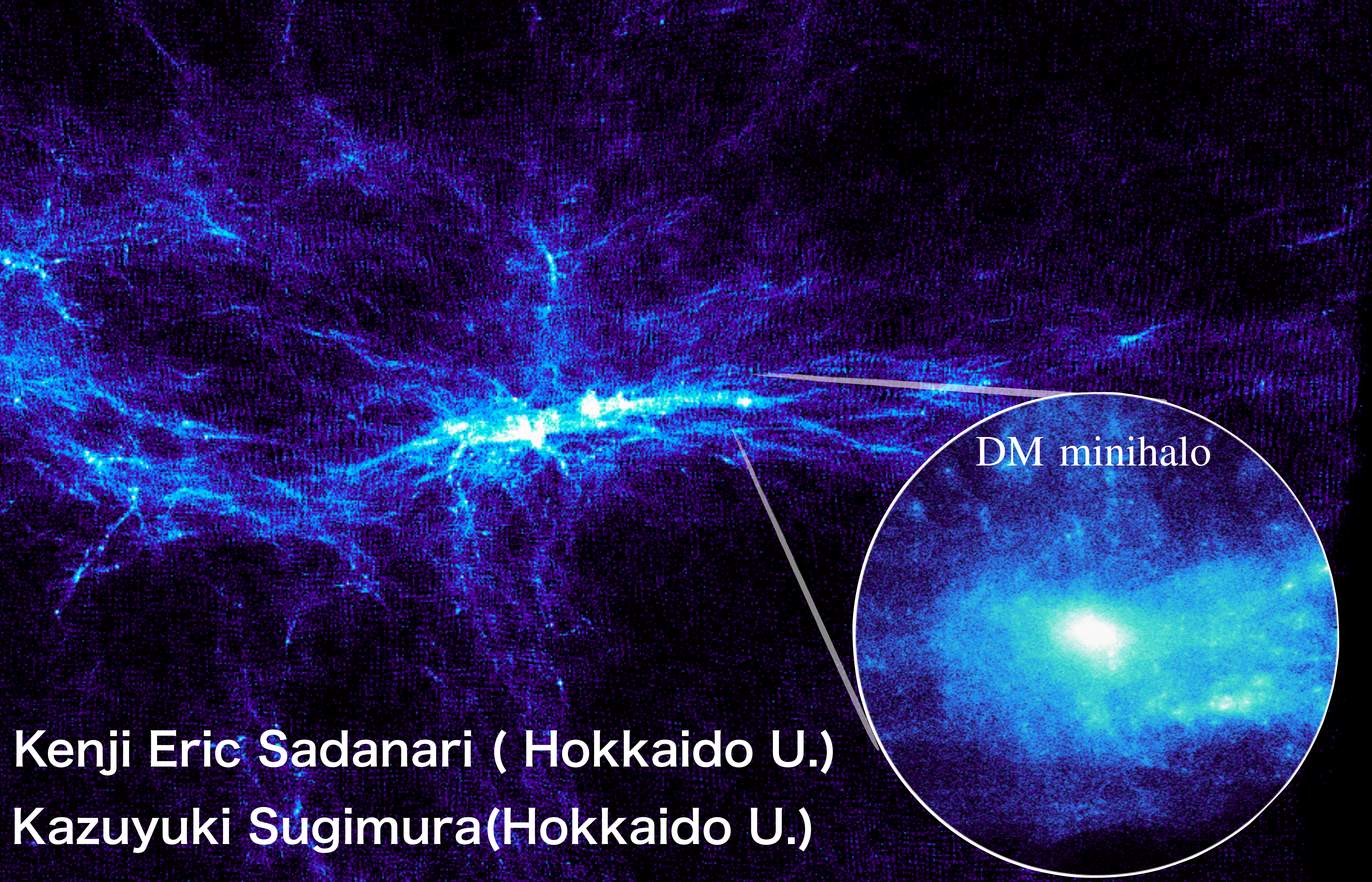
Exploring the Nature of PopIII Star-Forming Clouds with Zoom-in Cosmological Simulation



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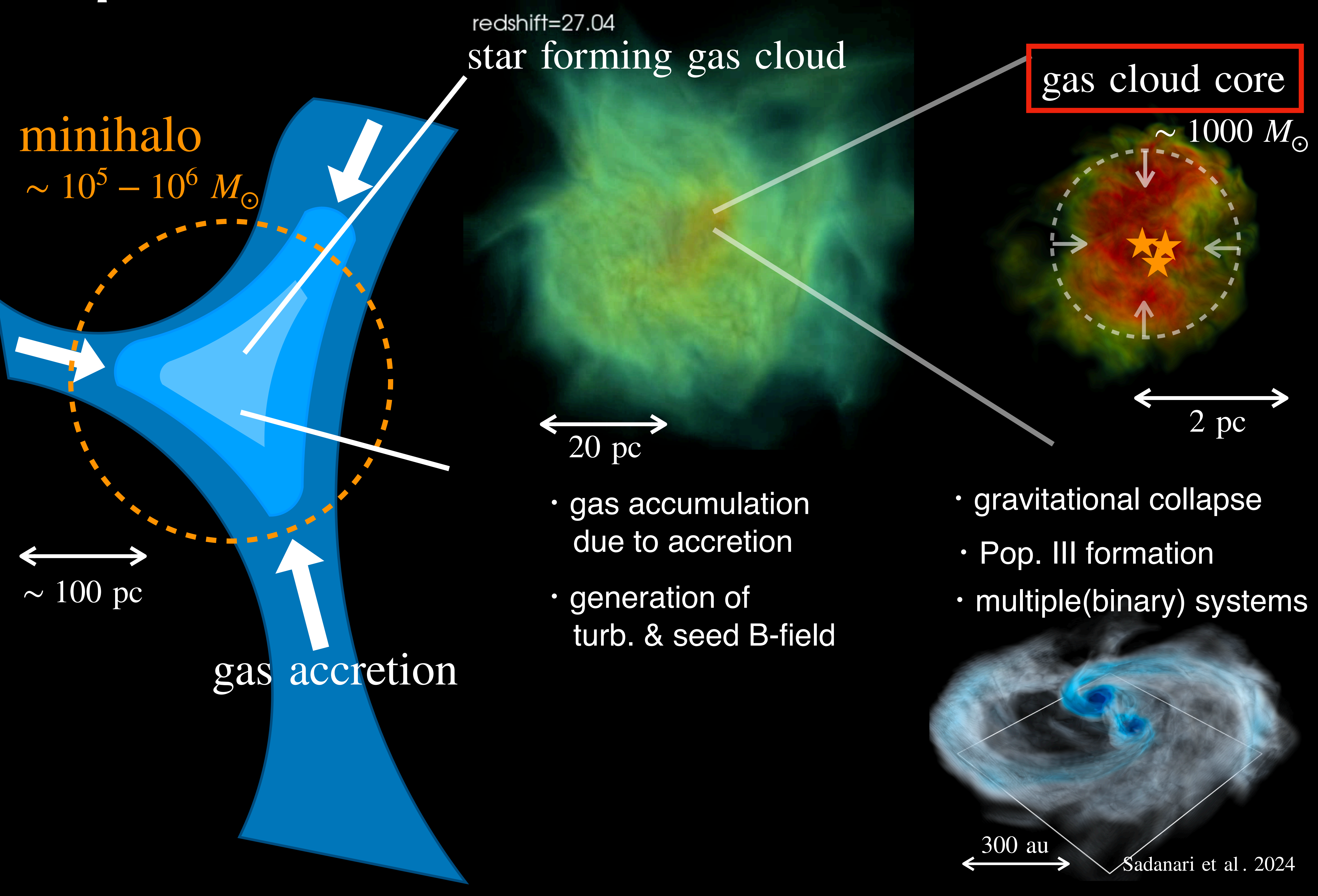
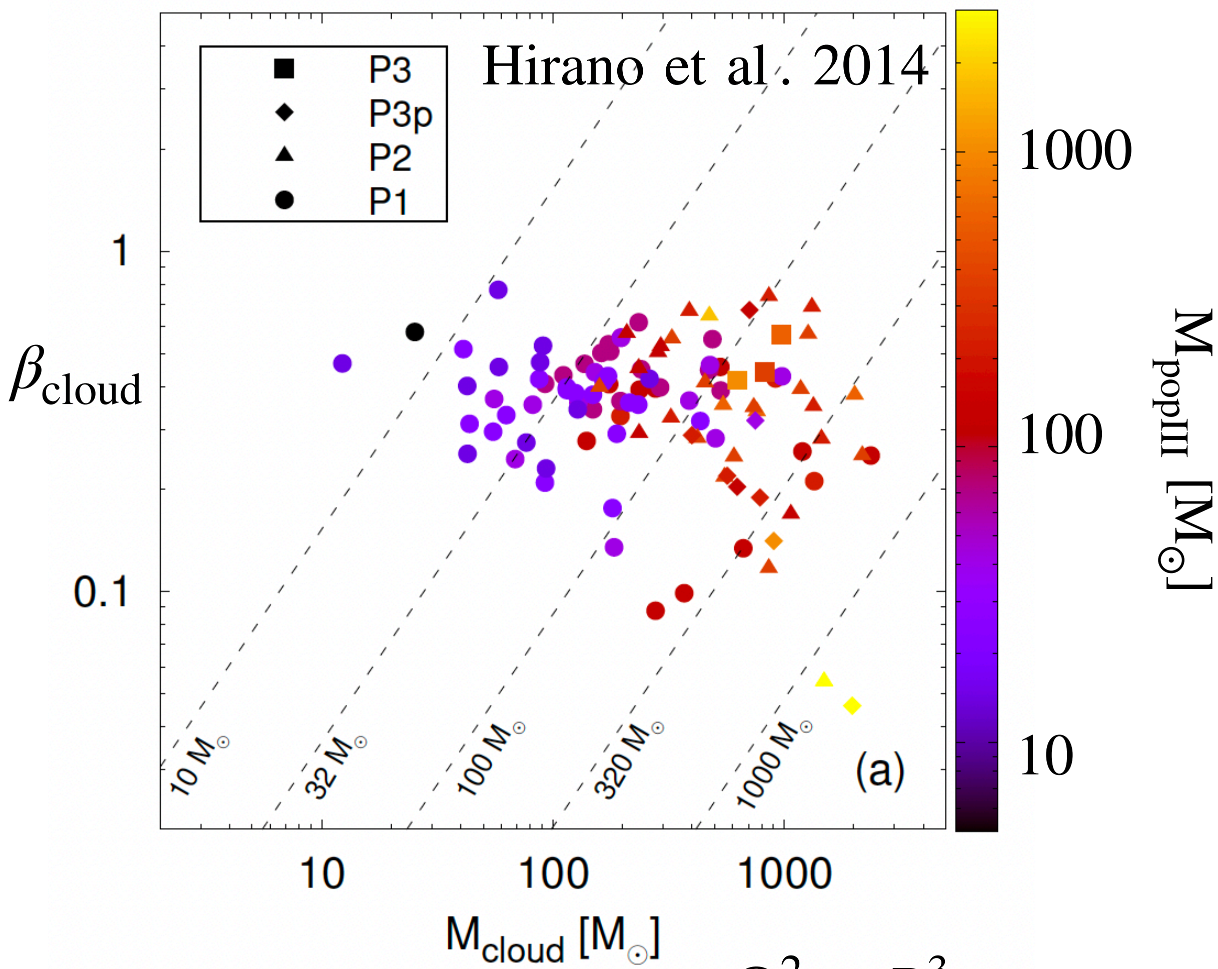
Pop. III star formation within minihalo



