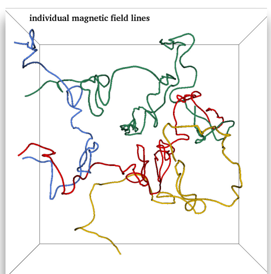
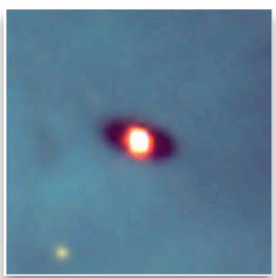
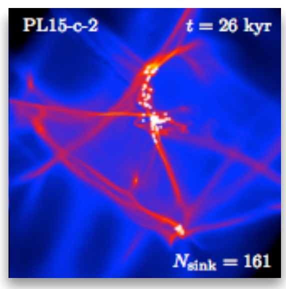
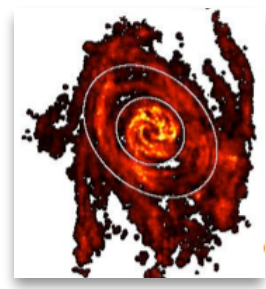
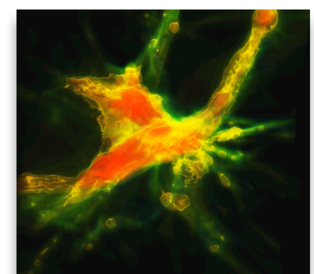
ISM Dynamics and Star Formation











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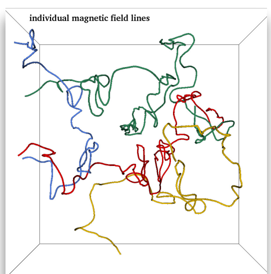
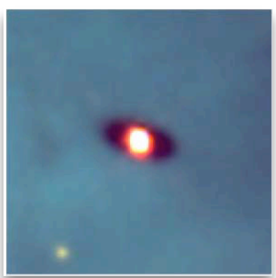
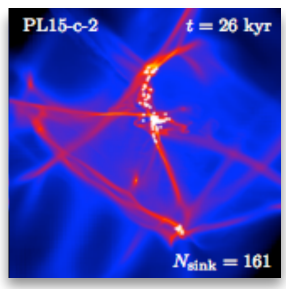
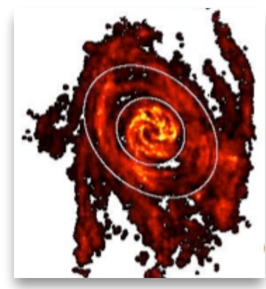
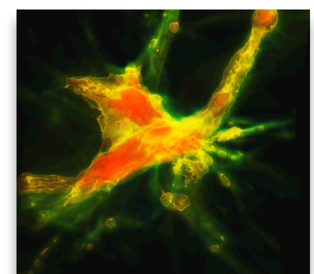
Some Open Issues in Star Formation



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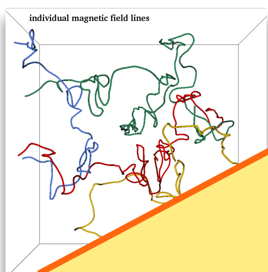
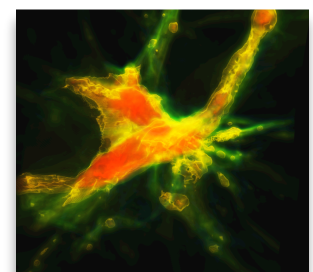
Some Open Issues
Star Form

DISCLAIMER





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thanks to ...

... people in the group in Heidelberg:

Christian Baczynski, Erik Bertram, Frank Bigiel, Rachel Chicharro, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs, Svitlana Zhukovska

... former group members:

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

... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft

HGSFP

IMPRS

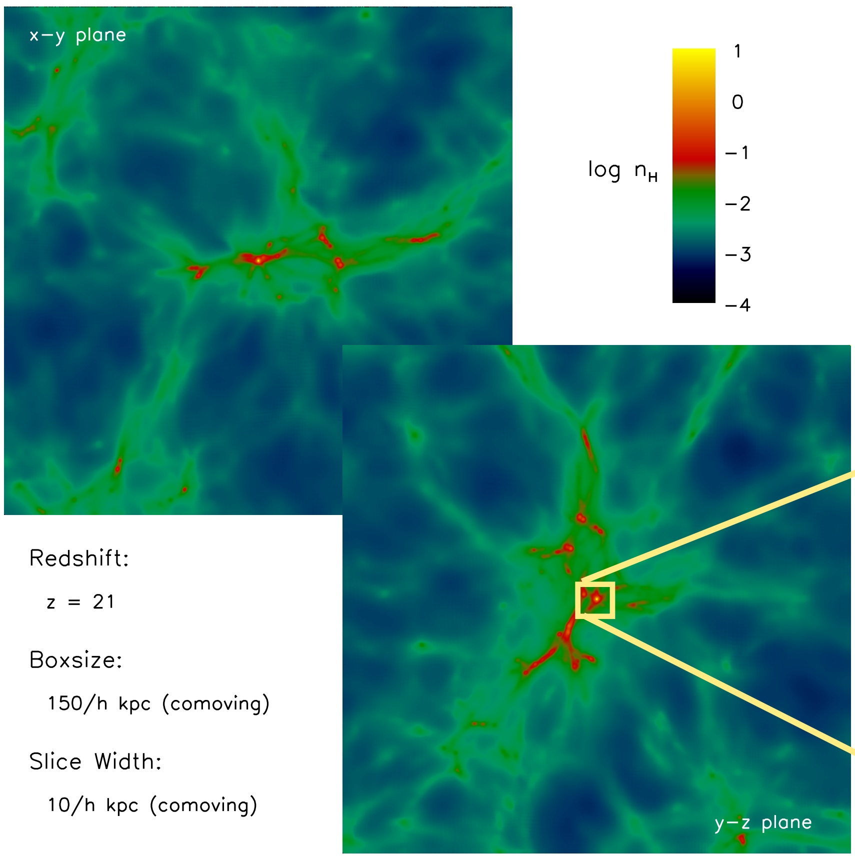
agenda

- first star formation
  - influence of magnetic fields
  - influence of dark matter annihilation
- global star formation
  - non-universal and sub-linear Kennicutt-Schmidt relation

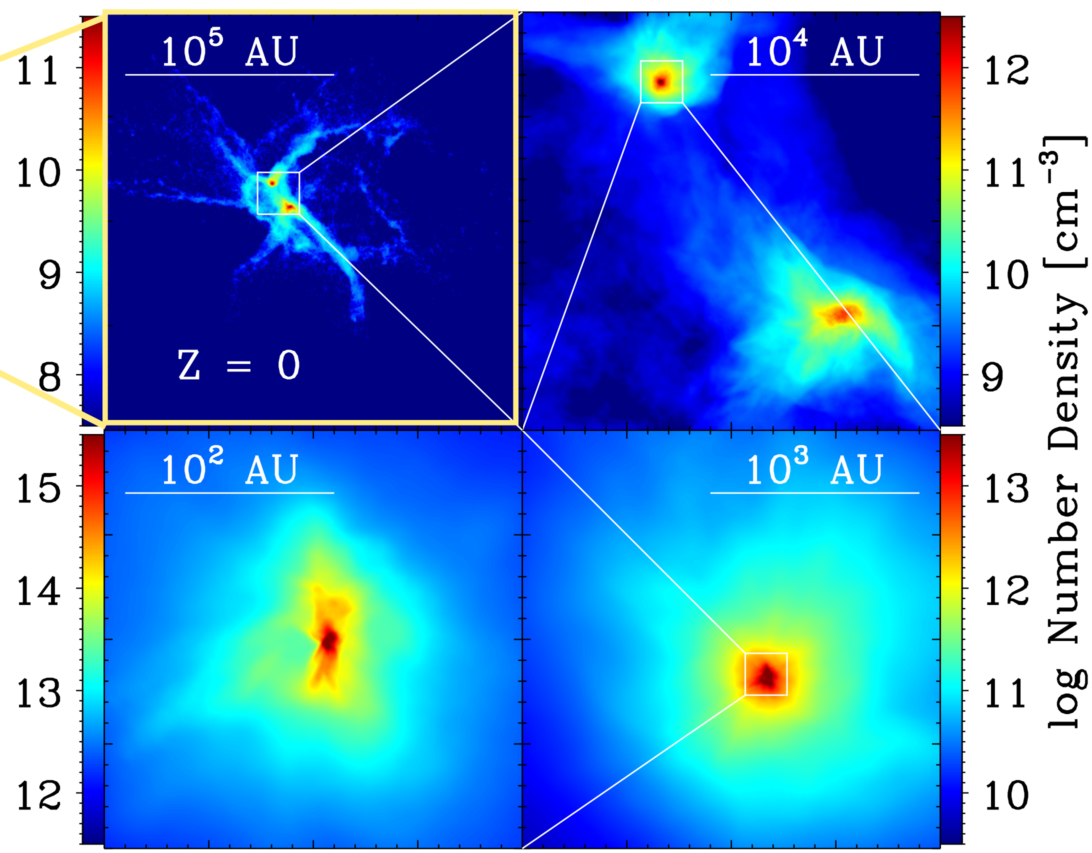
NGC 3324 (Hubble, NASA/ESA)

… following up on
Volker’s talk …

model the formation of the first stars



successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

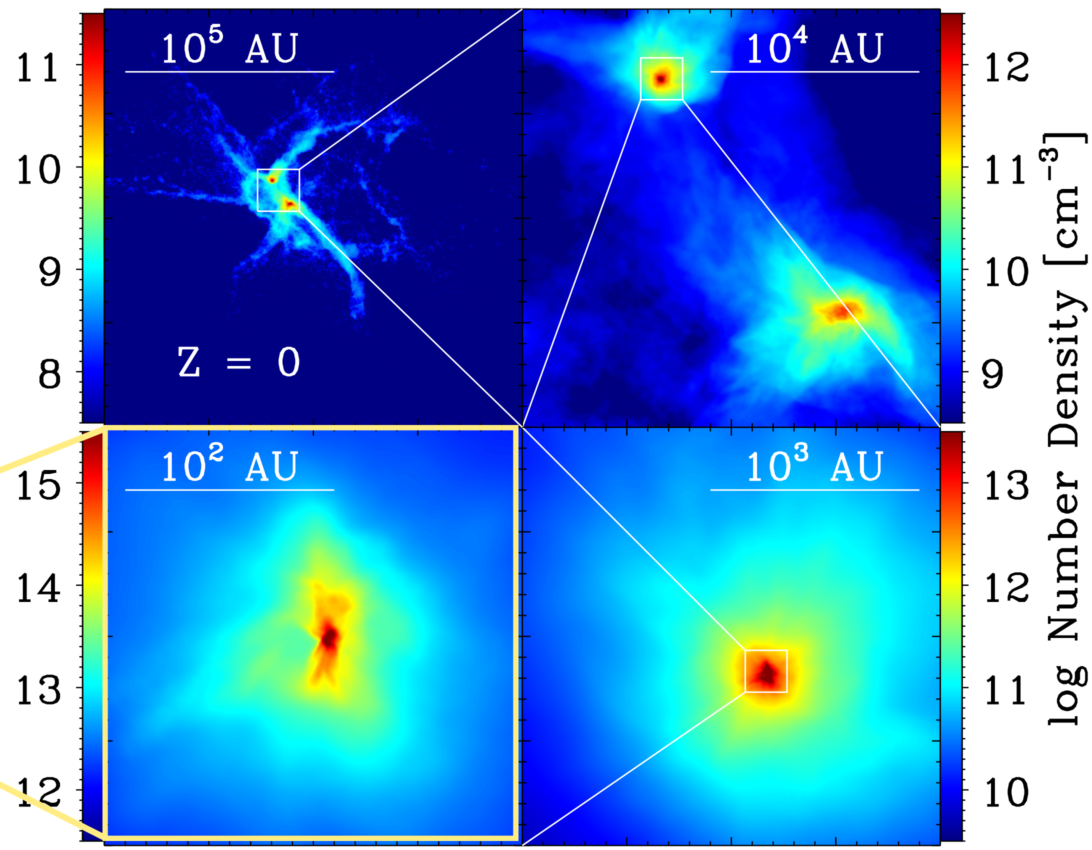


(Greif et al., 2007, ApJ, 670, 1)

(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2013, ApJ, 776, 103)

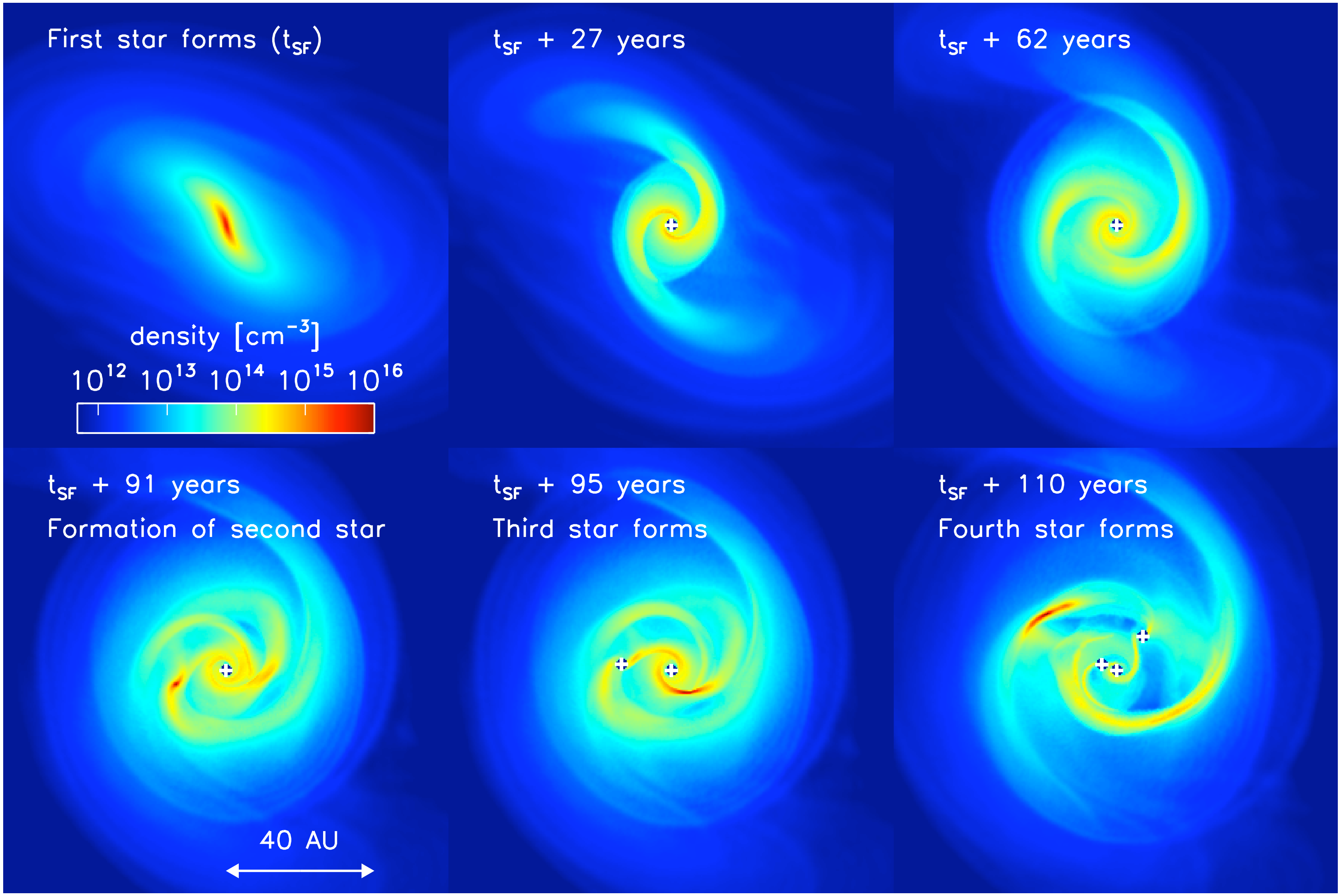
detailed look at accretion disk around first star

successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



what is the time evolution of accretion disk around first star to form?

