[Dust induced] Polarization:
Extinction/Emission

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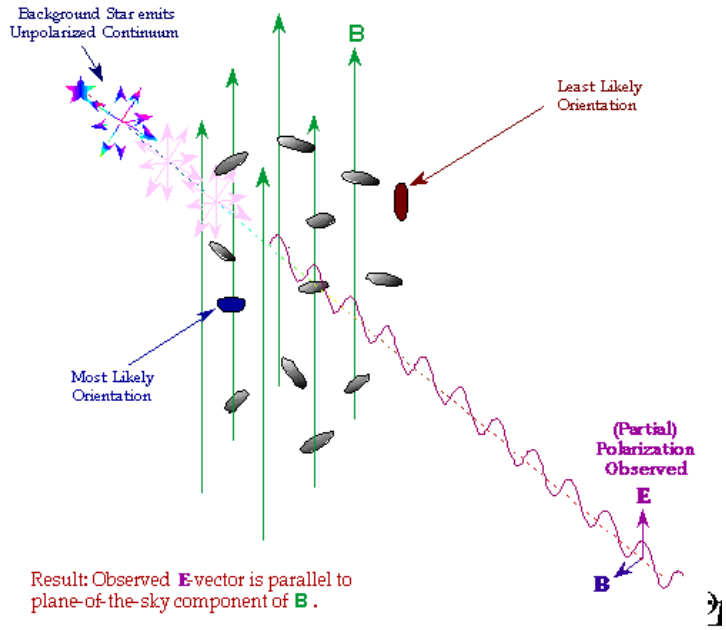
Why is the light Polarized?

Extinction Polarization

Discovered by Hiltner and Hall in in 1949

Polarization of Background Starlight

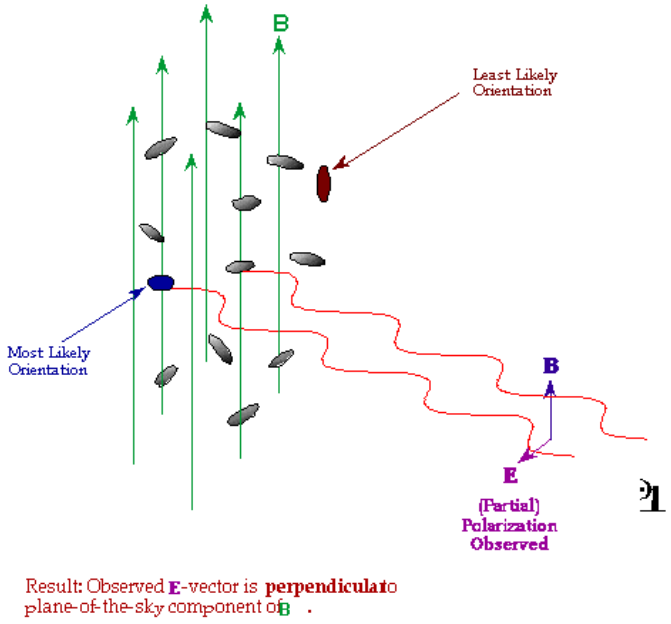


λ ~ UV - NIR

Emission Polarization

First detected by Cudlip in 1982

Polarization of Thermal Radiation

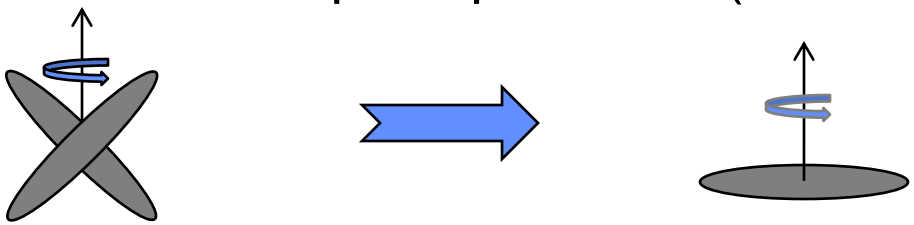


λ ~ FIR - MM

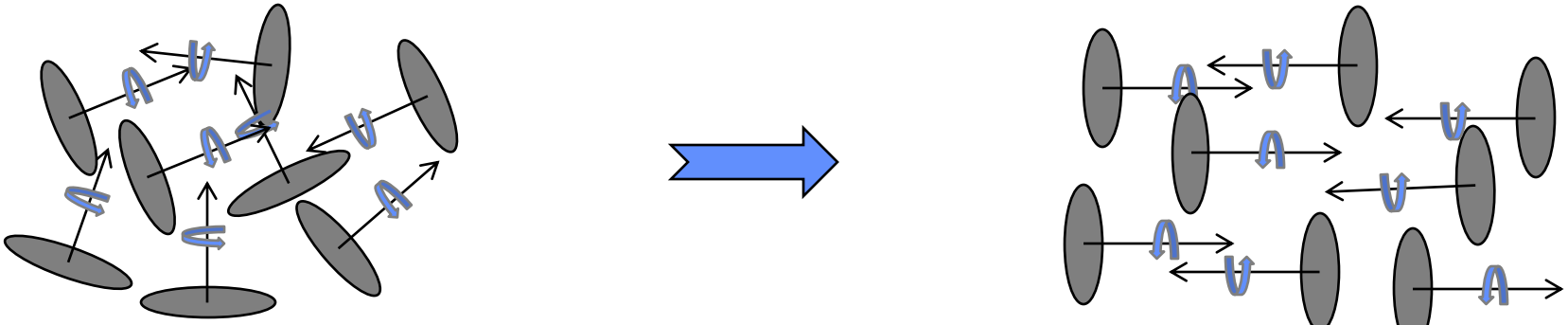
Diagrams after A. Goodman: http://cfa-www.harvard.edu/~agoodman/ppiv/

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



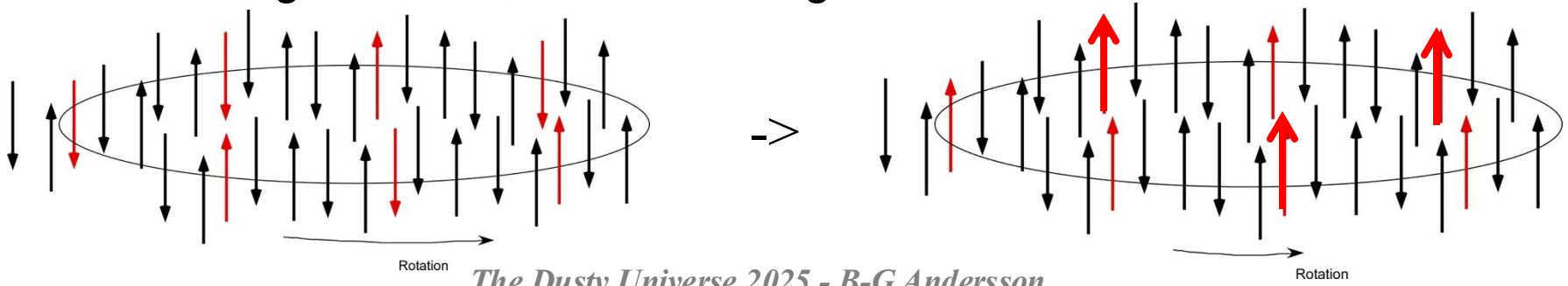
How can this be achieved?