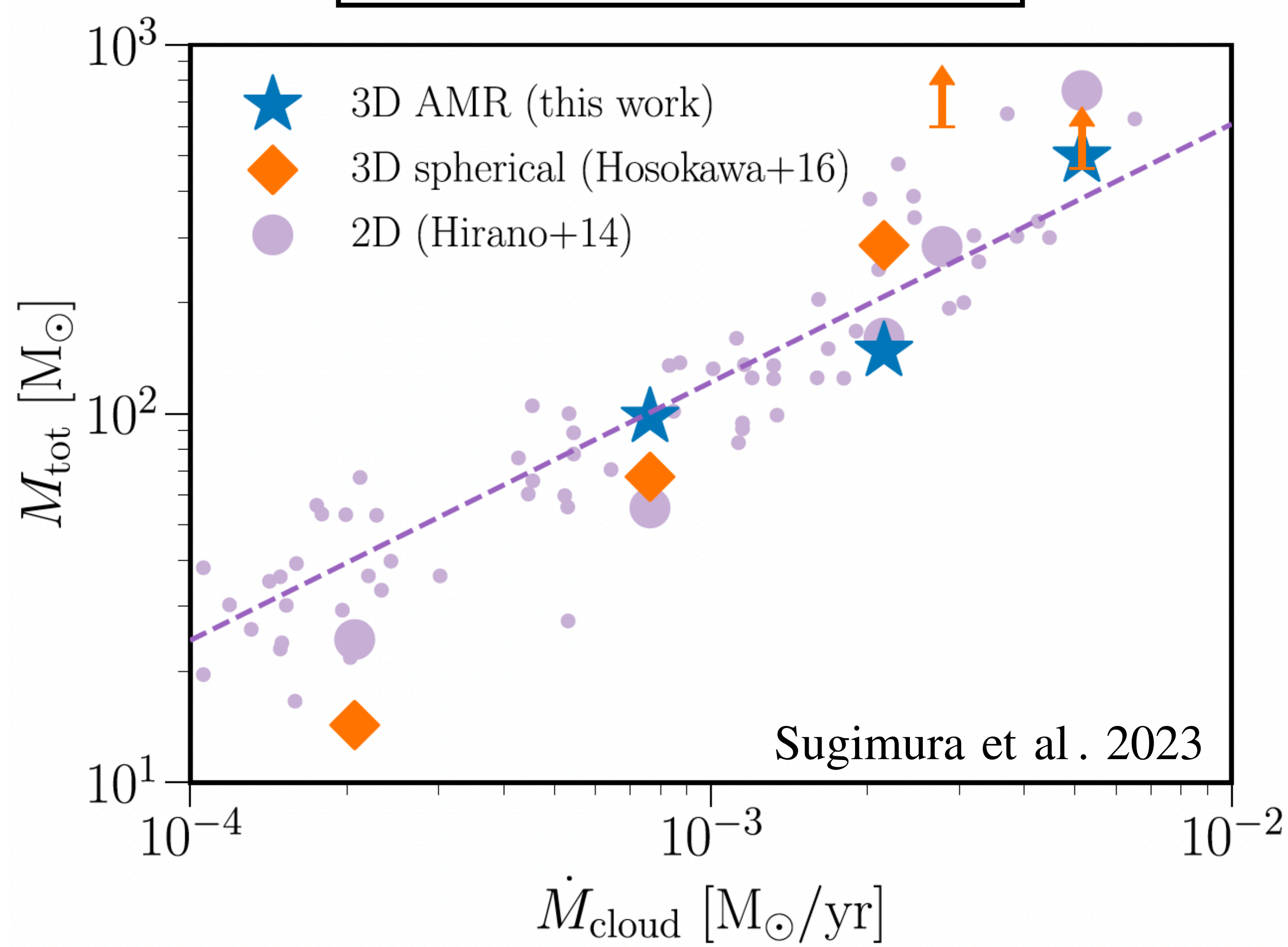
connection between gas cloud core and Pop III stars

stellar mass M_{popIII}
vs
core mass M_{cloud} & rotation β_{cloud}



$$\beta_{\mathrm{cloud}} = E_{\mathrm{rot}}/|E_{\mathrm{grav}}| = \frac{\Omega_{\mathrm{cloud}}^2 R_{\mathrm{cloud}}^3}{3GM_{\mathrm{cloud}}}$$

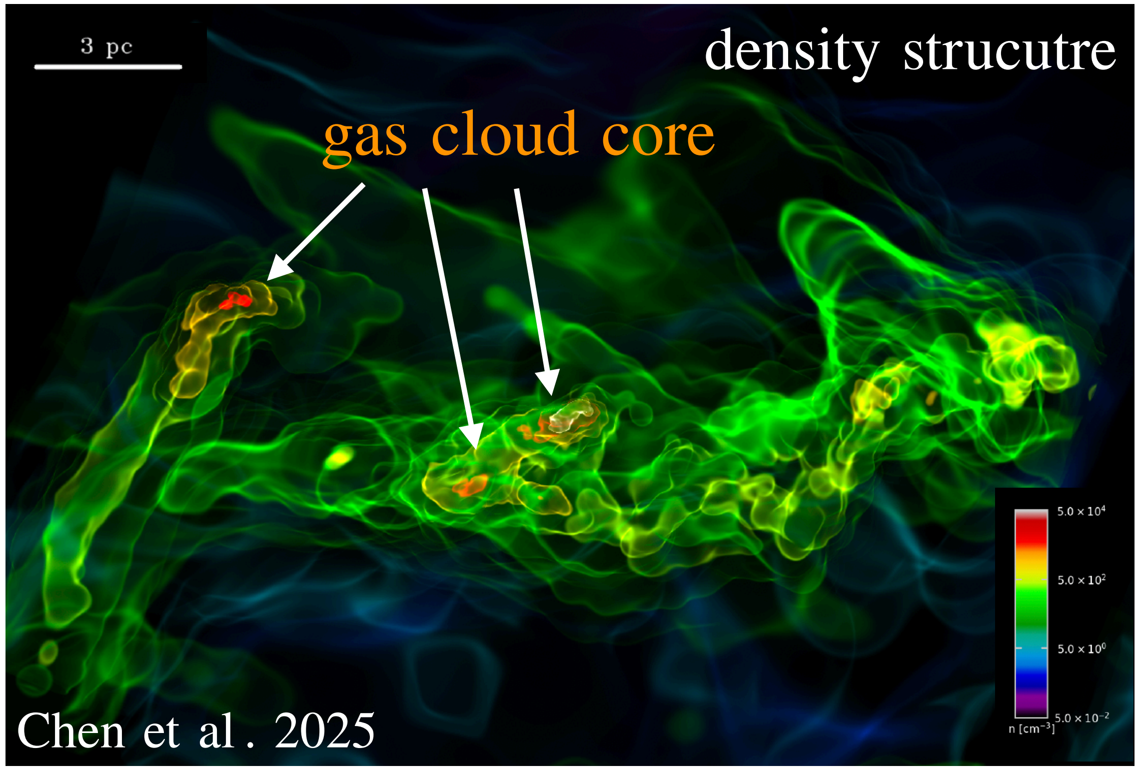
accretion rate $\dot{M}_{\mathrm{cloud}}$
vs
total stellar mass M_{tot}



- massive cloud core leads to larger stellar mass.
- Rapidly rotating clouds tend to form smaller-mass stars.
- Higher accretion rate leads to larger total stellar mass.

