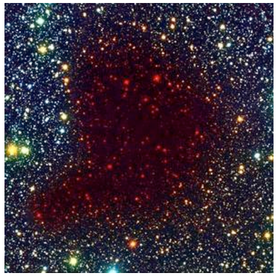
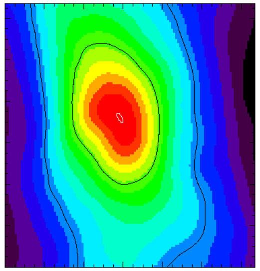
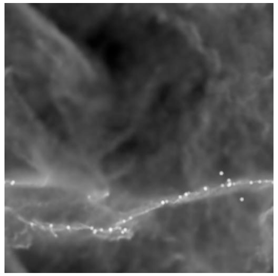
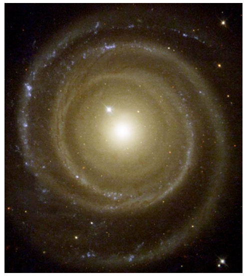
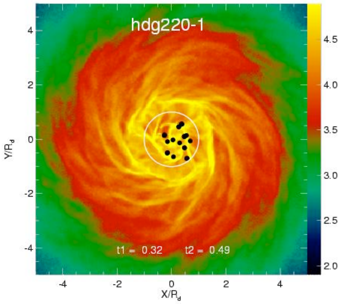
Star Formation: Stellar Birth Today and in the Early Universe

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Institut für Theoretische Astrophysik

thanks to ...

... people in the group in Heidelberg:

Robi Banerjee, Simon Glover, Rahul Shetty, Sharanya Sur, Daniel Seifried, Milica Milosavljevic, Florian Mandl, Christian Baczynski, Rowan Smith, Gustavo Dopcke, Jonathan Downing, Jayanta Dutta, Faviola Molina, Christoph Federrath, Erik Bertram, Lukas Konstandin, Paul Clark, Stefan Schmeja, Ingo Berentzen, Thomas Peters, Hsiang-Hsu Wang

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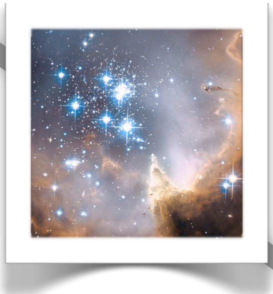
Emmy Noether-Programm DFG
ASTRONET
LANDESSTIFTUNG Baden-Württemberg
HGSFP
IMPRS

agenda

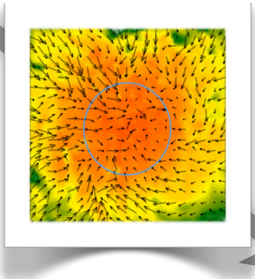
- a simple cartoon picture of dynamic star formation theory
- some applications, open issues, and questions

agenda



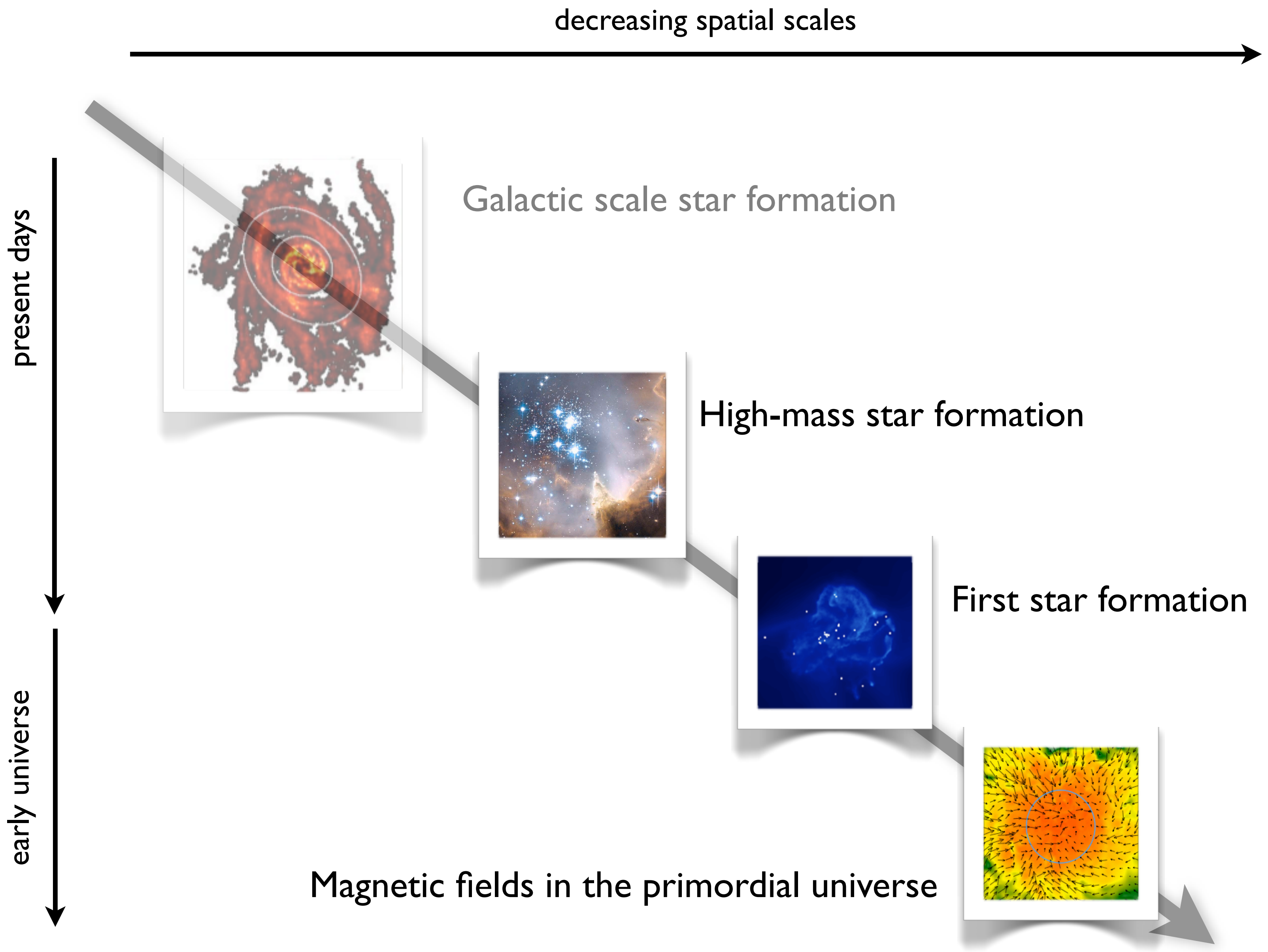
High-mass star formation

First star formation



Magnetic fields in the primordial universe

agenda



decreasing spatial scales

present days

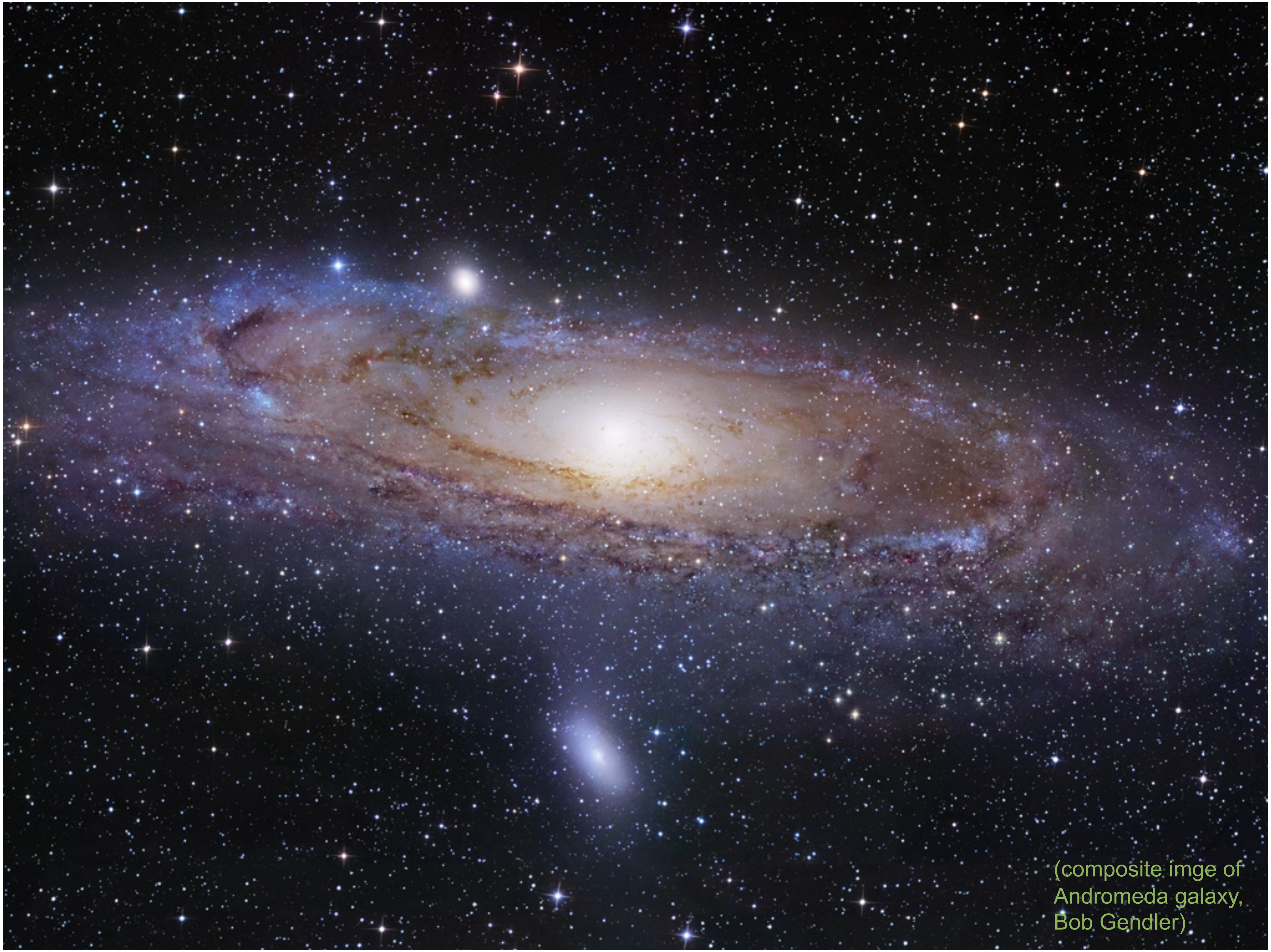
early universe

Galactic scale star formation

High-mass star formation

First star formation

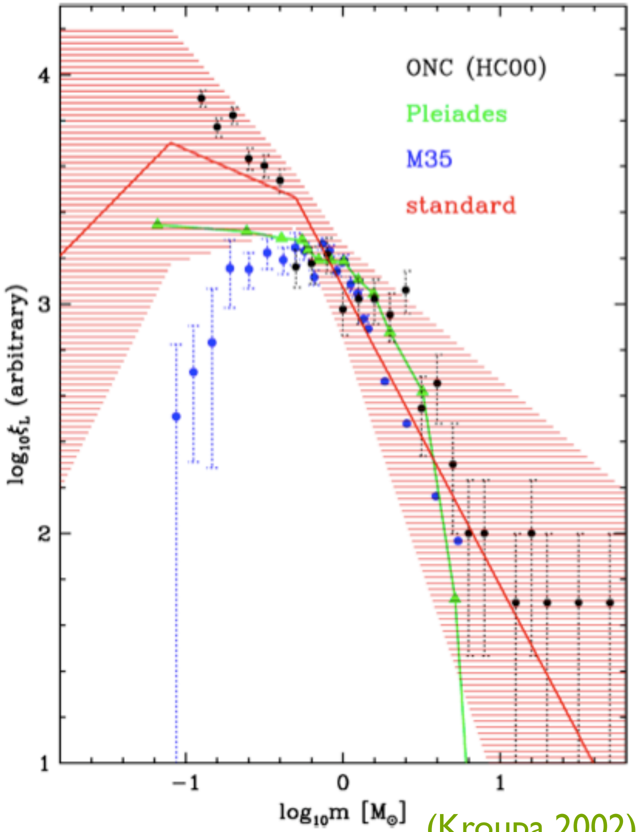
Magnetic fields in the primordial universe


(composite imge of
Andromeda galaxy,
Bob Gendler)

NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

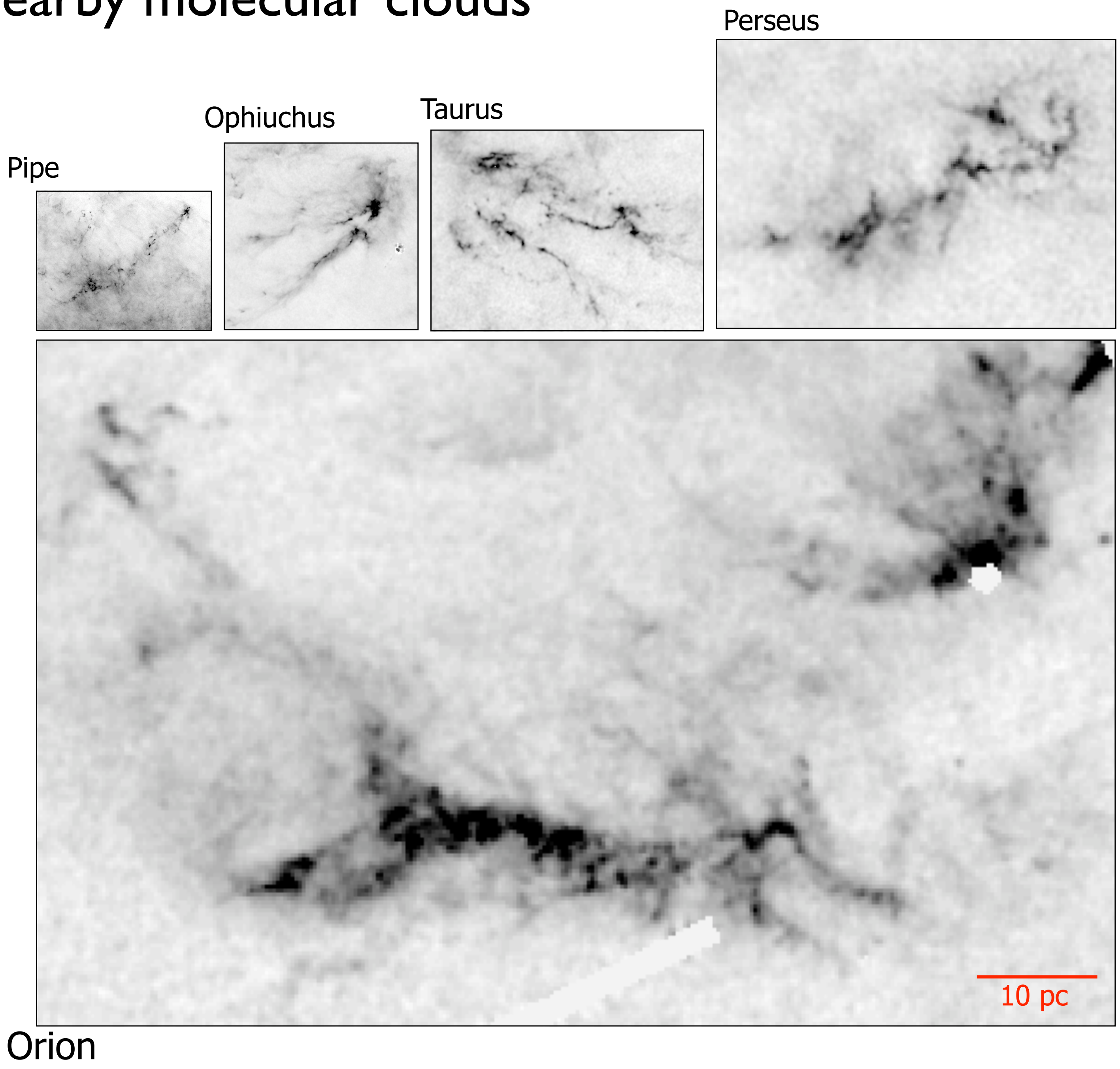
stars seem to follow a universal
mass function at birth --> IMF



(Kroupa 2002)

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

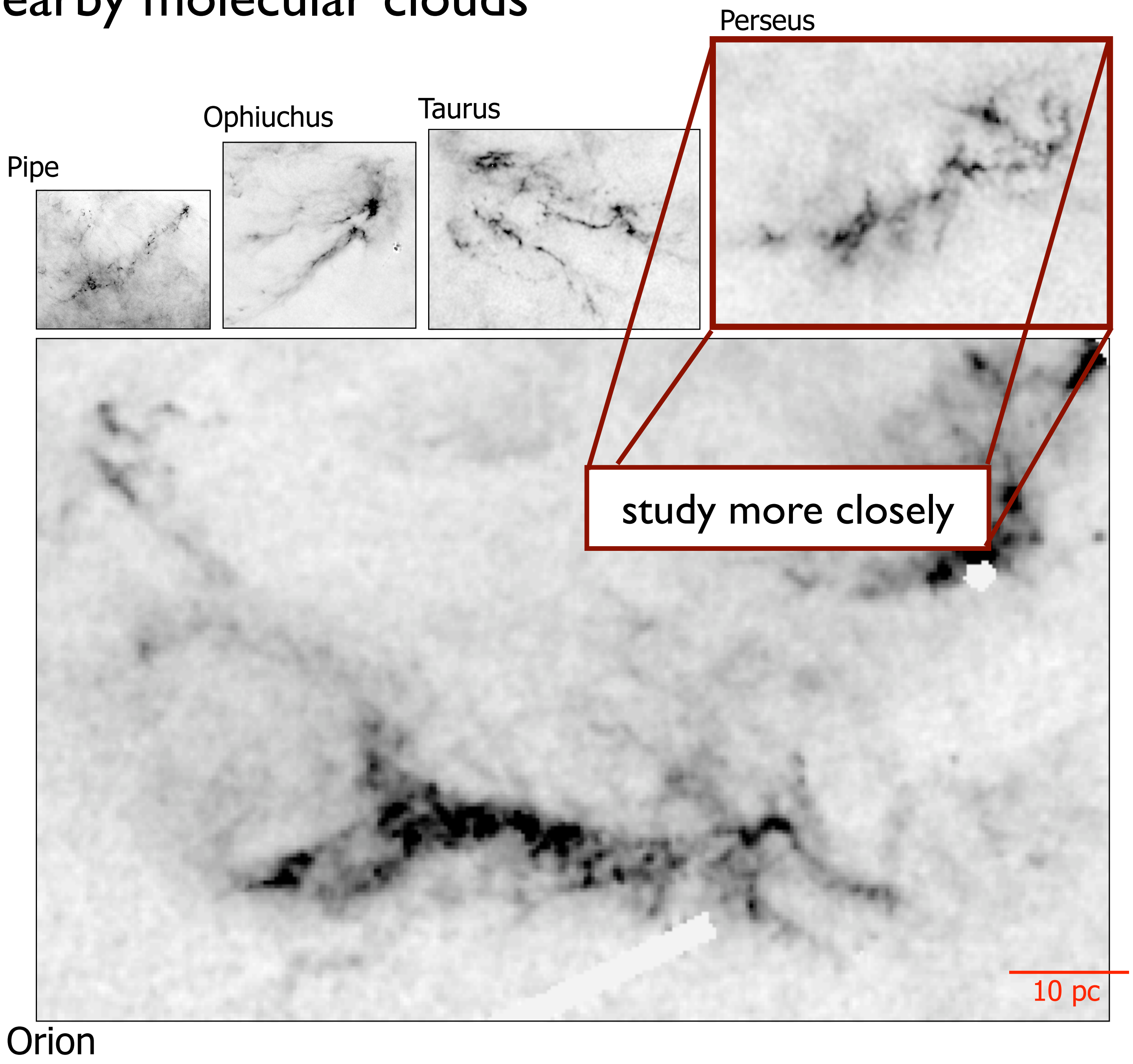
nearby molecular clouds



scales to same scale

(from A. Goodman)

nearby molecular clouds



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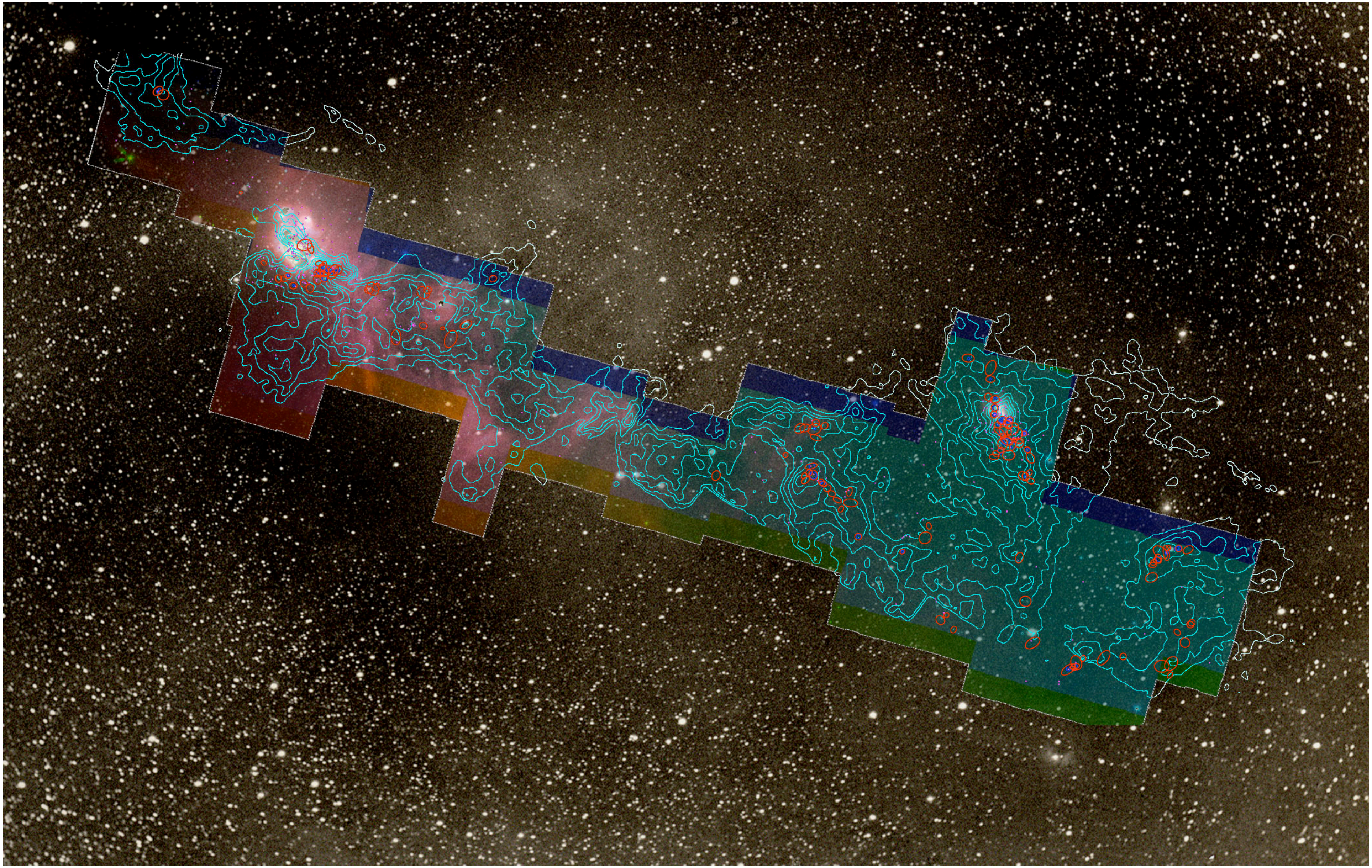
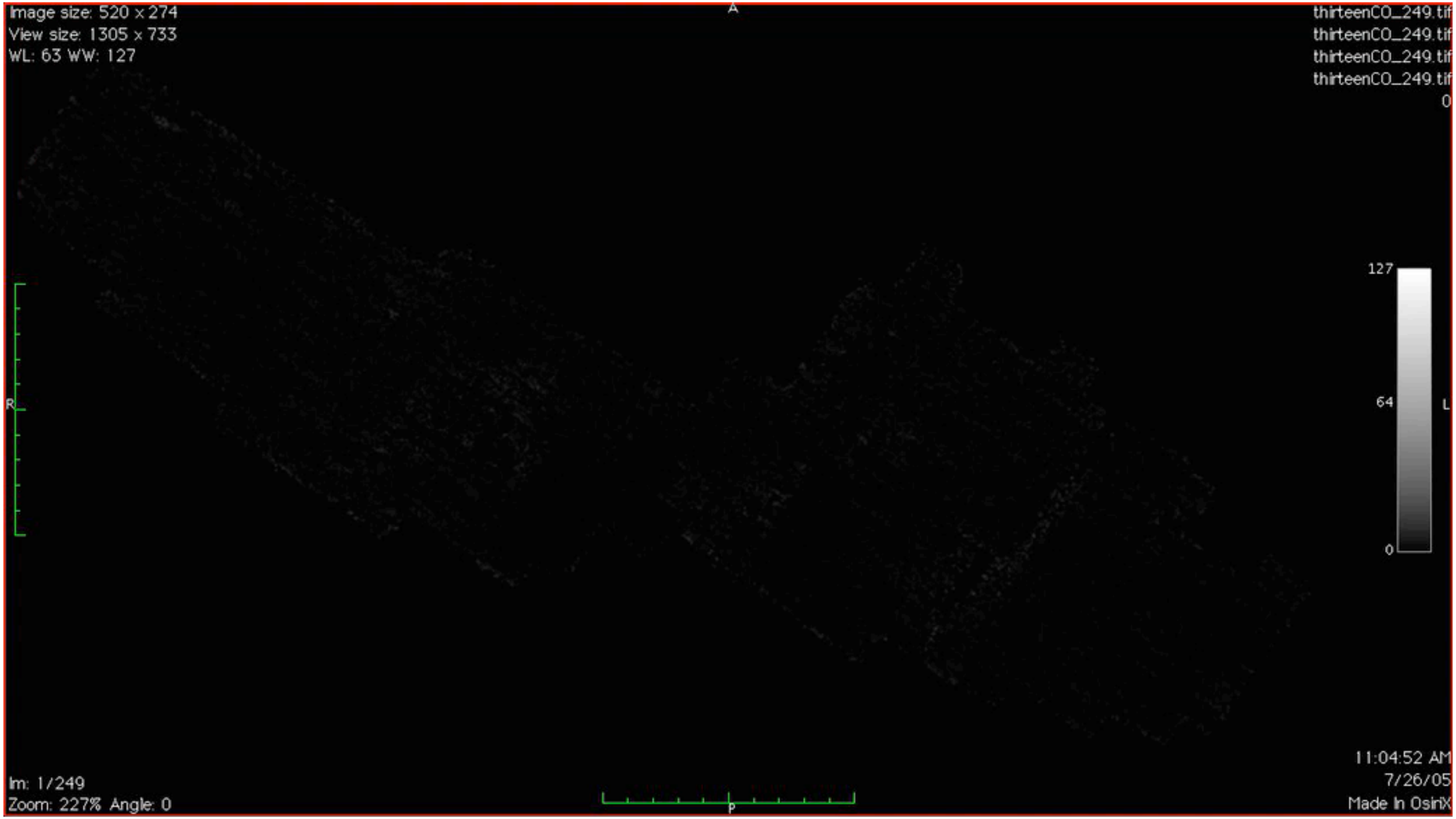
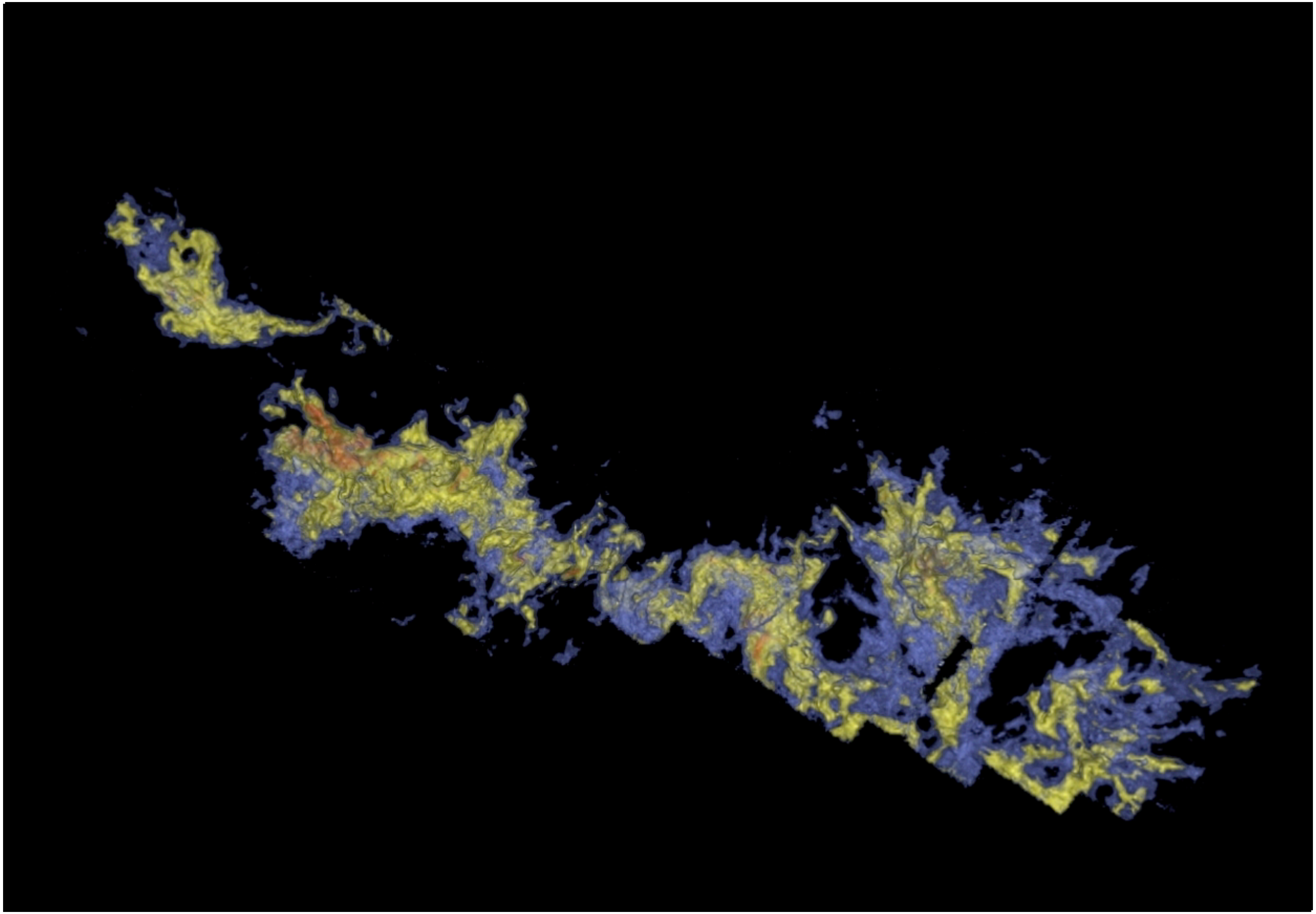


image from Alyssa Goodman: COMPLETE survey



velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey



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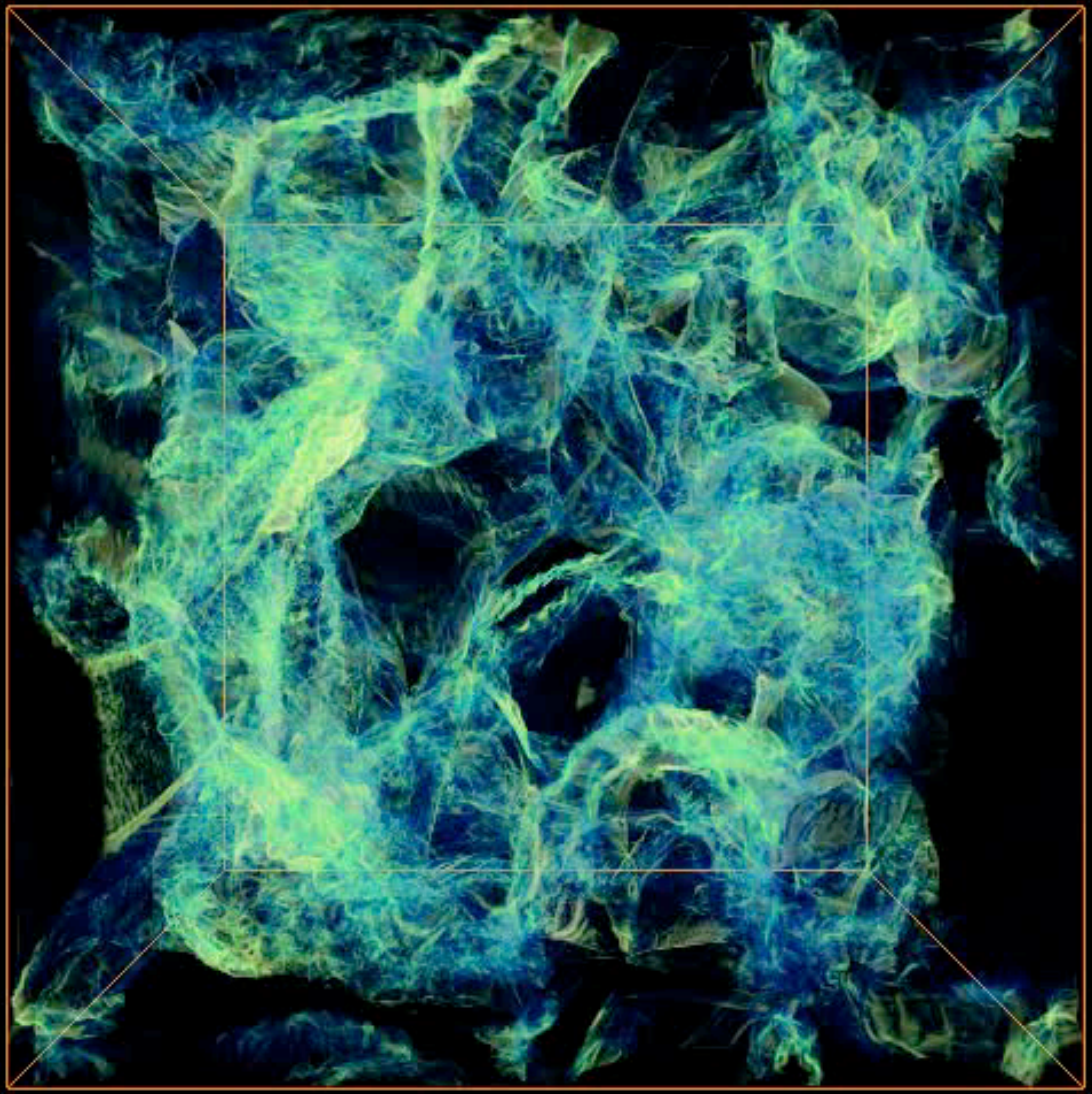
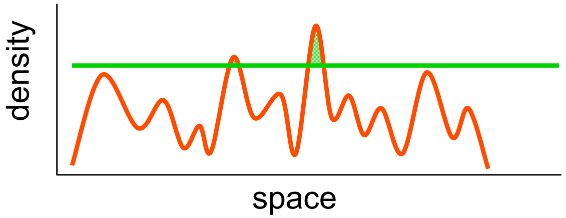


