Disk Formation and Jet Driving in Collapsing Cloud Cores

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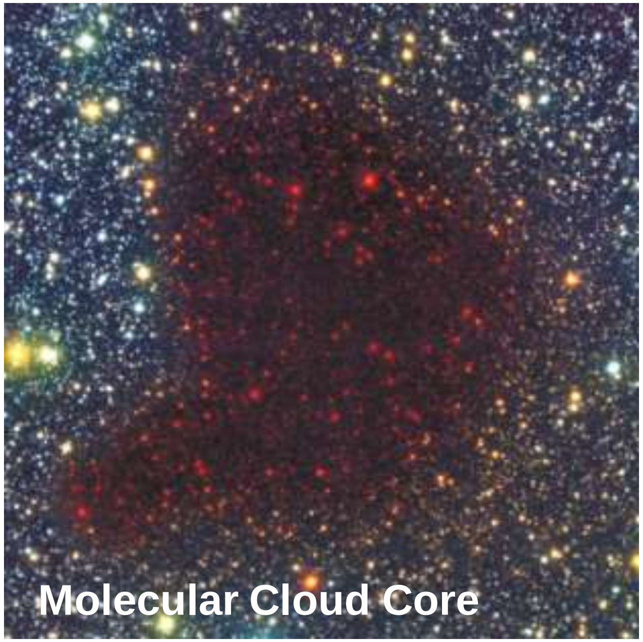
Star Formation Process



Observations have shown that

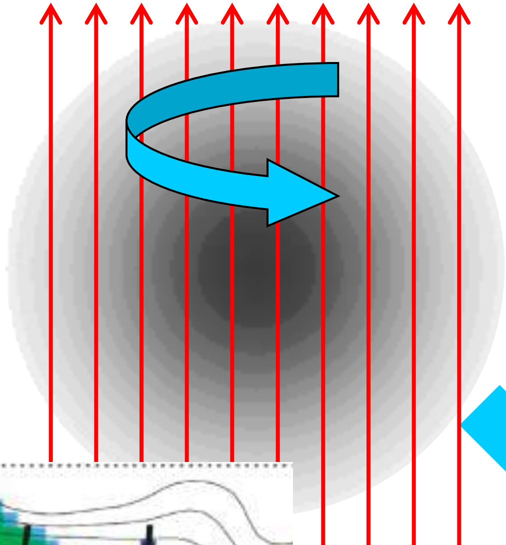
- Low-velocity outflows and high-velocity jets are ubiquitous
- Circumstellar disk formation in the Class 0 stage (Tobin et al. 2012,2015, Murillo et al. 2013, Codella et al.. 2014, Lee et al. 2014, Yen et al. 2015)
- Planet formation in the early stage (?)

To understand star and disk formation process, we need to clarify

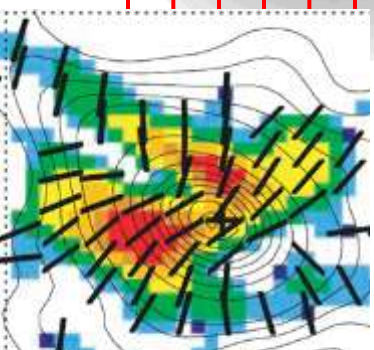
- Driving mechanism of low-velocity outflows and high-velocity jets
- Circumstellar disk and planet formation process

in collapsing cloud core

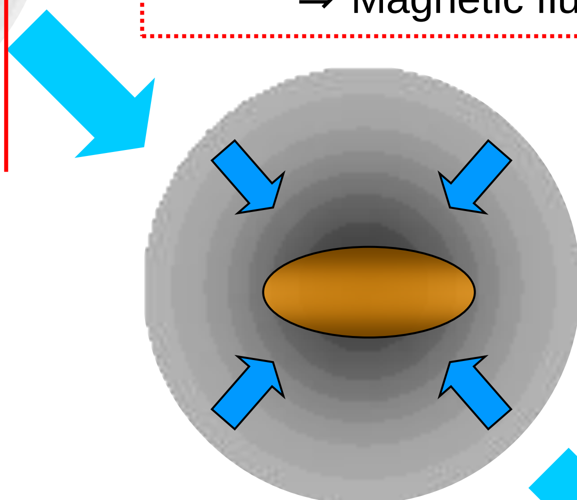
Star forms in Gravitationally Collapsing Cloud

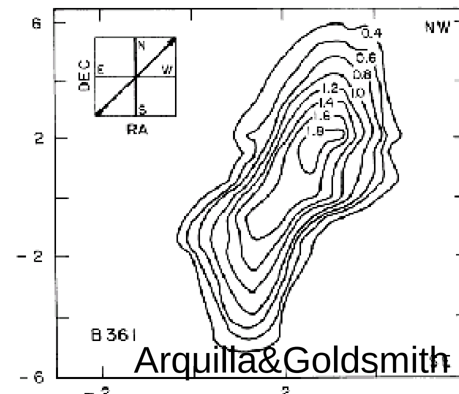


- Is star formation simple ? Spherical symmetry?
- Magnetic field and rotation cause complexities
  - Both are an anisotropic force
    ⇒ Anisotropic structure formation (disk, jet and outflow)
  - Both are conserved
    ⇒ Magnetic flux and angular momentum problem



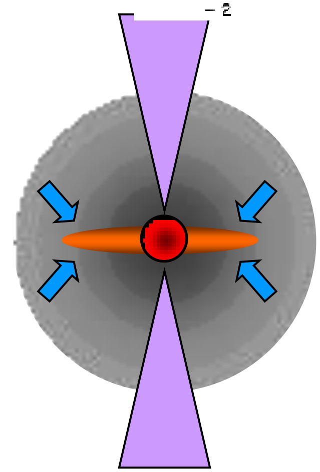
Girart+ 09



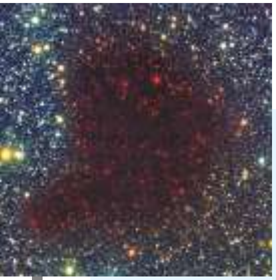


Arquilla&Goldsmith 86

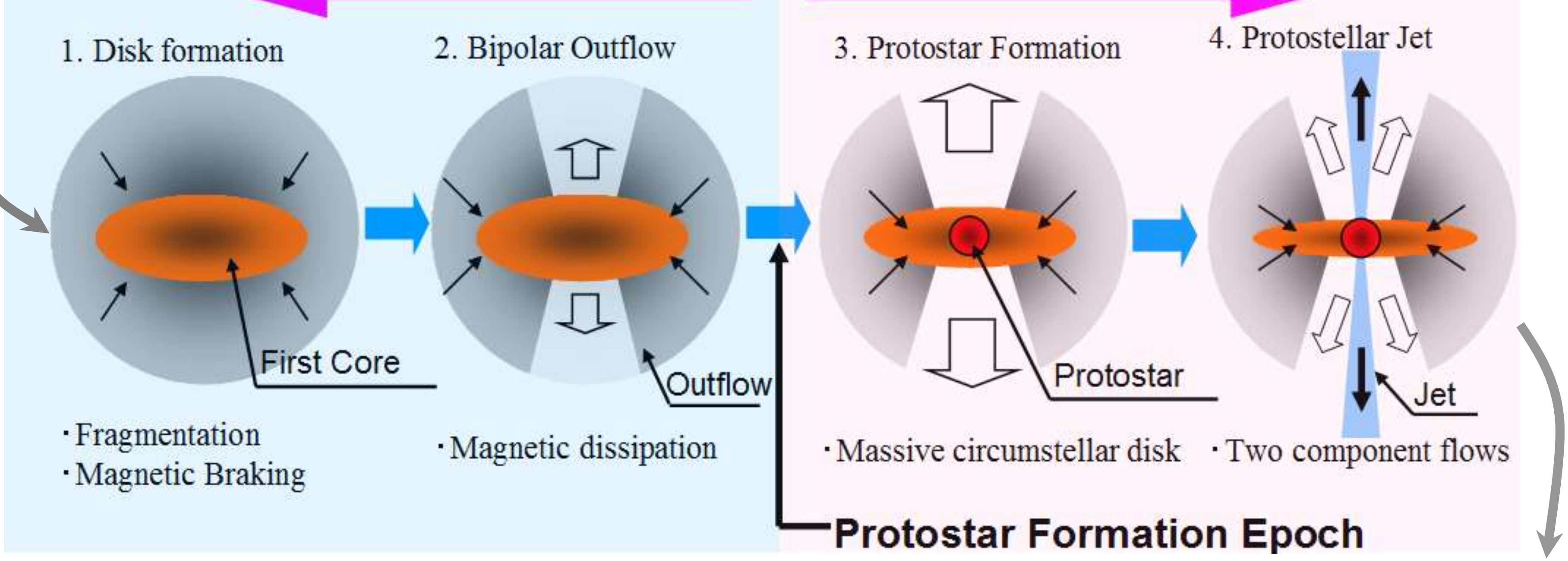
- Disk formation, outflow and jet driving are closely related to *B* and Ω
- We need to understand the star formation process with *B* and Ω



Star Formation Process can be Divided into Two Stages



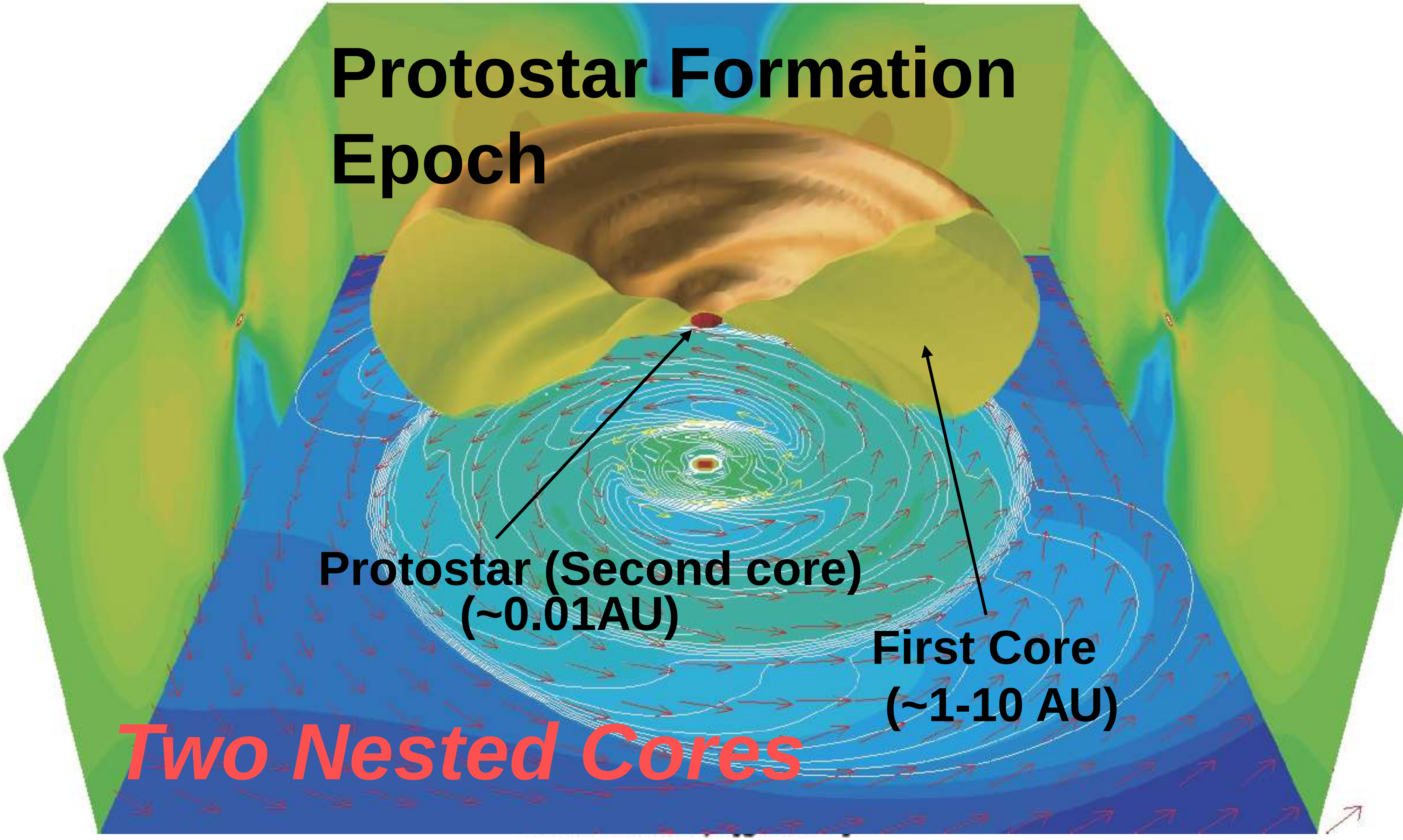
Molecular Cloud Core



- Gas collapsing stage (before p.s. formation)
- Protostar Formation
- Gas accretion stage (after p.s. formation)

Pathway for Protostar Formation: Gas Collapsing Phase

Larson(1969), Winkler & Newman (1980), Tscharnuter(1987), Masunaga & Inutsuka(2000), Whitehouse & Bate(2006), Stematellos et al.(2007), Bate (2010), Tomida et al.(2010)

