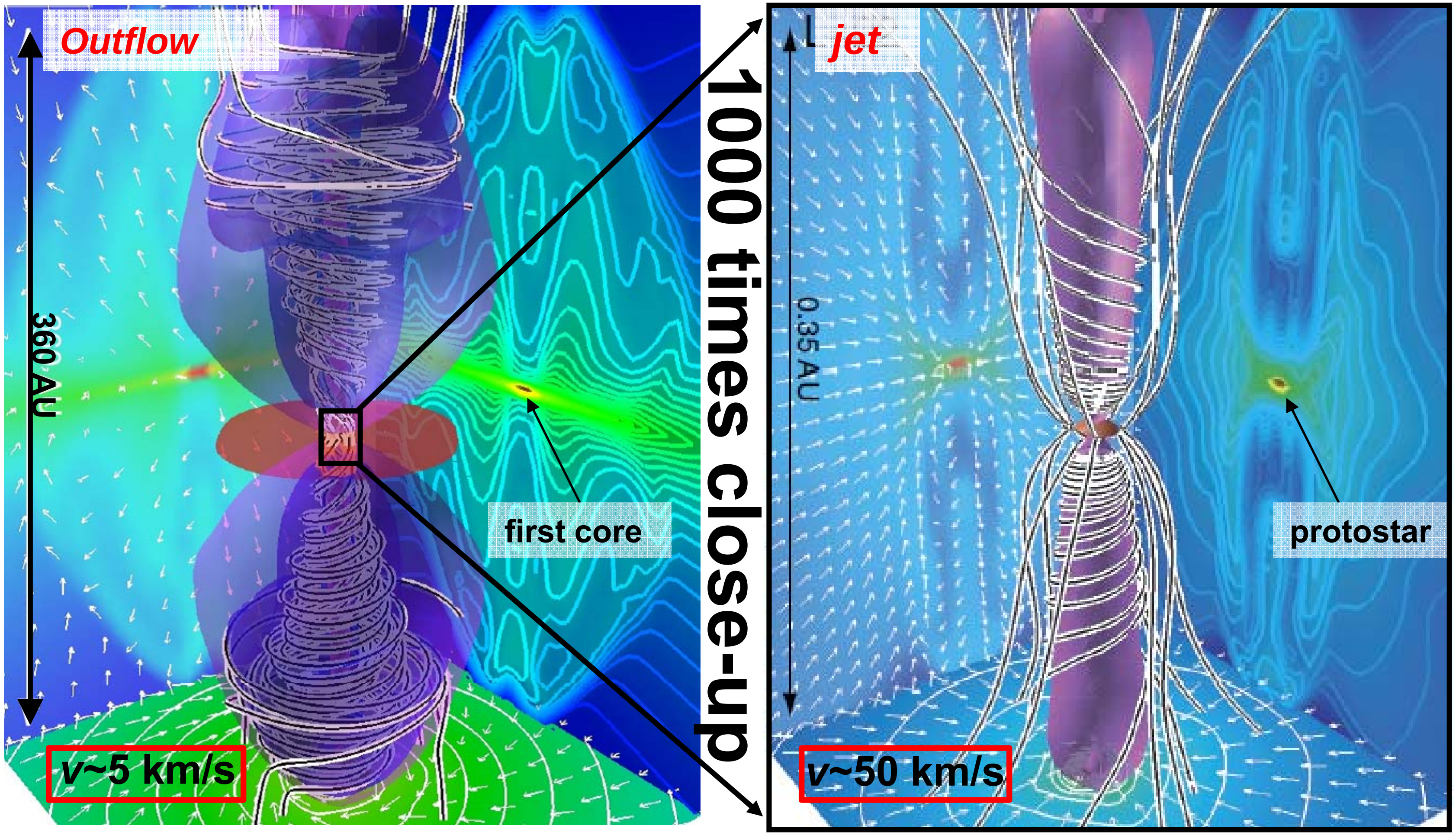
Protostellar Jet and Outflow in the Collapsing Cloud Core



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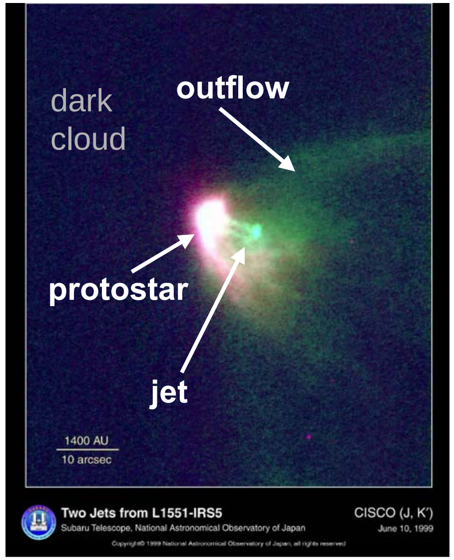
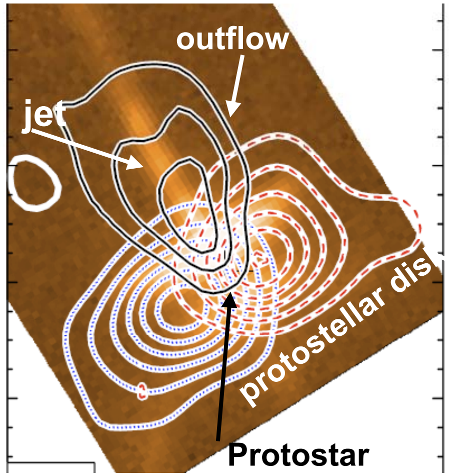
Protostellar Outflows and Jets

- In star-forming regions, there are two distinct flows: Outflows and Jets
  - Molecular Outflow：low velocity (~10 km/s), wide opening angle
  - Optical Jet: high velocity (~100 km/s), well-collimated structure
- Optical Jet is enclosed by Molecular Outflow
- But, Mechanism is still unknown

