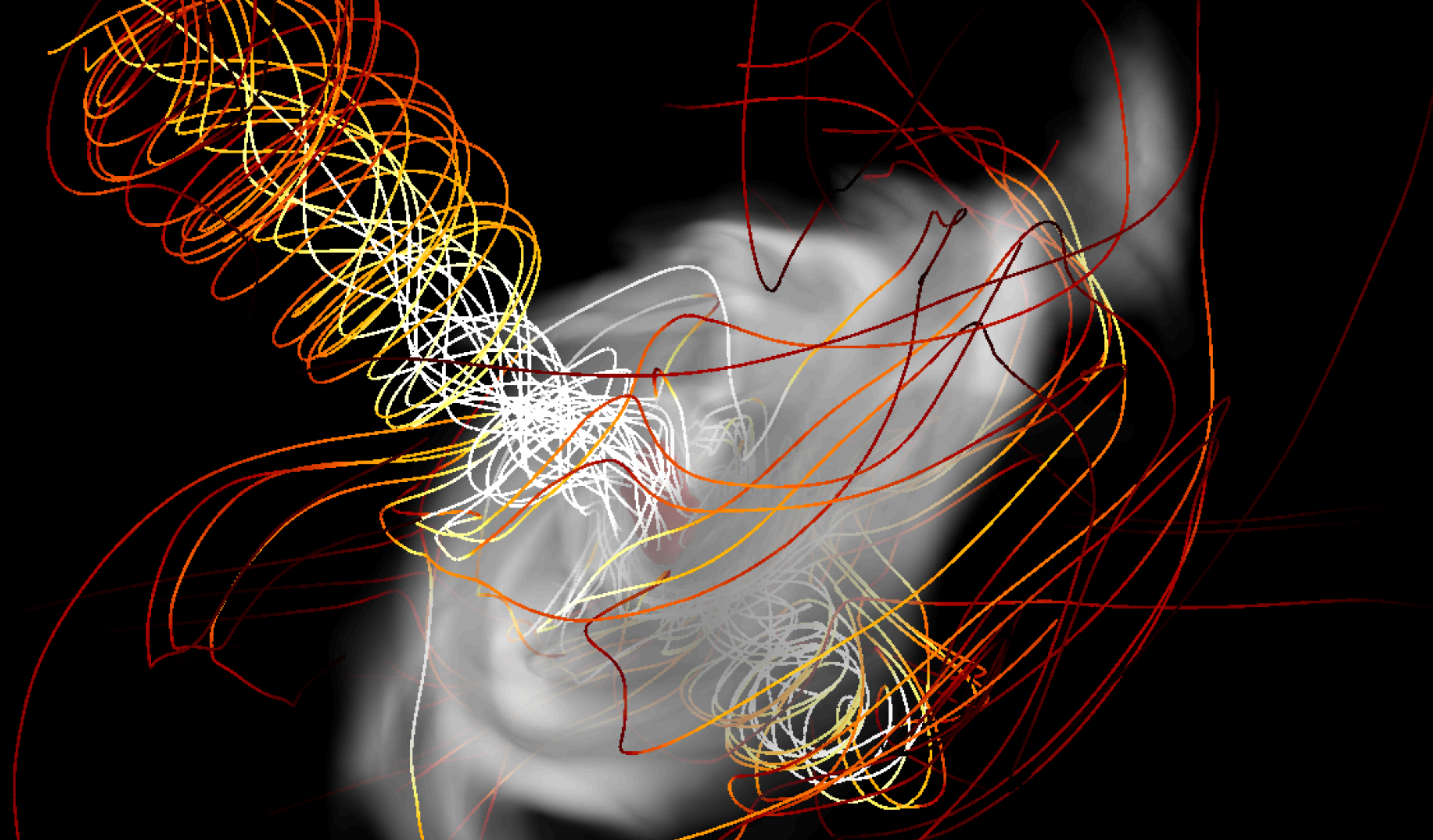
初代星形成における円盤分裂に対する乱流磁場の影響



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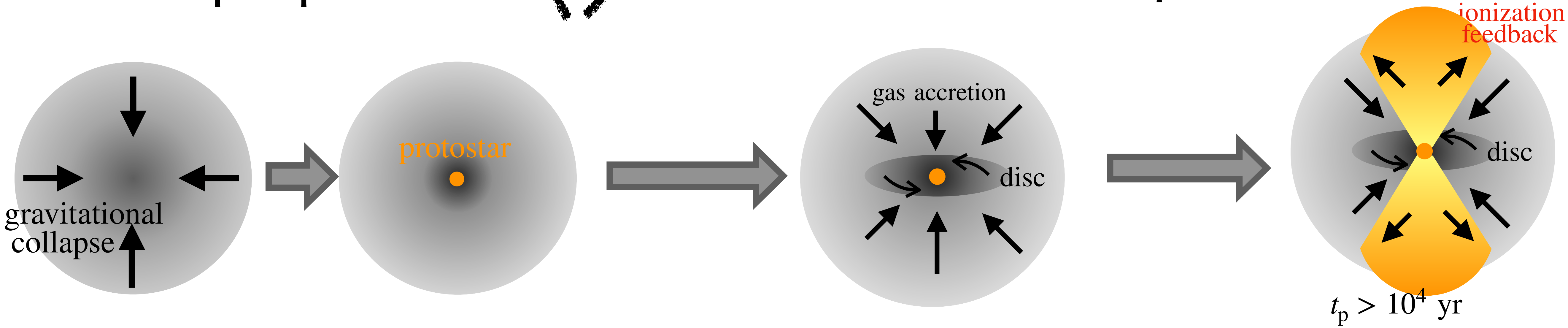
star formation process

collapse phase — accretion phase

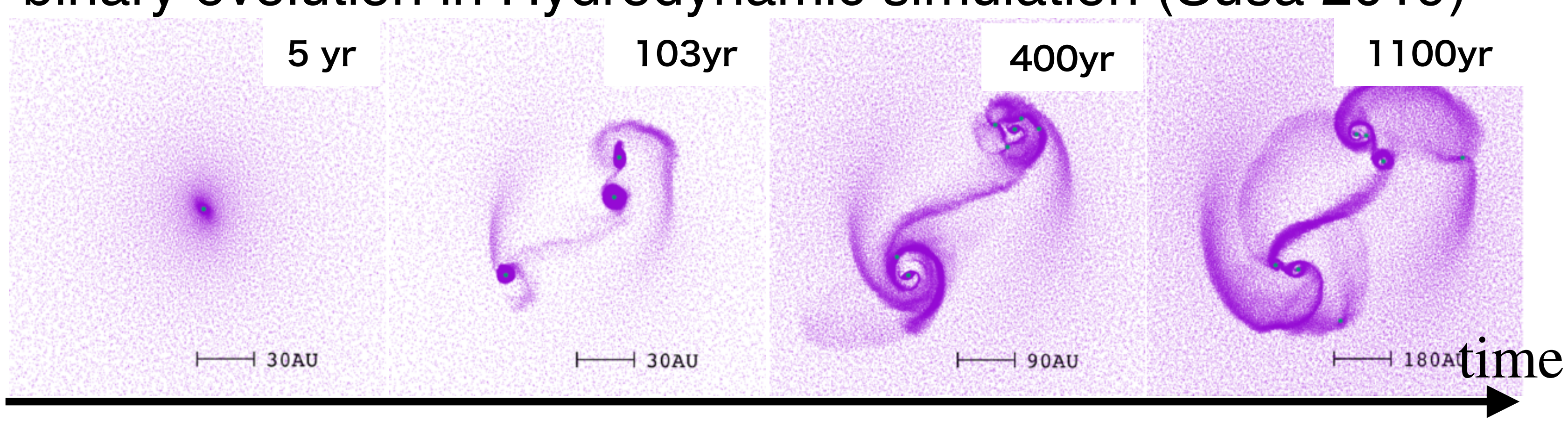


protostar formation

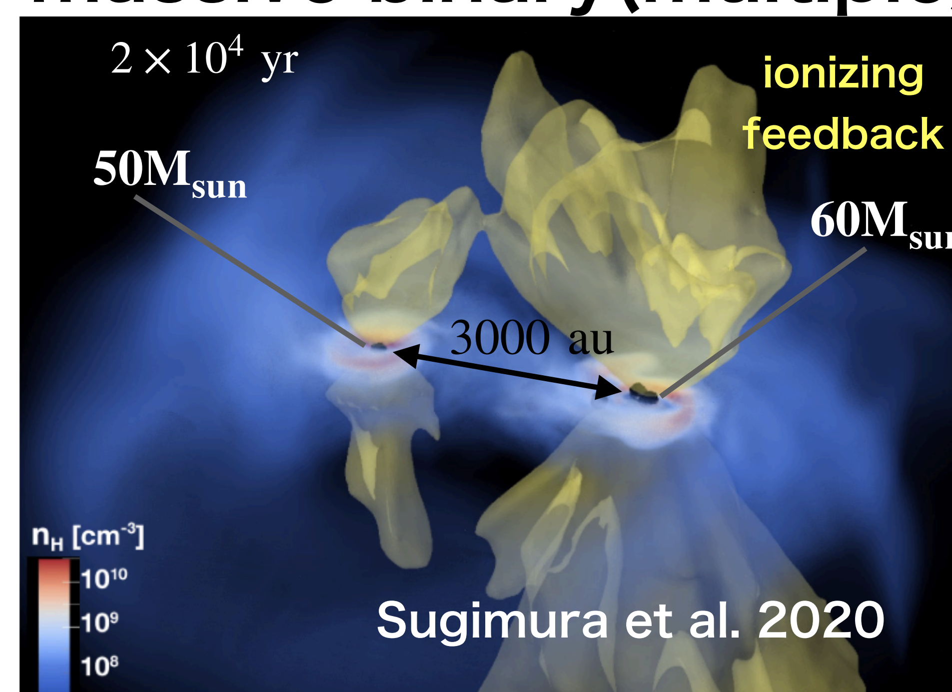
disc formation
& fragmentation

ionization
feedback

binary evolution in Hydrodynamic simulation (Susa 2019)



massive binary(multiple)



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

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)

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

There is definitely a B-field in the early universe, but its strength is too weak.

amplification of seed B-field by dynamo

Turbulence in the minihalo can rapidly amplify seed B-fields through dynamo effects.

