Magnetohydrodynamics of Population III Star Formation

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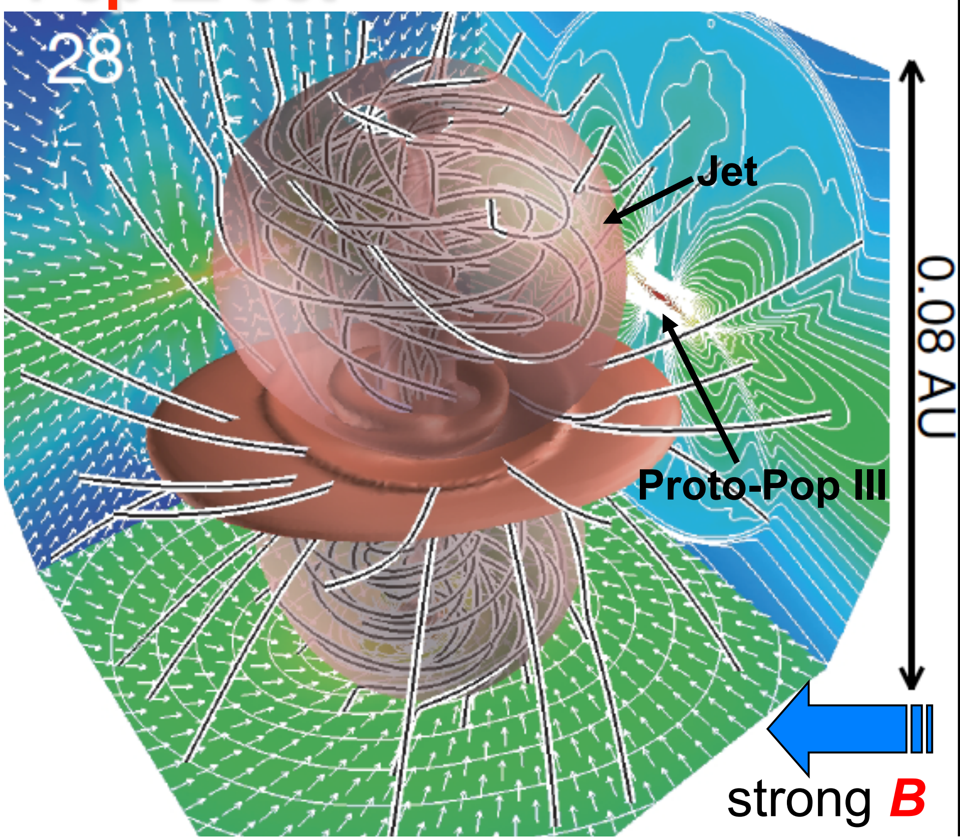
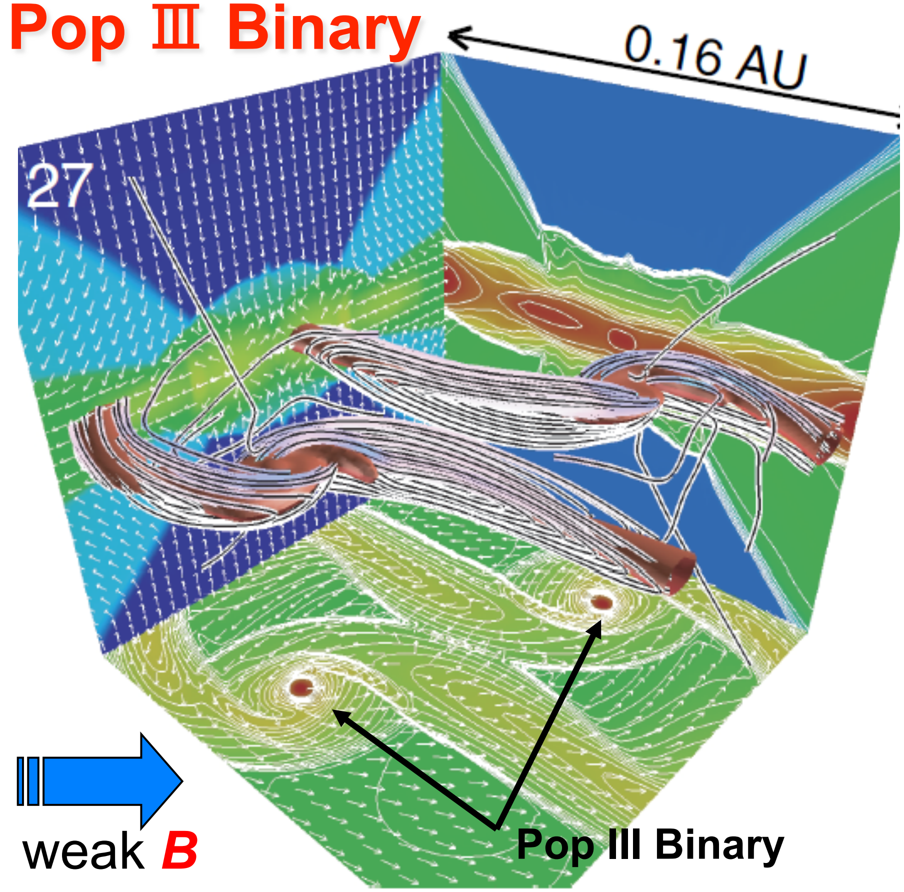
Pop Ⅲ Jet



Pop Ⅲ Binary



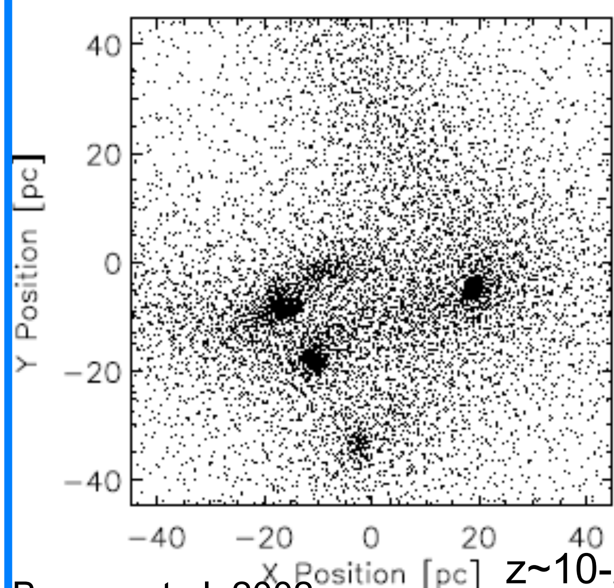
Star Formation in Early Universe and Present Day

Difference of Host Clouds for Star Formation

Early Universe

Primordial Gas Cloud

- No Dust grains, No Metals
- Cosmological Simulations
- $n \sim 10^{3\text{-}4}$ cm^{-3}, T~200 K
- Very weak(?) Magnetic field



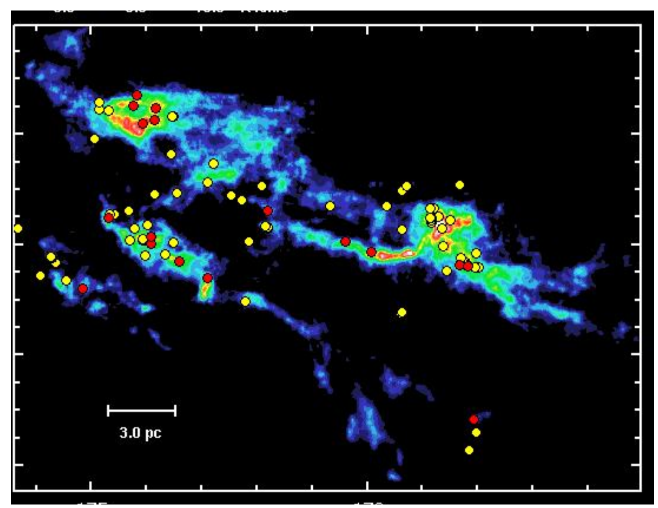
z~10-20

Bromm et al. 2002

Present Day

Present Day Gas Cloud

- Dust grains, Metals
- Direct Observations
- $n \sim 10^{4\text{-}6}$ cm^{-3},T~10 K
- Strong Magnetic field

