Grain Alignment by Radiative Torques: Theory, Modeling and Observations

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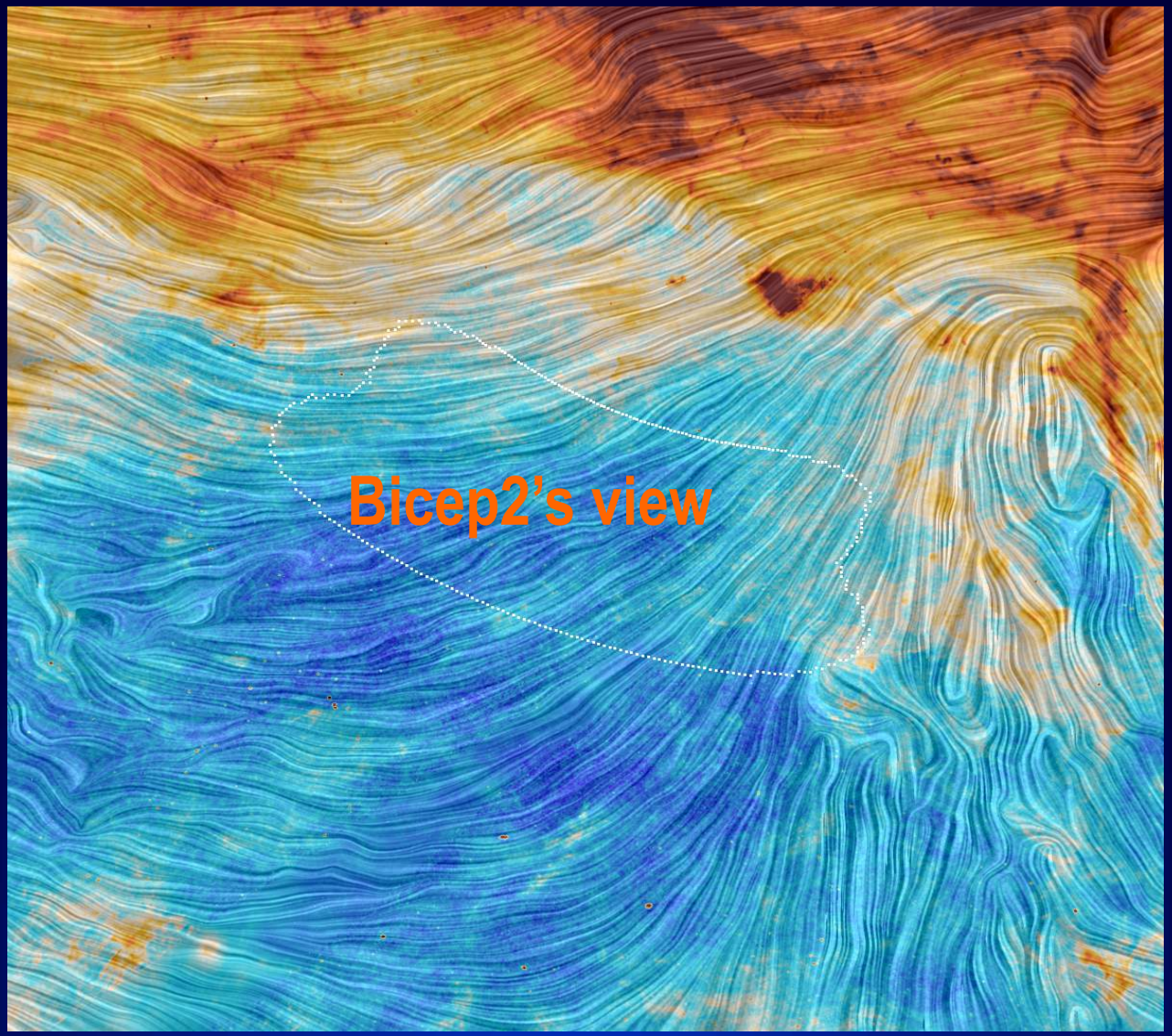
Special thanks to:
A. Lazarian, B-G Andersson, J. Cho, T. Jones, P. G. Martin, G. Novak

Corsia, Oct 5-9, 2015

Outline

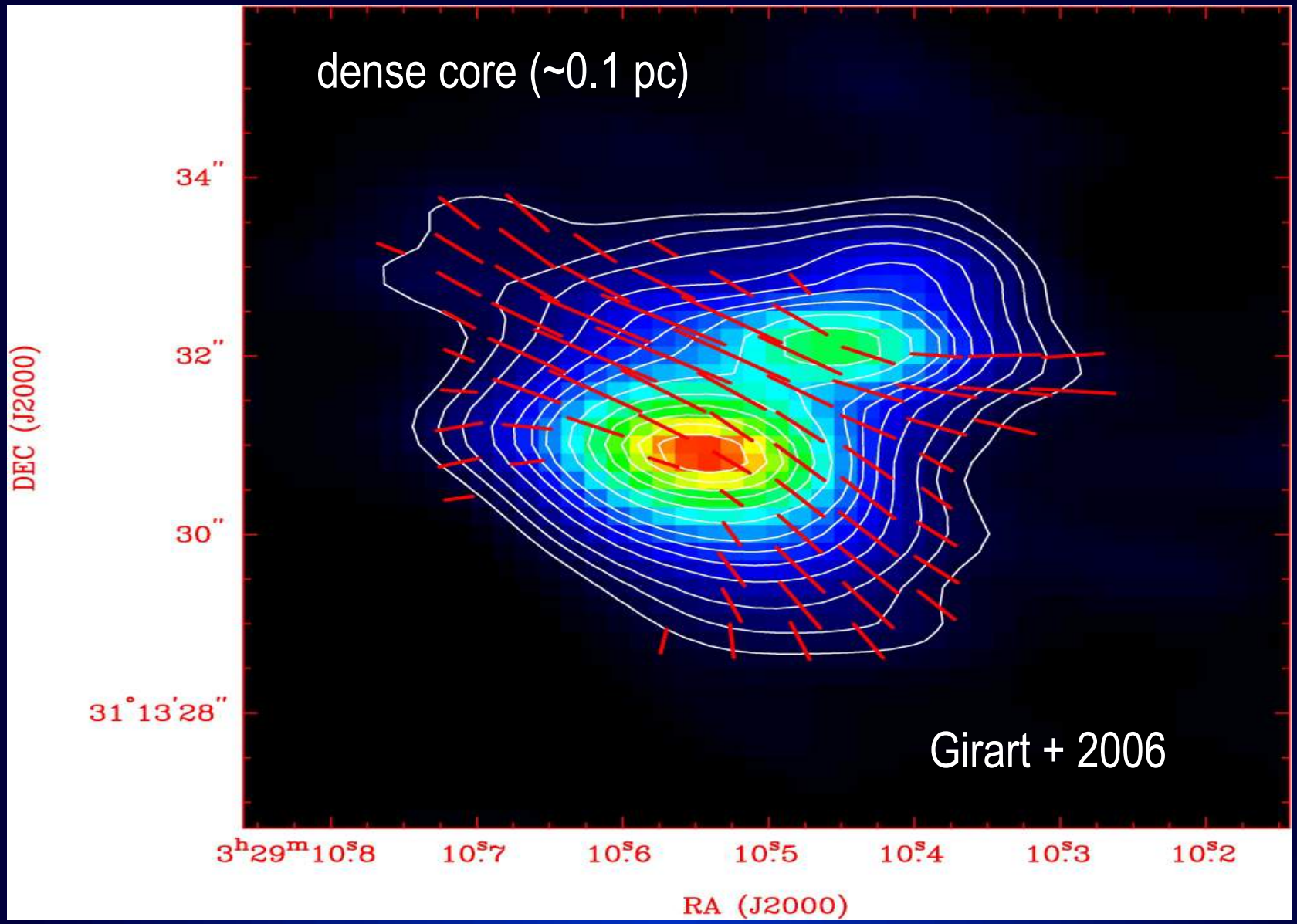
- Introduction
- Review of RAT alignment:
  - ✧ Analytical Model of Radiative Torques (RATs)
  - ✧ Basic/Testable Properties of RAT Alignment
- Modeling vs. Observations:
  - ✧ Modeling of dust polarization using RAT alignment
  - ✧ Comparison with observational data
- How to bring RAT alignment further?
  - ✧ Grain alignment in extragalactic ISM using SN polarimetry
  - ✧ Unified theory of RAT alignment, SRAT?
- Summary

Dust polarization is crucially important for CMB B-mode detection

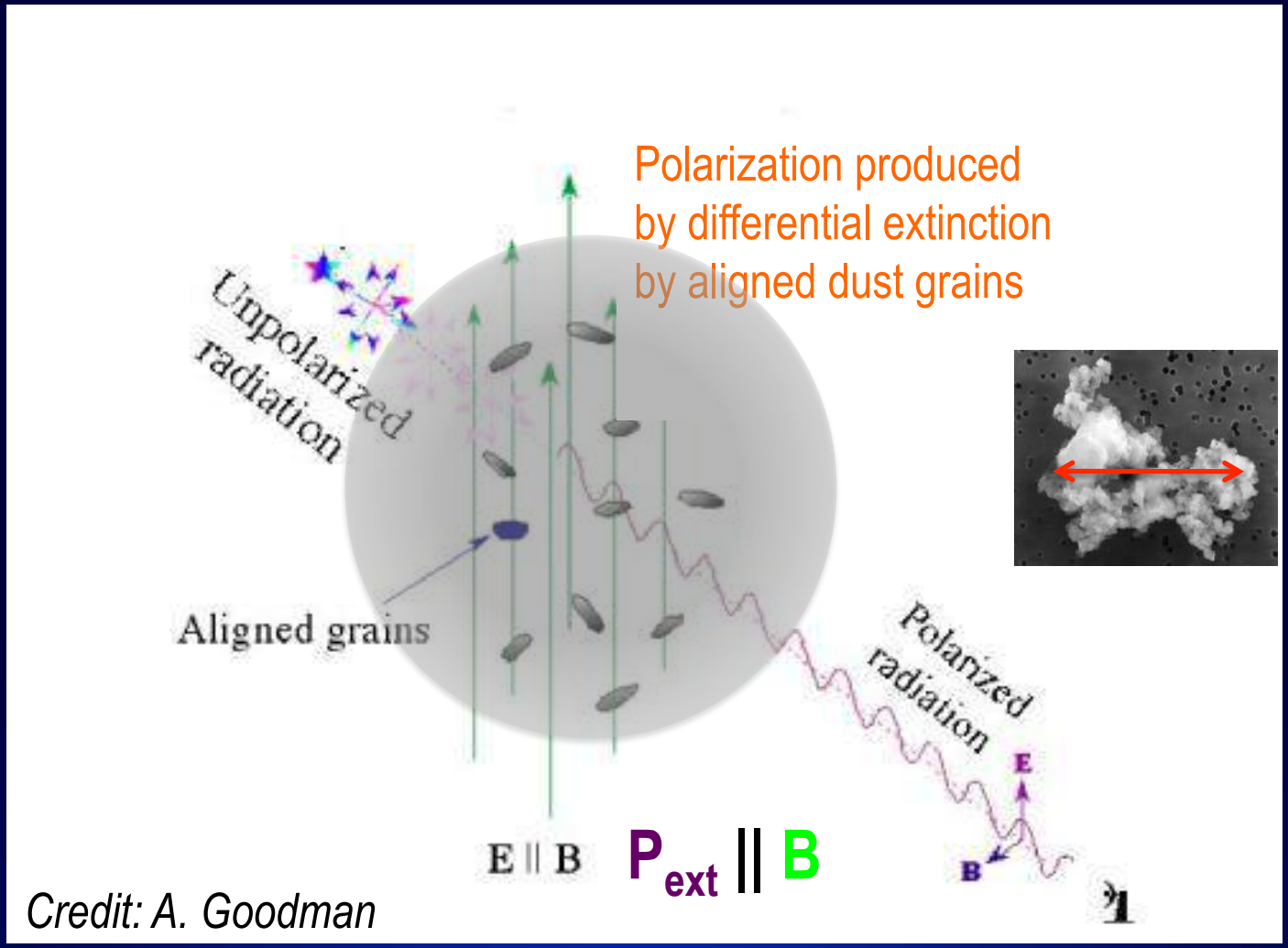


Bicep/Planck+2015

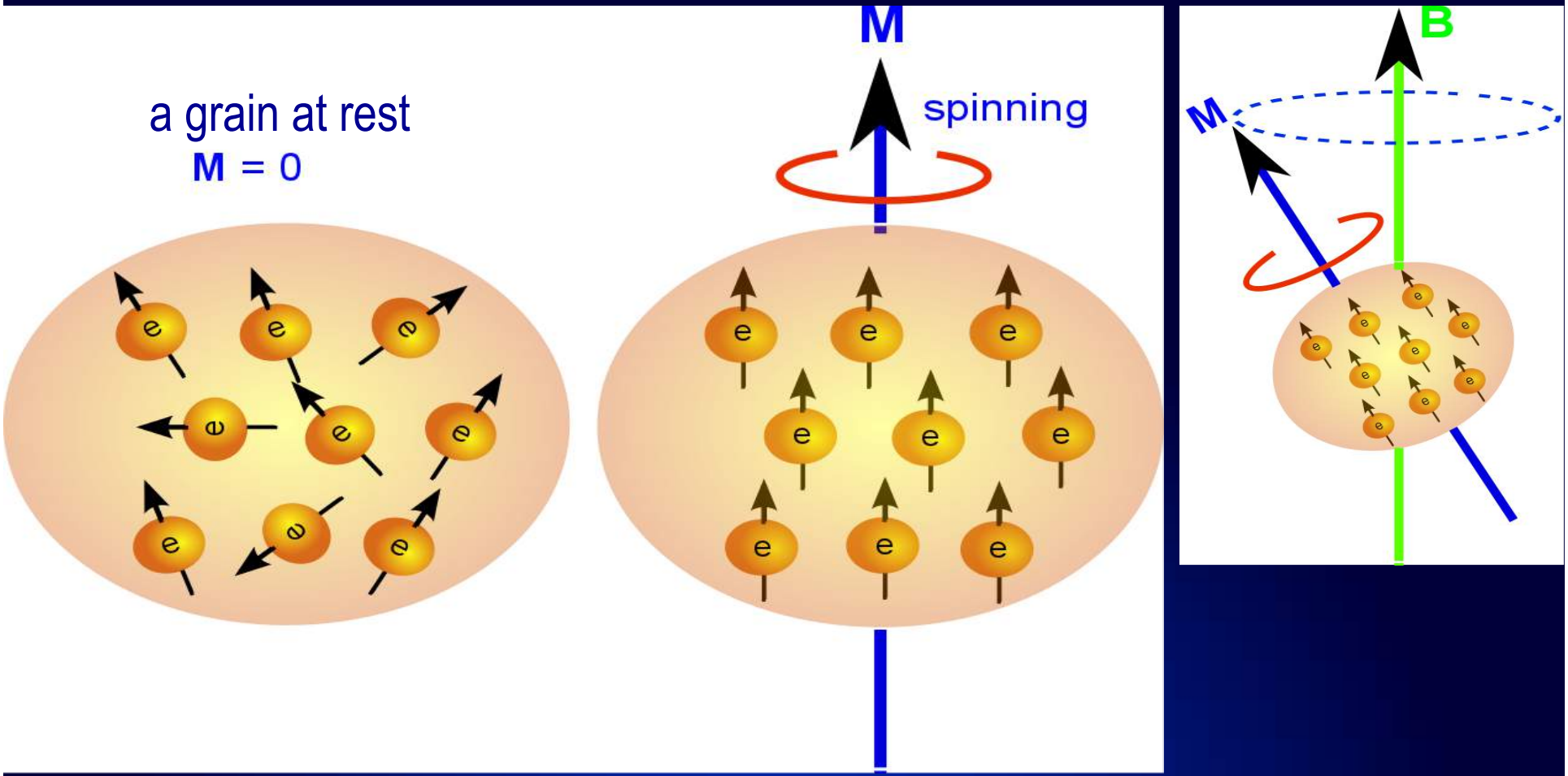
Dust polarization allows tracing magnetic field and testing star formation theory



Dust grains aligned with B-field polarize starlight and emit polarized thermal emission



How does dust grain interact with the magnetic field?



Magnetization by spinning (Barnett effect)

Theory of Grain Alignment

1949: Spitzer & Turkey: Ferromagnetic alignment (first proposed alignment of magnetic needles in interstellar magnetic field)

1951: Davis & Greenstein: Paramagnetic Relaxation Alignment

1951: T. Gold: Mechanic Alignment

1976: Dolginov & Mitrophanov: Helicity and Radiative Torques (RATs)

1979: E. Purcell: Pinwheel torques + paramagnetic relaxation

1986: J Mathis: Superparamagnetic inclusion of iron clusters

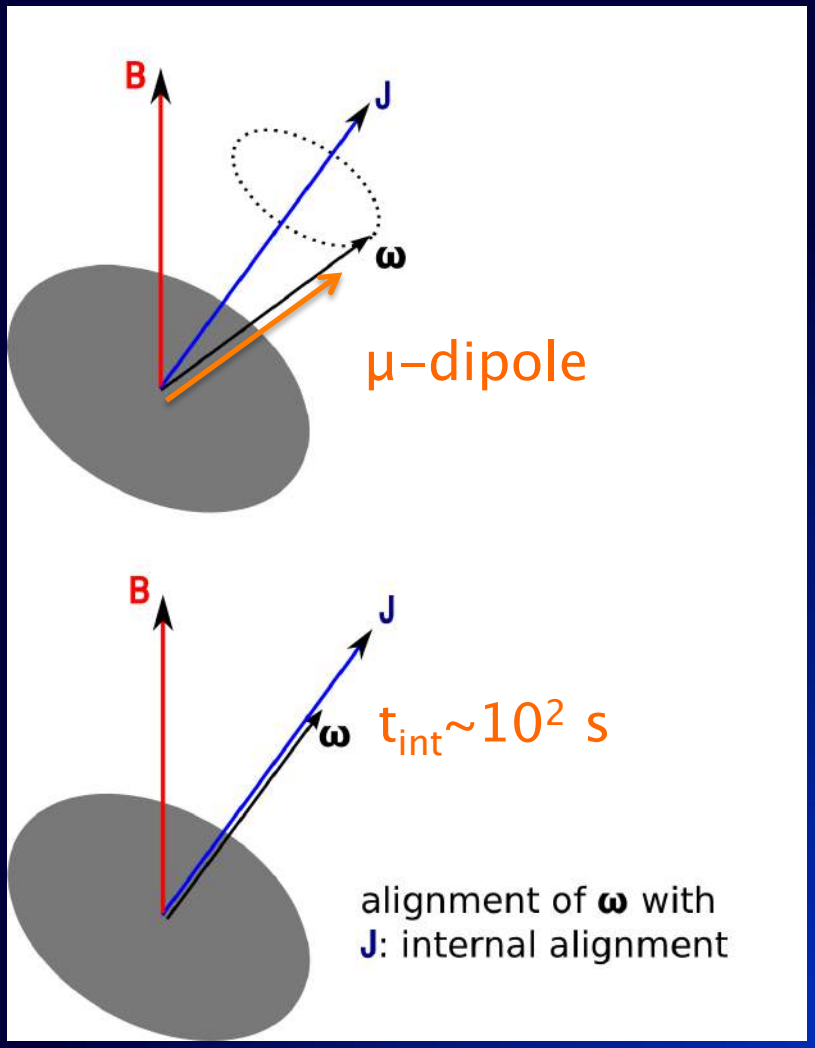
1997: Lazarian & Draine: thermal flipping and trapping

1996- 2003: Draine & Weingartner: pioneering study of RATs and RAT alignment for three grain shapes

