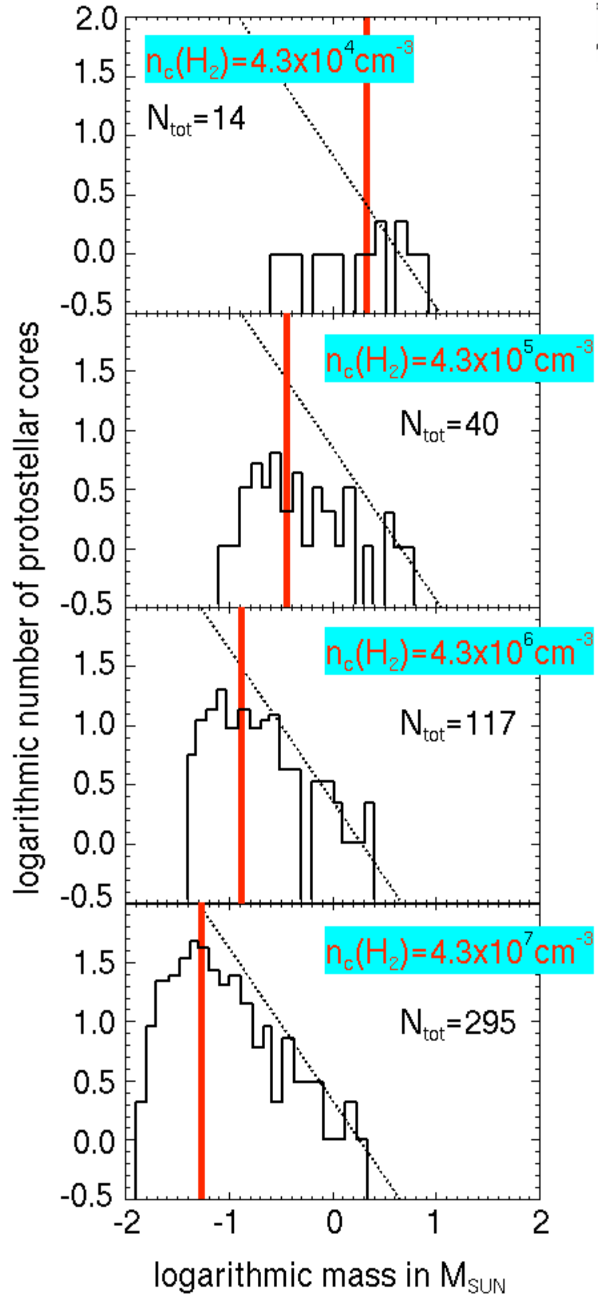


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

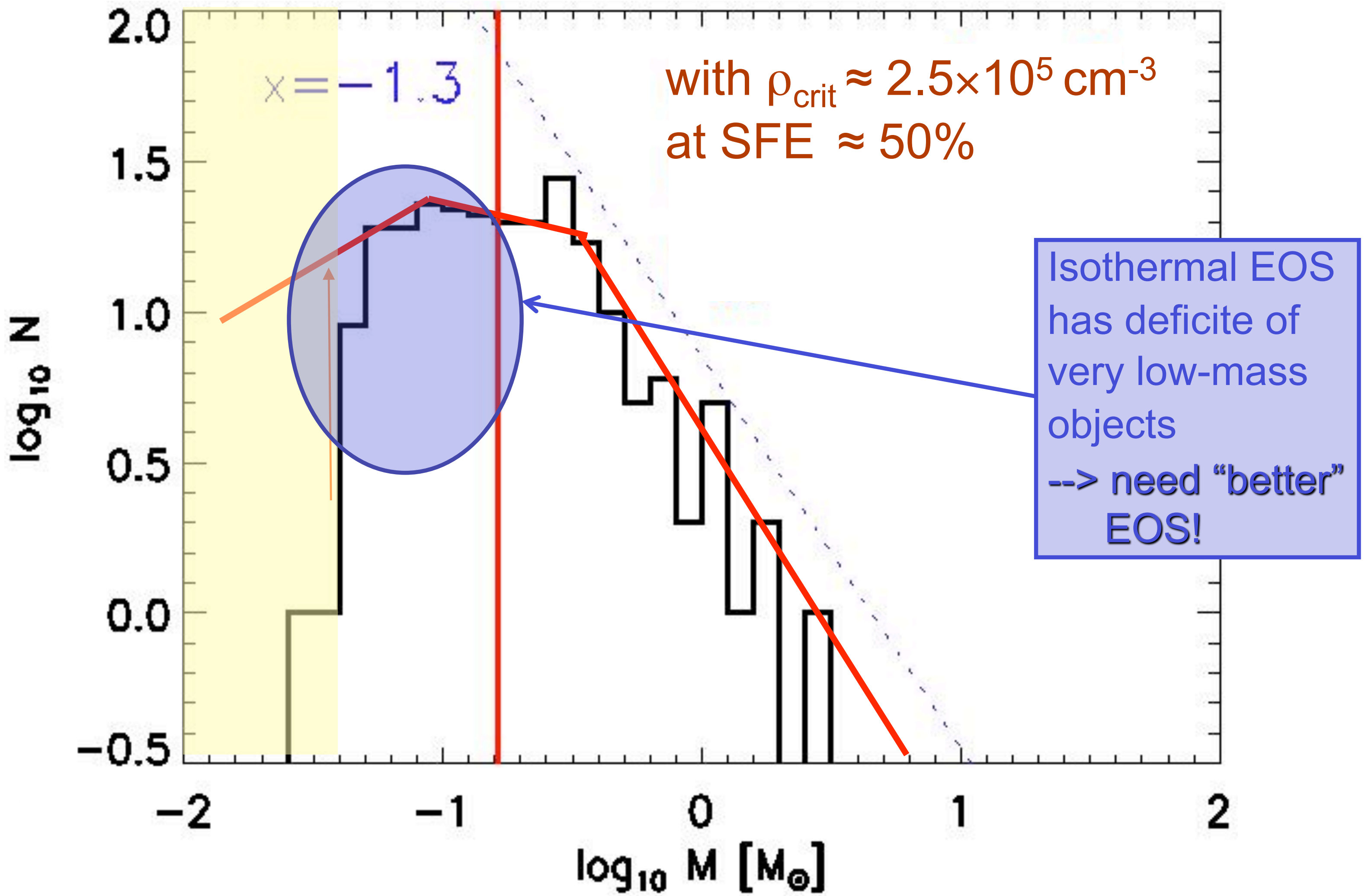
critical density ⬆ ⟹ median mass ⬇





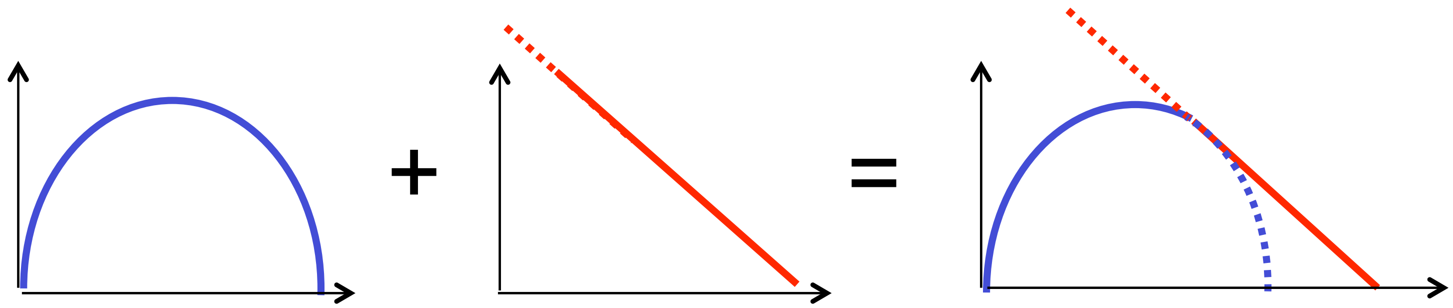
(Jappsen et al. 2005)