(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

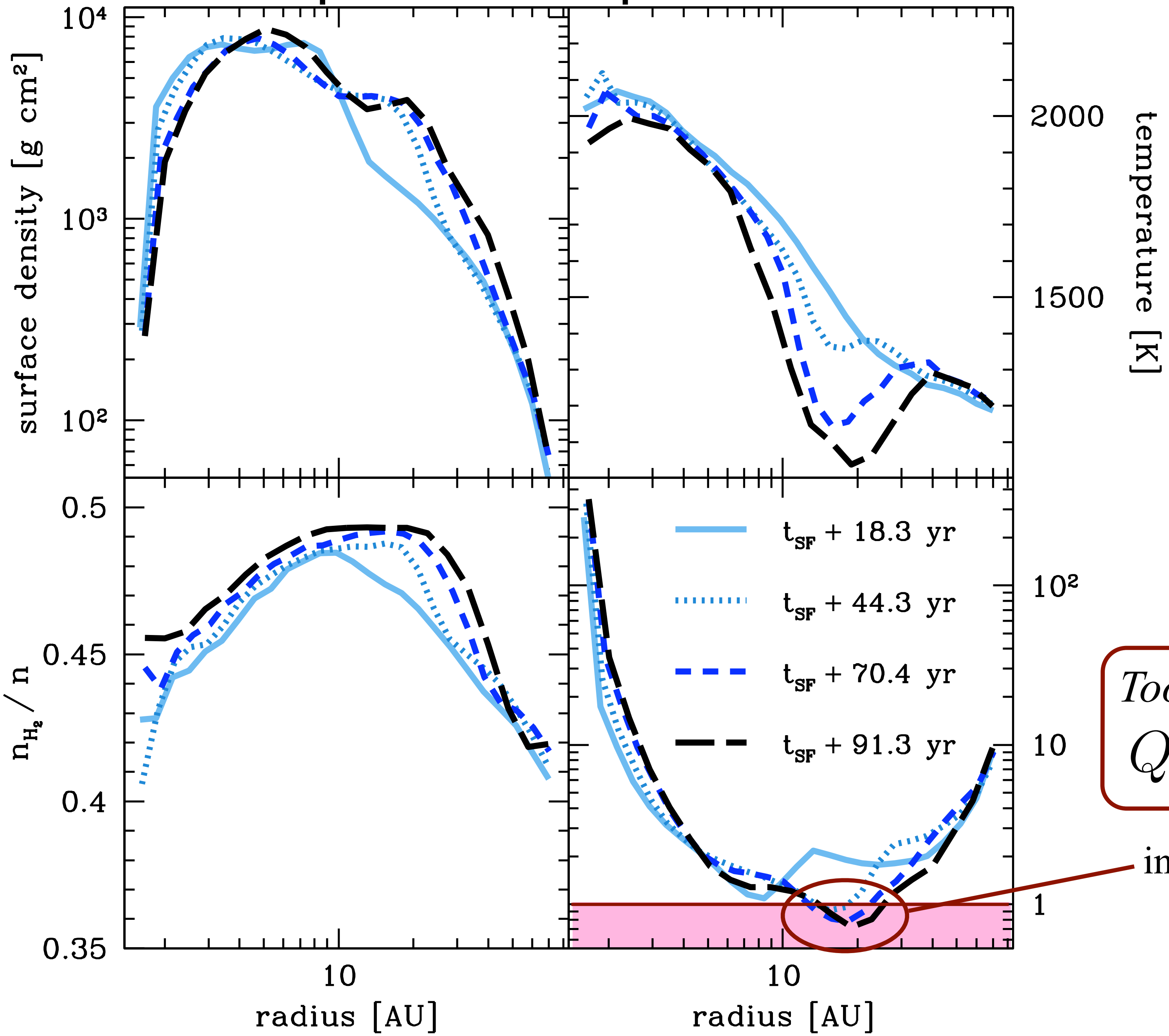


detailed look at accretion disk

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)

important disk parameters

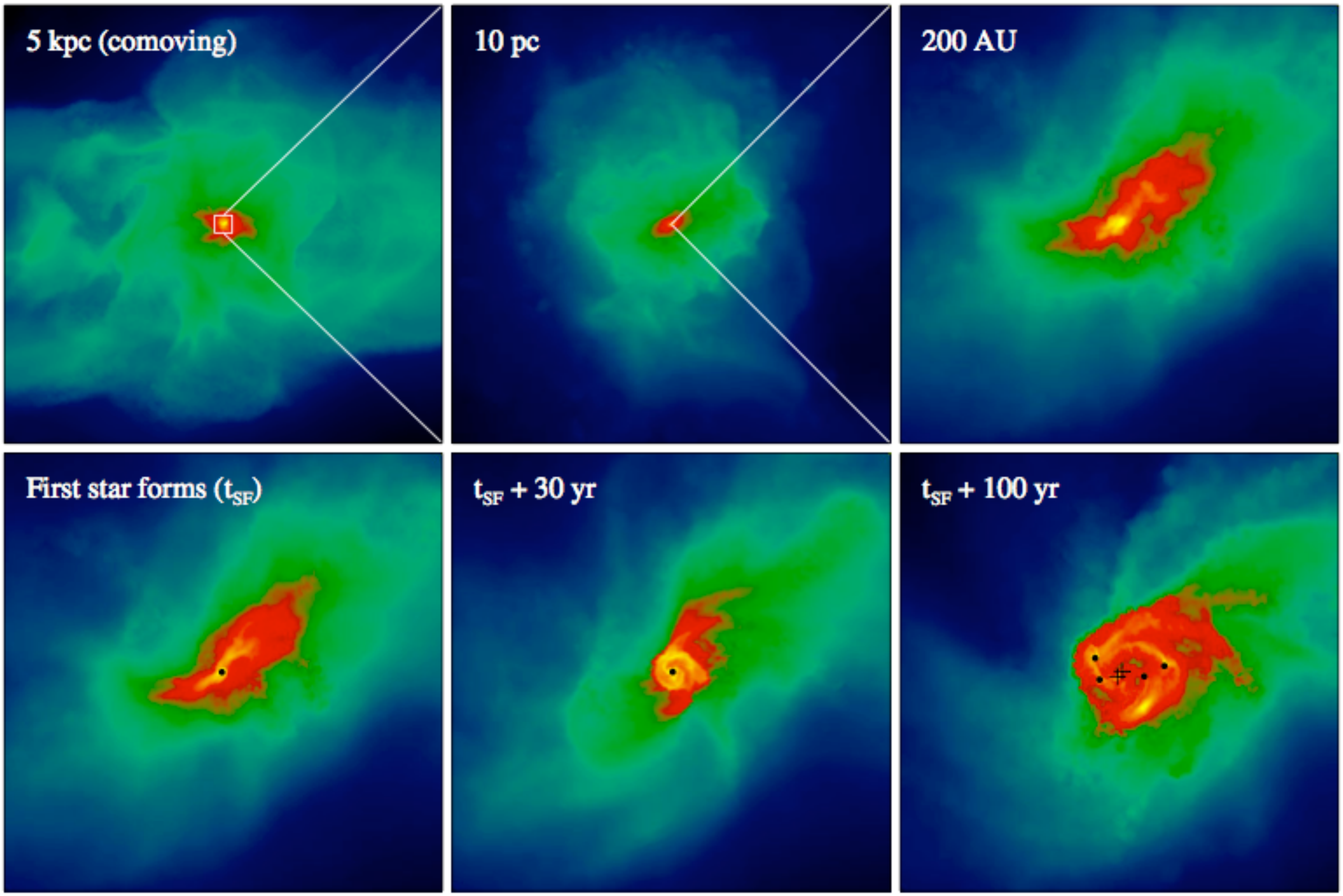


Toomre Q:

$$Q = c_s \kappa / \pi G \Sigma$$

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

similar study with very different numerical method (AREPO)

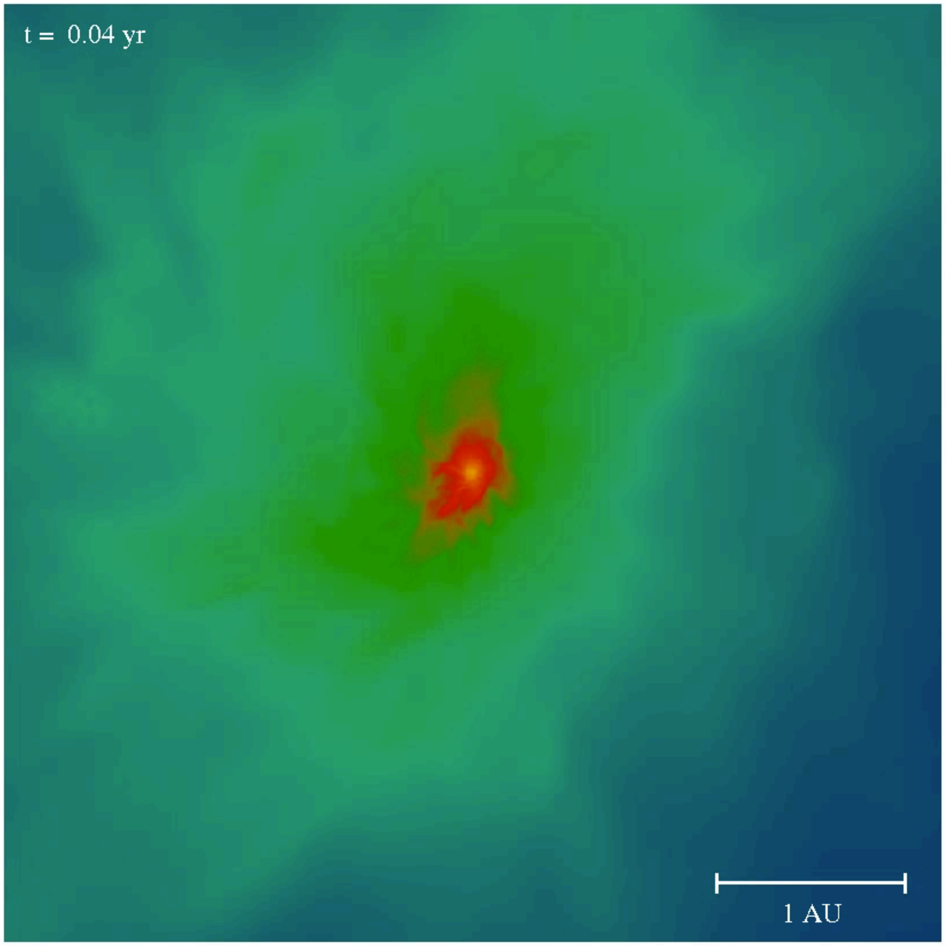


one out of five halos

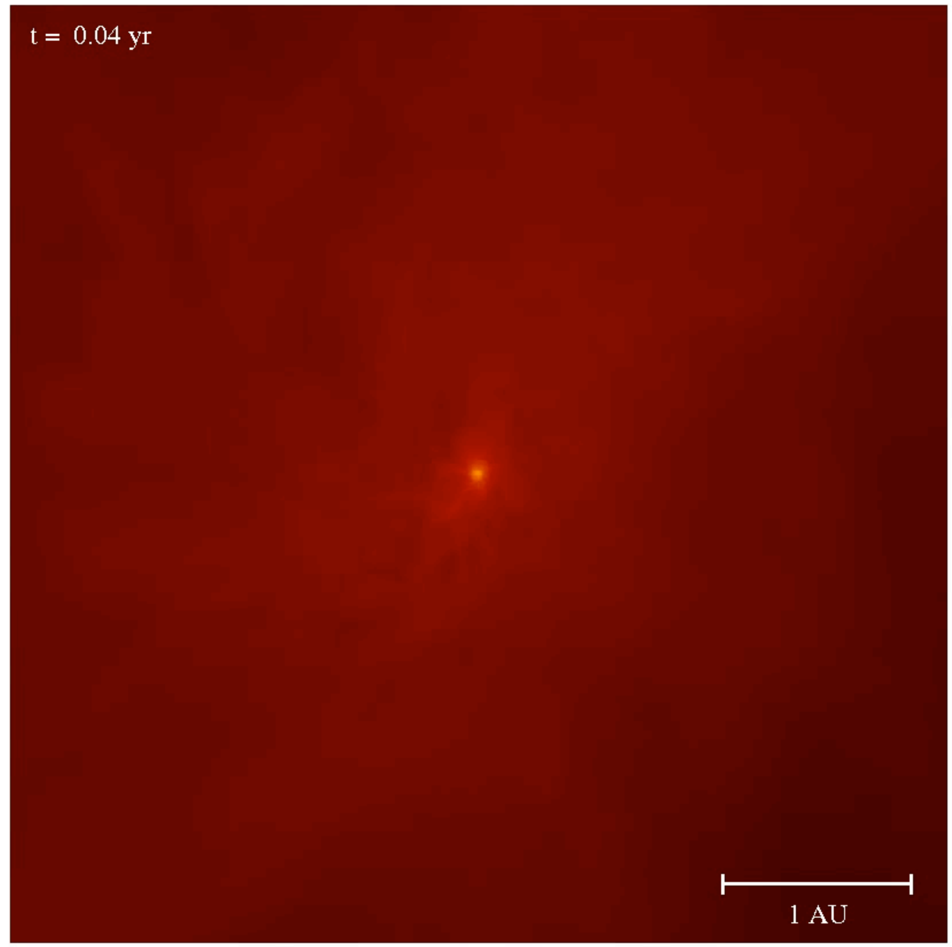
(Greif et al. 2011a, ApJ)

Most recent calculations:

fully sink-less simulations, following the disk build-up over ~10 years
(resolving the protostars - first cores - down to 10^5 km ~ 0.01 $R_\odot$)



density

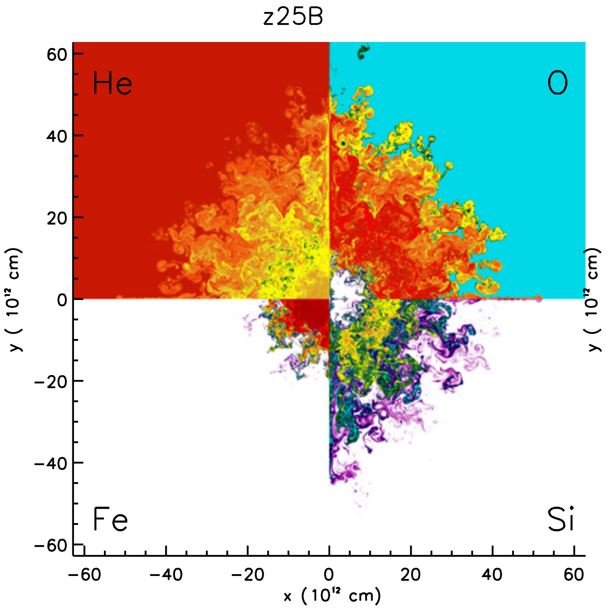


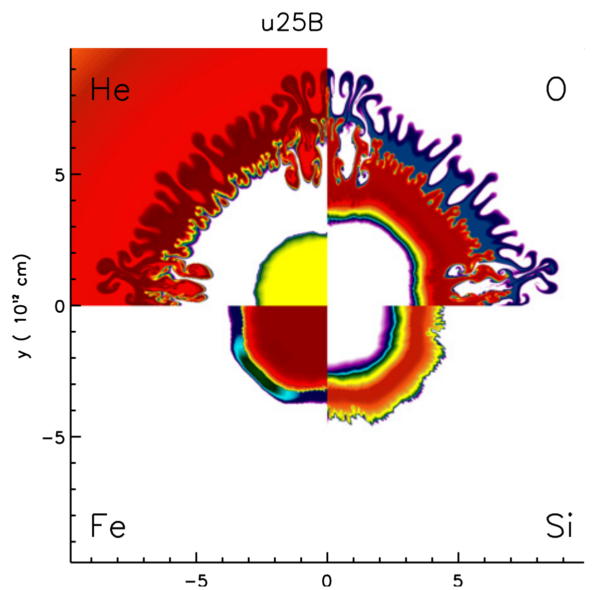
temperature

(Greif et al., 2012, MNRAS, 424, 399)

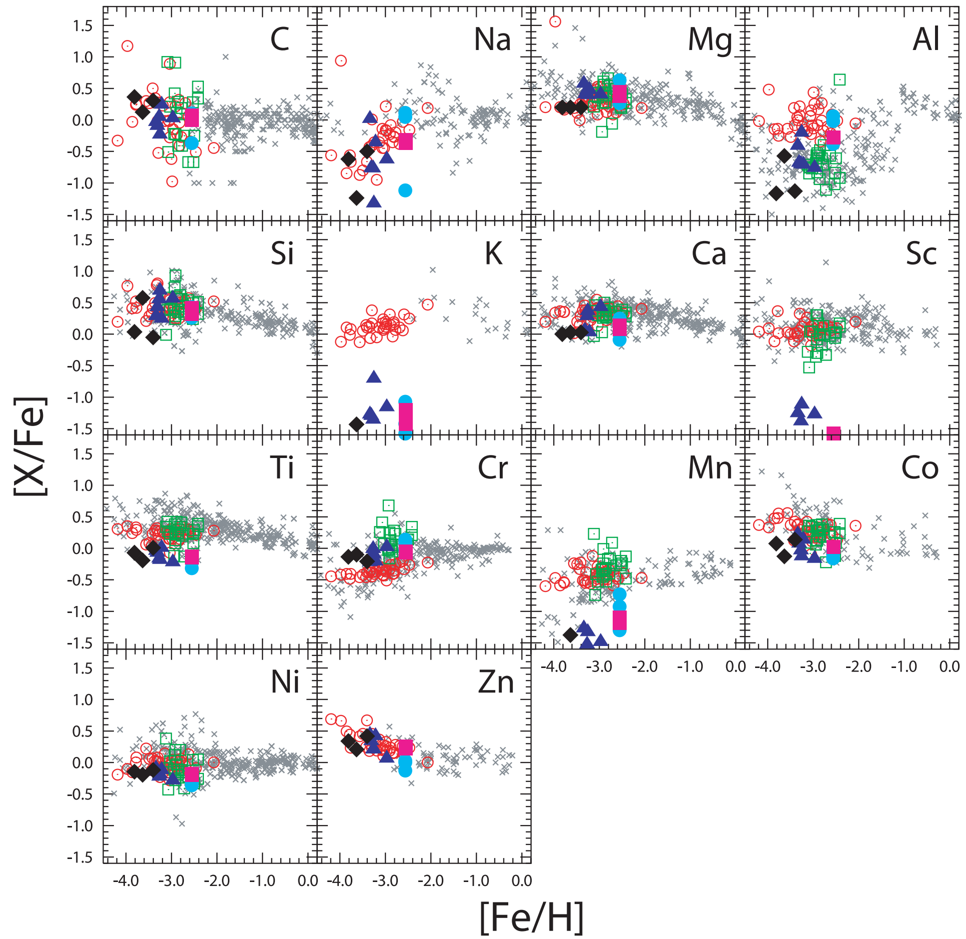
expected mass spectrum

- *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)

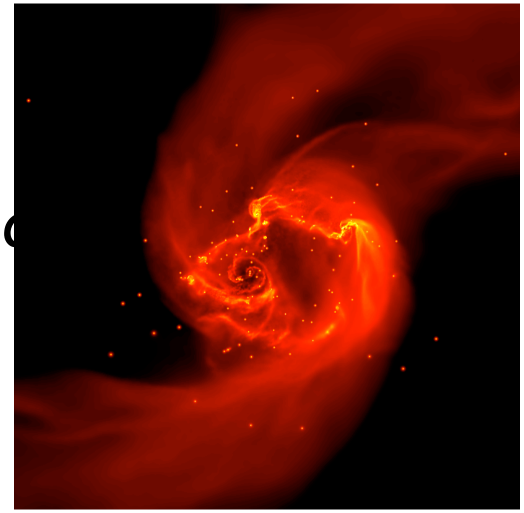
The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 M$_\odot$

(e.g. Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

primordial star formation

- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics (i.e. balance between hea*
  - *feedback*
  - *magnetic fields*

  to influence first star formation.



- masses of first stars still *uncertain*, but we expect a *wide mass range* with *typical masses* of *several 10s of* $M_\odot$
- disks unstable: first stars in *binaries* or *part of small clusters*
- current frontier: include *feedback* and *magnetic fields* and possibly *dark matter annihilation*...

