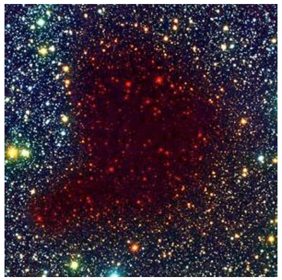
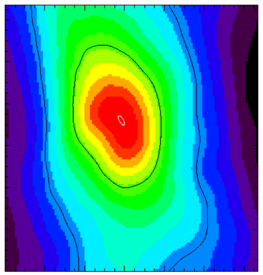
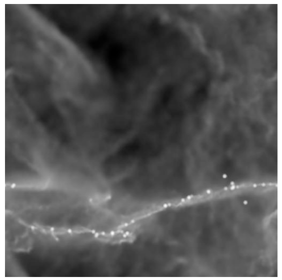
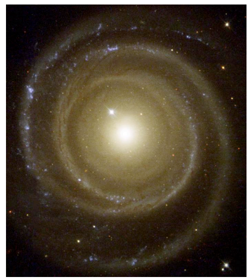
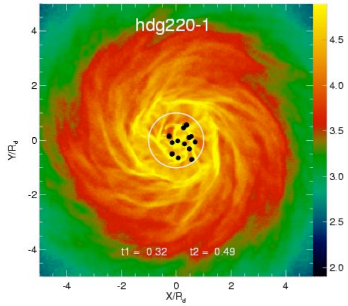
First star formation







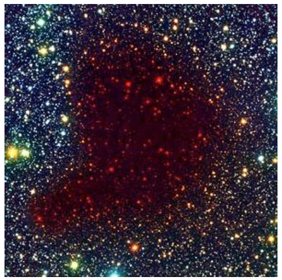
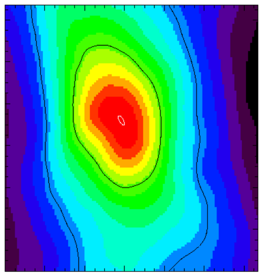


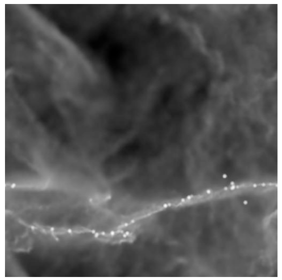


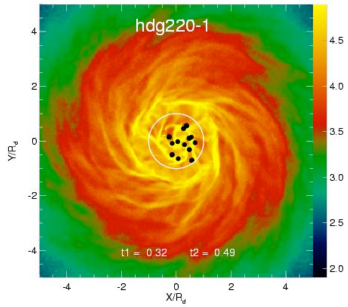
Ralf Klessen

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:

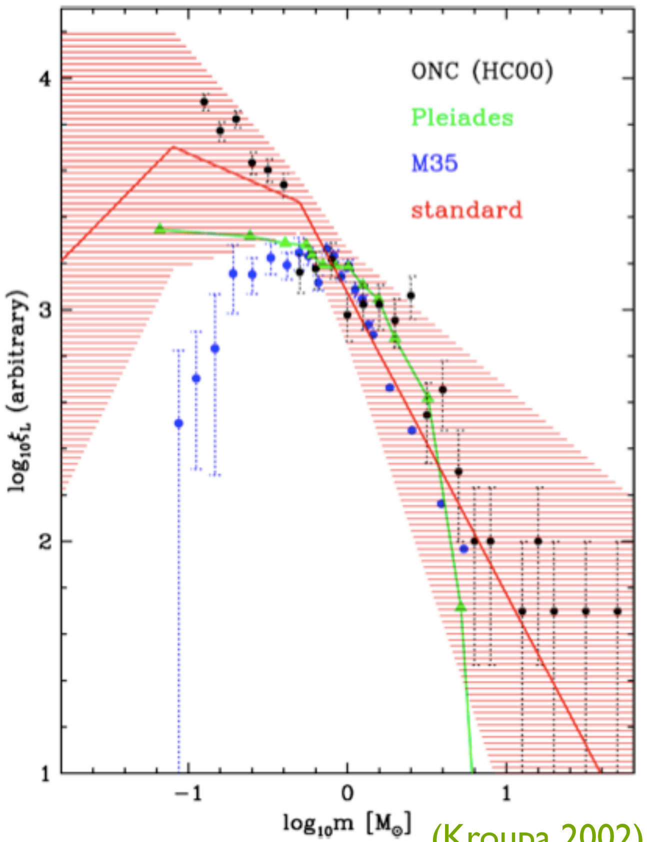
Robi Banerjee, Simon Glover, Rahul Shetty, Sharanya Sur, Daniel Seifried, Milica Milosavljevic, Florian Mandl, Christian Baczynski, Rowan Smith, Gustavo Dopcke, Jonathan Downing, Jayanta Dutta, Faviola Molina, Christoph Federrath, Erik Bertram, Lukas Konstandin, Paul Clark, Stefan Schmeja, Ingo Berentzen,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

... many collaborators abroad!


NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

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



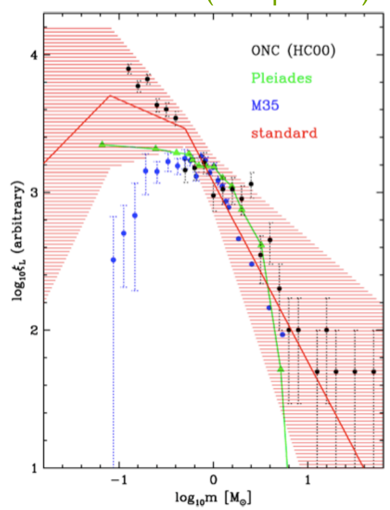
(Kroupa 2002)

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

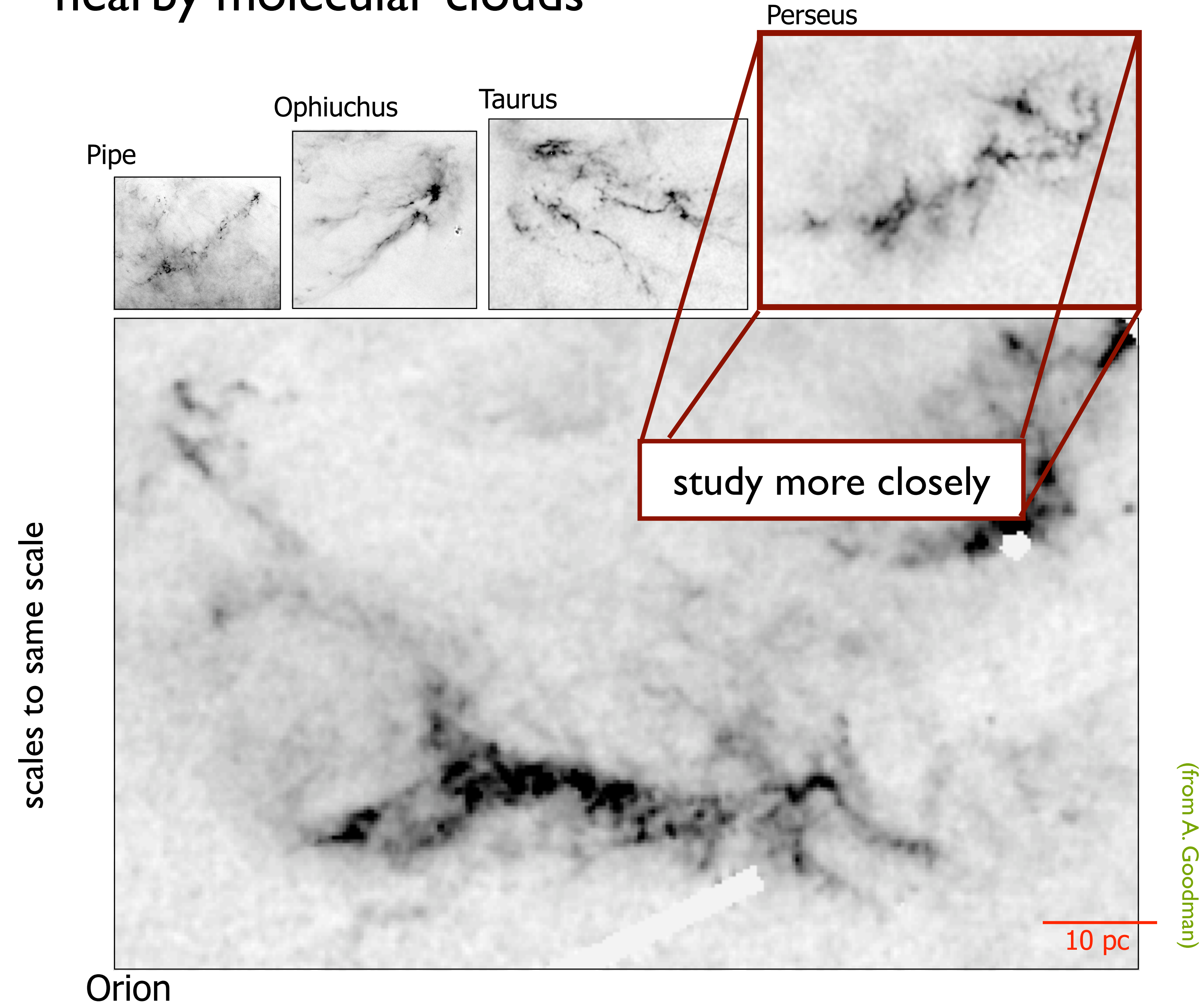
stellar masses

- 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

(Kroupa 2002)



nearby molecular clouds



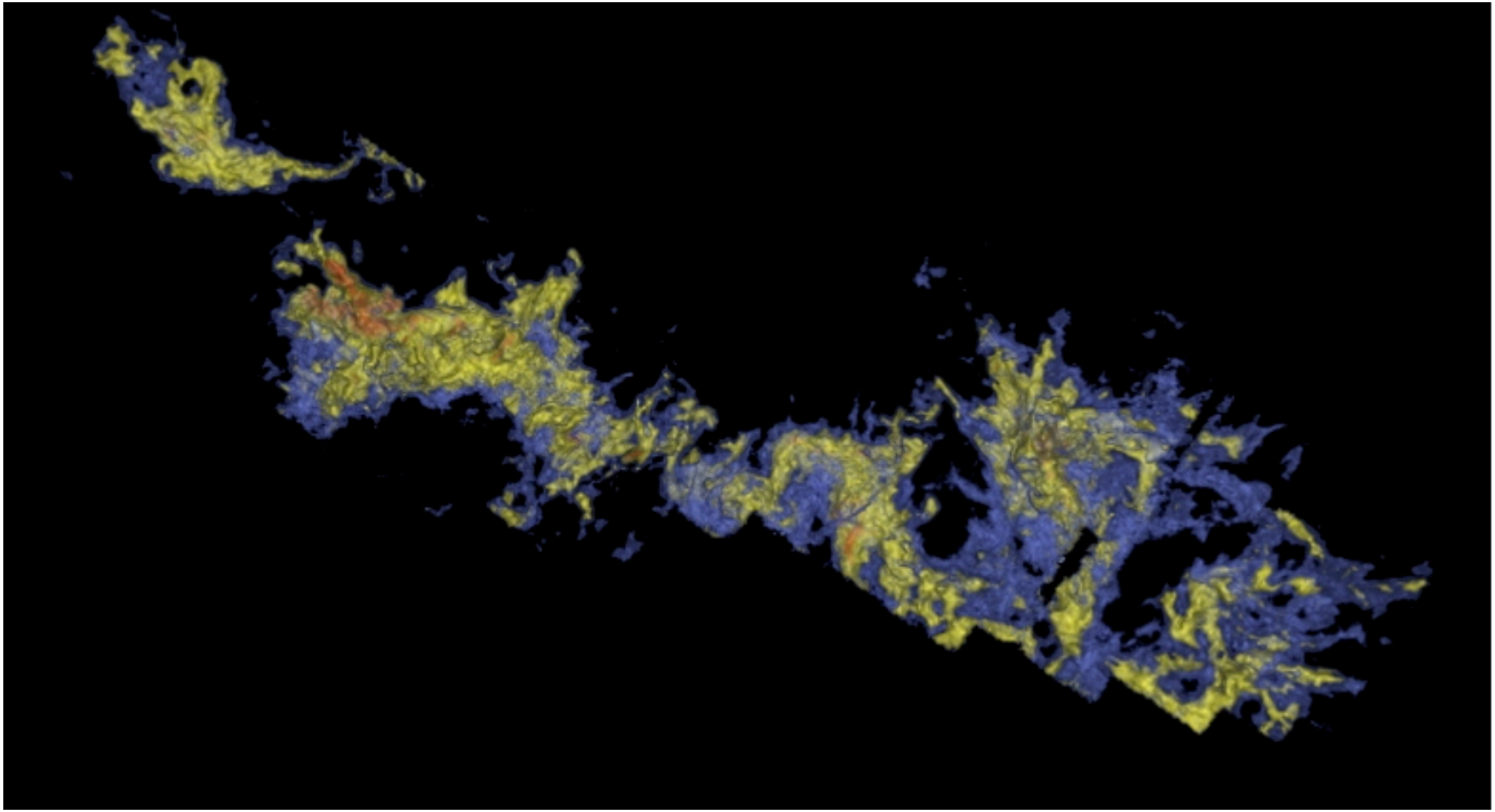
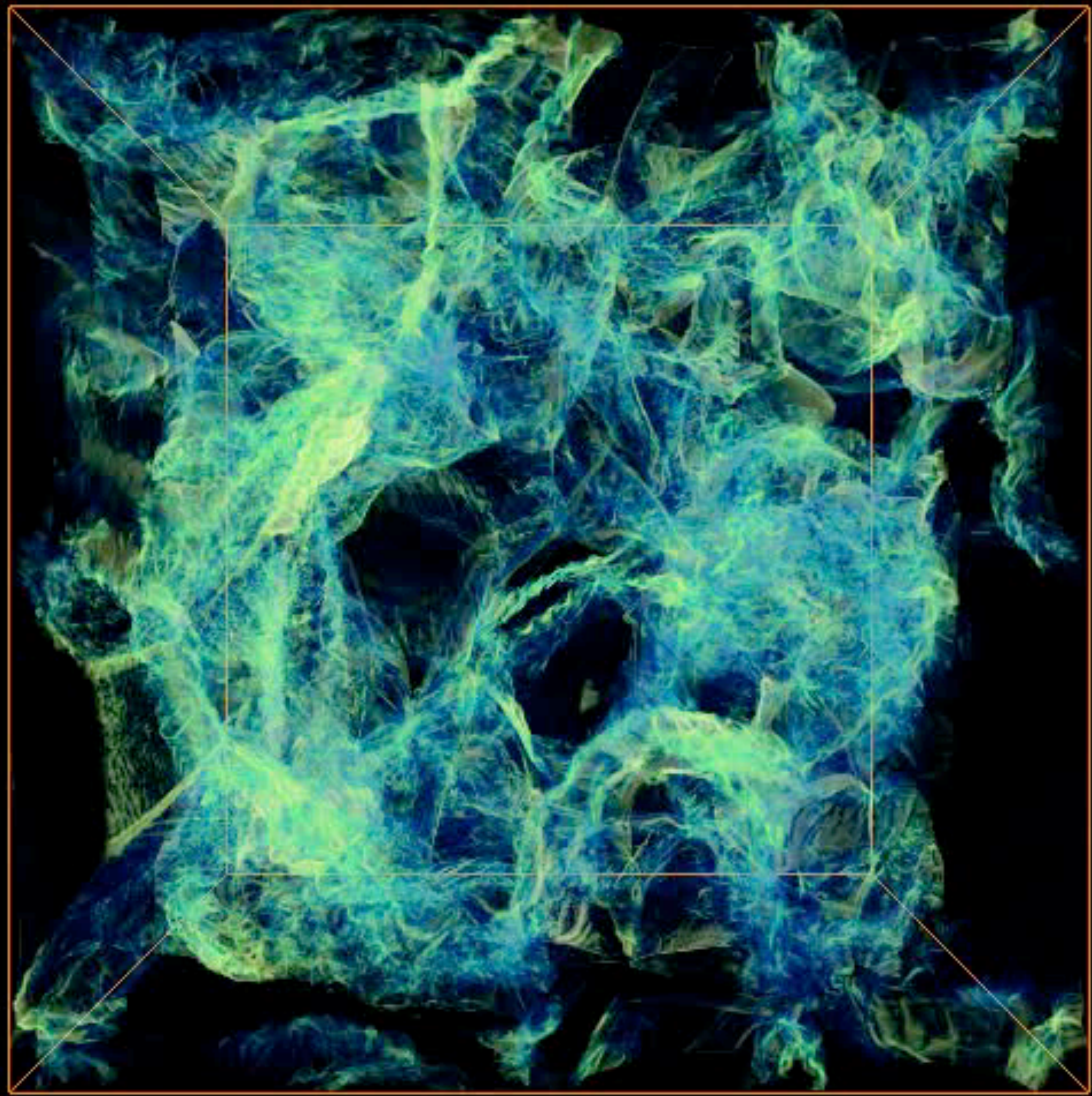