IMF in nearby molecular clouds



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

Plausibility argument for shape



- Supersonic turbulence is scale free process

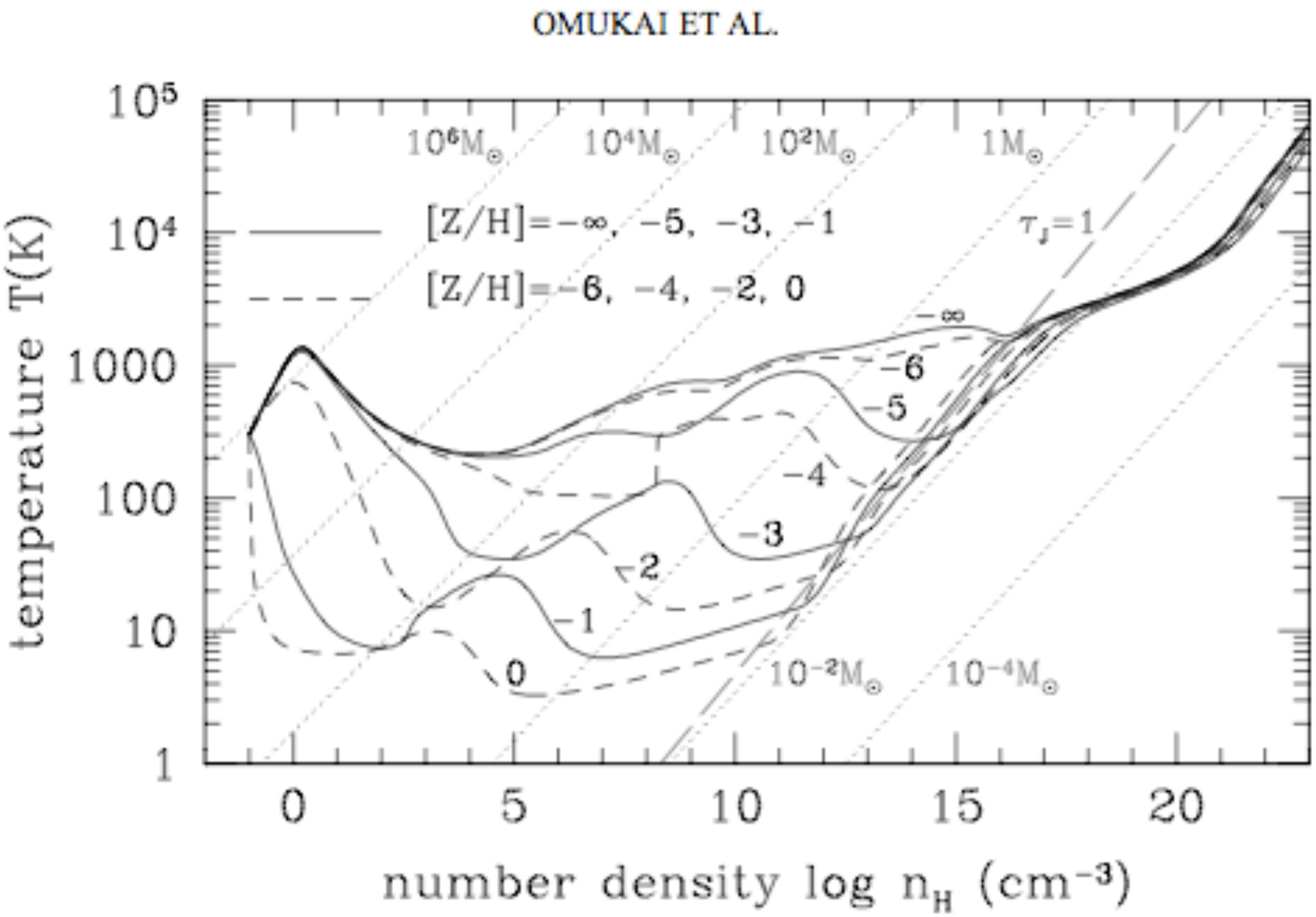
  → *POWER LAW BEHAVIOR*

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

  → *GAUSSIAN DISTRIBUTION*

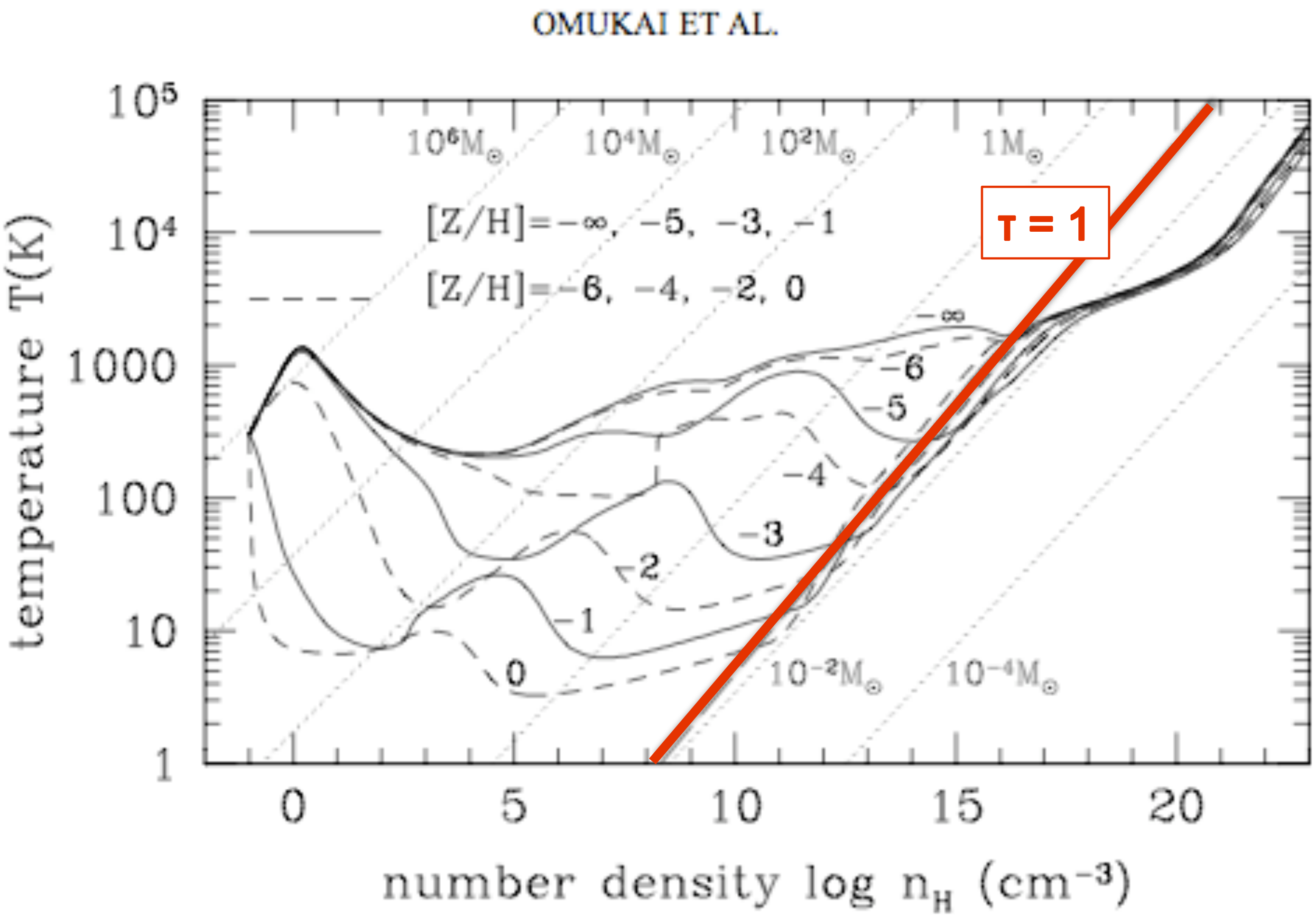
metallicity dependence

EOS as function of metallicity



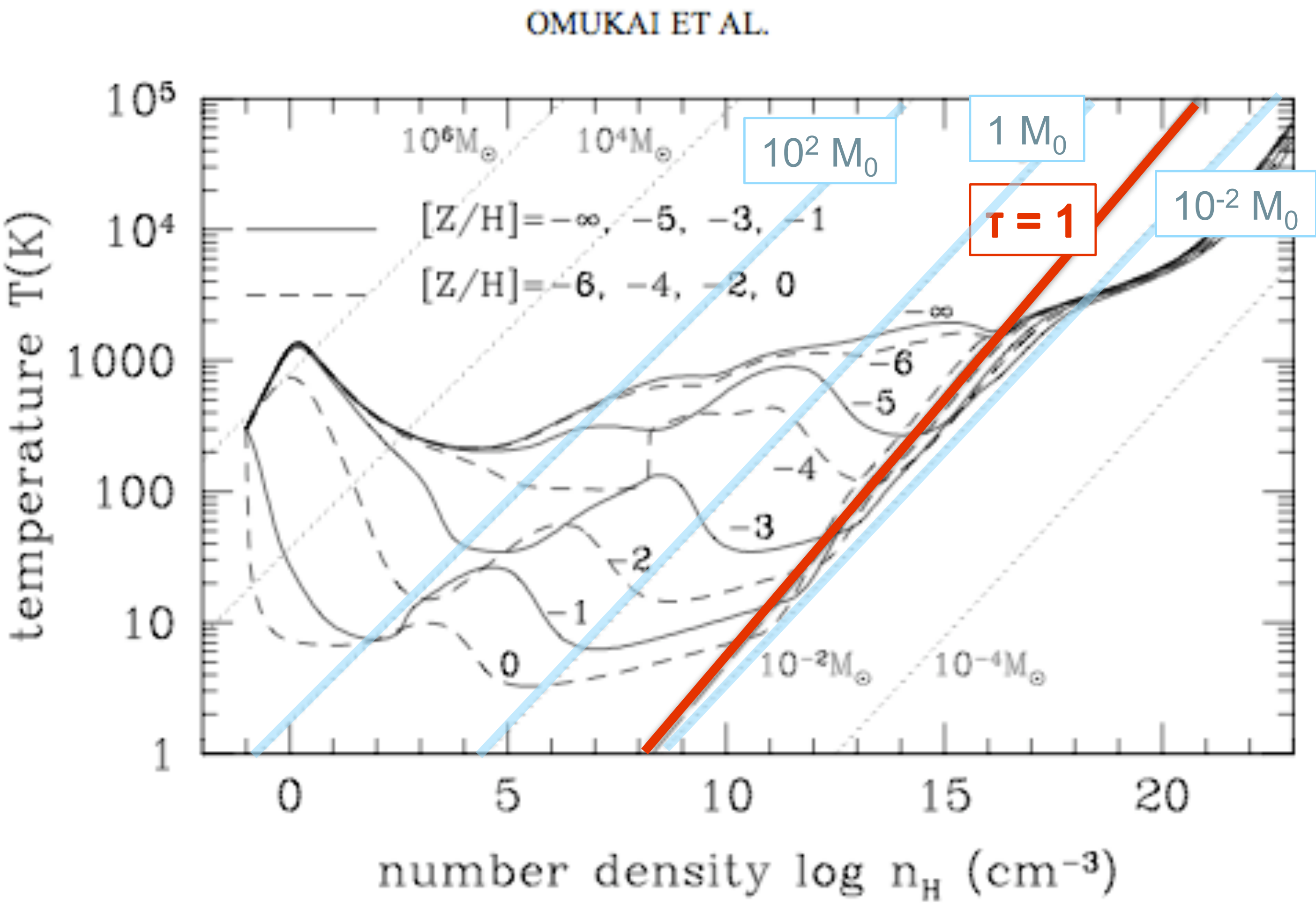
(Omukai et al. 2005)

EOS as function of metallicity



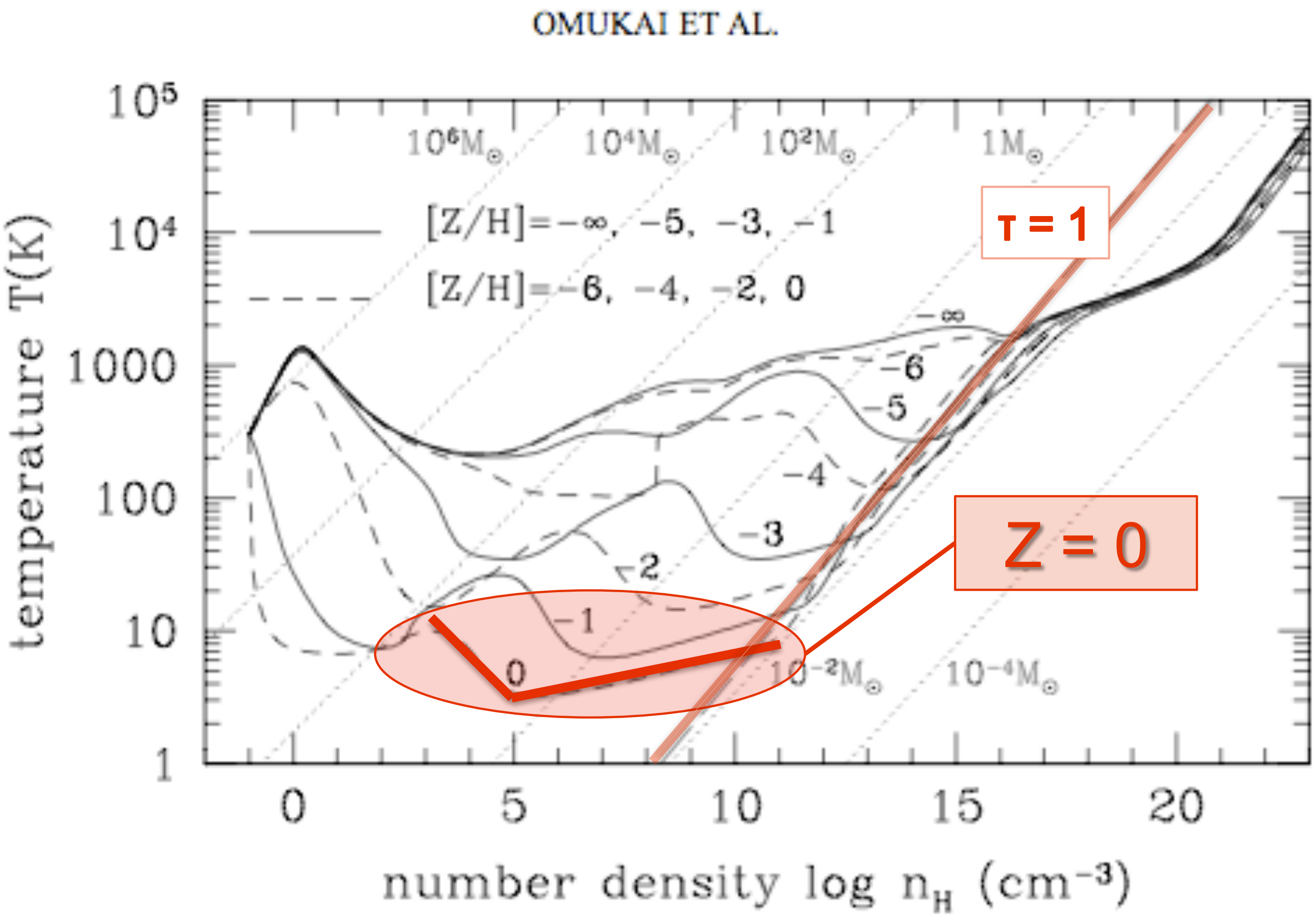
(Omukai et al. 2005)