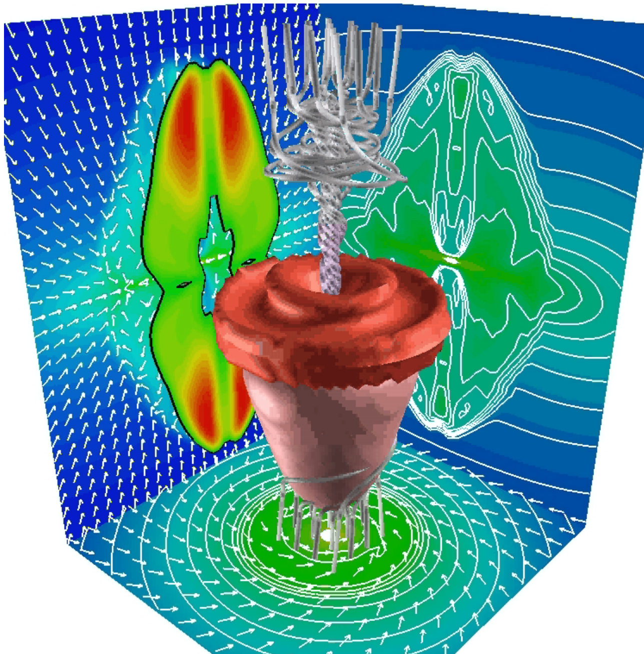


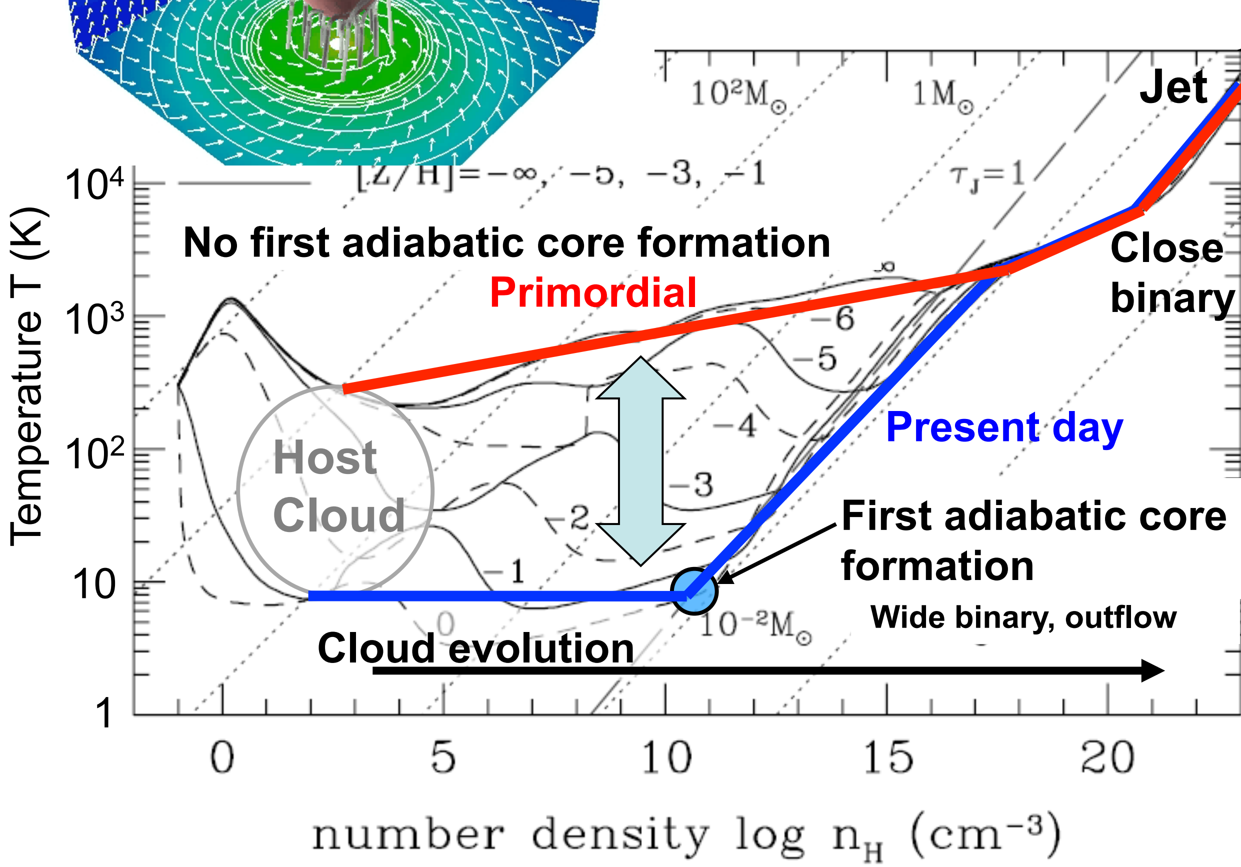
Nanten Telescope@Nagoya University

z~0

Low velocity outflow from First adiabatic core
(Present day star formation)

ce in Thermal Evolution





Omukai et al. (2005)

Protostar Formation
($n \sim 10^{21}$ cm^{-3})

Differences are caused by cooling processes of metals and dusts

- Primordial Composition
  - He, H, H_2, HD Cooling without Dust and Metal cooling
  - High temperature (T>300K)
  - No adiabatic first core formation
- Present Day Composition
  - Metal and Dust Cooling are effective
  - Keeping low T (~10K for $n < 10^{10} cm^{-3}$) a
  - Adiabatic first core formation

  ⇒Two component outflows, wide binary
- $n > 10^{16} cm^{-3}$, thermal evolutions are converged, because the dust and metal coolings becomes ineffective

Difference in Magnetic Evolution

Primordial Clouds

Ideal MHD

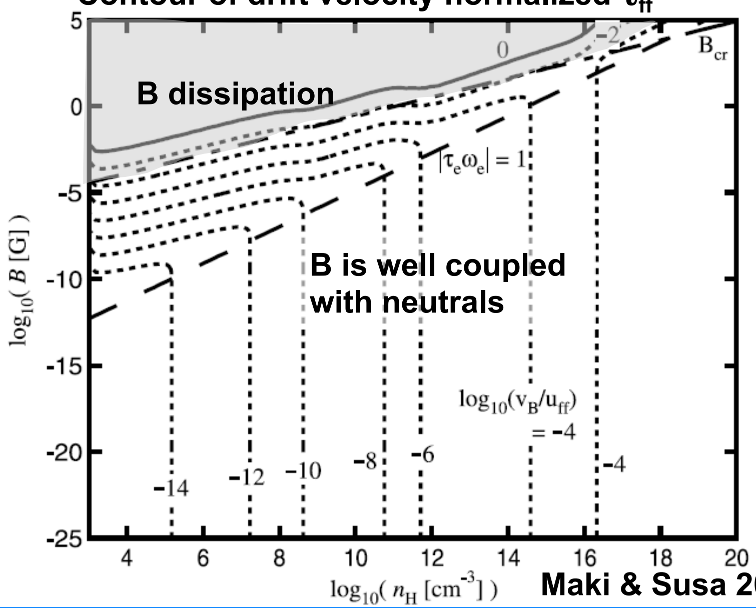
- Initially **Weak** Magnetic Field
  - $B<10^{-20}$G (Ichiki etal. 2006), ~10^{-11}G (Langar etal. 2003 also see Poster by Susa)
- ***Frozen-in*** Condition

$$B_{\text{Inial Cloud}} \leq 10^{-5}(N_H / 10^3\,\text{cm}^{-3})^{0.55}\ \text{G}$$

(Maki & Susa 2002, 2007)

- ✓ ***B*** is always coupled with **neutral gas**
- ✓ ***B*** continues to be amplified without dissipation

