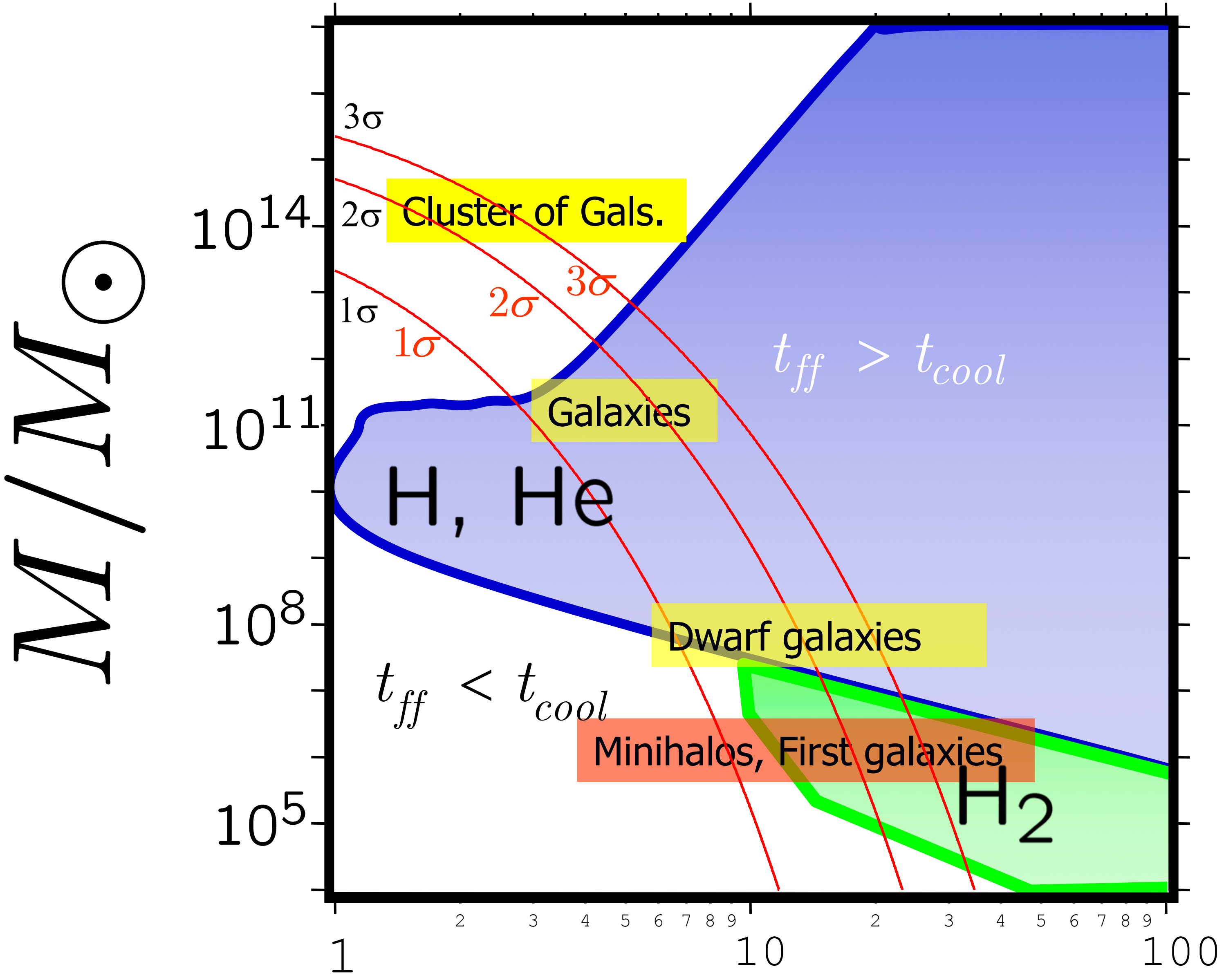
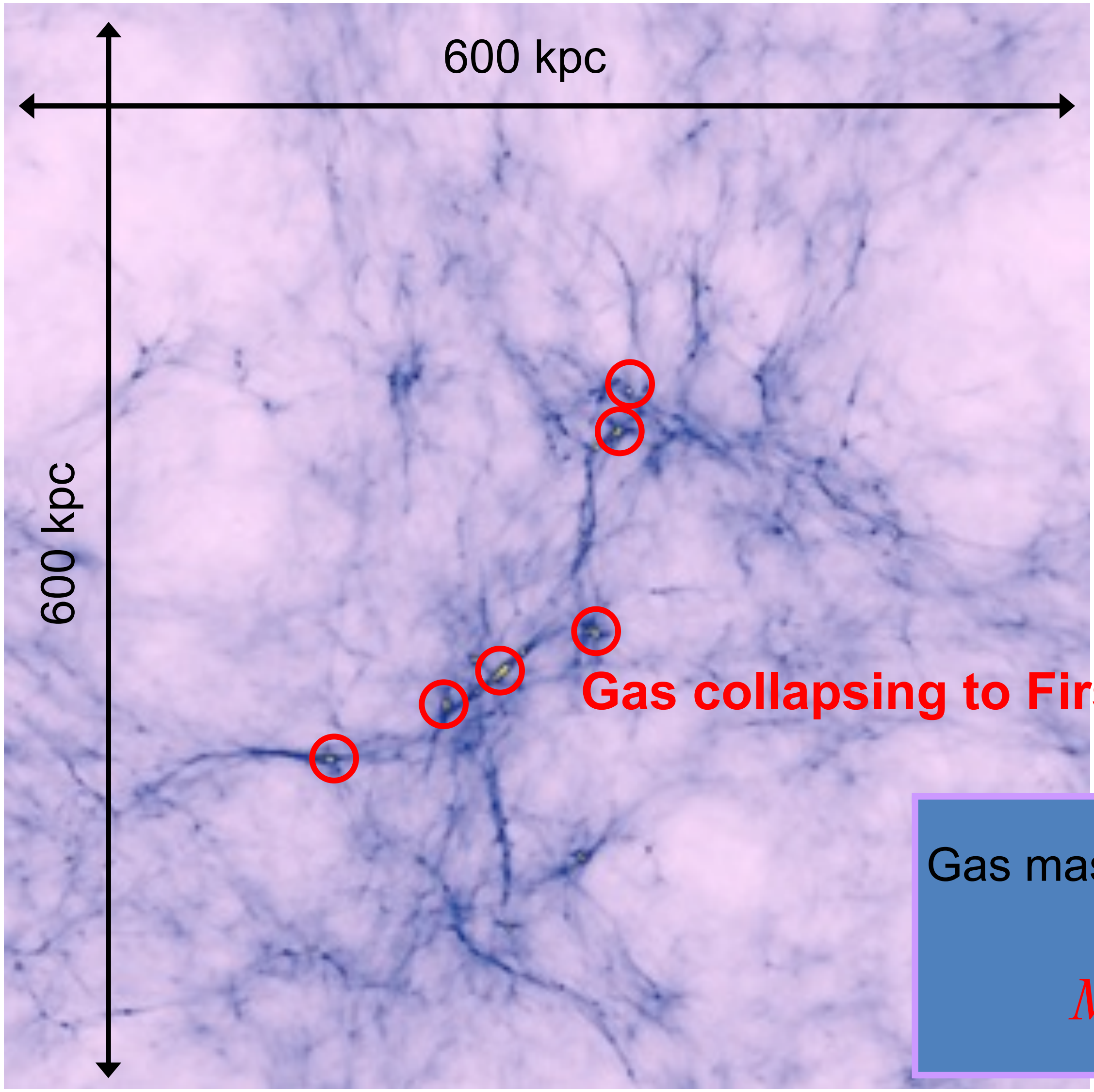
Present status of the formation theory of First stars

Hajime Susa (Konan University)

