Interstellar Grain Alignment

-

Q: *The String-Theory of Astrophysics?**

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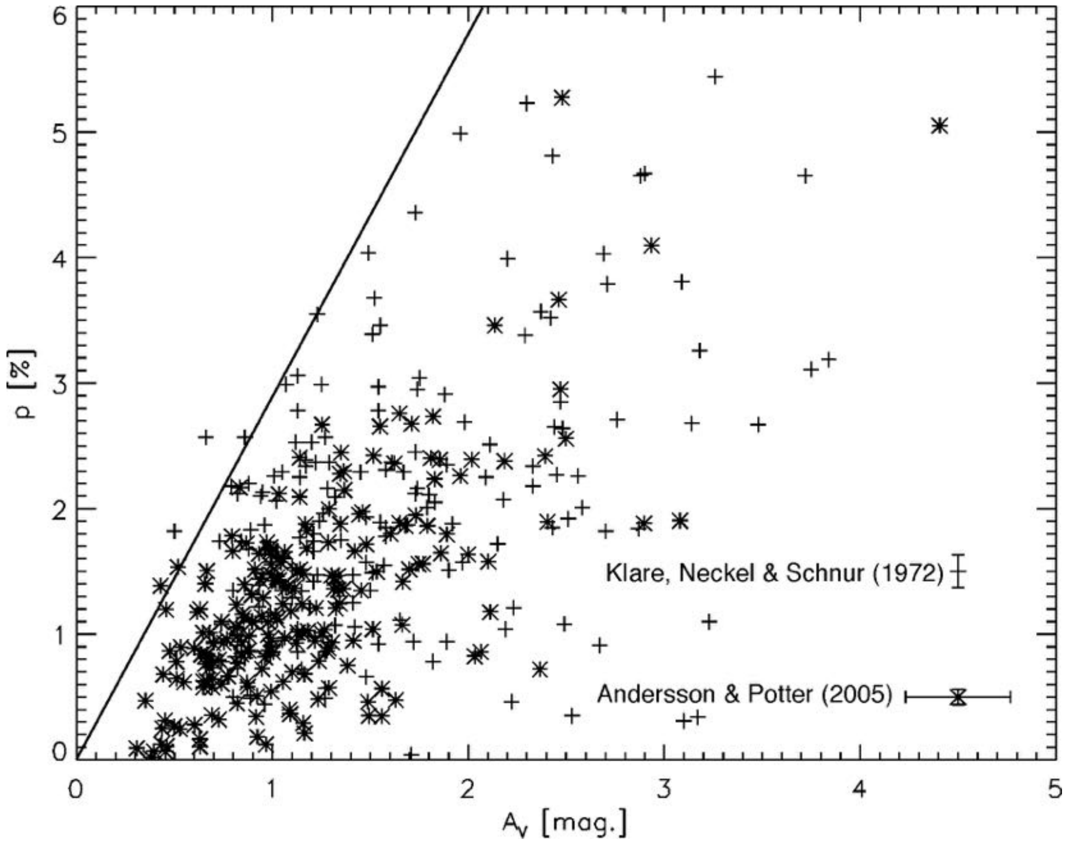
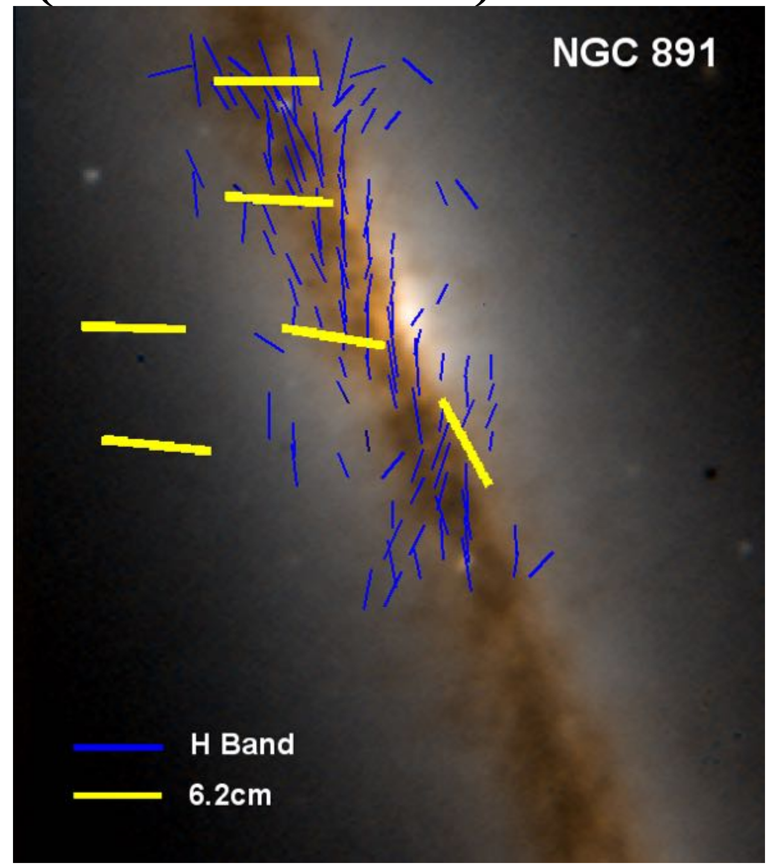
Thanks to: S. Potter, J. Vaillancourt, D. Clemens, T.J. Jones, M. Charcos-Llorens, S. Shenoy, V. Piirola, A. Lazarian, T. Hoang, etc.

* A: Not anymore

O/IR continuum polarization is due to asymmetric dust grains, aligned with the magnetic field (Hiltner 1949b!!)





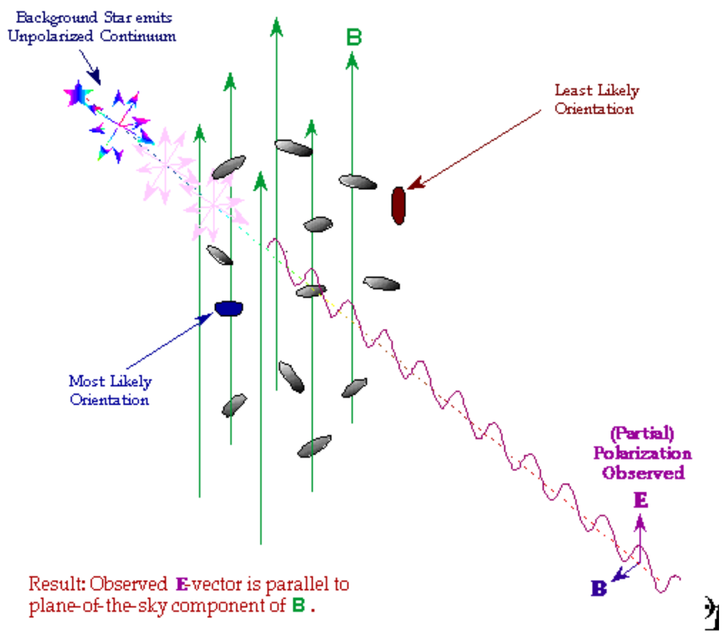
- The upper envelope of the polarization is correlated with the column density
- The P.A. of O/IR polarization is related (±90˚) to that of synchrotron radiation

But the detailed physics of the grain alignment has been unsettled

Why is the light Polarized?

Polarization by Absorption

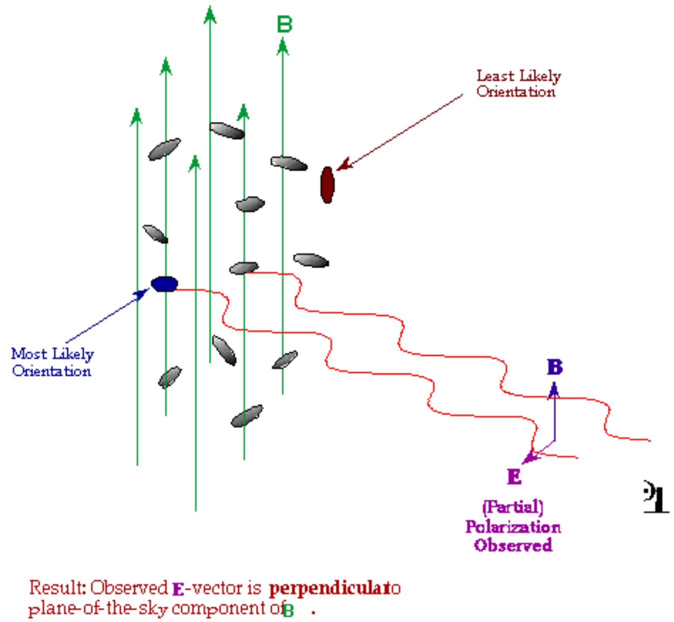
Polarization of Background Starlight



λ ~ UV - NIR

Polarization by Emission

Polarization of Thermal Radiation



λ ~ FIR - MM

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

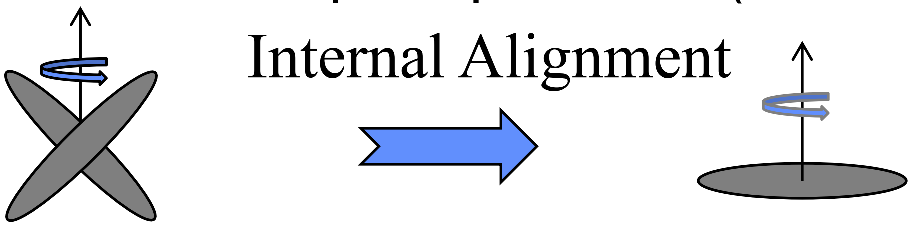
Why should you care?