Contour of drift velocity normalized τ_{ff}

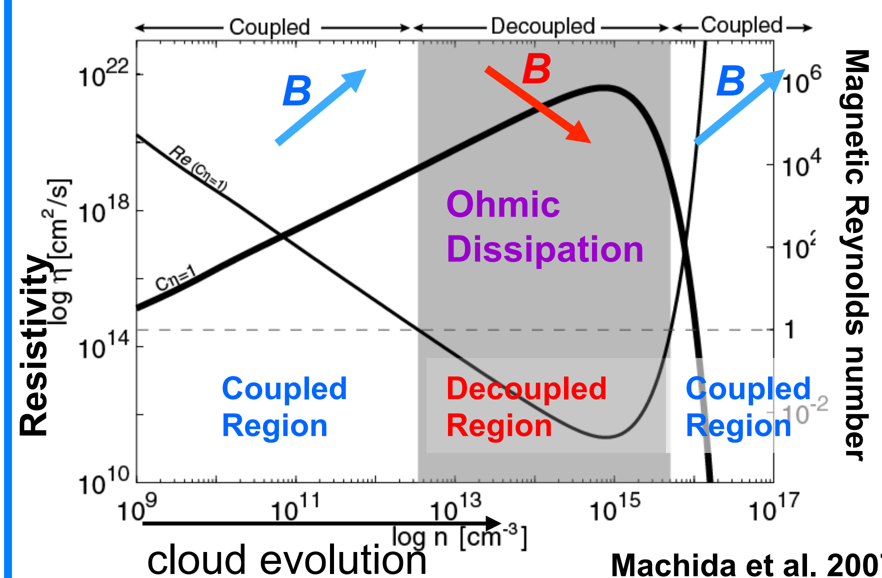


Maki & Susa 2004

Present Day Clouds

Resistive MHD

- Initially **Strong** Magnetic Field
  - $B > 10^{-6}$ G (e.g., Crutcher 1999)
- ***Magnetic dissipation***
  - ✓ Very low ionization degree
  - ✓ Ohmic dissipation is effective for $10^{11}\,\text{cm}^{-3} < n < 10^{16}\,\text{cm}^{-3}$ (Nakano et al. 2002)
- Very weak ***B*** at protostar formation: $\beta_p \sim 10^2 - 10^6$ (Machida et al. 2007)



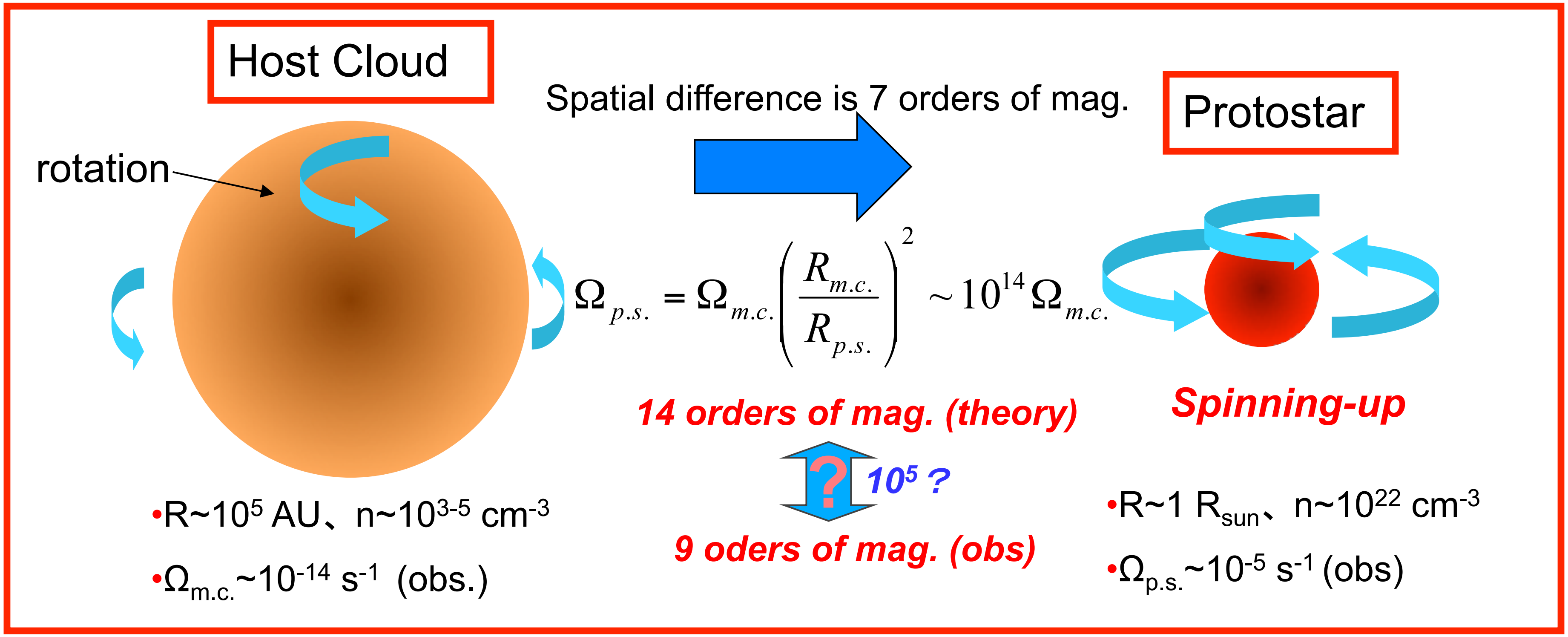
Machida et al. 2007

Angular Momentum Problem

- Most serious problem in the present-day star formation

  $j \sim 10^{21}$ cm^{2}s^{-1} (molecular cloud) ⇔ **$j \sim 10^{16}$ cm^{2}s^{-1}** (Protostar)

- Conservation of J ⇒ Without J transfer, star is never born



- Present-day solution：Protostellar Jet and Binary formation

- Primordial Solution: Pop III star rotates with Ω_{ps} ~ 1 s^{-1} ? (centrifugal barrier)
  Global spiral structure? Binary (Turk, Clark at this meeting)?
  or Magnetically driven Jet?

Purpose of this study

- We investigate the influence of ***B*** on the Population III Star formation, parameterizing cloud's rotation rate and magnetic field strength
- In the collapsing primordial gas clouds, ***B*** can be amplified without dissipation **(Maki & Susa 2002, 2007)**
- Even if initial ***B*** is weak, the amplified ***B*** may affect the formation process of Pop.Ⅲ

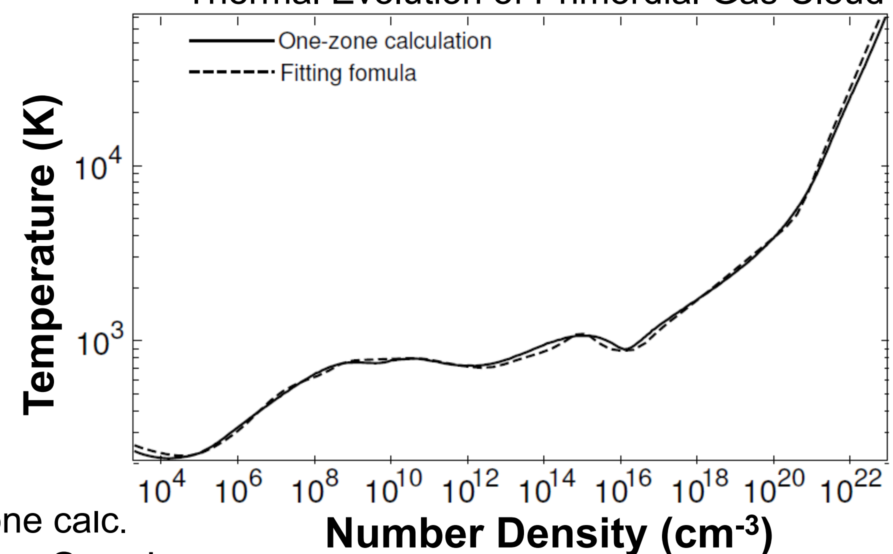
Basic Equations

Ideal MHD eqs. with self-gravity

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \\ \rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} \\ \quad = -\nabla P - \frac{1}{4\pi}\boldsymbol{B} \times (\nabla \times \boldsymbol{B}) - \rho \nabla \phi, \\ \frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}), \\ \nabla^2 \phi = 4\pi G \rho, \end{cases}$$

$P=F(\rho)$:Barotropic E.O.S modeled using one-zone calc.

