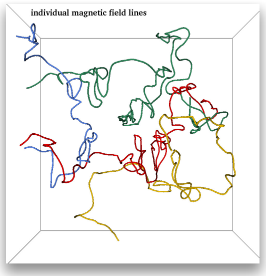
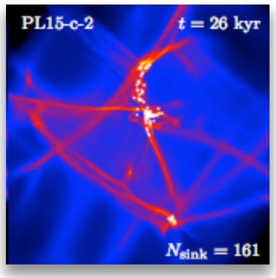
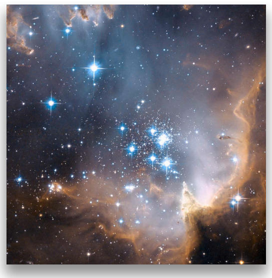
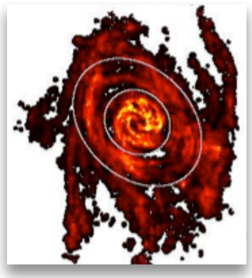
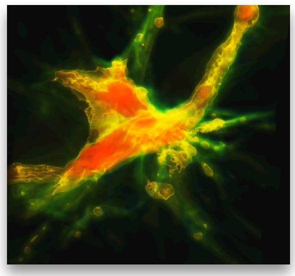
Star formation at low metallicities











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Institut für Theoretische Astrophysik

thanks to ...

... people in Heidelberg:

Richard Allison, Christian Baczynski, Erik Bertram, Frank Bigiel, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Dimitris Gouliermis, Lukas Konstandin, Faviola Molina, Milica Micic, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs

... former group members:

Robi Banerjee, Ingo Berentzen, Christoph Federrath, Philipp Girichidis, Thomas Greif, Thomas Peters, Dominik Schleicher, Sharanya Sur

... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft

HGSFP

IMPRS

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Tom Abel, Robi Banerjee, Volker Bromm, Christoph Federrath, Thomas Greif, Kazu Omukai, Dominik Schleicher, Sharanya Sur, Naoki Yoshida

Deutsche Forschungsgemeinschaft DFG

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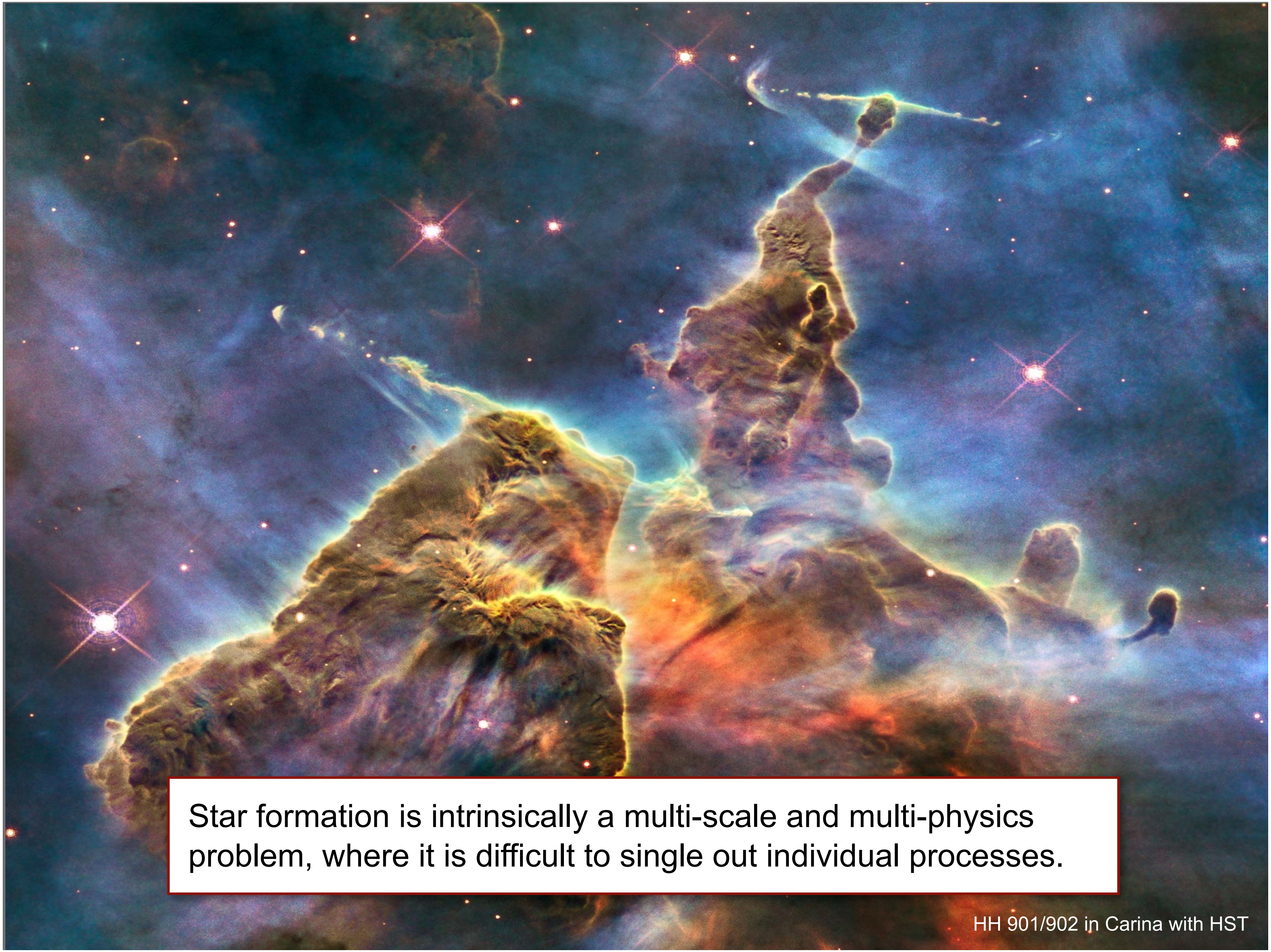
IMPRS

Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

Carina with HST


Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.
HH 901/902 in Carina with HST

open questions

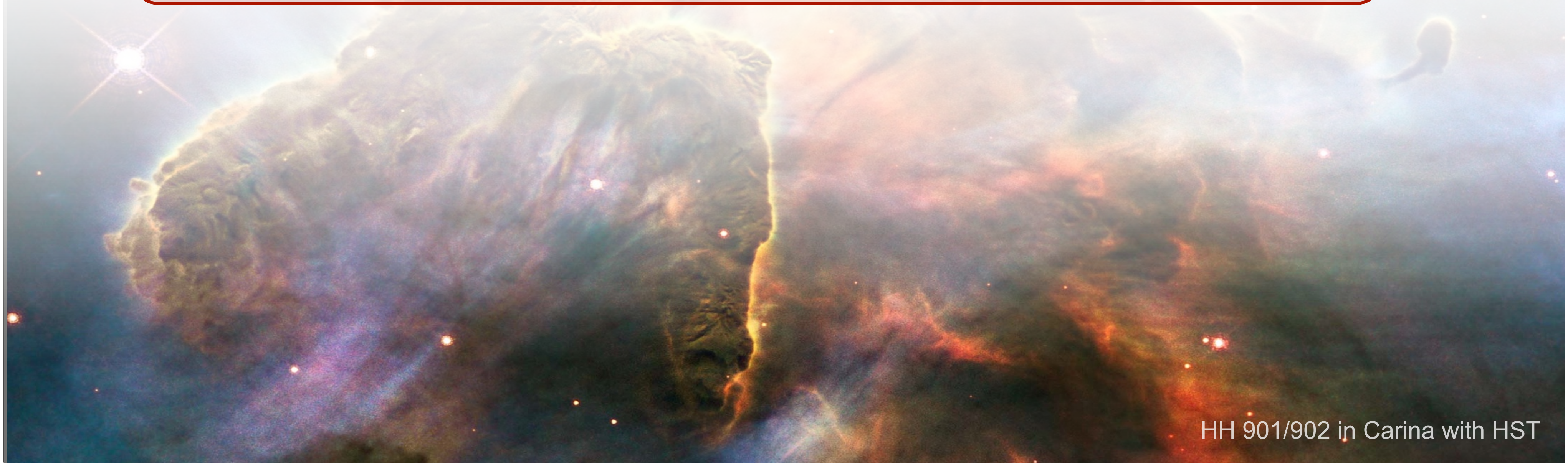
- what processes determine the initial mass function (IMF) of stars?
- how does star formation depend on metallicity?
  how do the first stars form?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?

HH 901/902 in Carina with HST

open questions

- what processes determine the initial mass function (IMF) of stars?
- how does star formation depend on metallicity?
  how do the first stars form?

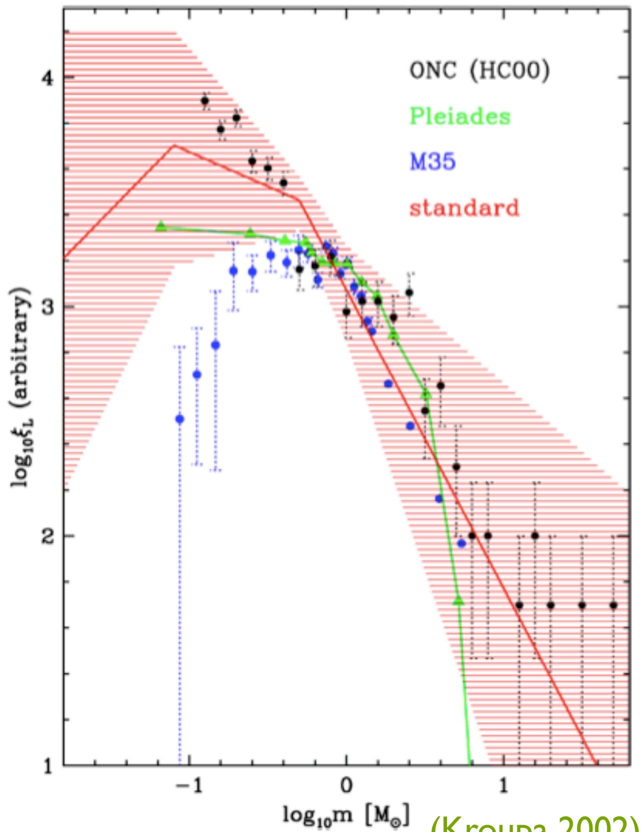
Under what condition does widespread fragmentation occur, and when is it inhibited?



HH 901/902 in Carina with HST

stellar mass fuction

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



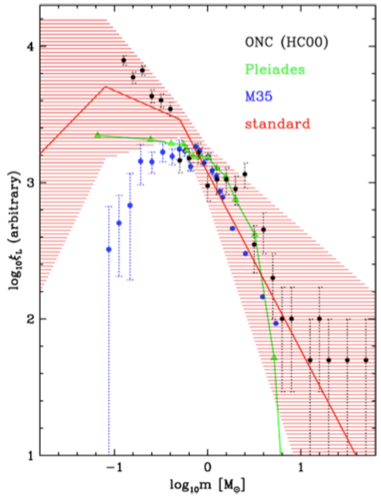
(Kroupa 2002)

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)

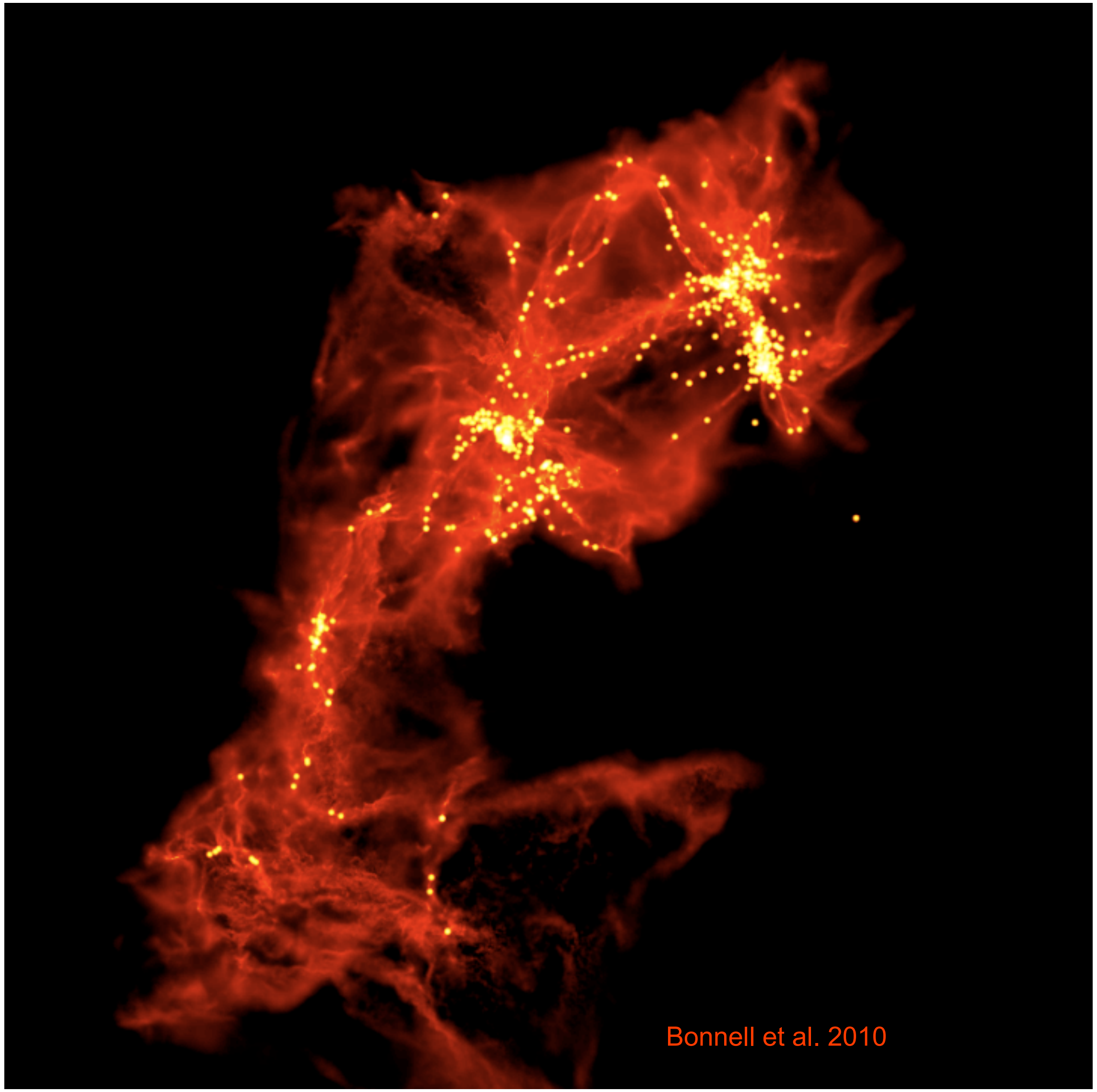


model of Orion molecular cloud

„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)

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

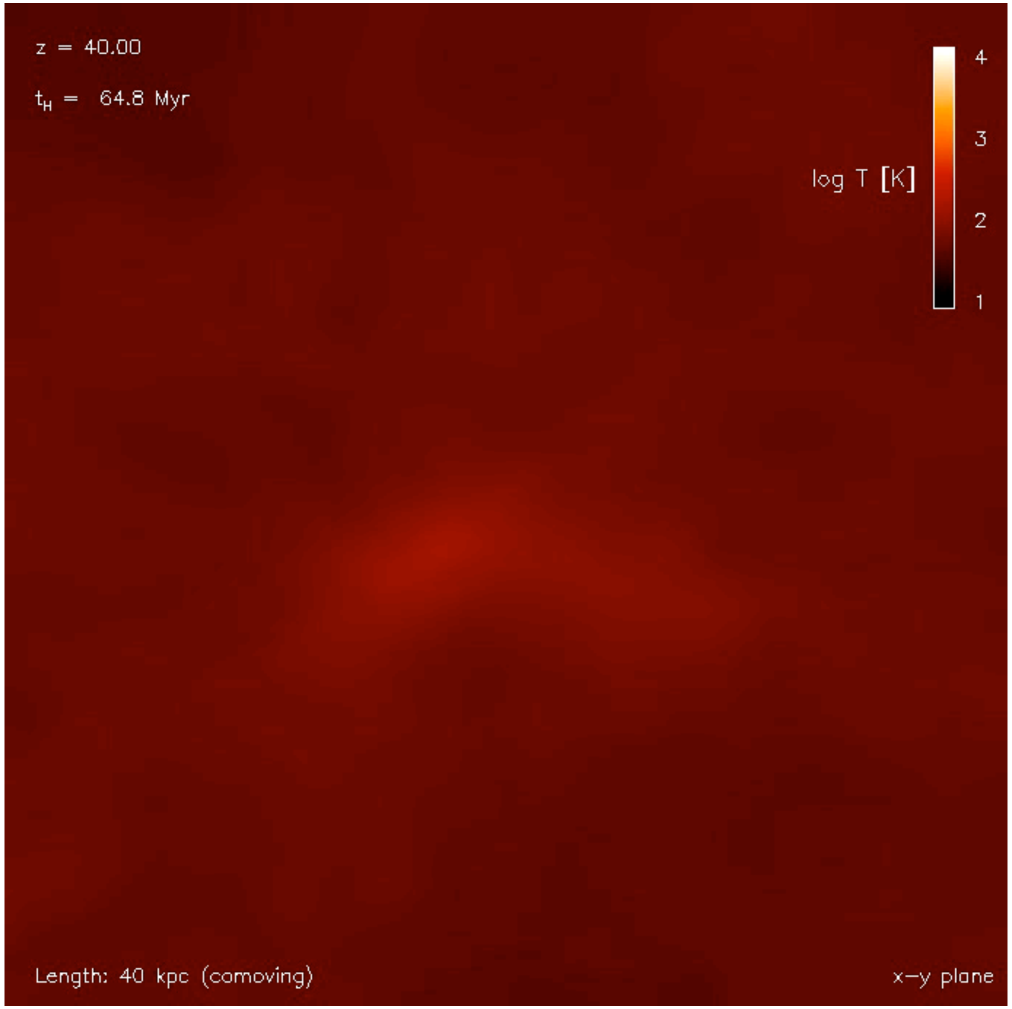
LOW-MASS STARS
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion



turbulence in high-z halos

- fragmentation and star formation will depend on *degree of turbulence* in proto-galactic halo (e.g. Clark et al. 2011a)
- for details on the turbulence properties of high-z halos see, e.g., Turk et al., Wise et al., Greif et al., Clark et al., etc.

