Formation of collapsing cores in magnetically subcritical clouds : three-dimensional simulations

Takahiro Kudoh (NAOJ)
Shantanu Basu (UWO)

国立天文台 NAOJ National Astronomical Observatory of Japan

Western

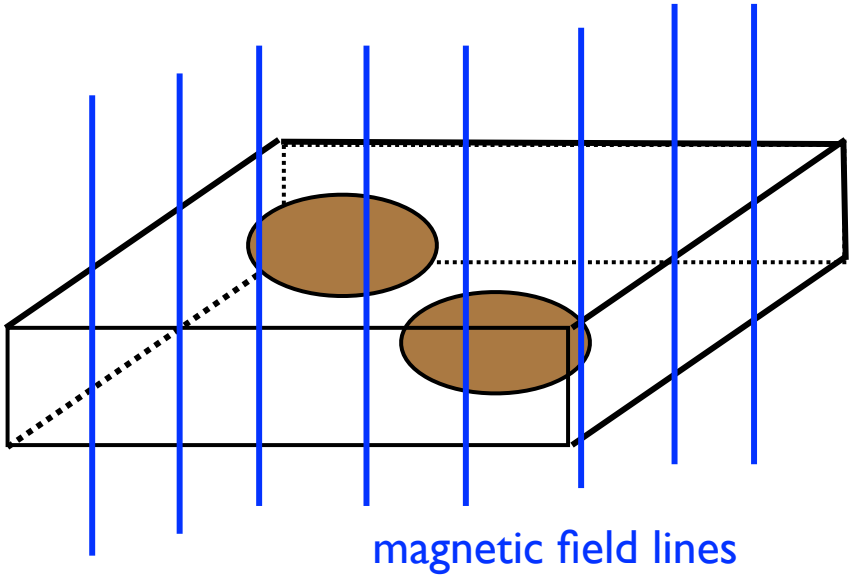
Magnetic fields : From Core Collapse to Young Stellar Objects, May 19, 2010

Gravitational instability of a gas layer

The gas layer is gravitationally unstable

$$\lambda \simeq 4\pi H_0$$

H_0 : scale height



Effect of the magnetic field

Where magnetic flux-freezing applies; Nakano & Nakamura 1978

$\mu = 2\pi G^{1/2}\dfrac{\Sigma}{B} > 1$ Supercritical cloud: fragmentation

$\mu = 2\pi G^{1/2}\dfrac{\Sigma}{B} < 1$ Subcritical cloud: no fragmentation

Ambipolar diffusion

Molecular clouds have weakly ionized gas: $\frac{n_i}{n_n} \simeq 10^{-7}$ for $n_n \simeq 10^4 \mathrm{cm}^{-3}$

Ambipolar diffusion occurs

Even “subcritical” clouds can undergo fragmentation instability due to ambipolar diffusion, i.e. ion-neutral slip.

- Gravitational Fragmentation (linear perturbations)

dynamic
if supercritical

$$\mu = 2\pi G^{1/2}\frac{\Sigma}{B} > 1$$

~10^6 years

quasistatic ambipolar-diffusion
if subcritical

$$\mu = 2\pi G^{1/2}\frac{\Sigma}{B} < 1$$

~10^7 - 10^8 years
slow core formation

- Turbulent fragmentation (nonlinear perturbations)

supercritical

many studies...

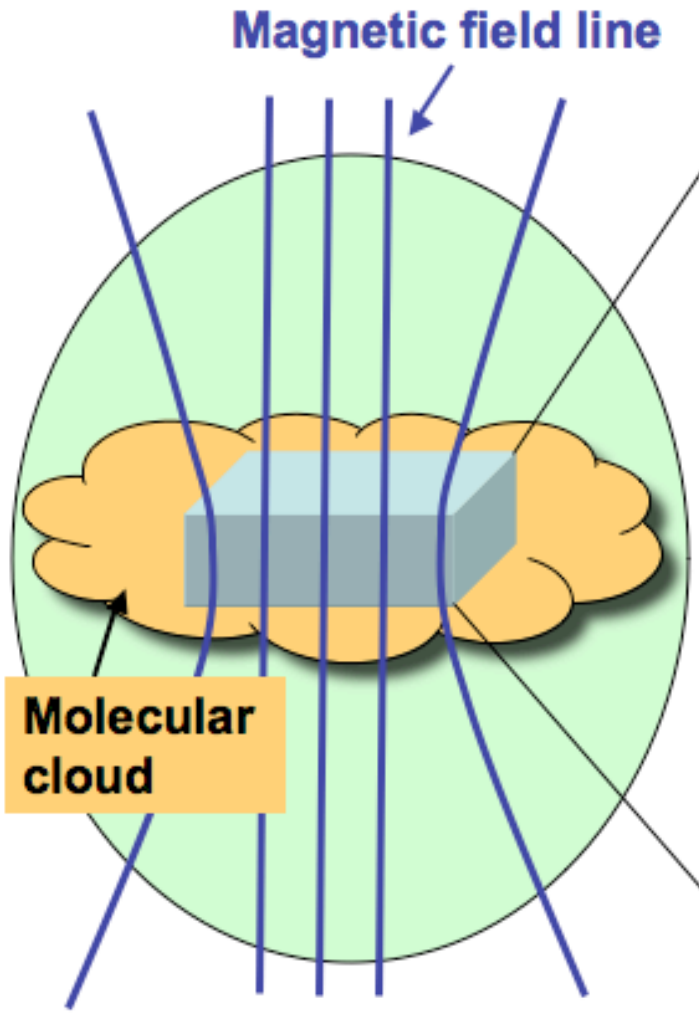
subcritical

~10^6 years

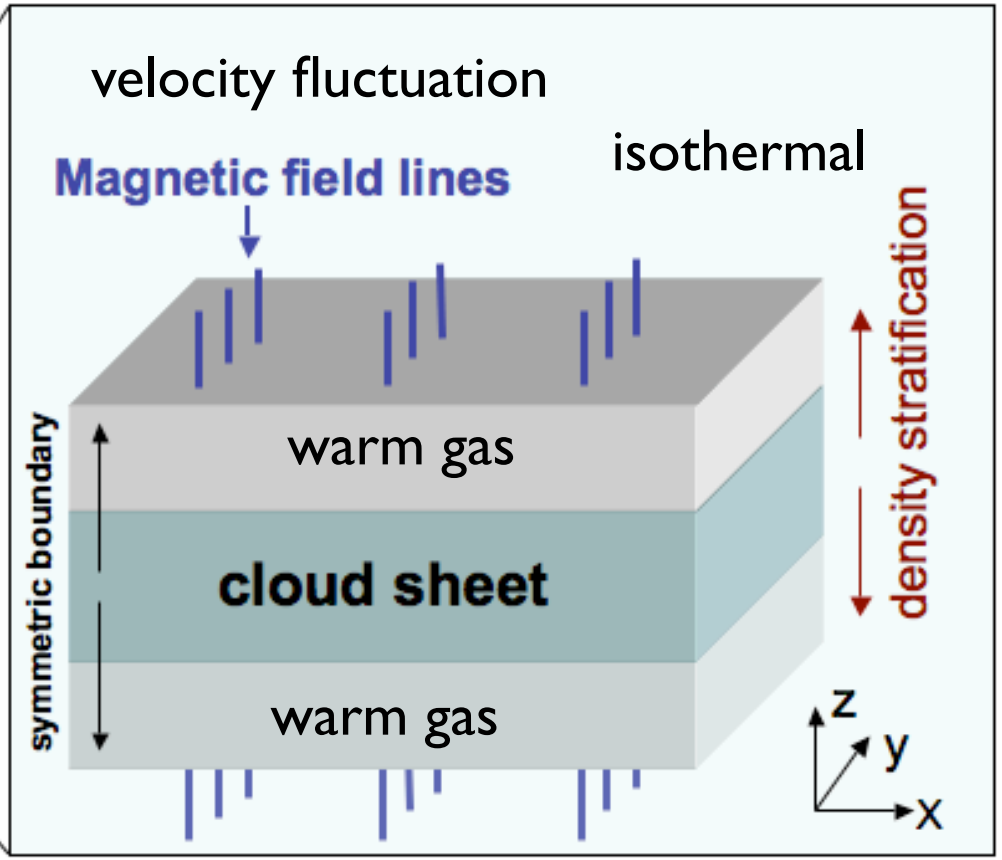
Zweibel (2002), Li & Nakamura (2004)
Basu et al. (2009), Nakamura & Li (2008)

