The far-infrared polarization spectrum of Rho Ophiuchi A from HAWC+/SOFIA observations

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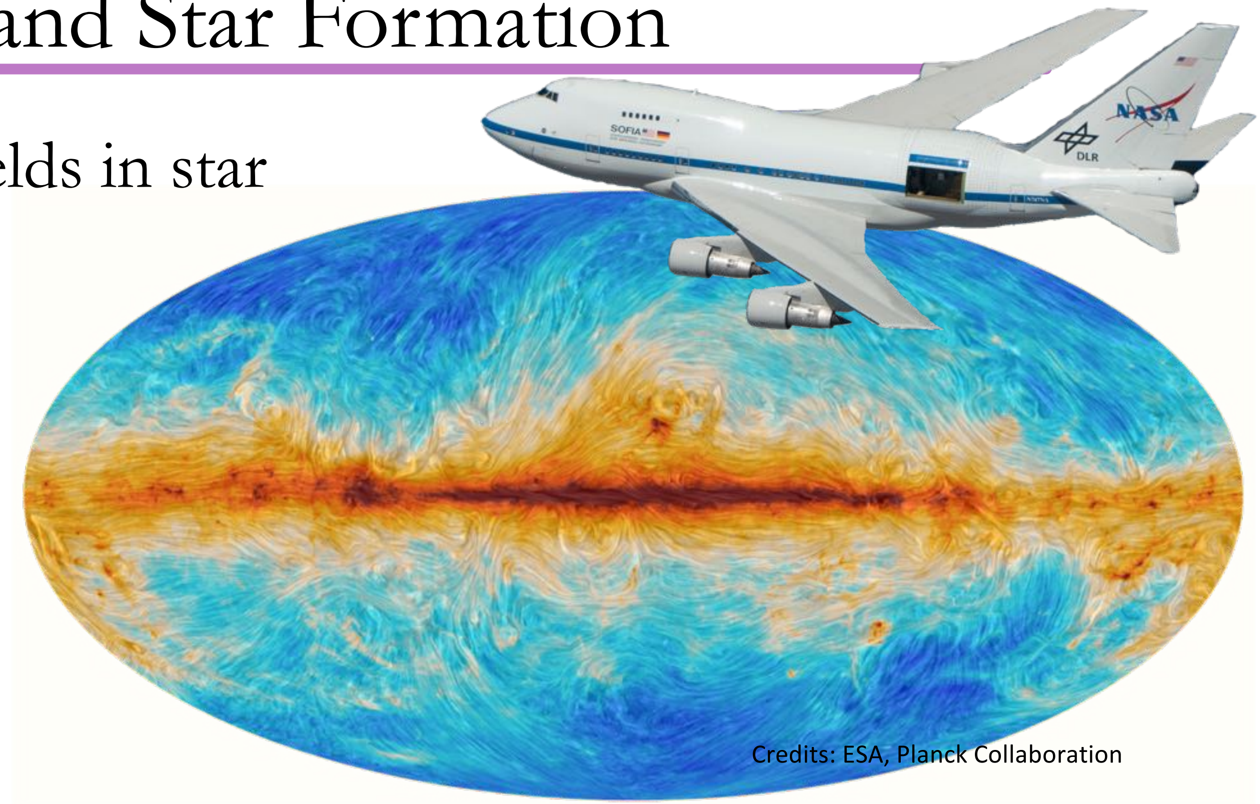
Magnetic Fields and Star Formation

- Role of magnetic fields in star formation
- Interstellar polarization from dust emission
- How to interpret polarization maps? Indirectly traces magnetic fields
  - Grain alignment

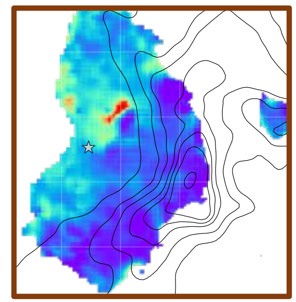
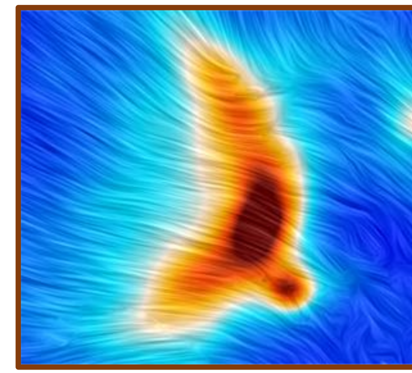
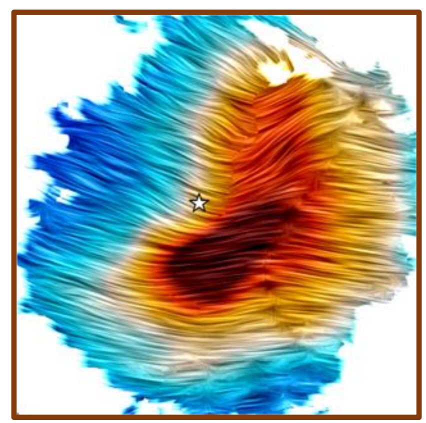
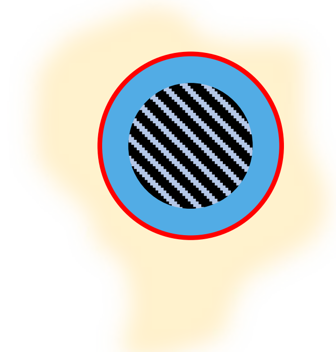


Magnetic fields in the Milky Way mapped through observations of interstellar polarization

