原始惑星系円盤におけるダスト偏光と磁場

Grain alignment in protoplanetary disks

Ryo Tazaki

Astronomical Institute, Tohoku University

Collaborators: A. Lazarian and H. Nomura

1. Introduction
2. Grain alignment in the ISM
3. Grain alignment in protoplanetary disks
4. Discussion : Alignment efficiency
5. Summary

原始惑星系円盤におけるダスト偏光と磁場

Grain alignment in protoplanetary disks

Ryo Tazaki

Astronomical Institute, Tohoku University

Collaborators: A. Lazarian and H. Nomura

1. Introduction
2.
3.
4.
5. Summary

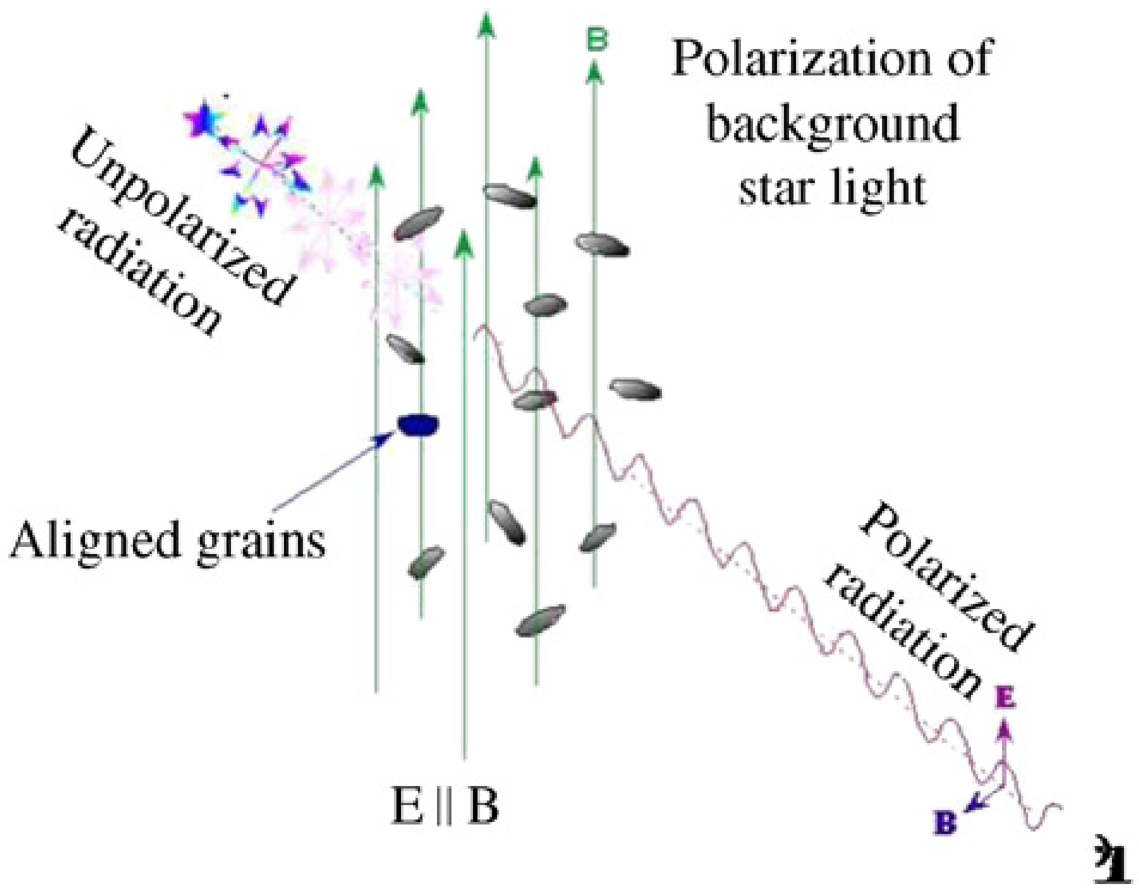
Take home message:
Radiative torque alignment theory predicts that alignment axis is not necessary to be B-field!

Grain alignment and polarization

Lazarian (2007)

a

optical

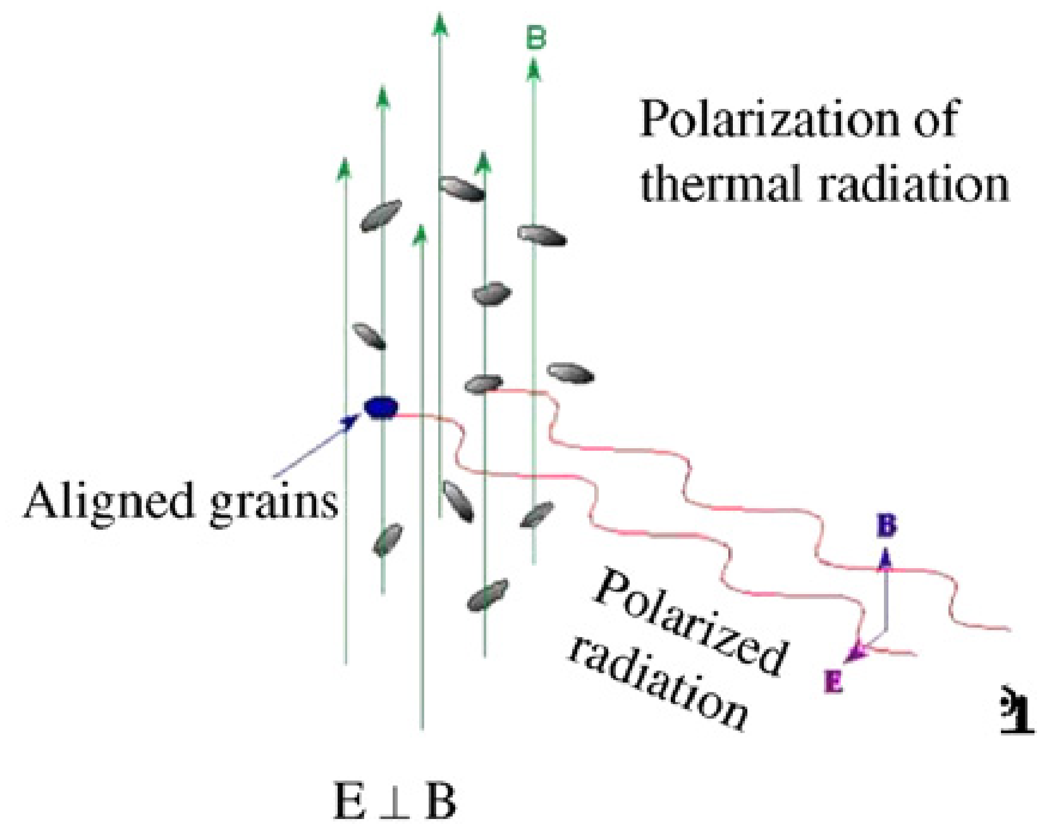


polarization E || B

(absorption)

b

FIR/mm



polarization E ⊥ B

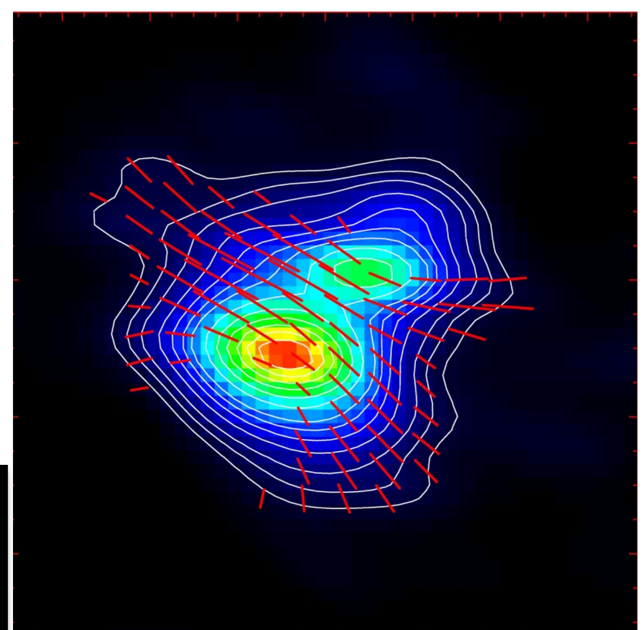
(emission)

Tracing tool of B-field structure

Protoplanetary disks
(~ 100 au)

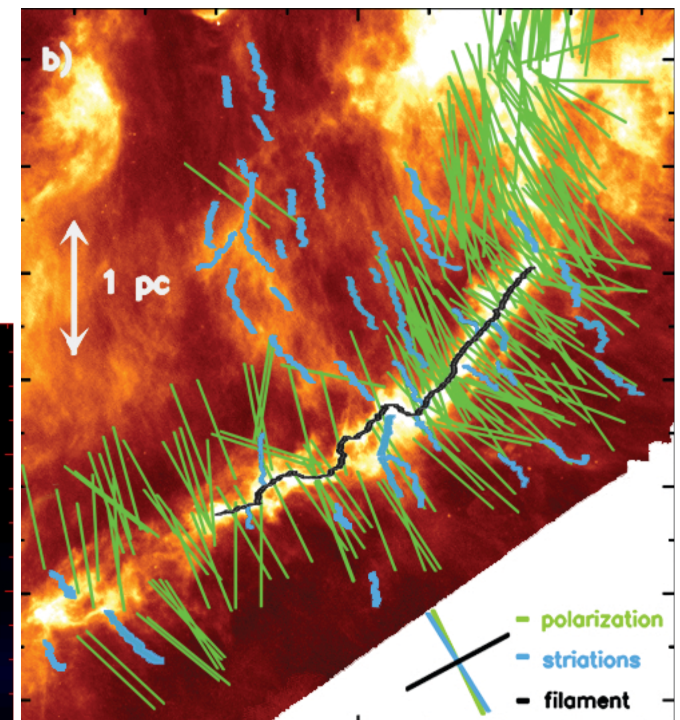
ALMA!

cloud core
(~1000 au)



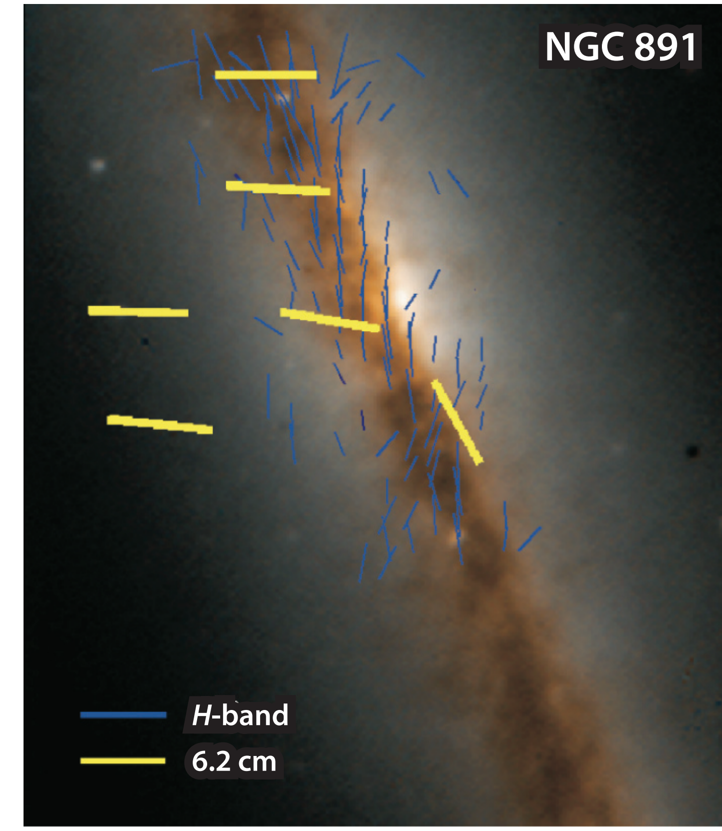
Girart+ (2006)

molecular cloud



Palmeirin+ (2013)

ISM



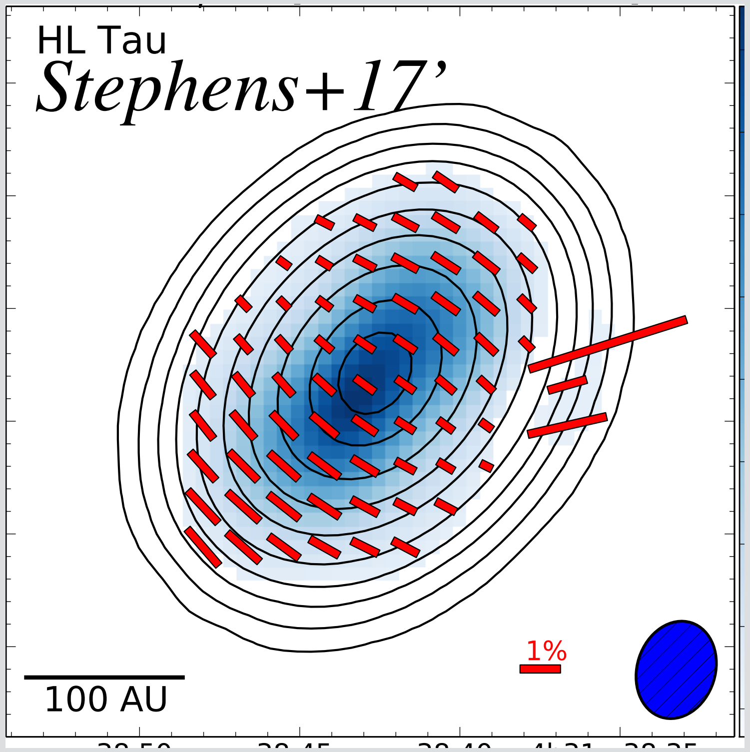
Andersson et al. 2015

Linear polarization of HL Tau by ALMA

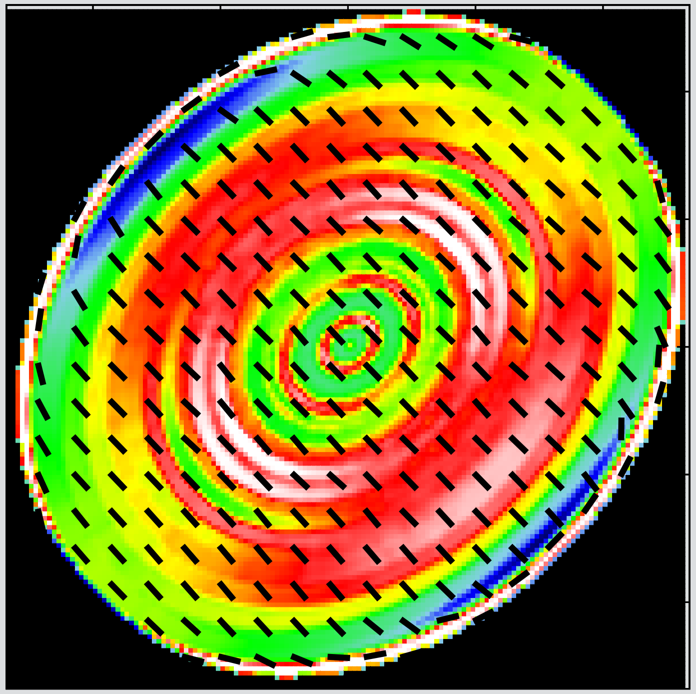
＊ E-vectors are shown!

