Quantitative Theory of Grain Alignment: tracing magnetic fields and cleaning CMB polarization

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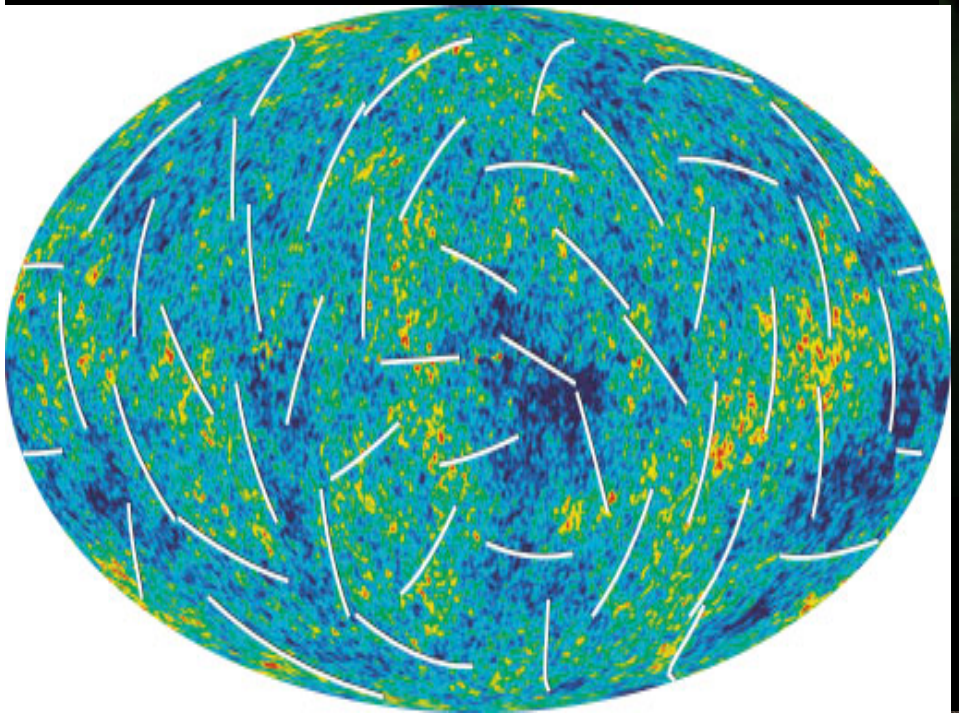
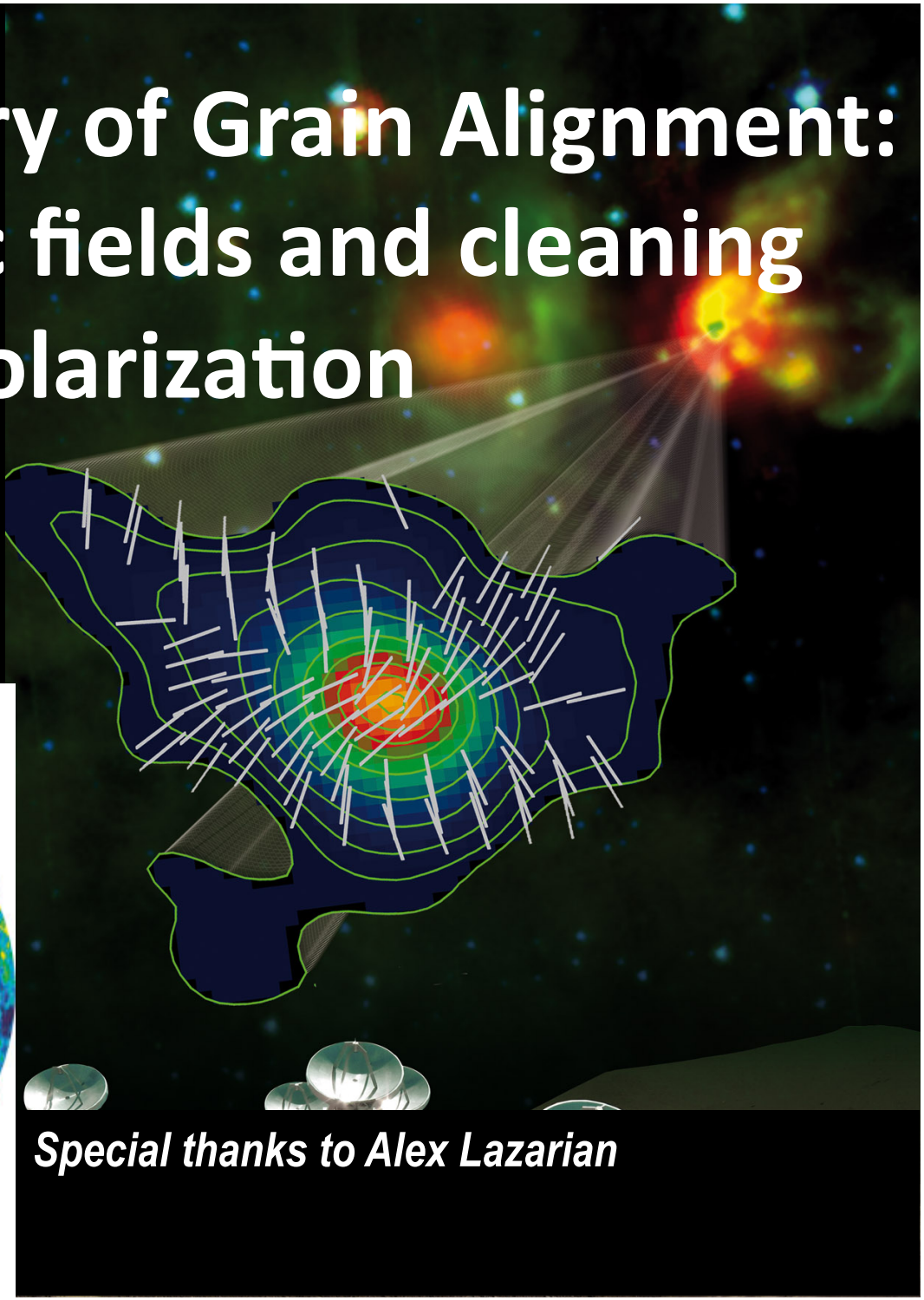


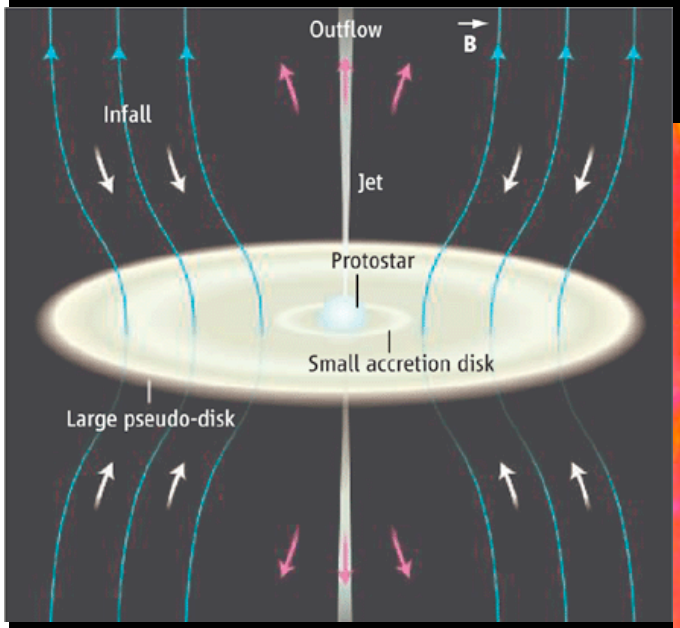


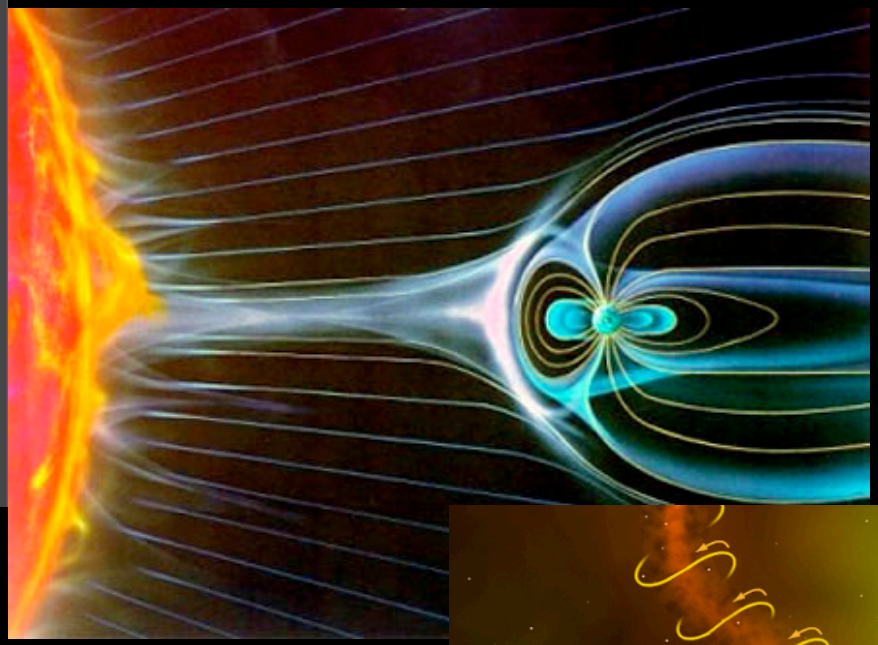
Special thanks to Alex Lazarian

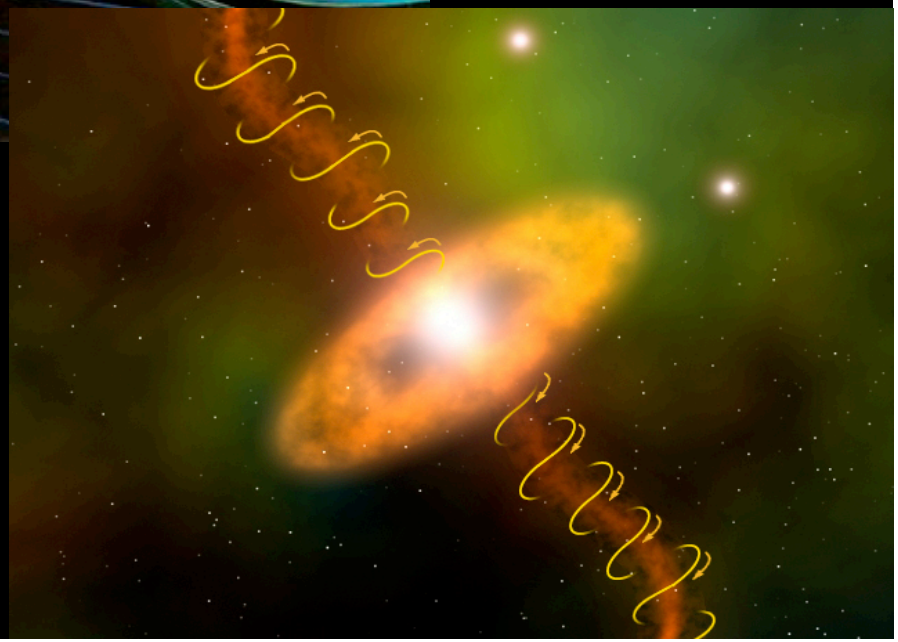
Outline

- Motivation: Magnetic fields, CMB polarization
- **New model of radiative torques (RATs) alignment**
- **Testing RAT alignment: observational evidences**
- **Predictions for polarization in MCs and Zodiacal cloud**
- Summary

Magnetic fields in Universe



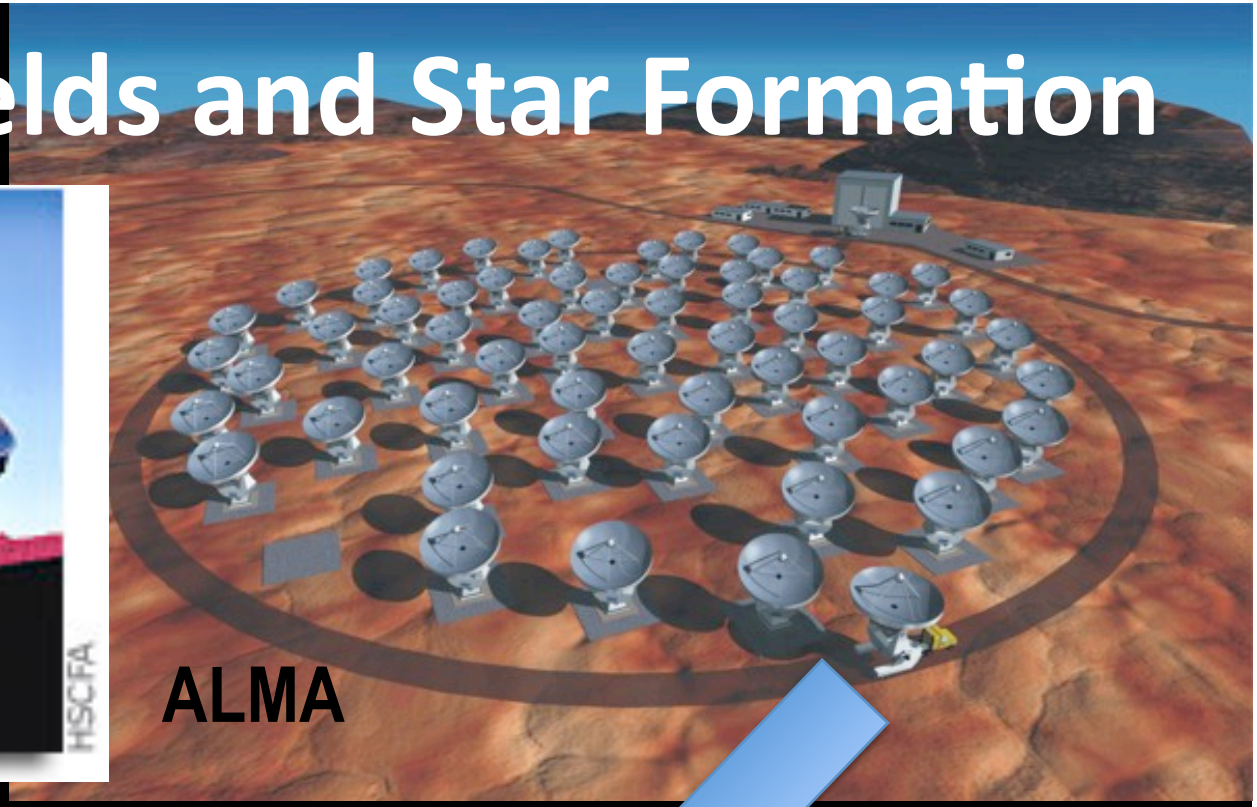




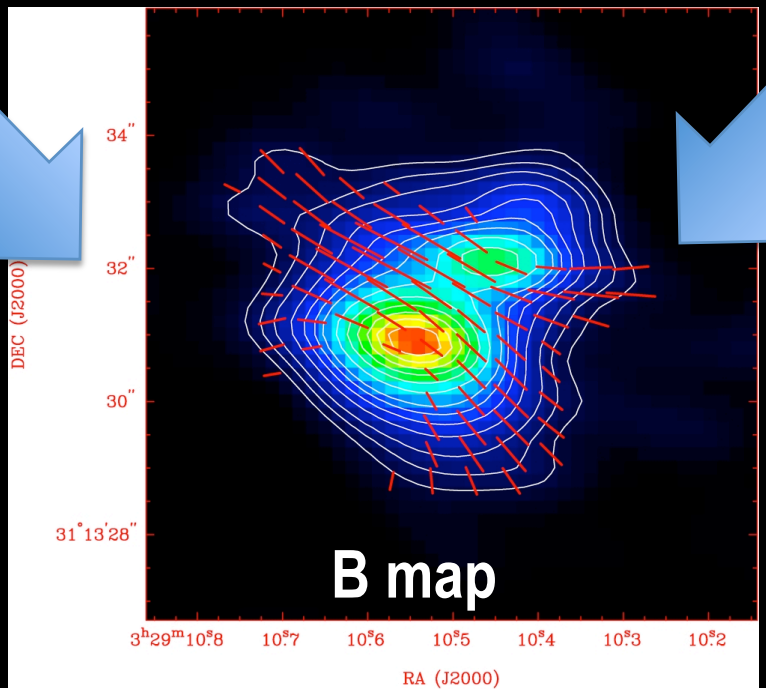
Diagnostics of Magnetic Fields

- Zeeman effect → B_{los} (Dick's talk)
- Faraday rotation → B_{los}
- Dust polarization → direction of B_{sky} (talks by Mario, Patrick, Tang…)
- Synchrotron polarization → B_{sky} (talk by Rainer) →
- Atomic alignment: direction of 3D field (see Huirong's poster)