- O/IR polarimetry traces the (large scale) magnetic field
- Dispersion in position angles can be used to measure field strength
  (Chadrasekhar & Fermi 1953; Ostriker, Stone & Gammie, 2001)
- O/IR polarimetry available "everywhere"
  - There are "almost always" either background stars or dust emission that can probe a gas parcel
- O/IR polarimetry "Telescope cheap"
  - Polarization mapping can – usually – be done on medium sized telescopes with moderate exposure times
  - σ_p~0.05% on a V=11 star with a 2m telescope requires ~10min
- **BUT:** *Line of sight effects and efficiencies means we can't reliably say where and how well the polarization traces the magnetic field - unless we have an observationally supported, quantitative, theory for grain alignment*

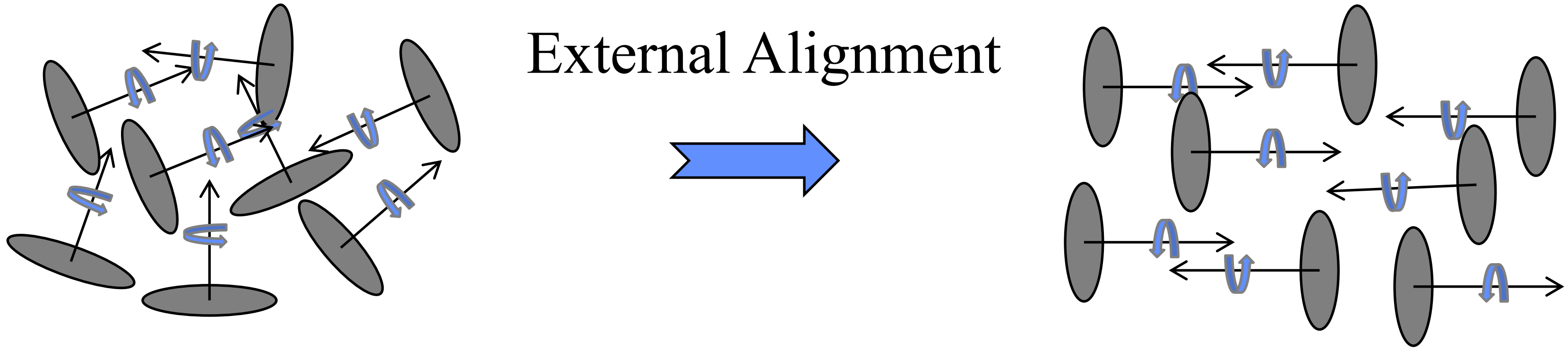
Grain Alignment –
Internal and External

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)



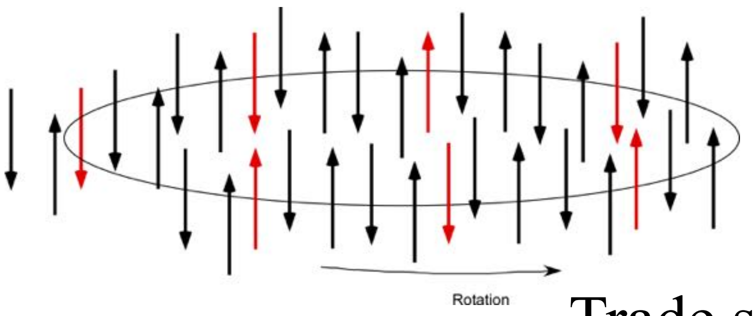
- Then, "all" the grains have to line up along a common direction



What causes this alignment?

Unpaired spins in a rotating body yield magnetization

- If the grain material has unpaired spins (==paramagnetic, e.g. silicates) it can minimize energy while keeping angular momentum fixed by trading rotation for spin-flips ⇔ magnetization
- This is known as the **Barnett effect** (inverse of the Einstein-De Haas effect) The Einstein-De Haas effect is observed in the lab as torques on the equipment when applying a magnetic field to a paramagnetic sample
- No unpaired spins (==diamagnetic, e.g. carbon grains) ⇔ no magnetization



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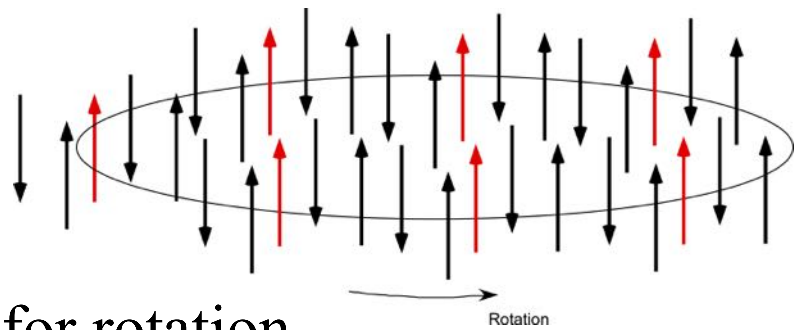


Trade spin-flips for rotation

If the grain is not rotating around a principal axis the Barnett effect causes dissipation and internal alignment

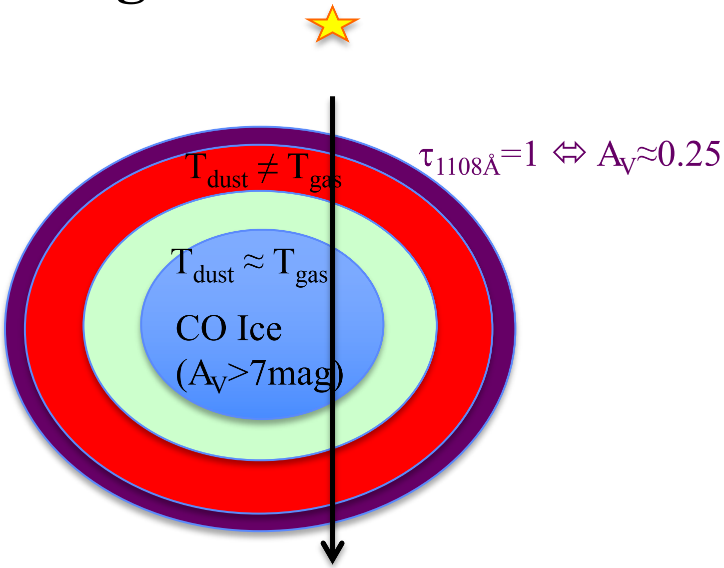
Grain Alignment – Possibilities

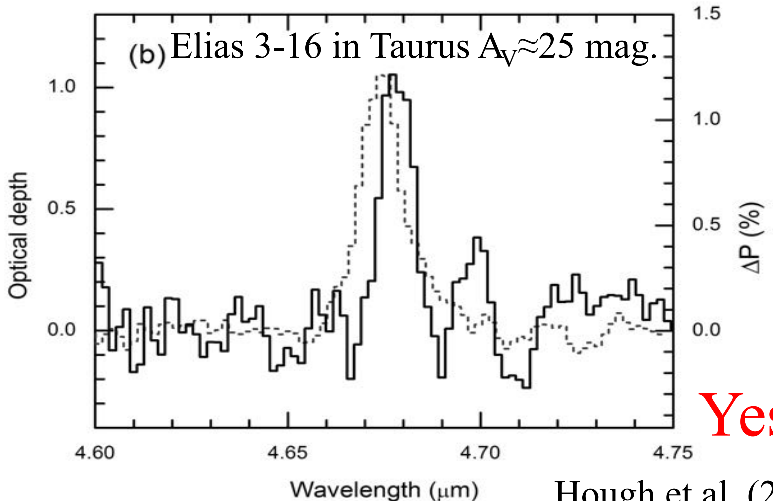
Three Main Theoretical Candidates
- And what they require

- *Paramagnetic Alignment* (Davis & Greenstein, 1951, Purcell 1979, Mathis 1986)
  - Requires $T_{spin} \neq T_{dust}$ and a **significant magnetic susceptibility** of the dust material (and/or H_2 formation on the grain surfaces) (Jones & Spitzer 1967)
- *Mechanical Alignment* (Gold 1952)
  - Requires Gas-dust flow (won't discuss – but – has never been seen)
- *Radiative Torque Alignment* (Dolginov & Mytrophanov, 1976; Drain & Weingartner 1996; Lazarian & Hoang, 2007)
  - Requires anisotropic radiation field with $\lambda < 2a$

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)

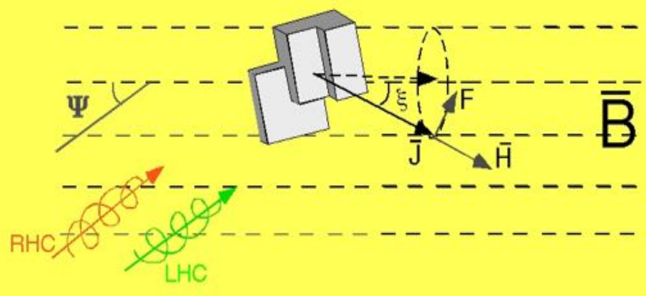
Grain Alignment –
Radiative Alignment Torques

