Grain Alignment by Radiative Torque: Theory and Modeling Dust Polarization

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A. Lazarian (*UW-Madison*)

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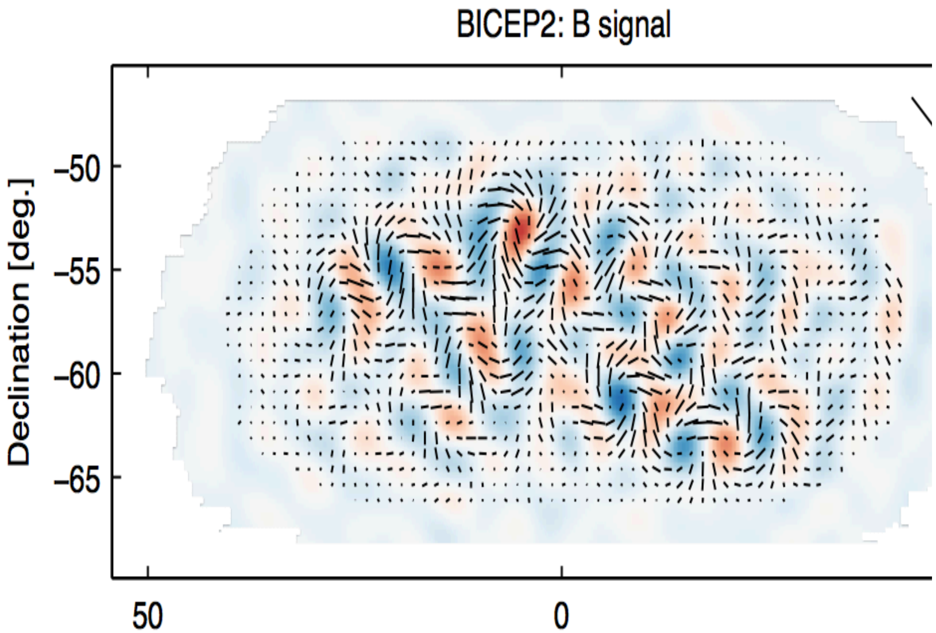
Outline

- Motivation: Star formation and CMB polarization
- Theory:
  - ✧Analytical Model of Radiative Torques (RATs)
  - ✧Basic Properties of RAT Alignment
- Modeling:
  - ✧ Predictions of Dust Polarization using RAT alignment Theory
  - ✧ Comparison with Observational Data
- Summary

Dust polarization affects precise measurement of CMB polarization.

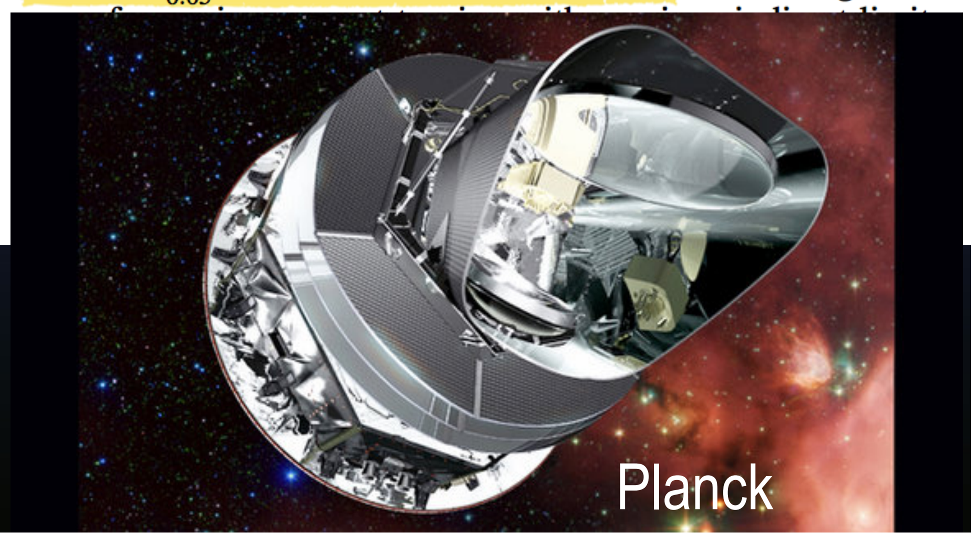


Bicep2 (2014)

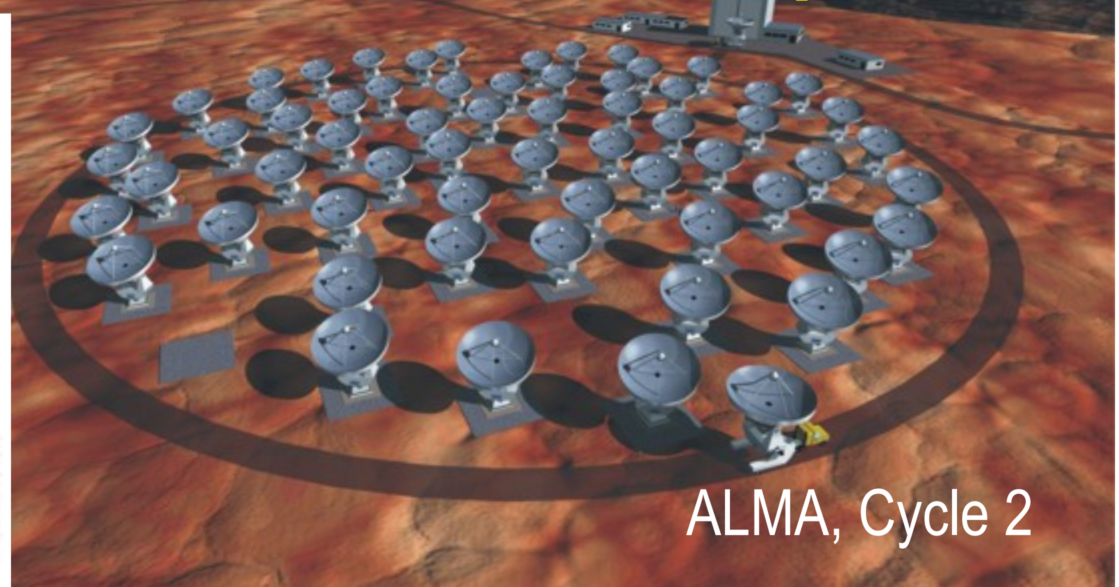
The simplest and most economical remaining interpretation of the *B*-mode signal which we have detected is that it is due to tensor modes — the IGW template is an excellent fit to the observed excess. We therefore proceed to set a constraint on the tensor-to-scalar ratio and find $r = 0.20^{+0.07}_{-0.05}$ with $r = 0$ ruled out at a significance of 7.0σ. Multiple lines of evidence have been presented that foregrounds are a subdominant contribution: i) direct projection of the best available foreground models, ii) lack of strong cross correlation of those models against the observed sky pattern (Figure 6), iii) the frequency spectral index of the signal as constrained using BICEP1 data at 100 GHz (Figure 8), and iv) the spatial and power spectral form of the signal (Figures 3 and 10).

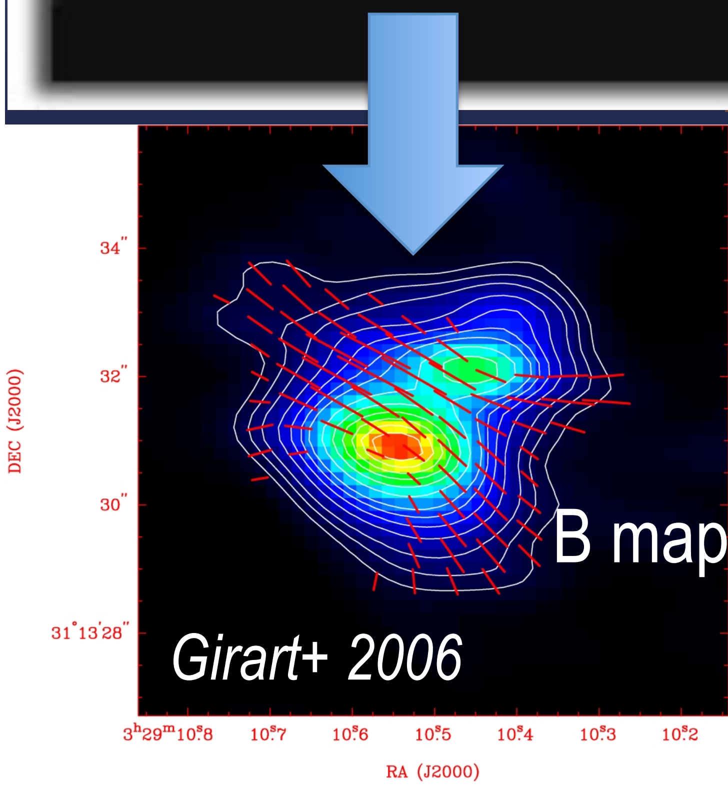
Subtracting the various dust models and re-deriving the r constraint still results in high significance of detection. For the model which is perhaps the most likely to be close to reality (DDM2 cross) the maximum likelihood value shifts to $r = 0.16^{+0.06}_{-0.05}$ with $r = 0$ disfavored at 5.9σ. These high val-

- Careful modeling of polarized dust emission is needed for CMB polarization analysis



Dust polarization traces magnetic fields, esp. in dense cores with potential star formation activity.





- Chandrasekhar-Fermi technique:

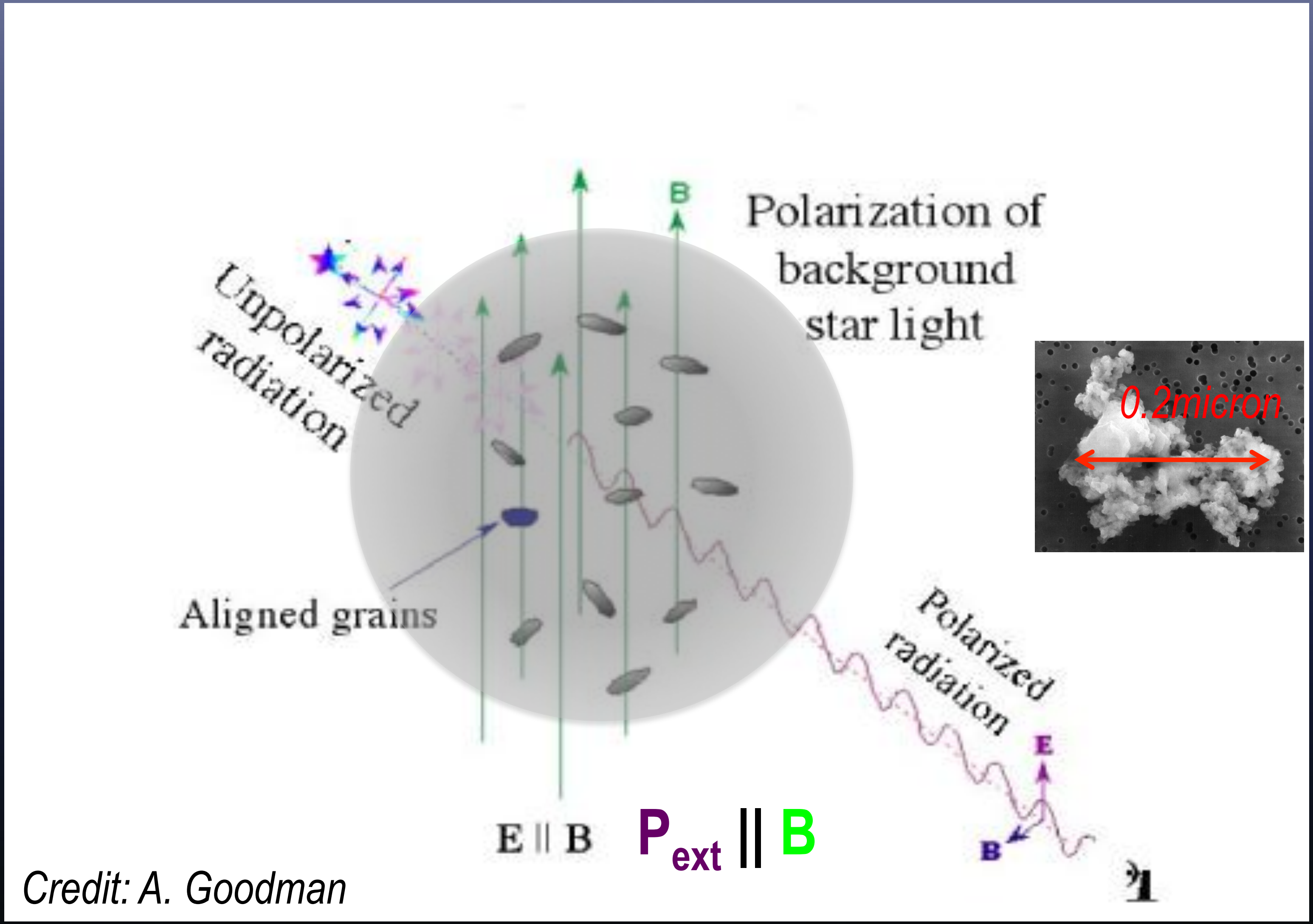
$$\frac{B_{\rm POS}}{\sqrt{4\pi\rho}} \propto \frac{\delta V}{\delta\phi}$$

