KOGAKUIN UNIVERSITY

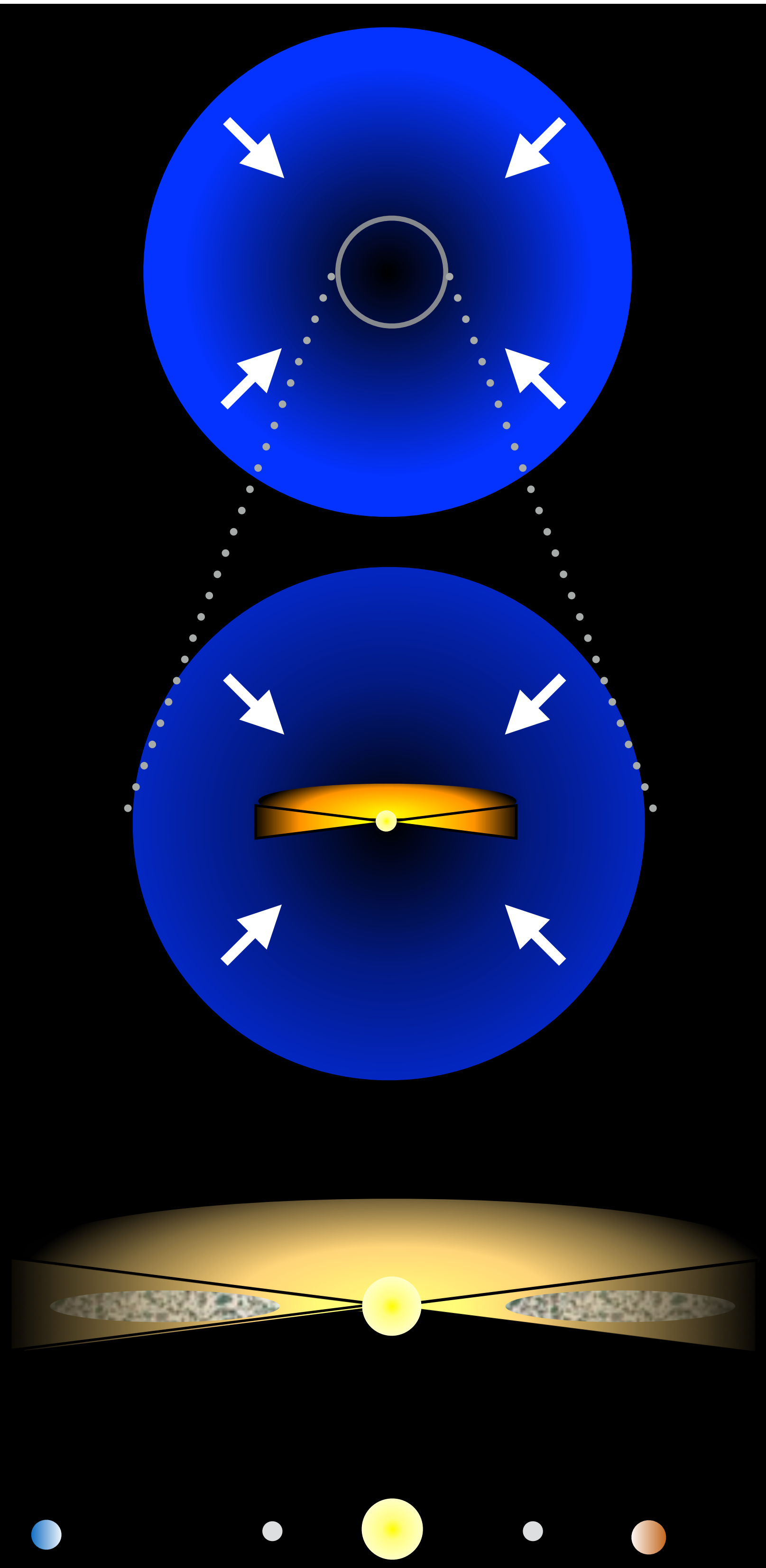
国立天文台 NAOJ National Astronomical Observatory of Japan

分子雲コアの角運動量・磁場構造と原始惑星系円盤の形成

Angular momentum and magnetic field structure of cloud cores and formation of protoplanetary disks

Sanemichi Takahashi
(Kogakuin University/NAOJ)

Formation and Evolution of Protoplanetary Disks



Gravitational collapse of cloud core

Formation of protostar
and protoplanetary disks

Dust grows in the disk.

Planet formation

Angular momentum problem

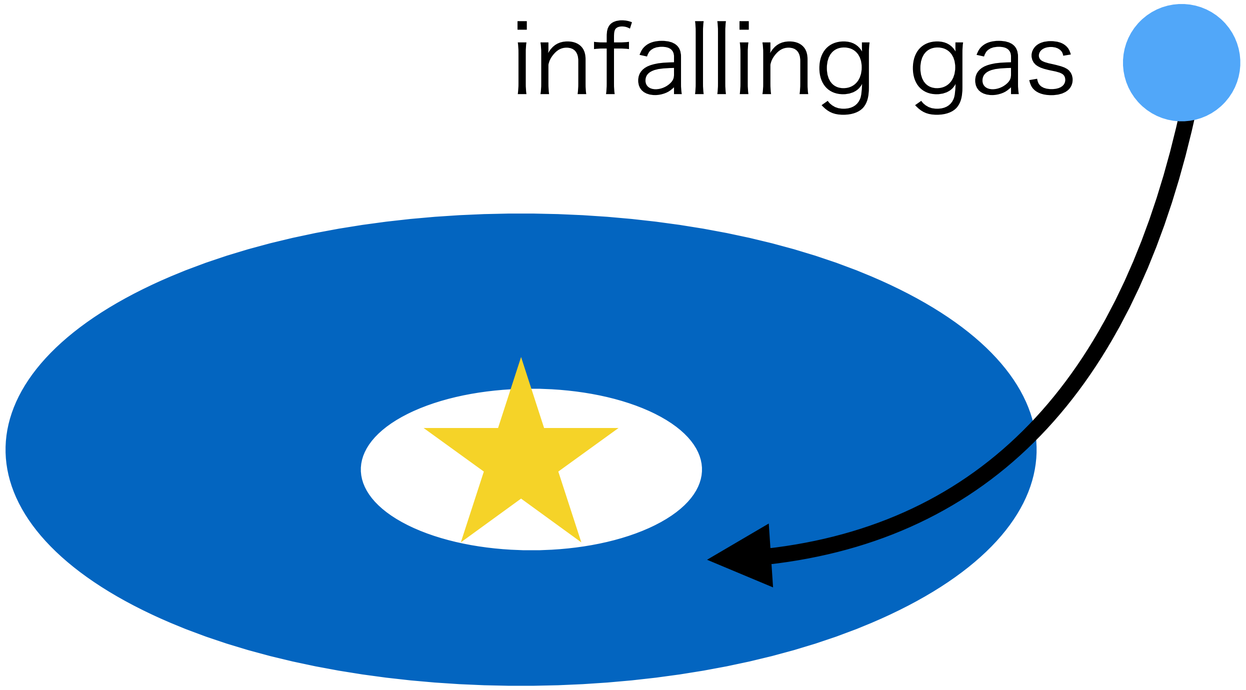
Assuming cloud core mass = Msun, r=0.1pc,
angular velocity 0.3 km s^{-1} pc^{-1}

⇒ centrifugal radius ~400 au

Gas cannot collapse to the central star directory

Gas make the **disk** and accrete onto the star due to the angular momentum redistribution in (or out of) the disk.

Angular momentum of core is important star, disk, and planet formation.



Outline

- Angular momentum of cloud cores
- Collapse of cloud cores and disk formation
    - without magnetic field
    - with magnetic field
- Analytic model of collapse of the cloud core

