What Does FIR Polarization Really Measure?

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Who’s Afraid of Polarimetry?
(- or should you be?)

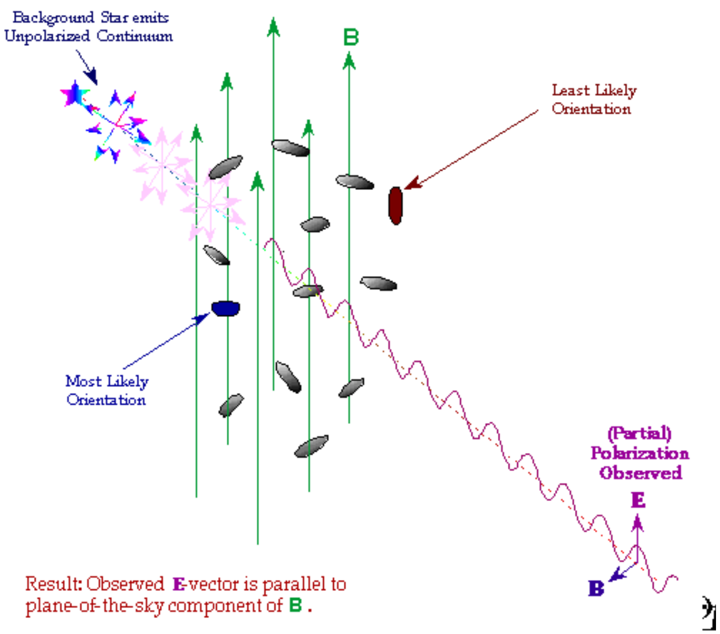
“The third leg of the observational astronomer’s tripod”

White papers to the 2010 Decadal survey

Why is the light Polarized?