Magnetic Fields and Star Formation



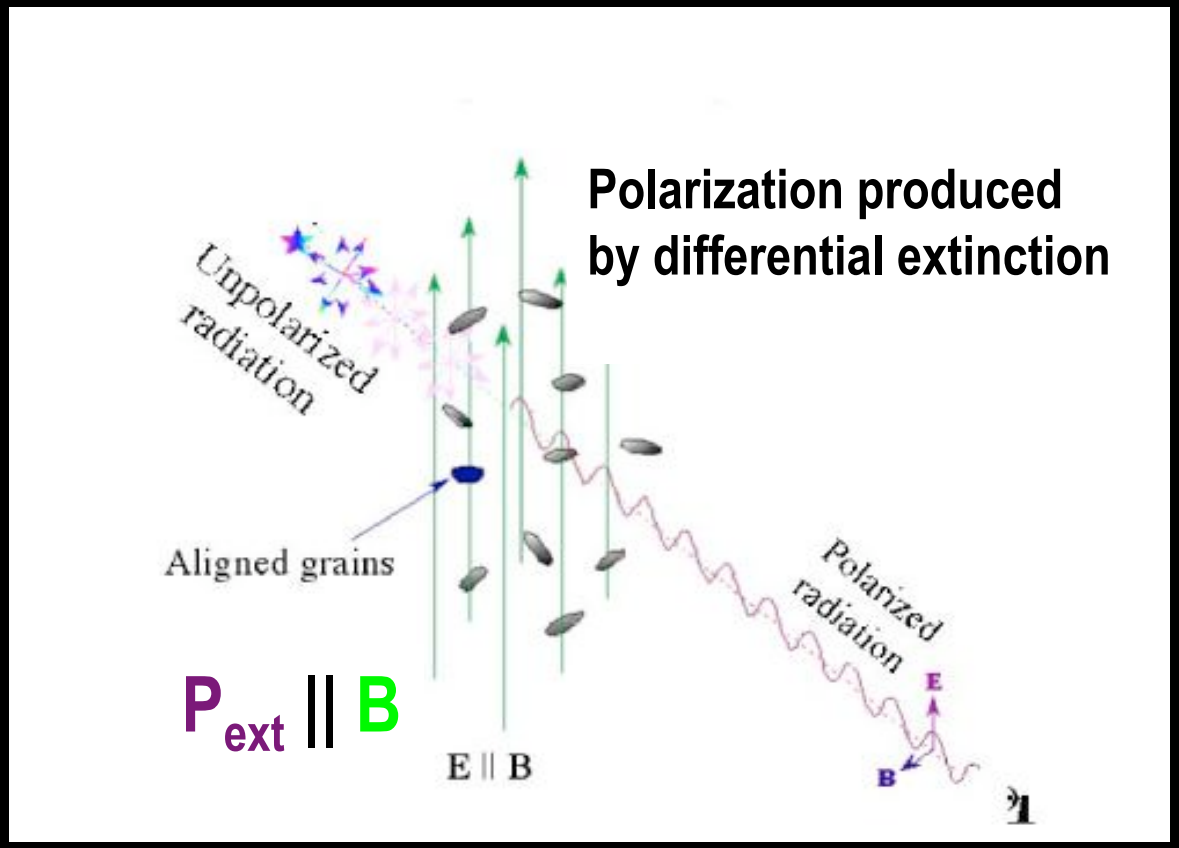
Observation provides P, how to infer B?



Chandrasekhar-Fermi technique:

$$\frac{B}{\sqrt{4\pi\rho}} \propto \frac{\delta V_{\rm los}}{\delta\phi}$$

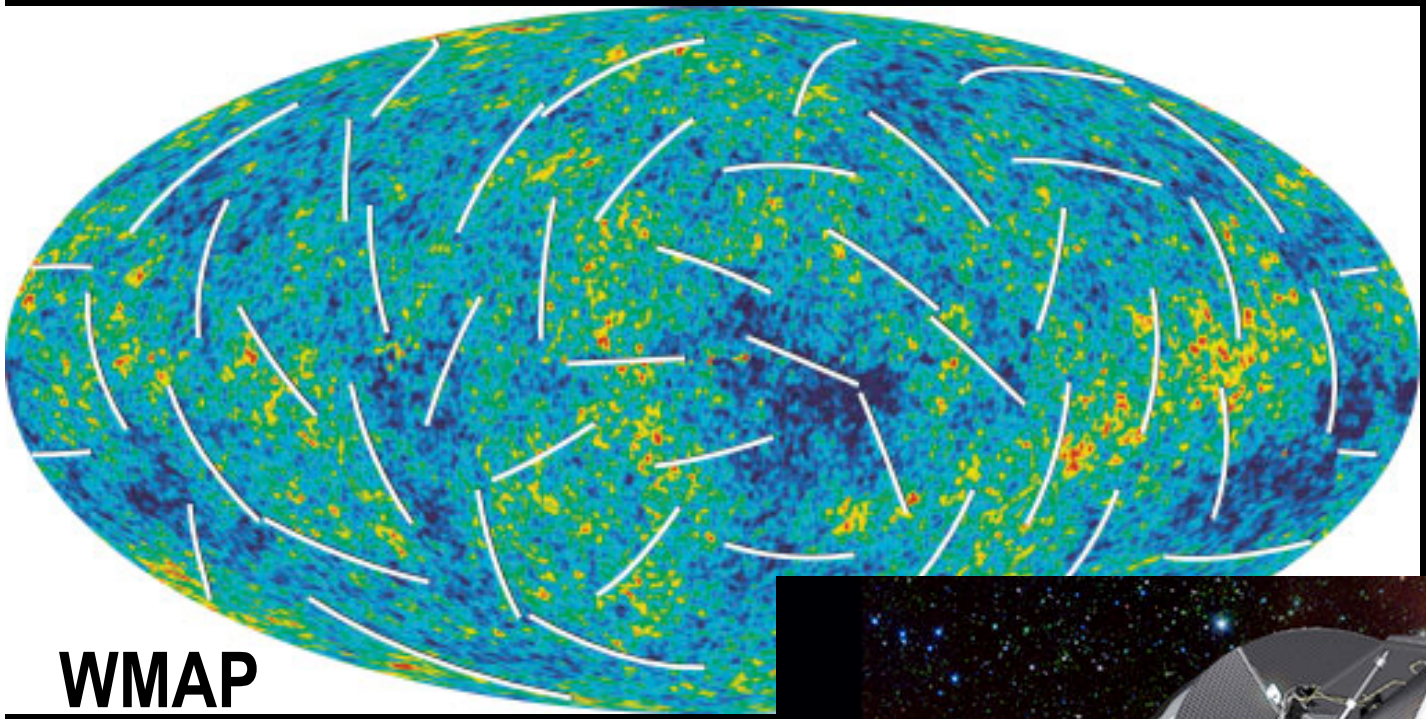
Aligned dust grains polarize starlight



Question 1: How do grains align with magnetic fields?

(E. Purcell, L Spitzer, A Lazarian, & B Draine worked on this question)

CMB Foreground Polarization



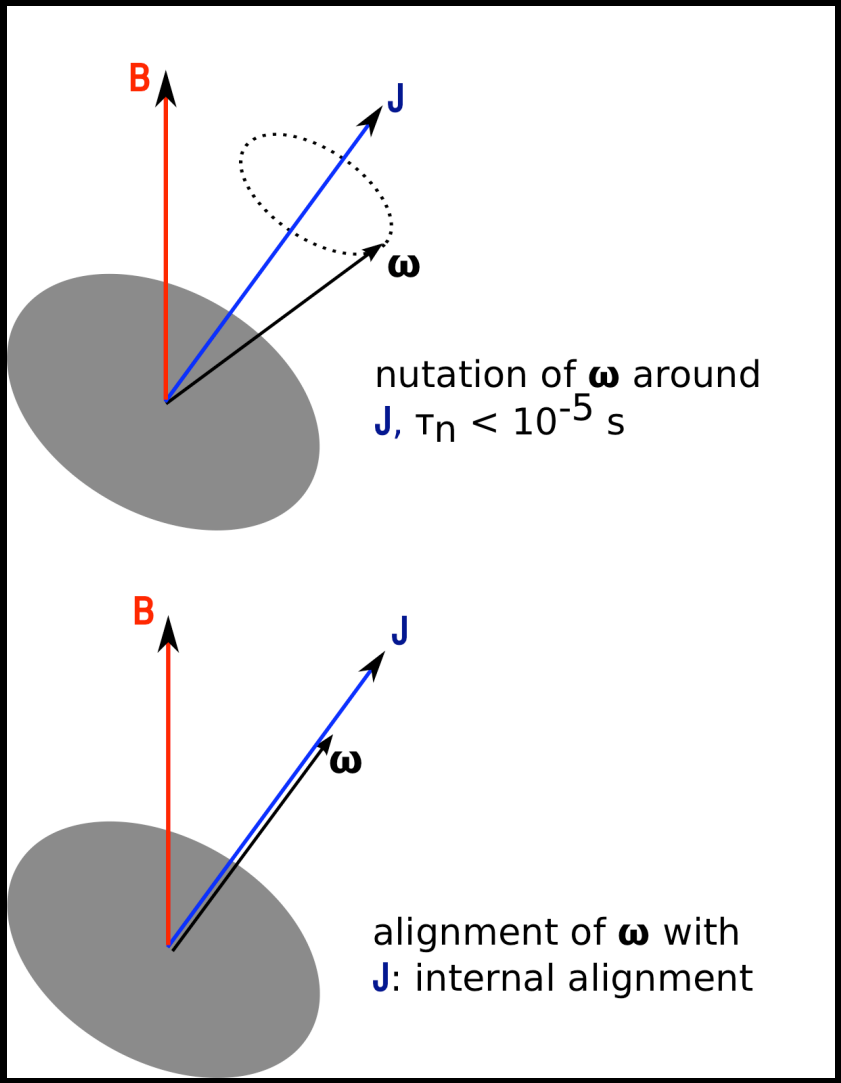
WMAP

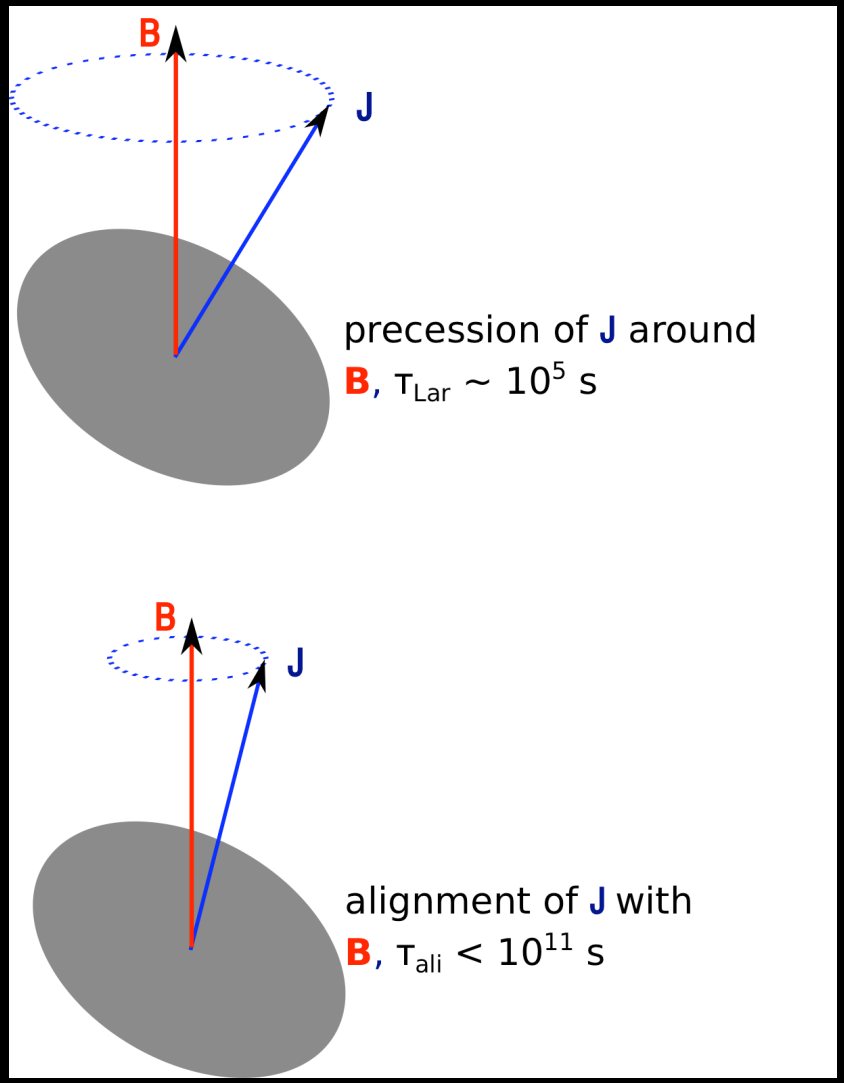
Remove Galactic dust polarization?

Question 2: Quantitative theory of grain alignment?

