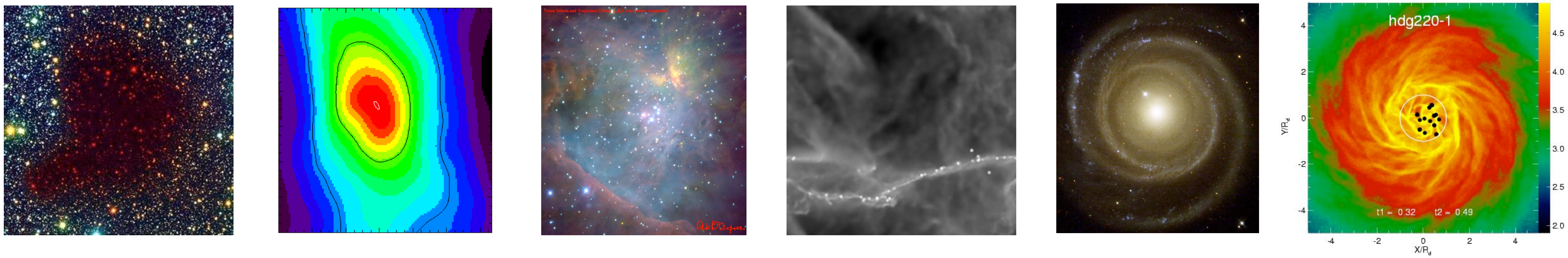
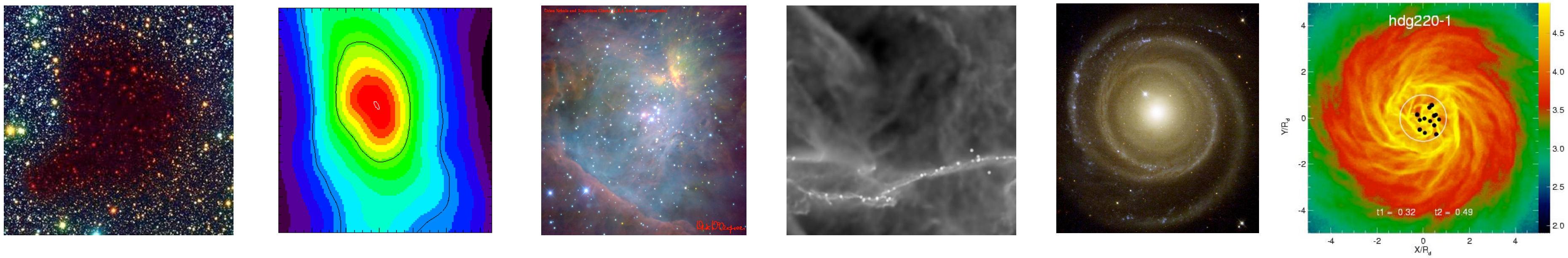
Better understand the IMF of the first stars



Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

What can we learn from present-day star formation about the first stars?



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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

... many collaborators abroad!

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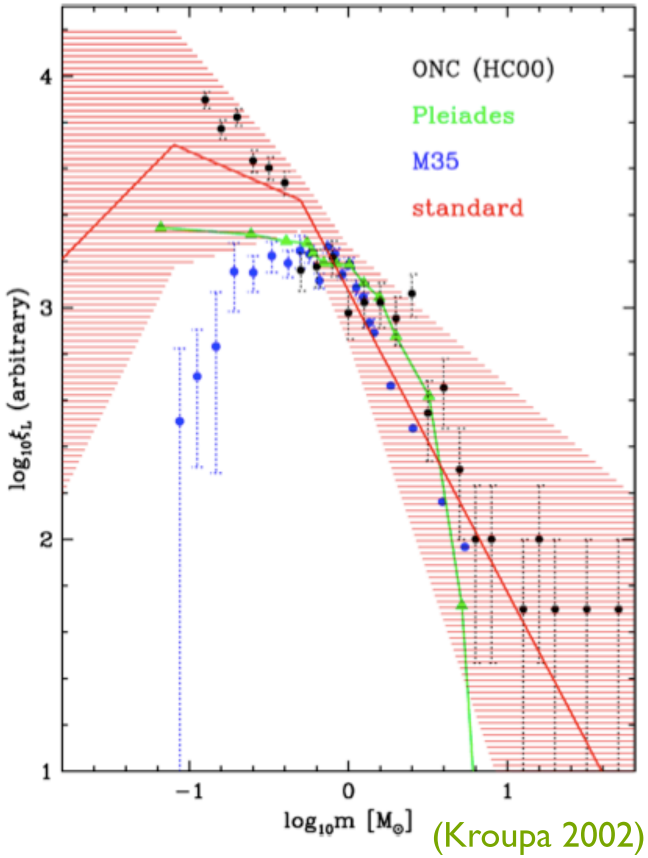
HGSFP

IMPRS

NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

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

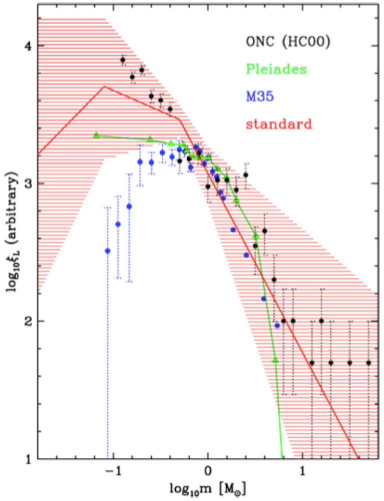


(Kroupa 2002)

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

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



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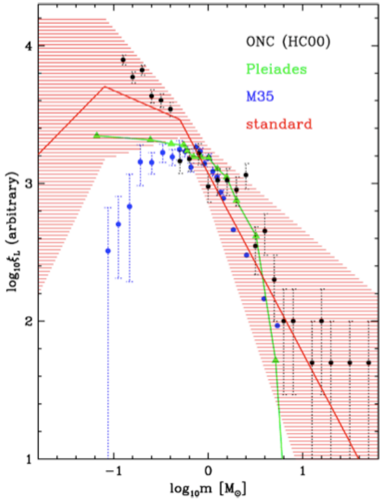
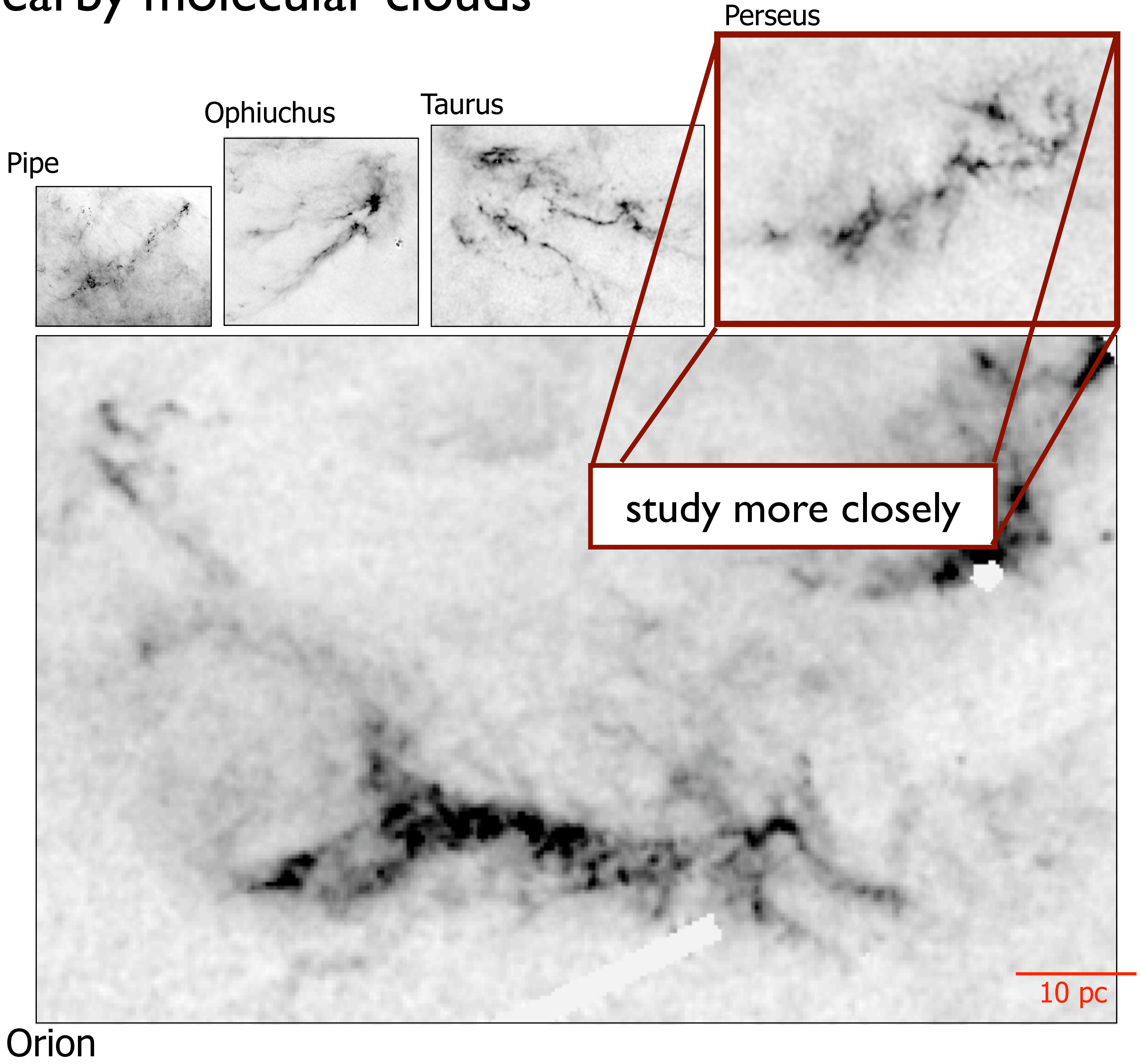


nearby molecular clouds



scales to same scale

(from A. Goodman)

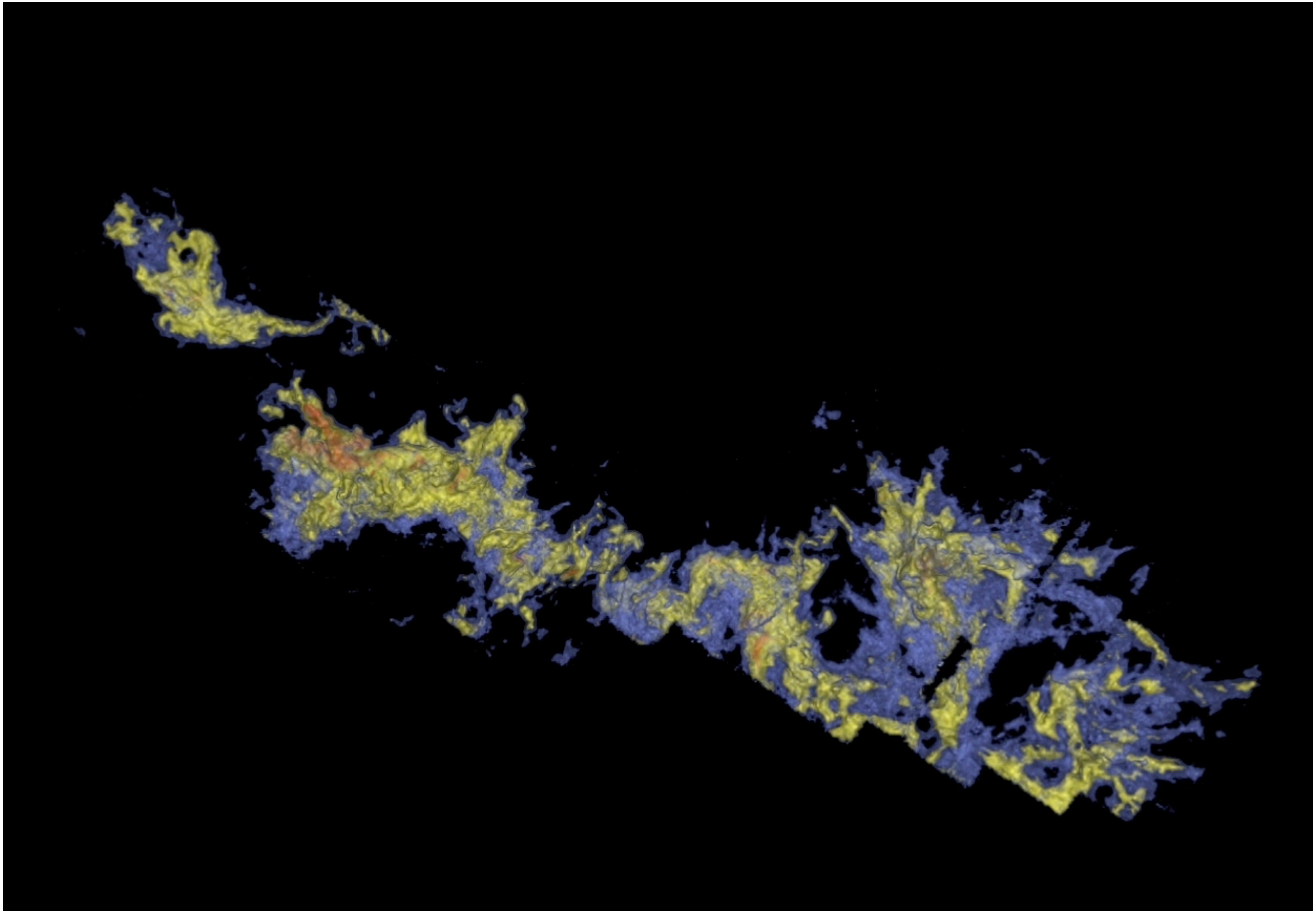
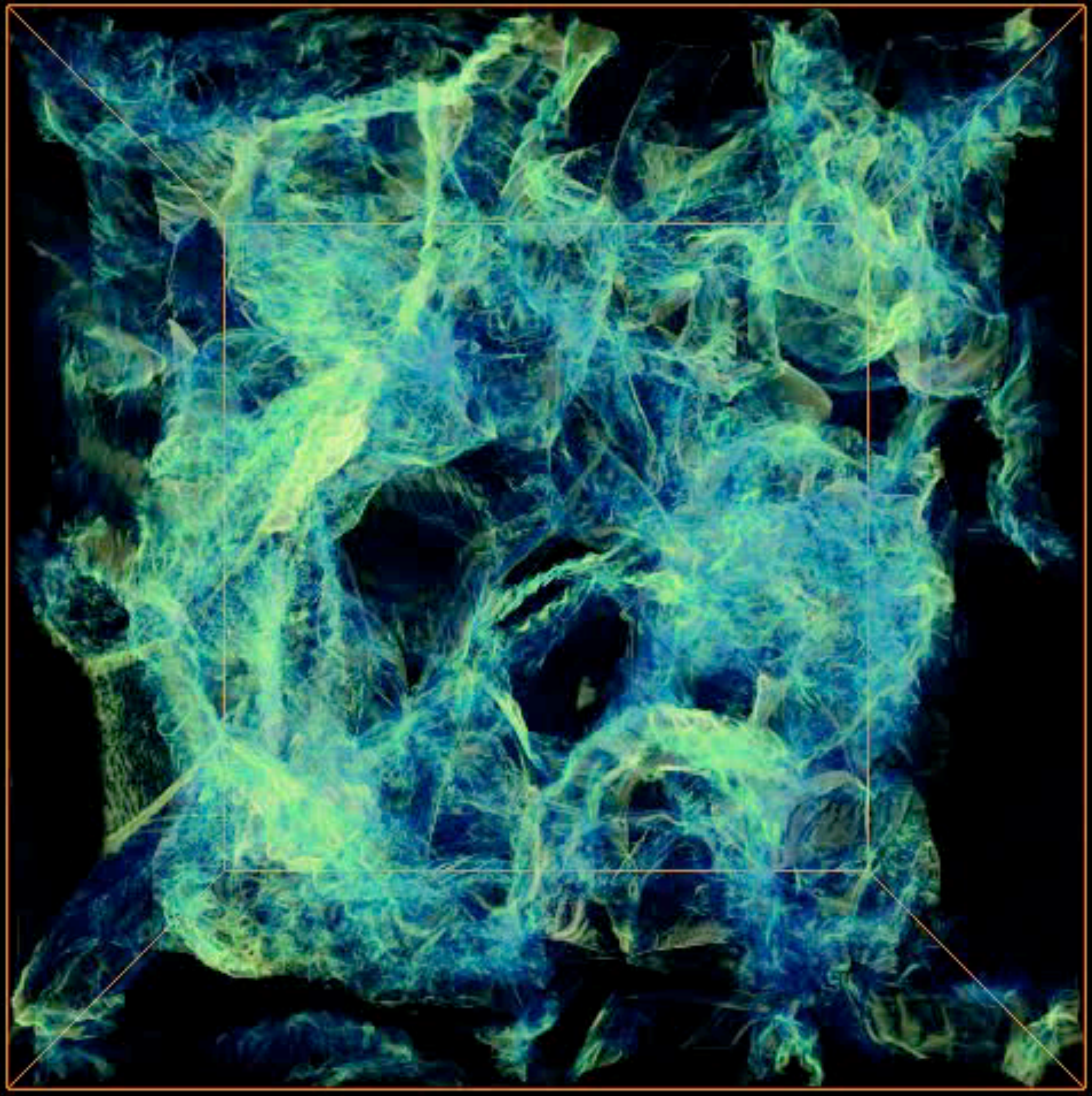


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

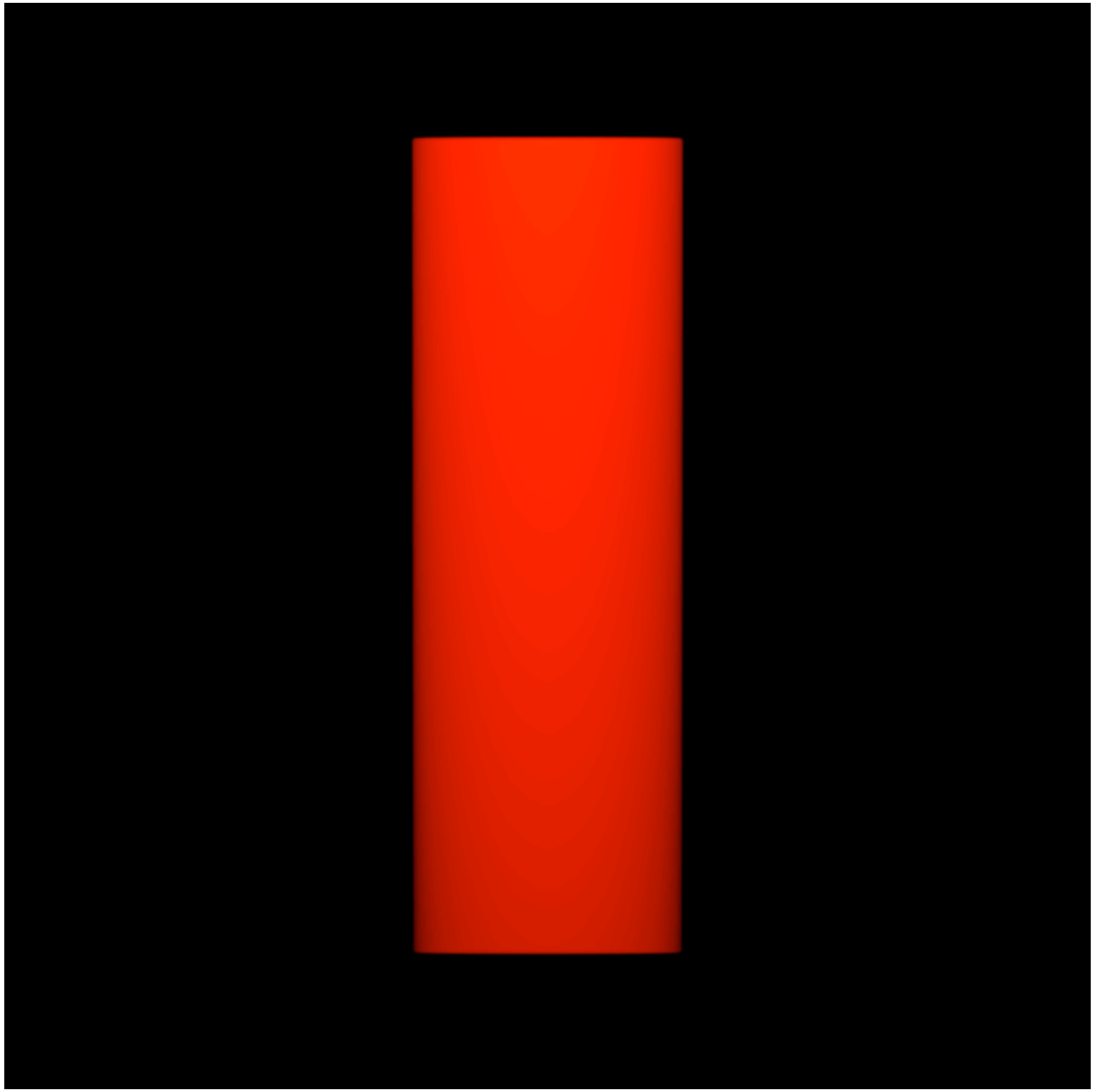
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

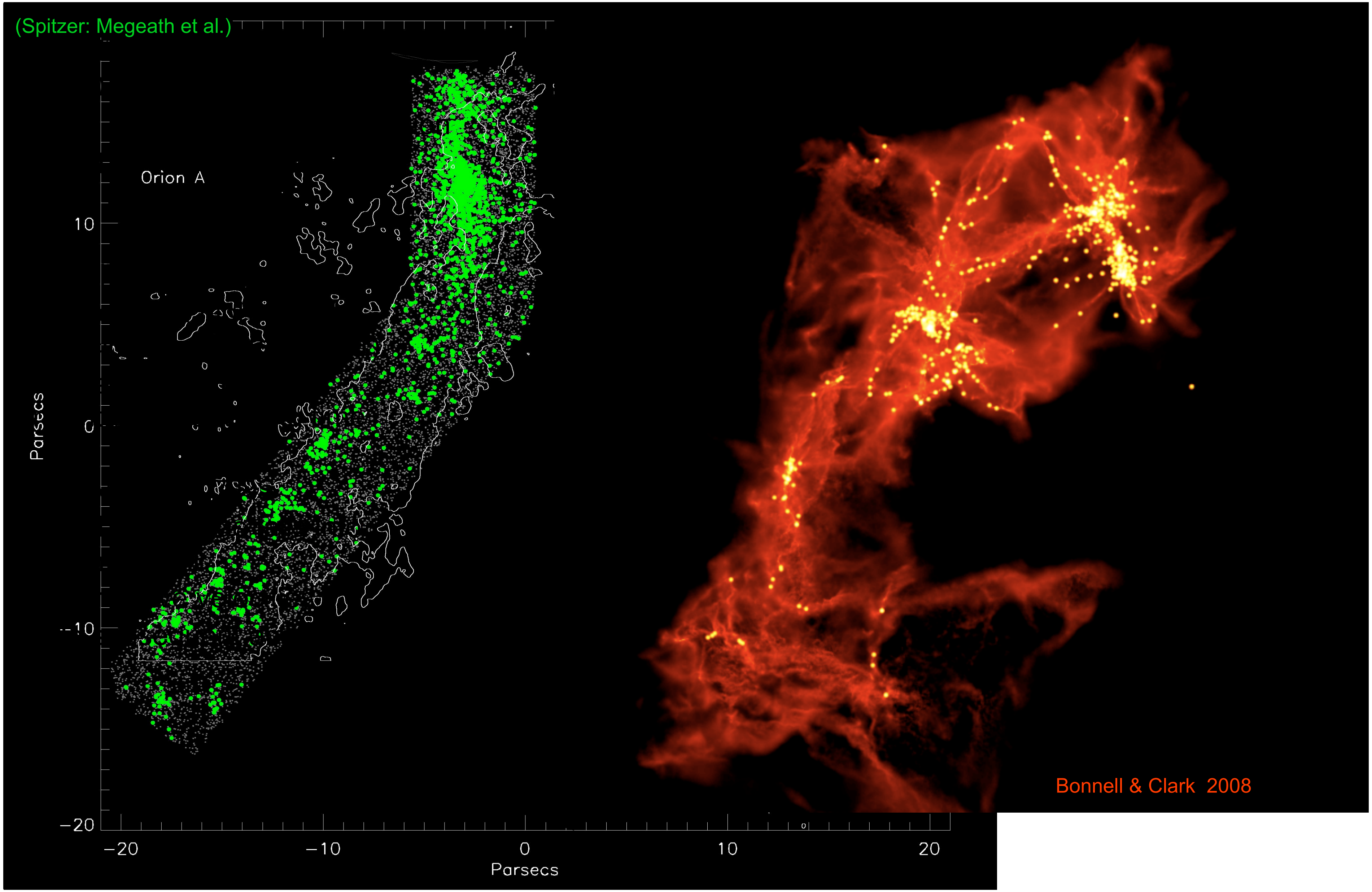
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



(Bonnell & Clark 2008)

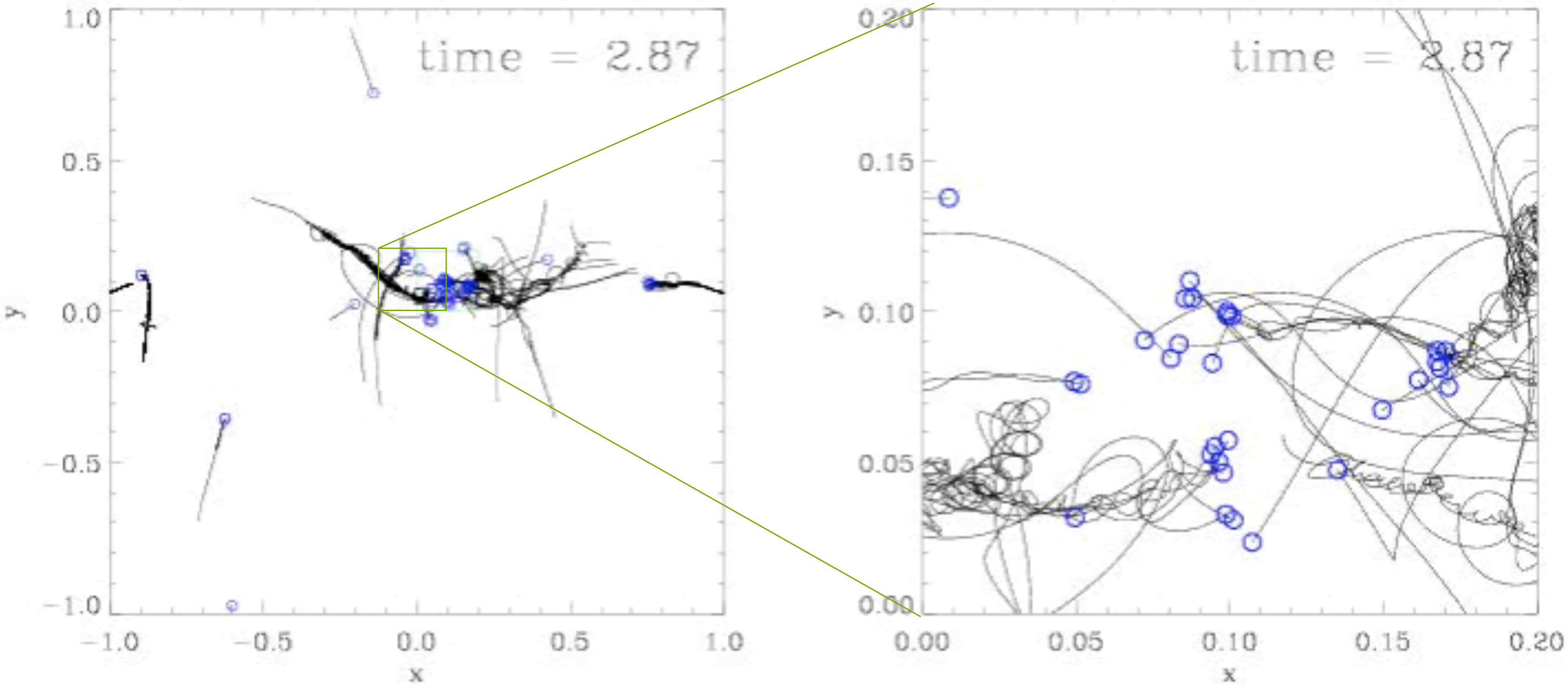
example: model of Orion cloud


(Spitzer: Megeath et al.)