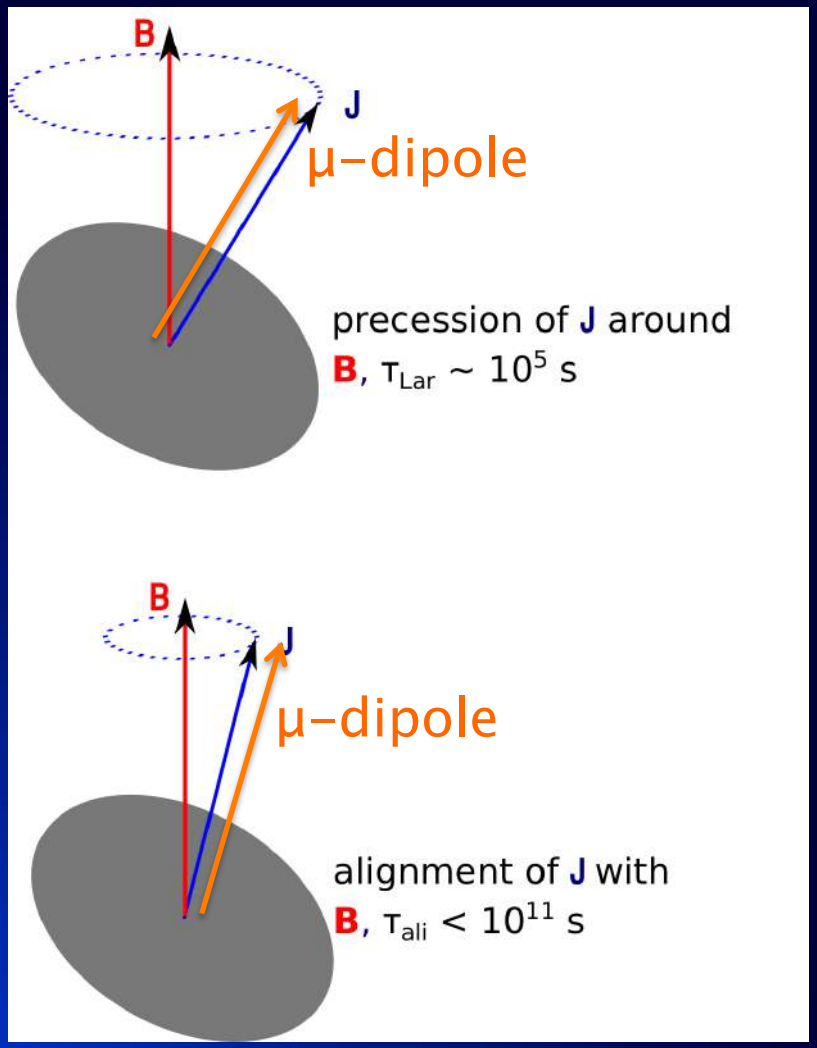
2007-ongoing: Analytical and Predictive Model of RAT Alignment

Internal and External Grain Alignment

Stage 1: ω align with J, a



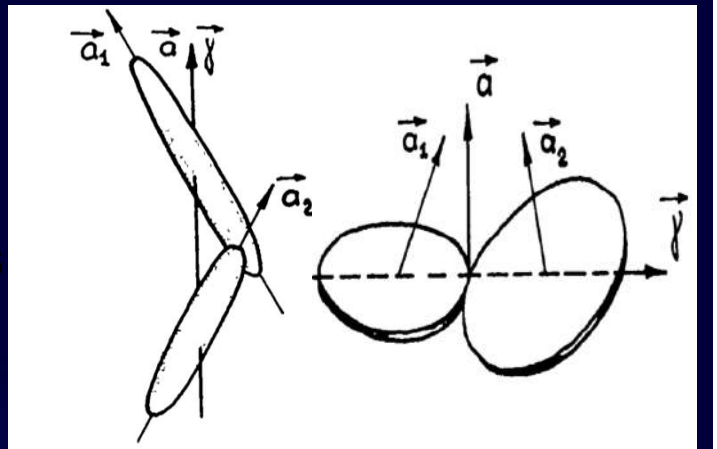
Stage 2: J gets aligned with B

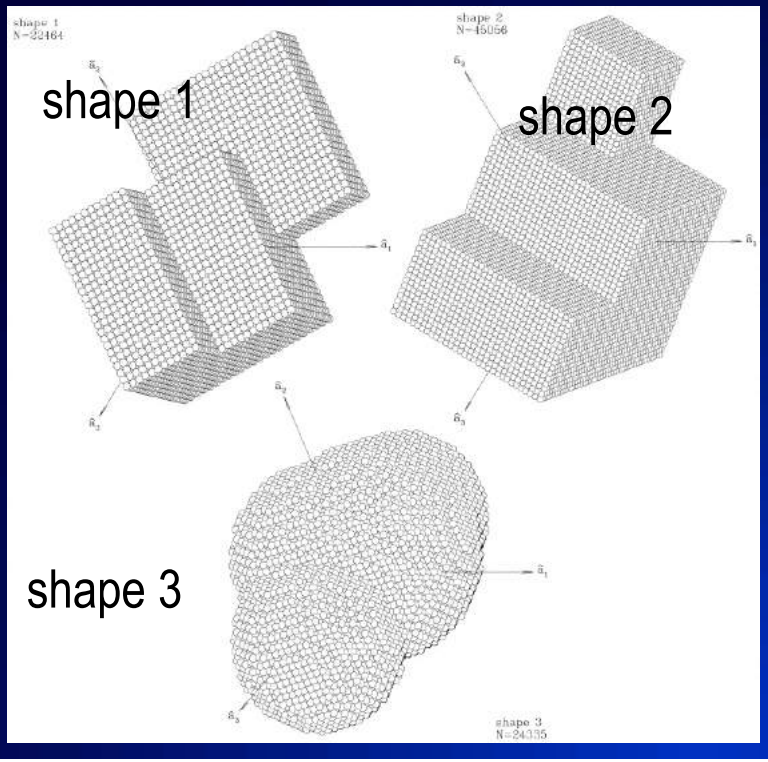


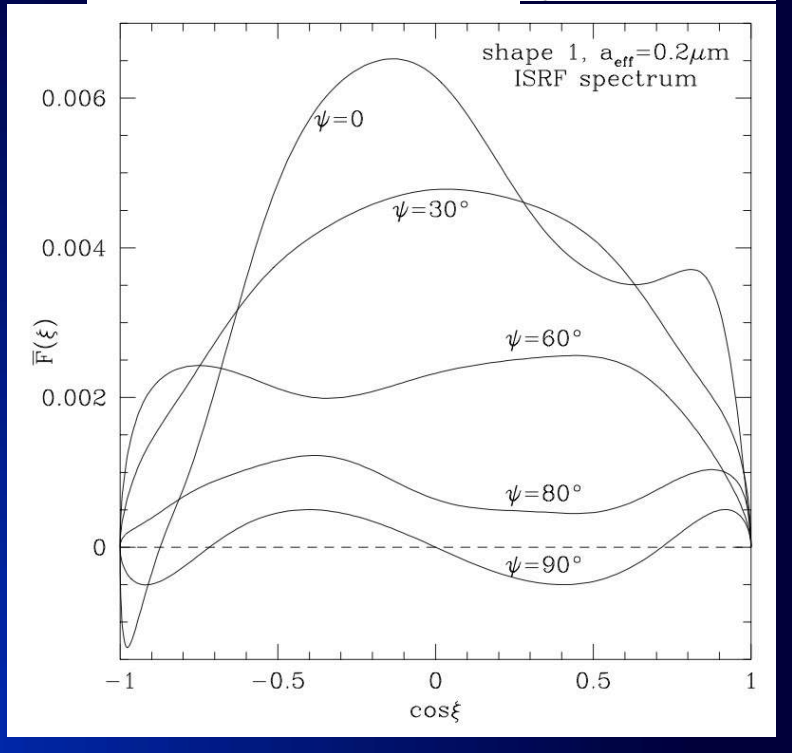
Radiative Torque (RAT) Alignment Mechanism

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

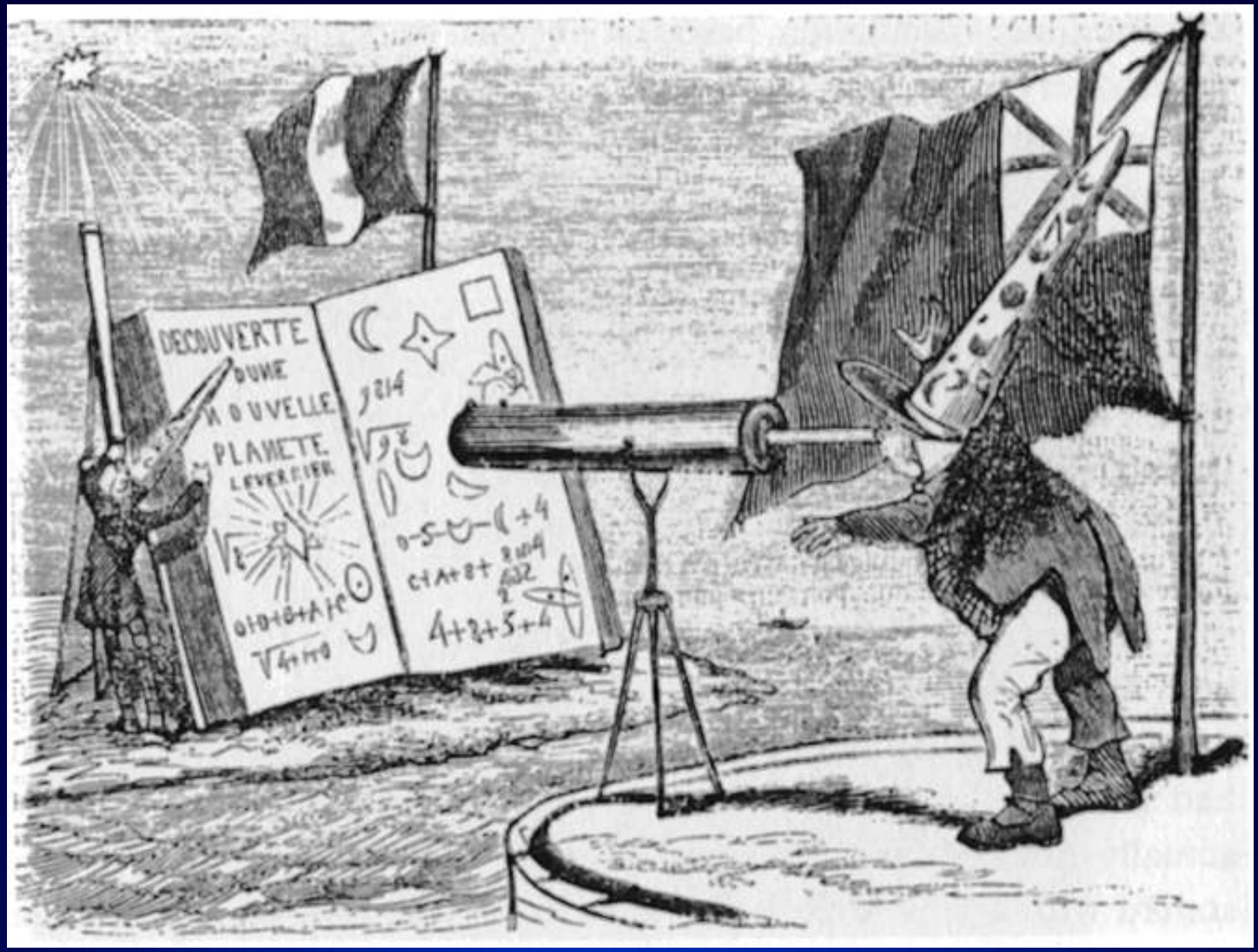
- B Draine (1996) introduced radiative torques in discrete dipole (DDSCAT) code





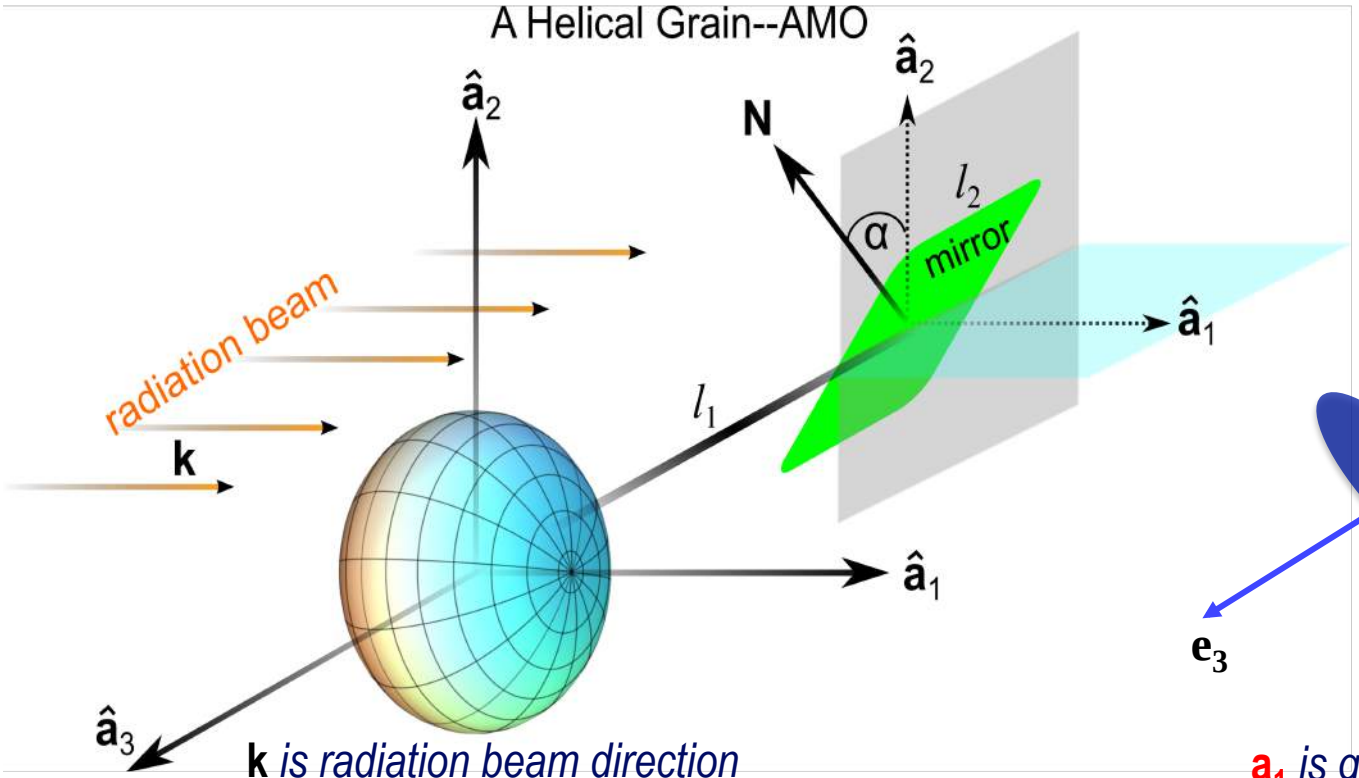


Predictive Model of RAT Alignment

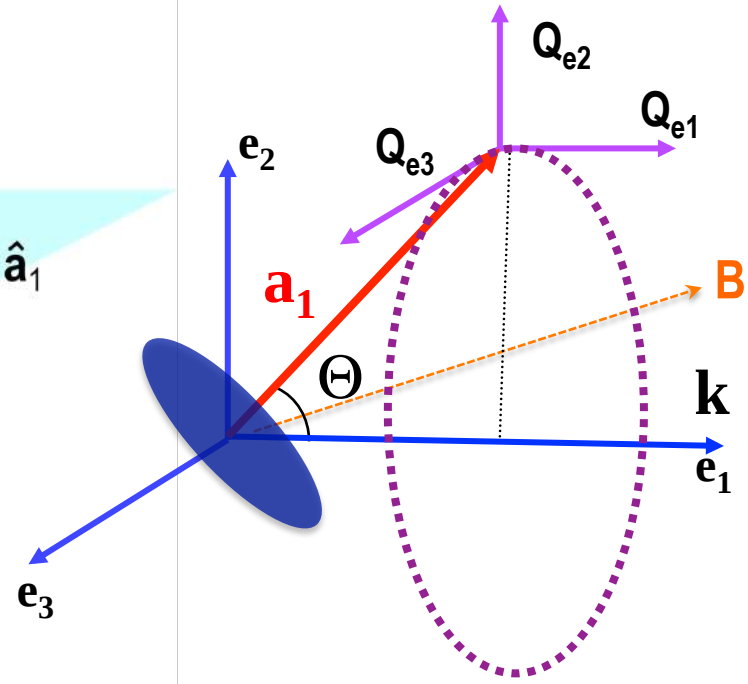


Analytical model (AMO) of Radiative Torques

Lazarian & Hoang 07a



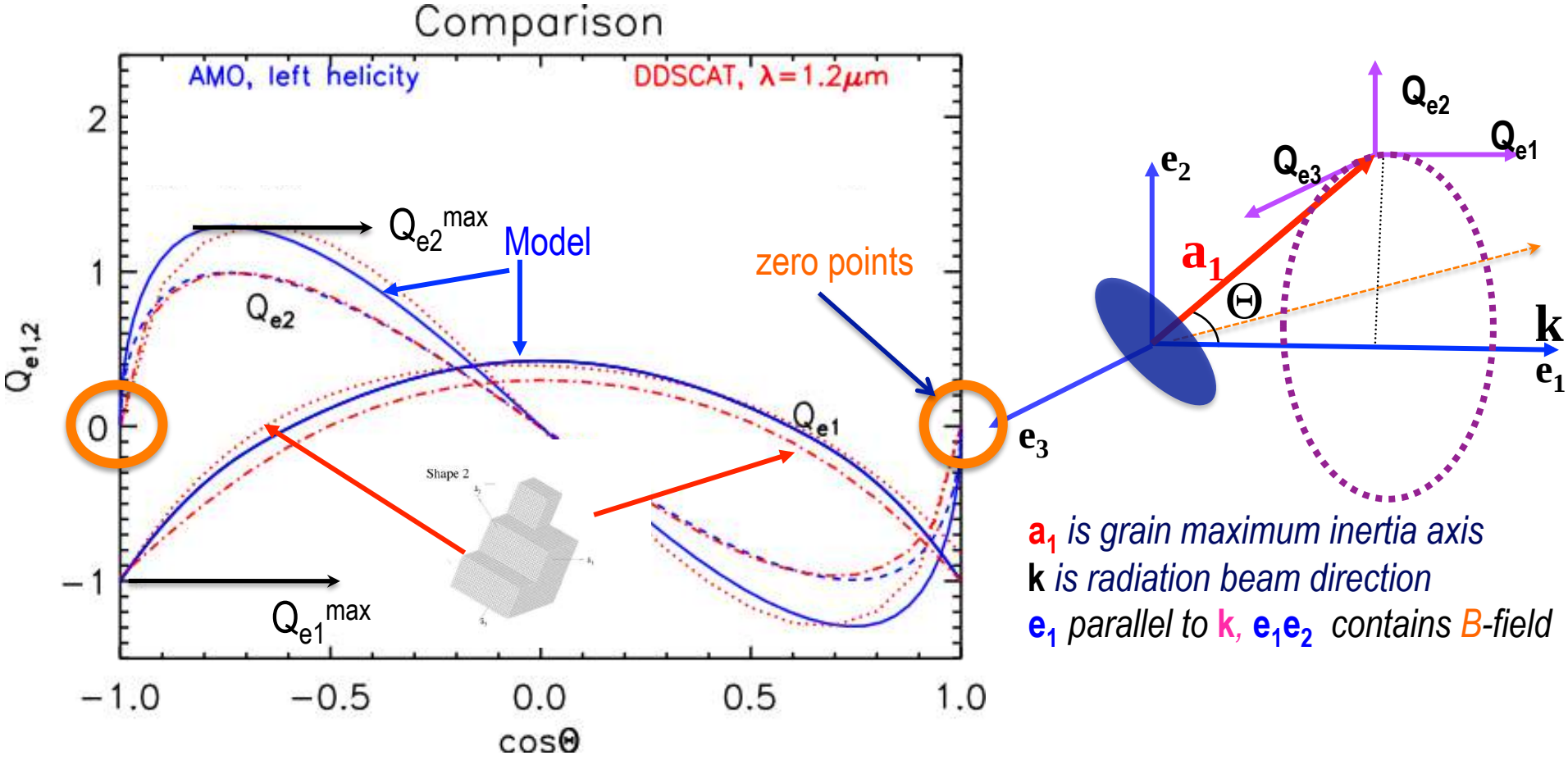
k *is radiation beam direction*
$\mathbf{a_1}$ *is grain maximum inertia axis*
$\mathbf{a_2a_3}$ *grain principal axes*
N, *normal vector of mirror, lies in* $\mathbf{a_1a_2}$
mirror plane tilted by angle α with $\mathbf{a_2a_3}$



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

- 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



$\mathbf{a}_1$ *is grain maximum inertia axis*
k *is radiation beam direction*
$\mathbf{e}_1$ *parallel to* **k**, $\mathbf{e}_1\mathbf{e}_2$ *contains B-field*

