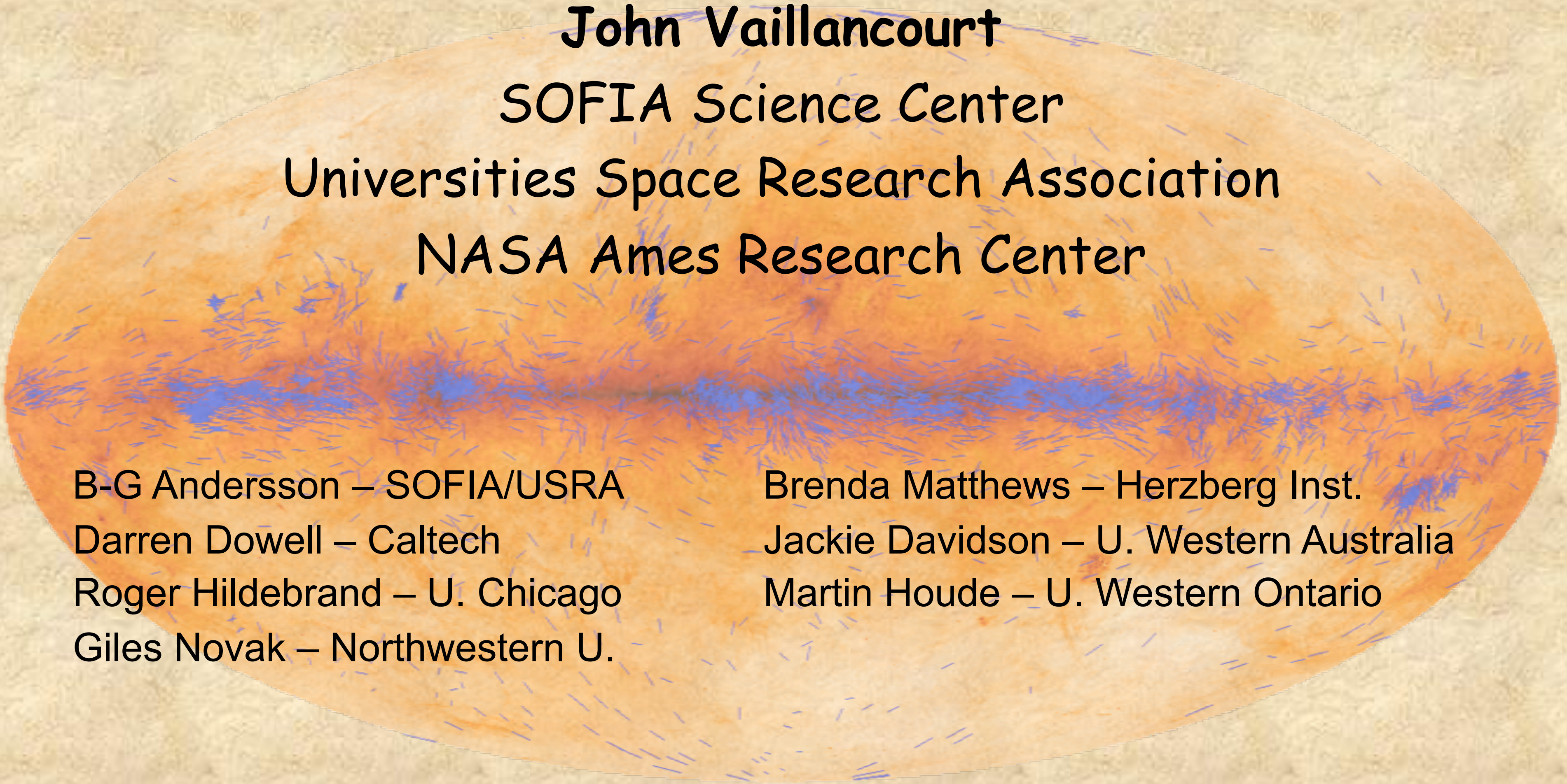
Dust & Polarization in the Interstellar Medium

John Vaillancourt
SOFIA Science Center
Universities Space Research Association
NASA Ames Research Center

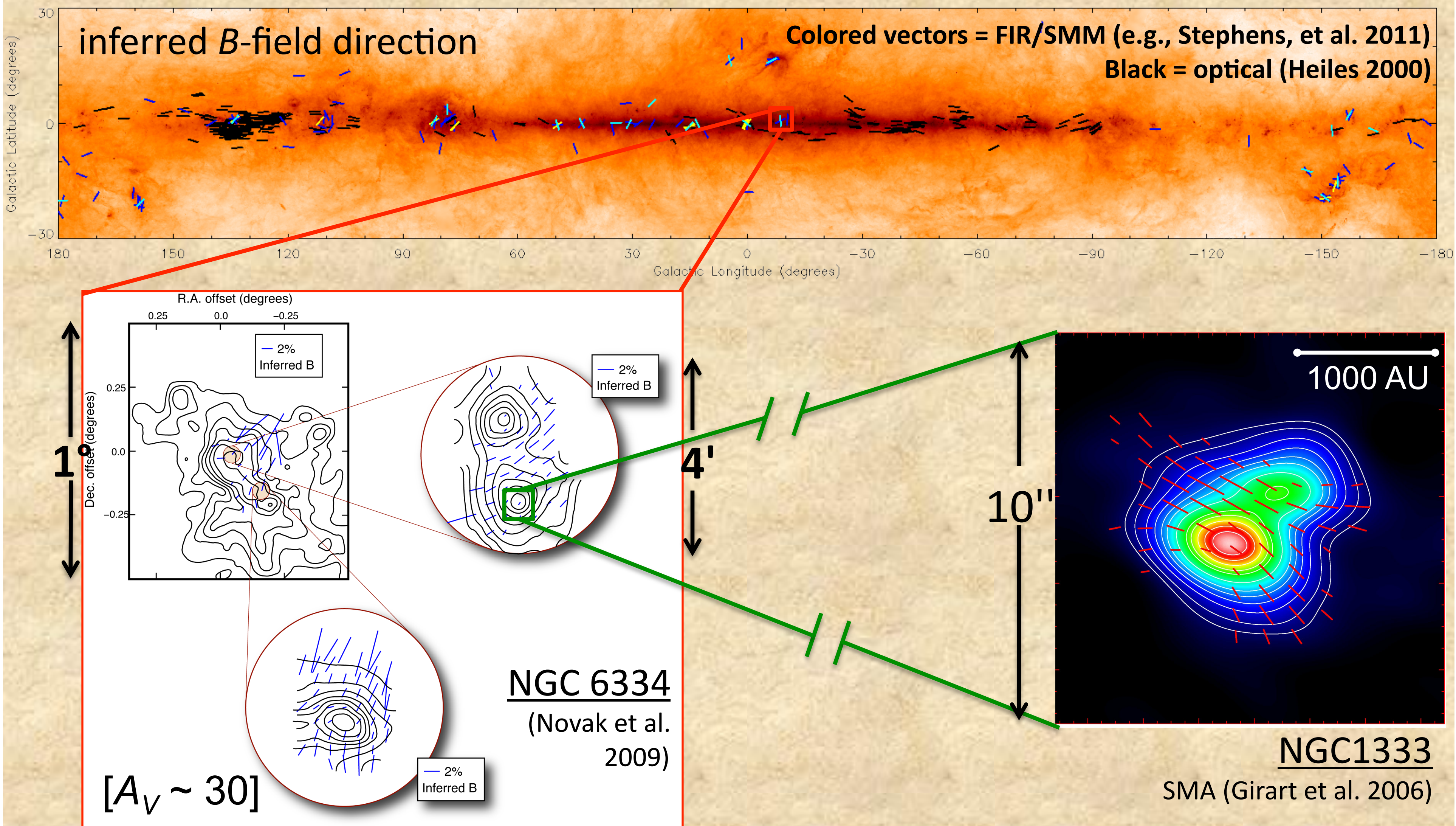


B-G Andersson – SOFIA/USRA
Darren Dowell – Caltech
Roger Hildebrand – U. Chicago
Giles Novak – Northwestern U.
Brenda Matthews – Herzberg Inst.
Jackie Davidson – U. Western Australia
Martin Houde – U. Western Ontario

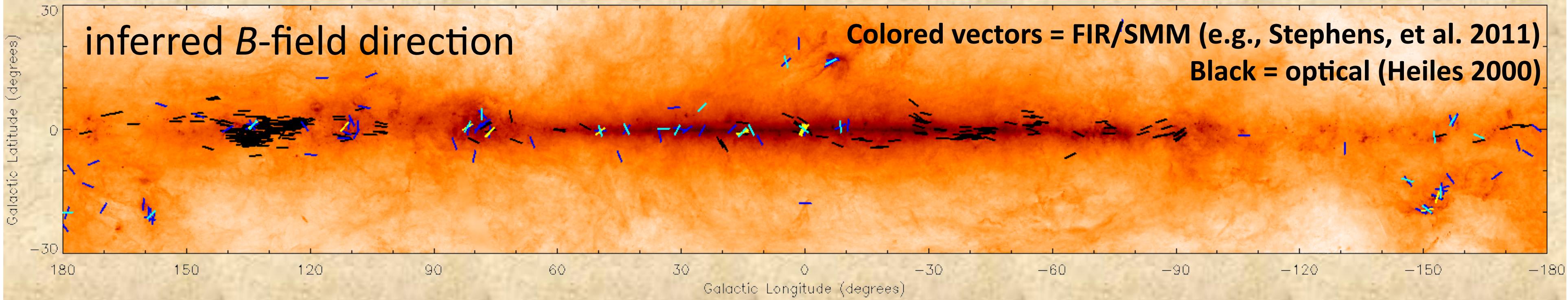
Polarized Dust in the ISM

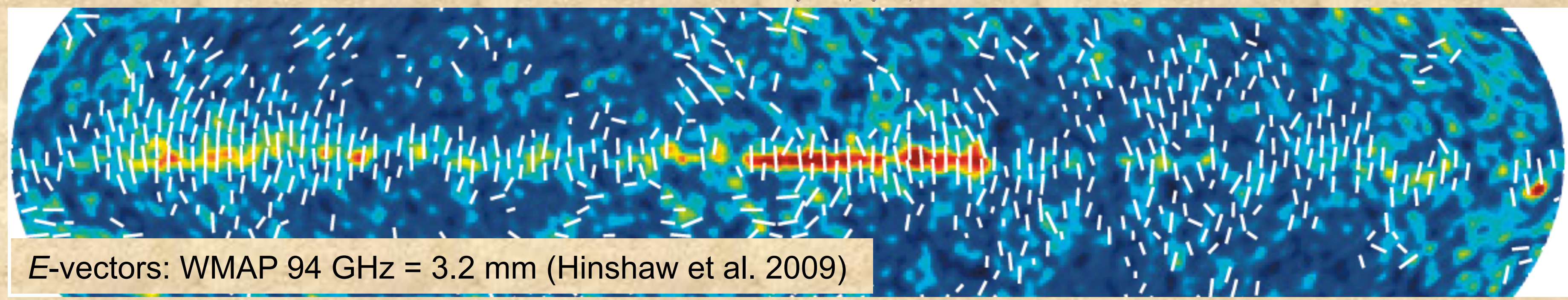
- Polarization: optical through mm wavelengths
  - Why is light polarized? → dust grains are aligned
  - Why, Where, and How are grains aligned with ***B***-field?
- Polarization spectra observations (among others)
  - optical extinction (near-UV thru near-IR) in diffuse ISM
  - FIR/MM emission in dense clouds
- "Unified" models to explain polarized emission & absorption
- Extension to …
  - emission from Dark clouds and the diffuse ISM
  - Longer wavelengths: $\lambda \rightarrow$ 3 cm, $\nu \rightarrow$ 10 GHz

Where is Dust/Light Polarized?



