Interstellar Dust Grain Alignment

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From Polarization to Magnetic Fields

To understand the influence of magnetic fields on the ISM we need to be able to measure then reliably.

All available methods have significant systematic uncertainties and most sample only part of space

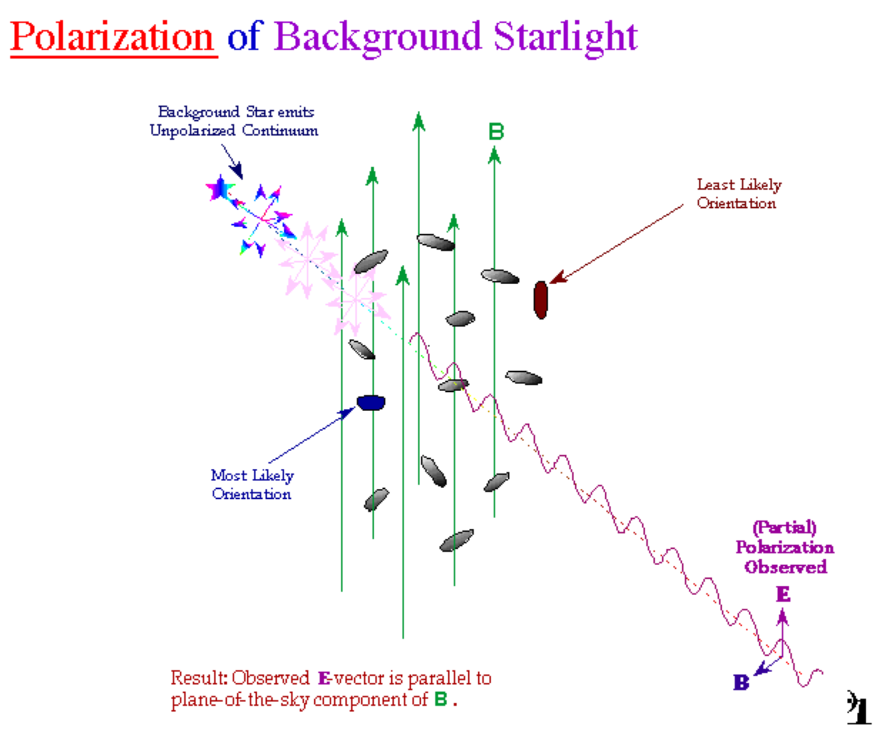
- Dust polarization relies on grain alignment and is prone to line-of-sight turbulence variations

But: Dust induced polarization is "easy" to observe and calibrate and with "recent" development in grain alignment physics it is now possible to use it quantitatively

Grain Alignment – Preliminary Physics

Light From the ISM is Polarized by Aligned Dust

Polarization by Absorption



$\lambda \sim$ UV - NIR

Understanding the mechanism of the grain alignment is required to probe the magnetic field in detail.

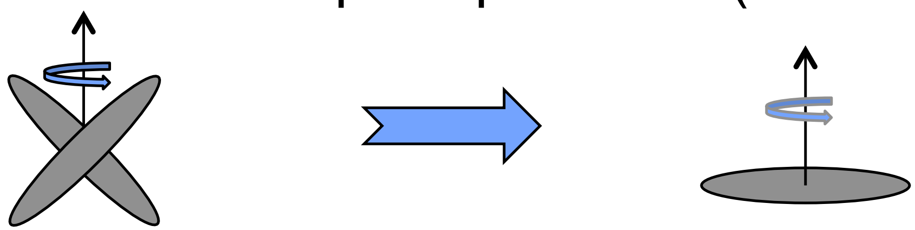
Generally easier to constrain grain alignment physics at shorter wavelengths (fewer turbulent cells, no complications from T_d and β). But, physics the same.

Bottom line: RAT established ("coupling constants" needed), but still complex.

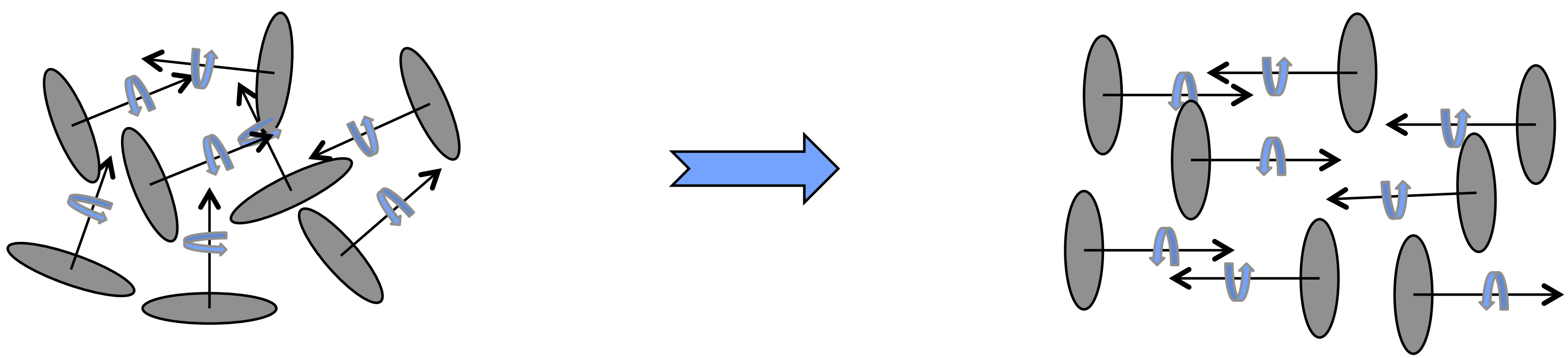
Diagrams after A. Goodman: http://cfa-www.harvard.edu/~agoodman/ppiv/

To Cause Polarization the Grains Must Line Up

- A dust grain in interstellar space will initially rotate around a random axis (and wobble).
- To cause polarization an individual grain first has to align its rotation with one of its “principal axes” (so it has a fixed projection)

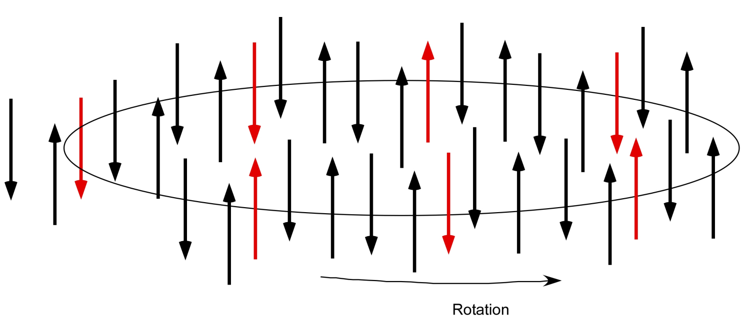


- Then, “all” the grains have to line up along a common direction



Preamble: Unpaired spins in a rotating body yield magnetization

- A paramagnetic grain (unpaired spins in bulk; e.g. silicates) can minimize its energy, **while conserving angular momentum**, by trading solid body rotation for spin-flips
  - – Barnett effect (inverse of the "Einstein-de Haas effect" – known in the lab.)
  - – Magnetization in equilibrium
- A grain rotating around a non-symmetry axis nutates , thus changing the direction of rotation
  - – Nutation is often faster than the equilibrium time for the Barnett effect
  - > Internal Alignment by dissipation (Purcell 1979)
- No unpaired spins (==diamagnetic, e.g. carbon grains) ⇔ no magnetization



