Expected Observations of the Star Formation Process: Magnetic Field[1] and First Hydrostatic Core[2]

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Based on:

[1] Kataoka, Tomisaka, & Machida (2012; ApJ in press)
[2] Tomisaka & Tomida (2011; PASJ, 63, 1151)

Observational Visualization

- How is the simulation result observed ?

  This enables us to compare simulation with observation directly.

- Identification of a first hydrostatic core
  - Radiation MHD simulation of molecular core collapse (Tomida, KT+2011,2012).
  - Apply non LTE radiation transfer (MC method)
  - Identification of FC by radio molecular line obs.

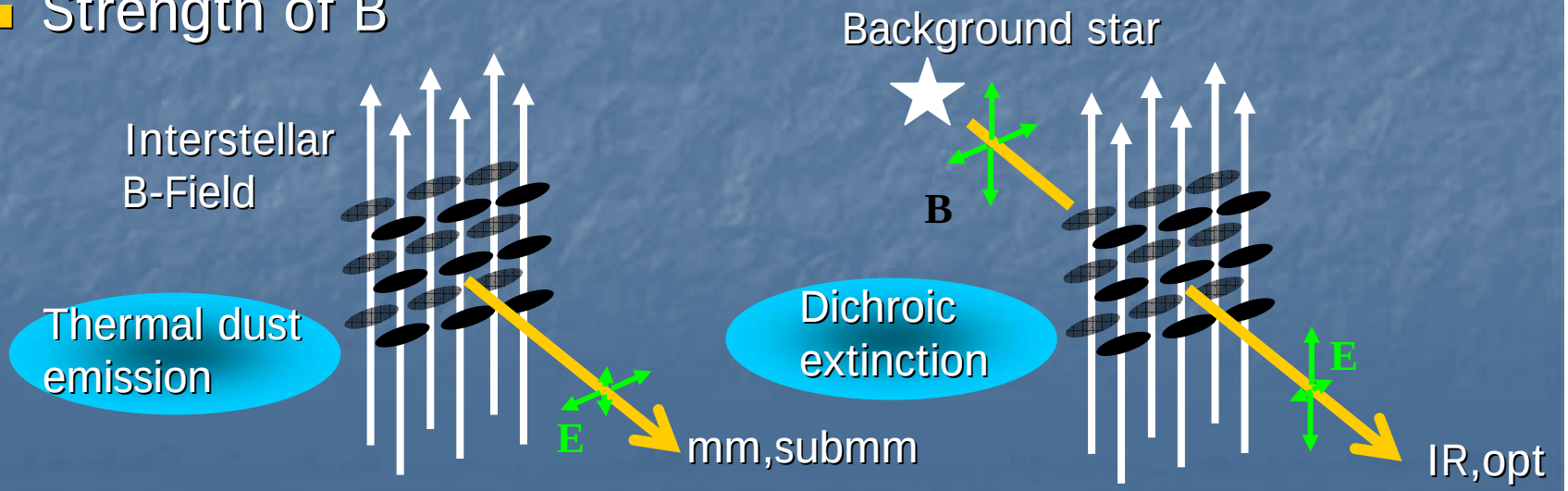
    KT & Tomida (2011)

- Configuration of B-field realized in star forming stage
  - Barotropic MHD simulation of grav. Contraction of molecular cores.
  - Sink cell method is applied for protostar phase.

    Kataoka, Machida & KT (2012; astro-ph this week)

Magnetic Field Observation

- Direction / Configuration← Linear Polarization
  - interstellar dust is aligned as its major axis is perpendicular to the interstellar magnetic field.
  - Polarization of thermal emission from interstellar dust➔ $E_{pol} \perp B_{ISM}$
  - Dichroic extinction leads ➔E_{pol} // B_{ISM}
- Zeeman splitting
  - Strength of B

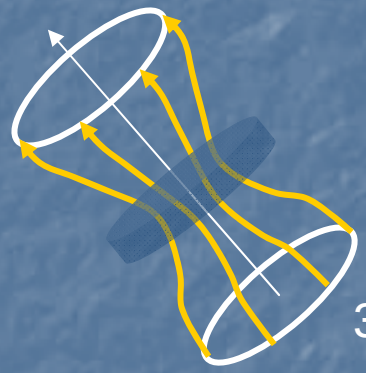


Hourglass B-Field

Polarization of dust thermal emission NGC1333 IRAS 4A

Girart + 2006

(1) Hourglass shape B-field



(2) Polarization degree is low in the direction of major axis of the disk.

