Protostellar collapse of magneto-turbulent cloud core: formation of protoplanetary disks and ouflows

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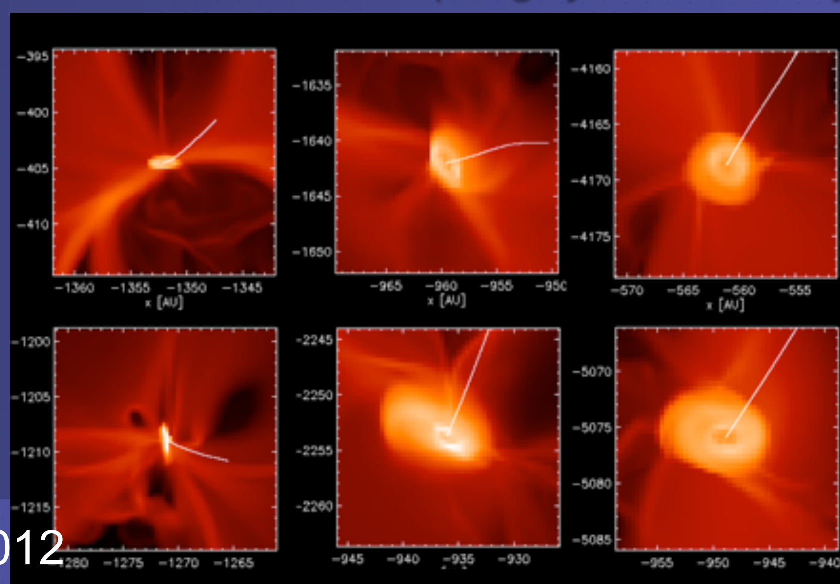
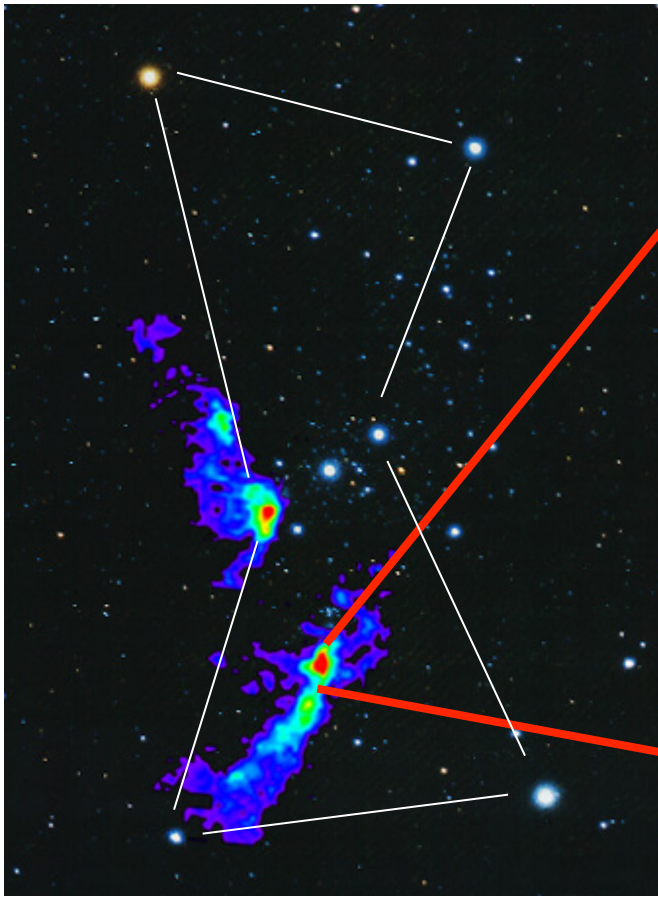


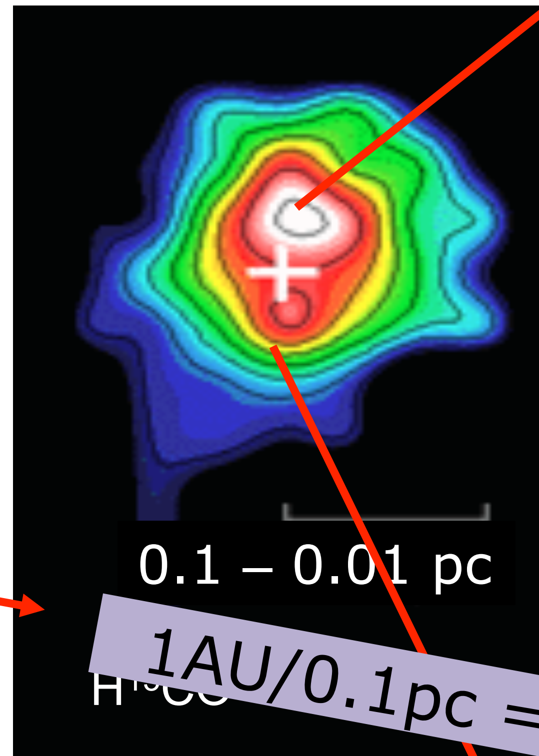
Scenario of star formation：from cloud to protostar



Orion molecular cloud
(optical＋radio)

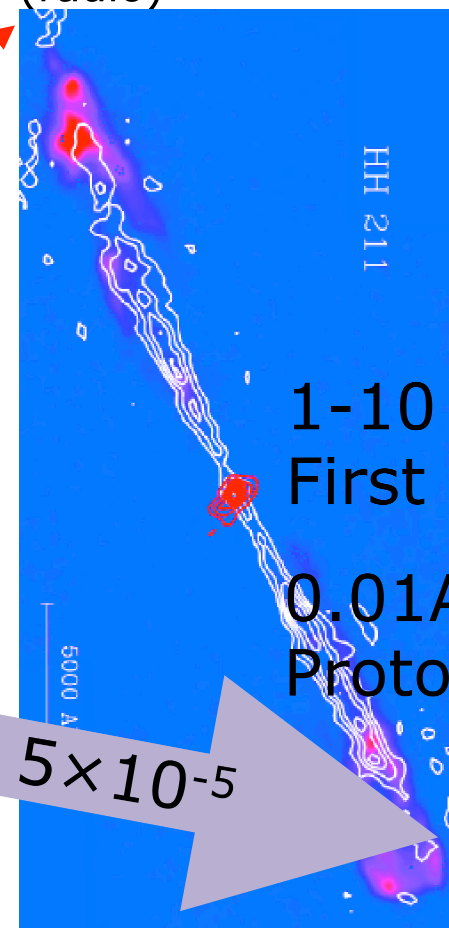
Sakamoto et al. (1994)

Cloud Core in Taurus
(radio)



Onishi et al. (1999)

Protostar and outflow
(radio)



Gueth & Guilloteau (1999)

Modeling of protostellar collapse

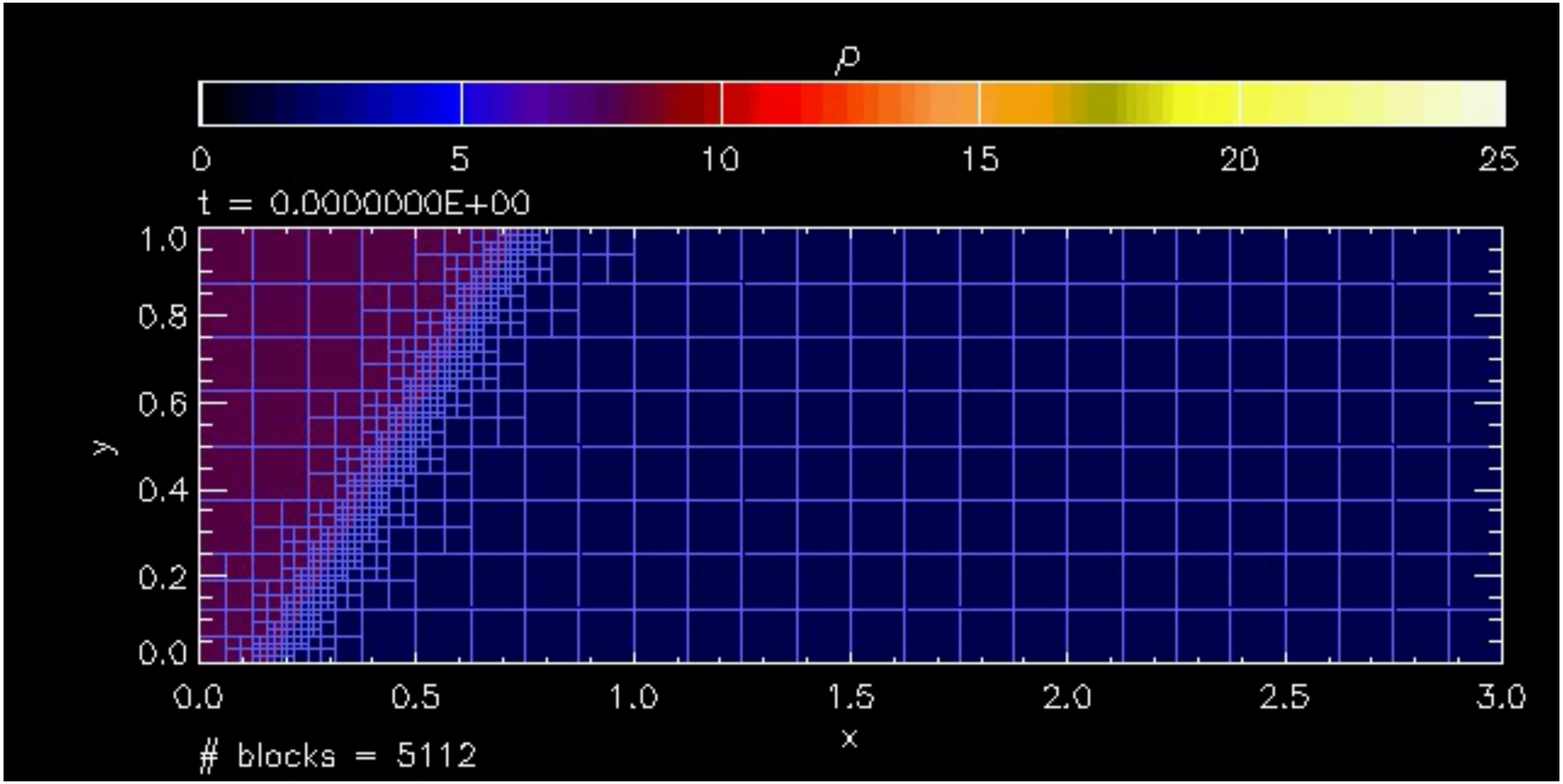
Physics	Numerical methods
■ Gravitational collapse	■ Adaptive mesh refinement (AMR) ■ Poisson equation for selfgravity with a multigrid method
■ Interstellar gas - partially ionized gas	■ MHD equation - Explicit HLLD scheme
■ Protostar	■ Sink particle - Lagranian particle
■ Magnetic diffusion - ambipolar diffusion, Hall effect, Ohmic dissipation	■ Implicit schemes with a multigrid method - advantage of our scheme!