Planck

Simplified model of alignment





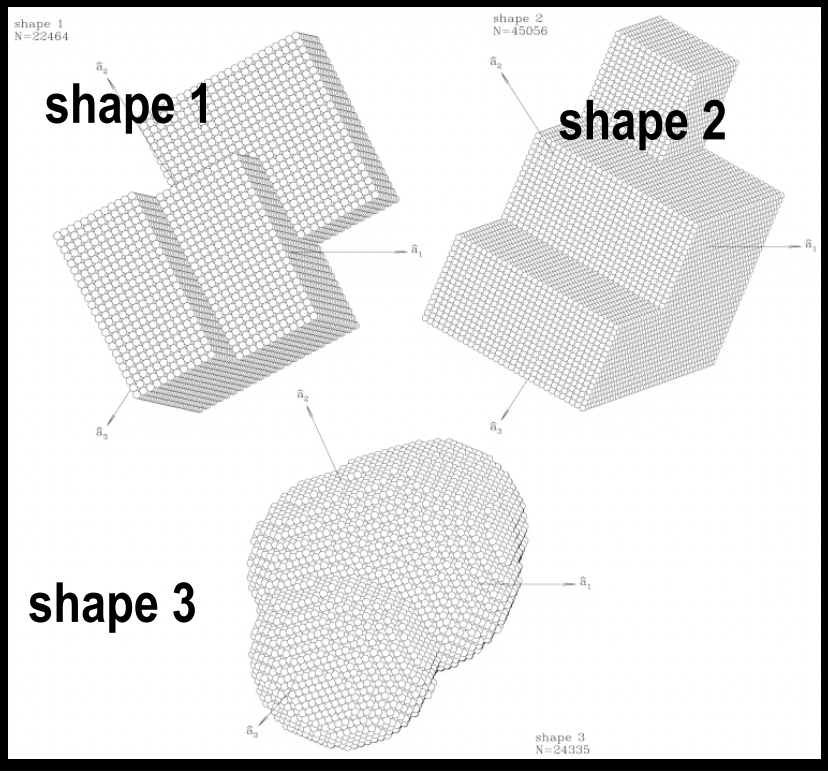
Stage 1: ω align with J

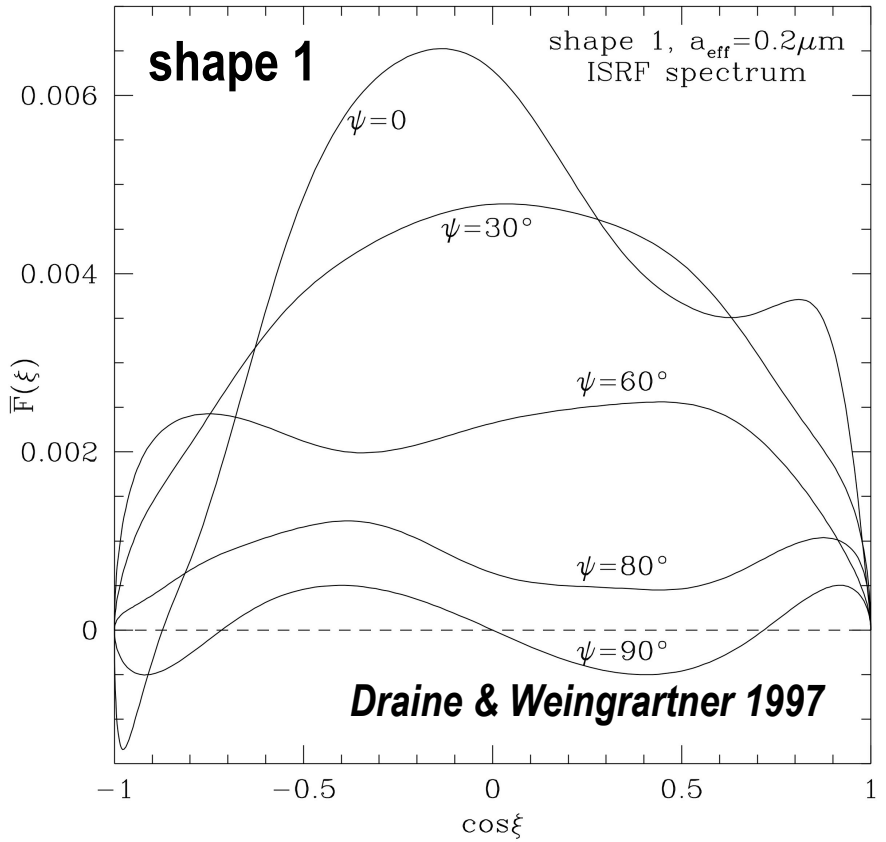
Stage 2: J gets aligned with B

“New” mechanism: Radiative torques alignment

Dolginov & Mytrophanov 76: radiative torques for two connected ellipsoids

B Draine introduced radiative torques in DDSCAT code





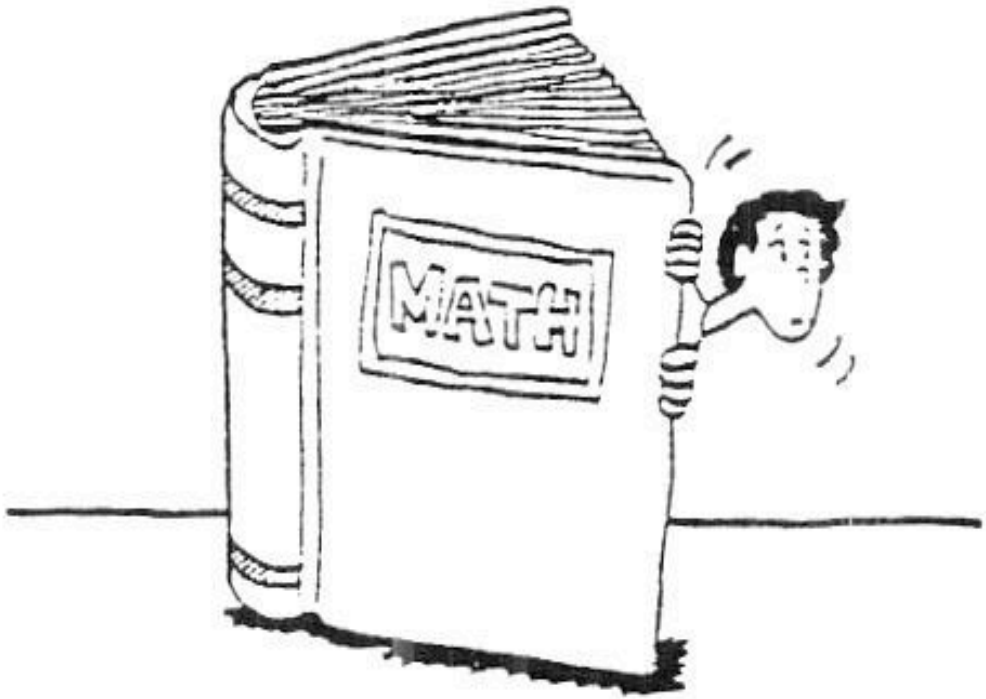
L. Spitzer: Alignment torques are not universal. How can a universal alignment exist?

The parameter space to study is huge: shapes of grains, wavelengths, sizes.

Analytical insight is required

Where's the best place to hide if you're scared?

Inside a math book because there is safety in numbers.

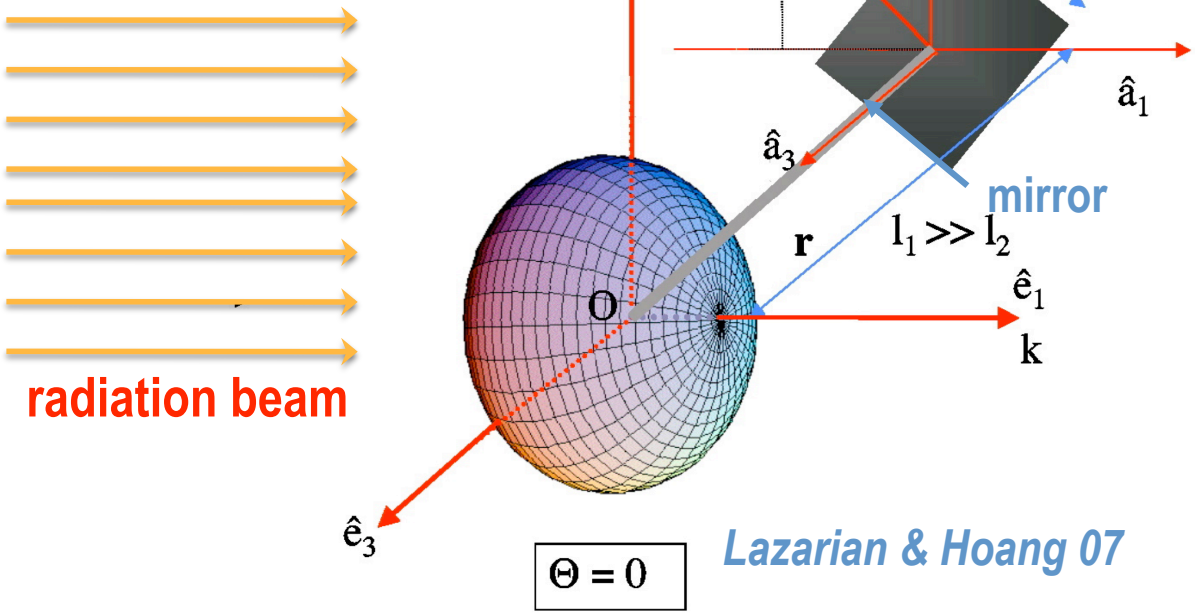


Based on 6 papers:

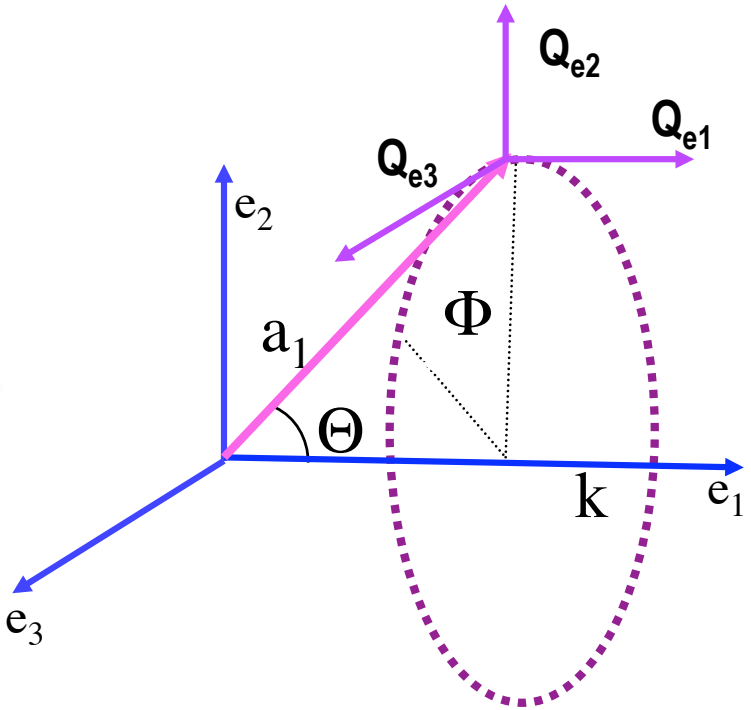
Lazarian & Hoang 07 MNRAS, 378, 910
Lazarian & Hoang 07 ApJ, 669, L77-L80
Lazarian & Hoang 08 ApJ, 676, L25-L28
Hoang & Lazarian 08 MNRAS, 388, 117-143
Hoang & Lazarian 09a ApJ, 695,1457
Hoang & Lazarian 09b ApJ, 697,1316
and some more in prep

Analytical model (AMO) of radiative torques (RATs)

simple model of a helical grain



Lazarian & Hoang 07

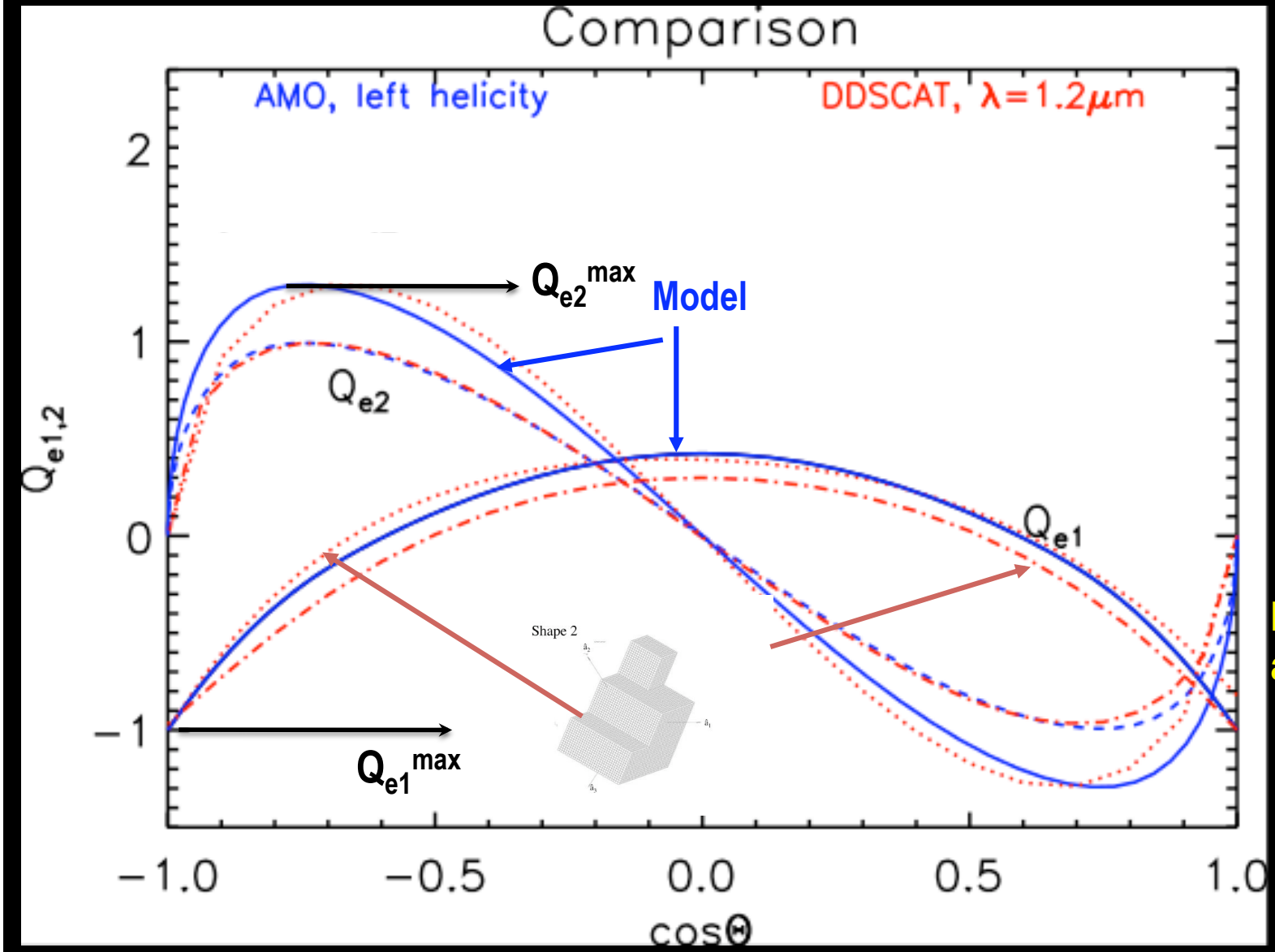


a_1 is grain max inertia axis

k is light direction

Simple analytical expressions are available for Q_{e1} and Q_{e2} torques.

RATs: AMO vs numerical calculations



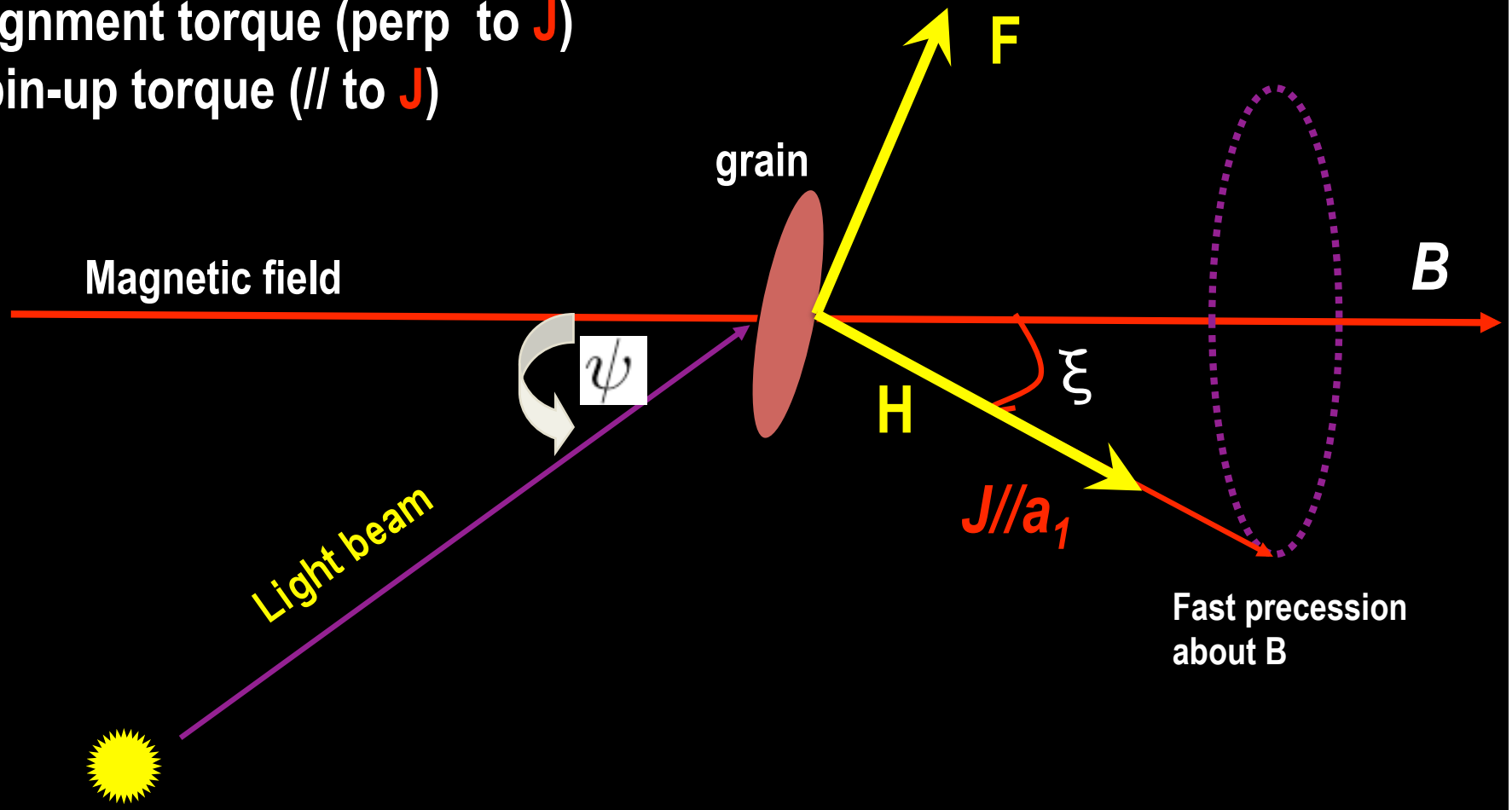
RATs functional forms are very similar.