Goncalves + 09

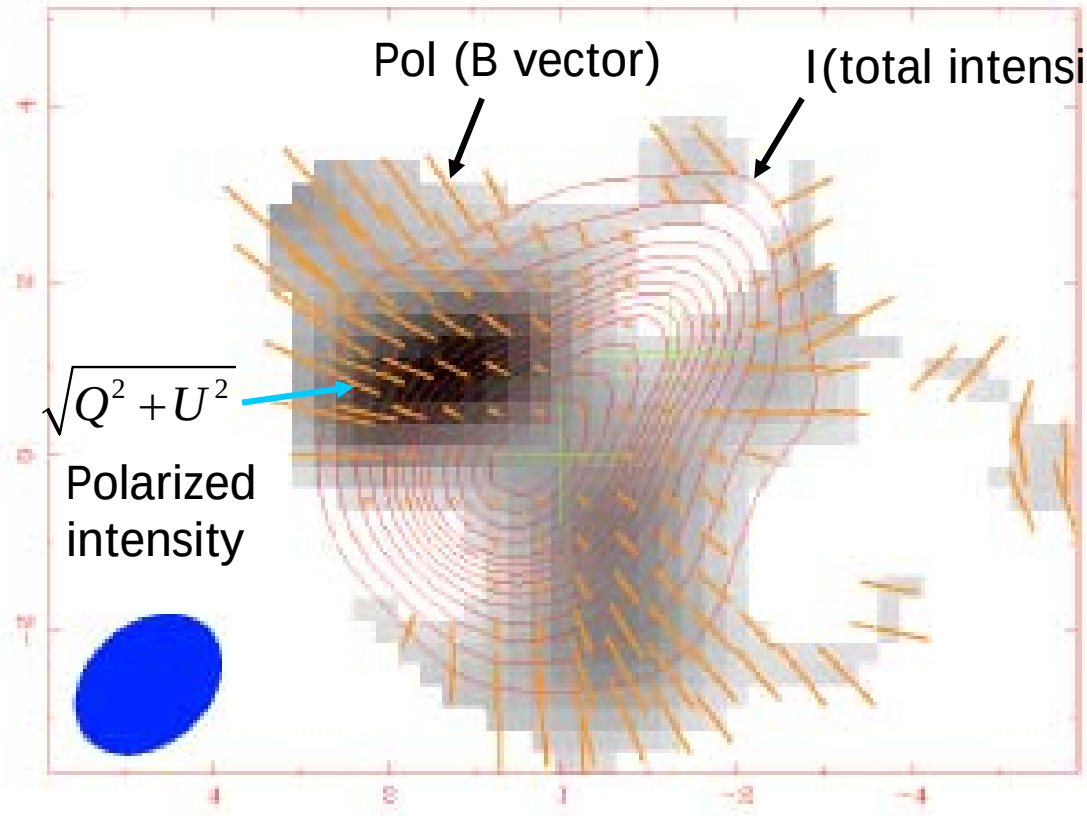
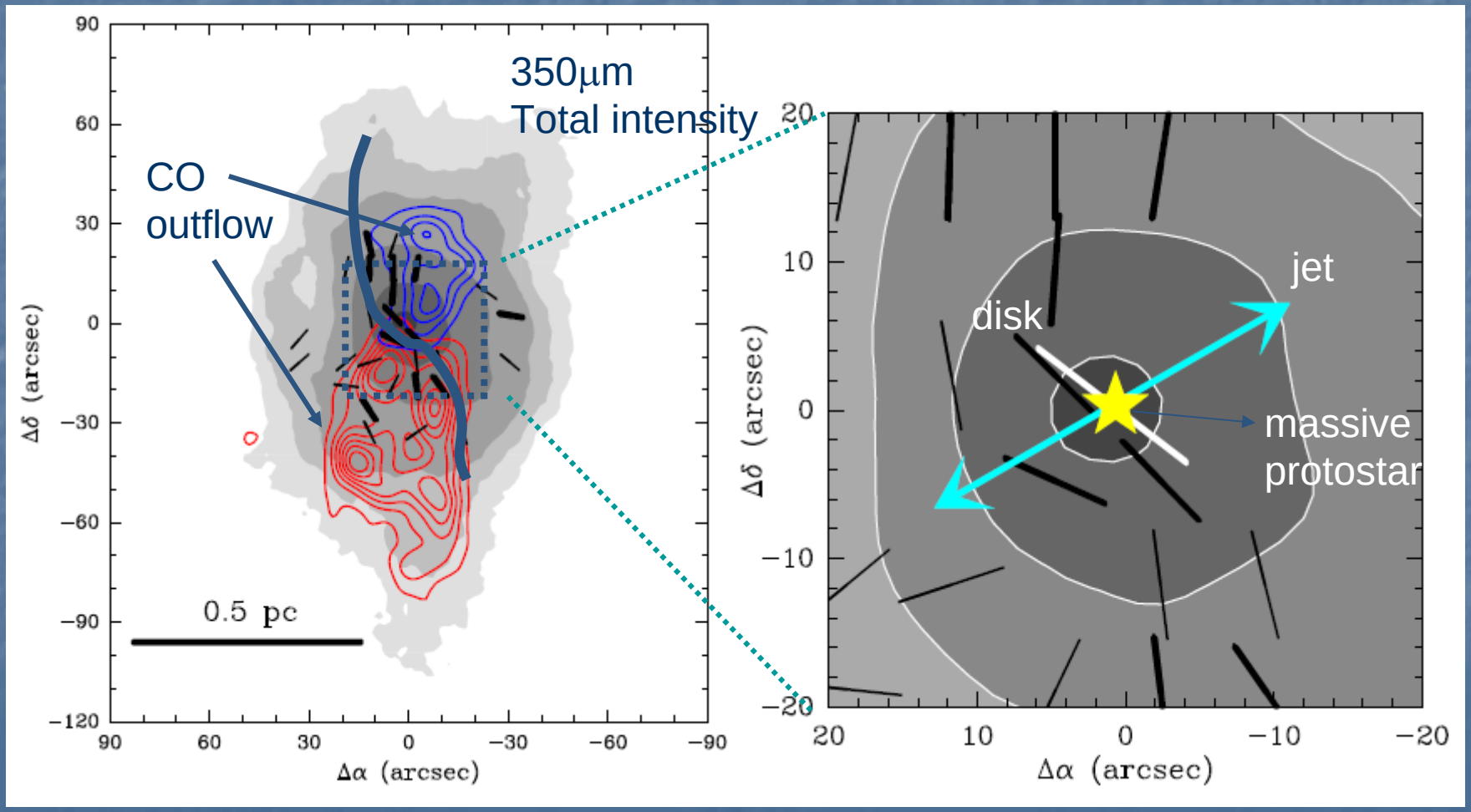


Fig. 1. Map of NGC 1333 IRAS 4A, from GRM06. Contours show the continuum emission at 877 μm, bars indicate the direction and degree of polarization (magnetic field vectors), and the color map shows the polarized intensity. At the distance of 300 pc, 1″ corresponds to 300 AU.

I S-shaped Magnetic Field hp
IRAS0126+4104

Shinnaga + 2012

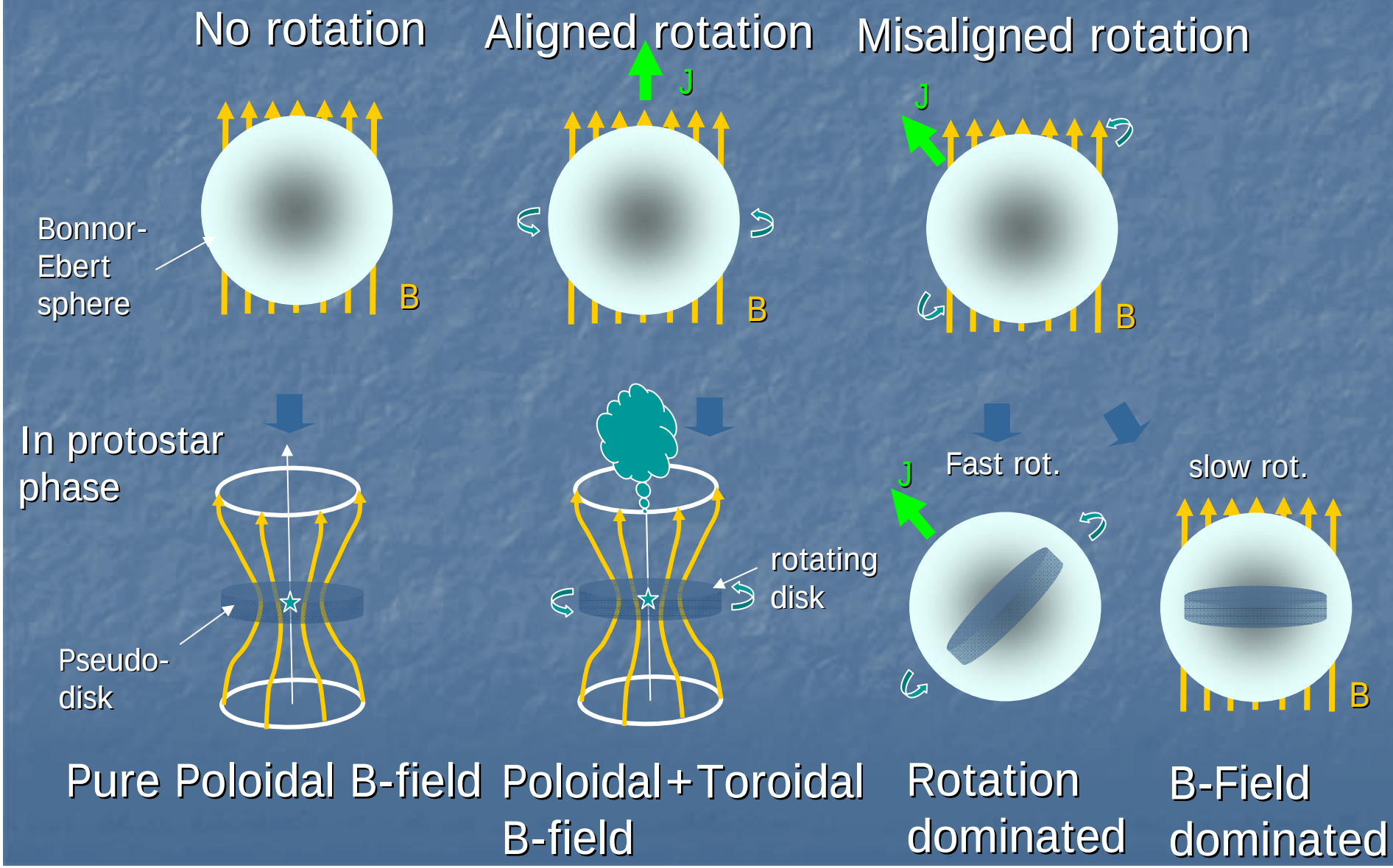
Polarization E-vector



- 2D polarization is a consequence of the 3D configuration of B-field.
- To study B-field from polarization, we have to solve ‘inverse problem’ 2D → 3D. However, this is hard to solve.
- We perform MHD gravitational collapse simulation. Then, evolution of polarization pattern is calculated for each snapshot.