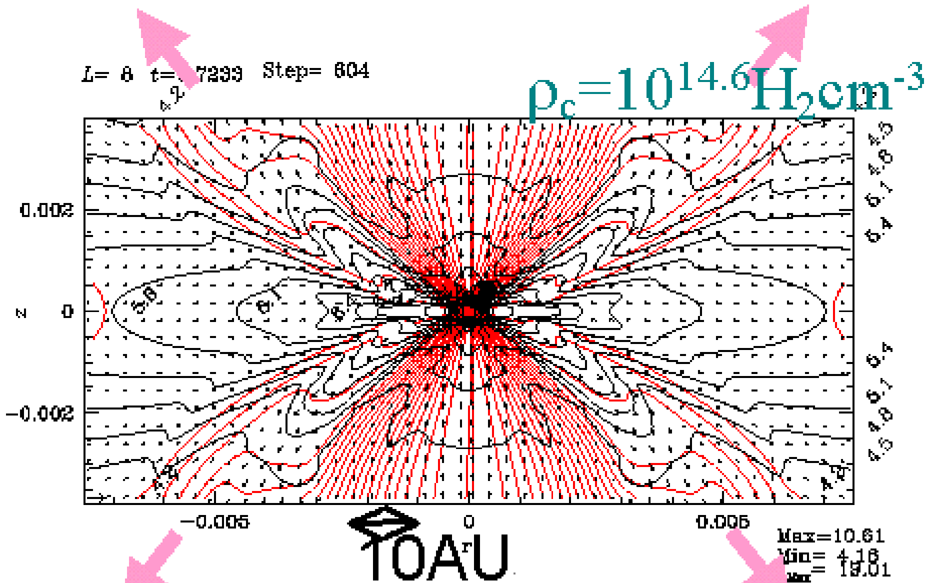


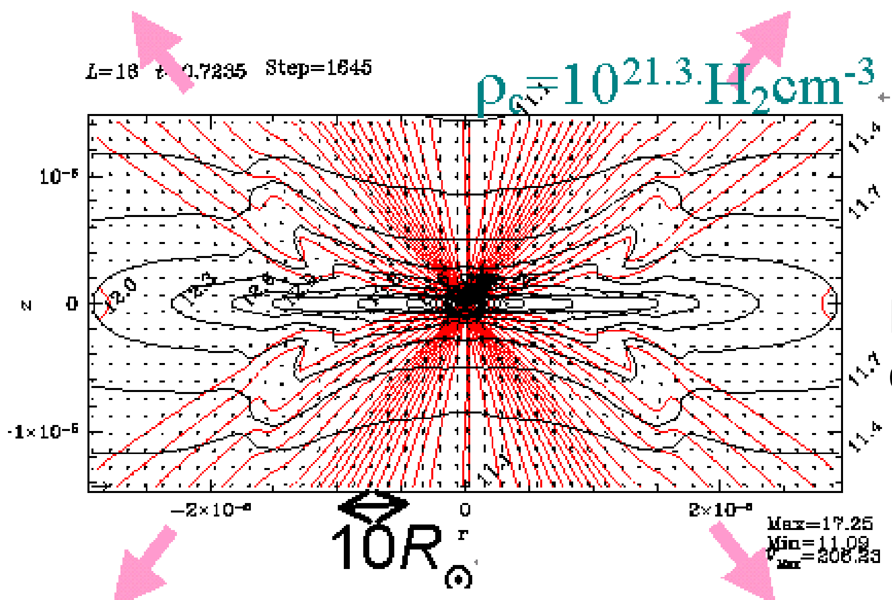
This Talk

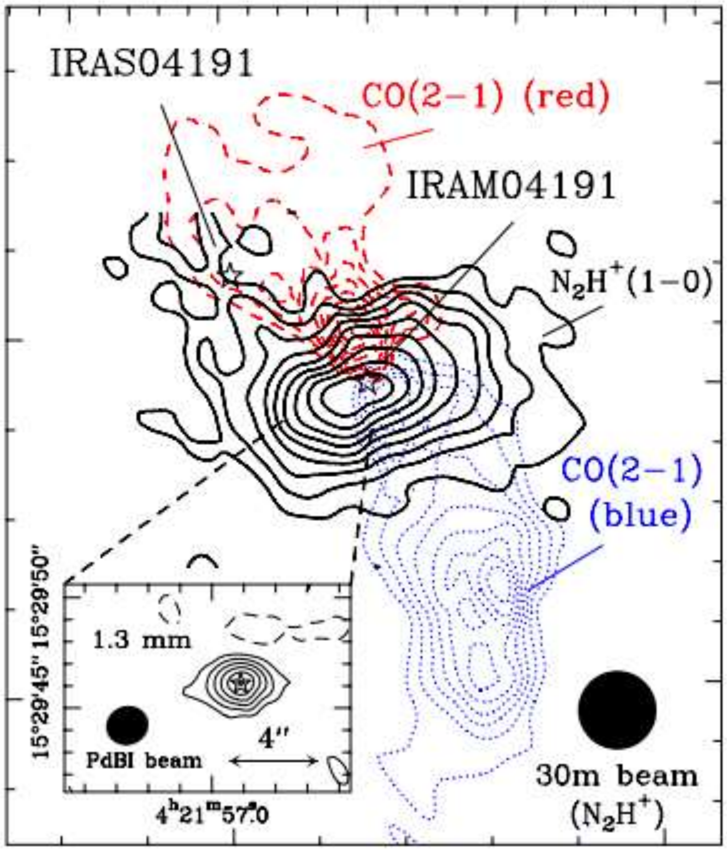
1. Gas Collapsing Phase before the Protostar Formation
2. Early Gas Accretion Phase ~500 years after the Protostar Formation
3. Long-term Evolution of Circumstellar Disk with Sink

1. Gas Collapsing Phase before the Protostar Formation

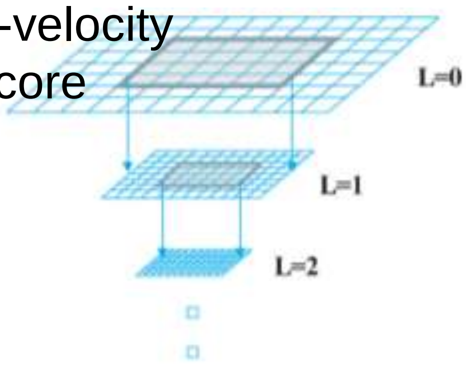
Gas Collapsing phase: 2D w/ *B* w/o non-ideal effects radiation







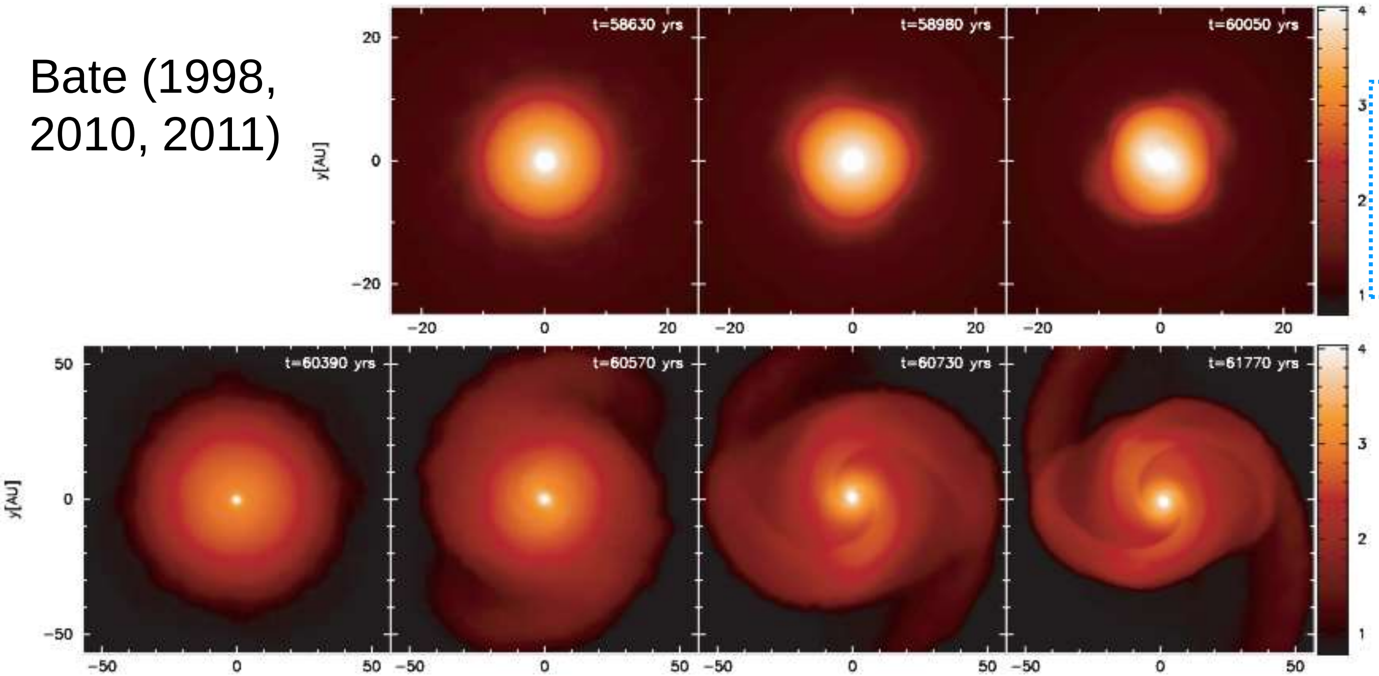
He could reproduced Low-velocity outflow driven by the first core



Tomisaka (1998 , 2000, 2002)

Gas Collapsing phase: 3D w/ *B* w/o non-ideal effects w/ radiation

Bate (1998, 2010, 2011)



First core is the origin of the rotation supported disk!!

- With rotation, the first core remains after the protostar formation
- (the remnant of) the first core is supported by the rotation and becomes to circumstellar disk

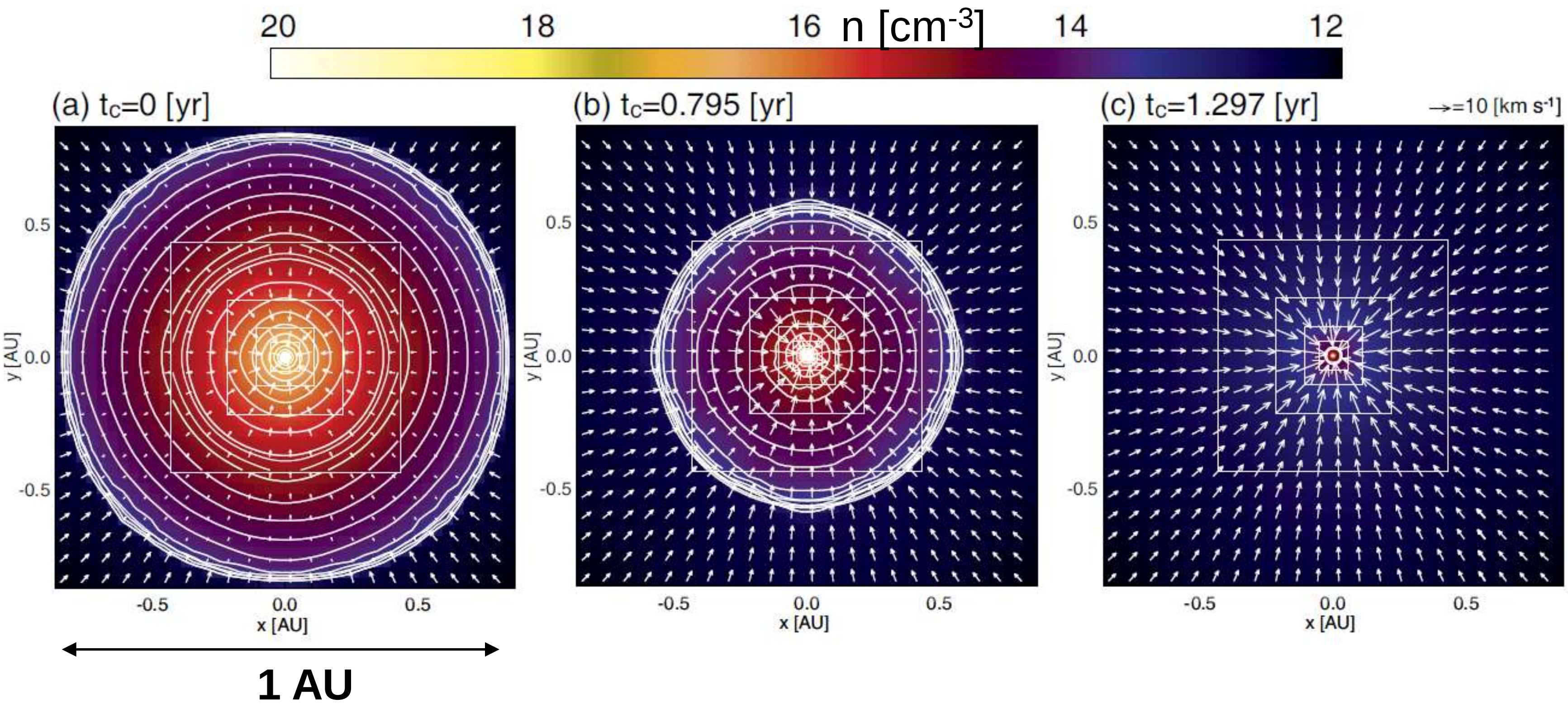
Abstract

…

rotation rates. In the most extreme case we model, a pre-stellar disc with a mass of 0.22 $M_\odot$ and a radius of ≈100 au can form in a 1-$M_\odot$ cloud and last several thousand years before a stellar core is formed. Such large, massive objects may be imaged using the Atacama Large

