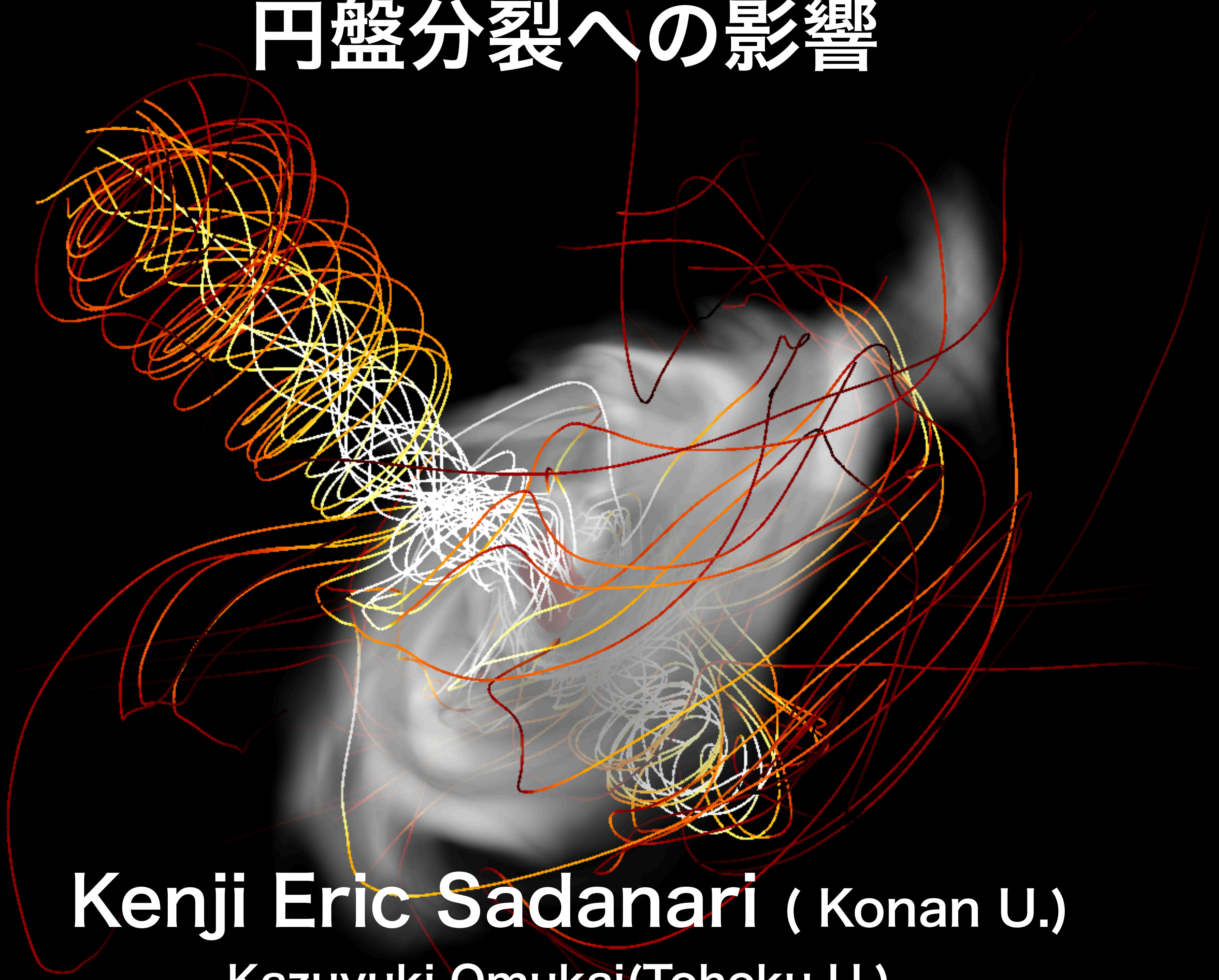
初代星形成における乱流磁場の増幅と円盤分裂への影響



Kenji Eric Sadanari (Konan U.)

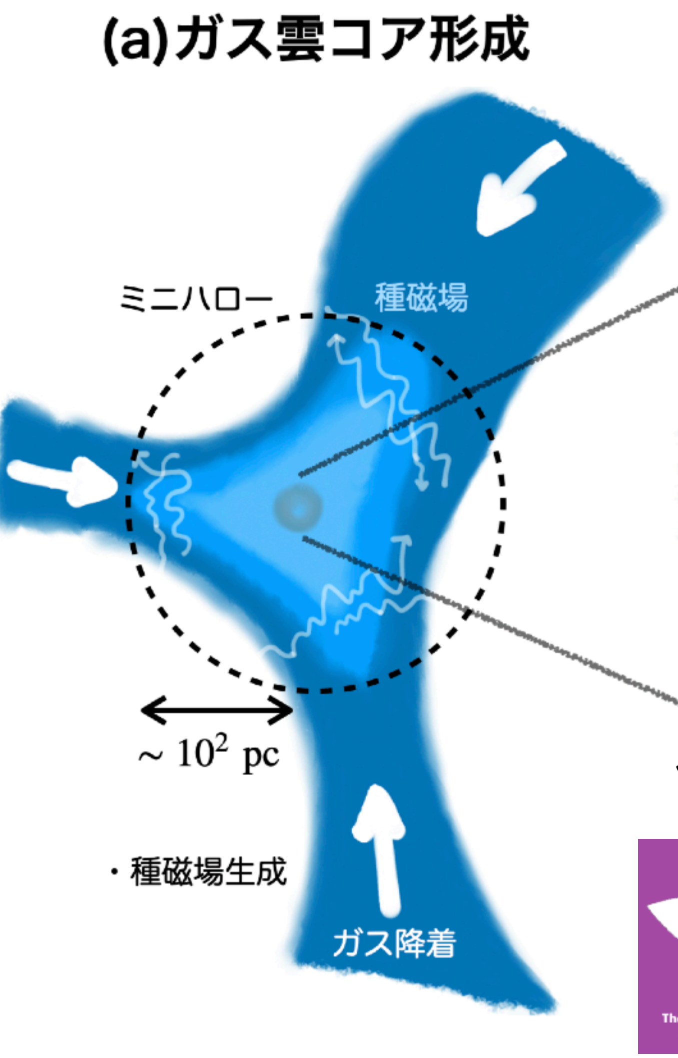
Kazuyuki Omukai(Tohoku U.)

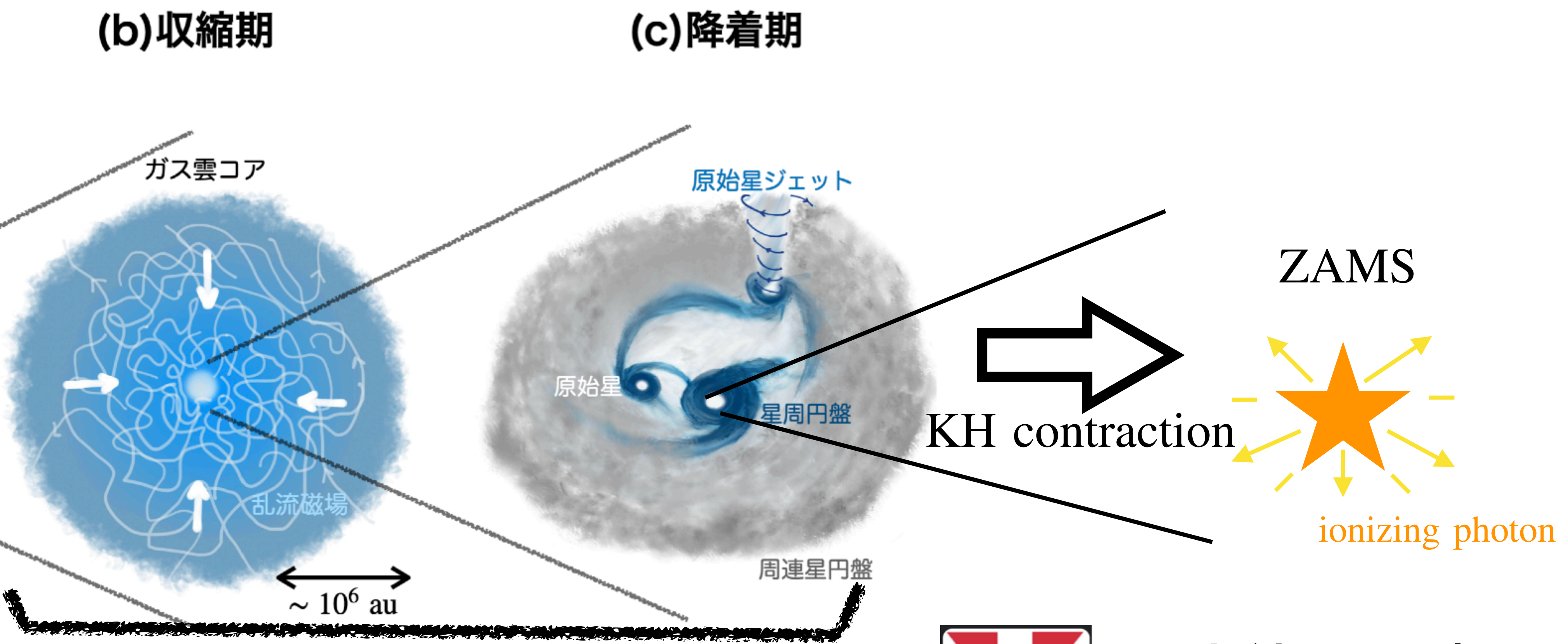
Kazuyuki Sugimura(Hokkaido U.)

Tomoaki Matsumoto(Hosei U.)

Kengo Tomida(Tohoku U.)

-星形成過程-



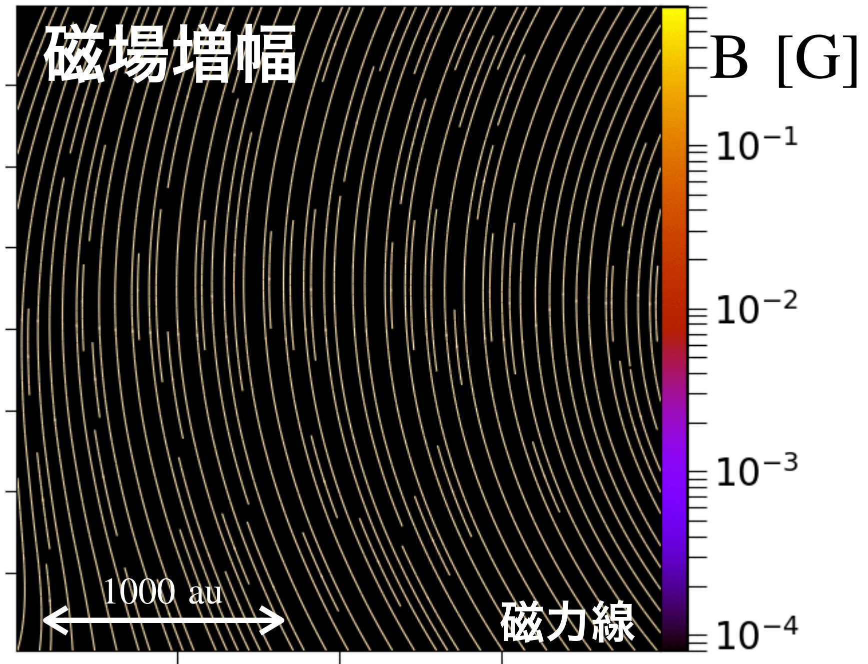


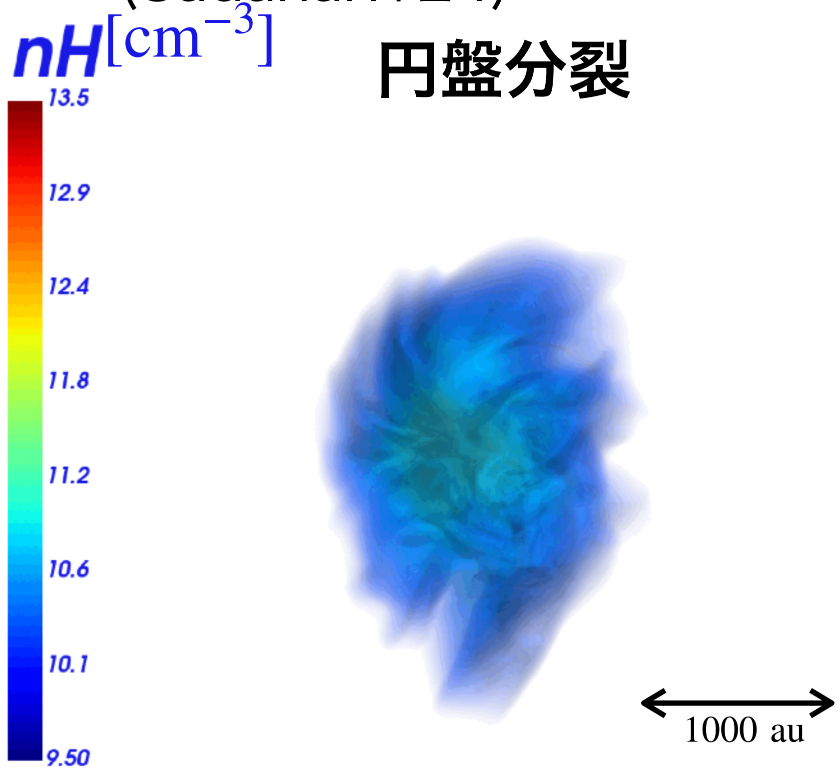
磁場を考慮した初代星形成

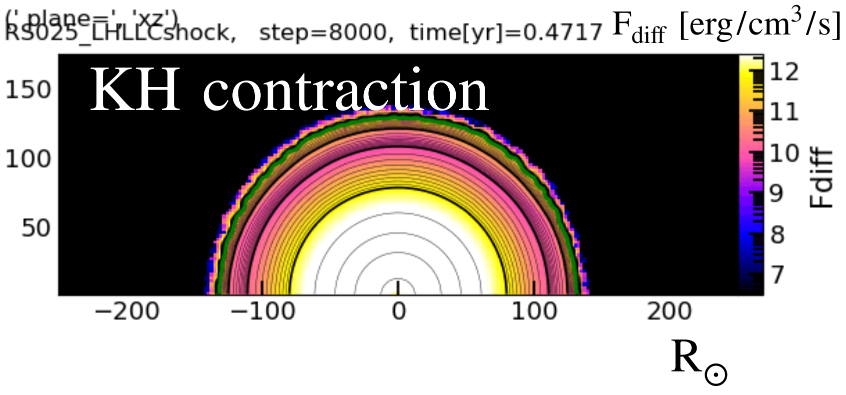
- 磁場増幅(Sadanari+21,23)
- 磁場の影響（eg., 星質量,連星,...）(Sadanari+24)

KH収縮する回転星

- 近接連星







Outlines

1. first star formation w/o magnetic field

2. magnetic fields in first star forming region

- generation & amplification of B-field

3. Magnetic effects on first star formation

(Sadanari et al. 2024)

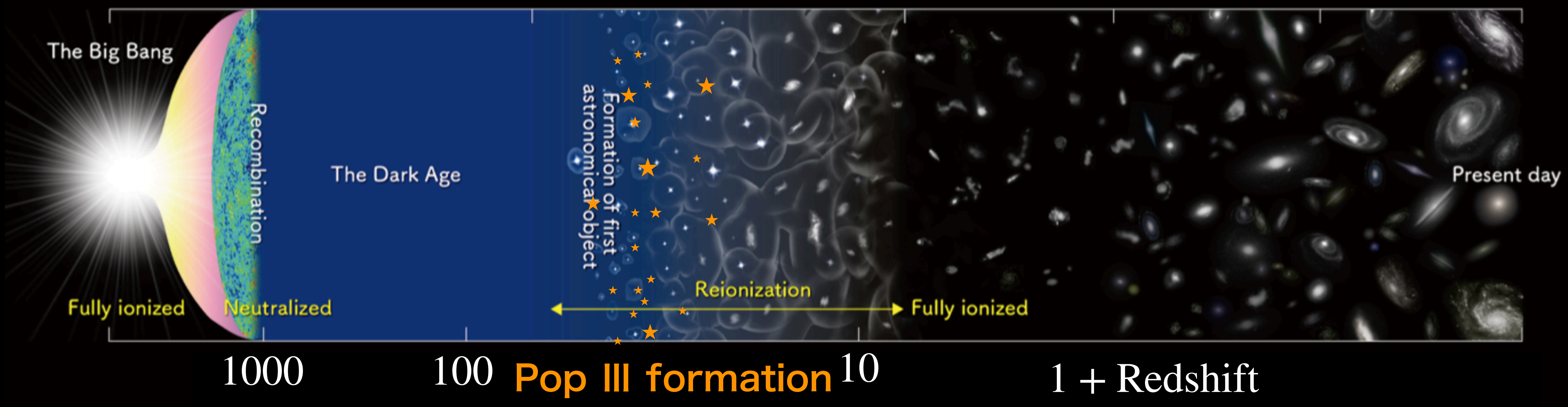
- turbulent B-fields effects on disk fragmentation
  - ・magnetic pressure
  - ・magnetic torques
  - ・MHD outflow

4. Summary

first star formation

first (Pop III) stars

starting points of the formation of astronomical objects



Pop III formation at $z \sim 10\text{-}30$

✔ **The properties of first stars determine the evolution of the universe**

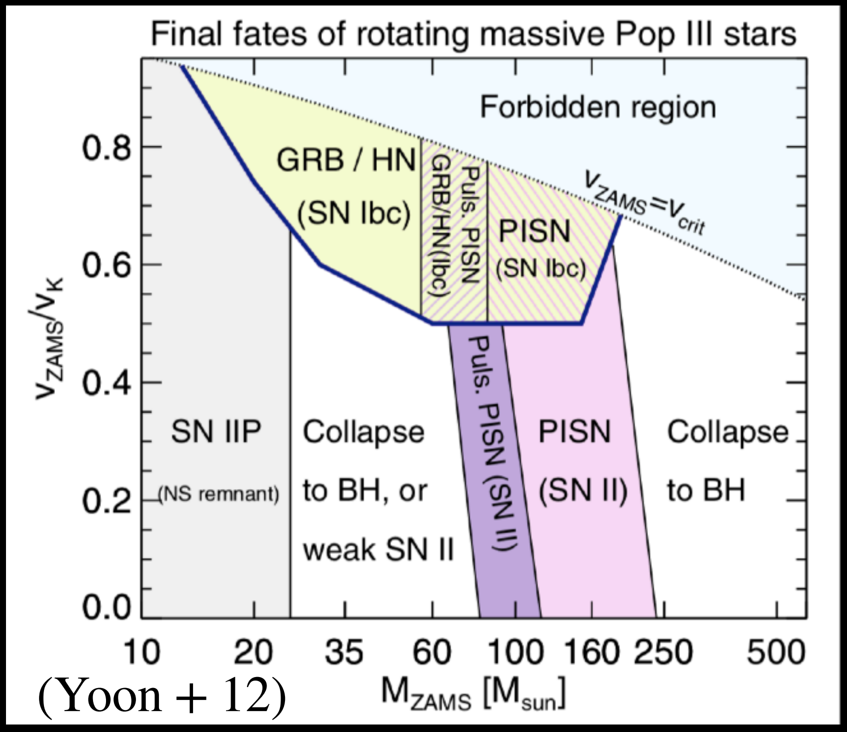
reionization by stellar radiation, metal enrichment by SNe, seeding BHs, metal poor stars, etc.

Big goal

determining the nature of first stars

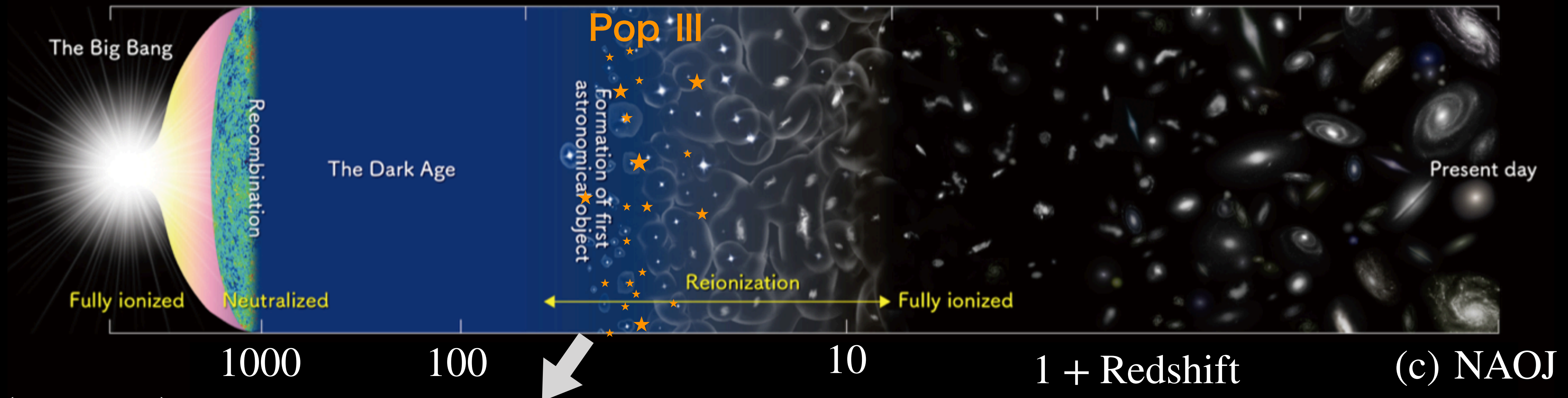
- mass, number of stars, spin, multiplicity, binary separation, eccentricity, etc.

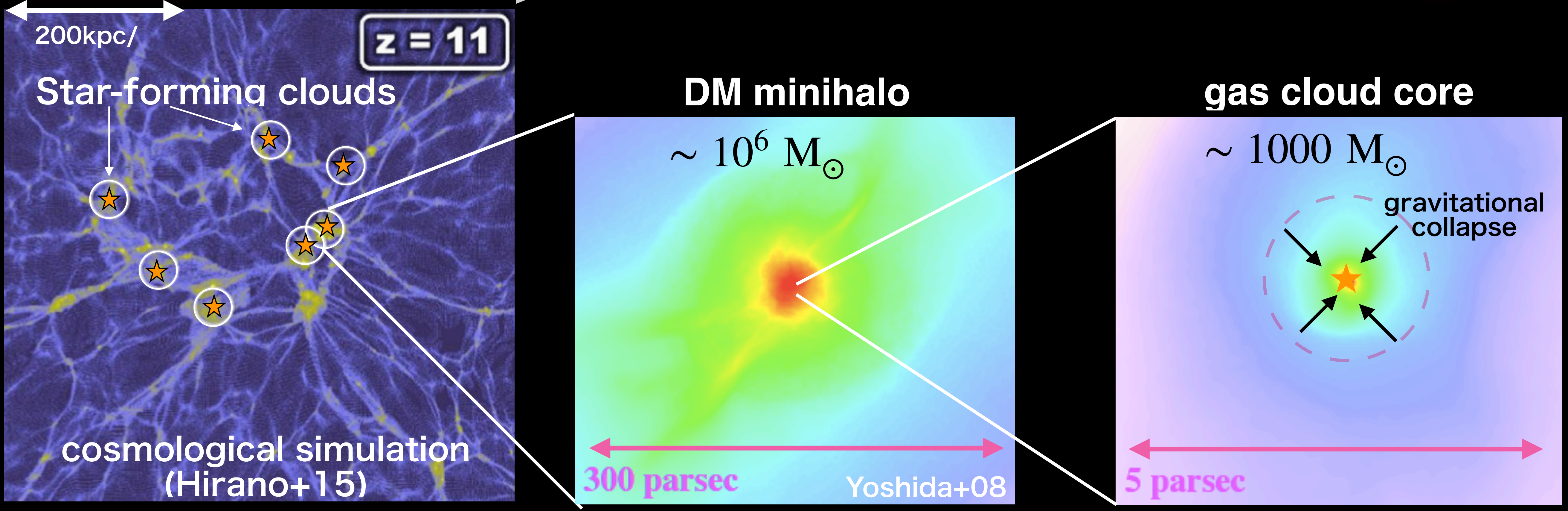
→ **we need to perform numerical simulations**



first (Pop III) stars

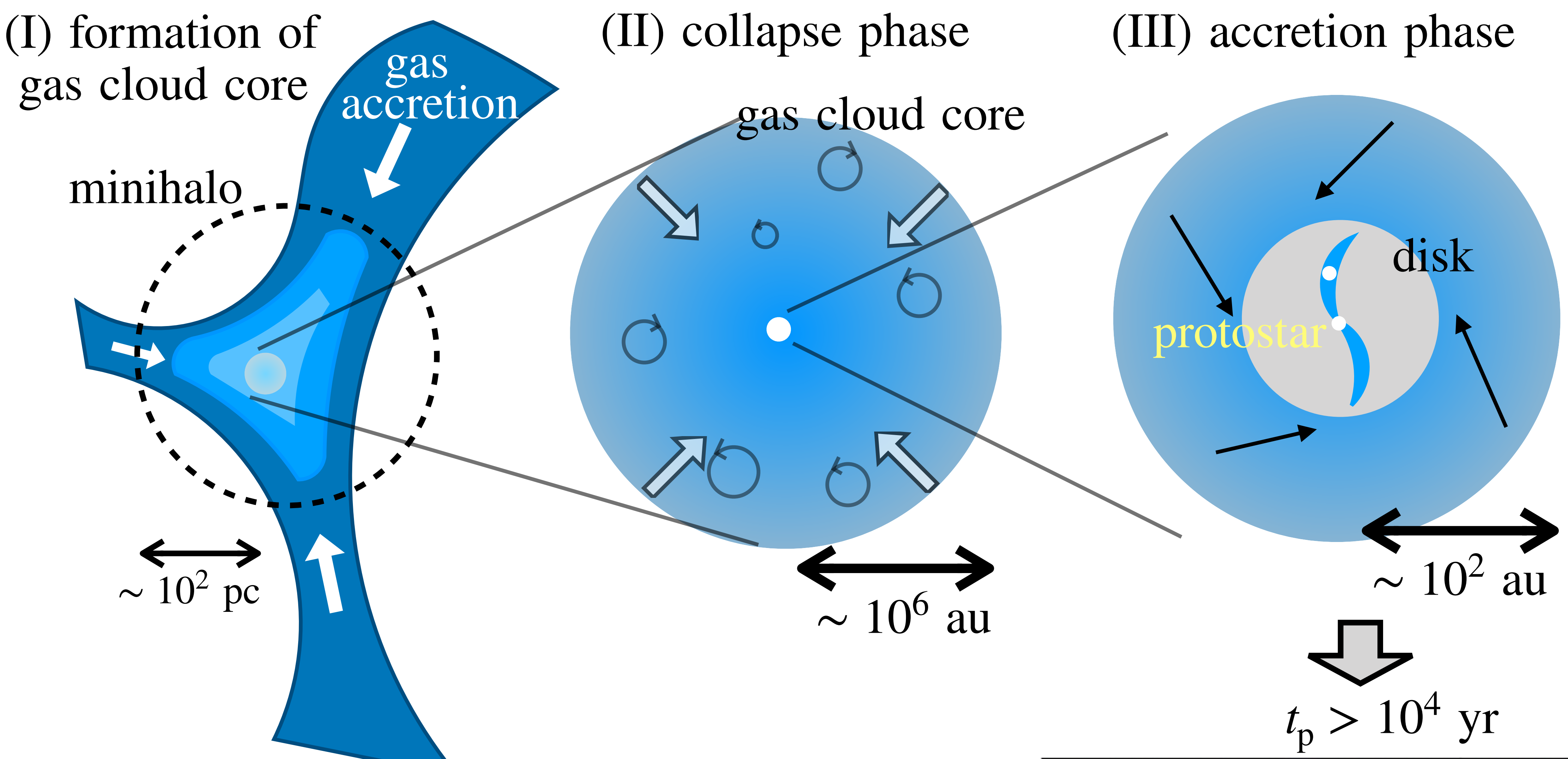
starting points of the formation of astronomical objects