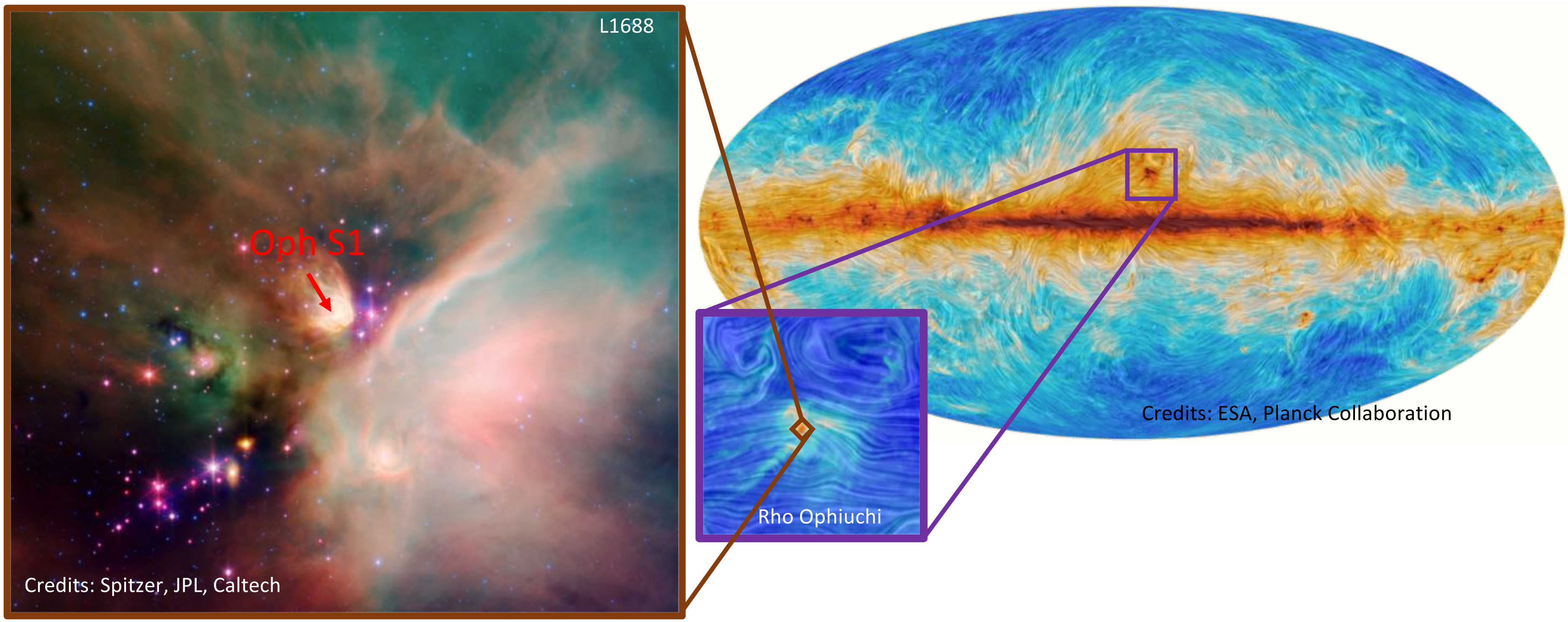
Outline

- The Rho Oph A molecular cloud
- Background on interstellar polarization spectrum and main science goals
- HAWC+/SOFIA Observations of Rho Oph A and polarization maps
- Evaluation of polarization spectrum spatial trends
- Comparison with a simple cloud model
- Upcoming work
- Conclusions and final remarks



Rho Oph A Molecular Cloud



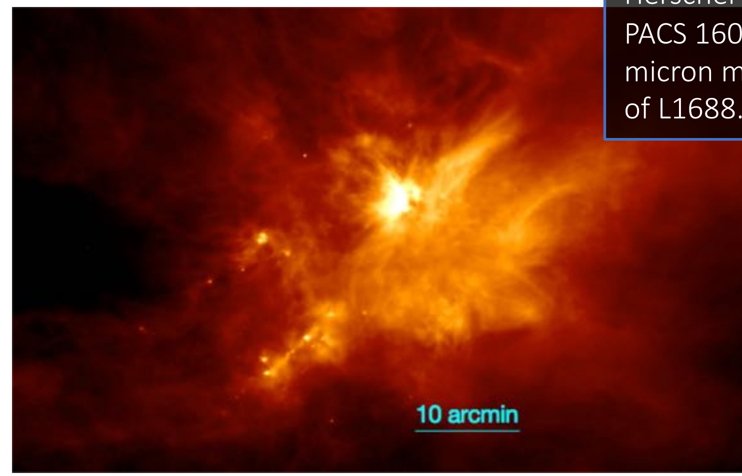
- Rho Oph A: ~130 pc
- Warmed up by Oph S1 - massive B3-4 star

Rho Oph A Molecular Cloud

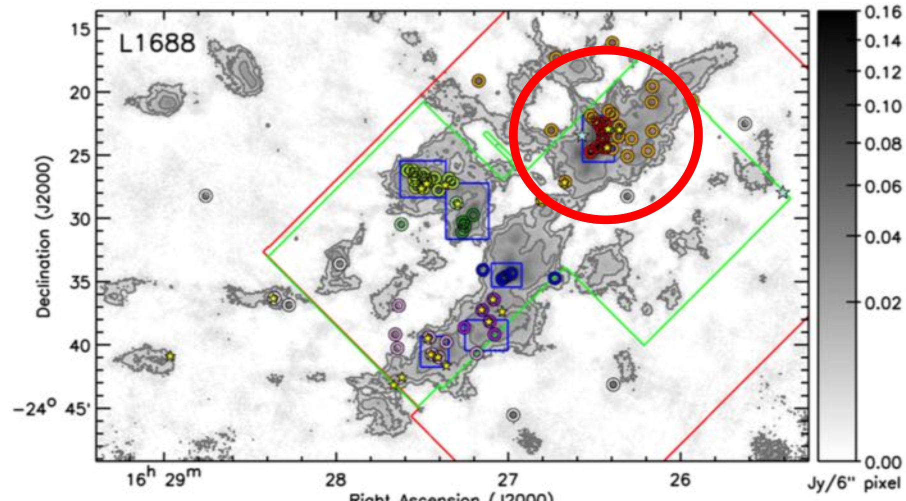
- Active star-forming region in Rho Ophiuchi (L1688)
  - Numerous YSO's at different evolutionary stages, many of them present infrared excess at H-Ks (near-infrared bands)

- Different surveys also revealed a population of starless cores (Motte, Andre, & Neri 1998, Pattle et al 2015)

- Rho Oph A - extinction levels near the core can reach Av > 100 mag



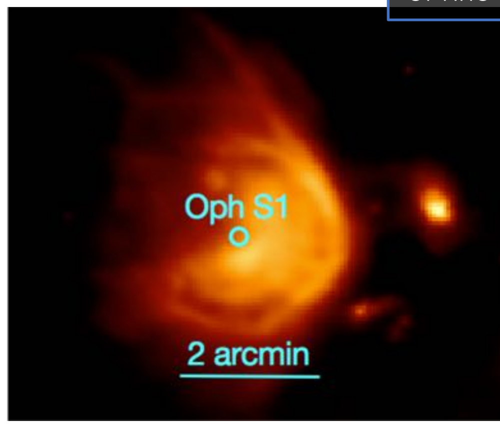
Herschel PACS 160 micron map of L1688.



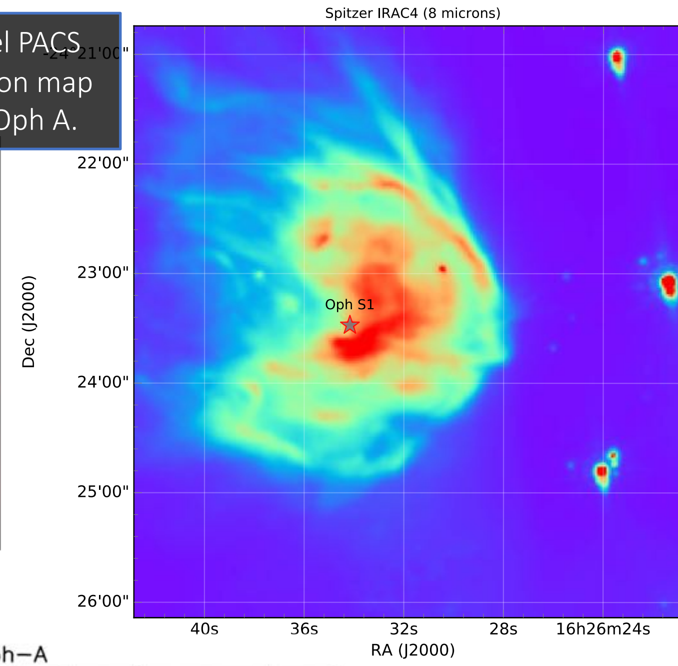
850 micron map from JCMT SCUBA-2 (Pattle et al. 2015), showing YSO's identified from this survey. Oph A is shown by the red circle.

