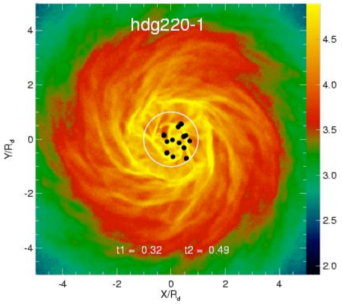
Star formation



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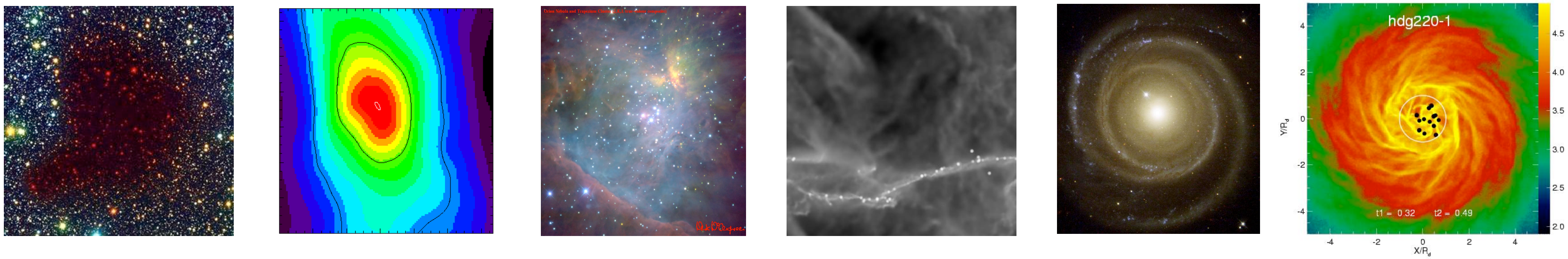
Similarities between primordial and present-day star formation



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thanks to ...

... people in the group in Heidelberg:

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ASTRONET

LANDESSTIFTUNG
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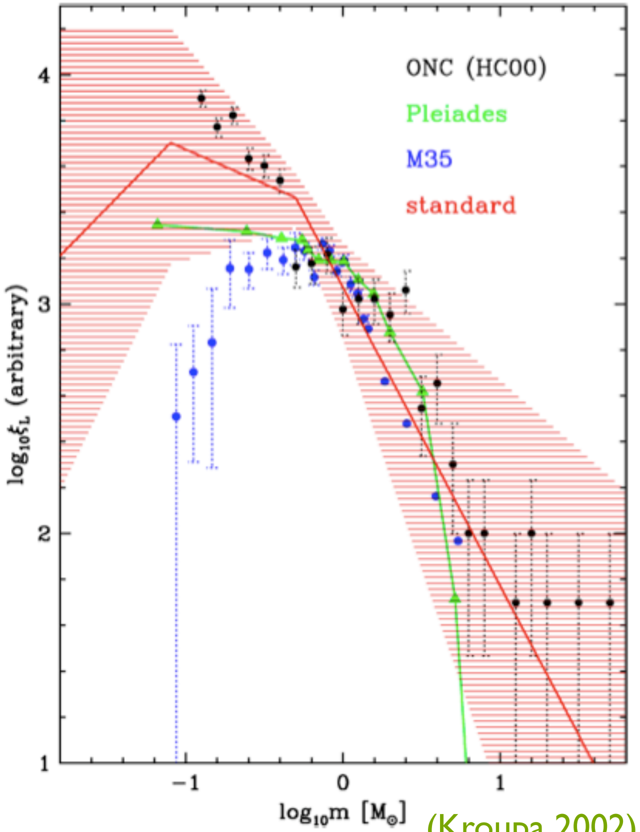
HGSFP

IMPRS

NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

stars seem to follow a universal
mass function at birth --> IMF



(Kroupa 2002)

Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

some history

Early dynamical theory

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

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

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

Sir James Jeans, 1877 - 1946

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

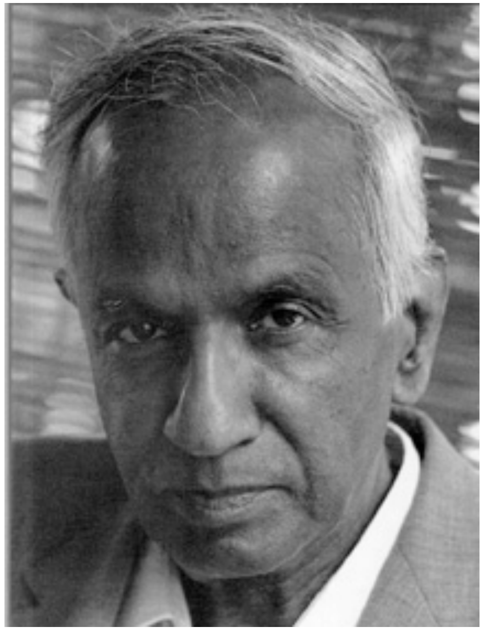
First approach to turbulence

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

    $\ell_{\rm turb} \ll \ell_{\rm dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

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

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



S. Chandrasekhar, 1910 - 1995

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

Problems of early dynamical theory

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

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

Magnetic star formation

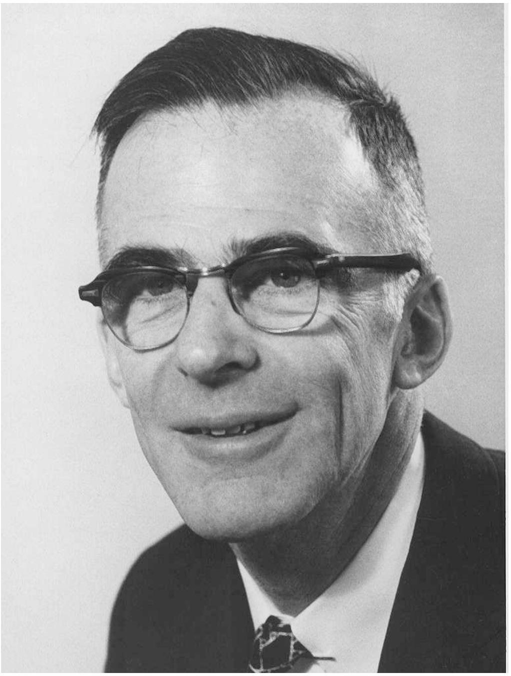
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

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

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

  - Ambipolar diffusion can initiate collapse

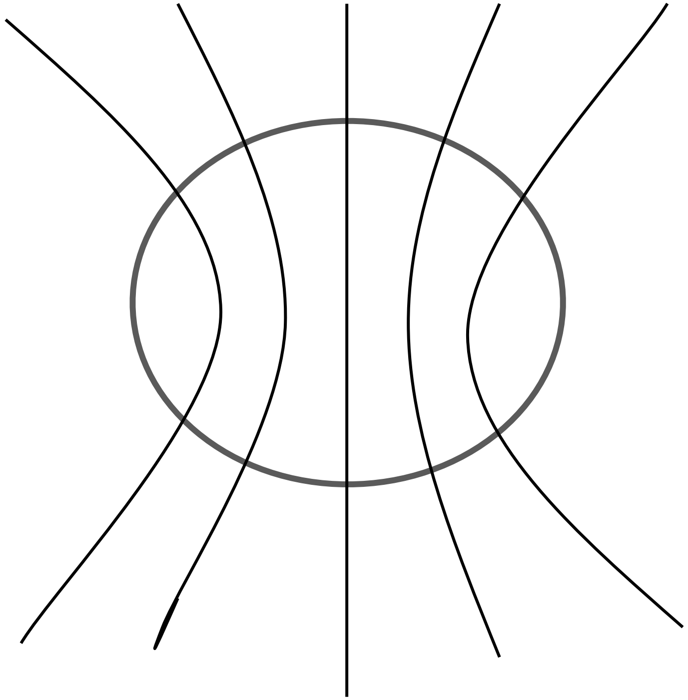


Lyman Spitzer, Jr., 1914 - 1997

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

The "standard theory" of star formation:

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



Problems of magnetic SF

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

Observed B-fields are weak

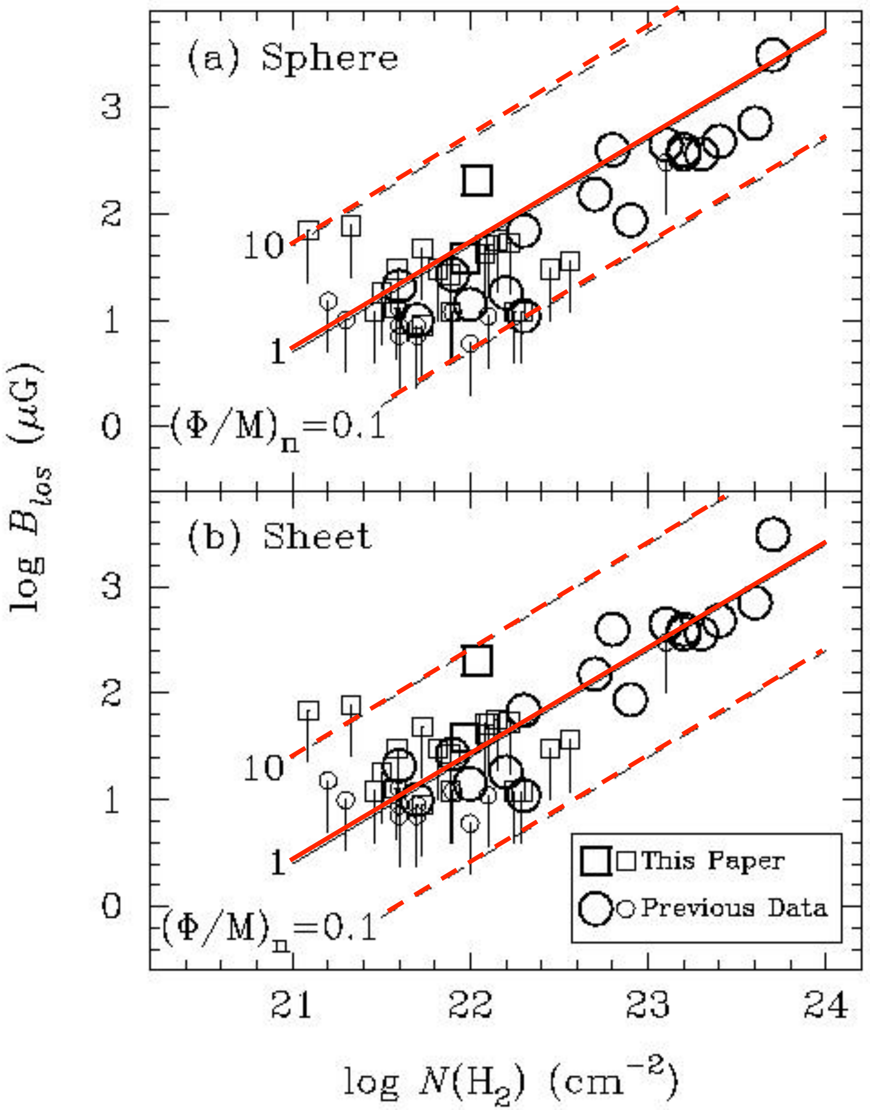
B versus ***N(H₂)*** from *Zeeman measurements*.
(from Bourke et al. 2001)

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

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

$(\Phi/M)_n < 1$ collapse

observed B-field



column density

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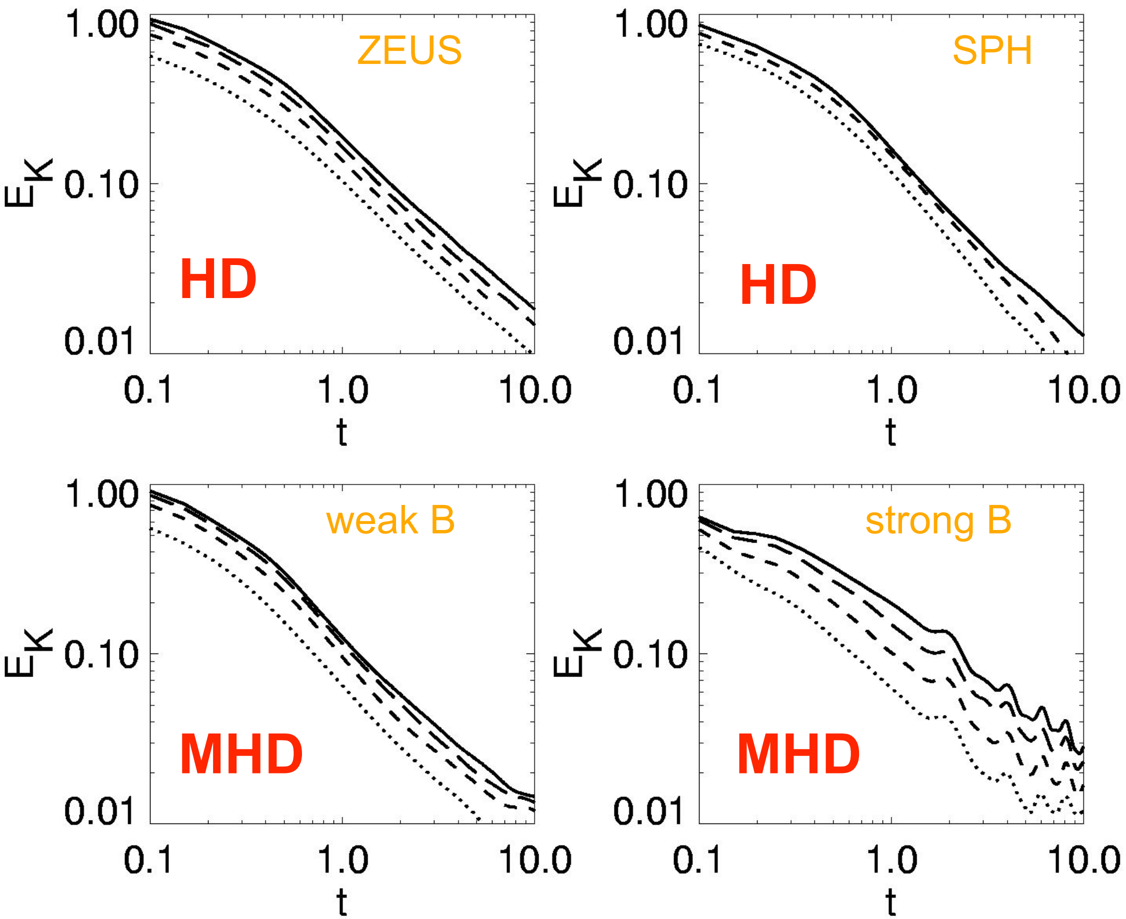
Molecular cloud dynamics

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

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

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



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

Problems of magnetic SF

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

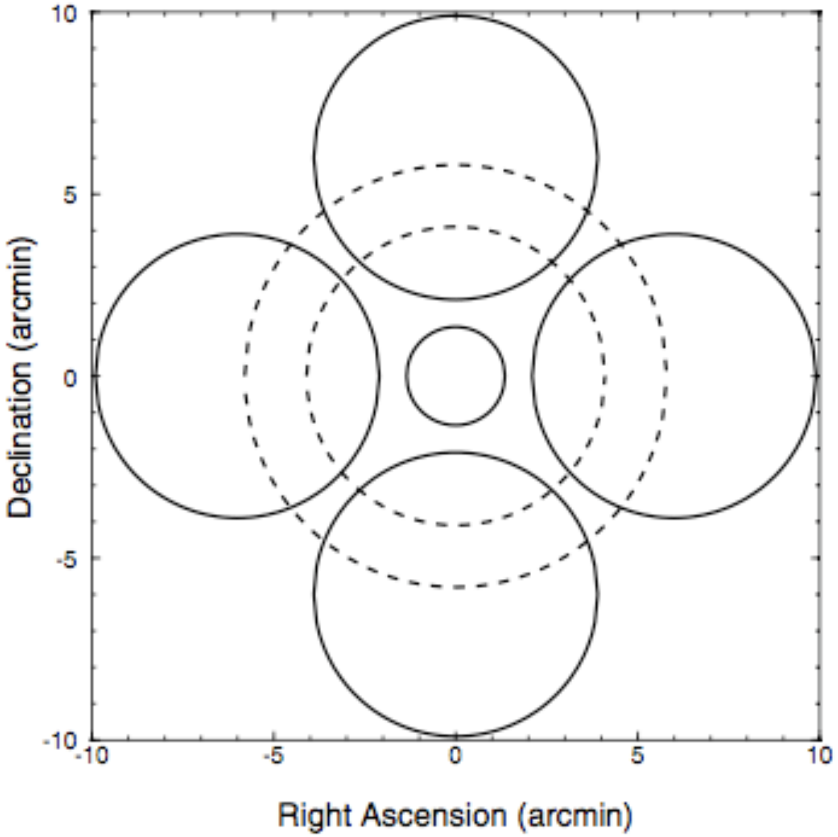
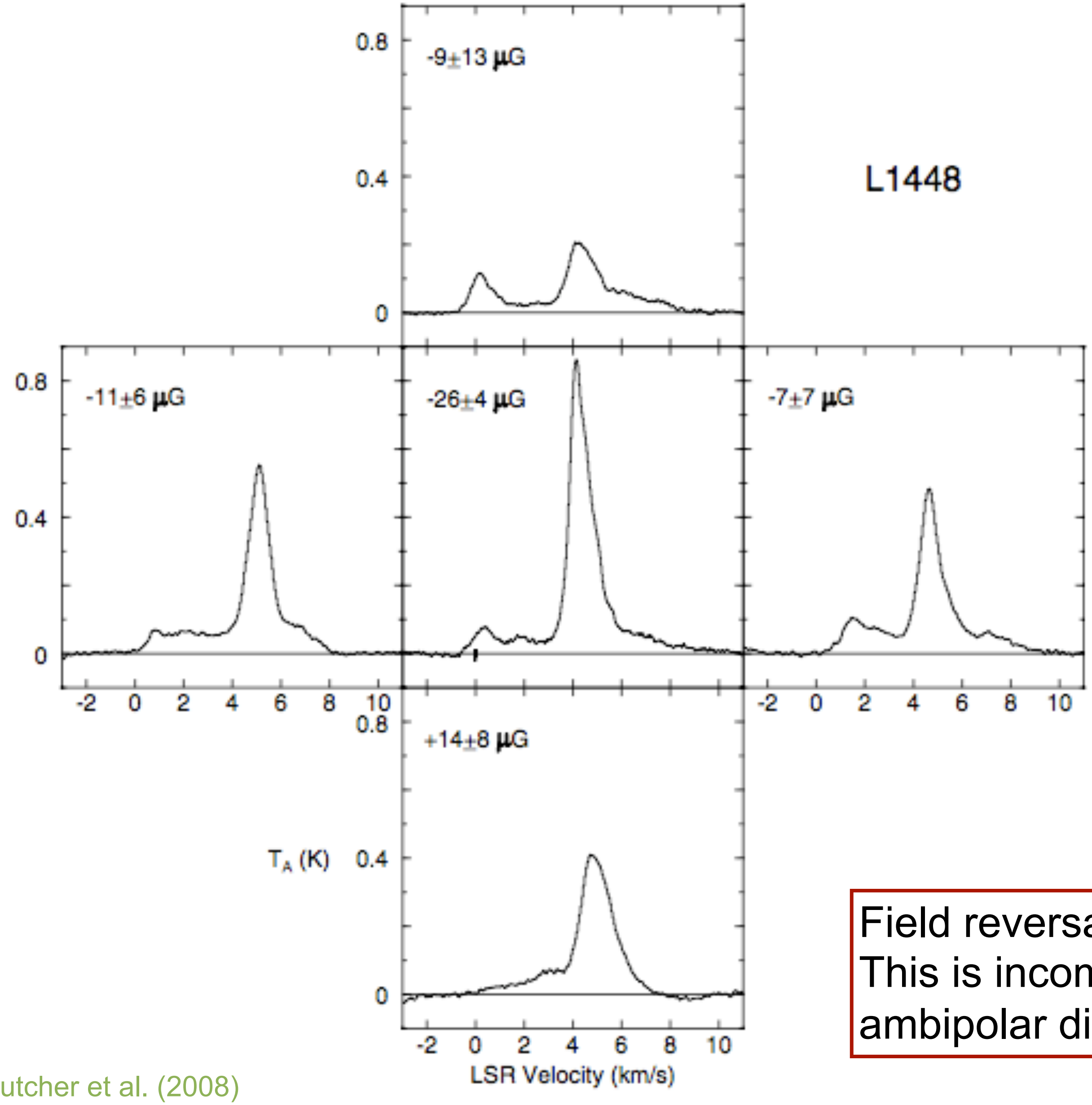


Fig. 1.— The Arecibo telescope primary beam (small circle centered at 0,0) and the four GBT telescope primary beams (large circles centered 6′ north, south, east, and west of 0,0. The dotted circles show the first sidelobe of the Arecibo telescope beam. All circles are at the half-power points.

Crutcher et al. (2008)



Field reversal in the outer parts.
This is incompatible with “standard” ambipolar diffusion theory!

Crutcher et al. (2008)

Fig. 2.— OH 1667 MHz spectra toward the core of L1448CO obtained with the Arecibo telescope (center panel) and toward each of the envelope positions 6′ north, south, east, and west of the core, obtained with the GBT. In the upper left of each panel is the inferred B_{LOS} and its 1σ uncertainty at that position. A negative B_{LOS} means the magnetic field points toward the observer, and vice versa for a positive B_{LOS}.

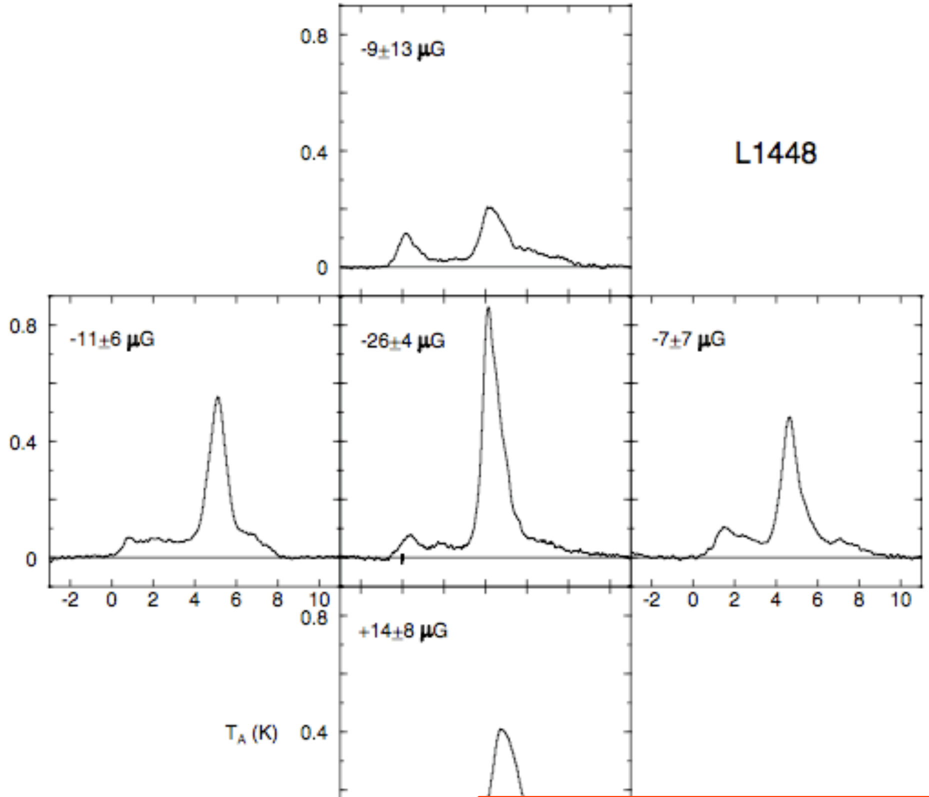


Fig. 2.— OH 1667 MHz spectra toward the
telescope (center panel) and toward each of the
west of the core, obtained with the GBT. In the
and its 1σ uncertainty at that position. A neg
toward the observer, and vice versa for a posit

example: L1448

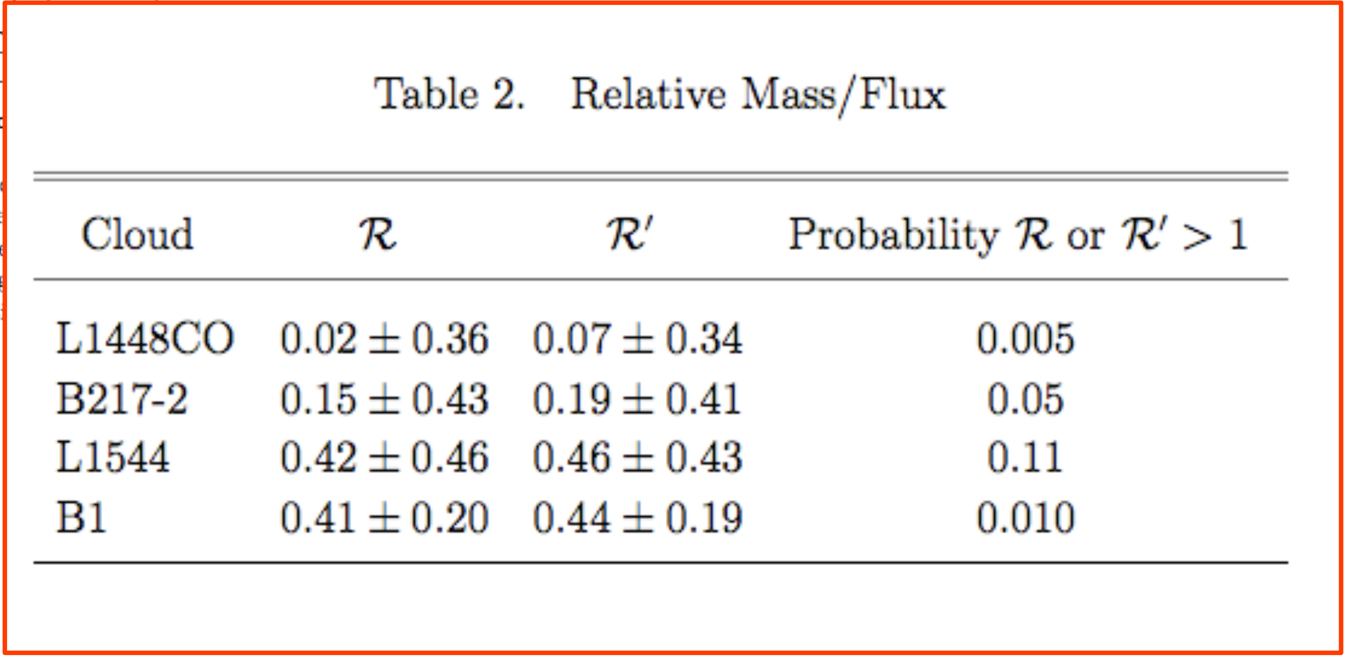
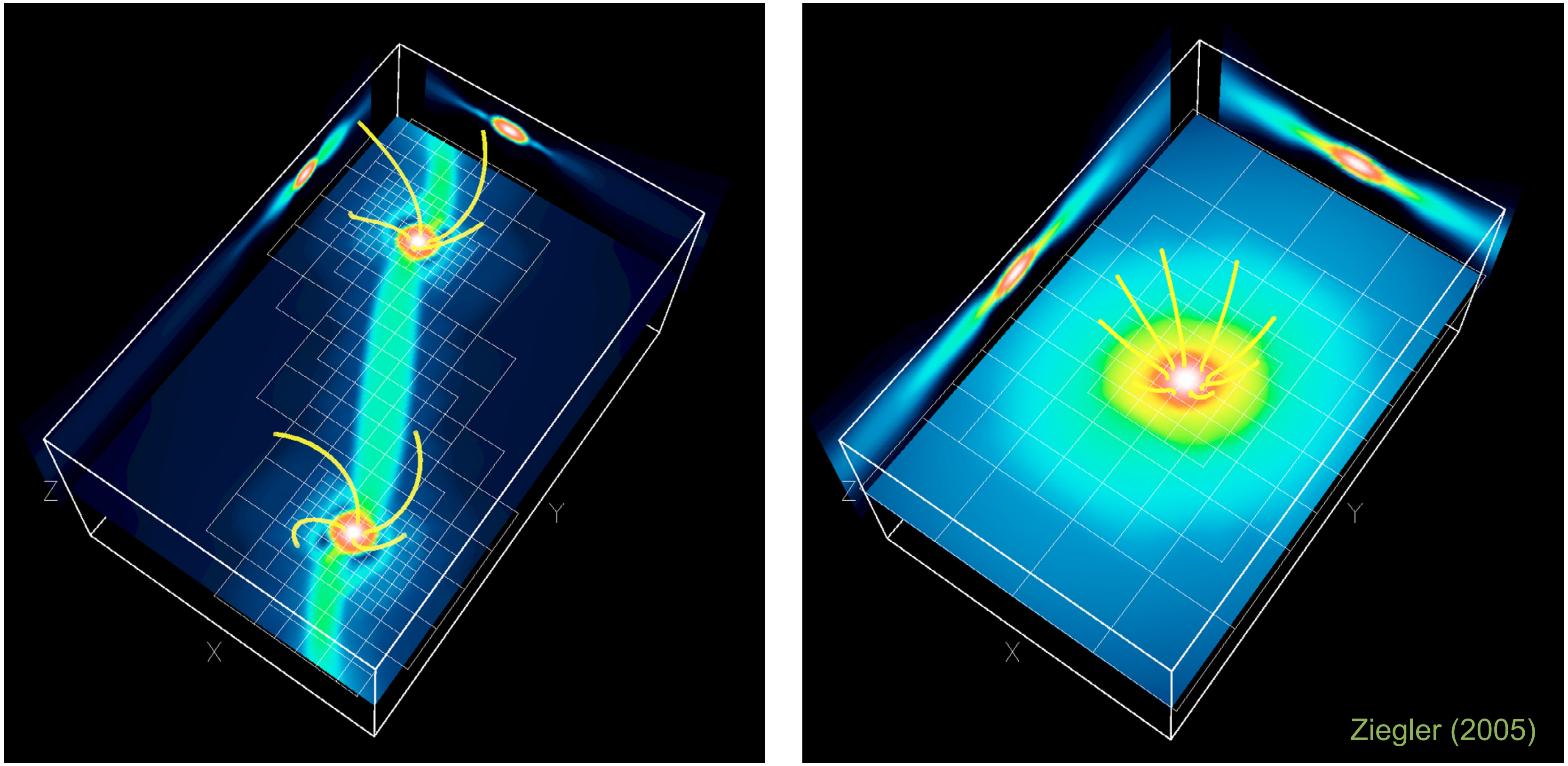