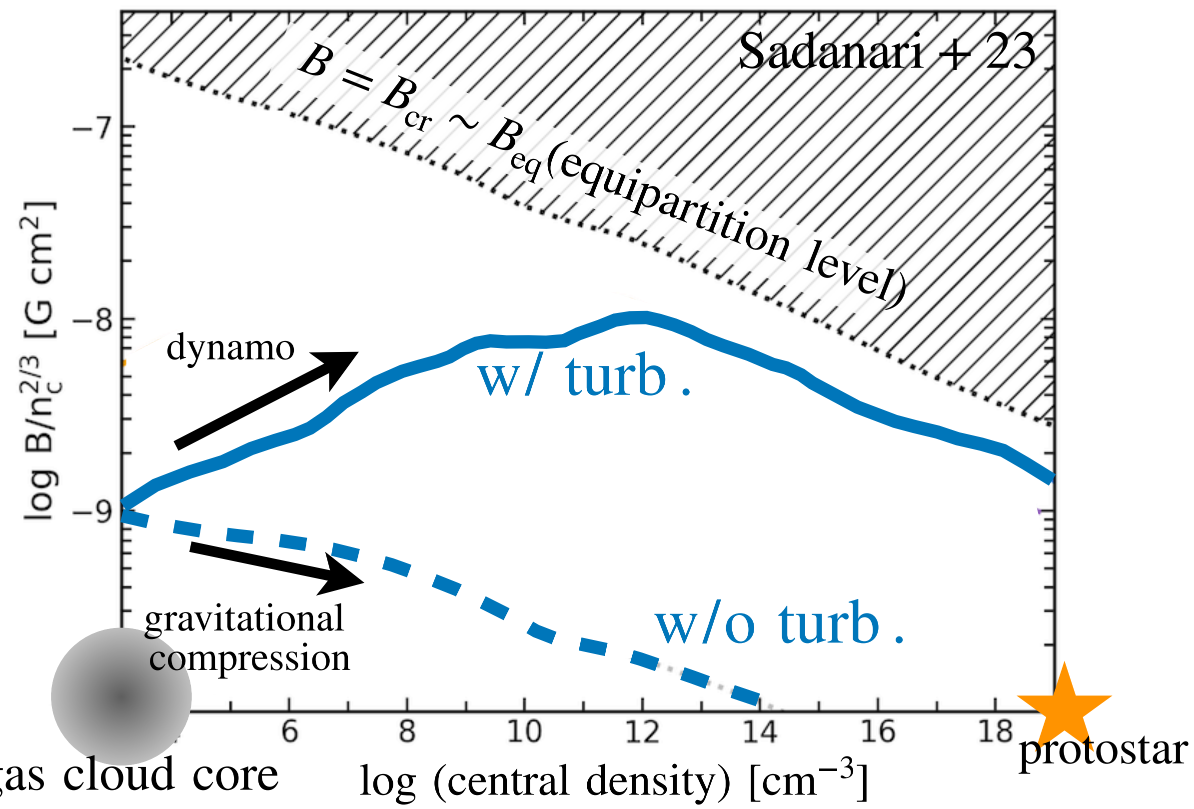
impact of turbulence of gas cloud core

✔ fragmentation of gas cloud

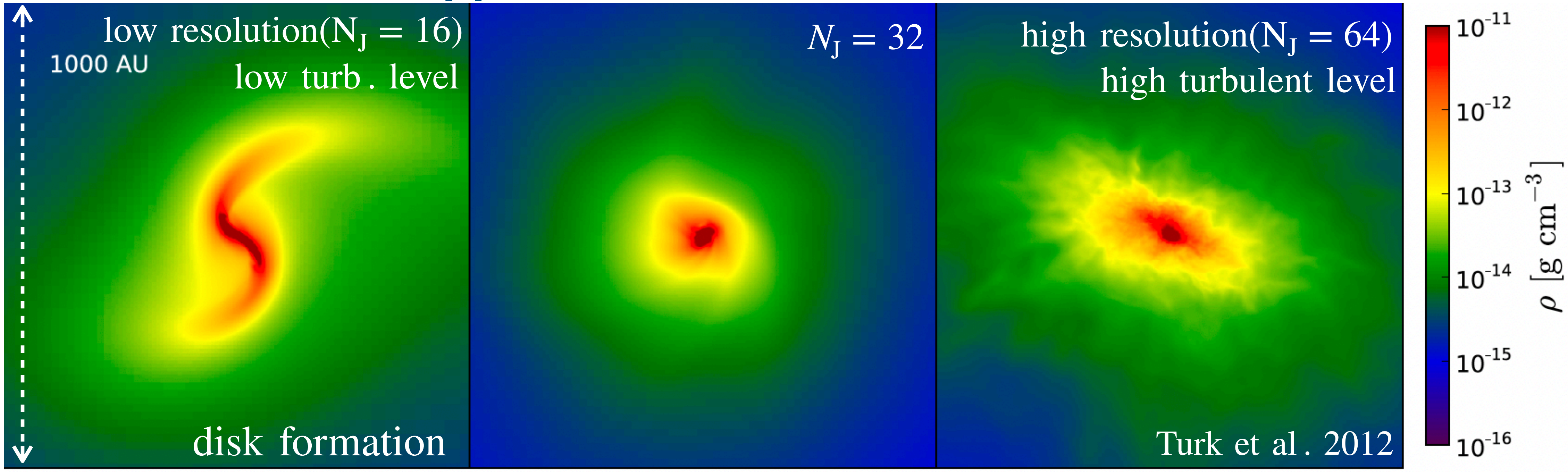


✔ magnetic amplification due to dynamo

B field evo. during gas cloud core collapse



✔ suppression of disk formation



→ effect of angular momentum transport induced by turbulence ?

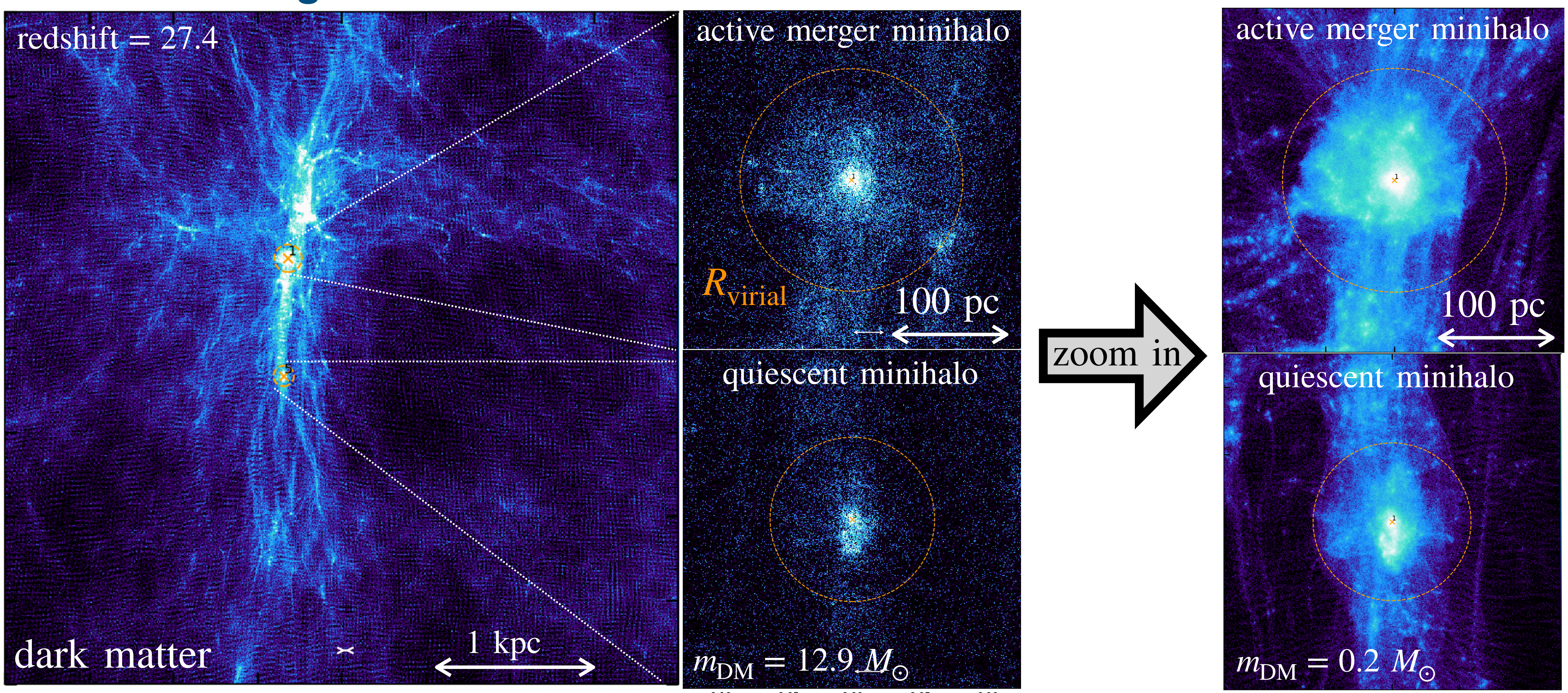
cosmological zoom-in simulation

✔ **RAMSES [DM (particles) + hydrodynamics (Adaptive Mesh Refinement)]** (Tessier 2002)

✔ **cosmological initial condition generated by Music (Hahn & Abel 2011)**

- Λ CDM Universe ($\Omega_m = 0.31$, $\Omega_b = 0.048$, $\Omega_\Lambda = 0.69$, $H_0 = 68$ km s^{-1} Mpc^{-1})

✔ **zoom-in to target minihalos**



✔ **cell refinement criteria**

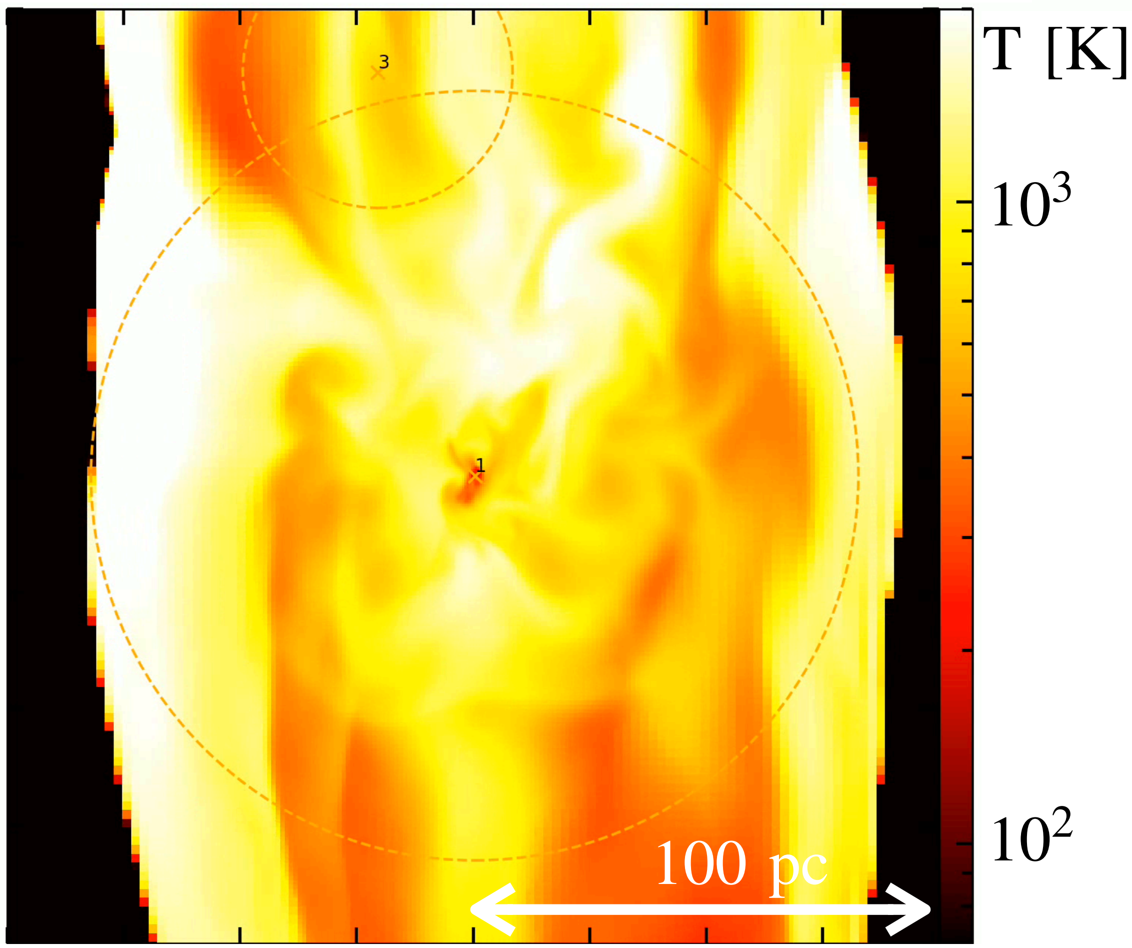
① Lagrangian refinement criterion: $M_{\rm cell,DM} > 8 m_{\rm DM}$ or $M_{\rm cell,gas} > 8 \times$ initial mean mass