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

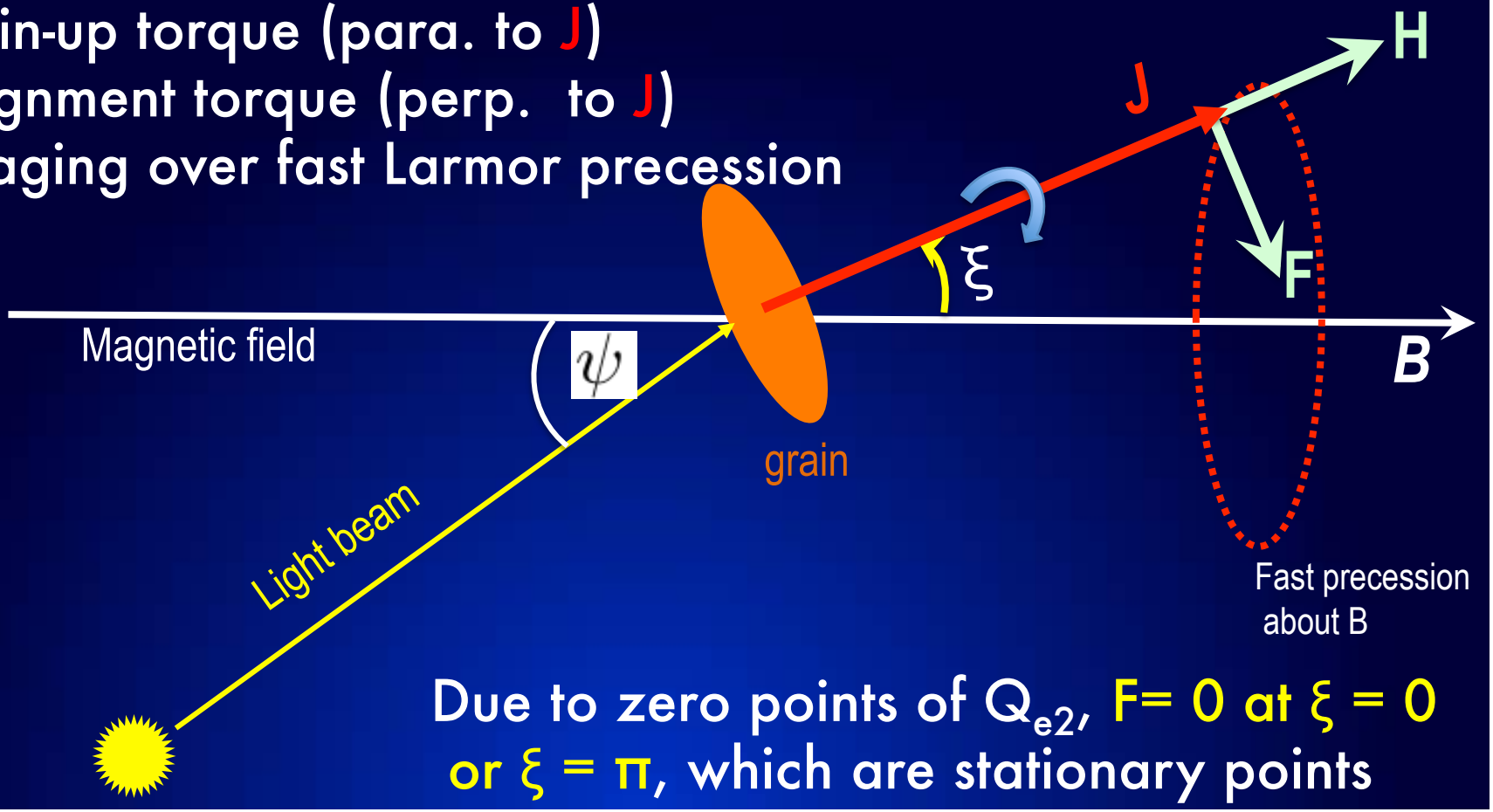
Lazarian & Hoang 07a

Basic Properties of RAT alignment: Method

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

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

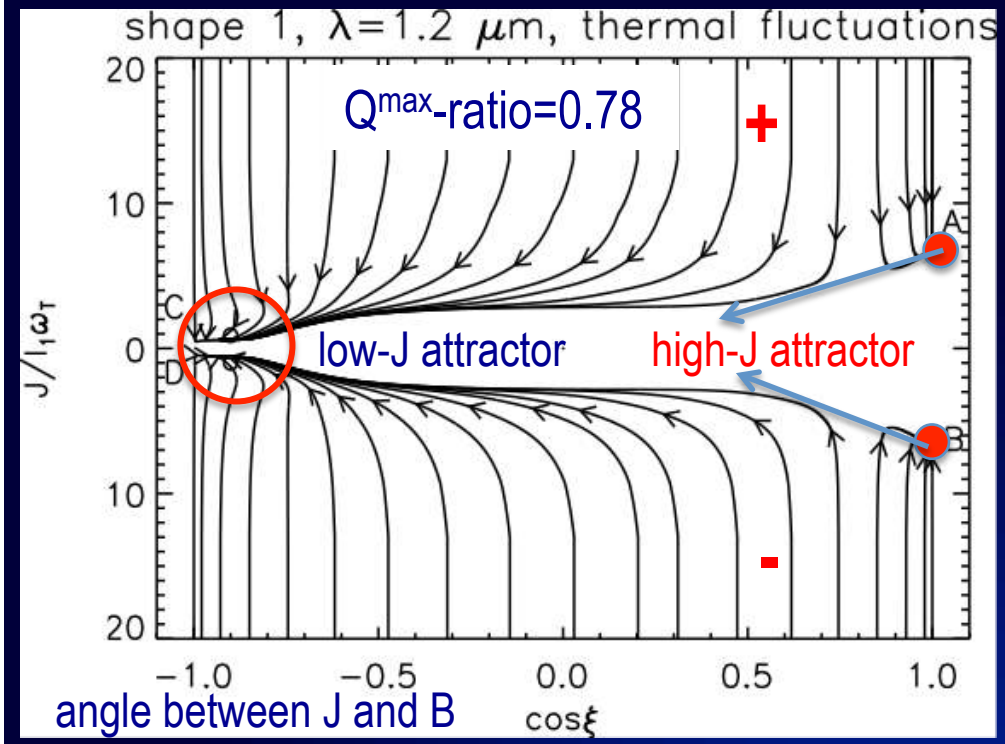
- H: spin-up torque (para. to J)
- F: alignment torque (perp. to J)
- Averaging over fast Larmor precession



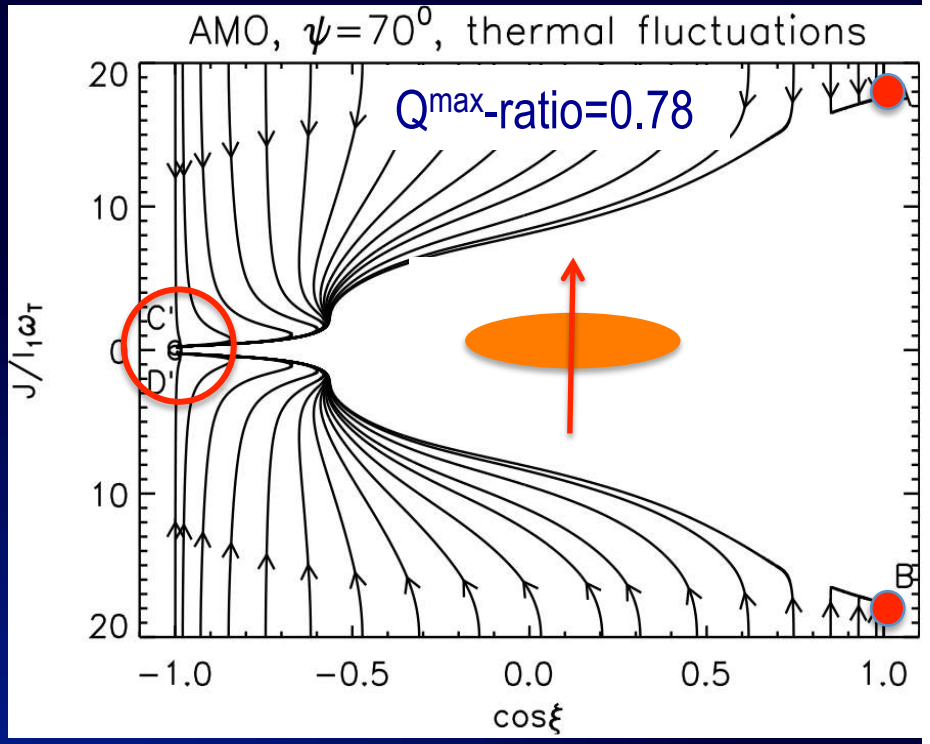
Due to zero points of Q_{e2}, F= 0 at ξ = 0 or ξ = π, which are stationary points

1. Grains are aligned with low-J and high-J attractors

DDSCAT



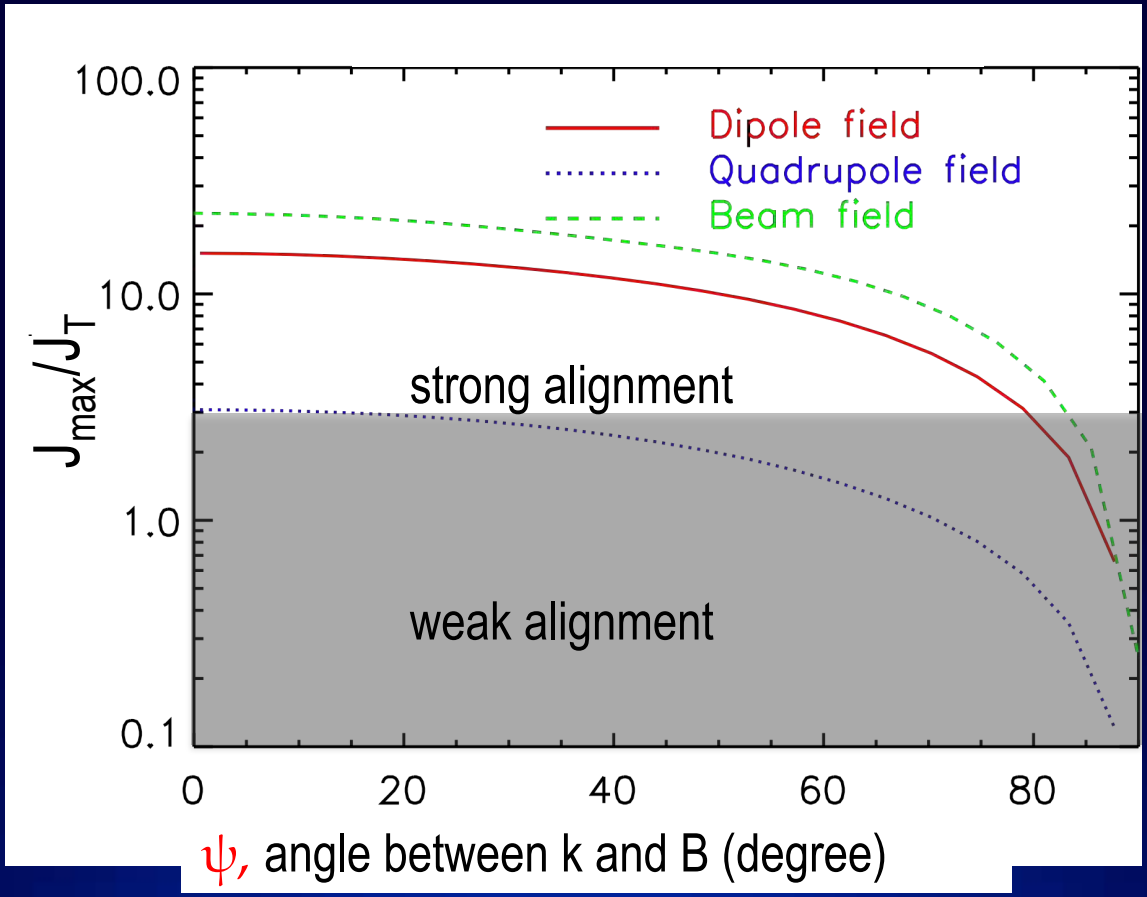
AMO



- 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

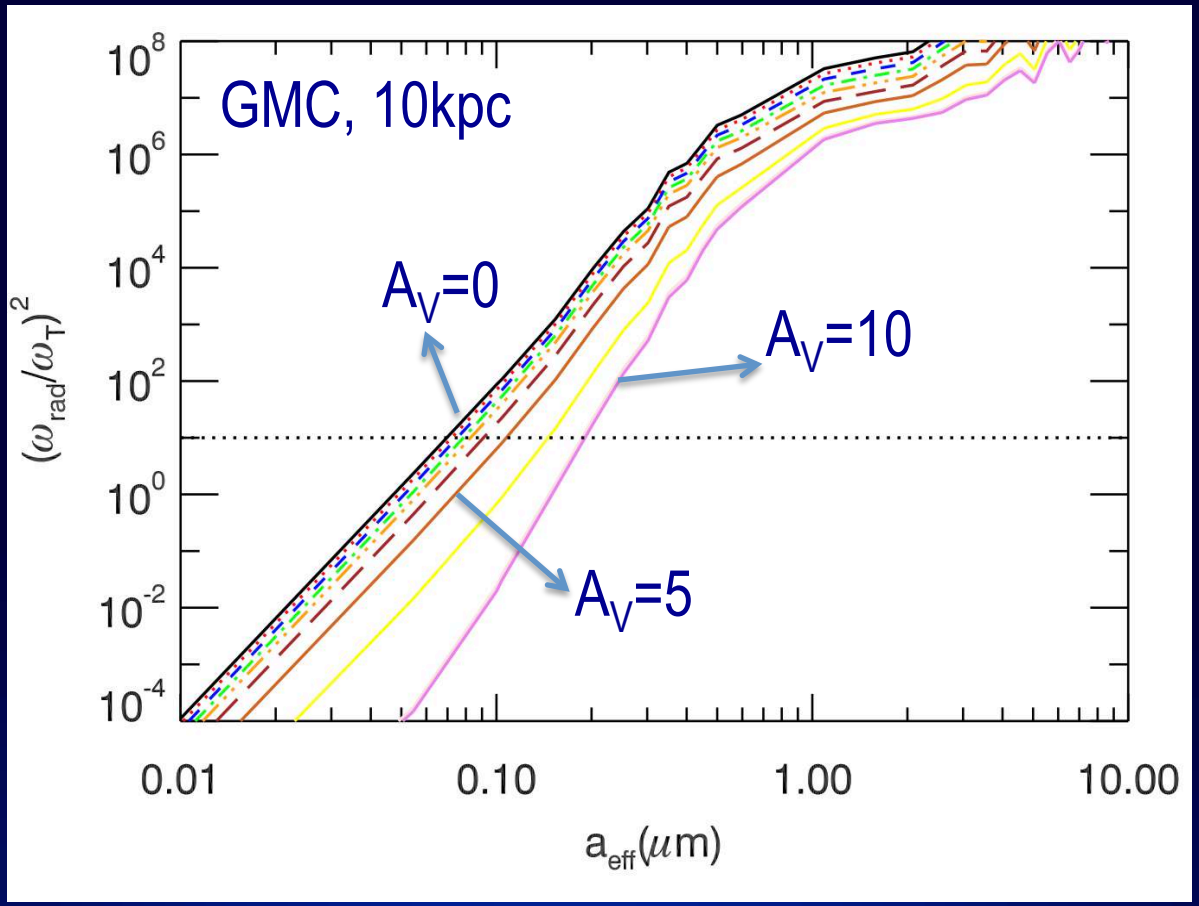
2. Maximum angular momentum decreases with the angle between radiation direction and B-field.



• The angle-dependence alignment was observationally confirmed by Andersson et al. 2011, Vaillancourt+Andersson 2015

Hoang & Lazarian 09a

3. Maximum angular momentum increases with grain size.

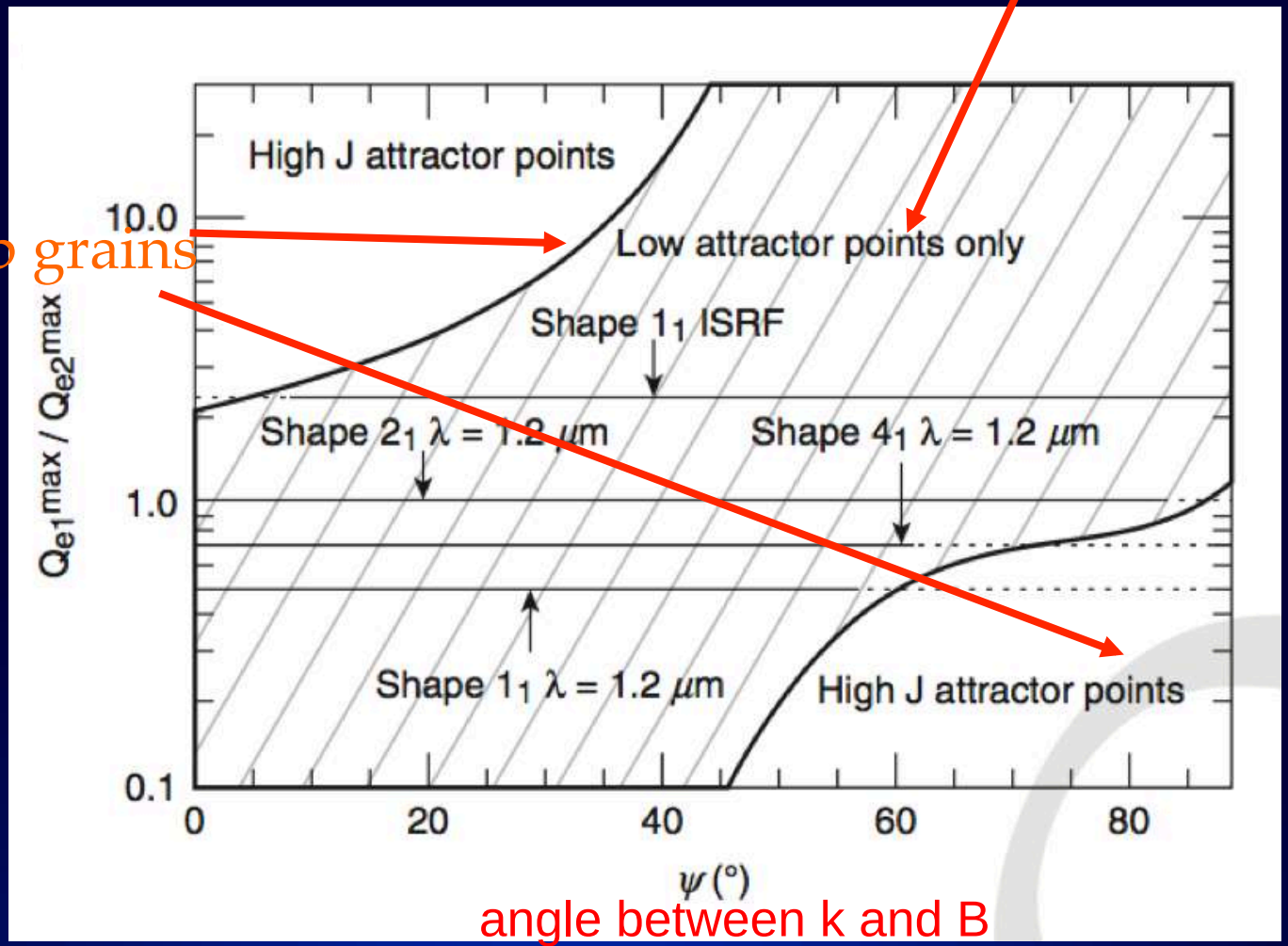


- Large grains are aligned more efficiently than small grains.
- Grains near cloud surface aligned better than those deep inside cloud.

4. Presence of high-J attractor depends on Ψ and Q^{max}-ratio

RAT only impede grain rotation

RAT spin up grains



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

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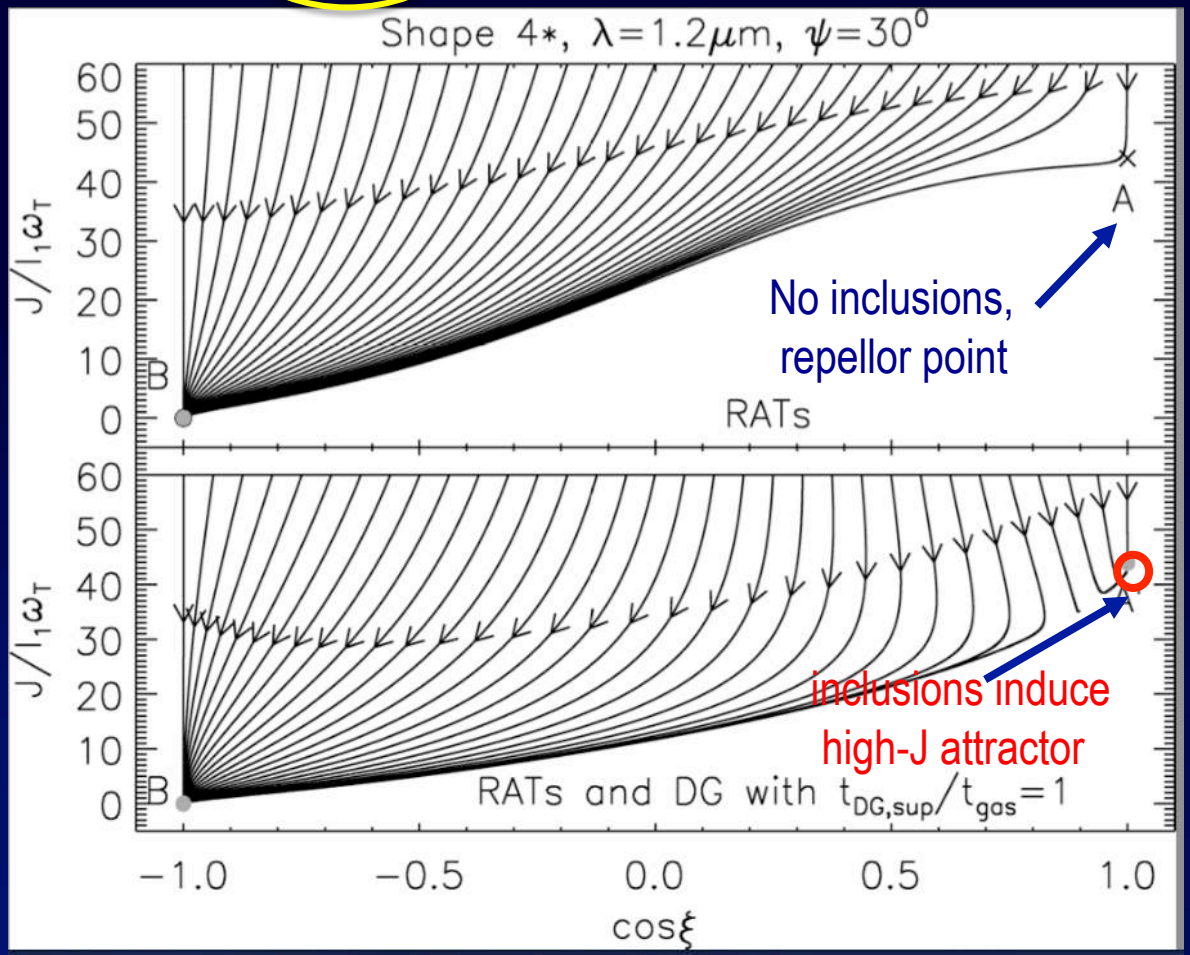
5. Superparamagnetic inclusions increase the degree of RAT alignment to ~100%.