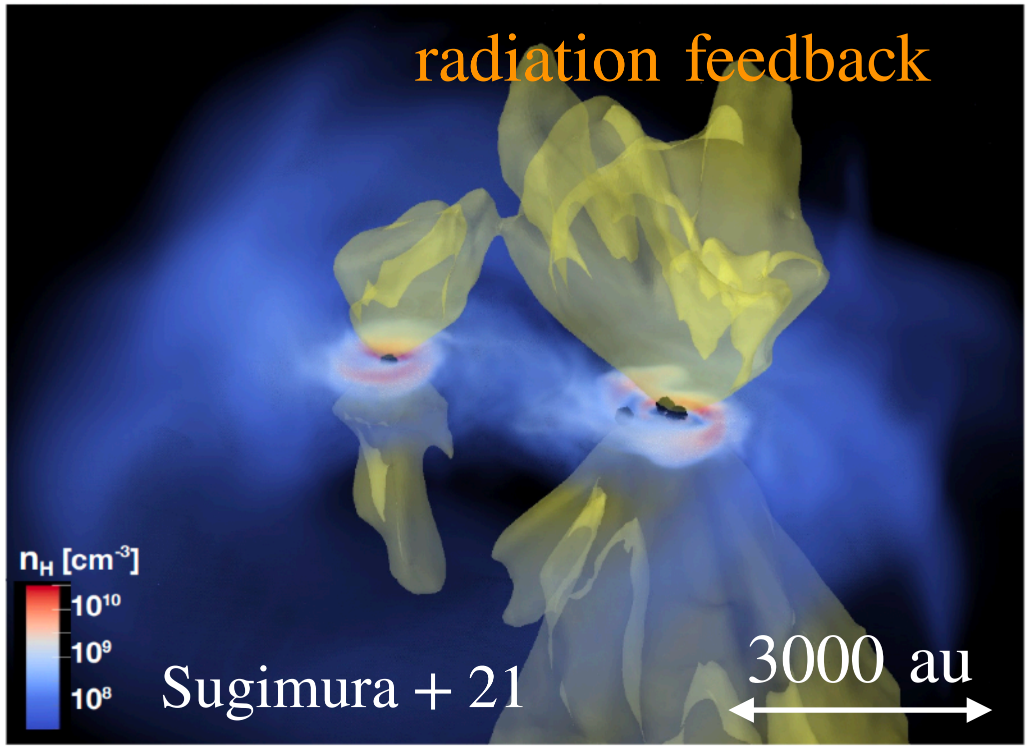




- accumulation of gas
- generation of turbulence & seed B-field

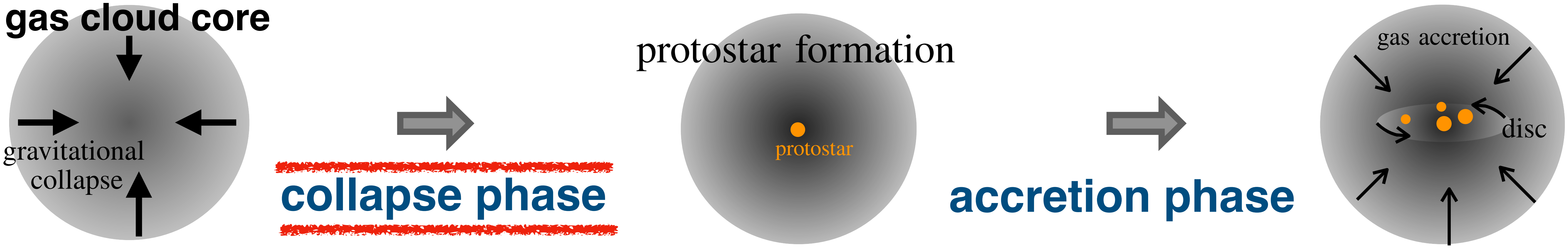
first star formation process

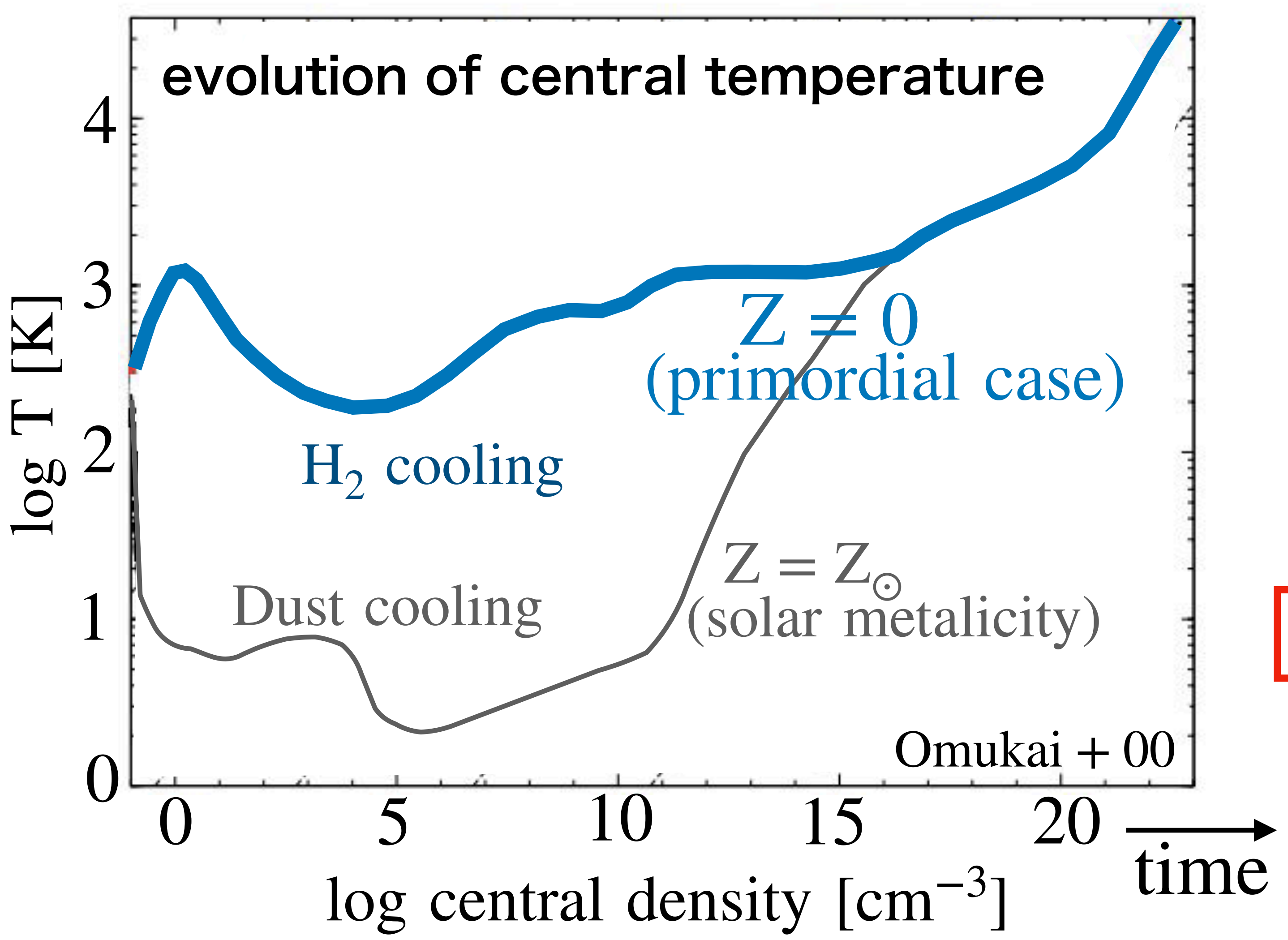




- quenching of gas accretion due to ionization feedback → stellar mass

collapse phase





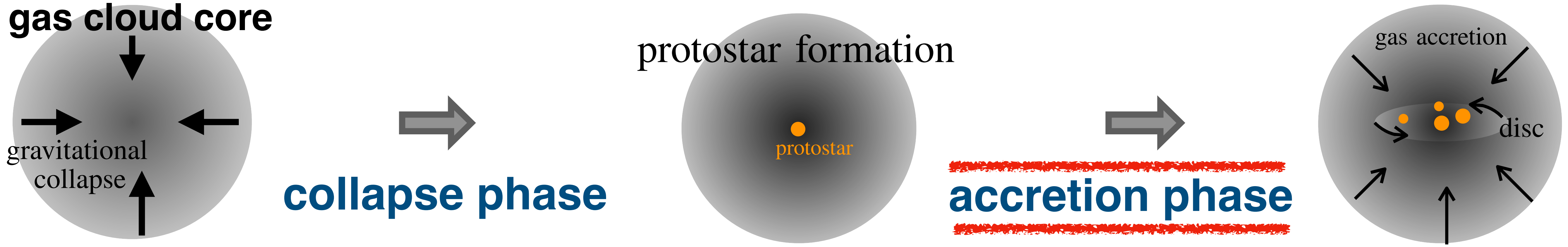
✔ accretion rate

$$\dot{M} \sim M_{\rm J}/t_{\rm ff} \sim c_s^3/G \sim T^{3/2}$$

→
- Pop III (T~200 K): $10^{-3}\ M_\odot$/yr
- Pop I (T~10 K): $10^{-6}\ M_\odot$/yr

Accretion rate is high in the primordial case.

accretion phase



gas cloud core

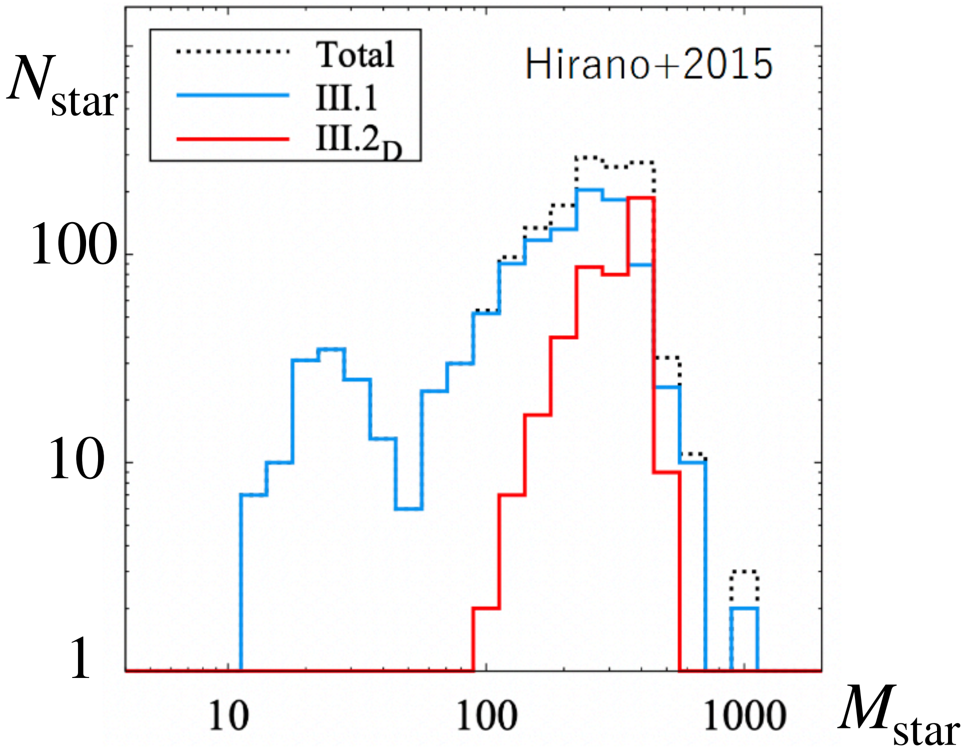
collapse phase

protostar formation

accretion phase

high accretion rate

✔ massive star

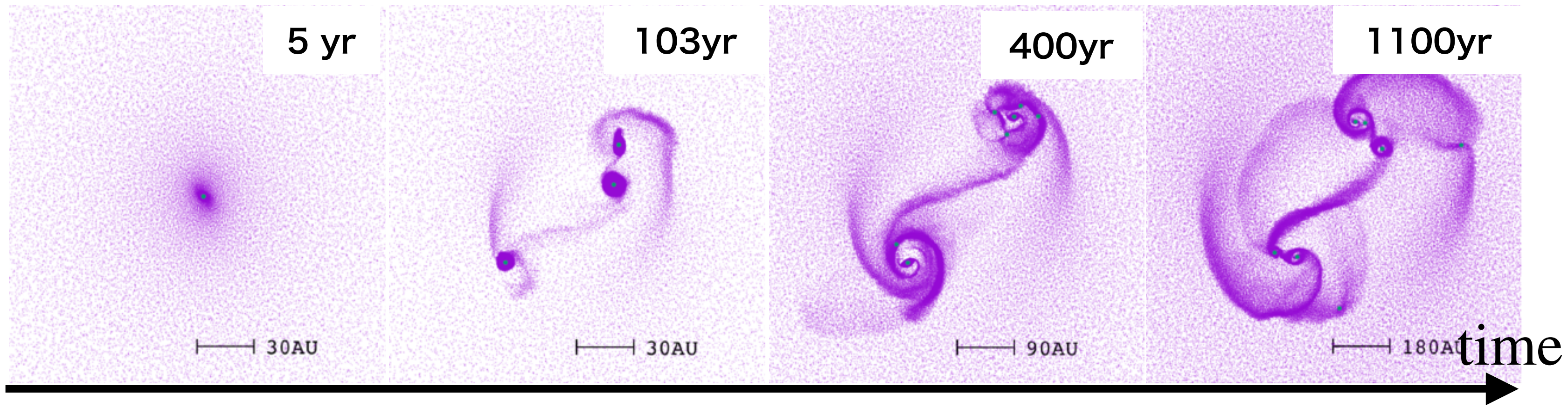


(e.g., Hirano+2015)

typical mass ~100 $M_\odot$

✔ binary/multiple system

3D hydrodynamic simulations (Susa 2019)

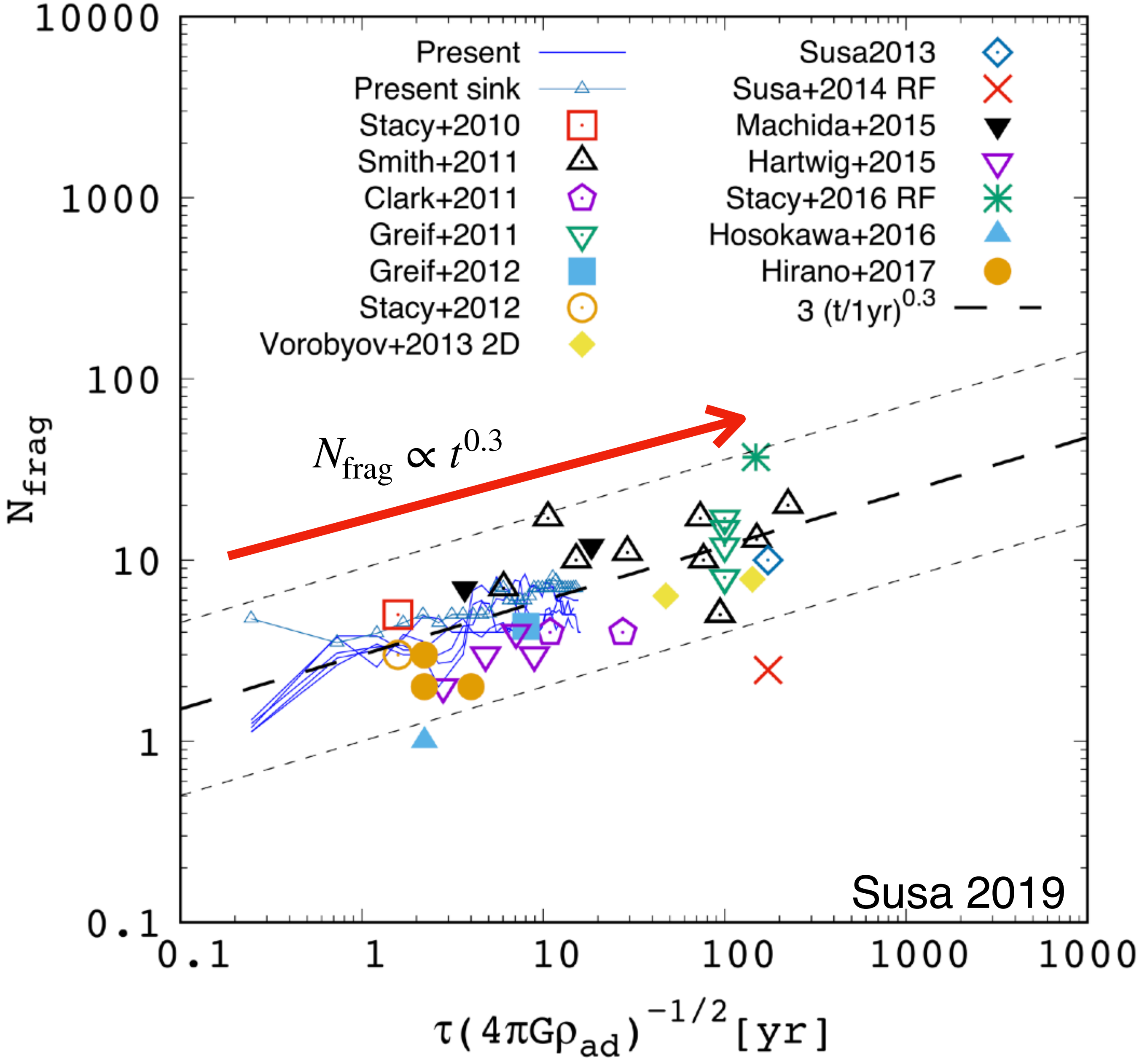


- High accretion rate easily leads to **disk fragmentation.**
  →multiple systems w/ massive binaries.

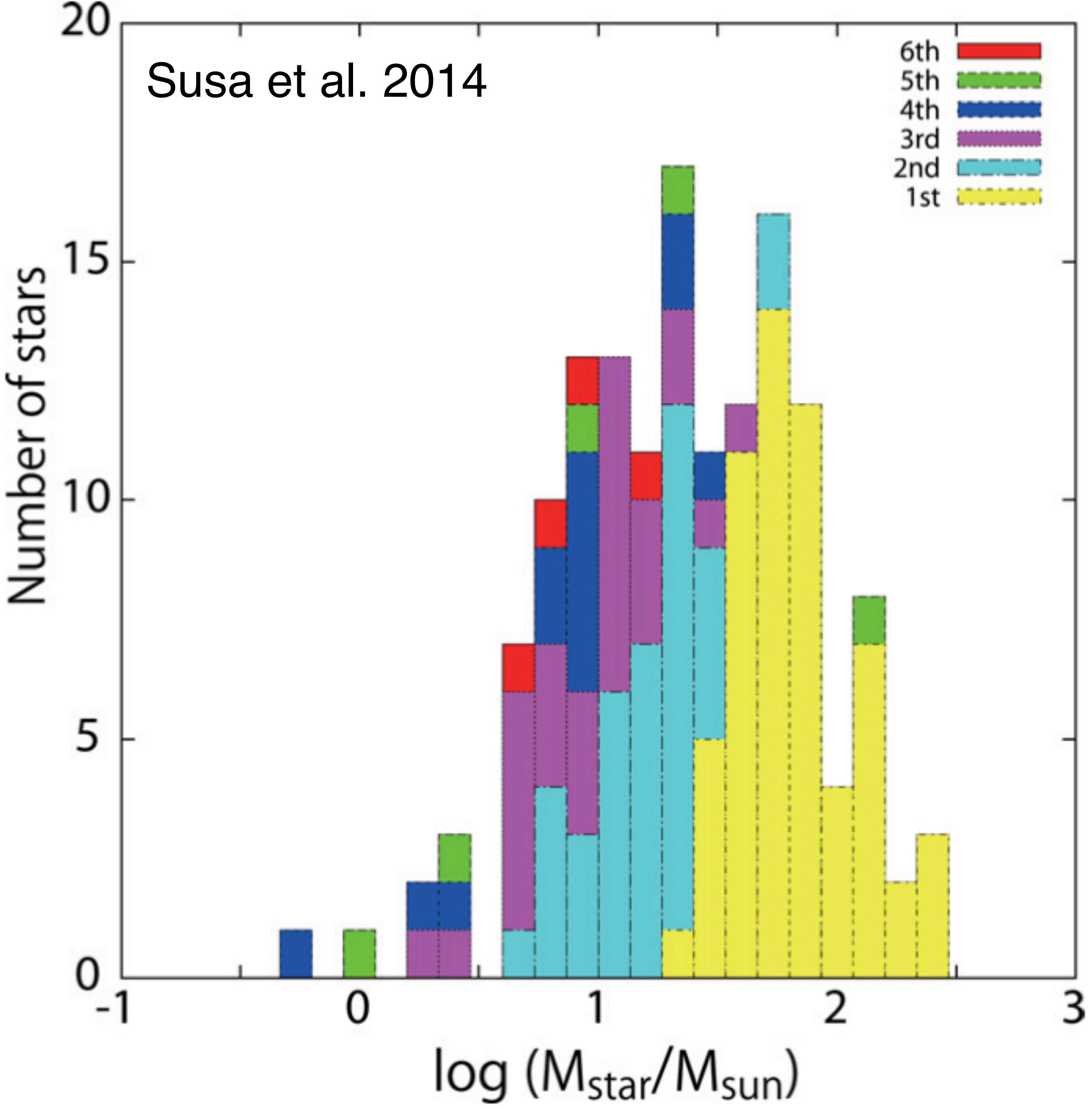
  → can be progenitors of observed BH mergers

disk fragmentation

the number of fragmentations



Mass spectrum



Hydrodynamics simulations suggest that number of protostars **continues to increase in time.**

→ first stars tend to form as a **higher-order multiple system**.

→ **Low-mass first stars** can also form.

How does this change in the presence of B-fields ?

magnetic fields in the first star-forming regions

- generation of seed magnetic fields
- magnetic amplification

seed magnetic field in the early universe

✔ Observational constrains

- Gamma rays observation of blazars

  $B > 10^{-20}$ G @ intergalactic voids (Takahashi+2012)

✔ Theory

Cosmological process

- during electroweak & QCD phase transition:
  $B \sim 10^{-65} - 10^{-9}$ G → depend on the model
- Second order fluctuations during recombination era (Saga+2015)

  $B \sim 10^{-24}$ G@ few Mpc

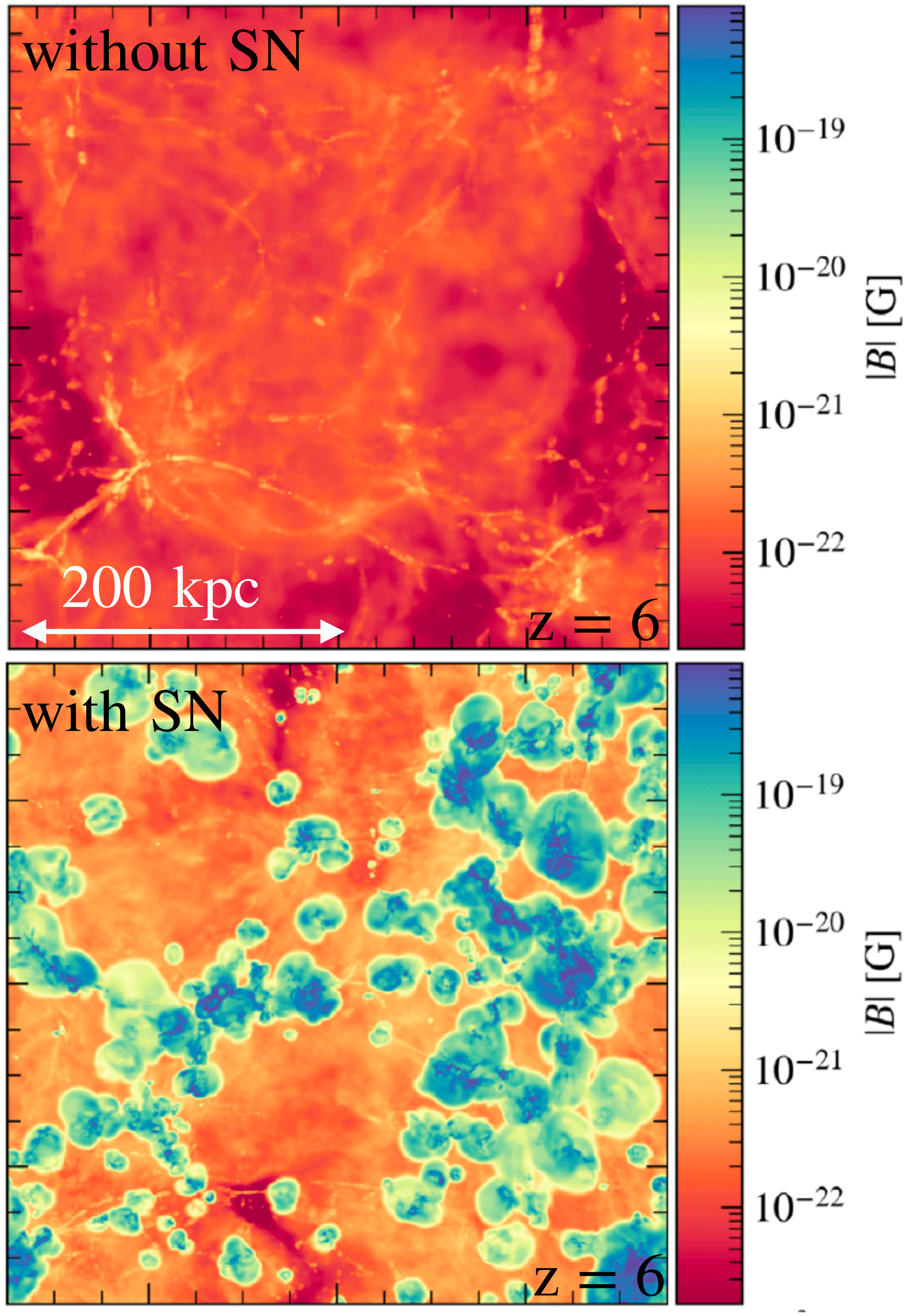
Astronomical process

→ **Biermann battery mechanism**

- Galaxy formation (Kulsrud+1997)
- Reionization (Gnedin+2005)
- SNe explosion (Hanayama+2005)
- **Virialization shock during minihalo formation** (Xu+2008)
- Radiation forces (Langer+2003; Doi&Susa2011)
- Streaming of cosmic rays (Ohira 2021)

→ **$B \sim 10^{-21} - 10^{-16}$ G at scale of astronomical object**

Attia + 21



magnetic field evolution in minihalos

step 1.