Micro-Physics

Unpaired spins in a rotating body can cause magnetization

- A paramagnetic grain (unpaired spins in bulk; e.g. silicates) will minimize its energy, **while conserving angular momentum**, by trading solid body rotation for spin-flips
  - Barnett effect
  - 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 Barnett-dissipation (Purcell 1979)
- No unpaired spins (==diamagnetic, e.g. **carbon** grains) ⇔ no magnetization, no internal alignment

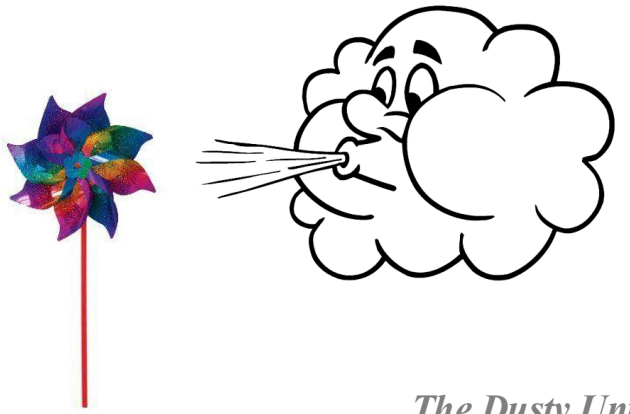
Micro-Physics

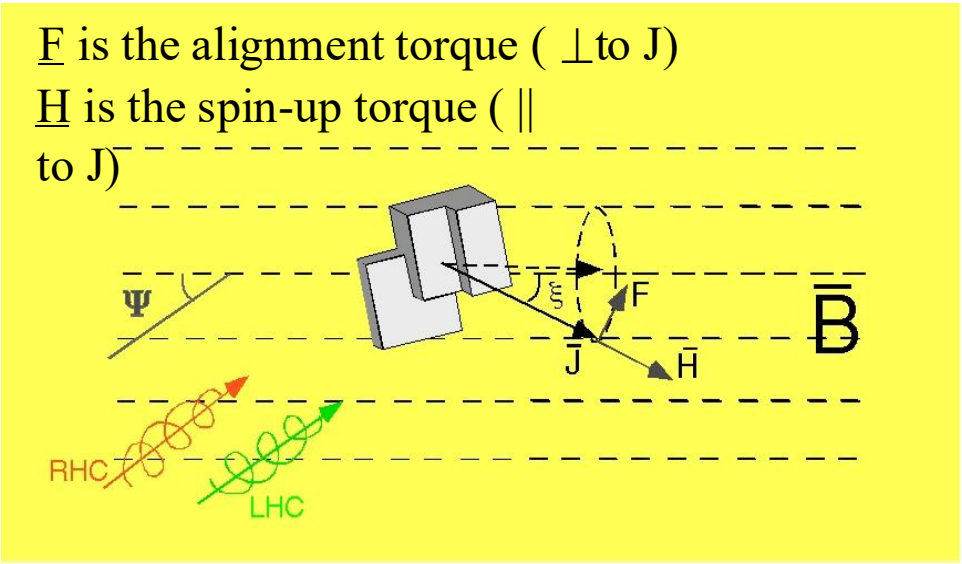


Radiation Aligns the Grains

Radiative Alignment

- 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 – to first order!)
  - First proposed by Dolginov & Mythropanov 1976
- The Barnett effects, again, magnetizes **paramagnetic** grains which then aligns their angular momentum vectors with the B-field
- Radiative Alignment Torque theory (e.g. Lazarian & Hoang 2007)





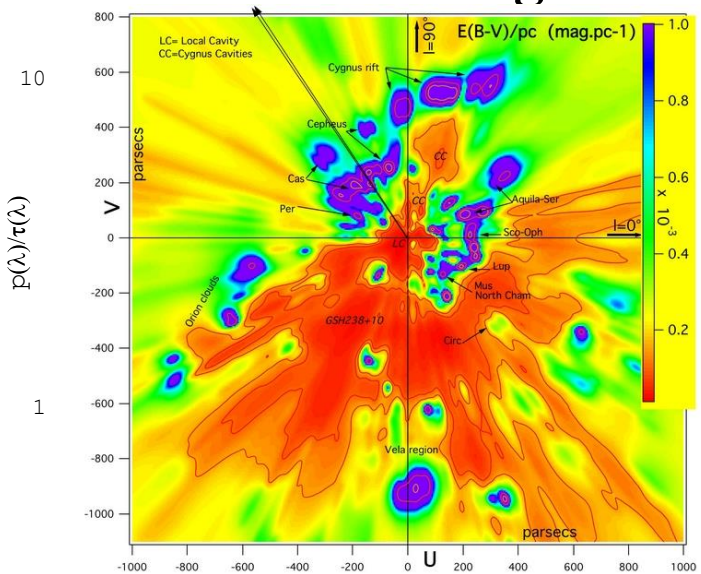
RAT conditions and diagnostics

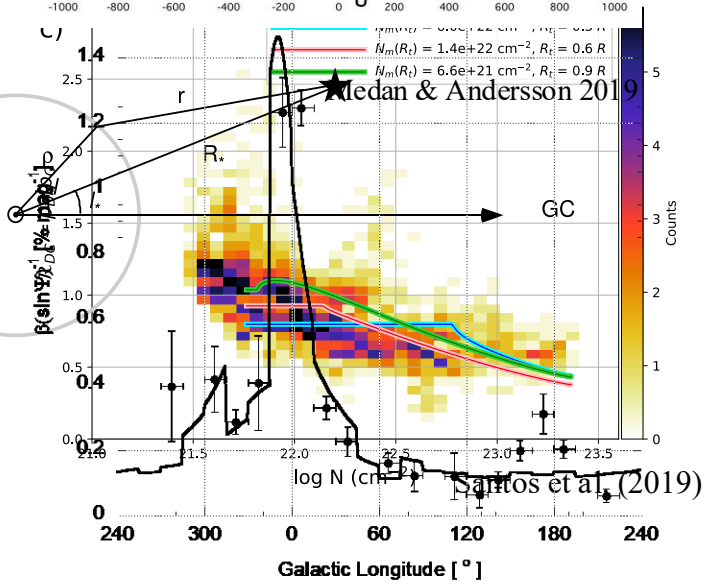
- **Paramagnetic** (or stronger) **grain material**
- $\lambda < 2a$
  - Intensity and SED of aligning radiation
- **Grain shape and structure**
  - Oblate/prolate
  - Tensile strength
- **Environment**
  - Gas-grain collisional damping
- These constraints/requirements provide unique probes of the dust
  - Emission polarization allows mapping and study of high A_V regions
  - Extinction polarization probes lower A_V, and avoids issues of T_d, β