3D-MHD numerical simulation:

e.g., Kudoh, Basu, Ogata, Yabe (2007), MNRAS, 380, 499



3D-MHD with ambipolar diffusion

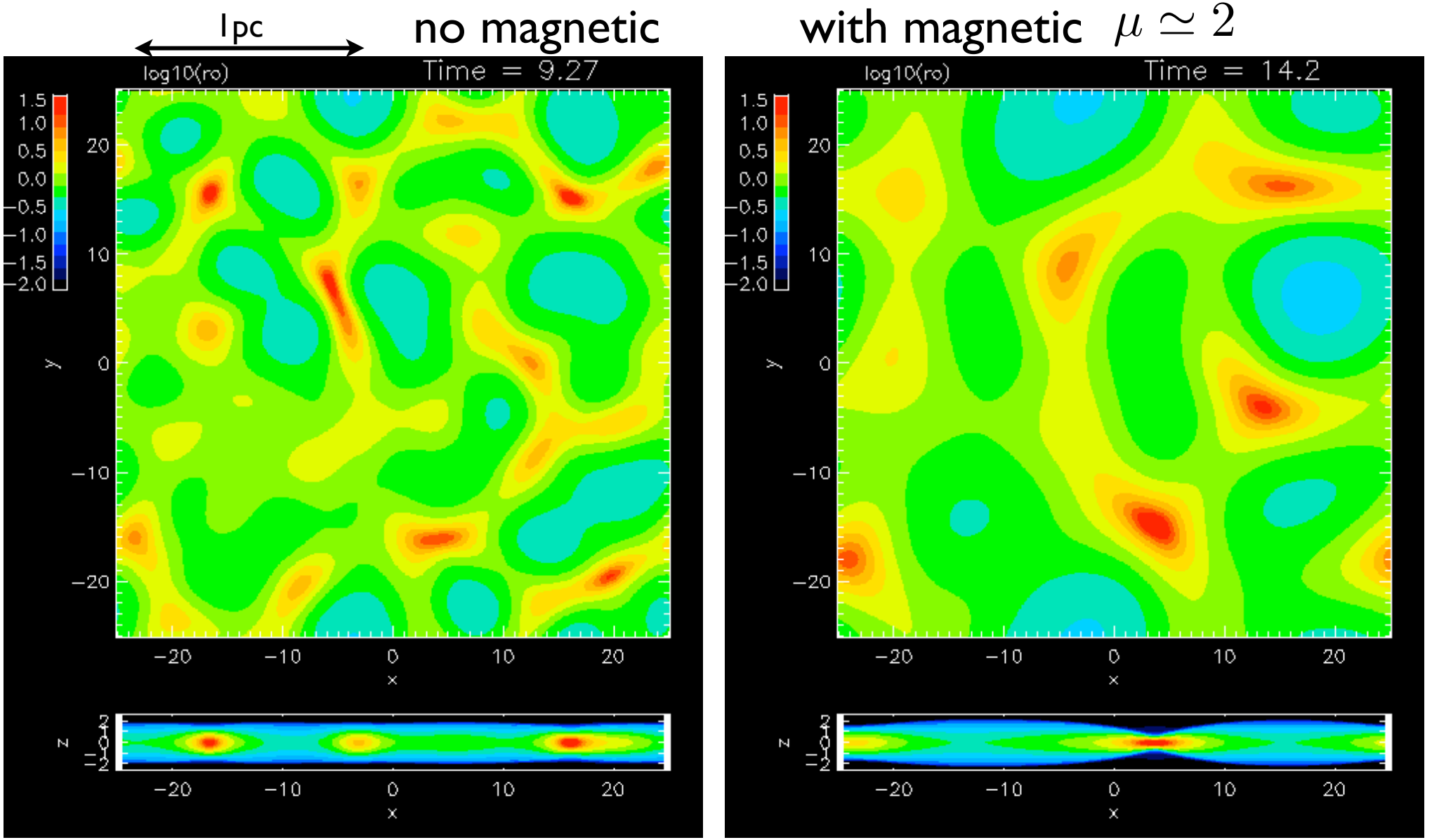


cf.

3D-HD: Miyama, et al. (1987)

Thin disk-MHD: Basu & Ciolek (2004)

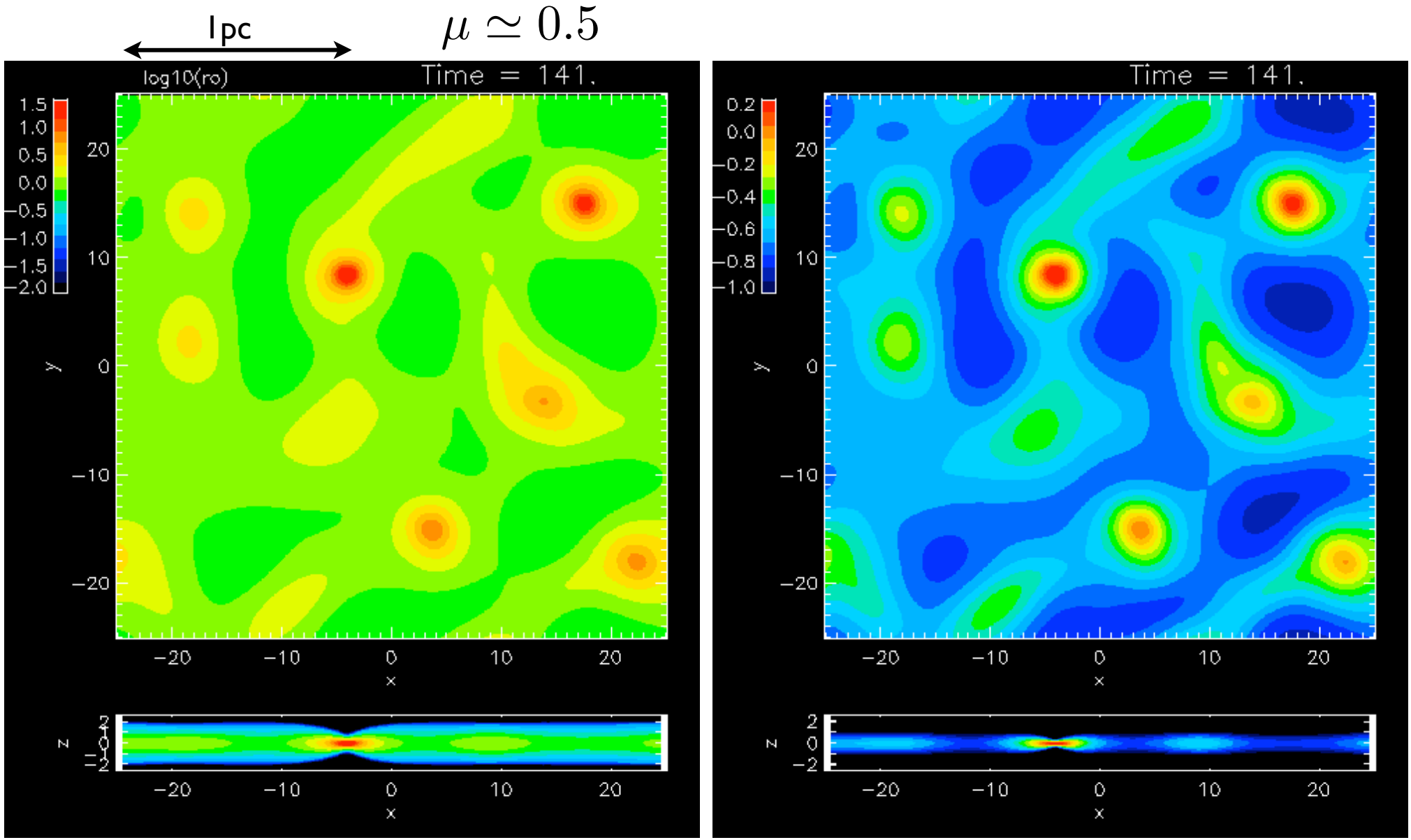
supercritical with small velocity fluctuation