Scattering polarization

HL Tau (λ=870 μm)

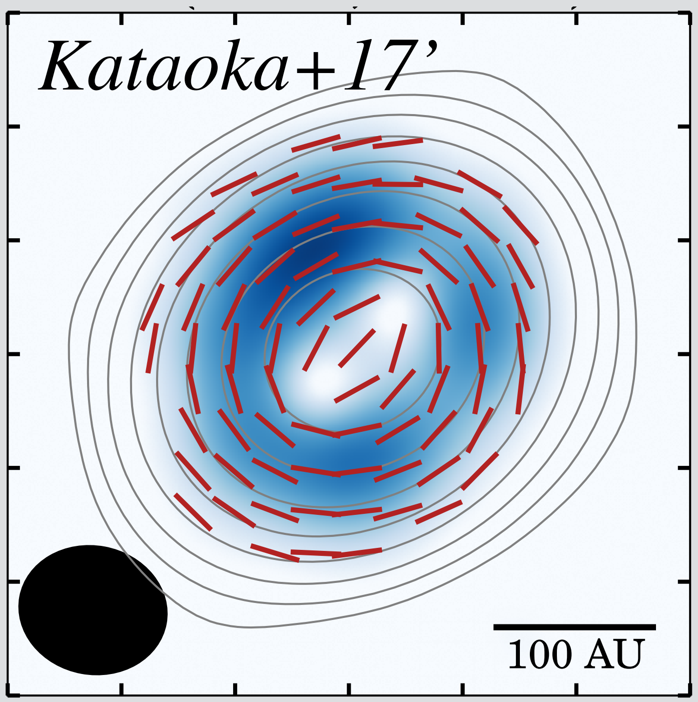


Model (Kataoka+15')



alignment…?

HL Tau (λ=3.1 mm)



Does grain alignment with B-field really happen?

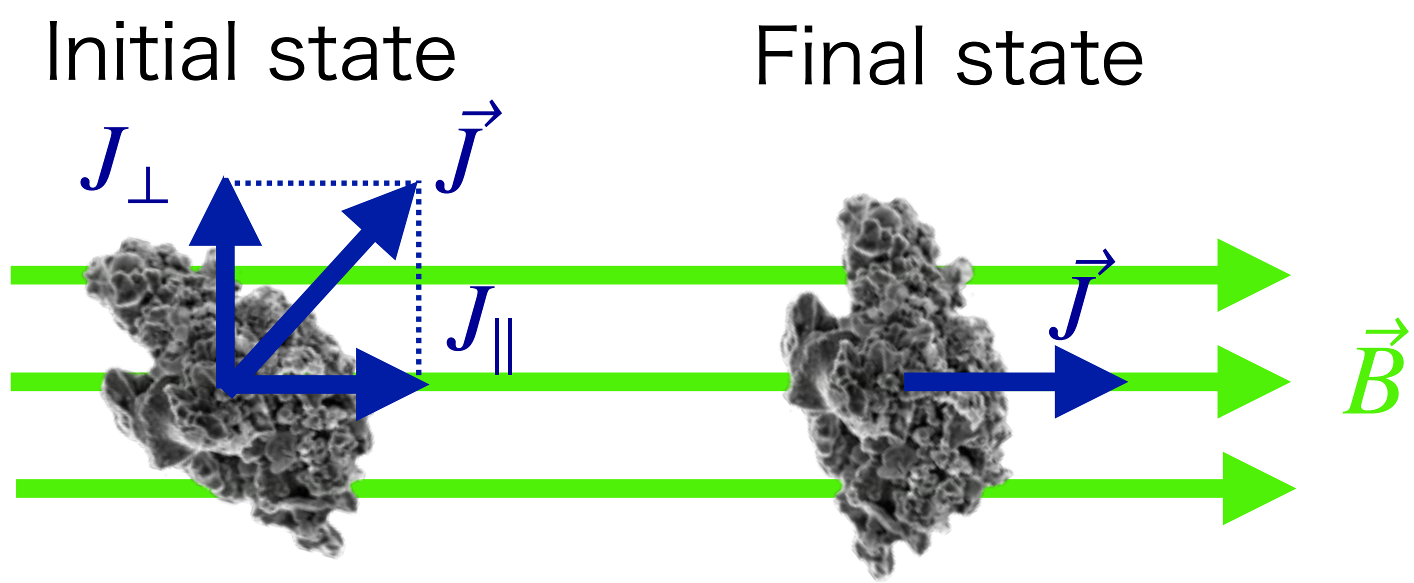
Outline

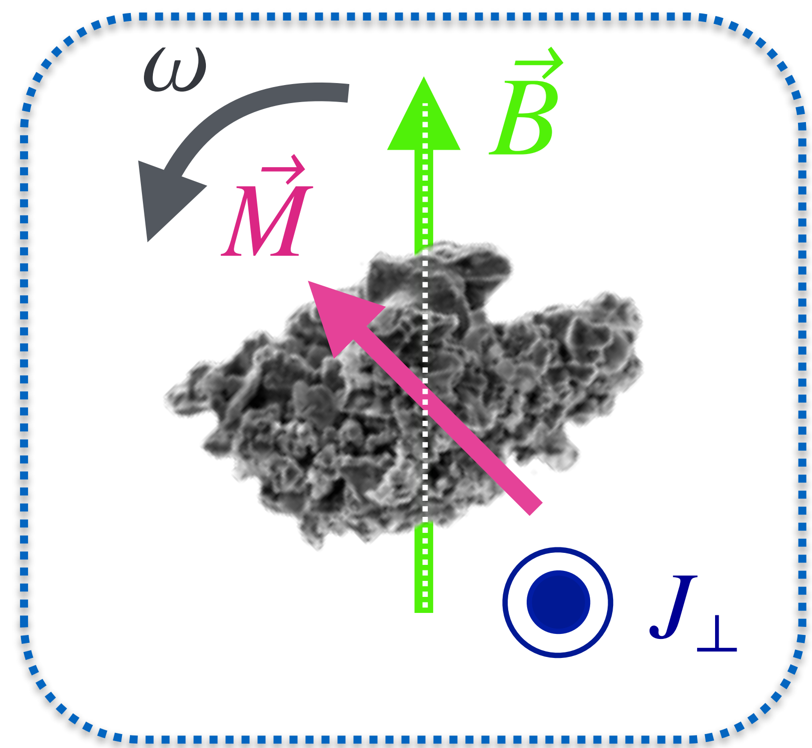
1. Introduction
2. Grain alignment in the ISM
3. Grain alignment in protoplanetary disks
4. Discussion : Alignment efficiency
5. Summary

Classical theory: Paramagnetic dissipation

Davis & Greenstein (1951), see also Spitzer (1978)

- Dissipation results in non-zero magnetic torque (M×B), which acts to reduce the component of angular momentum perpendicular to B.





※ assume angular momentum vector ll minor axis (so-called “internal alignment”)

- But, this alignment process takes place slowly…

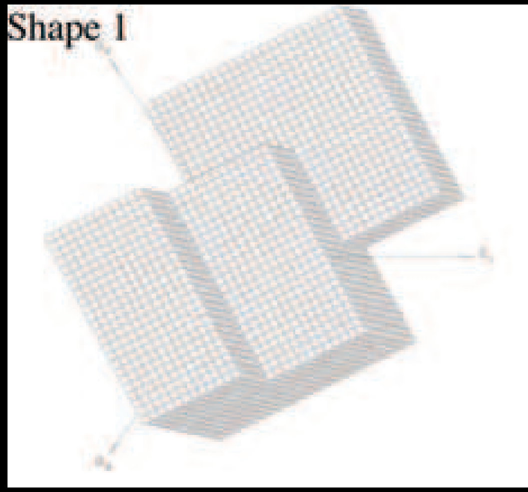
$$t_{\rm DG} \approx 1.5 \times 10^6 {\rm yr} \left(\frac{a}{0.1\ \mu{\rm m}}\right)^2$$ >> gas collision(damping) timescale

Fast alignment mechanism? → radiative torque (RAT)

- Dolginov & Mitrophanov (1976):
  Spin-up of helical grains by left- and right-handed photons
- Draine & Weingartner (1996, 1997)

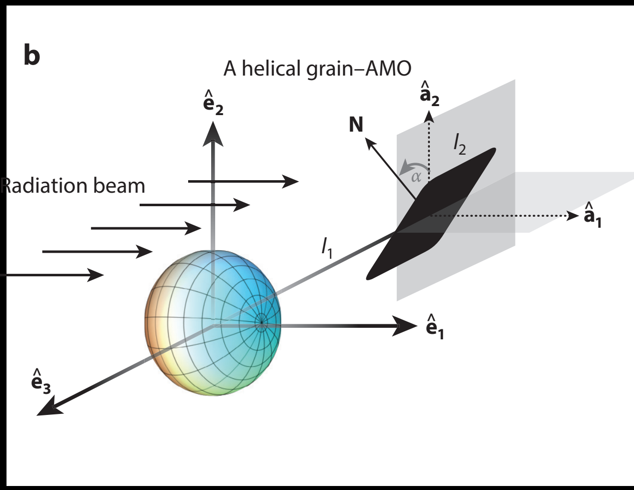
RAT is important! RATs from anisotropic radiation field result in *rapid grain alignment* with B-field even in the absence of the paramagnetic dissipation!

https://web.astro.princeton.edu/people/bruce-draine



- Lazarian & Hoang (2007)

RAT alignment can be understood by a simple helical grain model! The role of RAT is spin-up (down), alignment, and induce precession. RATs often tend to spin-down the grains (see also Weingartner & Draine 2003).

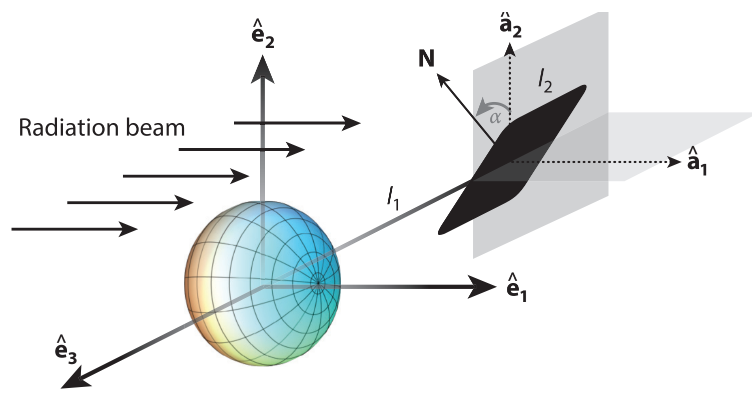


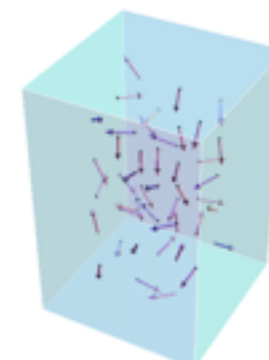
http://www.astro.wisc.edu/~lazarian/

Overview of RAT alignment

Lazarian & Hoang 2007

Helical grain



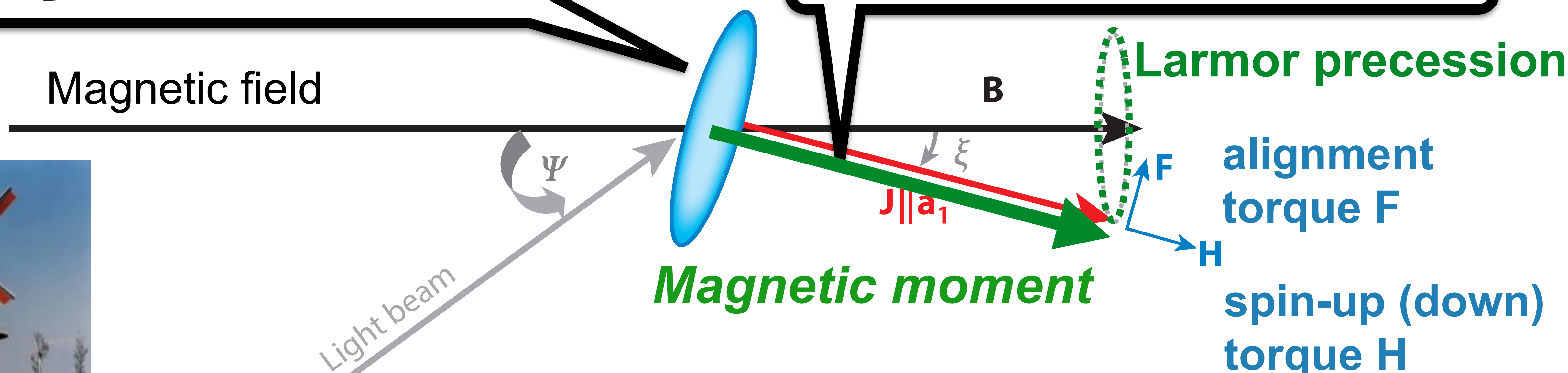


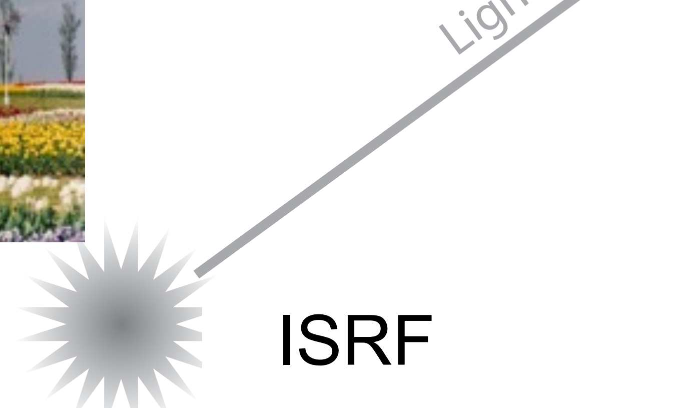
(© M Matsuo)