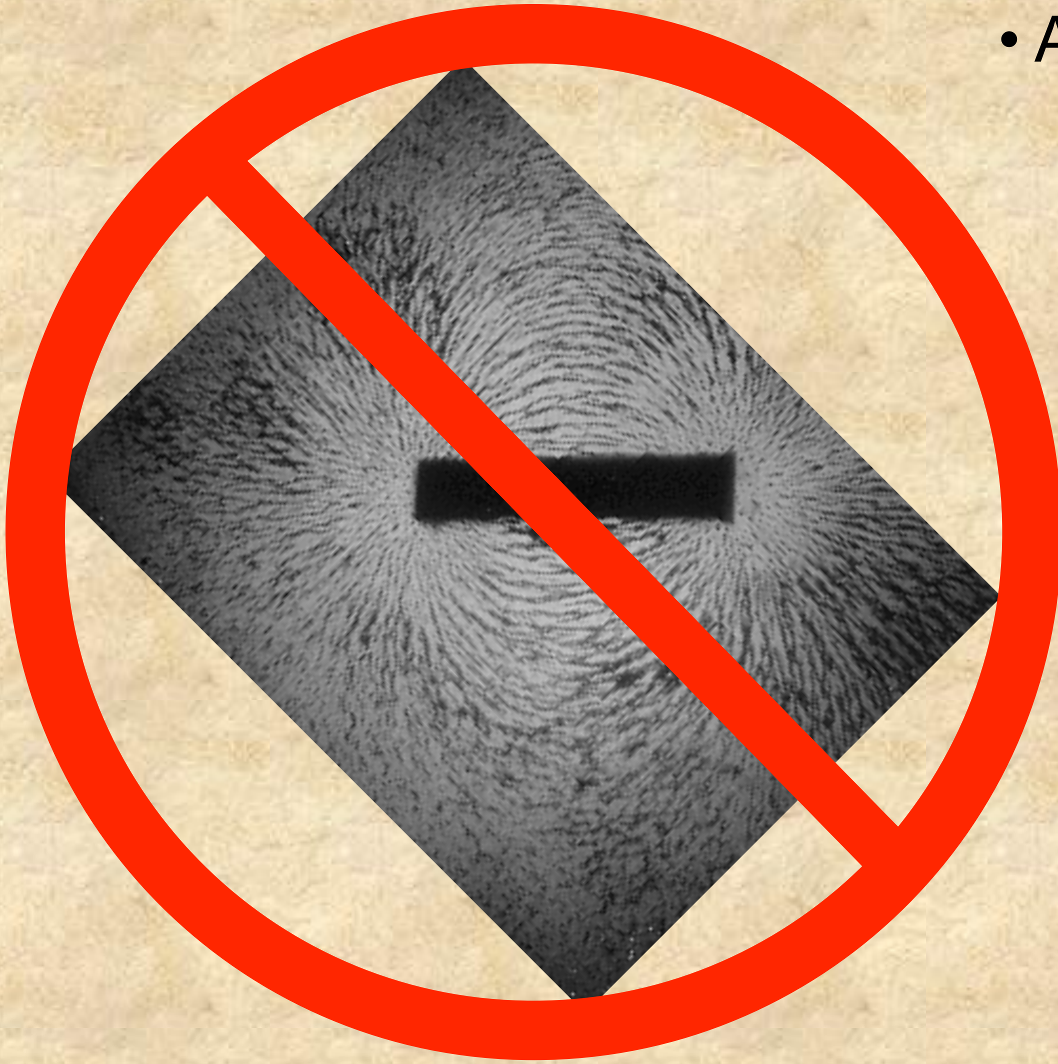
Where is Dust Aligned?





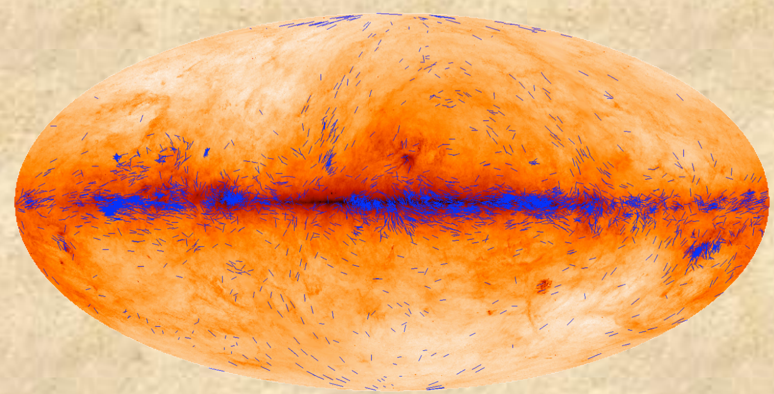
- Where is dust aligned? -- Polarization observed in both diffuse (A_V <~ 5) and dense (A_V > 10) regions of ISM
- Is polarization tracing *B*-fields in all these environments? – need consistent alignment model

Ferromagnetic alignment?



- Alignment easily disrupted by collisions
  - Insufficient Fe in dust
  - *B*-field too weak (< mG)
    - B_{MW} ~ few μG

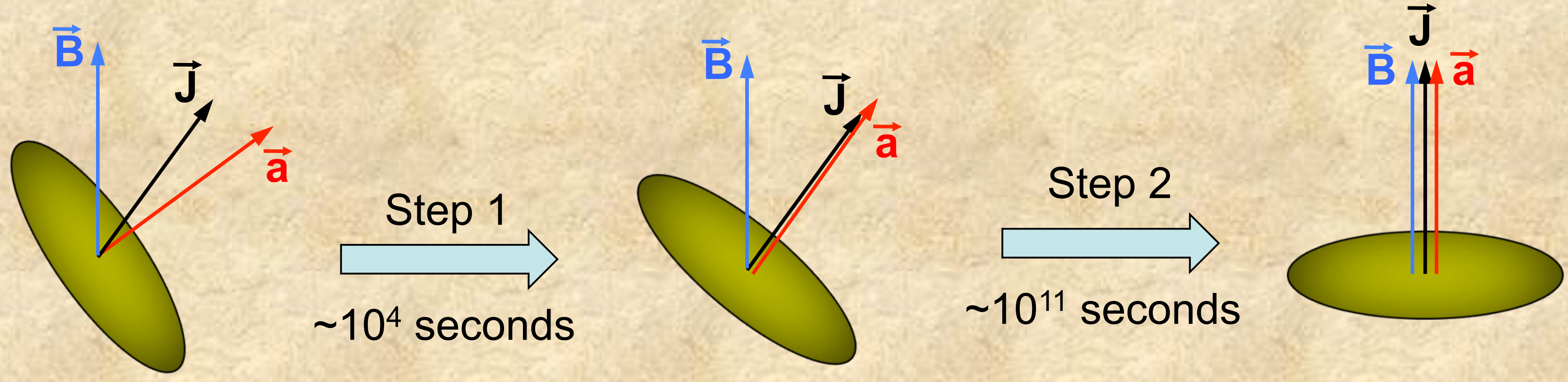
(Spitzer & Tukey 1951, ApJ, 114, 187)



Paramagnetic Grain Alignment

$\vec{B}$ – Magnetic Field direction
$\vec{J}$ – Angular momentum (spin axis)
$\vec{a}$ – grain's largest inertial moment

Goal: τ(align) < τ(collision) ~10^{13} sec.



Step 1: Internal Alignment

- internal relaxation / dissipation, via (nuclear) Barnett-effect

Step 2: Angular Momentum alignment

- paramag. dissipation, suprathermal rot'n & H_2 torques?
- radiative torques

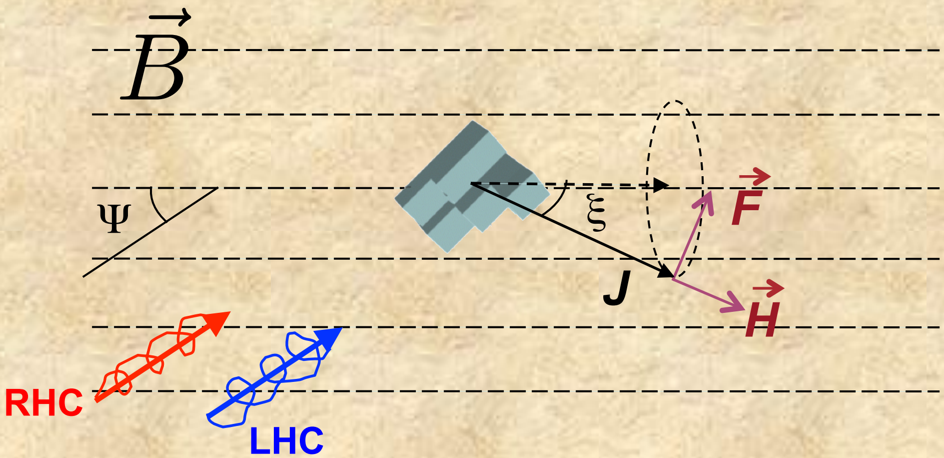
Davis & Greenstein 1951
Jones & Spitzer 1967
Purcell 1979
Lazarian & Draine 1999
Hoang & Lazarian 2008

Radiative Alignment Torques (RAT)

F is the alignment torque (⊥ to J)

H is the spin-up torque (|| to J)

Dolginov & Mytrophanov (1976)
Draine & Weingartner (1996, 1997)
Lazarian & Hoang (2007)
Hoang & Lazarian (2008, 2009)



An asymmetrical grain has different right- and left- handed helicity components and therefore couples differently to right- and left-handed circularly polarized radiation components

- What are values ξ_0 and J_0 such that $\langle F \rangle = \langle H \rangle = 0$, and $d\langle F \rangle / d\xi < 0$?
- Exact answer is a function of things like: radiation field, grain size, wavelength, Ψ, …

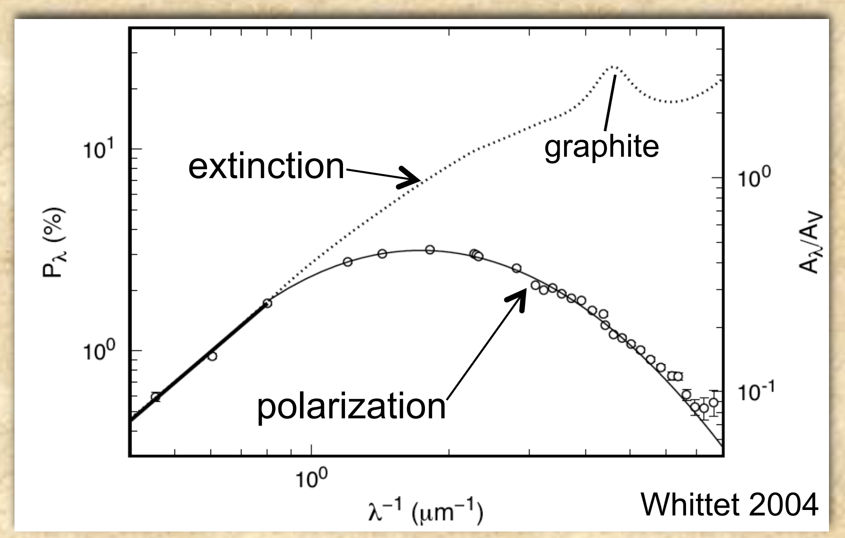
$\xi_0 \approx 0$ or π

Tests of Alignment Theories

- Predictions of the Radiative Torque Model:
  - Alignment efficient up to A_V~10, necessary for dense regions
    - compared to H_2 torques which drop at lower A_V (i.e., no more free-H)
    - difference in T_{gas} and T_{dust} not necessary
  - Increased grain alignment efficiency with exposure to photons
    - Drop in polarization with opacity; "polarization holes"
    - Drop in polarization with distance from radiation source
  - Larger grains are better aligned than small grains
    - shift in polarization spectrum
  - Polarization dependent on angle between radiation direction and magnetic-field

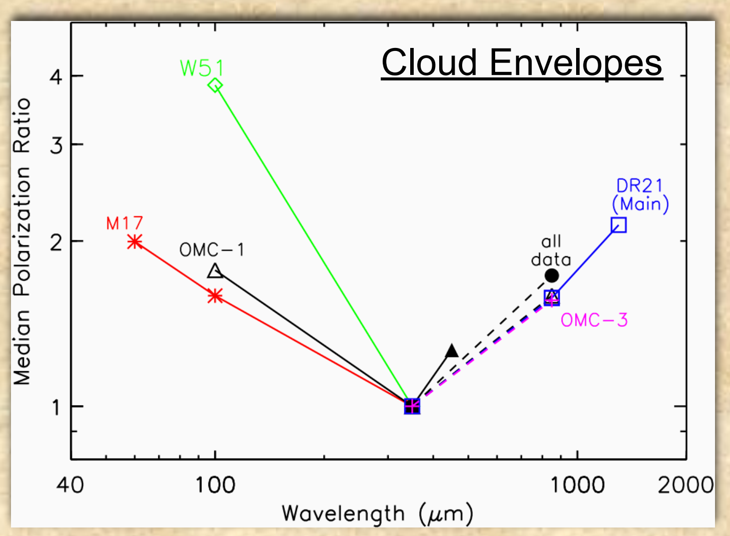
Polarization Spectra

Near-optical wavelengths (λ~*a*)