EOS as function of metallicity



(Omukai et al. 2005)

present-day star formation

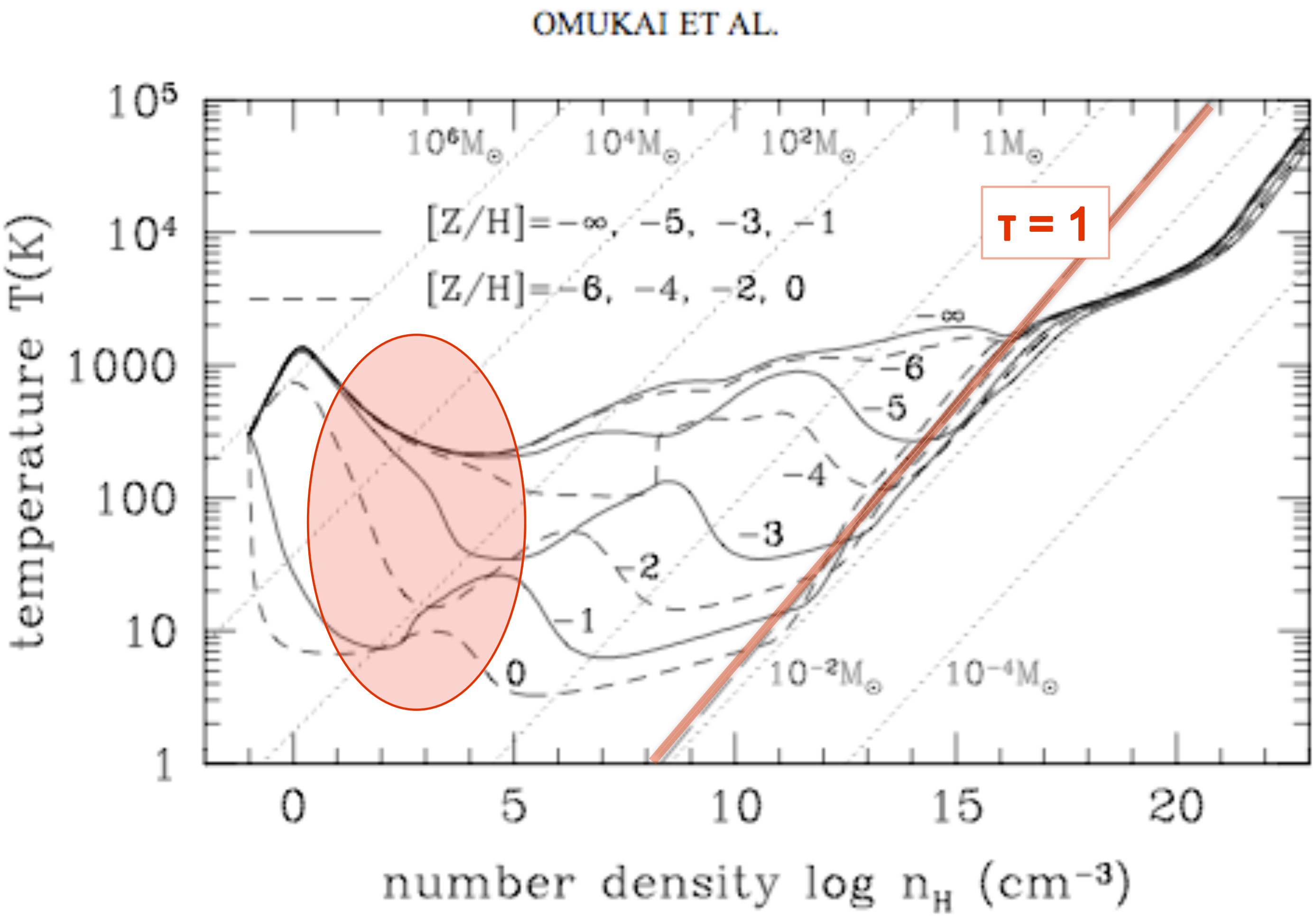


(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation

- *fragmentation behavior* depends on *EOS* (Li et al. 2003, ApJ, 592 ,975)
- *“kinck” in EOS* introduces *characteristic mass* (Jappsen et al. 2005, A&A 435, 611, Larson 2005, MNRAS, 359,211)
- *IMF* depends on *scale* (and *strength)* of *turbulence* (e.g. Klessen 2001, ApJ, 556, 837, Vazquez-Semadeni et al. 2003, ApJ, 585, L131, Clark et al. 2008, MNRAS, 386, 3)
- *characteristic mass* is (relatively) *insensitive* to *environmental parameters* → *universal IMF in local universe* (Elmegreen et al. 2008, arXiv:0803.441)

dependence on Z at low density

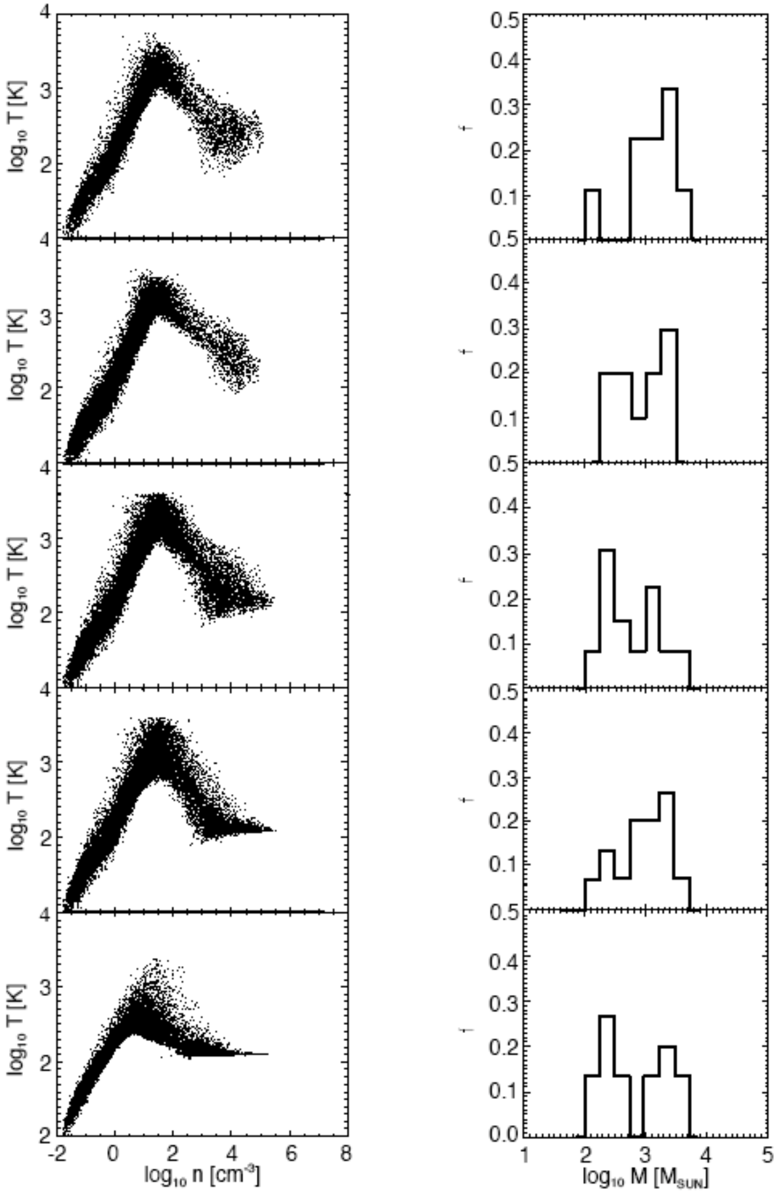


(Omukai et al. 2005)

dependence on Z at low density

- at densities below n ≈ 10^2 cm^{-3} ***H_2 cooling*** dominates the behavior. (Jappsen et al. 2007)
- fragmentation depends on ***initial conditions then***
  - example: *solid-body rotating top-hat* initial conditions with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime n ≤ 10^6 cm^{-3})
    → because *unstable disk* builds up
    (Jappsen et al. 2008a)

