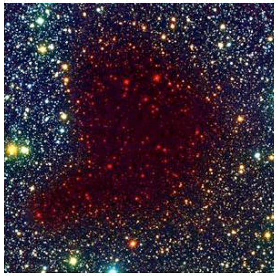
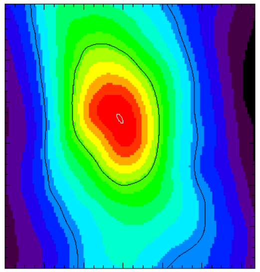
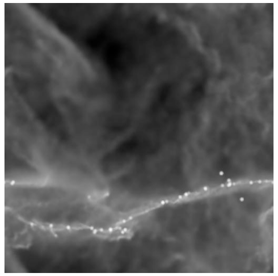
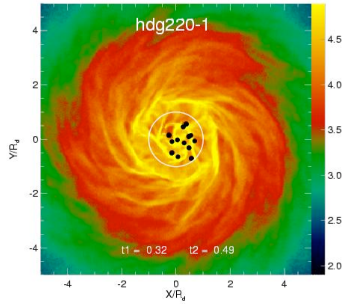
Formation of the First Star Clusters





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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

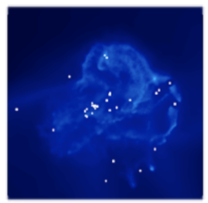
... many collaborators abroad!

agenda

First star formation

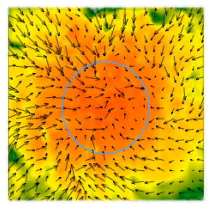
agenda

Star cluster formation



First star formation

Magnetic fields in the primordial universe

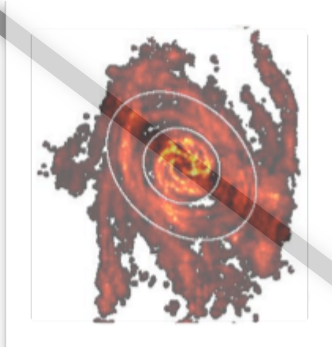


agenda

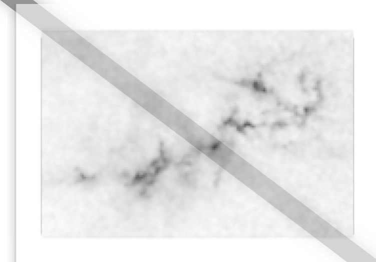
decreasing spatial scales

present days

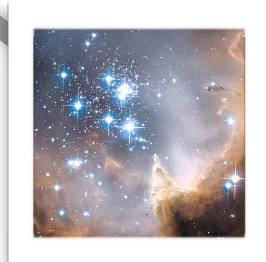
early universe



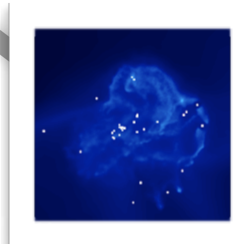
Global ISM dynamics



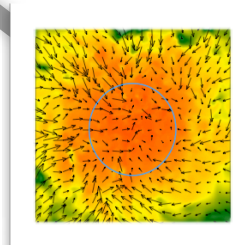
Formation of molecular clouds



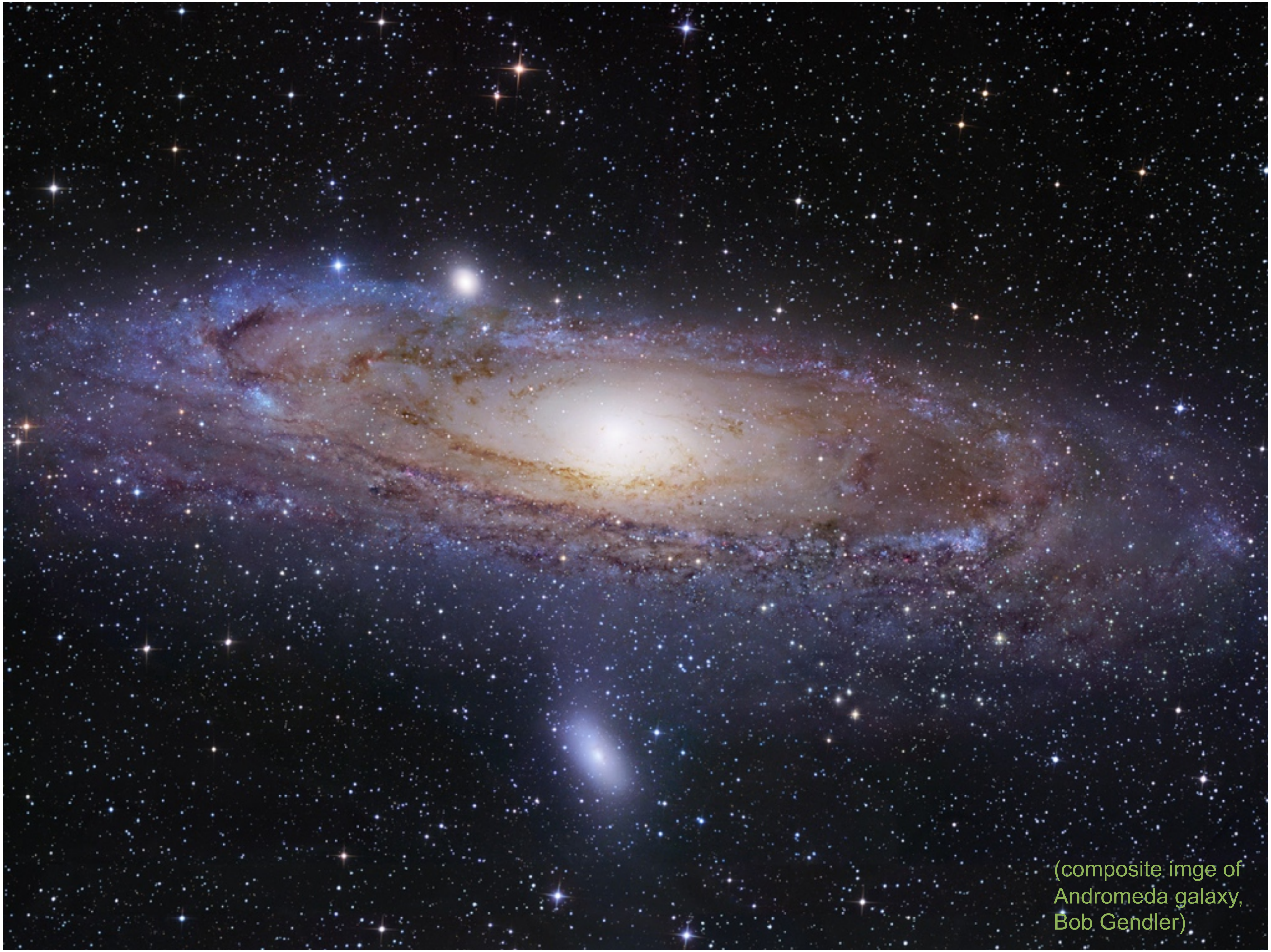
Star cluster formation



First star formation



Magnetic fields in the primordial universe

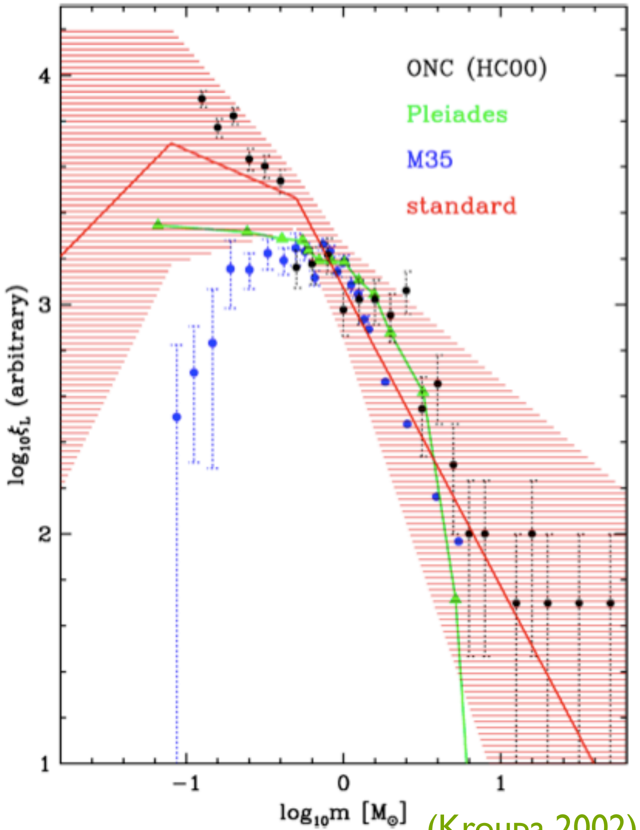


(composite imge of
Andromeda galaxy,
Bob Gendler)


NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

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

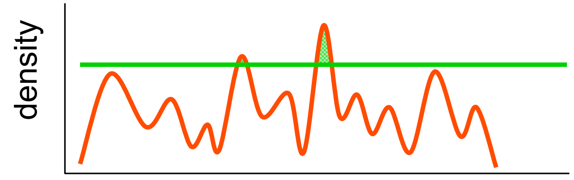


(Kroupa 2002)

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

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: $\mathcal{M} \approx 1...3$)



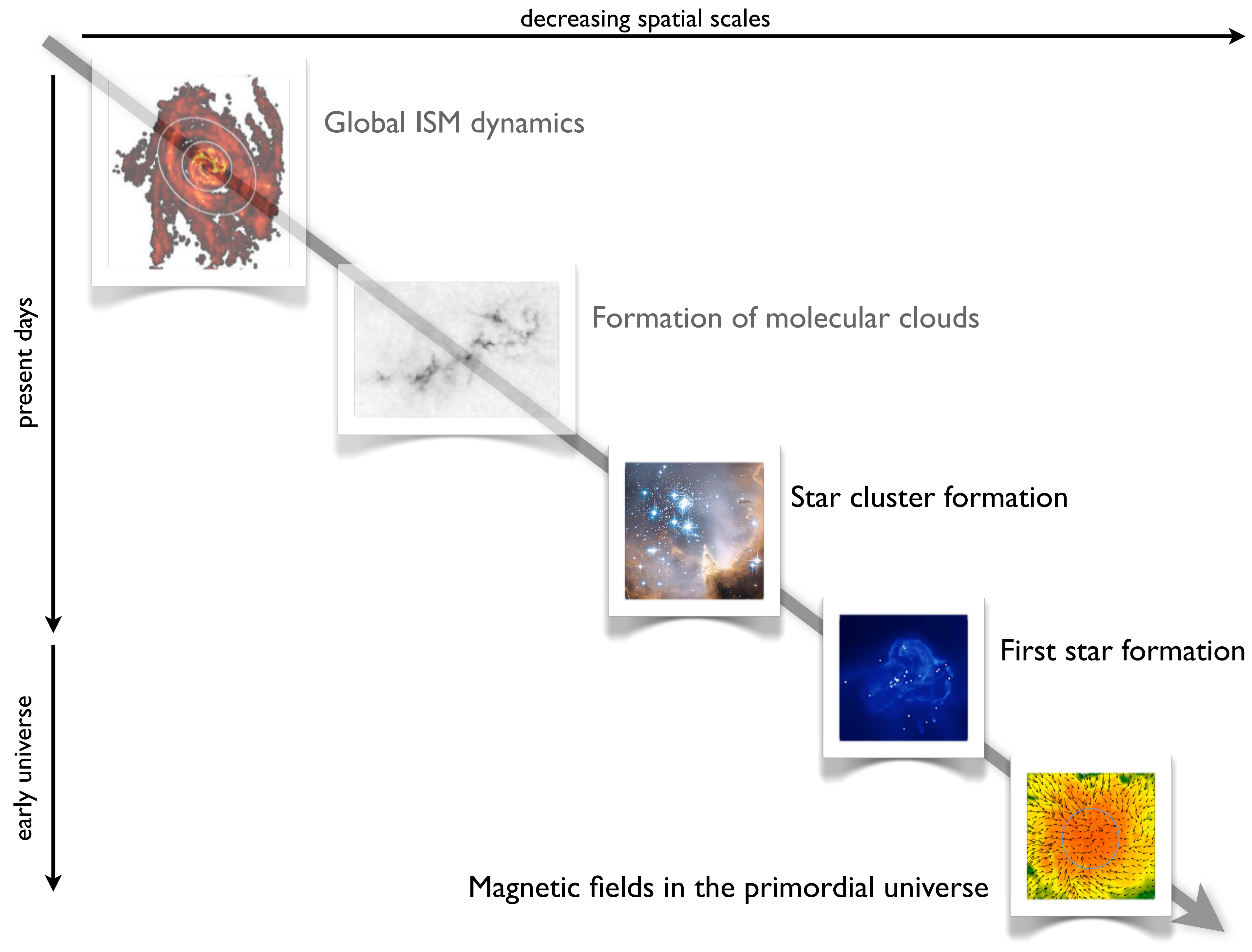
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M}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

controversial issues


decreasing spatial scales
present days
early universe
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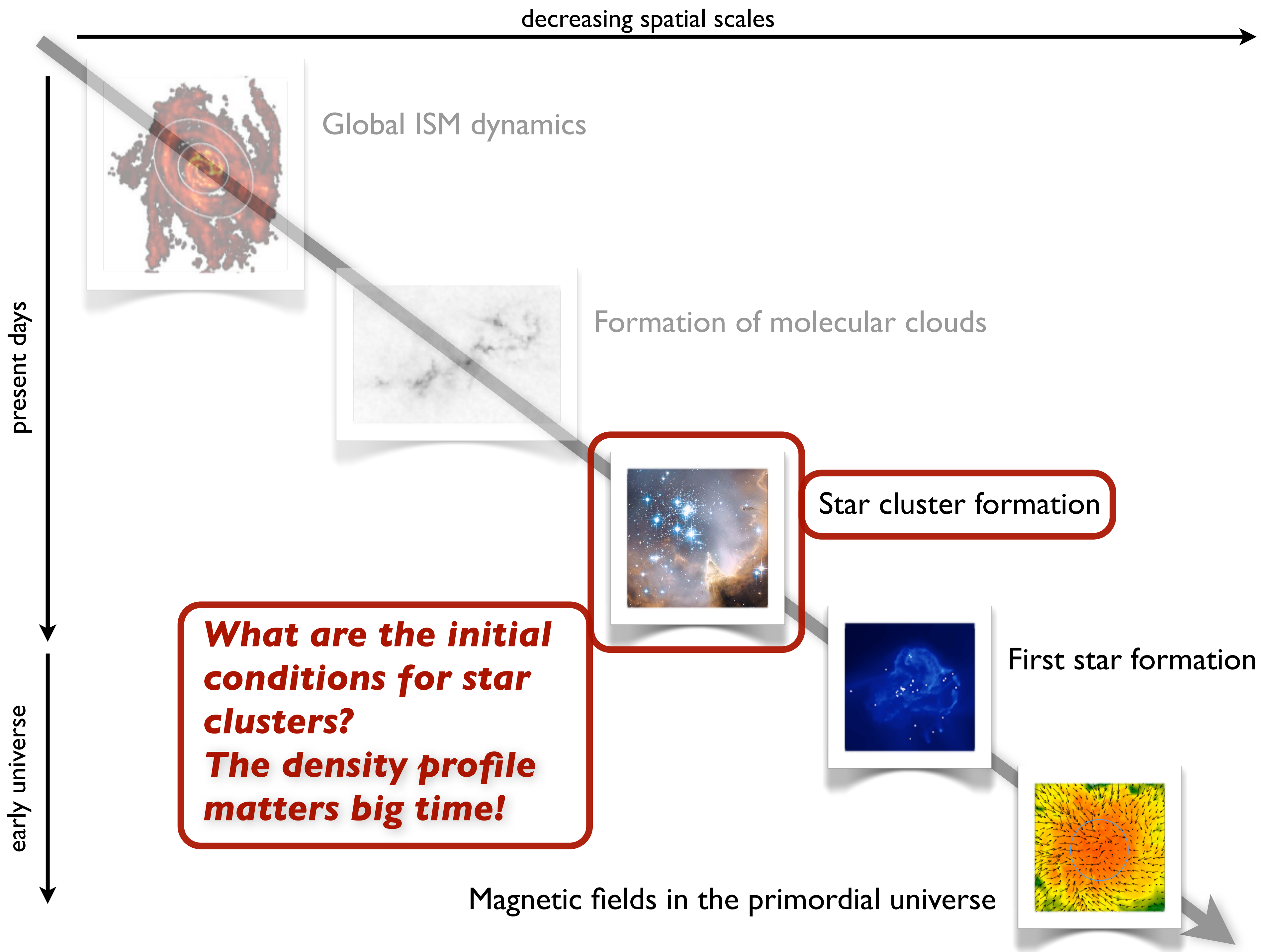
Formation of molecular clouds
Star cluster formation
First star formation
Magnetic fields in the primordial universe


decreasing spatial scales
present days
early universe
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Formation of molecular clouds
Star cluster formation
What are the initial conditions for star clusters?
The density profile matters big time!
First star formation
Magnetic fields in the primordial universe

ICs of star cluster formation

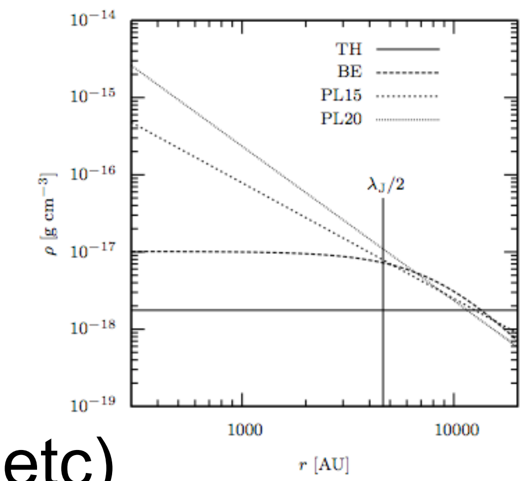
- one of the key questions in star formation:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?

ICs of star cluster formation

- one of the key questions in star formation:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observational answer:

ICs of star cluster formation

- one of the key questions in star formation:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- theorists answer:
  - top hat (Larson Penston)
  - Bonnor Ebert (like low-mass cores)
  - power law $\rho \propto r^{-1}$ (logotrop)
  - power law $\rho \propto r^{-3/2}$ (Krumholz, McKee, etc)
  - power law $\rho \propto r^{-2}$ (Shu)
  - and many more



different density profiles

- does the density profile matter?

  .

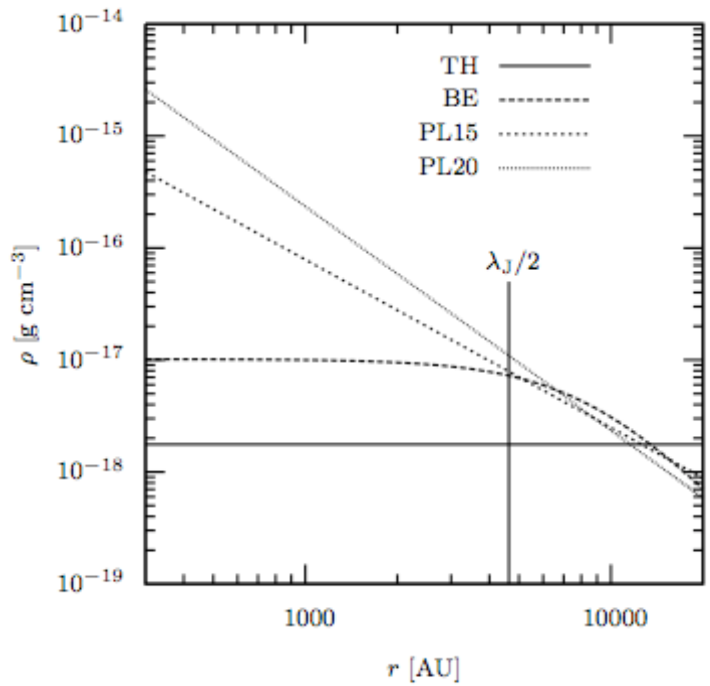
  .