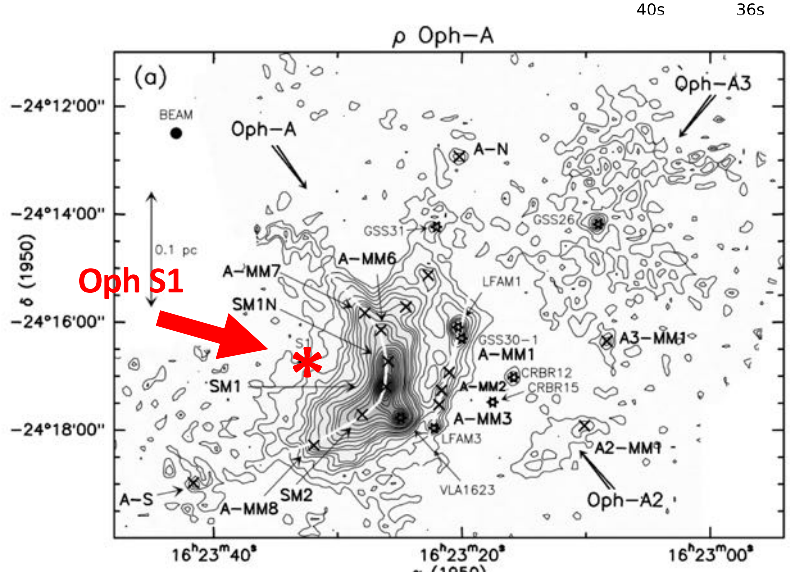
Rho Oph A Molecular Cloud / Oph S1 star

- Cloud morphology: 70 microns emission (Herschel): concentric arc-shaped filaments – centered on the **Oph S1 star**:
  - Dominating radiative/heating source for dust emission Rho Oph A (as can be seen from Spitzer and Herschel images):
  - B3-4 massive star (Hamaguchi et al. 2003, Andre et al 1992, 1988);
  - Surrounded by a compact HII region (~20 arcsec)
  - Indications of triggered star formation around S1 (Motte, Andre & Neri 1998)



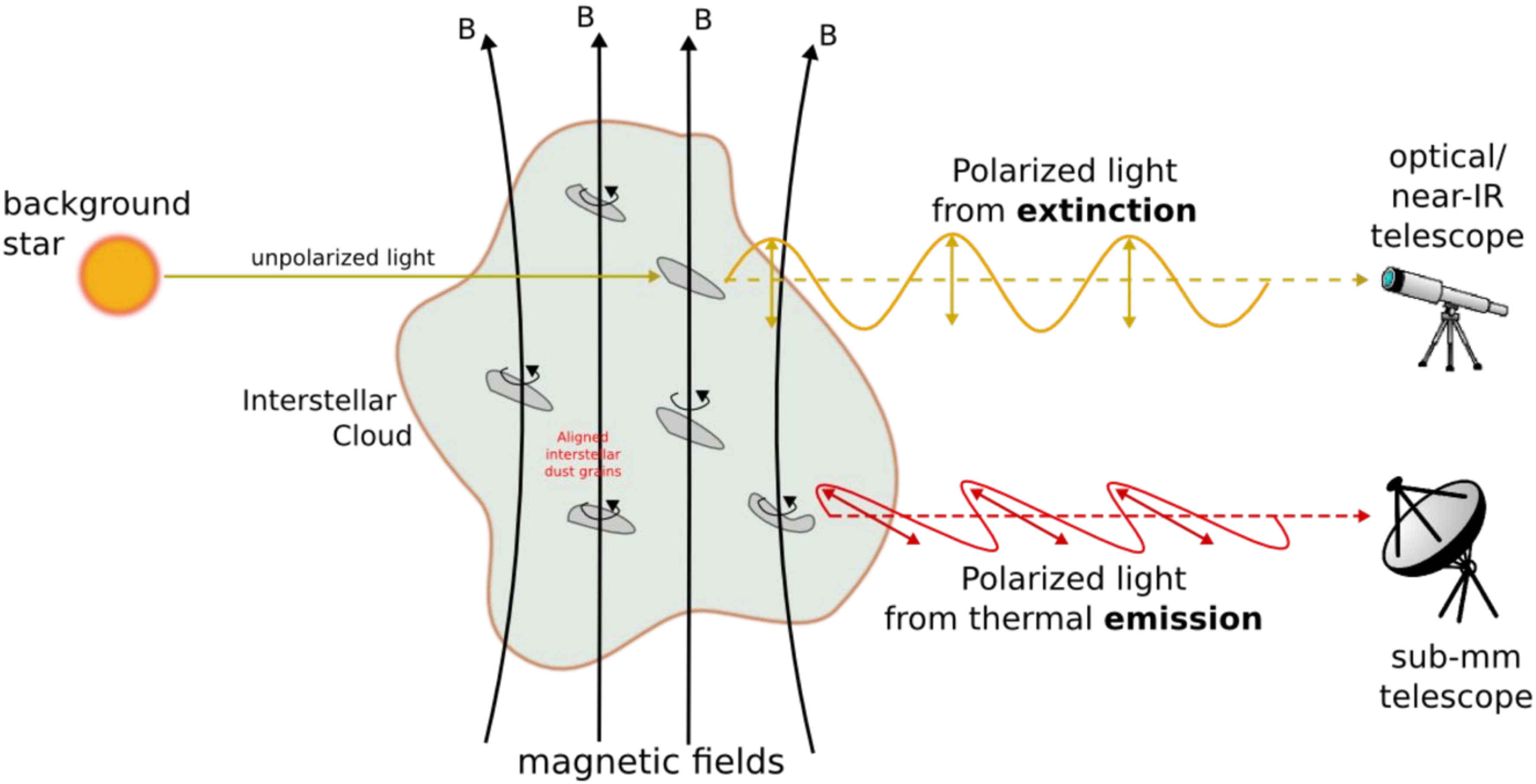
Herschel PACS 70 micron map of Rho Oph A.





1.3 mm map from Motte, Andre & Neri (1998): six protostellar clumps seen at 1.3 mm formed by fragmentation in the compressed gas layer at the interface between the PDR and the Oph-A cloud core.