dependence on Z at low density



Z = 0

Z = -4

Z = -3

Z = -2

Z = -1

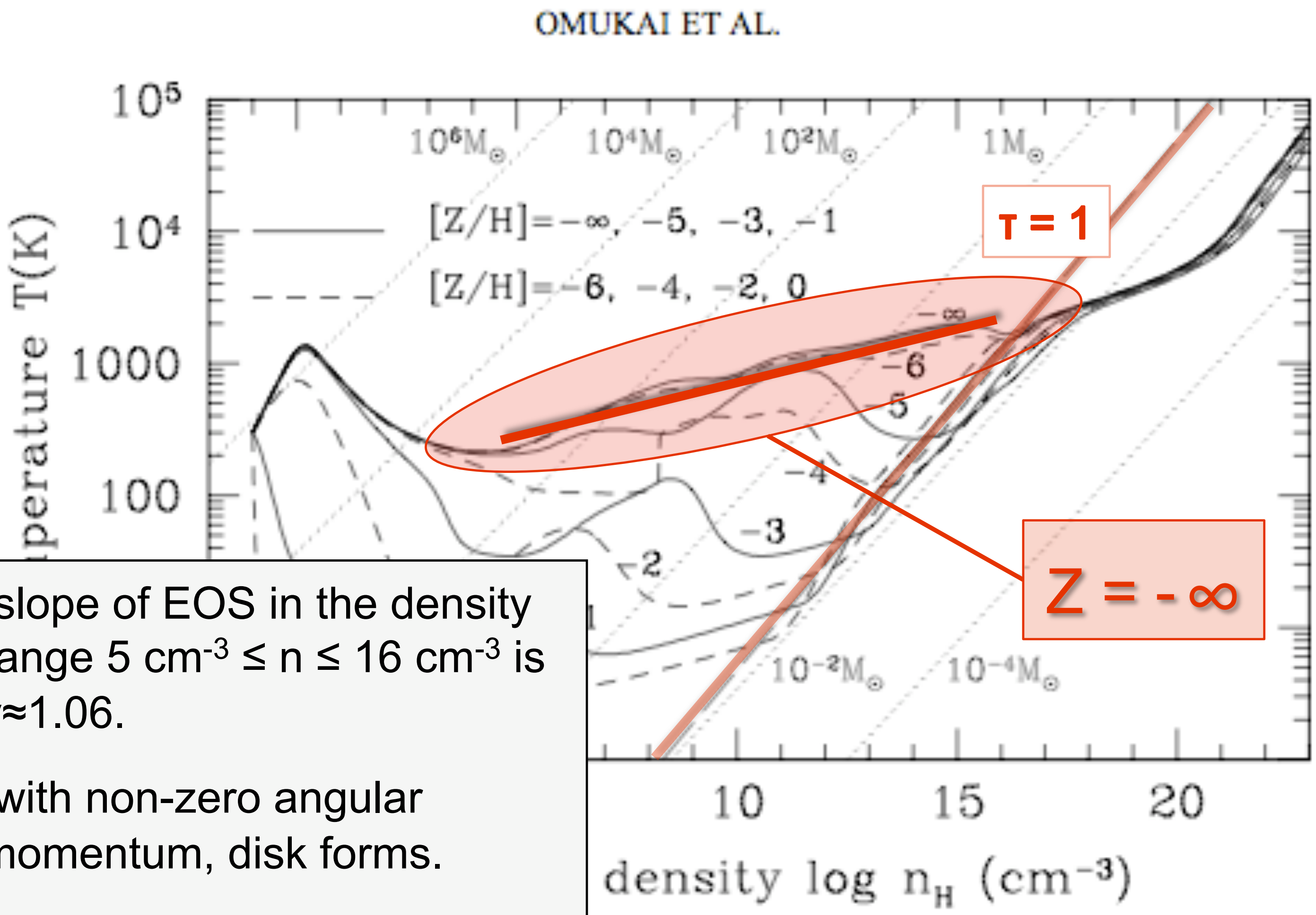
rotating top-hat with dark matter fluctuations fragments, no matter what

(Jappsen et al. 2008a, see also Clark et al. 2008)

dependence on Z at low density

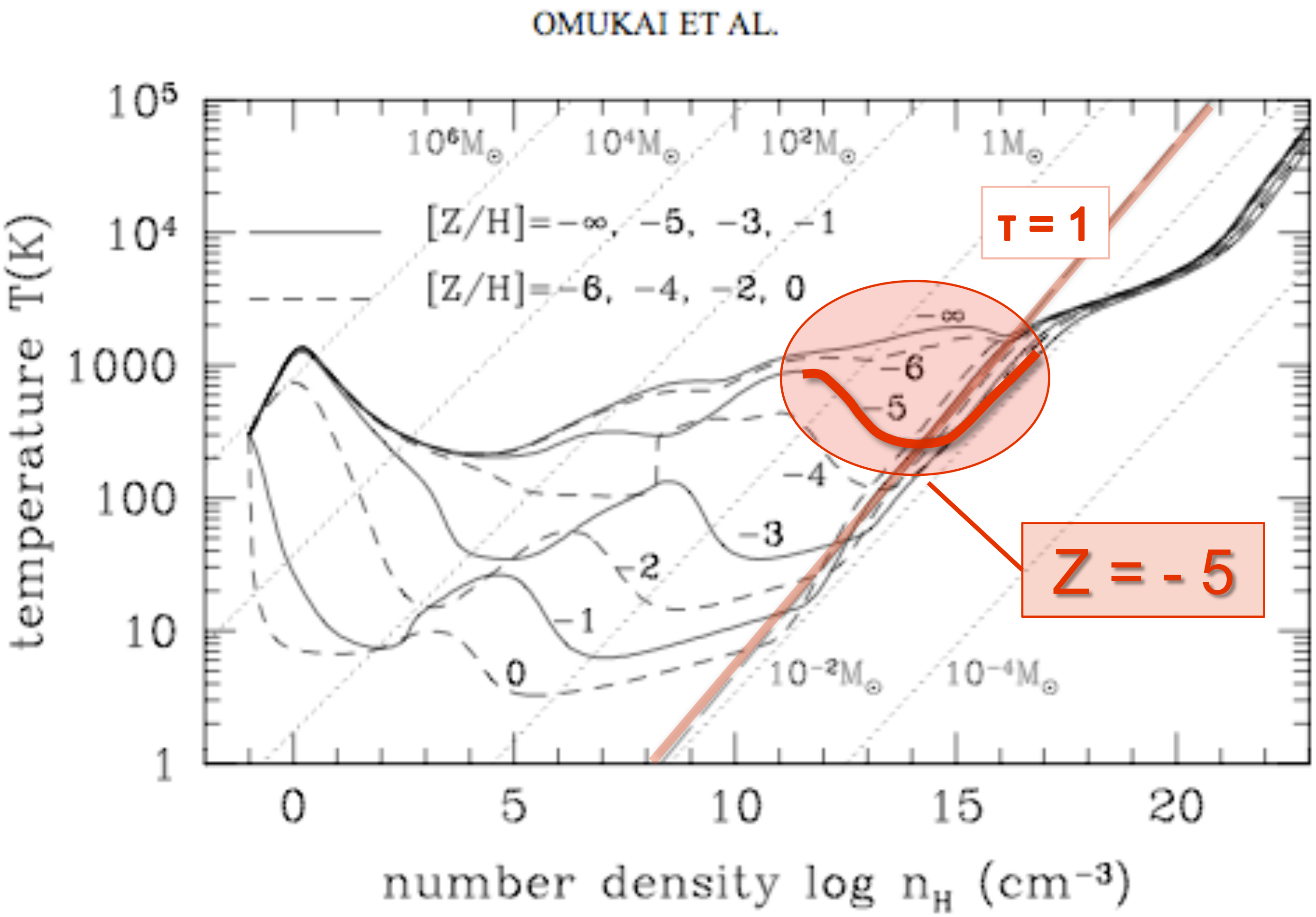
- fragmentation depends on *initial conditions then*
  - example: *centrally concentrated halo* does *not* fragment up to densities of n ≈ 10^6 cm^{-3} up to metallicities Z ≈ -1
    (Jappsen et al. 2008b)

metal-free star formation



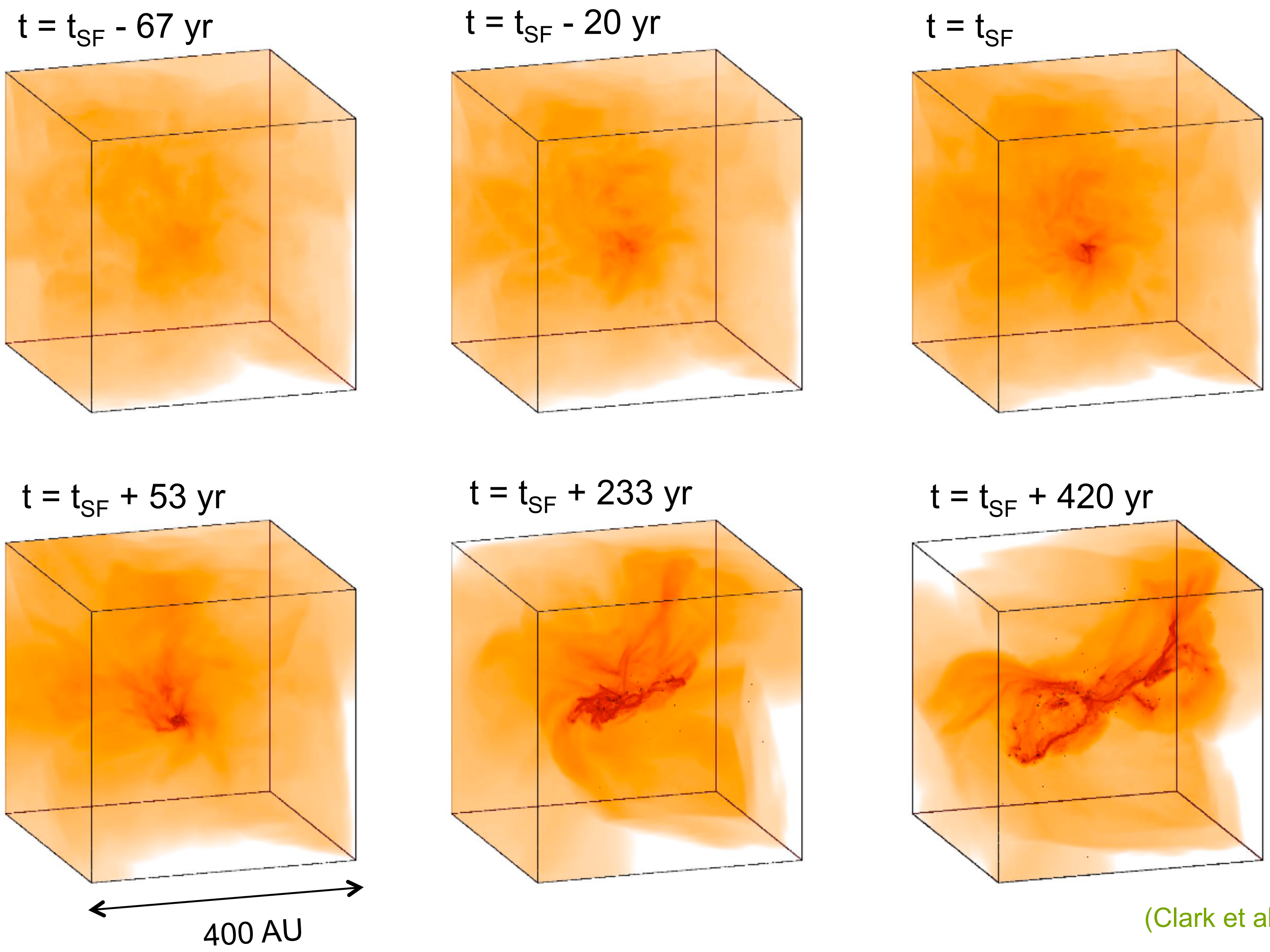
- slope of EOS in the density range 5 $cm^{-3} \leq n \leq 16\ cm^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