AMR

Block-structured AMR

Double Mach reflection by SFUMATO

Density



Sink particles

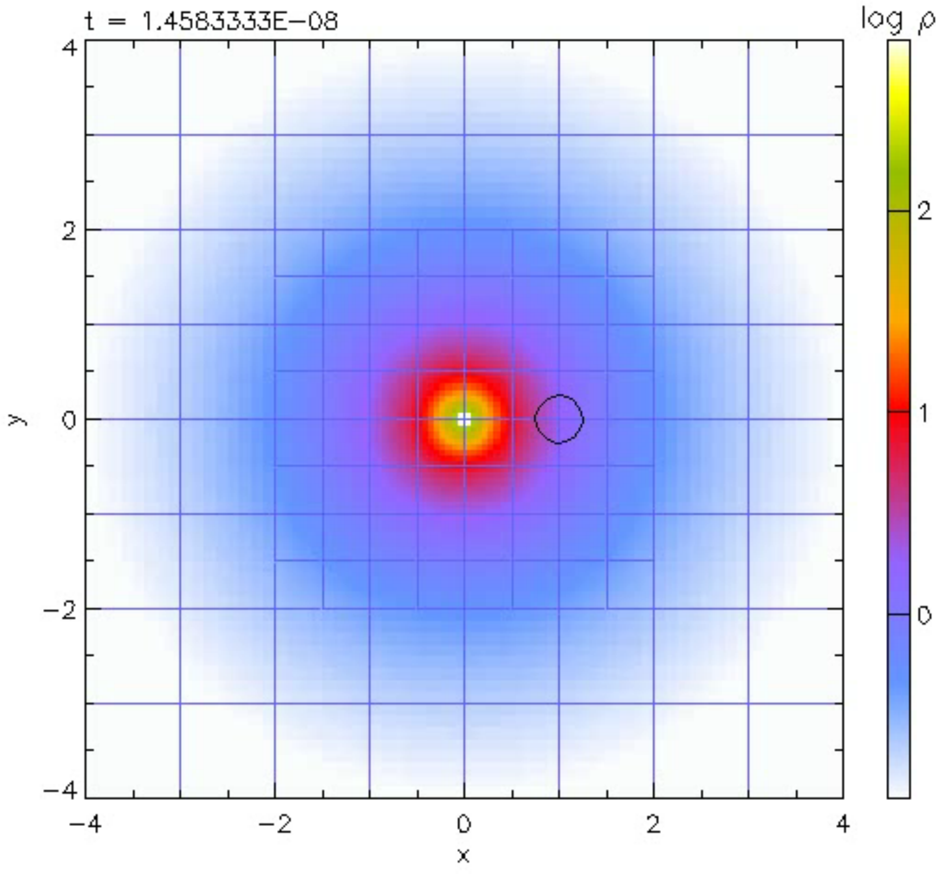
a subgrid model for a protostar

Tests for sink particles

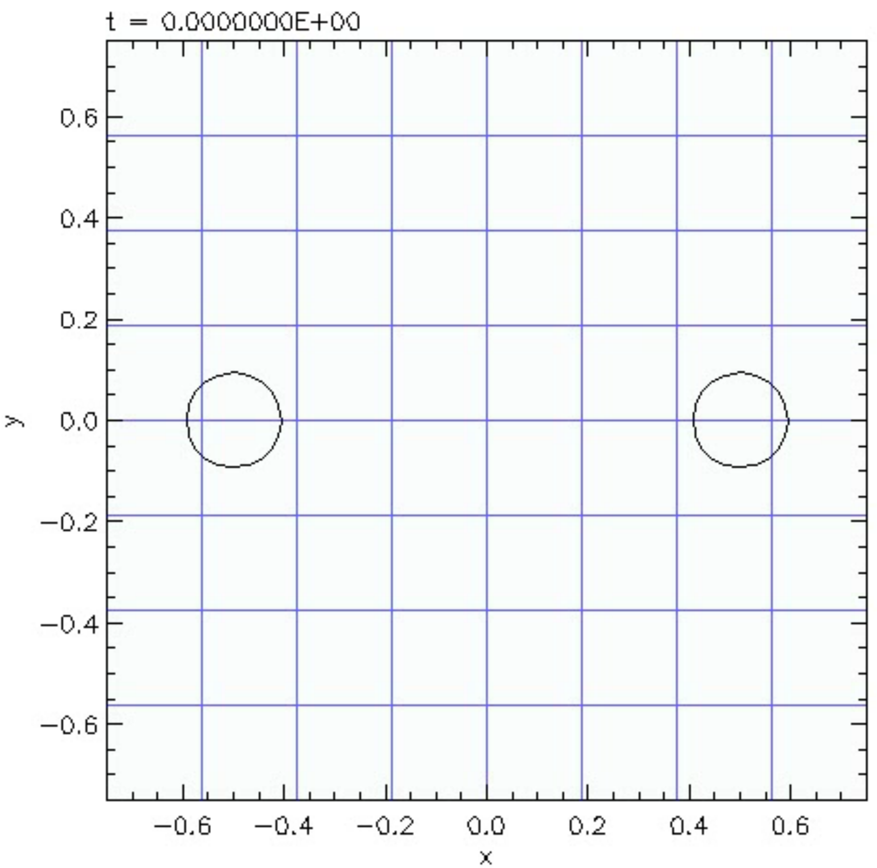
c.f., Krumholz+ 02 for ORION
Federrath+10 for FLASH

The sink particle is a Lagrangian particle moving on Eulerian grids.
It interacts with gas only via gravity and accretion.

