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Formation of Protostellar Cores and Circumstellar Disks

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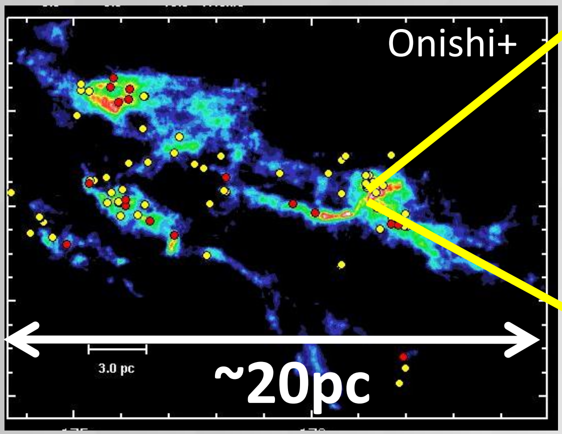
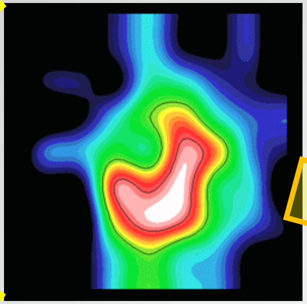
Tomida et al., submitted to ApJ, **arXiv:1206.3567**

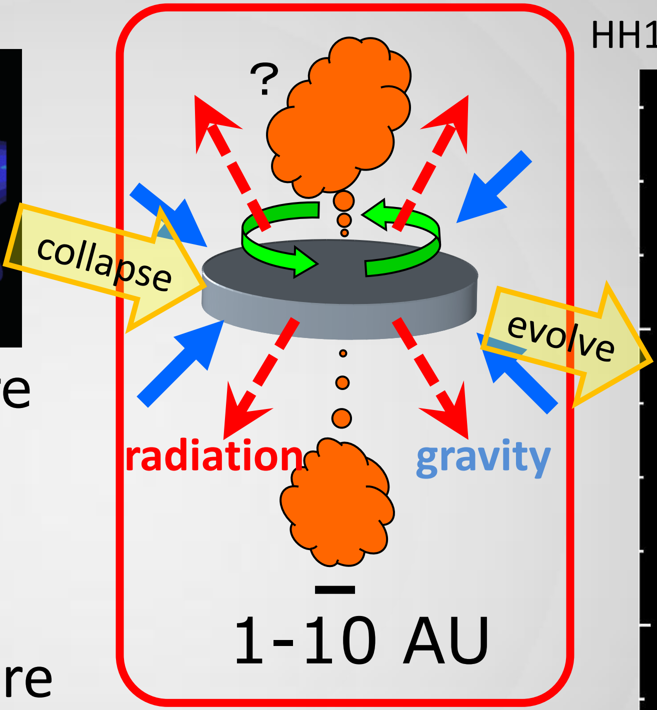
Introduction: Star Formation



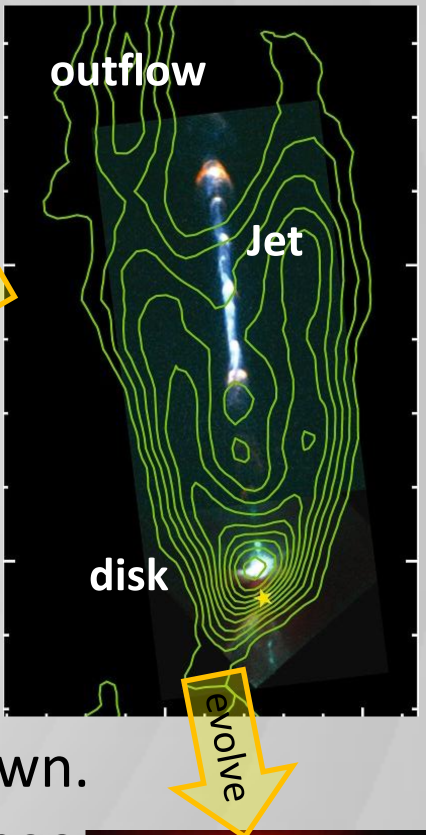
Taurus Molecular Cloud(Nagoya, 4m)



Cloud Core
∼0.1pc
n≳10^4/cc



Protostar, Disk, Outflow
HH111(Mckee&Ostriker 07)



Initial State: Molecular Cloud Core

Final State: Protostar, Disk, Jet, Outflow

Overall scenario is established, but details are left unknown.

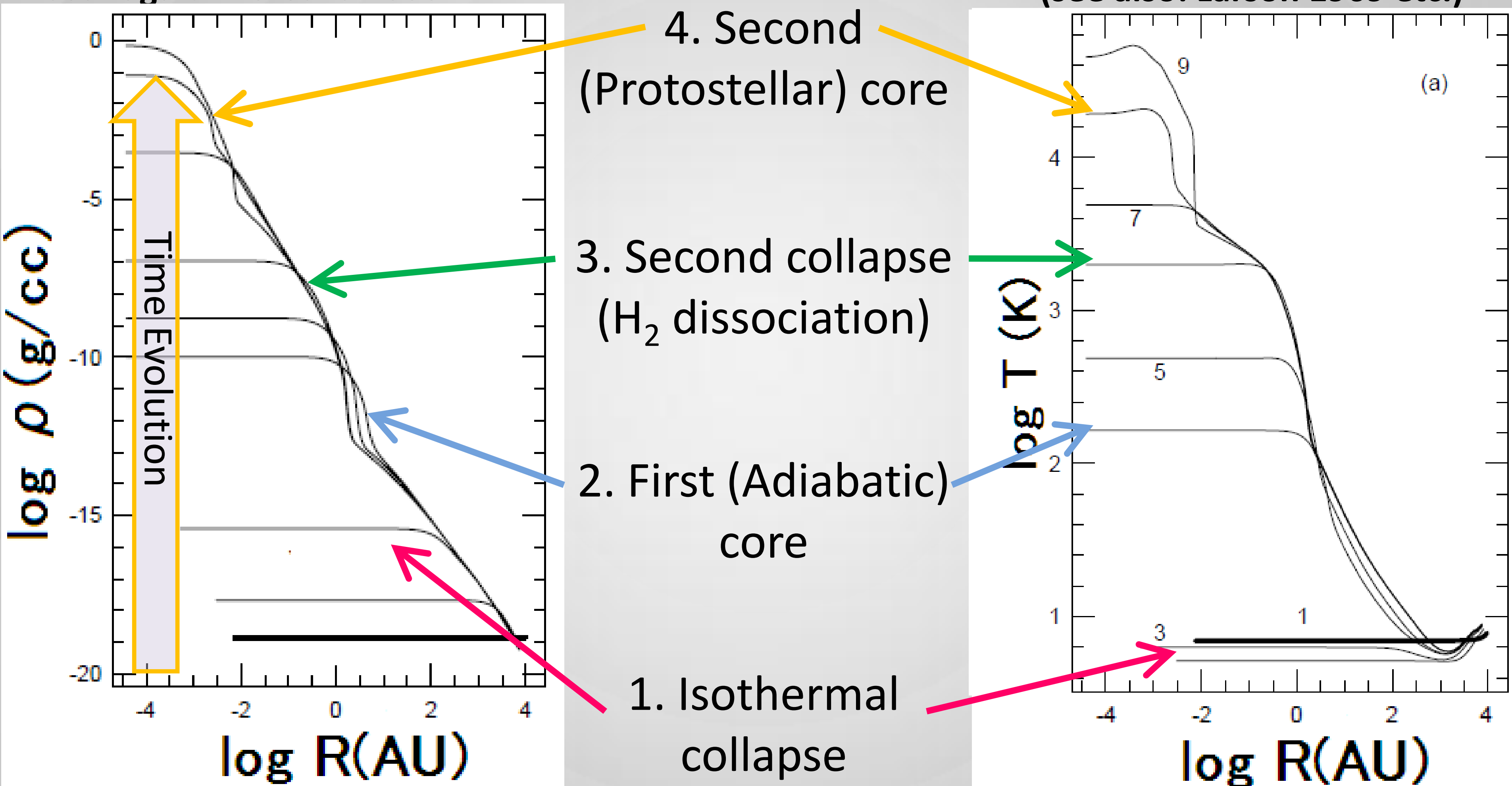
Complex physics : multi-dimensionality, large dynamic range
self-gravity, magnetic fields, radiation, chemistry, etc.