Polarization by Absorption

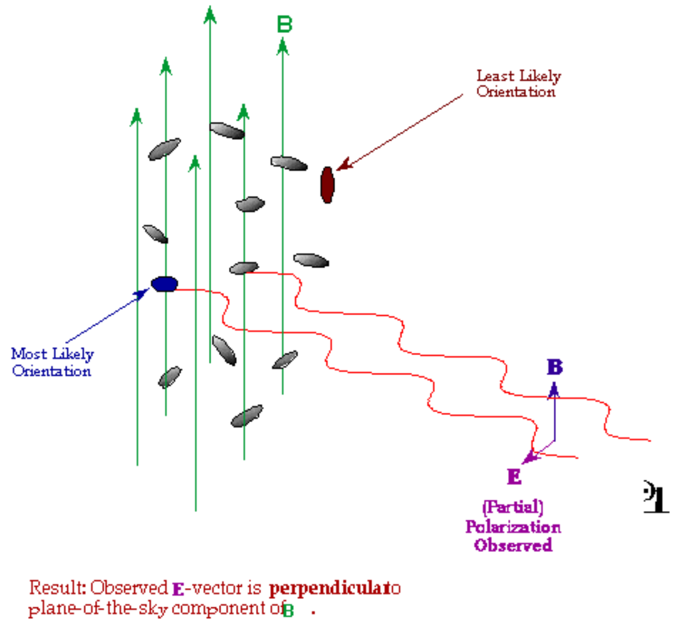
Polarization of Background Starlight



λ ~ UV - NIR

Polarization by Emission

Polarization of Thermal Radiation

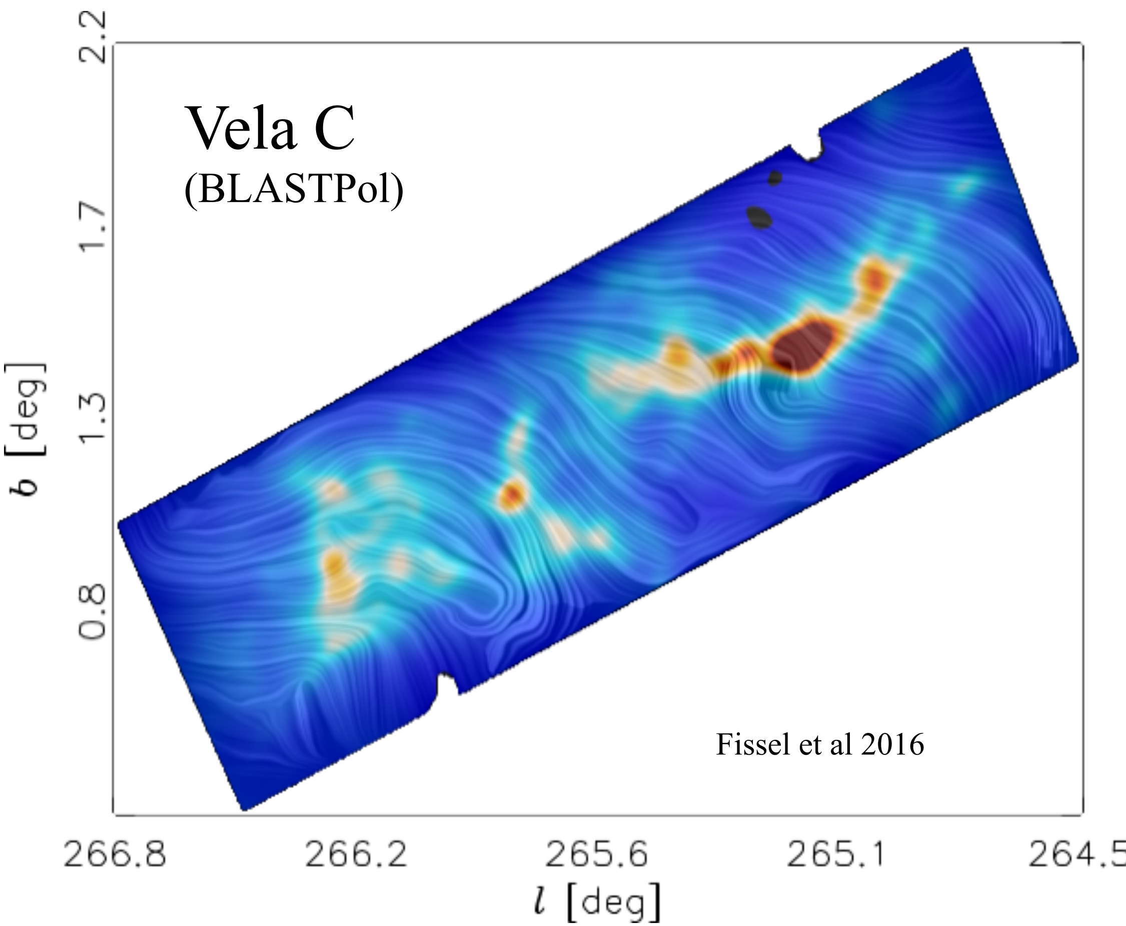


λ ~ FIR - MM

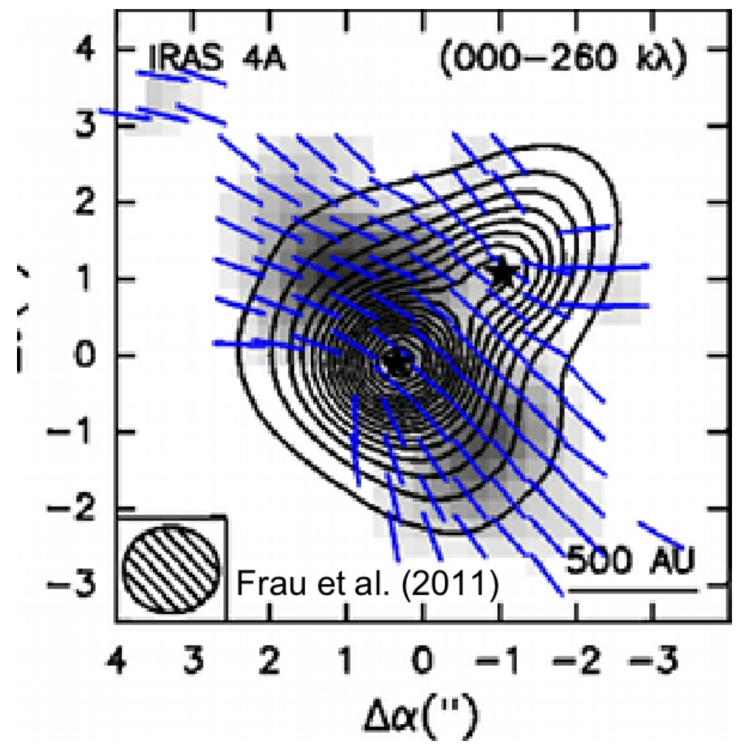
Diagrams after A. Goodman: http://cfa-www.harvard.edu/~agoodman/ppiv/

Magnetic Fields are [Probably] Important for Star Formation

- On large scales



- And, on small scales



Turbulent motions can "mimic" magnetic support in some situation

- So what is the polarization "really" measuring?