Biermann-Battery機構による種磁場生成

- Initial Biermann
- Turbulent Biermann

step 2.

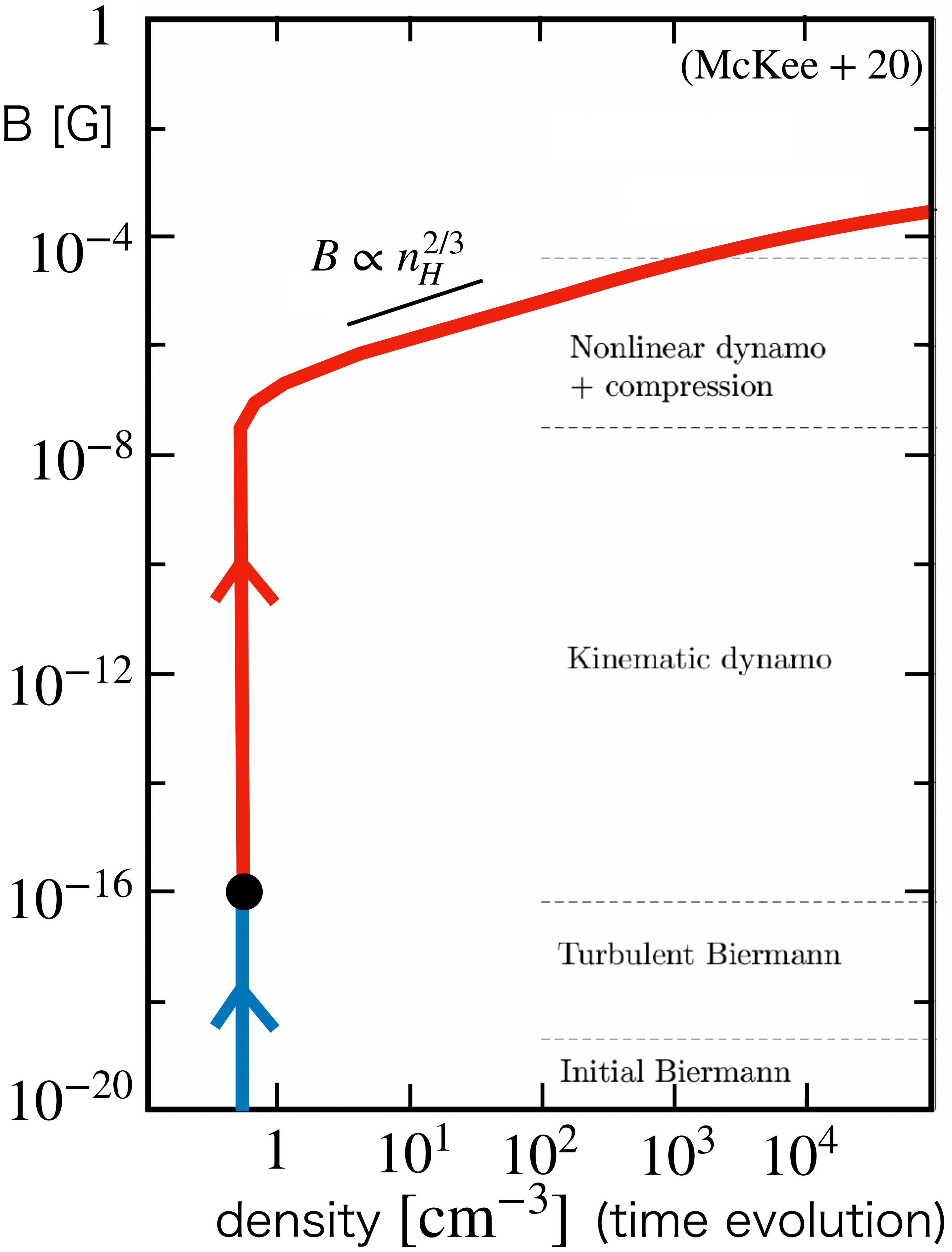
乱流ダイナモ+重力圧縮による磁場増幅

- Kinematic dynamo phase
- Nonlinear dynamo phase
- compression phase

induction equation

$$\frac{\partial \vec{B}}{\partial t} = \underline{\nabla \times (\vec{v} \times \vec{B})} - \underline{\frac{m_{\mathrm{a}} c}{e(1+\chi)} \left(\frac{\nabla \rho \times \nabla p}{\rho^2} \right)} + \eta \nabla^2 \vec{B}$$

(χ :電離度, η :磁気抵抗率, m_{a} :平均原子質量)



generation of seed magnetic fields

✔ Initial Biermann

- ガス降着に伴う衝撃波が磁場・渦度を生成

$$\nabla\rho \times \nabla p \neq 0$$

$$\left[\begin{aligned} \frac{\partial \vec{B}}{\partial t} &= \nabla \times (\vec{v} \times \vec{B}) - \frac{m_{\rm a} c}{e(1+\chi)} \left(\frac{\nabla\rho \times \nabla p}{\rho^2} \right) + \cancel{\eta \nabla^2 \vec{B}} \\ \frac{\partial \vec{\omega}}{\partial t} &= \nabla \times (\vec{v} \times \vec{\omega}) + \frac{\nabla\rho \times \nabla p}{\rho^2} + \cancel{\nu \nabla^2 \vec{\omega}}, \quad \vec{\omega} = \nabla \times \vec{v} \end{aligned}\right.$$

- 初期に渦度・磁場がなかった場合($\omega,\ B = 0$)

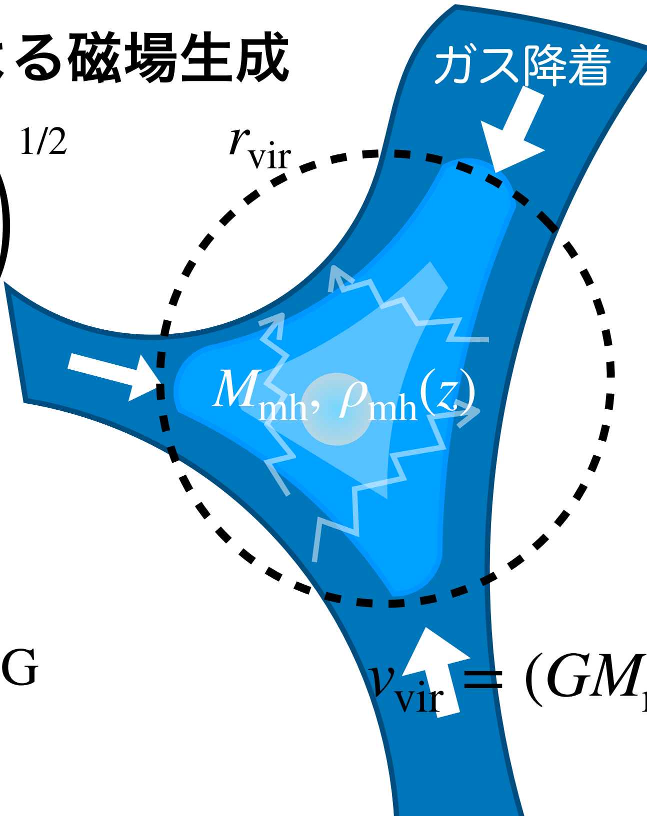
$$\vec{B}_{\rm seed} = -\frac{m_{\rm a} c}{(1+\chi)e} \vec{\omega} = -1.29 \times 10^{-4} \omega$$

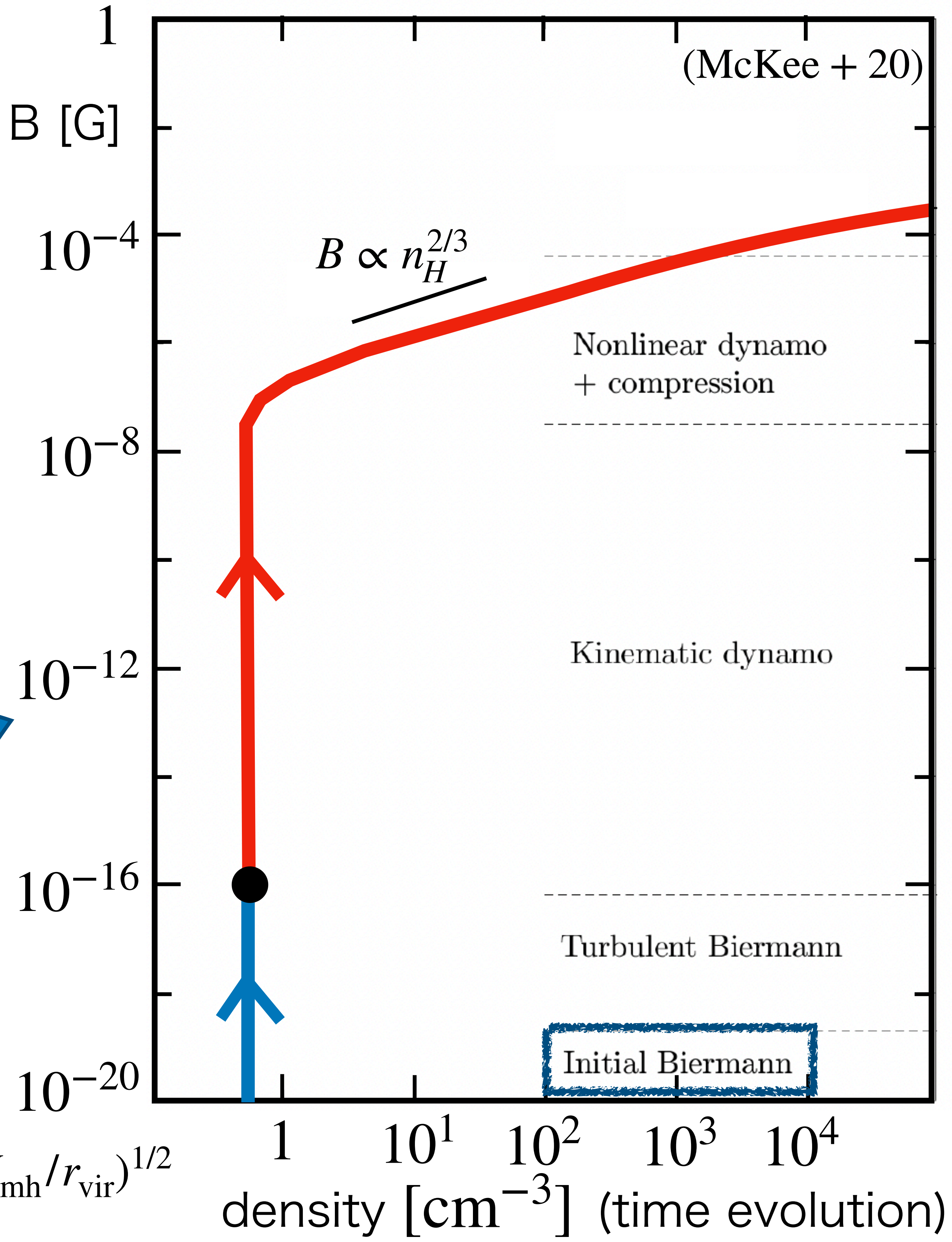
- haloスケールの渦度ω_Lによる磁場生成

$$\omega_L \sim \frac{\phi_{\rm t} v_{\rm vir}}{r_{\rm vir}} = \phi_{\rm t} \left(\frac{4\pi G \rho_{\rm mh(z)}}{3} \right)^{1/2}$$

$$B_{\rm seed} = \frac{m_{\rm a} c}{(1+\chi)e} \omega_L$$

$$\sim 2 \times 10^{-19} \left(\frac{z}{25} \right)^{3/2} \ {\rm G}$$





generation of seed magnetic fields

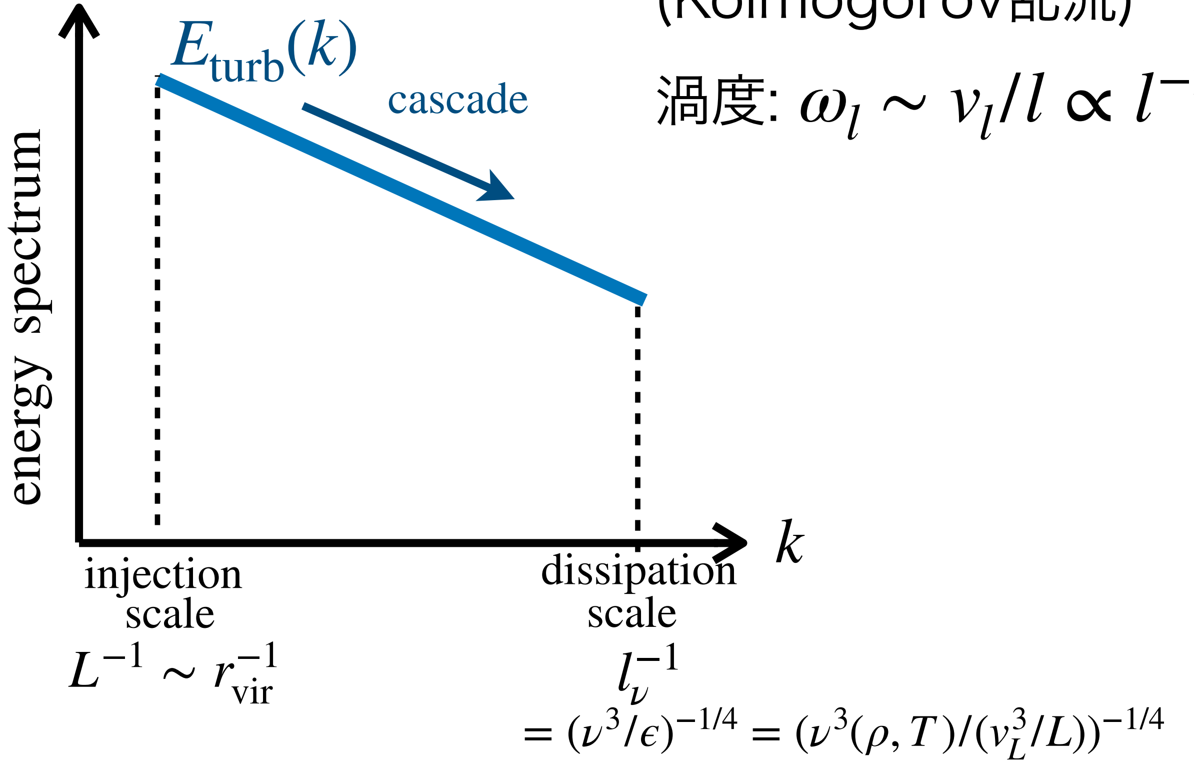
✔ Turbulent Biermann

- 乱流のカスケードに伴う渦度の増加

スケールlの乱流速度: $v_l = (\epsilon l)^{1/3}$

(Kolmogorov乱流)

渦度: $\omega_l \sim v_l/l \propto l^{-2/3}$

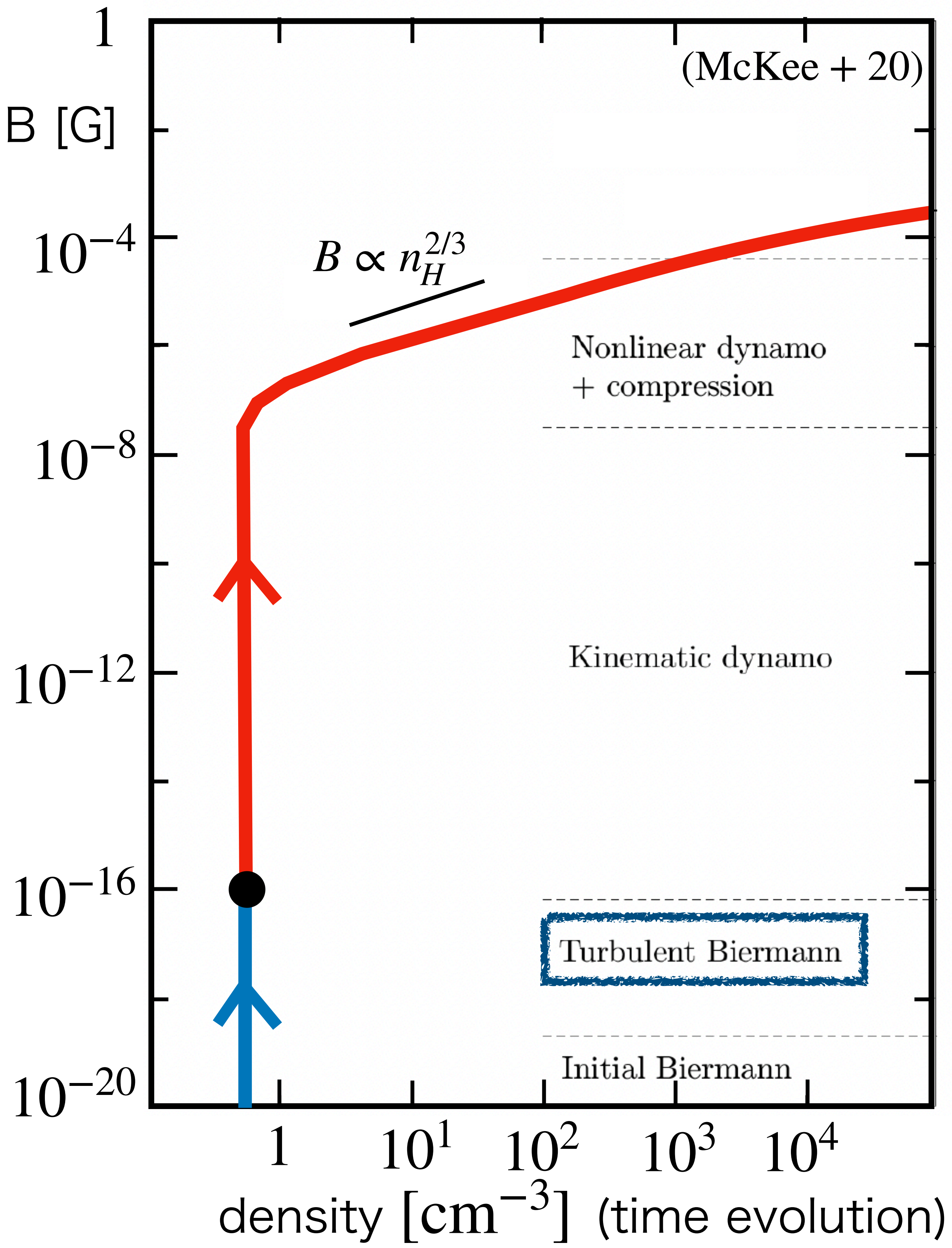


- 粘性スケールl_νにおける種磁場生成

$$B_{\rm seed} = \frac{m_{\rm a} c}{(1+\chi)e}\omega_{l_\nu} \sim \frac{m_{\rm a} c}{(1+\chi)e}\omega_L \left(\frac{l_\nu}{r_{\rm vir}}\right)^{-2/3}$$

$$\sim 3 \times 10^{-16} \phi_{\rm t}^{3/2} M_{\rm mh,6}^{1/3} z_{25}^{11/4} T_3^{-0.42}\ {\rm G}$$

$(M_{\rm mh,6} = M_{\rm mh,6}/10^6\ M_\odot,\ \ z_{25} = z/25,\ \ T_3 = T/10^3\ K)$



amplification of seed magnetic fields

✔ Kinematic dynamo phase

$$\frac{\partial \vec{B}}{\partial t} = \underline{\nabla \times (\vec{v} \times \vec{B})} - \frac{m_a c}{e(1+\chi)} \left(\frac{\nabla \rho \times \nabla p}{\rho^2} \right) + \eta \nabla^2 \vec{B}$$

磁場増幅： 圧縮 ＋ ダイナモ

（**重力**, 衝撃波） （**乱流**, 回転 ）

$\downarrow$ $B \propto \rho^{2/3}$ $\downarrow$

$$\varepsilon_{\rm mag} = \frac{B_o^2}{8\pi\rho_o} \left(\frac{\rho}{\rho_o} \right)^{1/3} \quad (k_p l_\nu)^{5/2} \exp\left(\frac{3}{4} \int \Gamma_\nu dt \right) \ [{\rm erg/g}]$$

$$\sim \varepsilon_{\rm mag,o} \xi^{1/3} \exp\left(\frac{3t}{4 t_{\rm eddy}(l_\nu)} \right), \quad t_{\rm eddy}(l_\nu) = l_\nu / v_\nu$$

・kinematic dynamoの増幅時間$t_{\rm nl}$

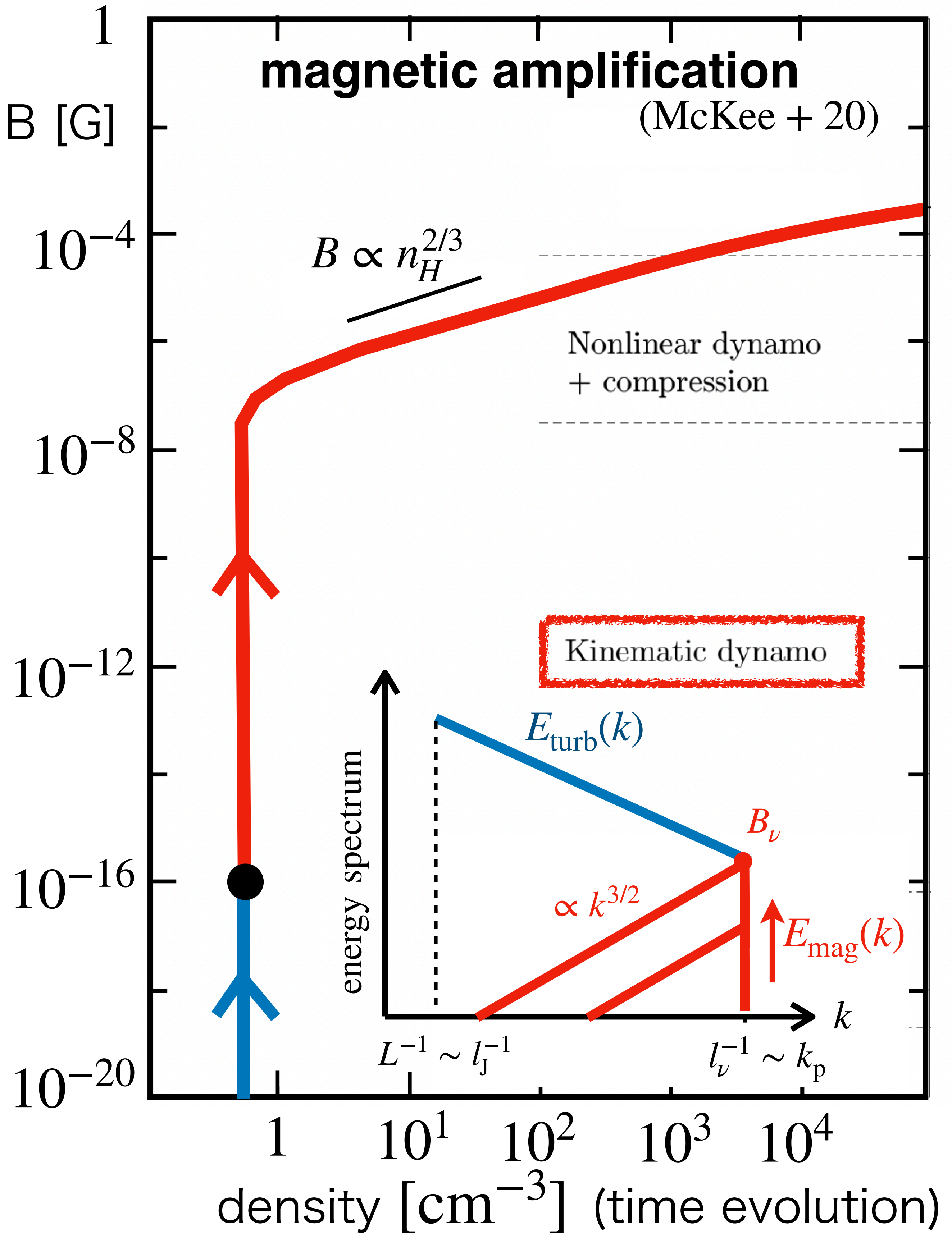
$$\varepsilon_{\rm mag}(t_{\rm nl}) = B_\nu^2/(8\pi\rho_\nu) = 0.5 v_\nu^2$$

$$t_{\rm nl} = \frac{8 t_{\rm eddy}(l_\nu)}{3} \ln\left(\xi^{-2/3} \frac{B_\nu}{B_o} \right) \sim \frac{8 t_{\rm eddy}}{3} \ln\left(\frac{B_\nu}{B_o} \right)$$

$$t_{\rm nl}/t_{\rm dyn} \simeq t_{\rm nl}/t_{\rm vir} = 0.1 T_3^{0.42} \ M_{\rm mh,6}^{-1/3} \ z_{25}^{-5/4}$$

$$t_{\rm vir} = r_{\rm vir}/v_{\rm vir}$$

収縮よりも早く、磁場増幅する



amplification of seed magnetic fields

✔ Non-linear dynamo phase

$$\varepsilon_{\rm mag}(t) = \underbrace{\left(\frac{\xi}{\xi_{\rm nl}}\right)^a \varepsilon_{\rm mag,nl}}_{\text{圧縮}} + \underbrace{\frac{\chi\epsilon_1\xi^a}{\xi_{\rm nl}^{1/2}}\int_{t_{\rm nl}}^{t} \xi(t')^{1/2-a}dt'}_{\text{non-linear dynamo}}$$