ALMA era→Precise modeling are strongly demanded.

⇒Highly sophisticated computational simulations

Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000 (see also: Larson 1969 etc.)



The scenario is well established based on 1D RHD simulations.

Interplay between radiation, thermodynamics and dynamics.

In reality: rotation, magnetic fields

(Historic) "Problems" in Star Formation Processes

- **Angular Momentum Problem**

Cloud Cores $j_{cl} \approx 5 \times 10^{21} \left(\frac{R}{0.1\mathrm{pc}} \right)^2 \left(\frac{\Omega}{4\mathrm{km\,s^{-1}pc^{-1}}} \right) \mathrm{cm^2 s^{-1}}$ **>>** $j_{*} \approx 6 \times 10^{16} \left(\frac{R_*}{2R_\odot} \right)^2 \left(\frac{P}{10\mathrm{day}} \right)^{-1} \mathrm{cm^2 s^{-1}}$ **Stars**

→Efficient angular momentum transport during protostellar collapse

⇒Gravitational torque, Magnetic braking, Outflow

- **Magnetic Flux Problem**

Similarly, magnetic flux in cloud cores >> stellar magnetic flux

→Magnetic fields must dissipate during the collapse

⇒Ohmic Dissipation, Ambipolar Diffusion, (Hall effect)

- "**Magnetic Braking Catastrophe**" (Mellon & Li 2008,09, Li+ 2011, etc.)

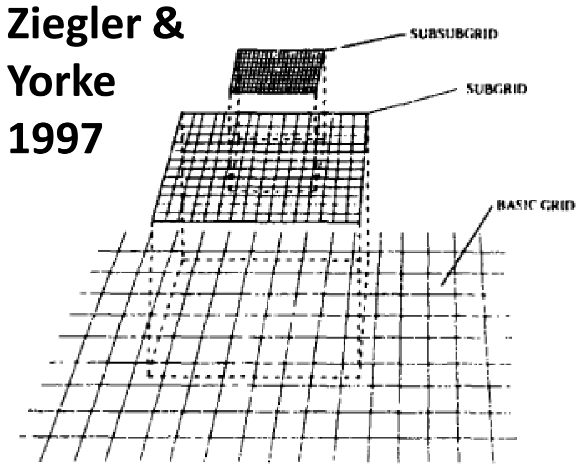
Magnetic barking is too efficient; no circumstellar disk is formed

⇒Long-term accretion, non-ideal MHD effects, etc. (Machida+ 2011)