Table 2. Relative Mass/Flux

Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010

Crutcher et al. (2008)

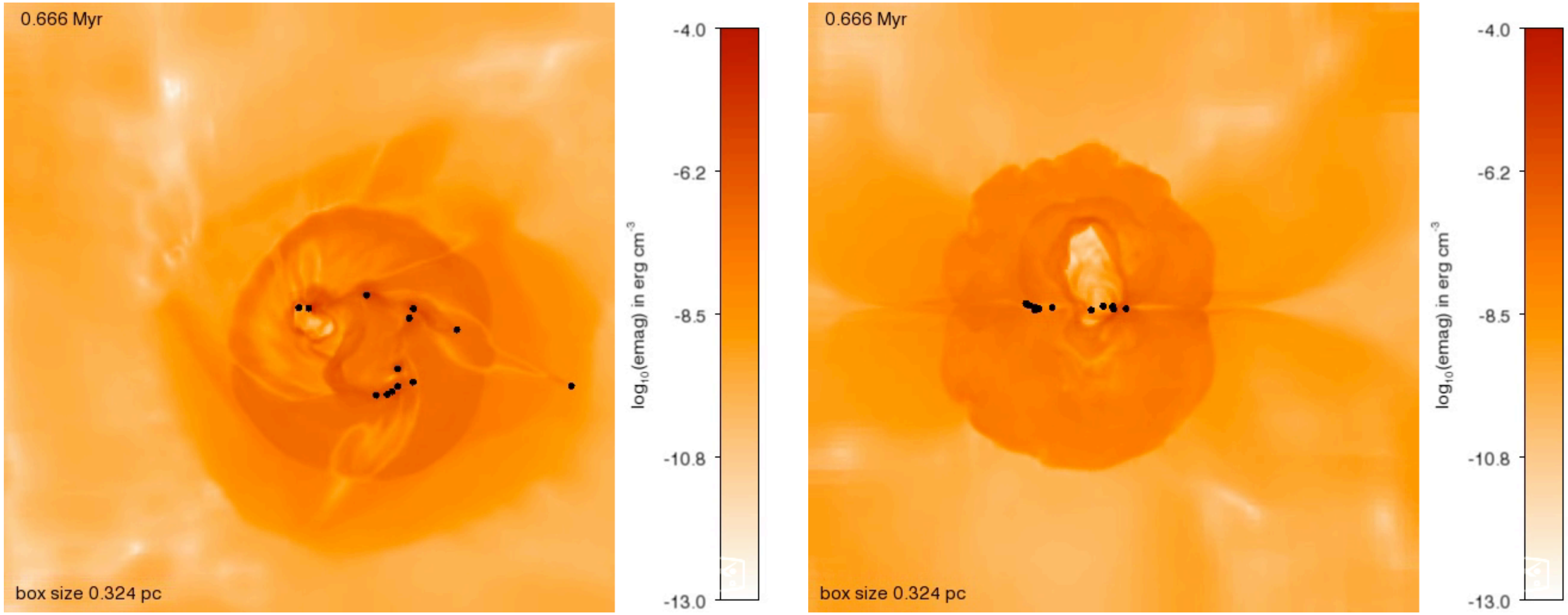
influence of B on disk evolution



Ziegler (2005)

magnetic fields suppress disk fragmentation in low mass star formation,
IF sufficiently strong!!
see Ziegler (2005), Hennebelle et al. (2008), Hennebelle & Ciardi (2009)

influence of B on disk evolution

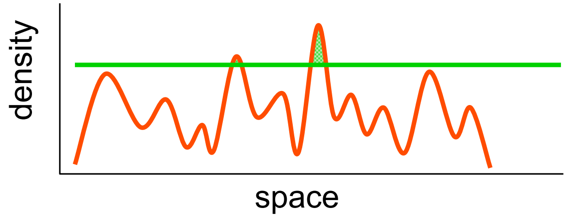


Peters et al. (2011)

in disk around high-mass stars, fragmentation is reduced but not suppressed

see Peters et al. (2011), Hennebelle et al. (2011)

gravoturbulent star formation



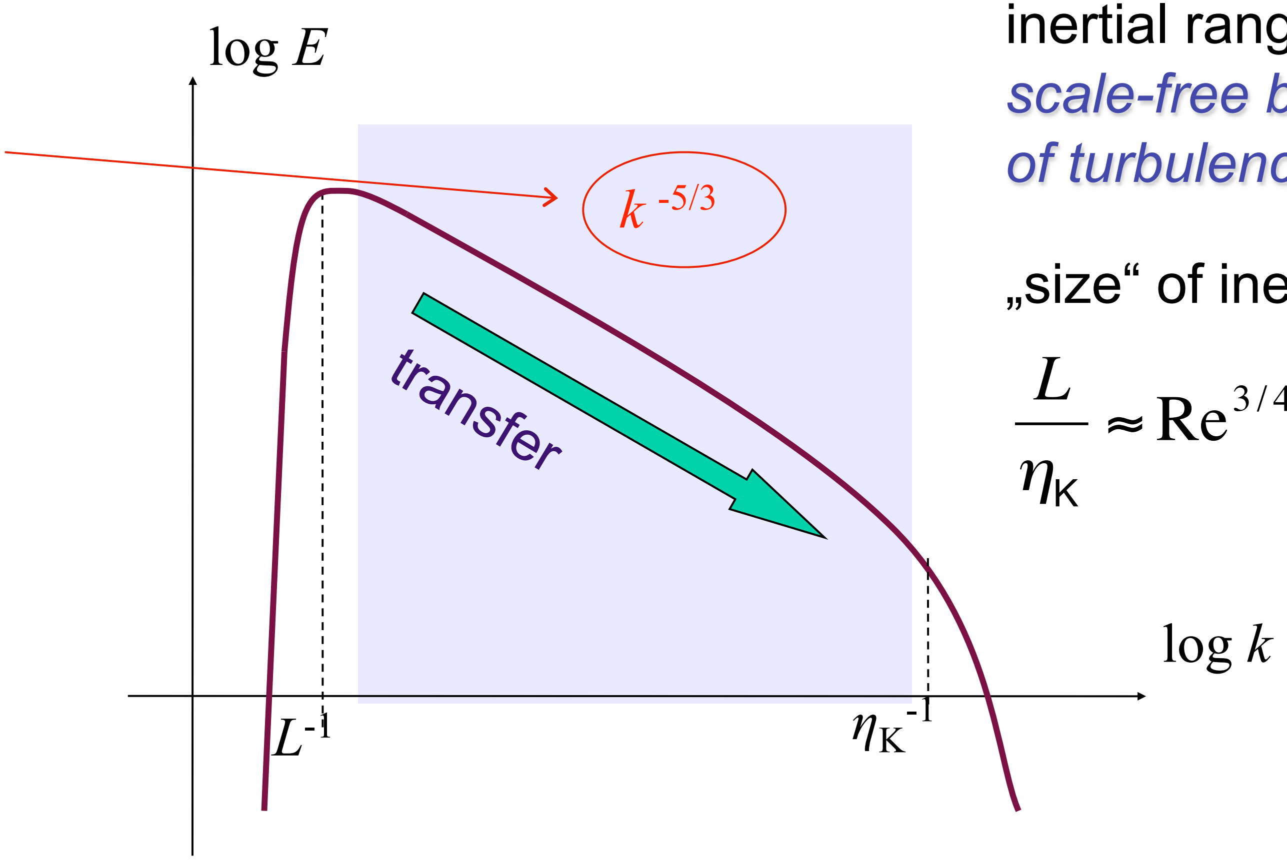
- interstellar gas is highly *inhomogeneous*
  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation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

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

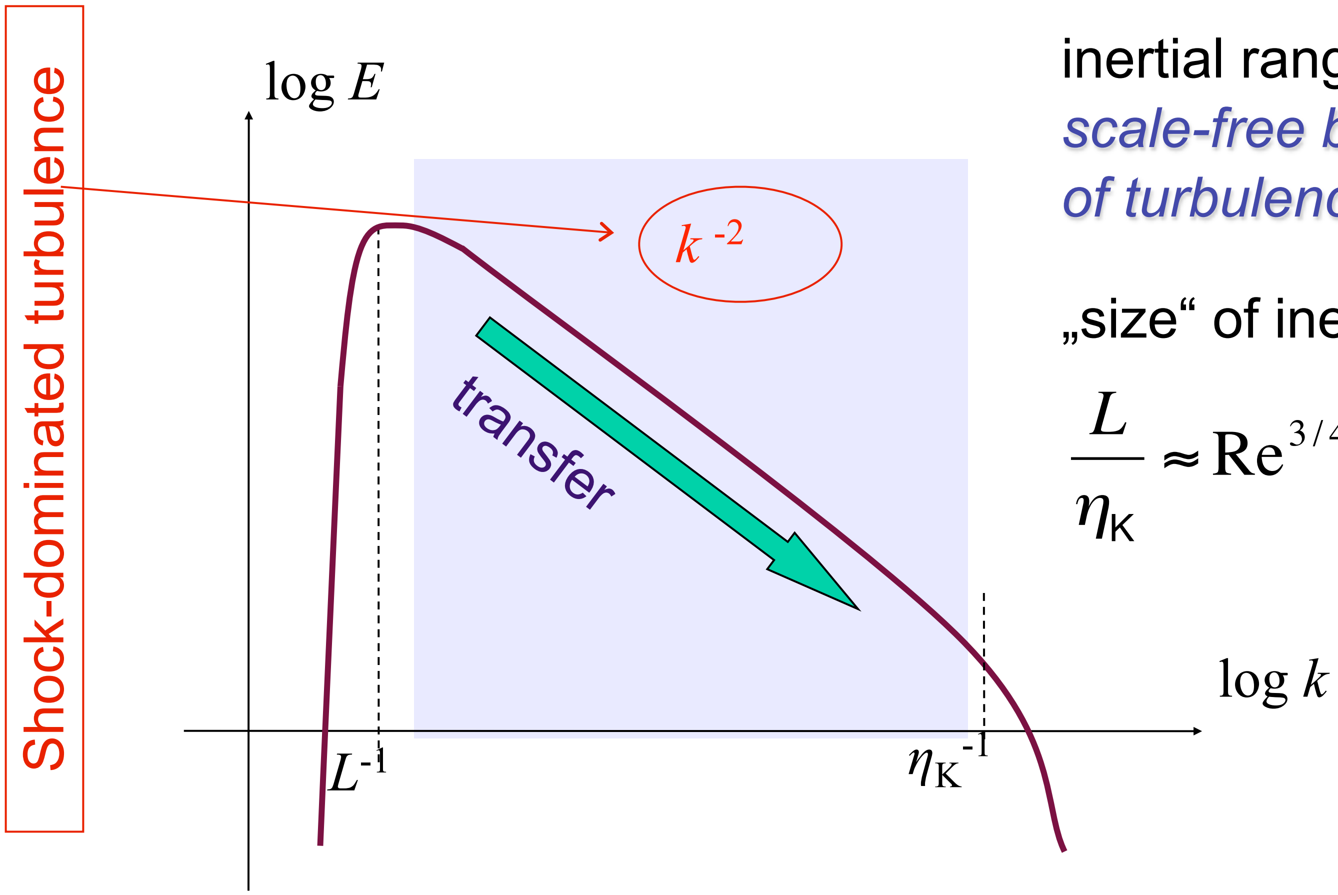
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade



Shock-dominated turbulence

energy
input
scale

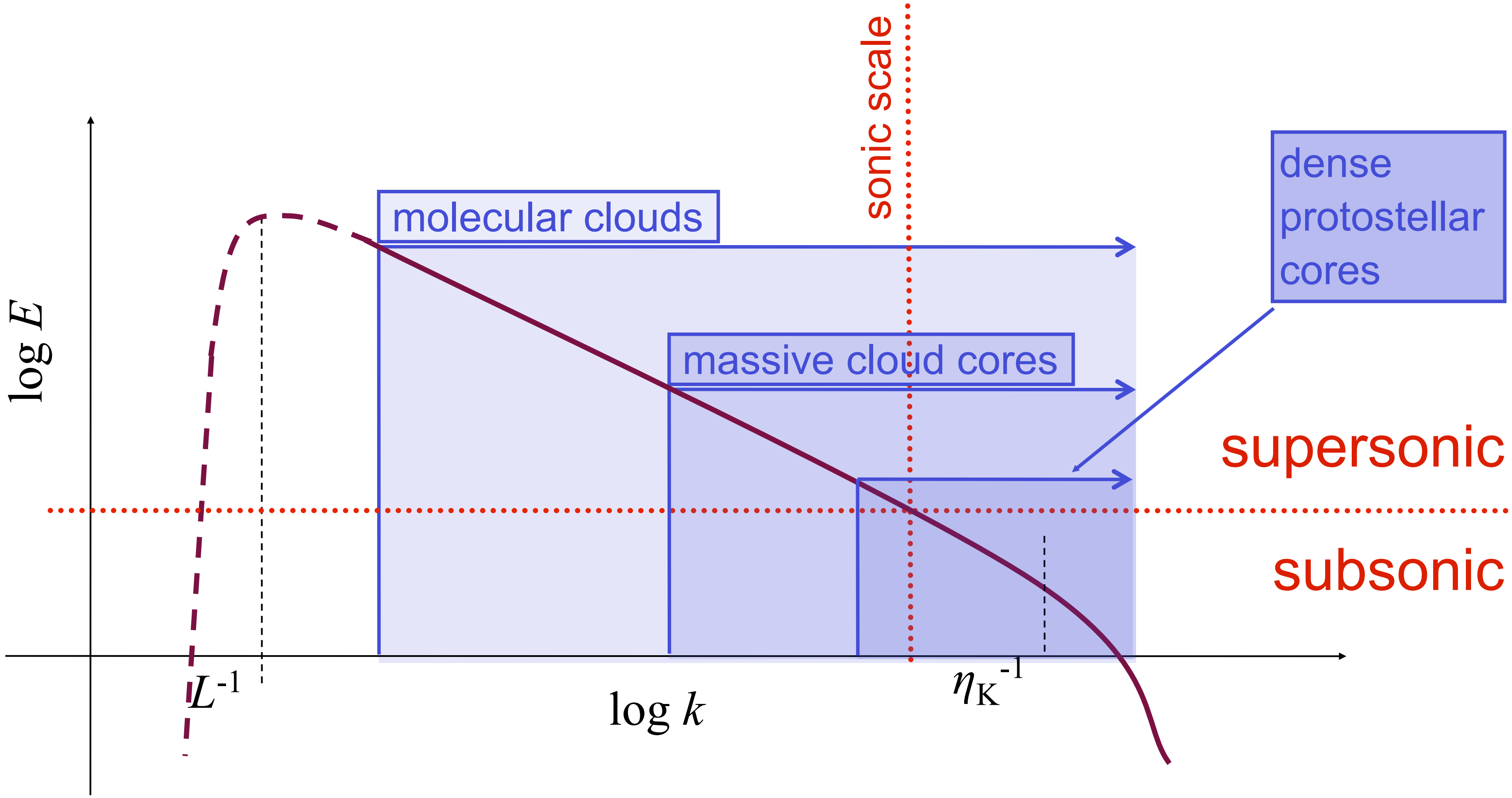
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade in ISM

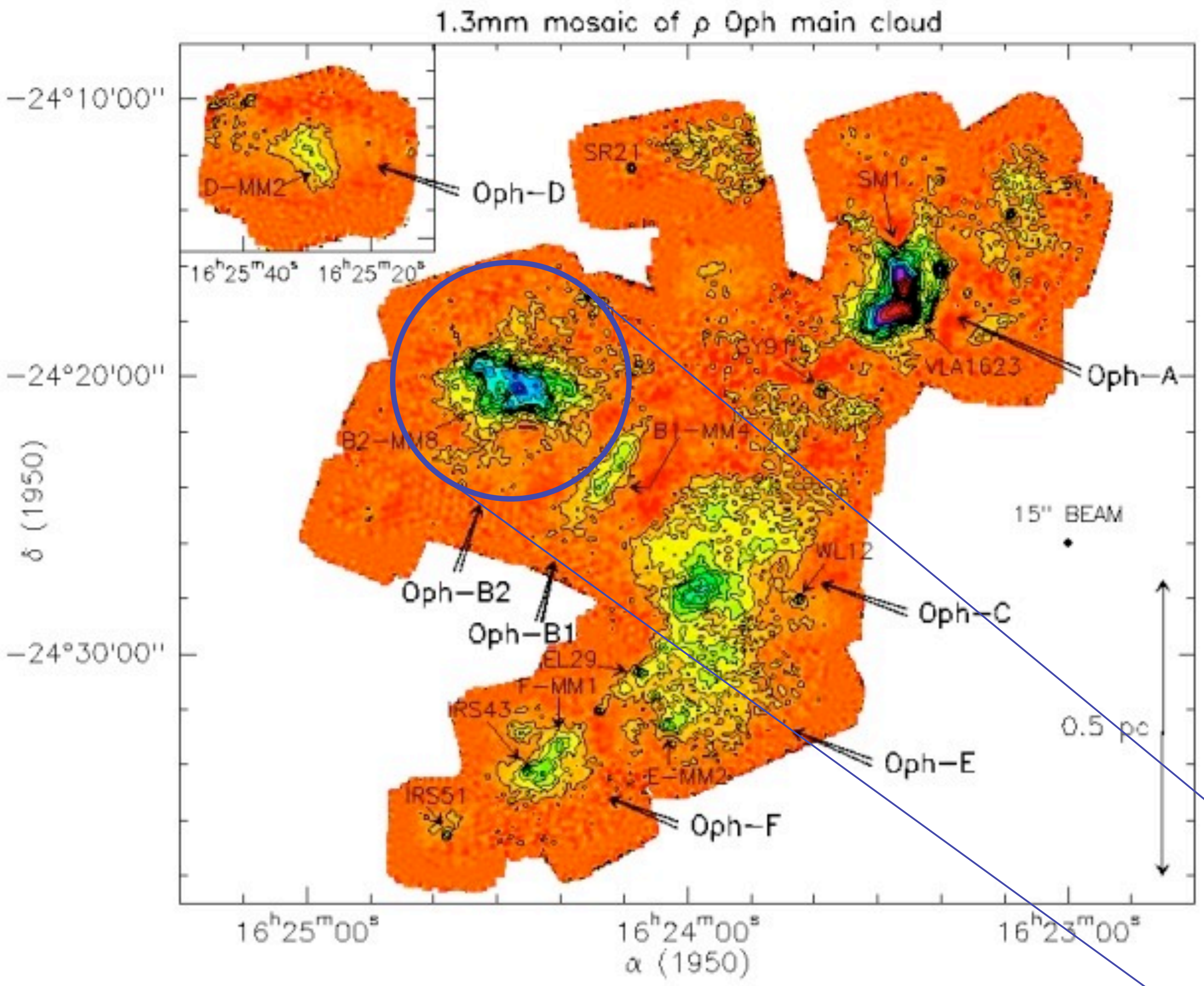


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

Density structure of MC's



(Motte, André, & Neri 1998)

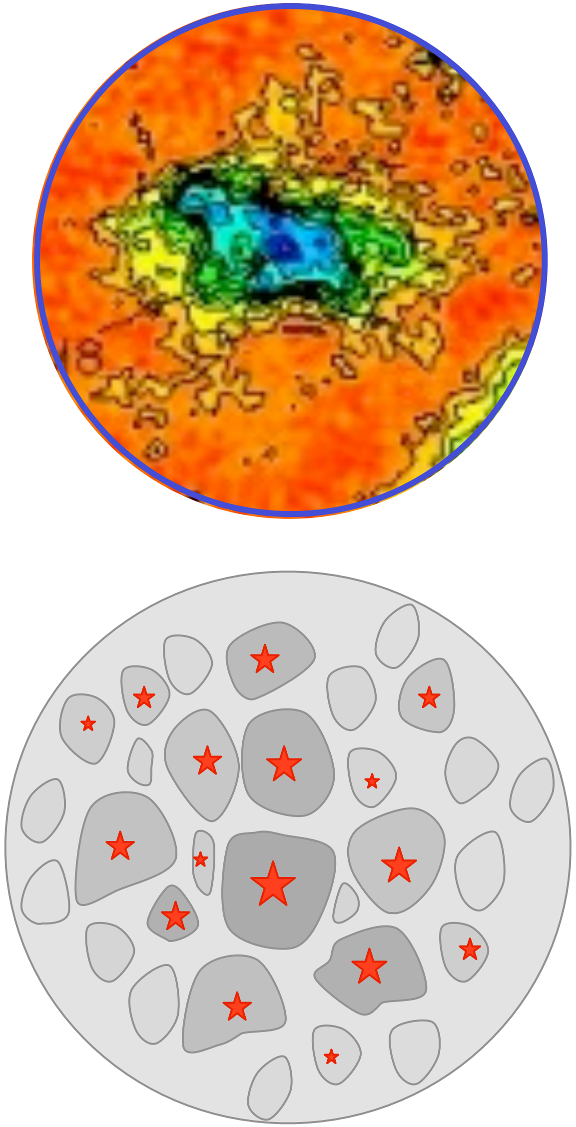
molecular clouds are highly inhomogeneous

stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

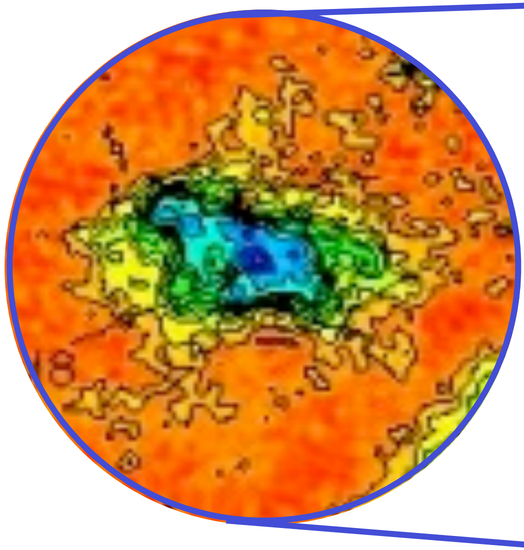
Evolution of cloud cores

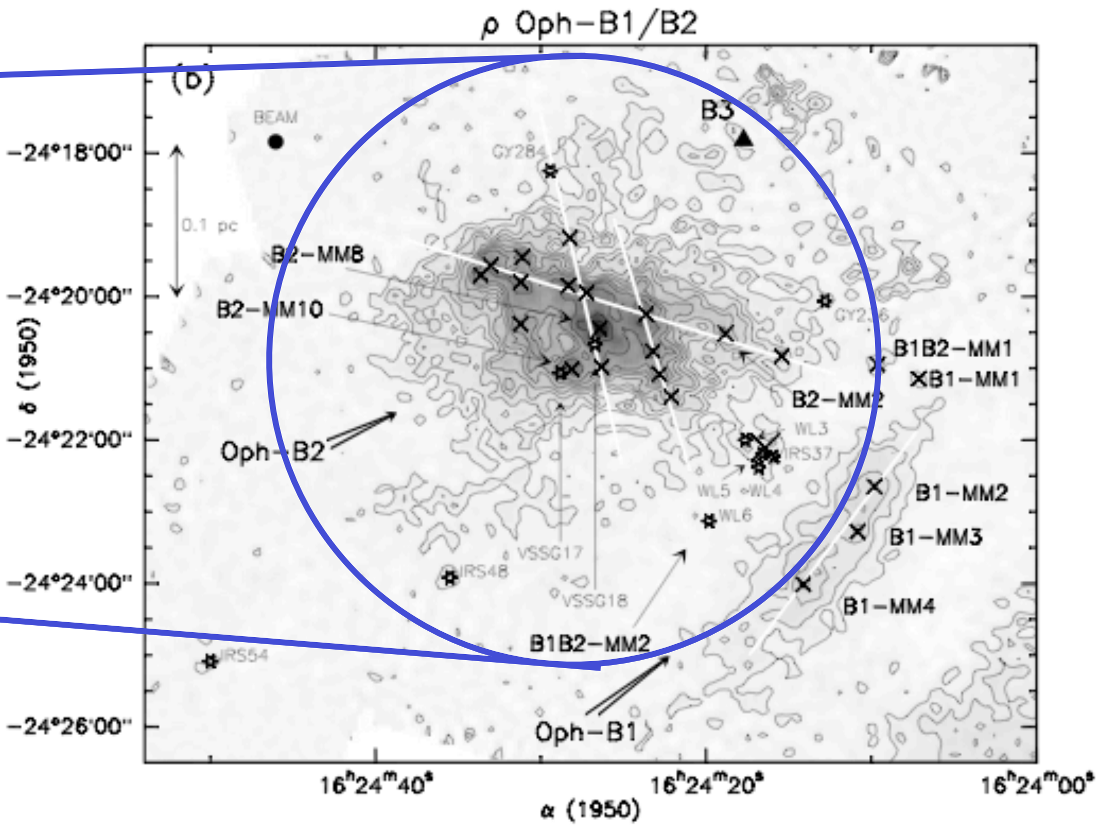


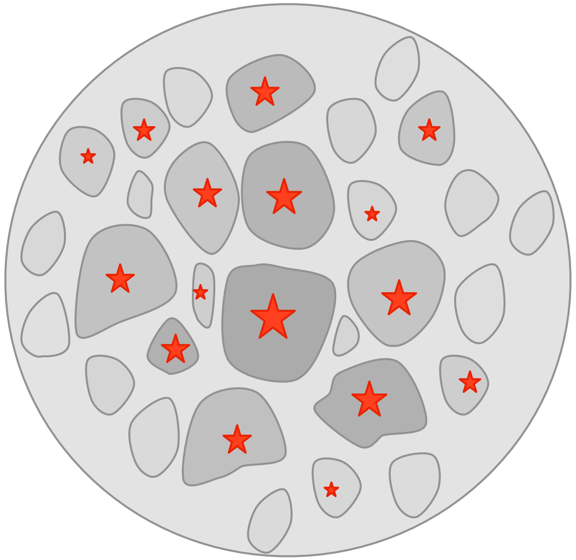
- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> with typical $M \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores





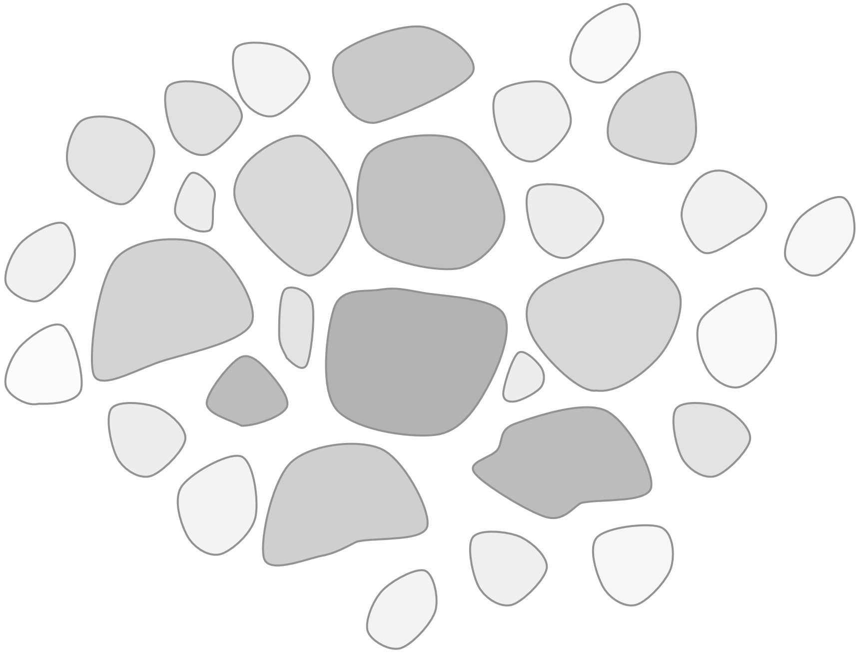


indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

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

--> individual cores do *not* interact

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

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

(2) turbulence decays, i.e. gravity dominates:

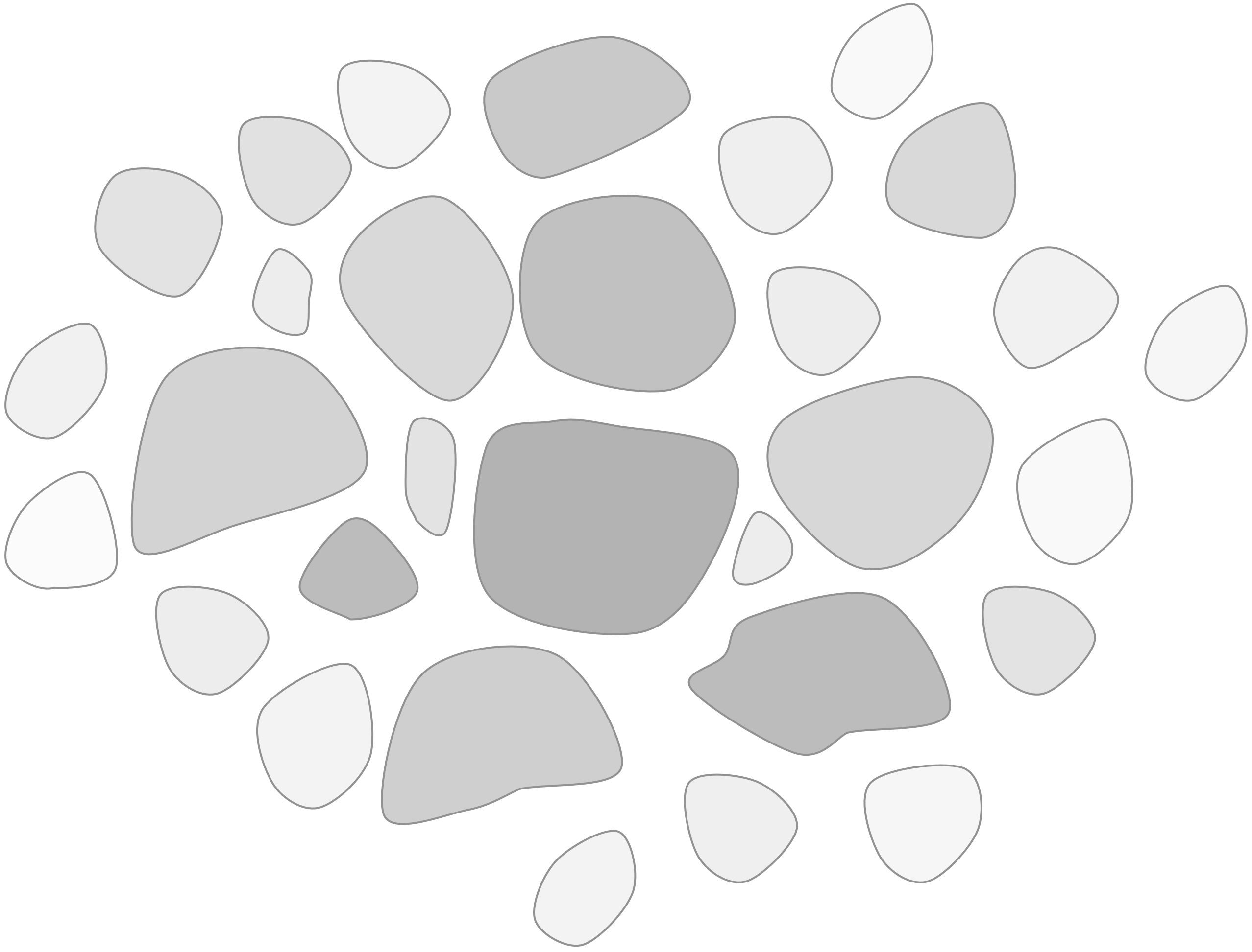
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

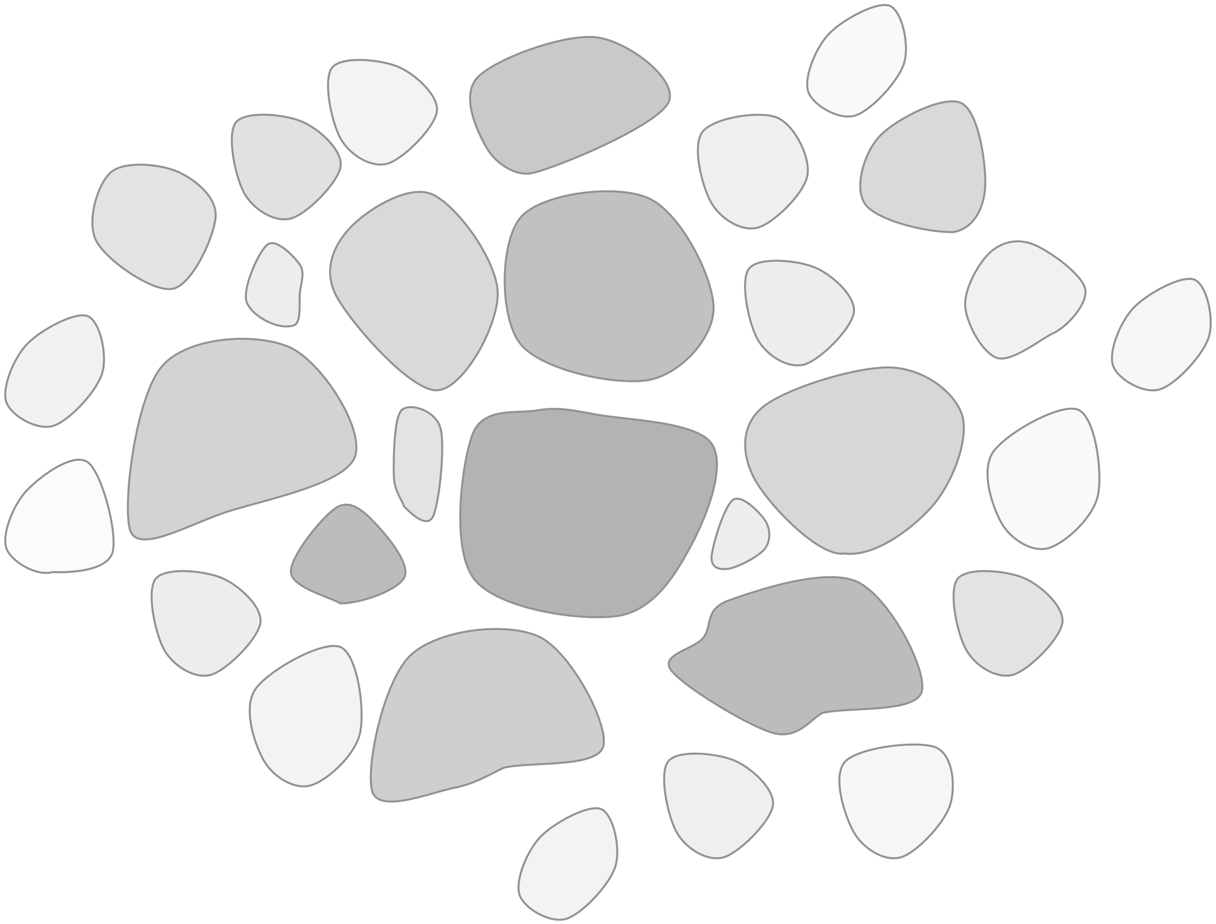
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

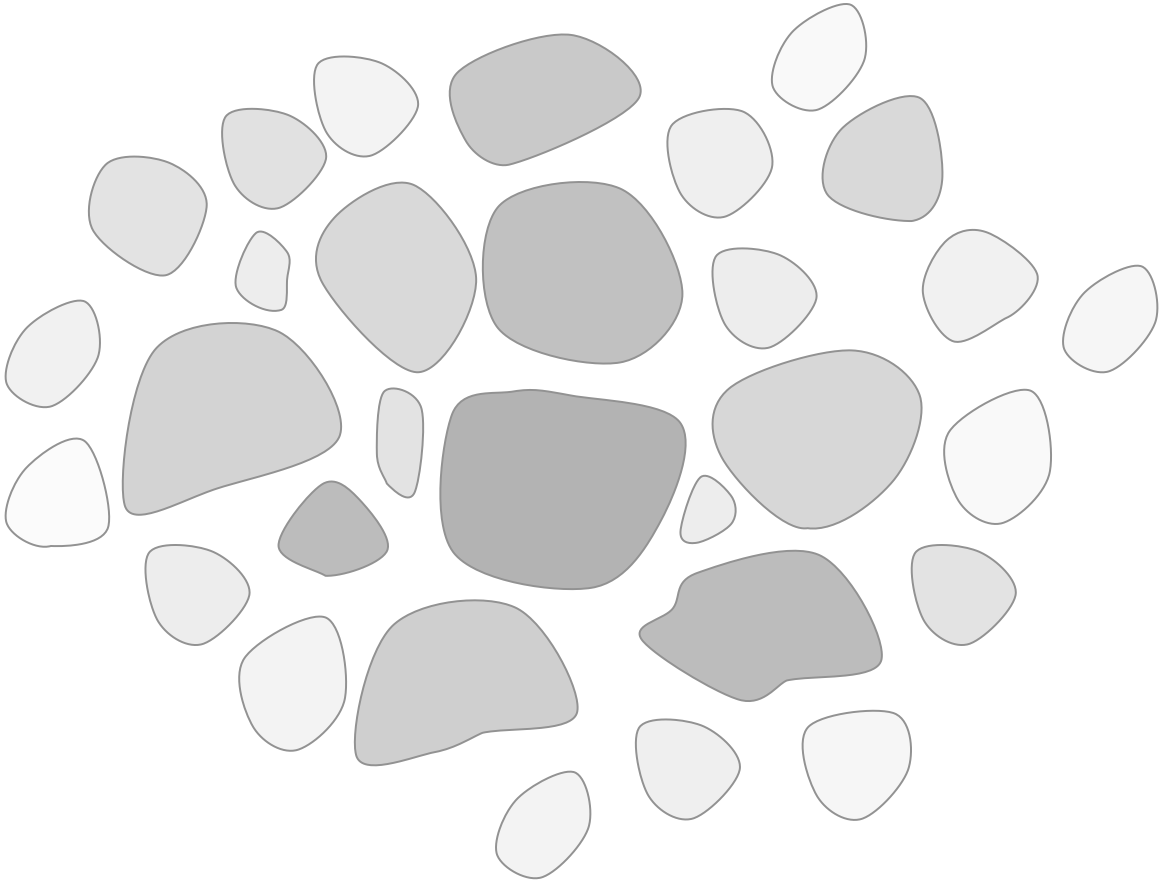
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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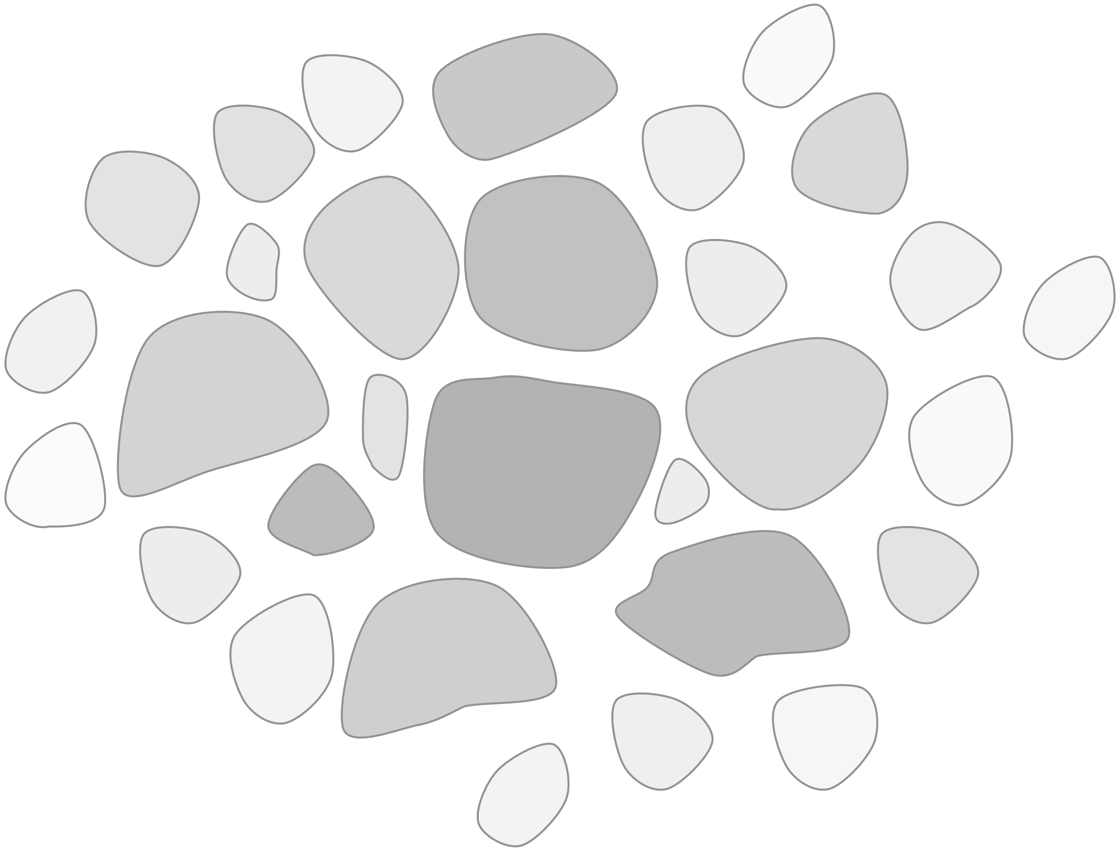
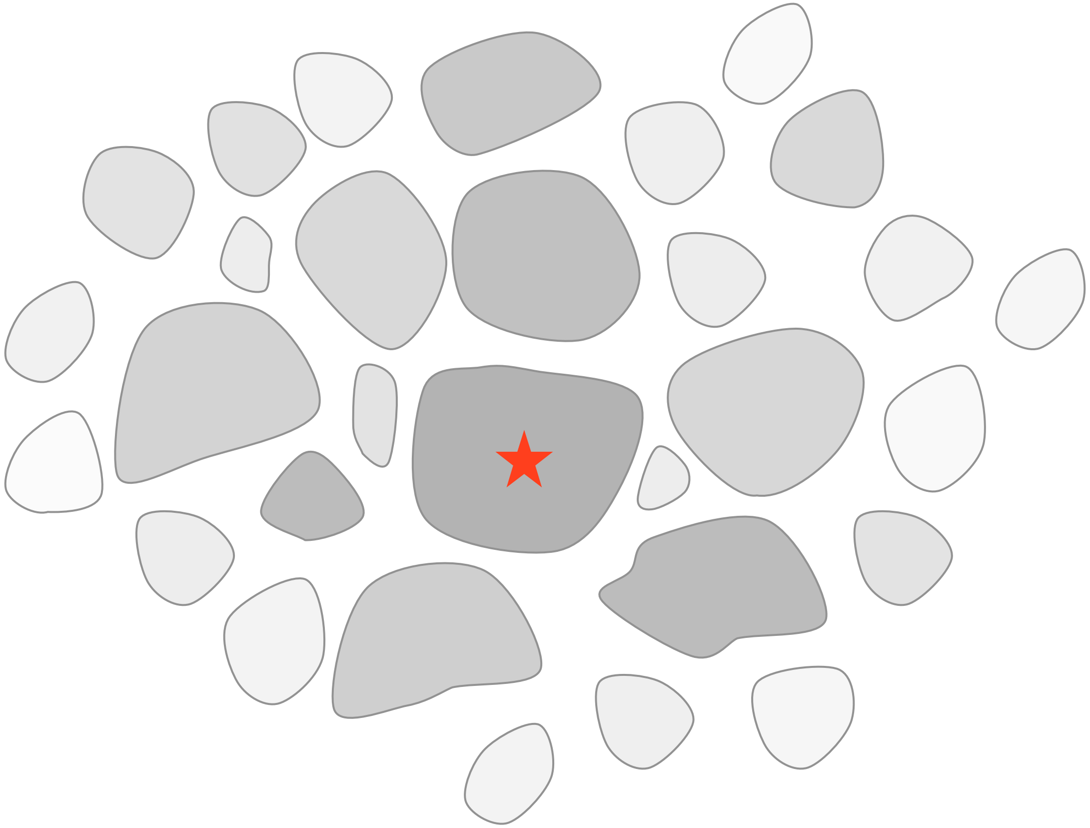


while region contracts, individual clumps collapse to form stars



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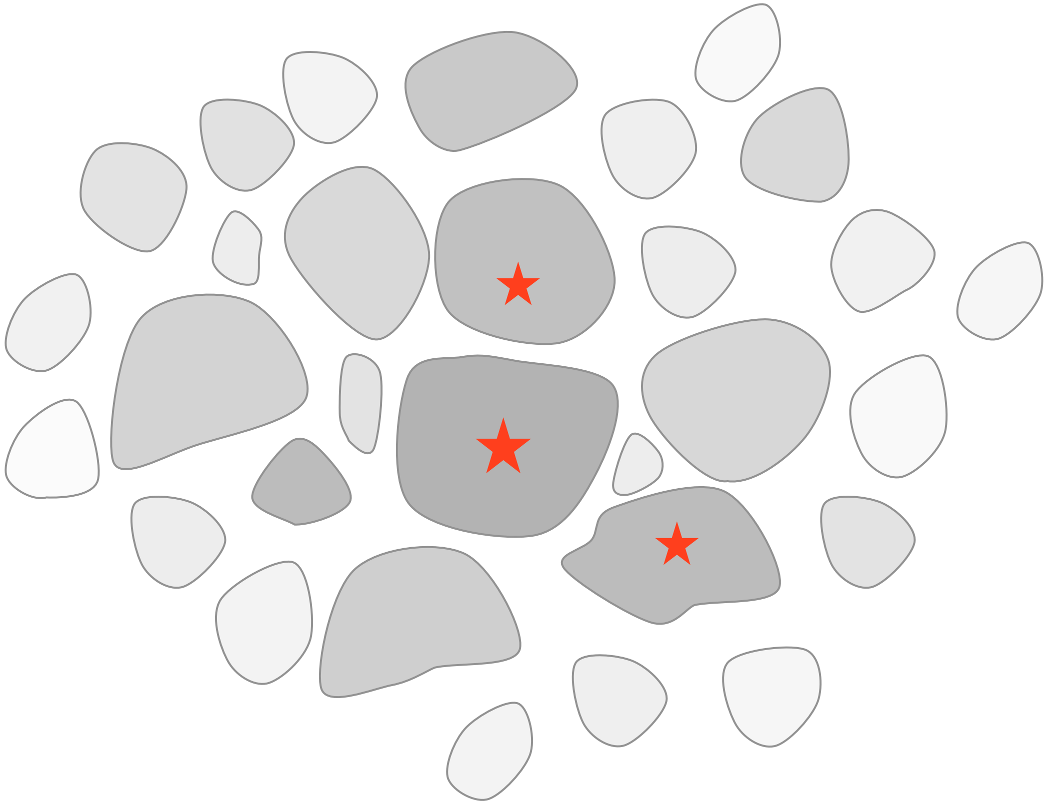
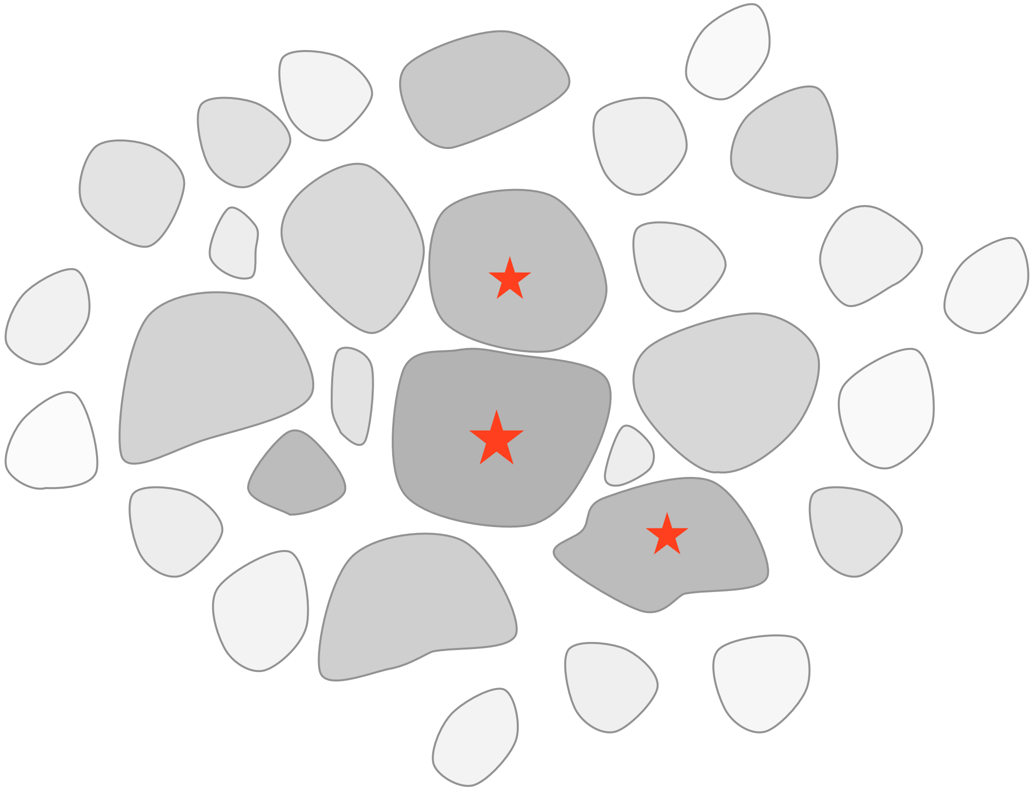
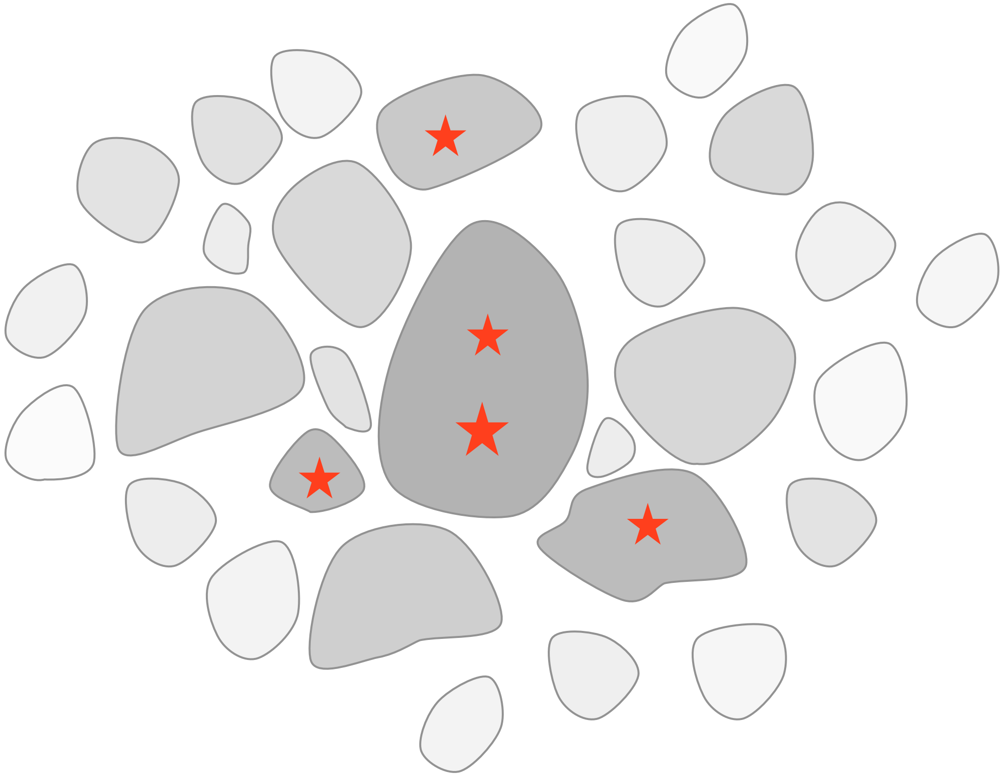


individual clumps collapse to form stars

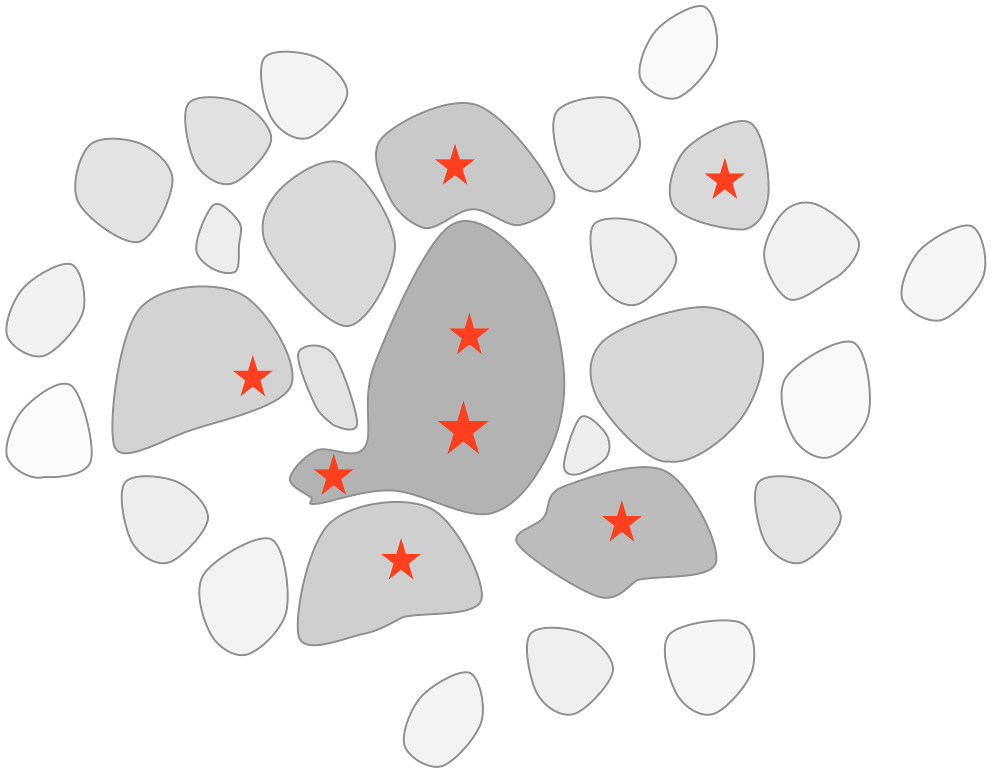


individual clumps collapse to form stars



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

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



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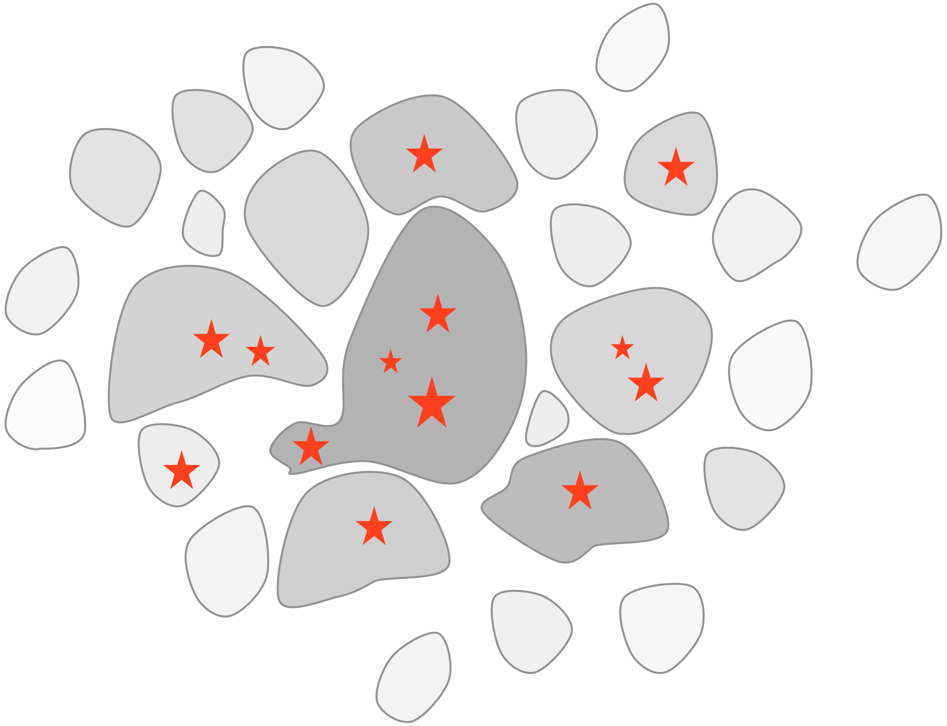