(movie from Christoph Federrath)

dynamical SF in a nutshell

- interstellar gas is highly *inhomogeneous*
  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)

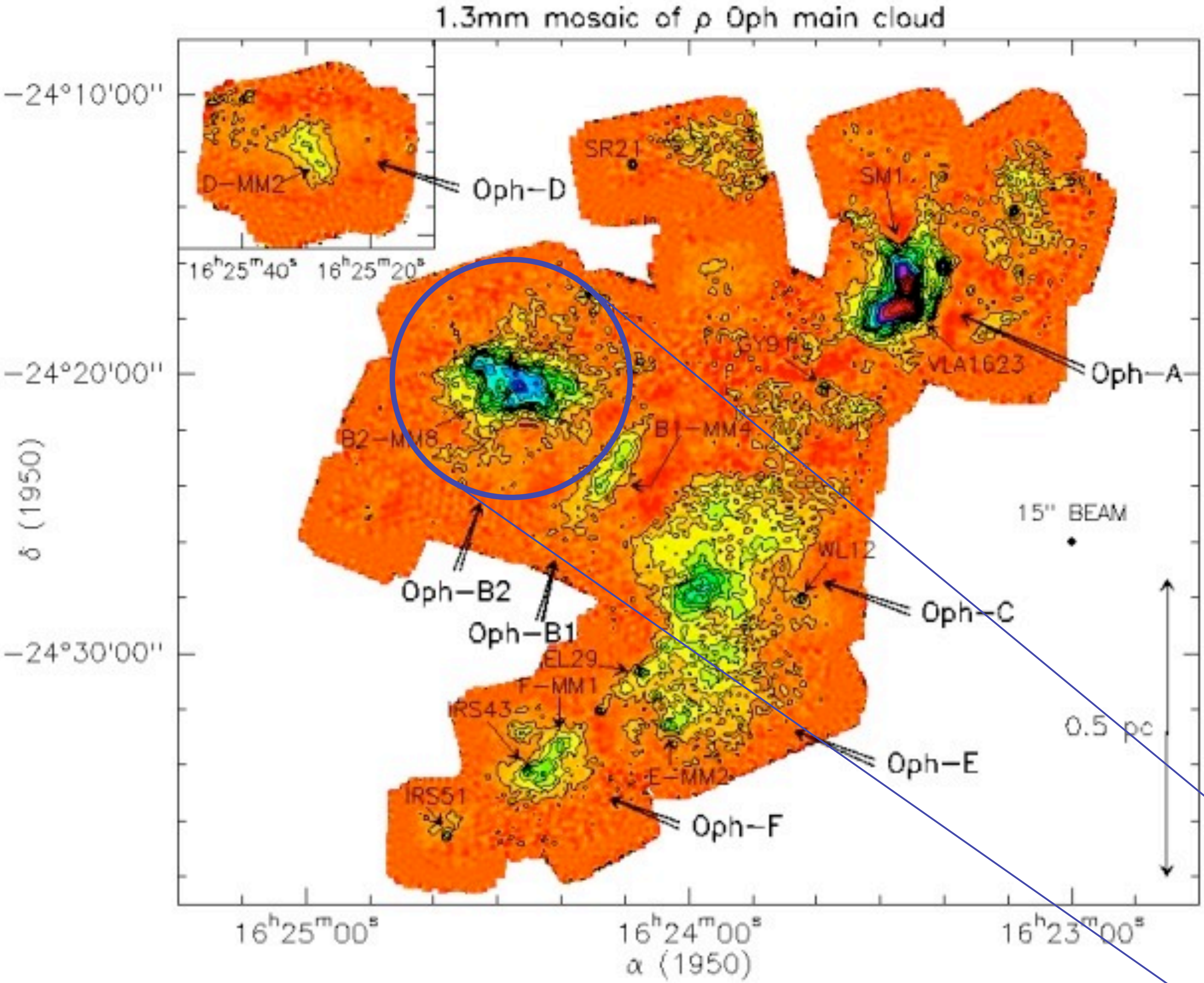


- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *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)

Density structure of MC’s



(Motte, André, & Neri 1998)

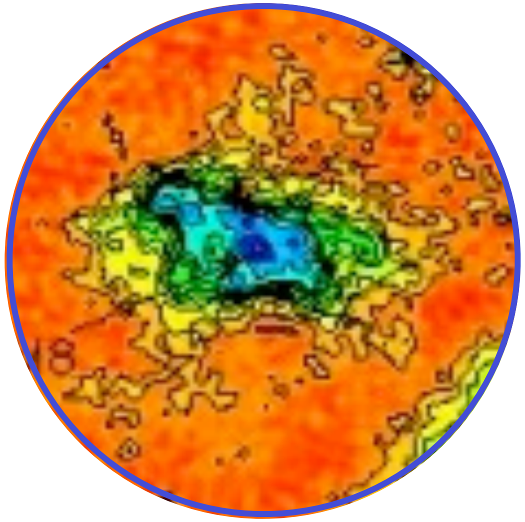
molecular clouds are highly inhomogeneous

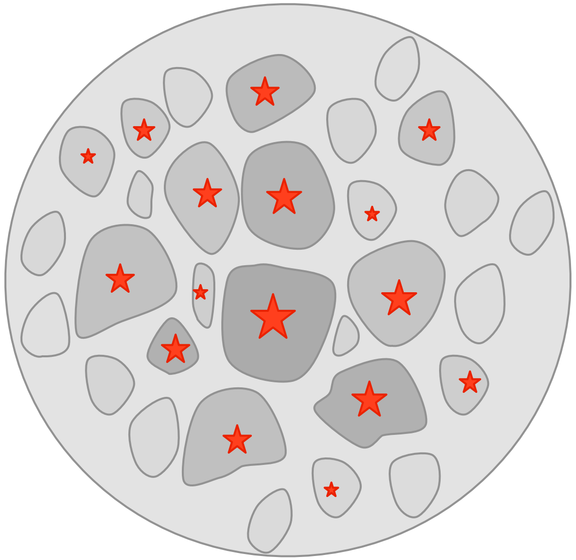
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let‘s focus on a cloud core like this one

Evolution of cloud cores

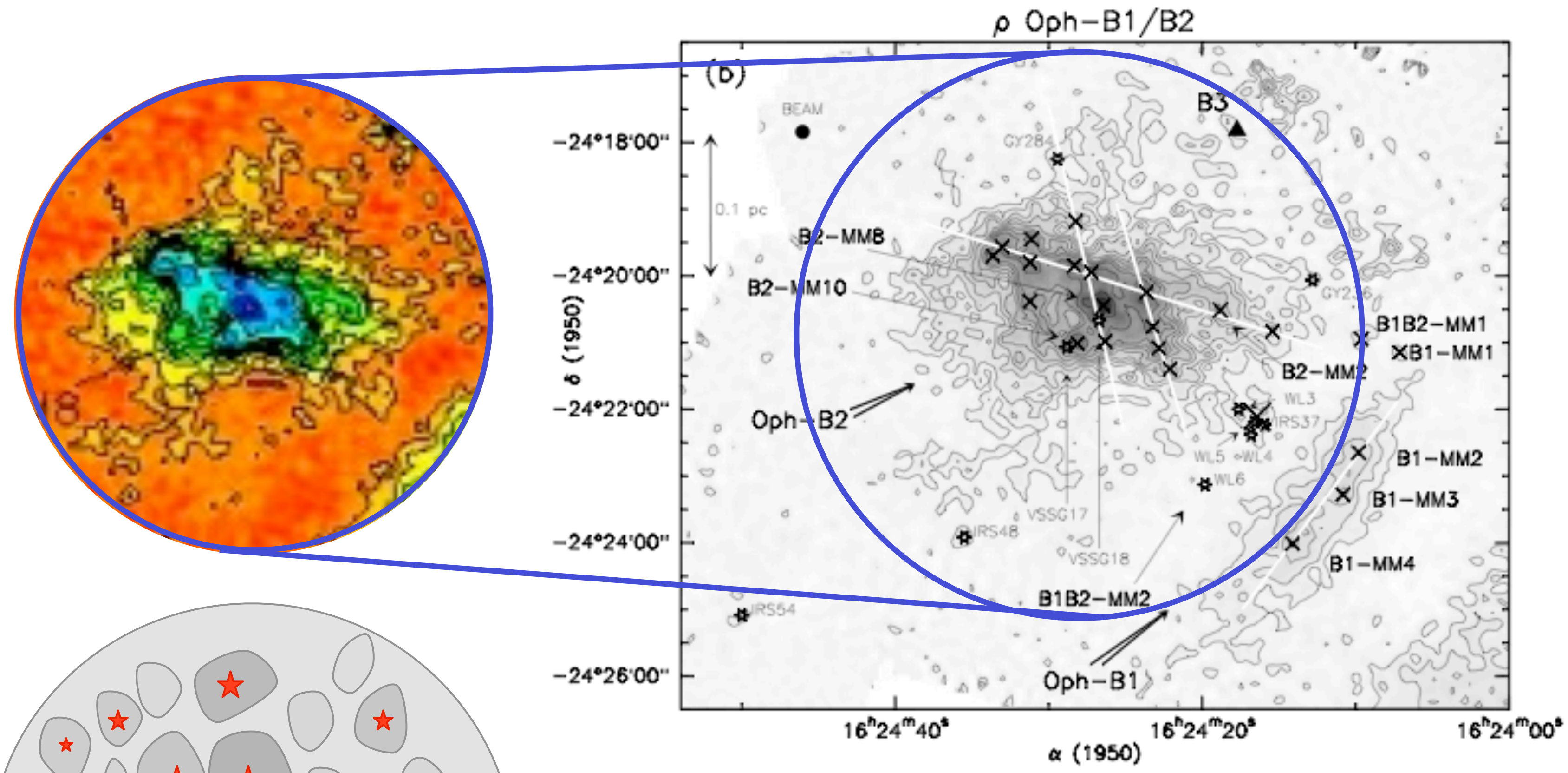


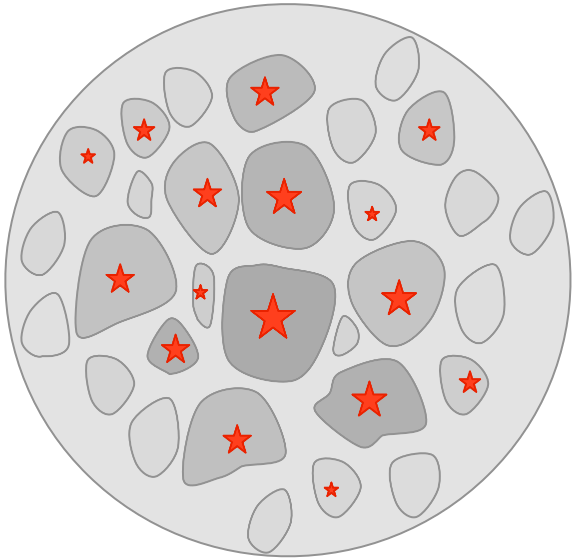


- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- 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



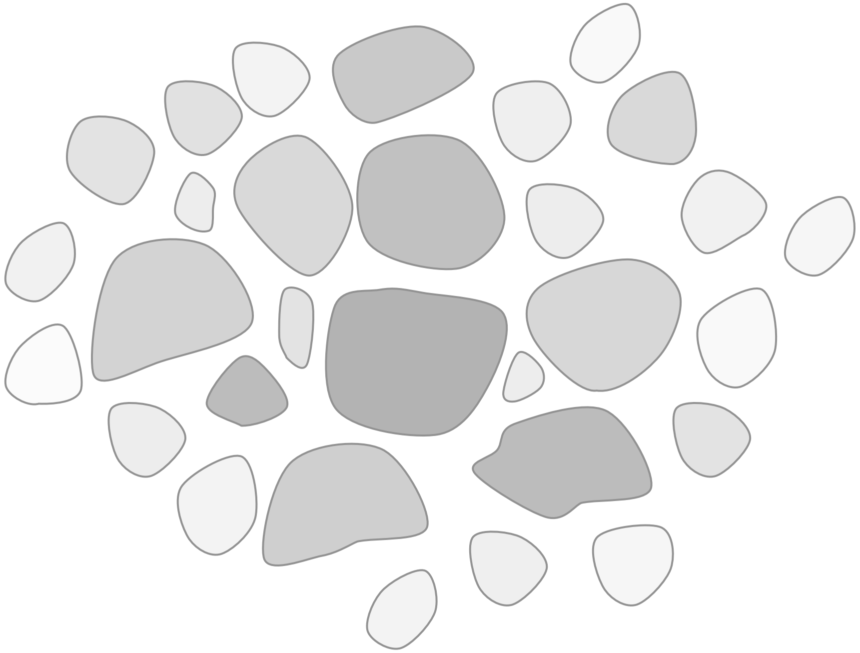


indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(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:

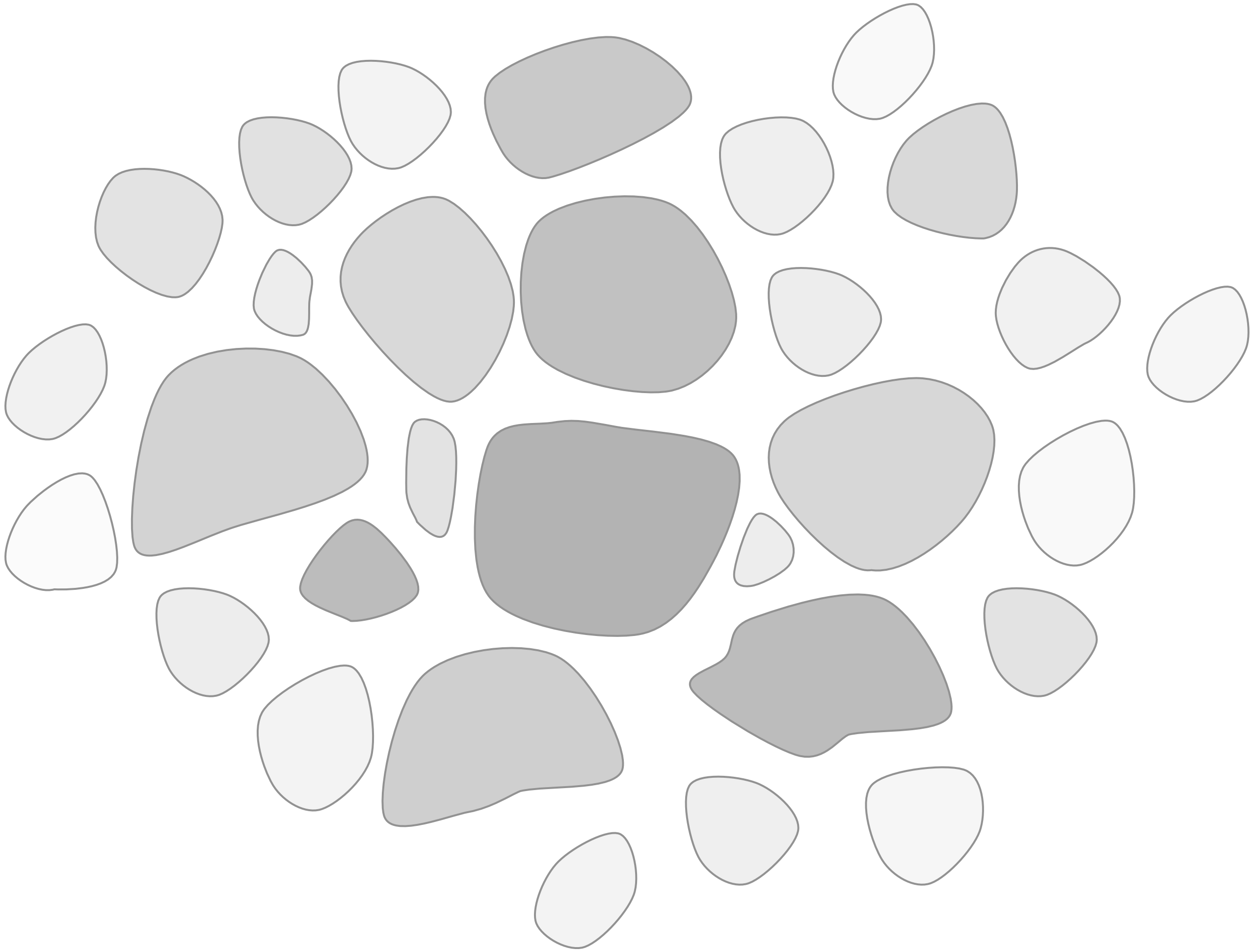
$\alpha=E_{kin}/|E_{pot}| < 1$

--> *global contraction*

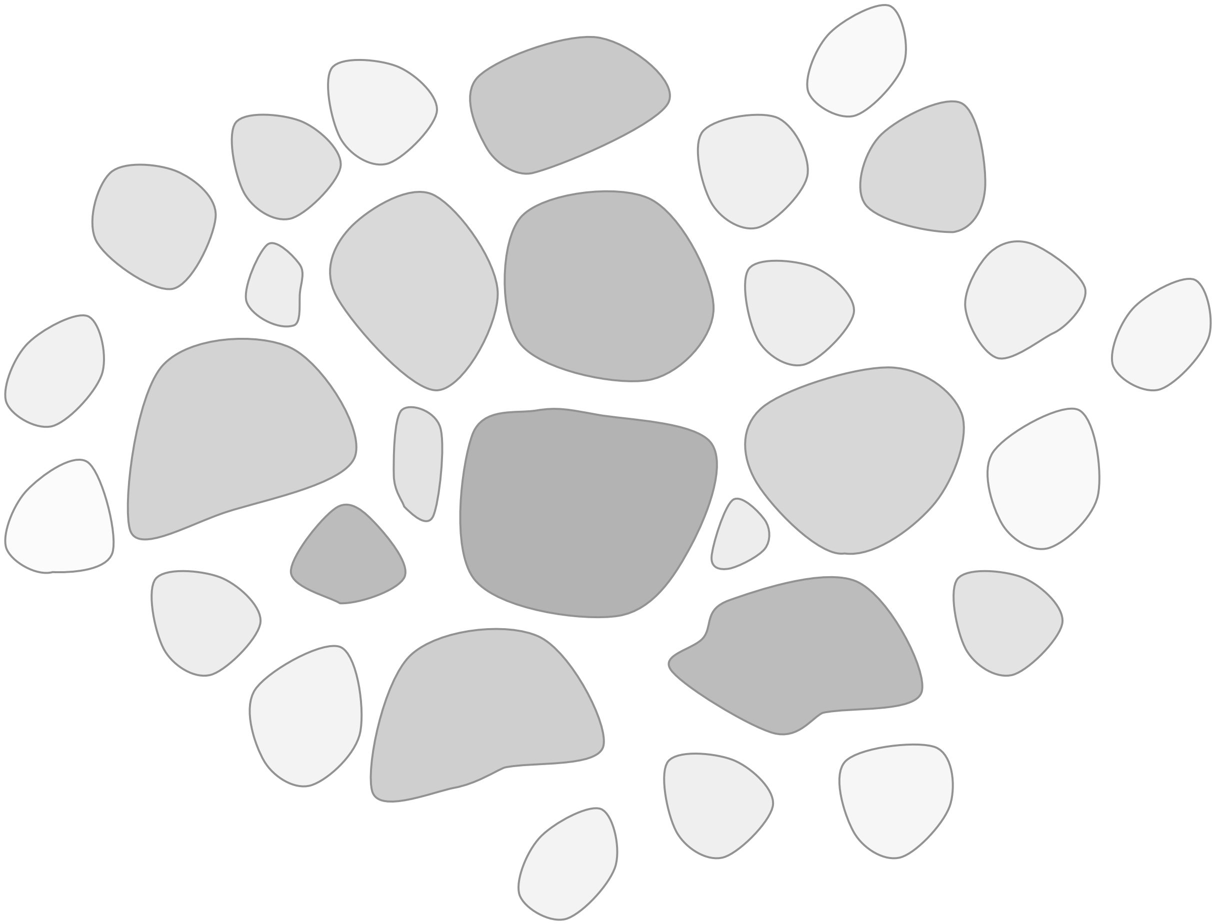
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

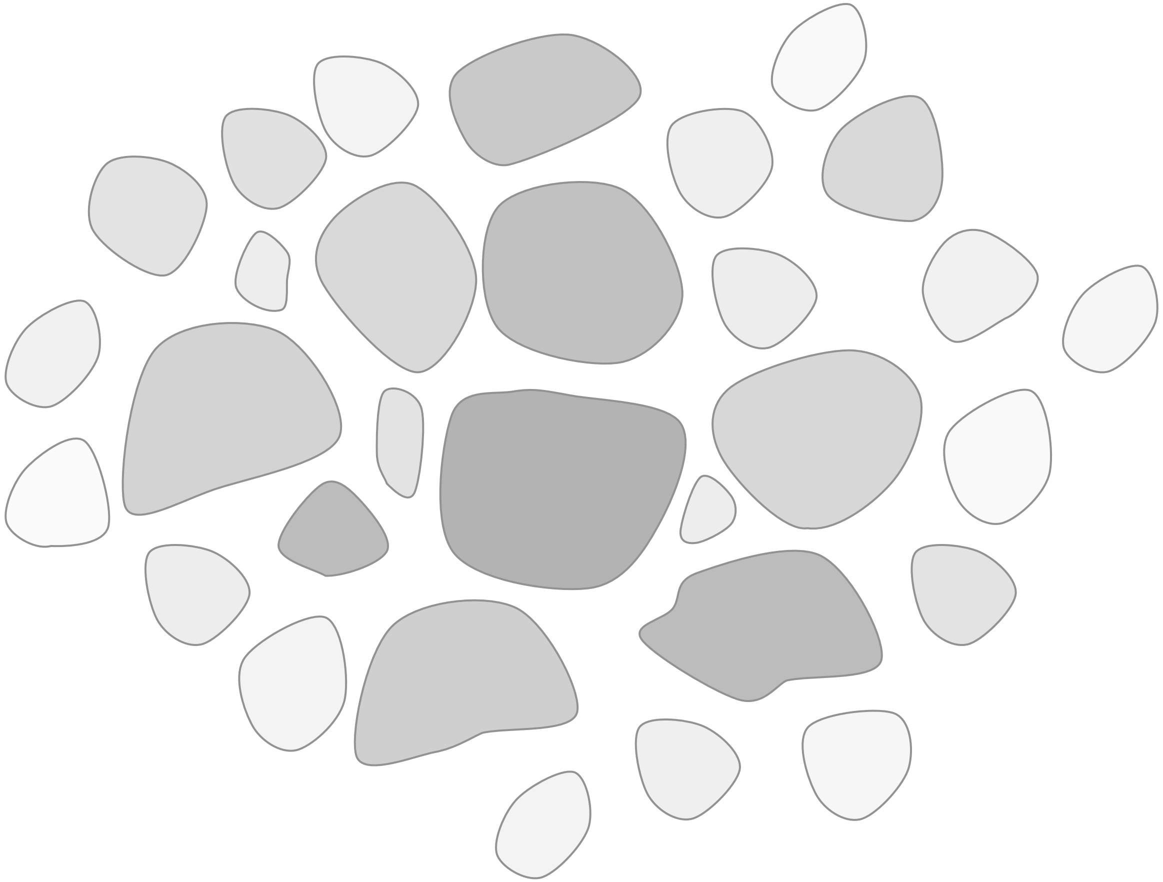
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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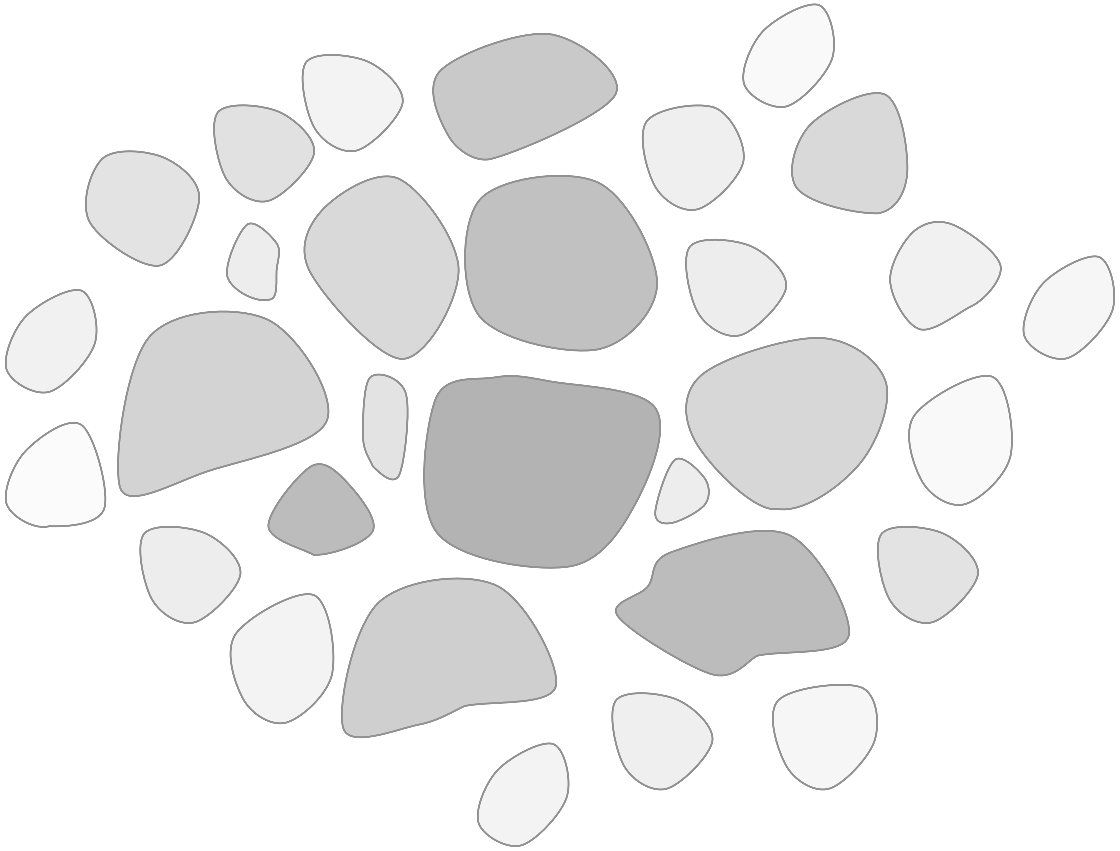
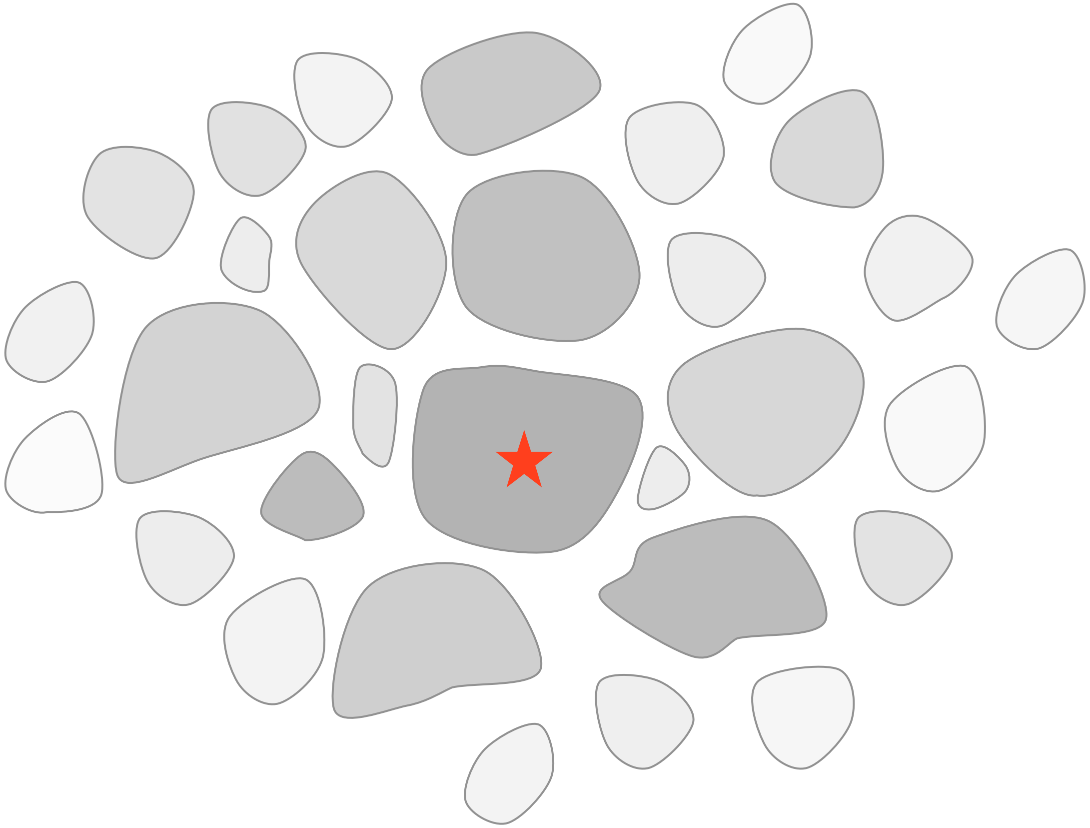


while region contracts, individual clumps collapse to form stars



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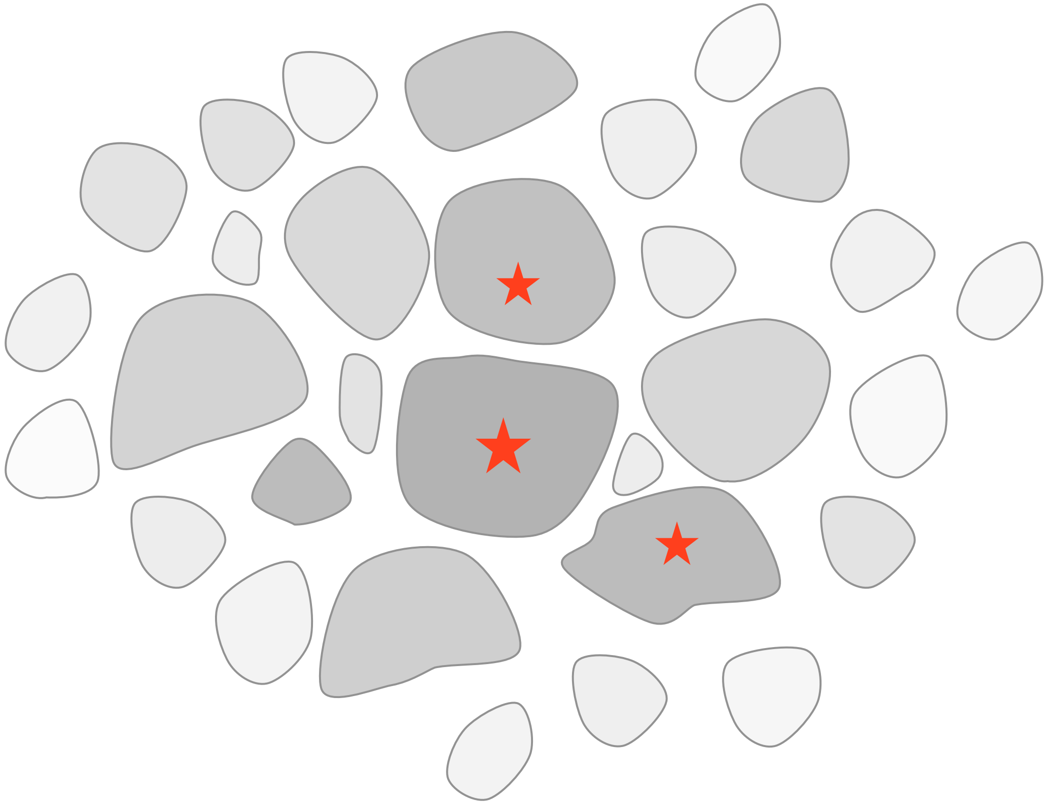