② Jeans refinement criterion: cell size > (Jeans length)/N_J, Jeans length = $\sqrt{\pi c_s^2/(G\rho)}$

Jeans number: $N_J = 16, 64, 256, 512$

zoom-in simulations of target minihalos

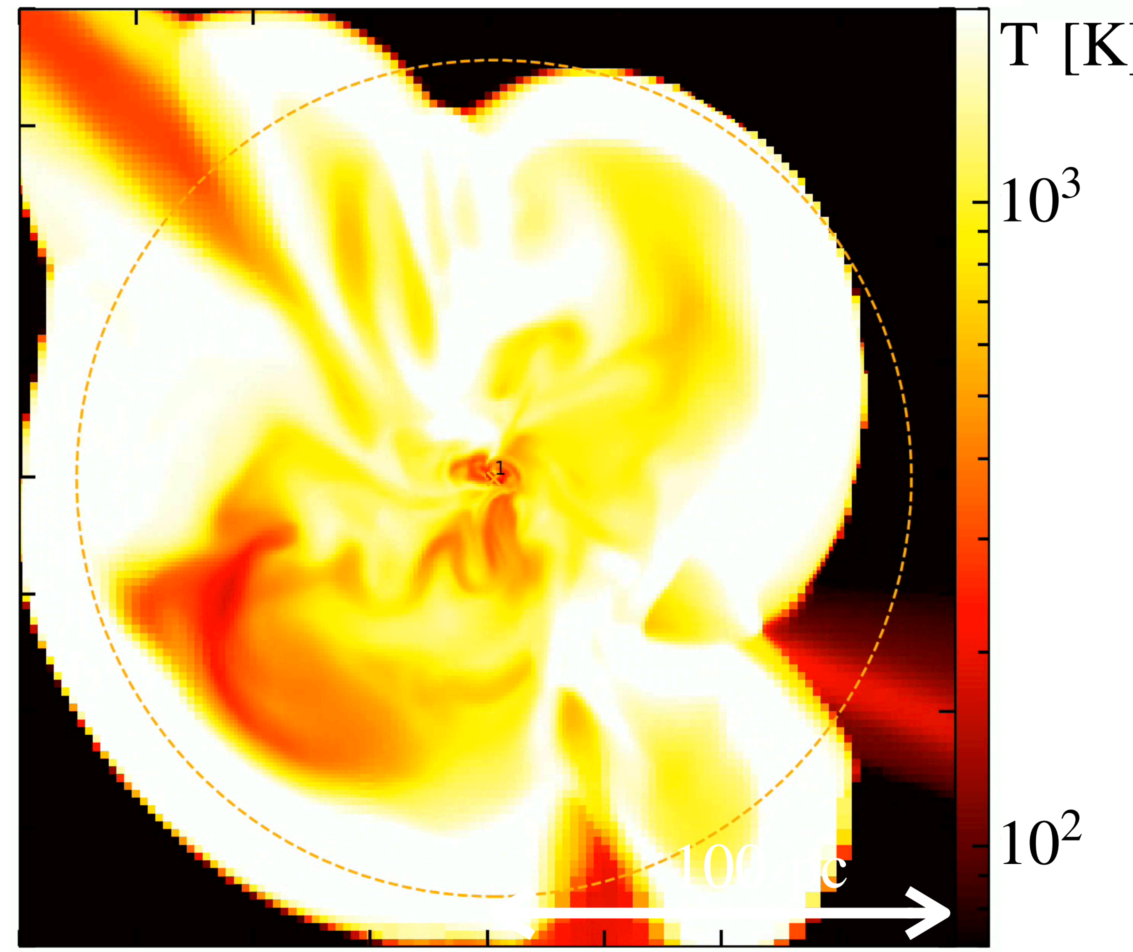
① quiescent minihalo



minihalo that experience few mergers with other DM clumps, so the gas cloud can evolve without being disturbed.

$$M_{\rm halo} \simeq 2.4 \times 10^5 \ M_\odot$$

② merger-active minihalo



minihalo where infalling DM clumps strongly disturb the dynamics of gas cloud.

$$M_{\rm halo} \simeq 4.2 \times 10^5 \ M_\odot$$

formation of gas cloud core

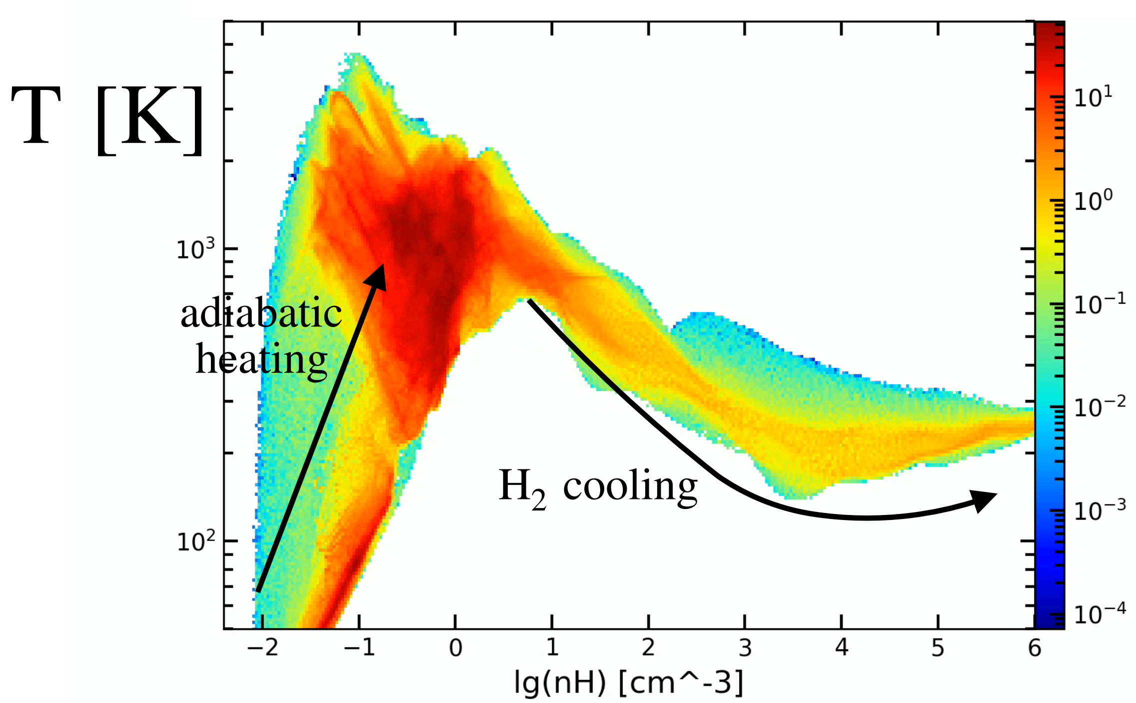
- gas is heated to virial temp. during accretion onto the minihalo.

$$T_{\rm vir} \simeq \frac{GM_{\rm halo}\mu m_{\rm p}}{5k_{\rm b}R_{\rm vir}}$$

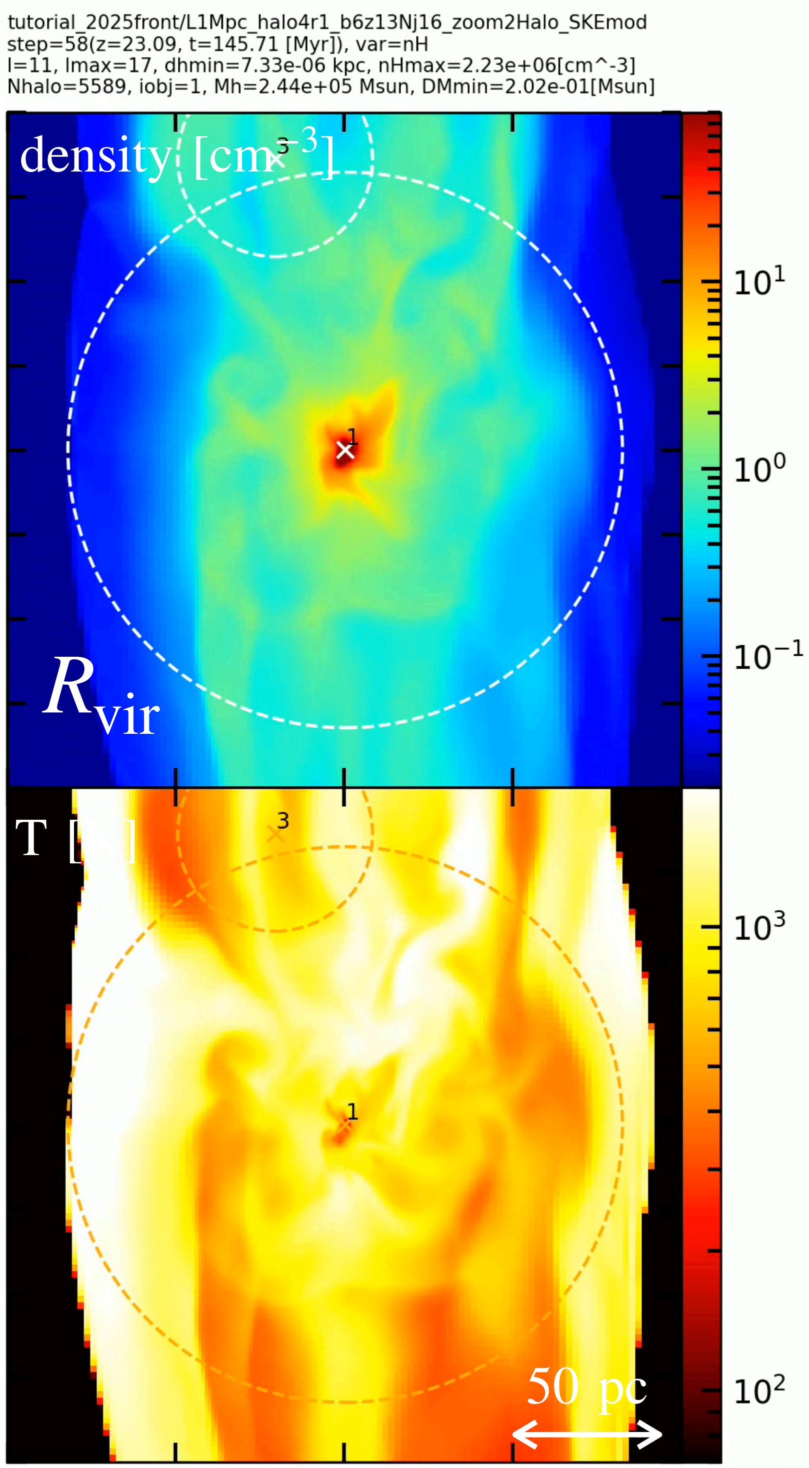
- once $T_{\rm vir}$ reaches 1000 K, enough H2 forms to cool the gas.