⇒Realistic **3D simulations with many physical processes!**

ngr^{3}mhd code

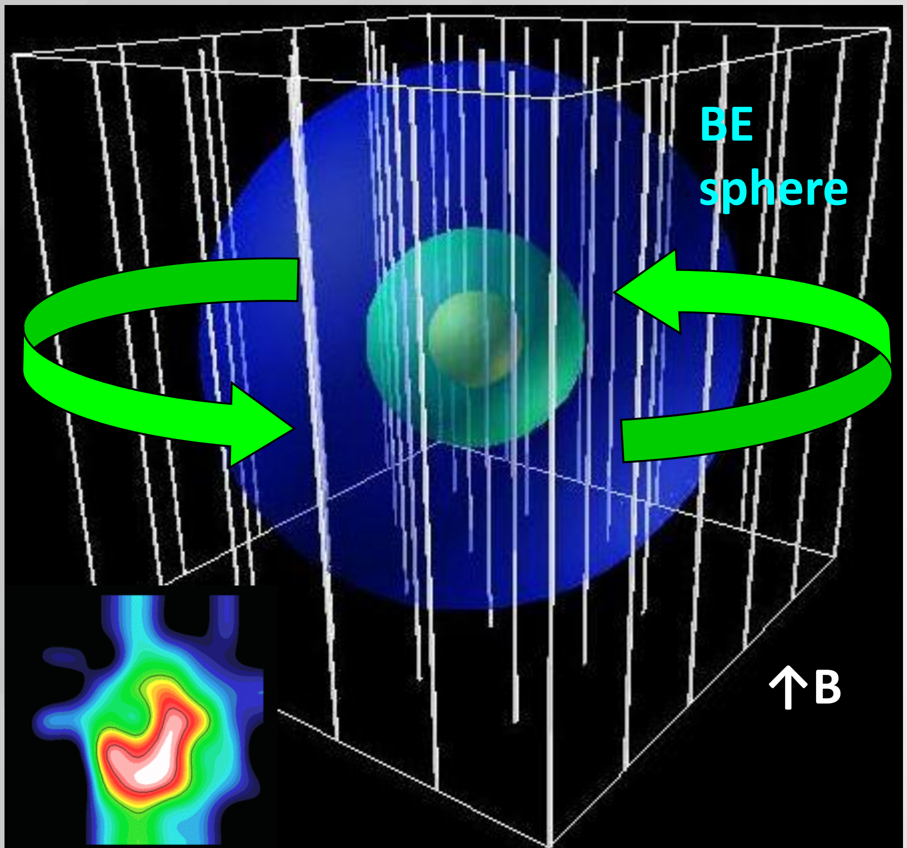
Required elements for SF studies



- Huge dynamic range: →3D nested-grids
- MHD → **HLLD**(Miyoshi & Kusano 2005)
  (+ Carbuncle care→shock detection + HLLD-)
  - ✓ Fast, robust and as accurate as Roe's solver
  - ✓ Independent from the details of EOS
- div **B**=0 constraint→Hyperbolic cleaning (Dedner+ 2002)
- Self-gravity→Multigrid (Matsumoto & Hanawa 2003)
- **Radiation→Gray Flux Limited Diffusion (Levermore & Pomraning 1981) +Implicit (BiCGStab + ILU decomposition (0) preconditioner)**
- **EOS including chemical reactions ← partition functions**
- **Ohmic dissipation→Super Time Stepping (Alexiades+ 1996)**
- Computers: NEC SX-9 at NAOJ, JAXA and Osaka-Univ.

⇒First 3D RMHD simulations of protostellar core formation!

Simulation Setups



Two rotating models:

- Ideal MHD model
- Resistive MHD model

64^3 x 23 levels, 16 cells / λ_{Jeans}

min(Δx)～**6.6 x 10^{-5}AU**～0.014Rs

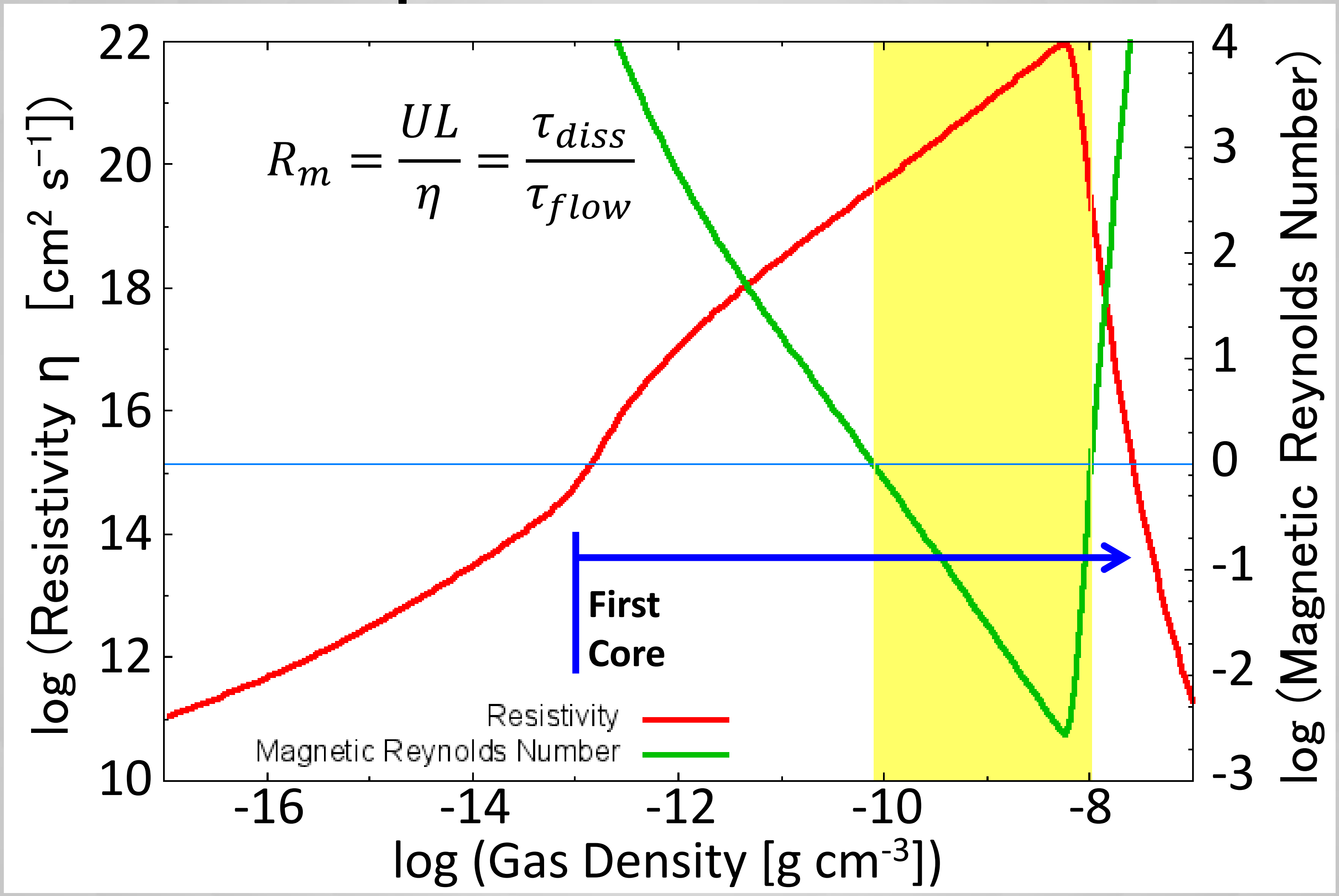
End of simulations: Tc～10^5 K,

~1 yr after 2nd core formation

> 10^8 !