Bonnell & Clark 2008

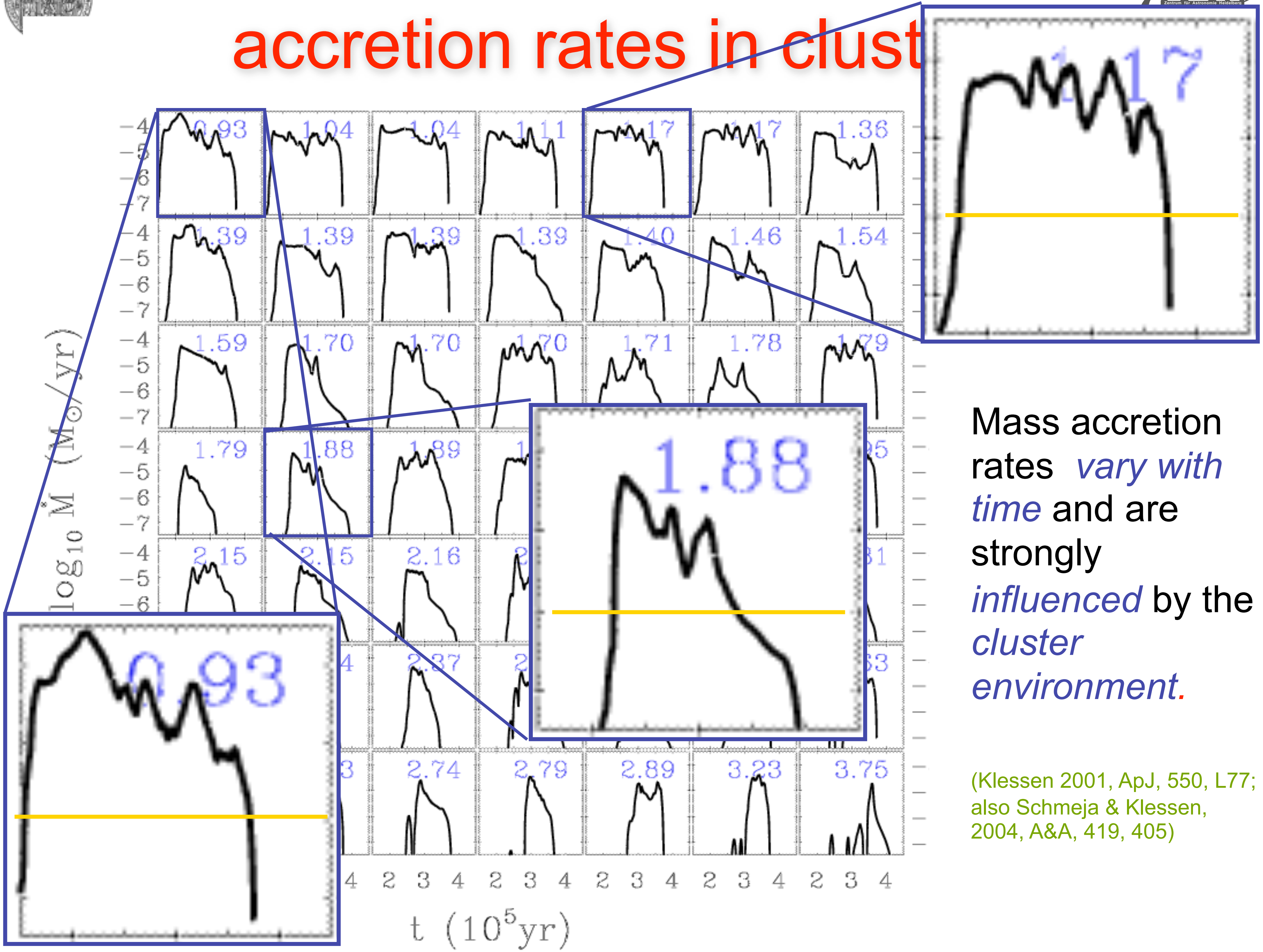
Dynamics of nascent star cluster

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)

stellar masses

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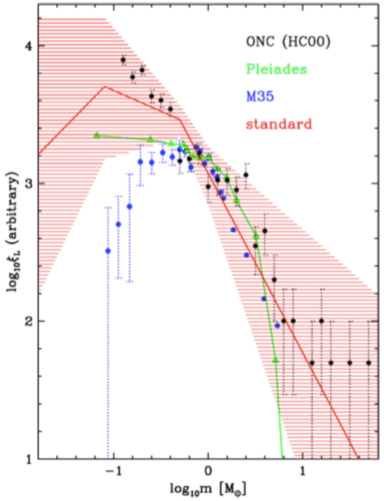
(Kroupa 2002)

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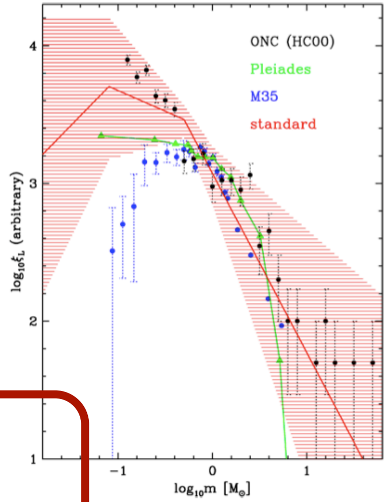
application to first star formation



(Kroupa 2002)

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

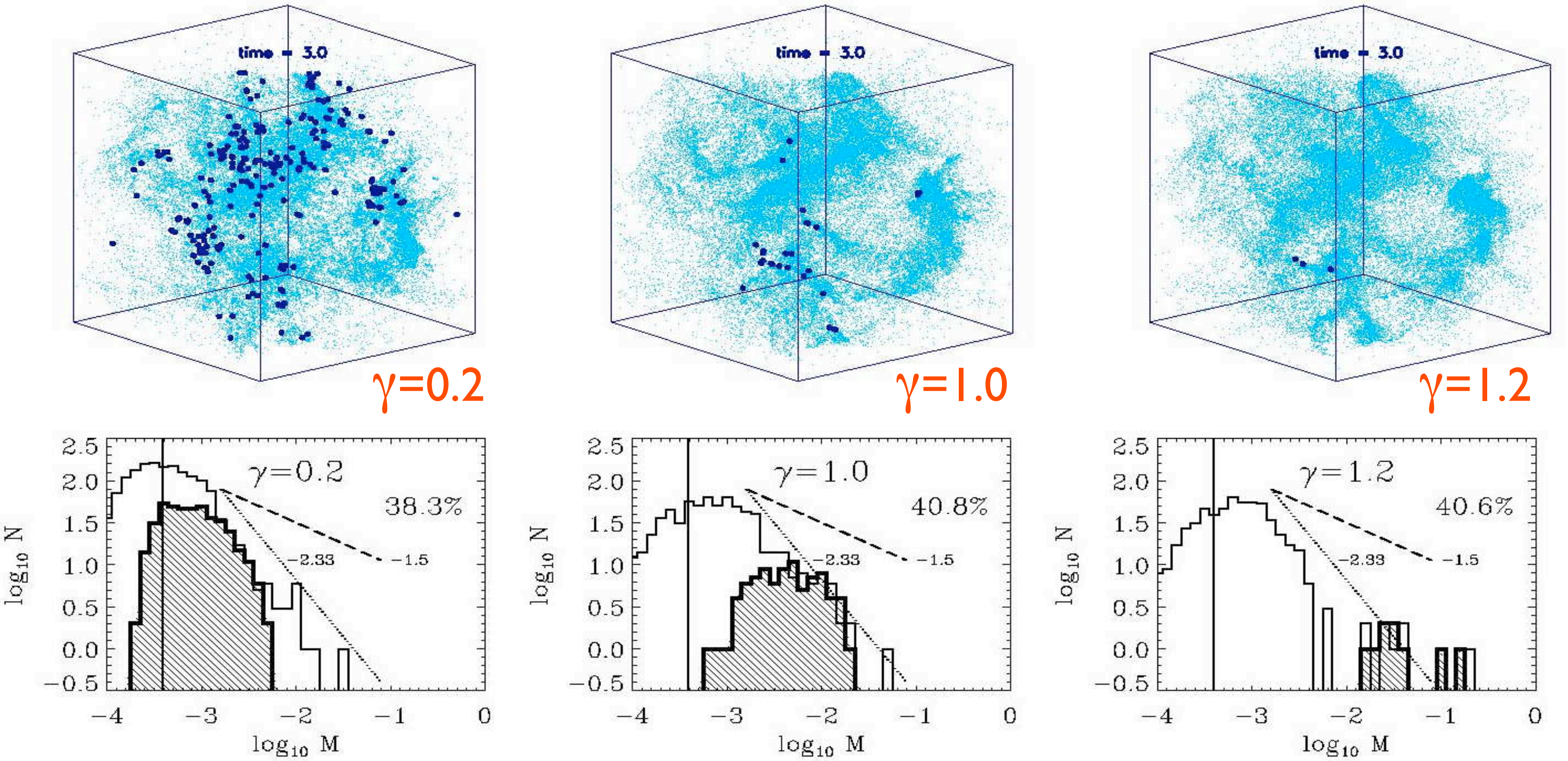
polytropic EOS: $\mathbf{p} \propto \rho^\gamma$

$\gamma<1$: 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*

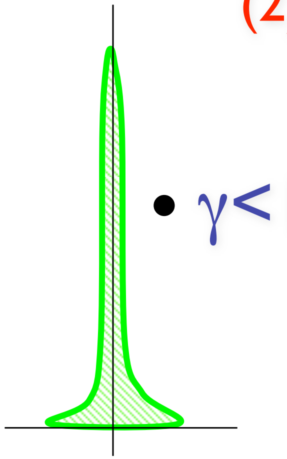
for γ>1 it is suppressed → formation of *isolated massive stars*

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

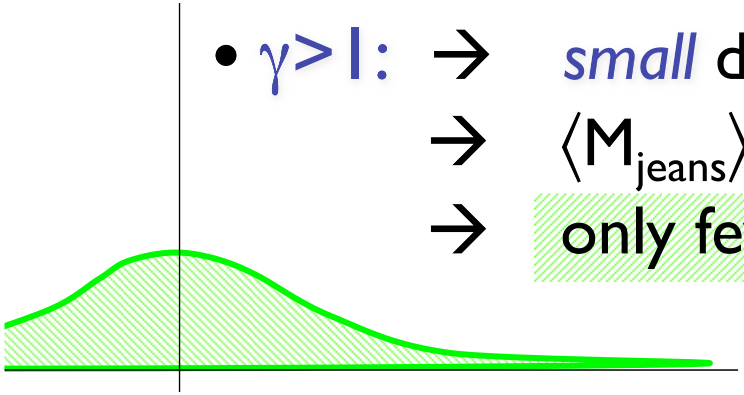
how does that work?

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

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

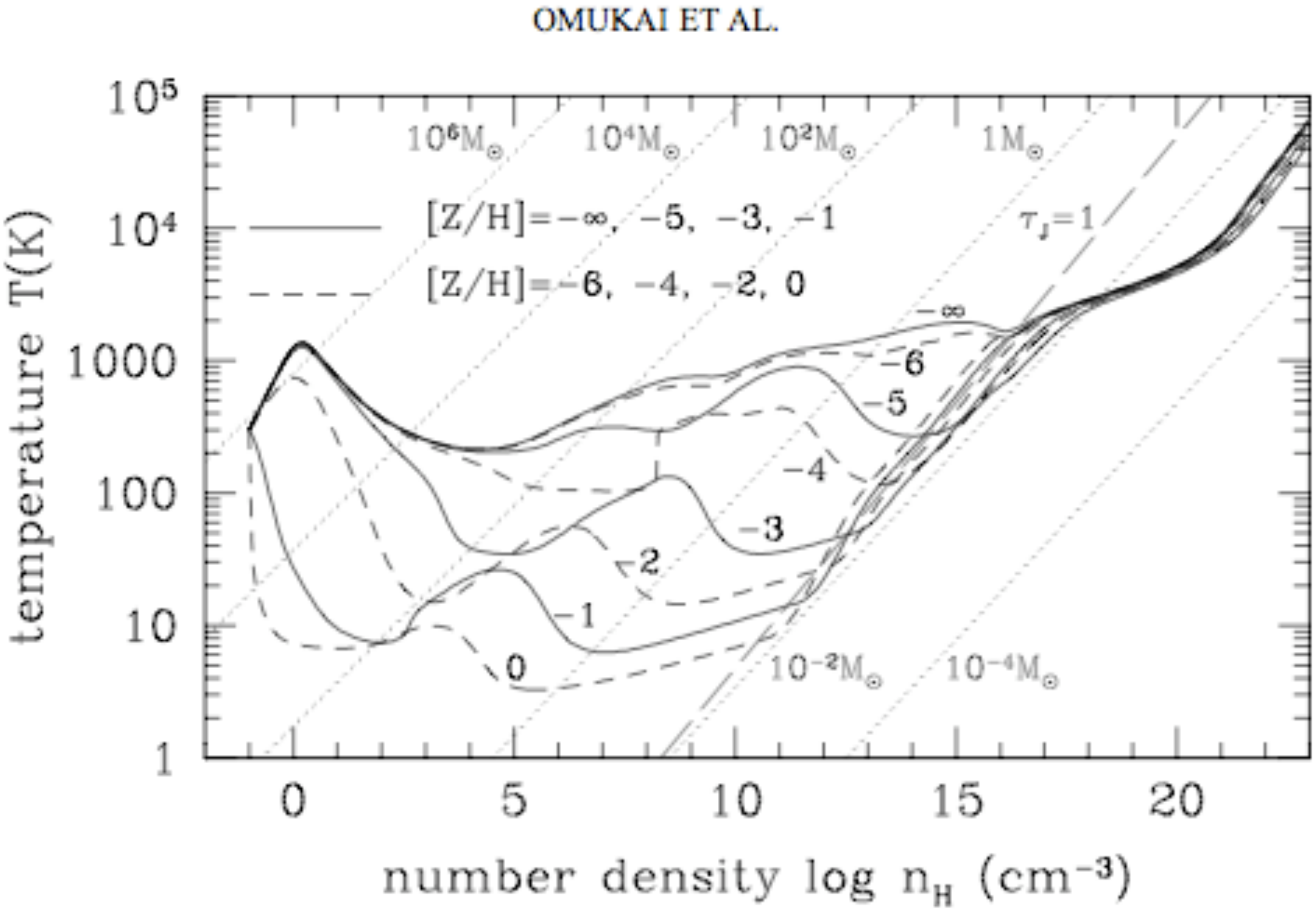


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



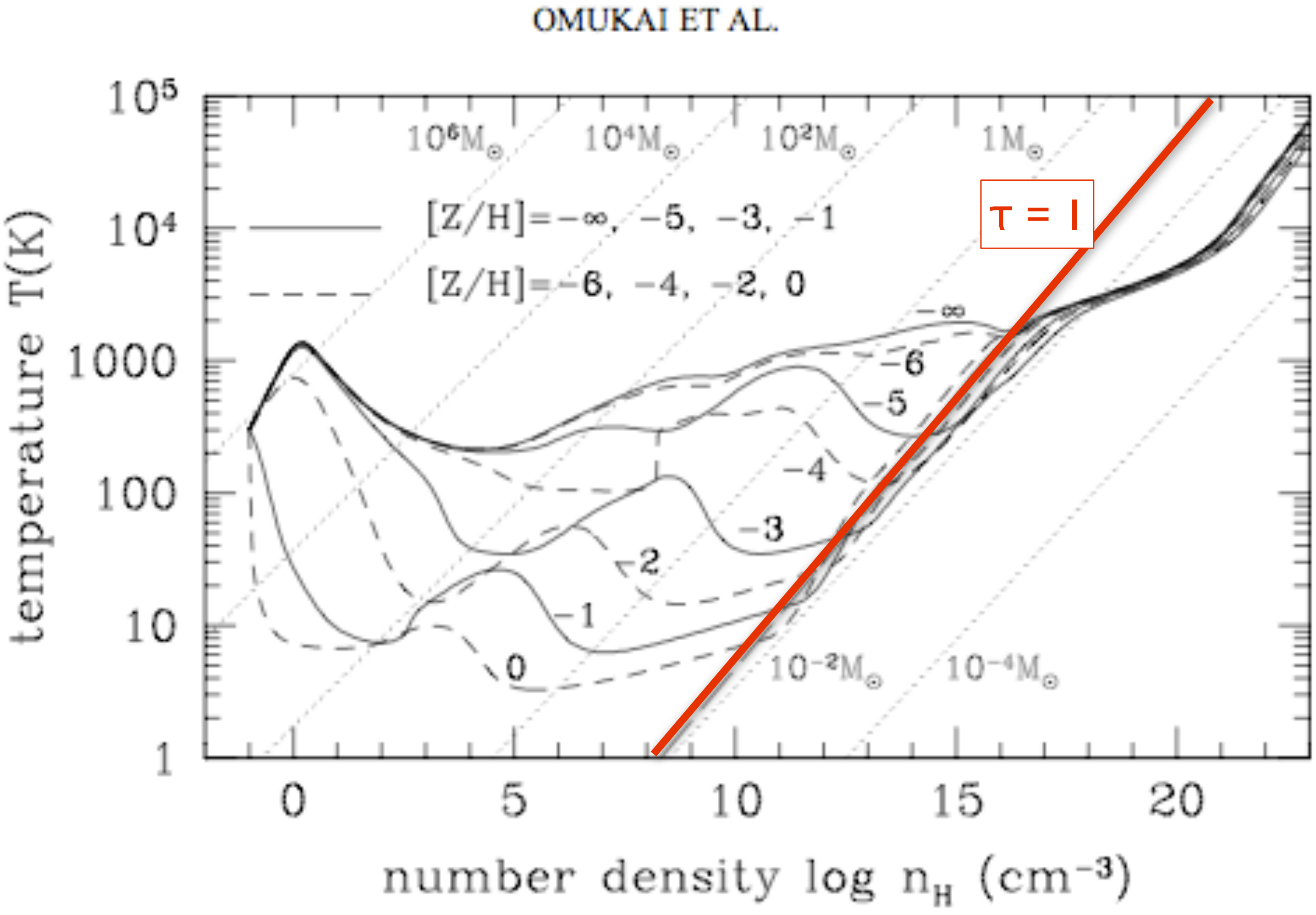
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



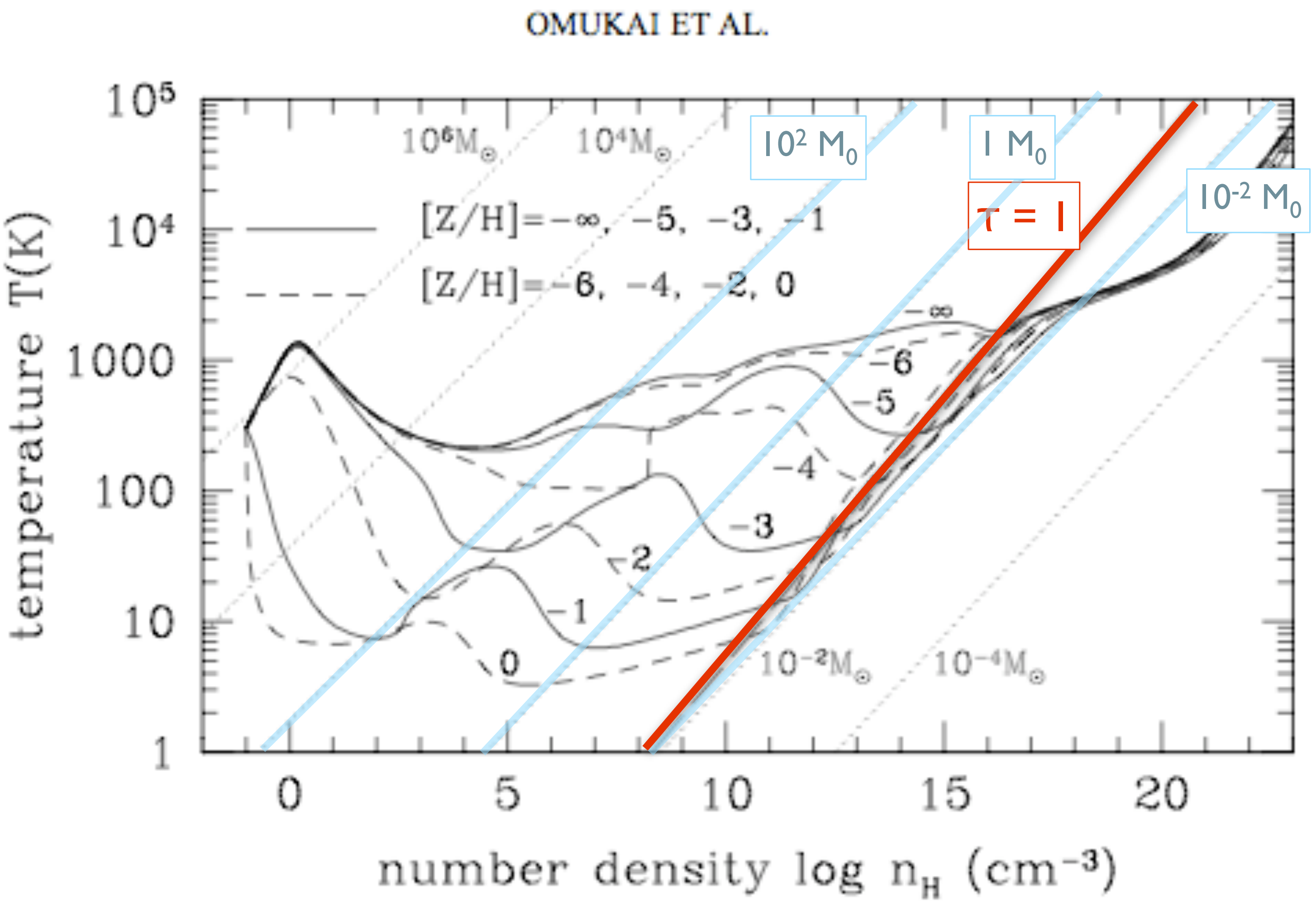
(Omukai et al. 2005)