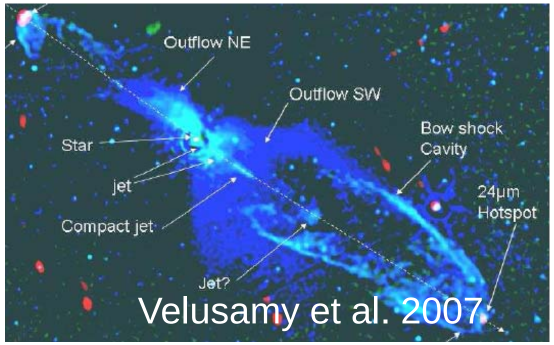




HH30, Pety et al. 2006

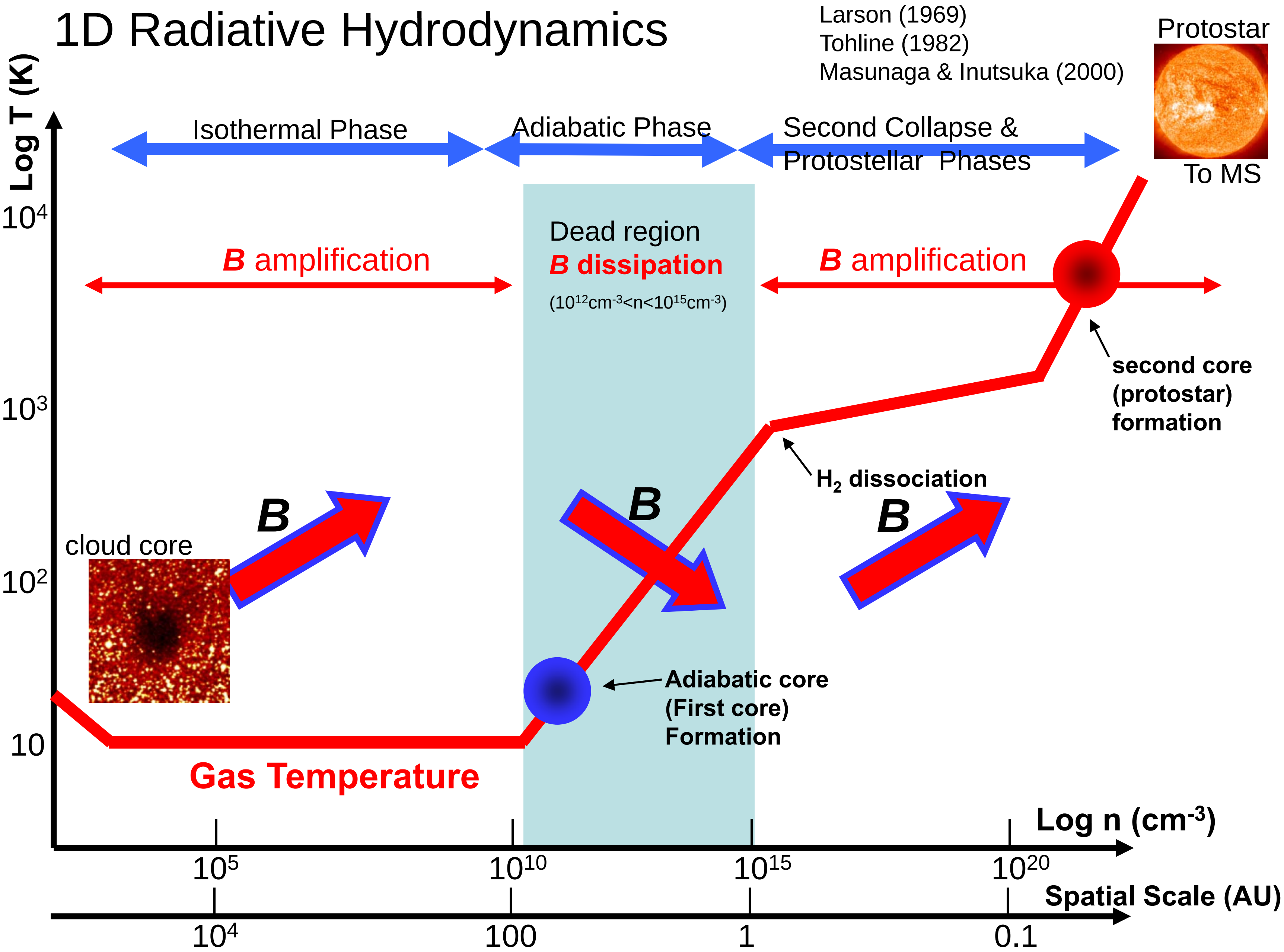
Purpose of This Study

- Understanding the driving mechanism of Jets / Outflows
- We calculated the cloud evolution **from the molecular cloud** ($n=10^4\ cm^{-3}$, $r\sim10^4$ AU) until **the protostar** ($n\sim10^{20}\ cm^{-3}$, $r \sim 1R_{sun}$) **formation**

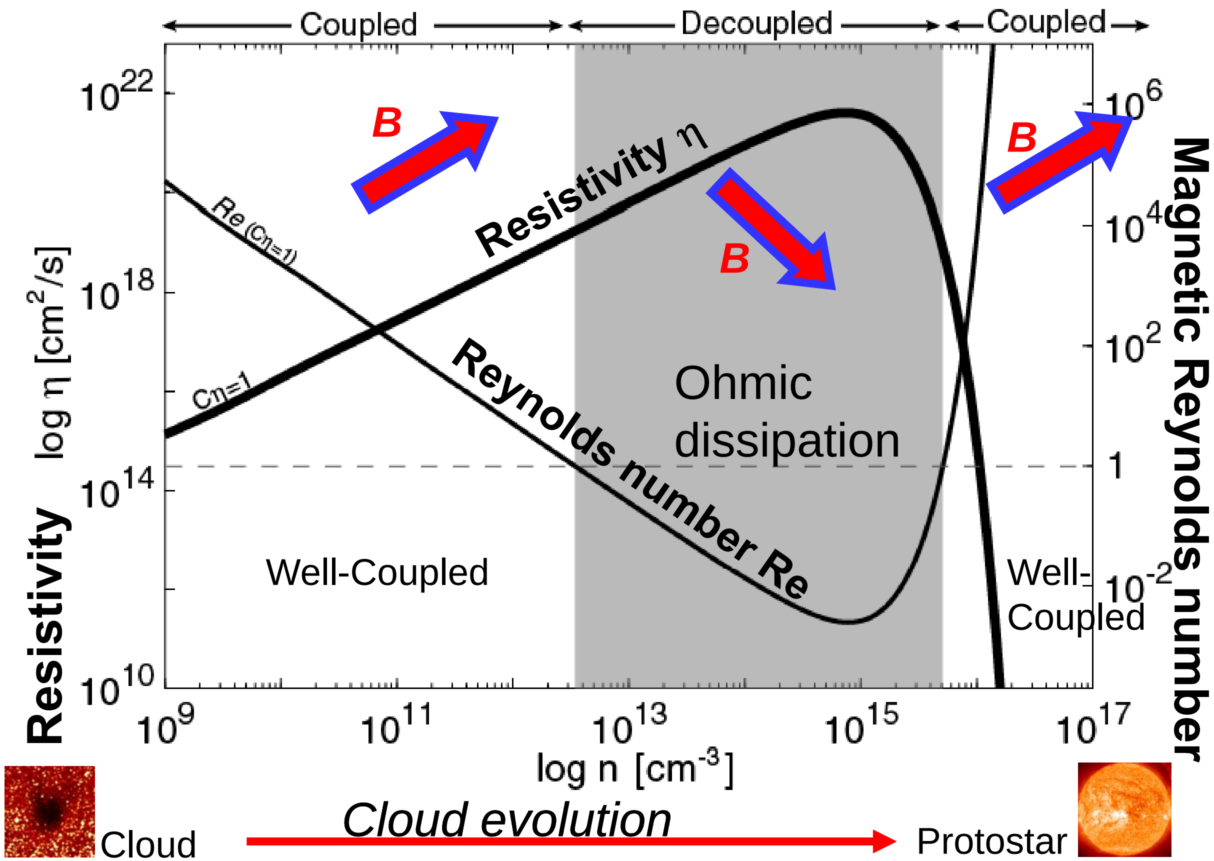


Thermal Evolution in the Collapsing Cloud

1D Radiative Hydrodynamics



Magnetic Evolution



◆ Basic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0,$$

$$\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v = -\nabla P - \frac{1}{4\pi} B \times (\nabla \times B) - \rho \nabla \phi,$$

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B,$$

$$\nabla^2 \phi = 4\pi G \rho,$$

◆ Resistivity is fitted as a function of n and T

$$\eta = \eta(n, T)$$

(Nakano et al. 2002)

◆ Magnetic Reynolds number

$$R_{e,M} \equiv \frac{vL}{\eta}$$

η: resistivity
v: free fall velocity
L: Jeans Length

◆ **Coupling between the magnetic field and neutral gas (weakly-ionized plasma)**

- Low density ($n<10^{12}$ cm^{-3}): Low ionization rate, but ***well-coupled*** due to $\tau_{ff} > \tau_{col}$
- Moderate density (10^{12}cm^{-3}$<n<10^{16}$cm^{-3}): Ionization rate decreases as density increases
  ⇒ Dissipation of ***B*** by Ohmic dissipation
- High density ($n>10^{16}$ cm^{-3}): Some metals are ionized, ***Well-coupled***