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

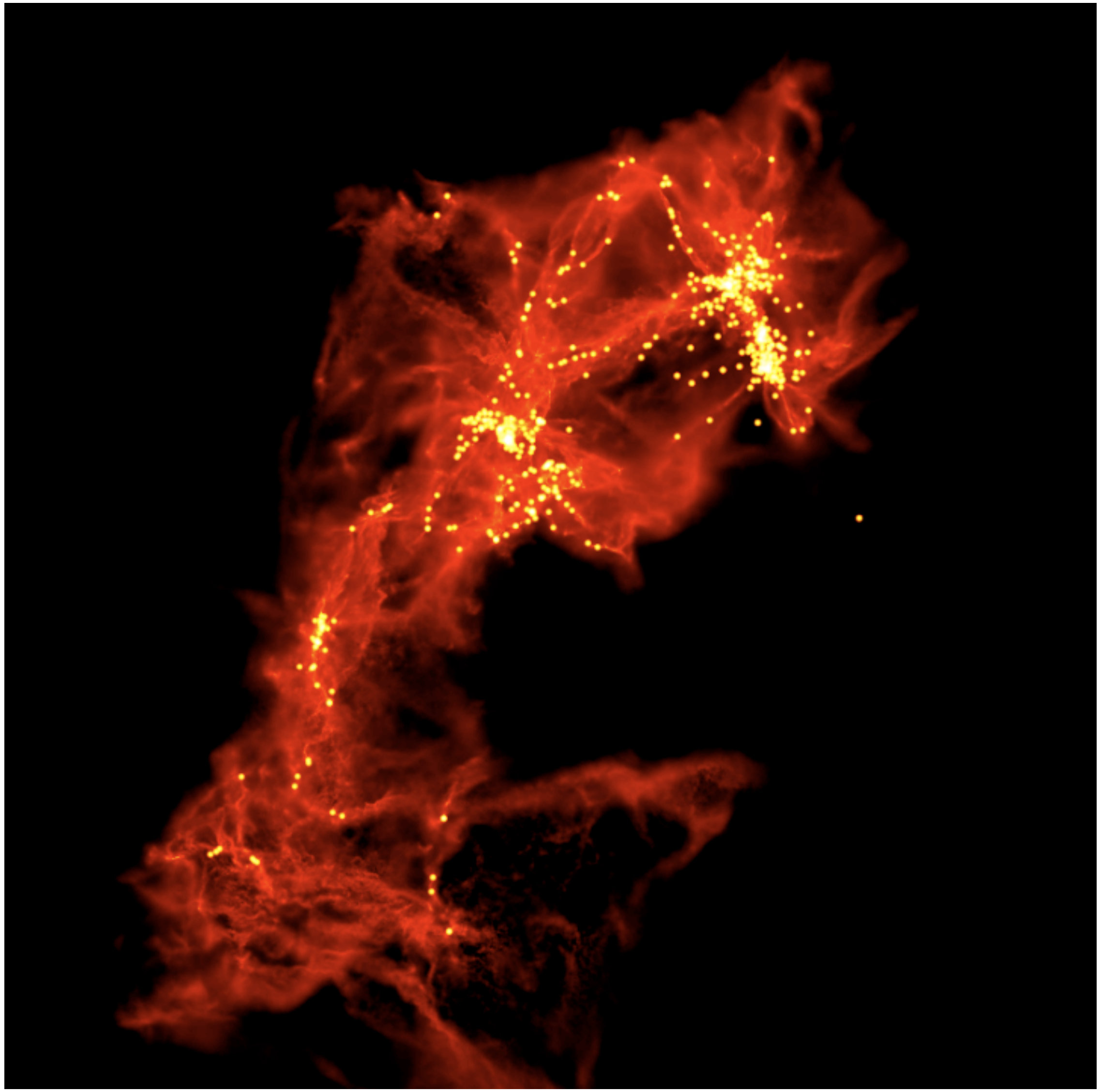
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

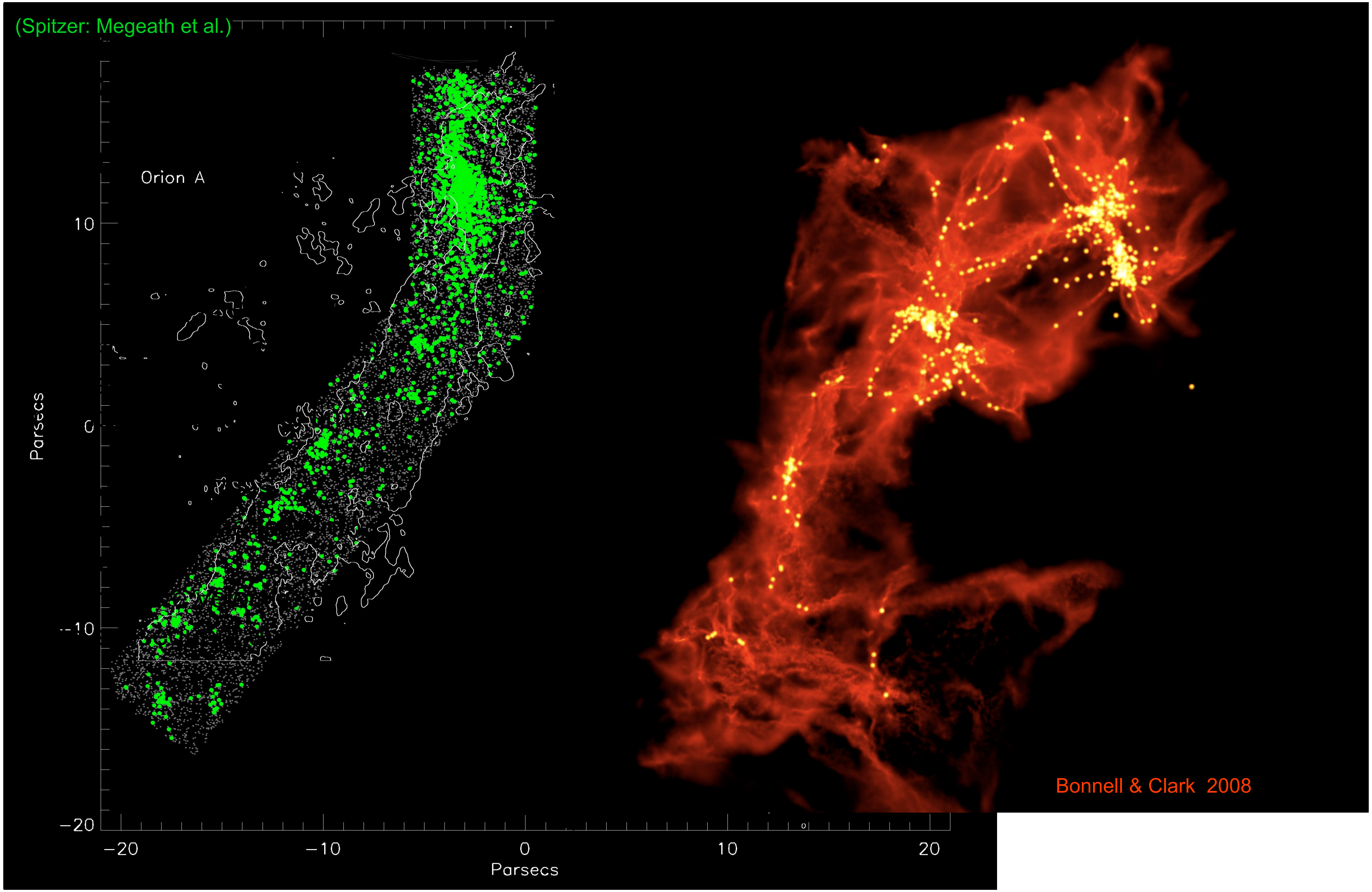
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



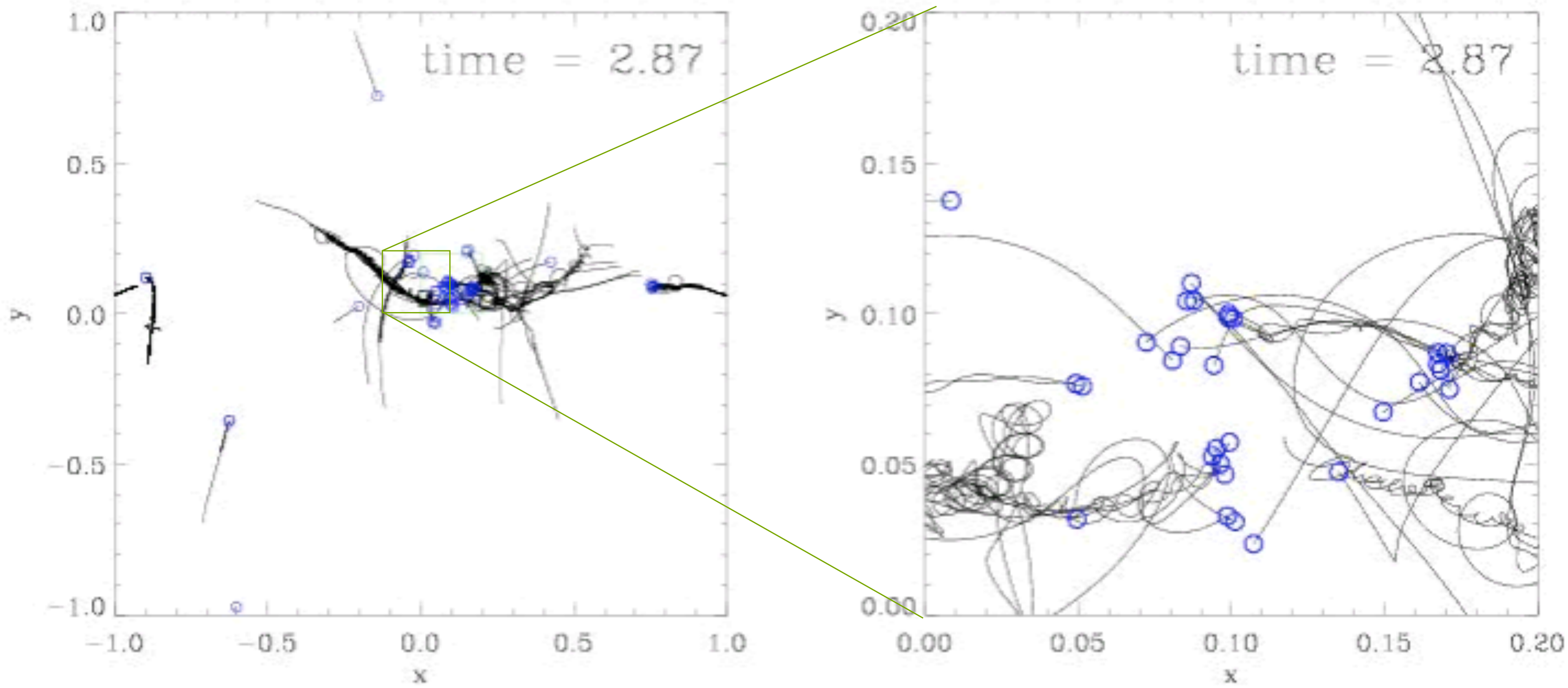
(Bonnell & Clark 2008)

example: model of Orion cloud



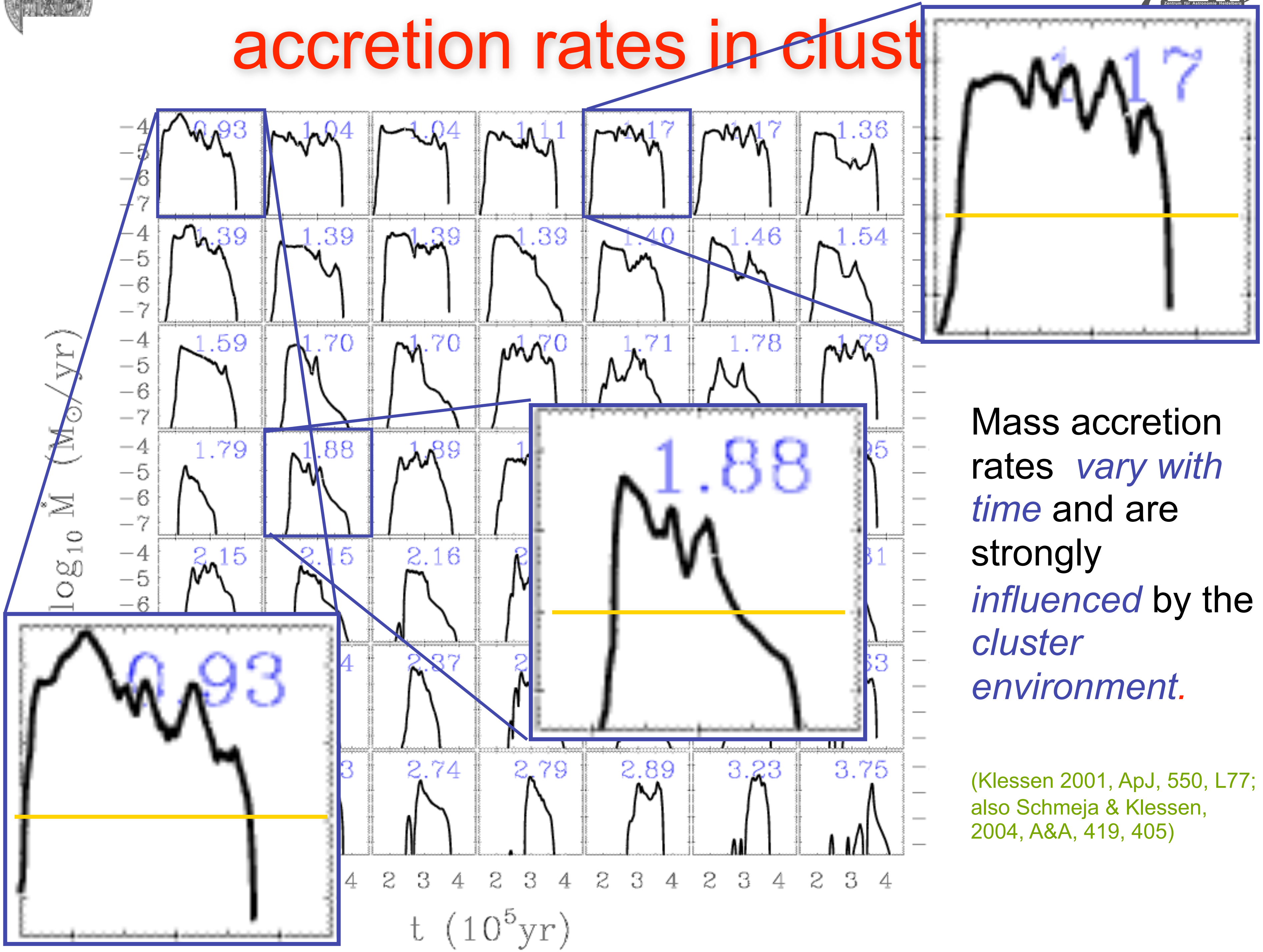
Dynamics of nascent star cluster

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



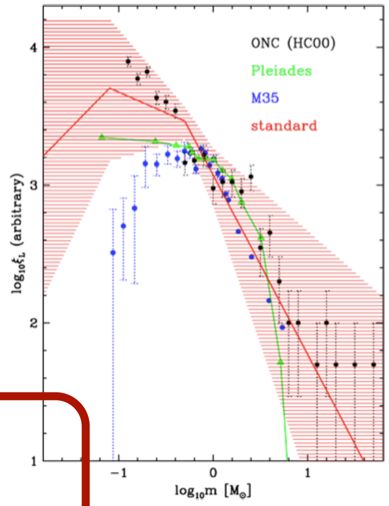
Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