✔ small scale dynamo ($E_{mag} \ll E_{turb}$)

① kinematic stage

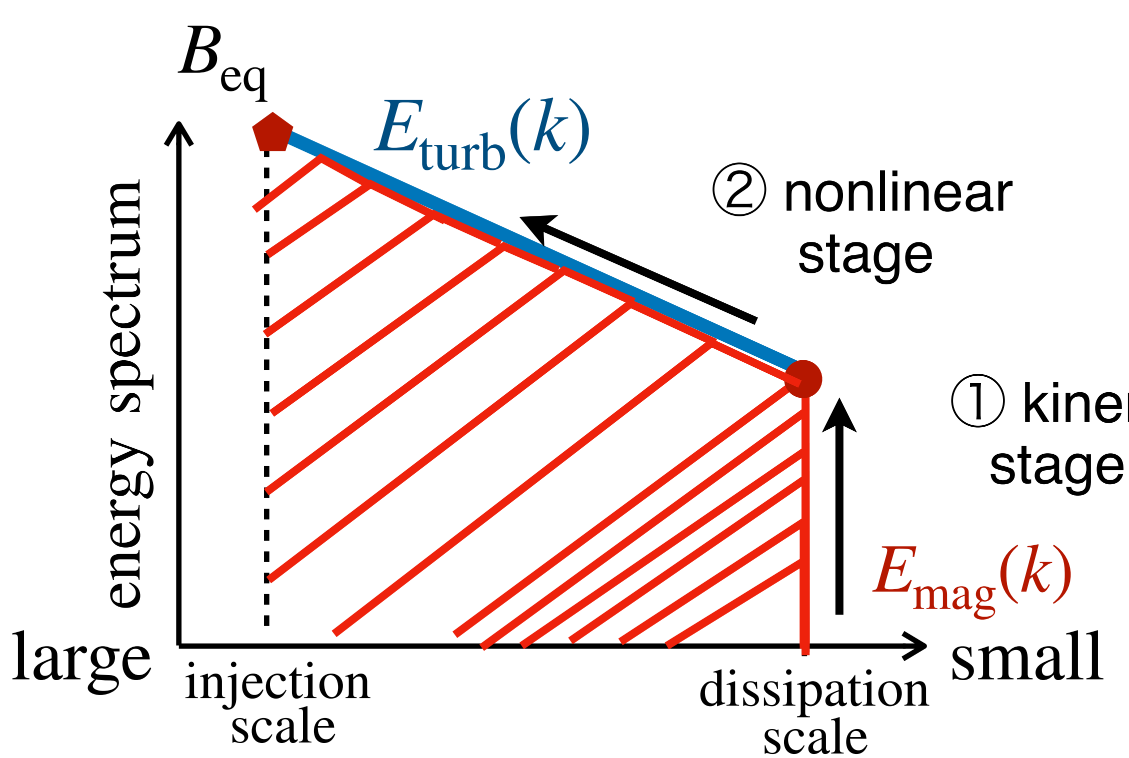
$B \propto \exp(t/t_{eddy})$

→ small scale B-field is dominant

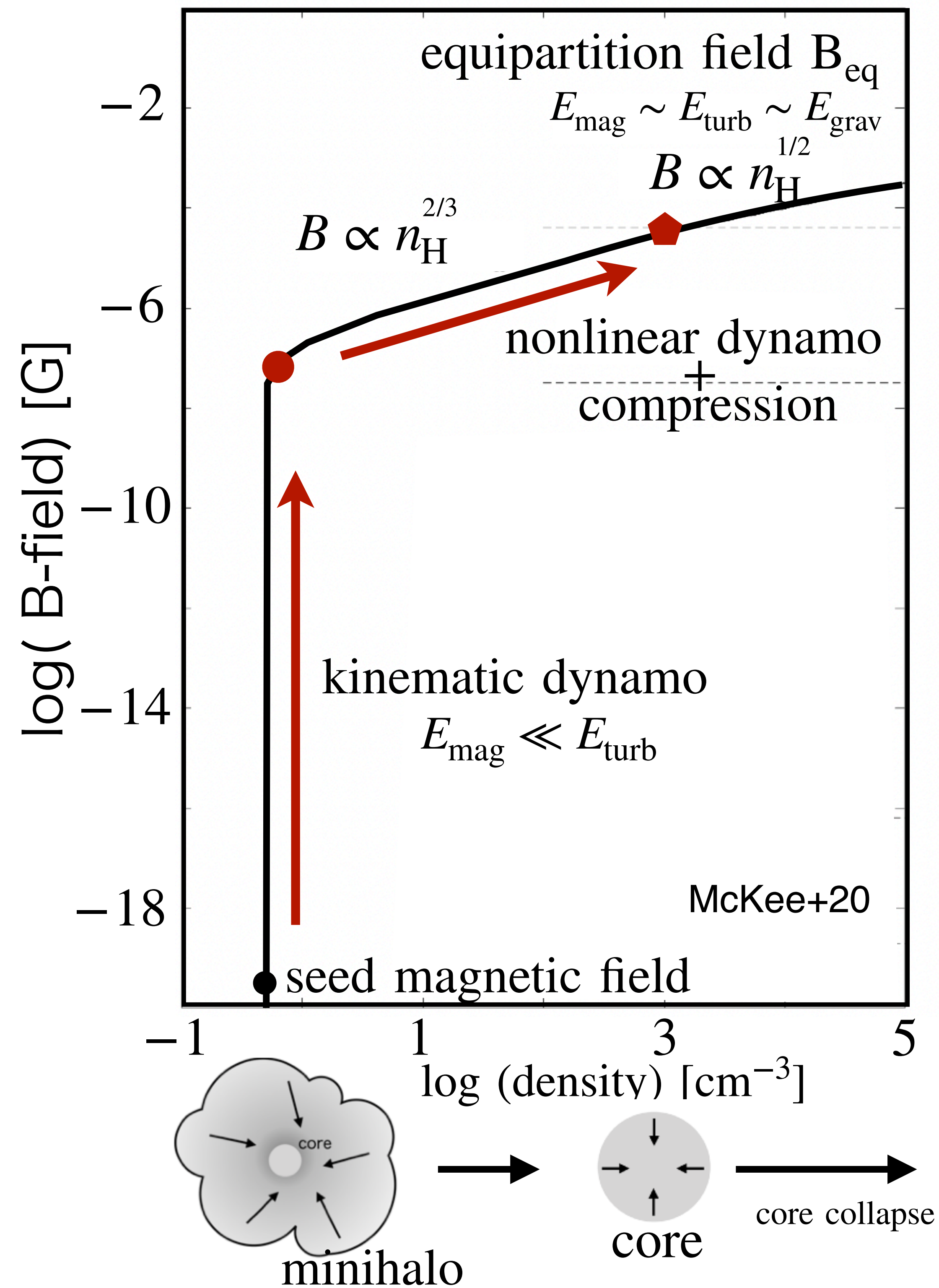
② non-linear stage

$B \propto t$ <—- comp. growth becomes dominant

→ large scale B-fields become dominant

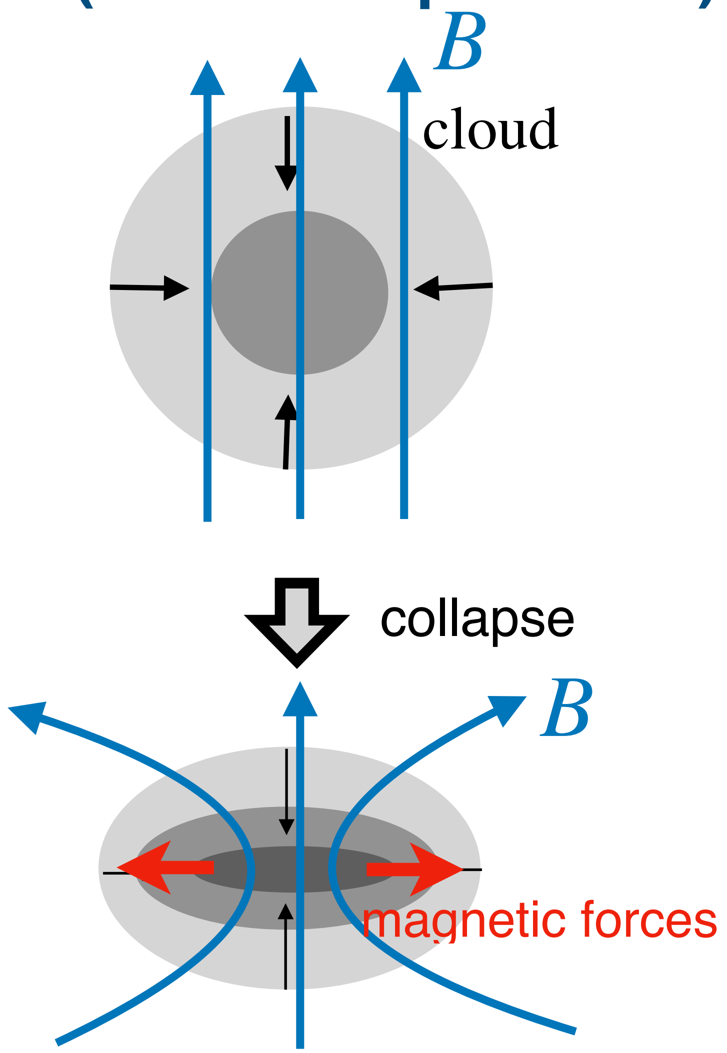


B-field growth during the collapse



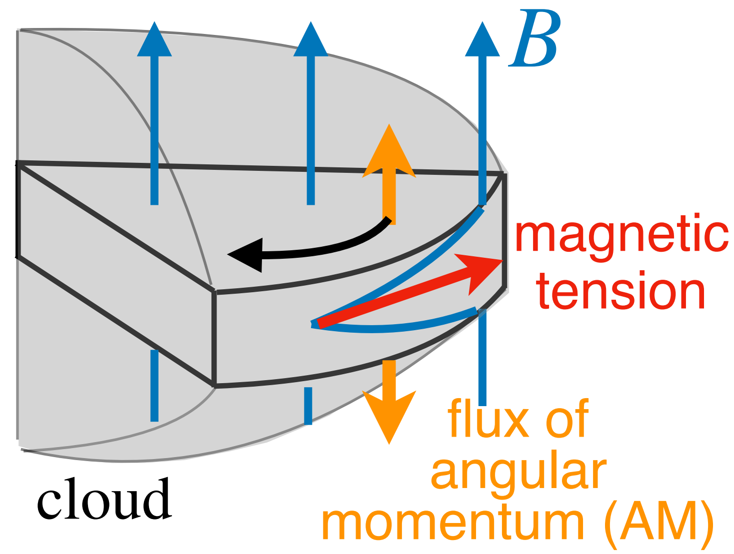
magnetic effects on star formation

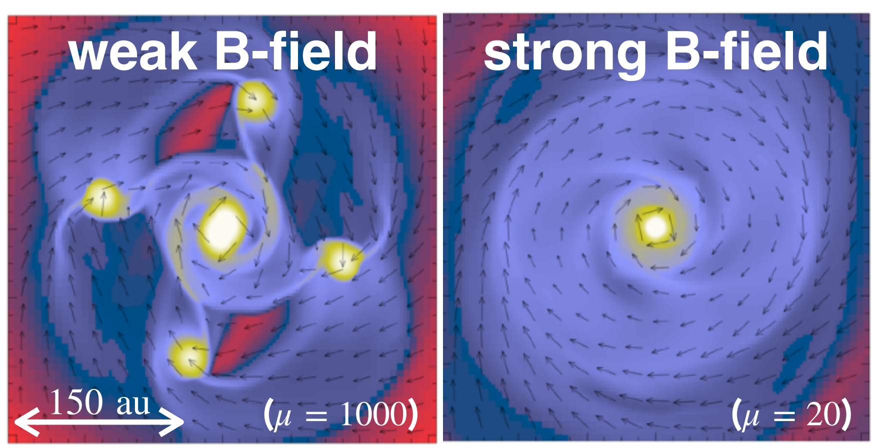
✔ magnetic forces (tension & pressure)



・Magnetic forces can deform the cloud shape & delay collapse.