Thermal Evolution of Primordial Gas Cloud



Species

H, H^+, H^-, He, He^+, He^{++}, H_2, D, D^+, HD, HD^+, e

Initial Settings

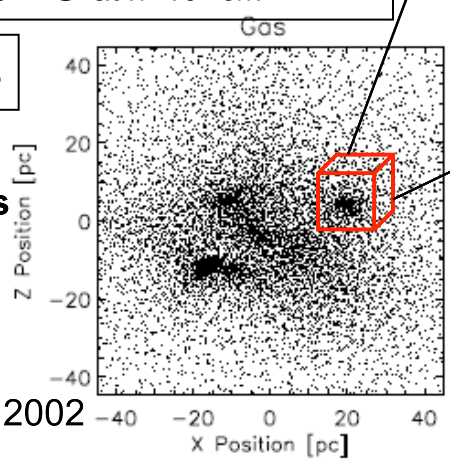
- Spherically Hydrostatic Core (Bonnor-Ebert Sphere)
- m=2 density perturbation (10%)
- B // Ω
- Parameters: β_0 and γ_0 (Ω_0 and B_0)

> **Cloud Rotation** $\beta_0 \equiv E_{rot} / E_{grav}$,
> $\beta_0 = 10^{-6} – 0.1$
> $\Omega_0 = 10^{-17} – 10^{-13}$ [s^{-1}] at $n = 10^3$ cm^{-3}

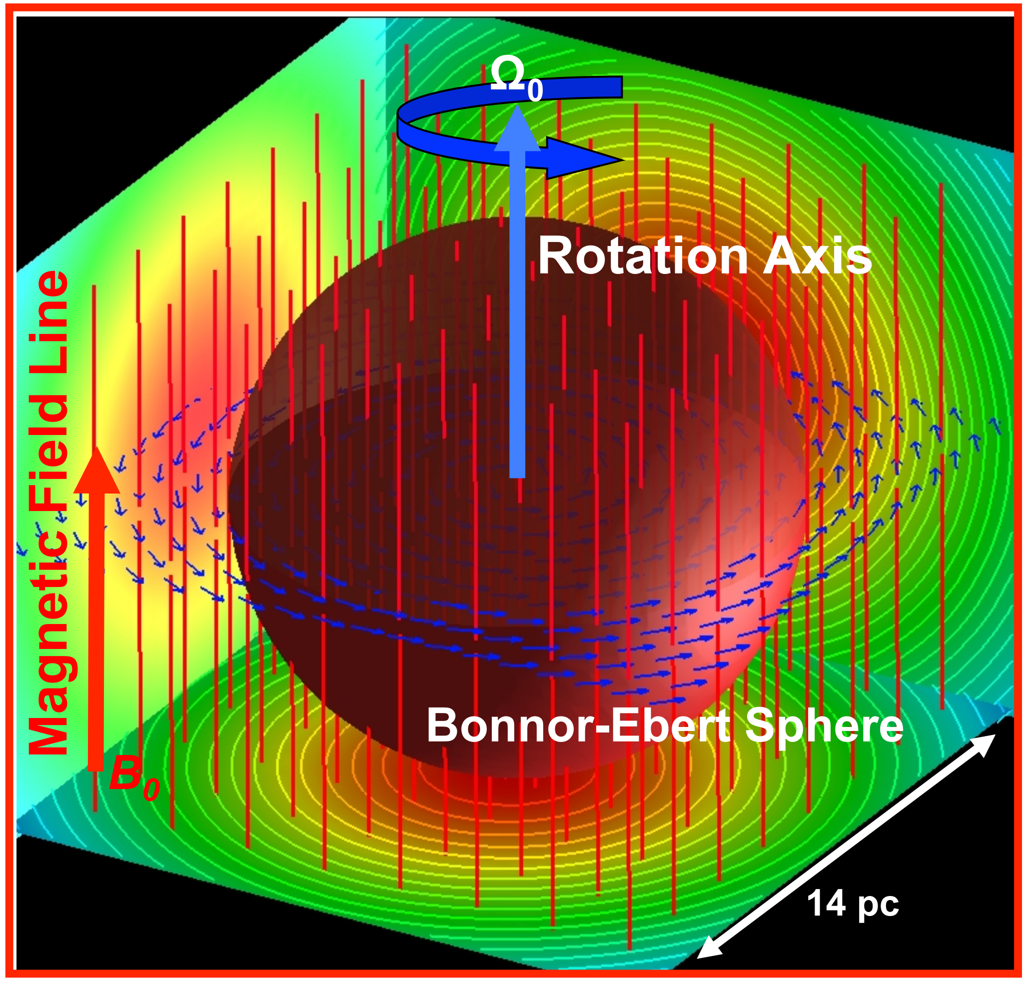
> **Magnetic Field** $\gamma_0 \equiv E_{mag} / E_{grav}$
> $\gamma_0 = 10^{-10}$ - 1
> $B_0 = 10^{-10}$ -10^{-5} G at $n = 10^3$ cm^{-3}

> **36 Models**

As the initial state, we mimicked results of the cosmological simulations



Bromm et al. 2002



- Initial Values
  - Central density : $n = 10^3$ cm^{-3}
  - Temperature : T=250K
  - B.E. Radius: 14 pc
  - Mass : $M_{cloud} = 6 \times 10^3$ Msun

Numerical Method

3D Ideal MHD Nested Grid Method (Machida et al. 2005, 2006)

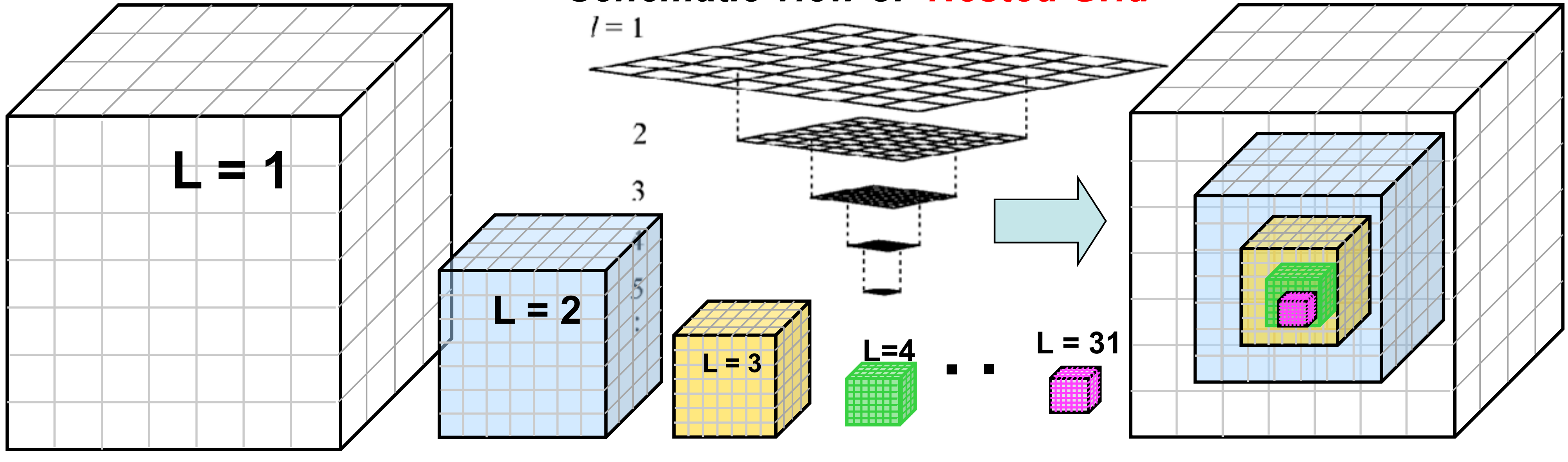
- **Grid size:** 128 x 128 x 128
- **Grid level:** l_{max}=31 (**l** : Grid Level)
- **Total grid number:** 128 x 128 x 128 x 31
- **Grid generation:** Jeans Condition

l =1: L_{box} = 14 pc, n = 10^3 cm^{-3} (initial)
l =31: L_{box} = 0.2 R_{sun}, n = 10^{23} cm^{-3} (final)