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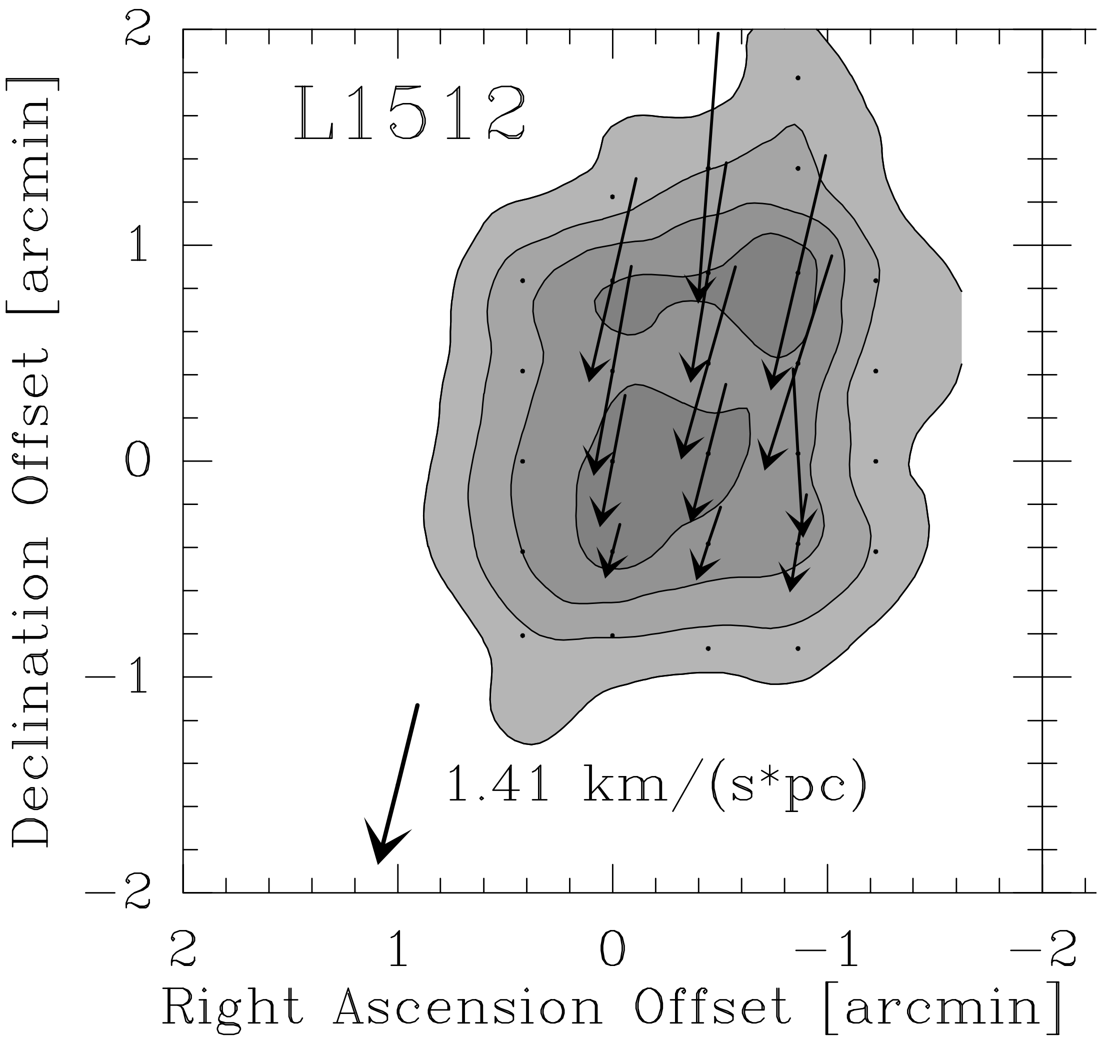
Rotation Velocity Profile

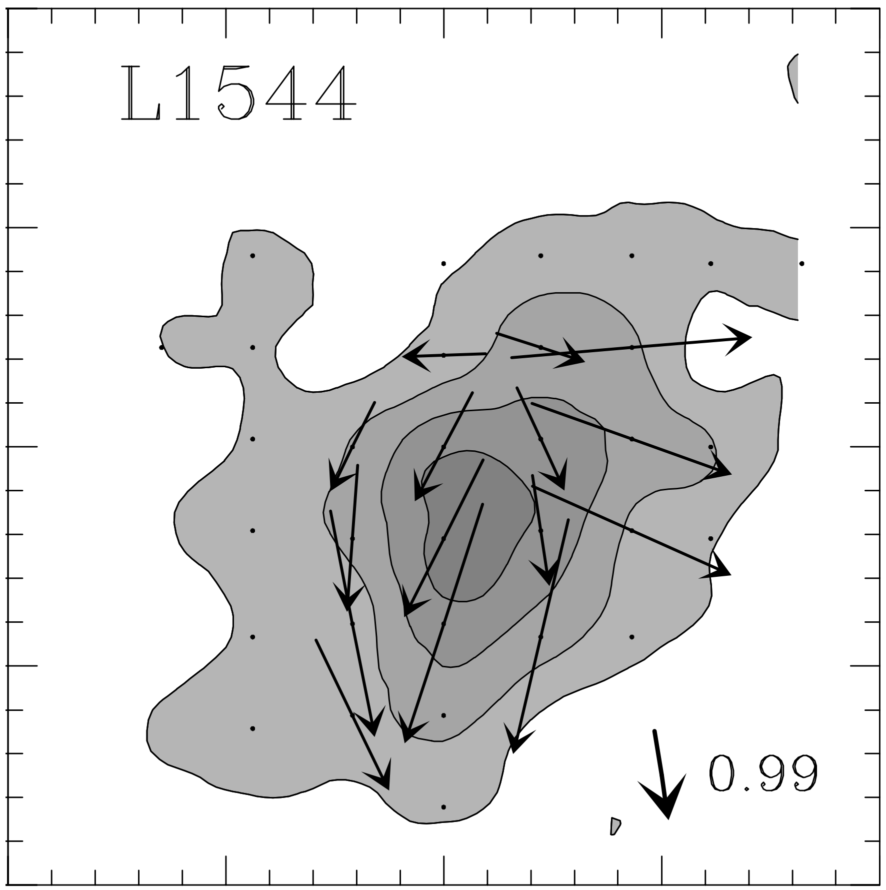
Caselli et al. 2002 : Velocity gradient

(ex. rigid rotation: $v=r\Omega$, $\mathrm{d}v/\mathrm{d}r=\Omega$)

Rigid rotation like

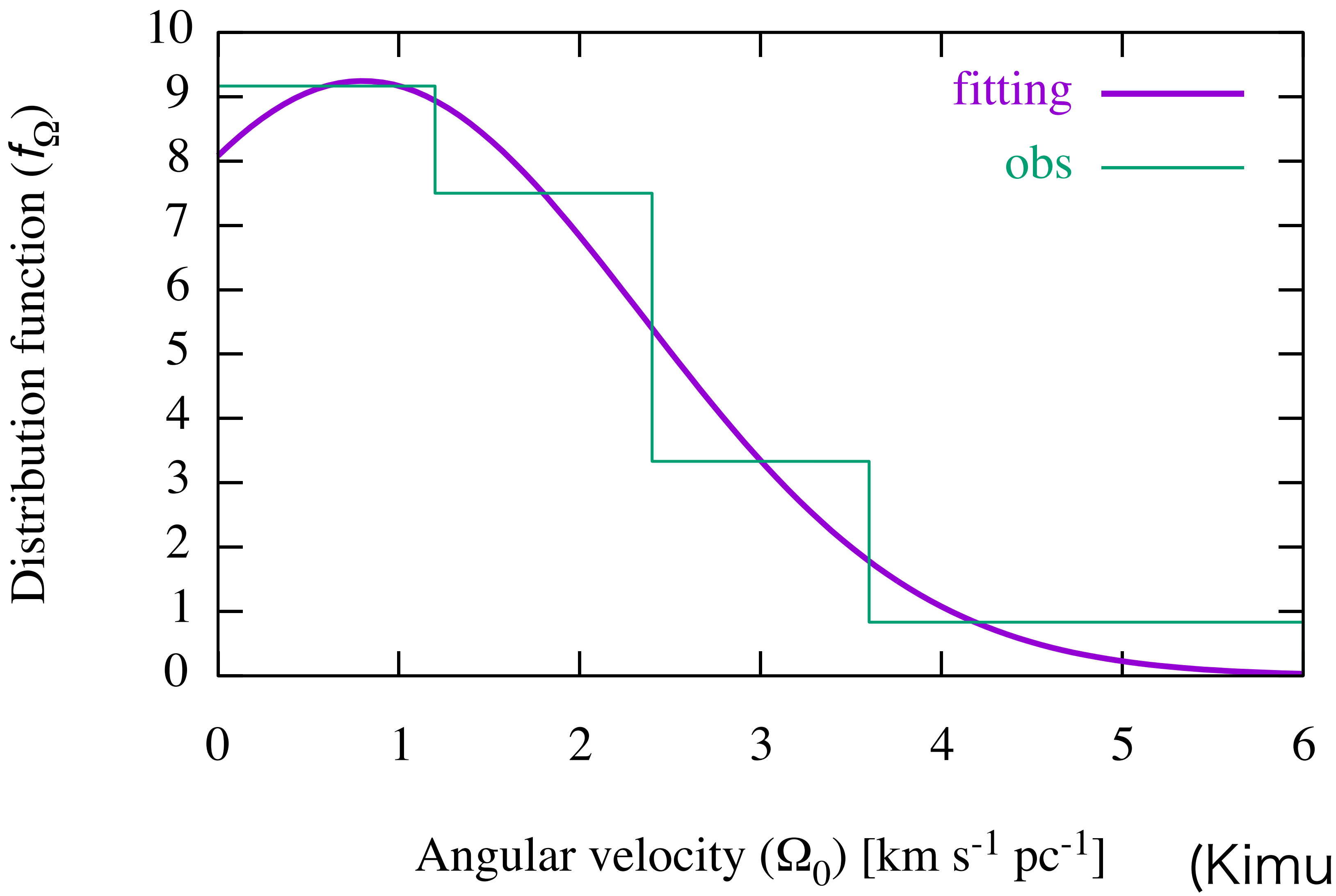
Complex profile





Angular Velocity Distribution

26 cores (Caselli et al. 2002, cf Goodman et al.1993)



