Does magnetic-field-angular-momentum misalignment strengthens or weakens magnetic braking ?

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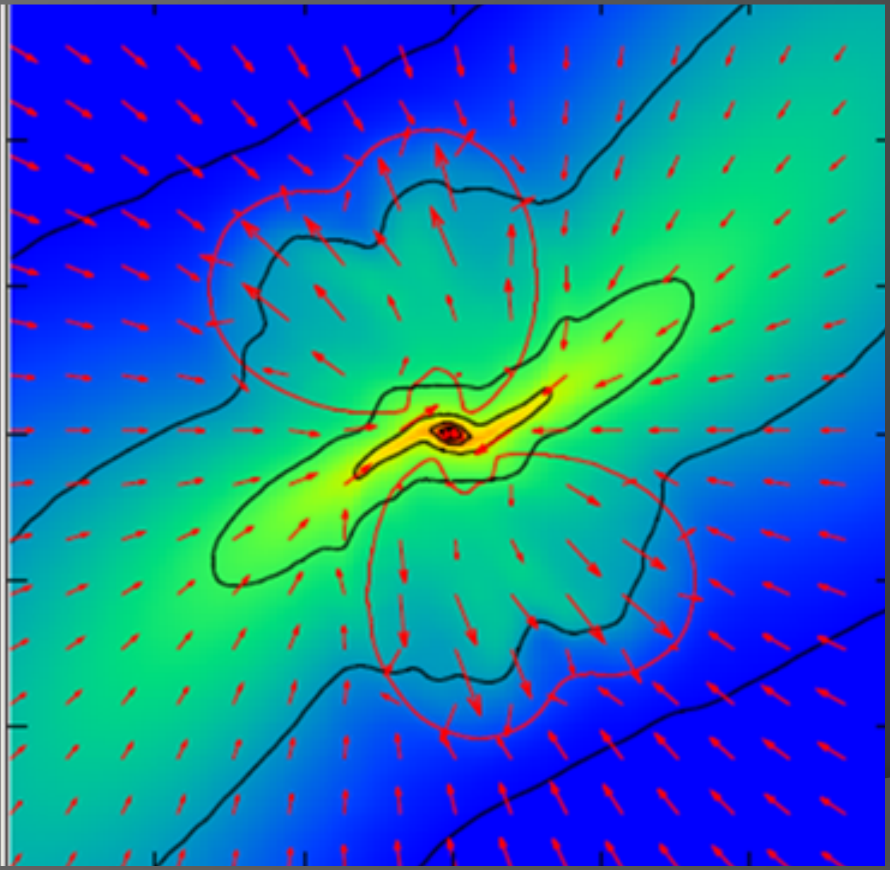
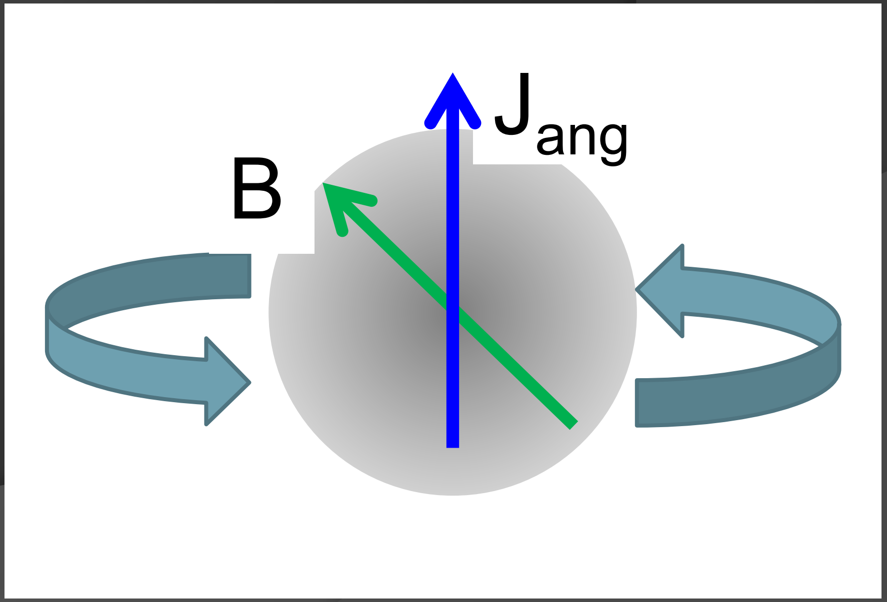




Outline

- Introduction:
  - Observation of magnetic field and turbulence of the cloud core
  - Magnetic braking and its anisotropic impact
  - Discrepancy among the previous studies
- Results
  - Dependency of central angular momentum evolution on the initial condition and magnetic resistivity
  - Strong magnetic braking in isothermal collapse phase in perpendicular cloud cores
- Summary and discussion

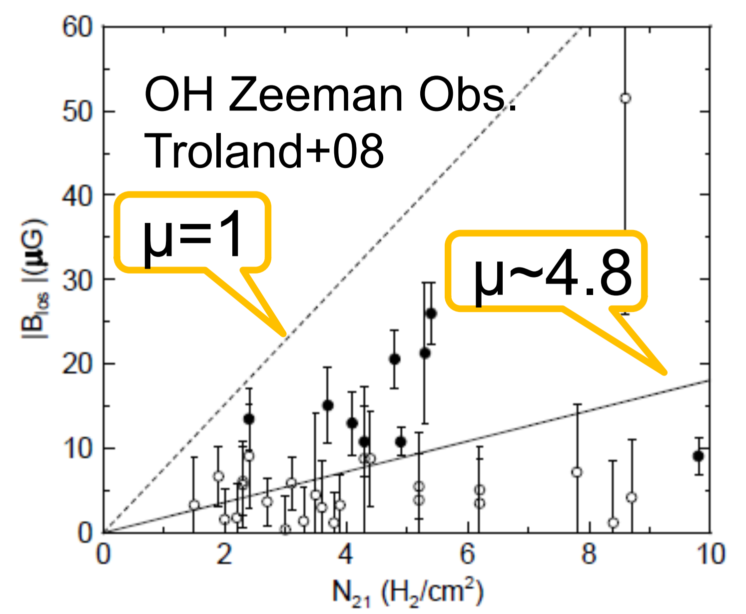
Strong magnetic field and weak turbulence in cloud cores

- Magnetic field of the cloud cores is strong.