stellar masses

- 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)



application to first star formation

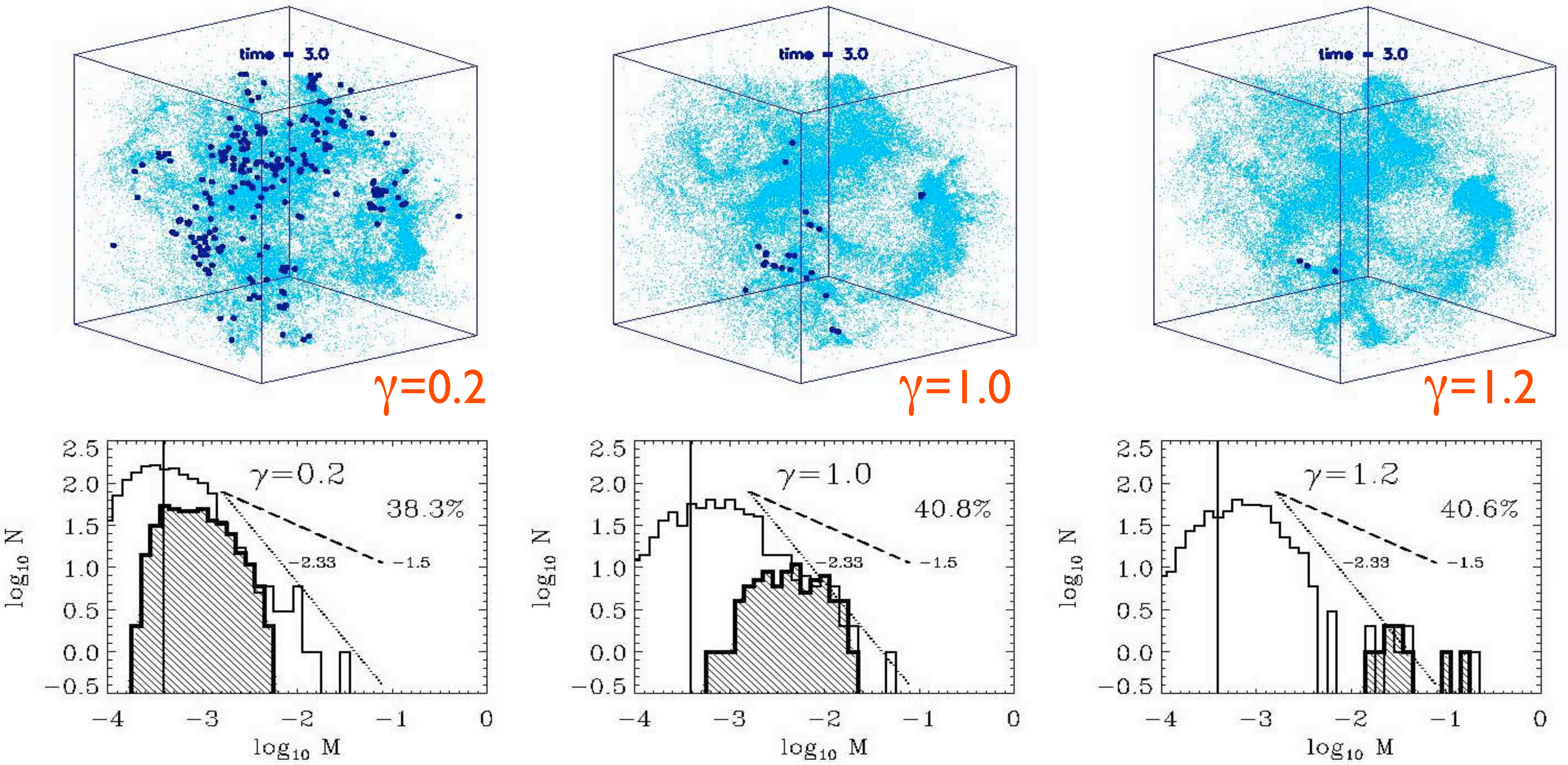
thermodynamics & fragmentation

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*

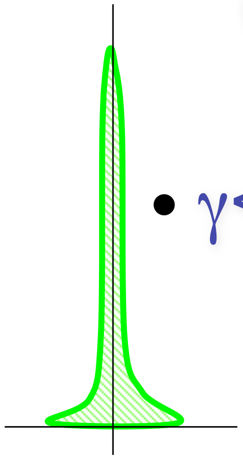
for γ>1 it is suppressed → formation of *isolated massive stars*

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

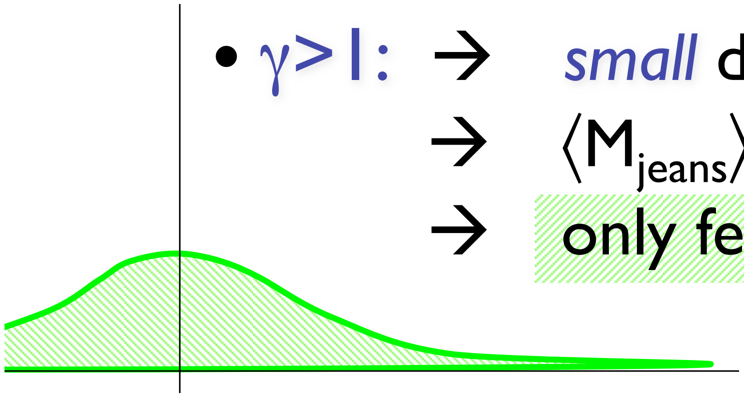
how does that work?

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

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

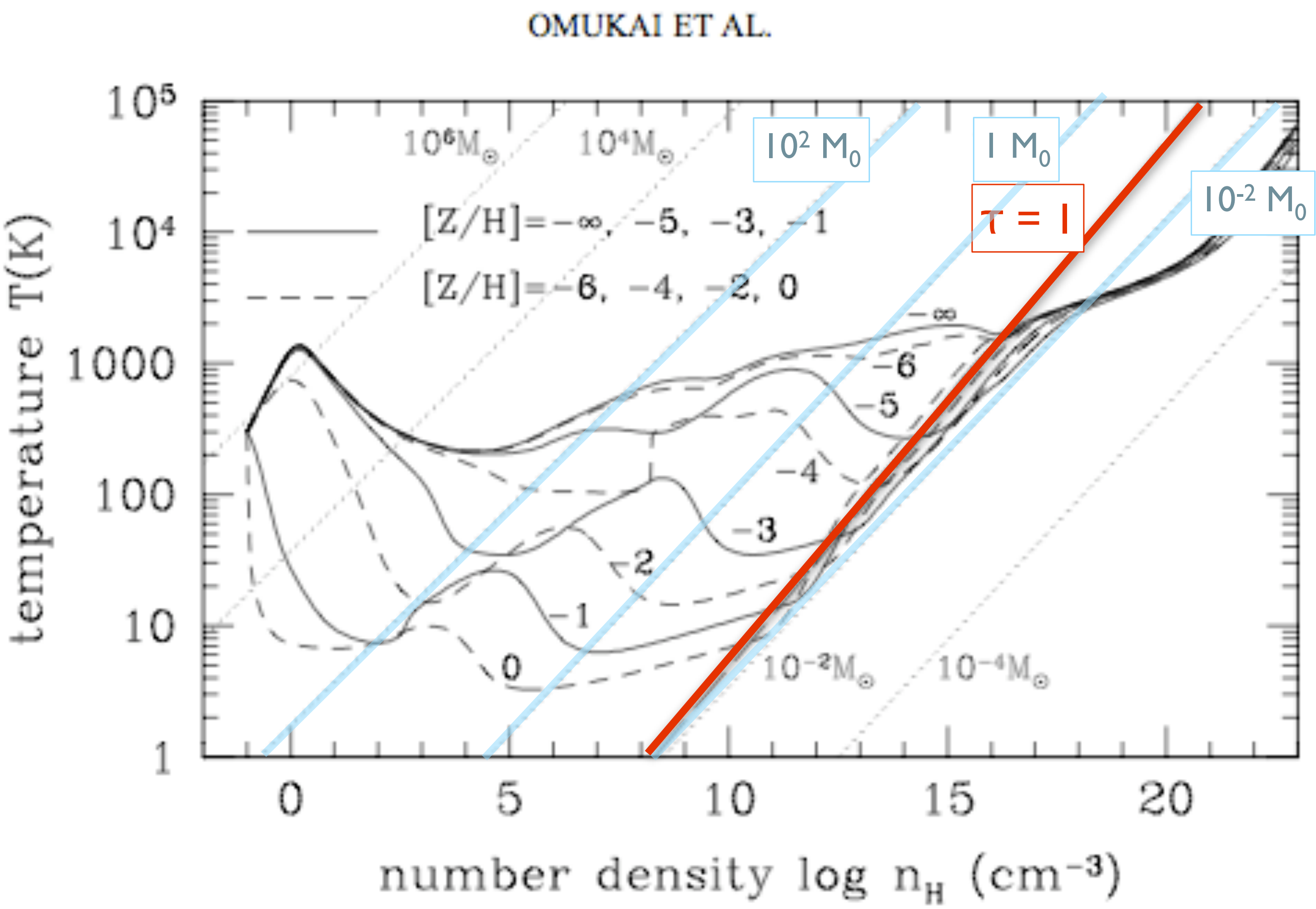


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



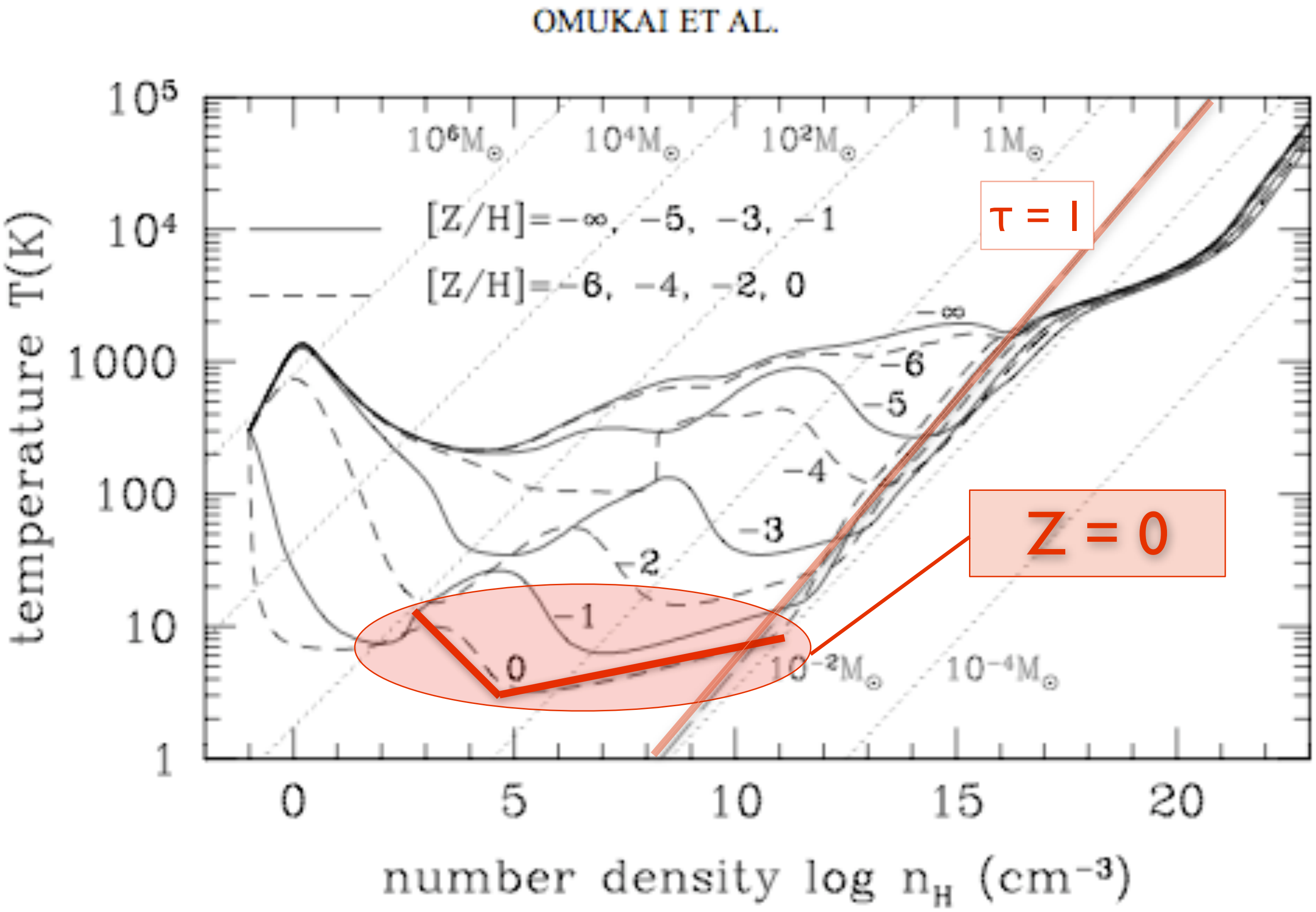
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005)