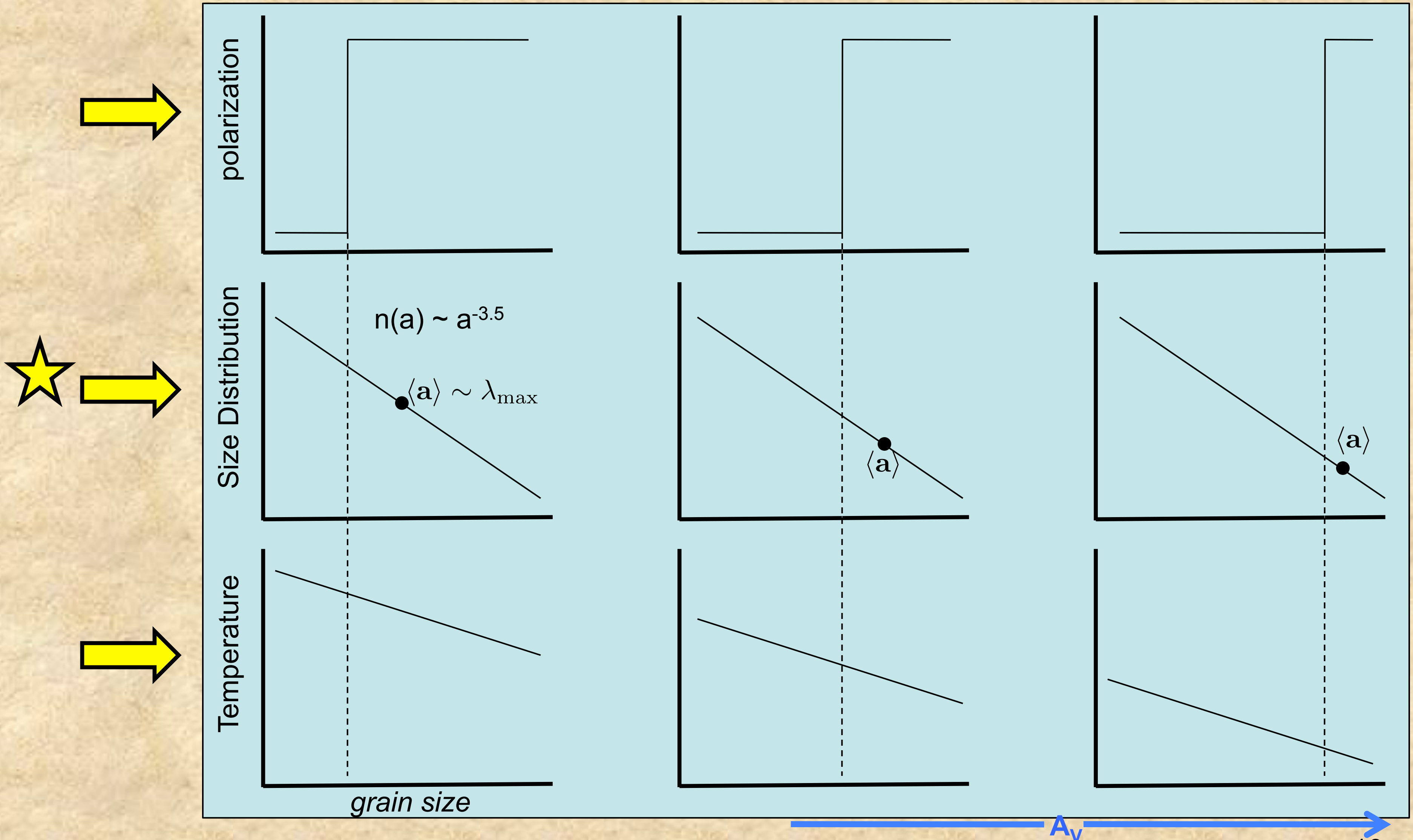
- large grains (traced by NIR) better aligned than small grains (traced by UV); e.g. Kim & Martin 1995

FIR–MM wavelengths (λ>>*a*)

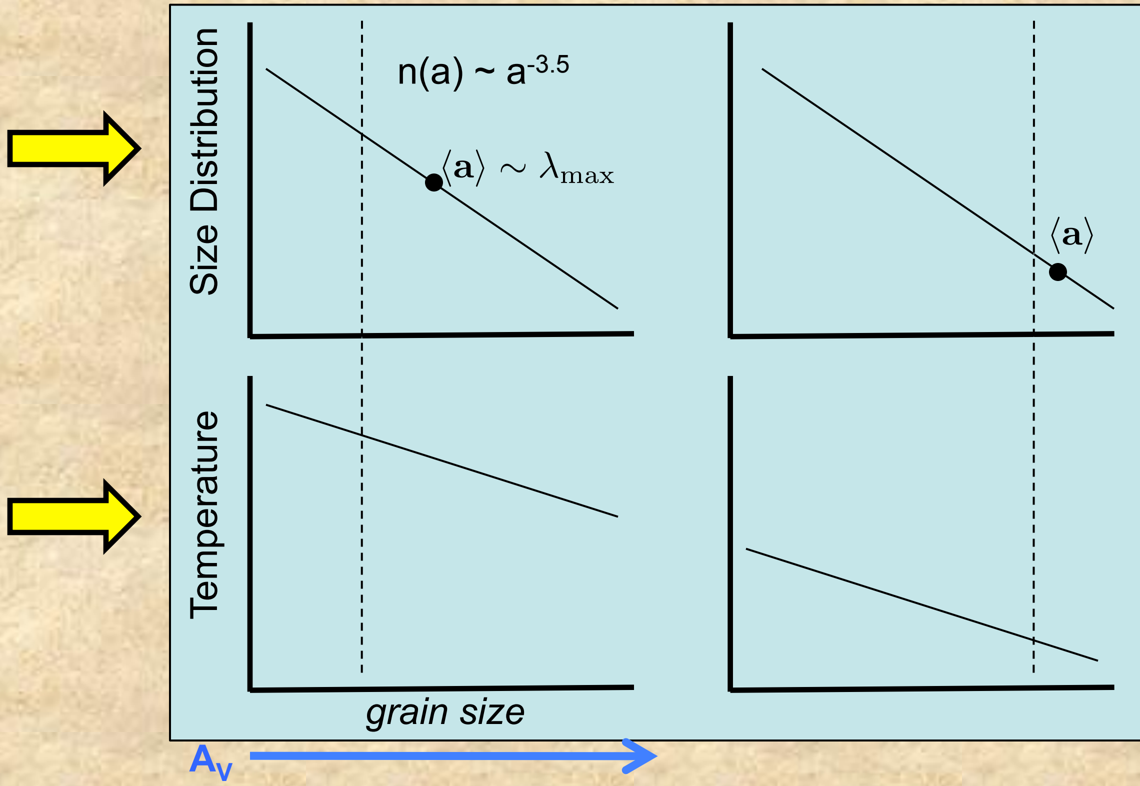


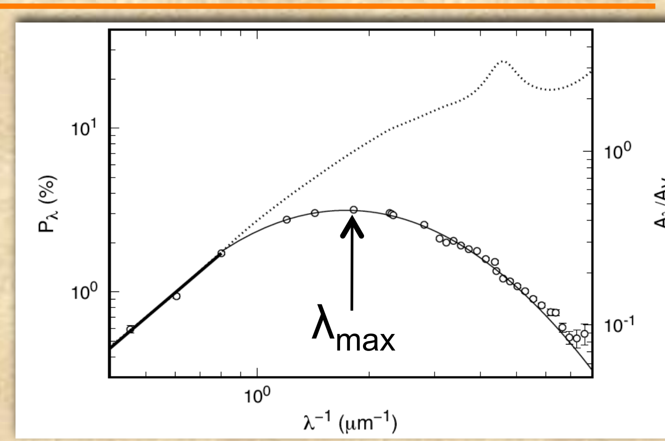
- multiple domains of grain temperature and polarization/ alignment; Hildebrand et al. 1999
- most recent: Vaillancourt & Matthews 2012