✔ magnetic braking

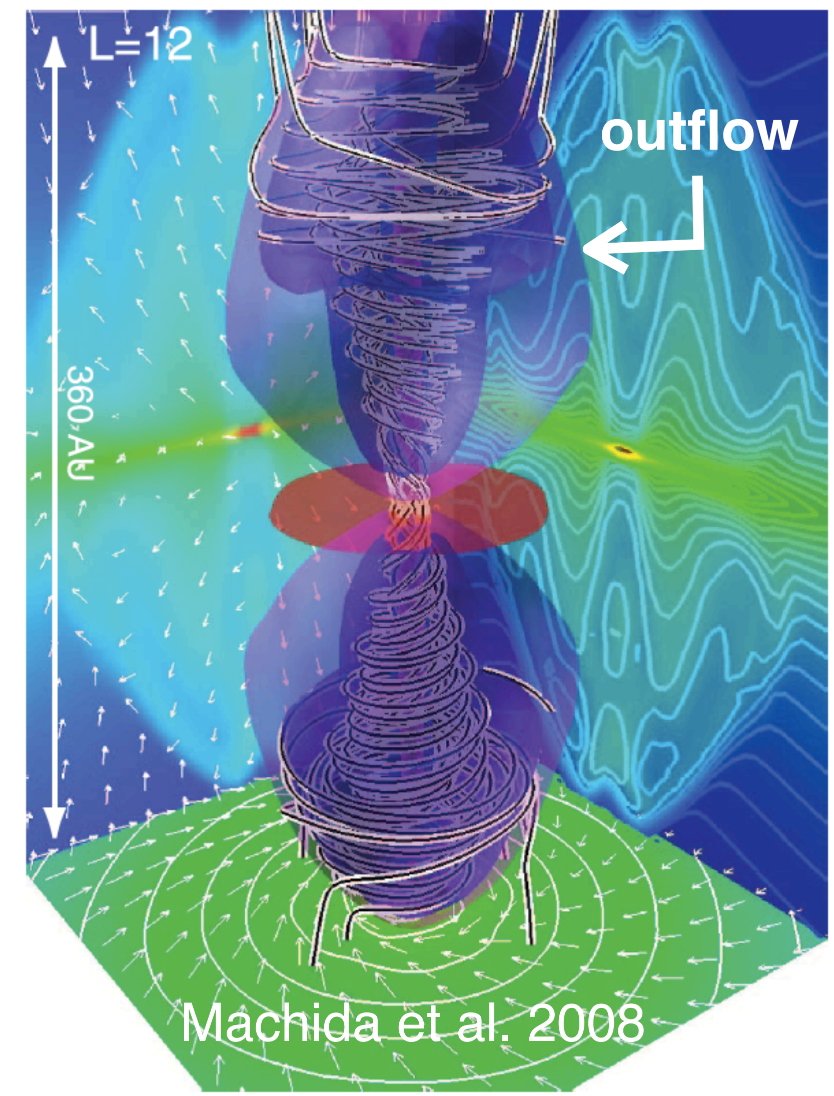




Hennebelle & Teyssier 2008

・Magnetic braking transports angular momentum (AM).

✔ MHD outflow



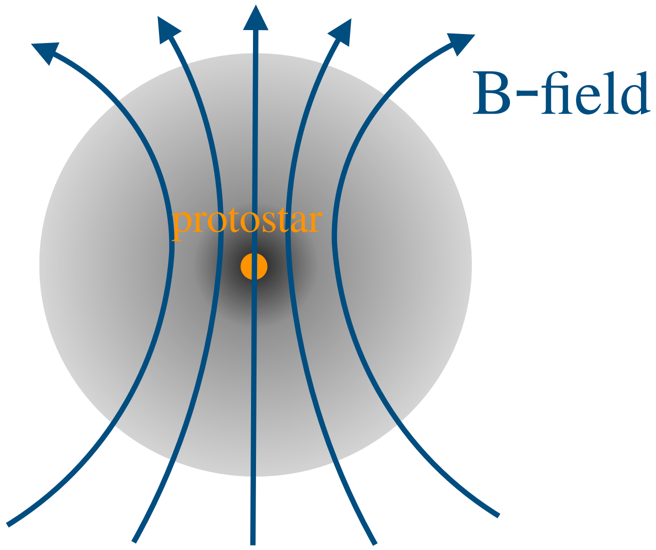
・MHD outflows eject the accretion gas with AM.

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

turbulent magnetic fields in first star formation

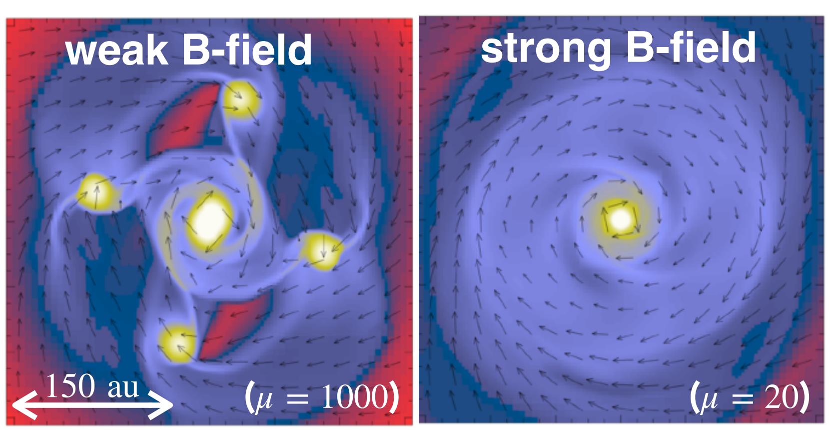
coherent B-field

(e.g., present-day)

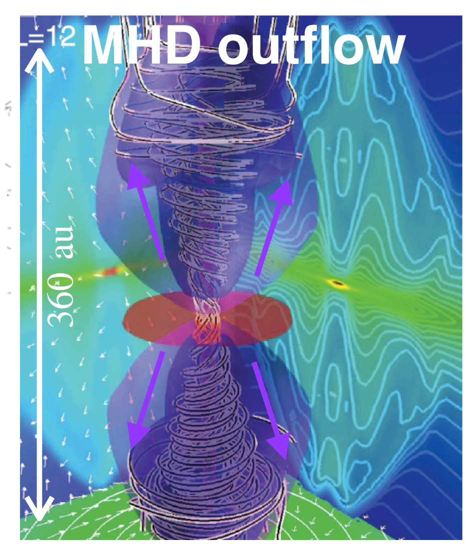


MHD outflow & magnetic braking can transport the angular momentum

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



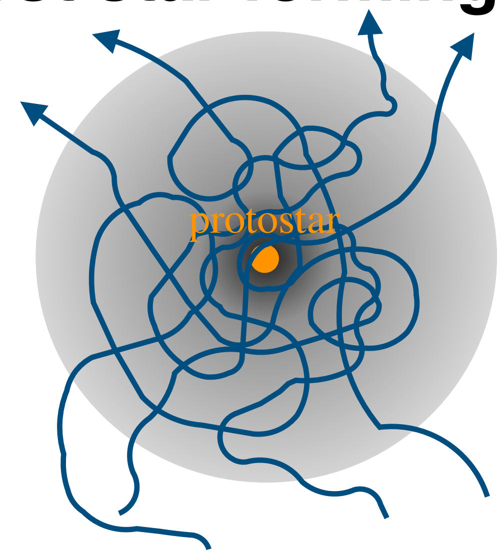
Hennebelle & Teyssier 2008



Machida+2008

turbulent B-field

(e.g., first star forming region)



Question ?

How turbulent B-fields affect on

- disk size
- number of fragmentation
- binary separation

We have investigated how turbulent B-fields affect the fragmentation process in the disk & number/spatial distribution of protostars.

set-up of MHD simulation

[simulation code]

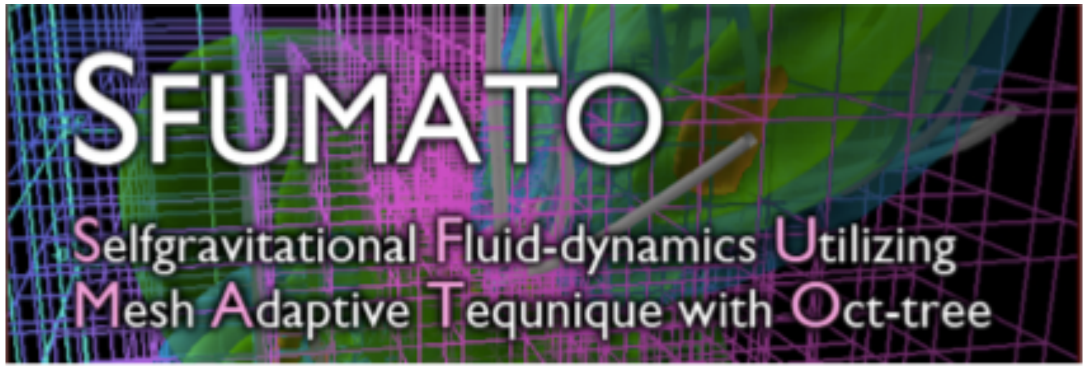
AMR(Adaptive Mesh Refinement) code

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

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

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

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



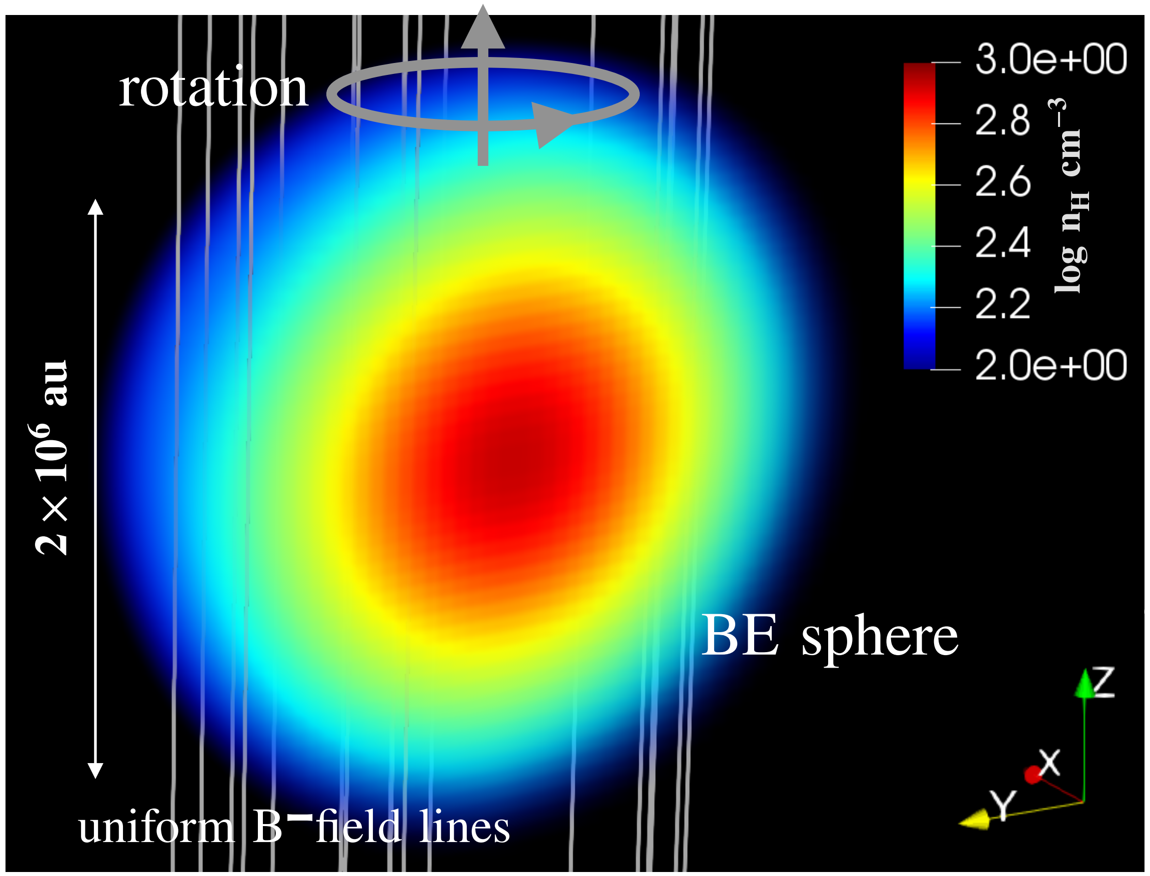
(Matsumoto 2007, Sugimura+2020)