Cooling Diagram



Cosmological simulation



Snapshot @ $z = 17$

Gas collapsing to First stars

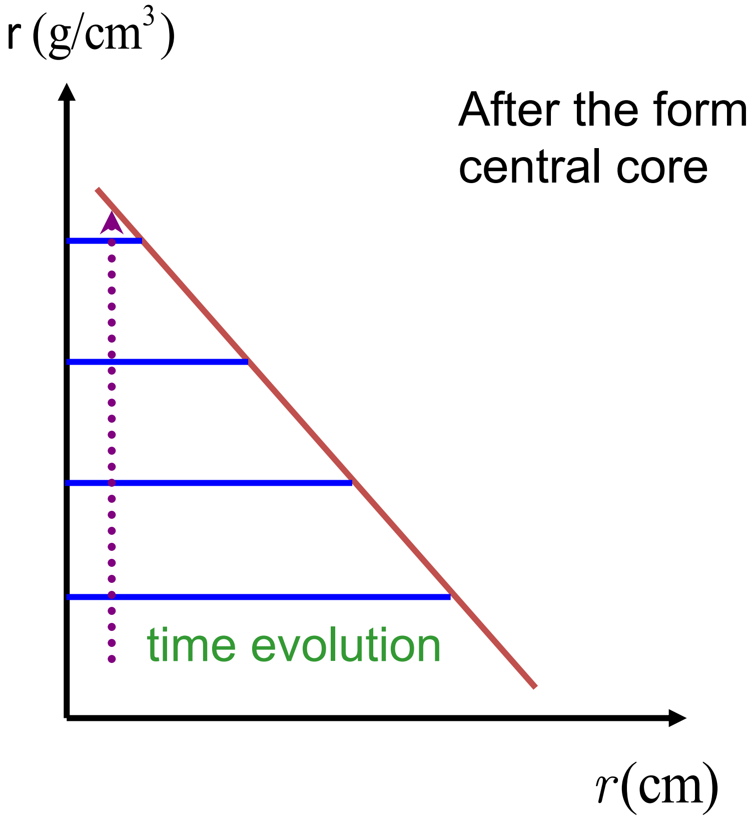
Gas mass collapsed：

$$M_{\mathrm{frag}} \approx 10^2 - 10^3 M_{\odot}$$

Yoshida et al. (2003)

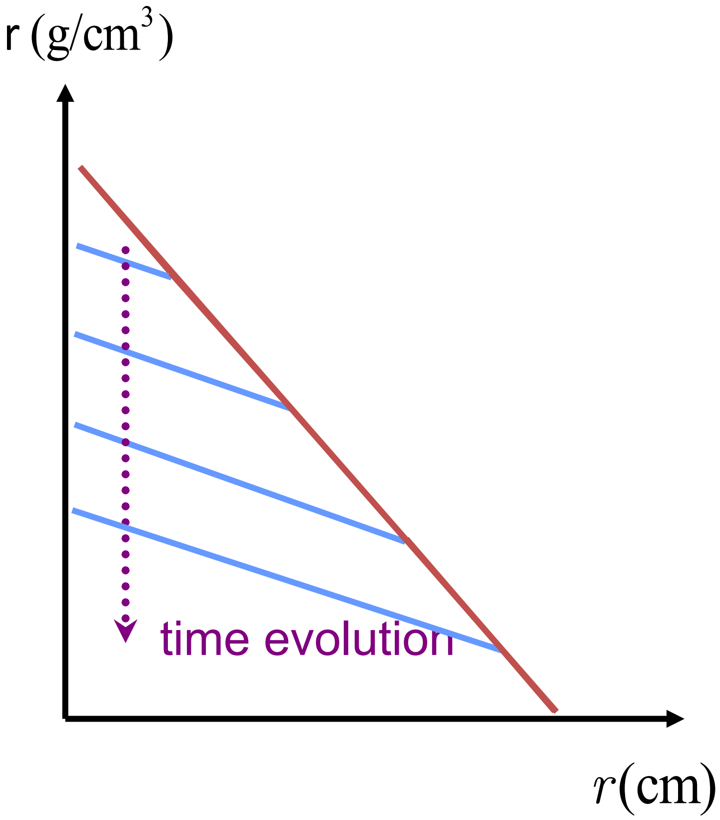
From run-way phase to mass accretion phase

run-away



After the formation of central core

mass accretion



Final mass

$$\dot{M} \sim 30 \frac{c_s^3}{G} \longrightarrow$$

1000K, for primordial gas,
Very high mass accretion rate
（c.f. 10K for interstellar gas)

$$\dot{M} \approx 10^{-2} M_{\text{sun}} \text{yr}^{-1} \longrightarrow \dot{M} \times 10^5 \text{yr} \approx 10^3 M_{\text{sun}}$$

If the accretion is spherical and is not quenched, POPIII stars are Very Massive.

Radius of the accretion disk

Definition of j of Kepler rot.

$$\frac{j_{Kep}^2}{r_c^3} = \frac{GM}{r_c^2}$$

Balance between the gravity and the centrifugal force with given **j**

$$\frac{j^2}{r_d^3} = \frac{GM}{r_d^2}$$

Specific ang.mom. of Run-away collapsing core

$$j = f\, j_{Kep}$$

$$\boxed{r_d = f^2 r_c}$$

f= 0.5
→ disk radius is 25% of core radius

Formation of rotationally supported disk is inevitable.

Rad.Feedback by protostar

Potential depth at the disk

$$\frac{GM}{r_{disk}} > f^{-2}\frac{GM_J}{r_J} = f^{-2}\frac{G\frac{4\pi}{3}r_J^3\rho}{r_J} = \frac{\pi^2\gamma f^{-2}}{3\mu_{env}m_p}kT_{env}$$

If the temperature exceed the following by some heating mechanisms, gas evaporate from the disk.

$$kT > \frac{GMm_p}{r_{disk}} = \frac{\pi^2\gamma f^{-2}}{3\mu_{env}}kT_{env} > 9.2kT_{env} \Rightarrow 9200K\left(\frac{T_{env}}{10^3 K}\right)$$

Photoheating heats the gas ∼a few x 10^4 K if fully ionized.

Numerical Studies of Accretion Phase

〜1000AU･“star cluster”(t>1000yrs)

- Stacy+2009 cosmological･n_{max}=1e12･r_{acc}=50AU
- Clark+2010 turbulent･n_{max}=1e13･r_{acc}=20AU
- Smith+2011 cosmological･ n_{max}=1e15･r_{acc}=20AU
- Hosokawa+2011 cosmological（2D）･Mesh･r_{acc}=10AU + UV
- Hosokawa+2012 cosmological.POP3.2（2D）･Mesh･r_{acc}=10AU + UV
- Stacy+2012 cosmological･n_{max}=1e12･r_{acc}=50AU + UV
- Stacy+2013 cosmological･n_{max}=1e13･r_{acc}=20AU 10 halos
- Susa 2013 BE sphere ･n_{max}=3e13･r_{acc}=30AU + UV
- Hirano+2014,2015 cosmological（2D）･Mesh･r_{acc}=10AU + UV 100 halos
- Susa+2014 cosmological ･n_{max}=3e13･r_{acc}=30AU + UV 60 halos
- Hosokawa+2015 Cosmological(3D) + UV

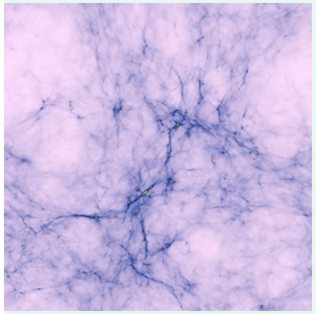
〜100AU･”inner disk fragmentation”(t < 1000yrs)

- Clark+2011 cosmological･n_{max}=1e17･r_{acc}=1.5AU
- Greif+2011 cosmological･ n_{max}〜1e17 (Arepo)･r_{acc}=0.46AU(=100Rsun)
- Machida+2013 BE sphere･change EOS n_{max}〜1e18-1e20 + MHD
- Stacy+2016 cosmological ･n_{max}=1e16･r_{acc}=1AU + UV
- Hirano+2017 cosmological(3D)

〜10AU･”resolve protostellar radius ”(t〜10yrs)

- Greif+2012 cosmological･Arepo･No sinks･r_{acc}=0.05Rsun

Numerical studies in space-time



0.01AU

Yoshida+

Bromm+

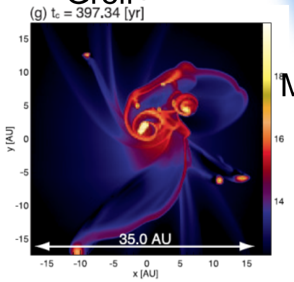
Abel+

…

10AU

Run-away phase

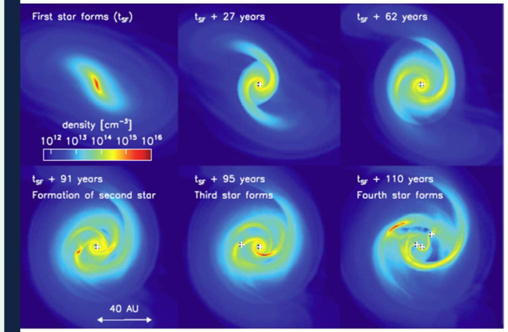
Greif+



Machida+

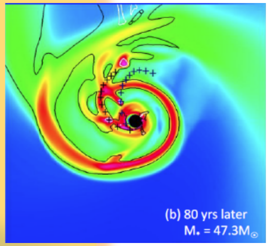
Clark+

Hirano17+



Accretion phase

Protostellar feedback (RHD)

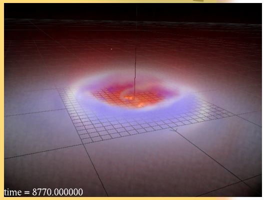


Smith+

Stacy+

Hosokawa+

Hirano+ Susa+



0

10yr

1000yr

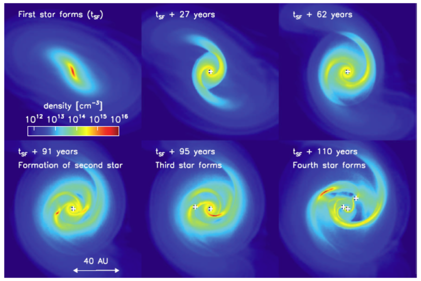
10^5yr

Time after the birth of protostar

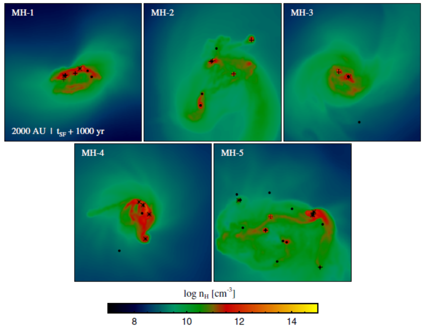
Merge or survive?