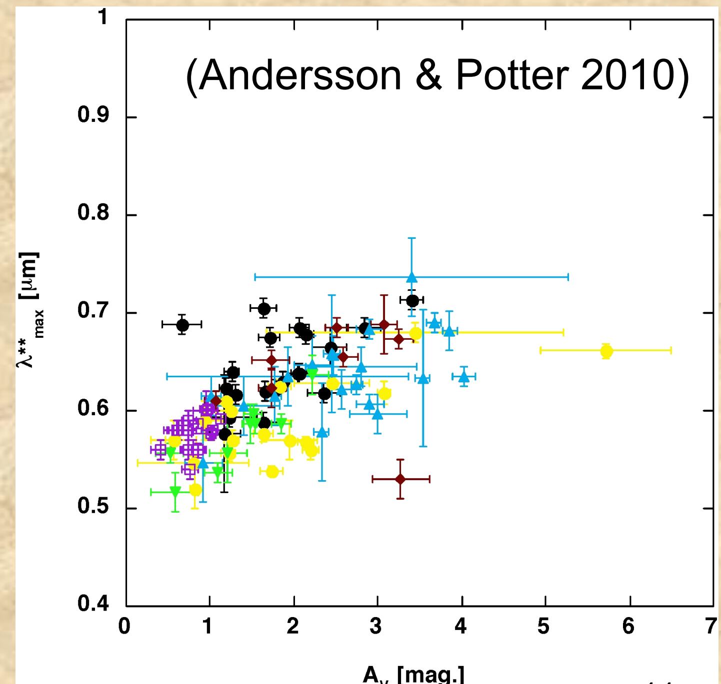
Simplified Cloud Model



Simplified Cloud Model - NIR

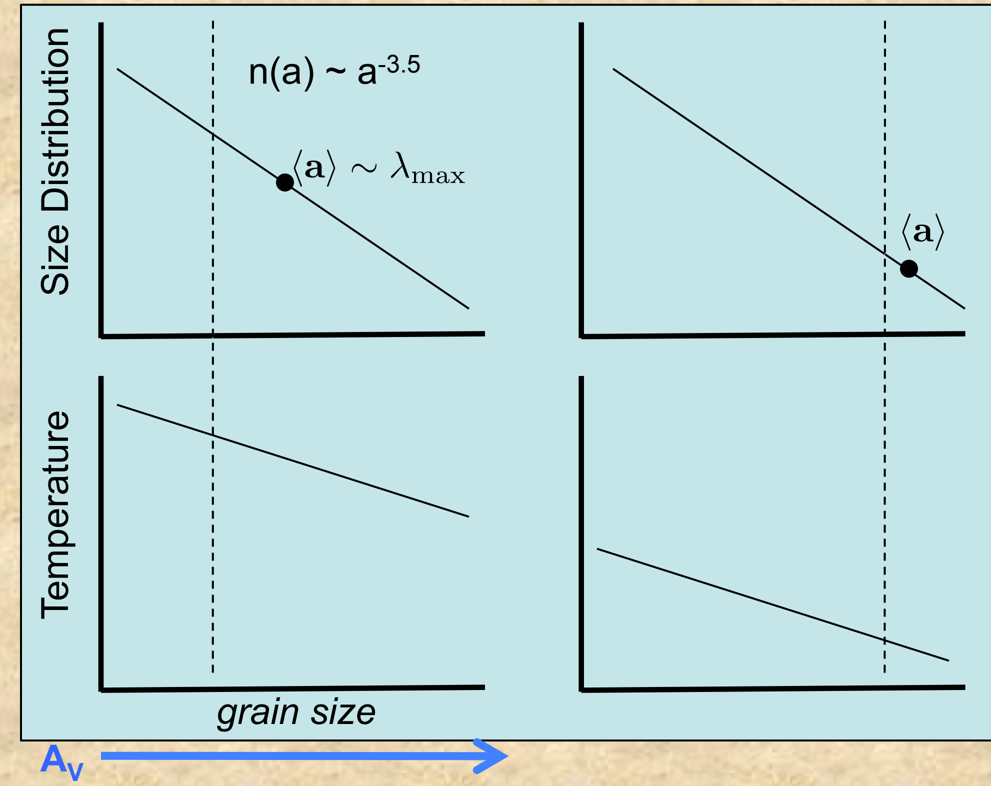




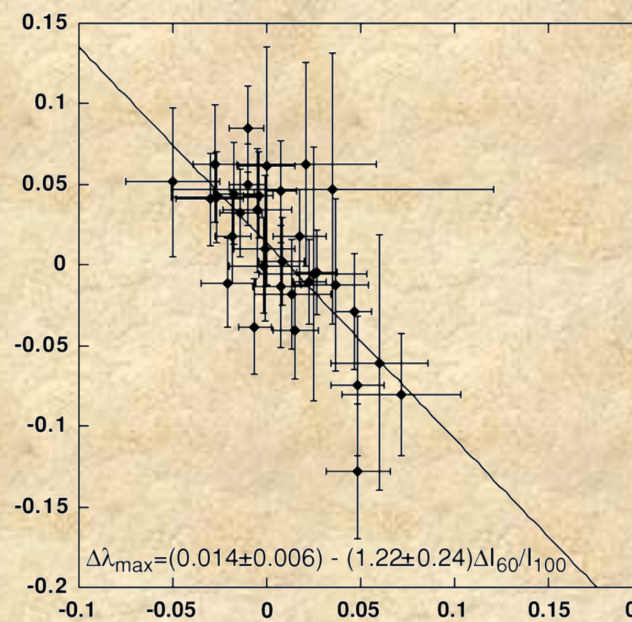


In near-visible ➔ correlation between λ_{max} and A_V

Simplified Cloud Model - NIR

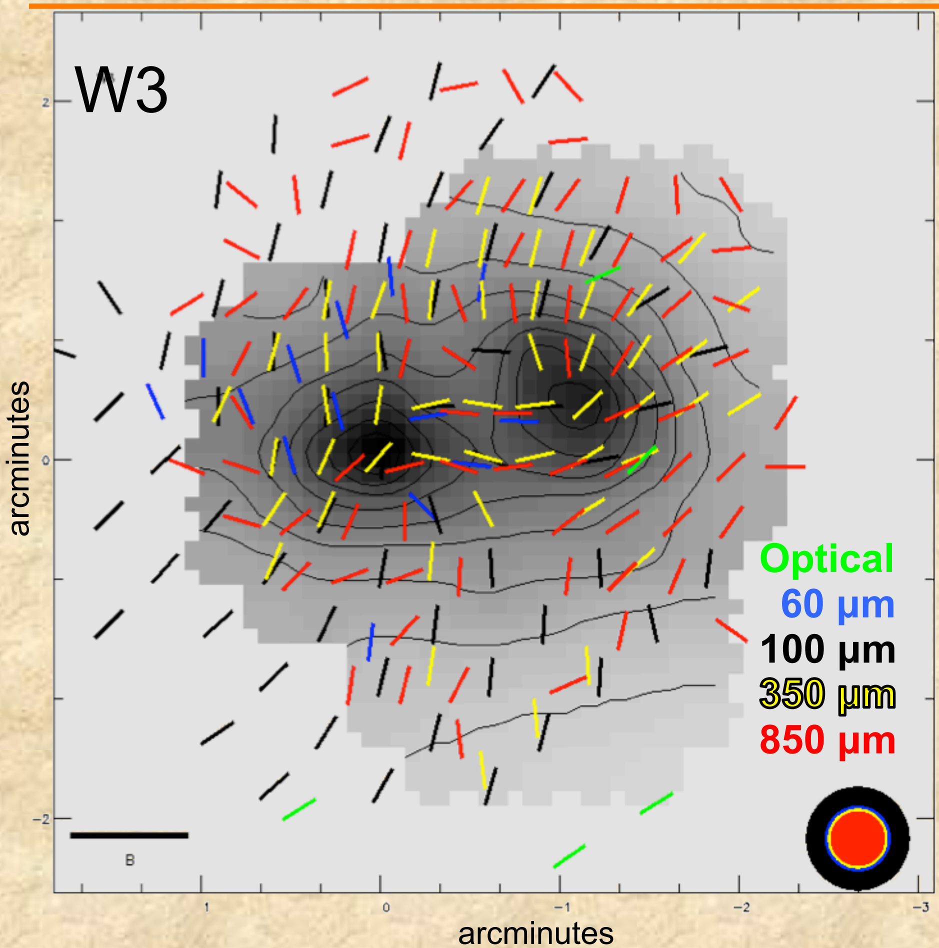


In near-visible ➔ anti-correlation between λ_{max} and Temperature

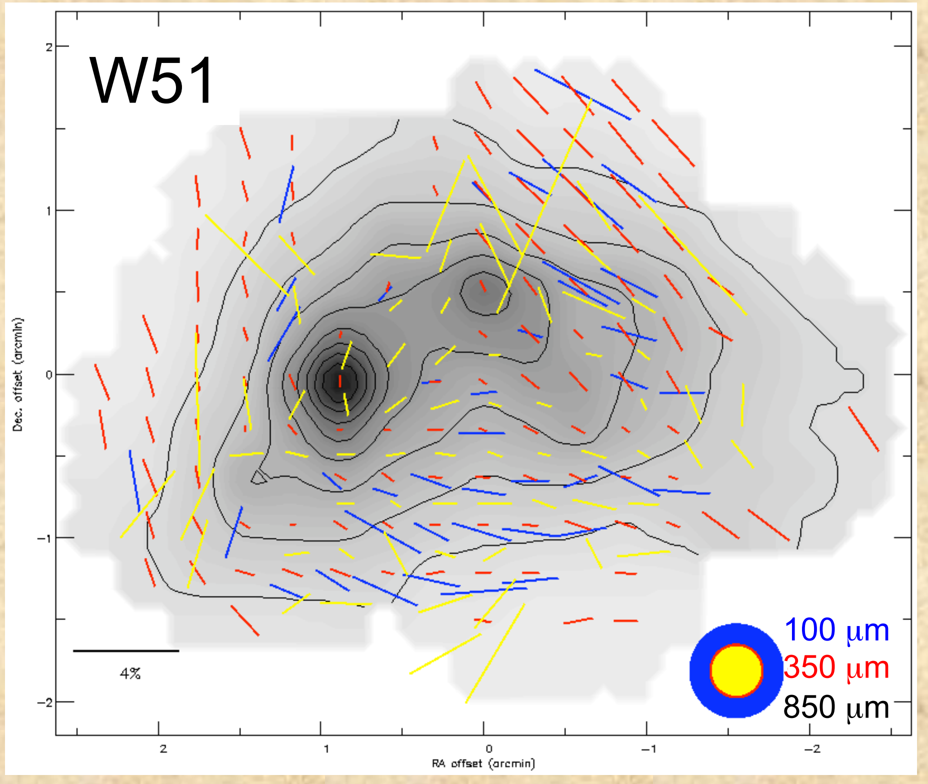


λ_{max} vs. Temperature (Andersson & Potter 2010)

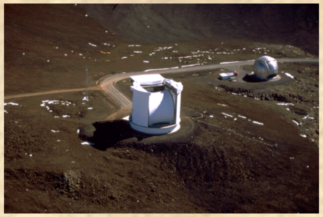
Polarized Emission vs. Wavelength



Schleuning et al. 2000, Matthews et al. 2009
(350 μm grayscale/contours)

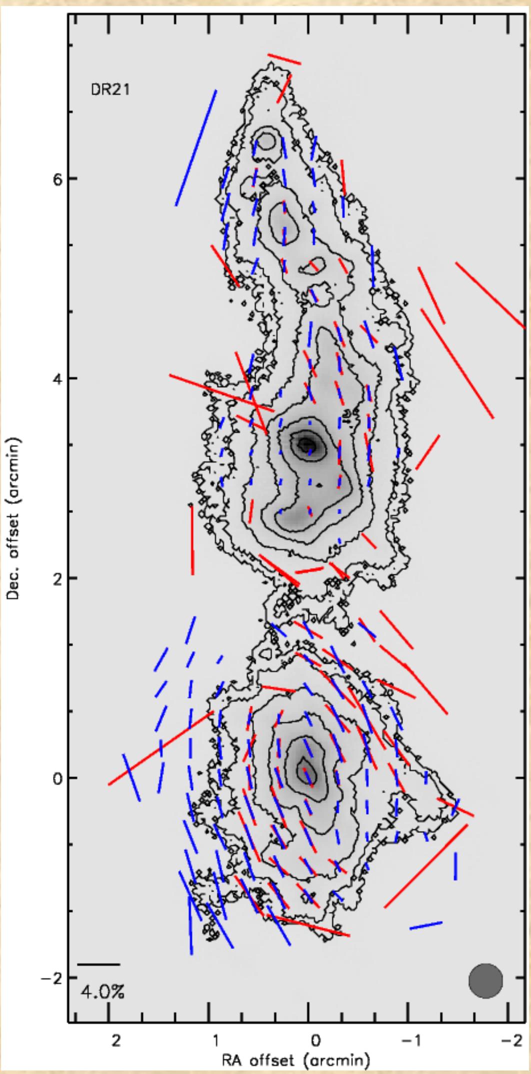


Dotson et al. 2000, 2010;
Chrysostomou 2002

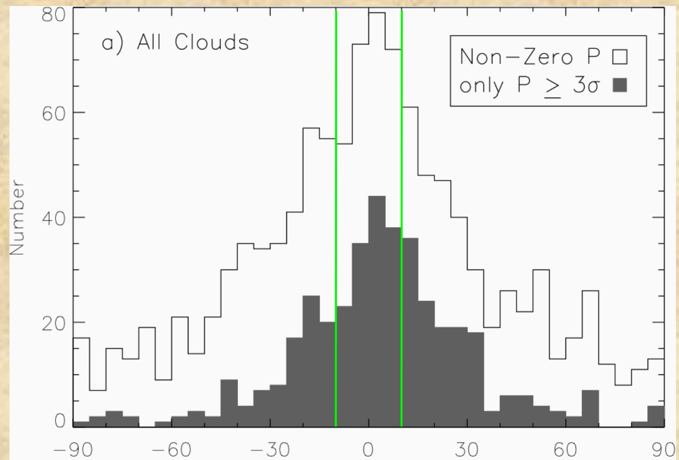


Comparing Hertz & SCUBA

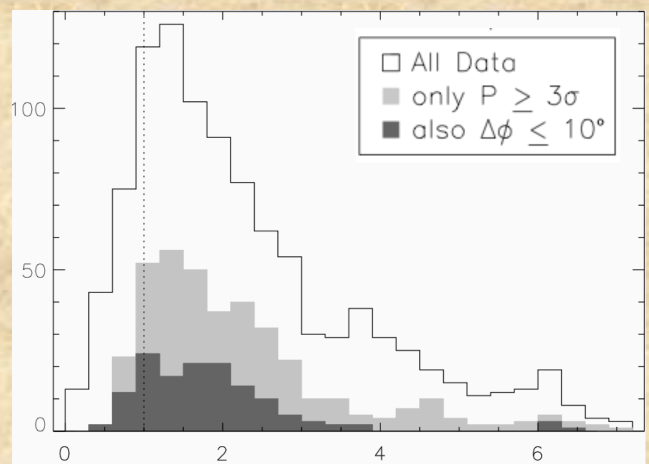
Hertz @ CSO 350 μm **SCUBA-pol @ JCMT 850 μm**



Vaillancourt & Matthews 2012



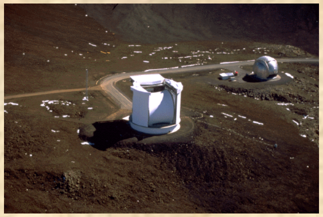
Position Angle Difference
$\phi(850)-\phi(350)$



Polarization Ratio
P(850) / P(350)

Data Cuts: $P > 3\sigma_p$ and $|\phi(850)-\phi(350)| < 10°$

All 14 Objects: Median *P*-ratio = 1.7 ± 0.6



Comparing *Hertz* & SCUBA

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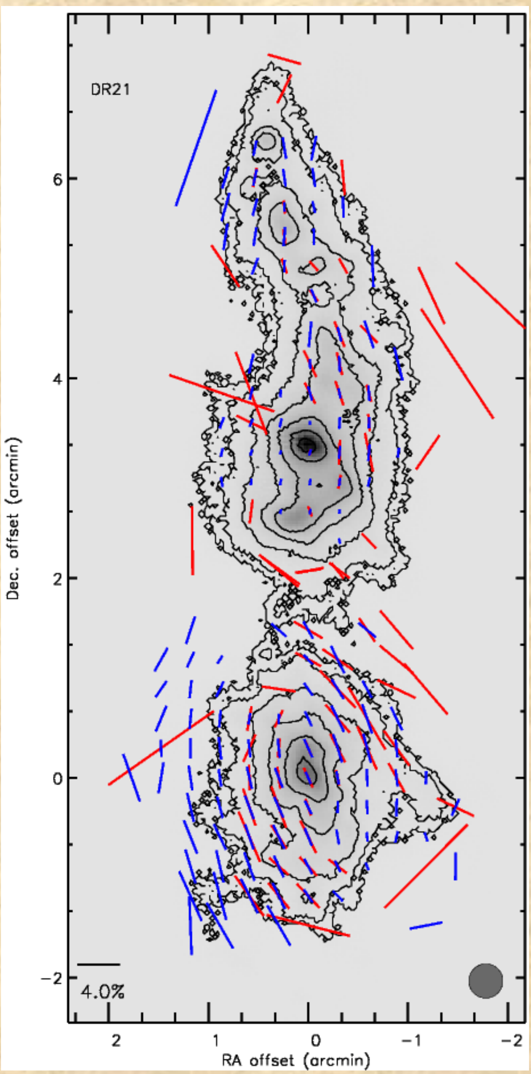
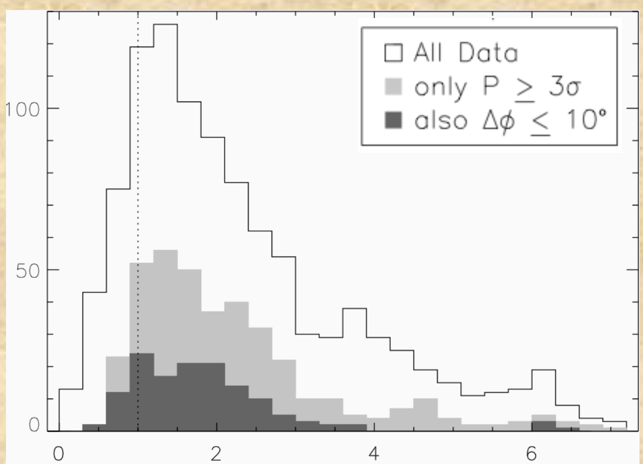
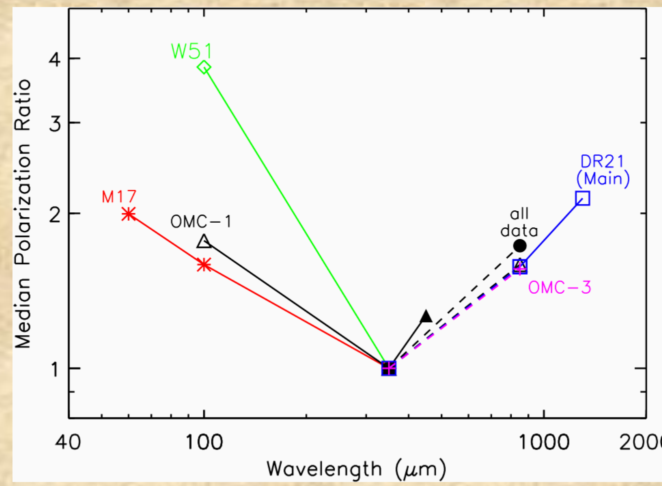