  .

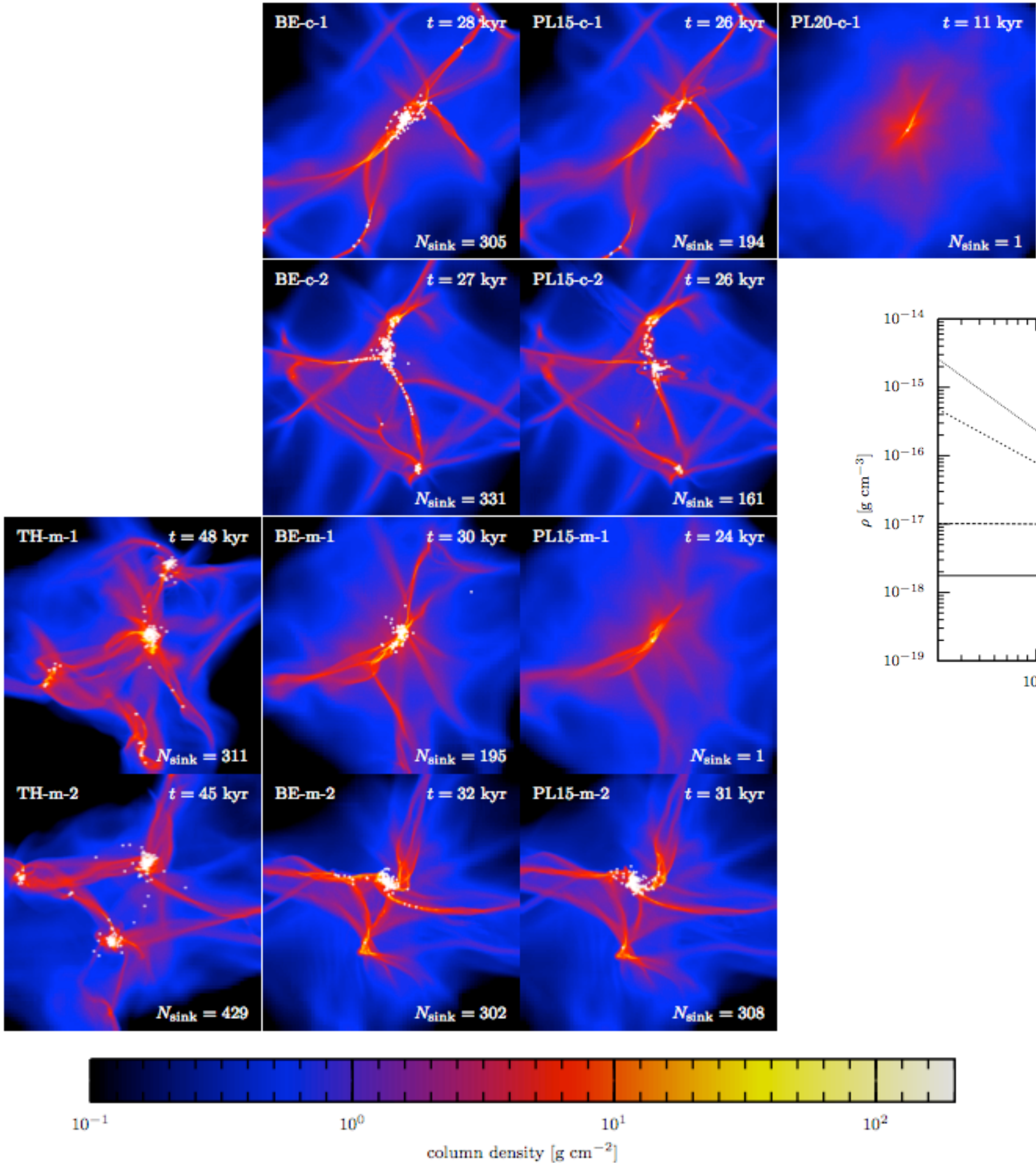
- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

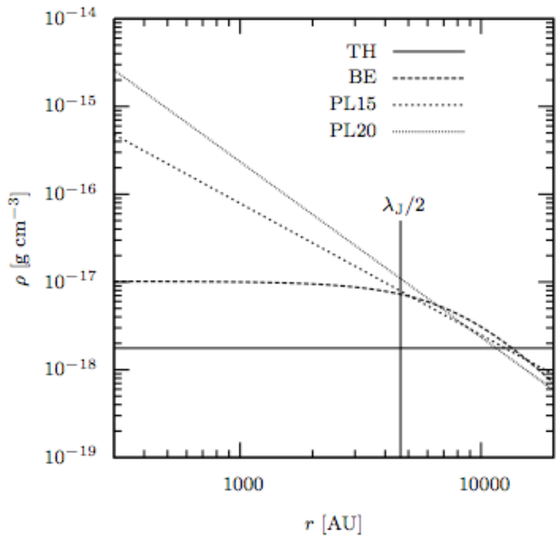
different density profiles

- answer: ***YES! it matters big time!***
- approach: extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both modes
  - no net rotation, no B-fields
    (at the moment)



Girichids et al. (2011)





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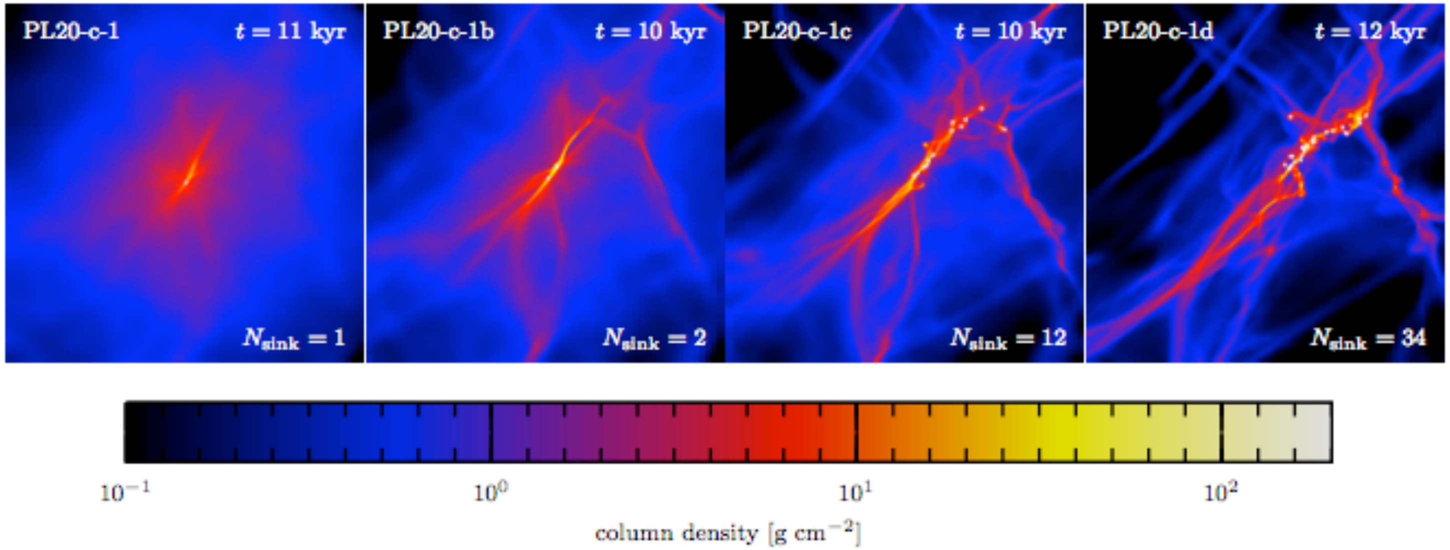

M=3 M=6 M=12 M=18

for the r^{-2} profile you need to crank up turbulence a lot to get some fragmentation!

Girichids et al. (2011)

Run	t_{sim} [kyr]	t_{sim}/t_{ff}^{core}	t_{sim}/t_{ff}	N_{sinks}	$\langle M \rangle$ [$M_{\odot}$]	M_{max}
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
BE-m-1	30.05	1.30	0.60	195	0.0873	1.42
BE-m-2	31.94	1.39	0.64	302	0.0616	0.54
BE-s-1	30.93	1.34	0.62	234	0.0775	1.14
BE-s-2	35.86	1.55	0.72	325	0.0587	0.51
PL15-c-1	25.67	1.54	0.51	194	0.0992	8.89
PL15-c-2	25.82	1.55	0.52	161	0.1244	12.3
PL15-m-1	23.77	1.42	0.48	1	20	20.0
PL15-m-2	31.10	1.86	0.62	308	0.0653	6.88
PL15-s-1	24.85	1.49	0.50	1	20	20.0
PL15-s-2	35.96	2.10	0.72	422	0.0478	4.50
PL20-c-1	10.67	0.92	0.21	1	20	20.0
PL20-c-1b	10.34	0.89	0.21	2	10.139	20.0
PL20-c-1c	9.63	0.83	0.19	12	1.67	17.9
PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3

solenoidal turbulence tends to form fewer sinks (see also Ant Whitworth's talk yesterday)

Girichids et al. (2011)

Run	t_{sim} [kyr]	t_{sim}/t_{ff}^{core}	t_{sim}/t_{ff}	N_{sinks}	$\langle M \rangle$ [$M_\odot$]	M_{max}
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however, the real situation is more complex: need to analyze time scales for local collapse with the one of global collapse, which depends on details of realization.....

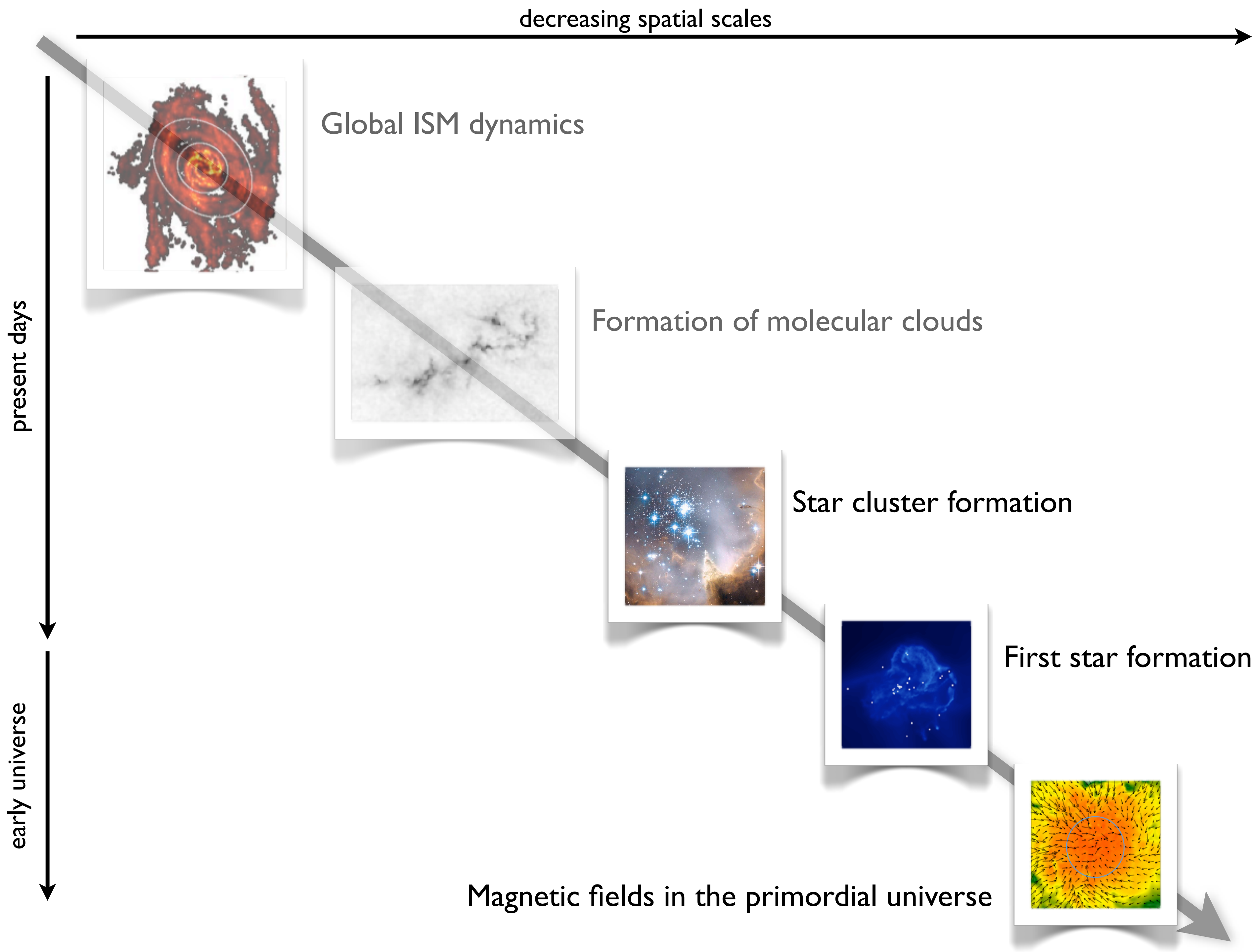
Girichids et al. (2011)

different density profiles

- answer: ***YES! it matters big time!***

- however: this is good, because it may explain some of the theoretical controversy, we (currently) have in the field
(hopefully).

Girichids et al. (2011)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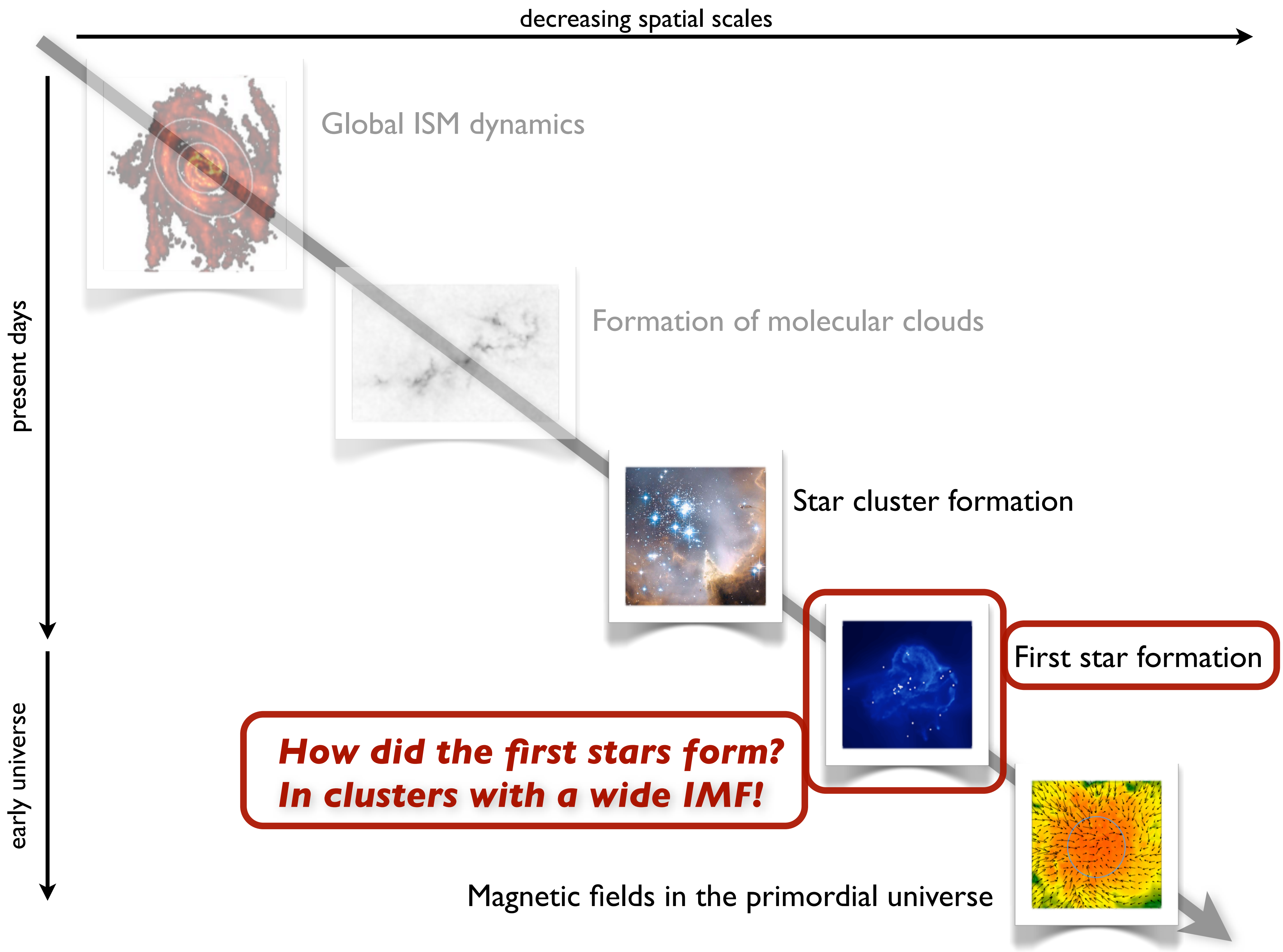
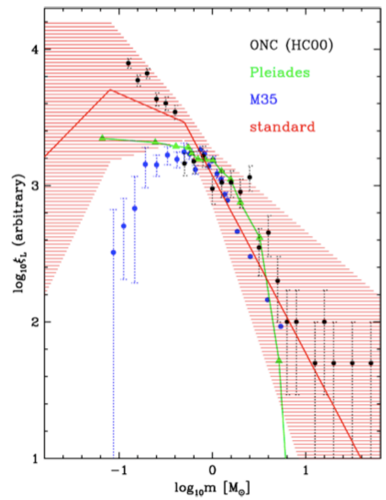

decreasing spatial scales
present days
early universe
Global ISM dynamics
Formation of molecular clouds
Star cluster formation
First star formation
How did the first stars form?
In clusters with a wide IMF!
Magnetic fields in the primordial universe

stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN



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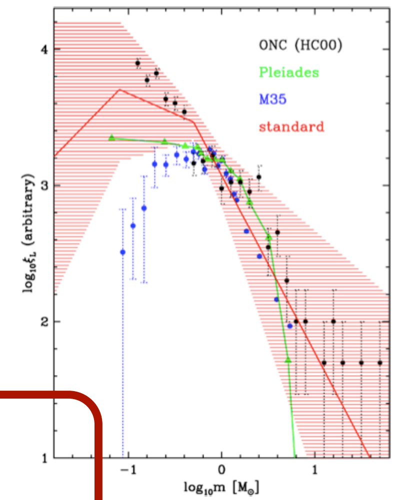
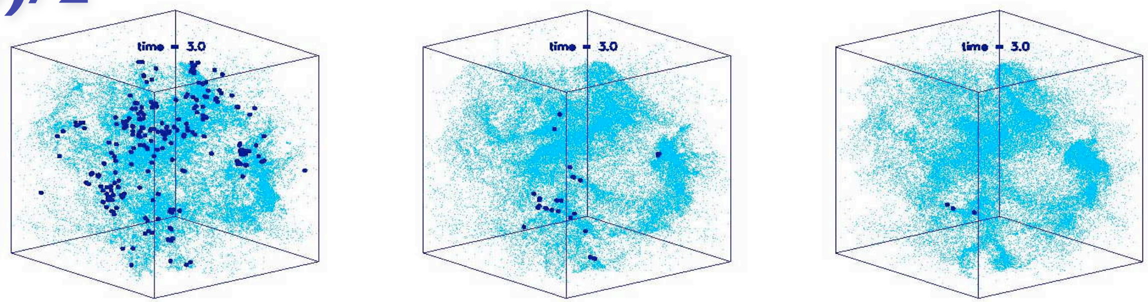