…

Gas Collapsing phase: 3D w/ *B* w/o non-ideal effects w/o radiation



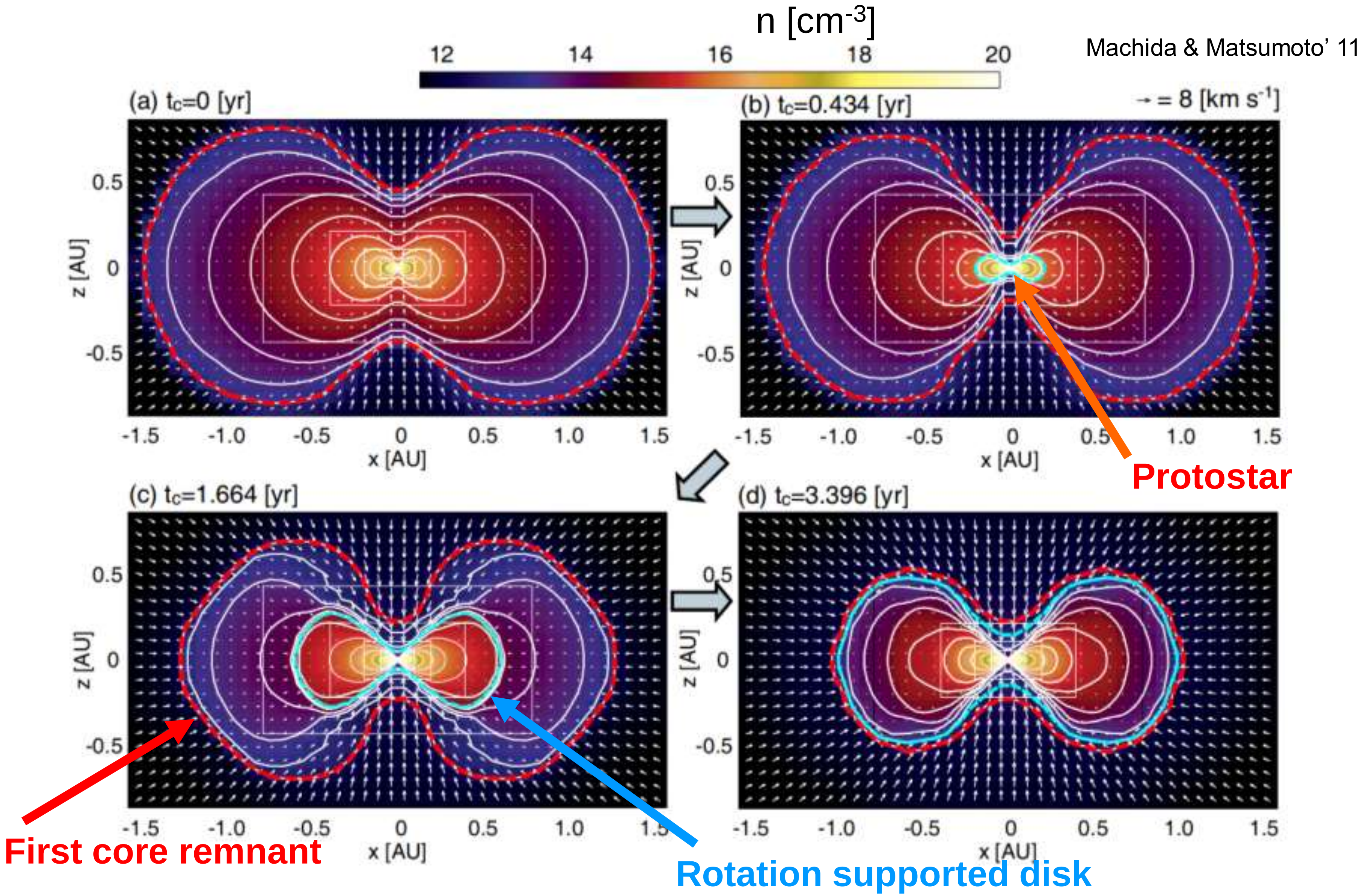
Without rotation, first core disappears in ~1 yr after the protostar formation

- Gas behaves adiabatically at n≧10^{11} cm^{-3}⇒ Adiabatic (or first core) formation
- Dissociation of H_2 at n≧10^{16} cm^{-3}⇒ Rapid collapse again (second collapse)
- Protostar formation⇒Collapse of the first core remnant⇒ Disappearance of F.C

Machida & Matsumoto' 11

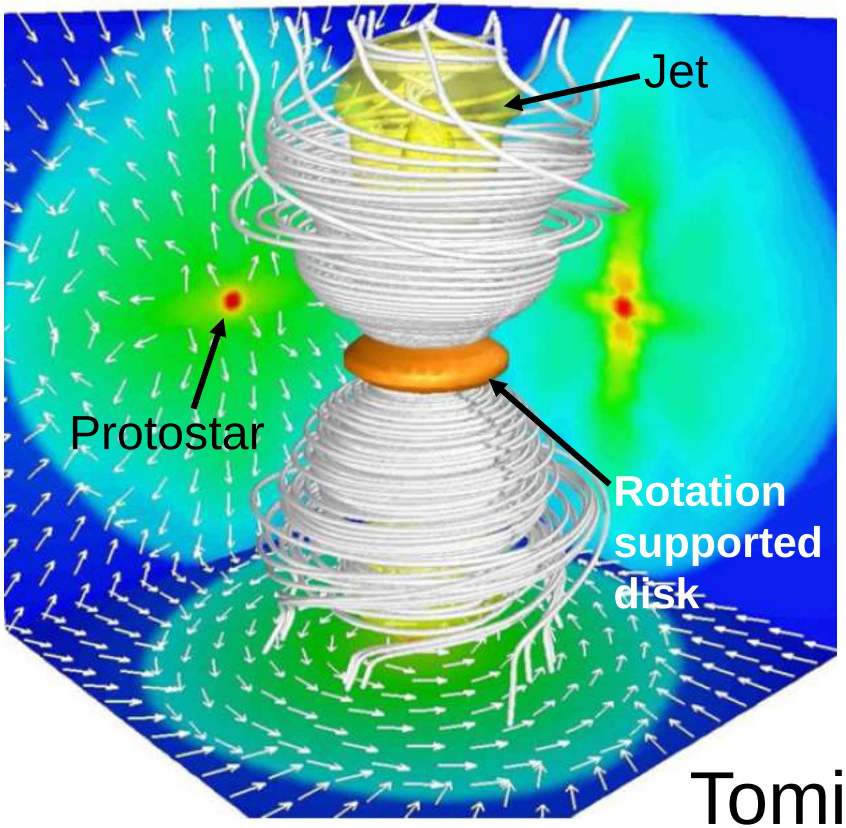
Gas Collapsing phase: 3D w/ *B* w/o non-ideal effects w/o radiation

With rotation, the first core evolves into the rotation supported disk



Gas Collapsing phase: 3D w/ *B* w/ non-ideal effects w/ radiation

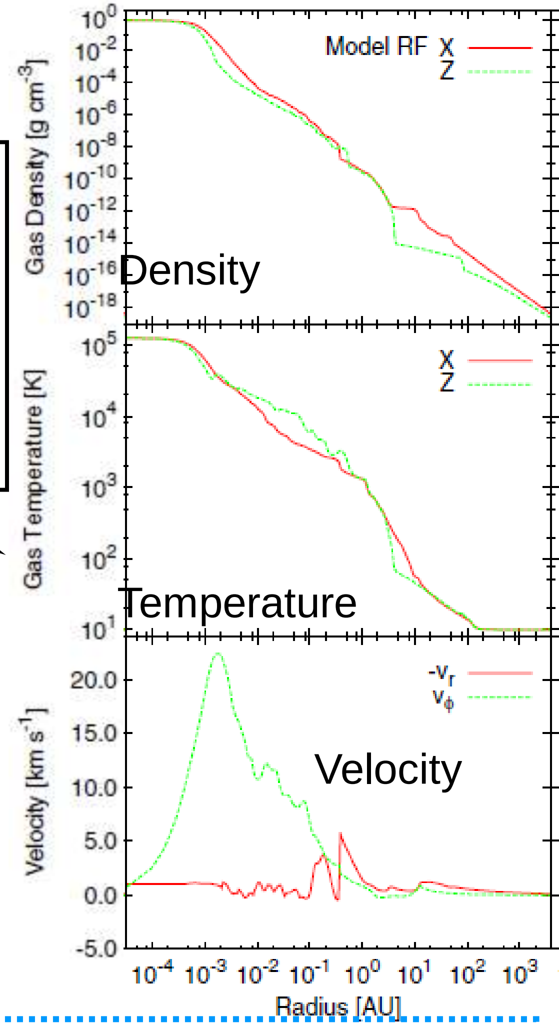
Both non-ideal effect of B and radiation are considered



Just after p.s. formation, we can see the **first core (remnant) or nascent disk** in density, temperature, and velocity profiles

Color: density

Tomida et al. (2013)



- The protostar formation process was successfully simulated
  - Protostar, nascent disk, low-velocity outflow, high-velocity jet were well reproduced
- But, only 1 years after protostar formation

Recent Study of Gas Collapsing phase

Induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times [\underbrace{\eta_{\mathrm{O}} \nabla \times \boldsymbol{B}}_{\text{Ohmic}} + \underbrace{\eta_{\mathrm{H}} (\nabla \times \boldsymbol{B}) \times \hat{\boldsymbol{B}}}_{\text{Hall}} + \underbrace{\eta_{\mathrm{A}} (\nabla \times \boldsymbol{B})_{\perp}}_{\text{Ambipolar}}],$$

w/ non-ideal effects w/ radiation

Both radiation non-ideal MHD effect of Ohmic, ambipolar and Hall terms are considered

- Tomida et al. (2015): Ohmic + ambipolar diffusion, just before the protostar formation epoch, Nested Grid
- Tsukamoto et al. (2015): Ohmic + ambipolar diffusion until the protostar formation, SPH
- Tsukamoto et al. in preparation: Ohmic + ambipolar diffusion + Hall term

Tomida + 15

Basic Equations (w/o div **B** cleaning)

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

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v} \otimes \mathbf{v} + \left(p + \frac{1}{2}|\mathbf{B}|^2 \right) \mathbb{I} - \mathbf{B} \otimes \mathbf{B} \right] = -\rho \nabla \Phi \boxed{+ \frac{\sigma_R}{c} \mathbf{F}_r,}$$
Eq. of motion

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left(\mathbf{v} \times \mathbf{B} \boxed{- \eta_O \mathbf{J}} \boxed{- \frac{\eta_A}{|\mathbf{B}|^2} \mathbf{B} \times \mathbf{F}} \right) = 0,$$
Induction eq.

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(e + p + \frac{1}{2}|\mathbf{B}|^2 \right) \mathbf{v} - \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) \boxed{+ \eta_O \mathbf{F}} \boxed{+ \frac{\eta_A}{|\mathbf{B}|^2} (\mathbf{B} \times \mathbf{F}) \times \mathbf{B}} \right] = -\rho \mathbf{v} \cdot \nabla \Phi \boxed{- c\sigma_P (a T_g^4 - E_r) + \frac{\sigma_R}{c} \mathbf{F}_r \cdot \mathbf{v},}$$
Gas Energy Eq.

$$\mathbf{J} \equiv \nabla \times \mathbf{B}, \qquad \mathbf{F} \equiv \mathbf{J} \times \mathbf{B},$$

$$\nabla \cdot \mathbf{B} = 0,$$
div B=0

$$\nabla^2 \Phi = 4\pi G \rho,$$
Poisson's Eq.

$$\frac{\partial E_r}{\partial t} + \nabla \cdot [\mathbf{v} E_r] + \nabla \cdot \mathbf{F}_r + \mathbb{P}_r : \nabla \mathbf{v} = c\sigma_P (a_r T_g^4 - E_r),$$
Radiation Transfer

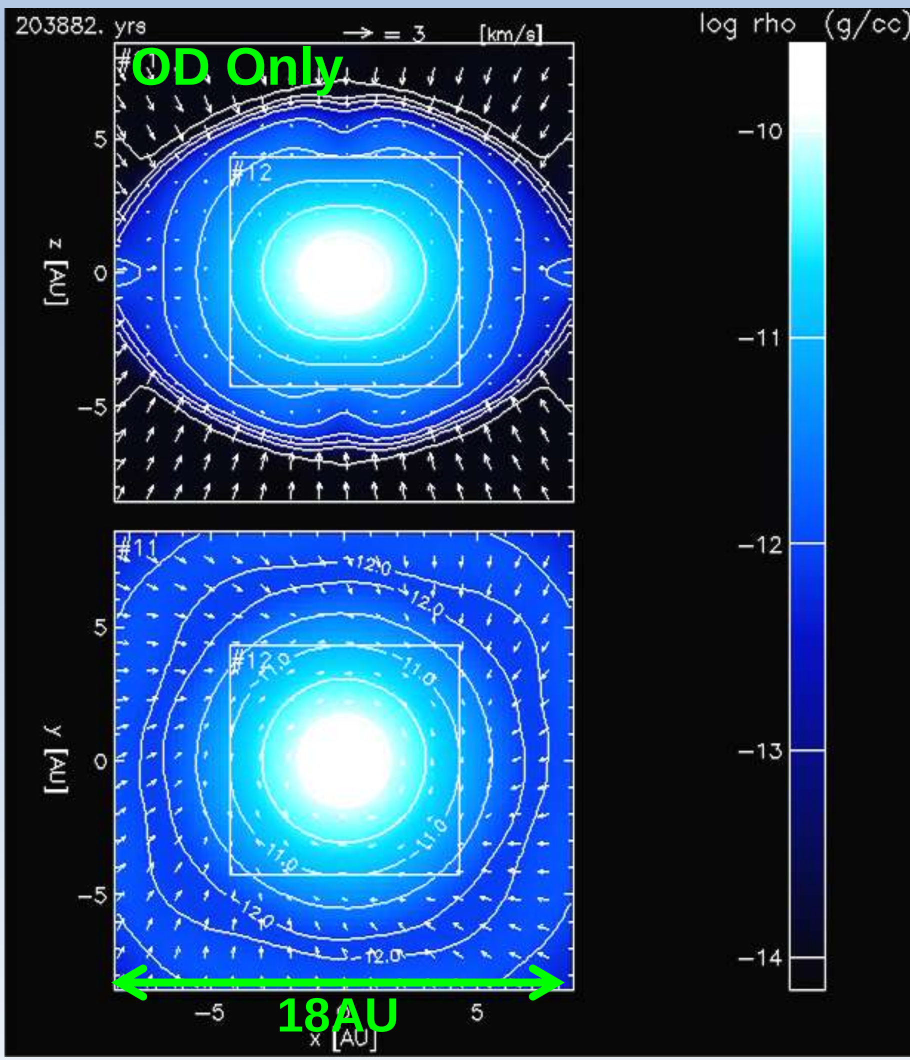
$$\mathbf{F}_r = \frac{c\lambda}{\sigma_R} \nabla E_r, \quad \lambda(R) = \frac{2+R}{6+2R+R^2}, \quad R = \frac{|\nabla E_r|}{\sigma_R E_r},$$