resolution: cell size < Jeans length/64

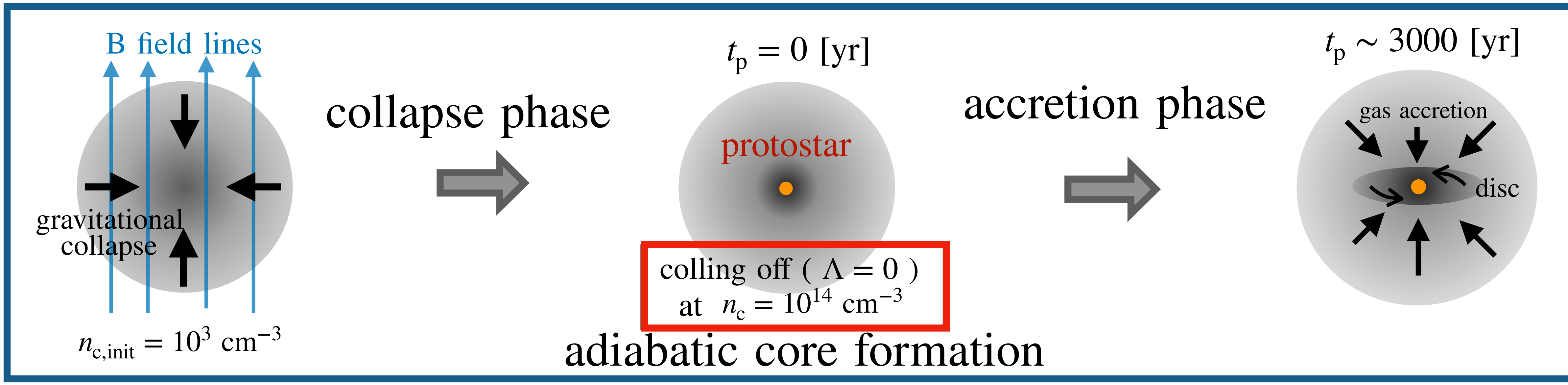
[initial set up]

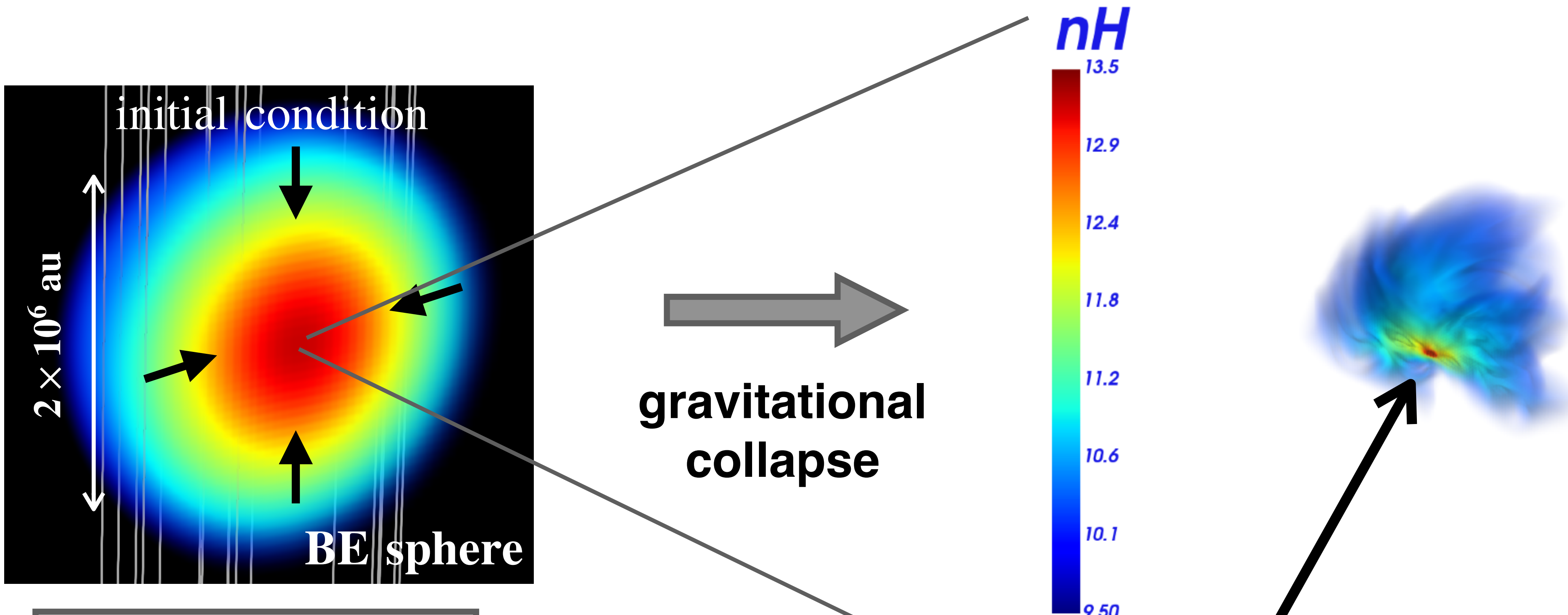
Bonnor-Ebert sphere (= gas cloud core)
(central density $n_{\mathrm{c,init}} = 10^3\ \mathrm{cm^{-3}}$)

- rigid rotation
  $E_{\mathrm{rot}}/|E_{\mathrm{grav}}| = 0.01$
- turbulent velocity ($V_{\mathrm{turb}} \propto k^{-1/2}$)
  $E_{\mathrm{turb}}/|E_{\mathrm{grav}}| = 0.03$
- uniform magnetic field
  $E_{\mathrm{mag}}/|E_{\mathrm{grav}}| = 0,\ \ 2\times10^{-7},\ \ 2\times10^{-5},\ \ 6\times10^{-4}$