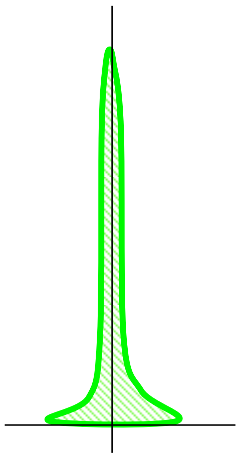
application to first star formation

fragmentation depends on EOS

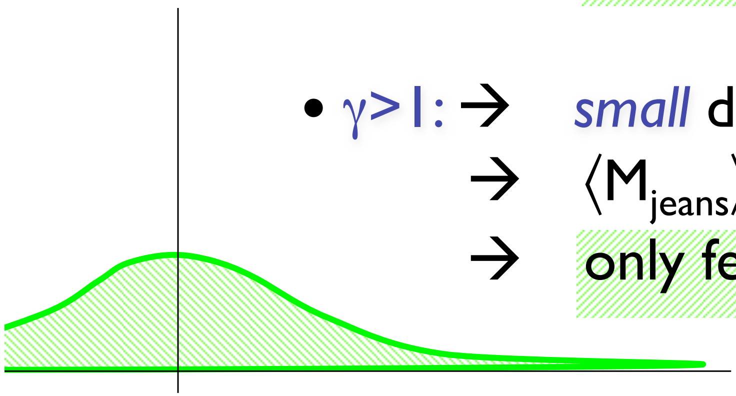
(1) $\mathbf{p} \propto \rho^{\gamma} \quad \rightarrow \quad \rho \propto \mathbf{p}^{1/\gamma}$

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





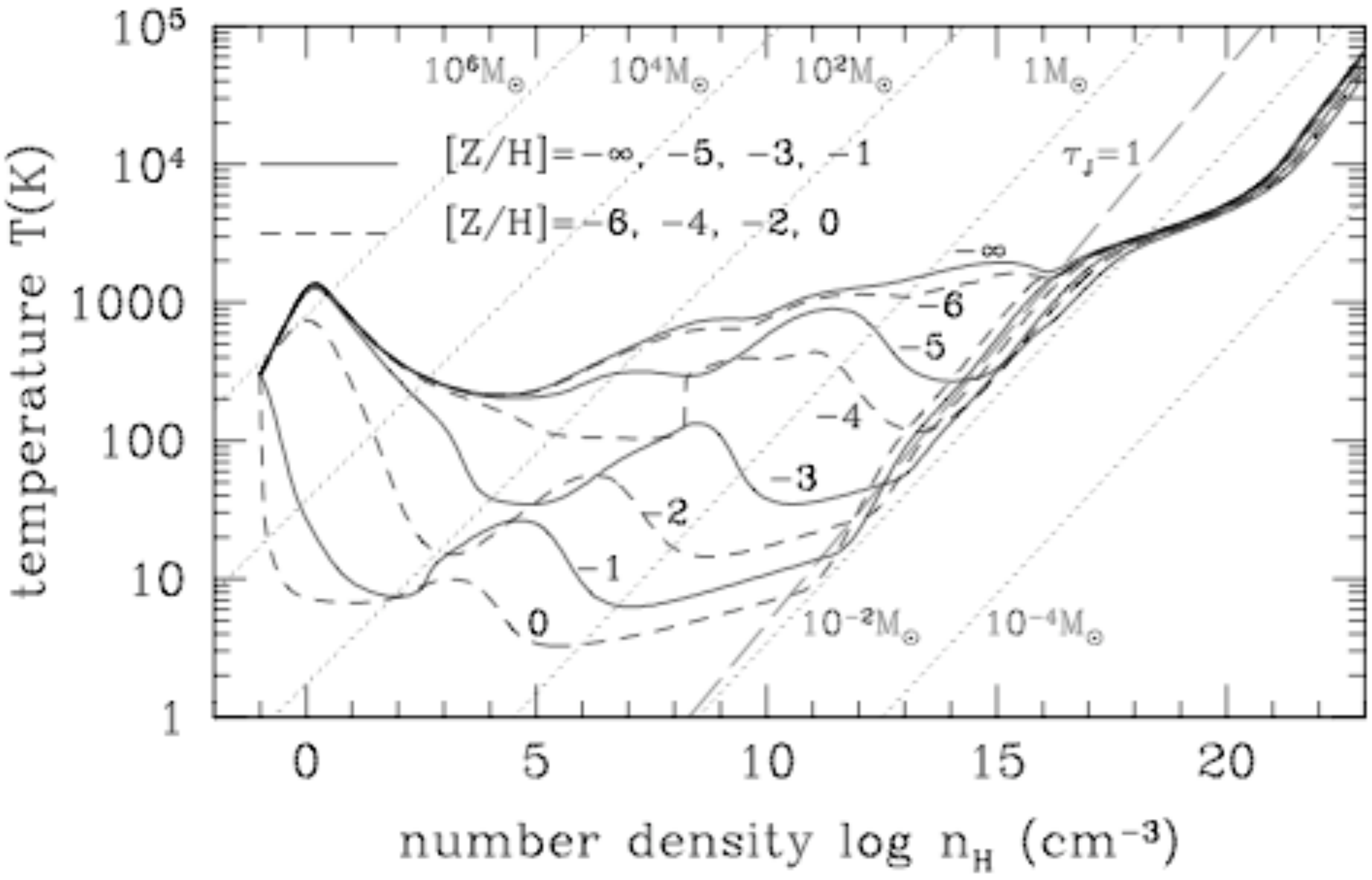
- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



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

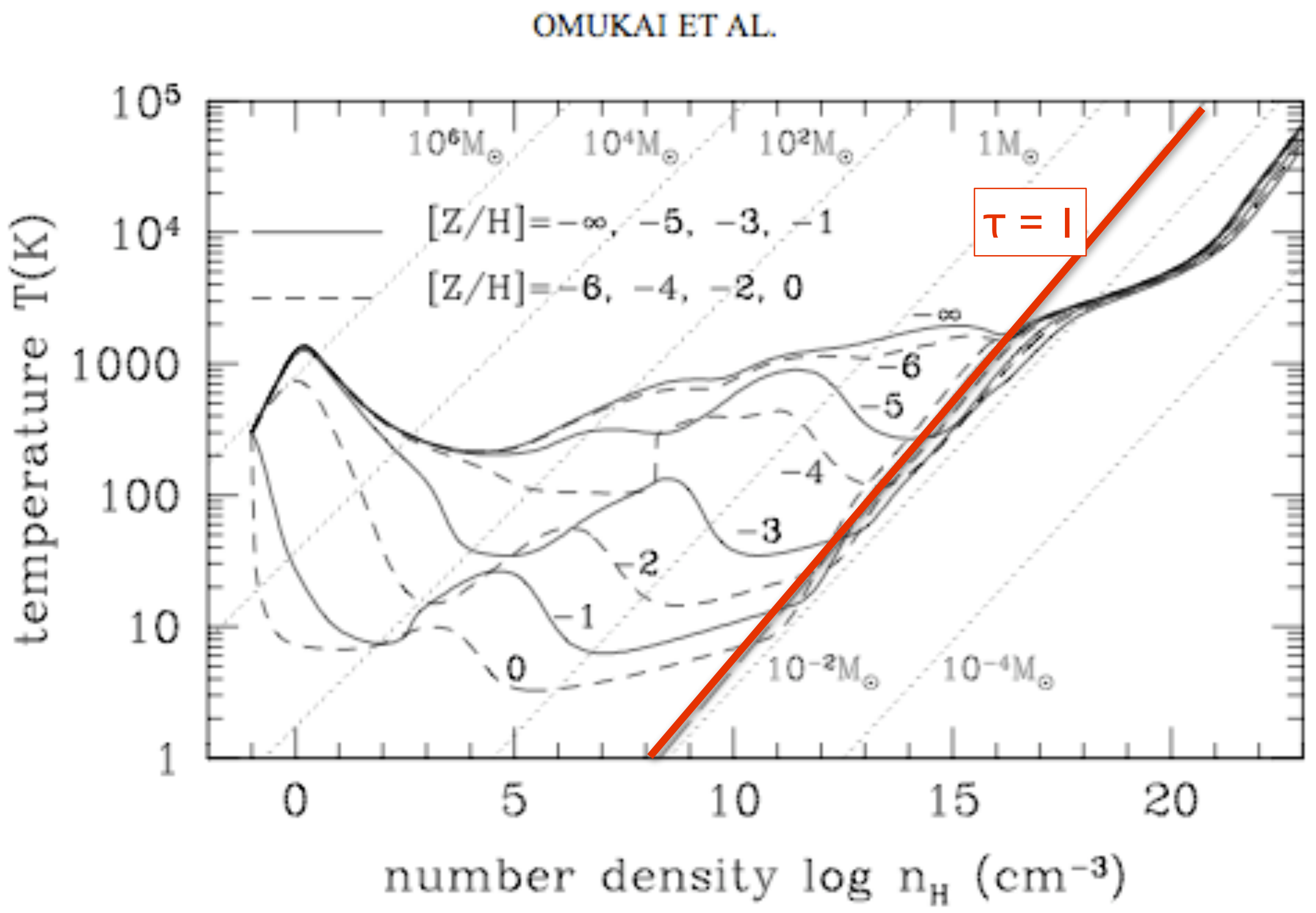
EOS as function of metallicity

OMUKAI ET AL.



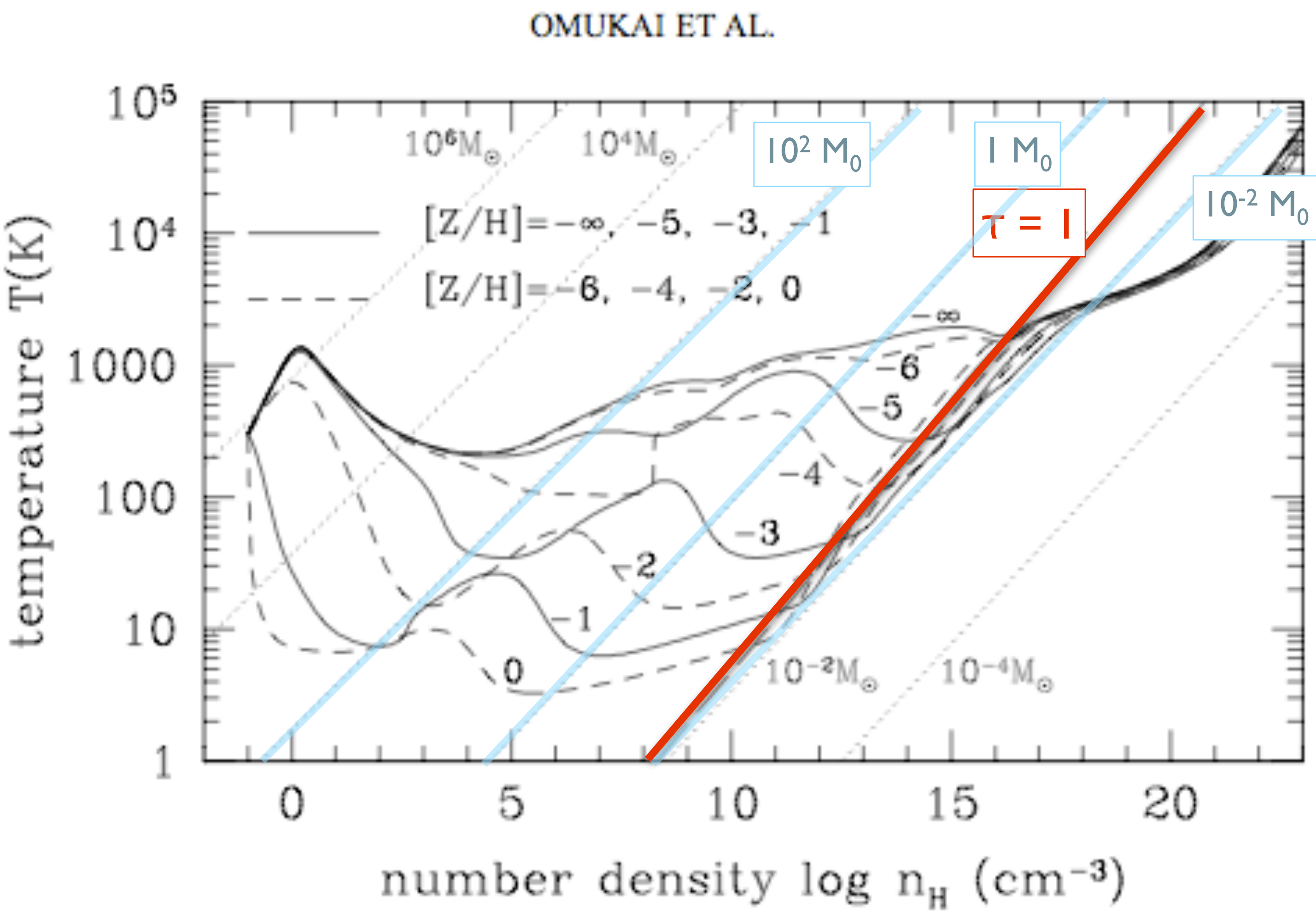
(Omukai et al. 2005)

EOS as function of metallicity



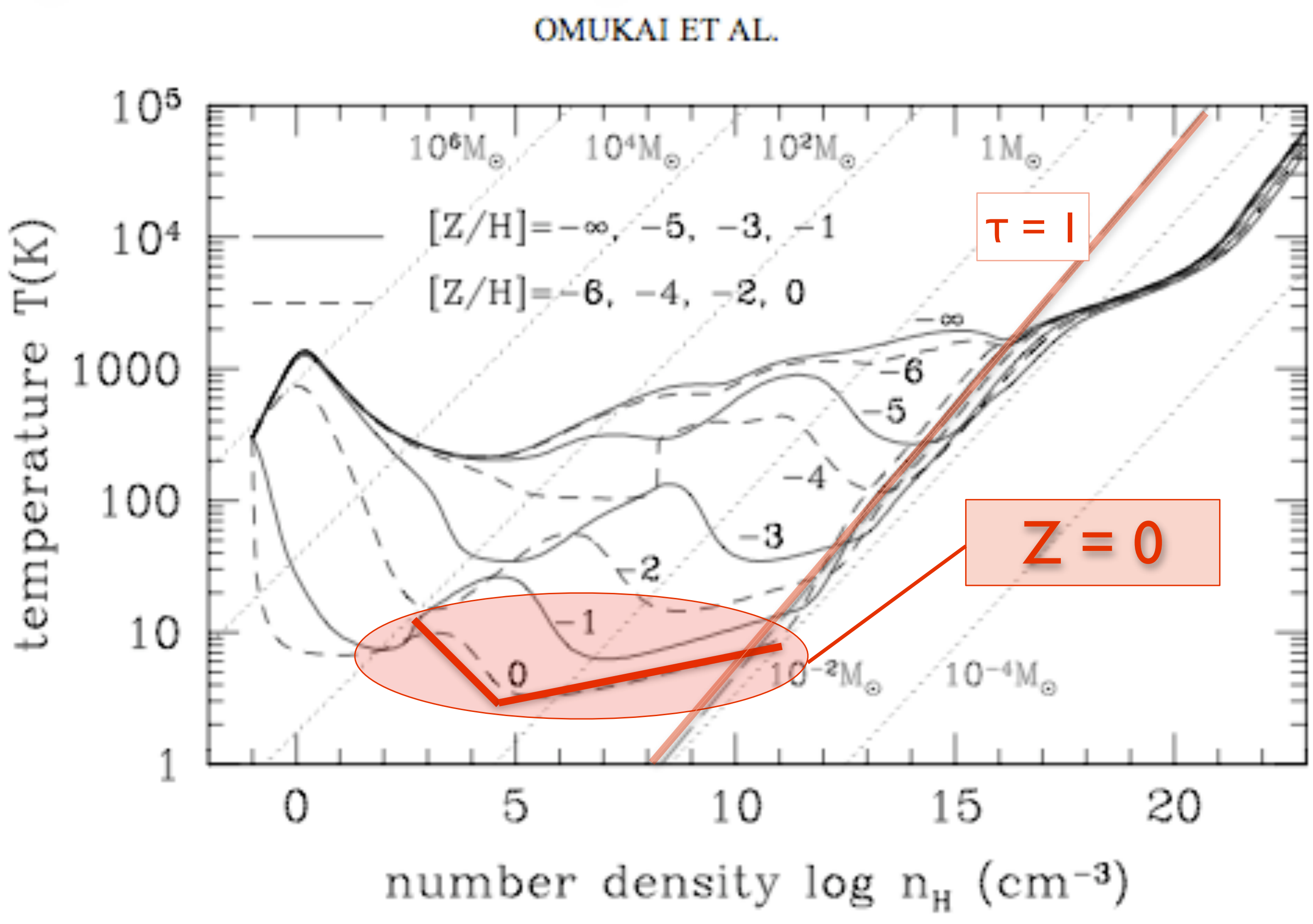
(Omukai et al. 2005)