$\Delta x_{l=31}$ = 0.0016 R_{sun}

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

Schematic view of Nested Grid



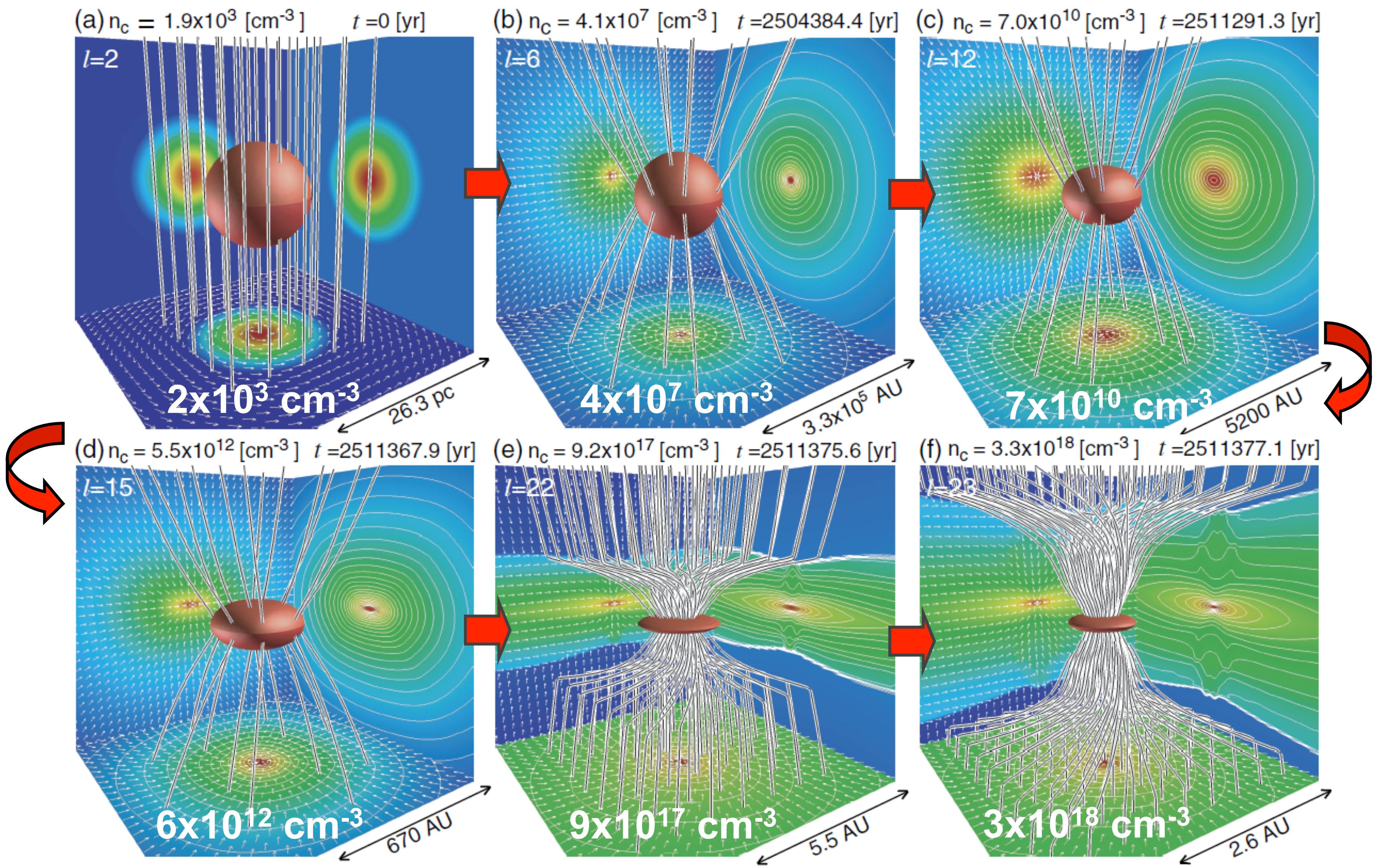
Results: Magnetic Field Lines

β_0: mag. eng, γ_0: rot eng

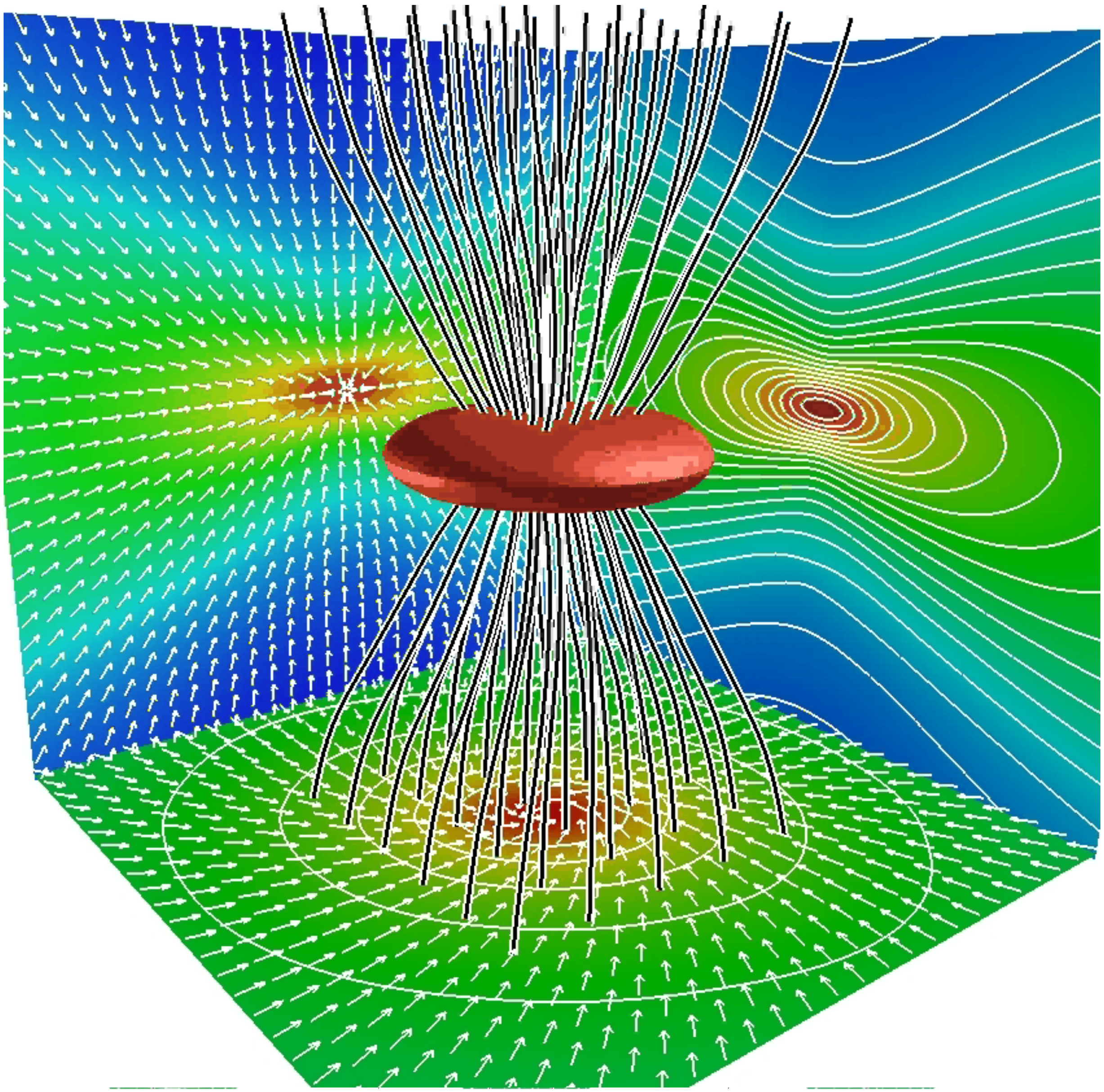
Magnetic dominated model: $\gamma_0 > \beta_0$