turbulence developing in an atomic cooling halo



(Greif et al. 2008)

stellar masses

- distribution of stellar masses depends on
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    --> mass spectrum of prestellar cloud cores
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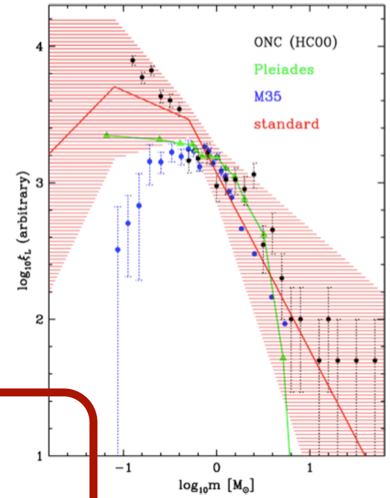


application to early star formation

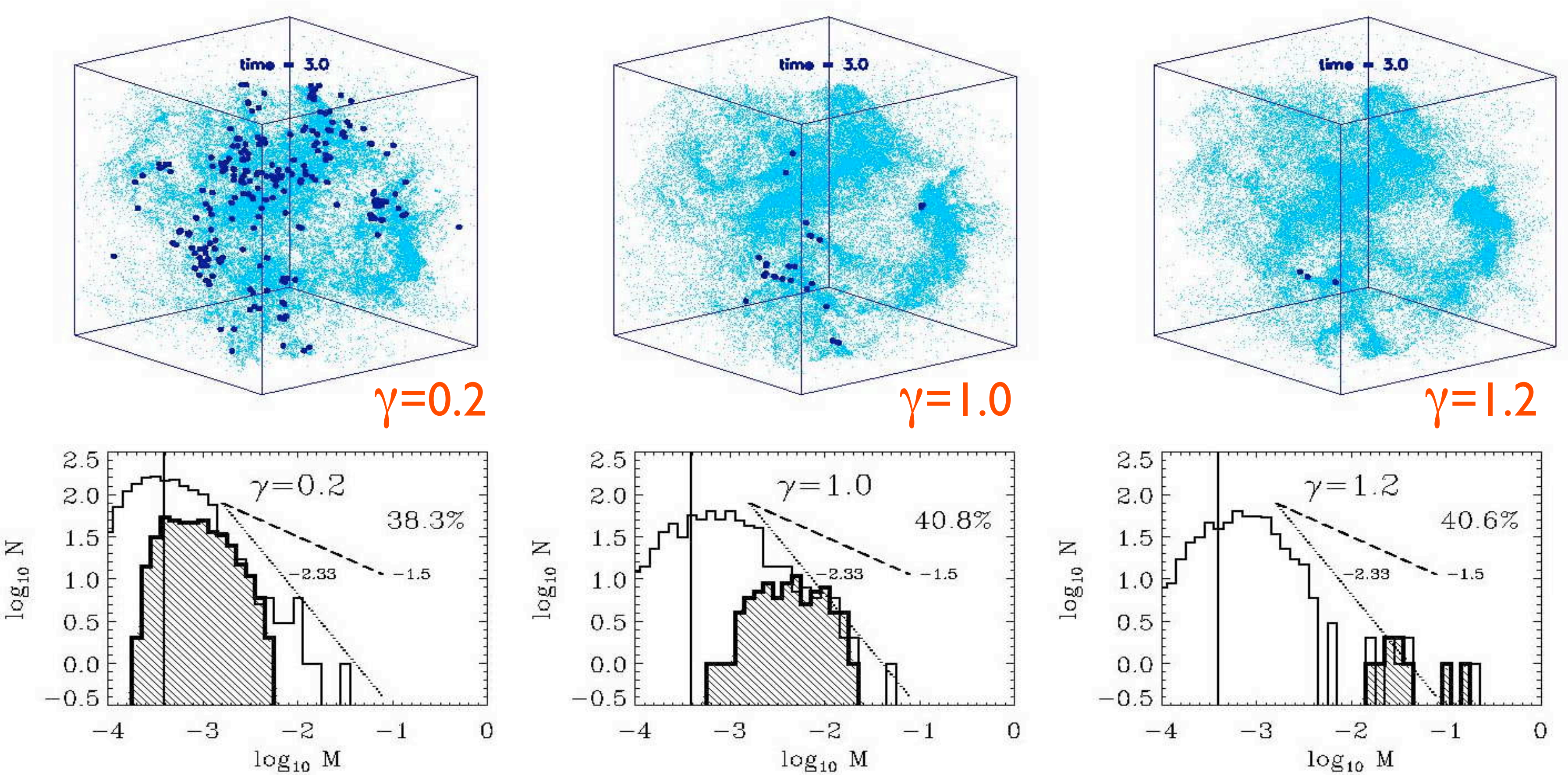
thermodynamics & fragmentation

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*

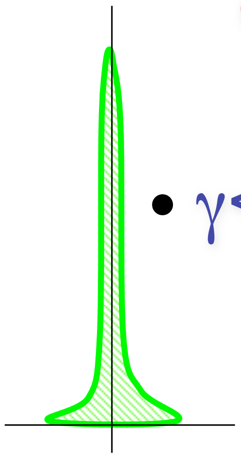
for γ>1 it is suppressed → formation of *isolated massive stars*

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

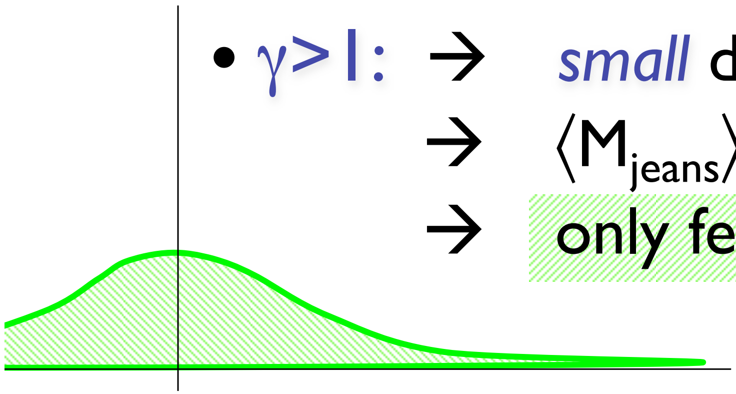
how does that work?

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

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

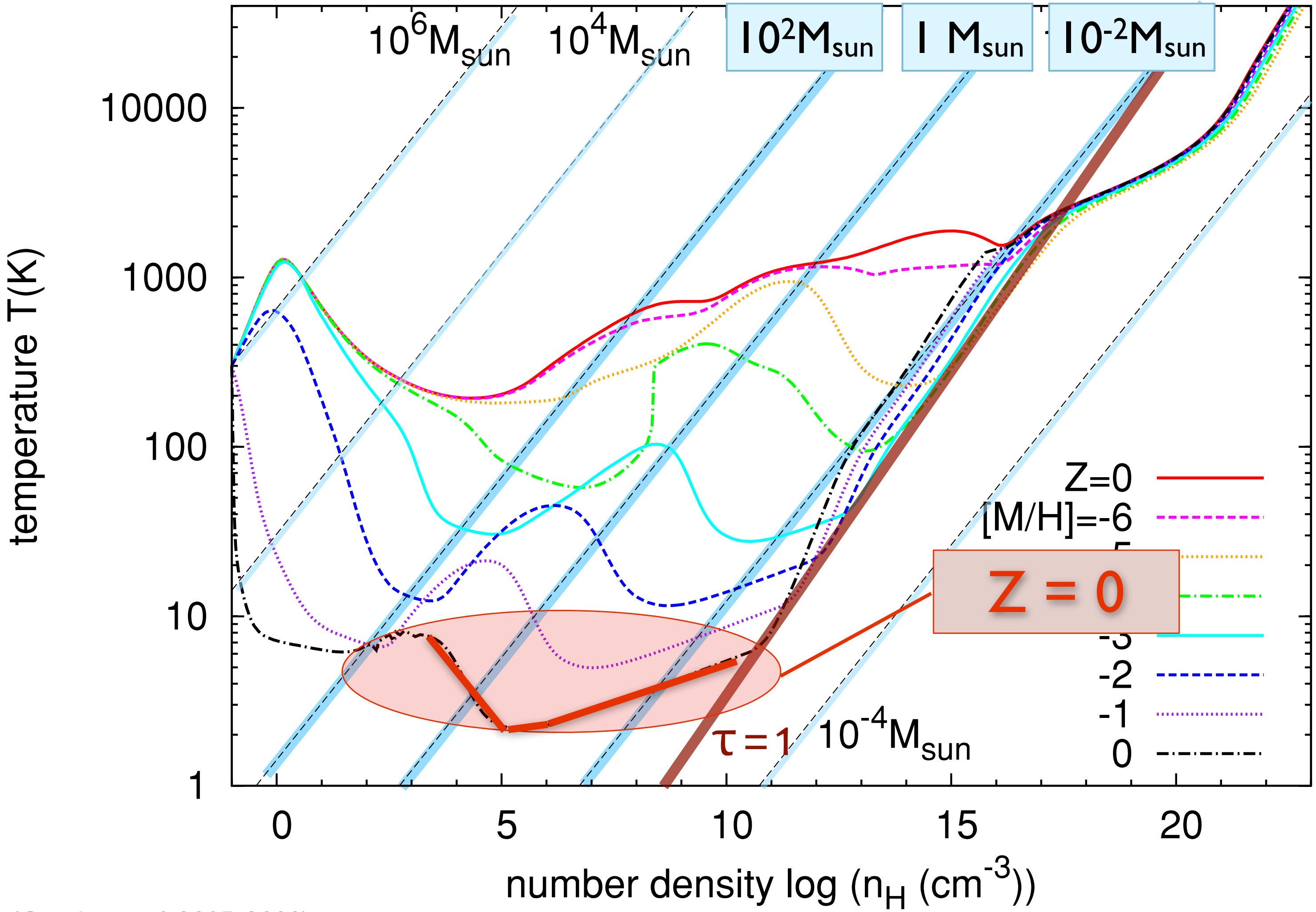


- $\gamma<1$: $\rightarrow$ *large* density excursion for given pressure
  $\rightarrow$ $\langle M_{jeans}\rangle$ becomes small
  $\rightarrow$ number of fluctuations with $M > M_{jeans}$ is large



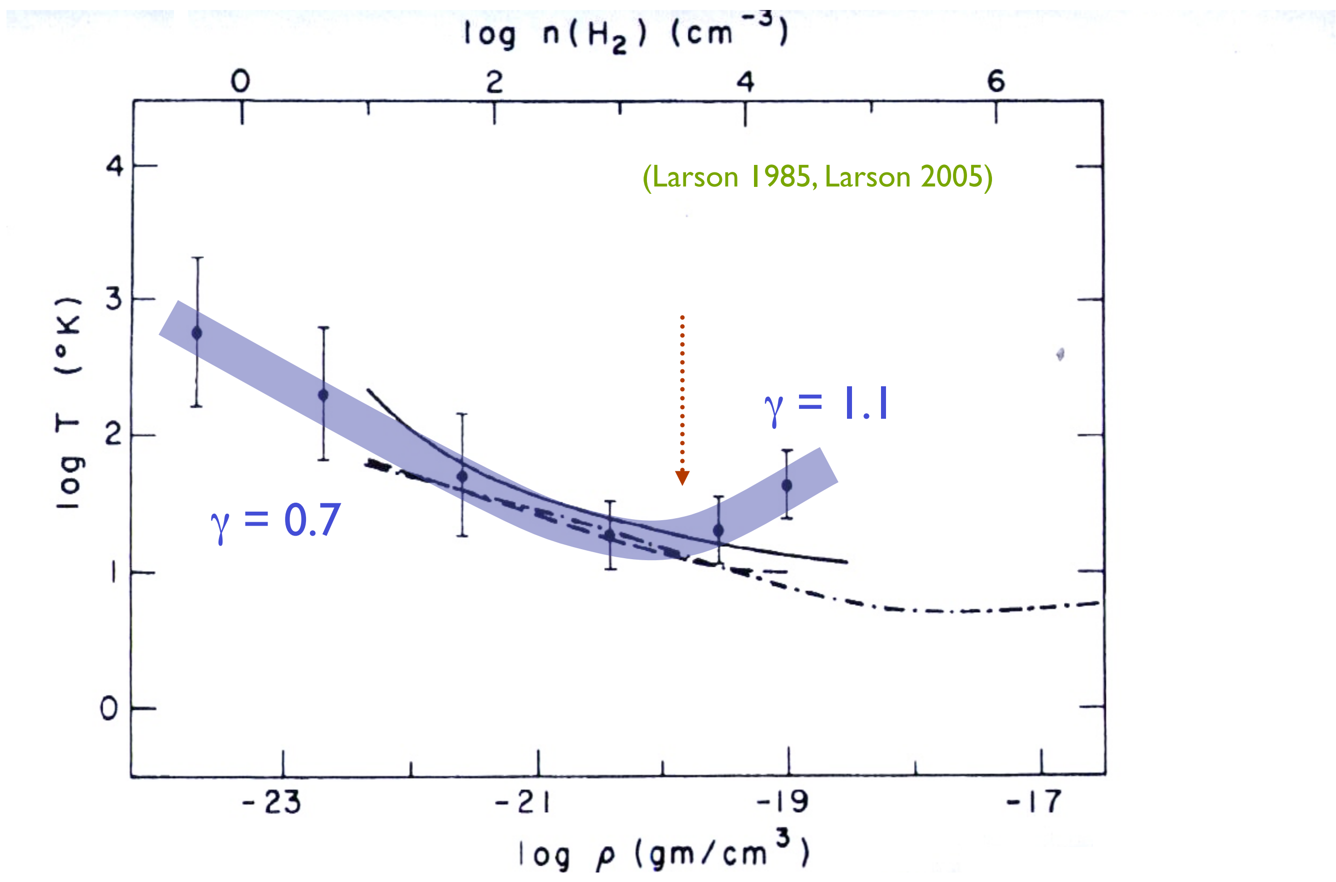
- $\gamma>1$: $\rightarrow$ *small* density excursion for given pressure
  $\rightarrow$ $\langle M_{jeans}\rangle$ is large
  $\rightarrow$ only few and massive clumps exceed M_{jeans}