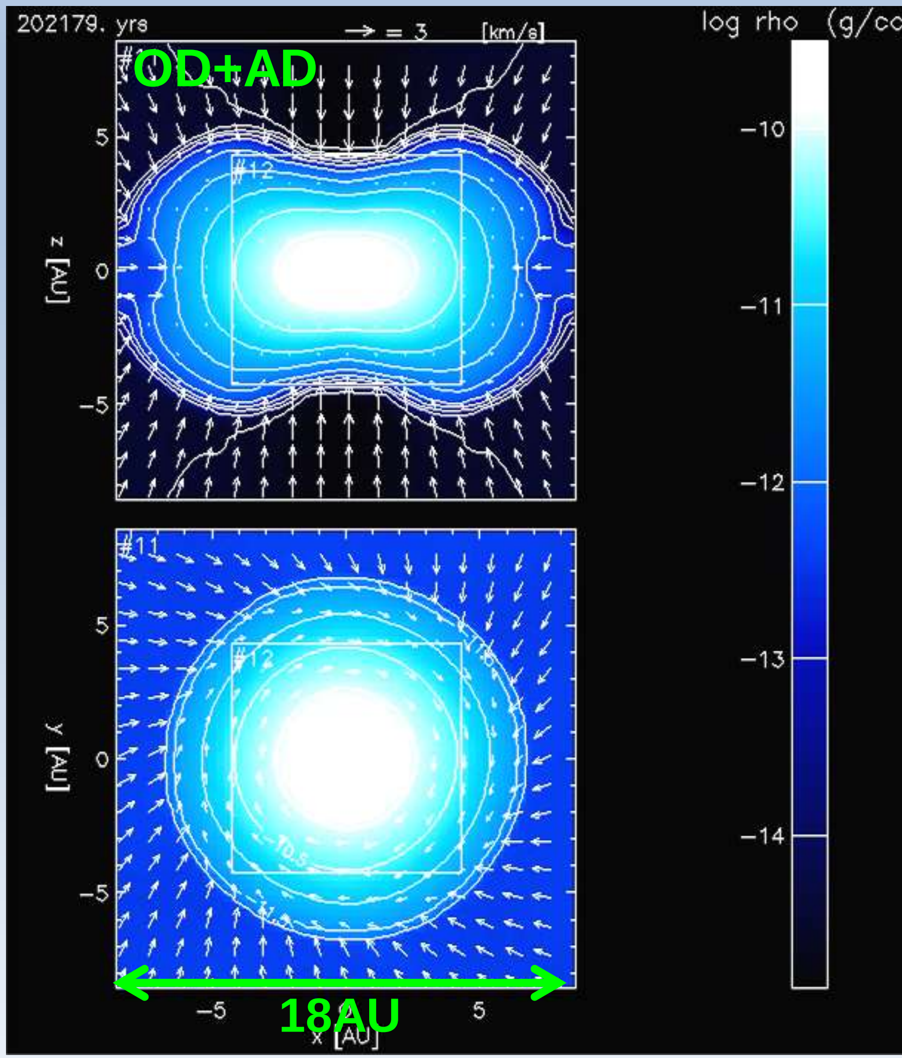
$$\mathbb{P}_r = \mathbb{D} E_r, \quad \mathbb{D} = \frac{1-\chi}{2} \mathbb{I} + \frac{3\chi - 1}{2} \mathbf{n} \otimes \mathbf{n}, \quad \chi = \lambda + \lambda^2 R^2, \quad \mathbf{n} = \frac{\nabla E_r}{|\nabla E_r|},$$

+ Eq. of state
+ AD & OD rates
+ Opacities

Tomida + 15

Non-ideal MHD Models: First Cores



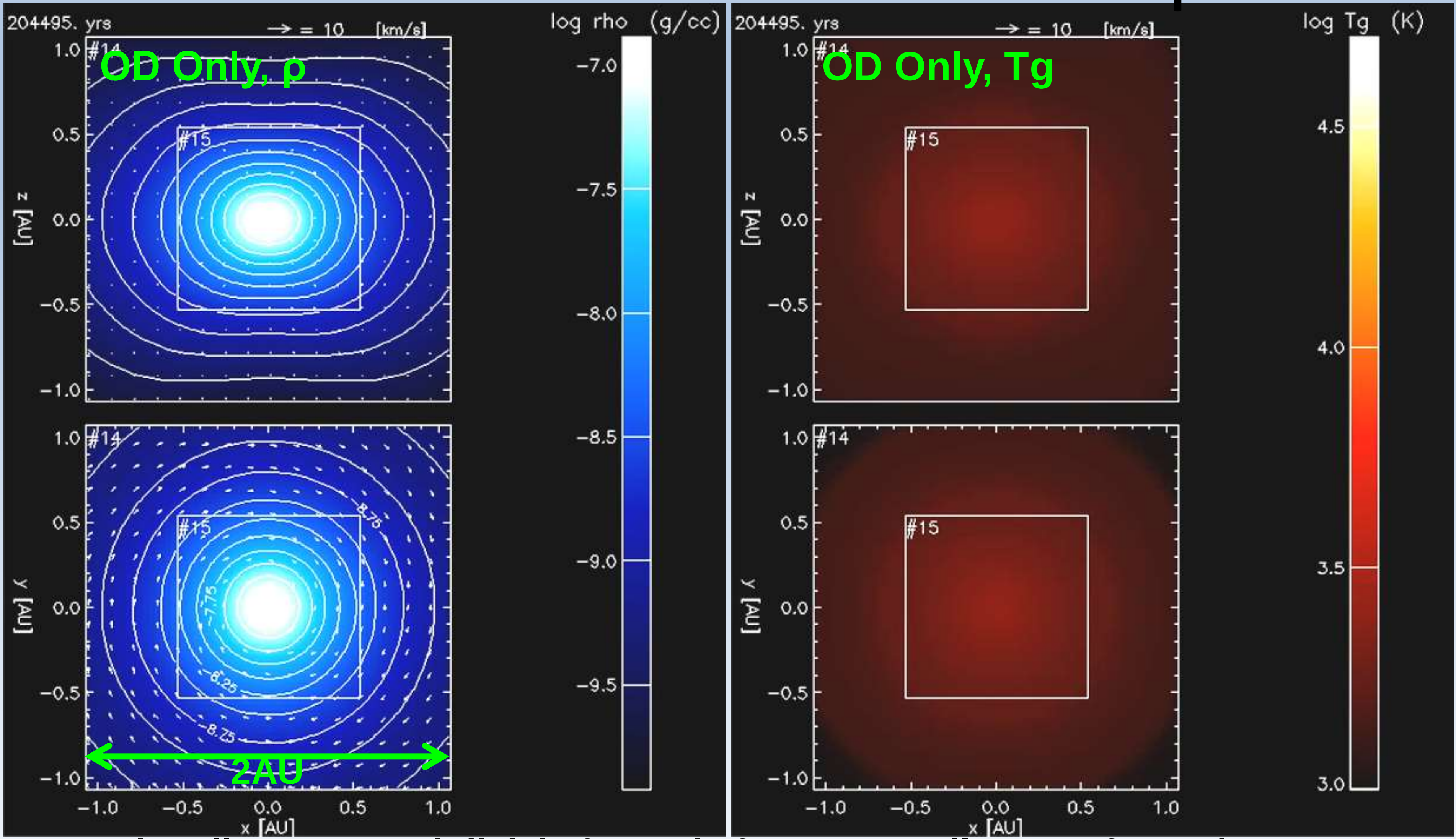


OD: Slow-rotating, vertical inflation by heating from second core

AD: Supported by rotation, non-axisymmetric (GI), but size is still small

Tomida + 15

Disk Formation after 2nd Collapse



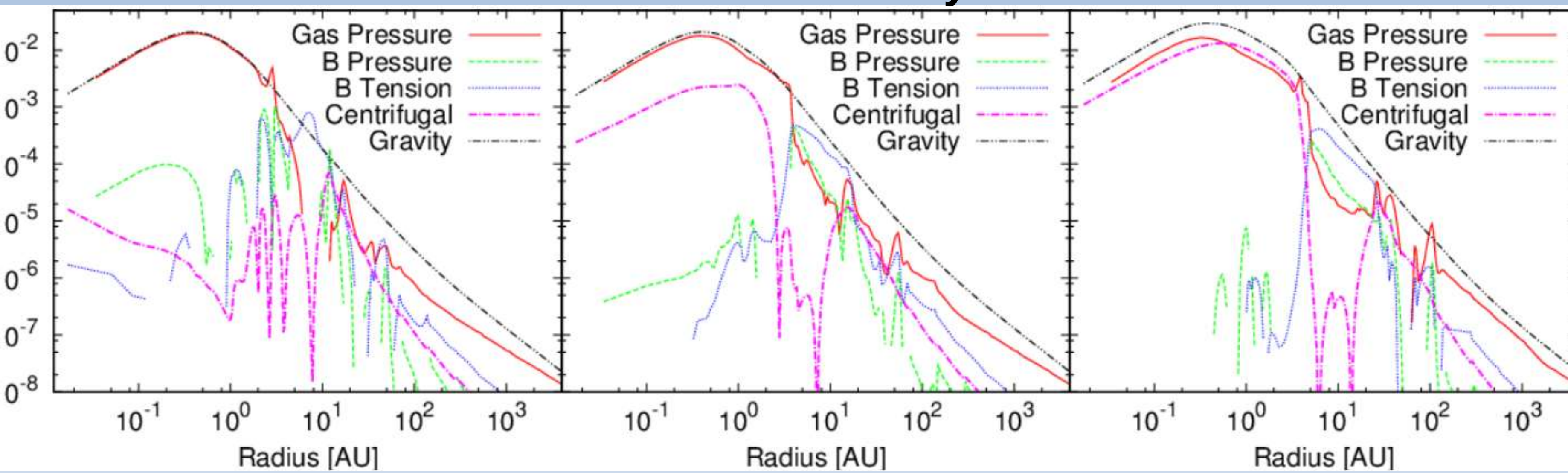
A rotationally-supported disk is formed after protostellar core formation.