Cf. Frau, P., Galli, D. & Girart, J. M. 2011
Padovani, M. et al. 2012

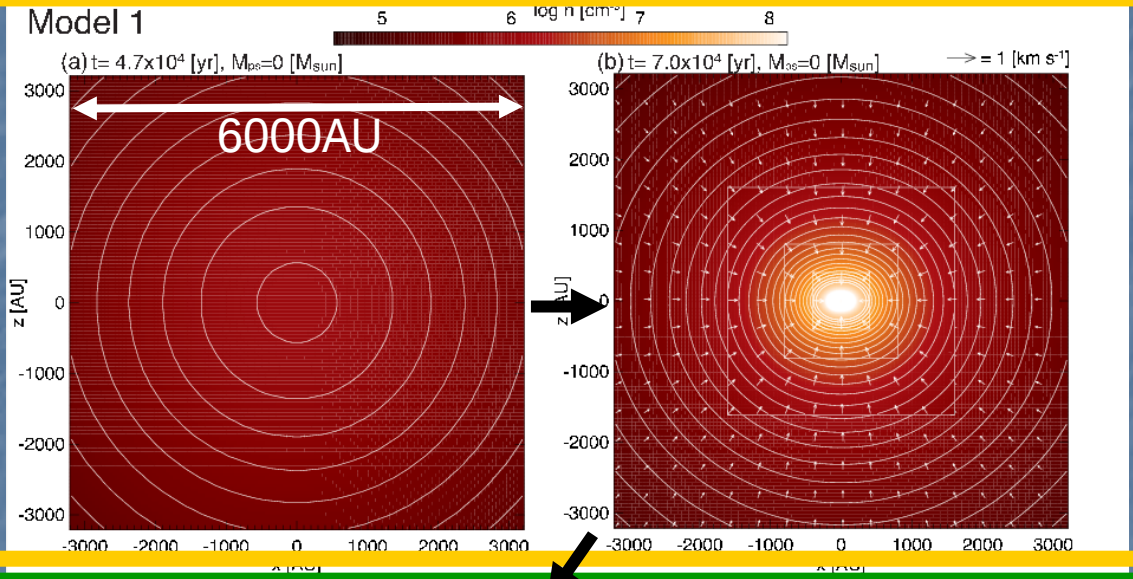
Initial models



No Rotation Model

Early Phase of Prestellar Stage

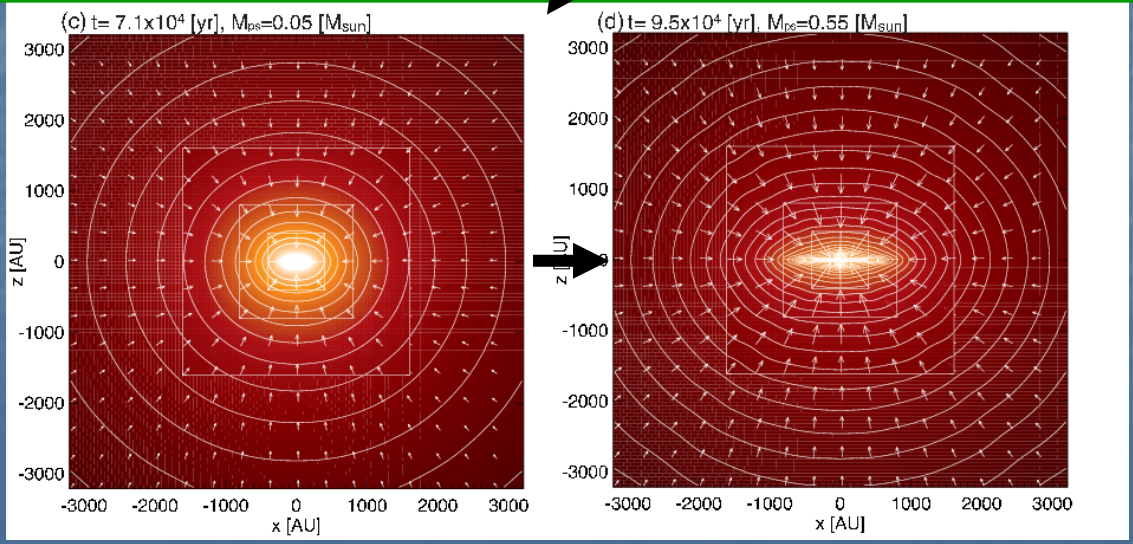
$M_{\rm cl} \simeq 1.1 M_{\odot}$



Late Phase of Prestellar Stage

Early Phase of Protostar Stage

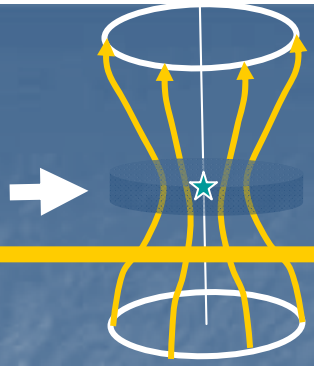
$M_{*} \simeq 0.05 M_{\odot}$



Late Phase of Protostar Stage

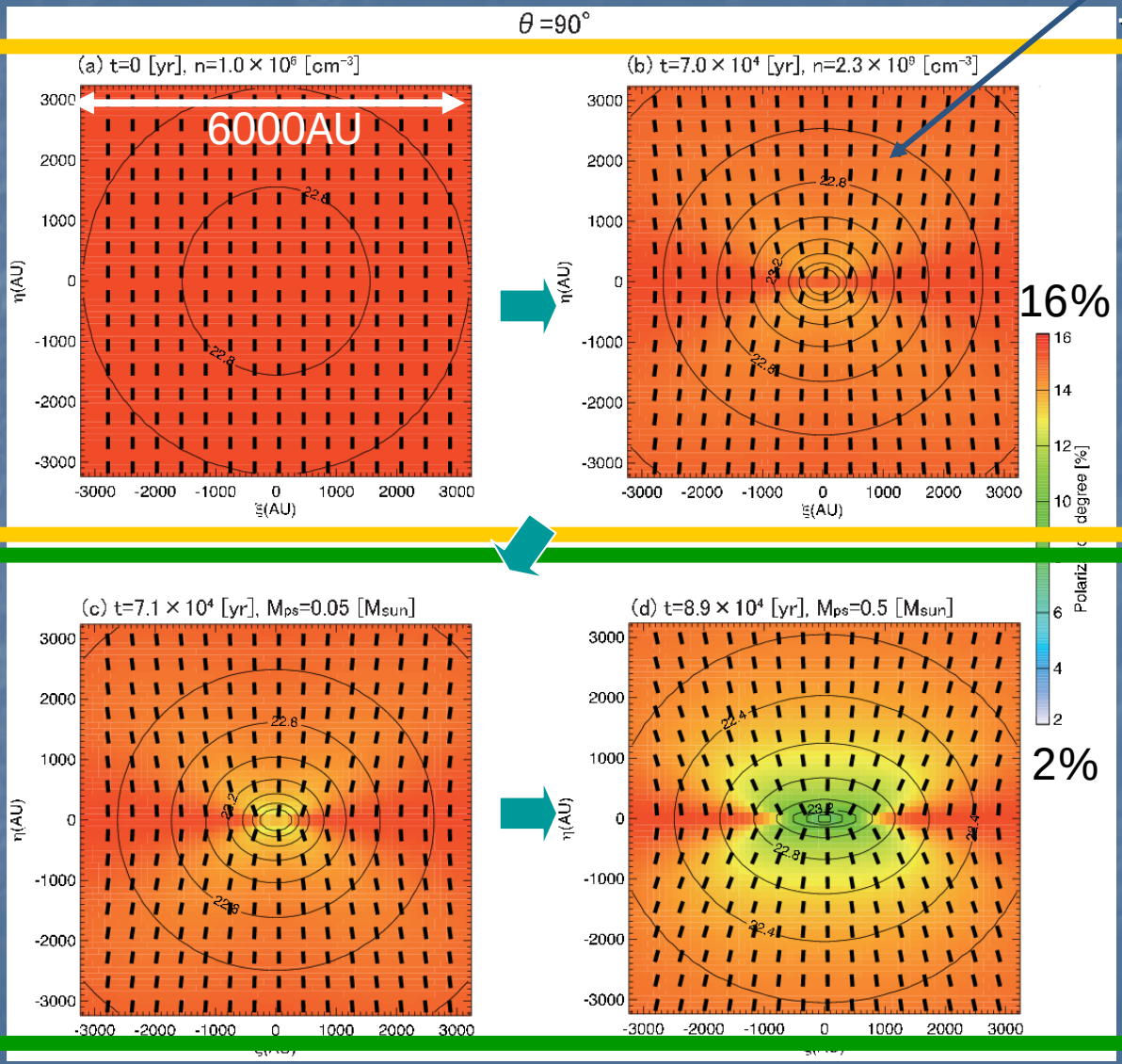
$M_{*} \simeq 0.55 M_{\odot}$

Edge-on Polarization



Early Phase of Prestellar Stage

$M_{\rm cl} \simeq 1.1 M_\odot$