Hildebrand et al. 1999, Vaillancourt et al. 2008,
Vaillancourt & Matthews 2012





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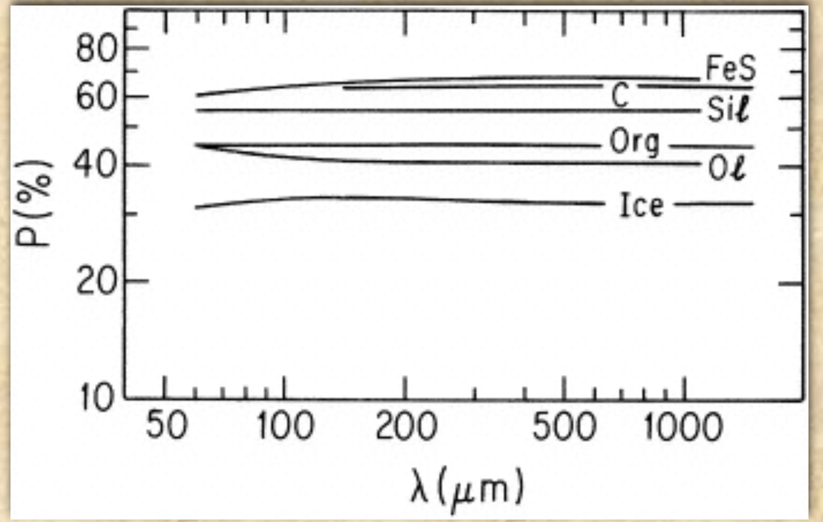
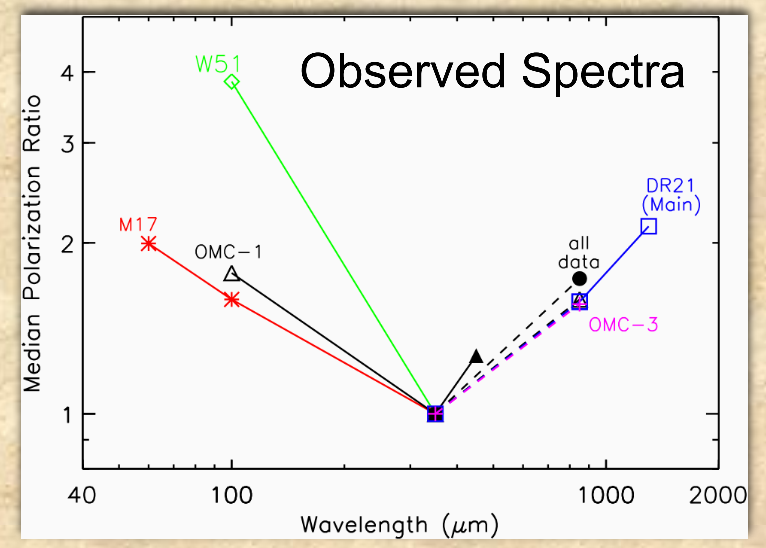
Predicted Polariz'n Spectrum (1)

Dust emission from
- A **single grain species** at
- A **single temperature**

(Hildebrand et al. 1999)



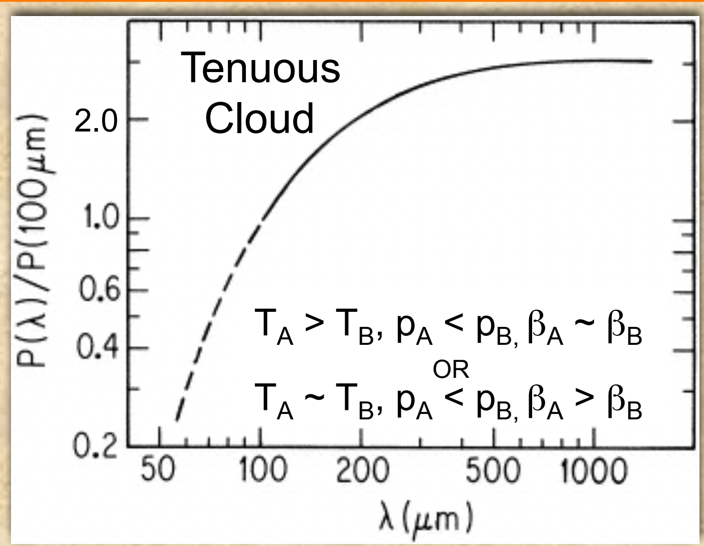
Does not match Observations !



Predicted Polariz'n Spectrum (2)

~~Dust emission from~~
- ~~A **single grain species** at~~
- ~~A **single temperature**~~

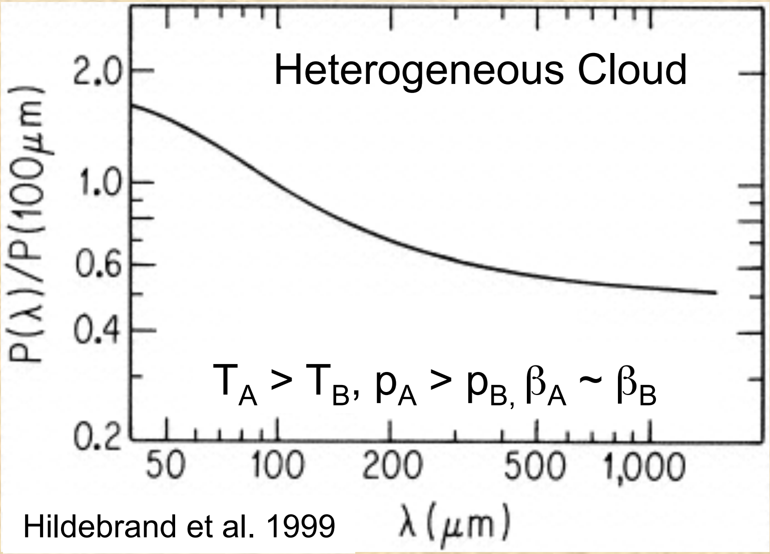
~~(Hildebrand et al. 1999)~~



Dust emission from
- **multiple grain species**
- **multiple temperatures or emissivities**

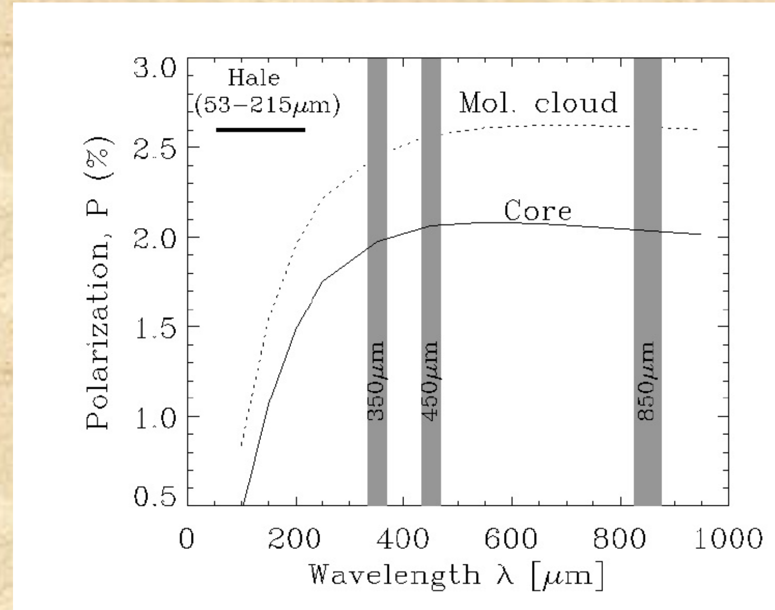
(Hildebrand et al. 1999)

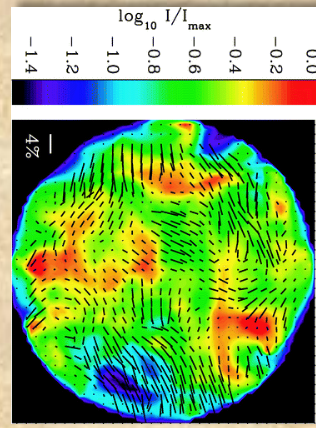
$$P_\nu F_\nu = \sum_i p_i \nu^{\beta_i} B_\nu(T_i)$$



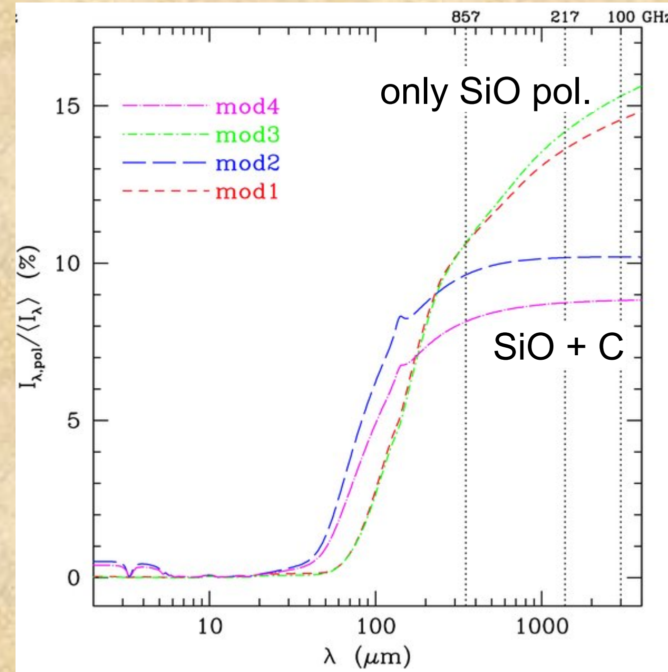
Hildebrand et al. 1999

Predicted Polariz'n Spectrum (3)





Bethell et al. 2007 (RAT)

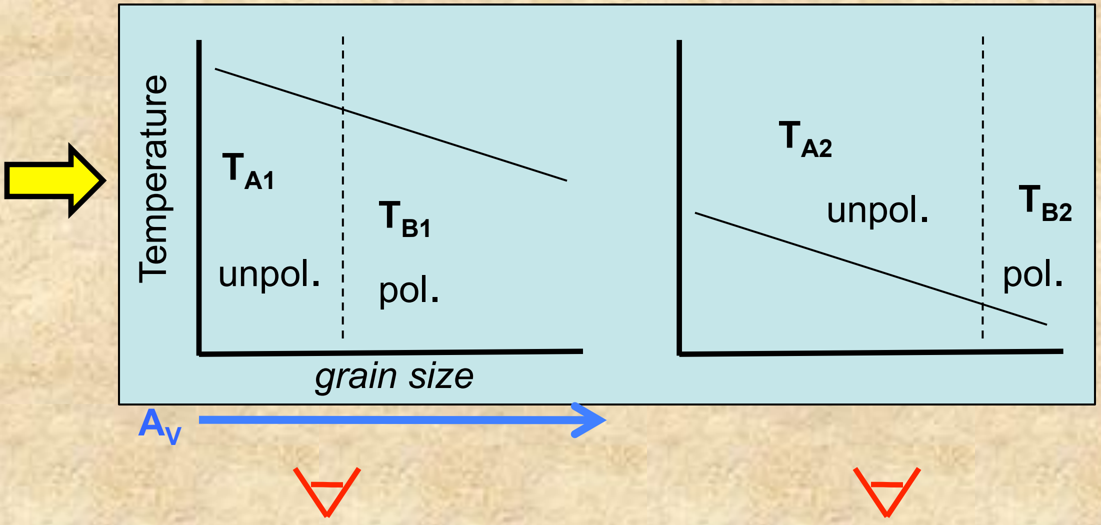


Draine & Fraisse 2009 (empirical ext. & pol.)