RAT alignment in a nut shell

- RAT alignment is phenomenologically simple, albeit a multi-step process:

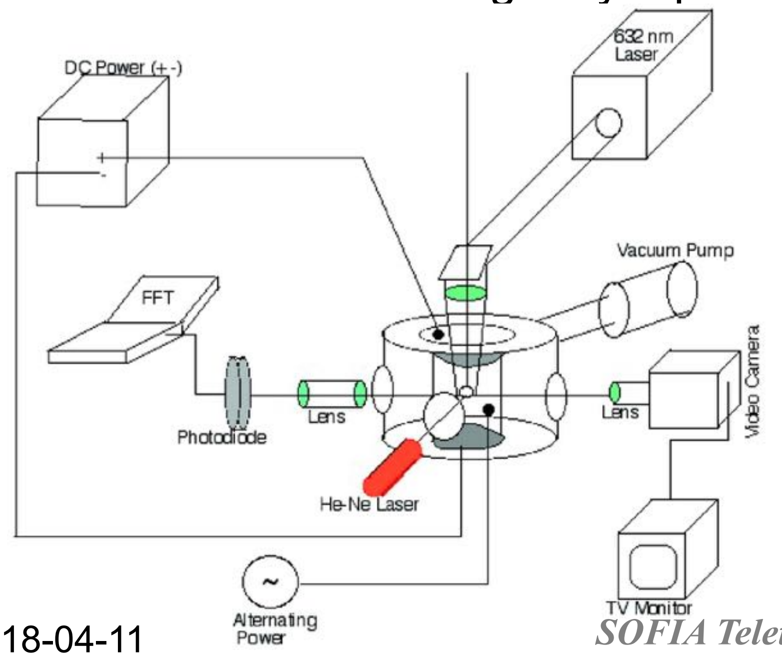
1. An **irregular** grain,
2. exposed to an **anisotropic radiation** field
3. with **λ<2*a***
4. will be spun up by the differential torques from the LHC and RHC components of the light.
5. For a **paramagnetic material**,
6. the **Barnett effect** gives the grain a magnetic moment which causes it to
7. **Larmor precess** around the magnetic field lines
8. Continued RATs on all the facets of the grain then causes the grain's angular momentum to **align with the B-field**
9. If the radiation field is strong and anisotropic enough, the alignment axis becomes the radiation k-vector

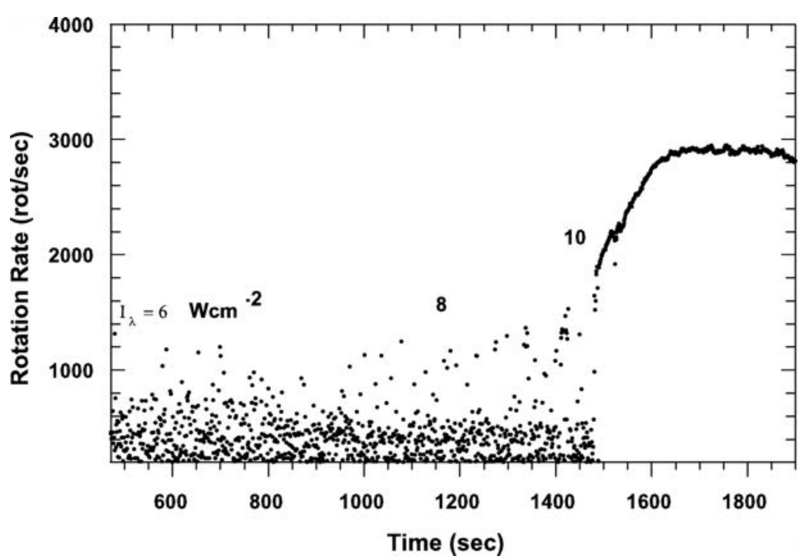
F is the alignment torque (⊥ to J)
H is the spin-up torque (ǁ to J)



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 rates were obtained by analyzing the signal of the scattered light by a photodiode detector.





Radiative Alignment Torque (RAT) Alignment ISM implications

- Fundamental prediction:

Grains are aligned if exposed to an anisotropic radiation field with λ<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

Radiative Alignment Torque (RAT) Alignment

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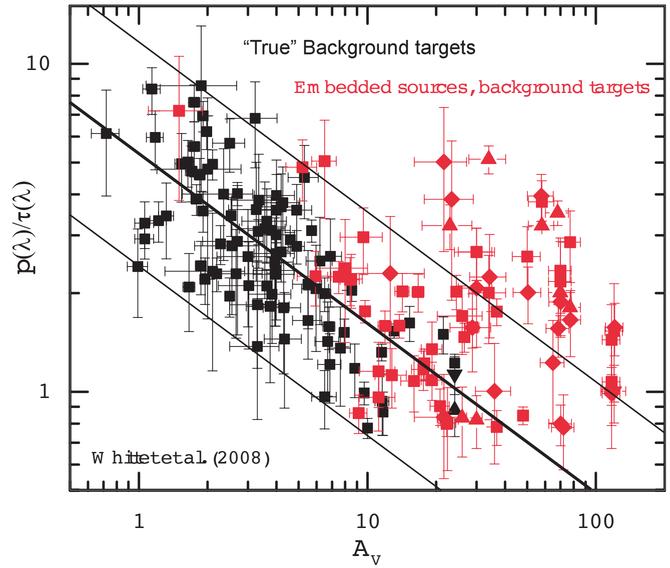
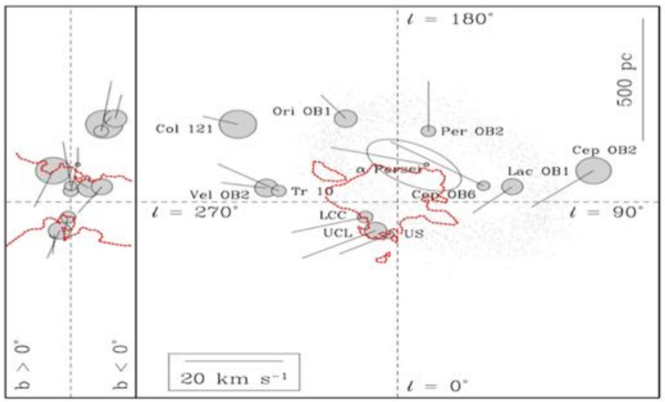
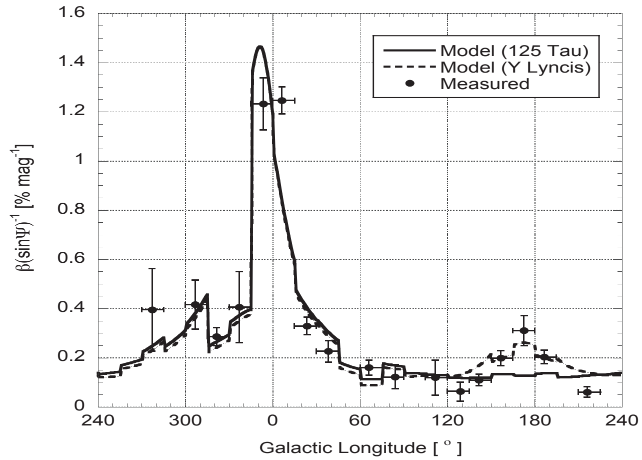
The grain alignment varies with radiation field strength

- The fractional polarization (p/τ) drops with opacity (Jones, Klebe & Dickey, 1992 (JKD); Whittet et al., 2008)
  - While magnetic field topology can explain much of this drop-off (JKD), models show observations are consistent with RAT

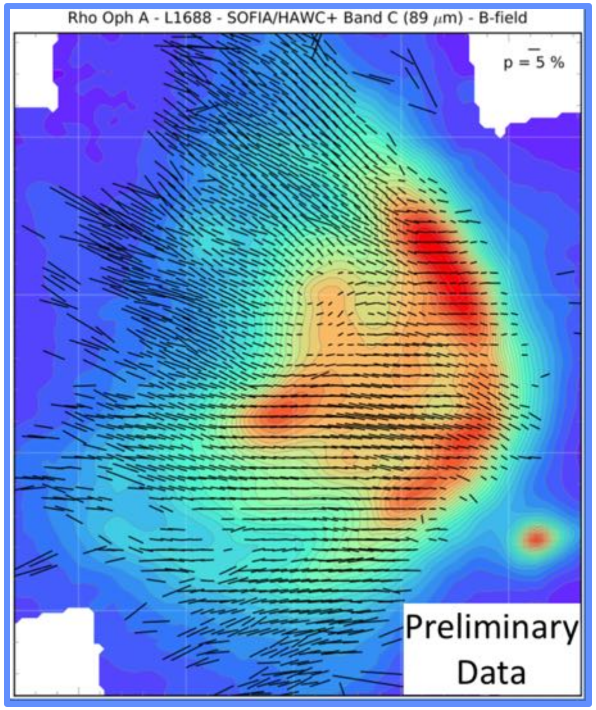


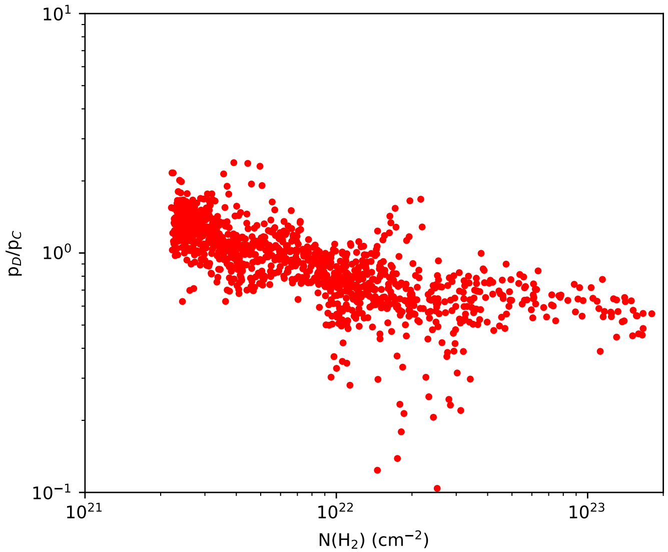
- The grain alignment in the wall of the Local Bubble is observed to be enhanced by the near-by OB associations