$$\mu = \frac{\mathrm{M}/\Phi}{(\mathrm{M}/\Phi)_{\mathrm{crit}}} = 2 - 4$$

- Turbulence is weak

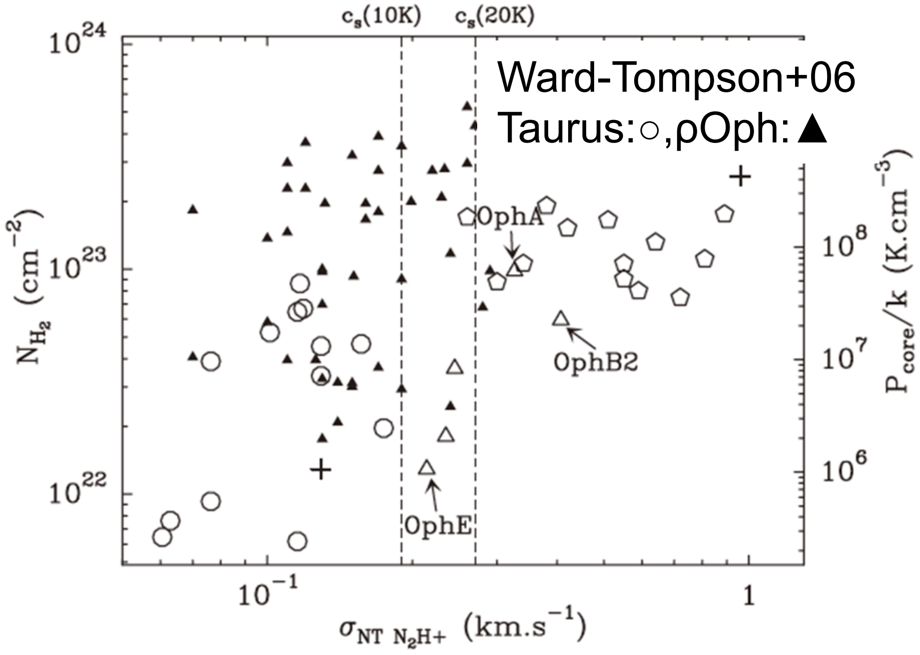
$$\mathrm{M}_{\mathrm{turb}} < 1$$



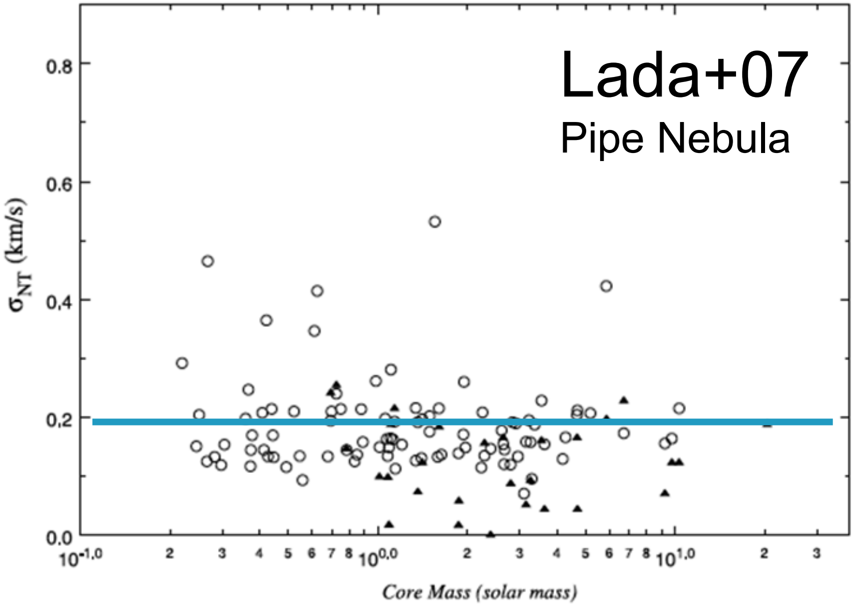
OH Zeeman Obs.
Troland+08

μ=1

μ~4.8



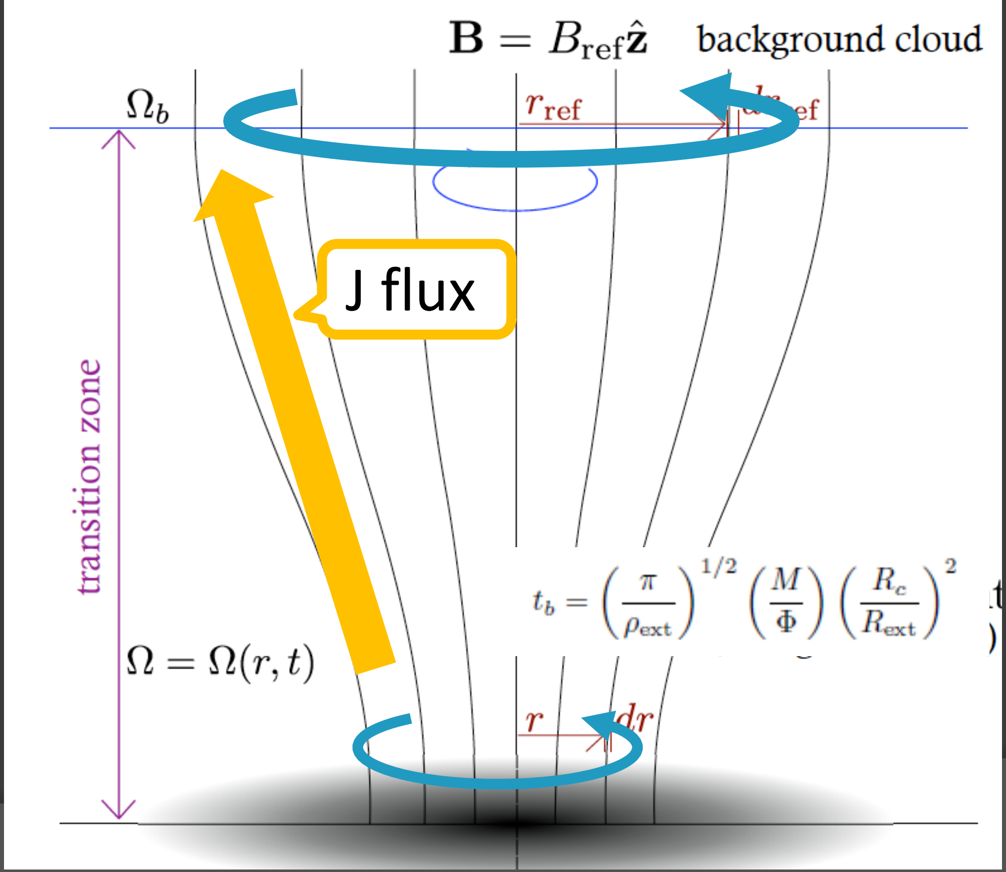
Ward-Tompson+06
Taurus:○,ρOph:▲

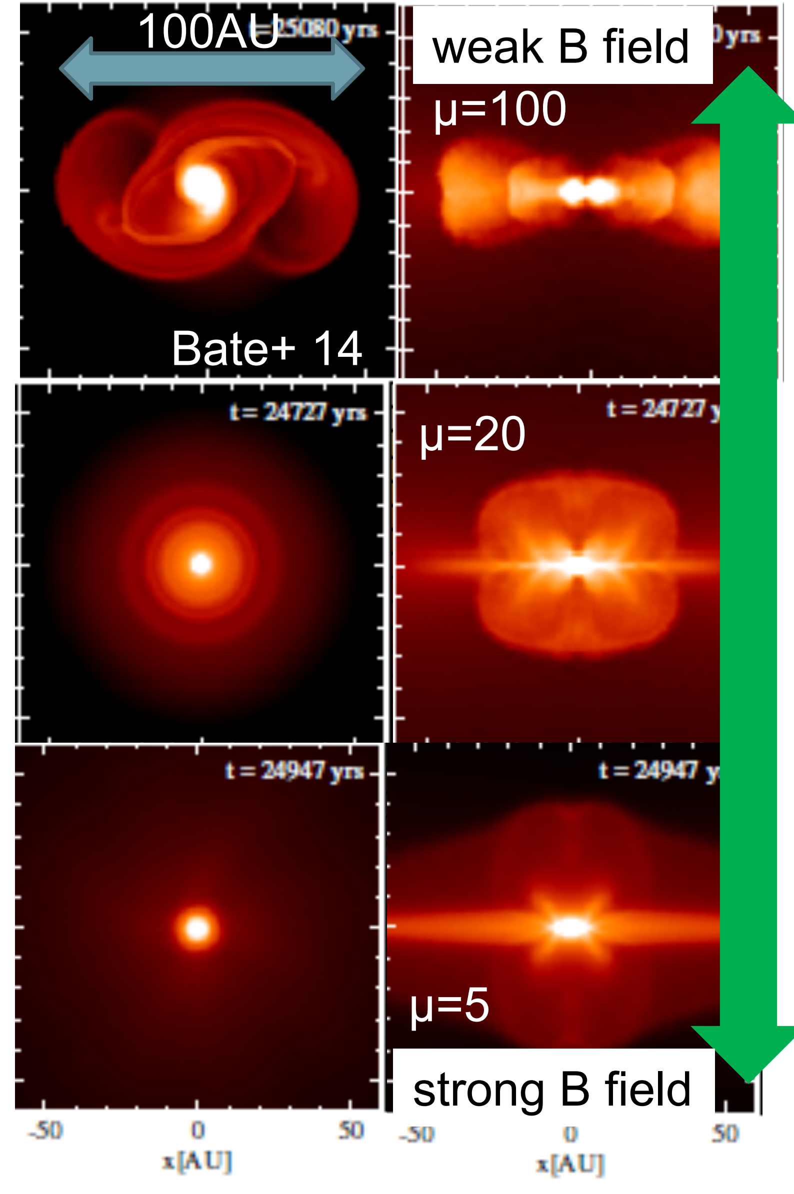


Lada+07
Pipe Nebula

Magnetic braking and its anisotropic impact

- In the core with observed B and subsonic turbulence, magnetic braking is dynamically important.



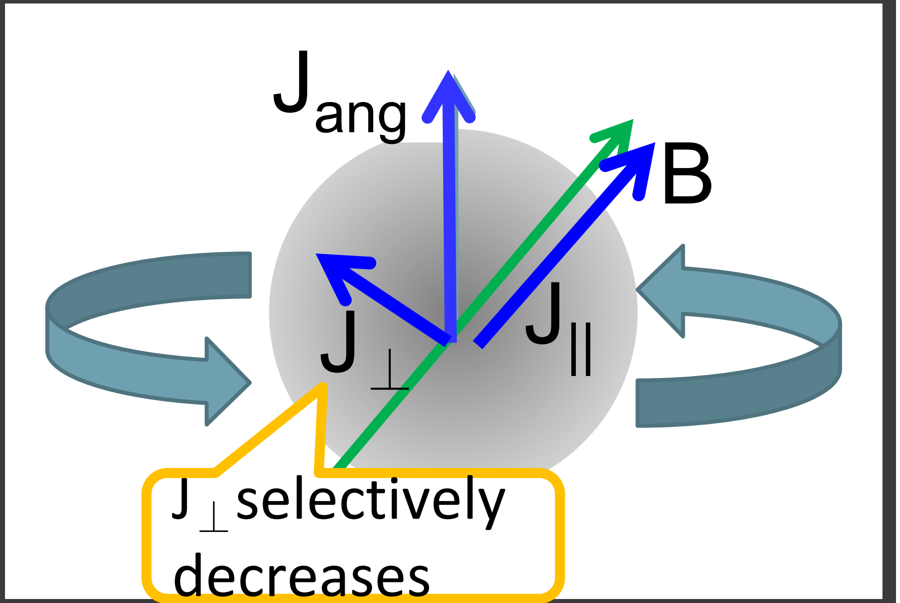


Magnetic braking and its anisotropic impact

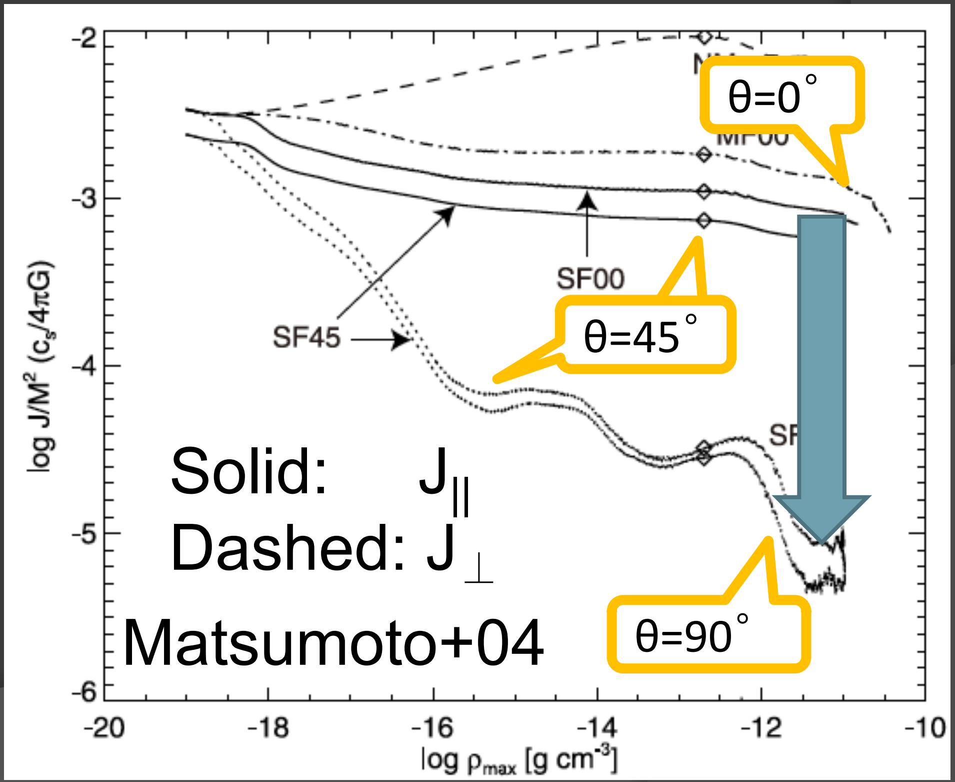
- What kind of structure does the magnetic braking imprint to the rotation structure?

→it introduces anisotropy of the angular momentum!

- Matsumoto+04 showed that magnetic braking enforces J and B to be aligned.



$J_\perp$ selectively decreases



θ=0°

θ=45°

θ=90°

Solid: $J_{||}$
Dashed: $J_\perp$

Matsumoto+04

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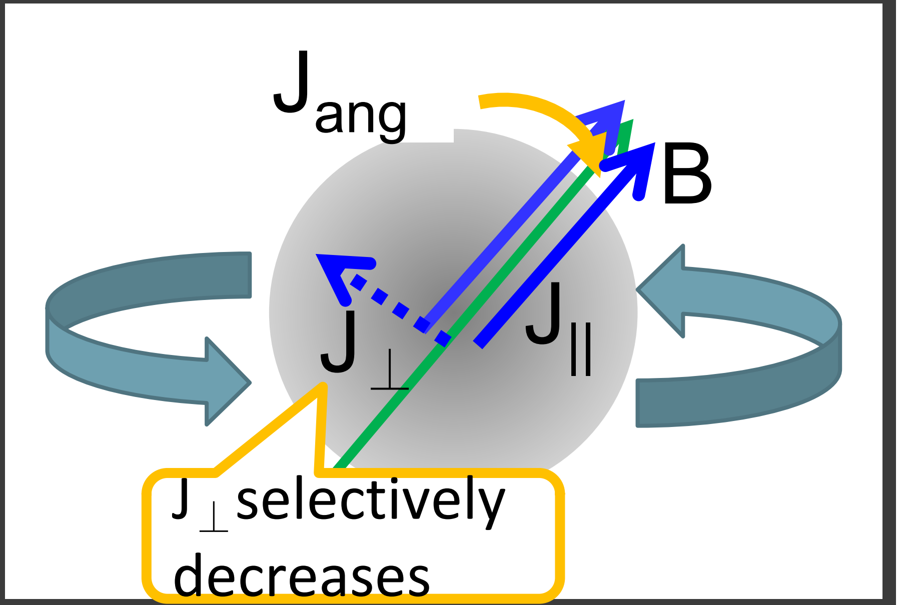

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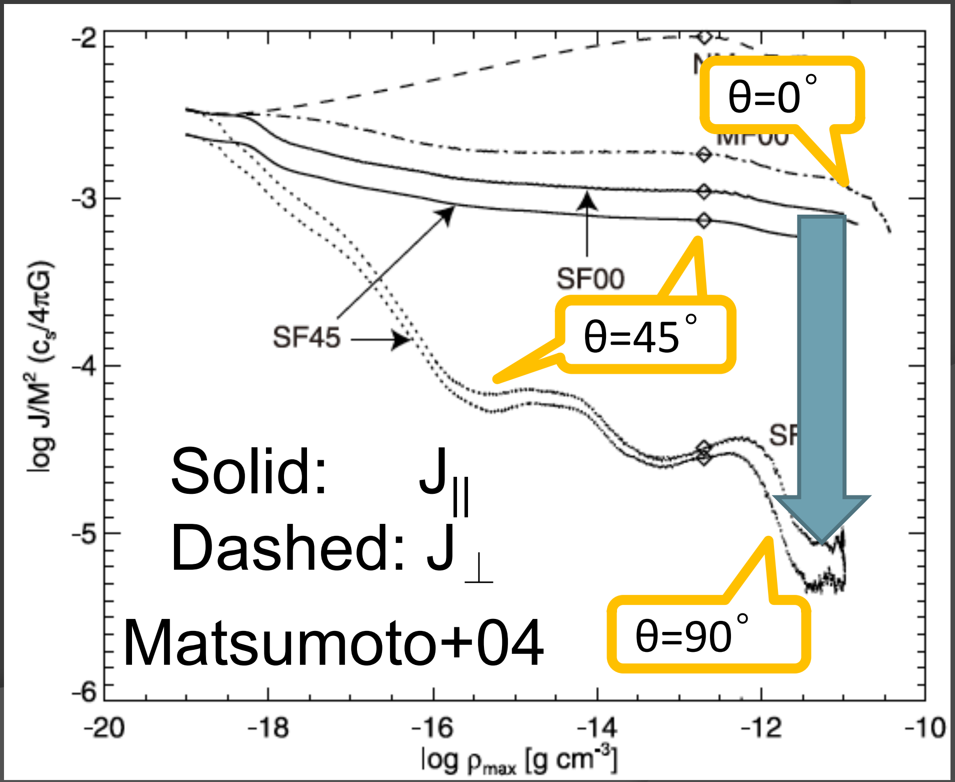


Solid: $J_{\parallel}$
Dashed: $J_{\perp}$

Matsumoto+04

Dependence of magnetic braking timescale on B direction

- Timescale of magnetic braking

→is given as the time in which Alfven wave sweeps the region whose inertia equals to the central inertia