Contour: Total intensity /

Late Phase of Prestellar Stage

Polarization degree

Early Phase of Protostar Stage

$M_* \simeq 0.05 M_\odot$

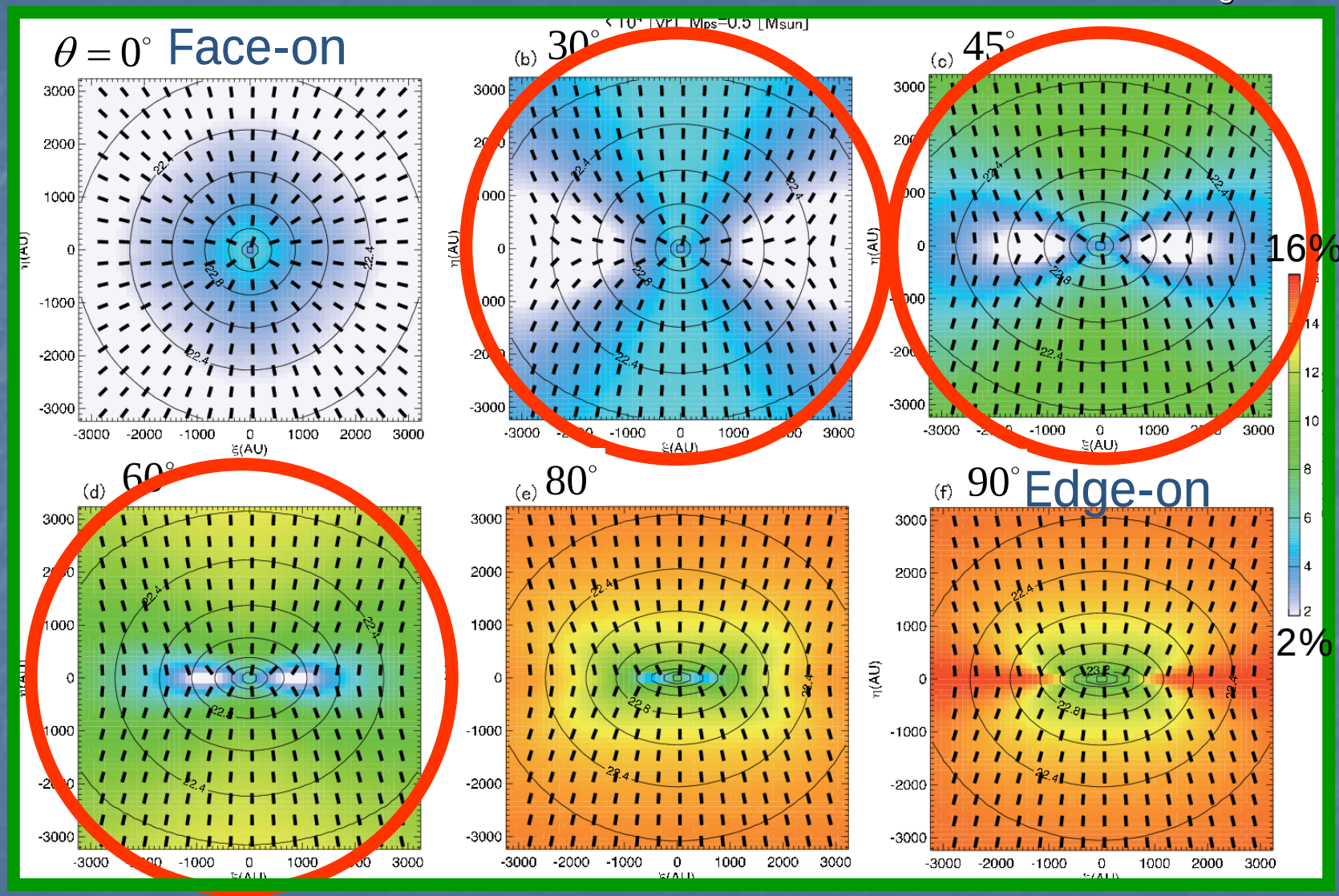
Late Phase of Protostar Stage

$M_* \simeq 0.55 M_\odot$

Hourglass type pol. pattern

Effect of Inclination

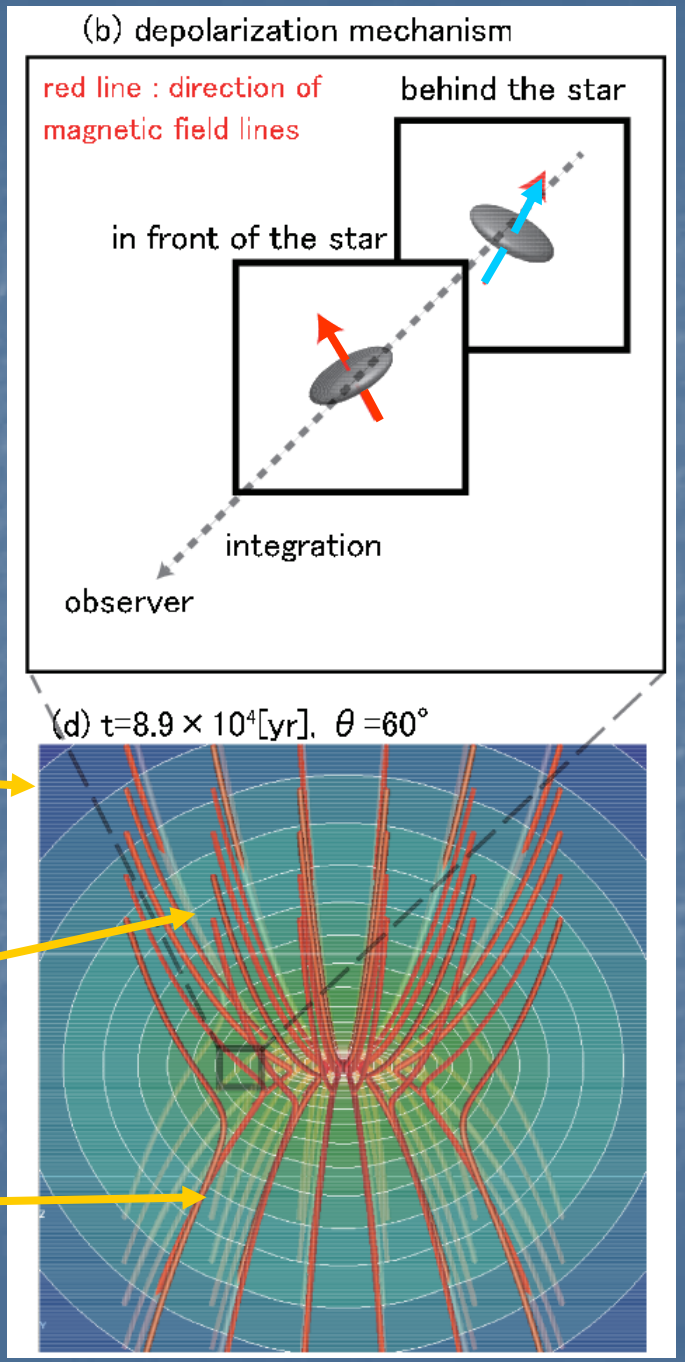
Late Phase of Protostar Stage



Low polarization degree region extends in the direction of major axis of the total column.

Depolarization

(1)Foreground and background B-field lines intersect each other with ~90deg.
(2)Dust alignment is perpendicular.
(3)This leads low polarization.