EOS as function of metallicity



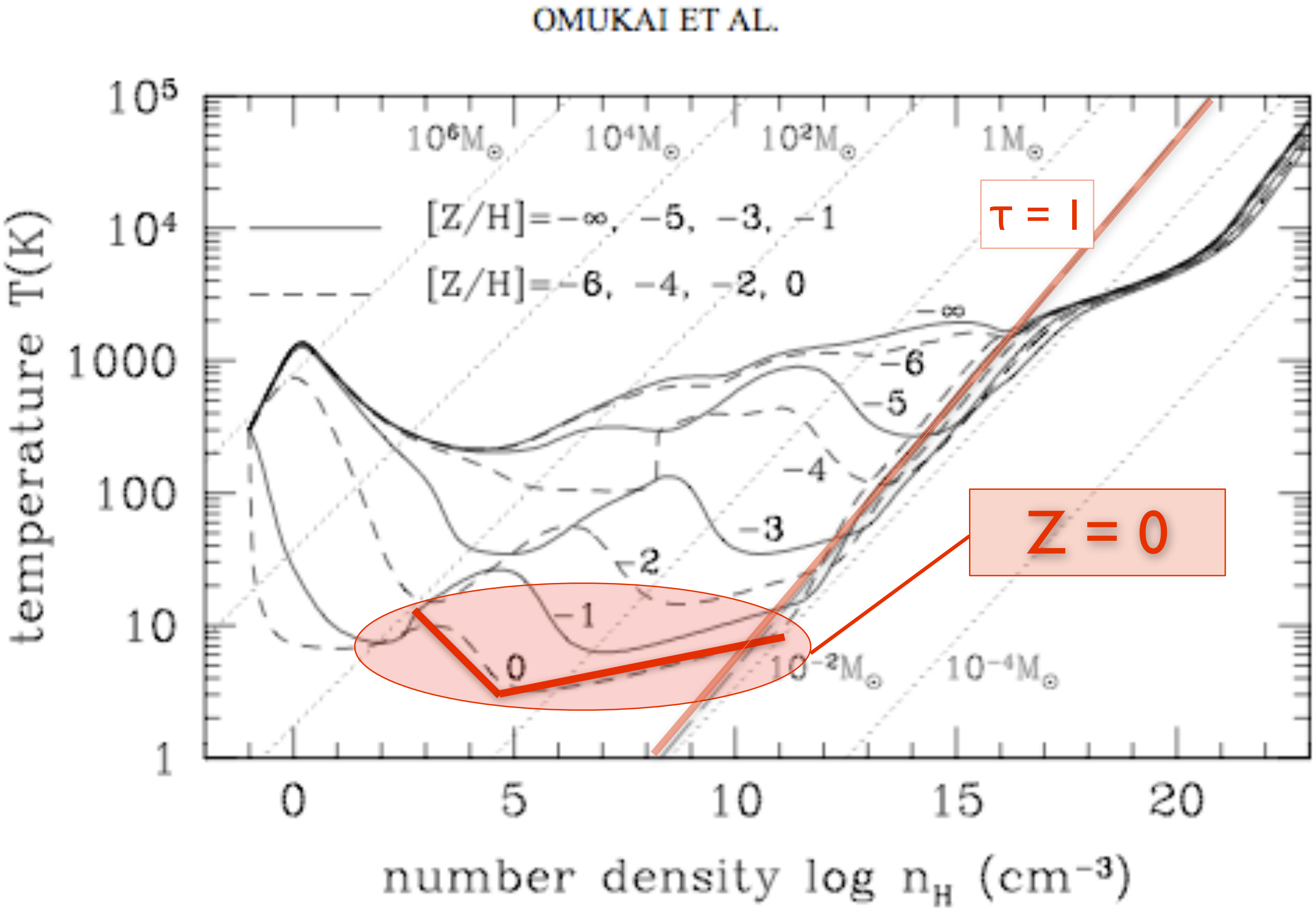
(Omukai et al. 2005)

EOS as function of metallicity



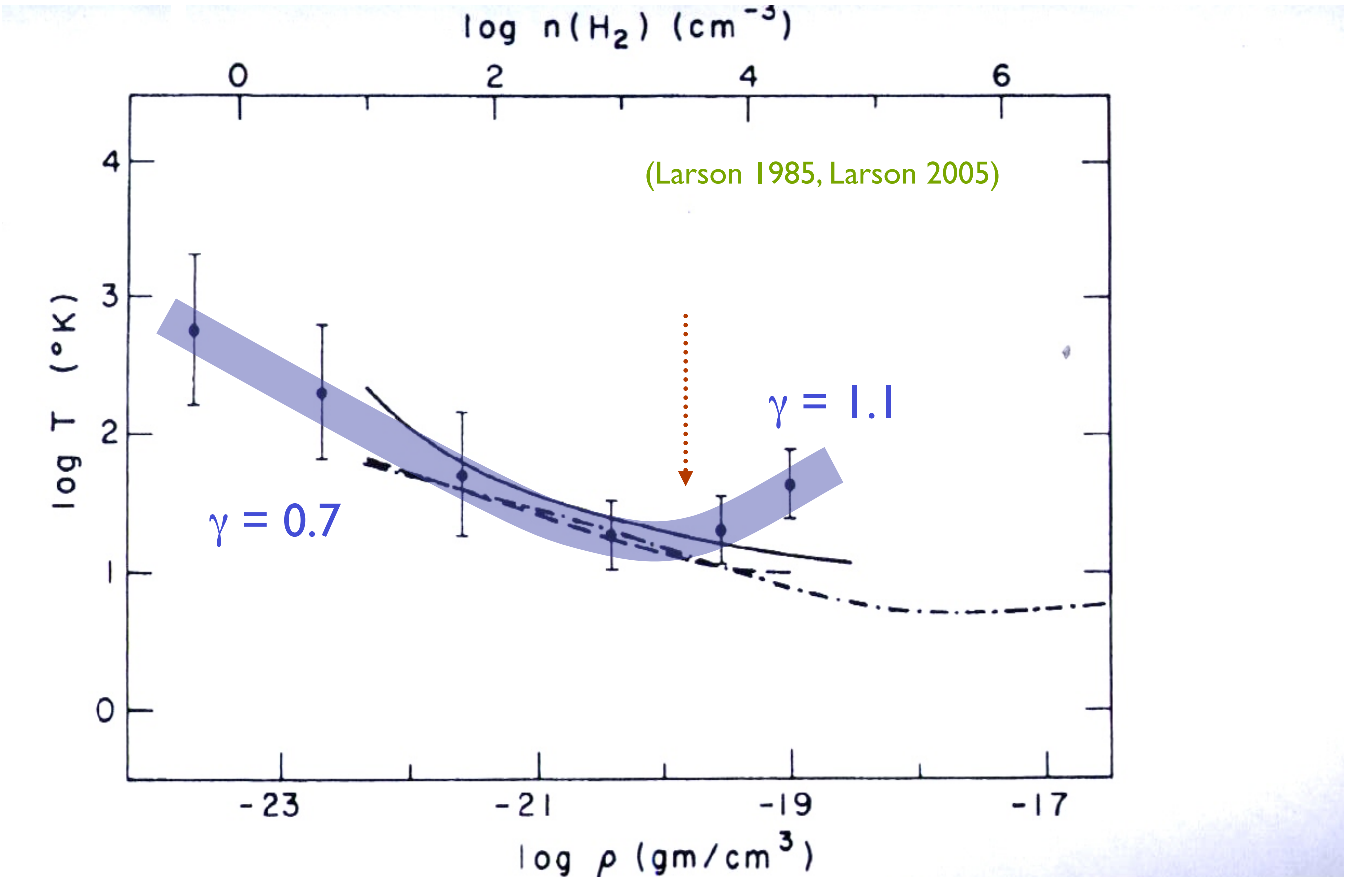
(Omukai et al. 2005)

present-day star formation



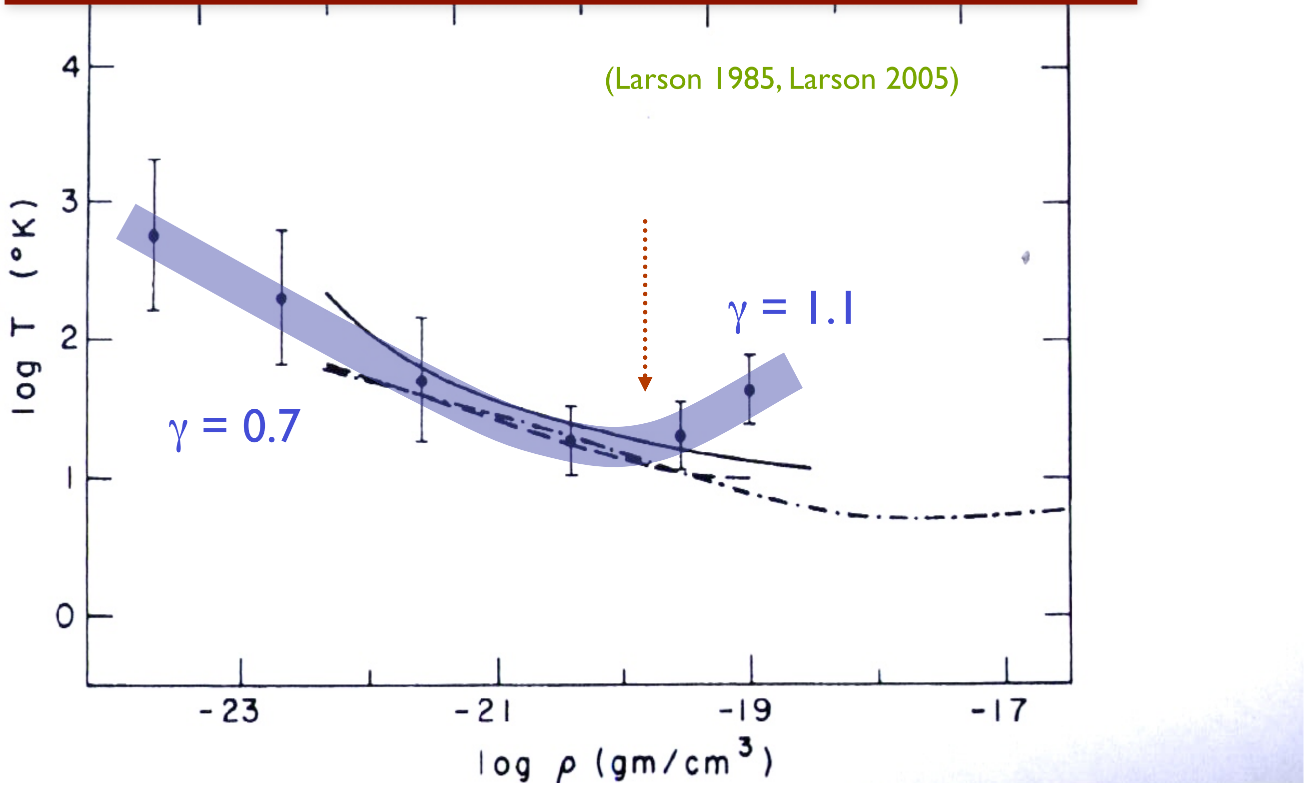
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation

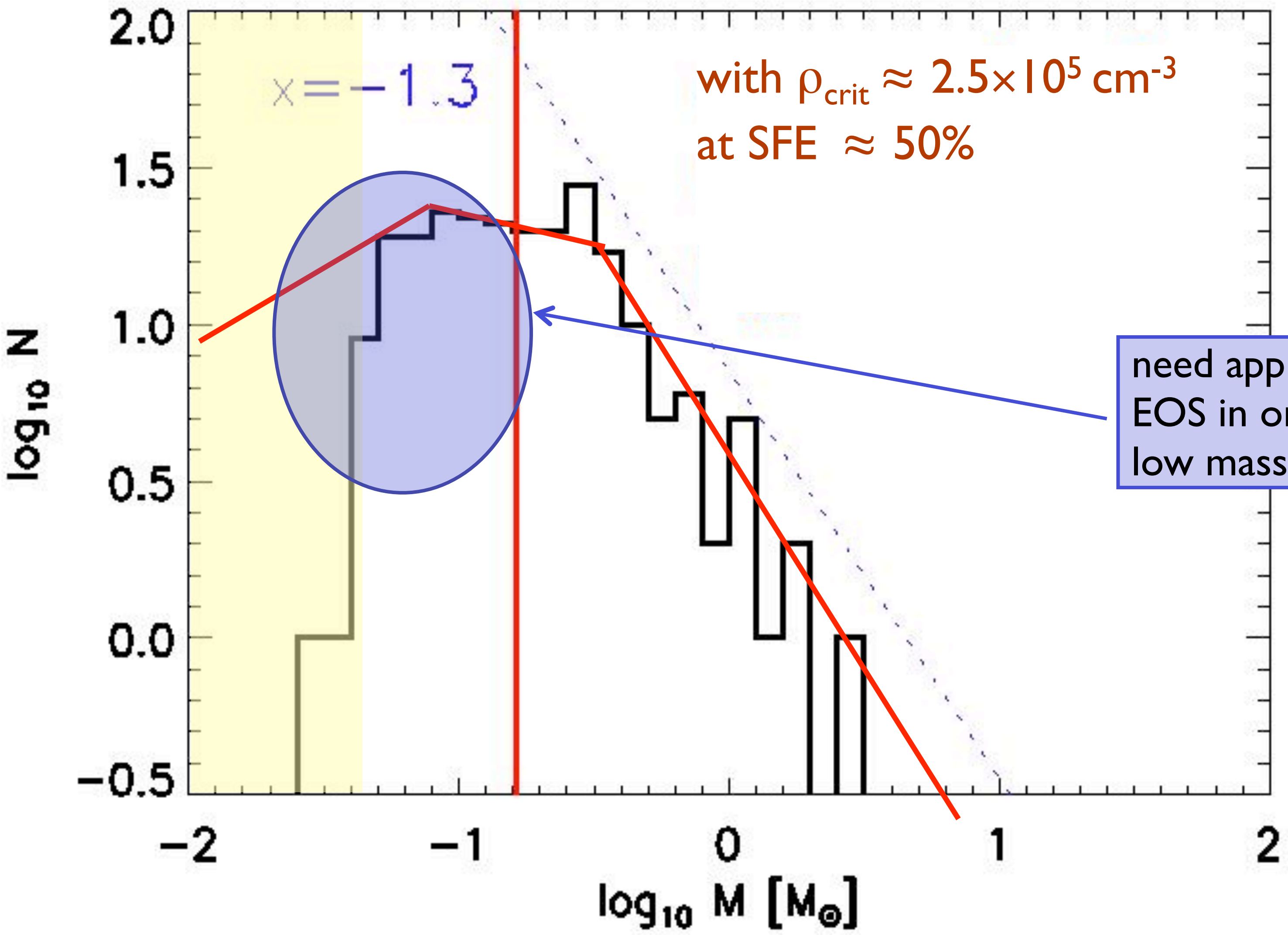


present-day star formation

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)



IMF in nearby molecular clouds



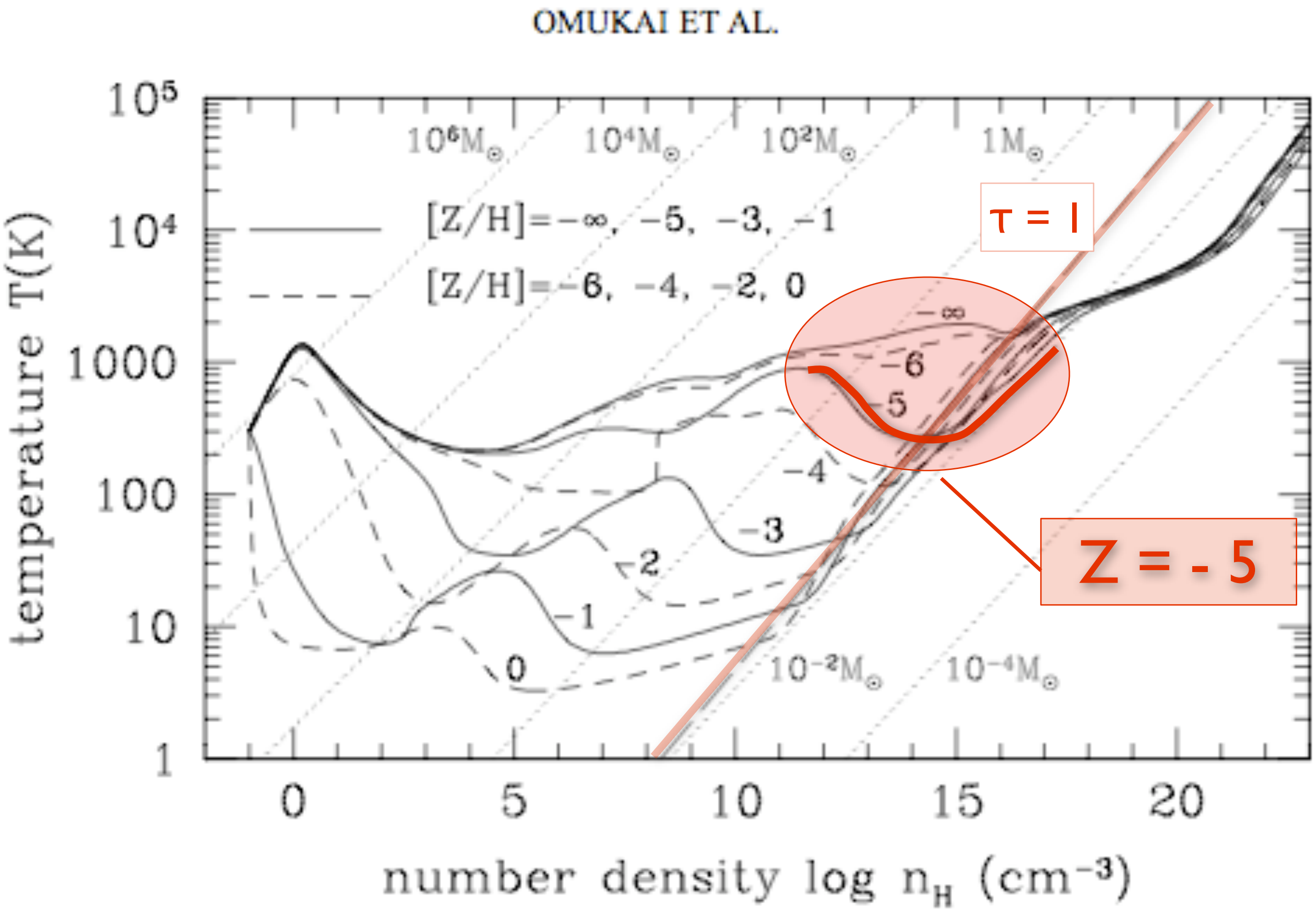
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

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

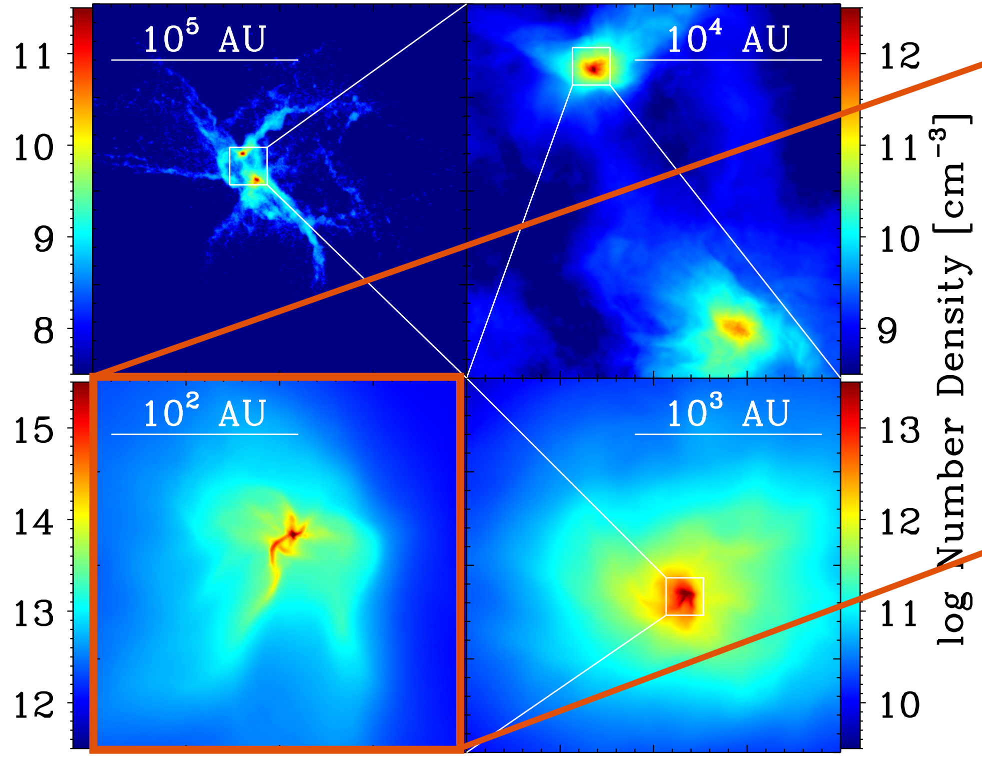


FIG. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

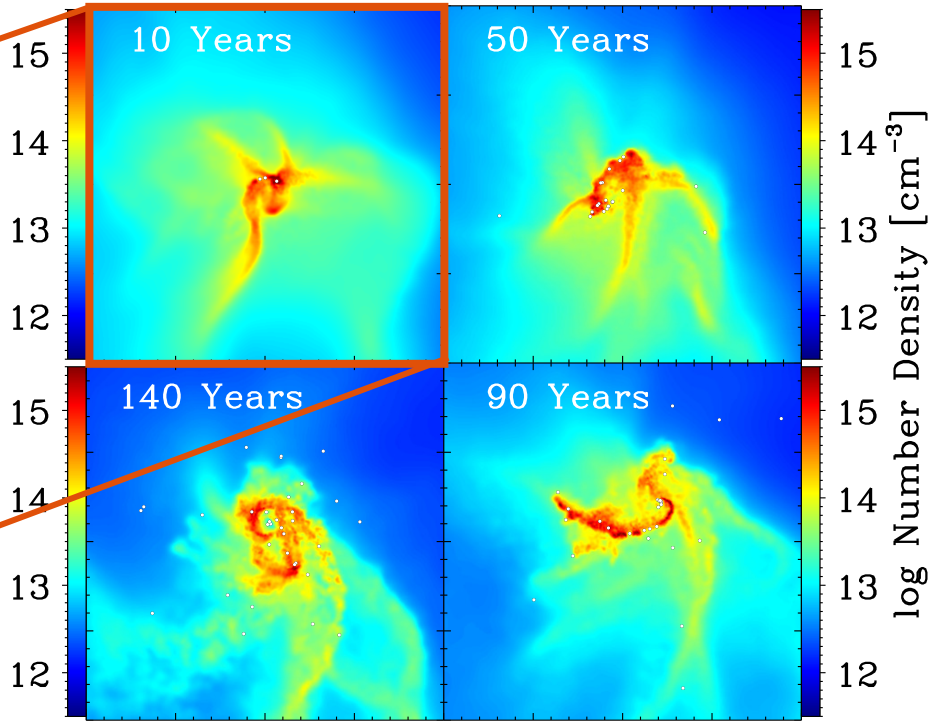
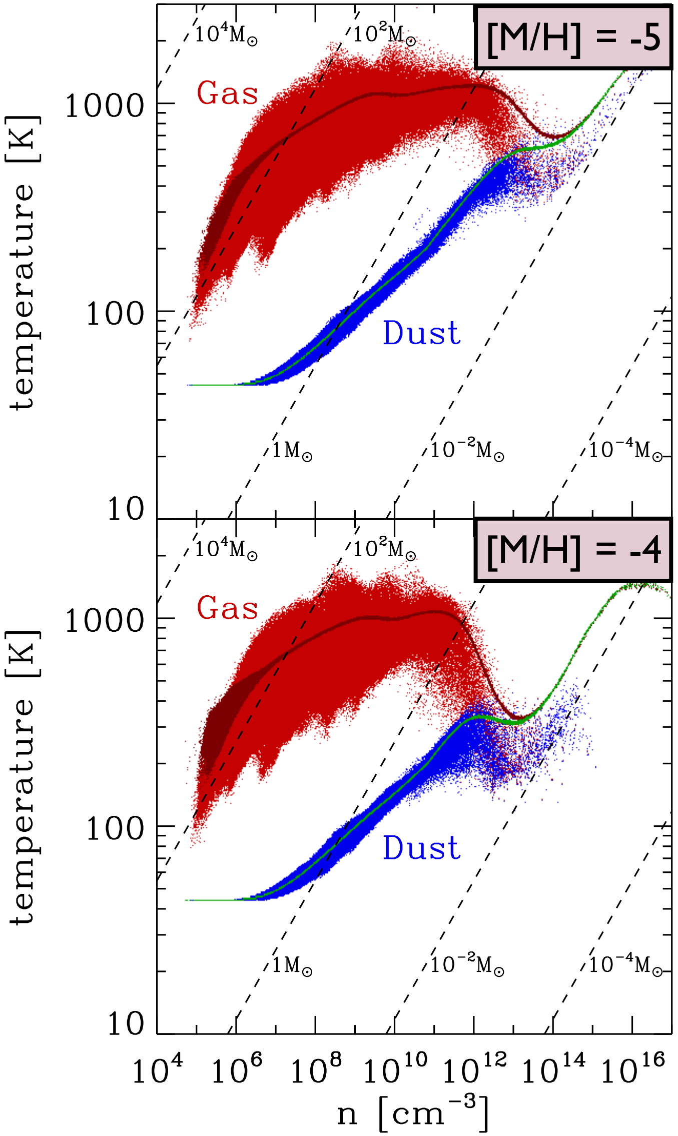


FIG. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and Z = $10^{-4}Z_{\odot}$. The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