EOS as function of metallicity



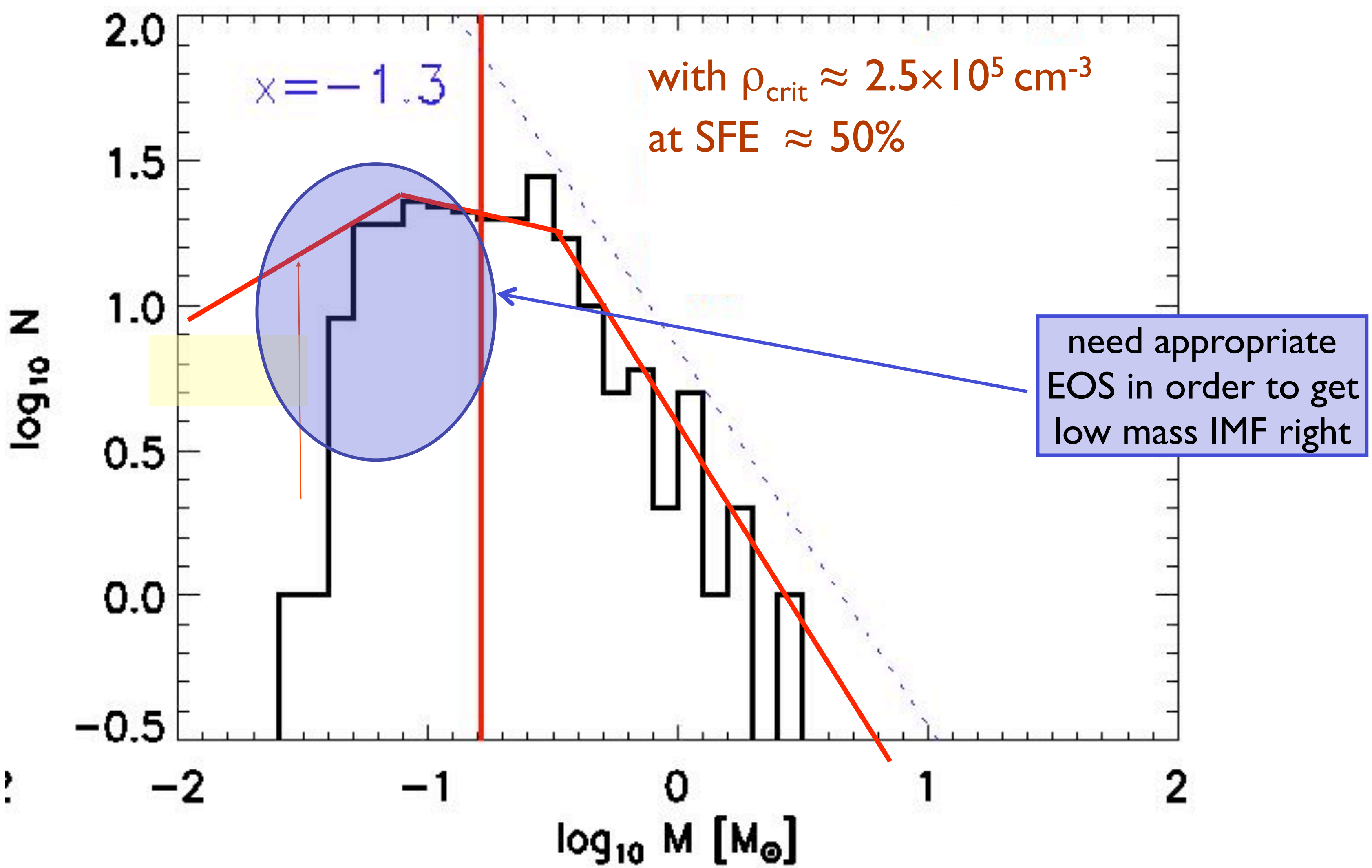
(Omukai et al. 2005)

present-day star formation



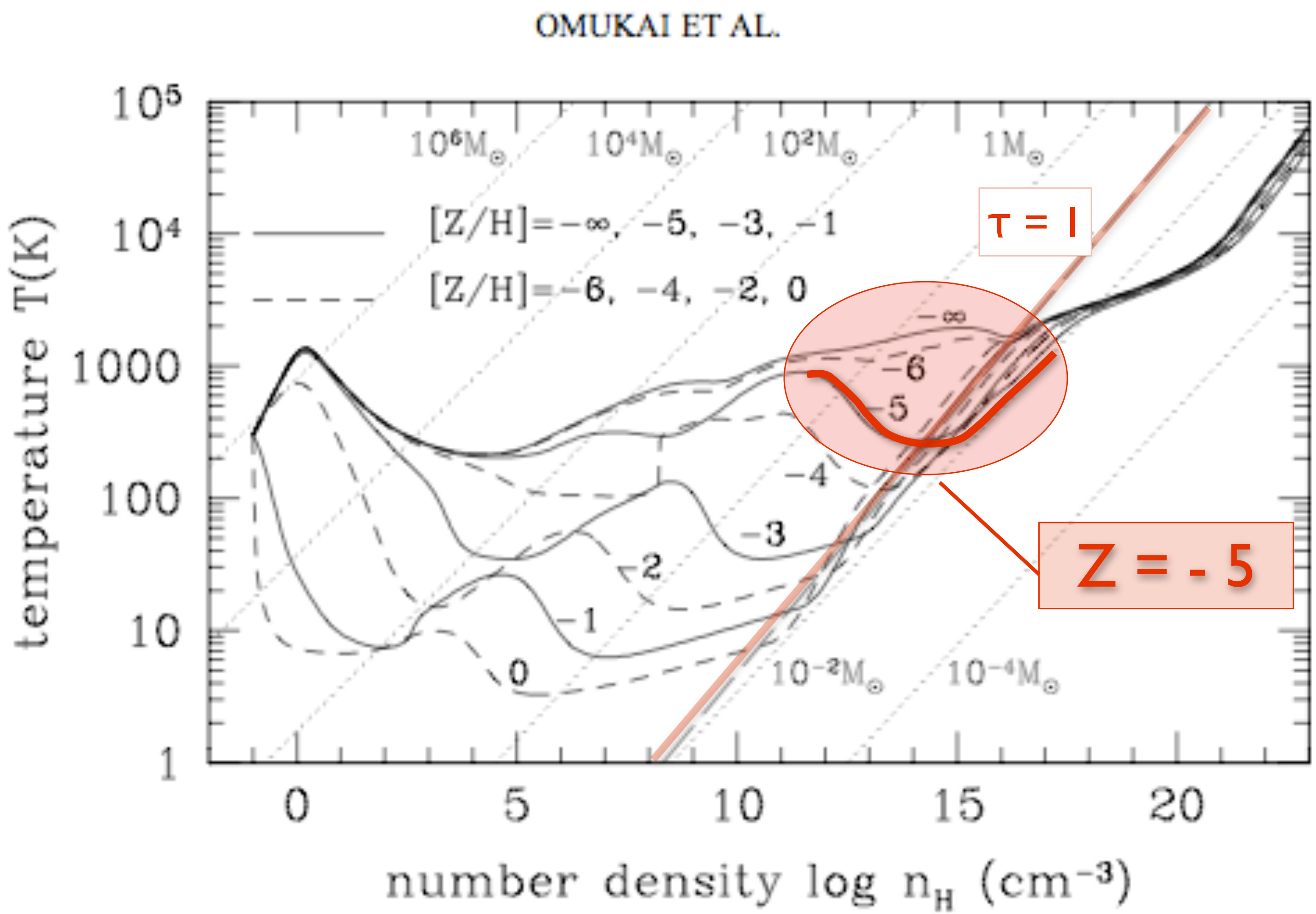
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

IMF in nearby molecular clouds



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

transition: Pop III to Pop II.5



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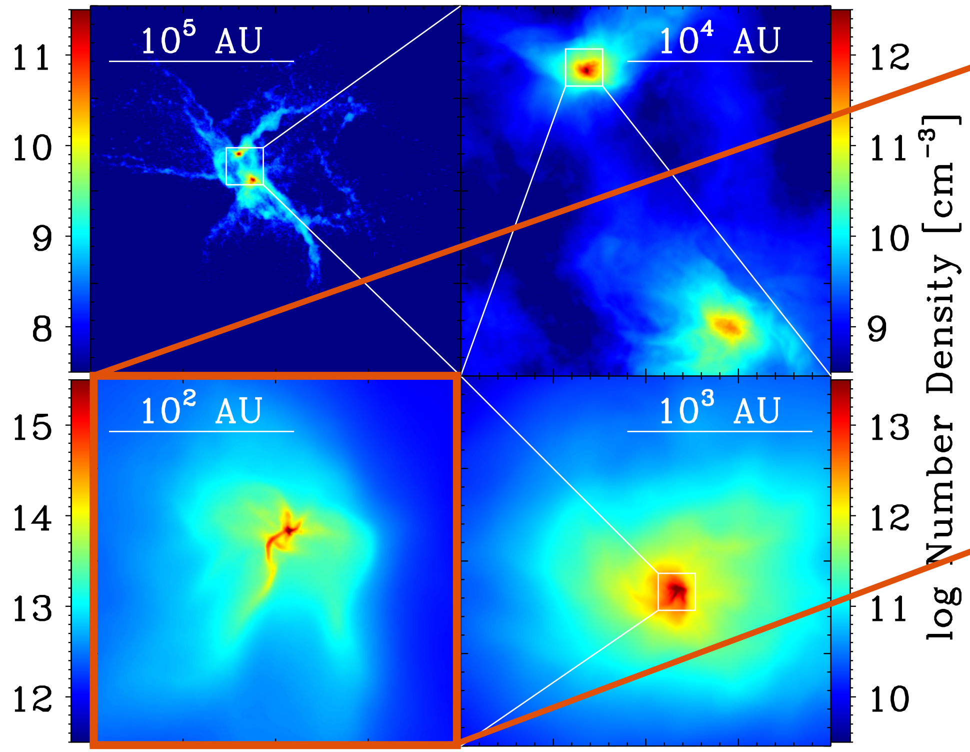


FIG. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

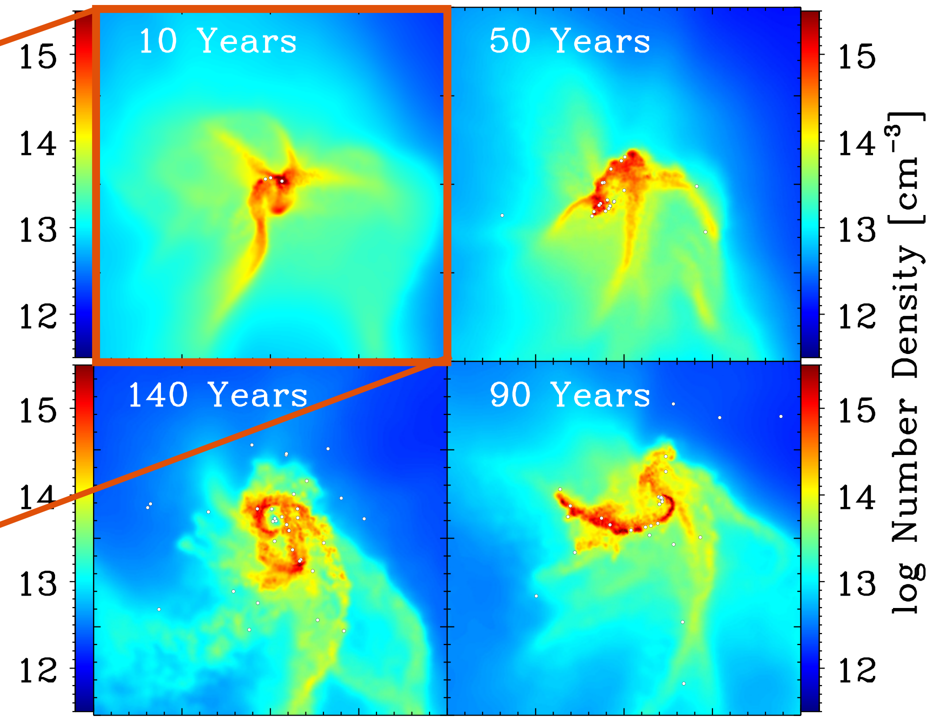
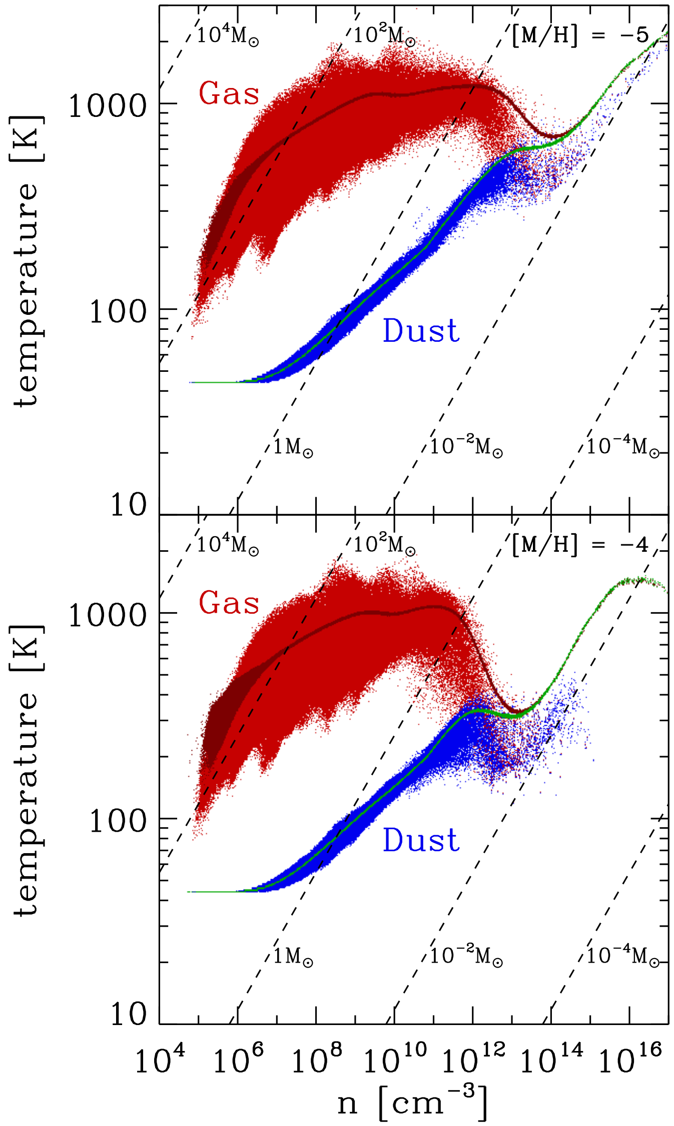


FIG. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and Z = $10^{-4}Z_{\odot}$. The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

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

transition: Pop III to Pop II.5



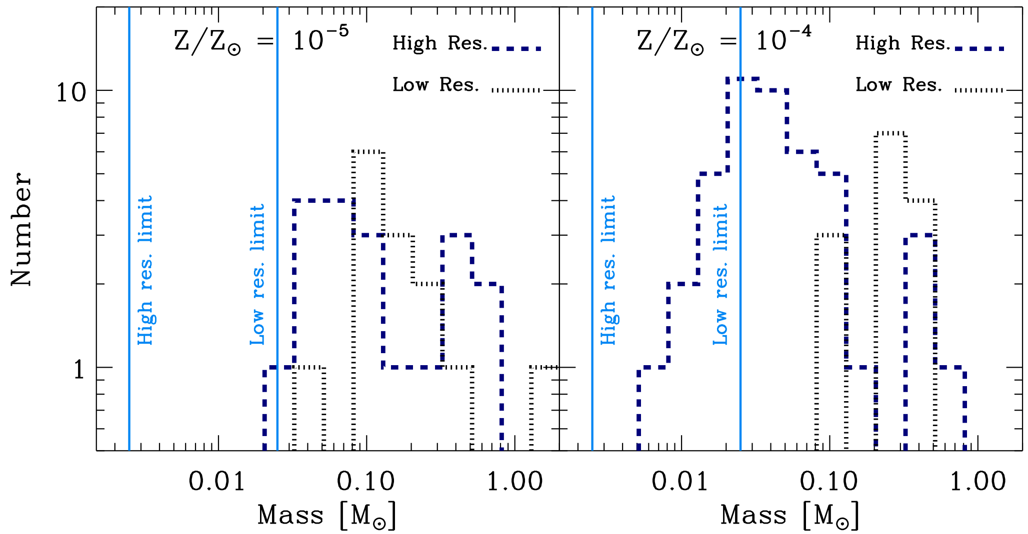
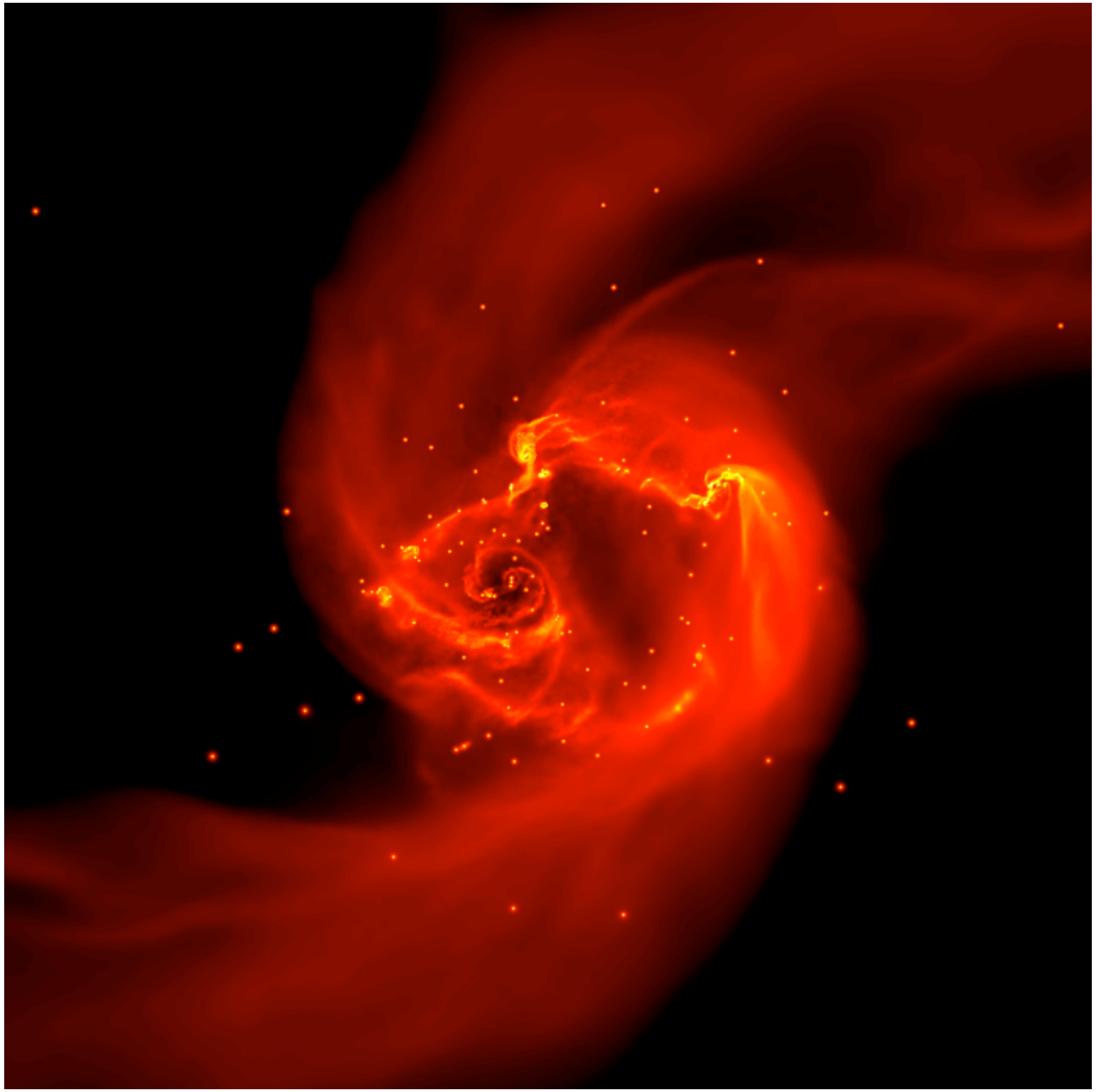


FIG. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas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

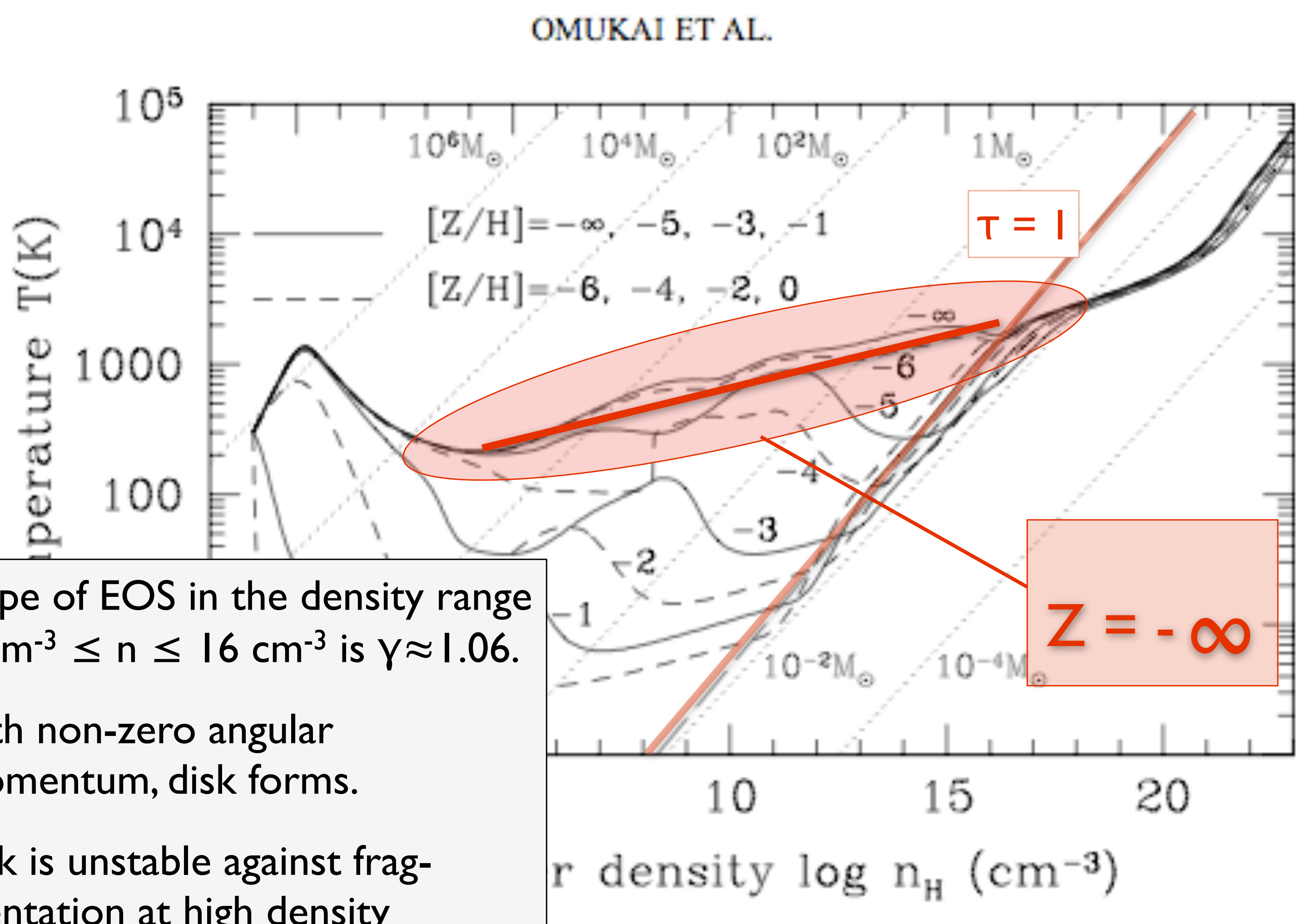


dense cluster of low-mass protostars builds up:

- 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)

metal-free star formation



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

(Omukai et al. 2005)

metal-free star formation

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

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

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

- there are some first hints of fragmentation, however

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

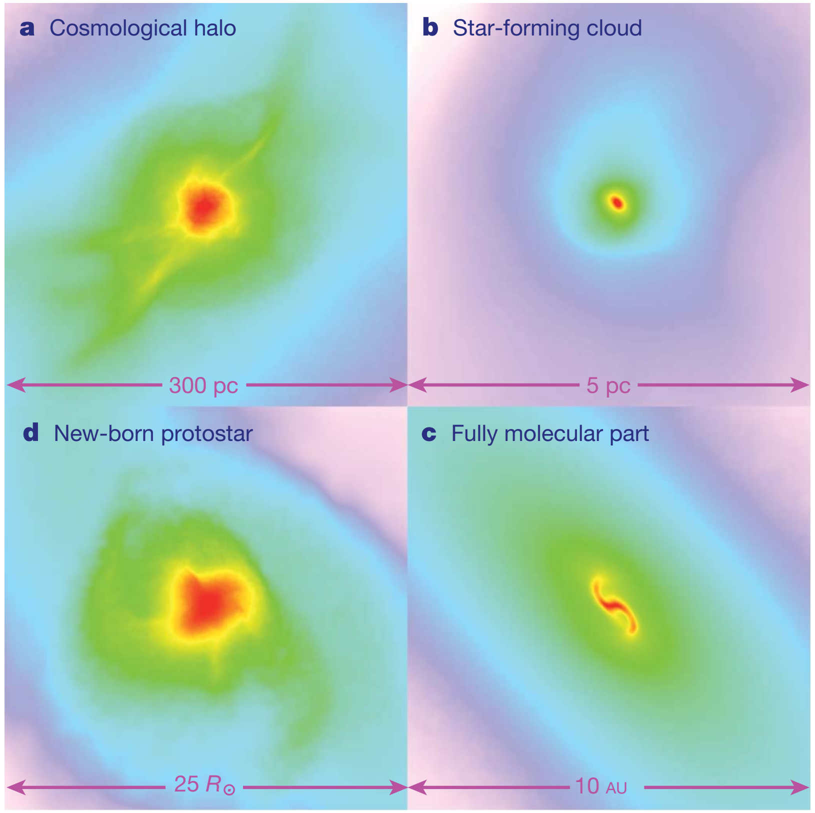
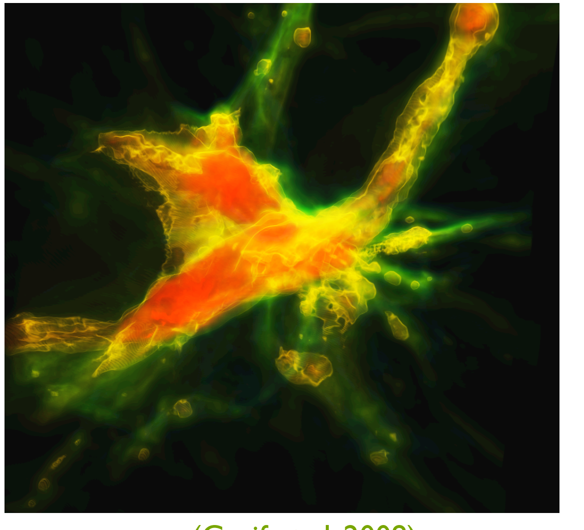


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming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

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

turbulence in Pop III halos

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

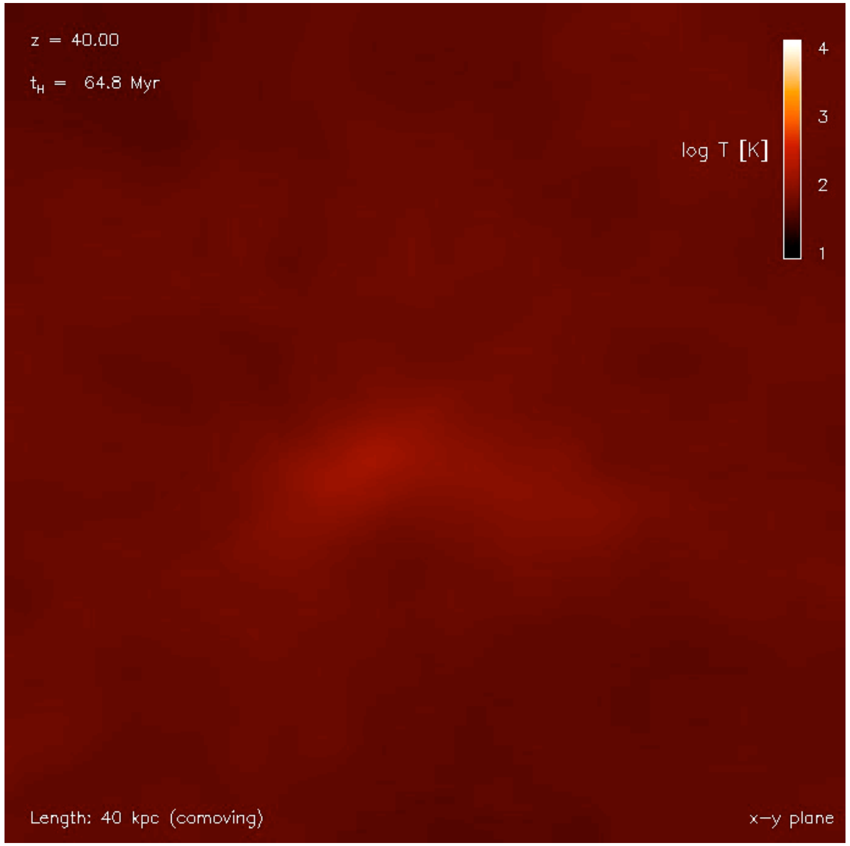


(Greif et al. 2008)

turbulence in Pop III halos

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

turbulence developing in an atomic cooling halo

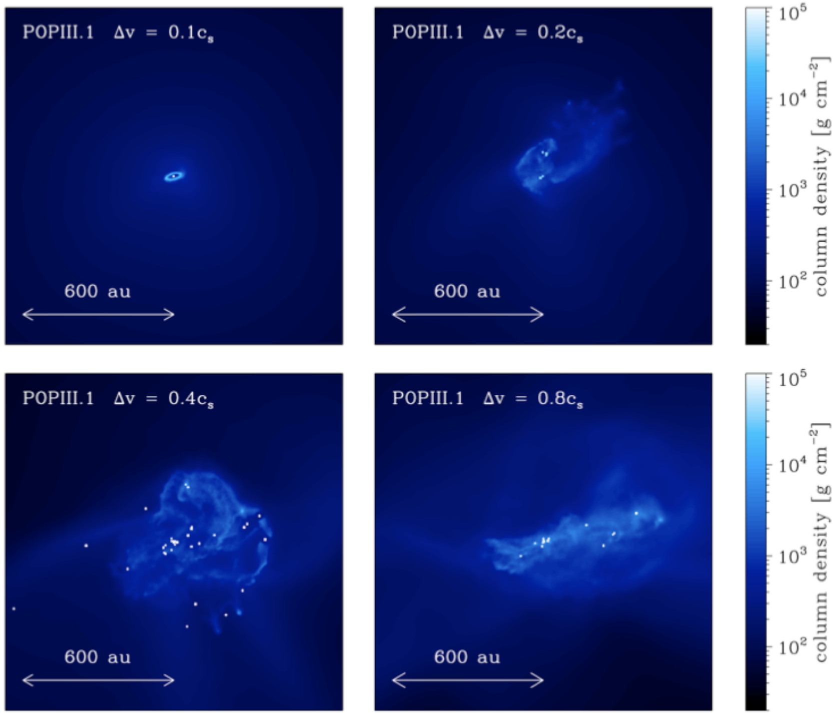


(Greif et al. 2008)

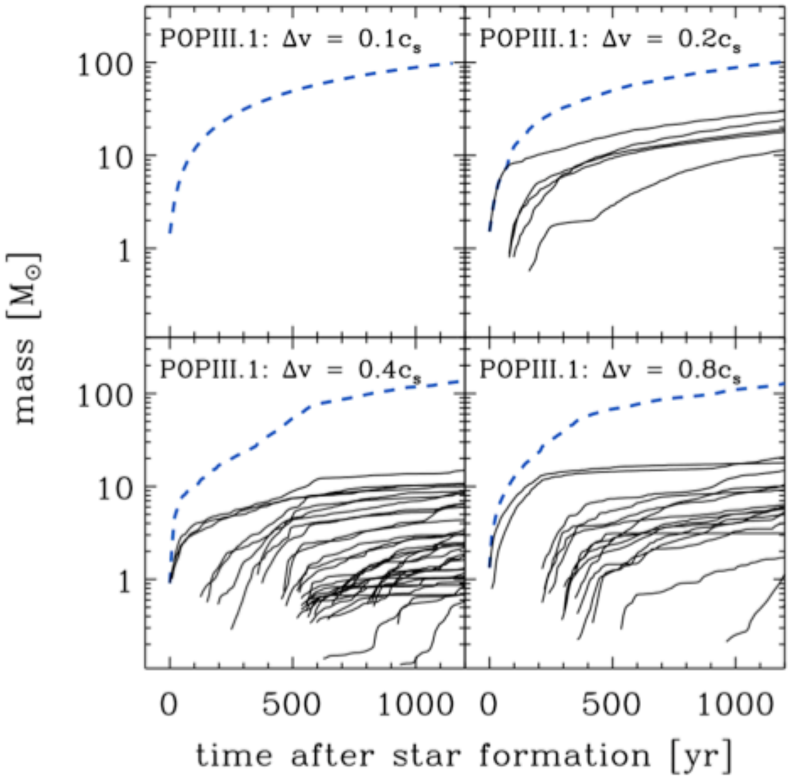
multiple Pop III stars in halo

- parameter study with different strength of turbulence using SPH: study Pop III.1 and Pop III.2 case (Clark et al., 2011a, ApJ, 727, 110)
- 2 very high resolution studies of Pop III star formation in cosmological context
  - SPH: Clark et al. 2011b, Science (arXiv:1101.5284)
  - Arepo: Greif et al. 2011a, ApJ, submitted (arXiv:1101.5491)
  - complementary approaches with interesting similarities and differences....

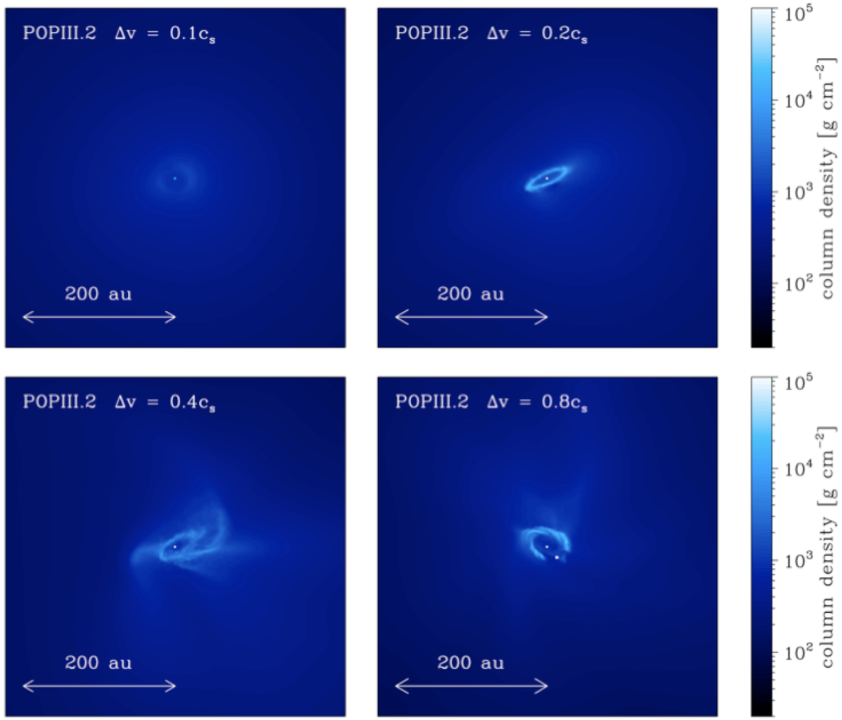
Pop III.1

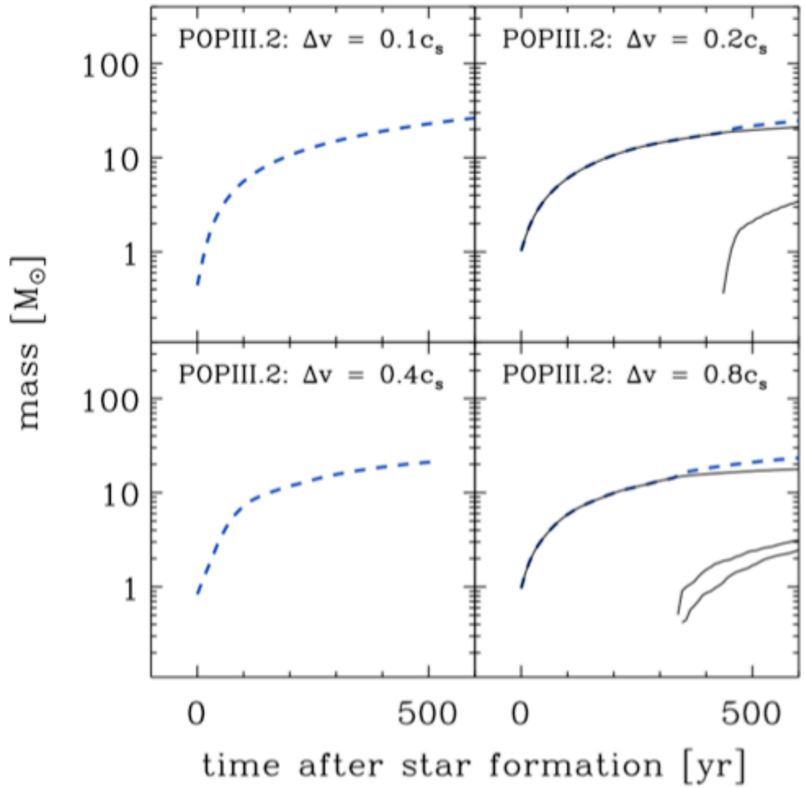


(Clark et al, 2011a)



Pop III.2





(Clark et al, 2011a)

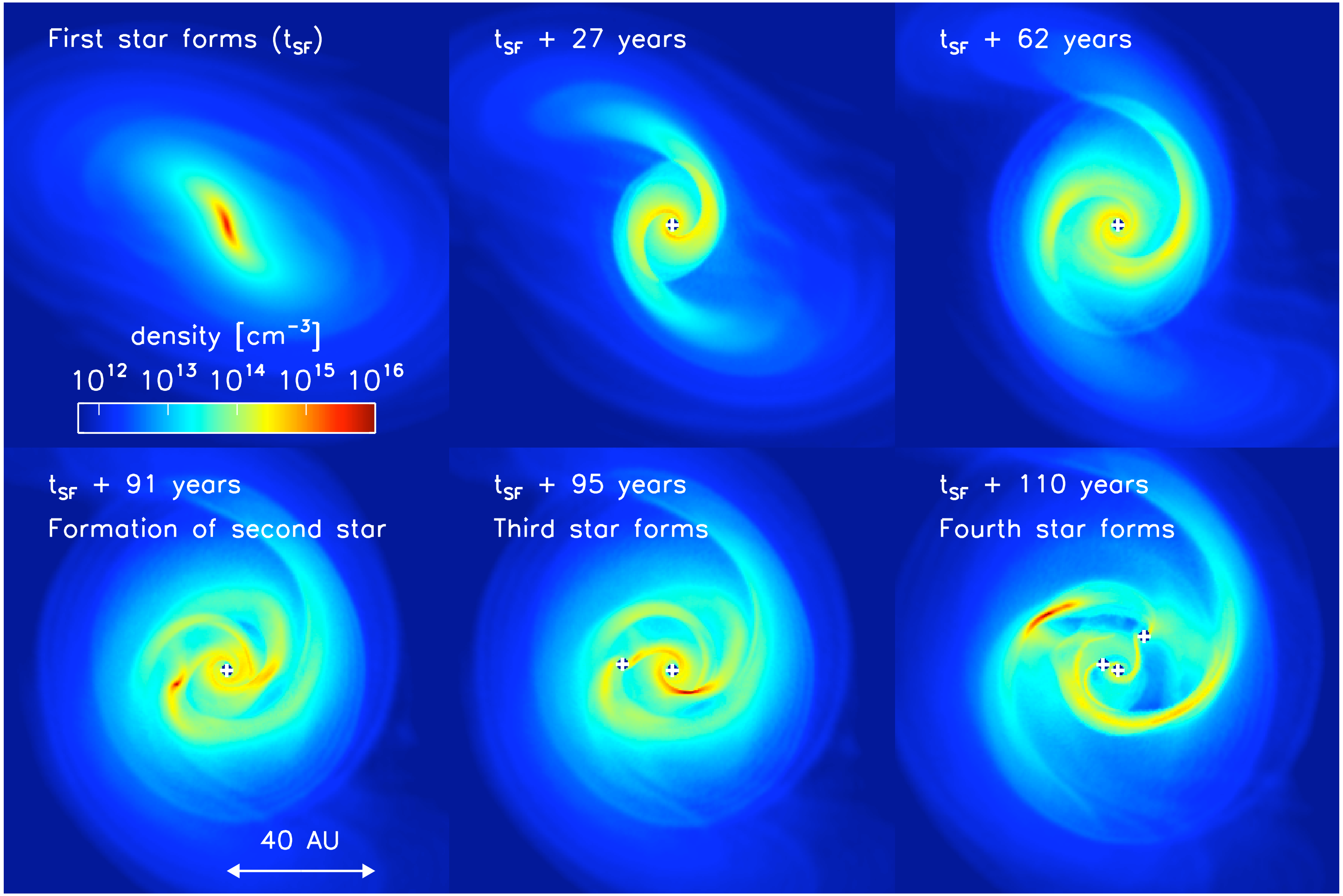


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

SPH study: face on look at accretion disk

(Clark et al. 2011b, Science)