(Kimura Kunitomo Takahashi 2016)

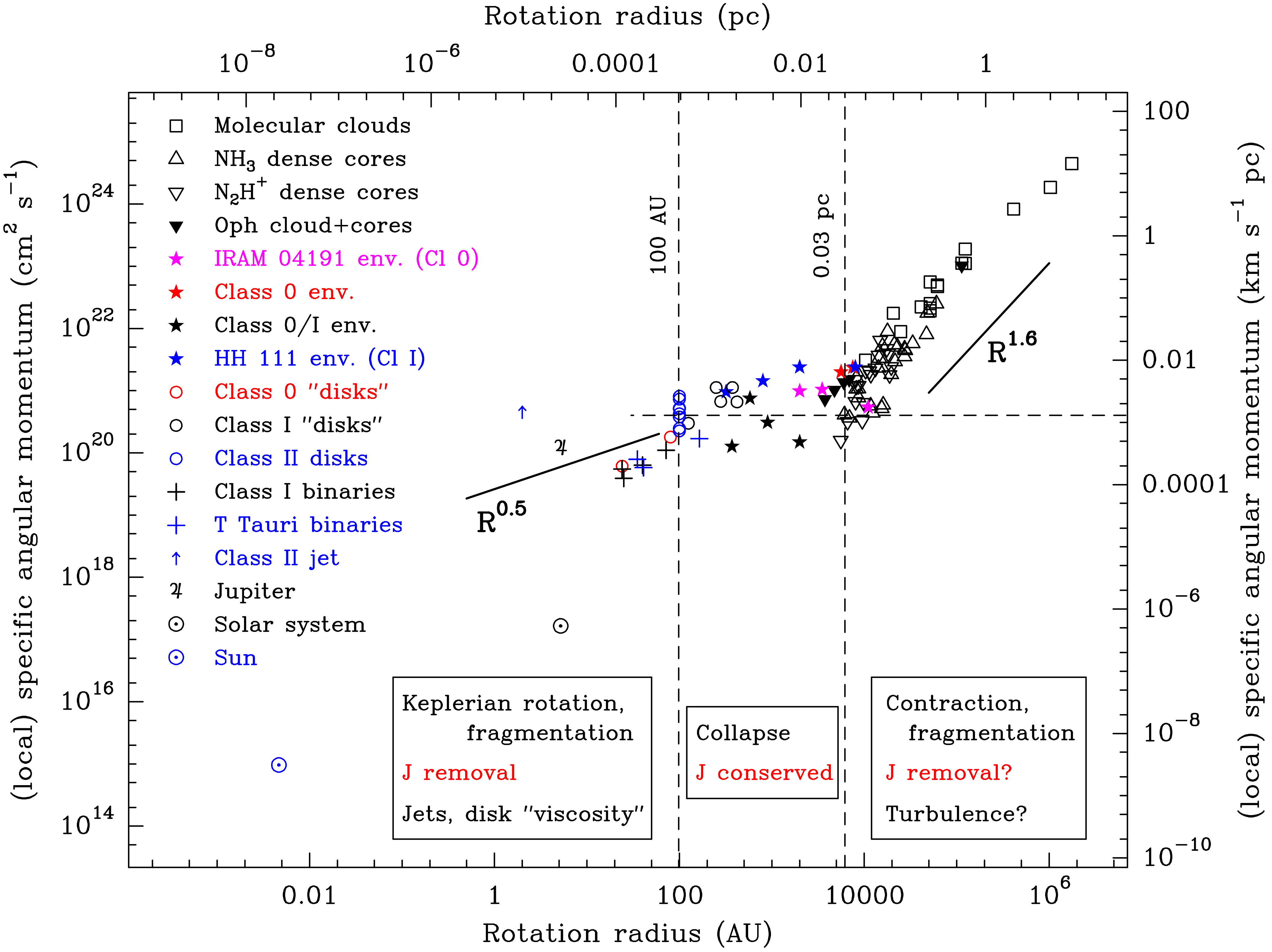
Angular velocity: 0.1-6 [km s^{-1} pc^{-1}]

Typically $\lesssim 1$ [km s^{-1} pc^{-1}] (?)

Angular Momentum of Cloud Cores

size-velocity relation

(Belloche2013,
cf Goodman et al. 1993, Ohashi et al. 1997)



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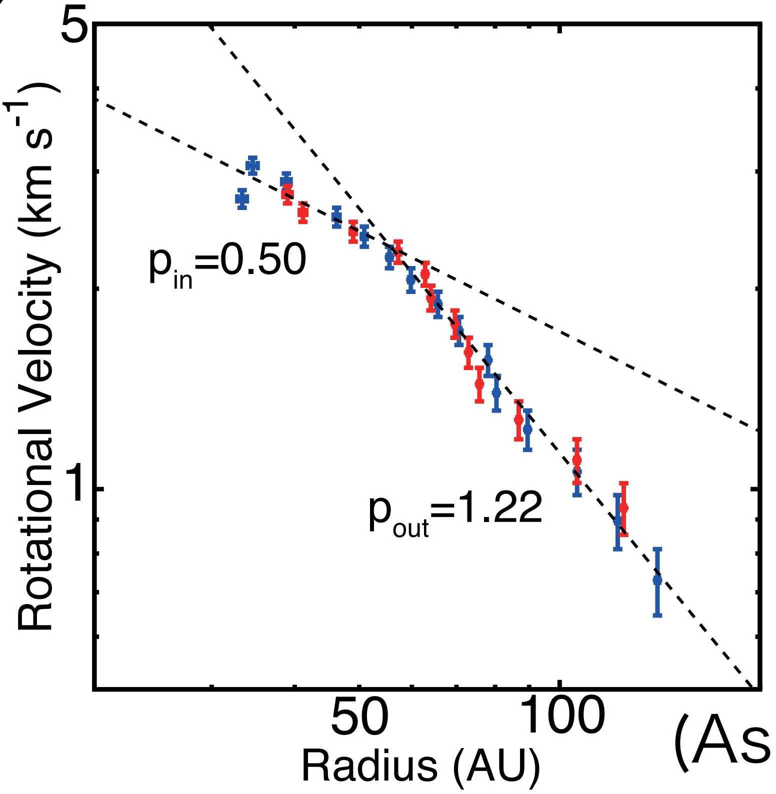
Observation of Infalling Envelope

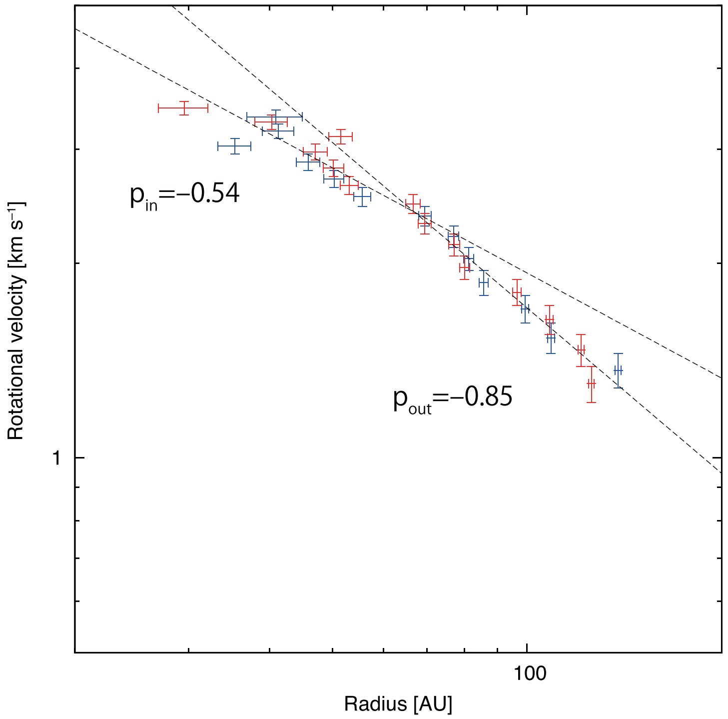
rotation velocity profiles

L1527



(Aso et al. 2017,
cf Ohashi et a. 2014)

TMC1-A



(Aso et al. 2015)

$v_{rot} \propto r^{-p}$

Inner region : p~0.5 → Keplerian diks

Outer region : p~1 (j~const)