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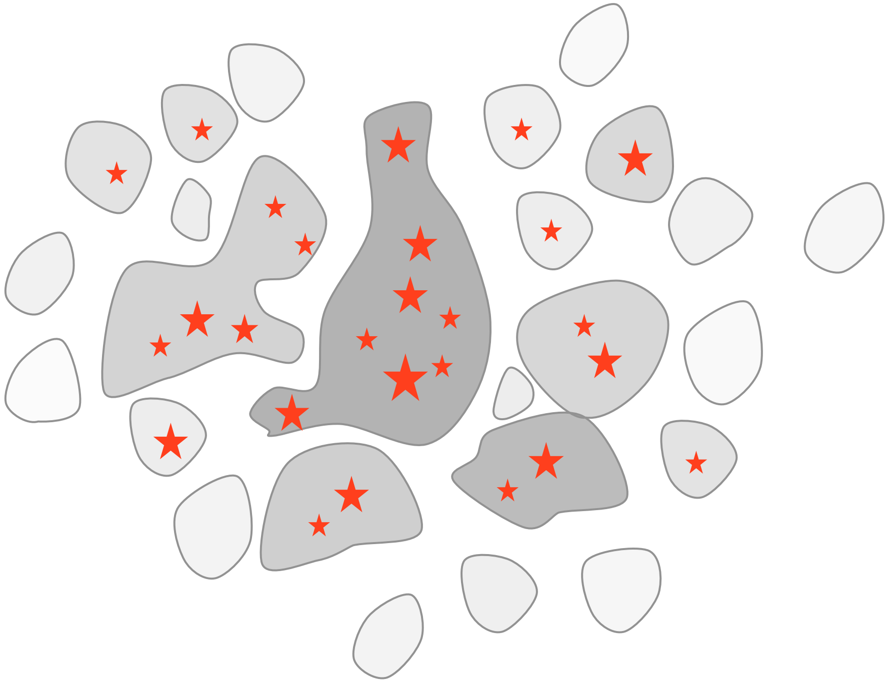
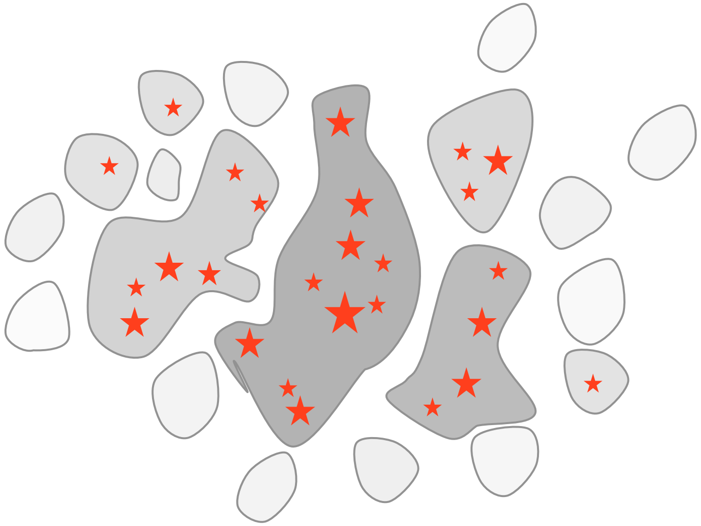


in *dense clusters*, competitive mass growth becomes important



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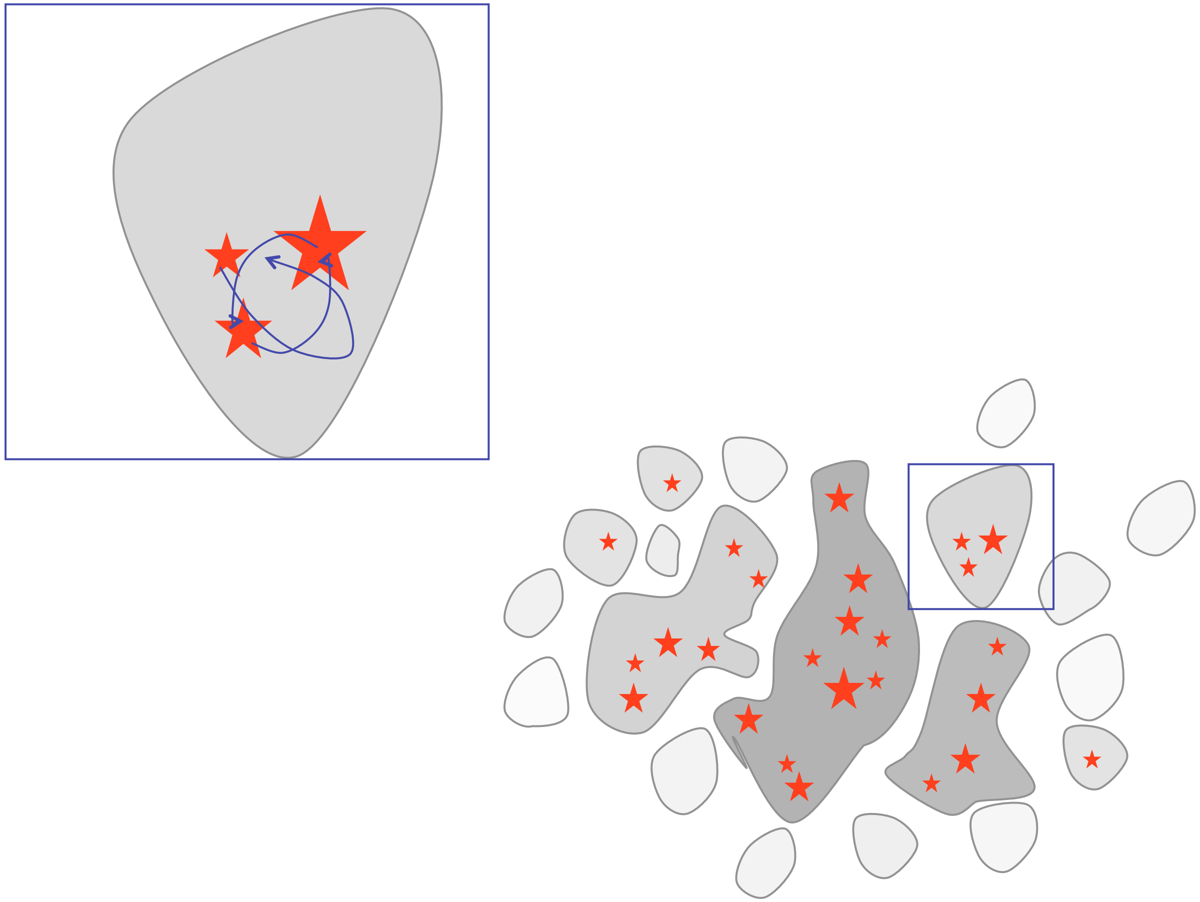
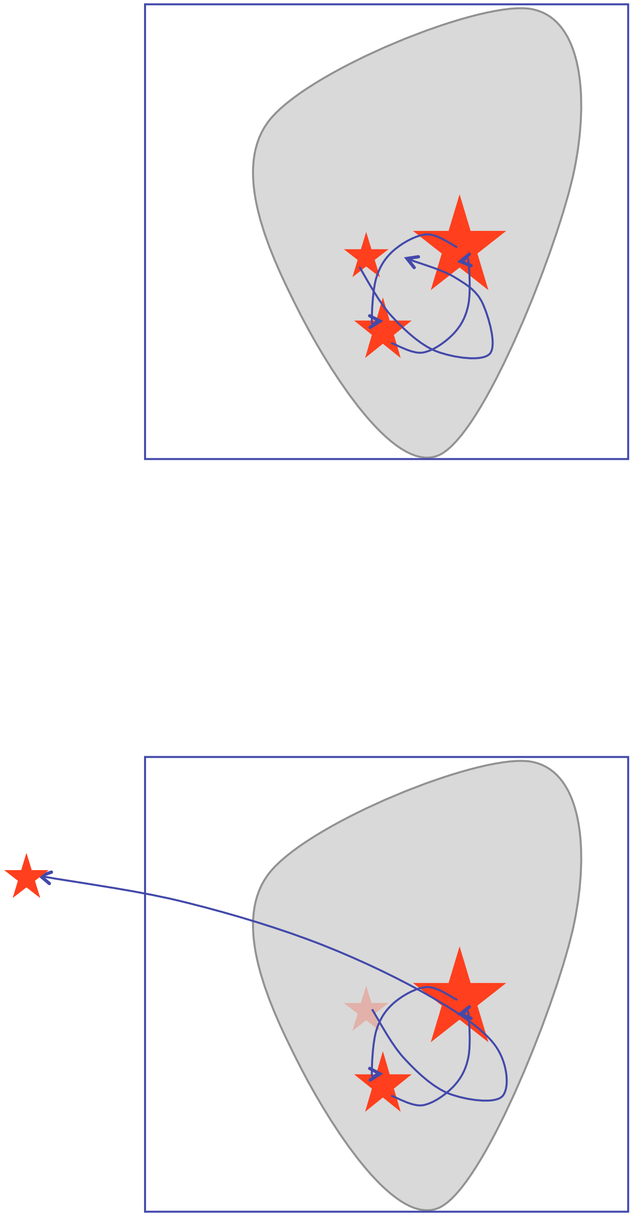
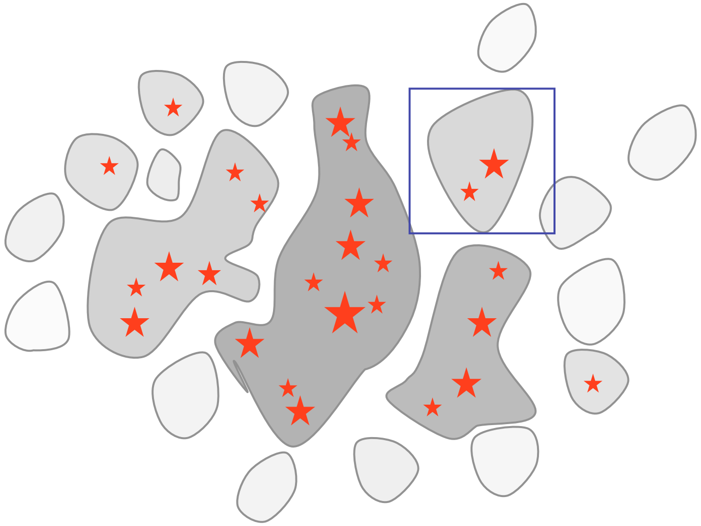
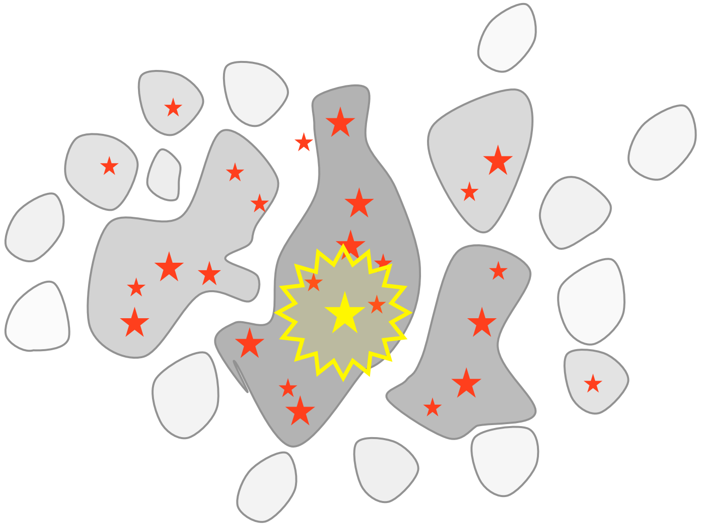


in *dense clusters*, *N*-body effects influence mass growth

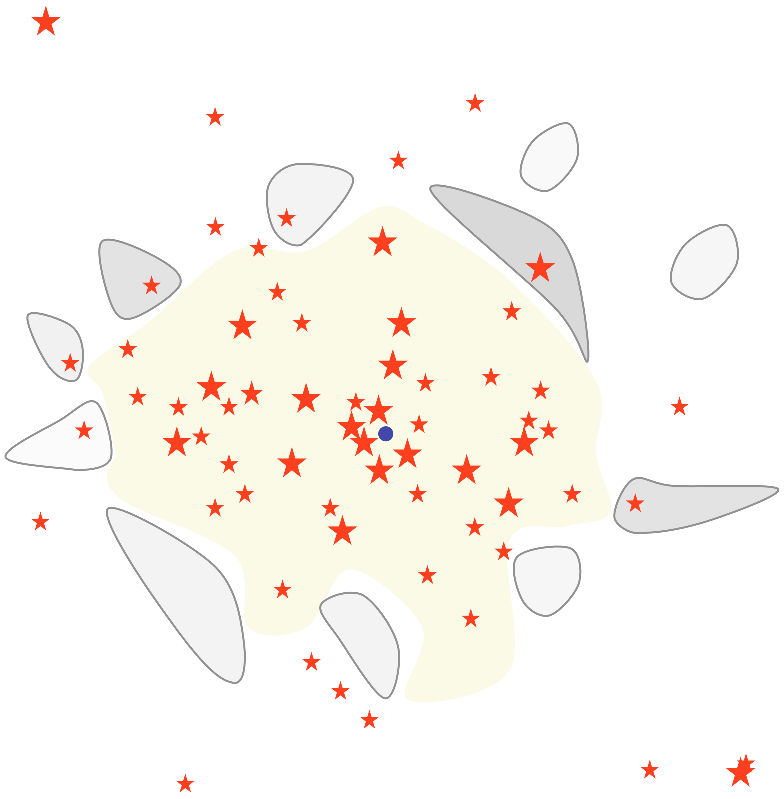




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with HII region

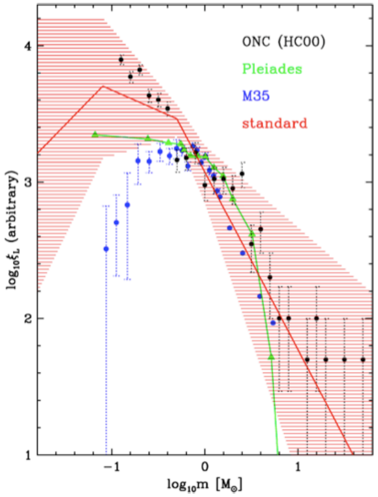
NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region

stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> 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

(Kroupa 2002)



stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
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  - collapse and interaction of prestellar cores
    --> accretion and *N*-body effects
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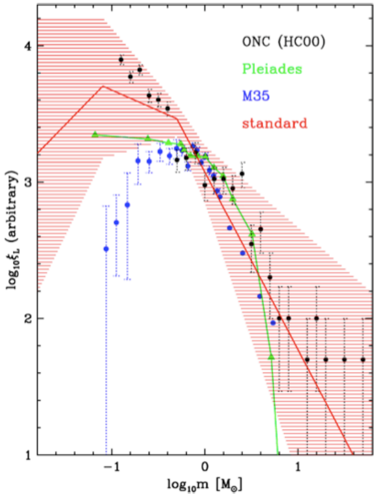
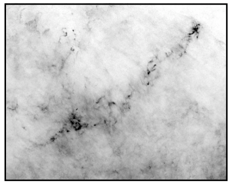

(Kroupa 2002)

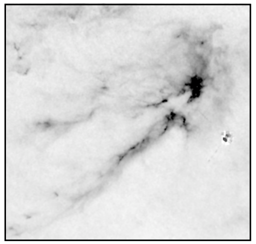
nearby molecular clouds

scales to same scale

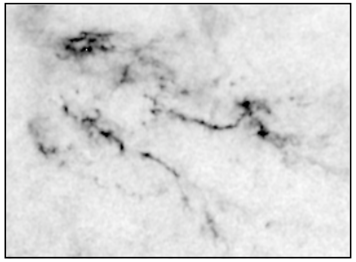
Pipe



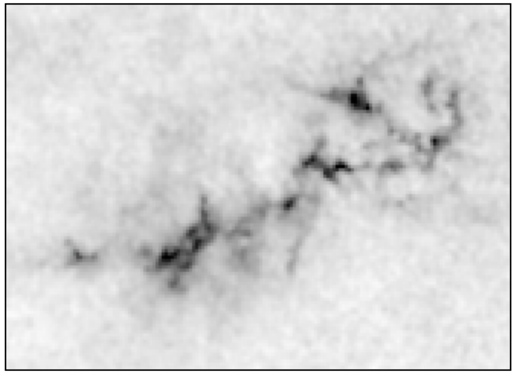
Ophiuchus

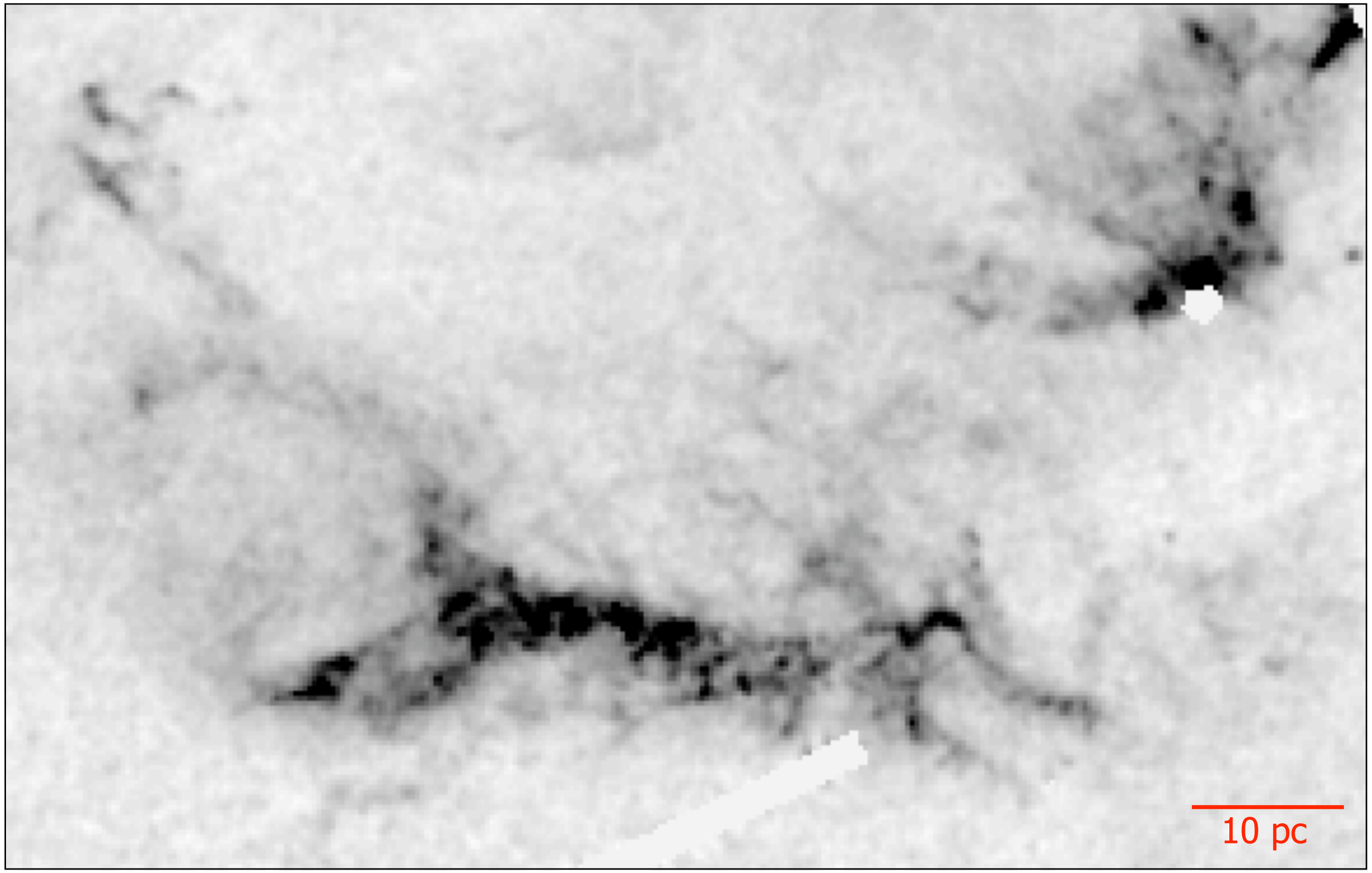


Taurus



Perseus

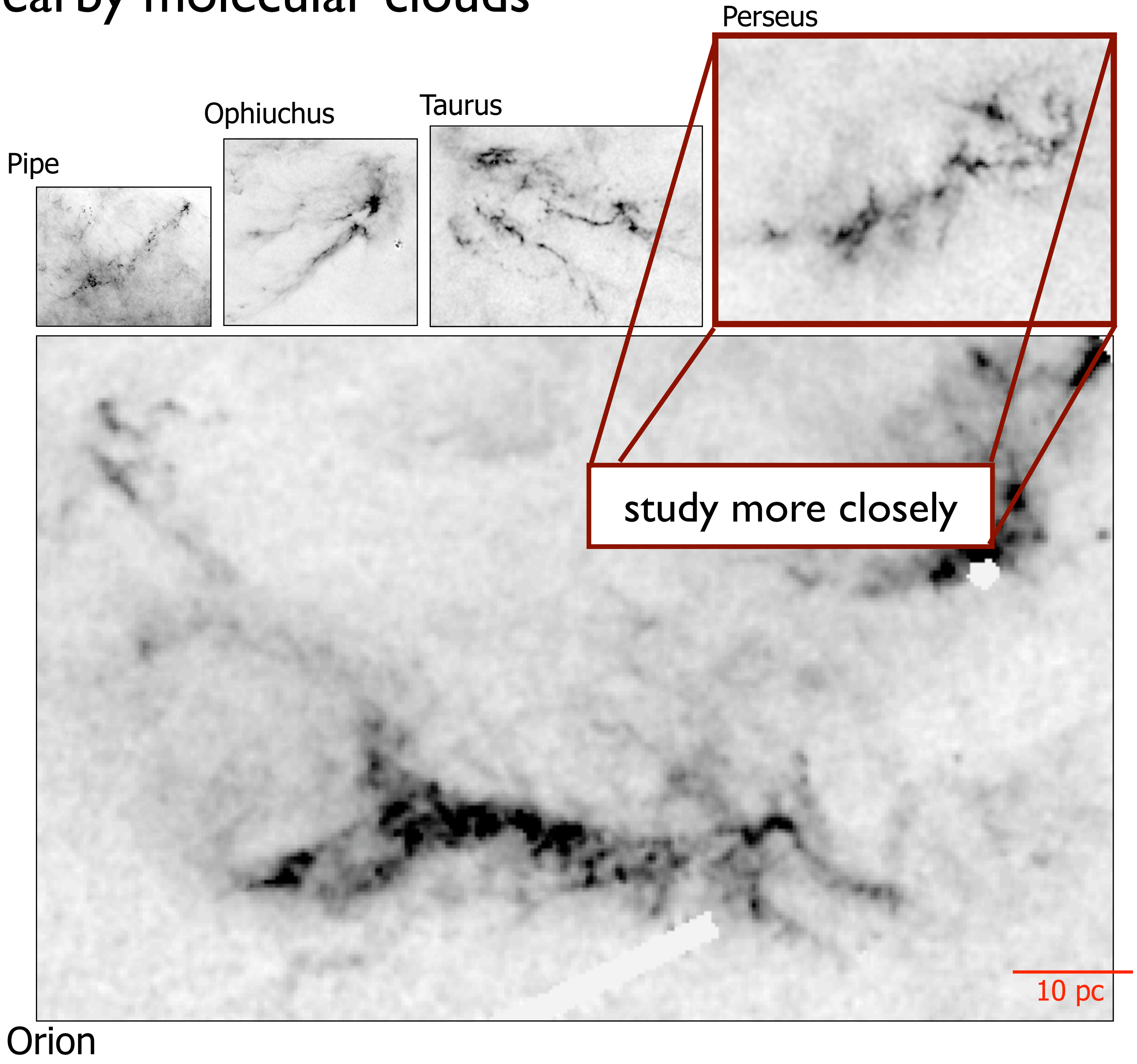




Orion

(from A. Goodman)

nearby molecular clouds



scales to same scale

(from A. Goodman)