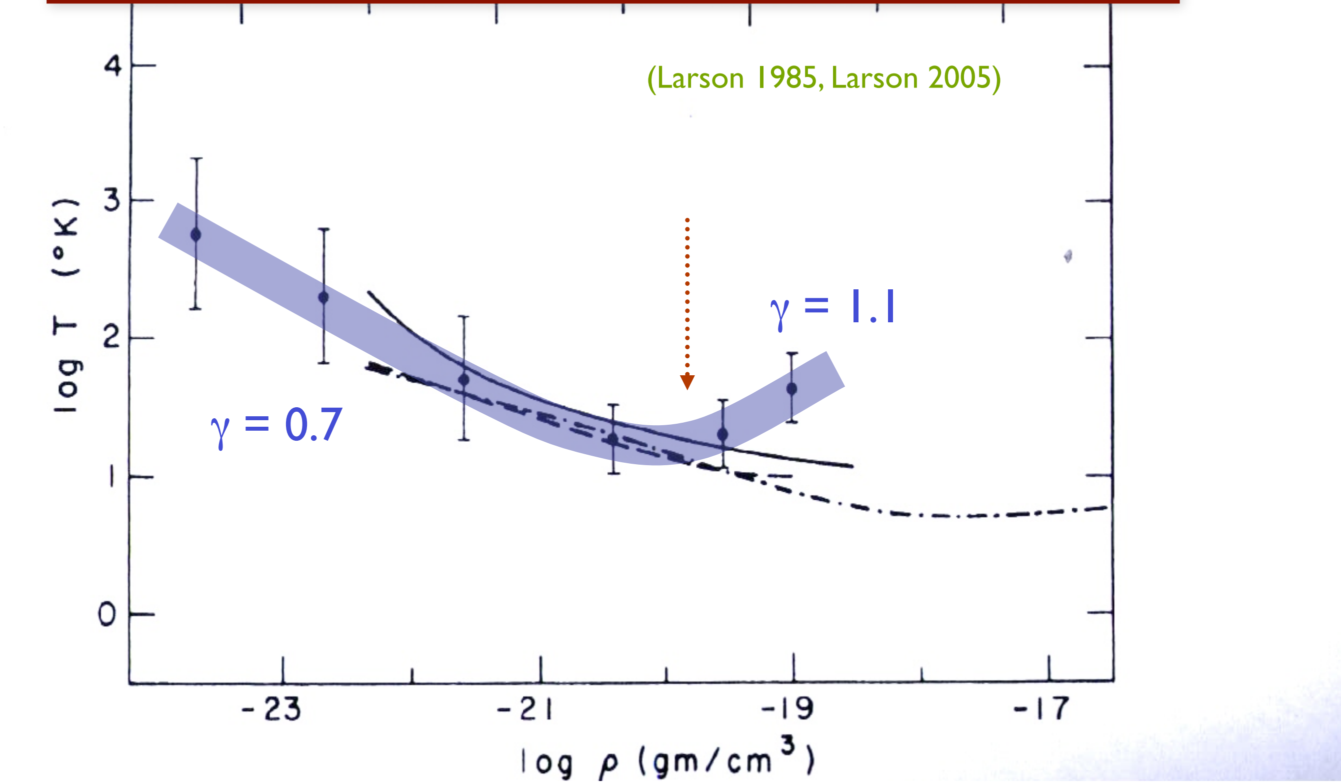
present-day star formation



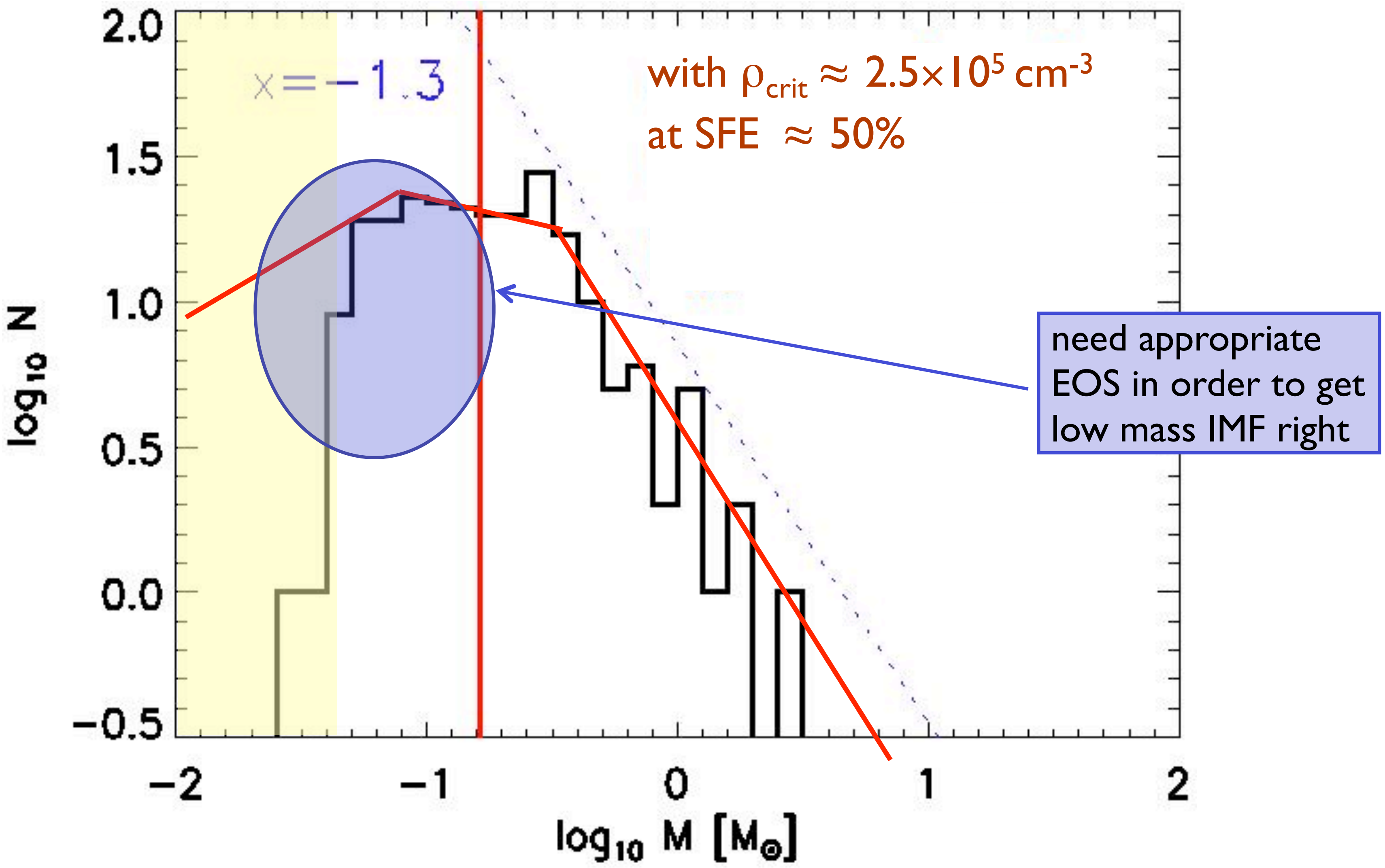
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

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)



IMF in nearby molecular clouds

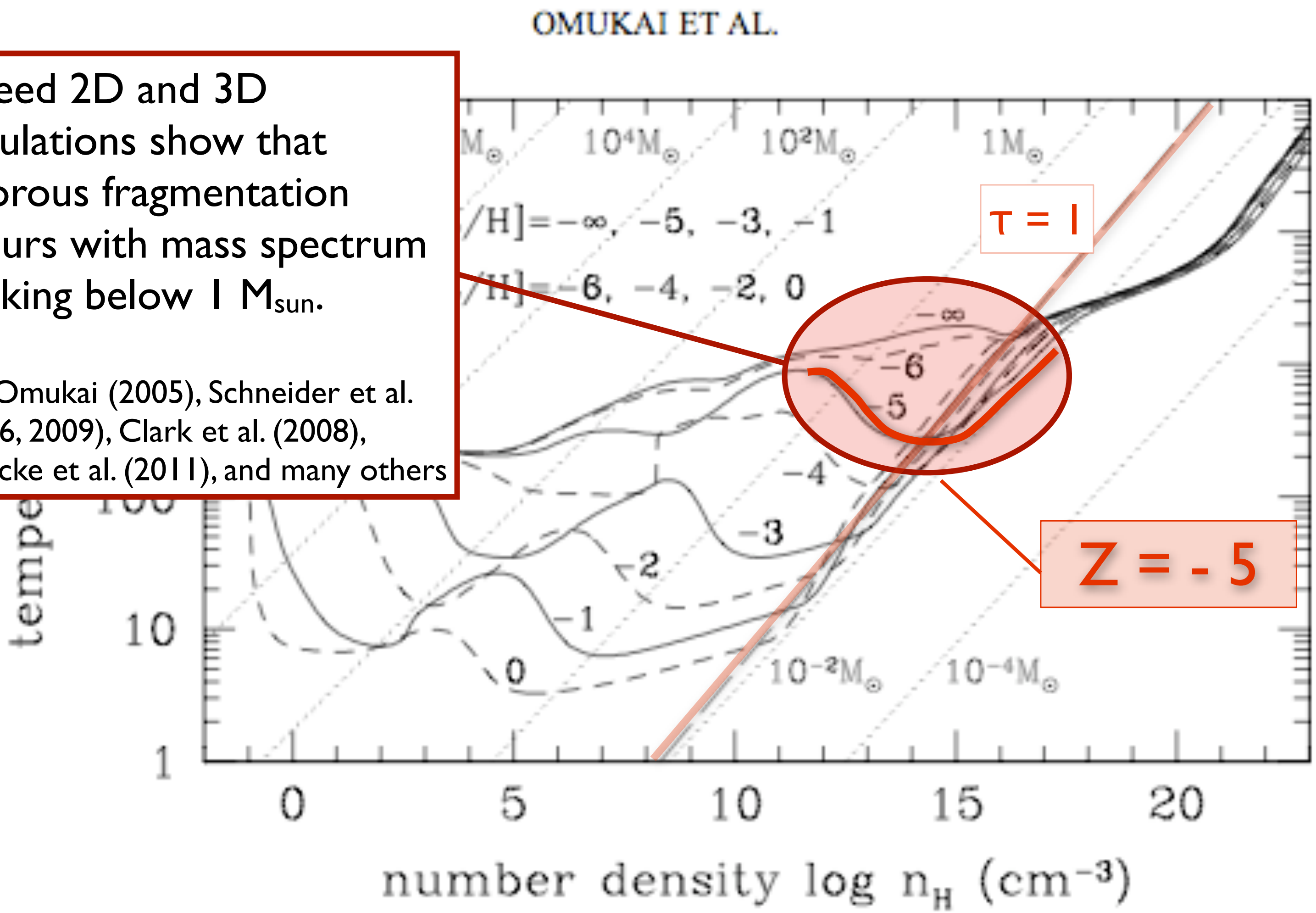


(Jappsen et al. 2005, A&A, 435, 611)

transition: Pop III to Pop II.5

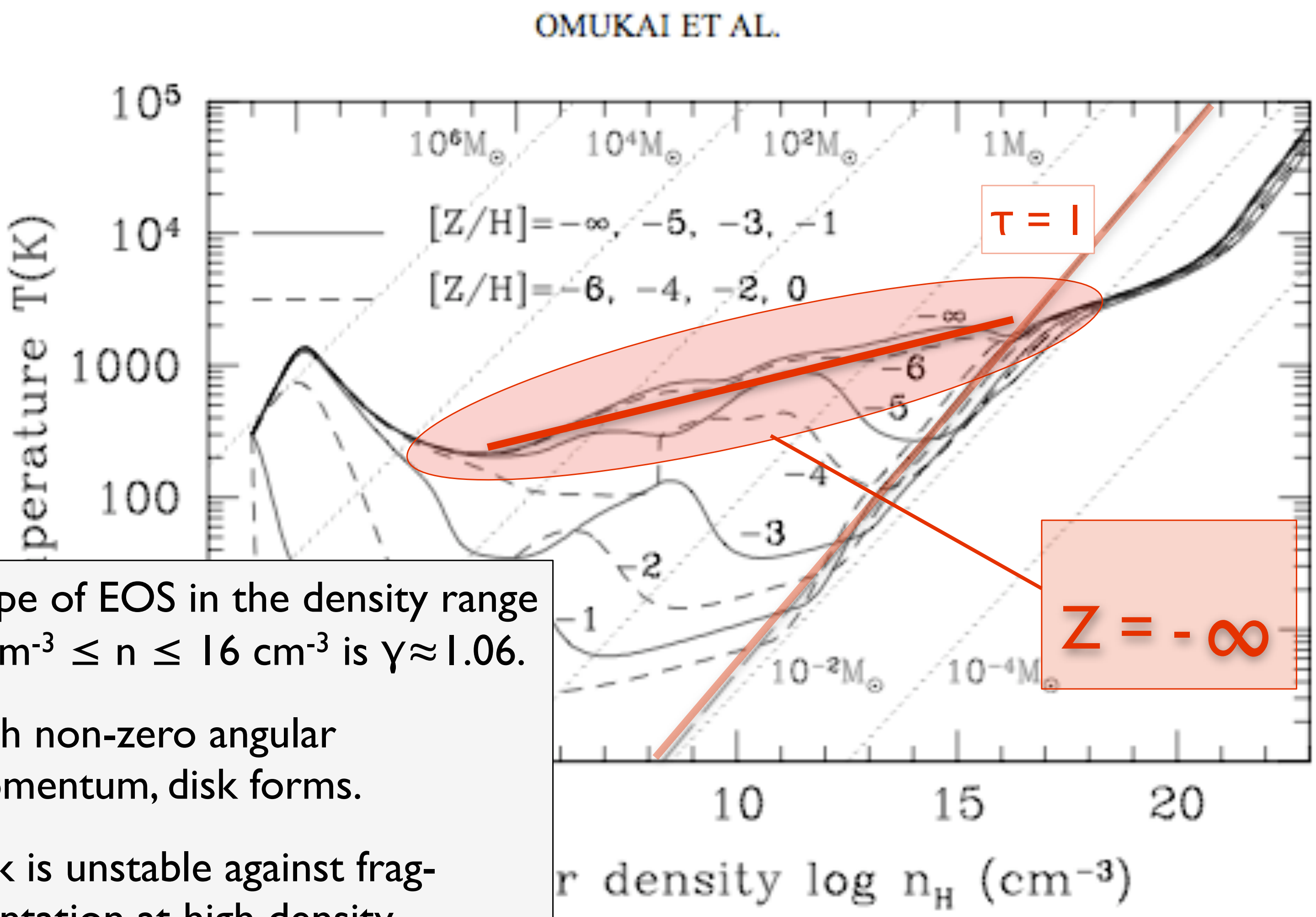
indeed 2D and 3D simulations show that vigorous fragmentation occurs with mass spectrum peaking below 1 M_{sun}.

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 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)

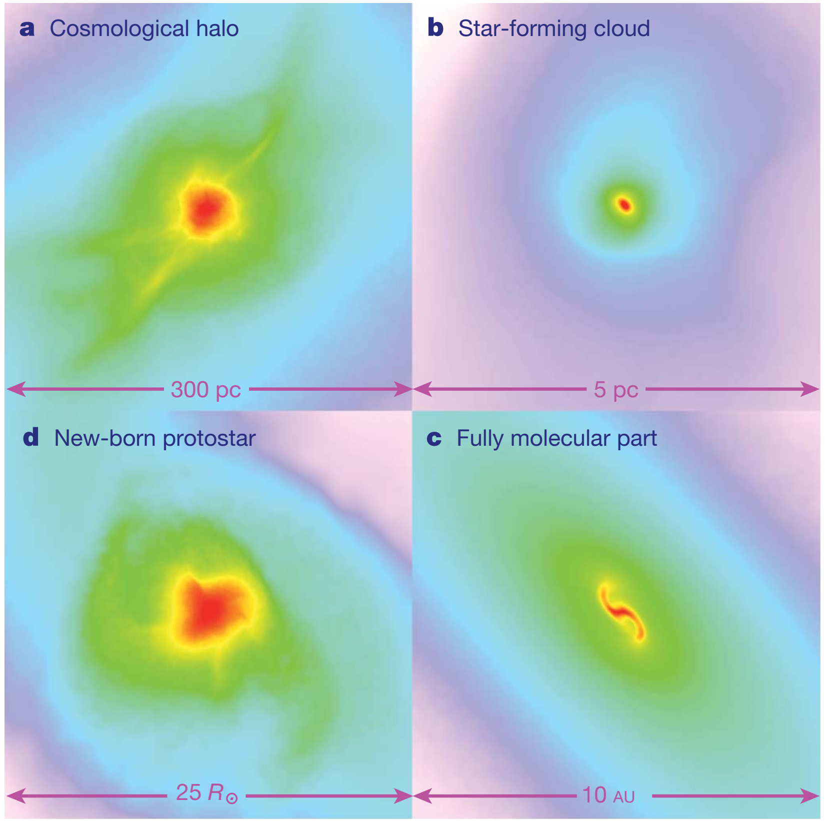
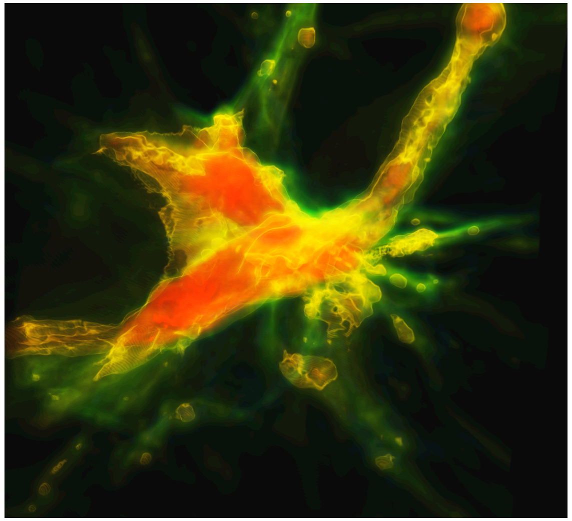


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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, in press (arXiv:1101.5491)
  - complementary approaches with interesting similarities and differences....