EOS as function of metallicity

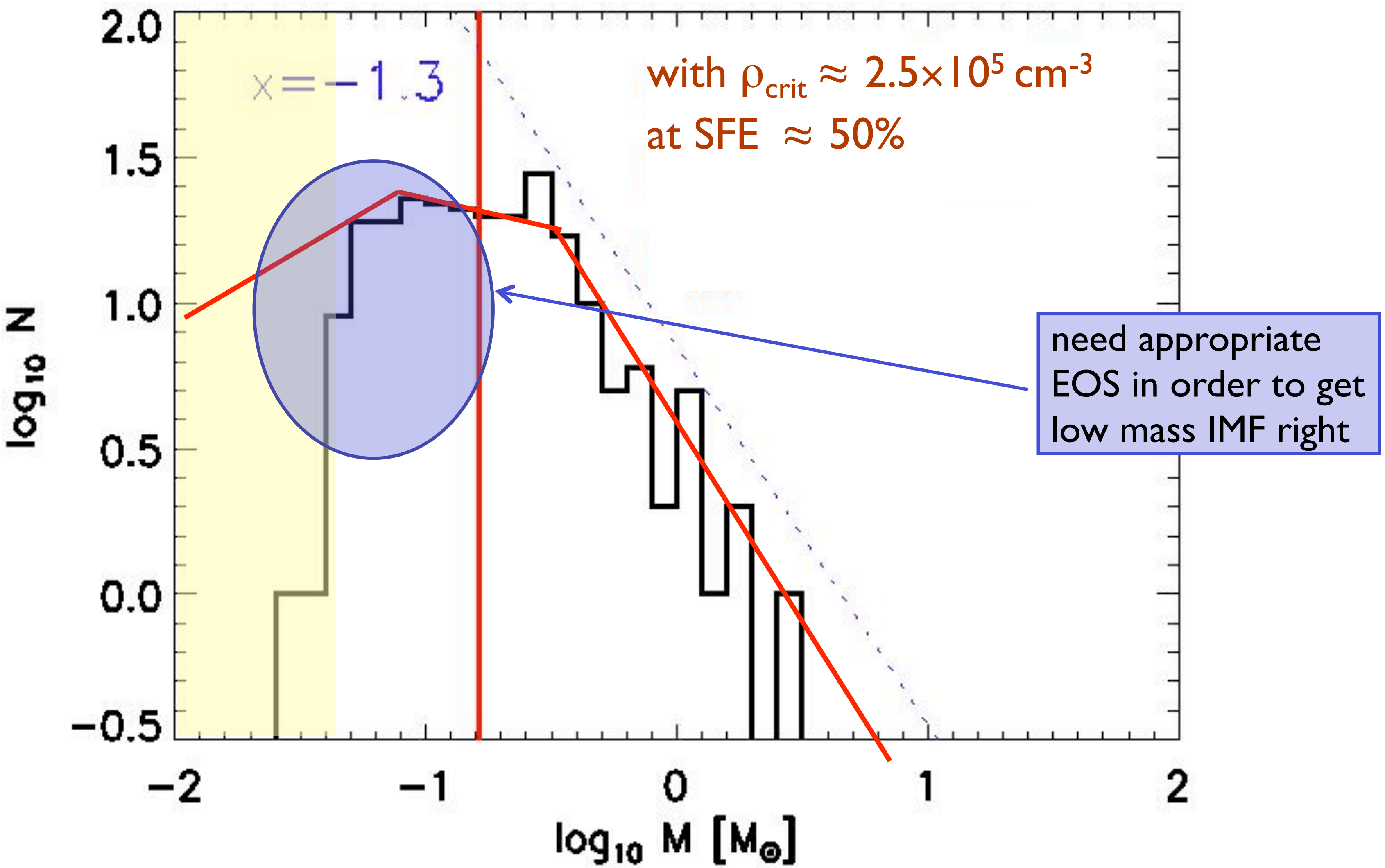


(Omukai et al. 2005, 2010)

present-day star formation

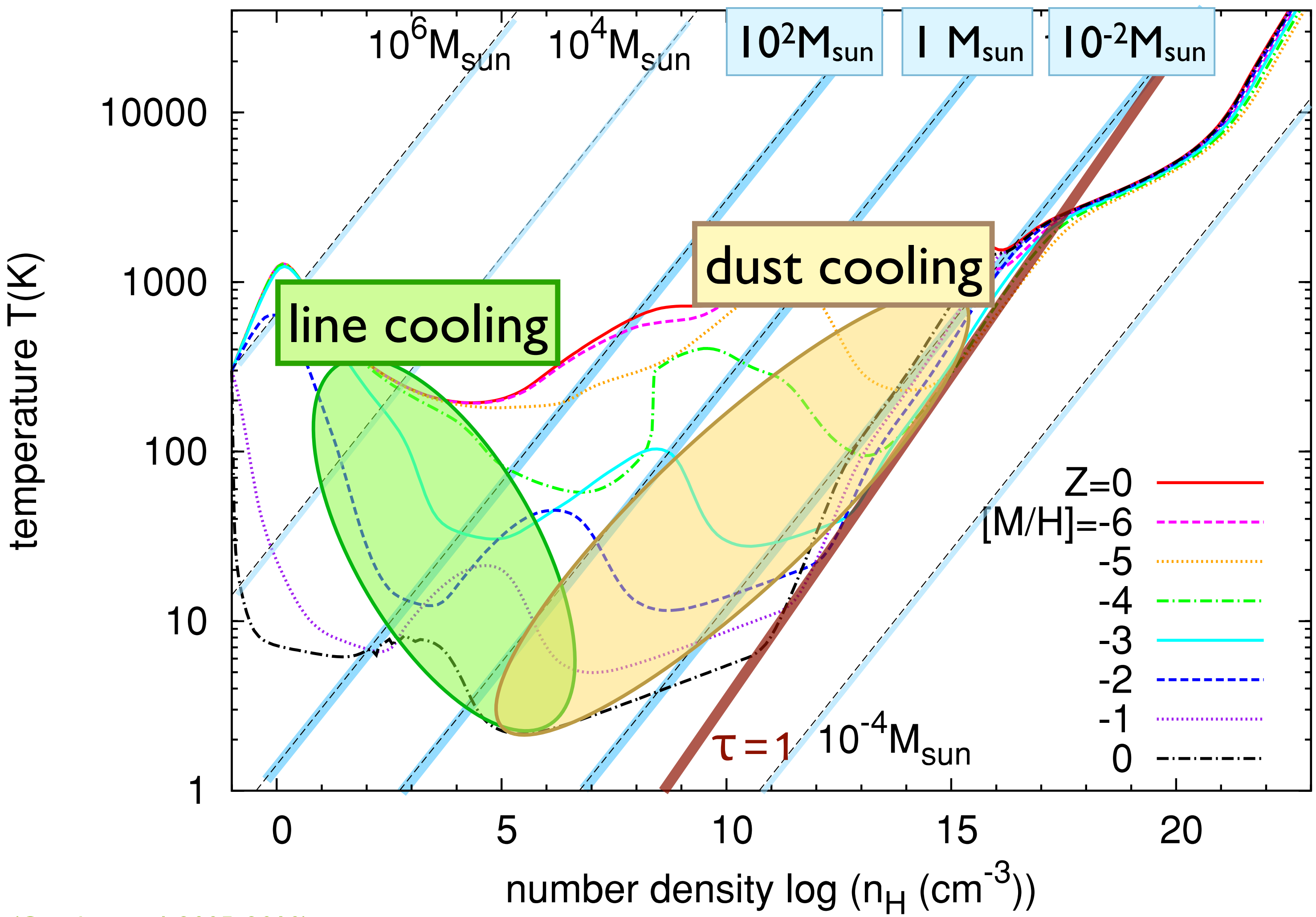


IMF in nearby molecular clouds



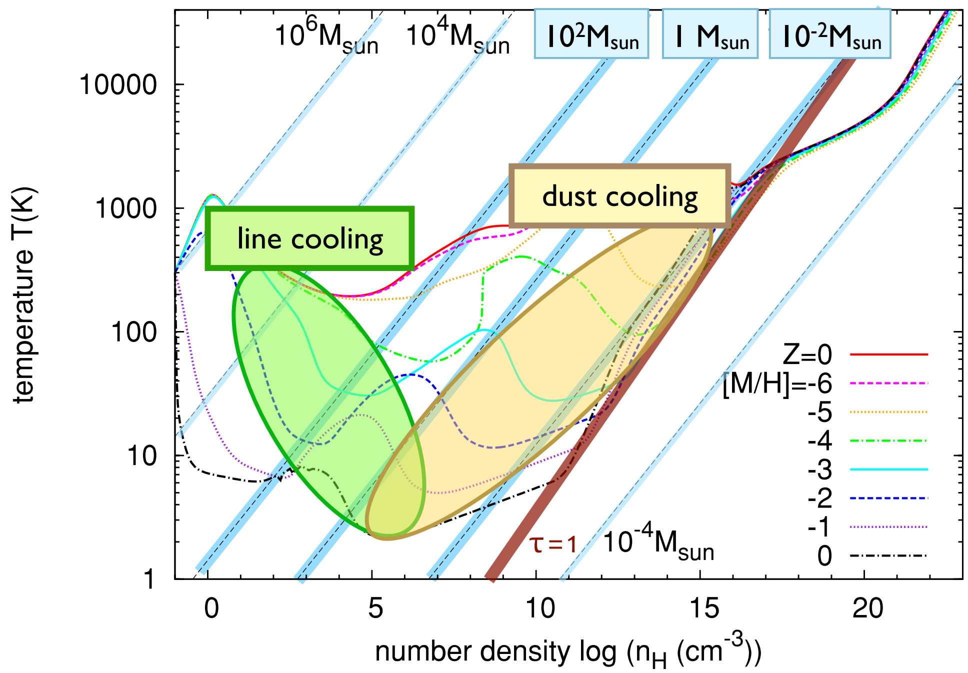
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



two competing models:

- cooling due to atomic fine-structure lines ($Z > 10^{-3.5} Z_{sun}$)
- cooling due to coupling between gas and dust ($Z > 10^{-5...-6} Z_{sun}$)

NB: line cooling would only make very massive stars, with $M >$ few $\times 10\ M_{sun}$.

(Omukai et al. 2005, 2010)

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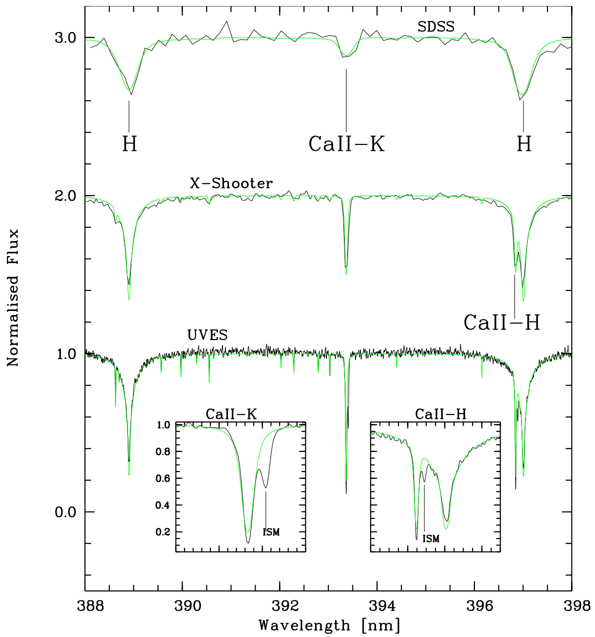

SDSS J1029151+172927

- is first ultra metal-poor star with Z ~ $10^{-4.5}$ Z_{sun} for all metals seen (Fe, C, N, etc.)
  [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

Element		+3Dcor.	$[X/H]_{1D}$ +NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	$A(X)_\odot$
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
Ca II	−4.81 ± 0.11	−4.93 ± 0.03	−5.02 ± 0.02	−5.15 ± 0.09	3	0.1	6.33
Ti II	−4.75 ± 0.18	−4.83 ± 0.16	−4.76 ± 0.18	−4.84 ± 0.16	6	1.0	4.90
Fe I	−4.73 ± 0.13	−5.02 ± 0.10	−4.60 ± 0.13	−4.89 ± 0.10	43	1.0	7.52
Ni I	−4.55 ± 0.14	−4.90 ± 0.11			10		6.23
Sr II	≤ −5.10	≤ −5.25	≤ −4.94	≤ −5.09	1	0.01	2.92

new ESO large program to find more of these stars (120h x-shooter, 30h UVES)
[PI E. Caffau]

(Caffau et al. 2011, 2012)

(Schneider et al. 2011,2012, Klessen et al. 2012)

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interesting results for masses of previous generations of stars based on the Leo star abundance patterns ---> see talk by Alex Heger!

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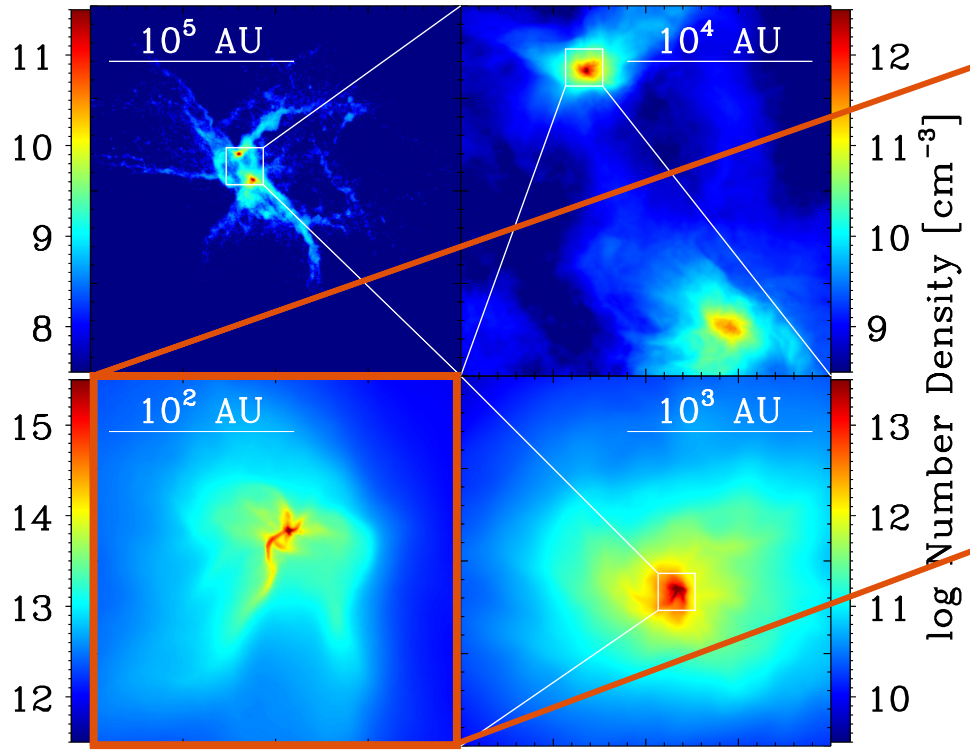


FIG. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

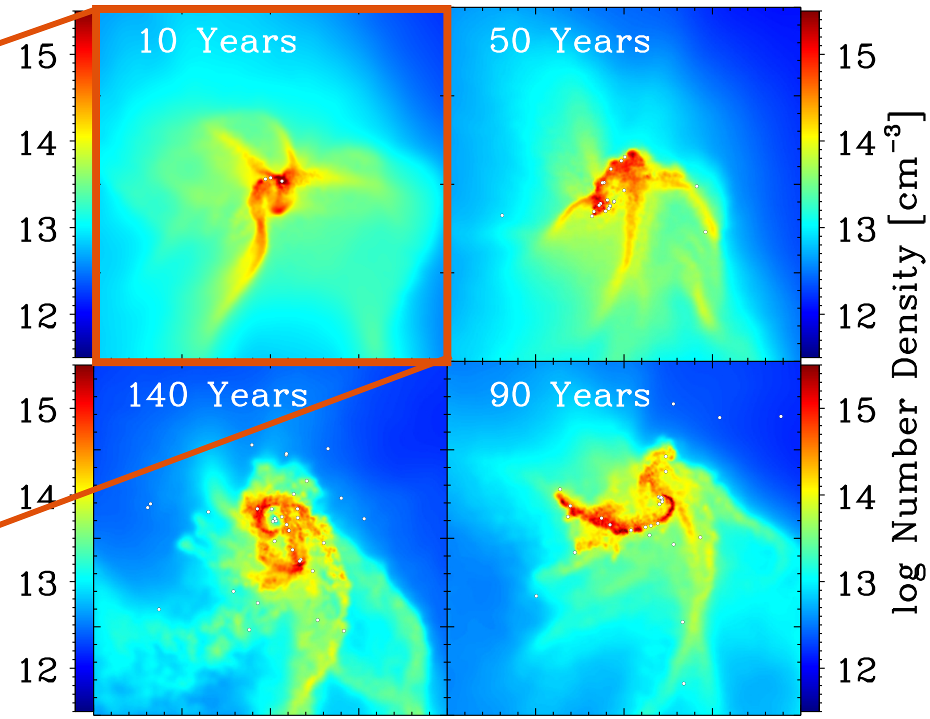
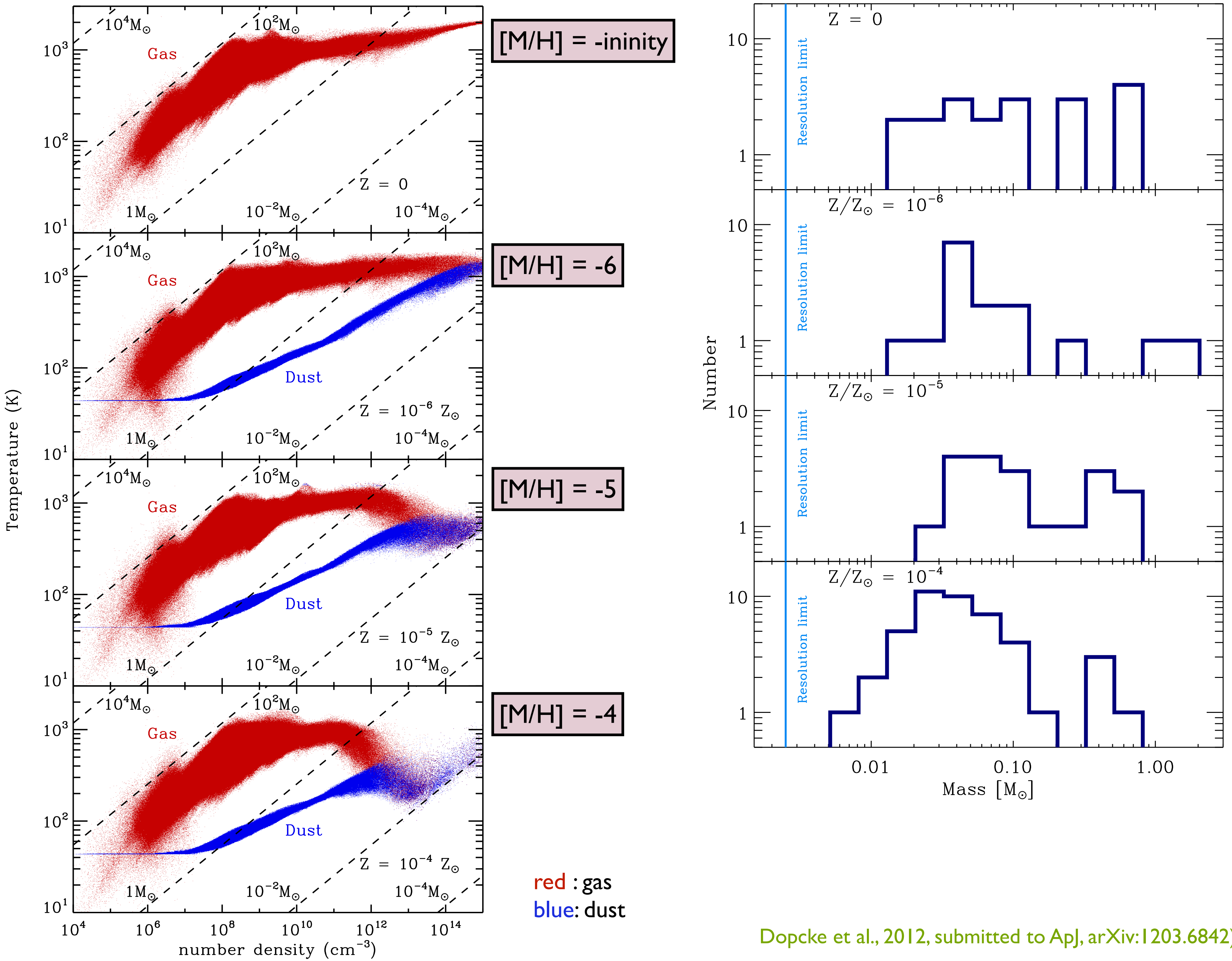