$$(t_{\rm ff} > t_{\rm cool} \propto n^{-1})$$

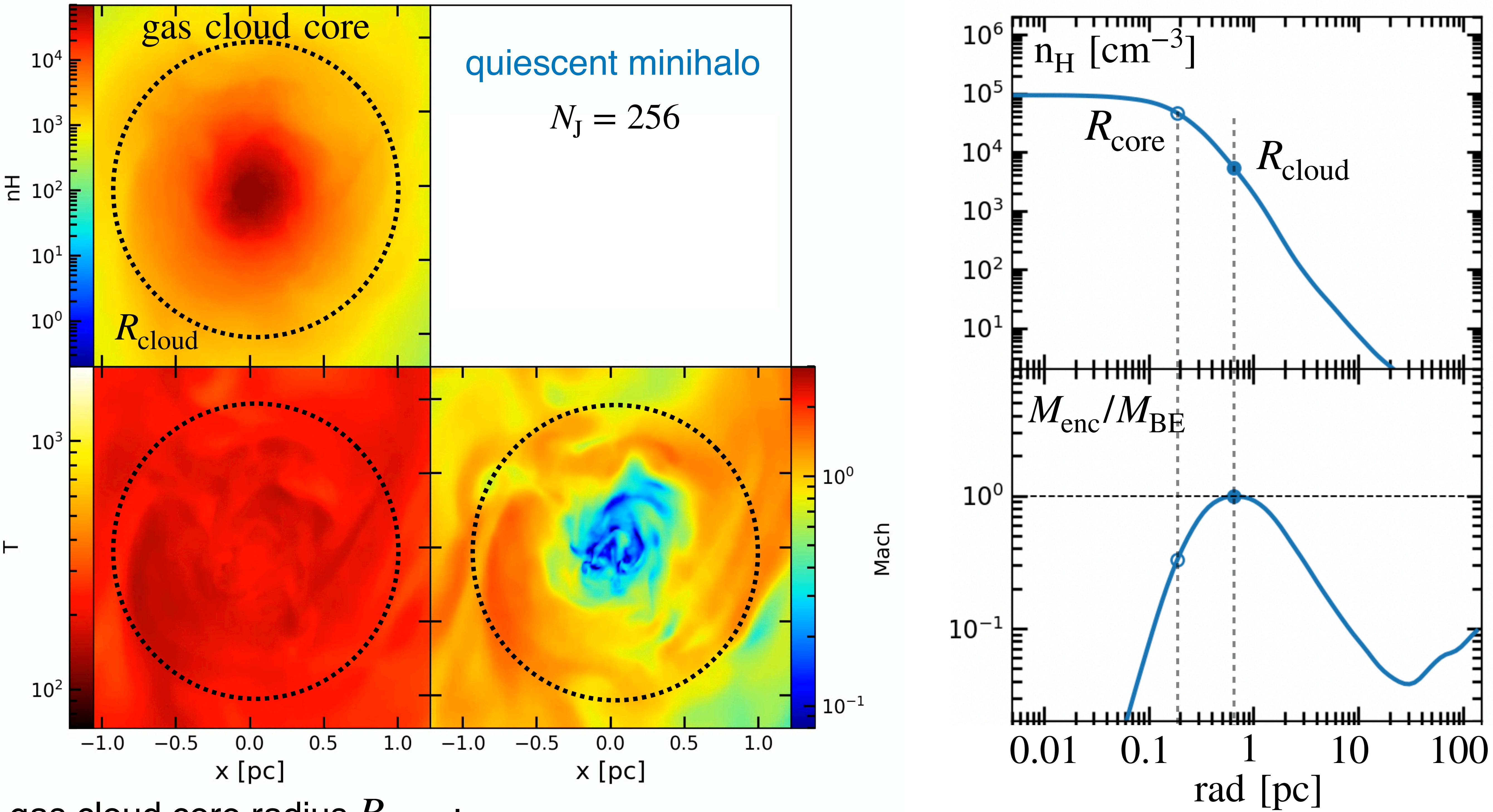
- The cooled gas starts collapsing to form a gas cloud core.
- Gas temp. starts to rise when the density is around $10^4\ {\rm cm}^{-3}$
- Since the core mass exceeds the Jeans mass, the core continues to collapse gravitationally (runaway collapse).



quiescent minihalo (NJ = 16)



definition of gas cloud core

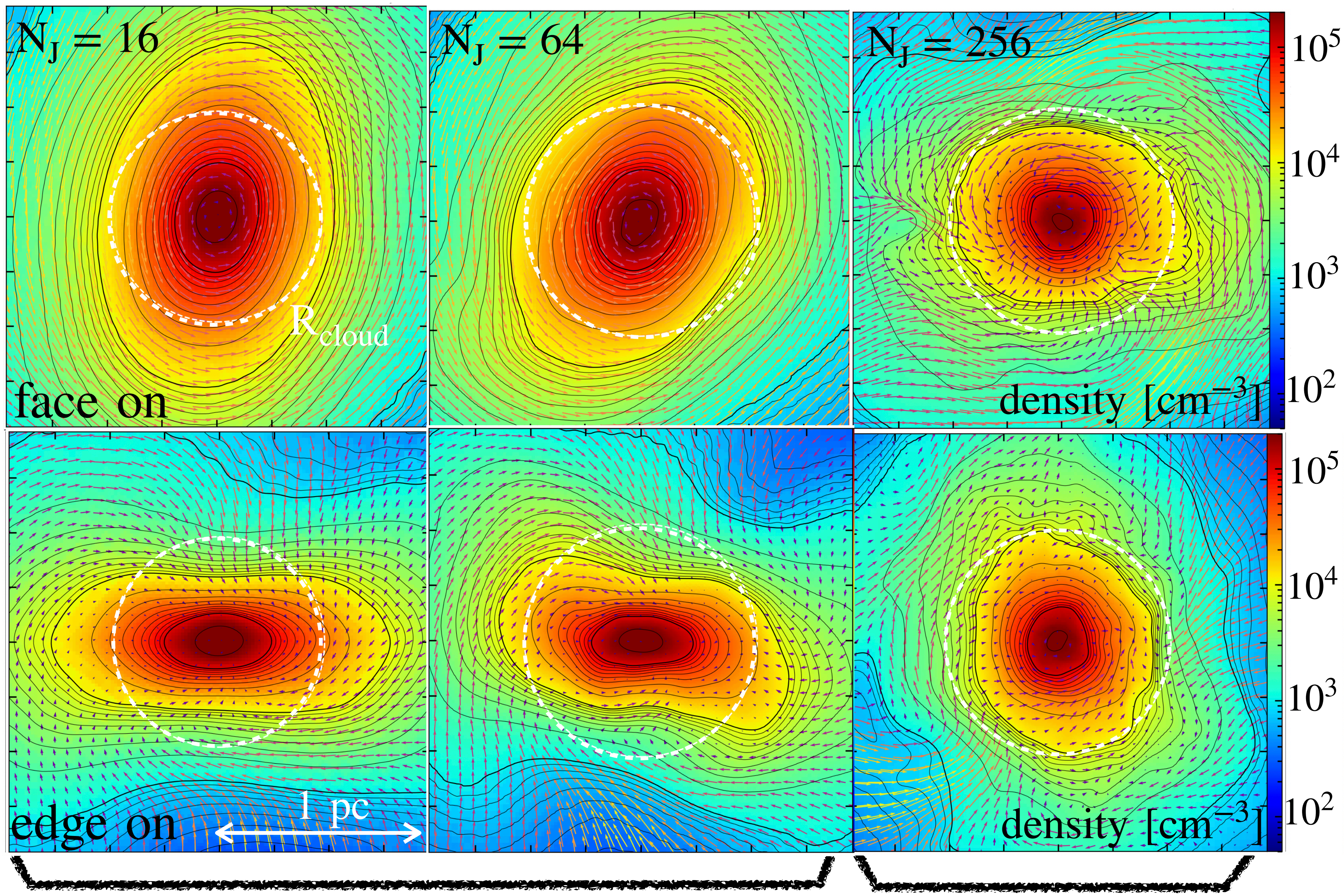


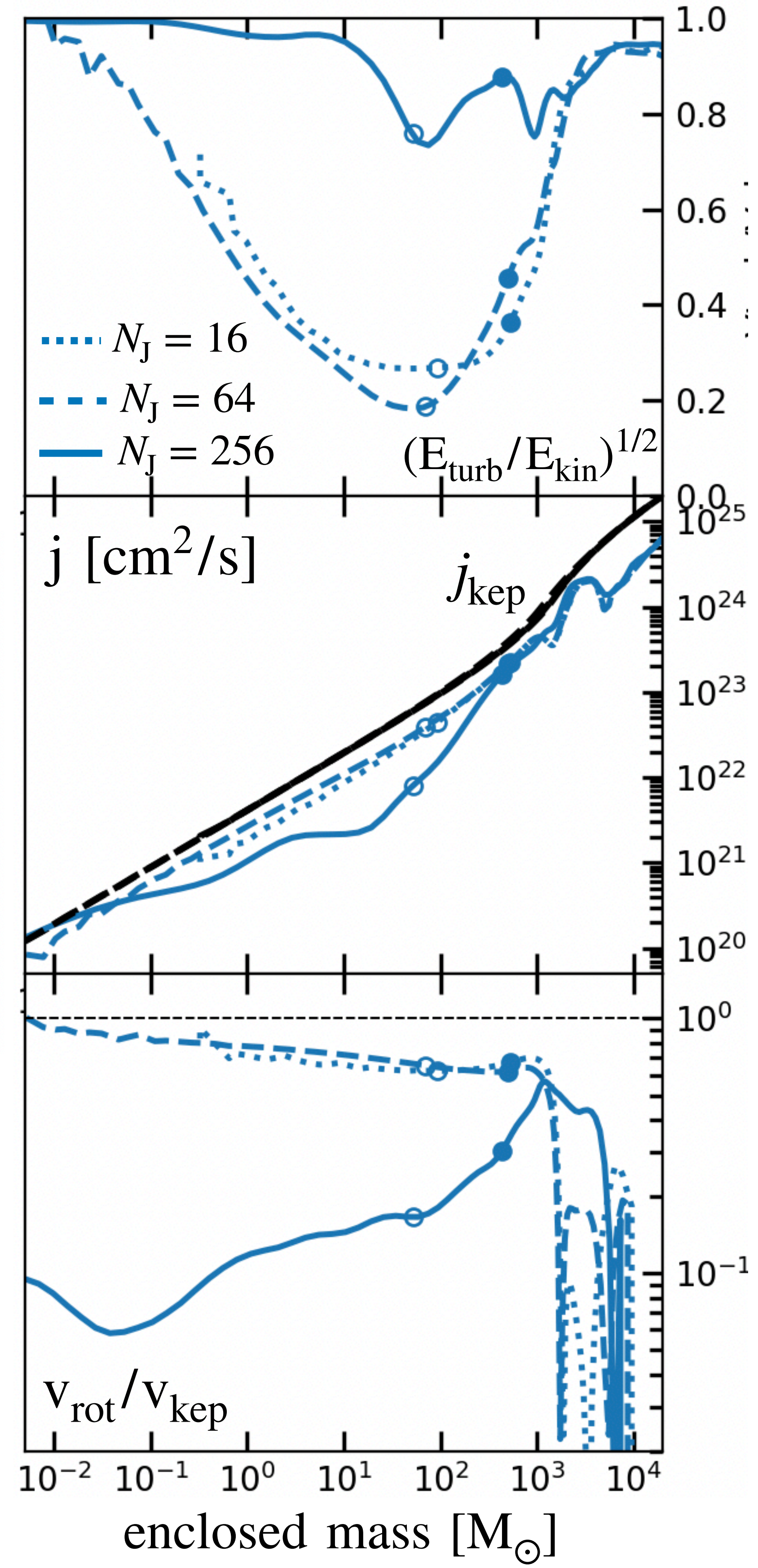
gas cloud core radius R_{cloud}:

where the ratio of M_{enc}/M_{BE} reaches its maximum (Hirano +14)