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

transition: Pop III to Pop II.5



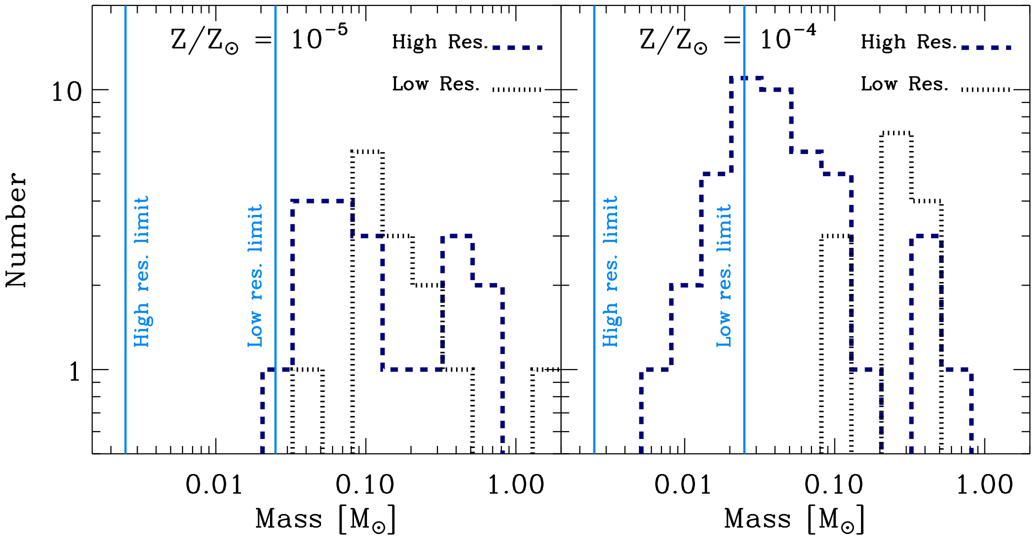
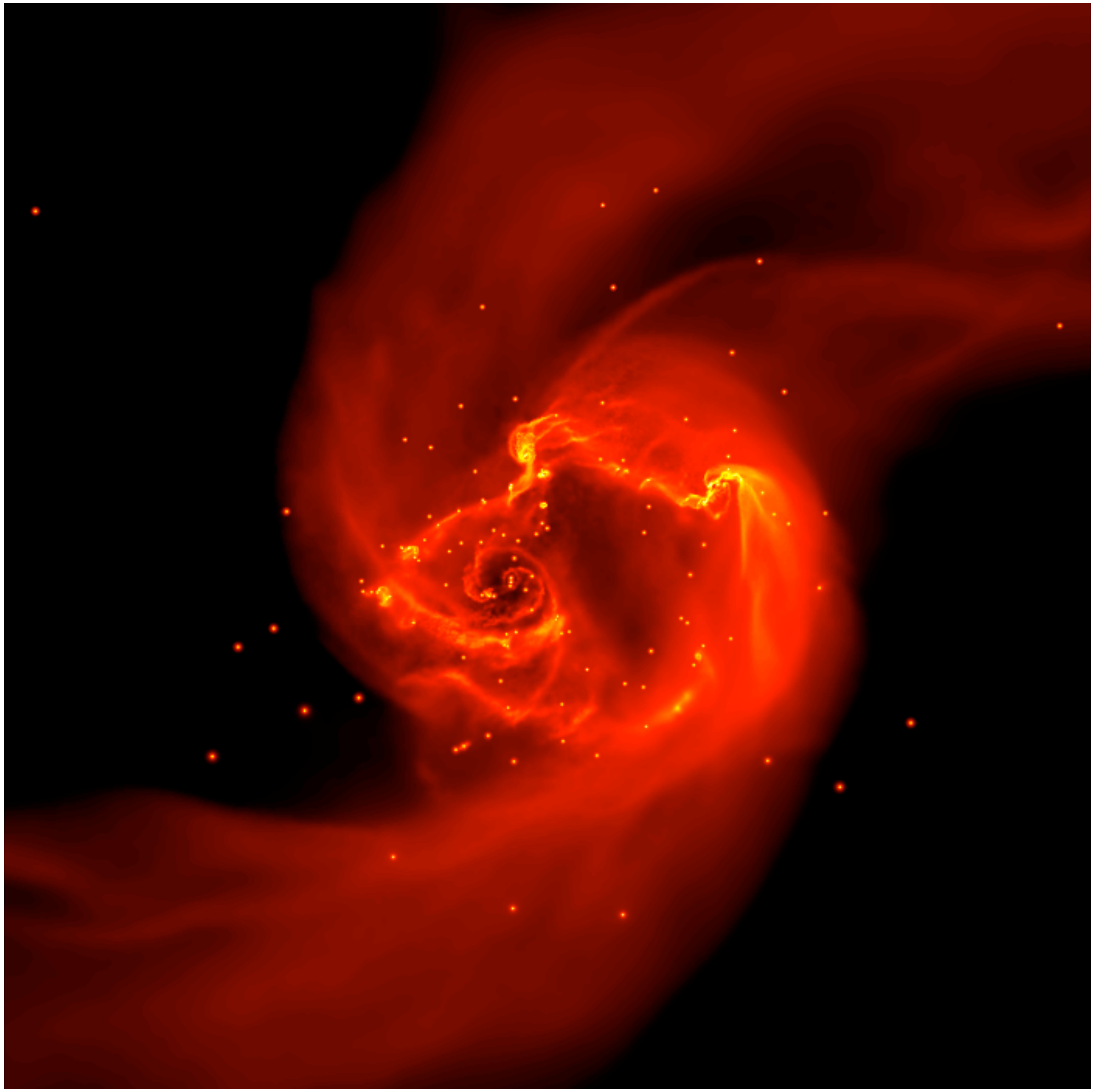


FIG. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas 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 $Z=10^{-5}$

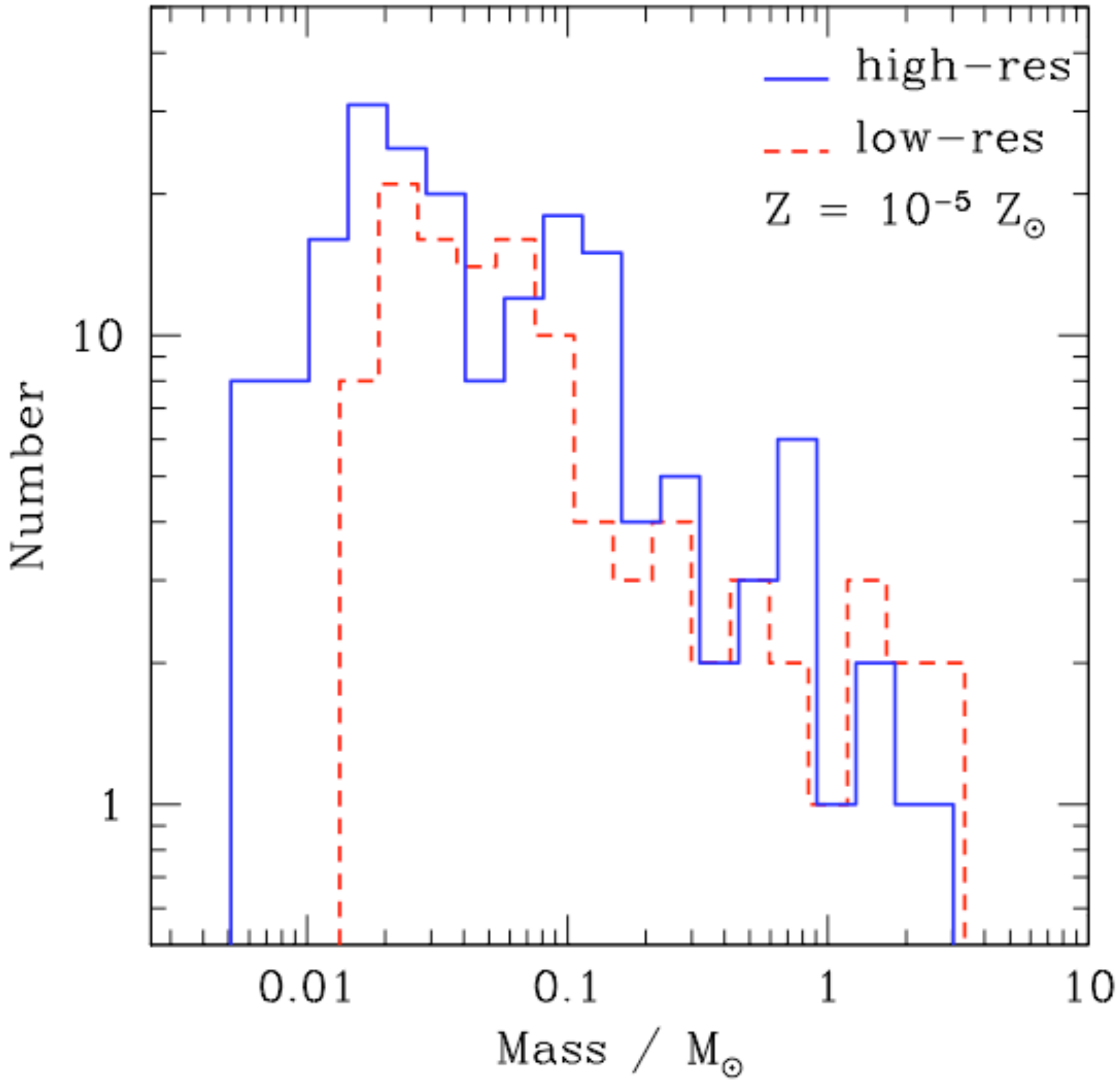


dense cluster of low-mass protostars builds up:

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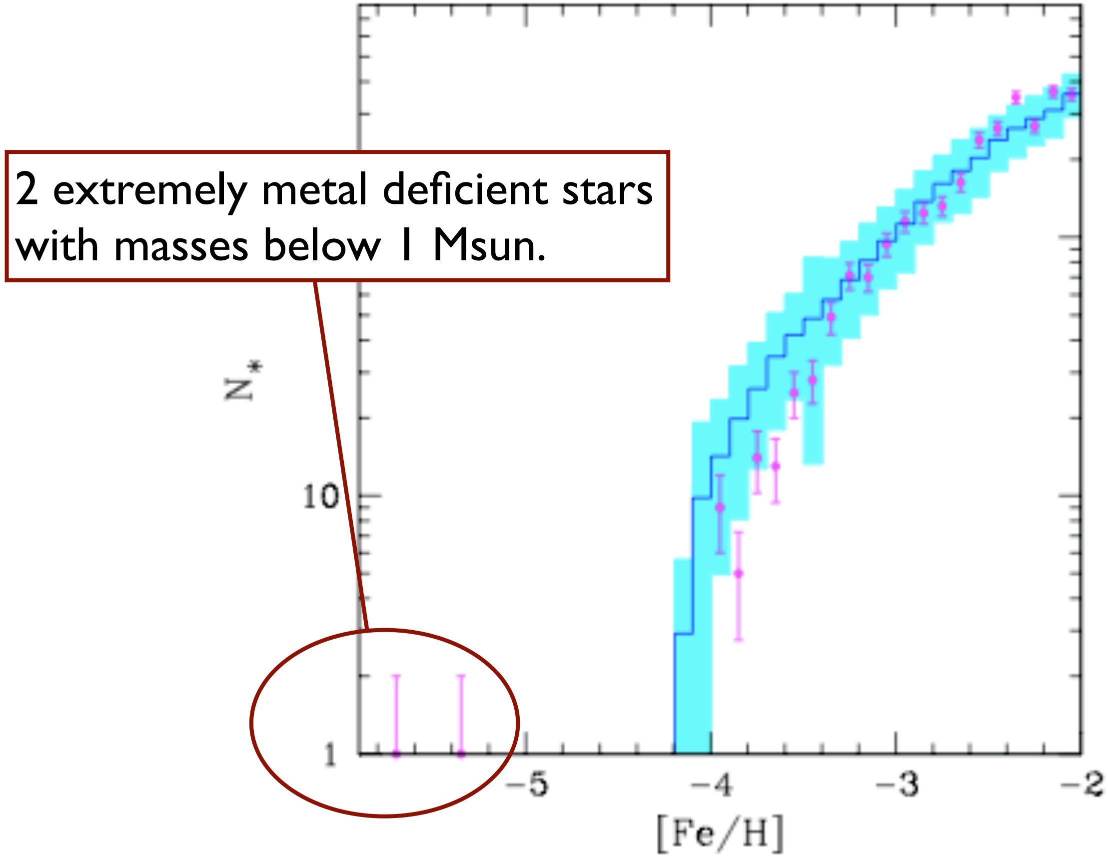
- *predictions:*
  * low-mass stars with [Fe/H] ~ 10^{-5}
  * high binary fraction

(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:

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- *predictions:*
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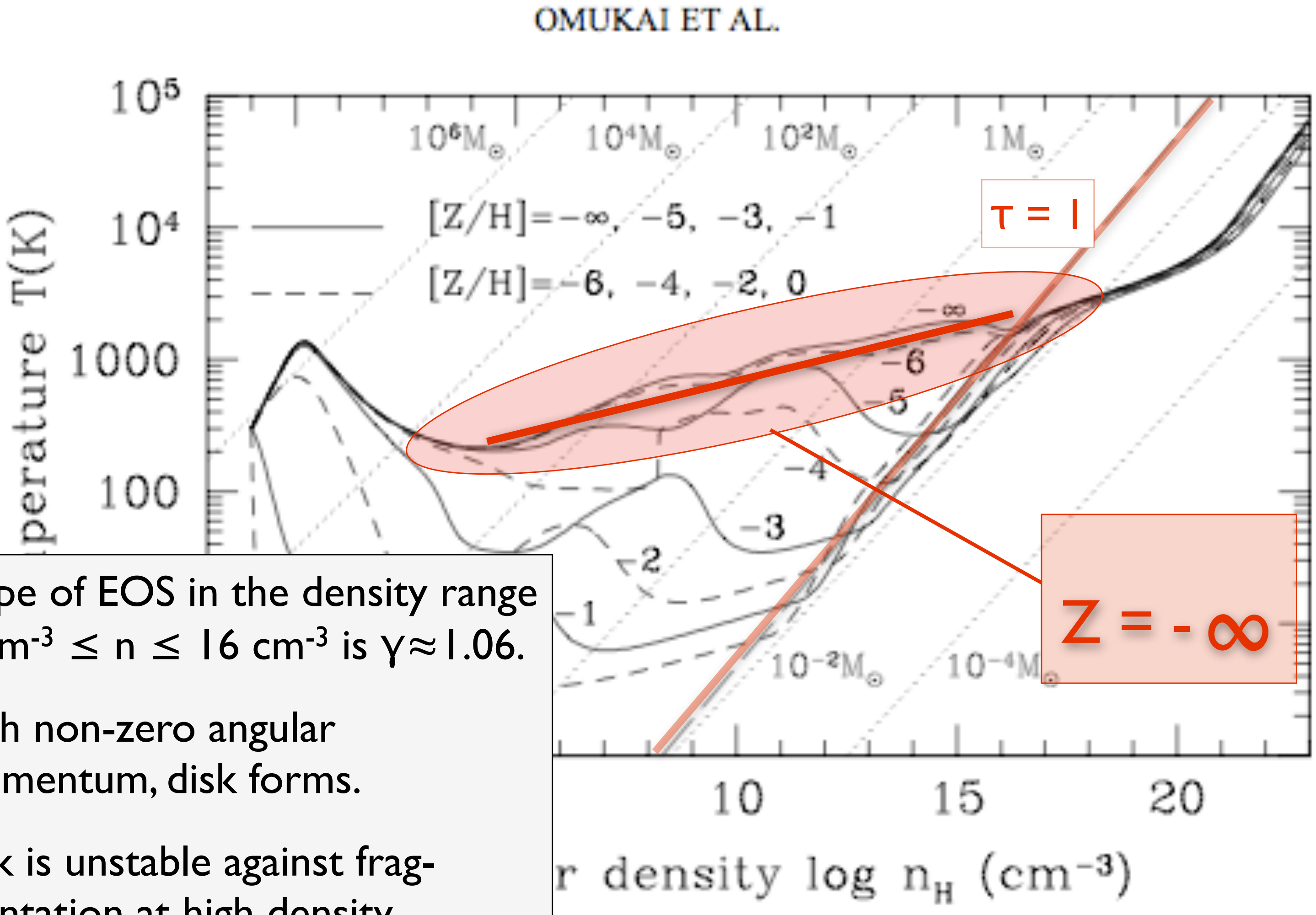
(Clark et al. 2008)

metal-free star formation



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

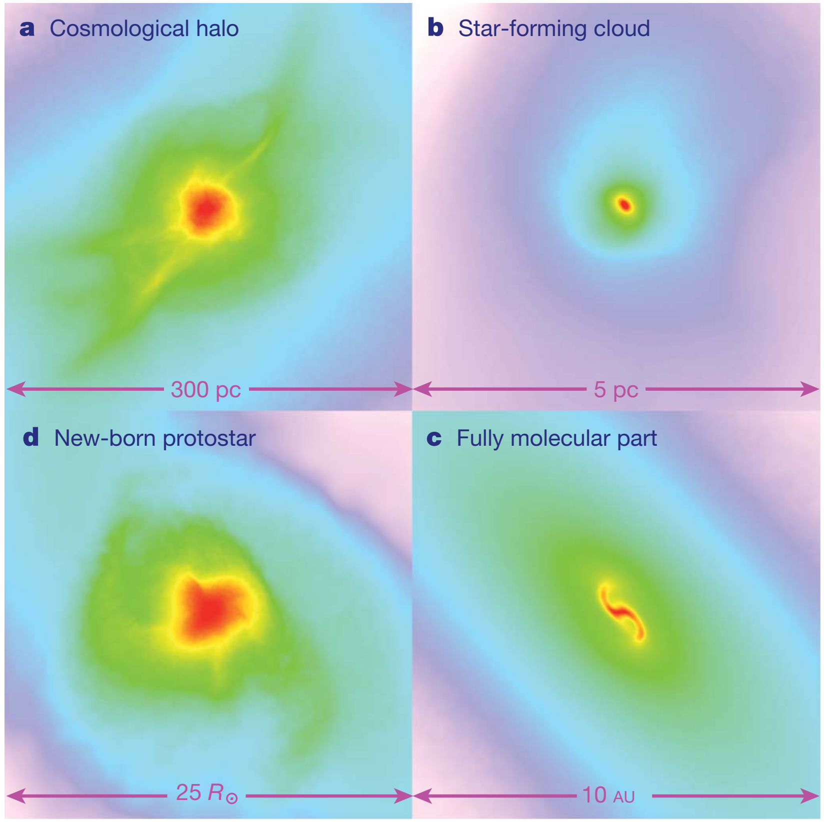
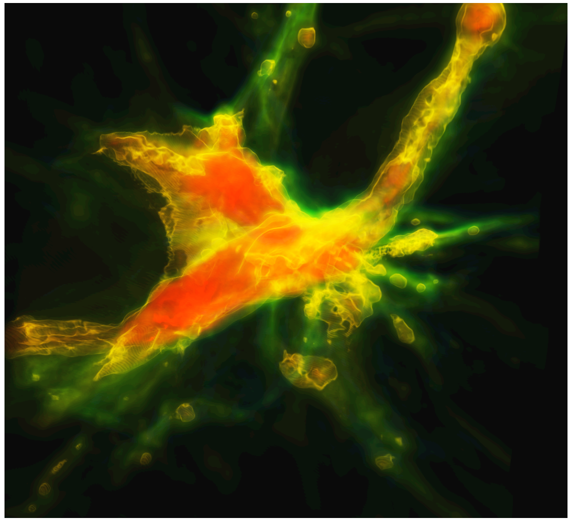


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming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

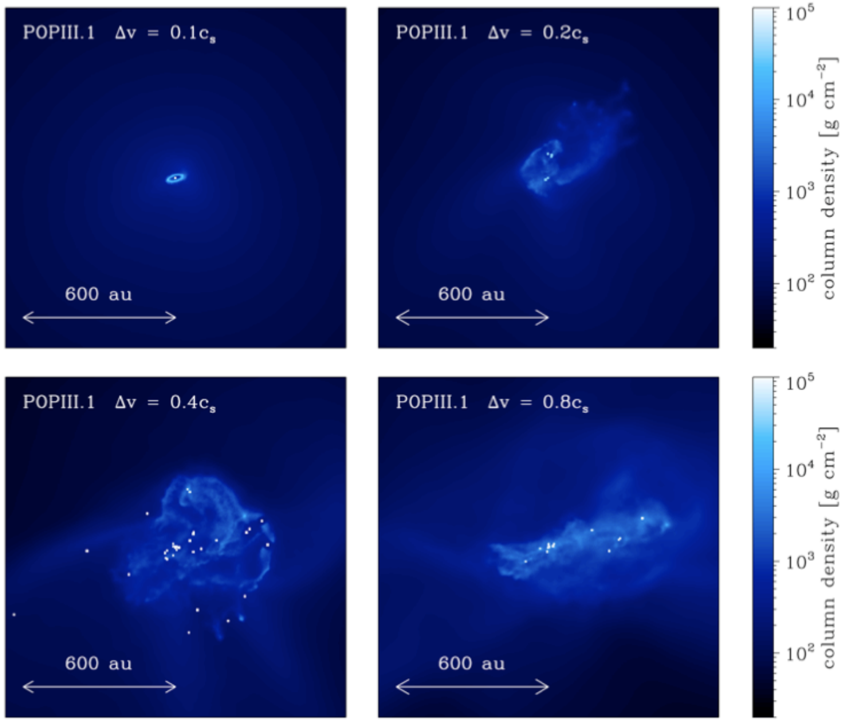


(Greif et al. 2008)

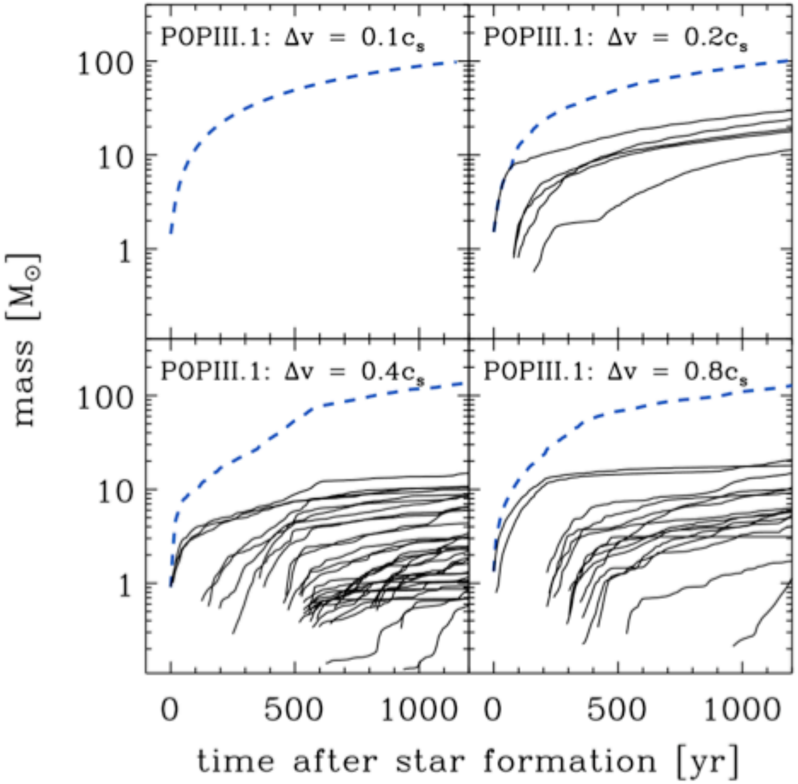
multiple Pop III stars in halo

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

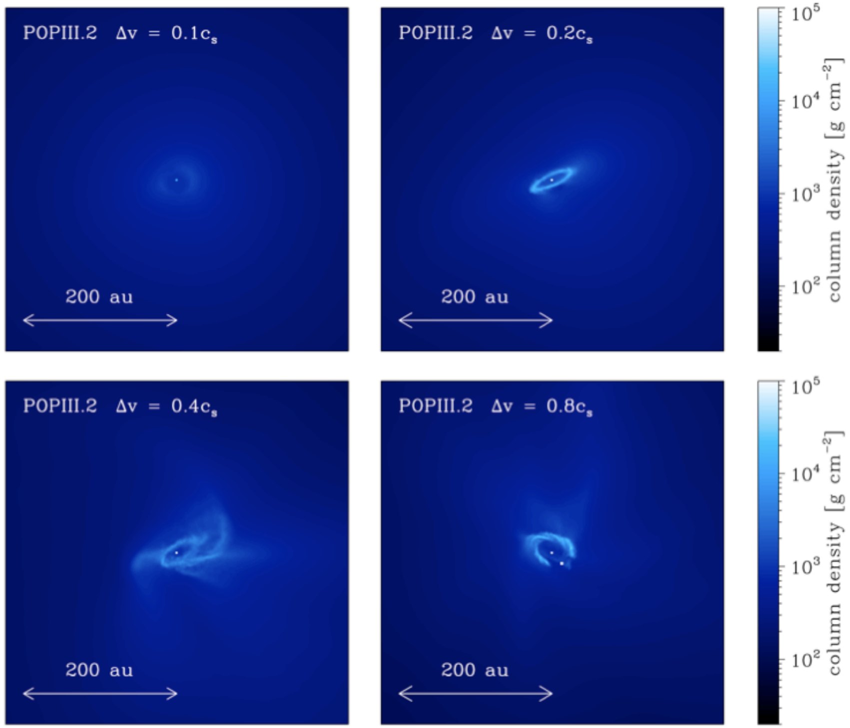
Pop III.1



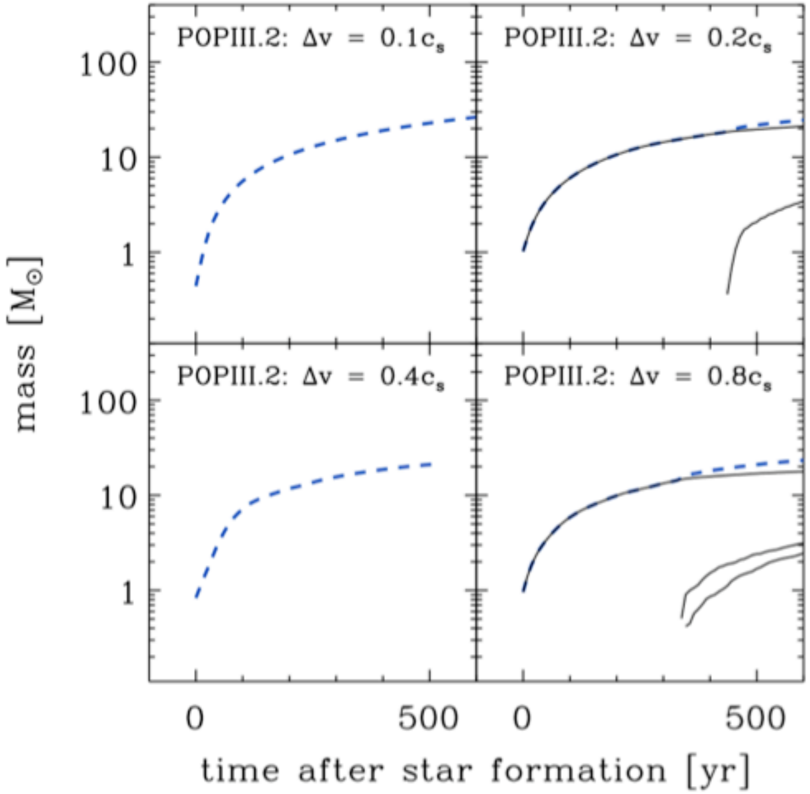
(Clark et al, 2011a, 727, 110)