The grain alignment varies with radiation field strength

- L.o.s towards embedded sources in Taurus show higher alignment that for true background stars
- 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
- Grain alignment in the LB wall reflects the known OB associations with d<500pc
- Far infrared data also shows a correlation of polarization efficiency and radiation field intensity

p/A_V vs. l





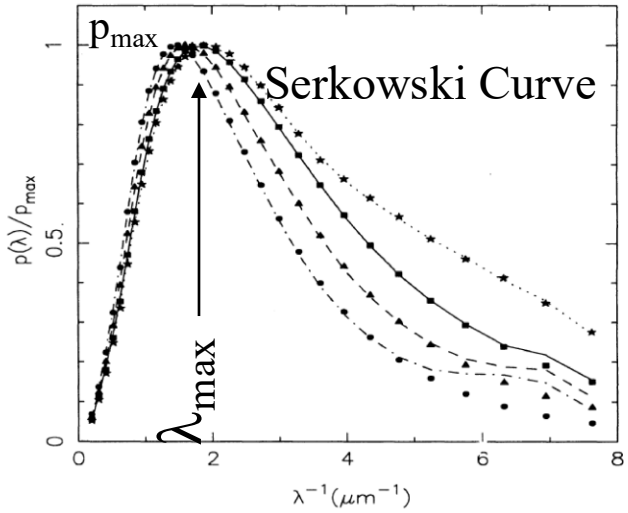
The size distribution of aligned grains will vary with the radiation field

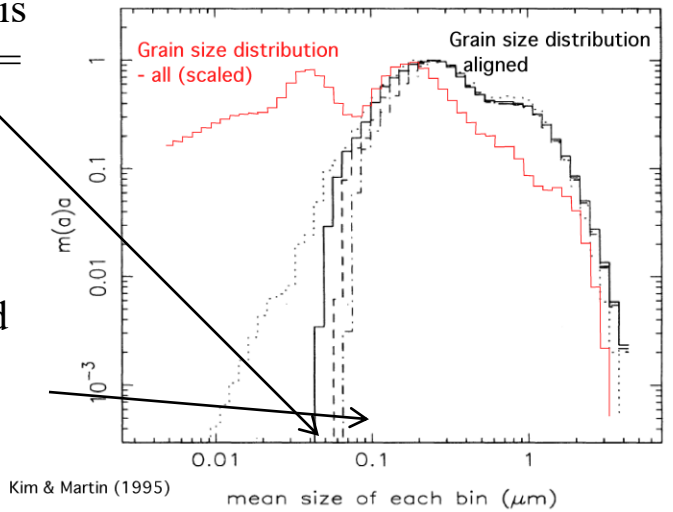
- Modeling of the extinction and polarization curves show that only the larger grains are aligned and that the peak of the polarization curve varies with the small cut-off in the aligned grain sizes
- Gas-grain collisions also limit the size of aligned grains

P(λ) vs. A_V

- 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





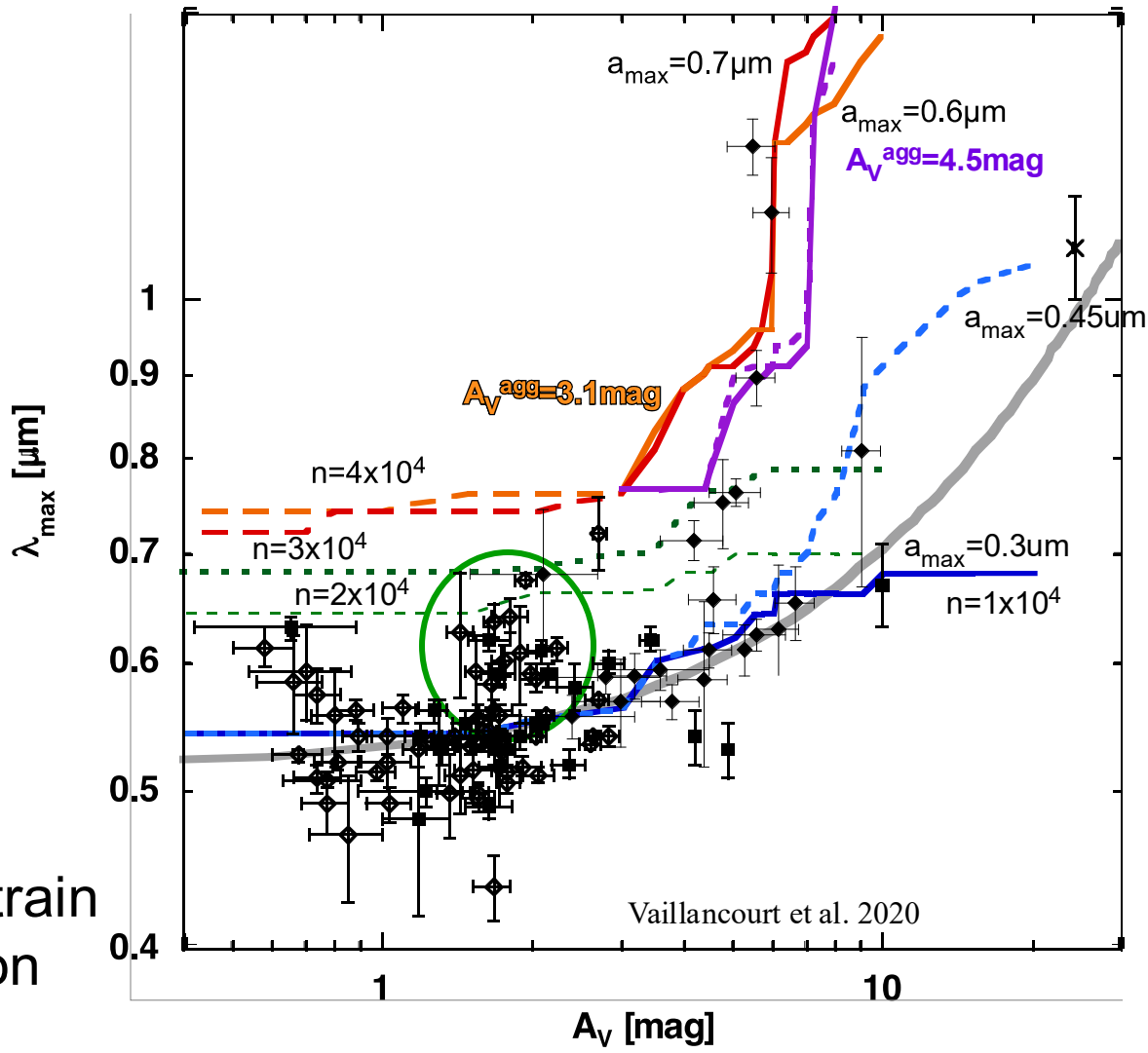
With reddening this cut-off increases and λ_{max} increases (Whittet et al. 2001; Andersson & Potter 2007)

Polarization Curve for Radiation Field, Gas Density and Grain Size ("in c-minor")

- The peak of the Serkowski curve is sensitive to
  - radiation field color
  - grain sizes
  - gas density
    - Disalignment is faster for smaller grains
- Compare p(λ,A_V) to *ab intio* RAT models

- We can fully model the observations and constrain the dust grains, radiation fields and gas density