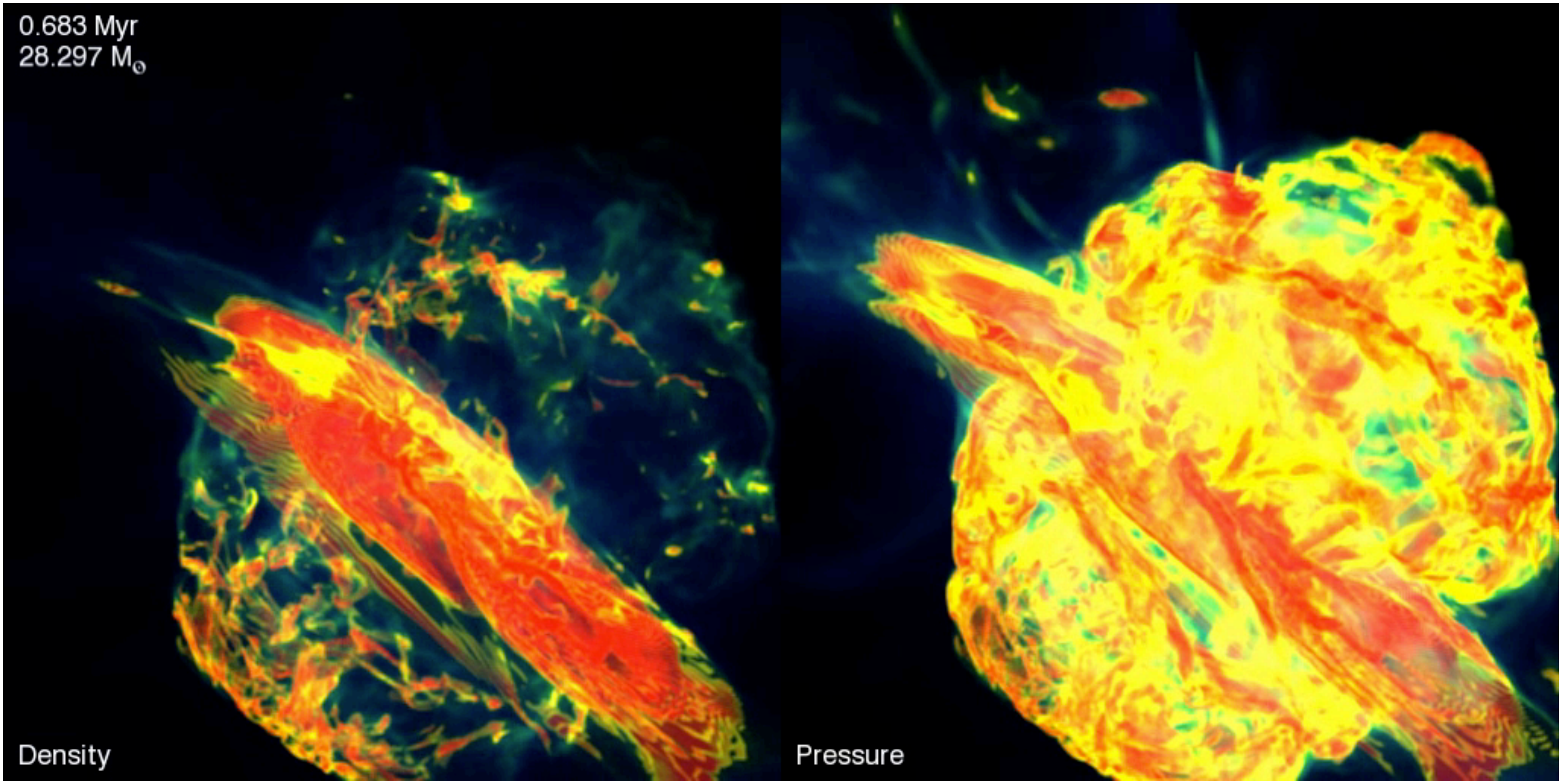
reducing fragmentation

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

  can influence the fragmentation behavior.
- in the context of Pop III
  - radiation: Hosokawa et al. 2012, Stacy et al. 2012a
  - magnetic fields: Turk et al. 2012, but see also Bovino et al. 2013
    Schleicher et al. 2010, Sur et al. 2010, Federrath et al. 2011, Schober et al. 2012ab, 2013
- all these will reduce degree of fragmentation
  (but not by much, see Rowan Smith et al. 2011, 2012, at least for accretion heating)
- DM annihililation might become important for disk dynamics and fragmentation (Ripamonti et al. 2011, Stacy et al. 2012b, Rowan Smith et al. 2012)

magnetic fields

influence of B on disk evolution



Peters et al. (2011)

in disk around high-mass stars, fragmentation is reduced but rarely fully suppressed
see Peters et al. (2011), Hennebelle et al. (2011), Seifried et al. (2011)

interplay of ionization and B-field

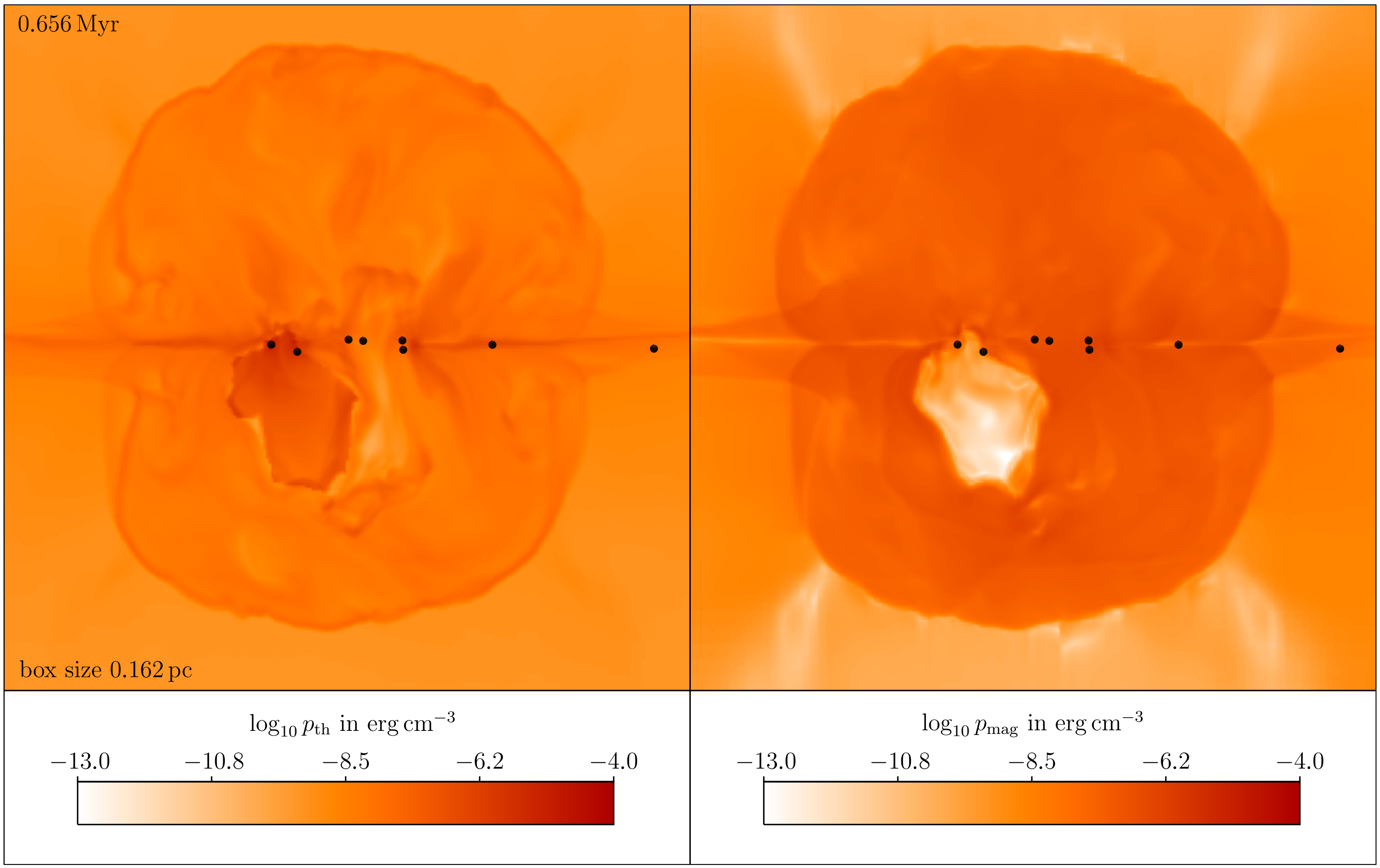
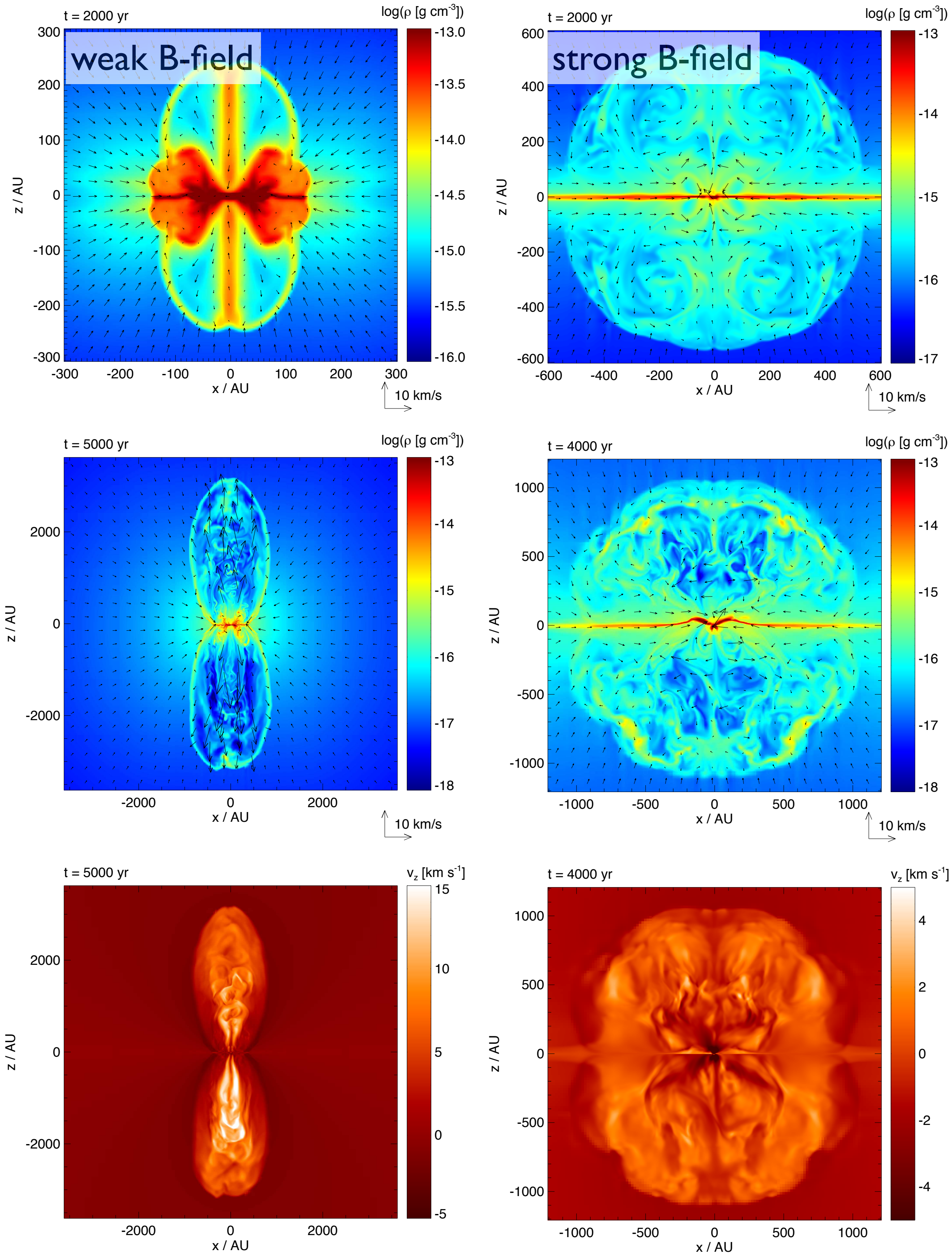


Figure 10. Comparison of thermal and magnetic pressure for the data from the lefthand panels in Figure 5. The thermal pressure $p_{\rm th}$ inside the H II region (left) is of comparable magnitude to the magnetic pressure $p_{\rm mag}$ outside the H II region (right). Thus, magnetic pressure plays a significant role in constraining the size of expanding H II regions. The black dots represent sink particles.

Peters et al. (2011)



density in inner region
and early times

density on larger scales
and later times

velocity on larger scales
and later times

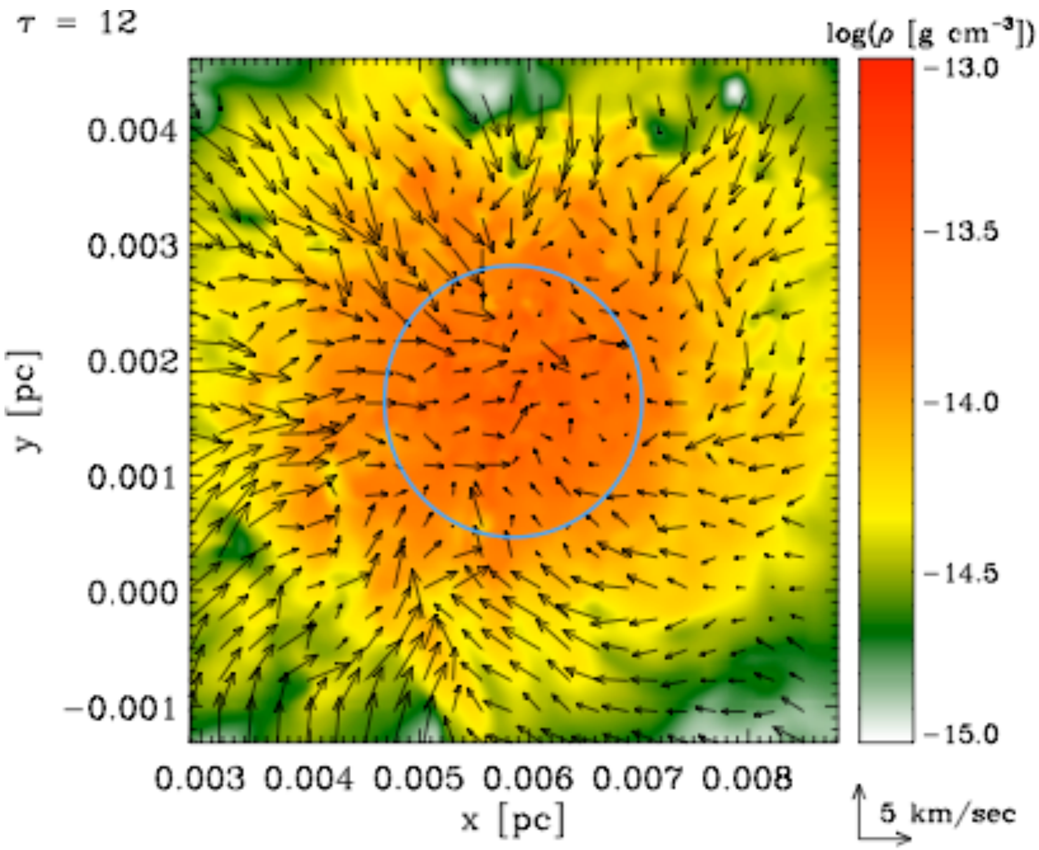
Seifried, Pudrith, Banerjee, Duffin, Klessen (2011)

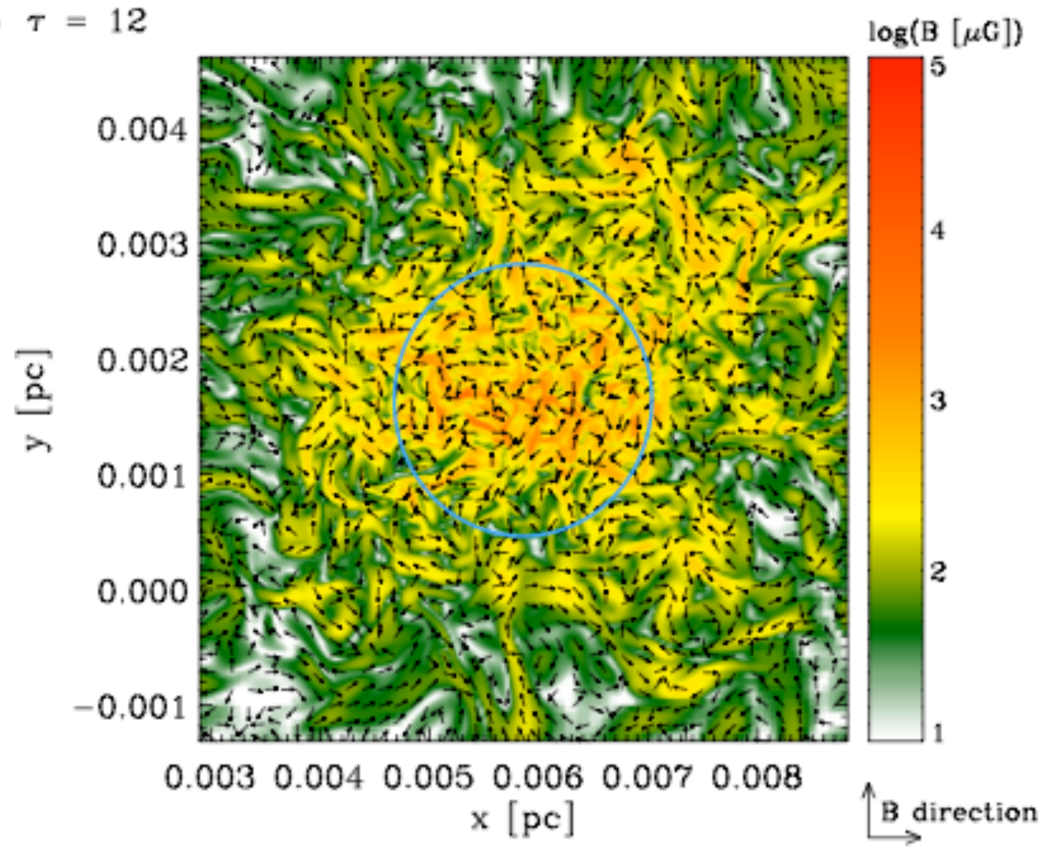
B fields in the early universe?