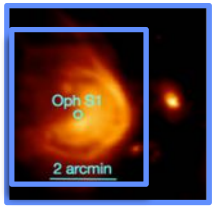


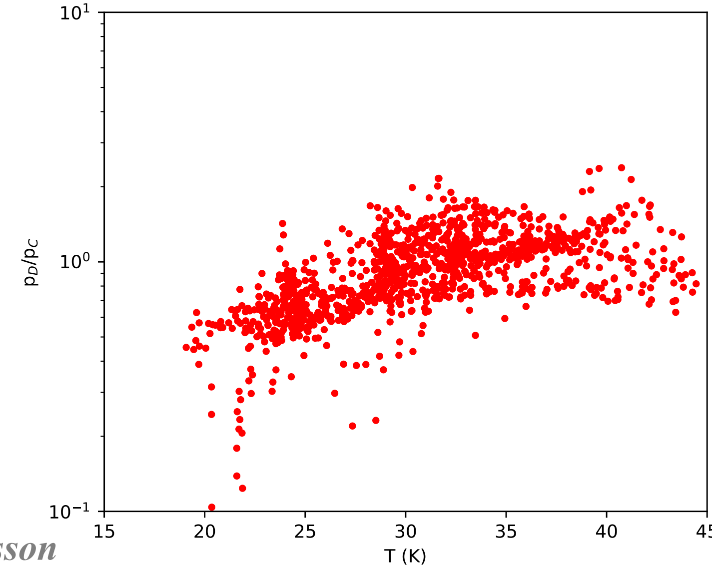
HAWC+ observations of ρ Oph A





(Pereira Santos et al., in prep)





The fractional band-D/band-C polarization drops with column density but rises with temperature, indicating that the alignment is better where the radiation field is stronger.
Need to account for collisional disalignment.

Radiative Alignment Torque (RAT) Alignment

- Fundamental prediction:

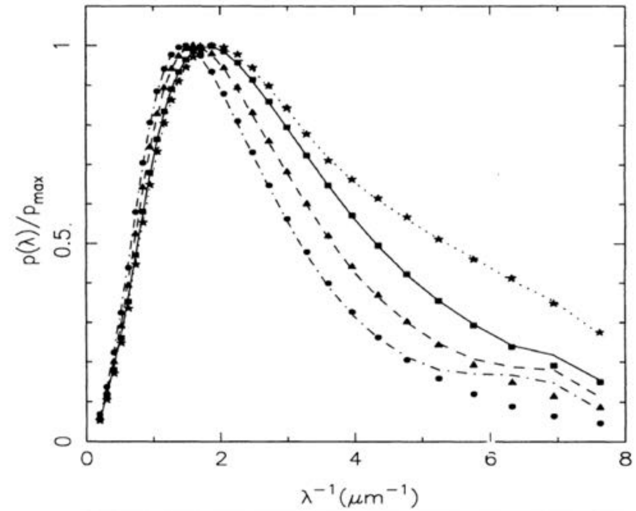
  Grains are aligned if exposed to an anisotropic radiation field with λ<2a

- 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

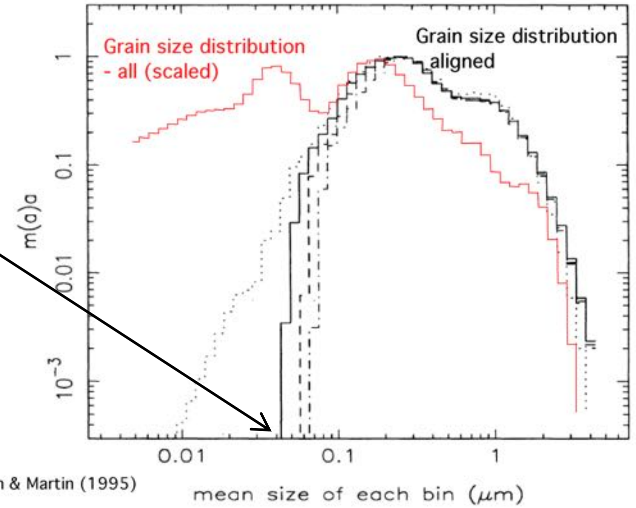
The size distribution of aligned grains will vary with the radiation field

- Modeling of the extinction and polarization curves show that only the larger grains are aligned and that the peak of the polarization curve varies with the small cut-off in the aligned grain sizes

- λ_{max} (the location of the peak of the polarization curve) can be used to measure the variations in the alignment – immune to l.o.s turbulence effects



For the general ISM the small size cut-off in aligned grains is at $a \approx 0.045\mu m$ = 912Å/2



Kim & Martin (1995)

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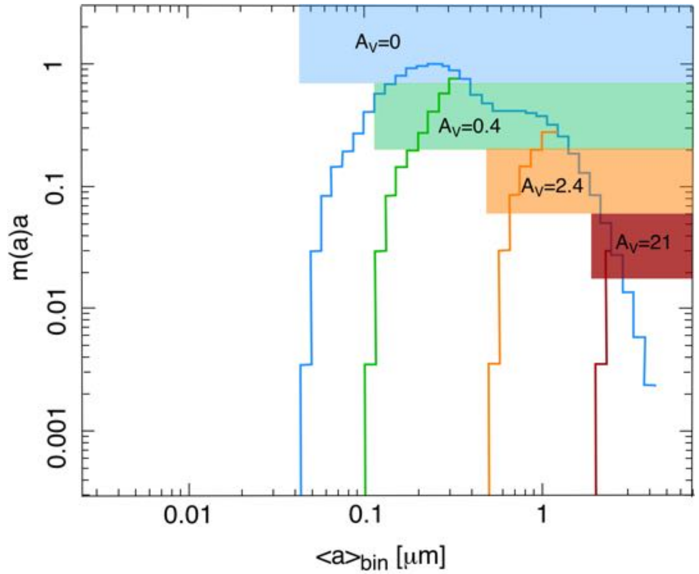
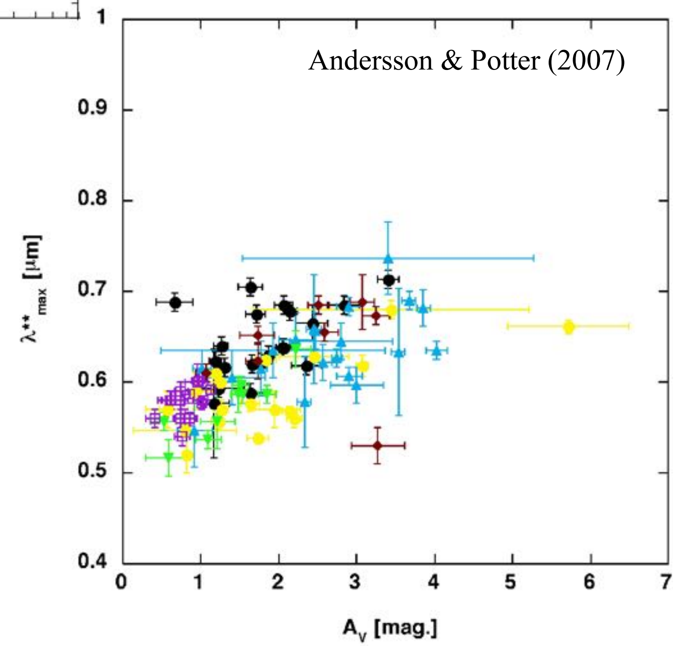
    - For moderate opacities the polarization curve will move to the red with A_V

The polarization spectrum depends on the opacity

- As the radiation field reddens into the cloud, the small size cut-off of aligned grains – in RAT alignment - should increase and λ_{max} should grow.