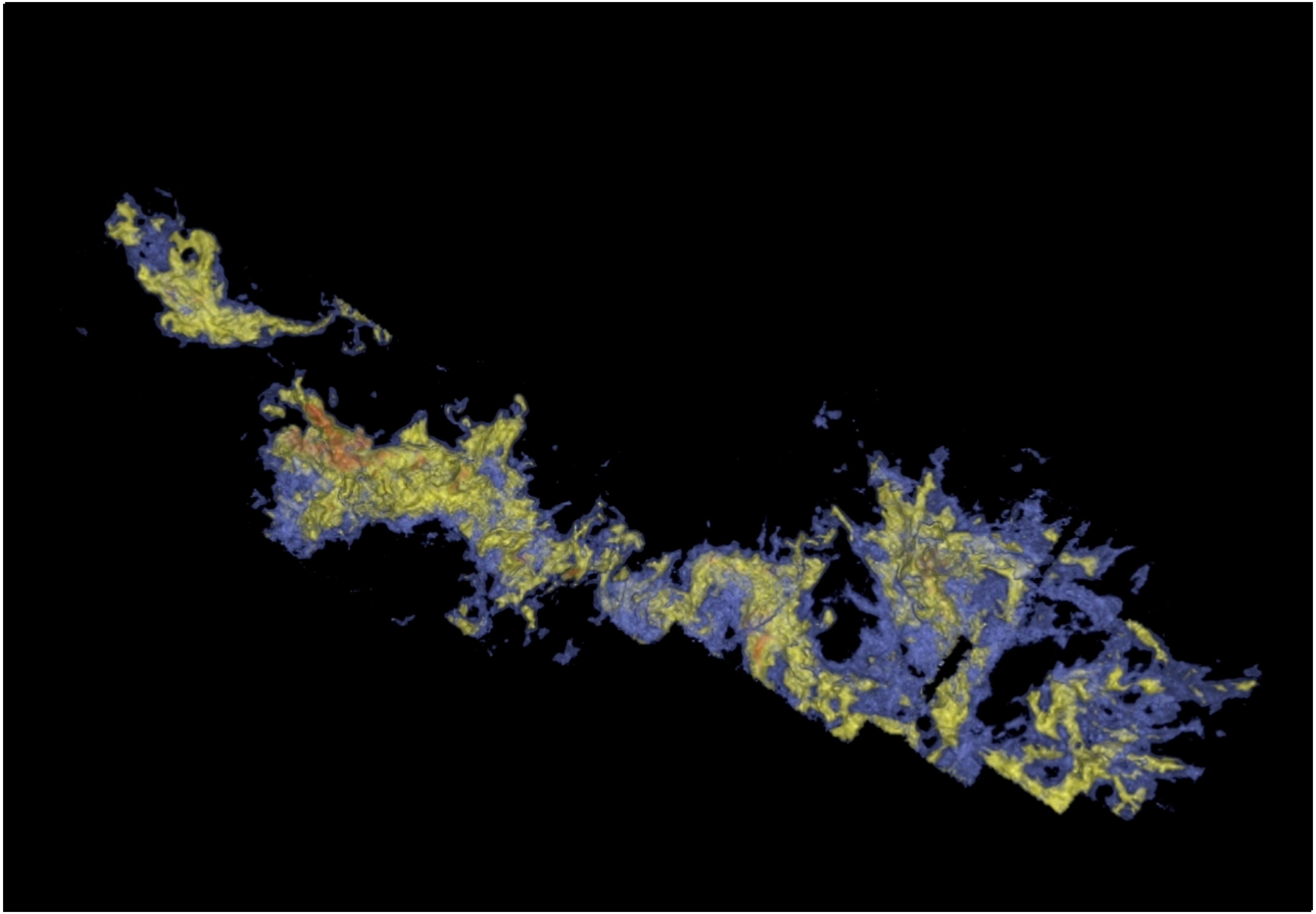
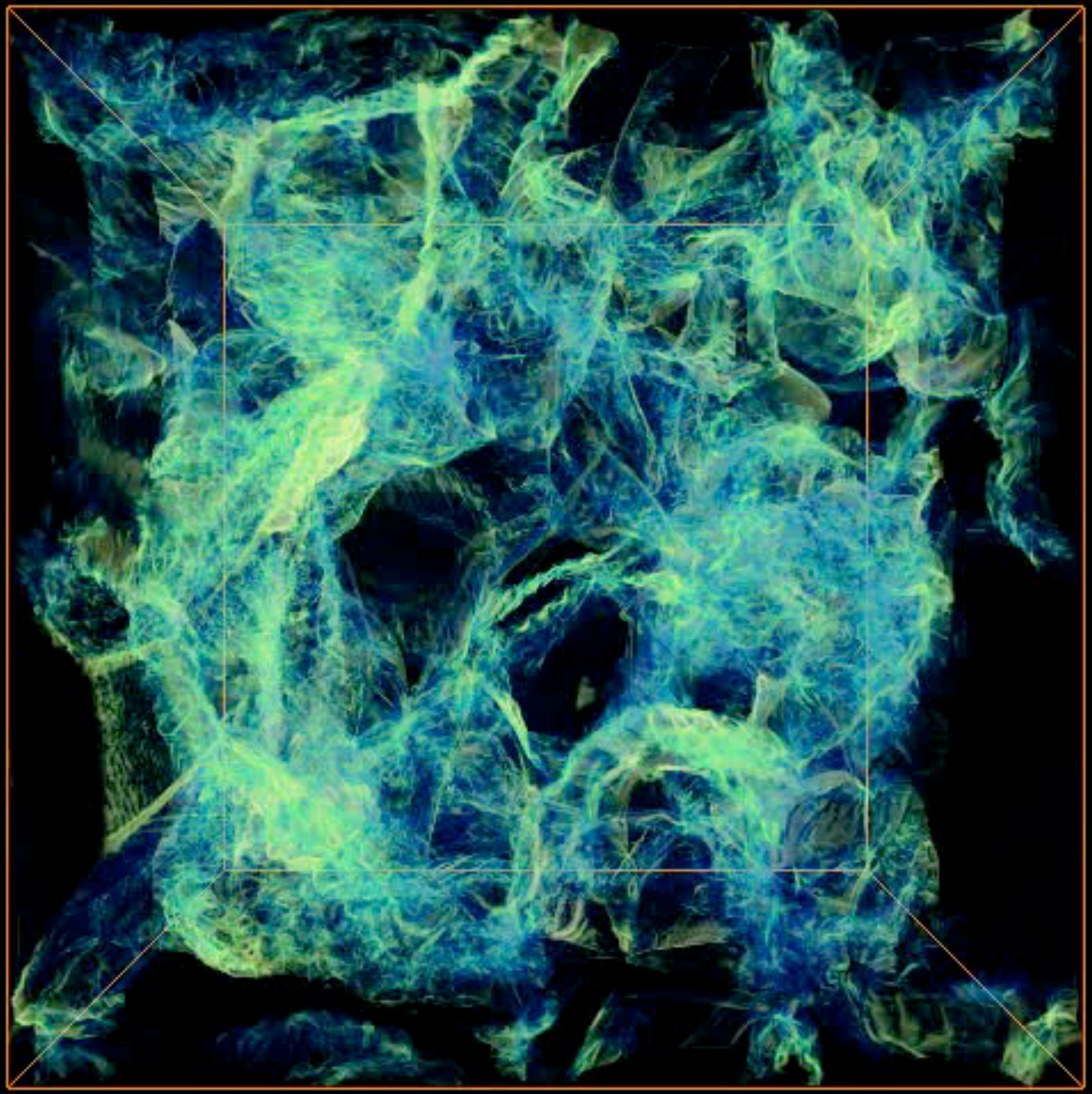


image from Alyssa Goodman: COMPLETE survey



Schmidt et al. (2009, A&A, 494, 127)

example: model of Orion cloud

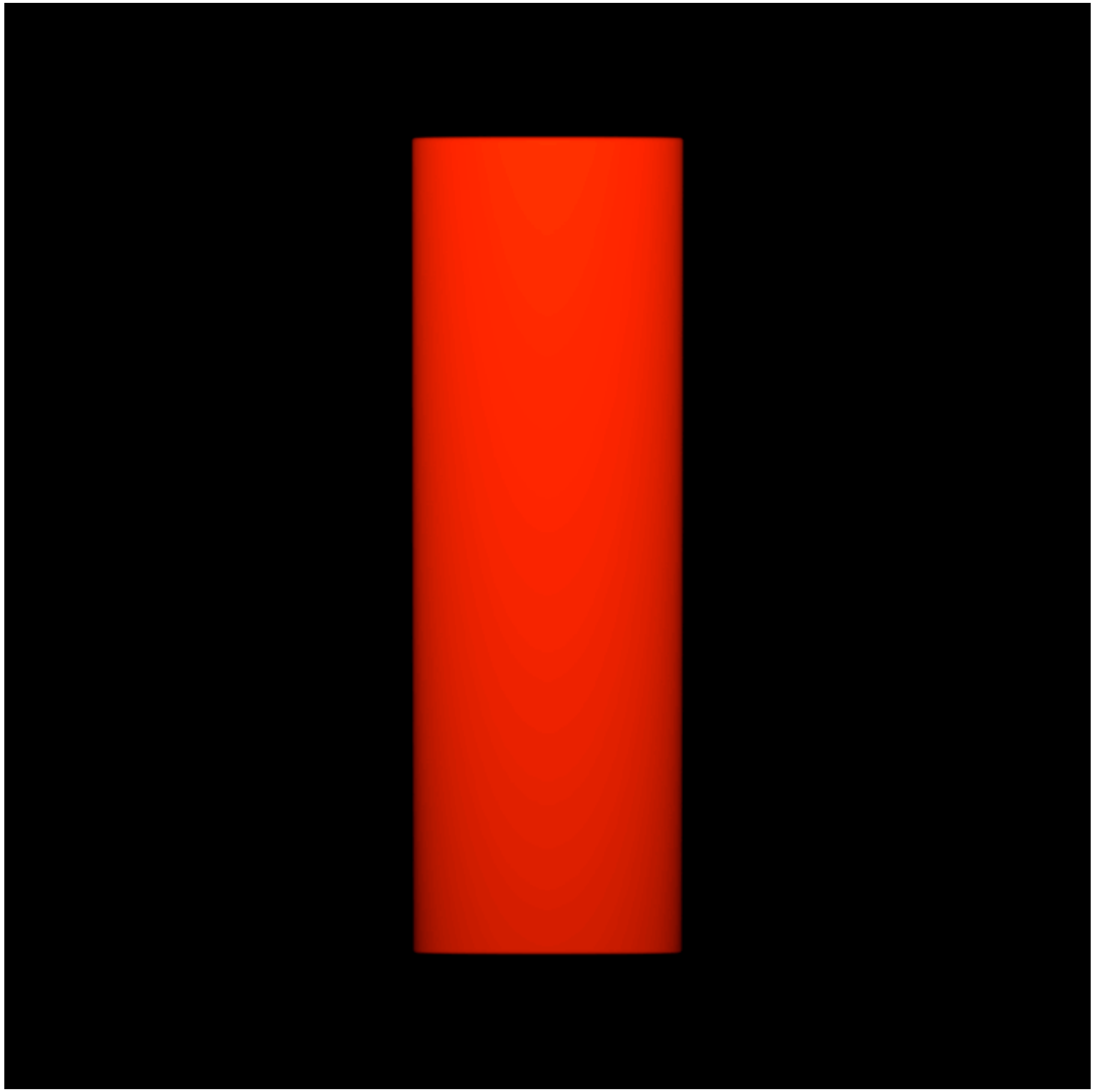
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

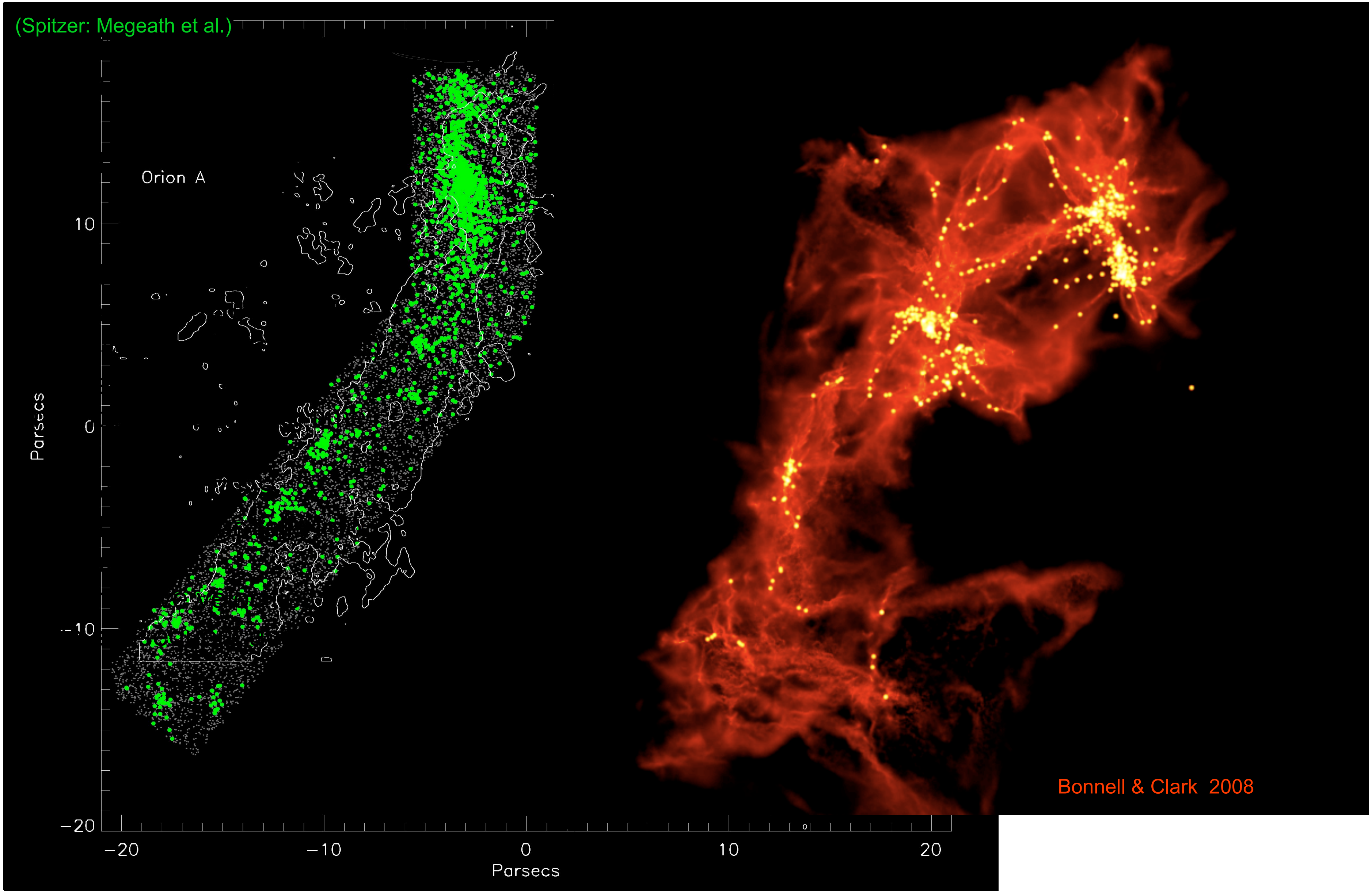
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



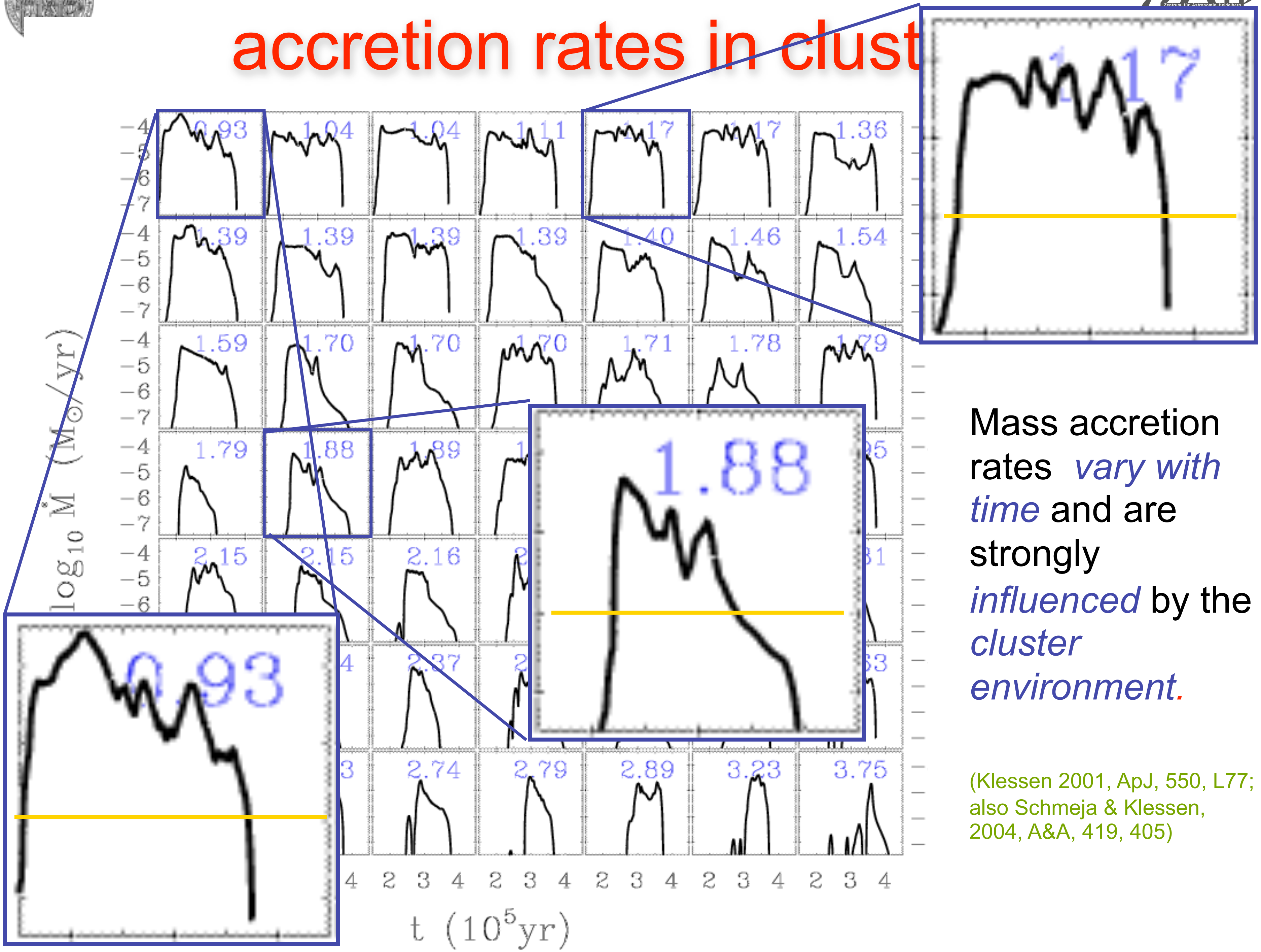
(Bonnell & Clark 2008)

example: model of Orion cloud


(Spitzer: Megeath et al.)

Bonnell & Clark 2008

accretion rates in clust



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)

stellar masses

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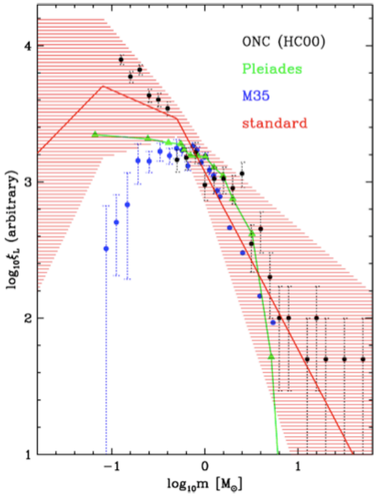

(Kroupa 2002)

stellar masses

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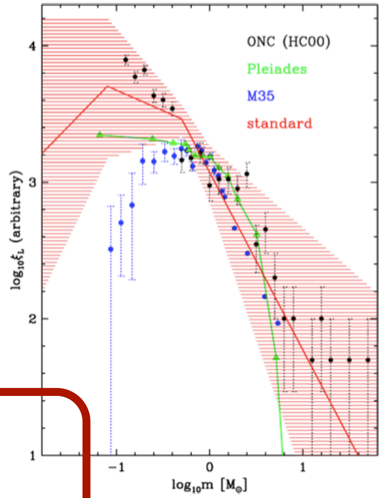
application to first star formation

(Kroupa 2002)



thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

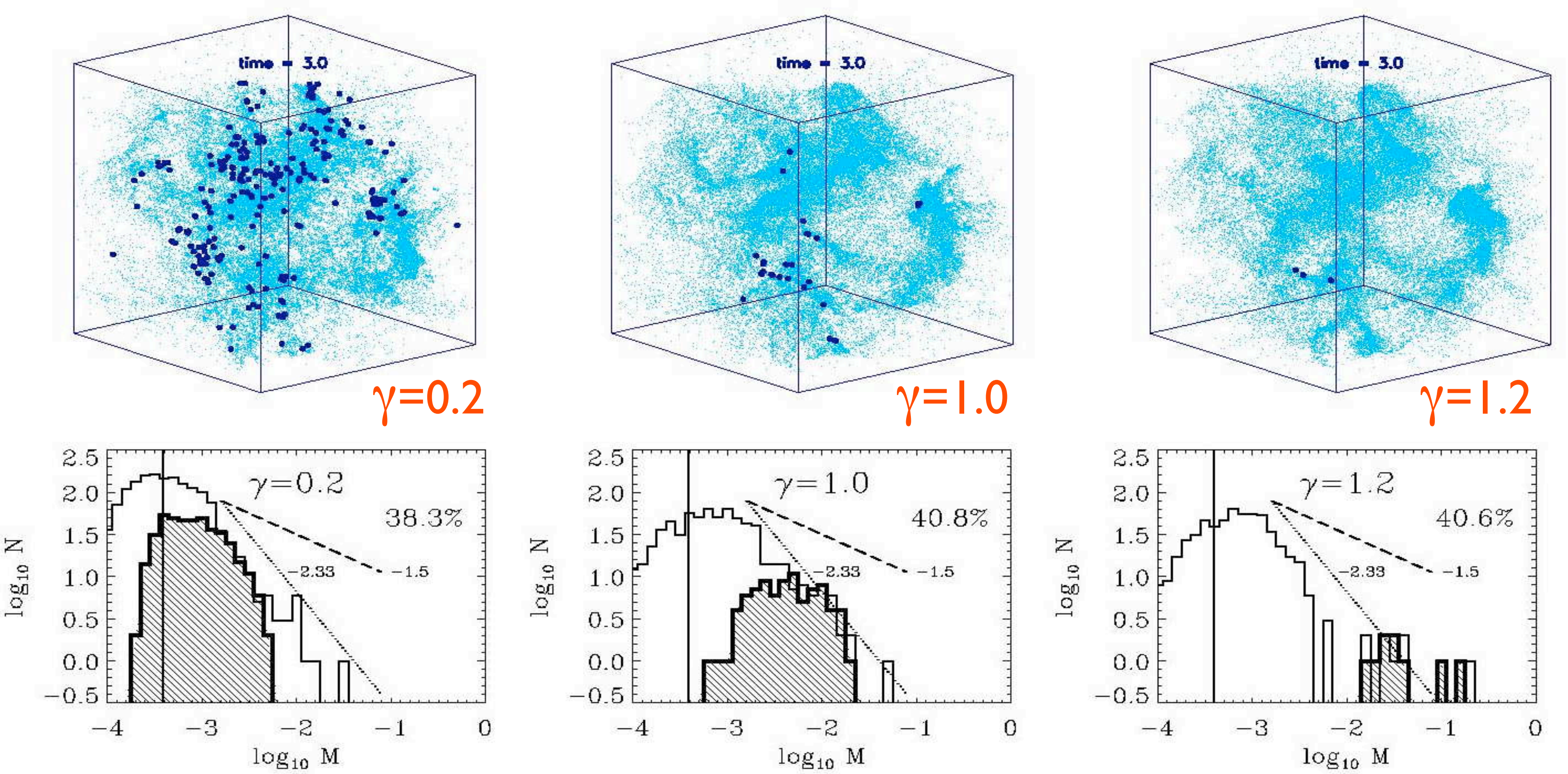
polytropic EOS: $p \propto \rho^{\gamma}$

$\gamma < 1$: dense cluster of low-mass stars

$\gamma > 1$: isolated high-mass stars

(see Li et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

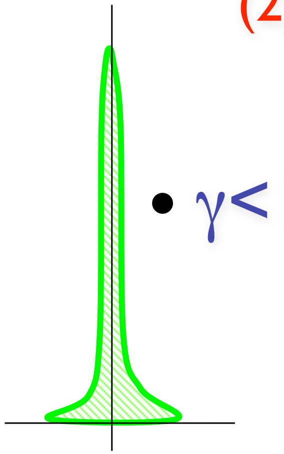
for γ>1 it is suppressed → formation of *isolated massive stars*

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

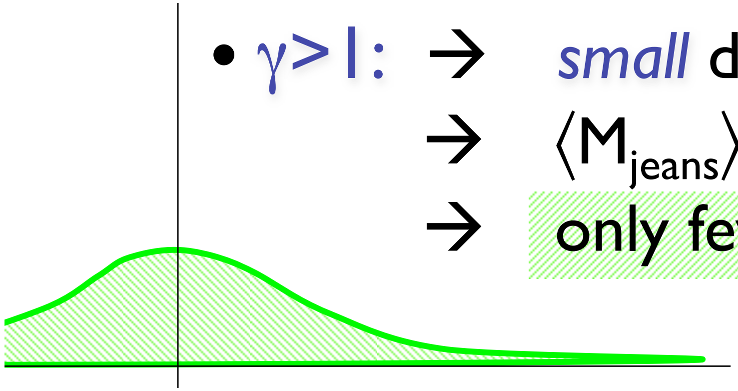
how does that work?