From Polarization to Magnetic Fields and Back Again

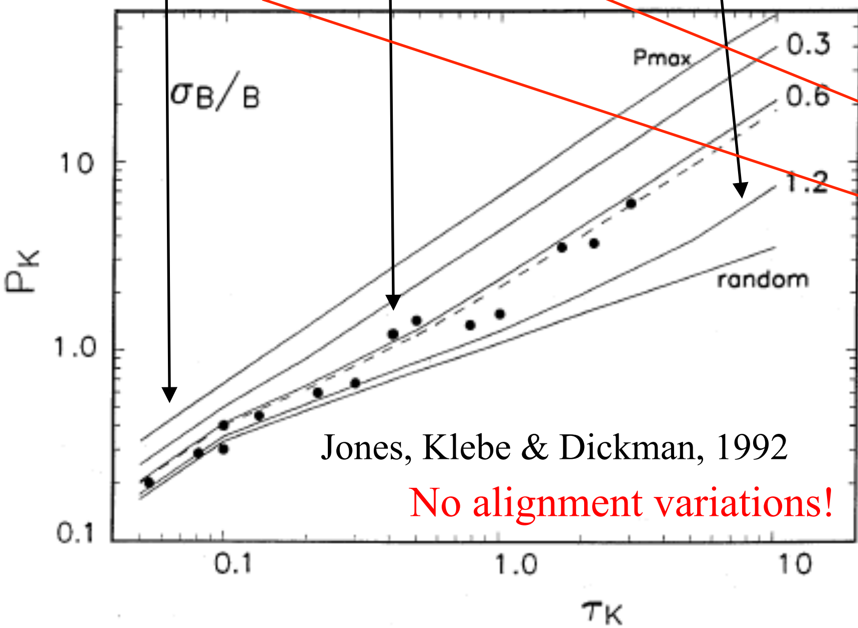
- Polarization is a pseudo-vector
  - Does not sum as a scalar
- Dust polarization only measures plane-of-the-sky B-field
- Dichroic polarization efficiency depends on environment and grain characteristics
  - Alignment efficiency, size distribution, emissivity, Mineralogy

- But there is hope! Particularly with high-resolution, multi-band, mapping, such as SOFIA/HAWC+

Line of Sight Averaging – Influence of Turbulence

- Because polarization adds as a vector crossing field lines, along the line of sight, changes decreases the observed polarization
- Sensitive to the opacity and hence temperature (in emission)

$p \propto \tau^1$ $(p/\tau \propto \tau^0)$ $p \propto \tau^{1/2}$ $(p/\tau \propto \tau^{-1/2})$ $p \propto \tau^1$ $(p/\tau \propto \tau^0)$

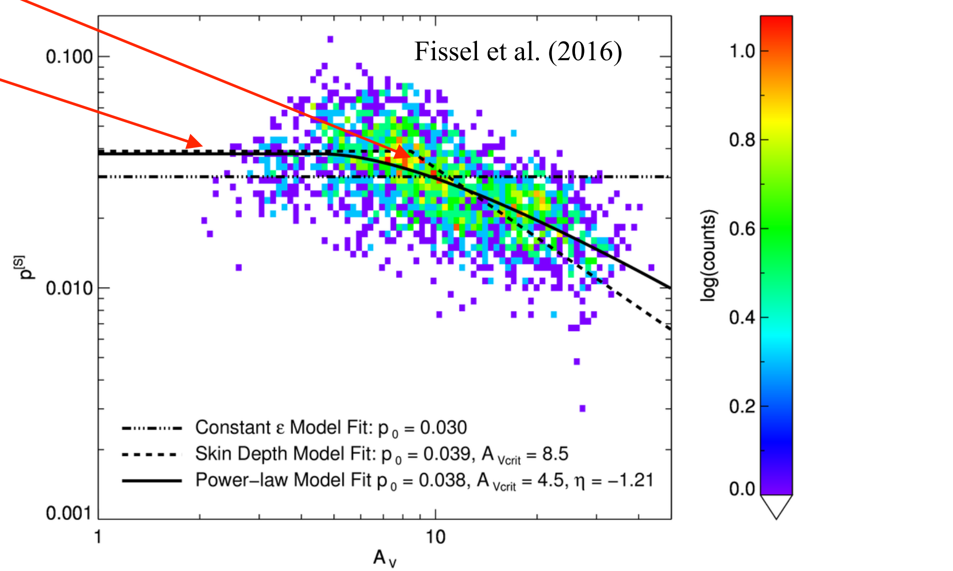


For a combination of constant field and random component (e.g. Meyer & Goodman 1991)

$p \sim N$ (small τ)

$p \sim N^{1/2}$ (medium τ)

$p \sim N$ (large τ)



Grain Alignment

- We now know that Davis-Greenstein alignment (paramagnetic relaxation) can't work for the larger grains
  - Thermodynamics says that when $T_{gas}=T_{dust}$ D-G alignment should fail, but polarization is seen at A_V>>1 mag
- Radiative Torque Alignment (RAT) alignment has now been thoroughly tested and works in most environments
  - Requires paramagnetic grains
  - Asymmetric radiation fields
  - Many details of the alignment – and disalignment – still needs to be elucidated

RAT alignment in a nut shell

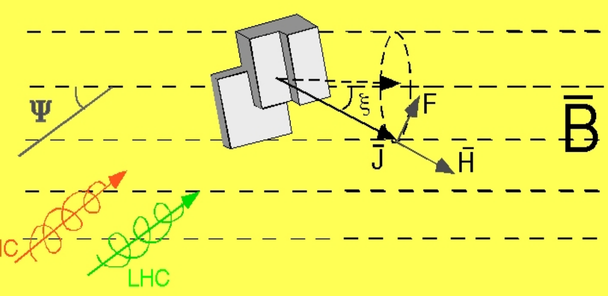
- RAT alignment is phenomenologically simple, albeit a multi-step process:

1. A **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

RAT yields a large number of specific, quantitative, predictions

<u>F</u> is the alignment torque ($\perp$ to J)

<u>H</u> is the spin-up torque ($\parallel$ to J)



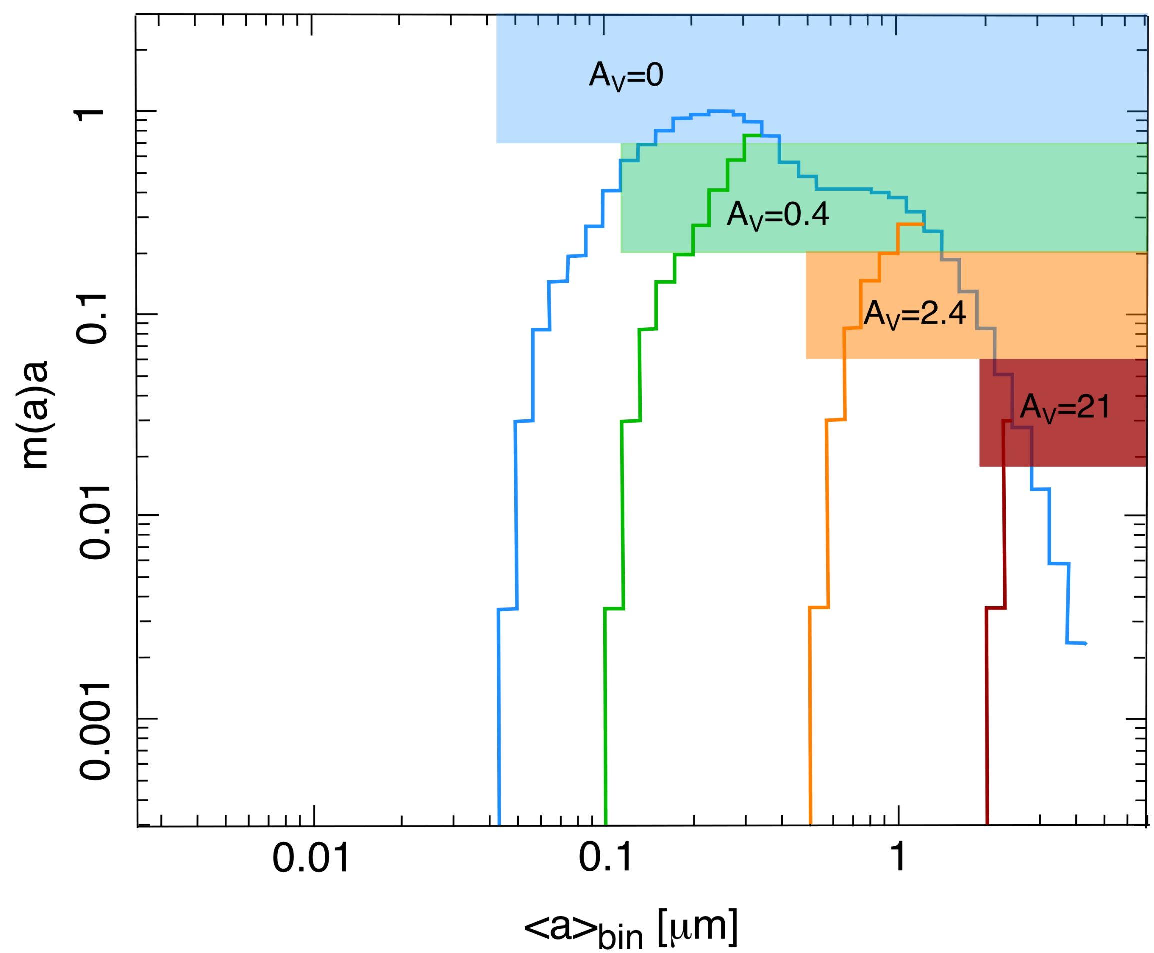
Grain alignment is lost deep into star-less clouds

- 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 satisfy

  $$\lambda < 2a$$

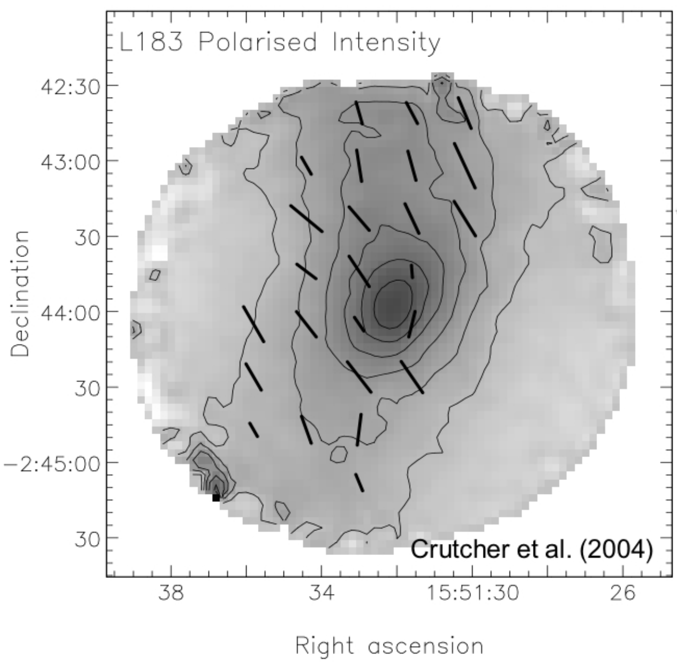
  When this happens $p/A_V \sim A_V^{-1}$