SPH study: some disk parameters

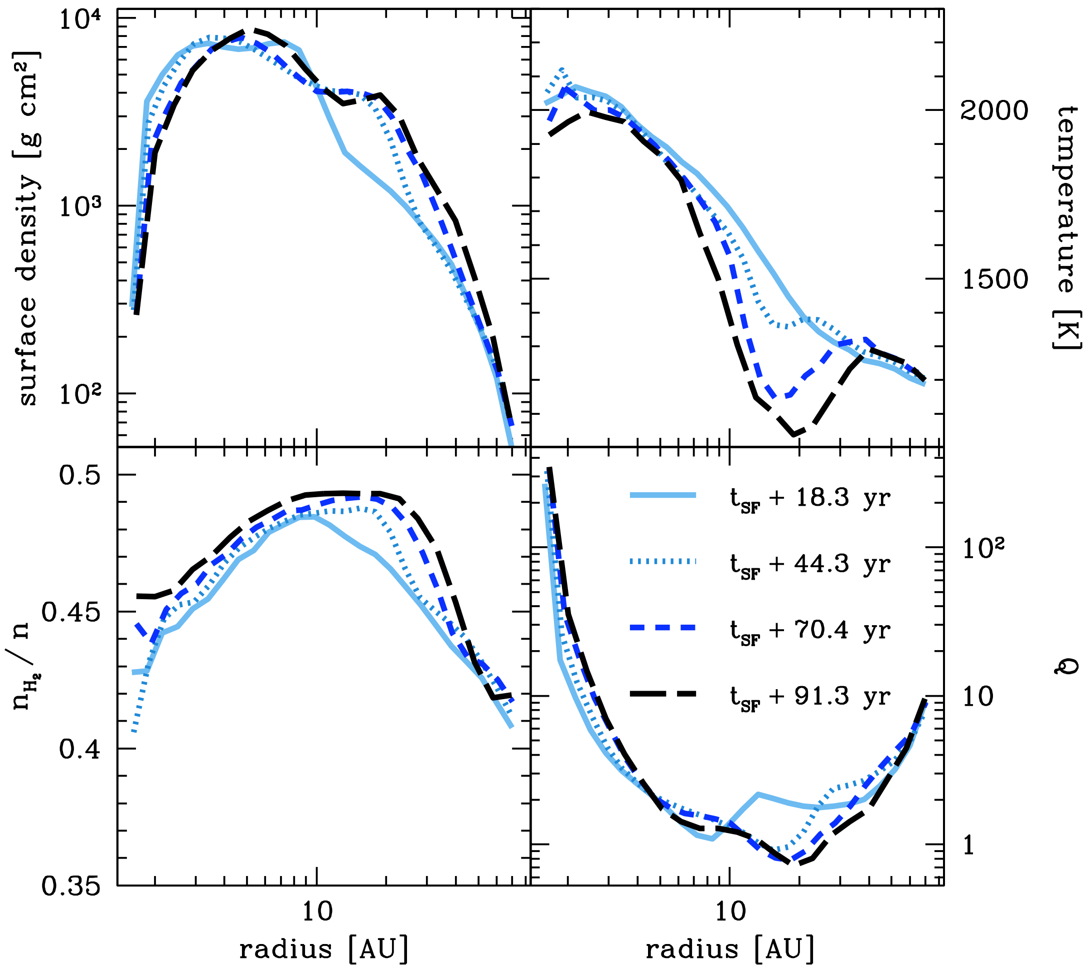


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi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

SPH study: mass accretion onto disk and onto protostars

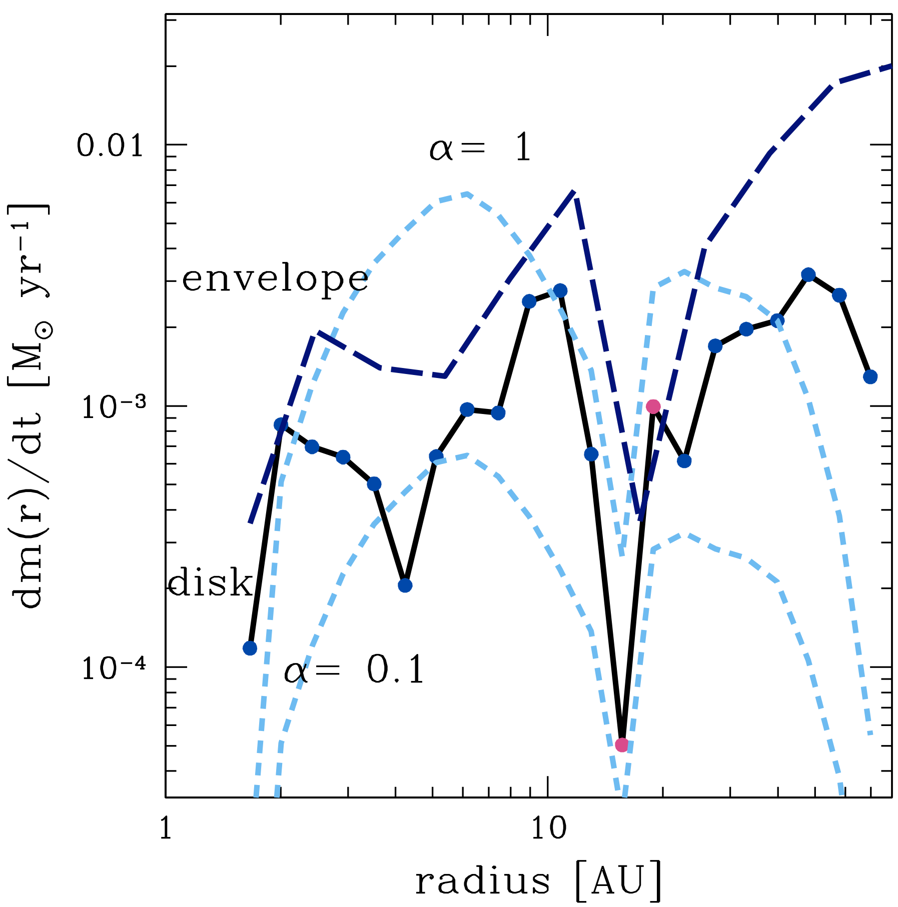


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure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

SPH study: comparison of all relevant heating and cooling processes

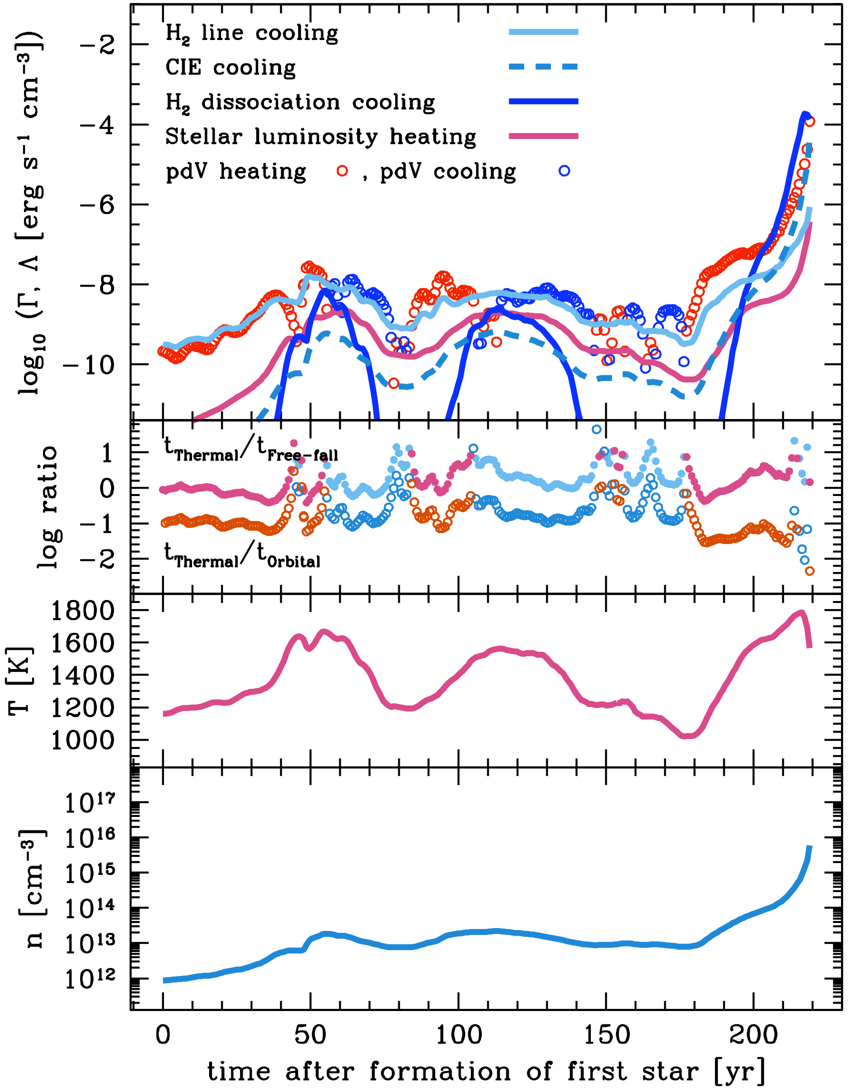
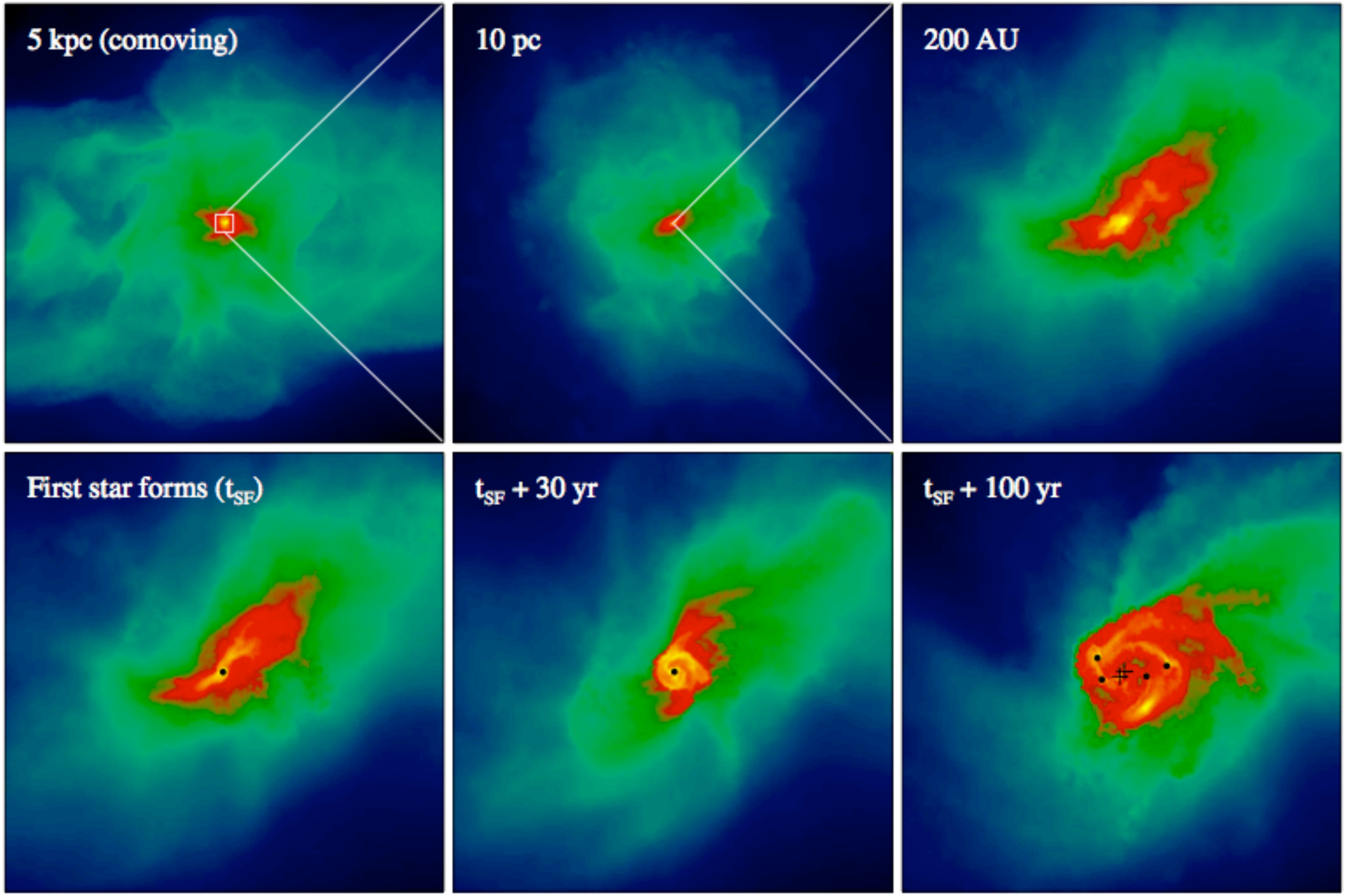


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated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

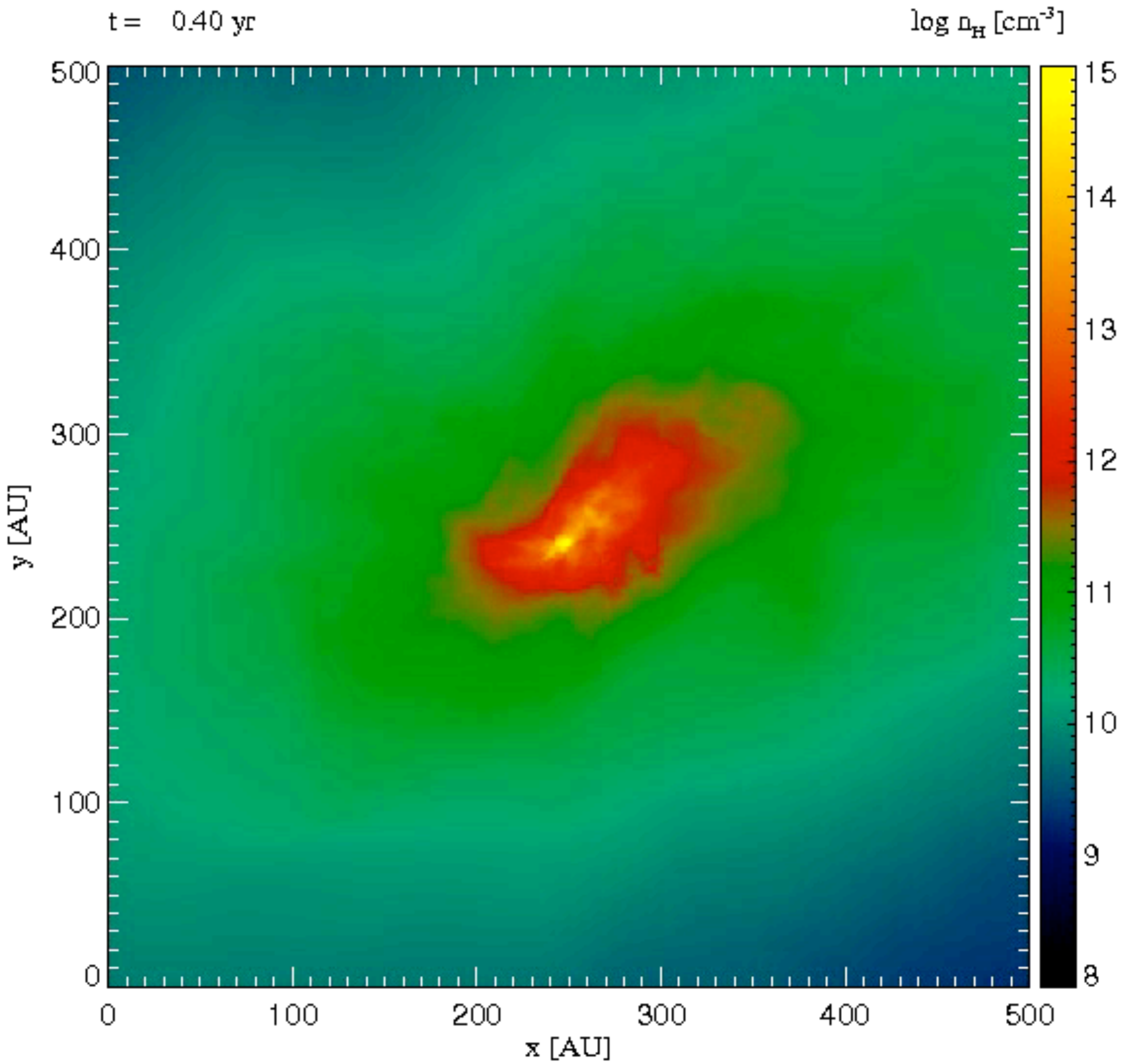
(Clark et al. 2011b, Science)

Arepo study: surface density at different times



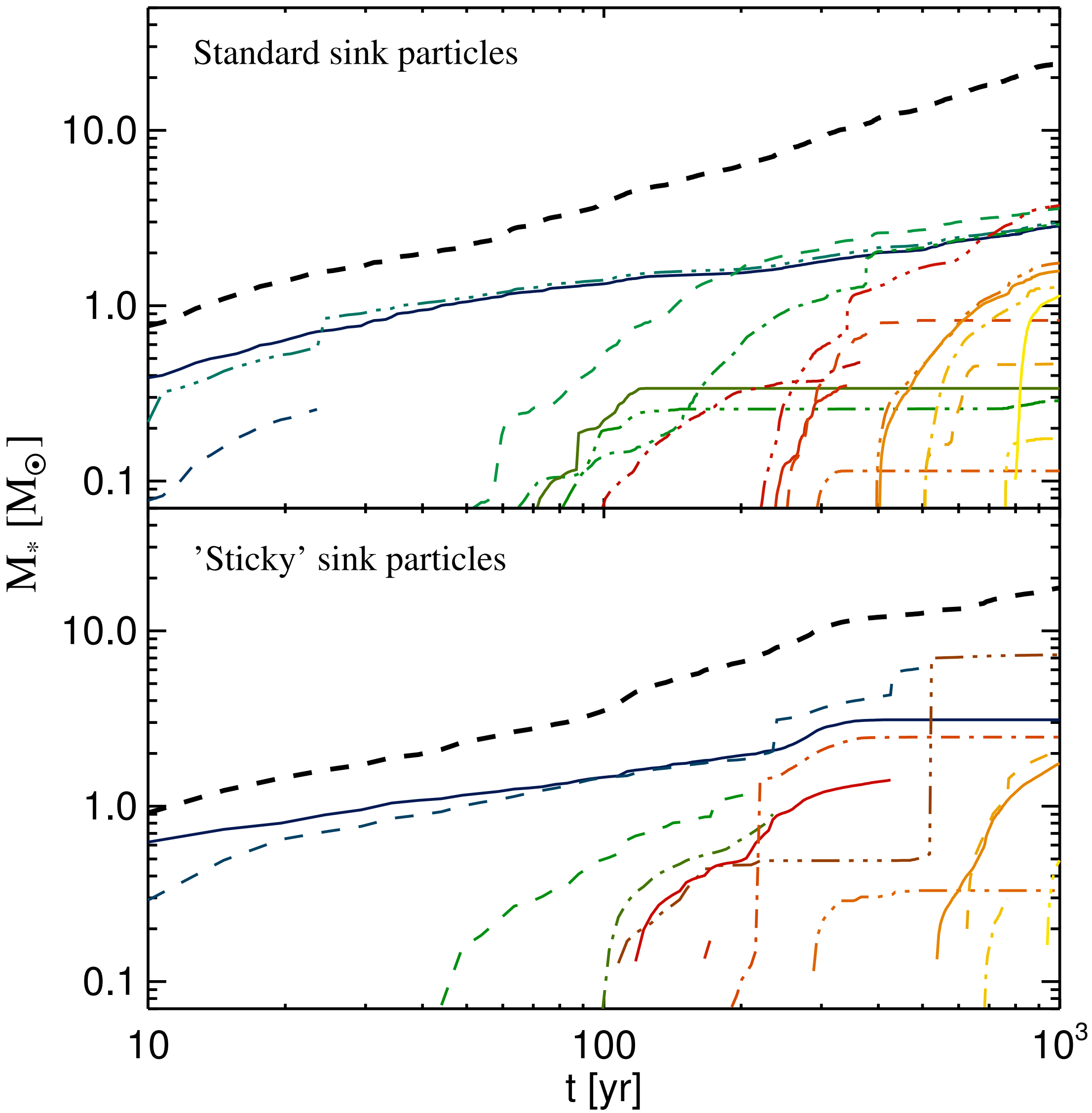
one out of five halos

(Greif et al. 2011a, submitted)