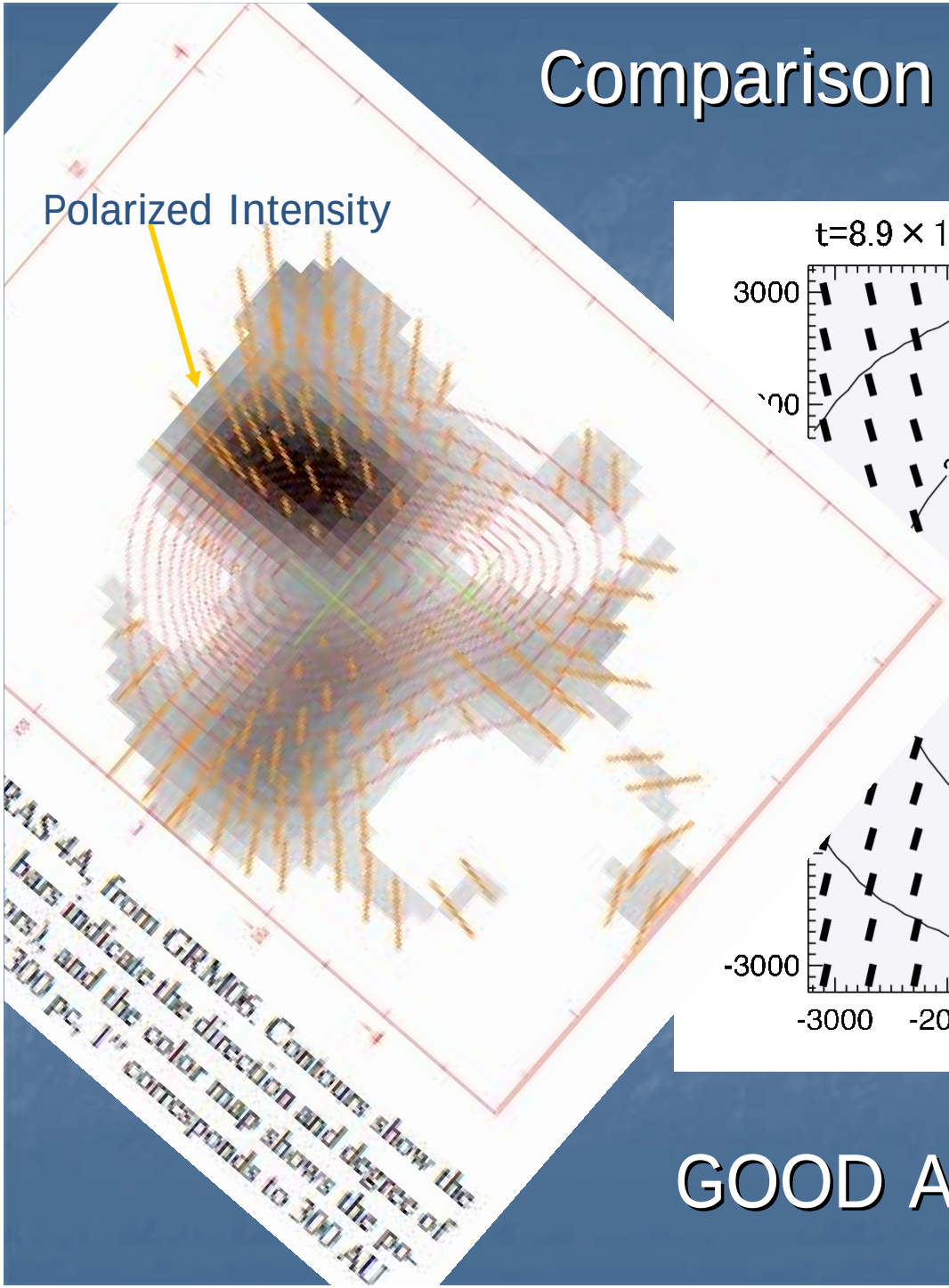
3D View of B-Field
θ=60deg

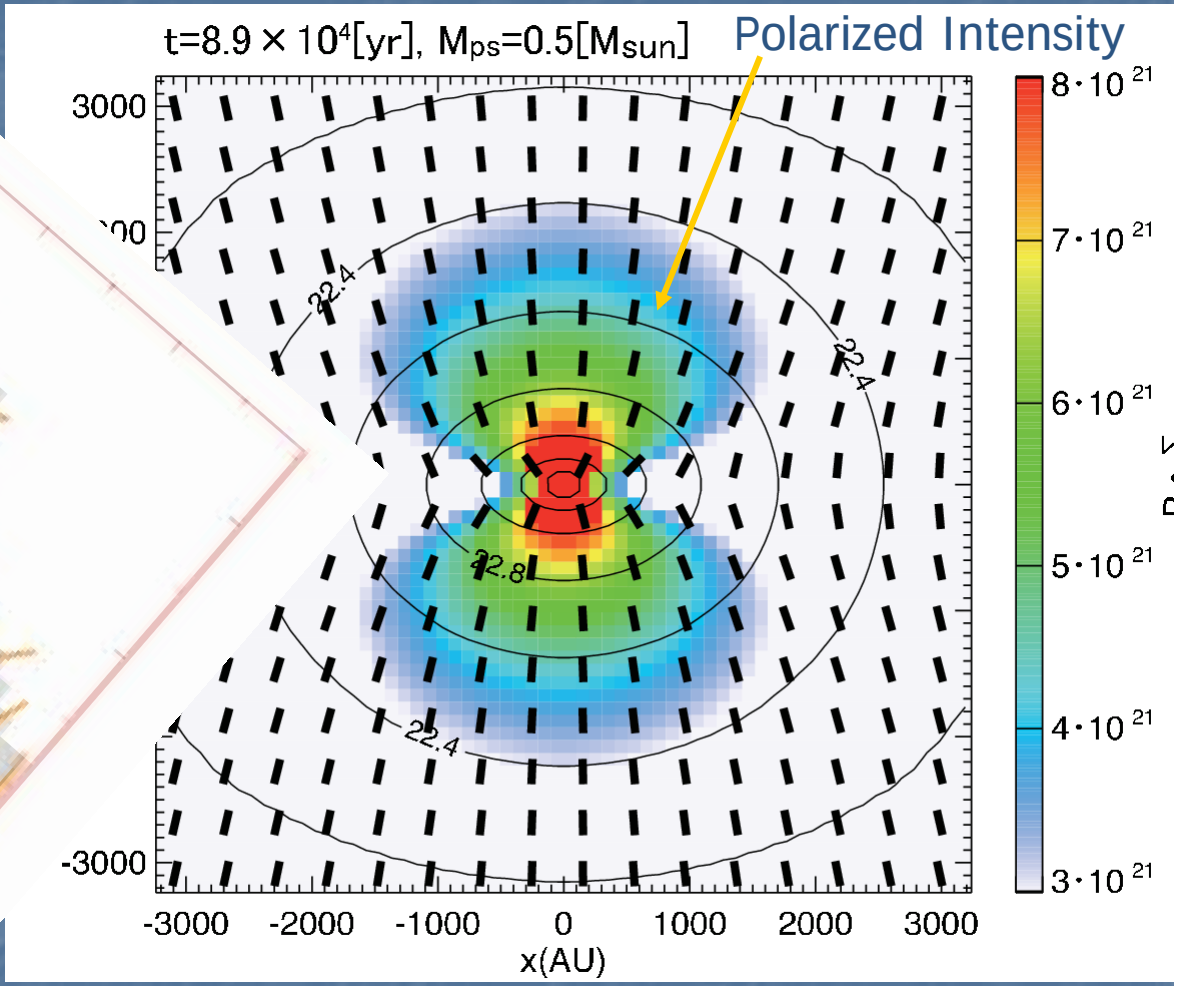
Rear-side B-Field

This does not occur for edge-on.

Front-side B-Field

