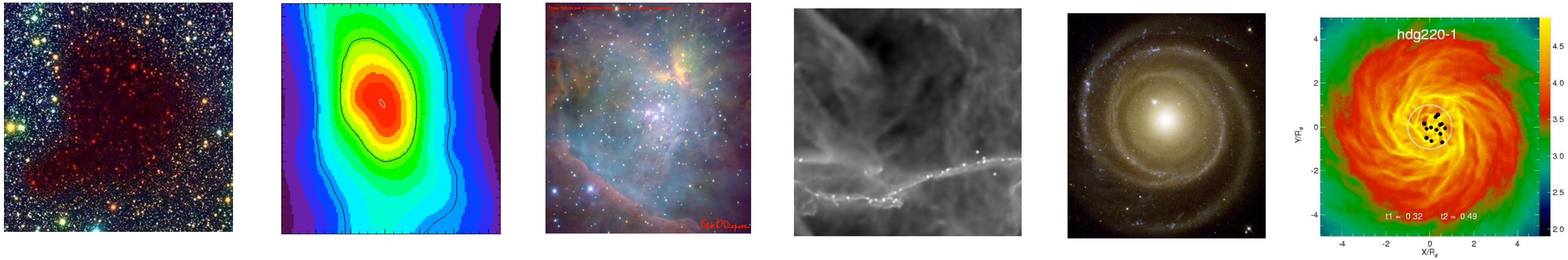
Star Formation - Now and Then



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ZAH
Zentrum für Astronomie Heidelberg
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*

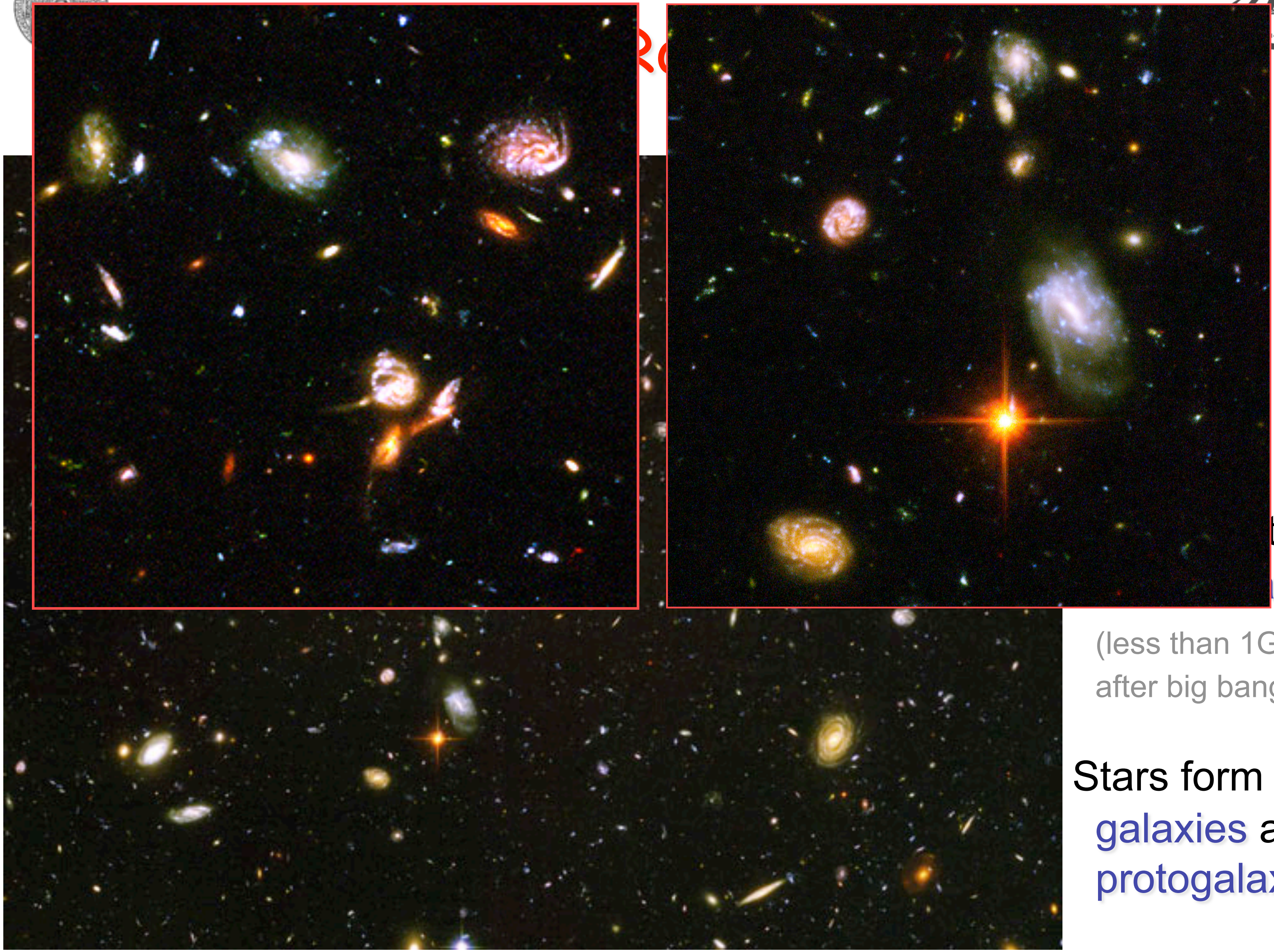
- Robi Banerjee
- Paul Clark
- Christoph Federrath
- Simon Glover
- Thomas Greif
- Susanne Horn
- Stefan Schmeja

- Thomas Peters
- Dominik Schleicher
- and many guests

agenda

- phenomenology
- formation of molecular clouds
  - on galactic scales
  - locally, in convergent flows
- fragmentation of molecular clouds
  - interplay between gravity and turbulence
- star formation: now and then
  - initial mass function at present days (models & caveats)
  - speculations about Pop III and transition to Pop II

observations



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

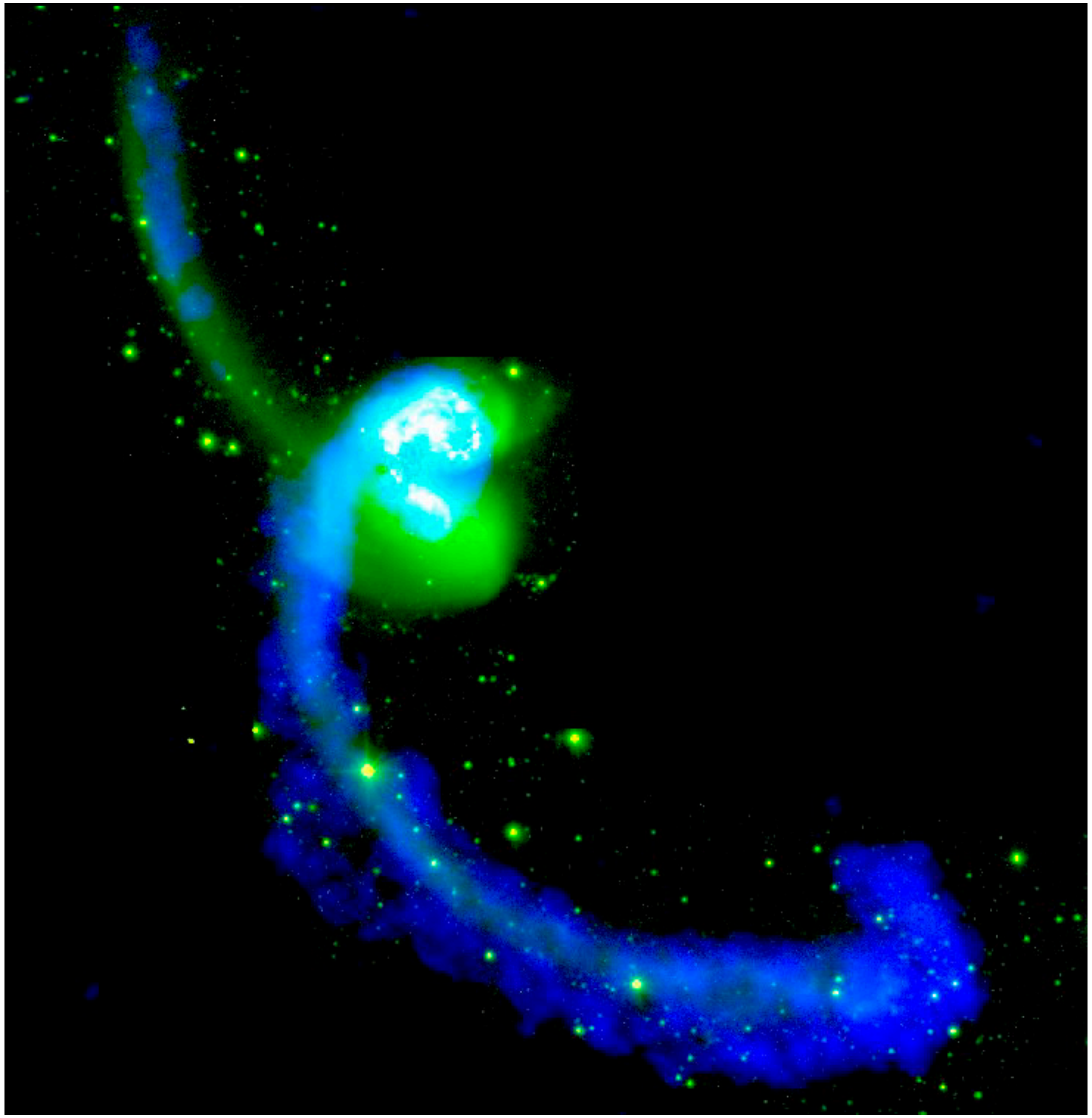
tion

rly

(less than 1Gyr
after big bangl)

Stars form in
galaxies and
protogalaxies

Star formation in interacting galaxies:

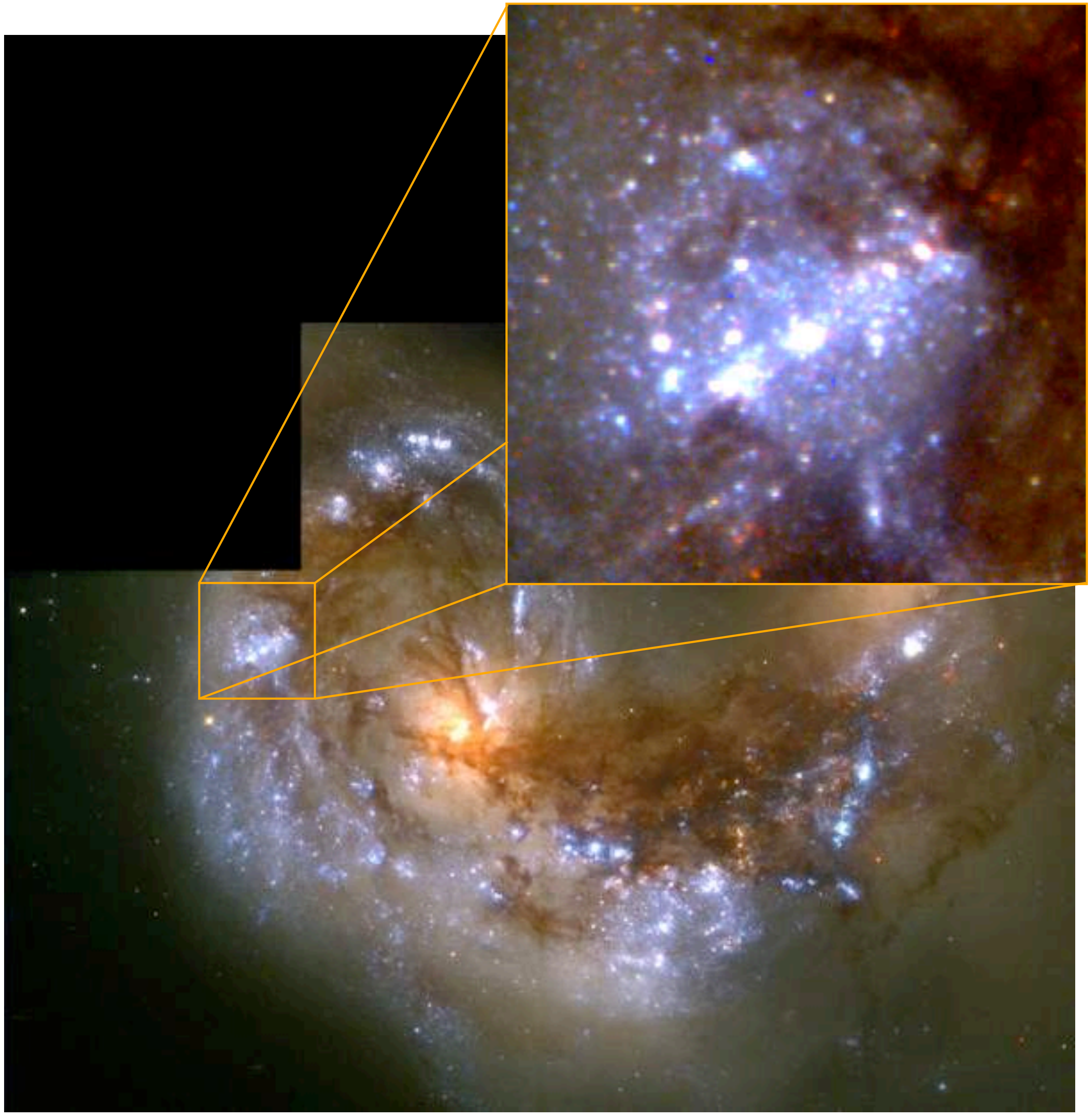


(from the Chandra Webpage)

Antennae galaxy

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

Star formation in interacting galaxies:



(HST: Whitmore & Schweizer 1997)

Antennae galaxy

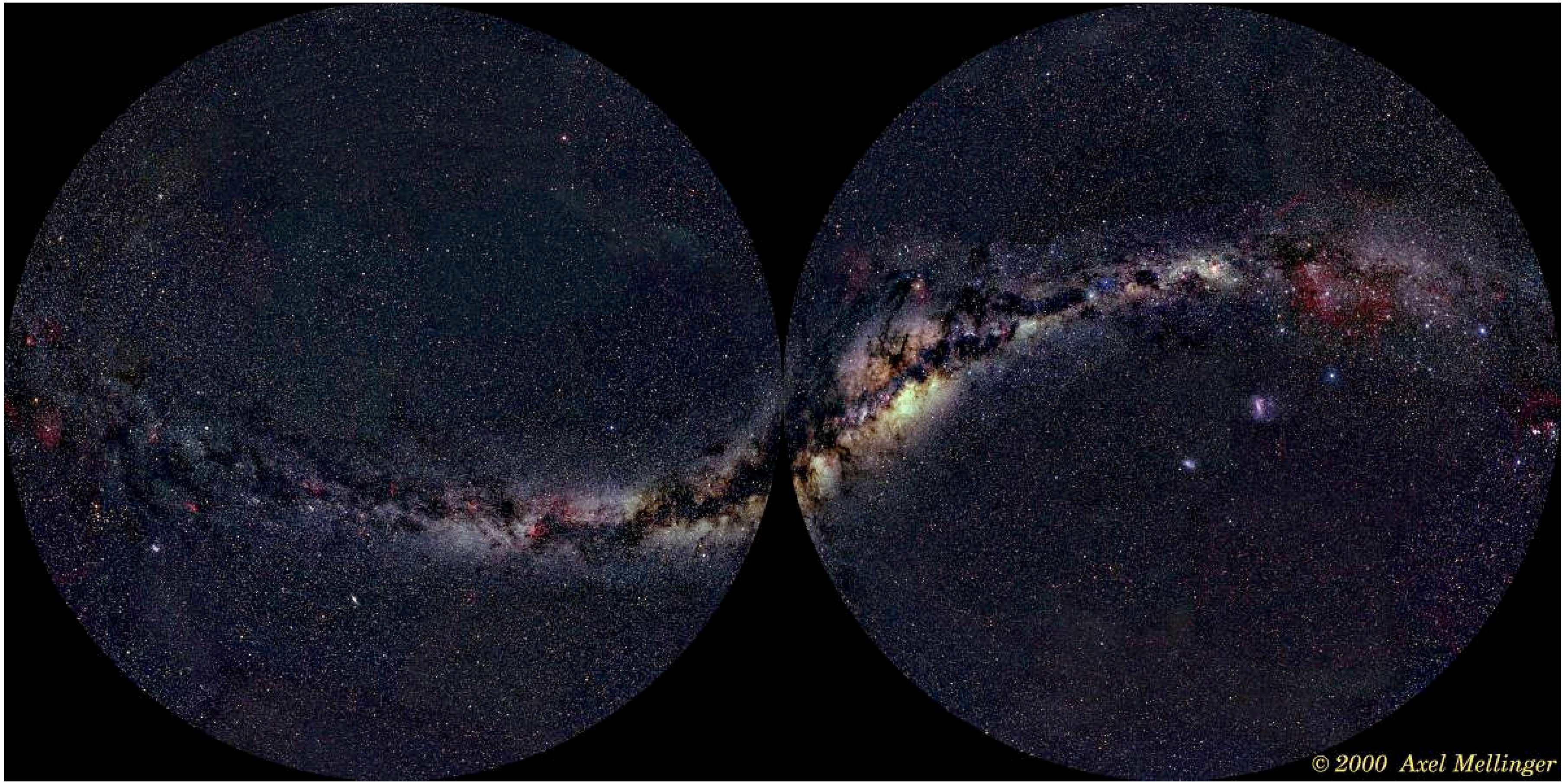
- Star formation burst in interacting (merging) galaxies
- Strong perturbation SF in tidal “tales”
- Large-scale gravitational motion determines SF
- Stars form in “knobs” (i.e. superclusters)

young stars in spiral galaxies

(NGC 4622 from the Hubble Heritage Team)

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

young stars in the Milky Way



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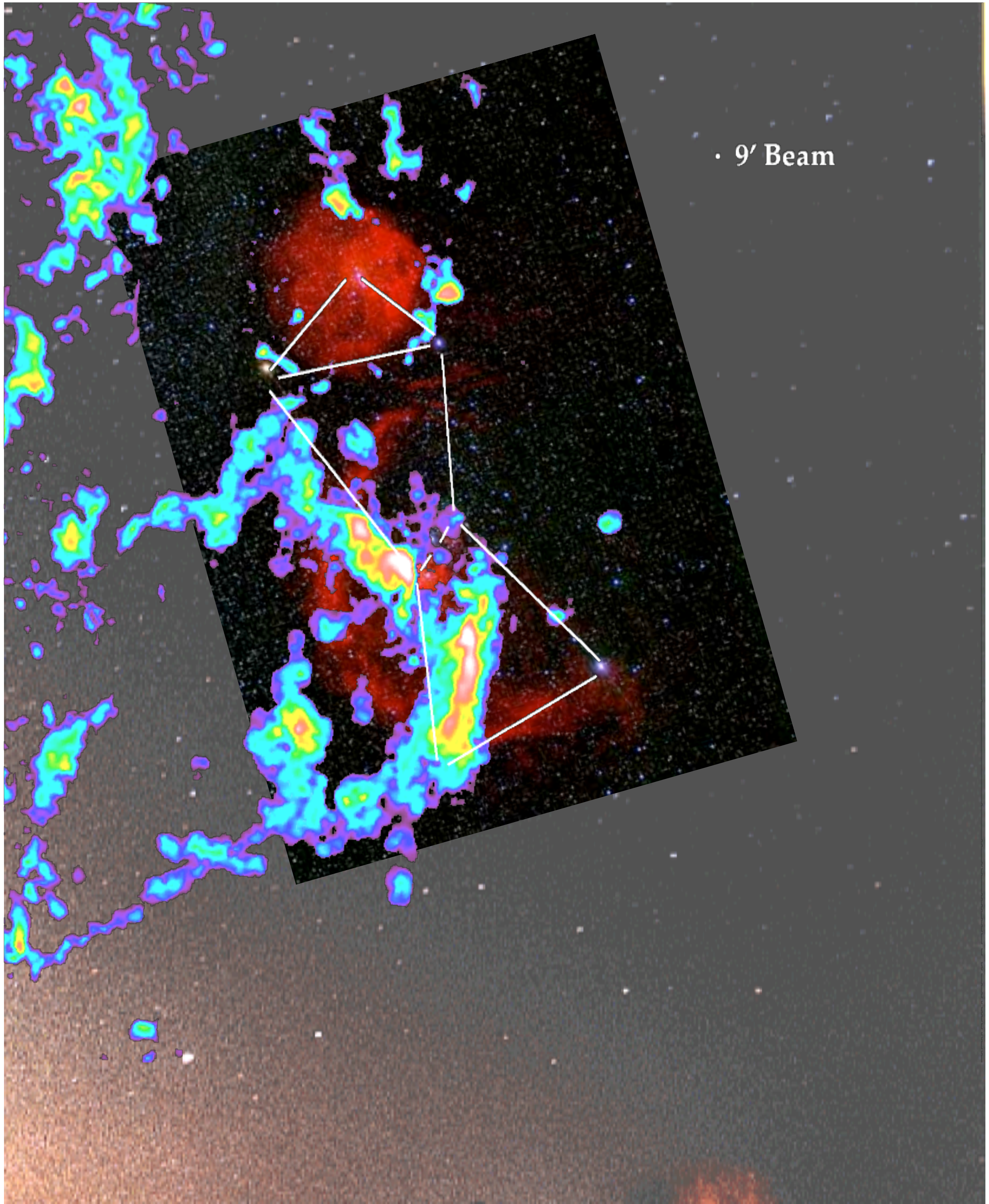
On the night sky, you see ***stars*** and ***dark clouds***:
The brightest stars are massive and therefore young.
→ Star formation is important for understanding the structure of our Galaxy

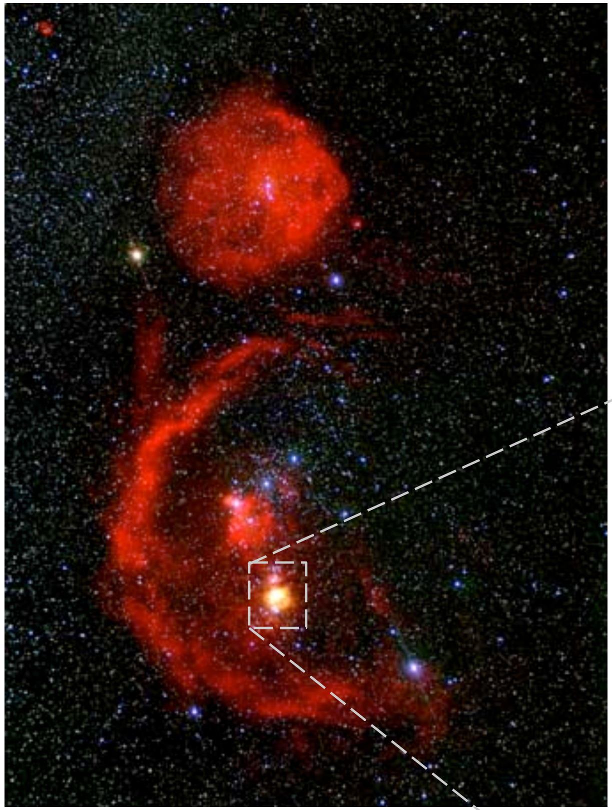


Star formation in Orion

We see

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

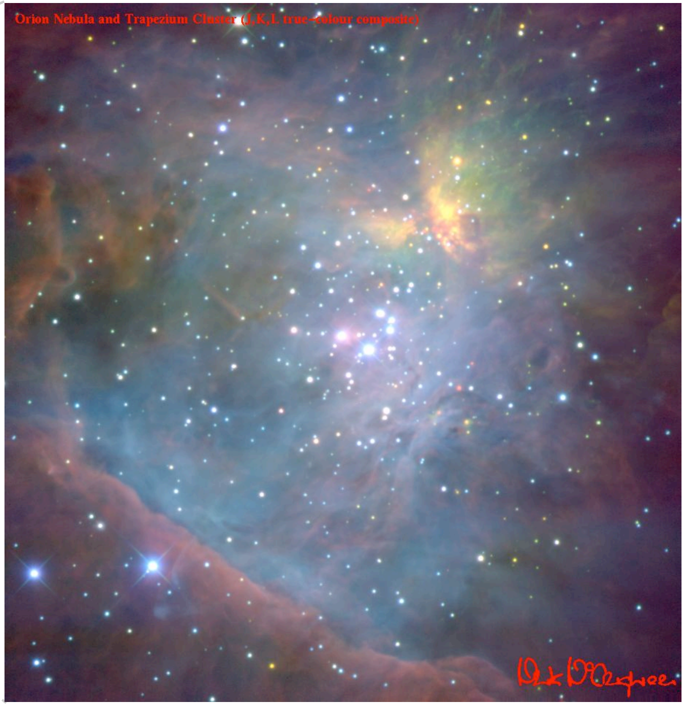
Local star forming region: The Trapezium Cluster in Orion



Orion molecular cloud

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

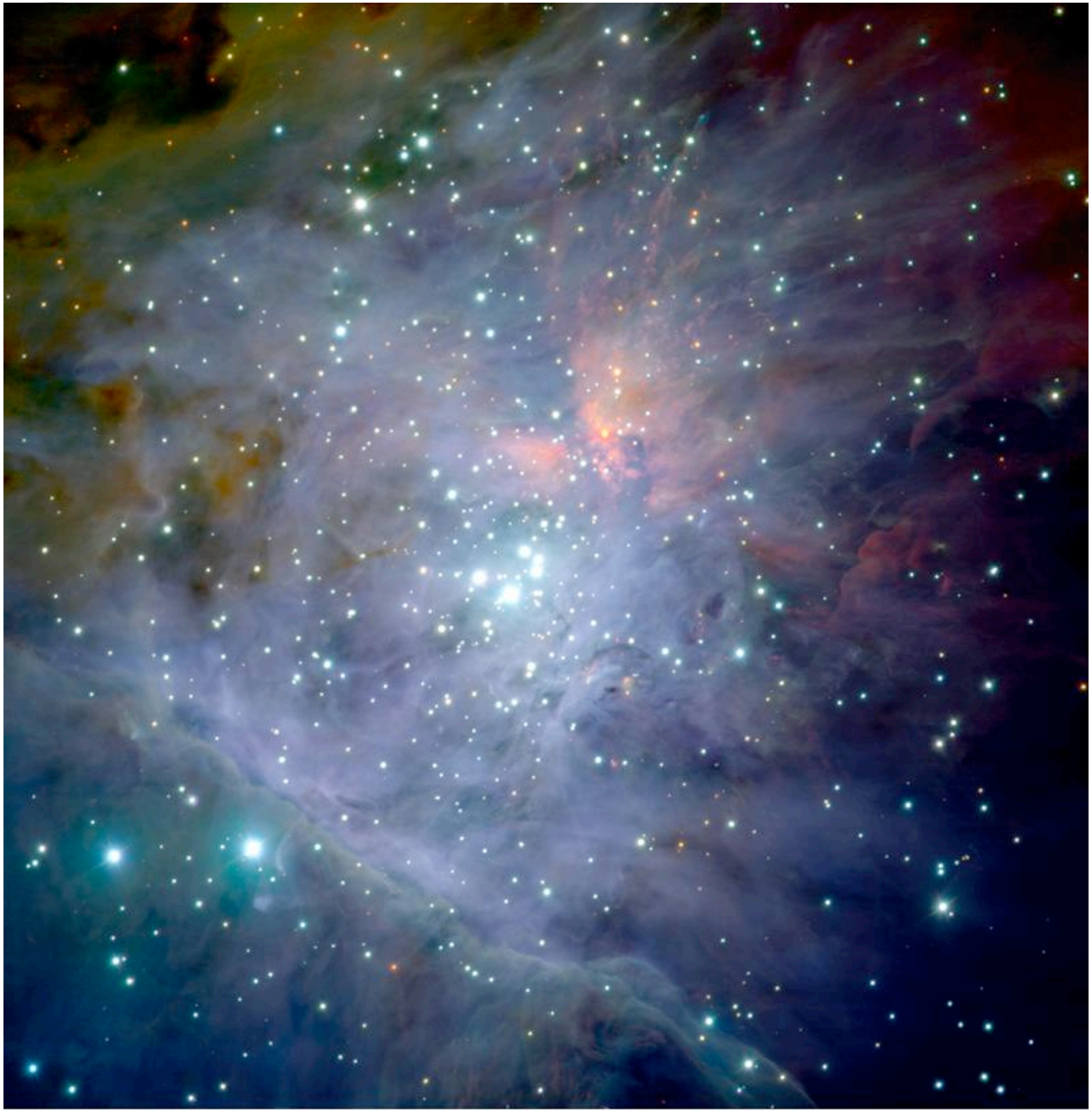
The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster

Trapezium Cluster

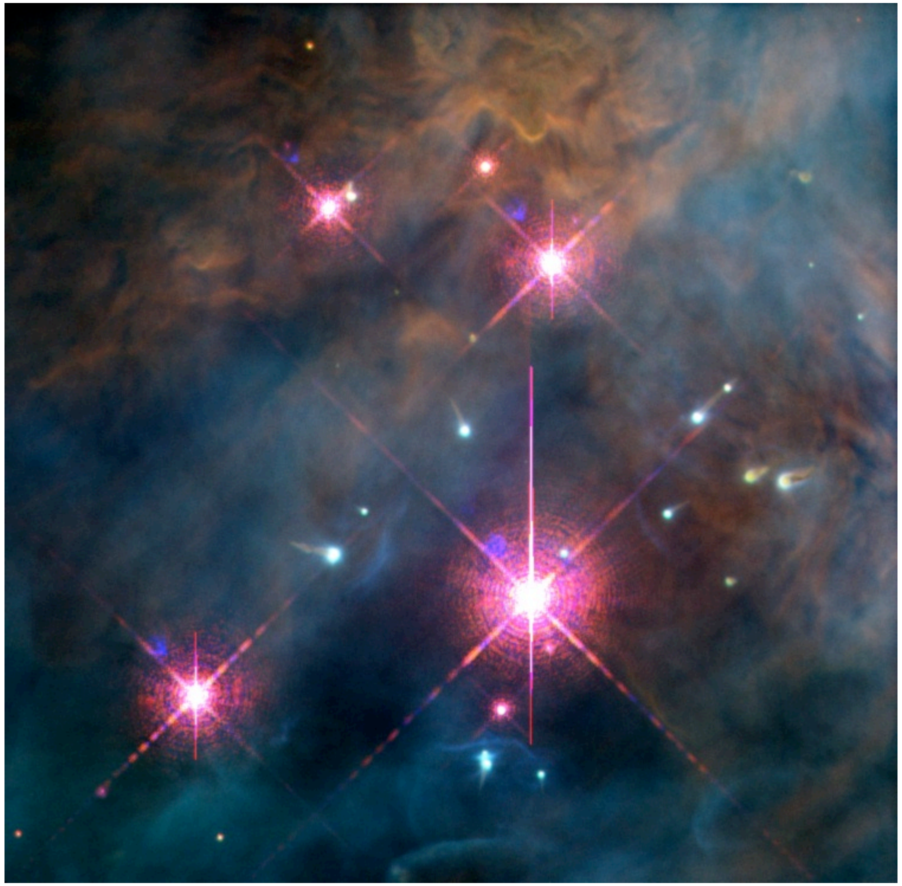
(detail)

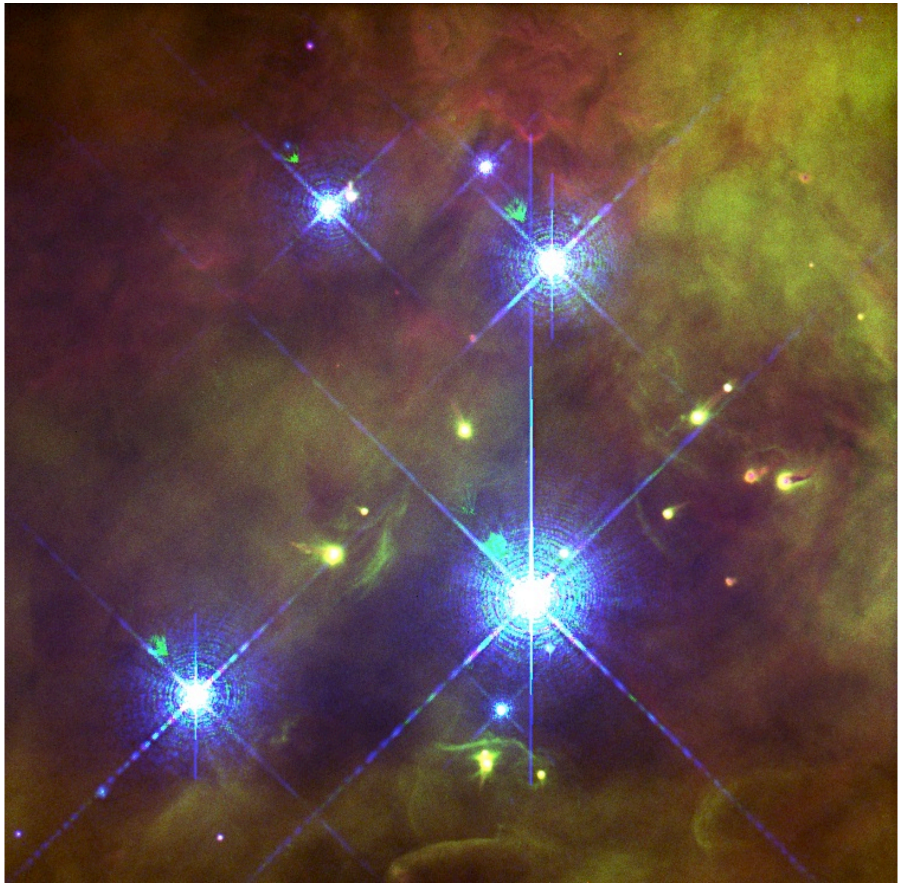


- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

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

Trapezium Cluster: Central Region



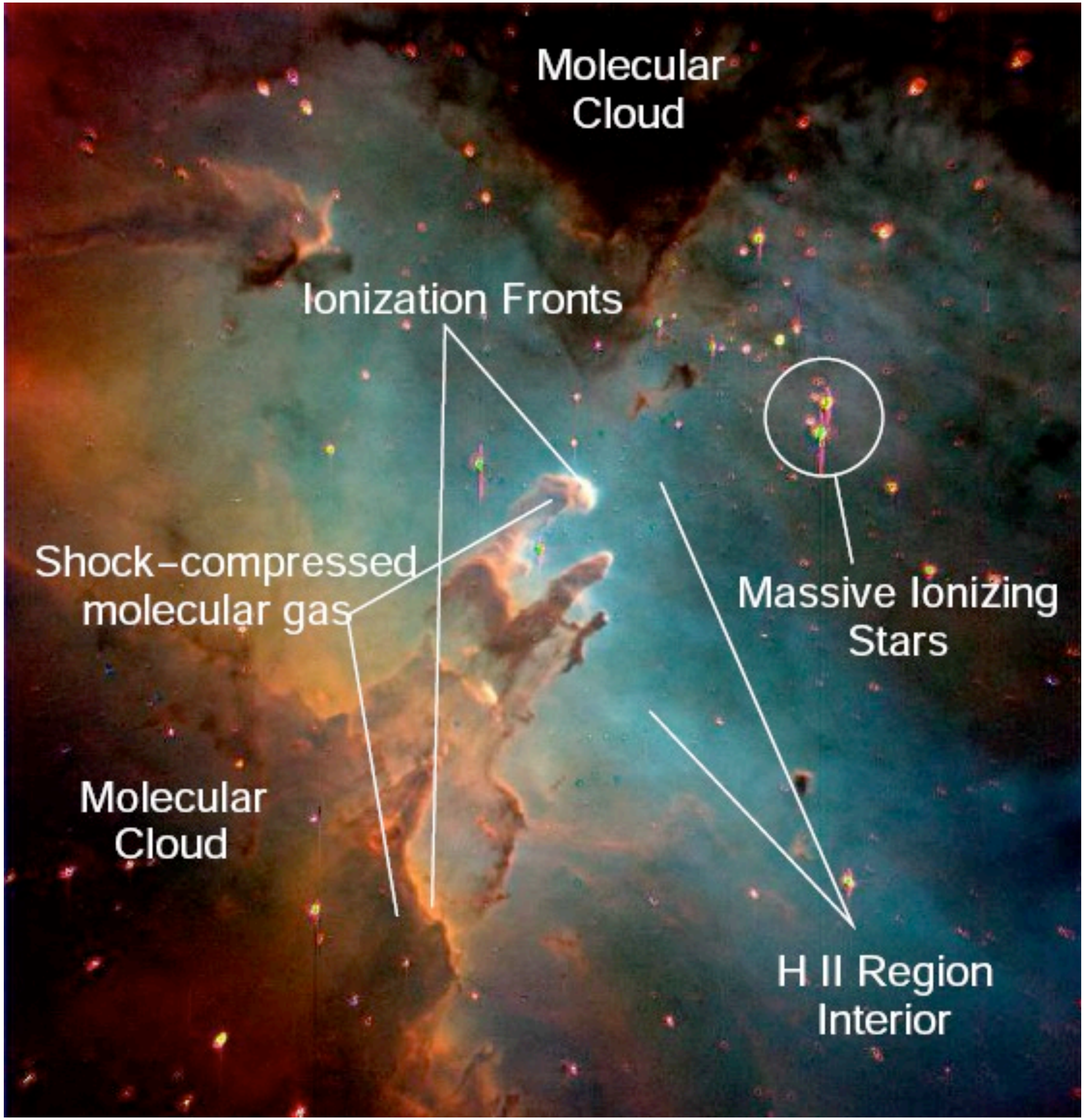


Ionizing radiation from central star
Θ1C Orionis

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

(images: Doug Johnstone et al.)

alles in einem Bild



working hypothesis

gravoturbulent star formation

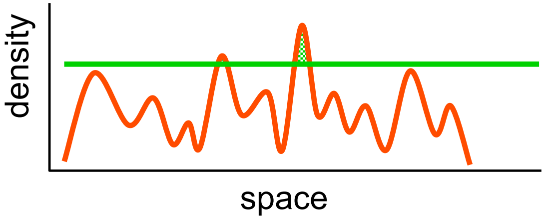
- idea:

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



- 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

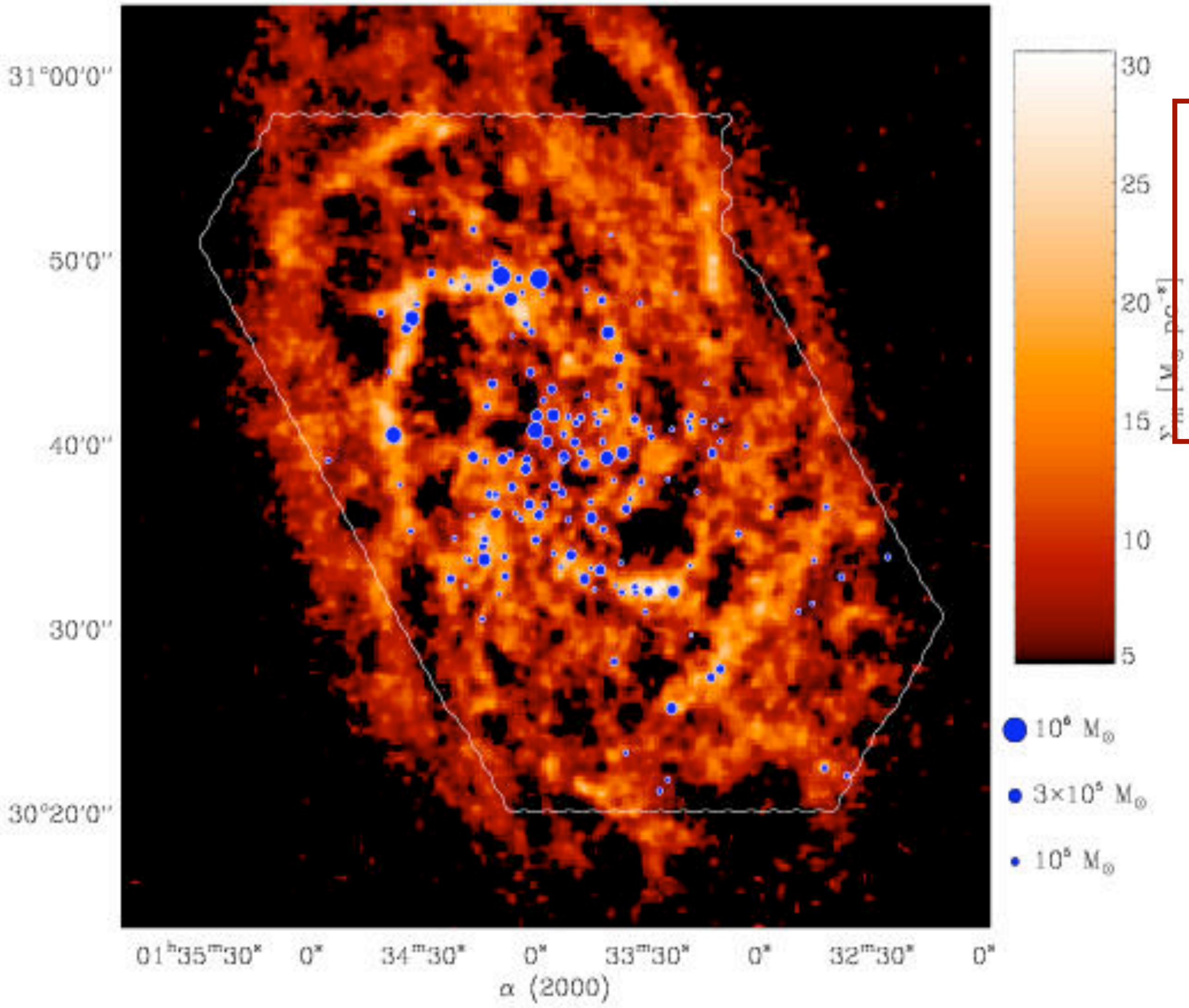
- *star formation on galactic scales*
  - global correlations: Schmidt-law
  - efficiencies, rates, timescales, and long-term evolution: starburst vs. low surface density gal.
  - formation of dense cold molecular clouds
    properties of these clouds (structure, turbulence, etc.)
- *star cluster formation within clouds*
  - SF efficiency and timescale
  - stellar mass function – IMF
  - multiplicity
- *early star formation*
  - Pop III.1, Pop III.2 and transition to Pop II