density

$t_0 \simeq 2.5 \times 10^5 years$

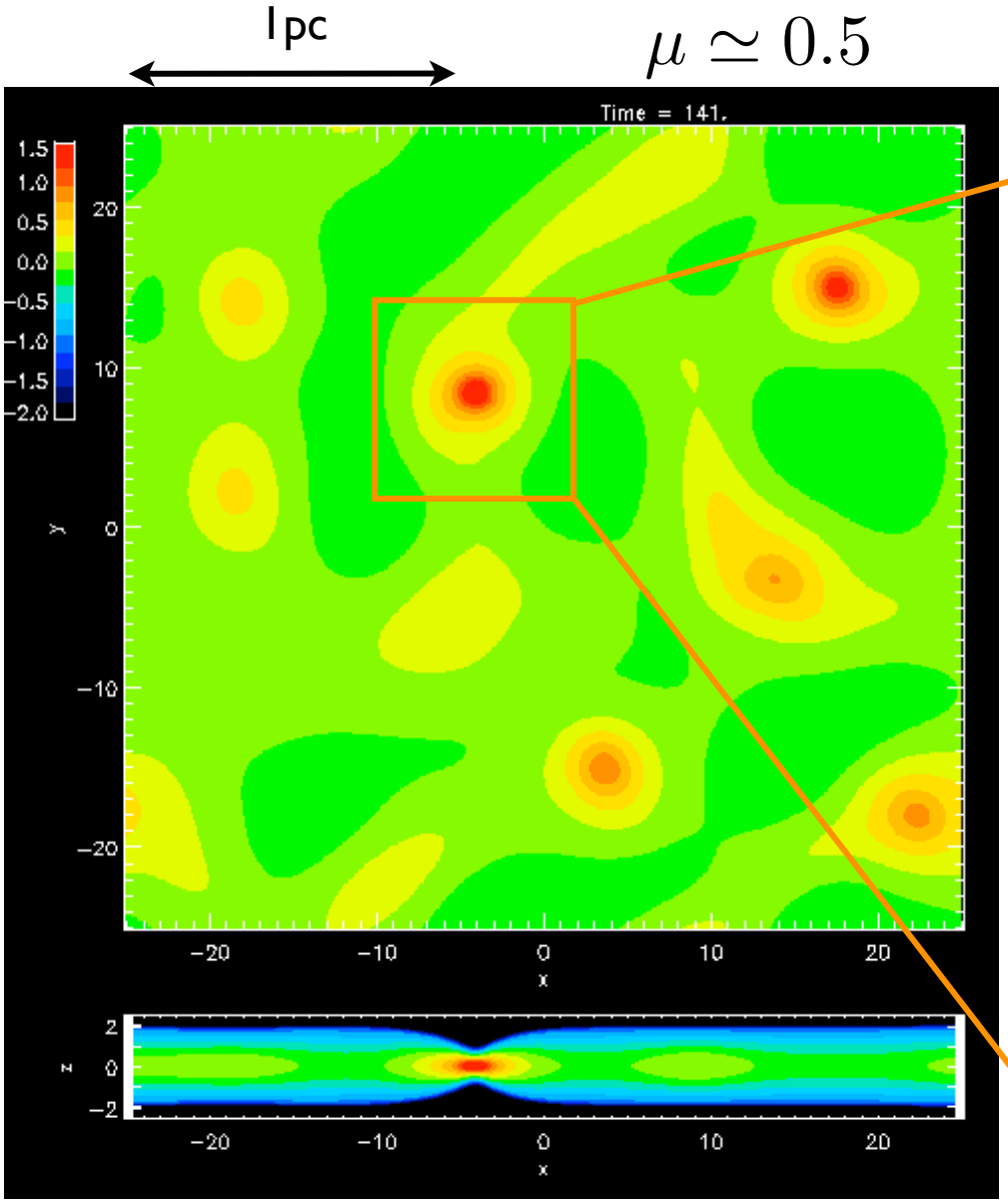
subcritical with small velocity fluctuation



density

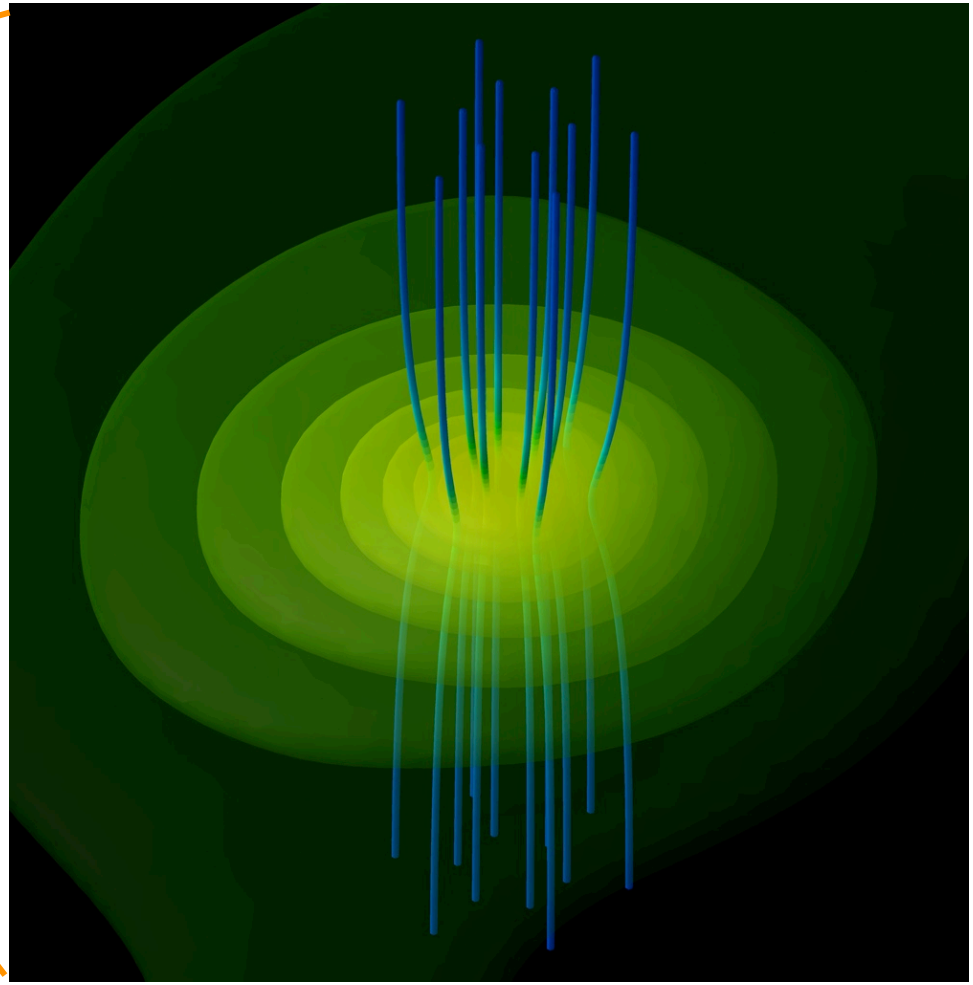
$\mu^2 \simeq \beta_{z=0} = P_{gas}/P_{mag}$