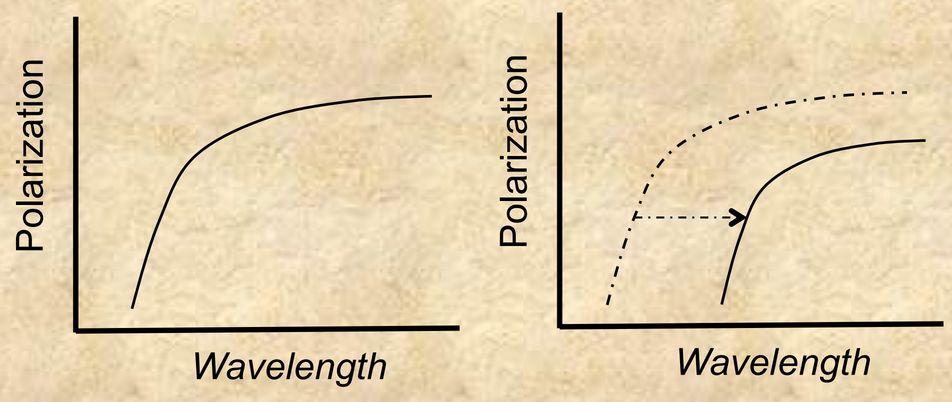
Grain alignment model in *starless* clouds:

- Nearly all grains exposed to same I.S. radiation field
- Large grains are more efficiently aligned
- Large grains cool more efficiently
  - ⇒ Colder grains better aligned than warm grains

Simplified Cloud Model - FIR



Homogenous Cloud: $T_A > T_B$, $p_A < p_B$



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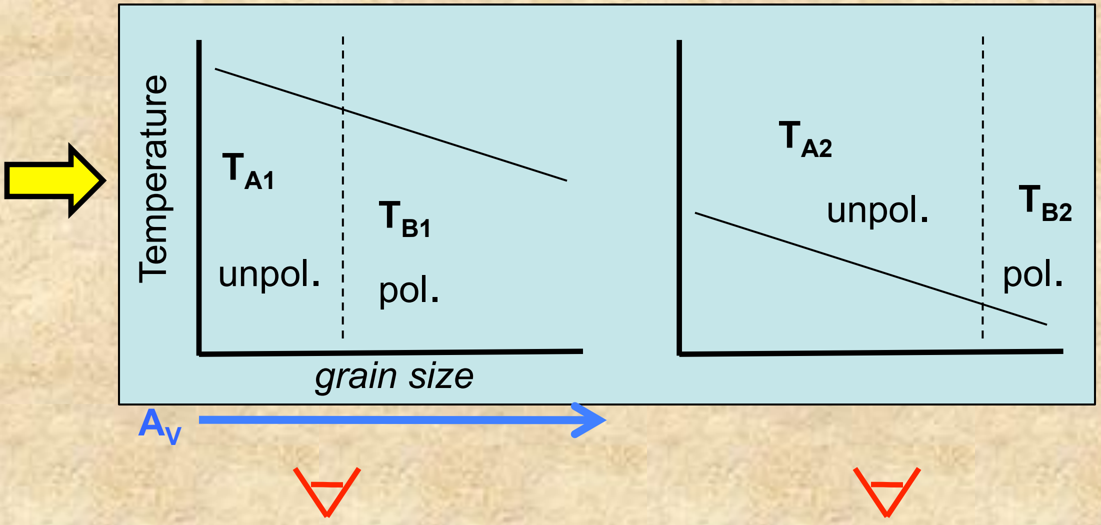

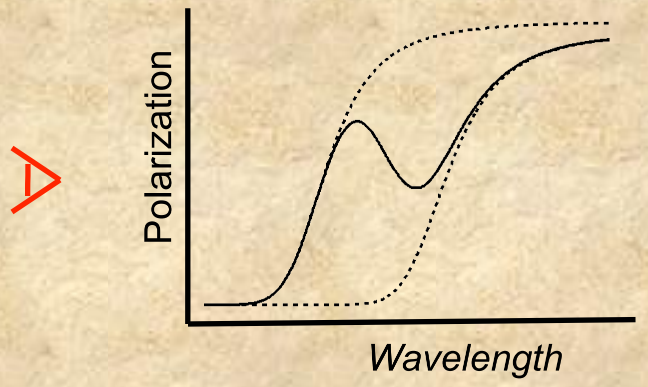

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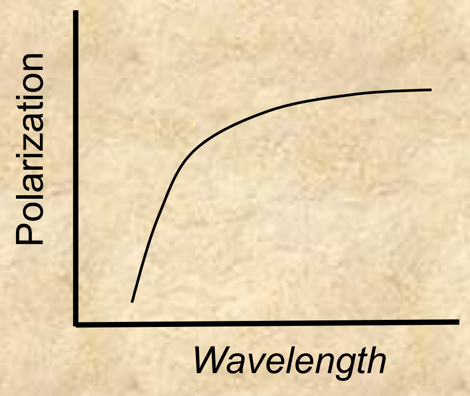

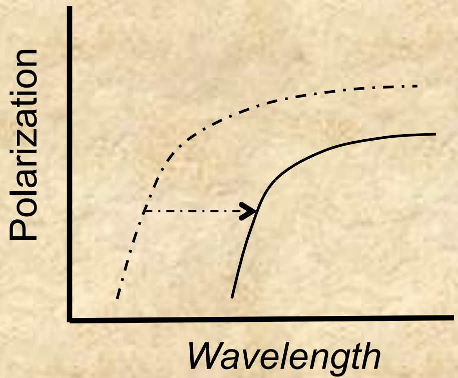

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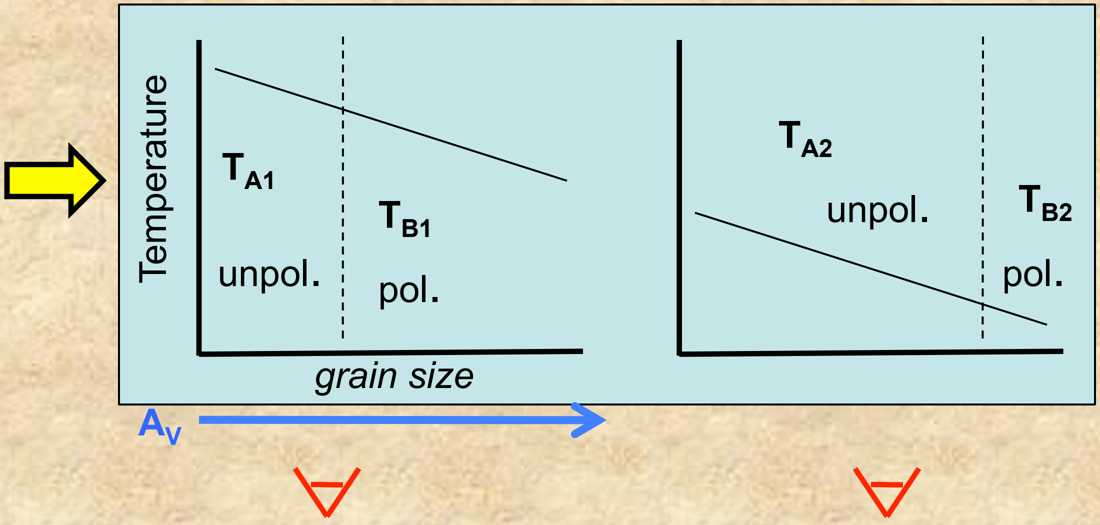

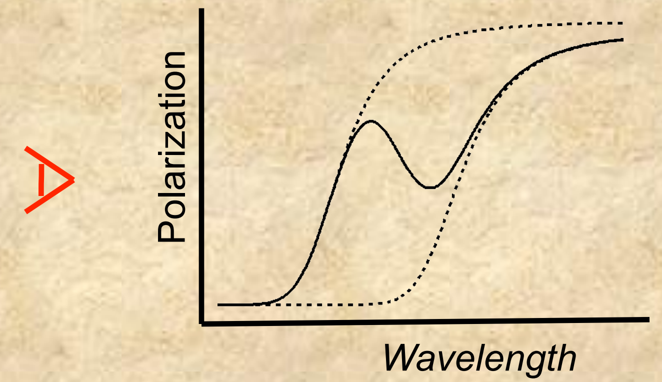

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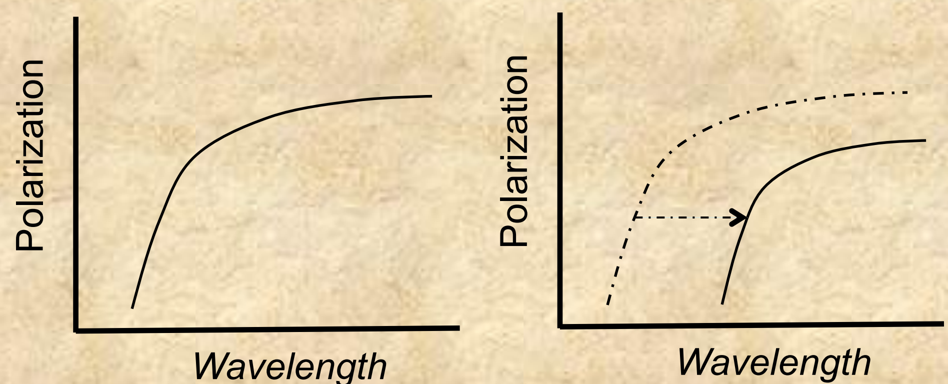
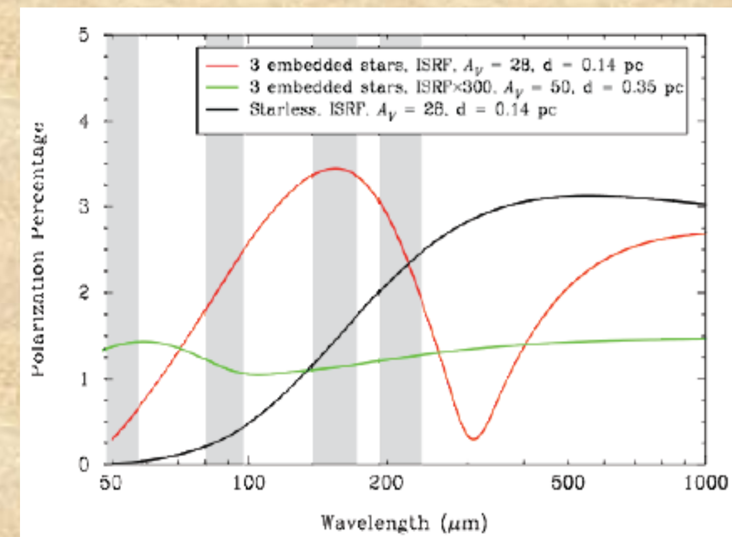
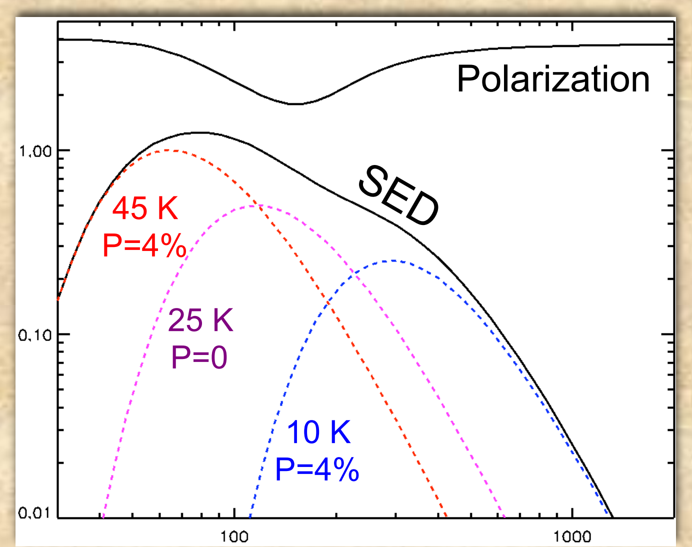




RAT model, Cherpunov & Lazarian, priv. comm.

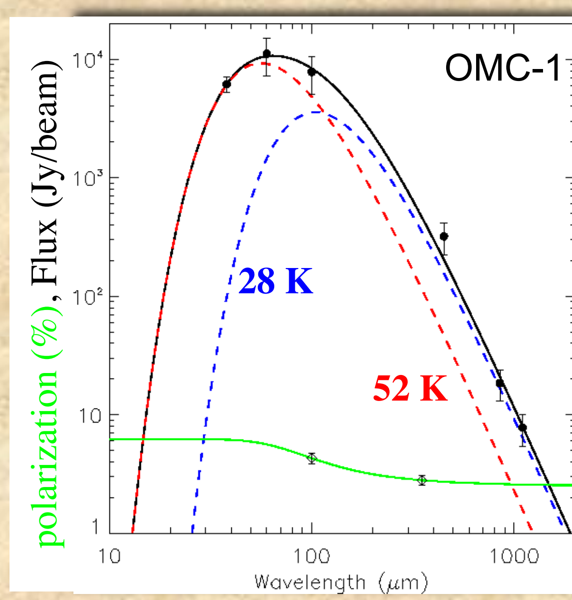
SEDs & the Polarization Spectrum

Models



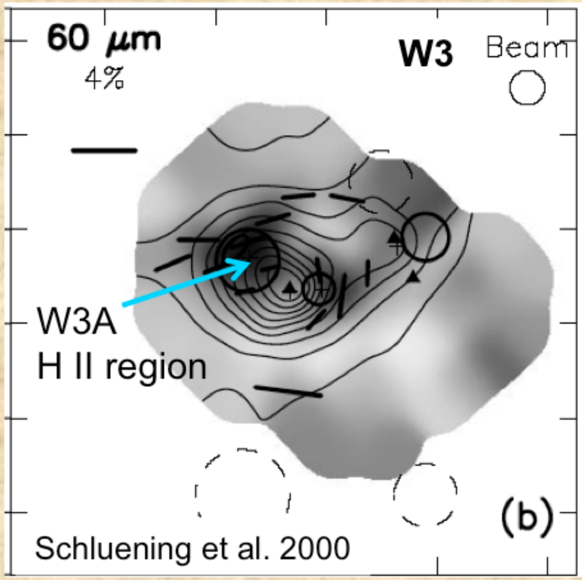
Wavelength (μm)