$a < 1/3$ $\qquad$ $\propto t$

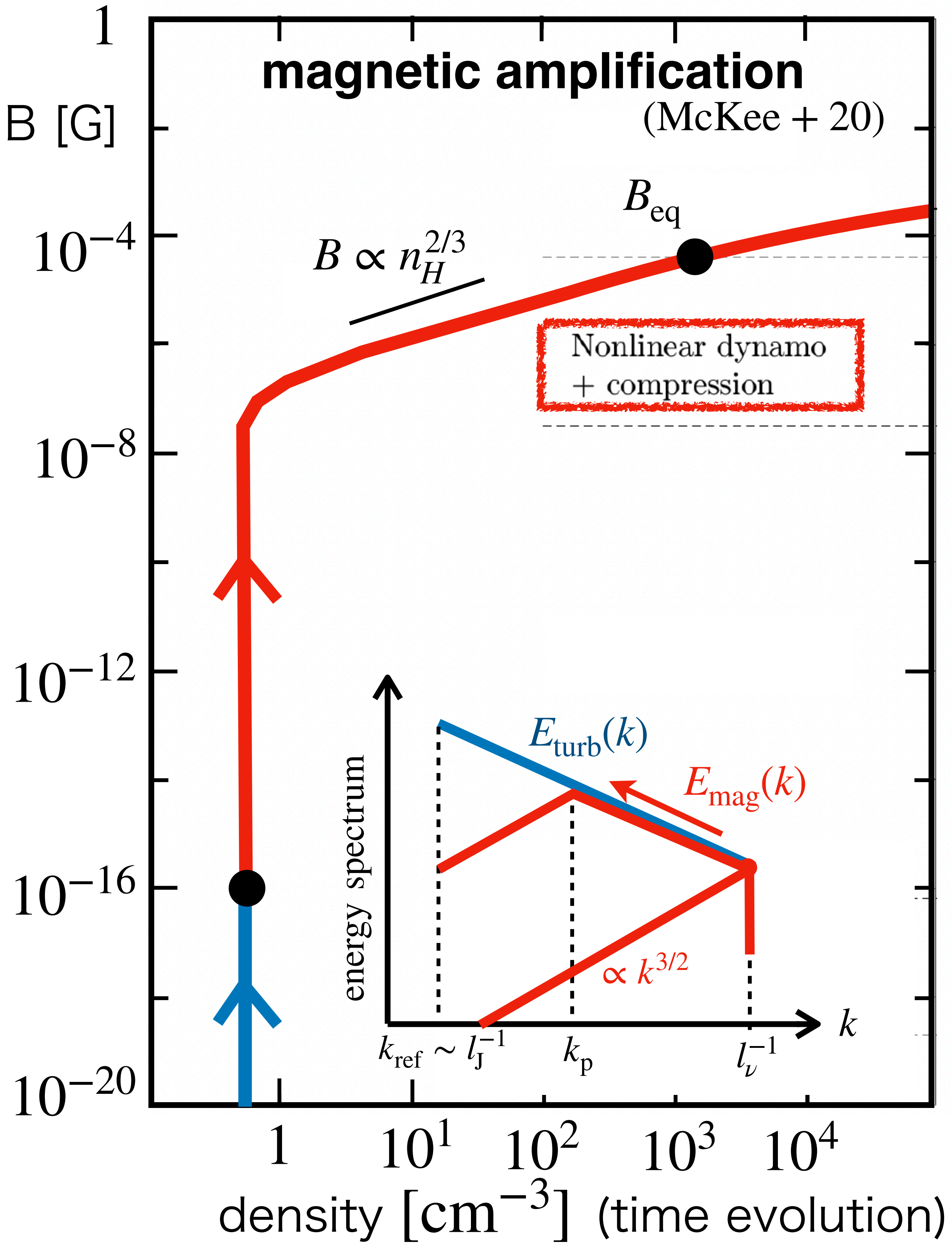
flux freezing が破られる

non-linear dynamoよりも重力圧縮による磁場増幅が支配的になる

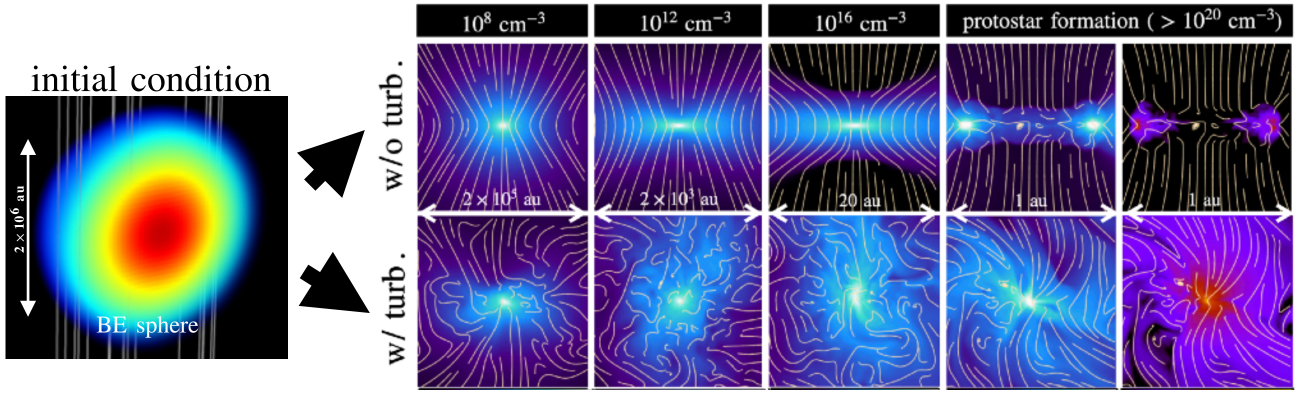
$$\varepsilon_{\rm mag} \propto \rho^{1/3} (B \propto \rho^{1/3})$$

最終的に、
磁場は乱流エネルギーとequipartiotionに達する

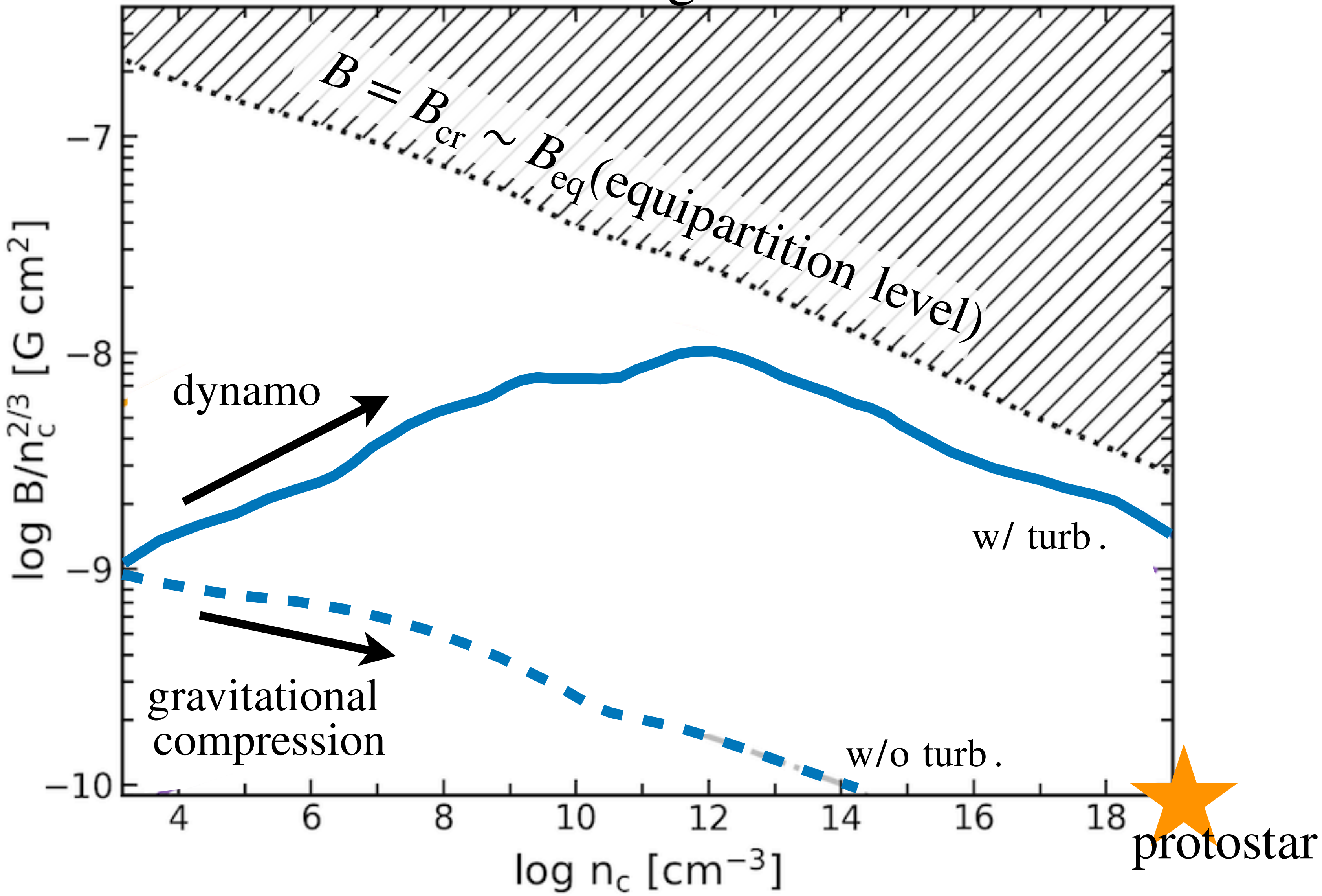
$$\frac{B_{\rm eq}^2}{8\pi\rho} \sim \frac{v^2(l_J)}{2}$$



magnetic amplification during the collapse



evolution of magnetic field



**Due to the dynamo amplification,
initially weak B-field can reach the equipartition level before the protostar formation.**

ambipolar diffusion effects

- Even with a strong magnetic field, AD heating rates are always smaller than cooling rates.

$$\Gamma_{\mathrm{AD}} < \Lambda_{\mathrm{net}}$$

- AD heating cannot change the thermal evolution in the collapsing primordial gas cloud.
- Similarly, AD cannot inhibit B-field amplification.

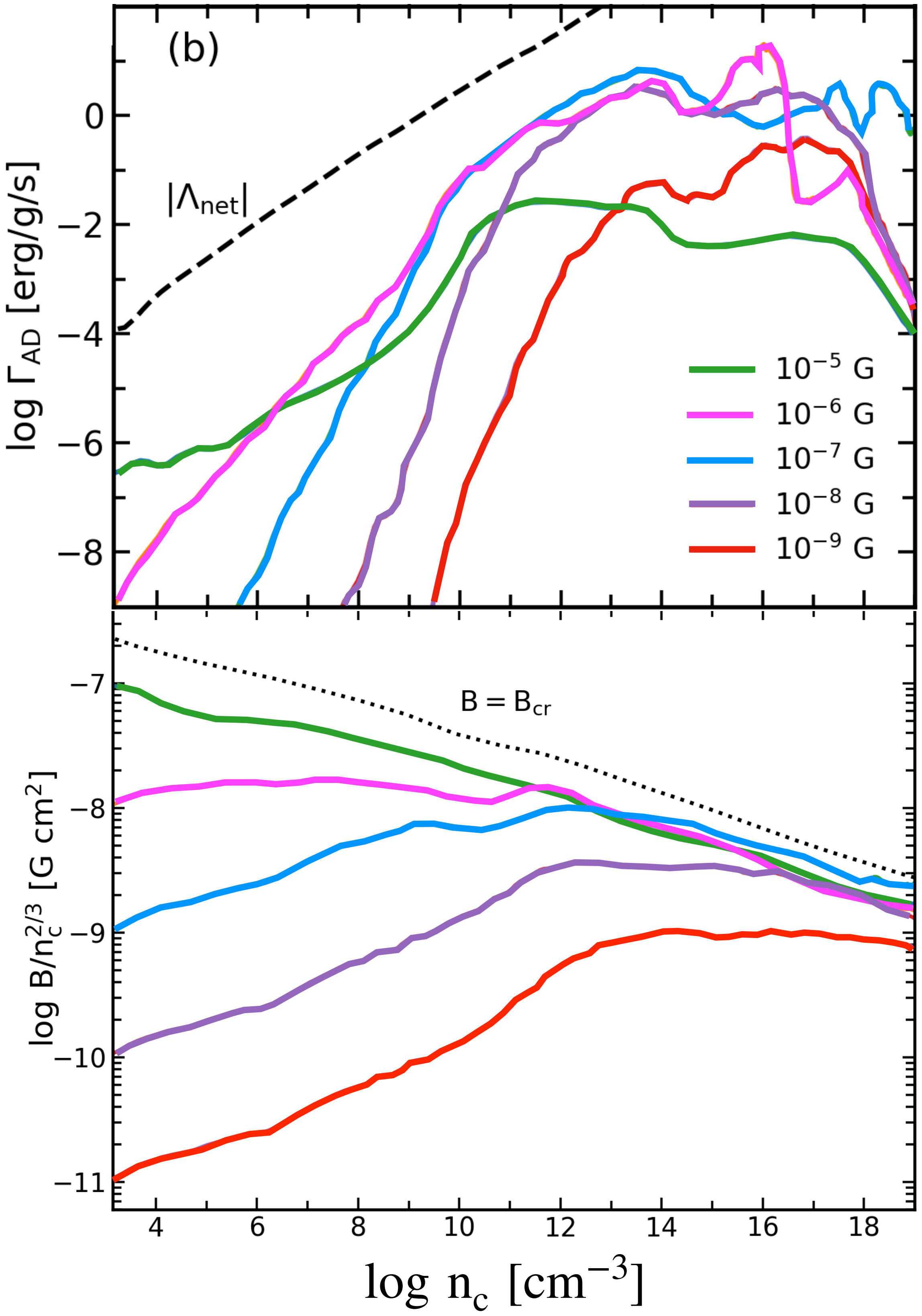
→ Ideal MHD is valid in the primordial case.

- As a results, B-fields around the protostar become stronger compared to the case of present day star formation.

$$\left(\begin{array}{l} \text{primordial gas: } B \sim 10^{4-5}\ \mathrm{G} \\ \text{present day : } B \sim 10^{2-3}\ \mathrm{G} \end{array} \right)$$

How does such amplified strong B-field affect the first star formation ?

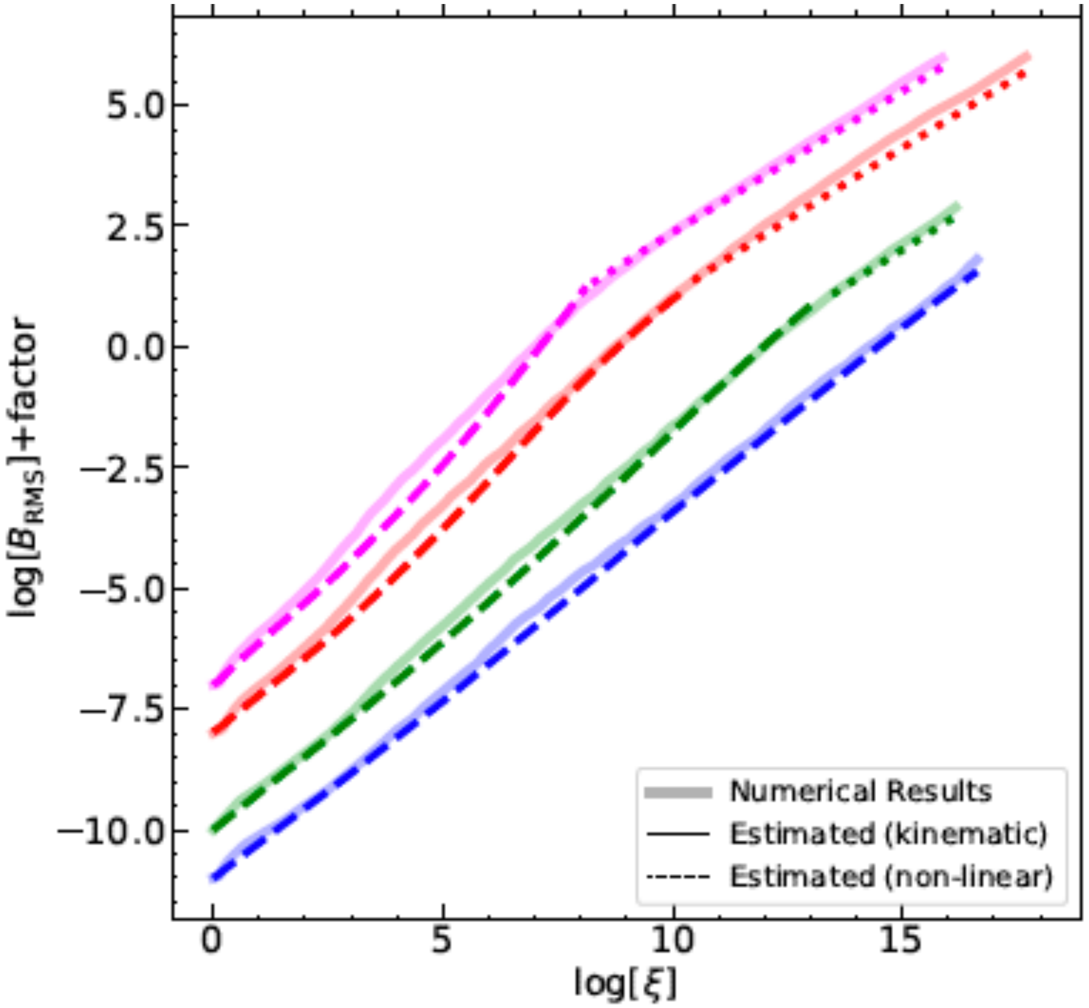
evolution of AD heating rates

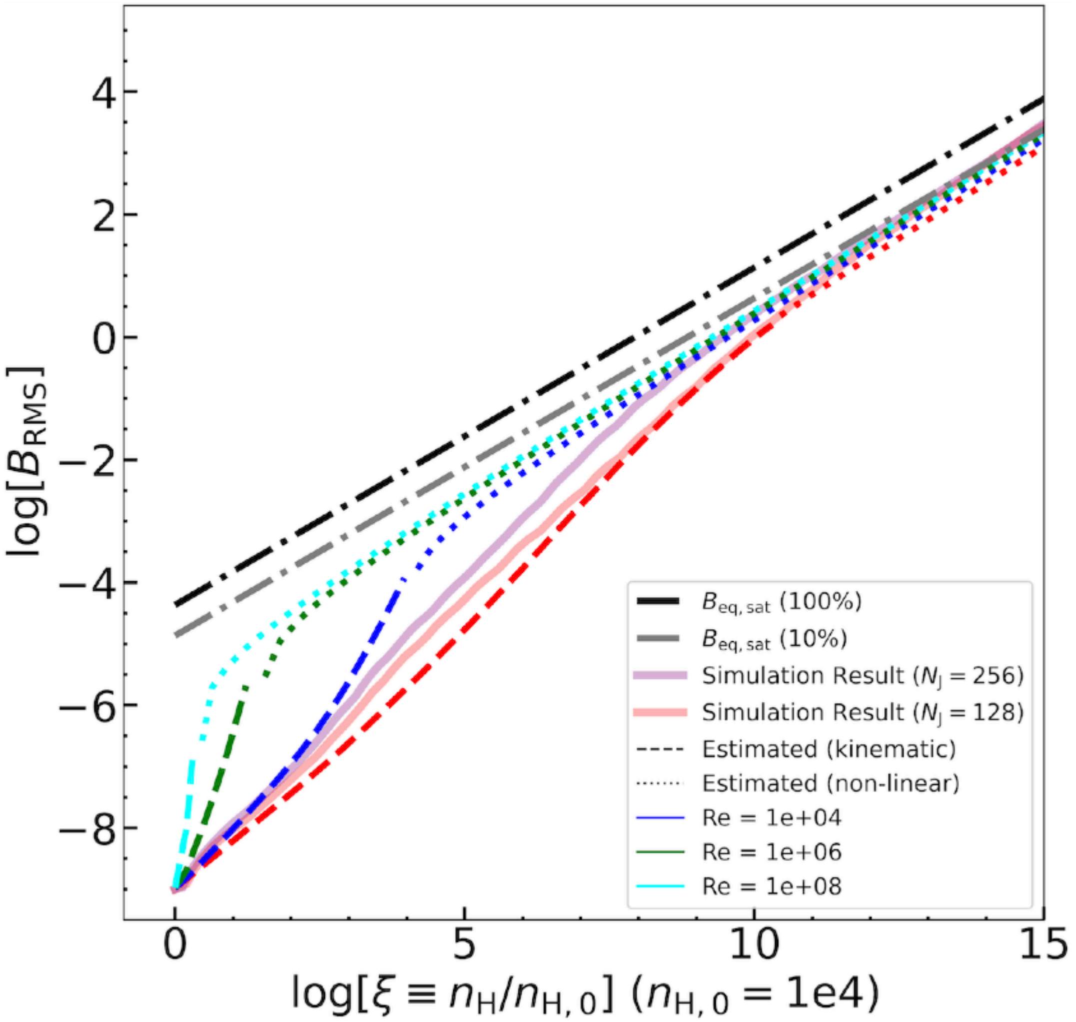


MHD simulations of turbulent gas cloud

Higashi et al. 2024

シミュレーションと解析解の比較



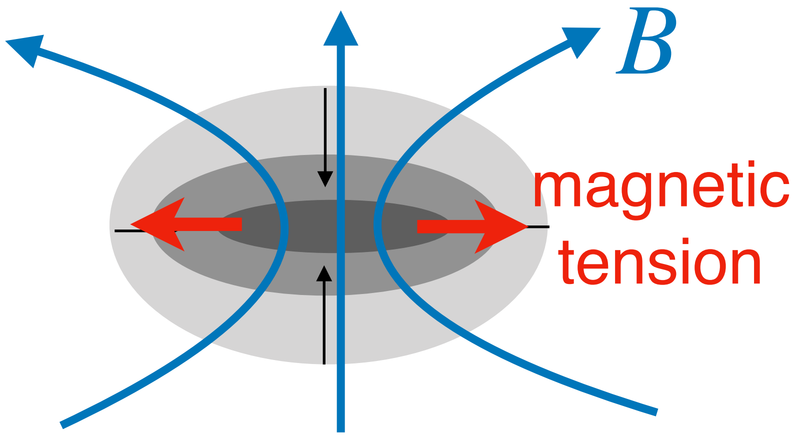


粘性スケールまでカスケードした乱流があれば、初代星形成領域においても強磁場が存在

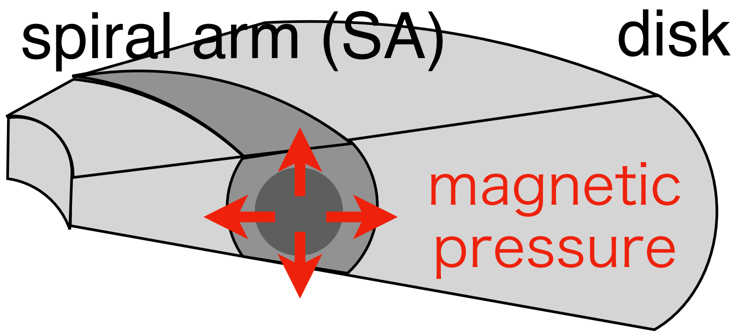
magnetic effects on first star formation

magnetic effects on star formation

✔ magnetic forces (tension & pressure)

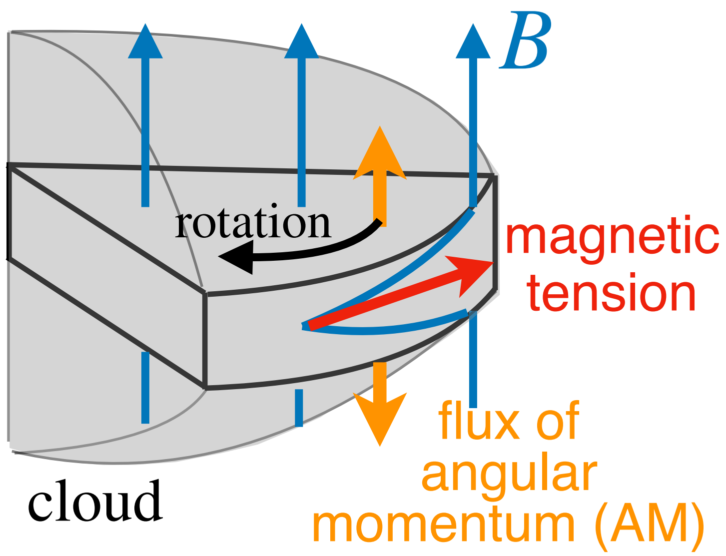


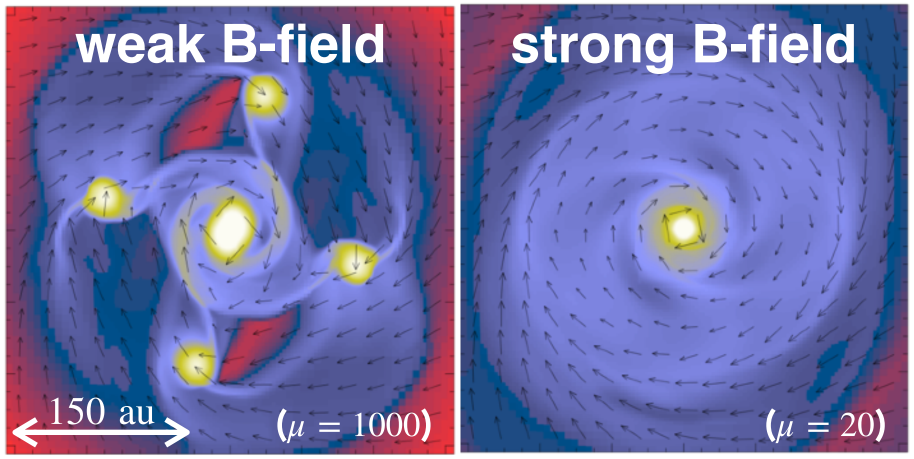
gas cloud deformation



stabilization of disk & SAs

✔ magnetic braking

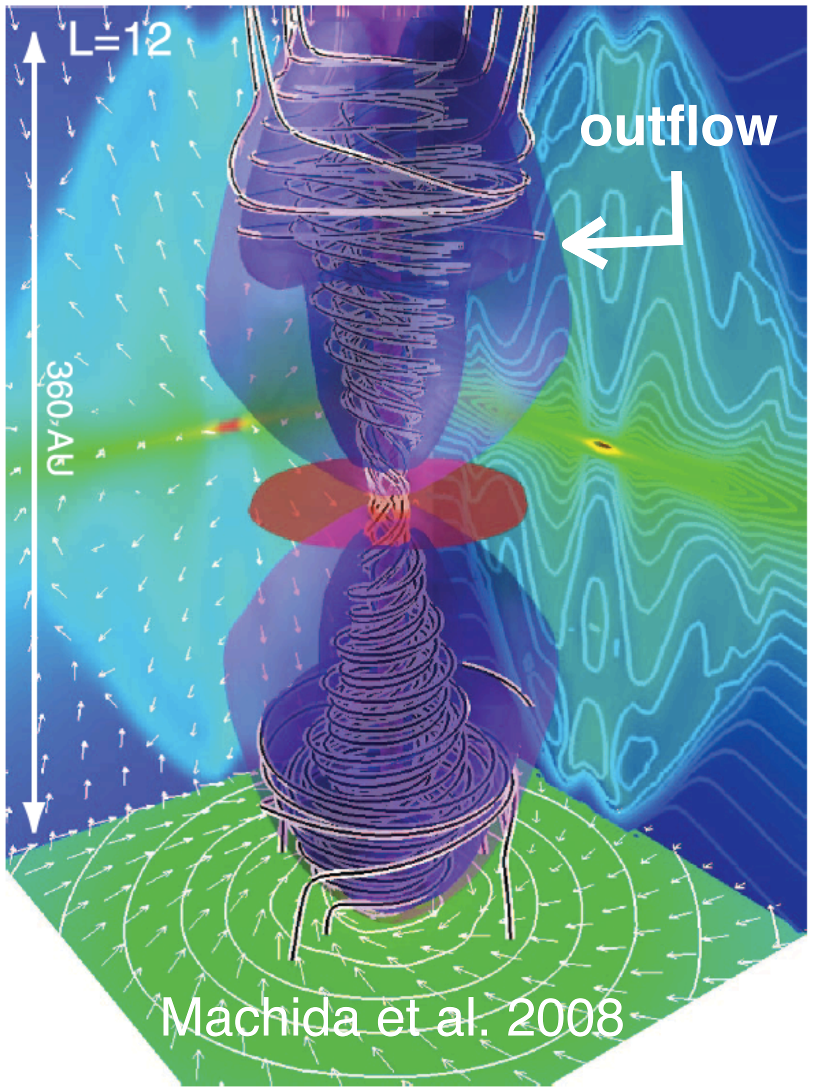




Hennebelle & Teyssier 2008

angular momentum transport
(AM)