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

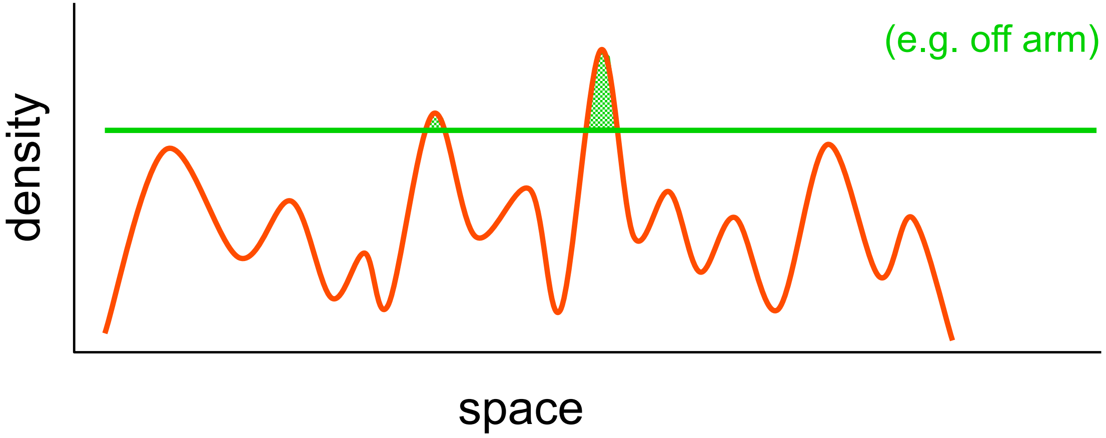


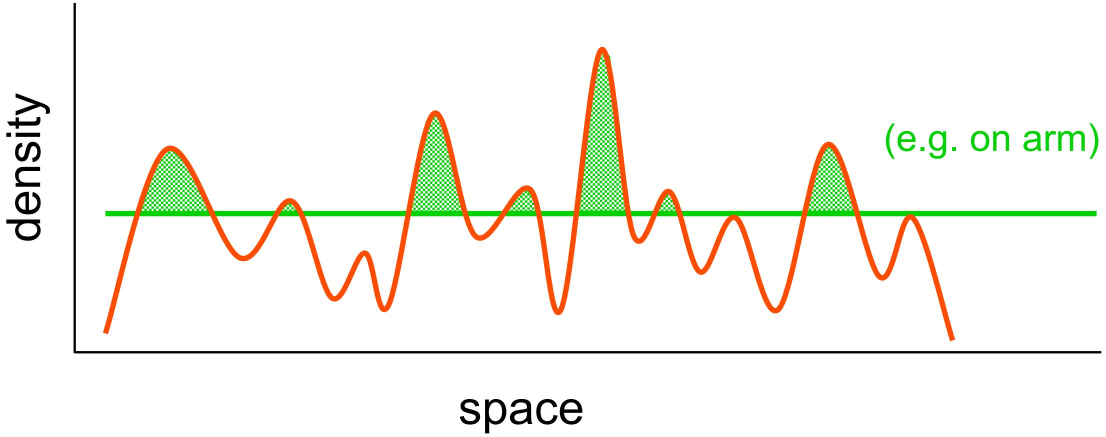
Thesis:

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*"

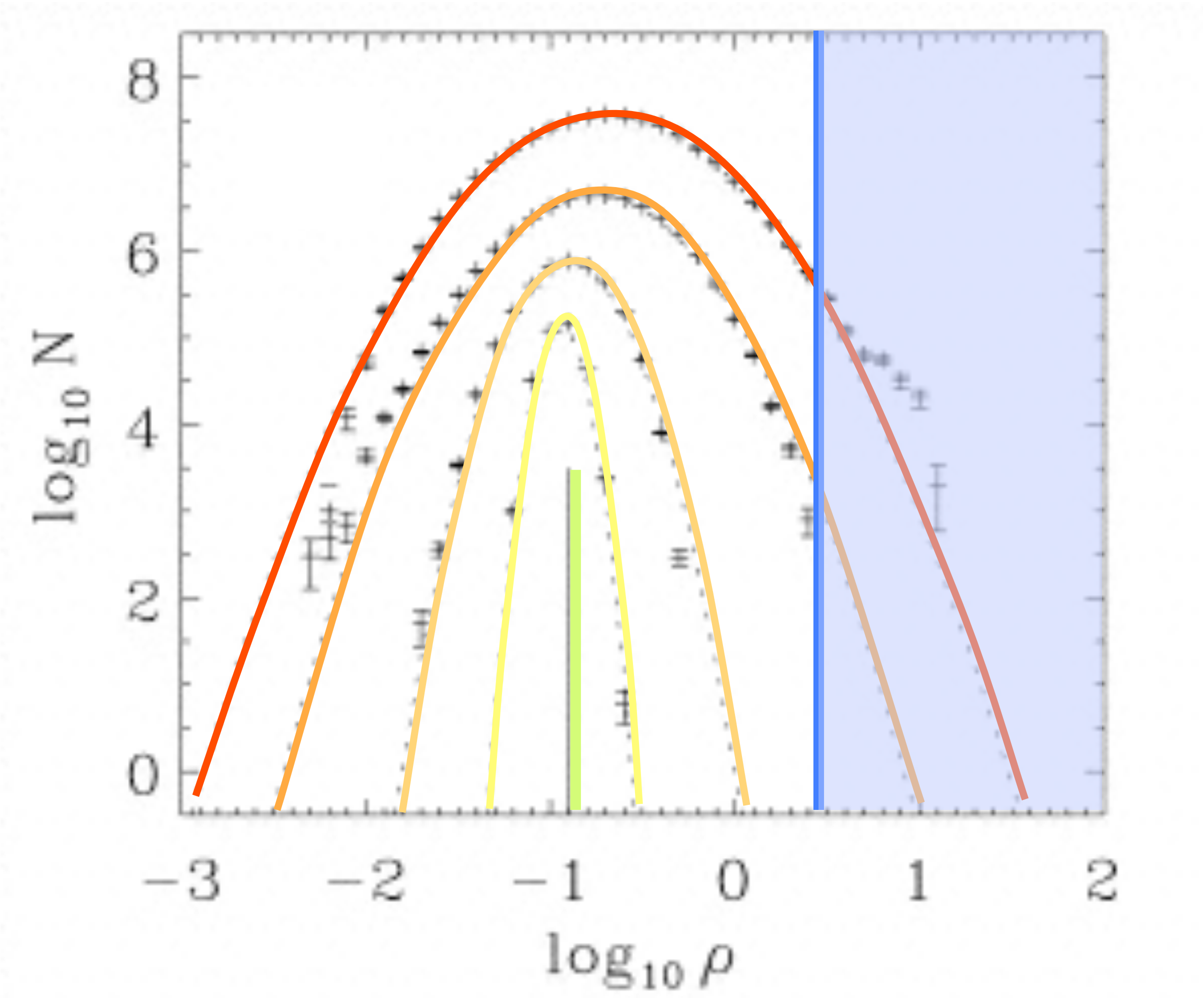
→ *molecular cloud*

(Glover & Mac Low 2007a,b)

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

(e.g. talk by Clare Dobbs)

star formation on *global* scales



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

(rate from Hollenback, Werner, & Salpeter 1971)

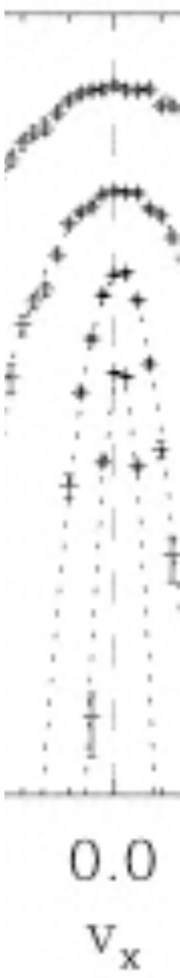
H_2 formation rate:

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

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

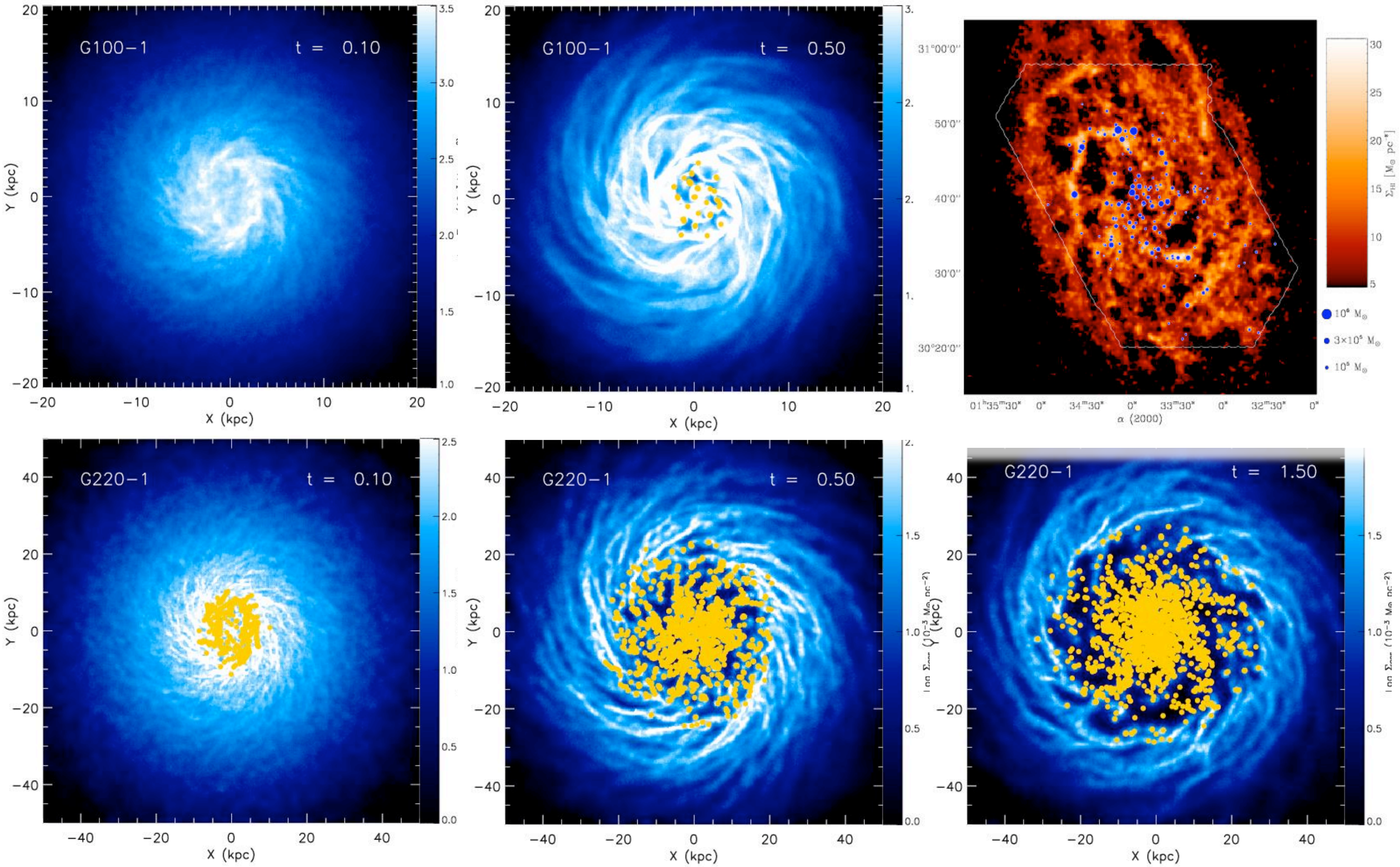
in turbulent gas, the H_2 fraction can become very high on short timescale

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

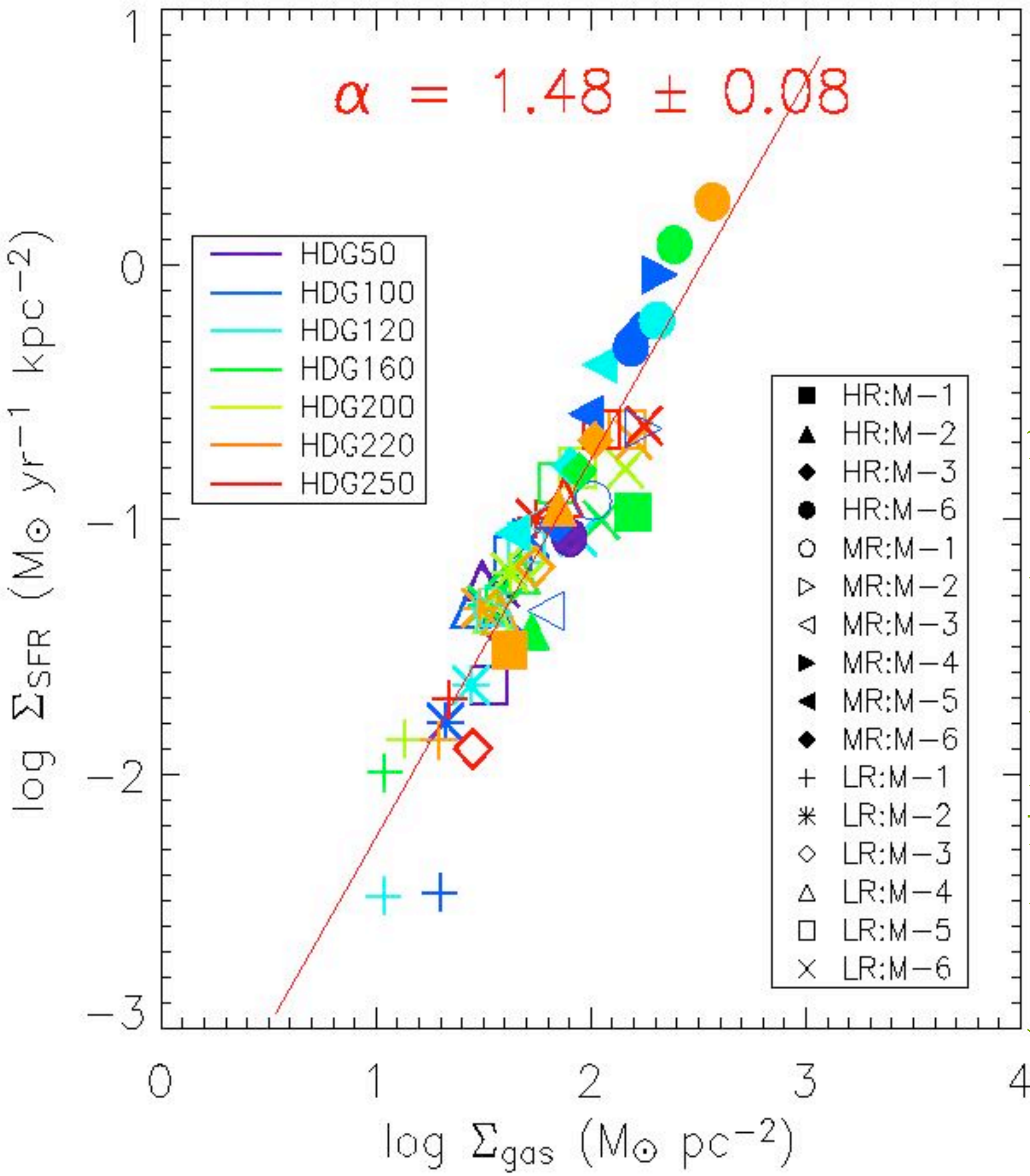


modeling galactic SF

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)



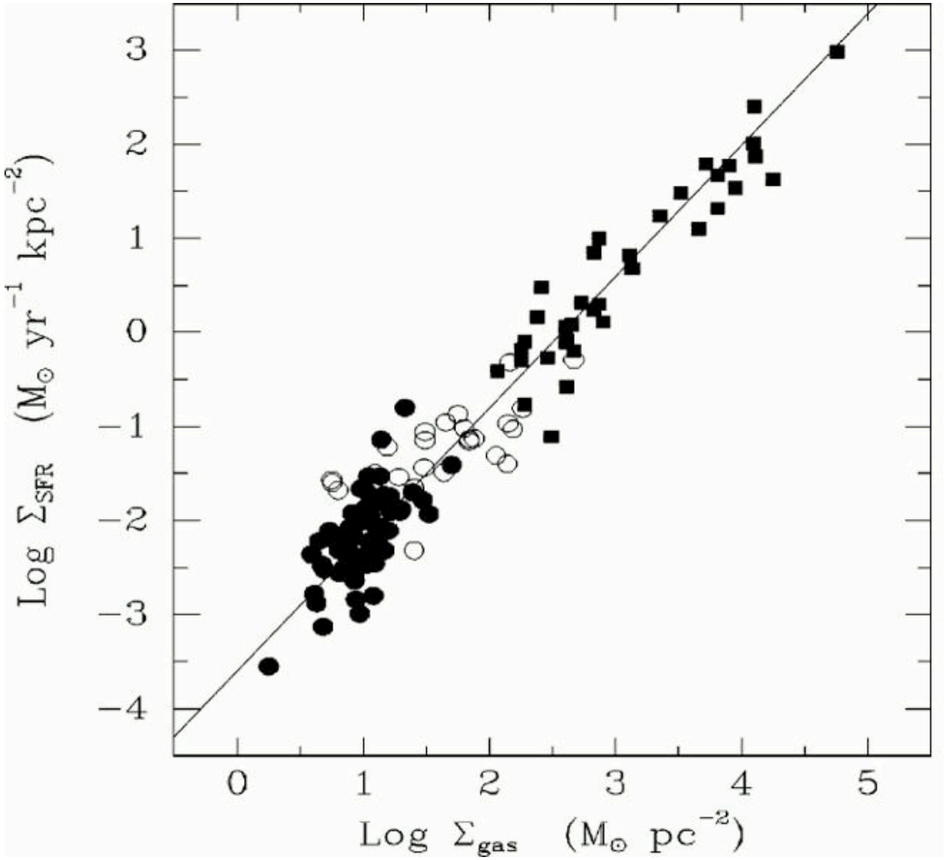
(Li, Mac Low, & Klessen, 2005, ApJ, 620, L19 - L22)

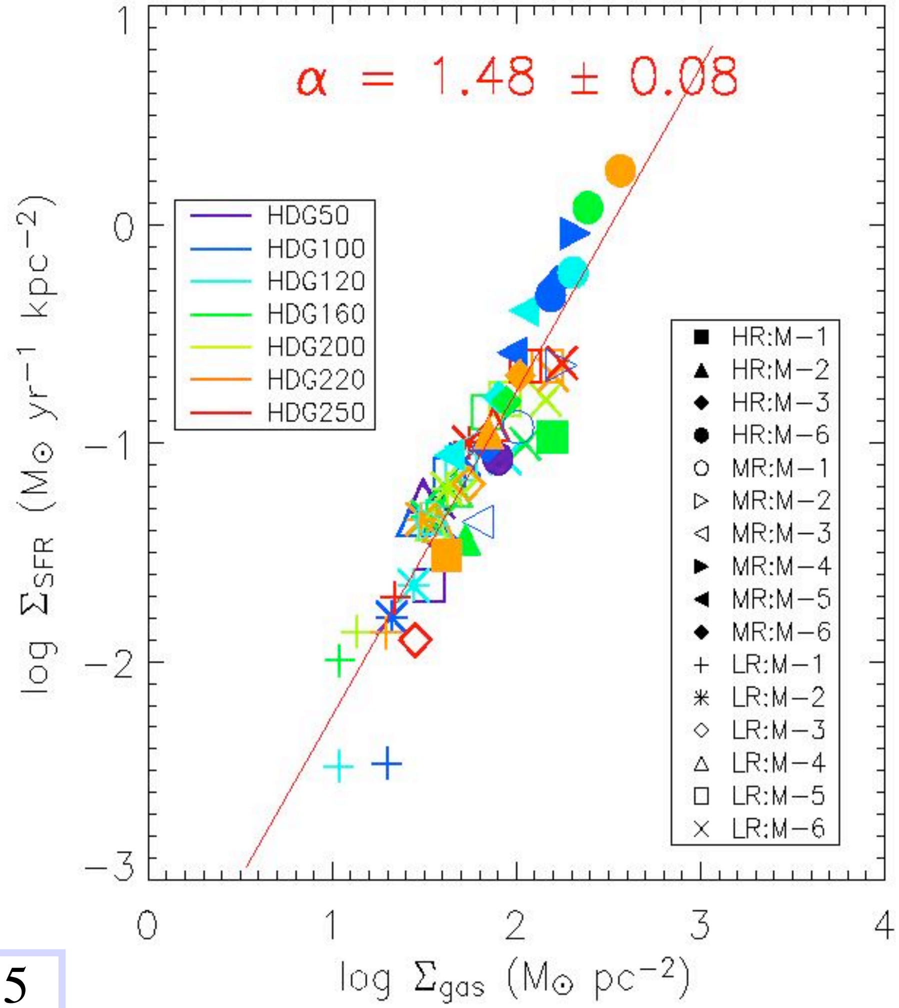
We find correlation between *star formation rate* and *gas surface density:*

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

global Schmidt law

observed Schmidt law

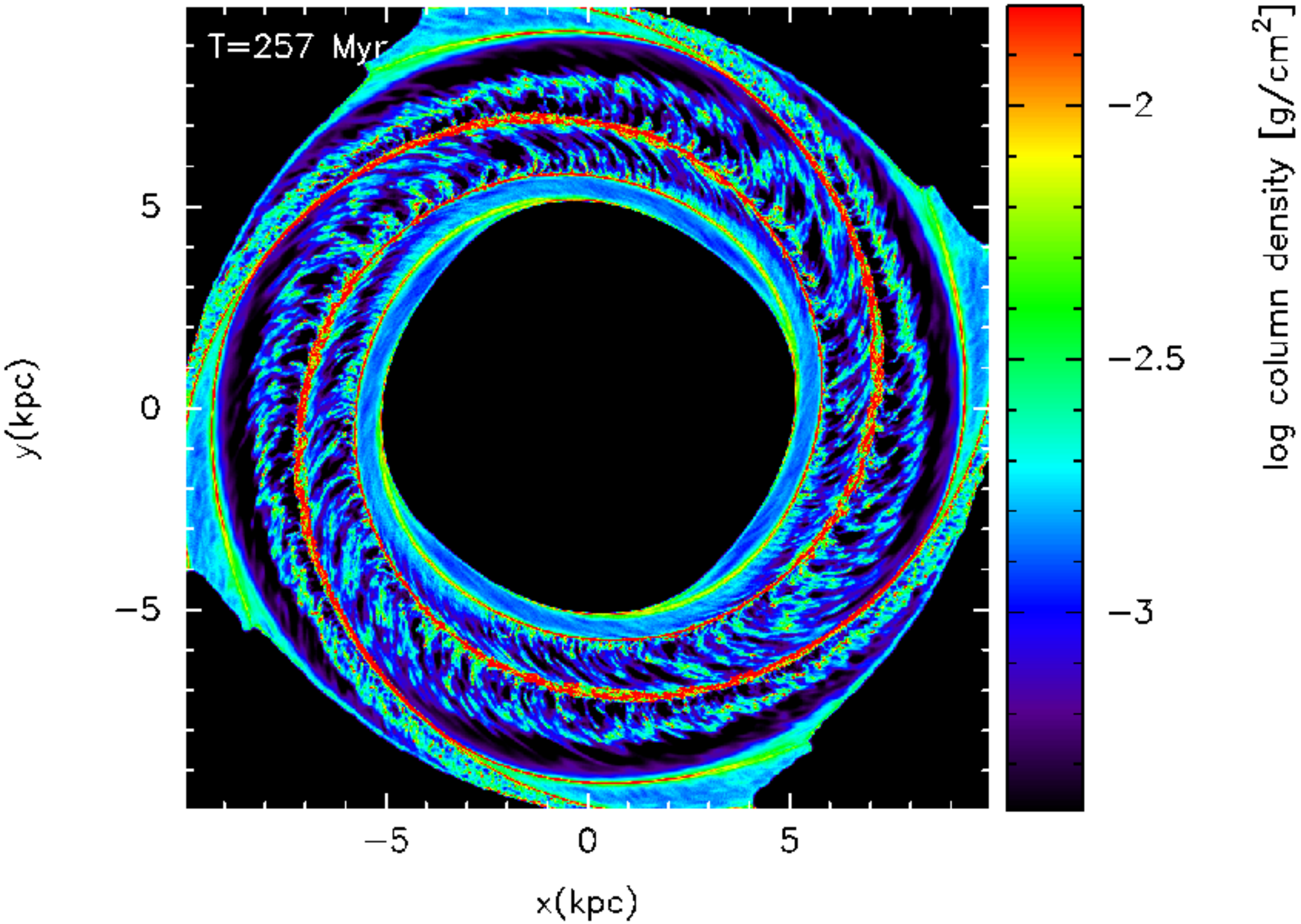




in both cases: $\boxed{\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}}$

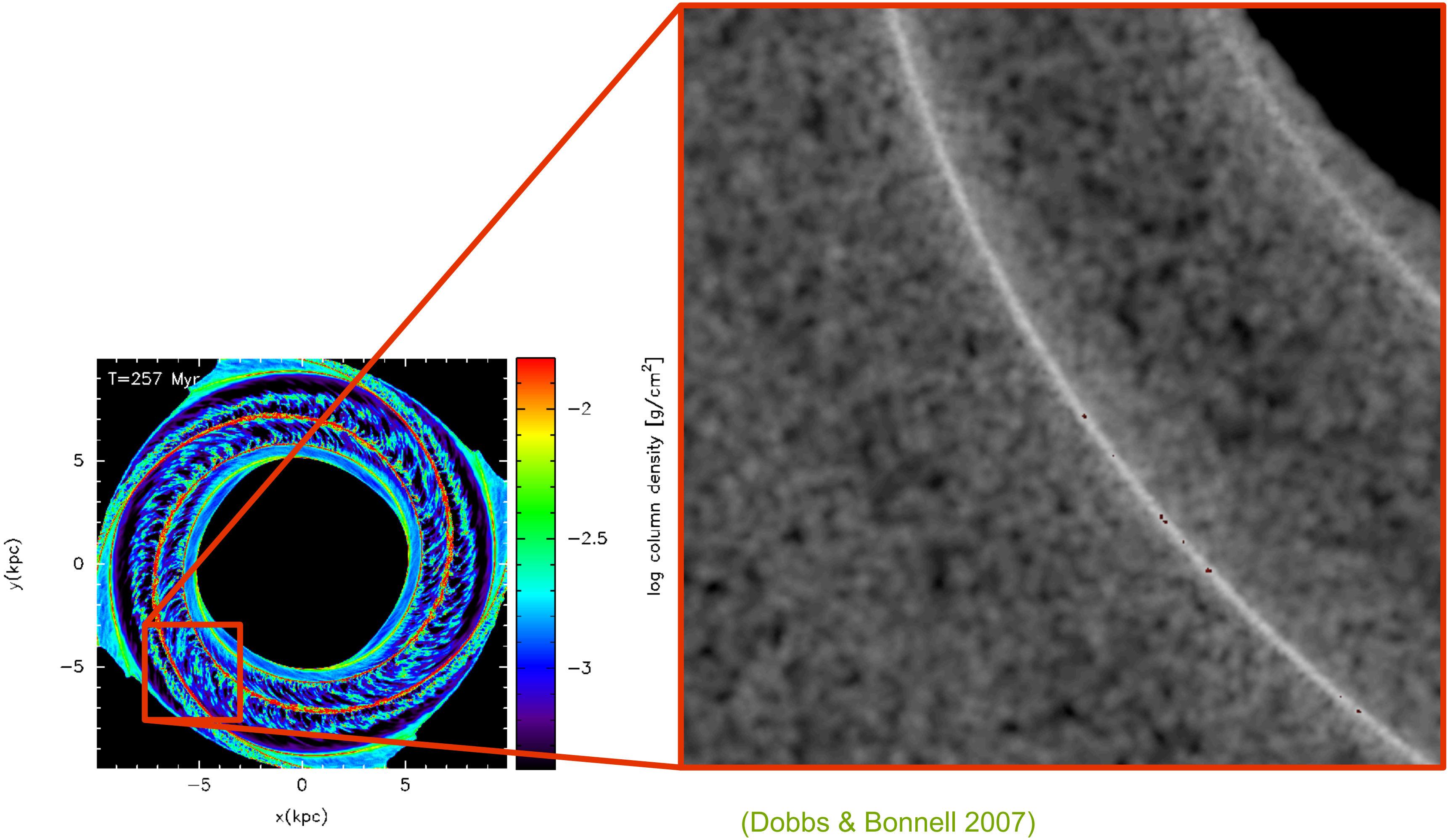
(from Kennicutt 1998)

molecular cloud formation



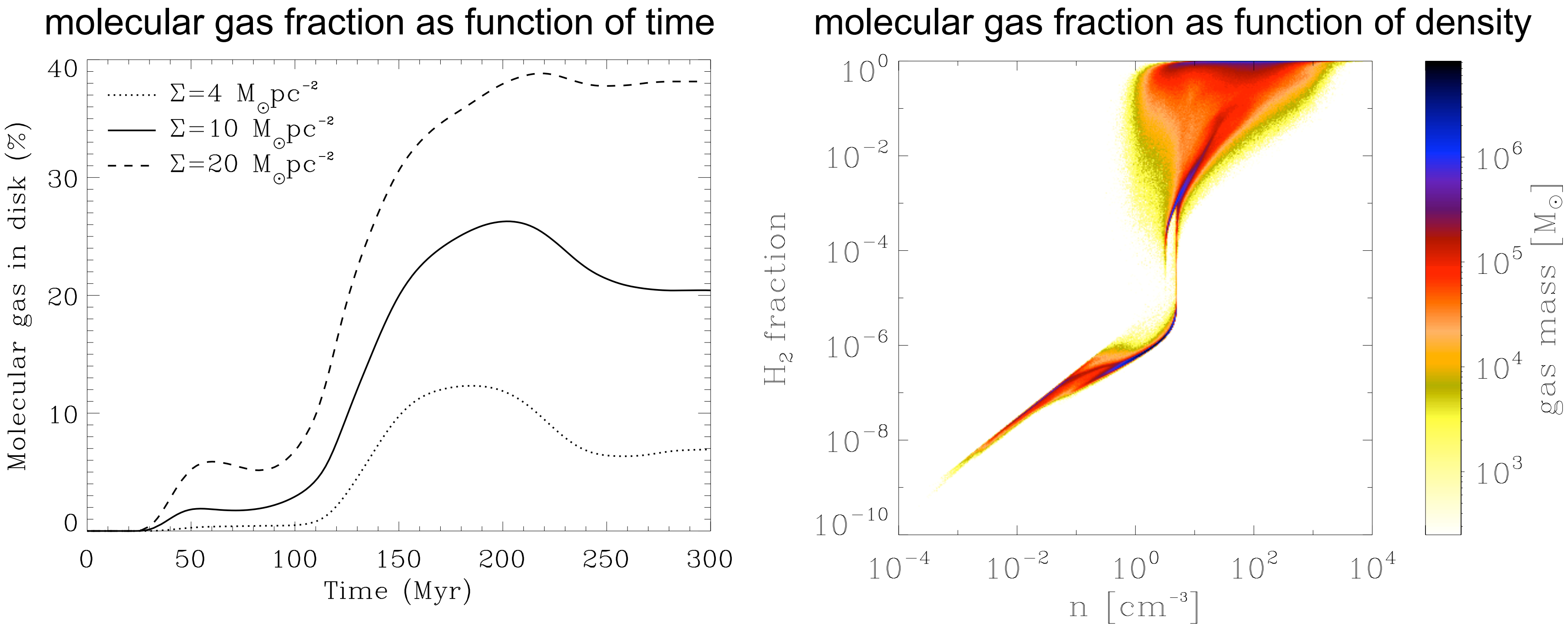
(from Dobbs, Glover, Clark, Klessen 2008)

molecular cloud formation



(Dobbs & Bonnell 2007)

molecular cloud formation

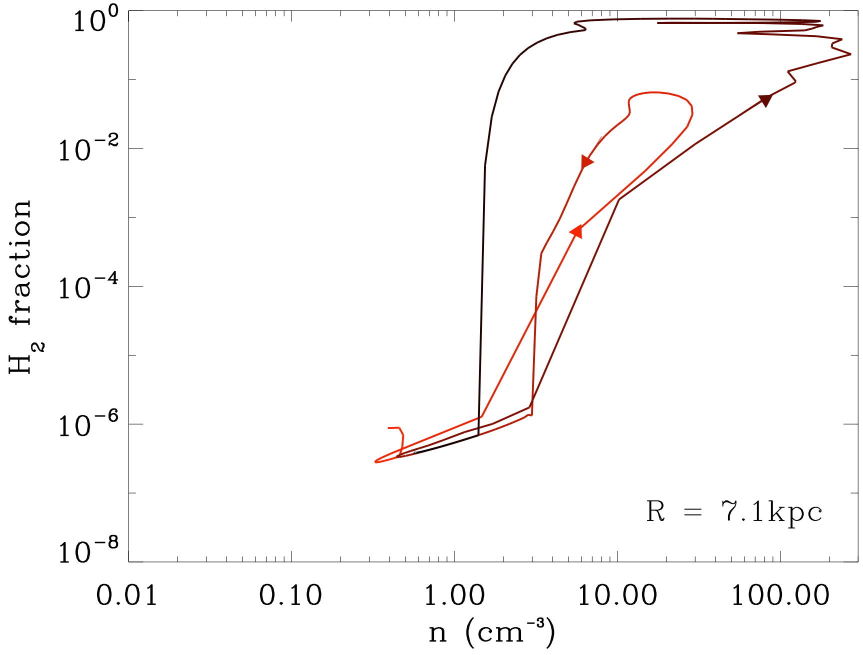

molecular gas fraction as function of time

molecular gas fraction as function of density

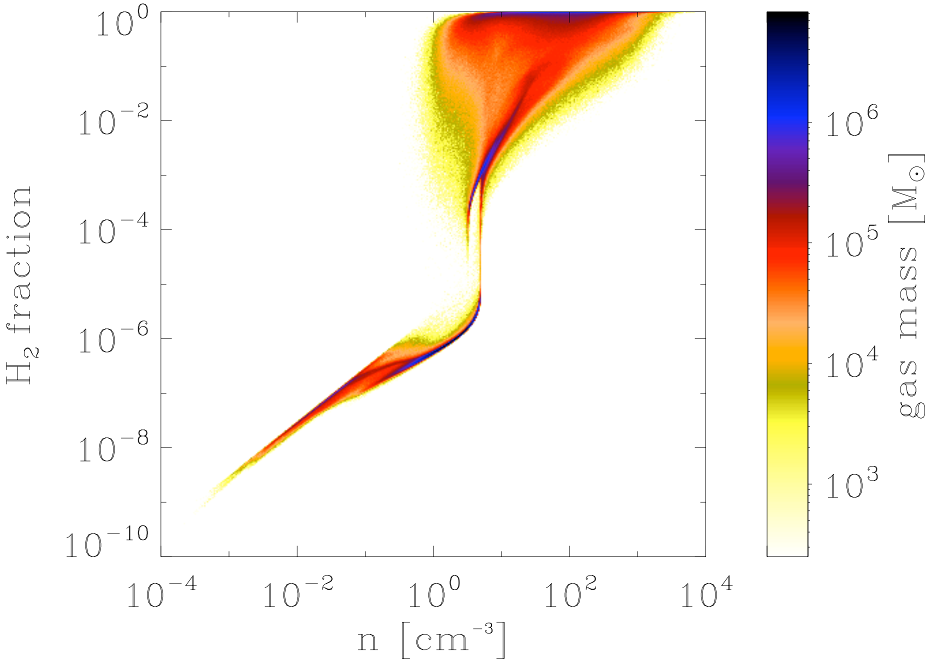
(Dobbs et al. 2008)

molecular cloud formation

molecular gas fraction of fluid element as function of time

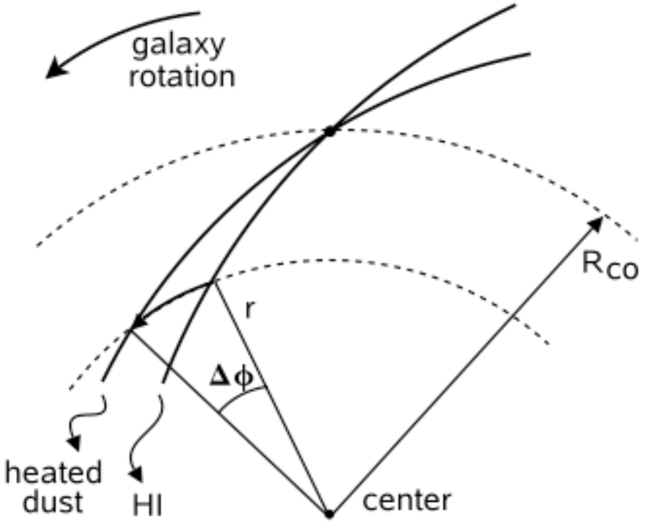


molecular gas fraction as function of density



(Dobbs et al. 2008)

observed timescales



Tamburro et al. (2008)

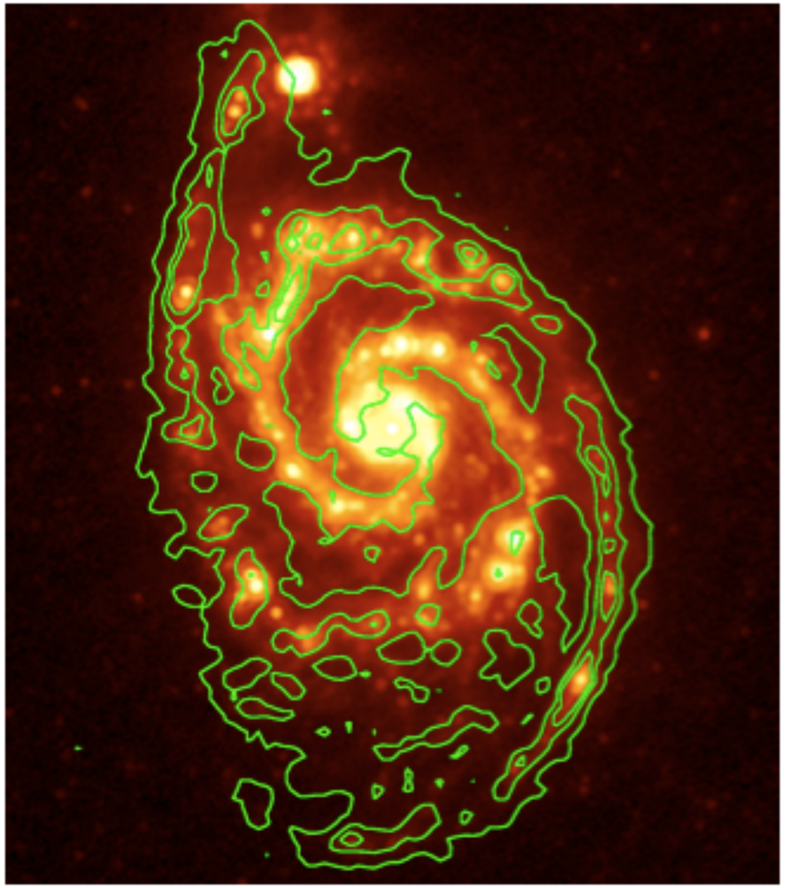
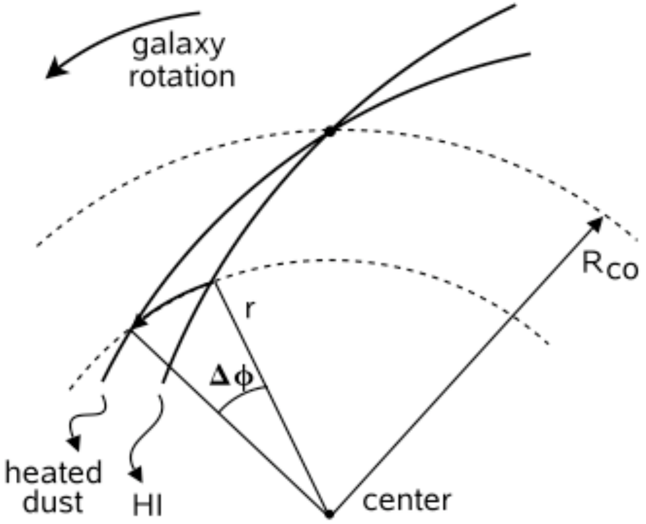


Fig. 1.— NGC 5194: the 24 μm band image is plotted in color scale; the H I emission map is overlayed with green contours.

observed timescales



Tamburro et al. (2008)

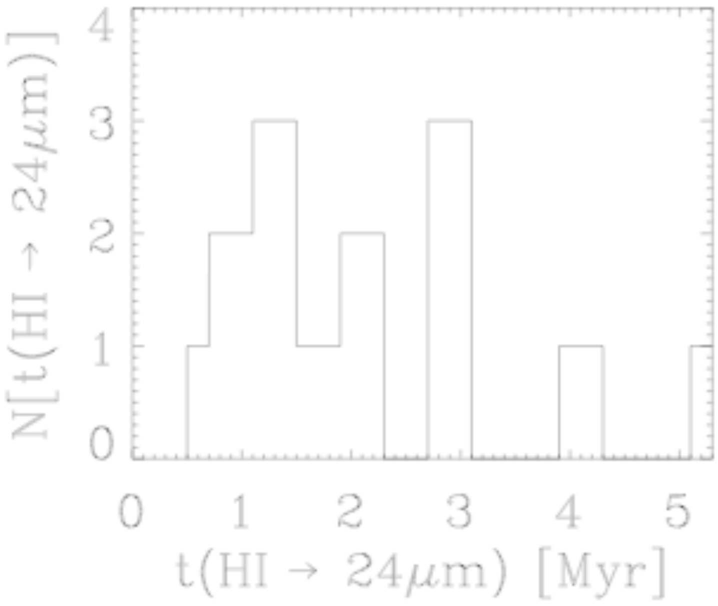


Fig. 5.— Histogram of the time scales $t_{\mathrm{HI}\mapsto 24\,\mu\mathrm{m}}$ derived from the fits in Figure 4 and listed in Table. 2 for the 14 sample galaxies listed in Table. 1. The timescales range between 1 and 4 Myr for almost all galaxies.