P(λ) vs. A_V

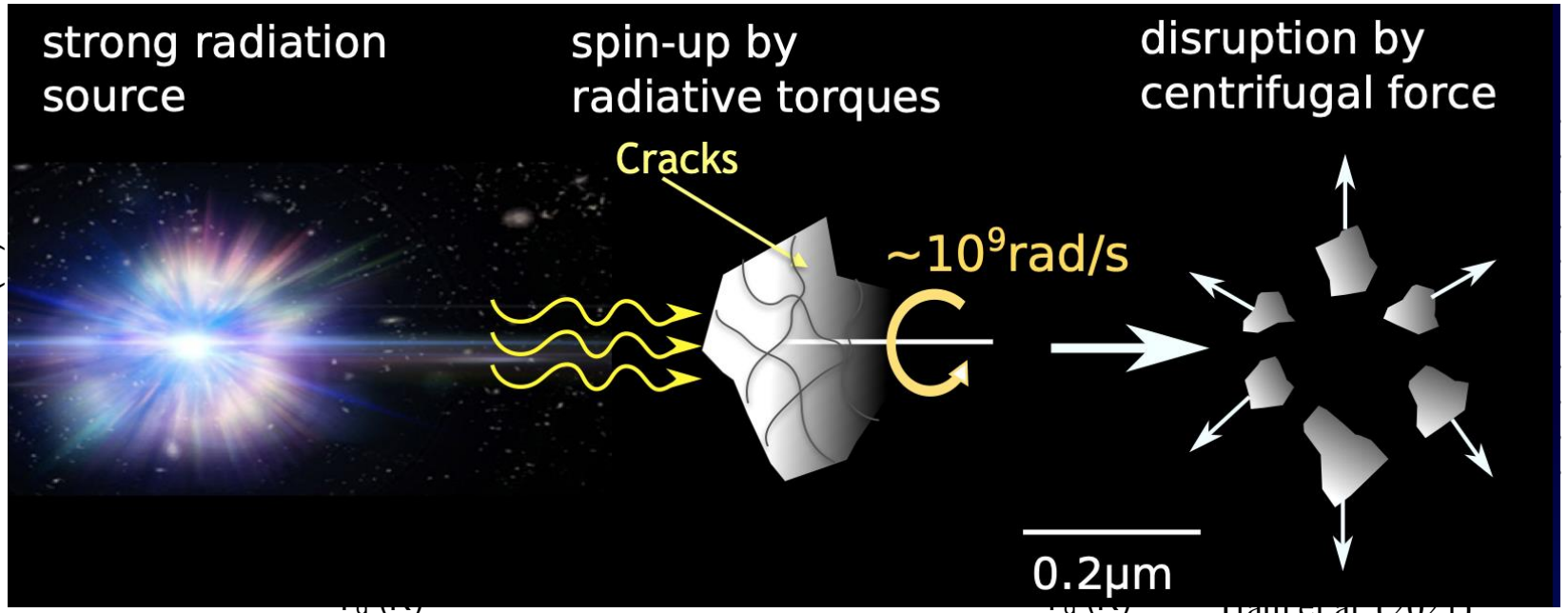


RAT-D

Very strong radiation fields can shatter the grains

- As shown by Hoang et al. (2019), radiative torques can spin up the grains beyond their tensile strength ("RATD"). This can explain FIR observations of star forming regions

Grain Destruction



P (%)

3.5
3.6
3.7
3.8
3.9
4.0
4.1
4.2
4.3
4.4
4.5

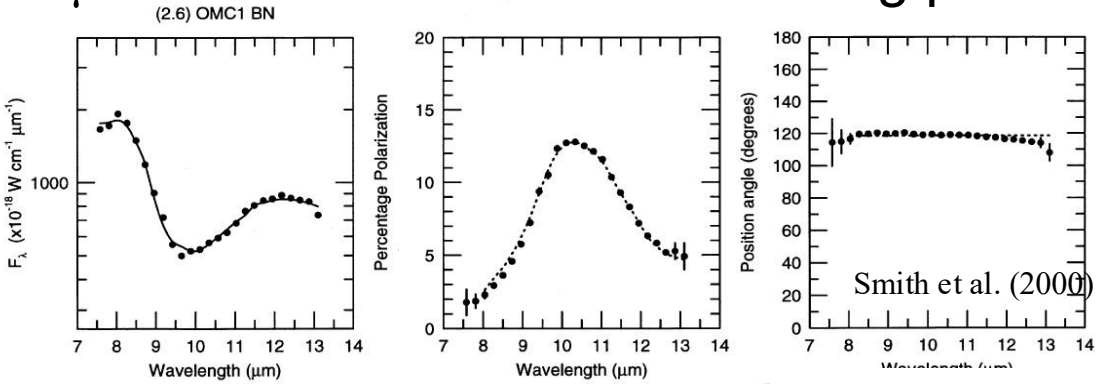
Hall et al. (2021)

- Can probe grain tensile strength, porosity, and structure
- Important for mantle release in YSOs chemistry

Grain Mineralogy

What about, diamagnetic, Carbon grains?

- The 9.7 μm silicate feature shows strong polarization



Grain Mineralogy

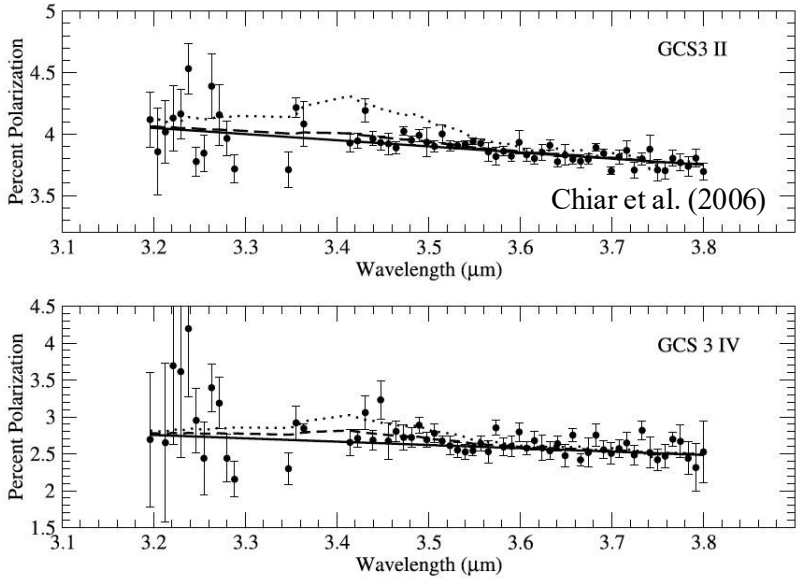
- Carbon solids are diamagnetic
- The 3.4 μm aliphatic CH feature is not polarized

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

  Silicate (9.7 μm): $\Delta p/\tau=2.7$

  CH (3.4 μm): $\Delta p/\tau<1$

  (Chiar et al. 2006)