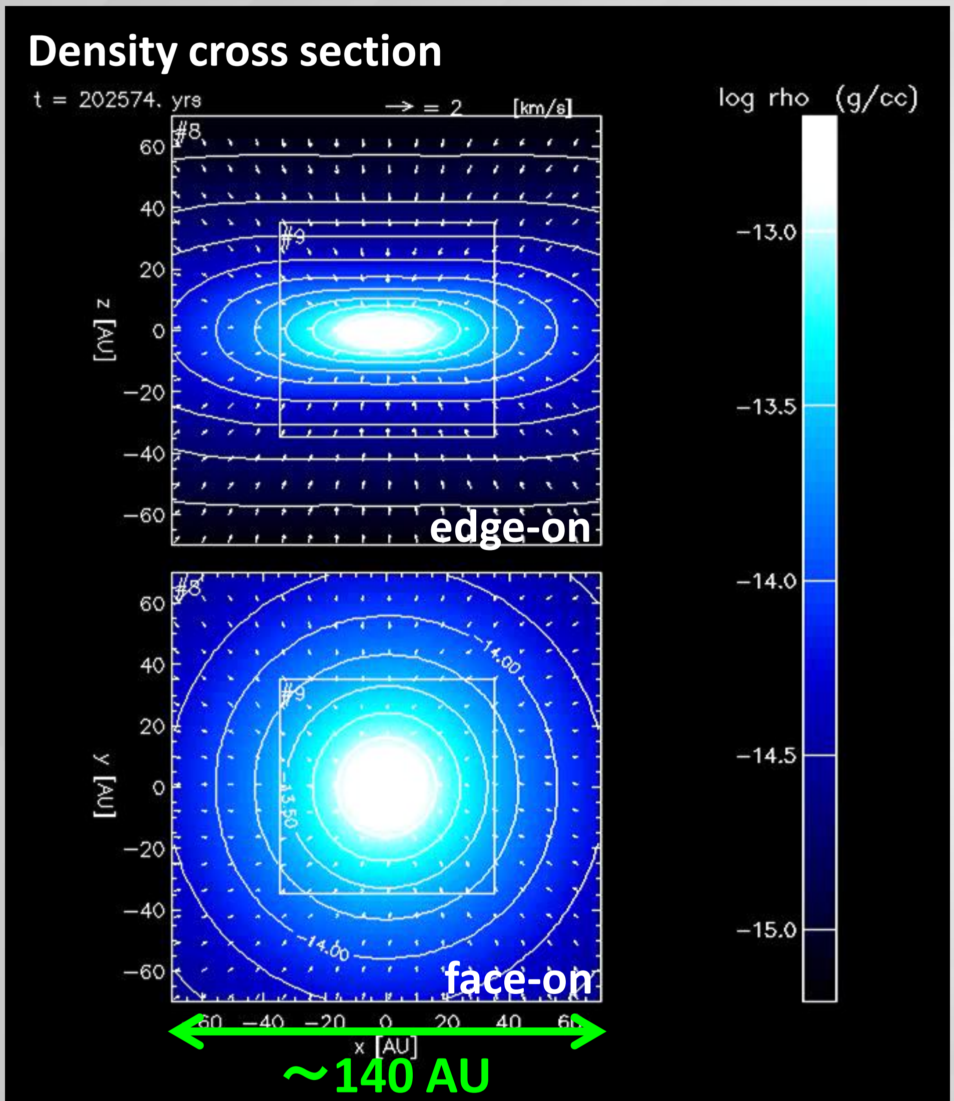
- 1Ms unstabilized BE sphere（ρ_c=1.2 x 10^{-18} g/cc, T=10K, **R=8800AU**）
- Bz=20μG (μ～3.8), Ω=0.046/t_{ff} ～2.4 x 10^{-14} s^{-1} , aligned rotator
- 10% m=2 density perturbation
- Resistivity (Umebayashi & Nakano 2009, Okuzumi 2009)

Ohmic Dissipation

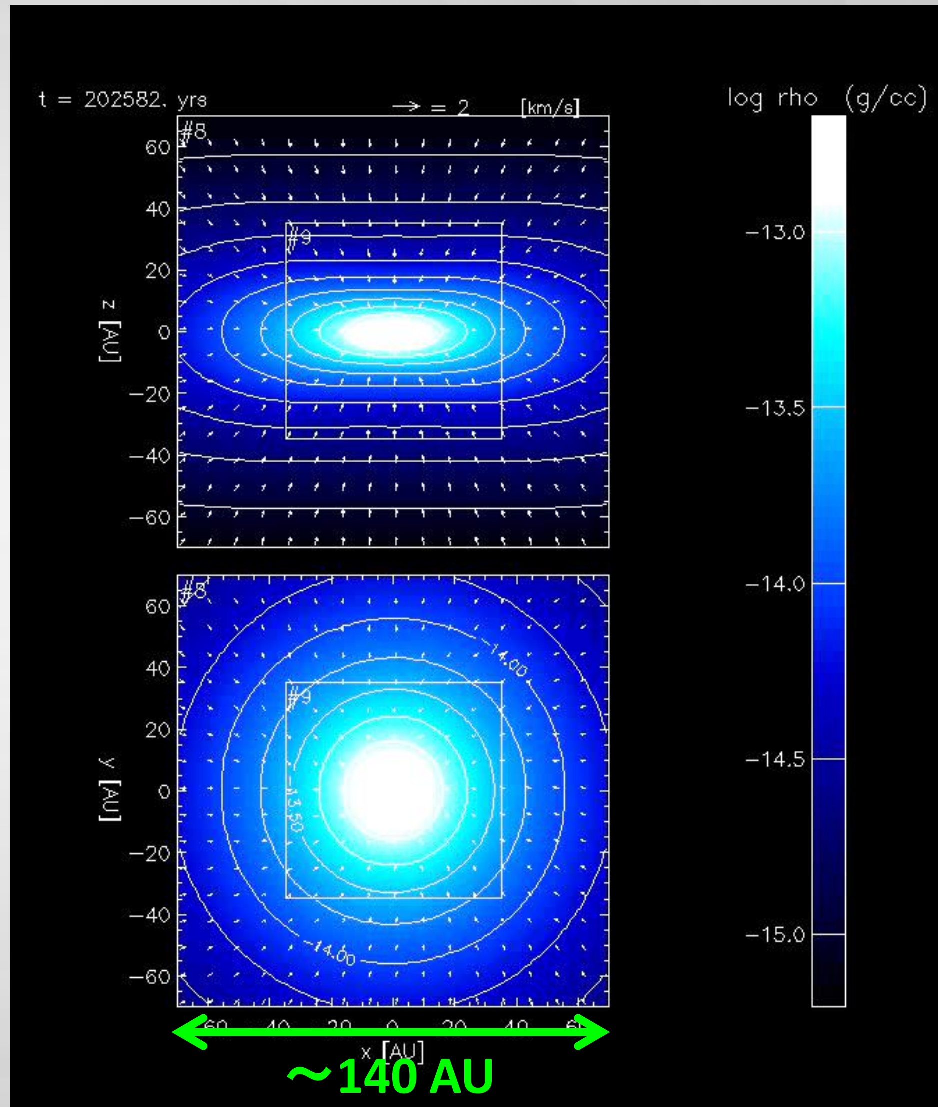


Resistivity (w/Dr. Okuzumi): $\xi = 10^{-17}$ s^{-1}, Neglect shielding of cosmic rays
Need no enhancement, but resolving small high-density region is crucial.