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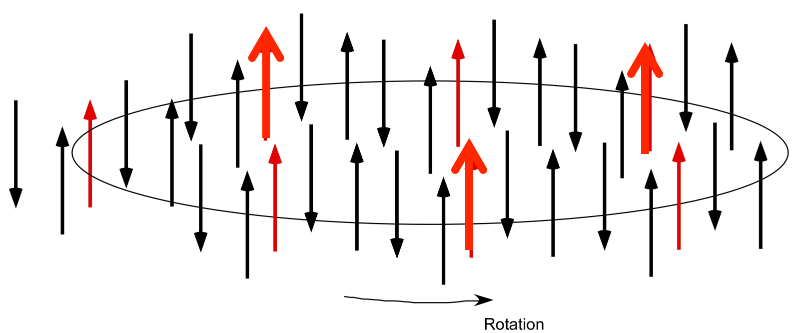
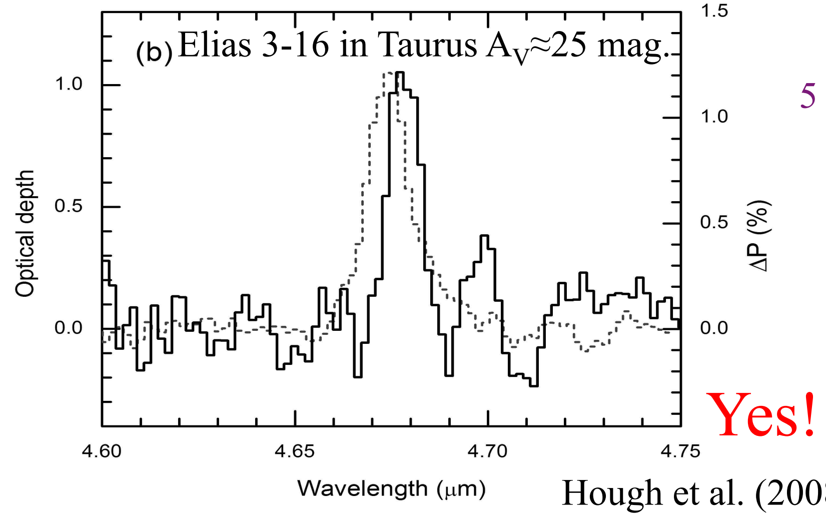


Alignment Mechanisms

Paramagnetic Alignment - Fails

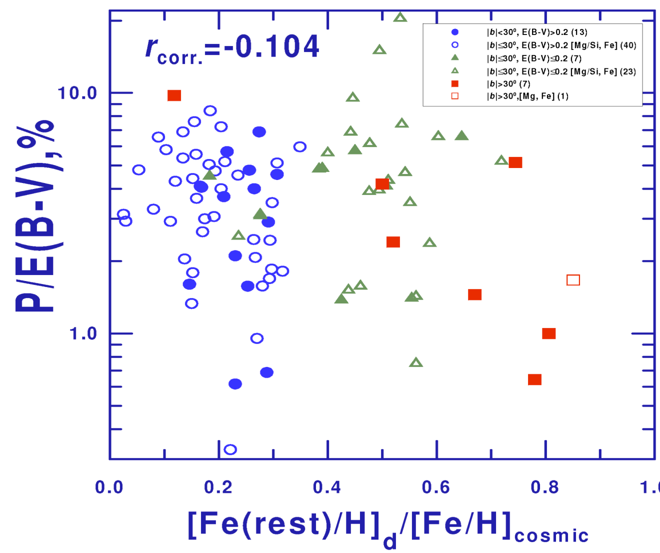
- Are dust grains aligned at depths into the cloud where CO ice can survive (A_V>6-10)?
  - At such opacities:
    - $T_{spin}=T_{gas}\approx T_{dust}$ (ignoring RAT)
    - No FUV radiation No H_2 formation or photoelectrons



Yes!

Hough et al. (2008)

- There is no correlation between the amount of “magnetic **solid** iron” on the line of sight and fractional polarization

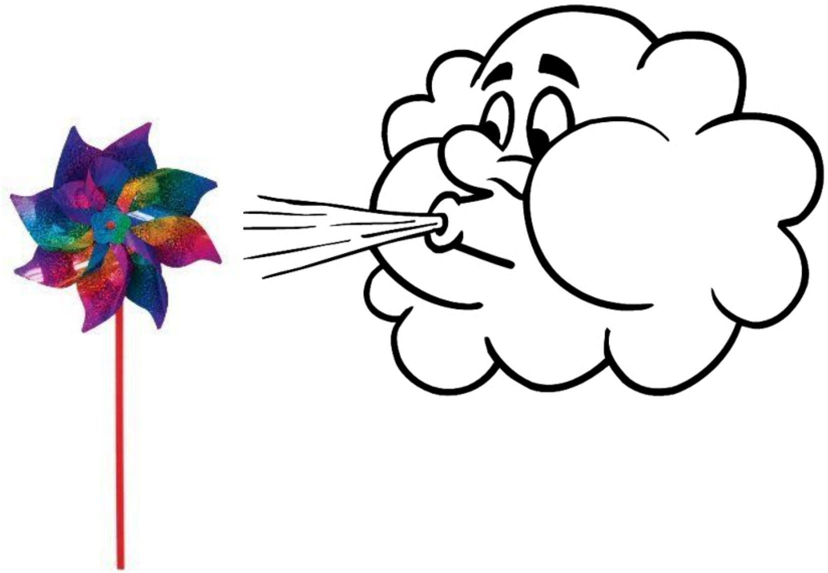


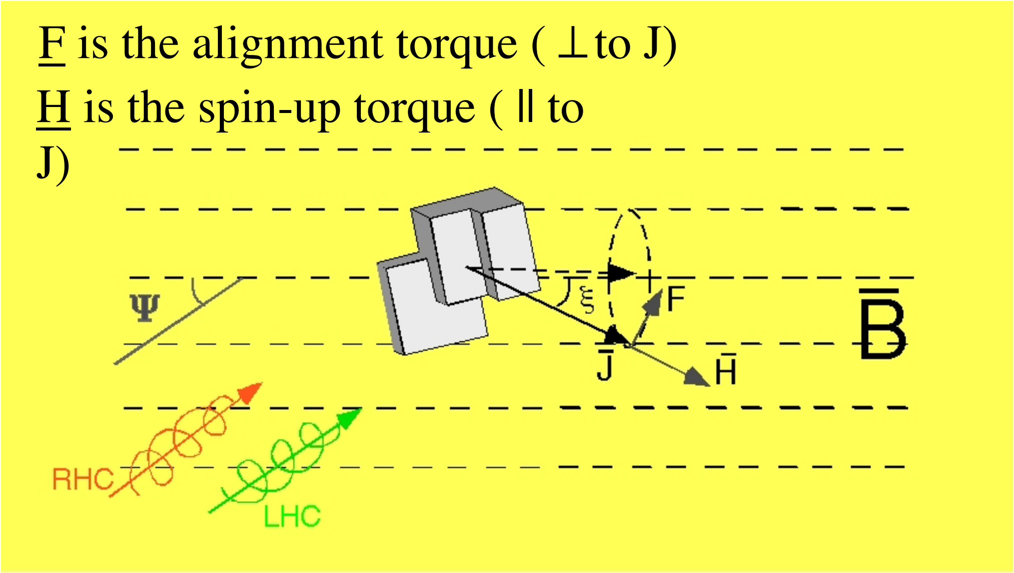
No!