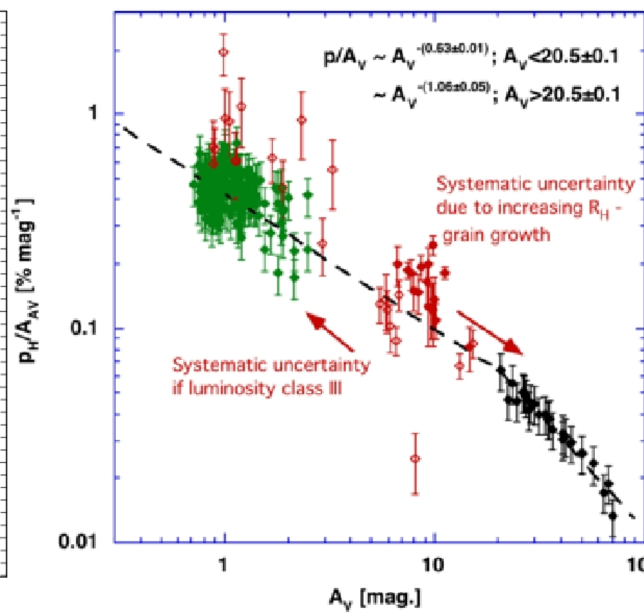
- In L183 we see an indication of this effect

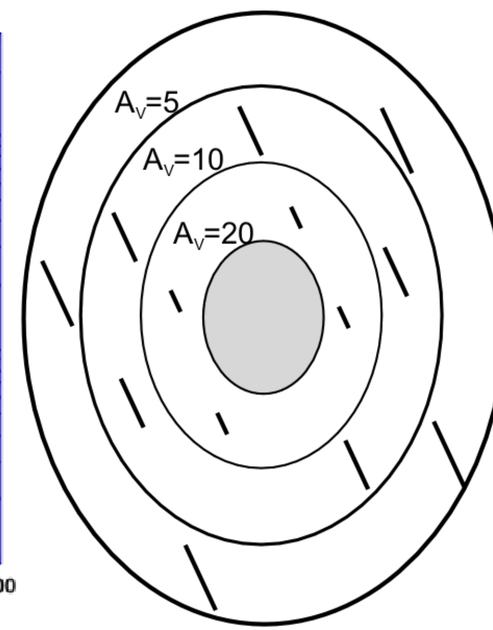


Loss of Alignment in Deep Cores

- Grains more than A_V~20 mag from the ISRF do not align
- Critically important for interpreting polarization maps







- For very large clouds with internals sources, an internal layer, A_V>20 mag from the ISRF and A_V> X mag from the central source may not have any alignment