Initial Settings

Gas sphere in hydrostatic equilibrium

- Critical Bonner-Ebert Sphere + Rotation + Magnetic Field

$$\rho(r) = \begin{cases} \rho_0 \varrho_{\rm BE}(r/a) & \text{for } r < R_c \\ \rho_0 \varrho_{\rm BE}(R_c/a) & \text{for } r \geq R_c \end{cases}$$

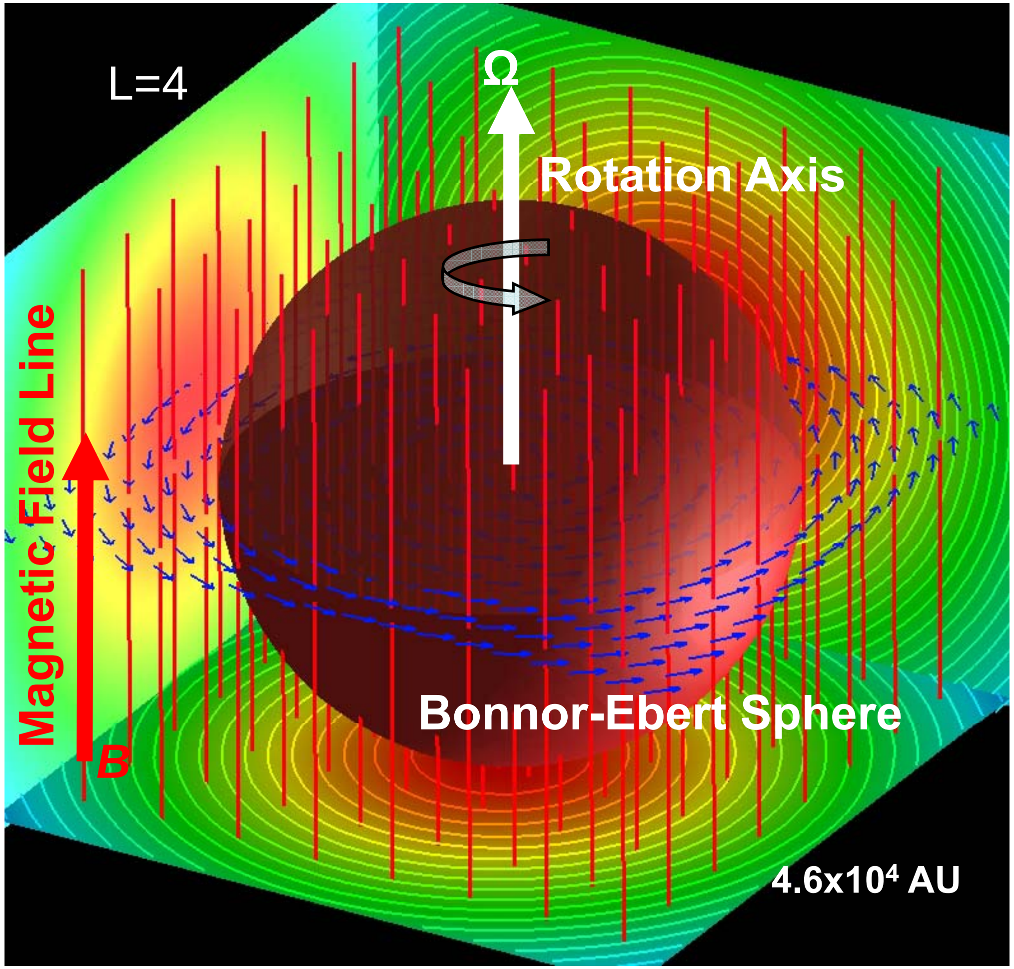
$$a = c_s \left(\frac{f}{4\pi G \rho_0} \right)^{1/2},$$

- Magnetic field lines are parallel to the rotation axis: $B /\!/ \Omega$

- Parameters: α , ω

  - $\alpha = B_c^2/(4\pi\rho c_s^2)$:magnetic field strength (ratio of the magnetic to thermal pressure)
  - $\omega = \Omega/(4\pi G\rho)^{1/2}$: angular velocity normalized by freefall timescale

- $(B_{x,0}, B_{y,0}, B_{z,0}) = (0, 0, (\alpha 4\pi\rho c_s^2)^{1/2})$
- $(\Omega_{x,0}, \Omega_{y,0}, \Omega_{z,0}) = (0, 0, \omega(4\pi G\rho)^{1/2})$



- Initial Value
  - Number density : $n=10^4$ cm^{-3}
  - Temperature : T=10K
  - Cloud scale: 4.6×10^4 AU
  - Mass : M_{tot} =14 Msun

Numerical Methods

3D Resistive MHD Nested Grid Method

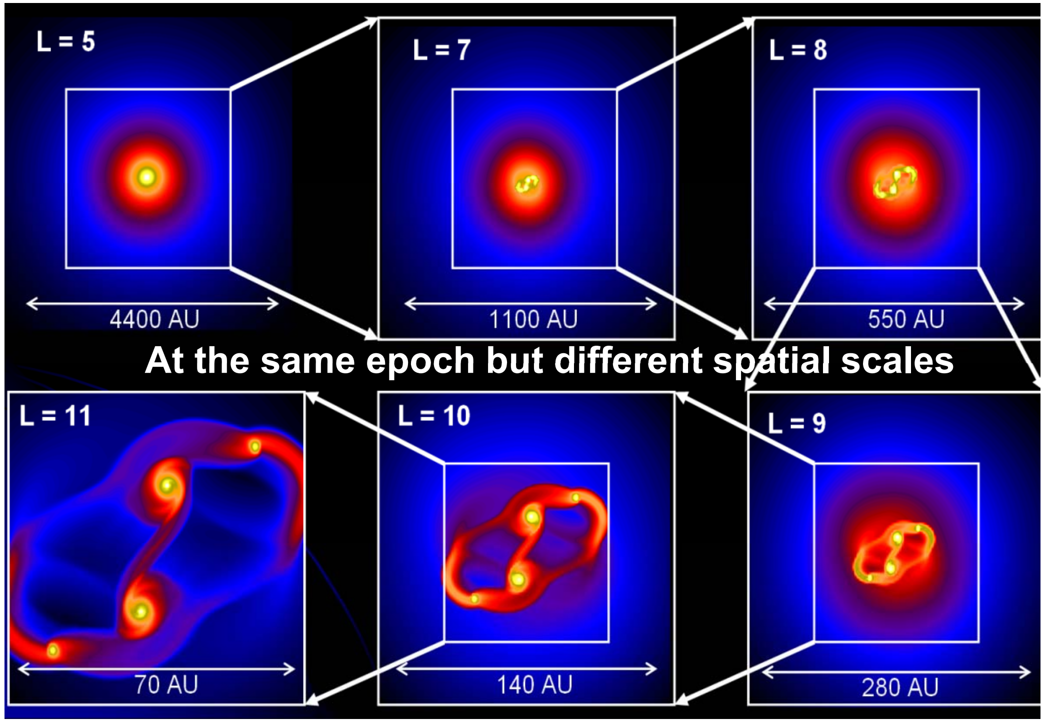
- **Grid size:** 128 x 128 x 64 (z-mirror sym.)
- **Grid level:** l_{max}=31 (l : Grid Level)
- **Total grid number:** 128 x 128 x 64 x 31

For uniform grid, $(128\times2\times10^{30})\times(128\times2\times10^{30})\times(64\times2\times10^{30})$ ~ $(10^{30})^3$ cells are necessary