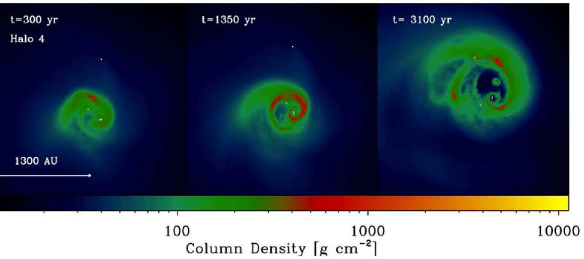
Clark+ 2011 O(10) sinks

Fig. 1. Density evolution in a 120-AU region around the first protostar, showing the buildup 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.



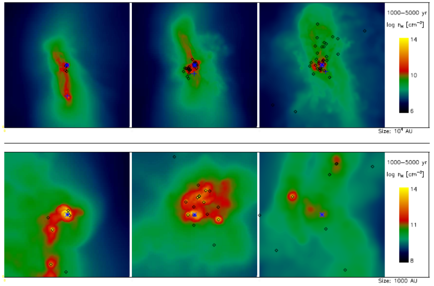
Greif+ 2011 O(10) sinks

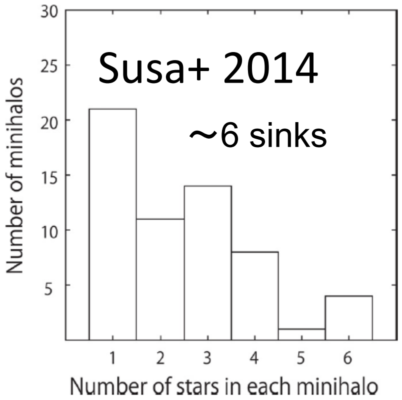




Smith+ 2011 O(10) sinks

Stacy+ 2016~50 sinks

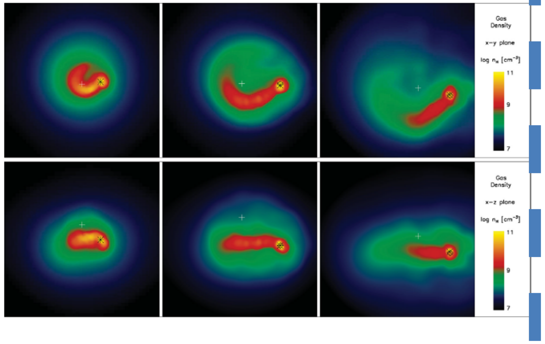




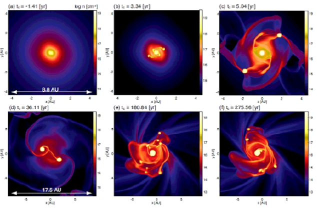
Susa+ 2014

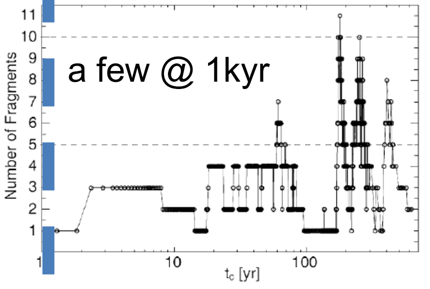
~6 sinks

Stacy+ 2012 a few sinks



Machida+2013

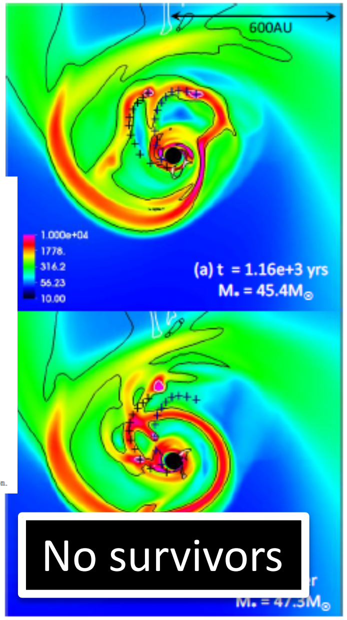




a few @ 1kyr

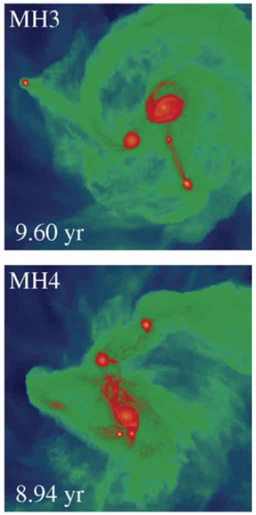
Figure 8. Number of clumps in the region of $r \leqslant 10$ AU against the elapsed time after protostar formation.

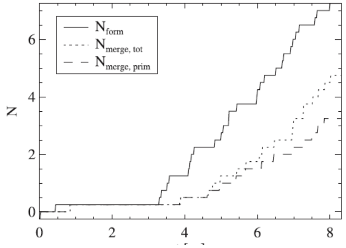
Hosokawa+2015



No survivors

Greif+2012





2/3 merge
within 10 yrs
(a few remains)

Hirano & Bromm 2017（adiabatic core）

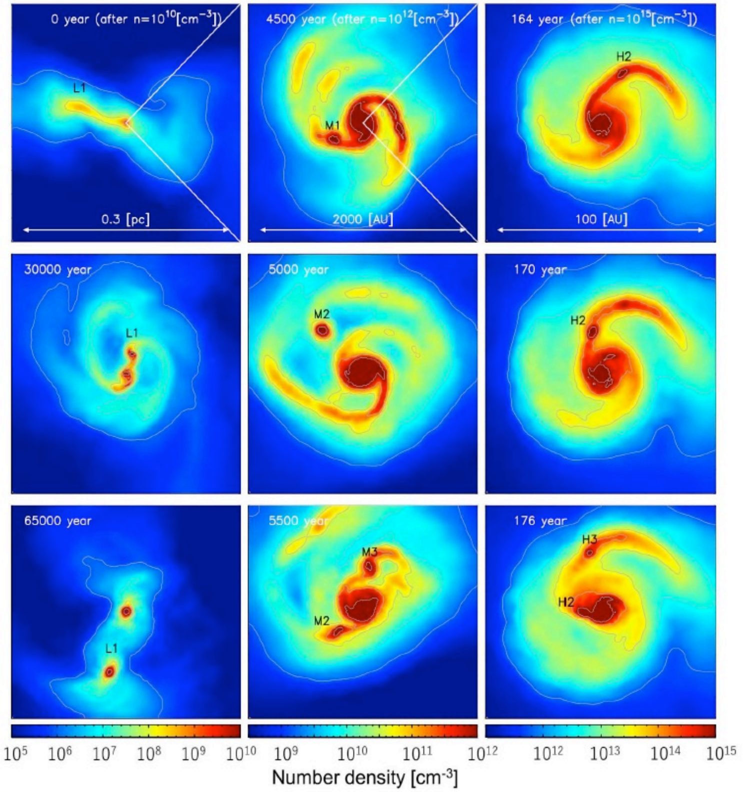
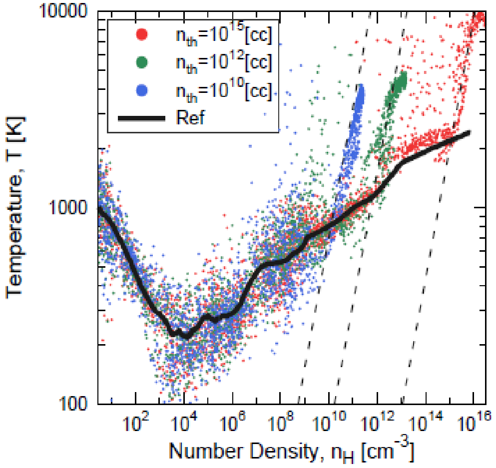
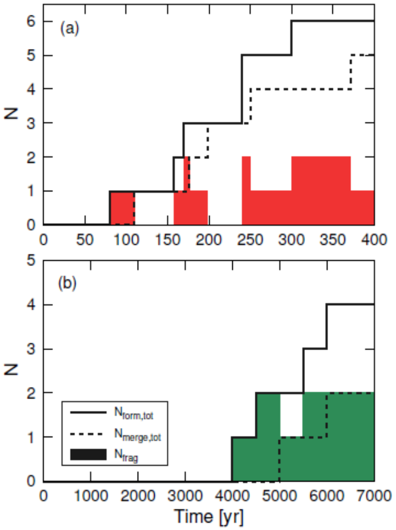
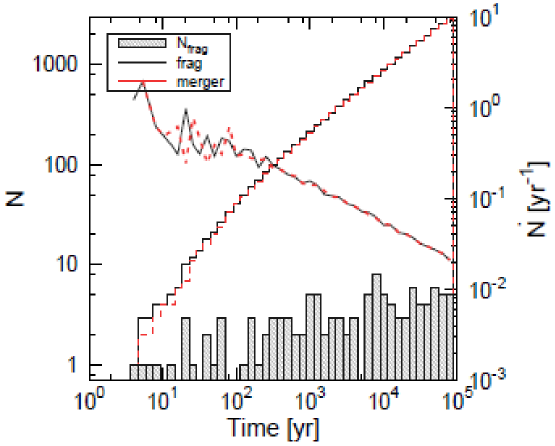