subcritical with small velocity fluctuation



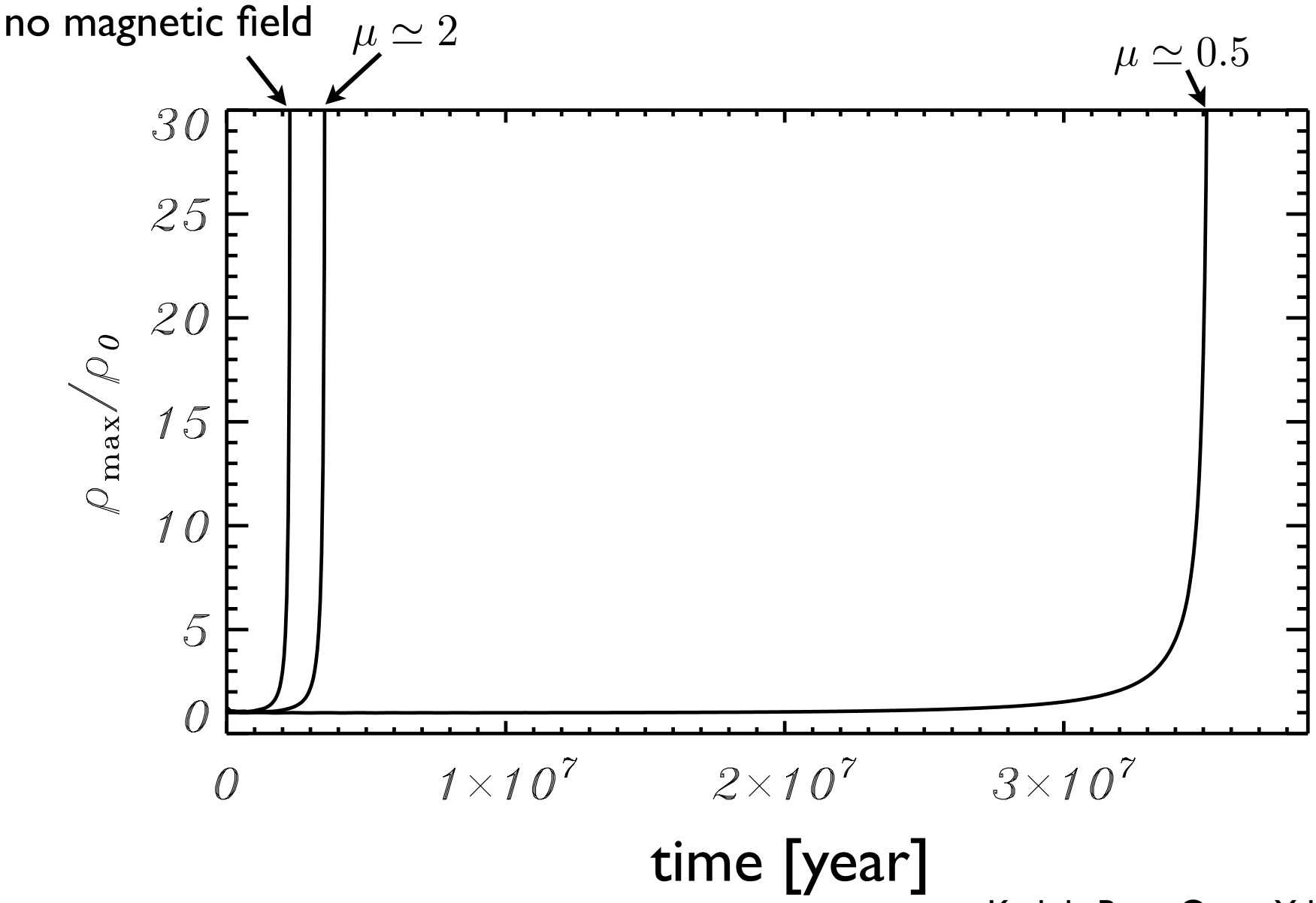
density

density and magnetic field lines



- Oblate-like structure of a core
- Hourglass-shaped magnetic field lines

Time evolution of the maximum density



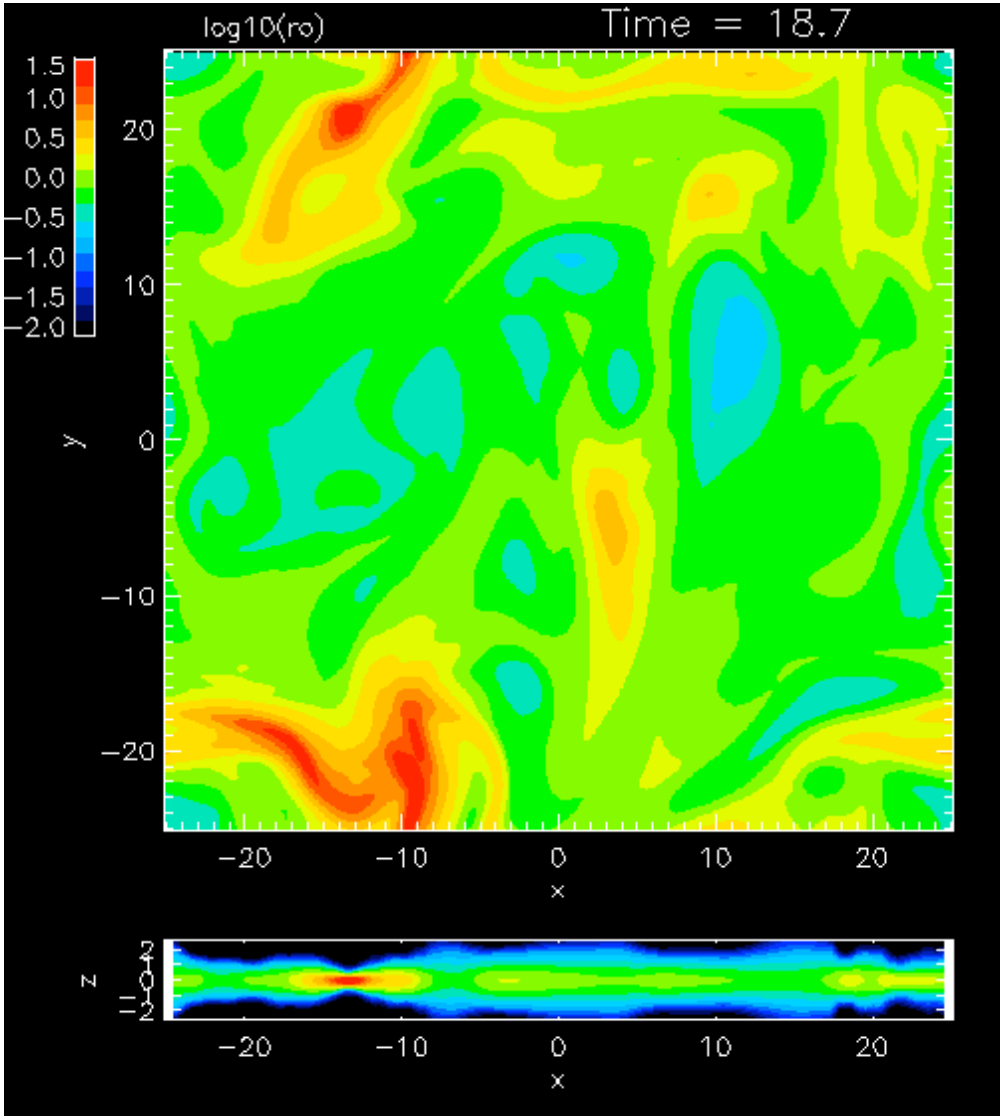
Kudoh, Basu, Ogata, Yabe (2007)