$(\beta_0, \gamma_0) = (10^{-4}, 10^{-3})$

Before proto-PopⅢstar formation: $n=10^3$ -10^{19} cm^{-3}

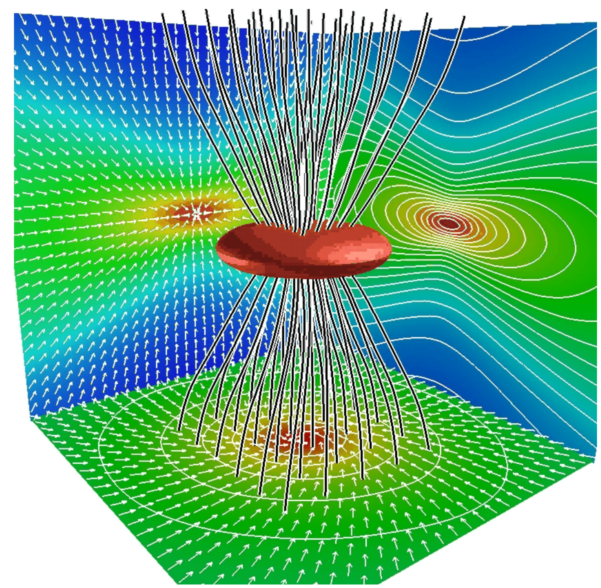


After Protostar Formation: Jet Driving

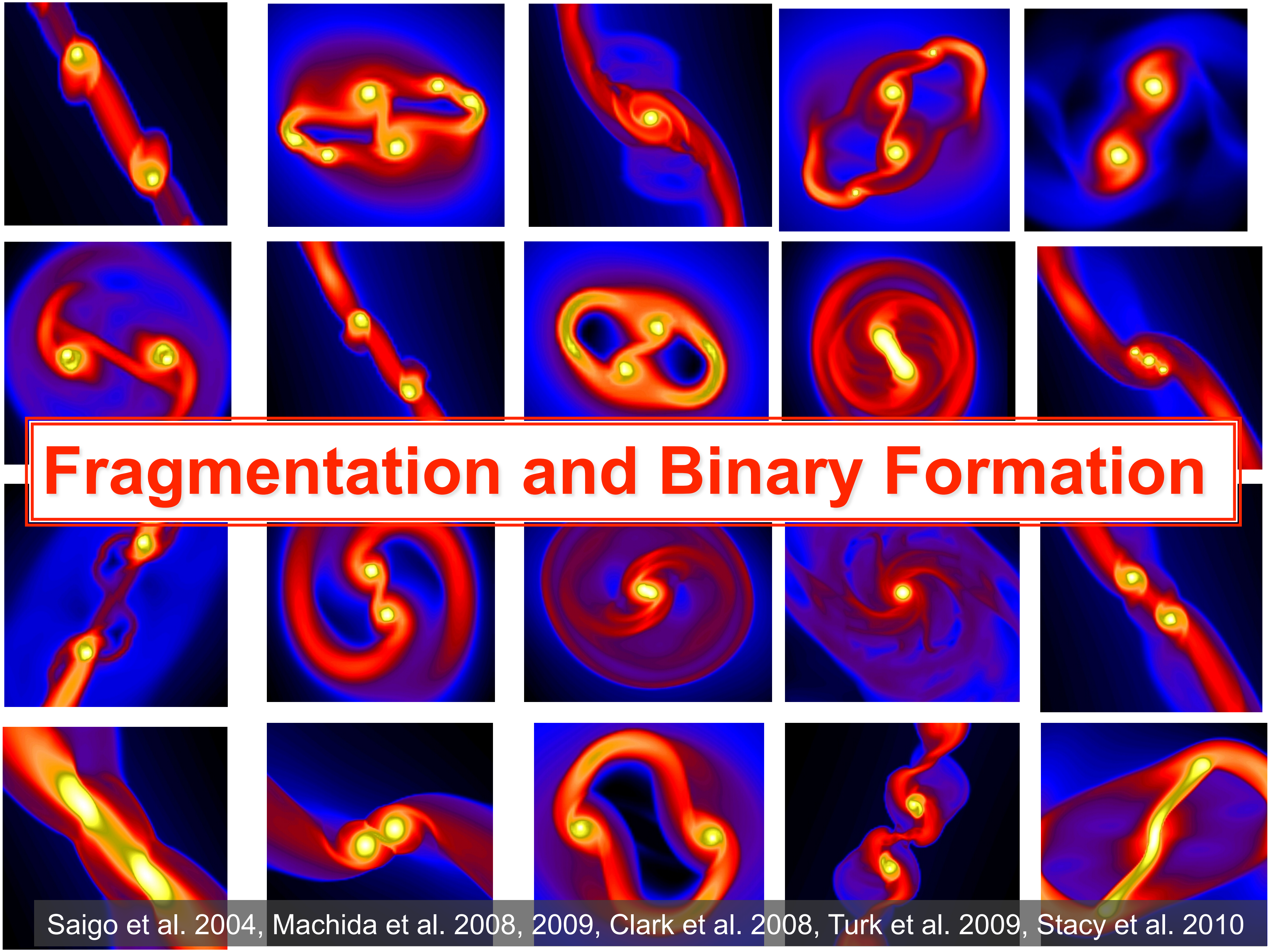


Jet Driving

- Proto Pop Ⅲ forms at n~10^{21} cm^{-3}
- Strongly twisted lines ($\tau_{rot} << \tau_{collapse}$)
- Protostellar Jet is driven from proto-Pop Ⅲ star
- v_{jet} ~100 km/s, clear bow shock, good collimation



Fragmentation and Binary Formation



Saigo et al. 2004, Machida et al. 2008, 2009, Clark et al. 2008, Turk et al. 2009, Stacy et al. 2010