Pop III.2



(Clark et al, 2011a)



once again: thermodynamics

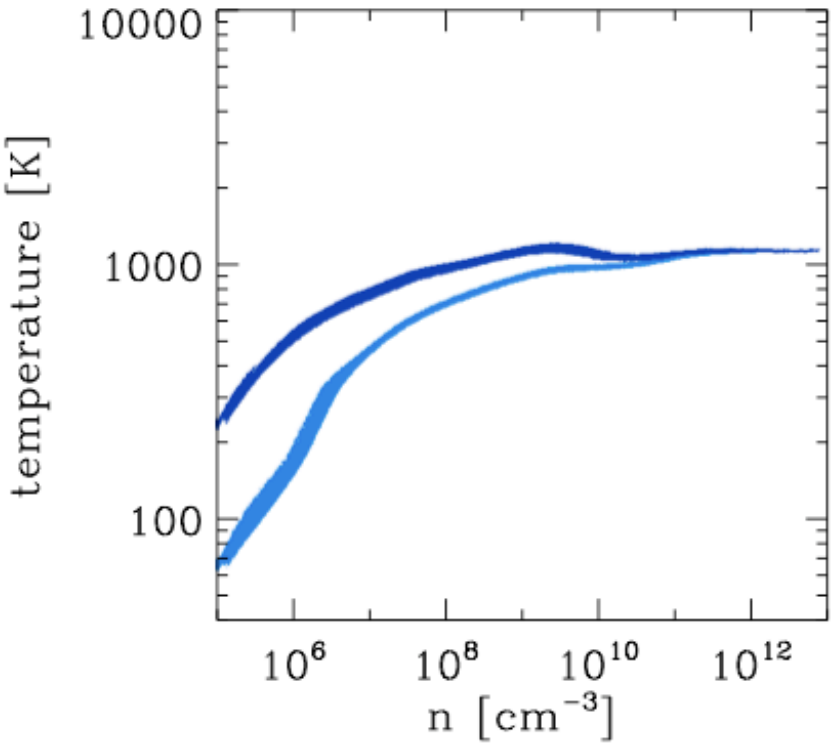


FIG. 6.— Temperature as a function of number density for the Pop. III.1 (dark blue) and Pop. III.2 (light blue) $\Delta v_{\rm turb} = 0.1\,c_s$ simulations. In both cases, the curves denote the state of the cloud at the point just before the formation of the sink particle.

also Pop III.2 gas heats up above the CMB

--> weaker fragmentation!

once again: thermodynamics

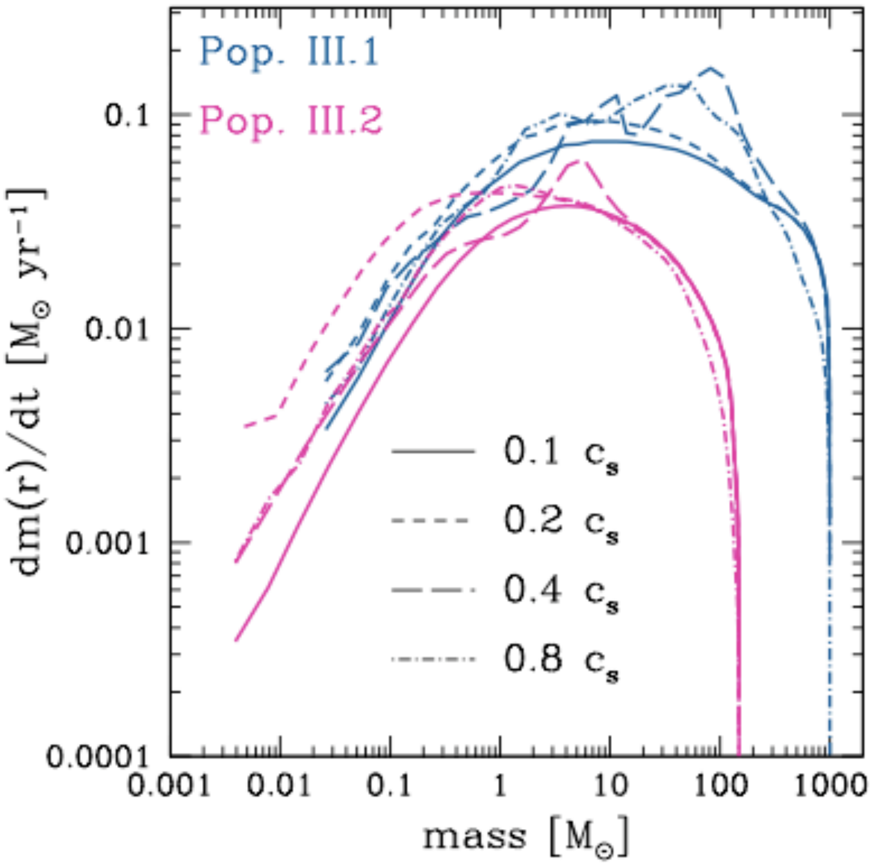


FIG. 8.— Accretion rates as a function of enclosed gas mass in the Pop. III.1 (upper lines; blue) and Pop. III.2 (lower lines; magenta) simulations, estimated as described in Section 4.1. Note that the sharp decline in the accretion rates for enclosed masses close to the initial cloud mass is an artifact 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

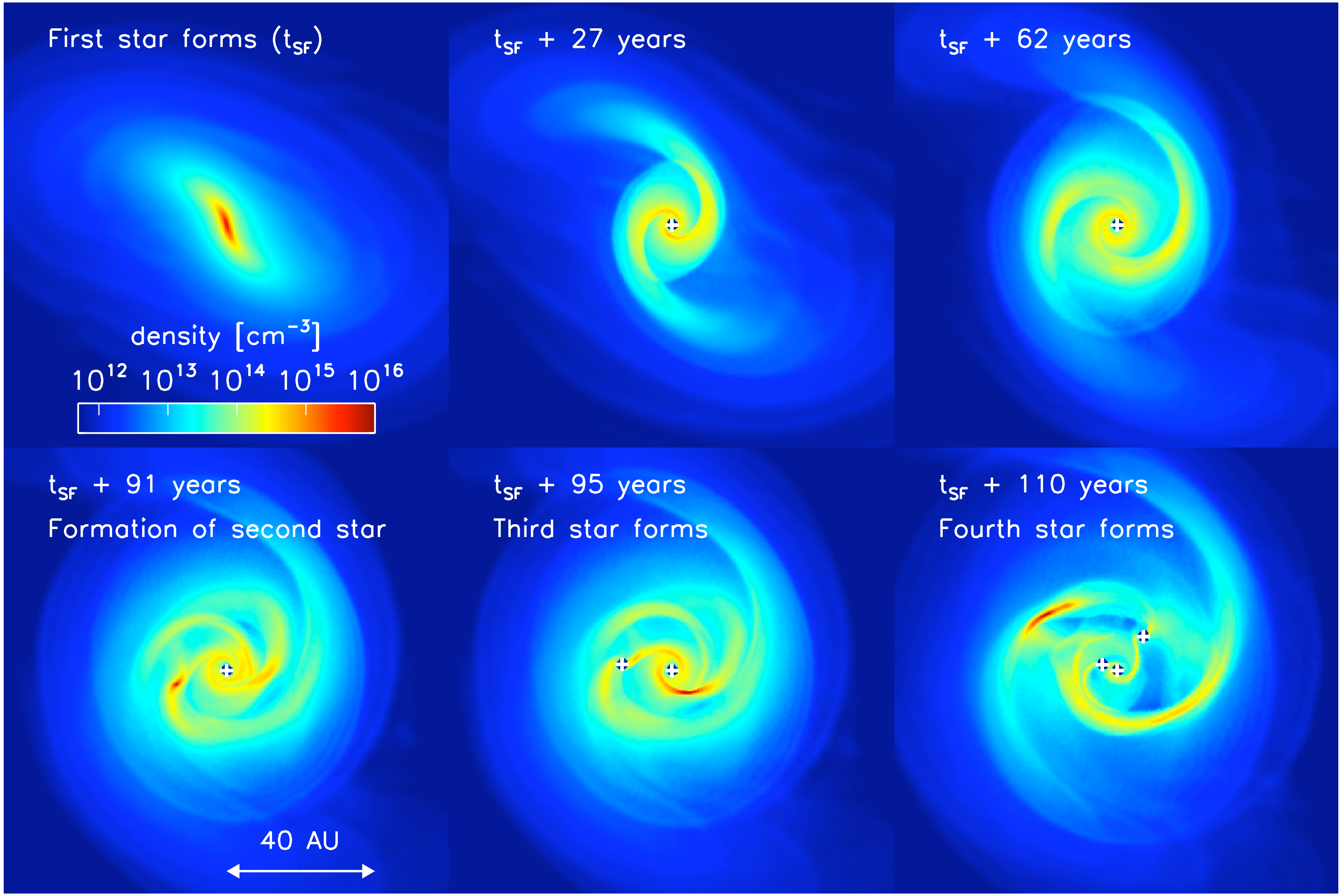


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.

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

SPH study: some disk parameters

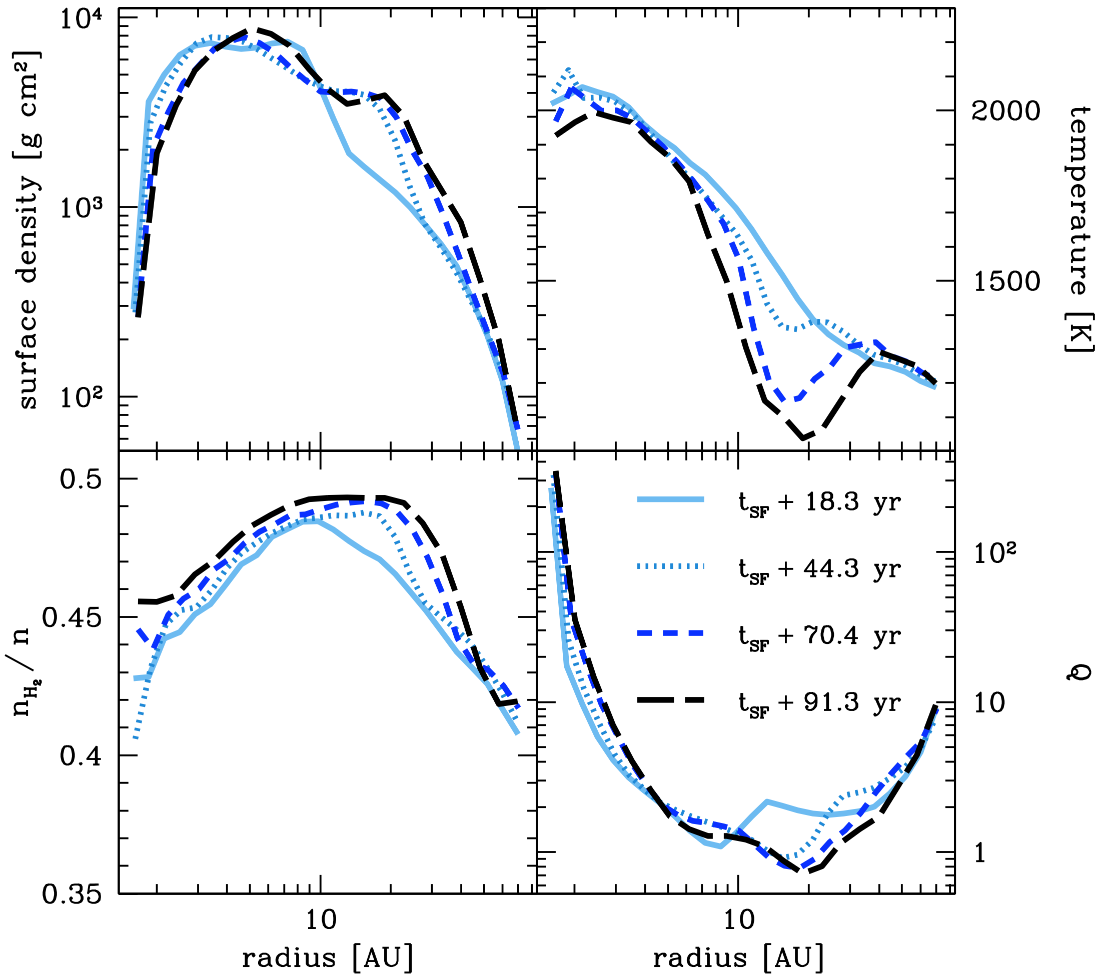


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi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

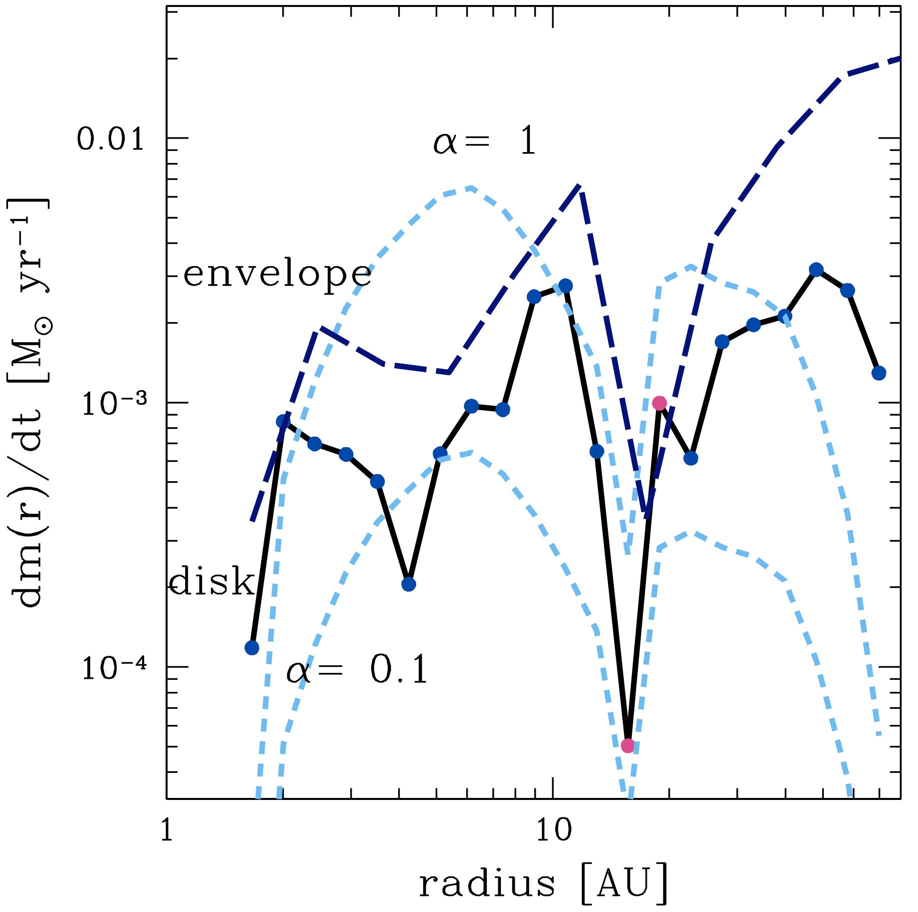


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure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

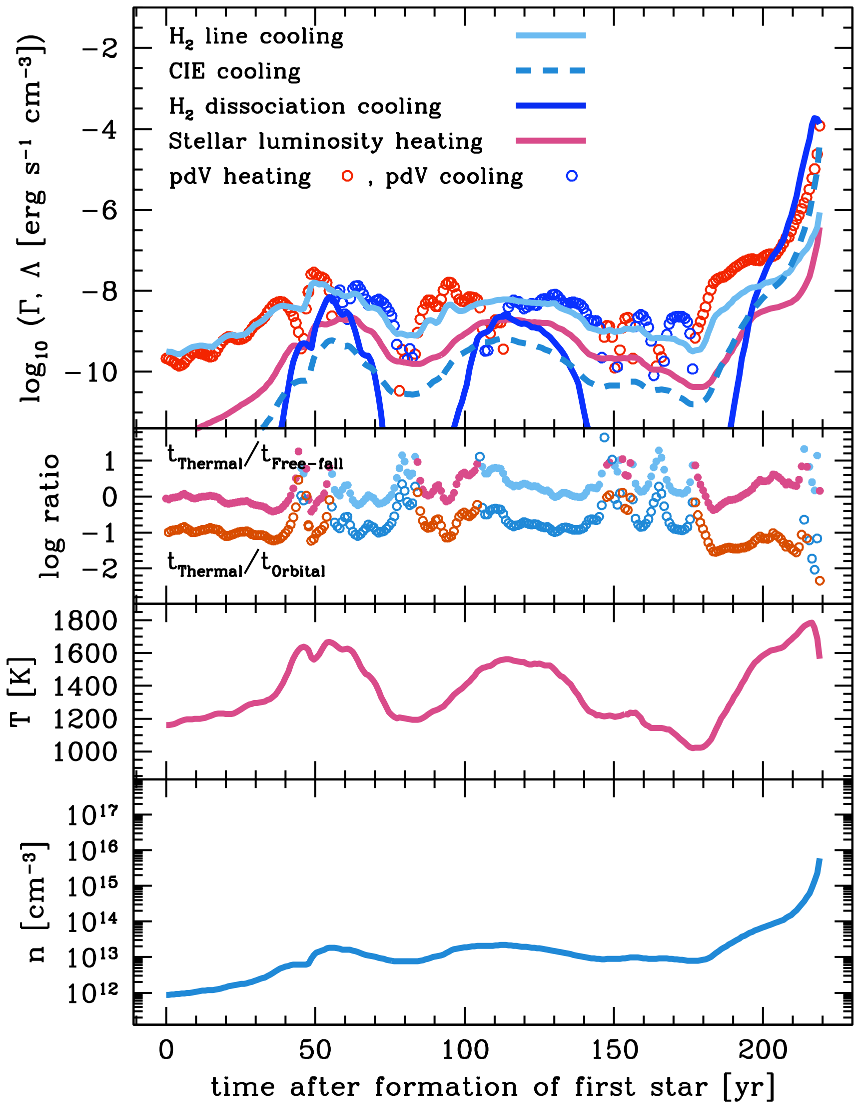
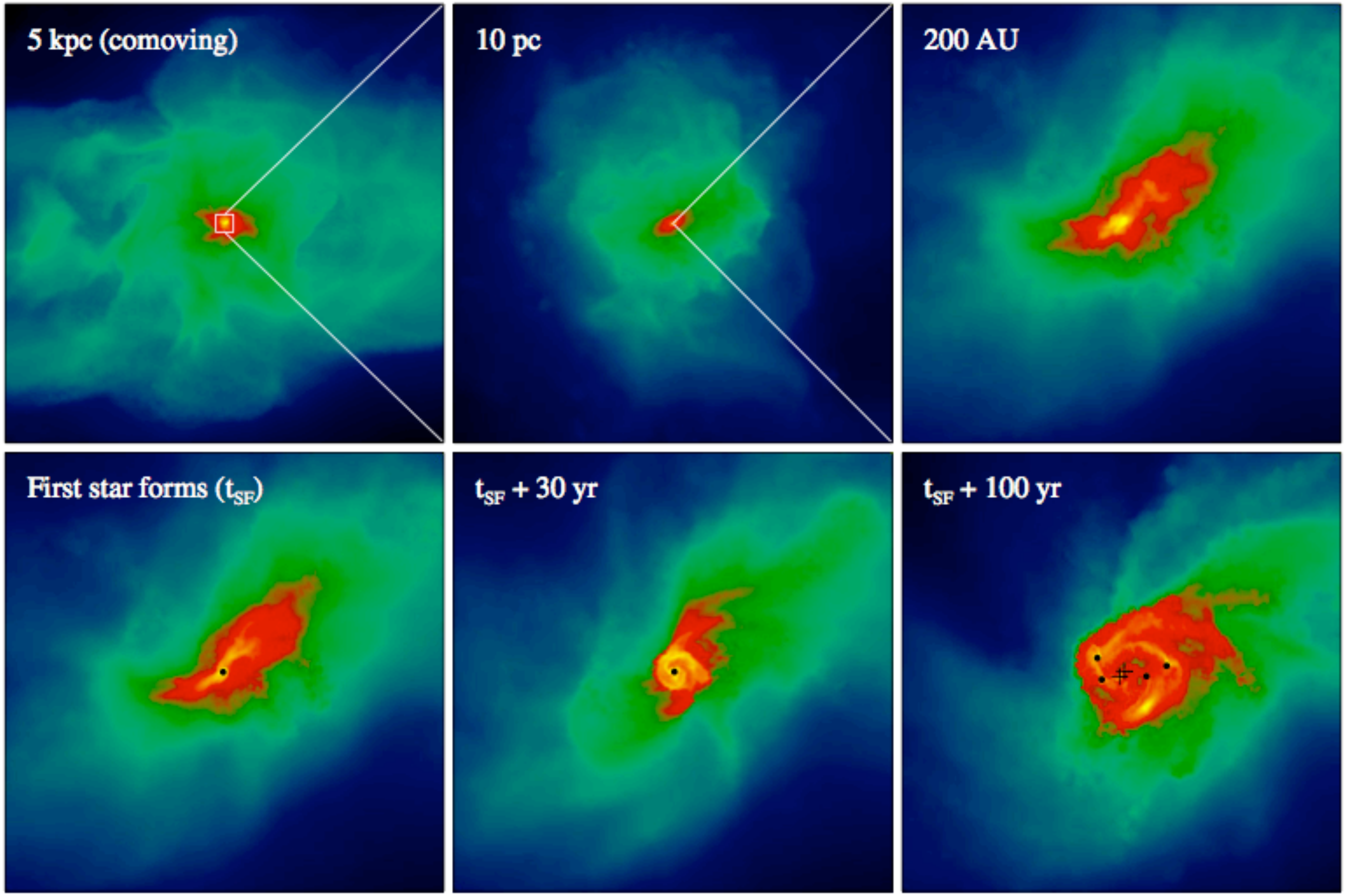


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated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