FIG. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and Z = $10^{-4} Z_{\odot}$. The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

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

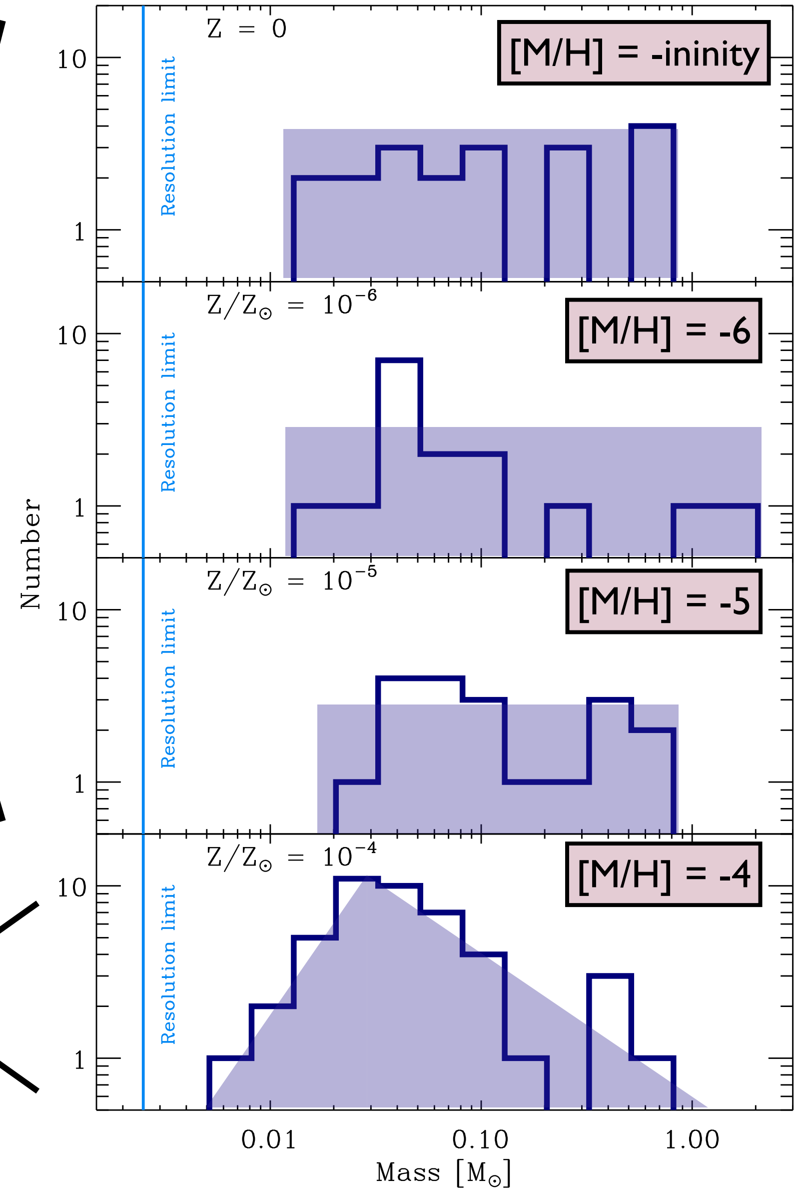


Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

hints for differences in mass spectrum

disk fragmentation mode

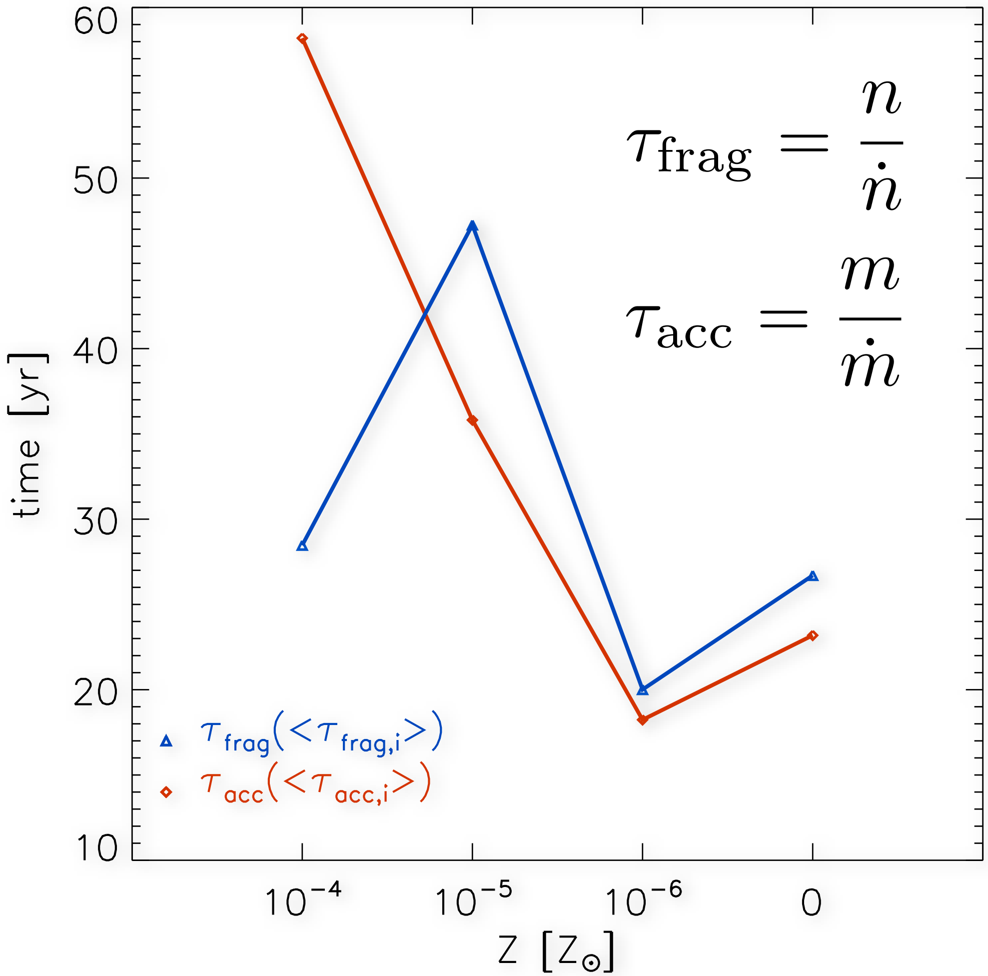
gravoturbulent fragmentation mode



Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

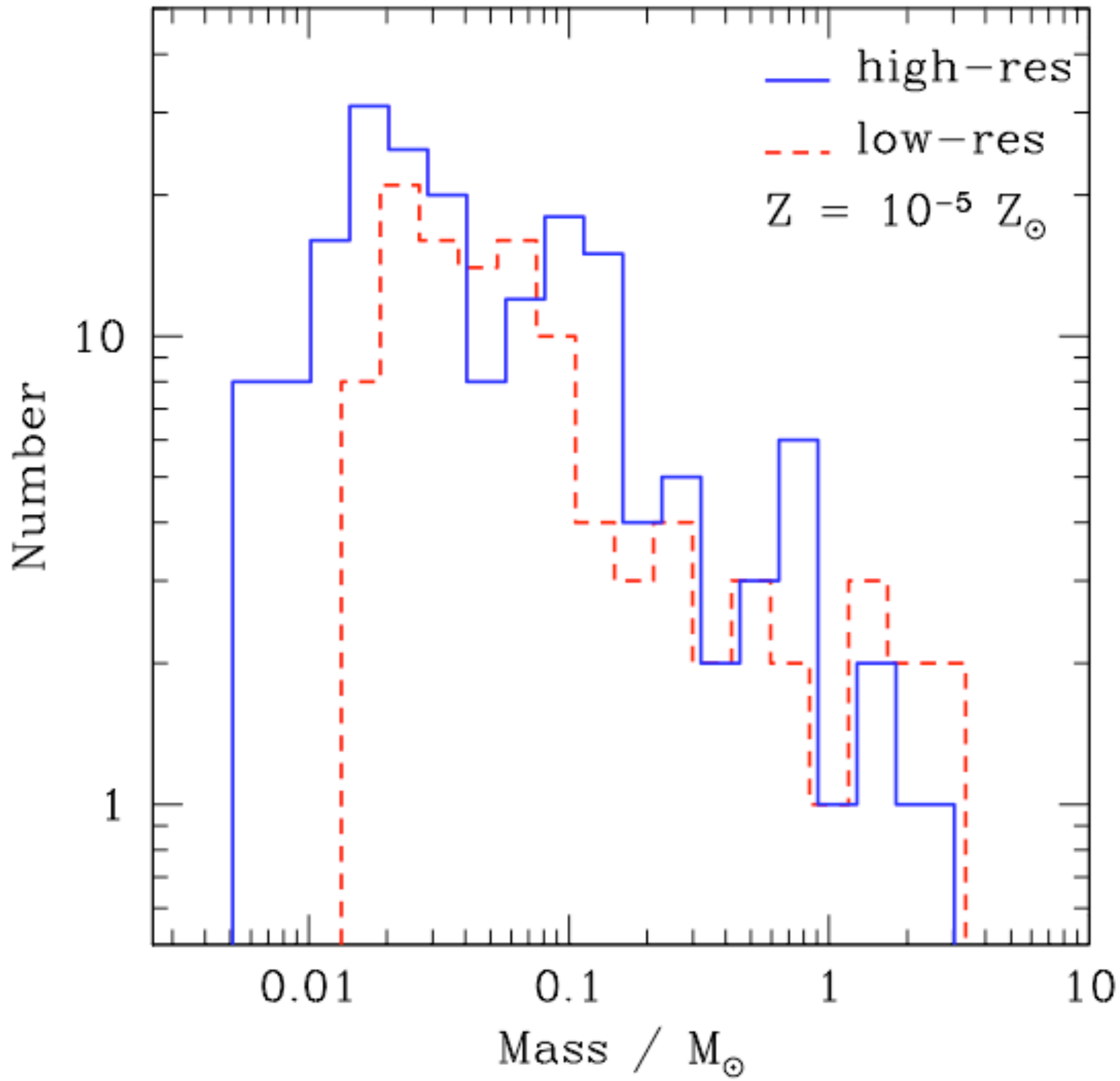
hints for differences in mass spectrum

for $Z > 10^{-5}\ Z_{sun}$,
fragmentation is "faster" than accretion,
that means more new protostars form more quickly than existing ones can accrete



Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

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



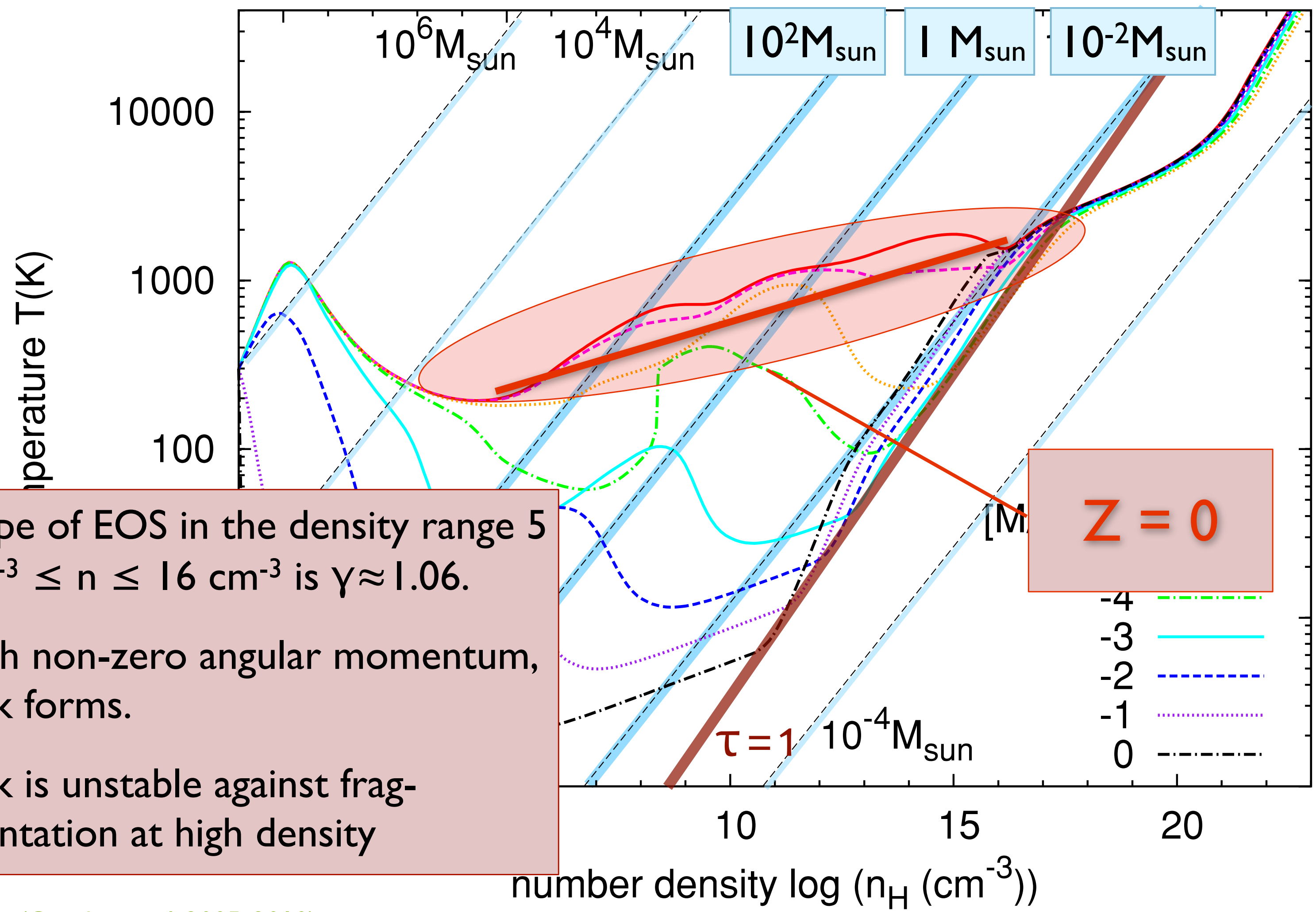
dense cluster of low-mass protostars builds up:

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

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

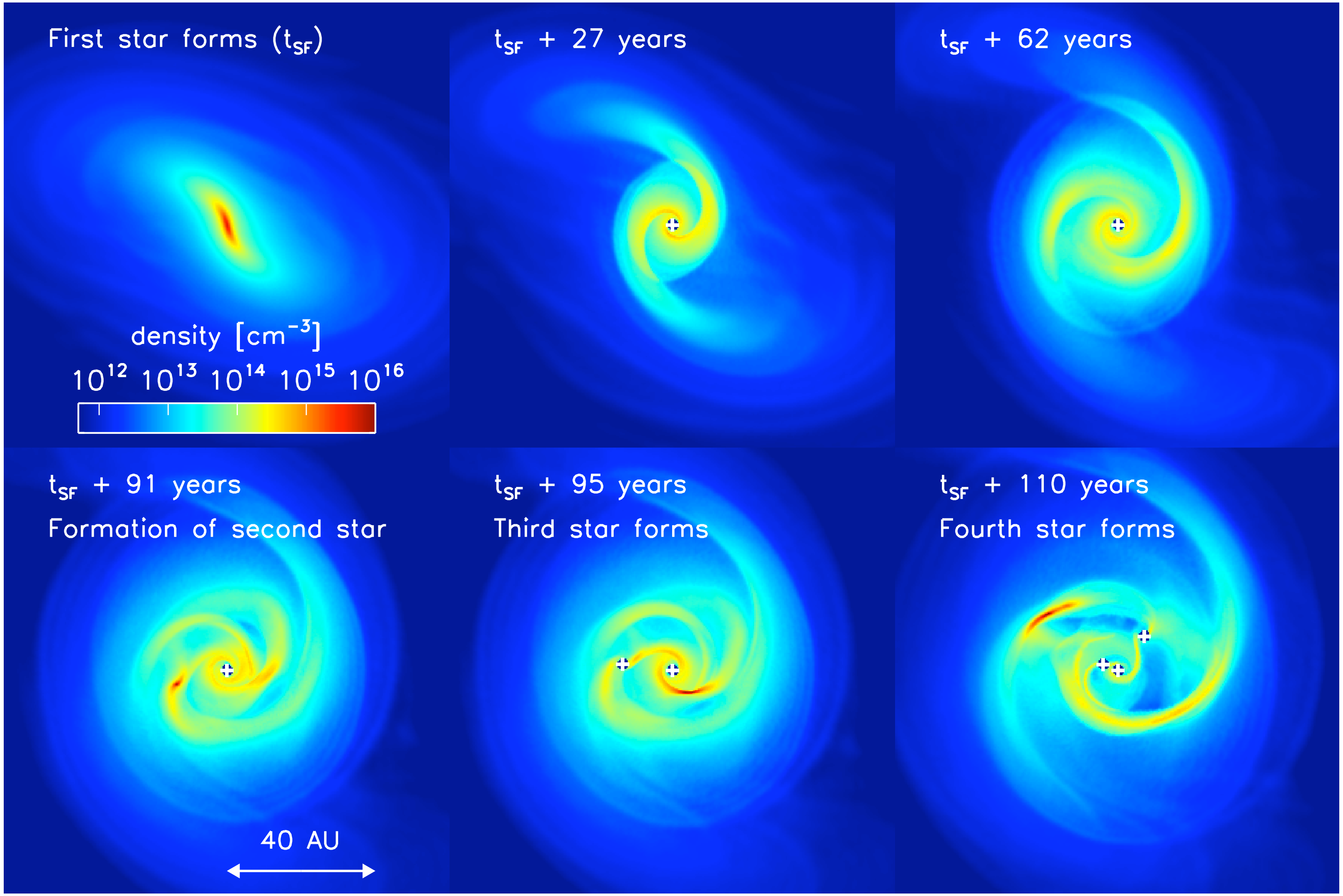
(Clark et al. 2008)

EOS as function of metallicity



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

(Omukai et al. 2005, 2010)

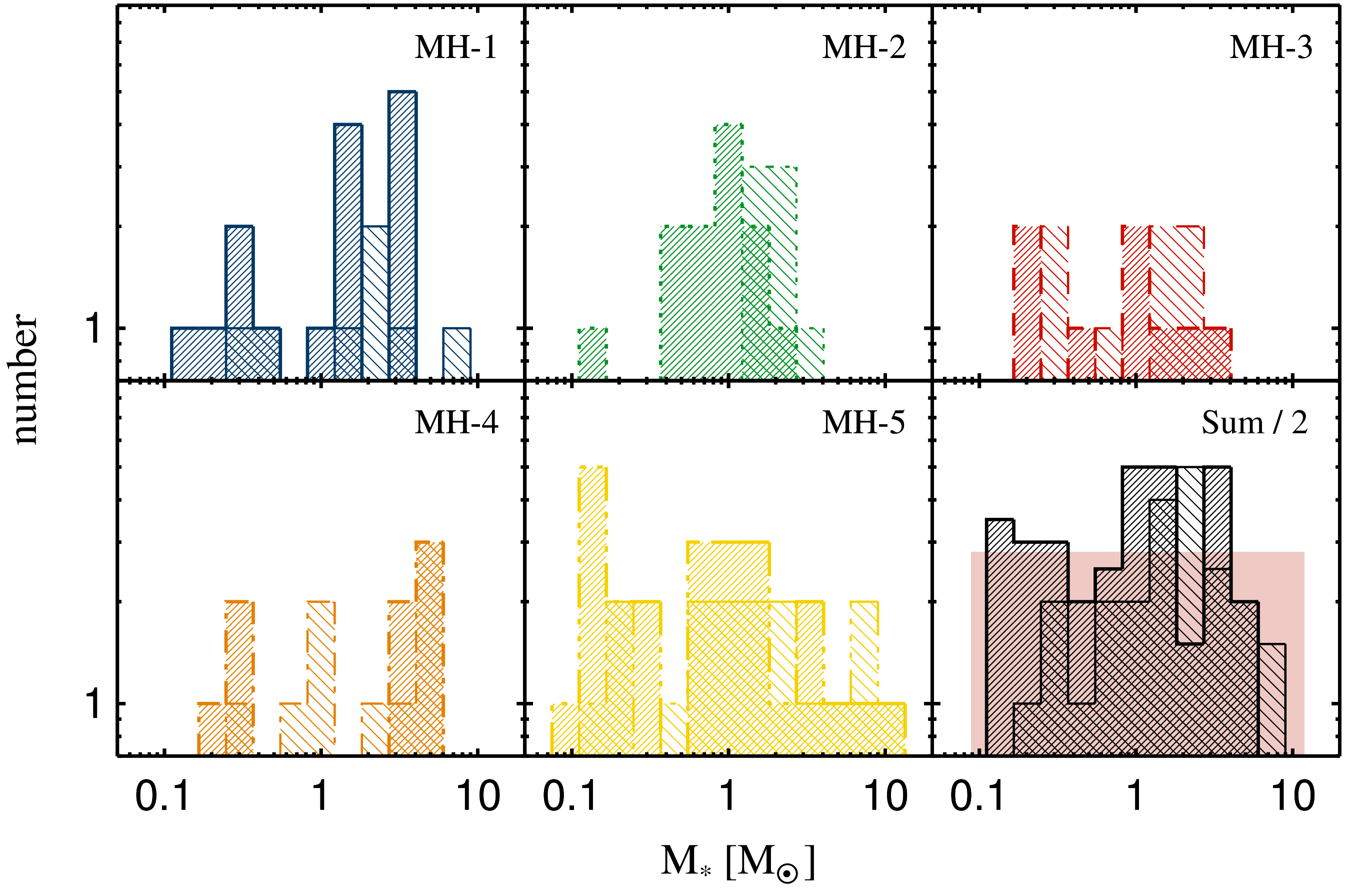


detailed look at accretion disk

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)

expected mass spectrum

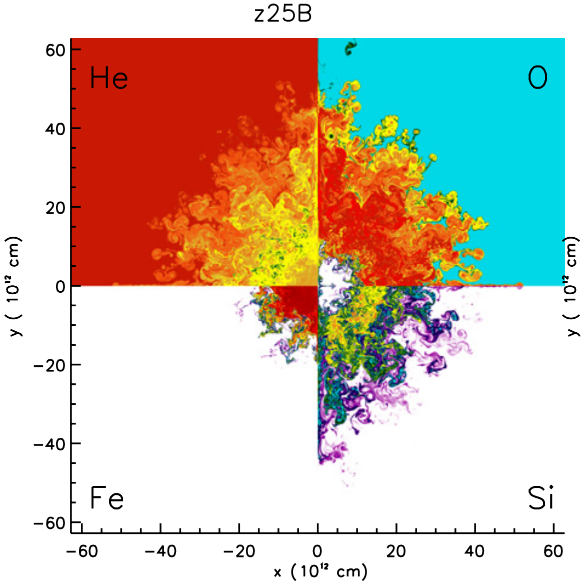


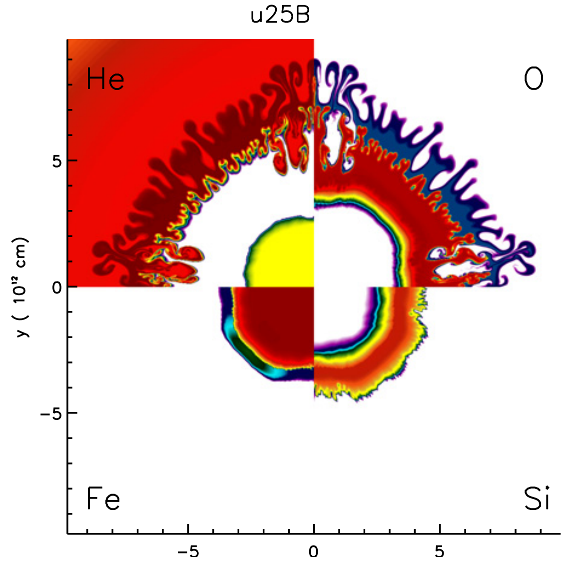
we see "flat" mass spectrum

Attention: the mass spectrum depends on the dynamic properties of the halo
---> need to understand the statistics of high-z halos! ---> see poster by Mei Sasaki

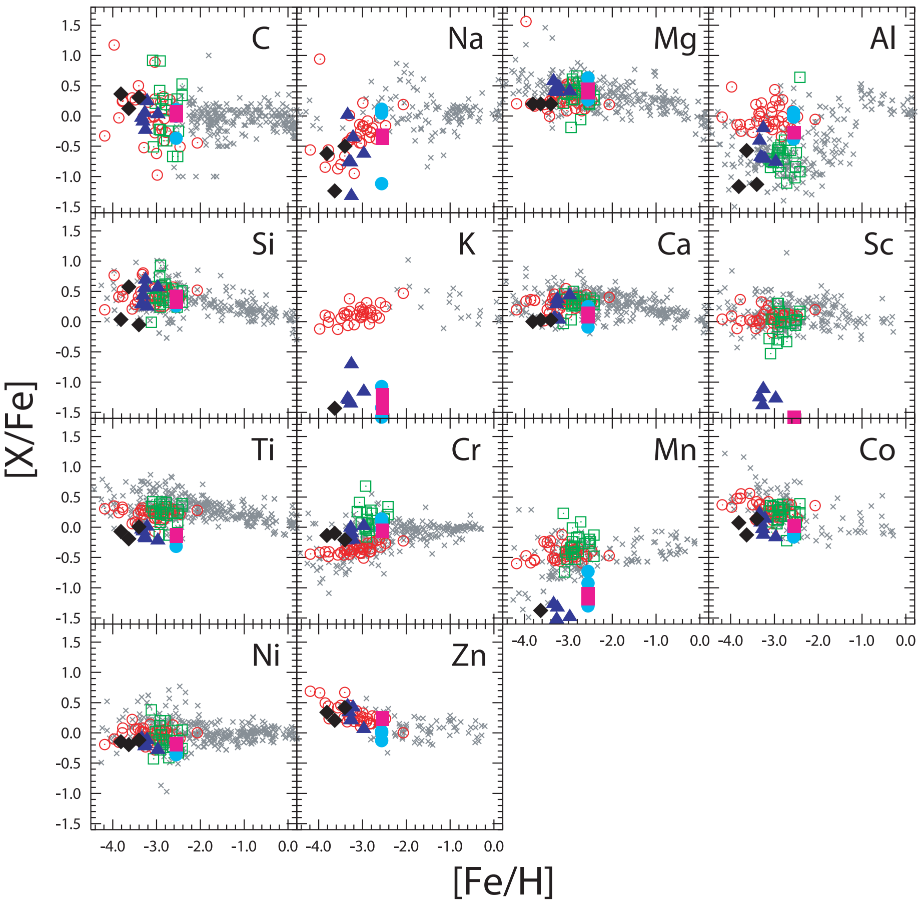
expected mass spectrum

- *expected IMF is flat* and covers a wide range of masses
- implications
  - because slope > -2, most *mass is in massive objects* as predicted by most previous calculations
  - most high-mass Pop III stars should be in *binary systems* --> source of *high-redshift gamma-ray bursts*
  - because of ejection, some *low-mass objects* ($< 0.8\ M_\odot$) might have *survived* until today and could potentially be found in the Milky Way
- consistent with abundance patterns found in second generation 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)

reducing fragmentation

- from present-day star formation theory we know, that
  - magnetic fields (e.g. Peters et al.2011, Seifried et al. 2012, Hennebelle et al. 2011)
  - accretion heating (e.g. Peters et al. 2010abc, Krumholz et al. 2009, Kuipers et al. 2011)

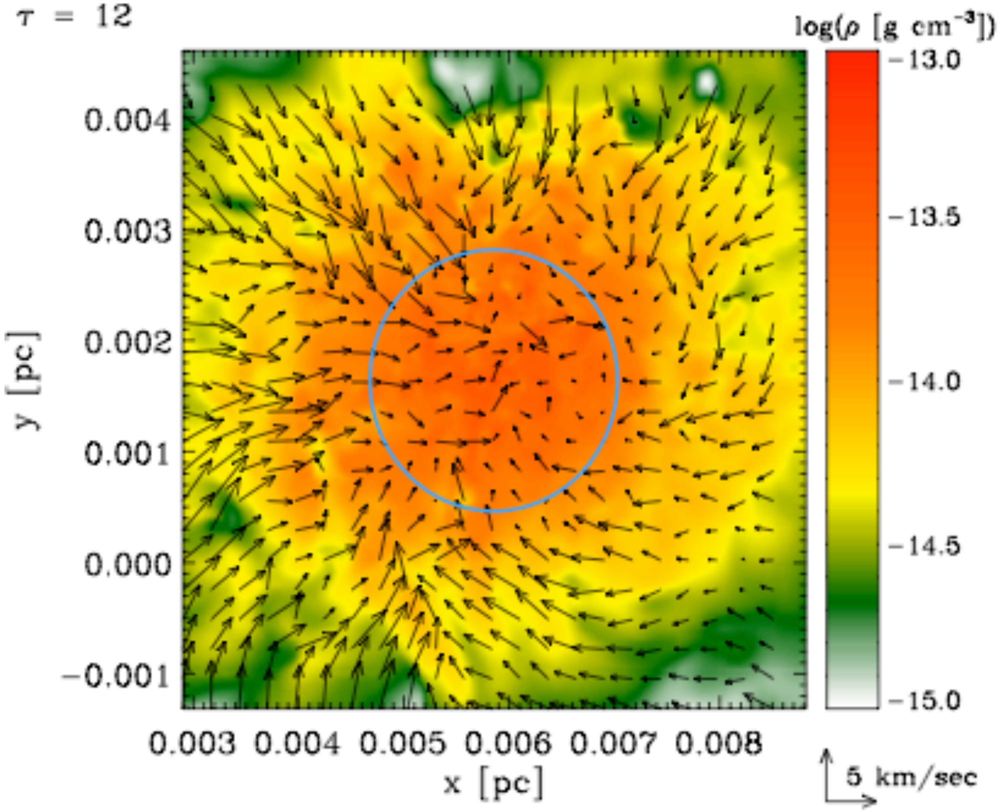
  can influence the fragmentation behavior.
- in the context of Pop III
  - radiation: talks by Hajime Susa, Athena Stacy ,Takashi Hosokawa
  - magnetic fields: talks by Jeff Oishi and Matt Turk
- all these will reduce degree of fragmentation (but not by much, see also Smith et al. 2011, 2012)
- DM annihililation might become important for disk dynamics and fragmentation (see talk by Fabio Iocco, and poster by Rowan Smith)

B fields in the early universe?

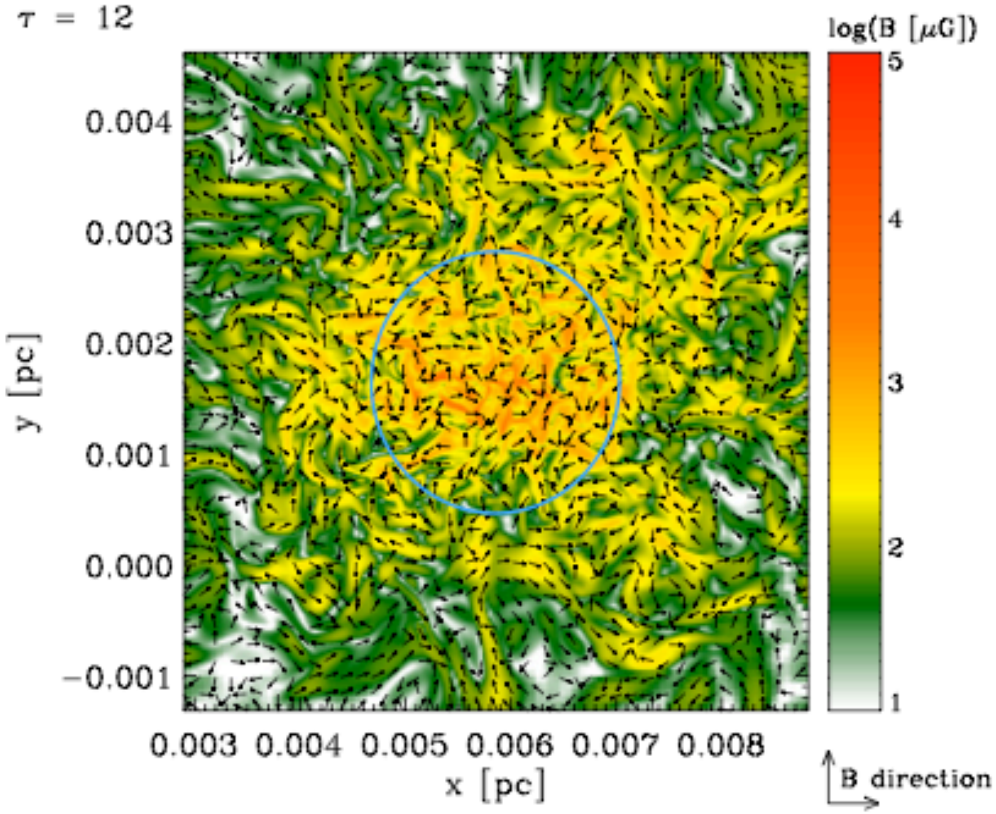
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, *THIS MAY BE WRONG*!