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



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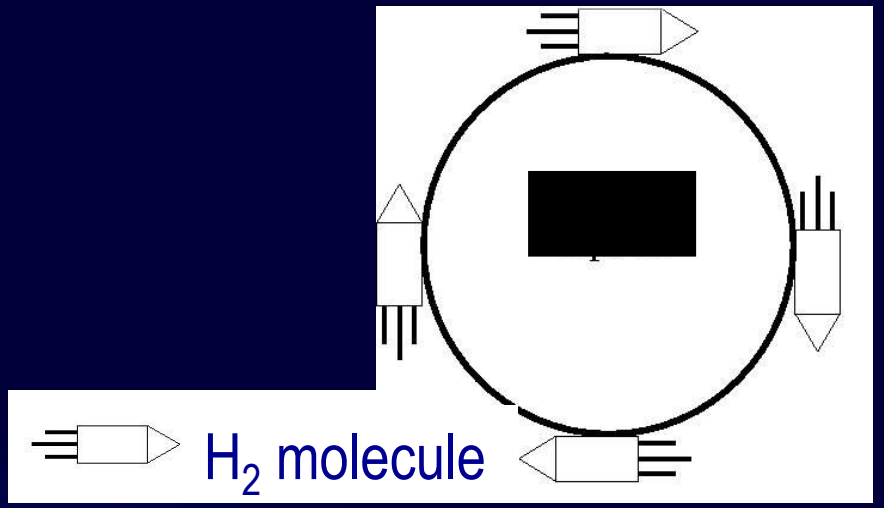
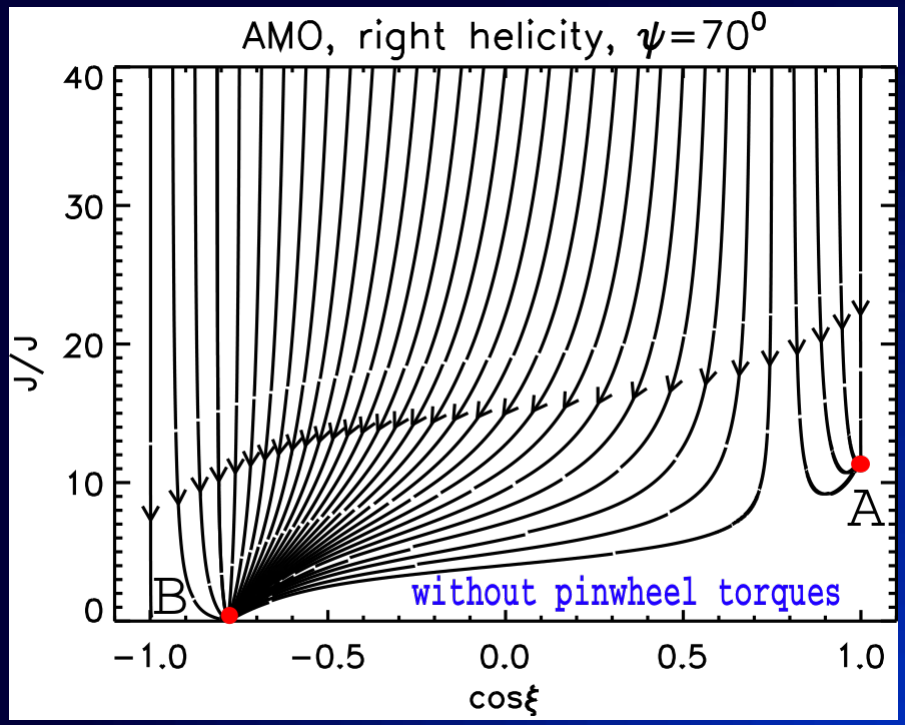
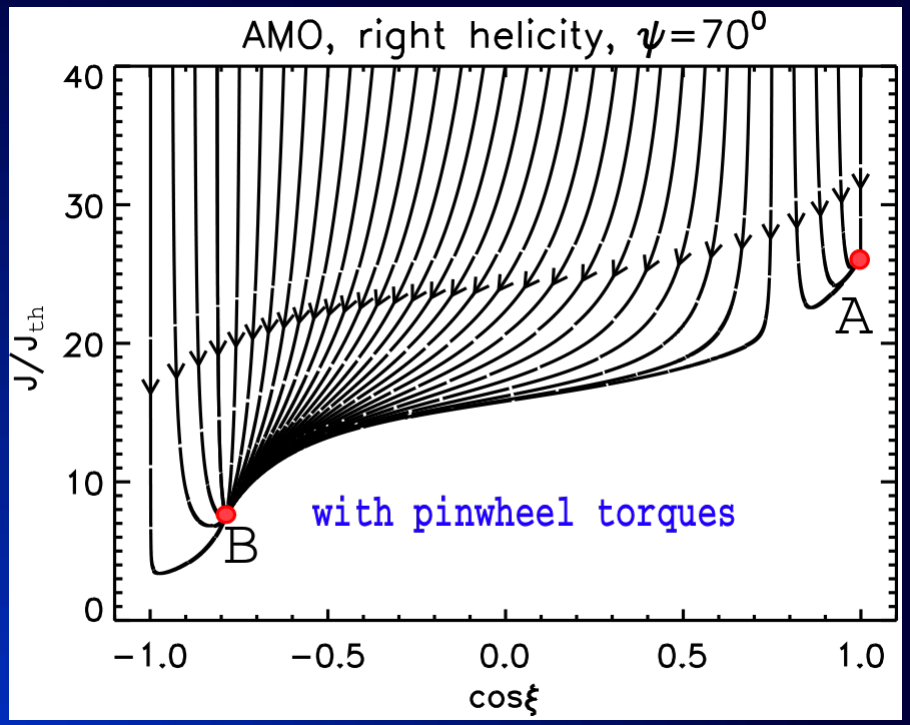
6. H_2 pinwheel torques increase the degree of RAT alignment.







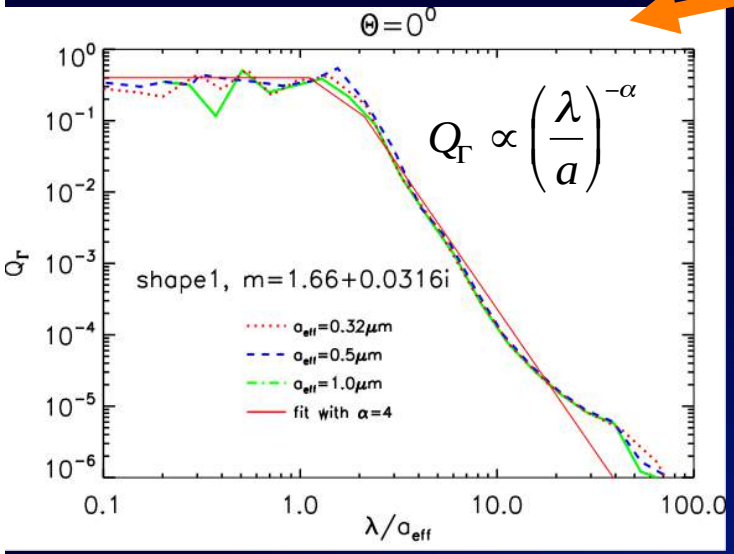
Hoang & Lazarian 09a

Ab Initio Modeling of Dust Polarization

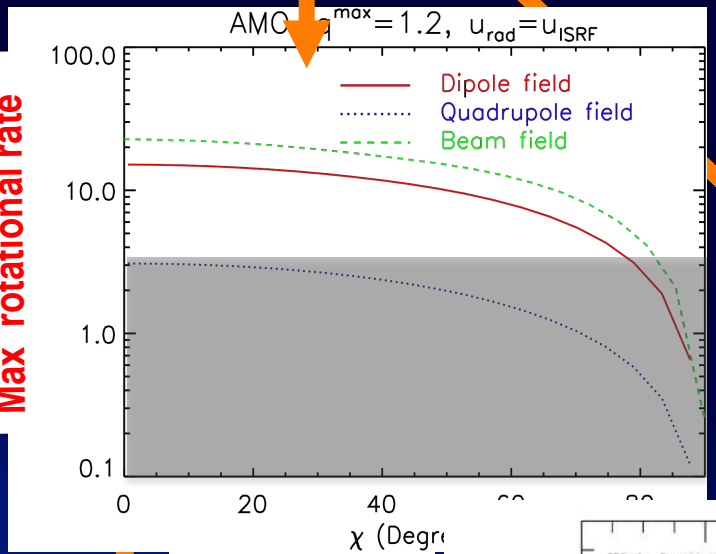
grain size, shape, n_{gas}, T_{gas}, radiation field (intensity, k and B angle), and Q^{max}-ratio

Theory

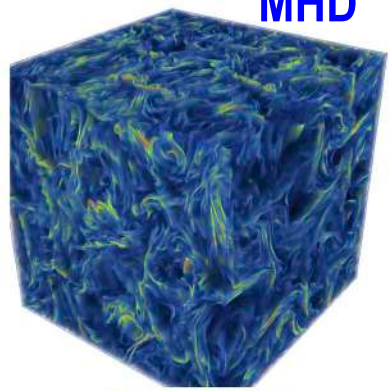
Polarization



Max rotational rate



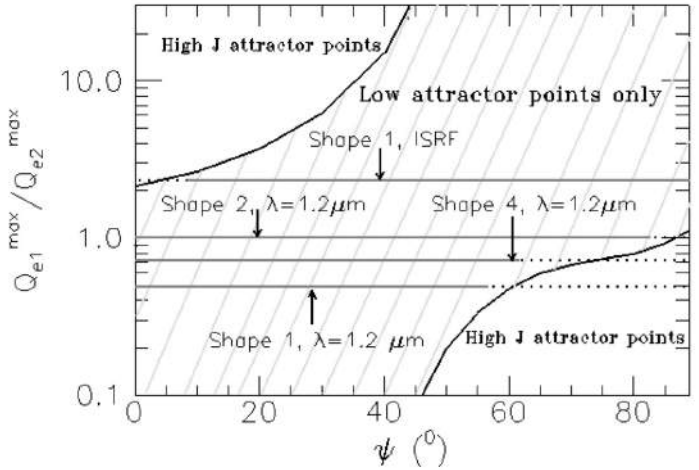
MHD



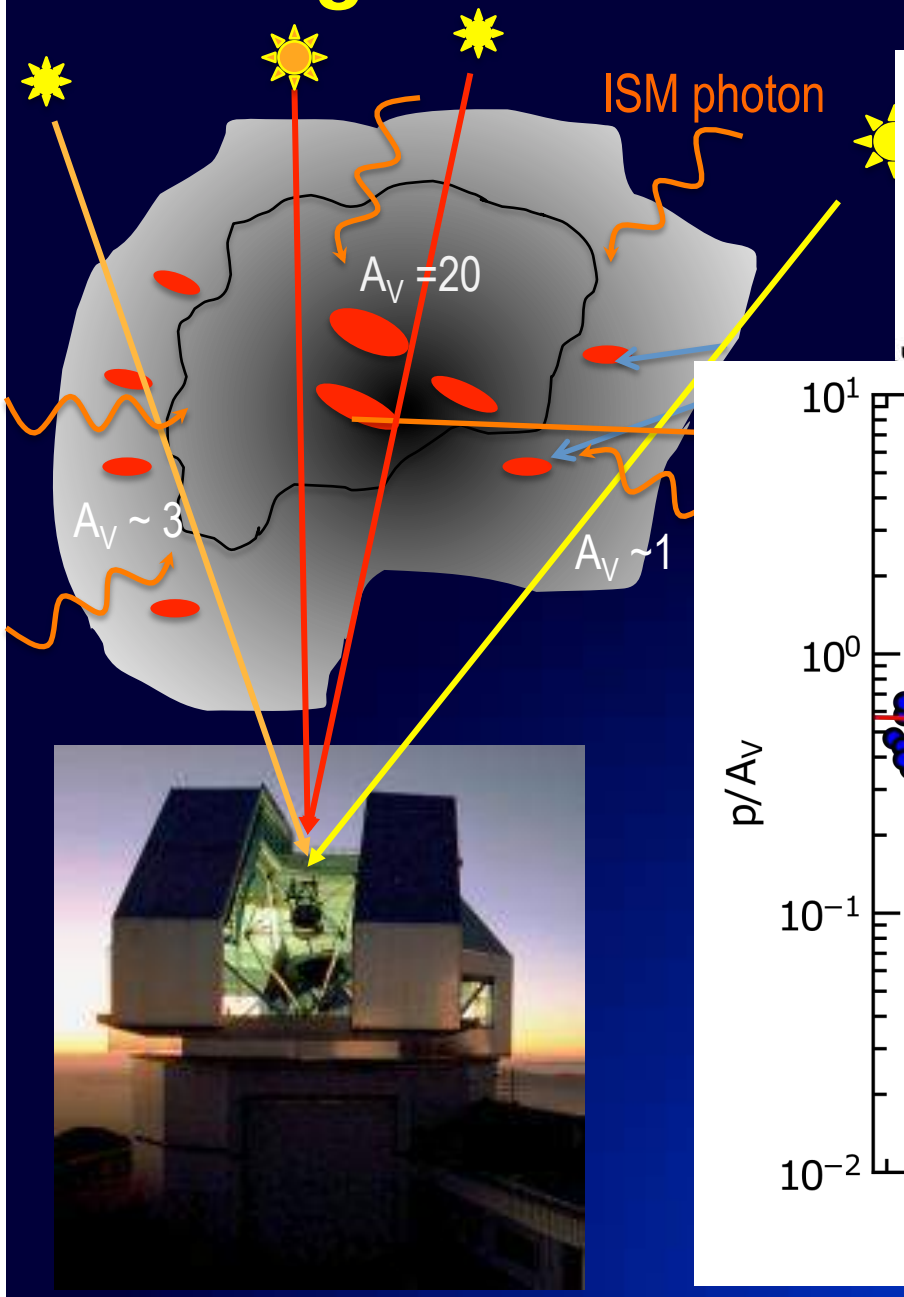
k and B angle

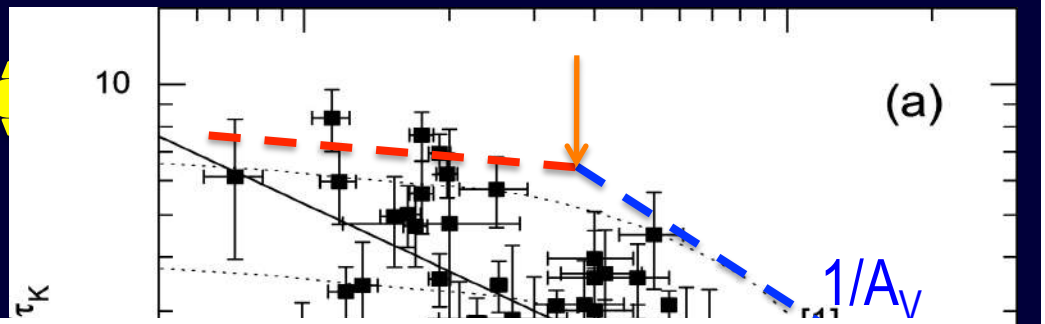
- Critical size of aligned grains: a_{ali}
- Degree of grain alignment: R

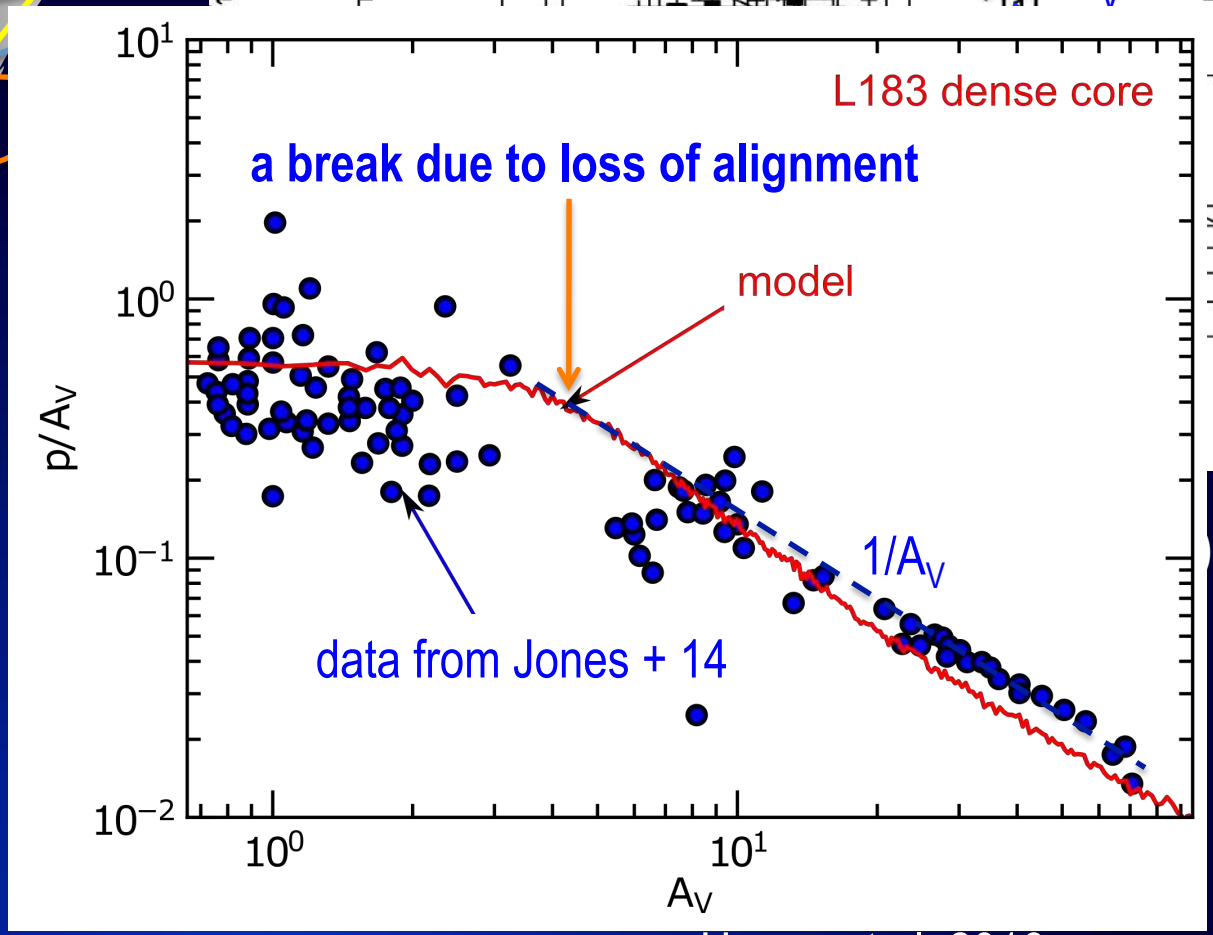
$$\frac{\sigma_{pol}}{N_H} = \int_{a_{ali}}^{a_{max}} da \frac{(C_\perp - C_\parallel)}{2} n_d(a) R(a) \cos^2\zeta$$