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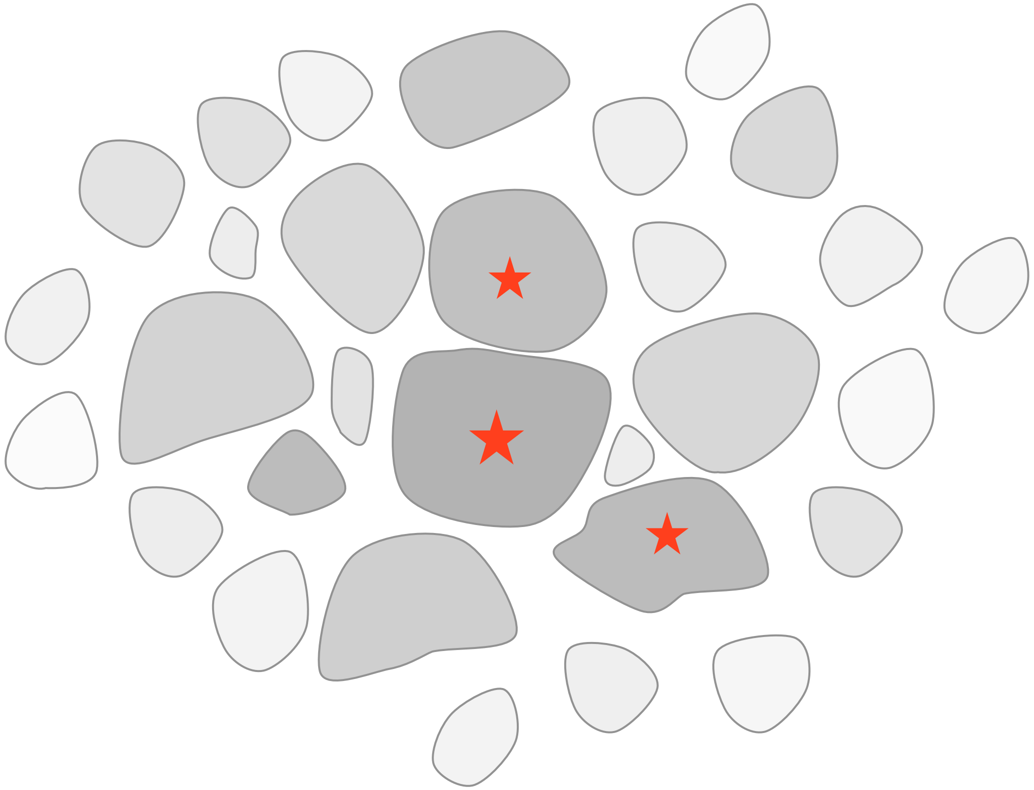

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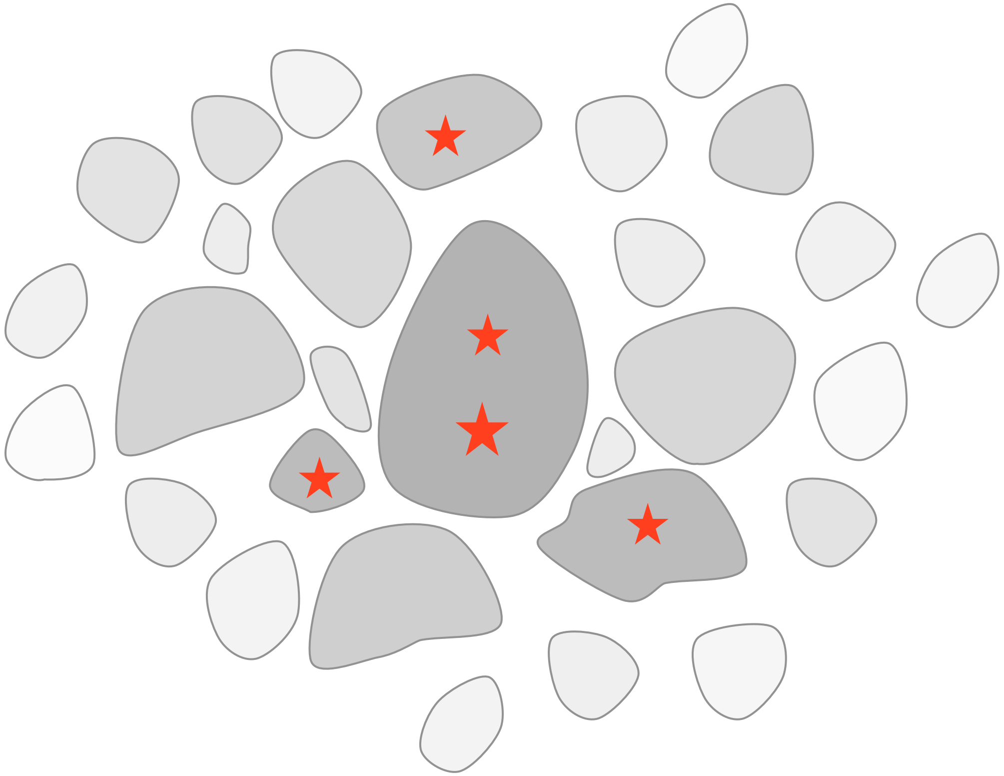
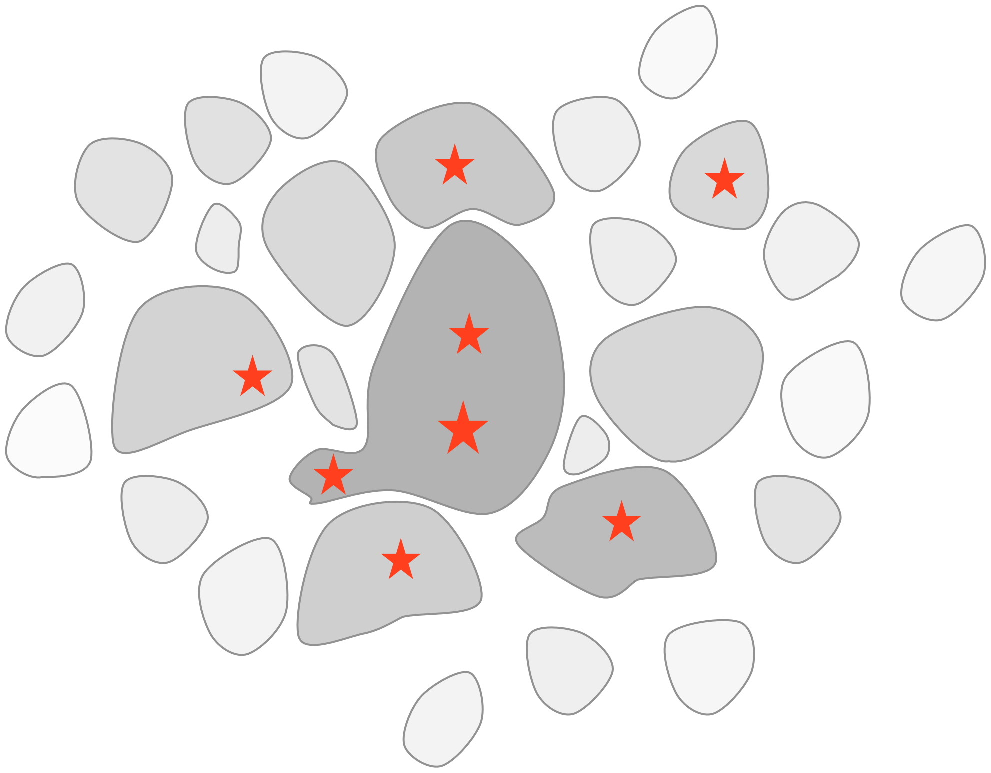


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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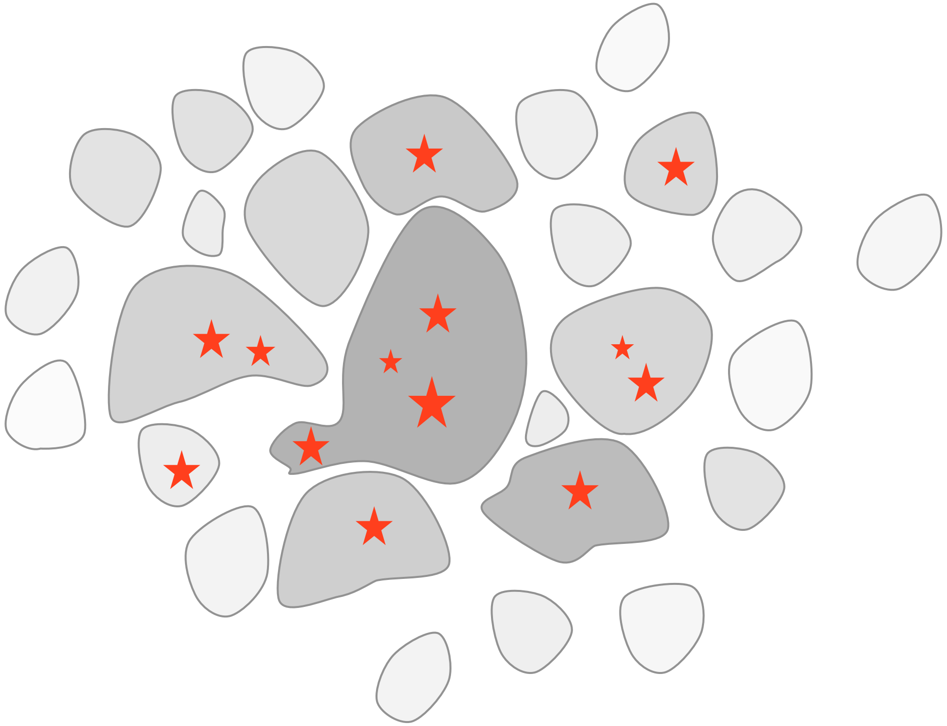

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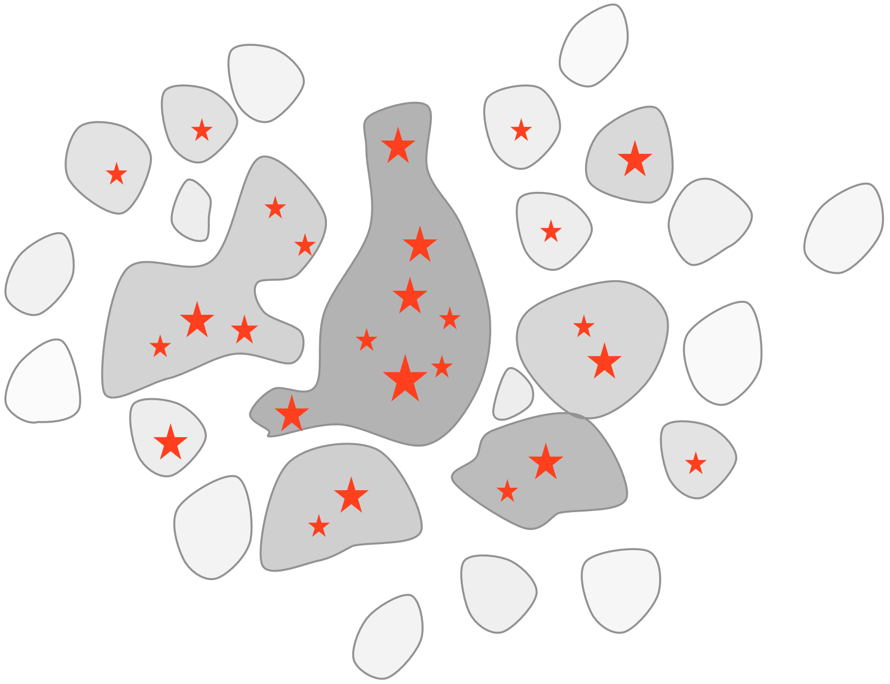
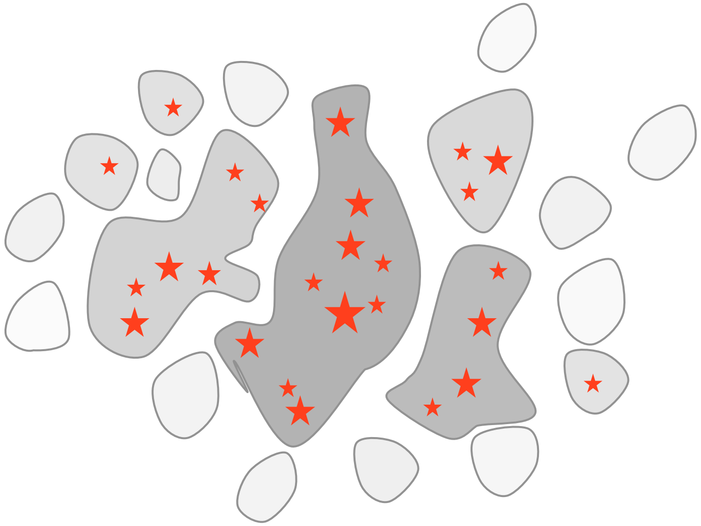


in *dense clusters*, competitive mass growth becomes important



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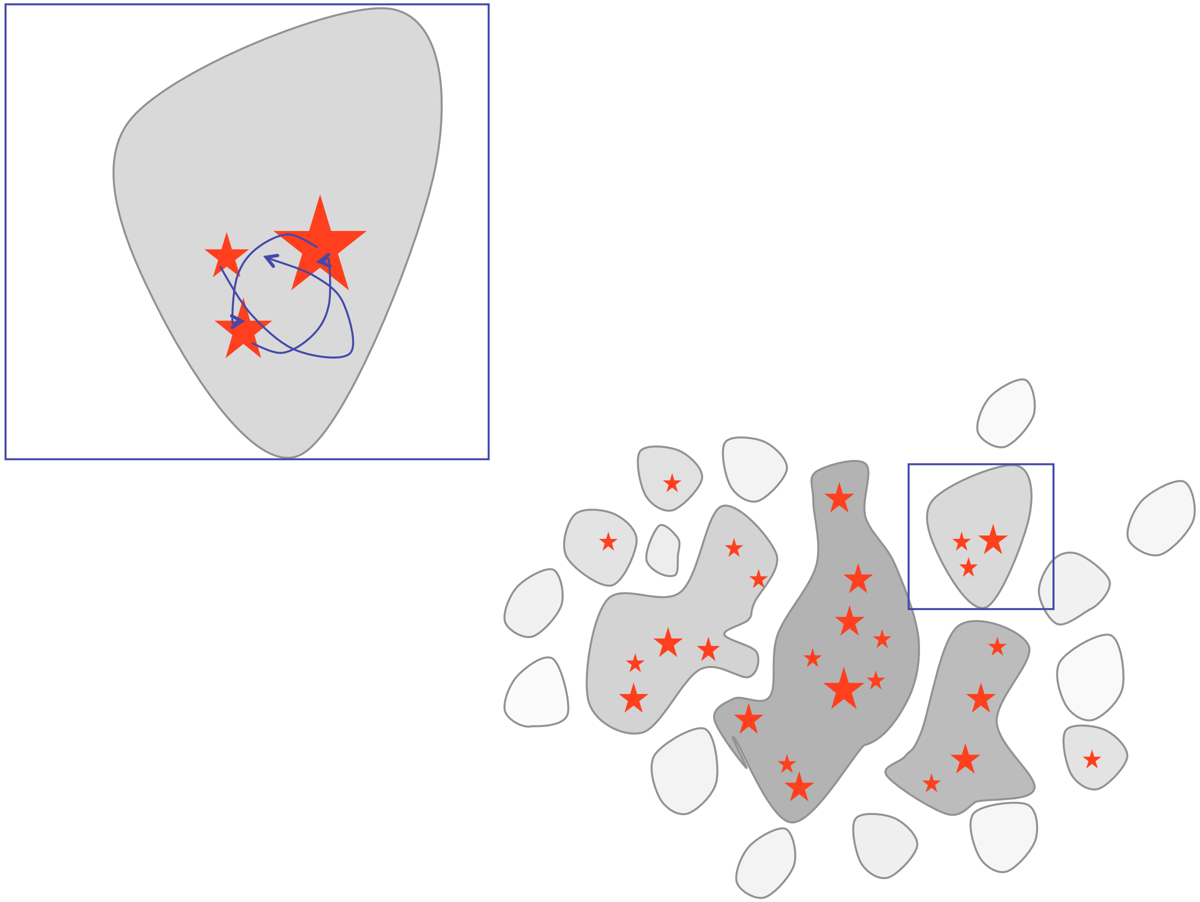
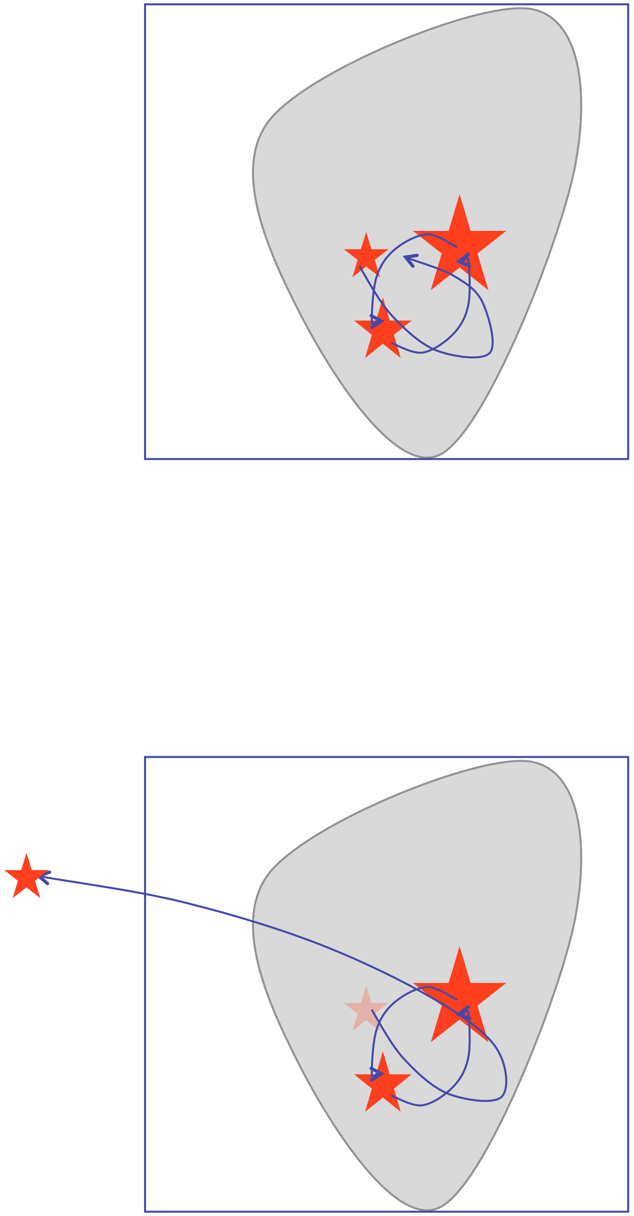
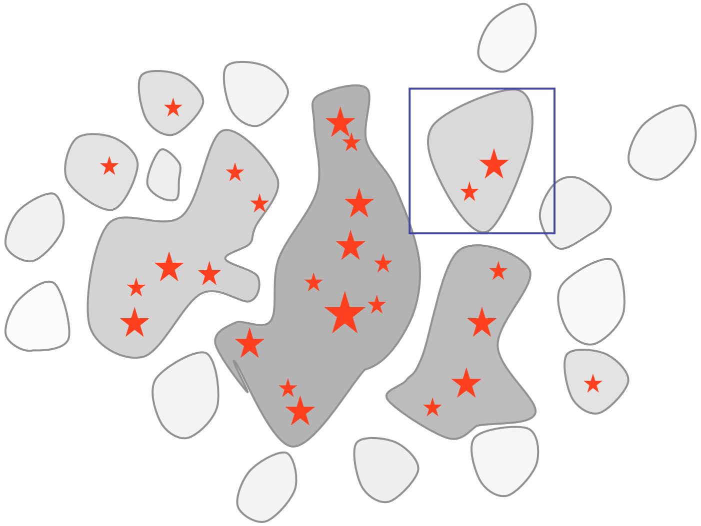
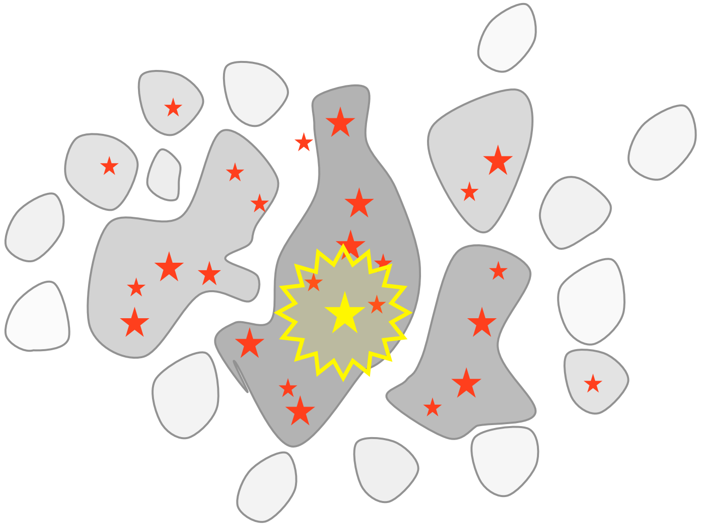


in *dense clusters*, *N*-body effects influence mass growth

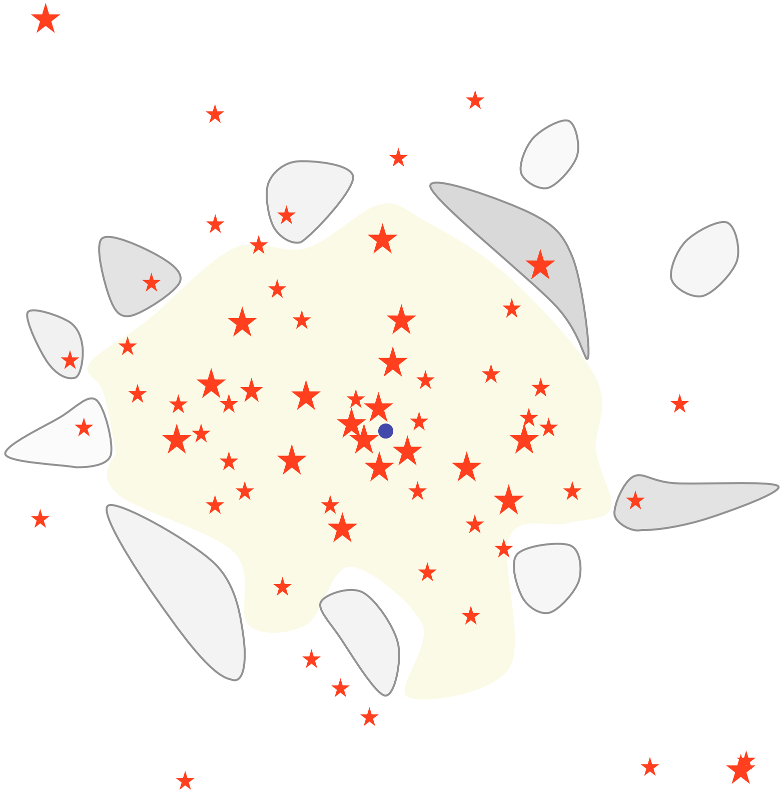




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation

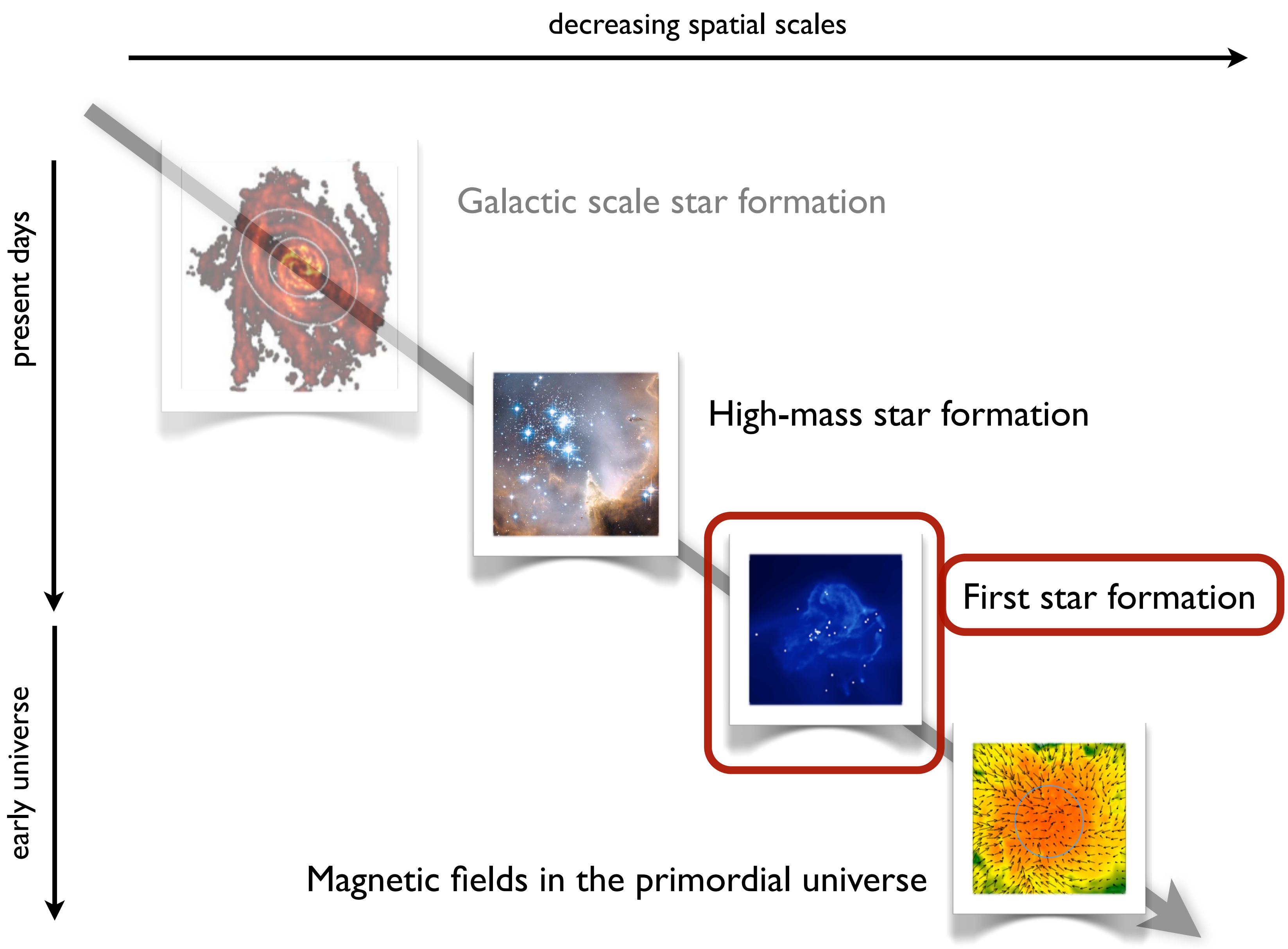


result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region

agenda



decreasing spatial scales

present days

early universe

Galactic scale star formation

High-mass star formation

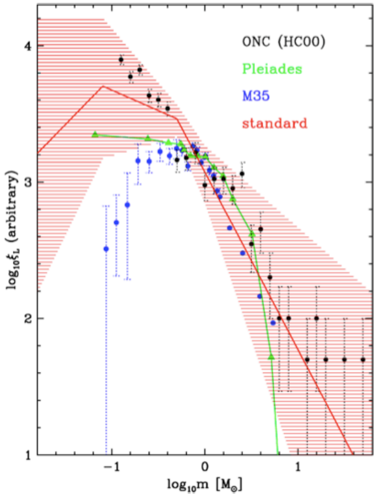
First star formation

Magnetic fields in the primordial universe

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)