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
- *method:* solve ideal MHD with very high resolution
  - grid-based AMR code FLASH
  - resolution up to 128^3 cells per Jeans volume (effective resolution 65536^3 cells)
  - see: Schleicher et al. 2010, A&A, 522, A115, Sur et al. 2010, ApJ, 721, L734, Federrath et al., 2011, ApJ, 731, 62, Schober 2012, PRE, 85, 026303, Schober et al. 2012, ApJ, submitted (1204.0658)

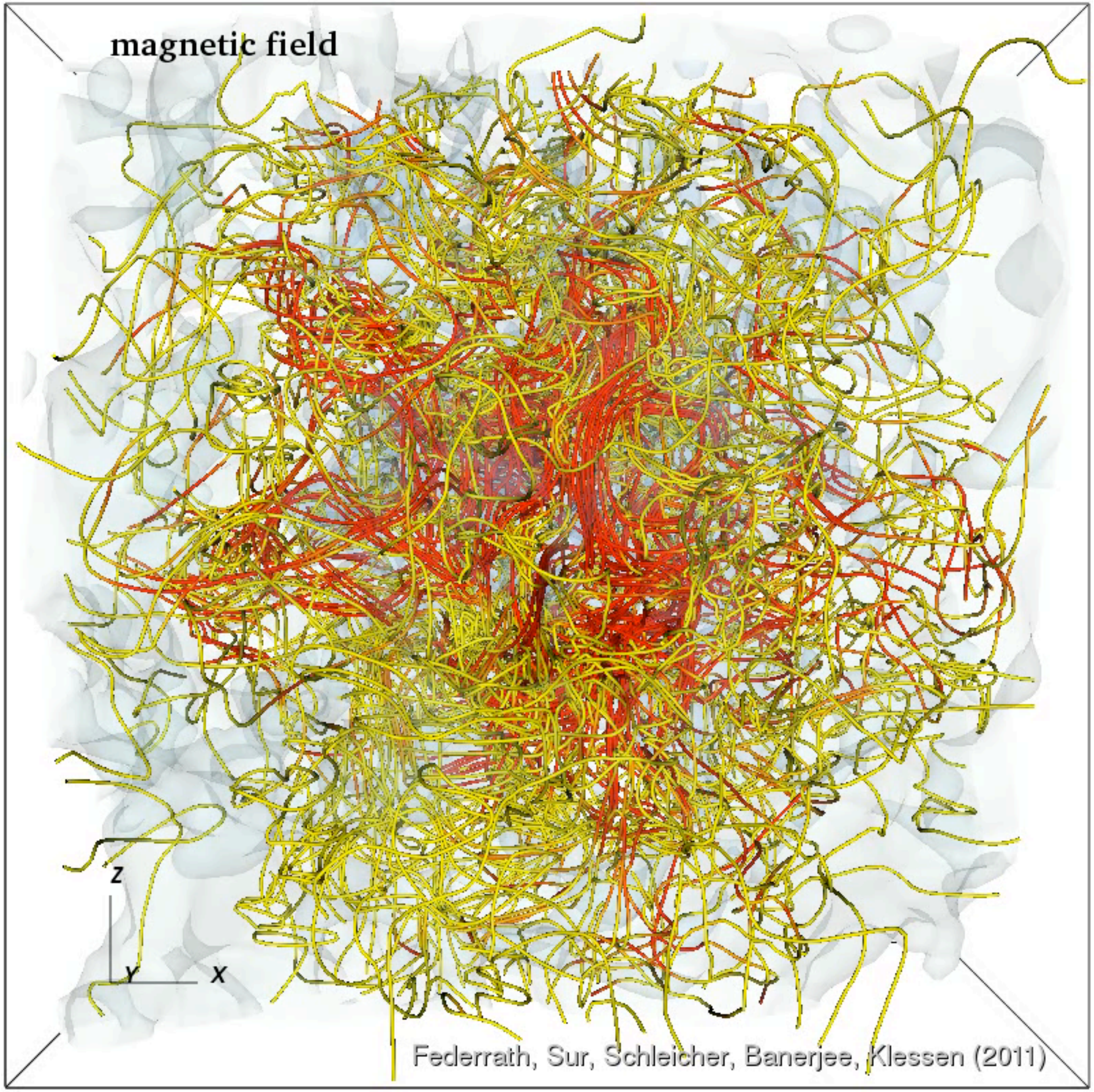


magnetic field structure

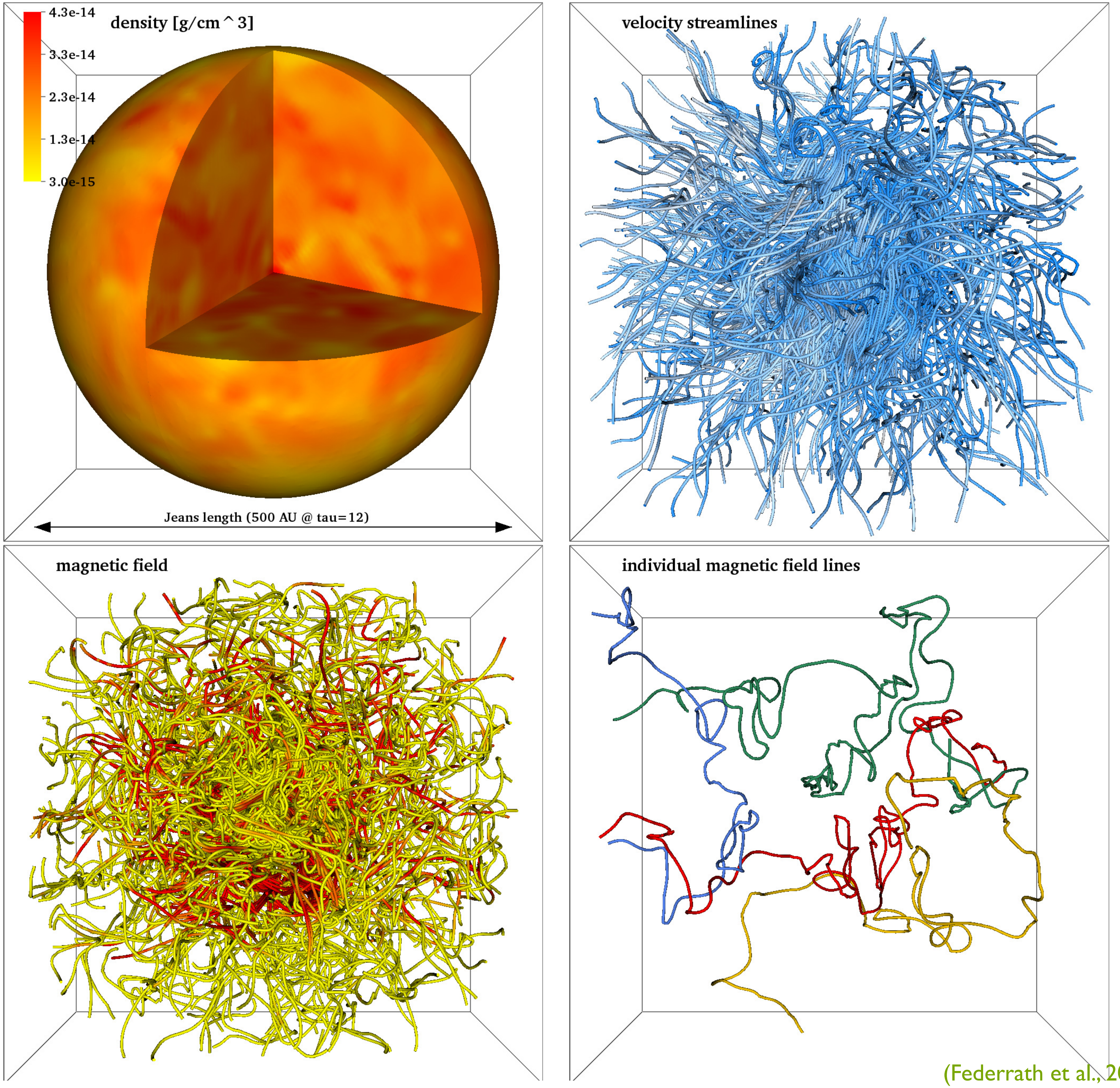


density structure

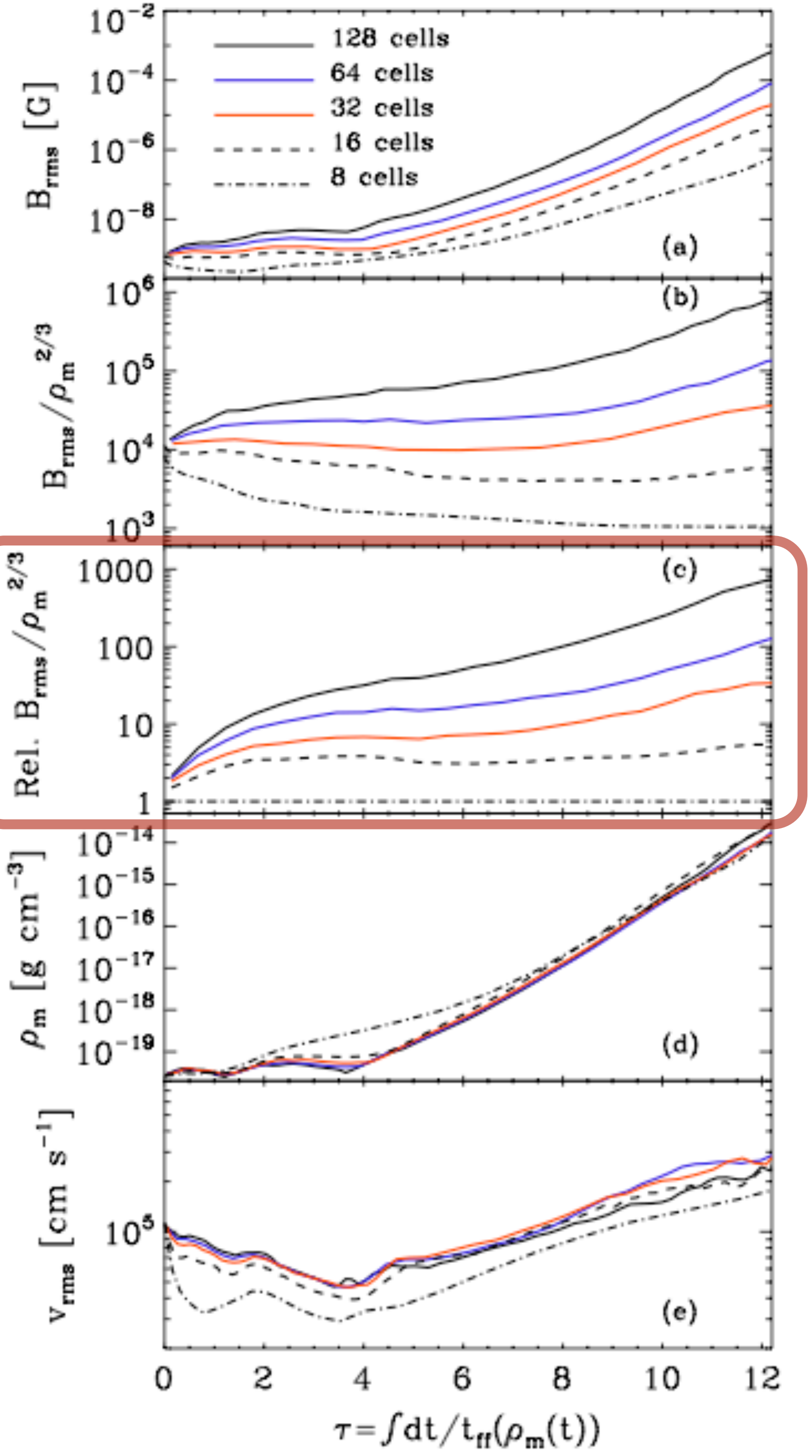
(Sur et al. 2010, ApJ, 721, L734)

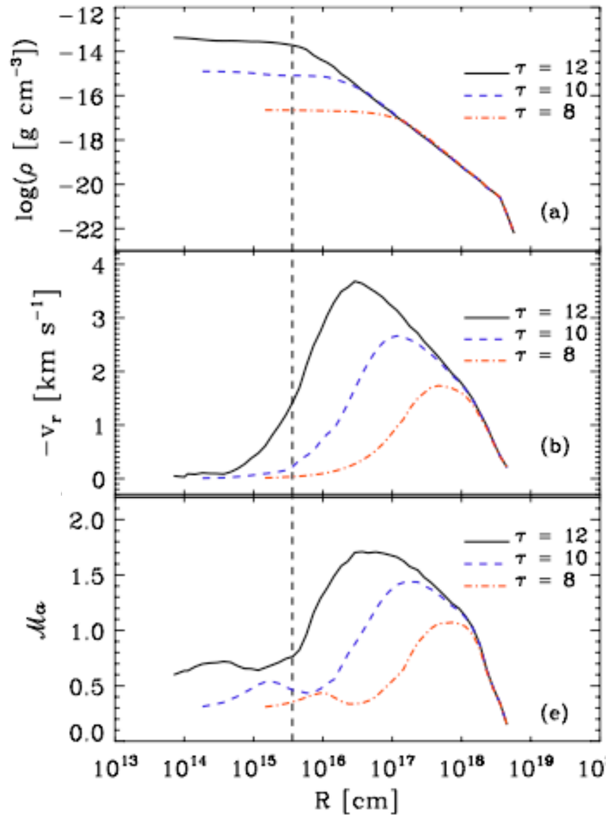


(Schleicher et al. 2010, A&A, 522, A115,   Sur et al. 2010, ApJ, 721, L734,   Federrath et al., 2011, ApJ, 731, 62)



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





radial density profile

radial velocity profile

Mach number profile

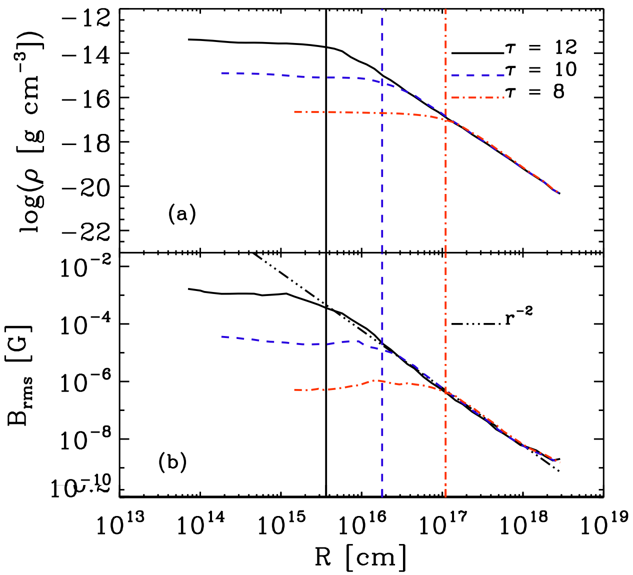
Field amplification during first collapse seems unavoidable.