Observation

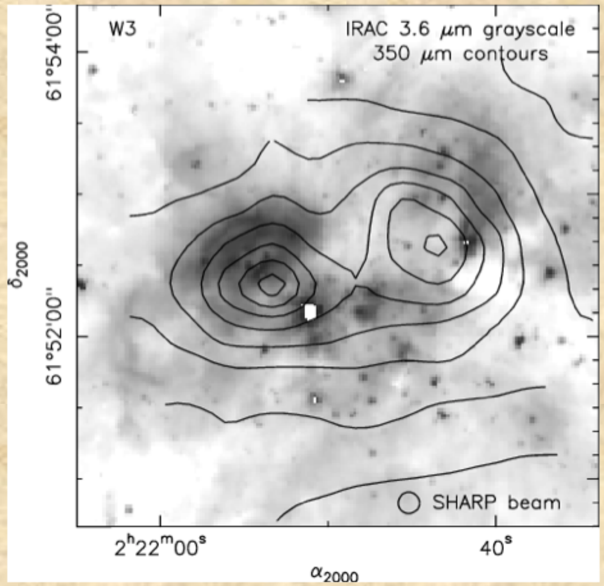


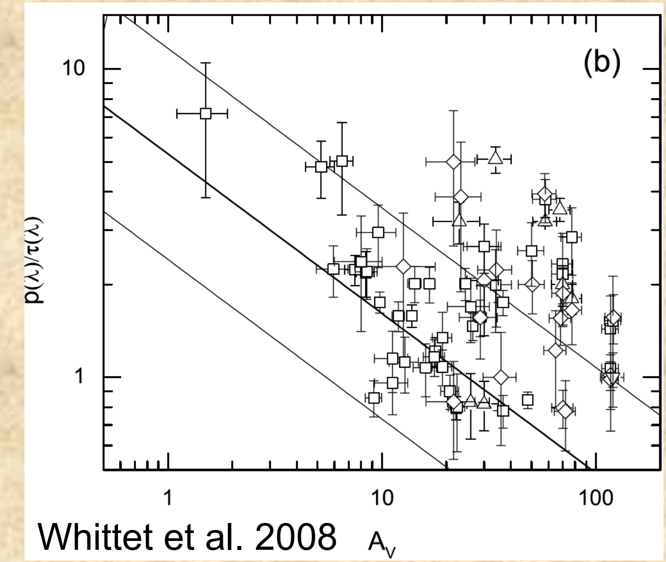
- Observed cloud SEDs indicate wide dust temperature distribution
- Polarization λ-minimum constrains SED models
  - Function of components' temperature *T*, and spectral index β
  - Independent of relative & total column densities

P-Spectrum & Stellar Location



Schlueníng et al. 2000





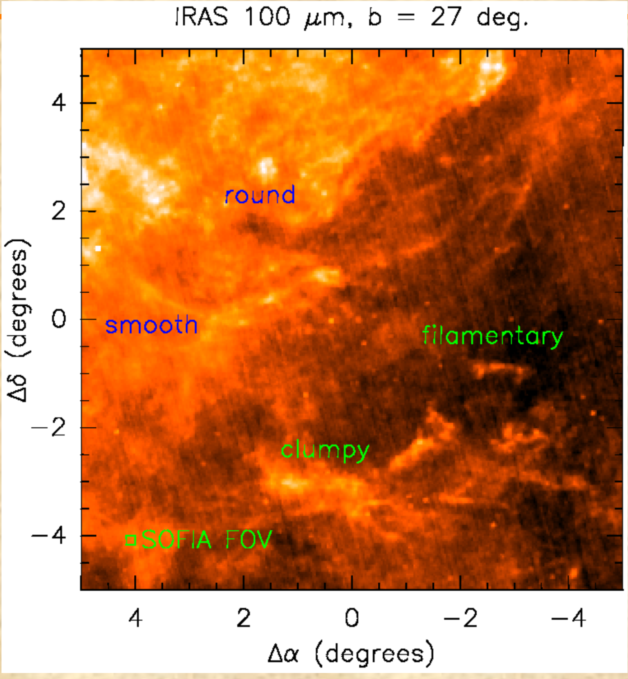
Whittet et al. 2008

- polarization enhanced towards embedded YSOs (squares) compared to field stars (lines)

- Correlation between Polarization and stellar locations
  - use *P*-spectrum (ratio) to eliminate change in spatial environment
- Existing SMM observations (20 arcsec) insufficient to resolve stars
- SHARP (10” at 350 μm) or SCUBA-2 (7” @ 450 μm) may resolve stars
- SOFIA (5” - 10” @ 50 - 100 μm), more sensitive to warm dust near stars

IR-Cirrus & High-Latitude Dust

- All grains likely exposed to same environment
- Finkbeiner, Davis, & Schlegel (FDS99) — high latitude dust
  - $T = 9.5$ K, $\beta = 1.7$ (silicate ?)
  - $T = 16$ K, $\beta = 2.7$ (graphite ?)
- If silicate is polarized and graphite unpolarized then $T_C > T_{Si}$, $p_C < p_{Si}$, $\beta_C > \beta_{Si}$
- Predictions at
  $\lambda > 1$ mm
  (Hildebrand & Kirby 2004;
  Bethell et al. 2007;
  Draine & Fraisse 2009)



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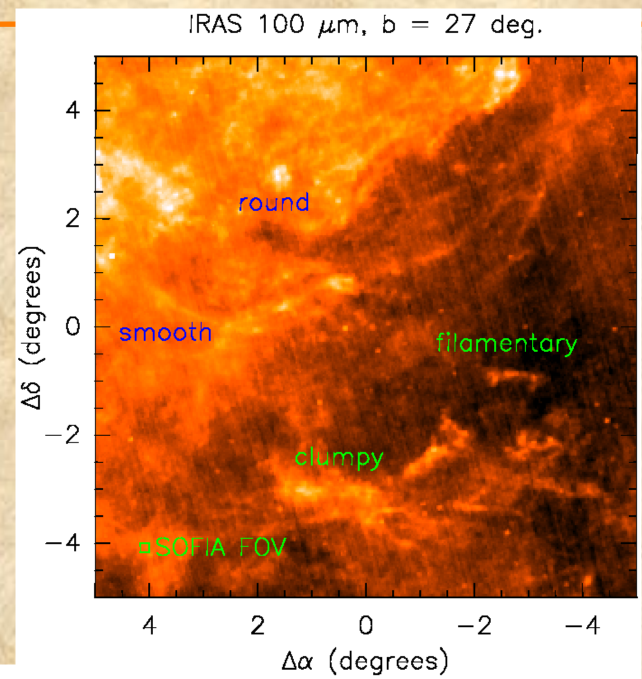

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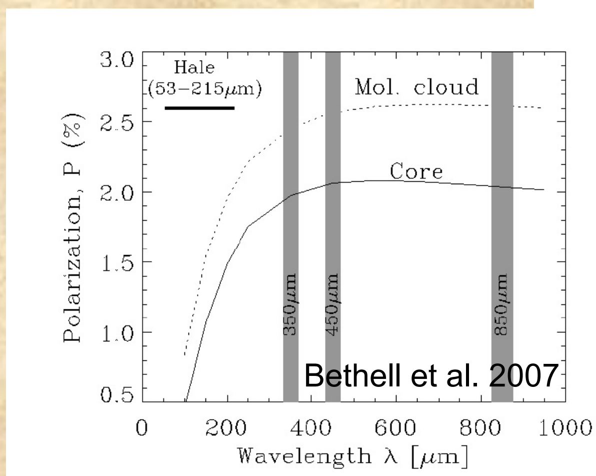
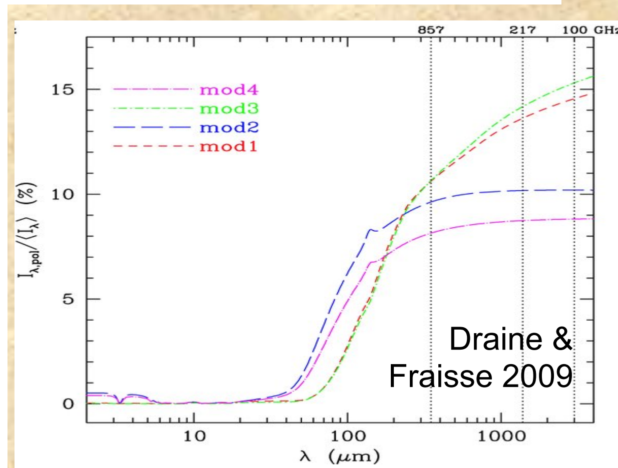
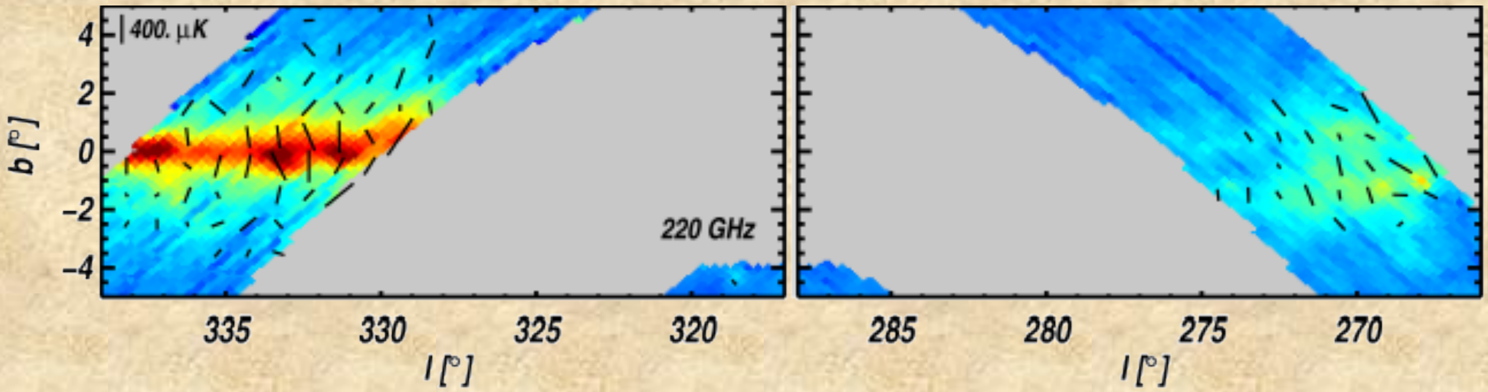


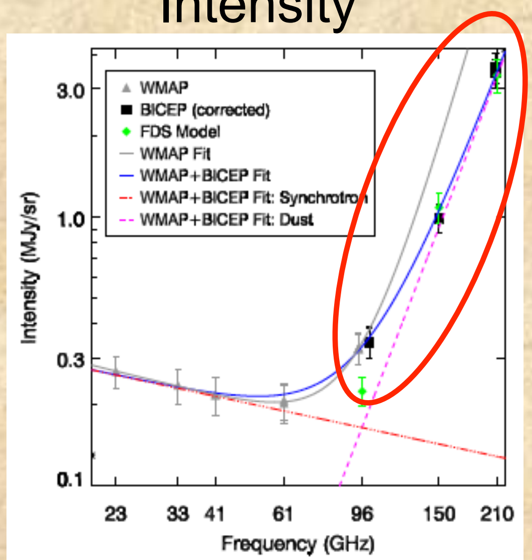


Millimeter Polarimetry

BICEP Polarimetry at 96, 150, 210 GHz (3.1, 2.0, 1.4 mm) [Bierman et al. 2011]



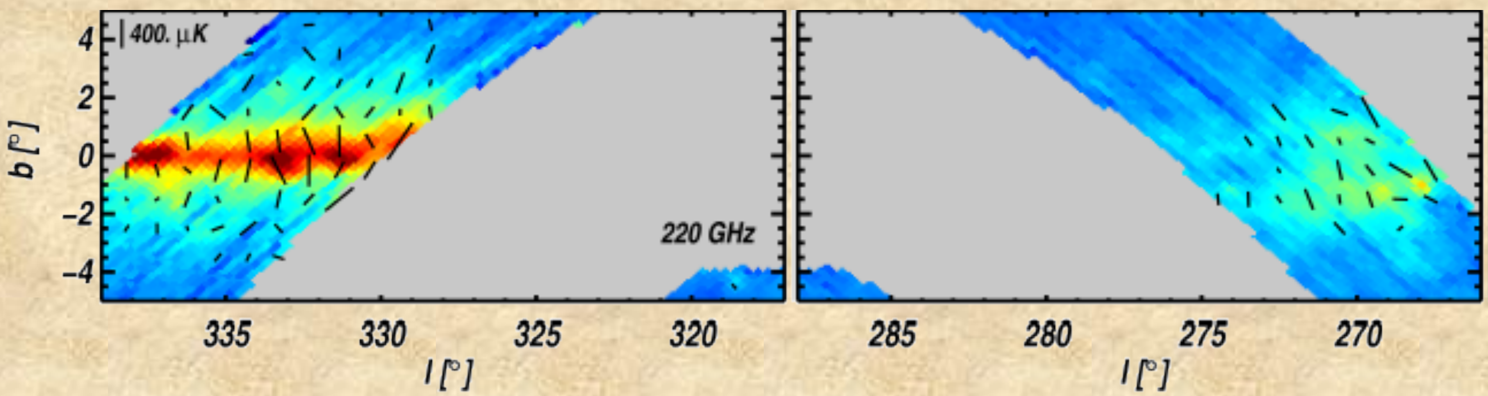
Intensity



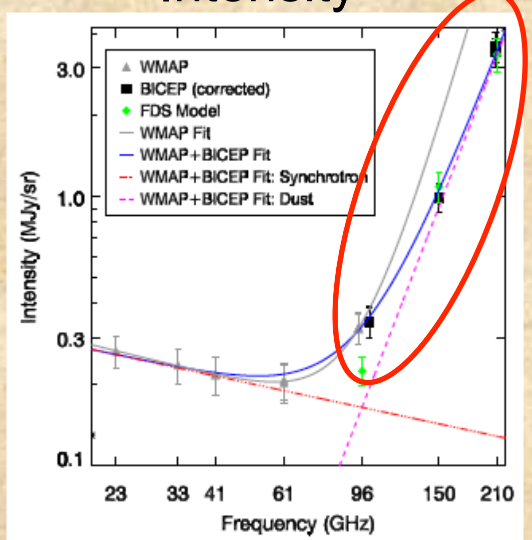
- High-frequency data is dominated by dust and