Figure 5. Cross-sectional view of the gas number density around the collapse centre of clouds. Left, middle, and right panels shows results in the low-resolution run at 0, 30000, and 65000 yr, medium-resolution run at 4500, 5000, and 5500 yr, and high-resolution run at 164, 170, and 176 yr, respectively. The box sizes are 0.3 pc, 2000, and 100 au, respectively. Labels indicate the corresponding fragment (Table 1).





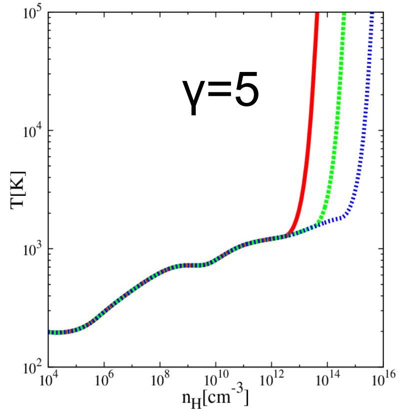
1－2個生き残り

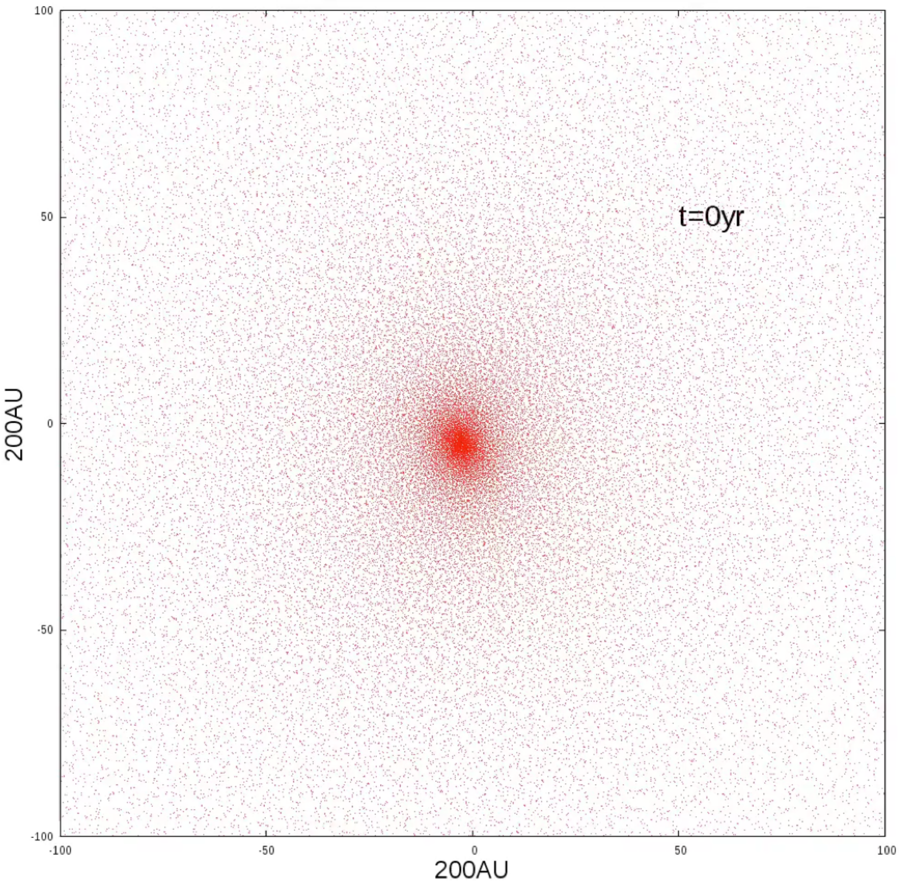


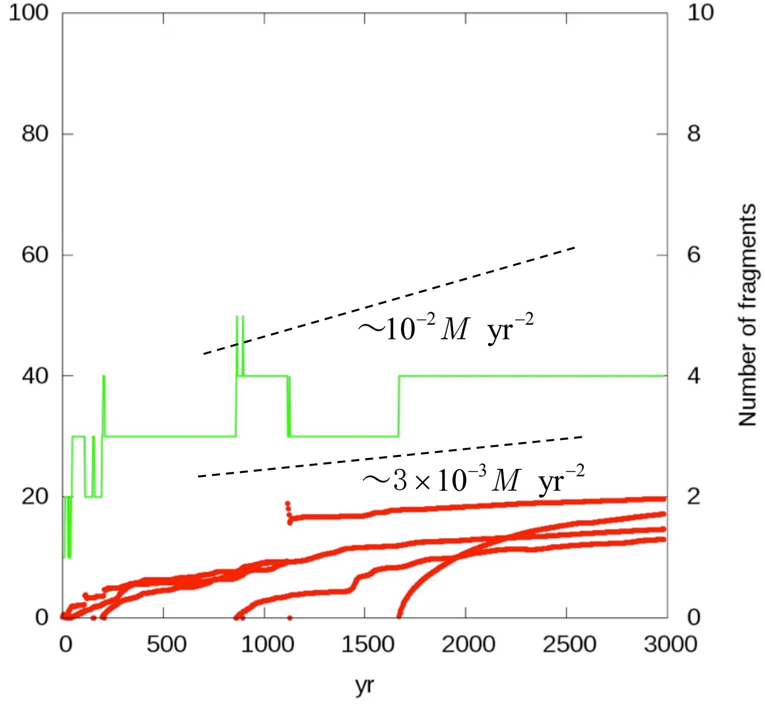
100－200 times the free-fall time

tmig と tfragのシミュレーションに基づく
解析的モデルからsurvivorの数を予測。 ➡ 数個−10個

$n_{th} = 3\text{x}10^{14}$/cc -$3\text{x}10^{15}$/cc, β~0.1



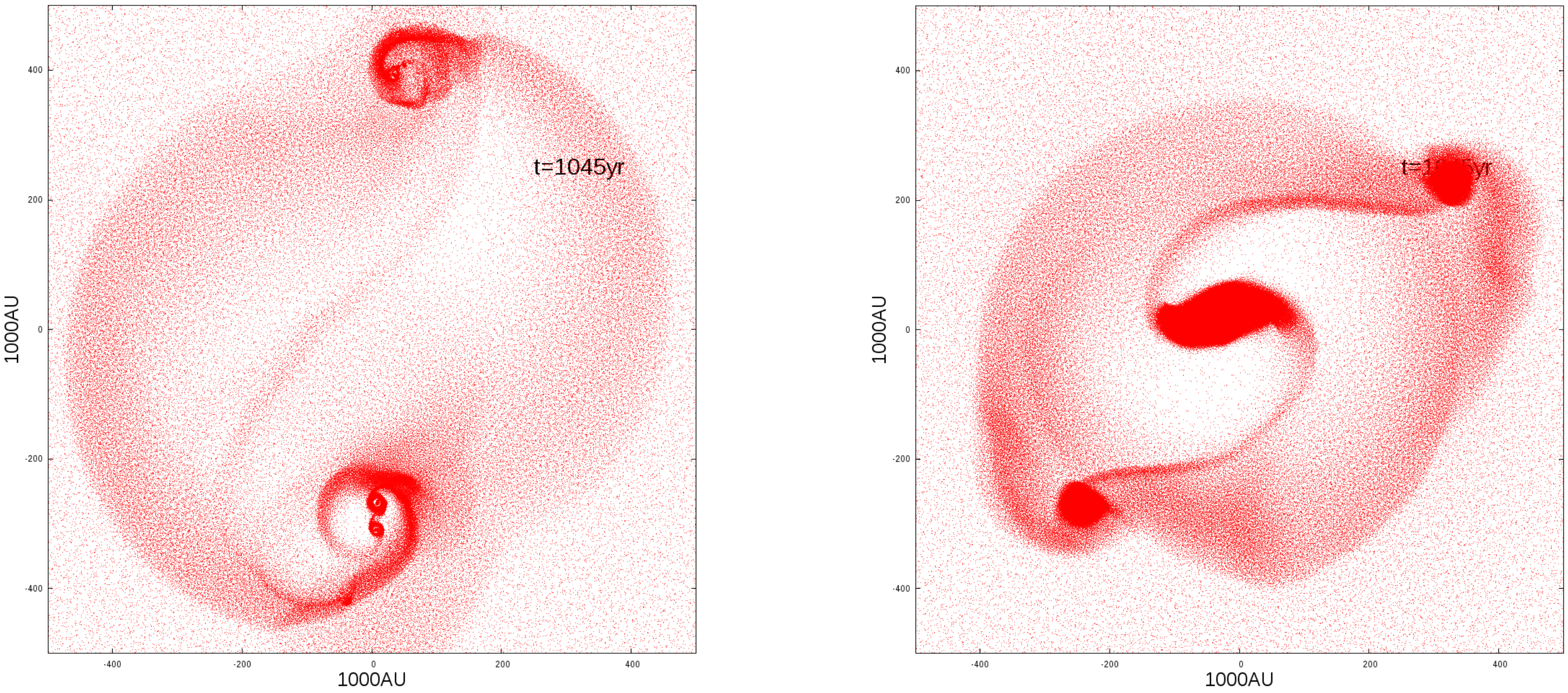




Repeated merger between clumps
But multiple stars survive

nth=1e16

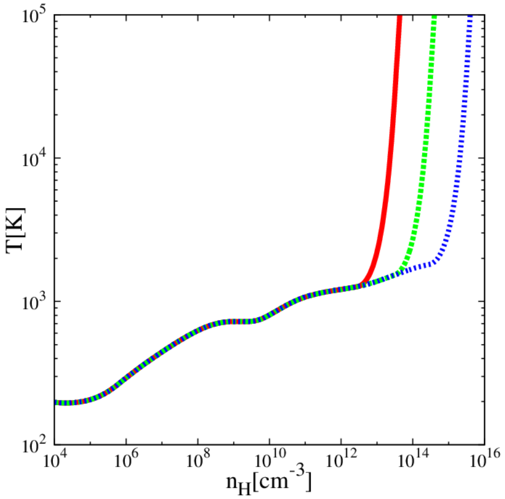
nth=1e13



Number of fragments gradually increases as the threshold density rise.

Stiff EOS v.s. Sinks – number of "stars" –

Stiff EOS runs



$3x10^{19}$ → $3x10^{20}$ Several - ten？

nth /cc	
$3x10^{15}$ → $3x10^{16}$	6
$3x10^{14}$ → $3x10^{15}$	4
$3x10^{13}$ → $3x10^{14}$	3
$3x10^{12}$ → $3x10^{13}$	4

radius of fragments

a few AU～10AU

slightly increase the number
of fragments as the threshold density increase

Sink runs

r_{sink} n_{sink}	1AU	3AU	10AU	30AU
$3x10^{15}$ /cc	12	5	3	3
$3x10^{14}$ /cc	>100	11	4	3
$3x10^{13}$ /cc	>100	45	4	3