- Mass to Flux ratio:

$$E_{gra}/E_{mag}=M/\Phi \sim N(HI)/B$$

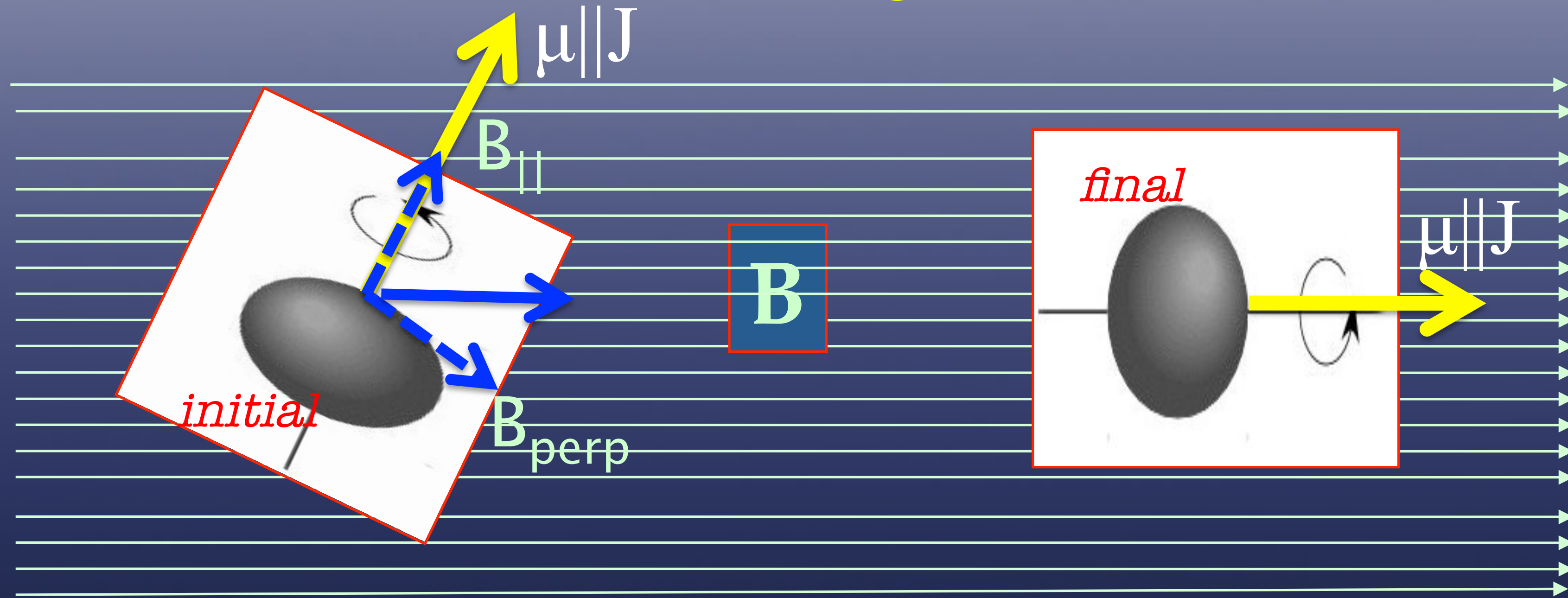
- M/Φ allows us to test star formation theory

Dust polarization is produced by dust grains aligned in interstellar magnetic fields.



Question: How do grains get aligned with magnetic field?

Davis-Greenstein: Paramagnetic Relaxation



• Rotating magnetization by B_{perp} induces energy dissipation, decreasing the angle between J and B.

ISM

$$\tau_{DG} \approx 1.2 \times 10^{6} \left(\frac{B}{5\mu G}\right)^{-2} \left(\frac{a}{0.1\mu m}\right)^{2} \left(\frac{K(\omega)}{1.2 \times 10^{-13}}\right)^{-1} \text{yr}$$

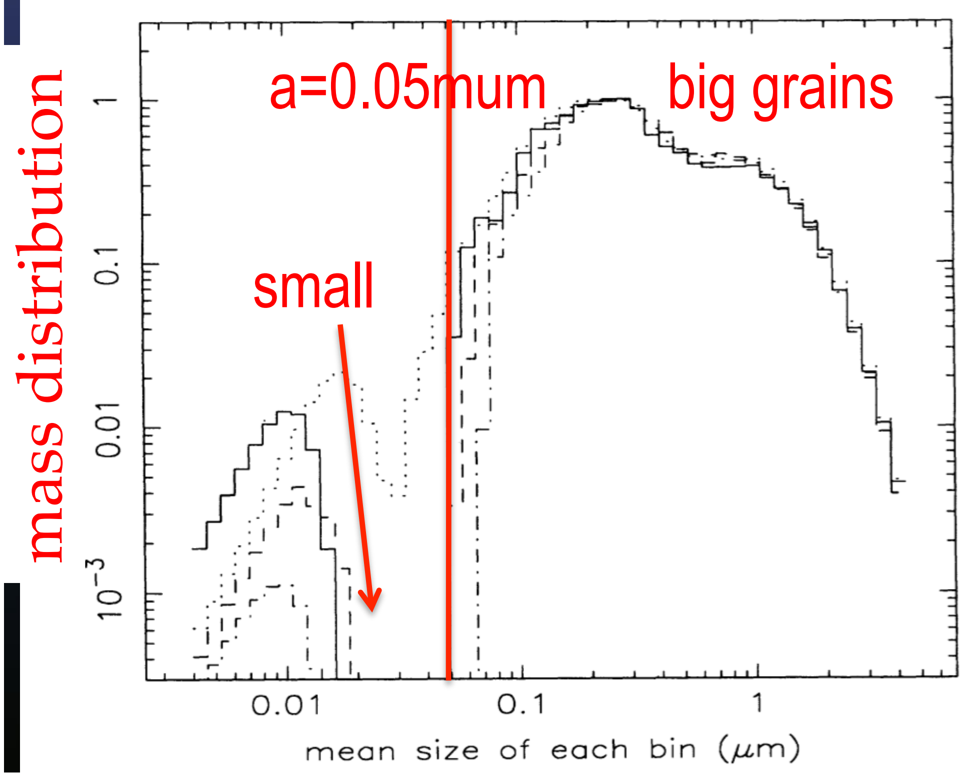
$$\tau_{drag} \approx 6.3 \times 10^{4} \left(\frac{a}{0.1\mu m}\right) \left(\frac{1}{1+F_{IR}}\right) \text{yr}$$

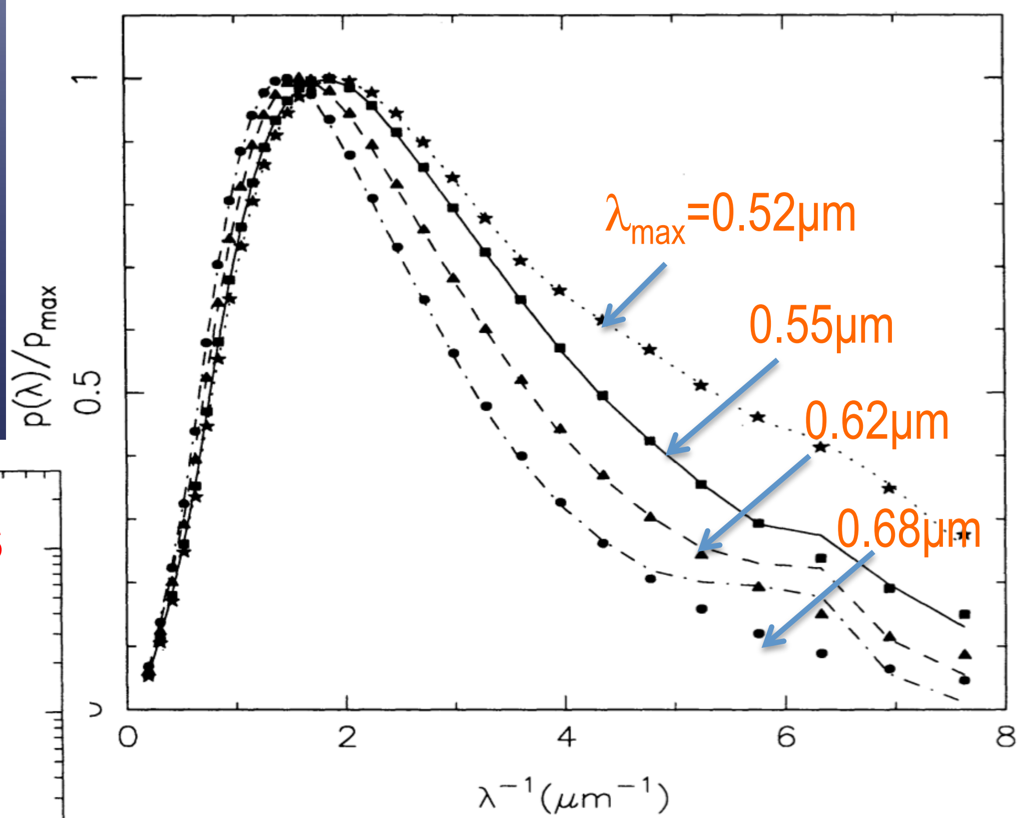
$$\frac{\tau_{DG}}{\tau_{drag}} \approx 20 \left(\frac{a}{0.1\mu m}\right)(1+F_{IR})$$

$\tau_{DG} >> \tau_{drag}$ for a>0.1 micron grains.

• Big grains are not aligned, small grains could be aligned

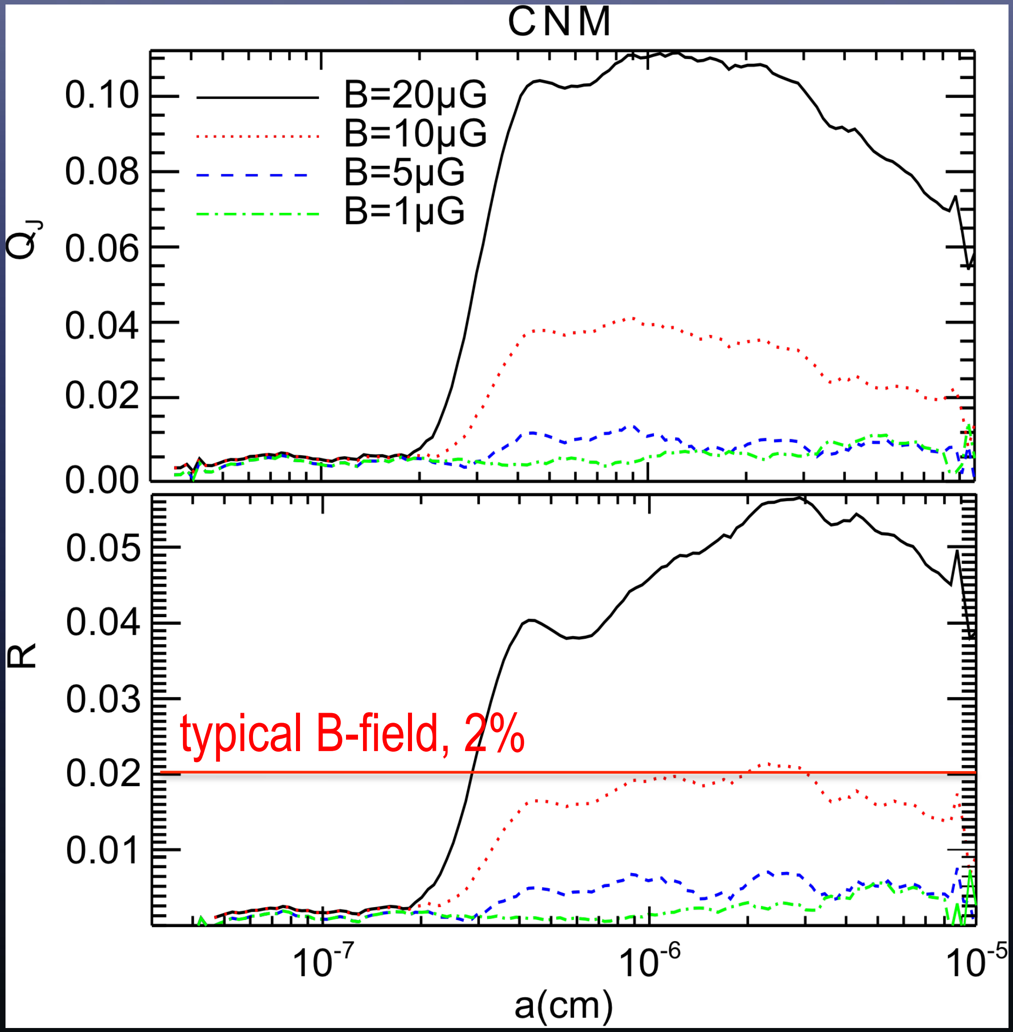
Observations reveal big grains are efficiently aligned whereas small grains are weakly aligned.