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

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

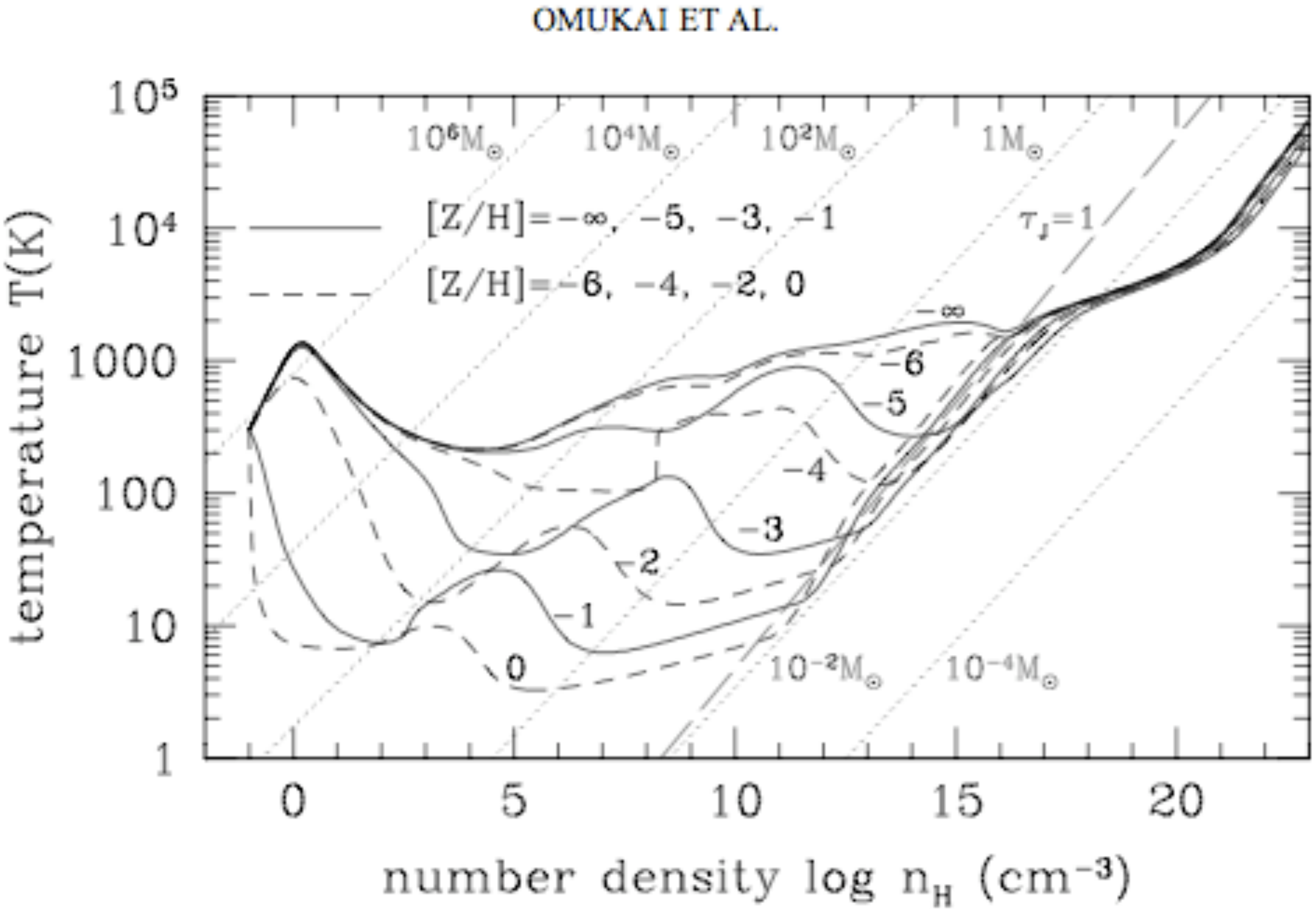


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



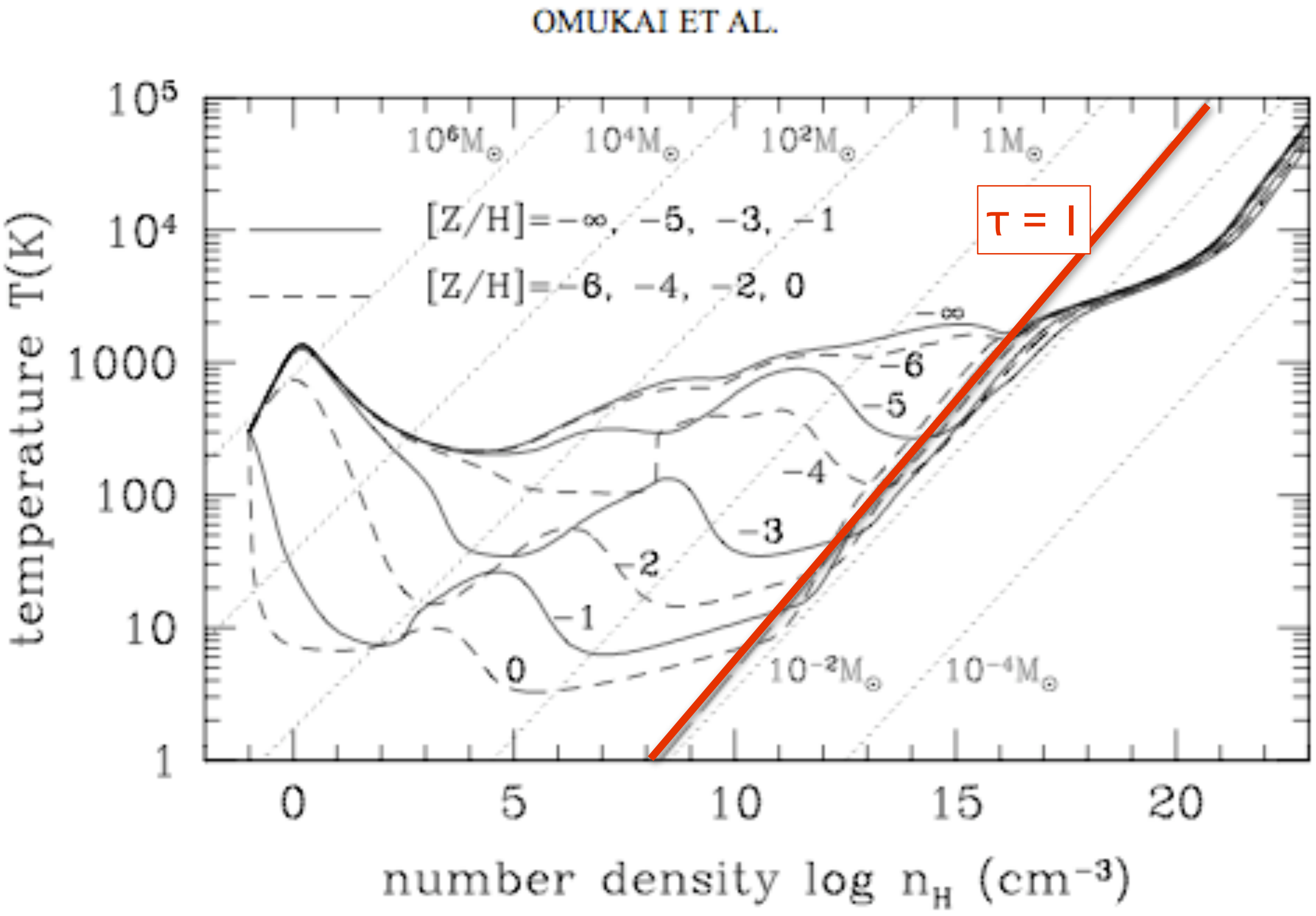
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



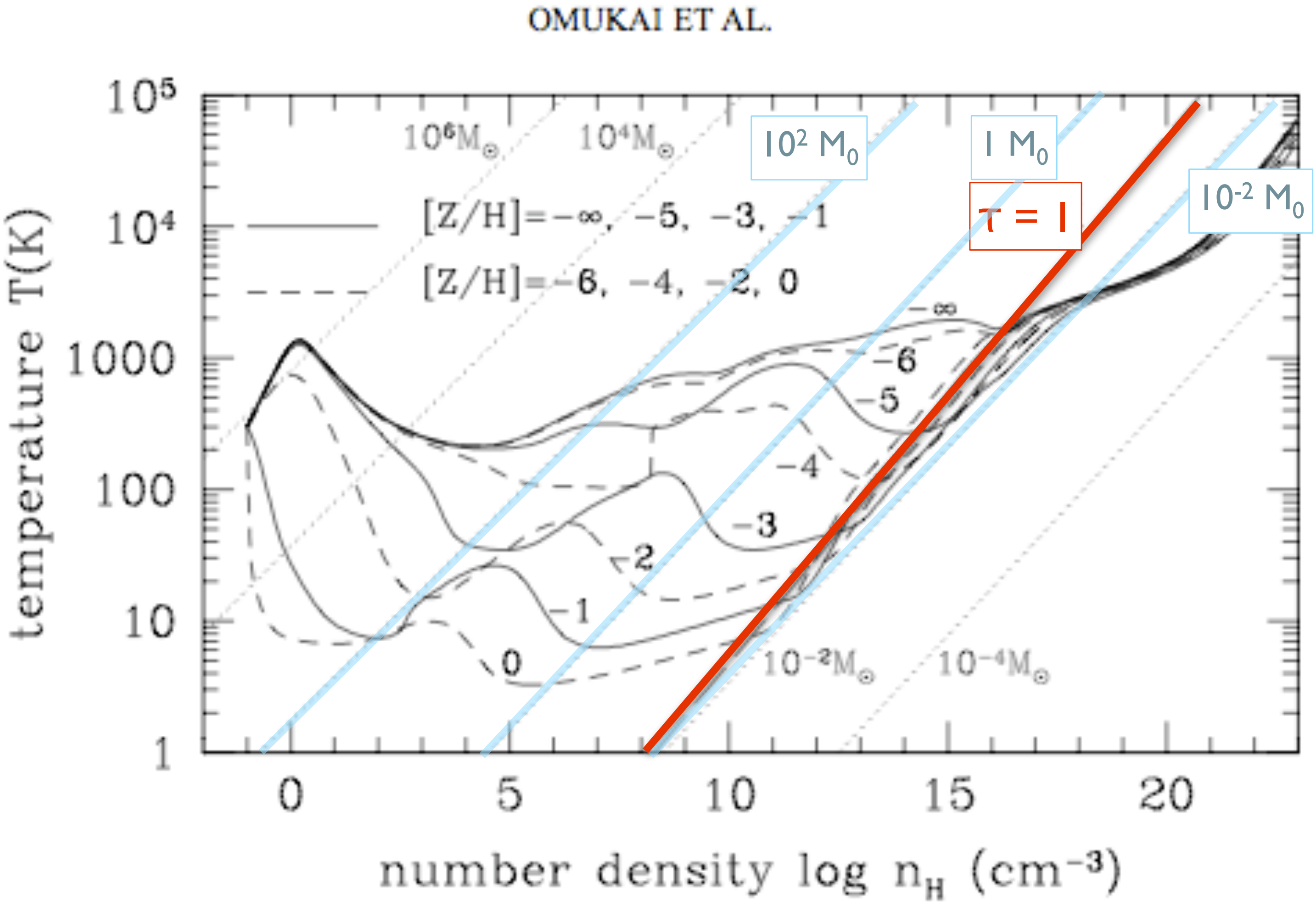
(Omukai et al. 2005)

EOS as function of metallicity



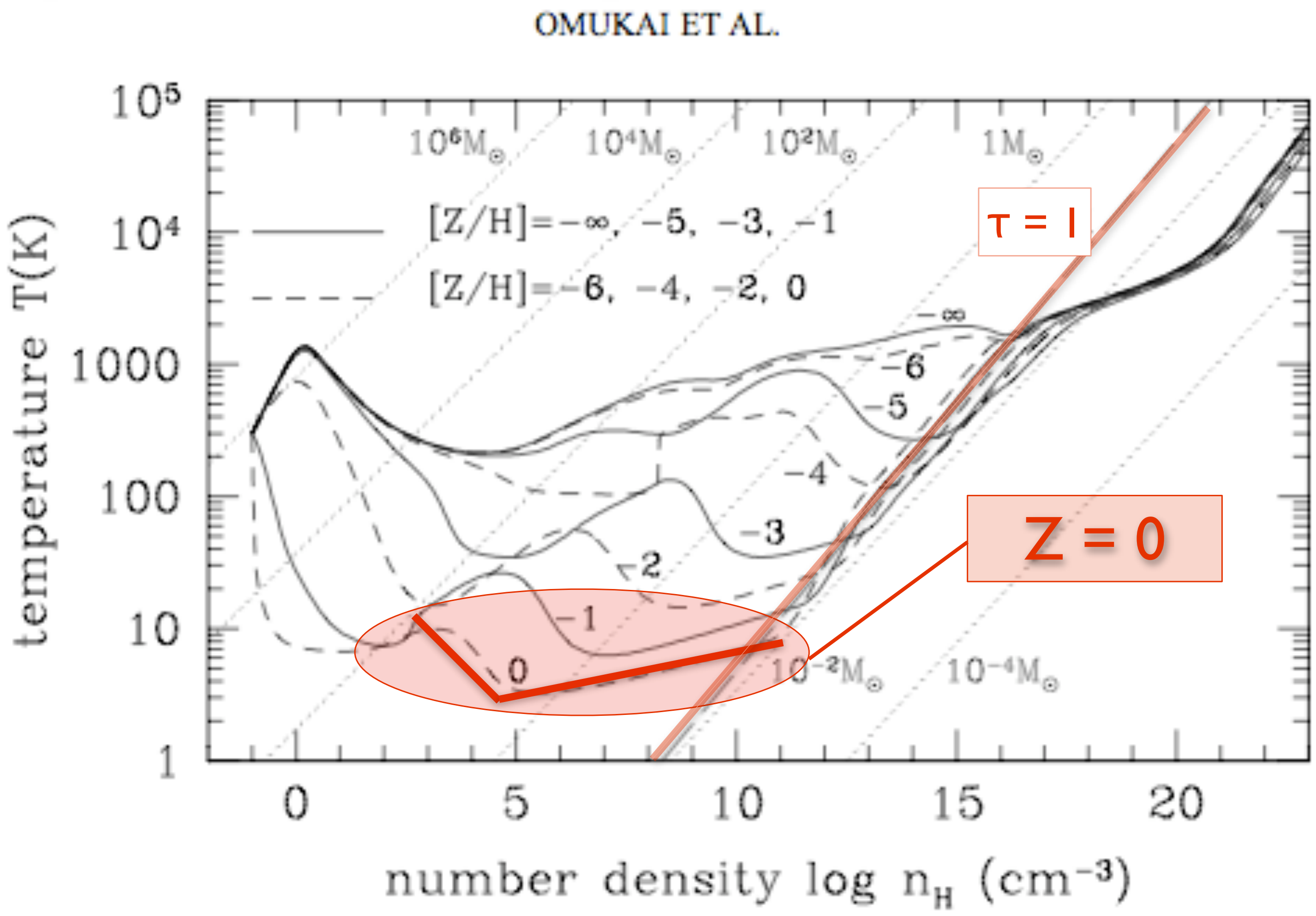
(Omukai et al. 2005)

EOS as function of metallicity



(Omukai et al. 2005)

present-day star formation

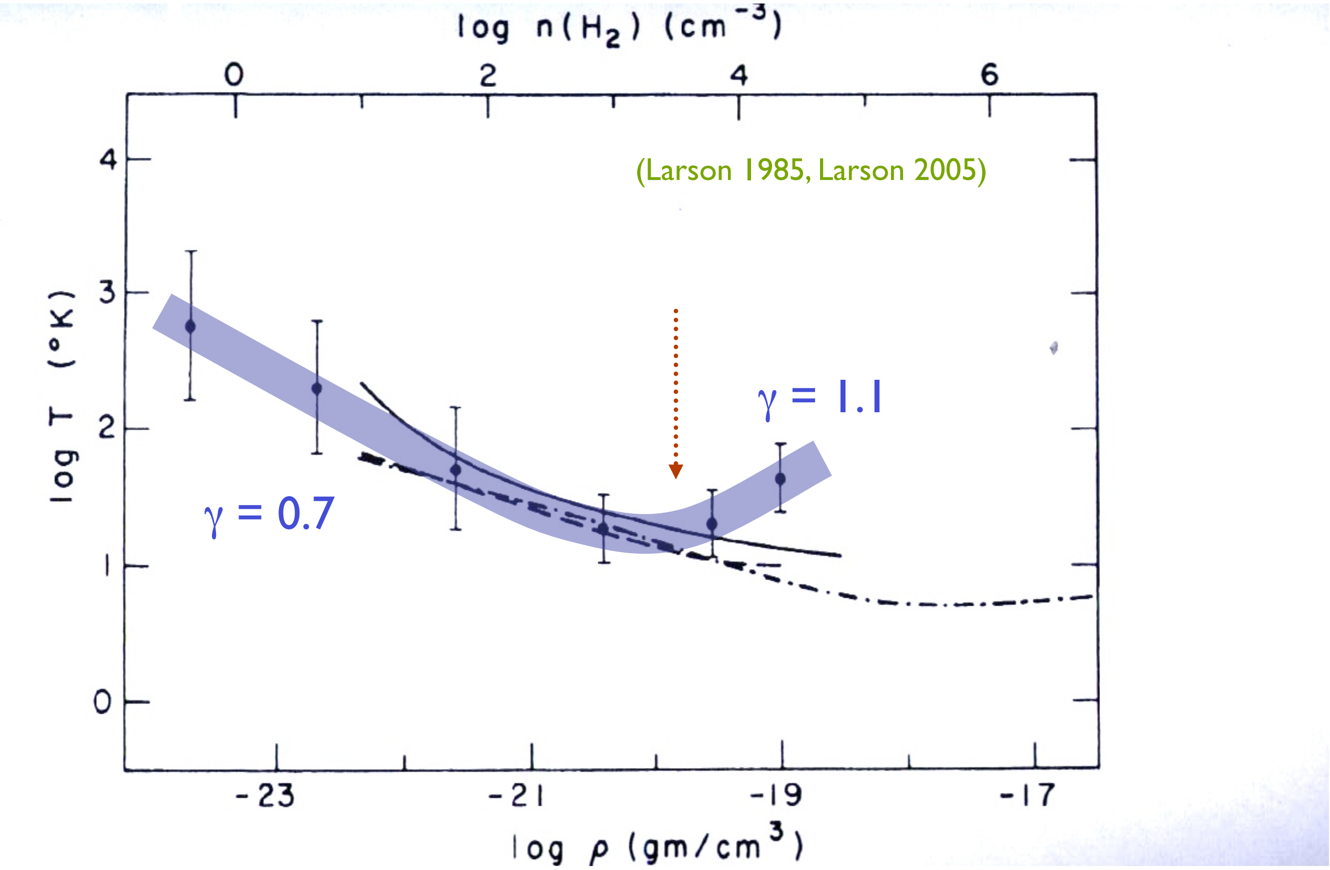


$\tau = 1$

Z = 0

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

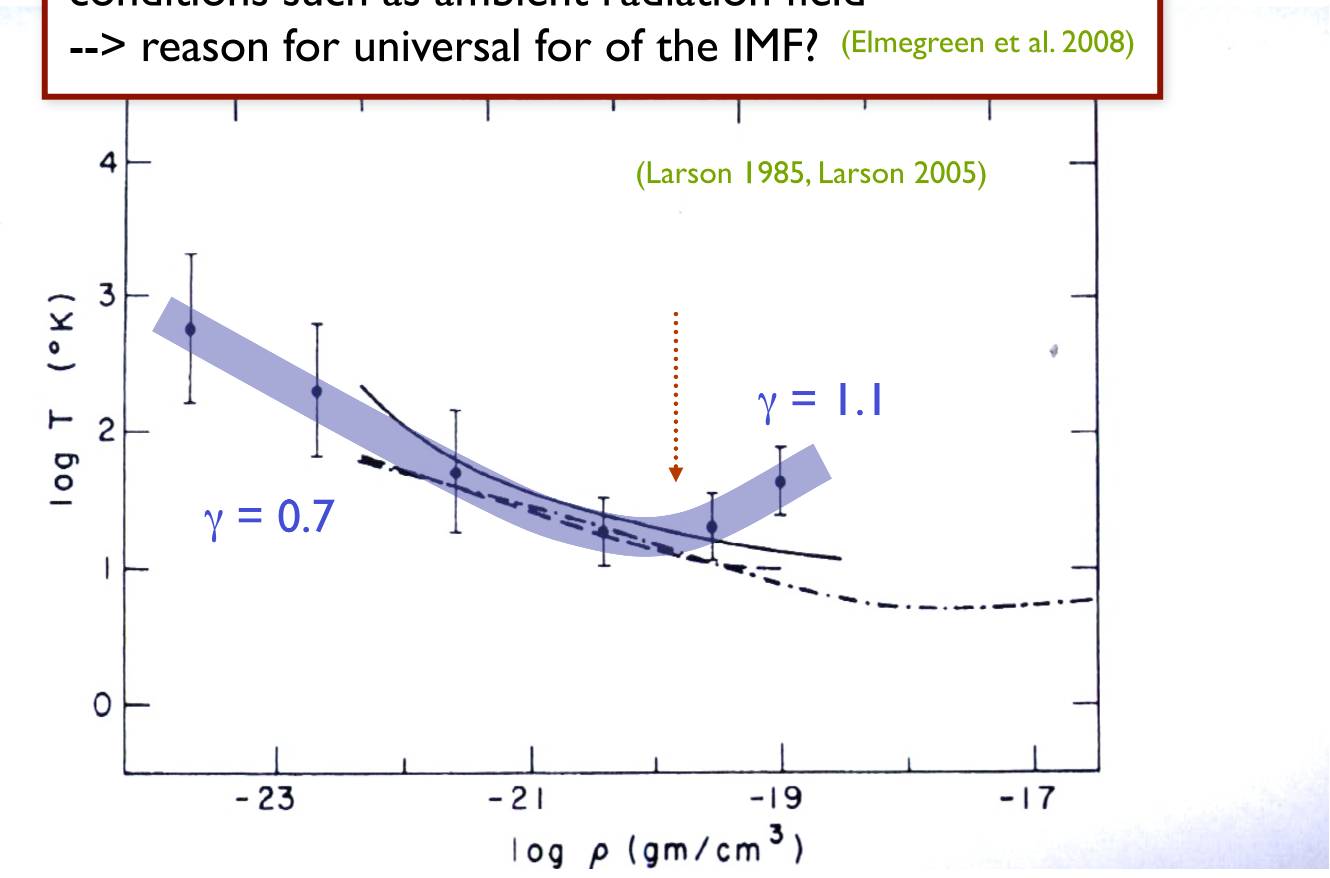
present-day star formation



(Larson 1985, Larson 2005)

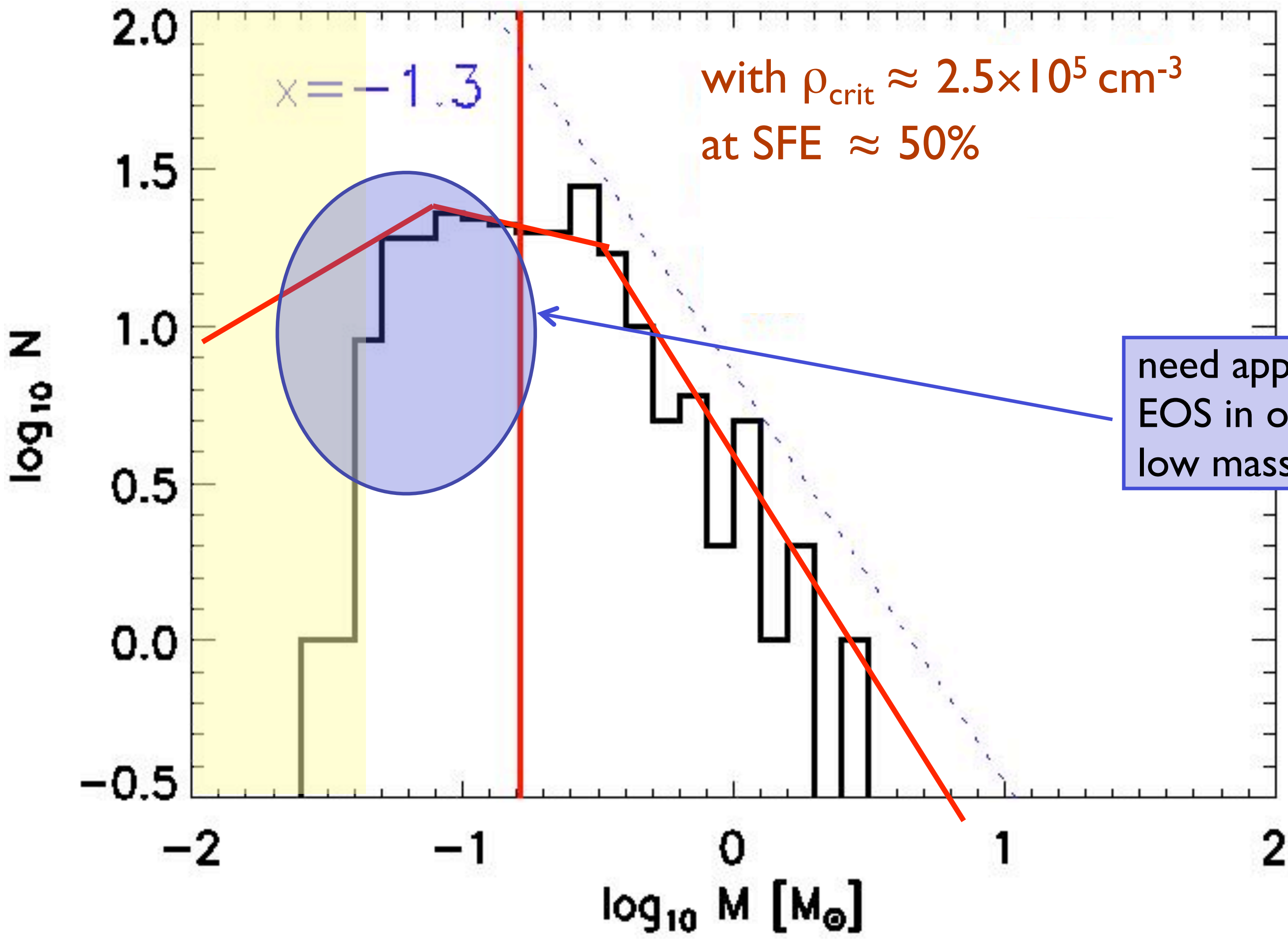
present-day star formation

This kink in EOS is very insensitive to environmental conditions such as ambient radiation field
--> reason for universal for of the IMF? (Elmegreen et al. 2008)



(Larson 1985, Larson 2005)

IMF in nearby molecular clouds



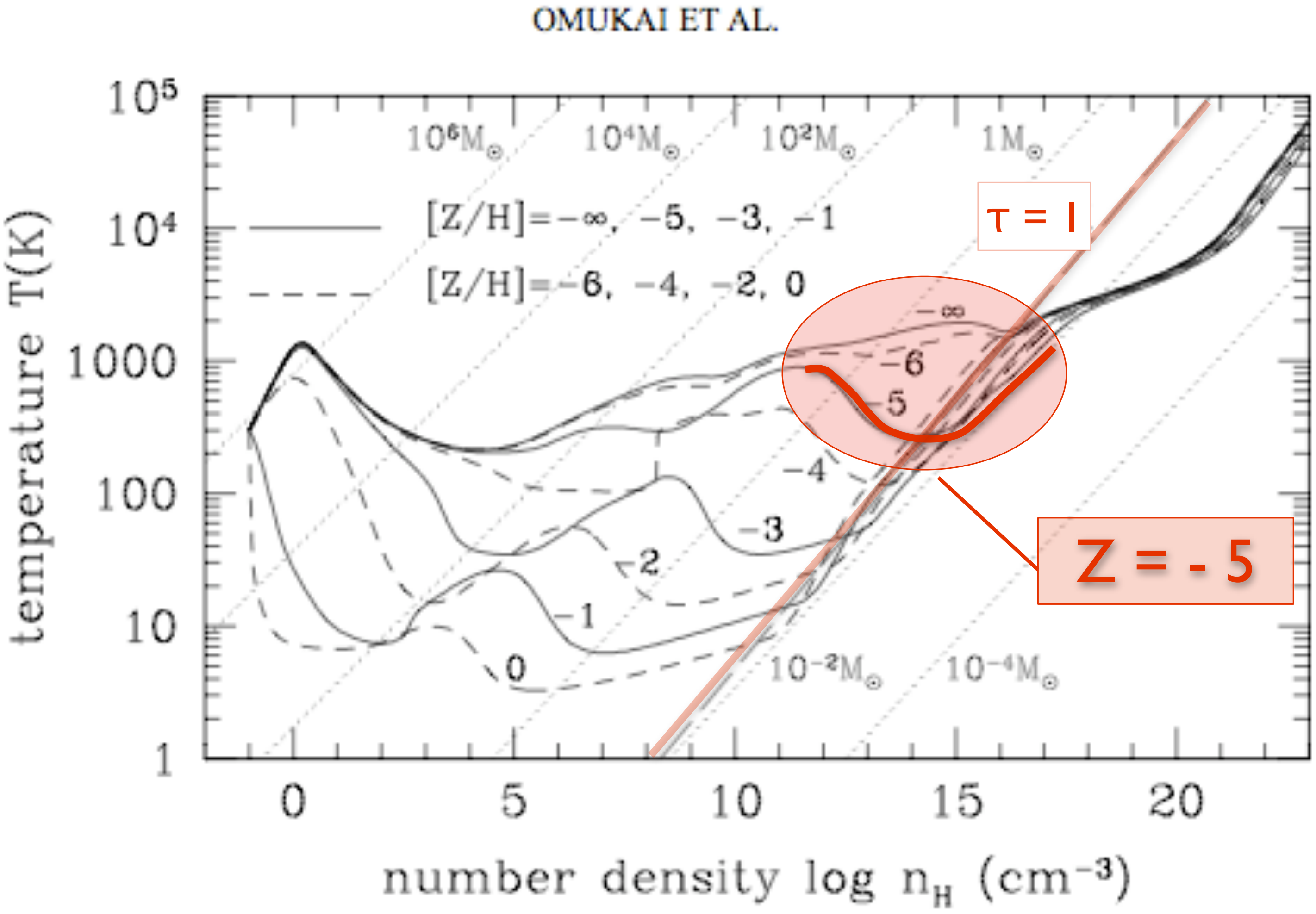
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