transition: Pop III to Pop II.5



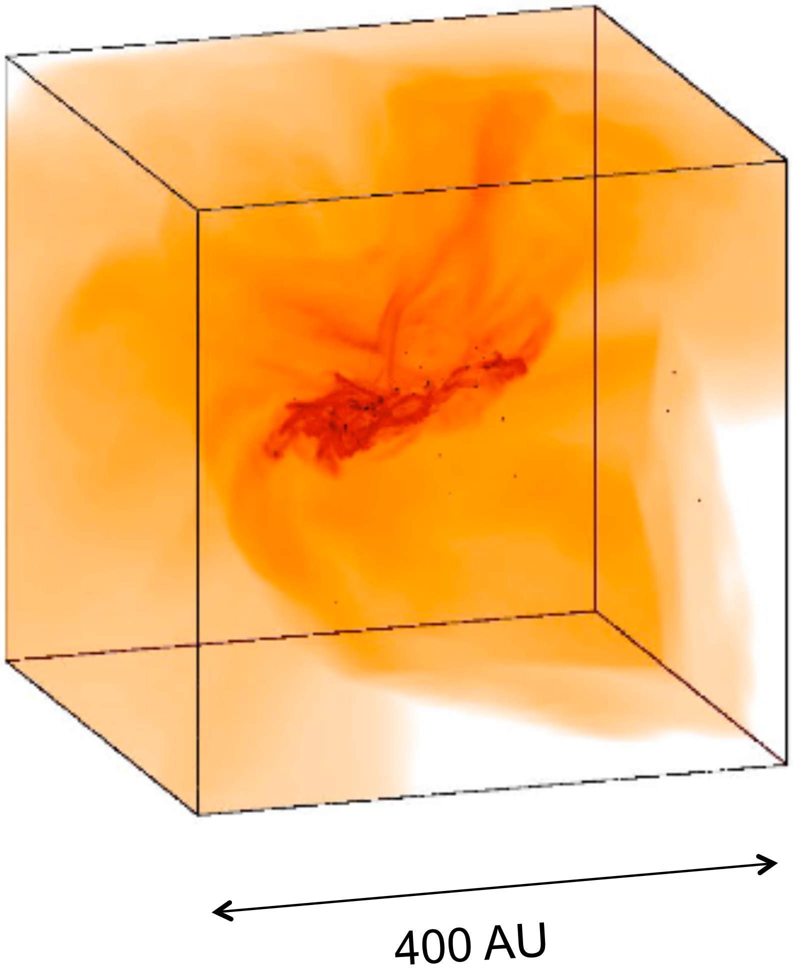
(Omukai et al. 2005)

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



(Clark et al. 2007)

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



dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9 \, pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13} \, cm^{-3}$

(Clark et al. 2007)

cluster build-up

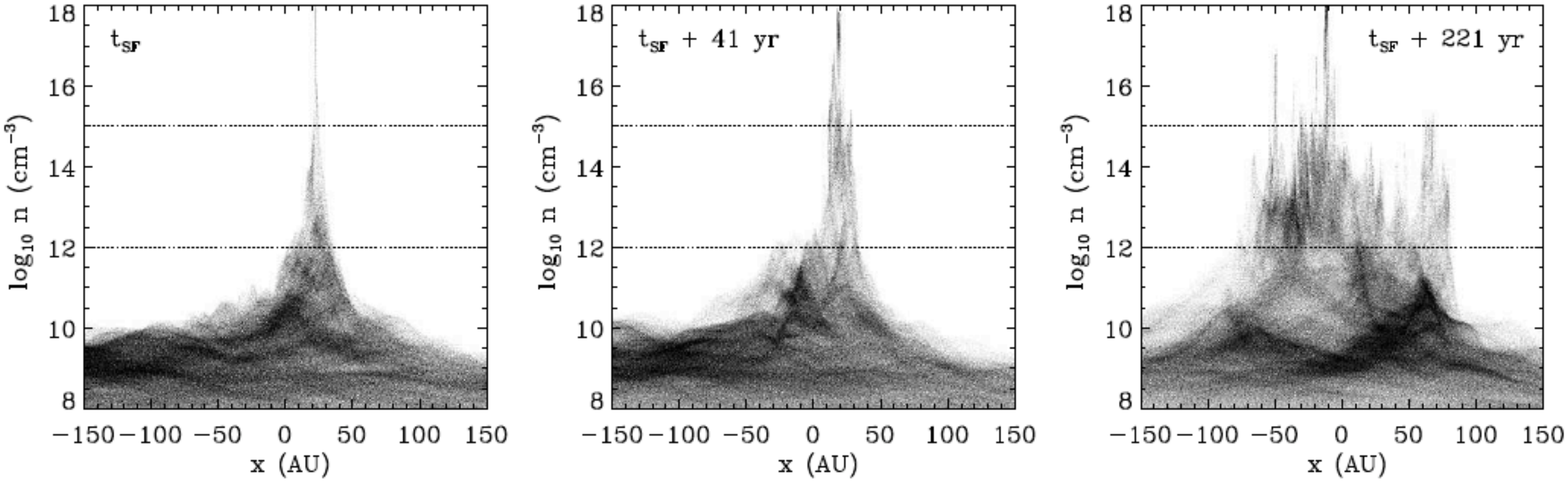
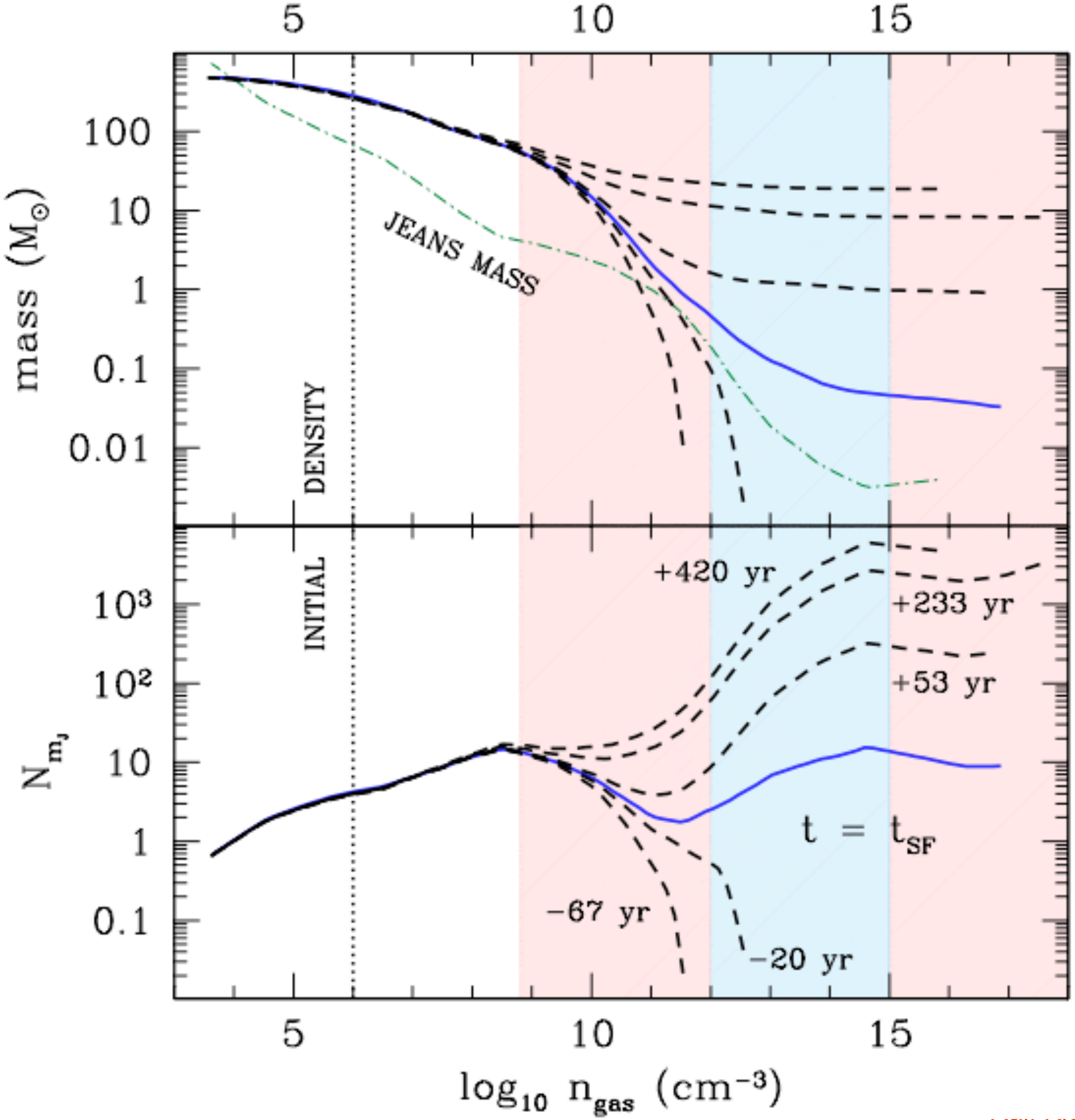
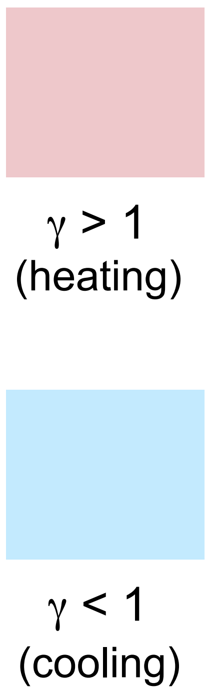


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_{\odot}$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We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