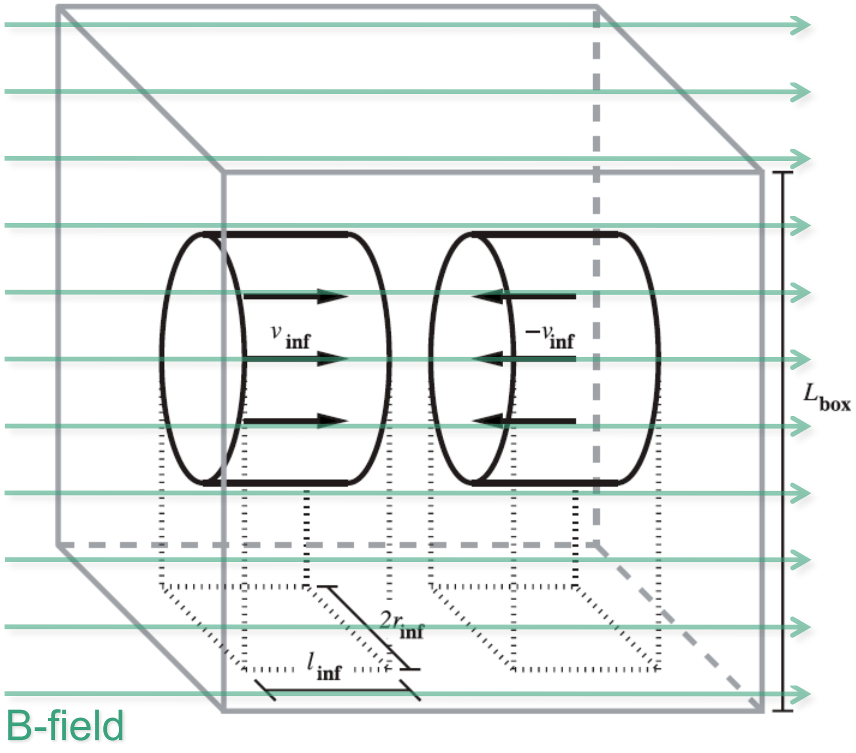
GMC scales

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?

convergent flows: set-up

numerical set-up



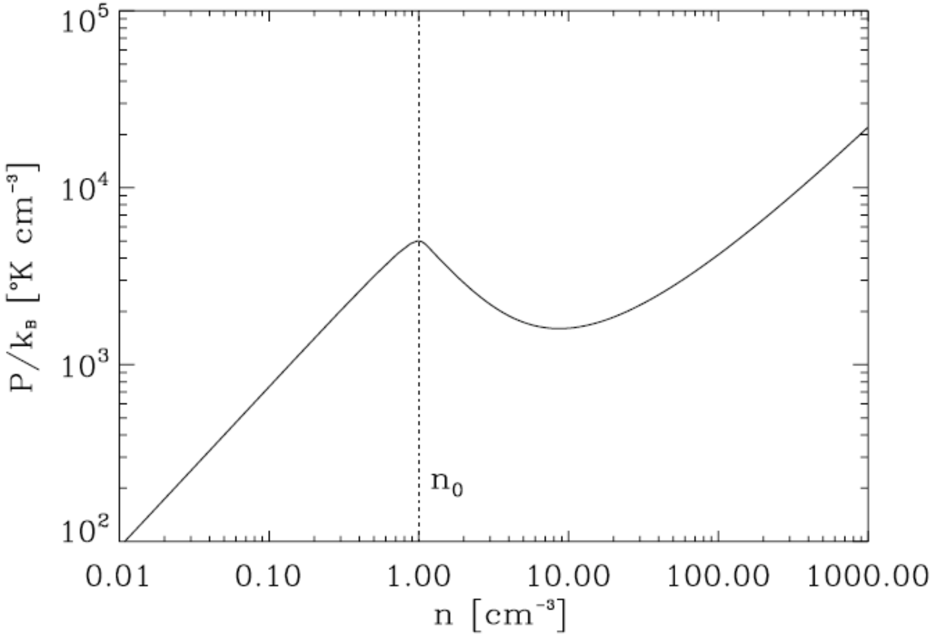
from Vazquez-Semadeni et al. (2007)

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

MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:

0.00 Myr

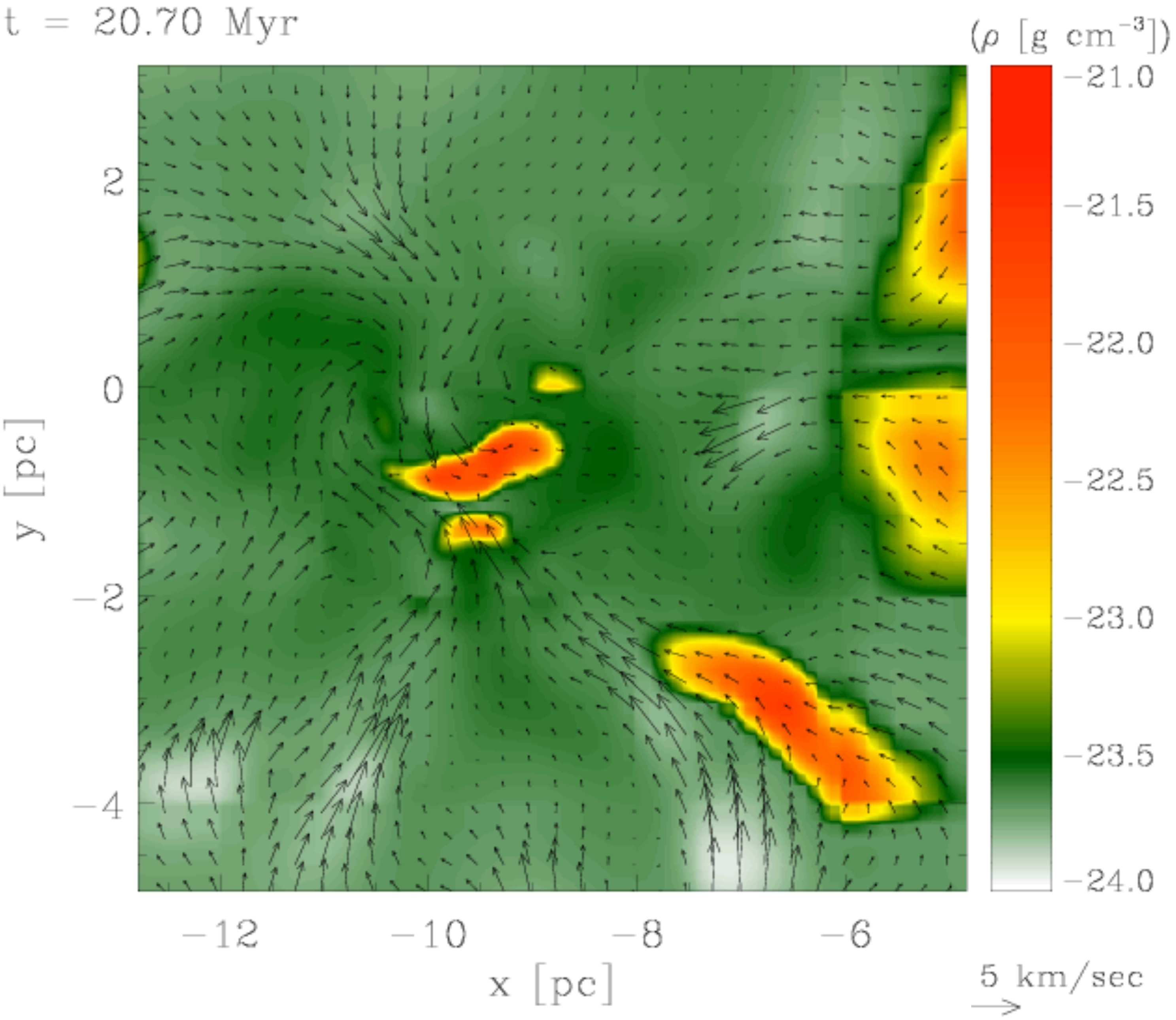
Boxsize 80.0 pc

0.00 Myr

Boxsize 80.0 pc

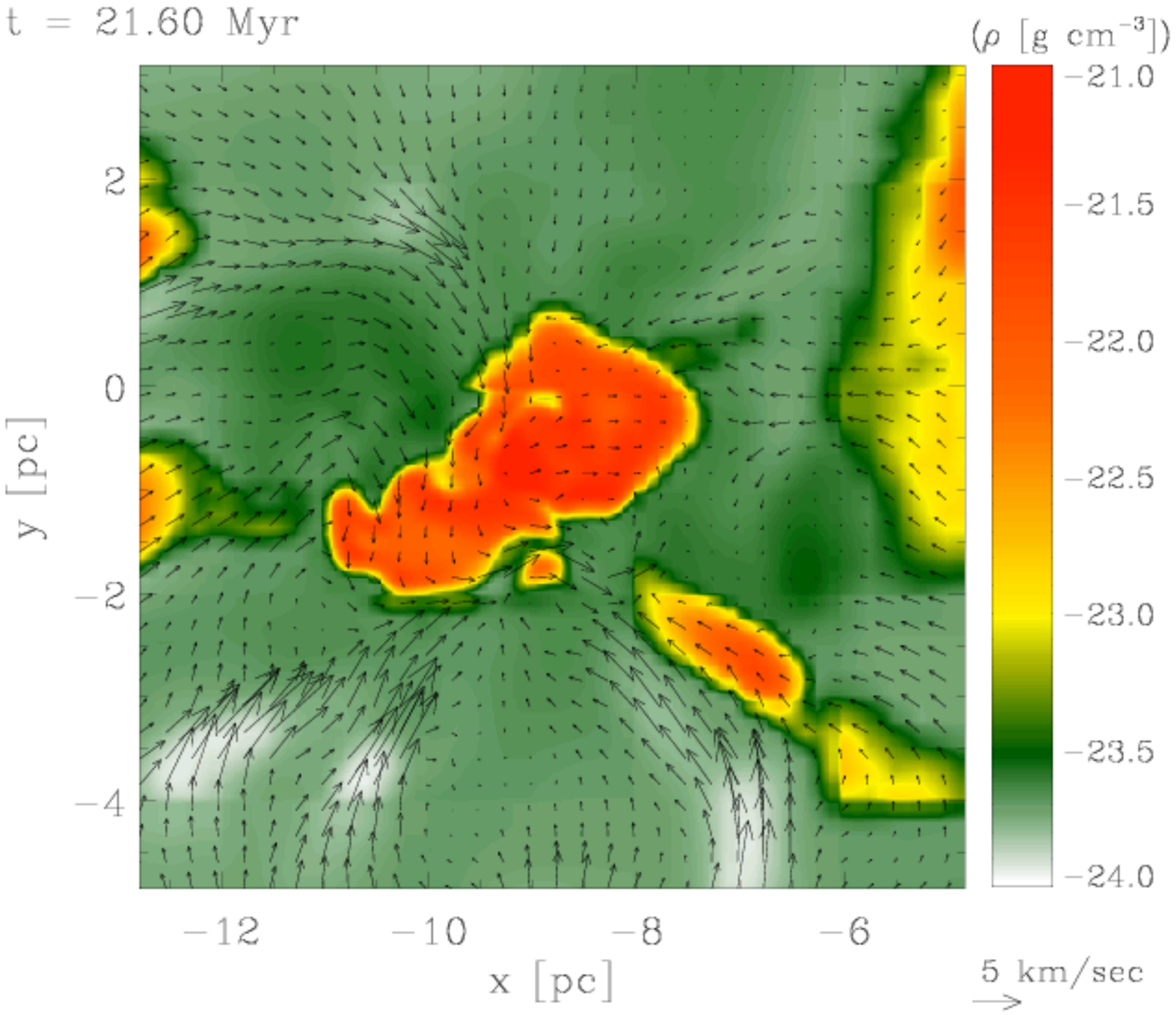
from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. as well as talk by Fabian Heitsch)

density and velocity



from Banerjee et al. (2008)

density and velocity



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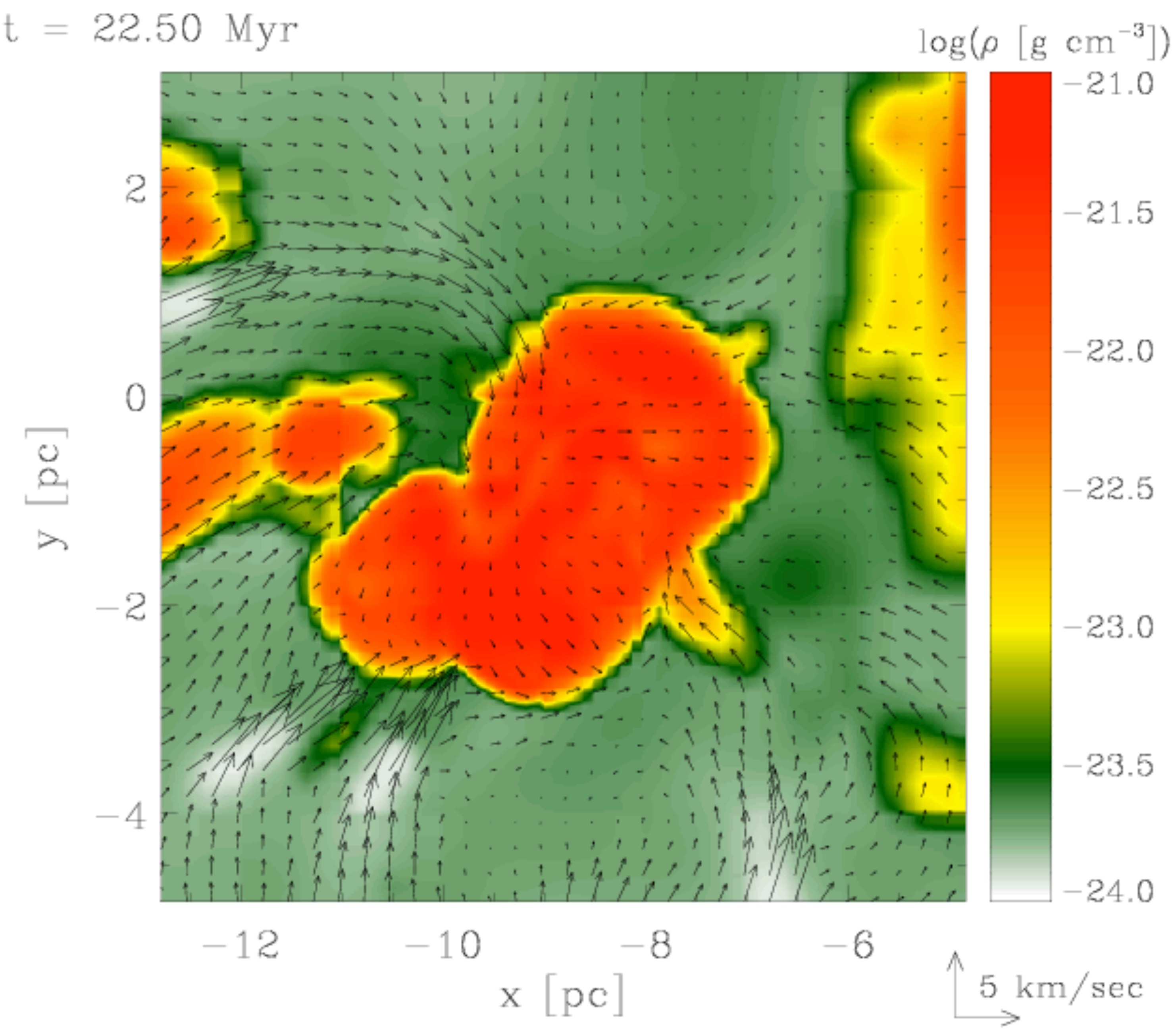


from Banerjee et al. (2008)

some results: growth of cores

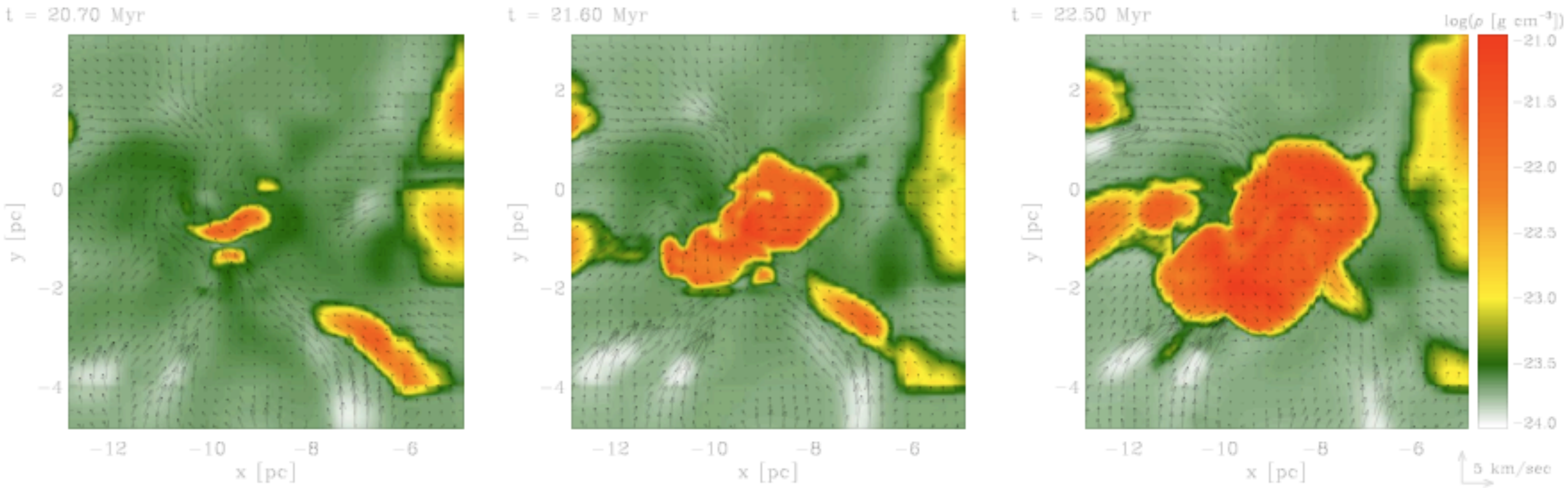
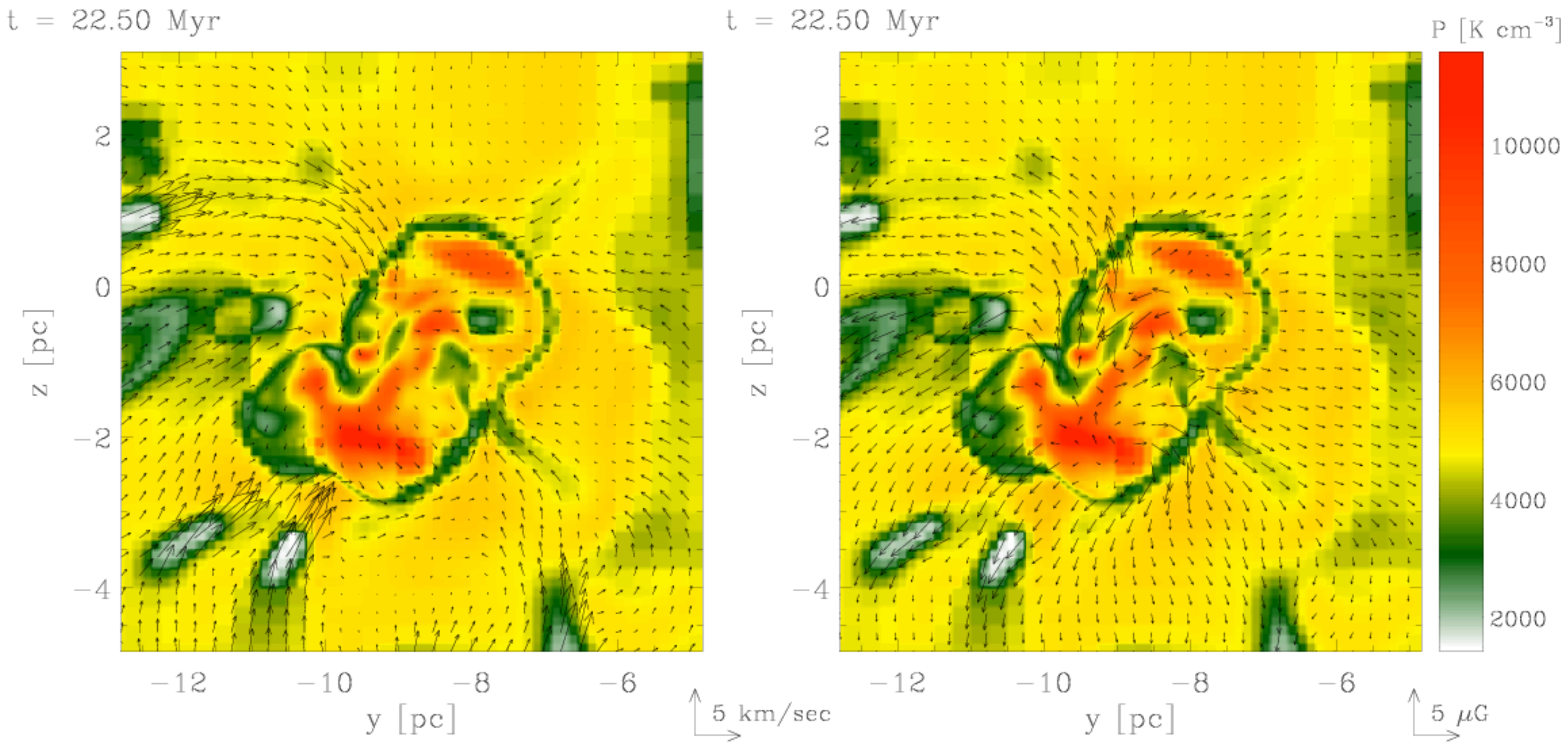


Figure 2. Shows the time evolution of a typical clump which initially develops out of the thermally unstable WNM in shock layers of turbulent flows. A small cold condensate grows by outward propagation of its boundary layer. Coalescence and merging with nearby clumps further increases the size and mass 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.

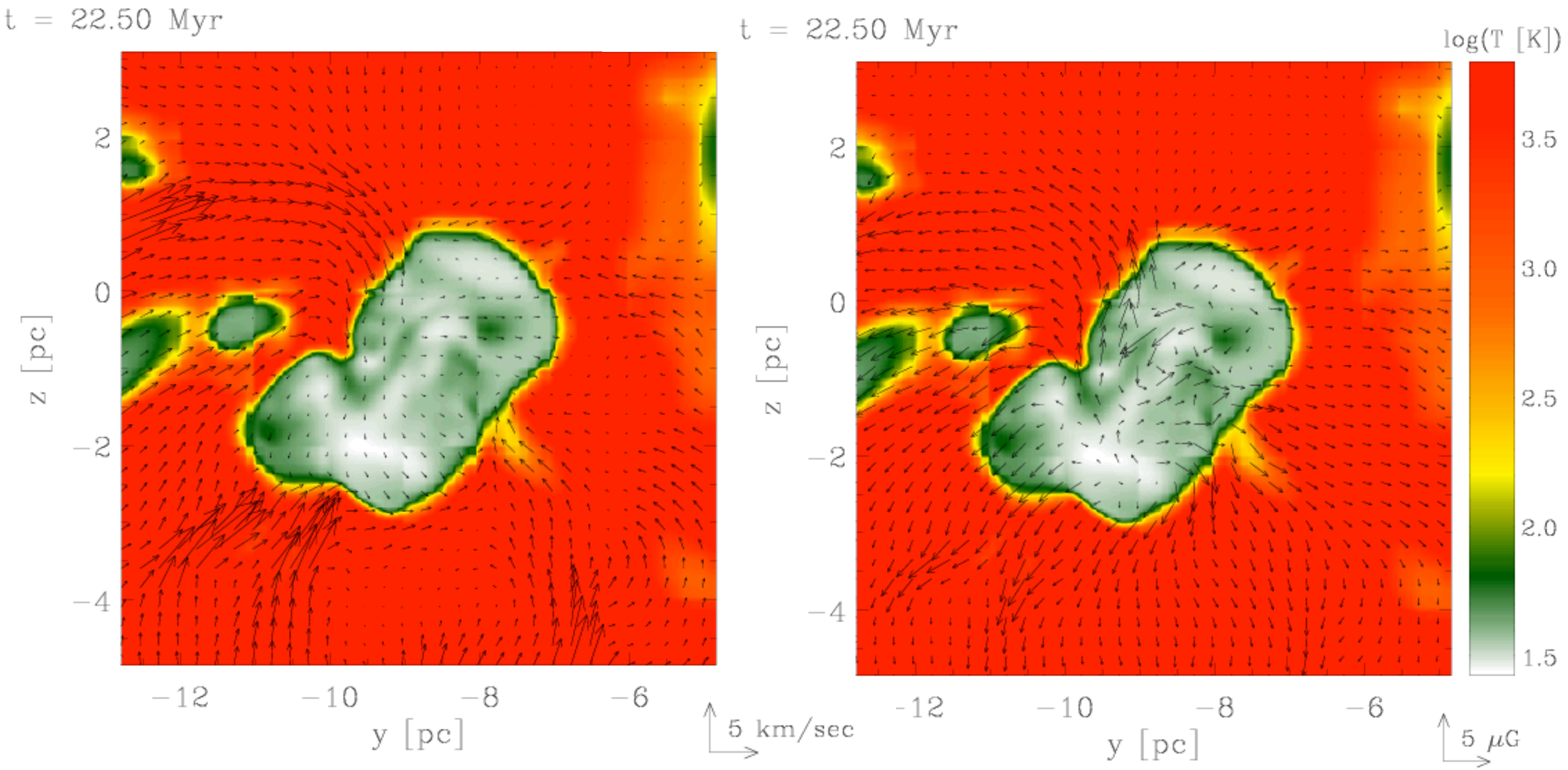
two phases of core growth:
(1) by *outward propagation* of *boundary layer* → Jeans sub-critical phase
(2) *core mergers* → super-Jeans → gravitational collapse & star formation
example: *Pipe nebula* ???

from Banerjee et al. (2008)



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

from Banerjee et al. (2008)



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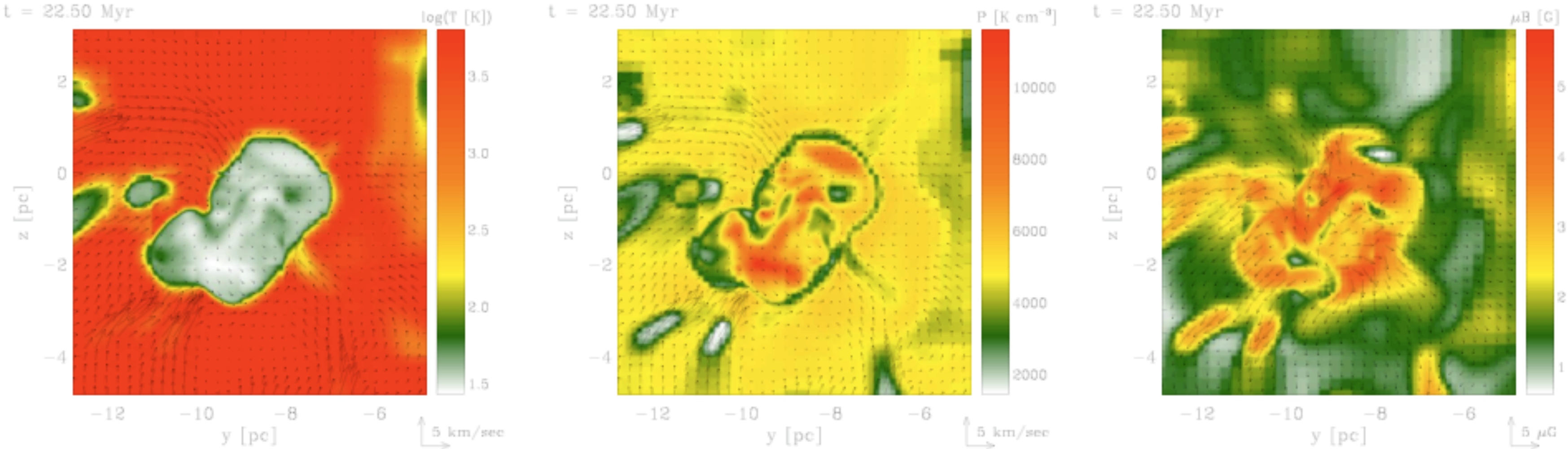


Figure 3. Shows the structure of one typical clump which forms in the thermally unstable WNM gas. The images show 2D slices of the temperature (left, log scale), thermal pressure (middle, linear scale), and magnetic field strength (right, linear scale). The arrows in the temperature and pressure plots 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).

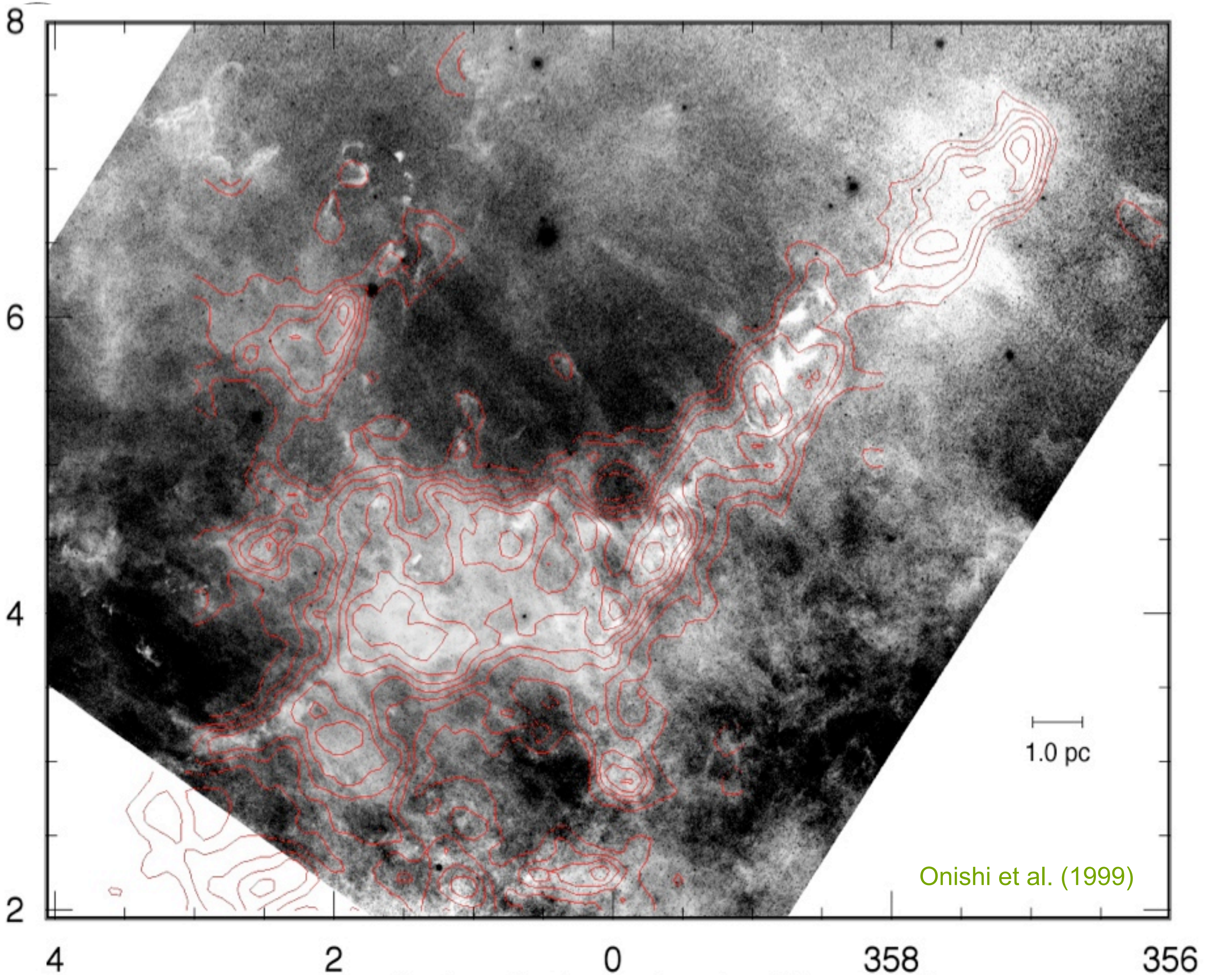
some properties of cores:

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

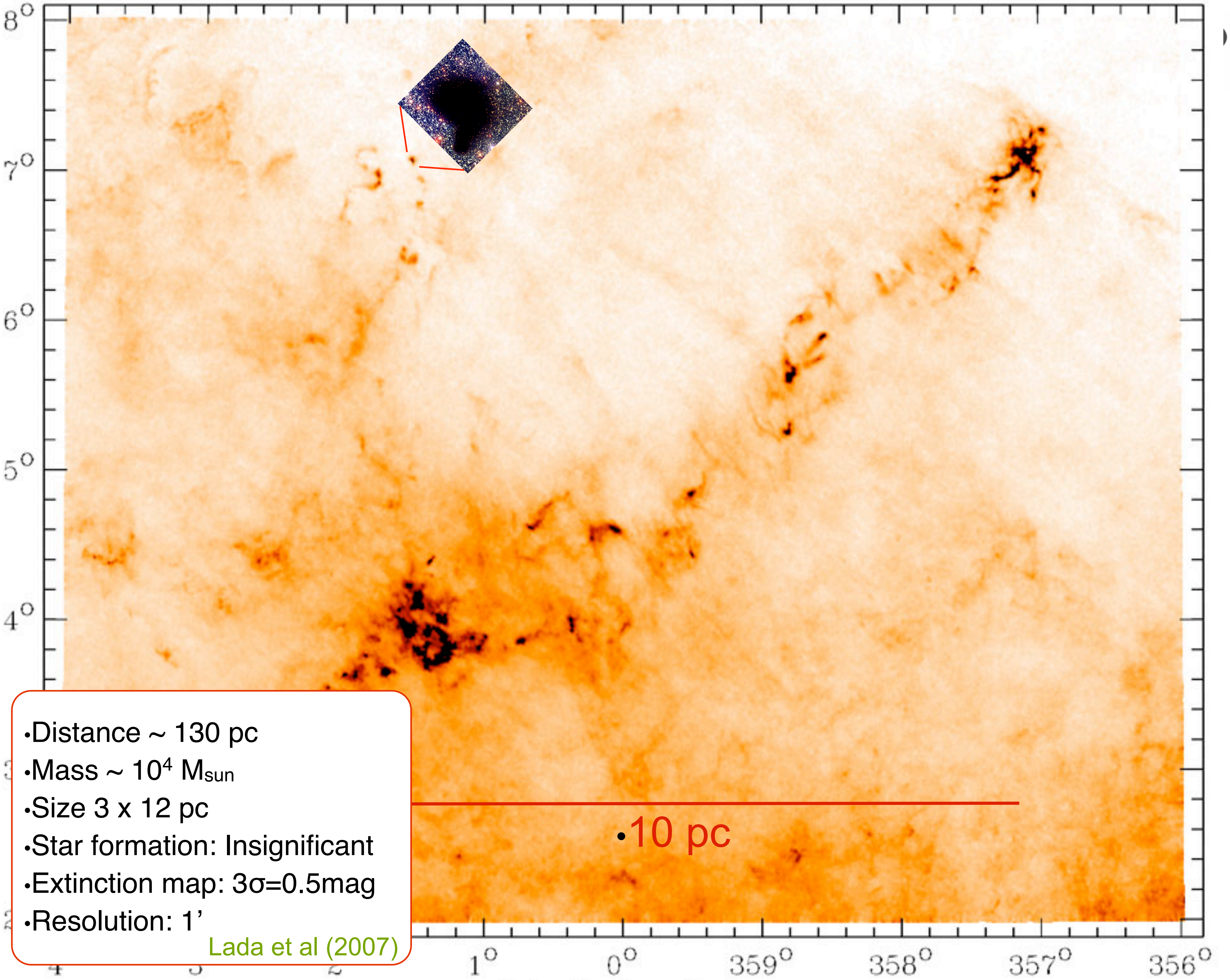
(2) accretion / mass flow mostly along magnetic field lines

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

from Banerjee et al. (2008)

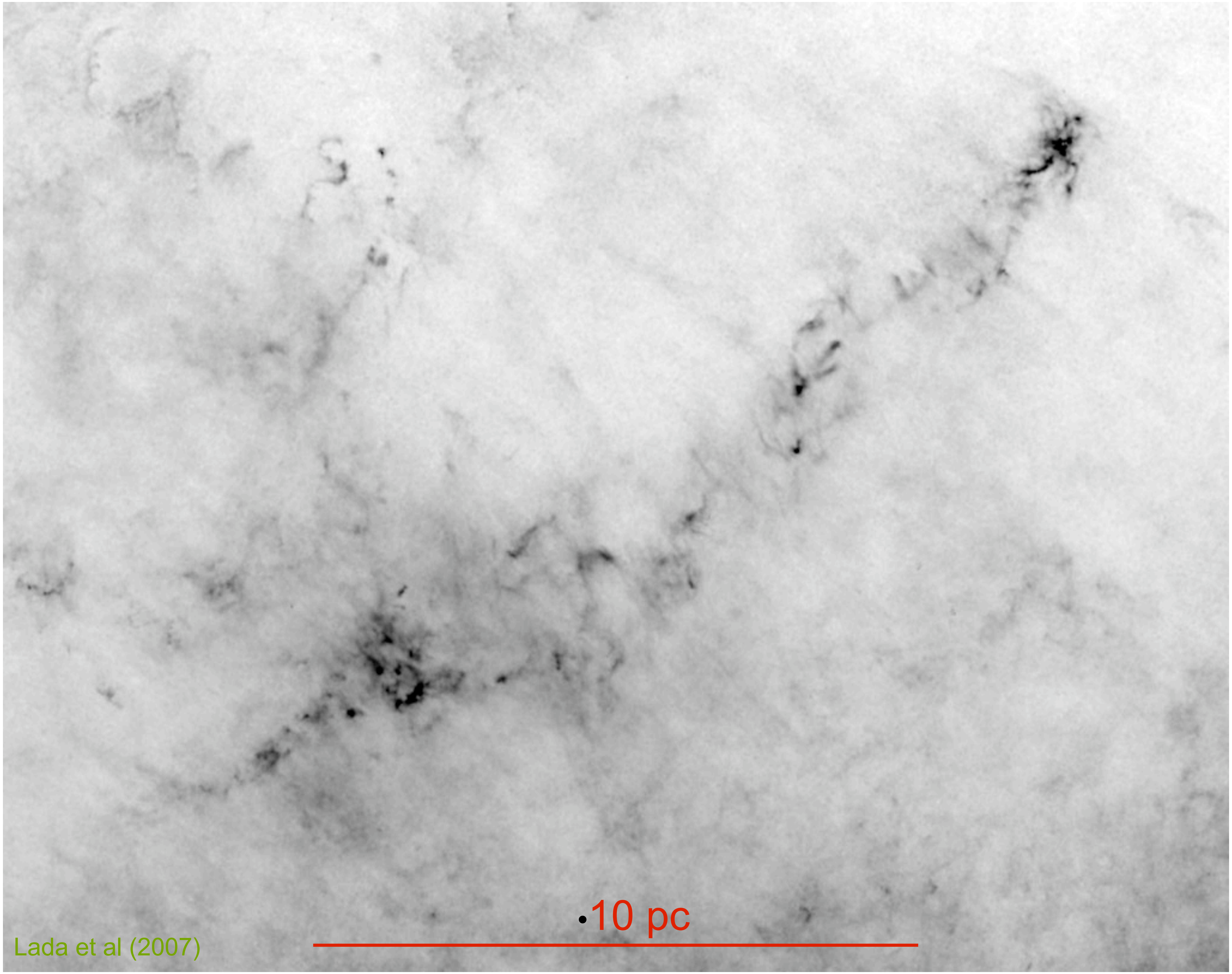


Onishi et al. (1999)