SPH study: face on look at accretion disk

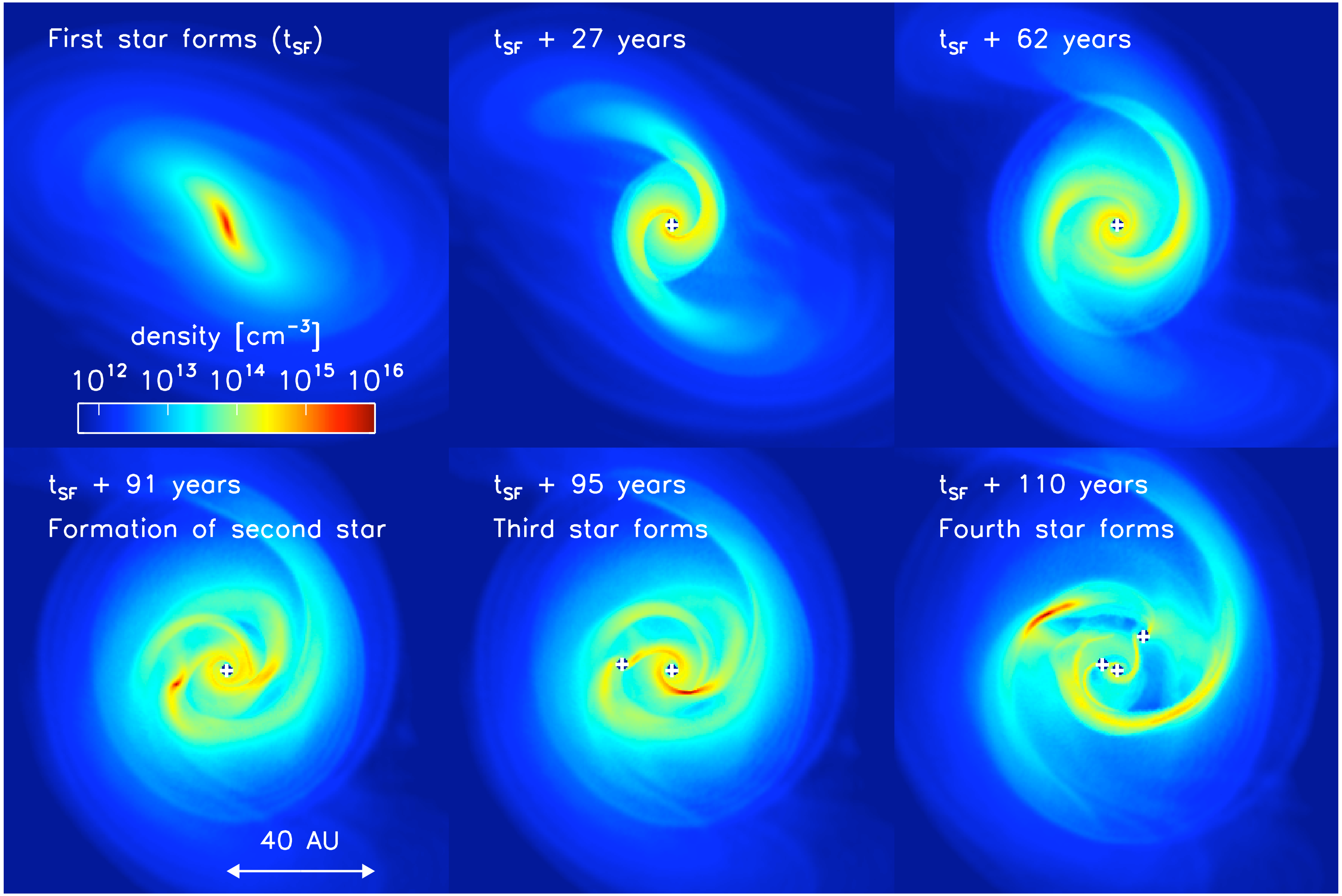


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

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

SPH study: some disk parameters

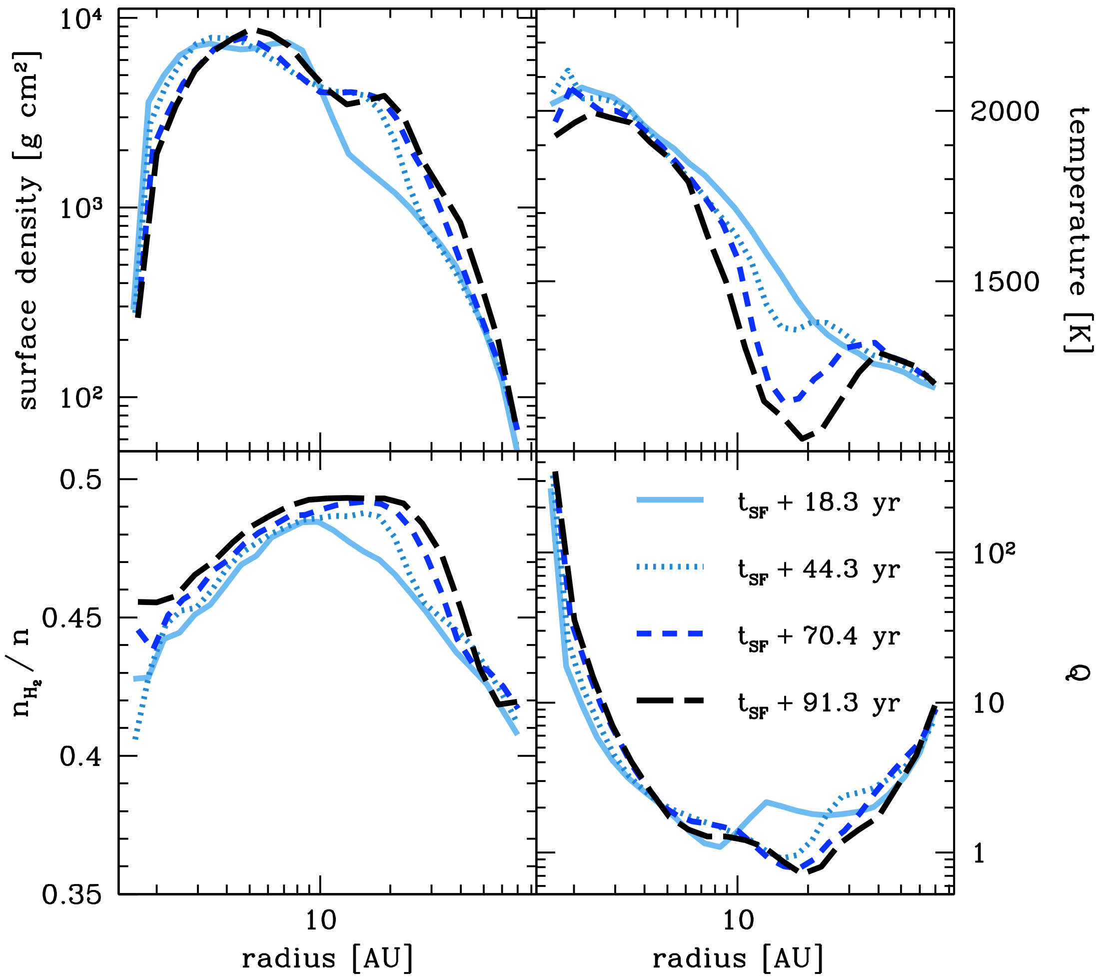


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_{\rm s}\kappa/\pi G\Sigma$, where $c_{\rm s}$ 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 ($n_{\rm H_2}$), 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

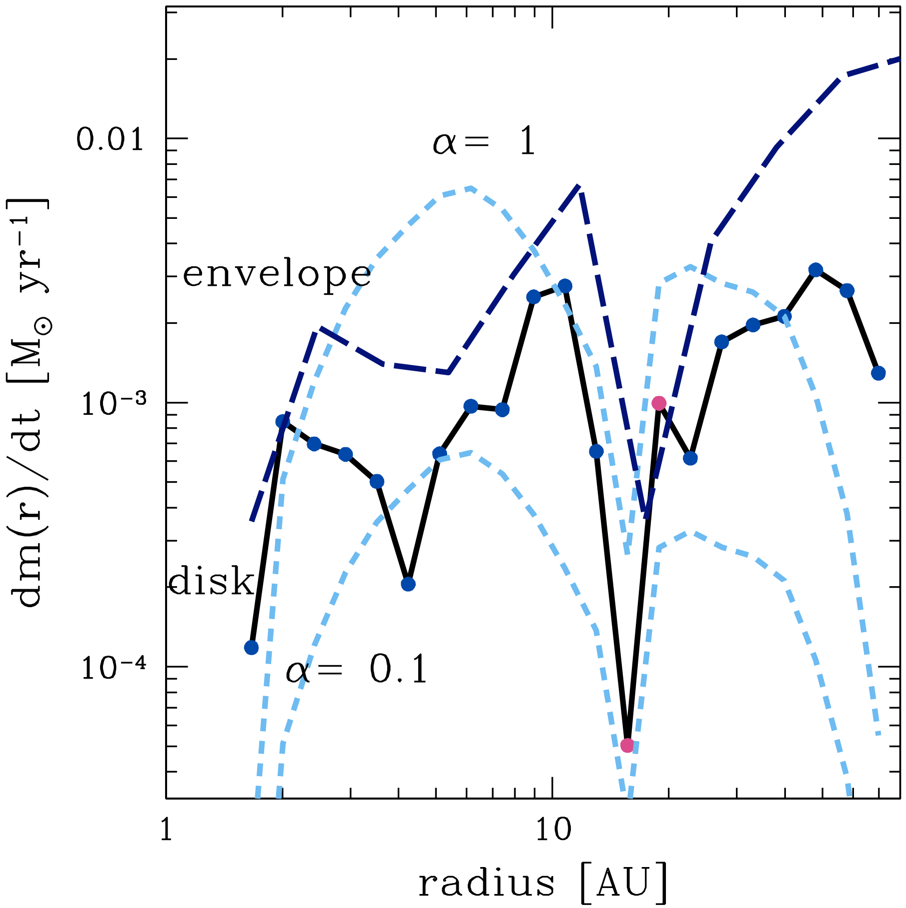


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure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

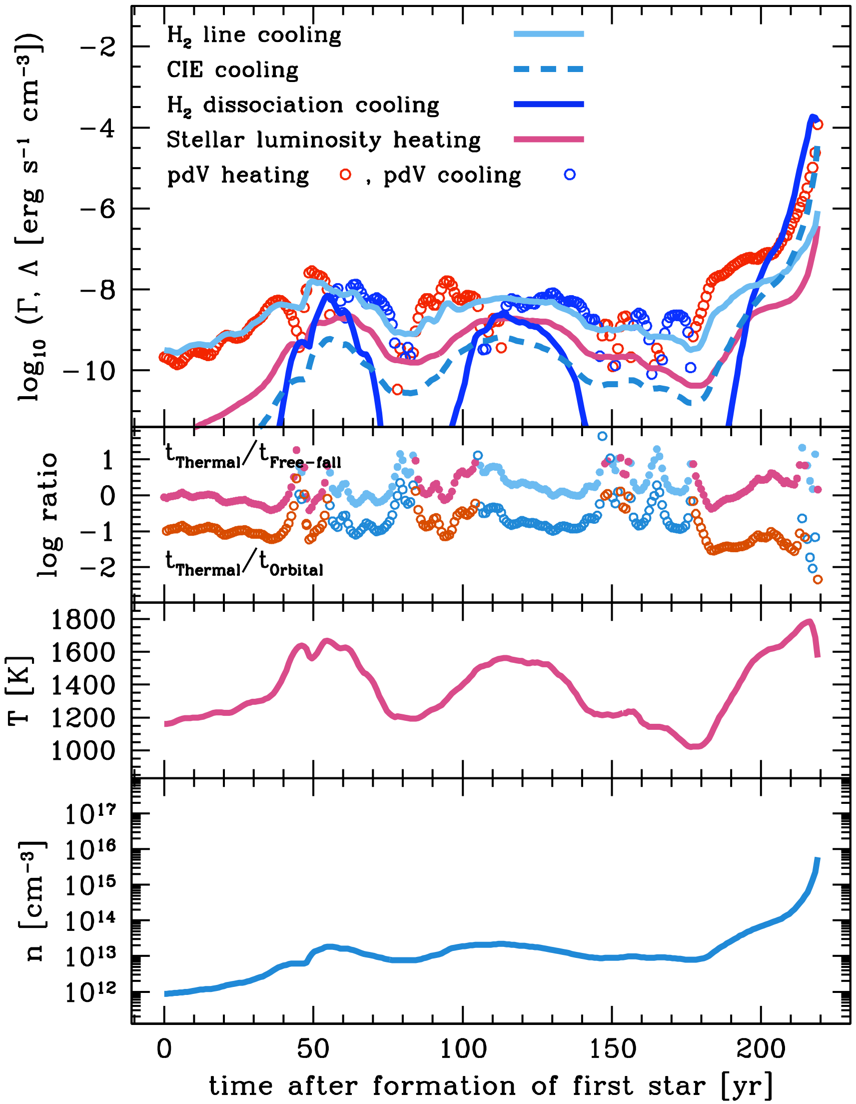


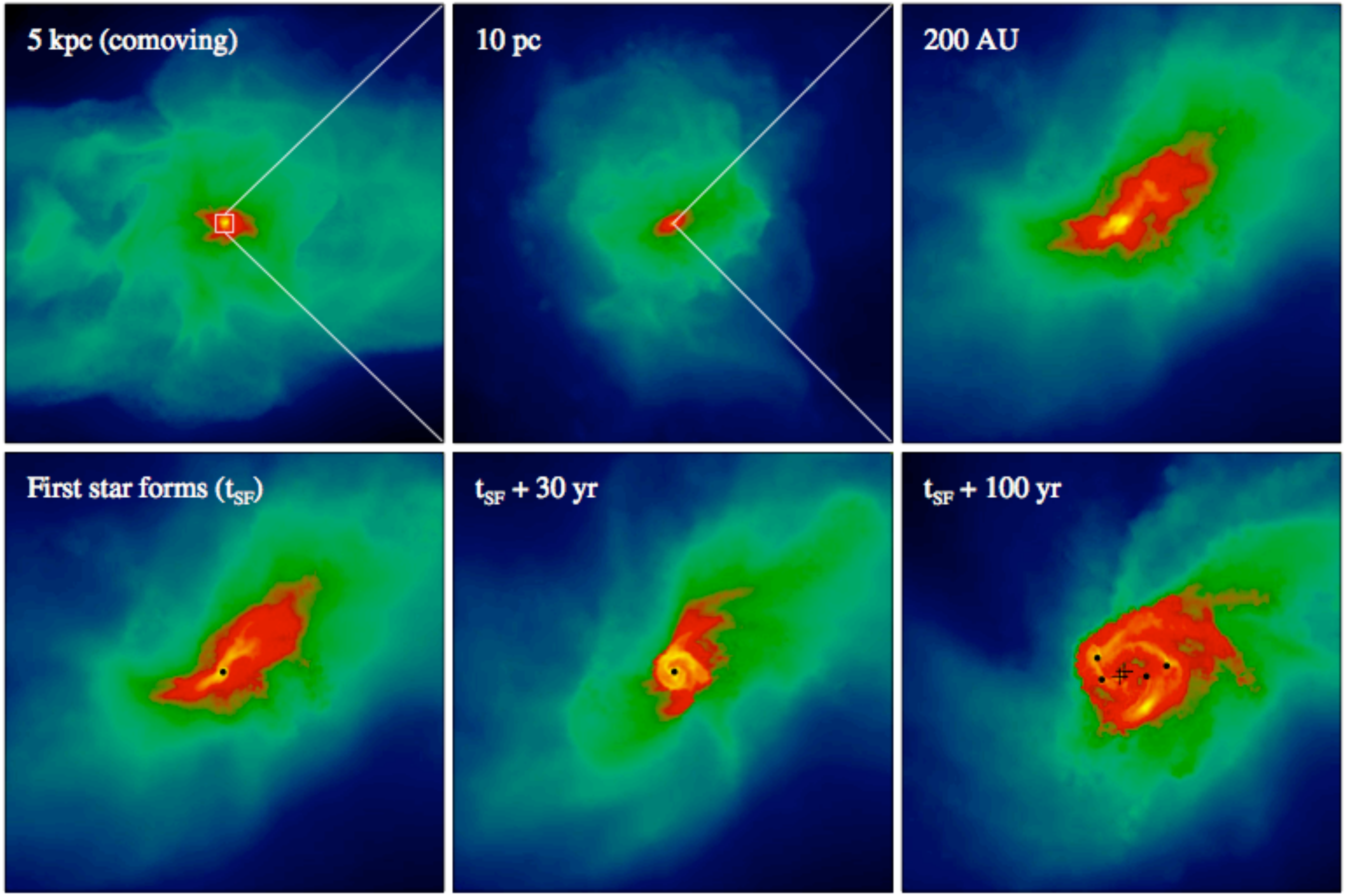
Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, t_{thermal}, to the free-fall timescale, t_{ff}, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated in blue,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

Finally, the results presented here allow us to understand why our conclusions regarding the stability of Population III accretion disks differ significantly from those of the previous analytical studies (*S20, S38, S39*). Figure S17 demonstrates that H_2 line cooling plays a hugely important role in the thermal balance of the disk, allowing the disk material to remain relatively cold, with a temperature of $T \sim 1000$–2000 K. However, this process was not included in any of these previous analytical studies. They therefore find much higher equilibrium temperatures for the gas in the disk. Neglect of H_2 bound-free opacity means that these studies predict inner disk temperatures $T \sim 6000$ K or more, the temperature at which H^- ions first become a major source of opacity. At a temperature of 6000 K, the molecular content of the gas is negligible, and so the predicted mean molecular weight of the gas in these models also differs by almost a factor of two from the value in our cold disks. Together, these effects lead to a significantly higher predicted sound-speed for the disk, and hence also a higher Toomre parameter Q. Our simulated disks are already marginally stable, and it is likely that a global increase in Q by a factor of a few would render them completely stable against fragmentation.