Rotating models: Outflows

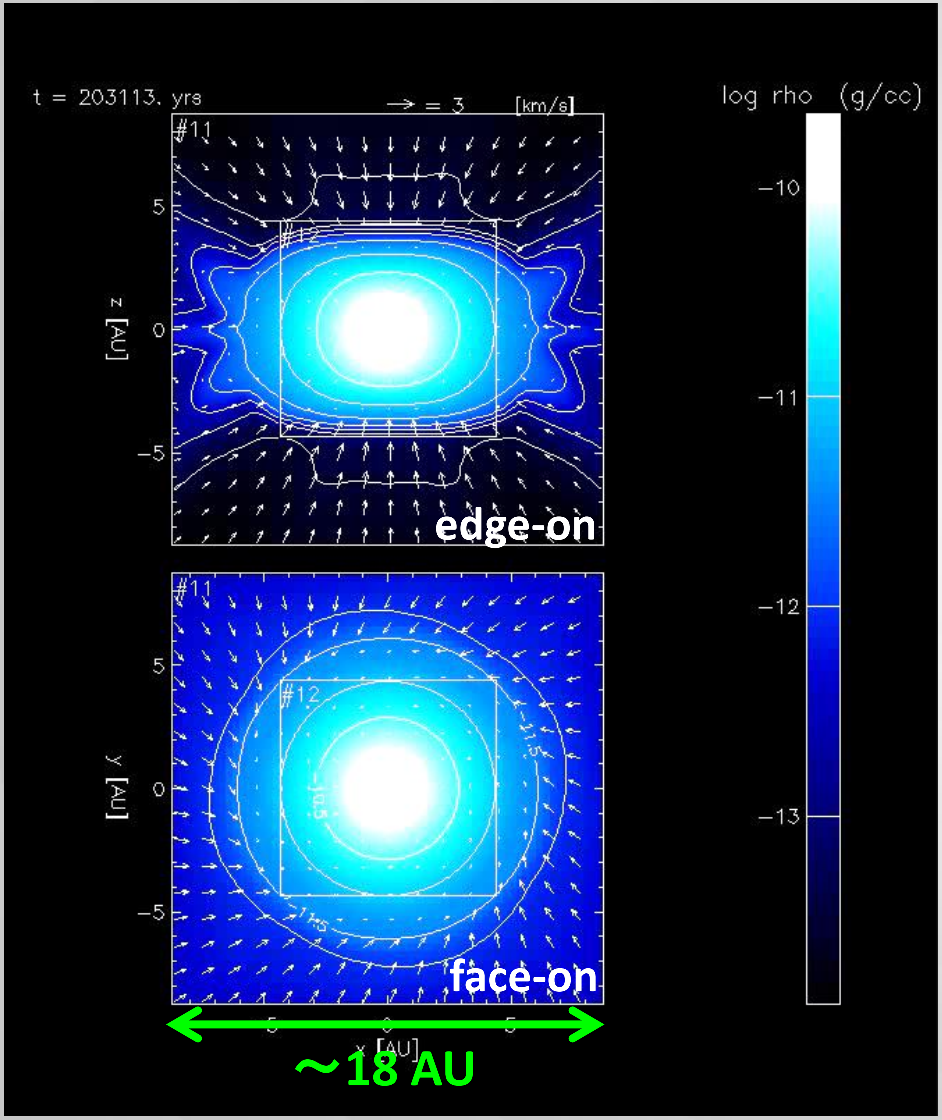


Ideal MHD

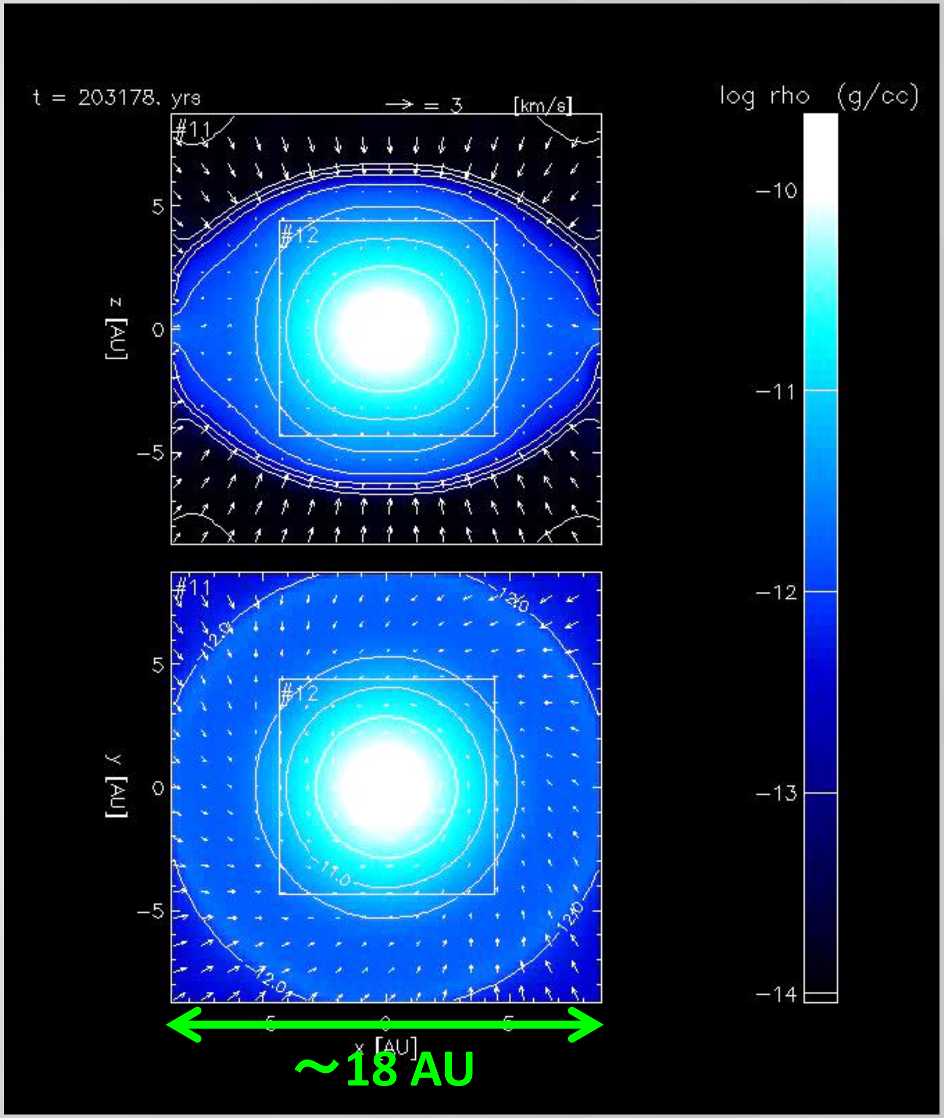


Resistive MHD

Rotating models: First cores

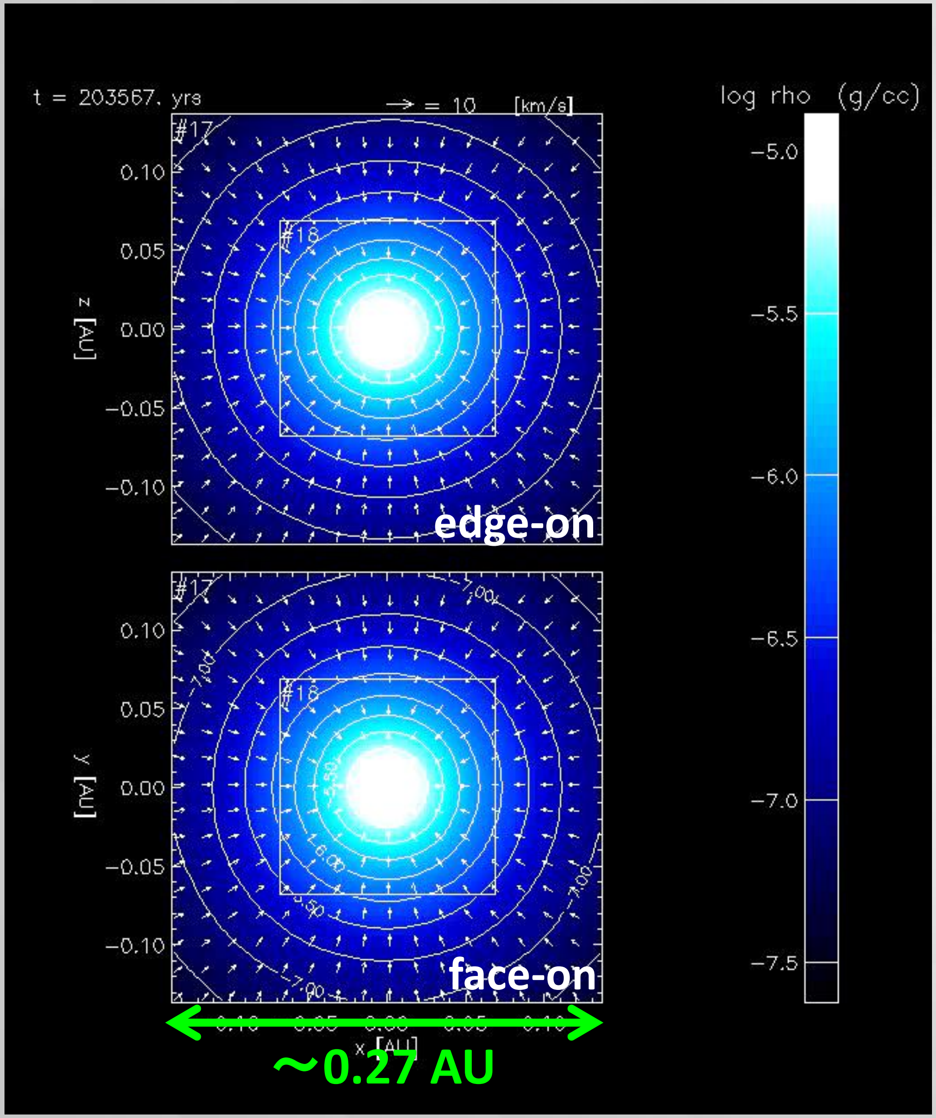