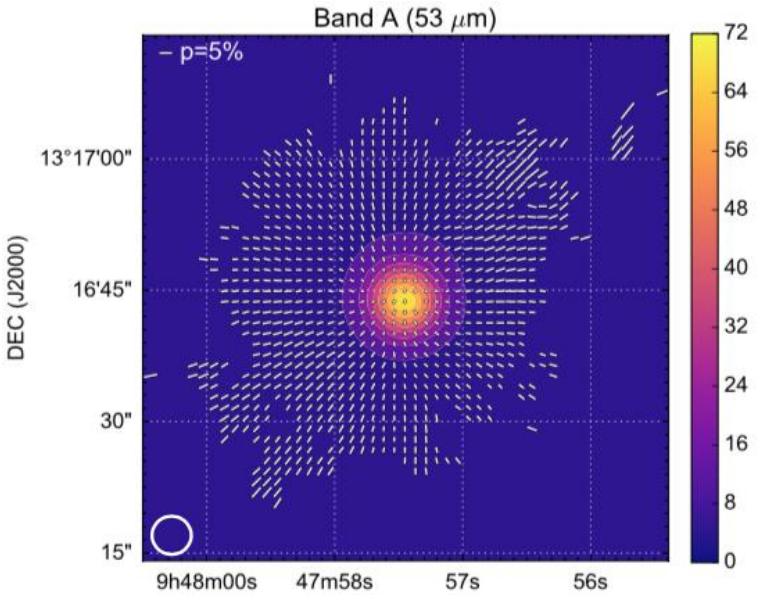


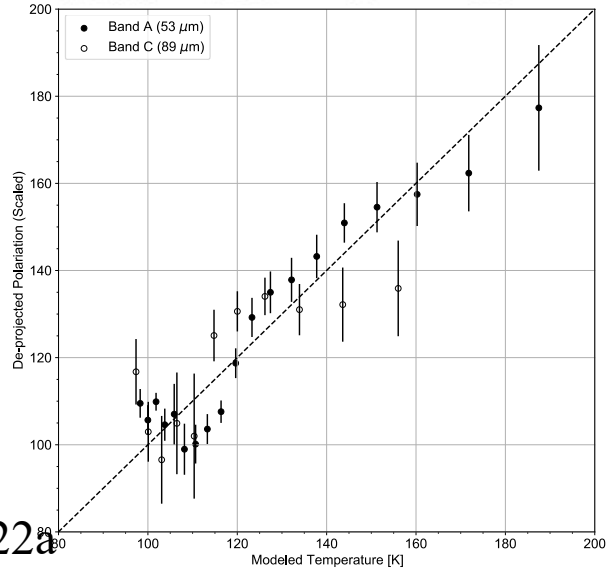
"The [...] polarization predicted for grains with organic mantles, assuming that p/τ is the same as for the silicates, is shown by the dotted line."
Chiar et al (2006)

The case of IRC+10˚216 - FIR

Carbon Grain Alignment

- AGB stars evolve from oxygen dominated dust to carbon dominated
- Ideal laboratory for testing carbon grain alignment
- SOFIA FIR polarimetry shows a centro-symmetric polarization where the polarization fraction is proportional to T_{dust}
- Explained by “second order” k-RAT
- Iron depletion is larger in IRC+10 216 (log(δ)=-2.24 than in the ISM (log(δ)=-2.00 (likely into FeSi)