overview of our simulations





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

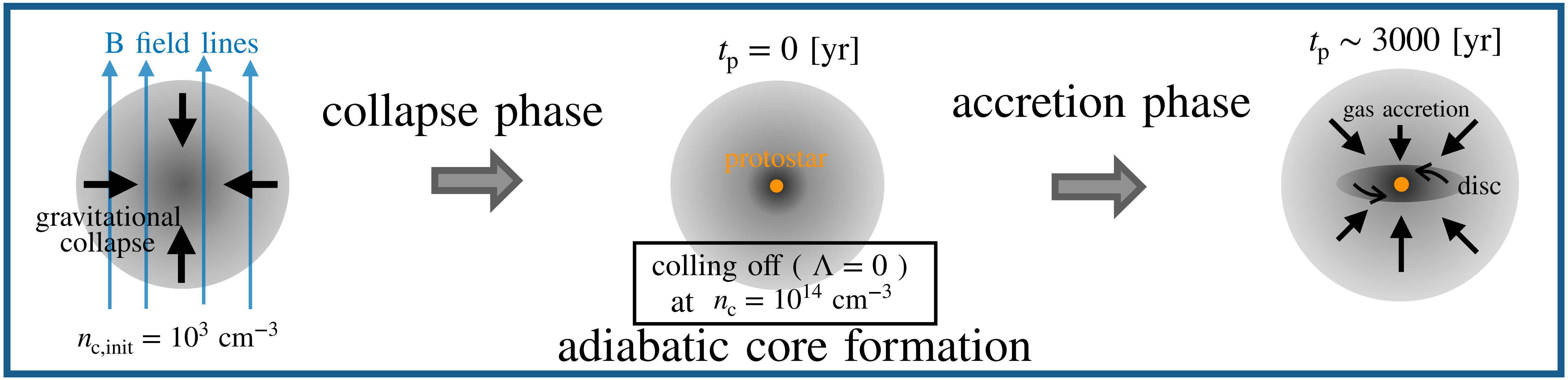
$B_{init} = 10^{-7}$ G

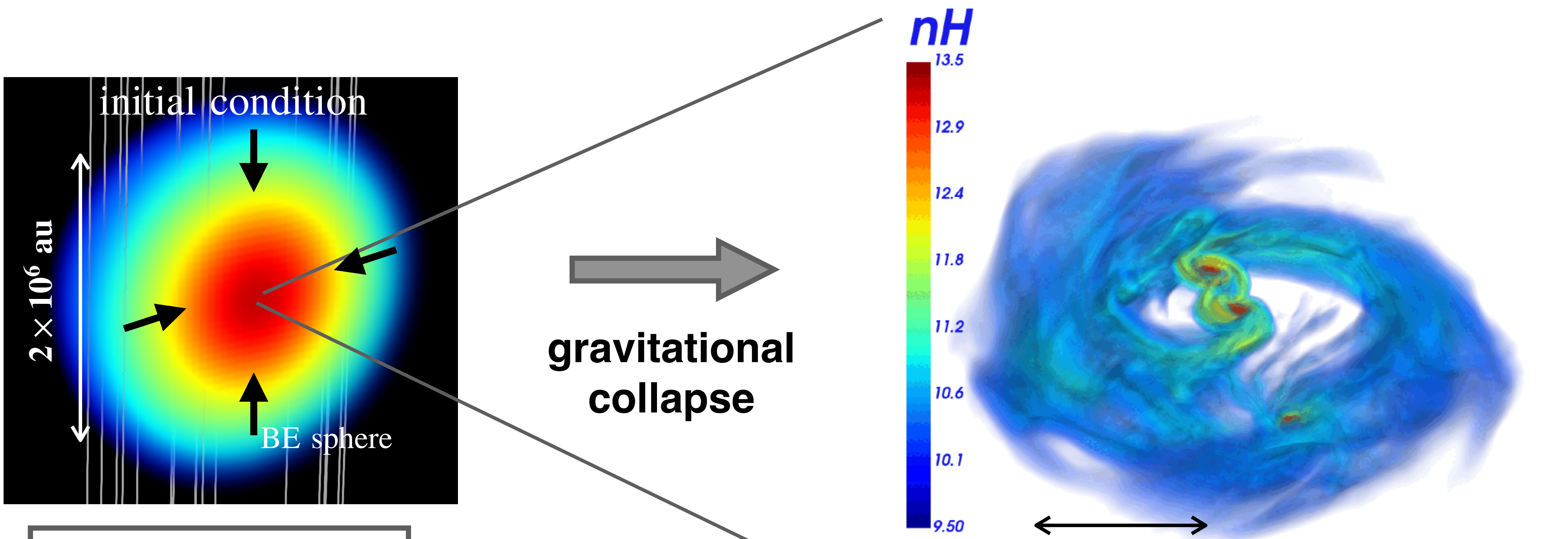
$B_{init} = 10^{-8}$ G

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

=> protostar

overview of our simulations





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

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

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

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

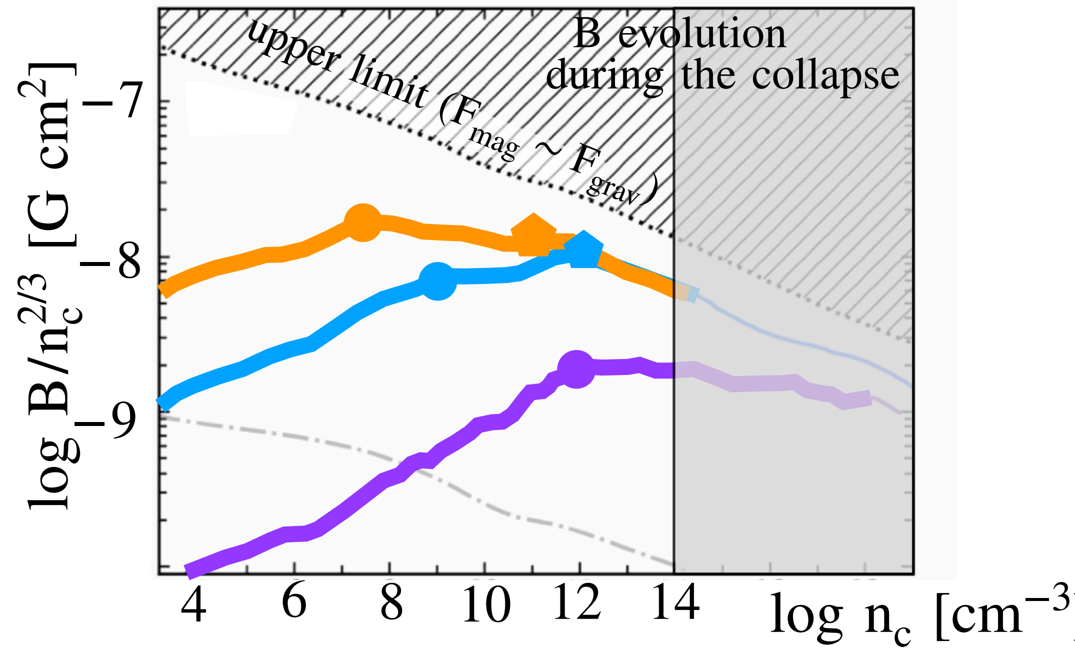
=> protostar

・disk formation

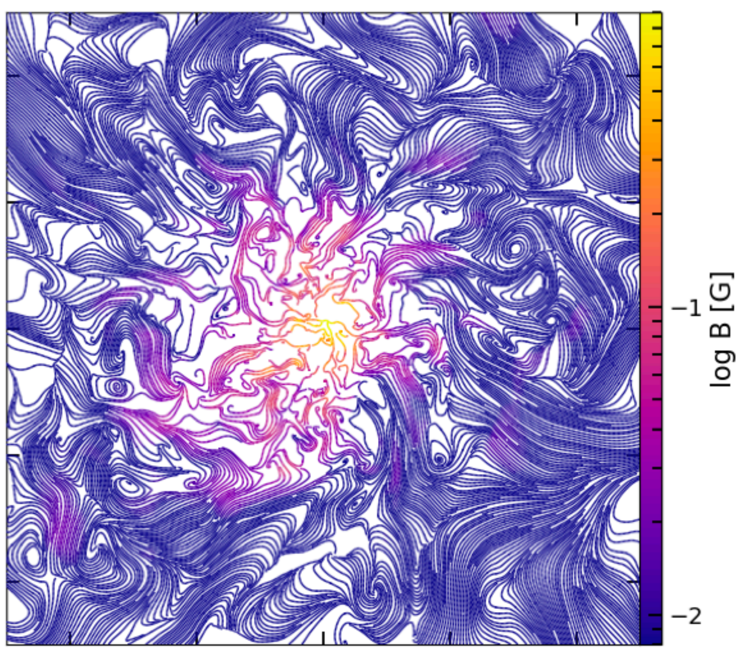
・disk fragmentation —> multiple protostar

turbulent B-fields @ protostar formation

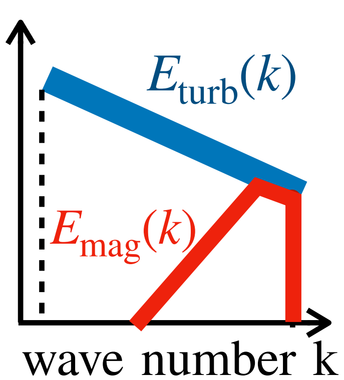
We generate different **turbulent fields** in terms of (strength, spatial distribution, configuration) @ protostar formation by varying the initial field strength, $B_{\rm init}$.



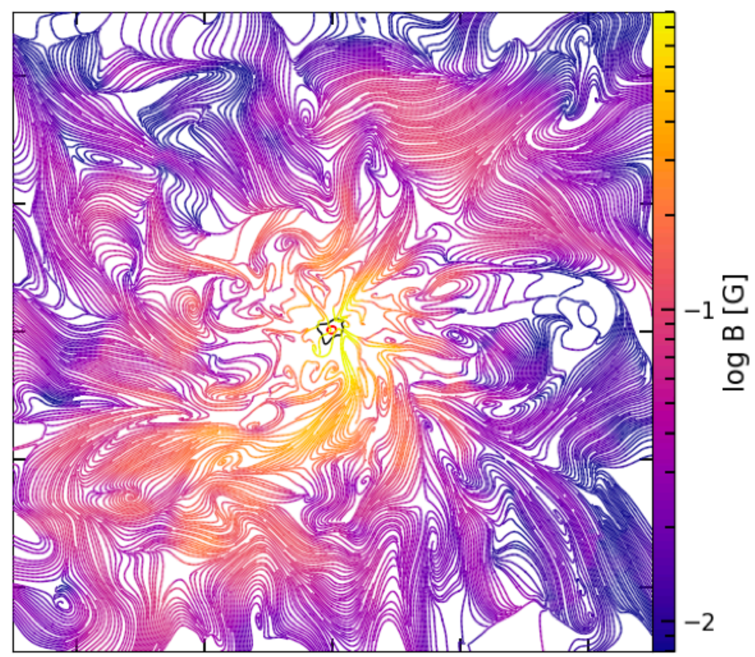
$B_{\rm init} = 10^{-8}$ G



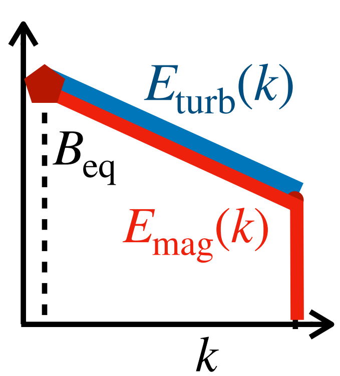
- $B_{\rm cent} < B_{\rm eq}$
- small scale-field



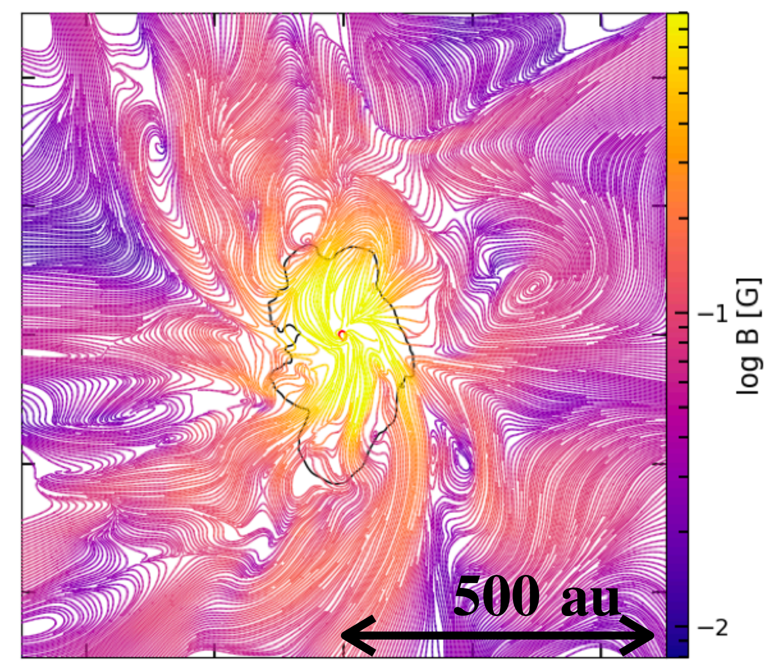
$B_{\rm init} = 10^{-7}$ G



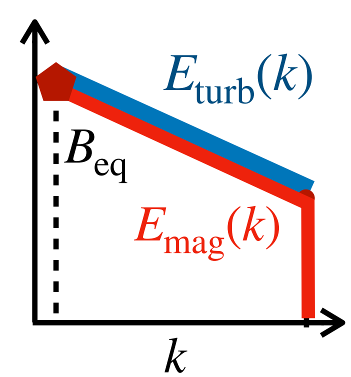
- $B_{\rm cent} \sim B_{\rm eq}$ in small area
- large scale-field