- 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
- *method:* solve ideal MHD with very high resolution
  - grid-based AMR code FLASH
  - polytropic EOS with $\gamma = 1.1$
  - 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, 754, 99

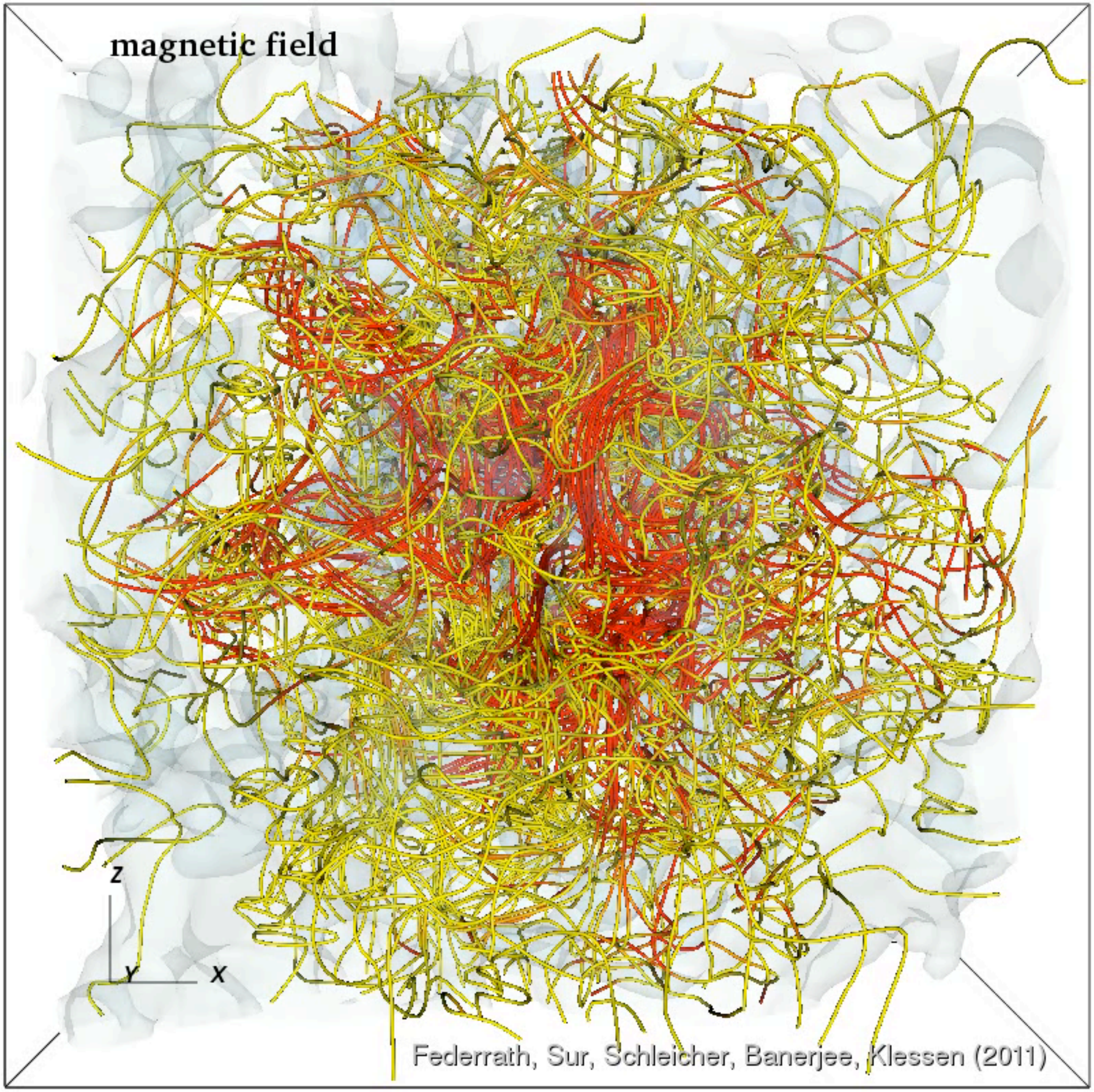




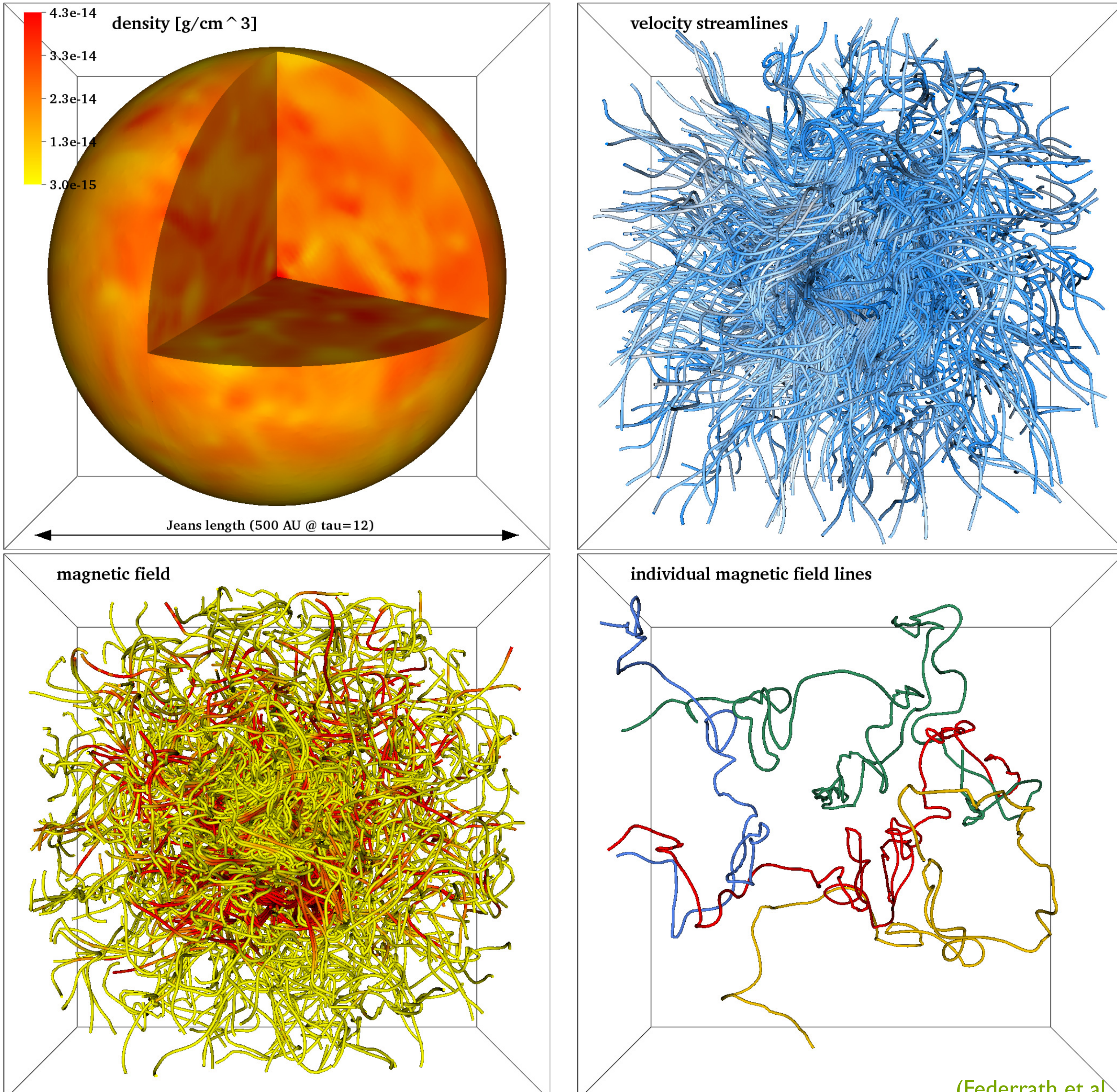
magnetic field structure

density structure

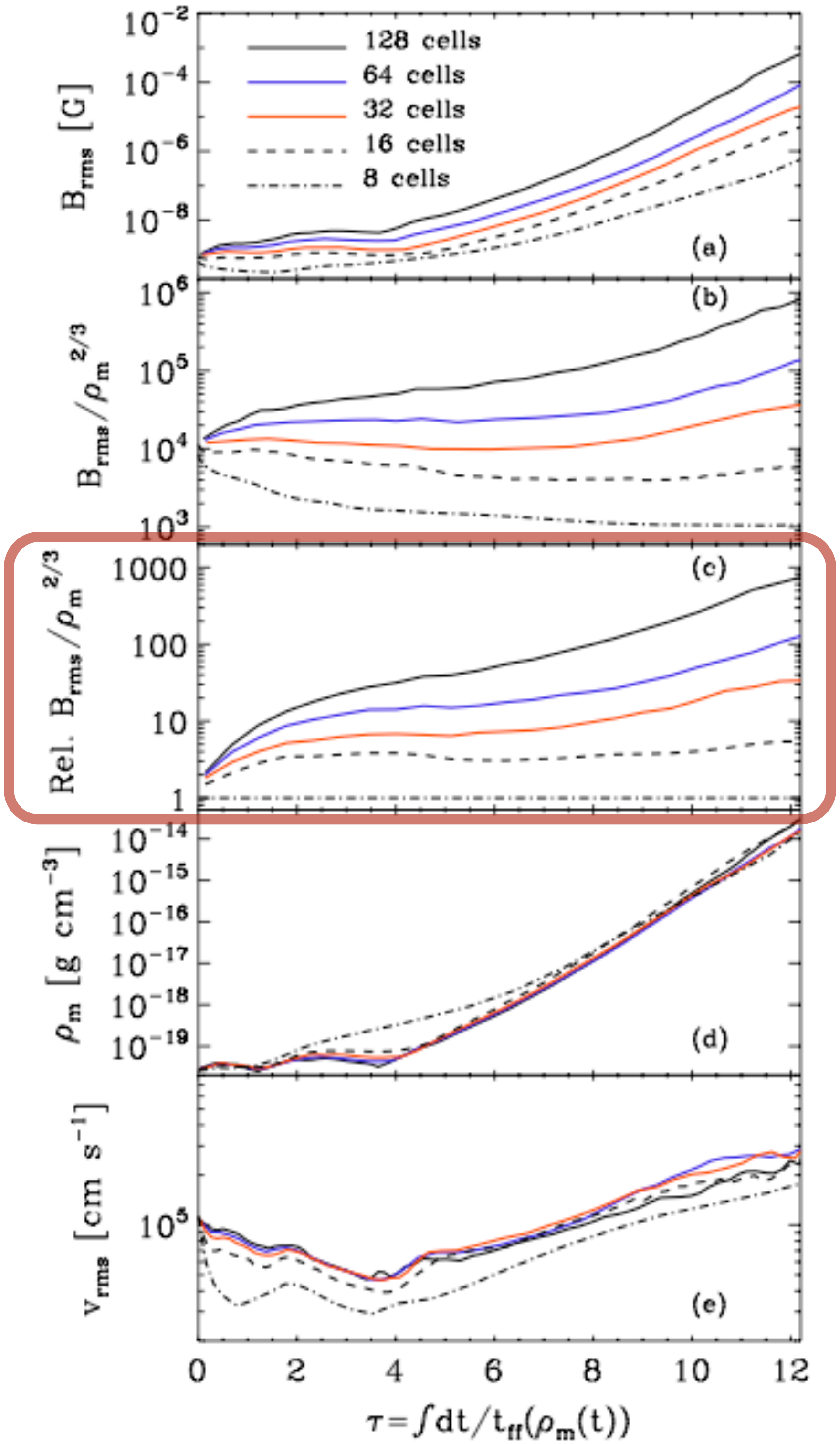
(Sur et al. 2010, ApJ, 721, L734)

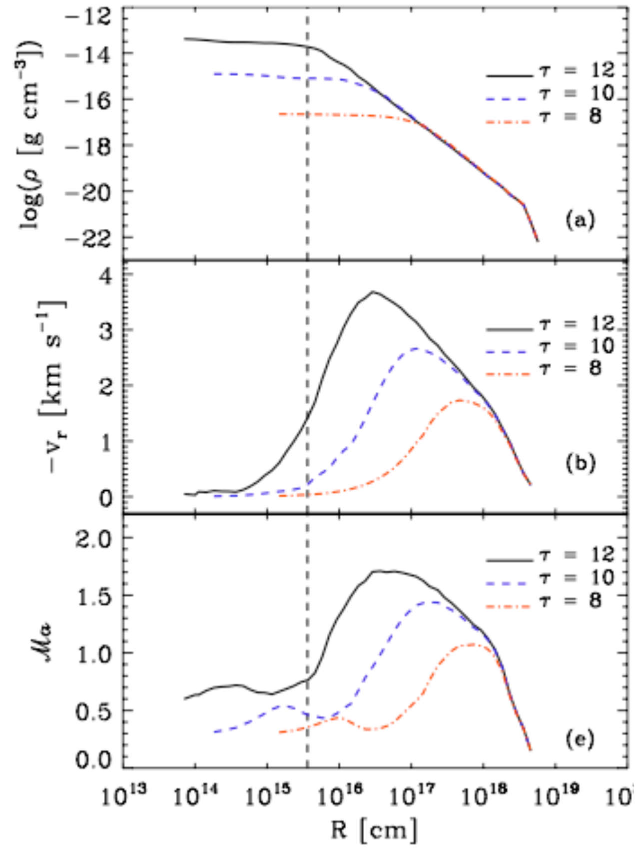


(Schleicher et al. 2010, A&A, 522, A115, Sur et al. 2010, ApJ, 721, L734, Federrath et al., 2011, ApJ, 731, 62)



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





radial density profile

radial velocity profile

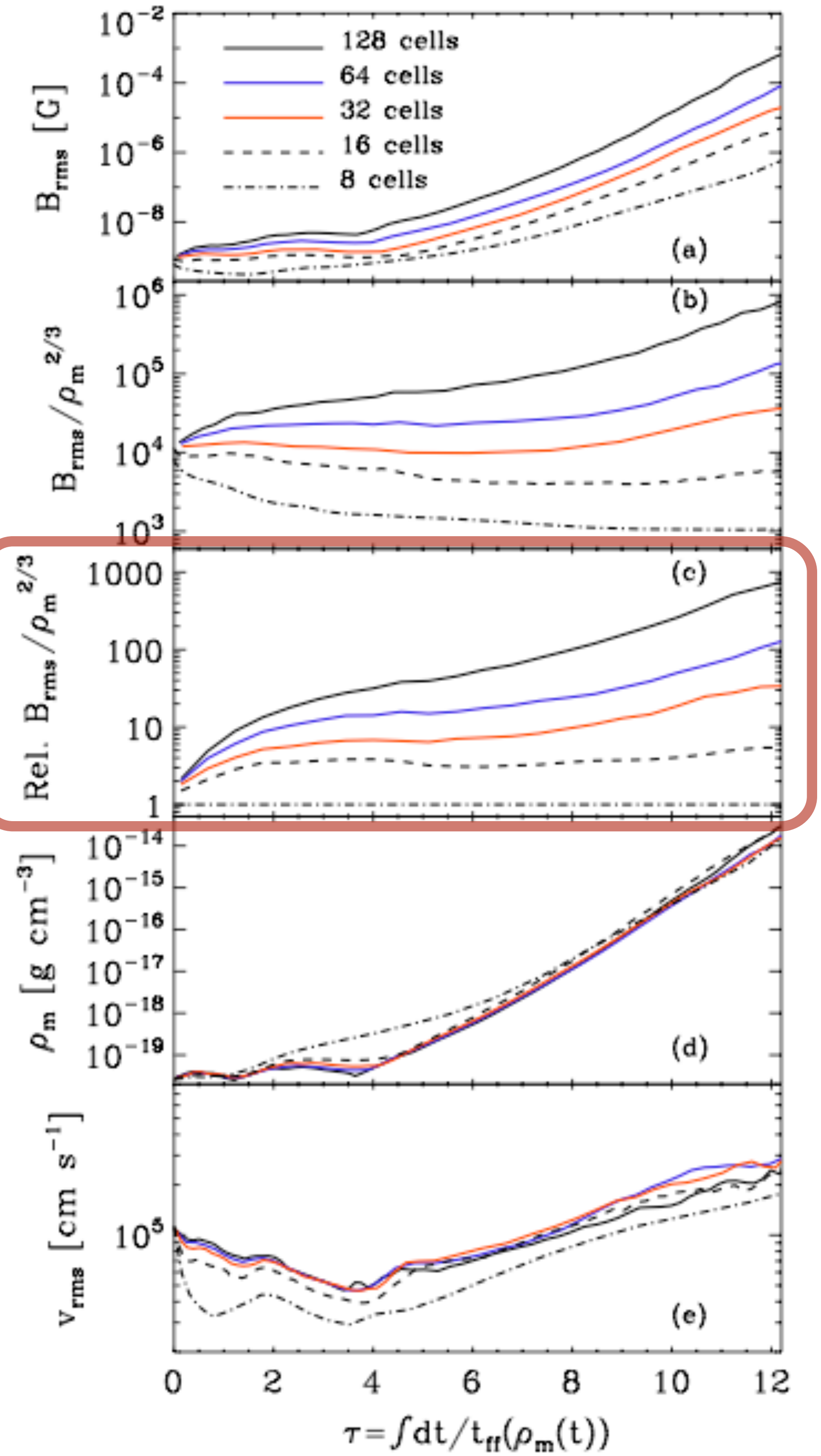
Mach number profile

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)



Field amplification during first collapse seems unavoidable.