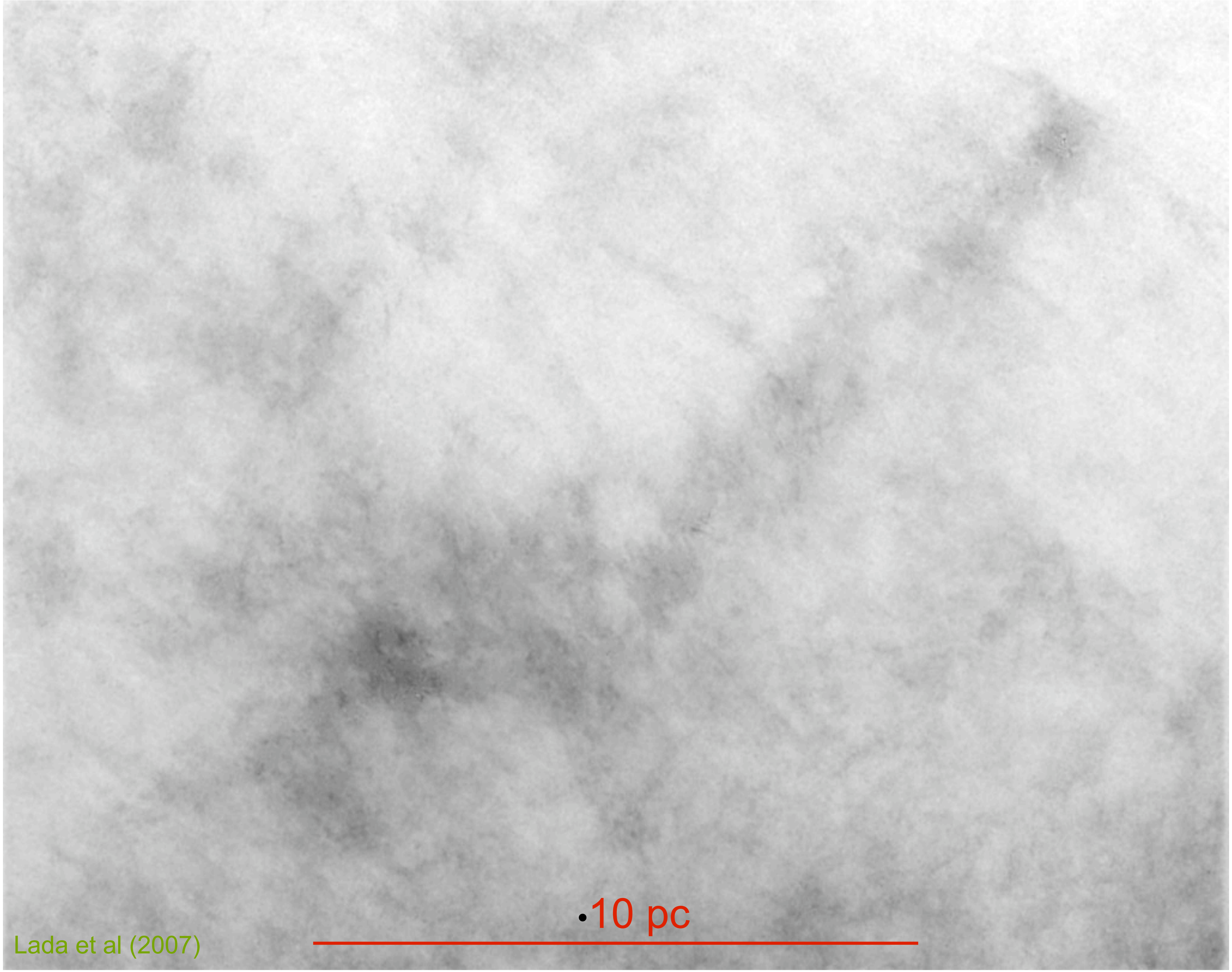


- Distance ~ 130 pc
- Mass ~ 10^4 M_{sun}
- Size 3 x 12 pc
- Star formation: Insignificant
- Extinction map: 3σ=0.5mag
- Resolution: 1’

Lada et al (2007)

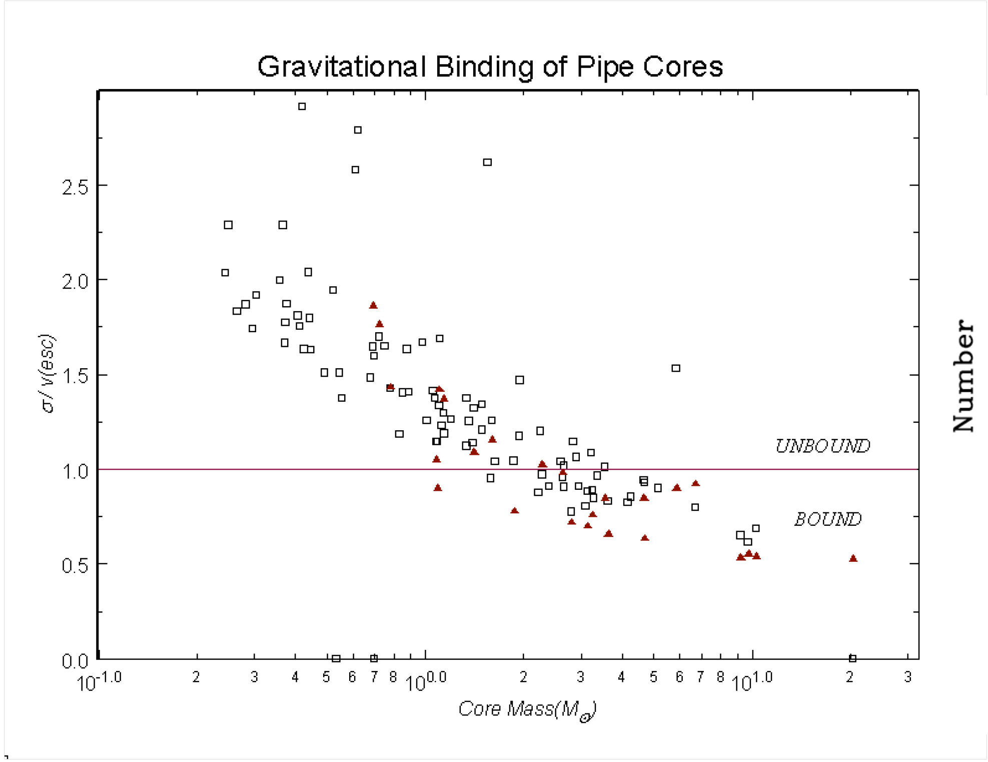


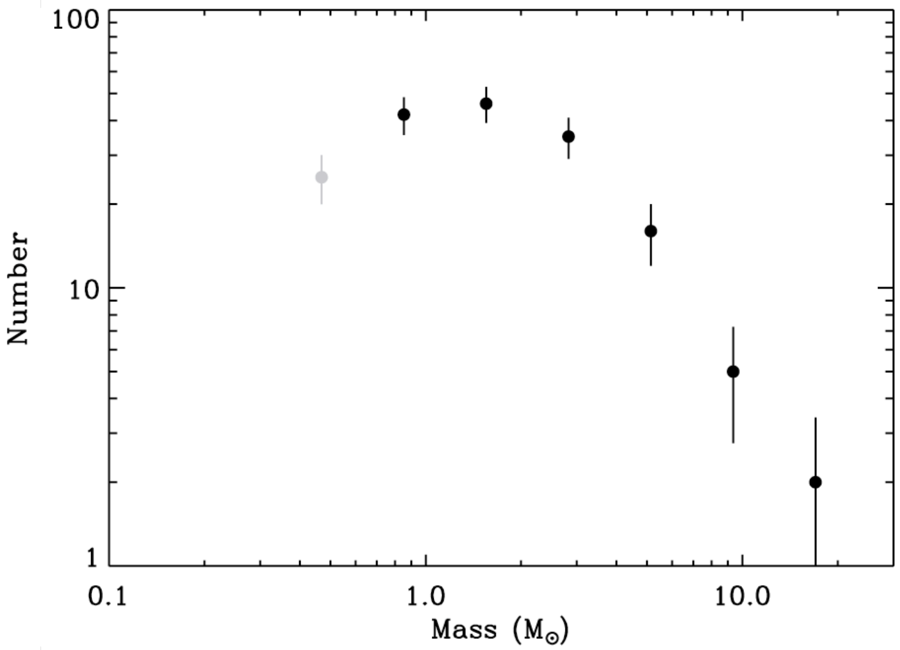
Lada et al (2007)



Lada et al (2007)

cores in the Pipe nebula





Lada et al (2007)

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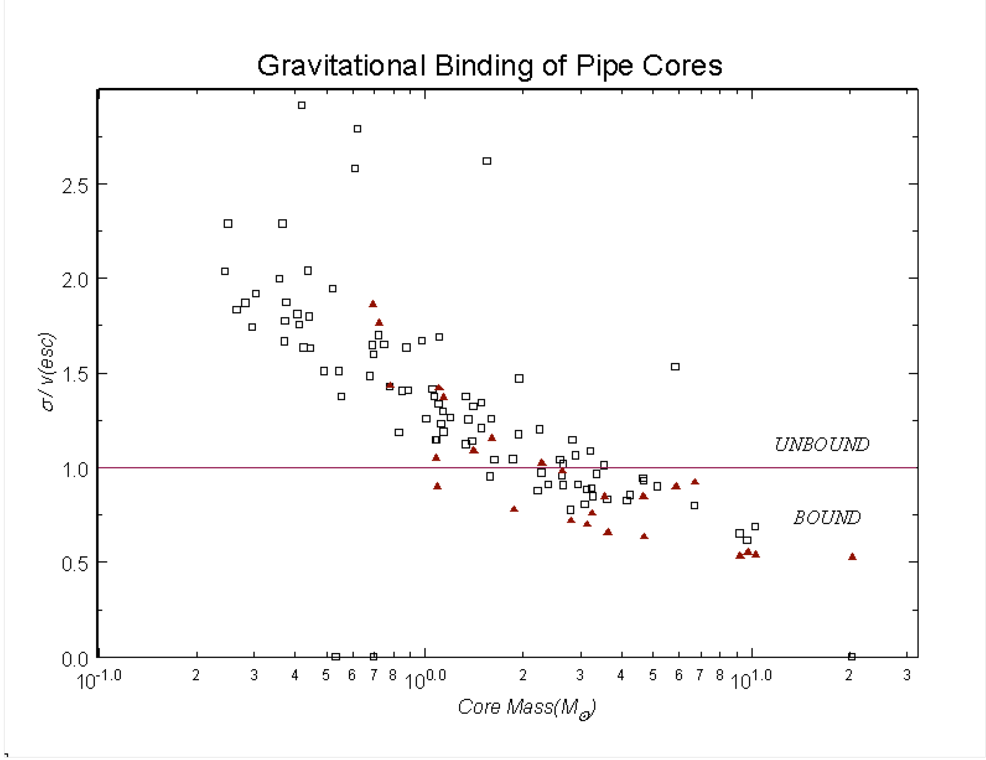
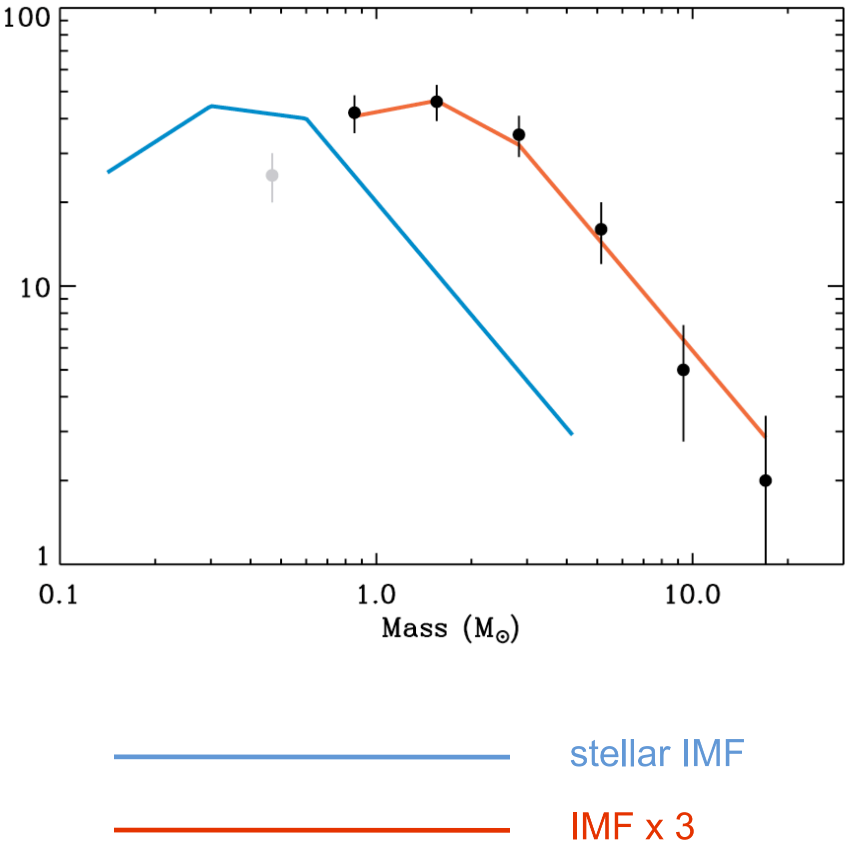




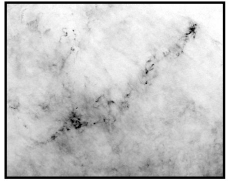
stellar IMF

IMF x 3

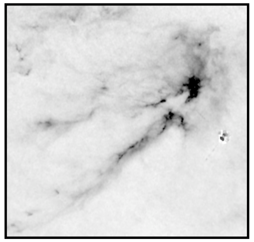
Lada et al (2007)

nearby clouds

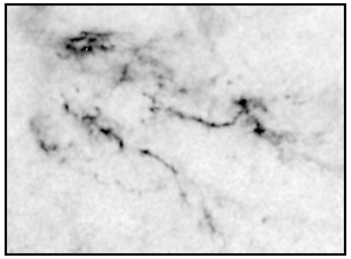
•Pipe



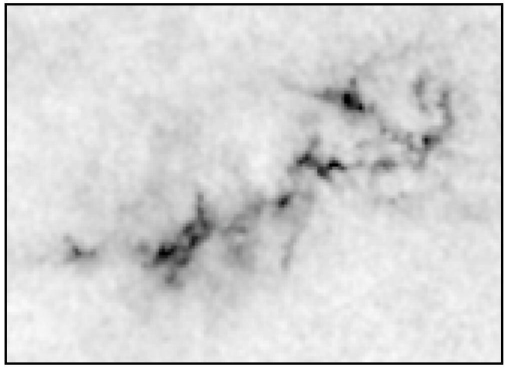
•Ophiuchus



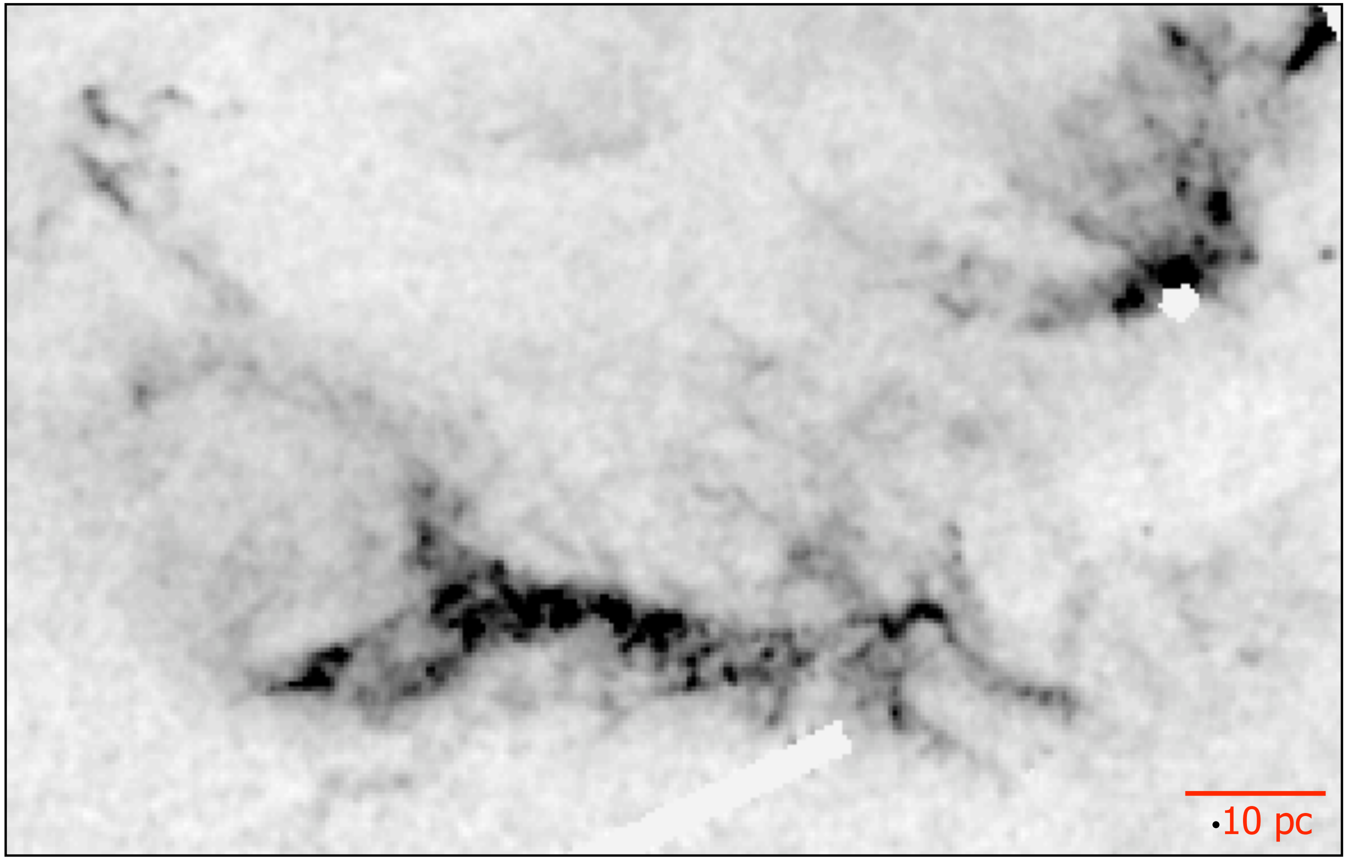
•Taurus



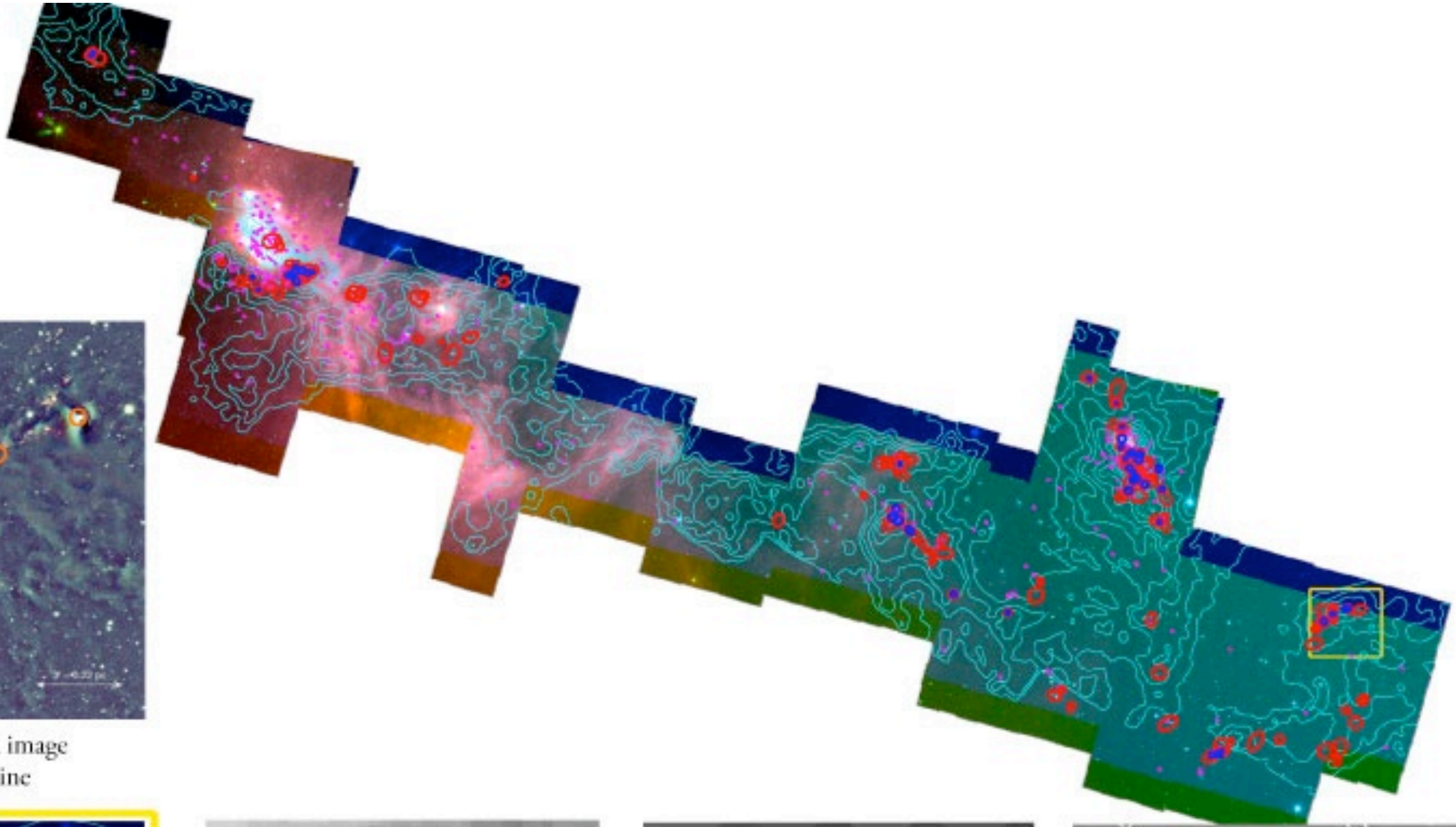
•Perseus

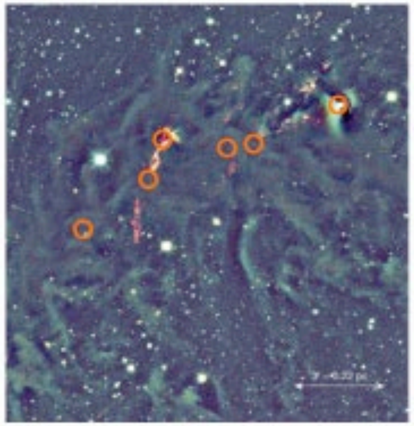


scales to same scale

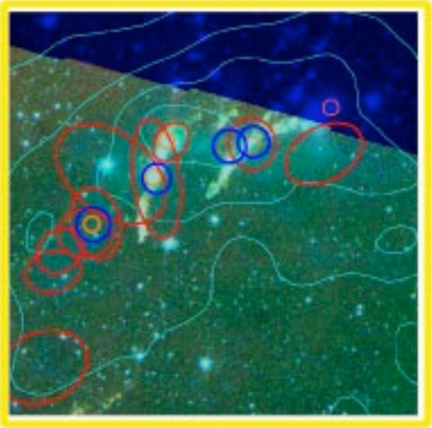


•Orion



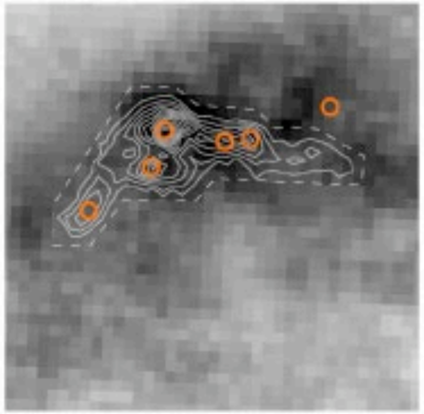


J,H,K Near-IR image
of Cloudshine



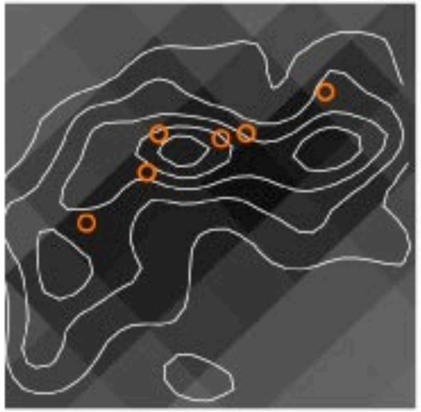
CO

850 micron and 1.1 mm
clumps on a c2d IRAC
3-color image



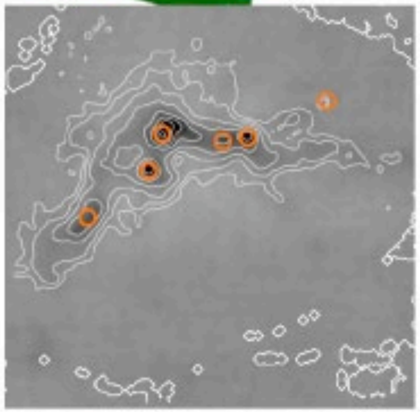
MPL

N_2H^+ on ^{13}CO
integrated intensity



E

Deep NIR Extinction on
2MASS Extinction



TE

1.2 mm (IRAM) on 850
micron (SCUBA)
continuum

images from Alyssa Goodman

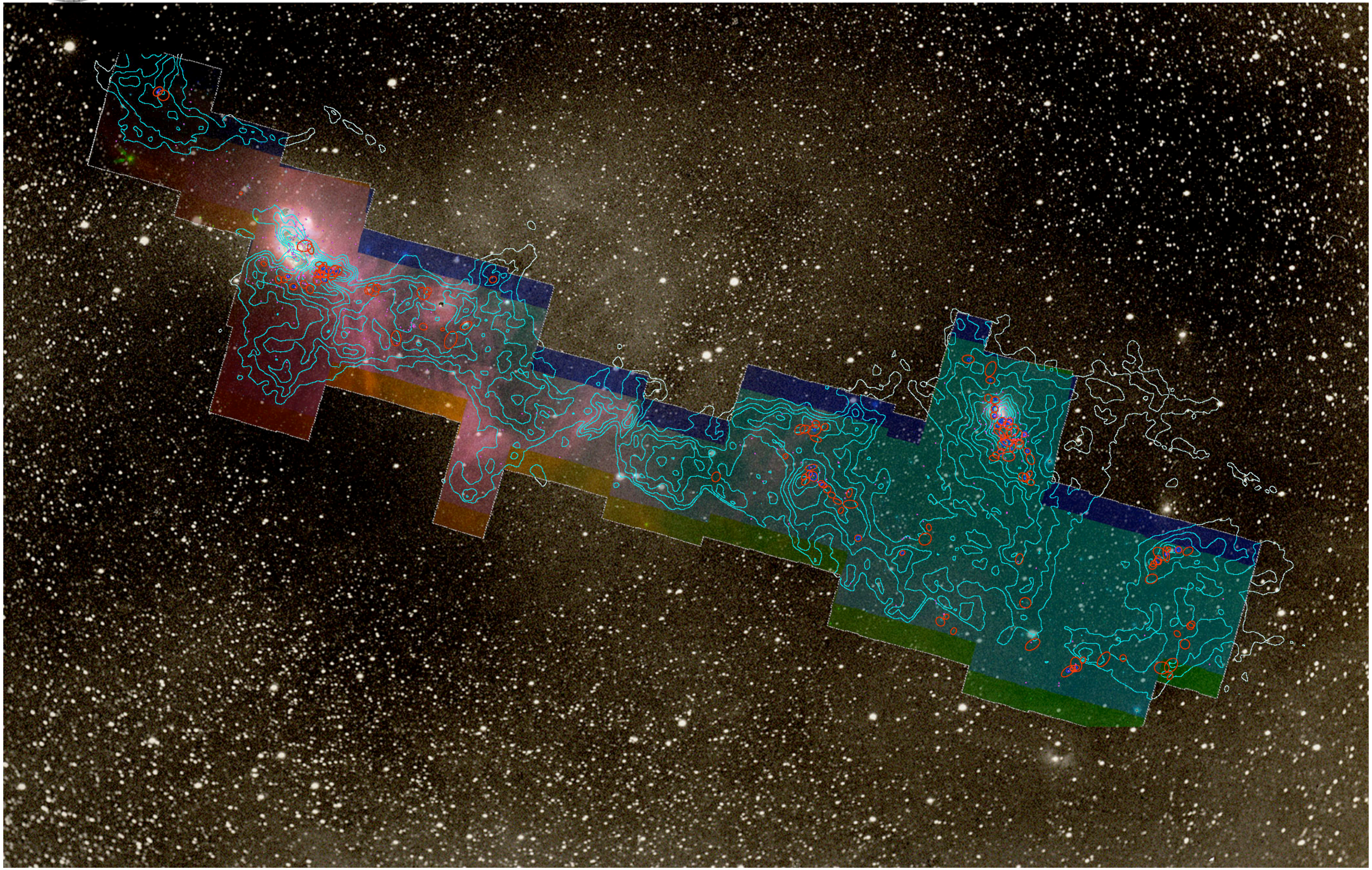
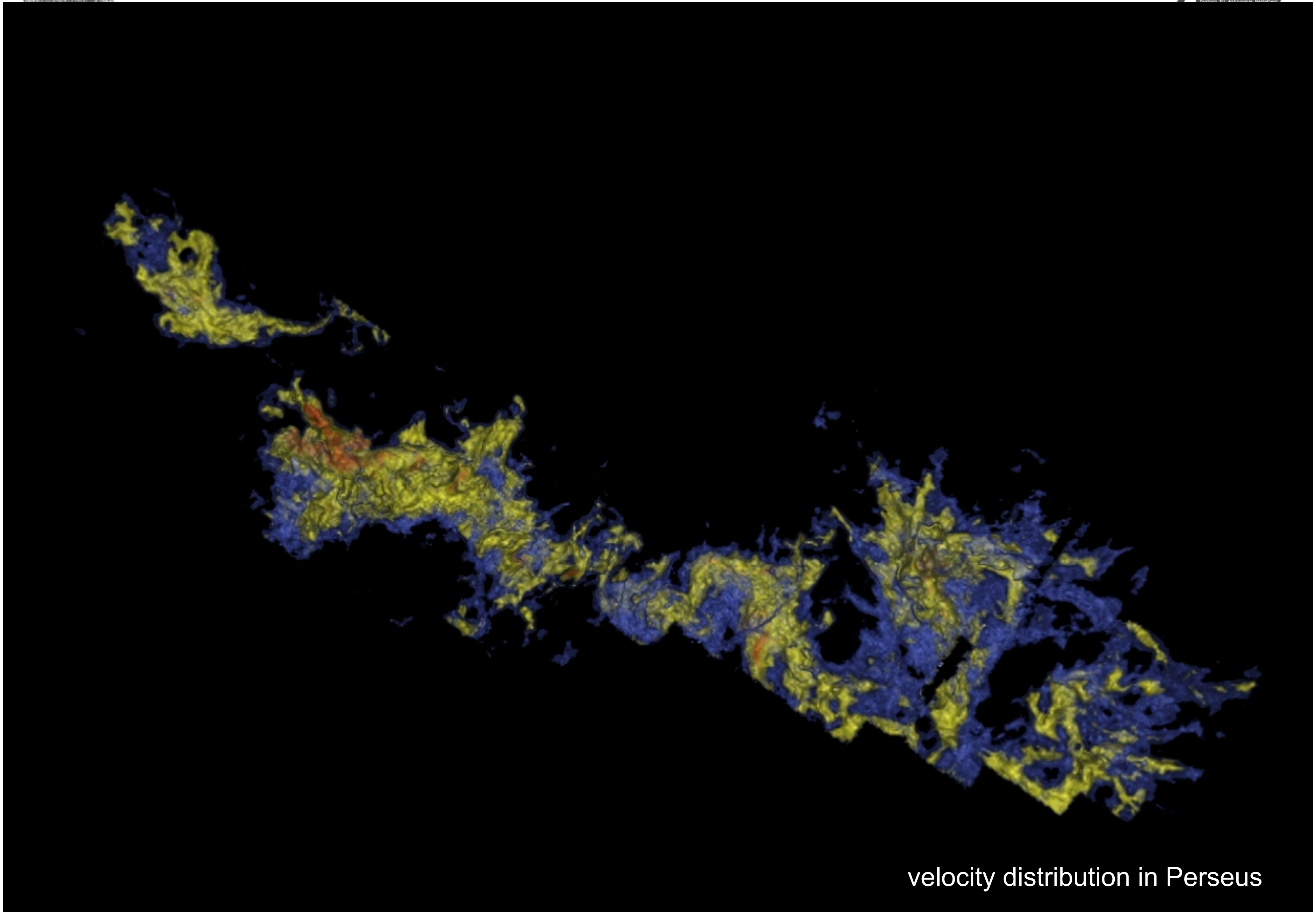


image from Alyssa Goodman: COMPLETE survey

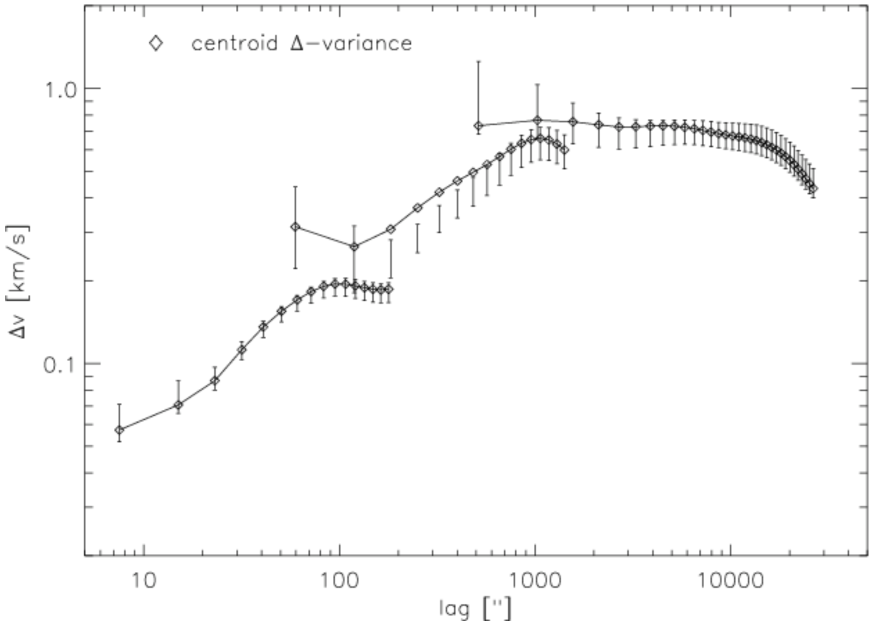


velocity distribution in Perseus

image from Alyssa Goodman: COMPLETE survey

turbulence

what drives turbulence?

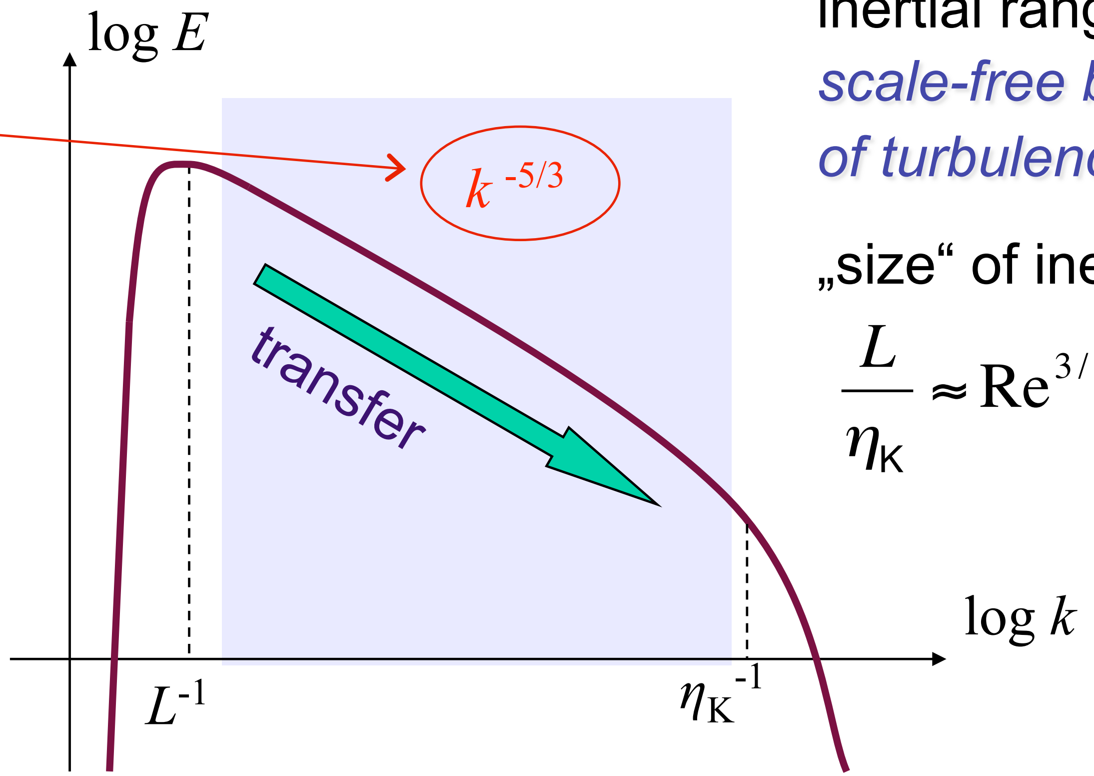


Polaris flare (from Ossenkopf & Mac Low 2002)

- 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 ..
    → caused by
    - *gravity (spiral shocks),*
    supernovae, HII regions?
  - alternative mechanisms:
    - internal sources: jets, outflows?