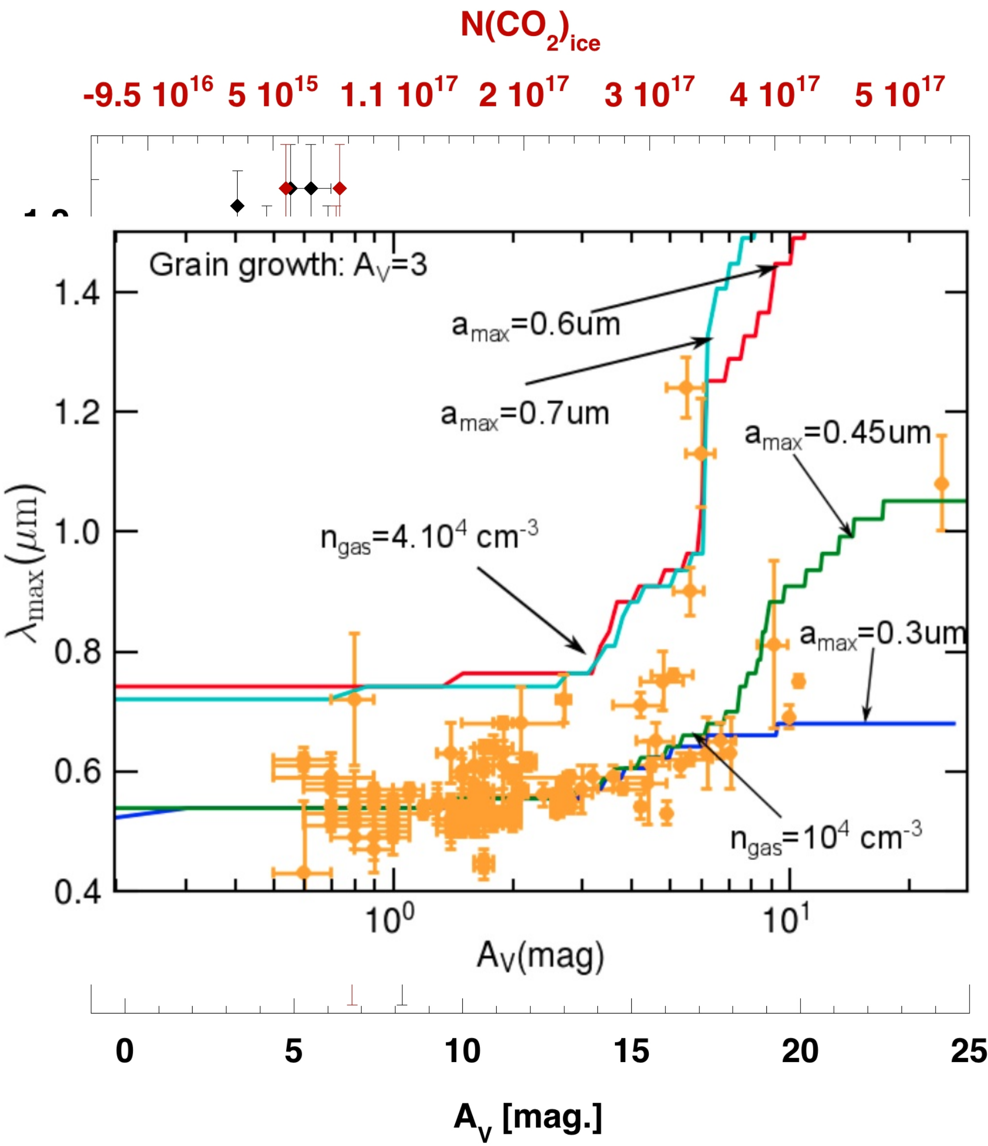
Dust Size and Shape Variations

- Column densities derived from FIR observations depend on the assumed dust emissivity
- Observations comparing (O/NIR) extinction and FIR emission indicate changes in the emissivity with N and T (e.g. Schnee, Goodman & Sargent 2008; Ysard et al. 2012, 2013)
- Grain growth is the most likely cause. Will affect:
  - The I -> N conversion (from variations in the emissivity)
  - The $\lambda<2a$ limit – alignment further away radiation sources
  - (likely) the grain axis-ratio – changes p/I

Polarimetry as a tool for grain growth studies

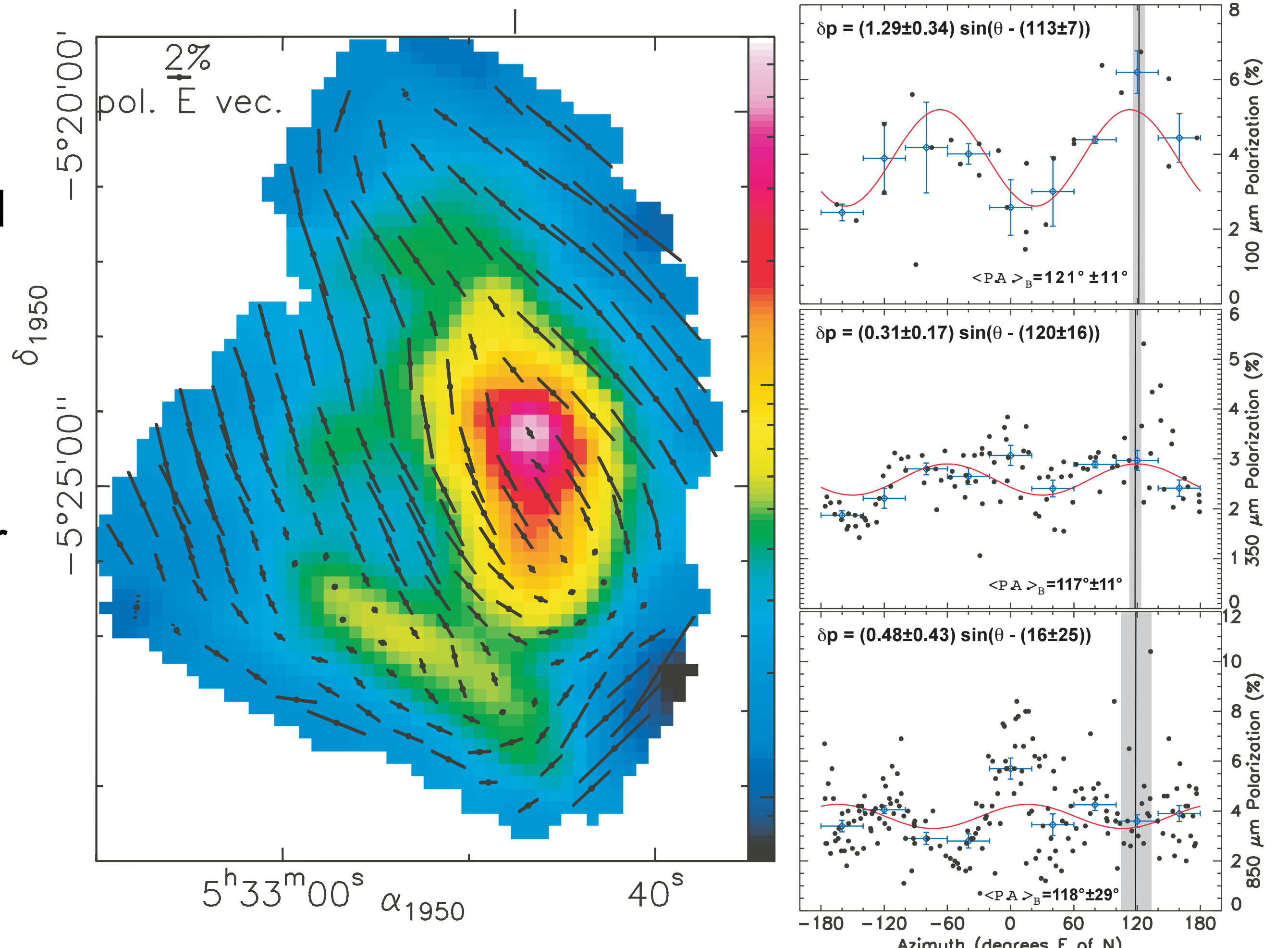
- The obserbed linear λ_{max} vs. A_V (for A_V<4 mag) assumes that the underlying – total – grain size distribution is fixed.
- If grain growth is taking place, we'd expect a steeper relation.
- Provides a direct way to study grain growth – independent of assumptions on grain emissivity and temperature
    - Observations of Taurus l.o.s. with Lick/Kast