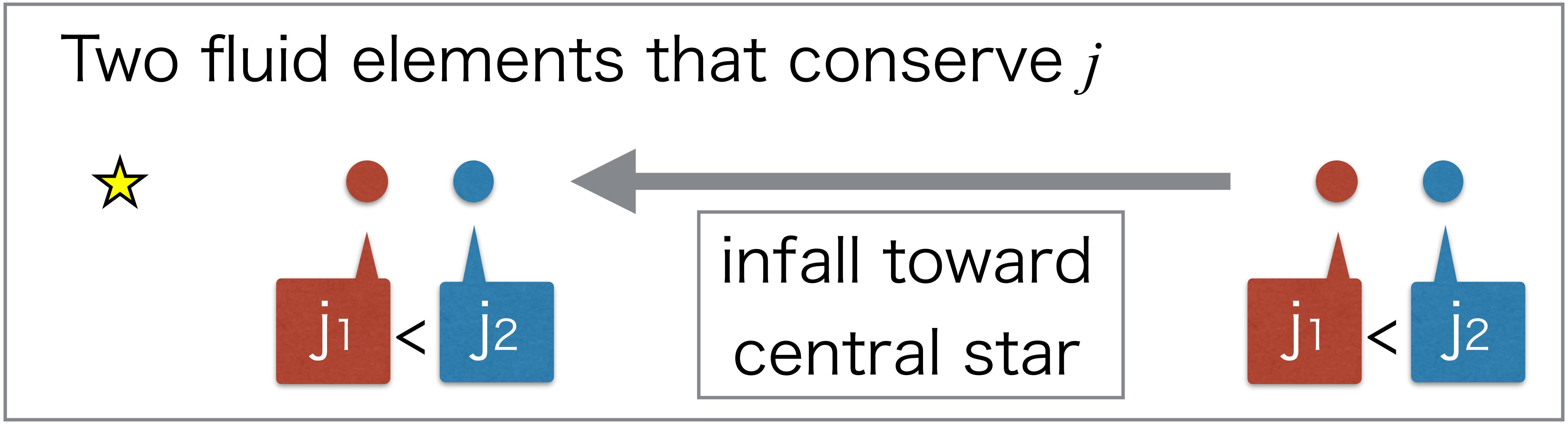
→ Infalling envelope

Dynamics of the envelope is directory observed.

Constant j in Infalling Envelope

Takahashi et al. 2016

- Is this region formed by the infalling gas that conserves j? (cf. Li et al. 2014)



Two fluid elements that conserve j

infall toward central star

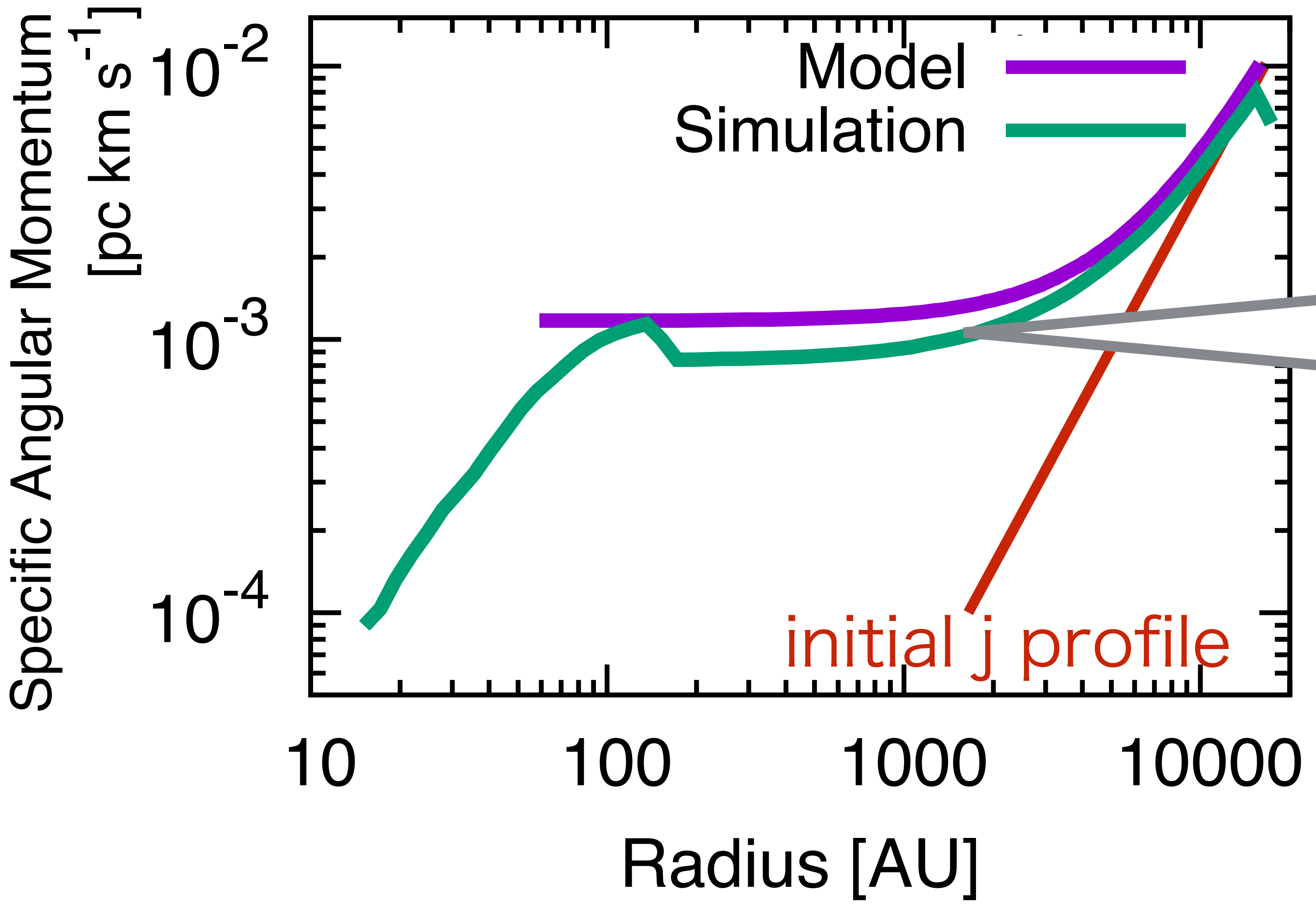
Even when the infalling gas conserves j, the constant specific angular momentum region does not appear.

Numerical Simulation and Analytic Model

Collapse of the cloud core (without magnetic field)

3D numerical simulation (Machida et al. 2010)

Analytic model (Takahashi et al. 2013, 2016)



Specific angular momentum is almost constant in

$100\mathrm{AU} \lesssim r \lesssim 1000\mathrm{AU}$

Constant j region is formed even with the initially rigid-rotating core

Origin of “constant j region”

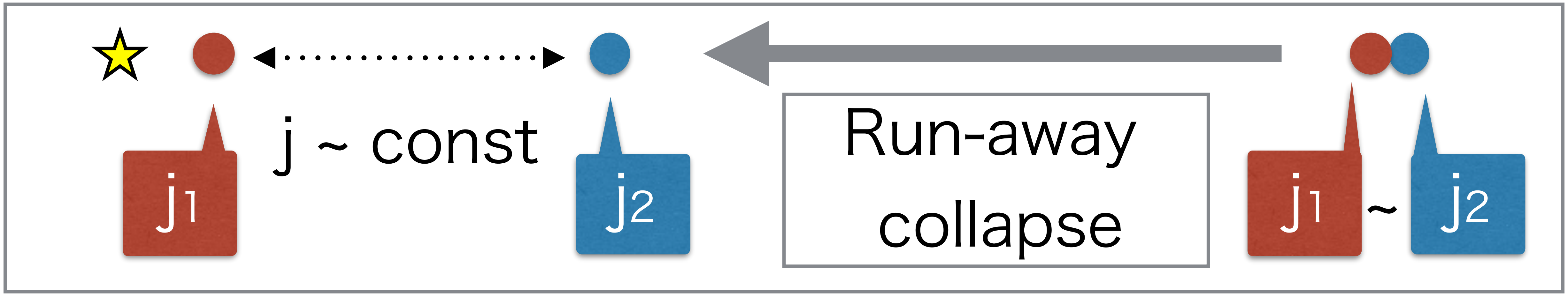
Analytic model :

Conservation of j in the envelope is assumed

j~const ⇔ r_{ini}~const

Star formation : Run-away collapse

➜ prolongate the envelope radially.



j_1

j ~ const

j_2

Run-away collapse

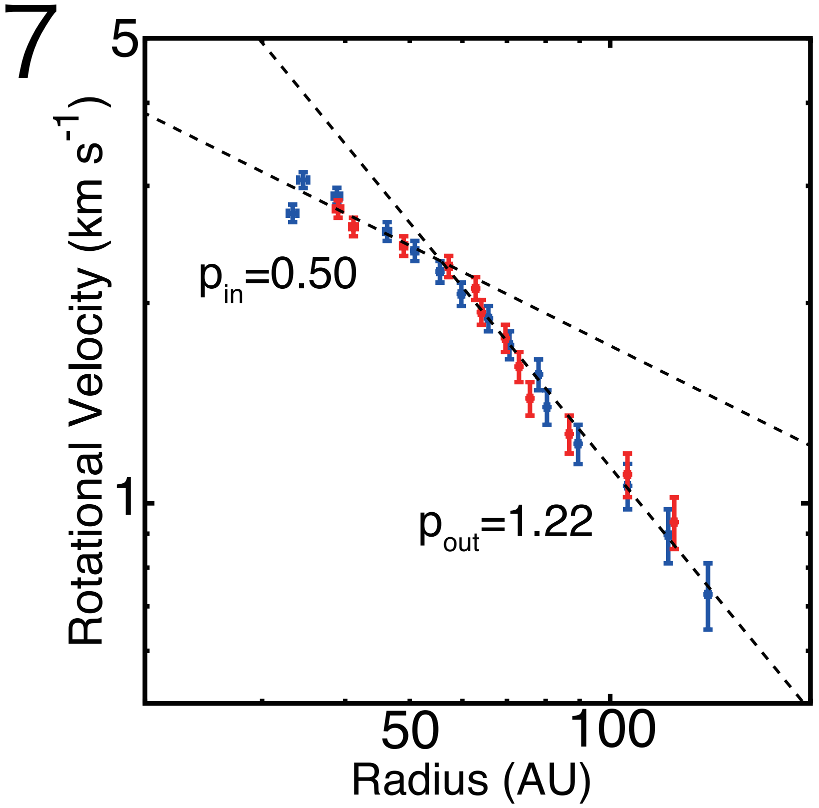
j_1 ~ j_2

The region with constant specific angular momentum can be formed as a consequence of strong prolongation in a run-away collapse.