Outflows by radiation+shock heating -> magnetic pressure driven jets

Tomida + 15

Force Balance

Ideal MHD **OD Only** **OD+AD**

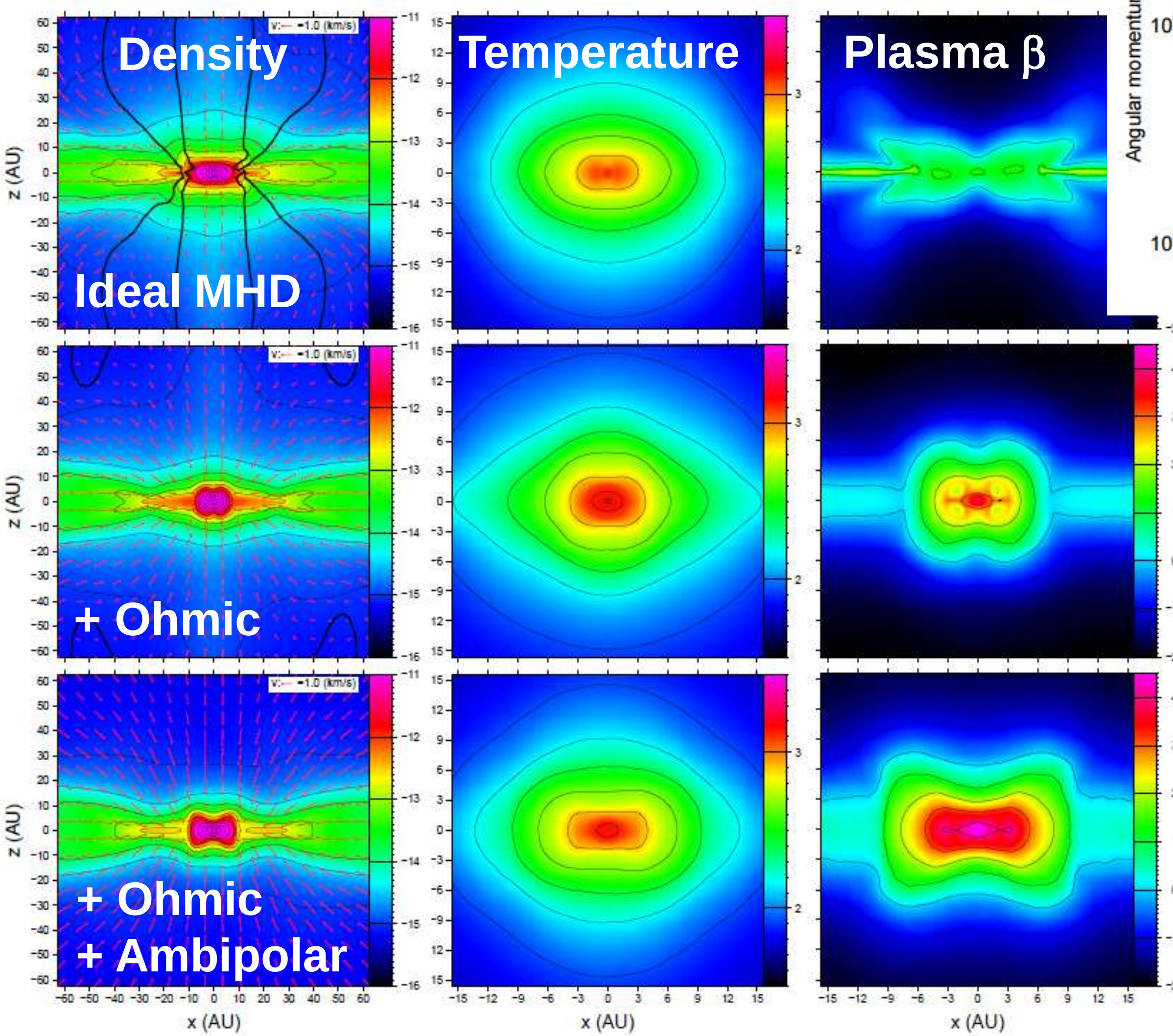


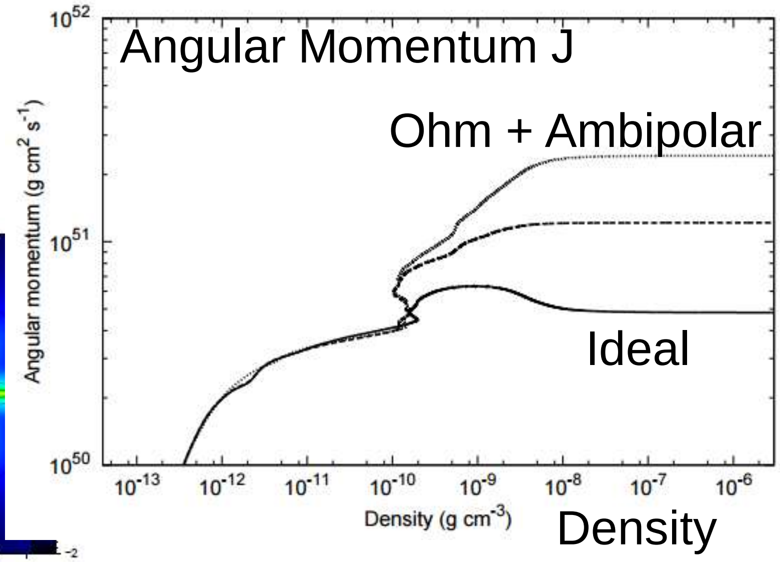
- **Ideal MHD model is essentially not rotating, and is totally supported by the gas pressure.**
- **OD model has considerable rotation, but not enough to support the first core and it is still pressure supported.**
- **Rotation is dominant, but not by far, in OD+AD model. The gas pressure is still contributing.**

SPH: Non-Ideal (Ohmic + Ambipolar diff.) Radiation MHD

Tsukamoto+ 15

Rotation supported disk forms at the same epoch of the protostar formation with B diffusion





- Disk is massive and gravitationally unstable
- G.I. is expected to play an important role in a further evolutionary stage

2. Early Gas Accretion Phase ~500 years after the Protostar Formation

Gas Accretion phase: 3D w/ *B* w/o non-ideal effect w/o radiation

Resistive MHD eqs.

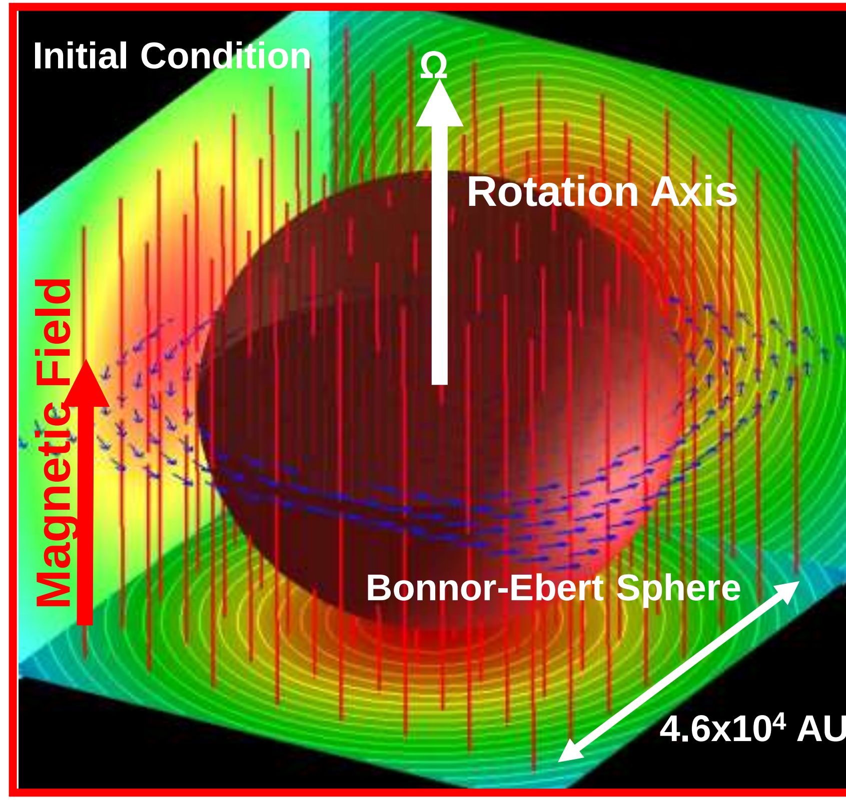
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

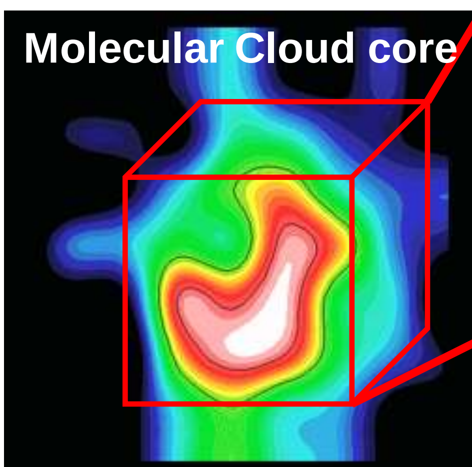
$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} = -\nabla P - \frac{1}{4\pi} \boldsymbol{B} \times (\nabla \times \boldsymbol{B}) - \rho \nabla \phi,$$

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

$$P = P(\rho),$$

(Barotropic eos + Protostellar Model)

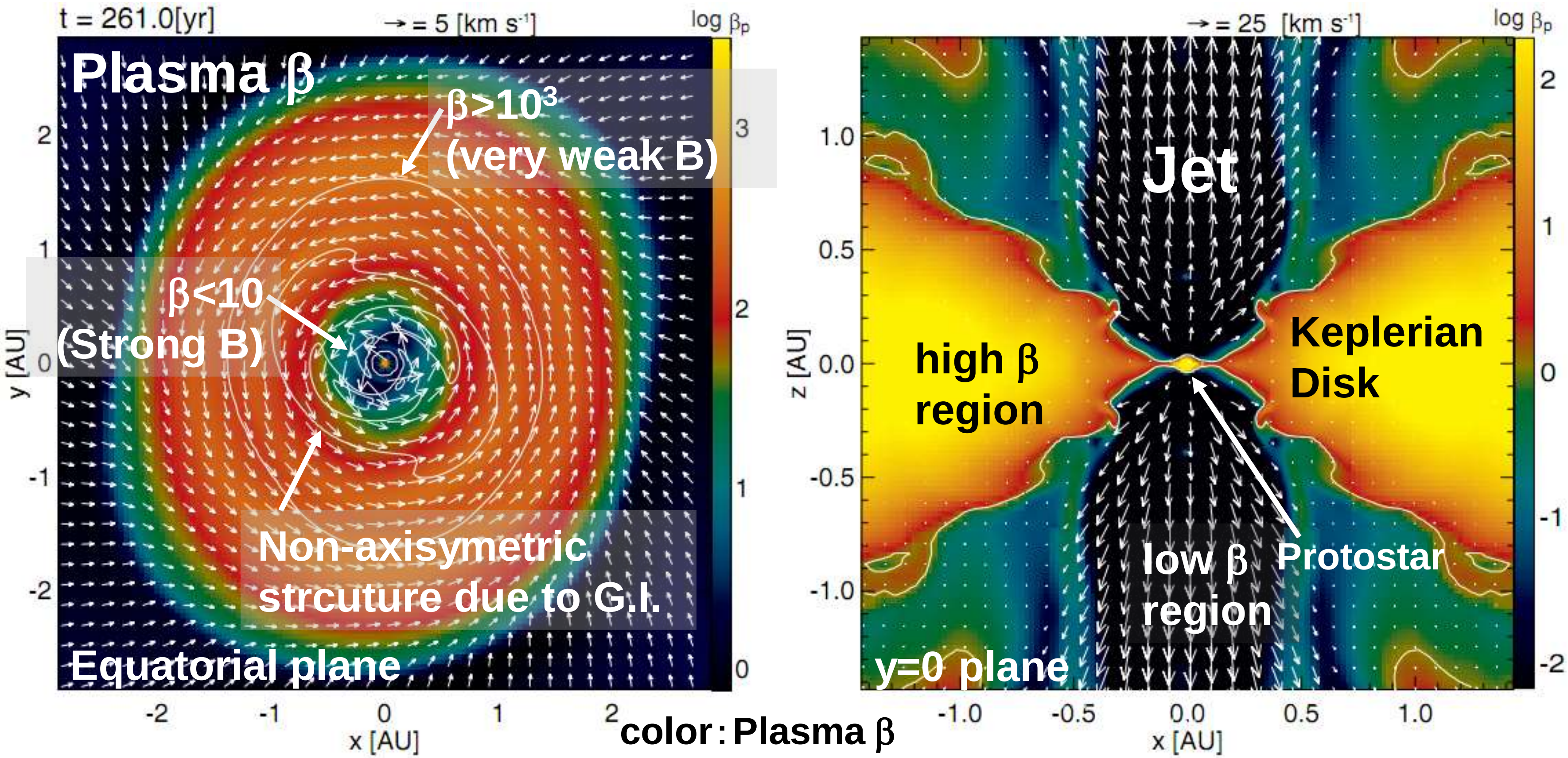




In this study,

- Both protostar (h<0.01AU) and molecular cloud core >10^5 AU are spatially resolved
- Cloud evolution was calculated for >500 years after the protostar formation
- ***Without Sink***
- With huge computational time (~10 months (wall clock time))

Gravitational Instability & Magnetic Effects



color：Plasma β
contour: density (left)、β (right)

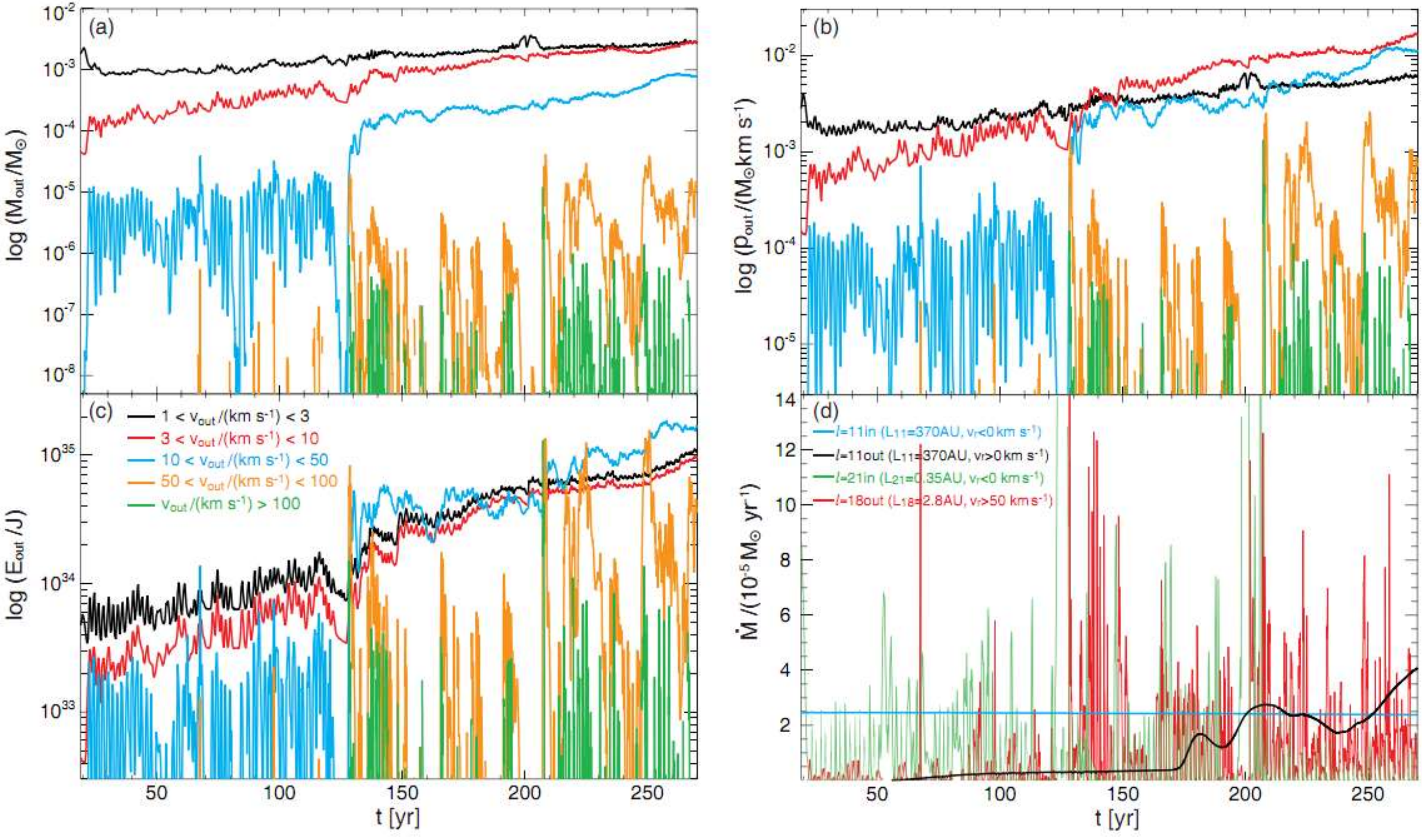
Magnetic field dissipates in a high density gas region