✔ MHD outflow



Machida et al. 2008

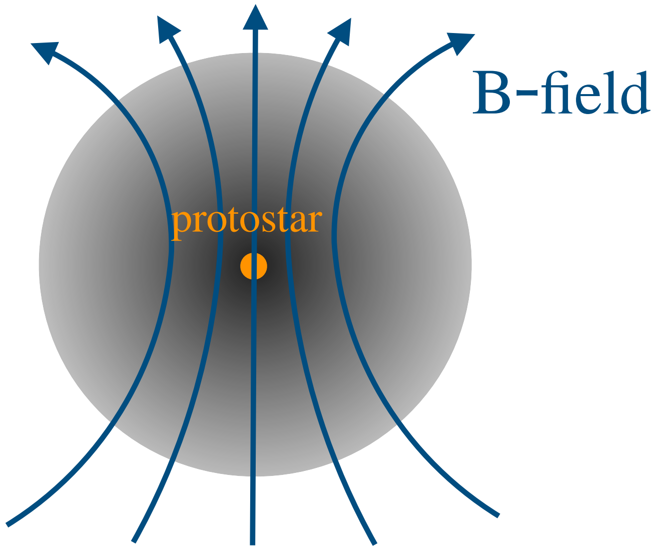
ejection of mass and AM

Magnetic fields reduce the disk size and binary separation, suppress fragmentation and decrease the star formation efficiency.

turbulent magnetic fields in first star formation

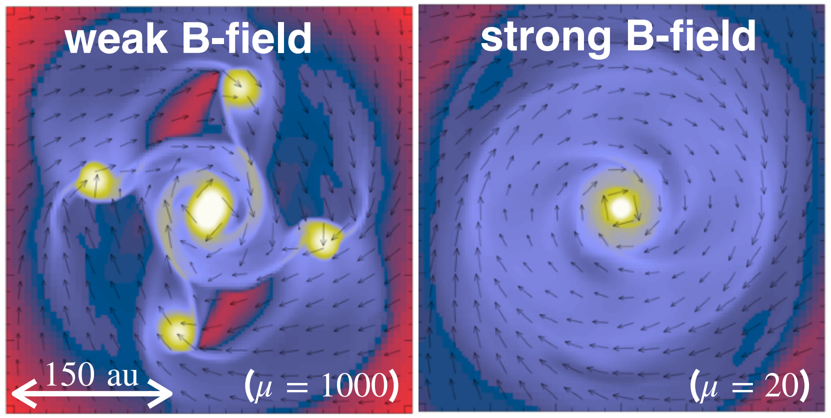
coherent B-field

(e.g., present-day)

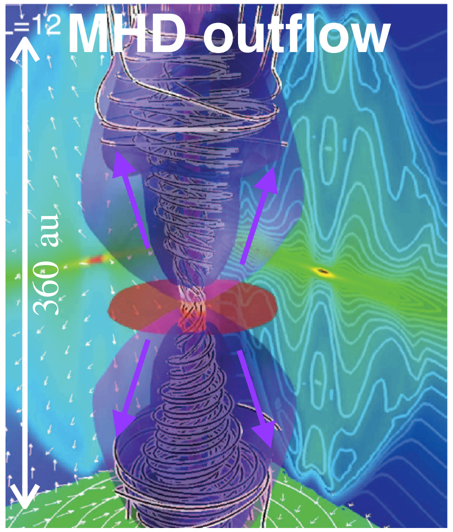


MHD outflow & magnetic braking
can transport the angular momentum

- reducing disk size
- suppressing disk fragmentation
- reducing the binary separation



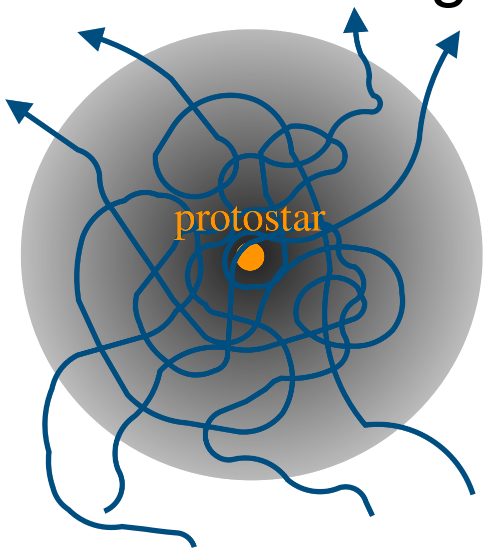
Hennebelle & Teyssier 2008



Machida+2008

turbulent B-field

(e.g., first star forming region)



Question ?

How turbulent B-fields affect on
disk size, fragmentation, binary separation,

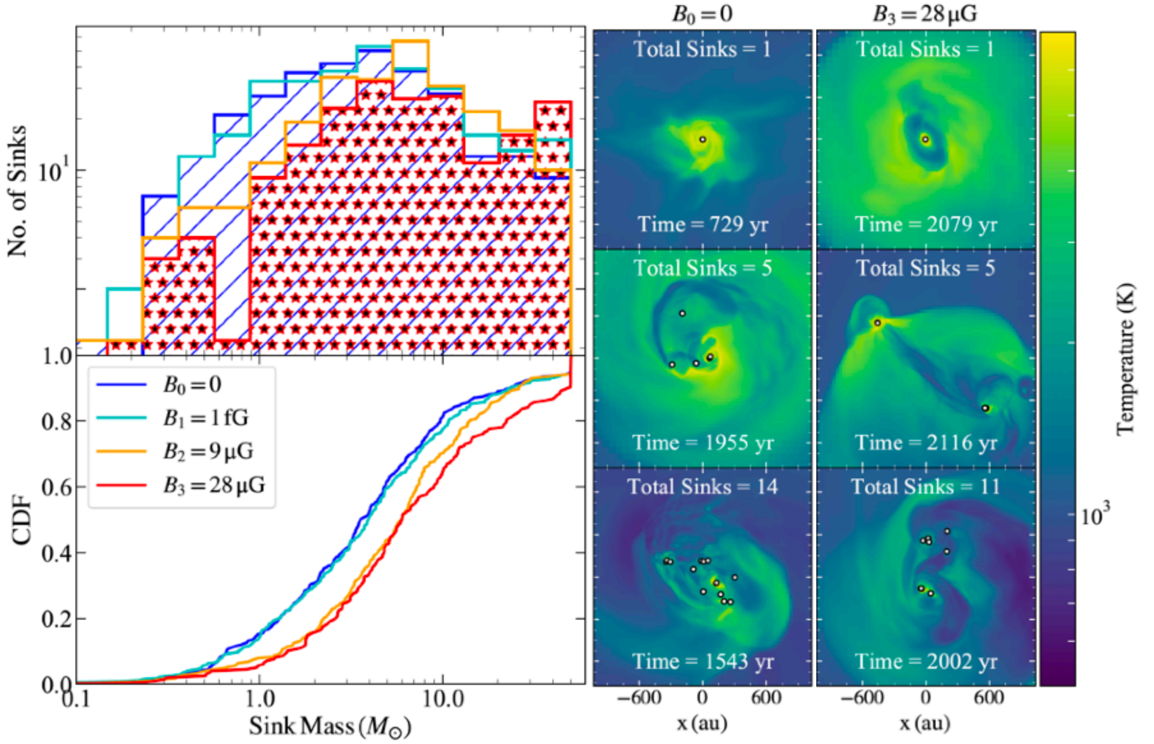
magnetic effects

- **magnetic pressure**
  —> disk stabilization
  (e.g., Stacy+2022)
- **magnetic torques** —> ?
- **outflow** —> ?

previous works of MHD simulations

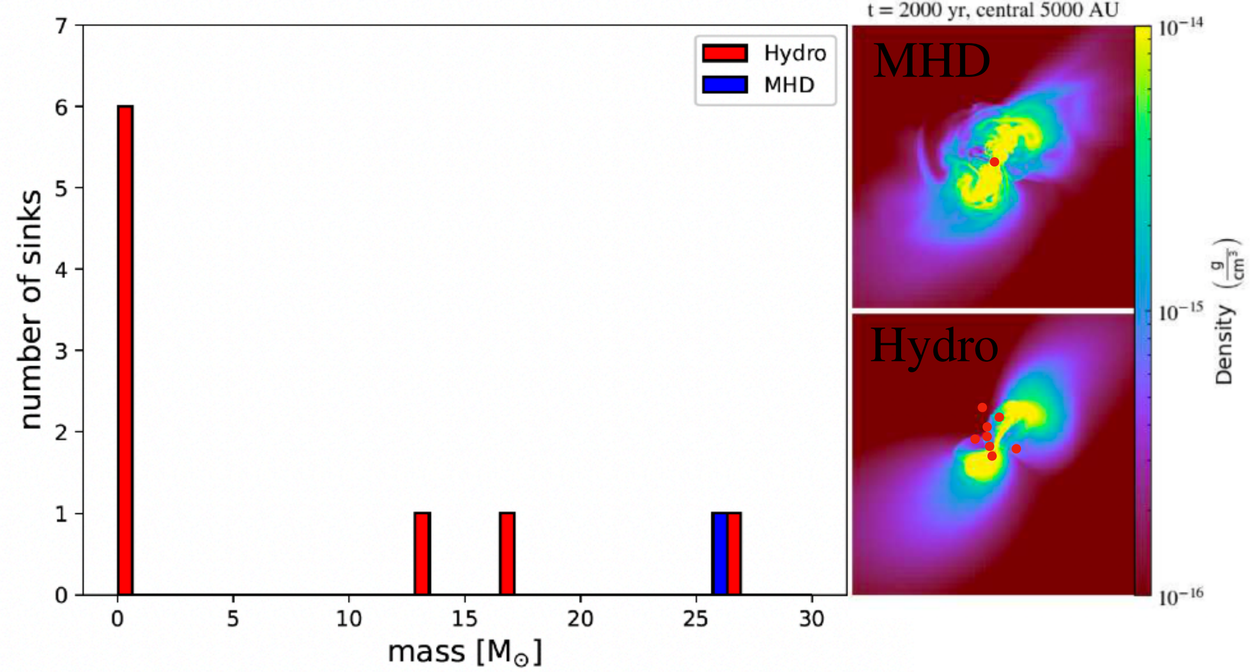
Machida & Doi 2013; Sharda + 20, 21; Stacy+2022; Prole+22; Hirano+22; Saad+22; Sadanari+24; Sharda+2024

Sharda et al. 2020



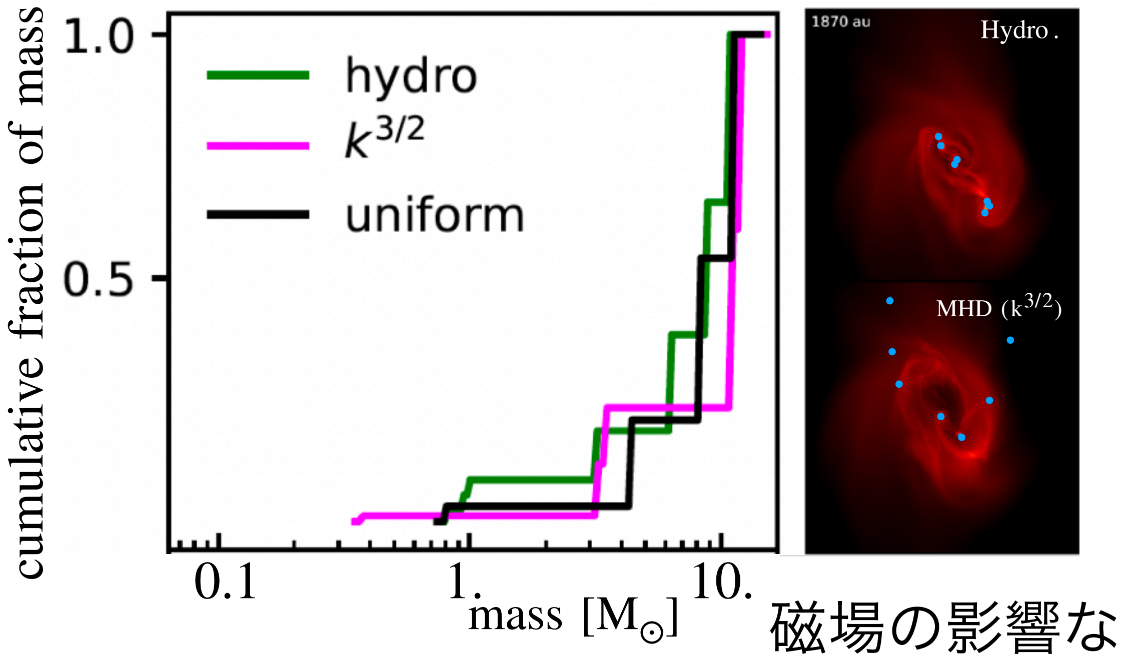
小質量星の形成を抑制

Stacy et al. 2022



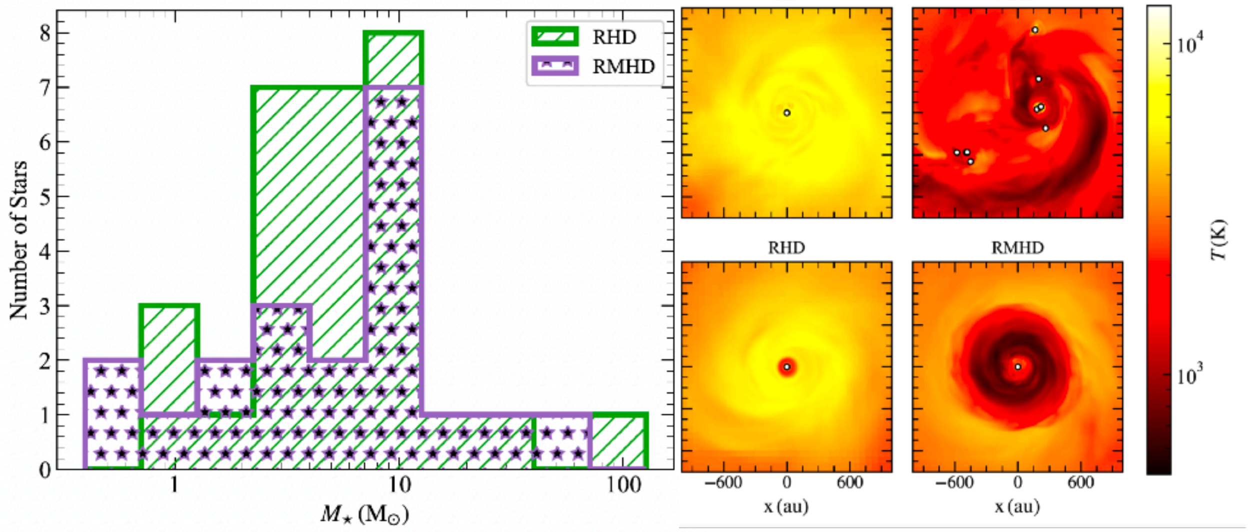
円盤分裂を強く抑制

Prole et al. 2022



磁場の影響なし

Sharda et al. 2024



降着率の低下により、円盤分裂を促進、

大質量星の形成を抑制

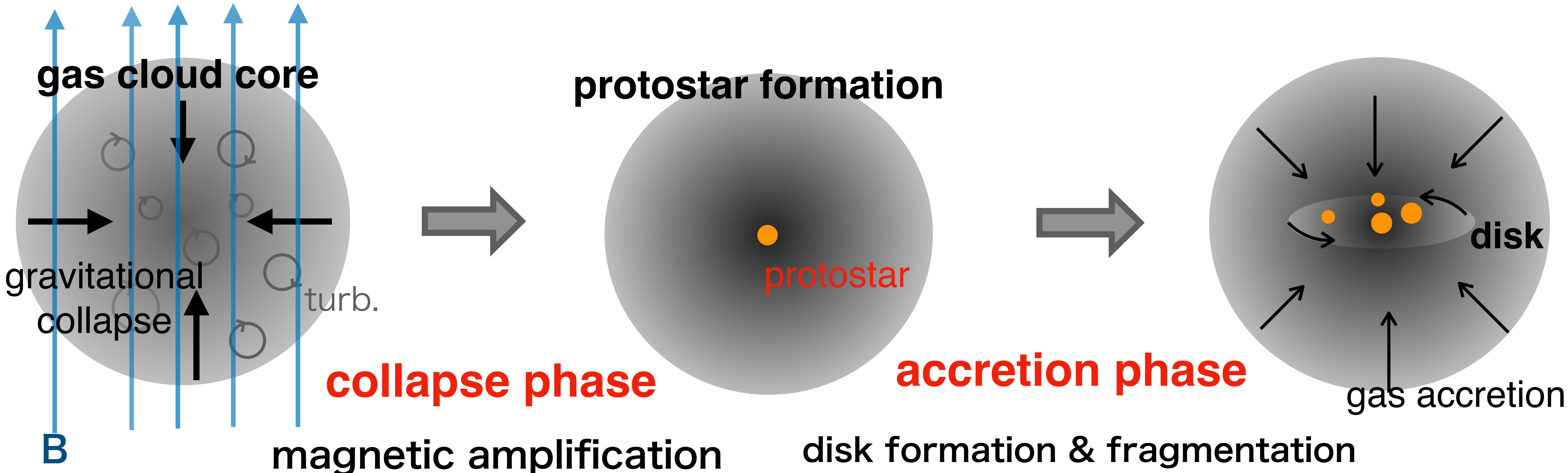
MHD simulation of first star formation

Impact of turbulent magnetic fields on disk formation and fragmentation in first star formation

Kenji Eric SADANARI,[1,*] Kazuyuki OMUKAI,[2] Kazuyuki SUGIMURA,[3] Tomoaki MATSUMOTO,[4] and Kengo TOMIDA[2]

overview of our studies

3D MHD simulations



gas cloud core

gravitational collapse

turb.

B

protostar formation

protostar

disk

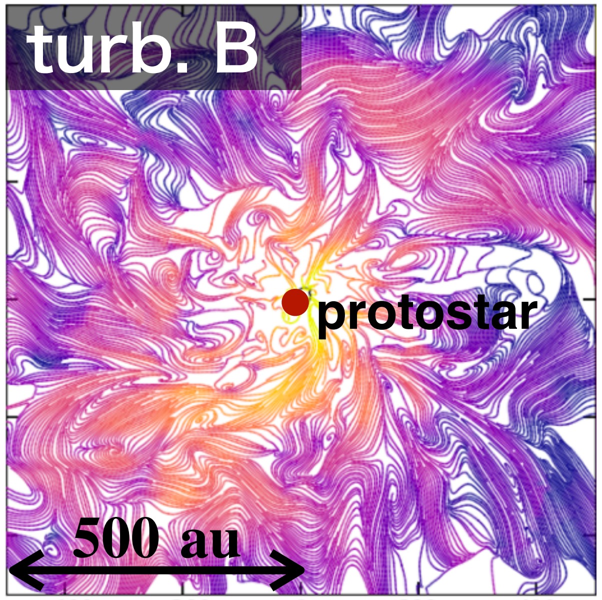
gas accretion

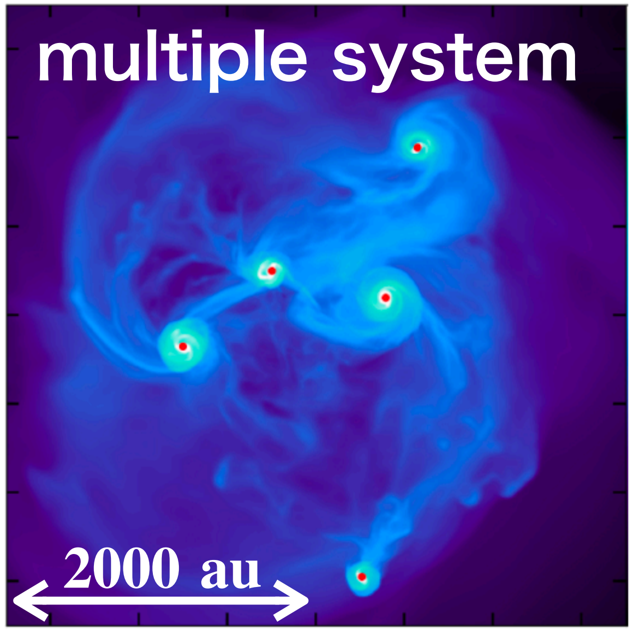
collapse phase

accretion phase

magnetic amplification

disk formation & fragmentation





magnetic pressure,
magnetic torques, outflow

set-up of MHD simulation

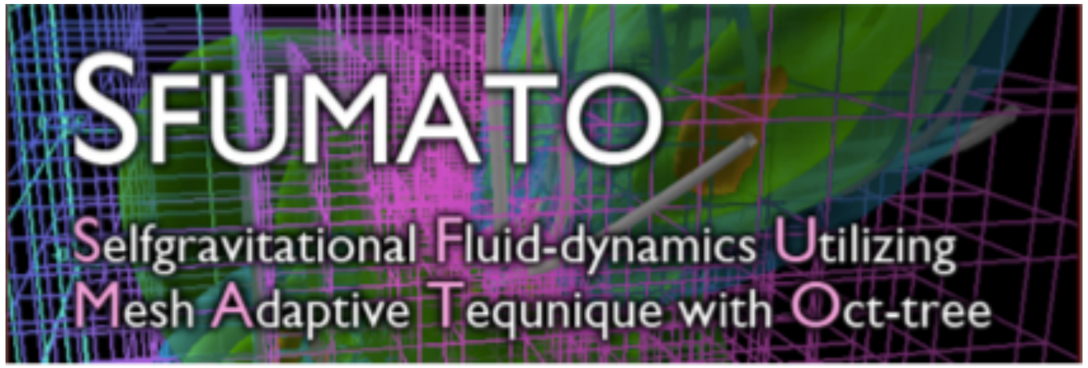
[simulation code]

AMR(Adaptive Mesh Refinement) code

- ideal MHD + self gravity
- energy eq. w/ cooling/heating

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(e + p + \frac{1}{8\pi} |\vec{B}|^2 \right) \vec{v} - \frac{1}{4\pi} \vec{B} \left(v \cdot \vec{B} \right) \right] + \rho \vec{v} \cdot \nabla \phi + \underline{\Lambda} = 0$$

- 14 chemical reactions among 6 species : $\mathrm{H}, \mathrm{H_2}, \mathrm{e}, \mathrm{H^+}, \mathrm{H^-}, \mathrm{H_2^+}$



(Matsumoto 2007, Sugimura+2020)

radiation cooling
(H2, HD lines, gas continuum)
chemical cooling/heating

resolution: cell size < Jeans length/64

[initial set up]

Bonnor-Ebert sphere (= gas cloud core)
(central density $n_{\rm c,init} = 10^3\ \mathrm{cm^{-3}}$)

- rigid rotation

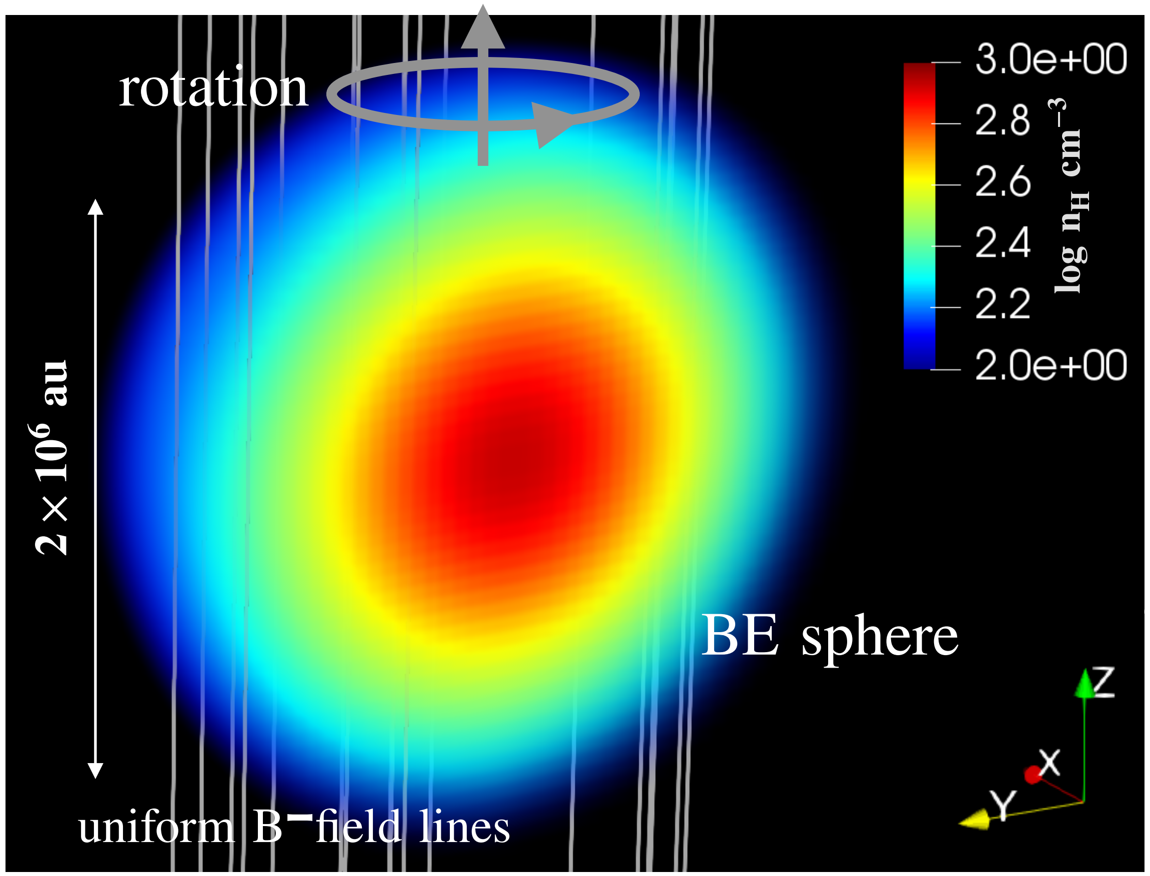
  $E_{\rm rot}/|E_{\rm grav}| = 0.01$

- turbulent velocity ($V_{\rm turb} \propto k^{-1/2}$)