QUESTIONS:

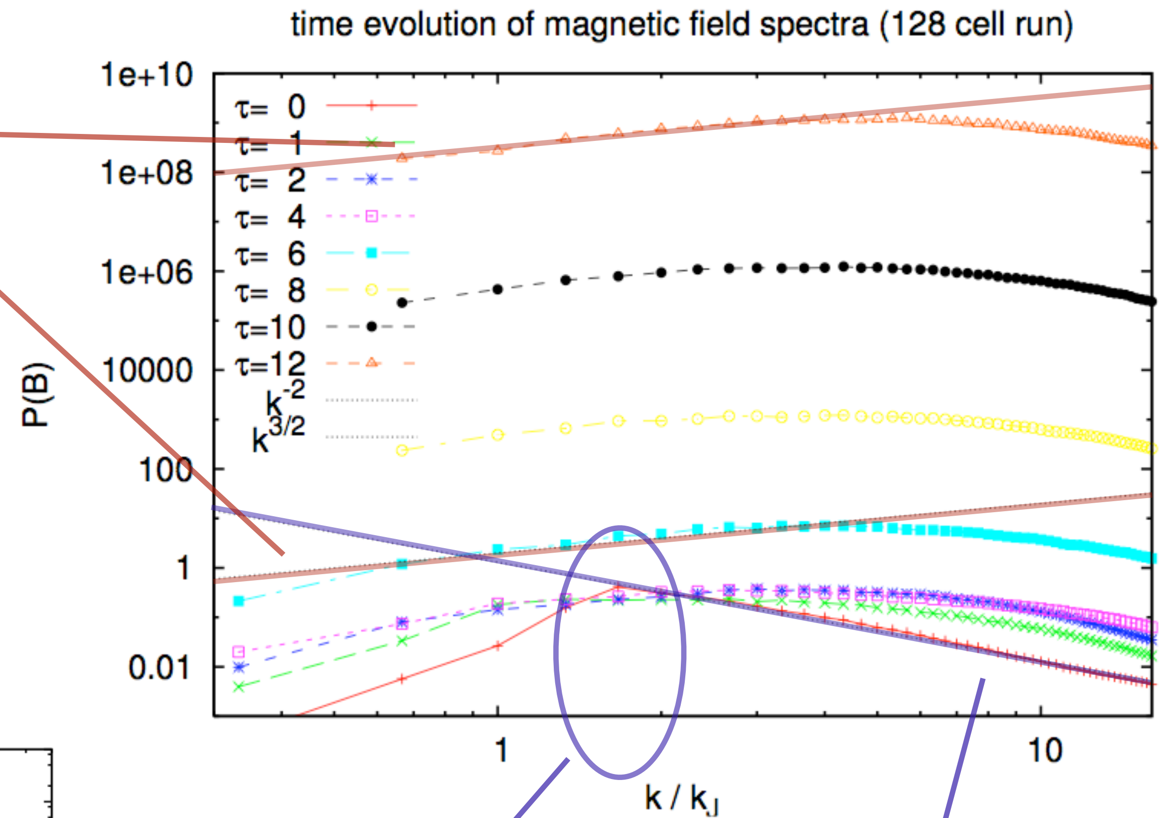
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?
- How does it depend on the thermodynamics of the gas (i.e. on the EOS)?

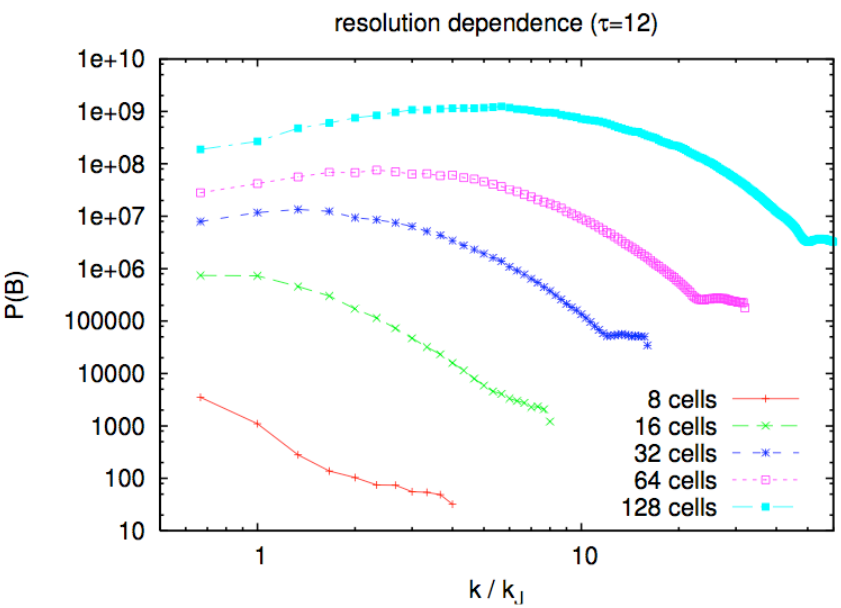
(Sur et al. 2010, ApJ, 721, L734)

Kazantsev behavior

Slope +3/2 of
Kazantsev theory

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



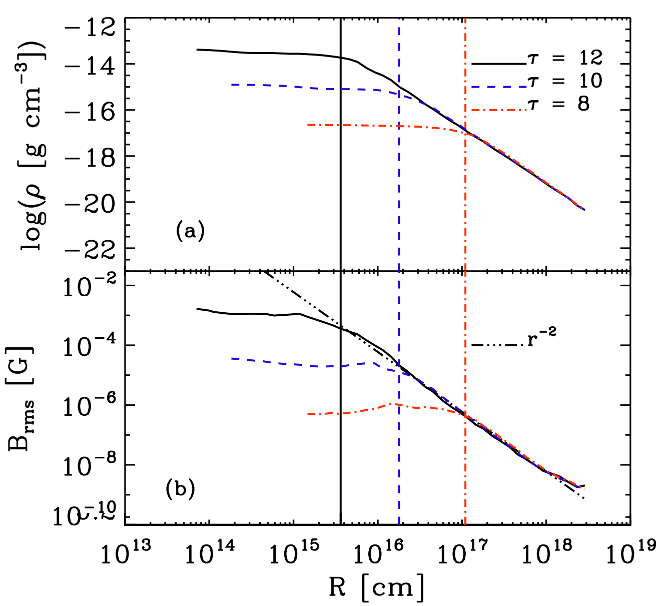


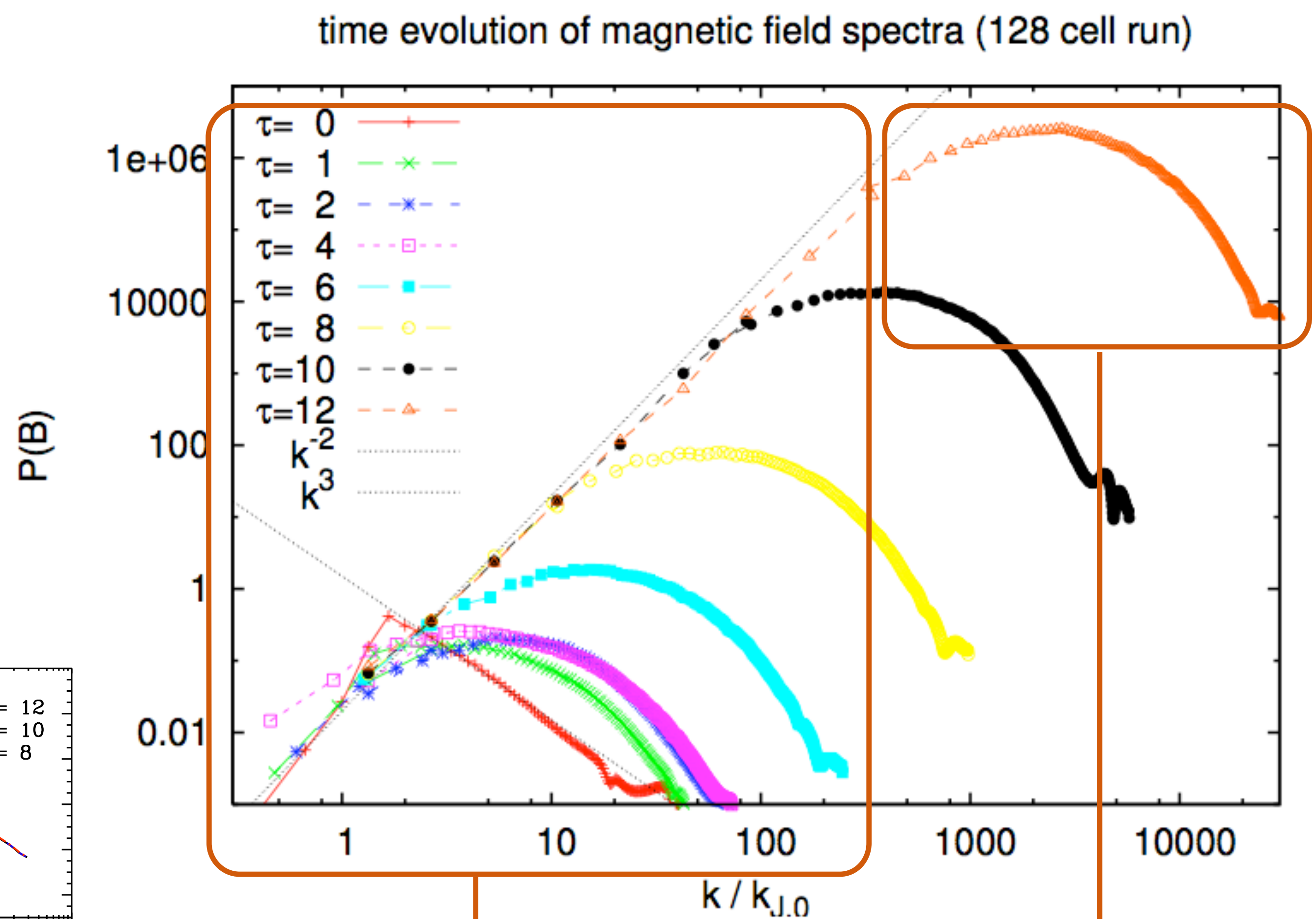
initial peak of
B fluctuation
spectrum

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

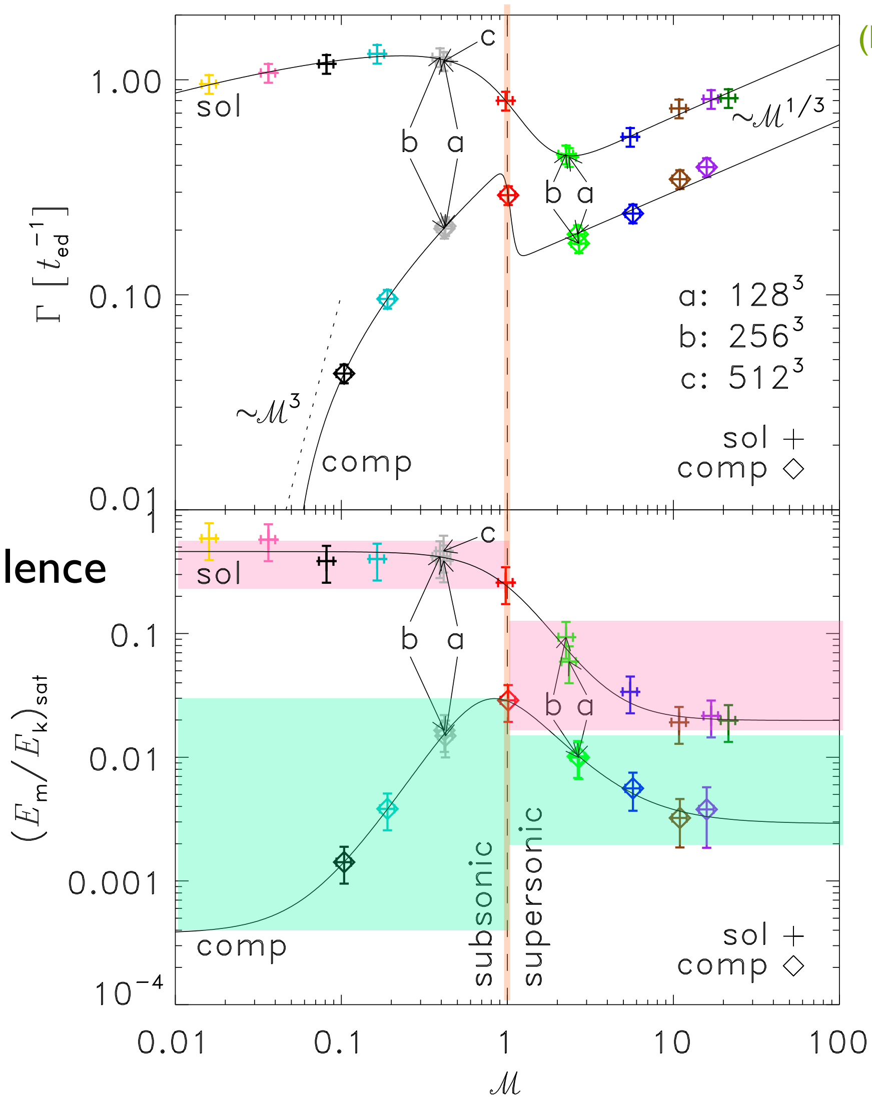
(Federrath et al., 2011, ApJ, 731, 62)

Saturation level

(Federrath et al., 2011, PRL, 107, 114505)

subsonic, solenoidal turbulence

subsonic, compressive turbulence



saturation level for supersonic, solenoidal turbulence

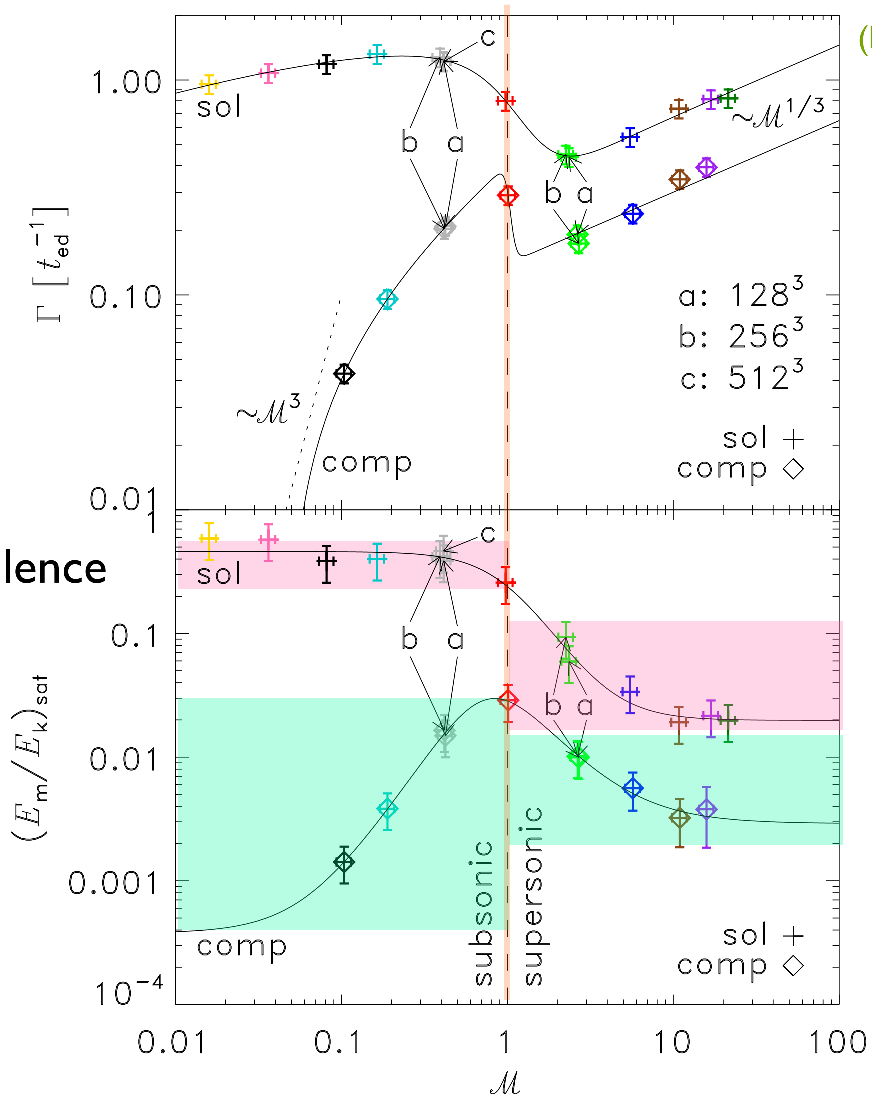
saturation level for supersonic, compressive turbulence

Saturation level

(Federrath et al., 2011, PRL, 107, 114505)

subsonic, solenoidal turbulence

subsonic, compressive turbulence



saturation level for supersonic, solenoidal turbulence

saturation level for supersonic, compressive turbulence

This behavior is reproduced *analytically* using the *Kazantsev* formalism for very large and very small Prandtl numbers, and for the range from Kolmogorov to Burgers turbulence.