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:
scale-free behavior
of turbulence

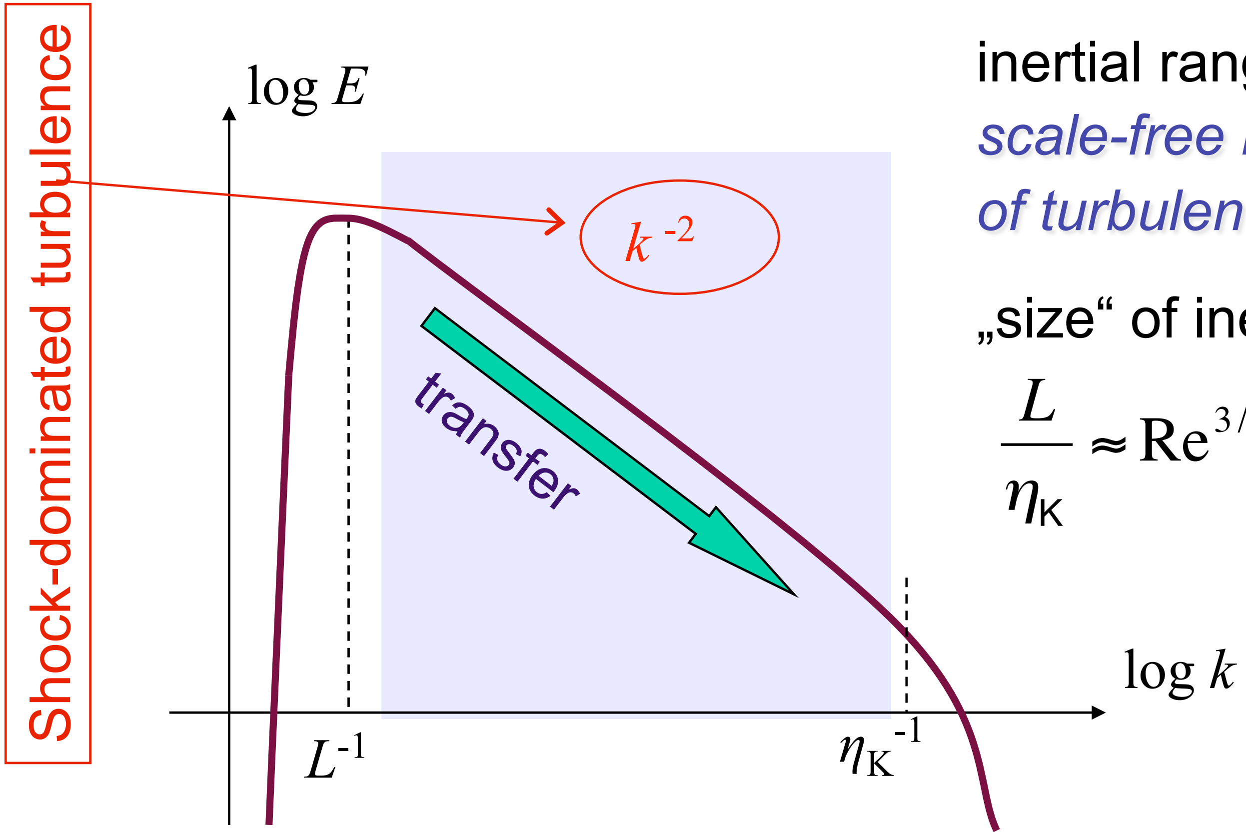
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:

scale-free behavior
of turbulence

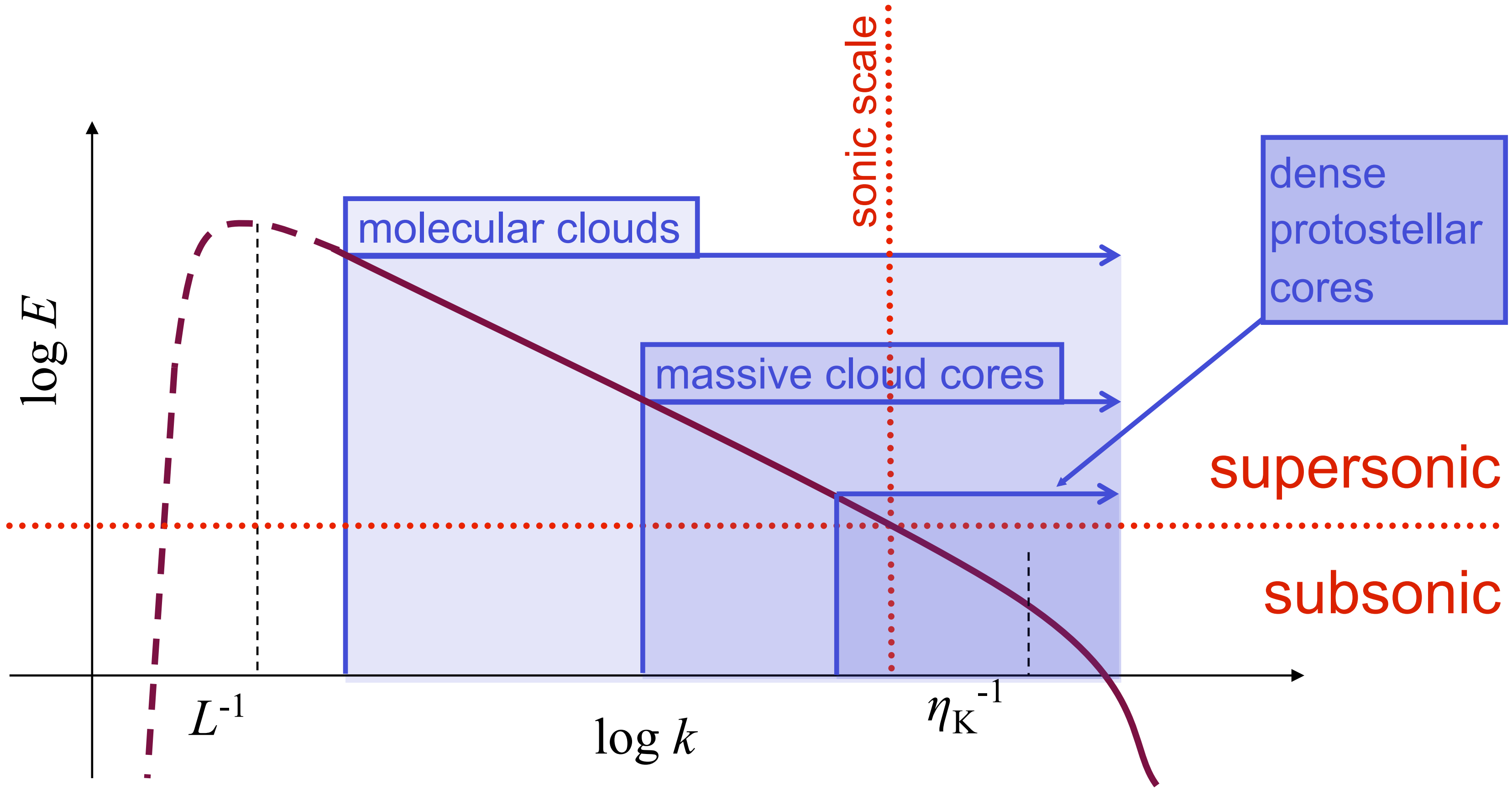
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM

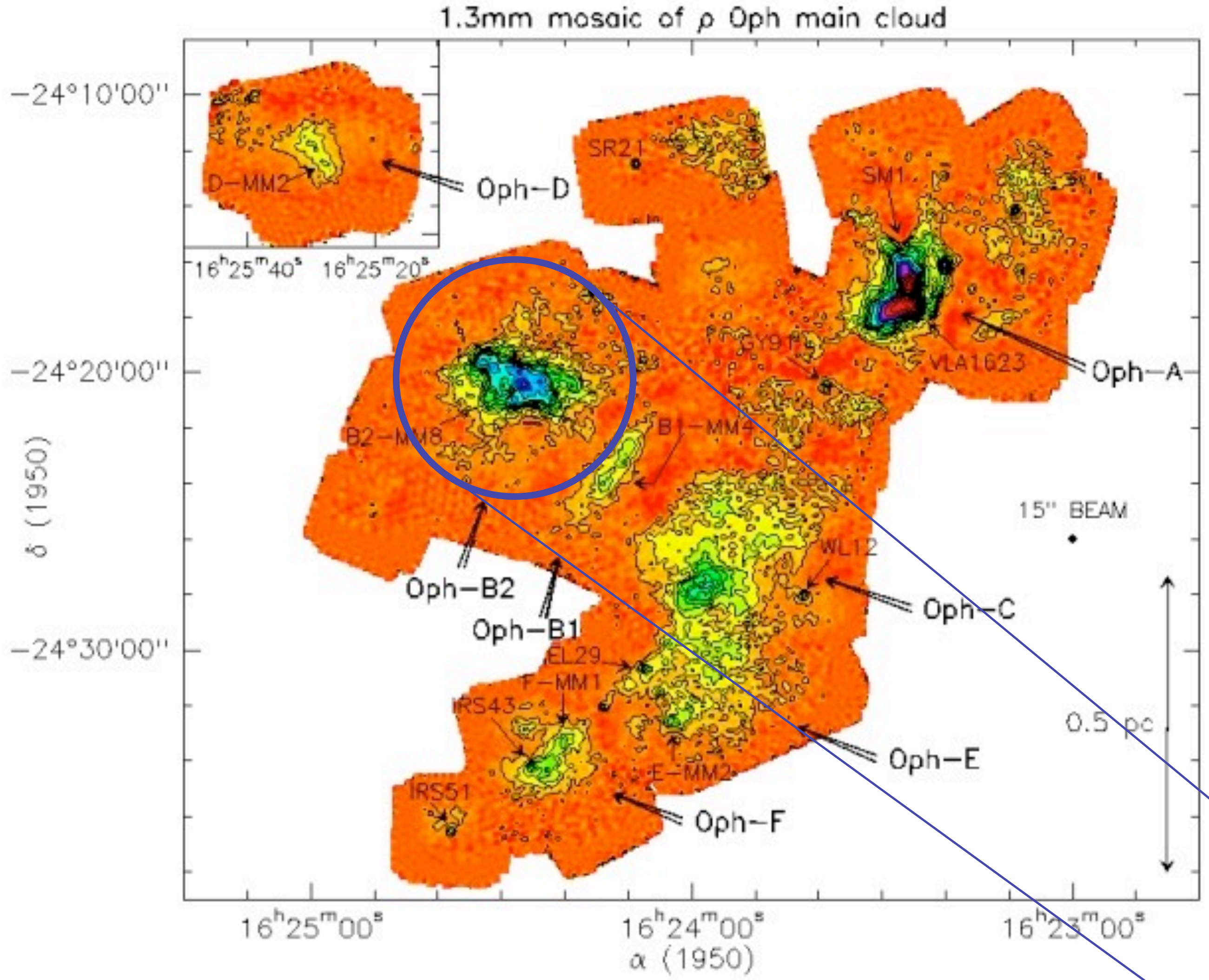


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

Density structure of MC’s



(Motte, André, & Neri 1998)

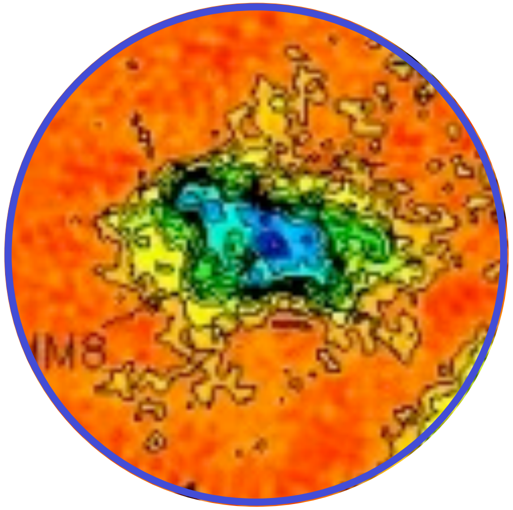
molecular clouds are highly inhomogeneous

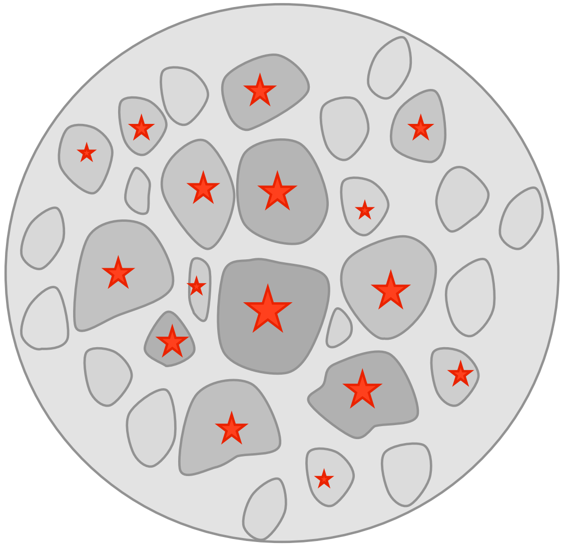
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let‘s focus on a cloud core like this one

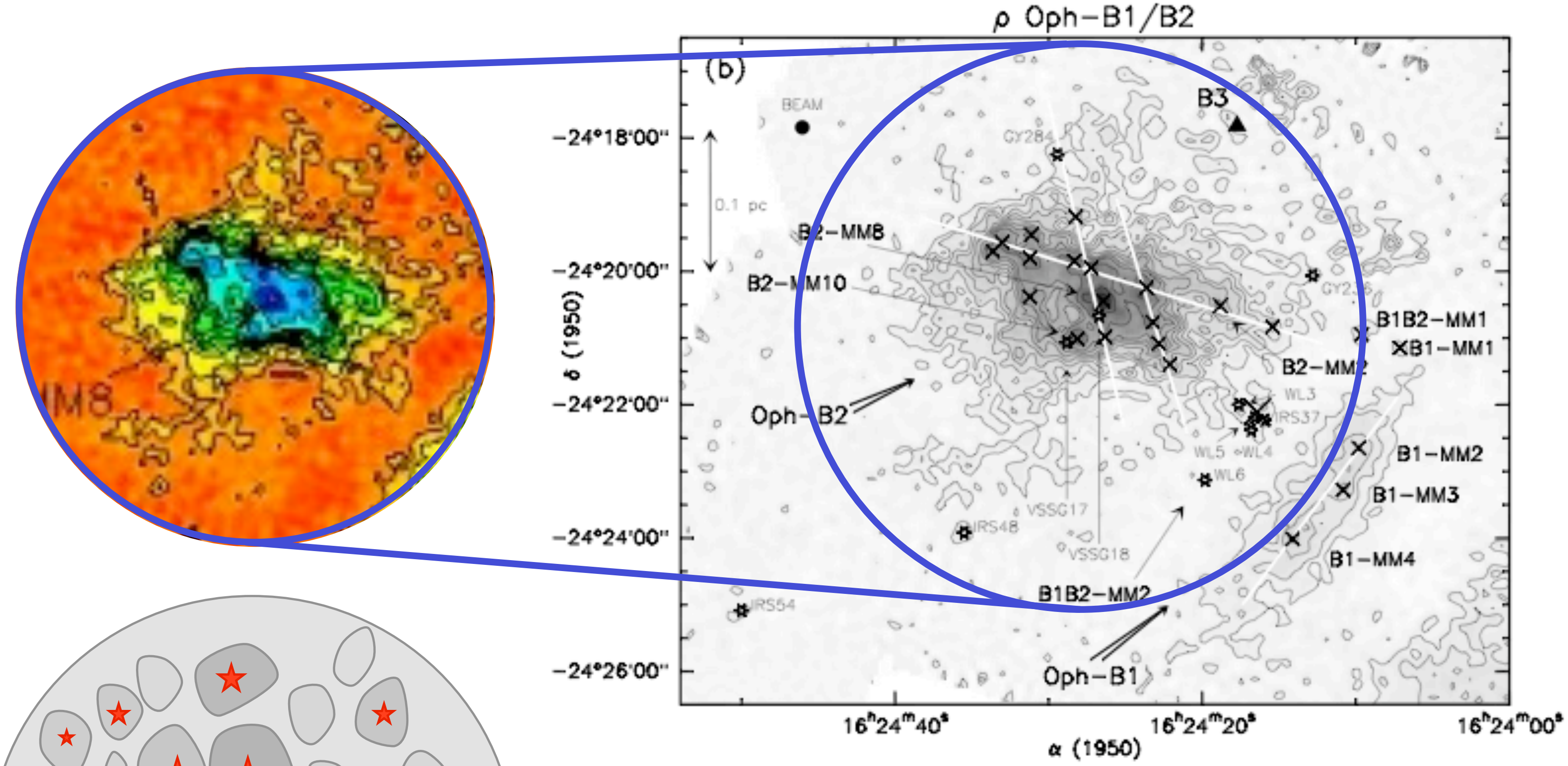
Evolution of cloud cores

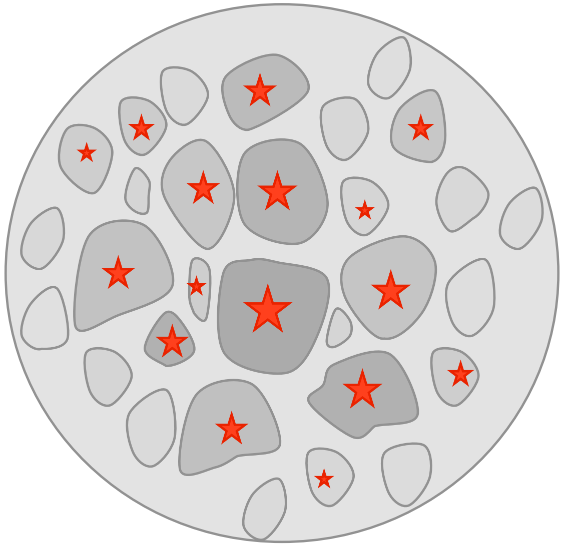




- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho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

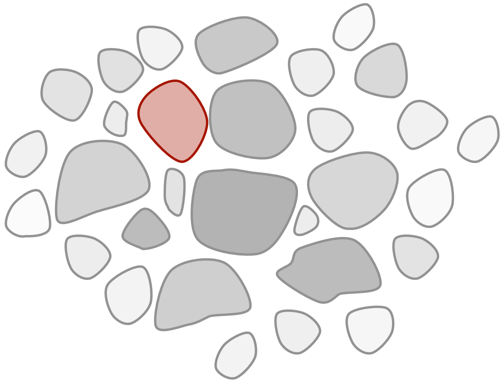




indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores



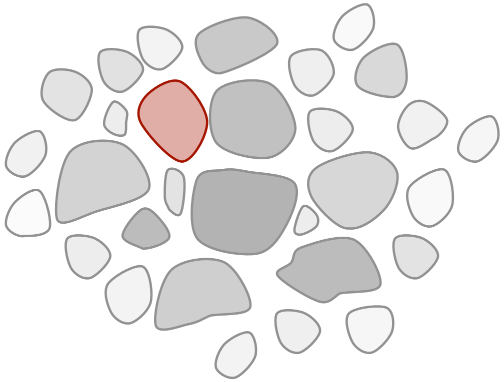
- protostellar cloud cores form at the *stagnation points* of *convergent turbulent flows*
- if $M > M_{\mathrm{Jeans}} \propto \rho^{-1/2}\, T^{3/2}$: collapse and star formation
- if $M < M_{\mathrm{Jeans}} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after external compression fades away

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

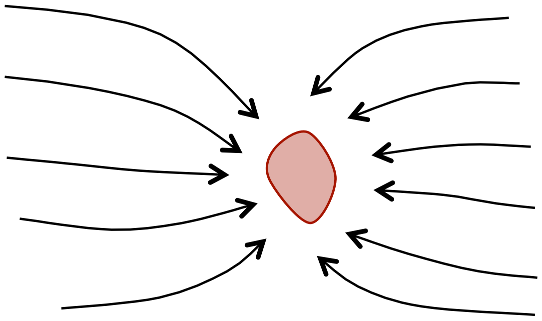
- typical timescales: $t \approx 10^4 \ldots 10^5$ yr
- because *turbulent* ambipolar diffusion time is *short*, this time estimate still holds for the presence of magnetic fields, in *magnetically critical cores*

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

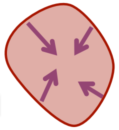
Formation and evolution of cores



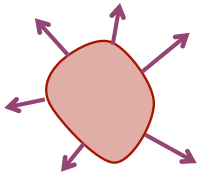
- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*



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



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

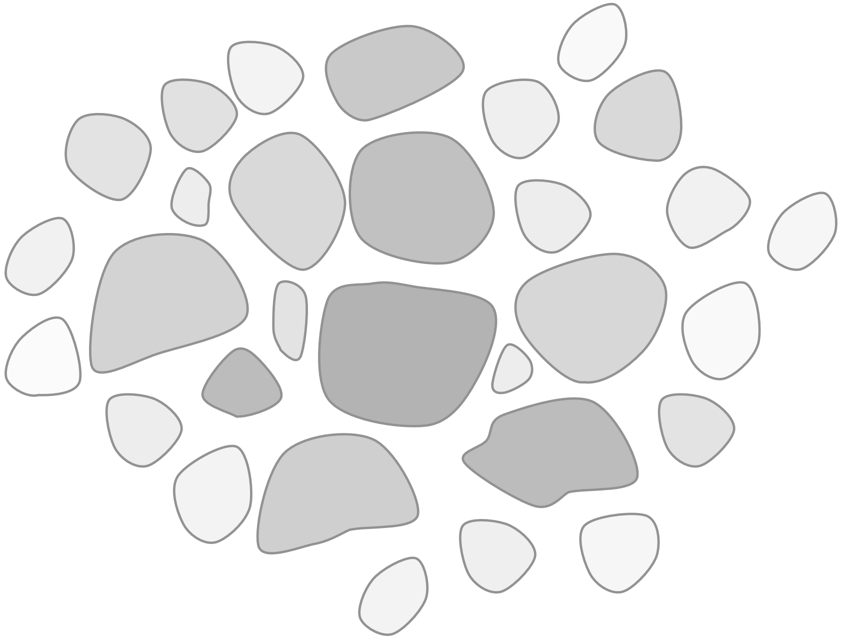


(e.g. Vazquez-Semadeni et al 2005)

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

Formation and evolution of cores

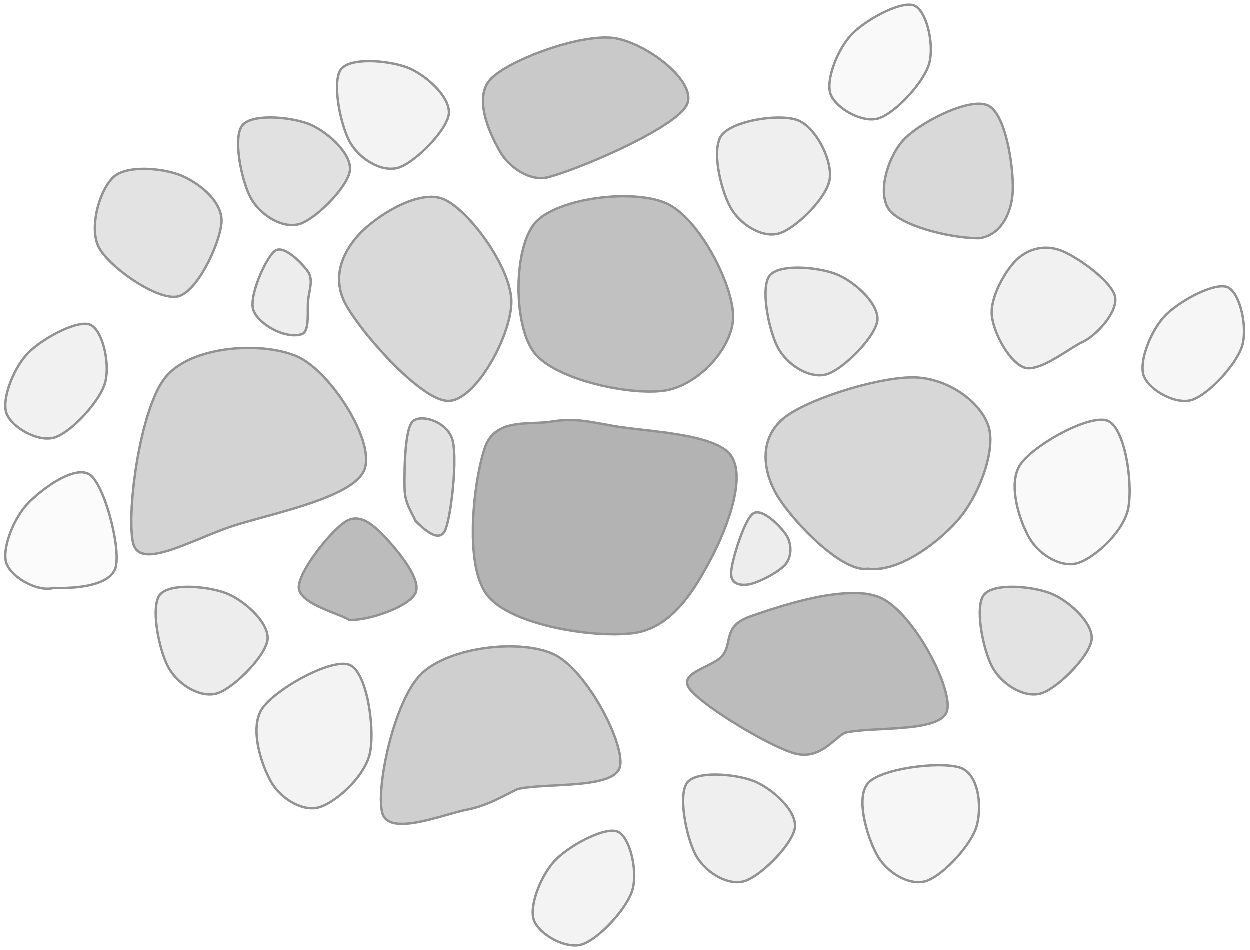
What happens to distribution of cloud cores?



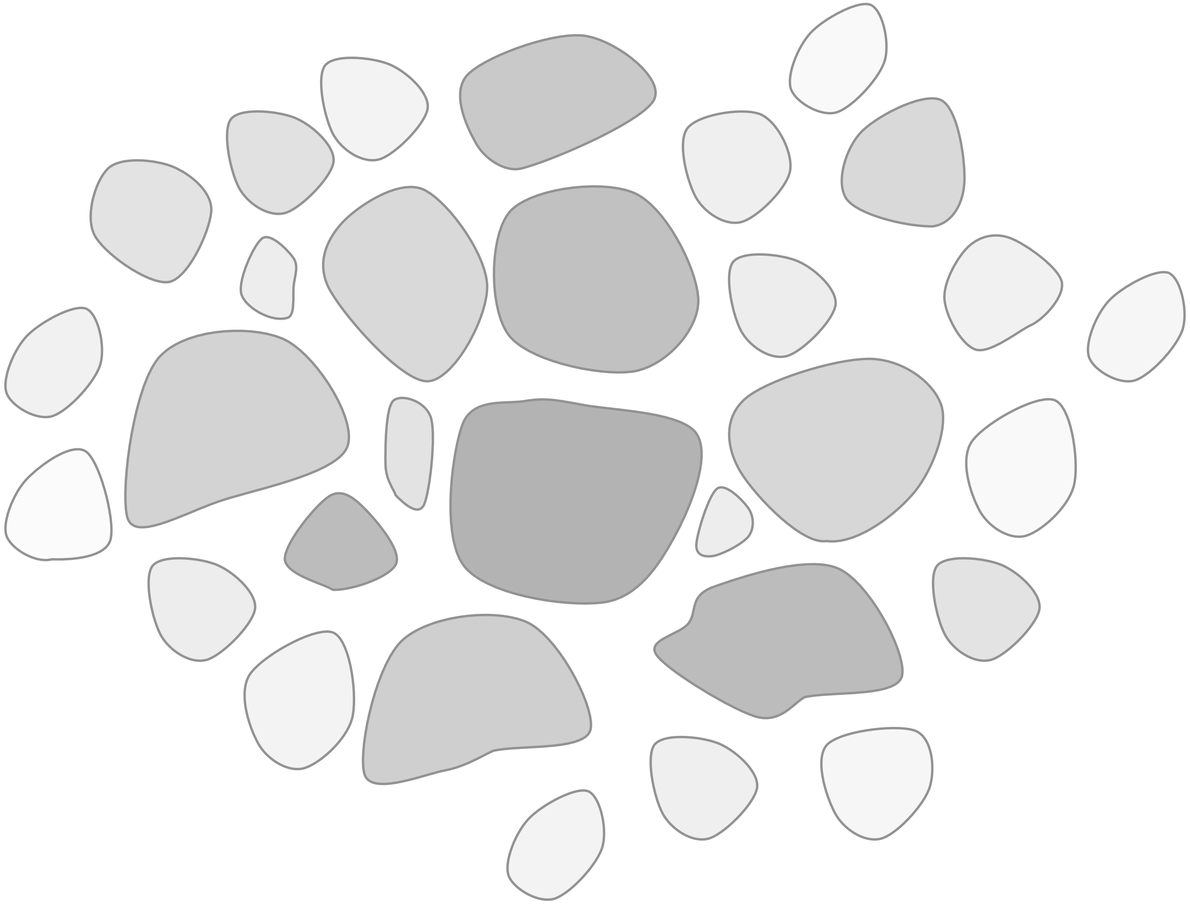
Two exteme cases:

(1) turbulence 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*

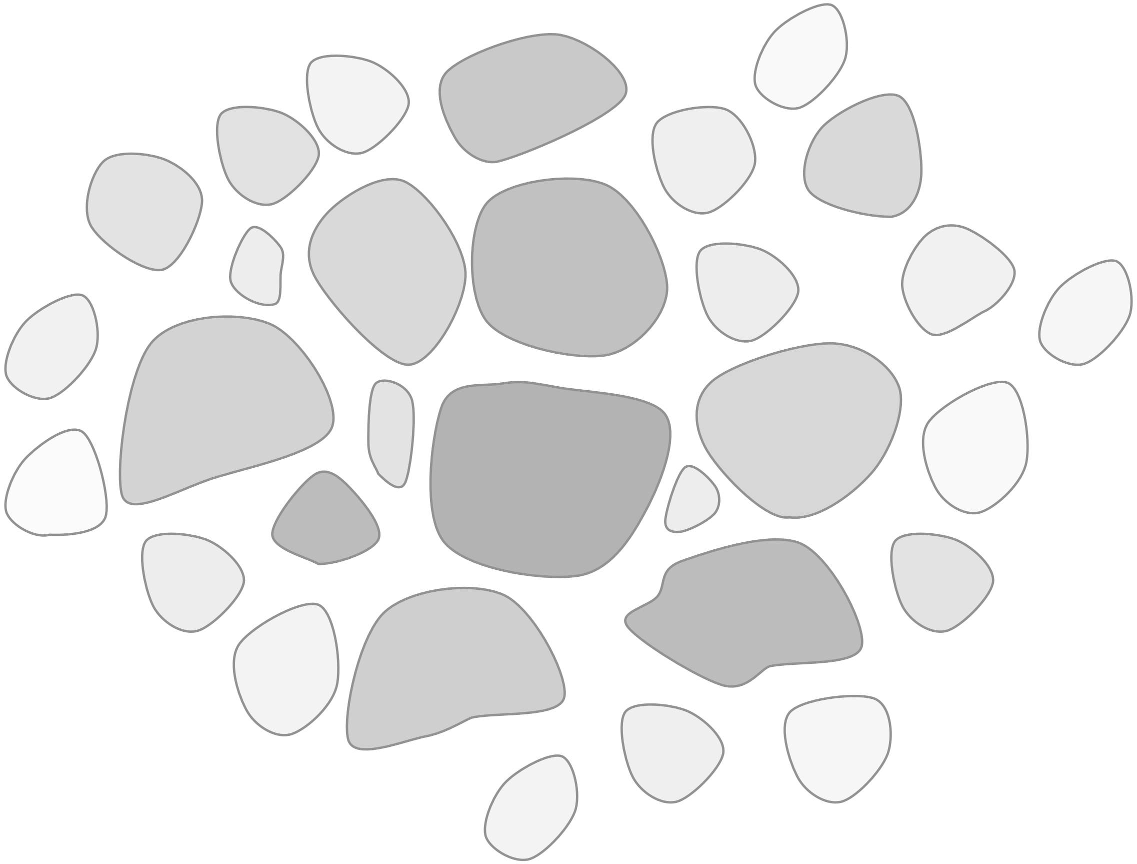
(2) turbulence dominates energy budget: $\alpha=E_{kin}/|E_{pot}| > 1$
--> individual cores do *not* interact
--> *collapse* of *individual* cores dominates *stellar mass growth*
--> *loose cluster of low-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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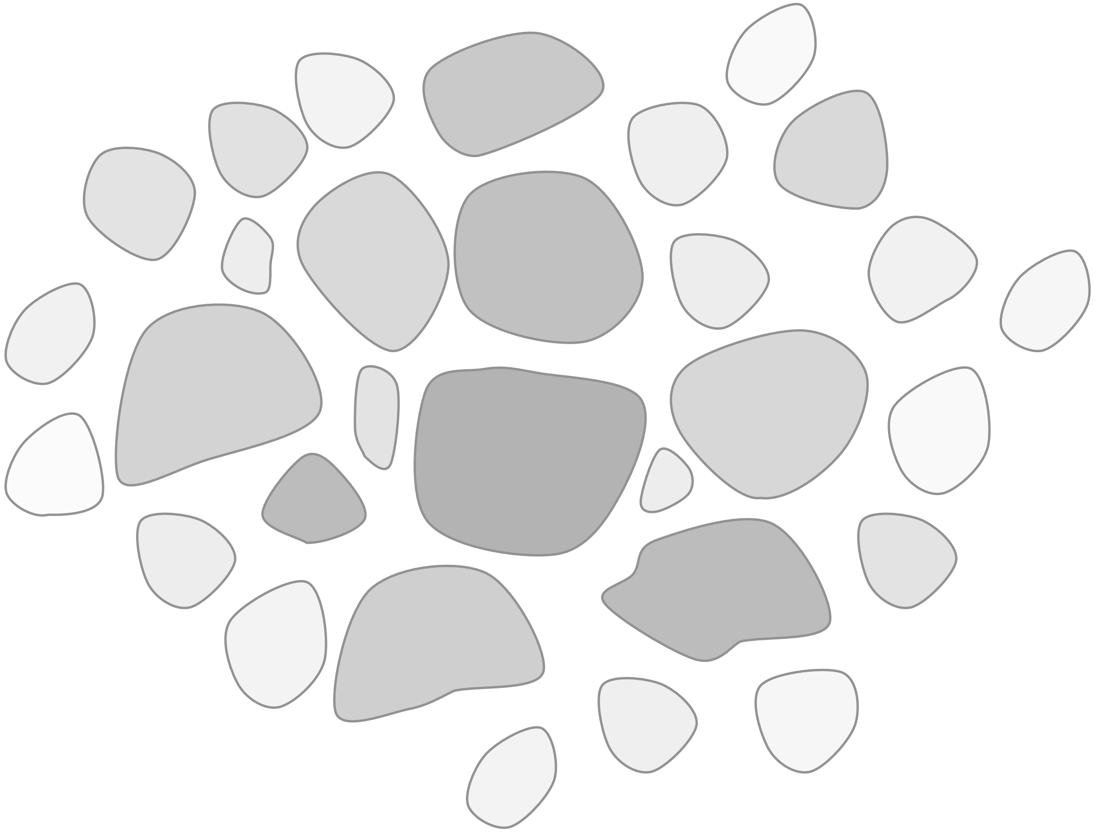
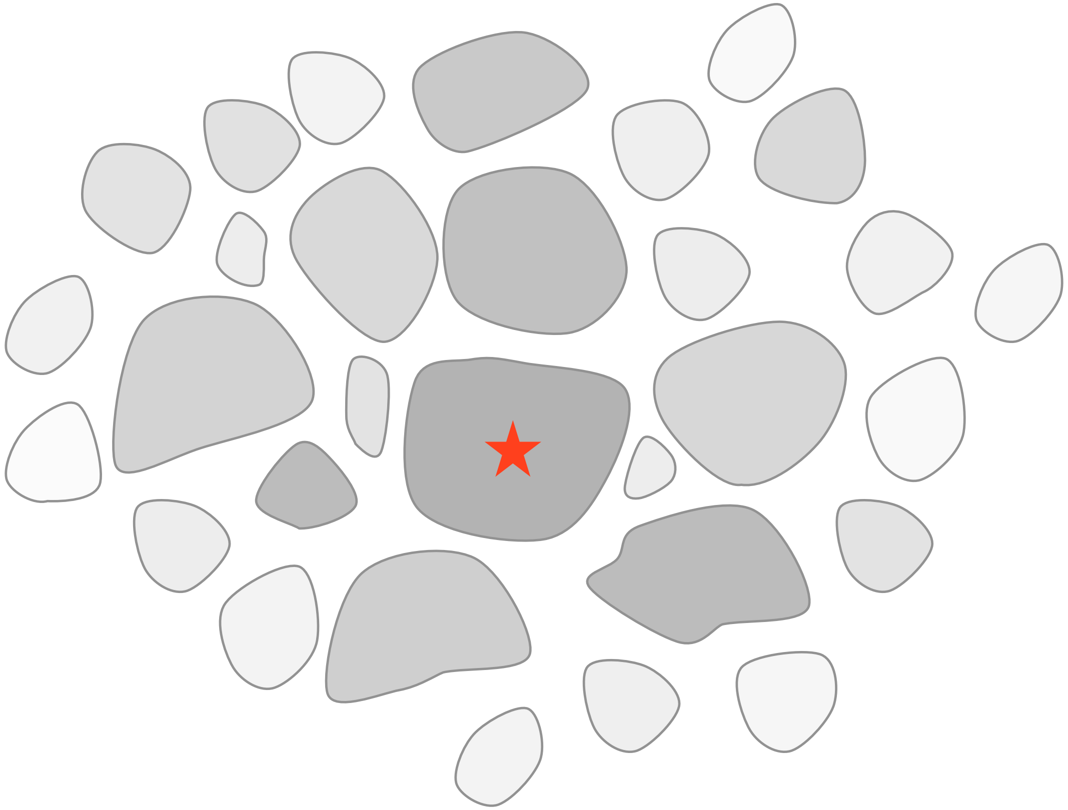


while region contracts, individual clumps collapse to form stars



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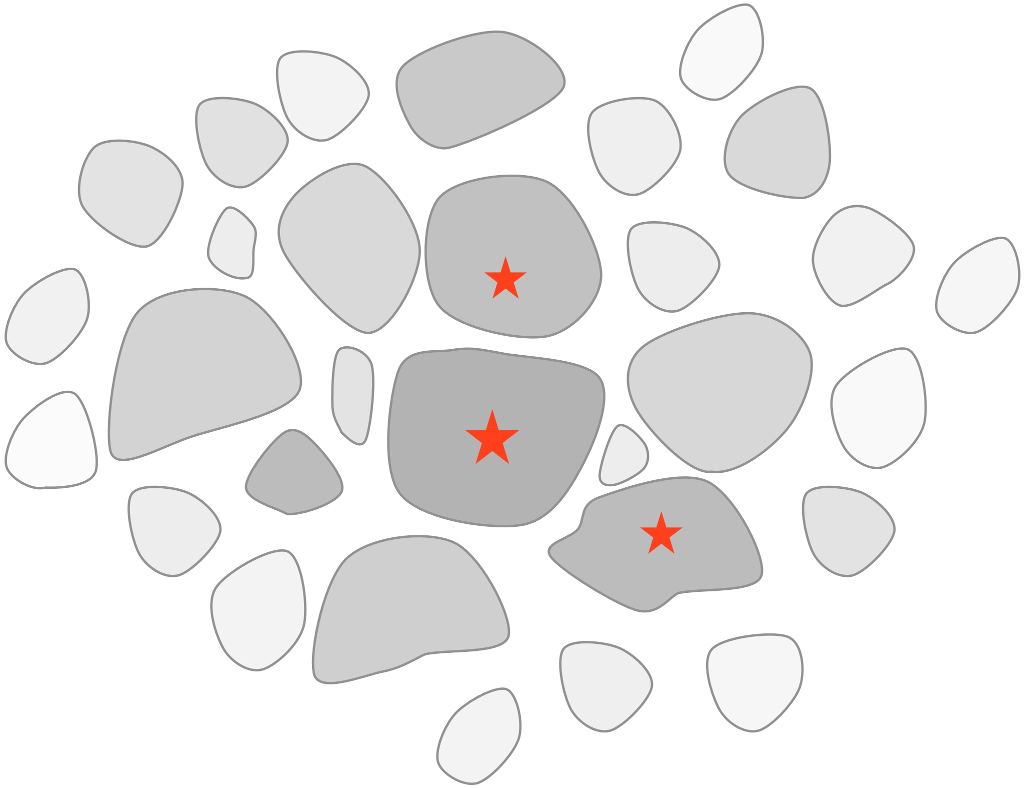

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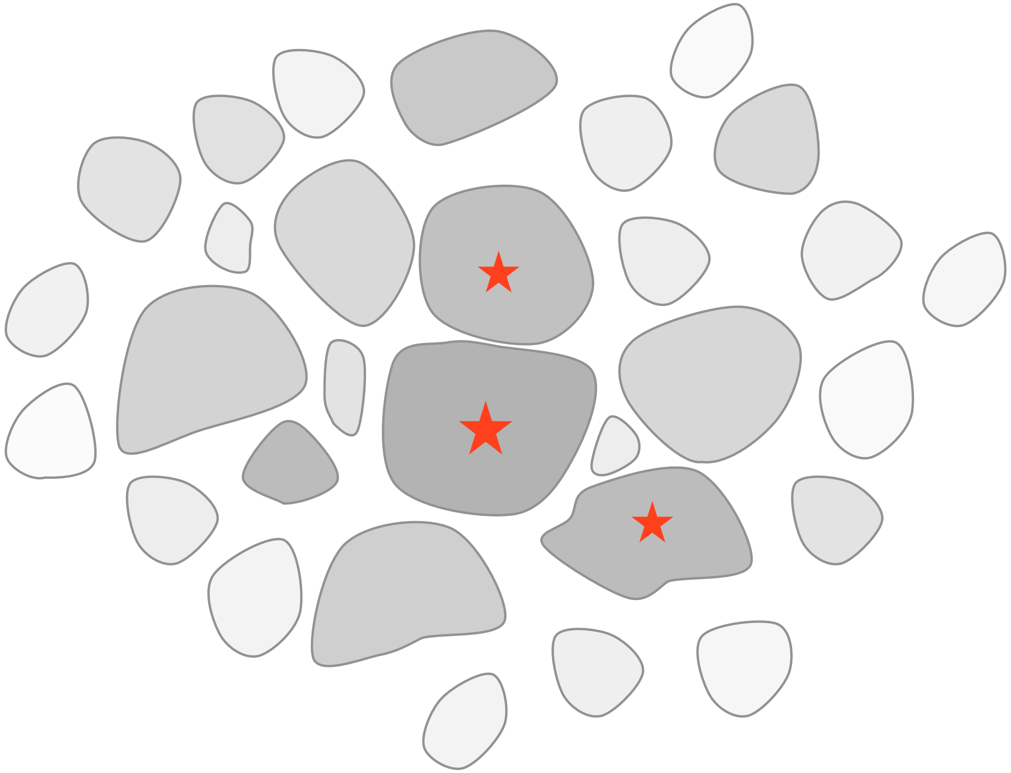