Ideal MHD

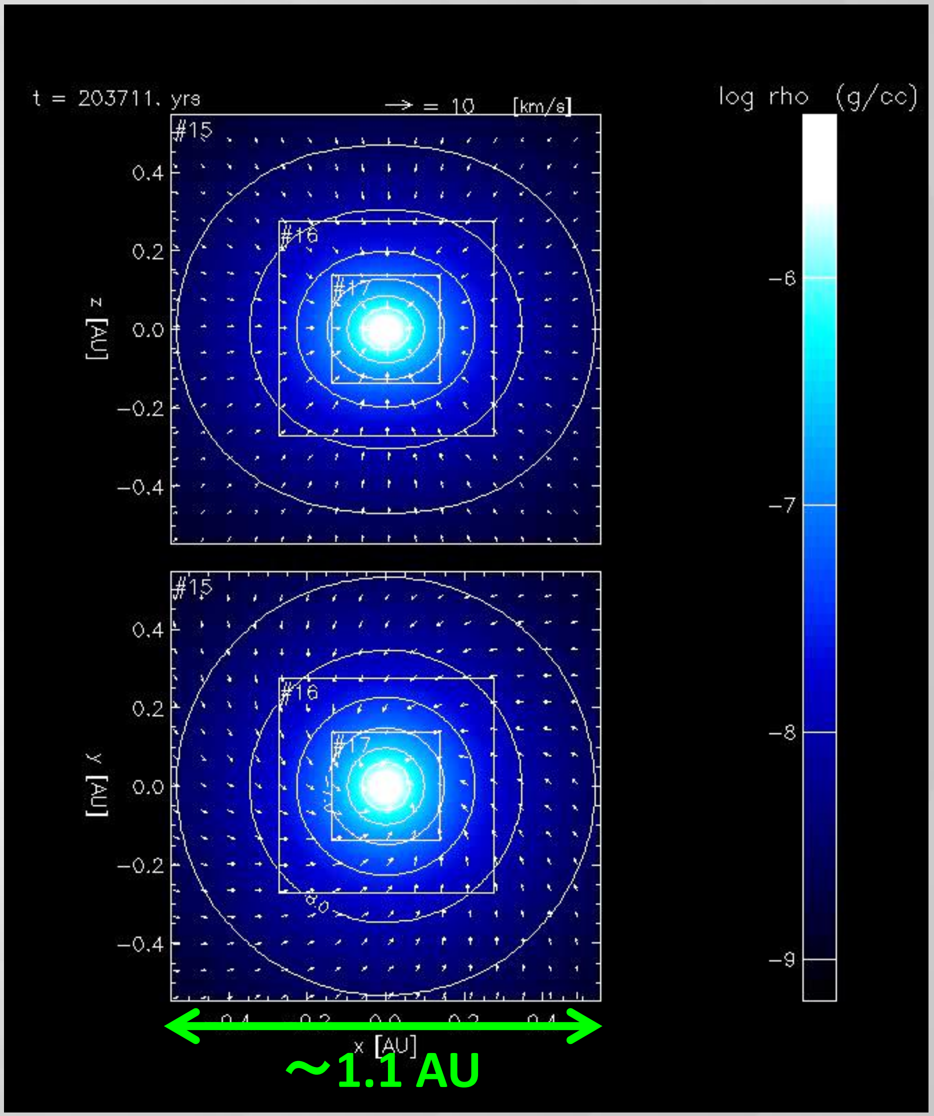


Resistive MHD

Rotating models: Protostellar cores



Ideal MHD



Resistive MHD

Protostellar Cores

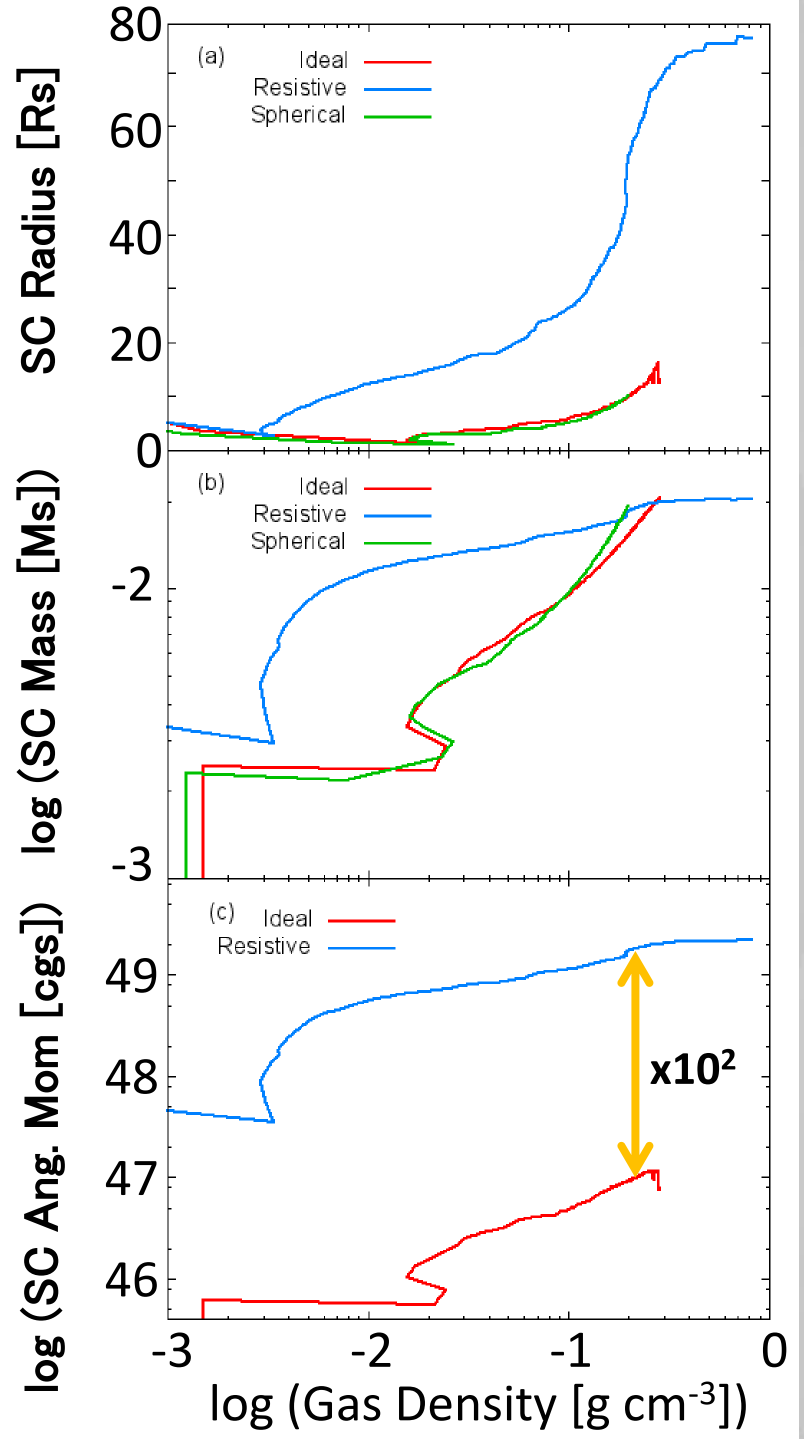
Radii, Masses, Angular momenta⇒