$Q_{e1}^{max}/Q_{e2}^{max}$ changes from grain to grain.

Lazarian & Hoang 07

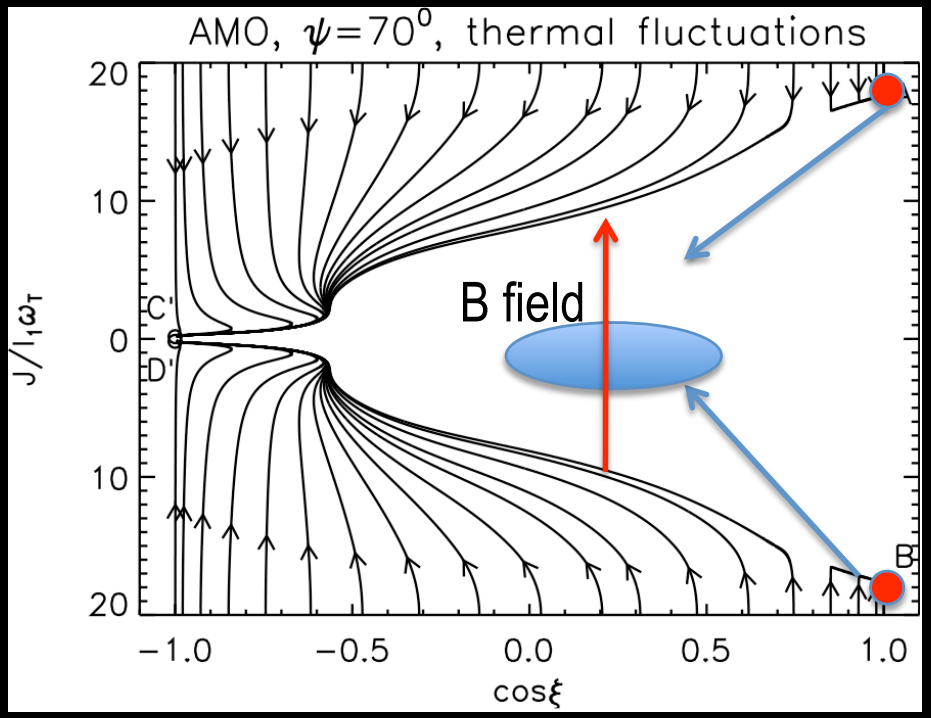
Grain Alignment by RATs

F is alignment torque (perp to J)
H is spin-up torque (// to J)

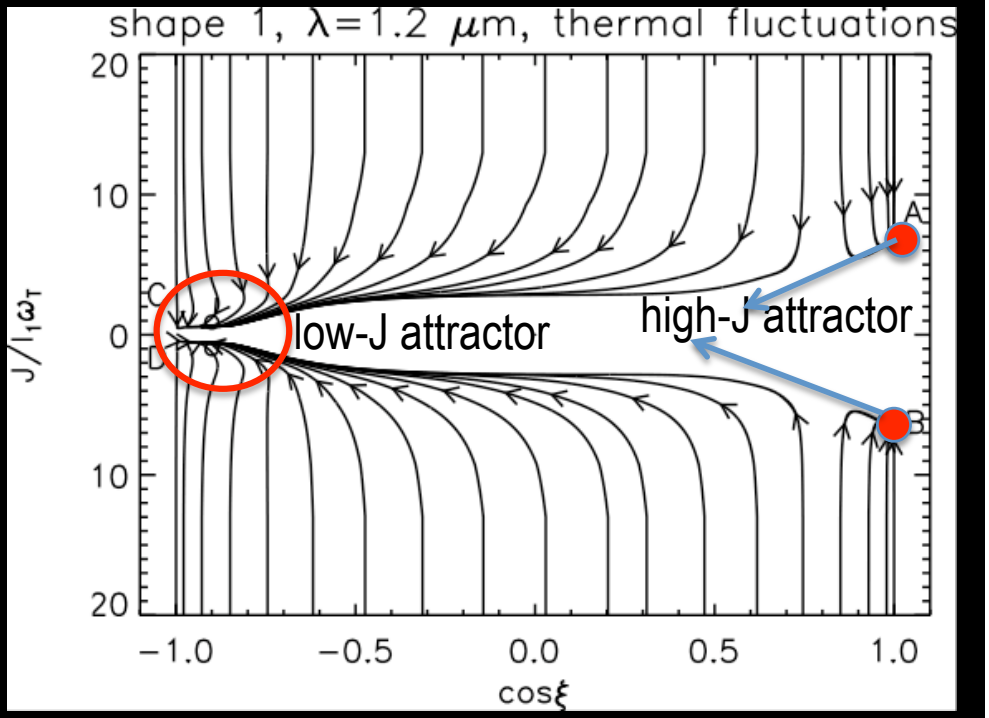


RAT alignment: trajectory map

AMO



DDSCAT



Hoang & Lazarian 08

➔AMO predicts the "right" alignment with long axes perpendicular to B.

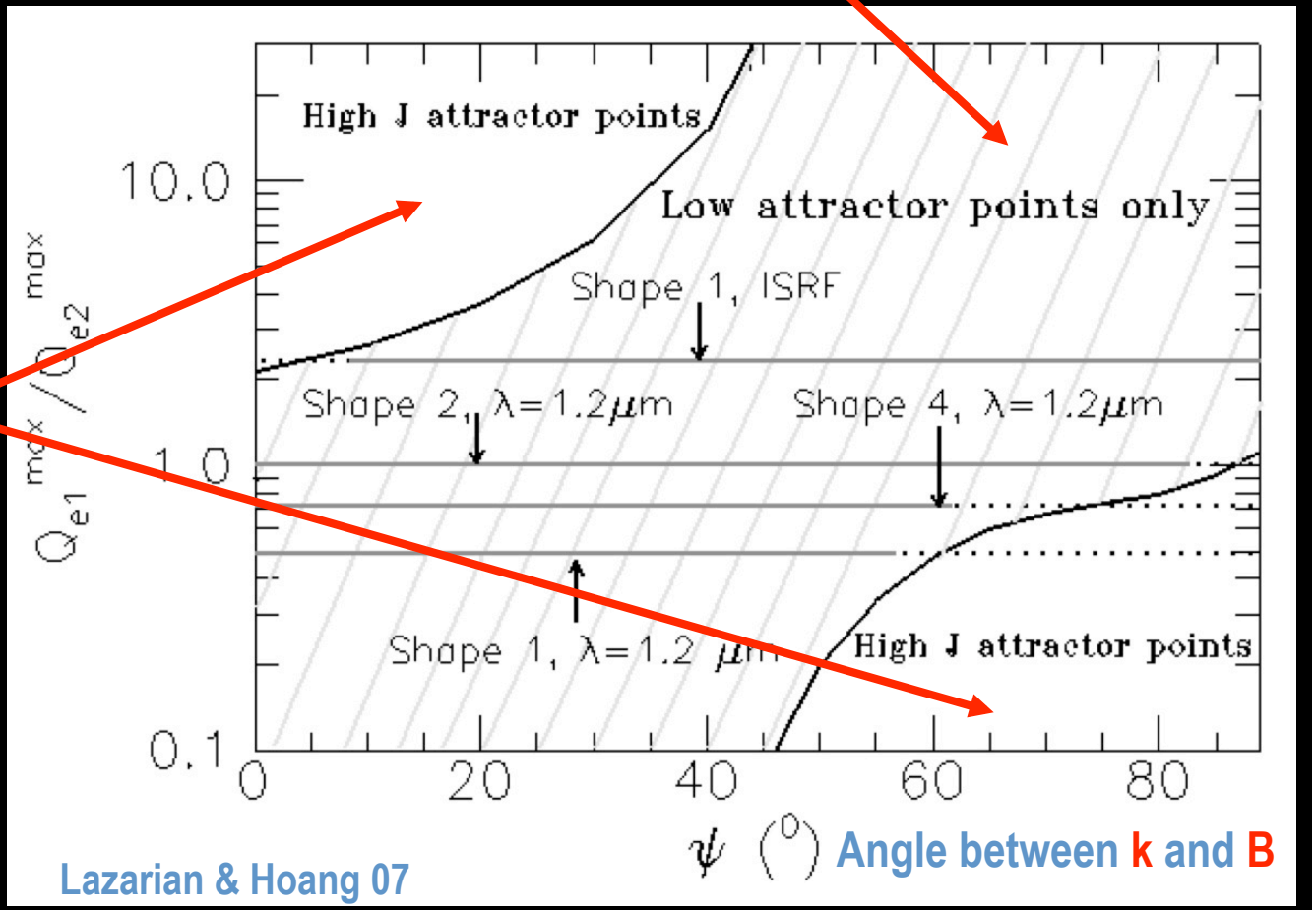
➔ P_{ext} || B

➔ P_{emiss} perpendicular to B

When high-J and low-J attractors exist?

RATs only impede grain rotation

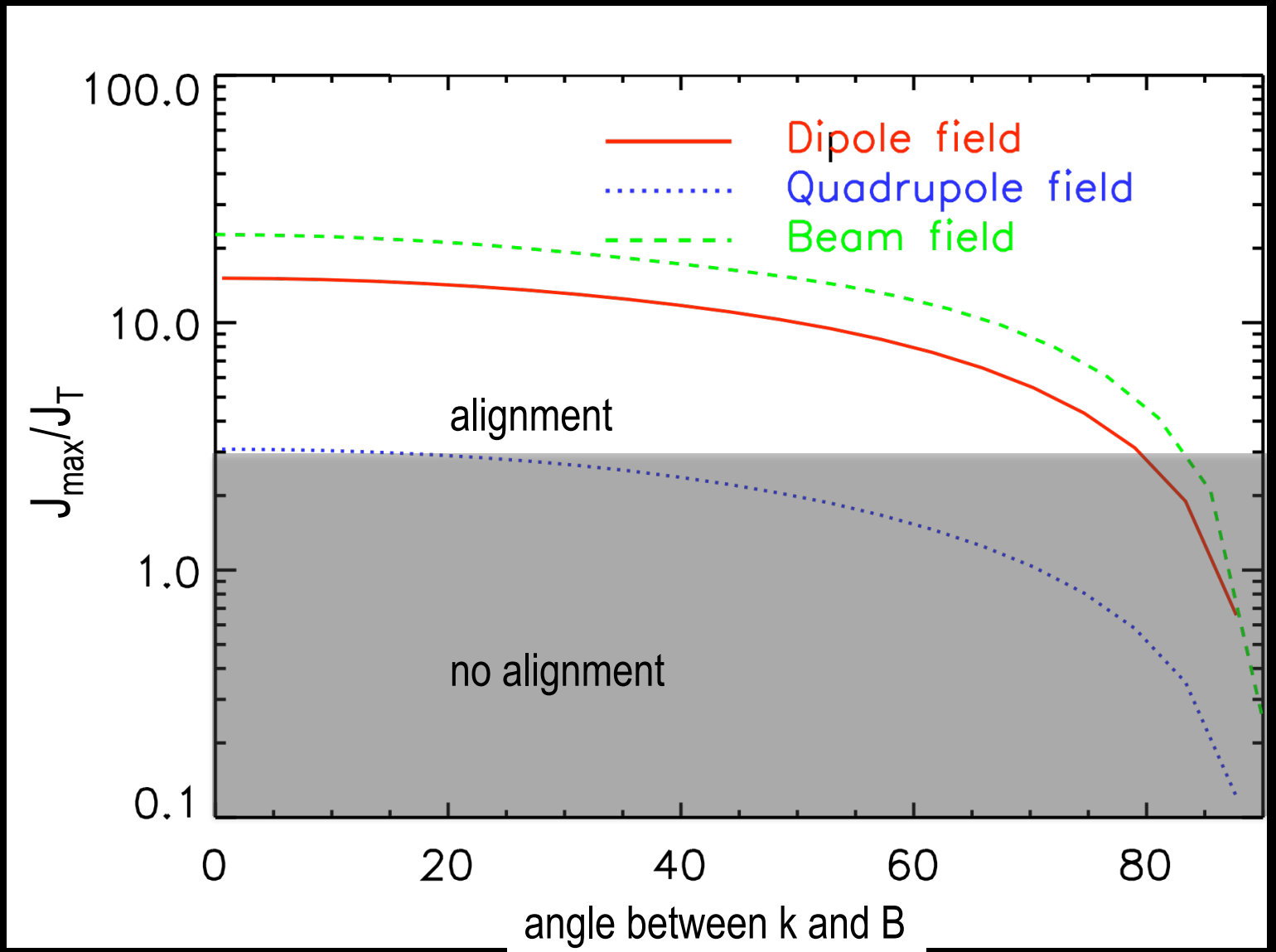
RATs spin up grains



Lazarian & Hoang 07

Ratio $Q_{e1}^{max}/Q_{e2}^{max}$ is as important for polarimetry as the grain axis ratio