Voshchinnickov et al. (2012)

Radiation Aligns the Grains

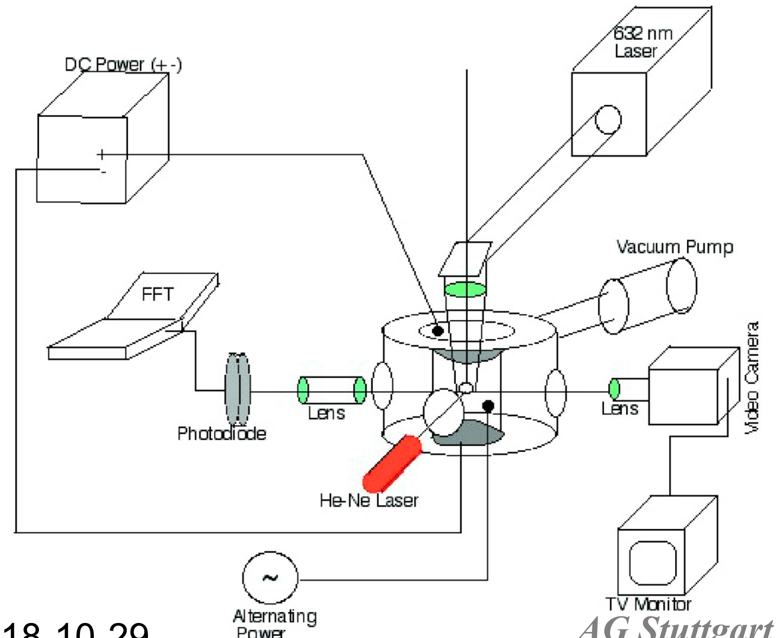
- Light consists of right- and left-hand circularly polarized components
  - impart torques to irregular grains and make them spin
    - λ<d (where d is the grain diameter)
- The Barnett effects magnetizes paramagnetic grains (silicates) which then aligns their angular momentum vectors with the B-field
- For [very] strong and anisotropic radiation: Alignment with k-vector
- Radiative Alignment Torque theory (e.g. Lazarian & Hoang 2007)

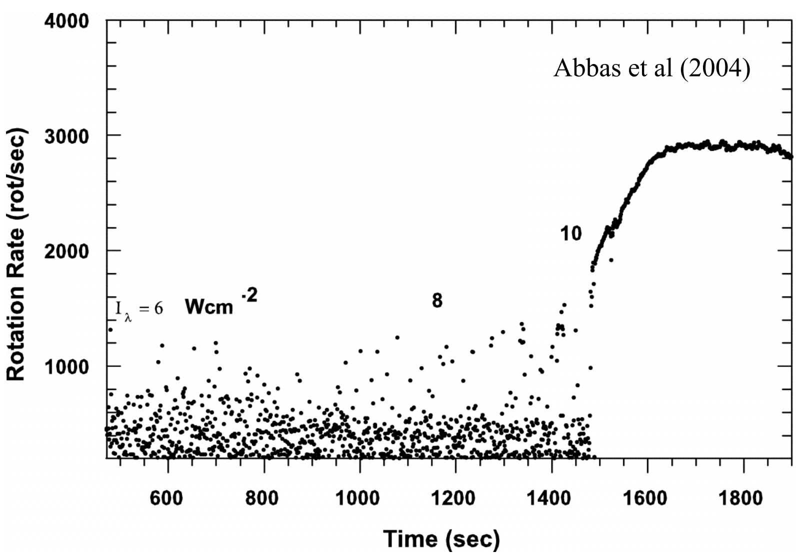




Radiative grain spin-up works in the lab

- Laboratory experiments on the rotation of individual micron/ submicron-sized, non-spherical dust grains (Abbas et al 2004) show that the grains are spun up by radiation
- The grains were
  - levitated in an electrostatic balance.
  - illuminated by laser light
  - the grain rotation was measured from the scattered light.





RAT Alignment – Tests and Consequences

Radiative Alignment Torque (RAT) Alignment ISM implications

- Fundamental prediction:

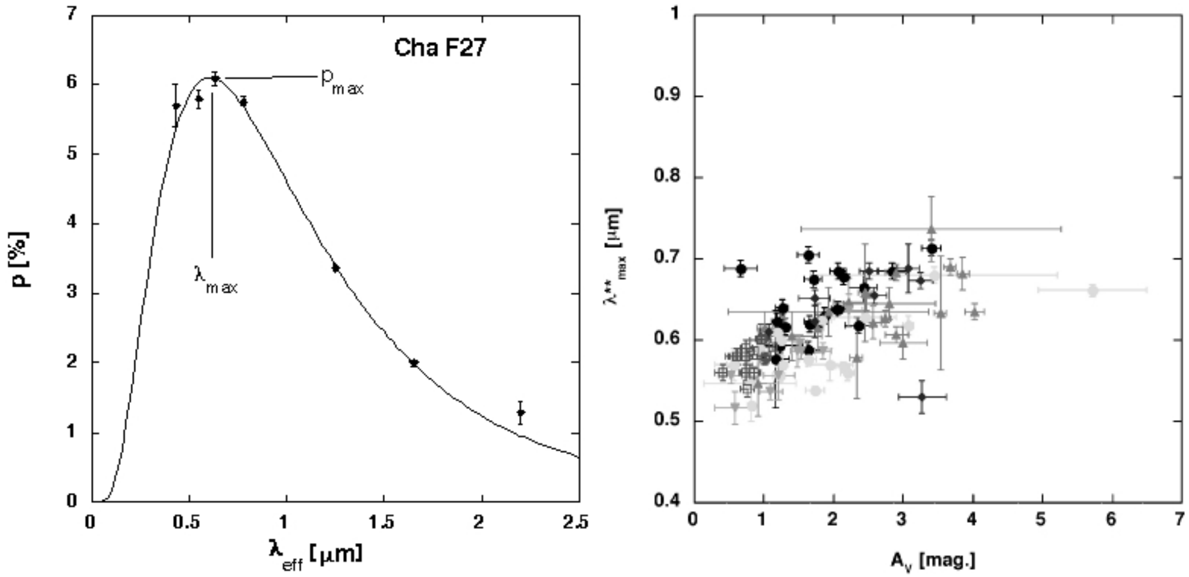
  Paramagnetic grains are aligned if exposed to an anisotropic radiation field with $\lambda<2a$

- Observational predictions:
  - The alignment efficiency will vary with radiation field intensity
  - The size distribution of aligned grains will vary with the radiation field
    - For the general ISM grain alignment will fail for a < 912Å/2
    - For moderate opacities the polarization curve will move to the red with A_V
    - For deep star-less cores there will be a depth beyond which no alignment takes place
  - The alignment will depend on the angle between the magnetic and radiation field anisotropy
  - For strong, anisotropic radiation fields, the reference direction changes from the magnetic field (B-RAT) to the radiation direction (k-RAT)
  - Carbonaceous grains are not susceptible to (B-RAT), but can be aligned with the radiation direction (k-RAT)
  - H_2 formation can enhance grain alignment