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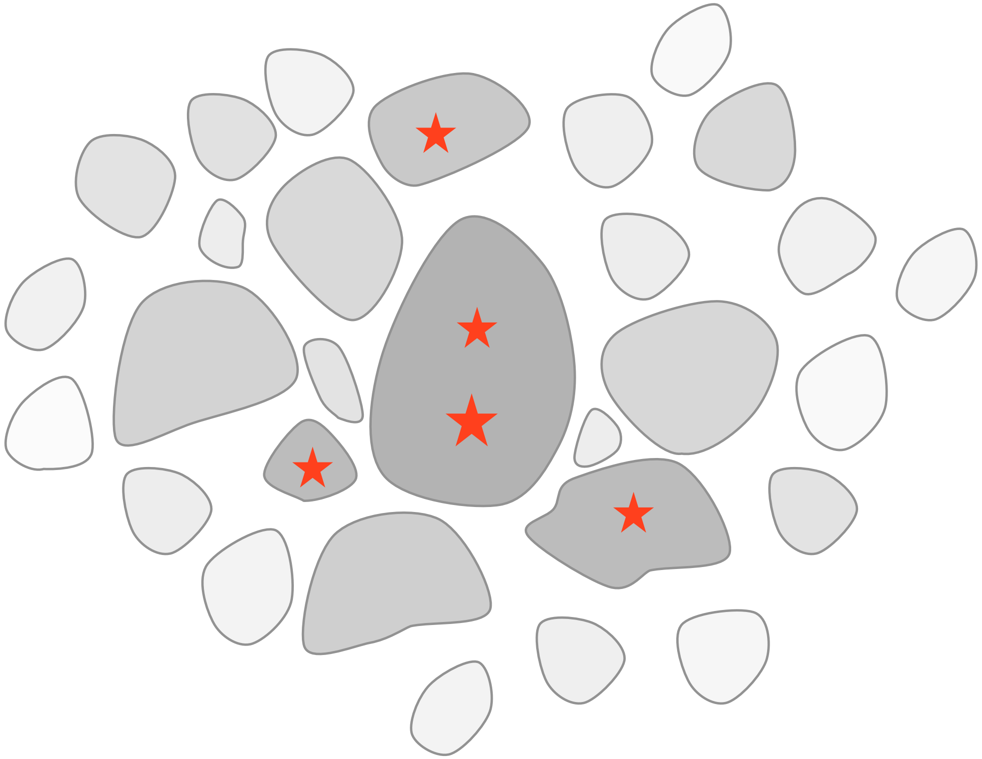
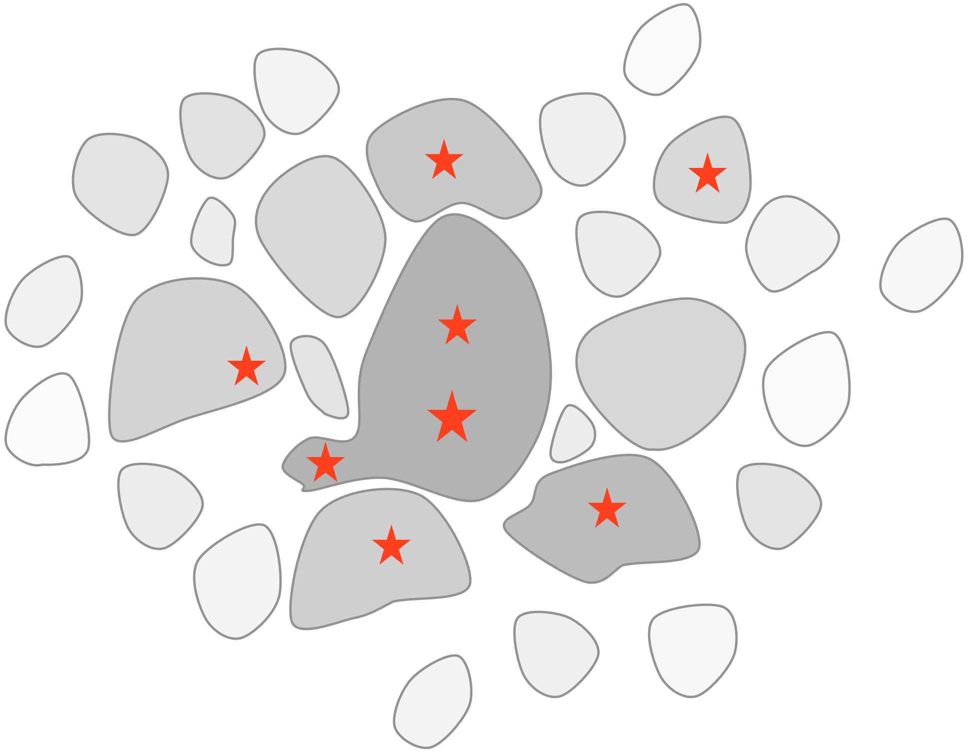


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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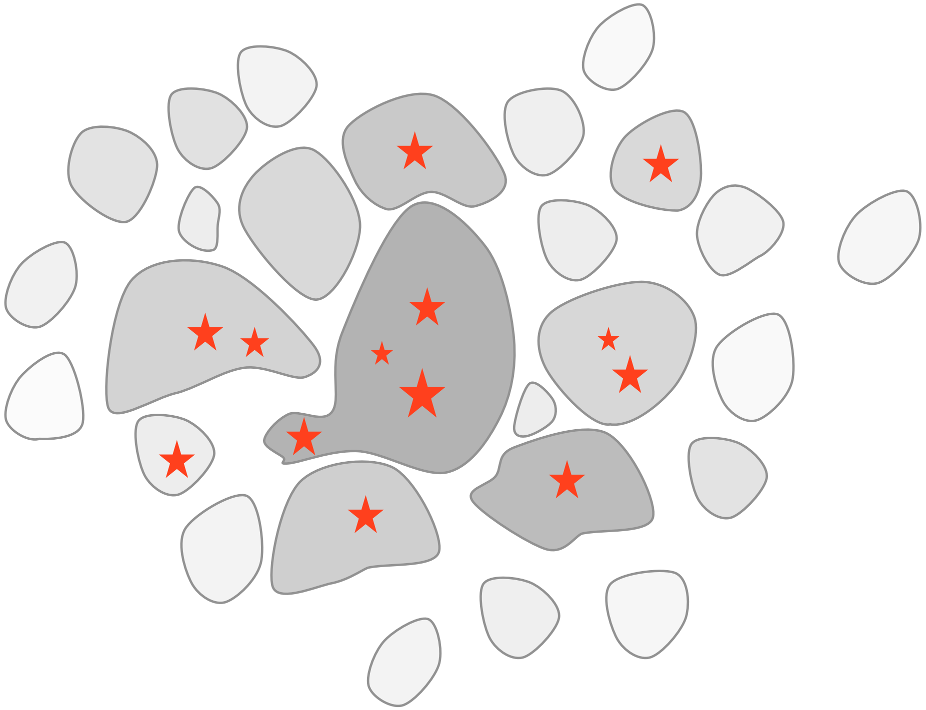

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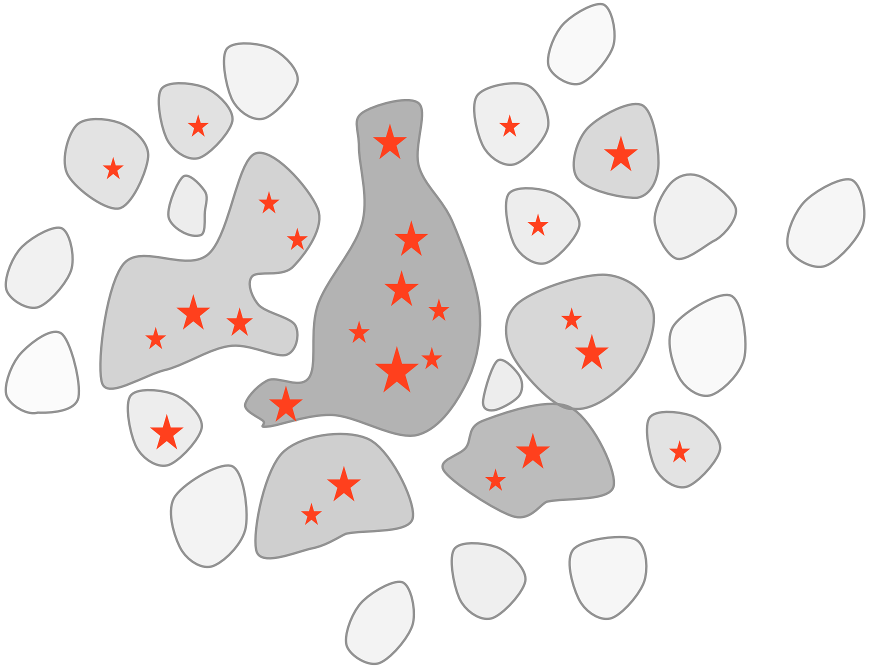
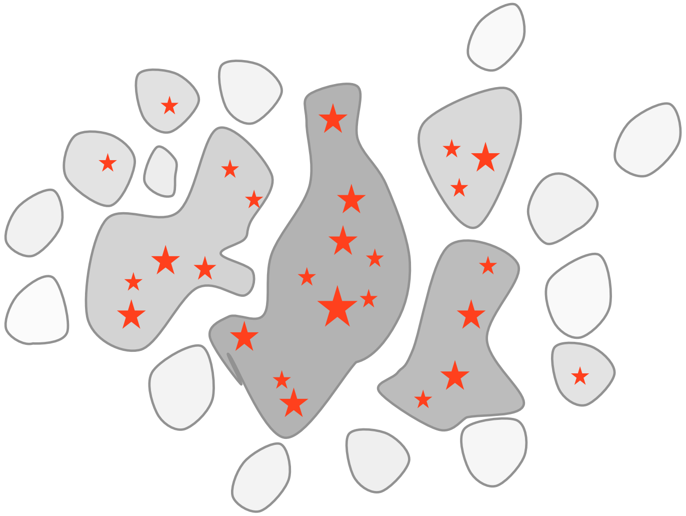


in *dense clusters*, competitive mass growth becomes important



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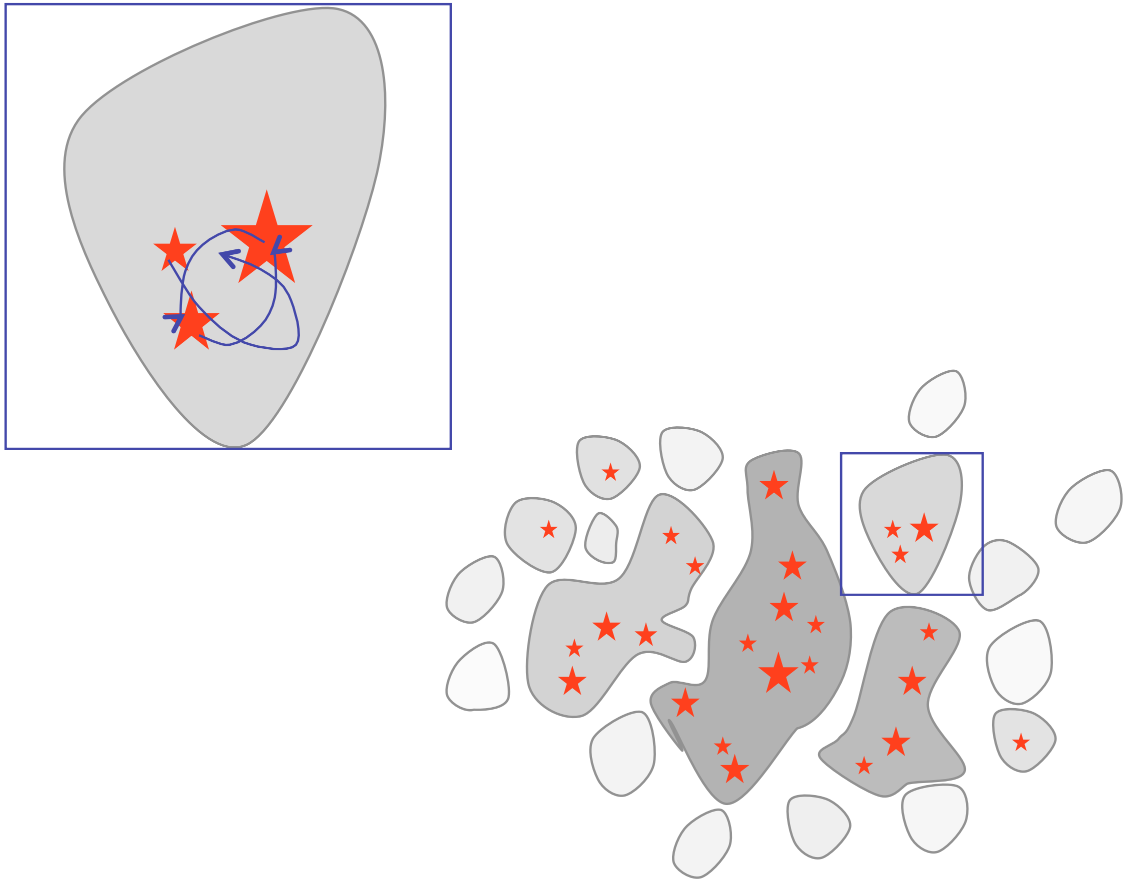
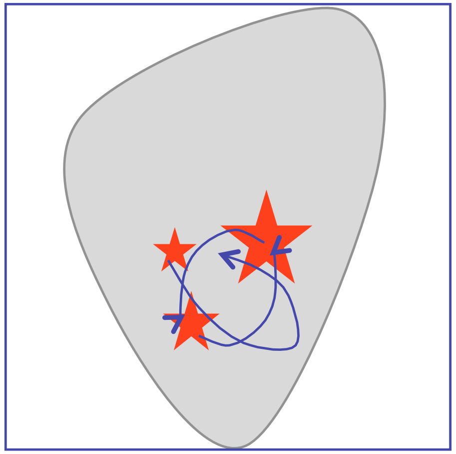
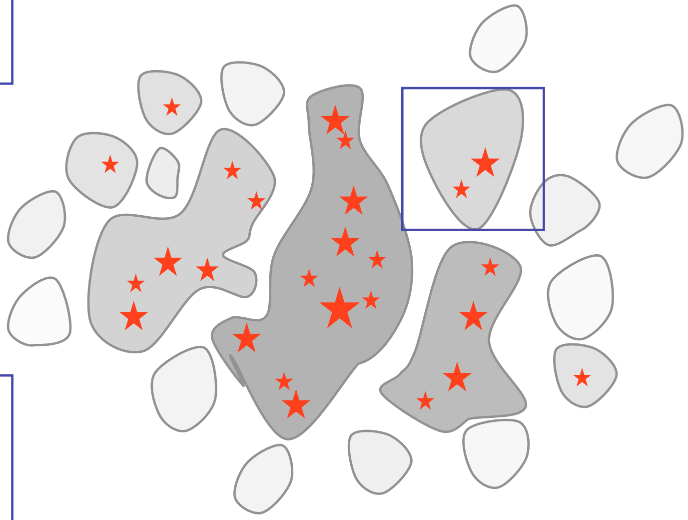
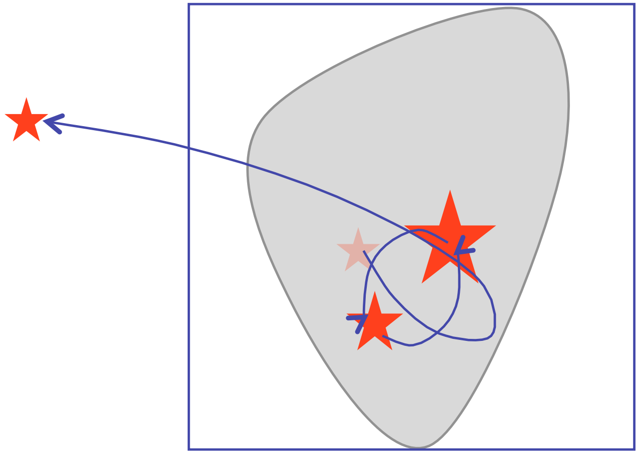


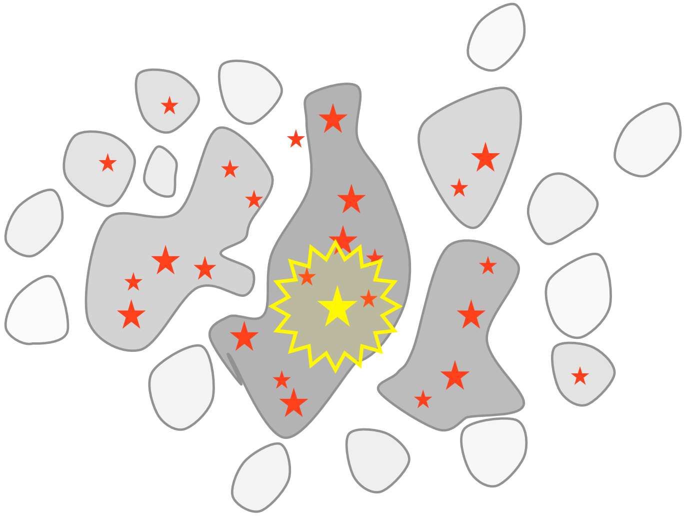
in *dense clusters*, *N*-body effects influence mass growth



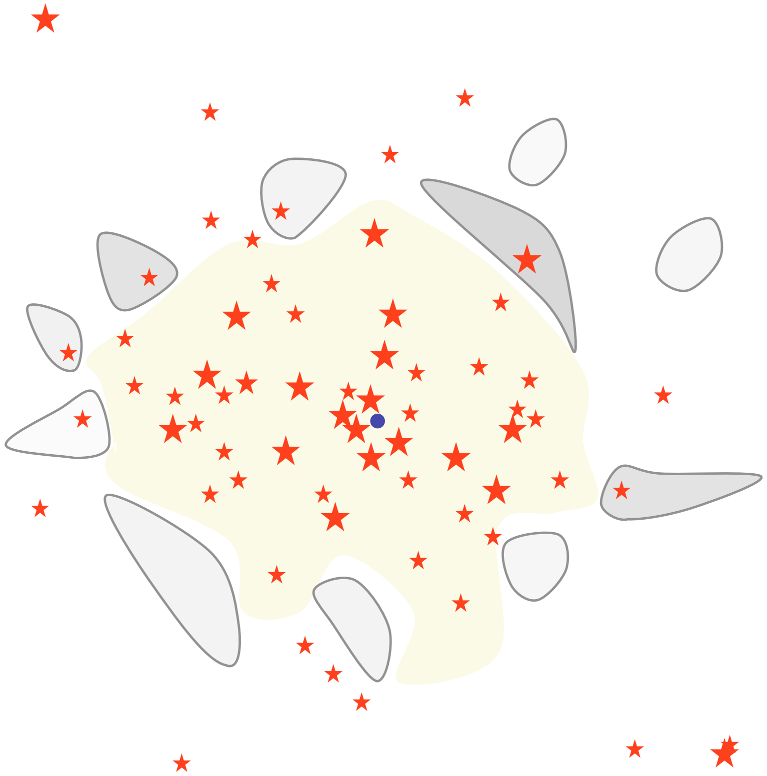




low-mass objects may
become ejected --> accretion stops



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*
  - protostellar *spin* (including disk)
  - *spatial distribution* + *kinematics* in young clusters
  - *magnetic field strength* and *orientation*

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

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

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

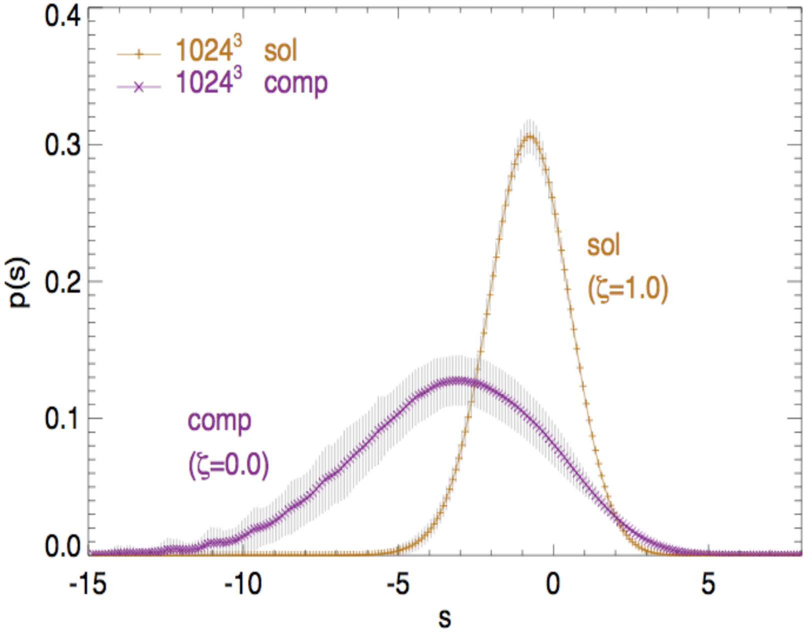


FIG. 2.— Volume-weighted density PDFs $p_s(s)$ in linear scaling where $s = \ln(\rho/\rho_0)$. The PDF obtained by compressive forcing (comp, $\zeta = 0.0$) is much broader compared to the solenoidal one (sol, $\zeta = 1.0$) at the same rms Mach number. The peak is shifted due to mass conservation (Vázquez-Semadeni 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

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

  - with b depending on ζ via

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

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

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

dilatational vs. solenoidal

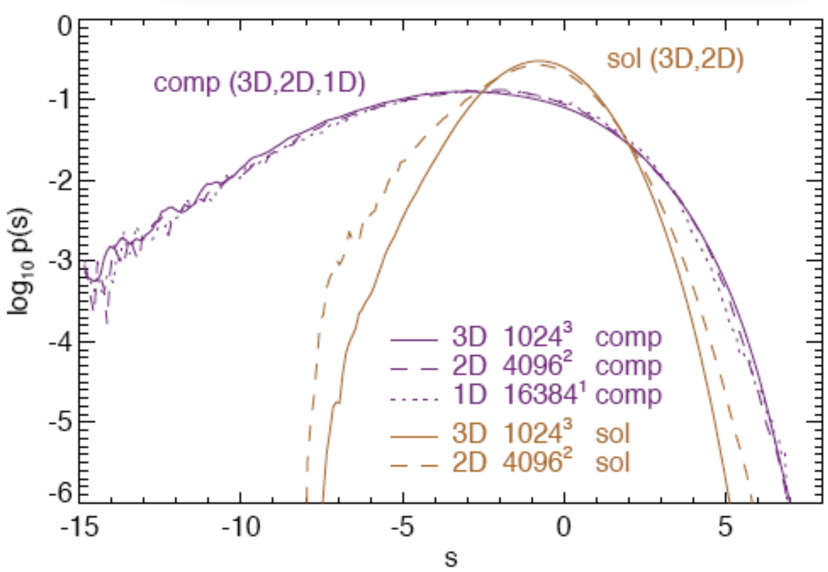


FIG. 3.— Volume-weighted density PDFs $p(s)$ obtained from 3D, 2D and 1D simulations with compressive forcing and from 3D and 2D simulations using solenoidal forcing. Note that in 1D, only compressive forcing is possible as in the study by Passot & Vázquez-Semadeni (1998). As suggested by eq. (5), compressive 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.

Federrath, Klessen, Schmidt (2008a)

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

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

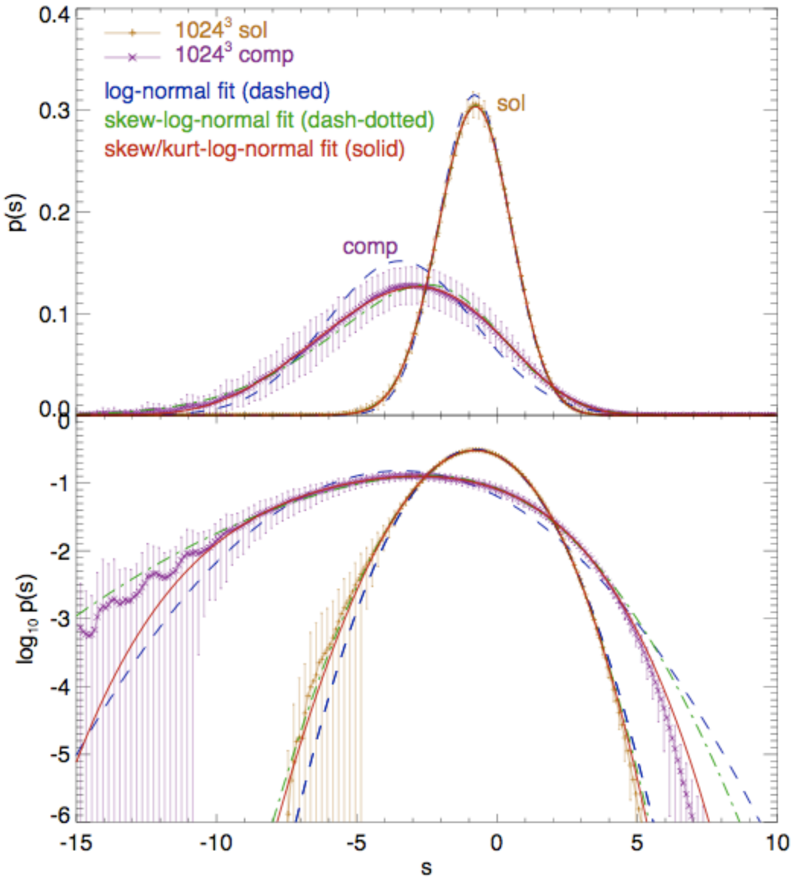
  - with b depending on ζ via

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

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

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

dilatational vs. solenoidal

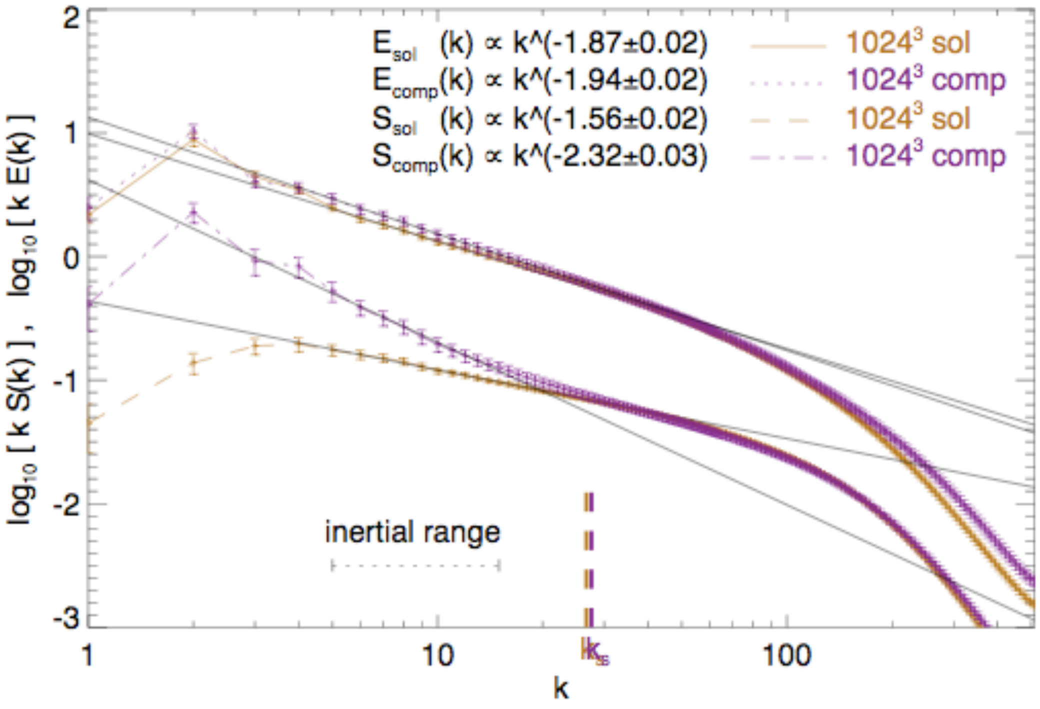


good fit needs 3rd and 4th moment of distribution!

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 ...

Federrath, Klessen, Schmidt (2008b)

- 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 ?

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)

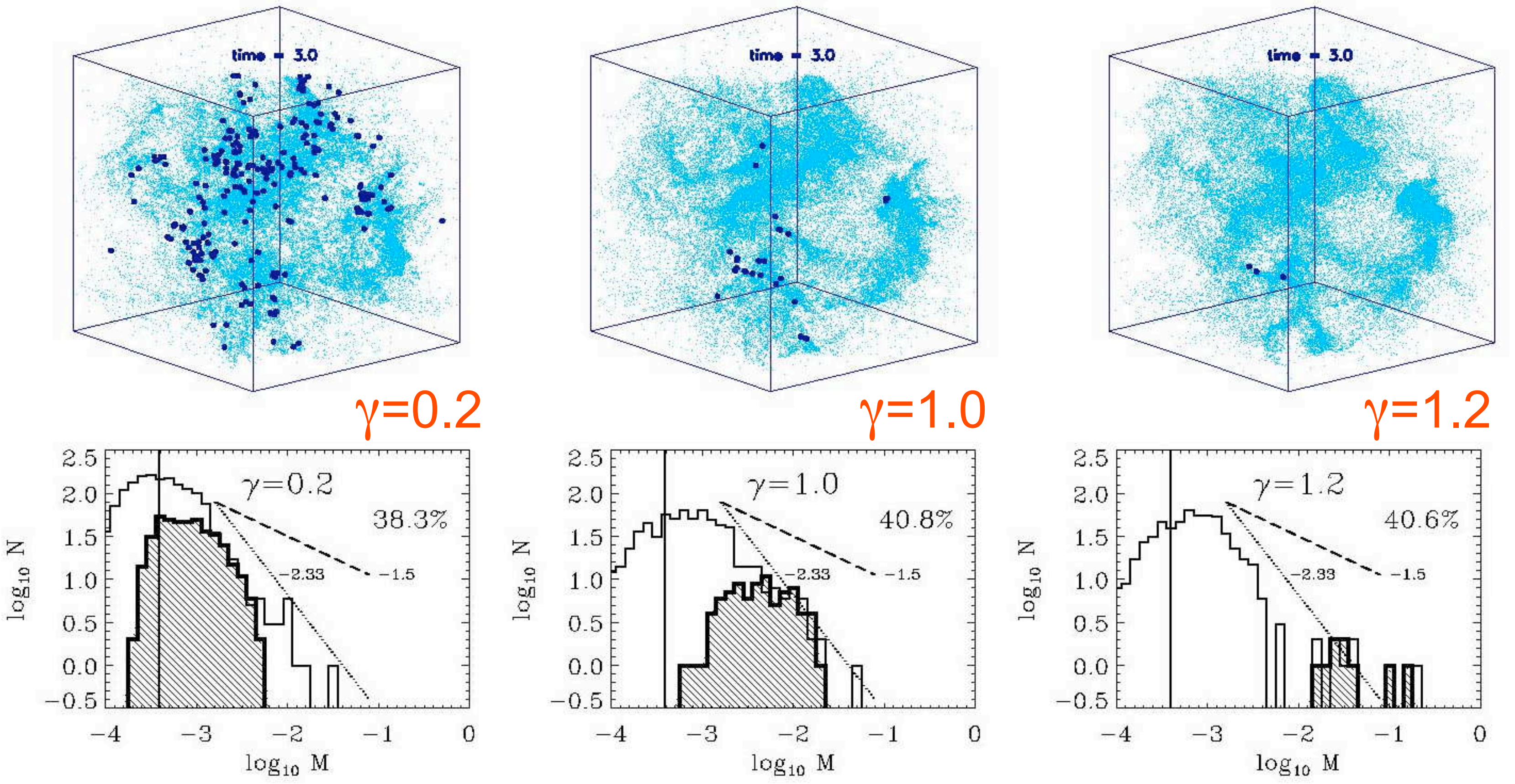
dependency on EOS

- 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*

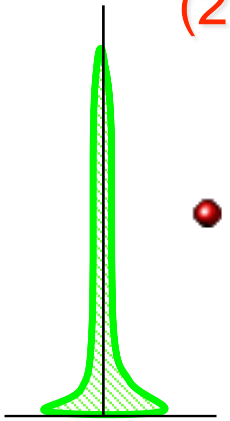
for γ>1 it is suppressed → formation of *isolated massive stars*

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

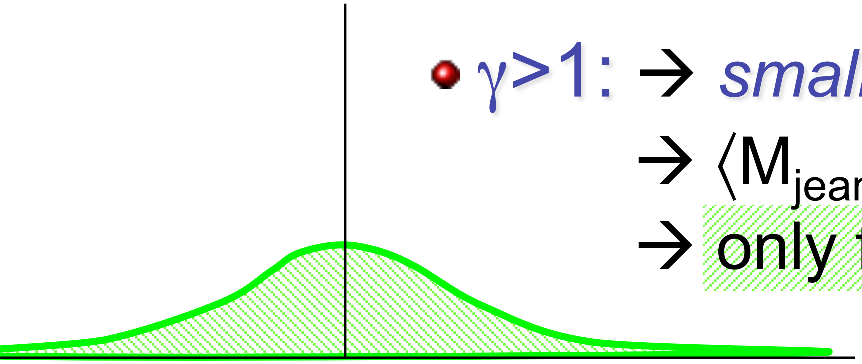
how does that work?

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

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



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

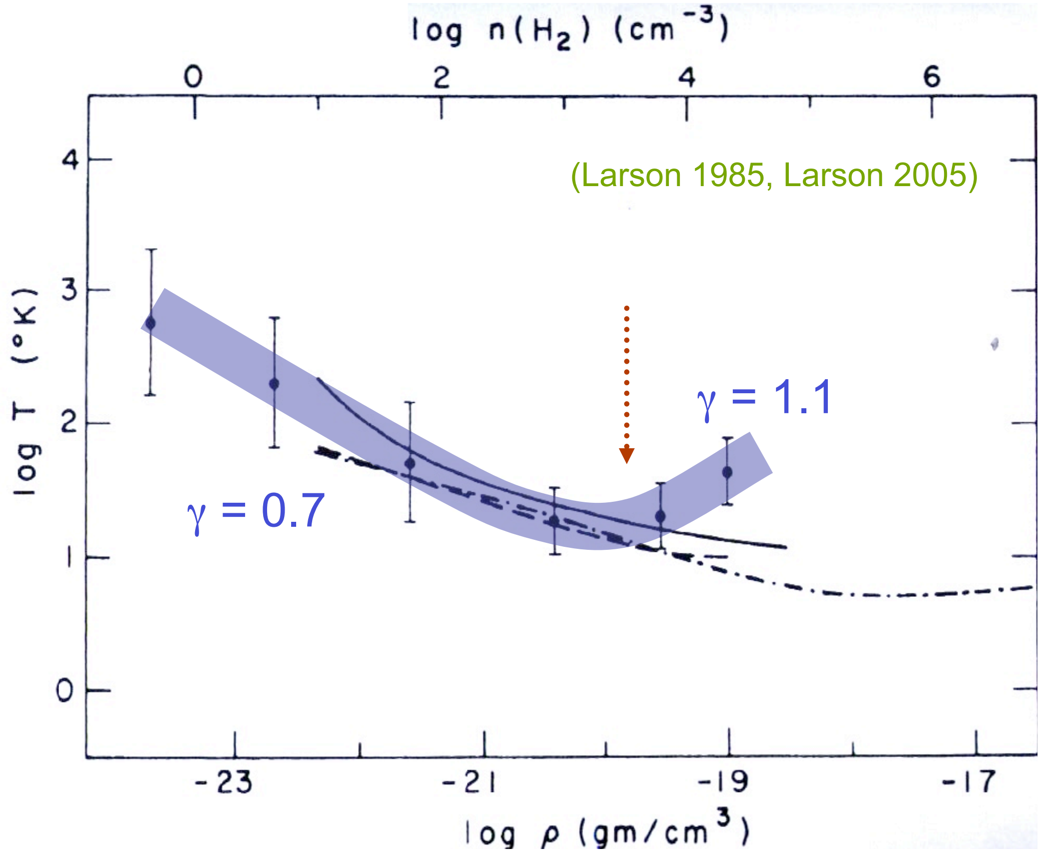


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans}\rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⇨ T ⬆



(Larson 1985, Larson 2005)

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

$$P \propto \rho T$$

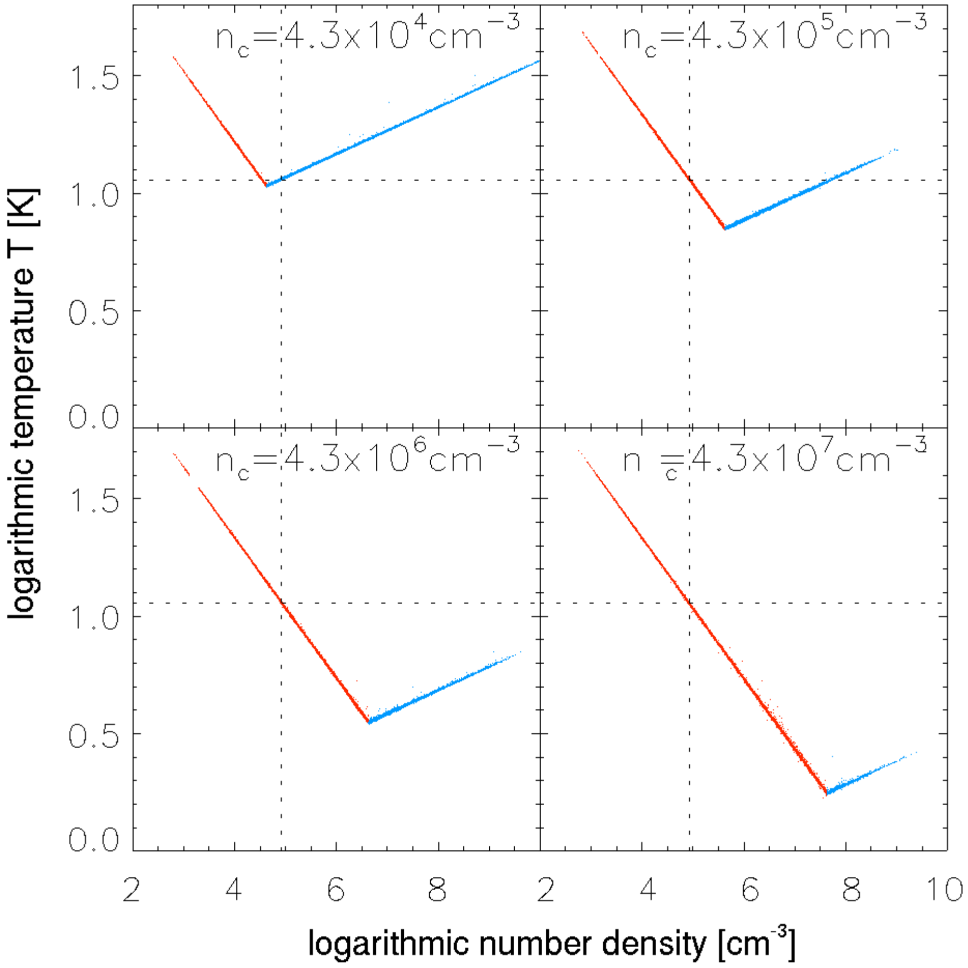
$$\rightarrow \gamma = 1 + d\ln T / d\ln\rho$$