(Clark et al. 2007)

cluster build-up

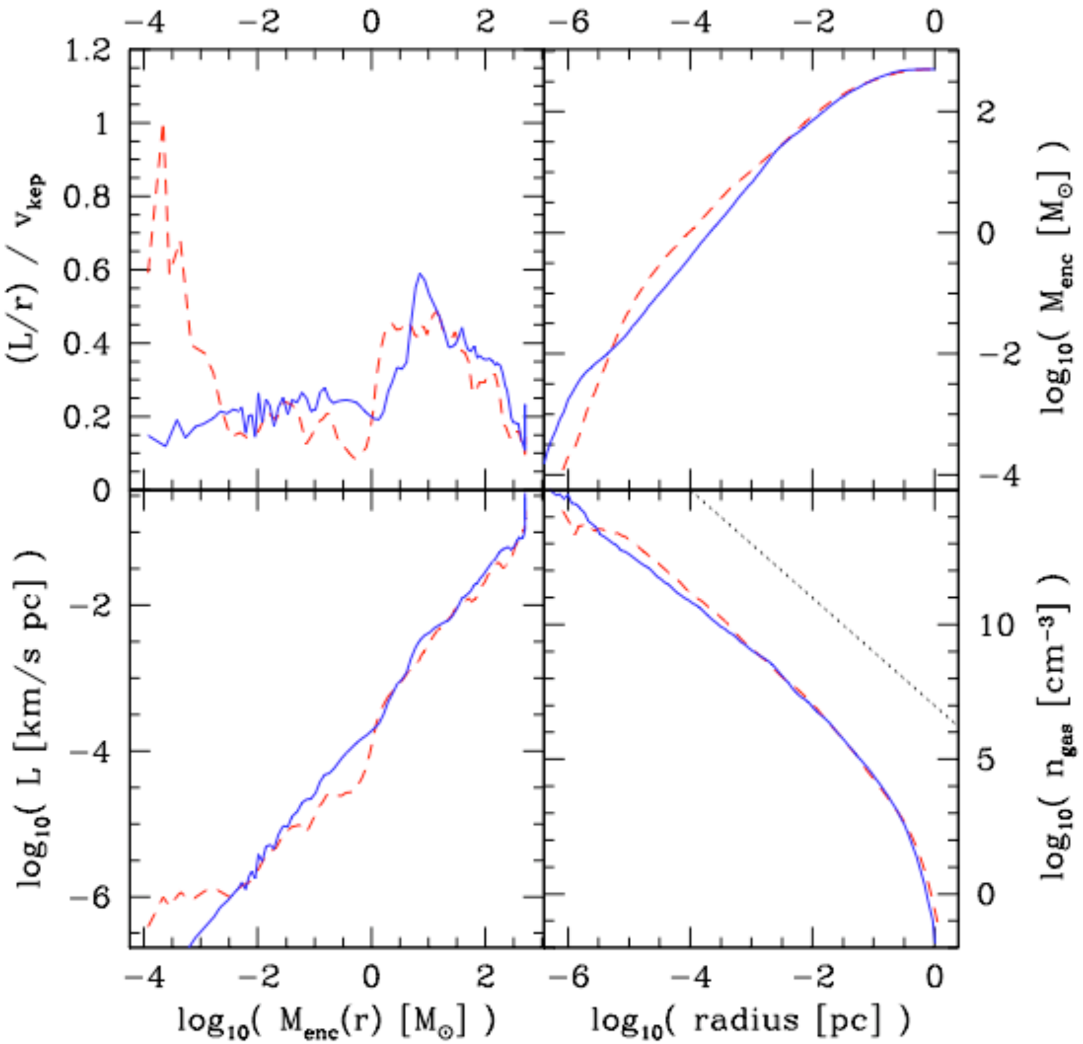




(Clark et al. 20

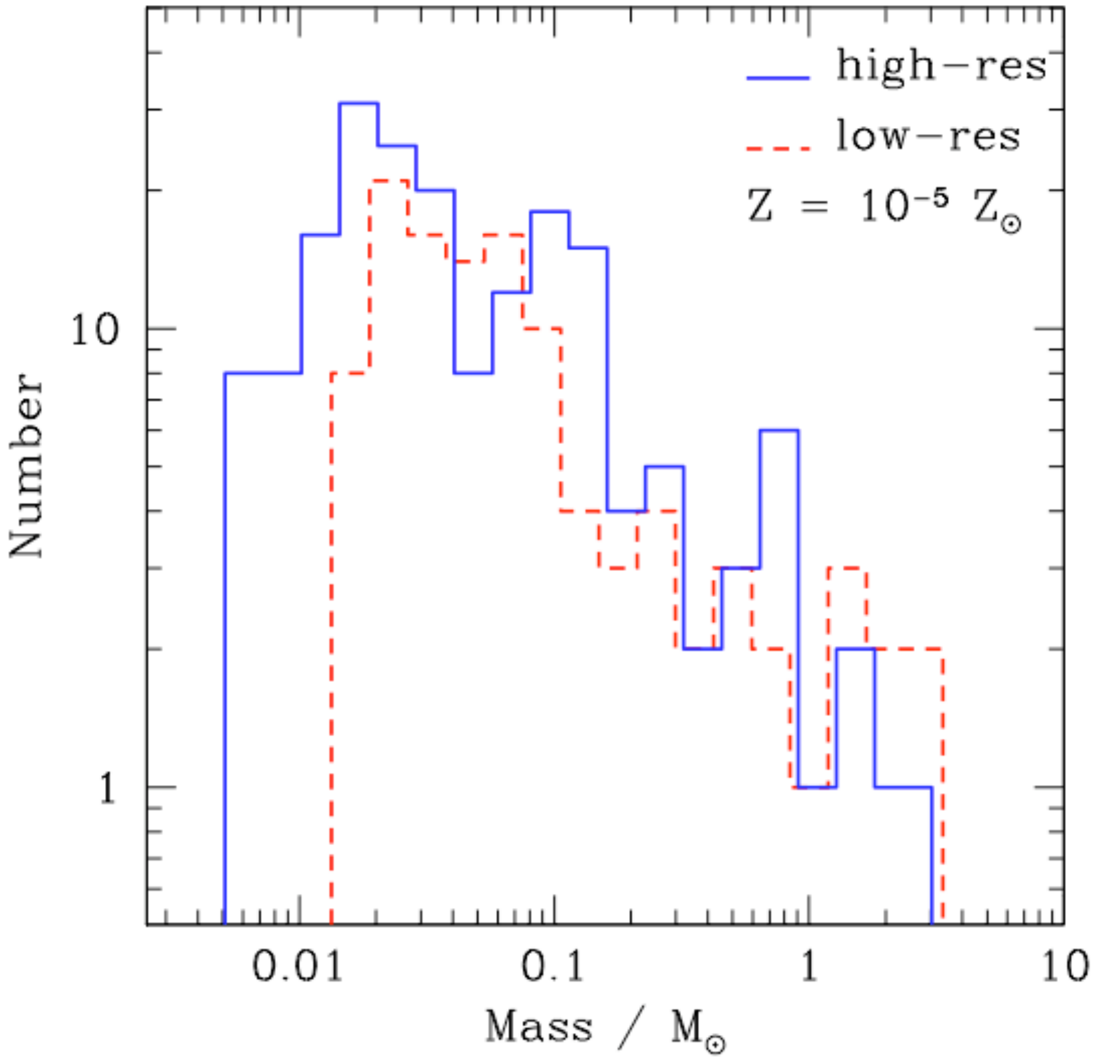
gas properties

gas properties at time when first star forms



(Clark et al. 2007)

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



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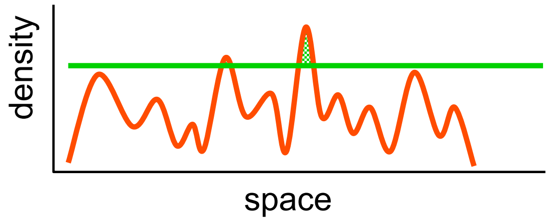
(Clark et al. 2007)

summary

Summary I

- interstellar gas is highly *inhomogeneous*



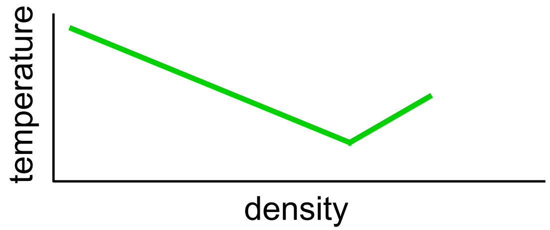
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*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

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

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

Summary II

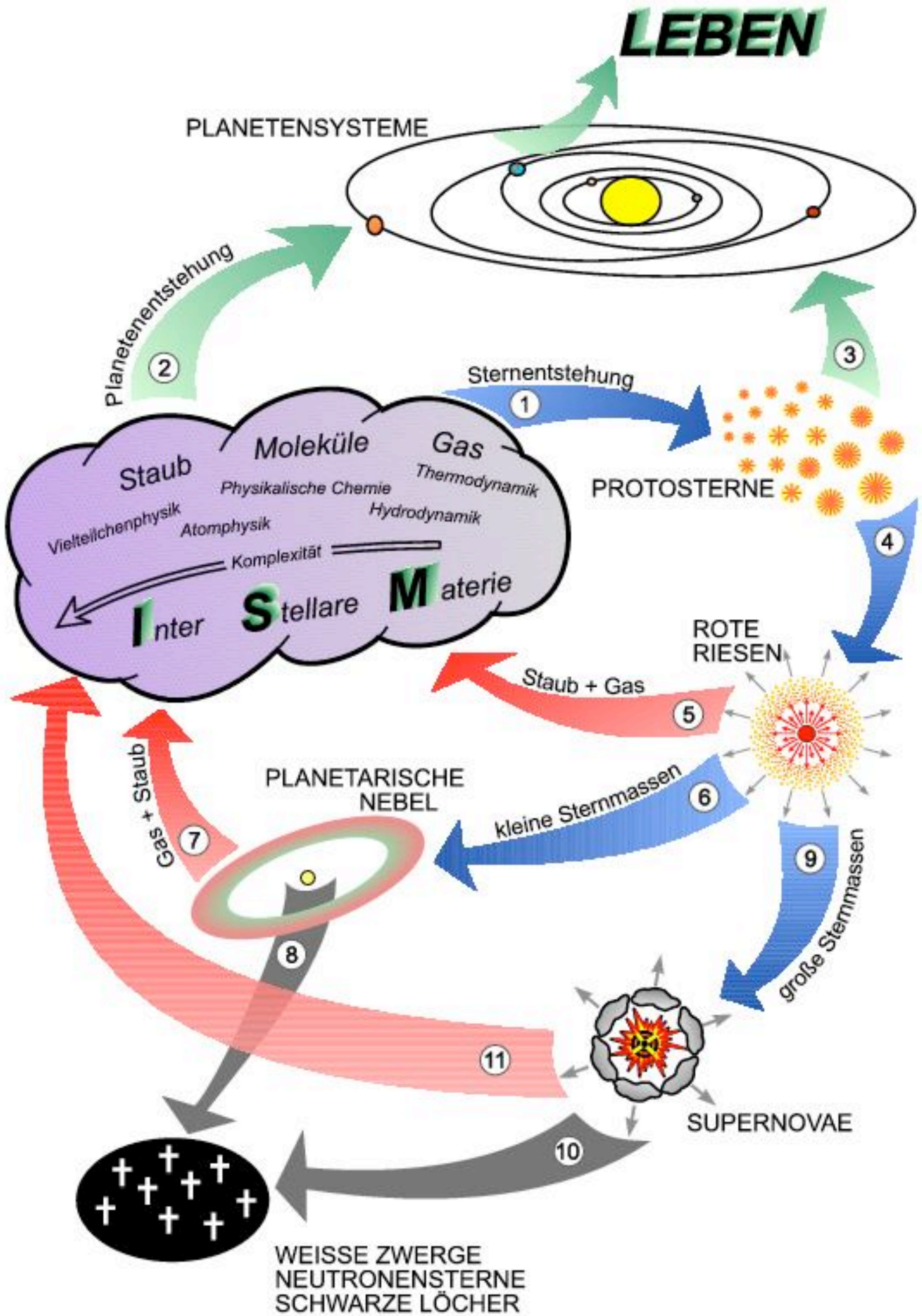
- *thermodynamic response* (EOS) determines fragmentation behavior
  - characteristic stellar mass from fundamental atomic and molecular parameters
    --> explanation for quasi-universal IMF?