"Barnett effect"

Magnetization due to grain spinning

(Inverse effect of Einstein-de Haas effect)





Andersson et al. 2015

Larmor precession + radiative torque

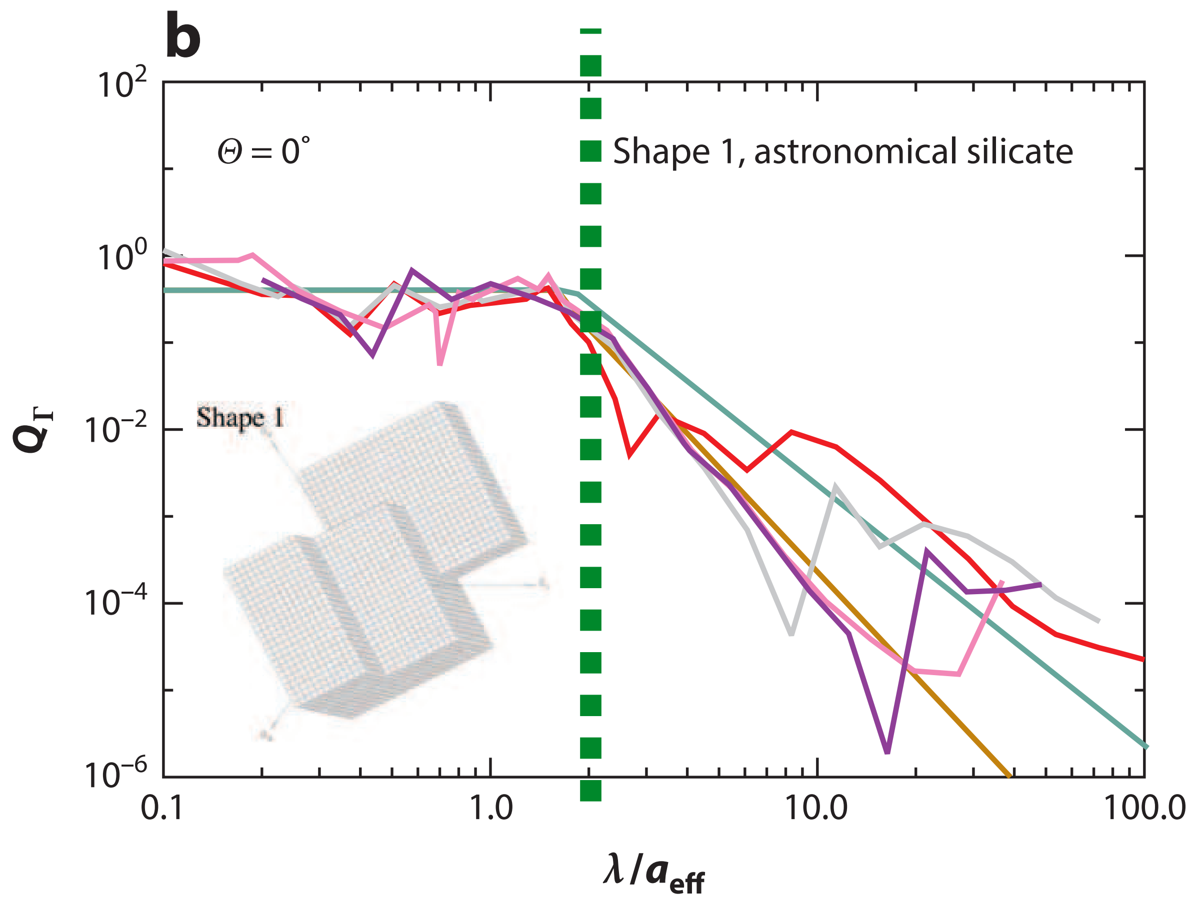
→ alignment with respect to B

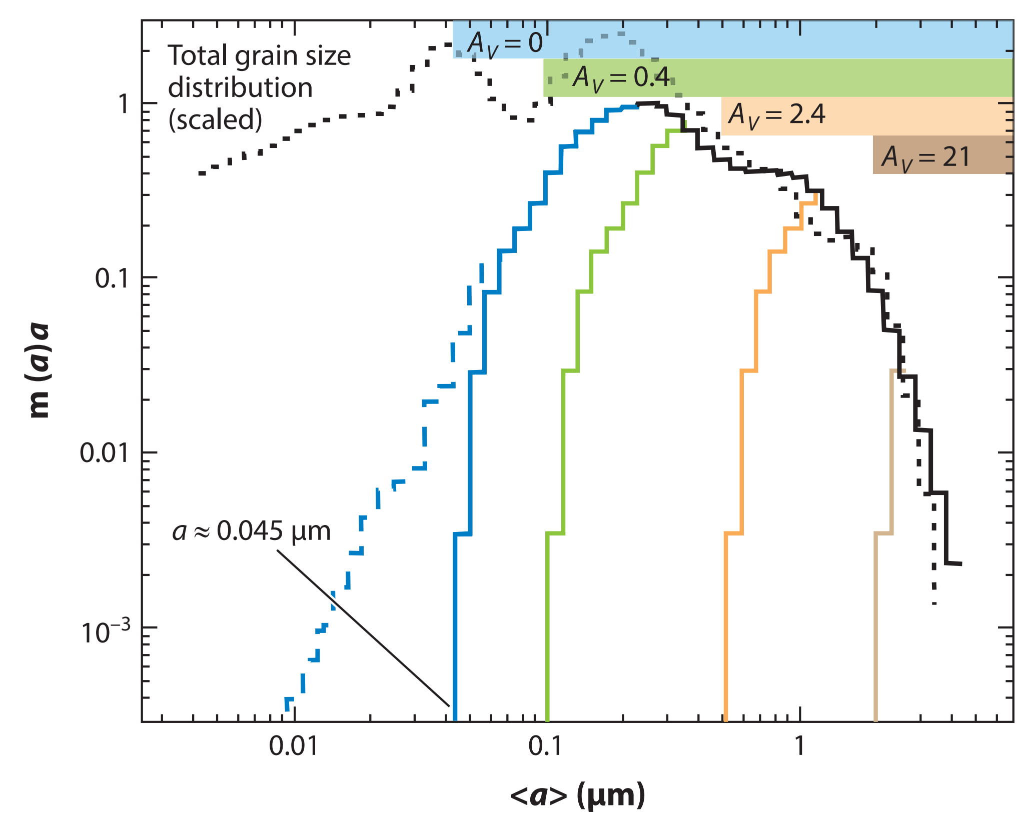
＊ precession axis = alignment axis

Test of RAT alignment by observations

see e.g., Andersson et al. 2015

- In the ISM, larger grains are better aligned.
  - minimum aligned grain size: a ~ 0.045 μm (Kim & Martin 1995)
- In RAT alignment, small grains do not align.
  - minimum aligned grain size : ~ λ(rad field)/2 (Lazarian & Hoang 2007).
  - short wavelength end of ISRF: λ=912 Å (Lyman limit)





Andersson et al. 2015 references therein

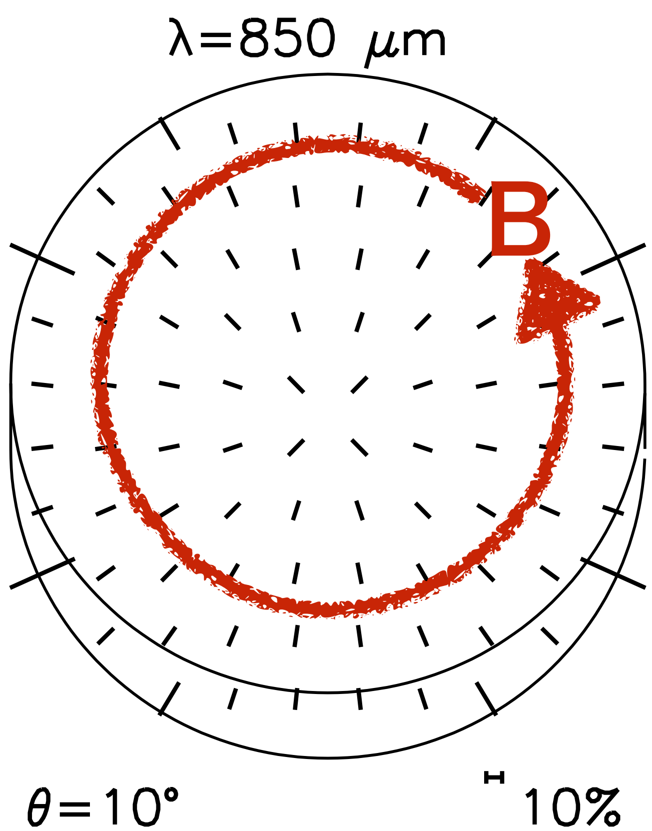
Outline

1. Introduction
2. Grain alignment in the ISM
3. Grain alignment in protoplanetary disks
4. Discussion : Alignment efficiency
5. Summary

Grain alignment in PPDs (Previous works)

Cho & Lazarian (2007)

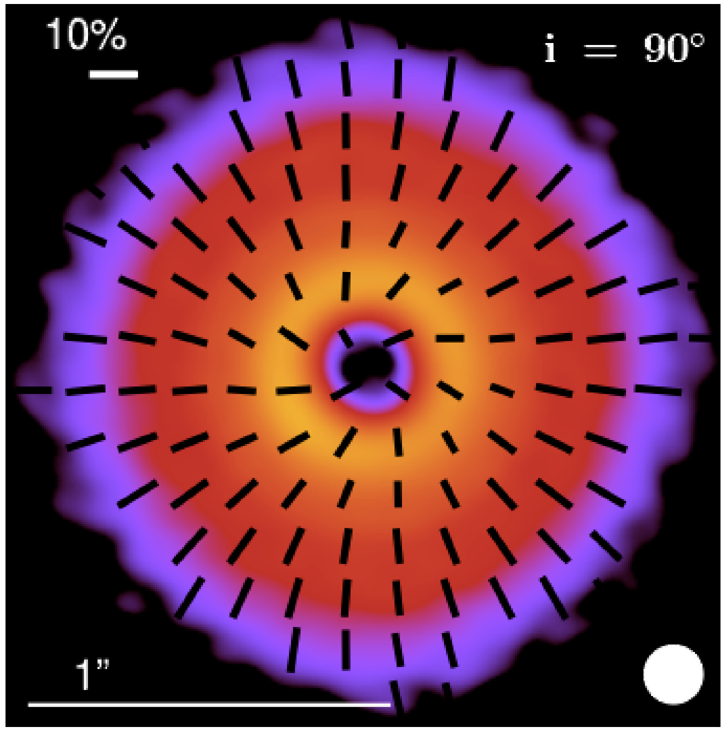
Based on the ***old RAT alignment theory***



Bertrang+ (2016)

MHD simulation

+ ***perfectly aligned grains***



- **In PPDs, radiation can be strong because of the presence of the central star. → RAT alignment is expected!** (Cho & Lazarian 2007)
- **Too optimistic conditions for grain alignment with B-field are used in previous studies.**

  e.g., grain precession is NOT included in Cho & Lazarian 07 model.

Grain alignment in PPDs (Our work)

RT, Lazarian and Nomura (2017)

- We apply RAT alignment theory (Lazarian & Hoang 2007) to PPDs, and calculate the expected polarization map to be compared with ALMA.

- **Radiative transfer calculation** (RADMC-3D, Dullemond et al. 2012)

  Central star：T-Tauri star (4000K, 2Rsun)

  Disk mass: 10^{-4} Msun

⇨ **Estimate the magnitude of radiative torque at each location of the disk**

- **Strength of toroidal magnetic field (Okuzumi et al. 2014)**

$$B(R) = 10\,\mu\mathrm{G}\left(\frac{R}{100\ \mathrm{AU}}\right)^{-2}$$

Can grains align with B-field in PPDs?