Kim & Martin 95

Detailed numerical calculations demonstrate low degree of paramagnetic alignment.



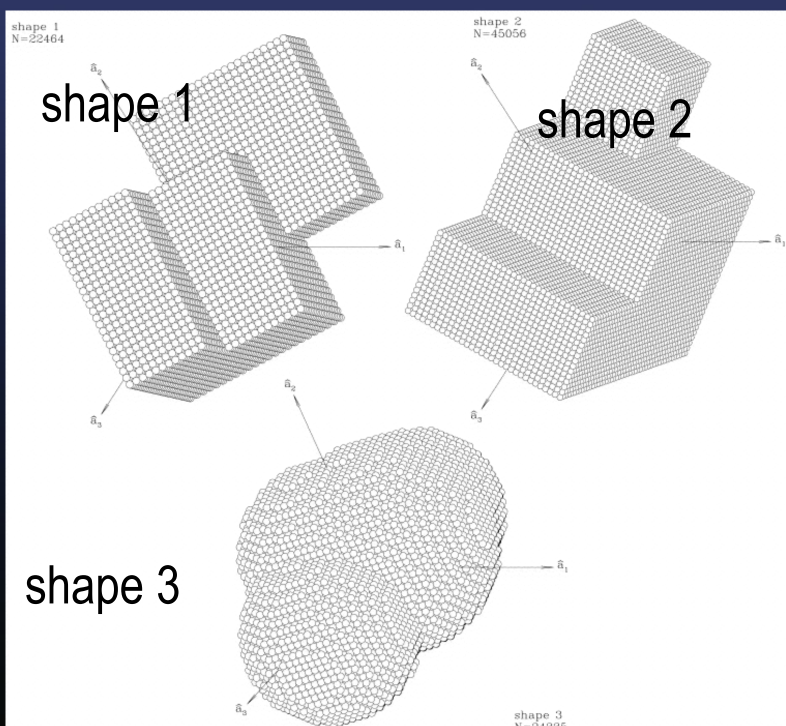
Hoang, Lazarian, Martin 14a

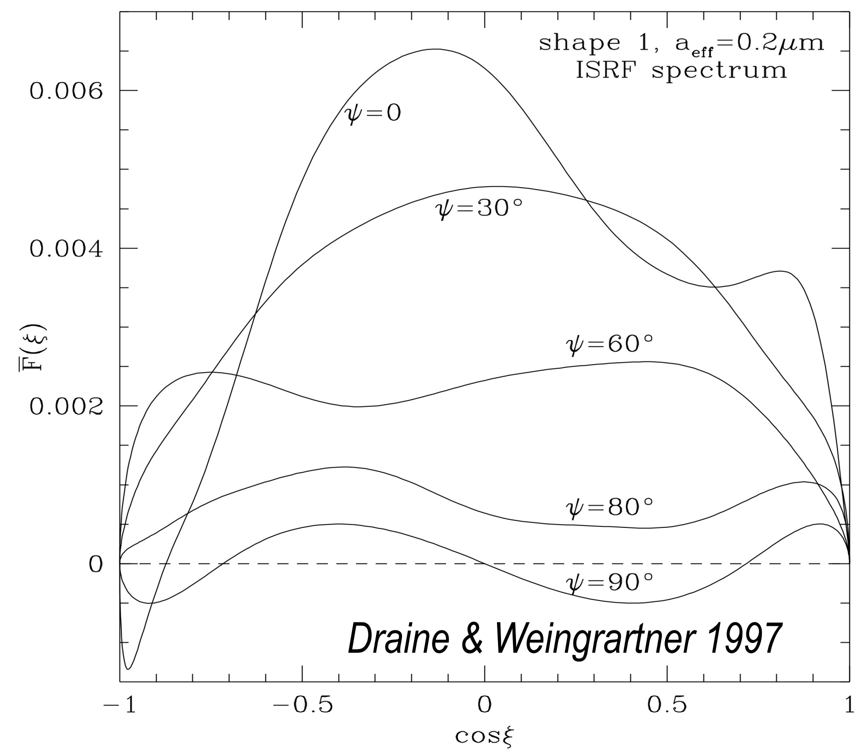
Crisis in Theory of Grain Alignment! ! !

New Mechanism: Radiative Torque Alignment

- Dolginov & Mytrophanov 76: computed radiative torques for two twisted ellipsoids

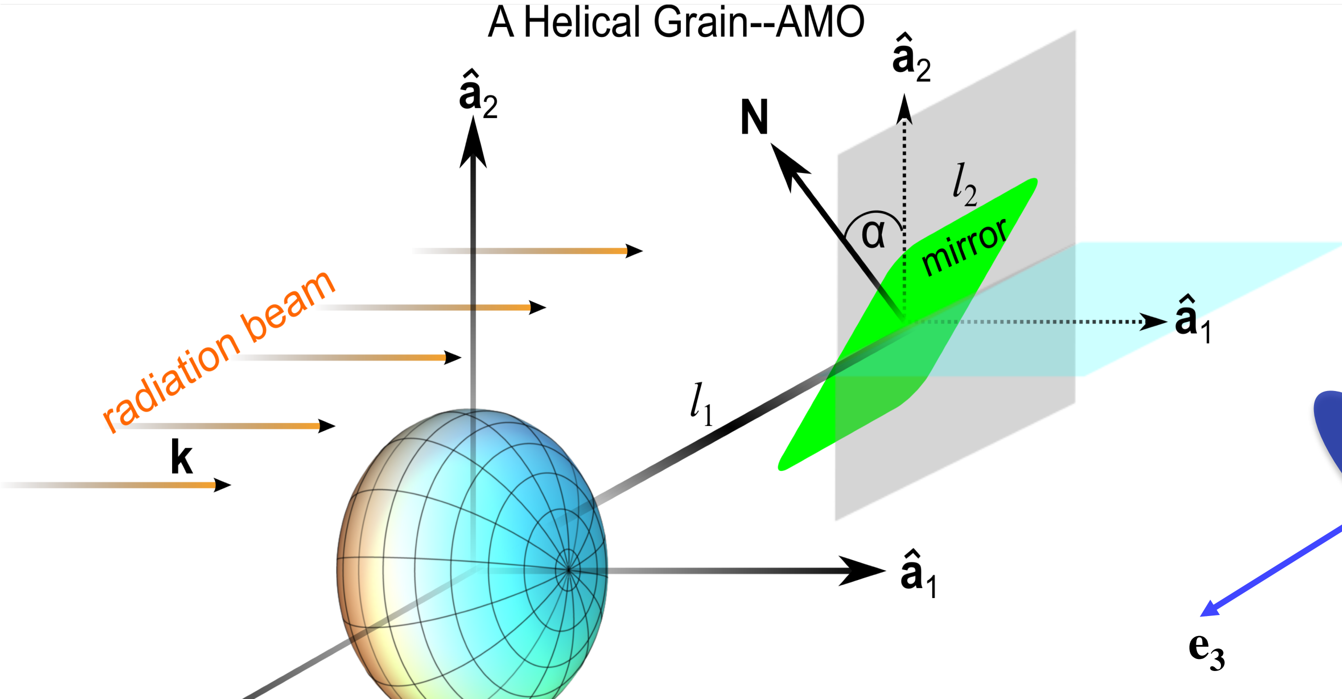
- B Draine introduced radiative torques in DDSCAT code



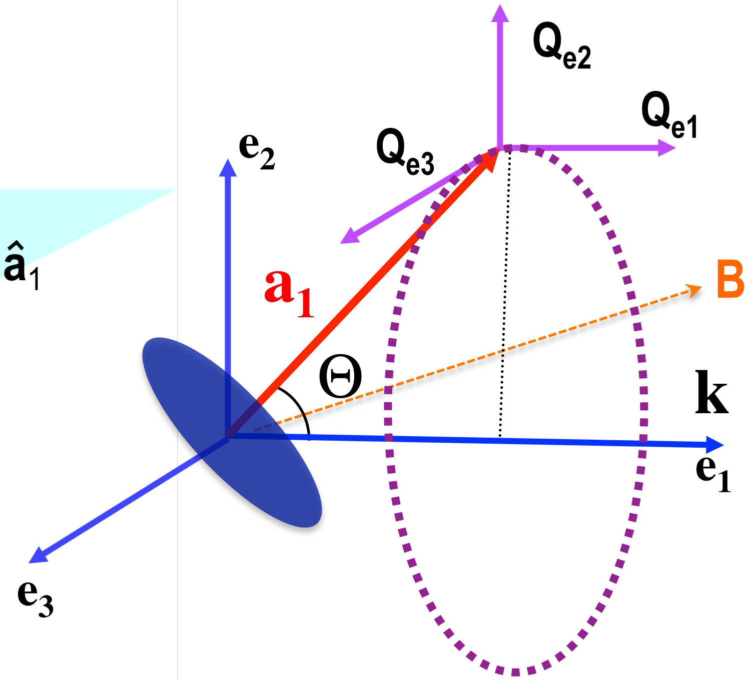


L. Spitzer: Alignment torques are not universal. How can a universal alignment exist?

Analytical model (AMO) of Radiative Torque (RAT) for a Helical Grain



k *is radiation beam direction*
a_1 *is grain maximum inertia axis*
a_2a_3 *grain principal axes*
N, *normal vector of mirror, lies in* **a_1a_2**
mirror plane tilted by angle α with **a_2a_3**

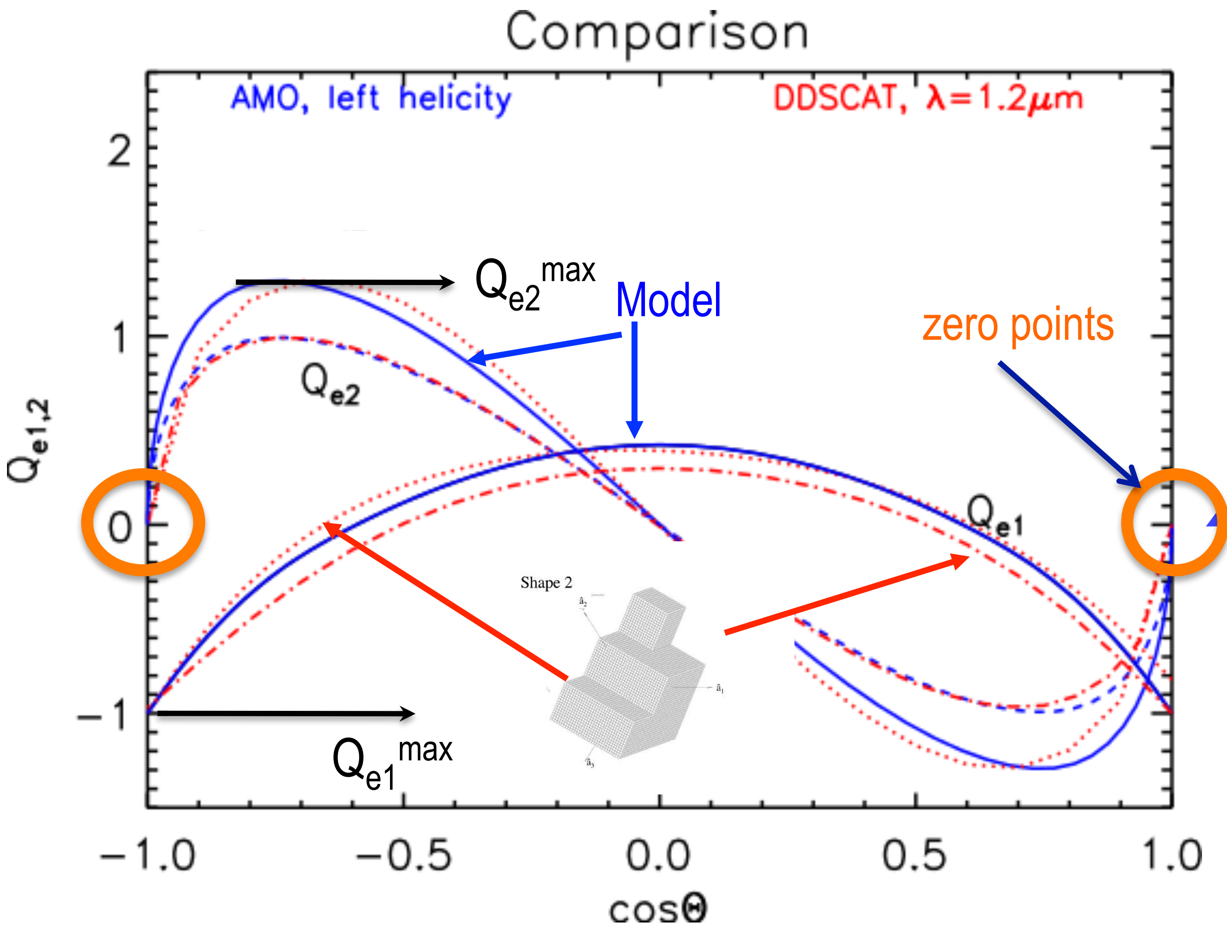


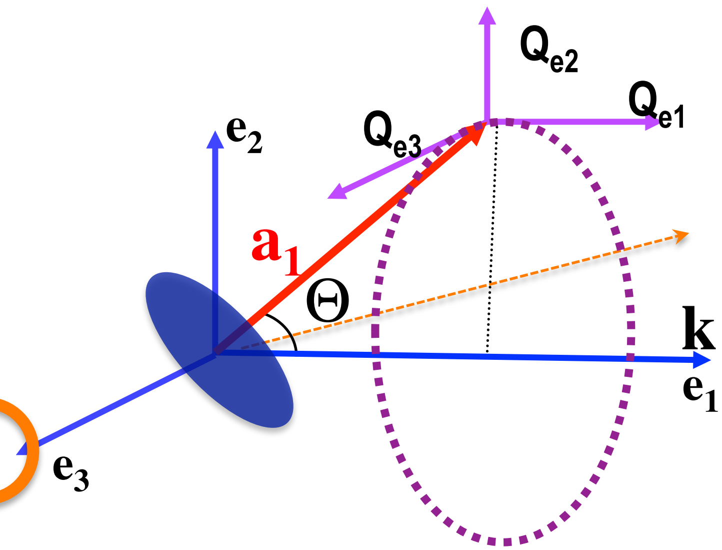
a_1 *is grain maximum inertia axis*
k *is radiation beam direction*
e_1 *parallel to* **k**, **e_1e_2** *contains B-field*