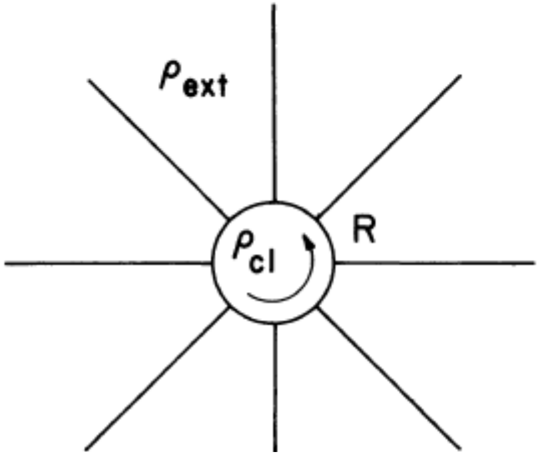
$$\boxed{I_{\rm ext}(t_b) = I_c.}$$

$$\tau_\perp \sim 2\left(\frac{\pi}{\rho_c}\right)^{1/2}\frac{M}{\Phi_B}.$$

$$\tau_\parallel \sim \left(\frac{\pi}{\rho_{\rm ext}}\right)^{1/2}\frac{M}{\Phi_B}.$$

$$\Rightarrow \quad \frac{\tau_\parallel}{\tau_\perp} = \frac{1}{2}\left(\frac{\rho_c}{\rho_{\rm ext}}\right)^{1/2}$$

- The magnetic braking is strong in the core with B ⊥ J with simple B geometry (Moschouvias+ 85)

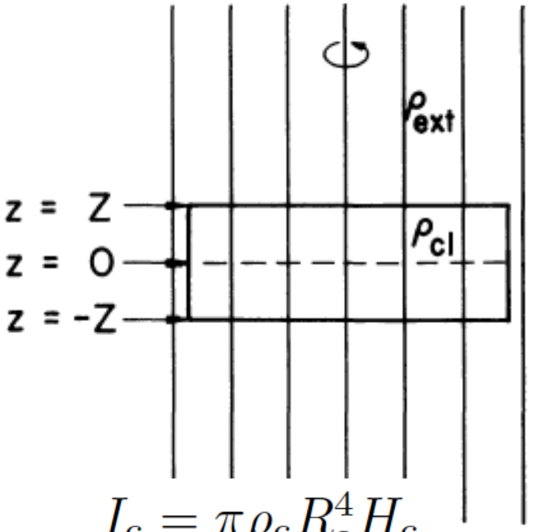


$$t_{b,\perp} = \int \frac{dr}{v_A(r)} = \int \frac{r\,dr}{B_c} = \frac{R_c^2 - R^2}{2\,B_c}$$

$$\rho_{\rm ext}\,(R^4 - R_c^4) = \rho_c R^4$$

$$t_{b,\perp} = \frac{1}{2}\left(\left(1+\frac{\rho_c}{\rho_{ext}}\right)^{\frac{1}{2}} - 1\right)\frac{(4\,\pi\rho_{ext})^{1/2}\,R_c}{B_c}$$

t = 0

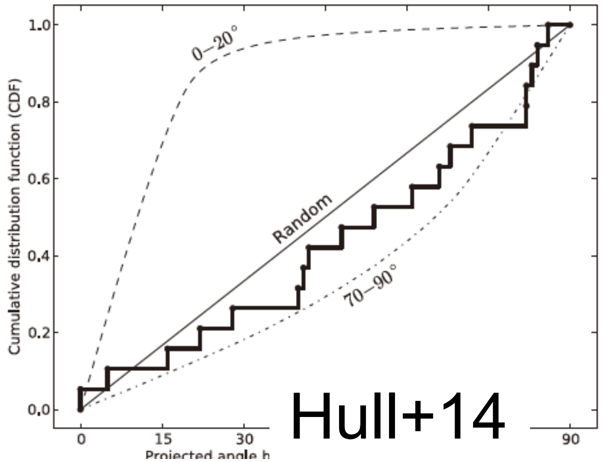


$$I_c = \pi\rho_c R_c^4 H_c$$

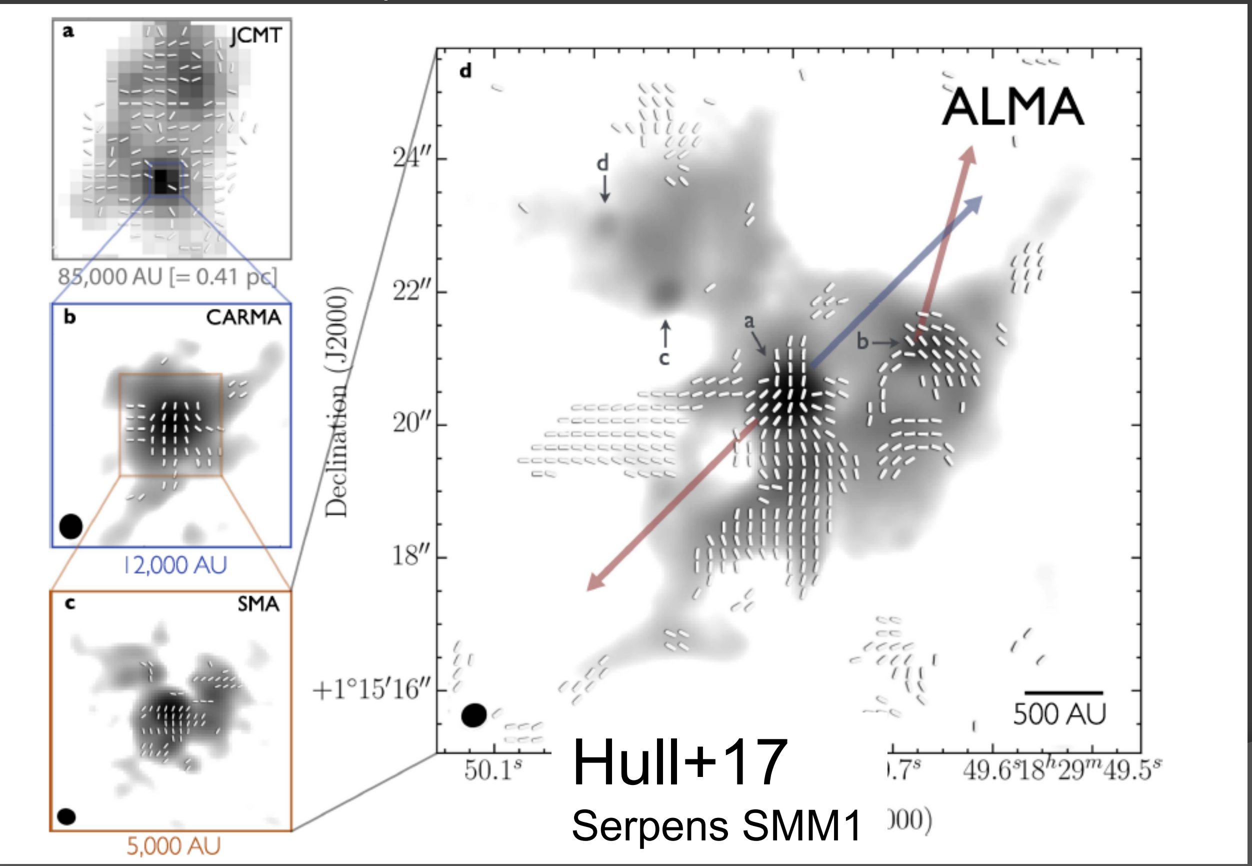
$$I_{\rm ext}(t_b) = \pi\rho_{\rm ext} R_c^4 v_A t_b$$

Random distribution of magnetic field and outflow direction

- This suggests:
  1. The magnetic braking is dynamically important but it does not enforce J || B.
  2. The magnetic field is dynamically unimportant at the observed scale(turbulence is strong or magnetic field is weak)

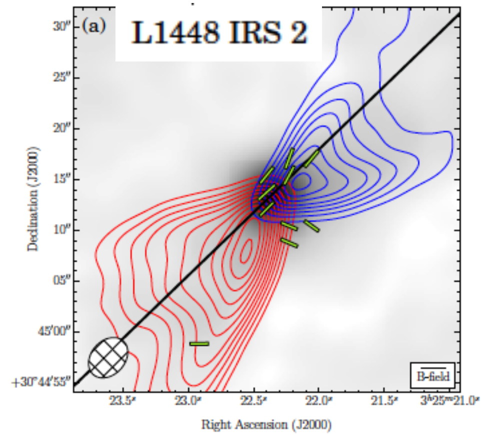


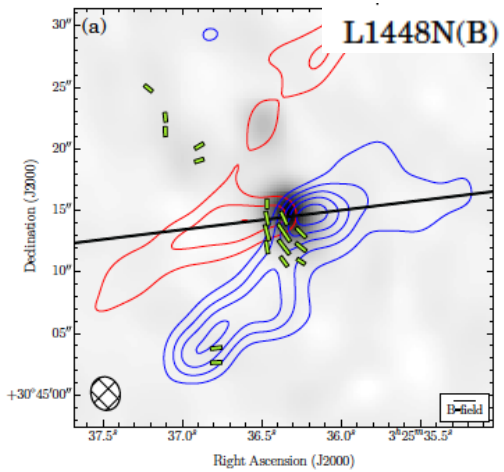
Hull+14



Hull+17

Serpens SMM1





magnetic braking timescale of hourglass B field

- ◎ エンベロープ内では磁場配位は砂時計型

→広がった分「腕」が稼げる

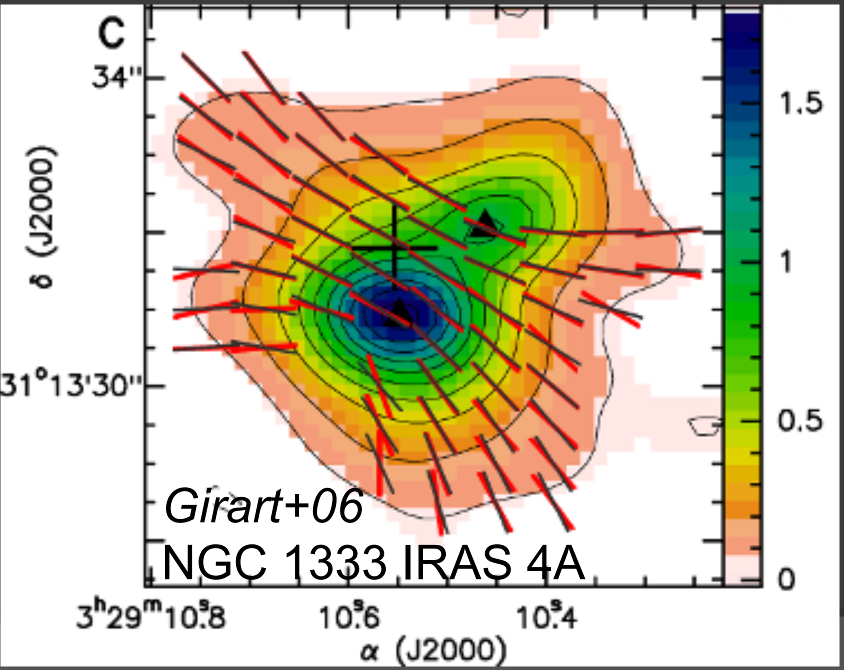
→より効率的な磁気ブレーキ

- ◎ Rc/R_{ext}は解析から決めるのは困難(Joos+12ではR_{ext}=R_{core}→過大評価)

→シミュレーションしてみる必要がある

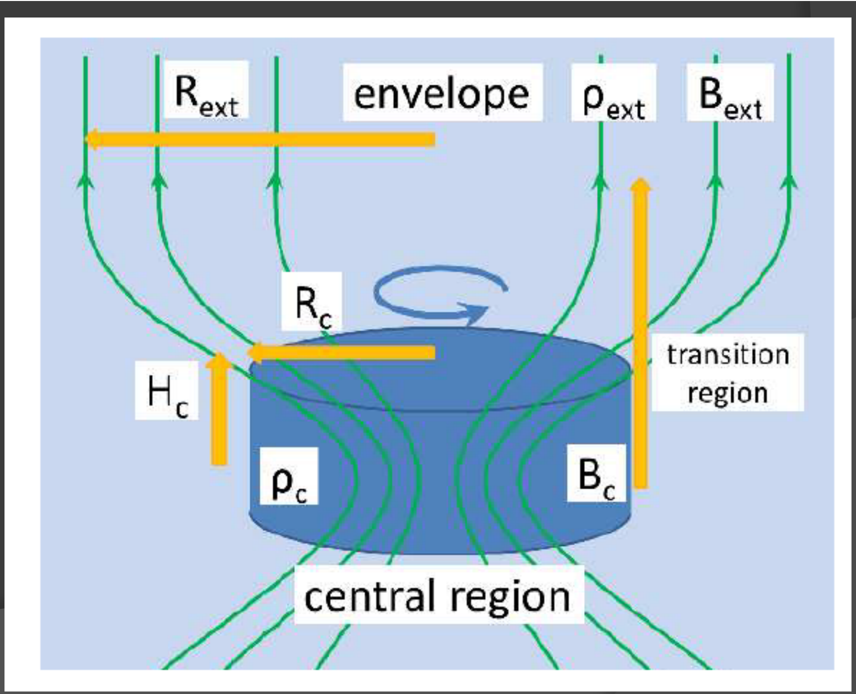
$$t_b = \left(\frac{\pi}{\rho_{\rm ext}}\right)^{1/2} \left(\frac{M}{\Phi}\right) \left(\frac{R_c}{R_{\rm ext}}\right)^2$$

$$\frac{t_\parallel}{t_\perp} = \left(\frac{R_c}{R_{ext}}\right)^2 \left(\frac{\rho_c}{\rho_{ext}}\right)^{\frac{1}{2}}$$