(Schober et al., 2012, PRE, 85, 026303, Schober et al. 2012, ApJ, 754, 99, Schober et al. 2012, PRE, submitted, Bovino et al., PRL, submitted)

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:

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

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

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, 754, 99)

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):

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

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

(Schober et al., 2012, PRE, 85, 026303,   see also Schober et al. 2012, ApJ, 754, 99)

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, 754, 99)

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, 754, 99)

Kazantsev theory

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

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

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

$\kappa_T(r) = \kappa_T(T_L(r), \eta)$ "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, 754, 99)

critical mag. Reynolds number

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

result (for Kolmogorov turbulence):

$$Rm > 110$$

result (for Burgers turbulence):

$$Rm > 2700$$

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

(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, 754, 99)

growth rate

growth rate for large magnetic Prandtl numbers:

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

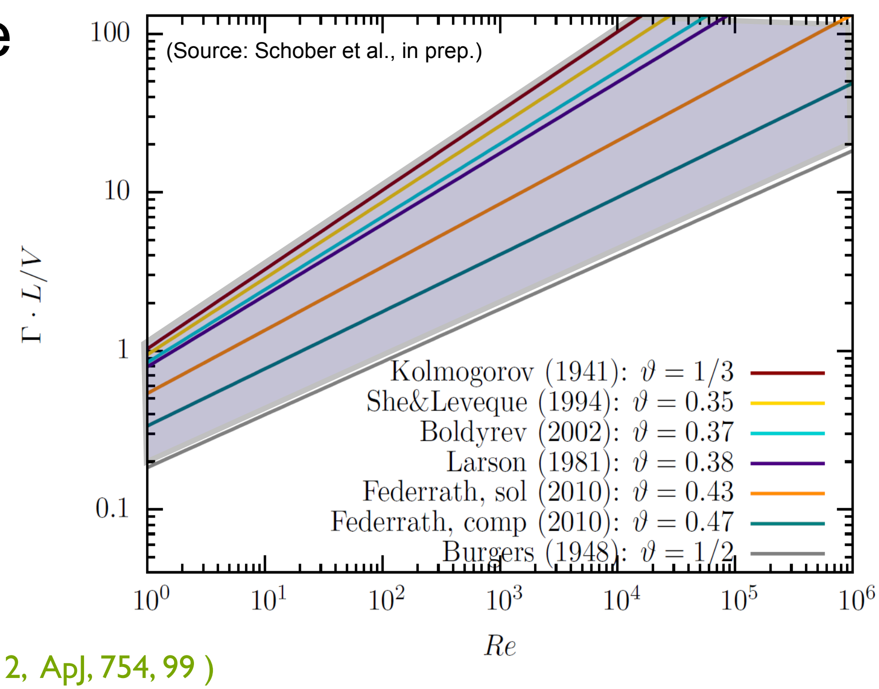
(with slope of the turbulent velocity spectrum $v(l) \propto l^{\vartheta}$)

example 1: Kolmogorov turbulence

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

example 2: Burgers turbulence

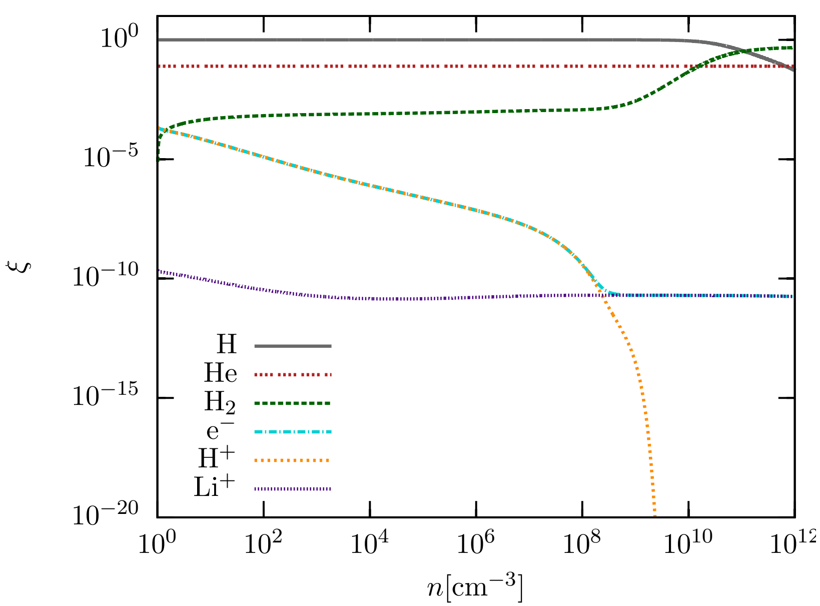
$$\Gamma \propto Re^{1/3}$$

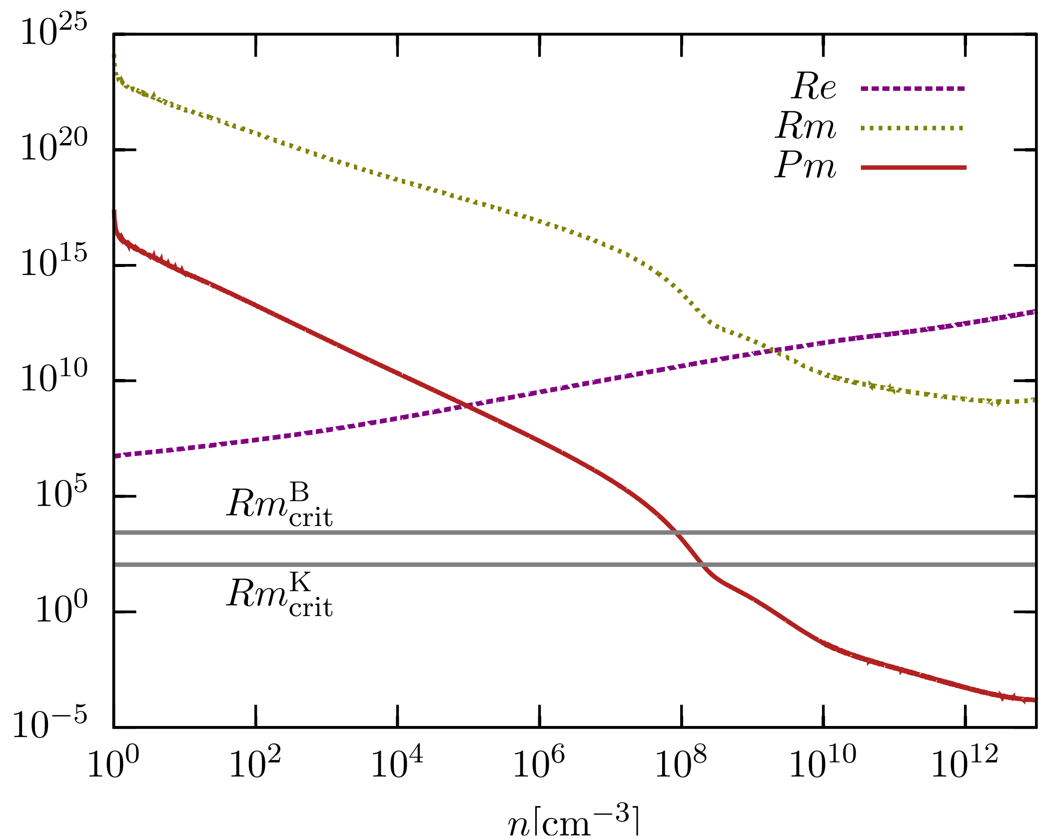


(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, 754, 99)

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, see also Schober et al. 2012, ApJ, 754, 99)

in primordial minihalos

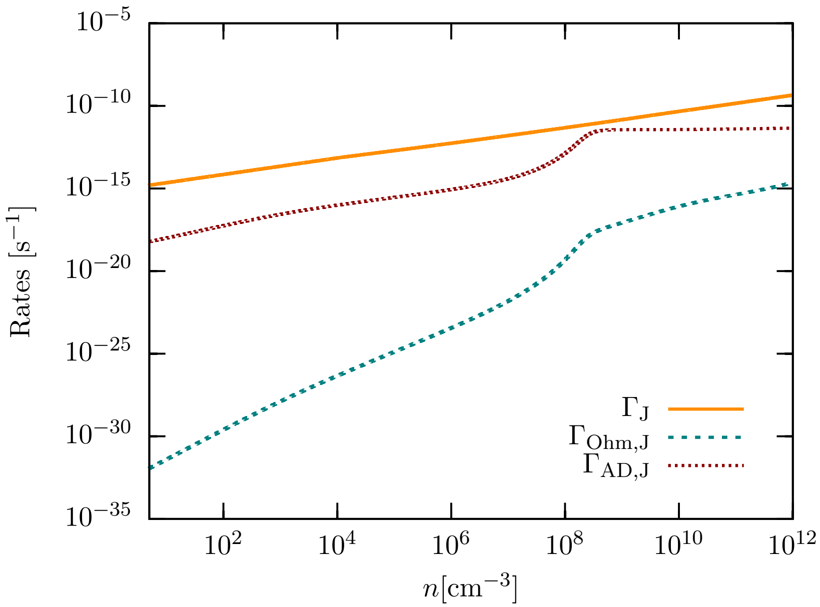


Figure 8. The growth rate on the Jeans scale Γ_J after the dynamo amplification compared to the diffusion rates as a function of the number density. $\Gamma_{Ohm,J}$ and $\Gamma_{AD,J}$ are the Ohmic and ambipolar diffusion rate, respectively.

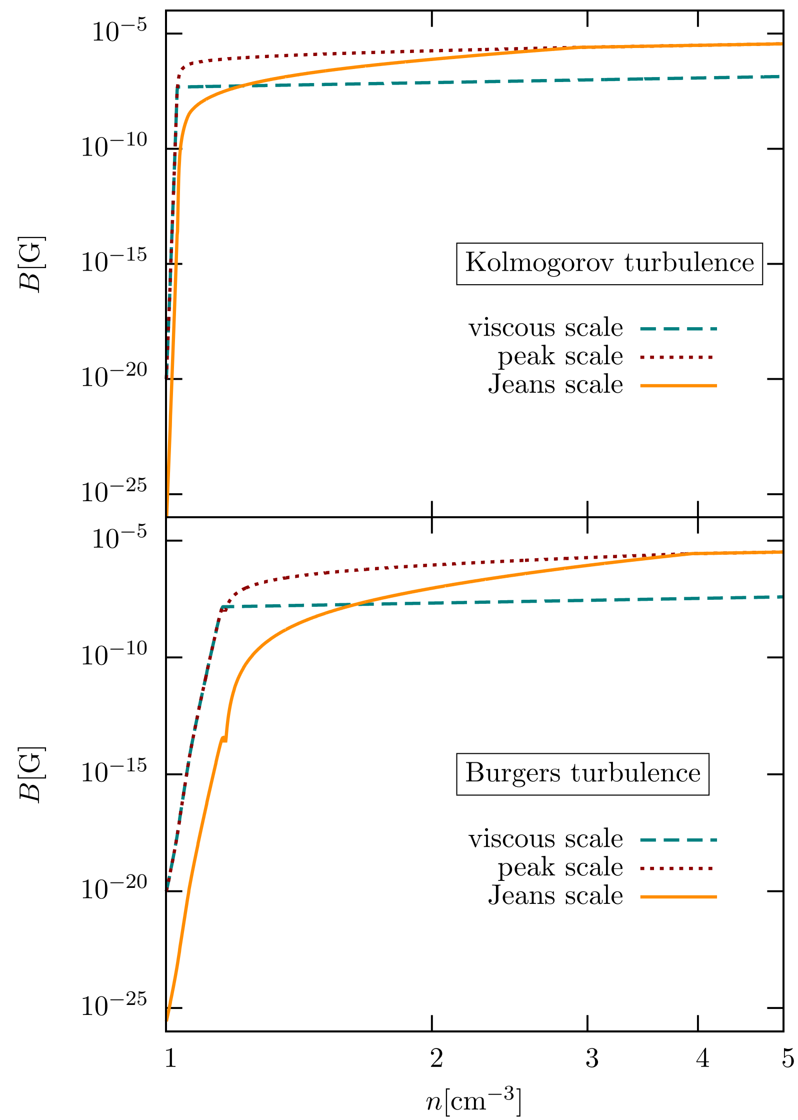


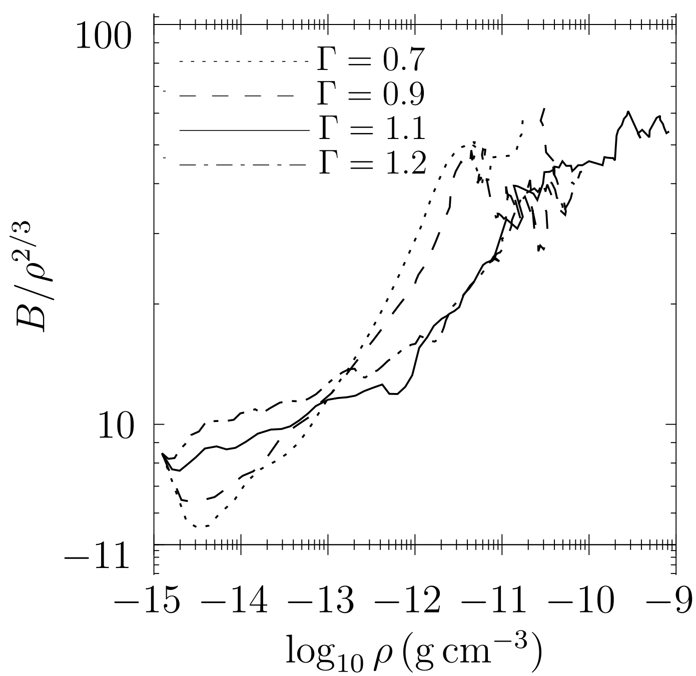
Figure 7. The magnetic field strength as a function of the number density on different scales. The dashed green line corresponds to the field evolution on the viscous scale, the dotted red line to the peak scale and the solid orange line to the Jeans scale. We show the results for Kolmogorov turbulence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

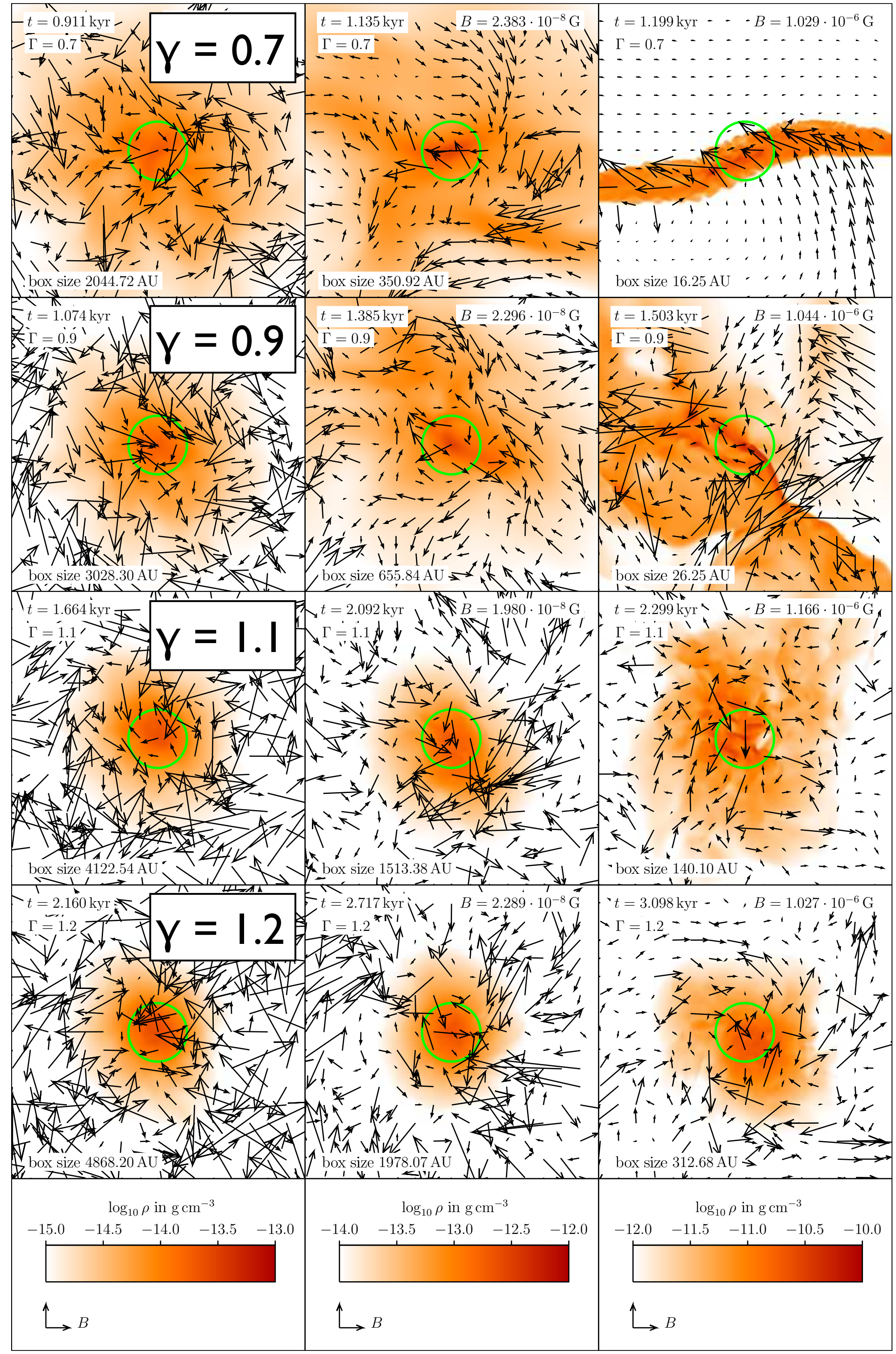
(Schober et al., 2012, PRE, 85, 026303, see also Schober et al. 2012, ApJ, 754, 99)

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?

Dependence on EOS



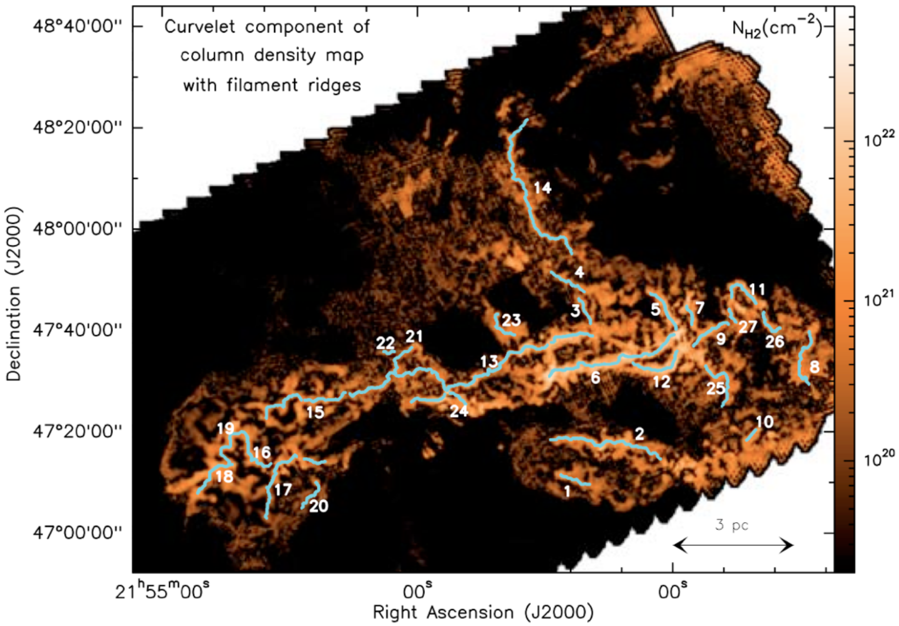


zooming in on collapsing core

- magnetic field amplification for all gamma.
- *BUT*: very different morphology:
  - *filaments for* γ <*1* and
  - *roundish structures for* γ >*1*
- implications for present-day molecular clouds?