Lazarian & Hoang 07a

- Simple analytical expressions available for Q_{ei} torques
- Allow us to infer **basic properties** of grain alignment

Generic Properties of RATs: Q_{e1} symmetry and Q_{e2} anti-symmetry with flipping





a_1 is grain maximum inertia axis

***k** is radiation beam direction*

e_1 parallel to k, e_1e_2 contains B-field

- Zero points: Q_{e2}=0 at Θ=0 or 180 degree.
- Q^{max} -ratio=$Q_{e1}^{max}/Q_{e2}^{max}$ changes from grain to grain.
- RATs from arbitrary shape can be described by functional forms from AMO with varying Q^{max}.

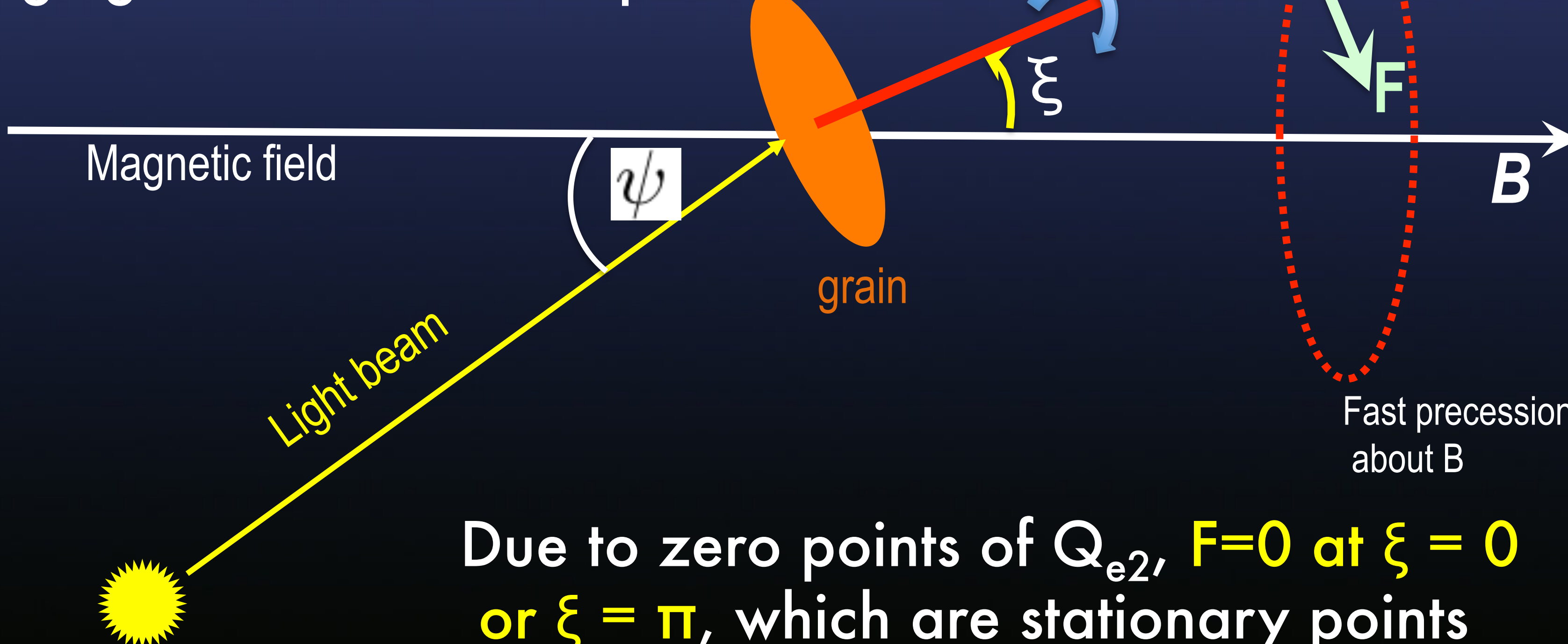
Lazarian & Hoang 07a

Basic Properties of RAT alignment: Method

- Follow evolution of grain momentum in spherical system (J, ξ) subject to RATs and drag:

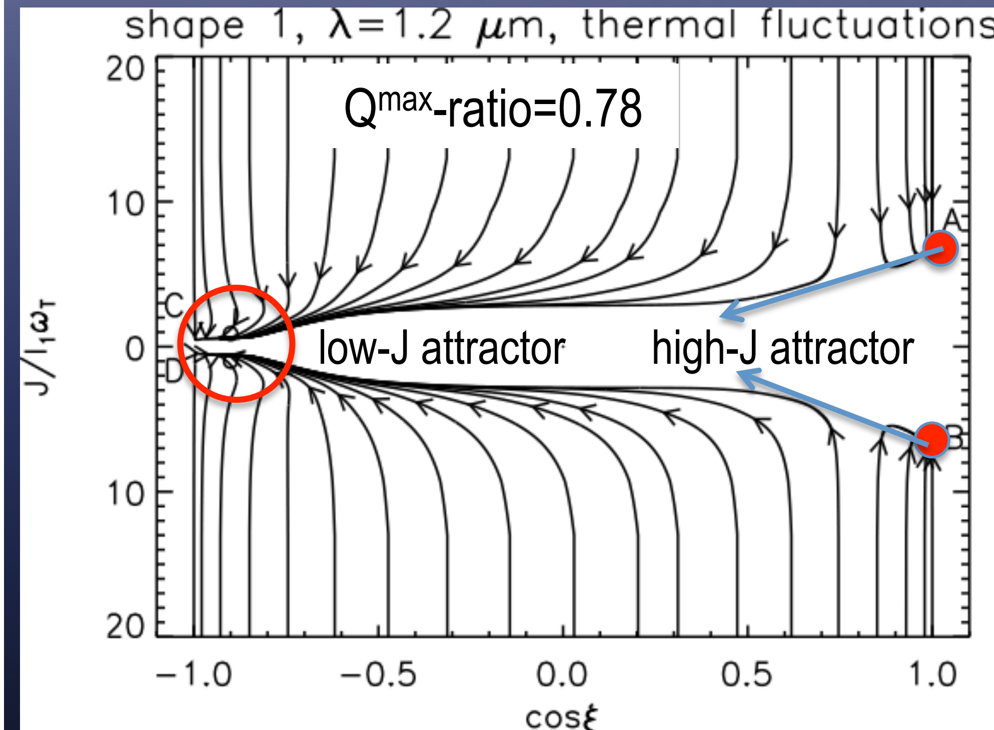
$$\frac{d\vec{J}}{dt} = \text{RATs} - \text{drag} = H\frac{\vec{J}}{J} + F\vec{\xi} - \frac{\vec{J}}{\tau_{\text{drag}}}$$

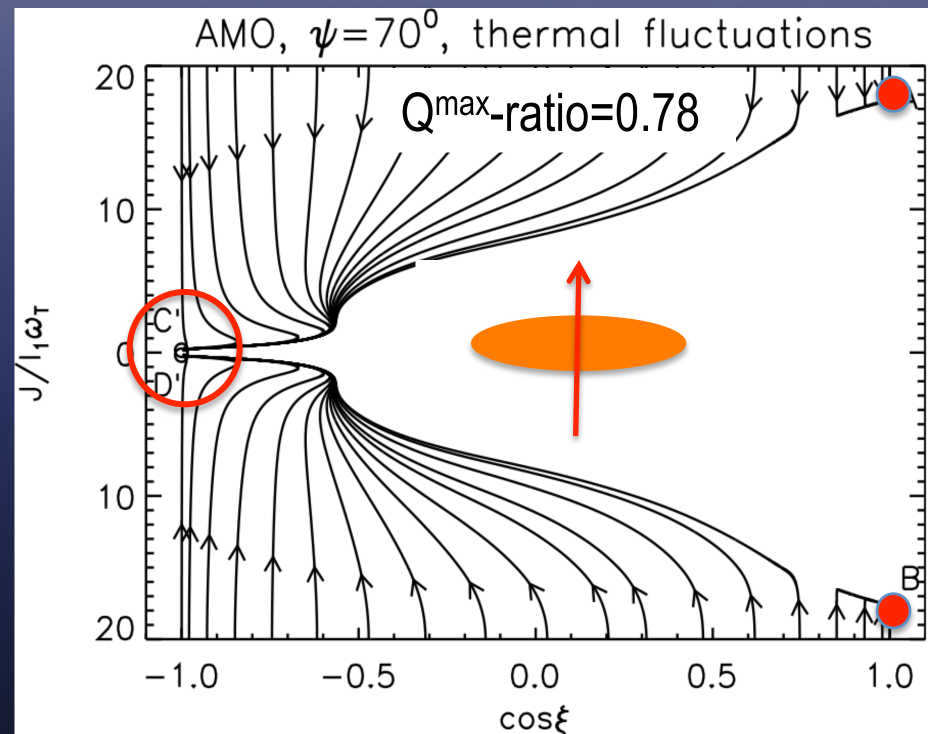
- H: spin-up torque (para. to J)
- F: alignment torque (perp. to J)
- Averaging over fast Larmor precession



Due to zero points of Q_{e2}, F=0 at ξ = 0 or ξ = π, which are stationary points

Basic Properties of RAT Alignment:
1. Grains are aligned with low-J and high-J attractors.

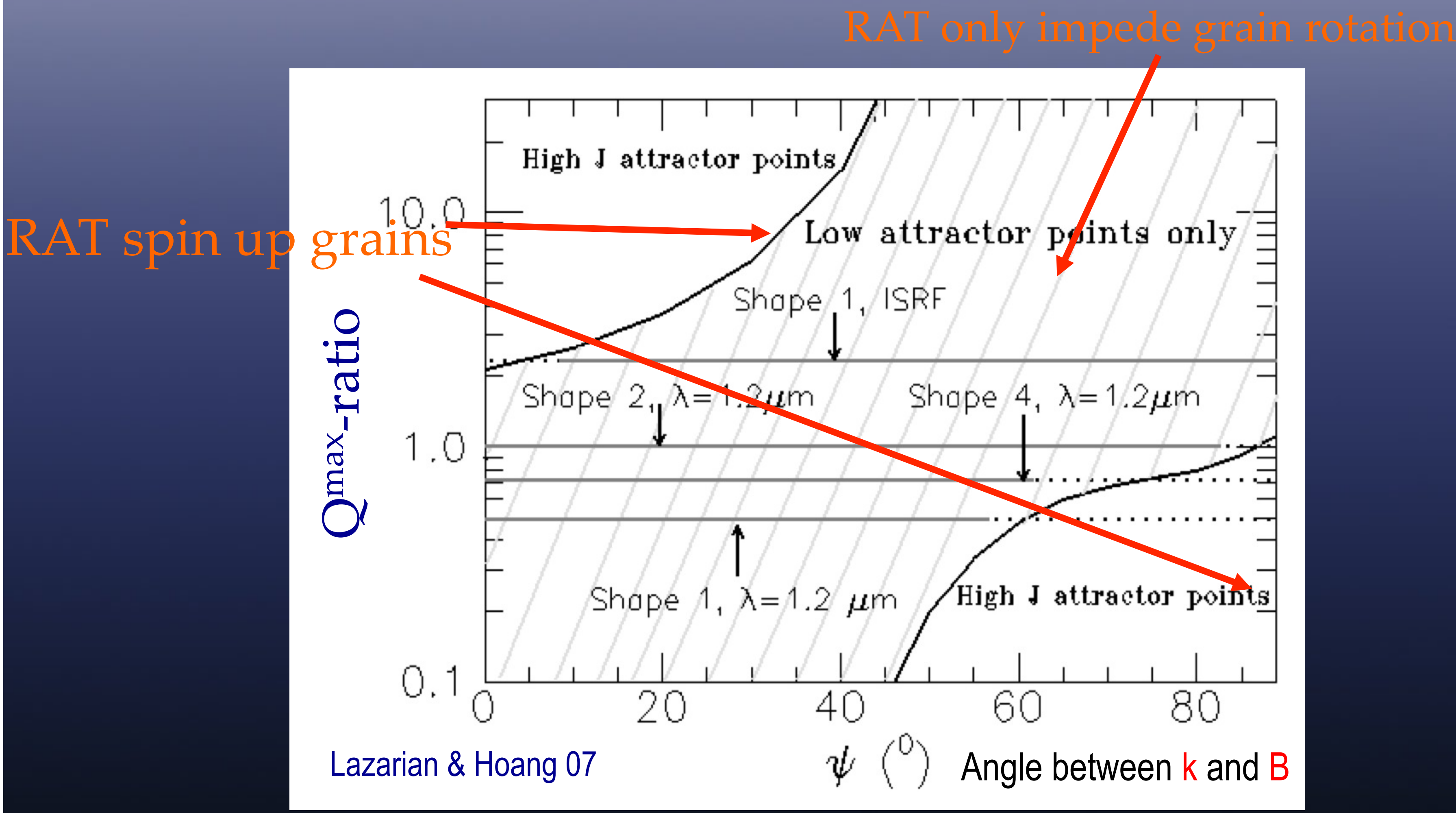




- Grains at high-J attractors are perfectly aligned, those at low-J attractors are partially aligned.
- AMO predicts the "right" alignment with long axes perpendicular to B.