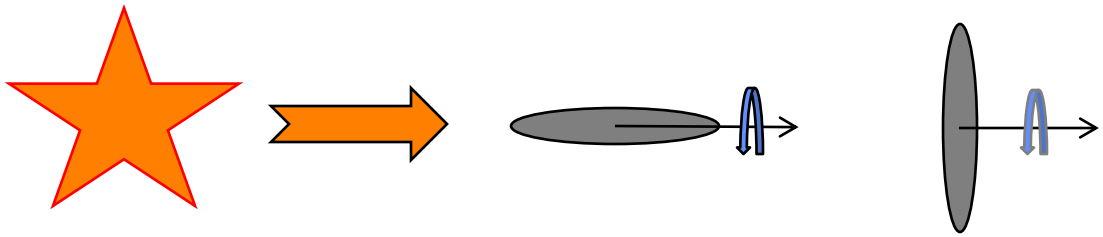




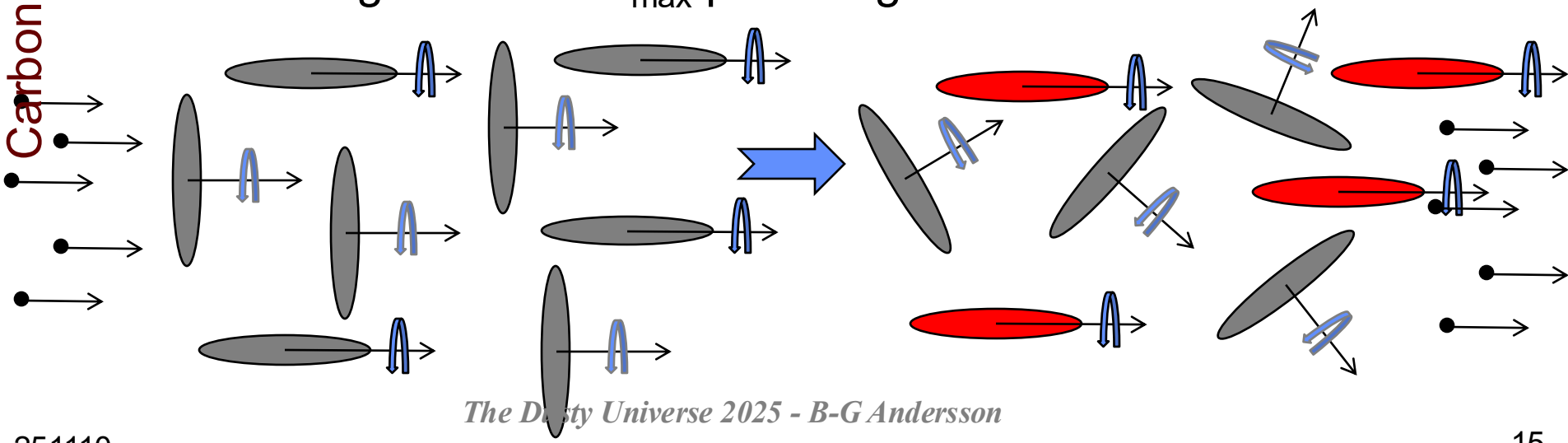
Andersson et al. 2022a

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

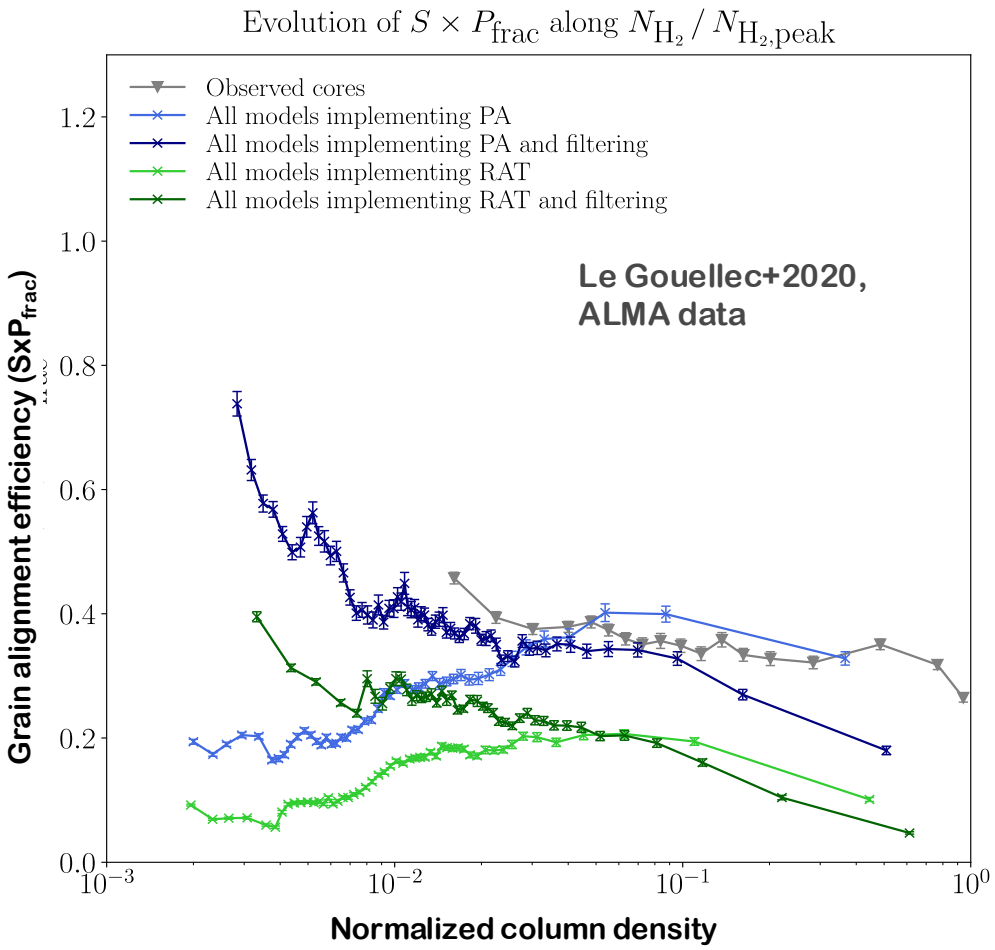


Carbon Grain Alignment

Super-paramagnetic Inclusions

Grain Mineralogy

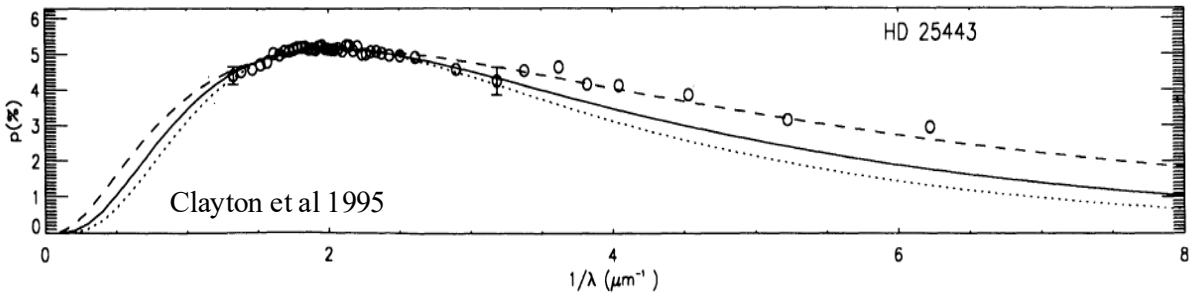
- The internal alignment is slow for large “Silicate” grains
- The polarization fraction in cores implies that the grains are perfectly aligned => Requires Super-paramagnetic grains (iron inclusions)
- But; is it consistent with elemental depletion?



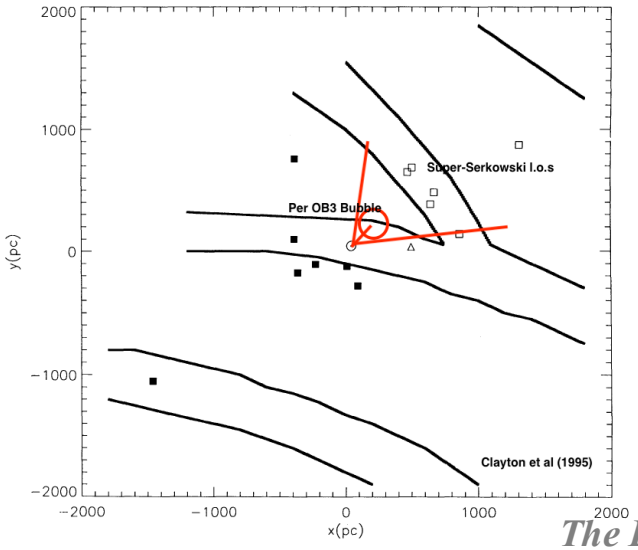
See also Akshaya & Hoang (2023)

Multi-Wavelength Observations [,the power of]

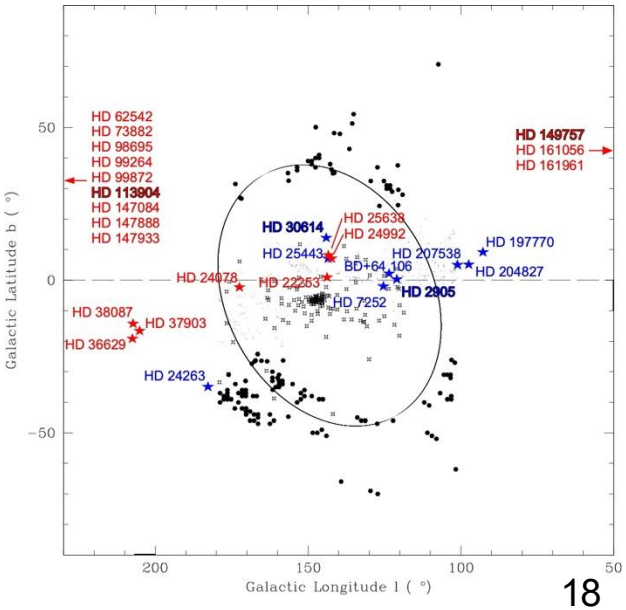
Grain alignment – and the EUV field



- Only 28 lines of sight has been probed in UV polarization (WUPPE + HST/FOS).
- In 9 of these, the UV polarization significantly exceeds the Serkowski-fit based on the O/NIR.
- Most of these are behind the Per OB3 bubble (Clayton et al. 1995)
- Grain alignment happens when $\lambda < d_{grain}$ so UV polarization implies small aligned grains
- The Super-Serkowski Polarization (SuSeP) [likely] traces sub-Lyman-limit radiation fields