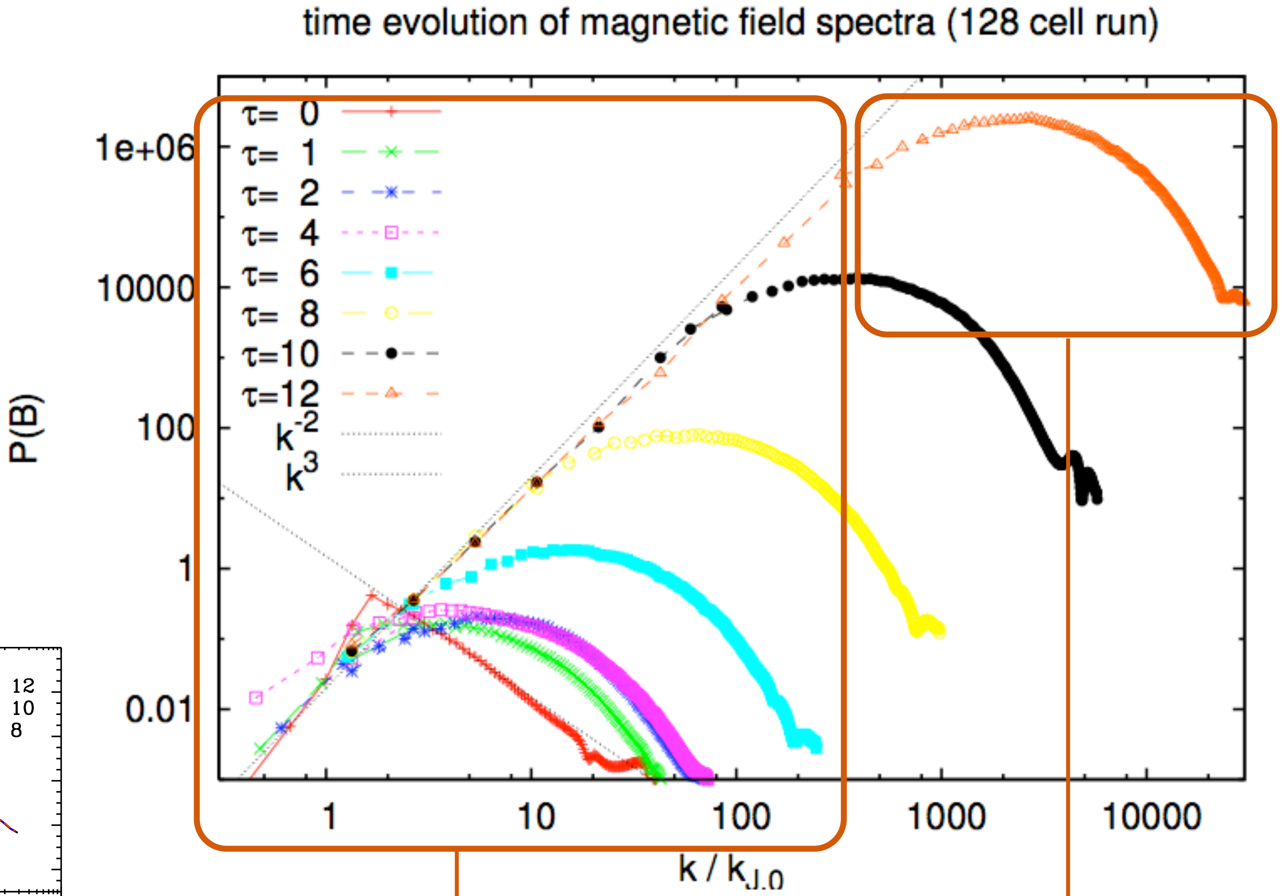
QUESTIONS:

- 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





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

B fluctuation spectrum in flat inner core

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

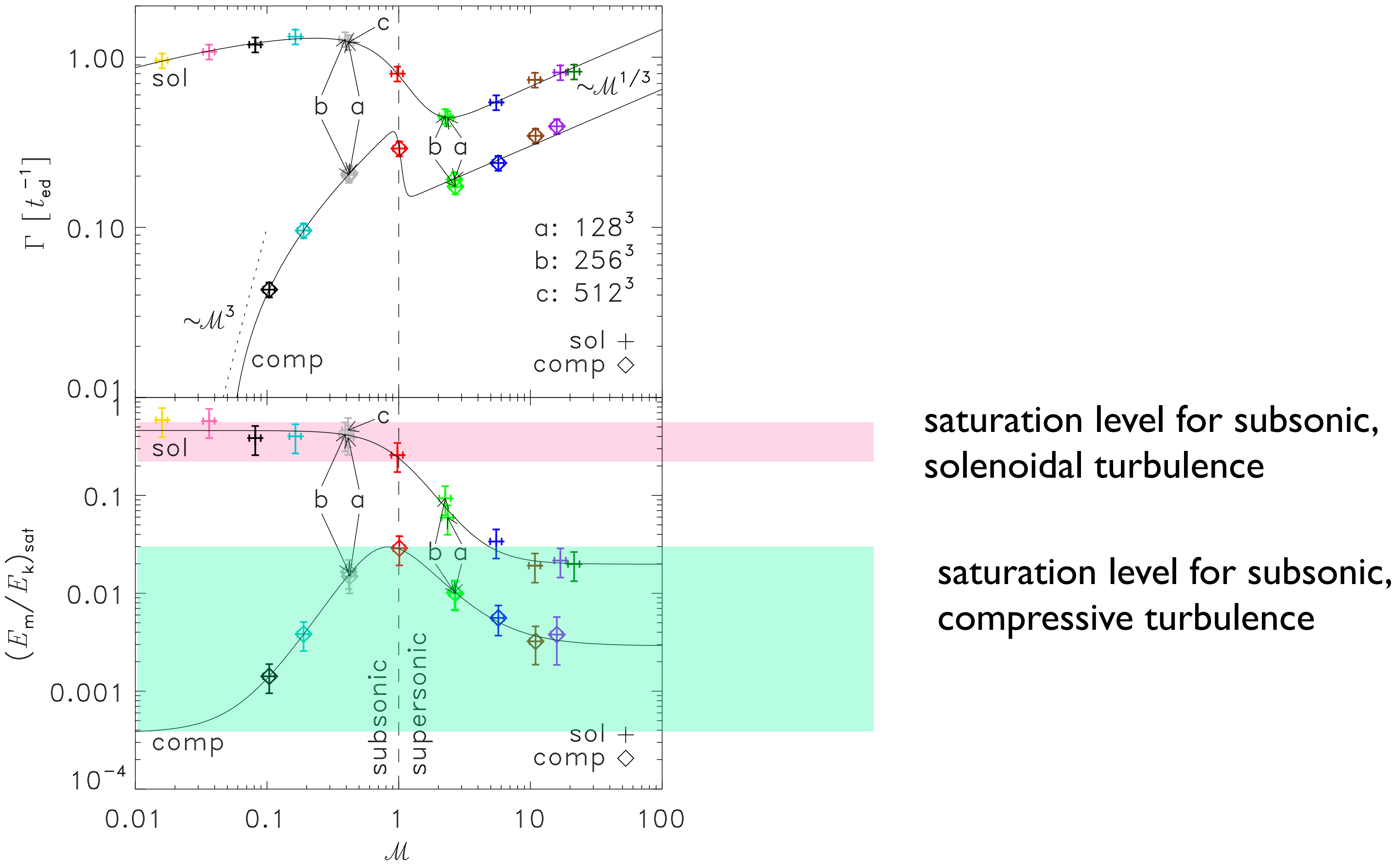


FIG. 3. (Color online) Growth rate (top), and saturation level (bottom) as a function of the Mach number for all runs with solenoidal (crosses) and compressive forcing (diamonds). The solid lines show empirical fits with equation (4). The labeled data points indicate four models ($\mathcal{M} \approx 0.4$, 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, 107, 114505)

turbulent velocity field

separation of smooth and turbulent component:

$$\vec{v} = \vec{v}_0 + \delta \vec{v}$$

properties of turbulent field $\delta \vec{v}$:

- isotropic and homogeneous
- Gaussian random field with zero mean
- delta-correlated in time

spatial two-point correlation of fluctuations:

$$\langle \delta v^i(\vec{x}, t) \delta v^j(\vec{y}, s) \rangle = T^{ij}(r) \delta(t-s)$$

$$T^{ij}(r) = (\delta^{ij} - \frac{r^i r^j}{r^2}) T_N(r) + \frac{r^i r^j}{r^2} T_L(r)$$

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

model for T_L

model for general turbulence:

$$T_L(r) \propto \begin{cases} \left(1 - Re^{(1-\vartheta)/(1+\vartheta)} \left(\frac{r}{L}\right)^2\right) & , r < l_c \\ \left(1 - \left(\frac{r}{L}\right)^{1+\vartheta}\right) & , l_c < r < L \\ 0 & , L < r \end{cases}$$

(l_c: cut-off scale, L: scale of largest fluctuations,
$Re = VL/\nu$: Reynolds number)

different turbulence models (in the inertial range):

$$\boxed{v(l) \propto l^{\vartheta}}$$

$1/3$ (Kolmogorov) $\leq \vartheta \leq 1/2$ (Burgers)

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

MHD dynamo

idea: divide also magnetic field into mean and turbulent component

$$\vec{B} = \vec{B}_0 + \delta \vec{B}$$

put into induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \eta \nabla^2 \vec{B}$$

=> evolution equations for mean and turbulent field (large-scale dynamo and small-scale dynamo)

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

Kazantsev theory

"Kazantsev Theory" (Kazantsev, 1968):
theory of the small-scale dynamo

correlation function of magnetic fluctuation:

$$\left\langle \delta B^i(\vec{x},t)\,\delta B^j(\vec{y},t)\right\rangle = M^{ij}(r,t)$$

$$M^{ij} = \left(\delta^{ij} - \frac{r^i r^j}{r^2}\right) M_N + \frac{r^i r^j}{r^2} M_L$$

with $\nabla \cdot \vec{B} = 0$:

$$M_N = \frac{1}{2\mathrm{r}} \frac{\partial}{\partial r}\left(r^2 M_L\right)$$

(Schober et al., 2012, PRE, 85, 026303,   see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

Kazantsev theory

put magnetic correlation function into induction equation
=> Kazantsev equation:

$$M_L(r,t) \propto \Psi(r) e^{2\Gamma t}$$

$$\boxed{-\kappa_T(r)\frac{\partial^2 \Psi(r)}{\partial^2 r} + U_0(r)\Psi(r) = -\Gamma \Psi(r)}$$

$$\kappa_T(r) = \kappa_T(T_L(r), \eta)$$ “mass”

$$U_0(r) = U_0(T_L(r), T_N(r), \eta)$$ “potential”

can be solved with WKB-approximation for large magnetic Prandtl numbers (ν/η)

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

critical mag. Reynolds number

Reynolds number for minimal growth rate:
set $\Gamma = 0$ in Kazantsev equation
and solve for Rm $(Rm = VL/\eta)$

result (for Kolmogorov turbulence):

$$\boxed{Rm > 110}$$

result (for Burgers turbulence):

$$\boxed{Rm > 2700}$$

=> need high resolution in order to see dynamo
in simulations

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

growth rate

growth rate for large magnetic Prandtl numbers:

$$\boxed{\Gamma \propto Re^{(1-\vartheta)/(1+\vartheta)}}$$

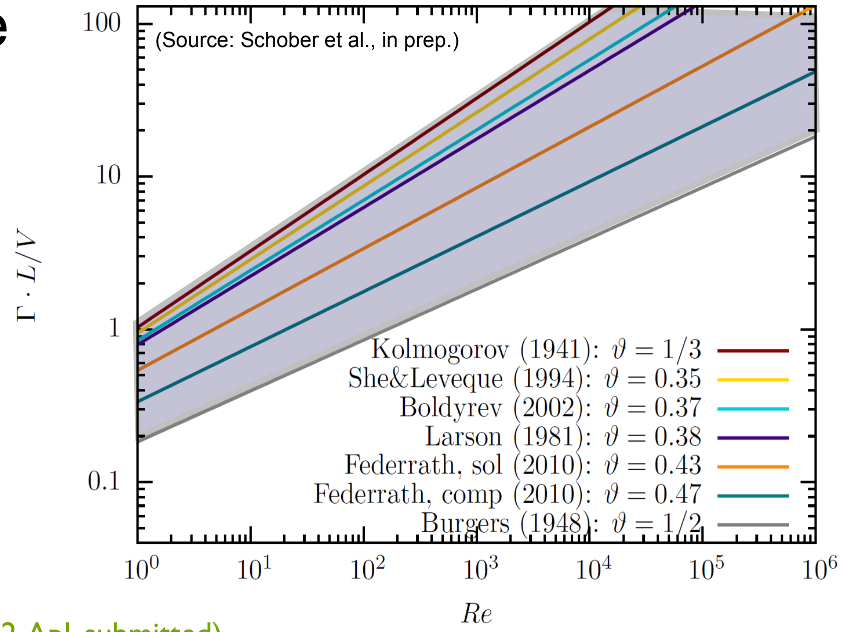
(with slope of the turbulent velocity spectrum $v(l) \propto l^{\vartheta}$)

example 1: Kolmogorov turbulence

$$\Gamma \propto Re^{1/2}$$

example 2: Burgers turbulence

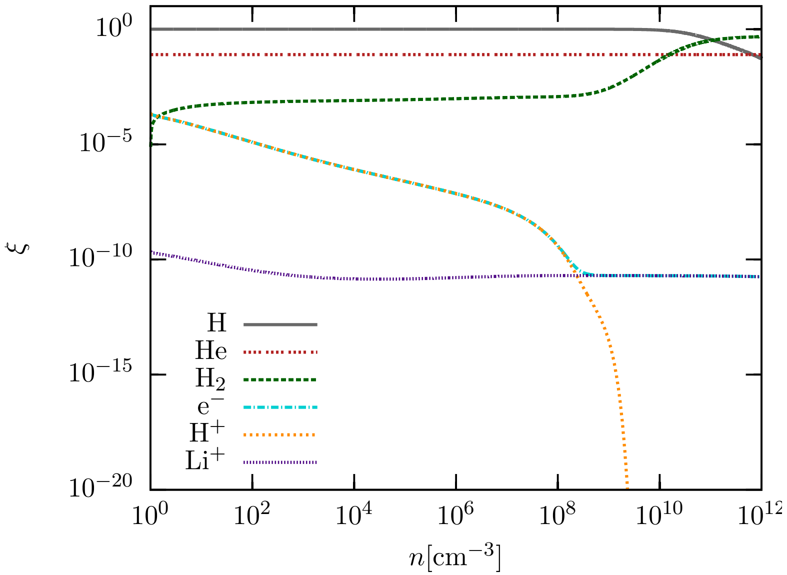
$$\Gamma \propto Re^{1/3}$$

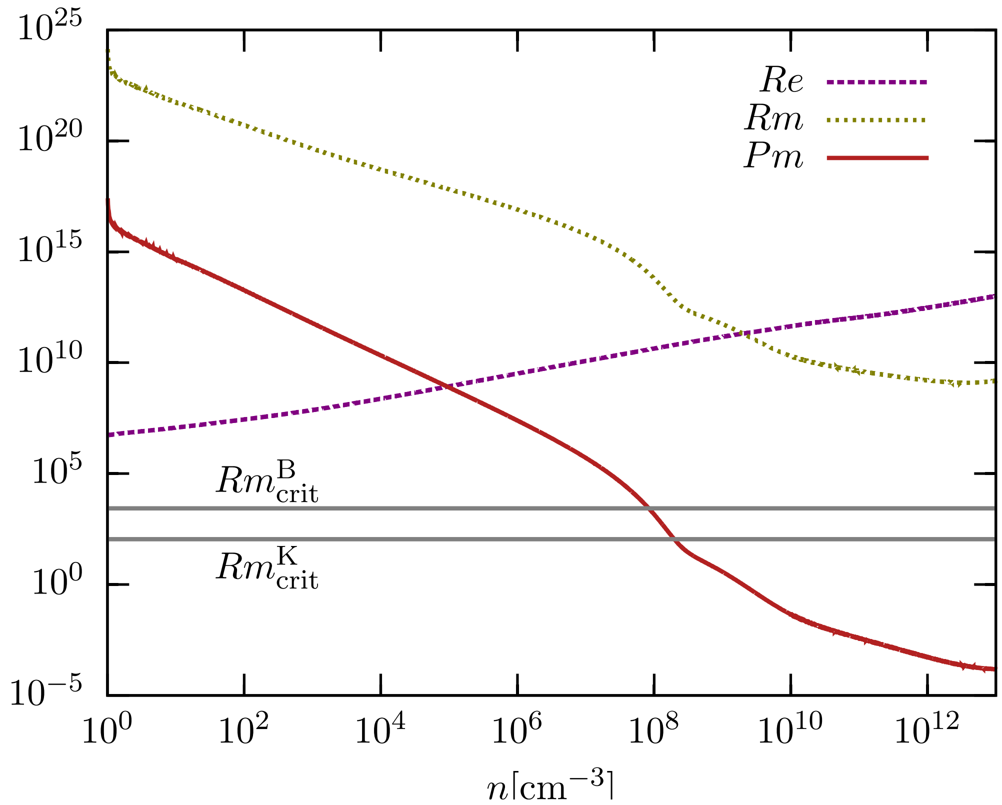


(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted)

dynamo in early universe

calculation of characteristic quantities in primordial gas with the chemistry code of Glover & Savin (2009)





(Schober et al., 2012, PRE, 85, 026303)

in primordial minihalos

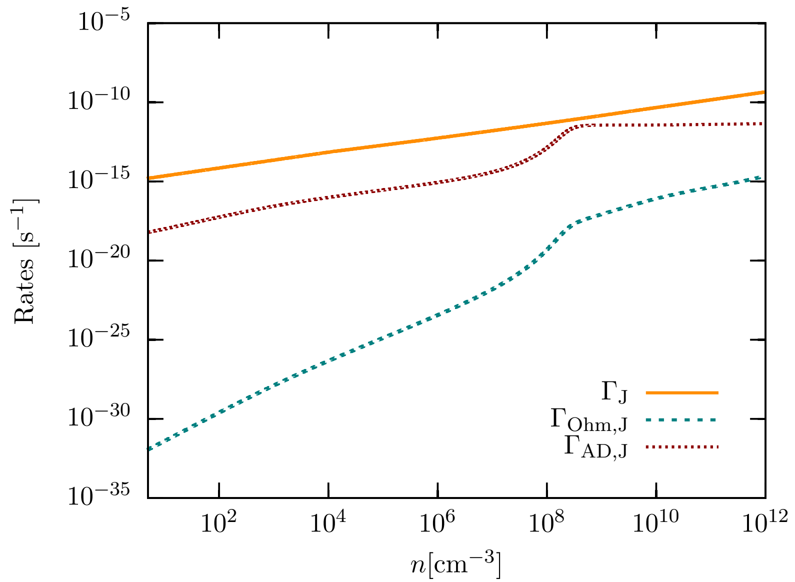


Figure 8. The growth rate on the Jeans scale Γ_J after the dynamo amplification compared to the diffusion rates as a function of the number density. $\Gamma_{Ohm,J}$ and $\Gamma_{AD,J}$ are the Ohmic and ambipolar diffusion rate, respectively.