Girart+06

NGC 1333 IRAS 4A

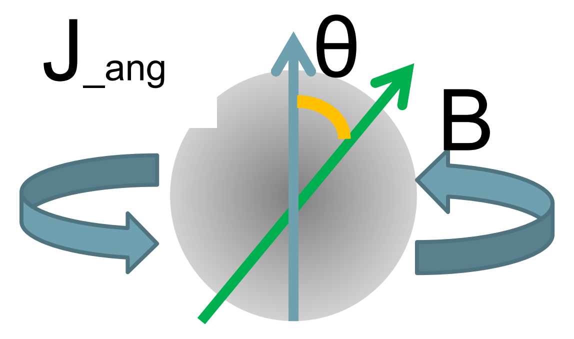


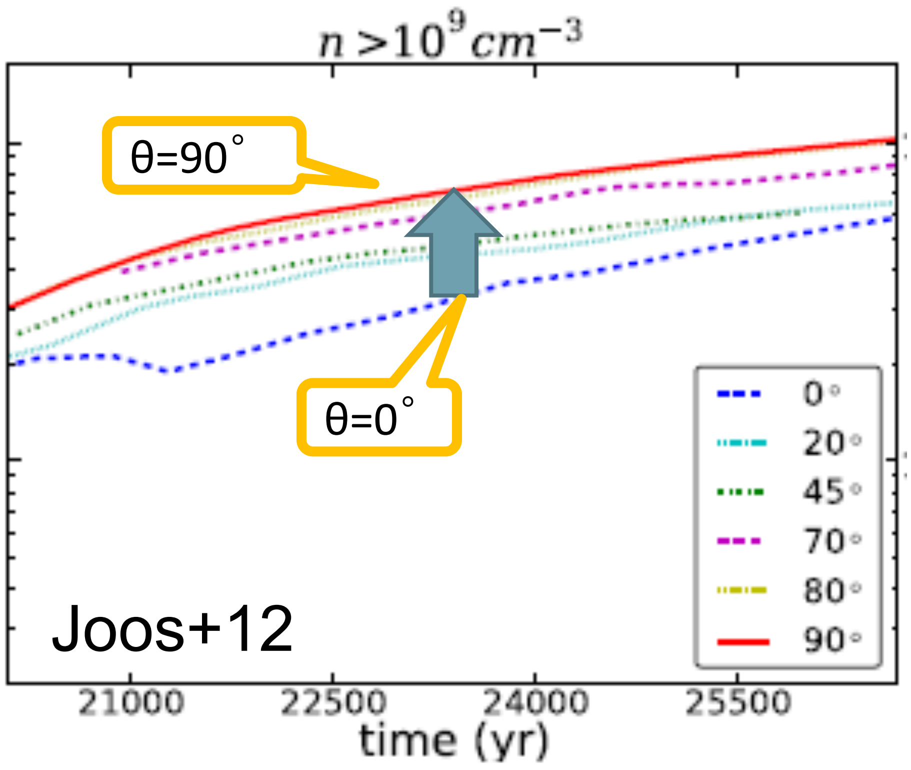
Does magnetic braking really enforce B || J?

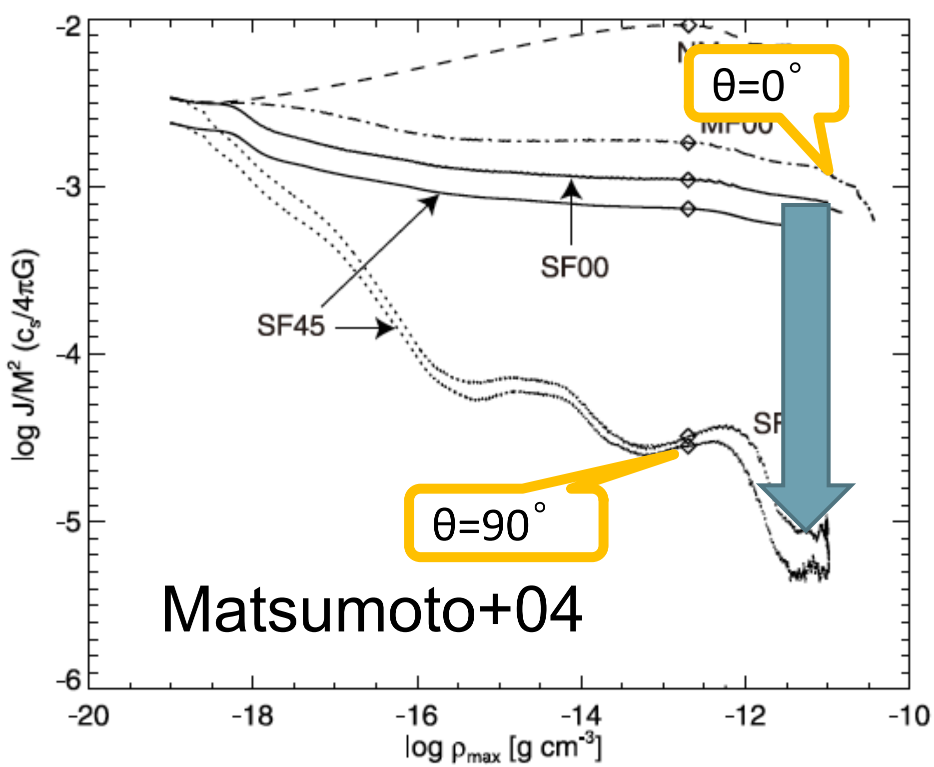
- Ideal MHD studies
  - Magnetic braking is efficient when B||J

→J⊥B tends to realized (Hennebell+09, Joos+12).
⇔ B||J tends to be realized (Mouschovias+85, Matsumoto+04)

- Resistive MHD study
  - Magnetic braking efficiency is almost unchanged (non-ideal MHD:Masson+16)







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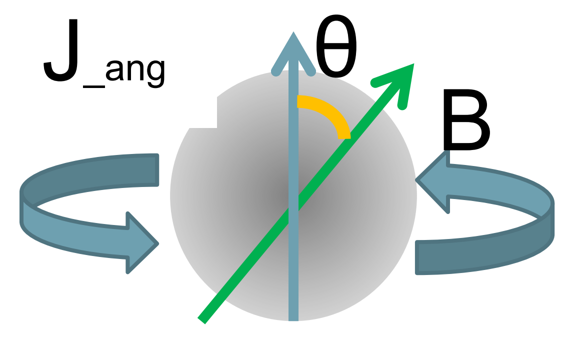
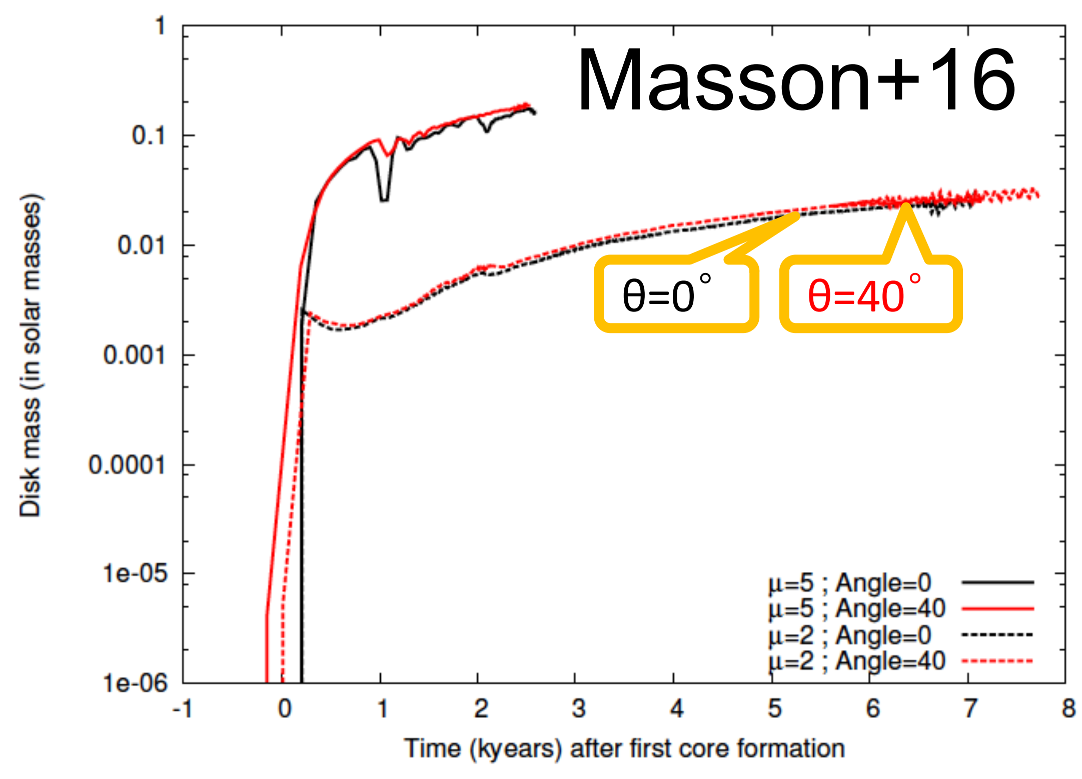




Purpose of this study

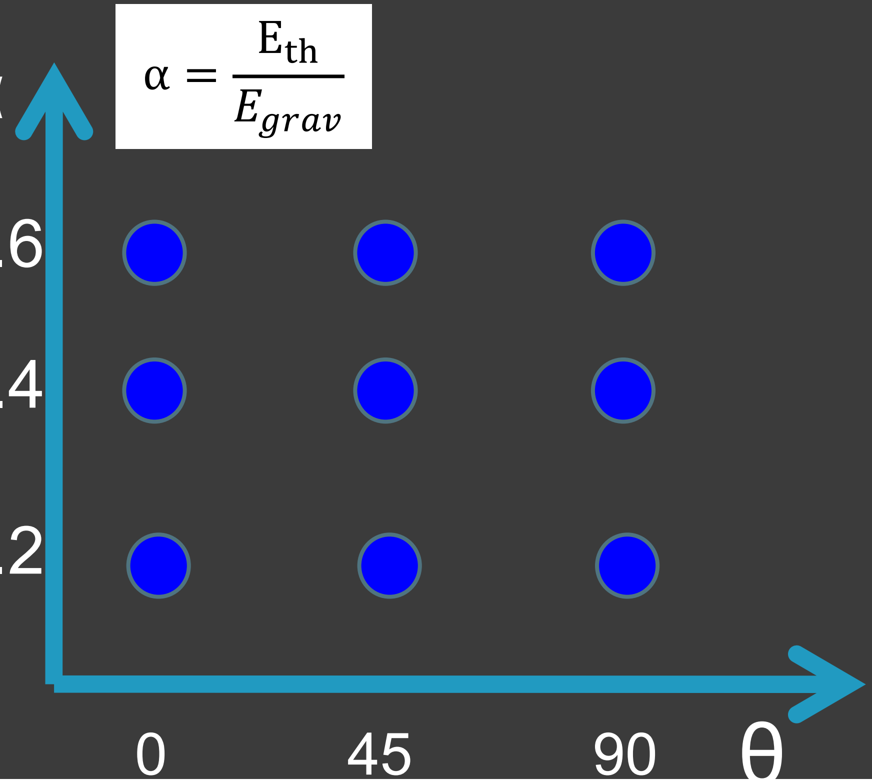
- Resolve the discrepancy of the previous studies
- Reveal the nature of the magnetic braking in cloud core collapse
- We particularly focus on
  - The Initial conditions
    - Matsumoto+04: Bonnor-Ebert sphere, $\alpha=0.5$
    - Joos+12: $\rho = \frac{\rho_0}{1+(r/r_0)^2}$, $\alpha=0.25$
  - Magnetic diffusion(ohm, ambipolar diff.)
    - Matsumoto+04, Joos+12:ideal MHD
    - Masson+: resistive MHD (uniform sphere, $\alpha=0.25$)