After Protostar Formation: Fragmentation

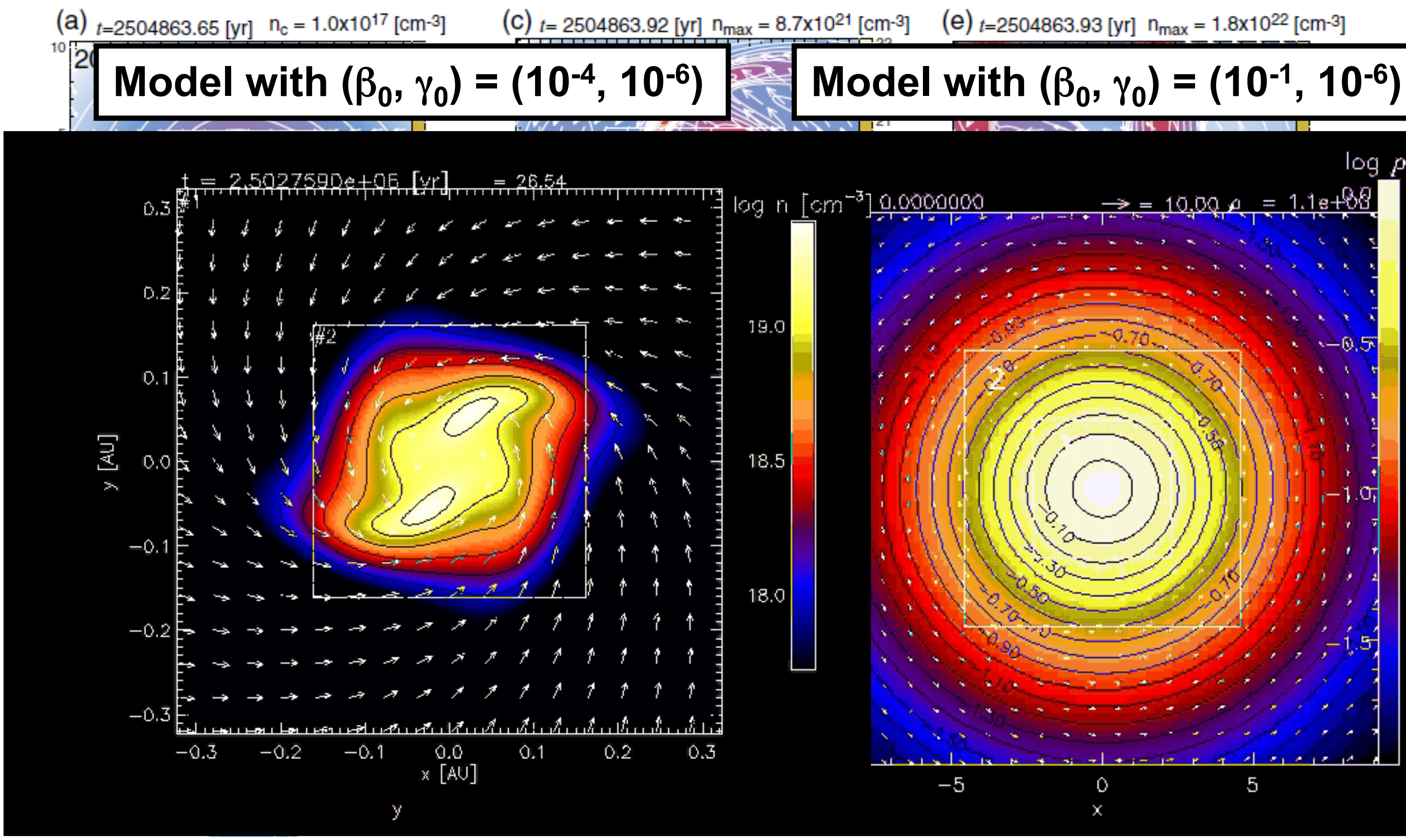
Fragmentation

Rotation dominated model: $\beta_0 > \gamma_0$

$(\beta_0, \gamma_0) = (10^{-4}, 10^{-6})$

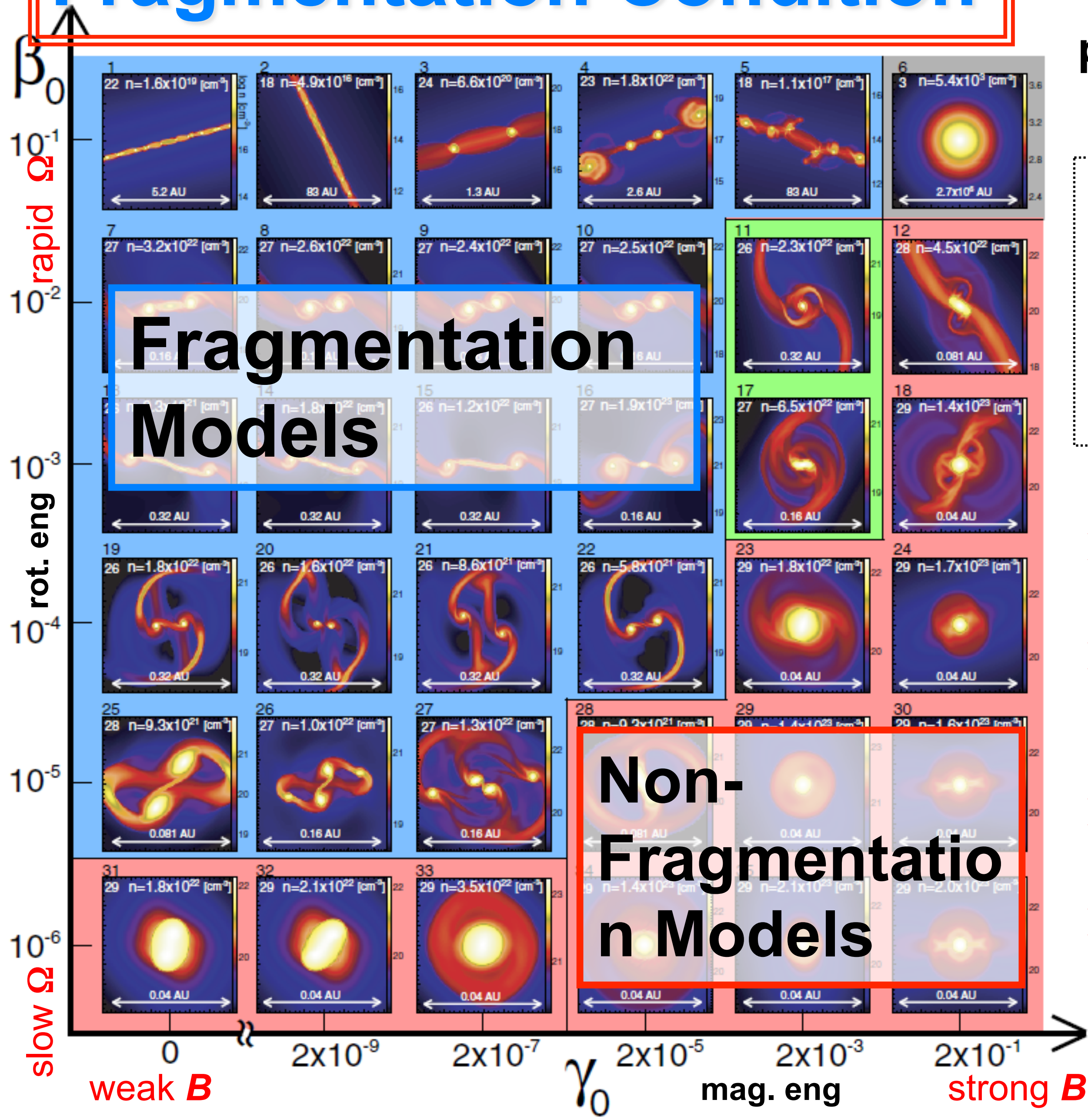
Model with $(\beta_0, \gamma_0) = (10^{-4}, 10^{-6})$

Model with $(\beta_0, \gamma_0) = (10^{-1}, 10^{-6})$



β_0: rot. eng, γ_0: :mag. eng

Fragmentation Condition



Final States on the z=0 plane against γ_0 and β_0

(Results of 36 models)

Background Colors

- **Blue: Fragmentation model**
- **Red: Non-fragmentation model**
- **Green: Merger model**
- **Gray: non-collapsing model**