- >~3 AU (magnetic coupling region): magnetic braking, low-velocity outflow
- ~0.5 < r < 3 AU (magnetic decoupling region): non-axisymmetric structure by G.I
- <~0.5 AU (magnetic coupling region): (tower) jet, magnetic braking, MRI (disk surface)

Time variability of Outflow and Jet

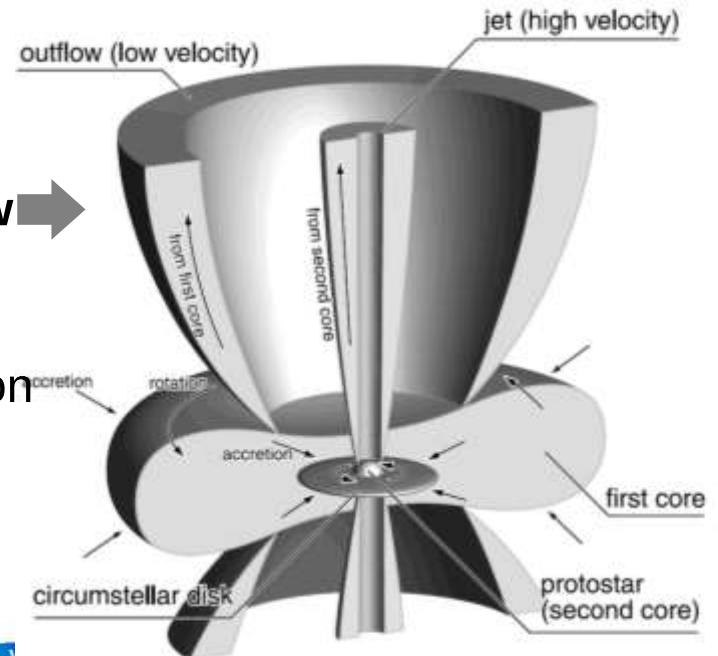
Episodic Jets cause Episodic Accretion

(a) Mass (b) Momentum (c) Kinetic energy (d) Outflow and inflow rates

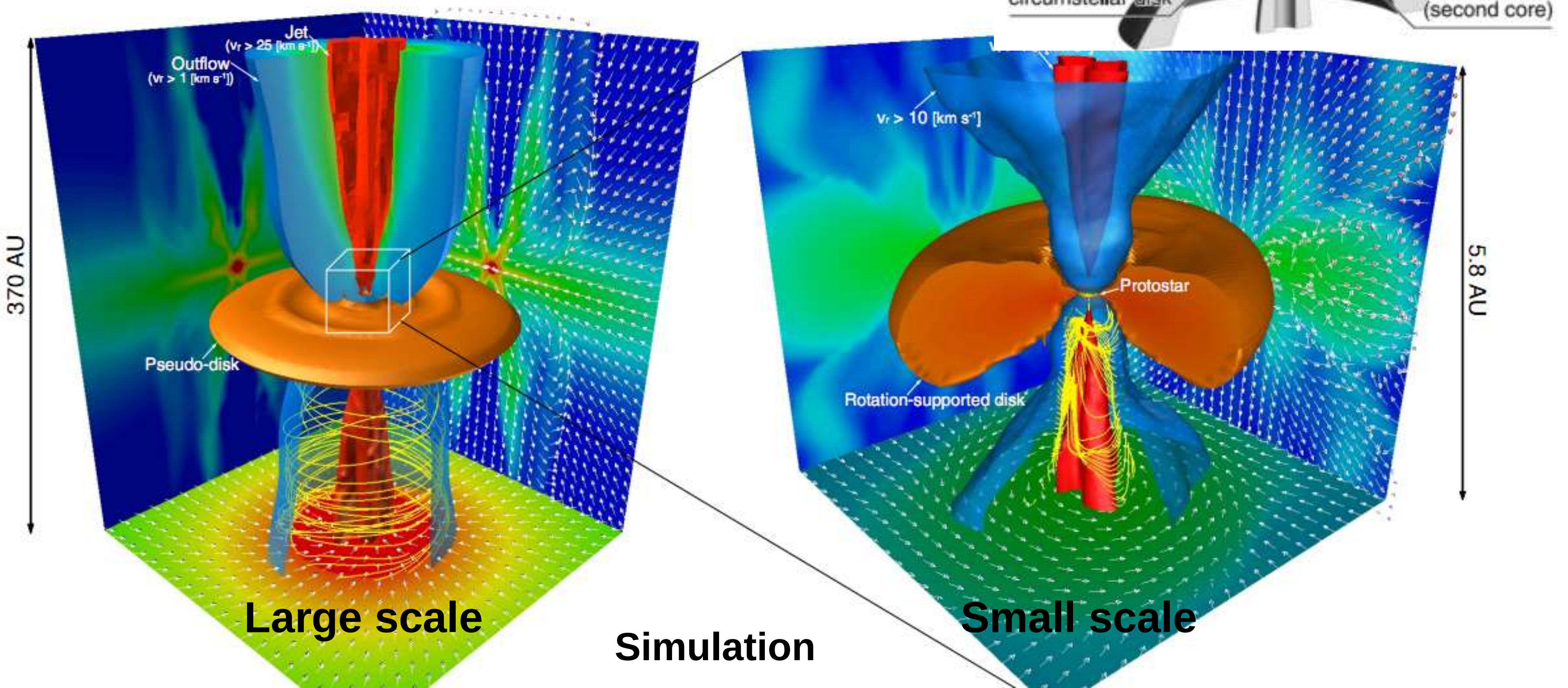


Jets, Outflow, Disk and Protostar

Schematic view



- High-velocity jet is driven near the protostar
- Low-velocity outflow is driven by the outer disk region
- High-velocity jet is enclosed by the low-velocity outflow

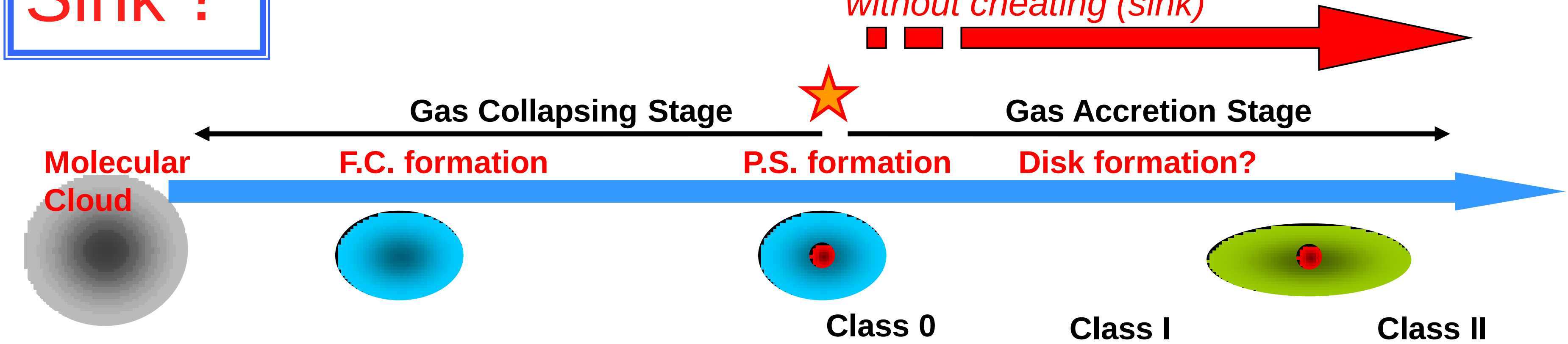


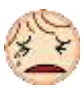
Simulation

3. Long-term Evolution of Circumstellar Disk with Sink

Sink？

We cannot calculate this phase for a long time
without cheating (sink)

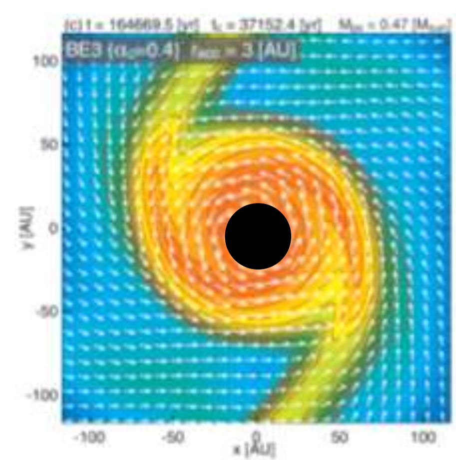


- To calculate the disk formation process
  - serious calculation without sink⇒ an impractically huge CPU time (power) is required 
  - easy calculation with sink⇒ we can easily acquire outcomes! 
    (However, we donot know whether the outcomes are correct or not)

- Sink method (there are many prescriptions)

A high-density gas region requires a short time step which impedes a long time disk evolution

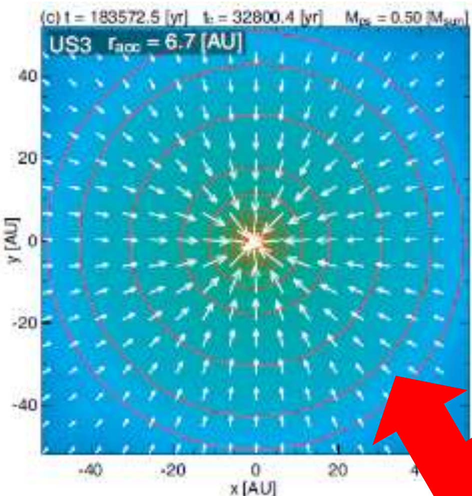
- a high density region is masked and is removed
- an inner boundary is imposed around the protostar



Serious Caution?

Machida, Inutsuka, Matsumoto (2014)

- Starting from the same initial condition, the disk formation was calculated with **different sink sizes**
- Results dramatically and qualitatively differ with different sink treatment (or sink radius)
- Sink radius of <1AU and spatial resolution of <0.1 AU are inevitably needed



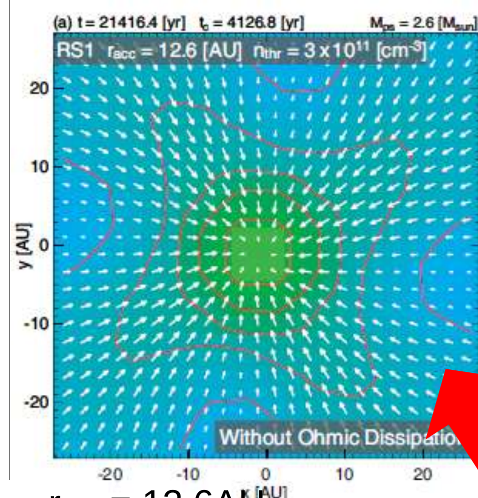
r_{acc}=6.7 AU

large sink

No disk forms

Uniform Sphere

Same initial condition



Same settings as in Seifried et al.

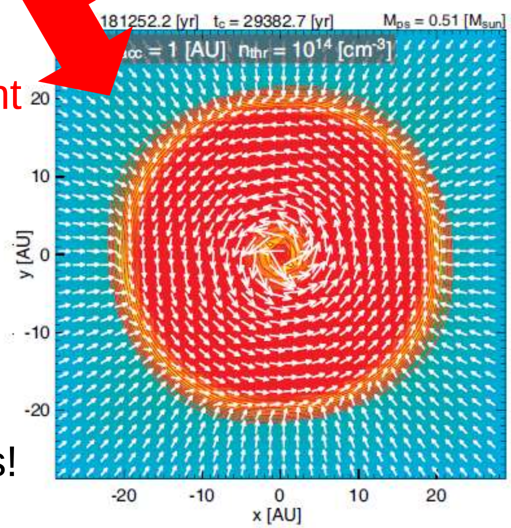
Same initial condition

r_{acc} = 12.6AU

n_{trh}=3x10^{11} cm^{-3}

No disk forms

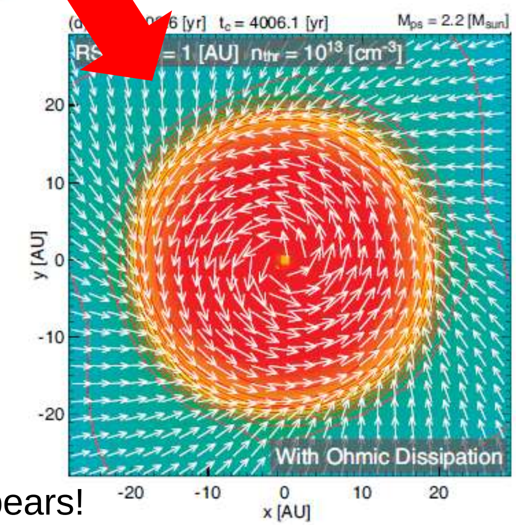
completely different outcome!



r_{acc} = 1AU

small sink

Disk forms!



r_{acc} = 1 AU

n_{trh} = 10^{13} cm^{-3}

Large disk appears!