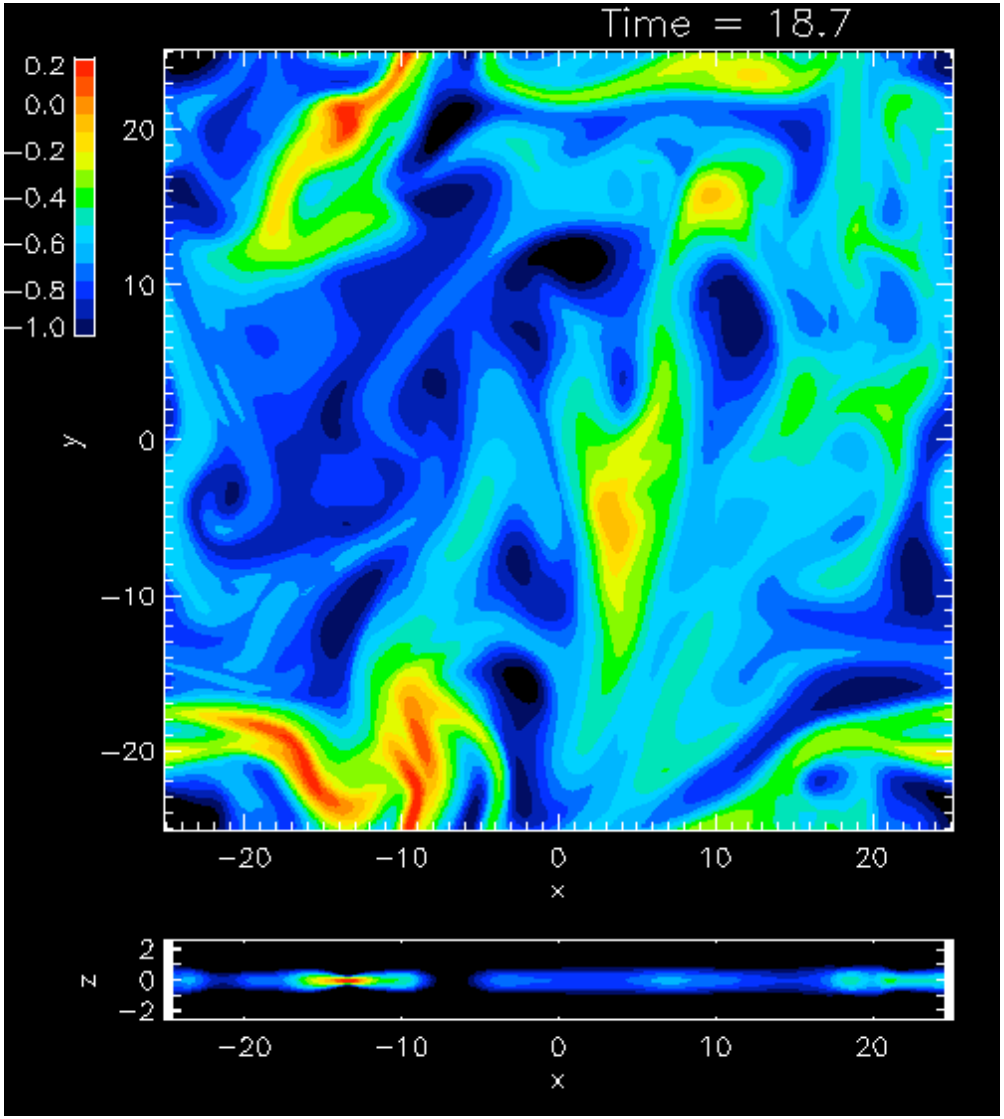
subcritical with large velocity fluctuation