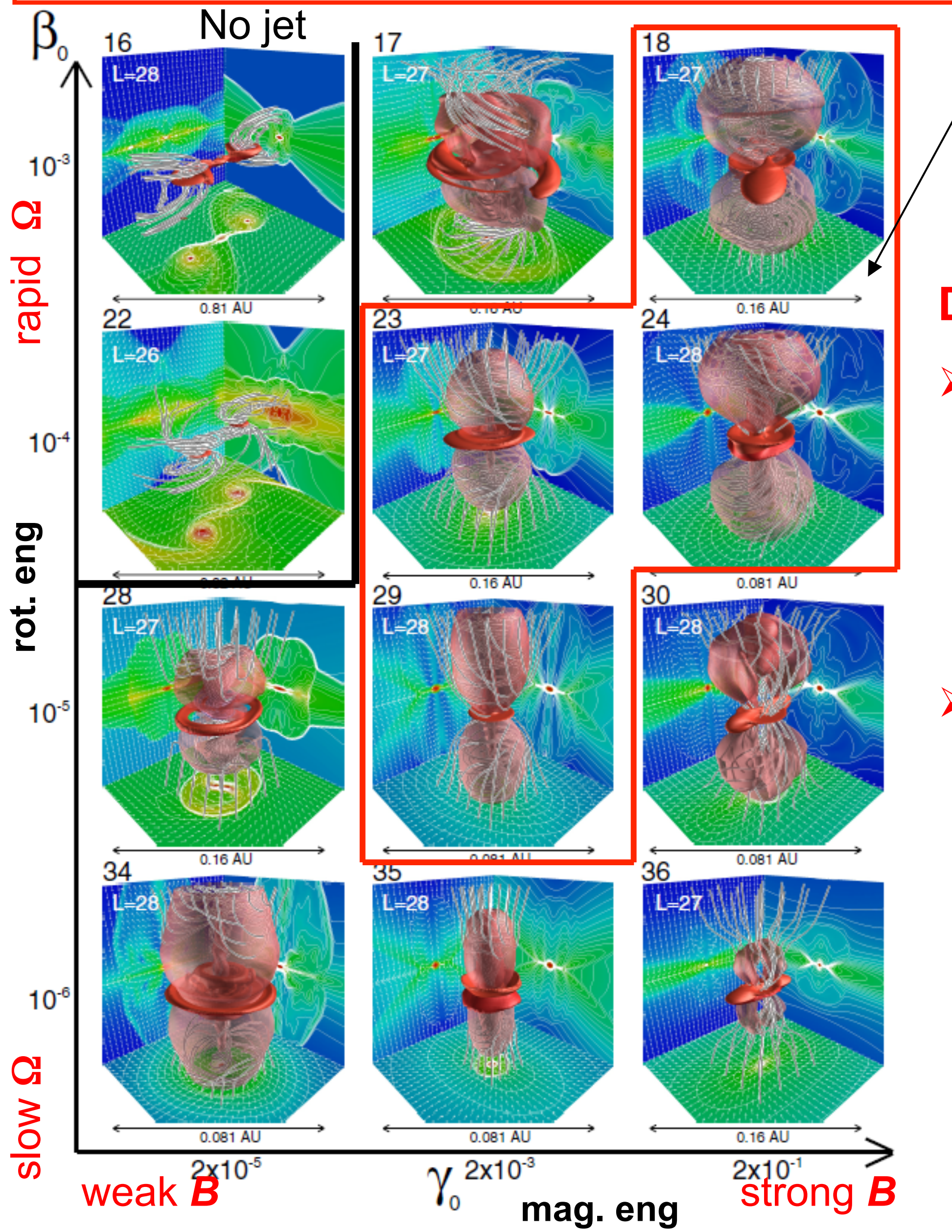
- Fragmentation occurs in model with large β_0 but small γ_0
- *Rotation promotes, but mag. field suppresses fragmentation (Klessen's Talk)*
- **Pop Ⅲ binary**: Cloud with large β_0 and small γ_0
- **Single Pop Ⅲ star** Cloud with small β_0 and large γ_0

β_0: rot. eng, γ_0: :mag. eng

Jet Driving Condition

Final States in 3D view against γ_0 and β_0

(Results of 12 models)



Driving Condition for Pop Ⅲ Jet

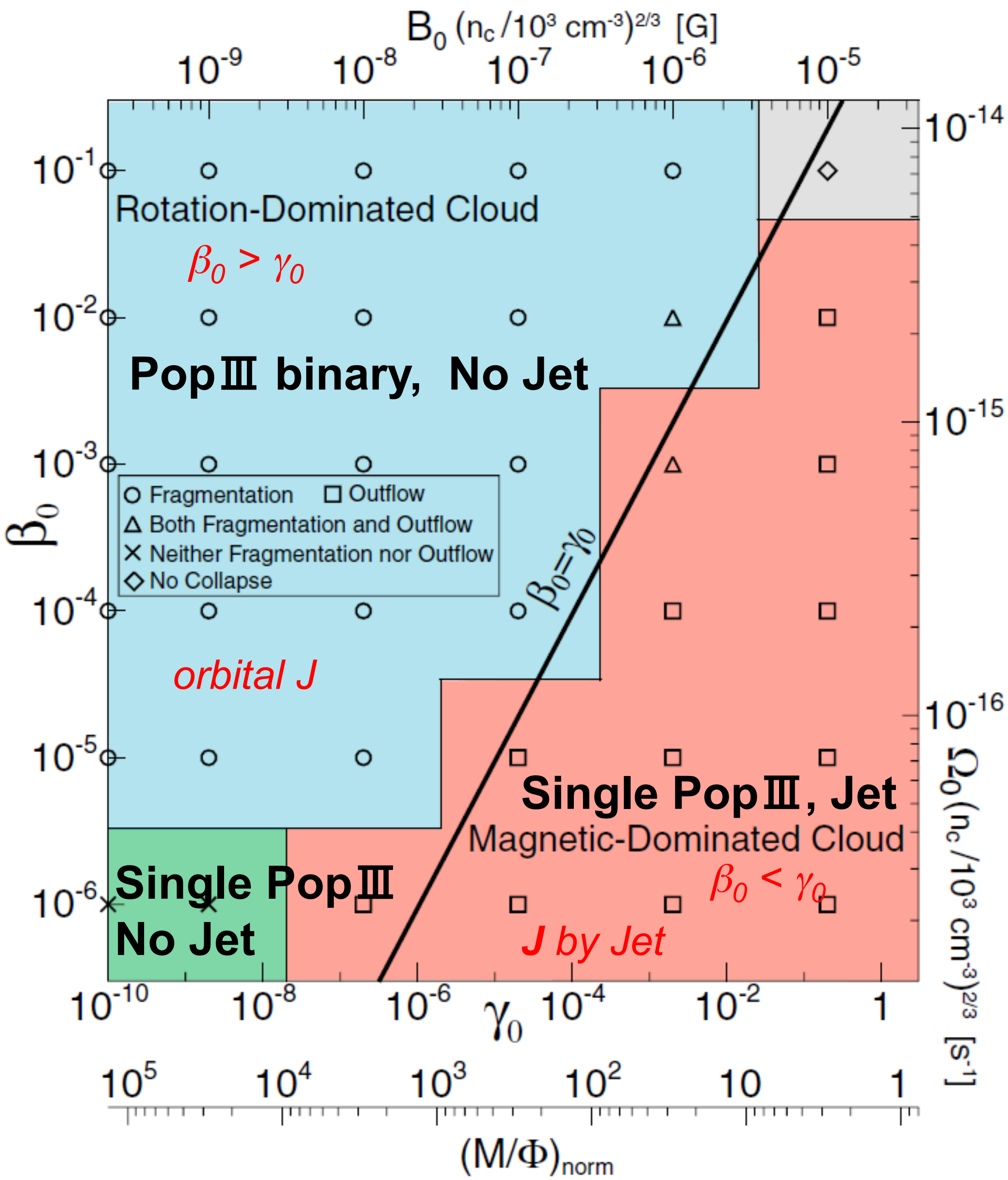
➤ ***Moderate Rotation Speed***

- ◻Rapid Rotation: fragmentation, inclined field lines, ***B***⊥Ω
- ◻Slow Rotation: ***B*** lines are not twisted

➤ ***Moderate strength of the Magnetic field***

- ◻Strong Field: Ω is removed by Magnetic Braking
- ◻Weak B: weak Lorentz force

Final Fate of Primordial Magnetized Clouds



Future evolution of PopⅢ

- **Rotation Dominated Cloud**
  - Massive PopⅢ Binary, Binary B.H.
  - Metal free low-mass star, and B.D. : fragments are ejected by 3 body interaction
- **Magnetic Dominated Cloud**
  - v_{jet} ~ 100-1000 km/s (large mass, dM/dt)
  - Disturbance of ISM: ***shock, turbulence***
  - Next generation star formation

Summary

β_0: rot. eng, γ_{0}: mag eng

- To investigate the magnetic effect, we calculated the evolution of primordial clouds until proto-PopⅢ star formation (10^3 cm^{-3} < n < 10^{23} cm^{-3})

- **Magnetic field and Jet driving**
  - Magnetic field can affect the evolution of primordial cloud when **$\gamma_0 > 10^{-8}$**

    B > 10^{-9} G at n=10^3 cm^{-3} (primordial cloud)

    B > 5×10^{-13} G at n=0.01 cm^{-3} (ambient medium)

- **Fragmentation and binary formation** (See also Tan & Blackman 2004)
  - Magnetic field suppresses fragmentation, while Rotation promotes fragmentation
  - Binary Pop III star appears when $\beta_0 > \gamma_0$

- **Angular momentum Problem**
  - *With weak B*, excess angular momentum is distributed into orbital one
  - *With strong B*, Protostellar Jet and magnetic braking transfer ***J***

- Further long-term calculations are necessary to determine fates of jet and binary