r_{sink} has to be less than the Jeans length (core radius)
c.f. Stacy+2016: nsink=$1x10^{16}$/cc r_{sink}=1AU

Summary

- Run-away phase : OK
- Accretion phase
  - high resolution to resolve the protostar (< 5kyr)
    - fragments merge or survive ? Some merge and Some survive
    - How many? Several
    - dependence on methodology Consistent
  - low resolution but longer time integration by RHD(~ 500kyr)
    - final mass & separation & multiplicity? wide spectrum

B-FIELD

Magnetic field on Star Formation

- Important ingredient of present-day SF
  - $E_B \sim E_{kin} \sim E_{grav}$
  - Jet/Outflow launching, A-mom transport
  - suppress fragmentation of disk

- Could be important for first star formation
  - Very weak seed field ($\sim 10^{-19}$G) but,
  - Strong coupling B and Gas
  - turbulence → small scale dynamo → equipartition?

B - Gas Coupling

- MHD effects such as Magnetic Breaking, Jet/Outflow Launching occurs if B and Gas are coupled.

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left(\boldsymbol{v} \times \boldsymbol{B} \right) + \underline{\kappa \nabla^2 \boldsymbol{B}} \qquad t_{diff} \approx \frac{L^2}{\kappa}$$

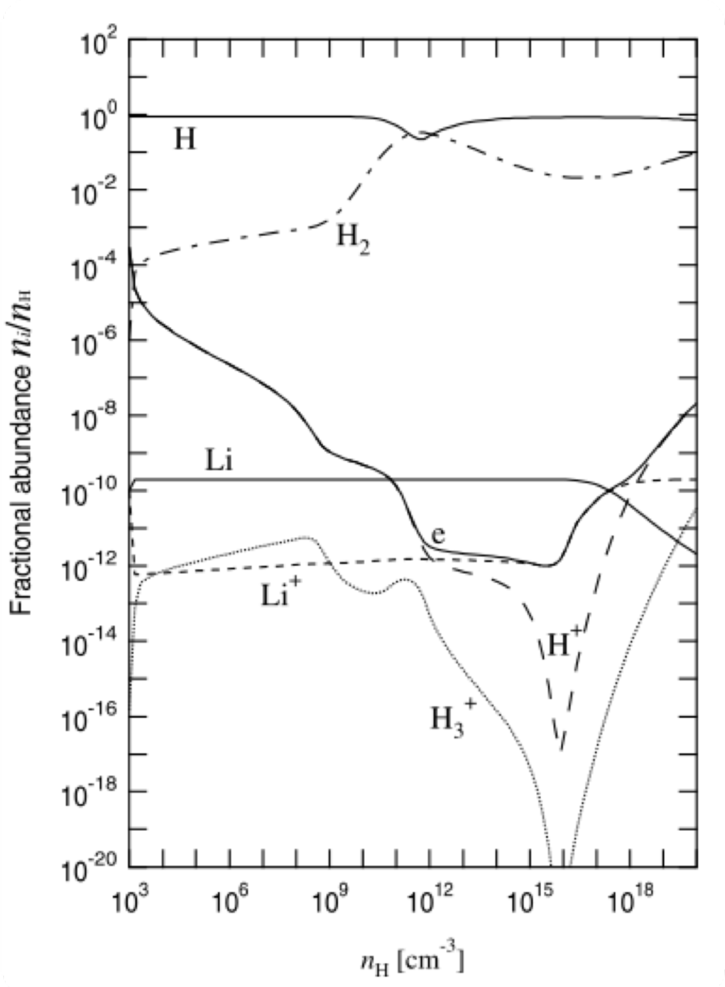
In case we consider cloud collapse of SF,

$t_{diff} << t_{ff}$ → Dissipative (resistive)

$t_{diff} >> t_{ff}$ → Well coupled (flux freezing)

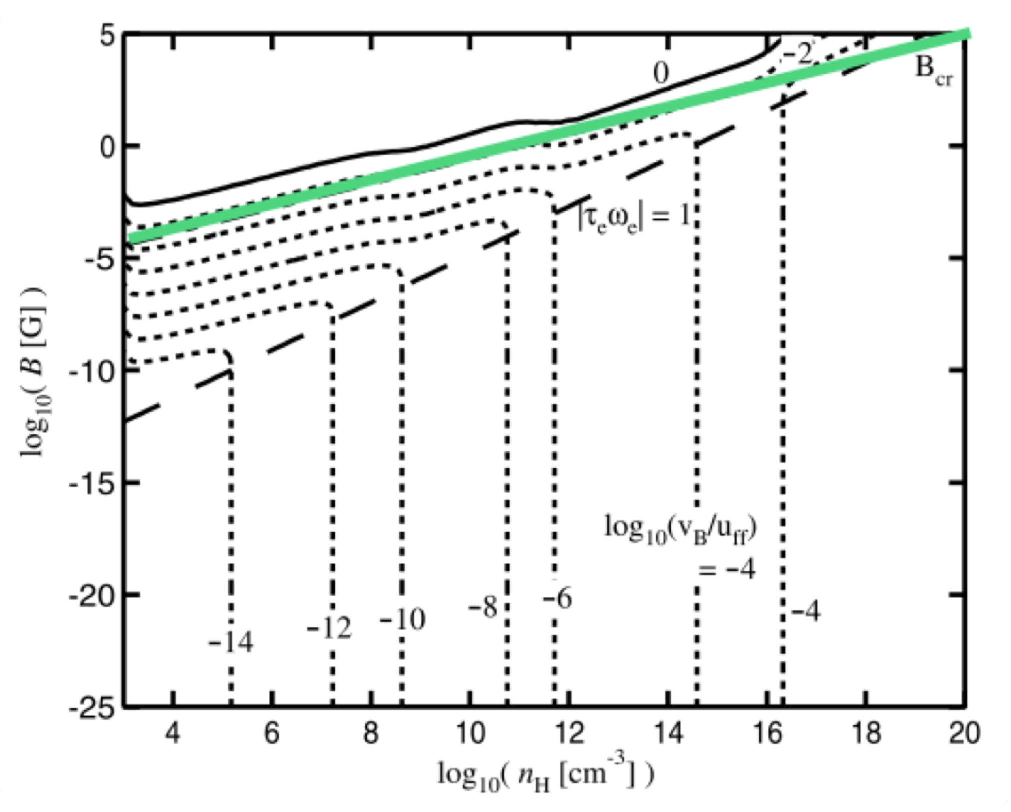
Magnetic field well couples to the primordial gas