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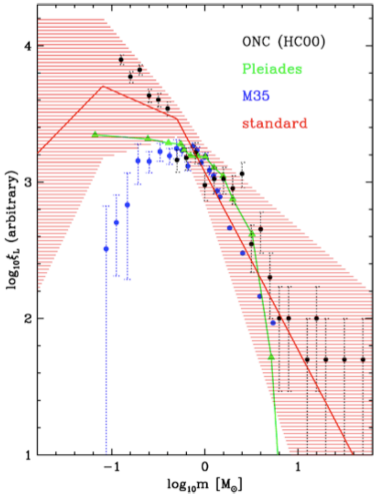


example: model of Orion cloud

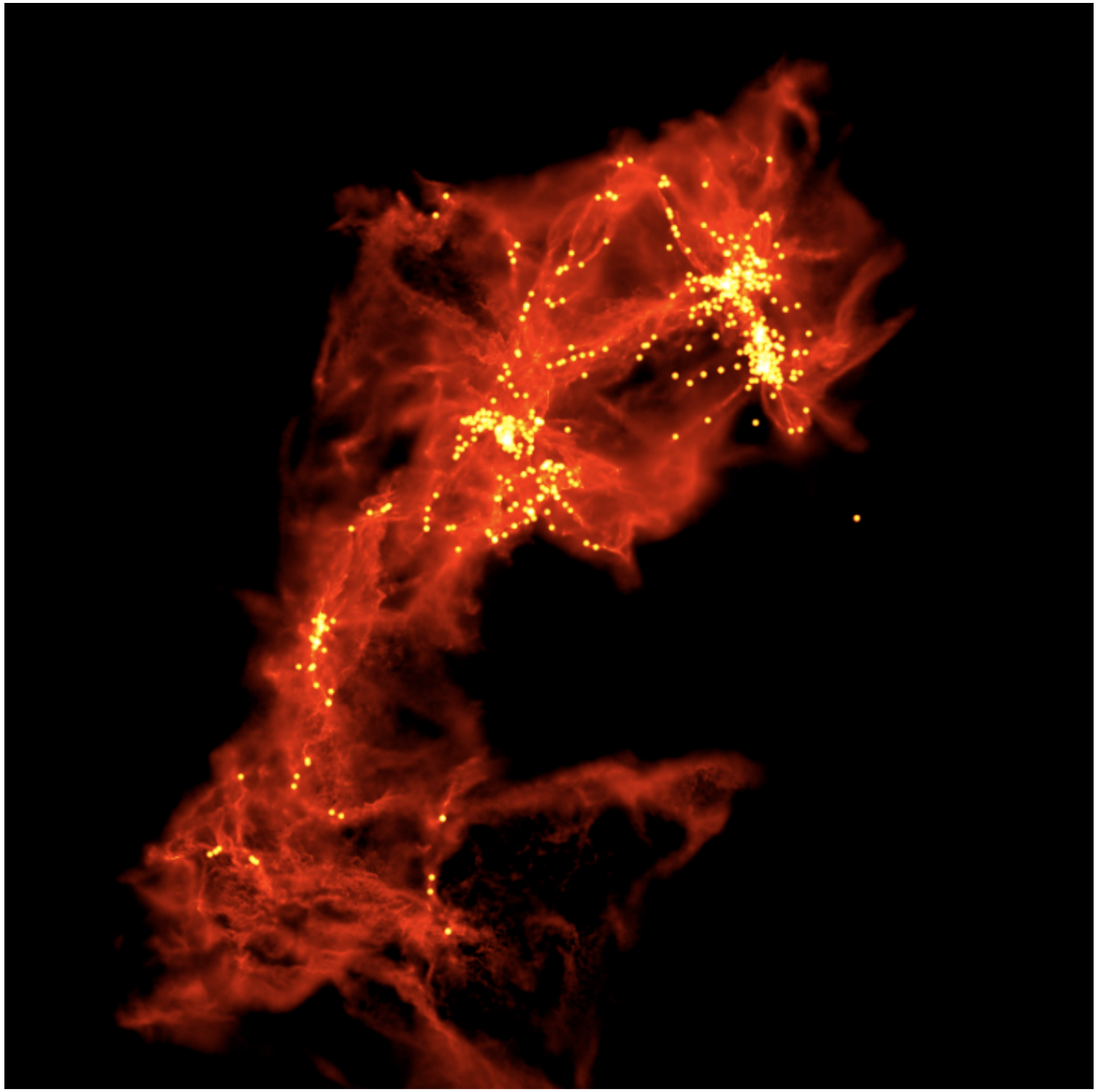
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

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)

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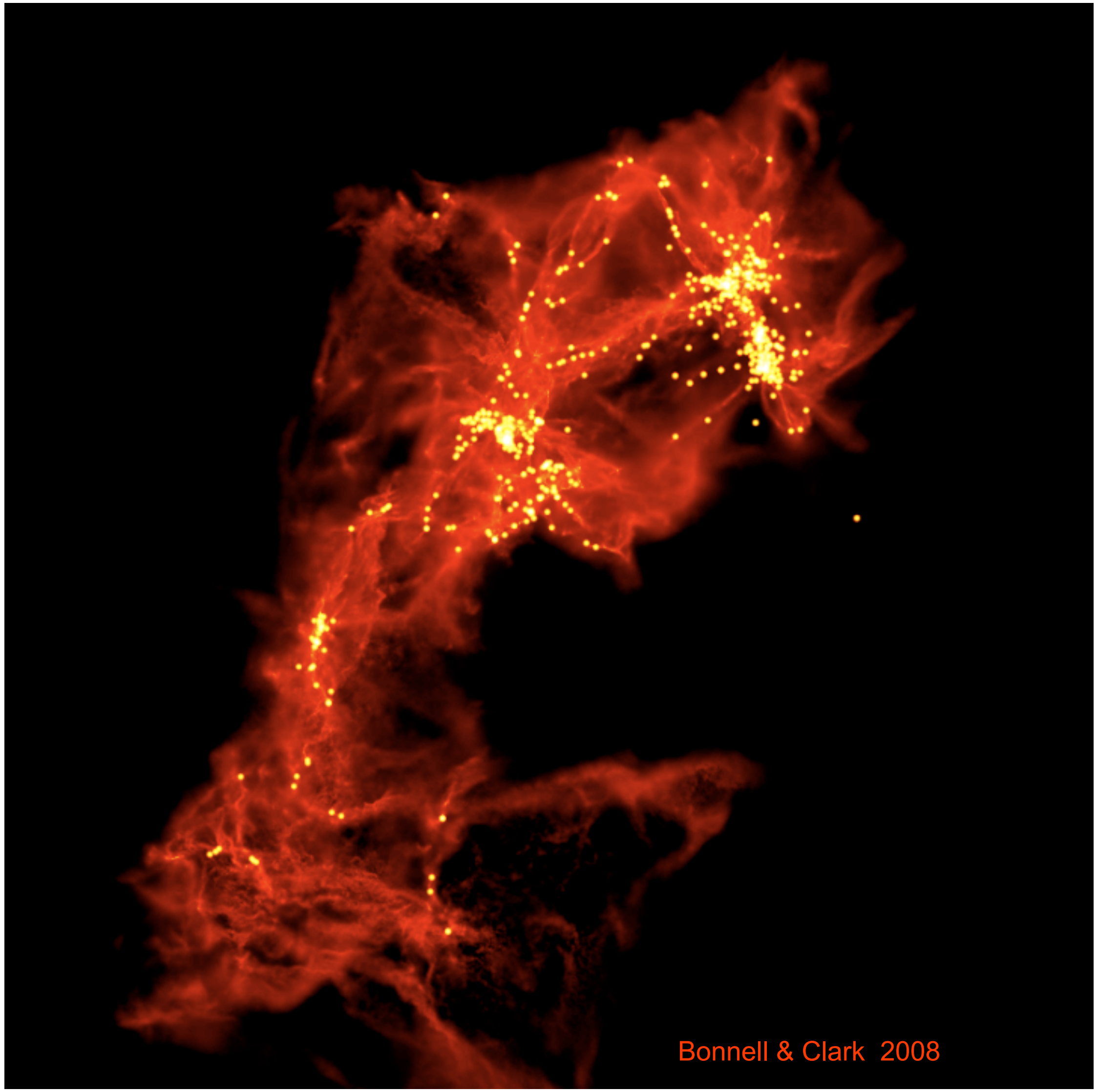
MASSIVE STARS

- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS

- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion



Bonnell & Clark 2008

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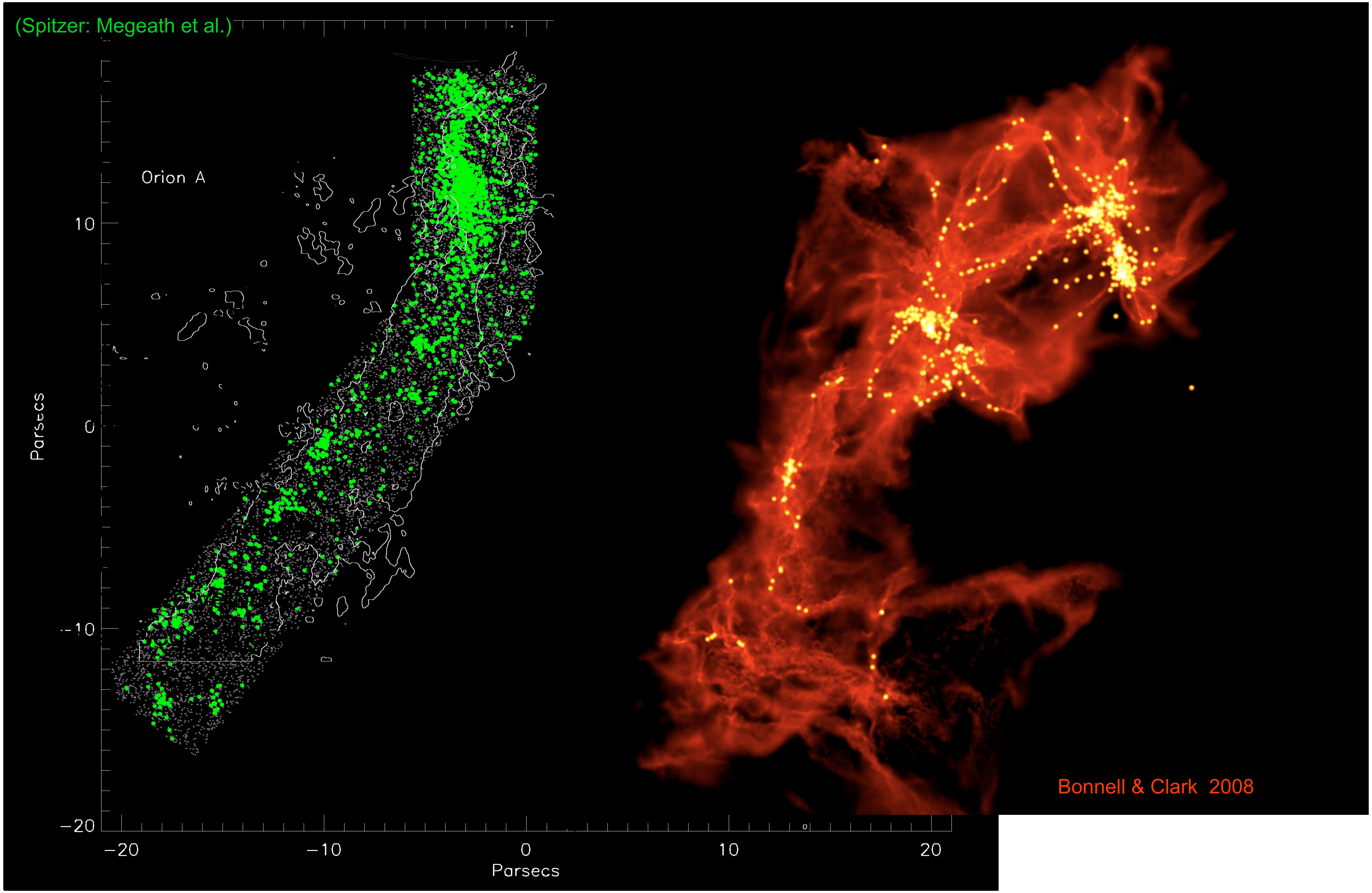
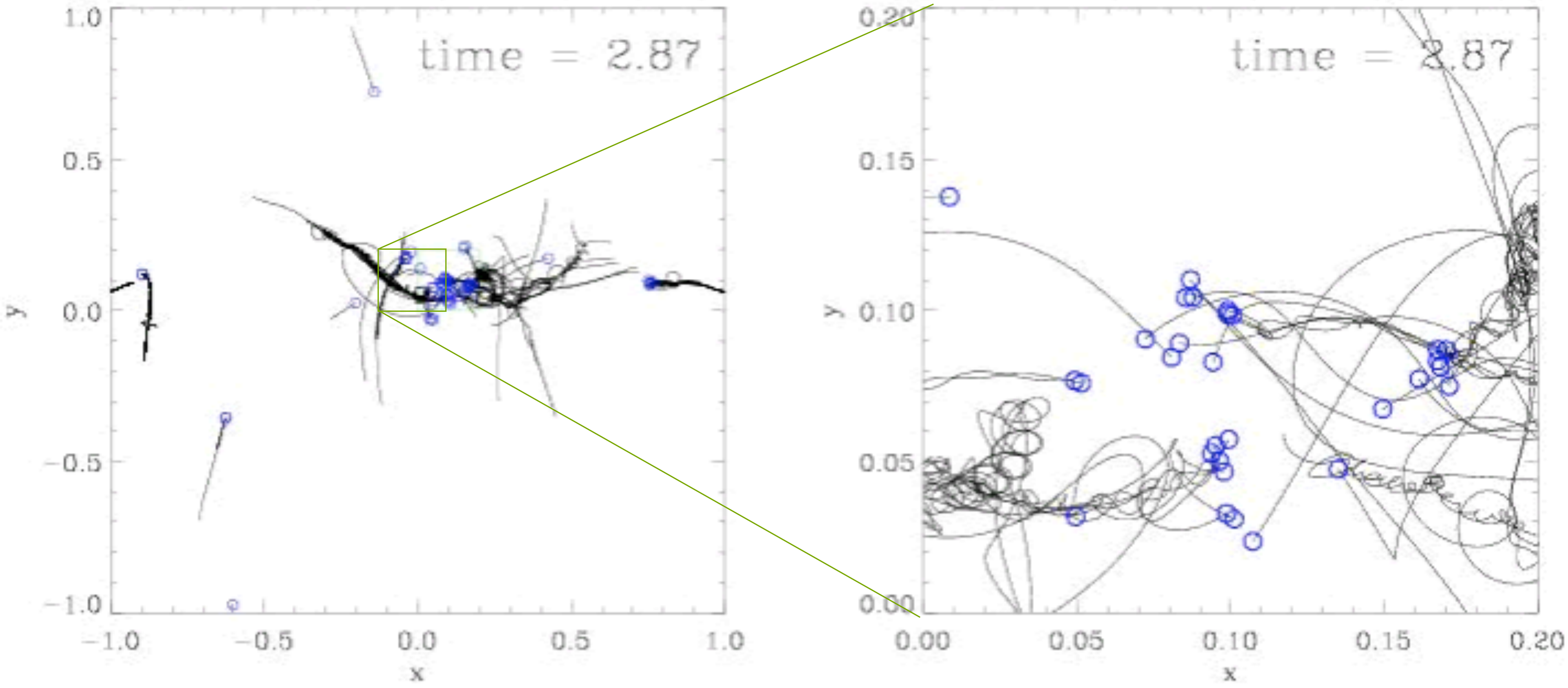

(Spitzer: Megeath et al.)

Bonnell & Clark 2008

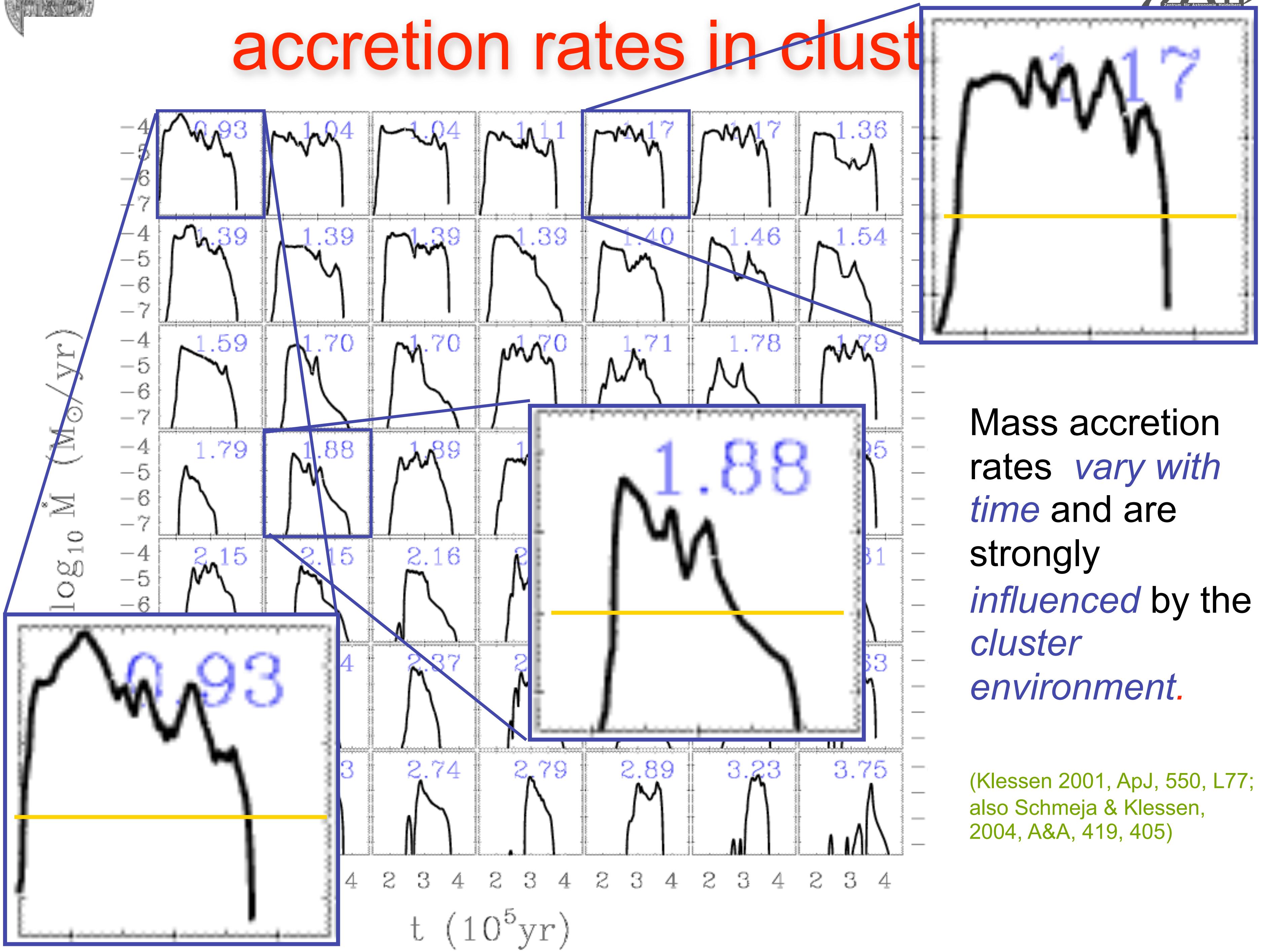
Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

accretion rates in 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)

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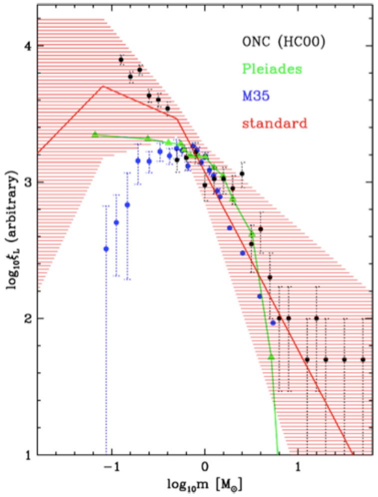

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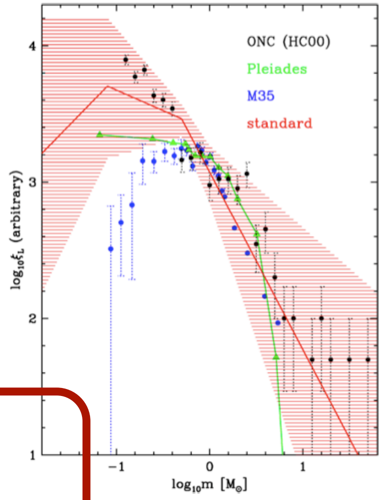
application to first star formation



(Kroupa 2002)

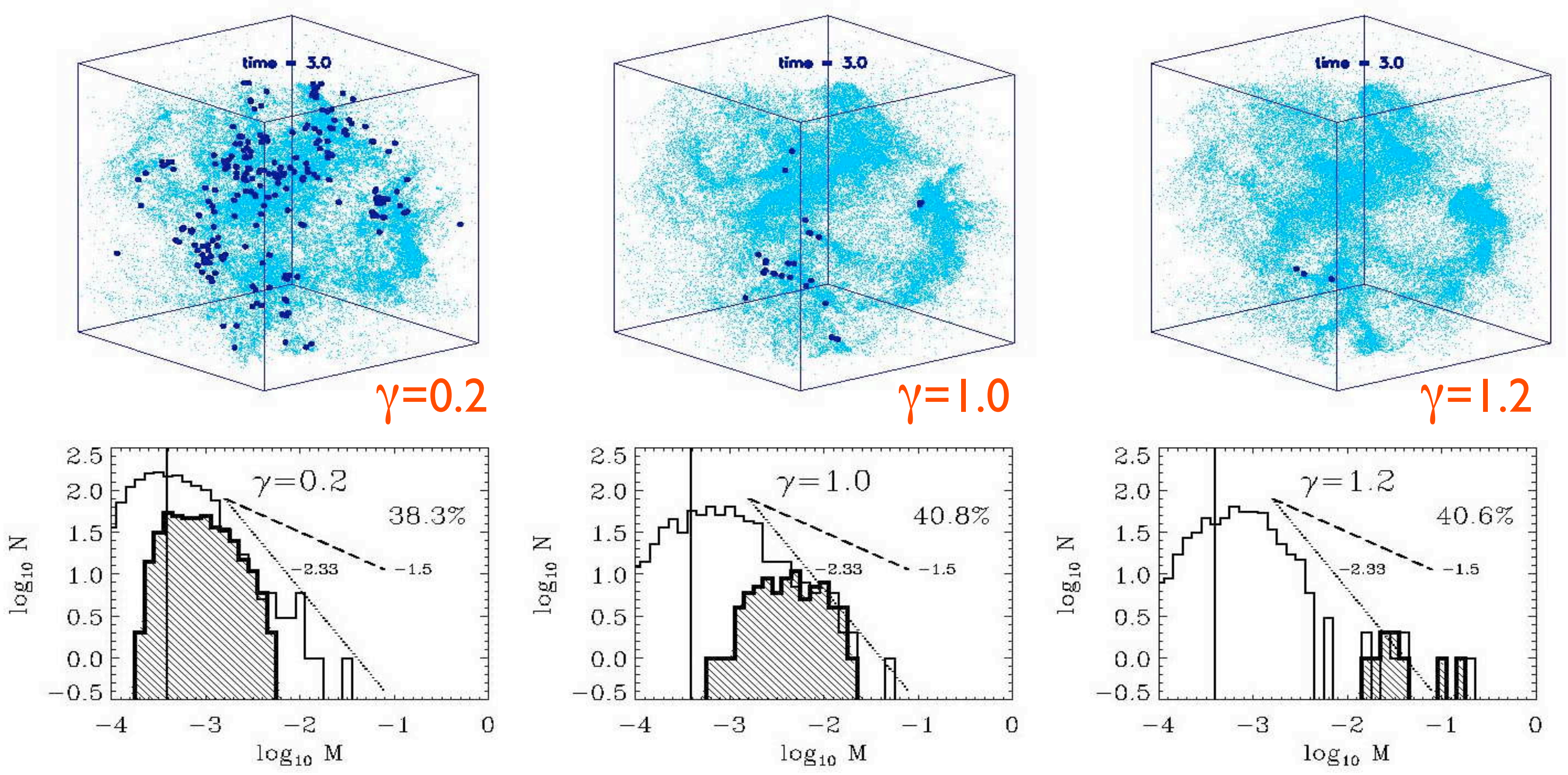
thermodynamics & fragmentation

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

dependency on EOS



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

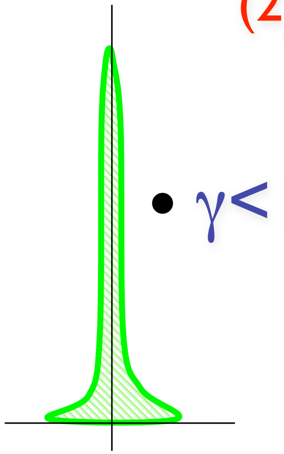
for γ>1 it is suppressed → formation of *isolated massive stars*

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

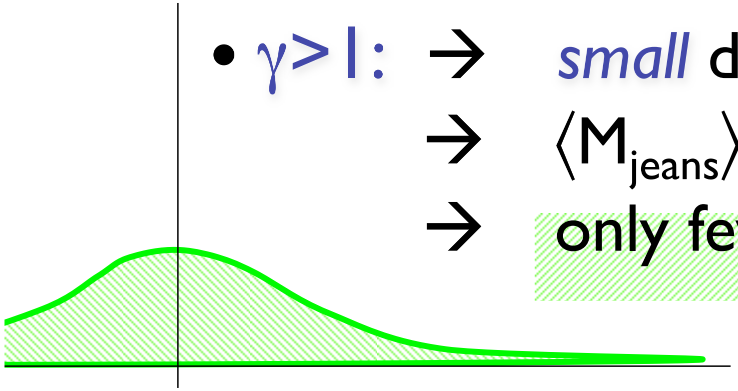
how does that work?

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

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

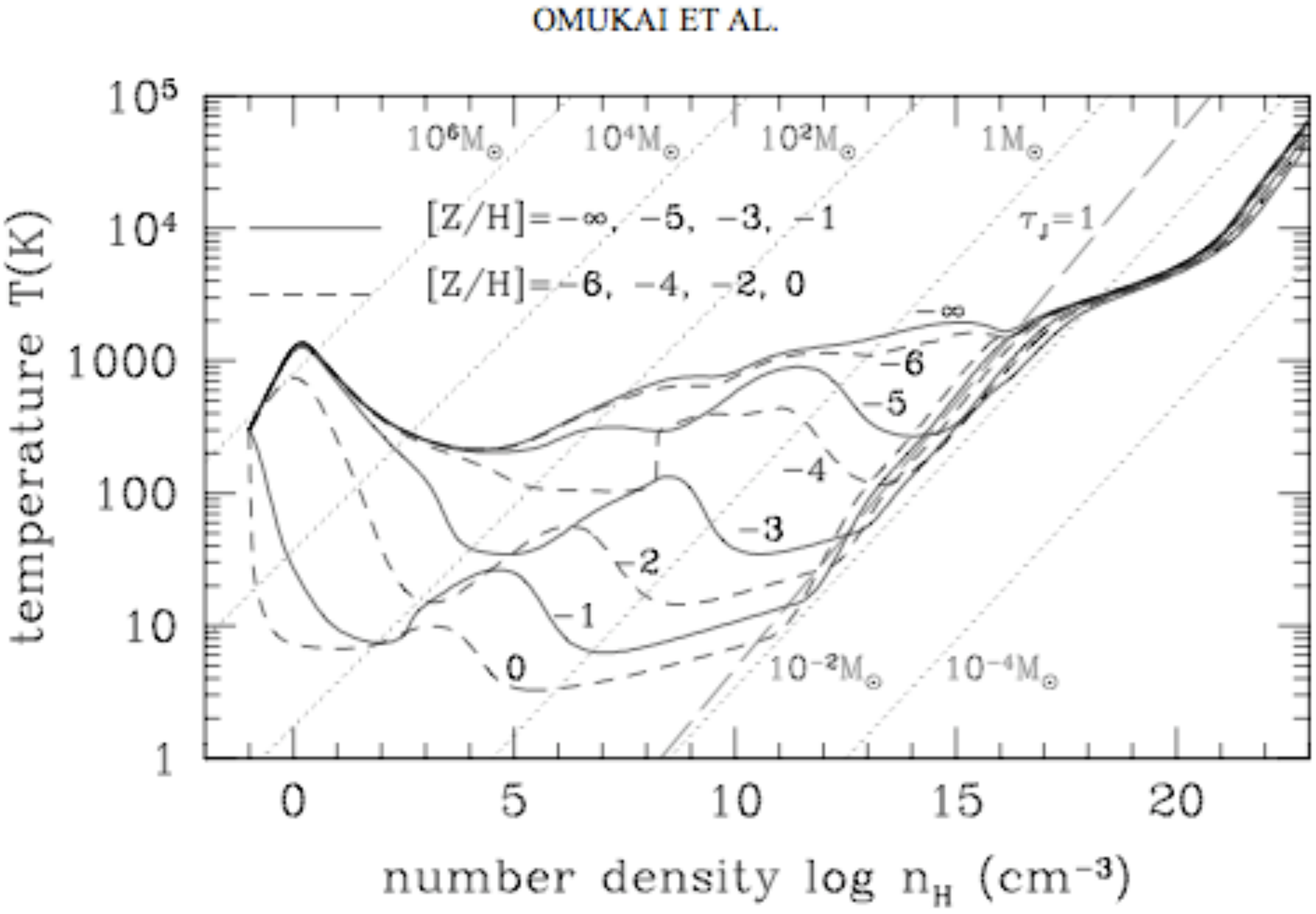


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



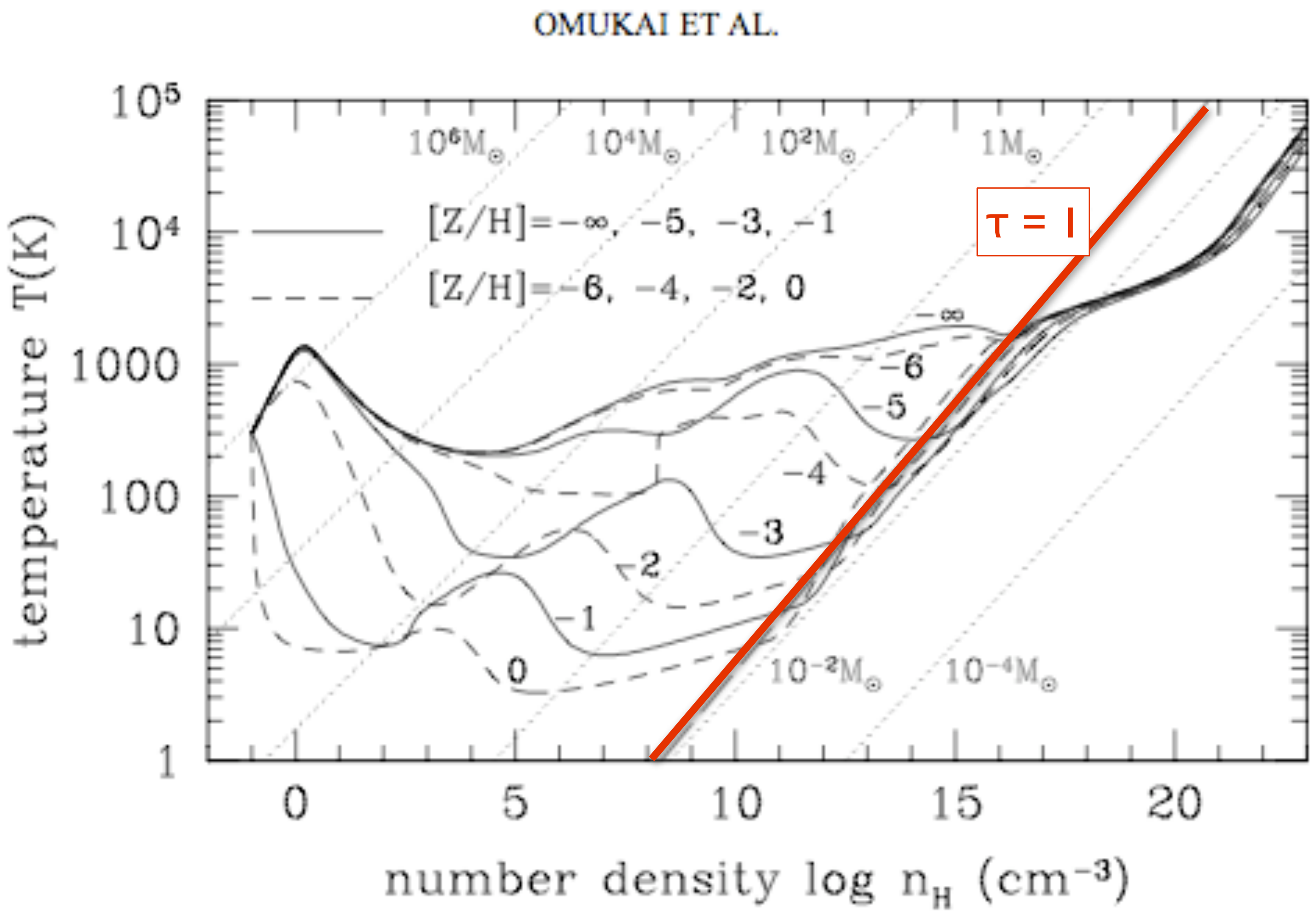
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