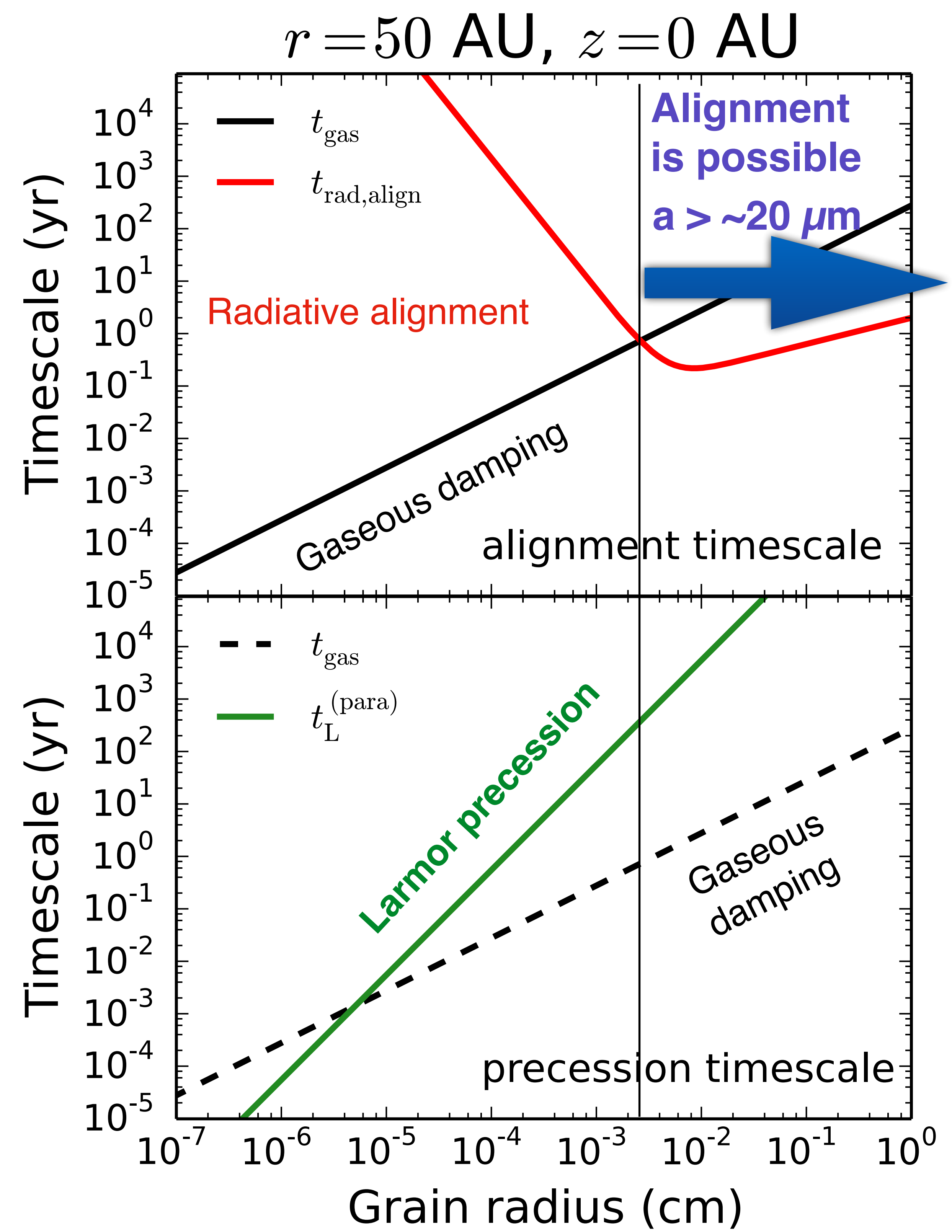
- Smaller grains do not align due to inefficient RAT.
- At r=50 au and midplane, grain size > 20 μm can align.

~ λ (rad. field)/2

~FIR@midplane

- For such grain sizes, Larmor precession is suppressed by the gaseous damping.

⇒ Grain alignment with B-field hardly occur!

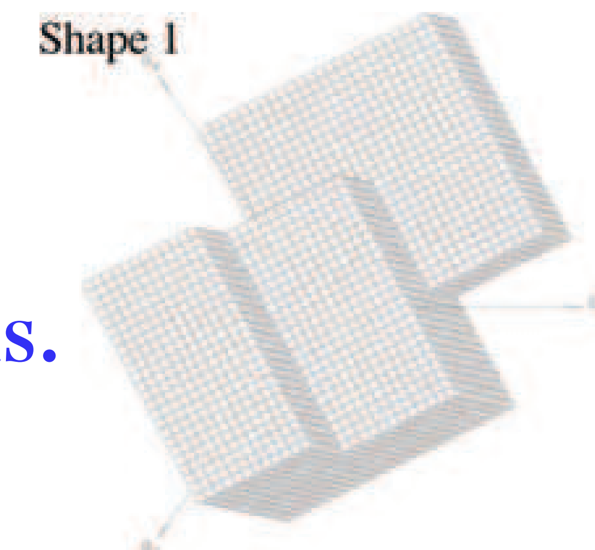


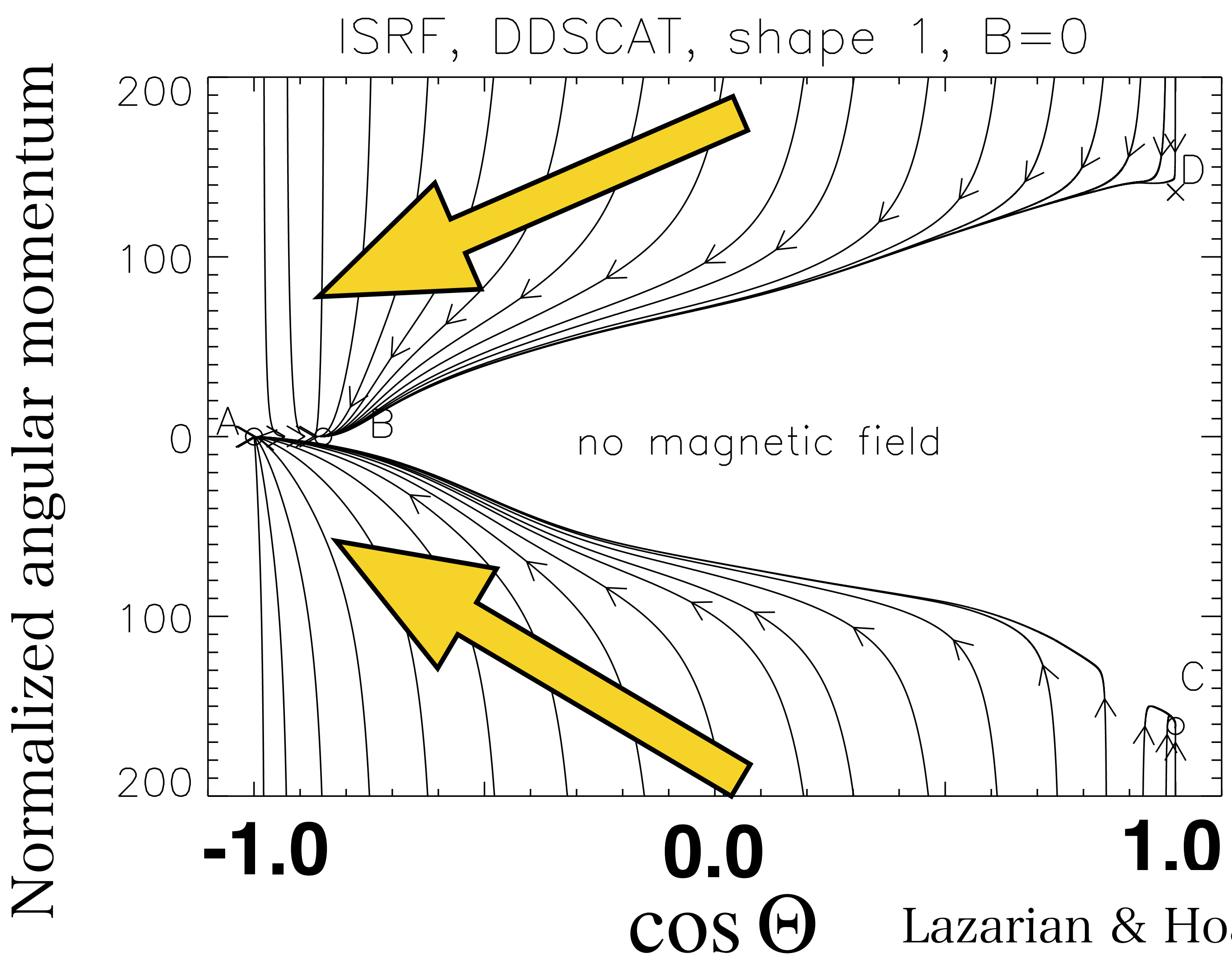
RAT alignment in the absence of B-field

Lazarian & Hoang 2007

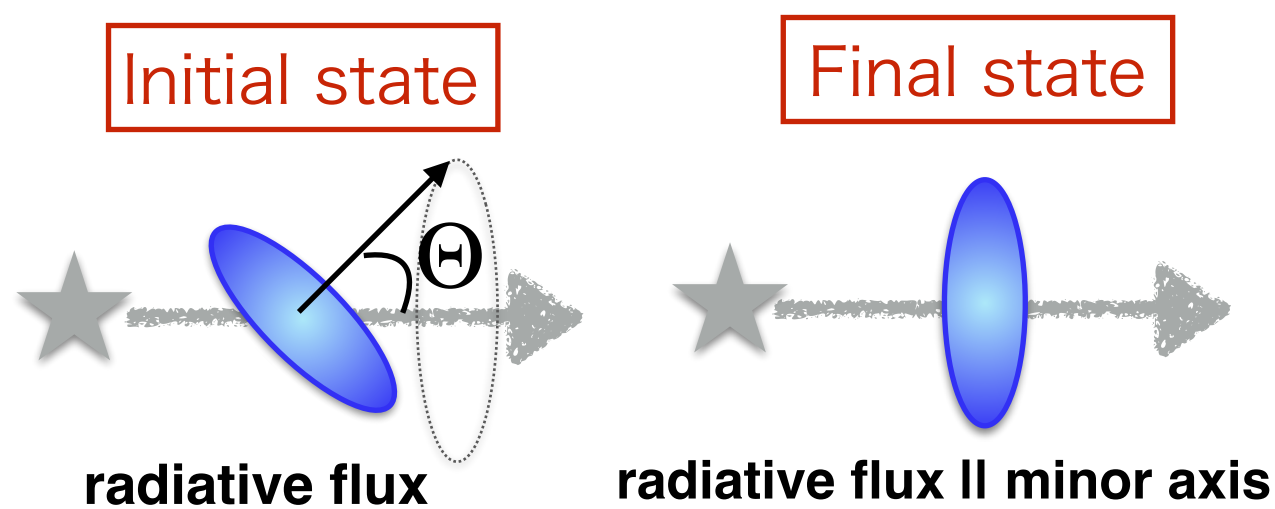
- RAT alignment with B → 0
  - No Larmor precession = No B-field alignment
  - RAT induces precession about radiative flux.

    → alignment with respect to radiative flux happens.