Maki & HS(2004,2007)



Li floors the ionization degree

No dissipative region in collapsing cloud



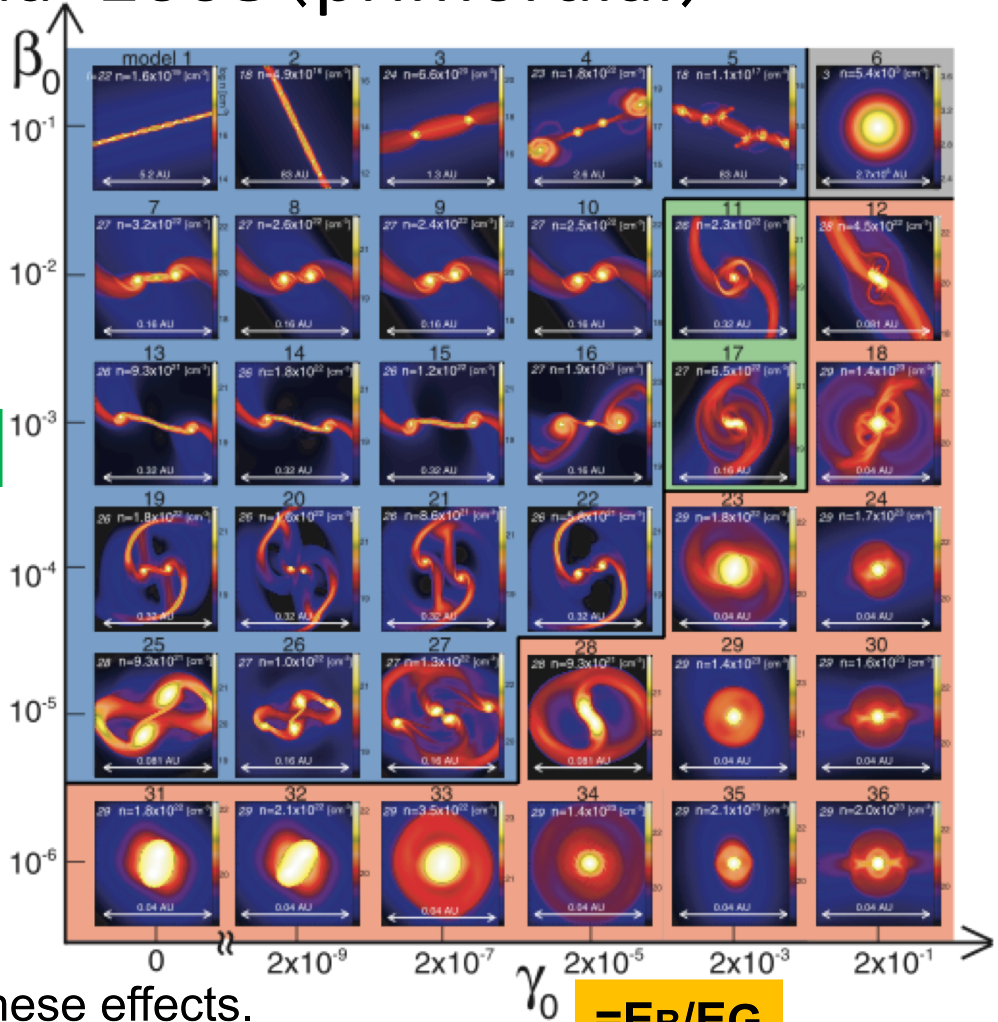
Effects of magnetic field

- Ideal MHD Machida+2008（primordial）

1. Suppress fragmentation
→Massive Single Star ？

2. Outflow launching
→ reduce the mass accretion

Outflow condition：
B>1nG @1000/cc



$=E_{rot}/E_G$

$=E_B/E_G$

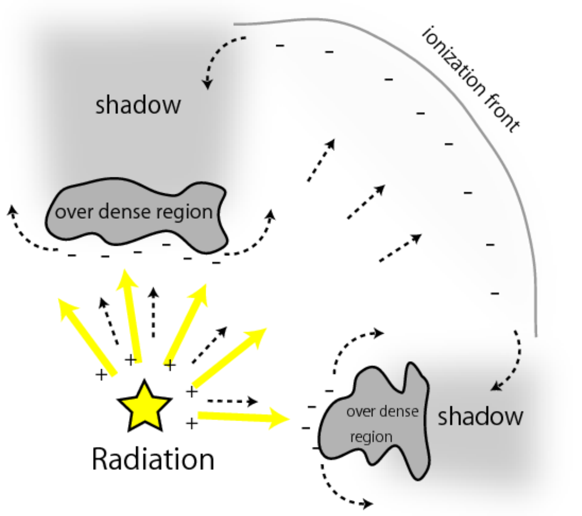
Seed field is not enough to have these effects.

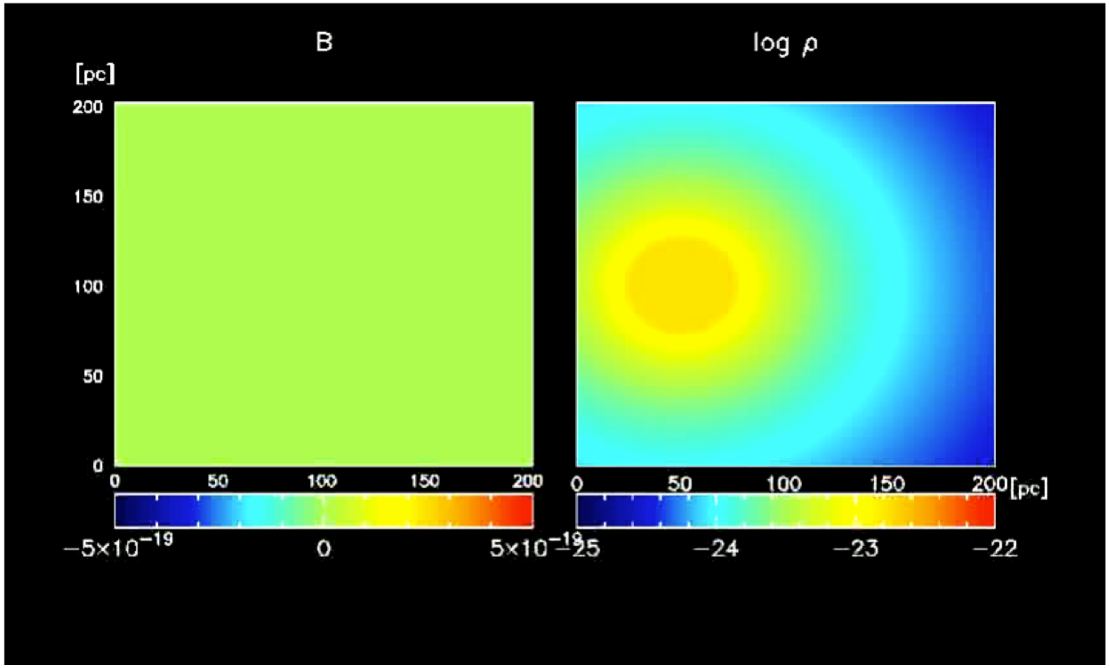
Seed B-field in the early universe

- Cosmological processes of seed field generation
  - Coupling of EM-field with other fields (10^{-9}-10^{-35}G)
  - second-order fluctuation while recombination era（Ichiki+ 2006 10^{-24}-10^{-20}G）
- Astrophysical Processes
  - Biermann Battery
    - Structure formaton Kulsrud+1997 10^{-21} -10^{-20}G, ＠comoving
    - Galaxy formation Davis & Widrow 2000; 10^{-17}G ＠galactic center
    - Minihalo formation Xu+2008 10^{-9}G@10^{10}cm^{-3}
    - Reionization Gnedin+ 2000 10^{-20}-10^{-18}G
  - Radiation force
    - Drag : Balbus 1993, Chuzhoy 2004, Silk & Langer 2006
    - Shadow: Langer+2003,2005 Ando+2010, Doi & HS 2011, Shiromoto+2014