Background and main science goals



- Grain alignment/Radiative Torques (RATs) – fundamental connection between B-fields and polarization measurements
- Main goals: evaluate grain alignment efficiency through calculations of the **polarization ratio** $p_{\lambda 1}/p_{\lambda 2}$

Main science goals – FIR Polarization spectrum

- Why polarization ratio ($\mathbf{p}_{\lambda 1}/\mathbf{p}_{\lambda 2}$) and not just polarization degree ($\mathbf{p}_{\lambda}$)?
  - Polarization degree (**p**) – depends on inclination of **B** along the line-of-sight
    … **but** the ratio $\mathbf{p_D/p_C}$ does not → map variations of grain alignment efficiency

- Polarization ratio traces the slope of the polarization spectrum. For Rho Oph A: bands D (154 μm) an C (89 μm):
  - **$\mathbf{p_D/p_C > 1}$: positive slope**
  - **$\mathbf{p_D/p_C < 1}$: negative slope**

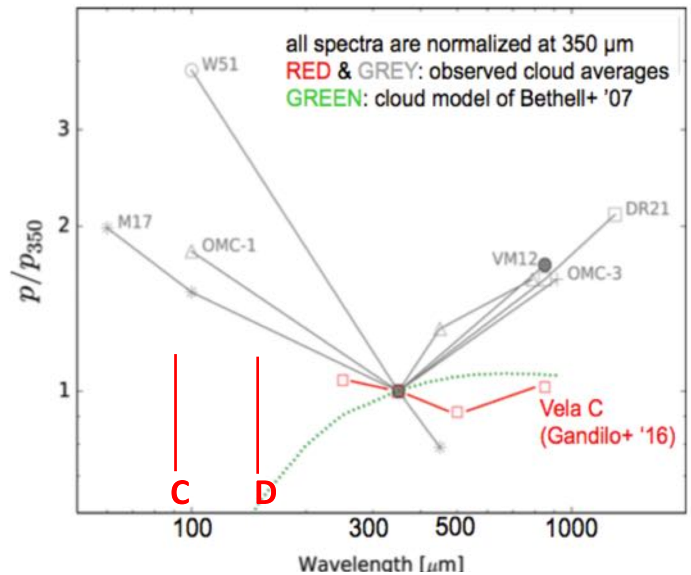
- But, from the literature, there is not much consensus between observations and theory…

Main science goals – FIR Polarization spectrum

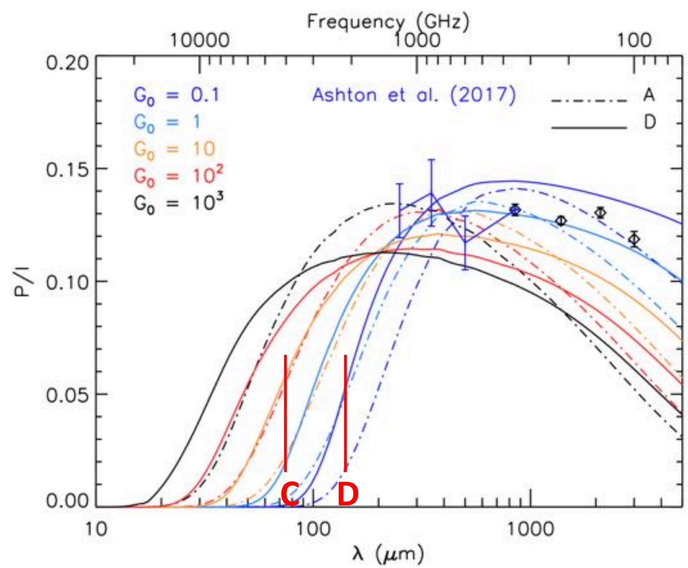
- What is the shape of the polarization spectrum in the far-infrared?
  - **<u>Observed – negative slopes</u>** (e.g., Vailancourt et al. 2012, Zeng et al. 2013):

$$\left(\frac{dp}{d\lambda}\right)_{FIR} < 0$$

<u>Proposed explanation</u>: mixture of cold and warm regions along LOS – assuming RATs **grain alignment**, hot regions are better aligned than cold regions;
Since the hot regions with well-aligned grains will be relatively brighter than the cold regions at the shorter wavelengths, we expect shorter wavelengths to be more polarized – **negative** slopes



Compilation of pol. spectrum observations (gray lines) compared to the dust grain models of Bethell et al. (2007) (green). **<u>Typically decreasing slopes observed in the FIR</u>**.



Polarization spectrum predictions from dust grain models by Guillet et al. (2018). **<u>Increasing slopes predicted in the FIR</u>**.

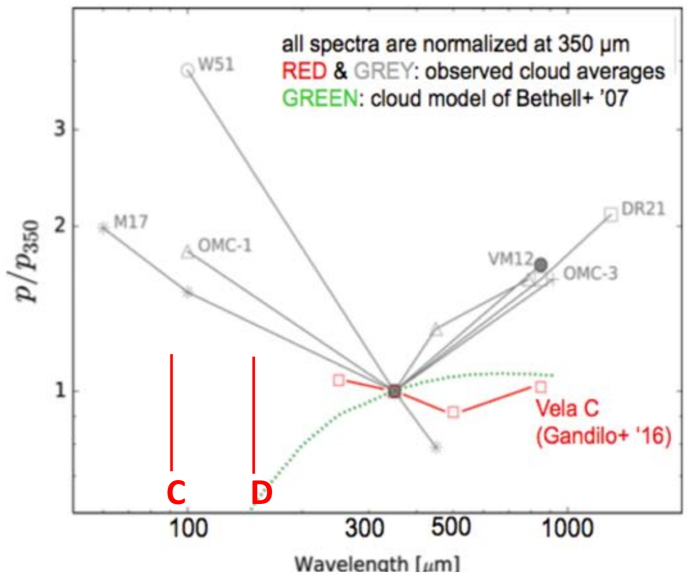
Main science goals – FIR Polarization spectrum

- What is the shape of the polarization spectrum in the far-infrared?
  - **Theory – positive slopes** (e.g., Bethell et al. 2007, Guillet et al. 2018):

$$\left(\frac{dp}{d\lambda}\right)_{FIR} > 0$$

Explanation: (1) larger-sized grains ($\gtrsim$0.2 μm) are relatively more efficiently aligned as compared to smaller-sized grains ($\lesssim$0.2 μm) (Kim & Martin 1995, also predicted from the RATs **grain alignment** theory; e.g., Lazarian 2007); (2) Even when subject to a uniform radiation field, smaller grains are relatively warmer than larger grains (Li et al. 1999) – **positive** pol. spectrum slopes

- Pol. Spectrum in Rho Oph A:
  - Important test for grain alignment theory;
  - Additionally, connection between observations and theory;