PCs acquire ~0.02 Ms in ~ 1yr

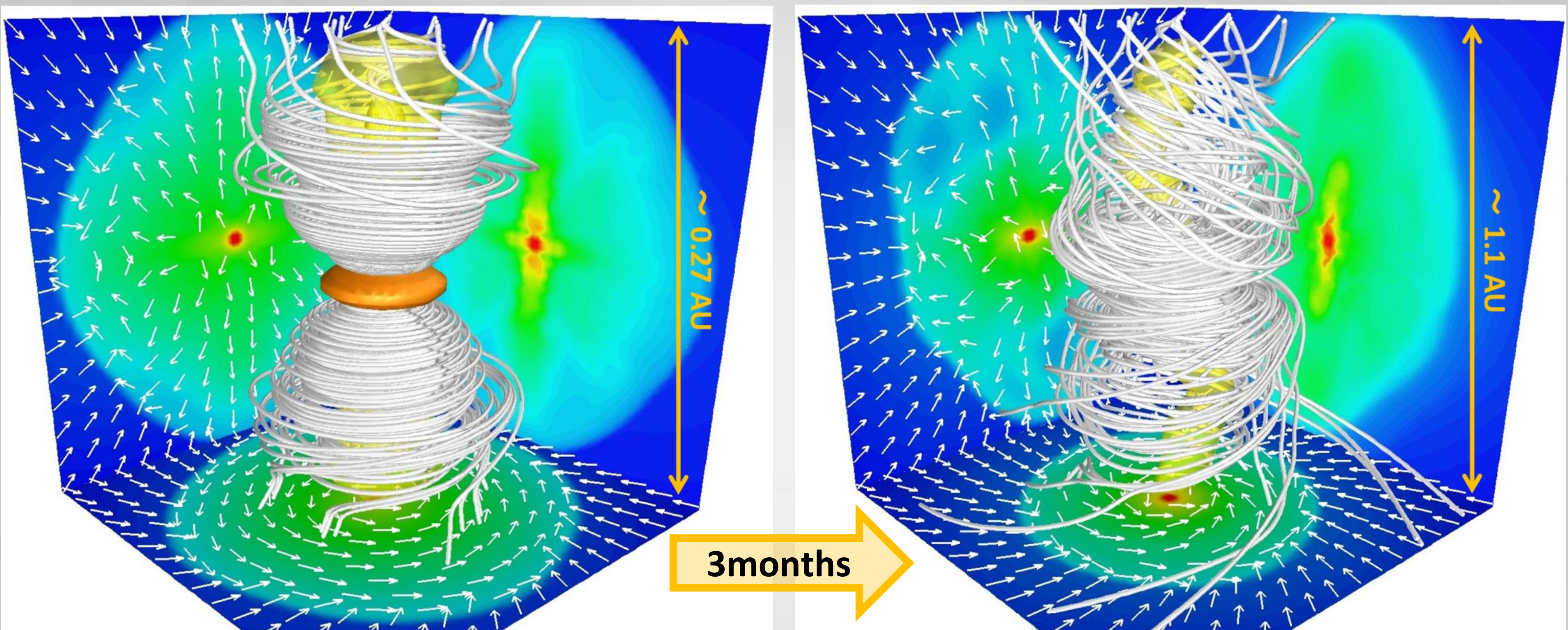
Ideal MHD model = virtually spherical
←very low angular momentum
Circumstellar disk is not formed
"**Magnetic Braking Catastrophe**"