Bonnor-Ebert mass: $M_{BE} = \frac{1.18 c_s^4}{G^{1.5} P_{ext}} \, M_\odot$

resolution dependence





disk-like shape due to centrifugal support

spherical shape

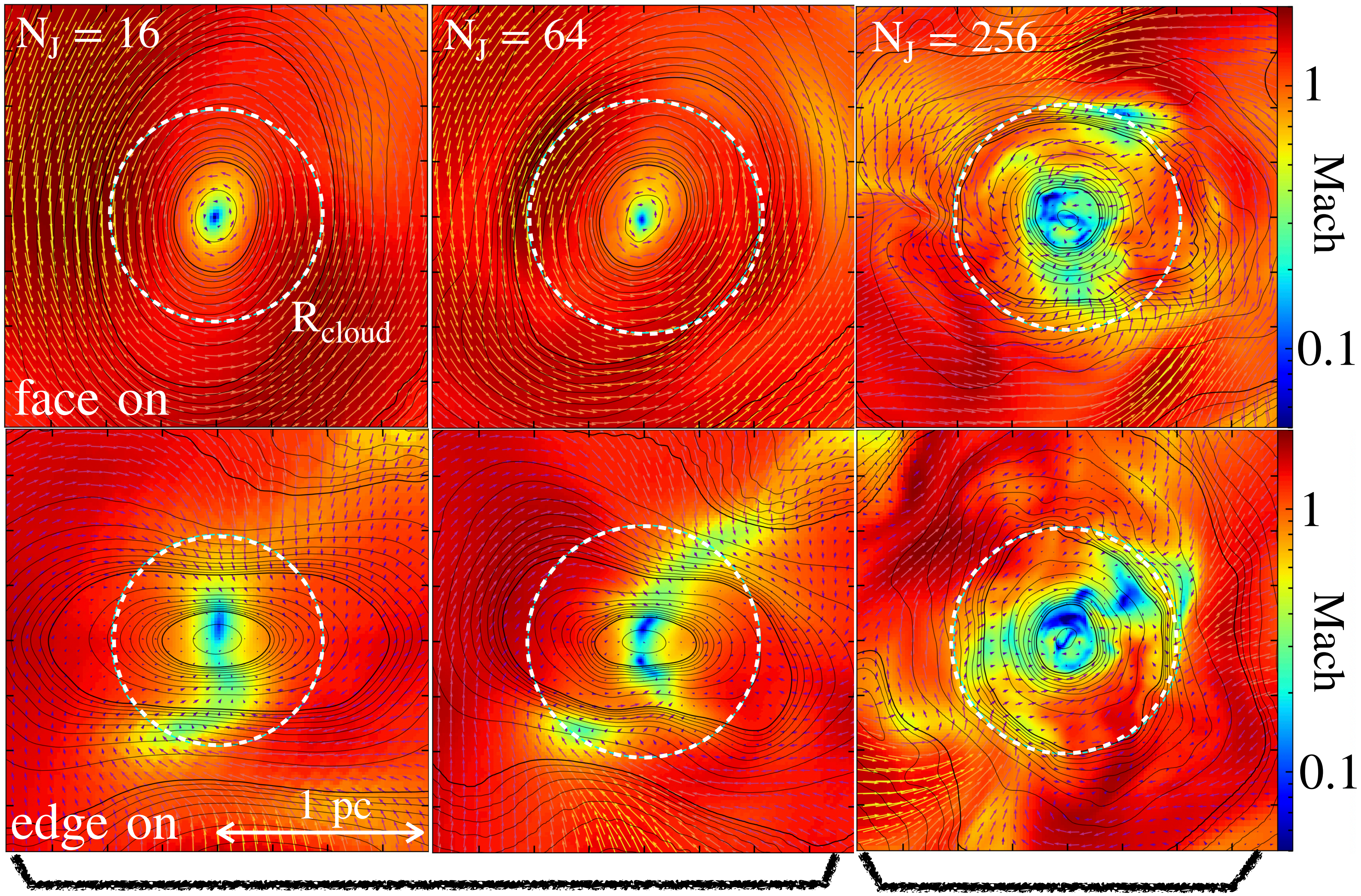
High resolution case ($N_J = 256$)

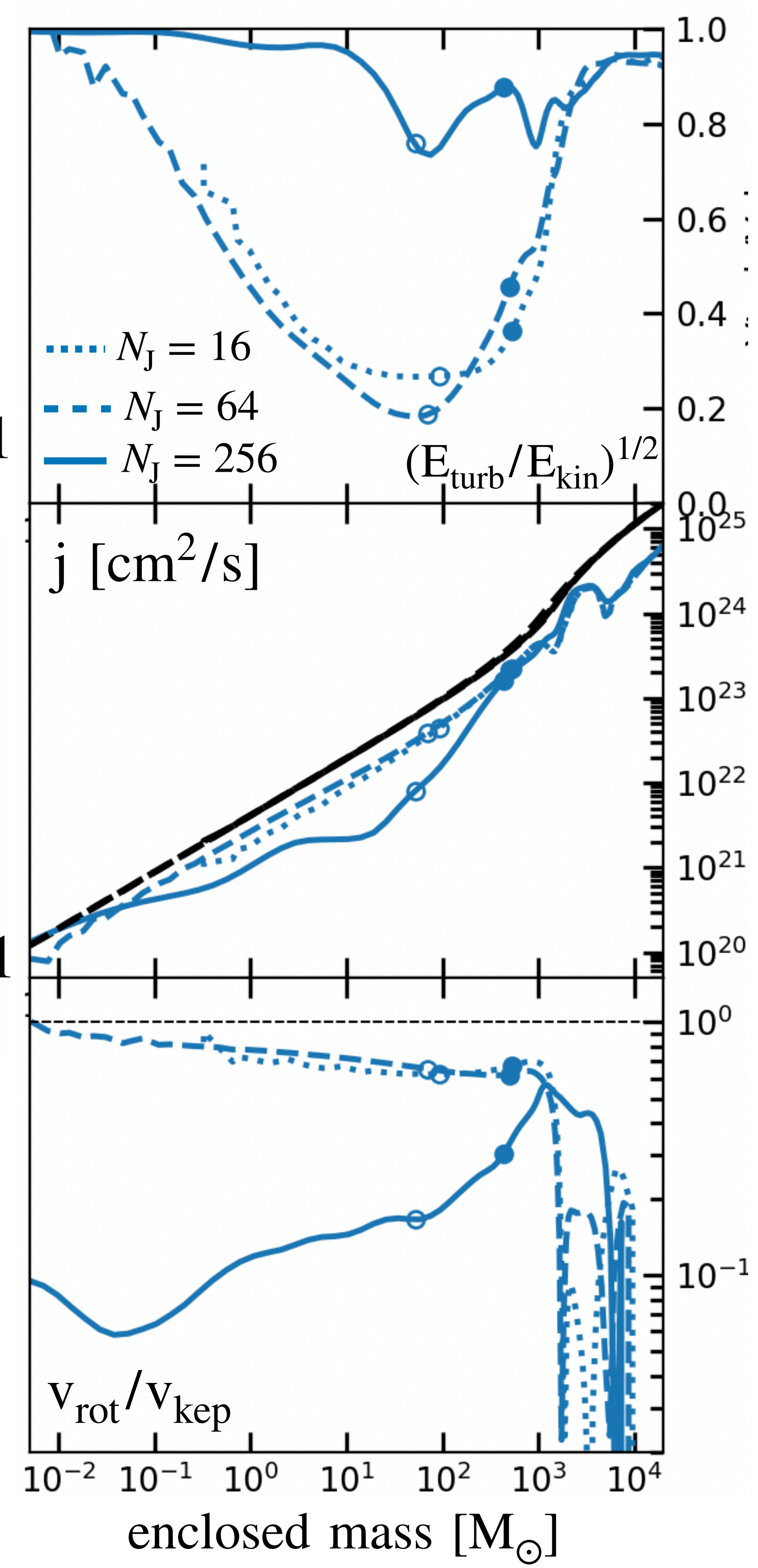
→ A turbulence-dominated gas cloud core forms.