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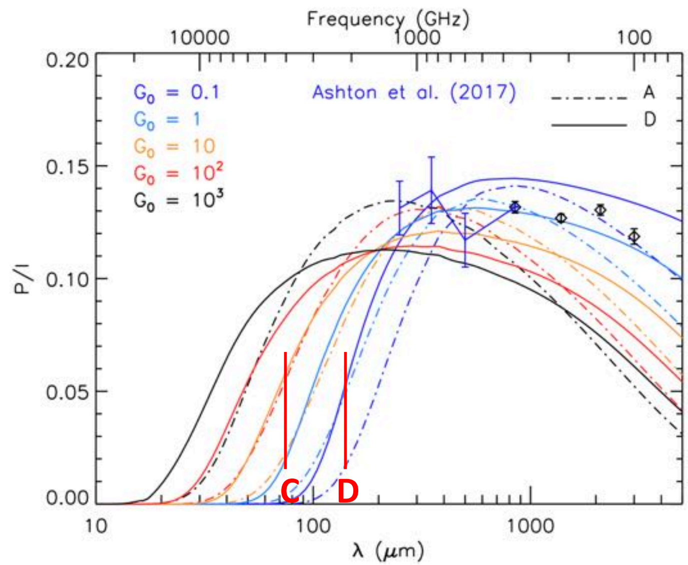
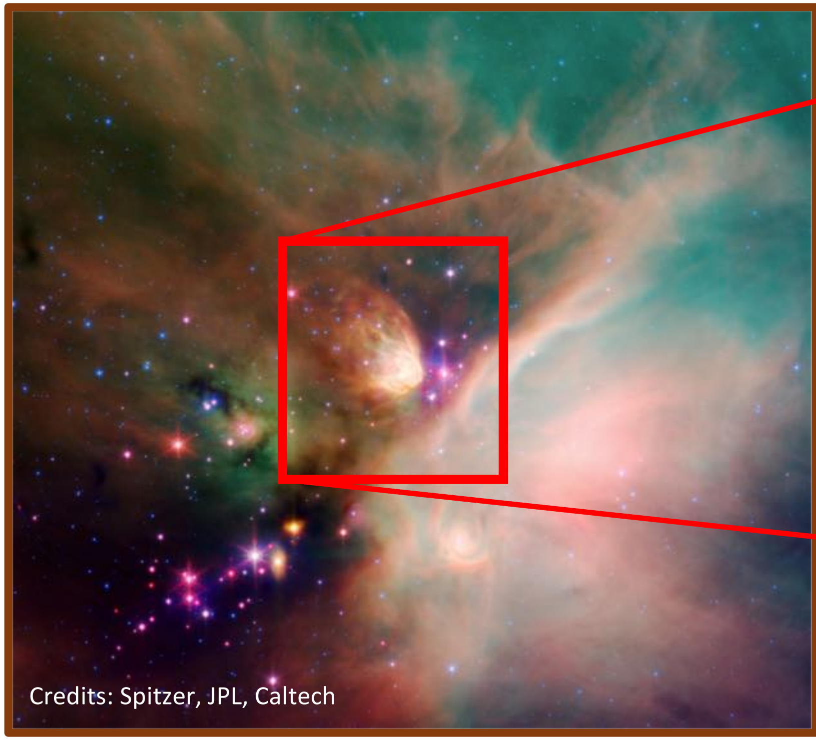
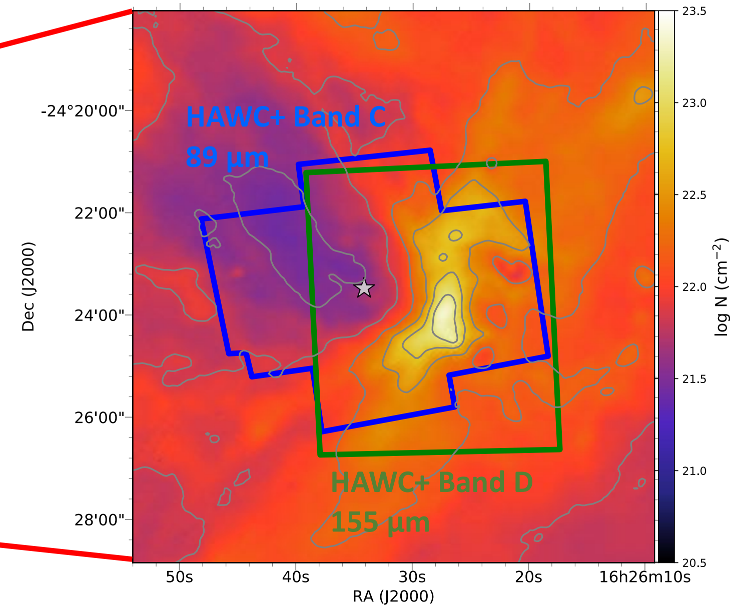


Polarization spectrum predictions from dust grain models by Guillet et al. (2018). **Increasing slopes predicted in the FIR**.

Rho Oph A – HAWC+ Observations





Column density map (based on Herschel)

- Peak extinction $A_V > 100$ mag

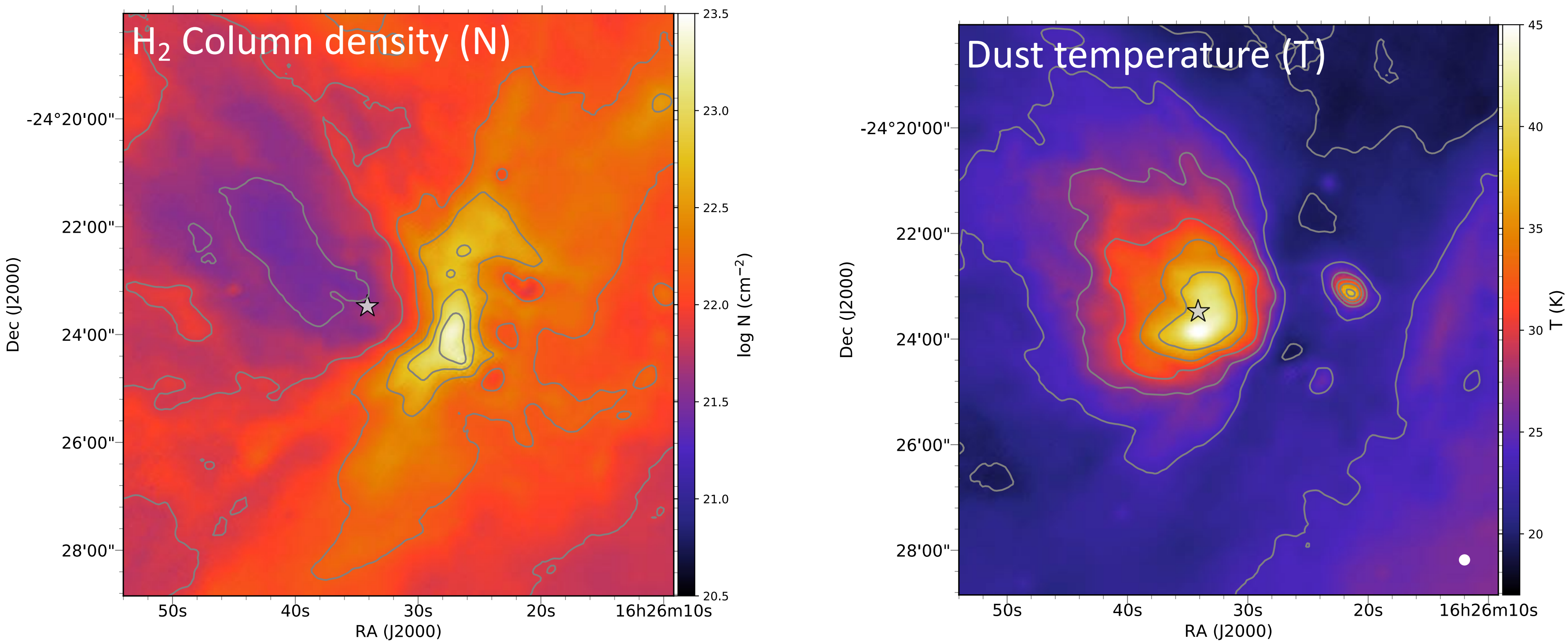
- HAWC+ Observations:
  - Band C: 89 μm
  - Band D: 154 μm