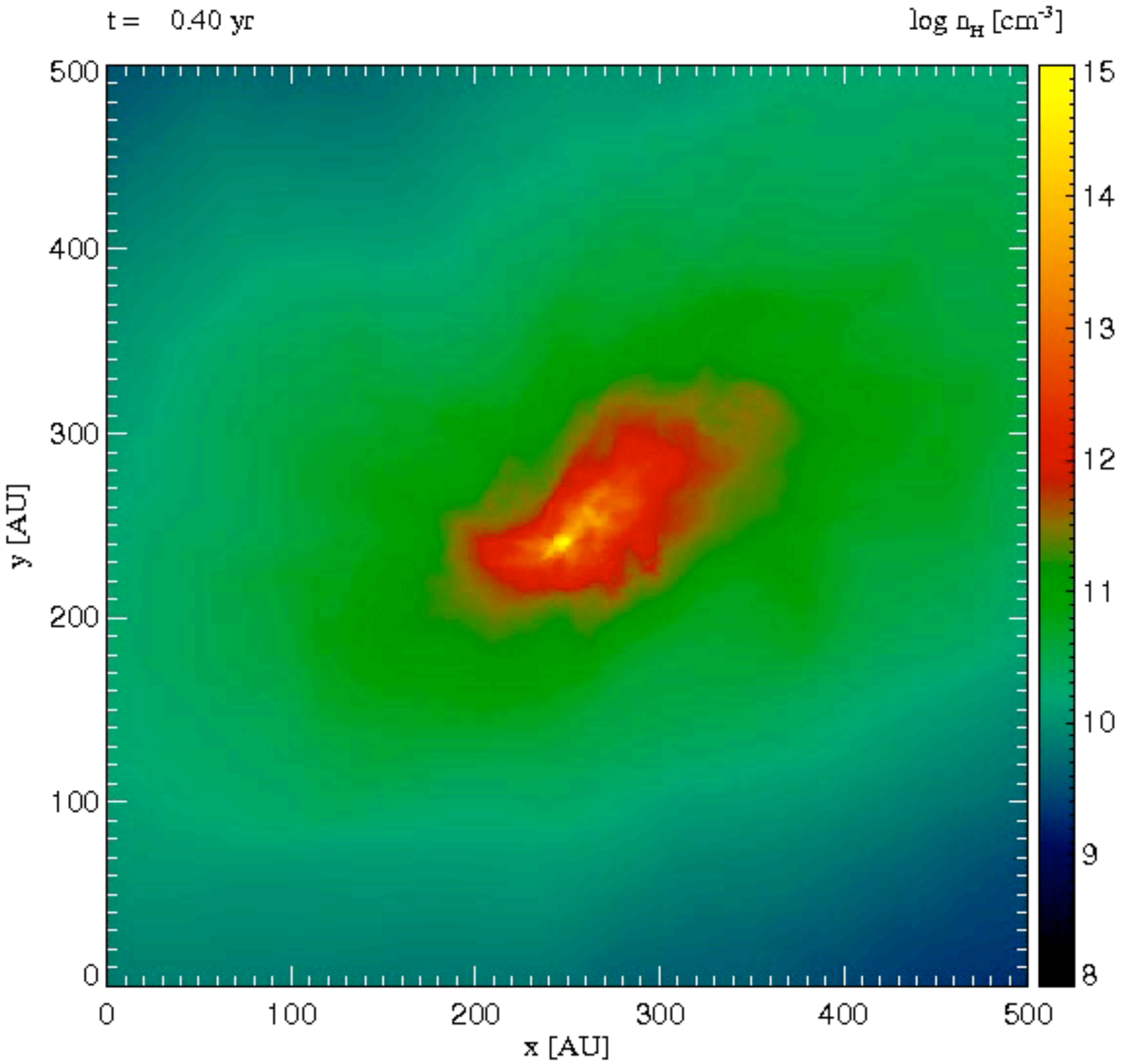
(Clark et al. 2011b, Science, 331, 1040)

Arepo study: surface density at different times



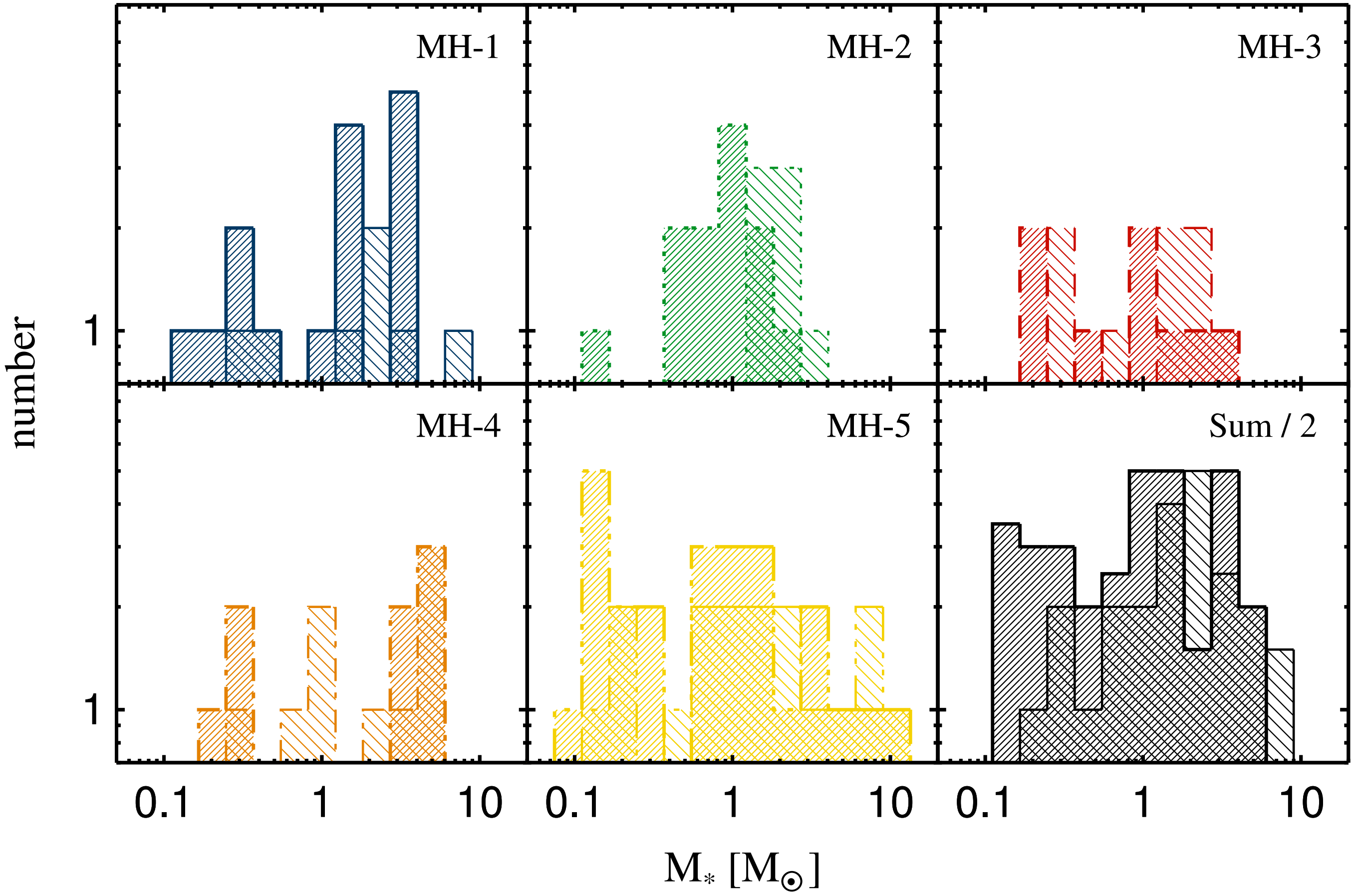
one out of five halos

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



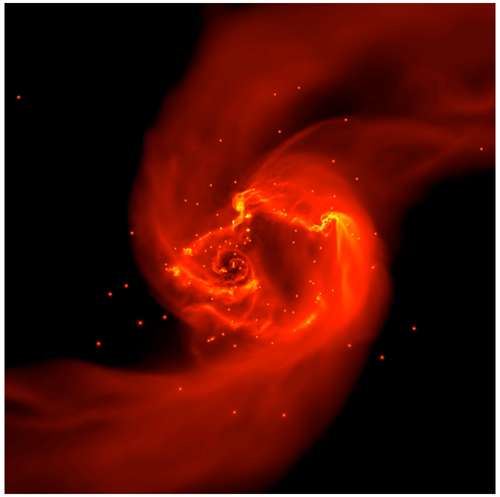
(Greif et al. 2011a, ApJ, in press, arXiv:1101.5491)

Arepo study: mass spectrum of fragments



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

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?

some more details

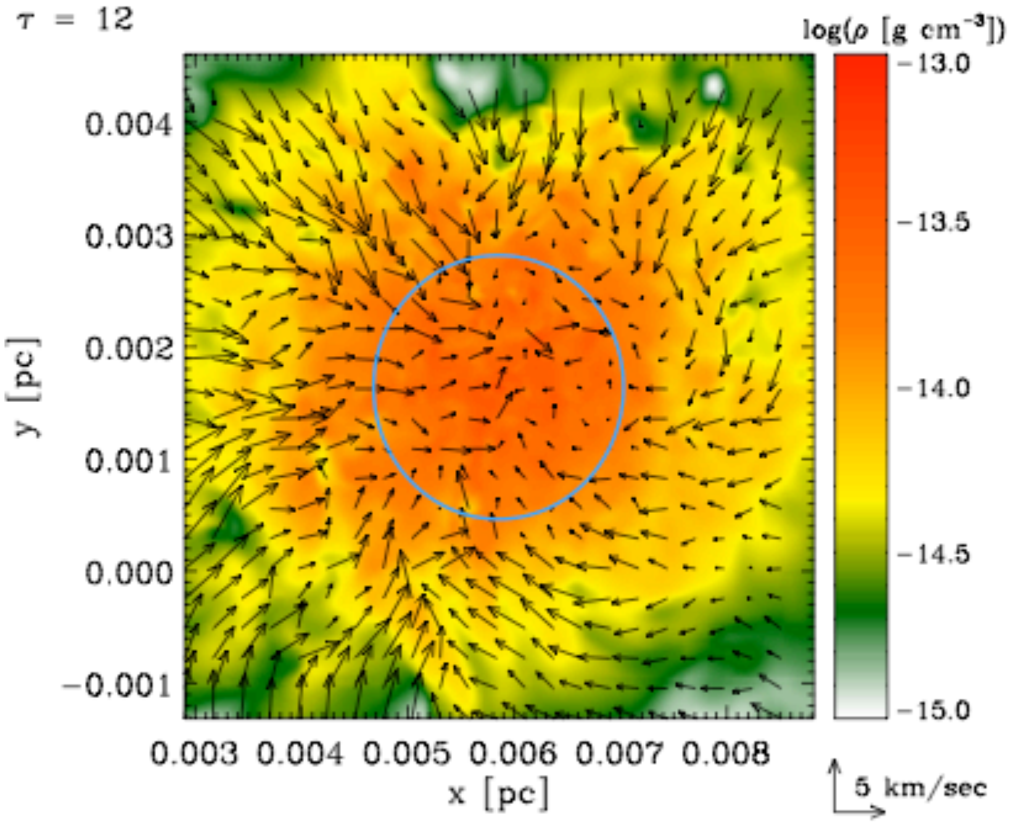
- magnetic field amplification in primordial collapse (see also talk by Dominik Schleicher)
- influence of streaming motions on collapse in primordial halos (see also talk by Thomas Greif)
- fragmentation-induced starvation as key to understand final stellar masses (Peters et al. 2010abc, 2011)

B fields in the early universe?

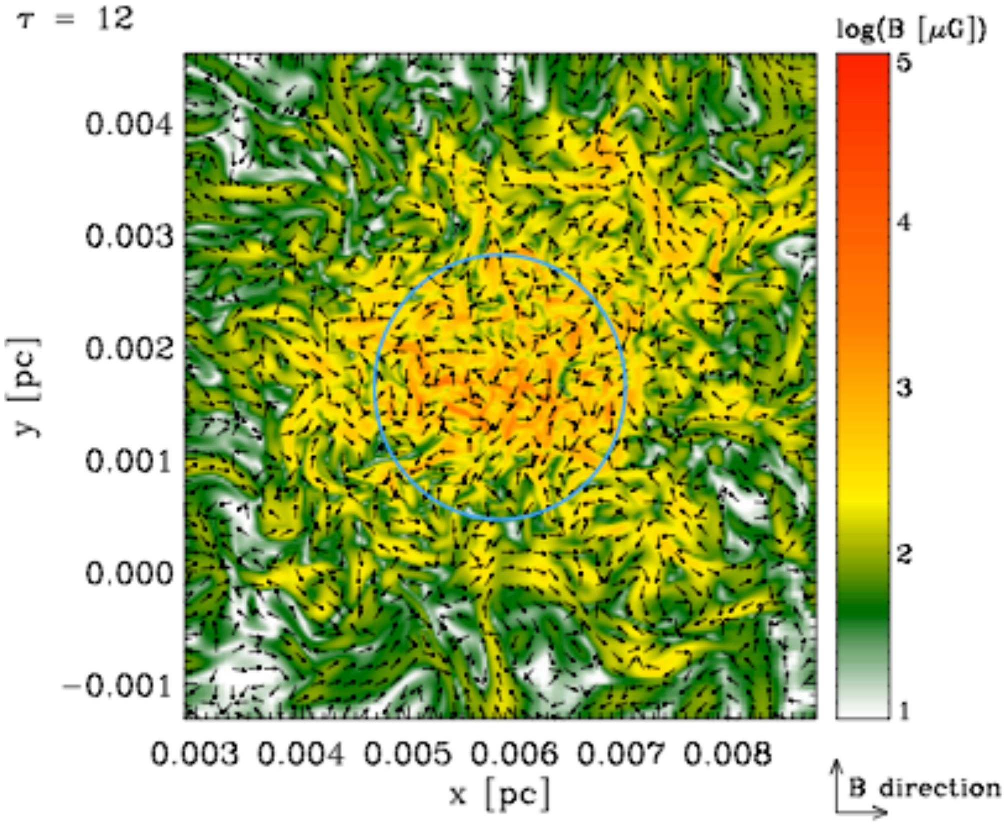
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, *THIS MAY BE WRONG!*

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)

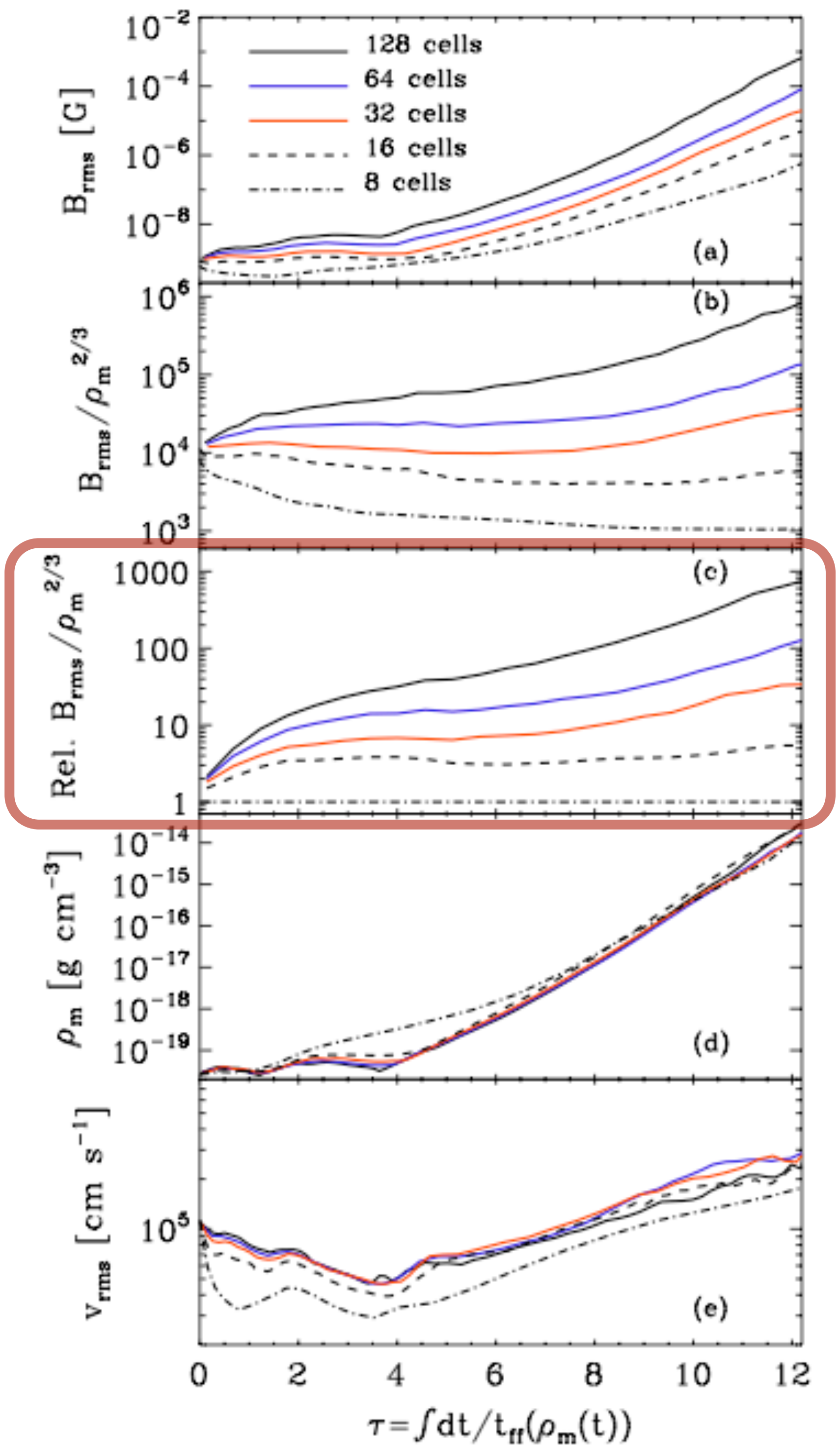


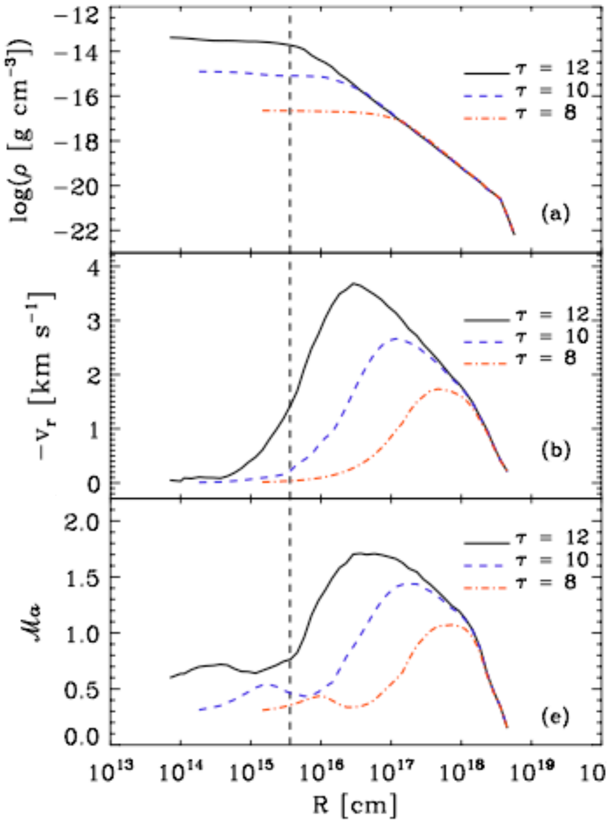
magnetic field structure



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:

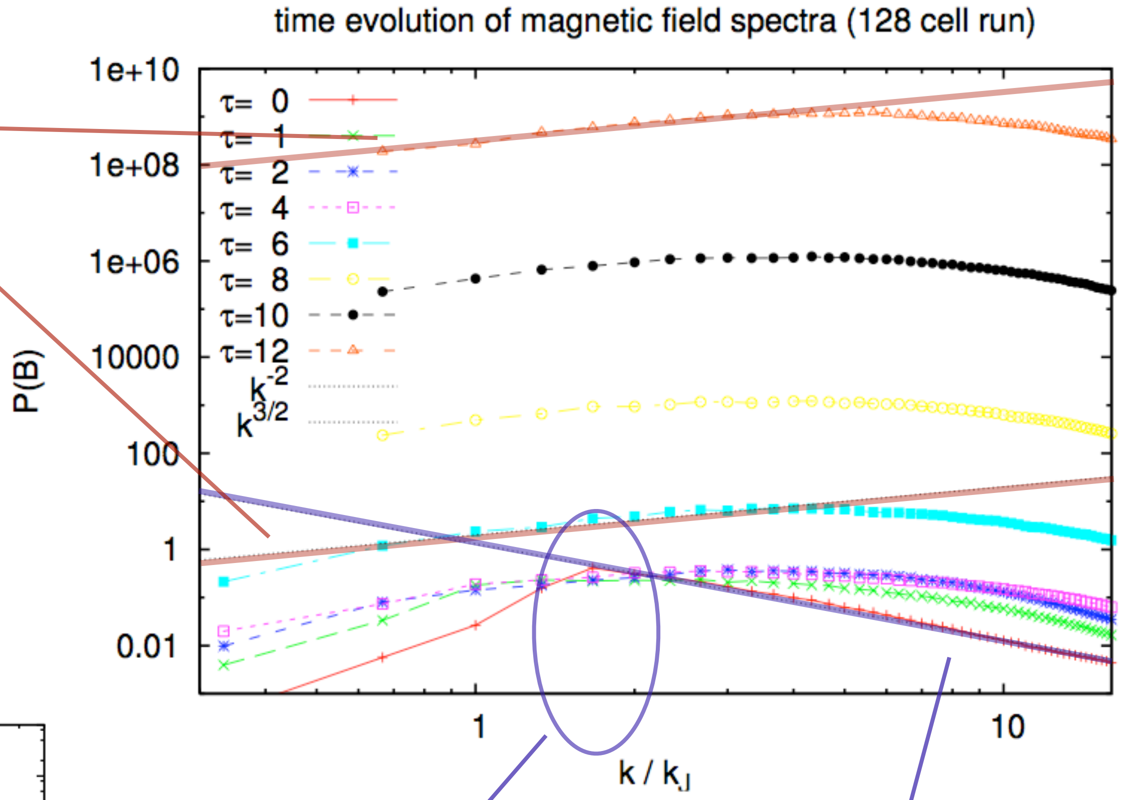
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

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

analysis of magnetic field spectra

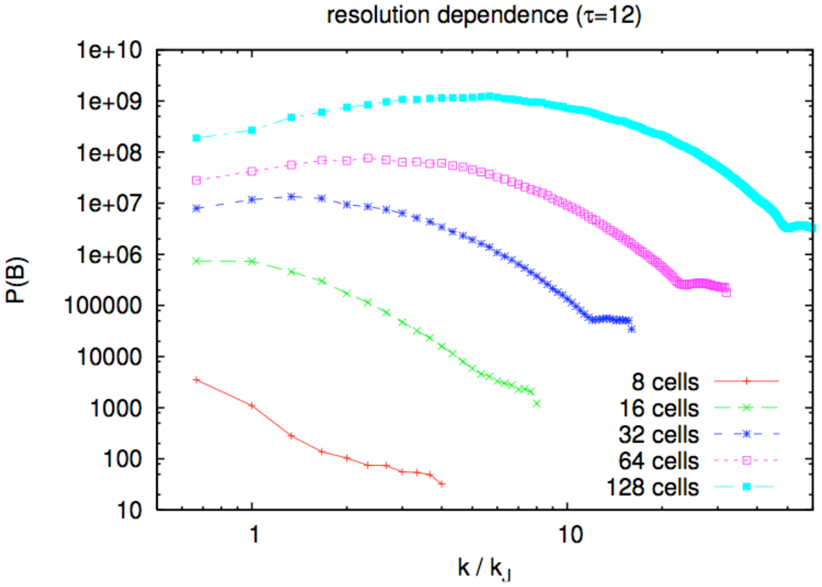
Slope +3/2 of Kazantsev theory

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



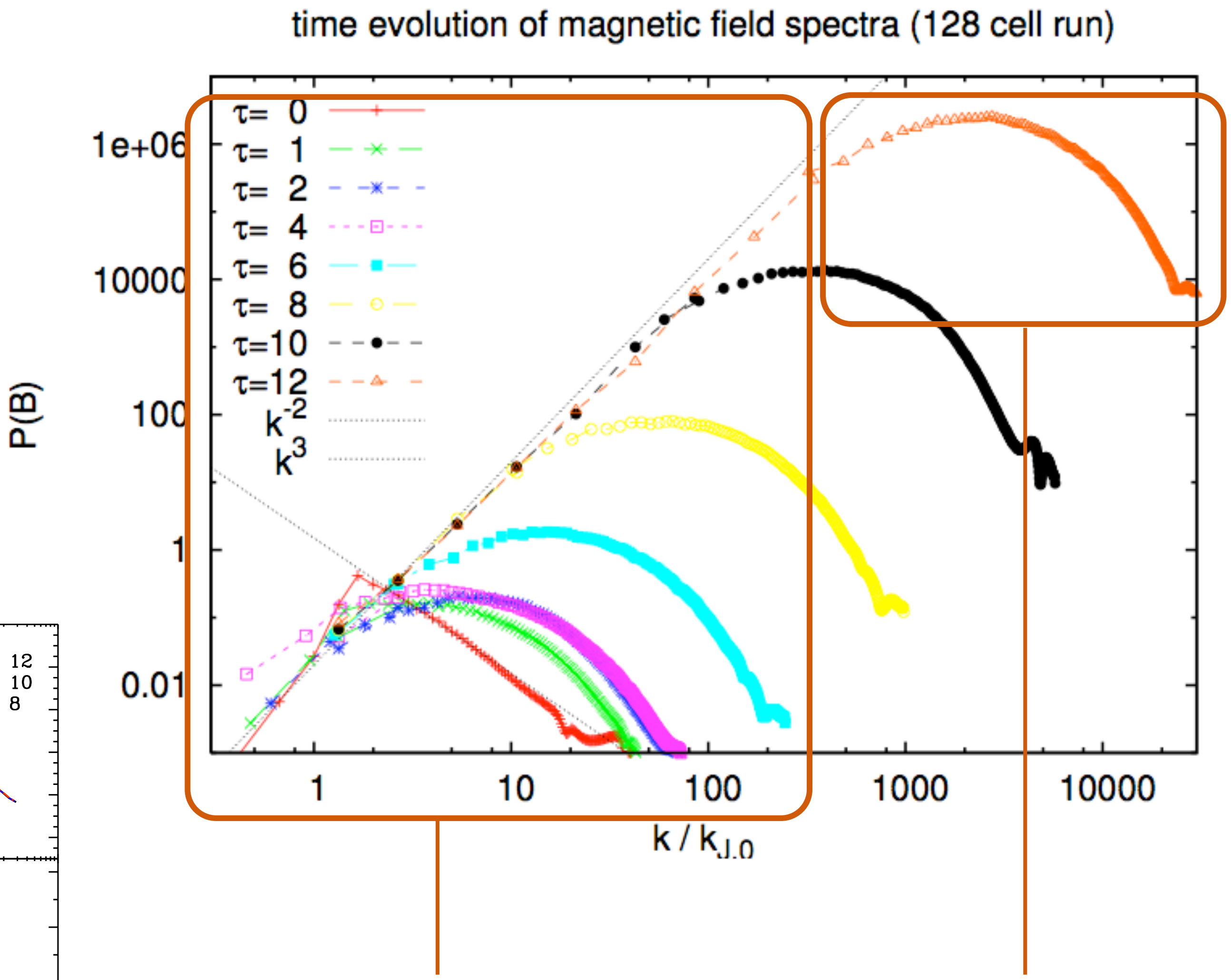
initial peak of B fluctuation spectrum

initial slope of B fluctuations



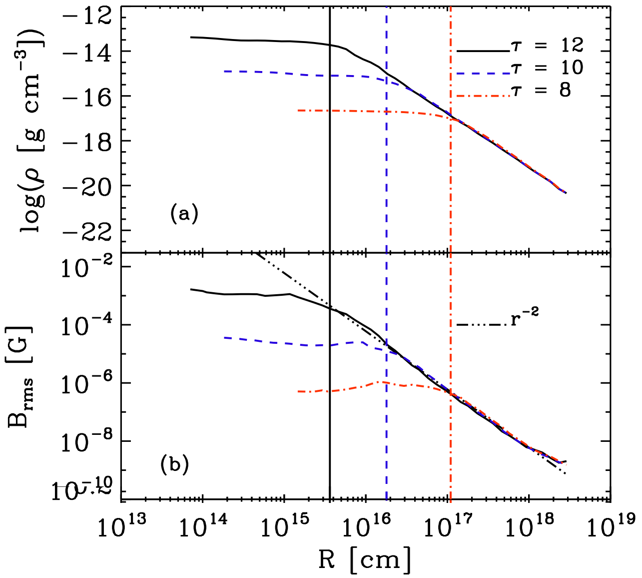
(Federrath et al., 2011, ApJ, 731, 62)