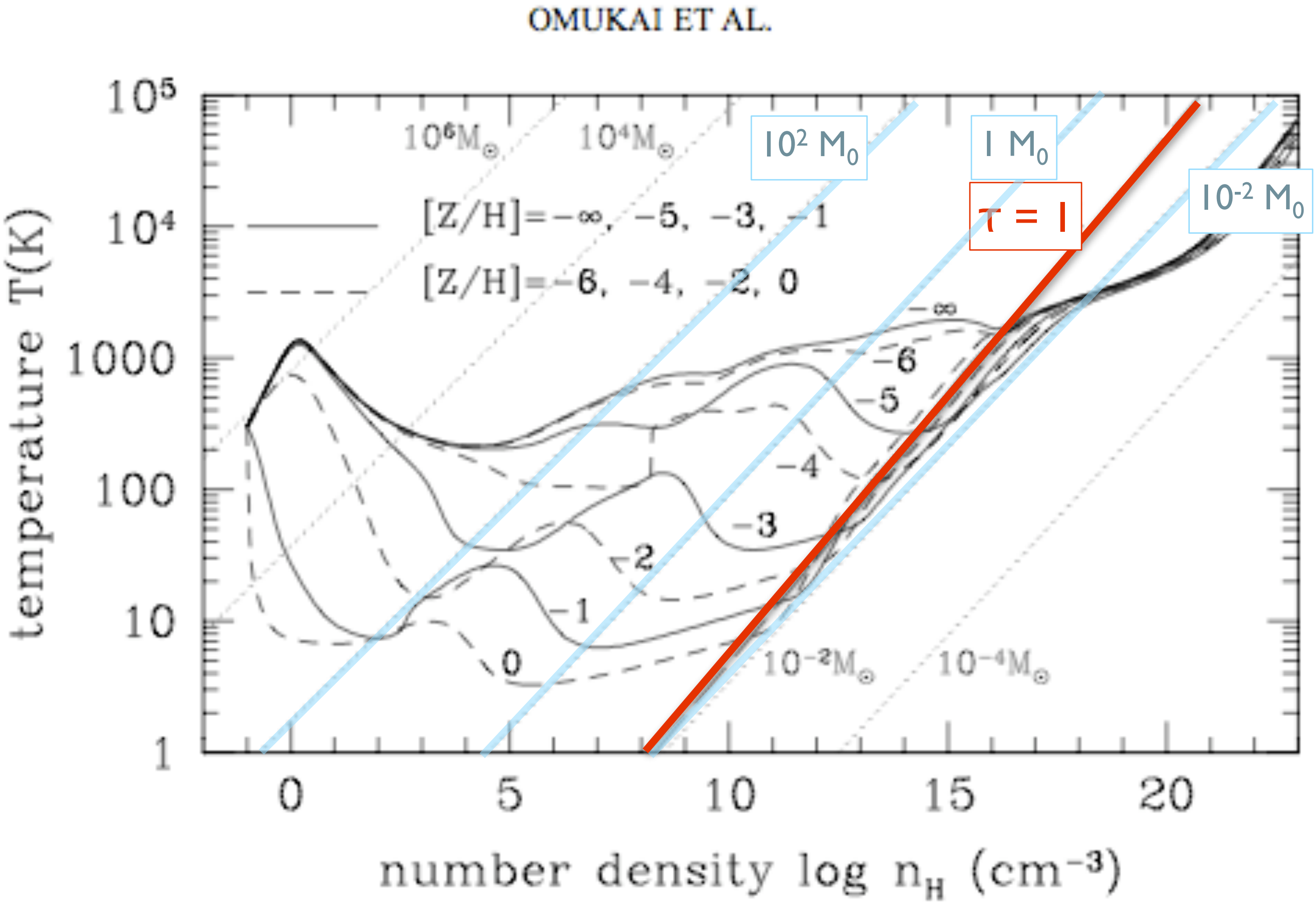
(Omukai et al. 2005)

EOS as function of metallicity



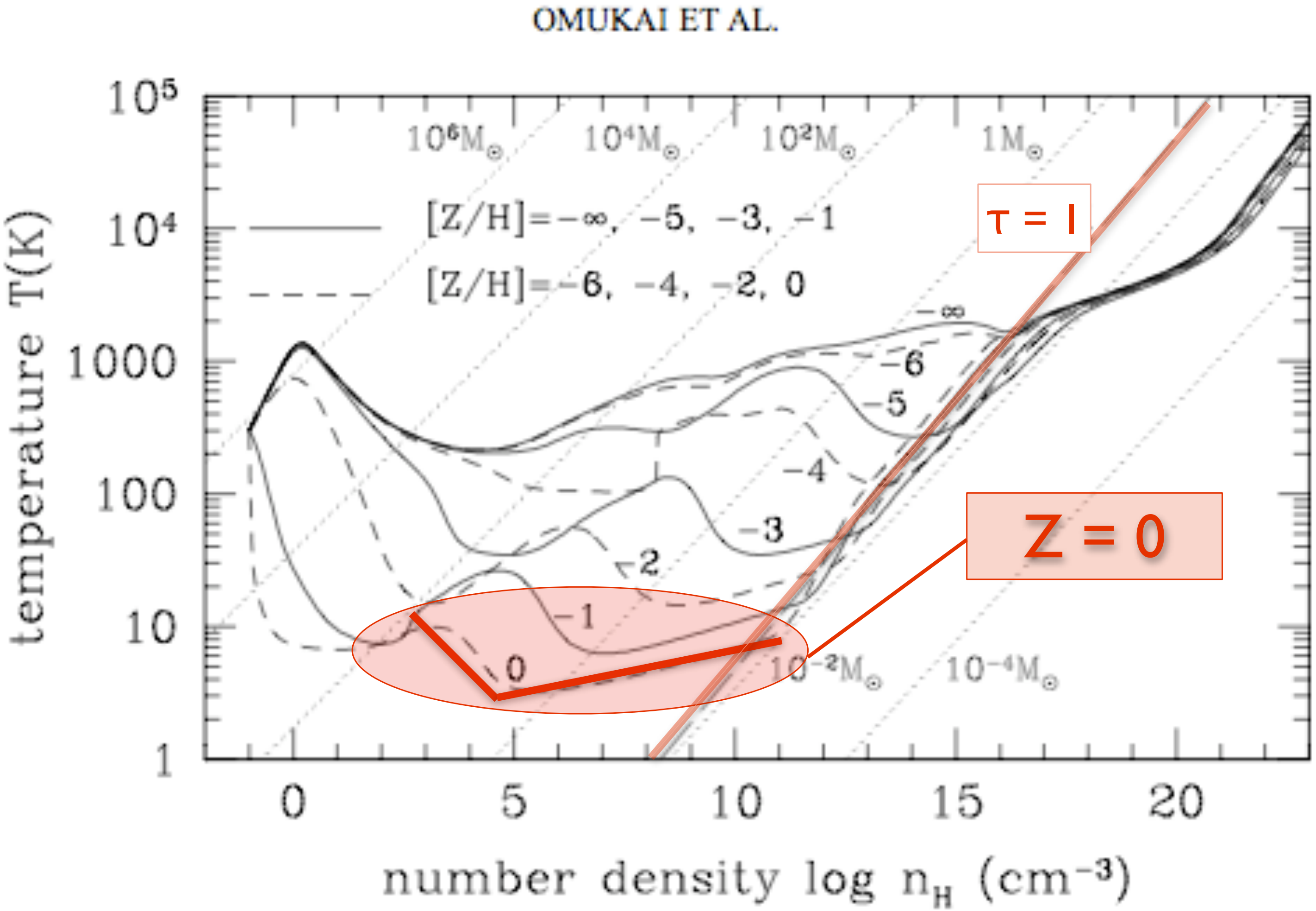
(Omukai et al. 2005)

EOS as function of metallicity



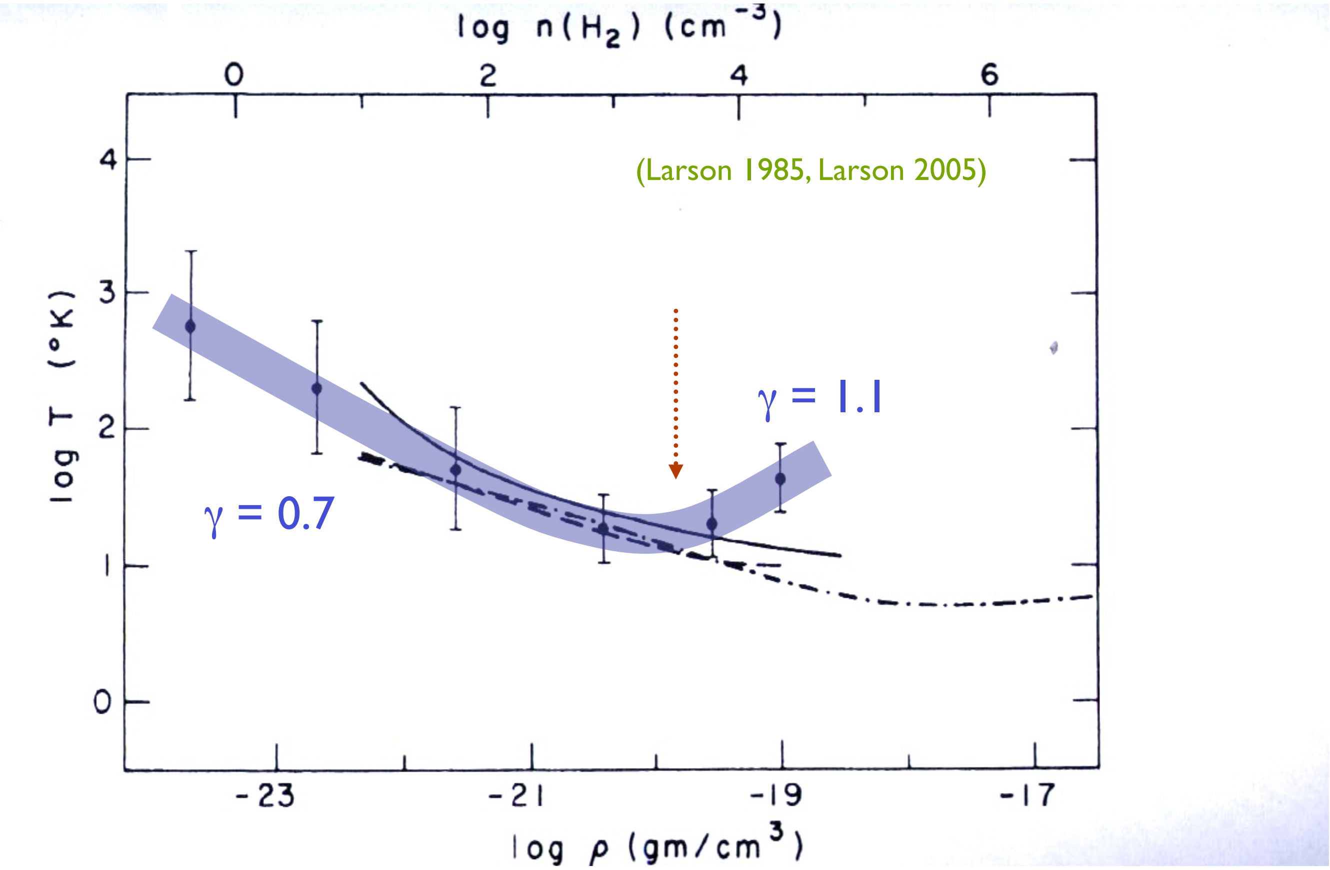
(Omukai et al. 2005)

present-day star formation



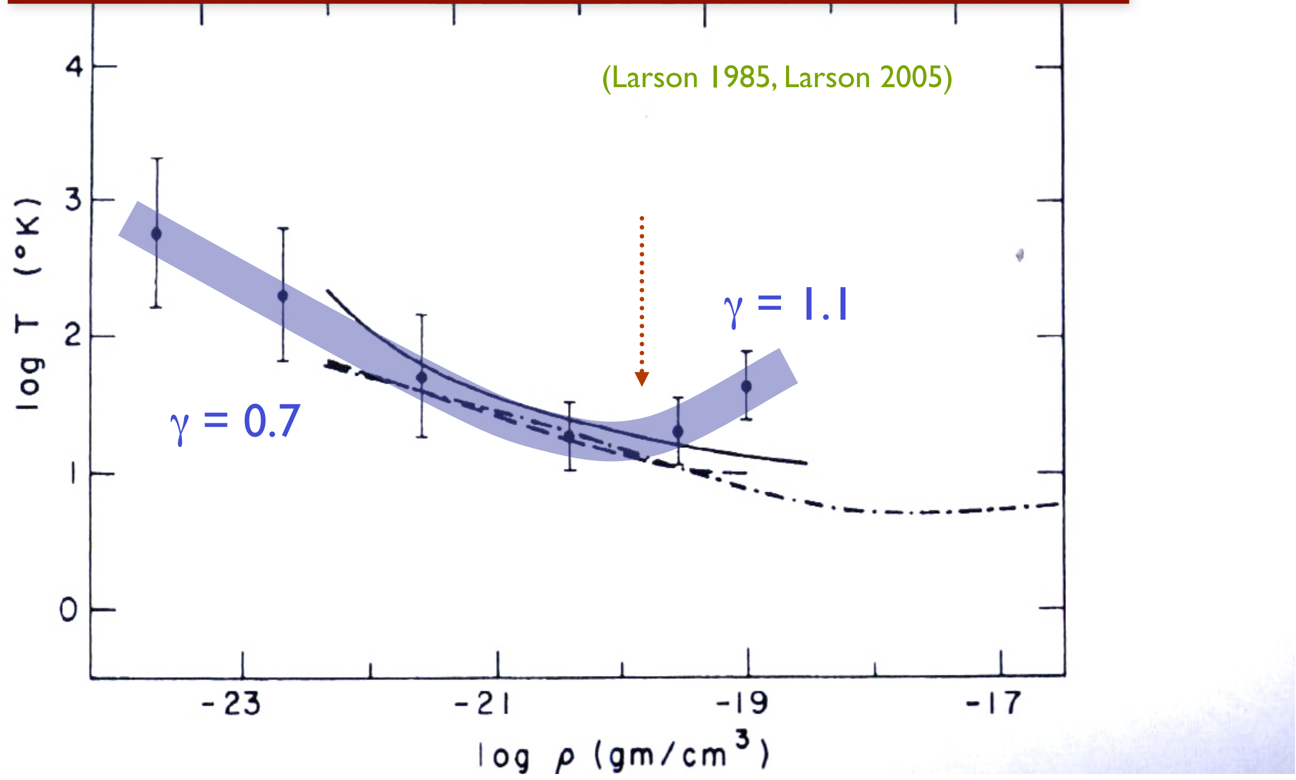
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation



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 from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

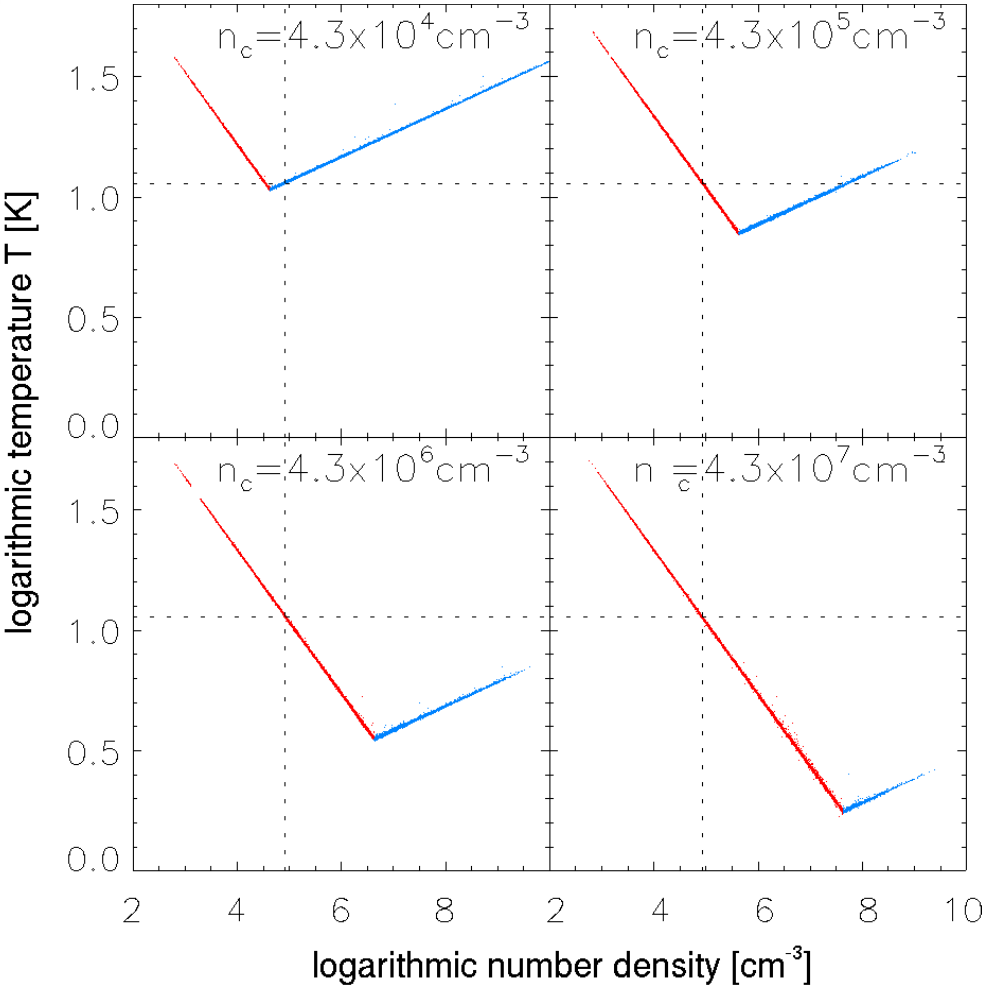
$$\boxed{T \sim \rho^{\gamma-1}}$$

EOS and Jeans Mass:

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

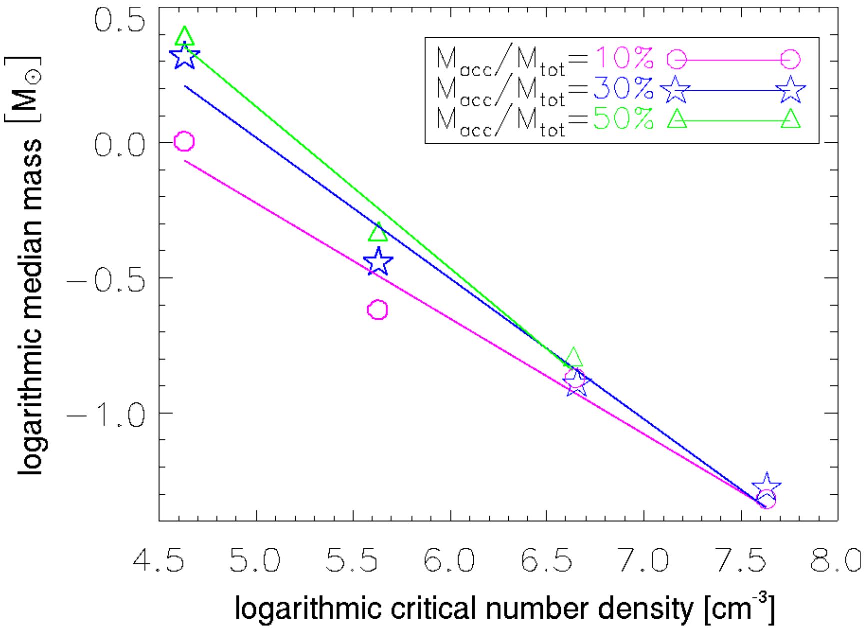
$\mathbf{M_{jeans}} \propto \gamma^{3/2}\,\rho^{(3\gamma-4)/2}$

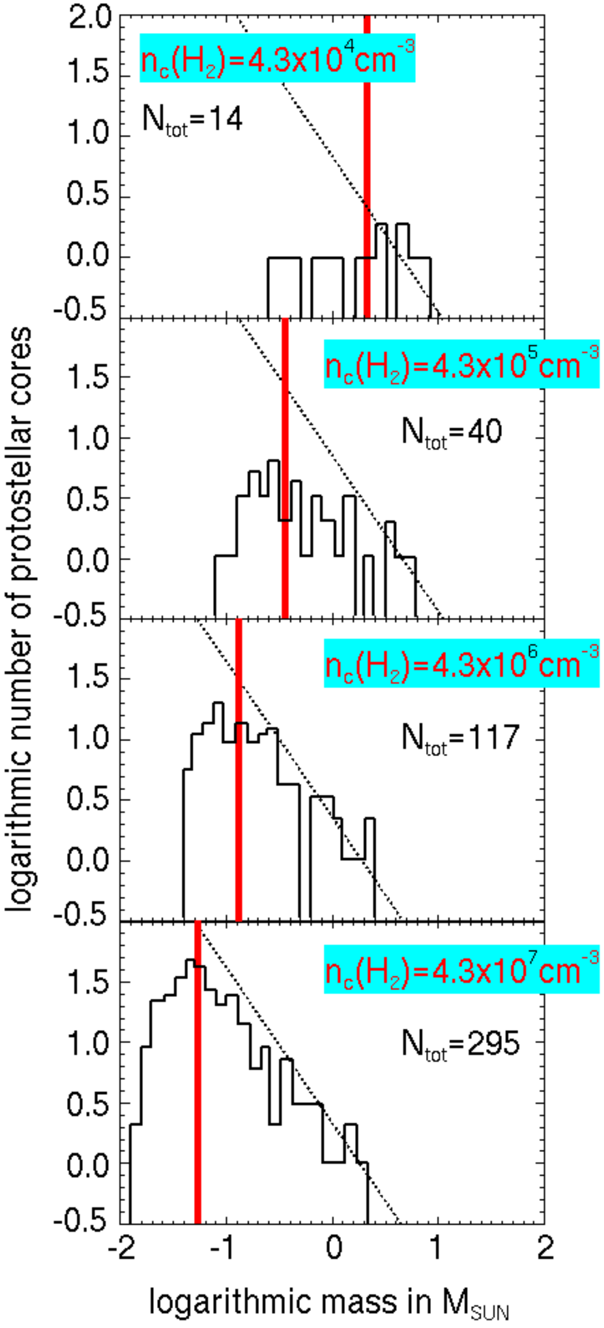
(Jappsen et al. 2005)



IMF from simple polytropic EOS

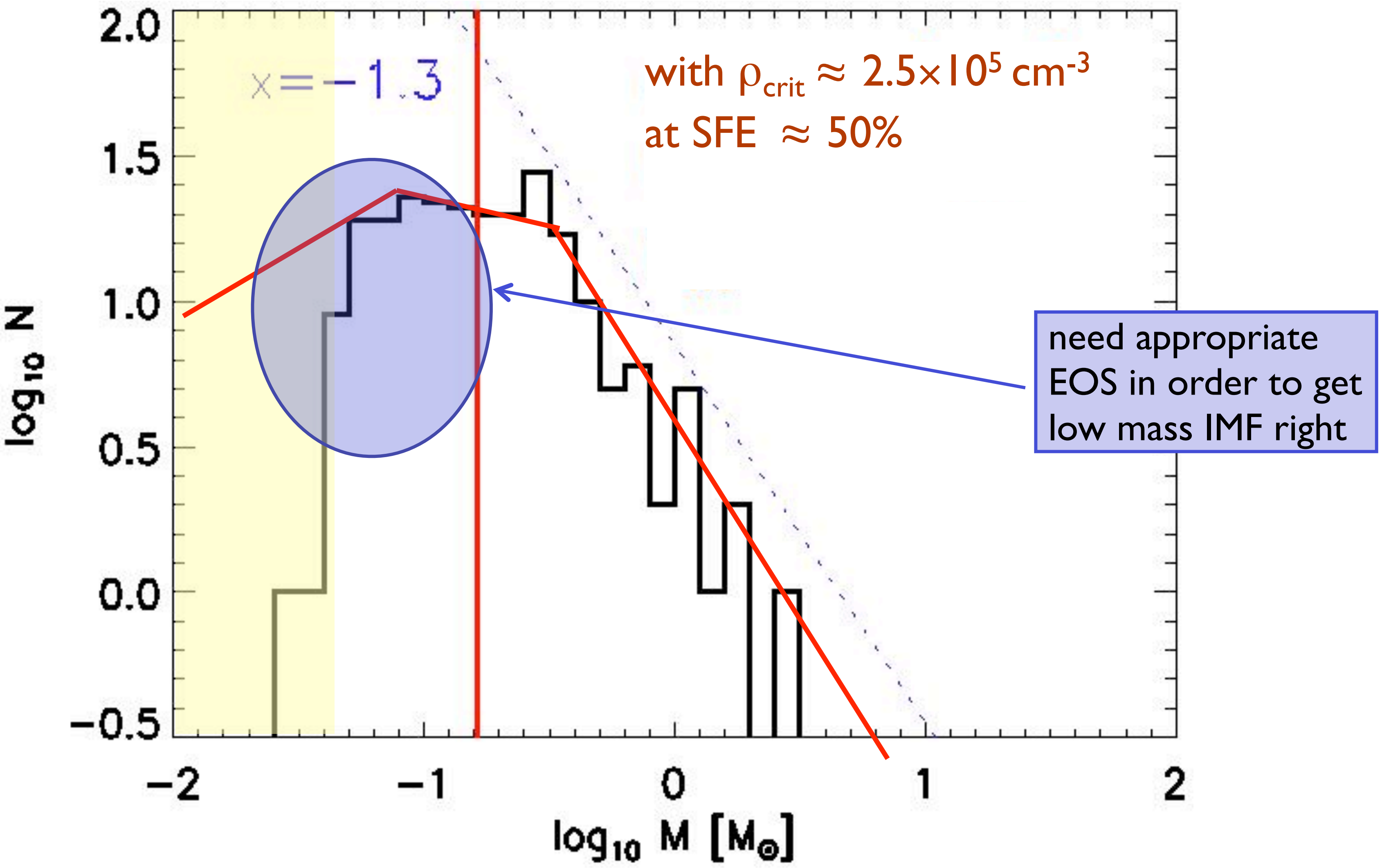
critical density ↑ ⇒ median mass ↓





(Jappsen et al. 2005)