Main Goal: combine pol. bands C and D

- Slope of polarization spectrum – probe grain alignment efficiency
- Test Radiative Torques (RATs)

Column density and temperature maps

- Based on mod. black-body fits to Herschel (70, 100, 160 μm) data

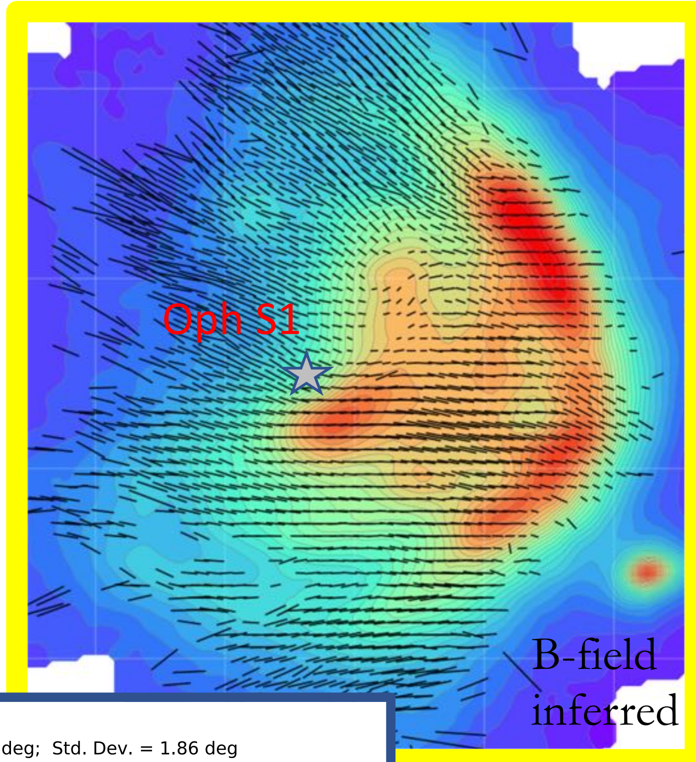


- Serve as proxies for highly illuminated (warm, more diffuse regions exposed to Oph S1 radiation) and highly obscured regions (cold and dense);

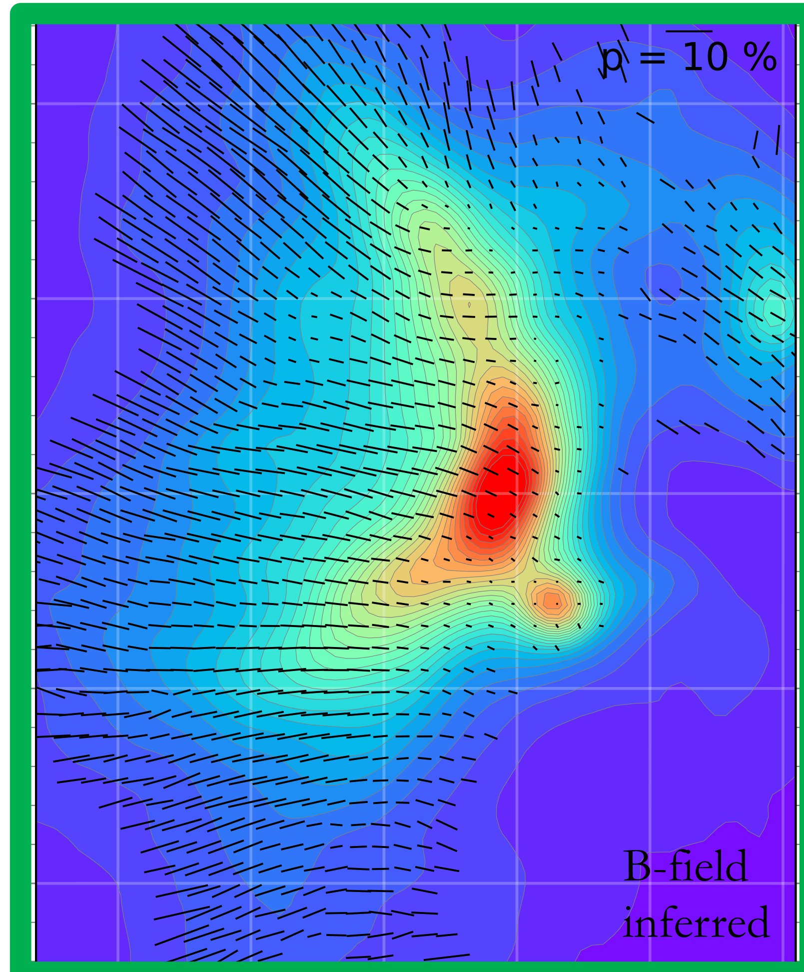
Santos et al. (2019, ApJ 882 2)