Observation of Infalling Envelope

rotation velocity profiles

L1527



(Aso et al. 2017,
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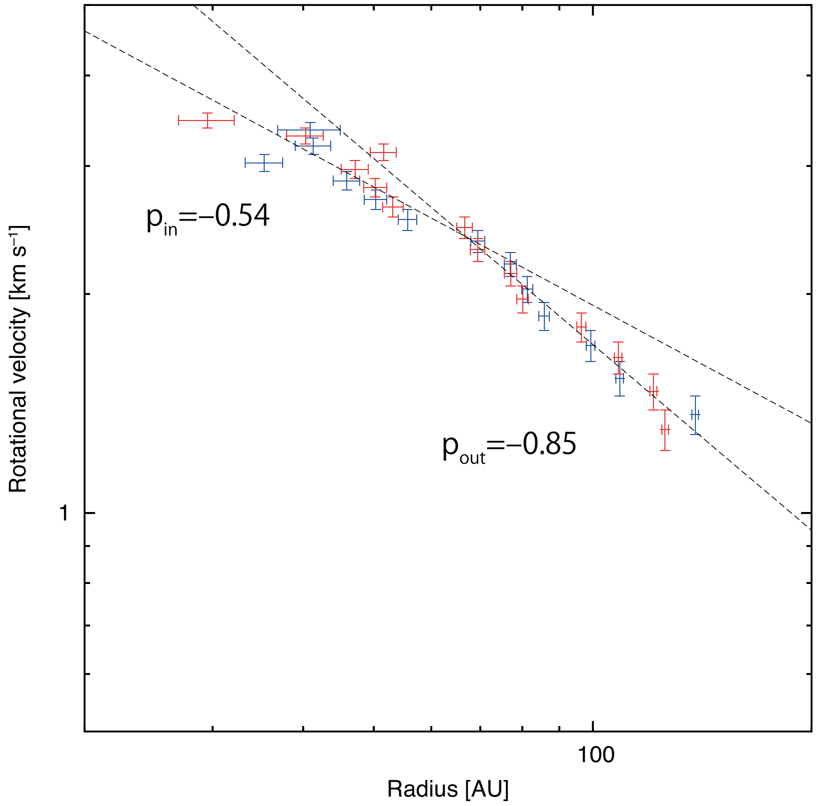
TMC1-A



(Aso et al. 2015)

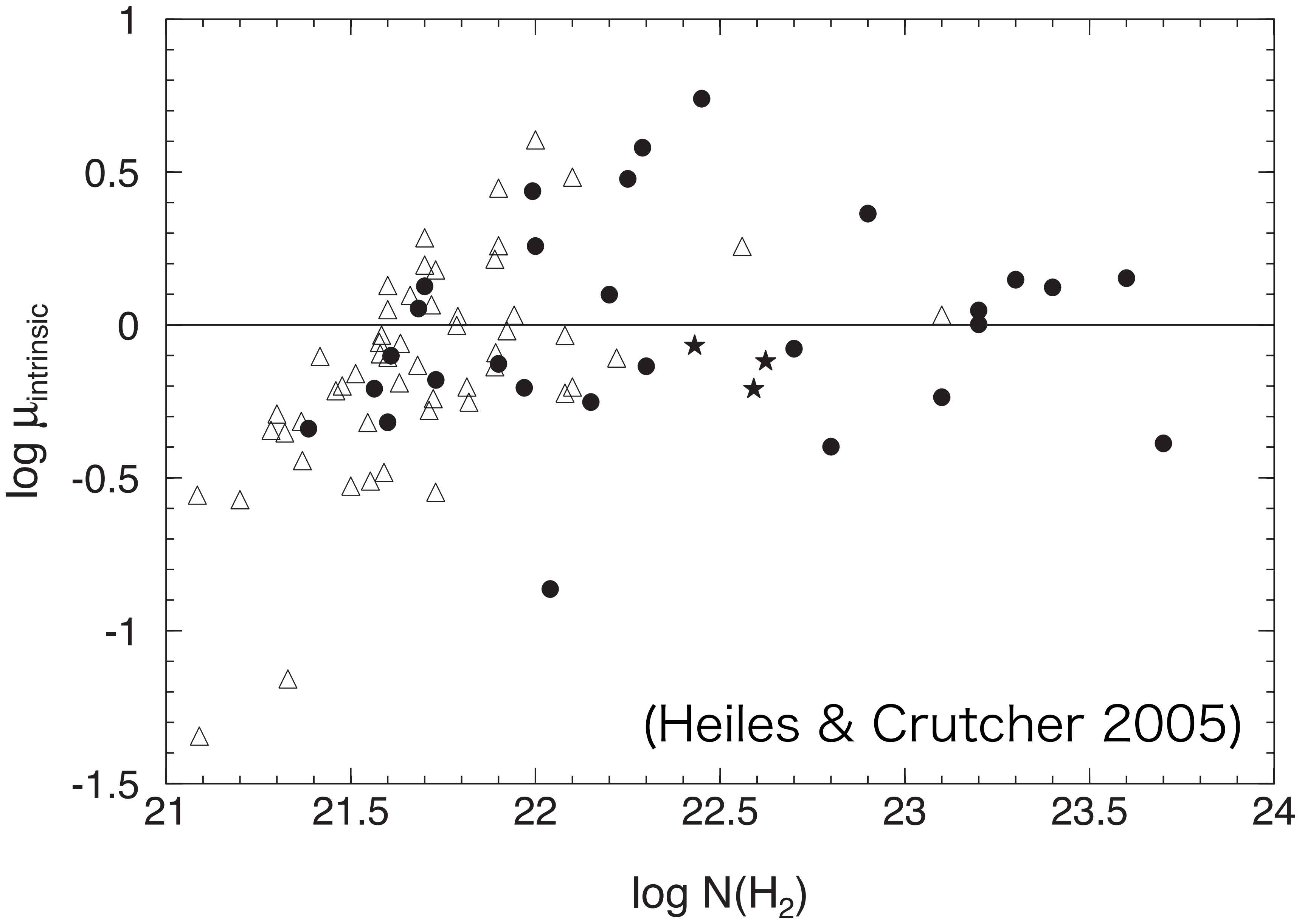
$V_{rot} \propto r^{-p}$ p=0.85<1: j of infalling gas decreases

⇒Magnetic braking ?

p=1.22>1: j of infalling gas increases ???

Magnetic Fields in Cloud Core

Mass-to-Flux ratio $\mu_{\mathrm{intrinsic}} \equiv 2\pi G^{1/2} M/\Phi_{\mathrm{cloud}}$