- **Grid generation:** Jeans Condition

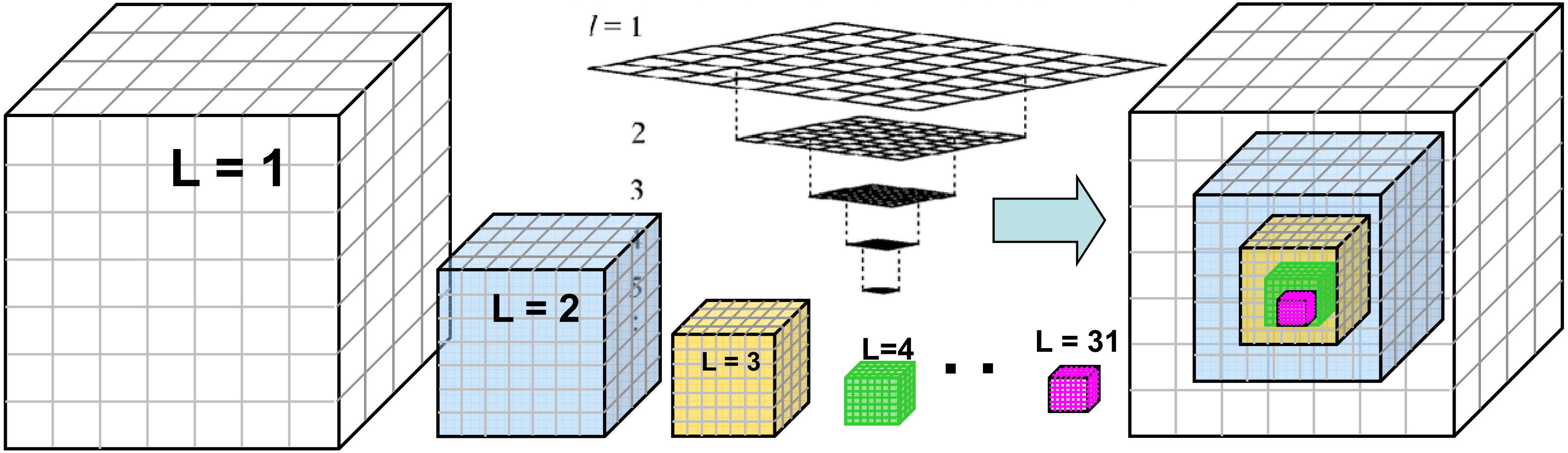
l =1:	L_{box} = 4 pc,	n = 10^3 cm^{-3}	(initial)
l =31:	L_{box} = 0.2 R_{sun},	n = 10^{23} cm^{-3}	(final)

10 orders of magnitude in spatial scale
20 orders of magnitude in density contrast