Hoang & Lazarian 08

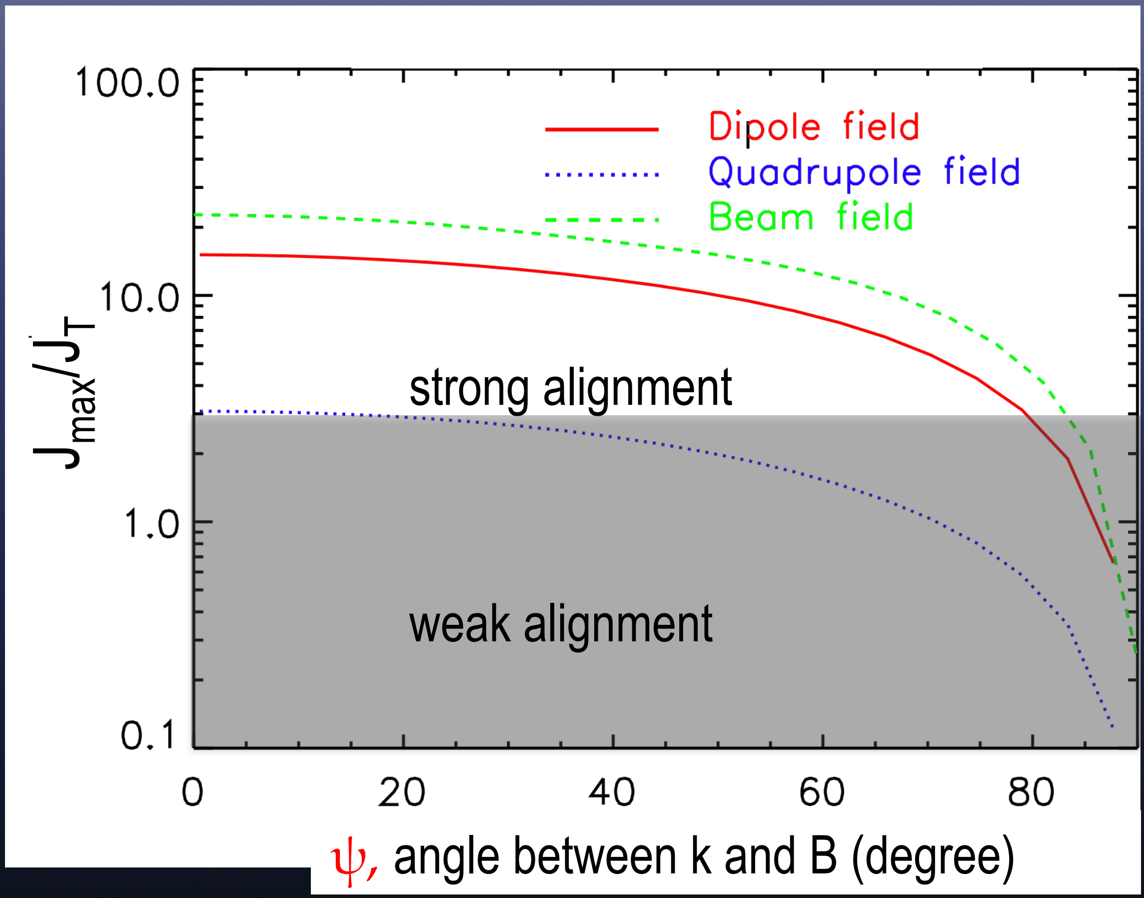
2. When do high-J and low-J attractors appear?



- Fraction of grains aligned with high-J attractor depends on Q^{max}-ratio and radiation direction ψ.

Lazarian & Hoang 07a

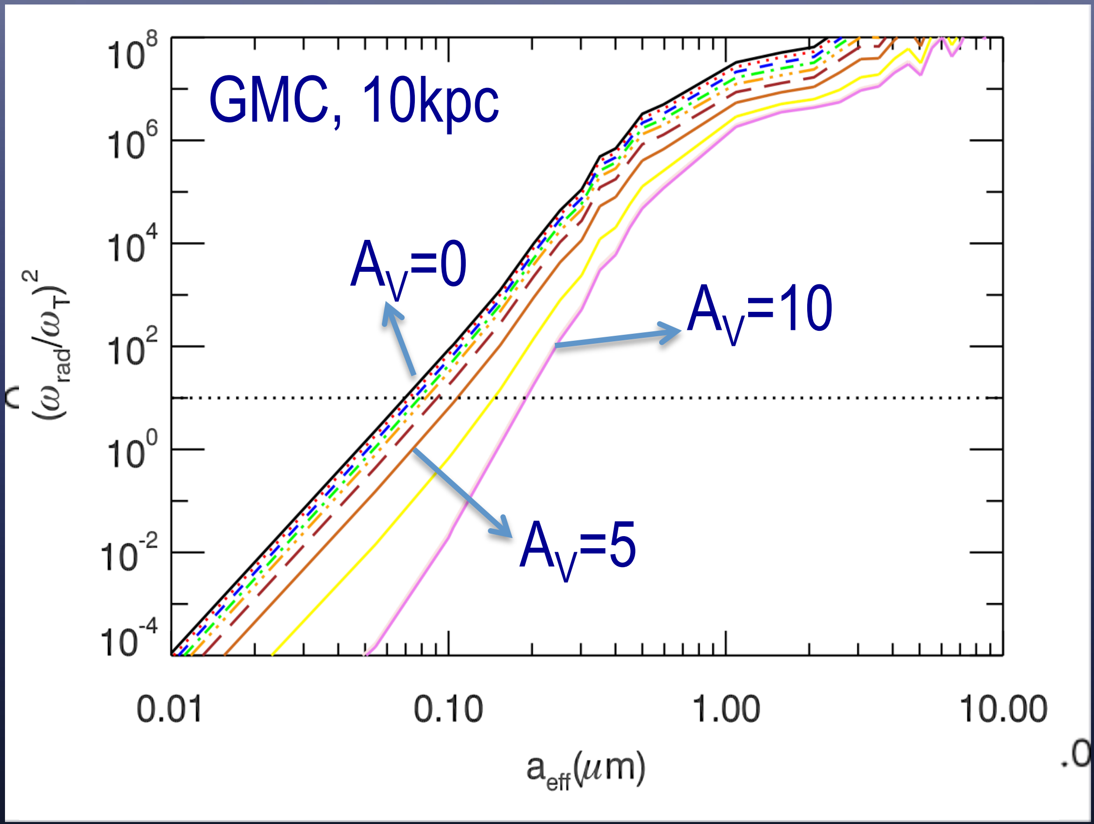
3. High-J momentum (J_{max}) decreases with increasing the angle between radiation direction and B-field.



• This angle-dependence alignment was observationally confirmed by Andersson et al. 2011.

Hoang & Lazarian 09a

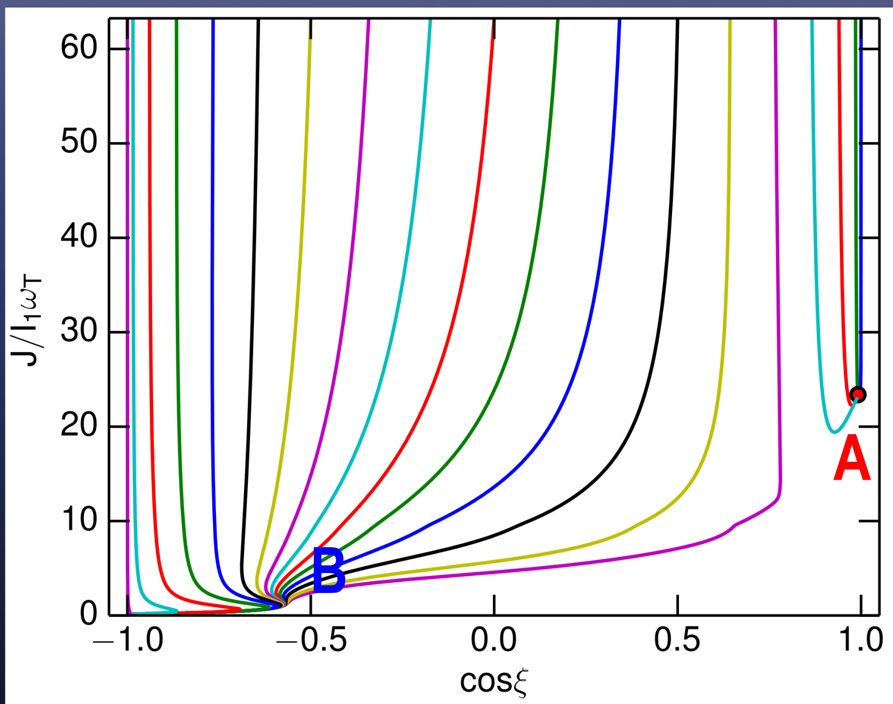
4. Maximum rotation rate increases with grain size.



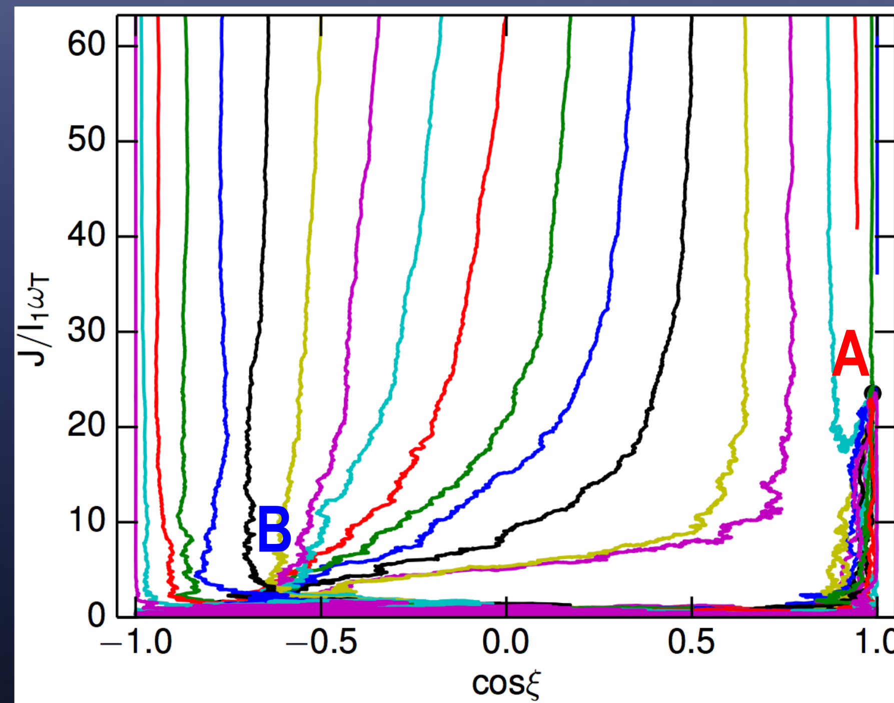
• Large grains are aligned more efficiently than small grains.
• Grains near cloud surface aligned better than those deep inside cloud.