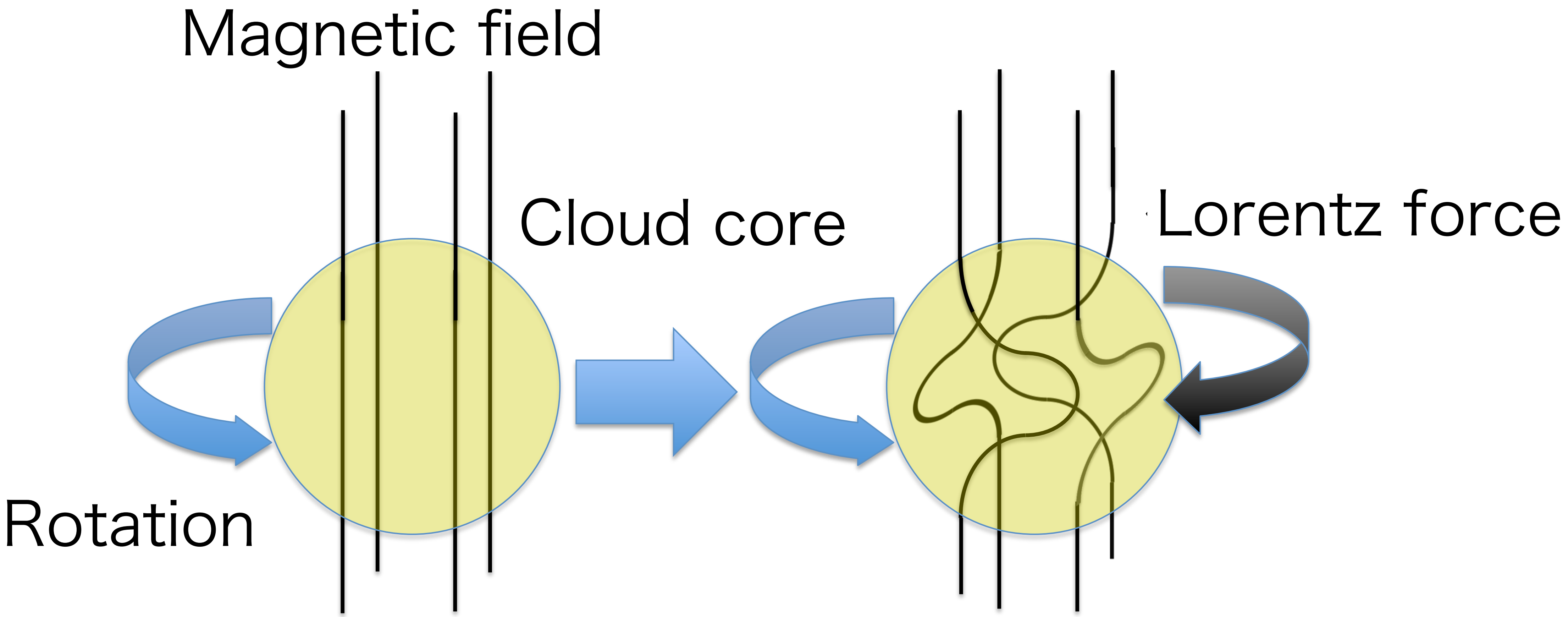
>1 supercritical

<1 subcritical

Mass-to-flux ratio is widely distributed around critical value.

Collapse with Magnetic Field

Angular momentum transfer in collapse phase
(Magnetic Braking)



Magnetic field transports the angular momentum upward.The angular momentum of the infalling gas decreases

Magnetic Braking Prevents Disk Formation?

Centrifugal balance: $j^2/r^3 = GM/r^2 \Rightarrow r=j^2/GM$

Disk forms when j>0.

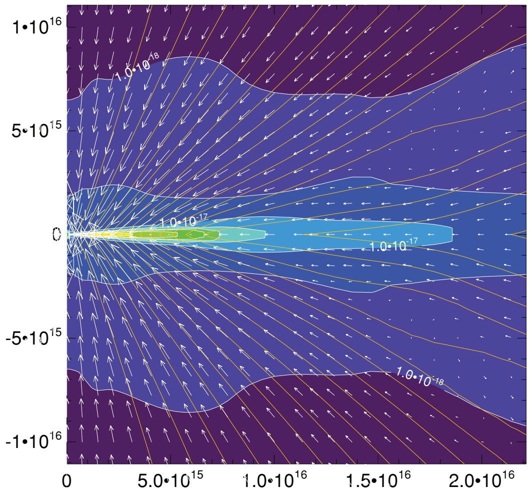
If magnetic braking efficient and $j<(GMr)^{1/2}$ is satisfied,

disk is not formed.

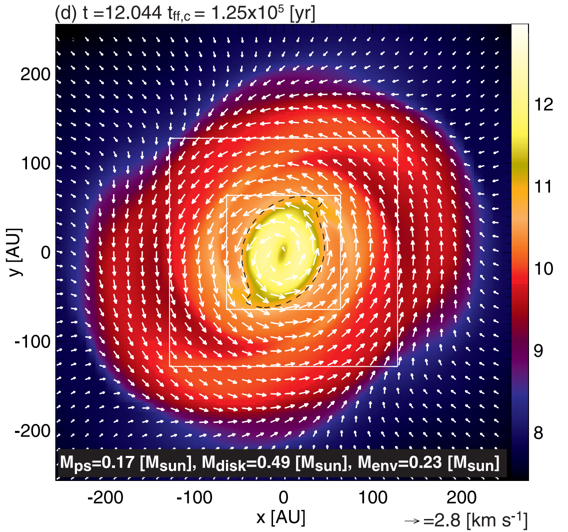
The effect of magnetic braking on the disk formation is still under debating.

turbulence, misalignment, non ideal MHD

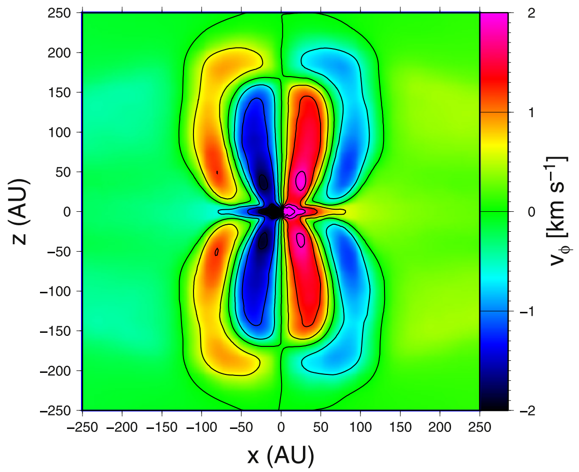
(cf. Seifried et al. 2012, Joos et al. 2012, Matsumoto et al. 2004)



(Li et al. 2011)



(Machida et al. 2011)



(Tsukamoto et al. 2015)

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Analytic Model of Infalling Envelope

◉Investigate the effect of the magnetic field from another pint of view of numerical simulations

We already develop the model
without magnetic field (Takahashi et al. 2013)

◉Advantage of the analytic model

Calculation of long term evolution
Parameter survey (Kimura, Kunitomo, Takahashi 2016)
Comparison with observations (Takahashi et al. 2016)
…

The analytic model is useful to investigate formation and evolution of disks

Collapse of Molecular Cloud Core

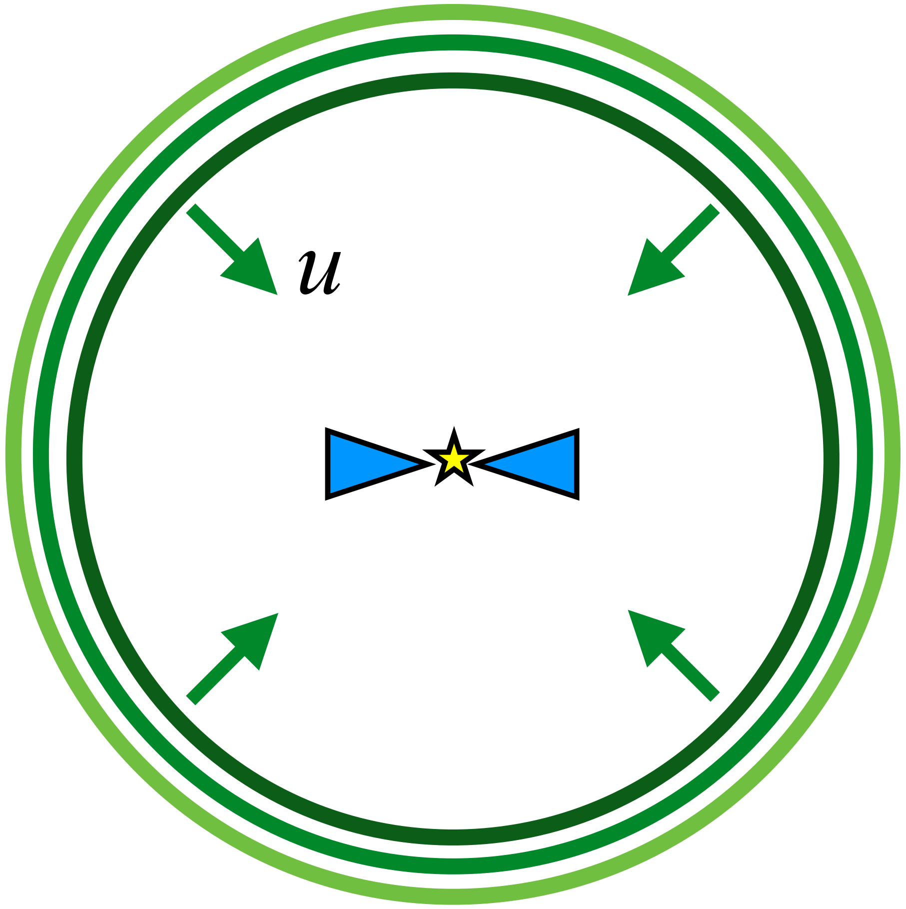
(Takahashi et al. 2013, 2016)

Assumption :

Spherical collapse, Isothermal,

(cf. Cassen and Moosman 1981)

Pressure gradient force ∝ r^{-1}



We calculate the **mass infall rate** approximately taking into account the effect of pressure.