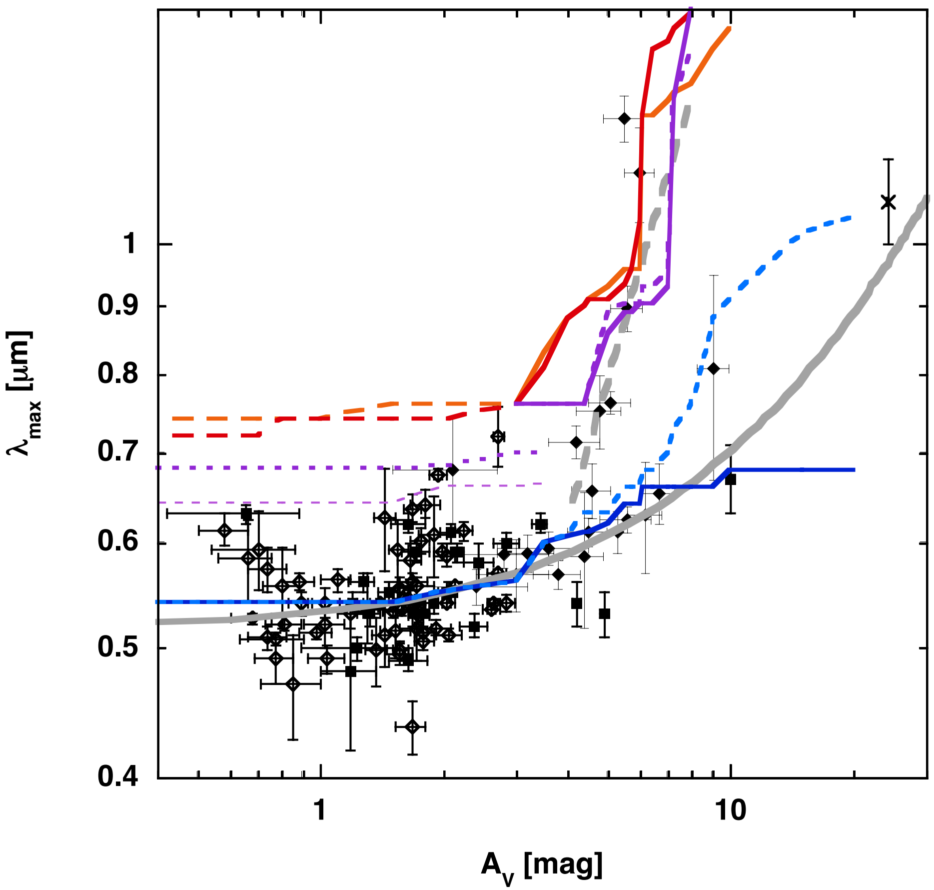


- When we correct for different [total] grain size distributions in different clouds a universal λ_{max} vs. A_V relation is observed



Polarimetry as a tool for grain growth studies – and collisional disalignment

- The linear λ_{max} vs. A_V assumes that the underlying – total – grain size distribution is fixed.
- If grain growth is taking place, we'd expect a steeper relation.
- Also sensitive to collisional disalignment
- Provides a direct way to study grain growth – independent of assumptions on grain emissivity and temperature



- Observations of Taurus with Lick/Kast

Vaillancourt et al. (2016)

Radiative Alignment Torque (RAT) Alignment

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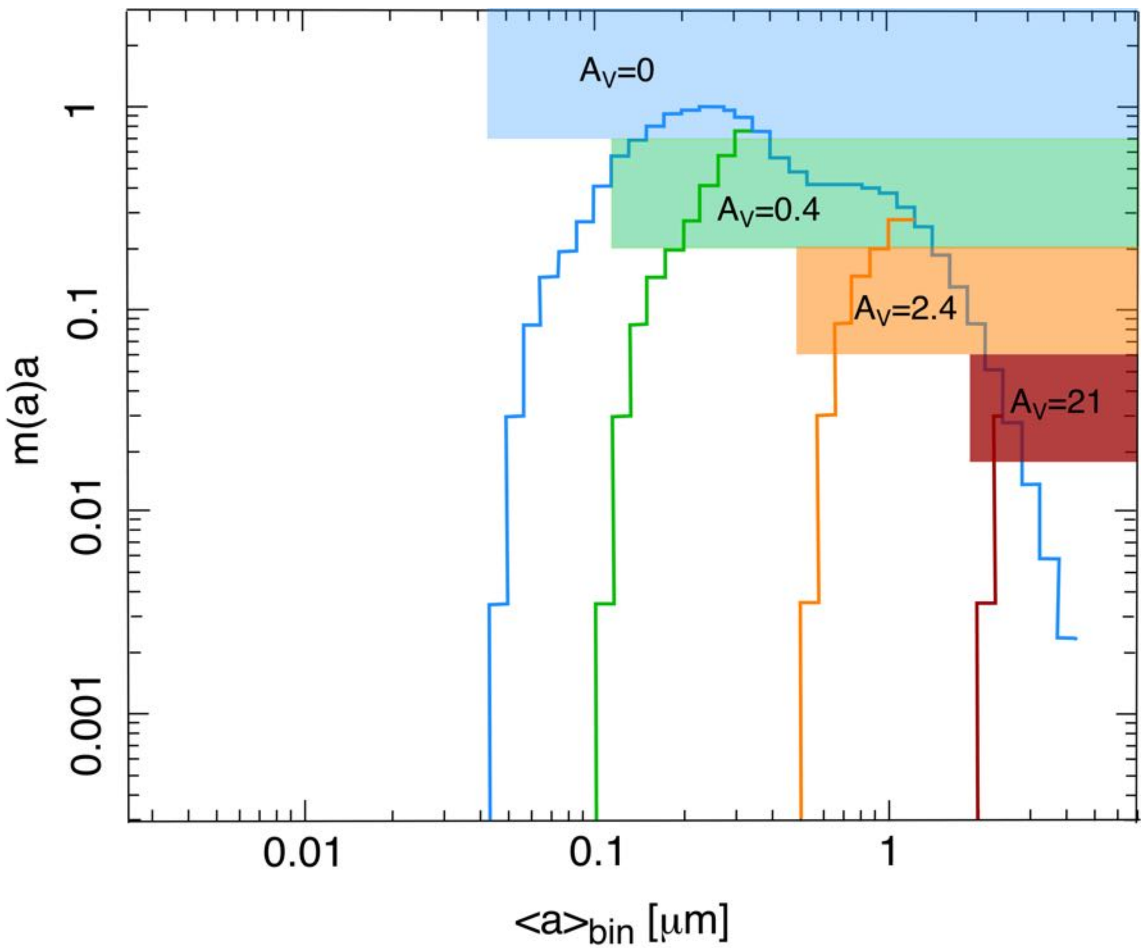
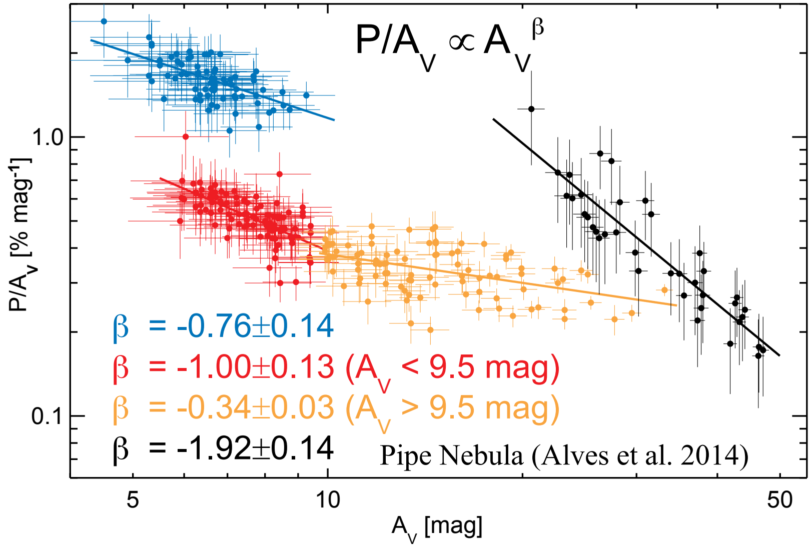
  - The size distribution of aligned grains will vary with the radiation field
    - For the general ISM grain alignment will fail for $a < 912$Å$/2$ ✔
    - For moderate opacities the polarization curve will move to the red with A_V ✔
    - For deep star-less cores there will be a depth beyond which no alignment takes place

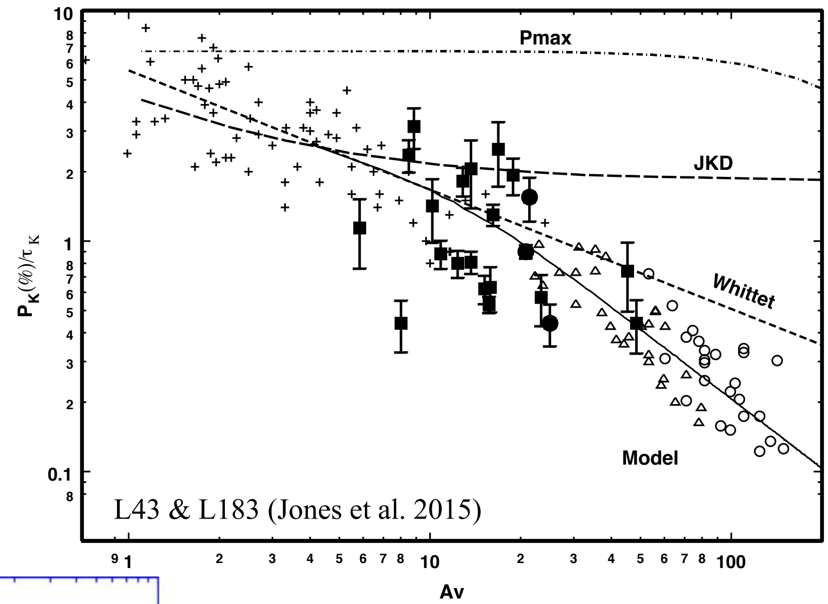
Grain alignment is lost deep into star-less clouds