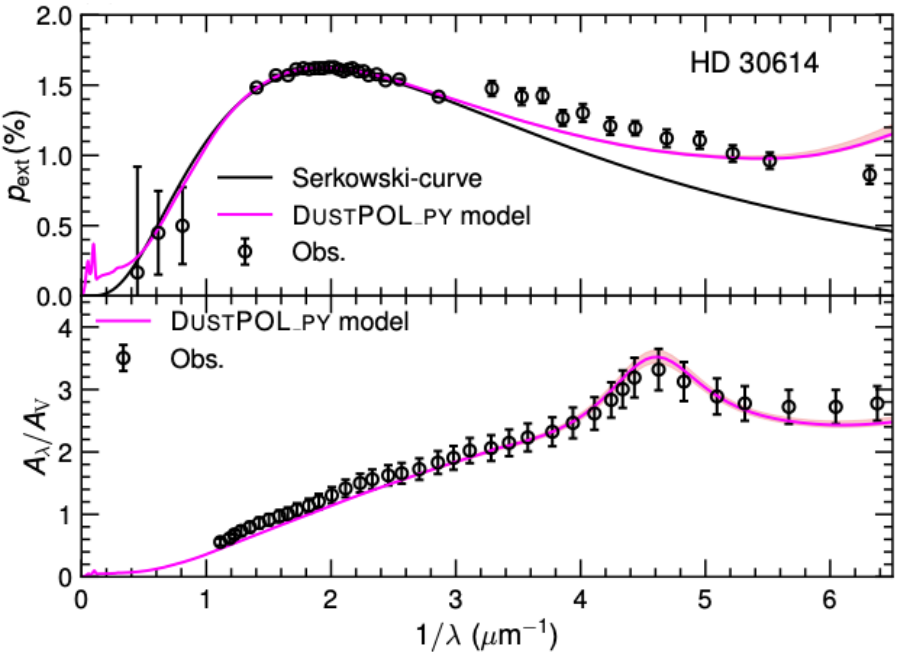


The SuSeP polarization can probe the EUV continuum and the B-field inside super bubbles and [large] H II regions
The spectrum of the SuSeP will trace the EUV field

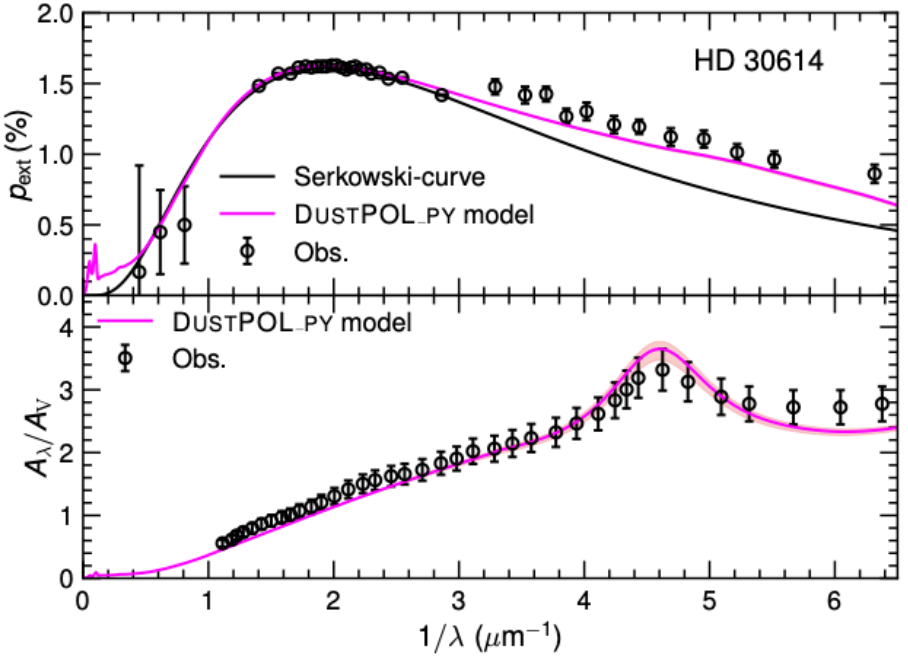


Super-Serkowski UV Polarization

- Tram et al. (2026, in prep) have modeled the SuSeP effect based on, either the inclusion DG alignment for the smallest grains, or EUV aligning radiation.
  - B-fields (for DG) from modeling of Faraday rotations data (B~5 μG)



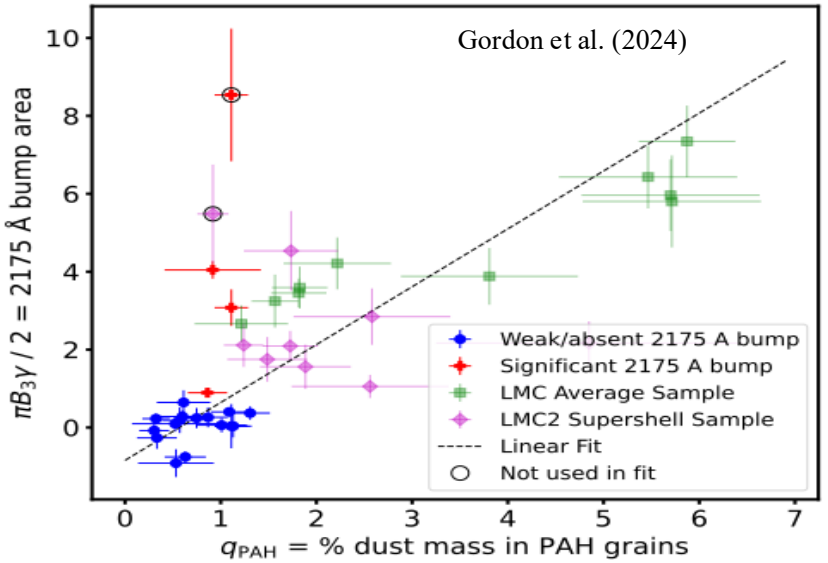
With DG for the smallest grains

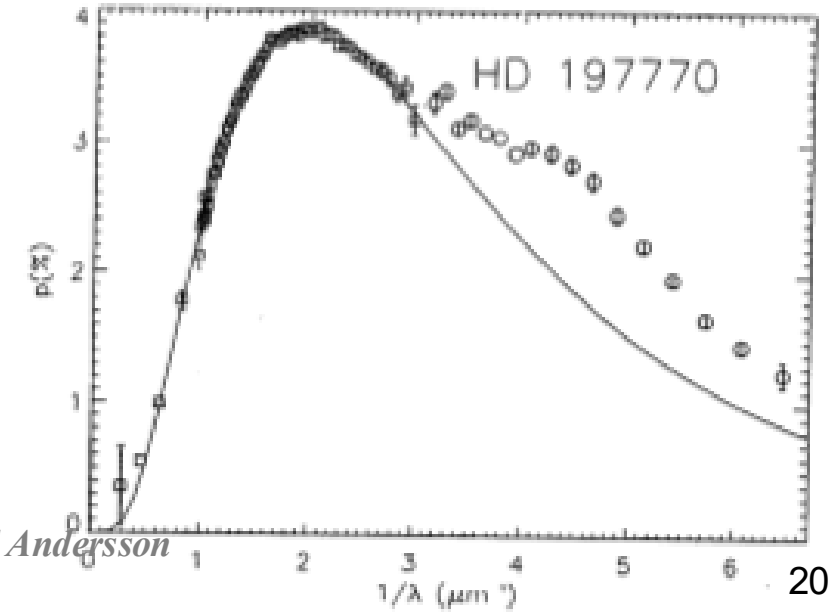


With EUV alignment of the smallest grains

[The rare] Polarization of the 2175Å extinction feature

- What is the carrier of the 2175Å extinction feature?
  - Abundance arguments favor an association with carbon solids
  - Recent observations show correlation with PAH emission
- The feature is polarized in [Only] 2 of 28 l.o.s.
  - Consistent with that carbon dust doesn't *usually* align
  - This is a potentially crucial constraint on the carrier and environment, but we NEED MORE DATA