Grain Sizes and Gas Collisions

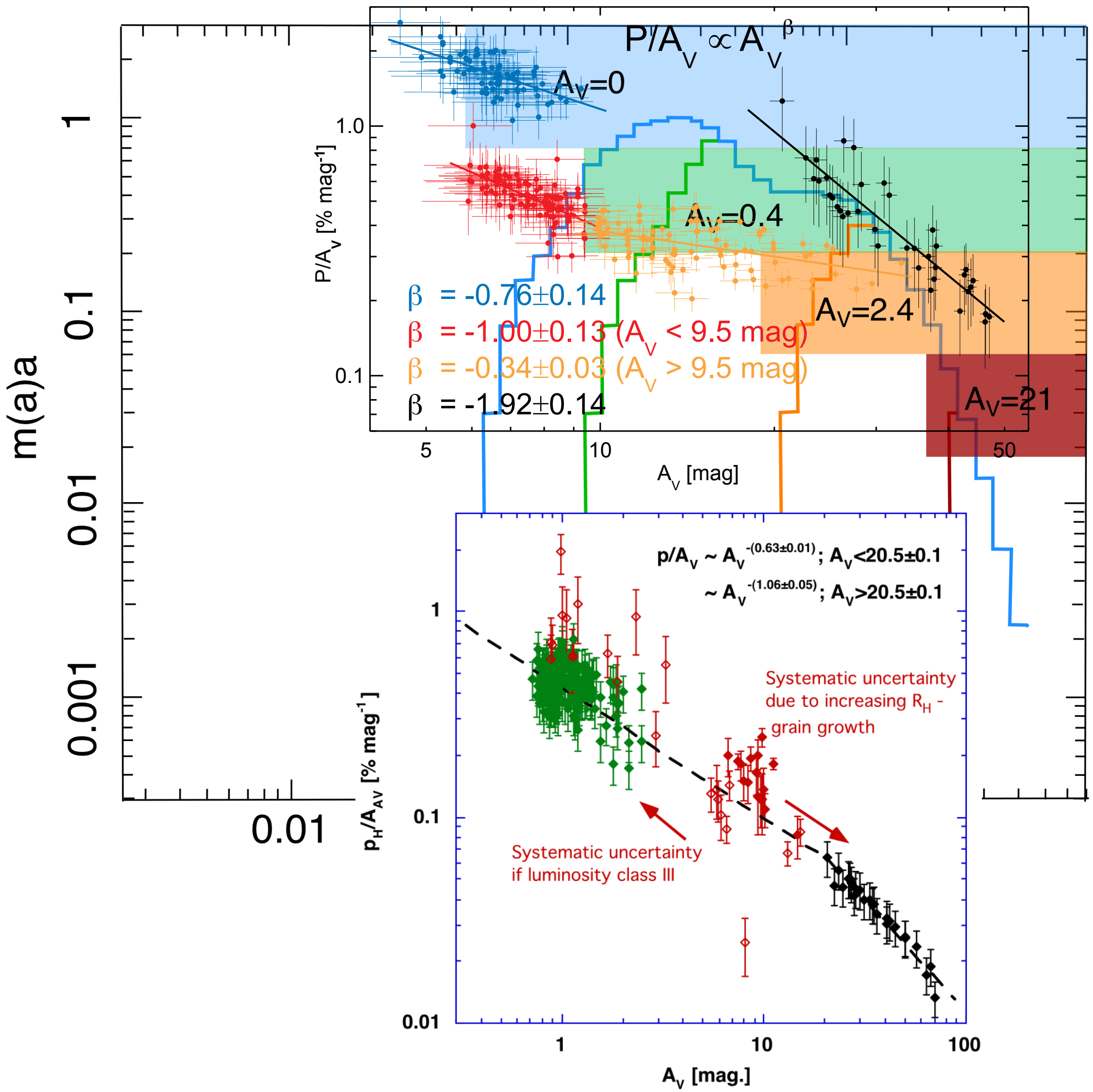
RAT Alignment - parameters

- Grains can be aligned if $\lambda<2a$
  - The polarization curve is a convolution between the radiation SED and the grain size population
    - λ_{max} is a good tracer of the average size of aligned grains
  - In the diffuse ISM the smallest aligned grain is [usually] determined by the Lyman limit (912Å) – i.e. a_{min}=0.045μm
  - Reddening moves a_{min} and hence λ_{max} to larger values



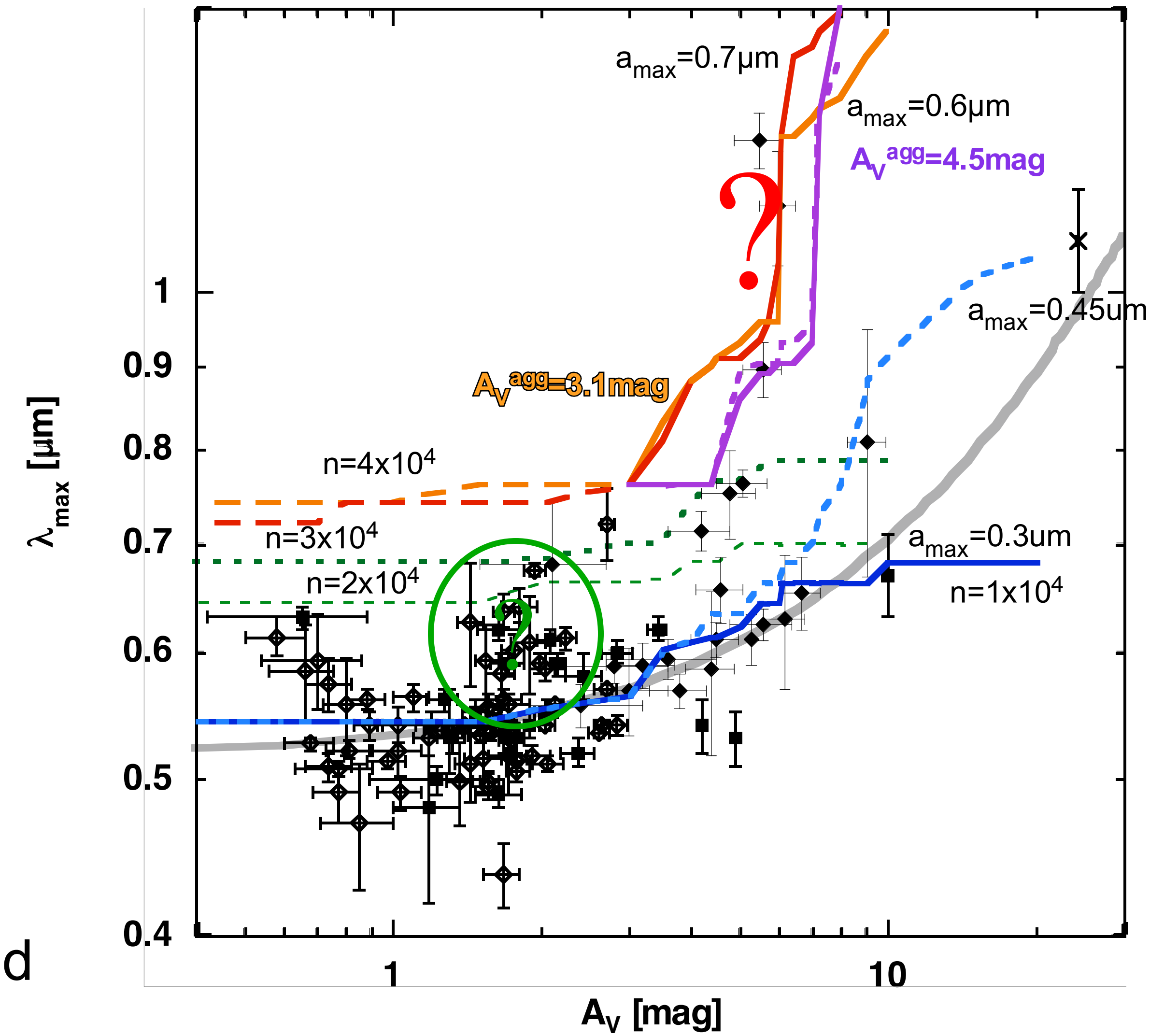
Grain alignment is lost deep into star-less clouds