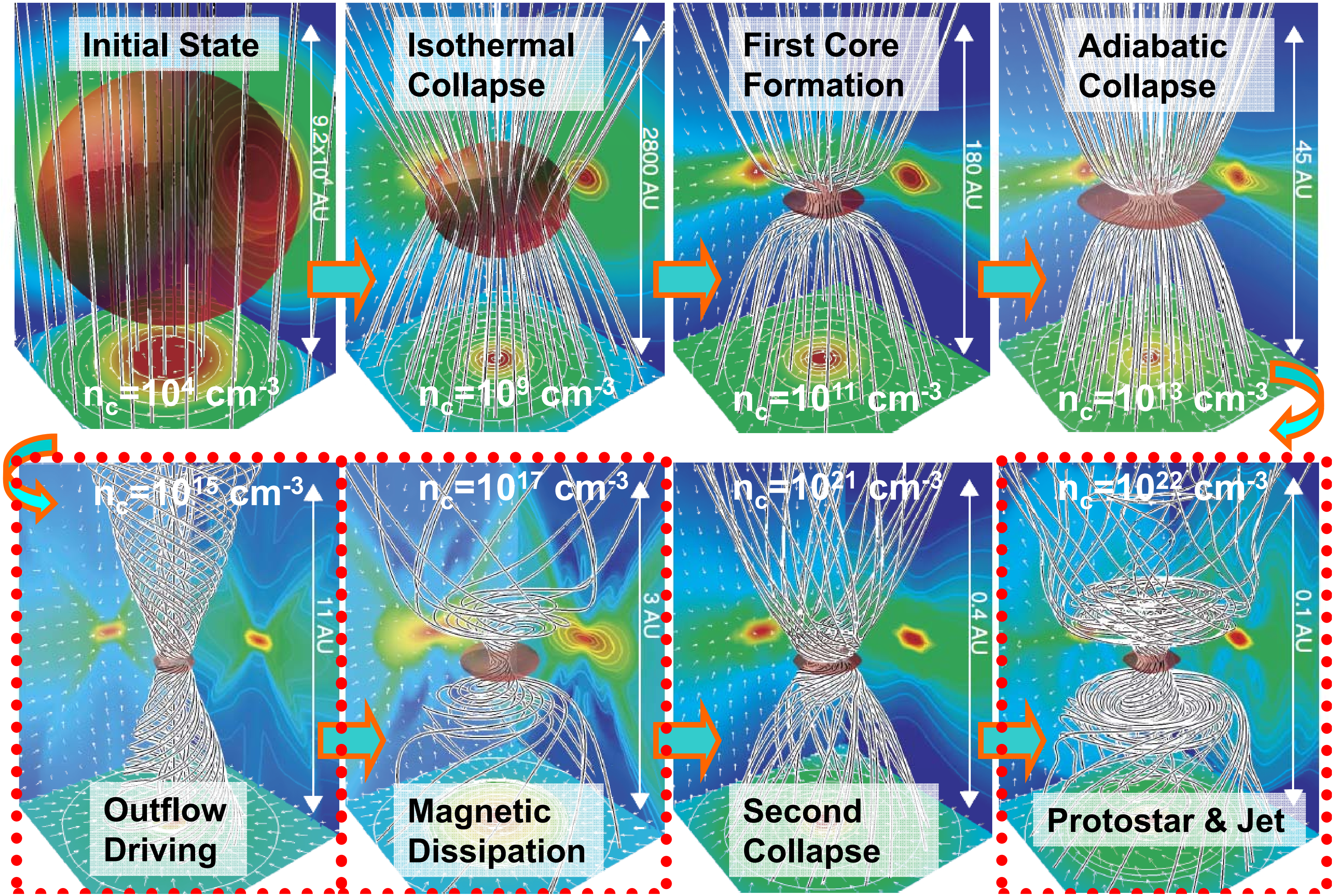


Example of Nested Grid

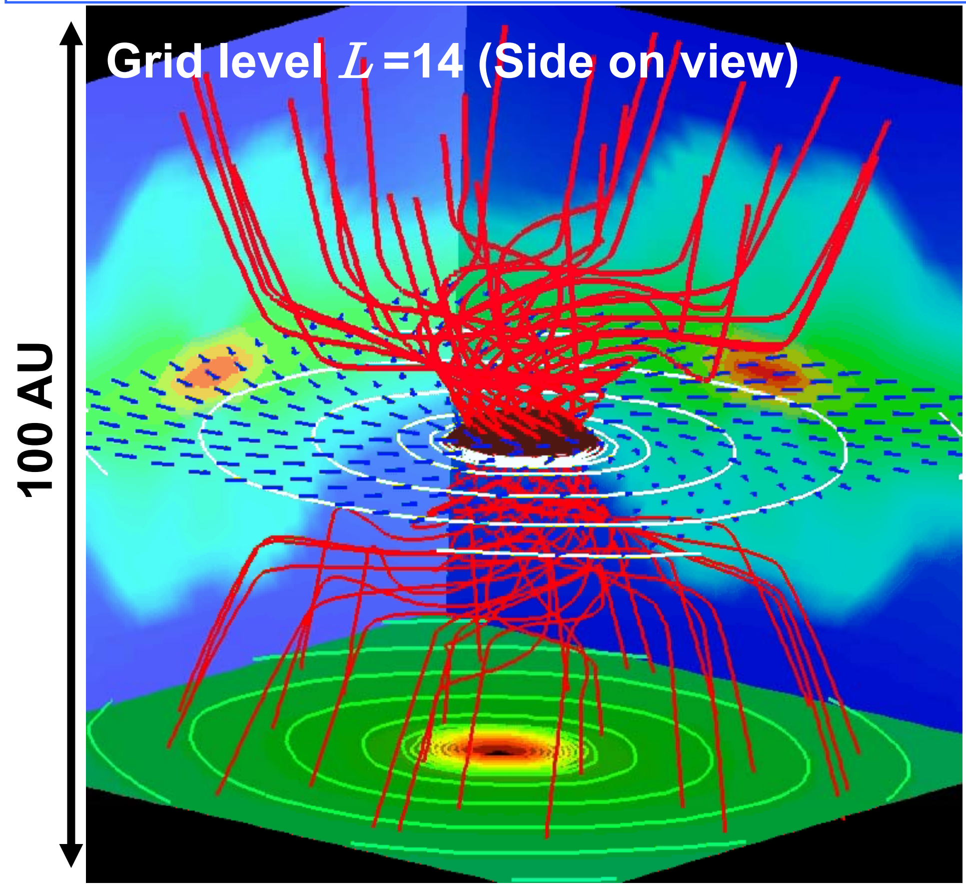
Schematic view of Nested Grid



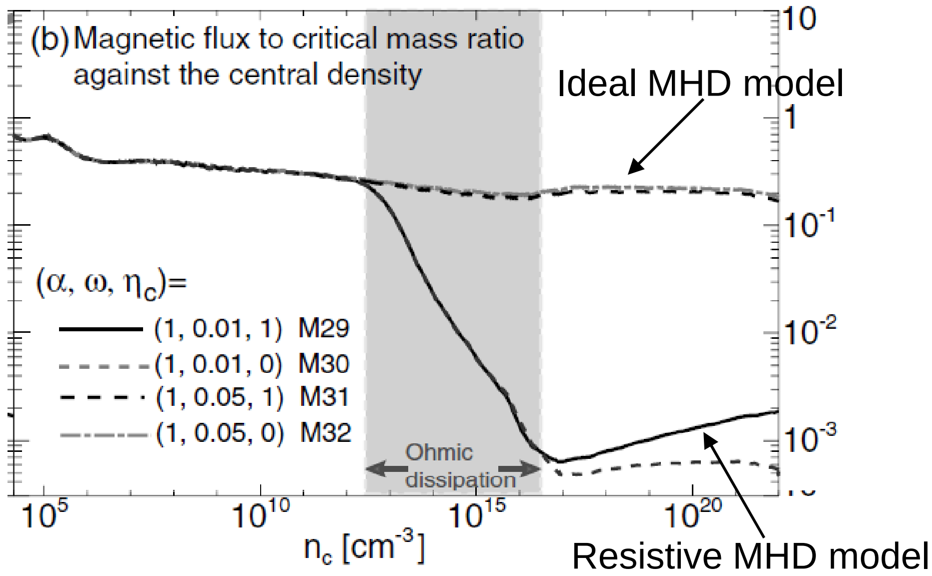
Cloud Evolution from **Molecular Cloud** to **Protostar**



Dissipation by the Ohmic Dissipation



Magnetic flux against the central density



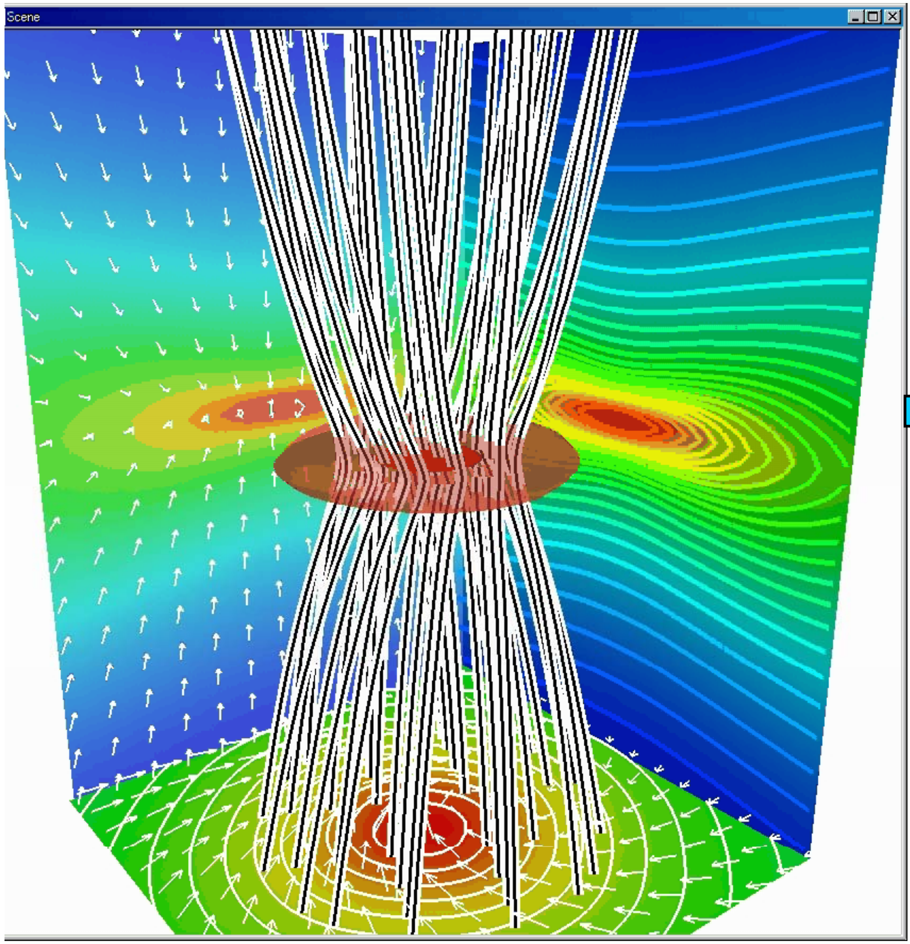
◆Magnetic flux is largely removed from the first core for 10^{12}-10^{16} cm^{-3}