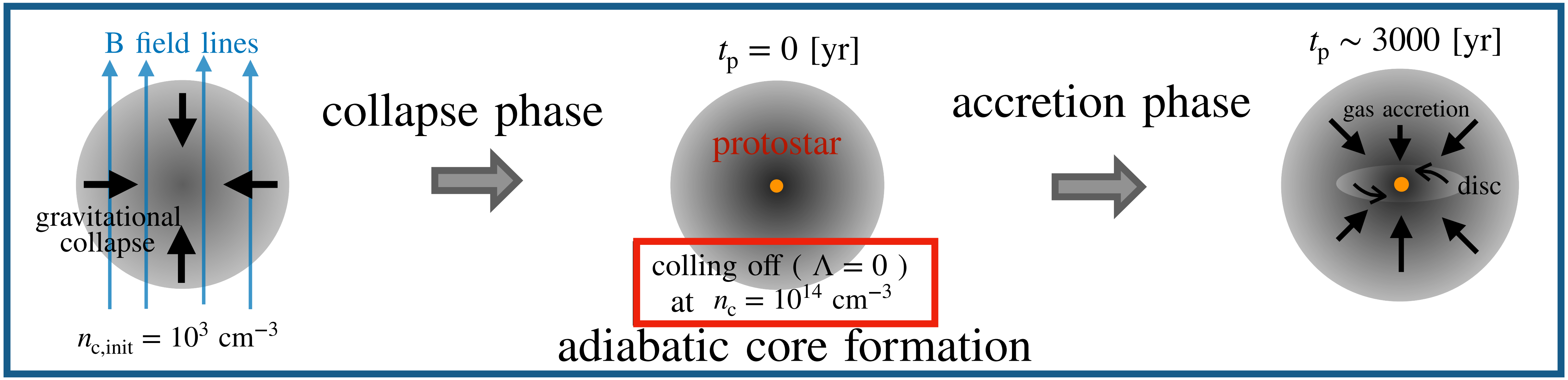
  $E_{\rm turb}/|E_{\rm grav}| = 0.03$

- uniform magnetic field

  $E_{\rm mag}/|E_{\rm grav}| = 0,\ 2 \times 10^{-7},\ 2 \times 10^{-5},\ 6 \times 10^{-4}$



overview of our simulations



collapse phase

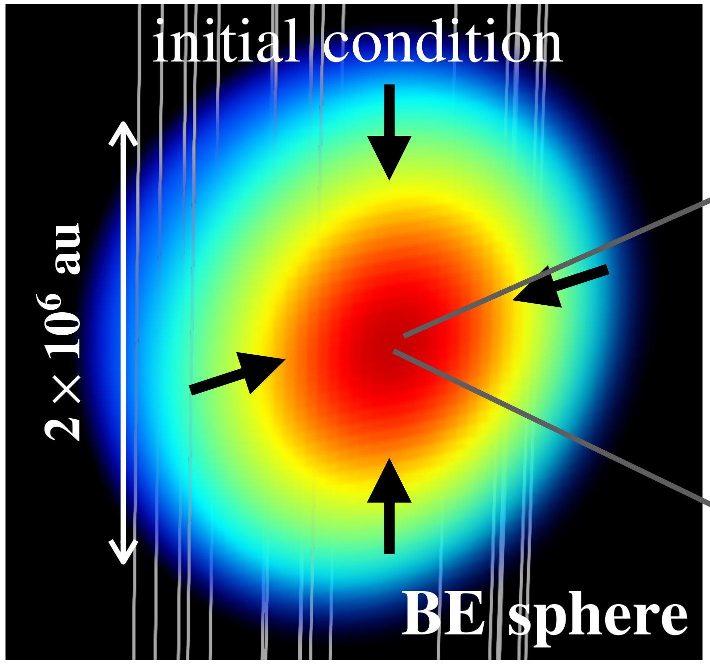
$t_{\mathrm{p}} = 0$ [yr]

colling off ($\Lambda = 0$)
at $n_{\mathrm{c}} = 10^{14}\ \mathrm{cm}^{-3}$

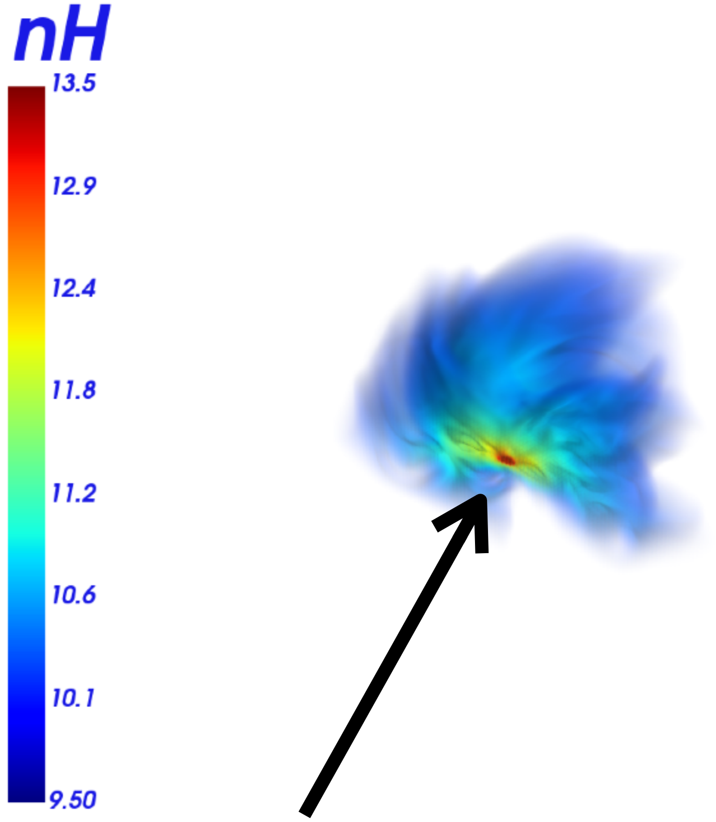
adiabatic core formation

accretion phase

$t_{\mathrm{p}} \sim 3000$ [yr]



gravitational collapse



$B_{\mathrm{init}} = 5 \times 10^{-7}$ G

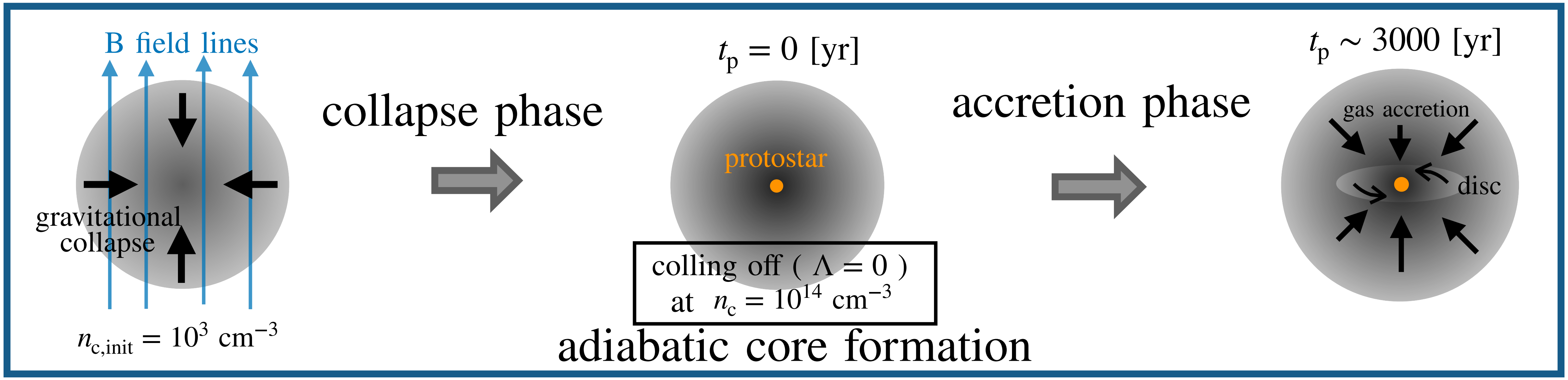
$B_{\mathrm{init}} = 10^{-7}$ G

$B_{\mathrm{init}} = 10^{-8}$ G

・formation of adiabatic core @ $10^{14}\ \mathrm{cm}^{-3}$

=> protostar

overview of our simulations



B field lines

gravitational collapse

$n_{\mathrm{c,init}} = 10^3\ \mathrm{cm}^{-3}$

collapse phase

$t_{\mathrm{p}} = 0$ [yr]

protostar

colling off ($\Lambda = 0$)
at $n_{\mathrm{c}} = 10^{14}\ \mathrm{cm}^{-3}$

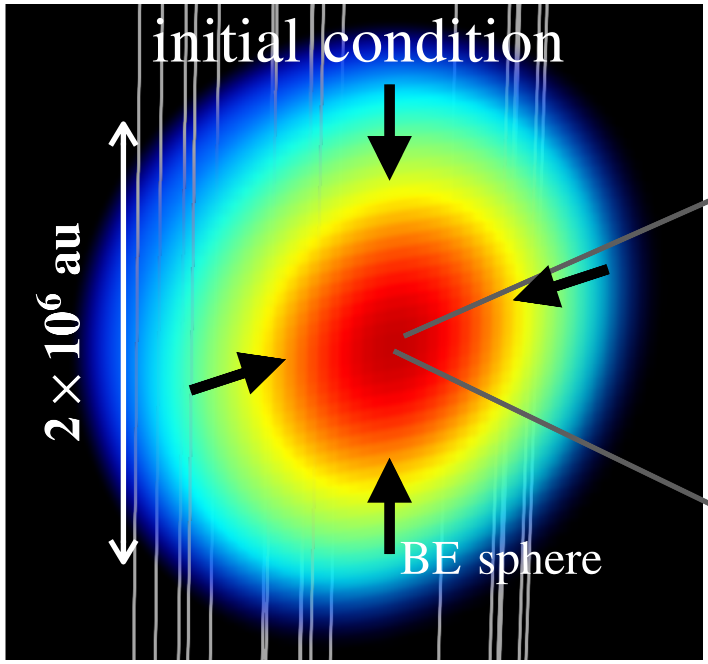
adiabatic core formation

accretion phase

$t_{\mathrm{p}} \sim 3000$ [yr]

gas accretion

disc

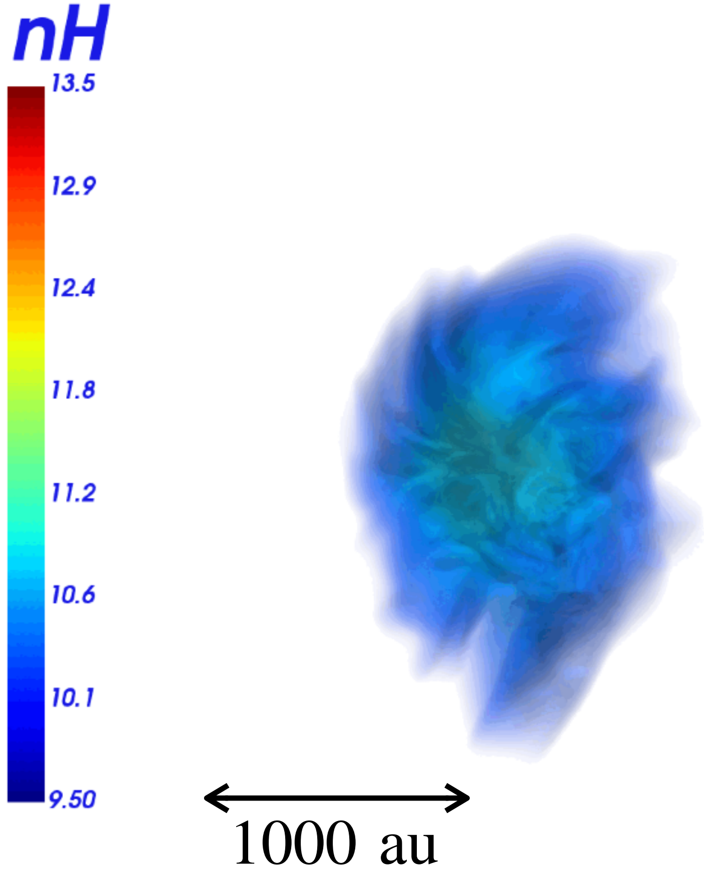


$B_{\mathrm{init}} = 5 \times 10^{-7}$ G

$B_{\mathrm{init}} = 10^{-7}$ G

$B_{\mathrm{init}} = 10^{-8}$ G

gravitational collapse



- formation of adiabatic core @ $10^{14}\ \mathrm{cm}^{-3}$

=> protostar

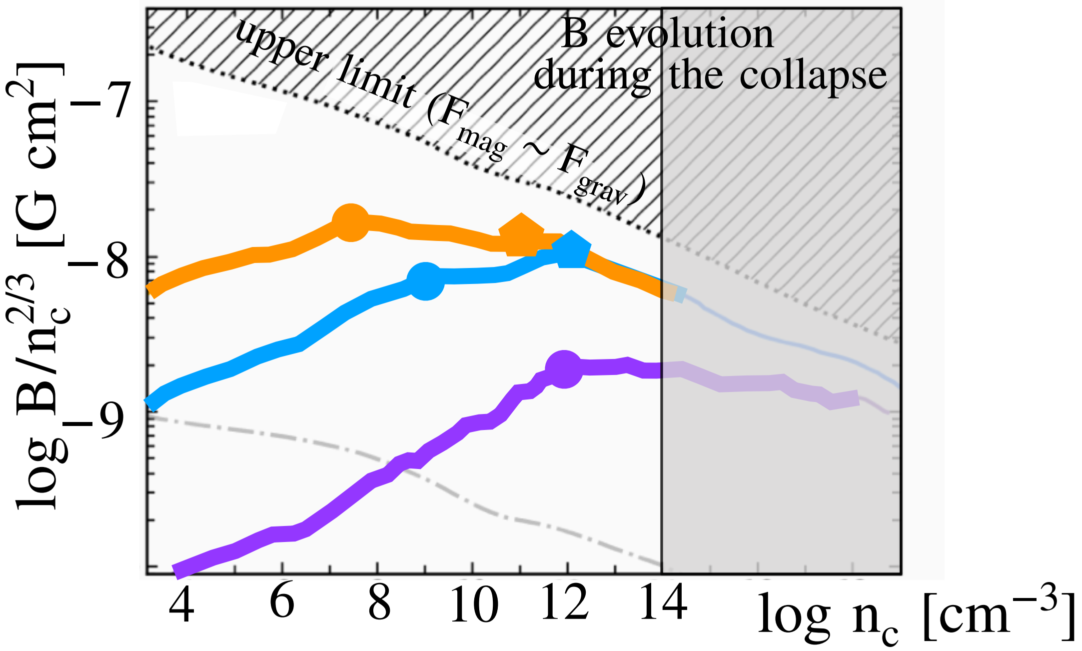
- disk formation and fragmentation
  —> multiple protostar

turbulent B-fields @ protostar formation

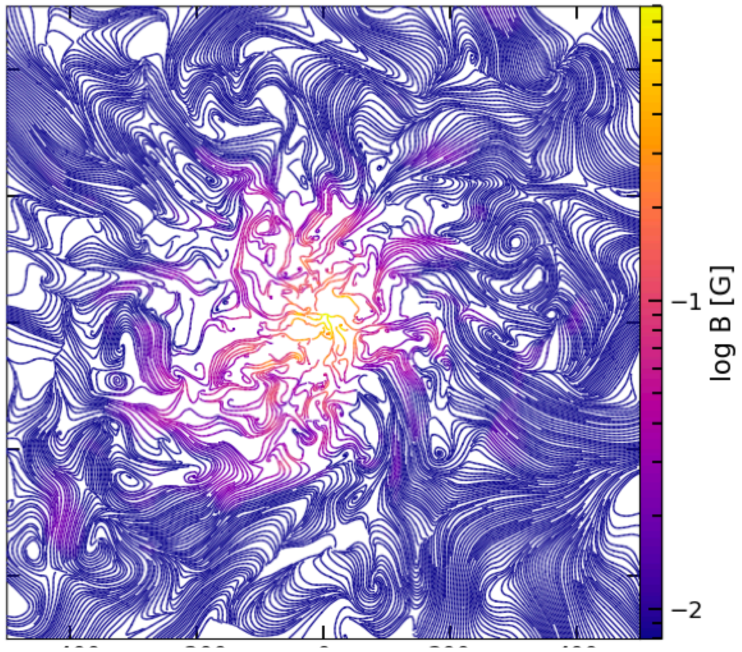
We generate different **turbulent fields** in terms of

$\left(\begin{array}{l} \text{strength,} \\ \text{spatial distribution,} \\ \text{configuration} \end{array} \right)$ @ protostar formation

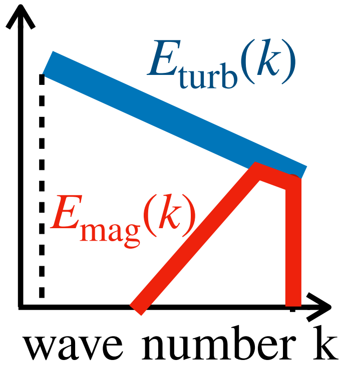
by varying the initial field strength $B_{\rm init}$



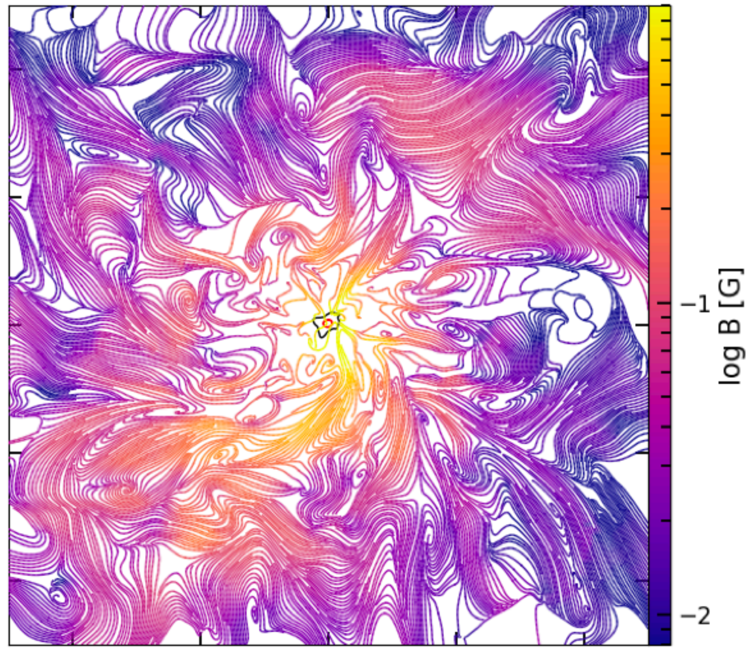
$B_{\rm init} = 10^{-8}$ G



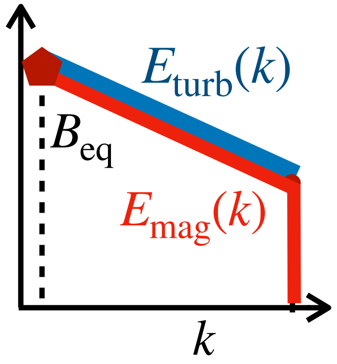
- $B_{\rm cent} < B_{\rm eq}$
- small scale-field



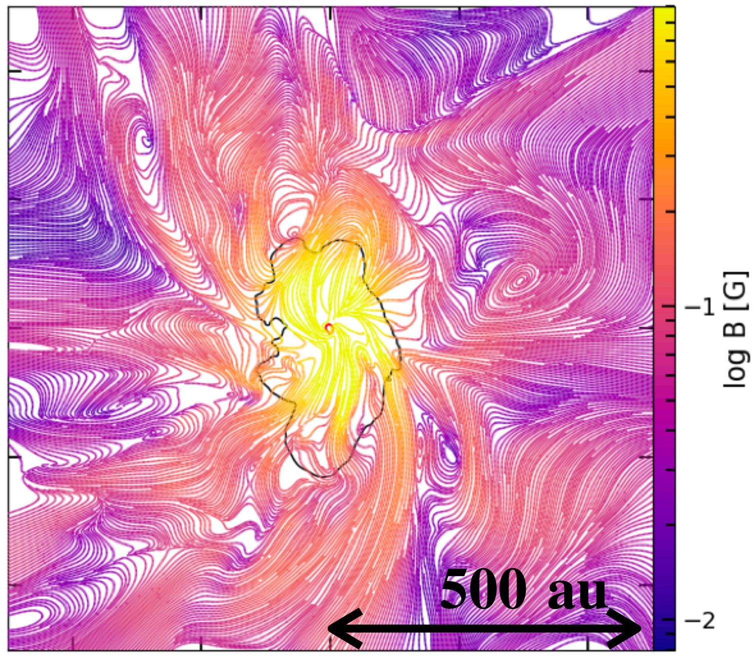
$B_{\rm init} = 10^{-7}$ G



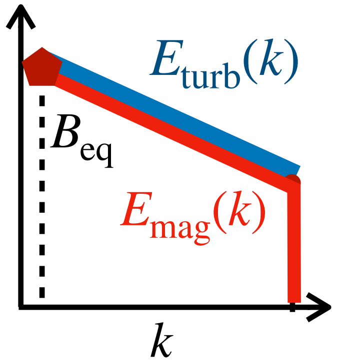
- $B_{\rm cent} \sim B_{\rm eq}$ in small area
- large scale-field



$B_{\rm init} = 5 \times 10^{-7}$ G



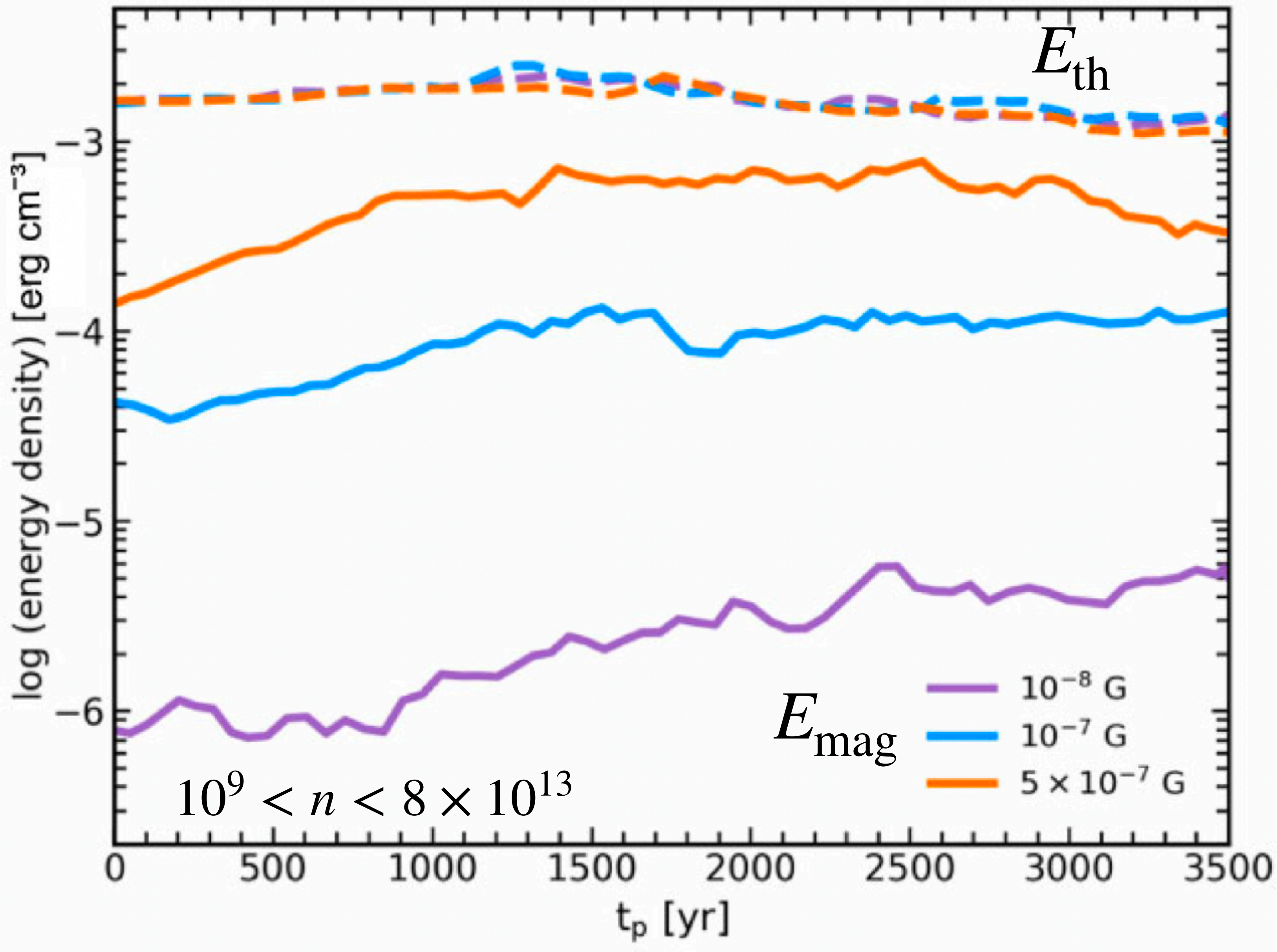
- $B_{\rm cent} \sim B_{\rm eq}$ in larger area
- large scale-field + coherent field by comp.