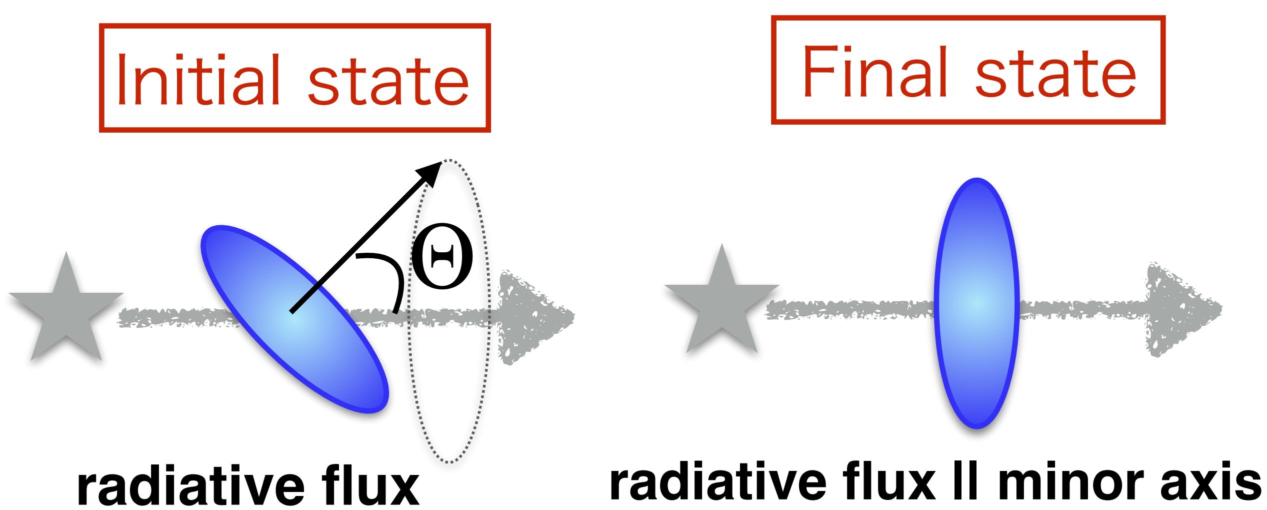


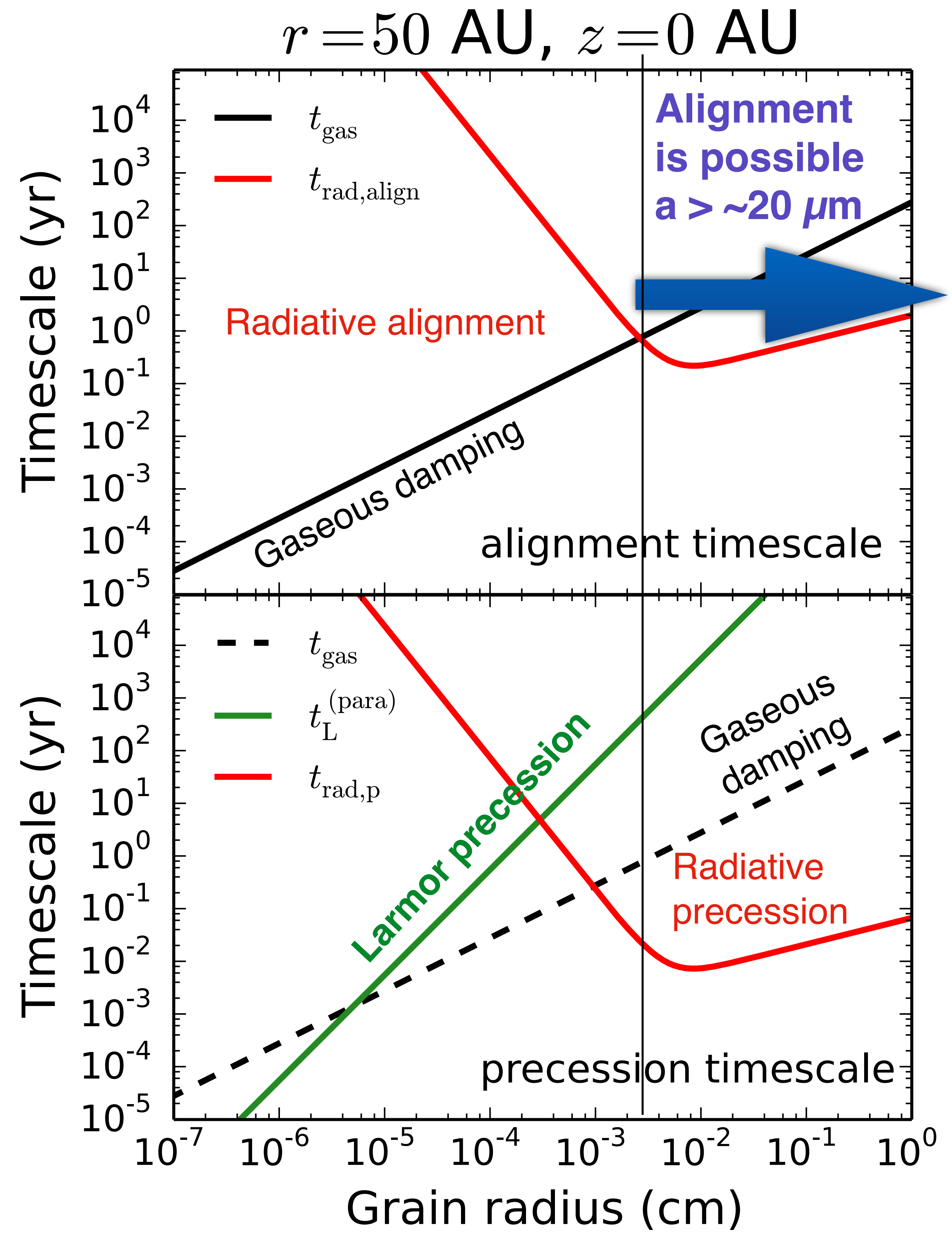
Lazarian & Hoang 2007



Alignment with radiation direction

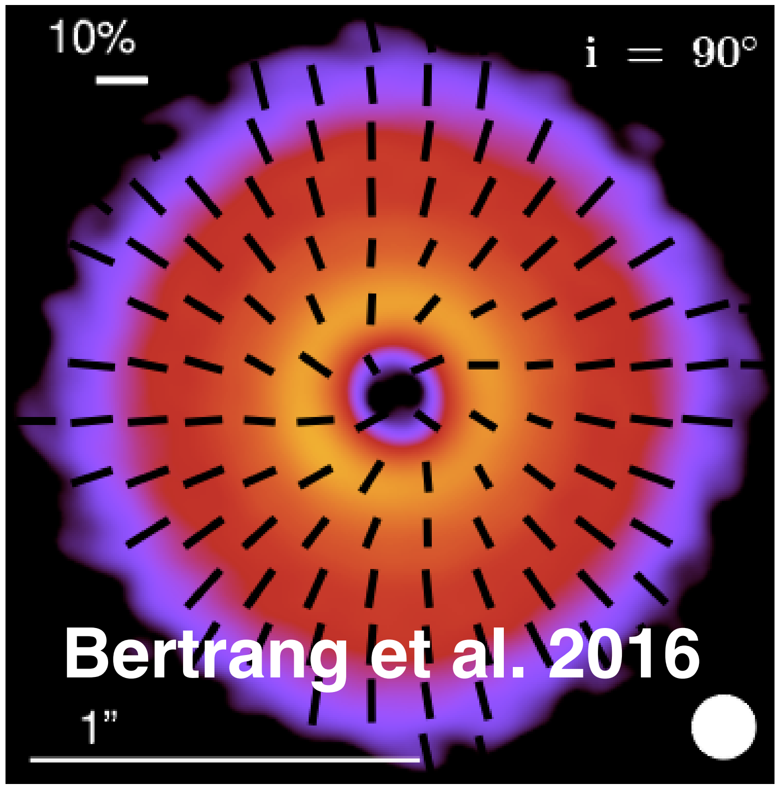
- RAT induce precession around radiation direction. (Lazarian & Hoang 2007)
- For grains > 20 μm, rad. precession is faster than Larmor precession and gaseous damping timescales. → "radiation alignment"



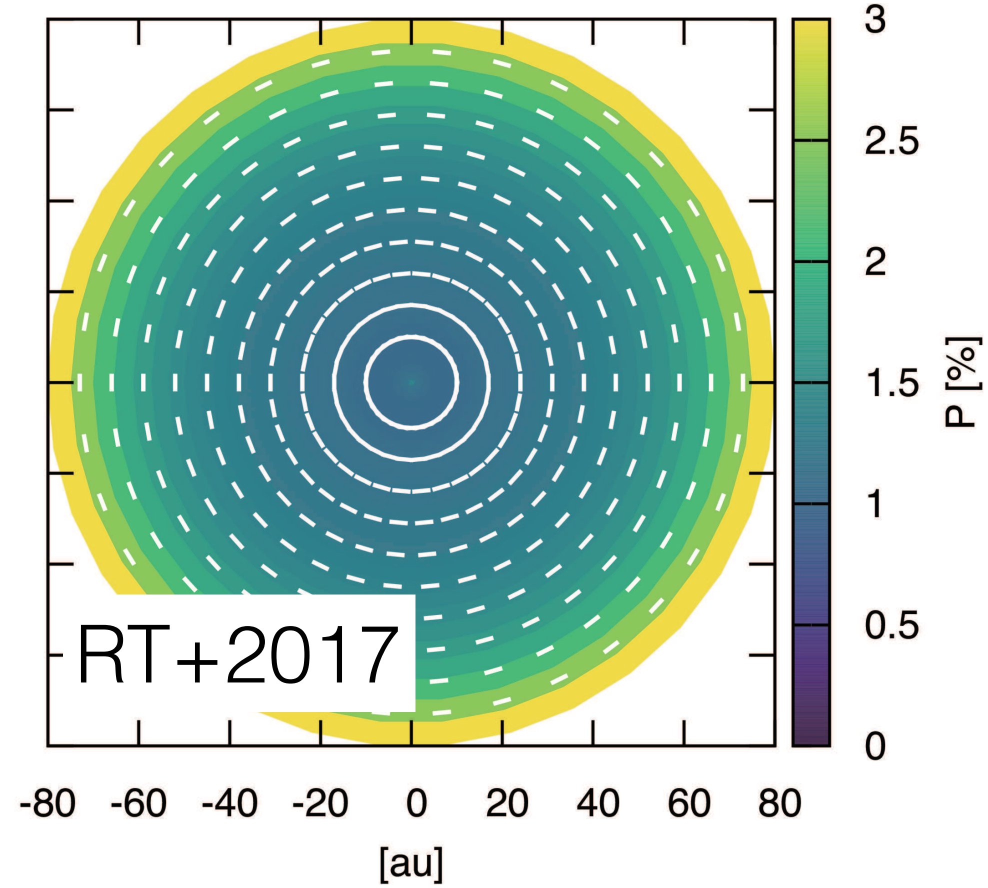


Millimeter wave polarization of disks

Previous study
(assumed B-field alignment)



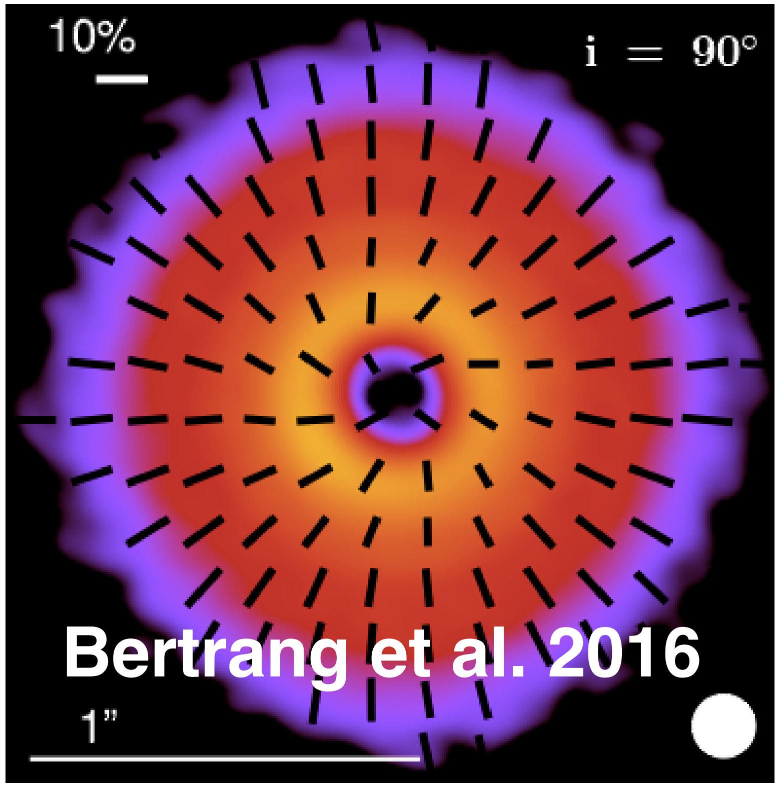
Our study
(**Based on the alignment theory**)



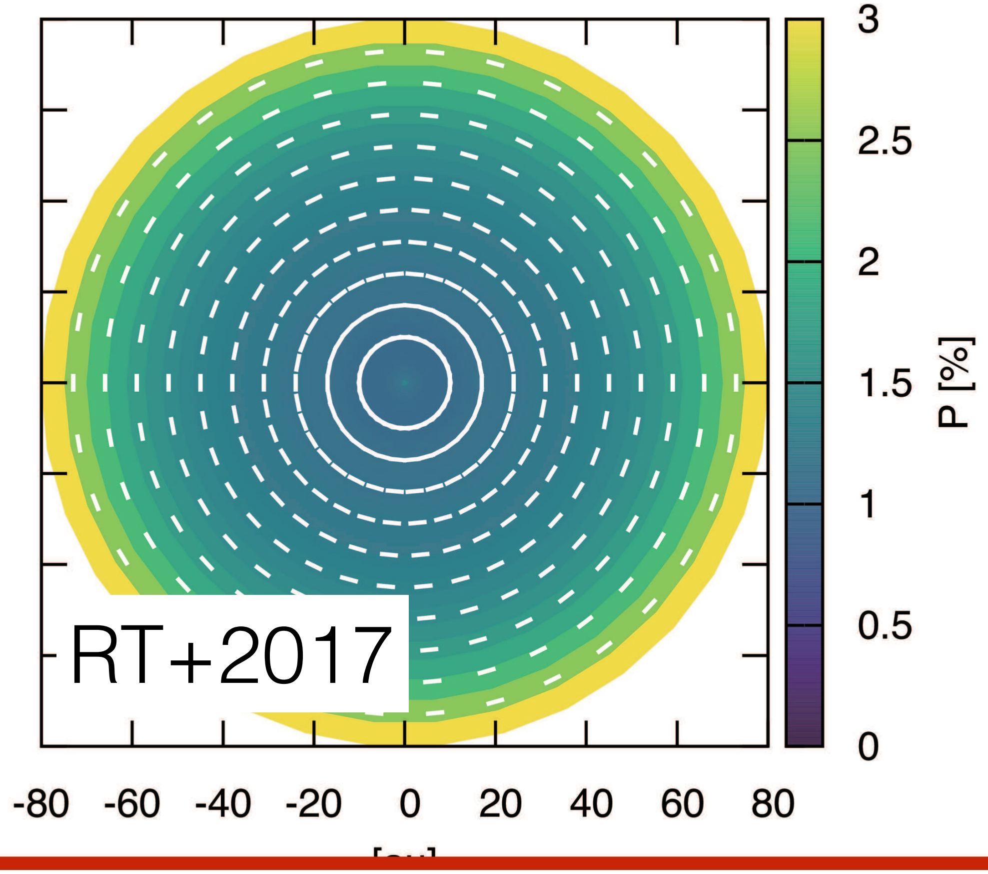
- Alignment theory predicts alignment with radiation direction happens, which results in azimuthal pol. vectors.
- Polarization vectors at (sub-)mm wavelengths do not trace the magnetic field structure in PPDs!