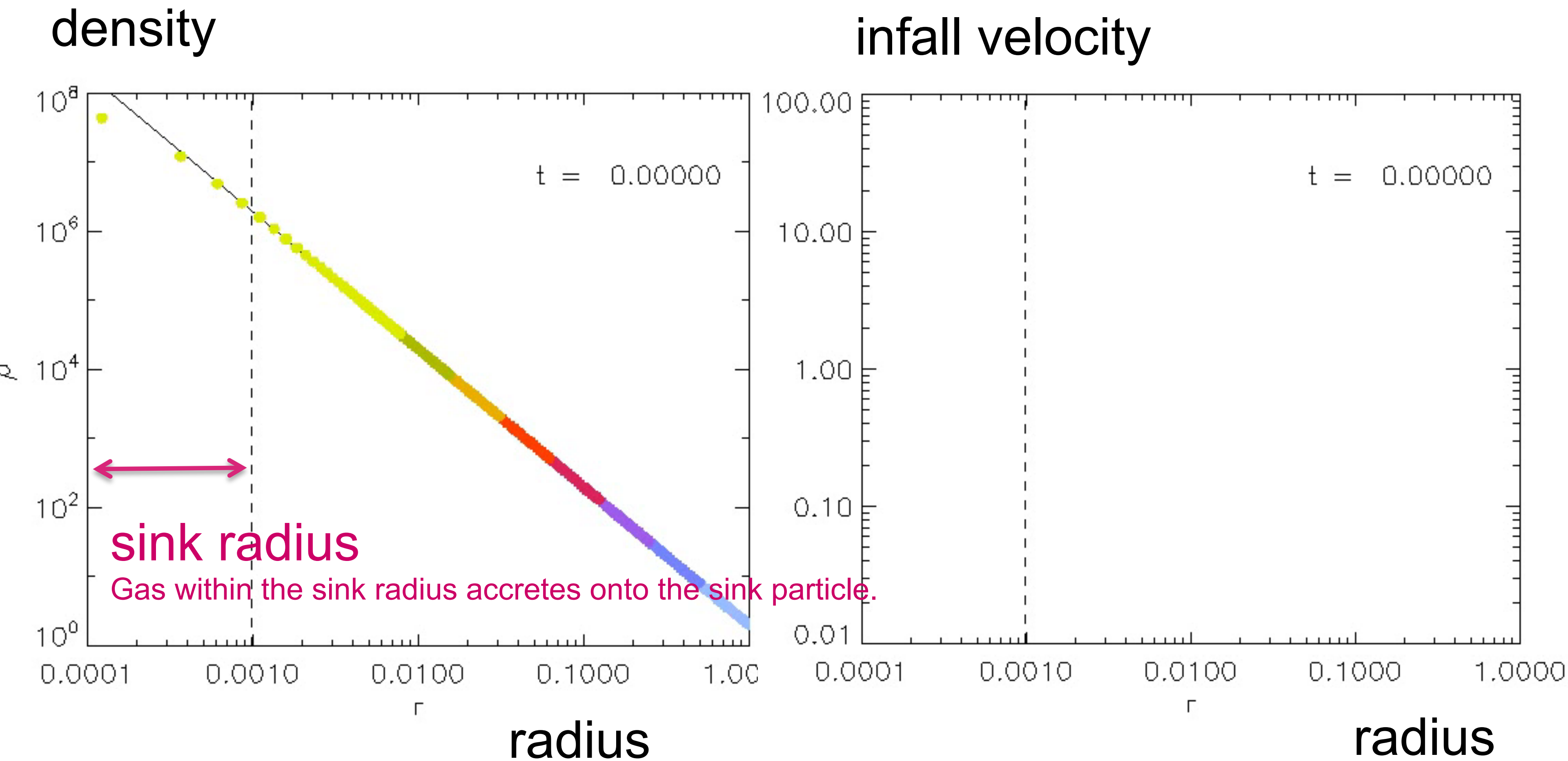
Circular motion around a gas cloud



Binary particles



Collapse of a singular isothermal sphere: Accretion onto a sink particle



dots: numerical solution
colors: grid level of AMR
black lines: exact solution

Magnetic diffusion

AD, HE, OD

Method for magnetic diffusion

Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$ advection → explicit scheme

$$-\nabla \times (\eta \nabla \times \mathbf{B})$$ Ohmic dissp.

$$+\nabla \times \left[\frac{c}{4\pi e n_e} \mathbf{B} \times (\nabla \times \mathbf{B}) \right]$$ Hall effect

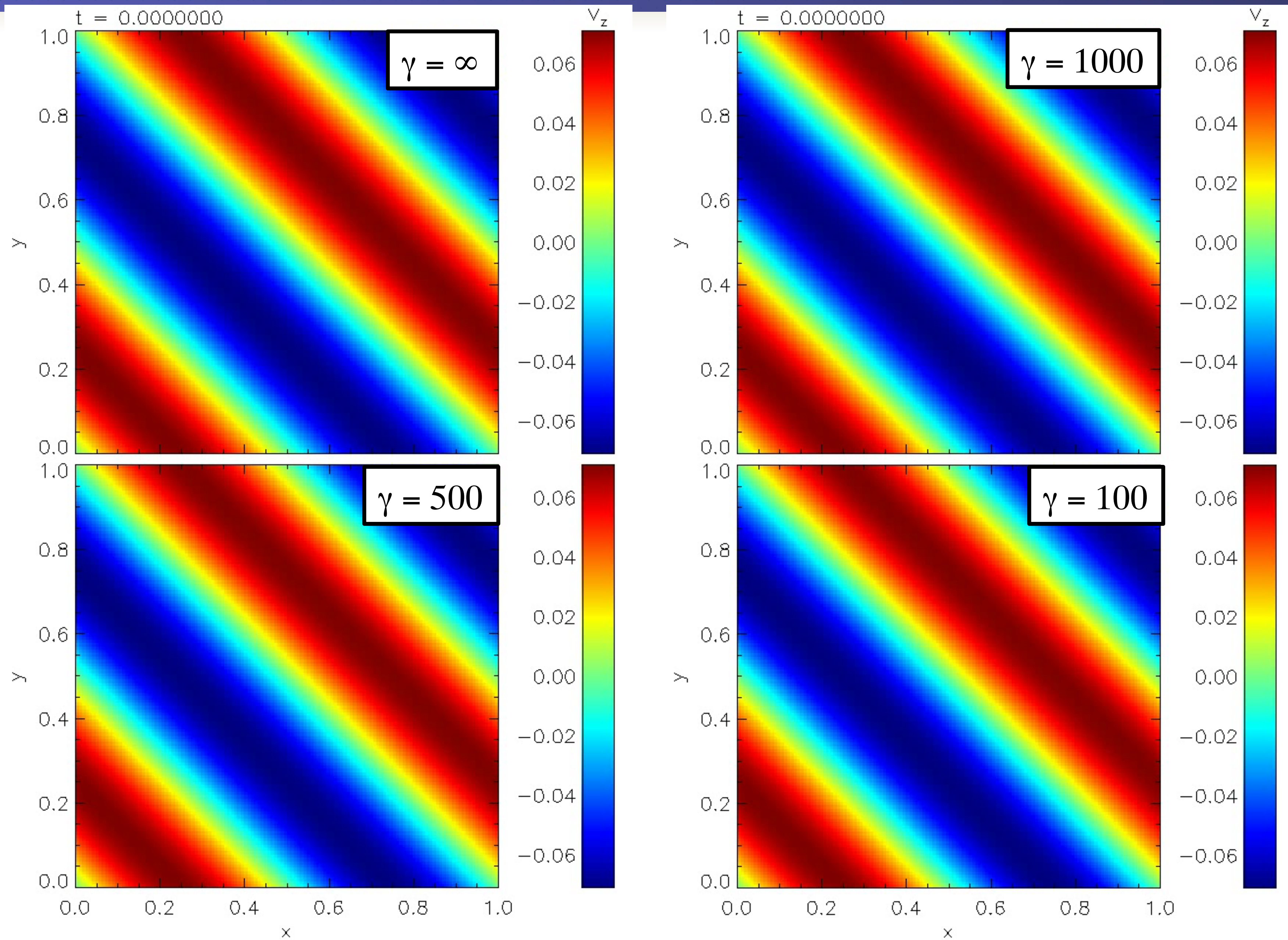
$$+\nabla \times \left\{ \frac{1}{4\pi \gamma \rho_n \rho_i} \mathbf{B} \times [\mathbf{B} \times (\nabla \times \mathbf{B})] \right\}$$ ambipolar diff.