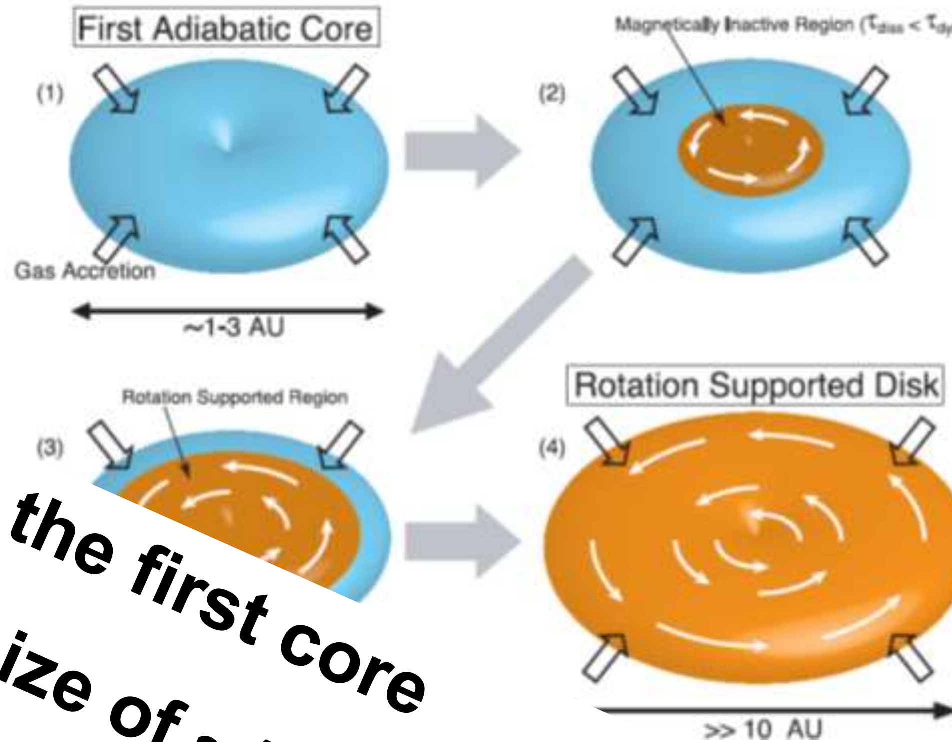
Long-term evolution of disk with r_{sink} < 1 AU

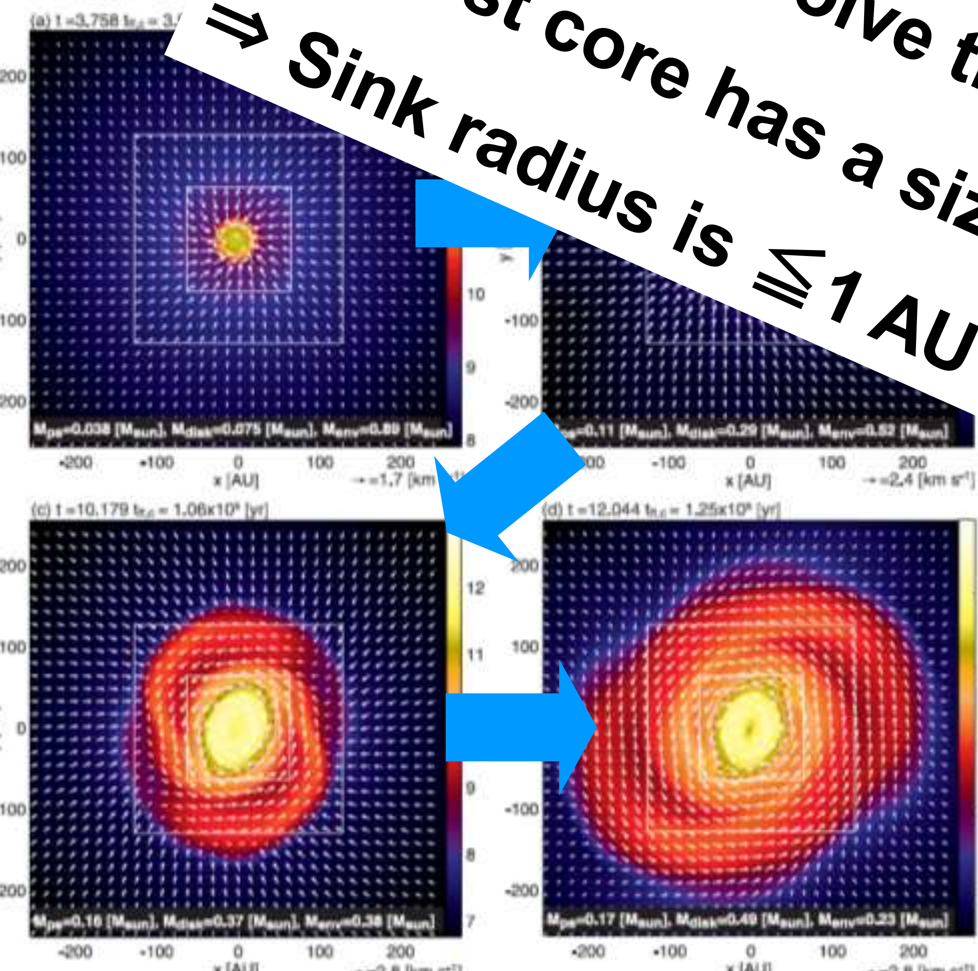
Even with s... field, the rotation s... very early phase of ...e)

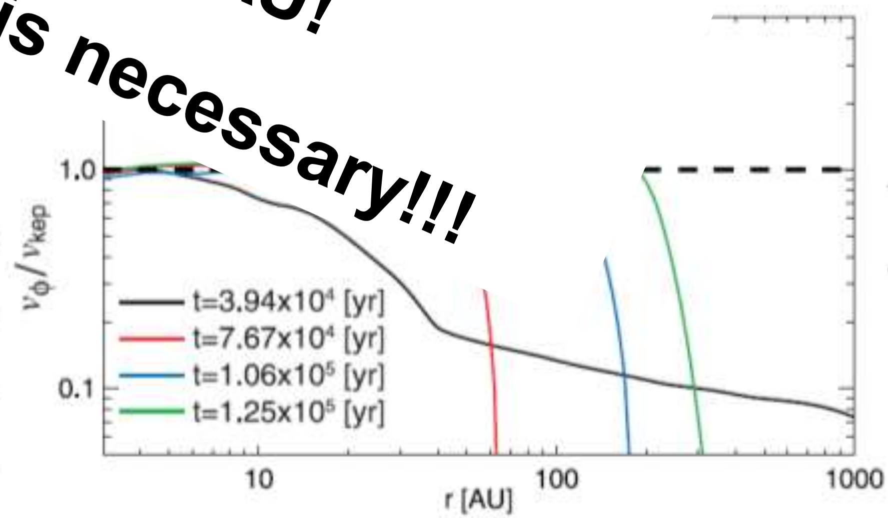
We need to resolve the first core

The first core has a size of ~1AU!

⇒ Sink radius is ≦1 AU is necessary!!!





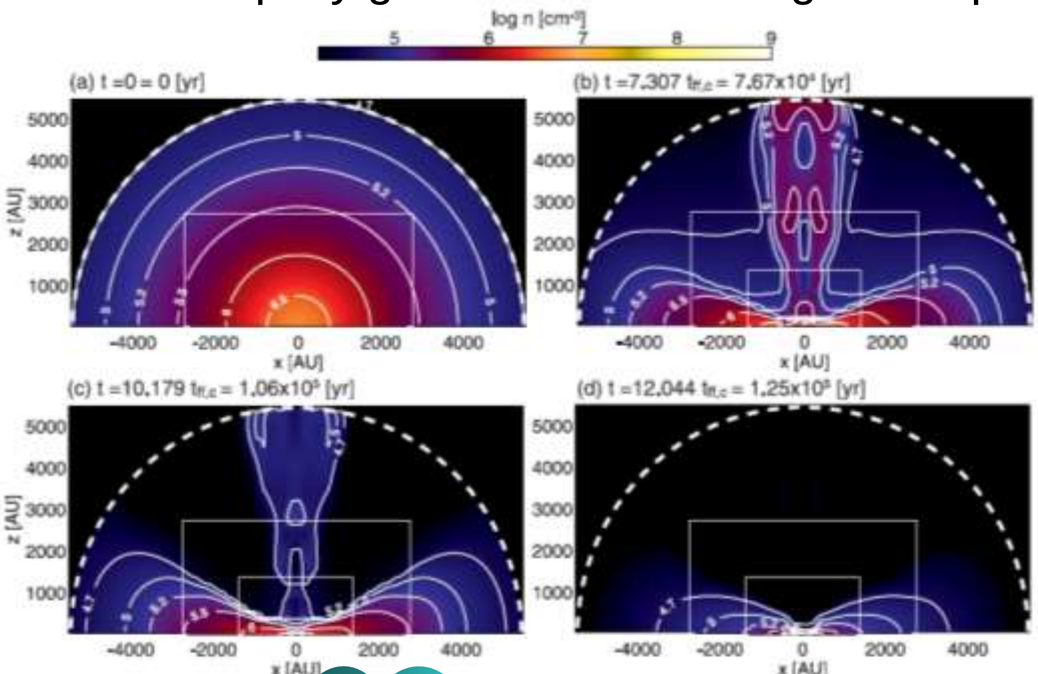


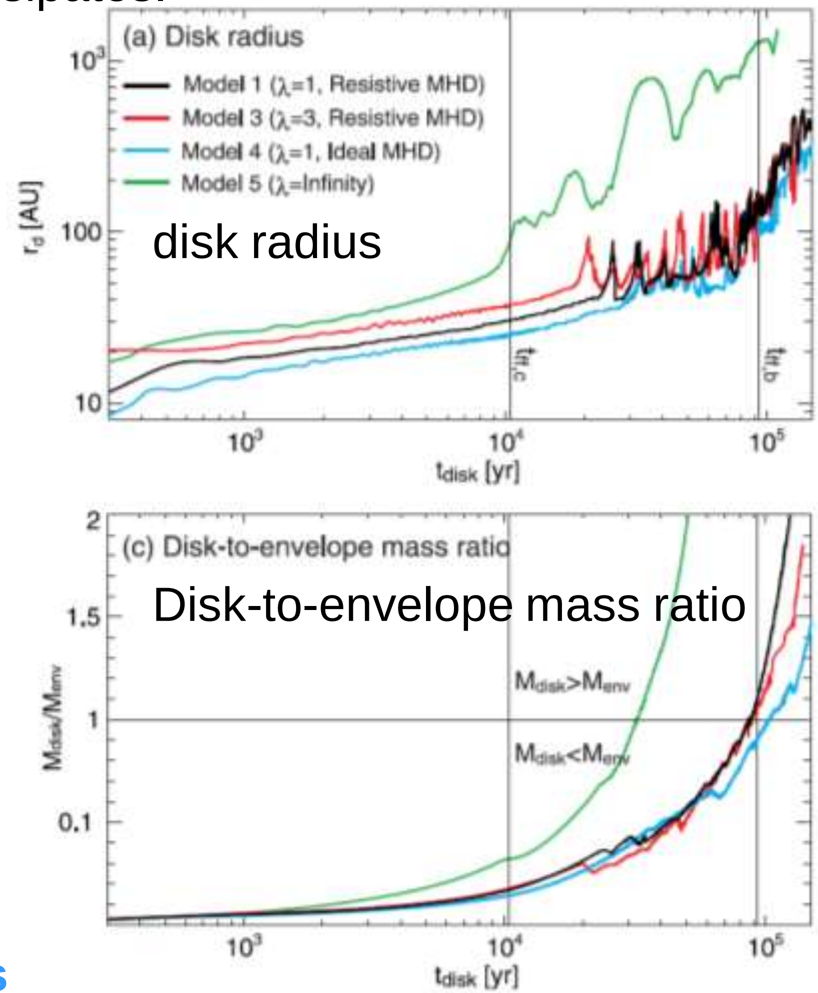
Machida, Inutsuka, Matsumoto (2014)

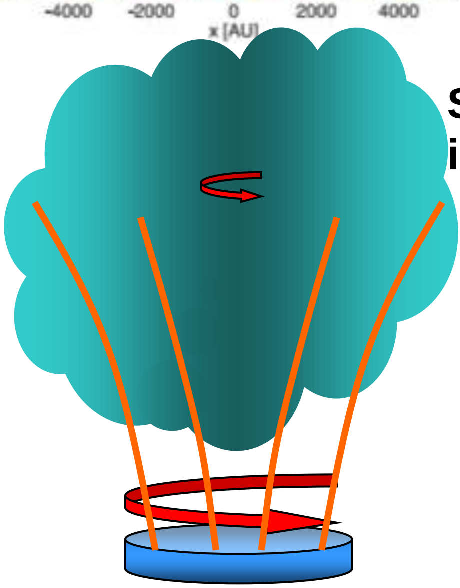
See also Dapp & Basu '10, 12

Exponential Disk Growth

The disk rapidly grows as the infalling envelope dissipates.