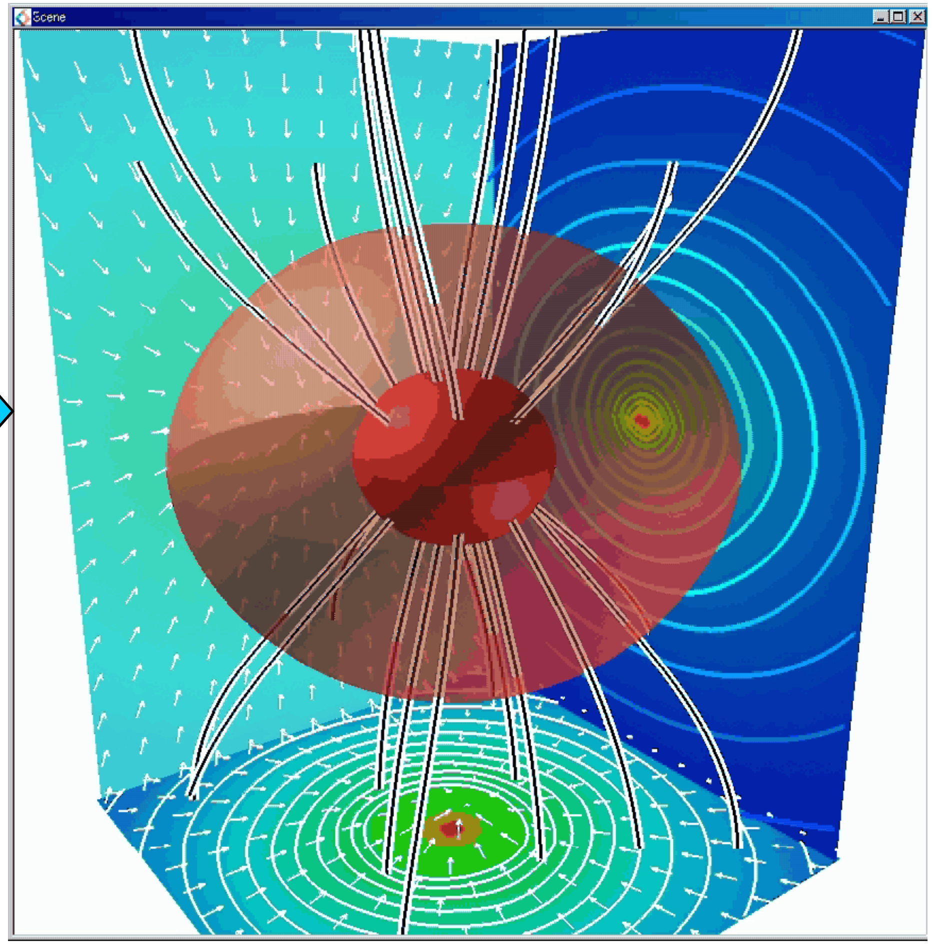
Evolution of the Magnetic field at center of the cloud

- ◆ ***n*= ~5x10^{11} cm^{-3}** **:First core formation, *B* field begins to be twisted**
- ◆ ***10^{11} cm^{-3} <n< 10^{13} cm^{-3}*** **: *B* field strongly twisted, outflow appears**
- ◆ ***10^{13} cm^{-3} <n< 10^{16} cm^{-3}*** **: *B* Field is dissipated by the Ohmic dissipation (Br, Bϕ)**
  ⇒ The magnetic field lines are uncoiled (Bz becomes major component)
- ◆ ***10^{16} cm^{-3} <n< 10^{20} cm^{-3}*** **: Second collapse, *B* is coupled with the neutral gas, amplified again**
- ◆ ***n*>10^{20} cm^{-3}** **: Protostar formation, B_r, B_ϕ increase again**

Outflow and Jet Driving Phase

Low-velocity Flow from First core | **High-velocity flow from Protostar**





~1000 times close-up of the central area

360 AU

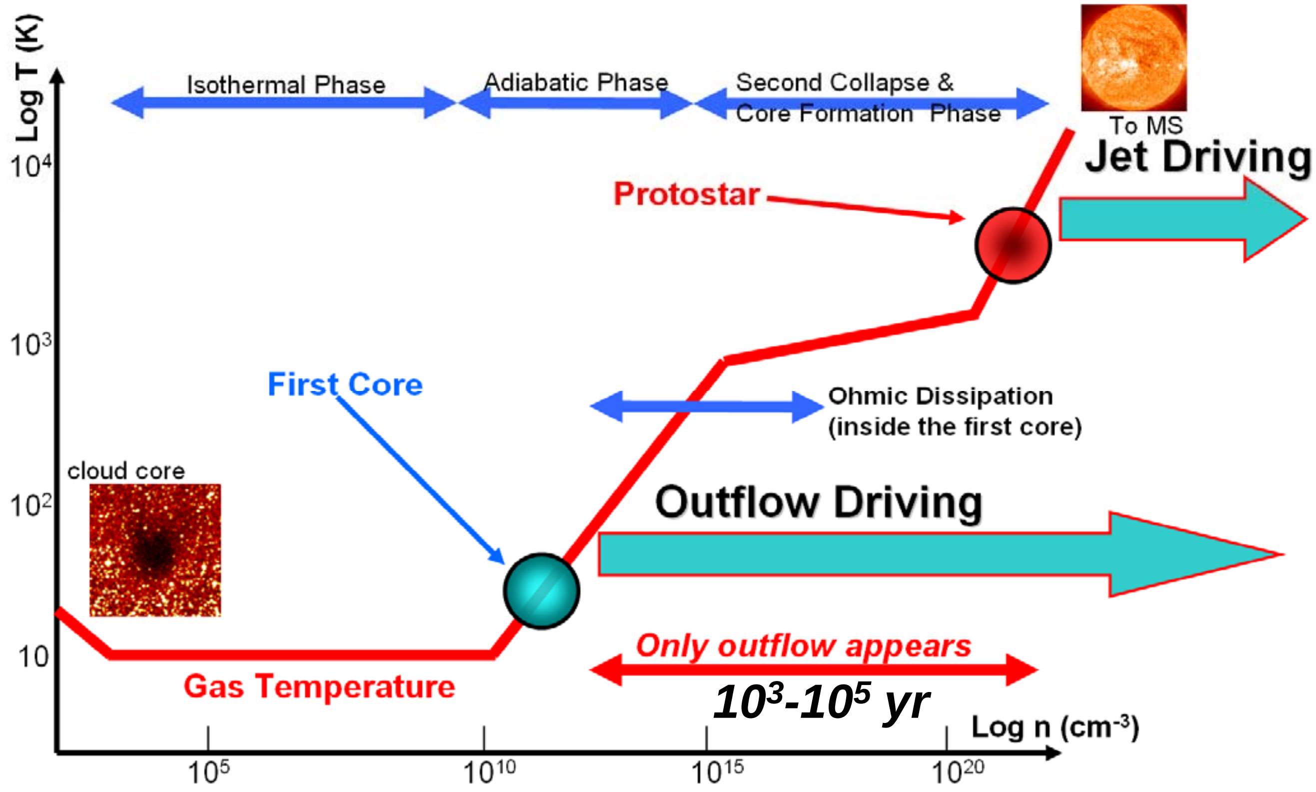
$v_{outflow}$~ 5 km/s

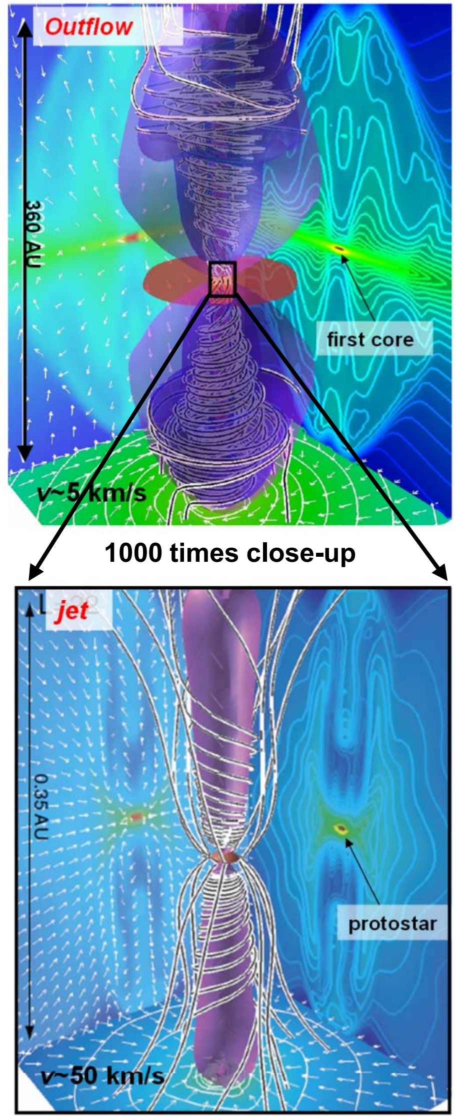
0.35 AU

v_{Jet}~50 km/s

- First Core : n~10^{11} cm^{-3}, r~10-100 AU
- Protostar : n~10^{21} cm^{-3}, r~0.01 AU