IMF from simple piece-wise polytropic EOS

γ_1 = 0.7

γ_2 = 1.1

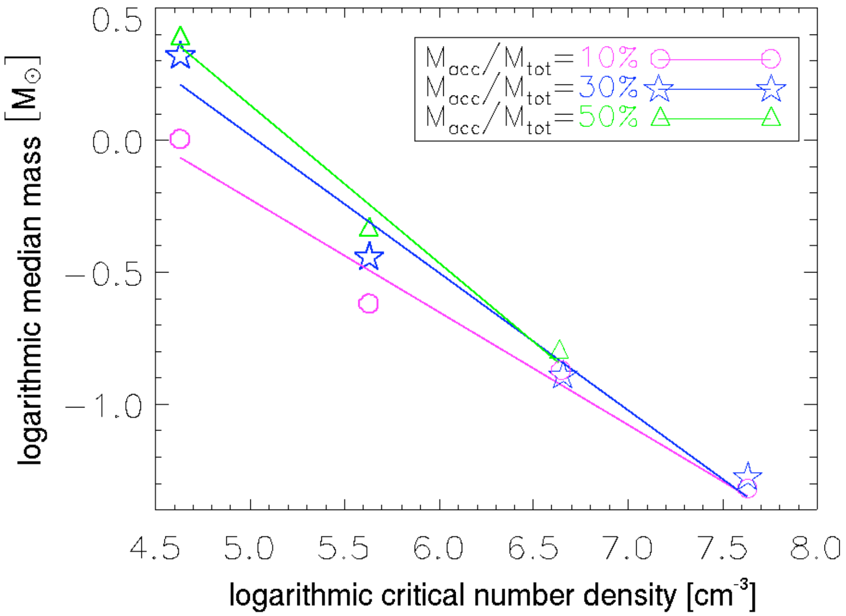
$\boxed{T \sim \rho^{\gamma-1}}$

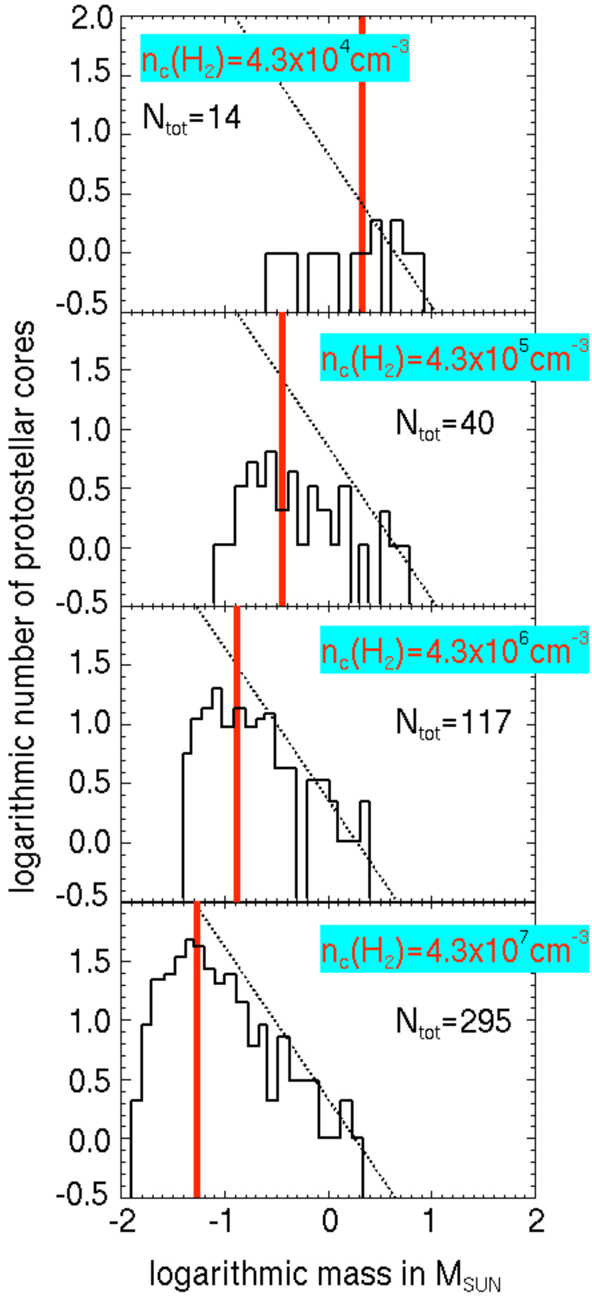


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

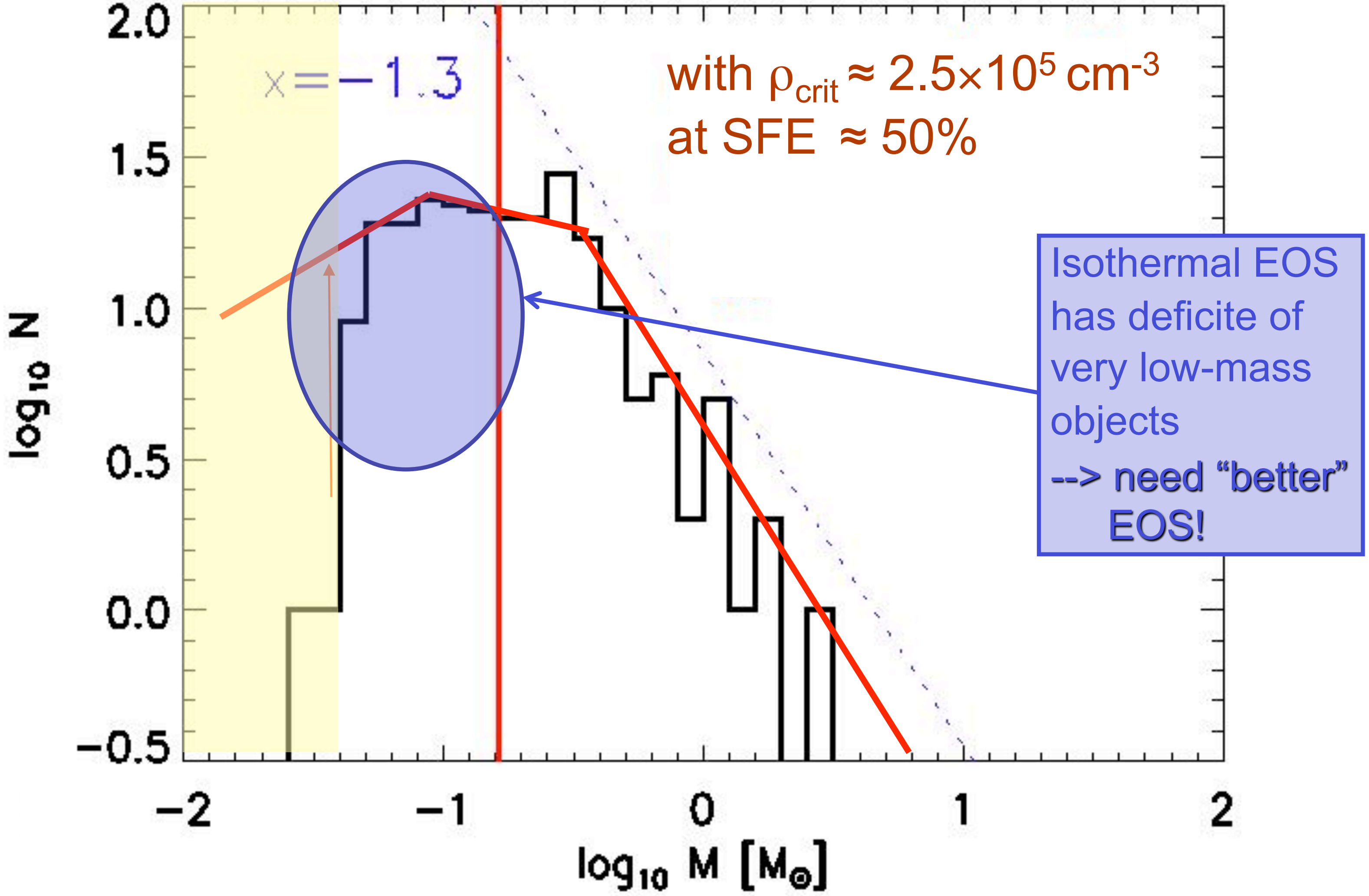
critical density ⬆ ⇨ median mass ⬇





(Jappsen et al. 2005)

IMF in nearby molecular clouds



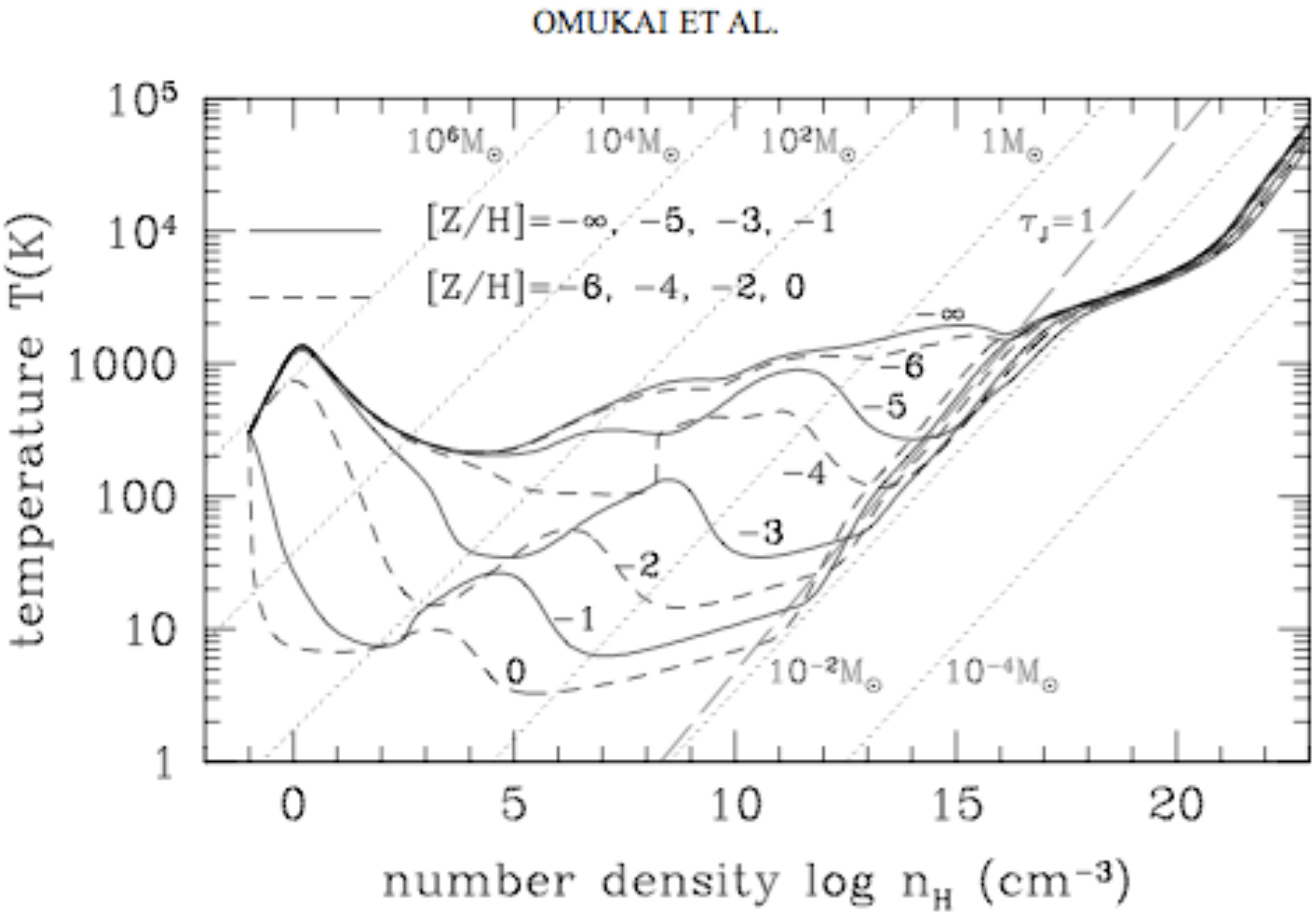
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}
at SFE ≈ 50%

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

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

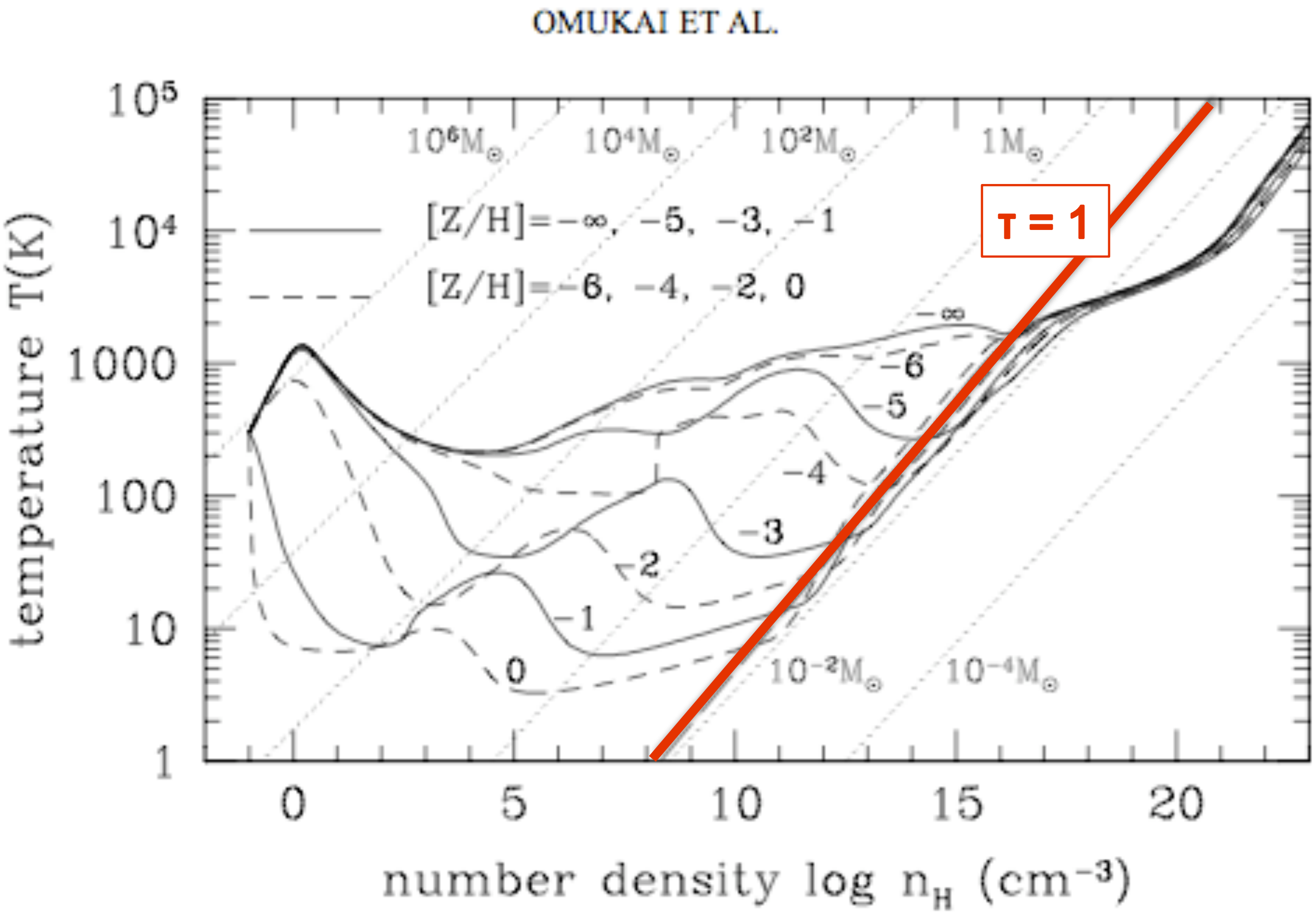
metallicity dependence

EOS as function of metallicity



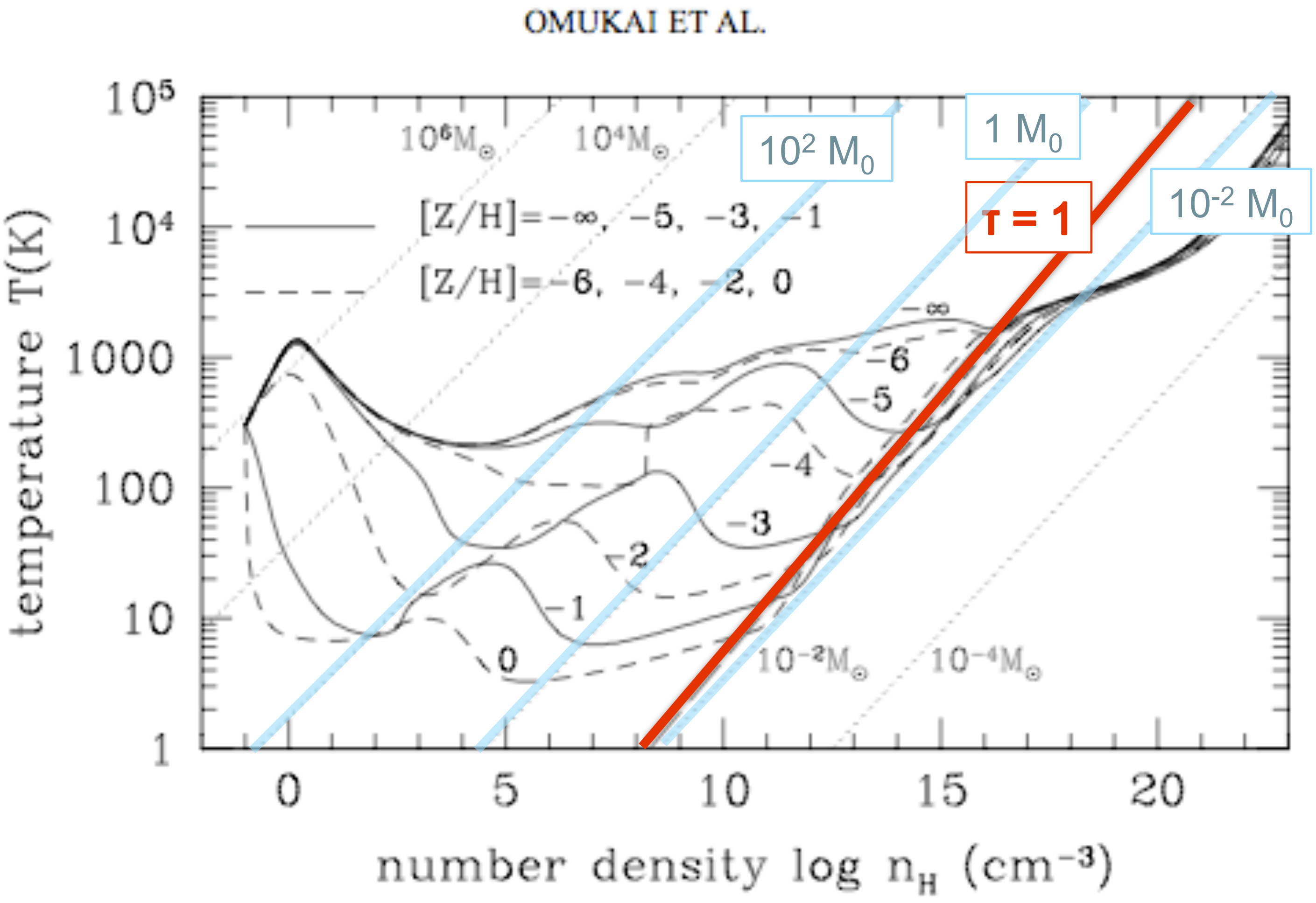
(Omukai et al. 2005)

EOS as function of metallicity



(Omukai et al. 2005)

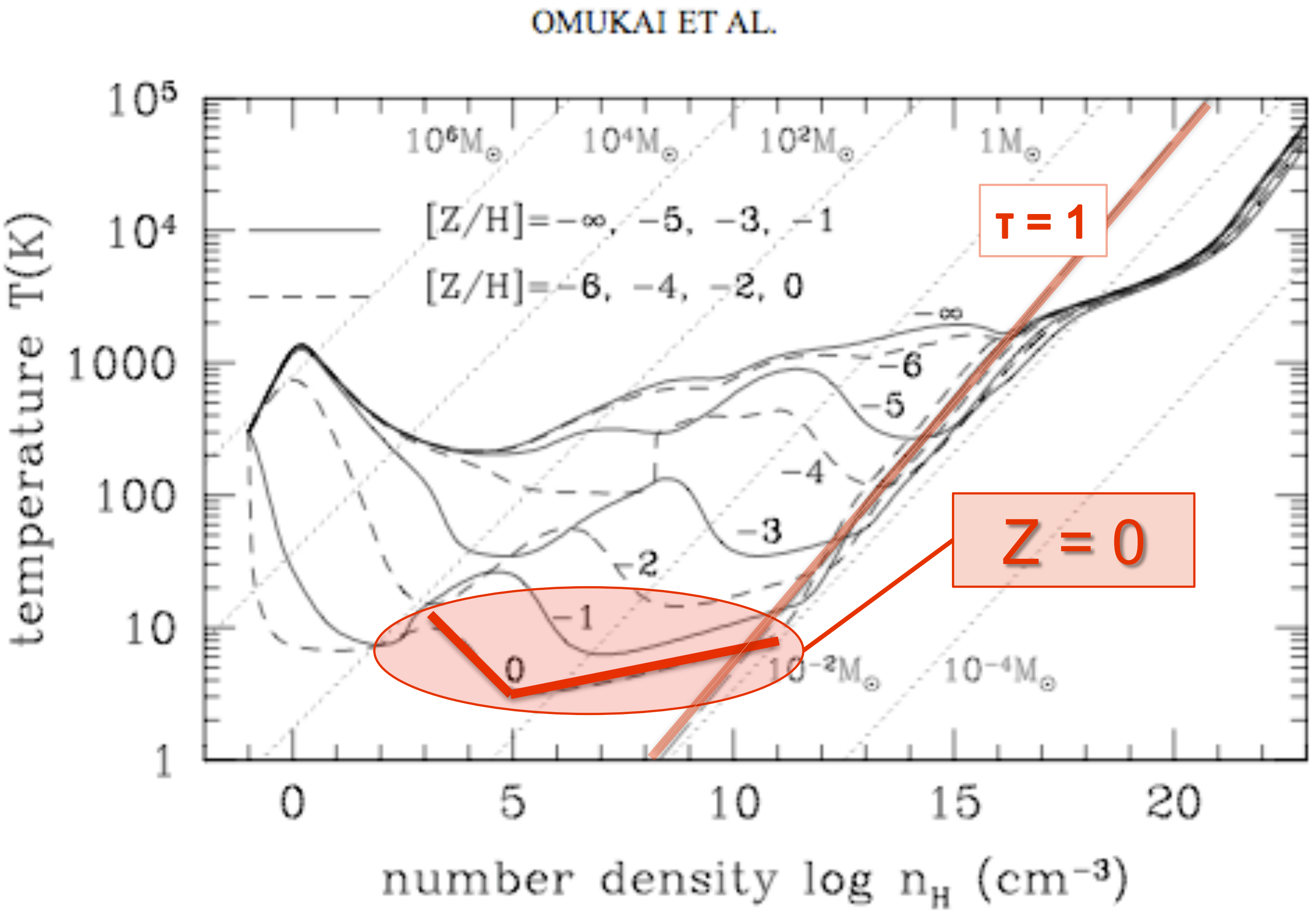
EOS as function of metallicity



(Omukai et al. 2005)

Ralf Klessen: JAC 25.09.2008

present-day star formation

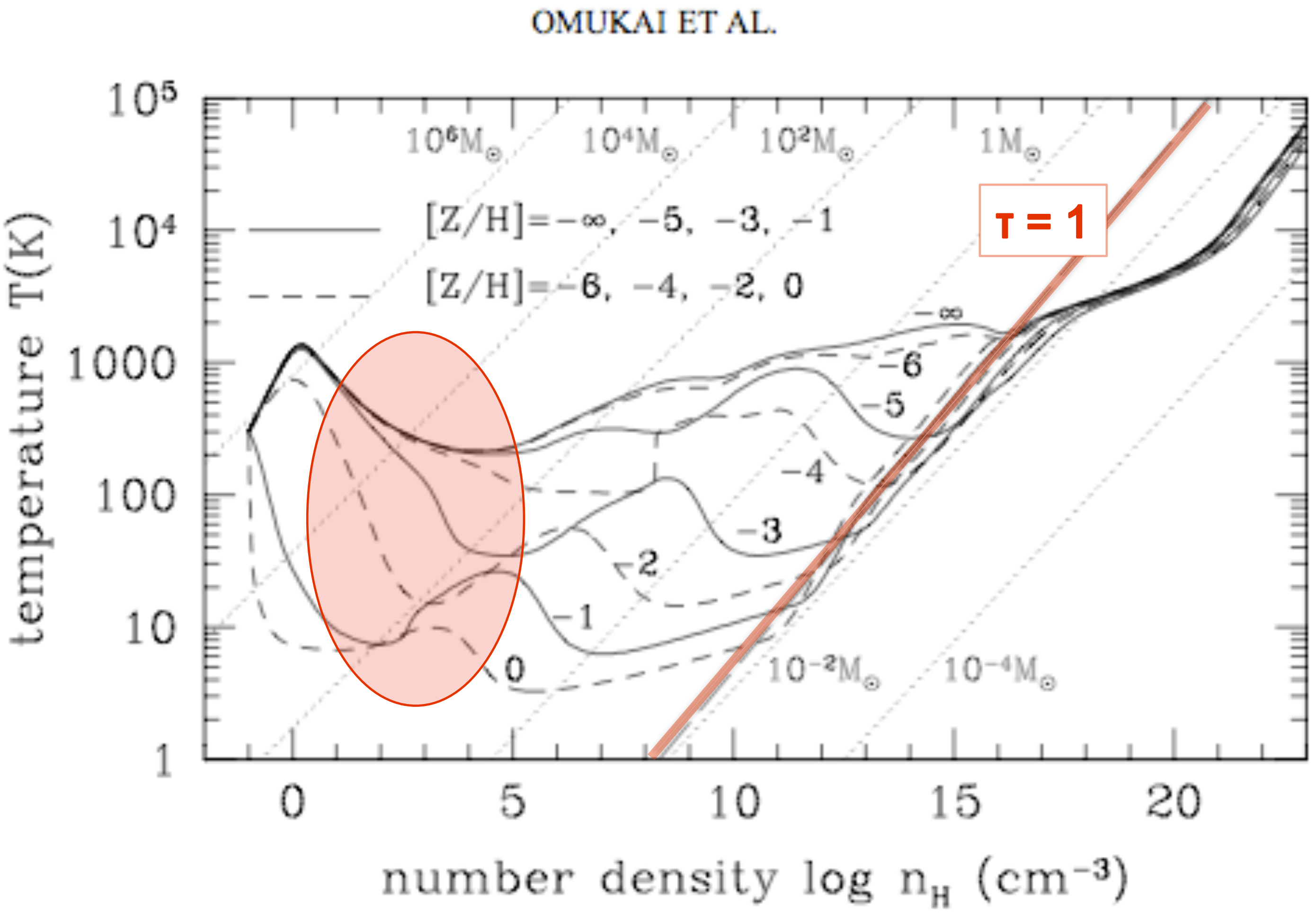


(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation

- *fragmentation behavio*r 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

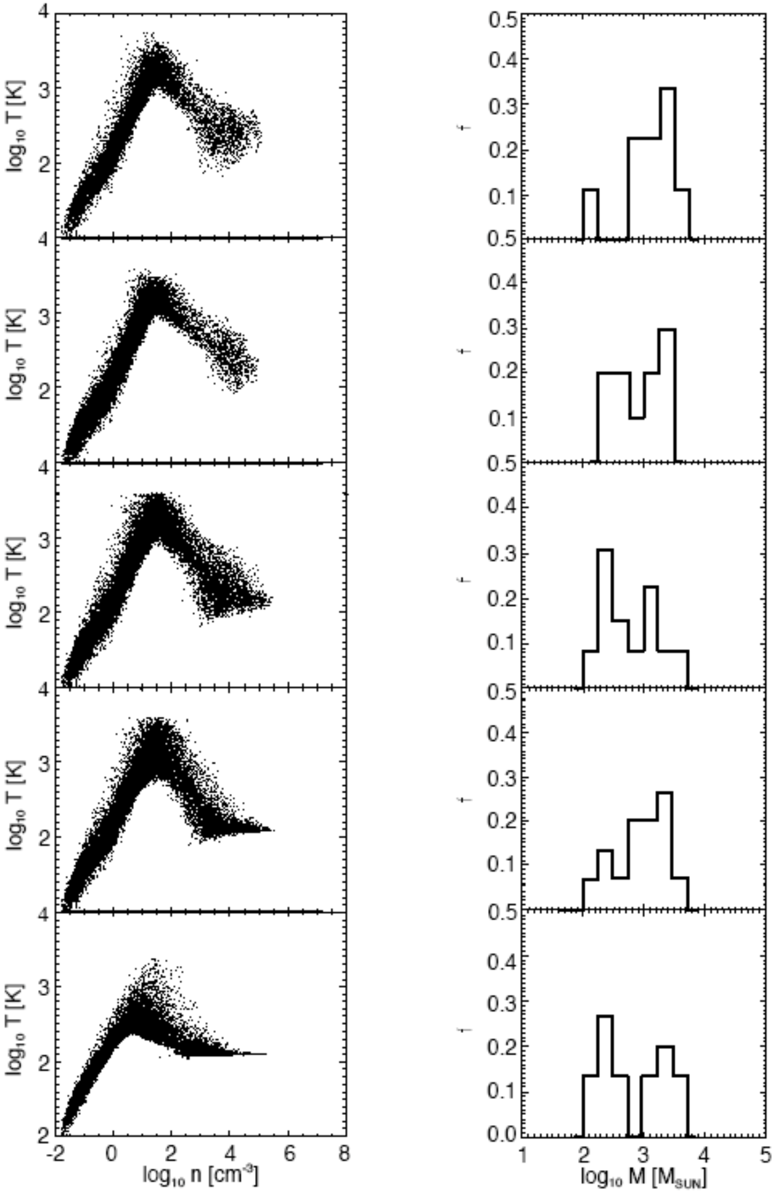


(Omukai et al. 2005)

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)

caveats

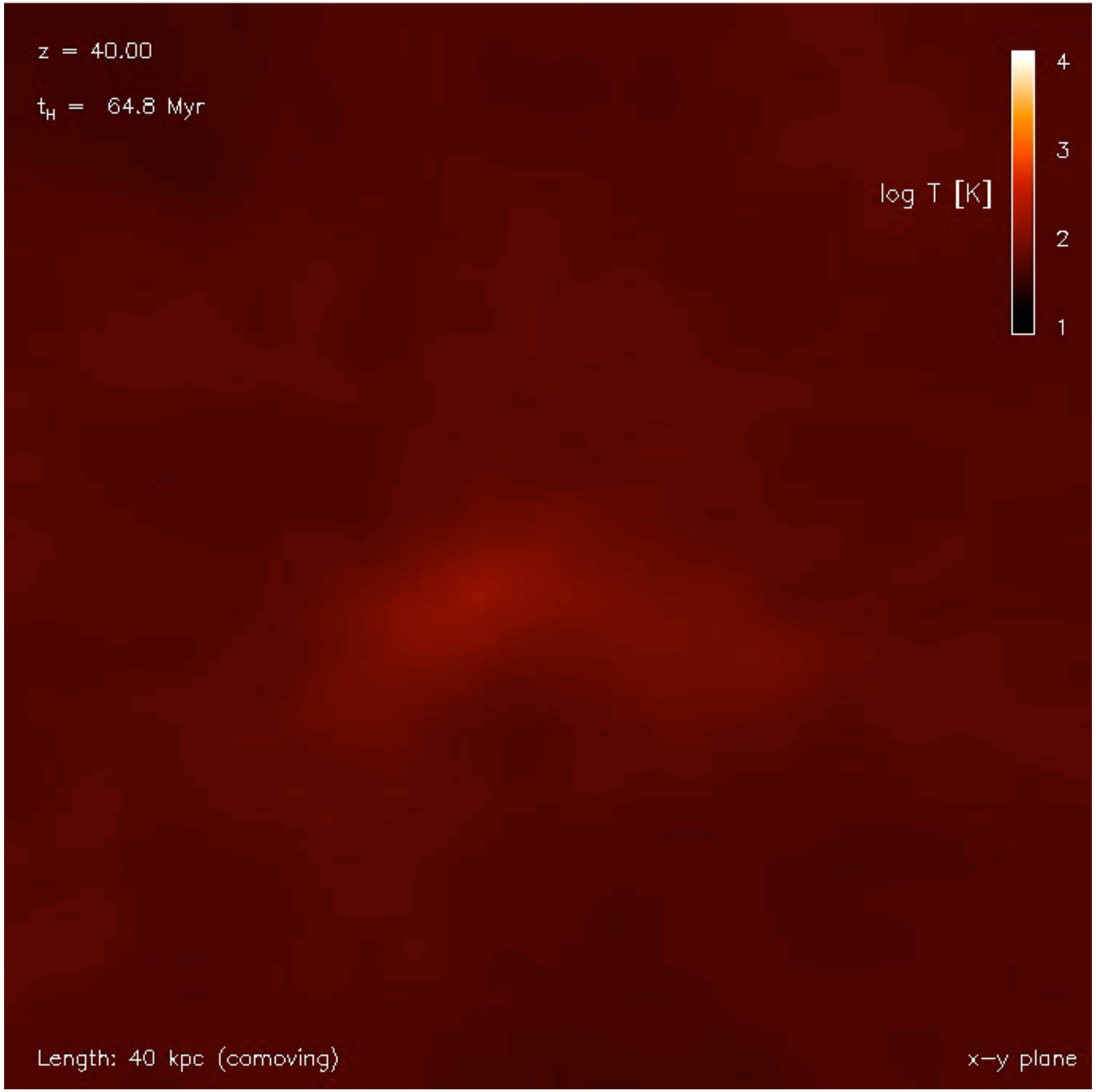
- mass spectrum depends on *scale of turbulence*
  → consistent IMF only for *large-scale turbulence* (Klessen 2001, ApJ, 556, 837)
  → dynamical effects are important
  (Bonnell et al., Clark et al.)

- result depends on *mechanism of turbulent driving*
  → *solenoidal* vs. *compressive driving*
  (Federrath, Klessen, Schmidt in prep.)

implications for Pop III

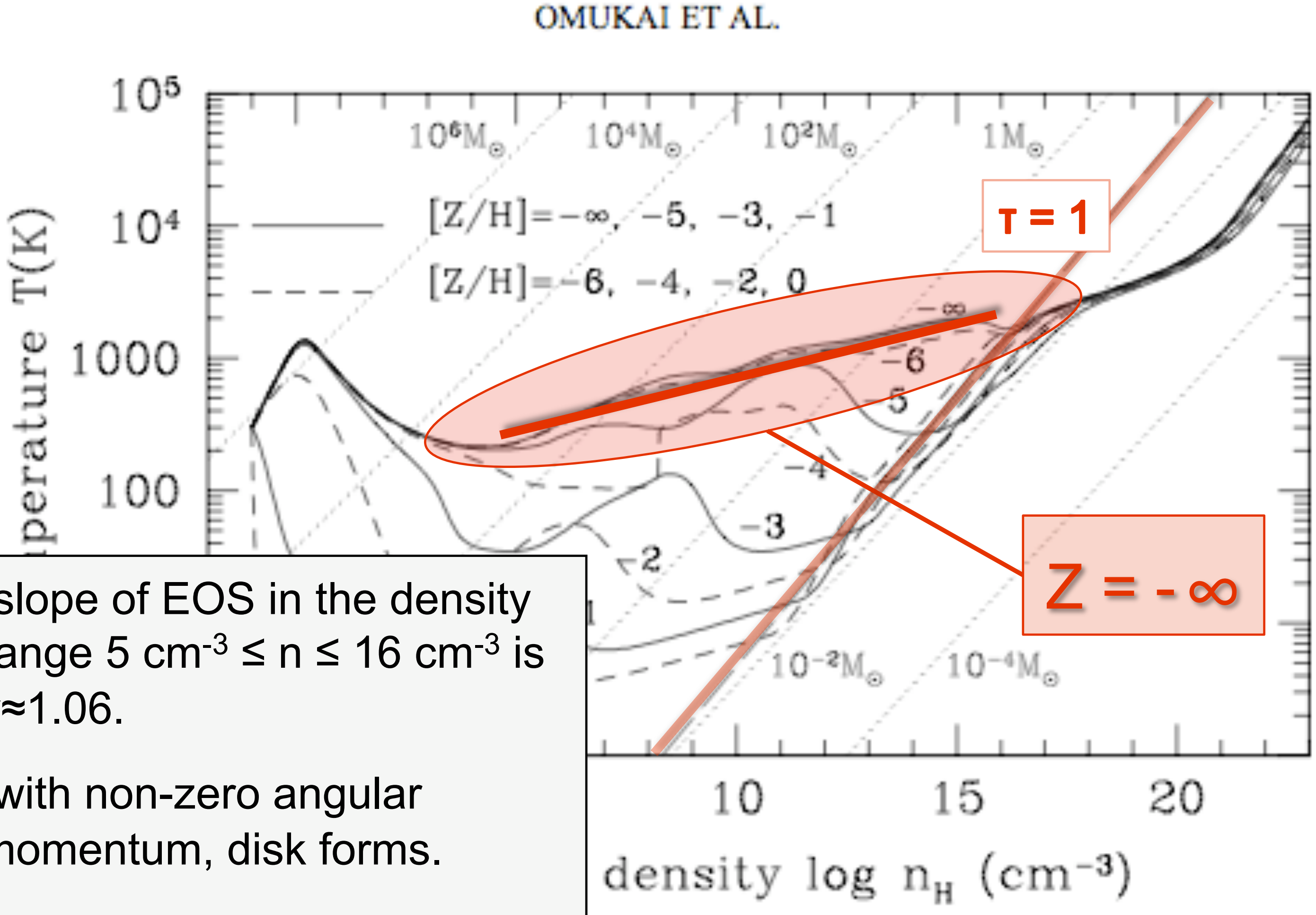
- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*?
- speculation:
  - low-mass halos → low level of turbulence → relatively massive stars
  - high-mass halos (atomic cooling halos) → high degree of turbulence → wider mass spectrum with peak at lower-masses?

turbulence developing in an atomic cooling halo



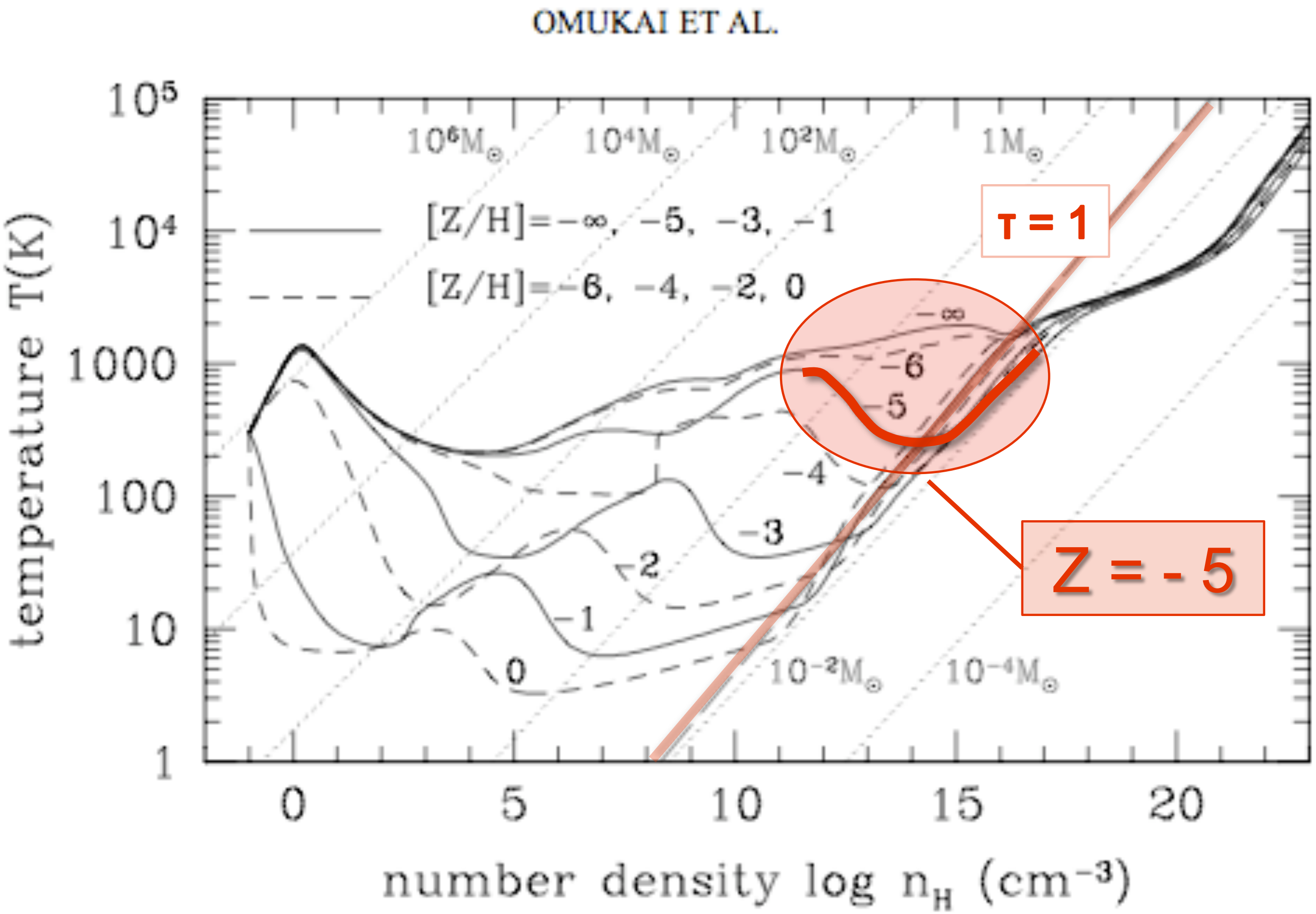
(Greif et al. 2008)

metal-free star formation



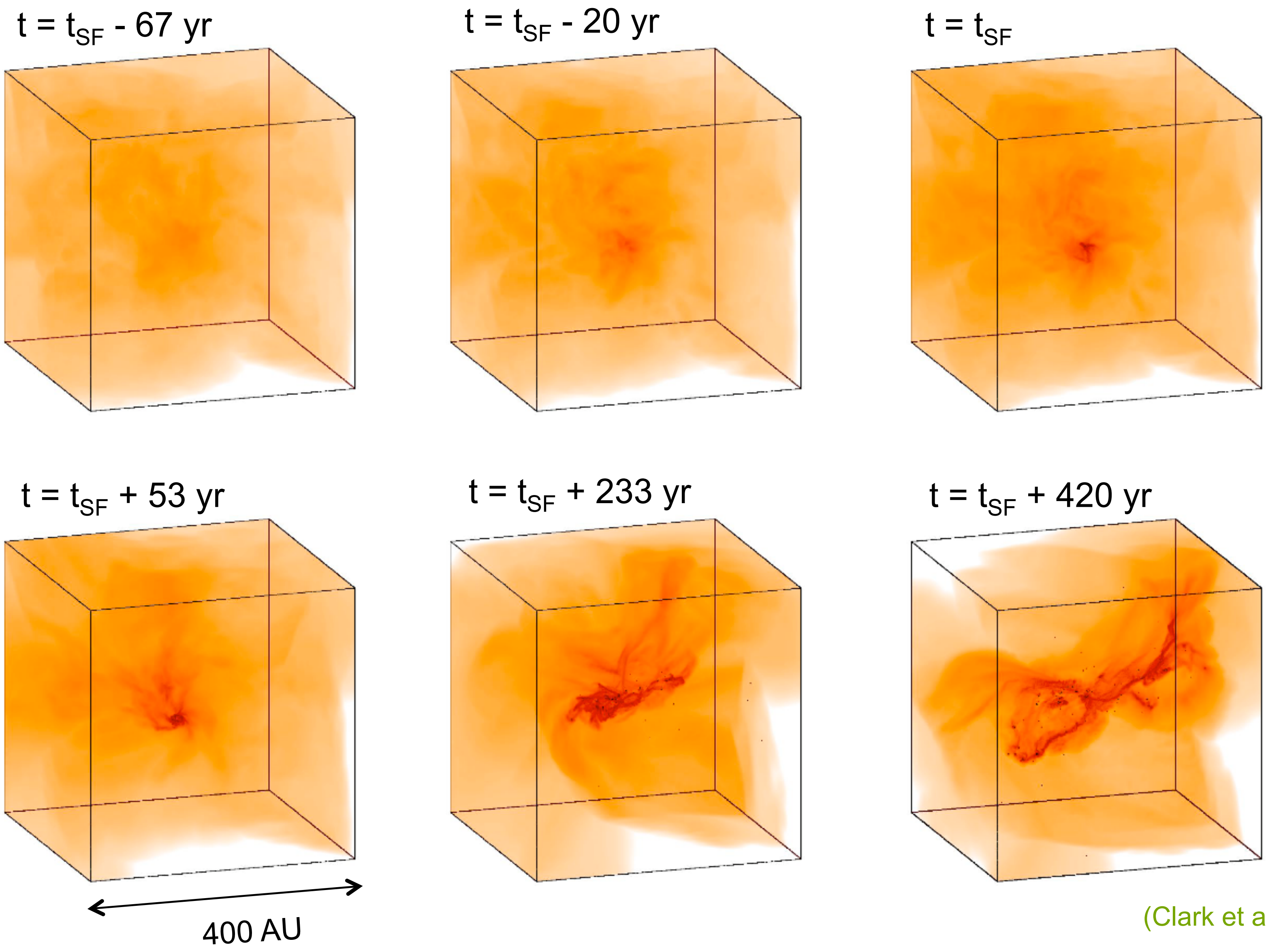
- slope of EOS in the density range 5 $cm^{-3} \leq n \leq 16$ cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

transition: Pop III to Pop II.5



(Omukai et al. 2005)