Radiation / Biermann Battery

Ando,Doi,HS 2010, Doi,HS+2011, Shiromoto,HS+2014

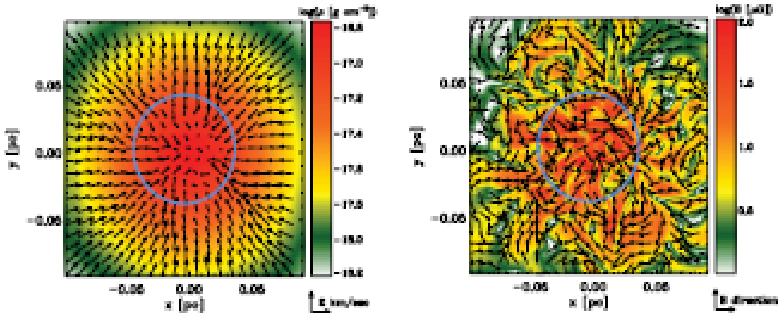




Most of normal processes predict < 10^{-18}G

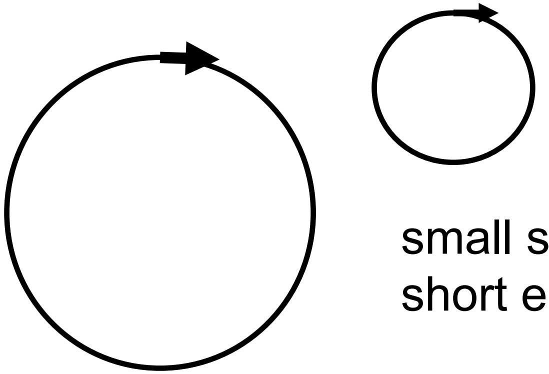
Small scale dynamo: Turbulence in Minihalos

S. Sur et al MONTHLY NOTICES 423 3148 3162



velocity field

B-field



small scale:
short eddy time

large scale:
long eddy time

Accretion flows inject kinetic energy into minihalos
→
Cascade to smaller scales down to the viscus scale, below which the motion dissipates by viscosity.

Kolmogorov turbulence requires

$$v_k \propto k^{-\frac{1}{3}} = l^{1/3}$$

Hence,

$$t = \frac{l}{v_k} \propto l^{2/3}$$

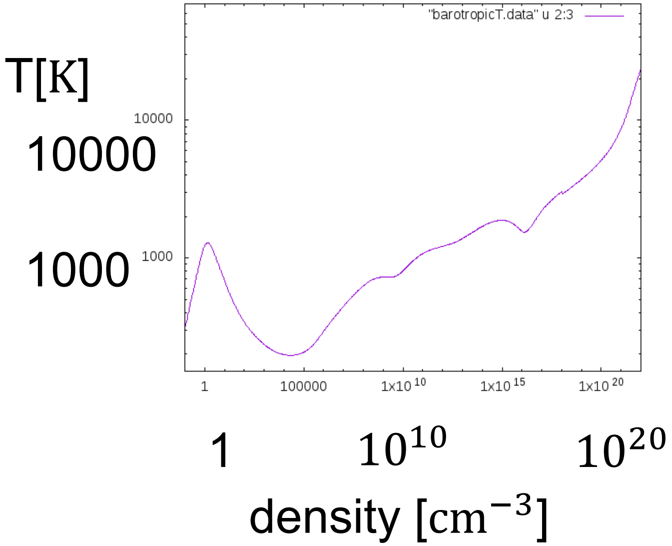
eddy time scale is shorter for smaller scales.

Magnetic field is twisted at very short time scale. → rapid amplification.

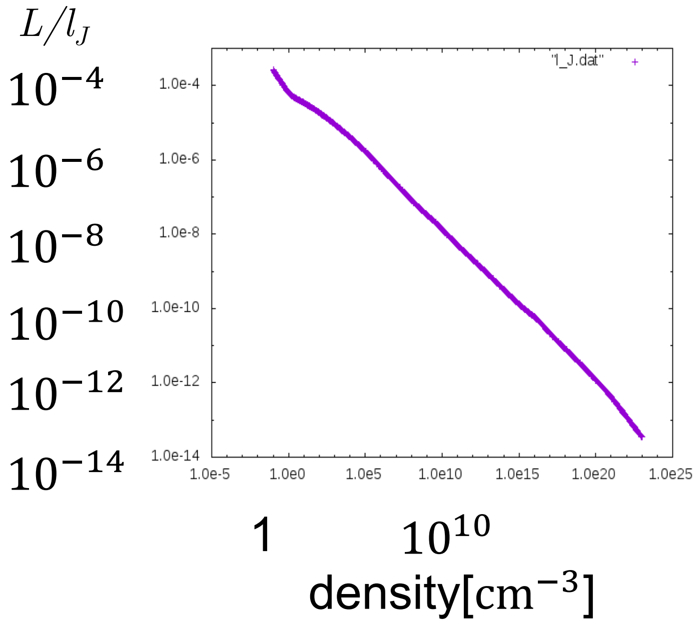
Viscous scale of the collapsing Minihalos

L : Viscous scale
l_J : Jeans scale ~ scale of the core

$$\frac{L}{l_J} = \left(\frac{m}{4d^2 n\pi}\right)^{\frac{3}{4}} \left(\frac{32Gn}{3kT}\right)^{\frac{3}{8}}$$



HS+2015



Mochizuki 2017 master thesis

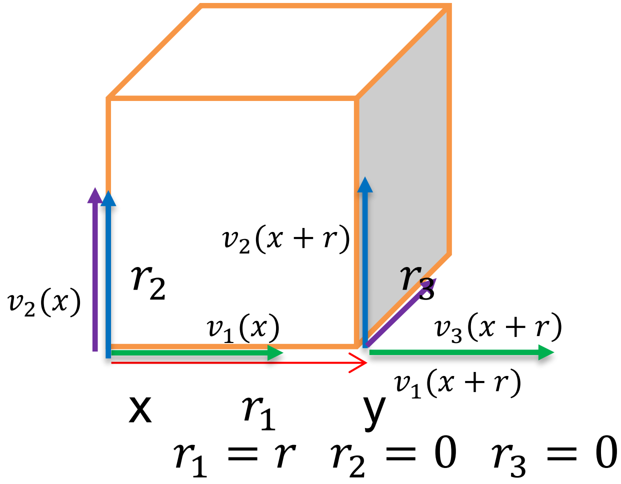
Too small to be resolved by numerical simulations → Semi-analytic method

2-point correlation function of turbulent velocity field/B-field

$$\langle v_i(x,t)v_j(y,s)\rangle = T_{ij}(r)\delta(t-s)$$

$$T_{ij}(r) = \left(\delta_{ij} - \frac{r_i r_j}{r^2}\right)T_N(r) + \frac{r_i r_j}{r^2}T_L(r) + \varepsilon_{ijk}r_k F(r)$$

Consider 2 points x and y separated by r_1.



Longitudinal correlation

$$\langle v_1(x)v_1(x+r)\rangle = T_{11}(r) = T_L(r)$$

Normal correlation

$$\langle v_2(x)v_2(x+r)\rangle = T_{22}(r) = T_N(r)$$

Helical correlation

$$\langle v_2(x)v_3(x+r)\rangle = T_{23}(r) = rF(r)$$

$$\langle B_i(x,t)B_j(y,t)\rangle = M_{ij}(r,t)$$

$$M_{ij} = \left(\delta_{ij} - \frac{r_i r_j}{r^2}\right)M_N(r,t) + \frac{r_i r_j}{r^2}M_L(r,t) + \varepsilon_{ijk}r_k C(r,t)$$

Derive evolutionary equiation of M_{ij} from the induction equation

$$\nabla \cdot B = 0 \rightarrow M_N = M_L + \frac{r}{2}M_L'$$

→Solve equation for M_L & C.