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

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

outlook


LEBEN
PLANETENSYSTEME
Planetenentstehung
2
Sternentstehung
1
3
PROTOSTERNE
Staub
Moleküle
Gas
Physikalische Chemie
Thermodynamik
Vielteilchenphysik
Atomphysik
Hydrodynamik
Komplexität
Inter Stellare Materie
4
ROTE
RIESEN
Staub + Gas
5
kleine Sternmassen
6
PLANETARISCHE
NEBEL
Gas + Staub
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9
große Sternmassen
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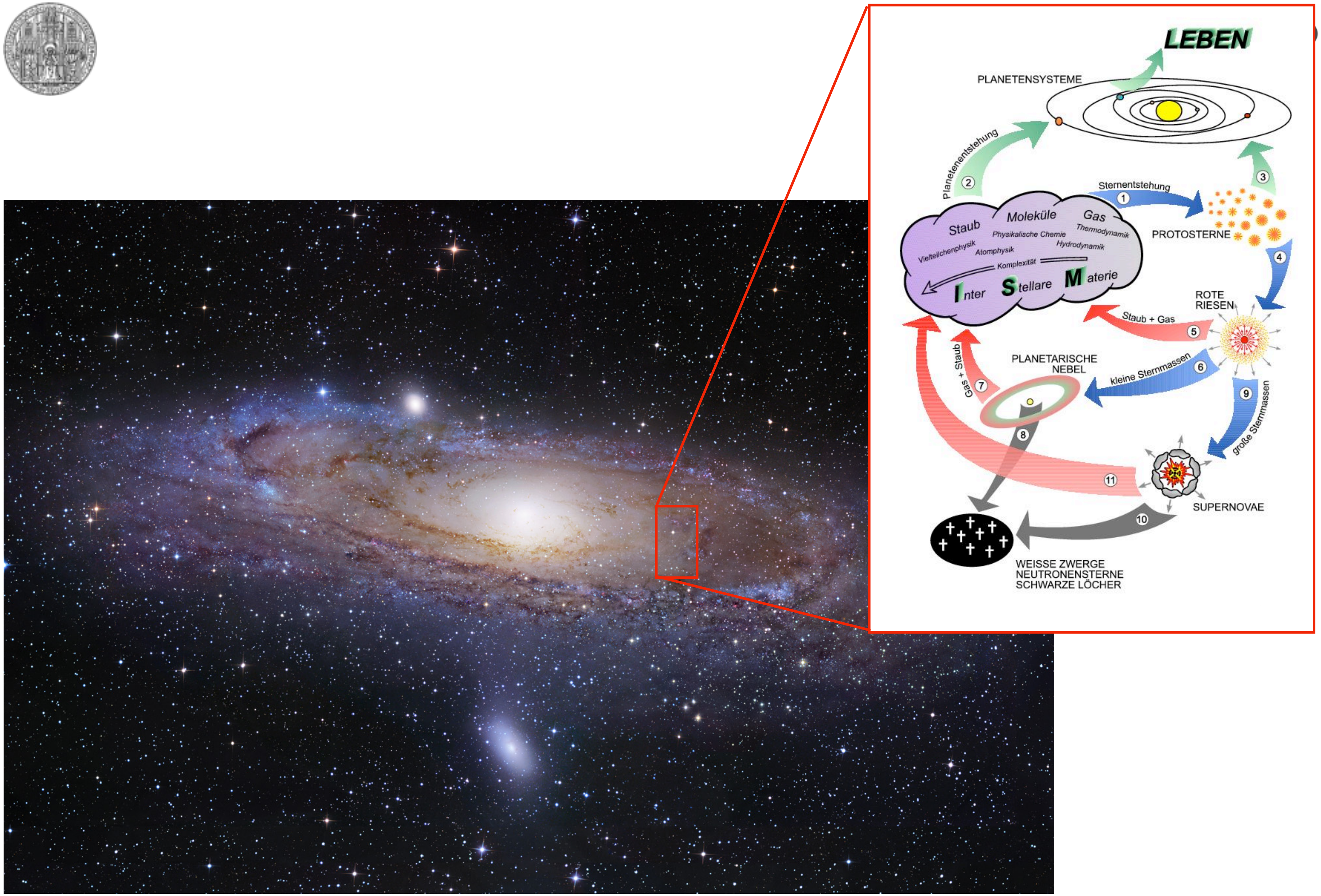
SUPERNOVAE
10
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER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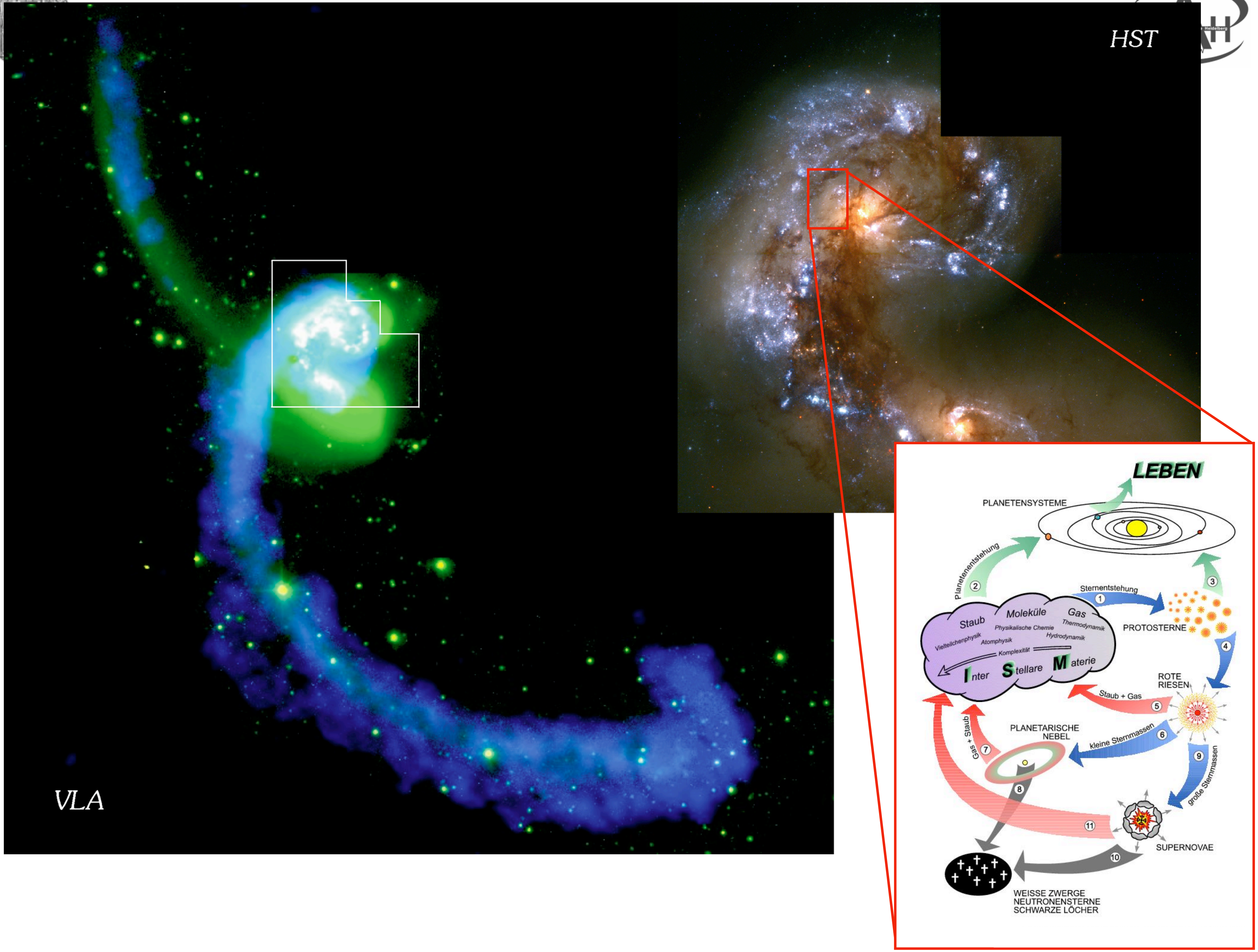
SCHWARZE LÖCHER


VLA
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große Sternmassen
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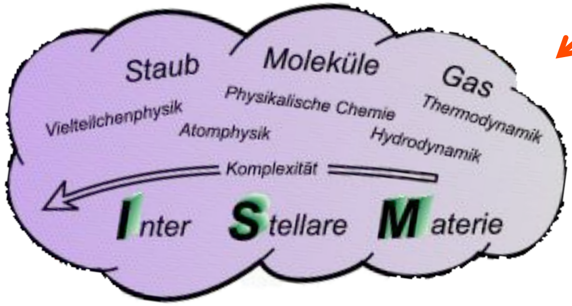
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER

what do we need ...
... to study ISM and star formation?



magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections,
dust coagulation properties, etc.)

what do we need?

- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

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stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

what do we need?

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydro-dynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

what do we need?

- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

what do we need?

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

what do we need?

- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

what do we need?

methods need to be combined!