Ohmic dissp., Hall effect, ambipolar diff. → implicit scheme with MG

Operator spliing

Decay of Alfven wave with AD

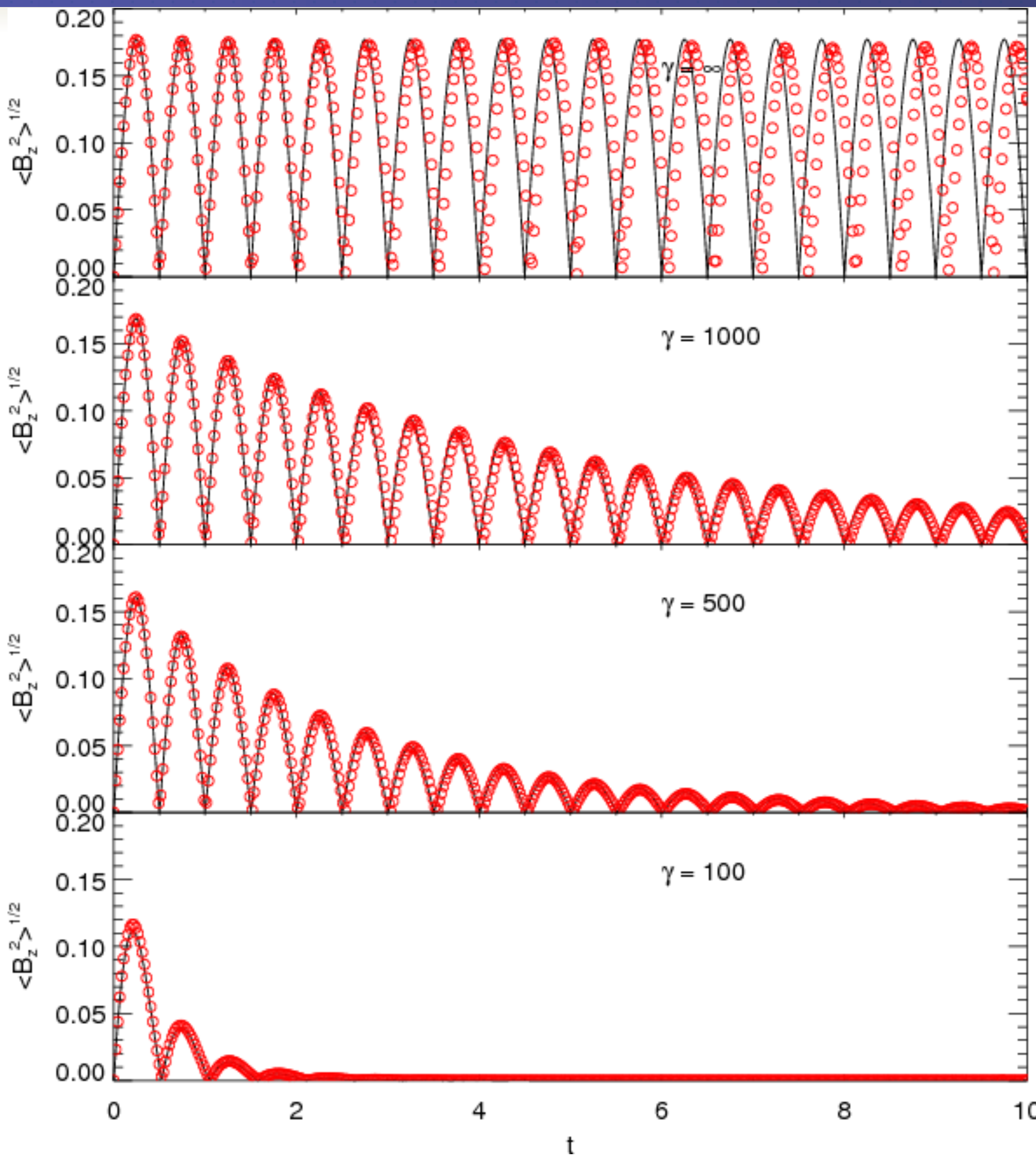
γ = drag coefficient



Decay of Alfven wave with AD

Ideal MHD

strong AD



approximate

numerical

γ = drag coefficient

$$\frac{D\Delta t}{\Delta t^2} = 0,\ 1.28,\ 2.56,\ 12.8$$

$$\text{for}\ \ \gamma = \infty,\ 1000,\ 500,\ 100$$

C-shock problem with AD.

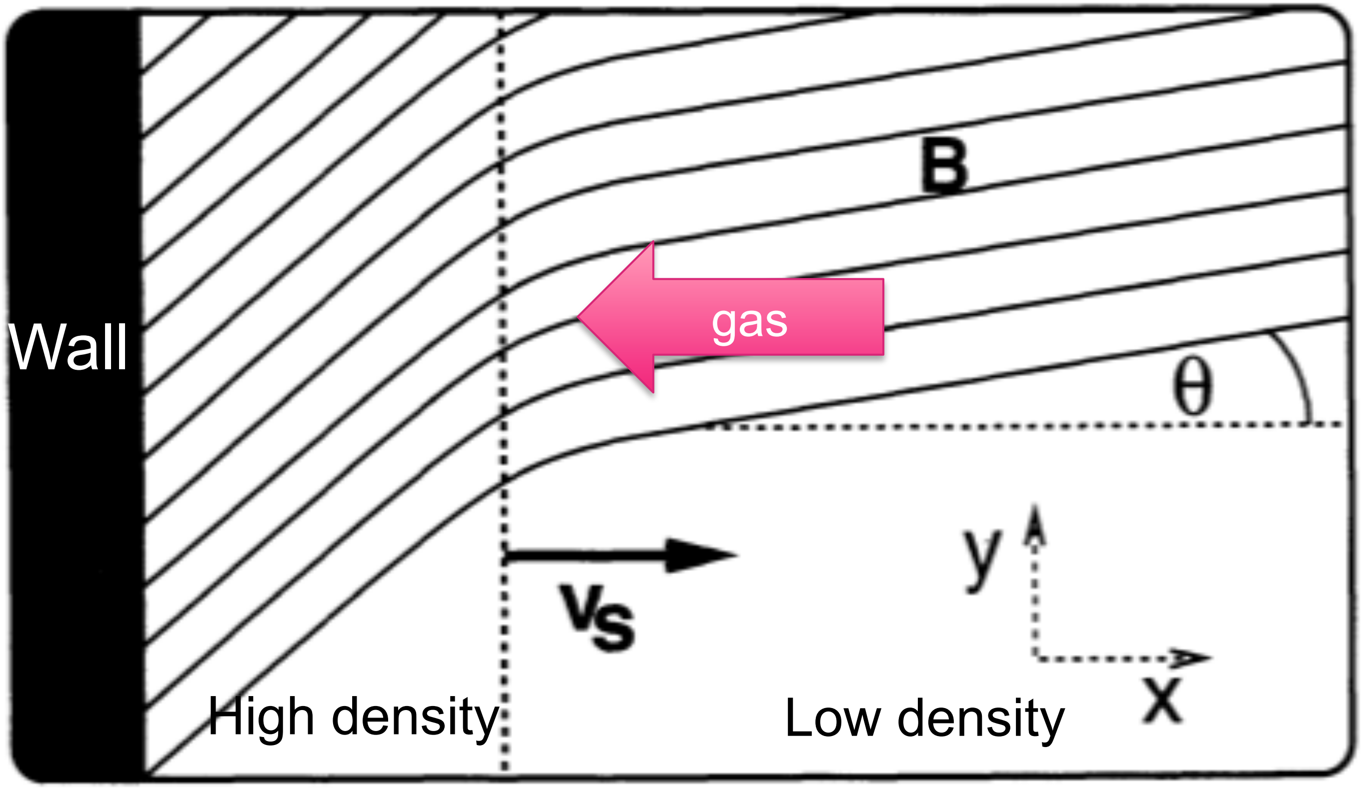
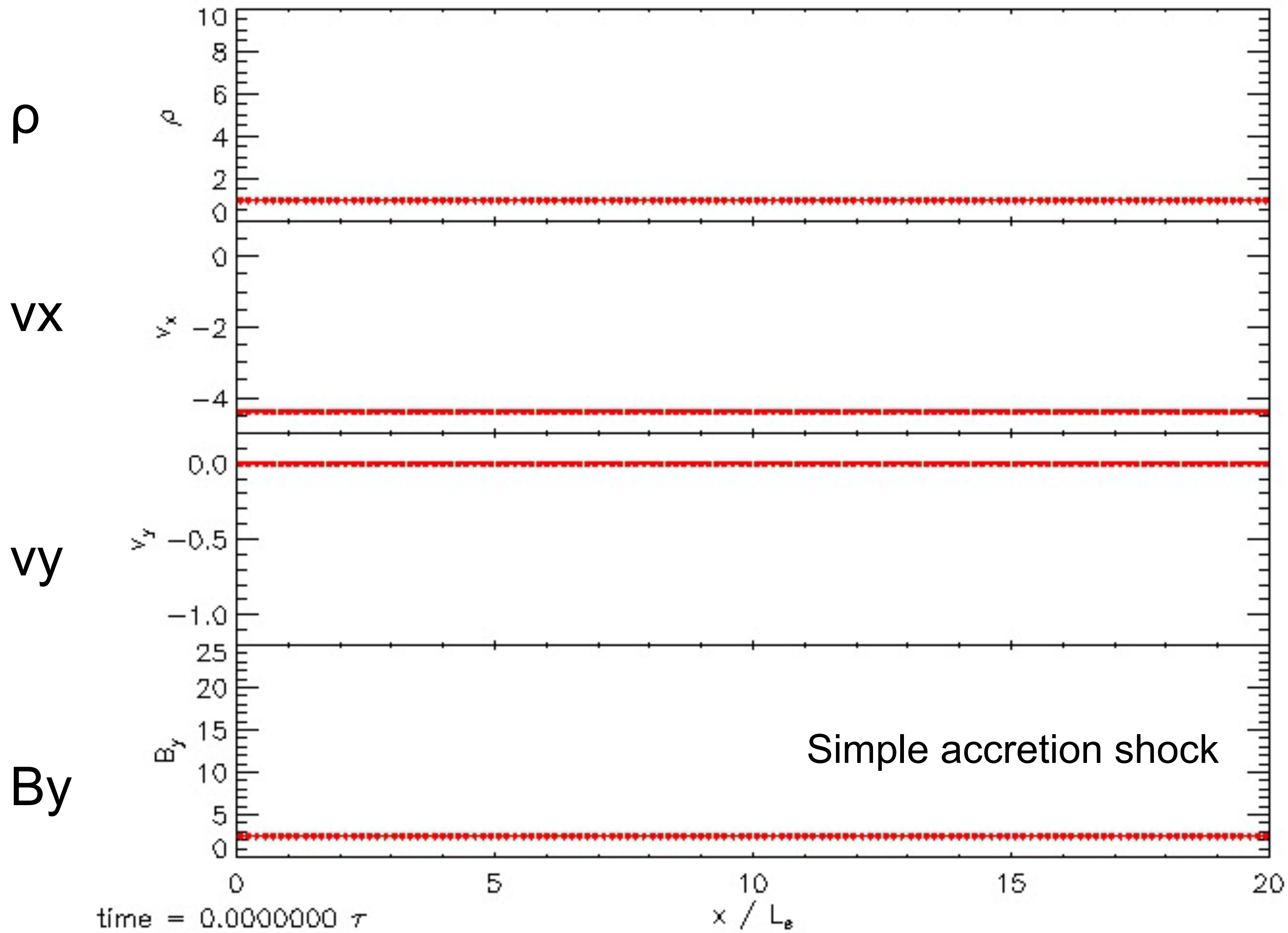


FIG. 2.—Cartoon of oblique C-shock structure, showing field lines, the direction of shock propagation, and the coordinate system. This problem is set up by starting off with a uniform flow toward the wall and allowing the C-shock to form naturally.