1pc

$\mu \simeq 0.5$

$< v_a > \simeq 3 c_s \;\; v_a^2 \propto k^{-4}$





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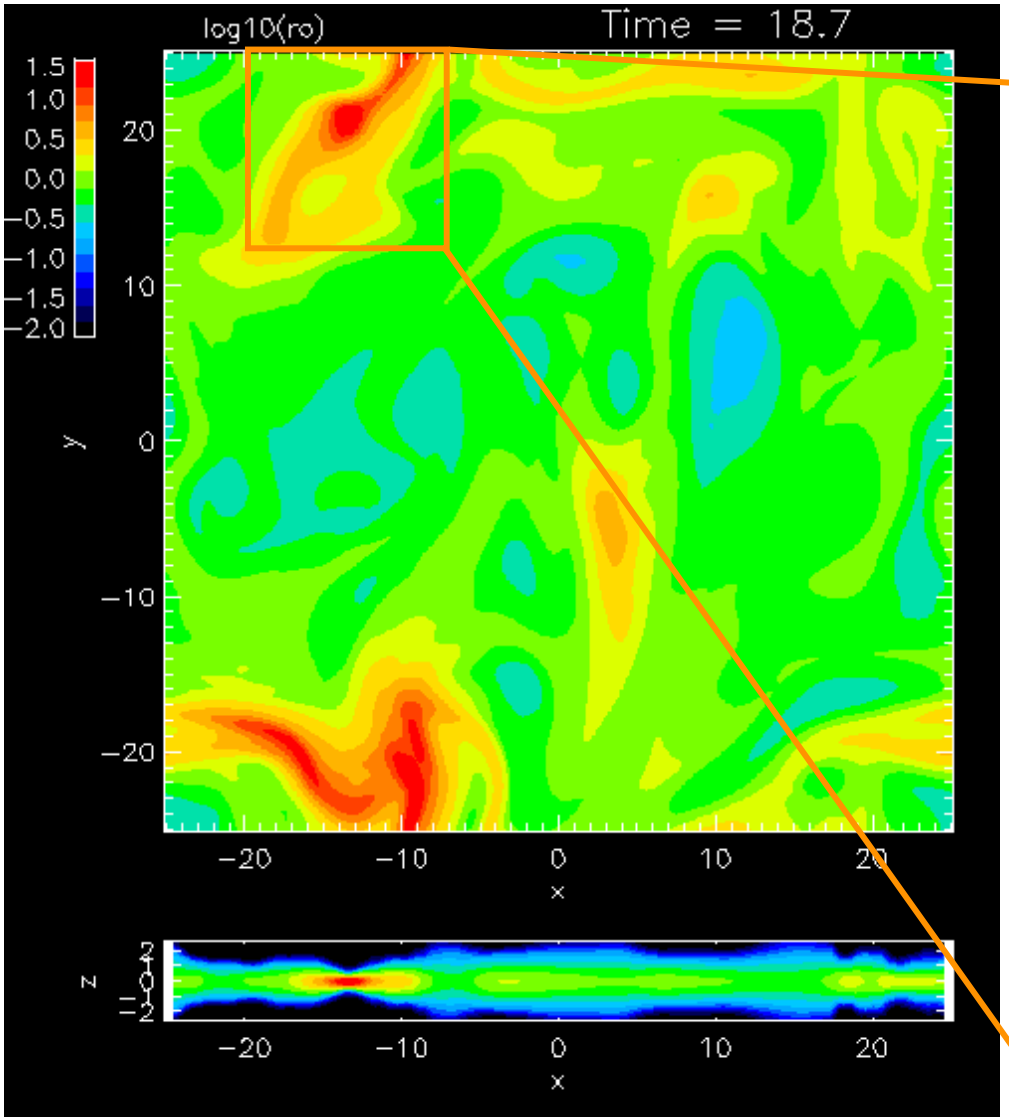
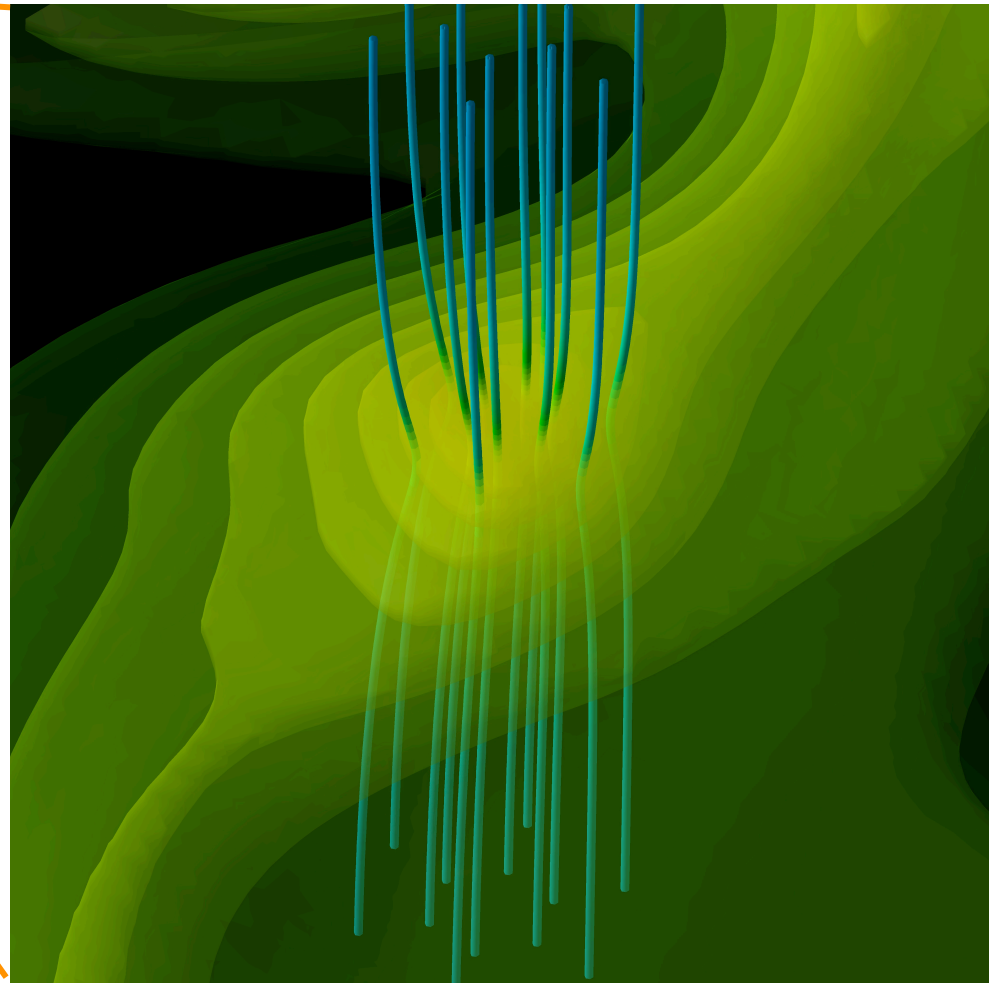
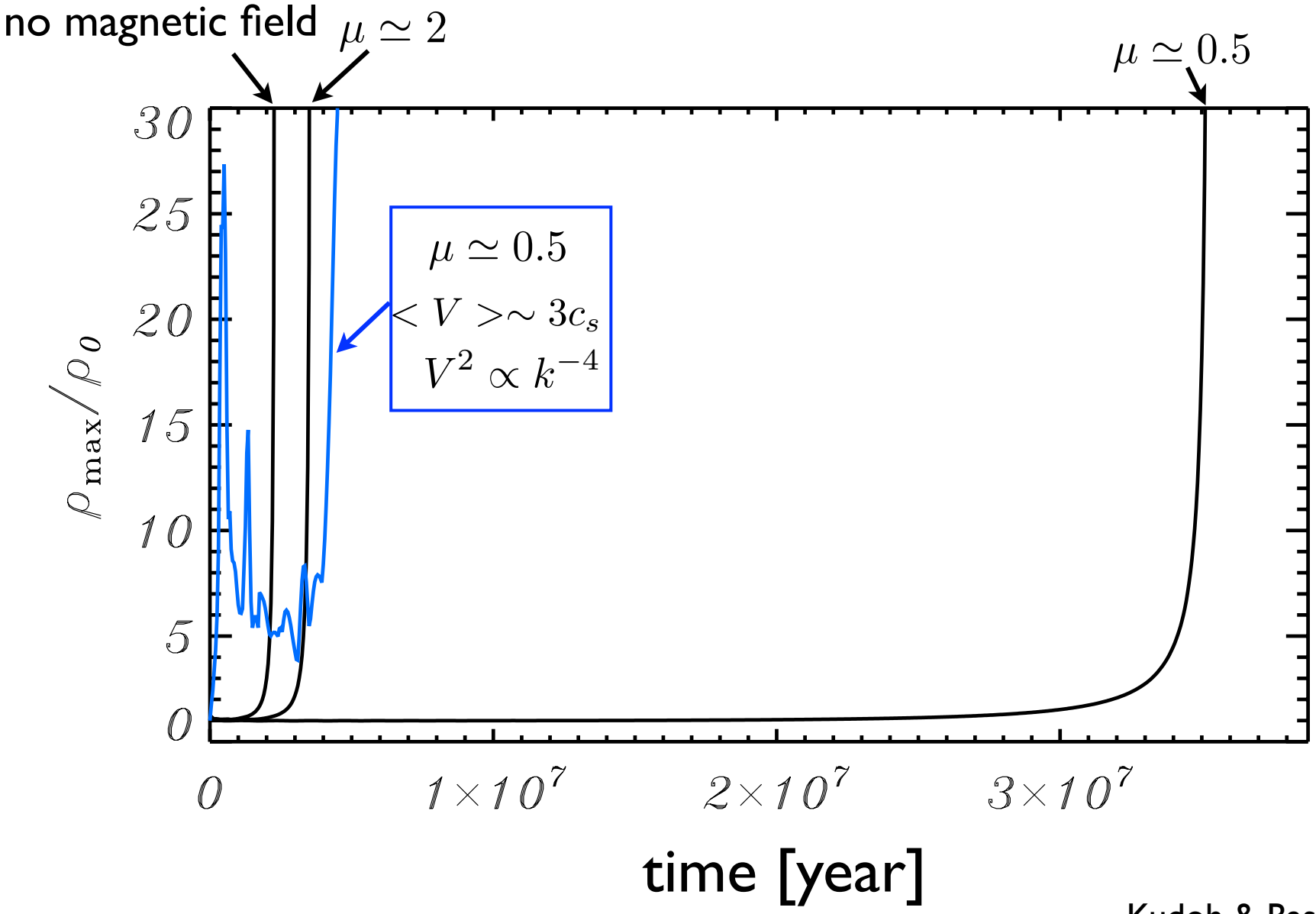


density and magnetic field lines



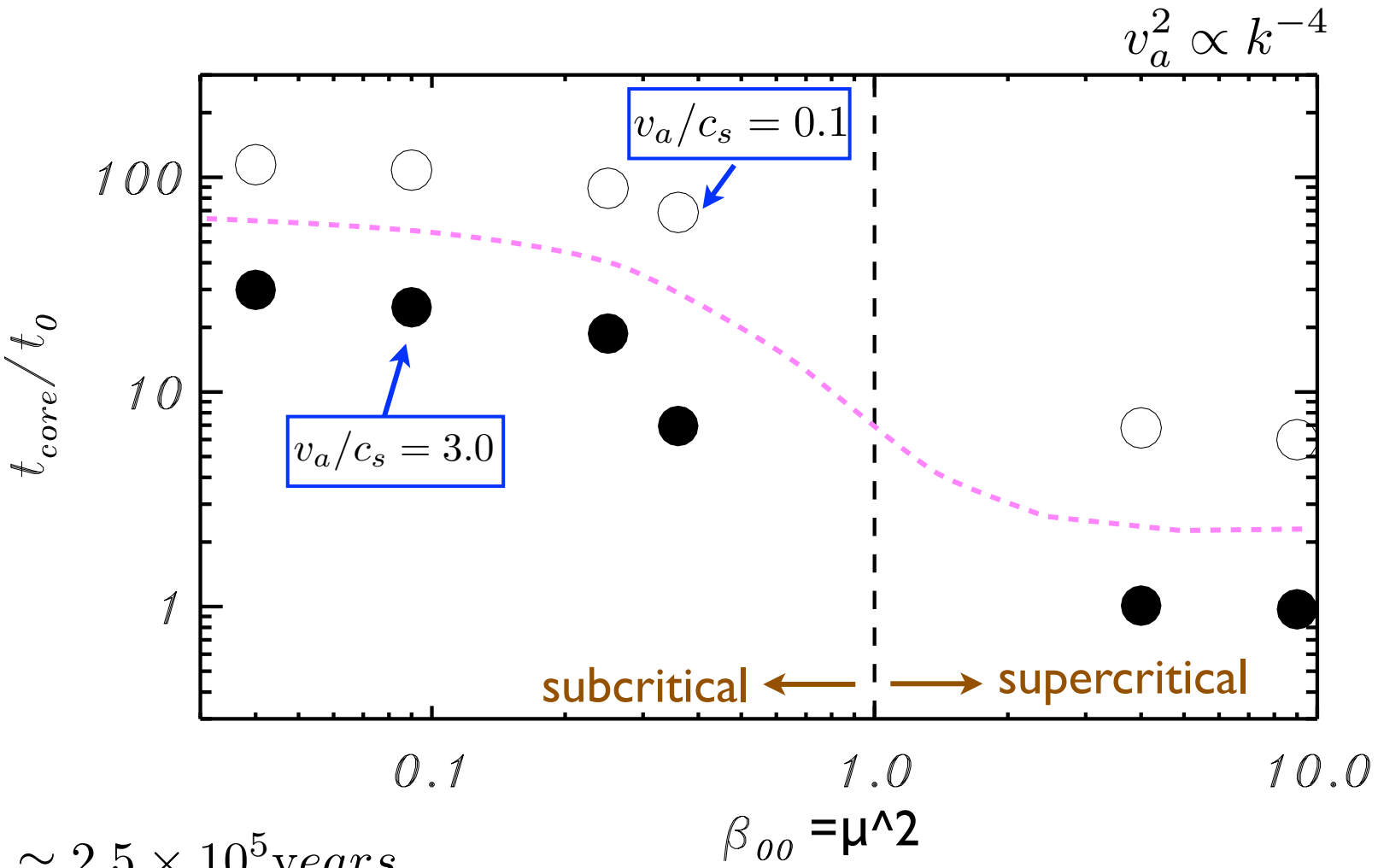
- A core in a filamentary structure
- Hourglass-shaped magnetic field lines