RAT alignment in Starless Core

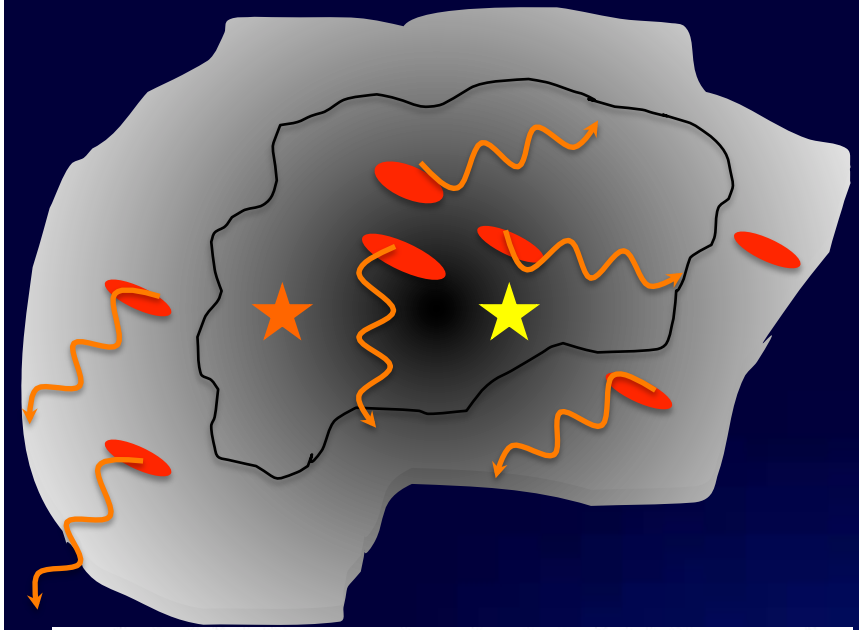


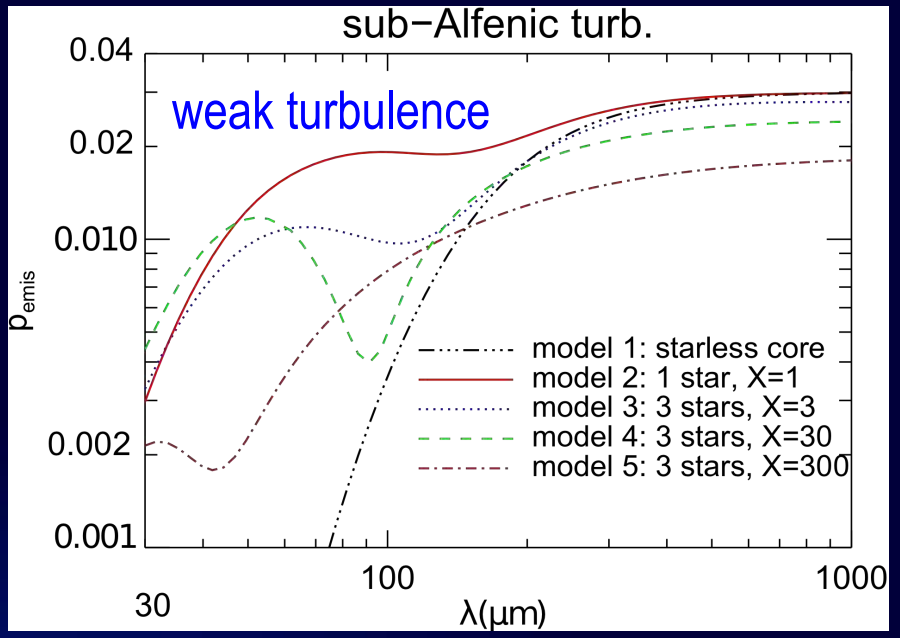


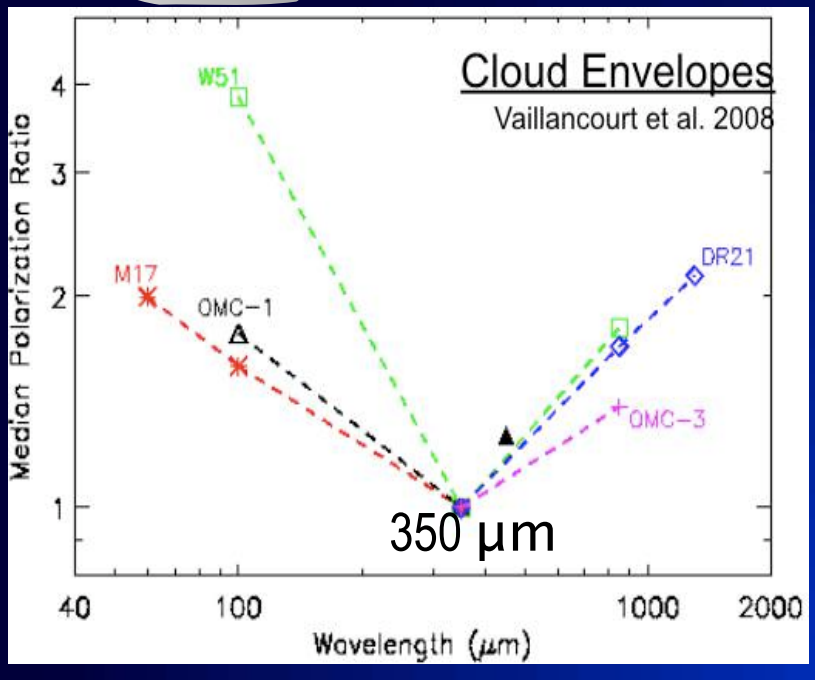


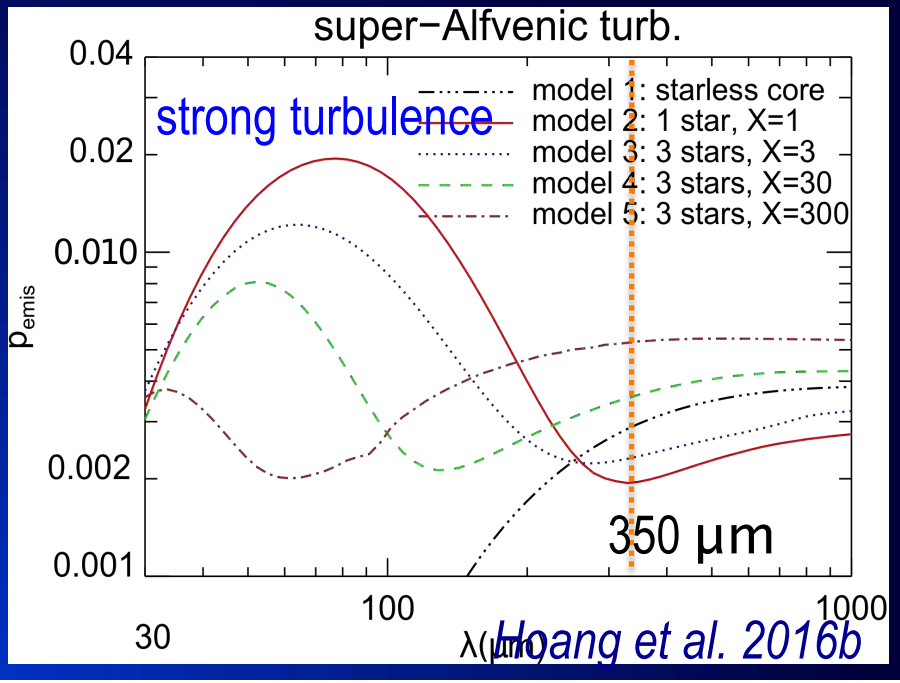
Hoang et al. 2016a

Polarized Emission from Molecular Cloud



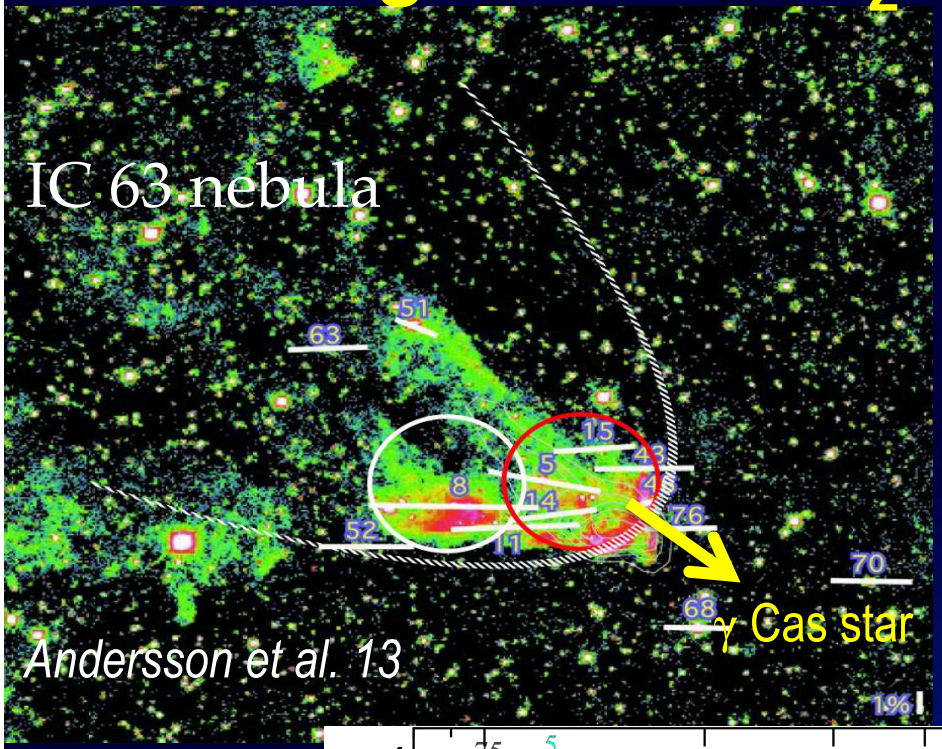




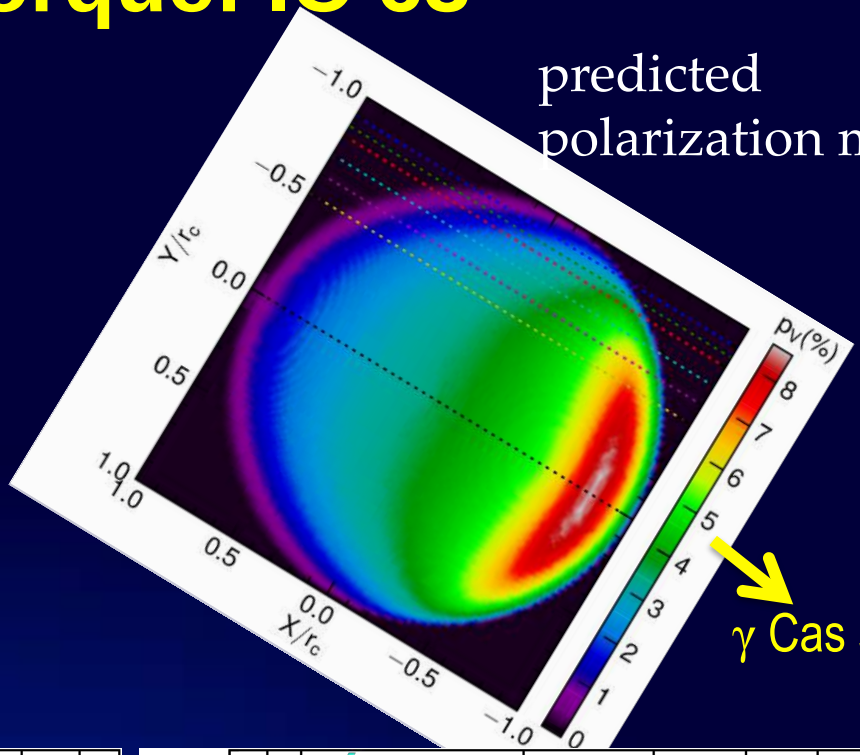


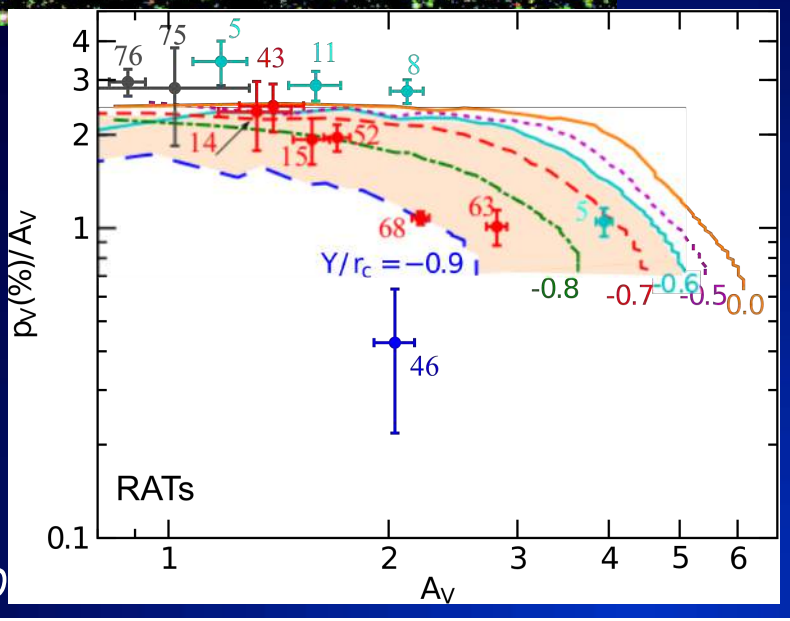
Hoang et al. 2016b

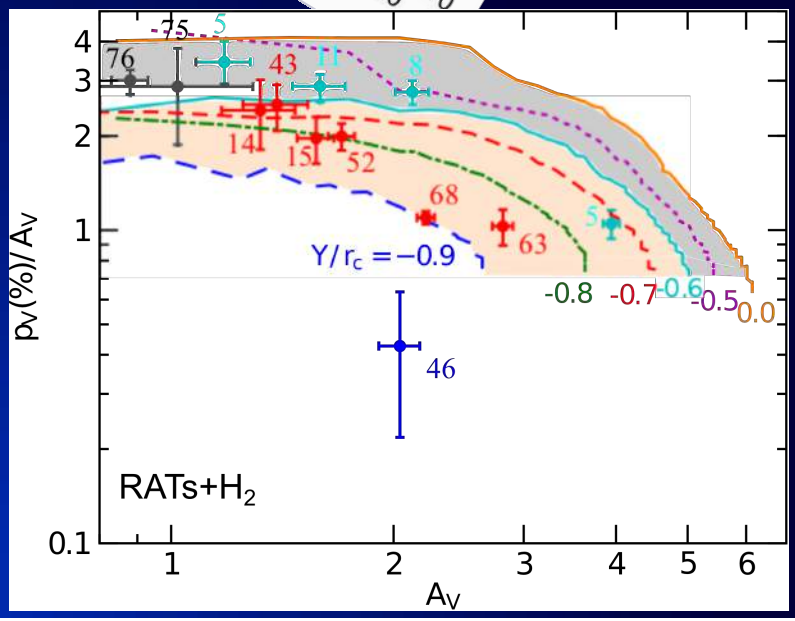
Revealing effect of H_2 torque: IC 63



predicted polarization map

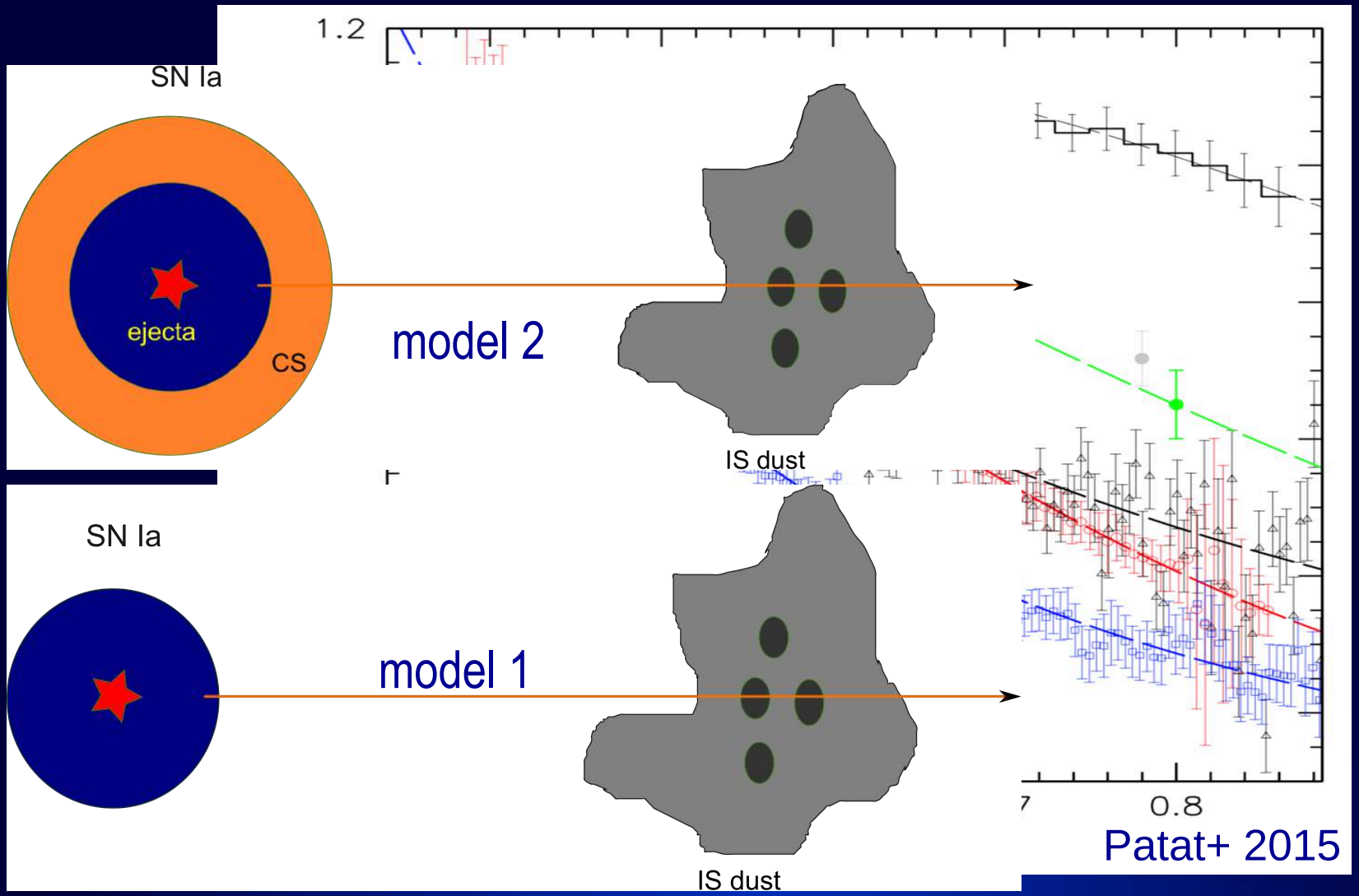




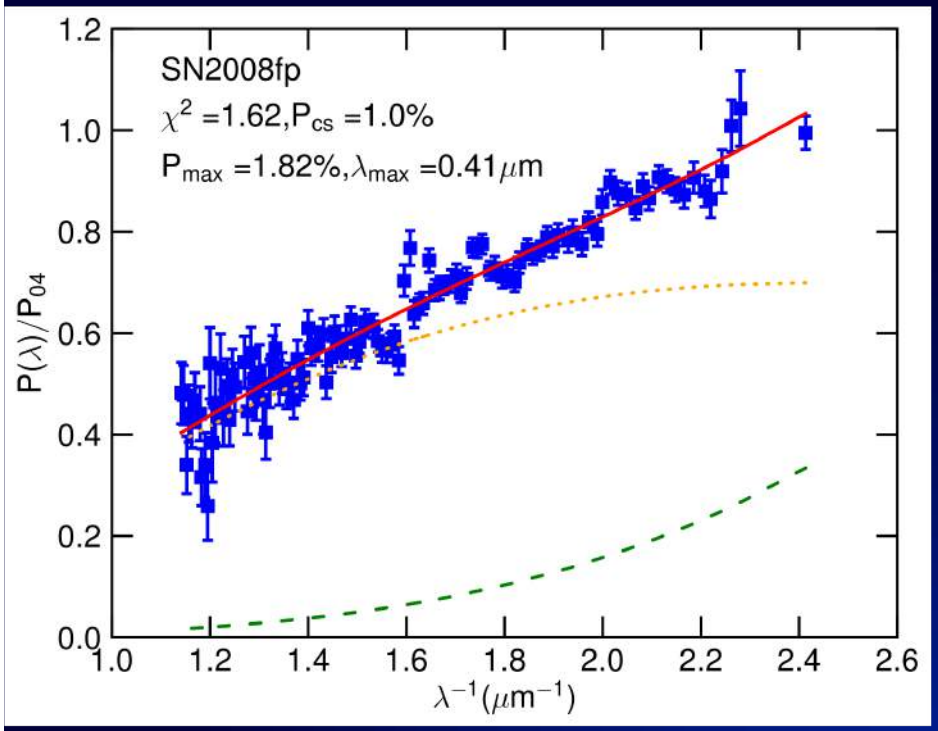


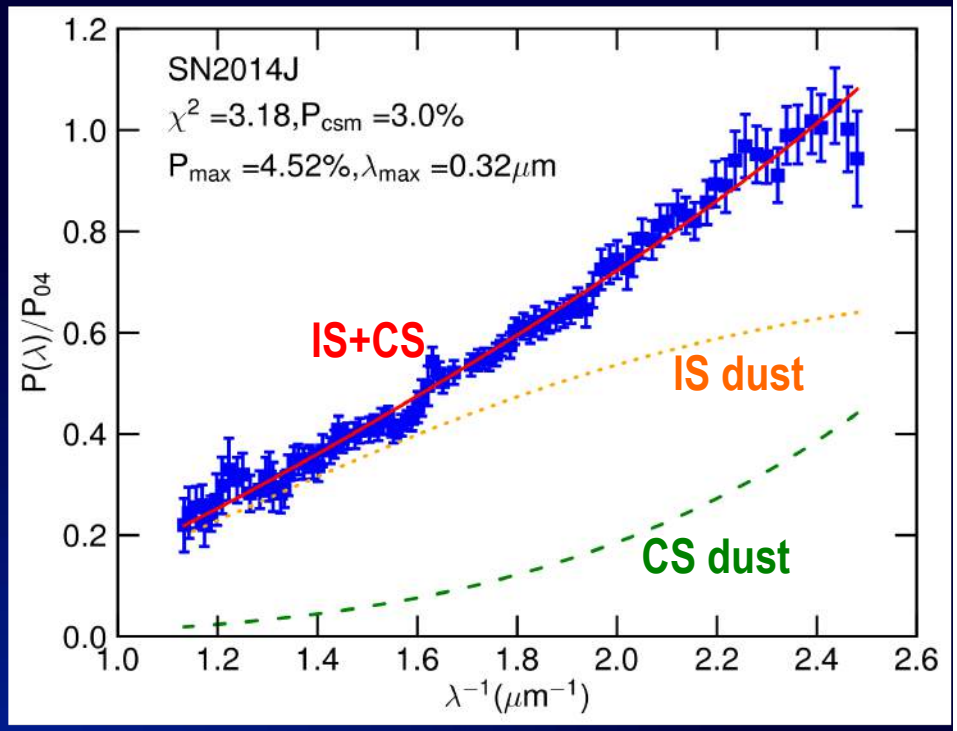
Hoang et al. 15b

SN polarimetry: polarization rises to UV wavelengths for some SNe Ia



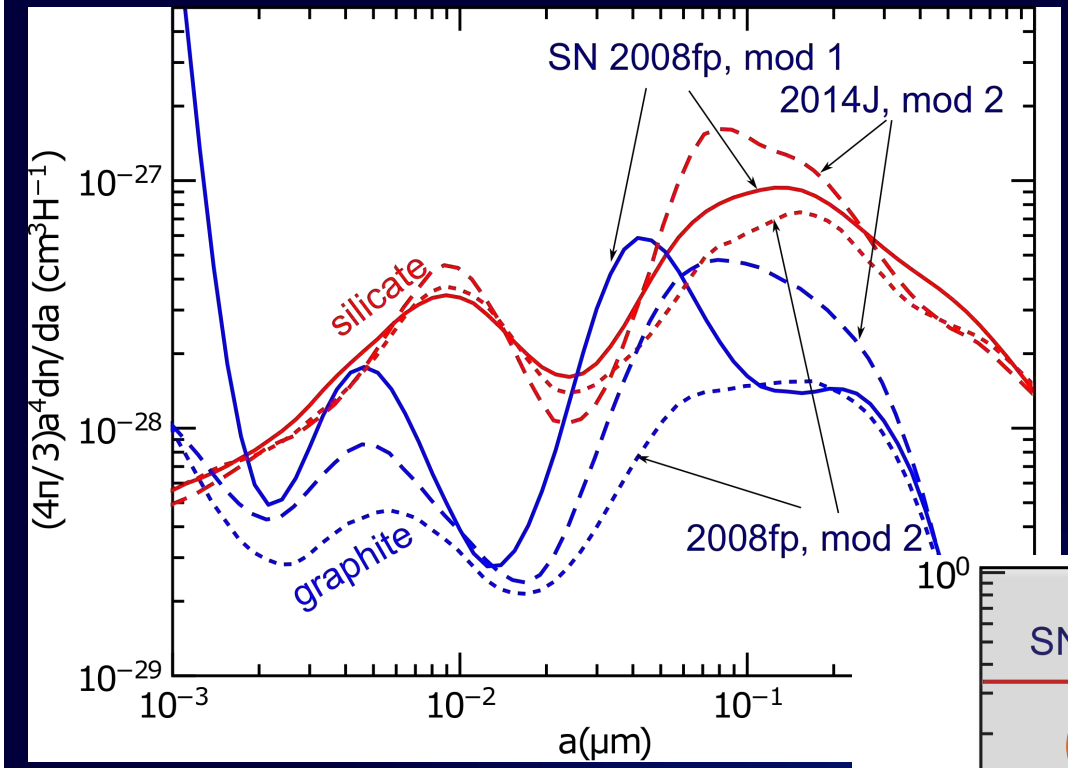
Polarization data for SNe 2008fp and 2014J

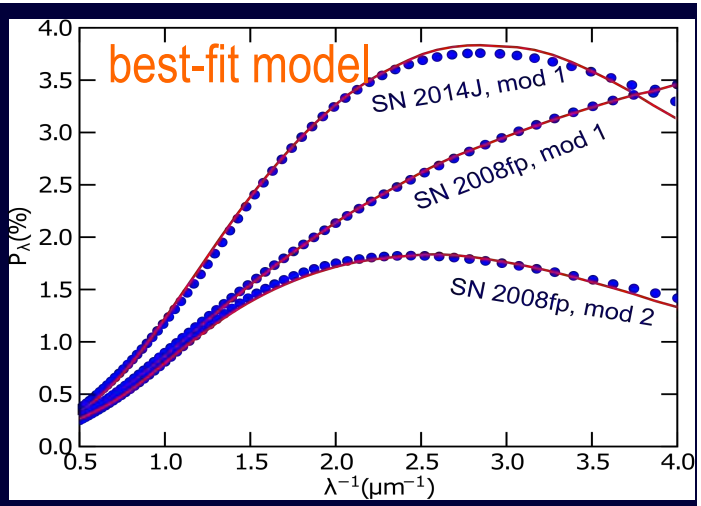




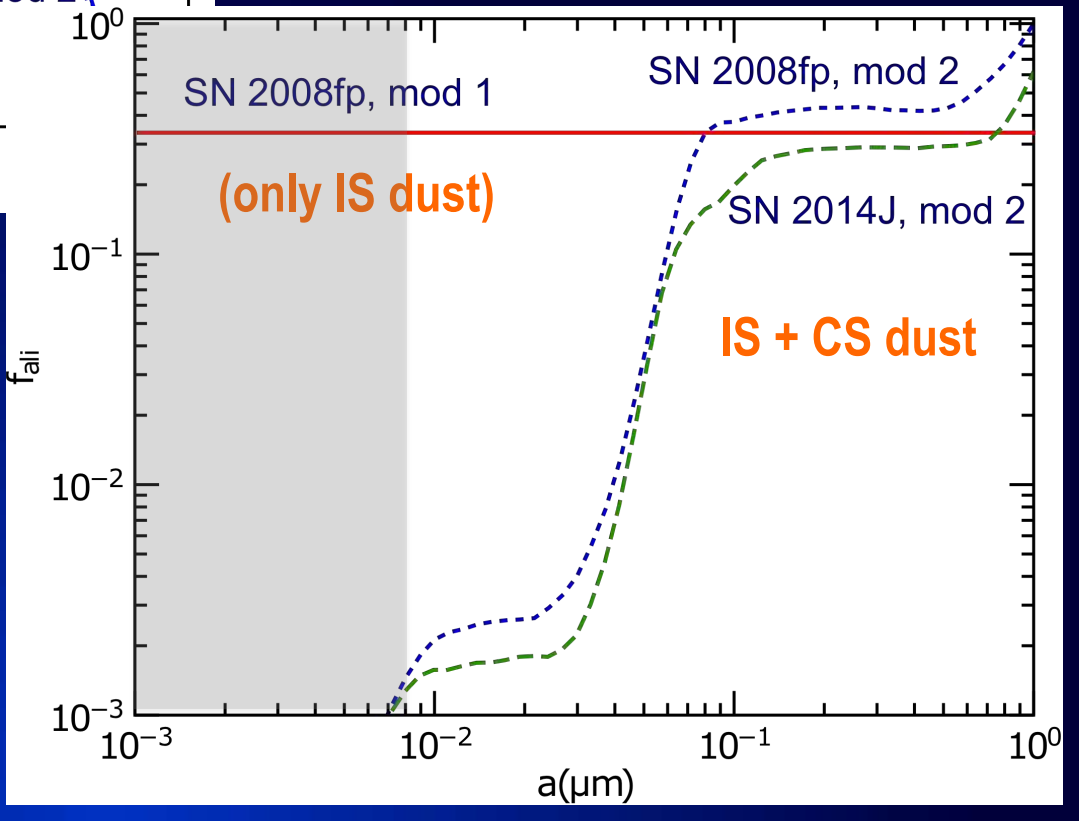
Hoang 2015, arXiv:1510.01822

Grain mass distribution





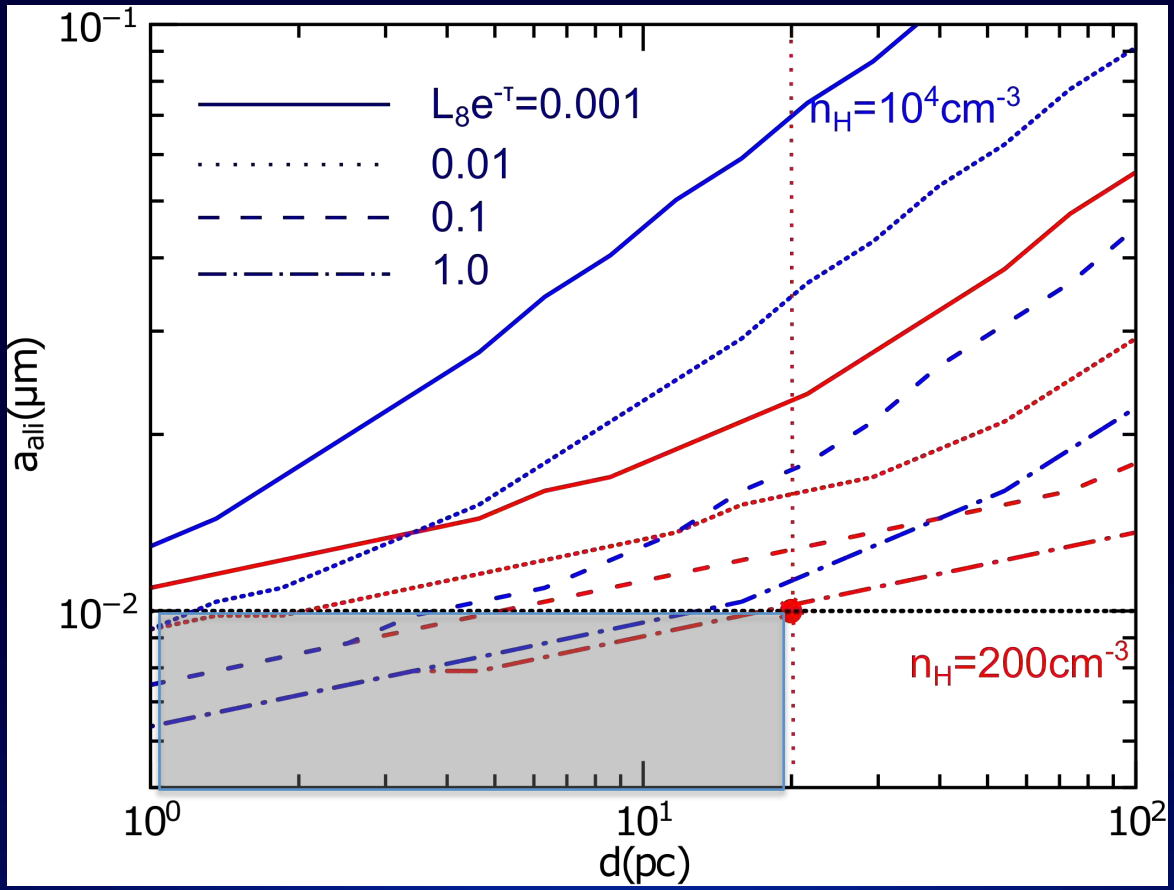
Grain alignment function



- SN 2008fp (only IS): very small grains required to be efficiently aligned

Hoang 2015, arXiv:1510.01822

Small grains may be efficiently aligned by RAT due to radiation from SN itself