5. New effect of random collisions by gas atoms

no randomization by gas



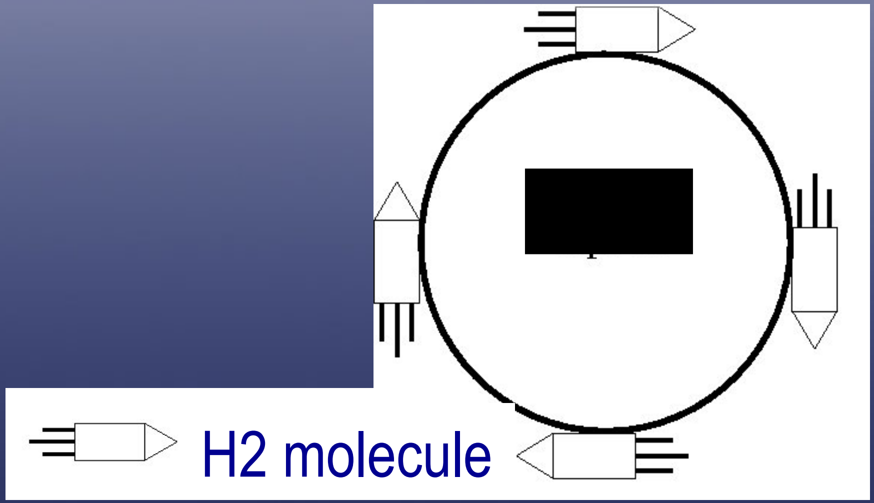
with randomization by gas

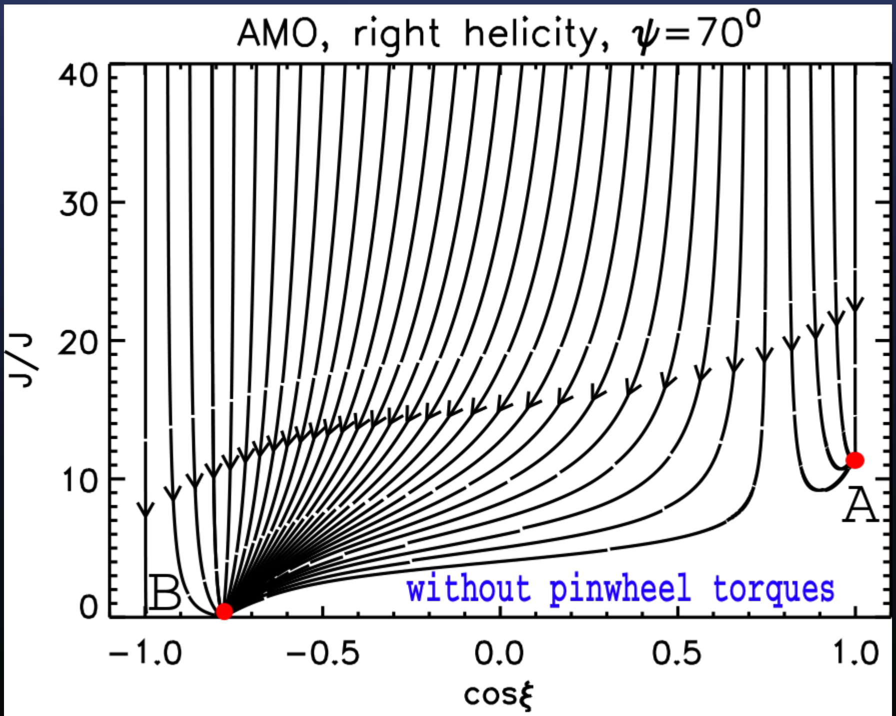


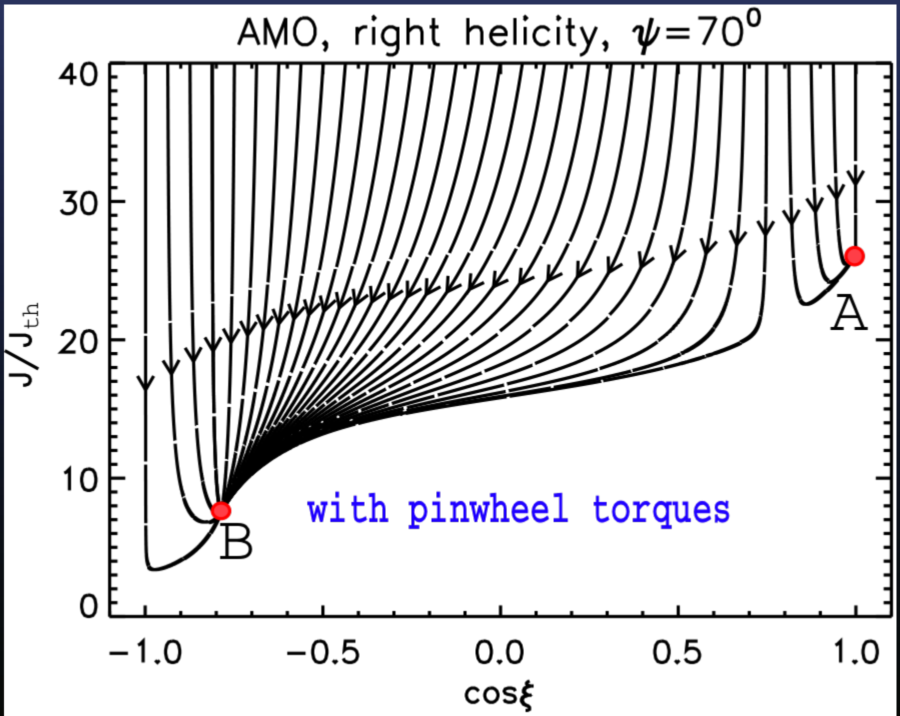
- New effect: random collisions increase degree of RAT alignment when high-J attractor point exists.

Hoang & Lazarian 08

6. H_2 pinwheel torques increase degree of RAT alignment.

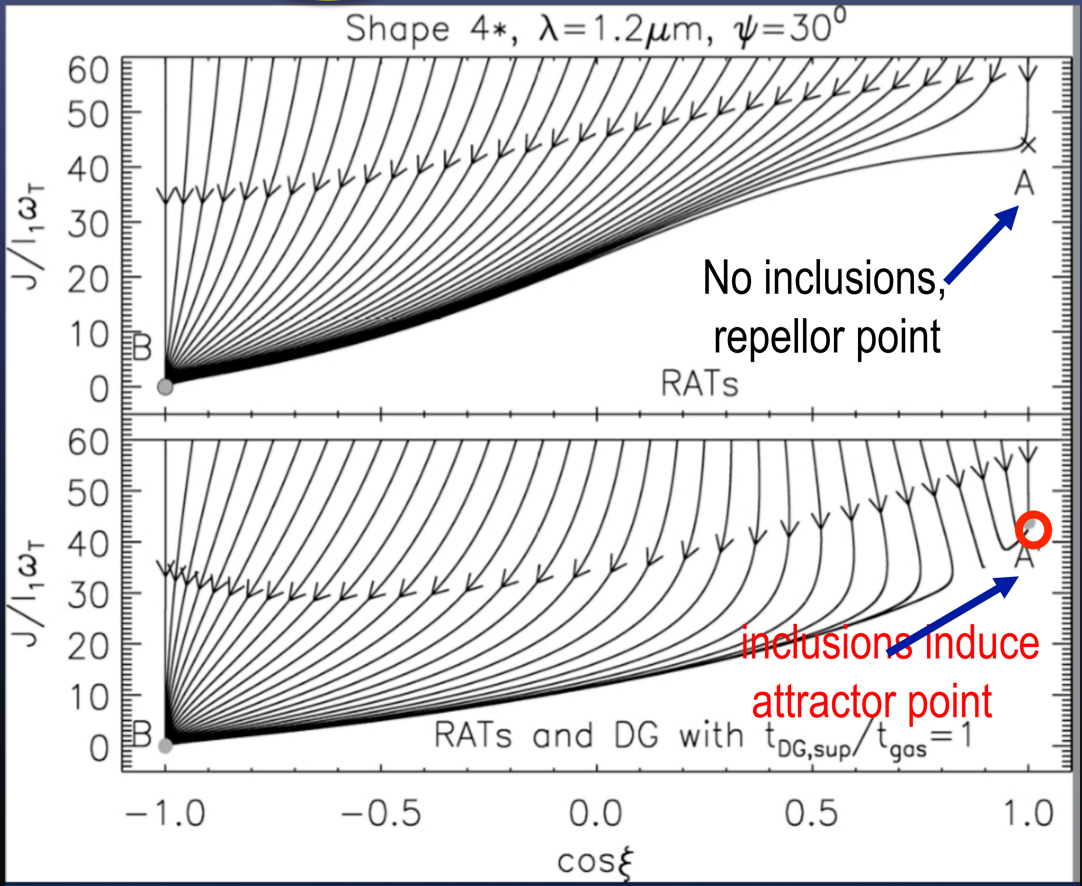






7. Super-paramagnetic Inclusions increases degree of RAT alignment to ~100%.

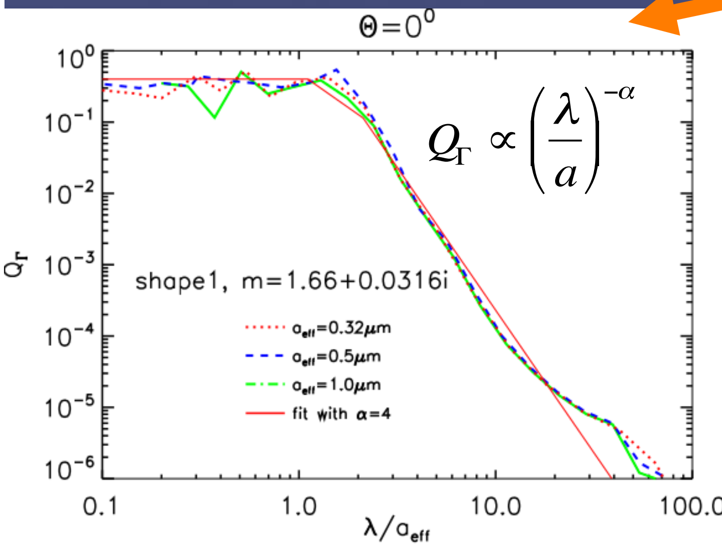
$$\frac{d\vec{J}}{dt} = H\frac{\vec{J}}{J} + F\vec{\xi} - \frac{\vec{J}}{\tau_{\rm drag}} - \frac{\sin\zeta\cos\zeta}{\tau_{\rm DG,sup}}\vec{\zeta}$$

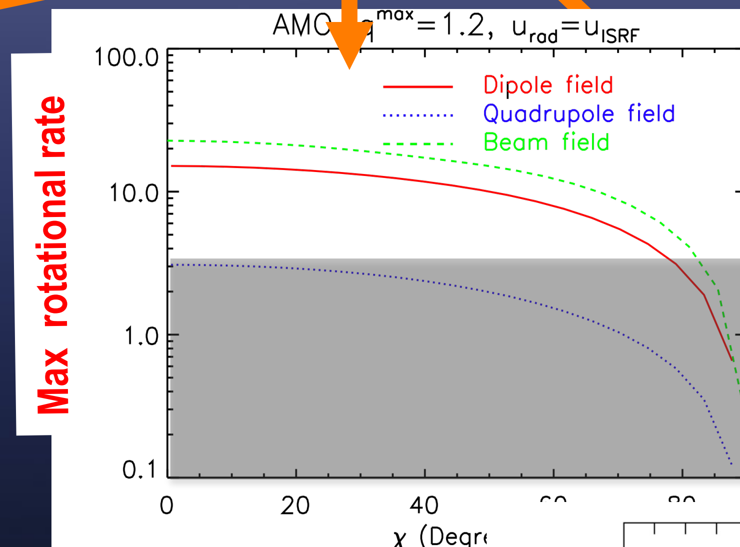


Lazarian & Hoang 08

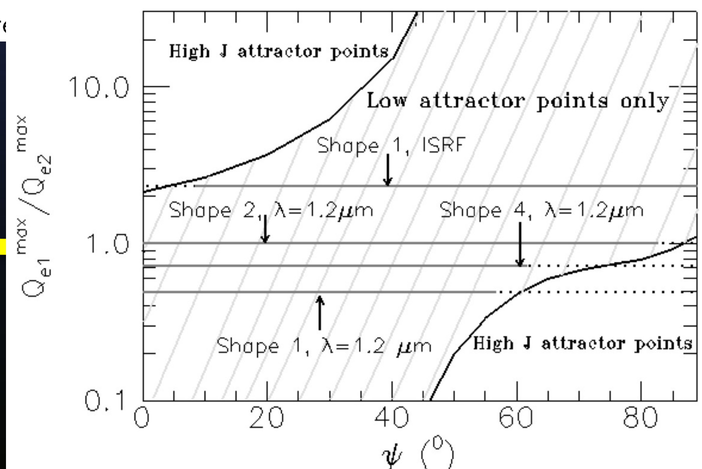
Modeling Dust Polarization by RAT alignment

grain size, shape, n_{gas}, T_{gas}, radiation field (intensity, k and B angle), and Q^{max}-ratio → Theory → Polarization