Driving Phase of Each Flow





- Adiabatic core (first and second core) formation ⇒ $\tau_{rot} < \tau_{collapse}$
  ⇒ Magnetic field lines are twisted ⇒ Flow driving
- Each core has different scale and different magnetic field strength
  - **First Core** does not experience the Ohmic dissipation: **Strong field**, **hourglass**
  - **Protostar** experiences the Ohmic dissipation: **Weak field**, **straight lines**

Collimation and Flow Speed

➢**Different degrees of the collimation are caused by different driving mechanisms**

Forces

Around First Core (Outflow)
Lorenz ≒ Centrifugal ≒Thermal Pressure (inflow)

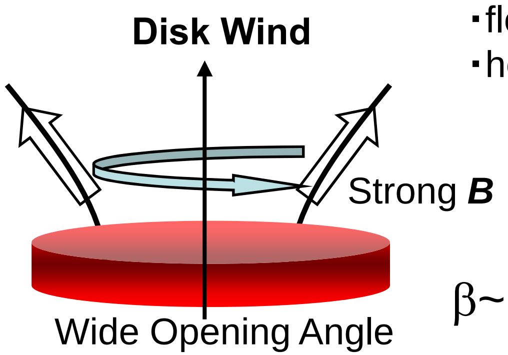
Driving Mechanism

Magnetocentrifugal wind
⇒ First core, Outflow

Around Protostar (Jet)
Centrifugal ≒ Thermal Pressure >> **Lorentz** (inflow)

Magnetic pressure gradient wind
+ MRI ⇒ Protostar, Jet

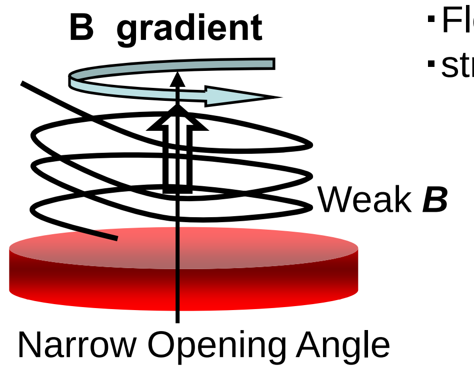
First Core



- Strong B
- flow along B lines
- hourglass B

β~1-10

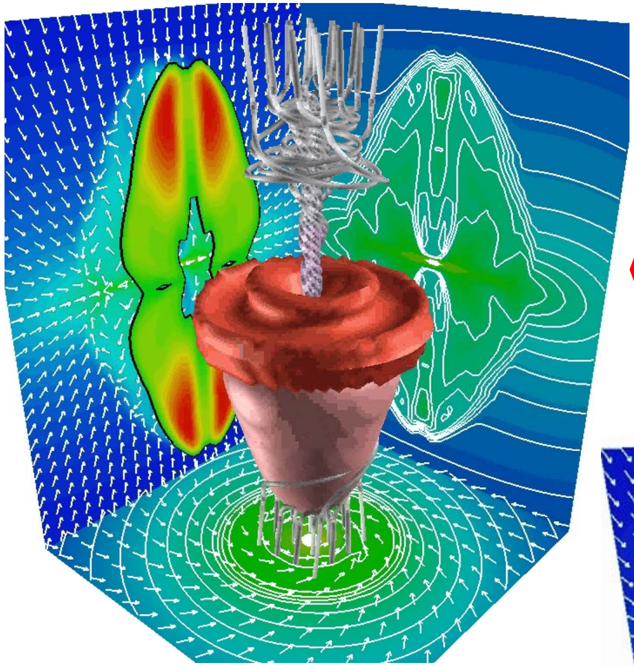
Protostar



- weak B
- Flow along rotation axis
- straight B

β>1000

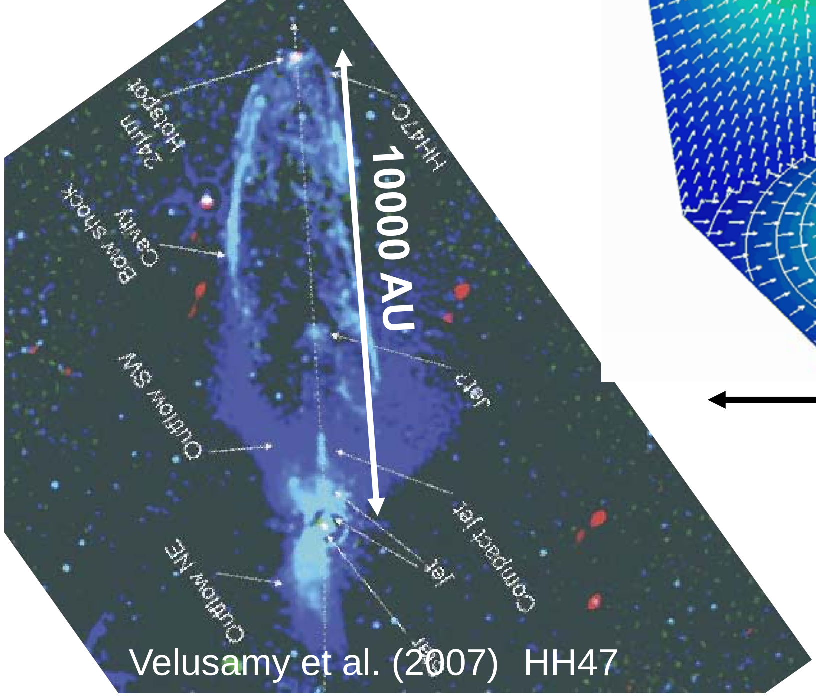
Interaction between outflow and molecular cloud



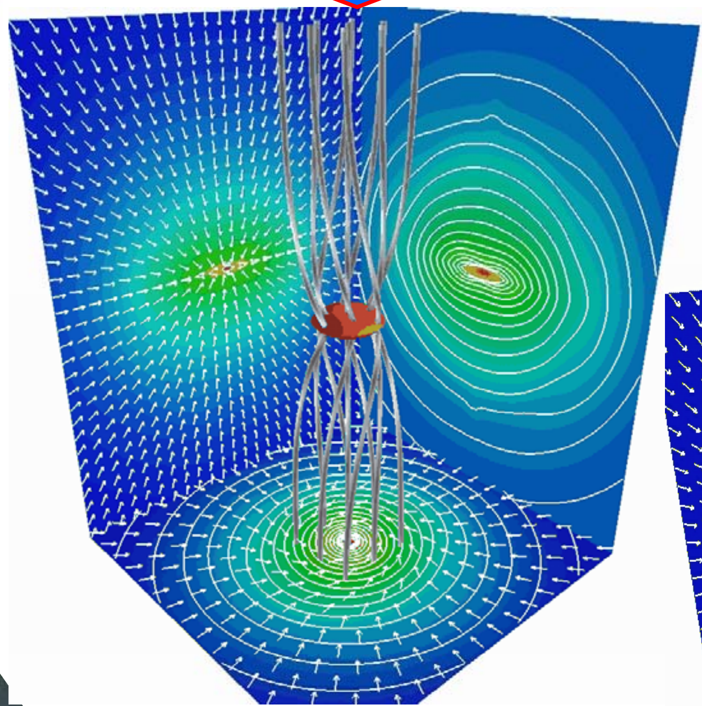
unsteady

Outflow driving point (small scale)