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

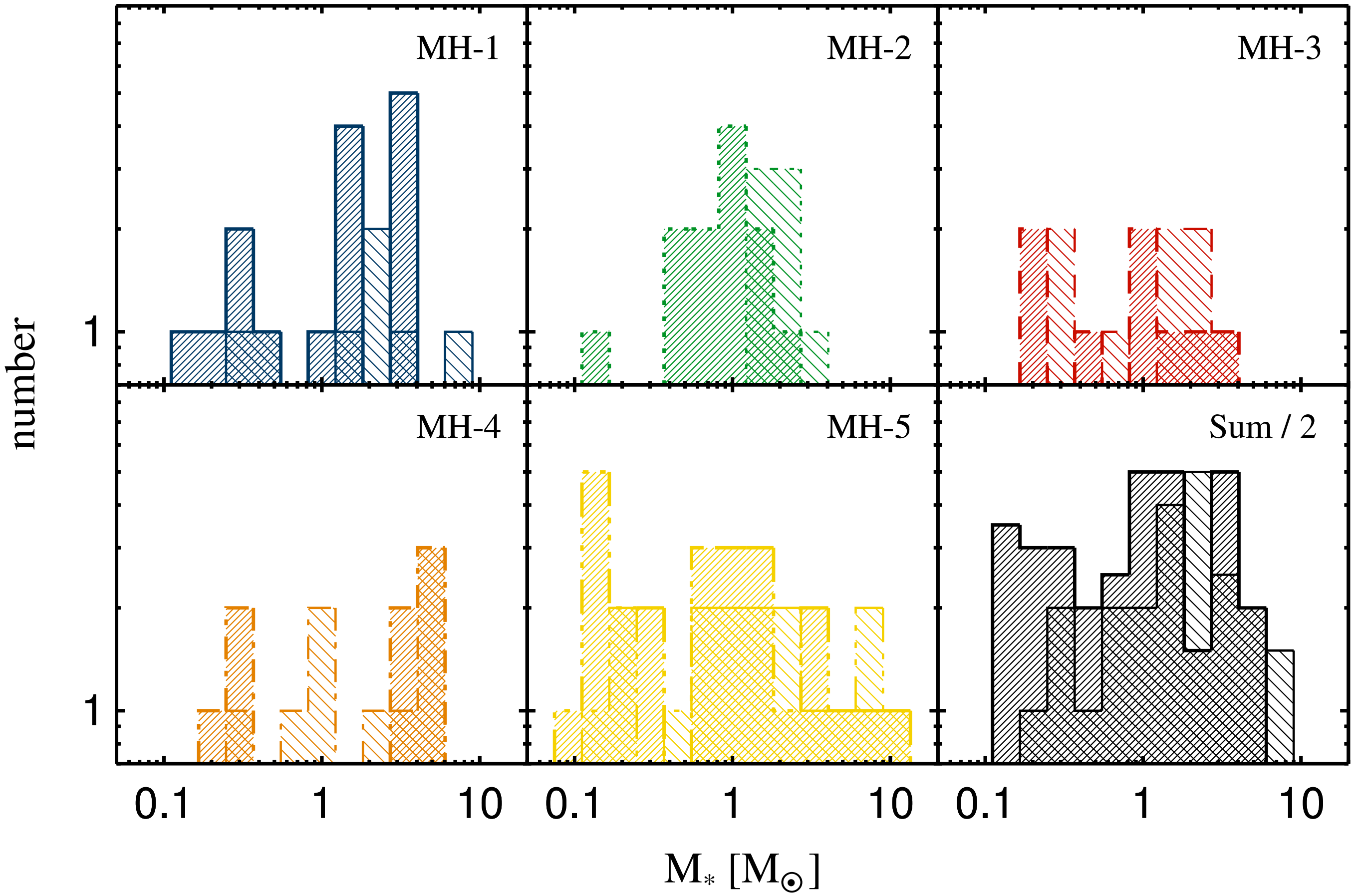
Arepo study: surface density at different times



one out of five halos

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

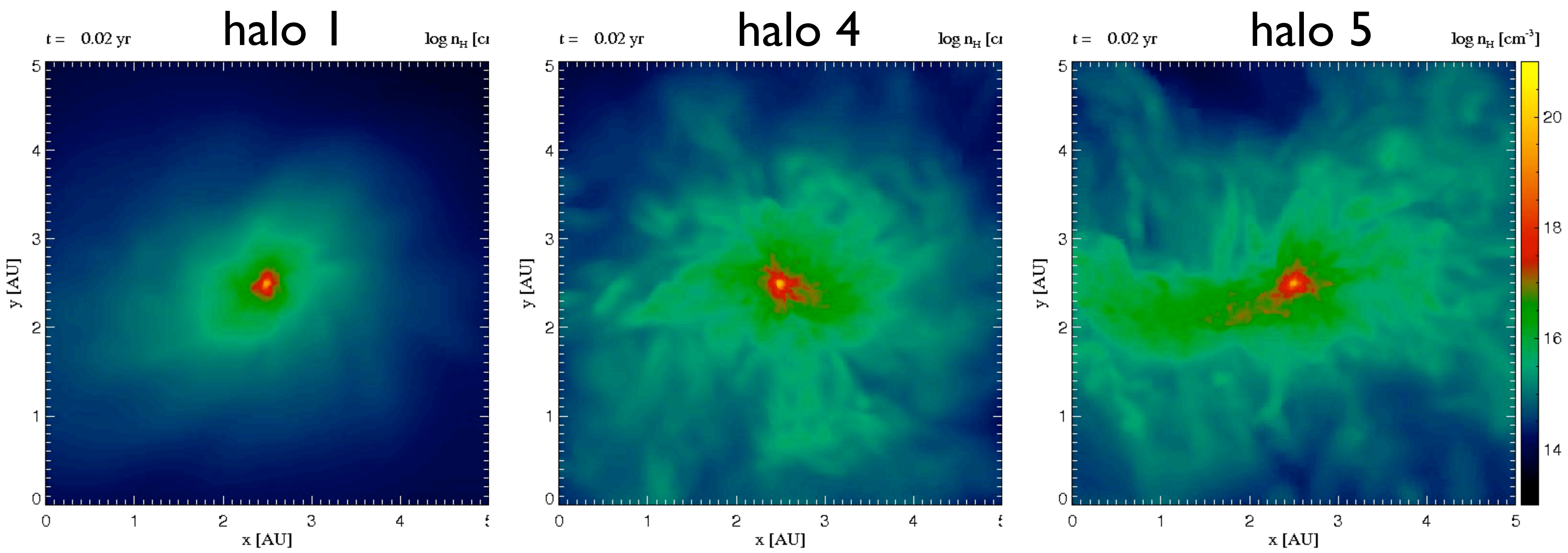
Arepo study: mass spectrum of fragments



(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

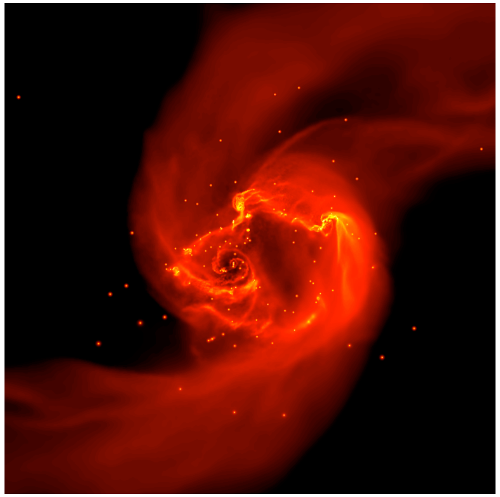


(Greif et al. in preparation)

primordial star formation

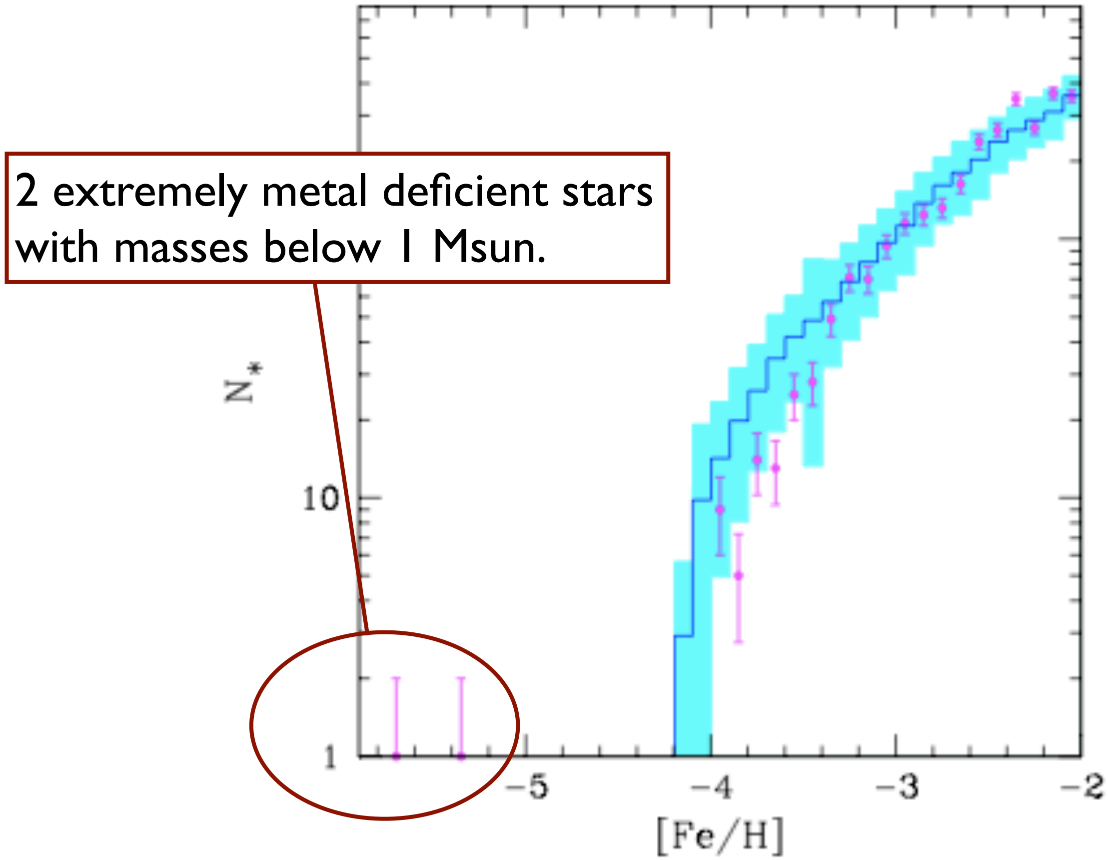
- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

  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

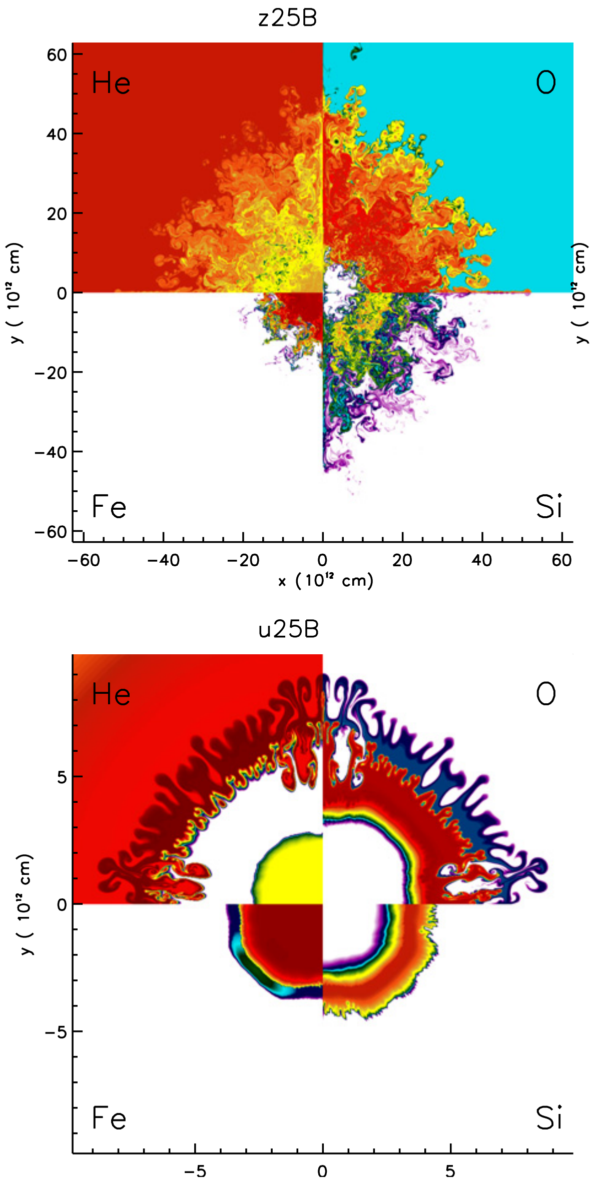
constraints from EMP stars in halo



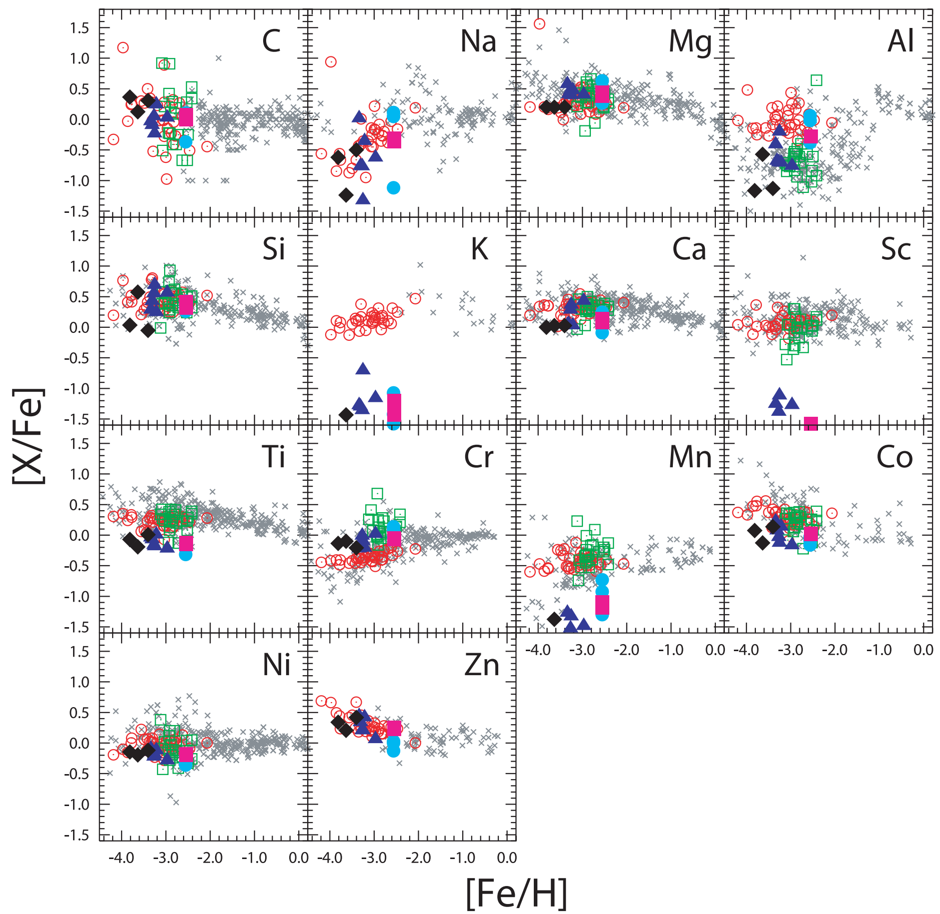
(plot from Salvadori et al. 2006, data from Frebel et al. 2005)