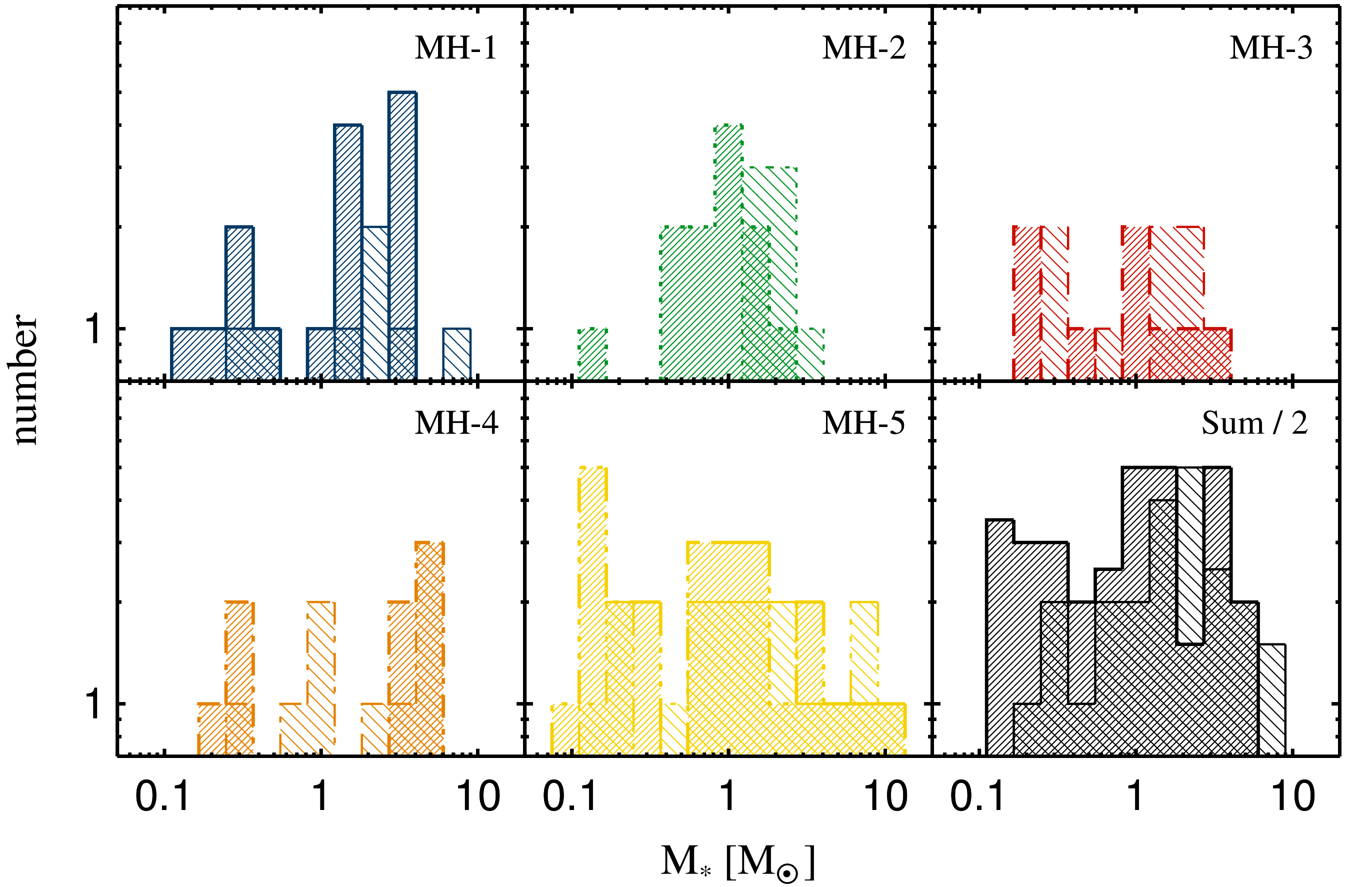
(Greif et al. 2011a, submitted)

Arepo study: protostellar mass accretion rates



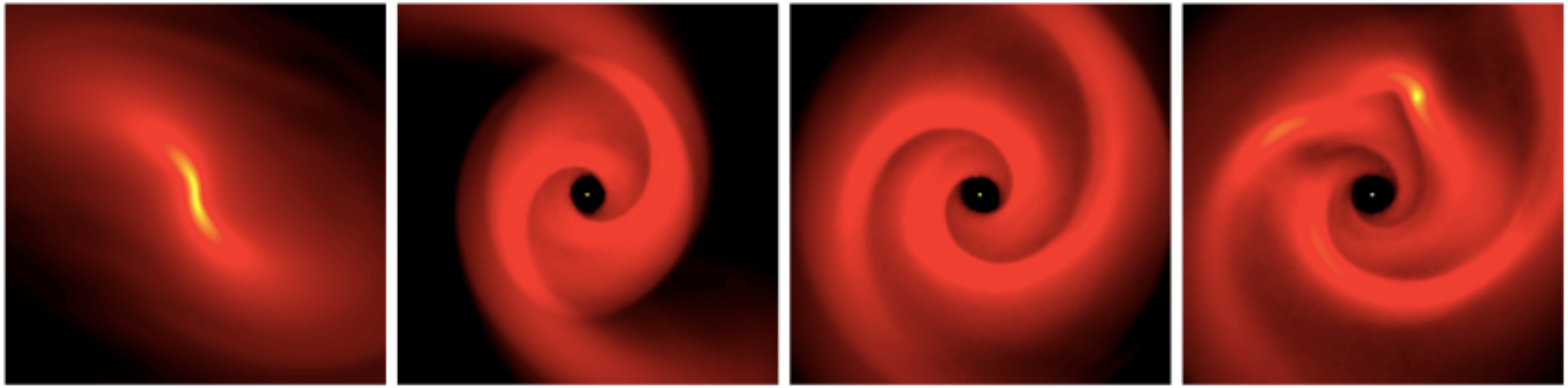
(Greif et al. 2011a, submitted)

Arepo study: mass spectrum of fragments



(Greif et al. 2011a, submitted)

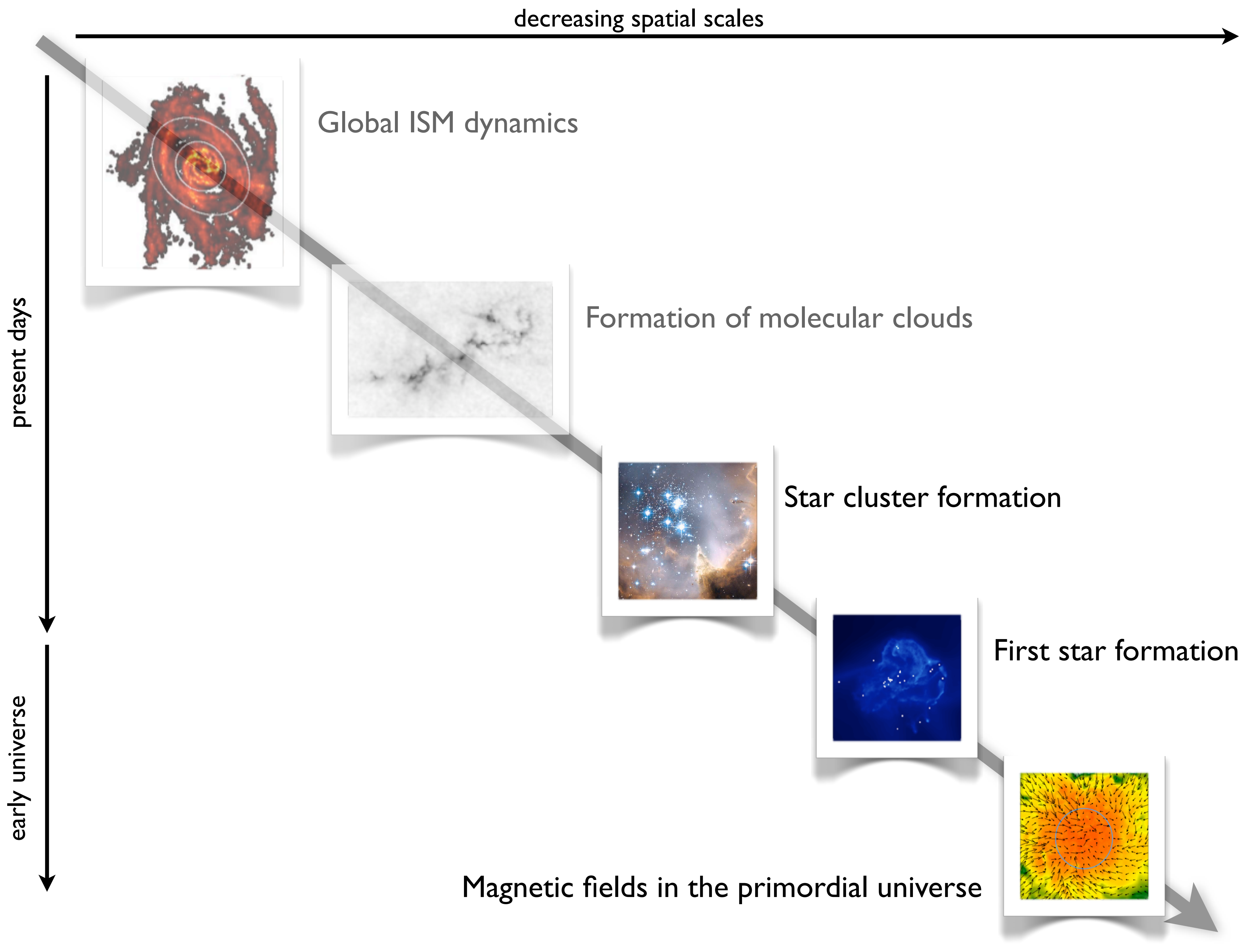
primordial star formation



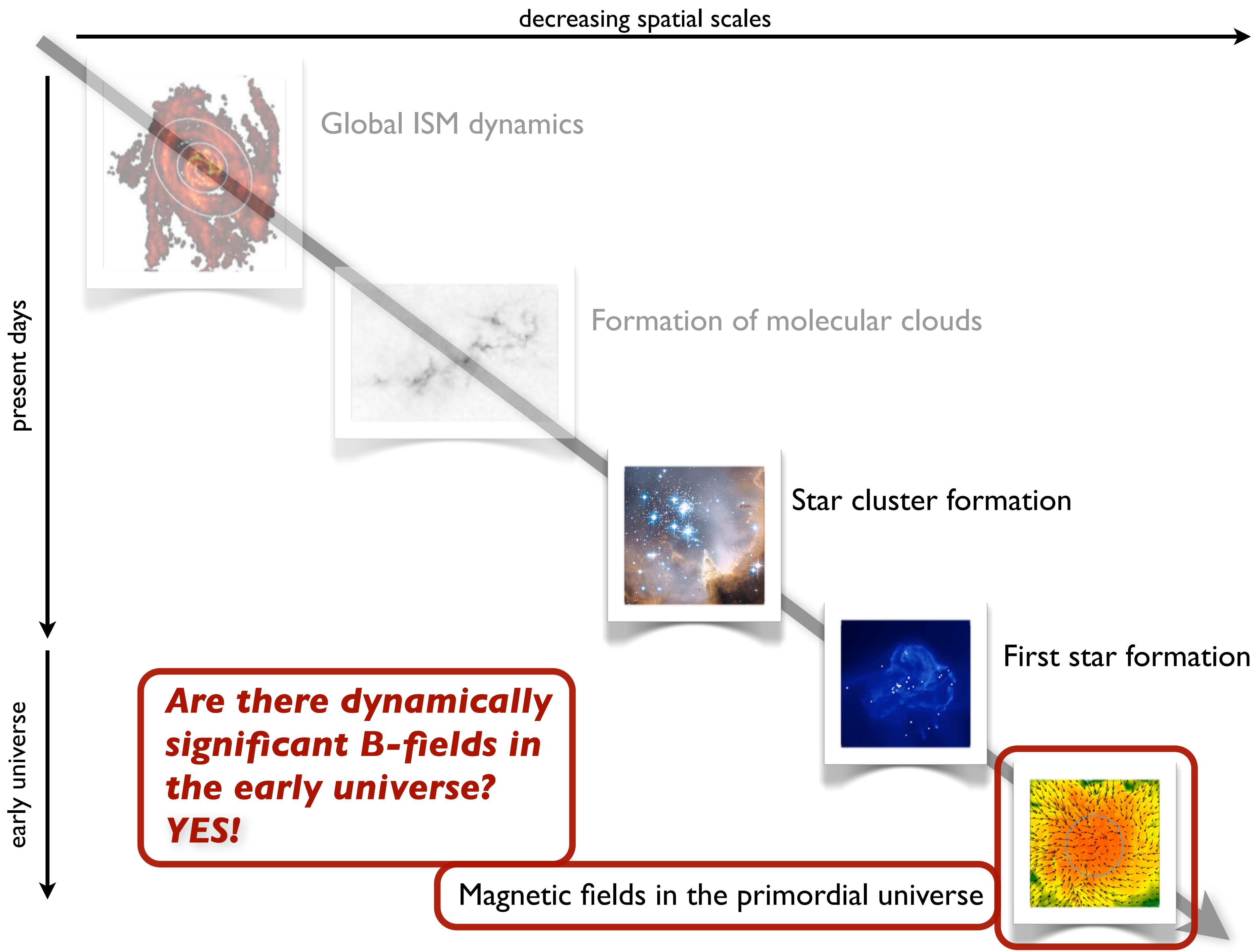
- first star formation is not less complex than present-day star formation
- brave claim: *all* Pop III stars form in multiple systems
- even braver claim: some Pop III stars fall in the mass range < 0.5 $M_\odot$ ---> they should still *be around*!!!!

questions

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



decreasing spatial scales
present days
early universe
Global ISM dynamics
Formation of molecular clouds
Star cluster formation
First star formation
Magnetic fields in the primordial universe


decreasing spatial scales
present days
early universe
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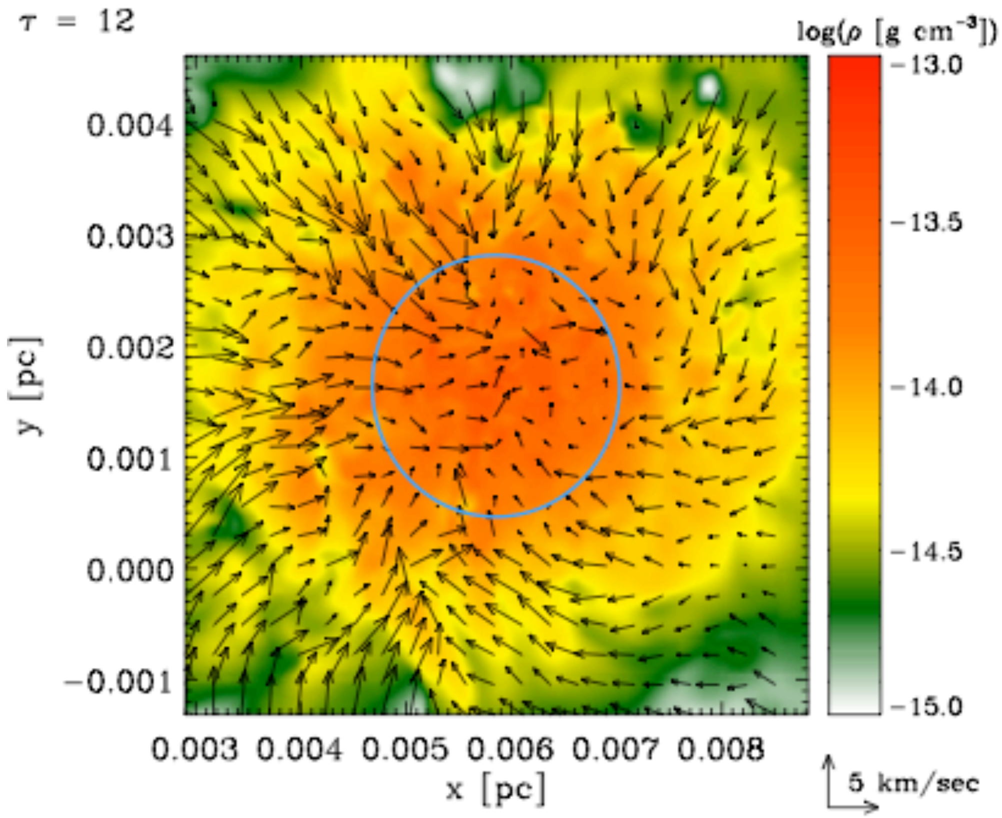
Formation of molecular clouds
Star cluster formation
First star formation
Are there dynamically significant B-fields in the early universe? YES!
Magnetic fields in the primordial universe

B fields in the early universe?