Vaillancourt et al. (2017)



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.



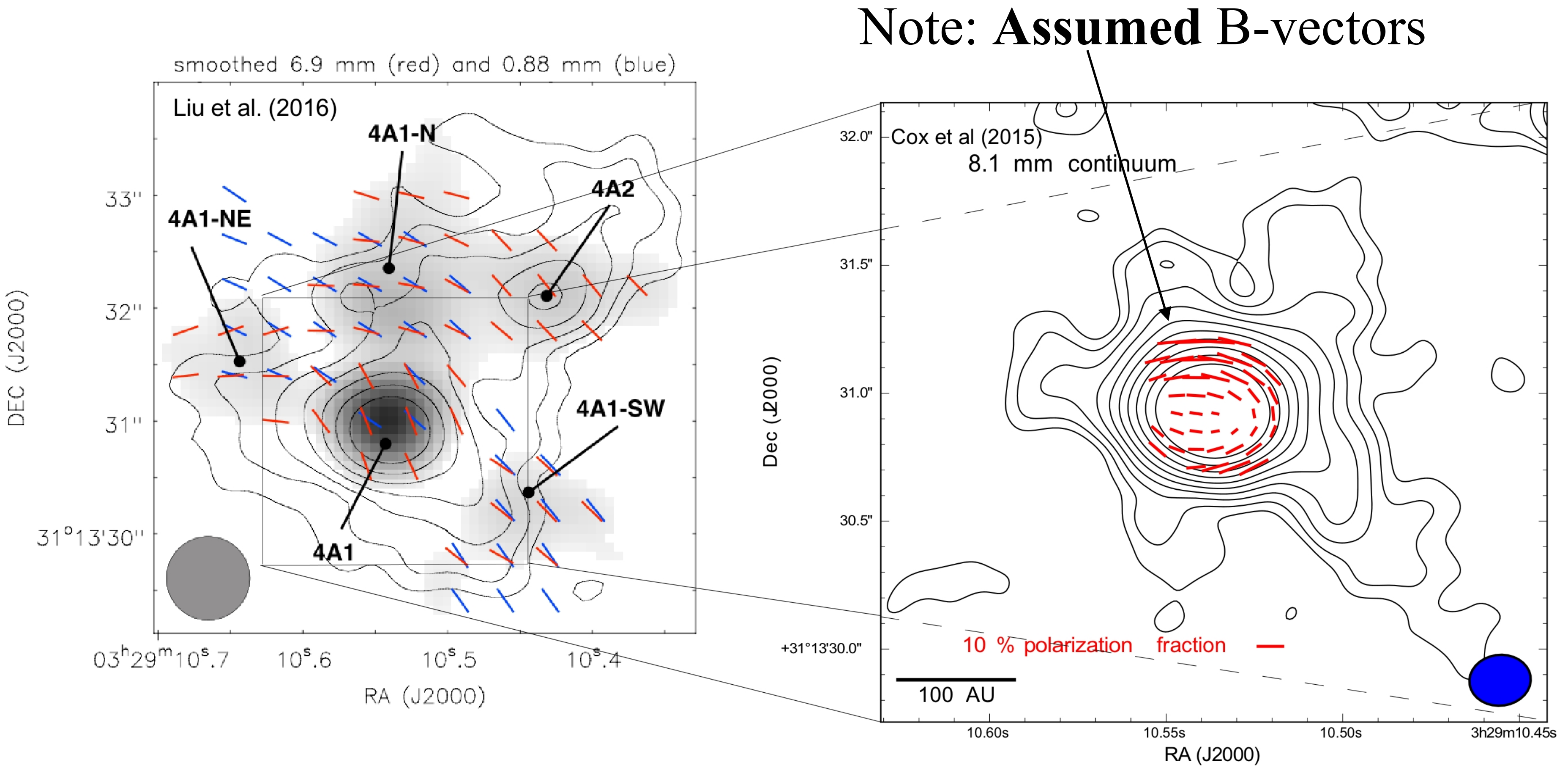
Vaillancourt & Andersson (2015)