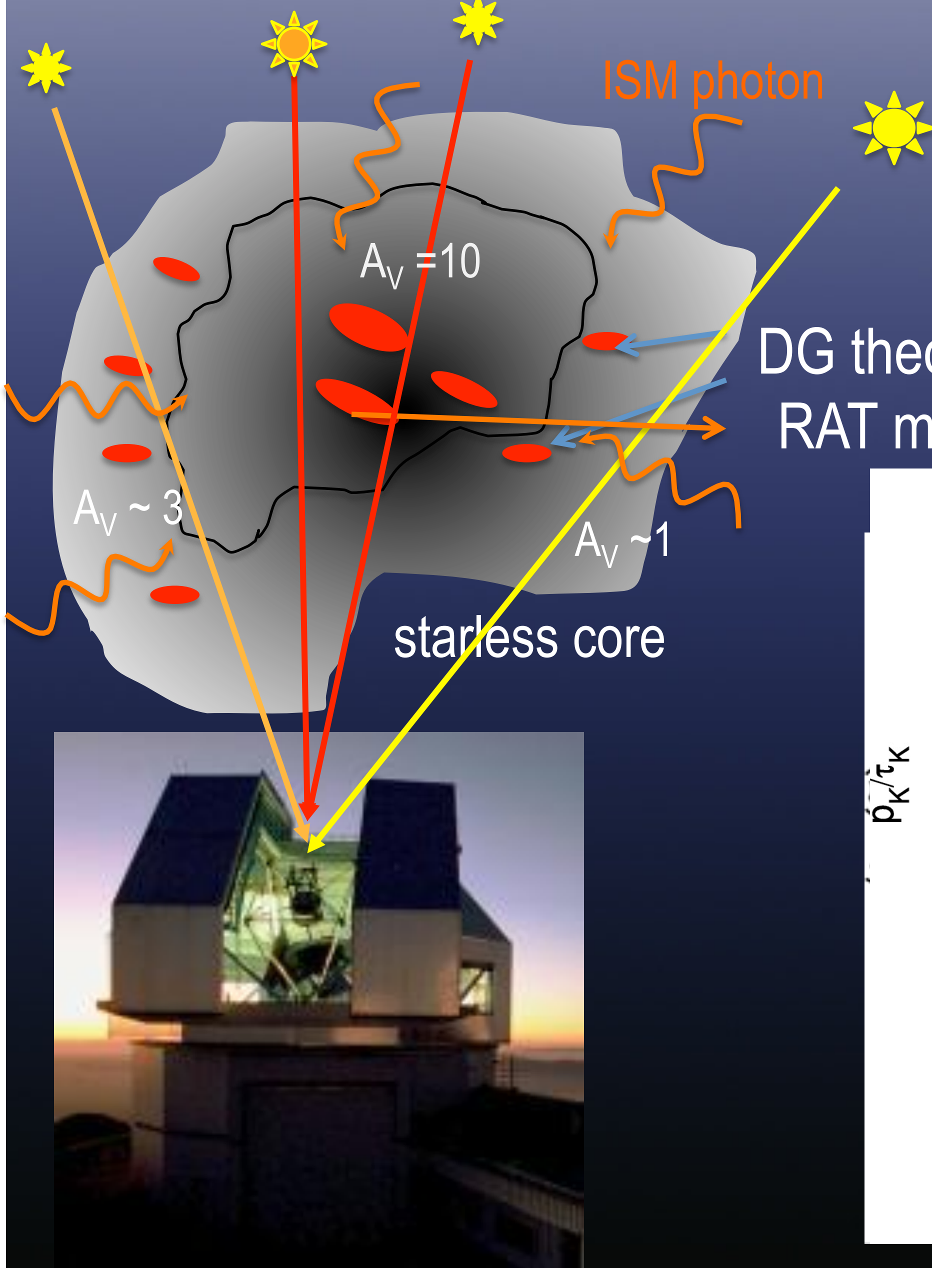
k and B angle



- Critical size of aligned grains: a_{ali}
- Degree of grain alignment: R

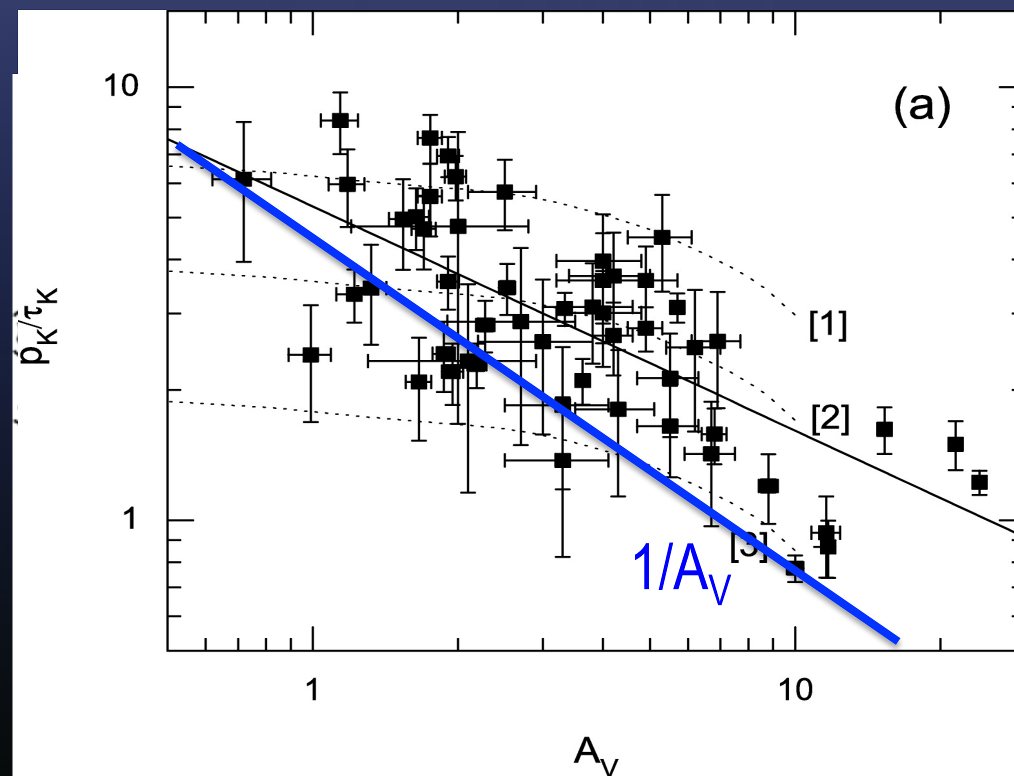
$$\frac{\sigma_{\rm pol}}{\rm N_H} = \int_{a_{\rm ali}}^{a_{\rm max}} da \frac{(C_\perp - C_\parallel)}{2} n_d(a) R(a) \cos^2 \zeta$$

1. RAT alignment exists deep inside Starless Cloud.



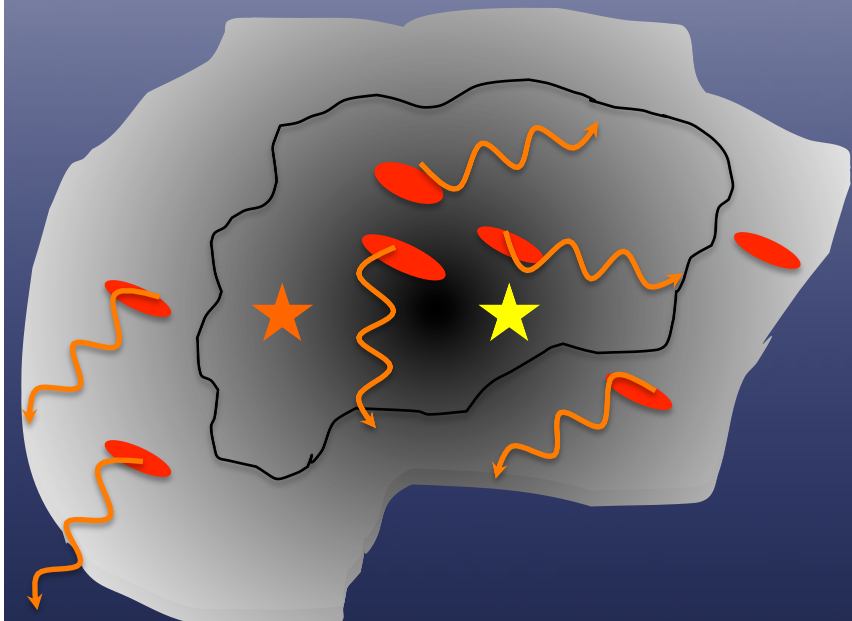
DG theory: grains aligned in interface, not core

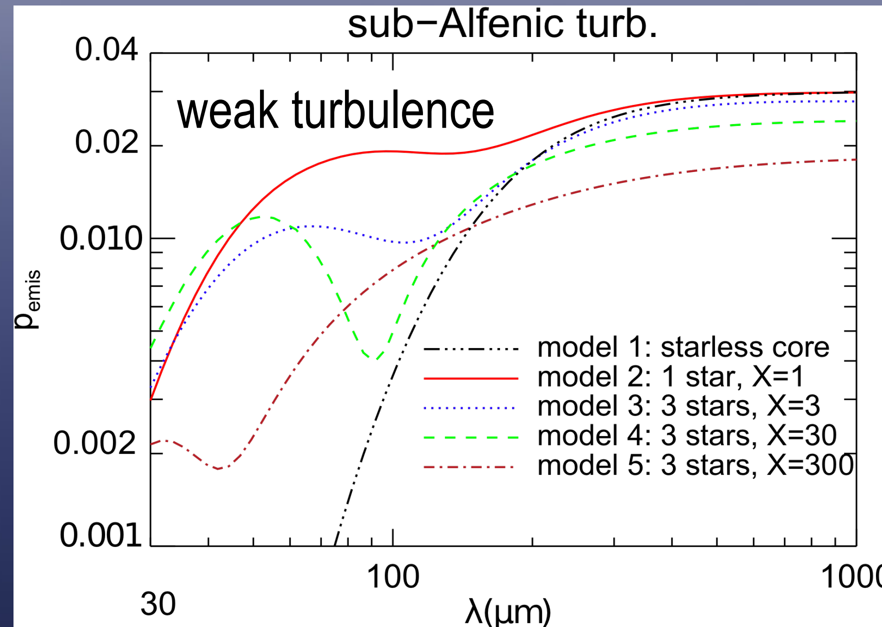
RAT model

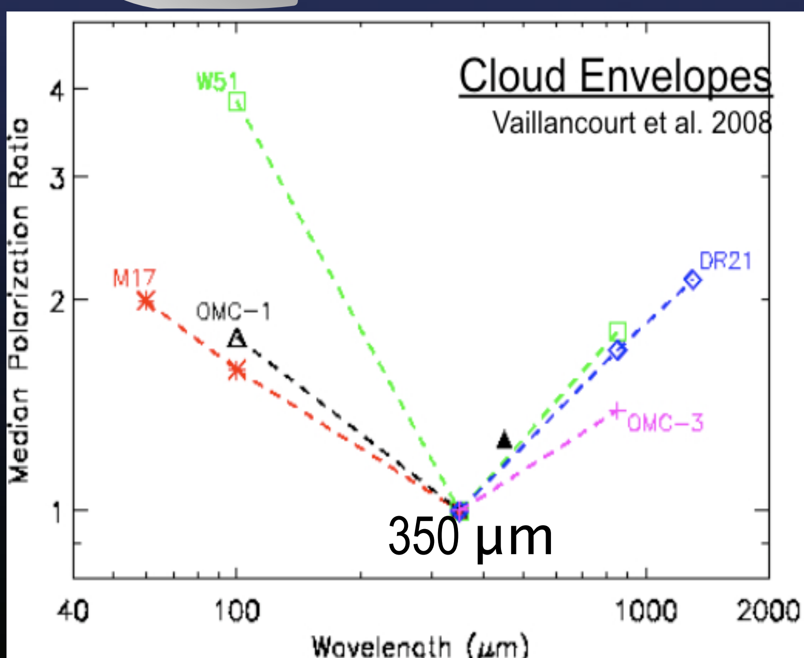


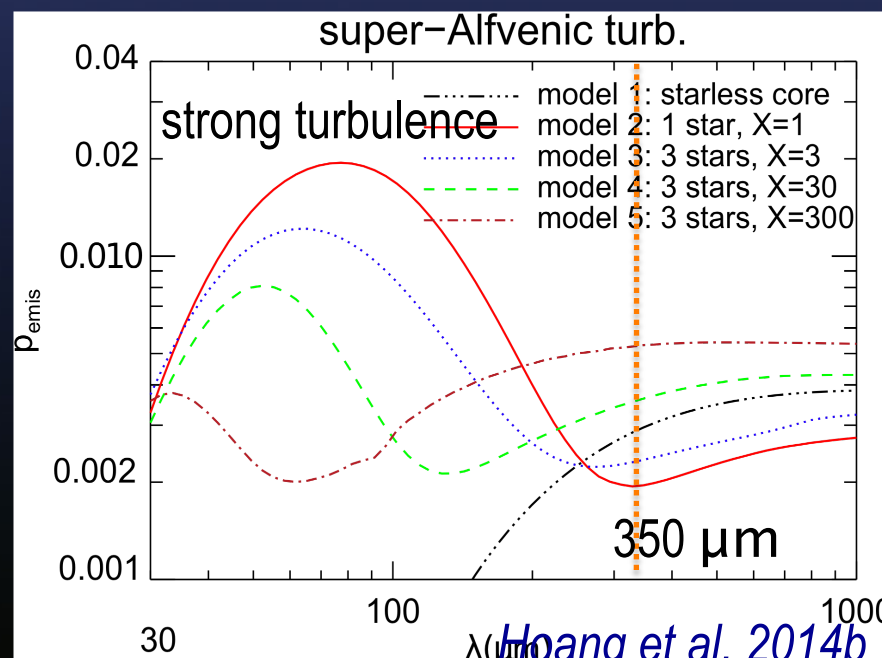
Whittet, Hough, Lazarian, Hoang (2008)