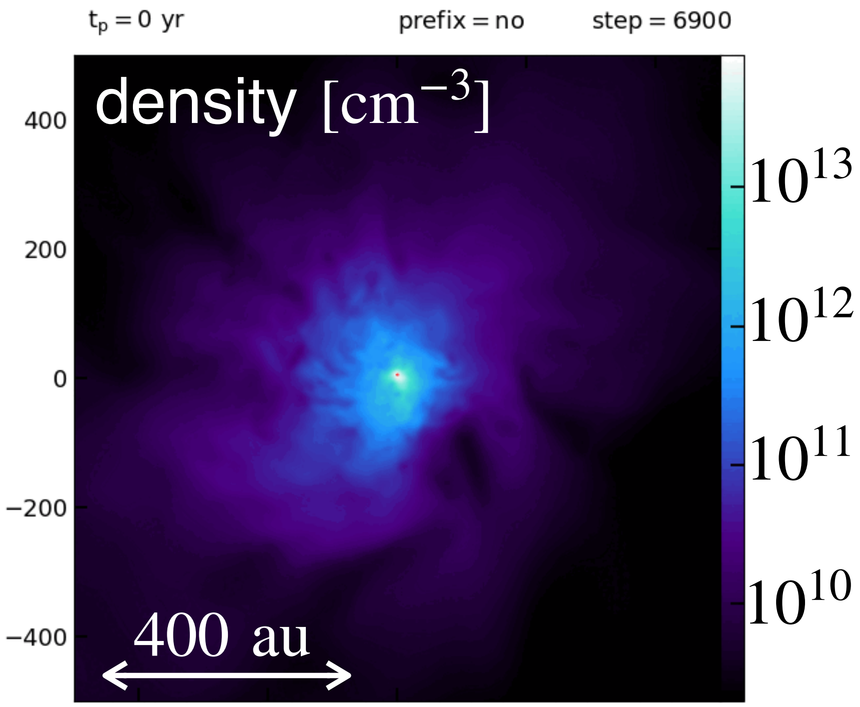


Results

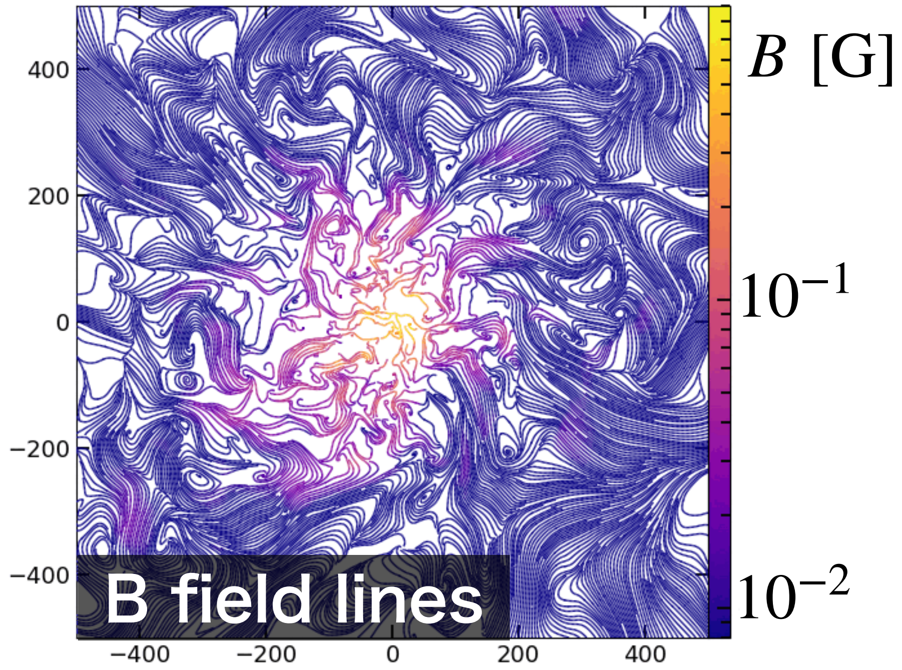
B-field evolution within the disk

magnetic energy density within the disk



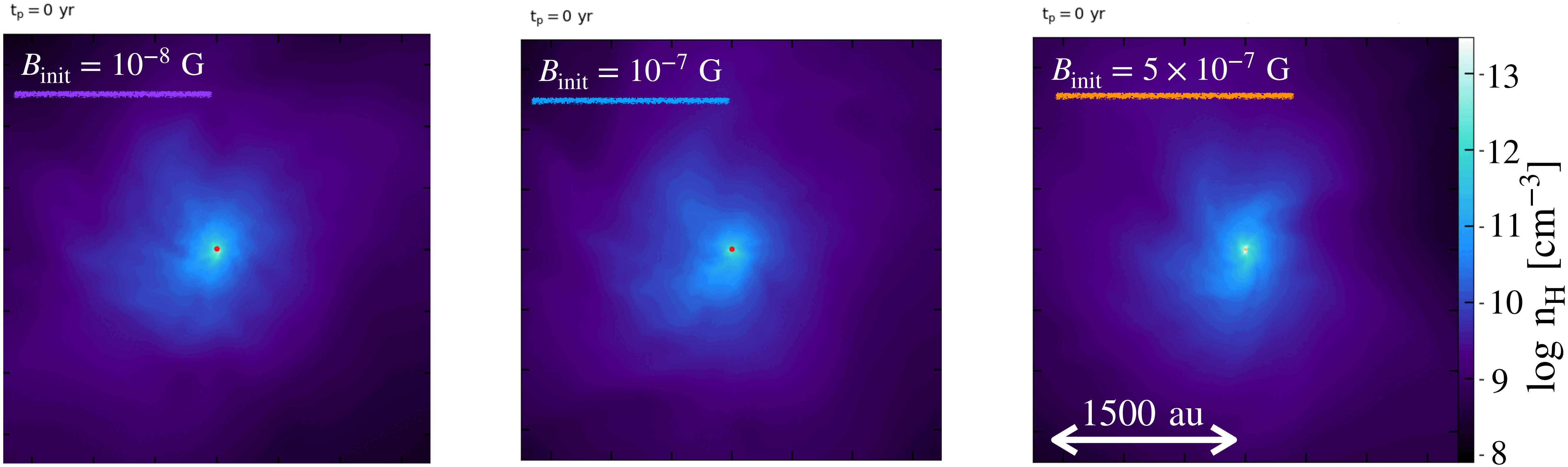


$B_{\rm init} = 10^{-8}$ G



- Disk rotation slowly amplifies B-field in the disk region.
- Diffusion by turbulent reconnection reduces the magnetic amplification rate.

disk fragmentation

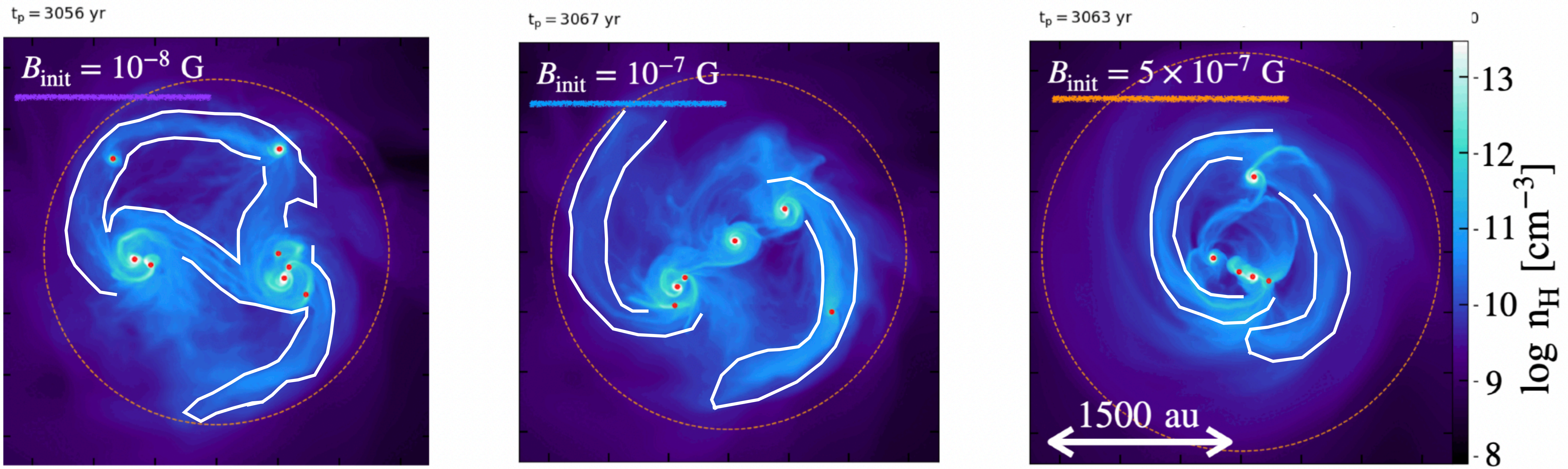


red point **:protostar**

disk region: $V_{\rm rot}(R) > 3V_{\rm rad}(R) \rightarrow R_{\rm disc}$

- **size of disk region**
  → almost the same across the all magnetized cases.
- **multiplicity**
  → Regardless of B-field strength within the disk, multiple systems are formed.

disk fragmentation



red point **:protostar**

disk region: $V_{\rm rot}(R) > 3V_{\rm rad}(R) \rightarrow R_{\rm disc}$

- magnetic pressure
- magnetic torques
- MHD outflow

- **size of disk region**

  → almost the same across the all magnetized cases.

- **multiplicity**

  → Regardless of B-field strength within the disk, multiple systems are formed.

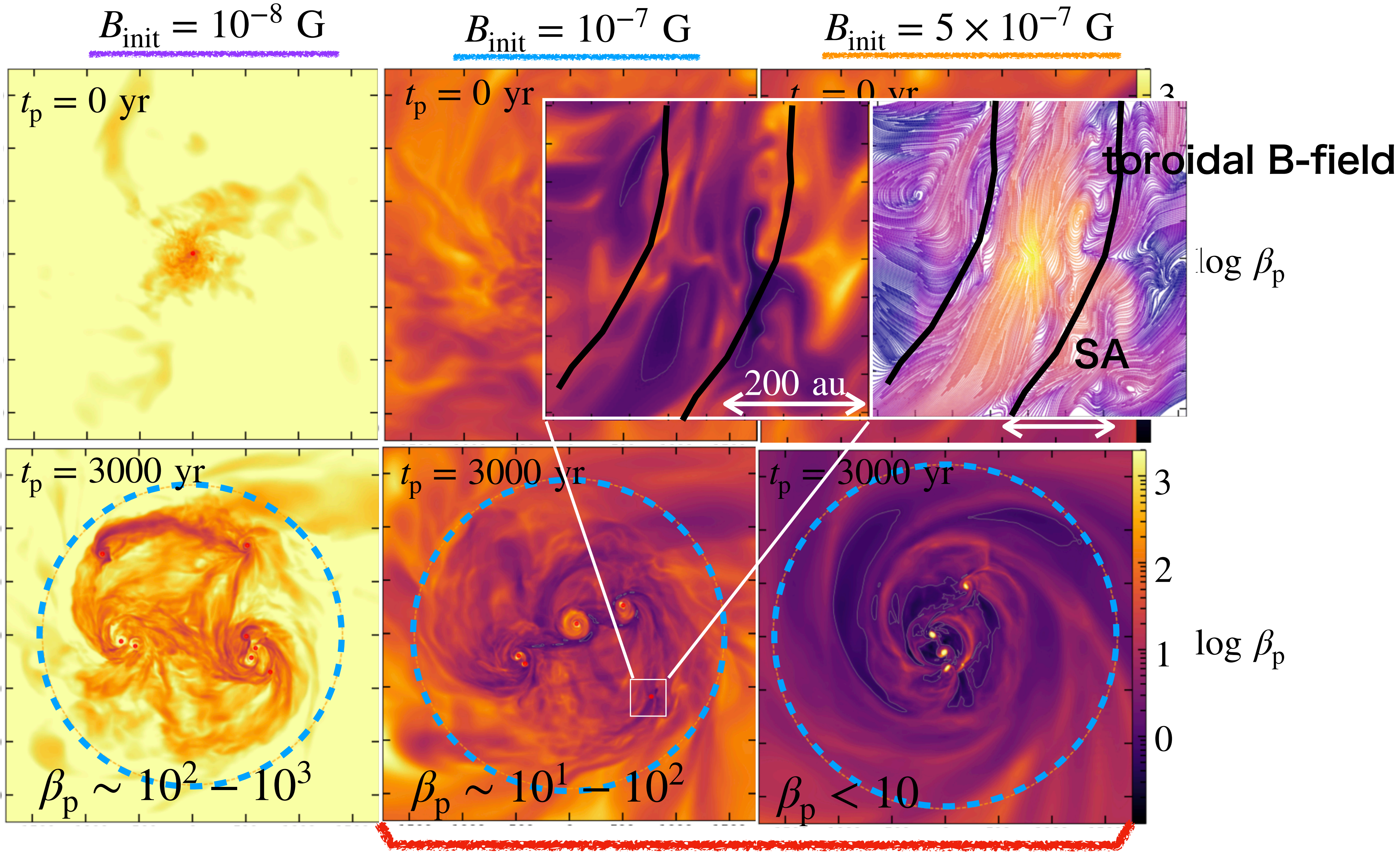
- **size of spiral arms(SAs) & gas distribution**

  → SAs in Binit = 5x10^-7 G case are shorter than other weaker case.

  → The gas within the disk concentrate to the center.

B-field effects : magnetic pressure

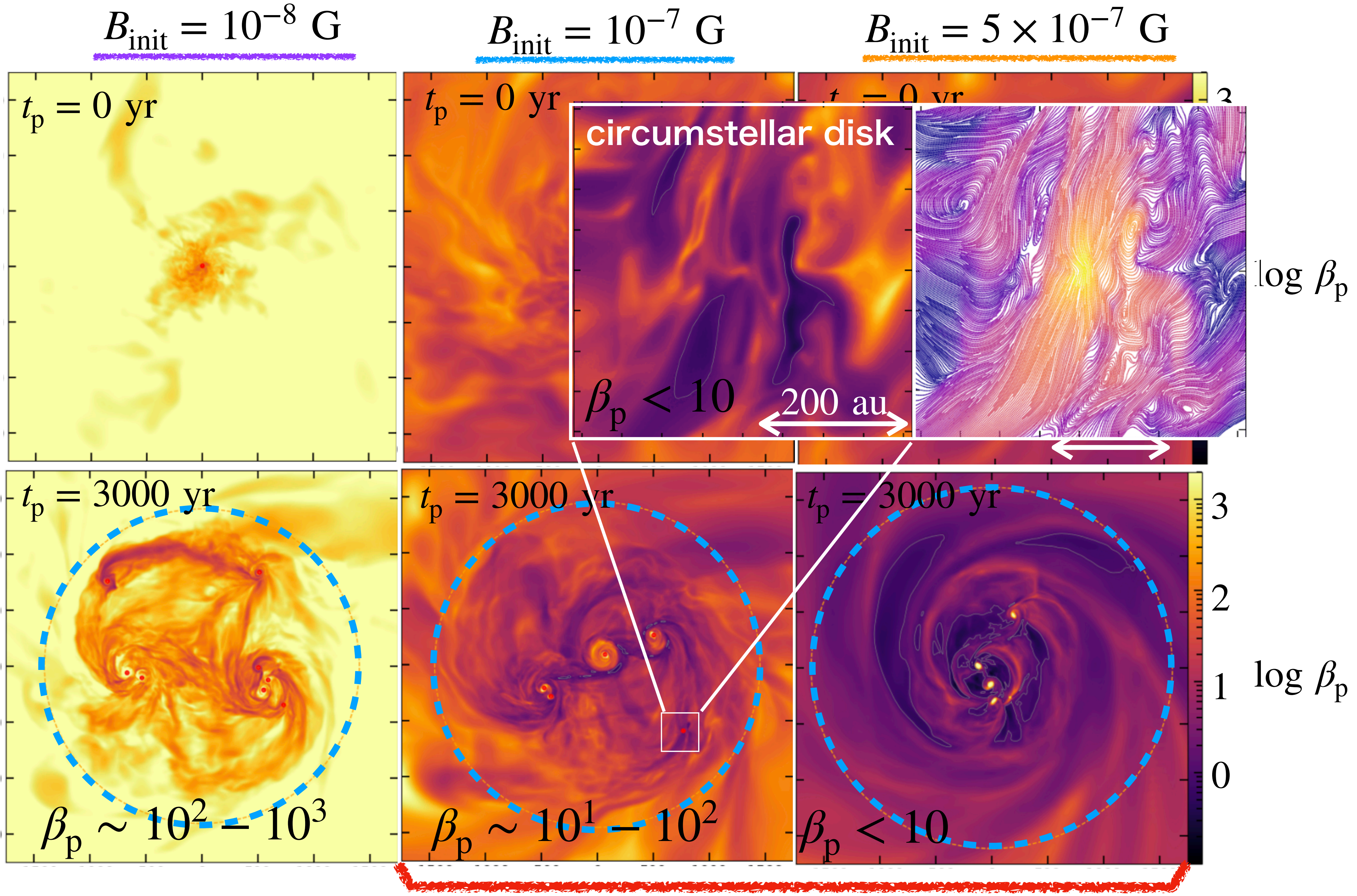
plasma beta $\beta_p = p_{th}/p_{mag}$



magnetic pressure stabilizes the disk → fragmentation ↓

B-field effects : magnetic pressure

plasma beta $\beta_p = p_{th}/p_{mag}$



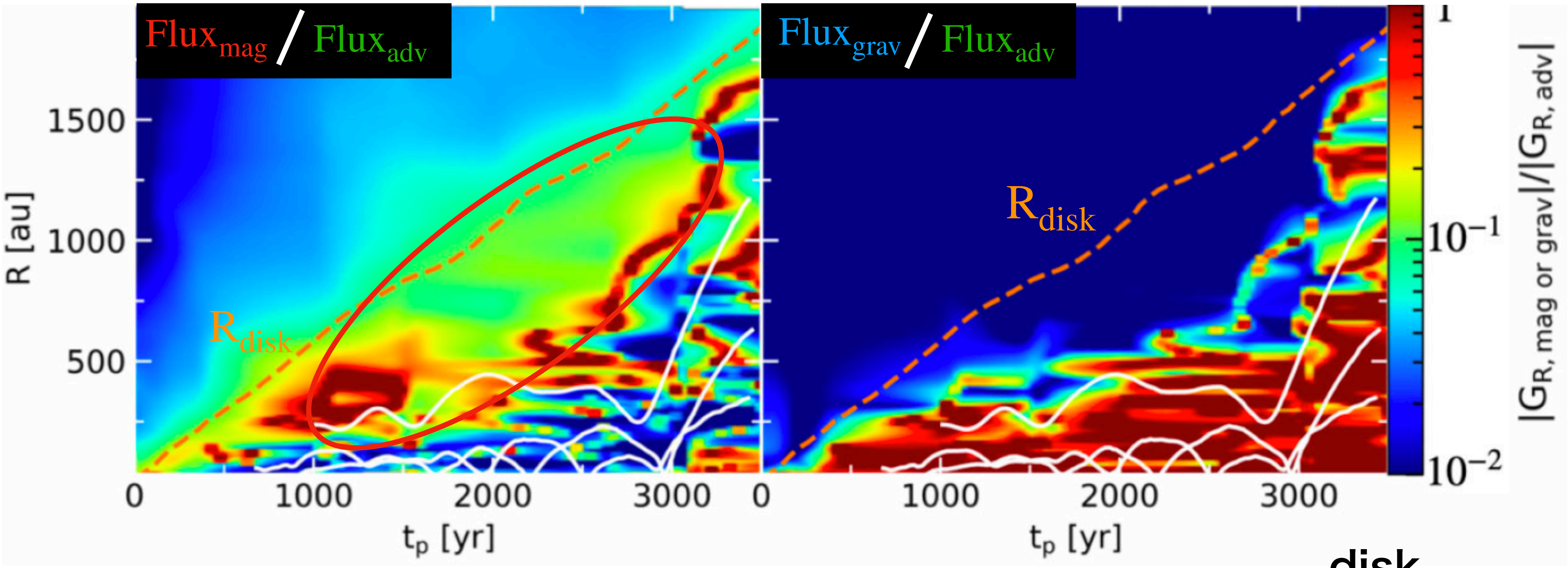
magnetic pressure stabilizes the disk → fragmentation ↓

B-field effects : magnetic torques

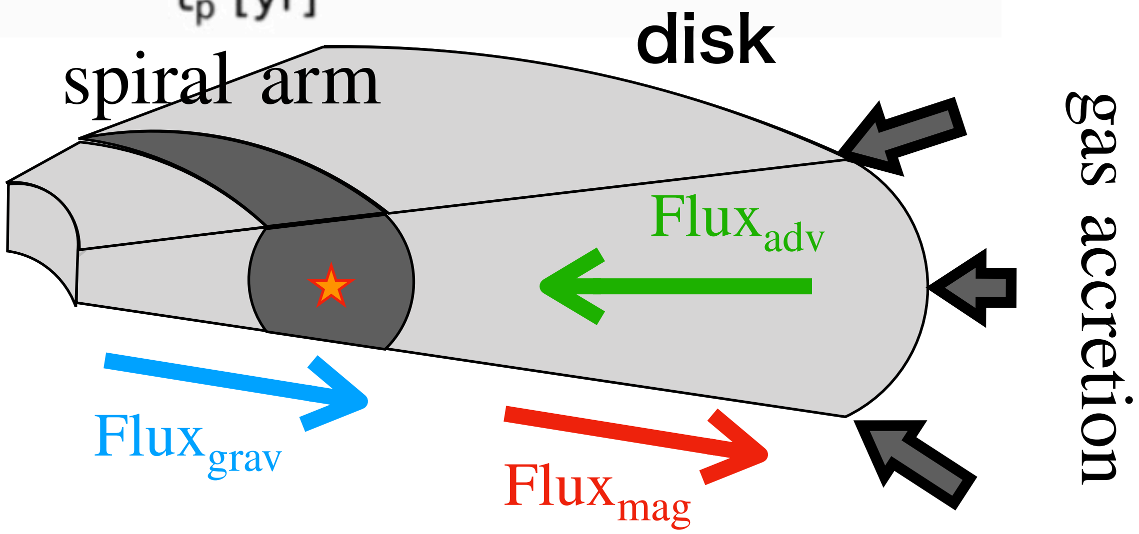
equation of AM conservation

$$\partial_t\left(\rho r v_\phi\right) + \nabla\cdot r\left[\underbrace{\rho v_\phi \boldsymbol{v}}_{\mathrm{Flux}_{\mathrm{adv}}} + \left(P + \frac{B^2}{8\pi} - \frac{g^2}{8\pi G}\right)\boldsymbol{e}_\phi - \underbrace{\frac{B_\phi}{4\pi}\boldsymbol{B}}_{\mathrm{Flux}_{\mathrm{mag}}} + \underbrace{\frac{g_\phi}{4\pi G}\boldsymbol{g}}_{\mathrm{Flux}_{\mathrm{grav}}}\right] = 0,$$

$B_{\mathrm{init}} = 5\times10^{-7}$ G



- **Magnetic torques transport AM along the direction of the disk.**
- **Effect of magnetic torque is dominant in the outer region of the disk.**



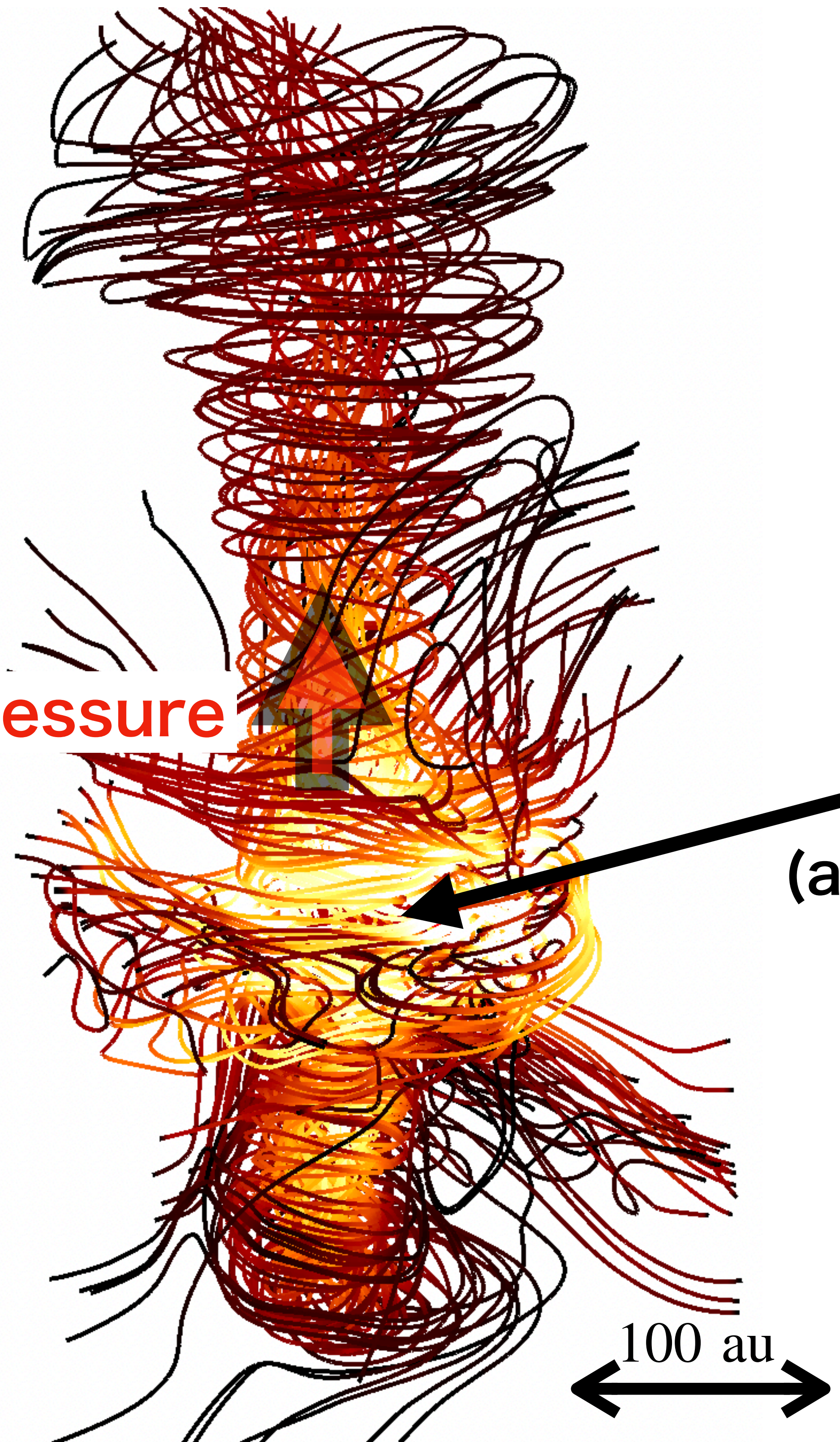
B-field effects : MHD outflow

$B_{\rm init} = 10^{-7}$ G

$B_{\rm init} = 5 \times 10^{-7}$ G

magnetic pressure wind

✔ generation of toroidal fields by protostellar rotation

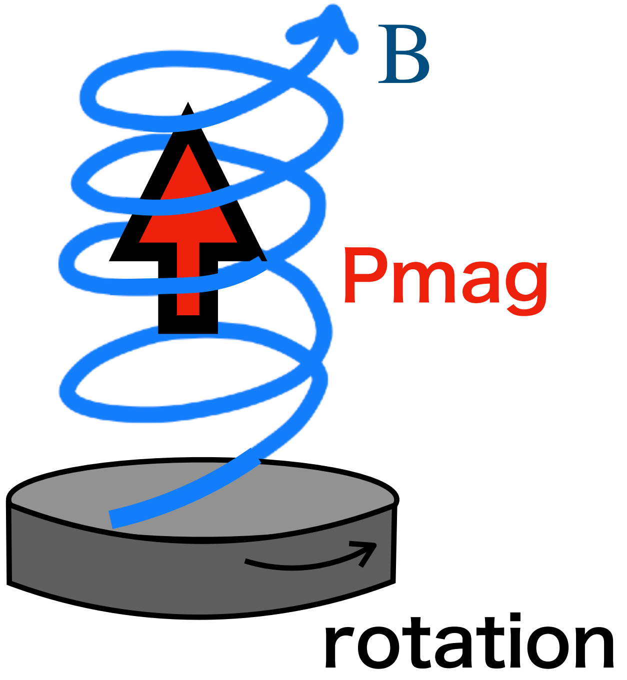


magnetic pressure

protostar
(adiabatic core)