Scattering polarization at mm-wavelengths

- Recent calculations show that FIR and mm-wave observations can be affected by scattering, if mm-sized dust grains are present
- Possible for dense protostellar disks
- Can be used to probe both for grain growth and for magnetic field strengths in the disks

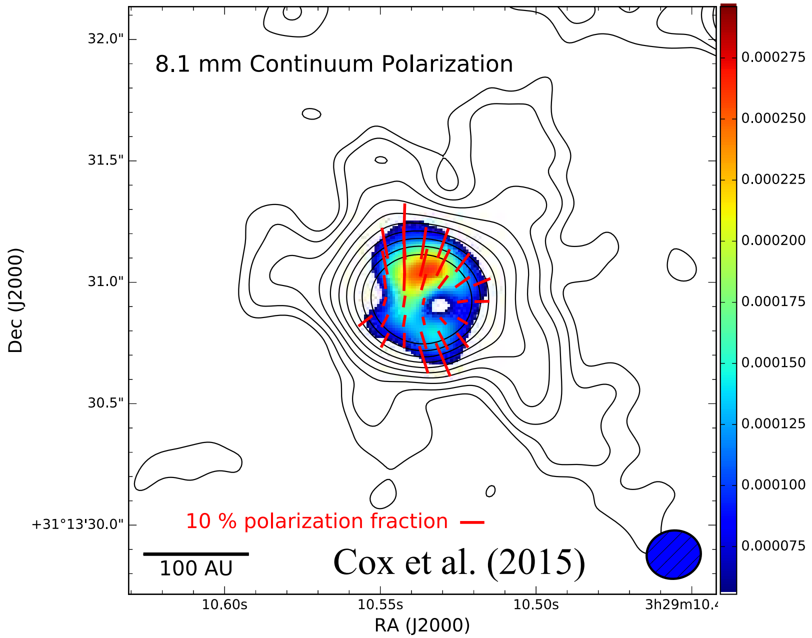
More Data is Better – but, Beware of Model Dependences

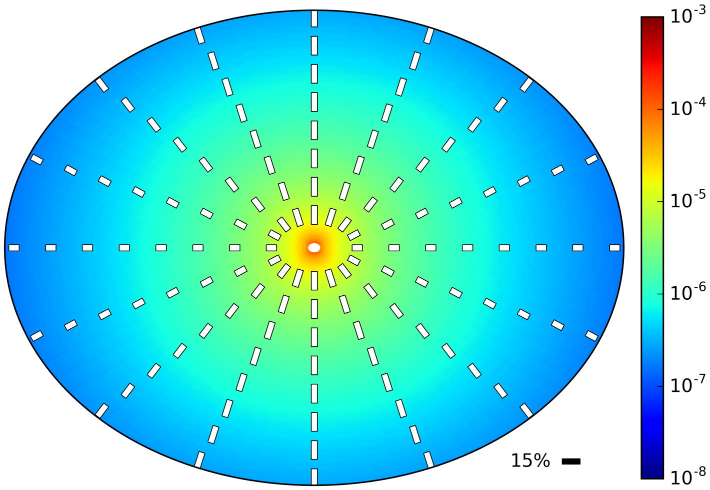
- Multi-wavelength, multi-scale observations allow a decomposition of opacity, depth and temperature and can constrain models



Scattering off of LARGE Grains – Protostellar Disks

- Yang et al. (2016) have modeled the polarization from a protostellar disk (Cox et al. 2015) originating both as dichroic emission and scattering off of large grains
- The polarization pattern at 8mm favors a combination of the two mechanisms, but require mm-sized grains
- If those grains are also responsible for the dichroic emission a ordered and strong magnetic field is required





Wrap-up

- We are starting to understand grain alignment, but FIR polarization is inherently complex.
- To understand the influence of magnetic fields on star formation, a quantitative understanding of the polarization is needed

To reliably interpret the polarization we need:

- Multi-band polarization, spanning the BB curve
- High spatial resolution imaging on multiple scales
- A quantitative understanding of alignment mechanisms
- Preferably Extinction data (NIR)
- Best if compared to *ab initio* 3D modeling
- SOFIA/HAWC+ will provide critical insights