Spin-up by RATs depends on radiation direction



Hoang & Lazarian 09a

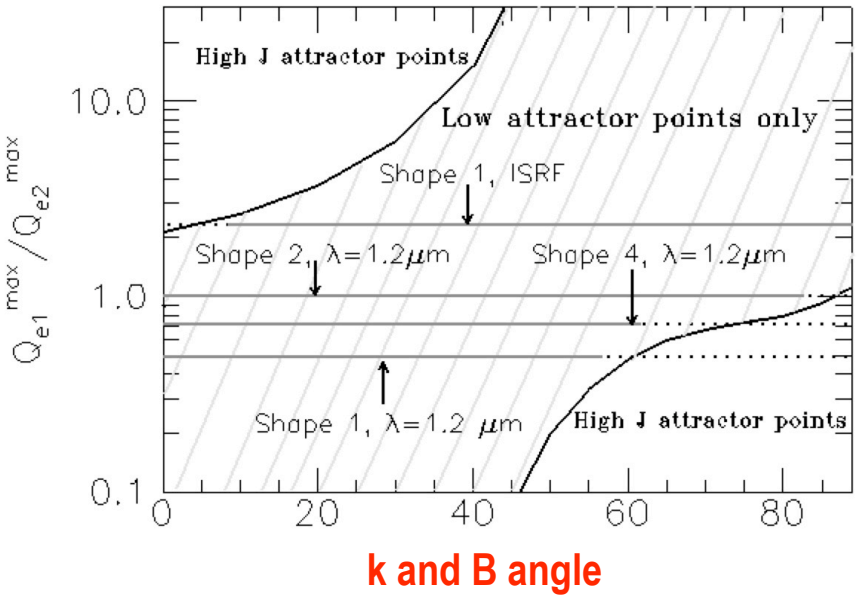
Modeling dust polarization

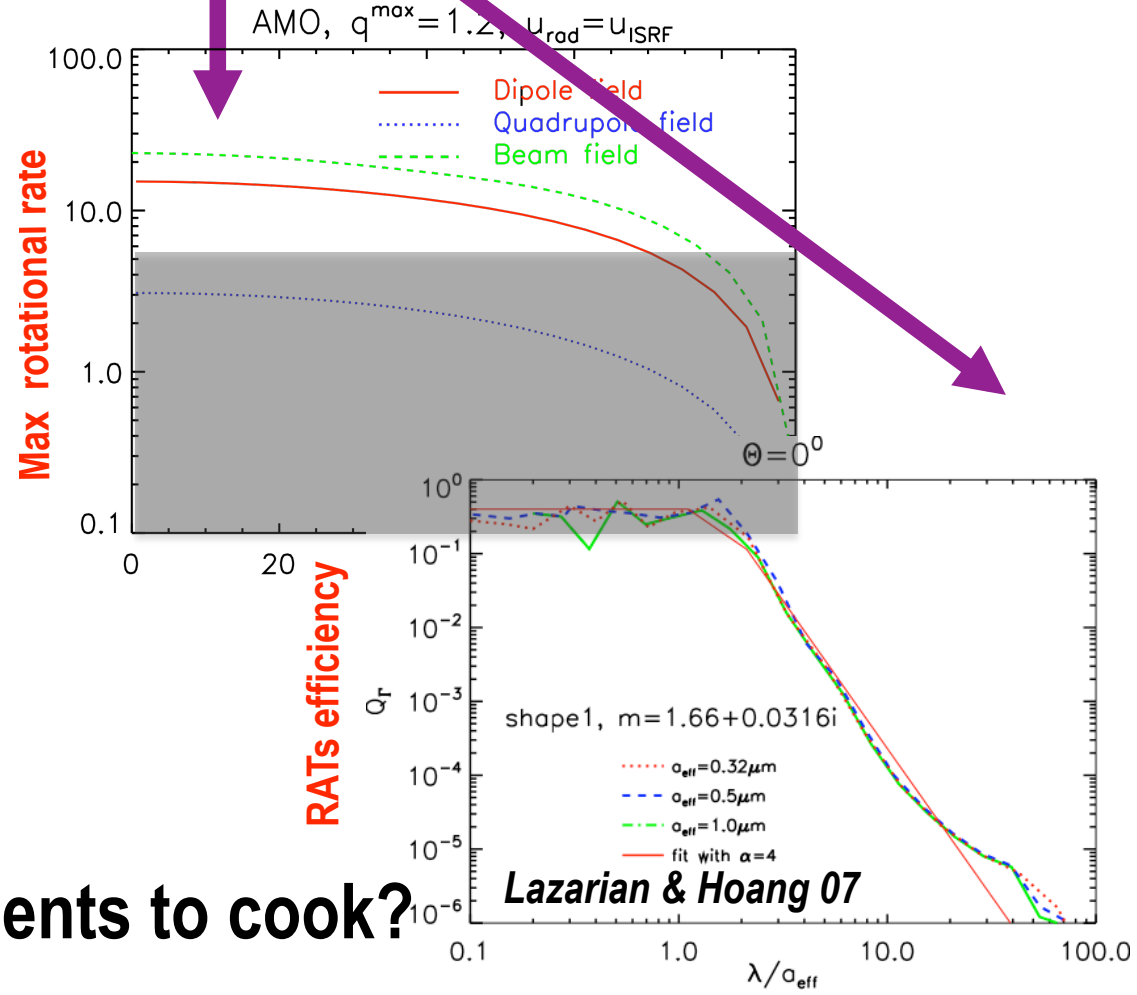
Axis ratio, $Q_{e1}^{max}/Q_{e2}^{max}$, k and B angle, radiation field, gas damping

Theory

Predicted polarization

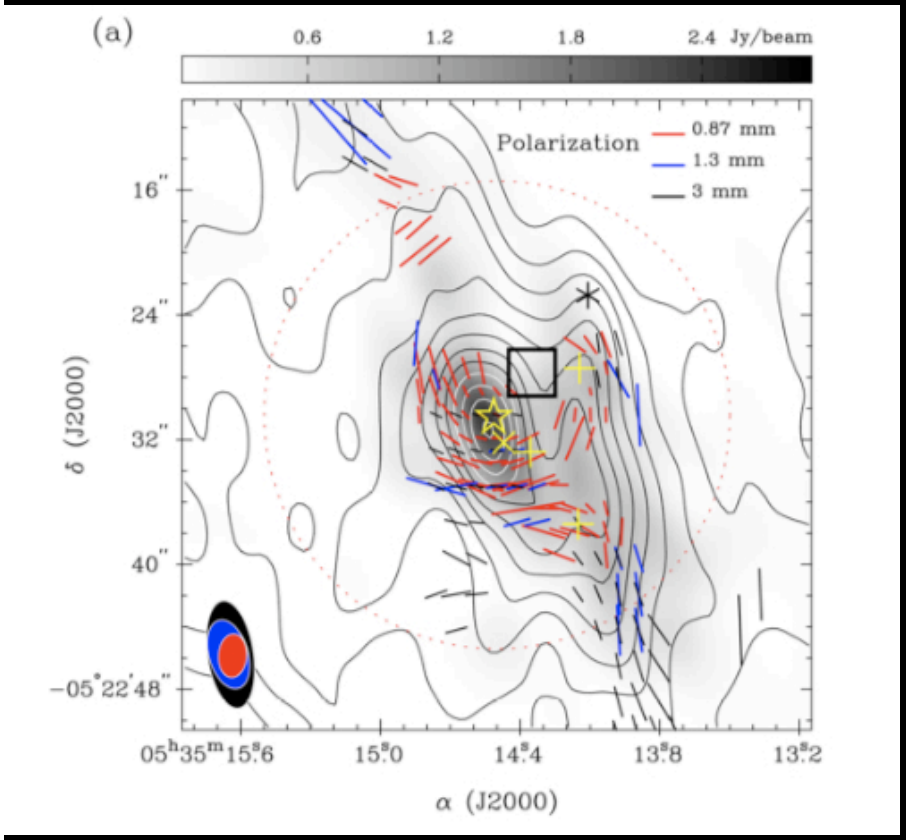
Hoang & Lazarian 09

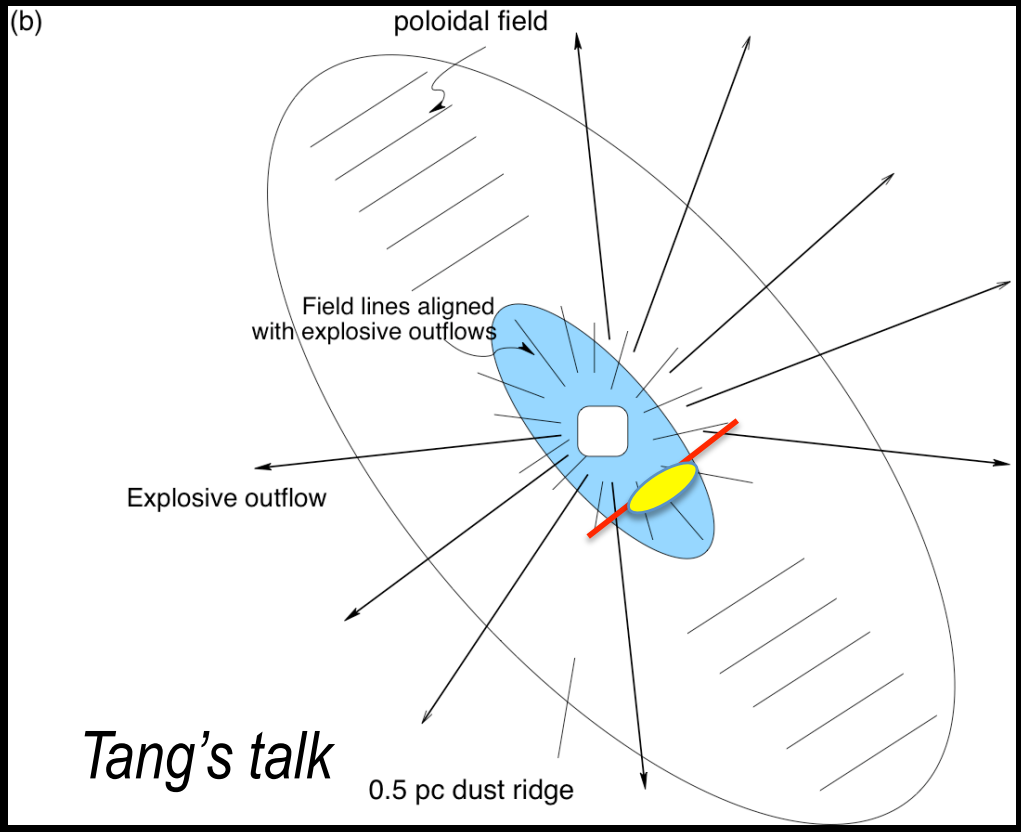




Do we have enough ingredients to cook?

Respond to Tang's "challenge": mechanical alignment?





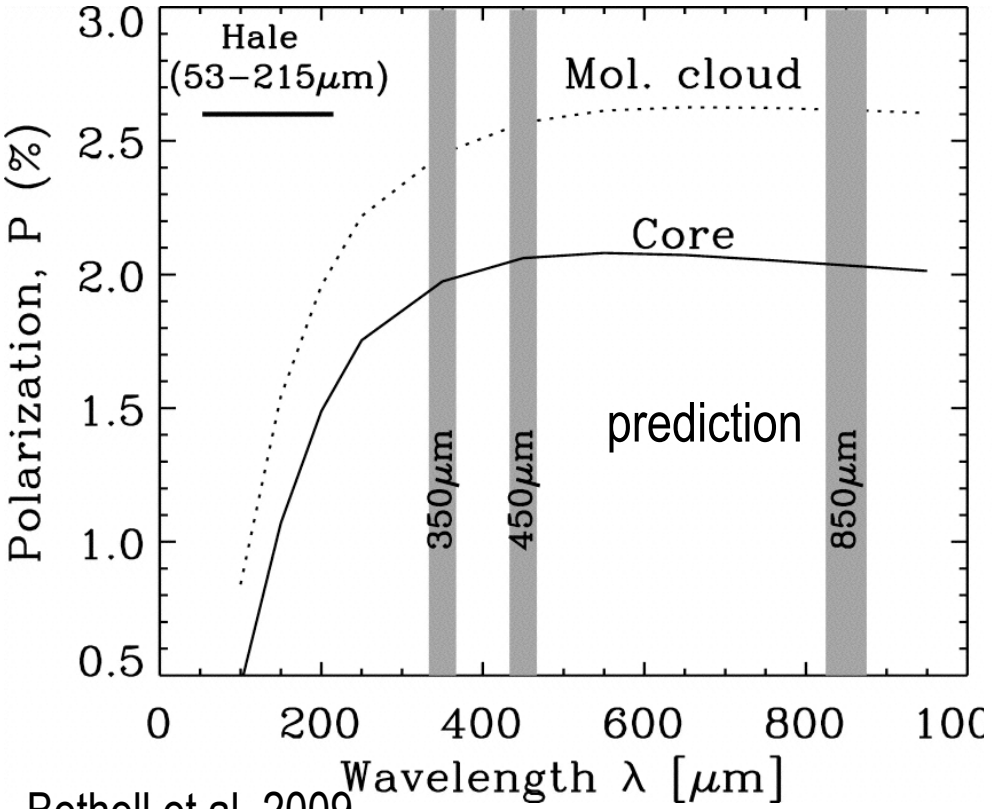
Timescales:

$$\frac{\tau_{\rm flow}}{\tau_{\rm B}} \approx 10^6 \left(\frac{v_{\rm flow}}{v_T}\right)^{-2} \left(\frac{T_{\rm gas}}{100{\rm K}}\right)^{-1/2} \left(\frac{n_{\rm gas}}{30{\rm cm}^{-3}}\right)^{-1} \left(\frac{B}{1\mu G}\right) \left(\frac{a}{10^{-5}{\rm cm}}\right)$$

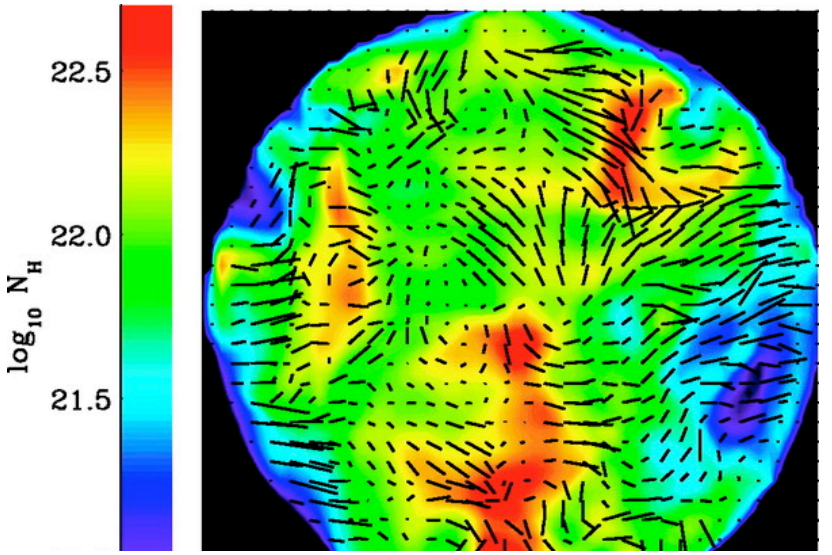
Lazarian & Hoang 07

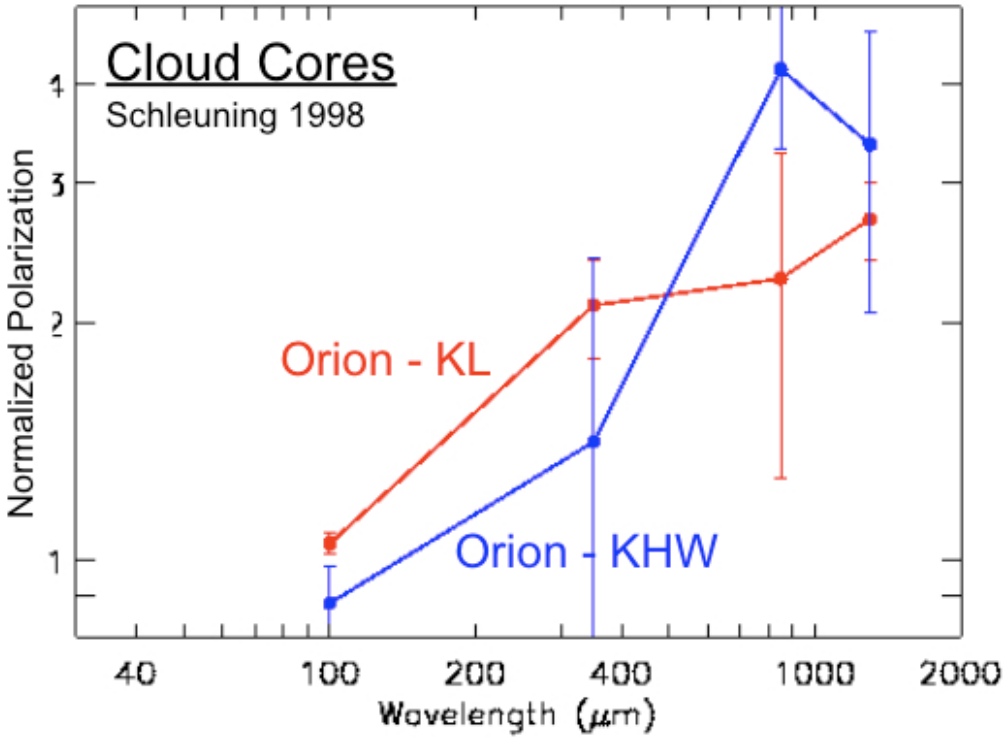
T_{gas}=1000 K, B=10 mG, n_{gas}=2 10^6 cm^{-3},v_{flow}=100 km/s (Tang et al. 2010), we get $\tau_{flow}/\tau_B \sim 10^2$ for a=10^{-5} cm