- Because of [refractory] elemental abundance limitation, an upper grain size cut-off at ~1-2μm is expected (poorly constrained)
- For star-less cores this should mean that at some opacity, [almost] no grains are present that can couple to the remaining radiation field. When this happens $p/A_V \sim A_V^{-1}$
- See in several clouds (Alves et al. 2013, Jones et al. 2015, ALV2015)



Polarization Curve for Gas Density and Grain Size

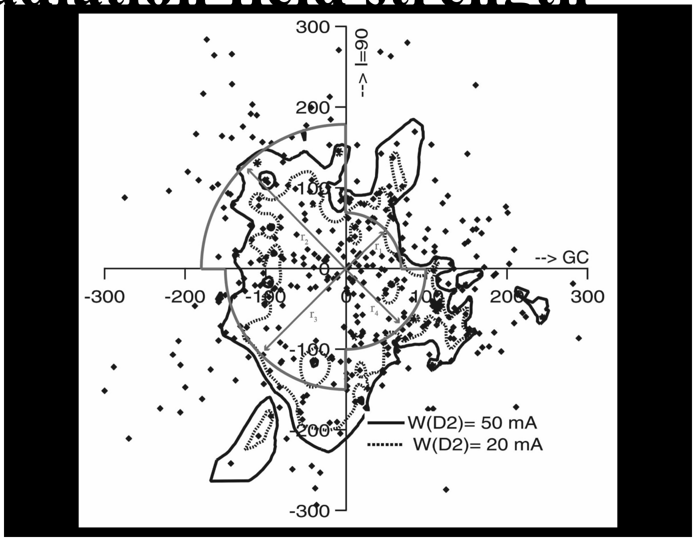
- The peak of the Serkowski curve is sensitive to radiation field color, grain sizes, and the gas density
  - Pol. curve is a convolution of grain size and radiation field
  - Disalignment is faster for smaller grains
- Compare $p(\lambda, A_V)$ to *ab intio* RAT models
- We see radiation color effects, grain growth, and collisional disalignment

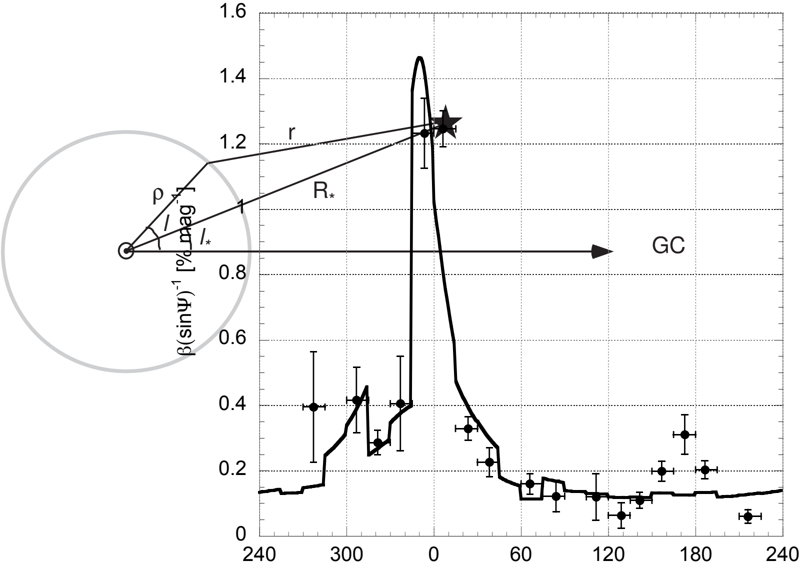


Radiation Field Strength
Alignment Efficiency and k-RATs

The grain alignment varies with radiation field strength

- The Local Bubble wall act as a screen through which we can see the aligned grains. The wall can be approximated as a cylinder of radius ~150pc
  - Lallement et al (2003) have mapped the geometry of the bubble
  - Berdyugin et al (2014) has measured polarization by the dust in the LB Wall
- Grain alignment in the LB wall reflects the known OB associations with d<500pc