500 AU



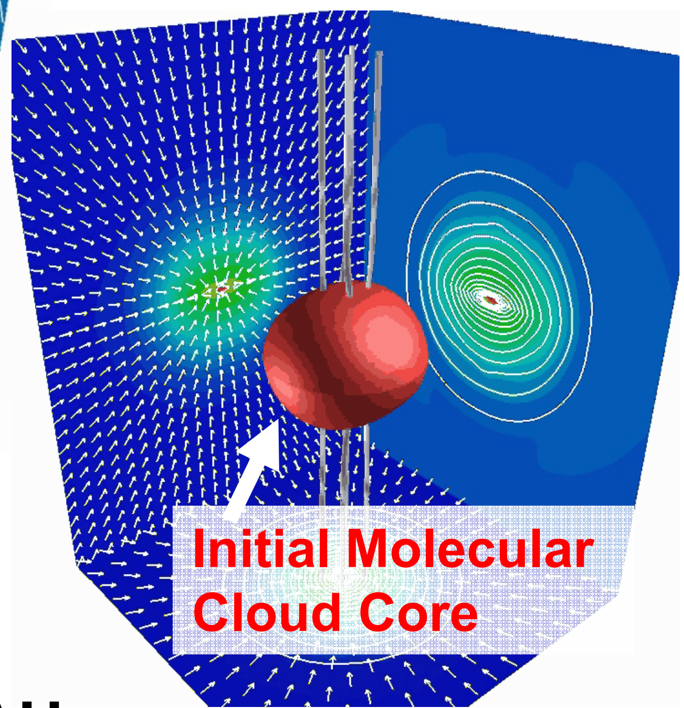
Outflow propagation (middle scale)



2000 AU

Bow shock, Cavity, Turbulence

Interaction between outflow and host cloud (large scale)



8000 AU

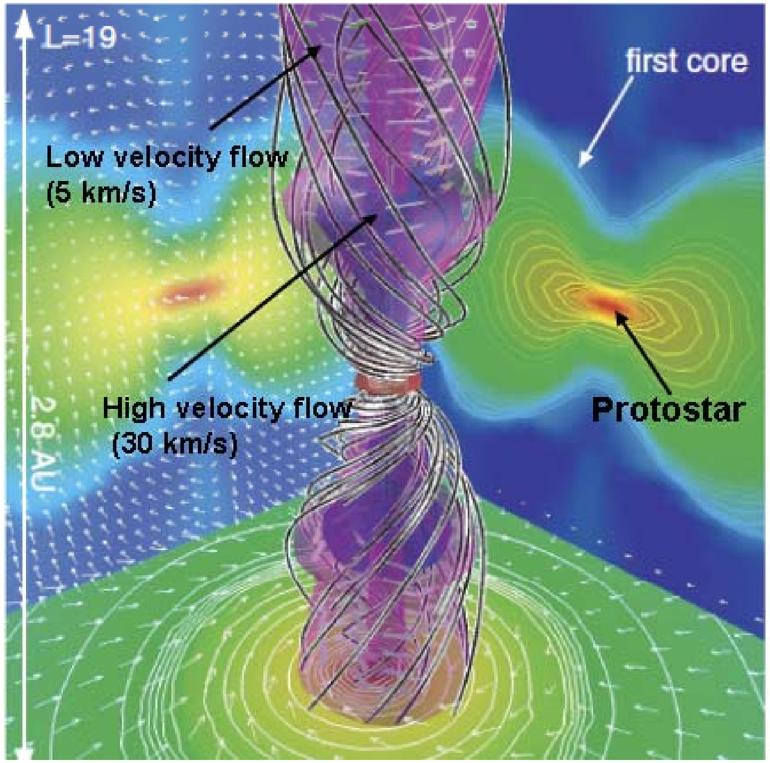
Properties of Outflow and Jet

- **Our simulation could naturally reproduce properties of outflows and jets**

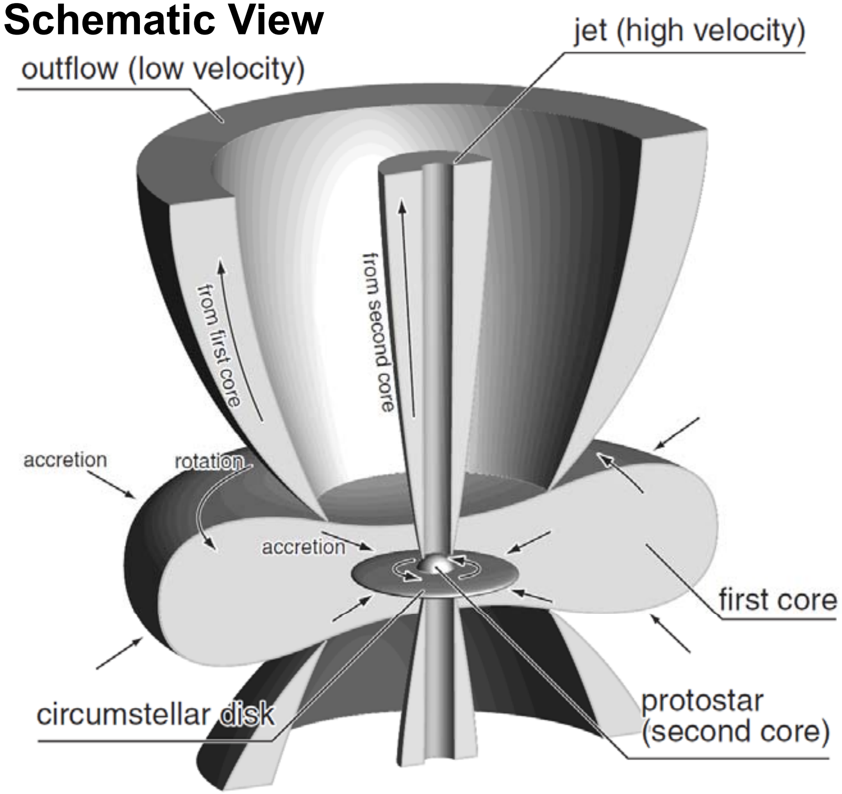
	Driver	Speed	collimation	Mechanism	Configuration of B
Outflow	First core	Slow (~10km/s)	△	Disk Wind	Hourglass
Jet	Protostar	High (~100km/s)	◎	Mag. pressure	Straight

- Outflow is directly driven from the first core (not entrainmented by jet)
- The differences between outflow and jet is caused by different strength of magnetic field, and depth of gravitational potential

Result of numerical simulation



Schematic View



Summary

- ***To avoid artificial settings around the protostar***, we calculated the cloud evolution from the molecular cloud **($n=10^4$ cm^{-3})** until the protostar formation **($n\sim10^{23}$ cm^{-3})**
- We ***only*** assumed the initial molecular cloud **($n=10^4$ cm^{-3})**
- So, ***we did not impose artificial settings around the protostar***:
  - ･artificial configuration of *B* lines, artificial strength of *B,* artificial accretion rate
  - ･artificial density profile, artificial disk properties,…
- Our calculation shows:
  - Two distinct flows: Outflow from the first core, Jet from the protostar
    - ✓Outflow: wide opening angle and slow speed
    - ✓Jet: well-collimated structure and high speed
  - Magnetic (Ohmic) dissipation is very important to determine flow properties : it influences the collimation
  - Different speeds cause by different gravitational potential of each core