$$t = \frac{2}{\pi} t_{\rm ff} \int_x^1 \frac{dx}{\sqrt{f^{-1} \ln x + x^{-1} - 1}}$$

$$x = r/r_{\rm i}$$

$r_{\rm i}$: initial radius

$t_{\rm ff}$: free fall time

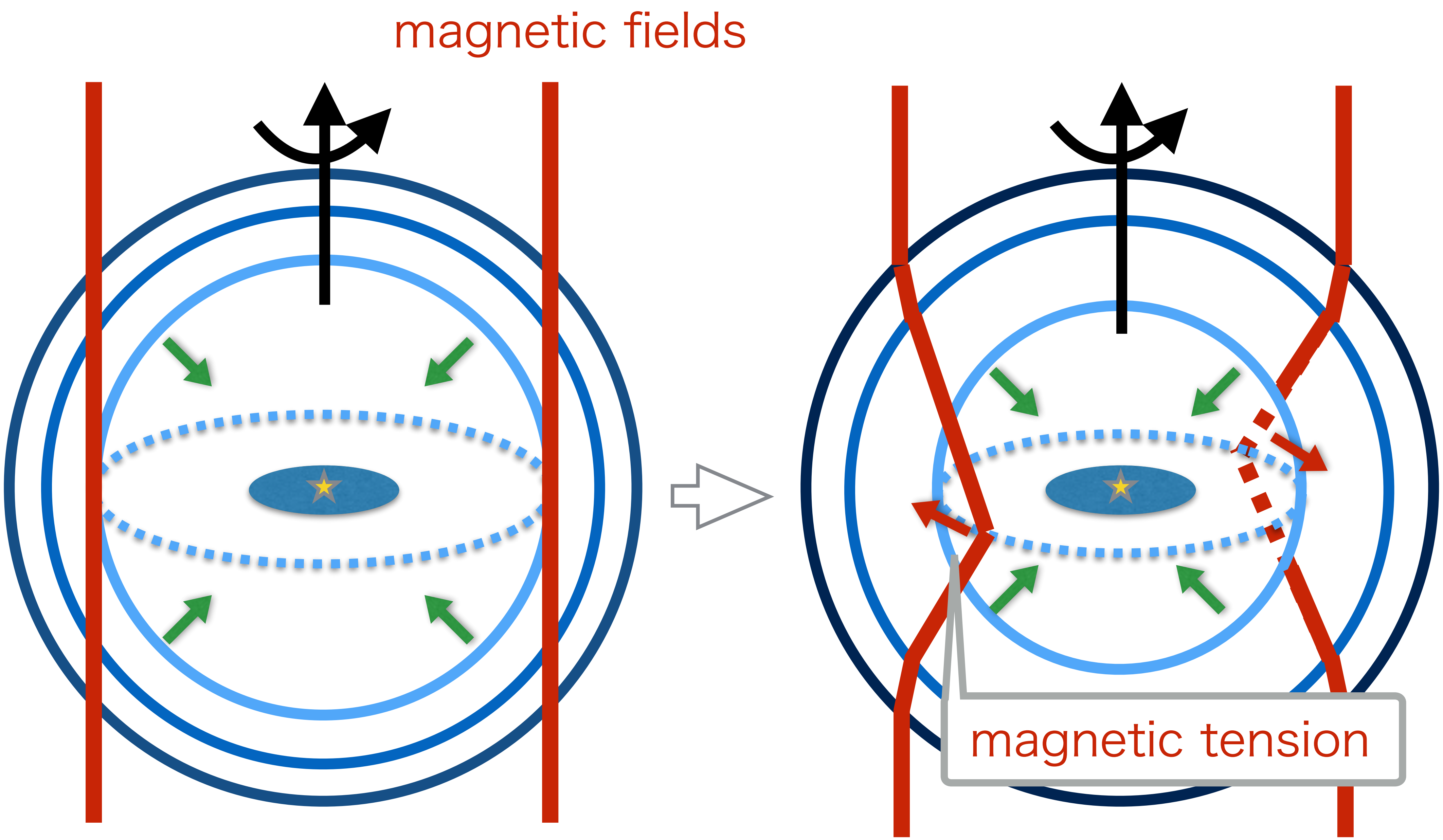
f: Initial gravity/pressrue

Effect of Magnetic Fields

We use ideal MHD in the envelope and aligned fields

Magnetic fields deforms with collapse

⇒magnetic tension

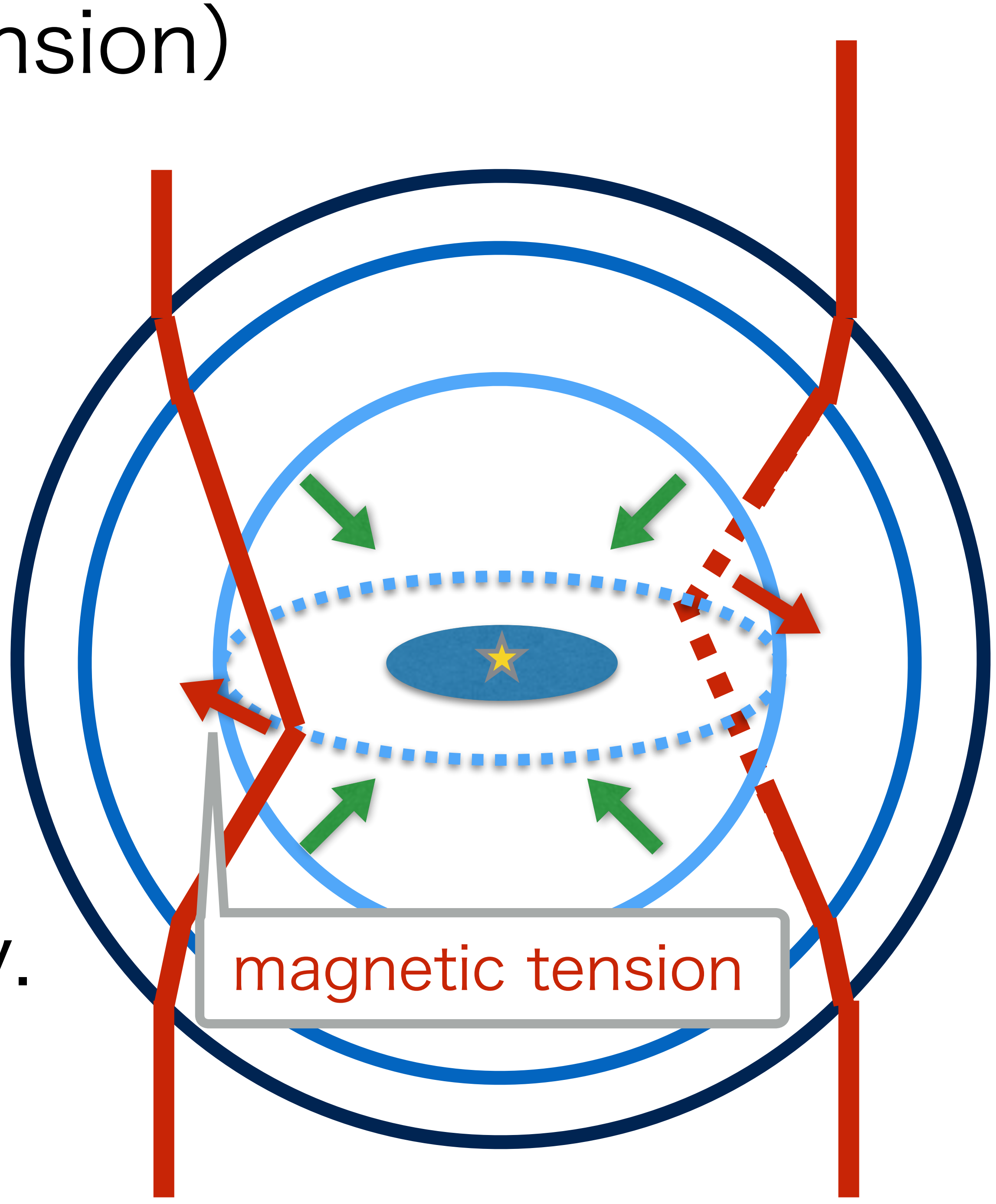


Magnetic Tension

Neglecting the **back reaction**
(~upper limit of magnetic tension)

We focus on midplane gas

We obtain time evolution of angular momentum and derive condition for disk formation approximately.