$$\alpha = \frac{\mathrm{E_{th}}}{E_{grav}}$$

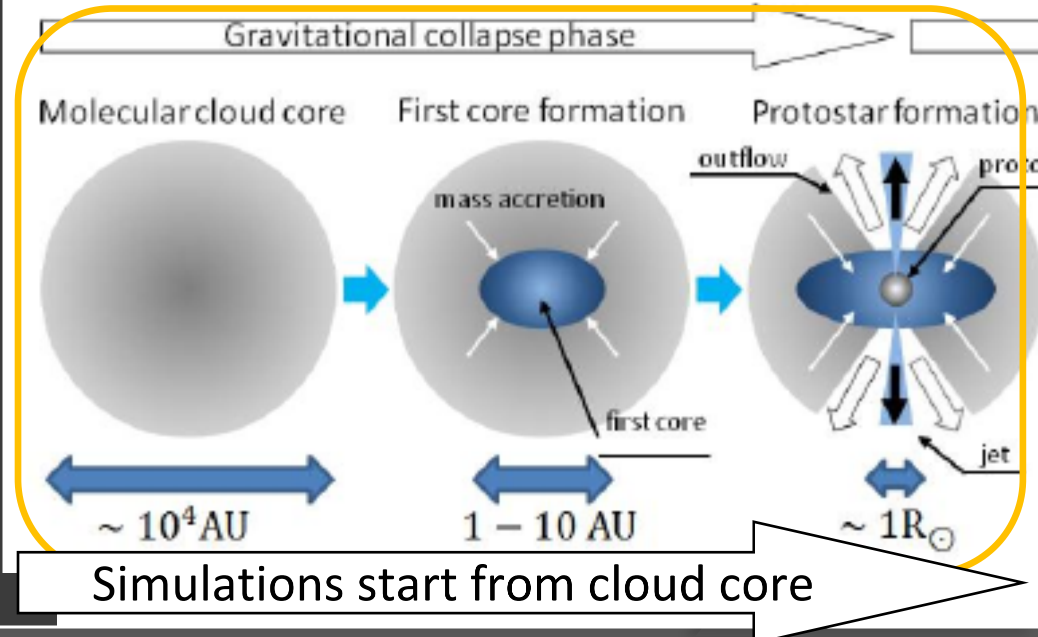
Numerical methods and models

- methods: non-ideal Godunov SPMHD (Iwasaki+11, YT13) with FLD (Whitehouse+05)
- Initial condtions: uniform cloud cores with M = 1 Msolar (β=0.03)
- Both ideal and resistive (Ohm+ambipolar diff.) MHD simulations are conducted.

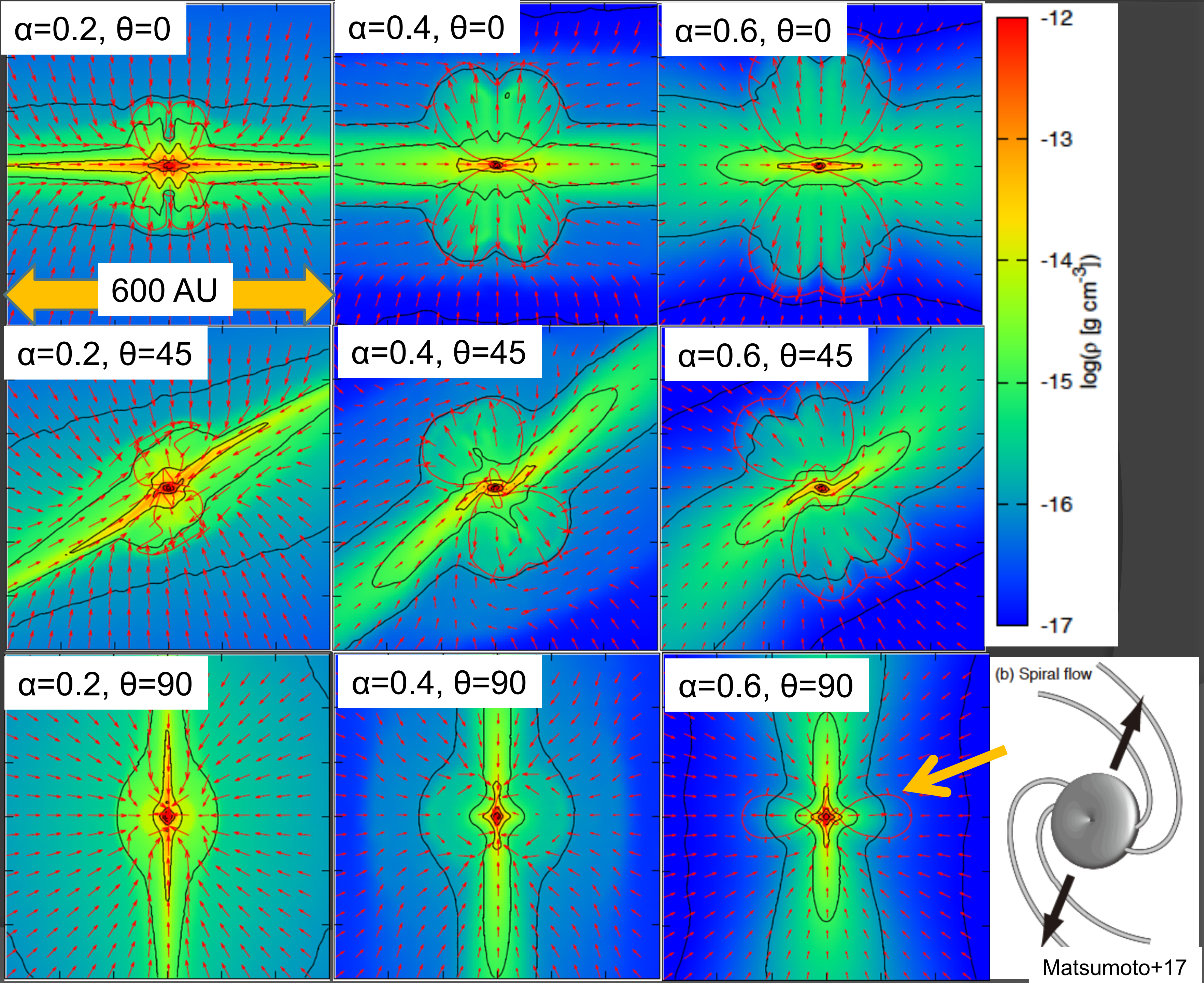
$$\alpha = \frac{E_{\rm th}}{E_{grav}}$$



$$\frac{M/\Phi}{(M/\Phi)_{\rm crit}} = 4.0$$



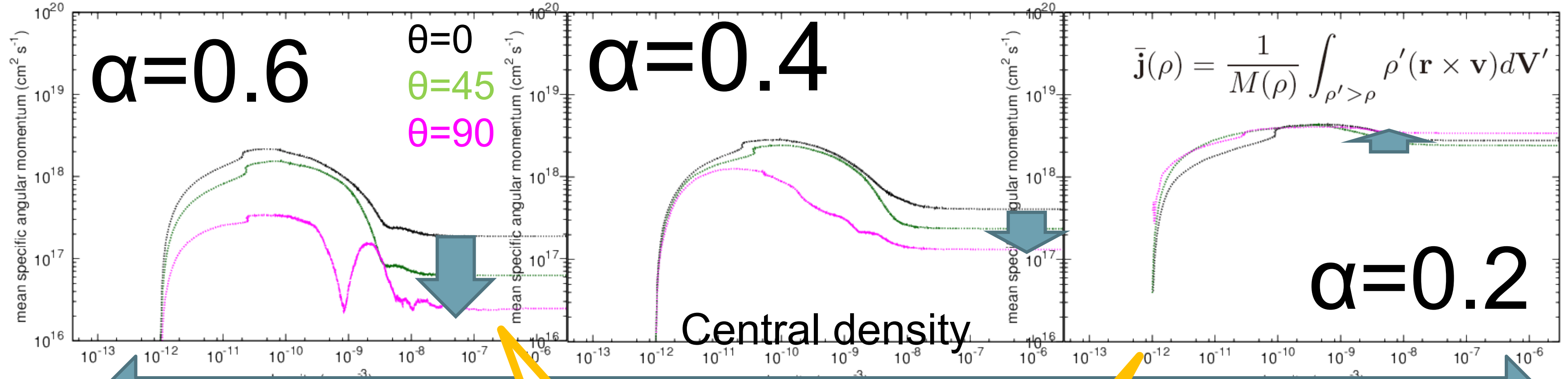
Simulations start from cloud core



Matsumoto+17

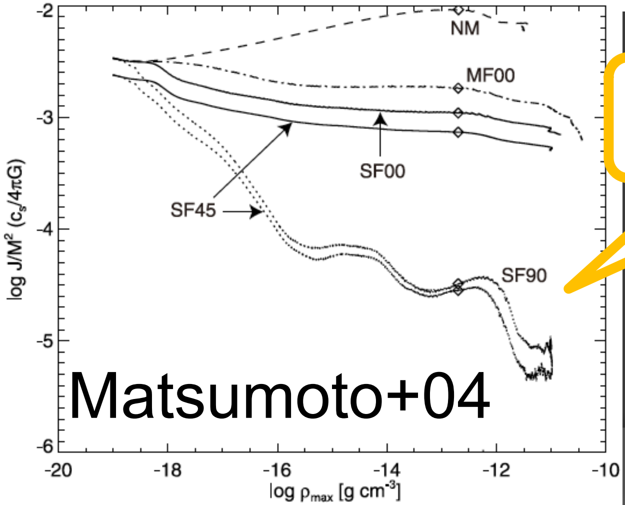
Evolution of central J ($\rho>10^{-12}$g/cc Ideal simulaiton)

- As α of initial core decreases, J of θ=90 increases quickly
- We obtained the consistent results with previous studies



$$\bar{\mathbf{j}}(\rho) = \frac{1}{M(\rho)}\int_{\rho'>\rho} \rho'(\mathbf{r}\times\mathbf{v})d\mathbf{V}'$$

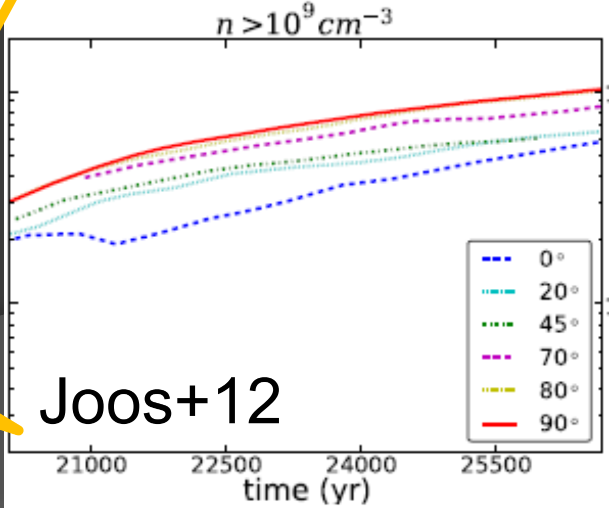
large α small



Matsumoto+04

consistent

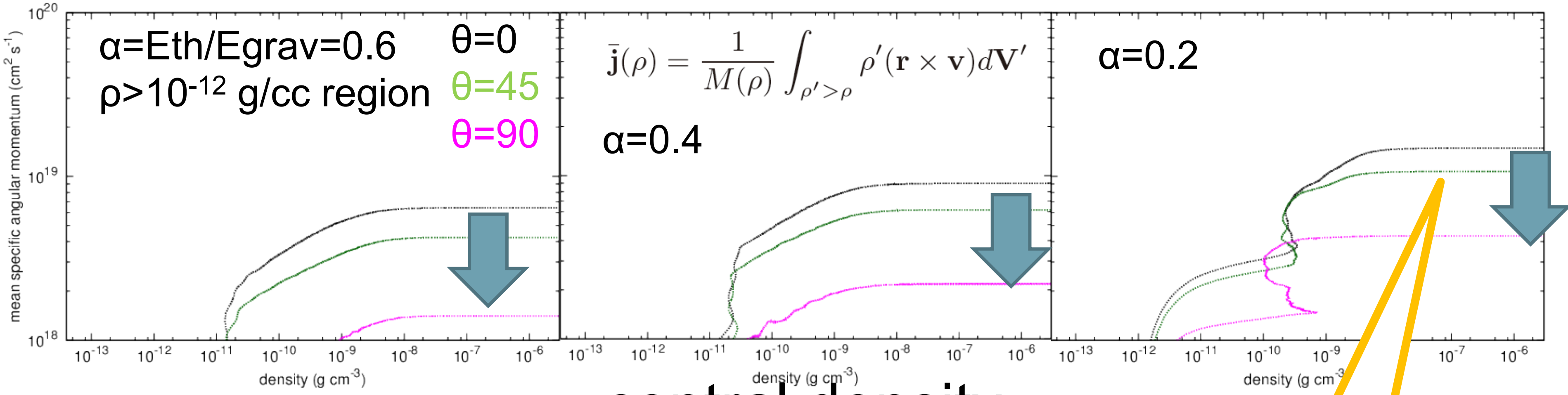
consistent



Joos+12

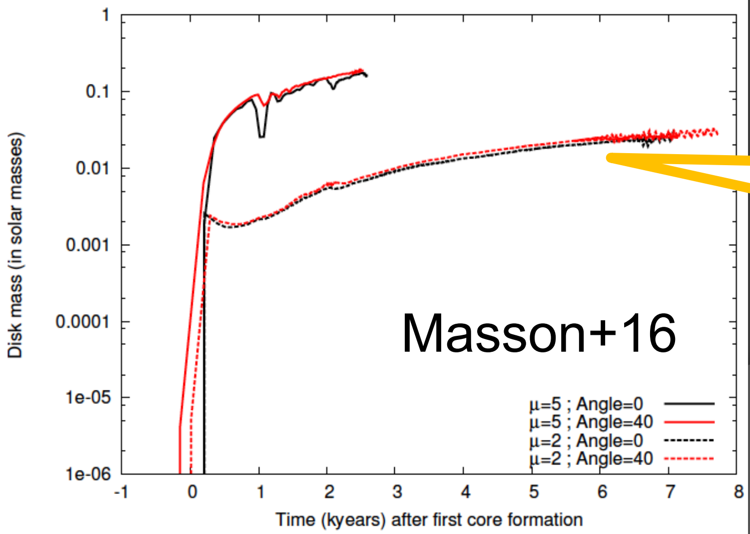
Evolution of central J ($\rho>10^{-12}$g/cc, resistive)