Mac Low+ 95

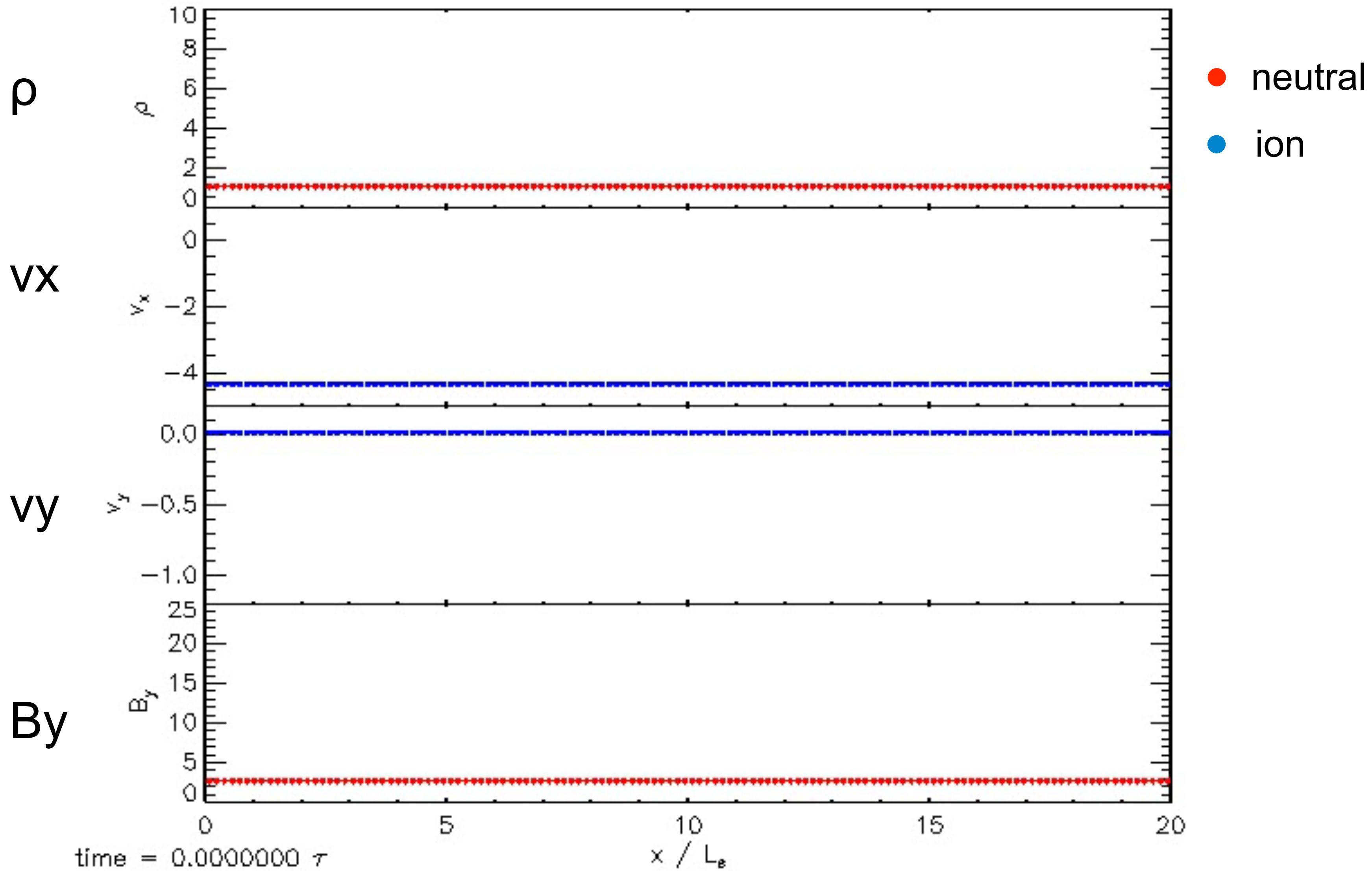
C-shock: without AD

M = 50, MA = 5, θ = 45°

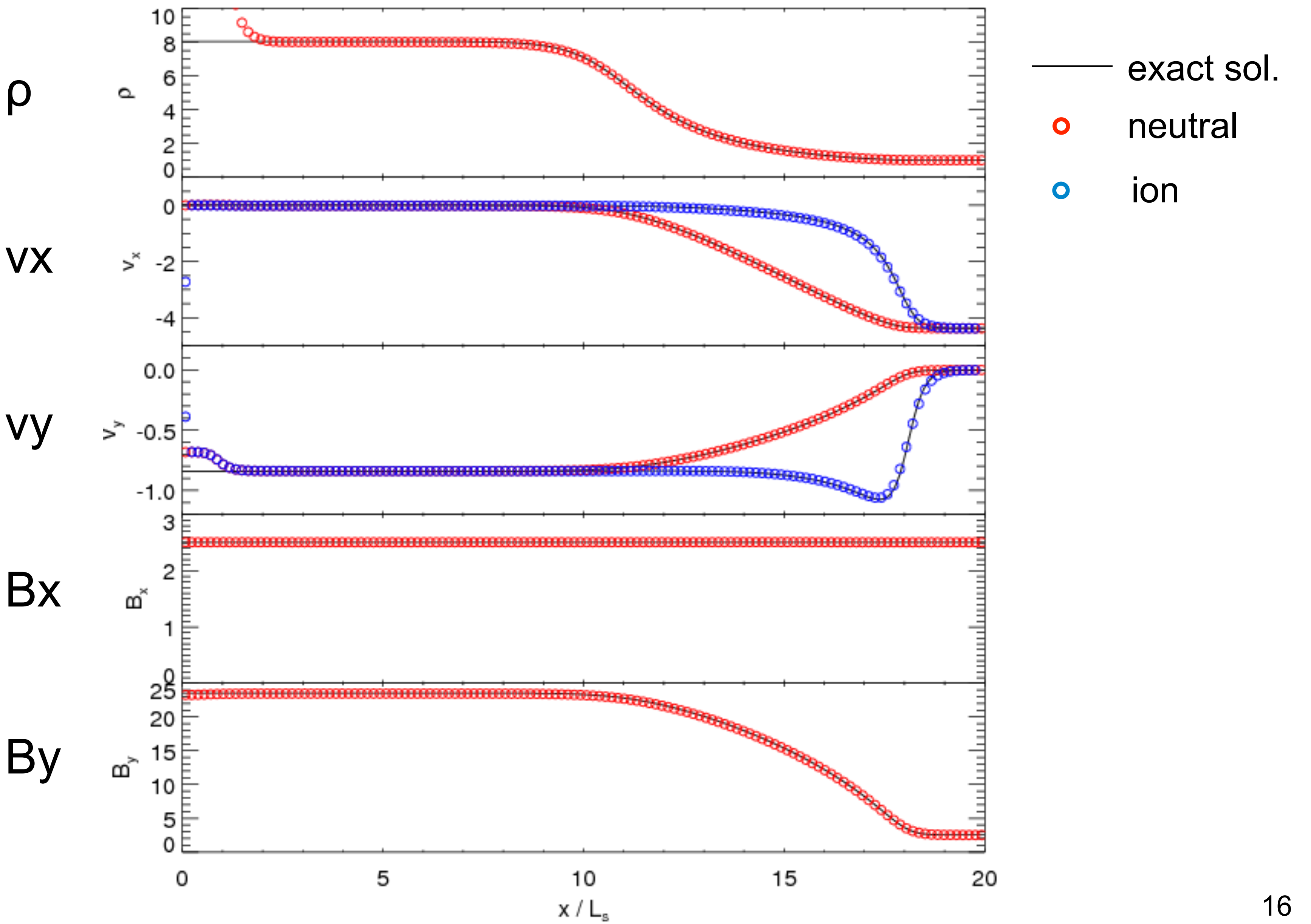


C-shock: with AD

M = 50, MA = 5, θ = 45°, $\rho_i = 10^{-5}$



Comparison with exact sol.： M=50, MA=5, θ=45°



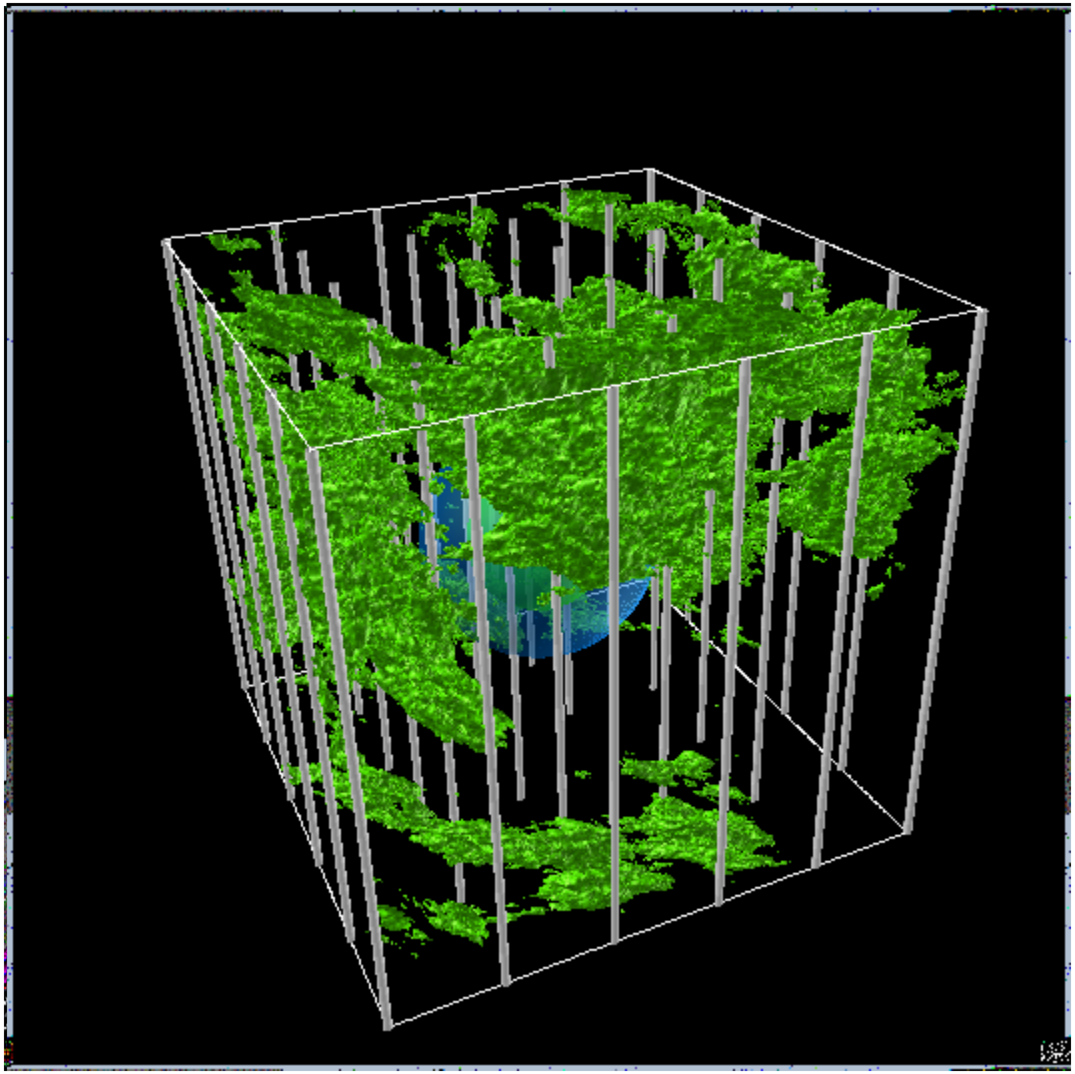
Protostellar collapse

Importance of turbulence and magnetic fields

- Turbulence
  - Interstellar medium is turbulent.
  - Supersonic turbulence on cloud scale
  - Subsonic turbulence on cloud core scale
  - Scaling law： $\Delta v \propto L^{1/2}$ (Larson 95)