Millimeter wave polarization of disks

Previous study
(assumed B-field alignment)



Our study
(**Based on the alignment theory**)



Short summary: Why is B-field alignment so inefficient?

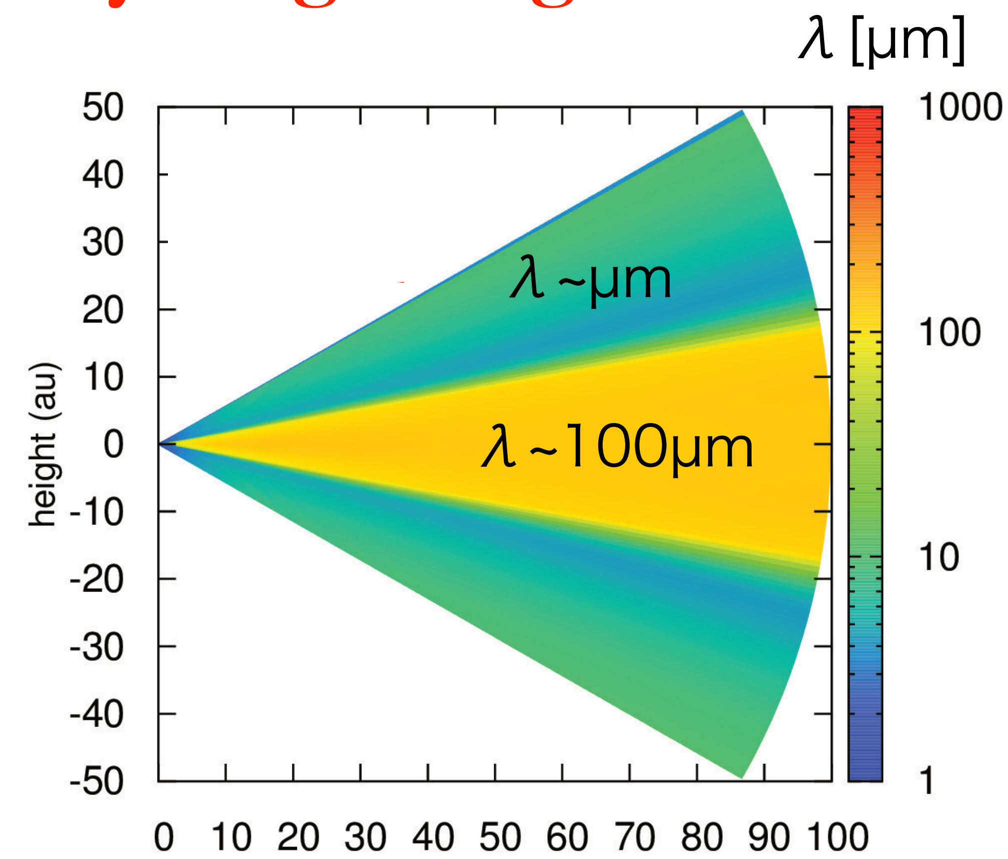
- **Alined grain size ~ λ(rad. field)/2 @ disk midplane**
  ~ a few tens of micron (>> ISM dust ~ 0.1μm)
- **Larger grains show slower Larmor precession, and then the Larmor precession is suppressed by gaseous collisions.**

In MIR, we may observe magnetically aligned grains!

Larmor precession timescale

$$t_{\mathrm{L}} \approx 1.3\ \mathrm{year} \left(\frac{a}{0.1\ \mu\mathrm{m}}\right)^{2} \left(\frac{B}{5\ \mu\mathrm{G}}\right)^{-1} \left(\frac{\chi(0)}{10^{-4}}\right)^{-1}$$

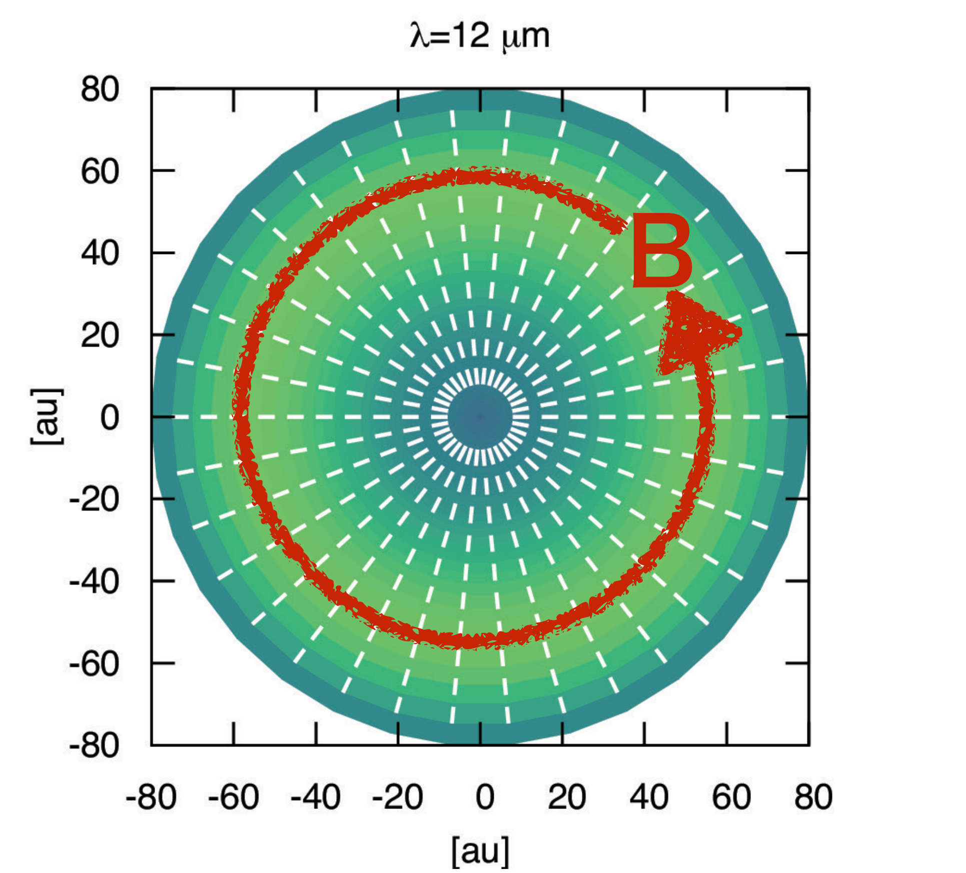
grain size being aligned ∼ λ(rad field)/2



When does B-field alignment happen?

- **Fast Larmor precession for grains being aligned.**
- **Less gaseous damping (low density)**

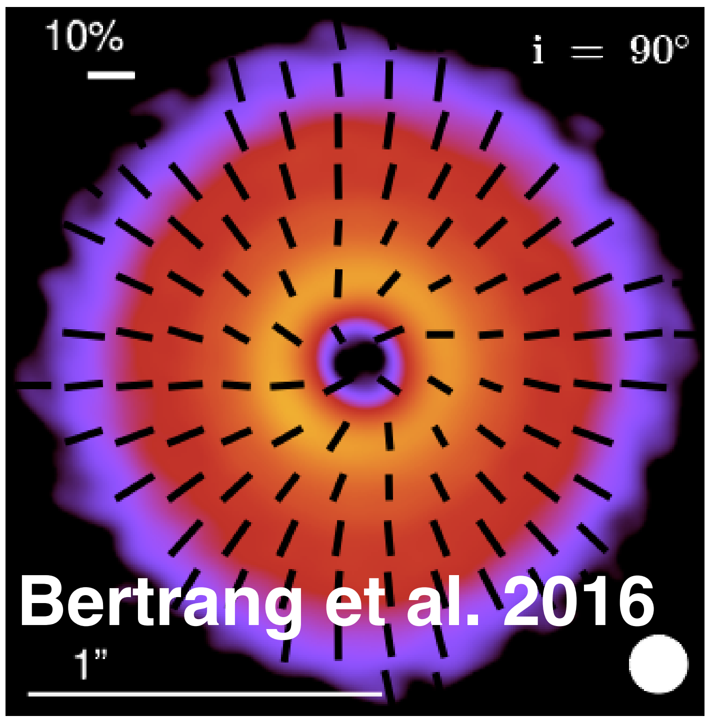
⇨ **Disk surface layer is favorable for B-field alignment!**



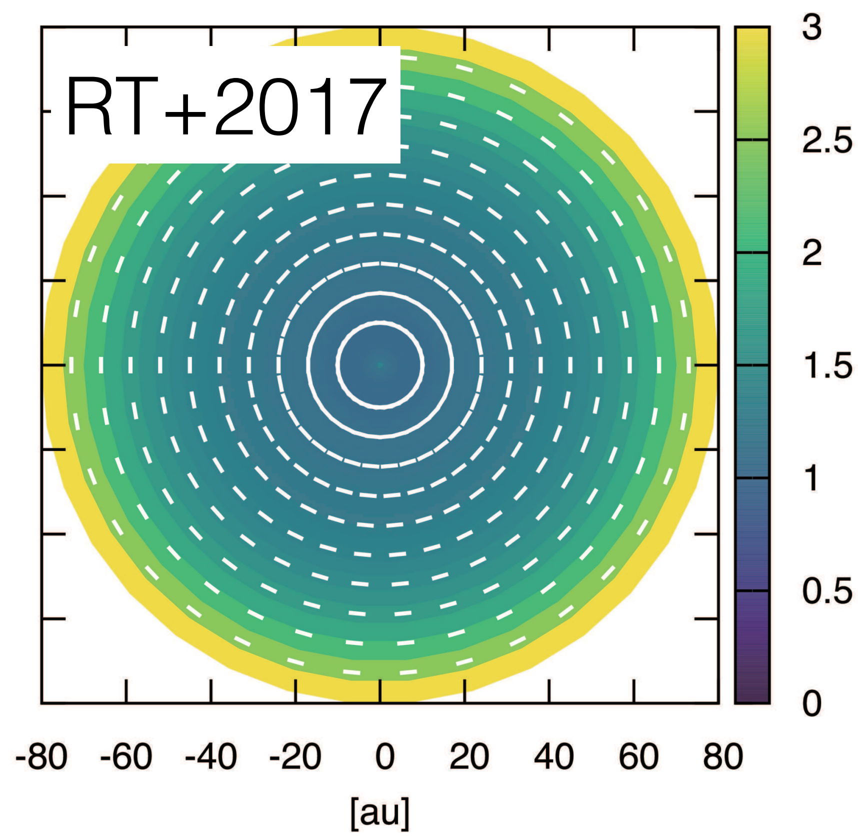
We can expect toroidal B-field alignment in MIR wavelength!

mm-wave polarization of PPDs

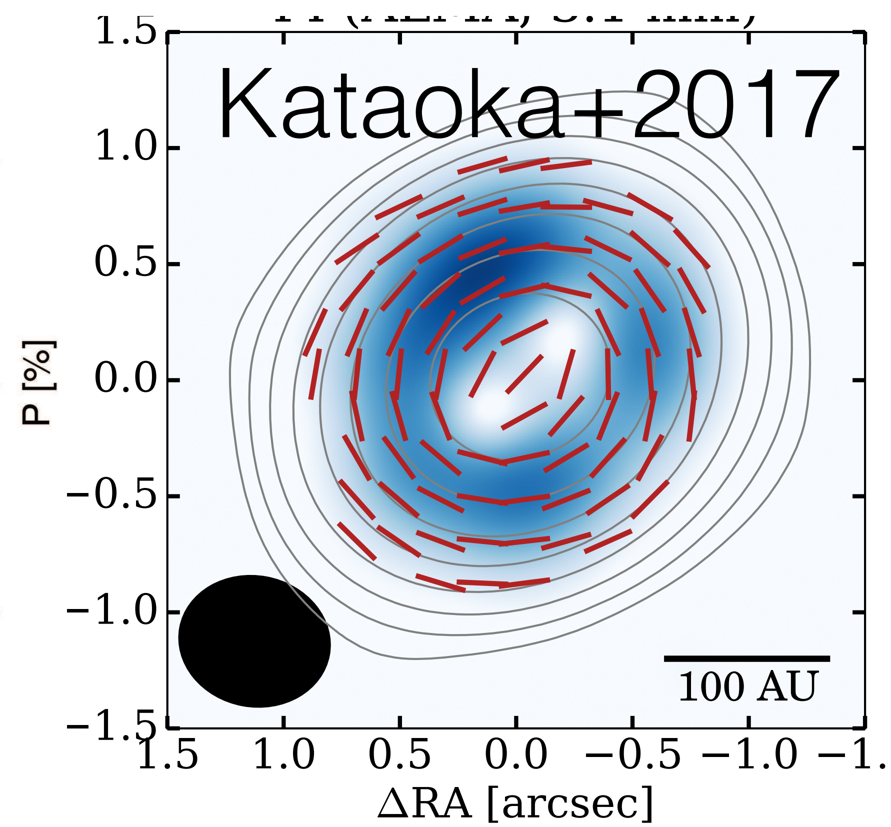
Alignment with magnetic field



Alignment with radiation direction



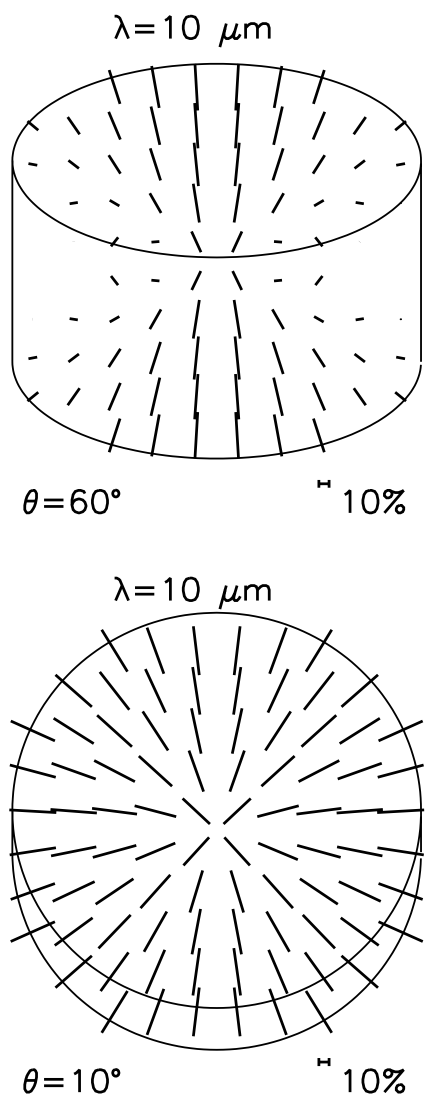
ALMA (Band 3, λ=3.1 mm)