B-field effects : MHD outflow

magnetic pressure wind

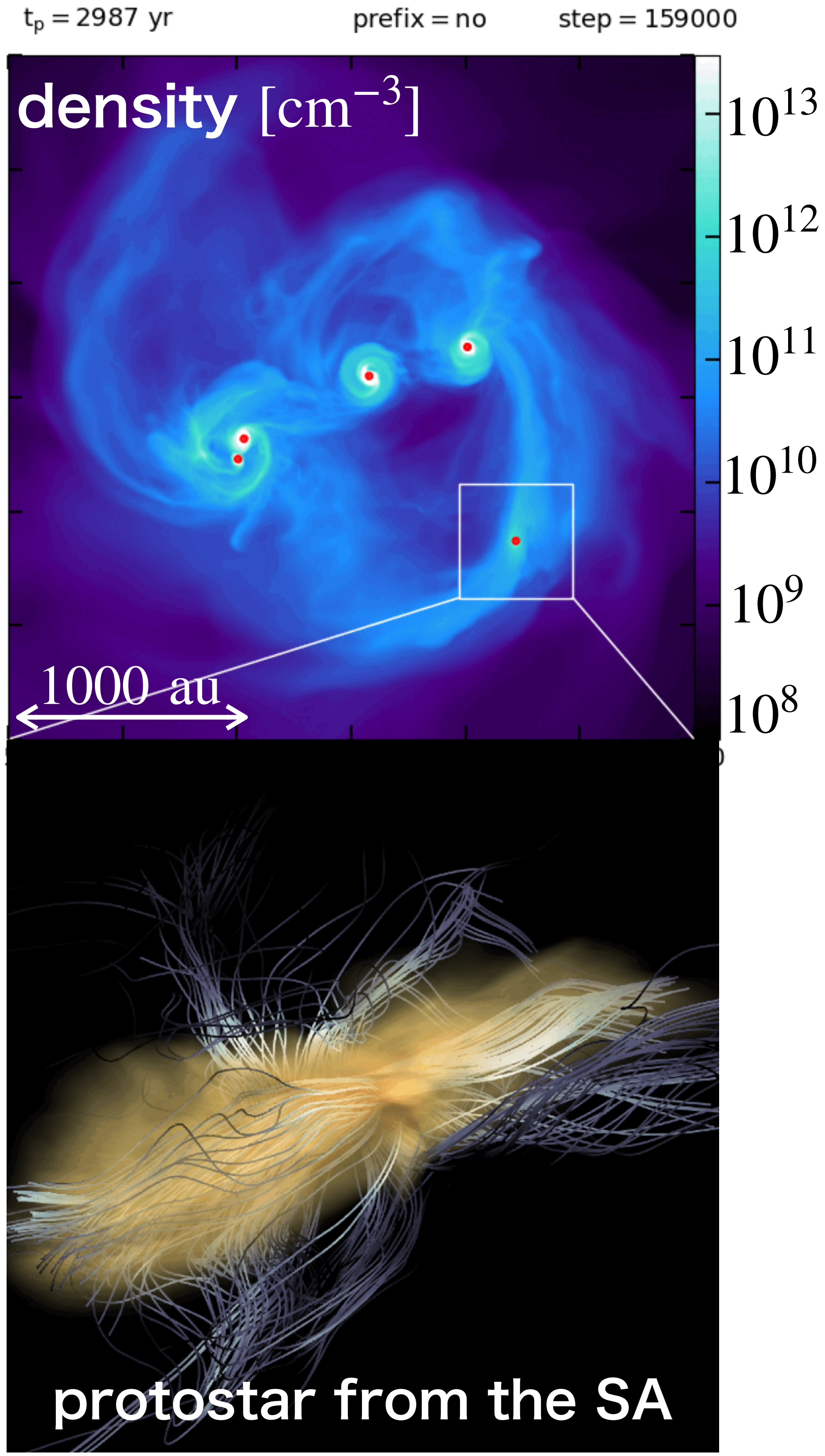


✔ generation of toroidal fields by protostellar rotation

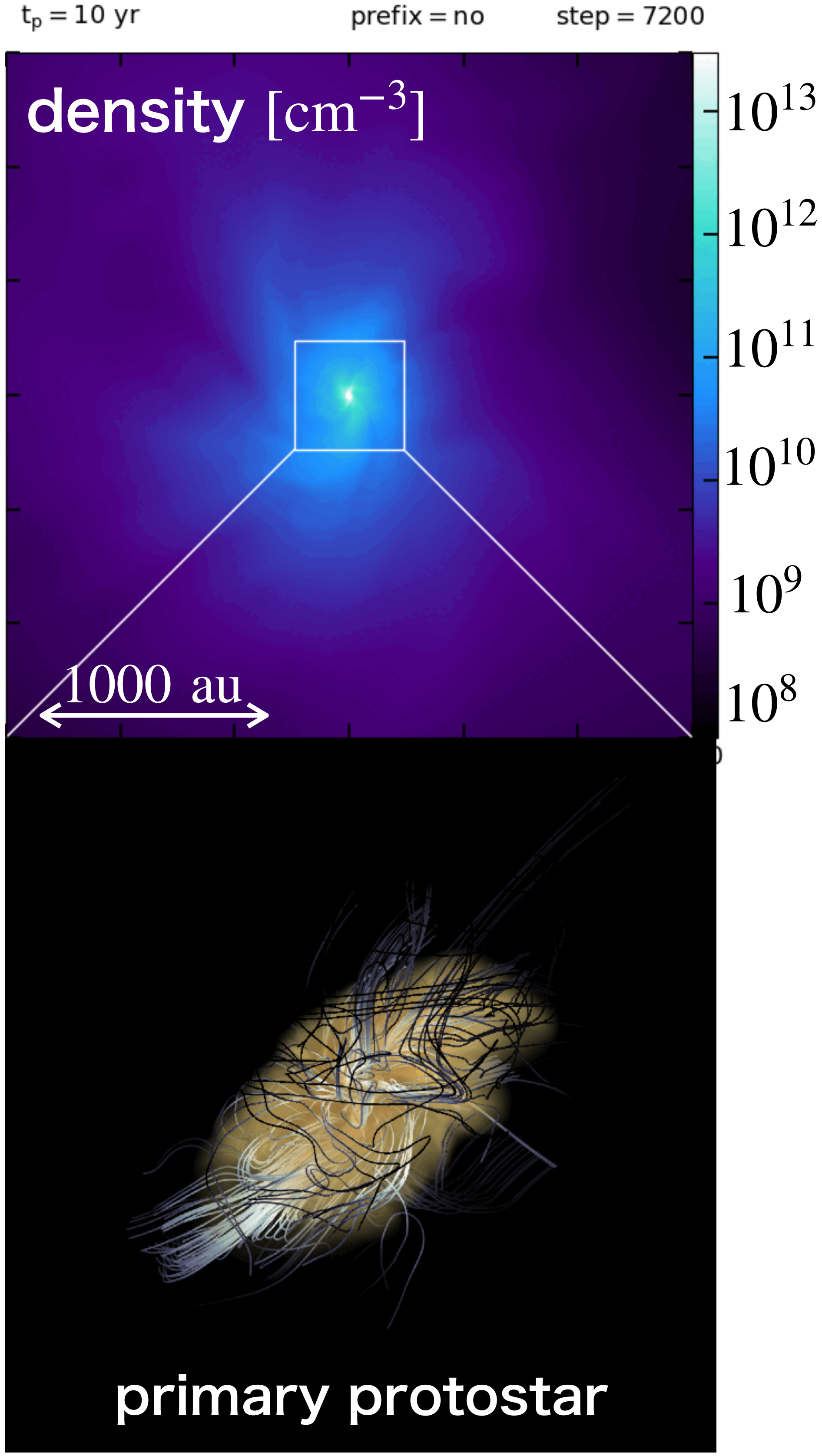
✔ Pram > Pmag
→ extinction of the jets

The impact of mass & AM ejection is minor

$B_{\rm init} = 10^{-7}$ G

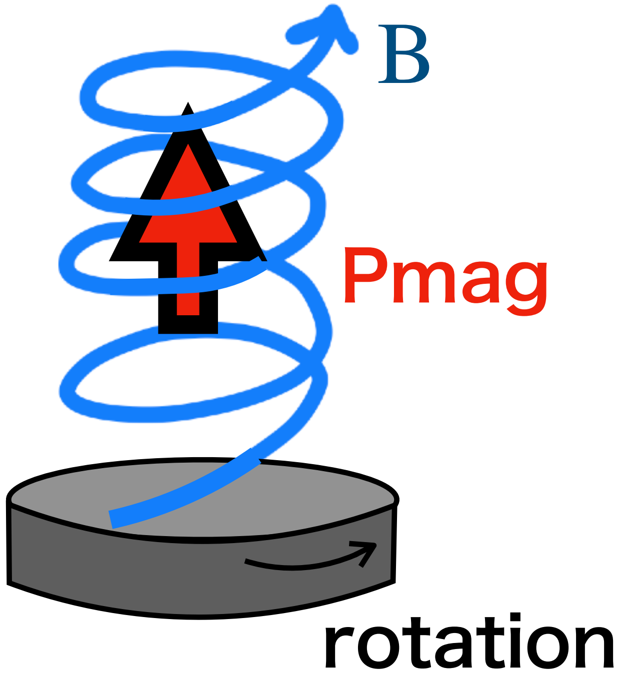


$B_{\rm init} = 5 \times 10^{-7}$ G



磁気効果：アウトフローによる質量放出

magnetic pressure wind

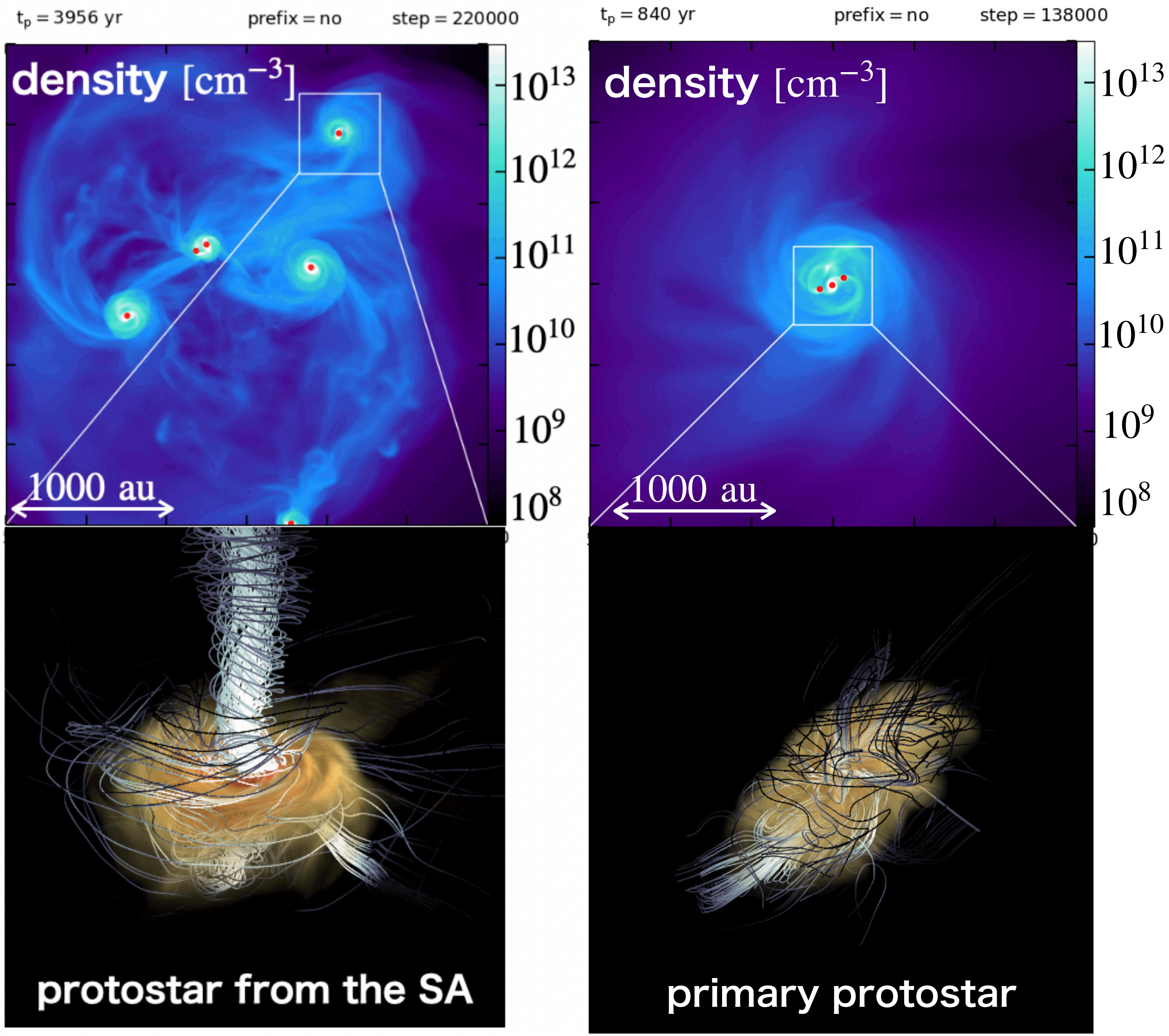


- ✔ generation of toroidal fields by protostellar rotation
- ✔ Pram > Pmag
  → extinction of the jets

The impact of mass & AM ejection is minor

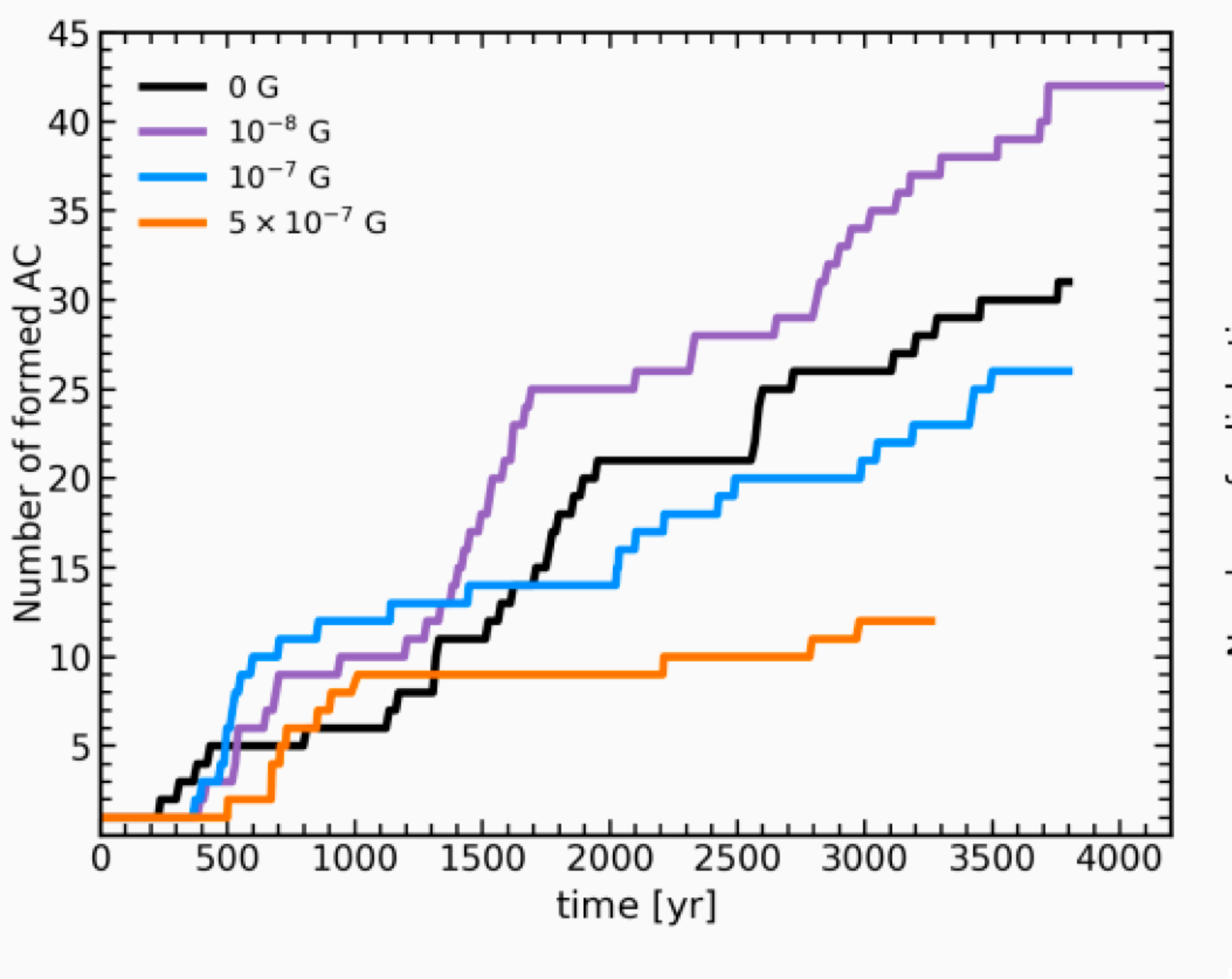
$B_{\text{init}} = 10^{-7}$ G

$B_{\text{init}} = 5 \times 10^{-7}$ G

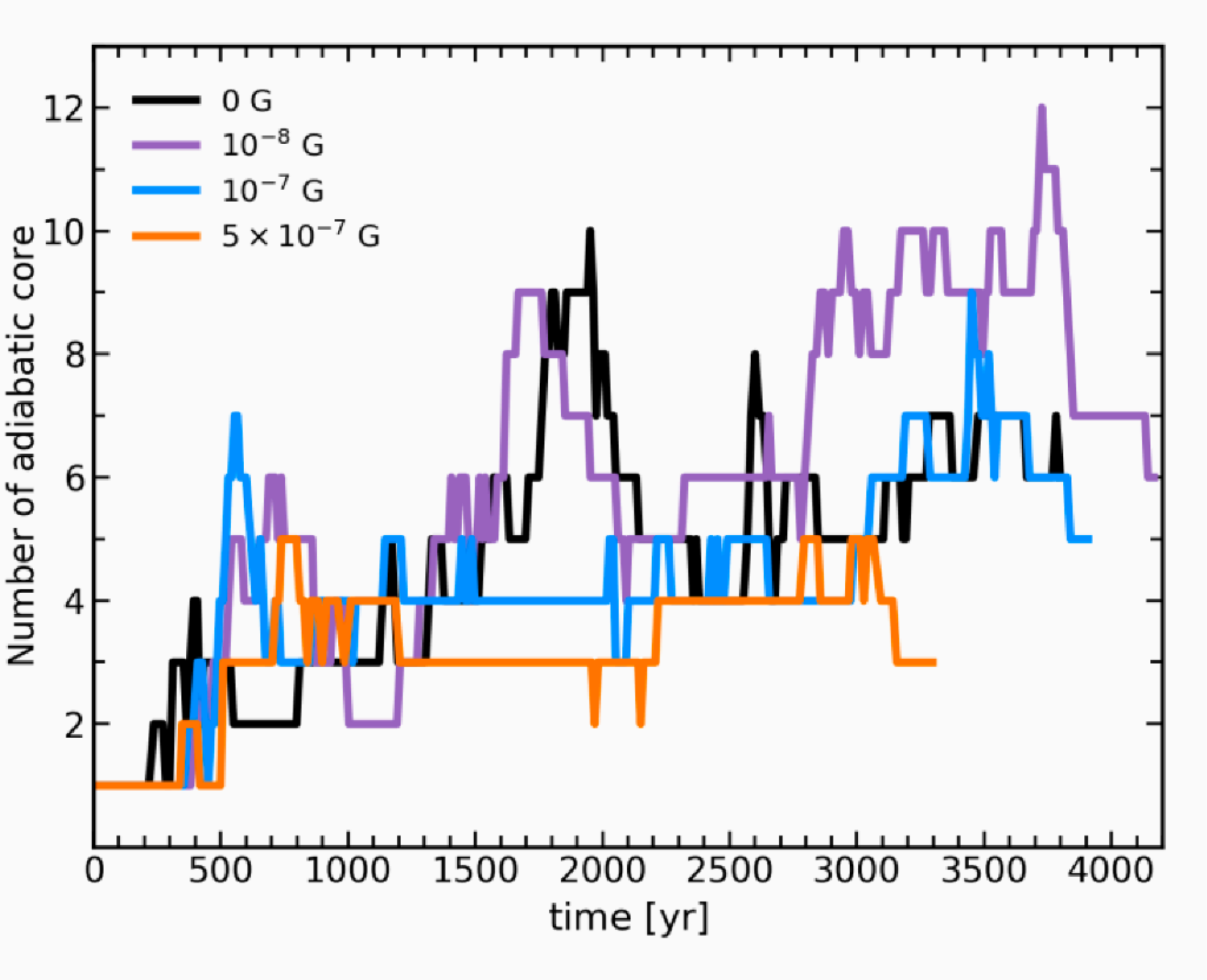


magnetic effects on disc fragmentation

cumulative number of fragments



number of fragments (protostar)



・Magnetic pressure & AM transport by magnetic torques stabilize circum-stellar/binary disks.

→ The cumulative number of fragments decreases with stronger B-field in the disc.

・However, most of the protostars **merger each other**.

→ we can see clear reduction of number of protostar only in the case of Binit = 5x10^-7 G.

Summary

We have performed 3D ideal MHD simulations of first star formation from collapse phase to accretion phase.

→ investigating whether turbulent B-fields affect the disk fragmentation.

[our findings]

magnetic amplification by rotational motion is slow due to the magnetic reconnection diffusion.

magnetic pressure

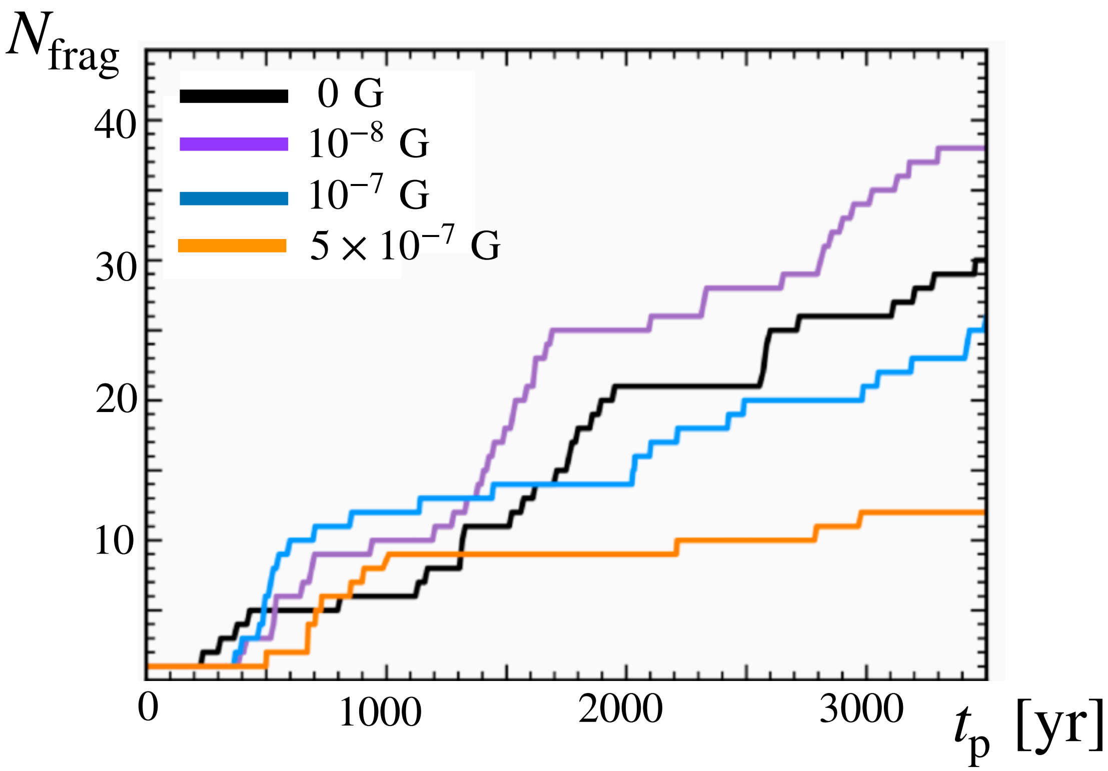
stabilizes the circum-stellar/binay disk.

magnetic torques

transport the angular momentum in radial direction, leading to stabilize the disk.

MHD outflow

Magnetic pressure winds are occasionally driven, but their impact on stellar mass is minor.

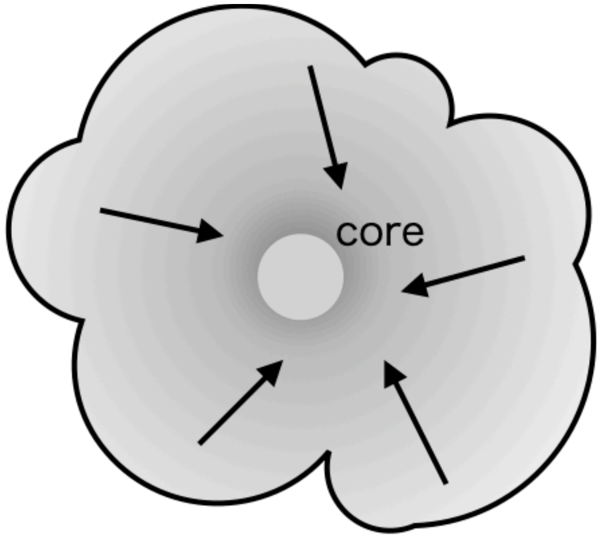


[conclusion]

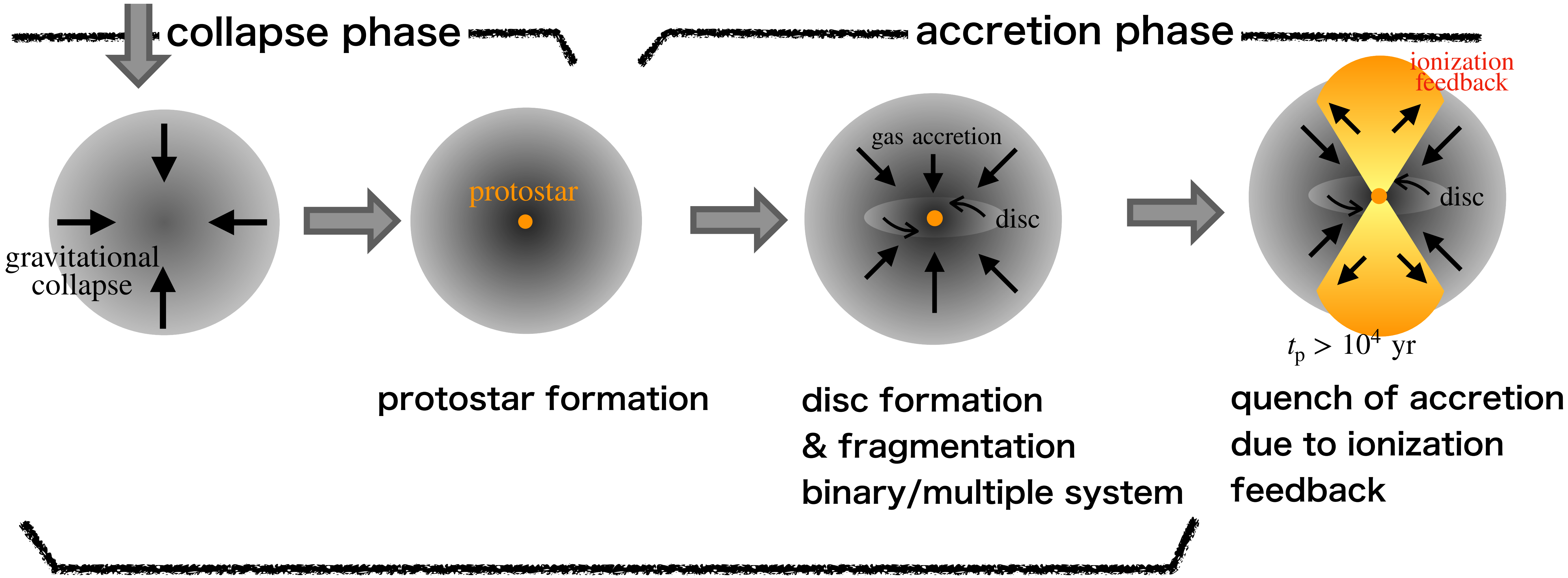
If B-fields can be amplified to about equipartition fields during collapse phase, the magnetic effects can reduce the number of protostar

→ top heavy IMF

future work



① Consistently calculating the dynamo growth from the seed magnetic field generation process through Biermann mechanism.



collapse phase

accretion phase

protostar formation

disc formation
& fragmentation
binary/multiple system

quench of accretion
due to ionization
feedback

our studies

②performing MHD simulation
w/ radiation feedback