analysis of magnetic field spectra



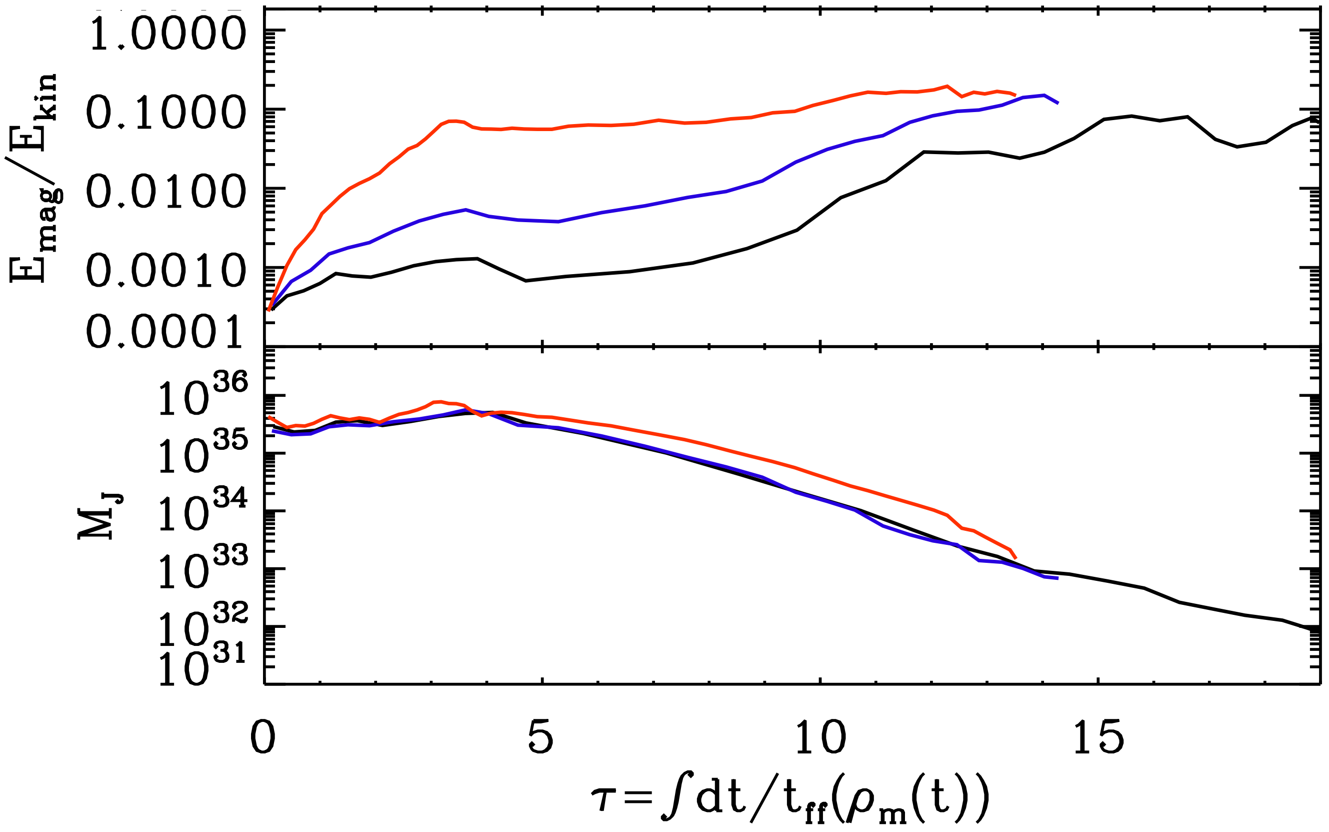
B fluctuation spectrum in 1/r^2 fall-off

B fluctuation spectrum in flat inner core



(Federrath et al., 2011, ApJ, 731, 62)

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

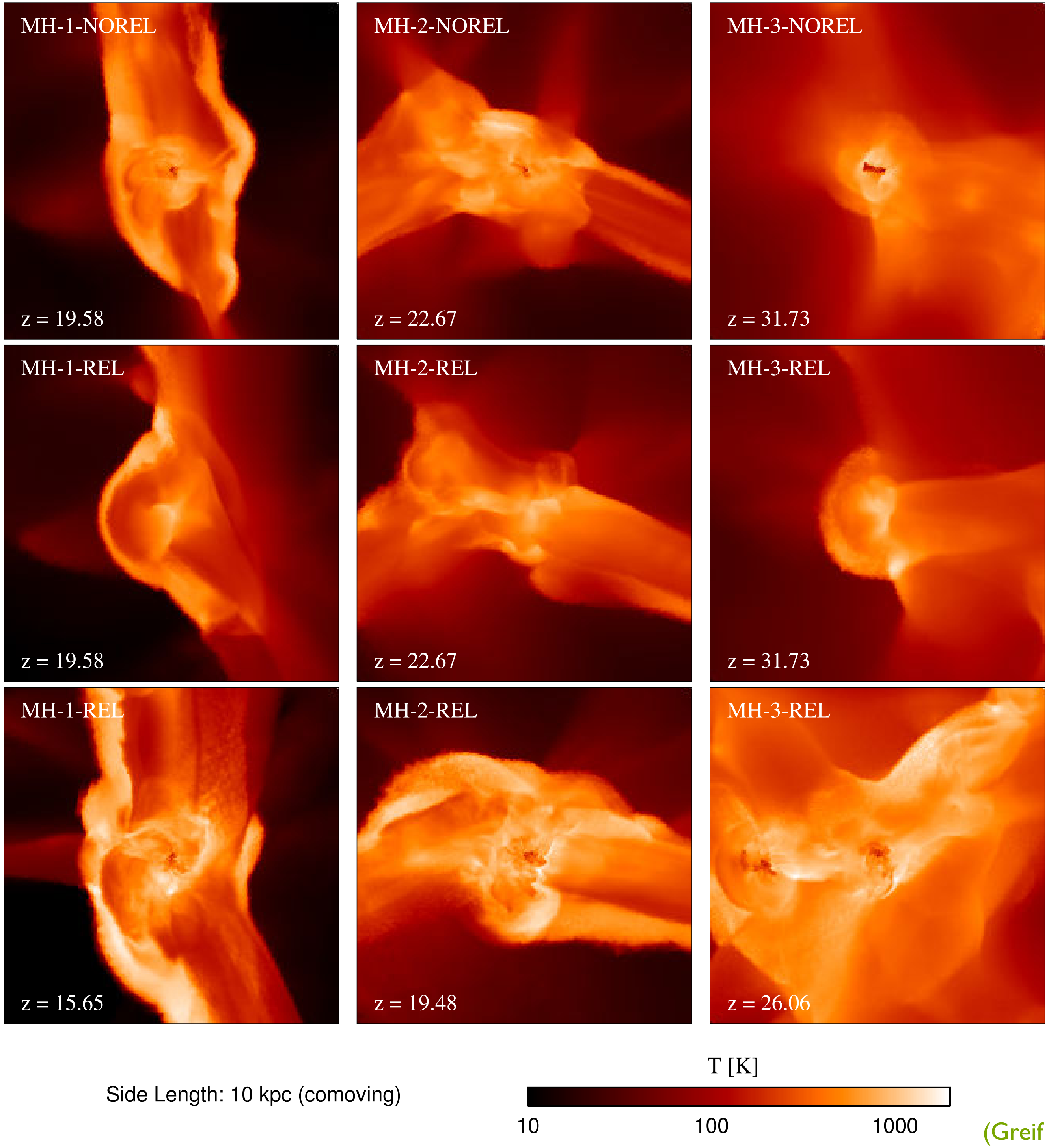
(Peters et al., in prep.)

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?

effects of streaming velocities

- relative velocity of gas and DM of a few km/s
  (Tseliakhovich & Hirata 2010)
- how does that influence formation and evolution of minihalos?

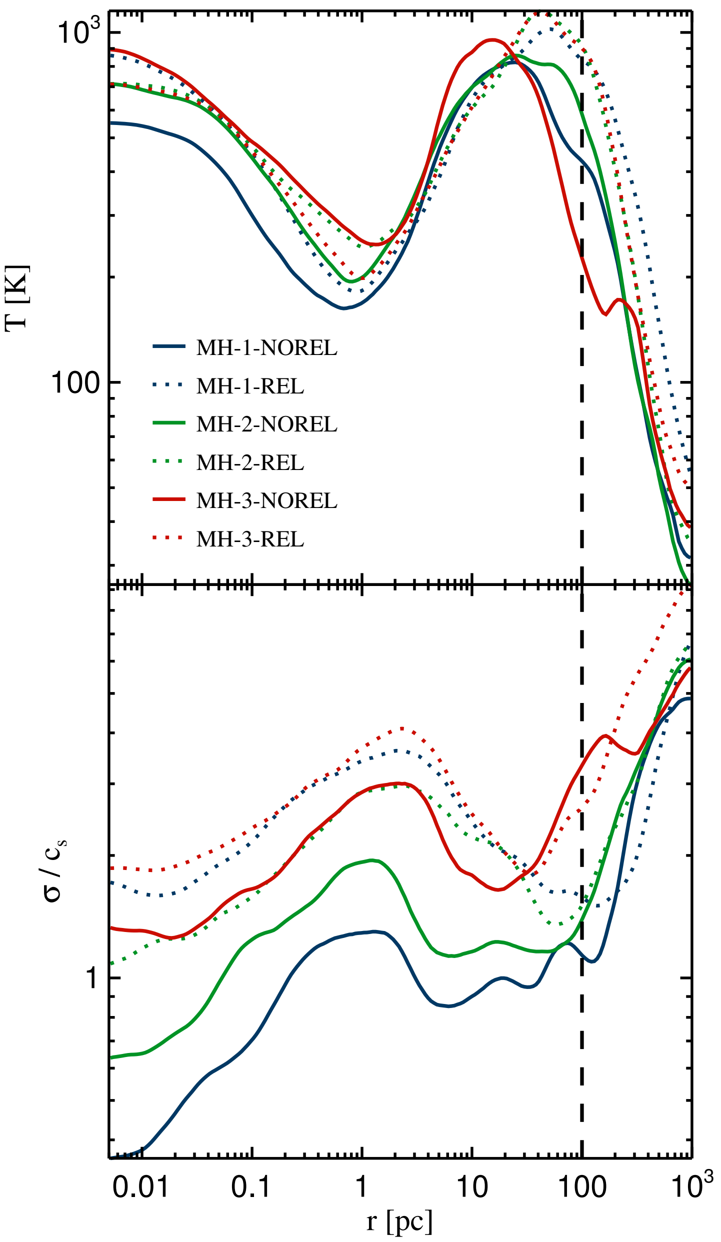


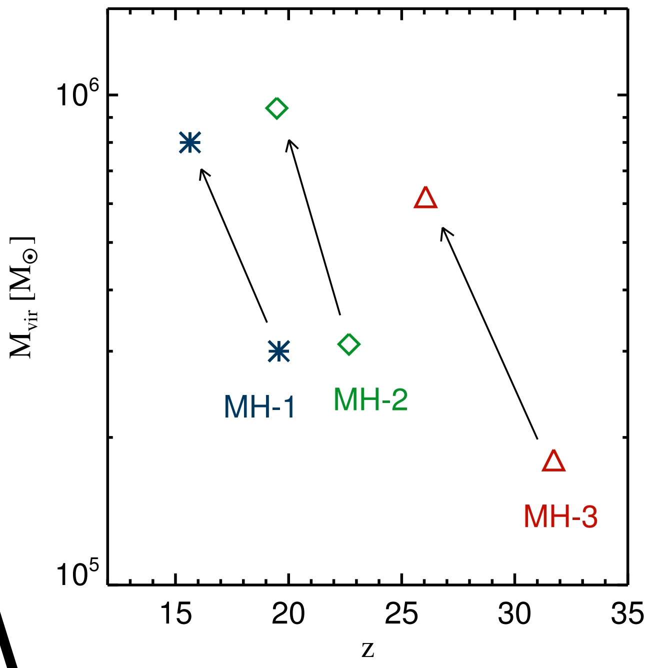
no streaming velocity

with $v_{\rm stream}$ at same time

with $v_{\rm stream}$ at same $\rho_{\rm max}$

(Greif et al. 2011a, ApJ, in press, arXiv:1101.5493)





delayed collapse because of

larger temperature at virial radius and

larger velocity dispersion

(Greif et al. 2011a, ApJ, in press, arXiv:1101.5493)

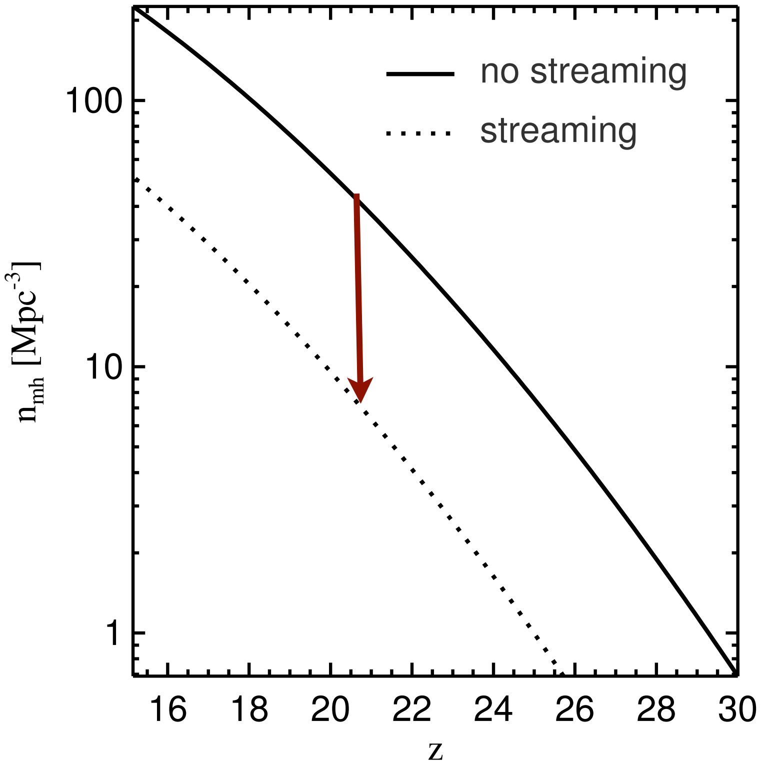


Figure 5. The comoving number density of minihalos that are expected to cool and form Pop III stars for no streaming velocity (solid line), and for an initial streaming velocity of $3\,\mathrm{km\,s^{-1}}$ at $z = 99$ (dotted line). The factor of $\simeq 3$ increase in minimum virial mass leads to a reduction of the number of star-forming minihalos by up to an order of magnitude. The influence of Pop III stars on observables such as the 21 cm background or the reionization of the universe might therefore be substantially reduced.

RESULT:

number of star forming minihalos at any redshift ***decreases*** by roughly ***factor of 10***

stronger turbulence should lead to ***higher degree of fragmentation***

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

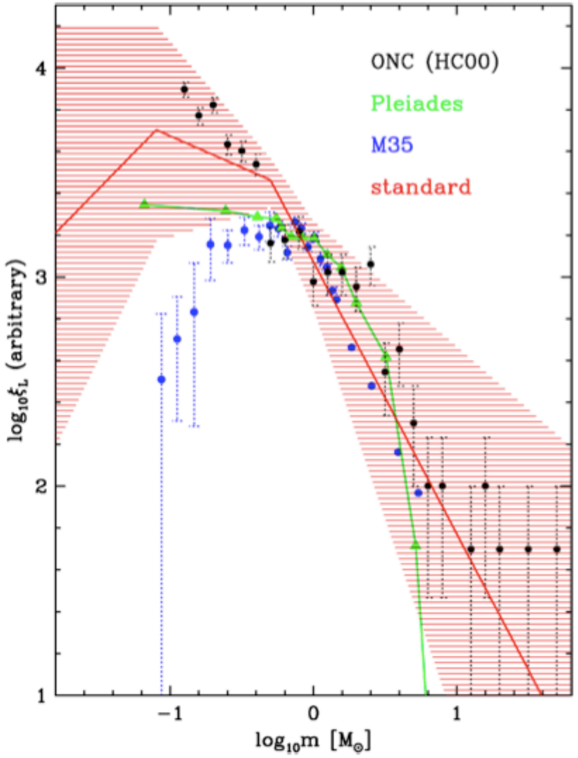
(Greif et al. 2011a, ApJ, in press, arXiv:1101.5493)

Effects of feedback: high-mass star formation at present day

- what is the role of feedback?
    - can non-ionizing radiation heat the gas and prevent fragmentation?
      →*ANSWER: to some degree yes, but not strong effect!*
    - can ionizing radiation stop mass accretion?
      →*ANSWER: probably no, as indicated by simulations*
- what determines the final mass of a star?
    - dynamical processes! (fragmentation-induced starvation, see Peters et al. 2010abc,2011)

We want to address the following questions:

- how do massive stars (and their associated clusters) form?
- what determines the upper stellar mass limit?
- what is the physics behind observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

our (numerical) approach

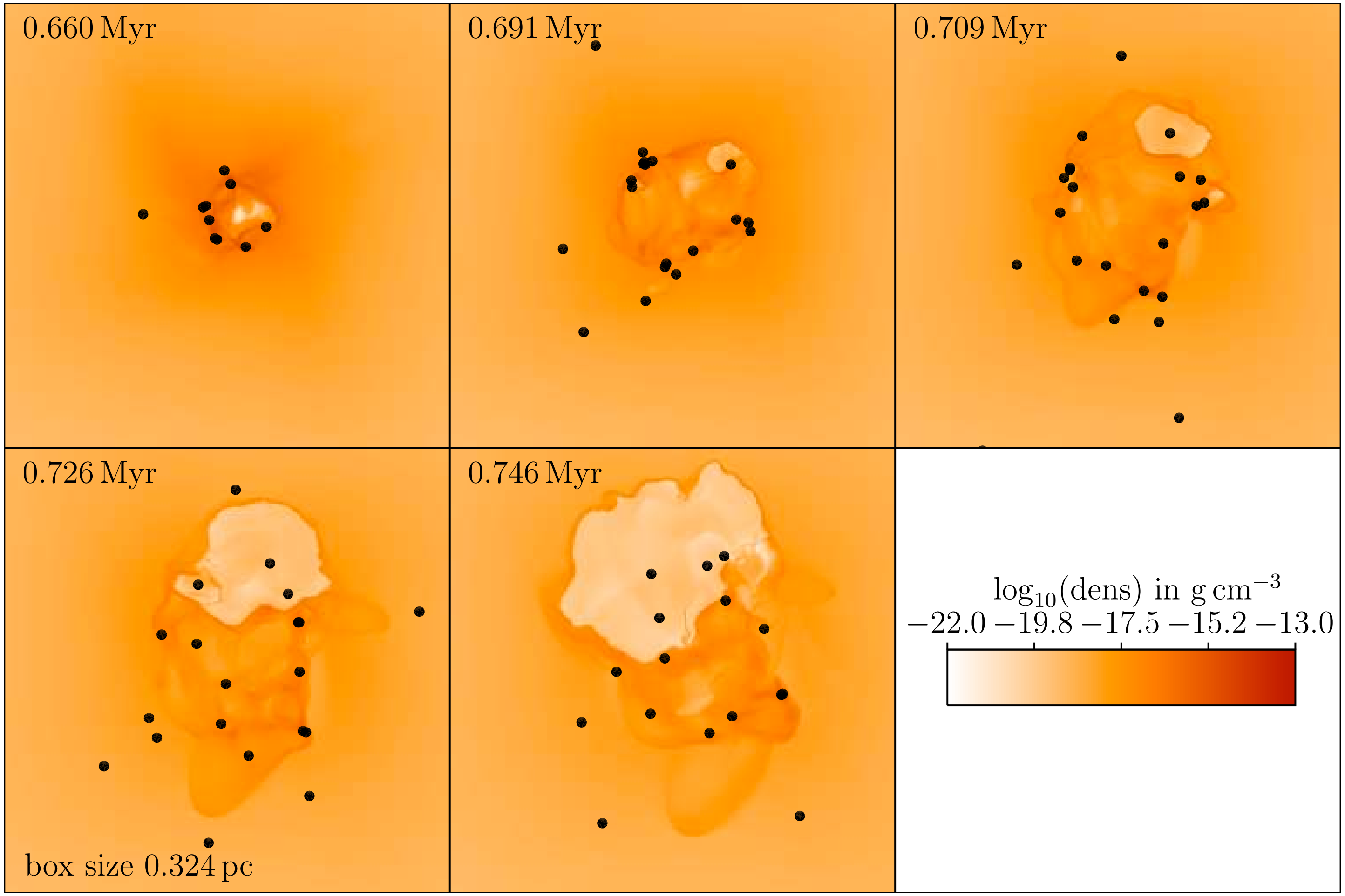
- focus on collapse of individual high-mass cores...
  - massive core with 1,000 $M_\odot$
  - Bonnor-Ebert type density profile
    (flat inner core with 0.5 pc and rho ~ $r^{-3/2}$ further out)
  - initial m=2 perturbation, rotation with $\beta = 0.05$
  - sink particle with radius 600 AU and threshold density of 7×10^{-16} g cm^{-3}
  - cell size 100 AU

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)

our (numerical) approach

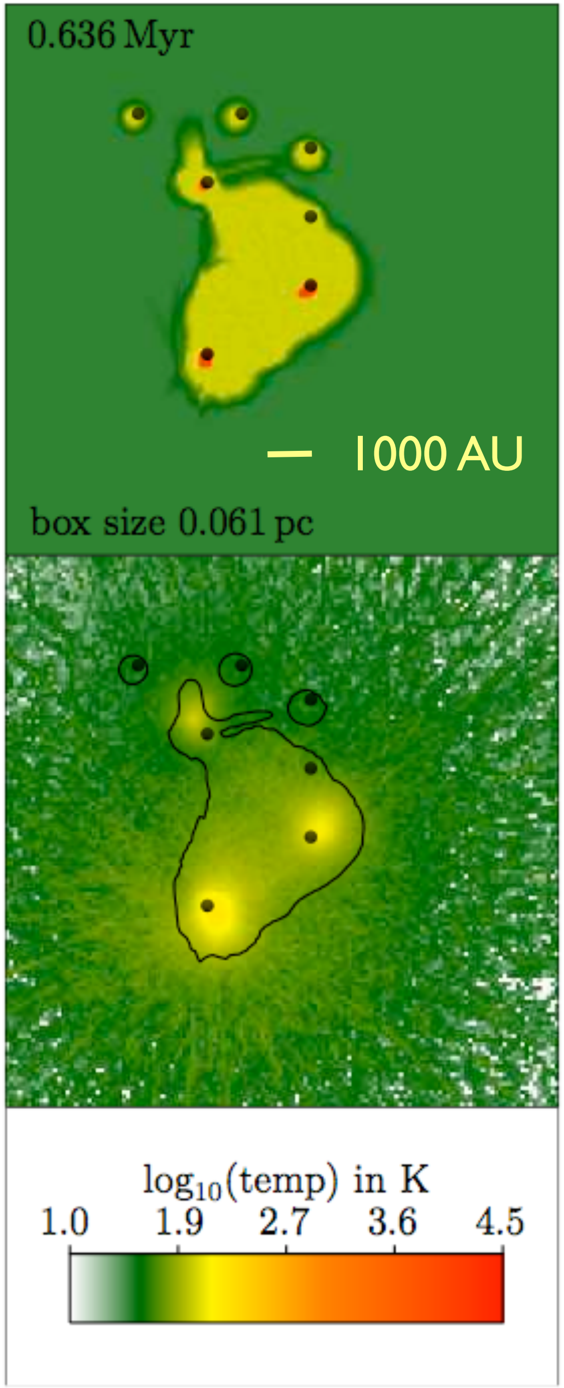
- method:
  - FLASH with ionizing and non-ionizing radiation using raytracing based on hybrid-characteristics
  - protostellar model from Hosokawa & Omukai
  - rate equation for ionization fraction
  - relevant heating and cooling processes
  - some models include magnetic fields
  - *first 3D MHD calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation*