Condition for Disk formation

$$\frac{(\Omega_{\rm i} r_{\rm i})^2}{GM_r/r_{\rm i}} > 16\pi^2 e^2 \left(\frac{GM_r/r_{\rm i}}{B_{0i}^2/\rho_{\rm i}} \right)^2 \exp\left[-8\pi \frac{GM_r/r_{\rm i}}{B_{0i}^2/\rho_{\rm i}} \right]$$

A function of the rotational to gravitational energy and magnetic to gravitational energy

Disk radius

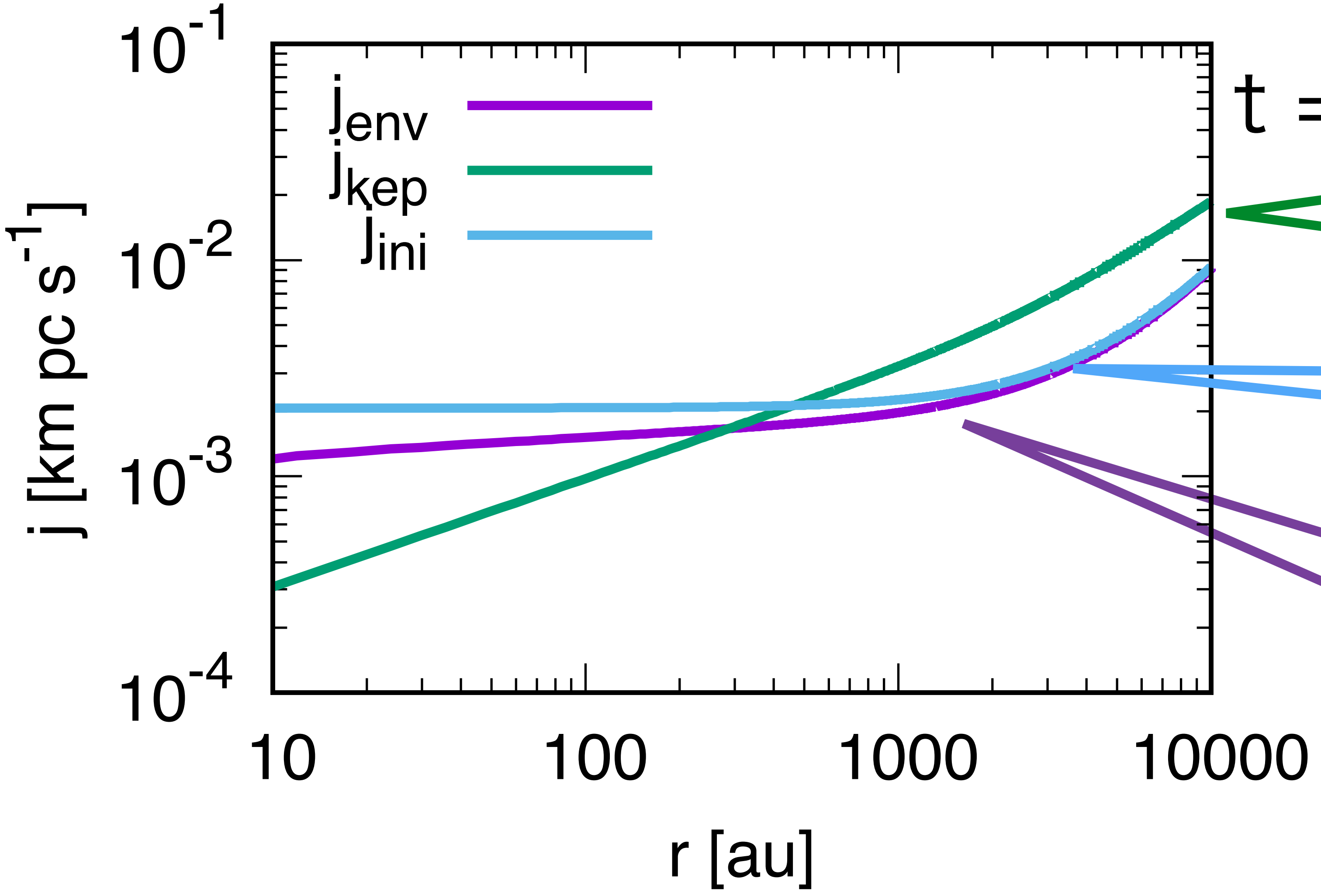
$$r = \frac{j_{\rm i}^2}{GM_r} \left[1 - \frac{2}{a} \ln(ab/2) + \frac{2}{a} \ln(a/2 - \ln(ab/2)) \right]^2$$

radius without magnetic field

$$a = \left[\frac{1}{8\pi} \left(\frac{B_{0\rm i}^2}{GM_r \rho_{\rm i}/r_{\rm i}} \right) \right]^{-1} \quad b = \left[\frac{GM_r/r_{\rm i}}{(\Omega_{\rm i} r_{\rm i})^2} \right]^{1/2}$$

Anglar Momentum in Envelope

$\Omega_\mathrm{i} = 8.1$ x $10^{-14}\ \mathrm{s}^{-1}$, $B_{0\mathrm{i}} = 14.3\ \mu\mathrm{G}$, $n_{0\mathrm{i}} = 10^5\ \mathrm{cm}^{-3}$



t = 2x10^5 yr (M_ps~$0.5M_\mathrm{sun}$)

Kepler rotation

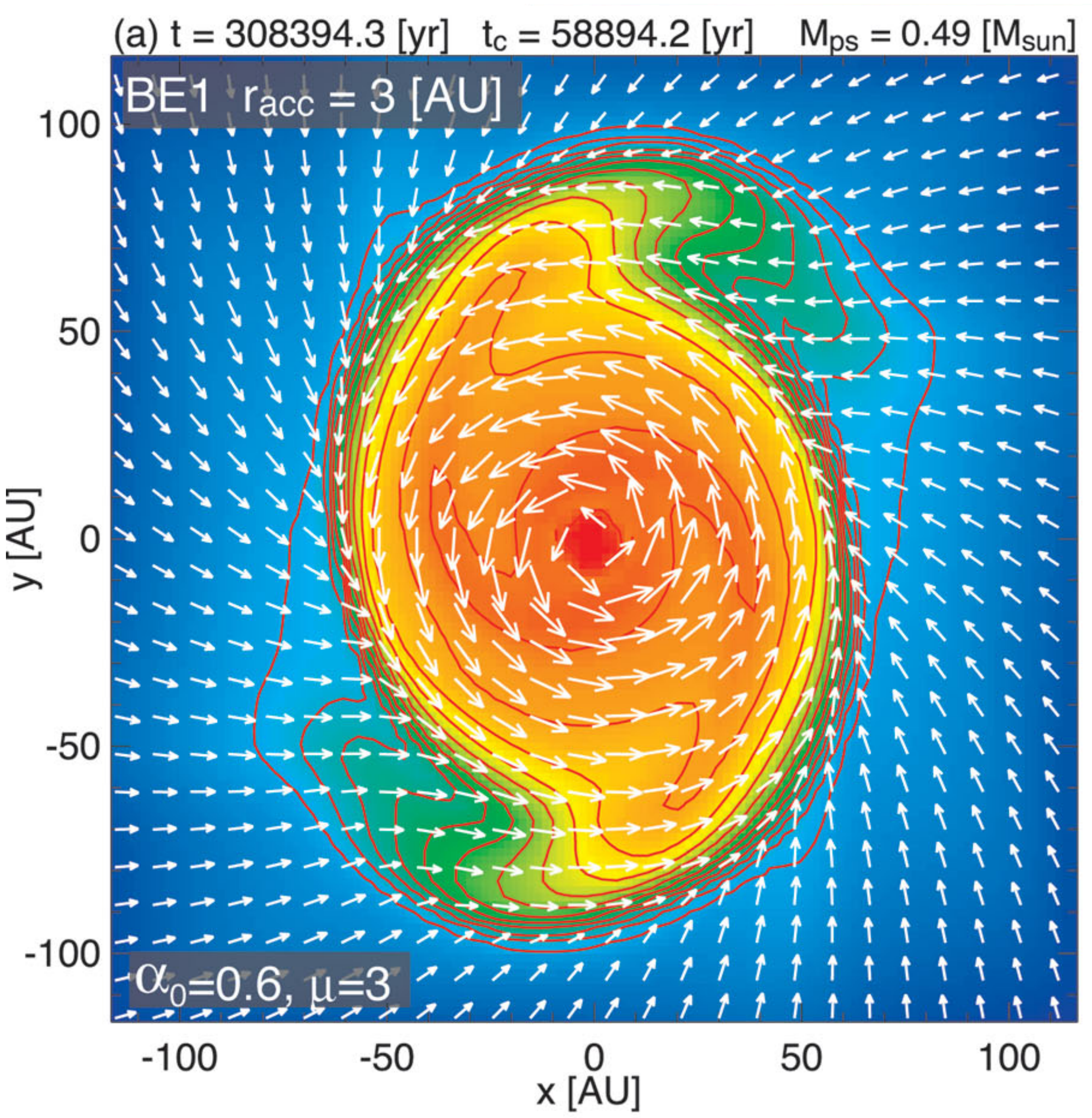
without magnetic field

result of the model

Model predict that disk radius is ~300 au

These results should be compared with simulations.

Comparison with a simulation



disk radius ~100 au

(model prediction is ~300 au)

$r_{disk} \propto j_i^2 \propto r_i^4$

Strongly depends on initial radius r_i

Farther comparison with the simulation and update of the model is required

Summary

- Angular momentum of cloud cores is important for protoplanetary disk formation, so that it is also important for star and planet formation.

- Without magnetic field, angular momentum of the infalling envelope is conserved and flat j profile is formed.

- Magnetic field transfers the angular momentum in the envelope and will strongly affect the disk formation.

- We develop the analytic model for the infalling envelope with magnetic field and investigate the time evolution of the angular momentum in the envelope.

- Compered with the numerical simulation, the model overestimate the disk radius. This may caused by the assumption of the spherical collapse in the model.

- Farther comparison with the simulations and update of the model is required.