IMF in nearby molecular clouds

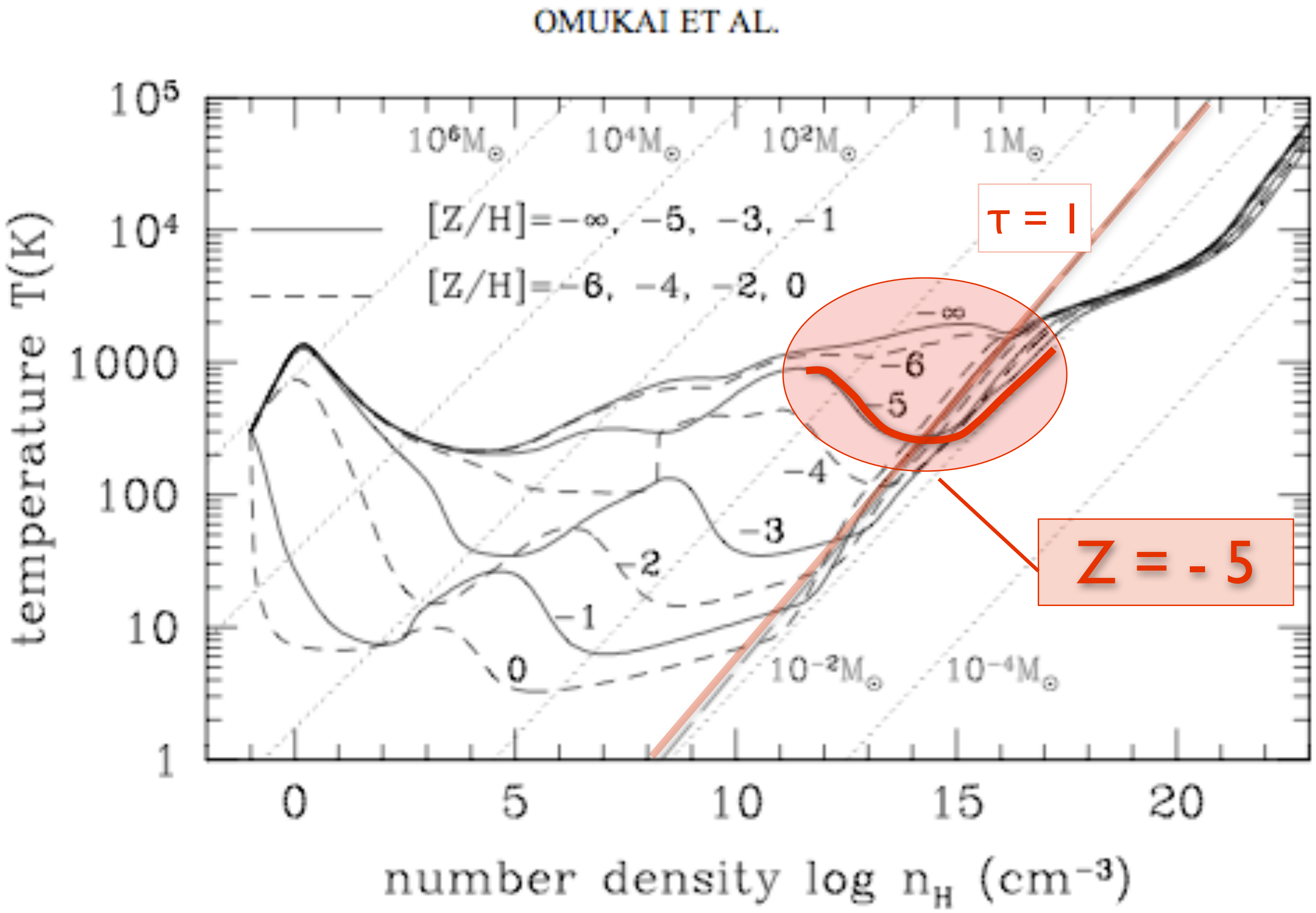


with $\rho_{crit} \approx 2.5 \times 10^5$ cm^{-3}
at SFE ≈ 50%

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

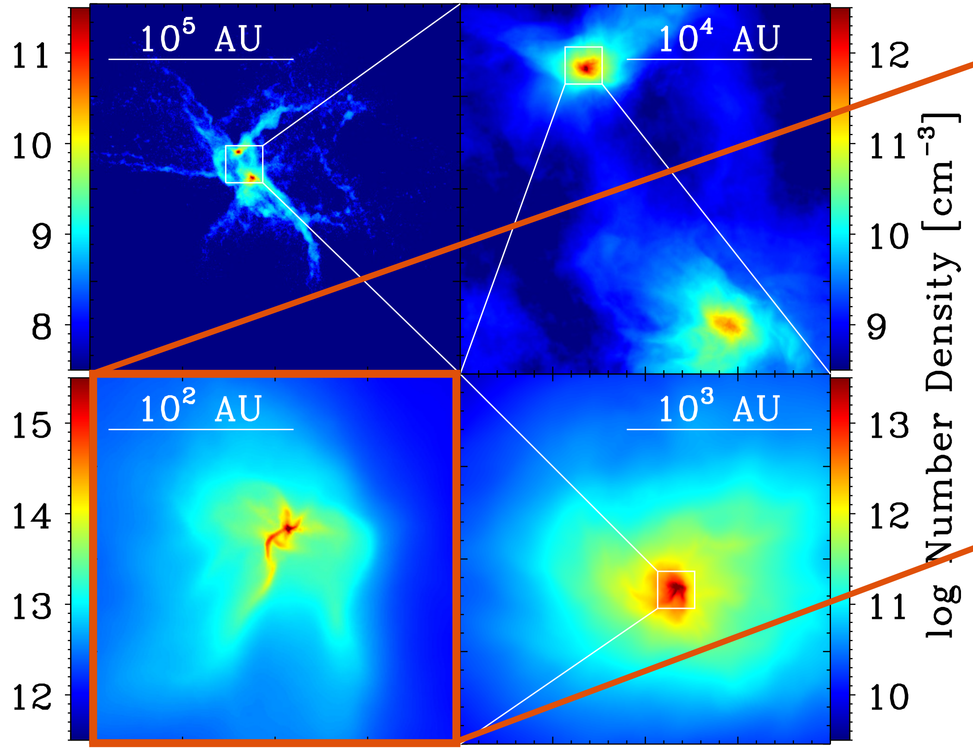


Fig. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

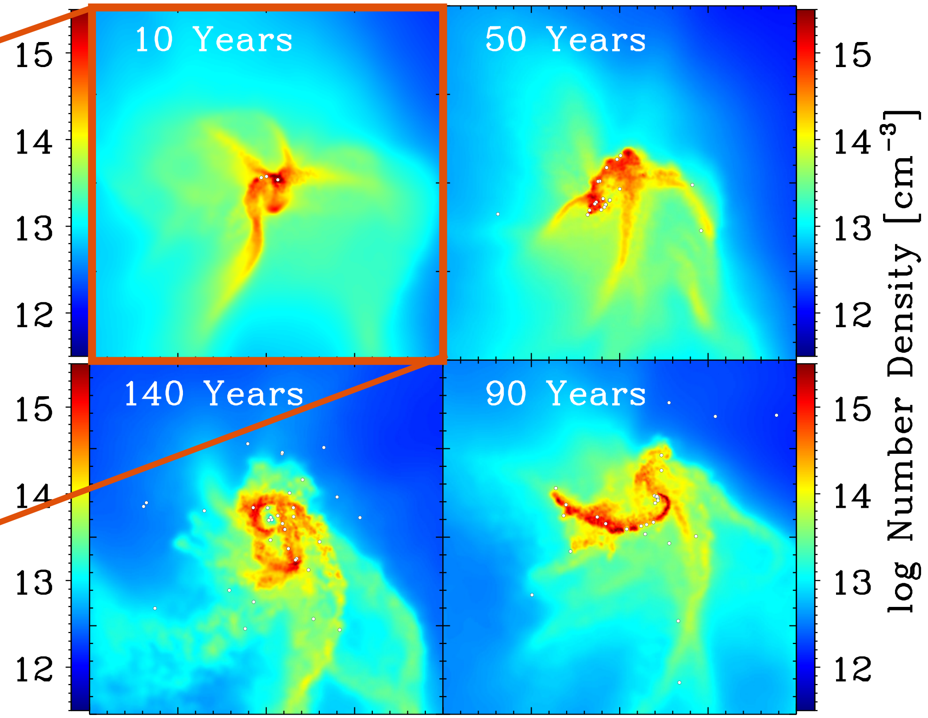
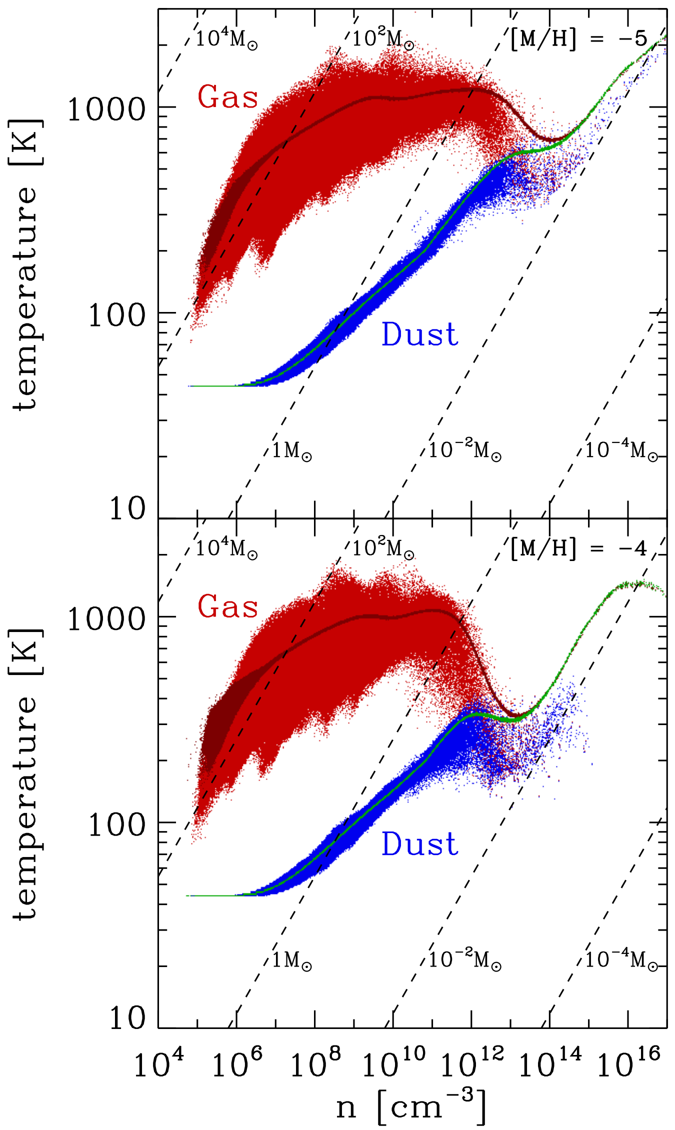


Fig. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and Z $= 10^{-4} Z_{\odot}$. The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

Dopcke et al. (2011, ApJ 729, L3)

transition: Pop III to Pop II.5



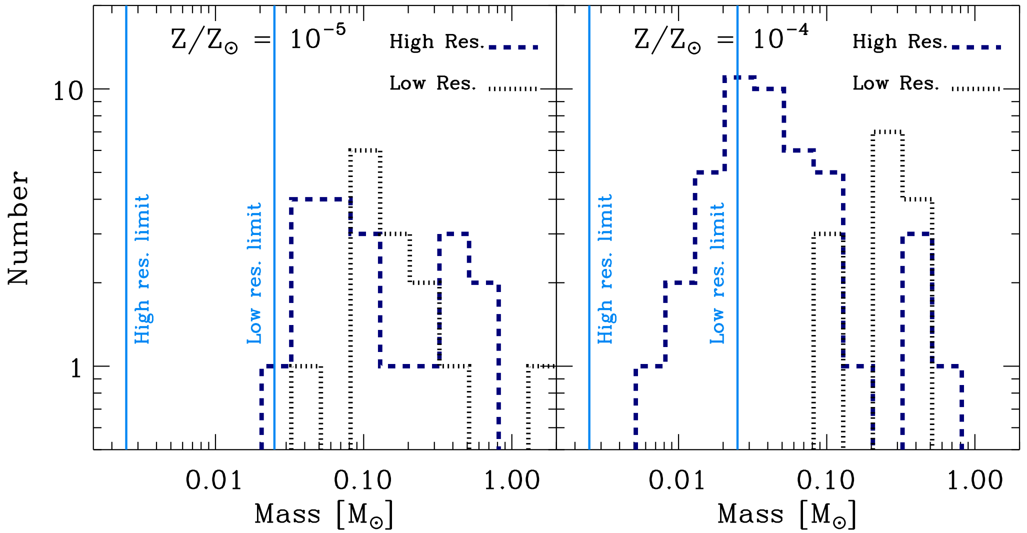
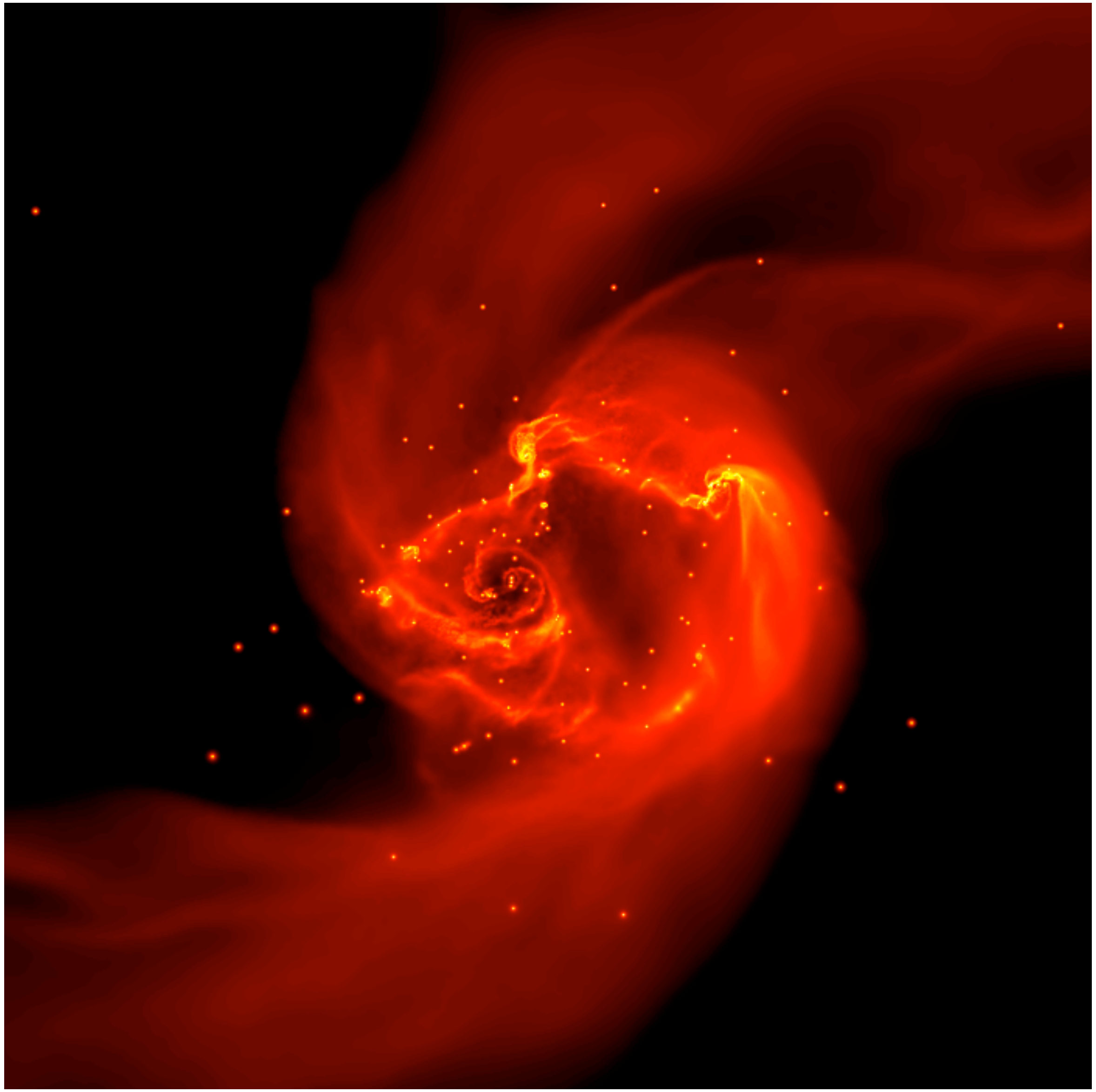


FIG. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas couple and the compressional heating starts to dominate over the dust cooling. At the time shown, around 5 $M_\odot$ of gas had been accreted by the sink particles in each simulation.

red / blue: turbulence and rotation
dark red / green: simple collapse

Dopcke et al. (2011, ApJ 729, L3)

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

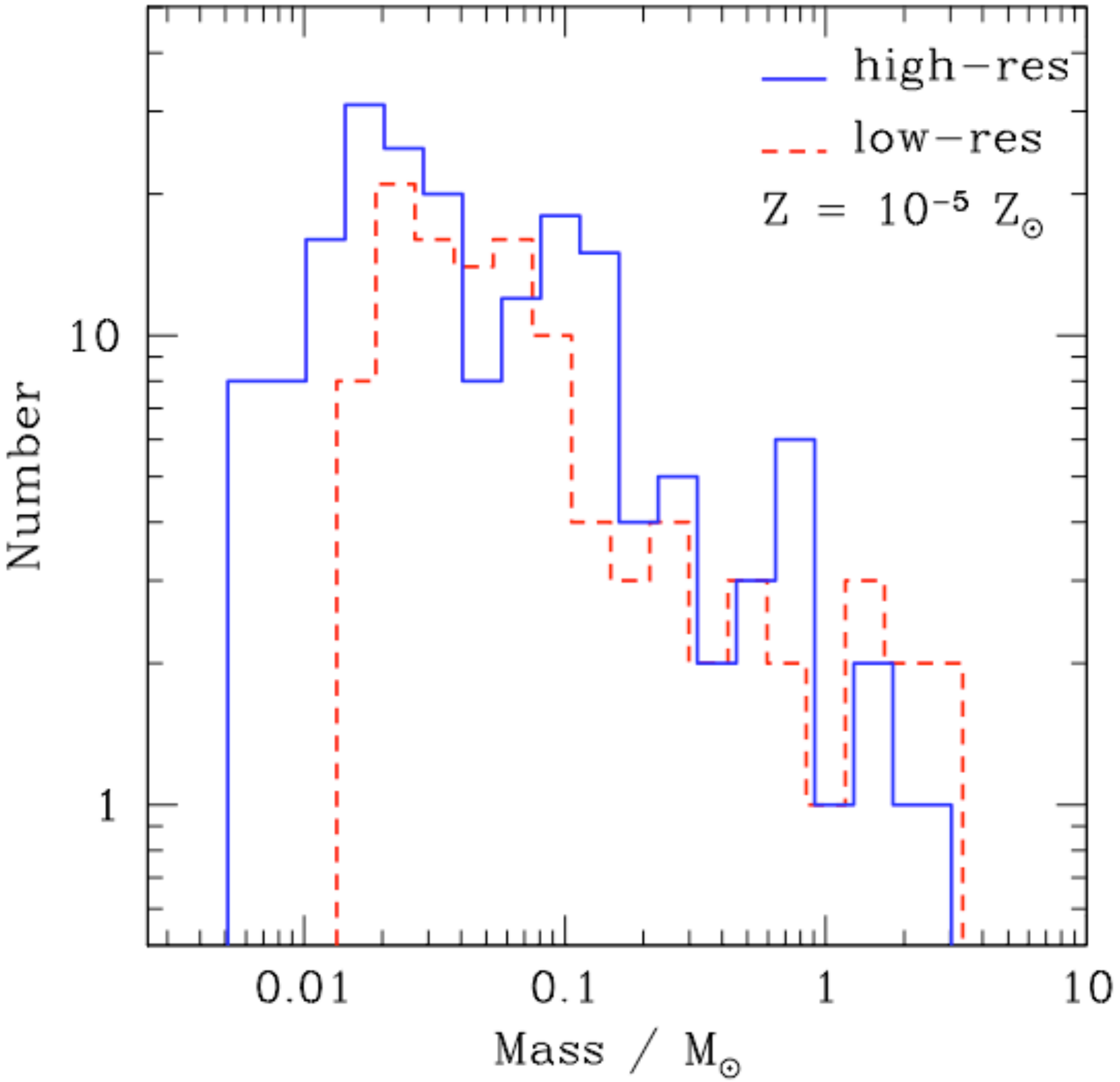


dense cluster of low-mass protostars builds up:

- 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. 2008, ApJ 672, 757)

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



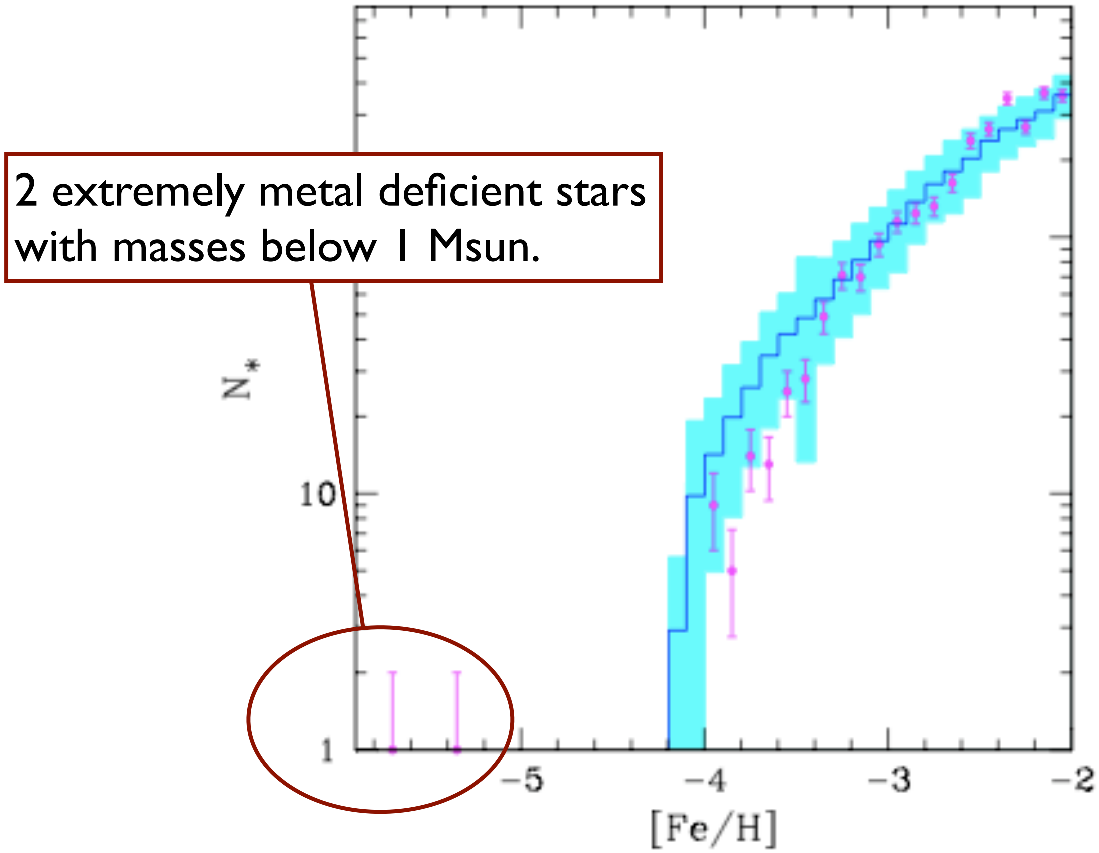
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$

- *predictions:*
  * low-mass stars with $[Fe/H] \sim 10^{-5}$
  * high binary fraction

(Clark et al. 2008)

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



2 extremely metal deficient stars with masses below 1 Msun.

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

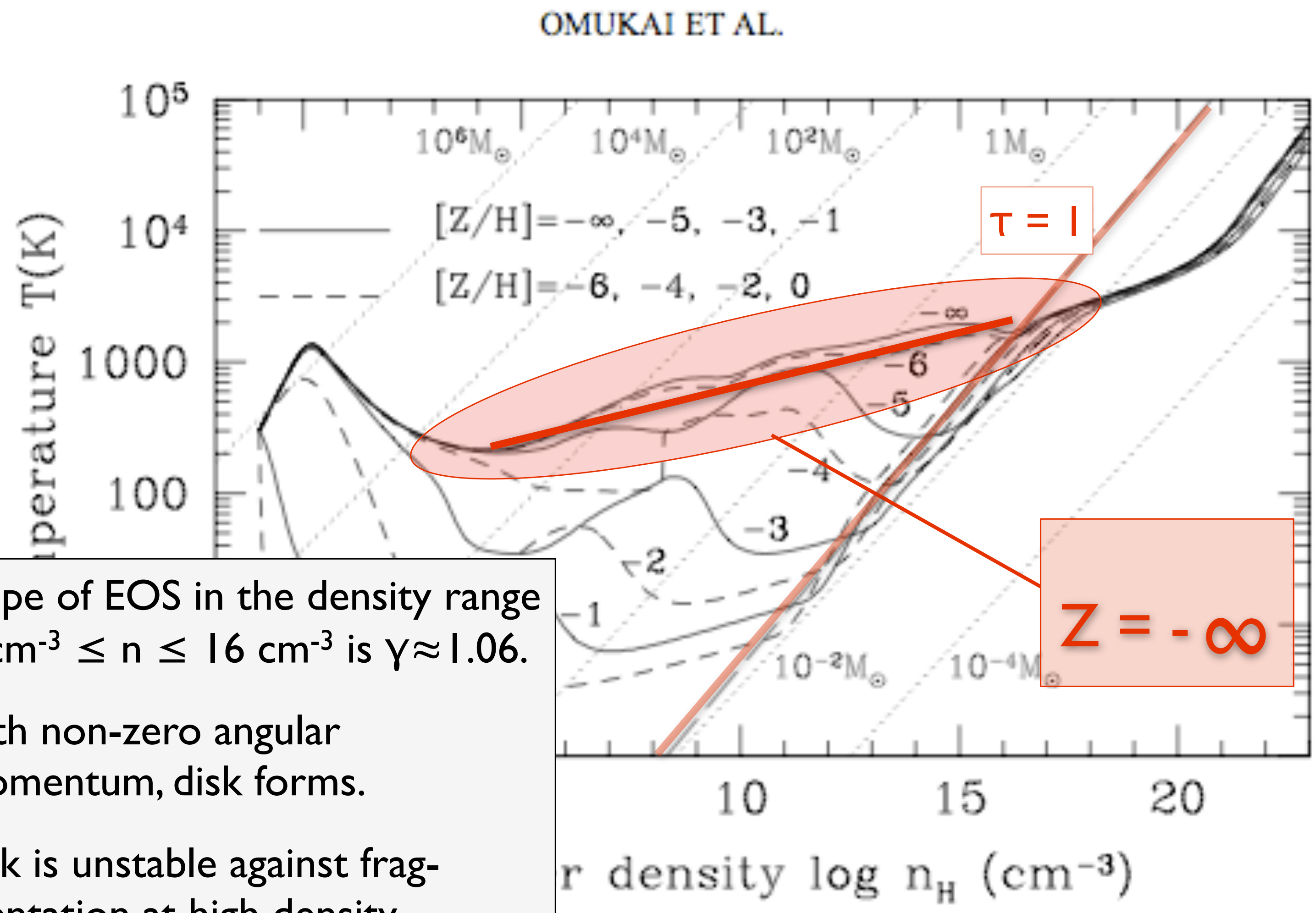
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9$ pc^{-3}

- *predictions:*
  - * low-mass stars with [Fe/H] ~ 10^{-5}
  - * high binary fraction

(Clark et al. 2008)

metal-free star formation



- slope of EOS in the density range 5 cm^{-3} ≤ n ≤ 16 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)

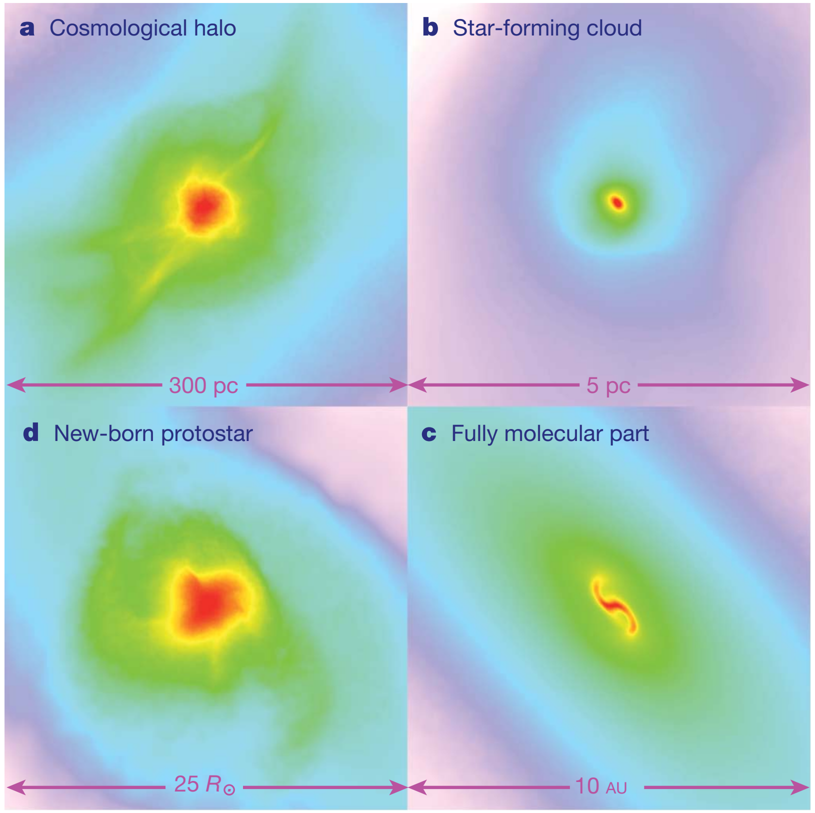
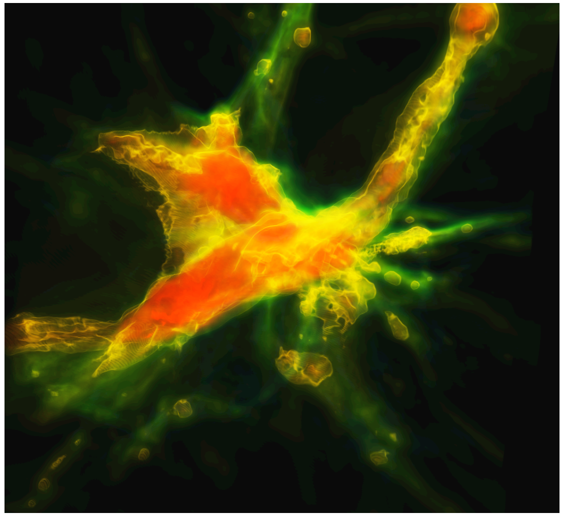


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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

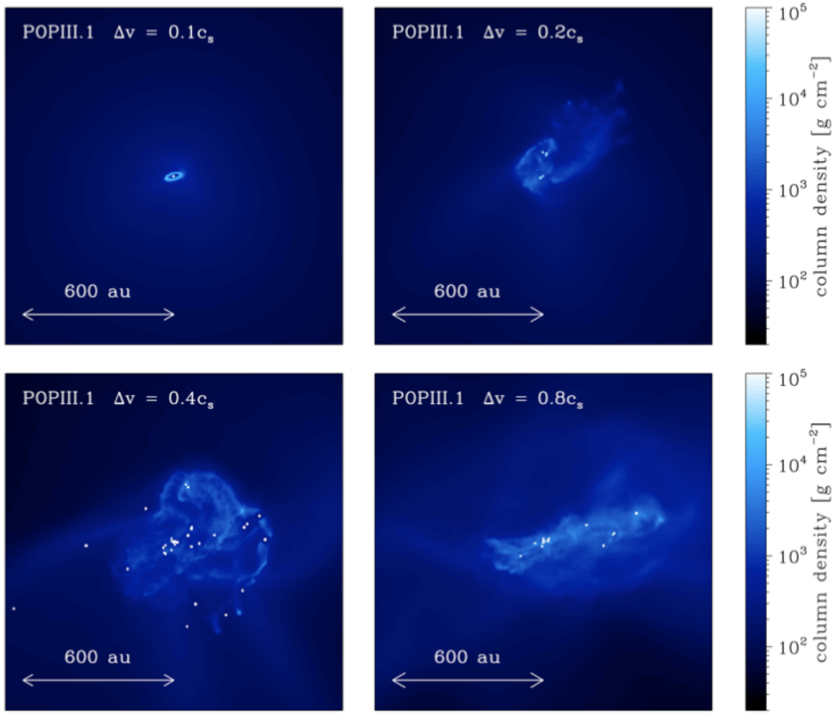


(Greif et al. 2008)

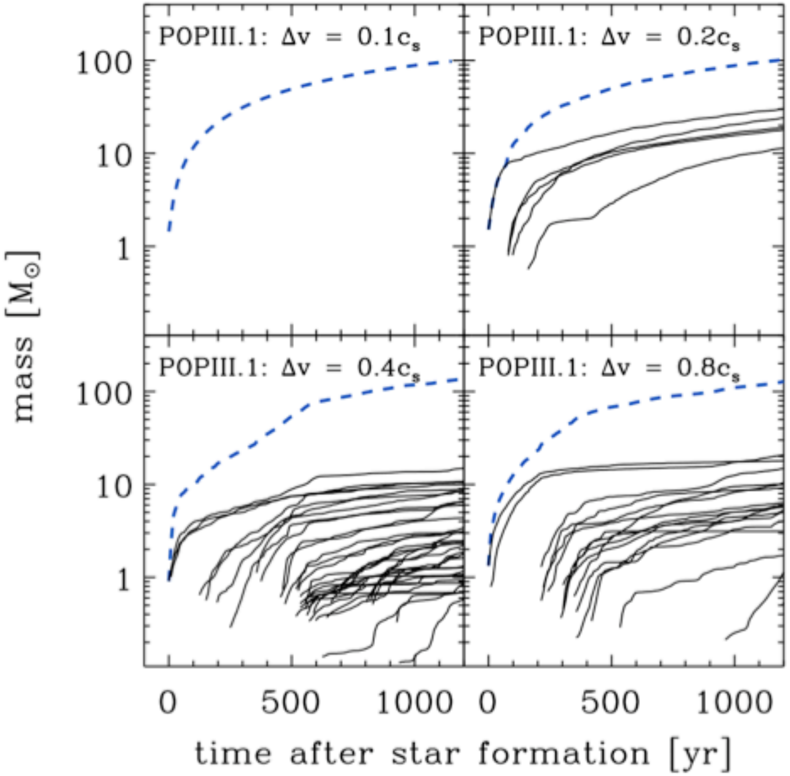
multiple Pop III stars in halo

- 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, submitted (arXiv:1101.5491)
  - complementary approaches with interesting similarities and differences....