Dusty cloud within d~ 20pc from explosion site can help, no need of circumstellar dust

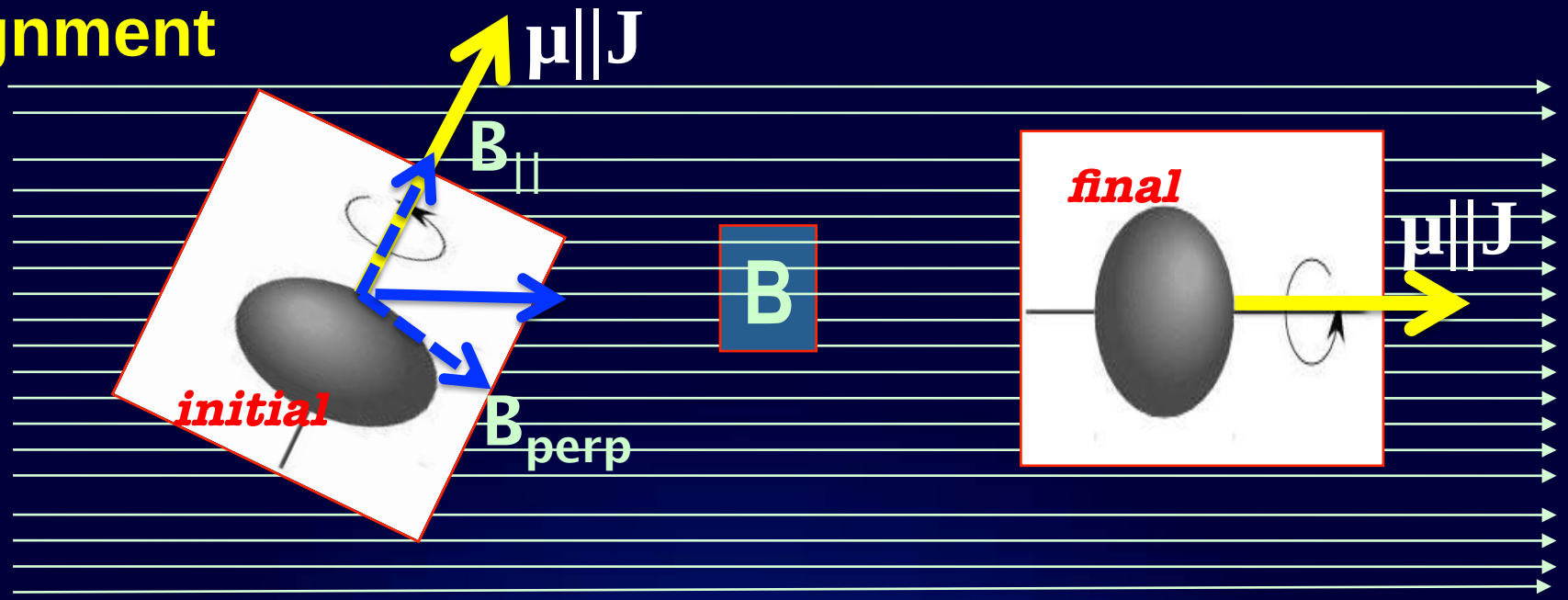
Hoang 2015, arXiv:1510.01822

Summary and Discussion

- RAT alignment is a principal mechanism, but paramagnetic relaxation is needed for small grains.
- RAT theory allows for "ab initio" 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.
- RAT alignment can explain anomalous polarization for SN 2008fp, without the need of CS dust, putting constraint on progenitors of SNe Ia.
- High-J attractor is not universal, how to get high polarization in ISM as seen by Planck?

Thank you very much!

Classical Theory: Davis-Greenstein Paramagnetic Alignment



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

ISM

$$\tau_{DG} \approx 1.2\times10^{6}\left(\frac{B}{5\mu G}\right)^{-2}\left(\frac{a}{0.1\mu m}\right)^{2}\left(\frac{K(\omega)}{1.2\times10^{-13}s}\right)^{-1} yr$$

$$\tau_{drag} \approx 6.3\times10^{4}\left(\frac{a}{0.1\mu m}\right)\left(\frac{1}{1+F_{IR}}\right) yr$$

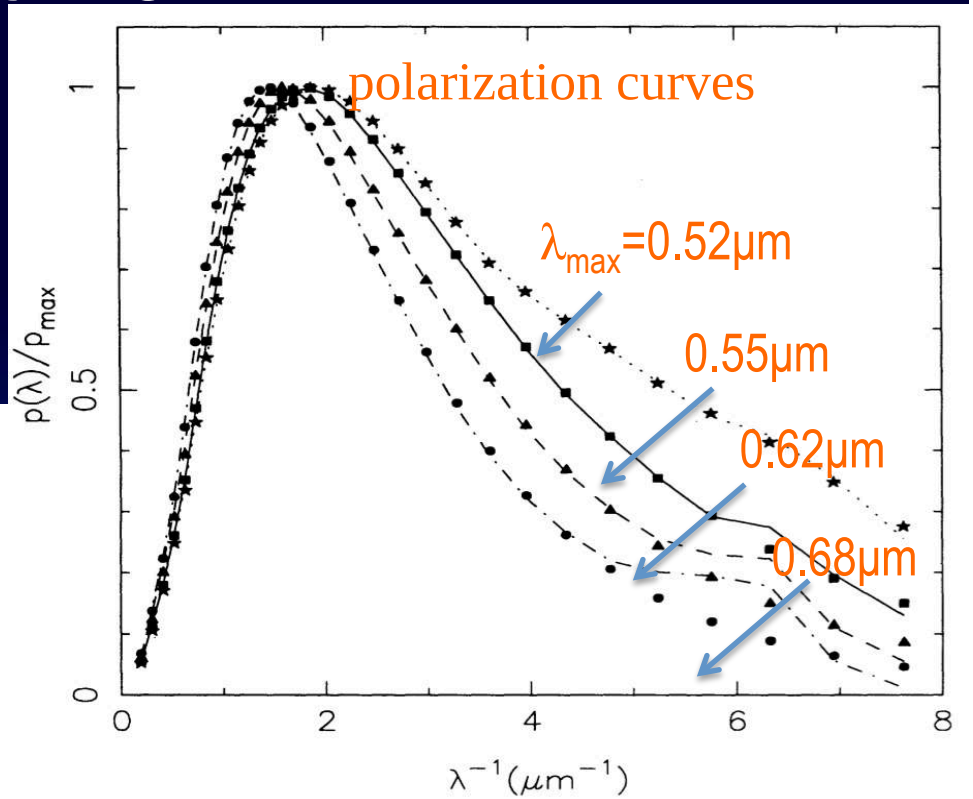
$$\frac{\tau_{DG}}{\tau_{drag}} \approx 20\left(\frac{a}{0.1\mu m}\right)\left(1+F_{IR}\right)$$

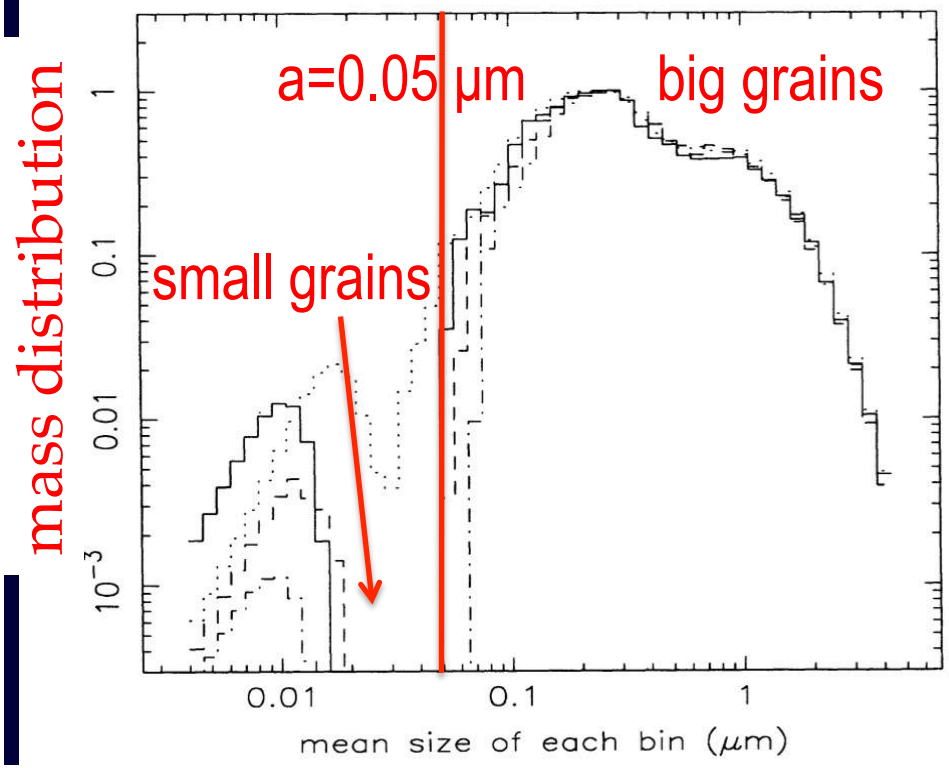
$\tau_{DG} < \tau_{drag}$ for a < 0.1 μm grains.