Millimeter Polarimetry

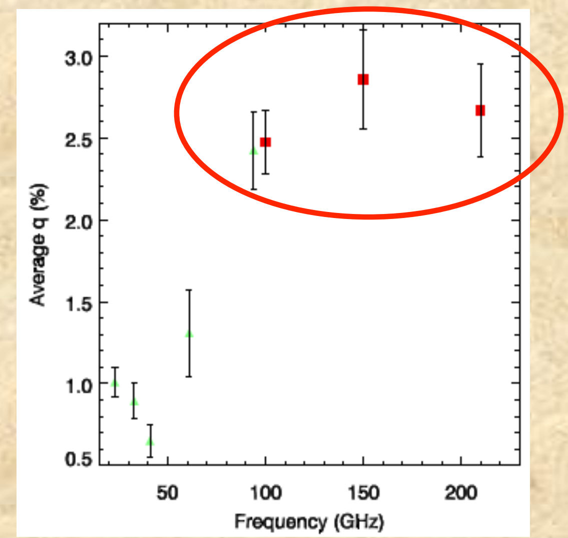
BICEP Polarimetry at 96, 150, 210 GHz (3.1, 2.0, 1.4 mm) [Bierman et al. 2011]



Intensity

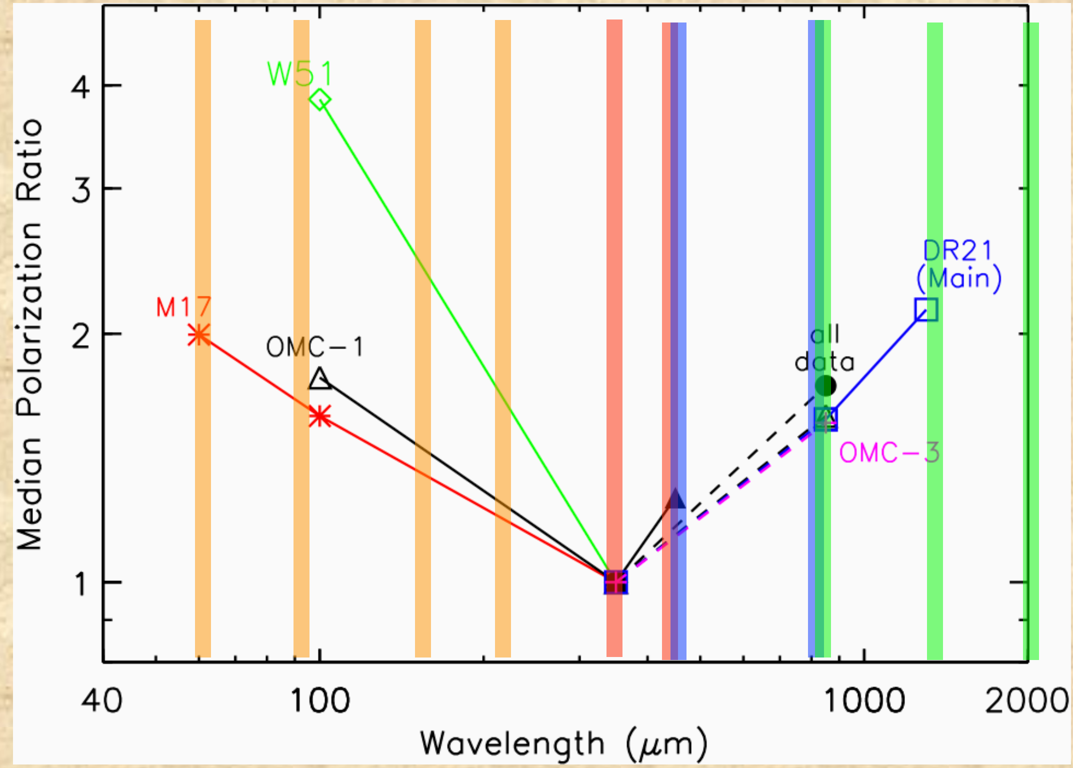


Polarization



- High-frequency data is dominated by dust and
- Polarization is approx. constant with frequency

The Future of Dust Polarimetry



SOFIA

CSO / JCMT

Planck ?

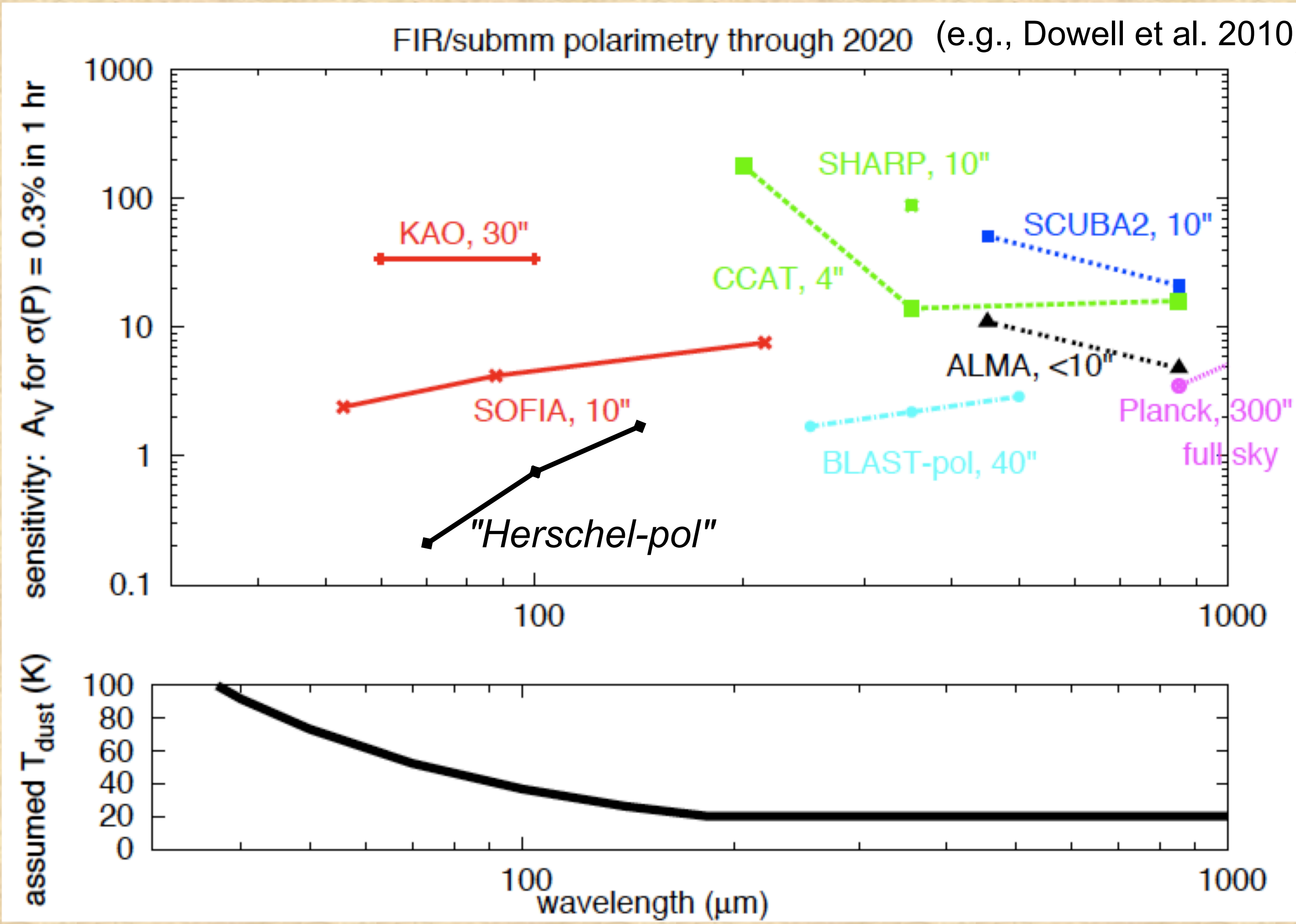
Need new instruments which

- Cover wide spectral range
- Better sampled polarization & total intensity SEDs
- Increases spatial resolution & sensitivity
- New environments, other than dense clouds

Instruments like...

- HAWC / SOFIA
- SHARP / CSO
- SCUBA-2 / JCMT
- CCAT
- ALMA
- Planck

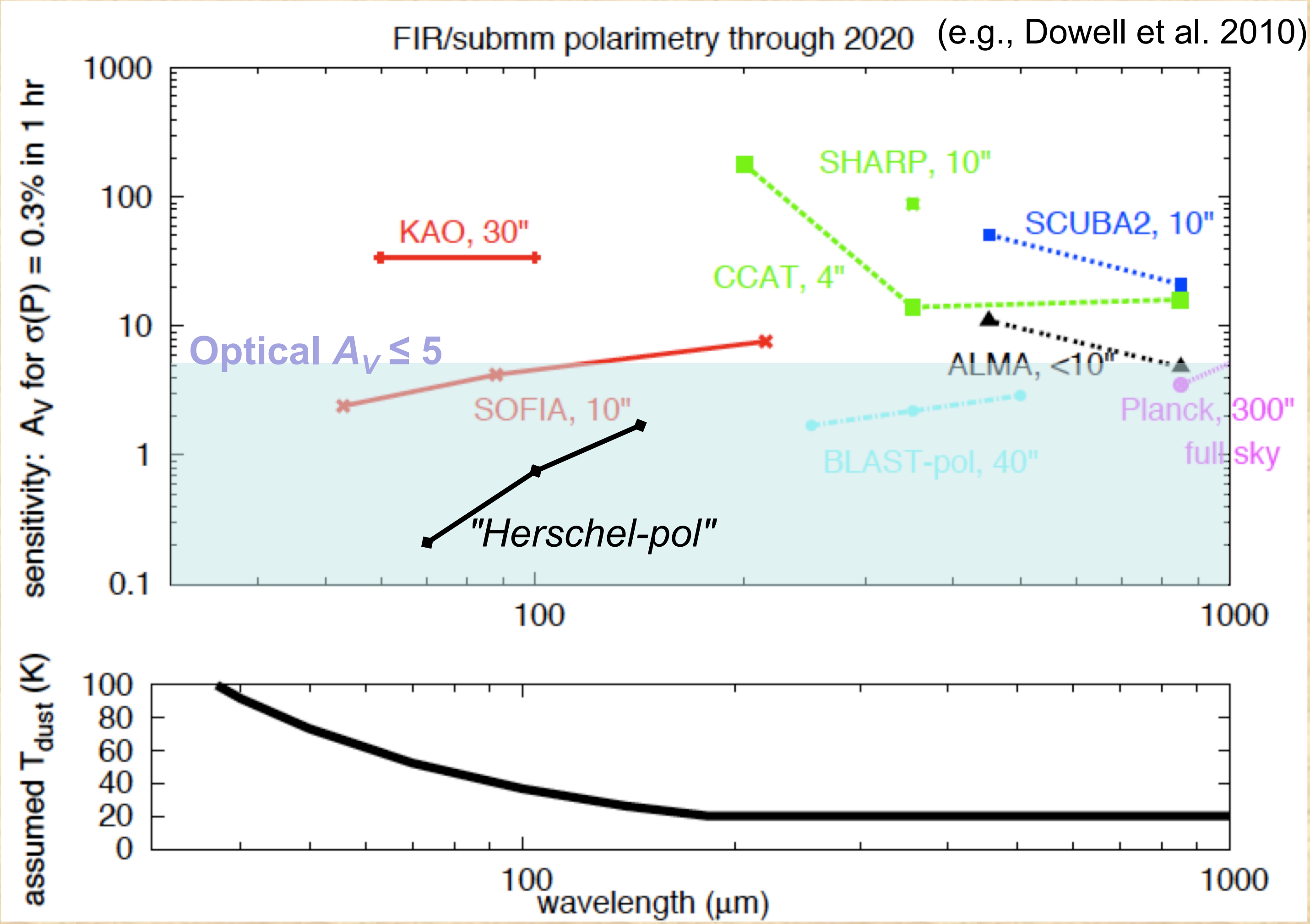
The Future of Dust Polarimetry



USRA

The Future of Dust Polarimetry

SOFIA
Stratospheric Observatory For Infrared Astronomy



Polarized Dust in the ISM

- Optical dust-extinction and FIR dust-emission is polarized, grains are aligned with *B*-fields
- Both optical and FIR polarization-spectra are consistent with multiple domains of grain size, temperature, and polarization
- Radiative Torques are consistent with polarization observations in both the optical/NIR (extincted starlight polarization) and FIR/MM (polarized emission)
- Future Tests
  - Better sampling of intensity & FIR-MM polarization spectrum
  - Observations in diffuse ISM; different environment from Galactic clouds
  - Look for correlation with stellar locations to test alignment models
  - Future instruments: HAWC/SOFIA, SCUBA-2, Planck, ALMA