Comparison with Observation





GOOD AGREEMENT

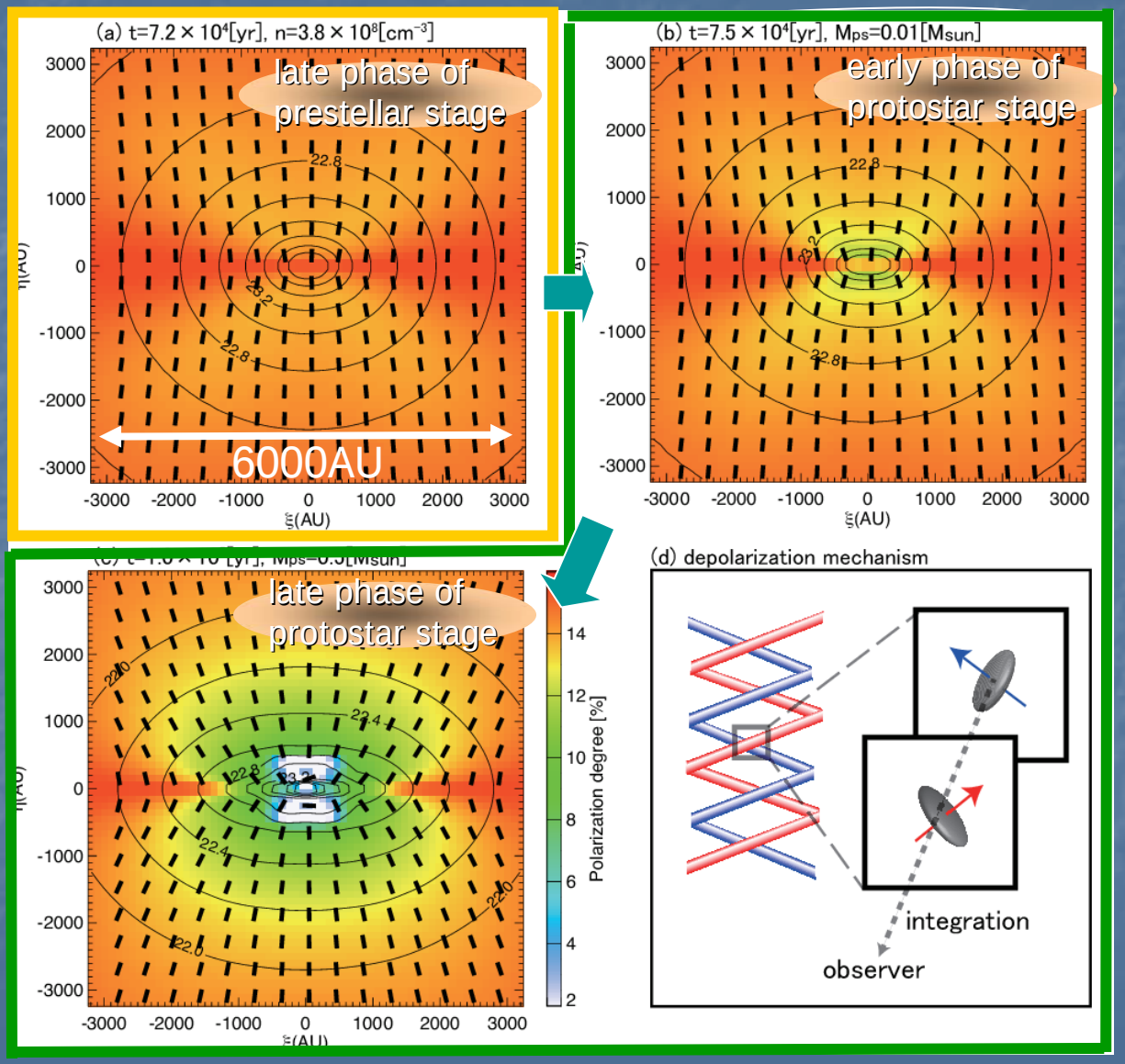
Rotating Case = Poloidal + Toroidal B-Field

(1) Disk rotation amplifies toroidal B-field from poloidal B-field.