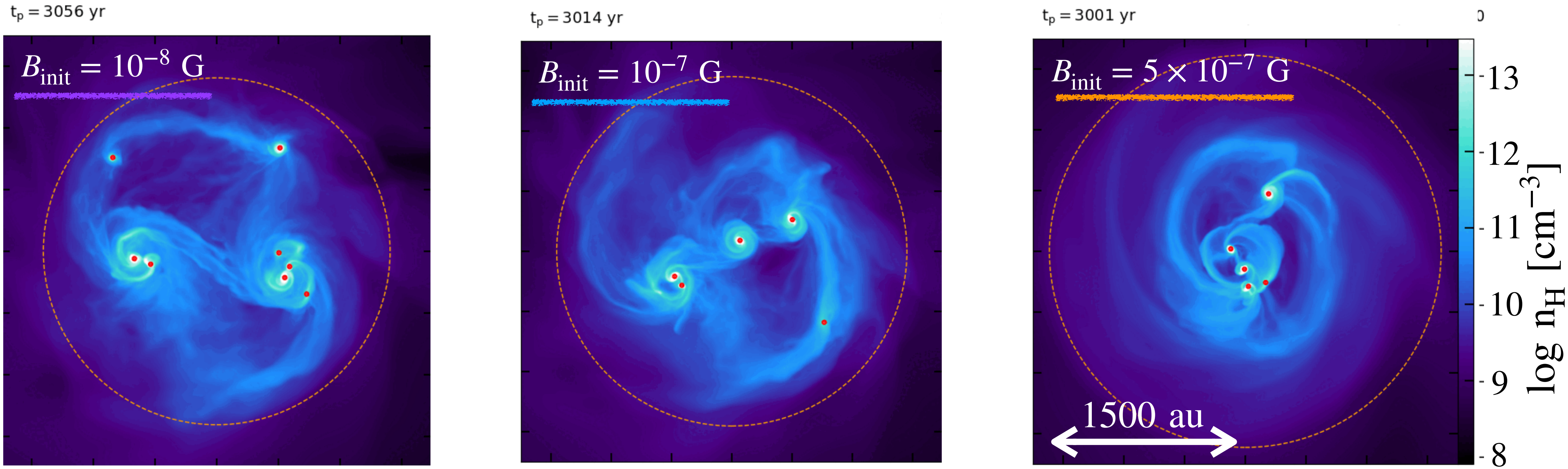
$B_{\rm init} = 5 \times 10^{-7}$ G



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



overview of accretion phase



orange circle indicates the disk region : $V_{rot}(R) > 3V_{rad}(R)$

- **multiplicity**

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

- **time evolution of the disk size and mass.**

  → almost the same in all different B-field cases.

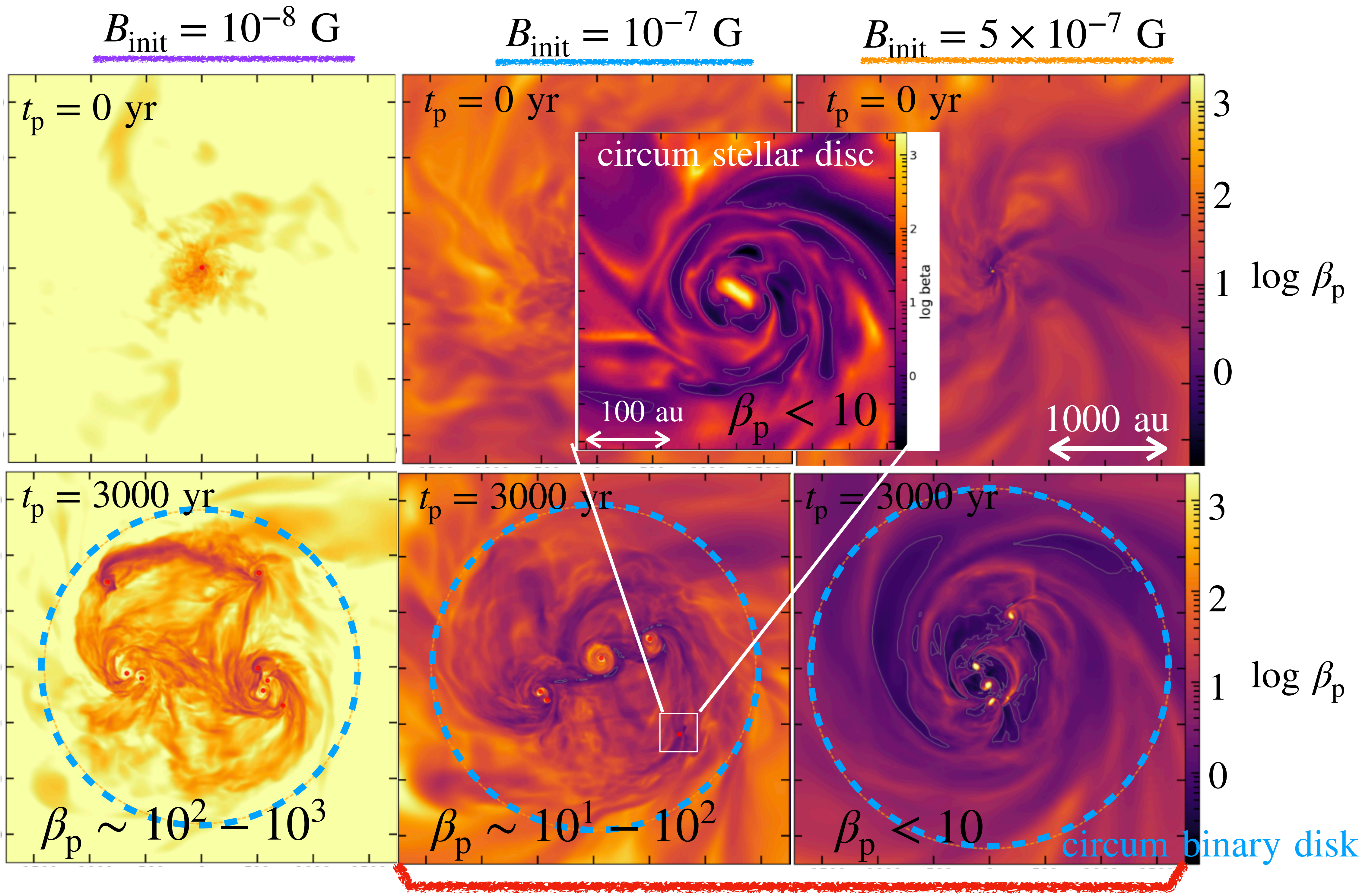
- **size of spiral arms(SAs) & gas distribution**

  → 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 circum-stellar/binary disks from the gravitational instability.