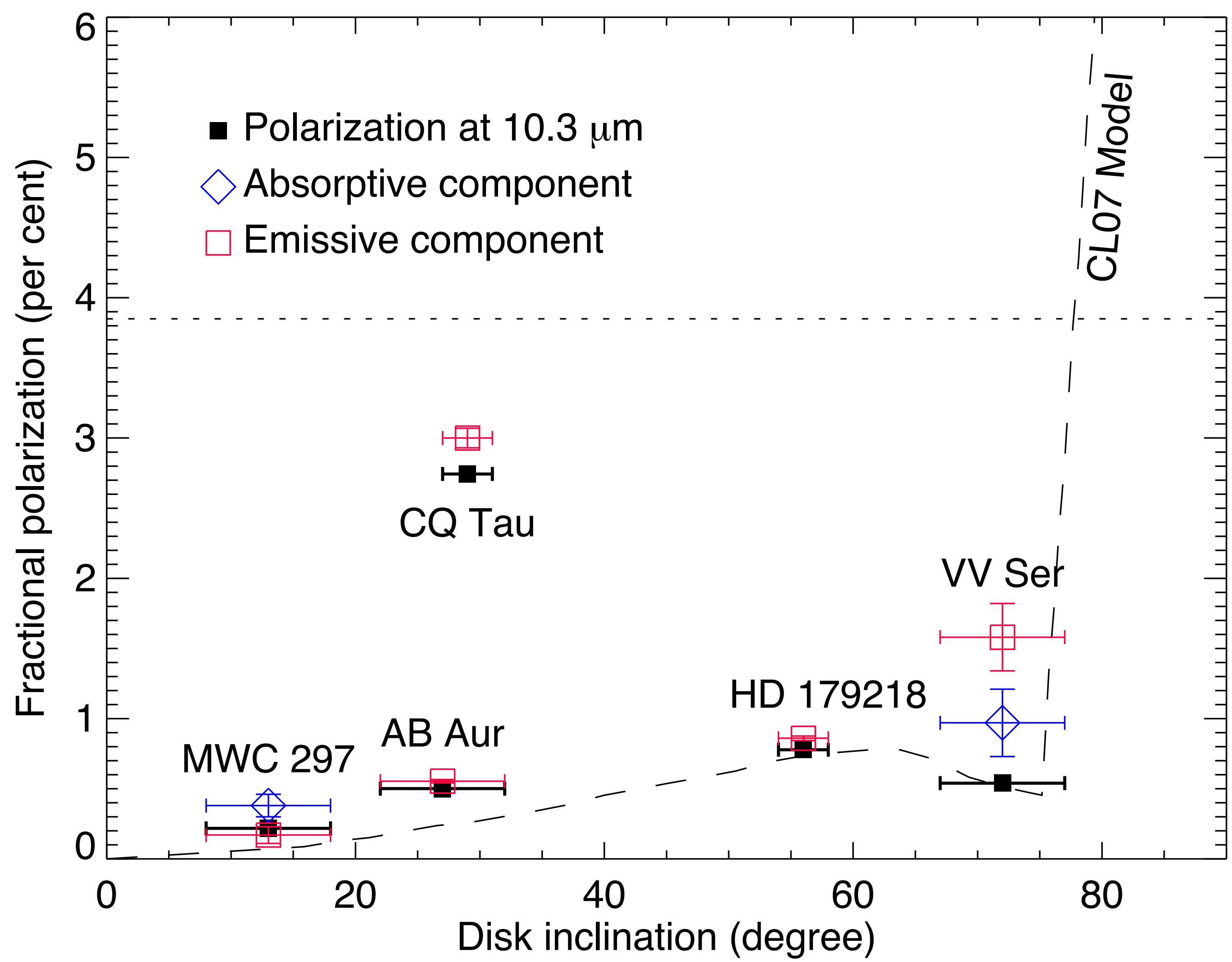
- HL Tau in Band 3 shows azimuthal polarization vectors.
  - seems to be consistent with grain alignment with radiative flux.

MIR polarization observations

Cho & Lazarian 2007



Li et al. 2017



- MIR polarization obs. traces toroidal B-field of surface layer of PPDs?

Outline

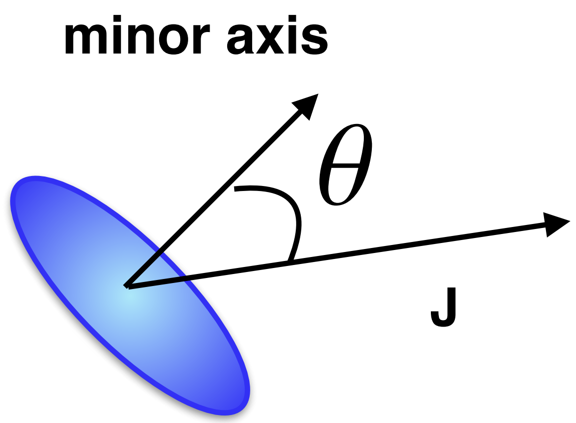
1. Introduction
2. Grain alignment in the ISM
3. Grain alignment in protoplanetary disks
4. Discussion : Alignment efficiency
5. Summary

Coupling of J and minor axis

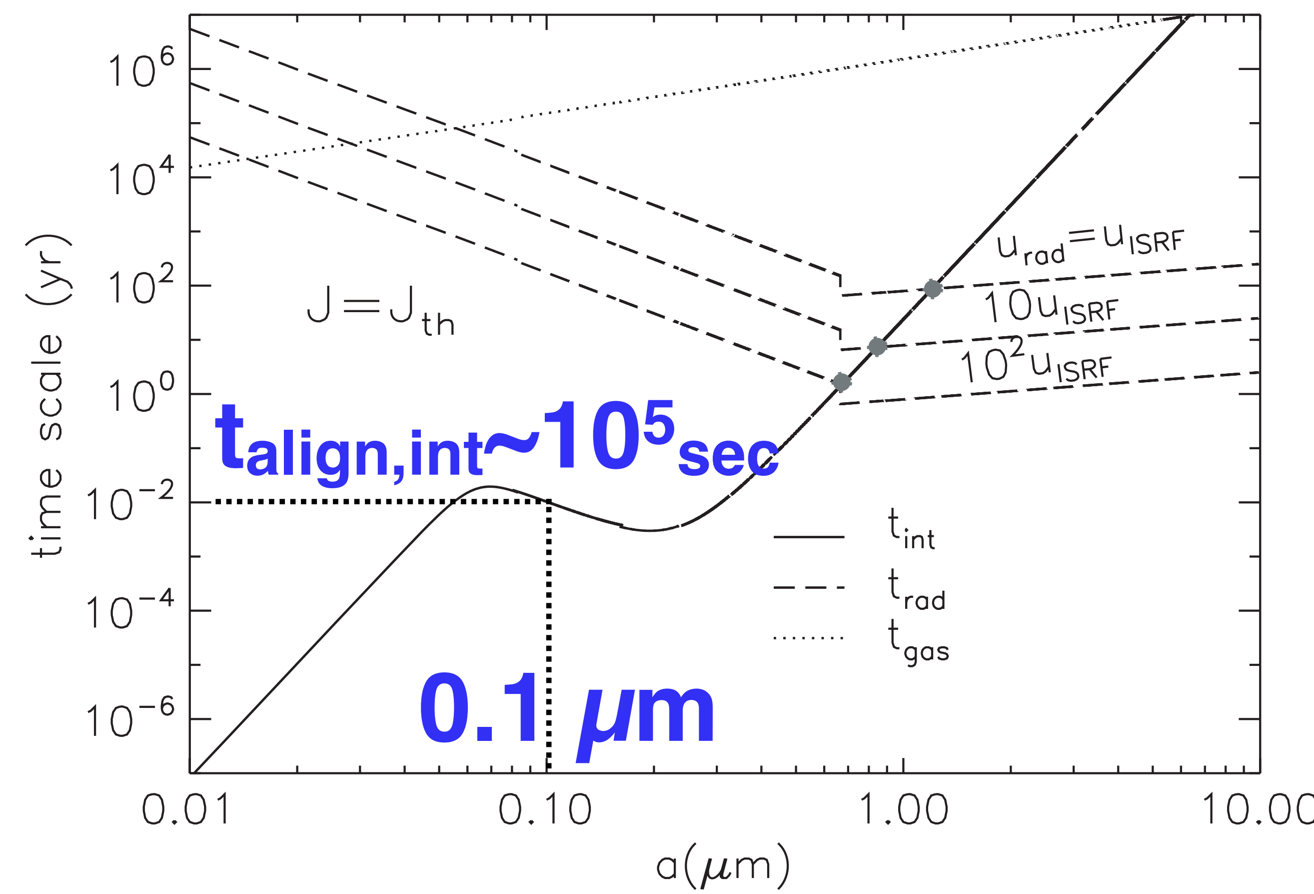
- Rotational kinetic energy

$$E(\theta) = \frac{J^2}{I_{\|}}(1 + \sin^2\theta(h - 1)),$$

- (Internal) Energy dissipation leads to $\theta \to 0$ ("Internal alignment")