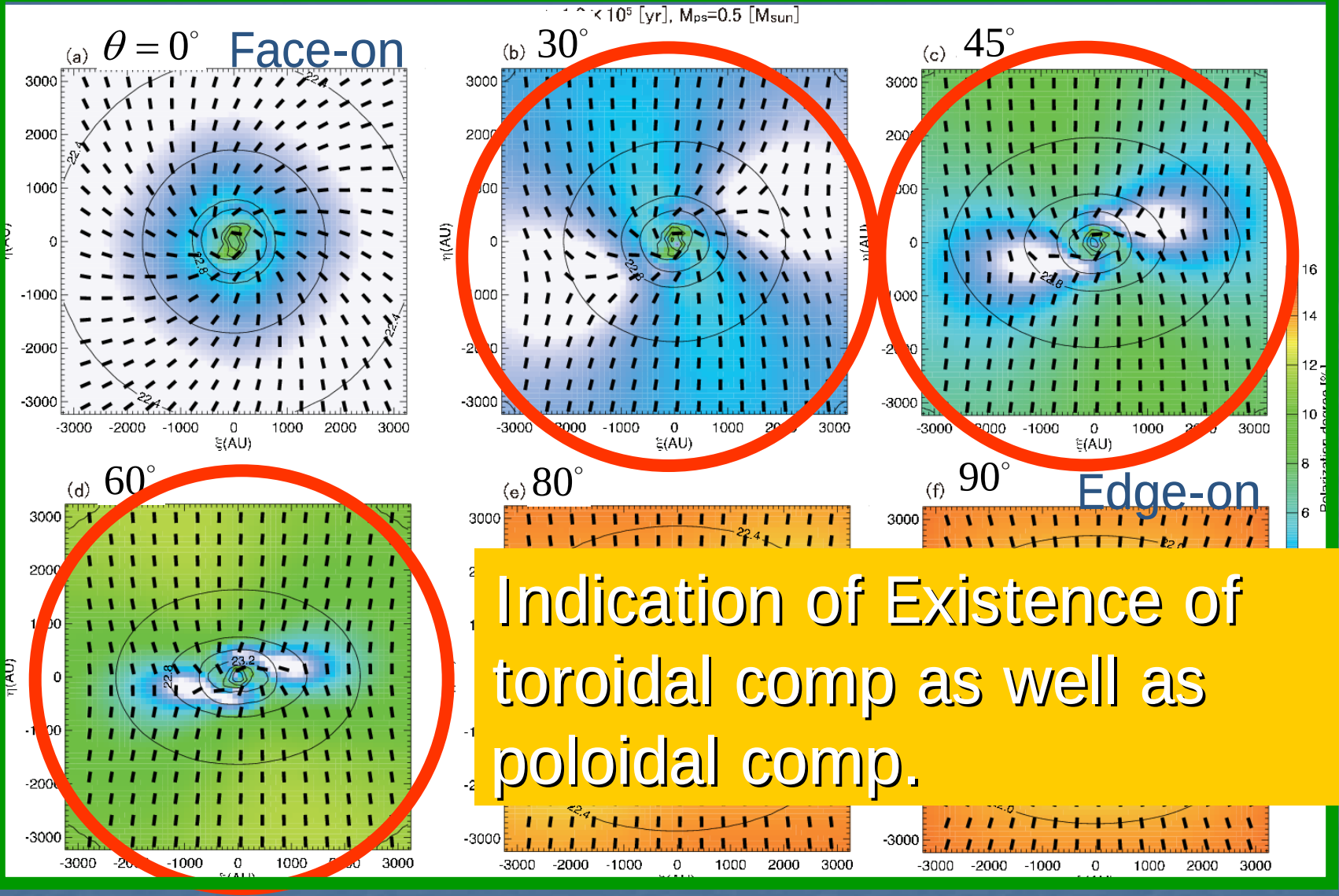
(2) B-field is composed of poloidal + toroidal components above the disk.

(3) When poloidal and toroidal components are approx. equal, cancelation occurs between fore and rear side of B-field.

(4) Low polarization regions and horizontal direction pol. are made above and below the disk.



Effect of Inclination Angle



Indication of Existence of toroidal comp as well as poloidal comp.

Low polarization degree regions extend in a point-symmetric way rather than the line-symmetric way.

Why do I emphasize the toroidal B-Field?

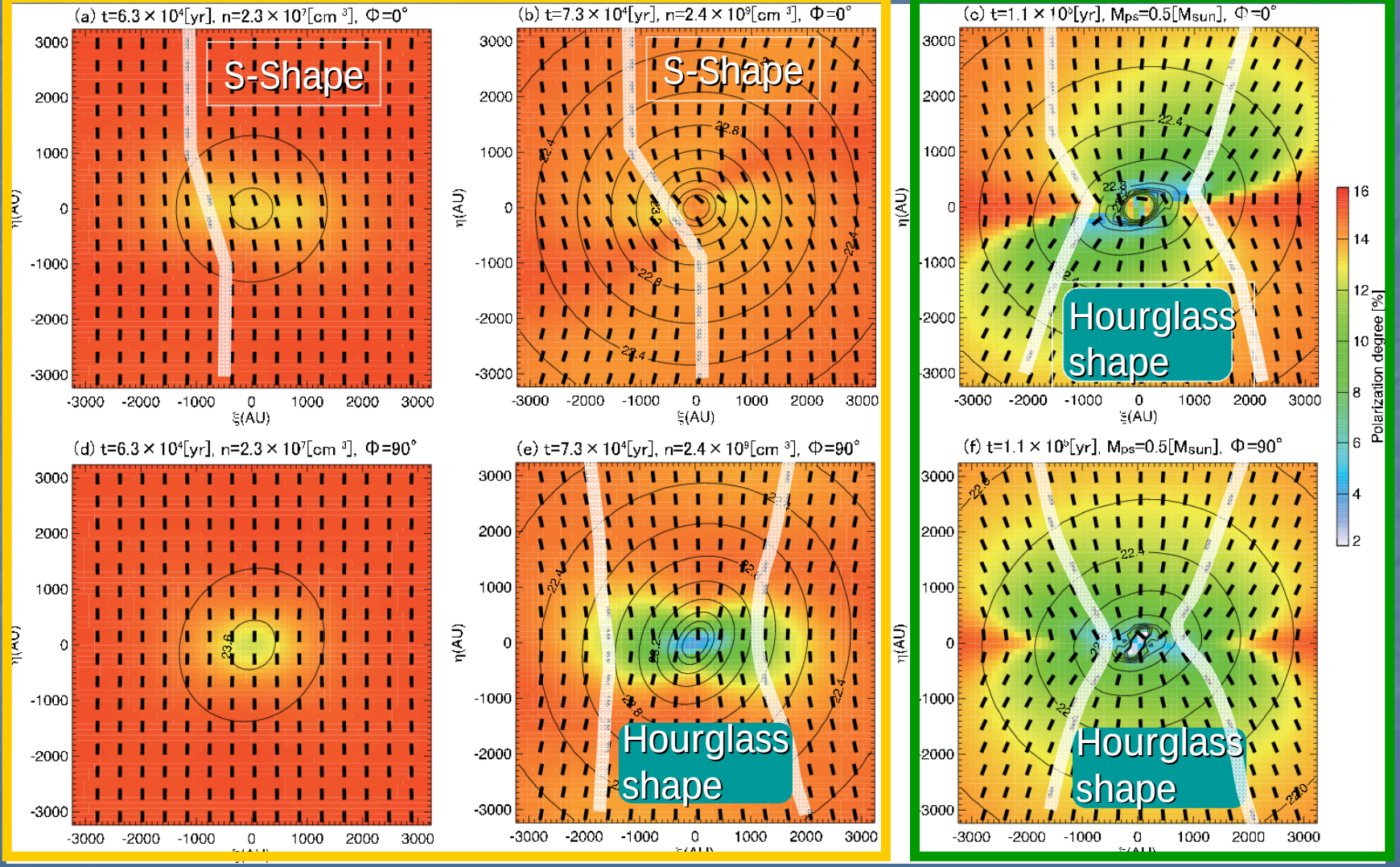
- To extract angular momentum, F_ϕ is needed.
- Lorentz jxB force in ϕ-direction comes from poloidal current Jp and poloidal B-field Bp.
- Jp comes from toroidal B-field B_ϕ.
- To extract angular momentum, both components of Bp and B_ϕ are important.