  - Turbulence is origin of rotation（Burkert & Bodenheimer 00)
    - spin of protostar, rotation of protoprametary disk, driven mechanism of outflow/jet, etc.

- Magnetic field
  - Interstellar magnetic fields are strong.
  - Magnetic energy ～ gravitational energy
  - Resistivity is effective in high density.

Initial condition of cloud cores



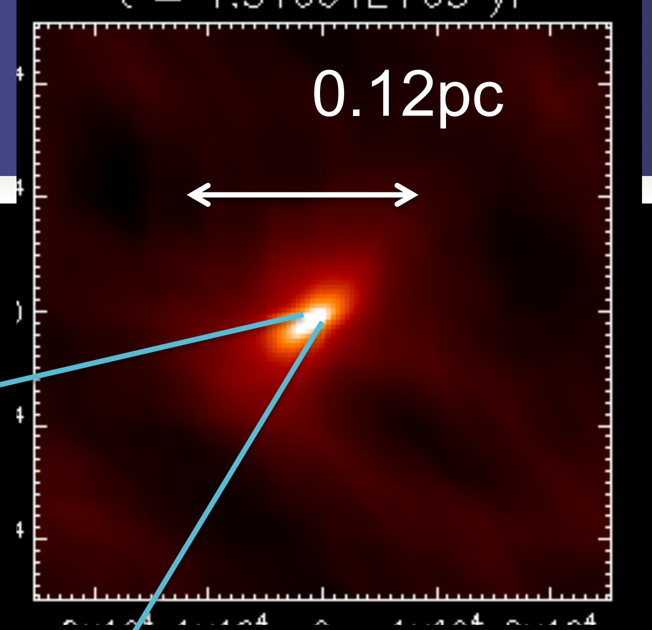
Density
- BE sphere ×(1.25–10)
- Center : 2×10^5/cc
- Radius : 0.049 – 0.14 pc
- Mass : 1.2 – 28 $M_\odot$
- Temp.: 10K

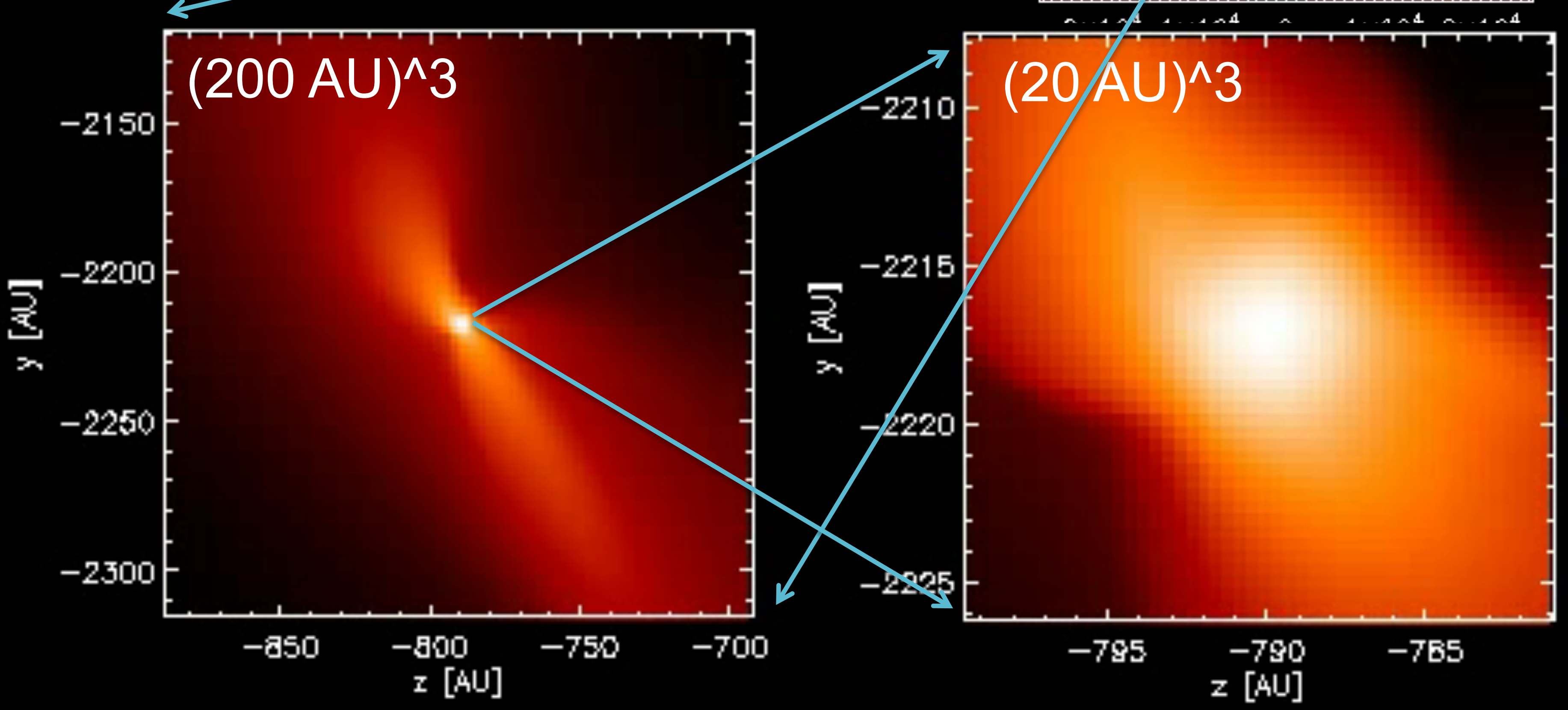
Magnetic fields with OD:
- 0.1, 0.25 B_{cr}
- 20 – 143 μG