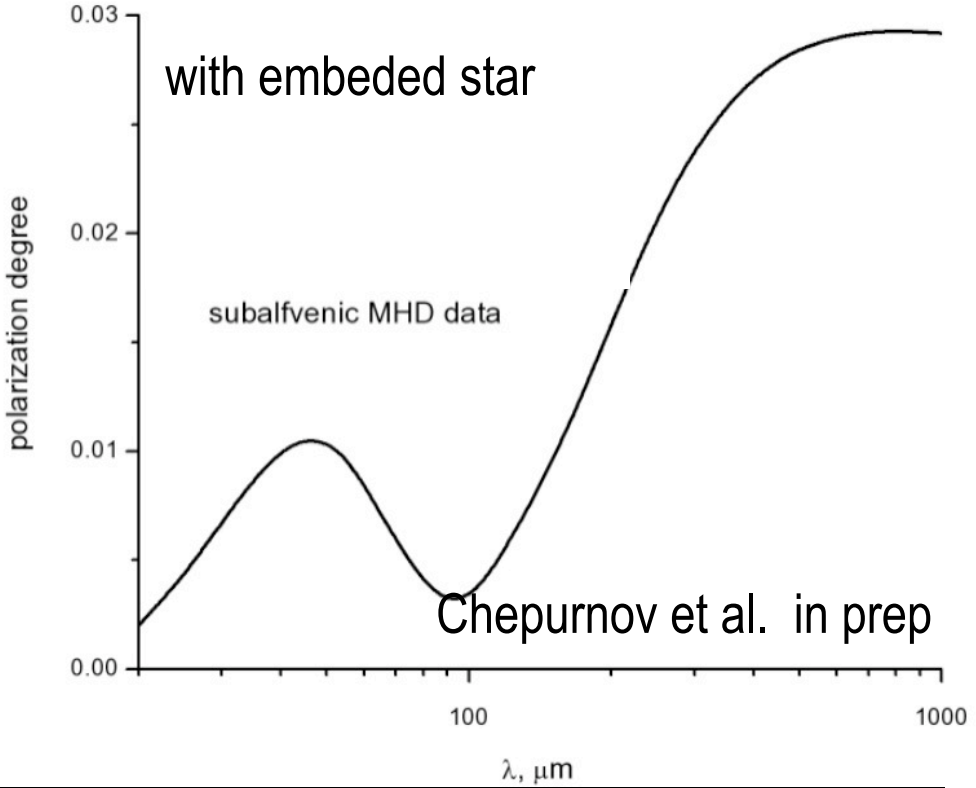
Polarized emission from aligned grains

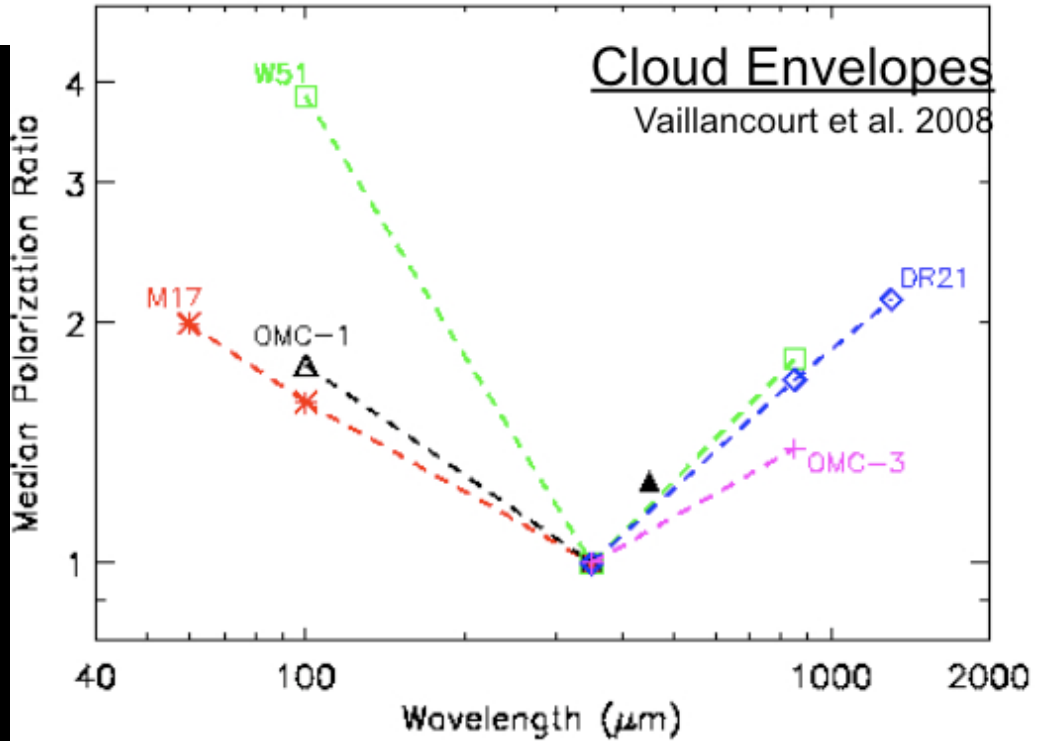


Bethell et al. 2009

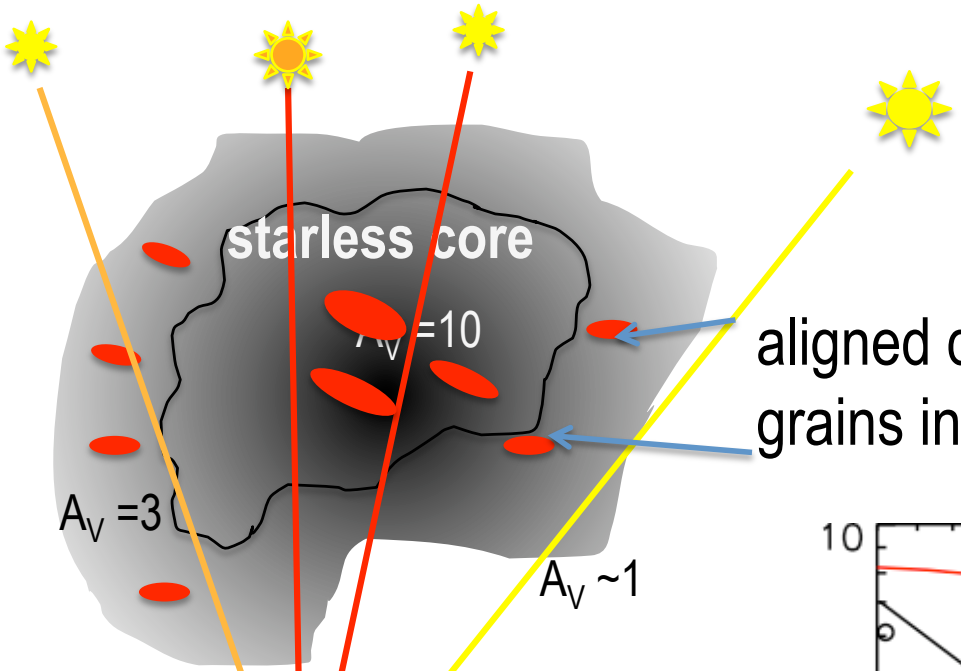


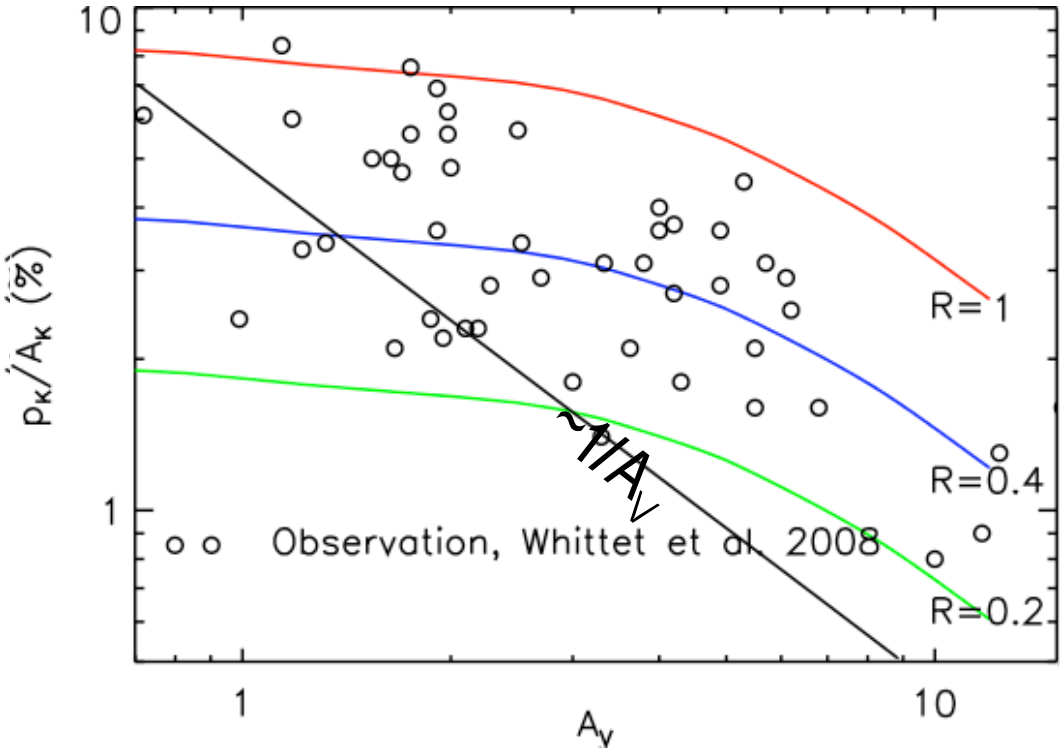



with embeded star
subalfvenic MHD data
Chepurnov et al. in prep
polarization degree
0.03
0.02
0.01
0.00
100
1000
λ, μm

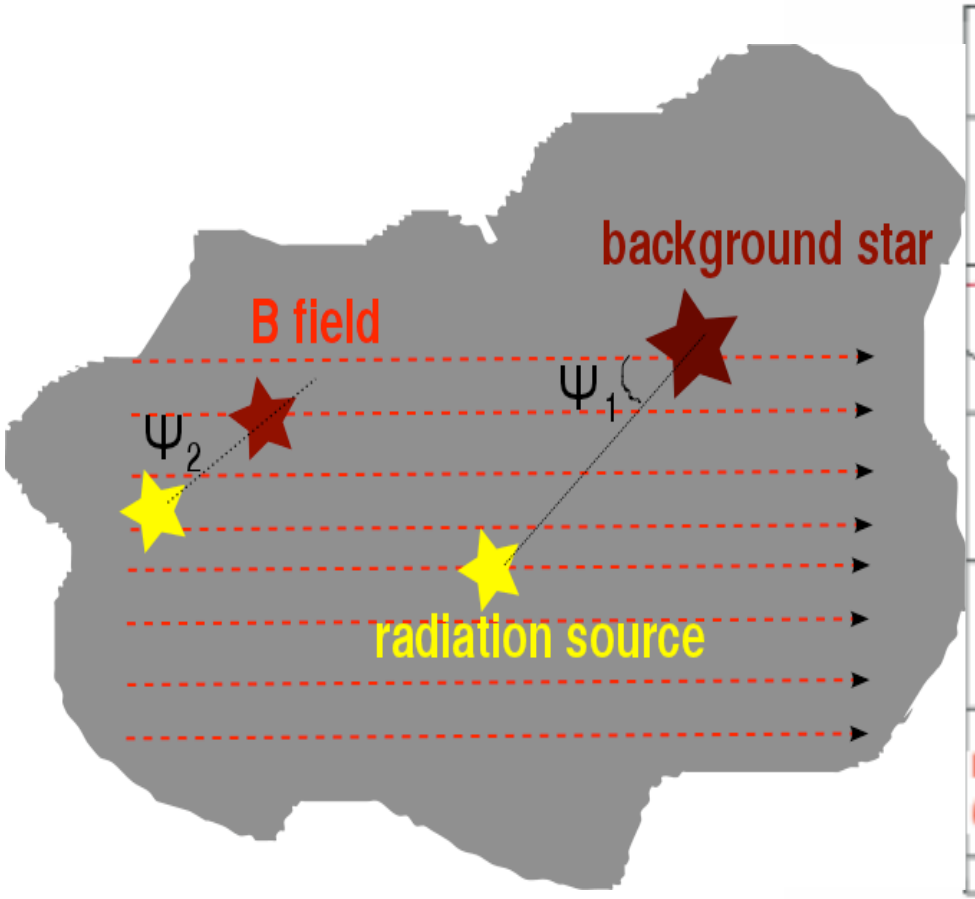

Cloud Envelopes
Vaillancourt et al. 2008
W51
M17
OMC−1
DR21
OMC−3
Median Polarization Ratio
4
3
2
1
40
100
1000
2000
Wavelength (μm)

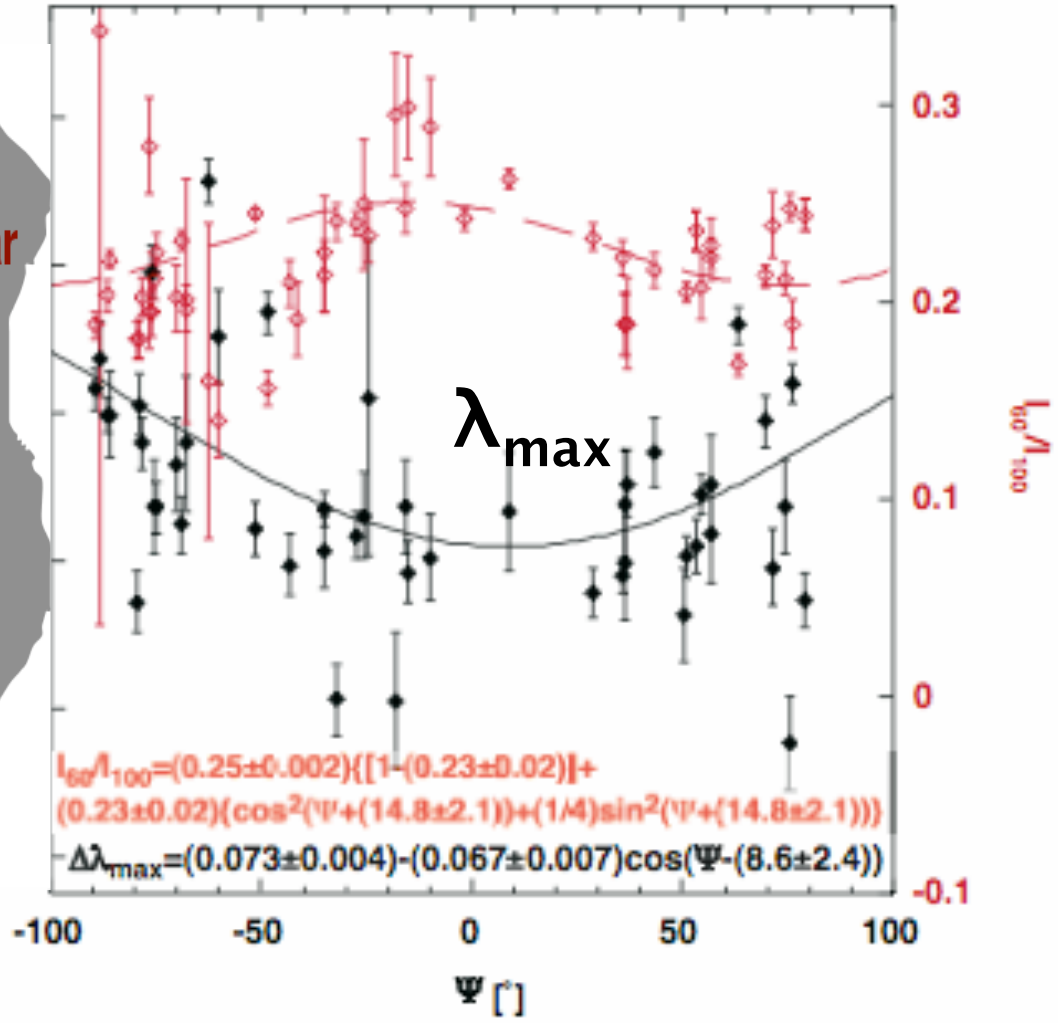
RAT alignment evidence: P vs. A_V in MCs