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)



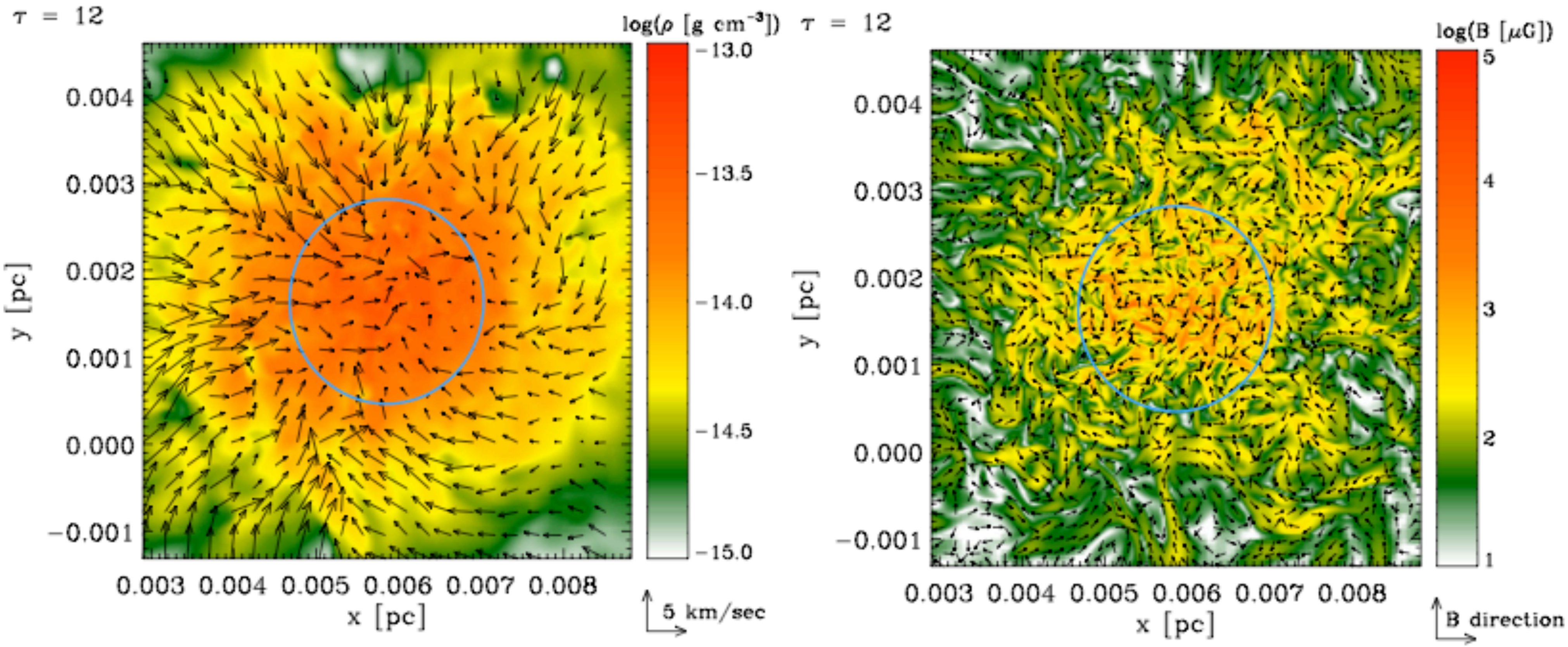
(Tominaga et al. 2007)

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)

B fields in the early universe?

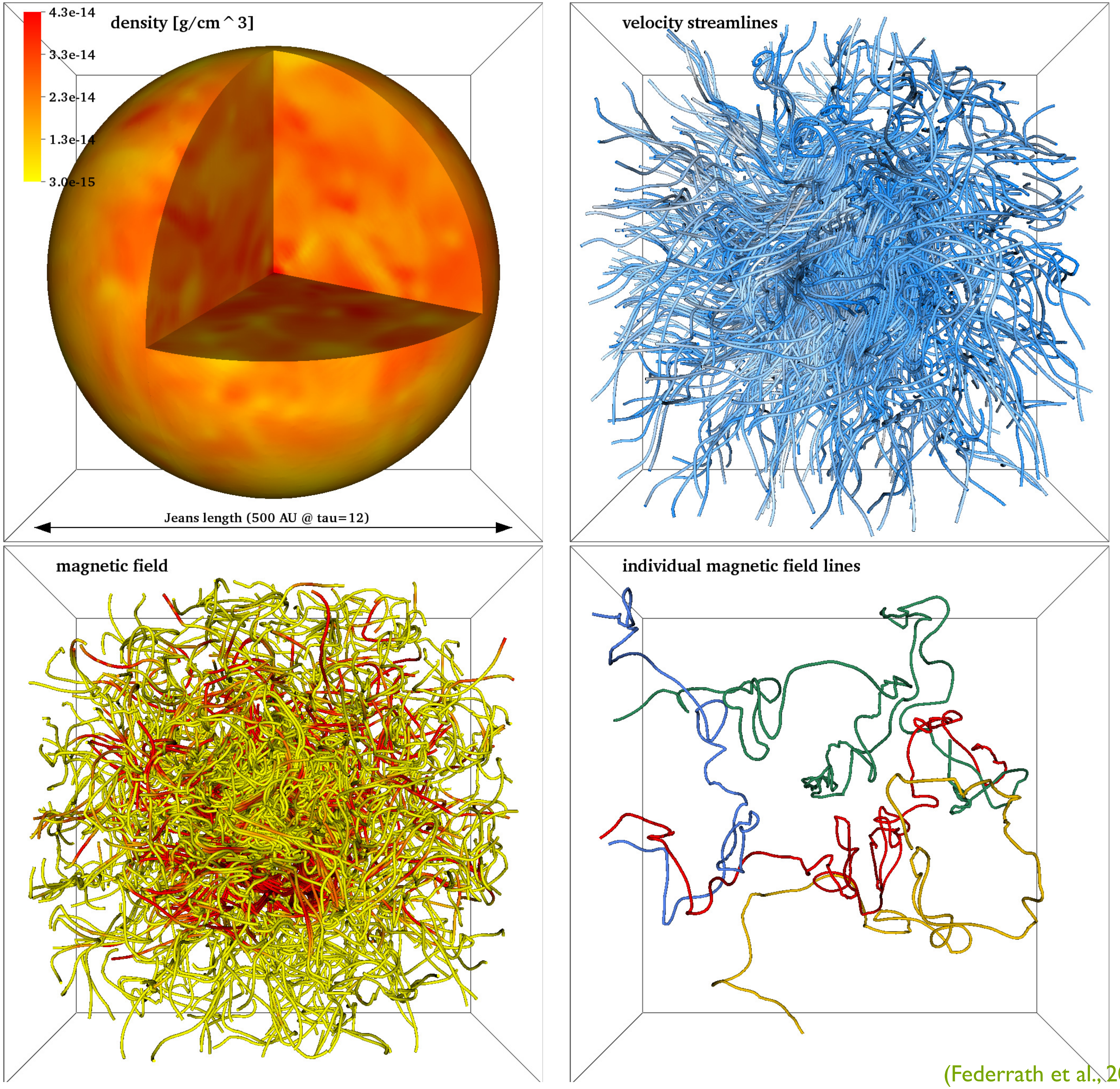
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, *THIS MAY BE WRONG*!



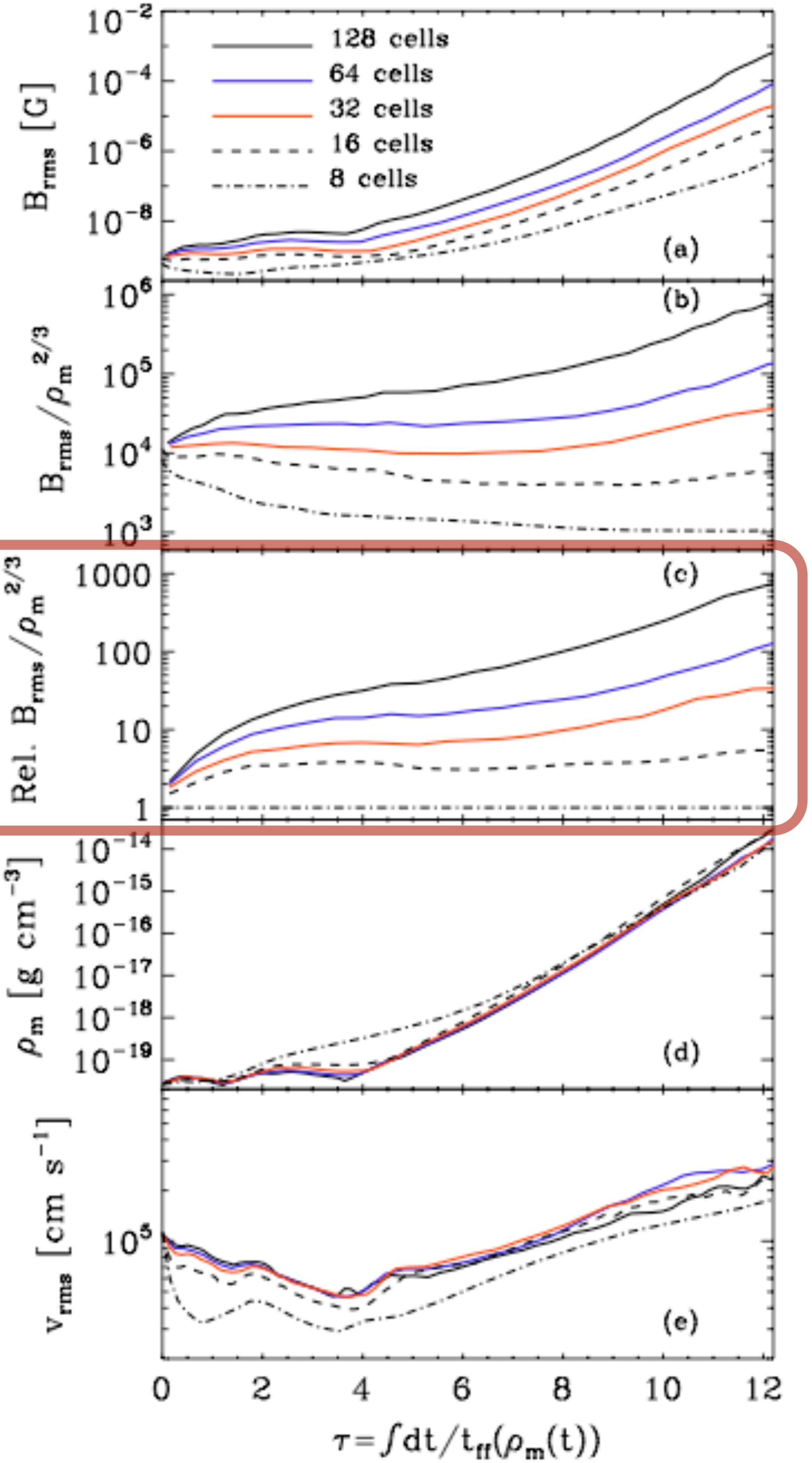
magnetic field structure

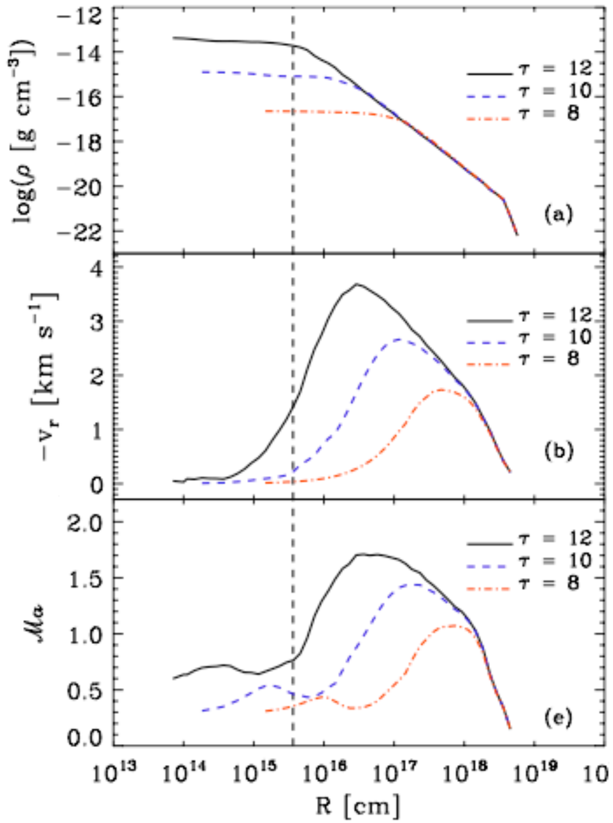
density structure

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



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





radial density profile

radial velocity profile

Mach number profile

Field amplification during first collapse seems unavoidable.