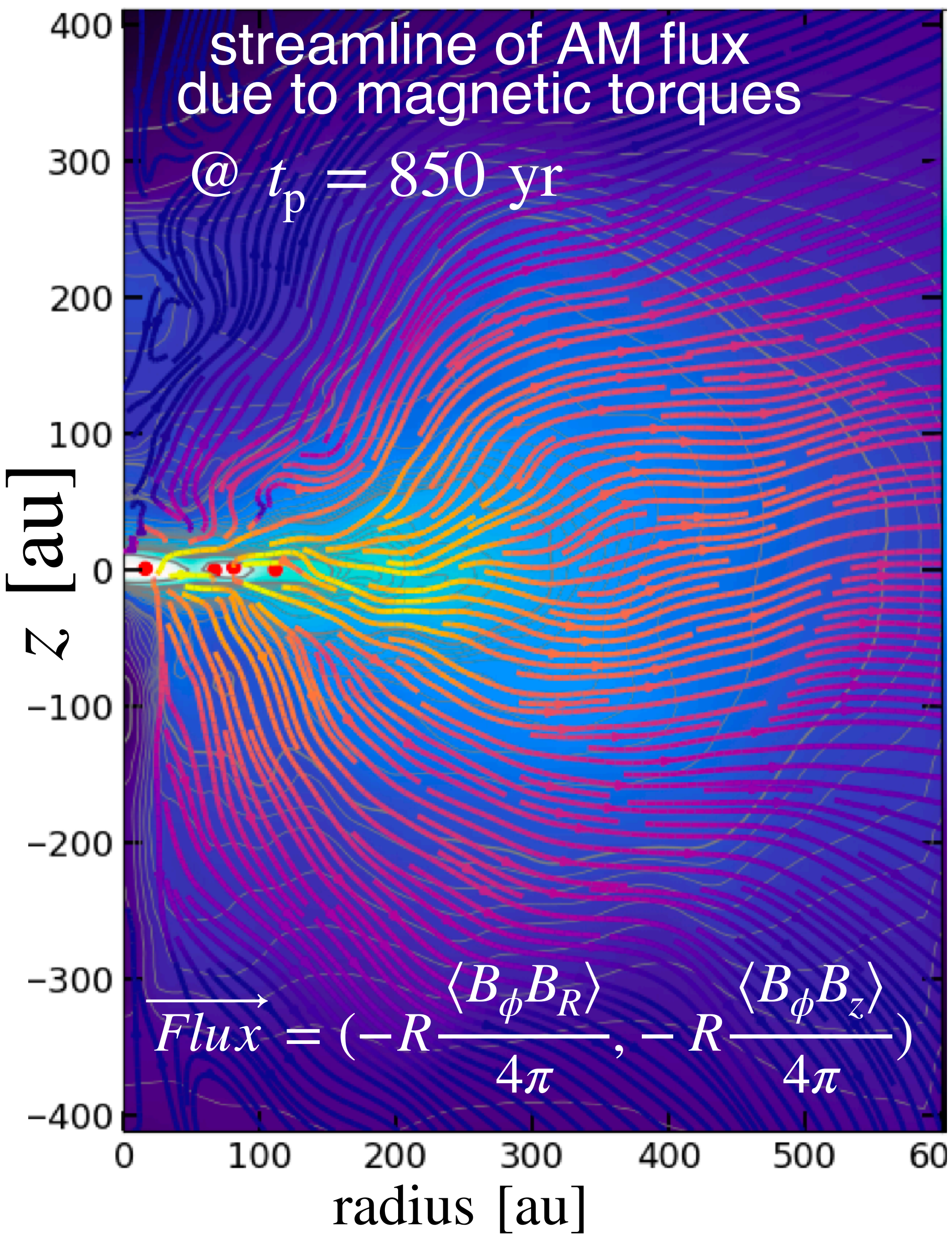
B-field effects : magnetic torques

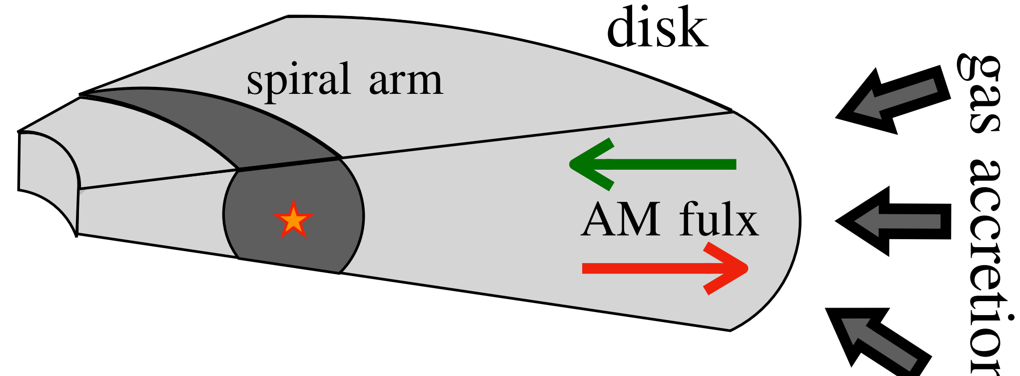
equation of AM conservation

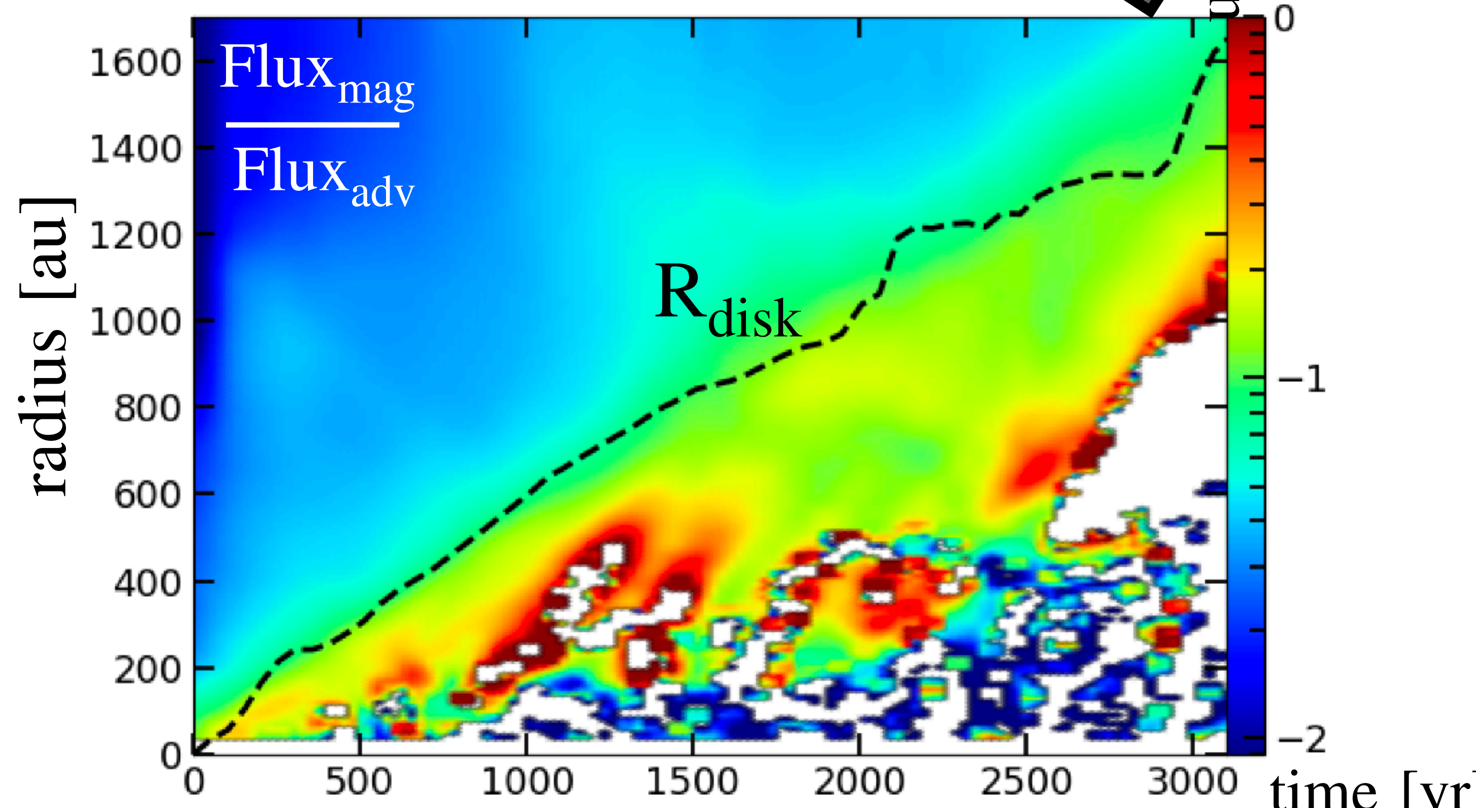
$$\partial_t \left(\rho r v_\phi\right) + \nabla \cdot r \left[\rho v_\phi \boldsymbol{v} + \left(P + \frac{B^2}{8\pi} - \frac{g^2}{8\pi G}\right)\boldsymbol{e}_\phi - \frac{B_\phi}{4\pi}\boldsymbol{B} + \frac{g_\phi}{4\pi G}\boldsymbol{g}\right] = 0,$$

$\mathrm{Flux_{adv}}$ (the $\rho v_\phi \boldsymbol{v}$ term) $\mathrm{Flux_{mag}}$ (the $\frac{B_\phi}{4\pi}\boldsymbol{B}$ term) $\mathrm{Flux_{grav}}$ (the $\frac{g_\phi}{4\pi G}\boldsymbol{g}$ term)

In the case of $B_{\mathrm{init}} = 5 \times 10^{-7}$ G





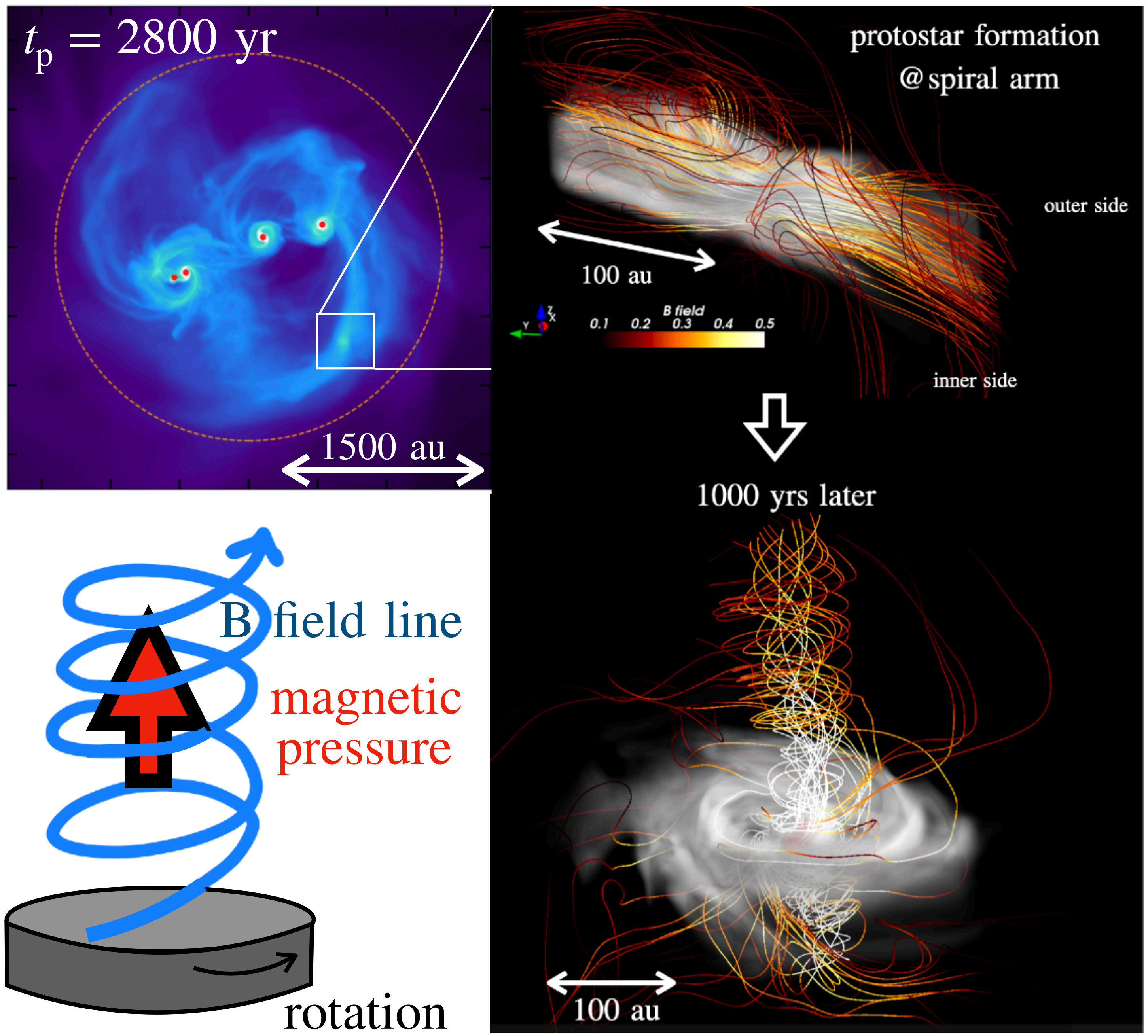


Magnetic torques transport AM radially within the disk.
→Gas accretion within the disk is promoted,
leading to the stabilization of the disk.