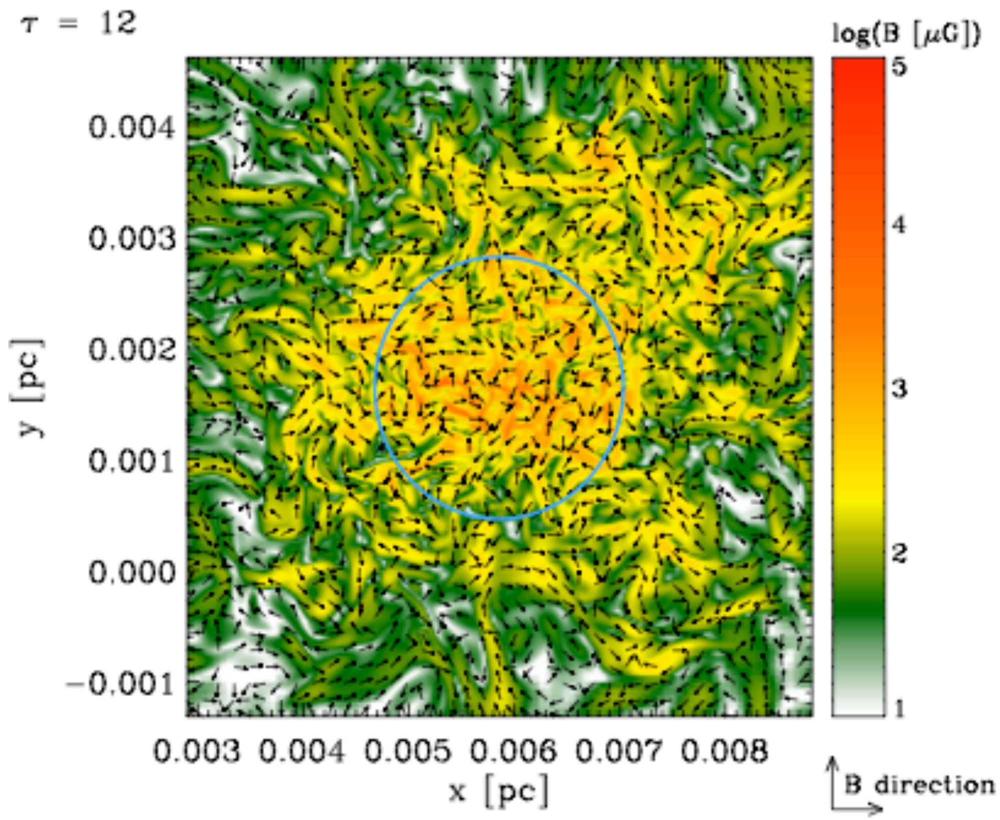
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

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 $z \sim 20$
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH (effective resolution 65536^3)

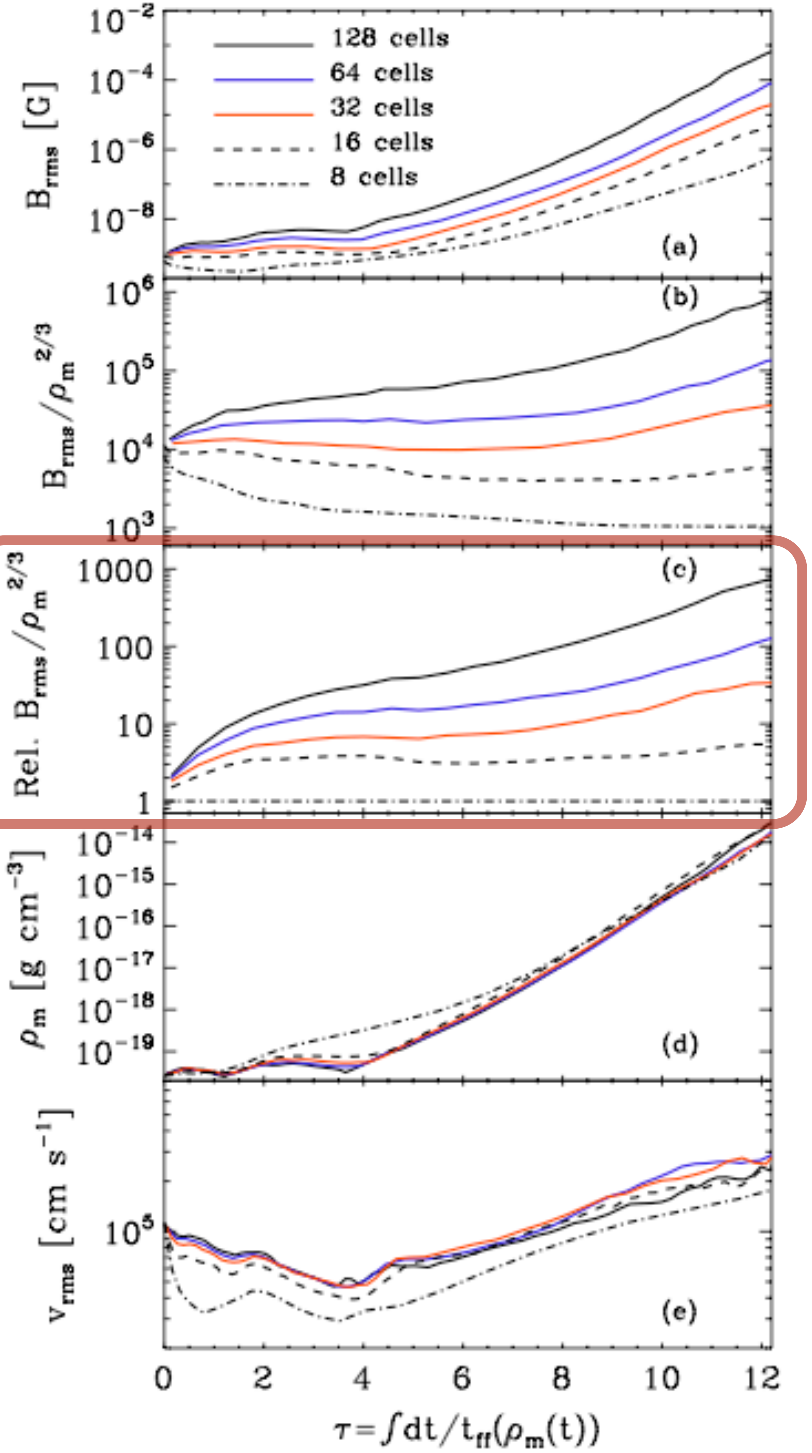


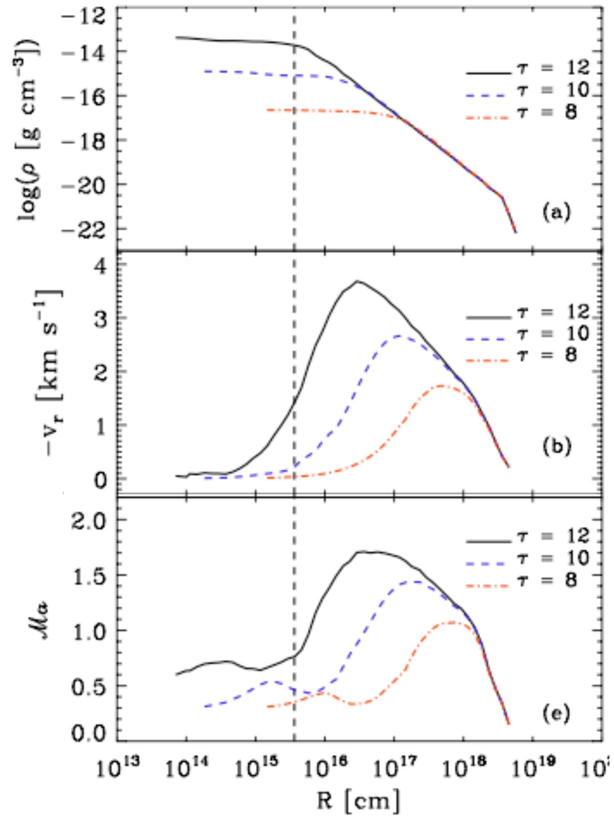
magnetic field structure



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:

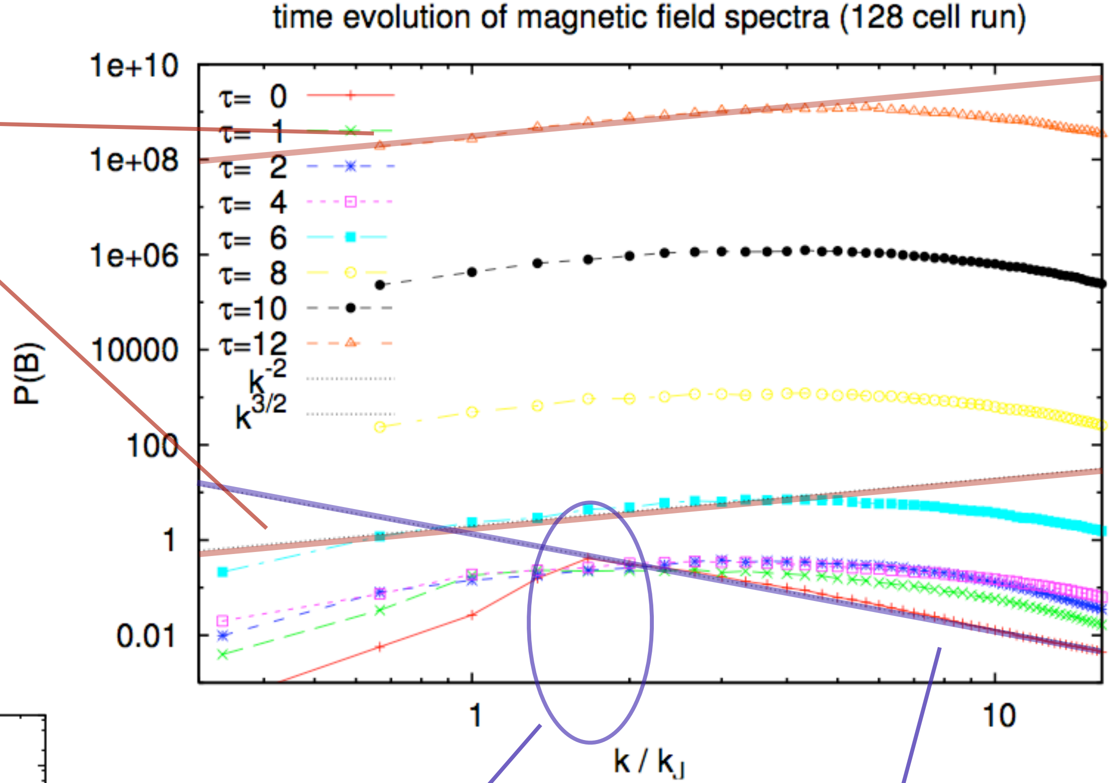
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

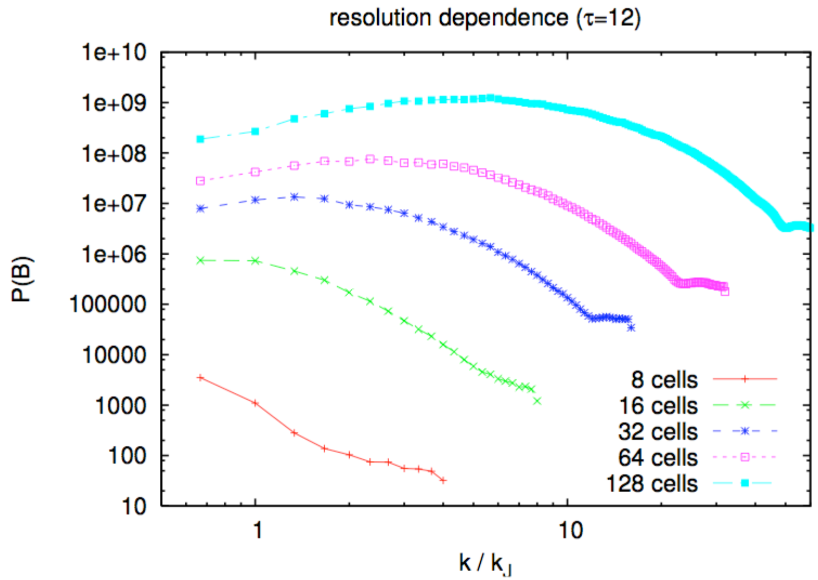
(Sur et al. 2010, ApJ, 721, L734)

analysis of magnetic field spectra

Slope +3/2 of Kazantsev theory

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



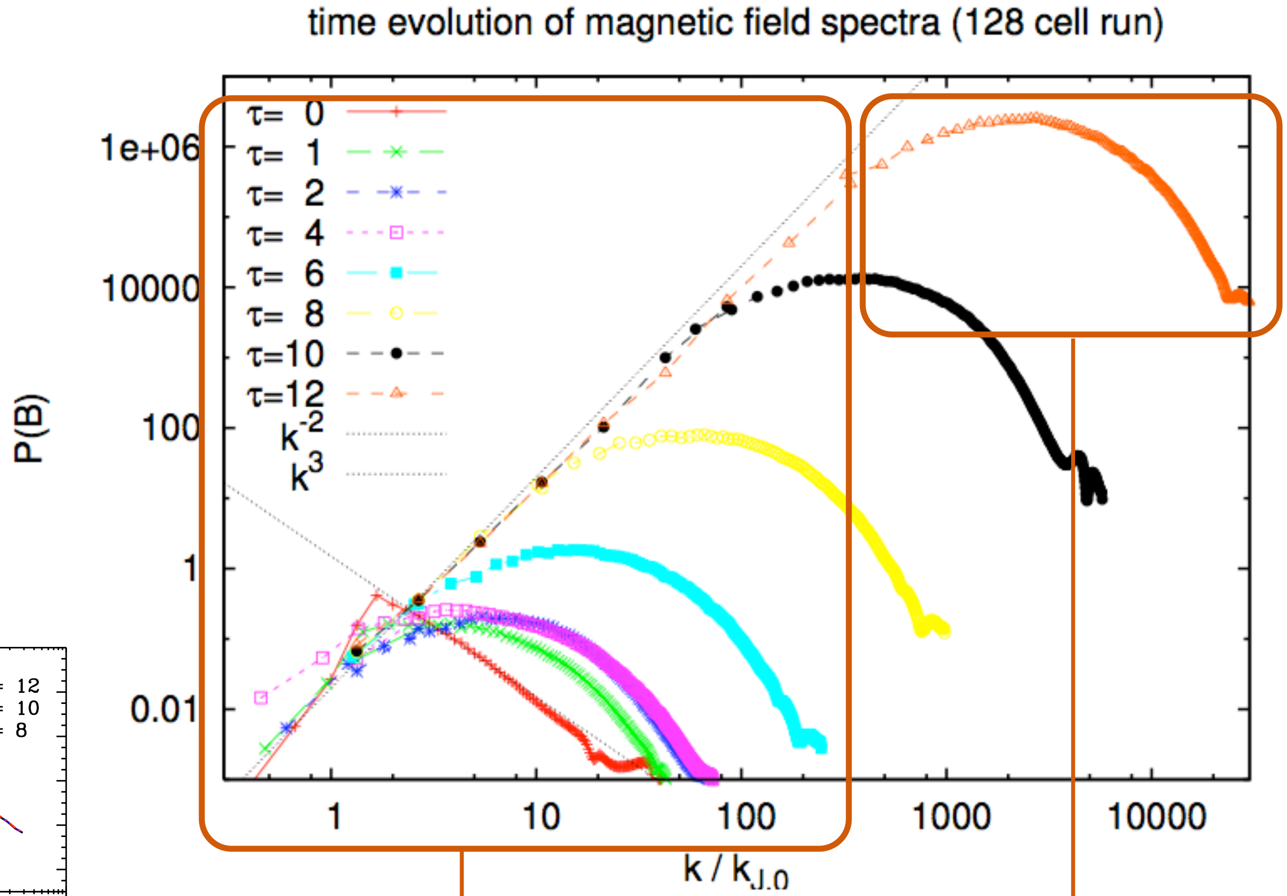


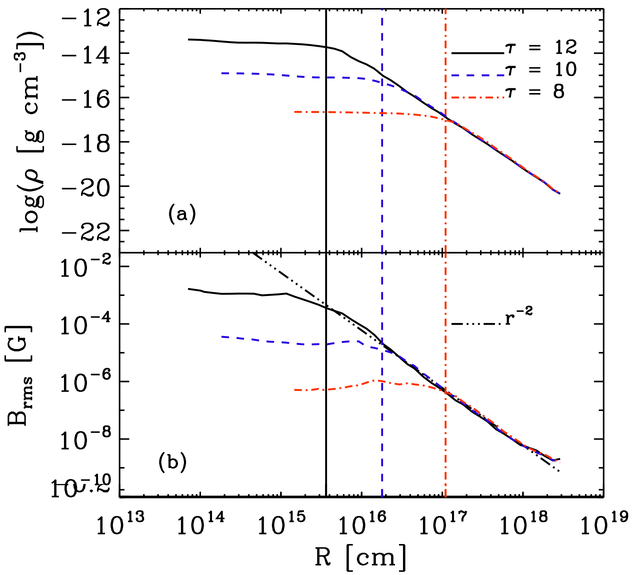
initial peak of B fluctuation spectrum

initial slope of B fluctuations

(Federrath et al., 2011, ApJ in press)

analysis of magnetic field spectra



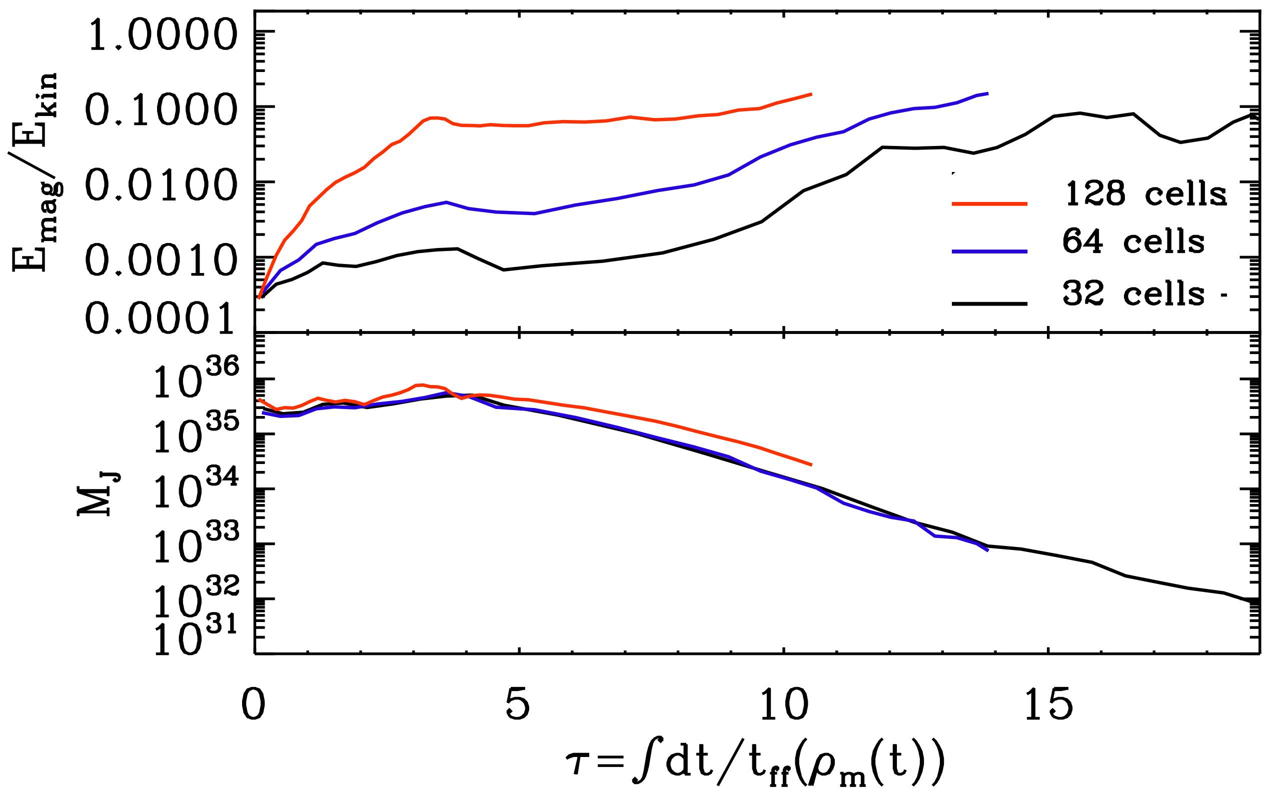


B fluctuation spectrum in $1/r^2$ fall-off

B fluctuation spectrum in flat inner core

(Federrath et al., 2011, ApJ in press)

first attempts to calculate the saturation level.



ratio of magnetic to kinetic energy

Jeans mass

We seem to get a saturation level of ~10%

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

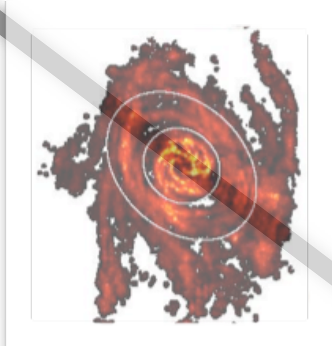
- *small-scale turbulent dynamo* is expected to operate during Pop III star formation
- simple models indicate *saturation levels of ~10%*
  --> larger values via $\alpha\Omega$ dynamo?
- *QUESTIONS:*
  - does this hold for "proper" halo calculations (with chemistry and cosmological context)?
  - what is the strength of the seed magnetic field?

summary

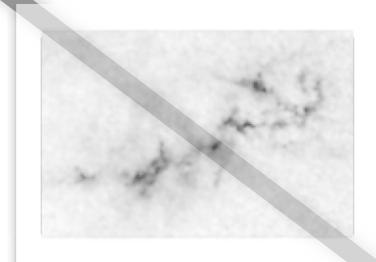
decreasing spatial scales

present days

early universe



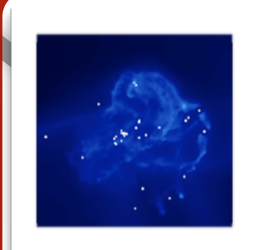
Global ISM dynamics



Formation of molecular clouds

Star cluster formation

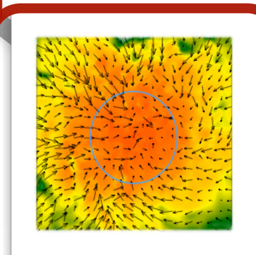
What is the density profile of IRDCs?



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?