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



$t = t_{SF}$ - 67 yr

$t = t_{SF}$ - 20 yr

$t = t_{SF}$

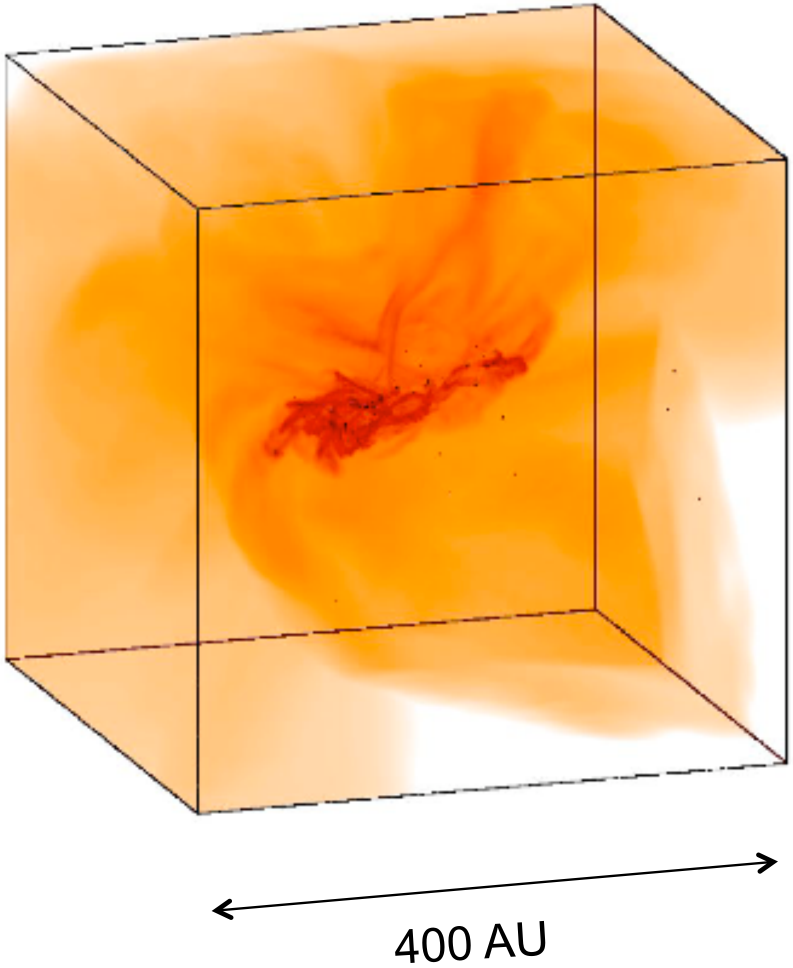
$t = t_{SF}$ + 53 yr

$t = t_{SF}$ + 233 yr

$t = t_{SF}$ + 420 yr

(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)

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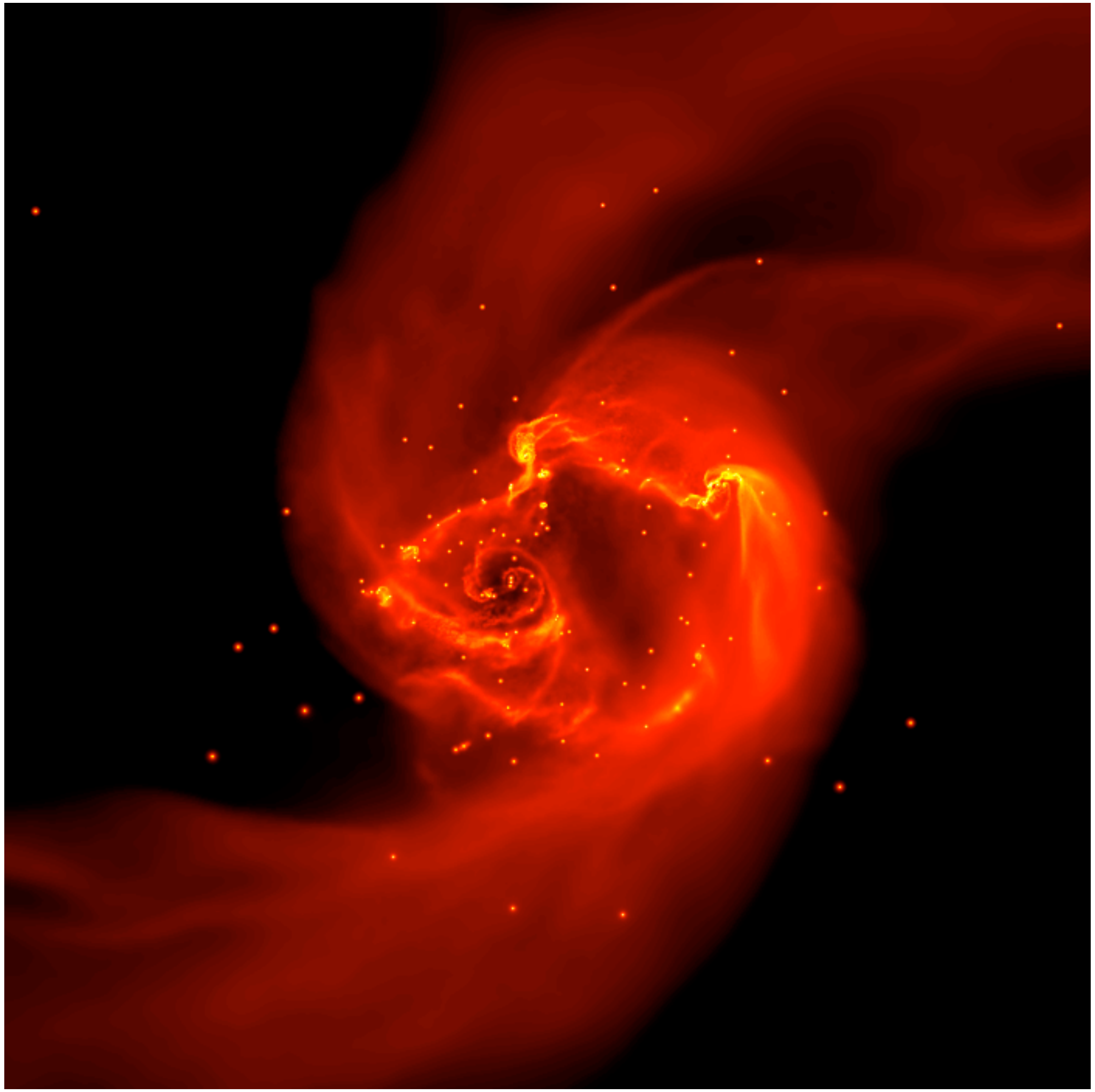

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- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008, ApJ 672, 757)

cluster build-up

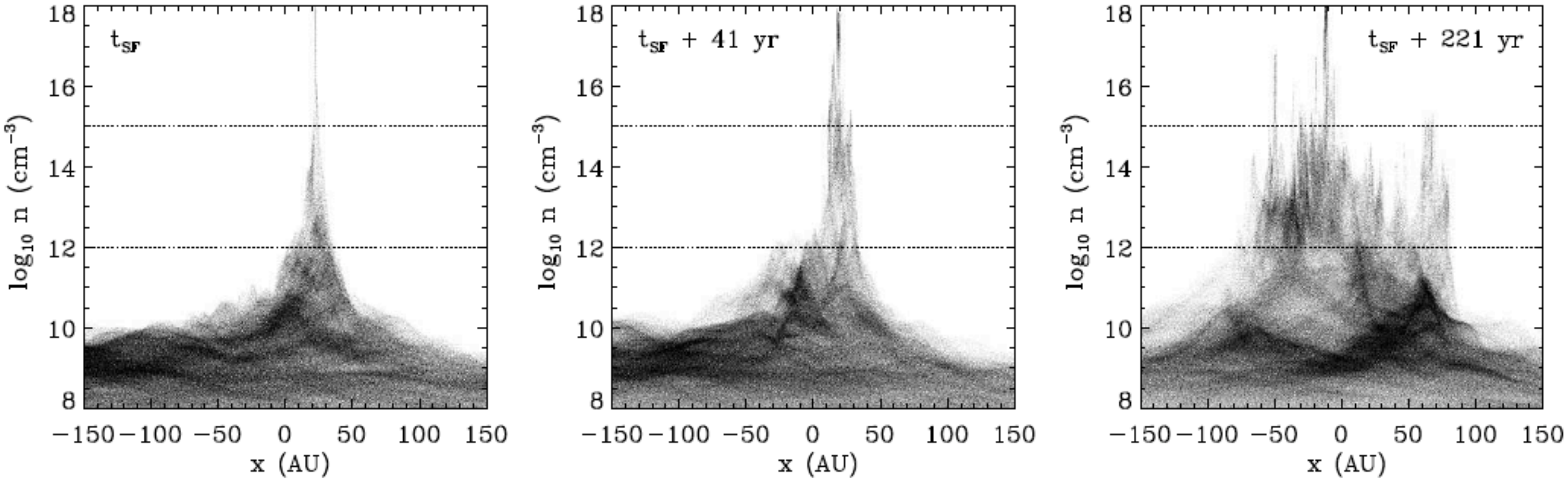
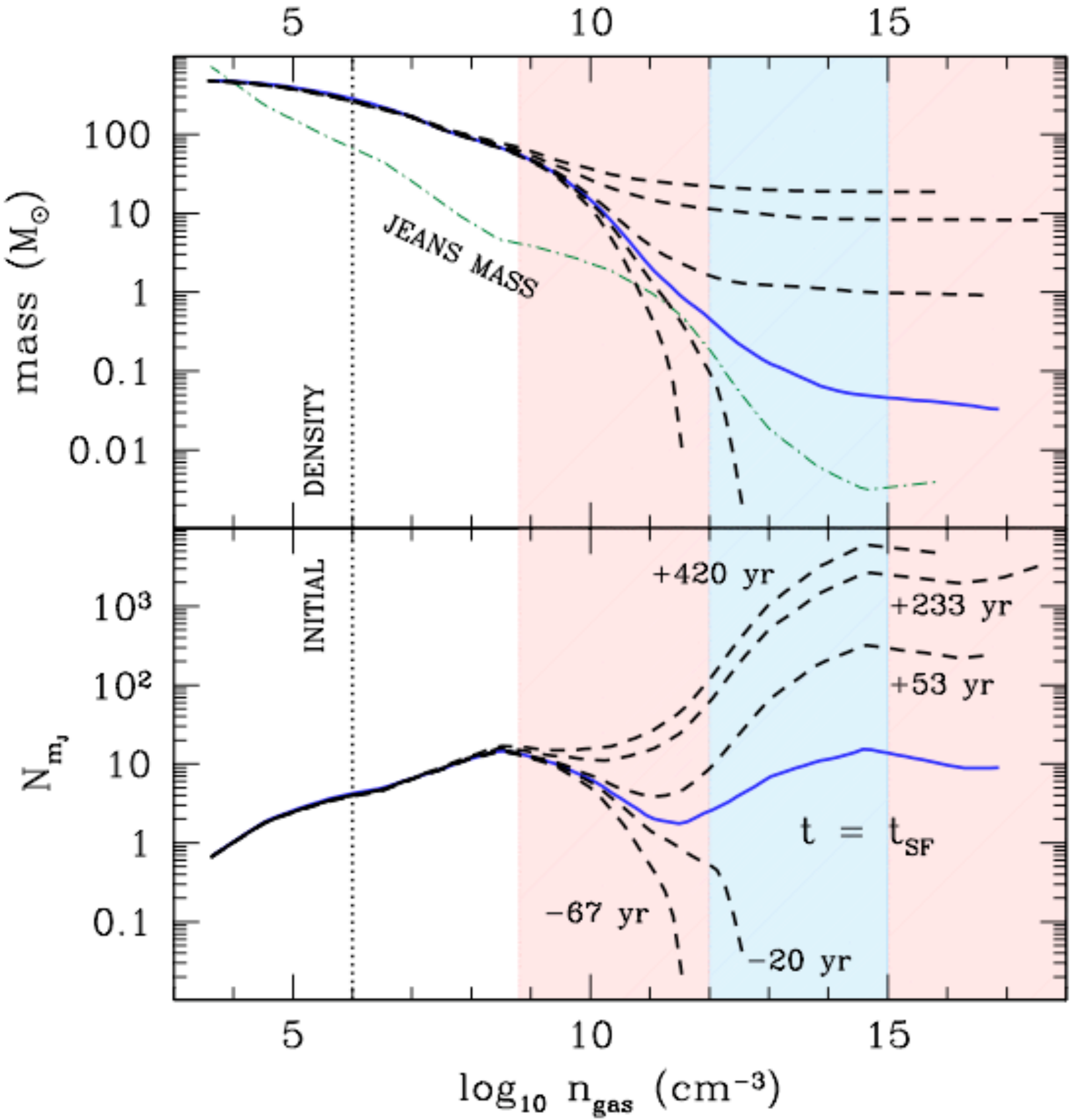


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_\odot$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We 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



🟥

γ > 1
(heating)

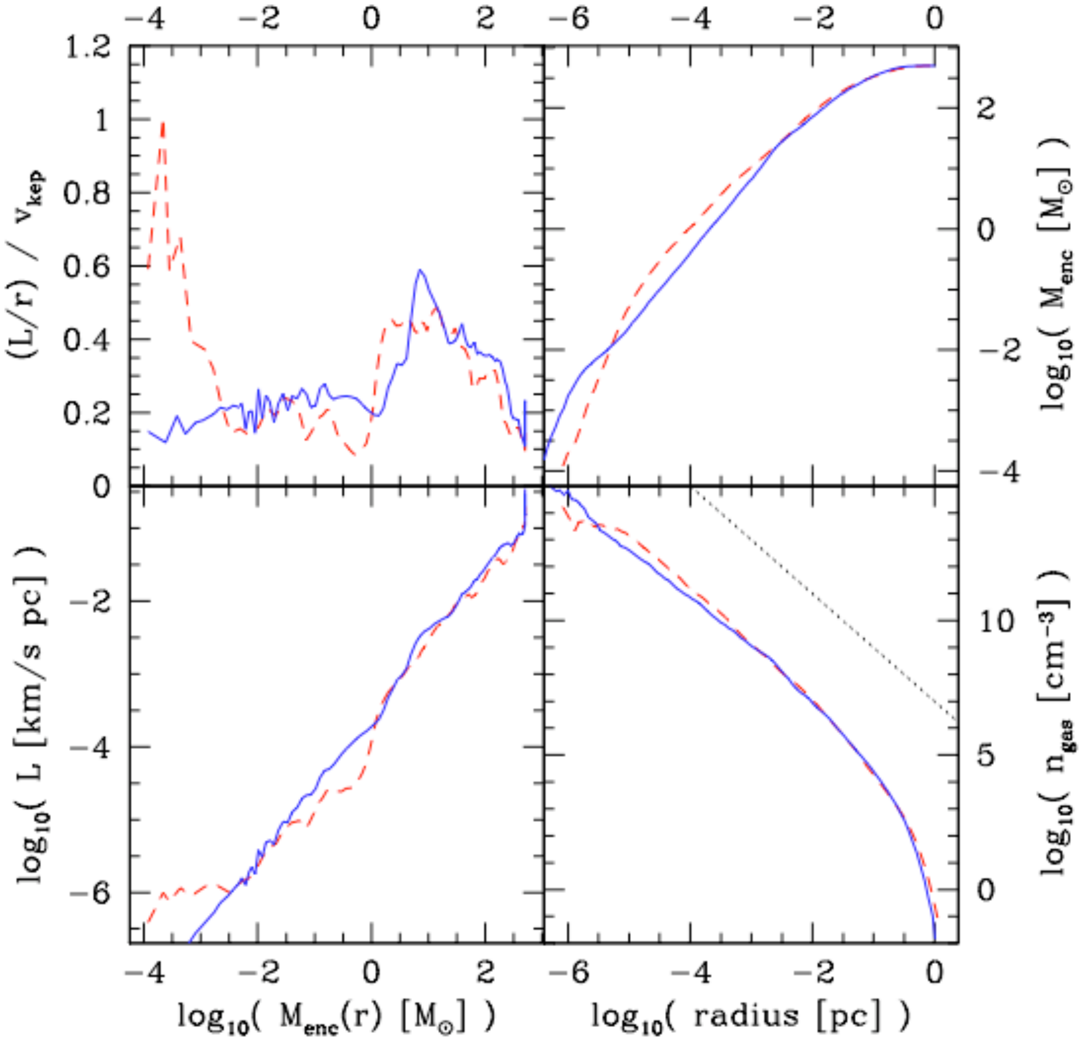
🟦

γ < 1
(cooling)

(Clark et al. 20

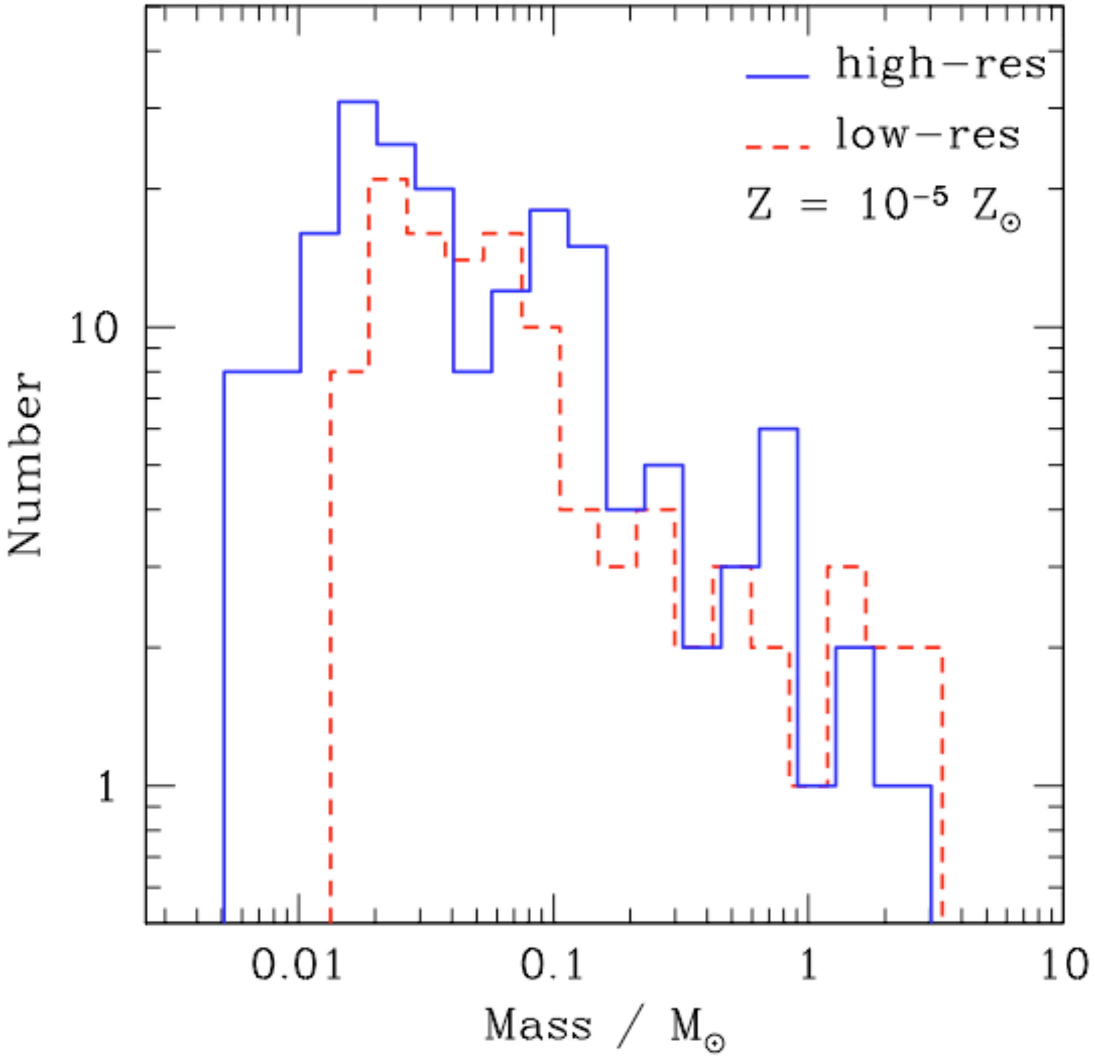
gas properties

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)

comparison for different Z

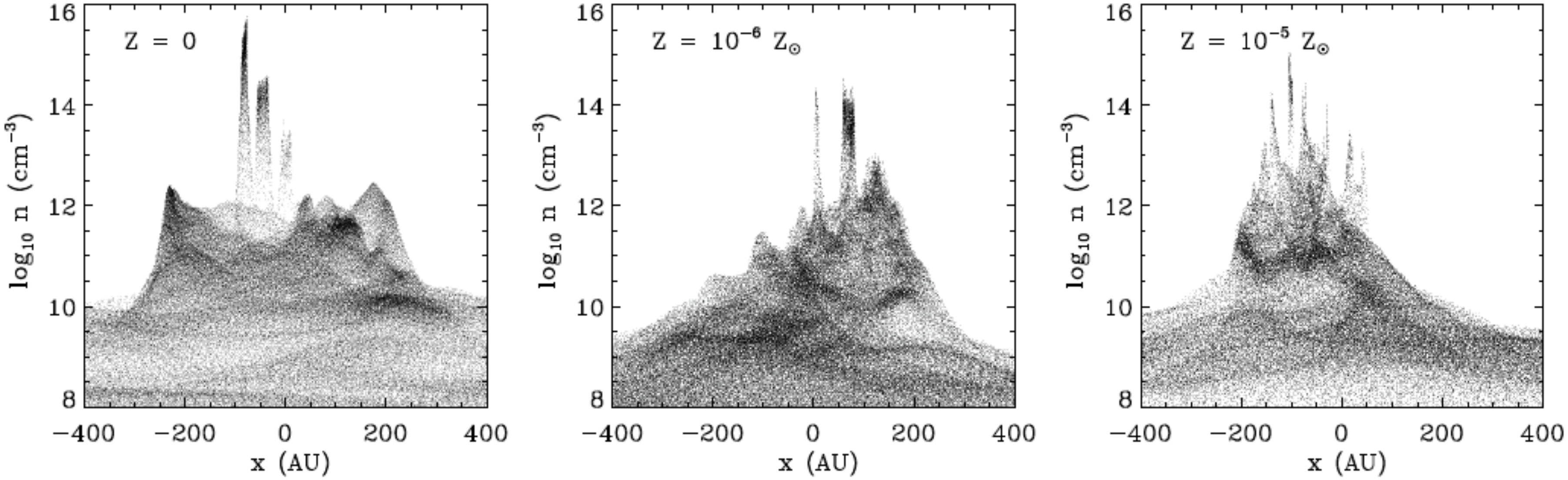


FIG. 6.— Particle densities as a function of position in the low-resolution simulations, for the primordial (left), $Z = 10^{-6}\, Z_\odot$ (middle) and $Z = 10^{-5}\, Z_\odot$ simulations (right). The particles are plotted once the protostars in each simulation have accreted 19 $M_\odot$ of gas.

even zero-metallicity case fragments
(although much more weakly)

(Clark et al. 2007)

comparison for different Z

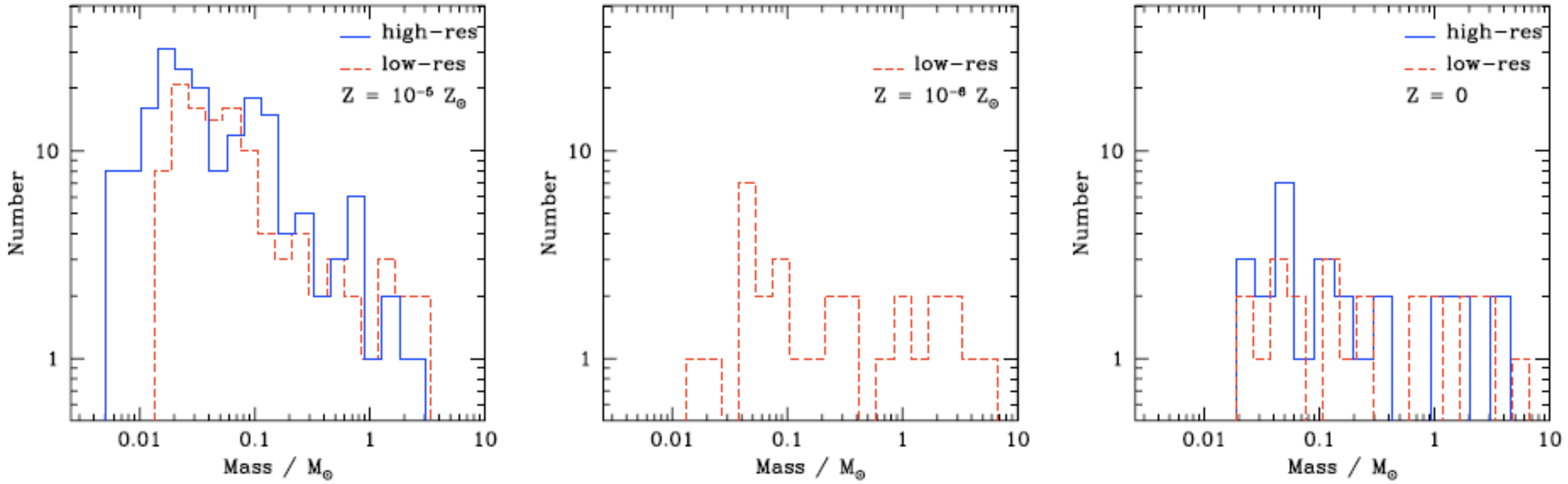


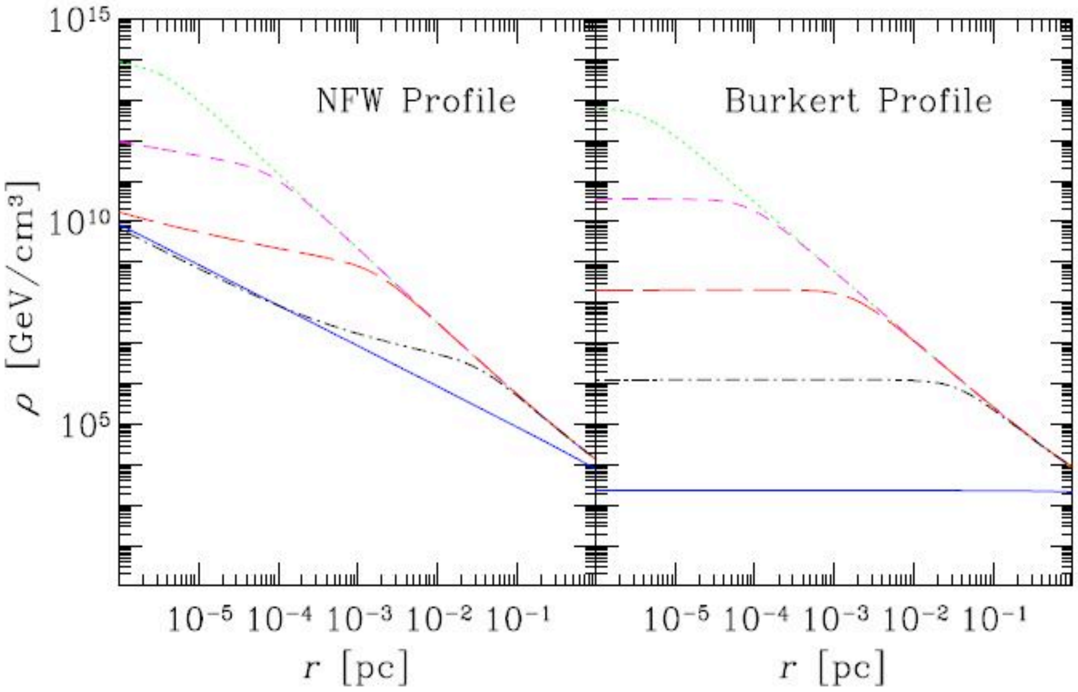
FIG. 4.— Mass functions resulting from simulations with metallicities $Z = 10^{-5}\ Z_\odot$ (left-hand panel), $Z = 10^{-6}\ Z_\odot$ (center panel), and $Z = 0$ (right-hand panel). The plots refer to the point in each simulation at which 19 $M_\odot$ of material has been accreted (which occurs at a slightly different time in each simulation). The mass resolutions are 0.002 $M_\odot$ and 0.025 $M_\odot$ for the high and low resolution simulations, respectively. Note the similarity between the results of the low-resolution and high-resolution simulations. The onset of dust-cooling in the $Z = 10^{-5}\ Z_\odot$ cloud results in a stellar cluster which has a mass function similar to that for present day stars, in that the majority of the mass resides in the lower-mass objects. This contrasts with the $Z = 10^{-6}\ Z_\odot$ and primordial clouds, in which the bulk of the cluster mass is in high-mass stars.

even zero-metallicity case fragments
(although much more weakly)

(Clark et al. 2007)

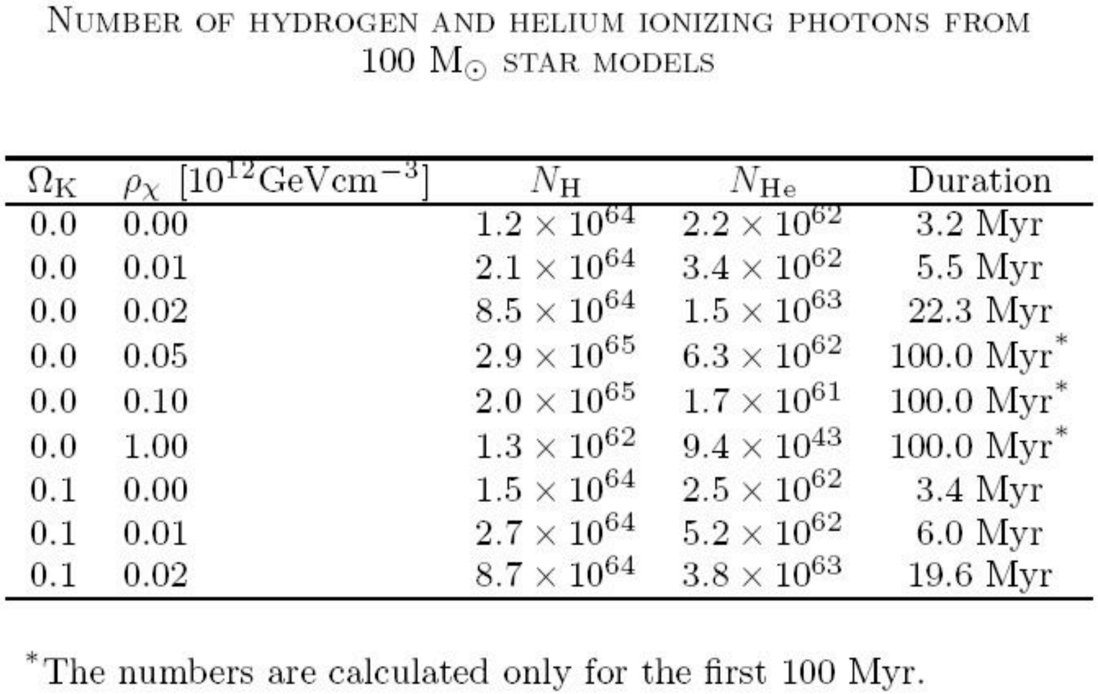
dark stars

- New phase of stellar evolution driven by dark matter annihilation (Spolyar et al. 2008)



dark stars

- Models suggest masses of order 800 M_solar
  (Freese et al. 2008)
- Very long-lived main-sequences phases
  (Iocco et al. 2008, Yoon et al. 2008, Taoso et al. 2008)



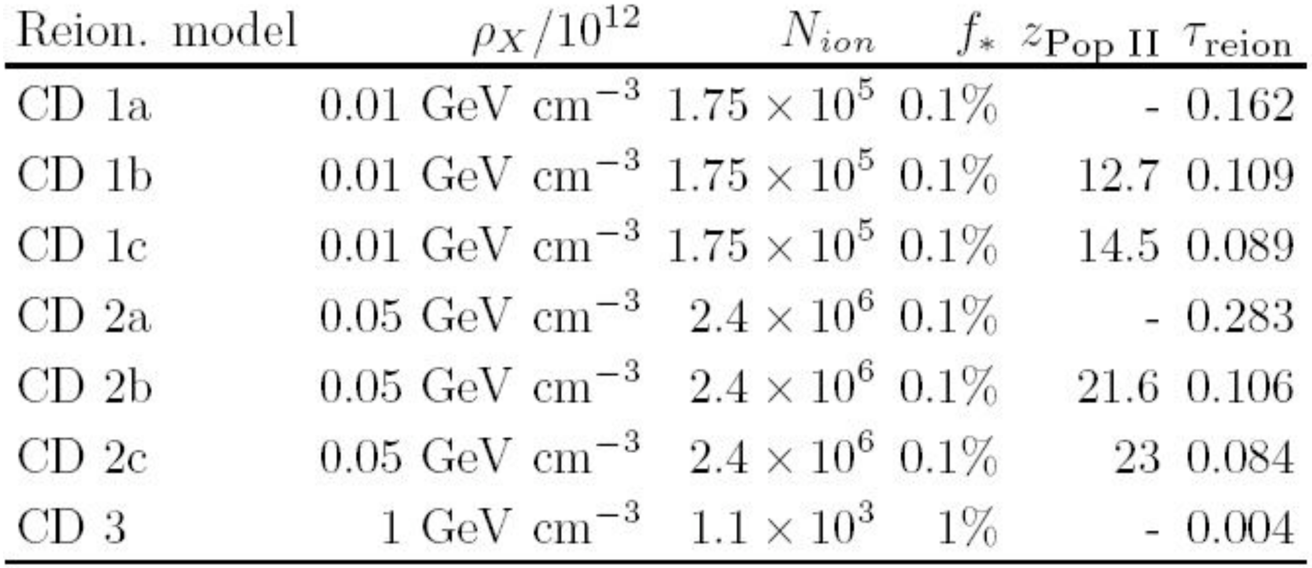
NUMBER OF HYDROGEN AND HELIUM IONIZING PHOTONS FROM
100 $M_\odot$ STAR MODELS

Ω_K	ρ_χ $[10^{12} \mathrm{GeV cm}^{-3}]$	N_H	N_{He}	Duration
0.0	0.00	1.2×10^{64}	2.2×10^{62}	3.2 Myr
0.0	0.01	2.1×10^{64}	3.4×10^{62}	5.5 Myr
0.0	0.02	8.5×10^{64}	1.5×10^{63}	22.3 Myr
0.0	0.05	2.9×10^{65}	6.3×10^{62}	100.0 Myr*
0.0	0.10	2.0×10^{65}	1.7×10^{61}	100.0 Myr*
0.0	1.00	1.3×10^{62}	9.4×10^{43}	100.0 Myr*
0.1	0.00	1.5×10^{64}	2.5×10^{62}	3.4 Myr
0.1	0.01	2.7×10^{64}	5.2×10^{62}	6.0 Myr
0.1	0.02	8.7×10^{64}	3.8×10^{63}	19.6 Myr

*The numbers are calculated only for the first 100 Myr.

dark stars and reionization

- Reionization very early!
- Followed by a neutral phase?
- Marginal agreement with observations if sudden starburst adopted near z=6 (Schleicher, Banerjee, Klessen 2008c)



Reion. model	$\rho_X/10^{12}$	N_{ion}	f_*	$z_{\mathrm{Pop\ II}}$	τ_{reion}
CD 1a	0.01 GeV cm^{-3}	1.75×10^5	0.1%	-	0.162
CD 1b	0.01 GeV cm^{-3}	1.75×10^5	0.1%	12.7	0.109
CD 1c	0.01 GeV cm^{-3}	1.75×10^5	0.1%	14.5	0.089
CD 2a	0.05 GeV cm^{-3}	2.4×10^6	0.1%	-	0.283
CD 2b	0.05 GeV cm^{-3}	2.4×10^6	0.1%	21.6	0.106
CD 2c	0.05 GeV cm^{-3}	2.4×10^6	0.1%	23	0.084
CD 3	1 GeV cm^{-3}	1.1×10^3	1%	-	0.004

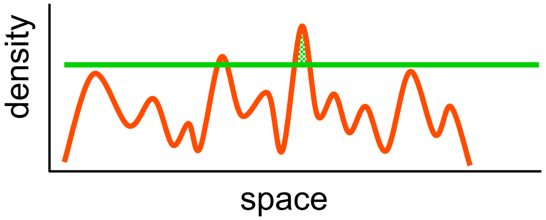
dark star constraints

- Models were more natural if dark stars behaved as Pop. III.
- Dark star masses of 1000 M_solar unlikely.
- Problem alleviated for dark matter masses above 100 Gev (see Iocco et al. 2008).
- Tighter constraints from 21 cm observations and Planck.

(more discussion in Schleicher et al. 2008c)

summary

Summary I



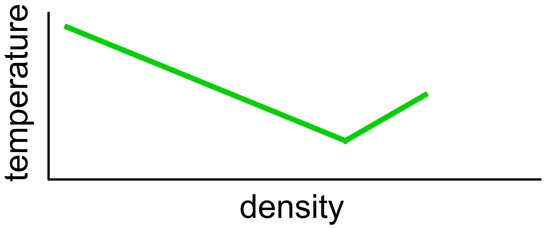
- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation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

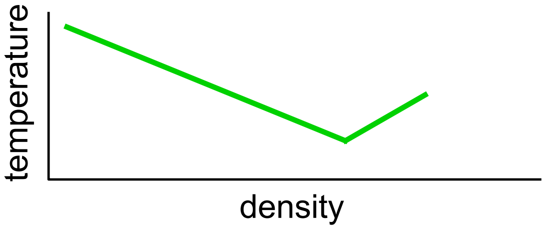


- *dependence* on *metallicity* and *turbulence*
  - different IMF accretion heating may reduce degree of fragmentation
  - ionizing radiation will set efficiency of star formation
- *CAVEATS:*
  - star formation is *multi-scale, multi-physics* problem --> VERY difficult to model
  - in simulations: 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)

Summary II

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



- *dependence* on *metallicity* and *turbulence*
  - different IMF in low-mass halos compare to atomic cooling halos (Pop III.1 / Pop III.2)
  - transition from Pop III to Pop II at $Z \approx 10^{-5}\ Z_{sun}$
  - fragmentation even in truely primordial case (effects of angular momentum)
- more exotic stellar objects: *dark stars*
  - if they exist at all, then only in low-mass halos
  - numbers and properties can be constrained by reionization and 21cm observations

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