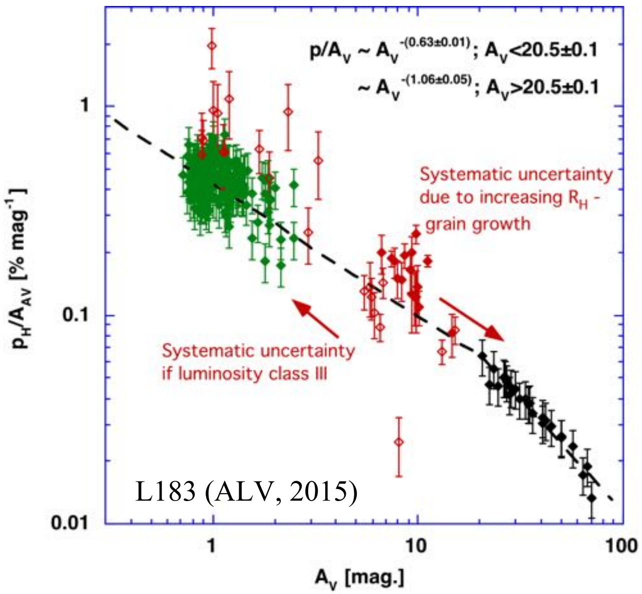
- Because of [refractory] elemental abundance limitation, an upper grain size cut-off at ~1-2μm is expected (poorly constrained)
- For star-less cores this should mean that at some opacity, [almost] no grains are present that can couple to the remaining radiation field. When this happens $p/A_V \sim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



Alignment loss is seen at A_V~20mag.







$p/A_V \sim A_V^{-1}$ implies no further alignment

Radiative Alignment Torque (RAT) Alignment

- Fundamental prediction:

Grains are aligned if exposed to an anisotropic radiation field with λ<2a

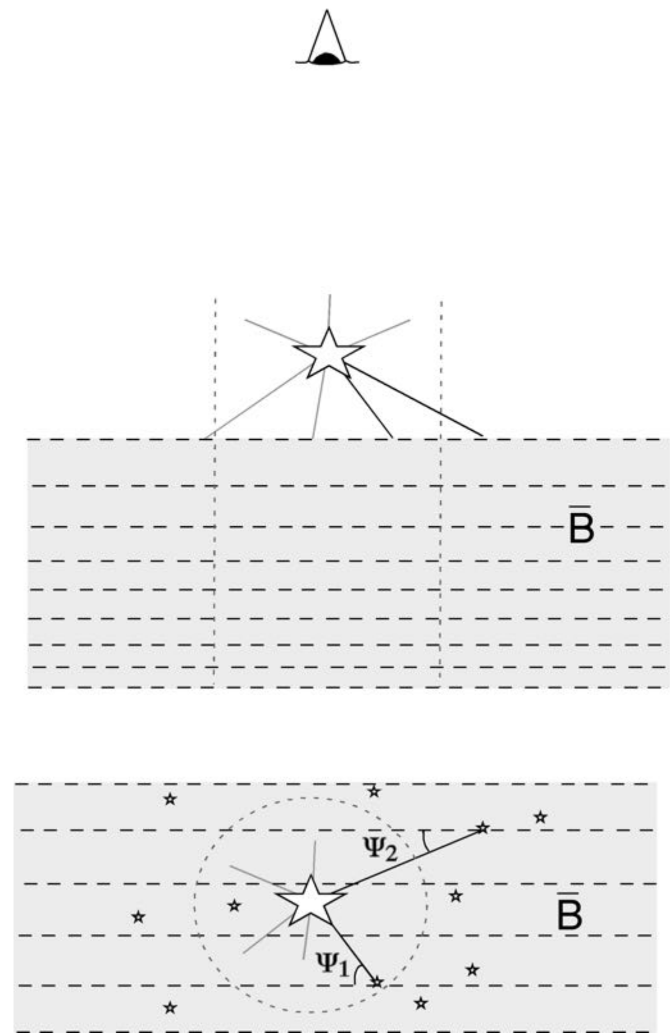
c.f. T. Hoang's talk for details

- 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

The alignment seems to depend on the angle of illumination

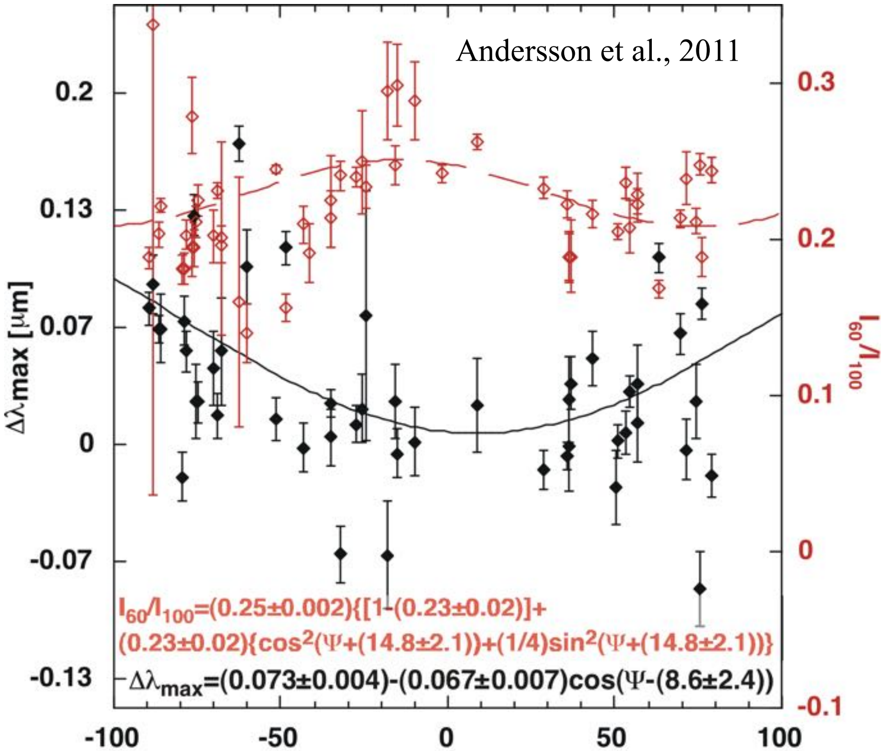
- Because the alignment of the grains with the magnetic field occurs through continual radiative torques during Lamor precession, the alignment is predicted to vary with the angle between the magnetic field and the radiation field anisotropy

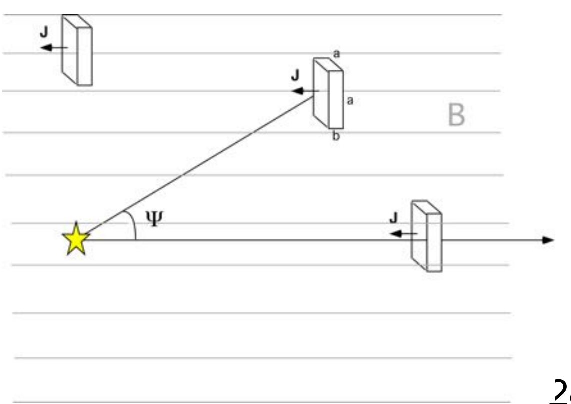
- Observing the polarization of background stars around a star illuminating the surface of a cloud can probe for this effect.



The alignment seems to depend on the angle of illumination II

- Observations of the polarization around HD97300 in Chamaeleon I indicates that grains **are** better aligned along the field lines than across.
- The (60/100mm) color temperature of shows a behavior consistent with alignment along the field, with an amplitude consistent with RAT theory