• Small grains can be aligned, big grains not

Results from Inversion Problem:

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





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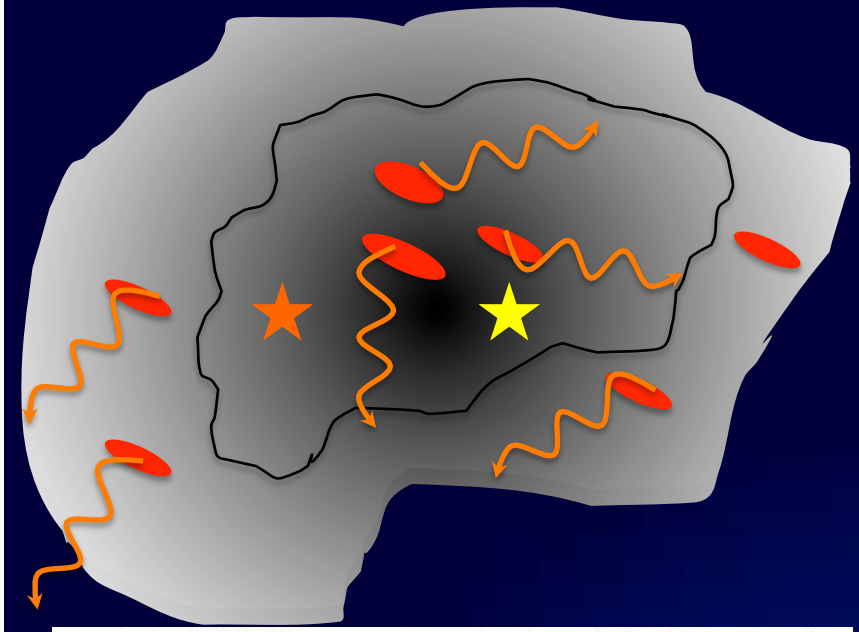
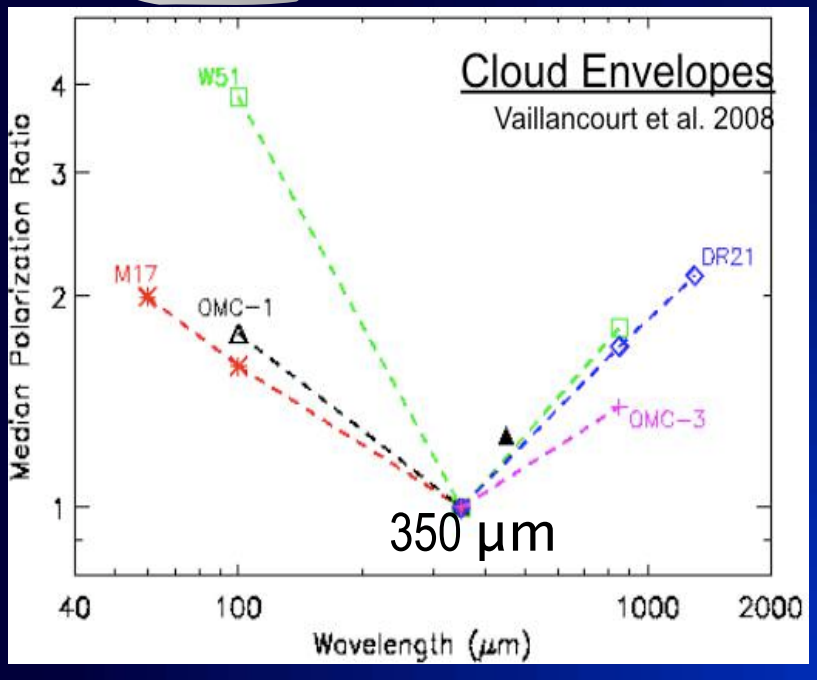
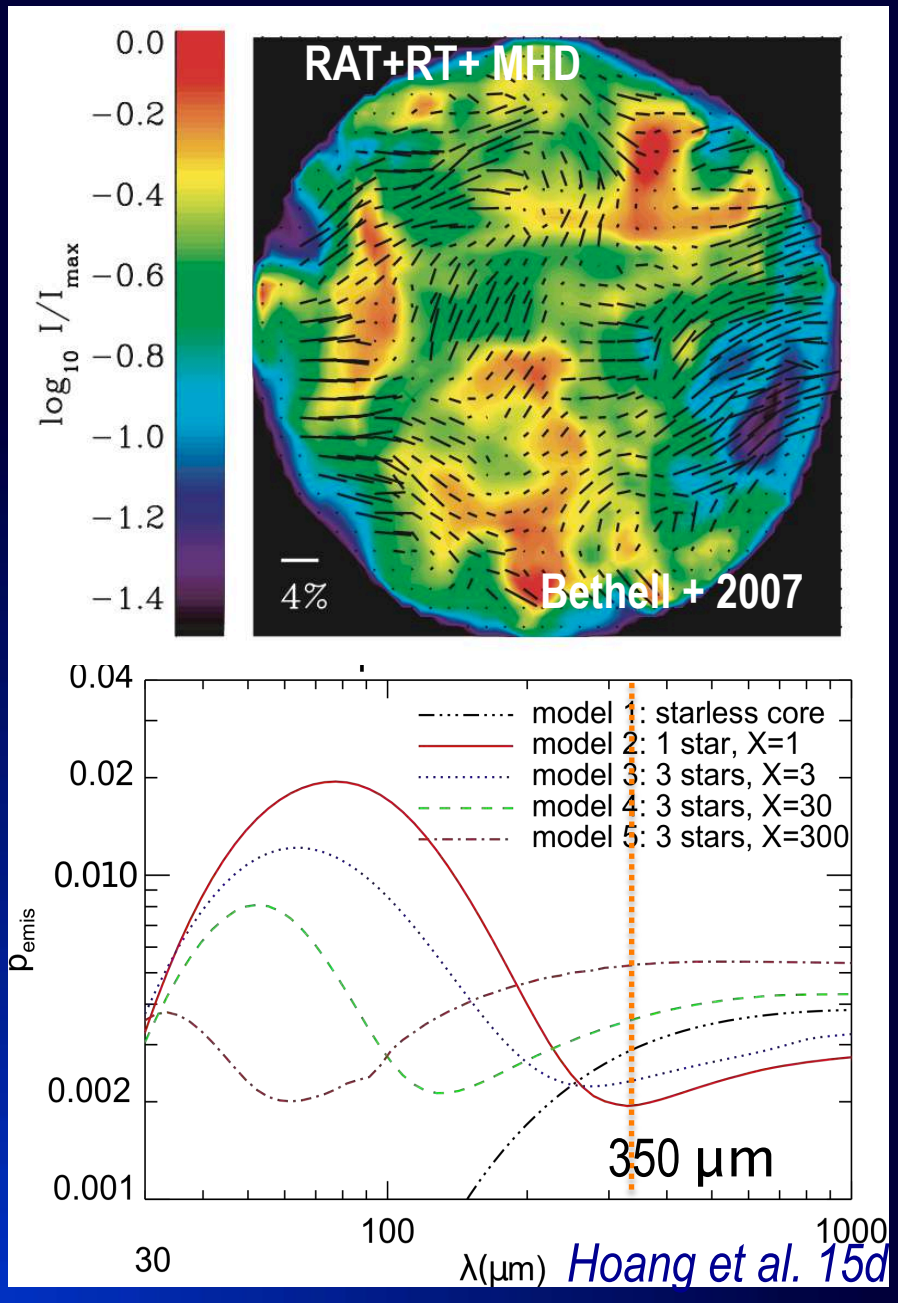
Polarized Emission from Molecular Cloud







Basic Properties of RAT alignment (continued)

2. RAT alignment decreases toward the center of molecular cloud (observation: Whittet+ 2008, Jones+15, Planck)

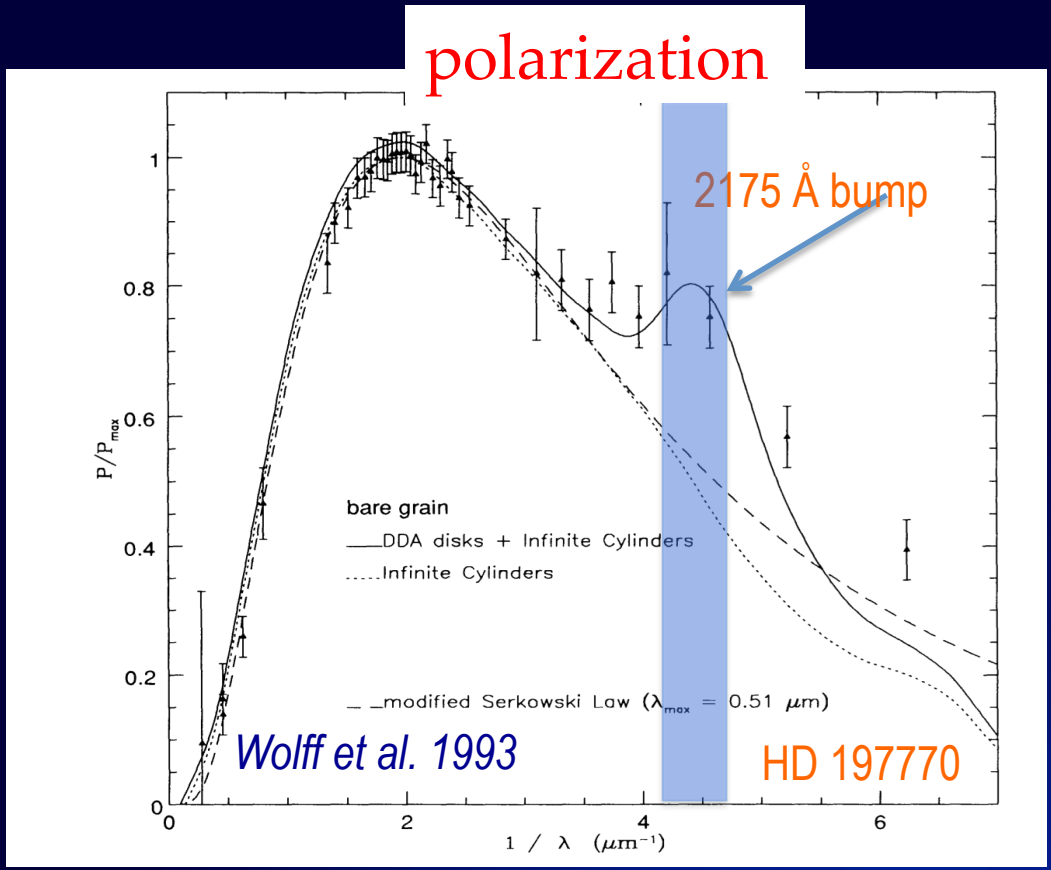
3. RAT alignment depends on the direction to the radiation source (observation: Andersson et al. 2009, 2010)

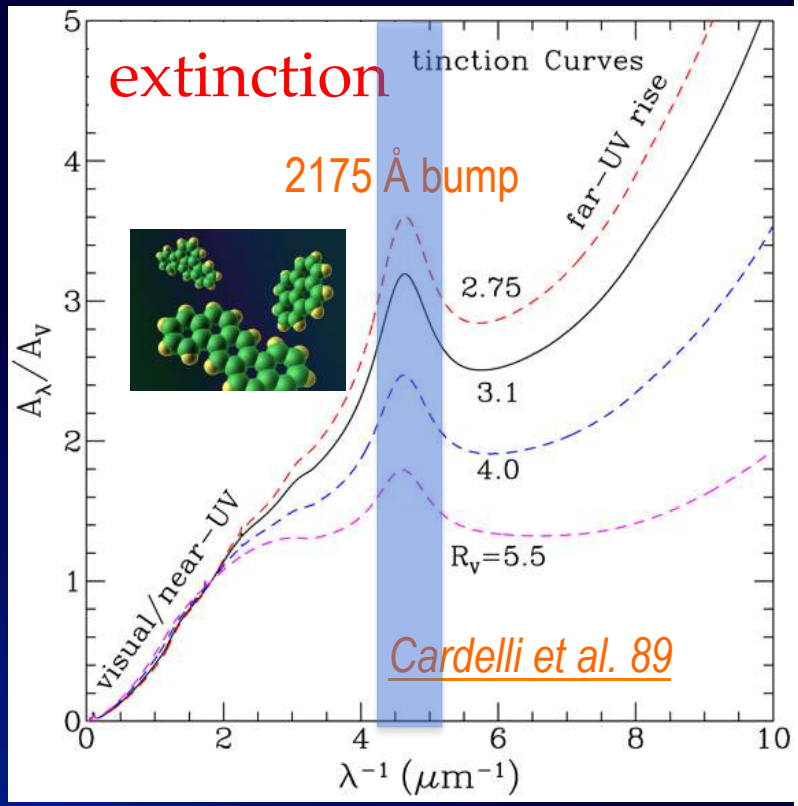
4. RAT alignment of superparamagnetic material is perfect

5. RAT alignment is enhanced by pinwheel torques from H2 formation (observation: Andersson et al. 2013)

6. RAT alignment sometimes is increased by random gas collisions

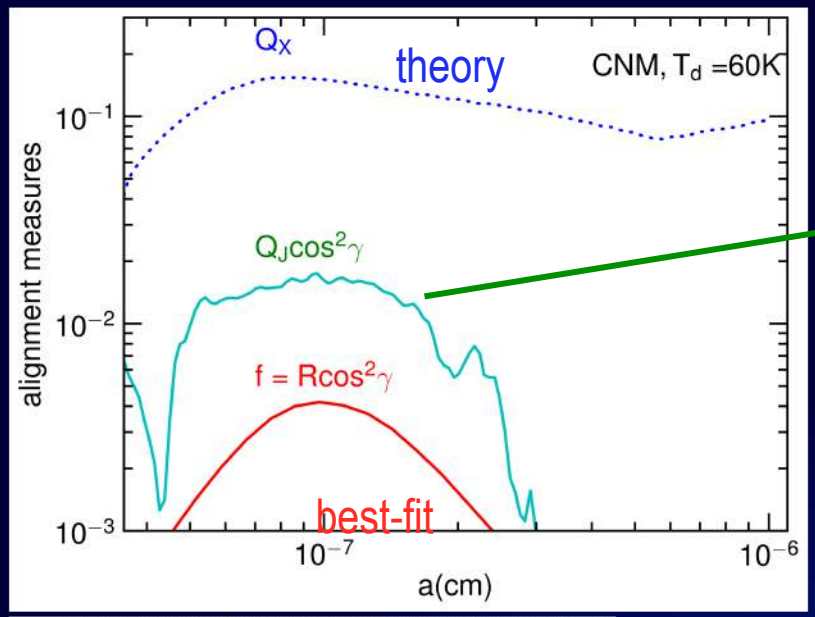
A particular star: HD 1977770
Alignment of PAHs and UV Polarization Bump



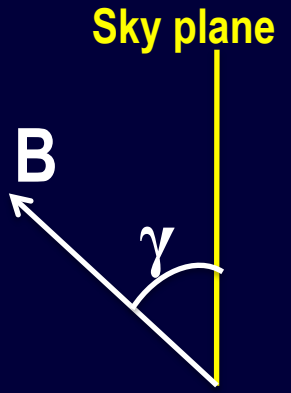


- PAHs produce 2175 Å features (Draine 89, Draine & Li 2007)
- PAHs radiate spinning dust emission (Hoang et al. 2010, 2011)
- How efficient are PAHs aligned observationally?

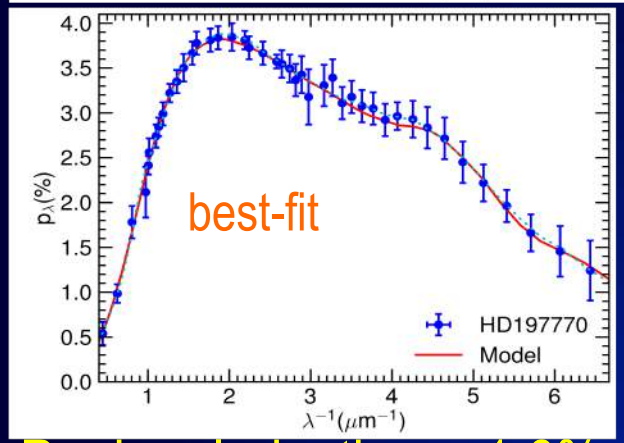
Maximum polarization of spinning dust ~1.6 percent

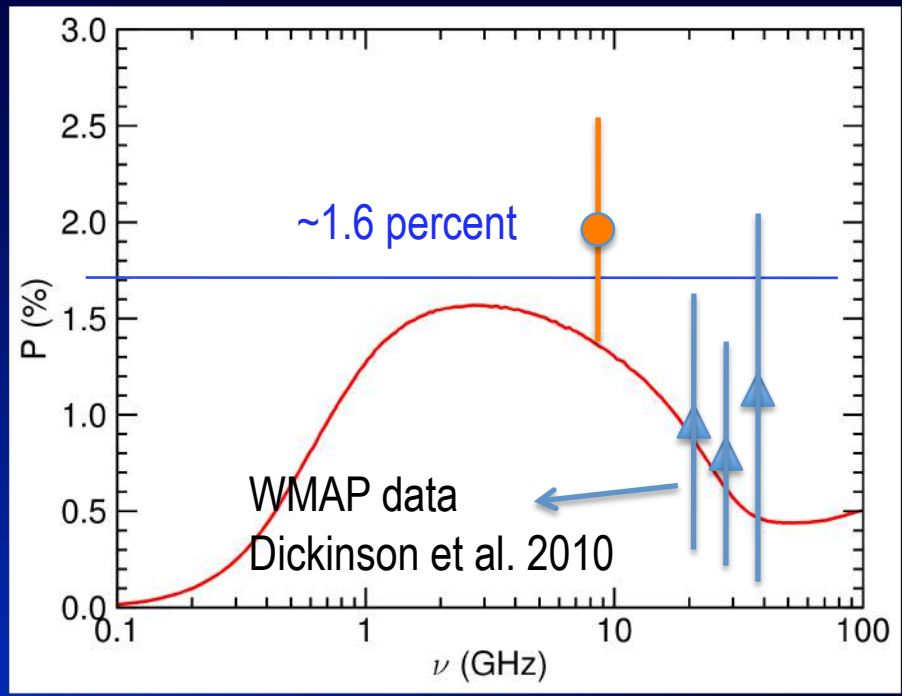


$$P \propto Q_J \cos^2 \gamma$$



Polarization

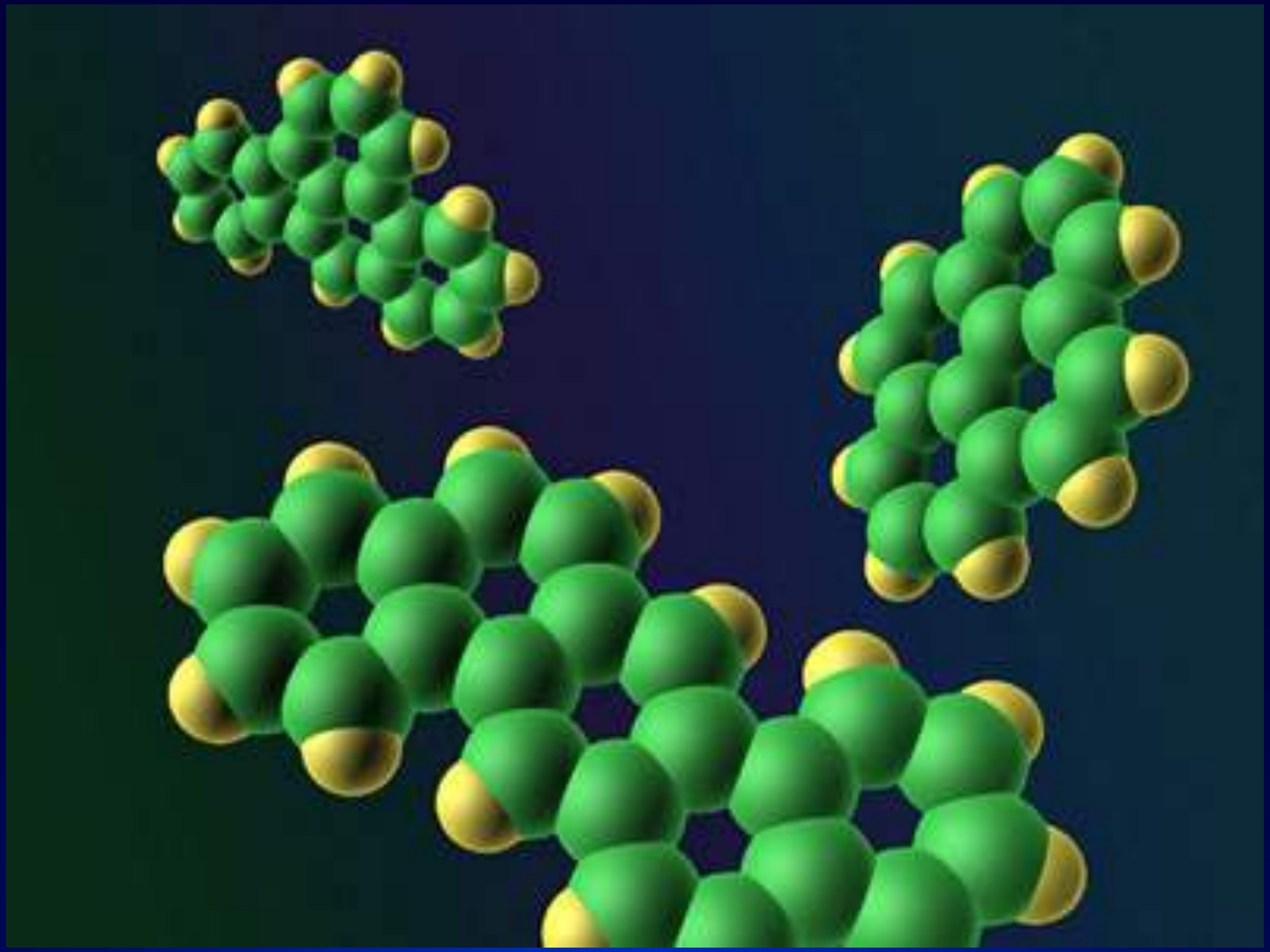




- Peak polarization ~ 1.6% at ν_{peak}=3 GHz
- P decreases with frequency > ν_{peak}
- Planck polarization data will test our predictions!