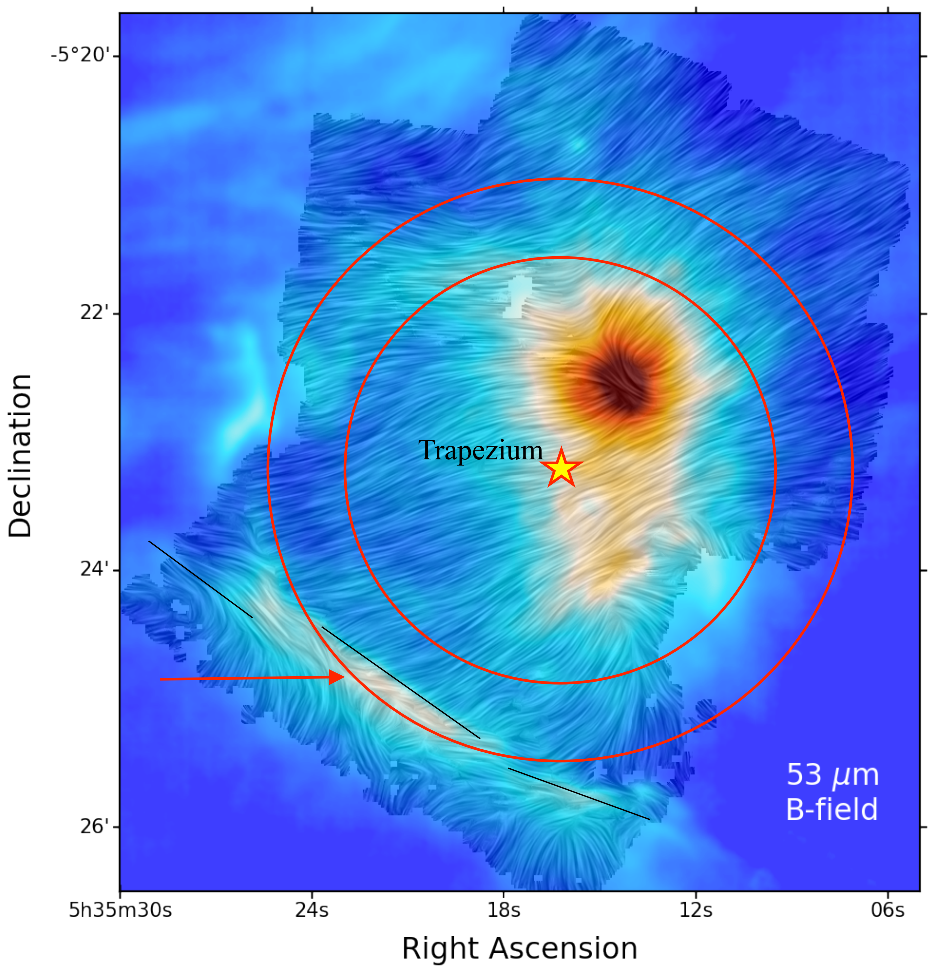


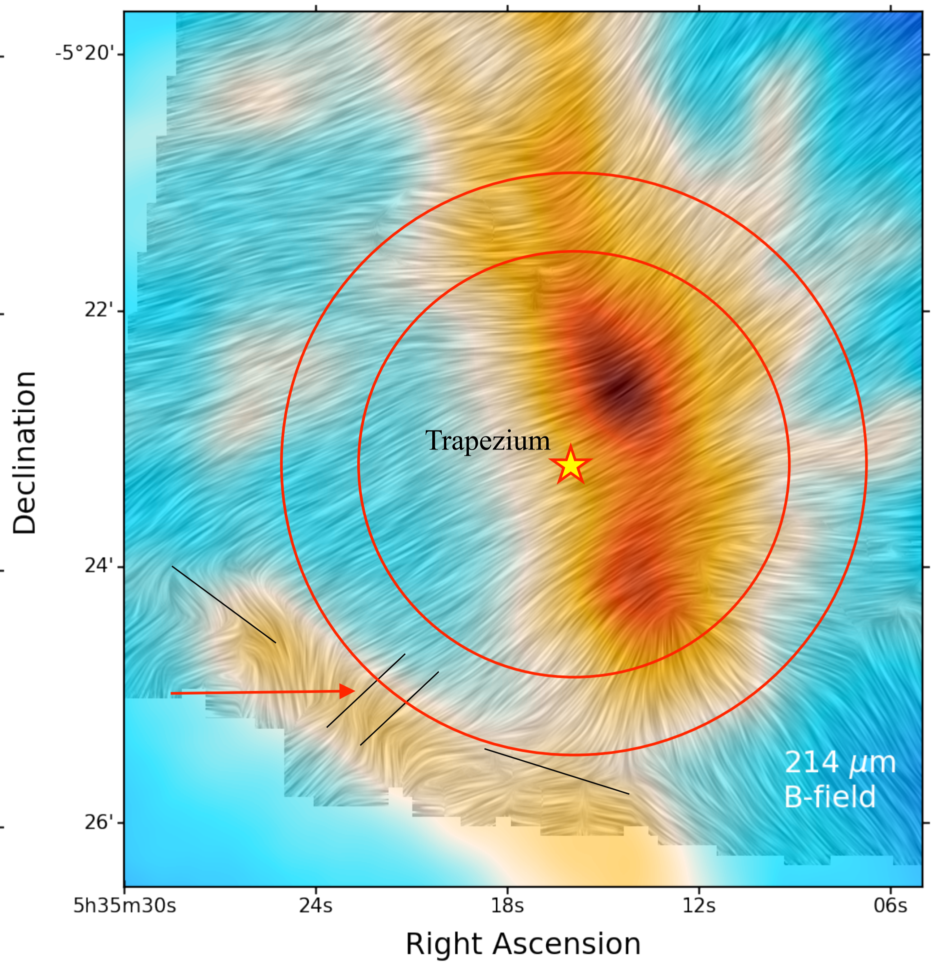


Pol. can trace the radiation field strength, and with multi-band also its color

Grain Mineralogy

k-RAT Alignment in the Orion Bar (?)



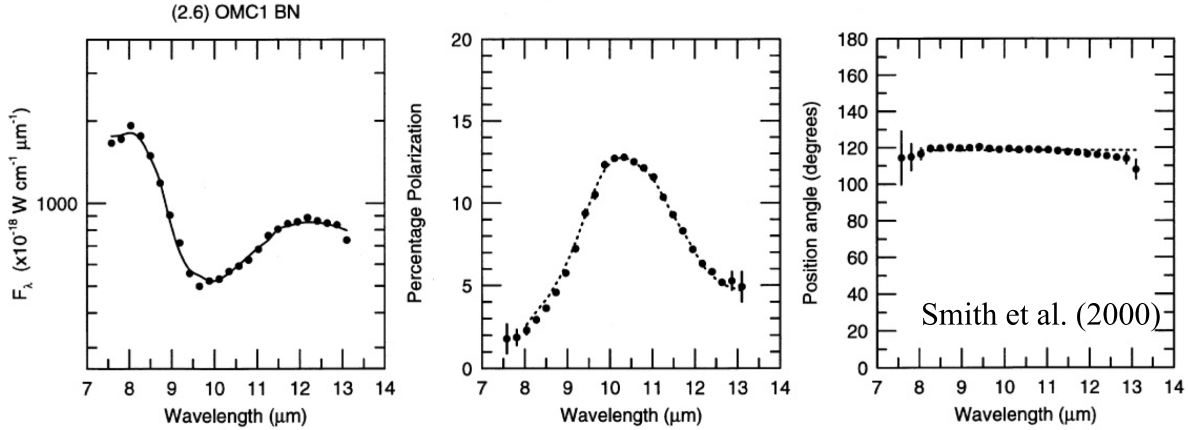


If the radiation field is strong and anisotropic the alignment is along the radiation
k-RATS are more efficient for larger grains (and higher radiation fields)

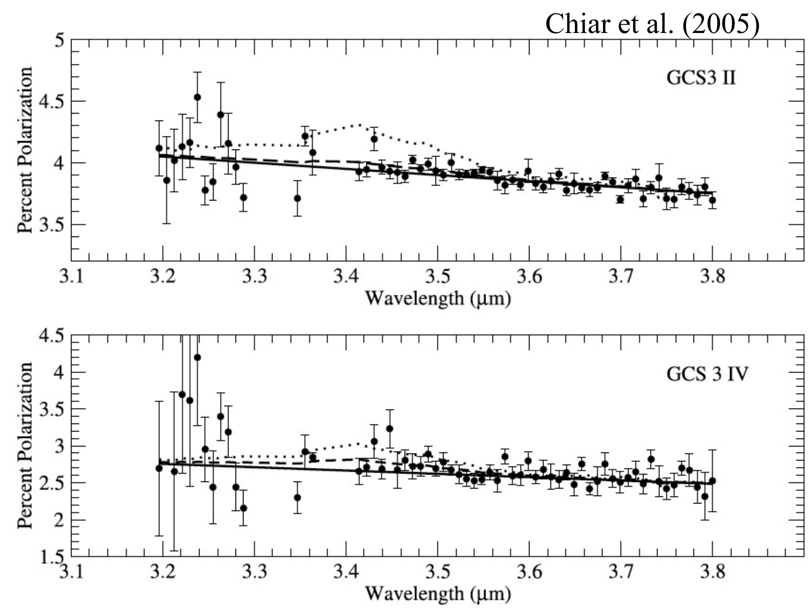
Grain Mineralogy

What about Carbon grains?