Turbulence
- $\langle v^2 \rangle \propto k^{-4}$
- Mean Mach number = 0.5, 1, 3

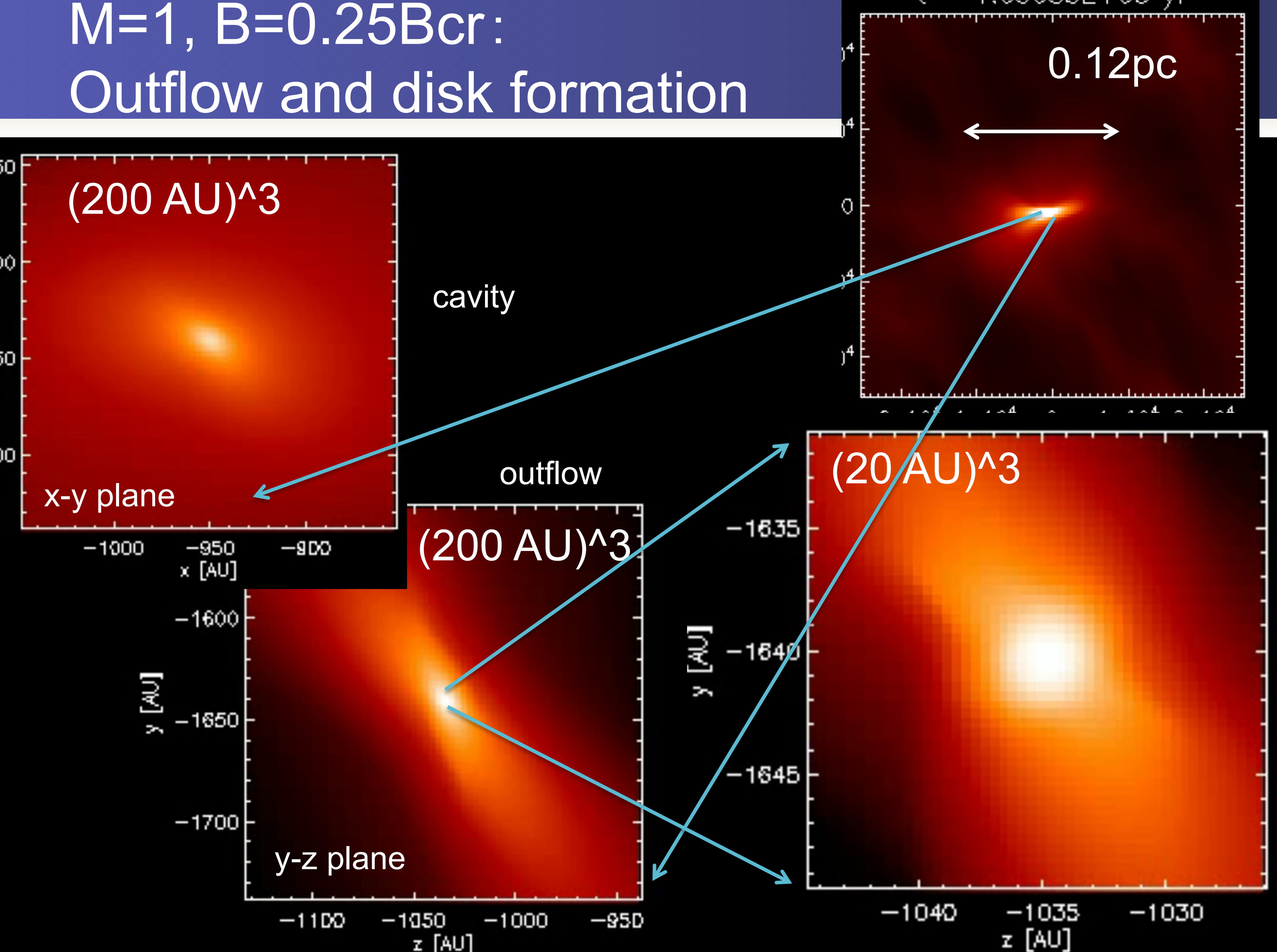
Calculation
- Cray-XT4@CfCA,
- Hitachi-HA8000@T2K