Peters et al. (2012, ApJ, in press -- arXiv:1209.5861)

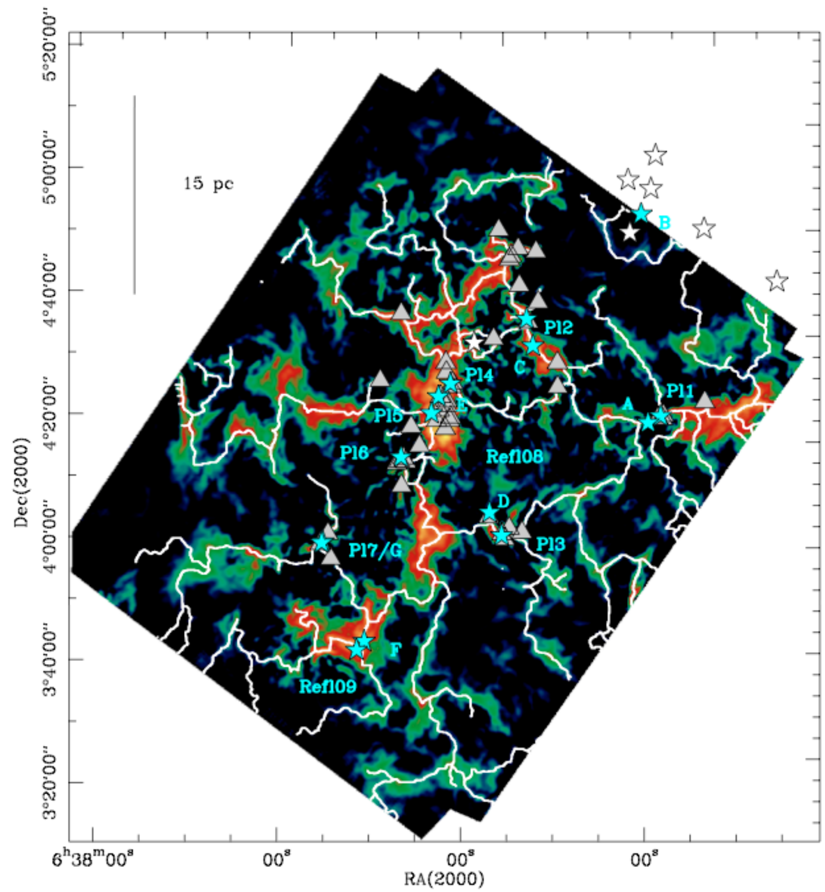
Filaments in nearby molecular clouds



IC 5146 as seen by Herschel

Arzoumanian et al. (2011, 529, L6)

- *QUESTION:* to what degree are the filaments seen in nearby molecular clouds caused by EOS effects.
- molecular clouds form in thermally unstable gas with γ ~ 0.7 (i.e. they are in a cooling regime)



Rosette as seen by Herschel

Schneider et al. (2012, A&A, 540, L11)

dark matter
annihilation

DM annihilation and SF

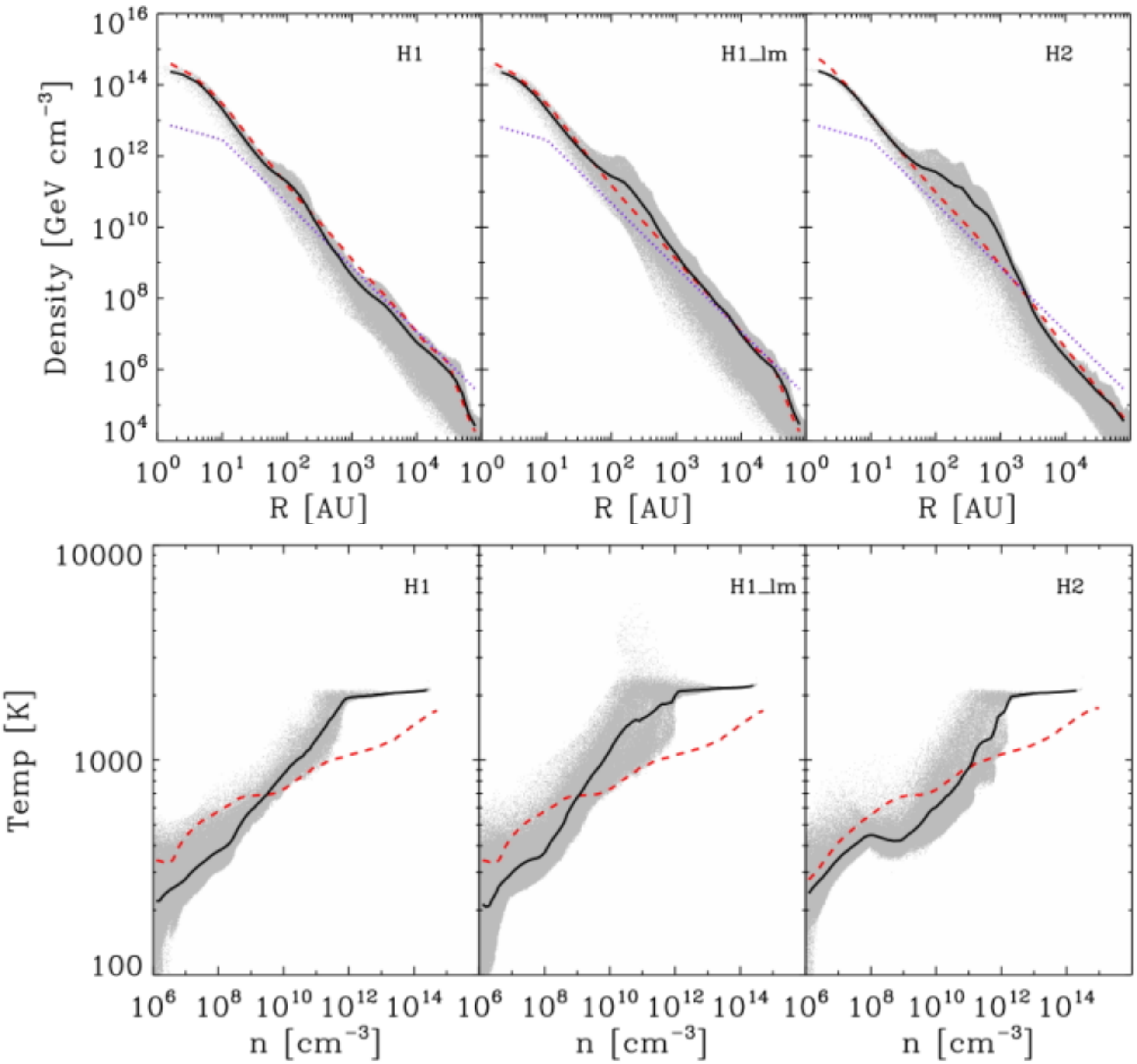
- assume there is DM and that the DM particles can self-annihilate (e.g. lowest-mass SUSY particle)
- adiabatic contraction will drag in DM particles as the gas collapses in the center of primordial halo
  --> as ρ increases, the annihilation rate goes up
- is there an evolutionary phase, when heating by DM annihilation compensates all cooling processes?
  --> *YES* say Freese et al. (2008), Spolyar et al. (2009), Gondolo et al. (2013, arXiv)
  --> *MAYBE NOT* say Iocco et al. (2008), Ripamonti & Iocco (2010), Hirano et al. (2011), Stacy et al. (2012), *Rowan Smith et al. (2013)*

Table 1
Overview of Simulations

Simulation	Annihilation	DM Particle Mass (GeV)
H1-ref	No	0
H1-lm	Yes	10
H1	Yes	100
H1-hm	Yes	1000
H2-ref	No	0
H2	Yes	100

Two different halo models with different assumptions of the DM particle mass.

Rowan Smith et al. (2012, ApJ, 761, 154)



mean gas density / temperature with DM annihilation

reference case without DM annihilation

DM density

DM annihilation leads to disk heating and reduced fragmentation

Rowan Smith et al. (2012, ApJ, 761, 154)

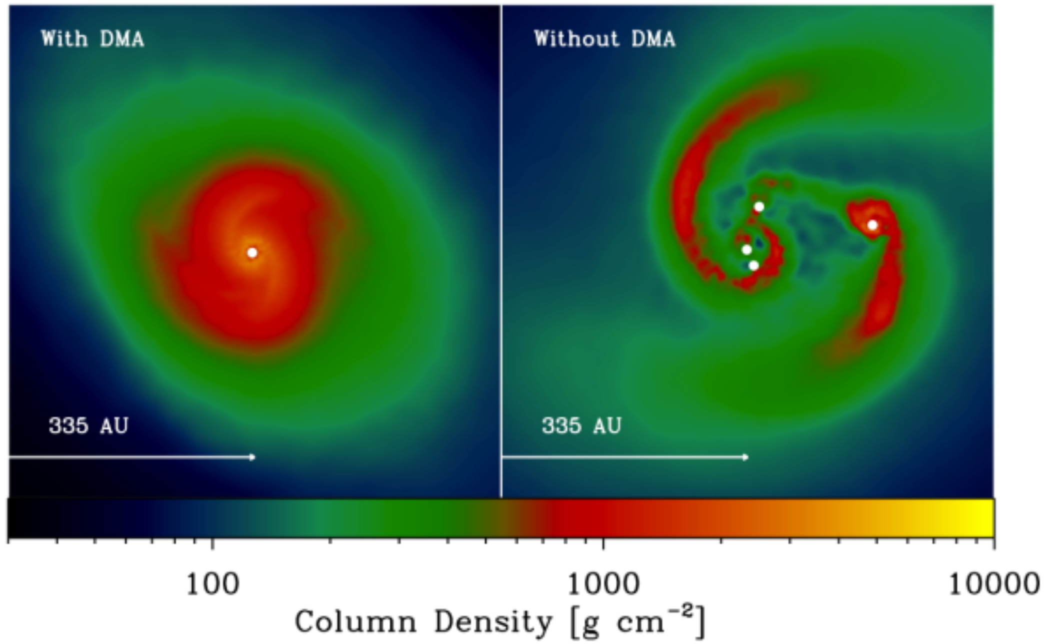
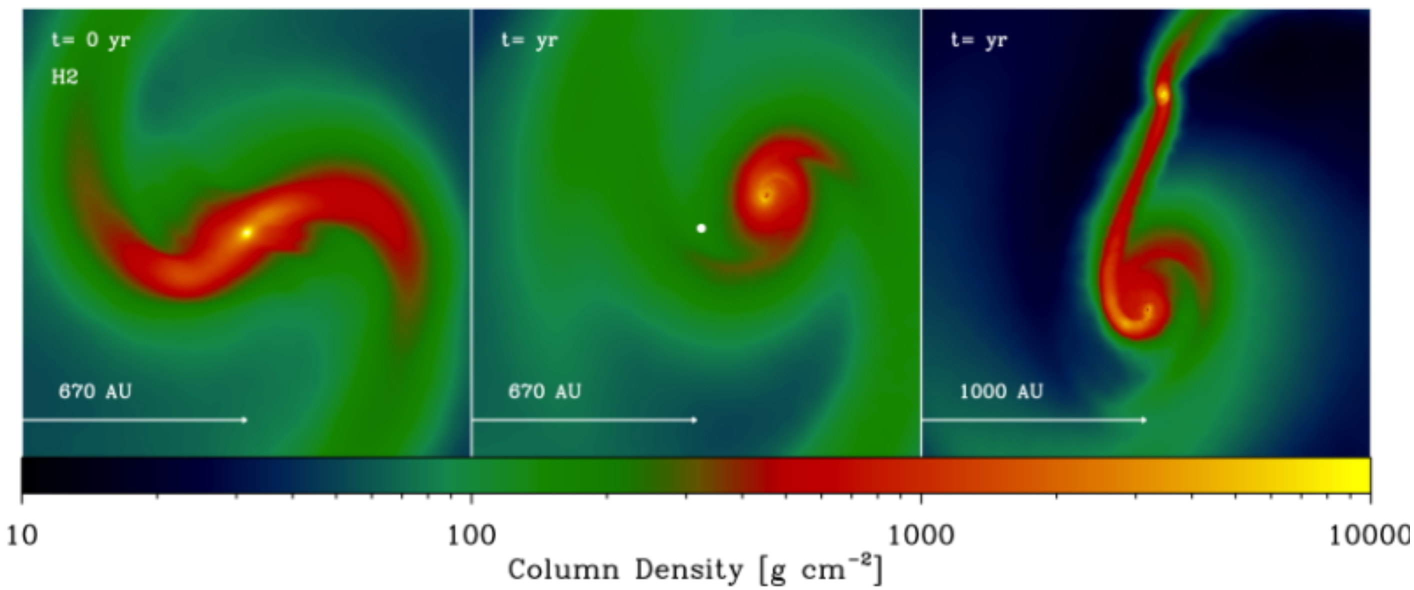


Fig 3: *The column density at the centre of H1 with and without DMA feedback 500 yr after the first sink forms. Without DMA three additional sink particles form, however with DMA the disk is stable and does not fragment.*

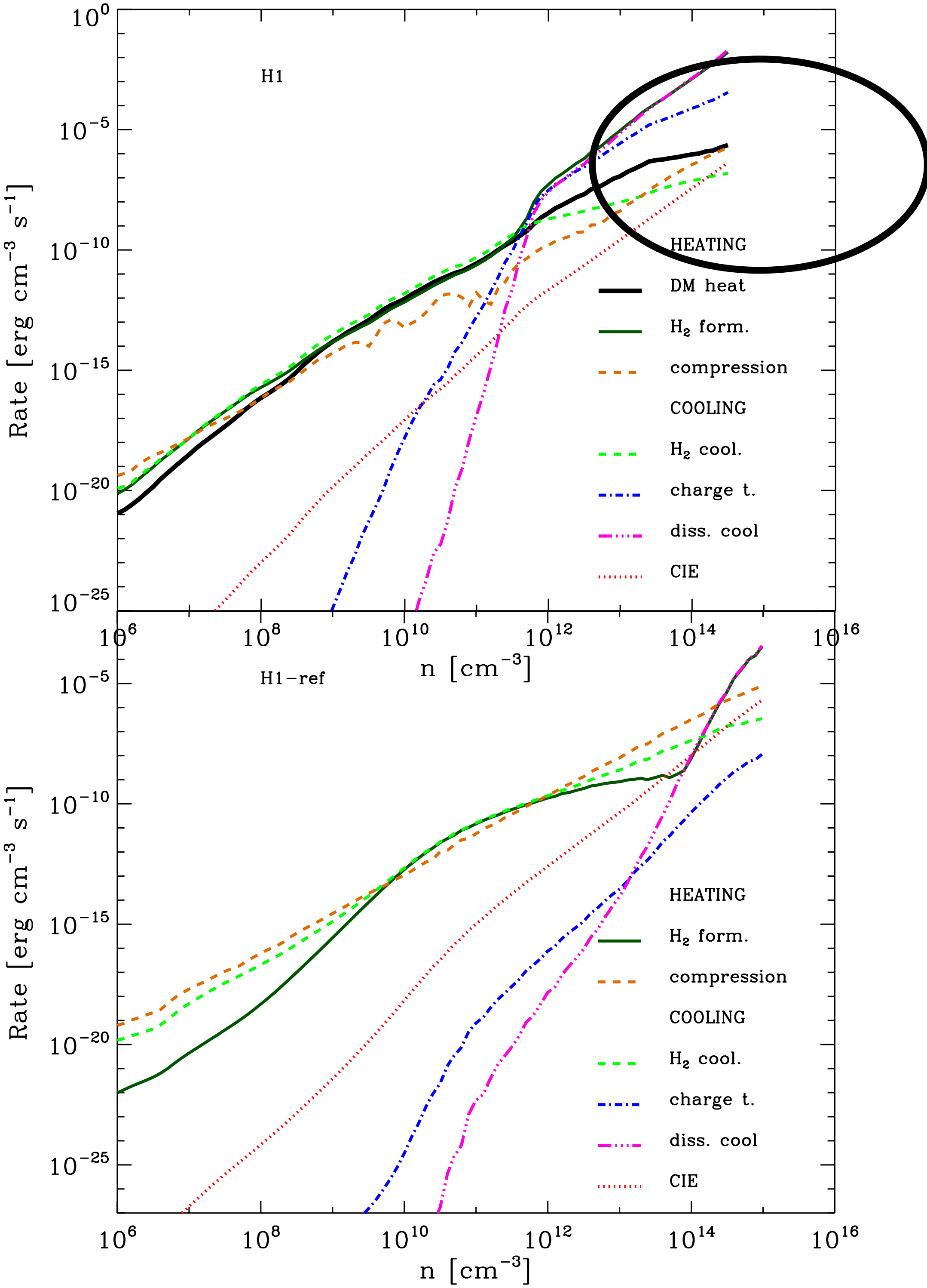
fragmentation without DM annihilation heating



reduced fragmentation with DM annihilation 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.*