Misaligned Rot.-Dominated Model

early phase of prestellar stage → final phase of prestellar stage → Late phase of protostar stage

From X-axis

From Y-axis

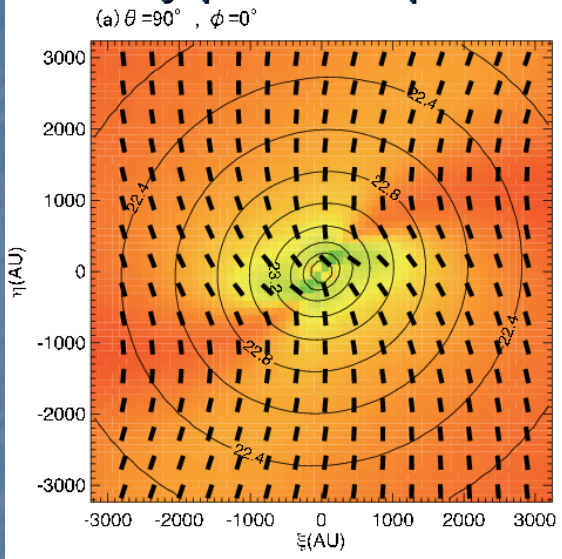


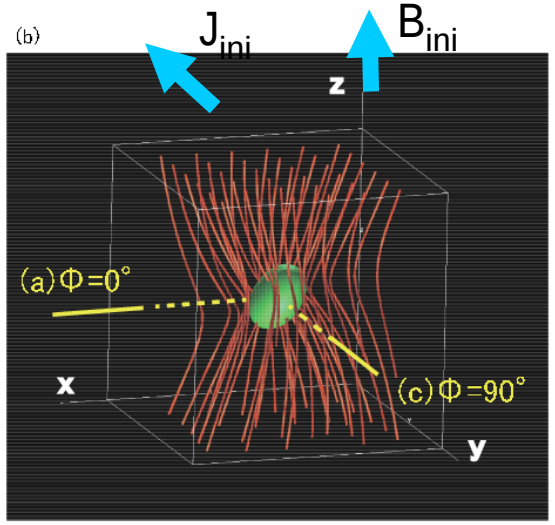
Another configuration S-shape appears as well as houtglass.

Hourglass axis and disk minor axis do not coincide.

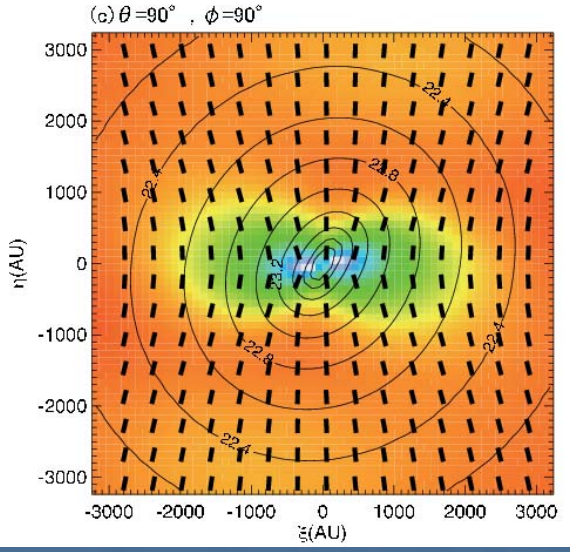
3D Configuration and Polarization

Early protostar phase $t=7.7\times10^4$[yr], $M_{ps}=0.1[M_{sun}]$



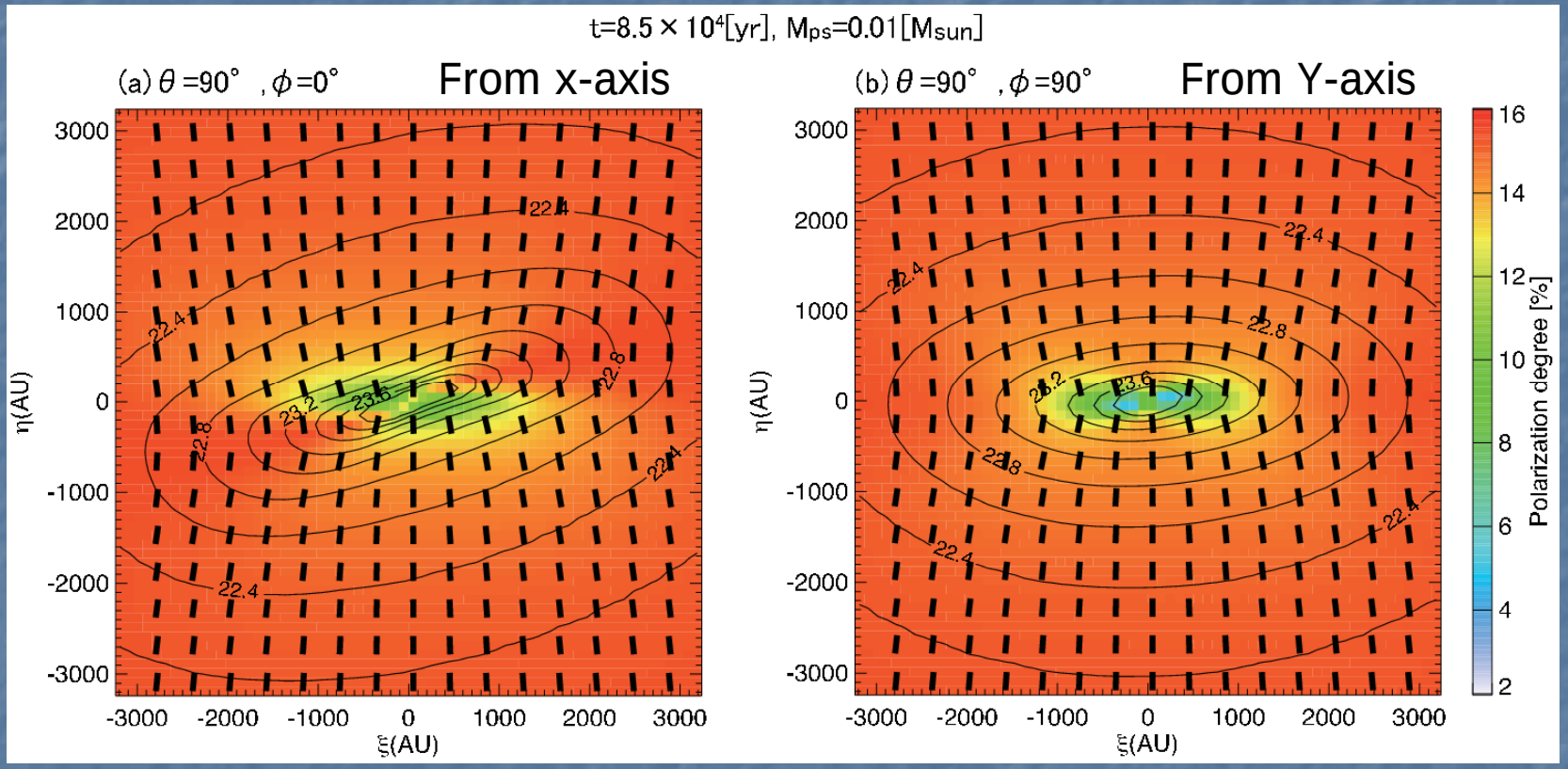


(1) A disk is made perp to the rotation axis.
(2) Viewing from the x-axis, S-shape pol. pattern is observed.
(3) Viewing from the y-axis, hourglass-shape pol. pattern is seen. But disk is inclined.



Misaligned Mag.-Dominated Model

The early phase of protostar phase



In both directions, an hourglass type polarization pattern is observed, even in the early phase of protostar phase. Magnetic axis perp to the disk.

Summary

- Linear polarization of thermal dust emission is calculated for gravitational collapse.
- Poloidal field gives hourglass shape.
  - Depolorization occurs in the direction of major-axis of the disk.
- Rotation amplifies toroidal B-field
  - Identification of toroidal is explored;
  - depolarization occurs just below/above the disk.
  - point-symmetric polarization degree distribution.
- In misaligned case, not only hourglass shape but also S-shape pol. pattern is expected, especially in rotation-dominated case
  - In B-dominated case, we expect hourglass shape.