M=1, B=0.1Bcr : Outflow and disk formation

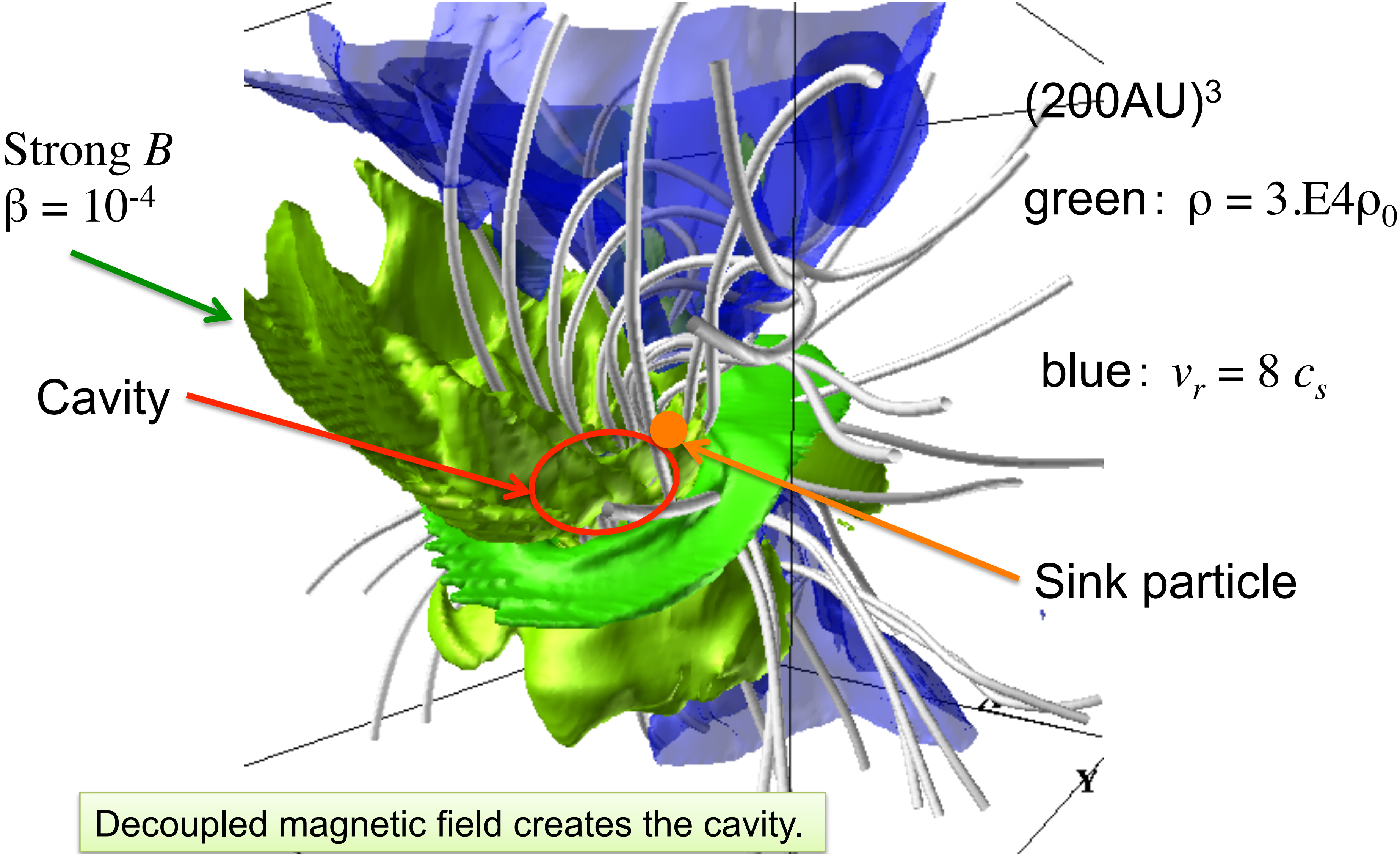




M=1, B=0.25Bcr: Outflow and disk formation



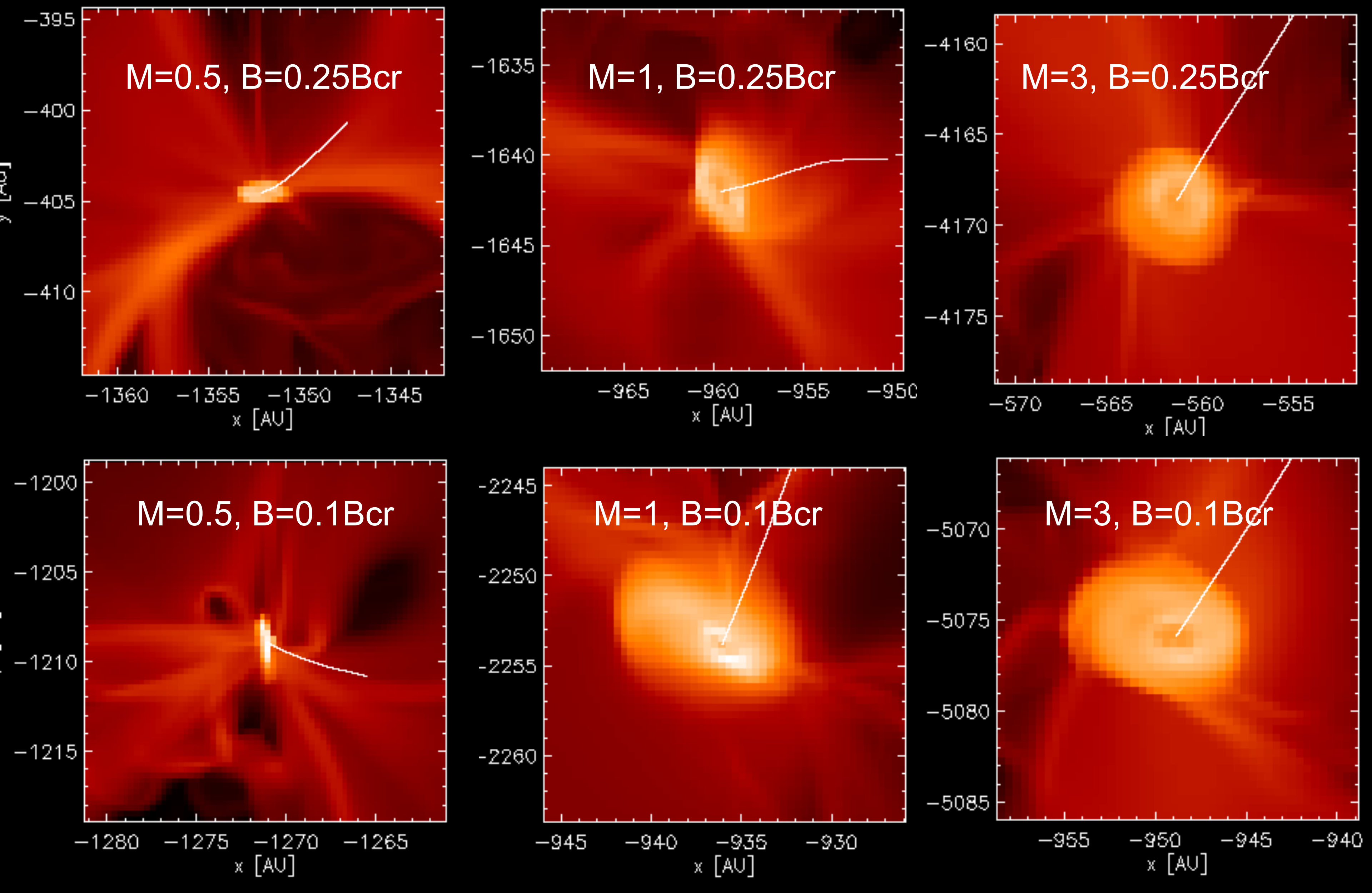
Cavity is filled by strong magnetic field.



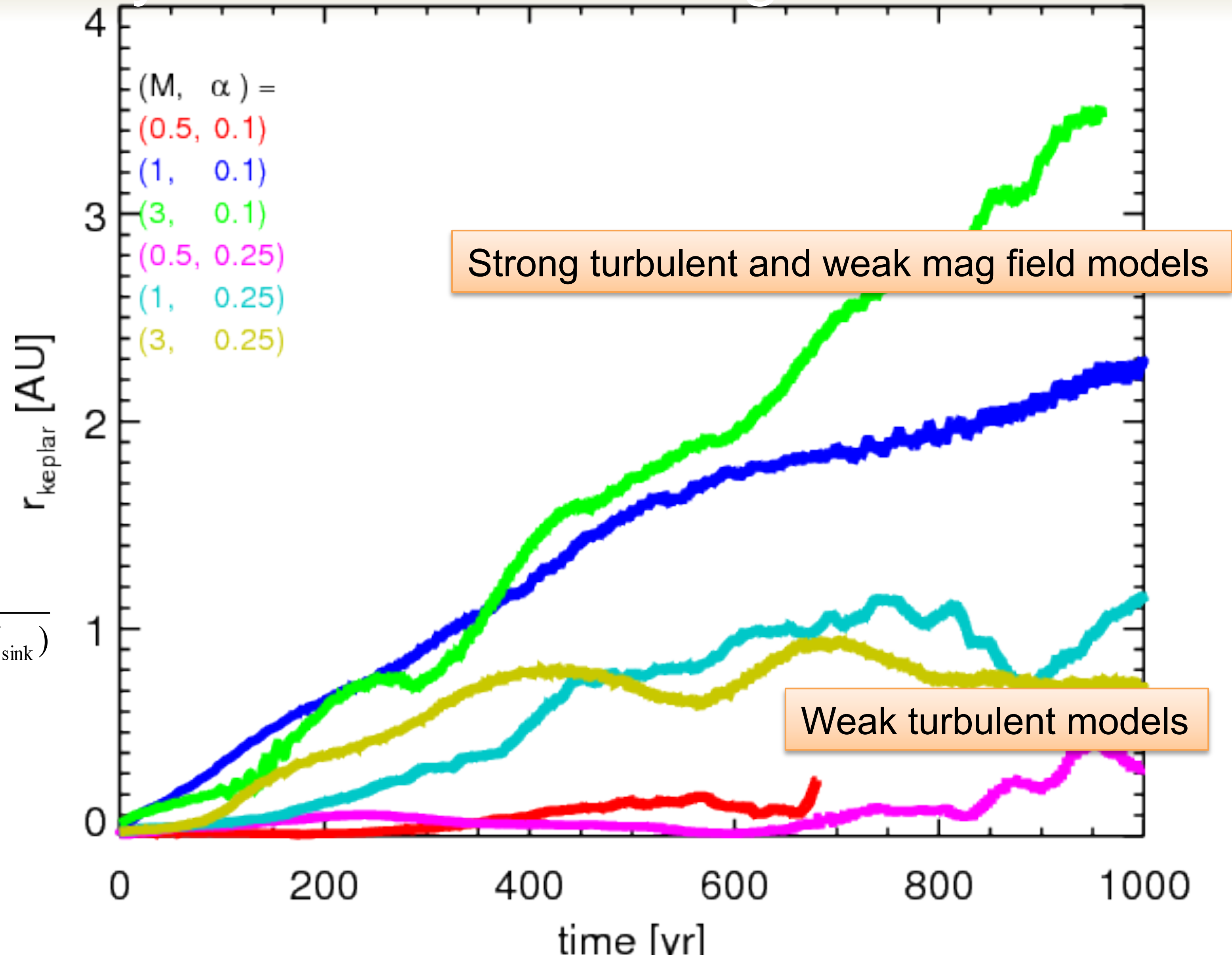
Decoupled magnetic field creates the cavity.

(20AU)^3

1,000 yr after protostar formation



Growth of disks: regulated by turbulence and magnetic field



Mean centrifugal radius

$$r_{\rm cent} = \frac{\bar{j}^2}{G(M_{\rm gas} + M_{\rm sink})}$$

$$\bar{j} = \frac{J_{\rm gas}}{M_{\rm gas}}$$

Elapse time after sink particle formation

Summary

- Our AMR code, SFUMATO:
  - A block-structured AMR is adopted.
  - Selfgravity, MHD, sink particles, magnetic diffusion are implemented.
- A turbulent magnetized cloud core produces a protostar with a protoplanetary disk and outflows.
  - Turbulence brings about rotation of a disk.
    - Strong turbulent models produces a large disk.
  - Rotation and magnetic field drive outflows.
  - Cavity is created by decoupled magnetic field.
    - which corresponds to “a magnetic wall” (Li & McKee 1996).