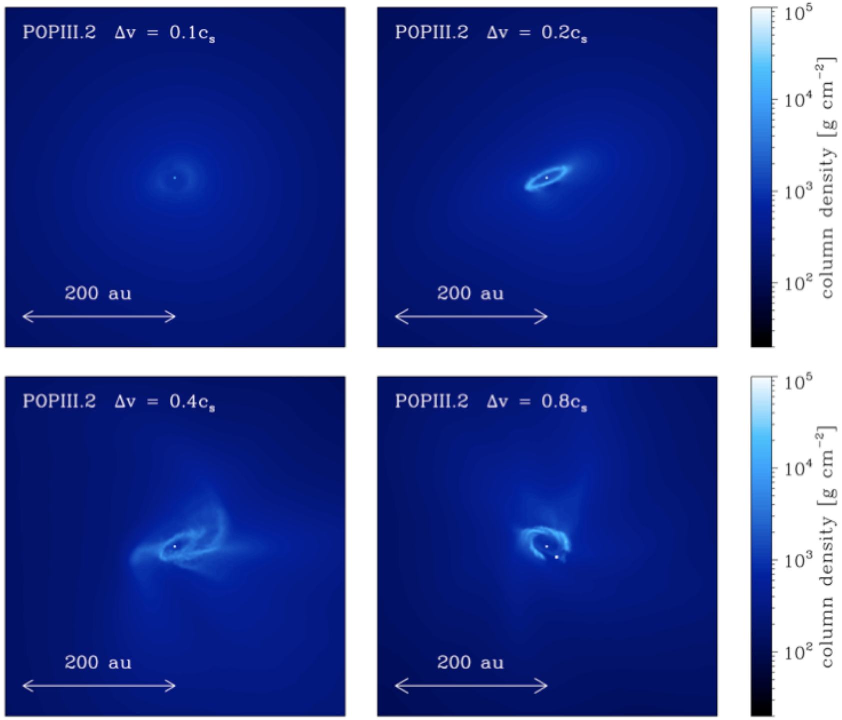
Pop III.1



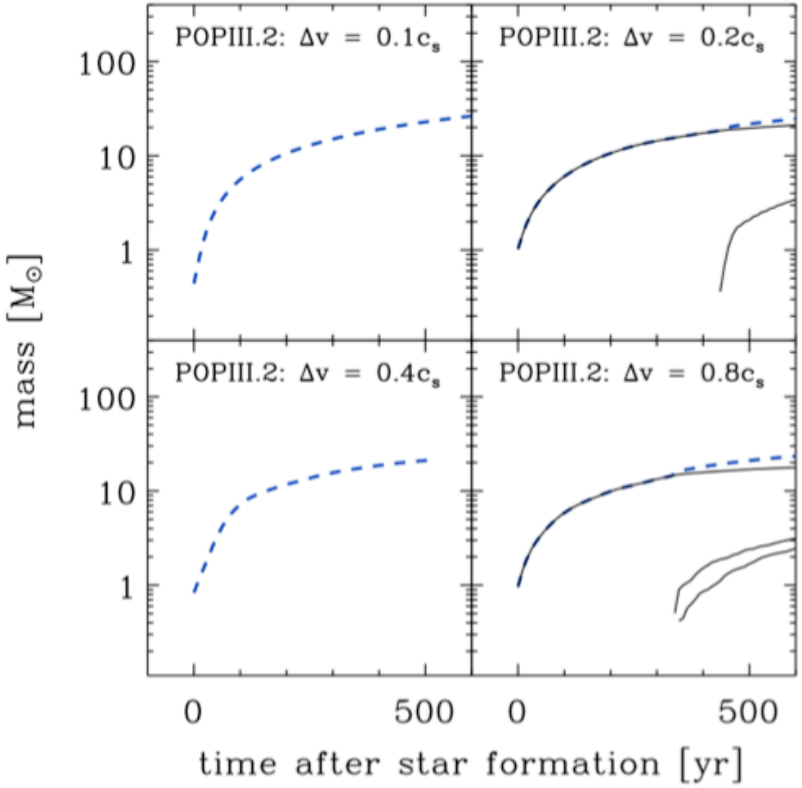
(Clark et al, 2011a, 727, 110)



Pop III.2



(Clark et al, 2011a)



once again: thermodynamics

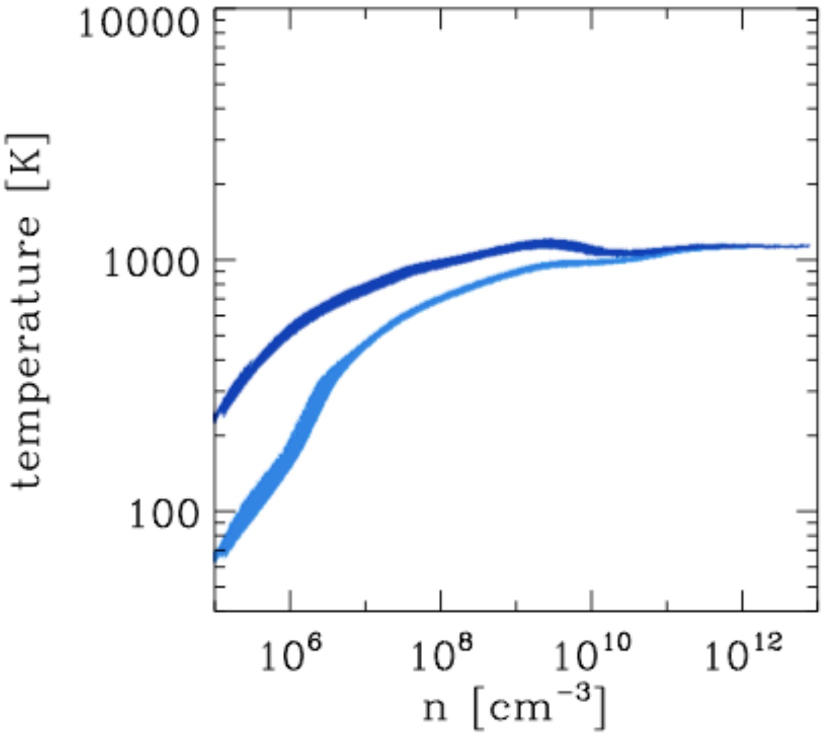


FIG. 6.— Temperature as a function of number density for the Pop. III.1 (dark blue) and Pop. III.2 (light blue) $\Delta v_{\rm turb} = 0.1\,c_{\rm s}$ simulations. In both cases, the curves denote the state of the cloud at the point just before the formation of the sink particle.

also Pop III.2 gas heats up above the CMB

--> weaker fragmentation!

once again: thermodynamics

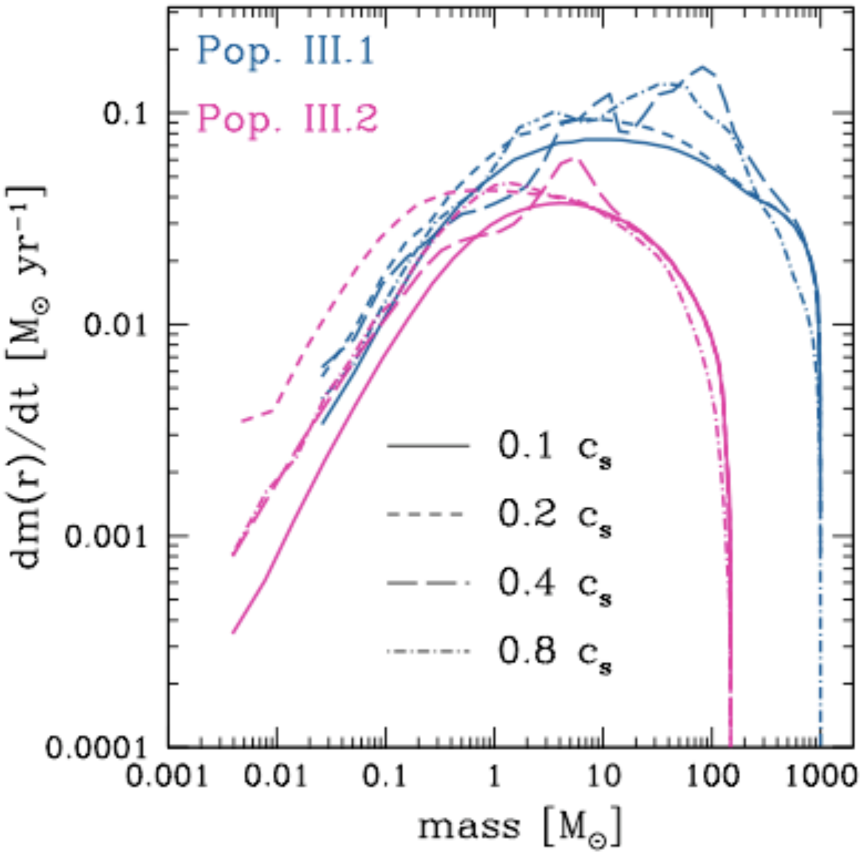


FIG. 8.— Accretion rates as a function of enclosed gas mass in the Pop. III.1 (upper lines; blue) and Pop. III.2 (lower lines; magenta) simulations, estimated as described in Section 4.1. Note that the sharp decline in the accretion rates for enclosed masses close to the initial cloud mass is an artifact of our problem setup; we would not expect to see this in a realistic Pop. III halo.

comparison of accretion rates...

SPH study: face on look at accretion disk

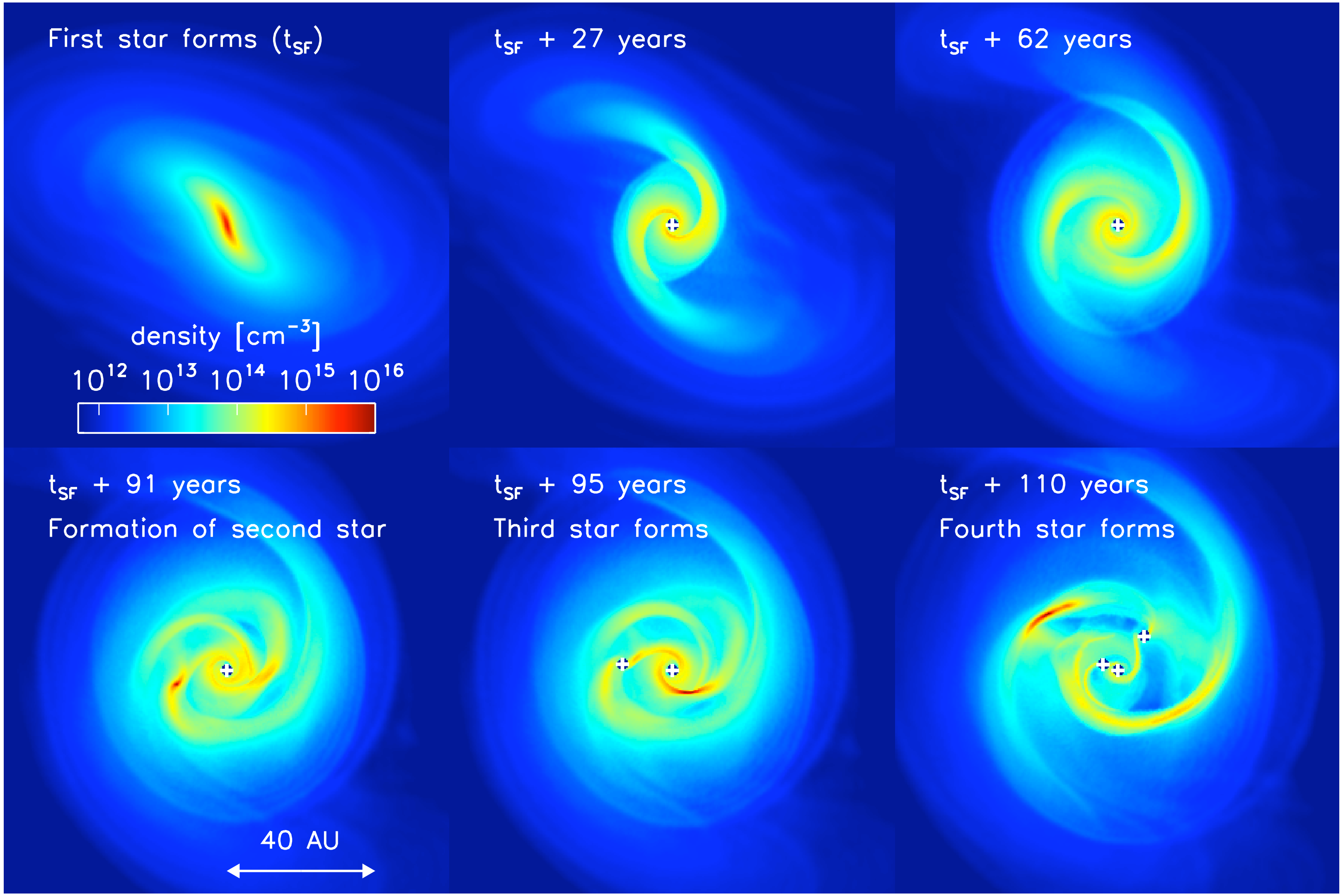


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

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

SPH study: some disk parameters

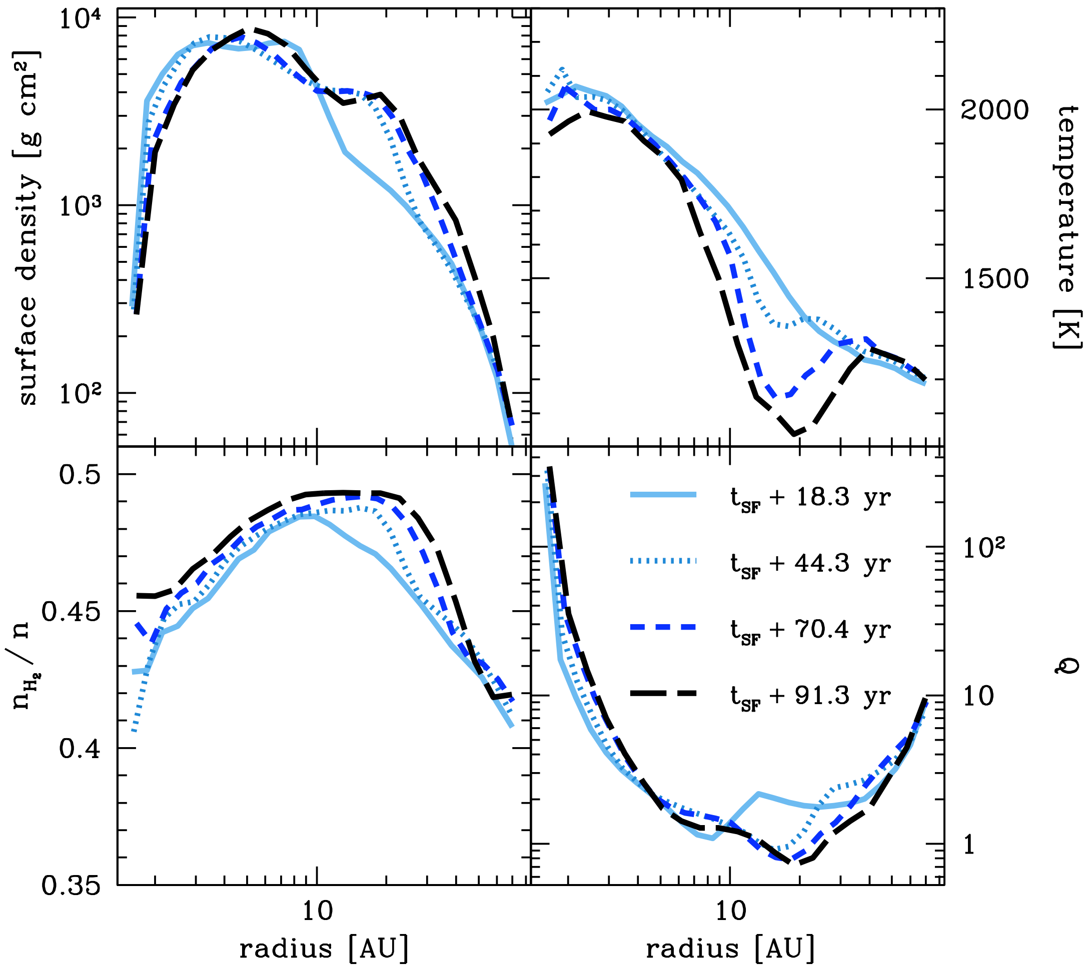


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi G\Sigma$, 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

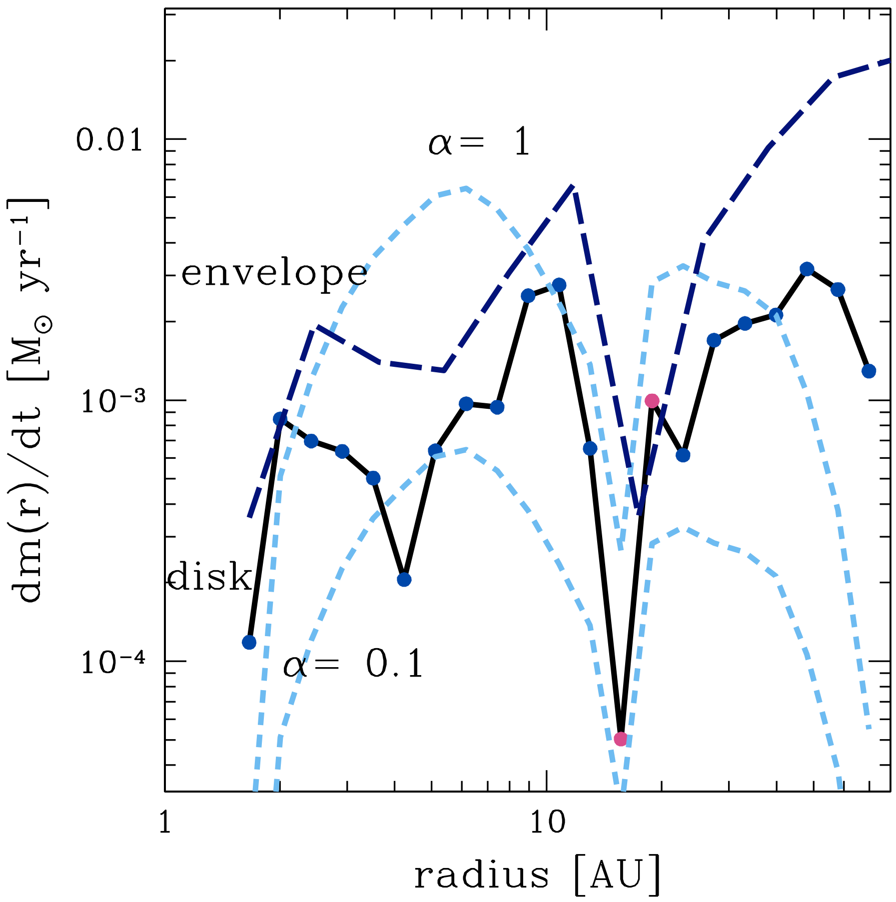


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure 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

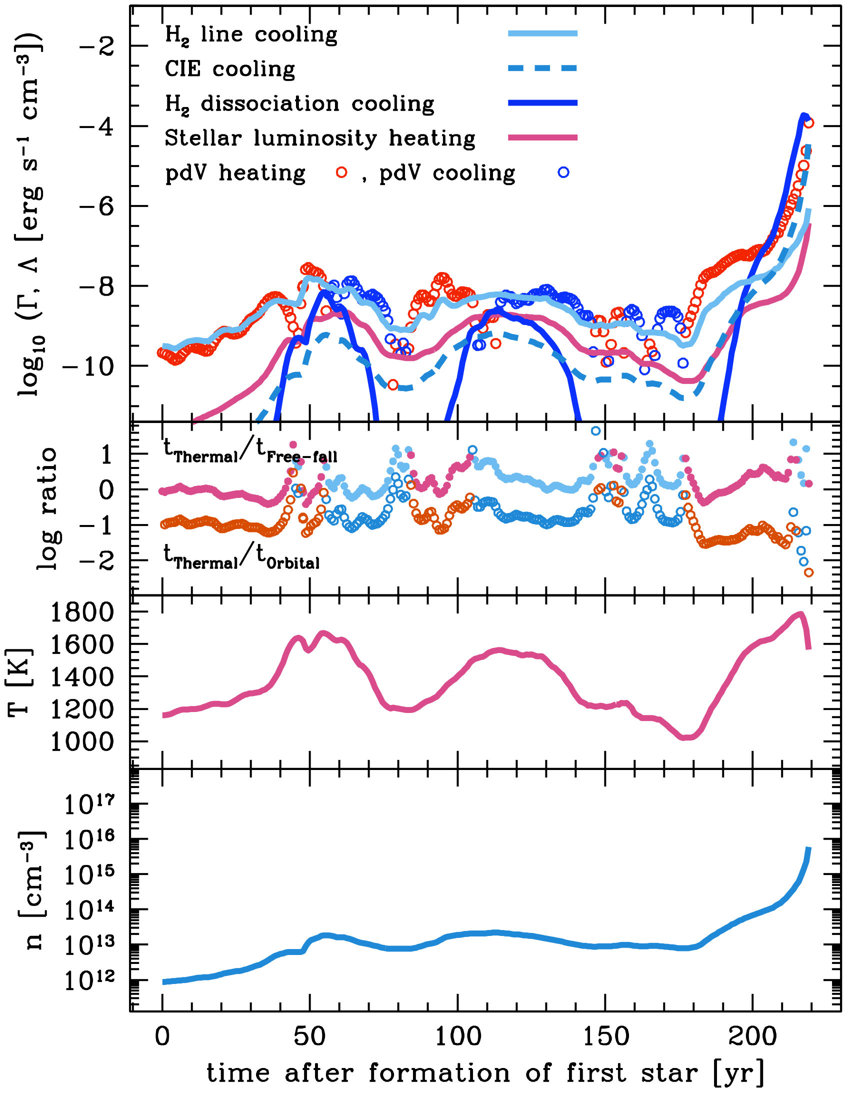
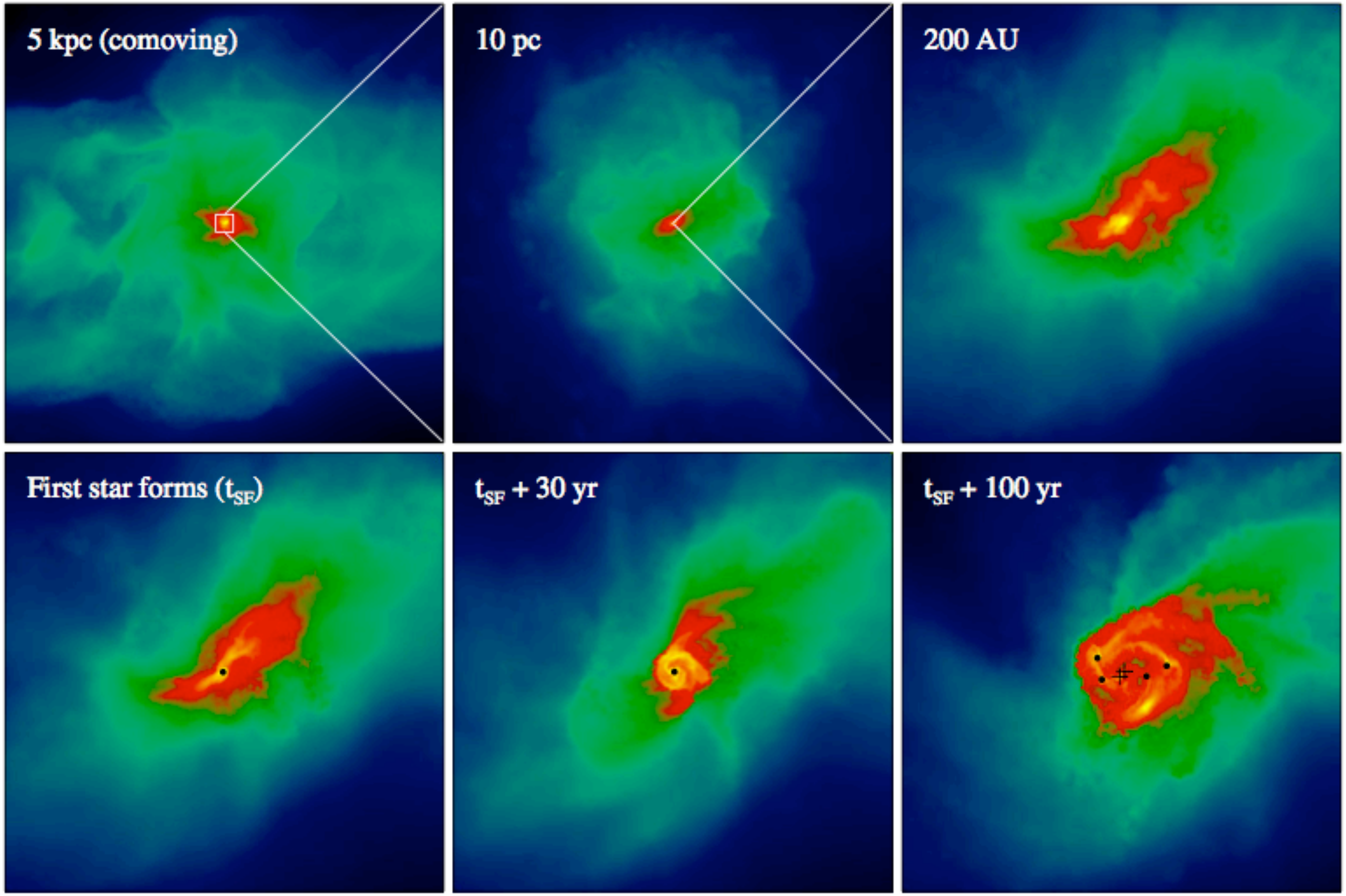


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated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

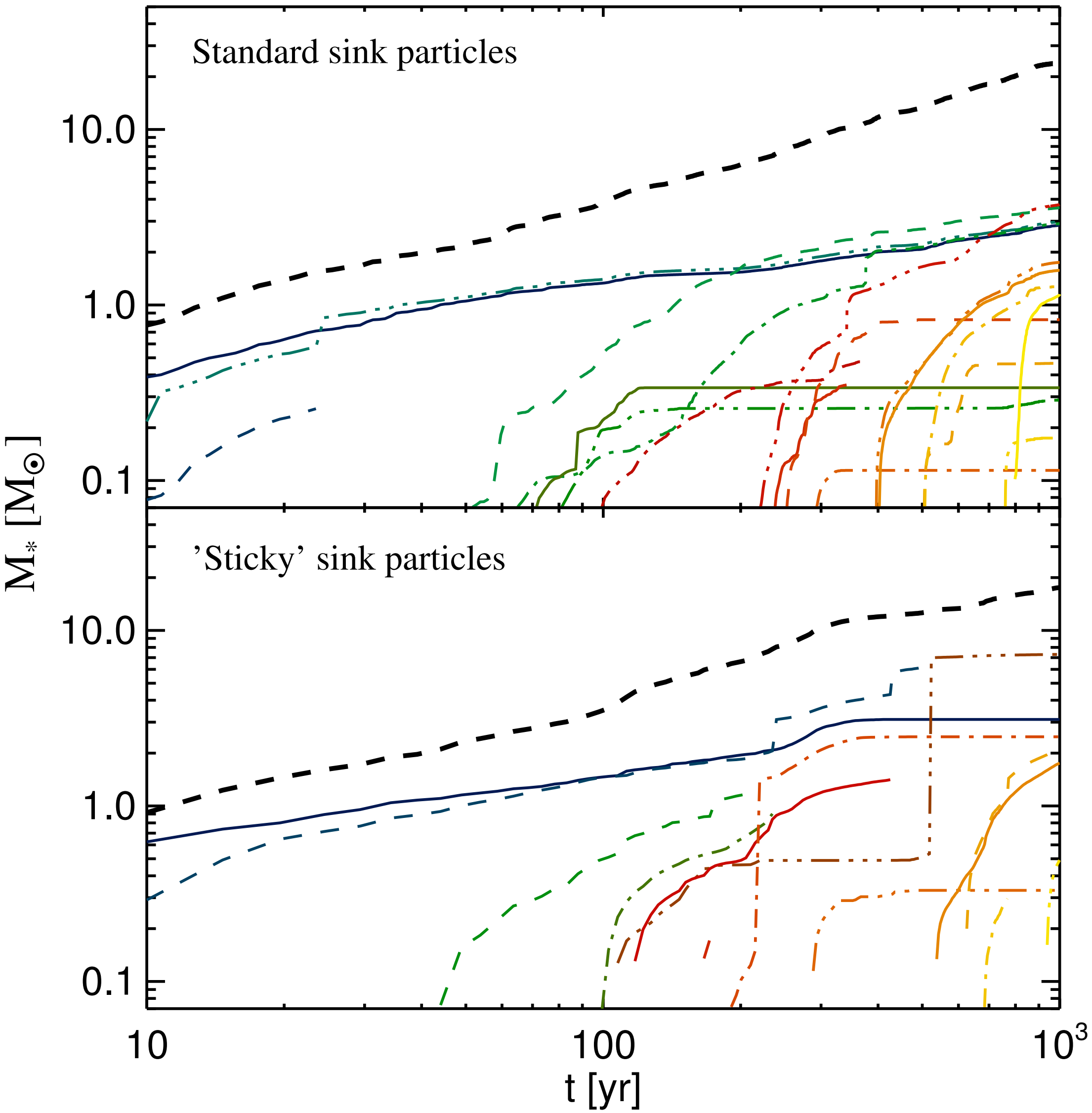
Arepo study: surface density at different times



one out of five halos

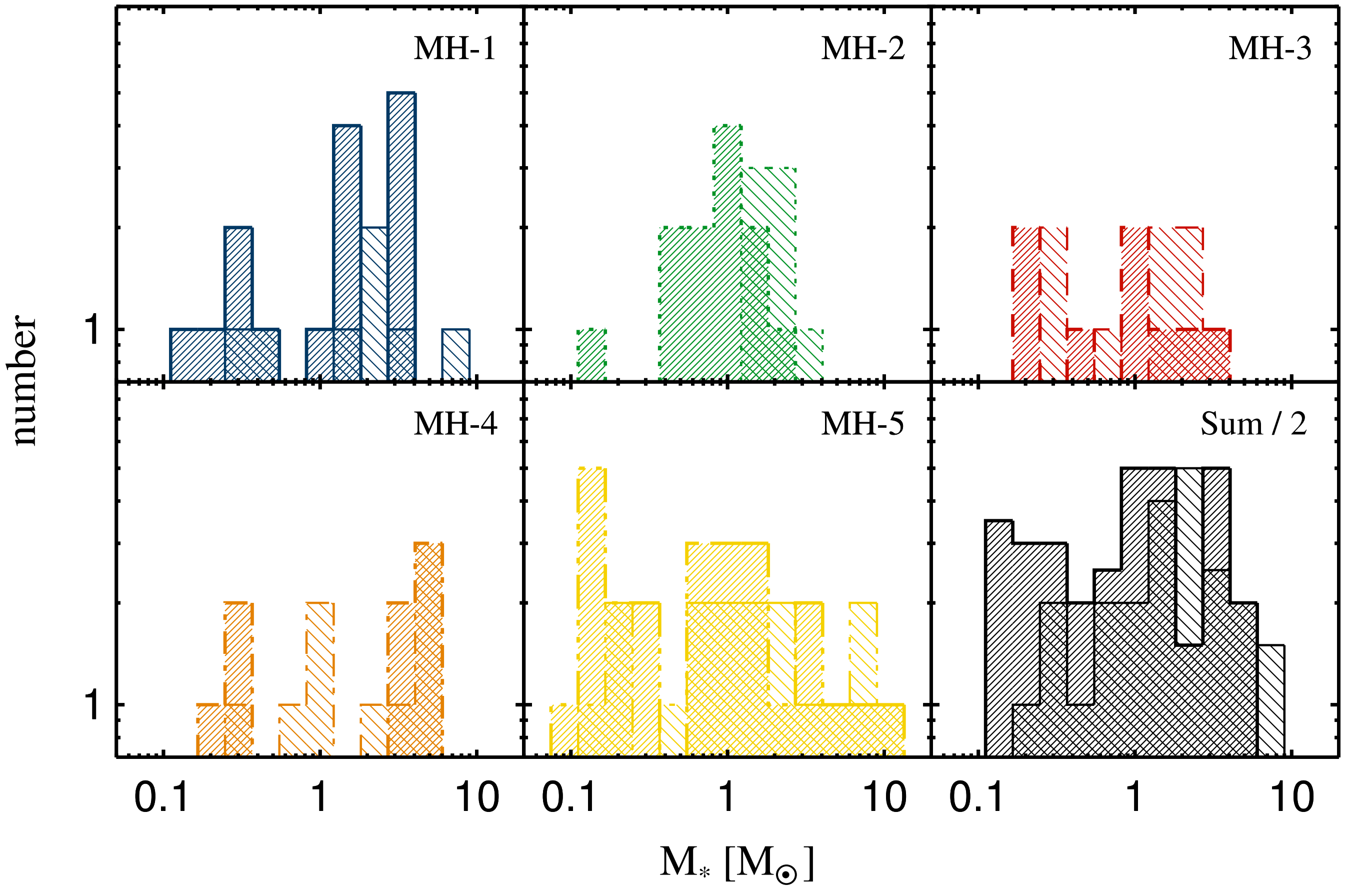
(Greif et al. 2011a, submitted)

Arepo study: protostellar mass accretion rates



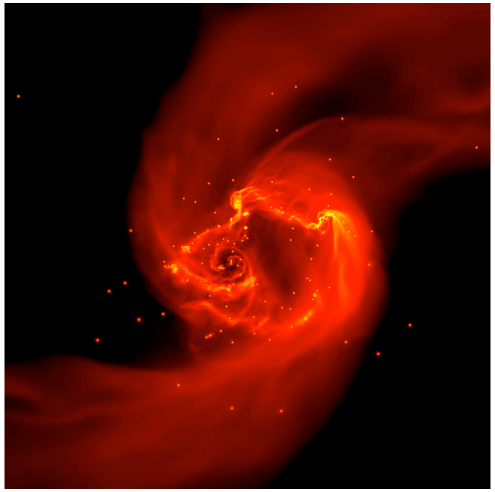
(Greif et al. 2011a, submitted)