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

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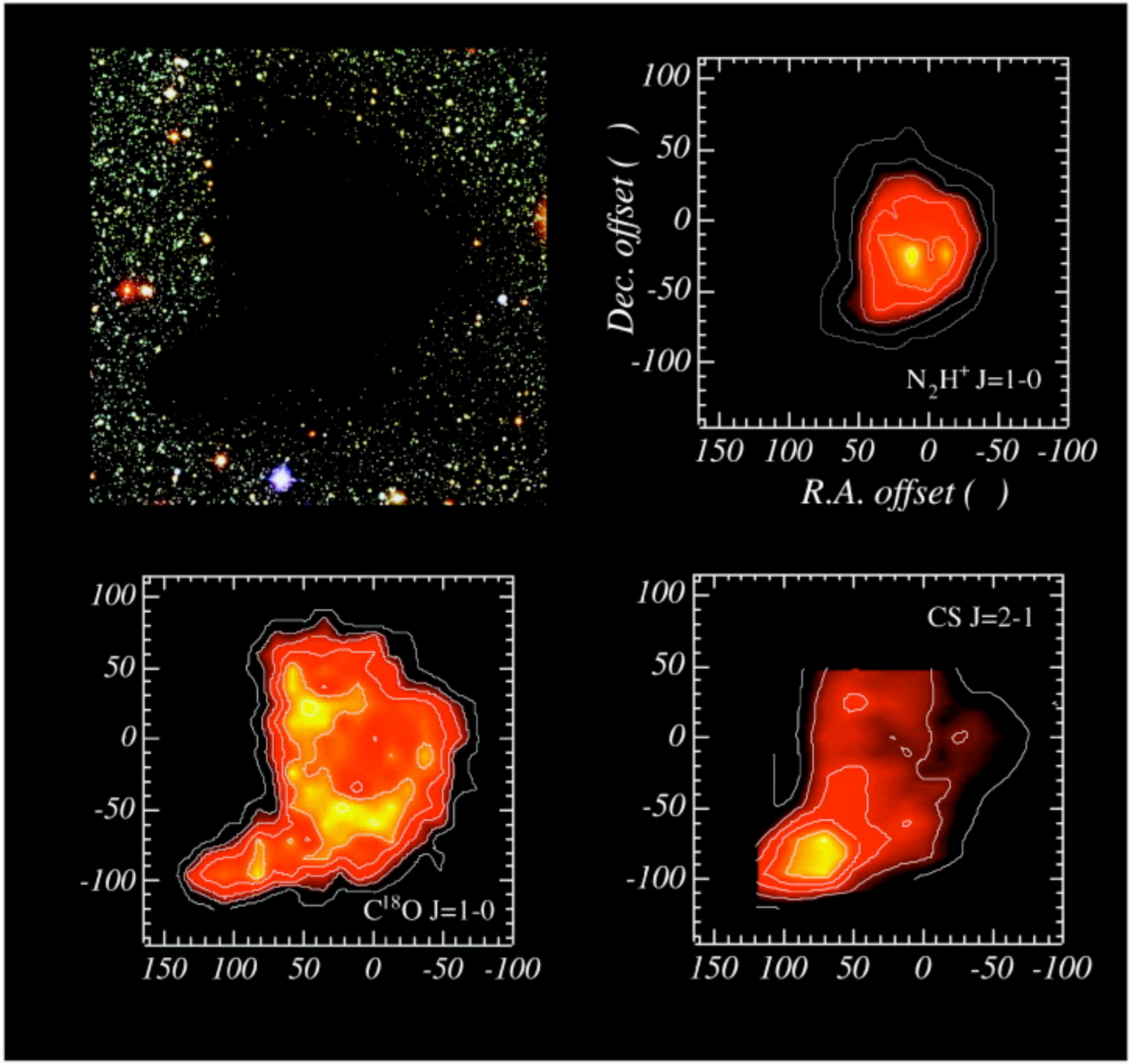
(feedback: radiation, winds, SN)

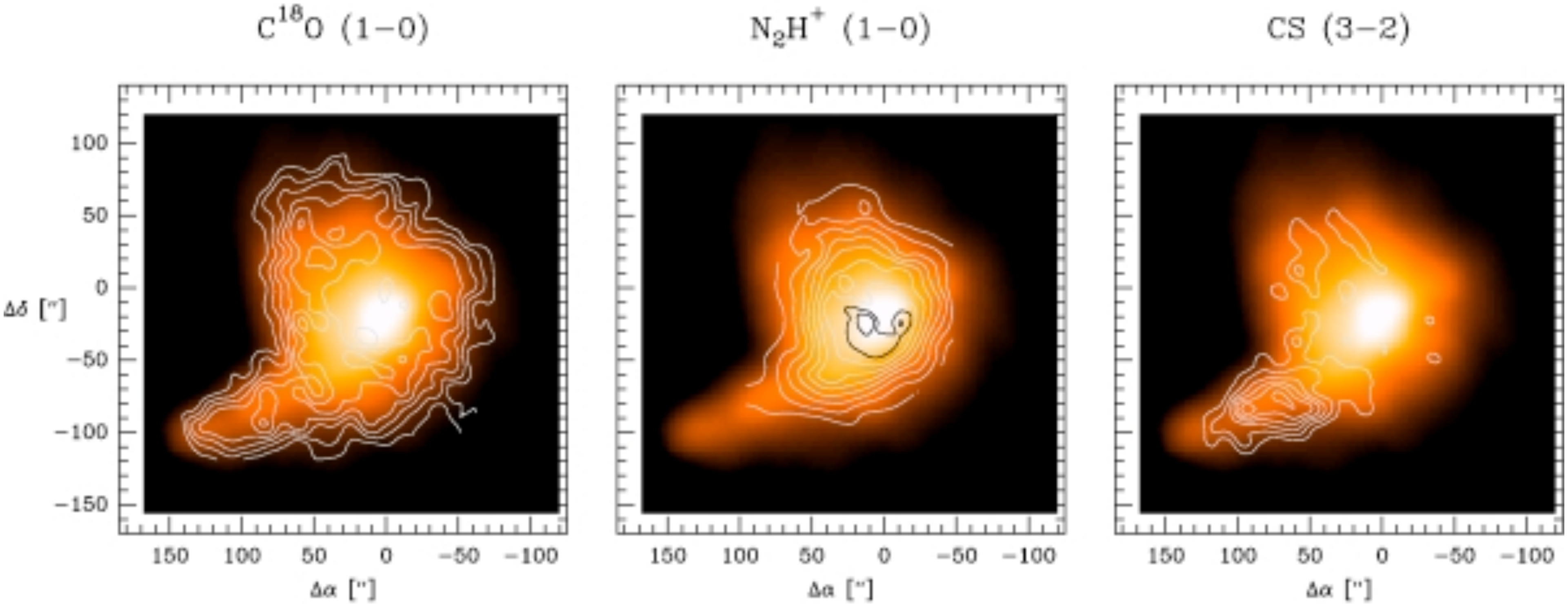
\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

Barnard 68: a well-studied isolated prestellar core



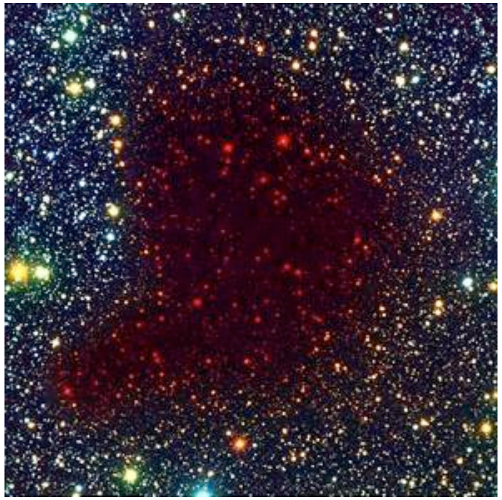
(Lada et al. 2003)

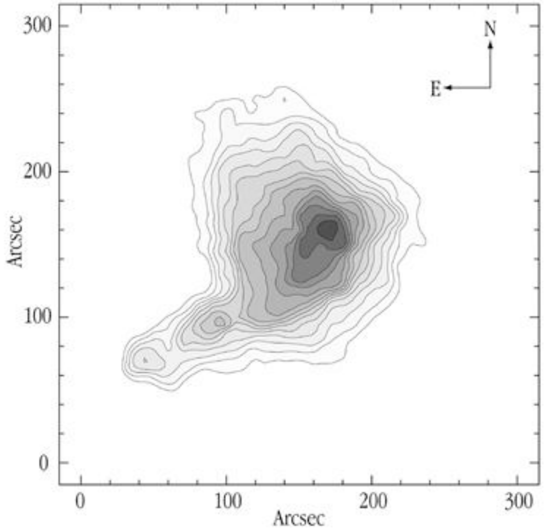
Barnard 68

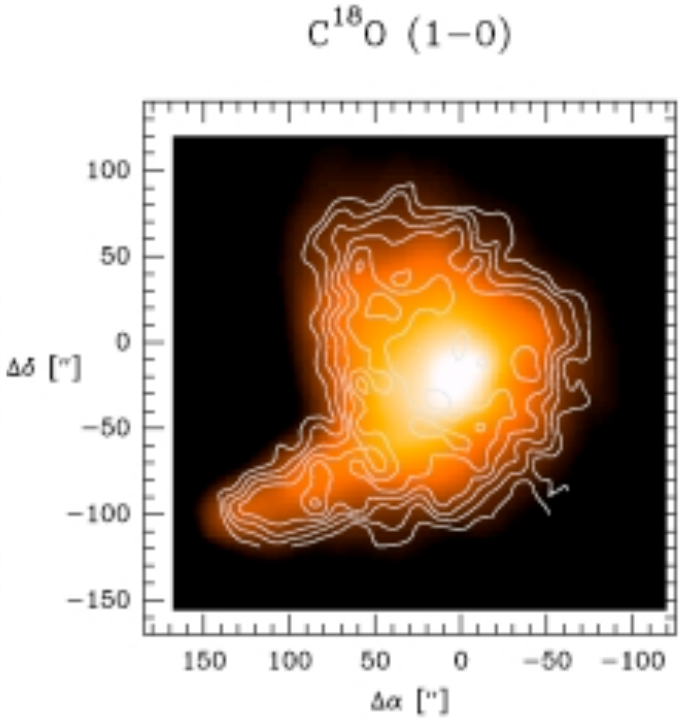


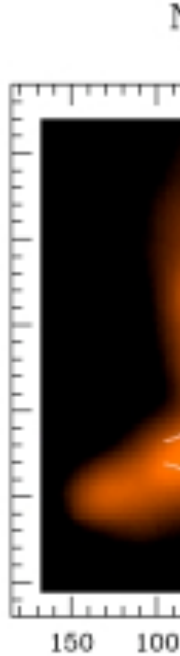
(Bergin et al.)

observations

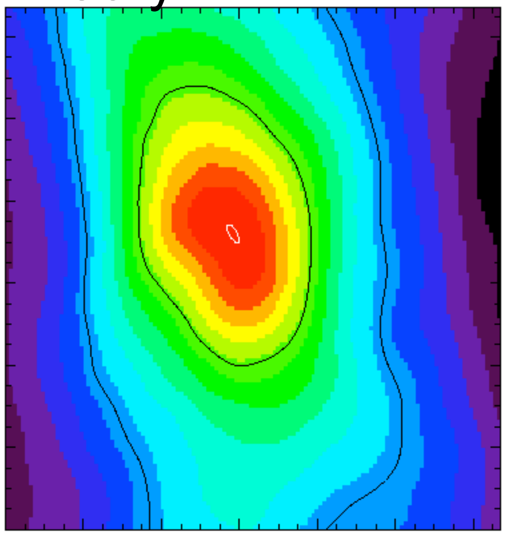








theory



MHD model with proper heating and cooling terms (EOS)

+

chemical model

line radiative transfer

synthetic images of model cores

compare

"Taste Testing Initiative → special discussion round lead by Alyssa Goodman

Thanks!