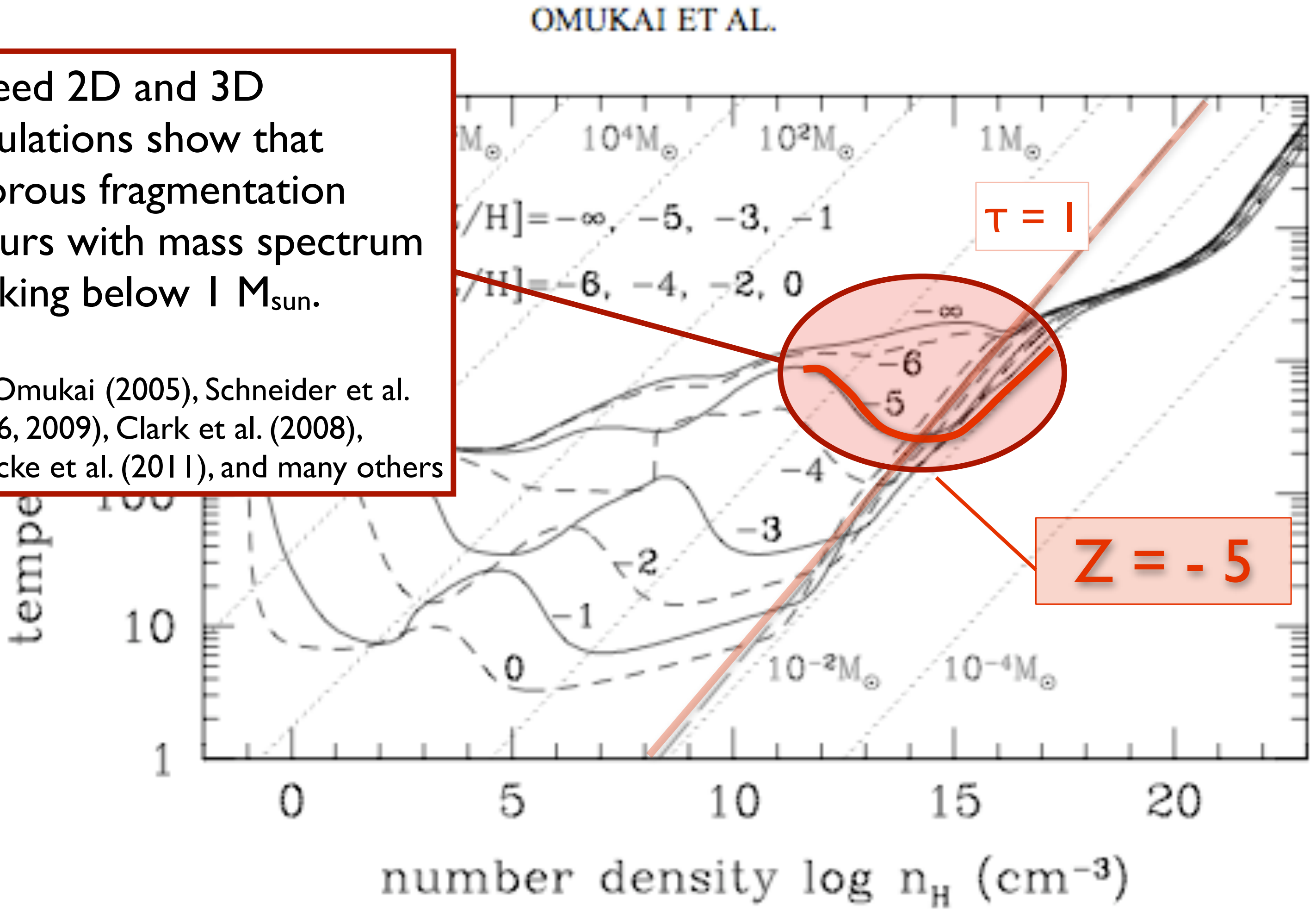
(Jappsen et al. 2005, A&A, 435, 611)

transition: Pop III to Pop II.5



(Omukai et al. 2005)

transition: Pop III to Pop II.5

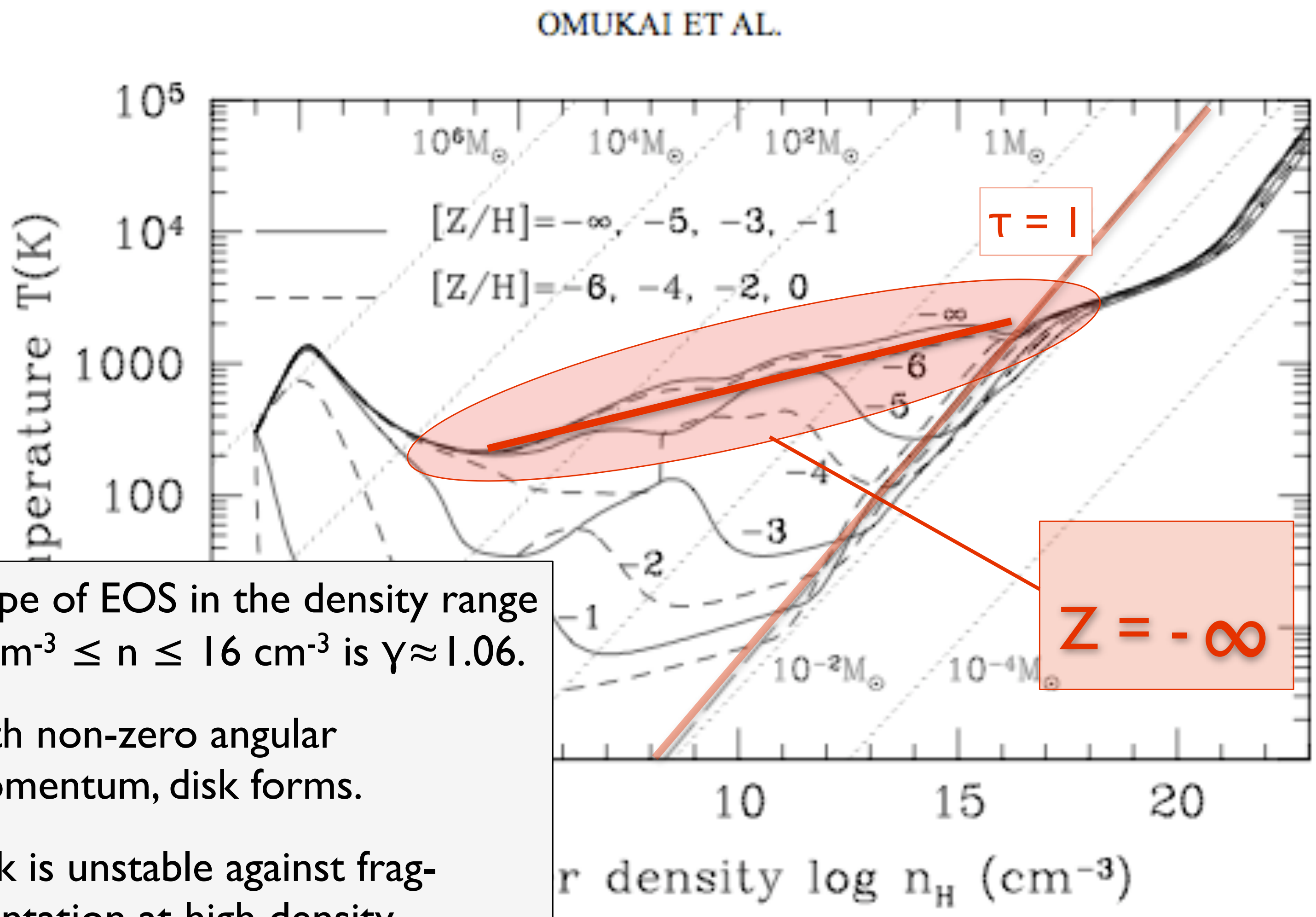


indeed 2D and 3D simulations show that vigorous fragmentation occurs with mass spectrum peaking below 1 M_{sun}.

see Omukai (2005), Schneider et al. (2006, 2009), Clark et al. (2008), Dopcke et al. (2011), and many others

(Omukai et al. 2005)

metal-free star formation



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

(Omukai et al. 2005)

metal-free star formation

- most current numerical simulations of Pop III star formation predict very massive objects

  (e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)

- similar for theoretical models (e.g. Tan & McKee 2004)

- there are some first hints of fragmentation, however

  (Turk et al. 2009, Stacy et al. 2010)

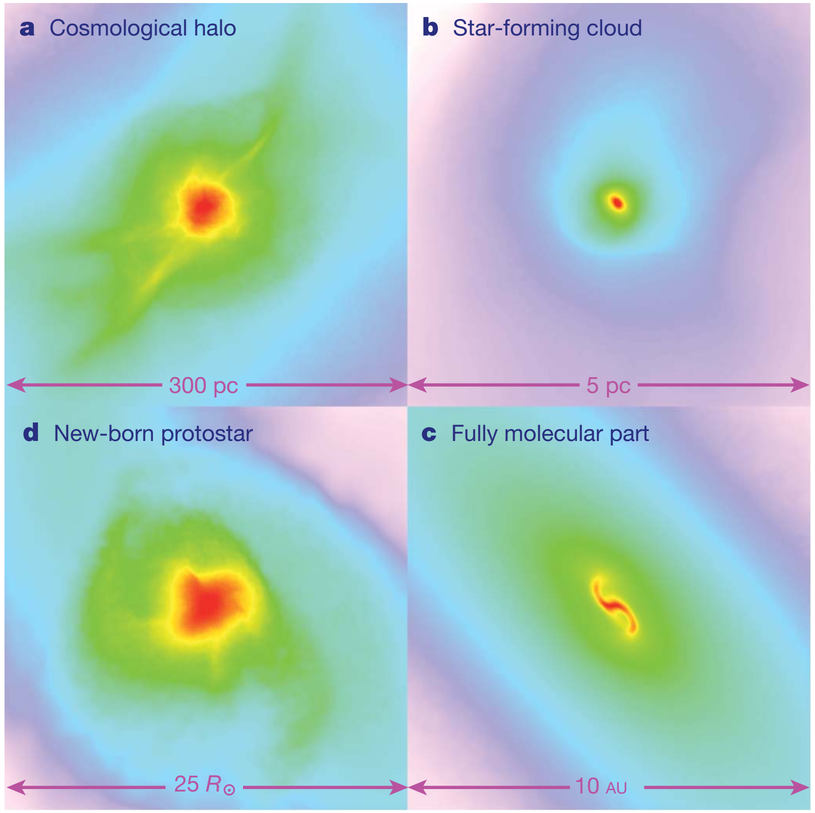
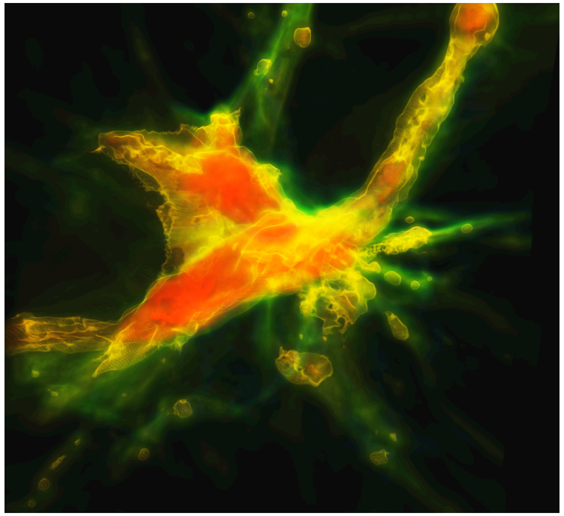


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming cloud; **c**, the central part of the fully molecular core; and **d**, the final protostar. Reproduced by permission of the AAAS (from ref. 20).

(Yoshida et al. 2008, Science, 321, 669)

turbulence in Pop III halos

- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*, just like in present-day star formation



(Greif et al. 2008)

turbulence in Pop III halos

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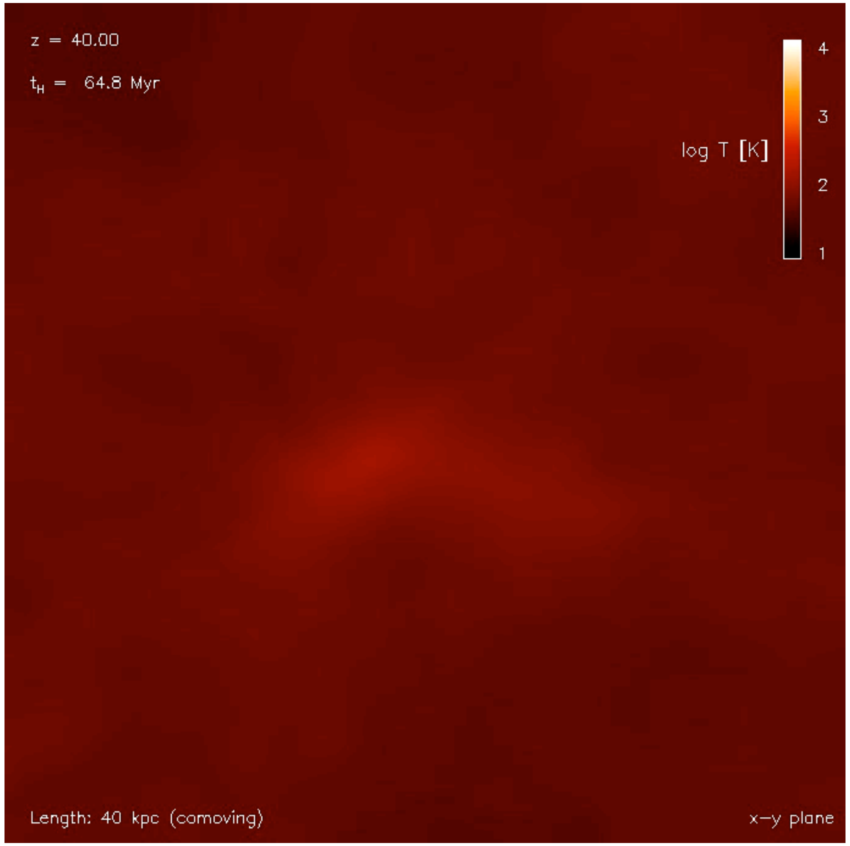
- speculation: *differences in stellar mass function*, just like in present-day star formation

turbulence developing in an atomic cooling halo



(Greif et al. 2008)

multiple Pop III stars in halo

- parameter study with different strength of turbulence using SPH: study Pop III.1 and Pop III.2 case (Clark et al., 2011a, ApJ, 727, 110)
- 2 very high resolution studies of Pop III star formation in cosmological context
  - SPH: Clark et al. 2011b, Science, 311, 1040
  - Arepo: Greif et al. 2011a, ApJ, in press (arXiv:1101.5491)
  - complementary approaches with interesting similarities and differences....

SPH study: face on look at accretion disk

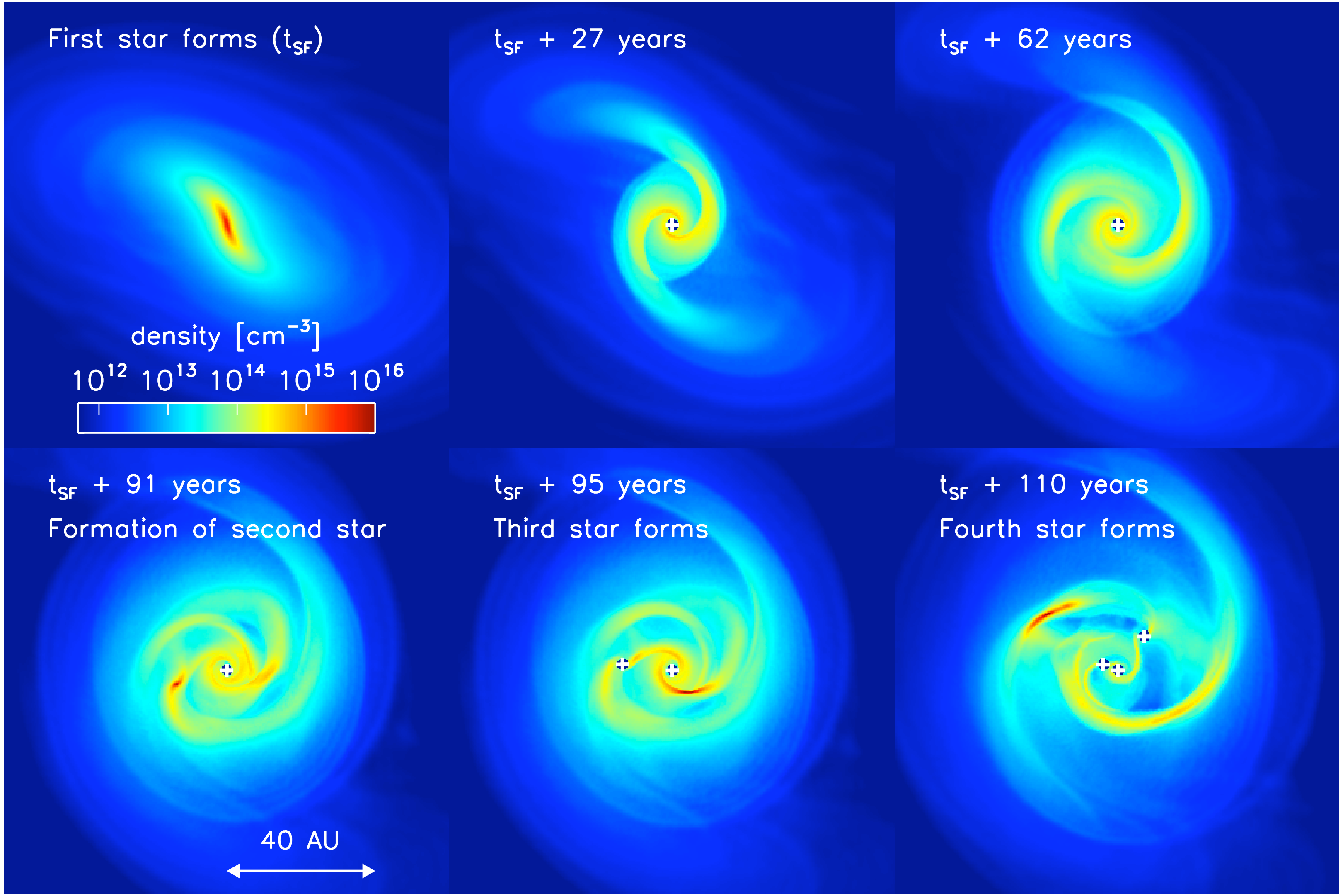


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.

(Clark et al. 2011b, Science, 331, 1040)

SPH study: some disk parameters

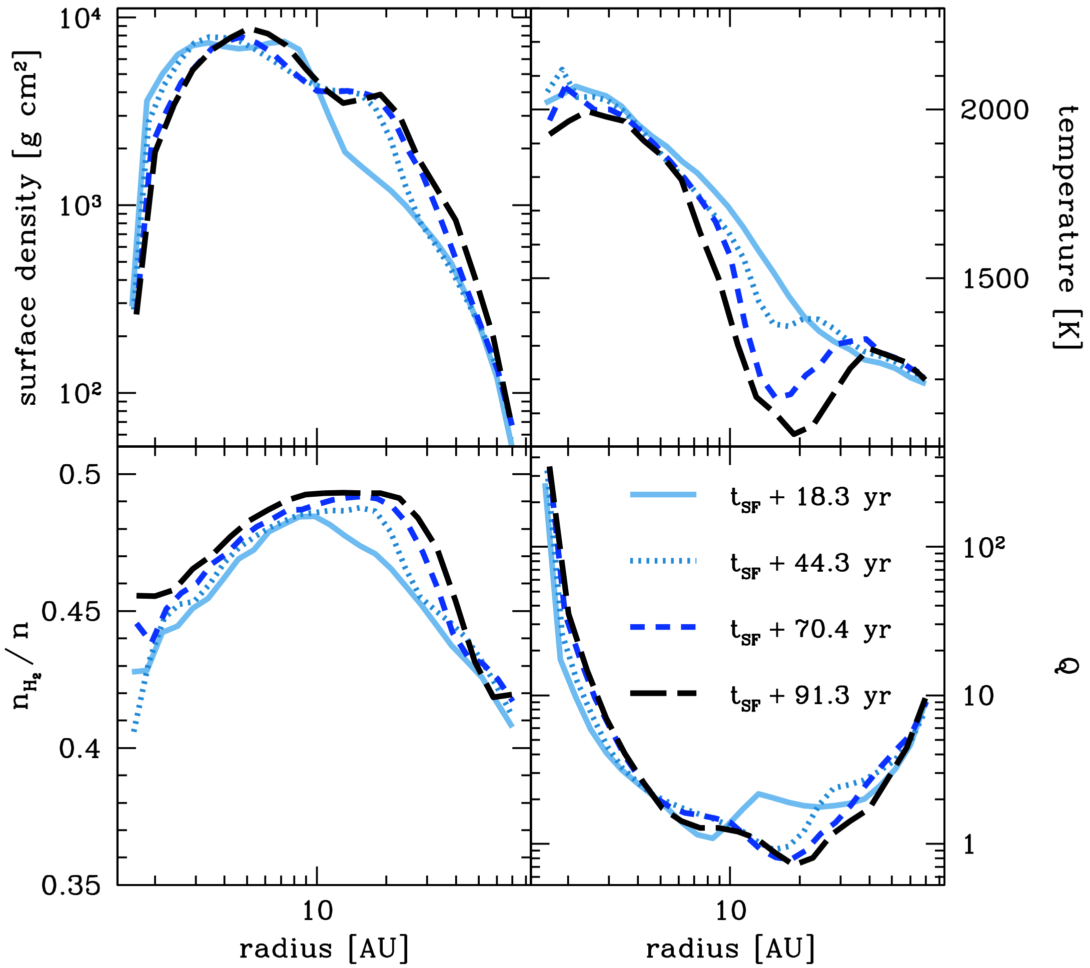


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi G\Sigma$, where c_s is the sound speed and κ is the epicyclic frequency. Beause our disk is Keplerian, we adopted the standard simplification, and replaced κ with the orbital frequency. The molecular fraction is defined as the number density of hydrogen molecules (n_{H_2}), divided by the number density of hydrogen nuclei (n), such that fully molecular gas has a value of 0.5

(Clark et al. 2011b, Science, 331, 1040)

SPH study: mass accretion onto disk and onto protostars

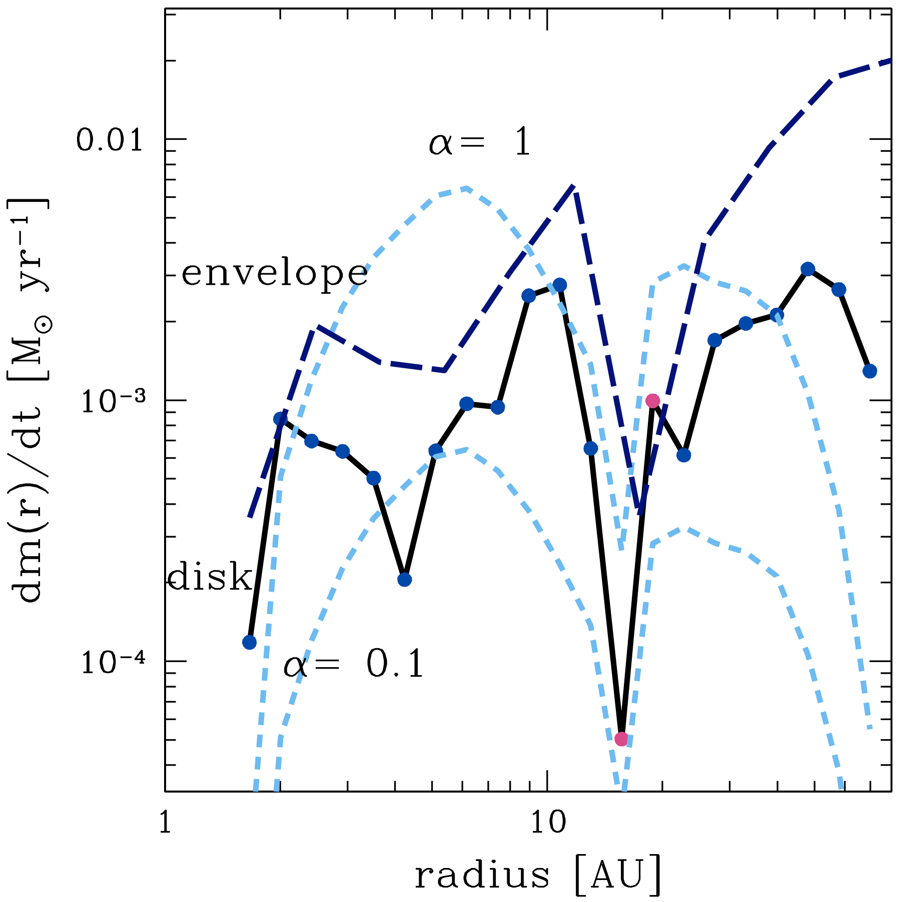


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure of the material flowing through *and onto* the disk at each radius. Both are shown at the onset of disk fragmentation. In the case of the disk accretion we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink (further details can be found in Section 6 of the online material). The light blue dashed lines show the accretion rates expected from an 'alpha' (thin) disk model, where $\dot{M}(r) = 3\,\pi\,\alpha\,c_{\rm s}(r)\,\Sigma(r)\,H(r)$, with two global values of alpha and where $c_{\rm s}(r)$, $\Sigma(r)$, and $H(r)$ are (respectively) the sound speed, surface density and disk thickness at radius r.