Arepo study: mass spectrum of fragments



(Greif et al. 2011a, submitted)

primordial star formation



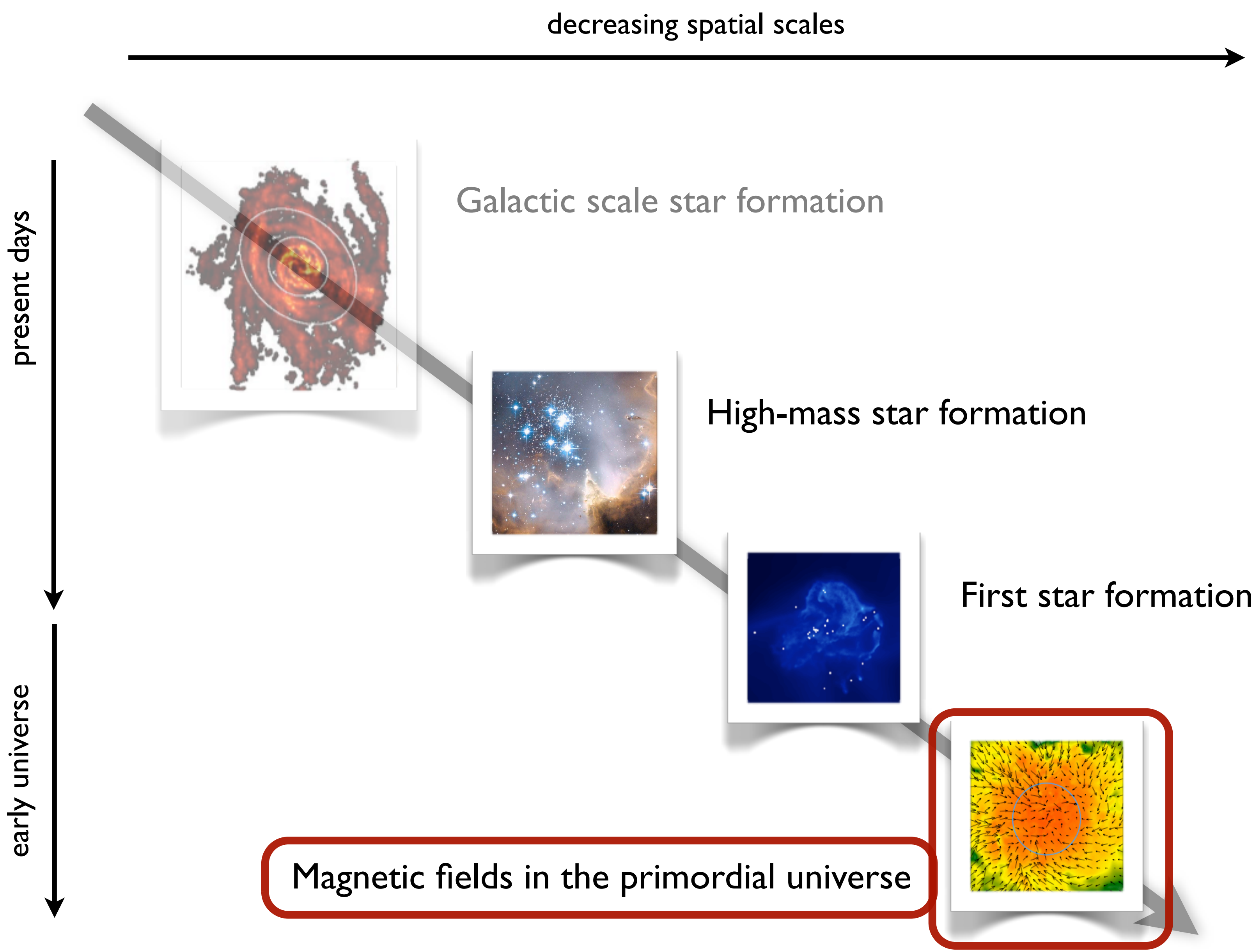
- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

  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

questions

- is claim of Pop III stars with M ~ 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?

agenda



decreasing spatial scales

present days

early universe

Galactic scale star formation

High-mass star formation

First star formation

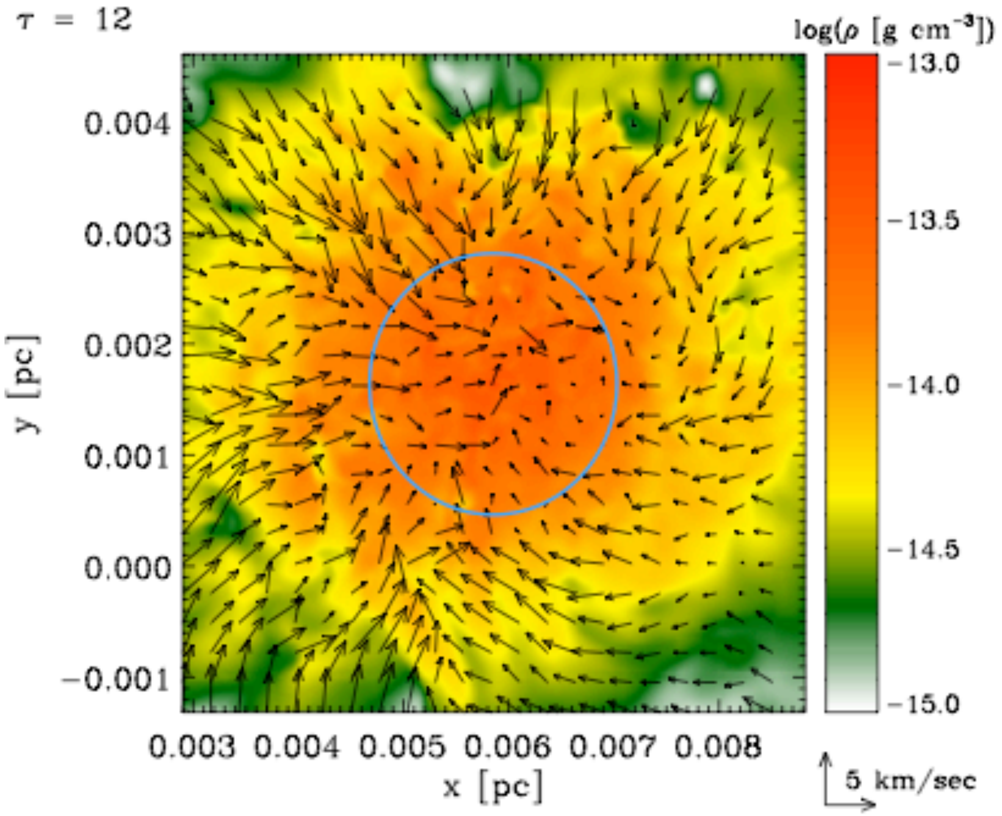
Magnetic fields in the primordial universe

B fields in the early universe?

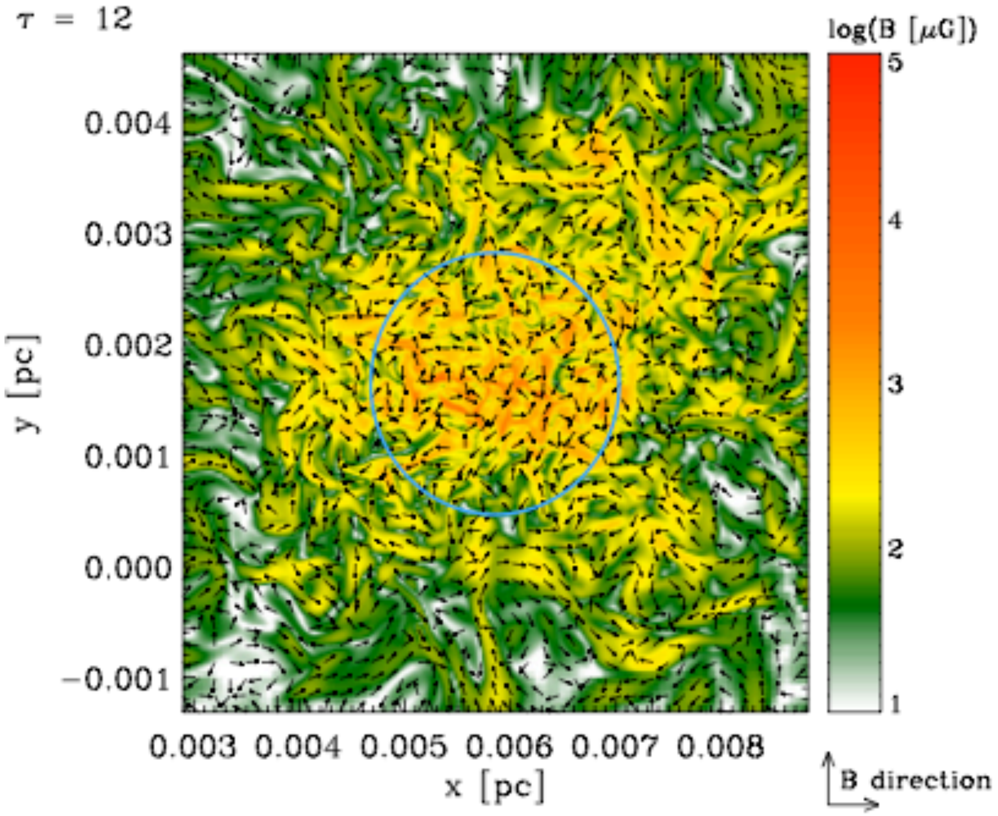
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
    - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, *THIS MAY BE WRONG*!

small-scale turbulent dynamo

- *idea:* the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields
- *approach:* model collapse of primordial gas ---> formation of the first stars in low-mass halo at redshift z ~ 20
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH (effective resolution 65536^3)

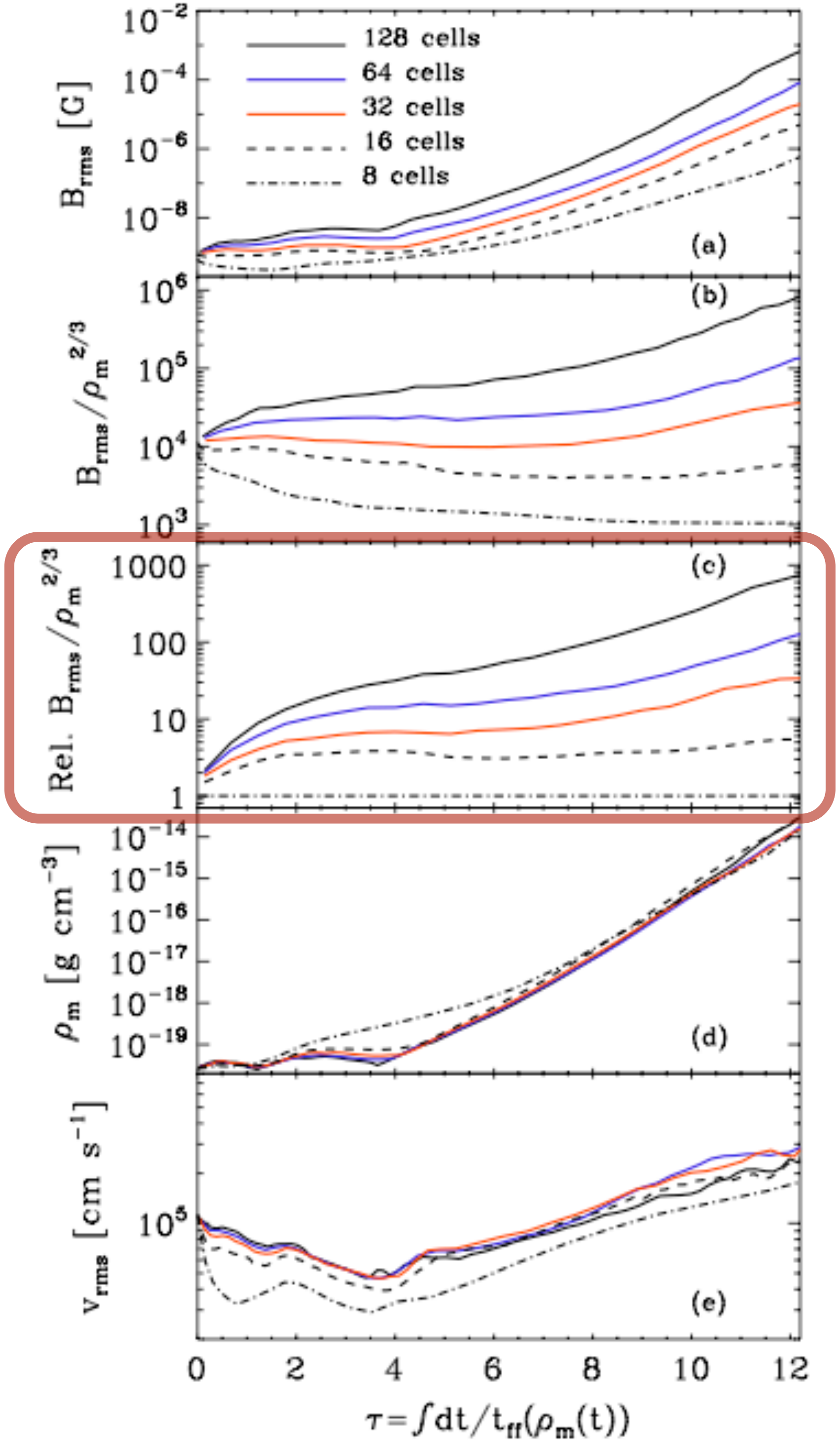


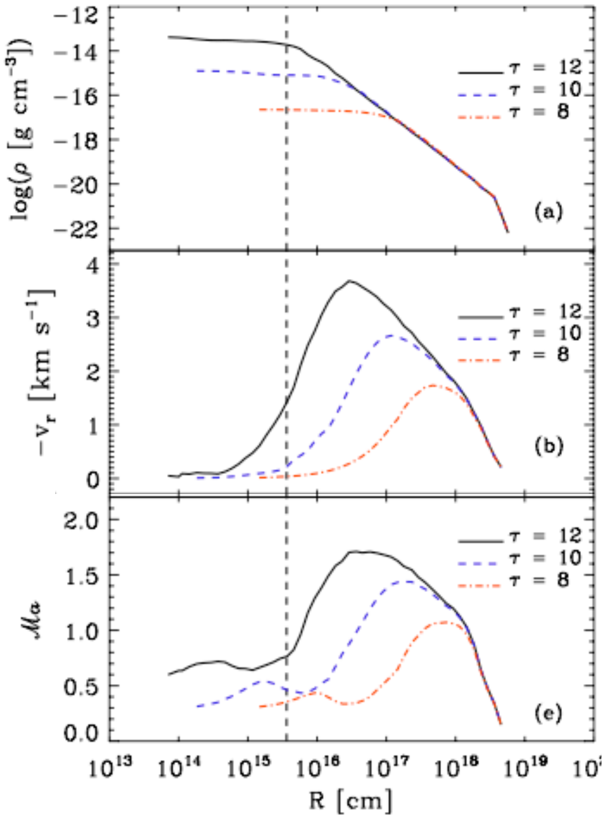
magnetic field structure



density structure

(Sur et al. 2010, ApJ, 721, L734)





radial density profile

radial velocity profile

Mach number profile

Field amplification during first collapse seems unavoidable.

QUESTIONS:

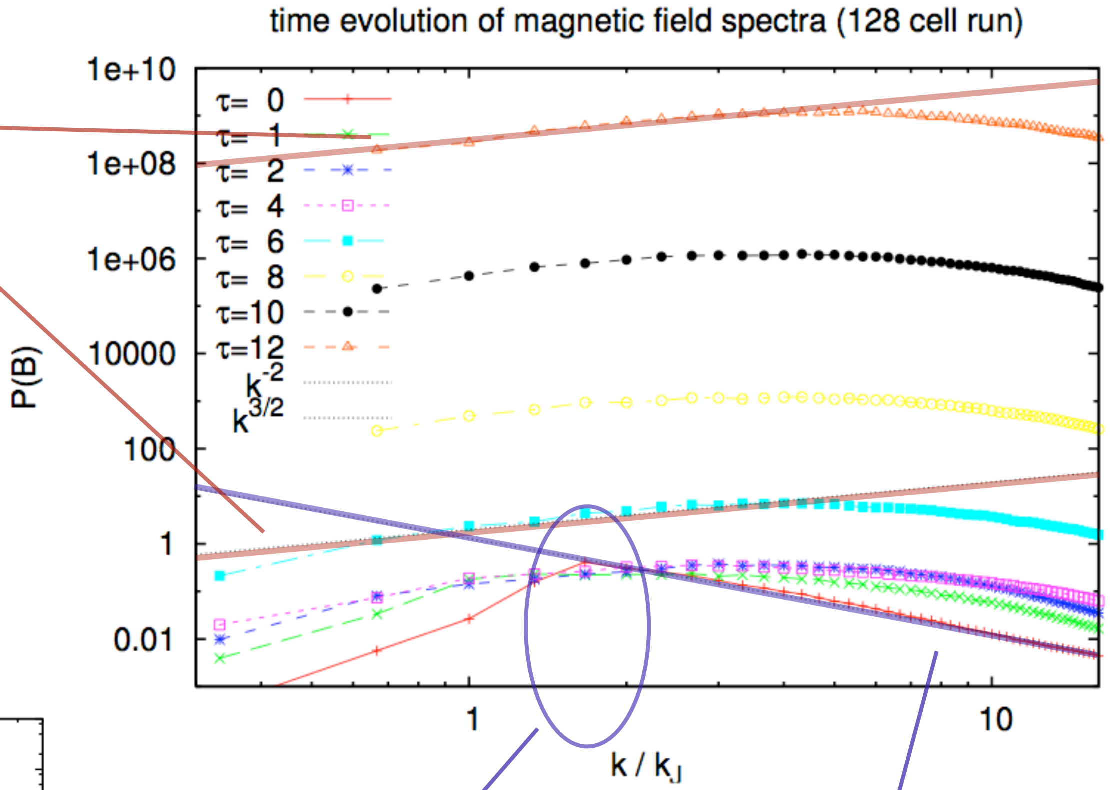
- Is it really the small scale dynamo?
- What is the saturation value? Can the field reach dynamically important strength?

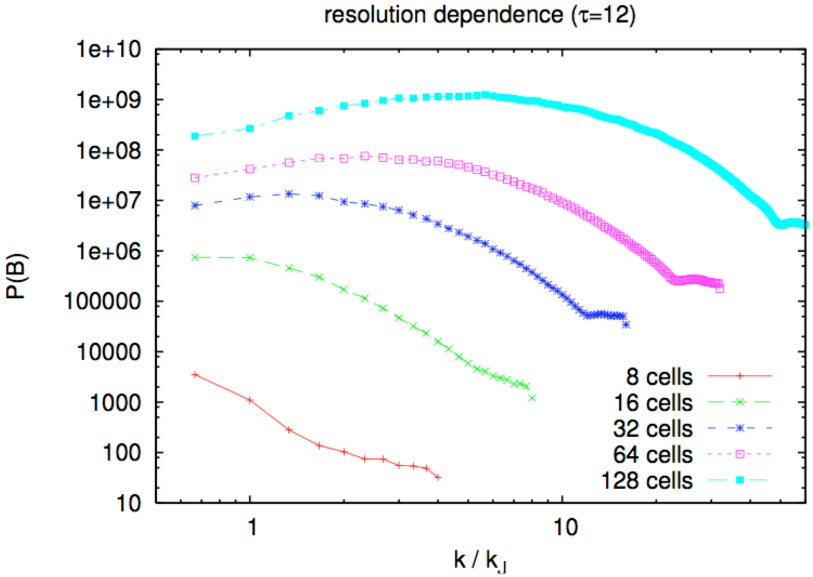
(Sur et al. 2010, ApJ, 721, L734)

analysis of magnetic field spectra

Slope +3/2 of Kazantsev theory

(e.g. Brandenburg & Subramanian, 2005, Phys. Rep., 417, 1)



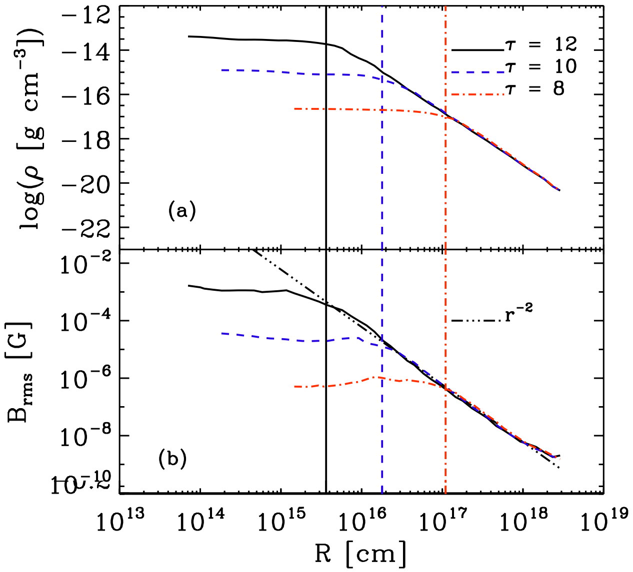


initial peak of B fluctuation spectrum

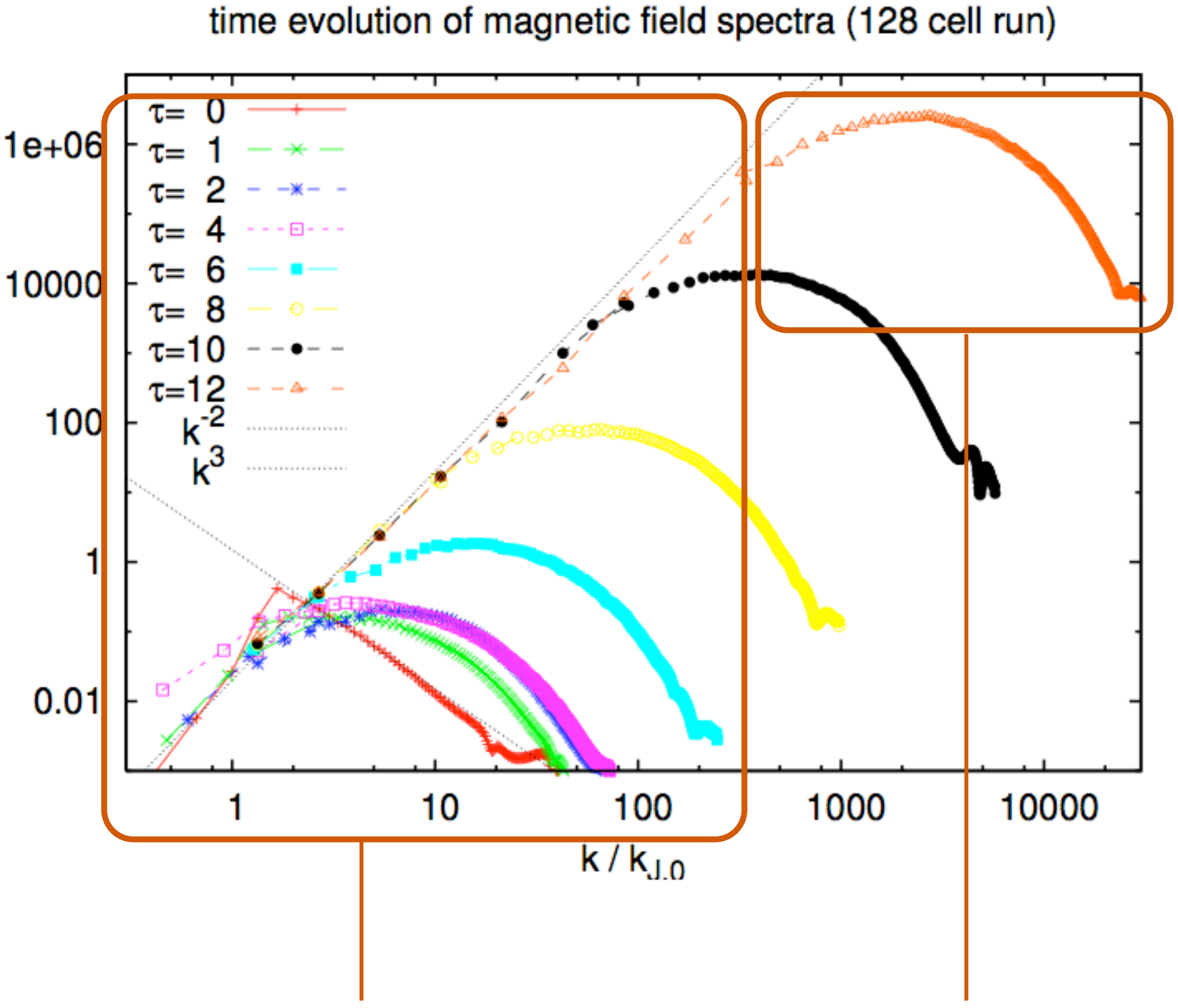
initial slope of B fluctuations

(Federrath et al., 2010, ApJ)

analysis of magnetic field spectra



time evolution of magnetic field spectra (128 cell run)

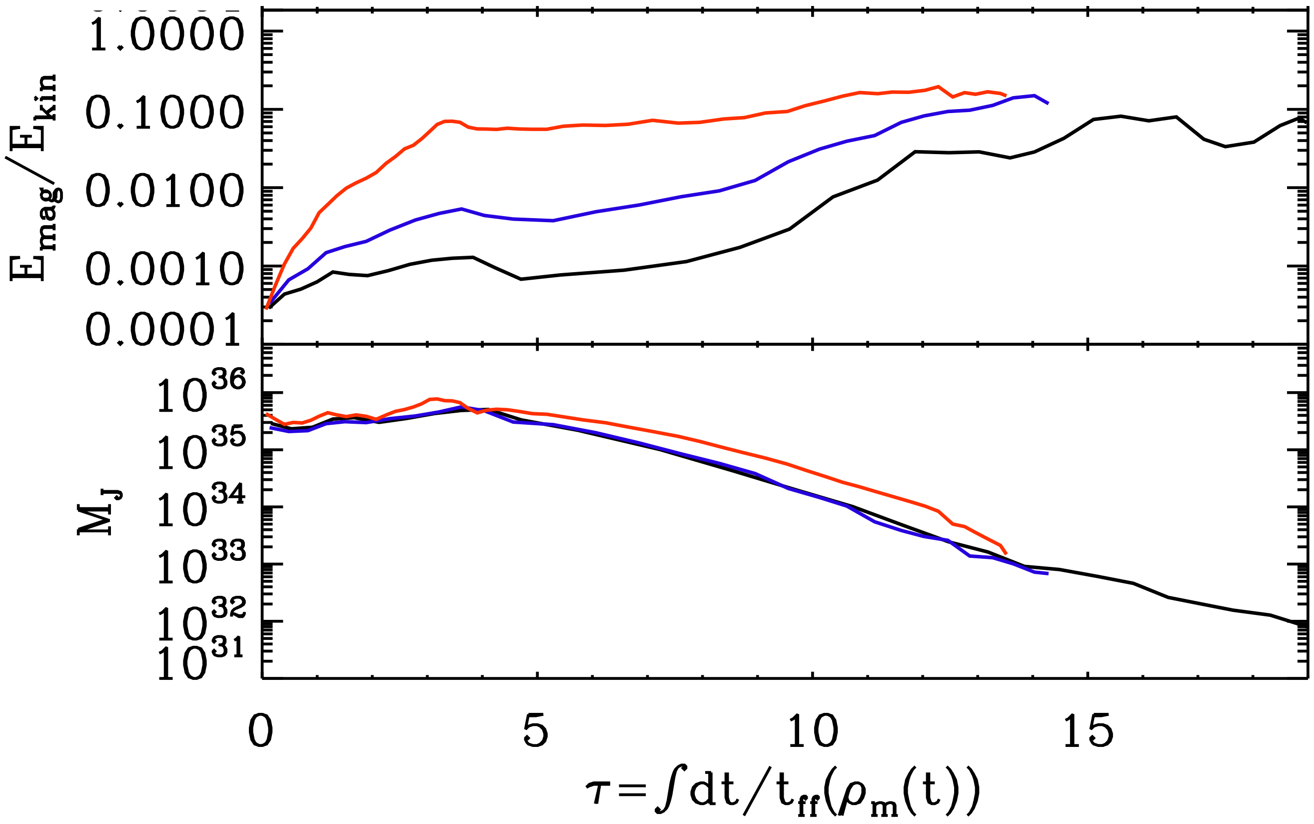


B fluctuation spectrum in 1/r^2 fall-off

B fluctuation spectrum in flat inner core

(Federrath et al., 2010, ApJ)

first attempts to calculate the saturation level.



ratio of magnetic to kinetic energy

Jeans mass

We seem to get a saturation level of ~10% (see, e.g., Subramanian 1997, or Brandenburg & Subramanian 2005)

QUESTIONS:
- Is this true in a proper cosmological context?
- What does it mean for the formation of the first stars

(Sur et al., in prep.)

questions

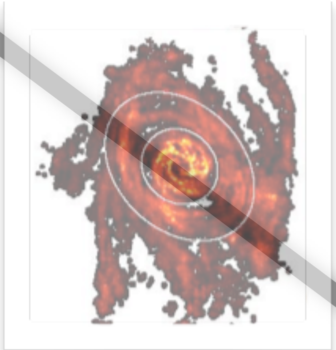
- *small-scale turbulent dynamo* is expected to operate during Pop III star formation
- process is *fast* ($10^4 \times t_{ff}$), so primordial halos may collapse with B-field at *saturation level!*
- simple models indicate *saturation levels of ~10%* --> larger values via $\alpha\Omega$ dynamo?
- *QUESTIONS:*
  - does this hold for “proper” halo calculations (with chemistry and cosmological context)?
  - what is the strength of the seed magnetic field?

summary

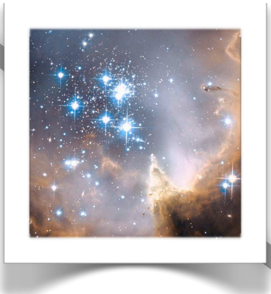
decreasing spatial scales

present days

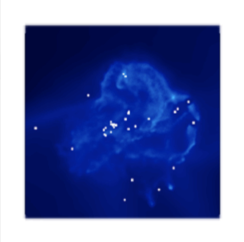
early universe



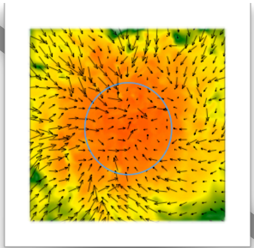
Galactic scale star formation



High-mass star formation



First star formation



Magnetic fields in the primordial universe

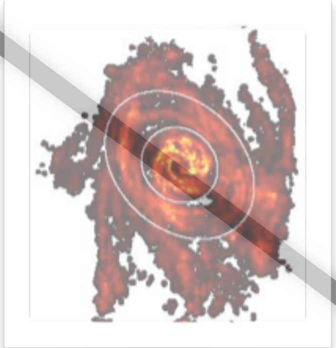
(Sur et al., in prep.)

summary

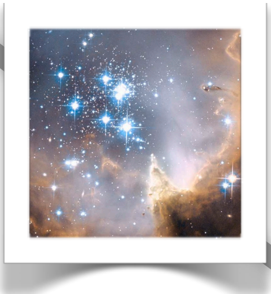
decreasing spatial scales

present days

early universe



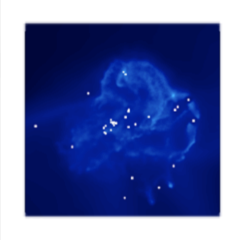
Galactic scale star formation



High-mass star formation:

What set upper stellar mass limit?

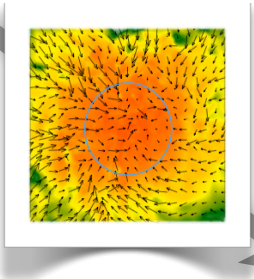
Can we see UC HII regions flicker?



First star formation:

Are there still Pop III stars around?

How can we see them? And where?



Magnetic fields in the primordial universe:

Is there a minimum primordial field?

What is the influence of B on Pop III star?