QUESTIONS:

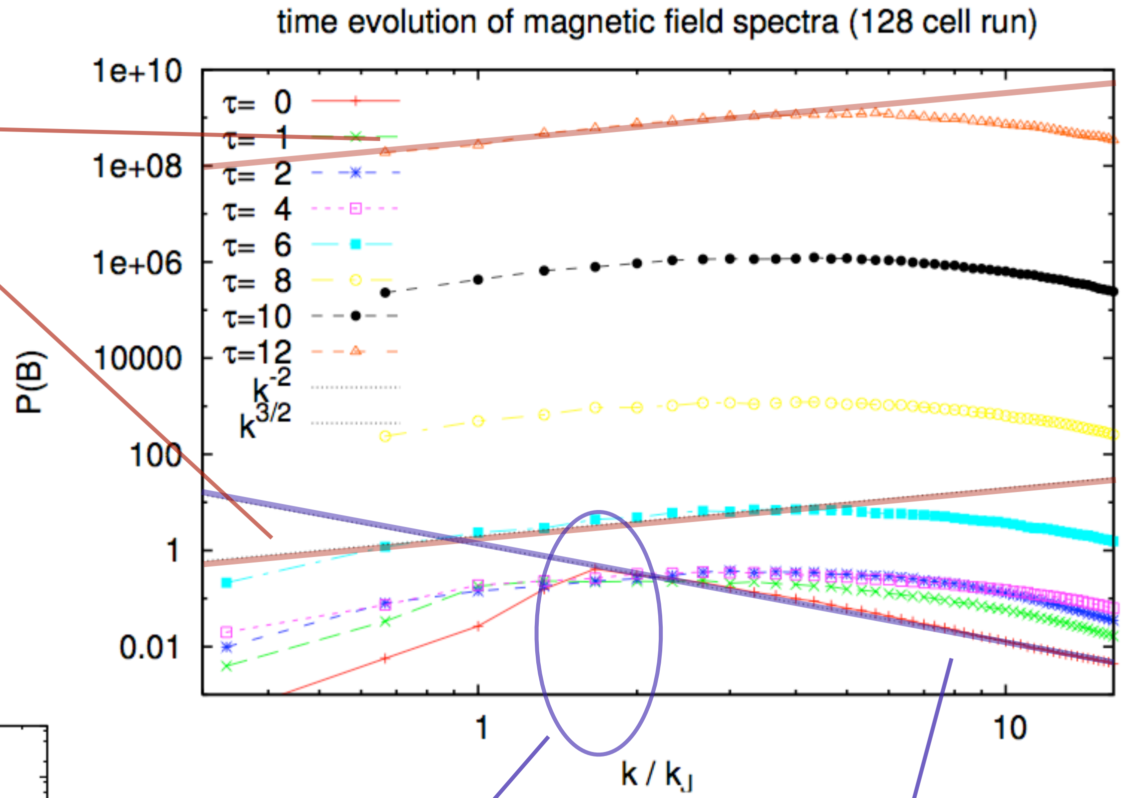
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

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

analysis of magnetic field spectra

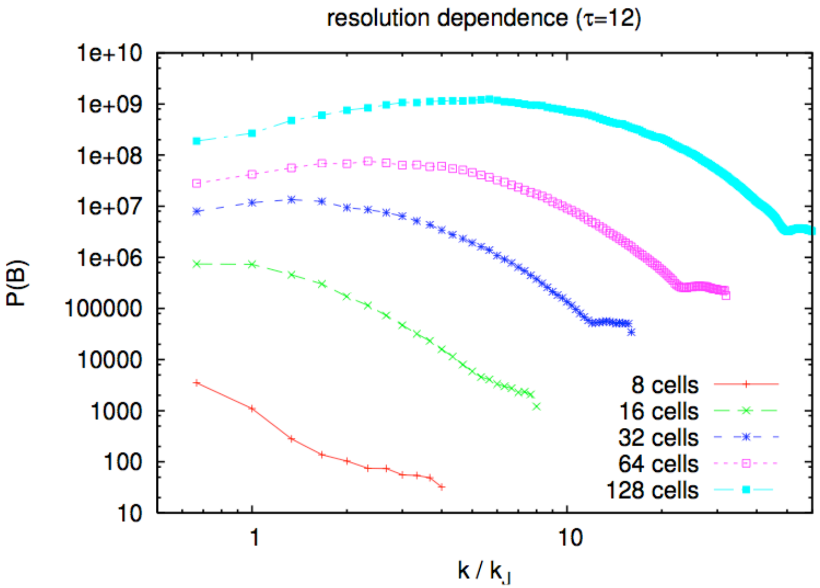
Slope +3/2 of
Kazantsev theory

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



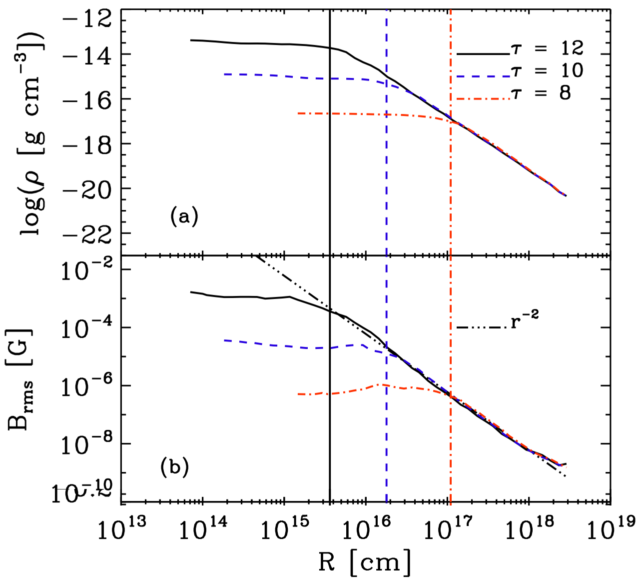
initial peak of
B fluctuation
spectrum

initial slope of
B fluctuations

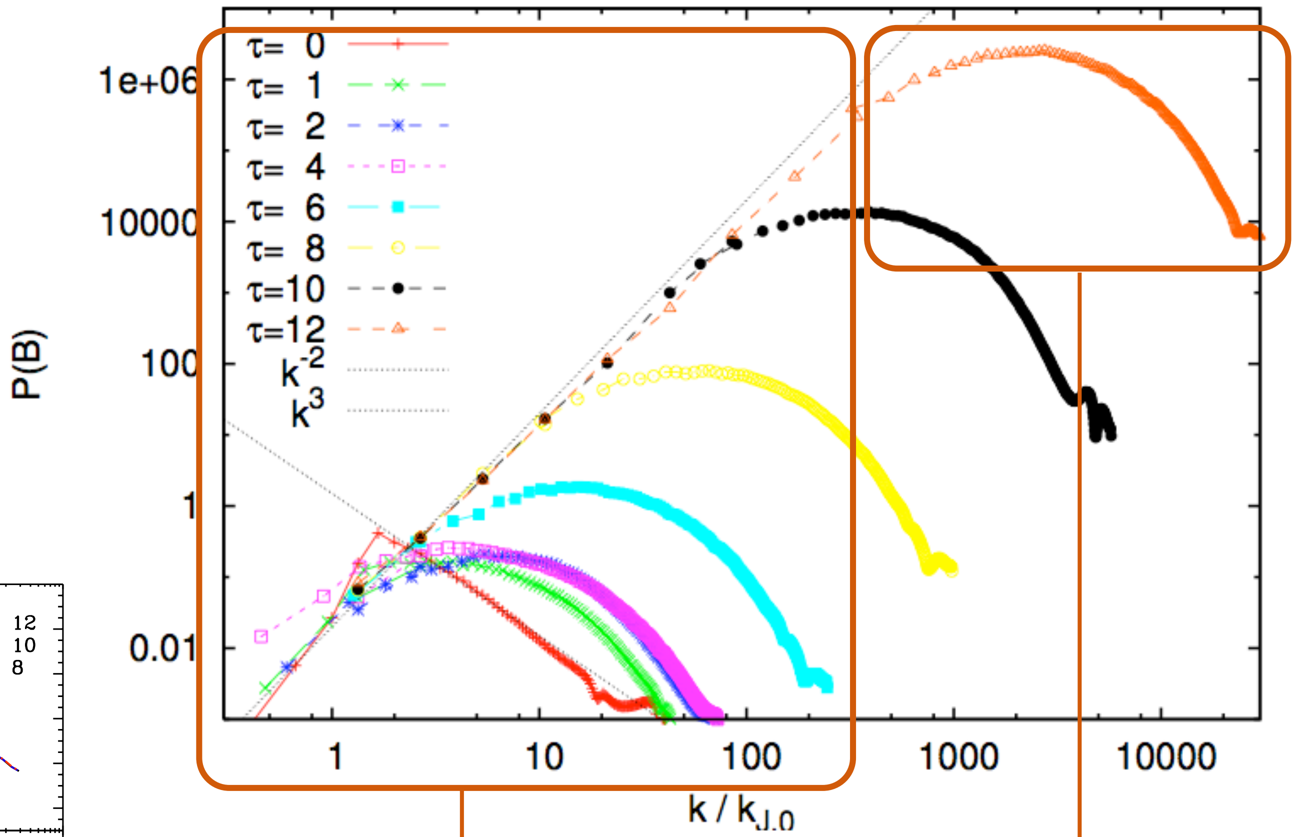


(Federrath et al., 2011, ApJ, 731, 62)

analysis of magnetic field spectra



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., 2011, ApJ, 731, 62)

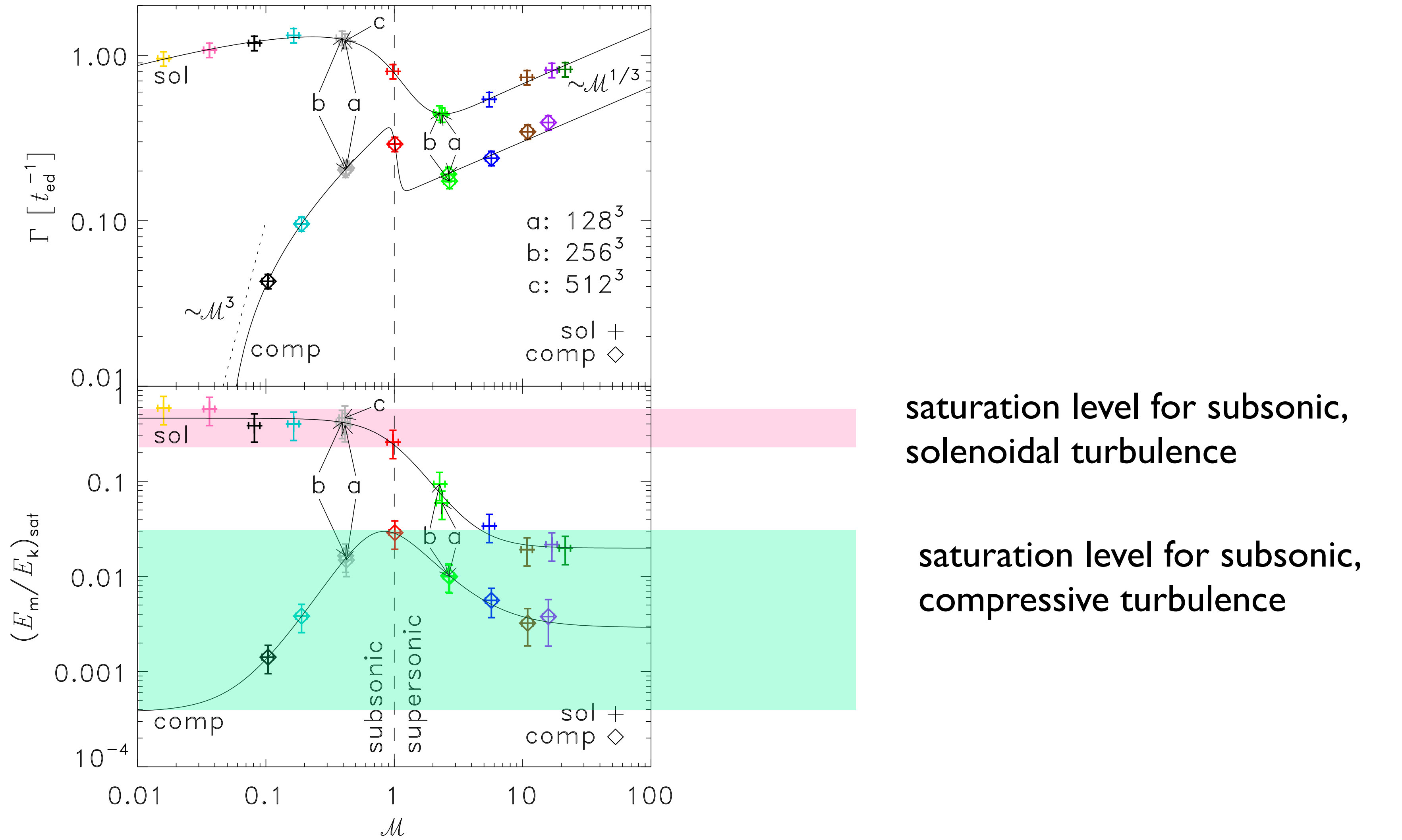


FIG. 3. (Color online) Growth rate (top), and saturation level (bottom) as a function of the Mach number for all runs with solenoidal (crosses) and compressive forcing (diamonds). The solid lines show empirical fits with equation (4). The labeled data points indicate four models ($\mathcal{M} \approx 0.4$, 2.5 for sol. and comp. forcing), using ideal MHD on 128^3 grid cells (a), non-ideal MHD on 256^3 (b), and 512^3 grid cells (c), demonstrating convergence for the given magnetic Prandtl (Pm = 2) and kinematic Reynolds number (Re ≈ 1500).

(Federrath et al., 2011, PRL submitted)

numerics: FLASH4

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\partial_t (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} - \mathbf{B} \otimes \mathbf{B}) + \nabla p_\star = \nabla \cdot (2 \nu \rho \boldsymbol{\mathcal{S}}) + \rho \mathbf{F},$$

$$\partial_t E + \nabla \cdot [(E + p_\star) \mathbf{u} - (\mathbf{B} \cdot \mathbf{u}) \mathbf{B}] = \nabla \cdot [2 \nu \rho \mathbf{u} \cdot \boldsymbol{\mathcal{S}} + \mathbf{B} \times (\eta \nabla \times \mathbf{B})],$$

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B},$$

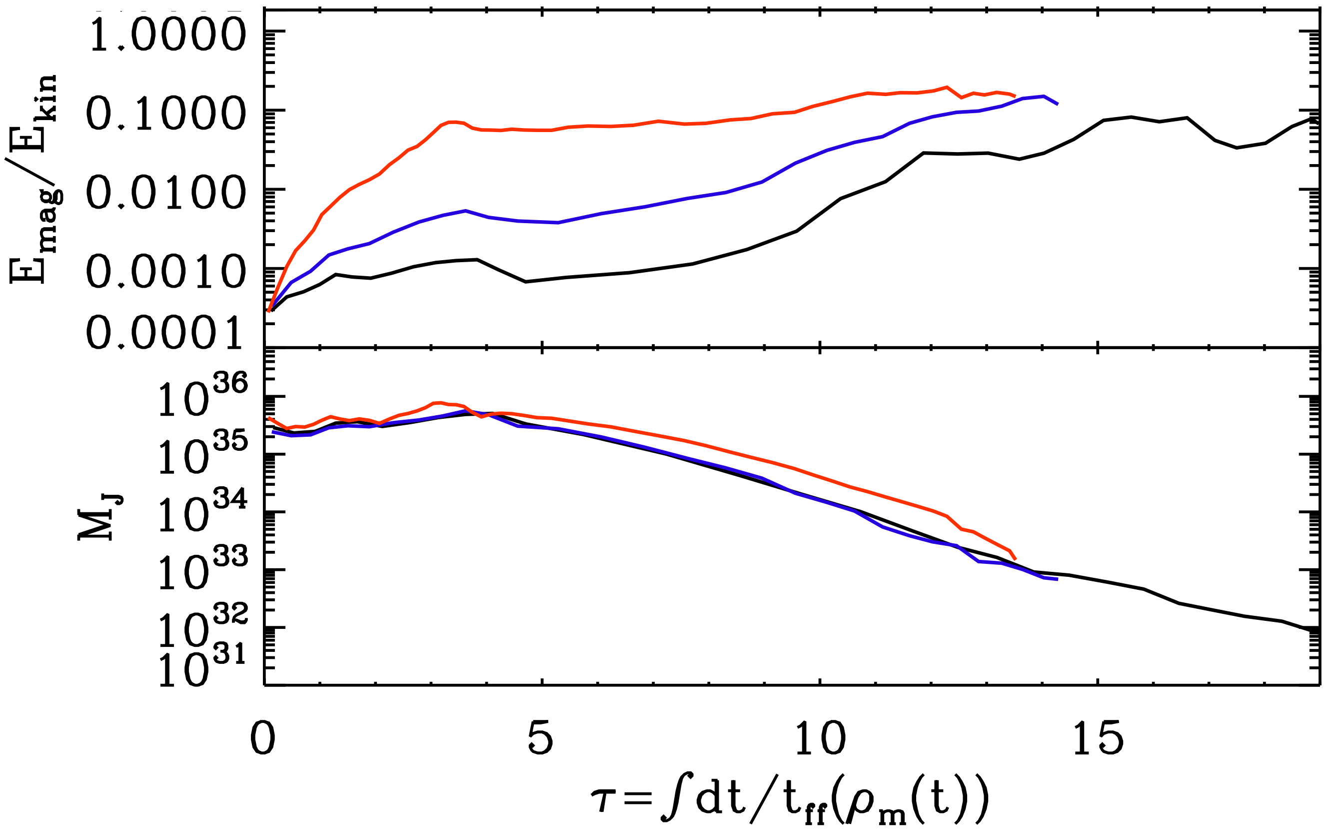
$$\nabla \cdot \mathbf{B} = 0,$$

with $\rho, \; \mathbf{u}, \; p_\star = p + (1/2) |\mathbf{B}|^2, \; \mathbf{B},$

$$E = \rho \epsilon_{\mathrm{int}} + (1/2) \rho |\mathbf{u}|^2 + (1/2) |\mathbf{B}|^2$$

$$\mathcal{S}_{ij} = (1/2)(\partial_i u_j + \partial_j u_i) - (1/3) \delta_{ij} \nabla \cdot \mathbf{u}$$

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 x 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?

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)