- The 9.7 μm silicate feature shows strong polarization

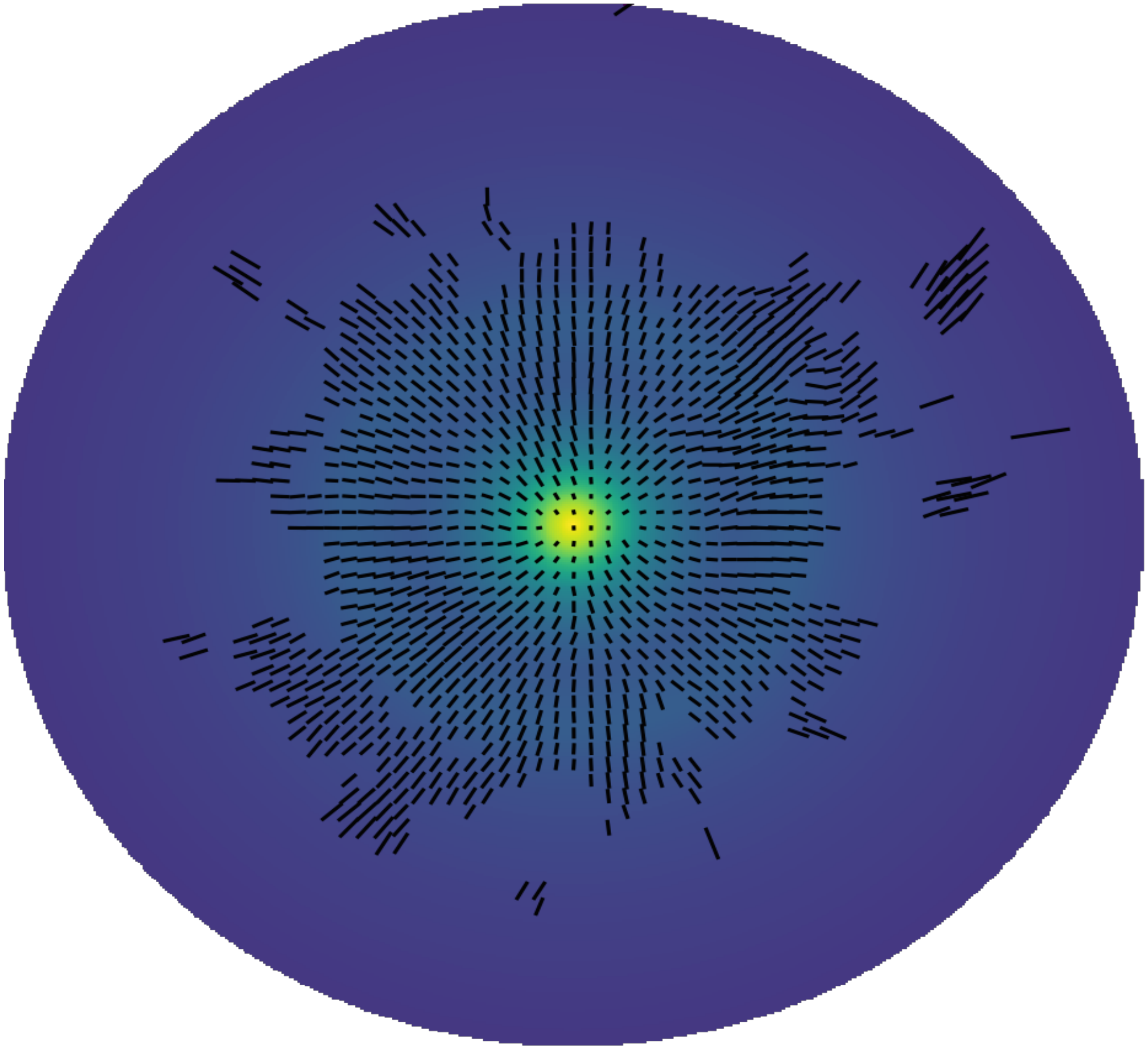


- The 3.4 μm aliphatic CH feature is not polarized
  Solid carbon exposed to UV and H atoms **will** form aliphatic bonds on the surface
- Can carbon grains be aligned?



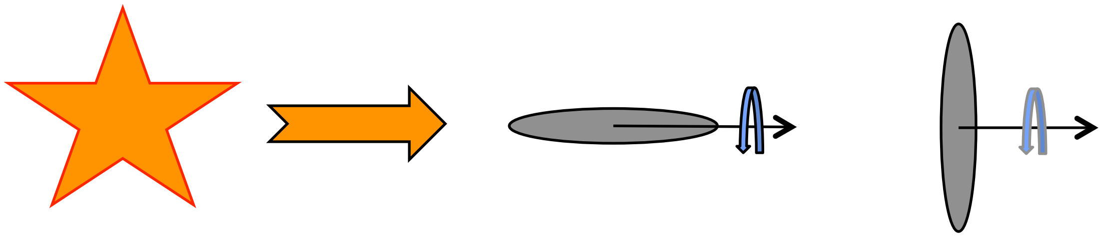
Alignment of Carbonaceous Grains

- To test carbon grain alignment we observed IRC+10216 with SOFIA/ HAWC+
- The dust in the envelope of IRC+10216 is fully carbonaceous
- The IRC+10216 envelope is radially polarized

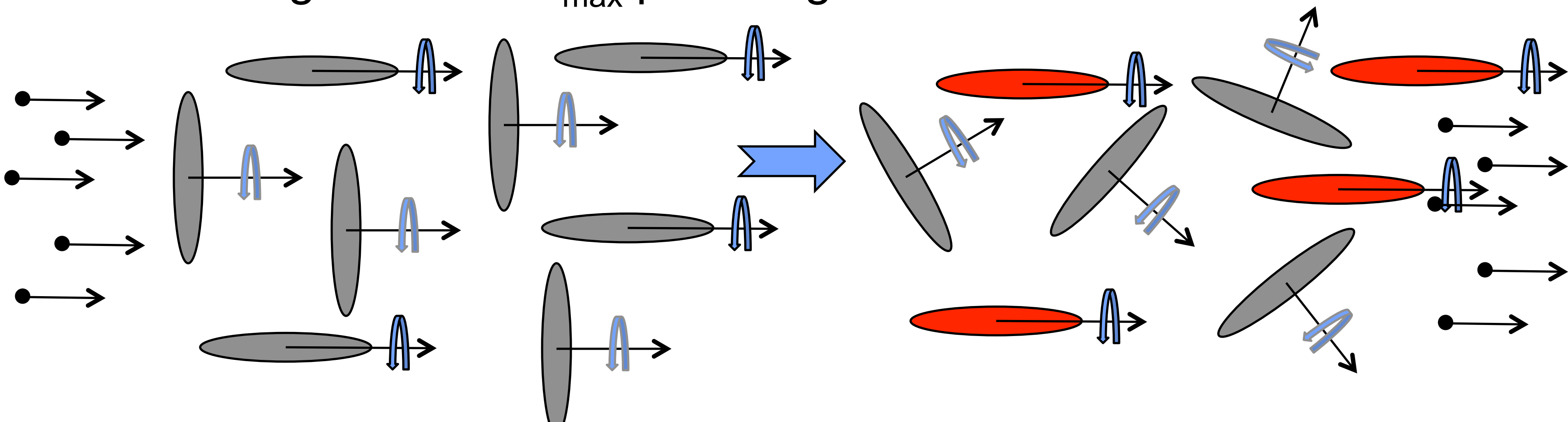


Alignment without Internal Alignment

- Grains without Internal Alignment (e.g. carbonaceous), but in an intense, directed, radiation field will have weak k-RAT attractors
  - With I_{max} parallel and perpendicular to the radiation field