2. Polarized Dust Emission from Molecular Cloud



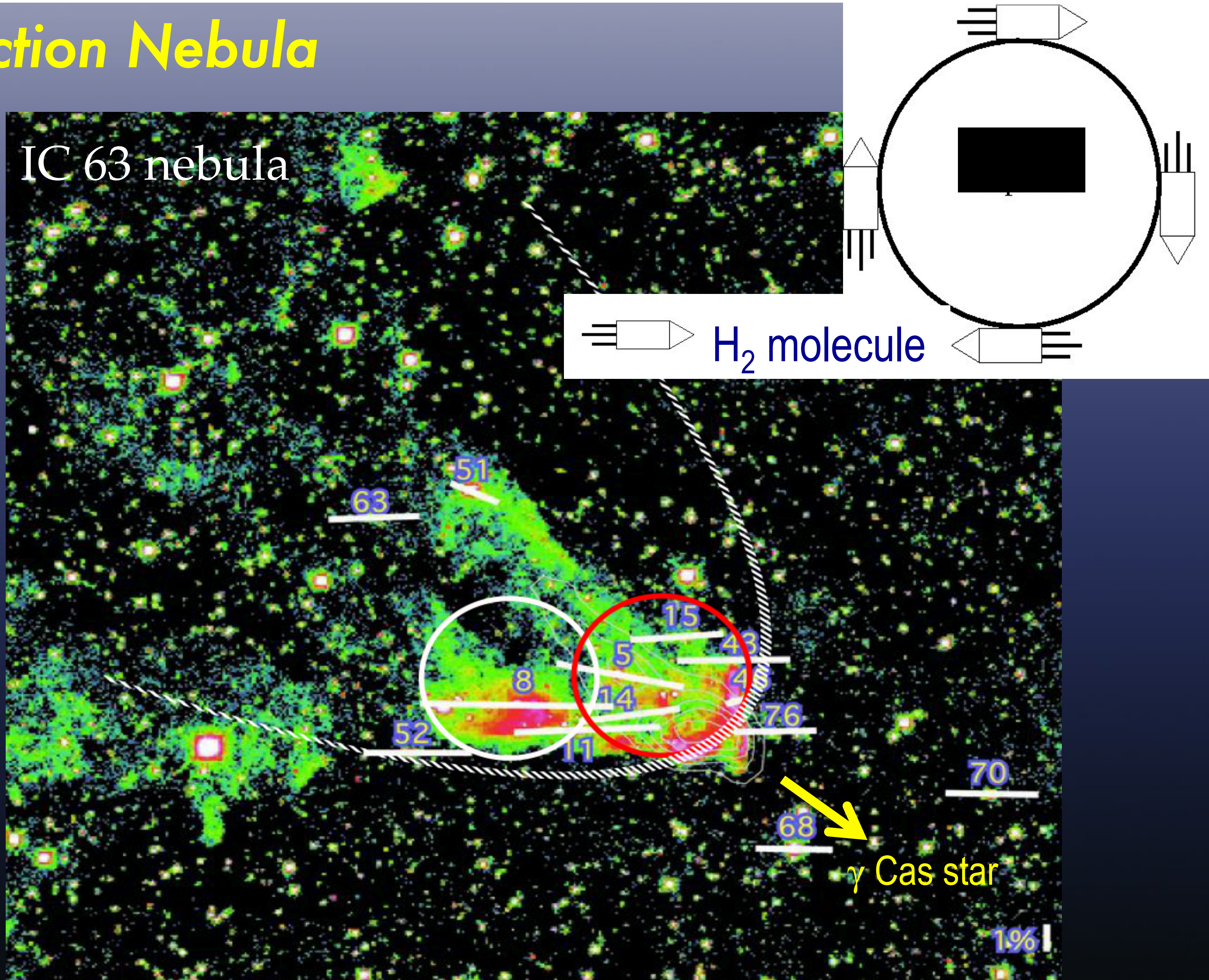






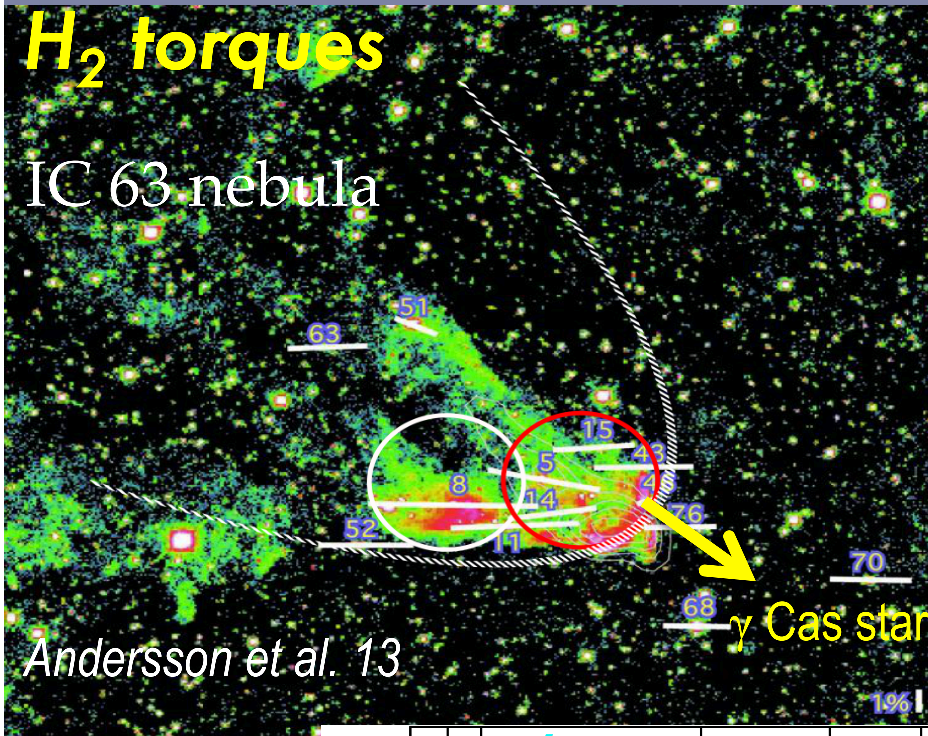
Hoang et al. 2014b

3. Reflection Nebula

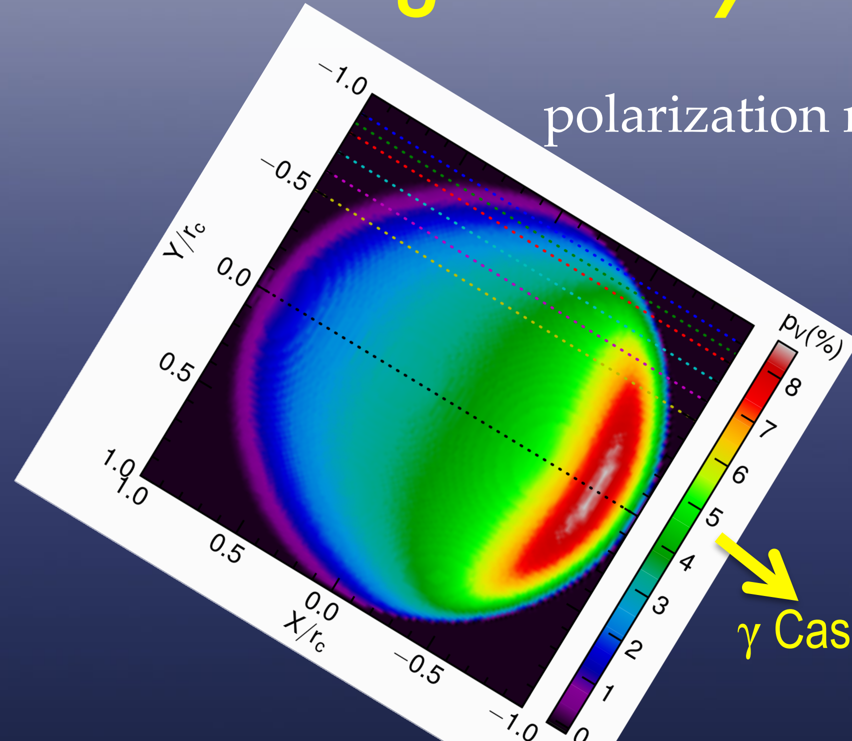


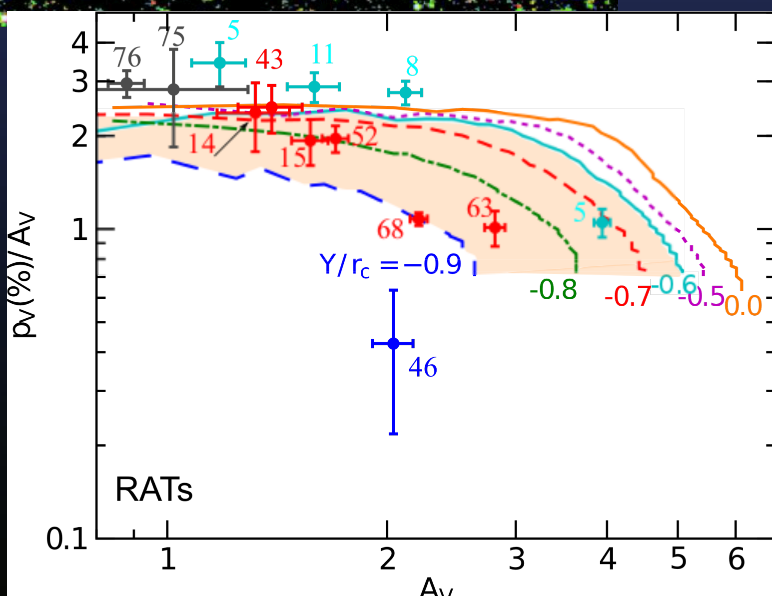
Andersson et al. 13

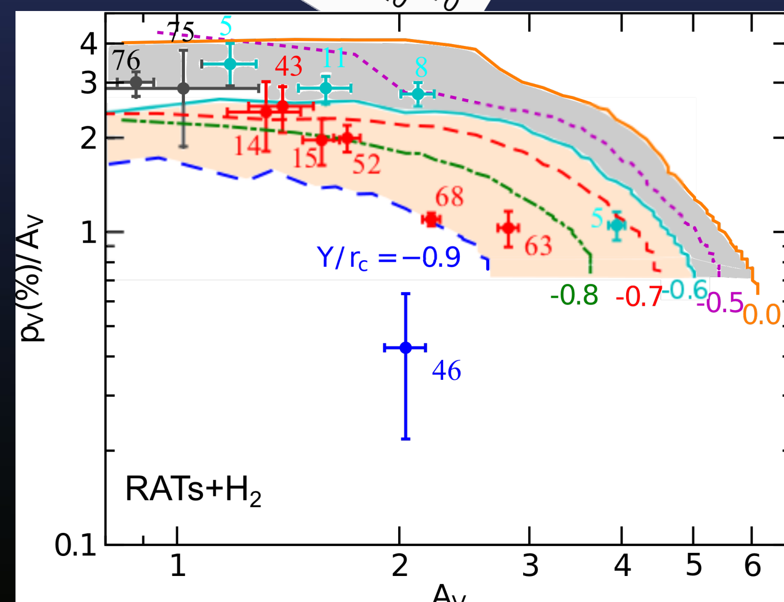
3. Reflection Nebula: Enhanced RAT Alignment by H_2 torques



polarization map







Hoang+ 14b

Summary

Finally, analytical theory of RAT alignment available:

- RATs agree well with numerical computations by DDSCAT.
- RAT alignment has basic properties that can be tested observationally.
- Theory allows for modeling of dust polarization spectra from optical to far-IR/mm wavelengths.
- Predictions from theory are supported by observational data from various media: molecular clouds, nebulae, Zodiacal cloud, etc.