→ Turbulence transports angular momentum outward

→ Rotation within the core is reduced

resolution dependence





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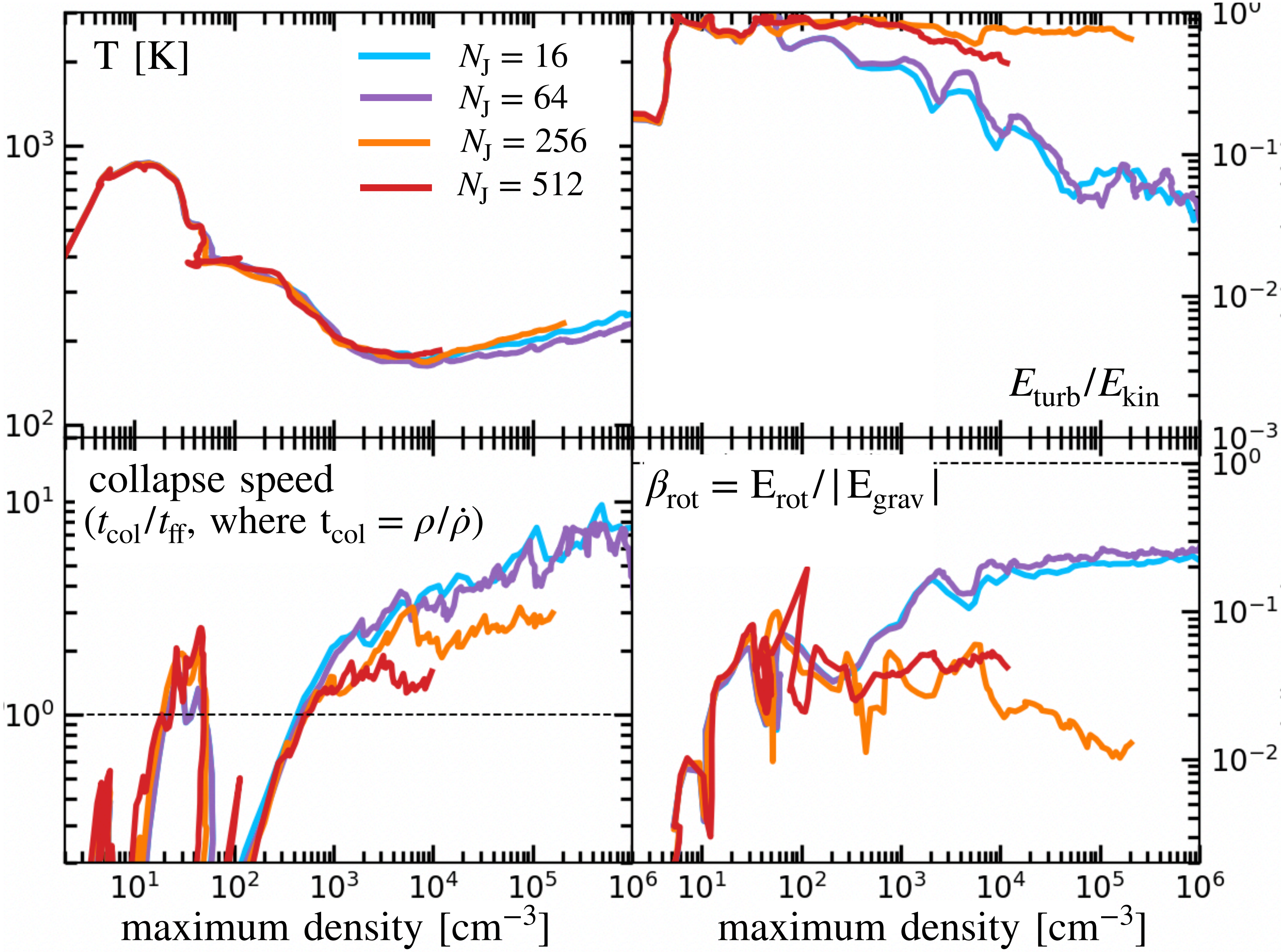
resolution convergence

Time Evolution of physical quantities in the central core(R_{core} : $n_H > 0.5 n_{H,max}$)

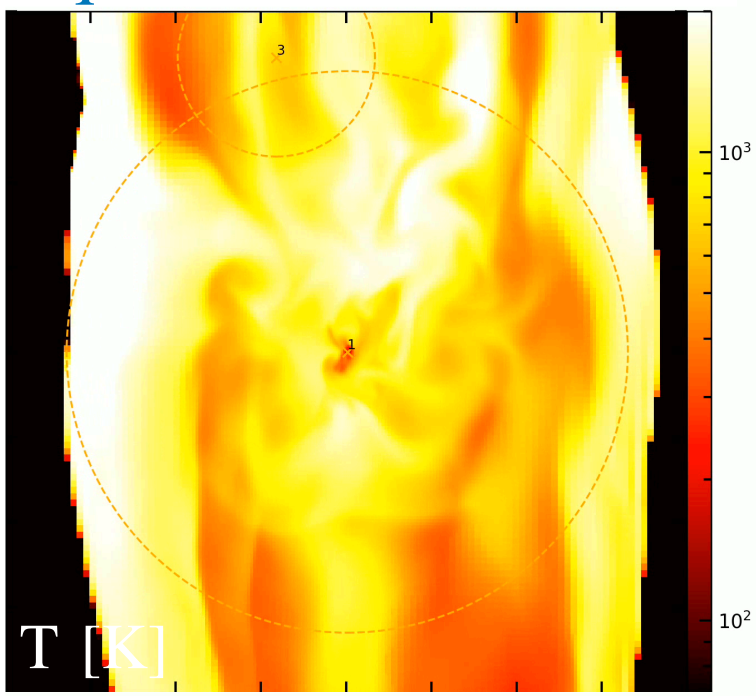


with $N_J > 256$, large-scale turbulence can be resolved,

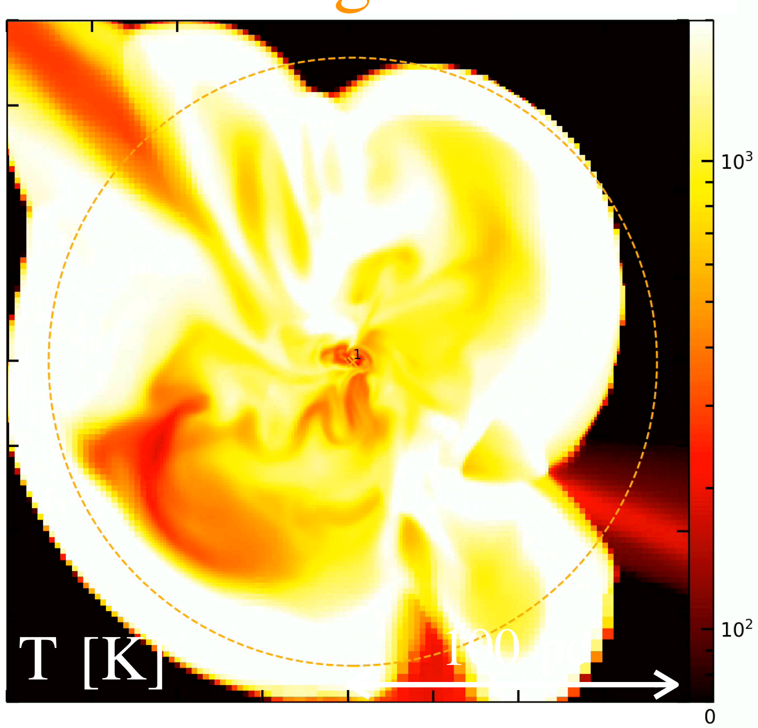
→ yields a realistic, turbulence-dominated gas cloud core.

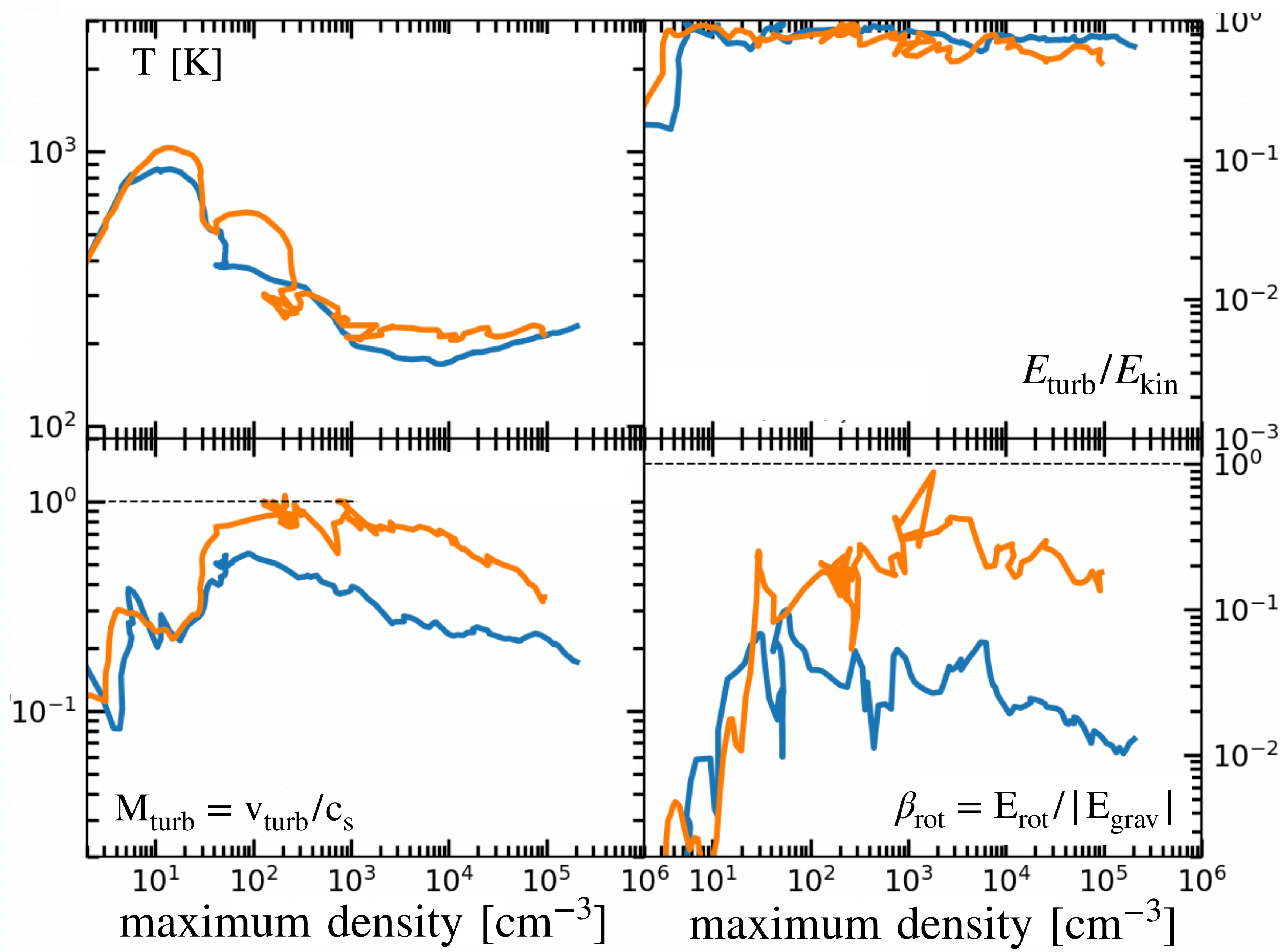
quiescent minihalo vs active-merger minihalo

quiescent minihalo



active merger minihalo





- Rotation is stronger in active merger halo
- turbulence in central core region becomes subsonic in both cases