RAT alignment evidence: alignment vs. radiation direction

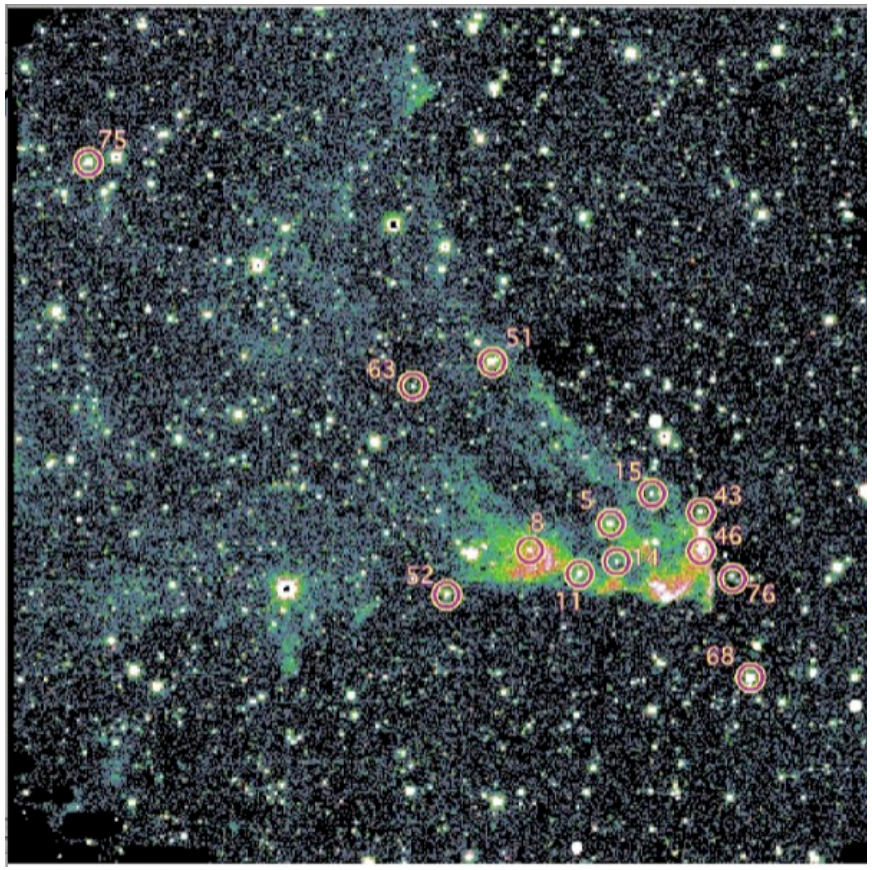


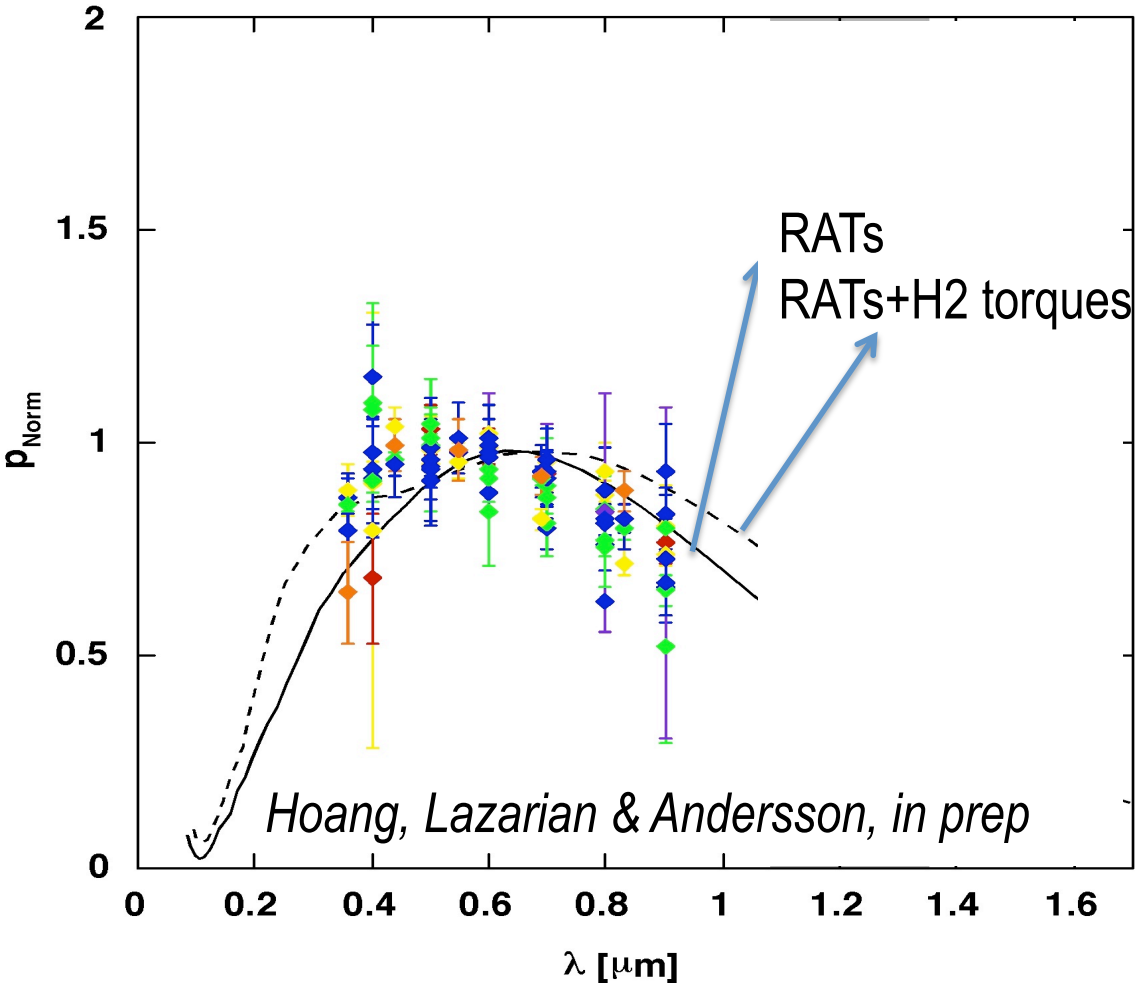


λ_{max} characterizes mean size of aligned grains.