Hoang & Lazarian 2009

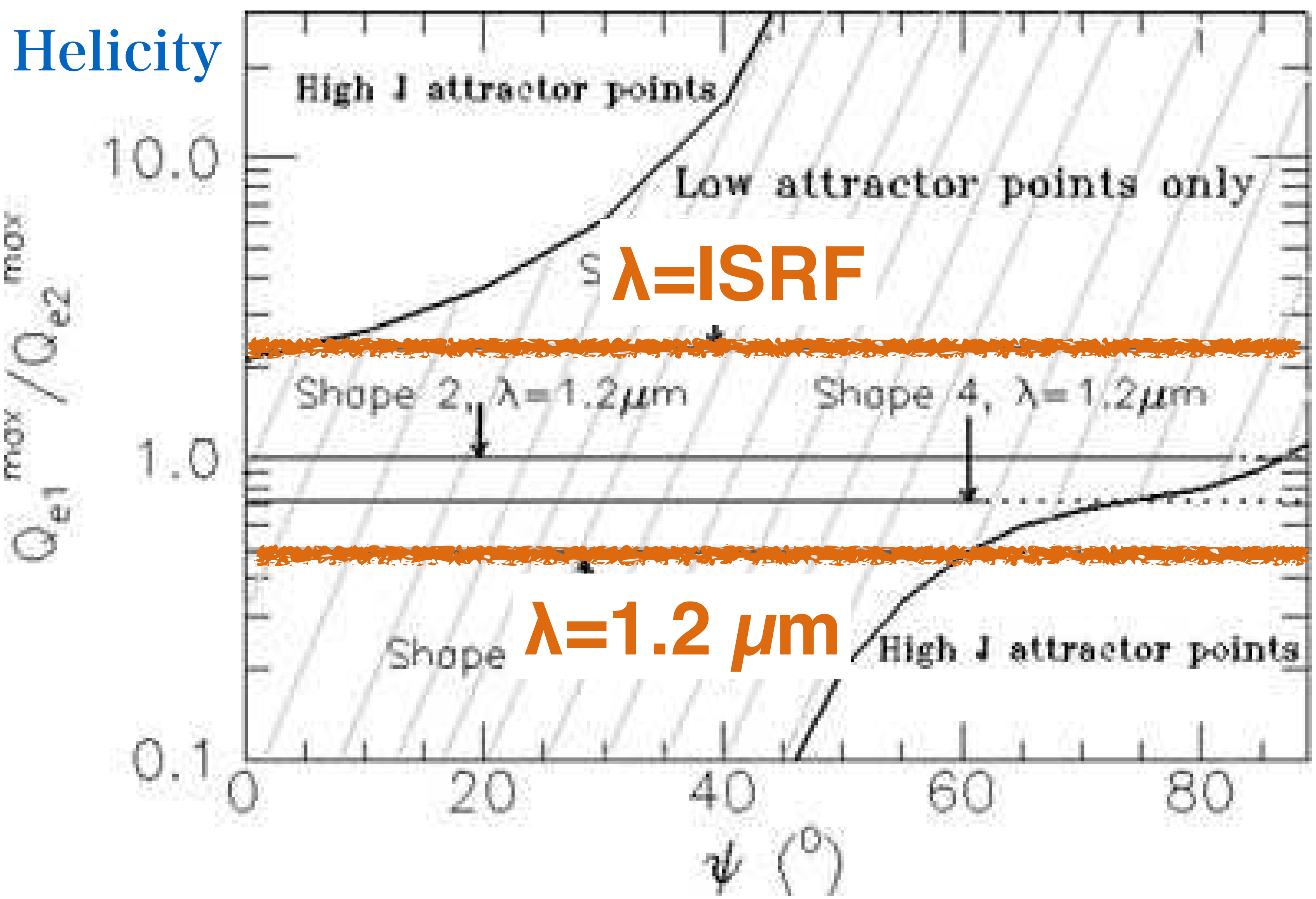


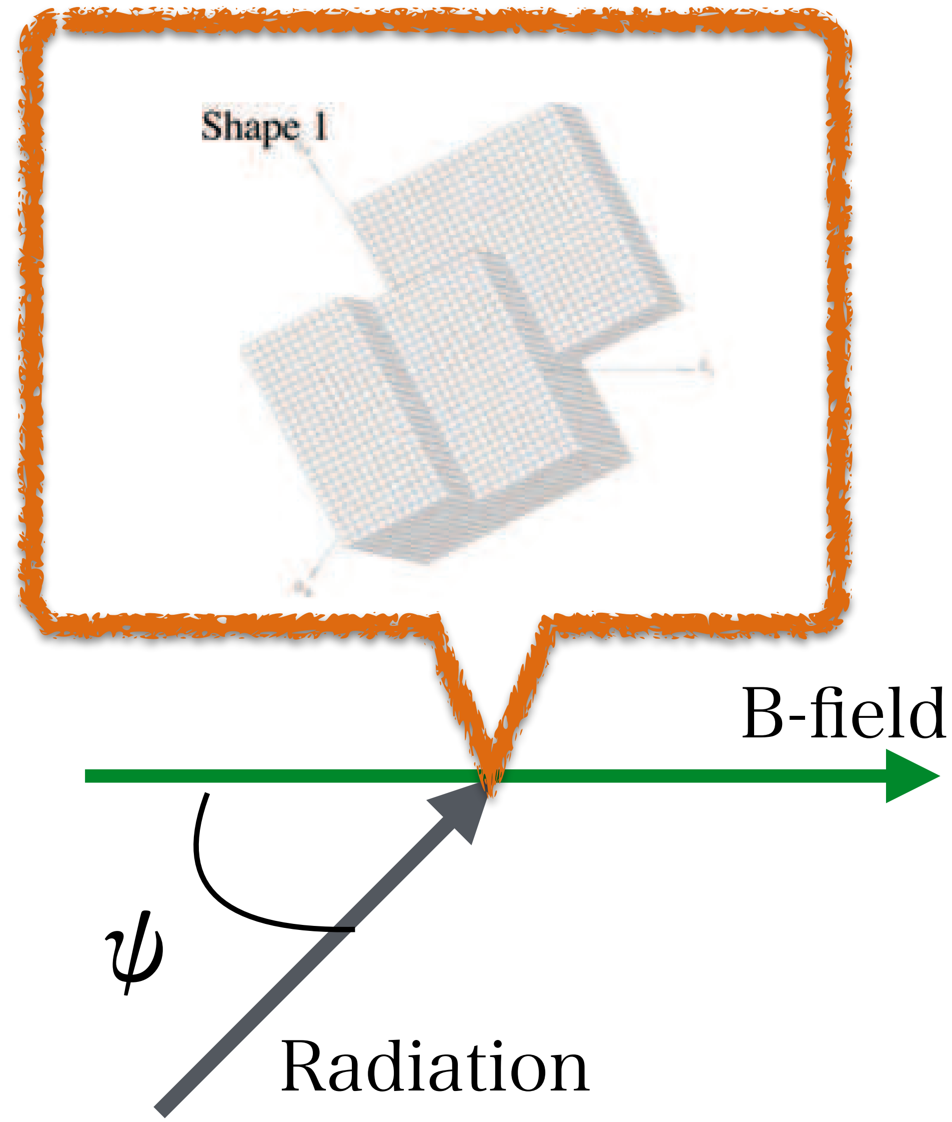
- Larger grains do not show internal alignment.
- Without internal alignment (Hoang & Lazarian 2009):
  - alignment efficiency: ~ 10% @ High-J attractor (spin-up state)

    ~ 100% @ Low-J attractor (spin-down state)

Alignment efficiency : High-J or Low-J?

Lazarian & Hoang 2007

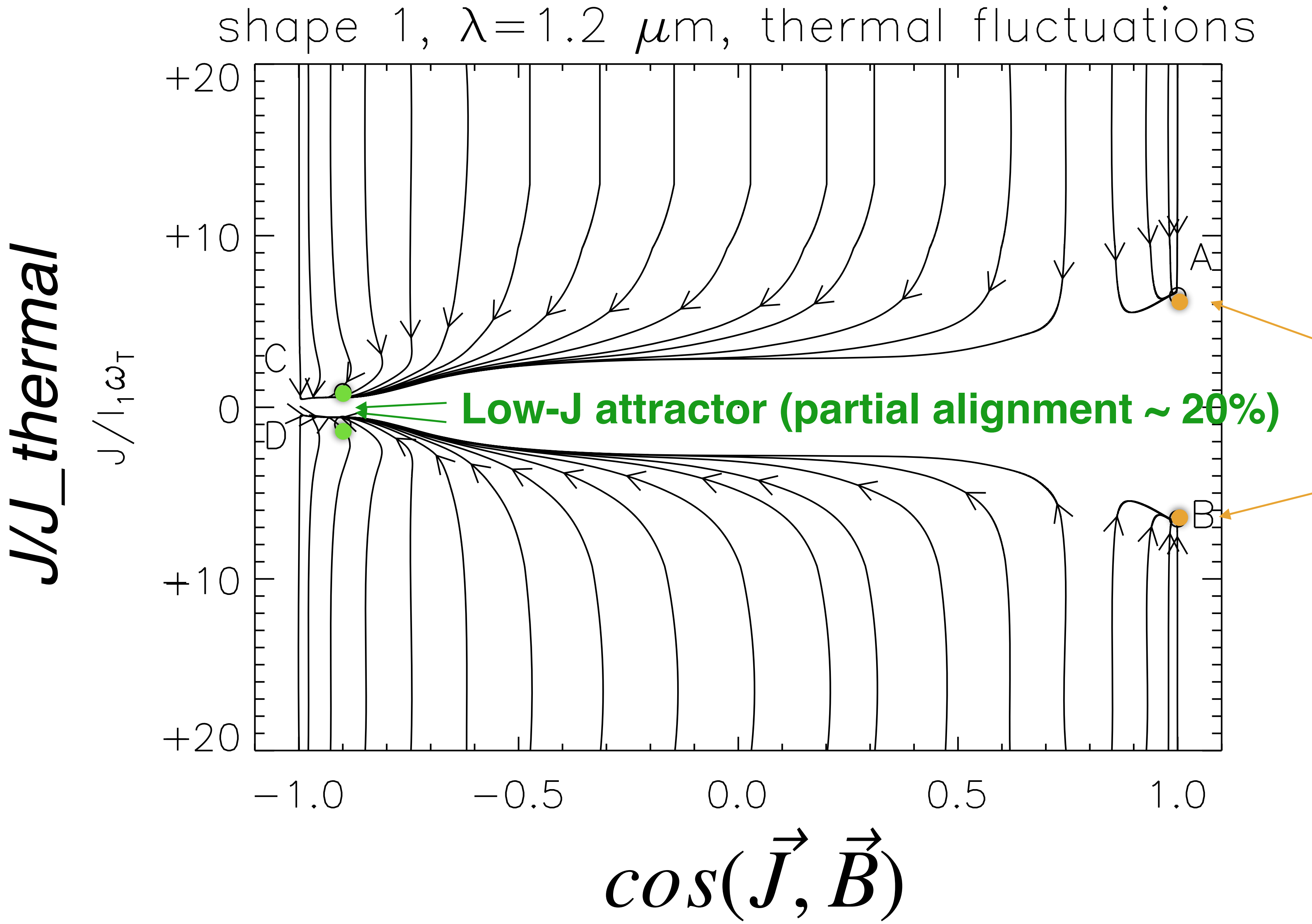


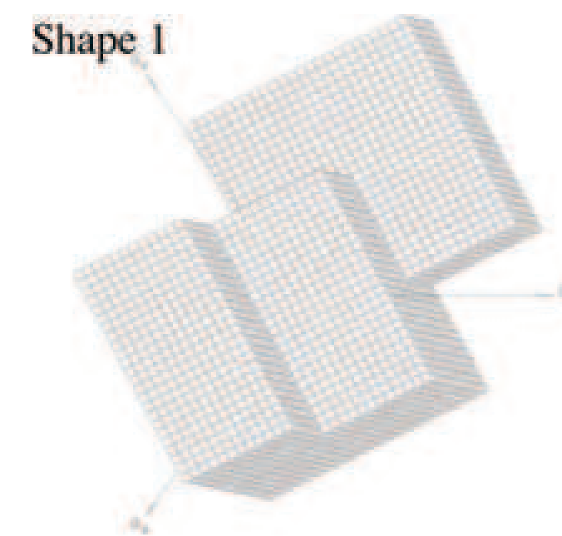


- For grain alignment with rad. direction, we should see ψ=0.
- Above condition depends on the amount of magnetic inclusions, such as superparamagnetic inclusions (Lazarian & Hoang 2008, Hoang & Lazarian 2016).

Example: RAT alignment calculation

Hoang & Lazarian 2008



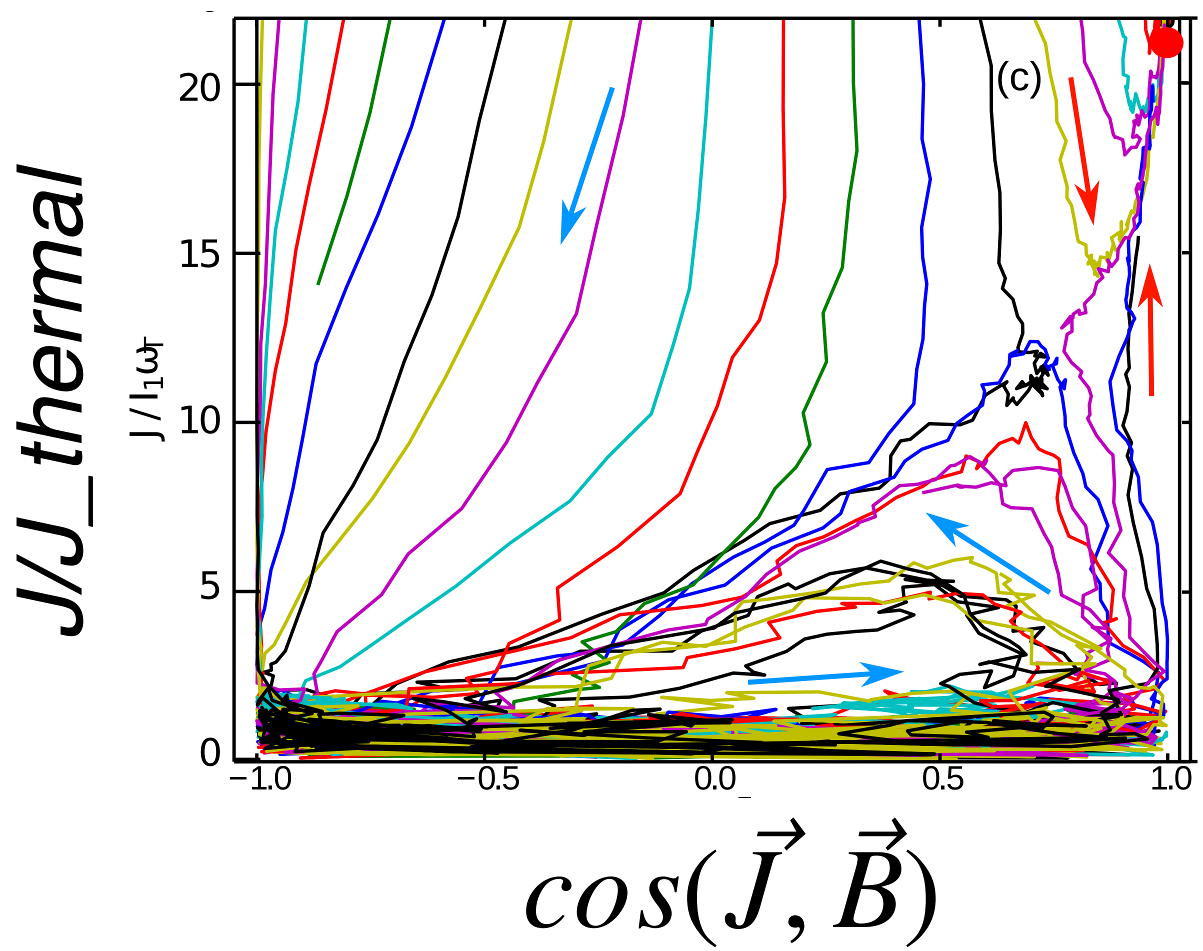


- Most grains evolve into Low-J attractor …
  → alignment efficiency of ~20%

Toward the higher alignment efficiency…

Hoang & Lazarian 2016, (see also Hoang & Lazarian 2008)

Low-J attractor → High-J attractor



- If high-J attractors are present, the stochastic perturbation, such as gas bombardment, brings the grains at Low-J attractors to high-J attractor! → almost perfect alignment occurs!

Outline

1. Introduction
2. Grain alignment in the ISM
3. Grain alignment in protoplanetary disks
4. Discussion : Alignment efficiency
5. Summary

Summary

- Now ALMA starts to observe linear polarization of protoplanetary disks in (sub-)mm-wavelengths.
- In disks, dust grains in midplane do not align with B-field.
  - Mainly because large grains show slow Larmor precession.

  →ALMA observations may not provide B-field structure of PPDs.
- RAT alignment theory predicts that large grains in the disk midplane may align with radiation direction instead of B-field.
- Magnetically aligned grains can present at surface layer of the disks, which can be verified by the MIR polarimetric obs.