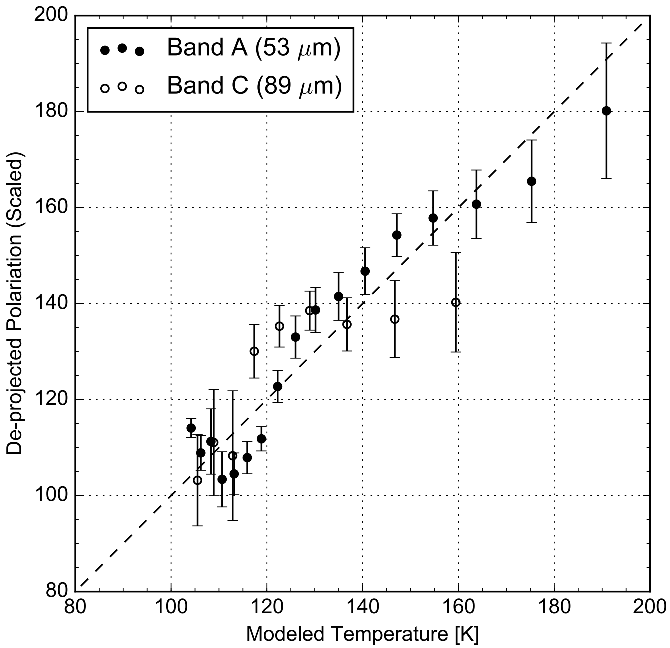


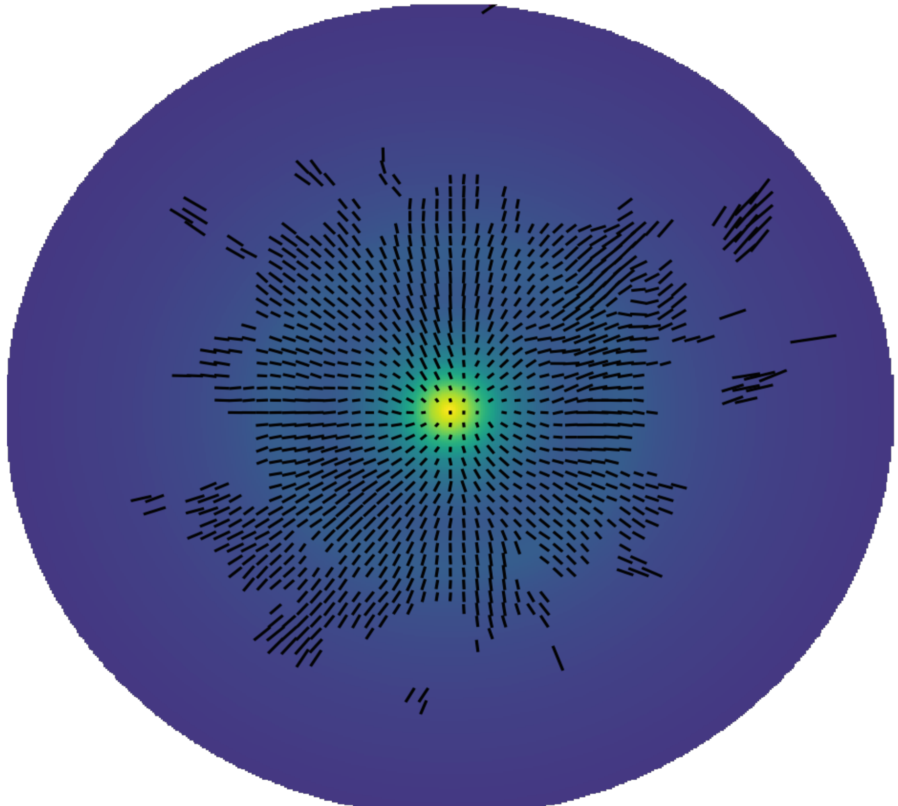
- In AGB star winds there is a gas-grain drift, and the collision rate will be higher for the I_{max} parallel grains



Radiation Aligns Carbonaceous Grains

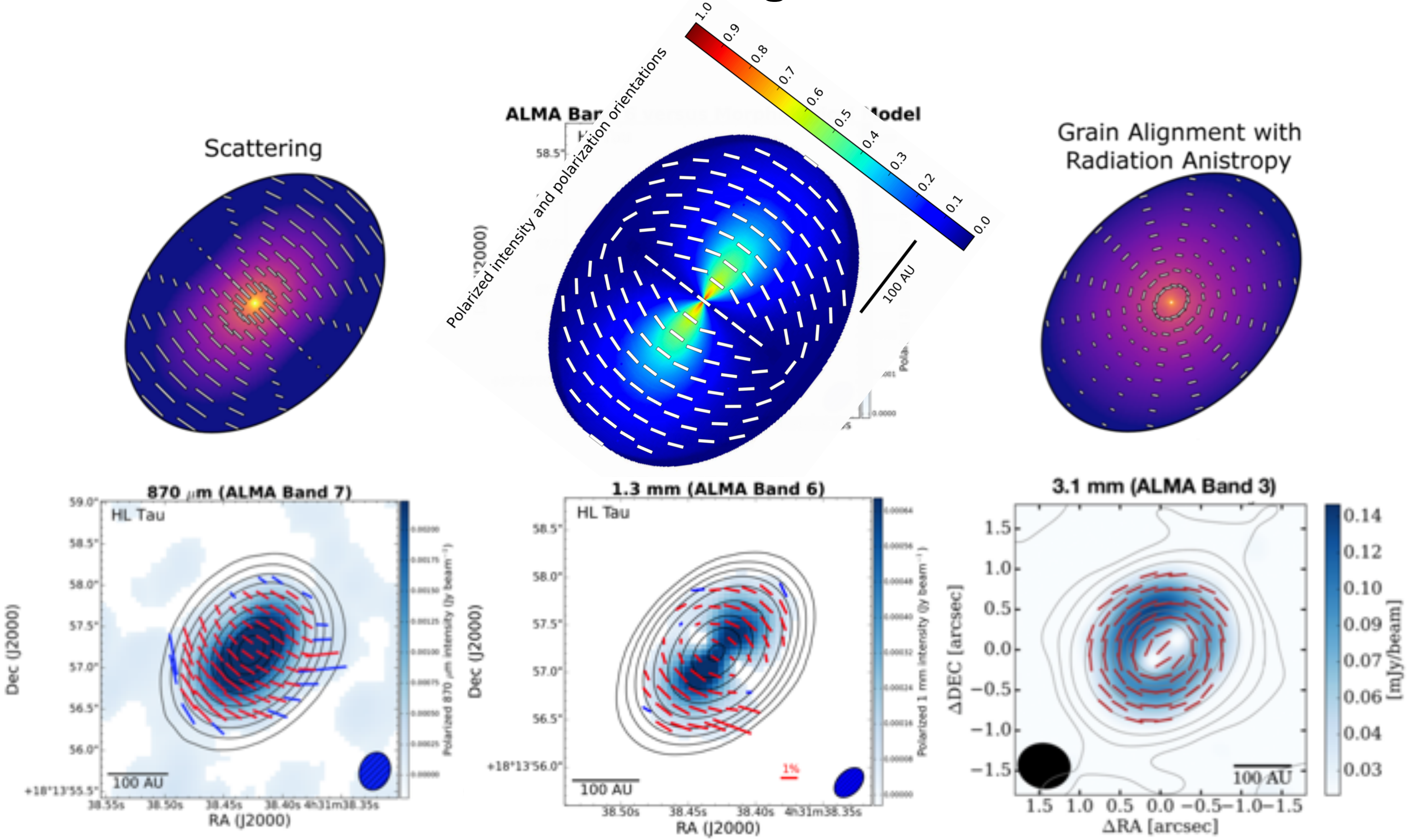
- The IRC+10216 envelope is radially polarized
- The amount of polarization follows the dust temperature
- Supports k-RAT alignment of carbon grains
  and the general concept of k-RAT (alignment along radiation field)





And all of them can happen in small areas…

New Best Friend: Multiwavelength Obs



Kataoka et al. 2017, Stephens et al. 2017

Slide courtesy of L. Looney

Summary

- Radiative Alignment Torque theory provides a powerful paradigm for grain alignment
- Provides a number of quantitative predictions
- Under this paradigm, polarimetry can be used to probe not only magnetic fields, but ISM environments and dust grain characteristics
  - Grain sizes and growth
  - Grain shapes
  - Grain mineralogy
  - Radiation field strength and color