Magnetic fields in Rho Oph A

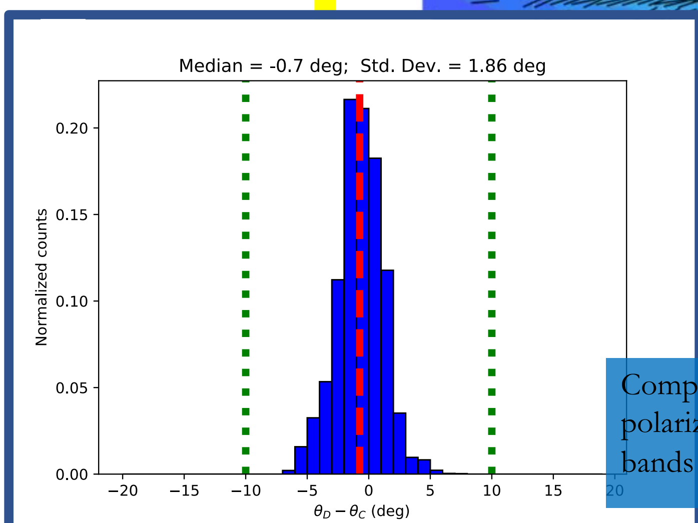
Rho Oph A



HAWC+ polarization map band C - 89 μm, ~7.8” beam size



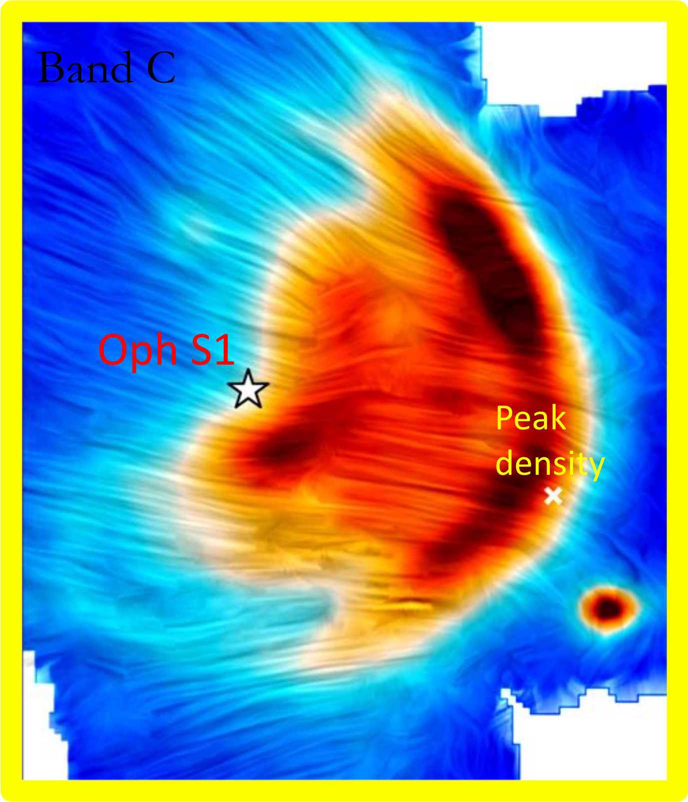
HAWC+ polarization map band D - 155 μm, ~13.6” beam size

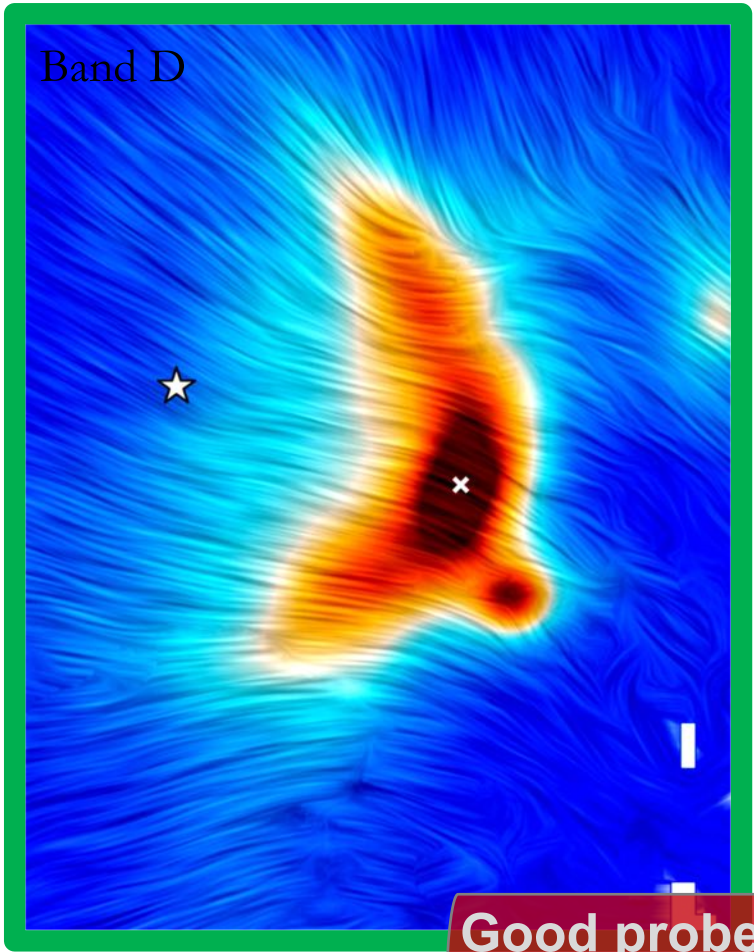


Comparison of polarization angles bands C & D

Magnetic fields in Rho Oph A

Rho Oph A





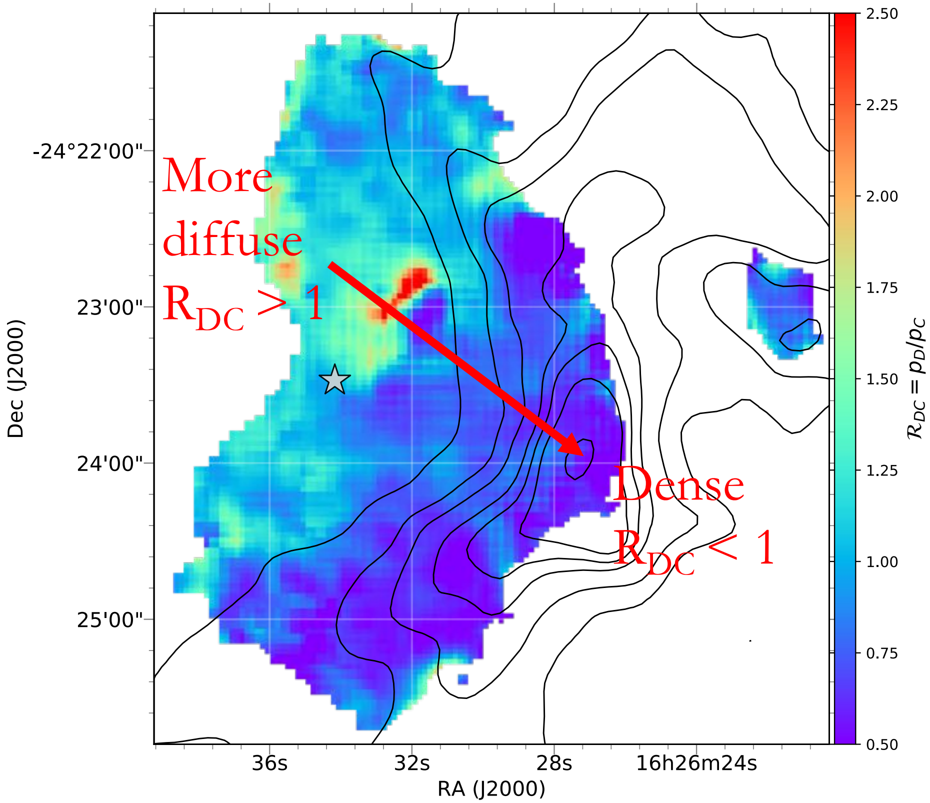
Good probe of grain alignment efficiency