Resistive MHD: large ang. momentum
→rotationally supported disk is formed
Rdisk ~ 0.3 AU at the end of simulation
It will continuously grow via accretion

⇒**NO Magnetic Braking Catastrophe**



Fast outflow from protostellar core



Toroidal fields are rapidly amplified by rotation in resistive case.
→Fast outflow（≳15km/s）is driven due to magnetic pressure
Consistent w/ previous MHD sims（Machida et al. 08 etc.）
The magnetic tower is disturbed by the kink instability.

Summary

First direct 3D RMHD simulations of protostellar core formation

- Spherical case: consistent with preceding studies.
- In ideal MHD cases, angular momentum transport is efficient

→Protostellar cores are not rotating, virtually spherical

- Angular momentum transport is suppressed in resistive cases

→Rotationally-supported disk and fast outflow, the disk is small because of short simulation time, but will grow (Machida+ 2011)

- Resistivity works in high density region→High resolution is critical

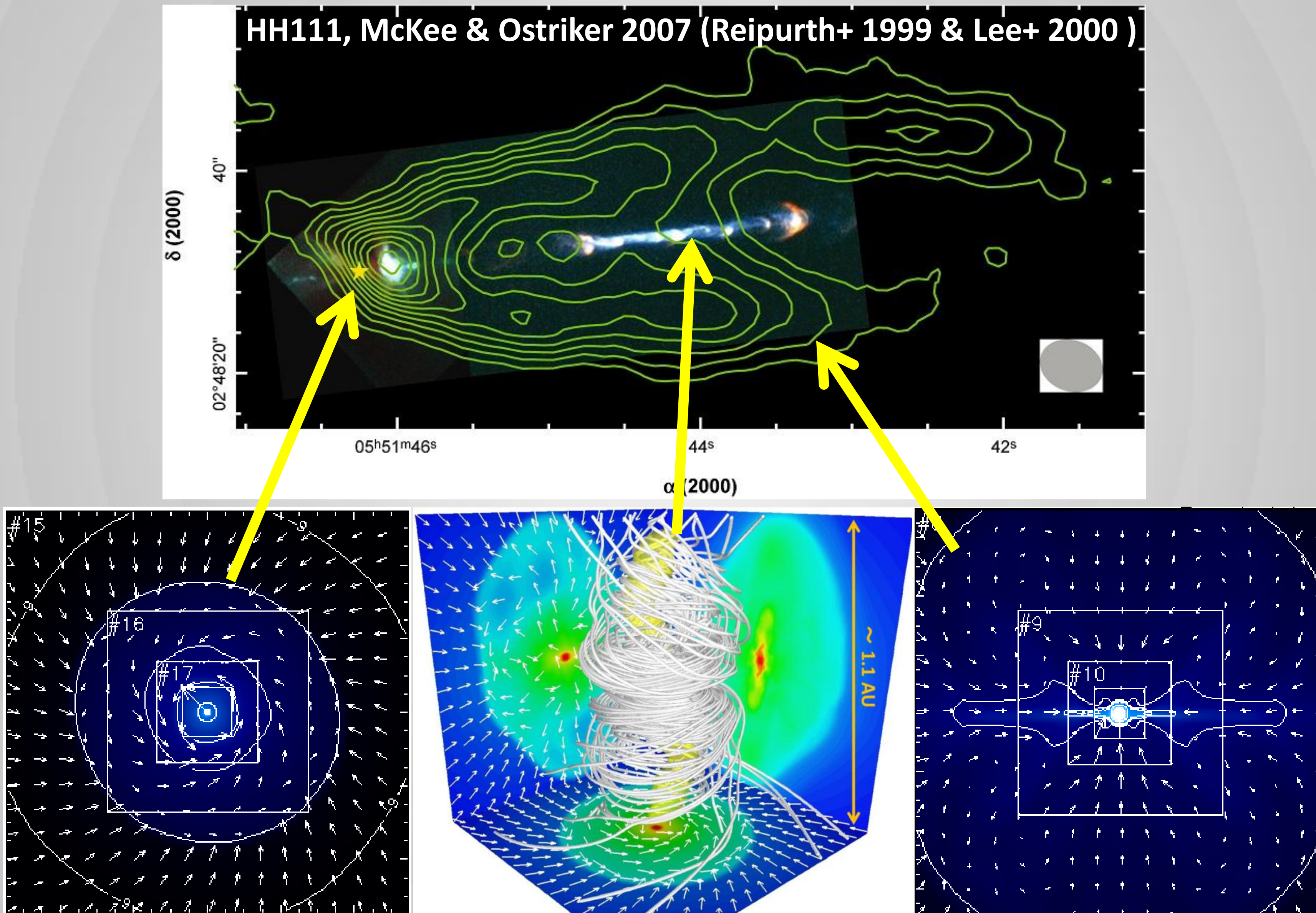
HOWEVER:

We simulated only 1 year after the protostellar core formation

Timestep is too short, it takes almost as long as real star formation.

⇒Long term simulations with accurate subgrid models

With some “imagination”…



Thank you