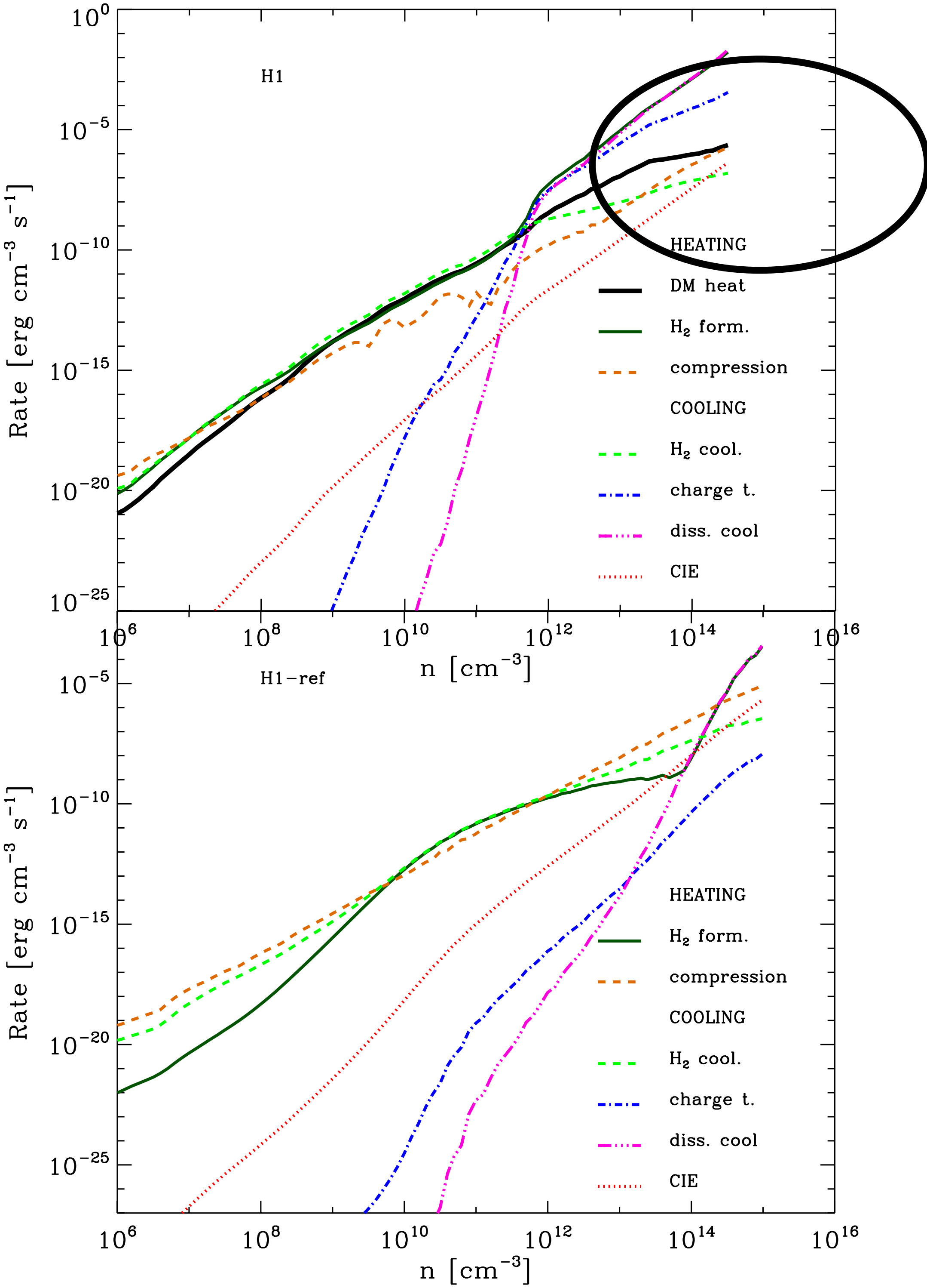
Rowan Smith et al. (2012, ApJ, 761, 154)



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

but at higher n, cooling dominates

Rowan Smith et al. (2012, ApJ, 761, 154)

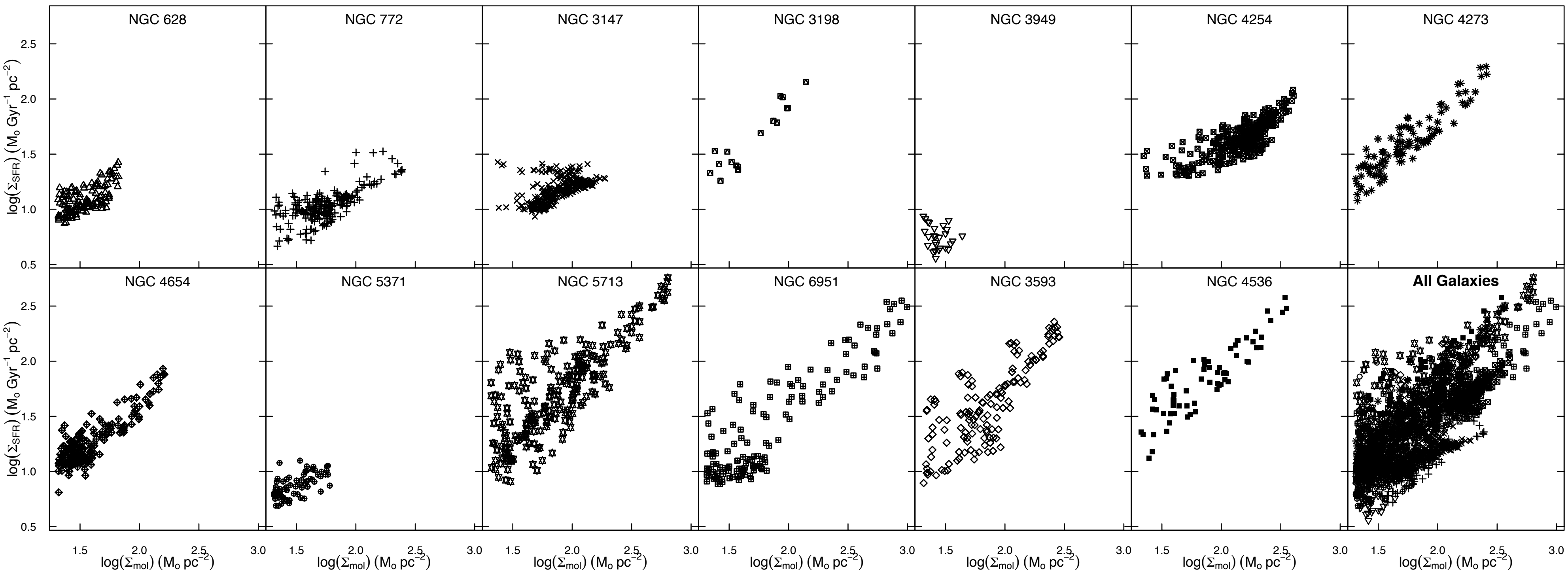


net heating in density range up to few x 10^{12} cm^{-3}

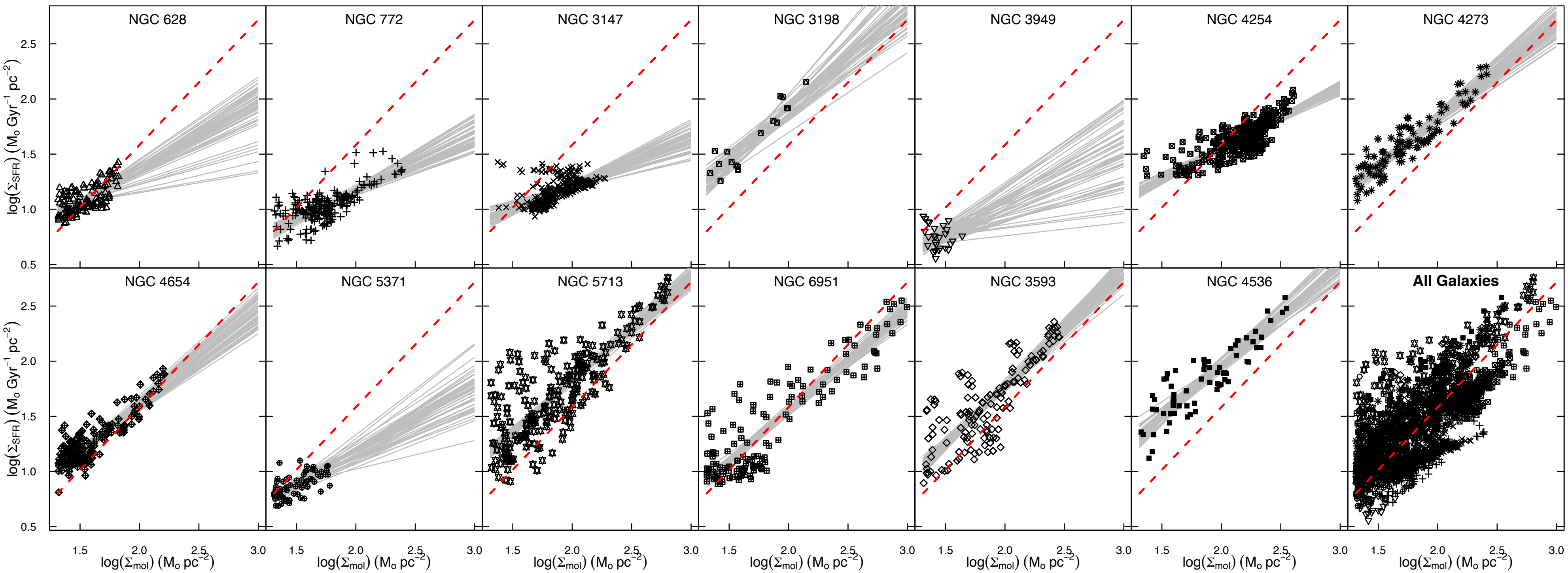
but at higher n, cooling dominates

- DM annihilation does not stop collapse (see also Ripamonti & Iocco 2010)
- *BUT*: maybe we did not go to high enough densities (Gondolo et al. 2013)
- *STILL TO DO*: consistent calculation with live DM halo

Rowan Smith et al. (2012, ApJ, 761, 154)

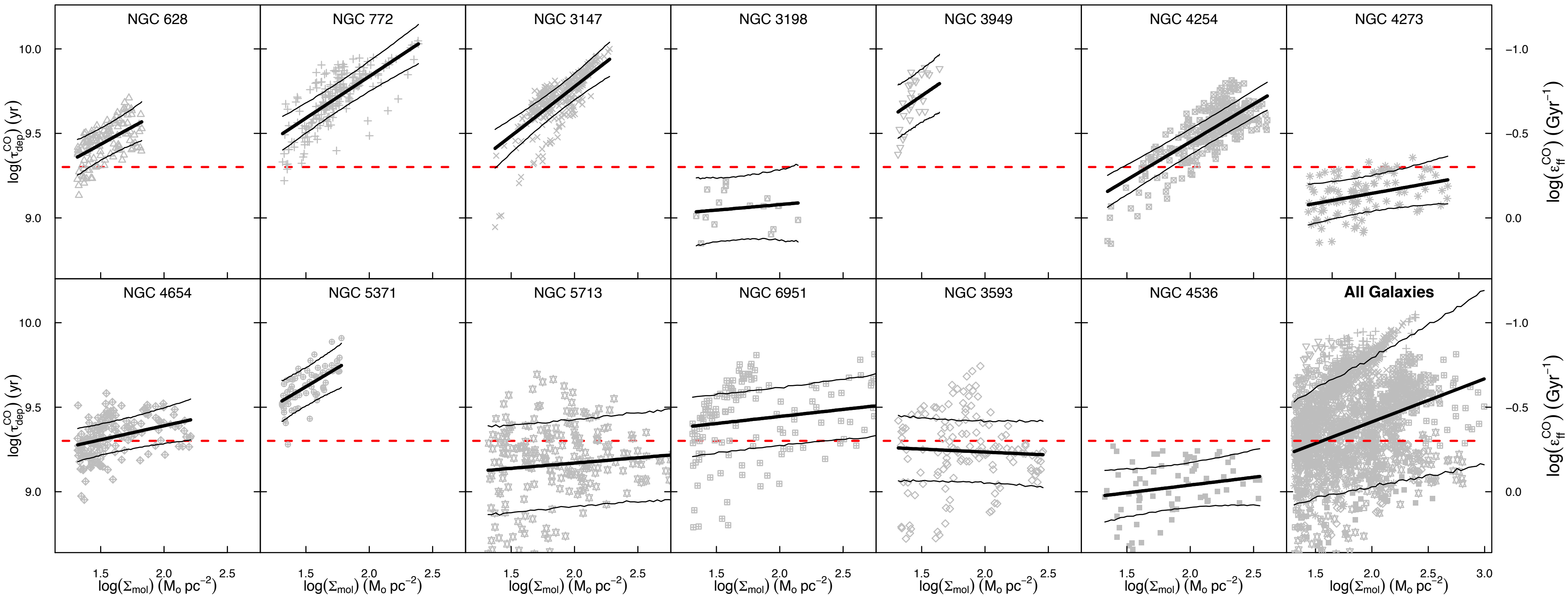


Shetty et al. (2013, arXiv:1306.2951)



Hierarchical Bayesian model for STING galaxies reveal large galaxy-to-galaxy *variations* and typically a *sublinear slope*.

Shetty et al. (2013, arXiv:1306.2951)



Hierarchical Bayesian model for STING galaxies indicate *varying depleting times*.

Shetty et al. (2013, arXiv:1306.2951)

Table 1. Bayesian estimated parameters for the STING galaxies

Subject	# Datapoints	A	$2\sigma_A$	N	$2\sigma_N$	$\sigma_{\rm scat}$	$\tau_{\rm dep}^{\rm CO}(\Sigma_{\rm mol}{=}50)^1$	$\tau_{\rm dep}^{\rm CO}(\Sigma_{\rm mol}{=}100)^1$	$\tau_{\rm dep}^{\rm CO}(\Sigma_{\rm mol}{=}150)^1$	$\tau_{\rm dep}^{\rm CO}(\Sigma_{\rm mol}{=}200)^1$
1. NGC 0337	3	0.33	[−0.16, 0.91]	1.08	[0.68, 1.45]	0.09	0.1, 0.3, 0.9	0.1, 0.3, 1.1	0.1, 0.3, 1.2	0.1, 0.3, 1.2
2. NGC 0628	131	0.05	[−0.23, 0.38]	0.67	[0.46, 0.86]	0.04	2.6, 3.3, 4.1	3.2, 4.4, 6.2	3.5, 5.2, 7.8	3.8, 5.8, 9.3
3. NGC 0772	217	0.14	[−0.08, 0.34]	0.51	[0.40, 0.64]	0.04	4.0, 4.9, 6.0	5.6, 6.9, 8.4	6.7, 8.4, 10.5	7.6, 9.7, 12.5
4. NGC 1637	47	0.18	[−0.12, 0.59]	0.61	[0.34, 0.82]	0.05	2.2, 3.0, 4.2	2.6, 4.0, 6.3	2.8, 4.7, 8.5	2.9, 5.3, 10.1
5. NGC 3147	298	0.36	[0.10, 0.60]	0.43	[0.31, 0.57]	0.03	3.3, 4, 4.8	5.0, 6.0, 7.2	6.2, 7.6, 9.4	7.1, 8.9, 11.4
6. NGC 3198	18	0.05	[−0.39, 0.47]	0.93	[0.69, 1.20]	0.07	0.7, 1.2, 1.8	0.7, 1.2, 1.9	0.7, 1.2, 2.1	0.7, 1.3, 2.2
7. NGC 3593	141	−0.28	[−0.51, 0.07]	1.02	[0.91, 1.14]	0.08	1.1, 1.8, 2.7	1.1, 1.7, 2.6	1.1, 1.7, 2.6	1.1, 1.7, 2.6
8. NGC 3949	27	0.02	[−0.39, 0.53]	0.51	[0.14, 0.79]	0.06	4.4, 6.7, 10.0	5.3, 9.4, 17.2	5.9, 11.6, 24.1	6.2, 13.3, 30.4
9. NGC 4254	308	0.40	[0.20, 0.59]	0.57	[0.49, 0.67]	0.04	1.7, 2.1, 2.5	2.4, 2.8, 3.4	2.8, 3.4, 4.0	3.2, 3.8, 4.6
10. NGC 4273	103	0.06	[−0.17, 0.25]	0.89	[0.78, 1.02]	0.05	1.1, 1.4, 1.7	1.1, 1.5, 1.9	1.2, 1.6, 2.1	1.2, 1.6, 2.2
11. NGC 4536	67	0.15	[−0.13, 0.40]	0.90	[0.77, 1.05]	0.06	0.8, 1.0, 1.4	0.8, 1.1, 1.5	0.8, 1.1, 1.6	0.8, 1.2, 1.6
12. NGC 4654	168	−0.06	[−0.42, 0.16]	0.83	[0.70, 1.05]	0.04	1.8, 2.2, 2.7	1.9, 2.5, 3.2	2.0, 2.6, 3.4	2.1, 2.8, 3.8
13. NGC 5371	65	0.01	[−0.36, 0.45]	0.58	[0.28, 0.82]	0.05	3.9, 5.1, 6.8	4.8, 7.0, 10.1	5.4, 8.4, 13.0	5.8, 9.6 , 15.5
14. NGC 5713	220	−0.04	[−0.20, 0.12]	0.94	[0.85, 1.01]	0.13	0.8, 1.4, 2.5	0.8, 1.5, 2.7	0.8, 1.5, 2.7	0.9, 1.6, 2.8
15. NGC 6951	135	−0.27	[−0.42, 0.11]	0.91	[0.83, 0.99]	0.08	1.8, 2.6, 3.9	1.9, 2.8, 4.1	1.9, 2.9, 4.3	2.0, 3.0, 4.4
Group Parameters	1948	**0.07**	**[−0.11, 0.27]**	**0.76**	**[0.60, 0.92]**	0.09	1.0, 2.2, 4.8	1.1, 2.6, 6.2	1.1, 2.9, 7.3	1.2, 3.1, 8.2

slope of KS relation

depletion times

Shetty et al. (2013, arXiv:1306.2951)

implications

- modern hierarchical Bayesian methods suggest the KS relation will vary from galaxy to galaxy and the slow of N_{H2} vs. N_{SFR} is sublinear.
- that implies the depletion time is *larger* at higher (column)densities
- why?
  - maybe CO is not a good tracer of SF (see also the extended discussion in Leroy et al. 2013)
  - maybe there is H_2 that is not traced by CO at low average densities (see Simon Glover's talk)
  - a large fraction of H2 may not be forming stars (low SFE)

Summary

summary

- magnetic fields will influence first star formation
  → influence on mass spectrum still not understood
- dark matter annihilation will not lead to "dark stars", but it could reduce the level of fragmentation in first disks and influence Pop III mass spectrum and multiplicity
- on global scales the relation between molecular gas surface density and star formation (Kennicutt-Schmidt relation) varies from galaxy to galaxy and it seem to be sublinear
  → varying depletion timescales

thanks