generation of seed B-field @ minihalo

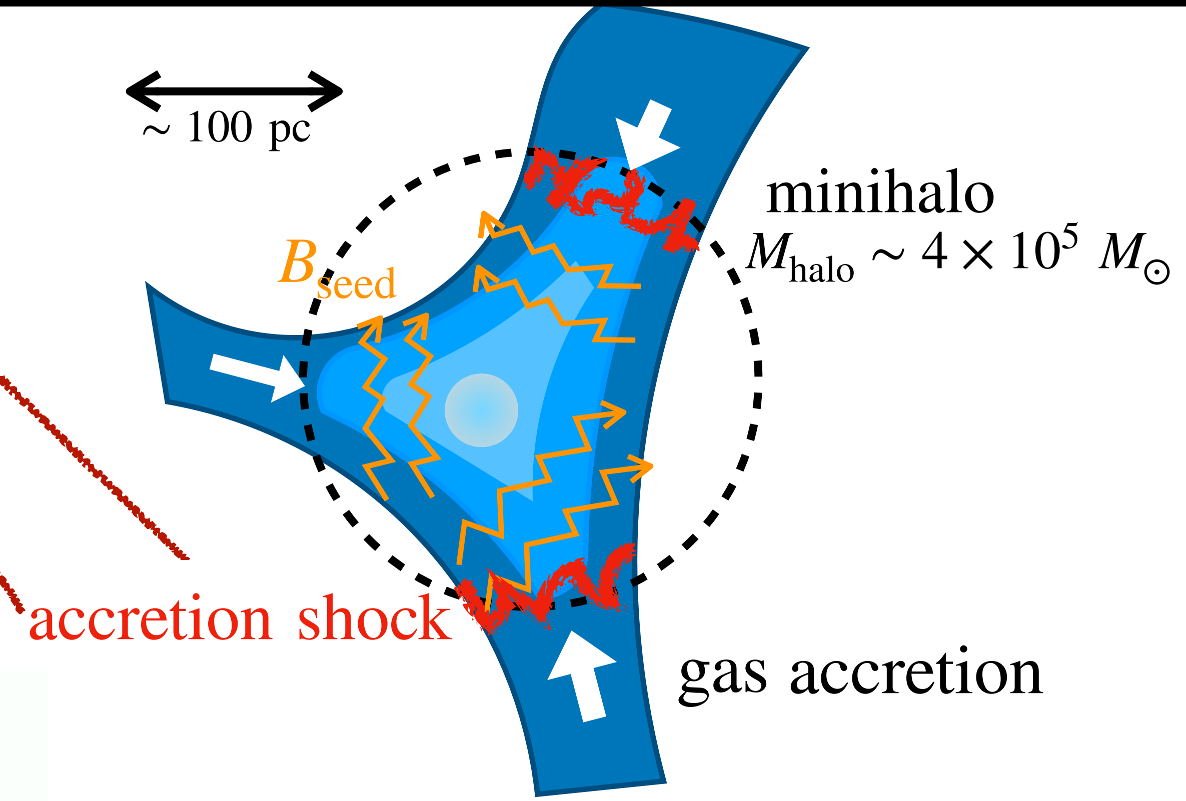
vorticity($\nabla \times \vec{v}$) eq. baroclinic term

$$\frac{\partial \vec{\omega}}{\partial t} = \nabla \times (\vec{v} \times \vec{\omega}) + \frac{\nabla \rho \times \nabla p}{\rho^2} + \nu \nabla^2 \vec{\omega}$$

induction eq. Biermann battery term

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

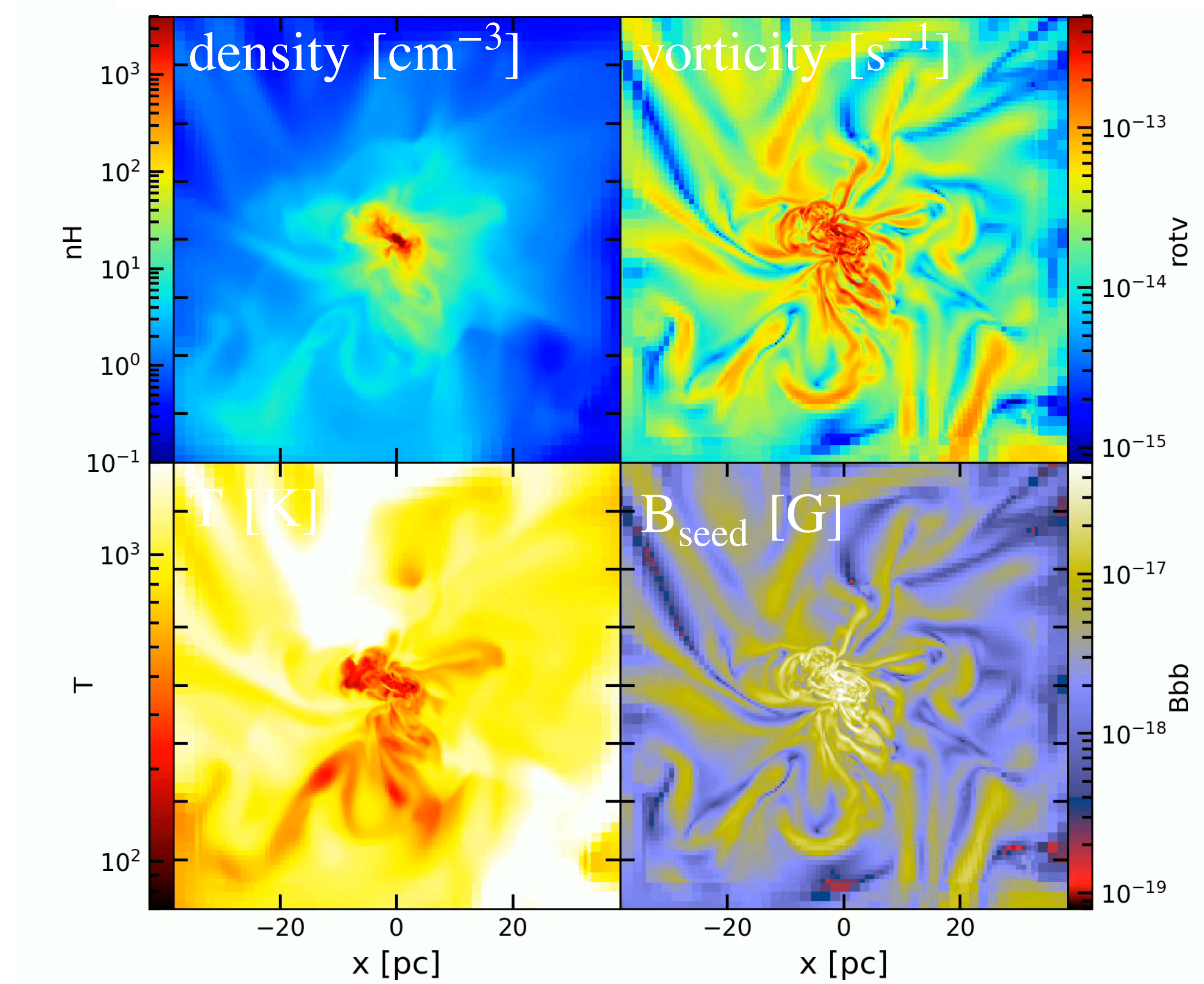
(χ :ionization fraction, η :magnetic resistivity, m_a :baryon mass)



- ω and B are generated by gas accretion (baroclinic and Biermann battery terms)
- When dissipation is negligible, ω and B evolve under the same equation.

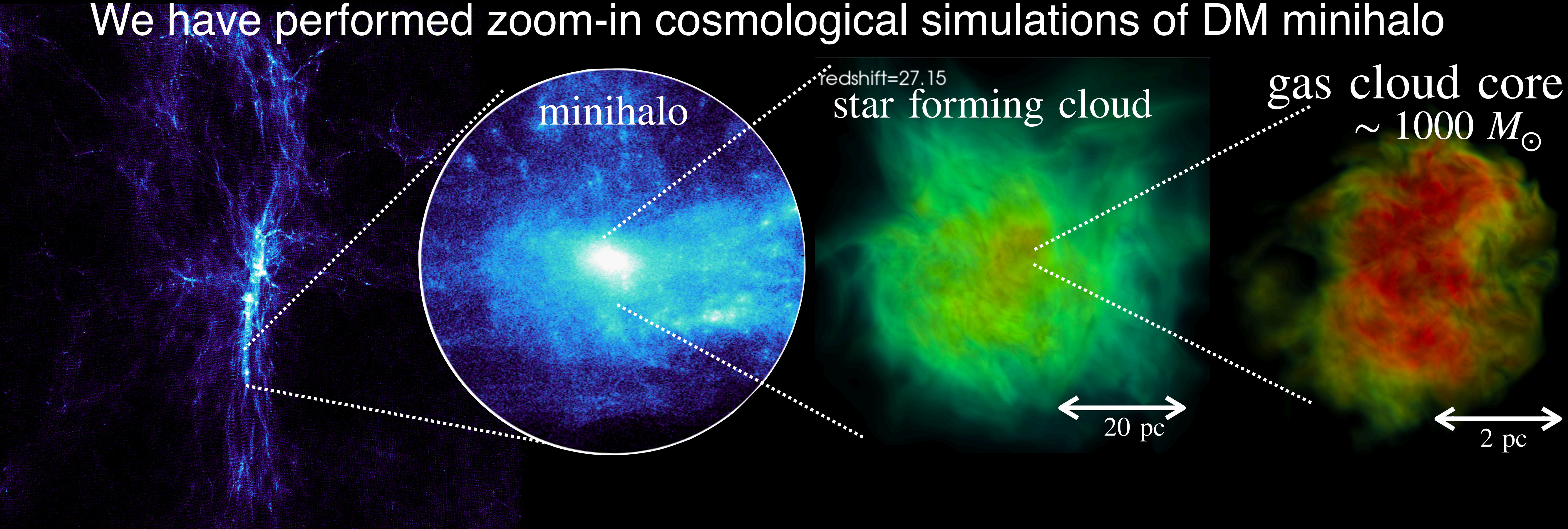
$$\longrightarrow B_{seed} = -\frac{m_a c}{(1+\chi)e}\omega \quad \text{(e.g., McKee + 2020)}$$

Simulations suggest that seed B-fields of at least 10^{-18}-10^{-16} G can be naturally generated within minihalos.



summary

We have performed zoom-in cosmological simulations of DM minihalo



・Accretion onto the minihalo naturally generates vorticity (turbulence).

・Turbulence typically dominates over rotation in the gas cloud within the minihalo.
→ reducing rotation via enhanced angular momentum transport

・Turbulence in the central core becomes subsonic at the onset of collapse, $M_{\rm turnb} \sim 0.2$.

・Mergers can enhance the kinetic energy of gas clouds, particularly in their rotational motion.

・Accretion shocks in minihalos can generate seed B-fields of at least $10^{-18} - 10^{-16}$ G.