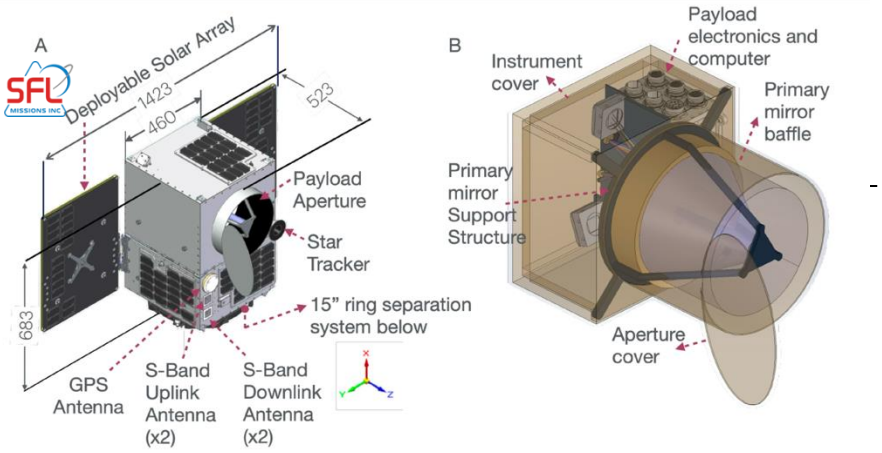
PUFFINS: a smallsat ("PIONEER") mission looking for UV spectropolarimetric signals in interstellar dust

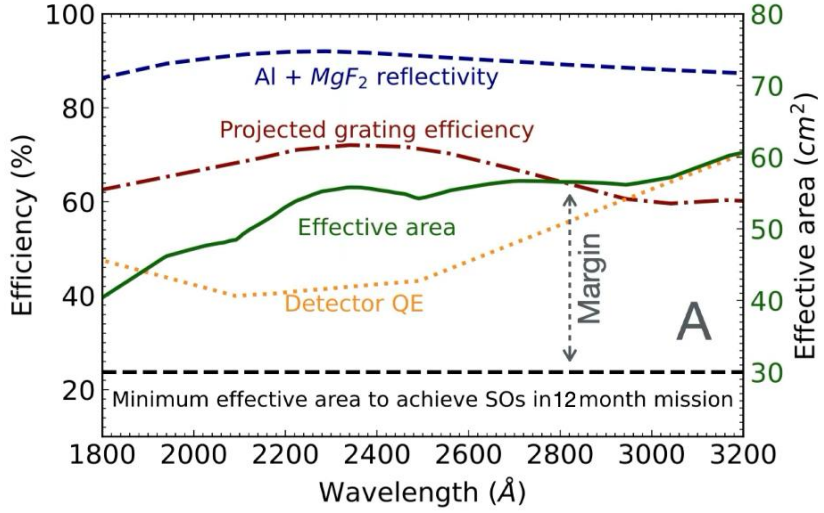
- *"PUFFINS: fishing for UV Spectro polarimetric signals from interstellar dust"*
- **PI: Ramya M Anche**, University of Arizona
- **Science PI**: **B-G Andersson**, McDonalds Observatory

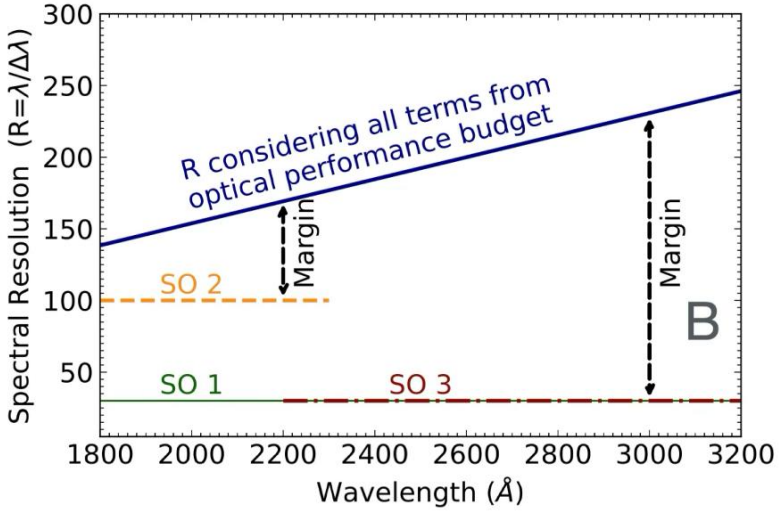
Science goals:

- What are the characteristics and dynamics of the small interstellar dust grains?
- How do they interact with and probe the magnetic fields?
- Declared **"Selectable"** pending clarification of budget and programmatic priorities in FY26

PUFFINS: A 25 cm space telescope with a spectropolarimeter







Summary

- RAT alignment is now the accepted main mechanism for IMS grain alignment
- Several “sub-classes” have been developed and [being] tested
- Under the RAT paradigm, polarimetry now allows unique tools for understanding not only the magnetic field, but many aspects of ISM grains and their environment
- BUT: We need [spectro-]polarimeters at all wavelengths!
  - Especially UV and NIR/MIR

Ad Astra,
Fratercula arctica[*],
Ad Astra!

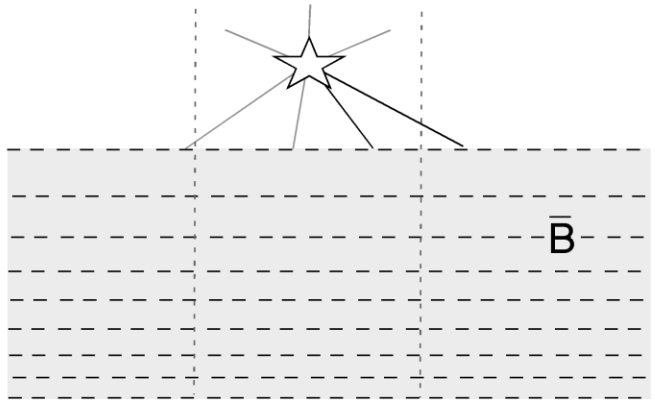
[*] Puffin

Back-up slides

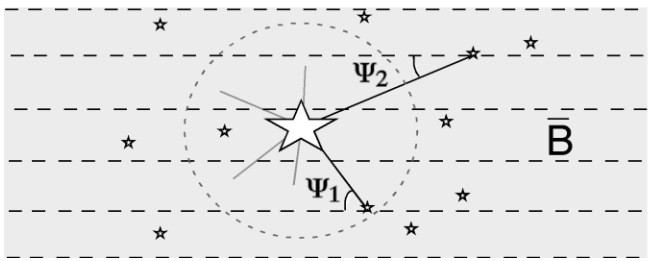
The alignment depends on the angle of illumination

Grain Shape

- 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 depends on the angle of illumination II

Grain Shape

- 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 – if the grains are **oblate**