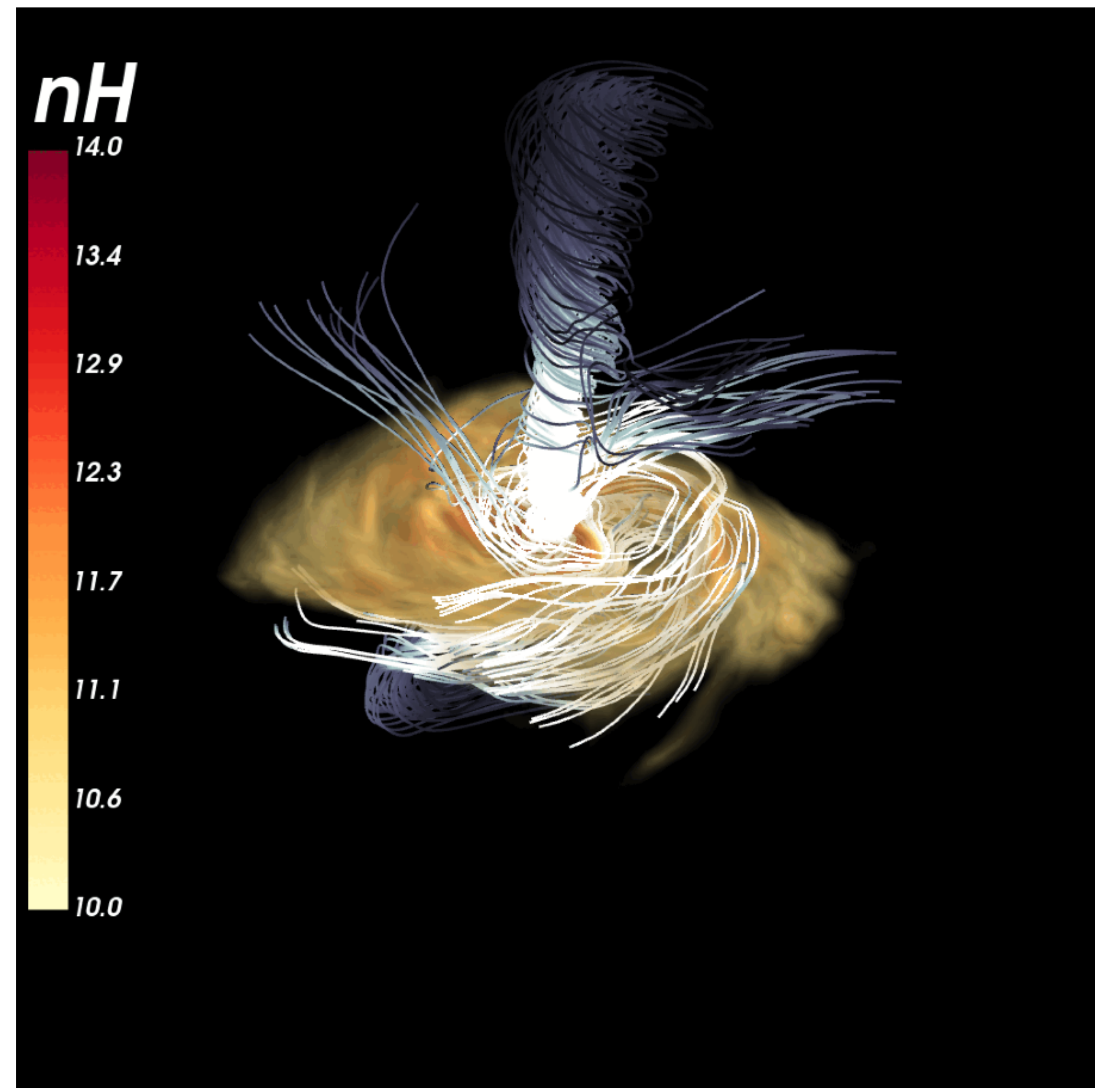
B-field effects : MHD outflow

magnetic pressure wind

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



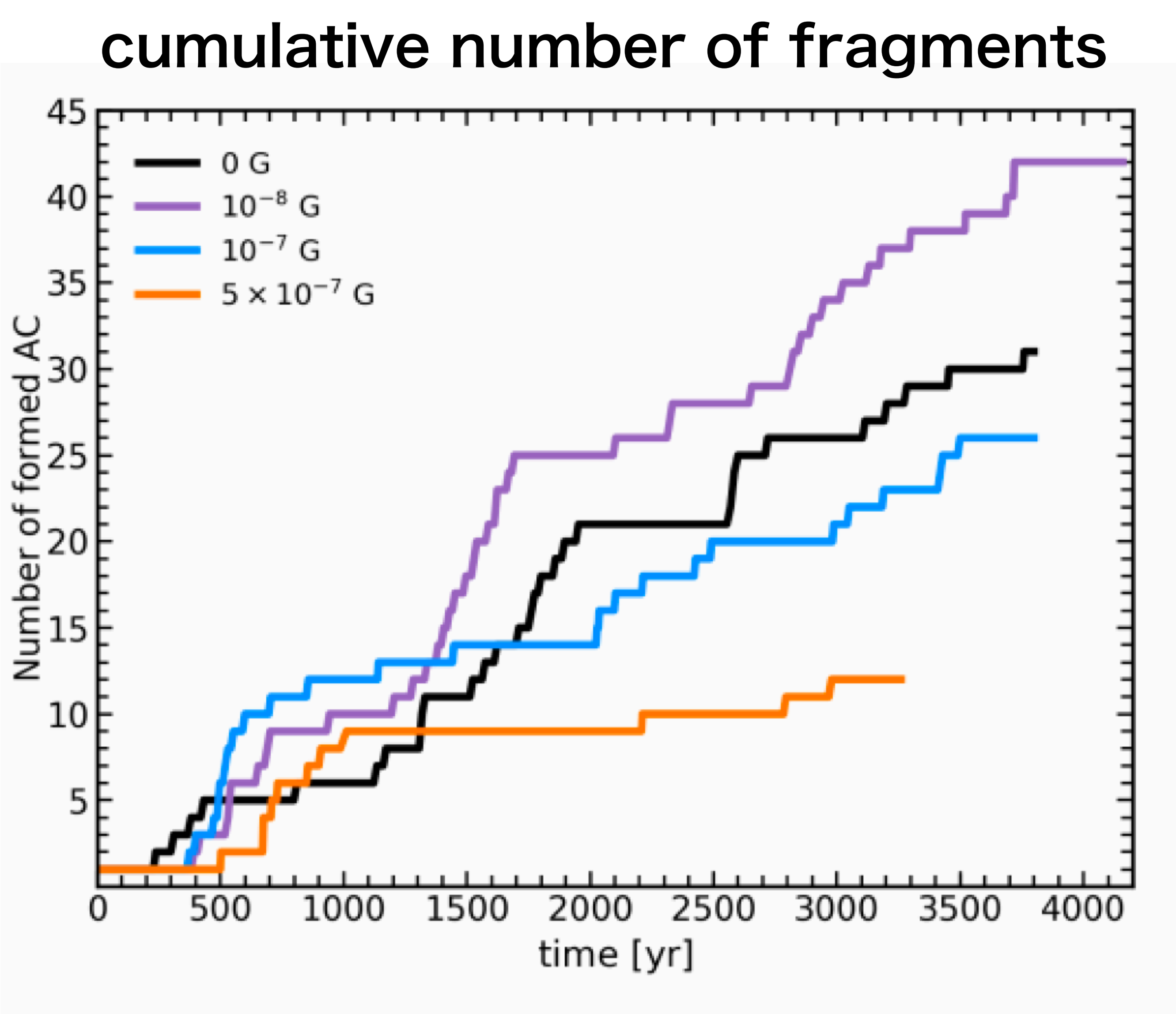
$B_{\rm init} = 5 \times 10^{-7}$ G

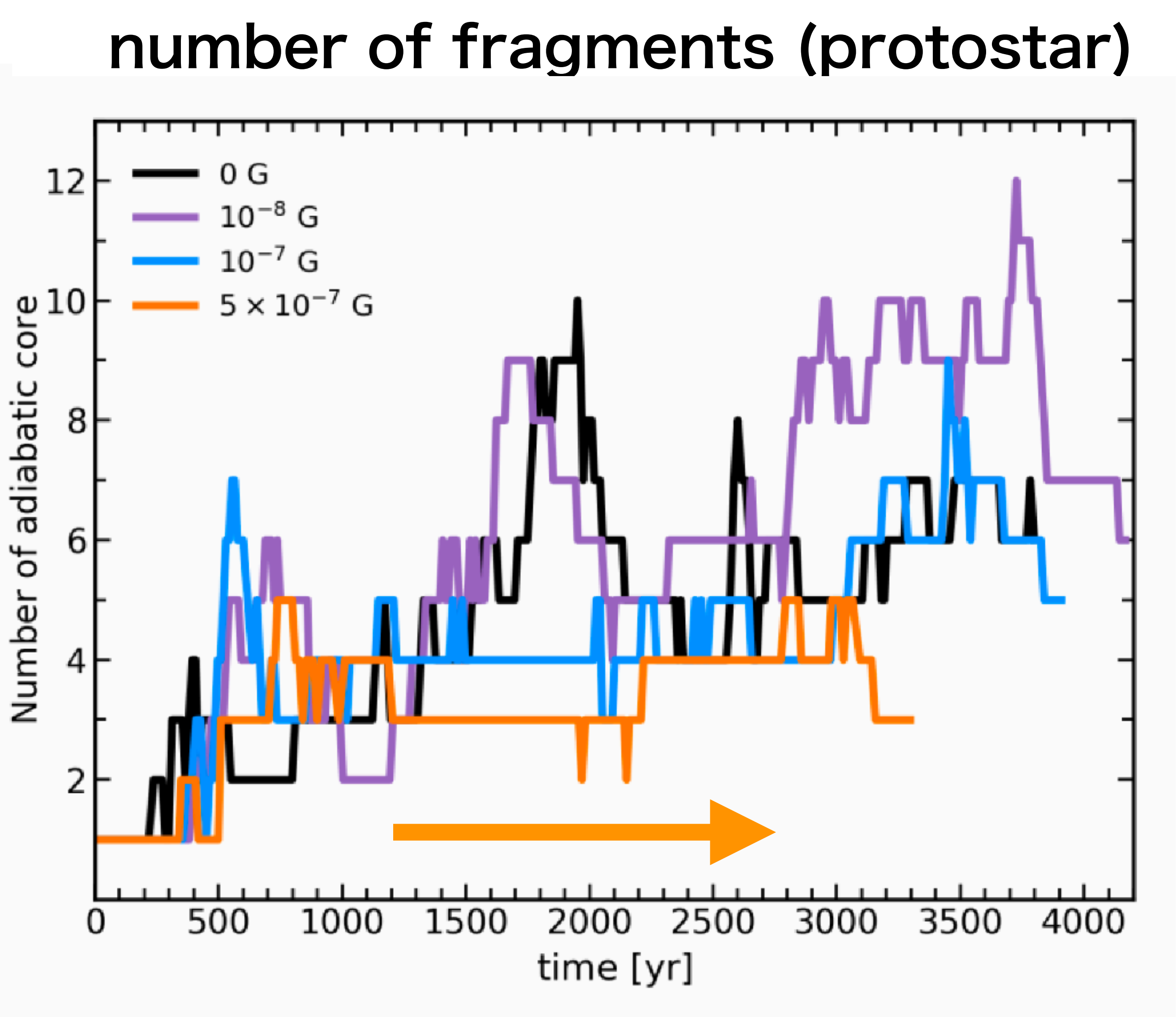


Due to being overpowered by the ram pressure of gas accretion, duration of winds are short.

The impact of gas ejection and angular momentum transport is minor.

magnetic effects on disc fragmentation





- 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

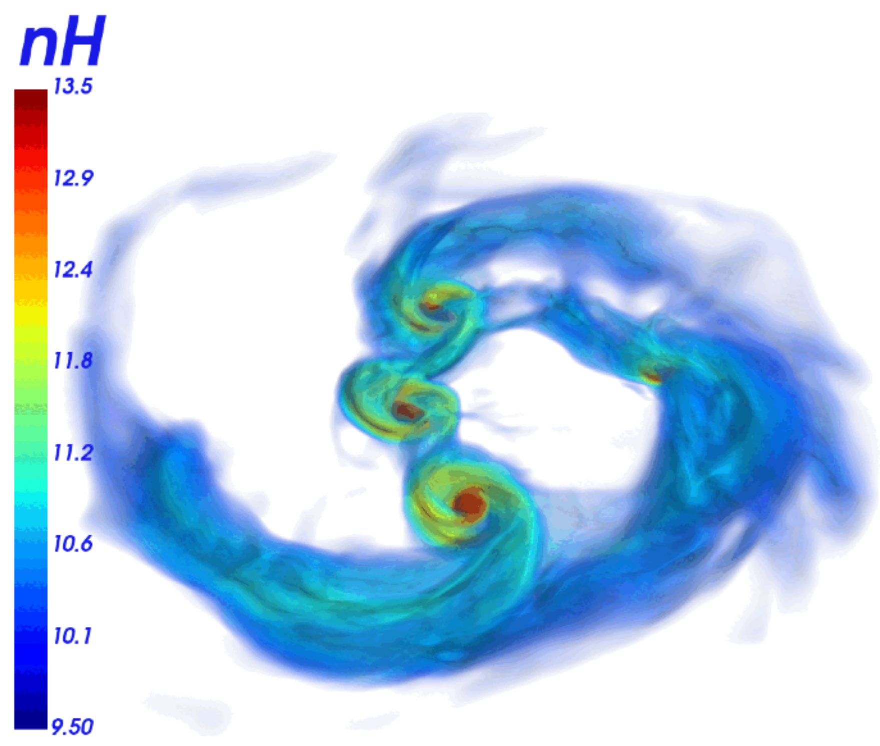
stabilizes the circum-stellar/binay disk.

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.