Derive evolution equation of M_{ij}

Turbulent velocity field is related to B-field by induction equation.

$$\frac{\partial B}{\partial t} = \nabla\times(U\times B) - \eta\nabla\times(\nabla\times B)$$

substitute the following identity by induction equation and integrate formally from 0 to δt.

$$\frac{\partial B_i B_j}{\partial t} = \frac{\partial B_i}{\partial t} B_j + B_i \frac{\partial B_j}{\partial t}$$

We have

$$B_{ij} = B_{ij}^0 + \int_0^{\delta t} dt\left[R_{ipq}^x U_p B_{qj} + R_{jpq}^y U_p B_{iq}\right] + \delta t\left[\eta\left({\nabla_x}^2 B_{ij} + {\nabla_y}^2 B_{ij}\right)\right]$$

here $B_{ij} \equiv B_i B_j$ and B_{ij}^0denotes the initial value at $t = 0$.

and $R_{ipq}^x \equiv \varepsilon_{ilm}\varepsilon_{mpq}\left(\frac{\partial}{\partial x_l}\right)$

$U = \overline{U} + v$ $\overline{U}$ bulk velocity v turbulent motion

Kazantsev equation

$$\frac{\partial M_L}{\partial t} = \boxed{\frac{2}{r^4}\frac{\partial}{\partial r}\left[r^4 \eta_T \frac{\partial M_L}{\partial r}\right]} + \boxed{G M_L}$$

$$\eta_T = \eta + T_L(0) - T_L$$

$$G = -2\left(T_L'' + 4\frac{T_L'}{r}\right)$$

$$T_L' < 0、T_L'' < 0 \quad \rightarrow G > 0$$

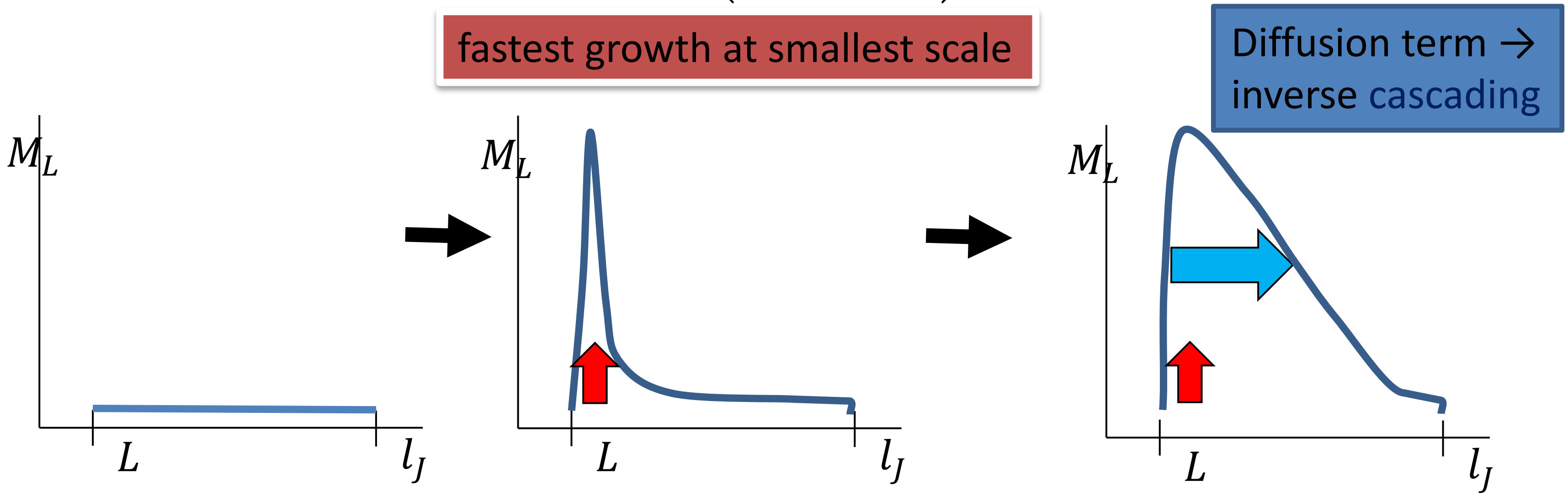
Brandenburg, Subramanian 2005

Behavior of the solution

$$\frac{\partial M_L}{\partial t} = \frac{2}{r^4}\frac{\partial}{\partial r}\left[r^4 \eta_T \frac{\partial M_L}{\partial r}\right] + G M_L$$

$$\eta_T = \eta + T_L(0) - T_L$$

$$G = -2\left(T_L'' + 4\frac{T_L'}{r}\right)$$



fastest growth at smallest scale

Diffusion term → inverse cascading

Magnetic field grow at the smallest scale, then inversely cascade to larger scales.

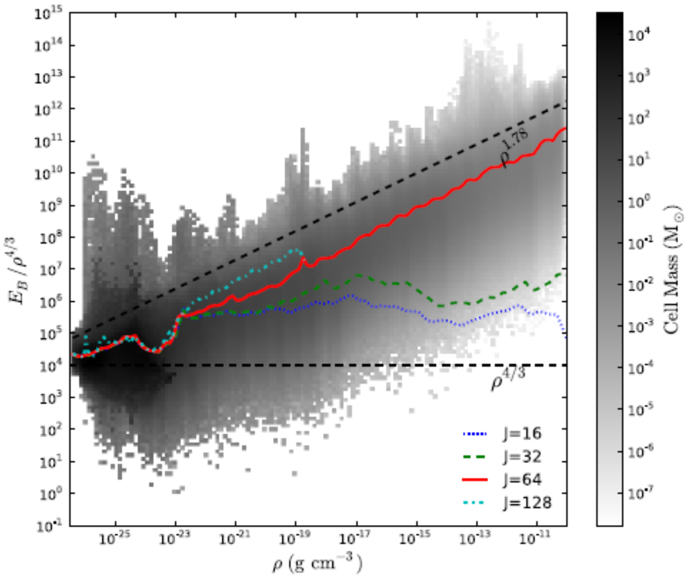
Time scales

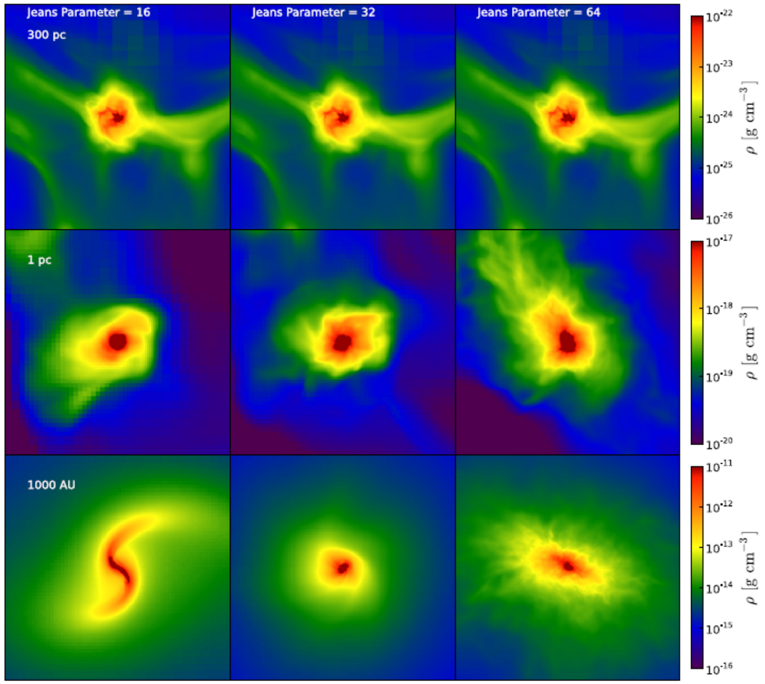
- L: viscose scale l_J: Jeans scale
  c_s: sound velocity (turbulent velocity at Jeans scale)
- $G \sim \frac{l_J c_s}{r^2} \sim \frac{l_J c_s}{L^2} \;\; \Rightarrow \;\; \tau_l \sim \frac{1}{G} \sim \frac{L^2}{l_J c_s} \sim \frac{l_J}{c_s}\left(\frac{L}{l_J}\right)^2 \ll \frac{l_J}{c_s}$
- $\tau_{icas} \sim \frac{r^2}{\eta_T} \sim \frac{r^2}{T_L(0) - T_L(r)} \sim \frac{L^2}{l_J c_s \left(\frac{L}{l_J}\right)^{\frac{4}{3}}} \sim \frac{L^{\frac{2}{3}} l_J^{\frac{1}{3}}}{c_s} \sim \frac{l_J}{c_s}\left(\frac{L}{l_J}\right)^{\frac{2}{3}} \ll \frac{l_J}{c_s}$

Simulations

Turk+2012
Sur+2010, 2012
Federrath+2011

- Unable to resolve viscous scale
  → cannot reach the equipartition level
- The smaller scale resolved, the larger amplitude obtained.
- Faster growth than free-fall observed





Turk+2012

B-field summary

- Very weak seed field
- tight coupling with gas $\simeq$ ideal MHD
- If B-field exists close to the level of equipartition, various MHD effects are expected.
- If the minihalo is highly turbulent, the weak seed field will be amplified to the level of equipartition.