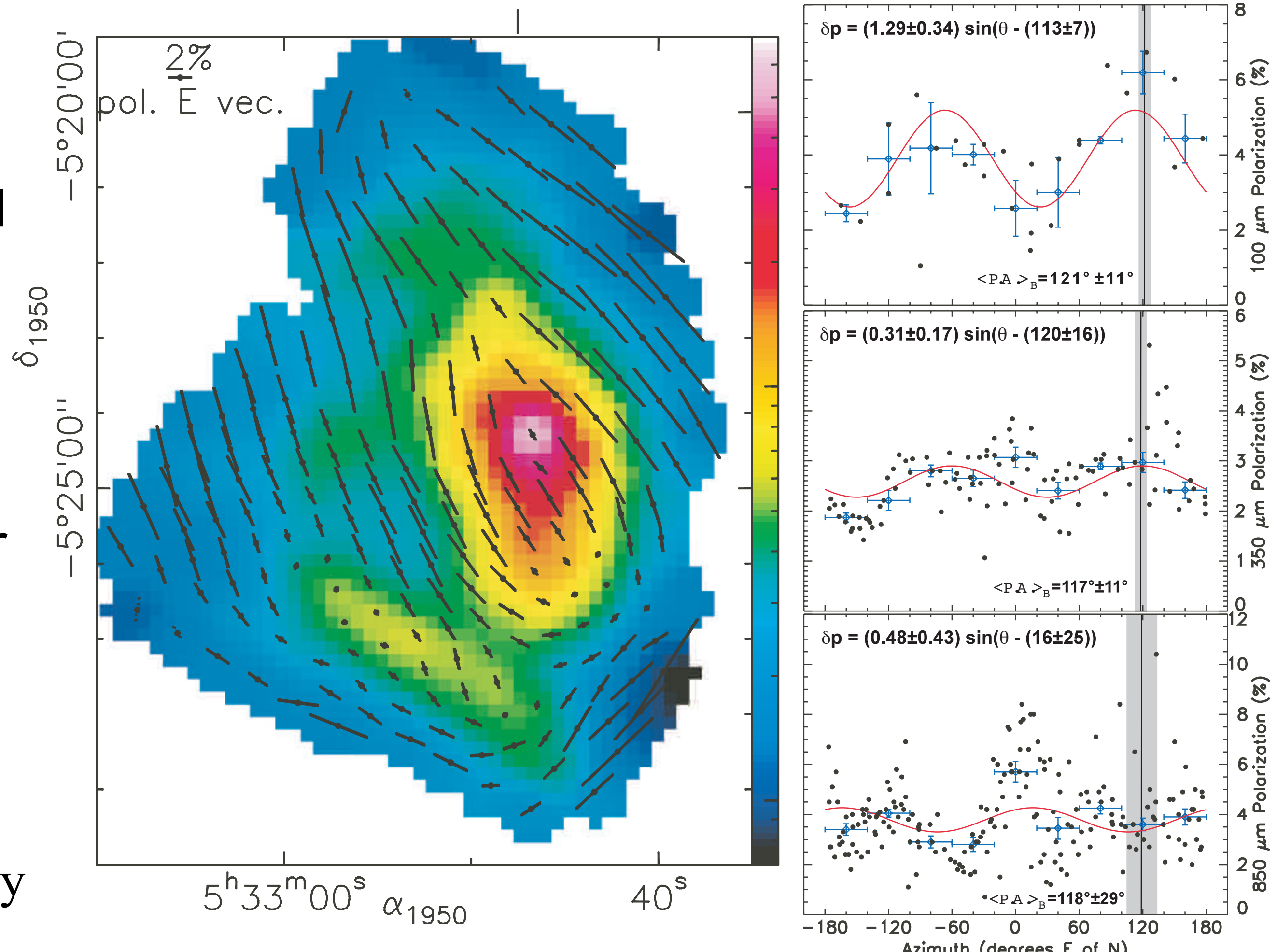




Ψ dependence also seen in the FIR

- KAO observations of the region around the BN object
- Variation phased with B-field (as expected)
- Larger amplitude for hotter grains – as expected for radiative effect.

HAWC+ study under way



Vaillancourt & Andersson (2015)

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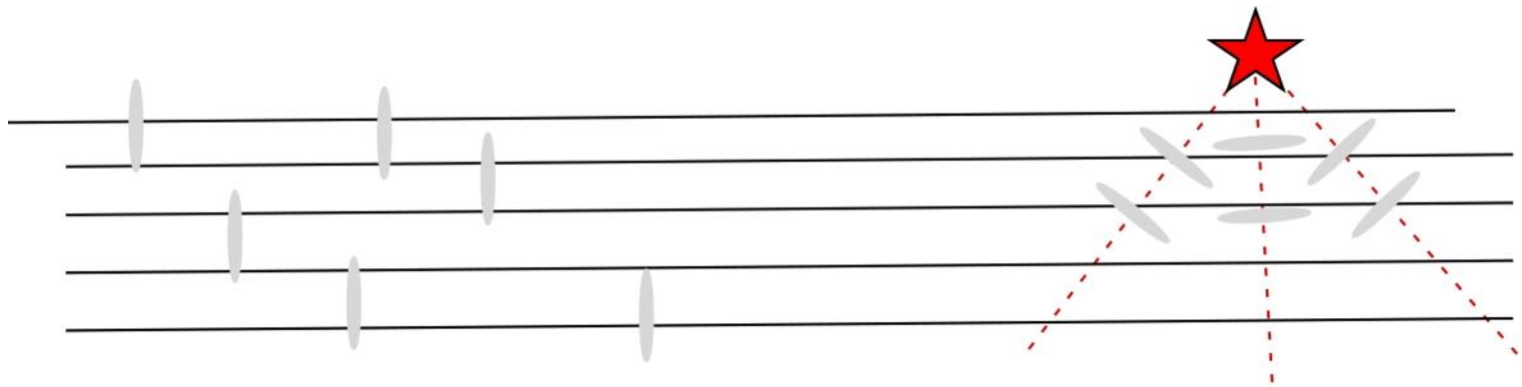
  - The alignment will depend on the angle between the magnetic and radiation field anisotropy ✔
  - For strong, anisotropic radiation fields, the reference direction changes from the magnetic field (B-RAT) to the radiation direction (k-RAT)

B-RAT vs. k-RAT

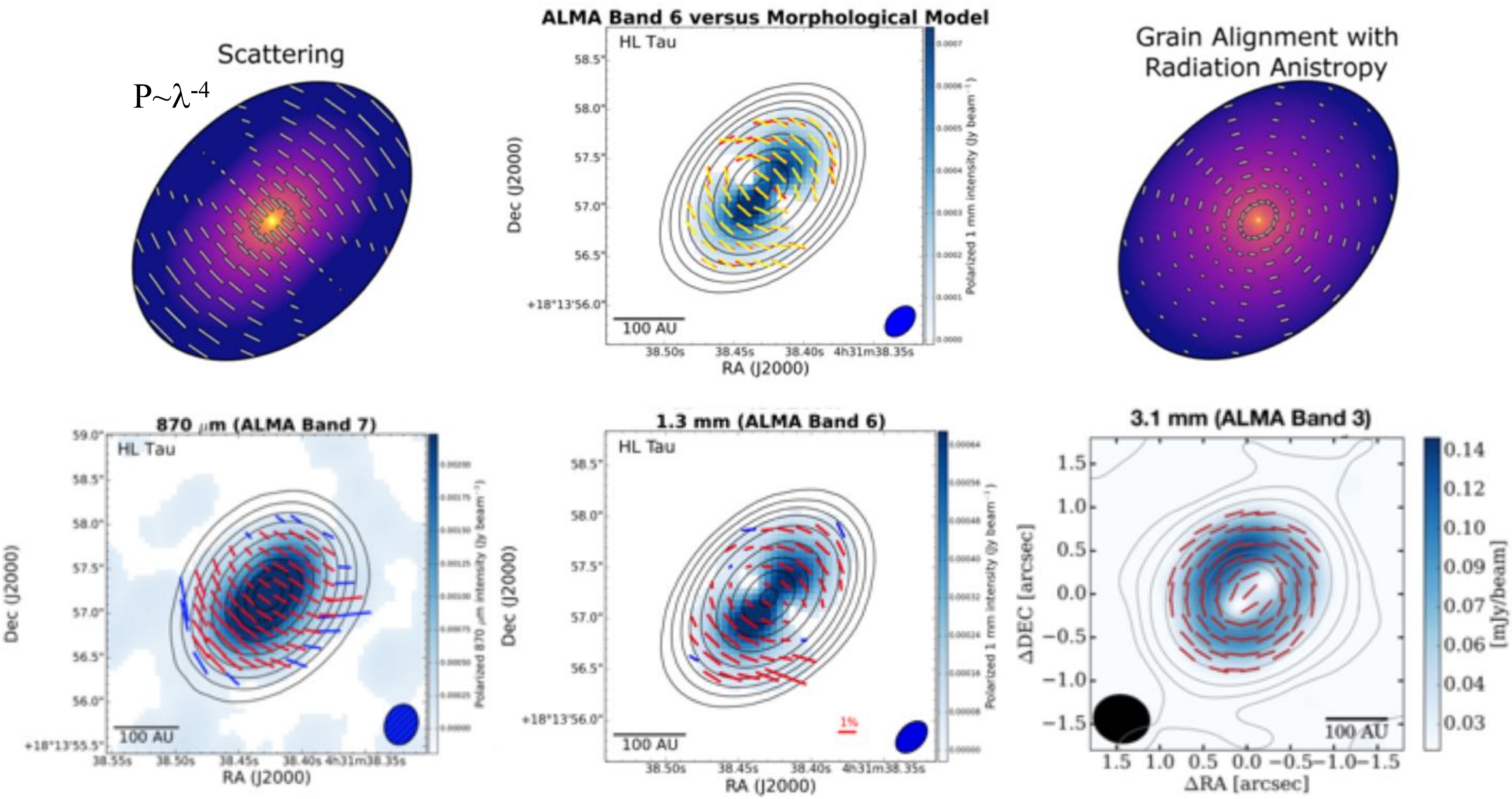
RAT alignment predicts that for a strong, and anisotropic enough, radiation field the reference direction for alignment should change from the magnetic field (B-RAT) to that of the radiation field’s k-vector (k-RAT)



k-RAT

B-RAT

New Best Friend: Multiwavelength Obs



Kataoka et al. 2017, Stephens et al. 2017

Slide courtesy of L. Looney

Radiative Alignment Torque (RAT) Alignment

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  - 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)

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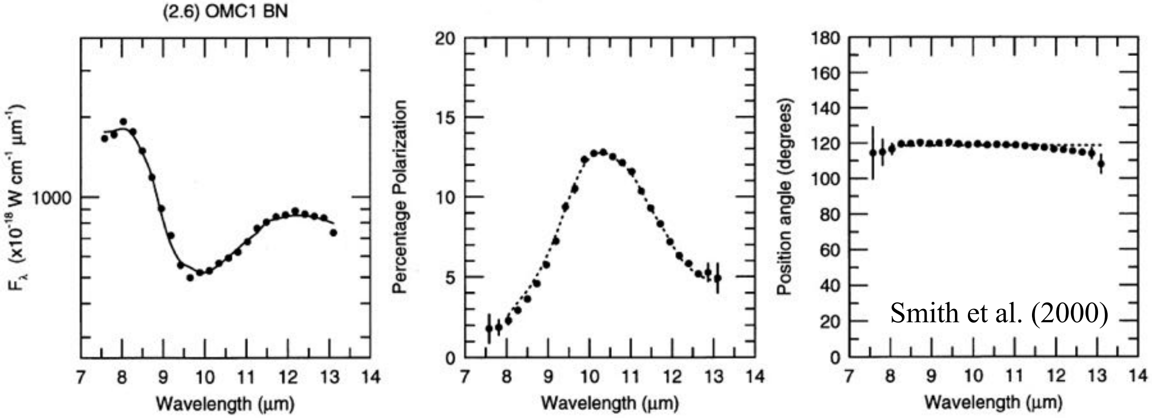
What about Carbon grains?