Hoang et al. 2013

Alignment of PAHs and Microwave Polarization

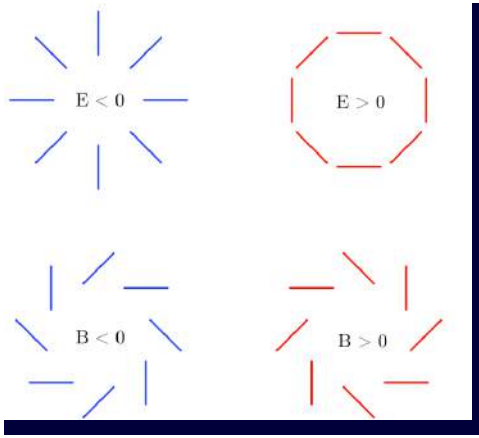


Remaining issues of RAT alignment:

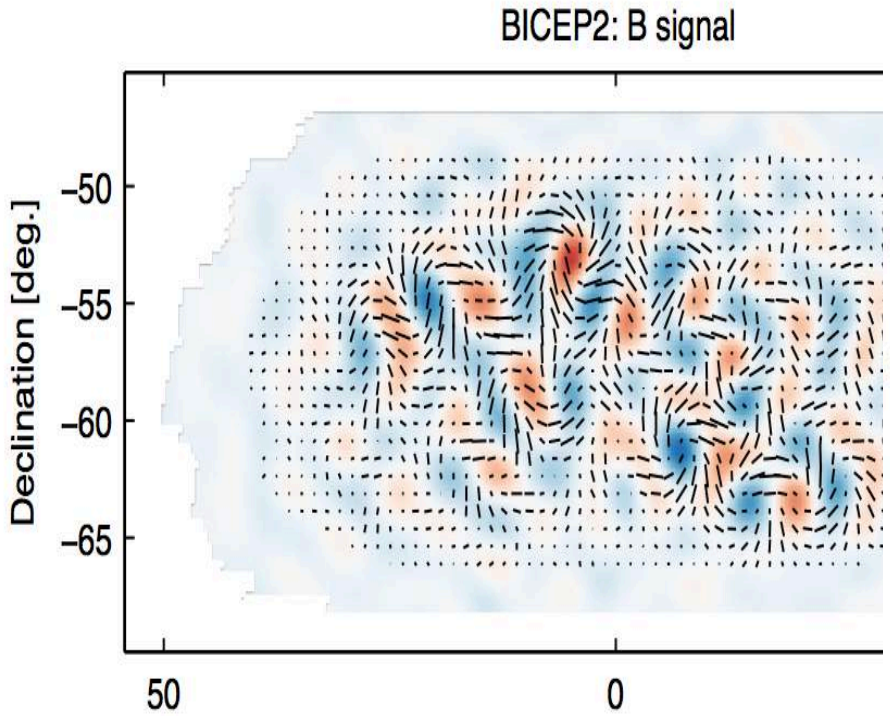
- High-J attractors are not universal (shape, radiation, angle). Why are there universal high alignment (high-J) of big grains?

- Alignment of carbon grains with helicity?

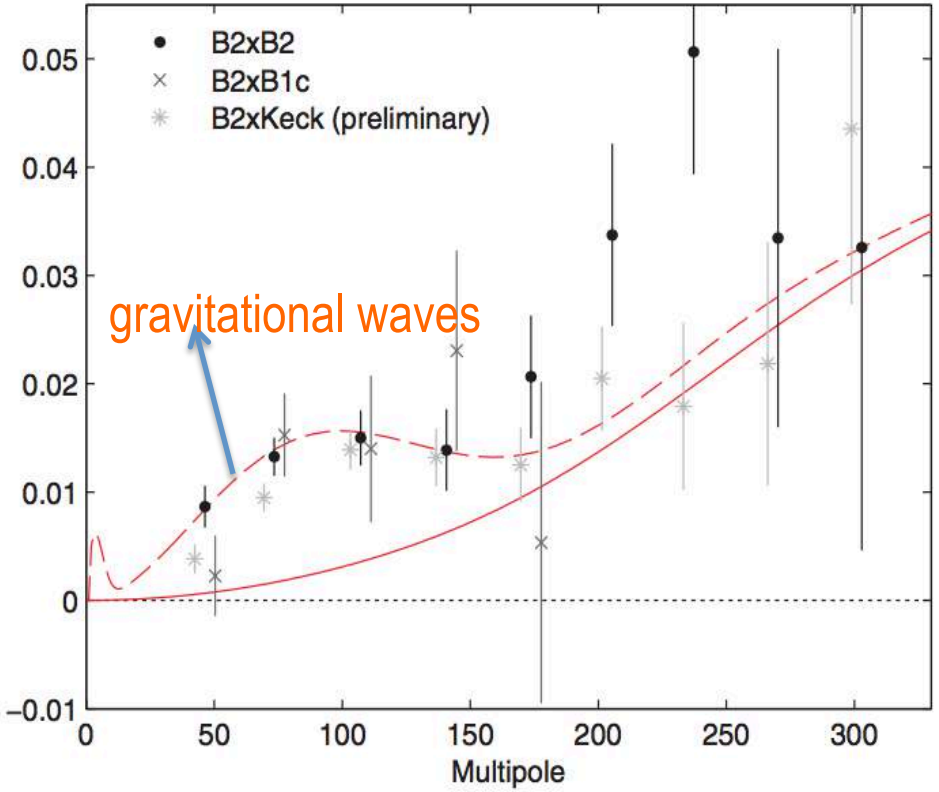
- RAT alignment cannot explain smooth increase of R with a?



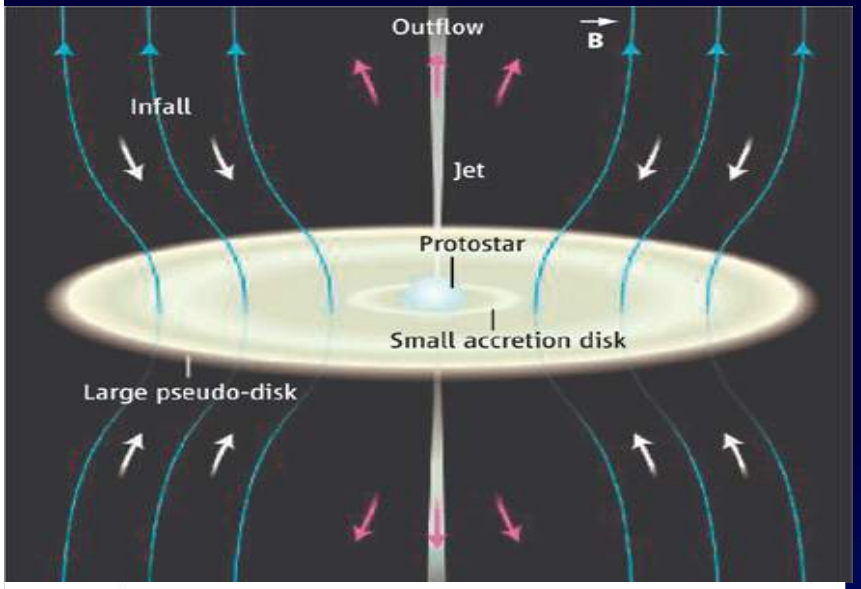
"BICEP2: B-mode polarization signal detected at r ~ 0.2"

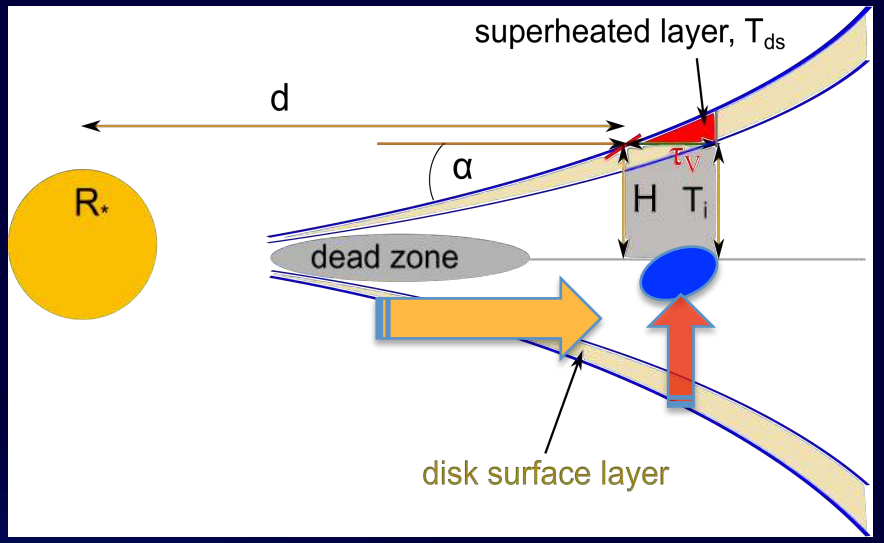


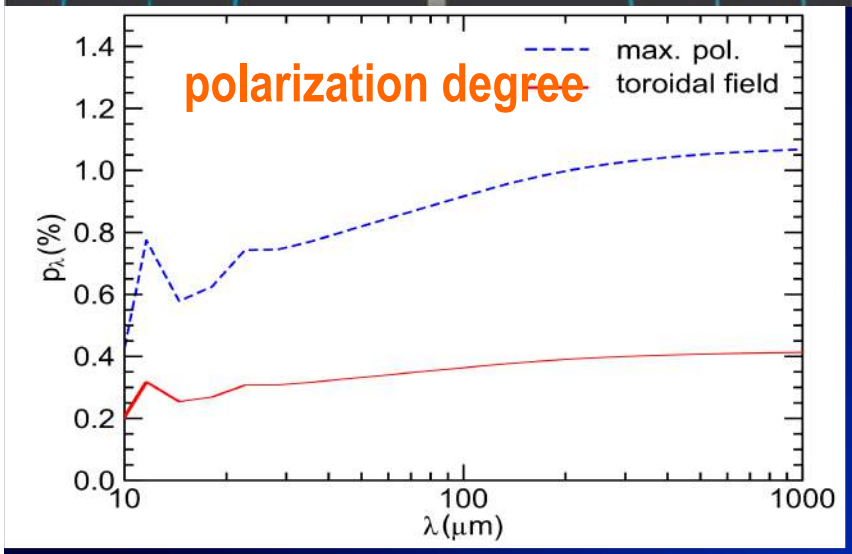
Bicep2 (2014)

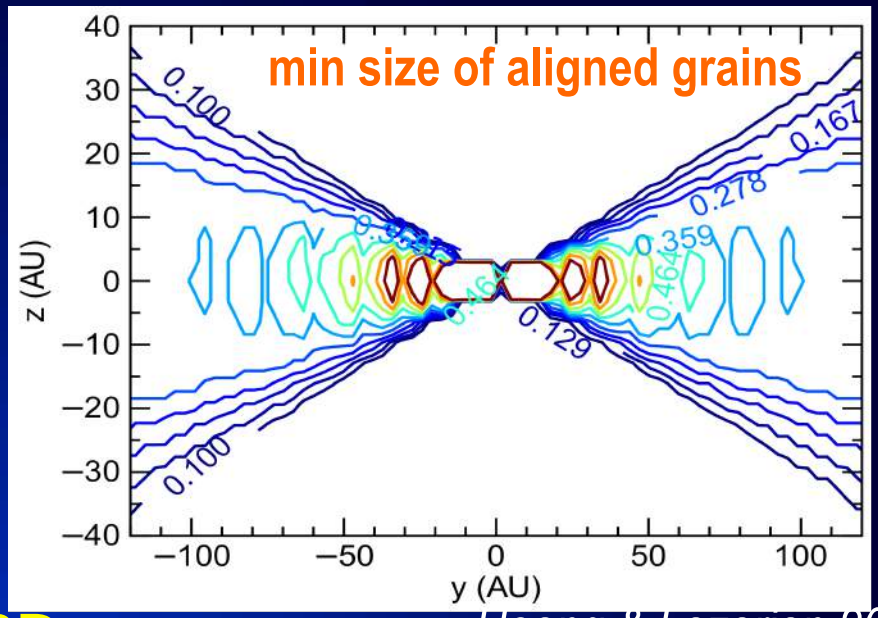


Polarized emission from protoplanetary disks





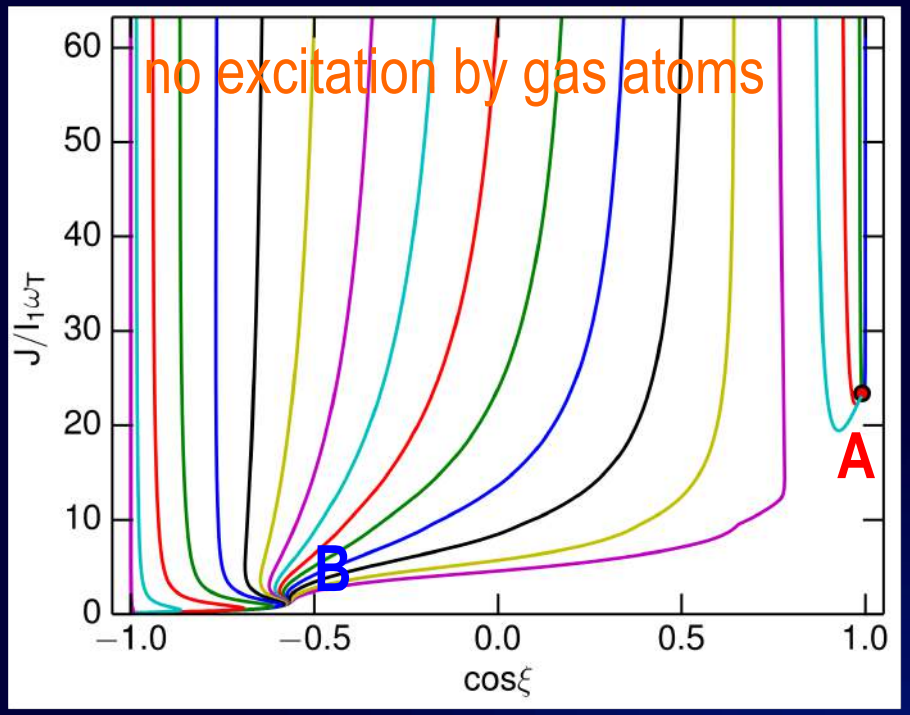


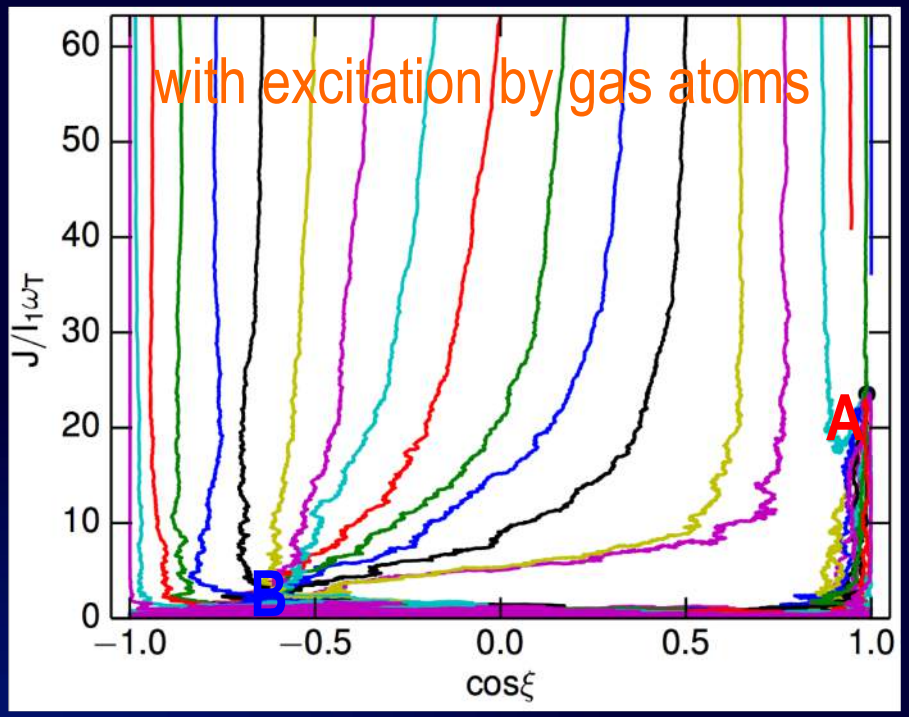


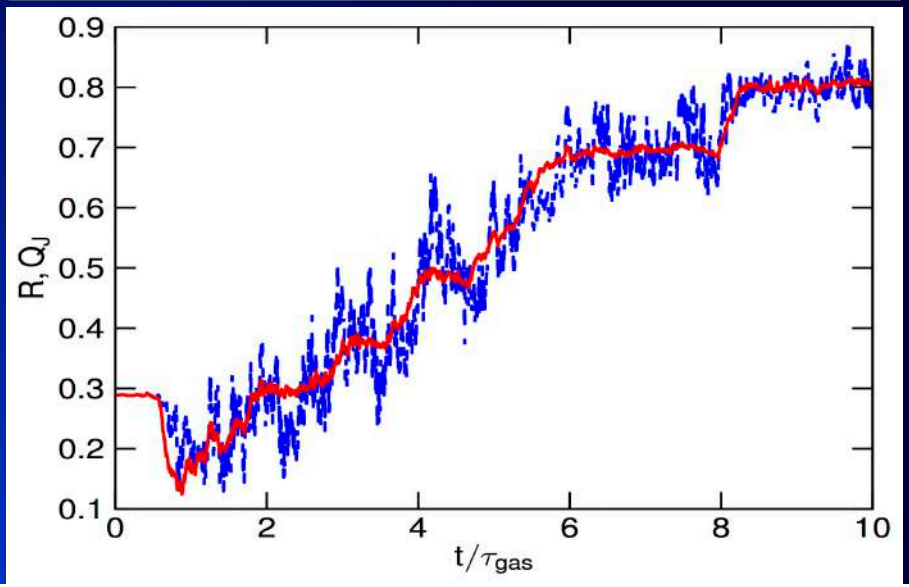
- Grains are weakly aligned in PPD
- Low polarization, consistent with observations (Hughes + 2013)

Hoang & Lazarian 2014

7. New effect: collisional pumping







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

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