(Clark et al. 2011b, Science, 331, 1040)

SPH study: comparison of all relevant heating and cooling processes

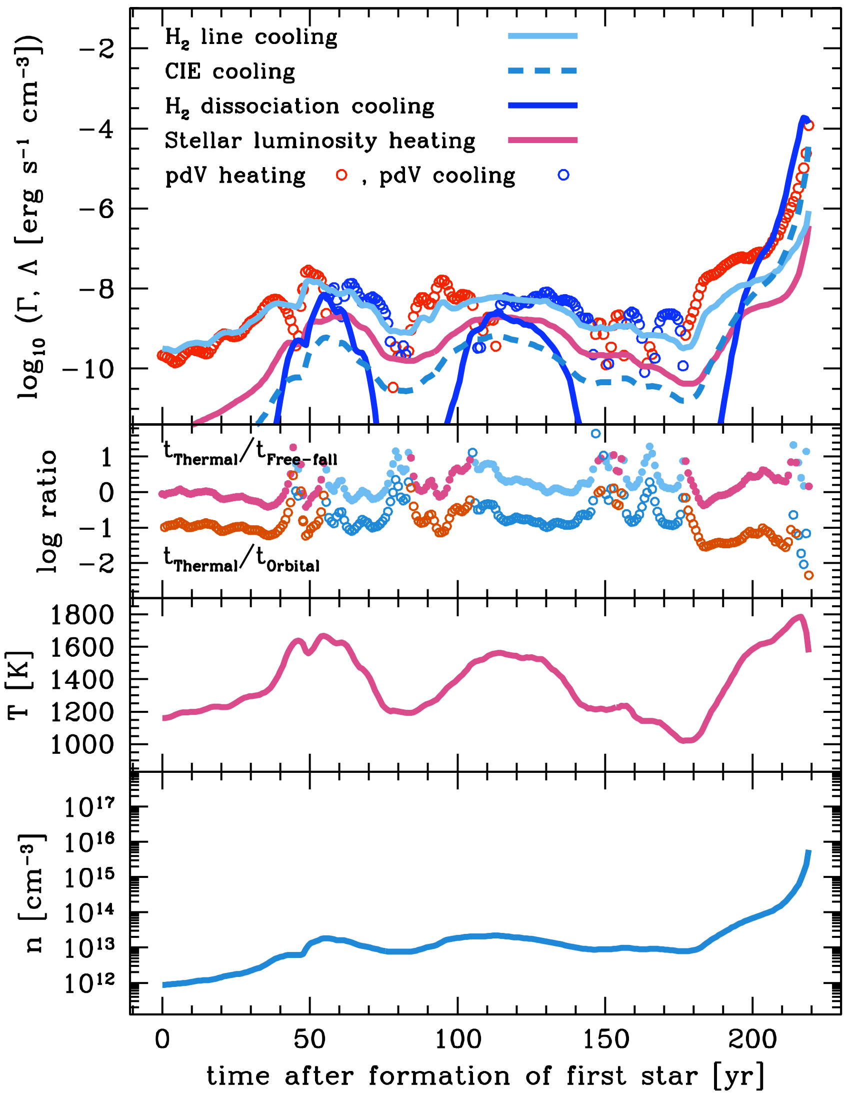
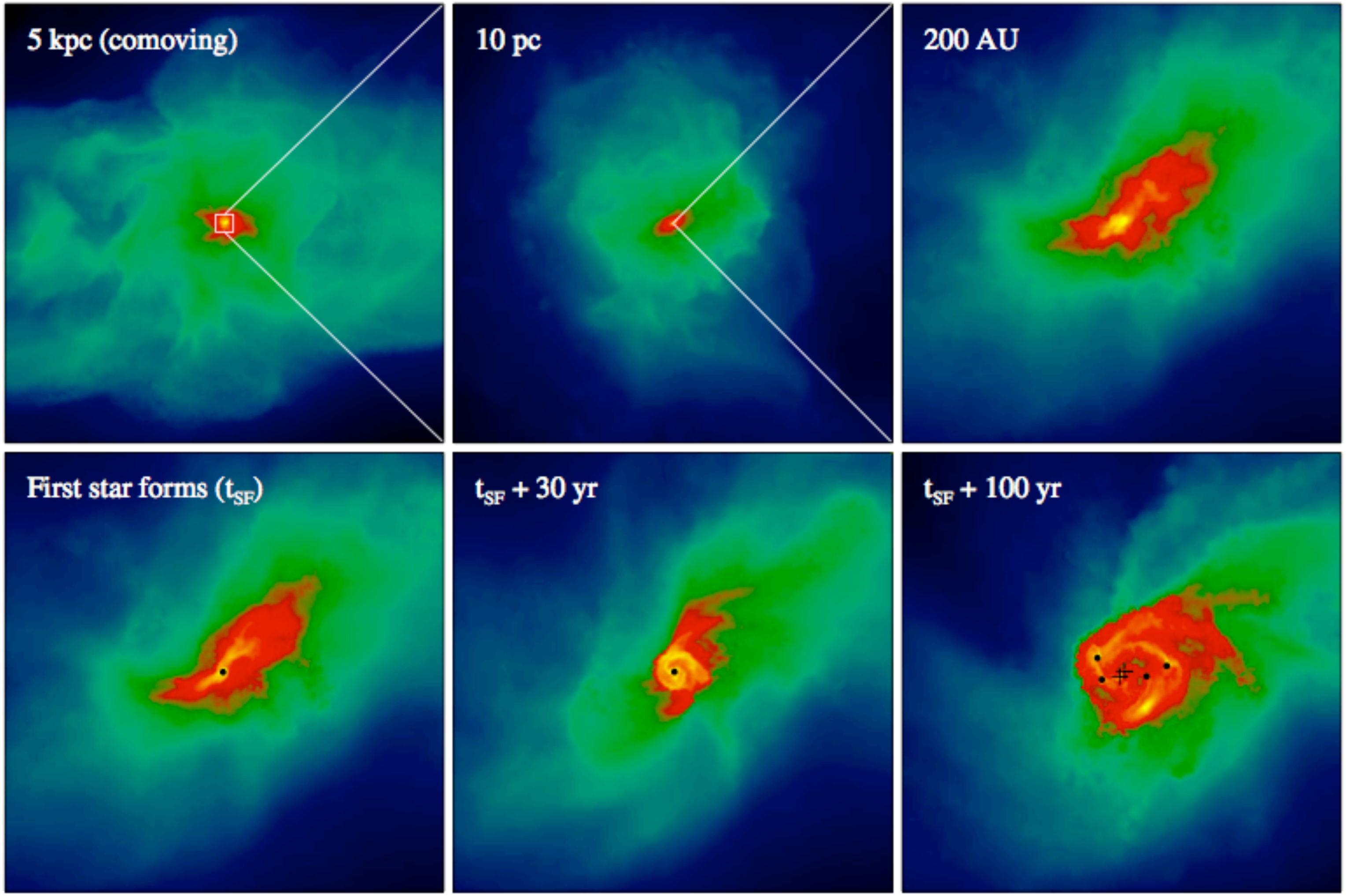


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, t_{thermal}, to the free-fall timescale, t_{ff}, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated in blue, while periods when the gas is heating are indicated in red. Lower line: ratio of t_{thermal} to the orbital timescale, t_{orbital}, for the same set of SPH particles (c) Temperature evolution of the gas that forms the second sink (d) Density evolution of the gas that forms the second sink

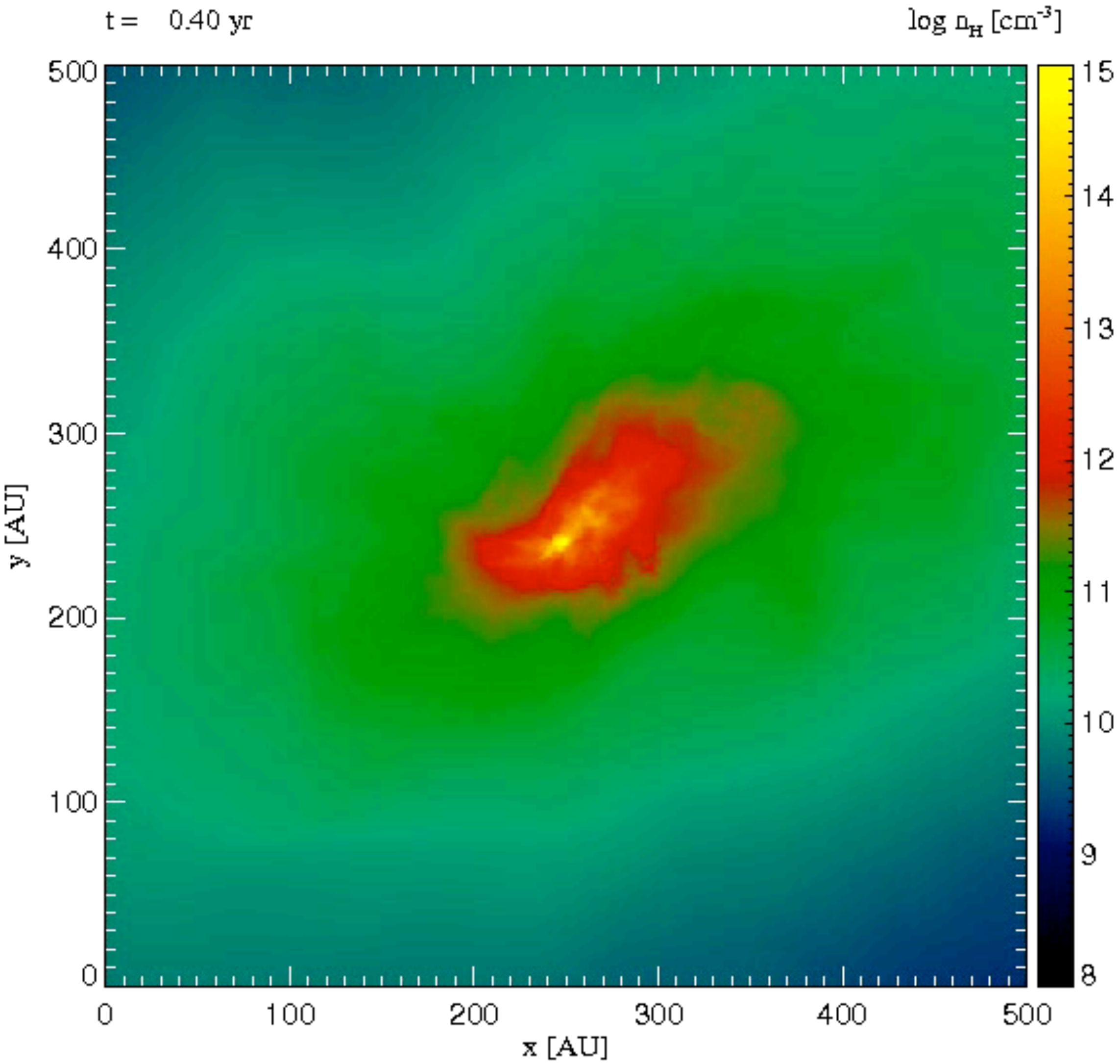
(Clark et al. 2011b, Science, 331, 1040)

Arepo study: surface density at different times



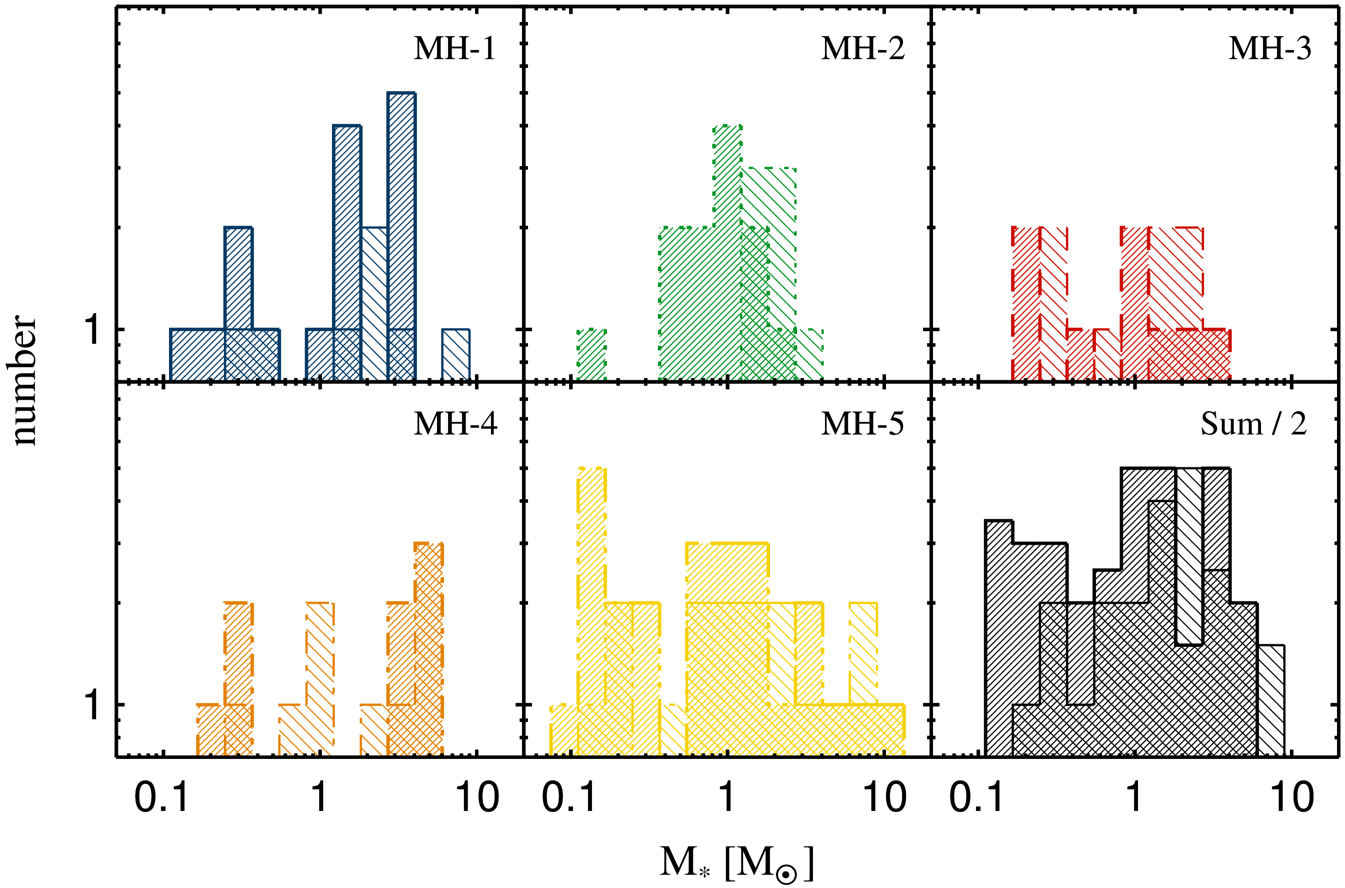
one out of five halos

(Greif et al. 2011a, ApJ, in press, arXiv:1101.5491)



(Greif et al. 2011a, ApJ, in press, arXiv:1101.5491)

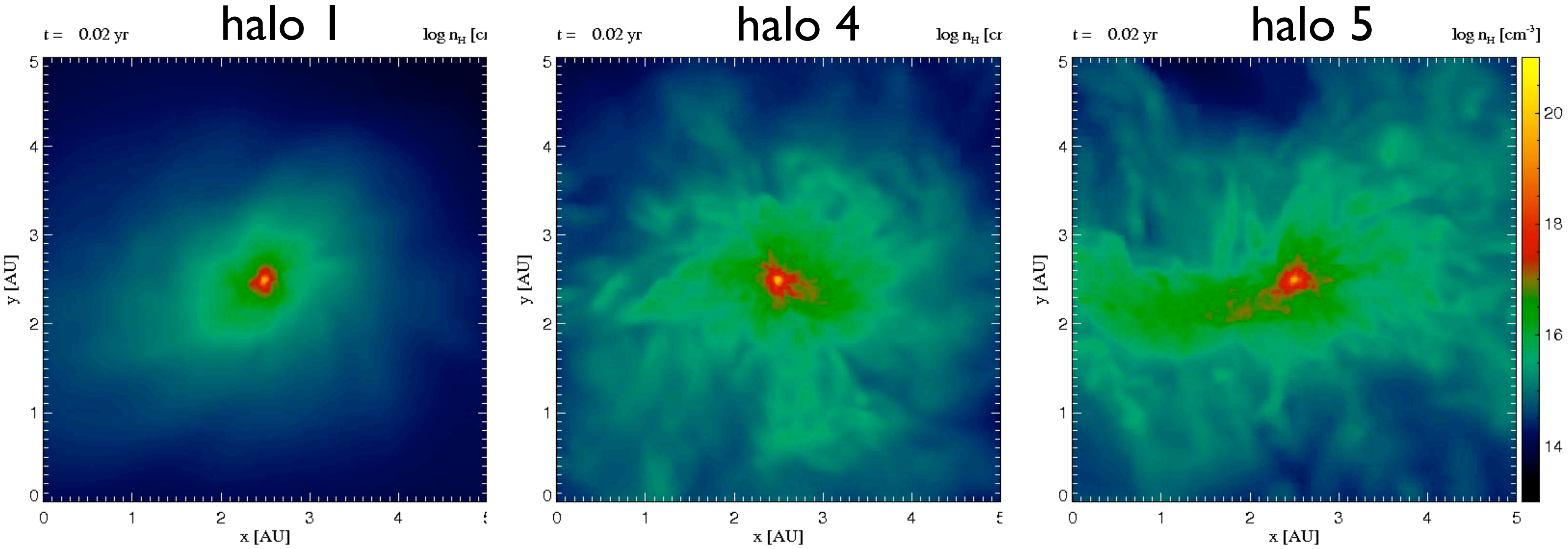
Arepo study: mass spectrum of fragments



(Greif et al. 2011a, ApJ, in press, arXiv:1101.5491)

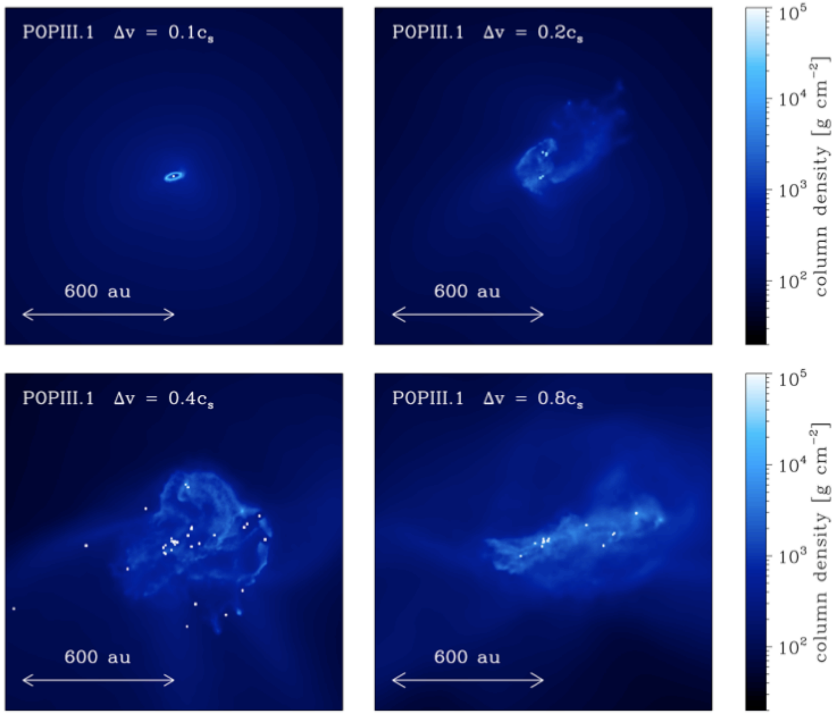
brand-new “sinkless” calculations

10 years need 1 month on the computer
--> we will never be able to follow full accretion history

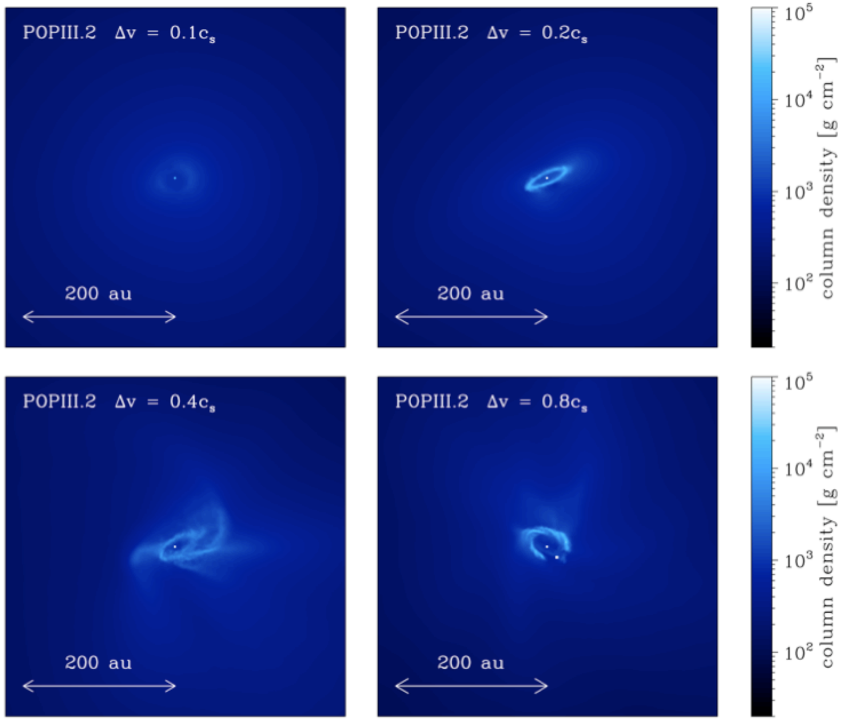


(Greif et al. in preparation)

fragmentation continues to larger scales



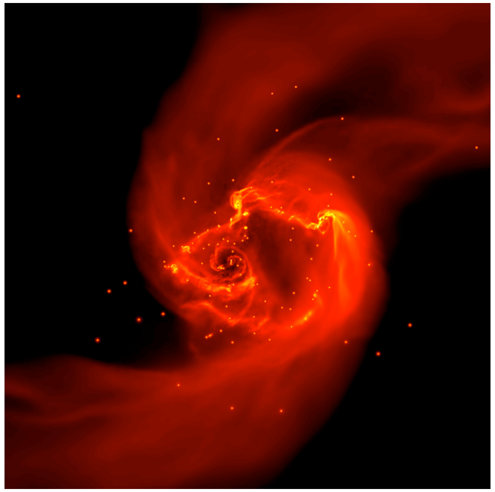
Pop III.1



Pop III.2

(Clark et al, 2011a, 727, 110)

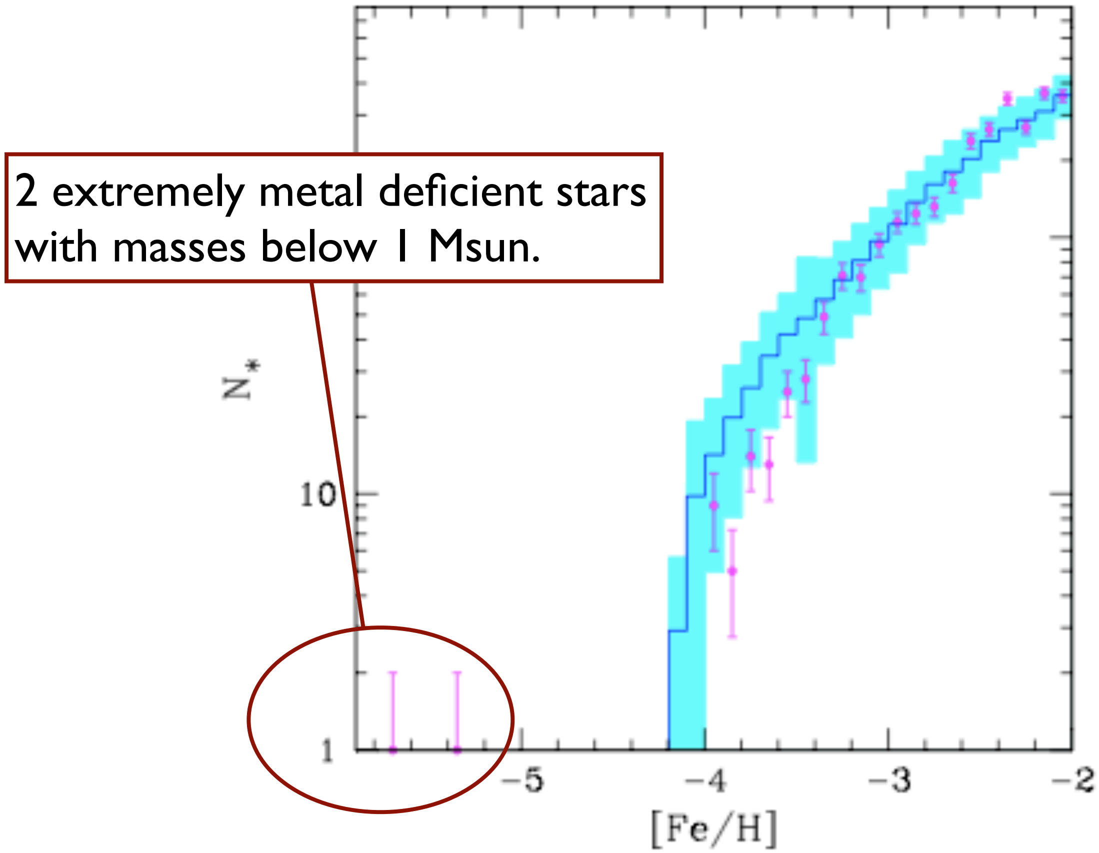
primordial star formation



- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

  to influence Pop III/II star formation.
- masses of Pop III stars still *uncertain* (surprises from new generation of high-resolution calculations that go beyond first collapse)
- disks unstable: Pop III stars should be *binaries* or *part of small clusters*
- effects of feedback less important than in present-day SF

constraints from EMP stars in halo

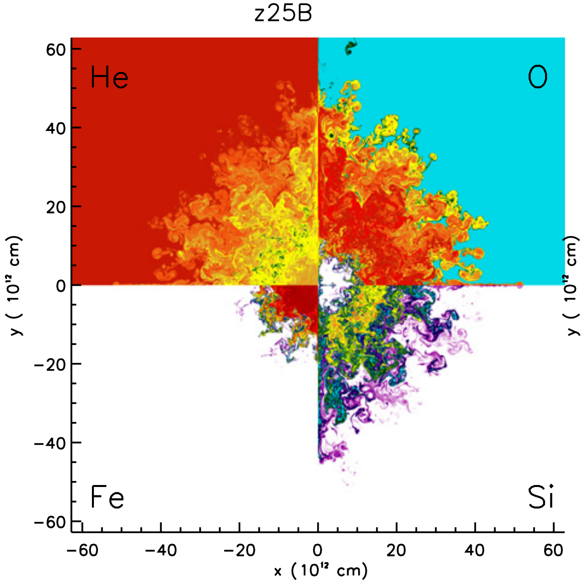


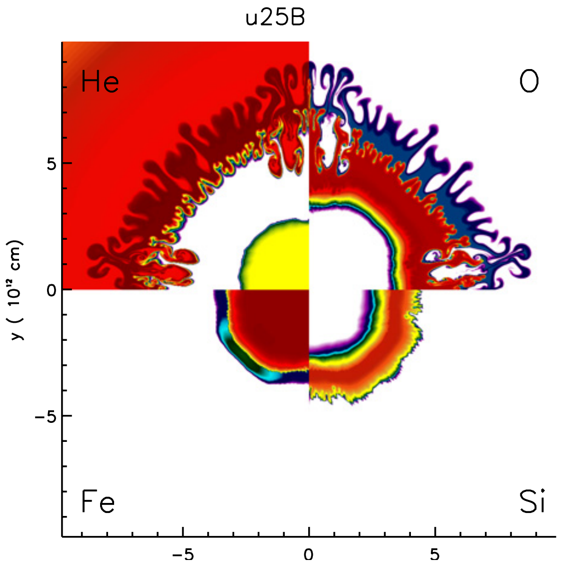
2 extremely metal deficient stars with masses below 1 Msun.

(plot from Salvadori et al. 2006, data from Frebel et al. 2005)

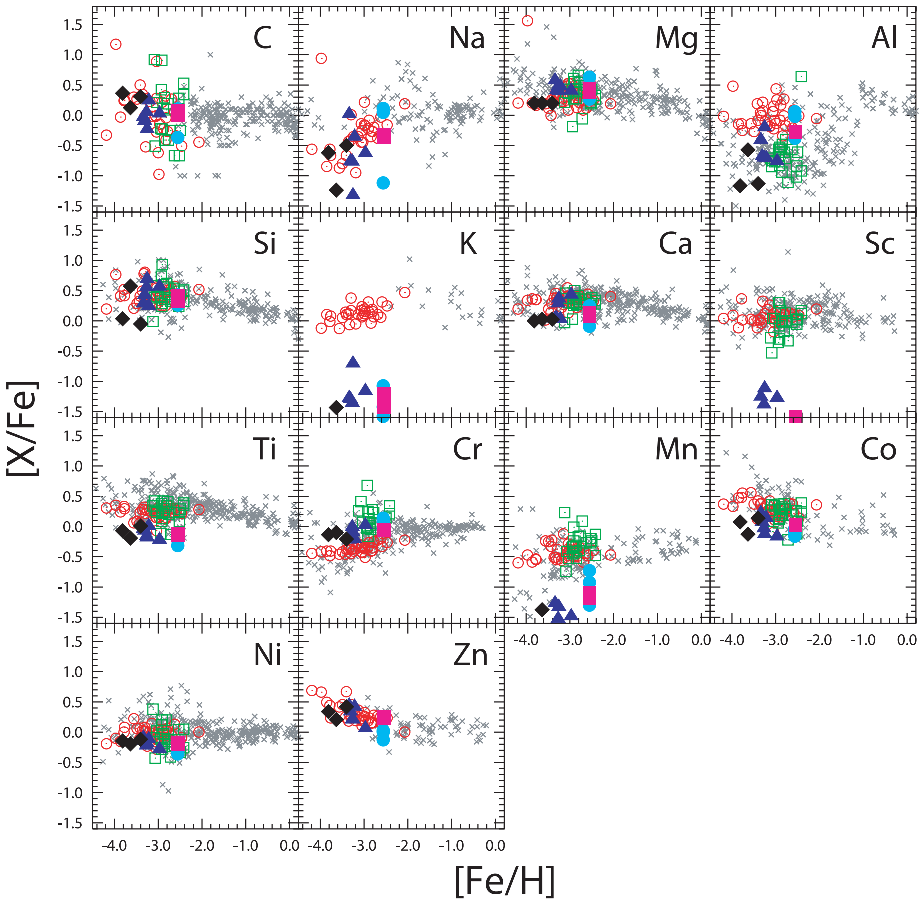
there are many extremely metal-poor stars in the halo (Beers & Christlieb 2005, ARA&A)

- mass range can be explained by dust-induced fragmentation (Clark et al. 2008)
- can use abundance pattern to learn about properties (yields) of progenitor stars





(Joggerst et al. 2009, 2010)



(Tominaga et al. 2007)

The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 $M_\odot$

(e.g. Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

questions

- is claim of Pop III stars with $M \sim 0.5\, M_\odot$ really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback
- how would we find them?
  - spectral features
- where should we look?
- what about magnetic fields?

some more details

- magnetic field amplification in primordial collapse (see also talk by Dominik Schleicher)
- influence of streaming motions on collapse in primordial halos (see also talk by Thomas Greif)
- fragmentation-induced starvation as key to understand final stellar masses (Peters et al. 2010abc, 2011)

conclusions

- primordial and present-day star formation exhibit *similar complexity:*
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

} all influence the end result of stellar birth

NGC 3324 (Hubble, NASA/ESA)