Time evolution of the maximum density



Kudoh & Basu (2008)

Core formation time as a function of (mass-to-flux ratio)^2

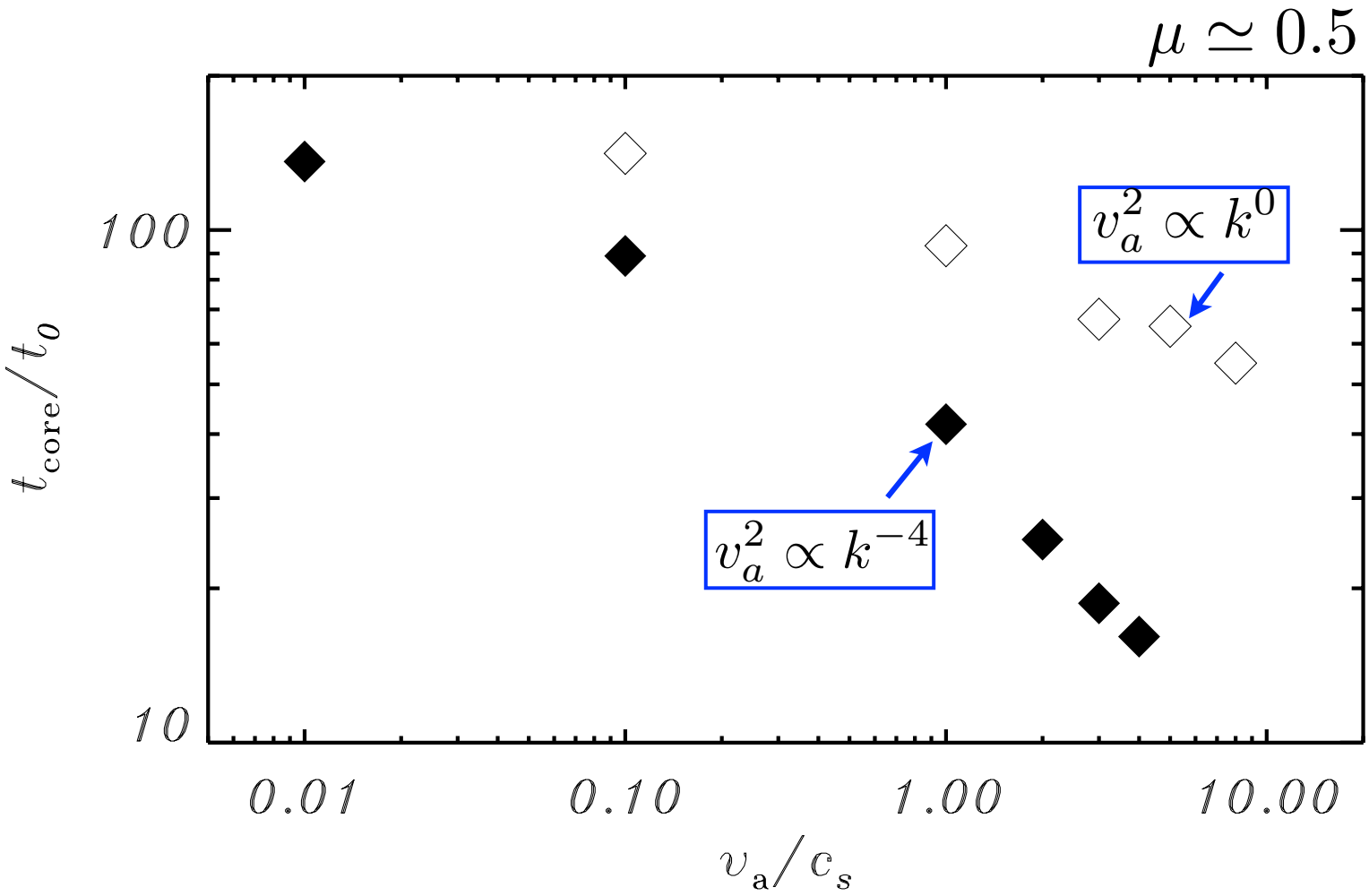


$t_0 \simeq 2.5 \times 10^5 years$

The same tendency as the linear theory.

Kudoh & Basu in prep.

Core formation time as a function of the strength of the initial velocity fluctuation