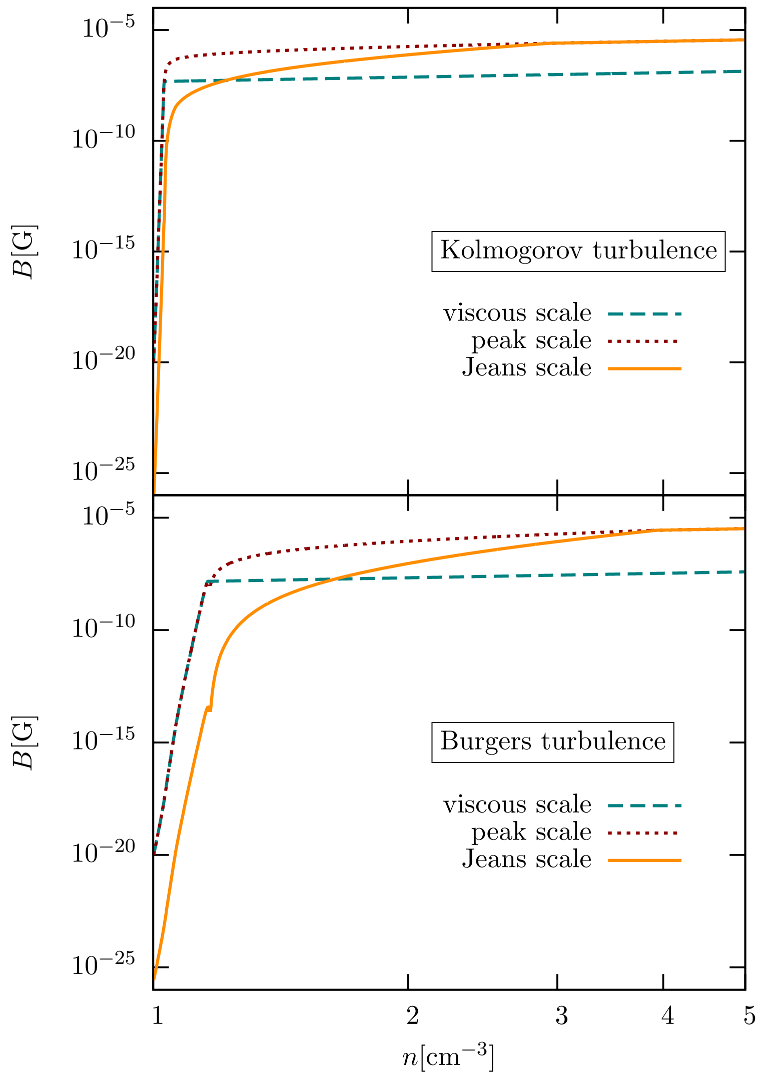
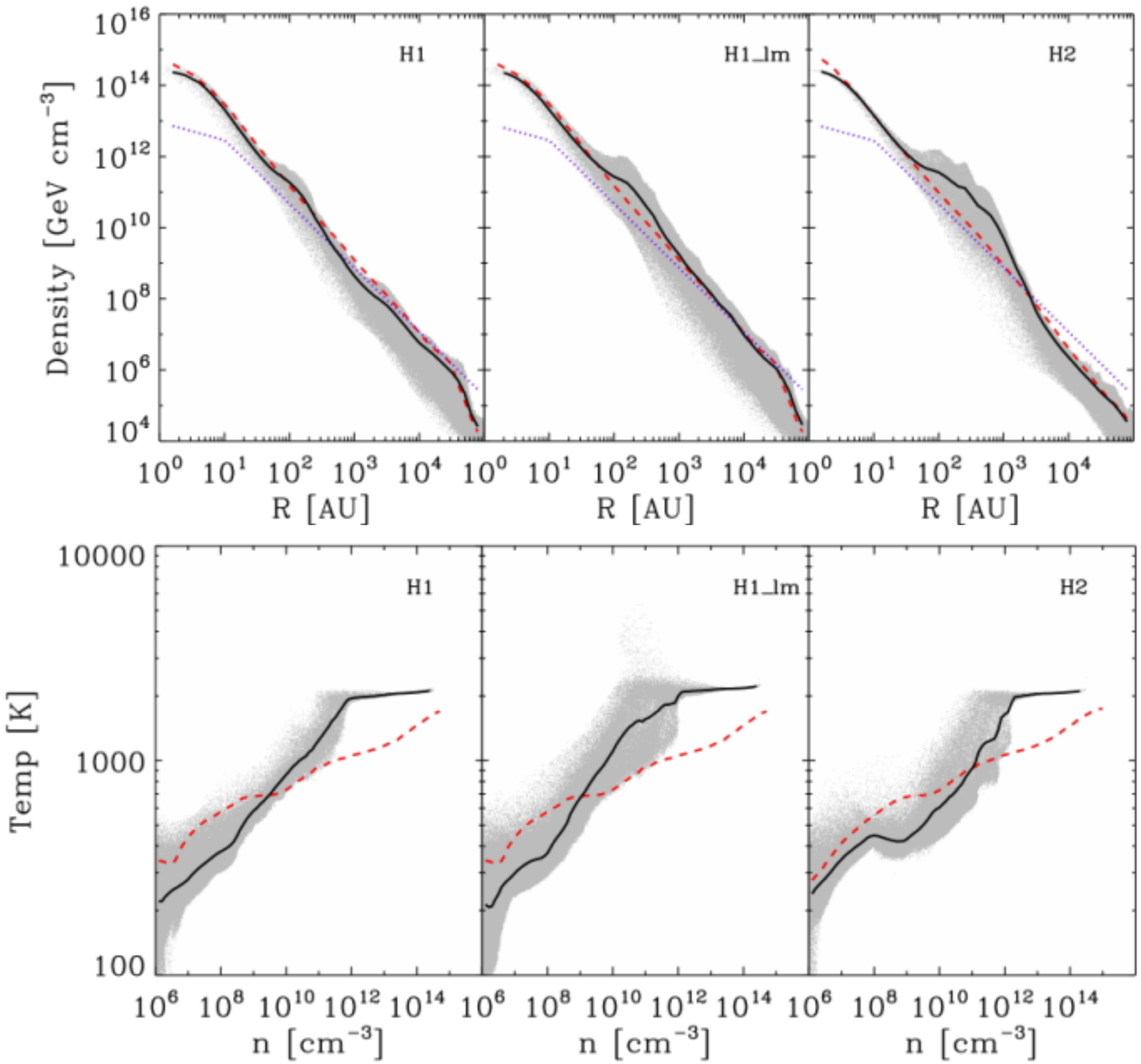


Figure 7. The magnetic field strength as a function of the number density on different scales. The dashed green line corresponds to the field evolution on the viscous scale, the dotted red line to the peak scale and the solid orange line to the Jeans scale. We show the results for Kolmogorov turbulence in the upper plot and the results for Burgers turbulence in the lower plot.

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, submitted -- arXiv:1204.0658)

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?



mean gas density / temperature with DM annihilation

reference case without DM annihilation

DM density

DM annihilation leads to disk heating and reduced fragmentation

see poster by Rowan Smith

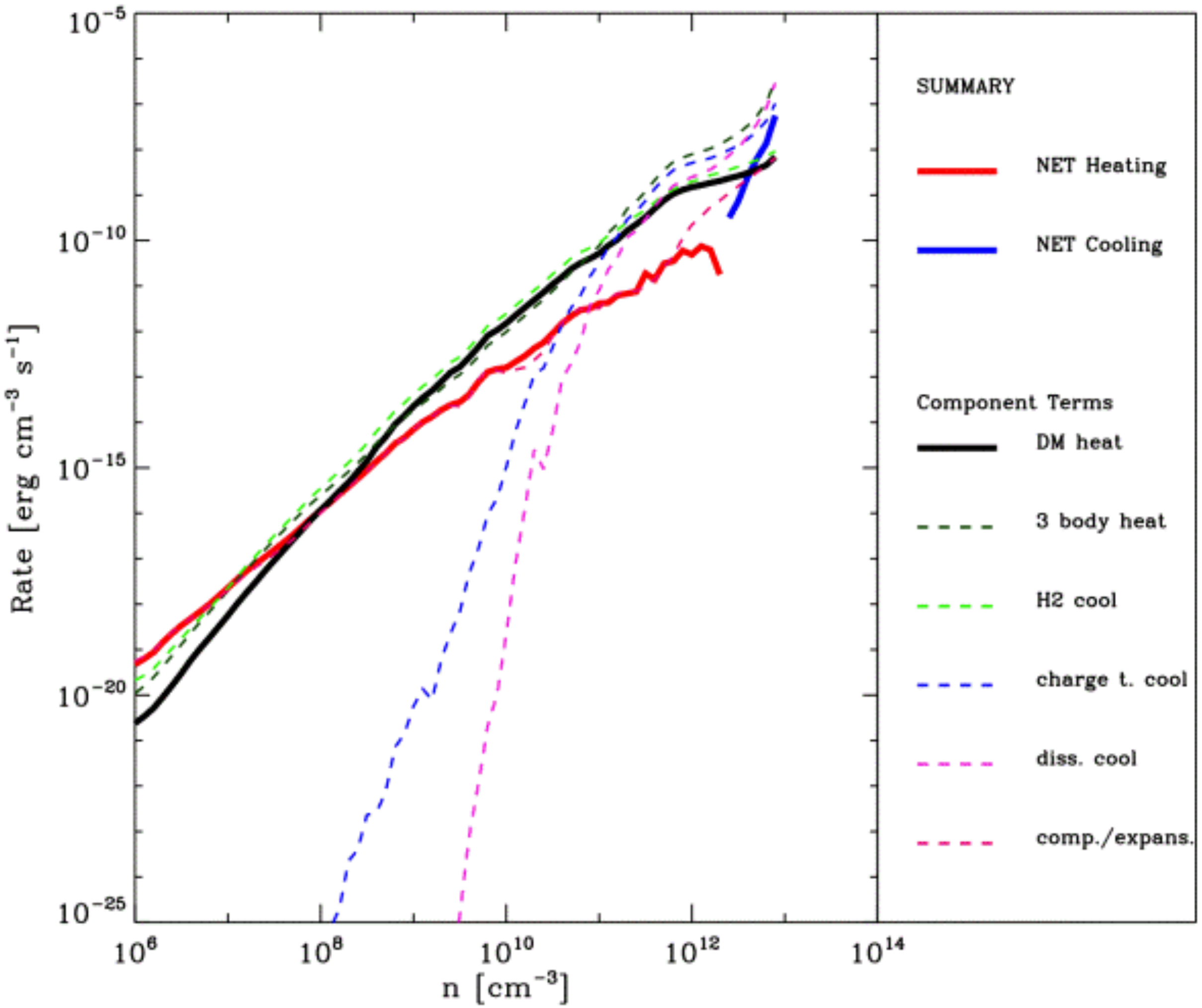


Fig 2: *The major heating and cooling processes active in H1 at the point where DMA heating is predicted to prevent collapse in Spolyar et. al. 2008. The DM heating is an important contributor to the net heating between densities of 10^9-10^{12} cm^{-3}. However the heating is insufficient to halt the collapse due to cooling at higher densities from the dissociation of H_2 and charge transfer cooling.*

net heating in density range up to few x 10^{12} cm^{-3}

DM annihilation leads to disk heating and reduced fragmentation

see poster by Rowan Smith

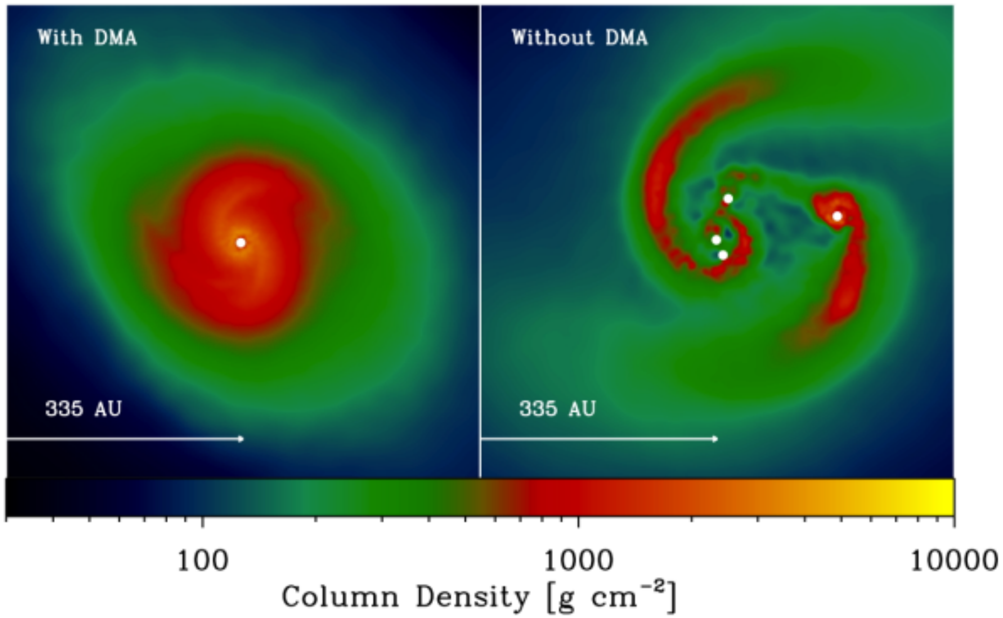


Fig 3: *The column density at the centre of H1 with and without DMA feedback 500 yr after the first sink forms. Without DMA three additional sink particles form, however with DMA the disk is stable and does not fragment.*

fragmentation without DM annihililation heating

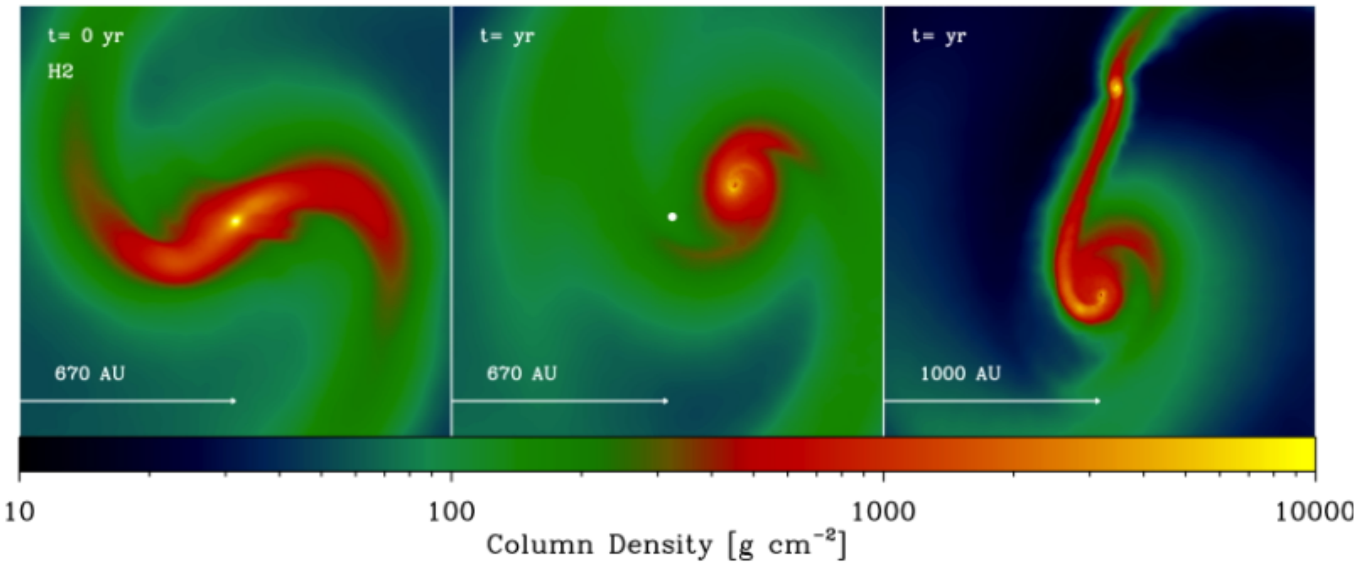


Fig 4: *The column density at the centre of H2 at three times after the sink particle forms. A sink particle is formed at a separation of 1000 AU from the central object after a period of ? Interestingly the sink protostar has become displaced from its original position in panel 2 introducing the possibility that the baryons may eventually decouple from the DM peak.*

reduced fragmentation with DM annihililation heating

see poster by Rowan Smith


Carina with HST

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

  to *strongly influence* first and second star formation.
- **masses** of first stars still *uncertain,* we expect a ***flat spectrum*** over a wide range of masses and a high ***binary fraction***
- transition to **power-law IMF** above 10^{-5} Z_{sun}, due to dust
- first and second generation stars should form in ***clusters***

Carina with HST