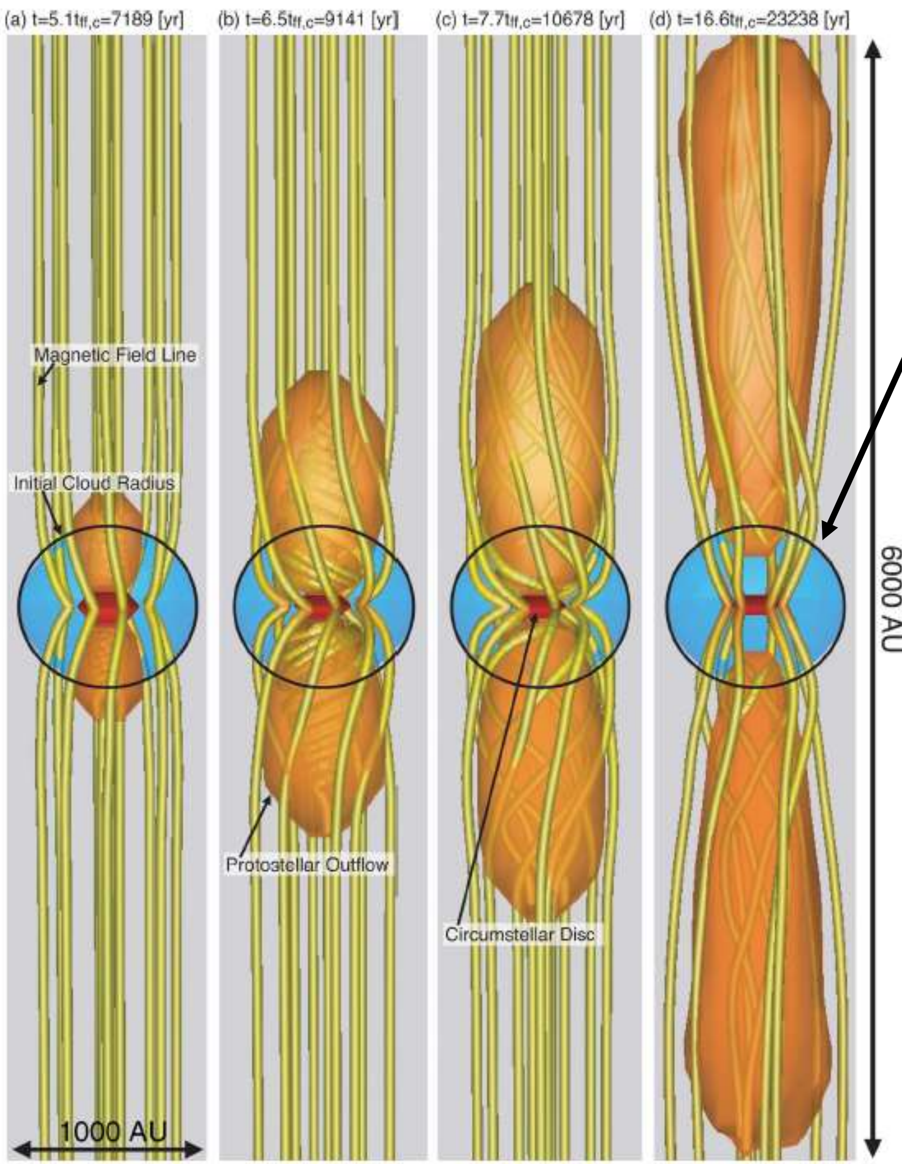
Slowly rotating massive infalling envelope

magnetic field lines

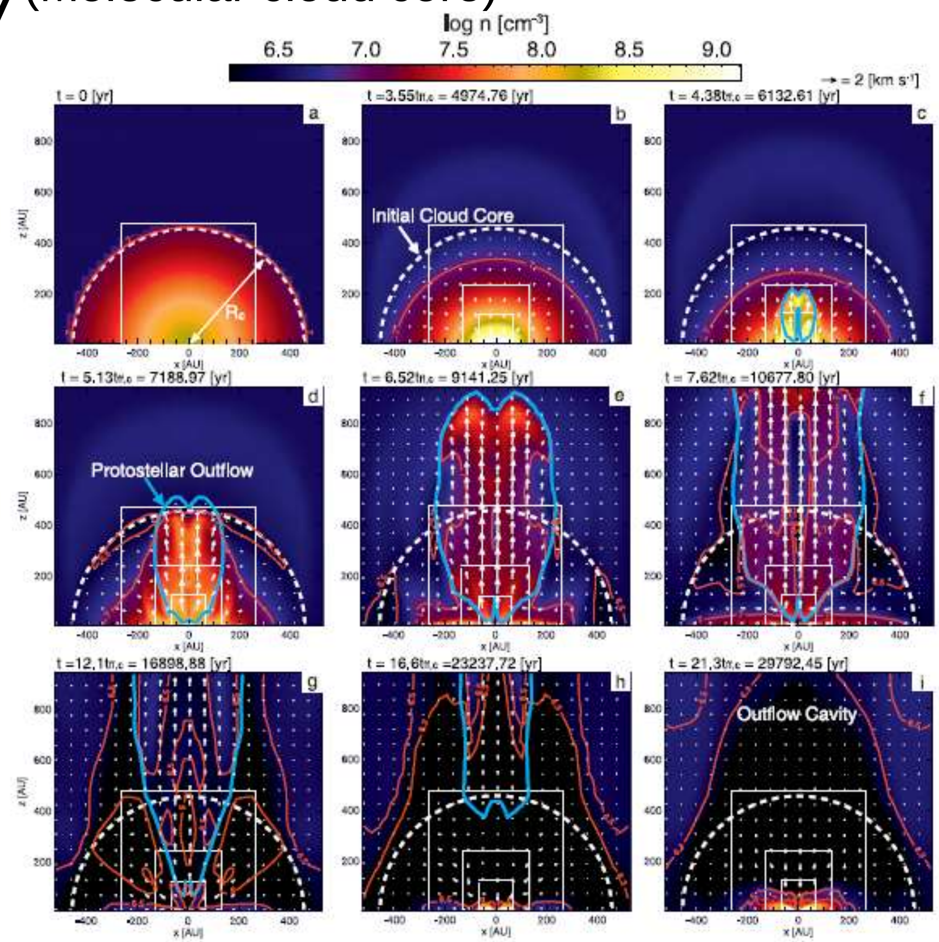
rapidly rotating less massive disk

Evolution of Outflow

- As the disk grows, the outflow also grows
- As the infalling envelopes dissipates, the outflow weakens and finally disappears



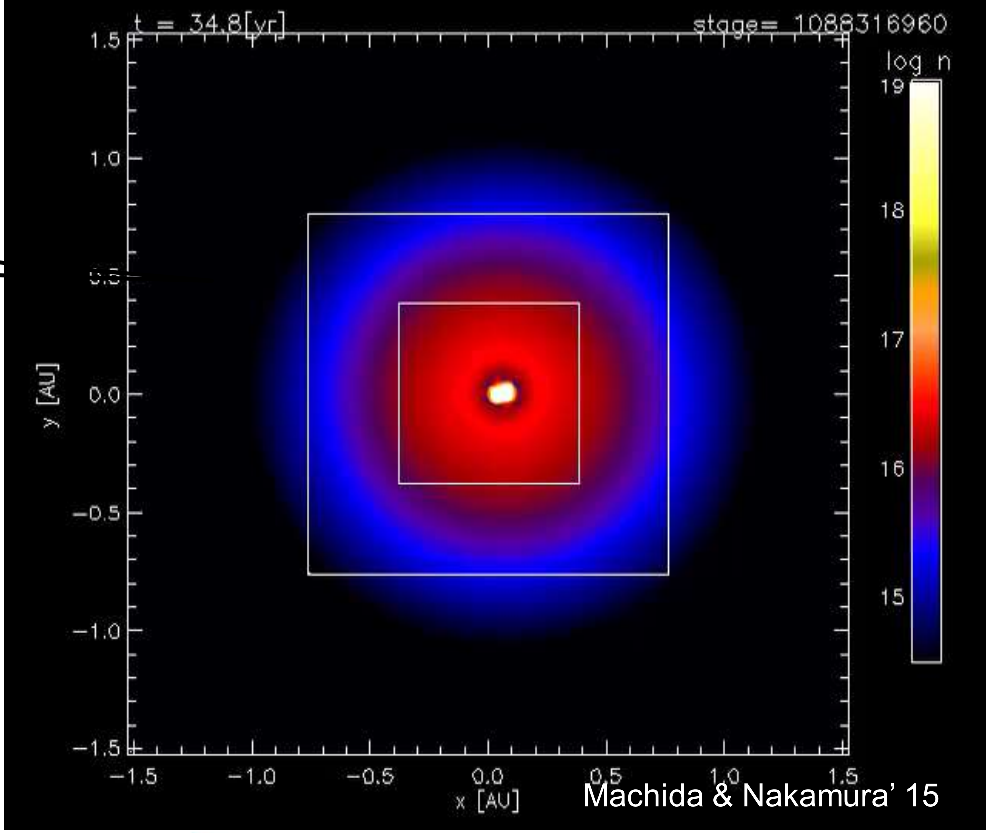
Star forming cloud
(Molecular cloud core)



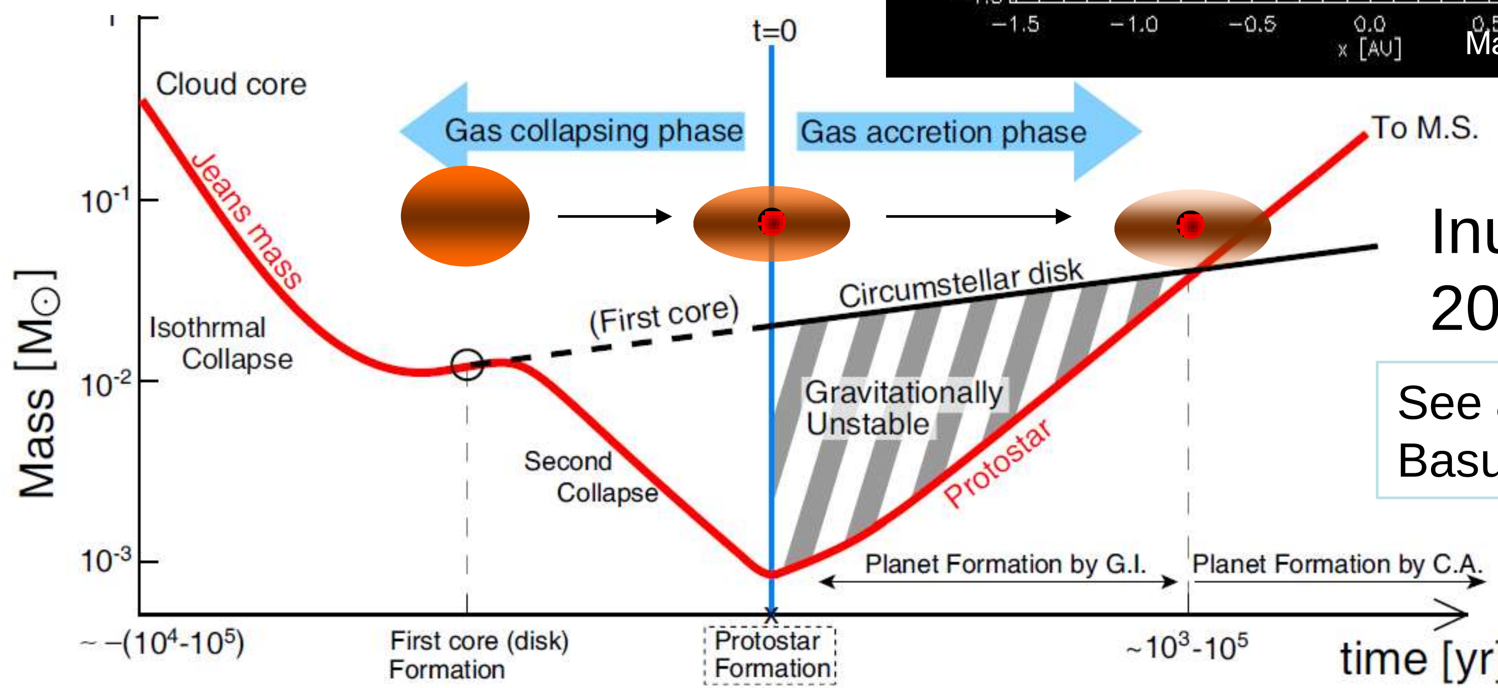
Gravitational Instability and Planet Formation

Disk gravitational instability without sink

- Fragmentation occurs in the disk
- But, fragments falls onto the protostar



Gravitational instability inevitably occurs during the early phase of star formation



Inutsuka et al. 2010

See also Vorobyov, Basu et al.

Summary

- The star formation process from prestellar cloud until protostar and circumstellar disk formation have been investigated using numerical simulations
- Recent theoretical studies indicates that
  - The first core forms before the protostar formation and evolves into the protostar formation: the first core is the origin of circumstellar disk
  - The low-velocity outflow is driven by the first core or outer disk region, while jets are driven near the protostar: the magnetic dissipation region causes two distinct flows
  - The dissipation of magnetic field occurs in the first core or nascent disk and alleviates the angular momentum transfer due to magnetic braking
  - To accurately investigate the disk formation, **sink radius of < 1AU and spatial resolution of ~0.1AU are inevitably needed**
  - The size of rotation disk is within ~10 AU during the Class 0 stage, while the disk size exponentially grows as the infalling envelope dissipates and reaches ~100 AU
  - Gravitational instability occurs and tends to form planetary mass objects during the (early) gas accretion phase