- In all simulations with magnetic diffusion, J of the central region decreases as θ increases. (consistent with Matsumoto+04)
- Difference between θ=0, 45 is quite small and roughly consistent with Masson+16



$$\bar{\mathbf{j}}(\rho) = \frac{1}{M(\rho)} \int_{\rho'>\rho} \rho'(\mathbf{r}\times\mathbf{v})d\mathbf{V}'$$

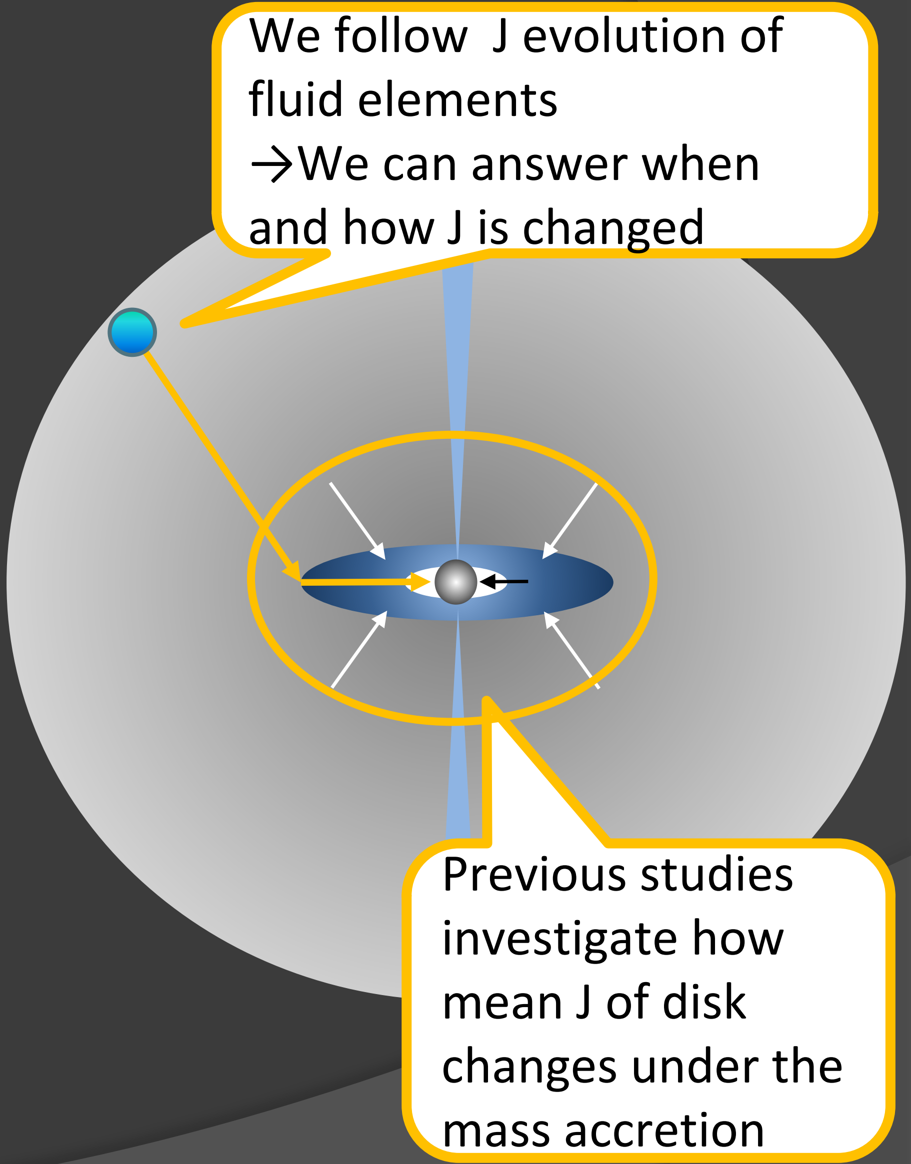
central density



Roughly consistent

Why do the results depend on the initial condition?

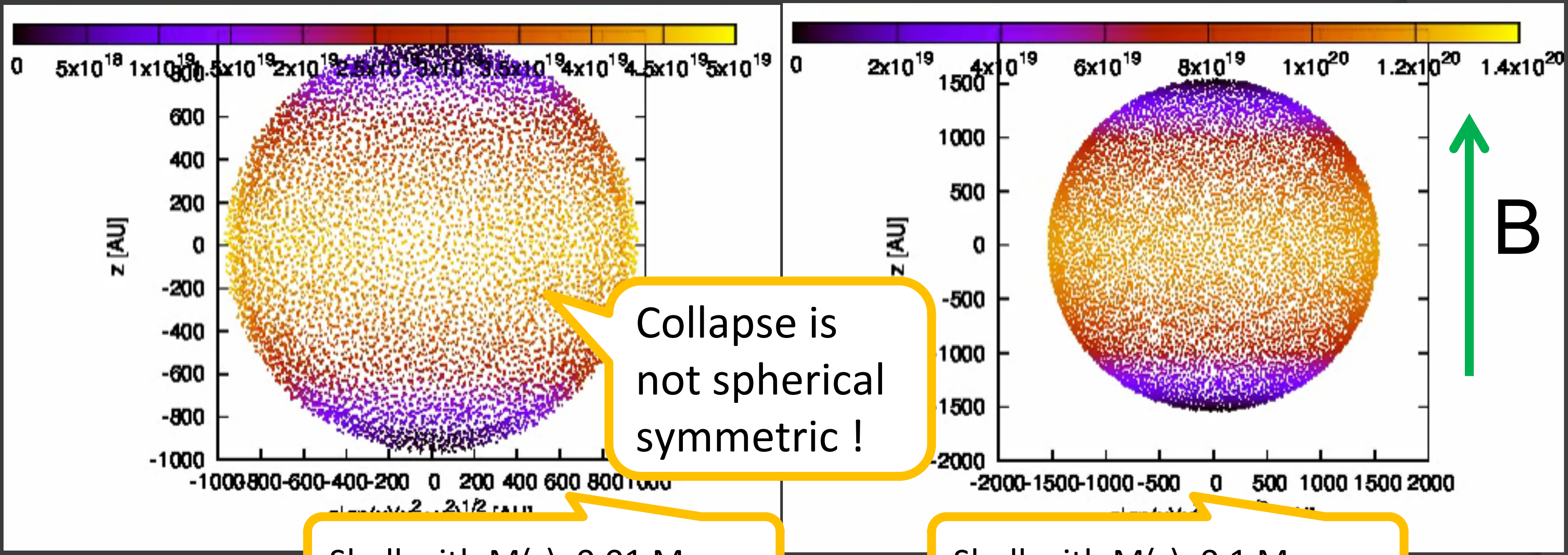
- When and how the magnetic braking changes the gas angular momentum have been ambiguous because previous studies only investigate the J evolution of the central disk
- To reveal the physical mechanism, we should investigate the angular momentum evolution of fluid elements.



We follow J evolution of fluid elements
→We can answer when and how J is changed

Previous studies investigate how mean J of disk changes under the mass accretion

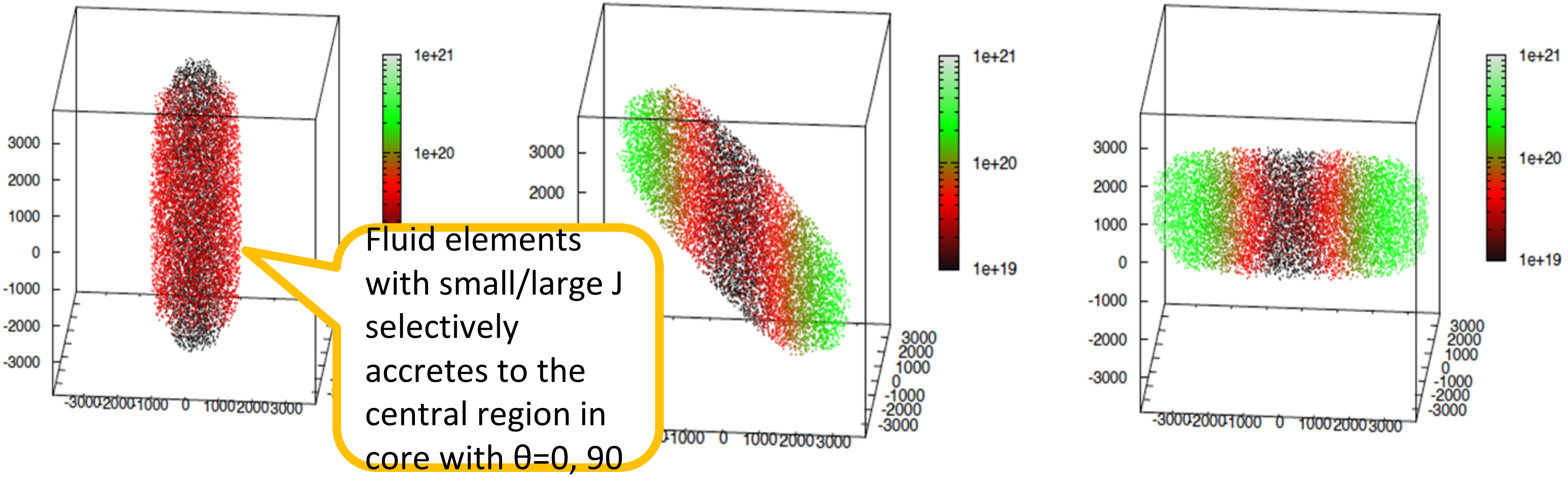
Non-spherical collapse and apparent enhancement of magnetic braking



Collapse is not spherical symmetric !