Peters et al. (2010a,b,c)



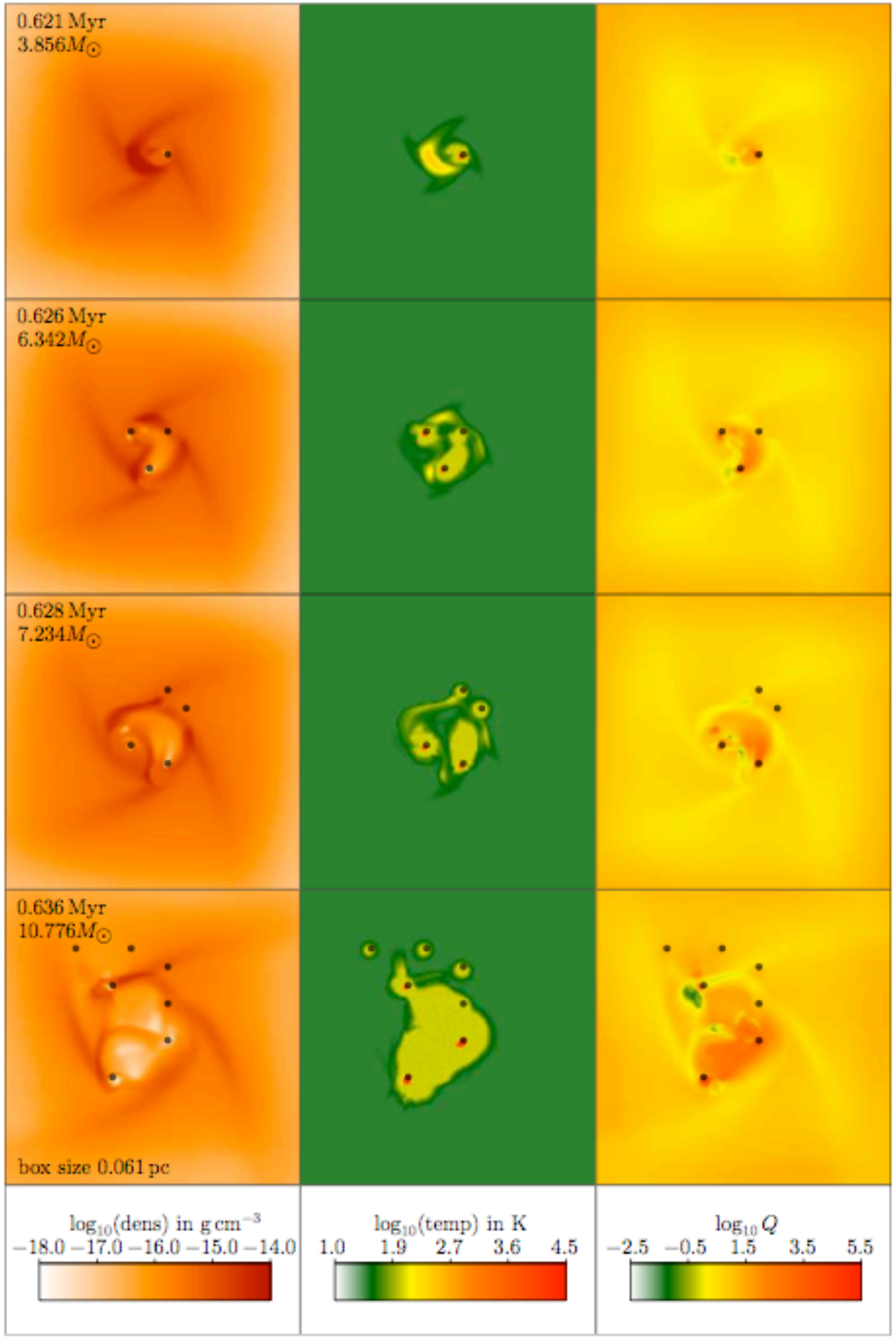
- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows “fragmentation-induced starvation”
- halting of accretion flow allows bubble to expand

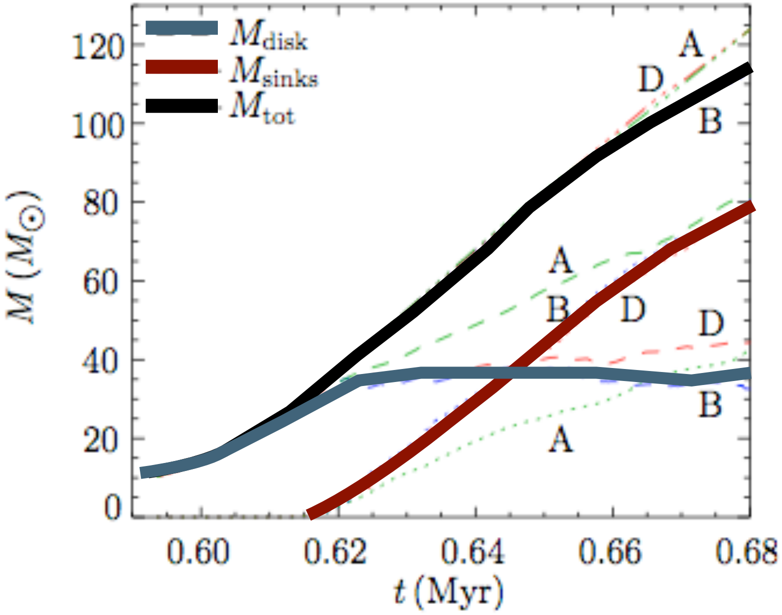
Peters et al. (2010a,b,c)



ray tracing method
(hydrid characteristics)

Monte Carlo: full RT
(with scattered radiation)



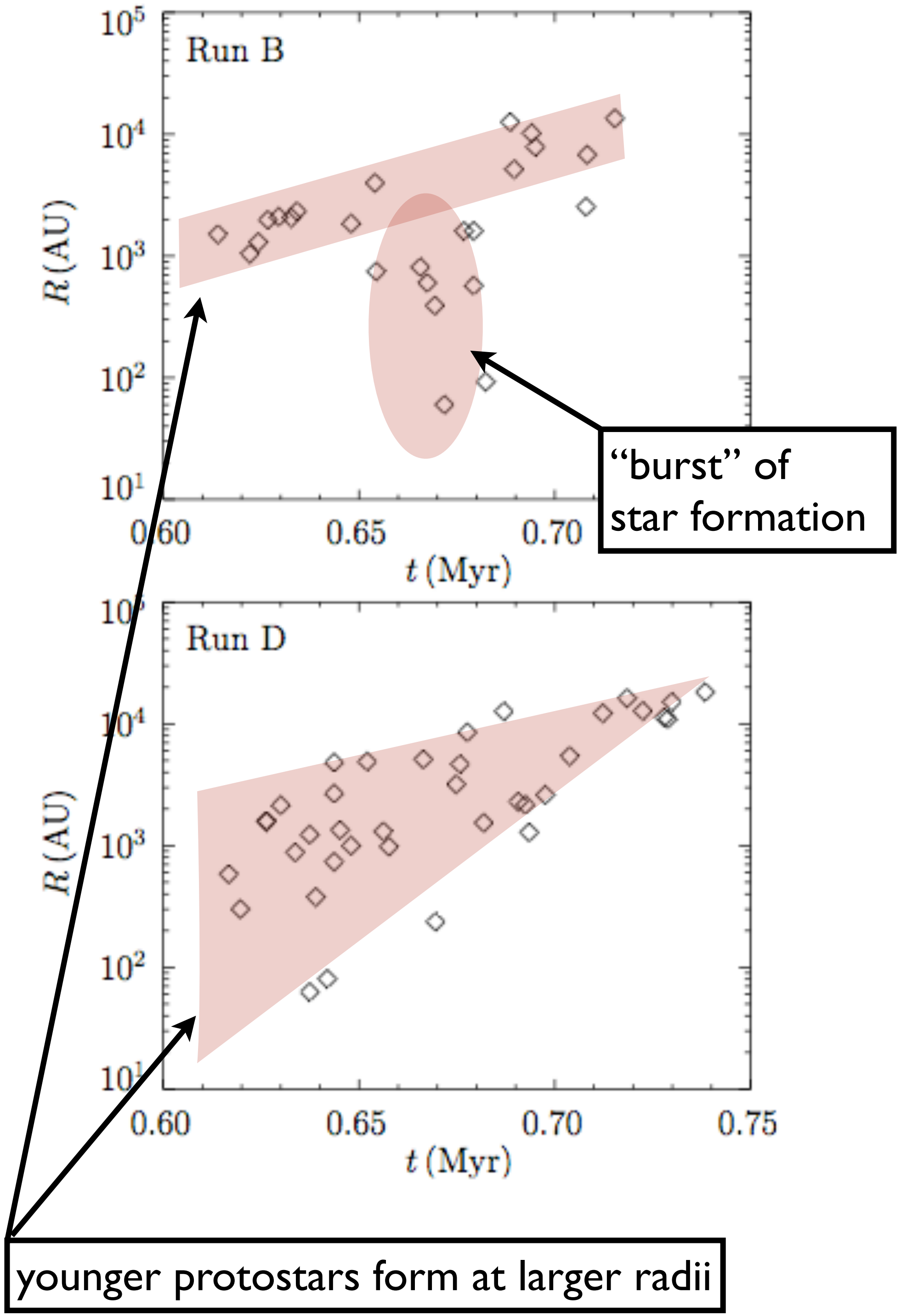


mass load onto the disk exceeds inward transport

--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

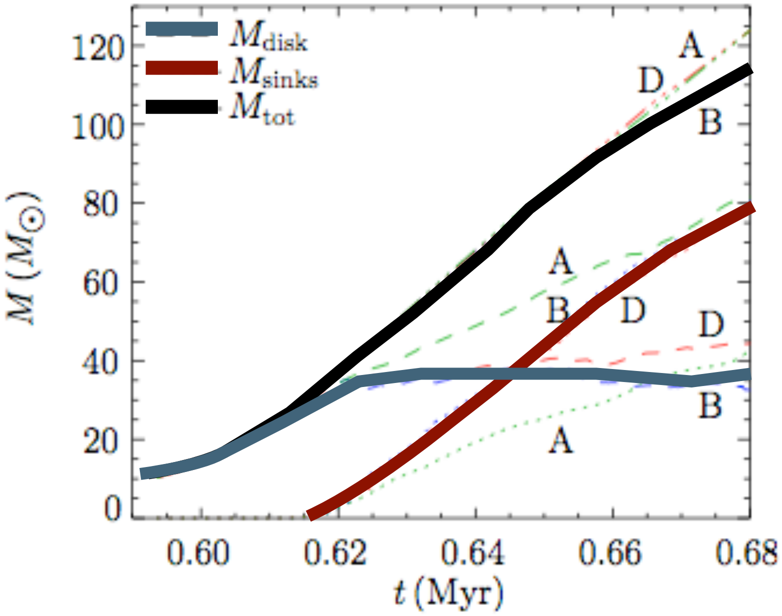
fragments to form multiple stars --> explains why high-mass stars are seen in clusters

Peters et al. (2010a, ApJ, 711, 1017),
Peters et al. (2010b, ApJ, 719, 831),
Peters et al. (2010c, ApJ, 725, 134)



"burst" of star formation

younger protostars form at larger radii



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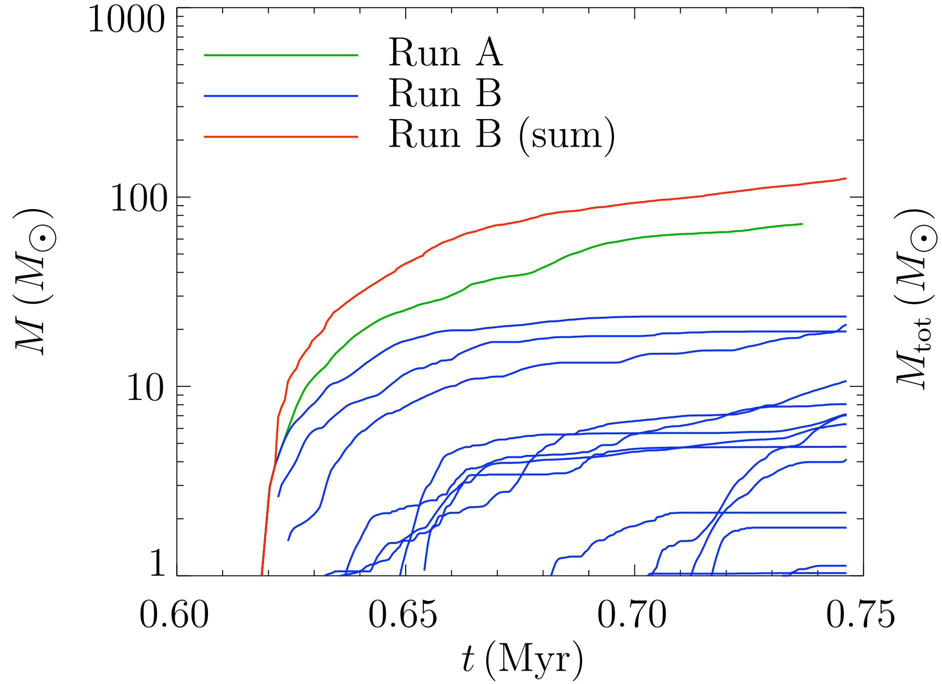
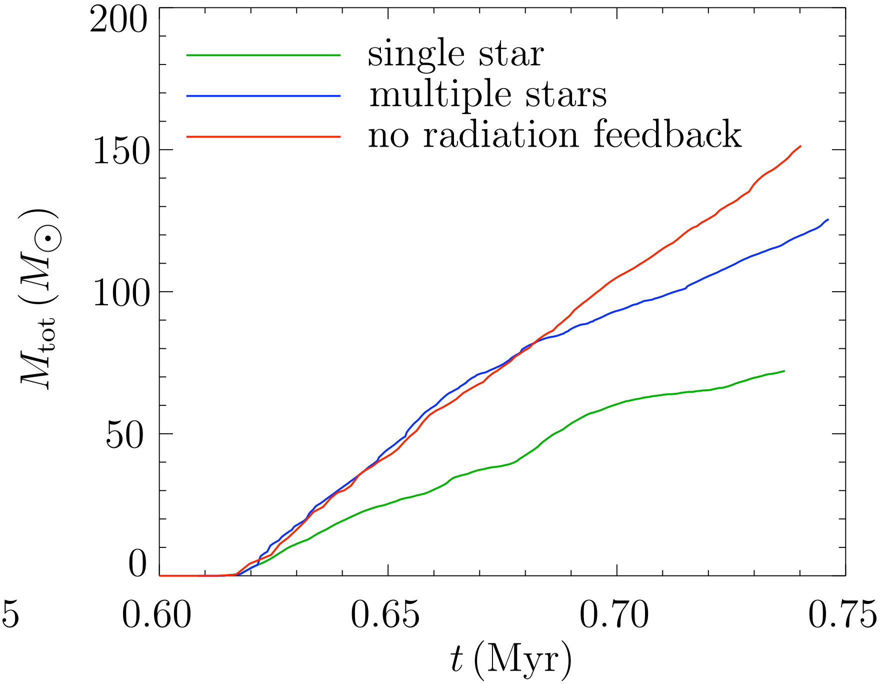
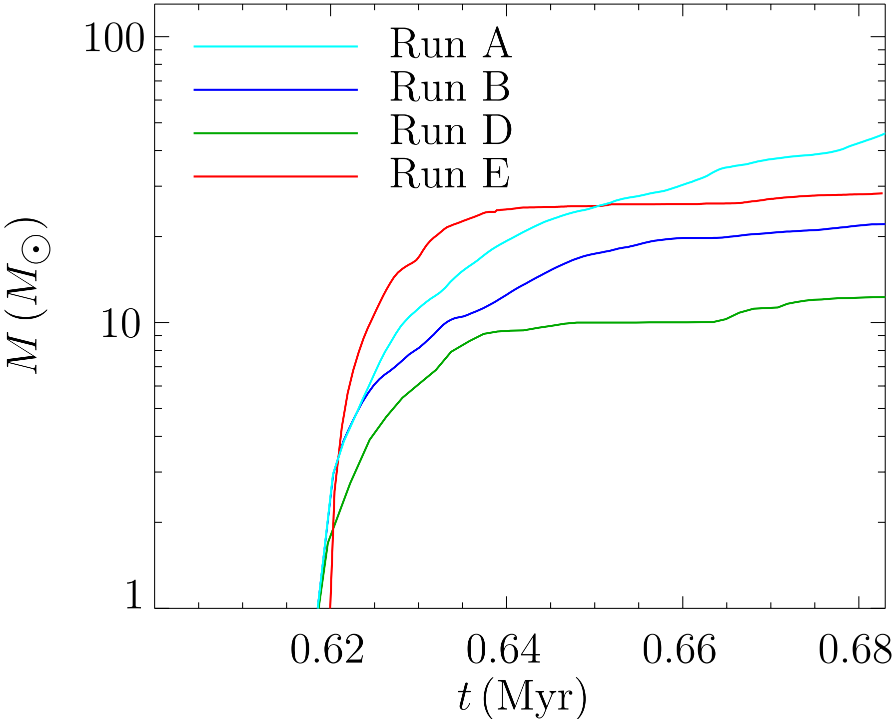
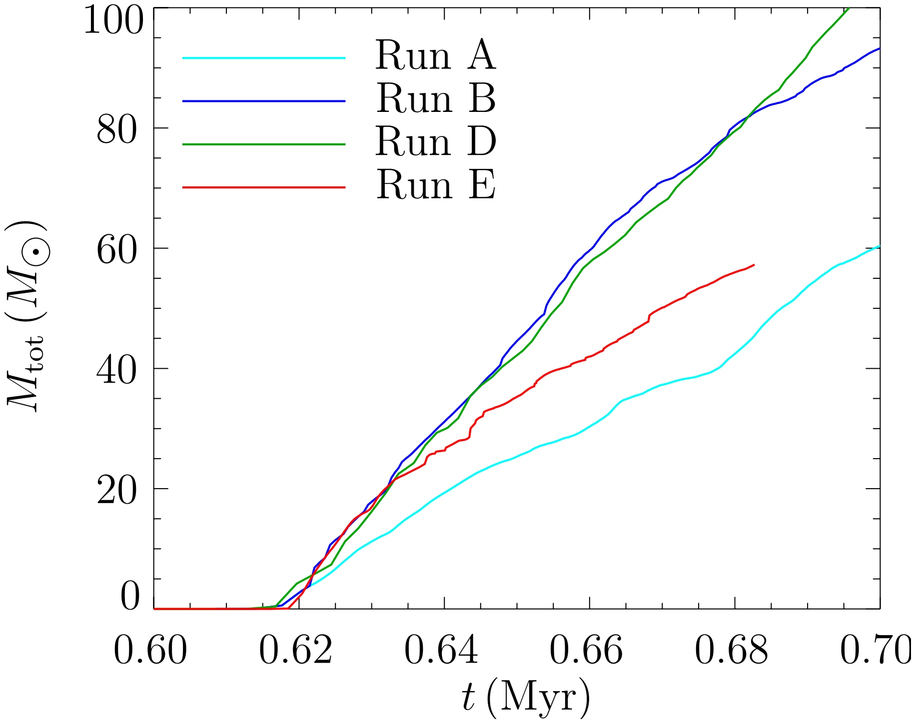




- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)

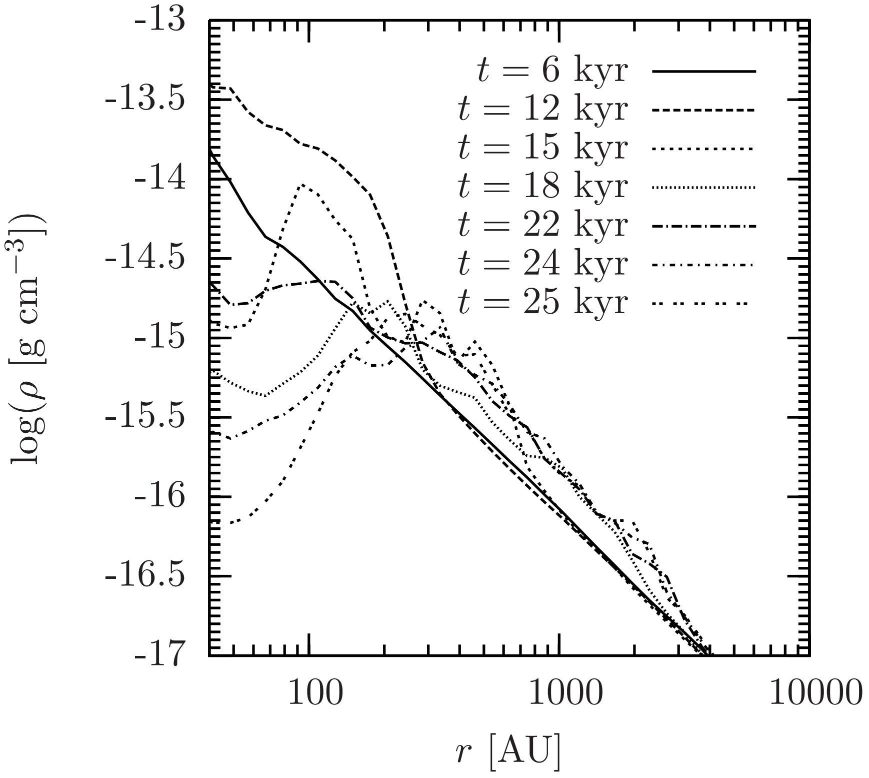




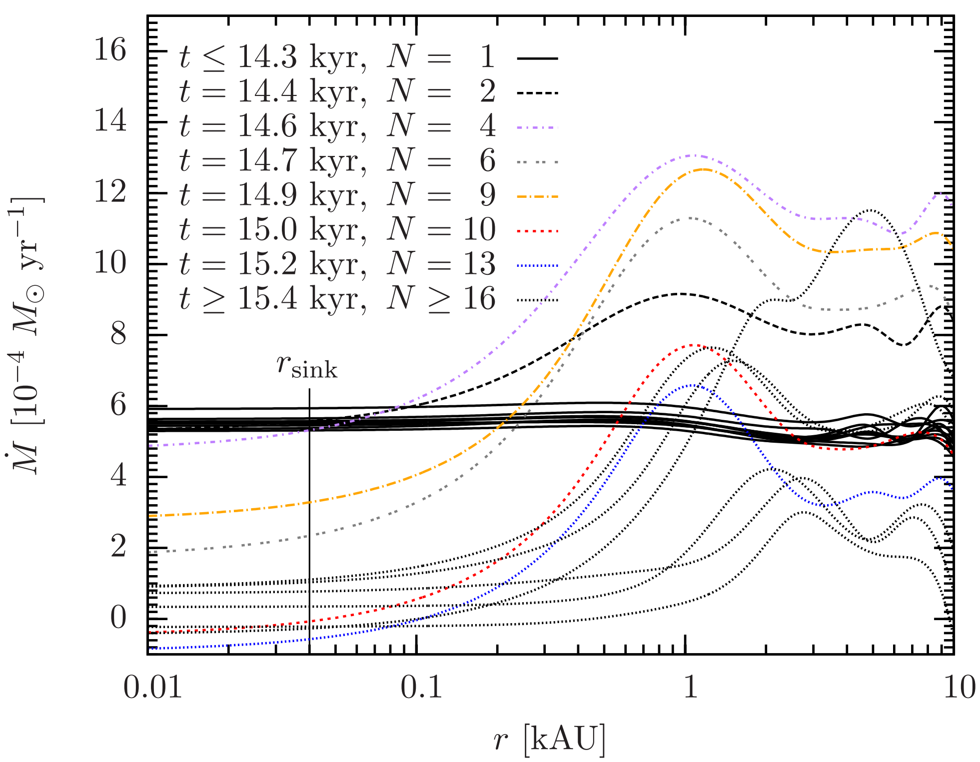
- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134), Peters et al. (2011, ApJ, 729, 72

Fragmentation-induced starvation in a complex cluster



gas density as function of radius at different times



mass flow towards the center as function of radius at different times

Girichidis et al. (2011a,b)

questions

- stellar masses strongly influenced by dynamics:
  fragmentation-induced starvation
- process depends on initial conditions:
  what are those for primordial halos? not only look at first halo but at 10th, 20th, etc.
- at present days, feedback cannot stop accretion:
  what about Pop III stars? *(Hosokawa et al. 2011)*

conclusions

- primordial star formation exhibits the *same complexity* as stellar birth at present days
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

} all influence Pop III and Pop II.5 star formation.

NGC 3324 (Hubble, NASA/ESA)