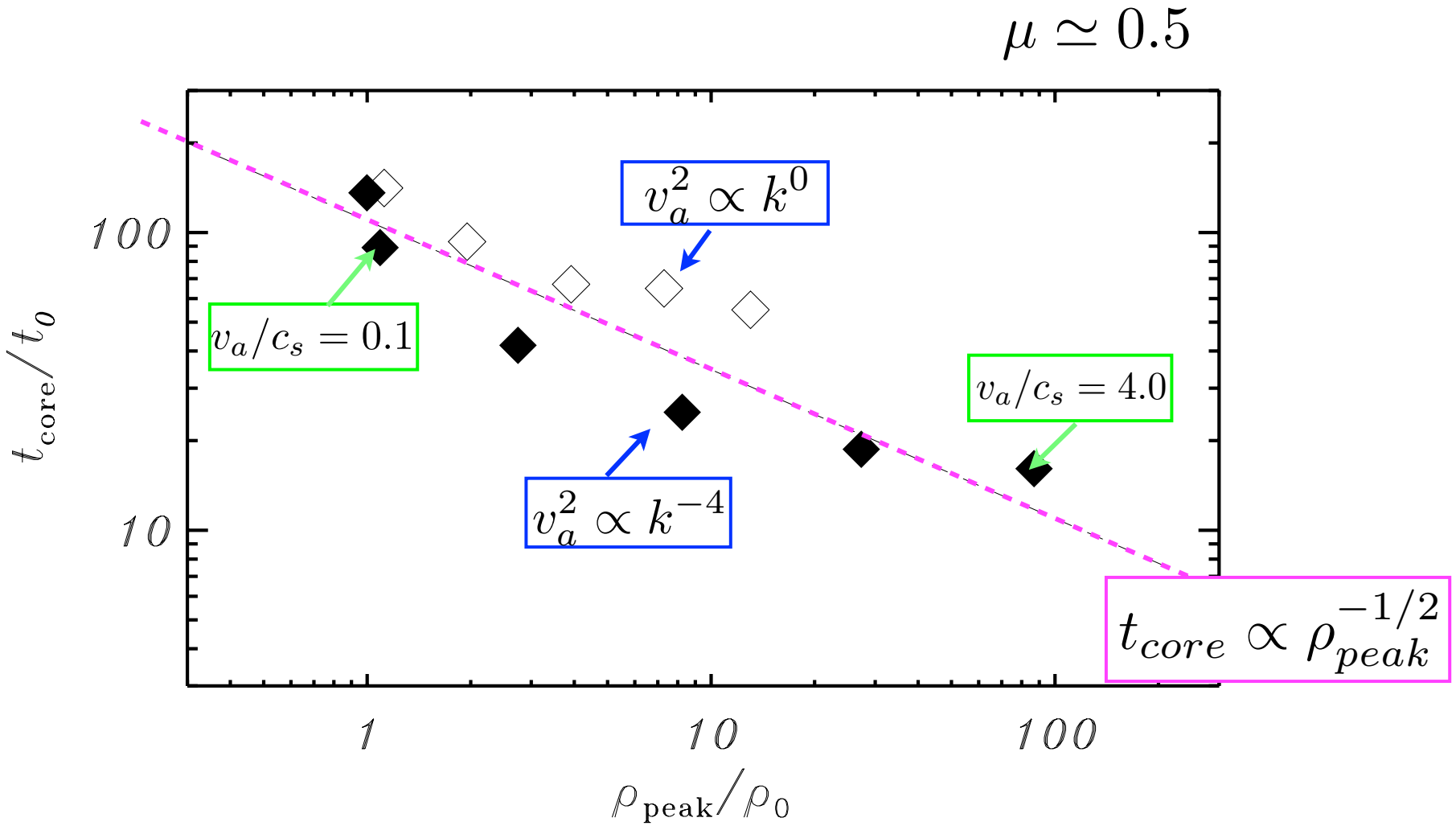


$t_0 \simeq 2.5 \times 10^5 years$

Kudoh & Basu in prep.

Larger velocity fluctuations shows smaller time.

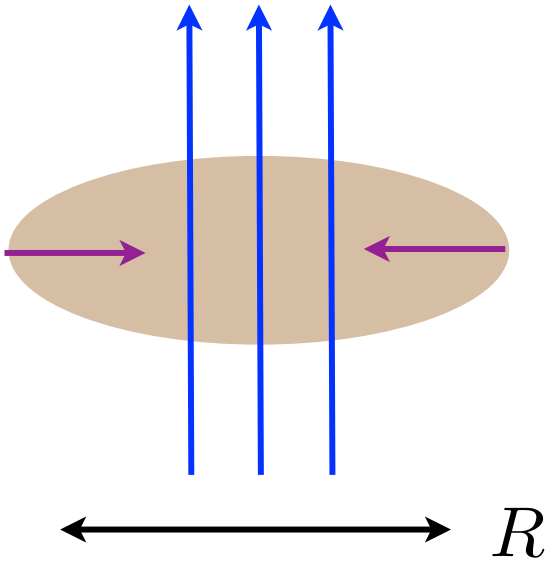
Core formation time as a function of the peak density in the initial compression



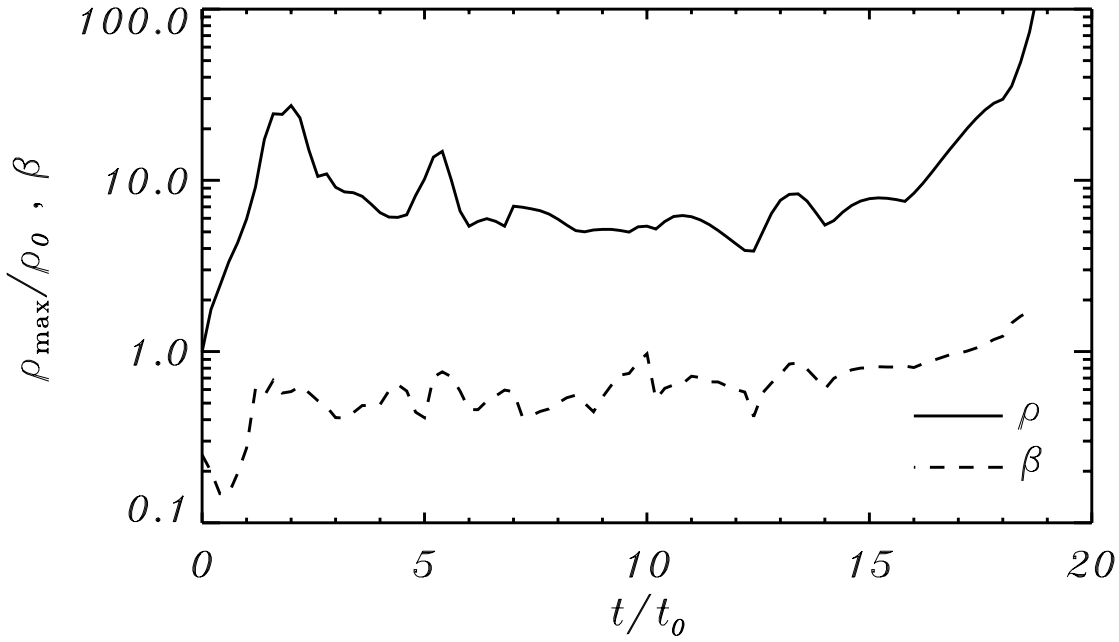
Kudoh & Basu in prep.

Ambipolar diffusion occurs very efficiently at the first strong compression.

assume 1D compression
before reaching force balance



time evolution of the maximum density

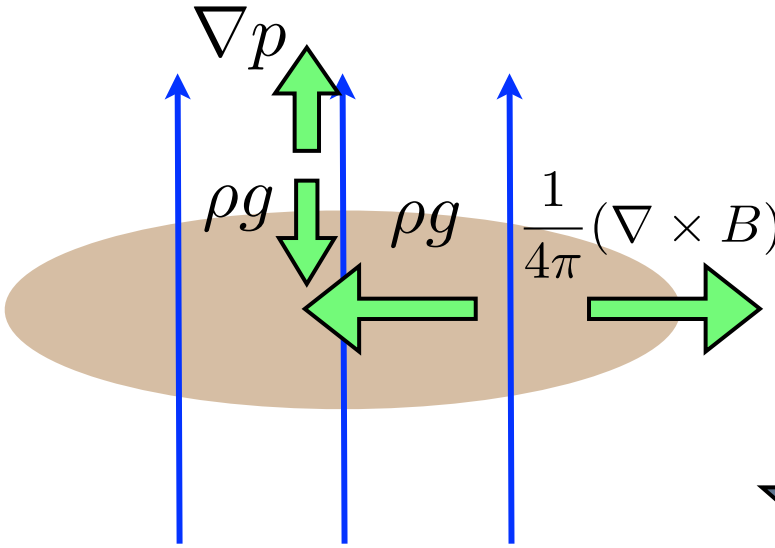


$$B \propto R^{-1}$$
$$\Sigma \propto B$$
$$\rho \propto \Sigma$$

$$\Rightarrow \quad \tau_{AD(sc)} \propto \frac{\rho^{3/2} R^2}{B^2} \propto R^{5/2} \propto \rho^{-5/2}$$

Σ :surface density

Time scale of the core formation in subcritical cloud (Mouschovias & Ciolek1999)



$$\rho g \simeq \frac{1}{4\pi}(\nabla \times B) \times B$$

if we assume the force balance

$$\tau_{AD(fb)} \propto \rho^{-1/2} \sim 10 - 100 \tau_{ff}$$

τ_{ff} :free fall time

$$\tau_{AD(fb)} >> \tau_{AD(sc)}$$

We can use the same formula with the peak density, even when the force balance is not exact.

Conclusions

- The core formation time is generally large (~10^7 years), but it is shortened (~10^6 years) by the large velocity fluctuation.
- The core formation time scales as

$$t_{core} \propto \rho_{peak}^{-1/2}$$

- Final hourglass shape of the magnetic field for both small and large initial velocity fluctuation.