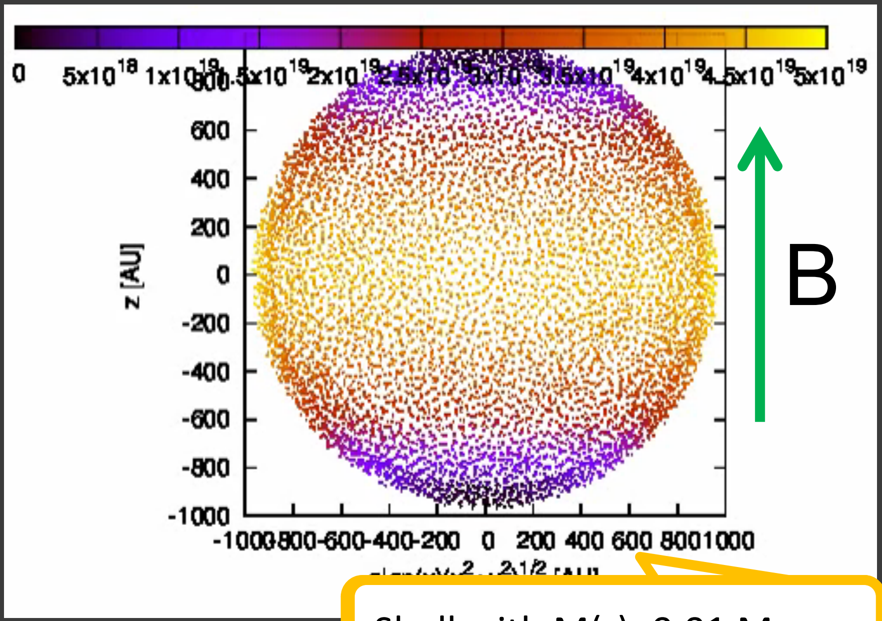
Shell with M(r)=0.01 Msun

Shell with M(r)=0.1 Msun



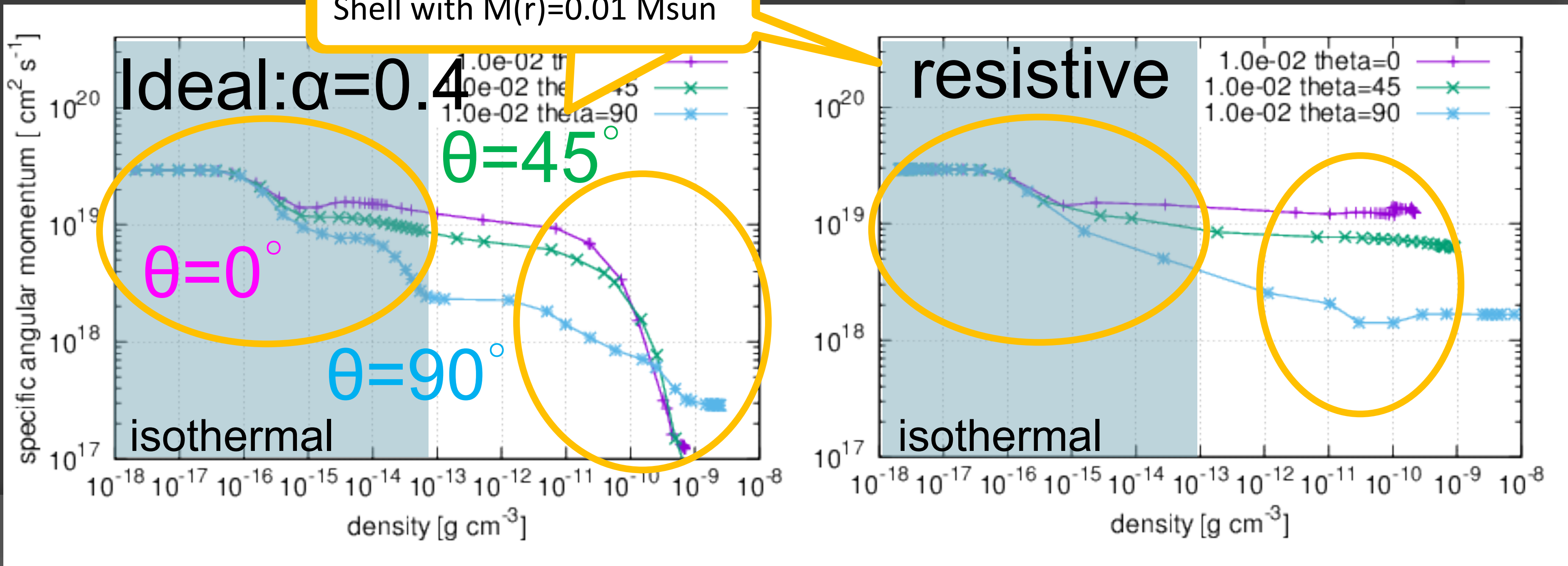
Fluid elements with small/large J selectively accretes to the central region in core with θ=0, 90

Angular momentum evolution of the spherical shell



- In isothermal collapse phase: magnetic braking is stronger in model with θ=90
- Ideal: strong magnetic braking in adiabatic/rotationally supported phase.
- Non-ideal: magnetic braking is suppressed in adiabatic/rotationally supported phase.

Shell with M(r)=0.01 Msun



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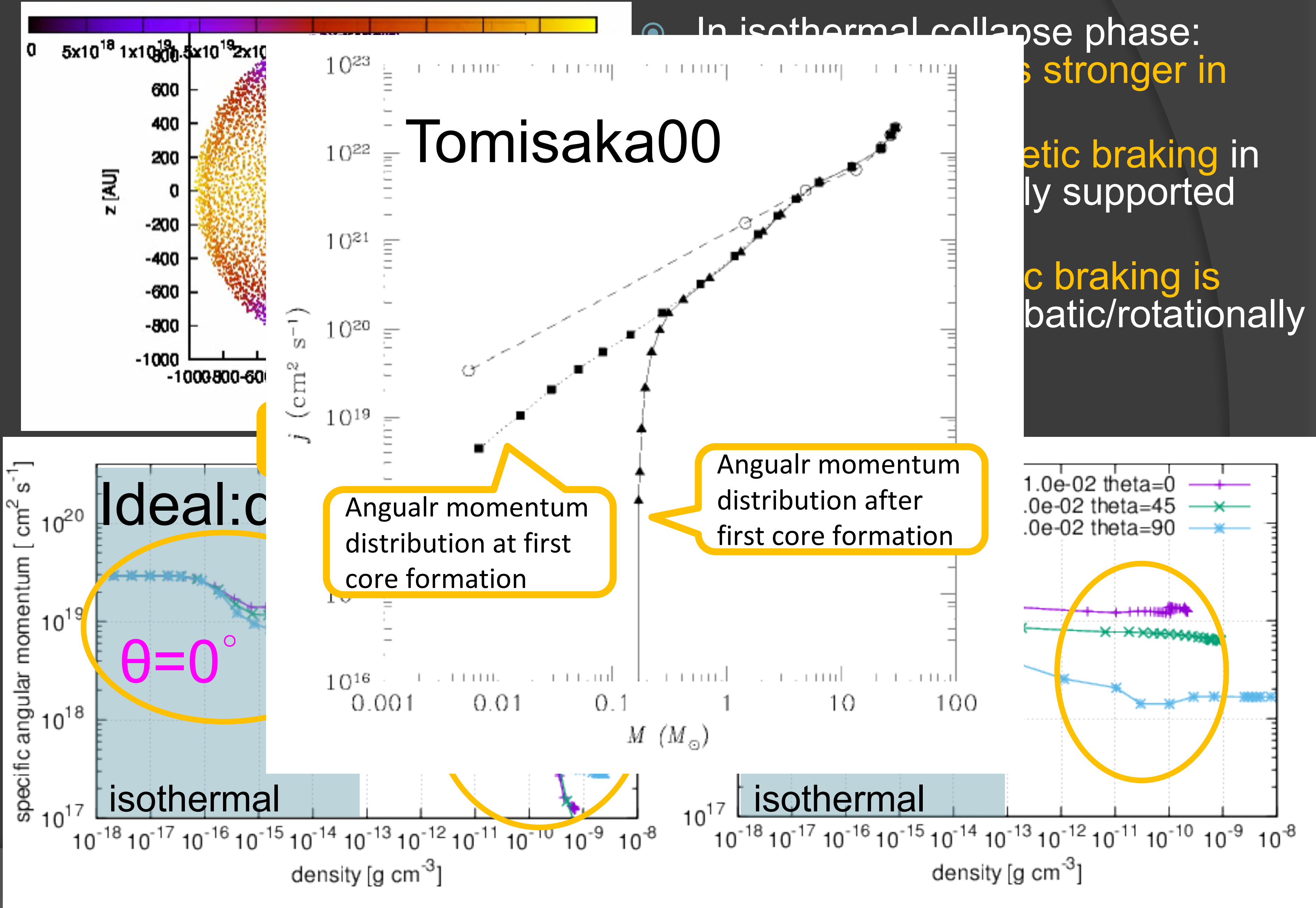
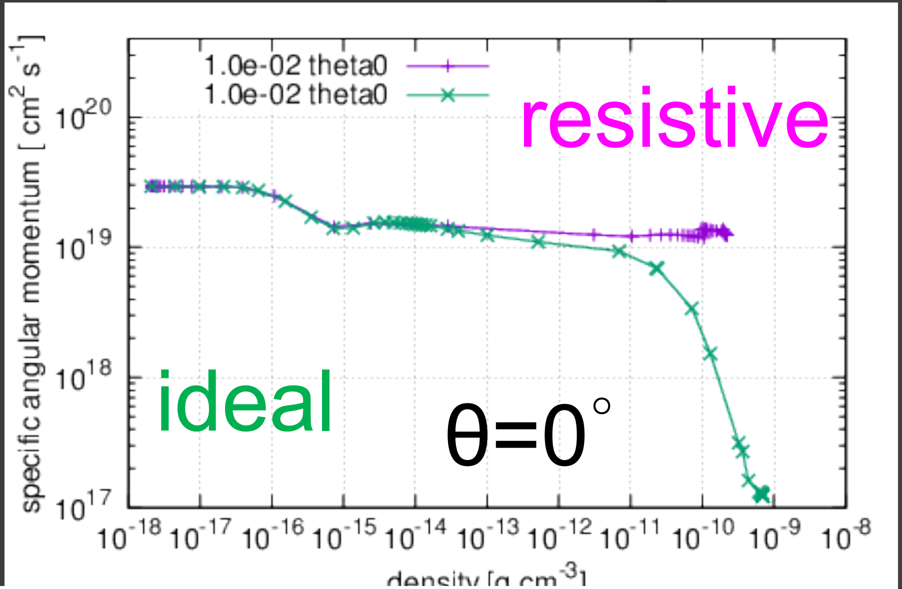


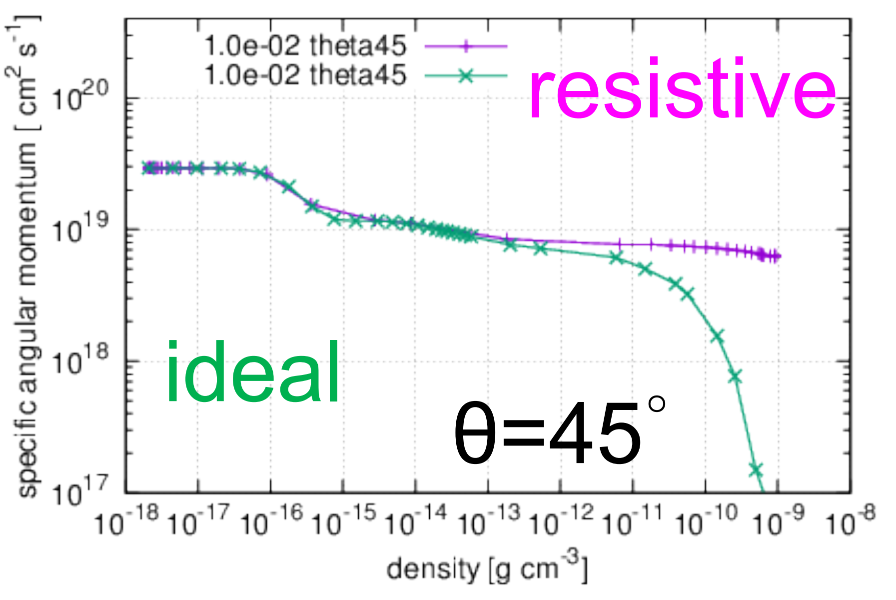
Angualr momentum distribution at first core formation

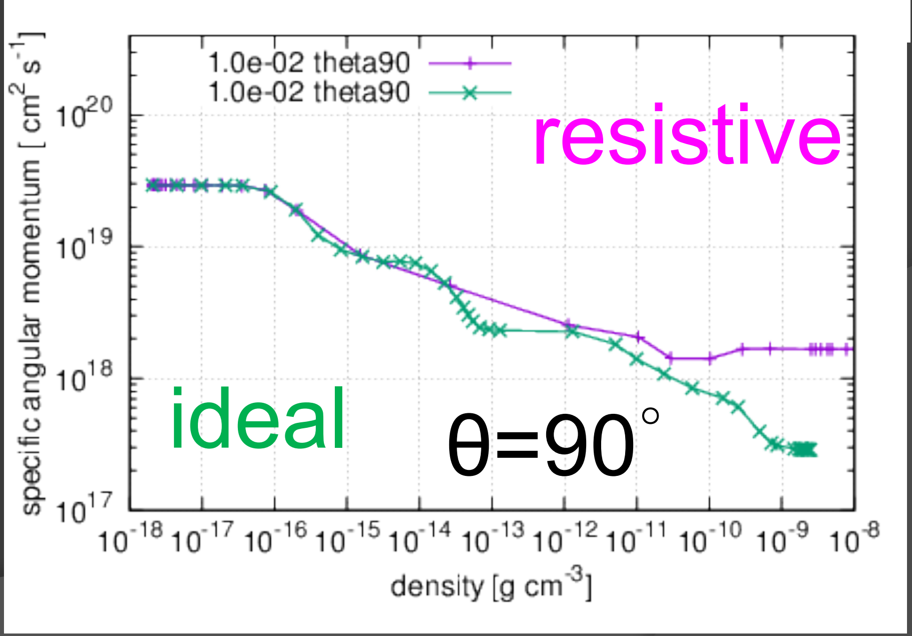
Angualr momentum distribution after first core formation

Comparison between ideal and resistive

- Evolution in isothermal phase is essentially the same.
- Magnetic resistivity (Ohm and ambipolar) changes the angular momentum evolution in $\rho>10^{-13}$g cm^{-3}