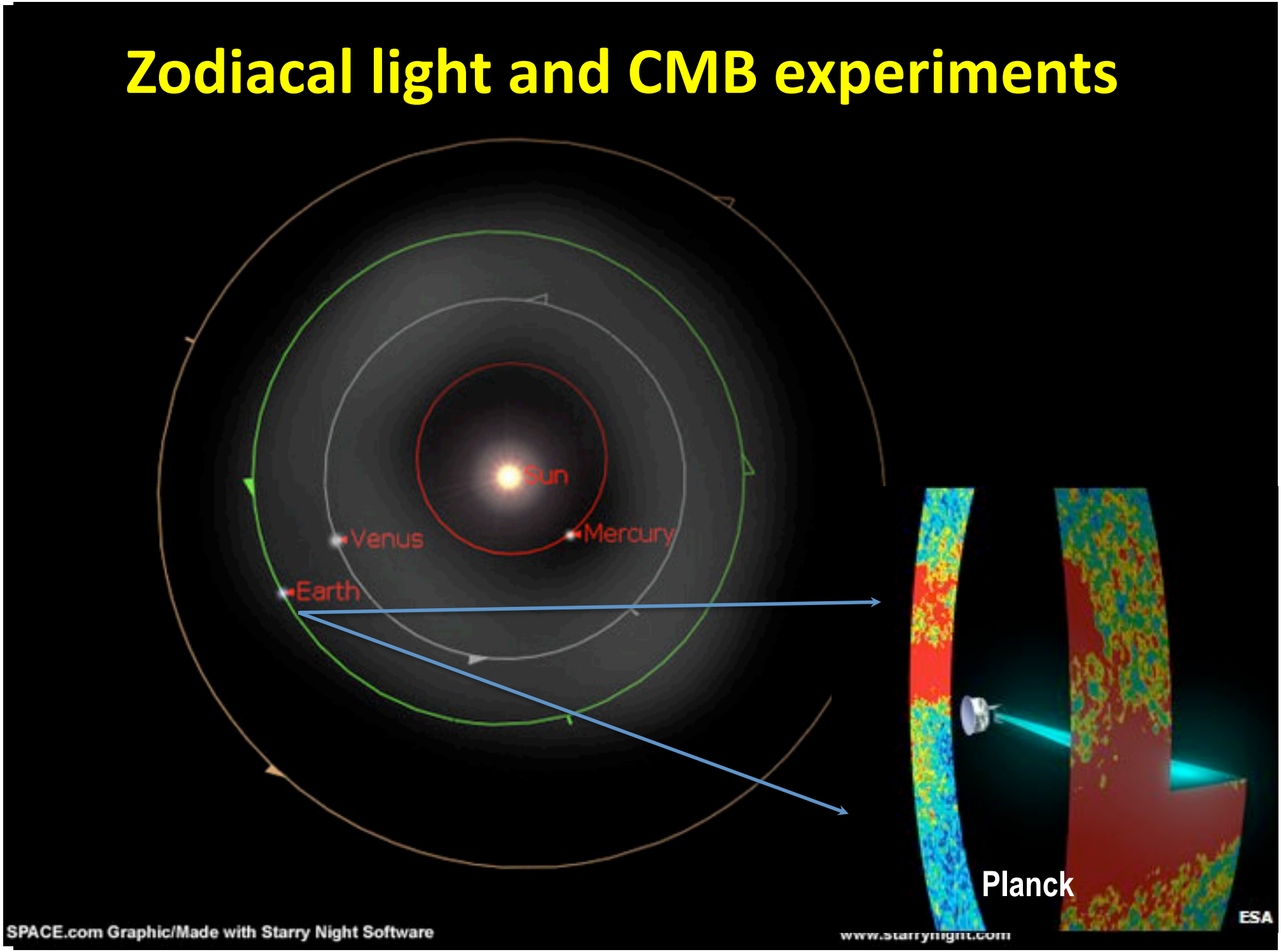
Andersson et al. 2011

Polarization in reflection nebulae

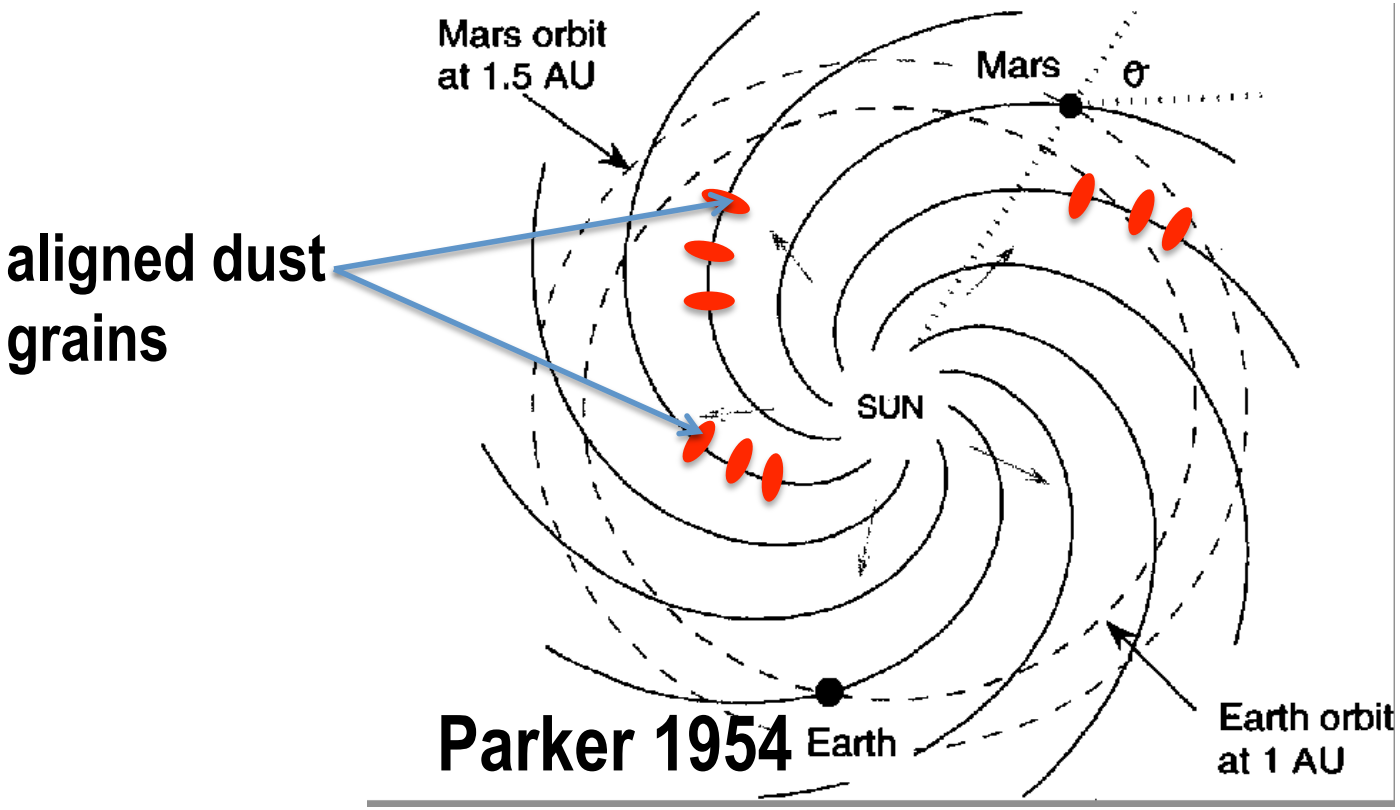




Zodiacal light and CMB experiments



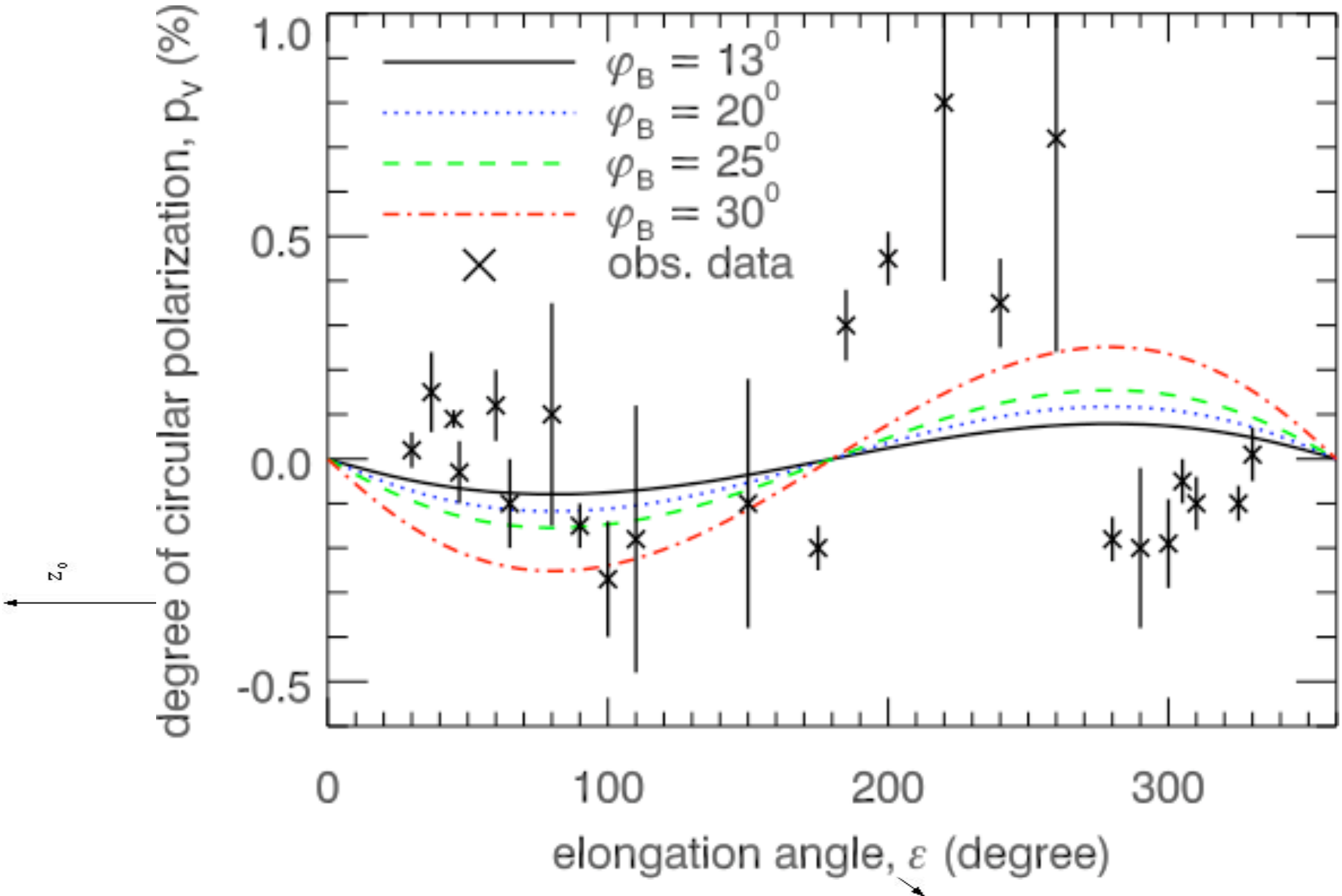
Zodiacal Light…



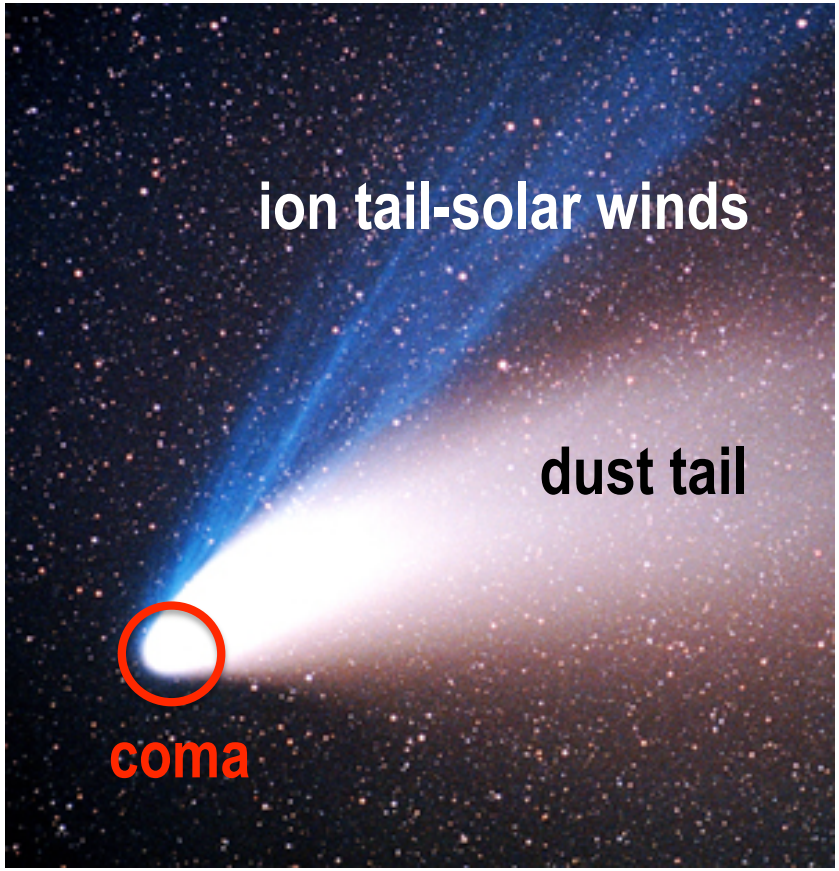
- Grain aligned in radial direction ➔ zero circular polarization
- Grain aligned with spiral magnetic field
- Scattering by aligned grains ➔ circular polarization:

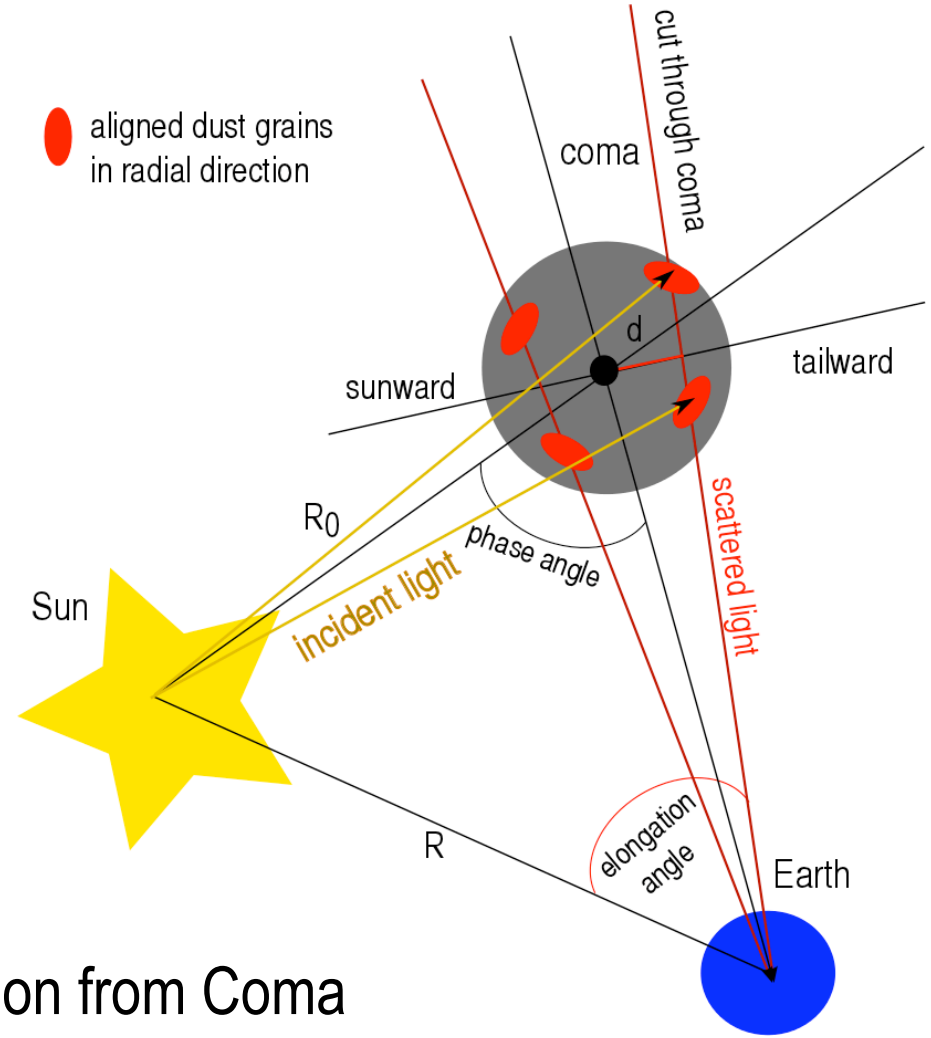
$$p_V \propto \sigma_V \left(\left[\vec{R} \times \vec{r} \right] . \vec{B} \right) \left(\vec{R} . \vec{B} \right)$$

Zodiacal Light: circular polarization



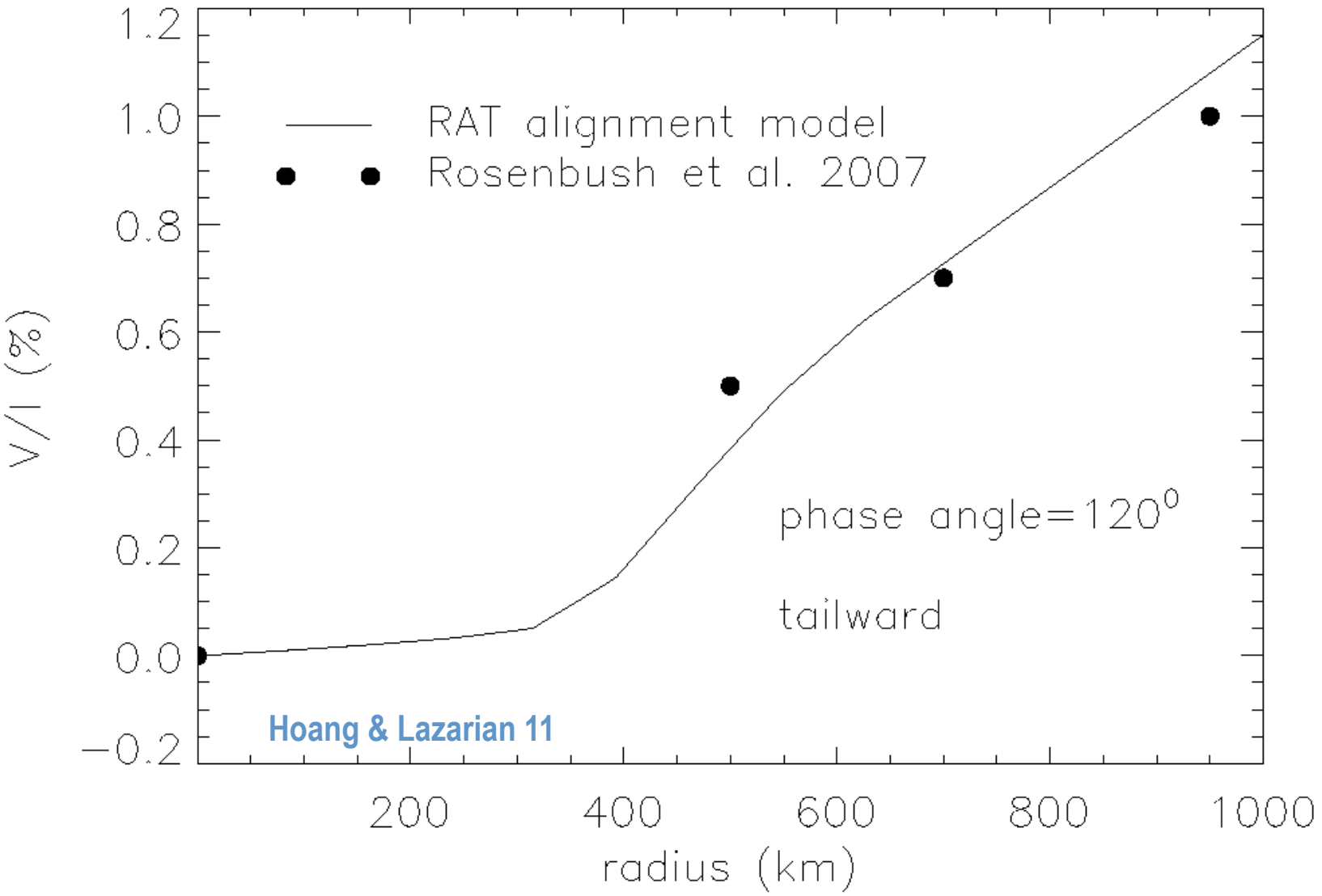
Comets: Circular Polarization





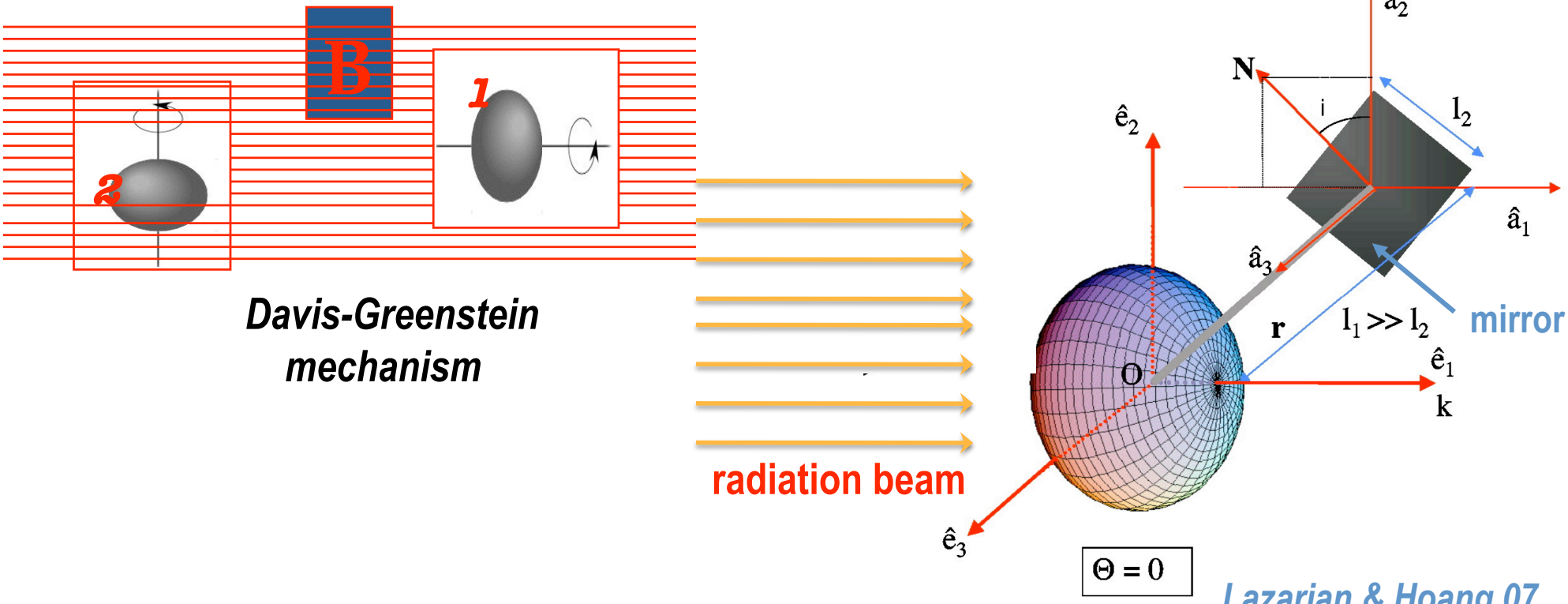
- Observation reveals circular polarization from Coma
- Dust grains should be aligned
- Grain alignment with electric field in radial direction

Circular Polarization



Summary

New analytical model of grain alignment:



Our new model of RAT alignment:

- is supported by observation data from molecular clouds, reflection nebulae.
- can predict polarization level for Zodiacal light, comets
- shows that CMB polarization should account for Zodiacal light polarization

Thank You!