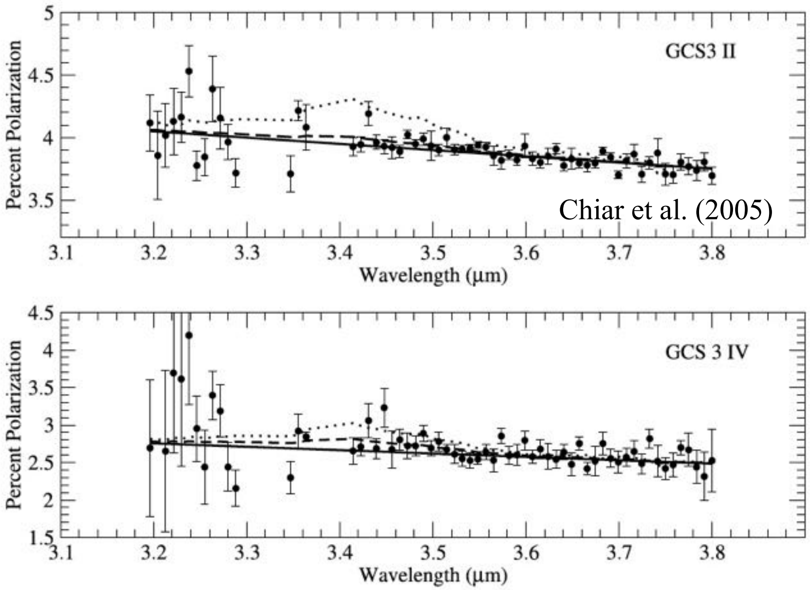
The 9.7 μm silicate feature shows strong polarization



The 3.4 μm aliphatic CH feature is not polarized

Solid carbon exposed to UV and H atoms **will** form aliphatic bonds

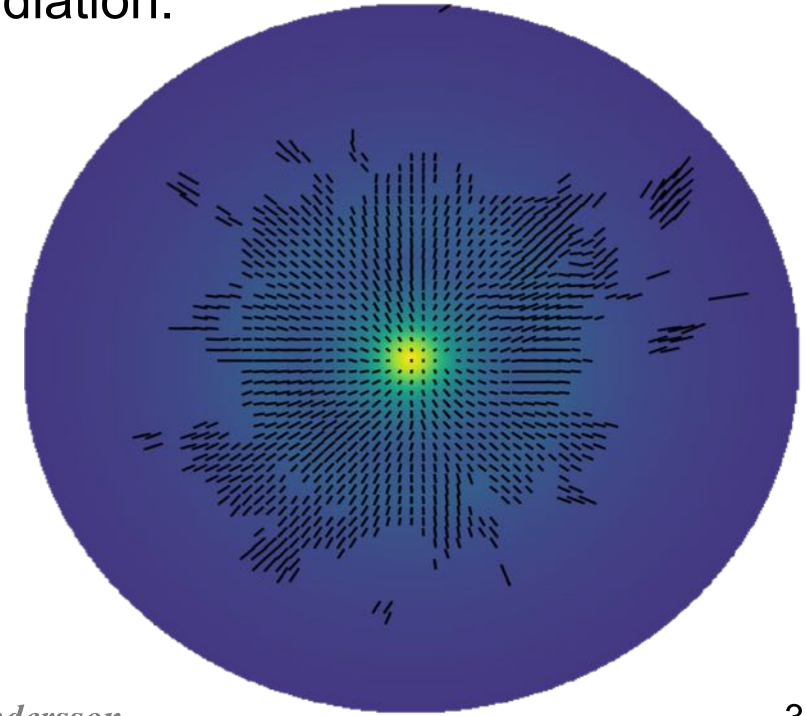
Since silicates are paramagnetic but carbon solids are diamagnetic, RAT predicts that silicate grains **will** align, but carbon grains **will NOT** align with the magnetic field (the will, however spin)



Radiation Aligns Carbonaceous Grains

- To align with the magnetic field, a grain must be "*paramagnetic*"
  (They must have free, unpaired quantum spins in the solid)
- Carbonaceous grains are diamagnetic
  - RAT therefore predicts that carbon grains do not align in the ISM
  - The lack of a Barnett effect, limits **both** internal and external (B-RAT) alignment
- RAT does predicts that for strong radiation fields, the alignment direction (for any grain) becomes the direction of the radiation.

- HAWC+ polarization of IRC+10216 shows a radial (centro-symmetric) polarization field
- The amount of polarization correlates with the dust temperature
- Consistent with RAT alignment – without internal alignment



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  - 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) ✔

Grain Alignment - Where we stand

Observation \ **Theory**	Larger grains are better aligned	General alignment only active for *a* >0.045μm	H_2 formation enhances alignment	H_2 formation is **not required** for alignment	Alignment seen when $T_{gas} \approx T_{dust}$	Alignment is **not** correlated with ferro-magnetic inclusions	Alignment is lost at $A_V \approx 20$ mag.	Alignment depends on angle between radiation and magnetic fields	Carbon grains are unaligned	Alignment direction can be either B-field or radiation field k-vector
Davis-Greenstein	-				-					
Super-paramagnetic	+				-	-				
Suprathermal			+	-						
Mechanical			-				-		-	
RAT	+	+	+				+	+	+	+

All

Green

Green – Direct observational **support** of the theory

Red – Direct observational **contradiction** of the theory

Gray – No prediction or ambiguous results

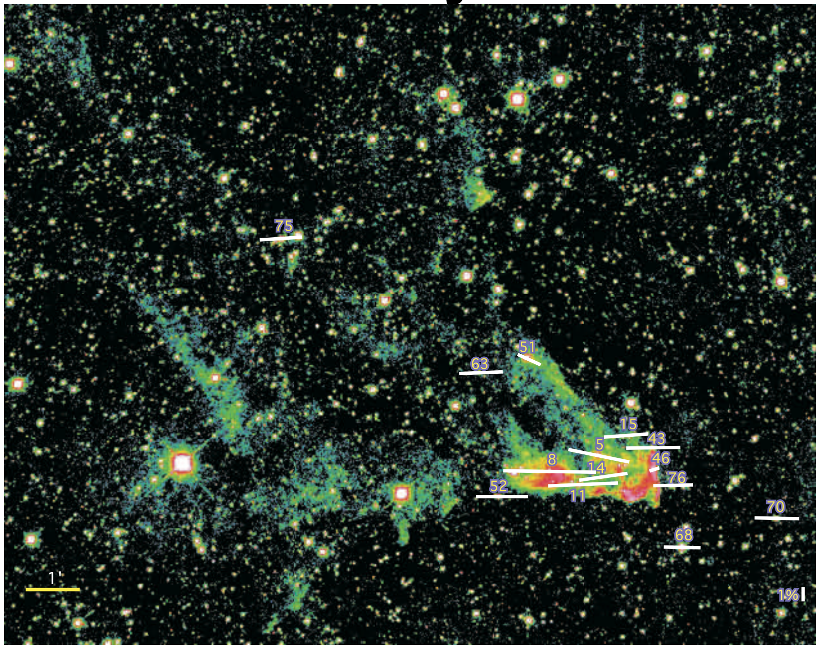
Summary
"*The String-Theory of Astrophysics*"? – no longer!

- Observational and theoretical arguments show that paramagnetic or mechanical alignment cannot contribute significantly to the dust grain alignment in the ISM
- Radiative Torque Alignment (RAT), theory provides a number of specific – observationally testable – predictions
  - So far, all the ones that have been tried, support RAT alignment
- An observationally supported grain alignment theory will not only allow reliable measures of the magnetic field geometry and strength but also of the micro-physics of the dust grains.
  - RAT Alignment provides such a paradigm

- Back-up Slides

Purcell alignment has a – secondary – role in RAT alignment

- By providing additional angular momentum to the grains, Purcell rockets (H_2 formation impulses) can lift grains out of “low-J traps” and enhance the alignment.



IC 63:
H_2 1-0 S(1)
and optical pol. vectors

Note: If SPM active, H2 torques should not matter!!

- Because H_2 destruction is initiated through line absorption and
  t_{PDR} >> $t_{photo\text{-}processes}$

=>
$I_{fluorescence}$ ~ R(H_2 ^{formation})

H_2 formation enhances alignment in the reflection nebula IC 63, consistent with RAT predictions.