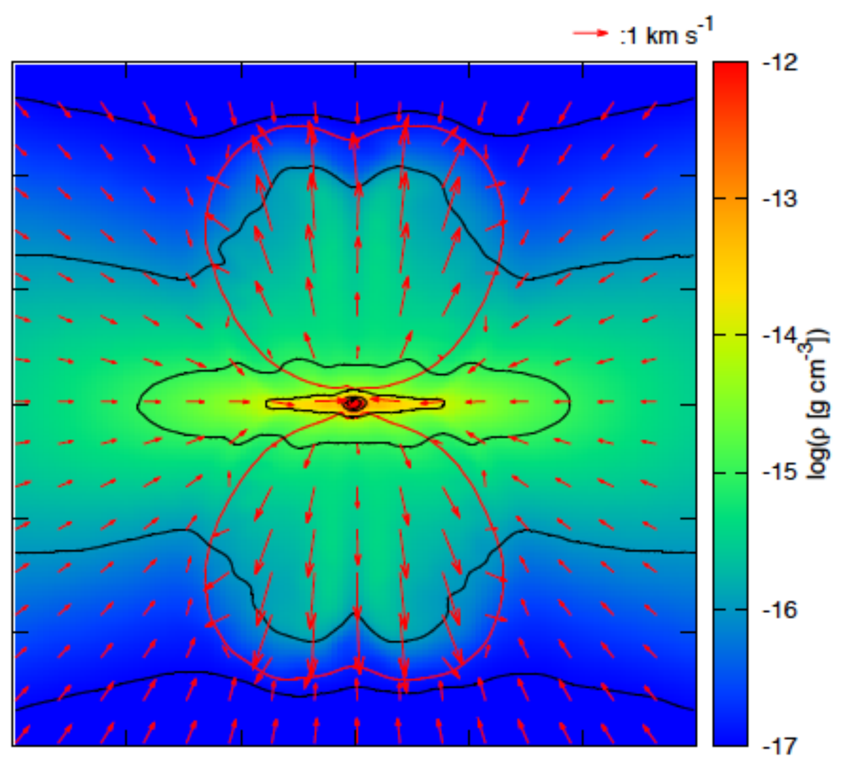


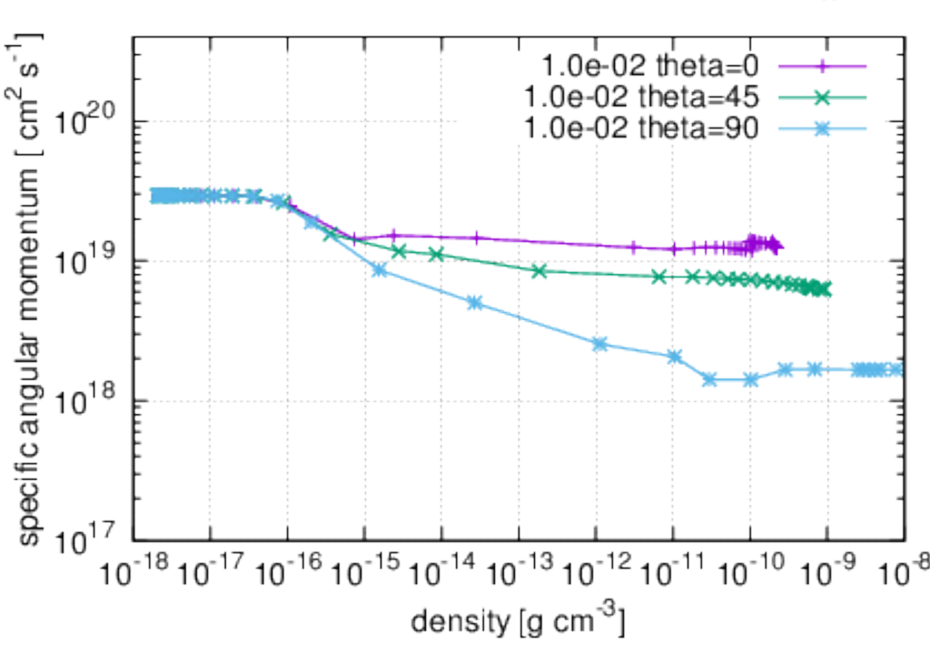
Summary and discussion

- We investigated the magnetic braking in misaligned cloud cores and almost all previous results are reproduced.
- Results
  - In isothermal collapse phase, magnetic braking is strong when B ⊥ J

  →If magnetic filed is dynamically important in isothemal phase or envelope (r~1000AU scale), B || J realizes!

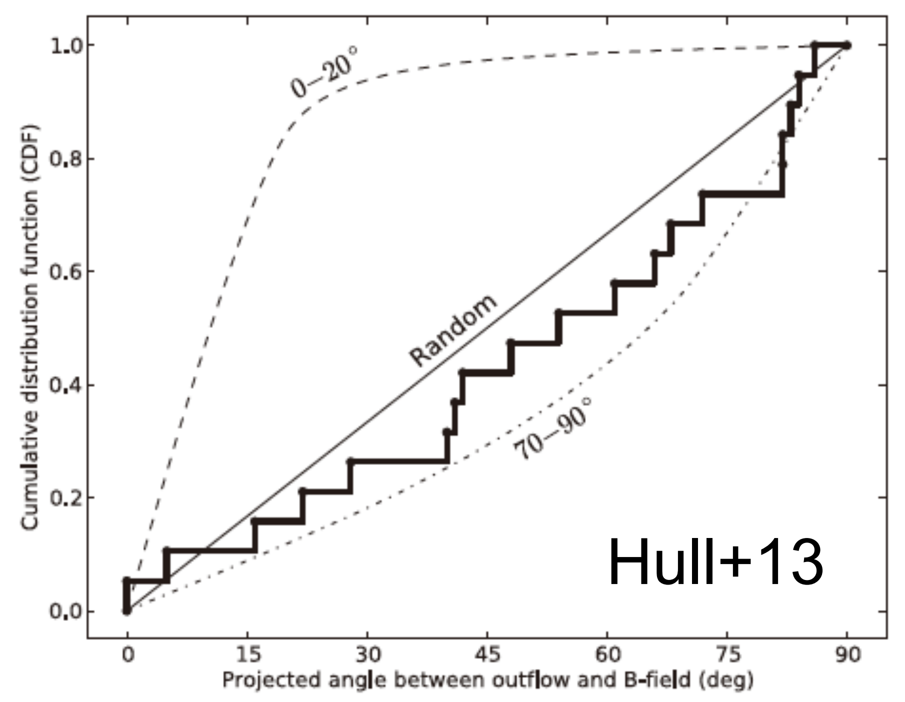
  - Once magnetic diffusion is included (more realistic simulation), the central angular momentum (or disk size) is always larger in B||J case
- Discussion
  - With multiscale observation of polarization, we can determine the scale at which the magnetic braking is dynamically important !

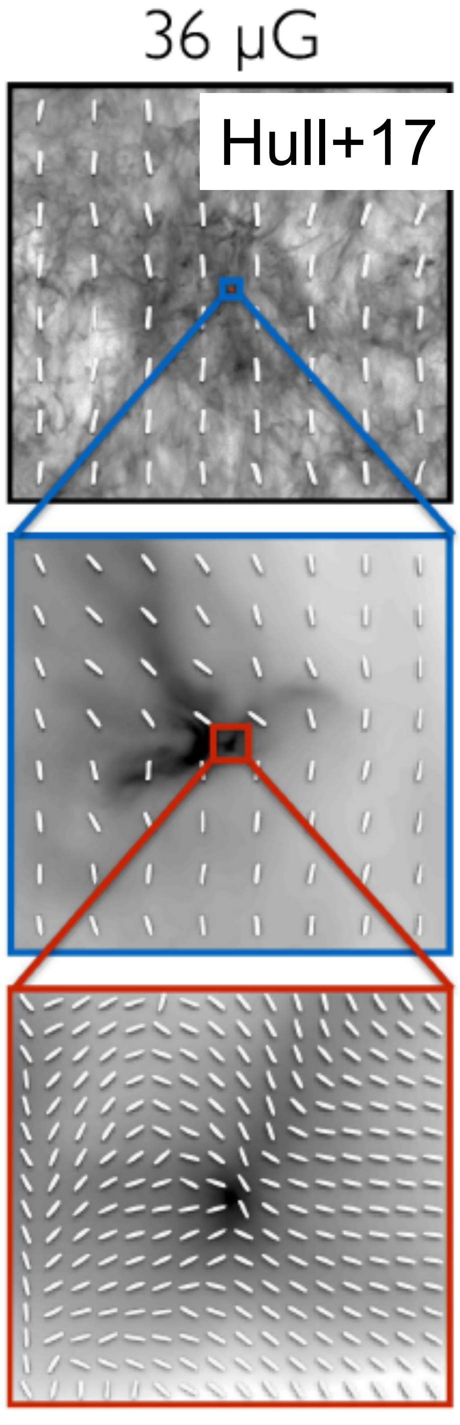




Summary and discussion

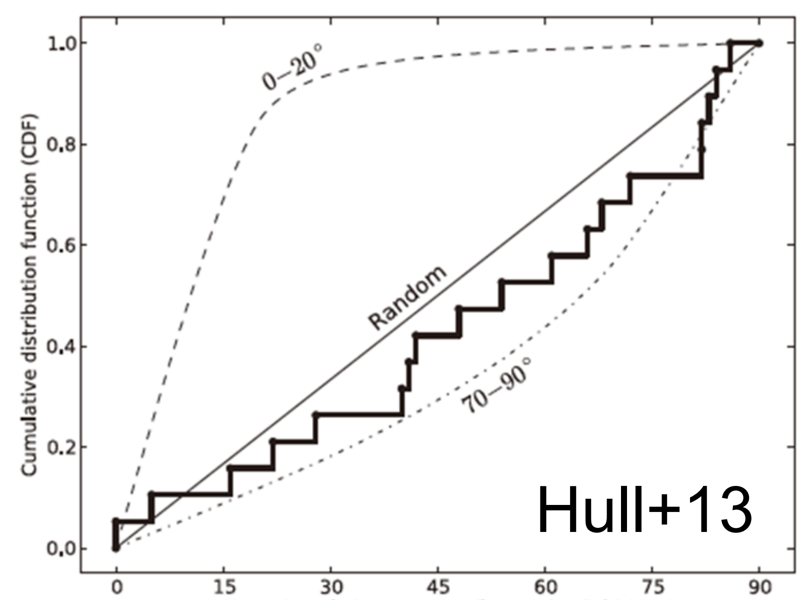
- Hull+13 showed that B of core scale is not aligned with outflow direction (J direction)
- This suggests :
  - ~~The magnetic braking is efficient but it does not enforce J || B.~~
  - The magnetic field is dynamically unimportant at the observed scale(turbulence is strong or magnetic field is weak)

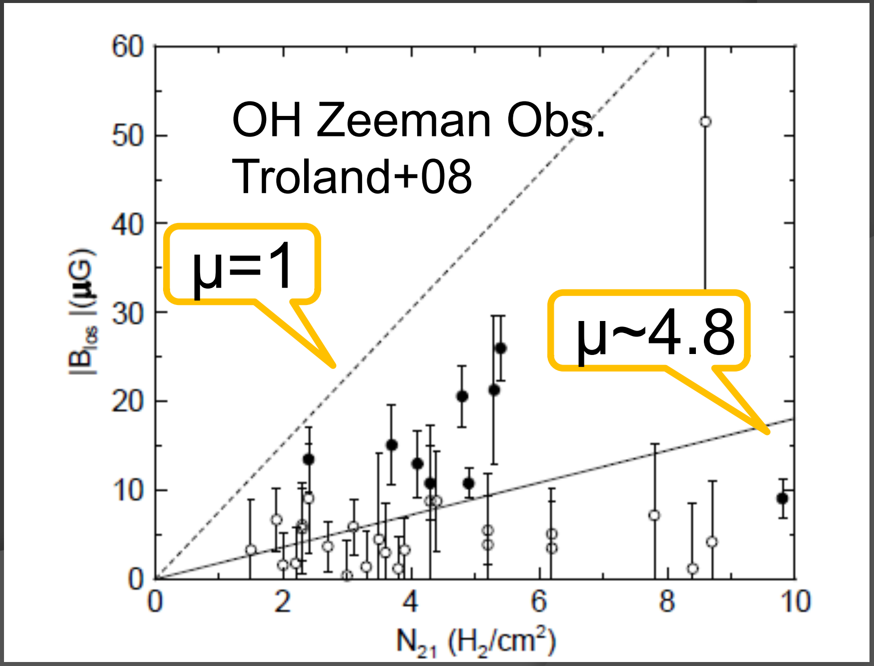




Remaining questions

- Magnetic field is weak in the core scale?
  - How can we explain the Zeeman obs?
- Turbulence in cloud core is strong?
  - Simulations tends to produce the cores with strong turbulence(supersonic, Klessen+05)
  - Observation does not show supersonic line width. i.e., subsonic turbulence (Andre+06, Lada+07). Angular momentum problem also becomes serious.





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