- Slope of polarization spectrum: $R_{DC} = p_D / p_C$

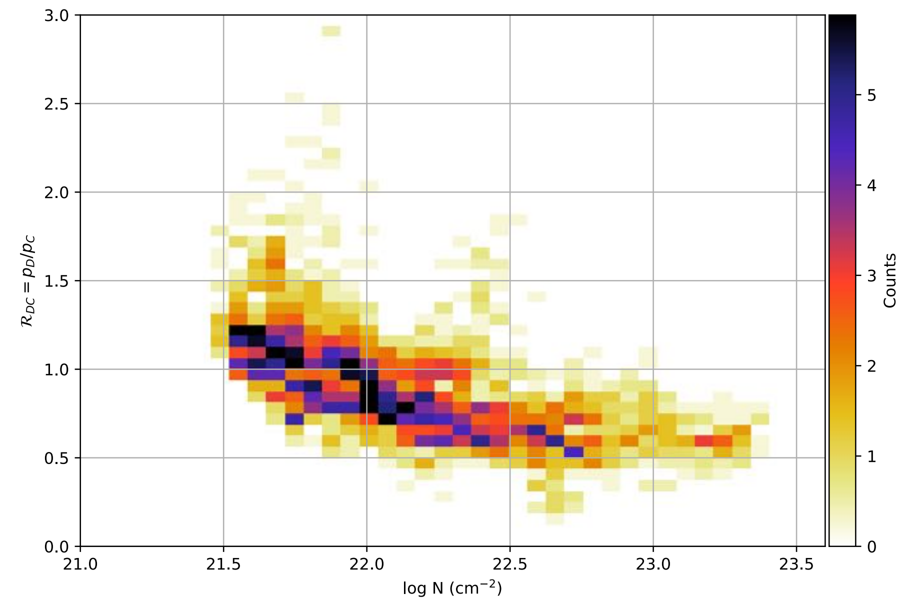
Santos et al. (2019, ApJ 882 2)

Far-IR polarization spectrum

Map of $R_{DC} = p_D / p_C$



R_{DC} as a function of column density log N



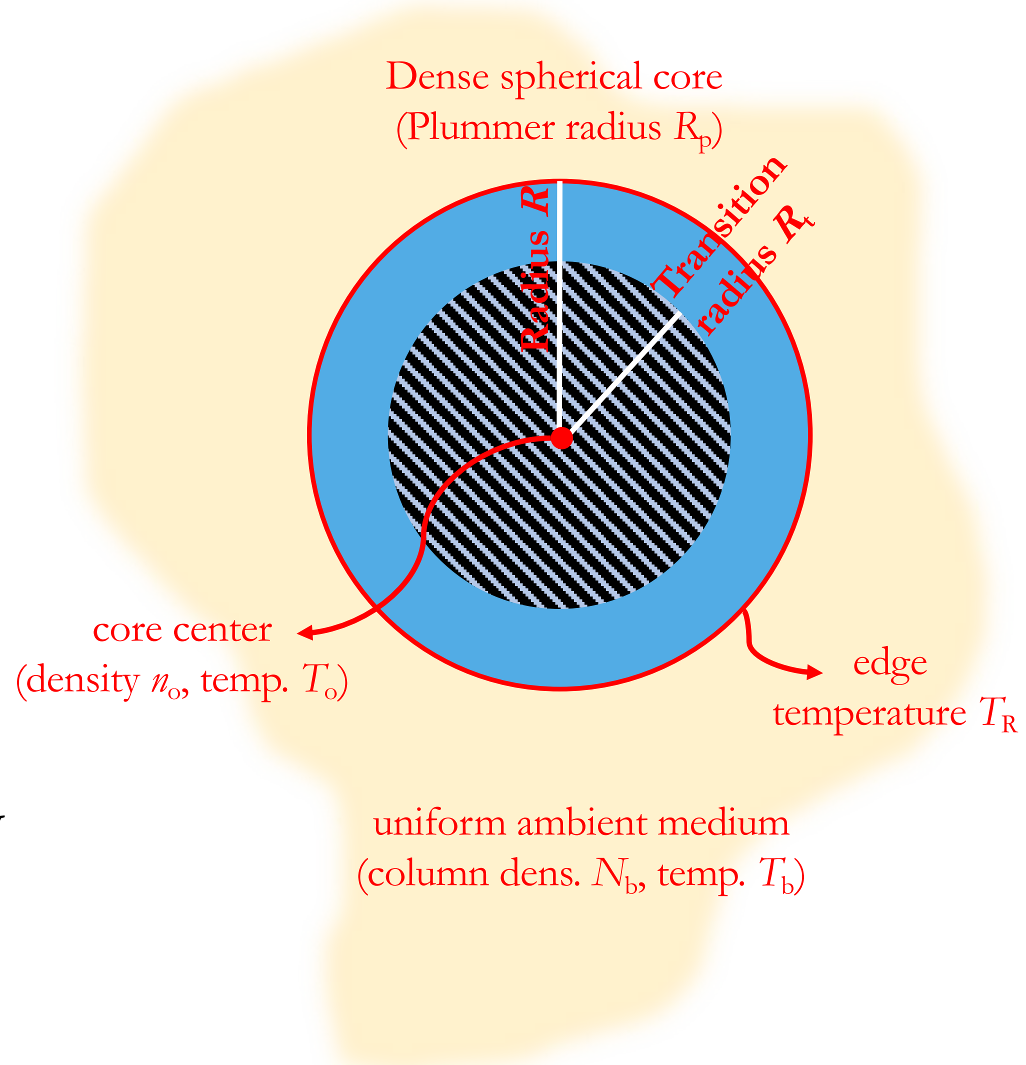
- Systematic dependence of polarization spectrum slope with cloud density

- Hypothesis: differences in grain alignment efficiency
  - outer (warm) grains, well aligned
  - inner (cold) grains, poorly aligned

Far-IR pol. spectrum: model *vs.* observations

- Very simple model:
  - Spherical dense core embedded in uniform background
  - Fit 7 model parameters based on *Herschel* data

- Transition radius R_T:
  - $r < R_T$: no polarized flux (no grain alignment) – **only free parameter**
  - Test for RATs



Far-IR pol. spectrum: model *vs.* observations

- Description of p_D / p_C calculation for simple model

$$P_\lambda(x) = p_{\lambda,o} I'_\lambda(x)$$

$$p_\lambda(x) = P_\lambda(x)/I_\lambda(x)$$

$$I_\lambda(x) = \kappa_{250}\, \mu m_{\mathrm{H}} \left(\frac{\lambda_o}{\lambda}\right)^\beta \int n(r) B_\lambda(T(r)) ds + I_{\lambda,b}$$

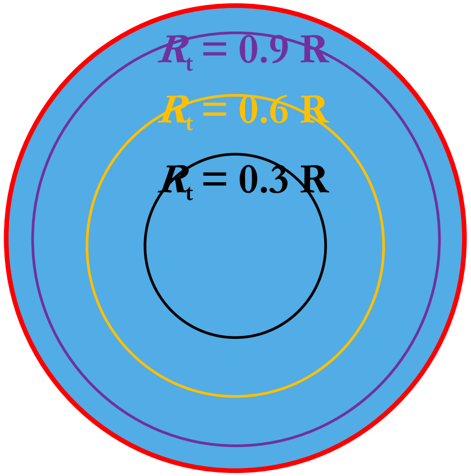
- The physical parameters used in the equations are chosen so that the model provides the best fit possible to the Herschel column density and temperature maps.

Parameter	Description	Determined Value
R	Core radius	0.074 pc
N_b	H_2 ambient column density	5.7×10^{21} cm^{-2}
T_b	Ambient dust temperature	30.7 K
T_R	Local dust temperature at the core edge ($r = R$)	38.9 K
n_o	H_2 number density at the core center ($r = 0$)	6.4×10^6 cm^{-3}
R_p	Core Plummer radius	0.244 R
T_o	Local dust temperature at the core center ($r = 0$)	13.9 K

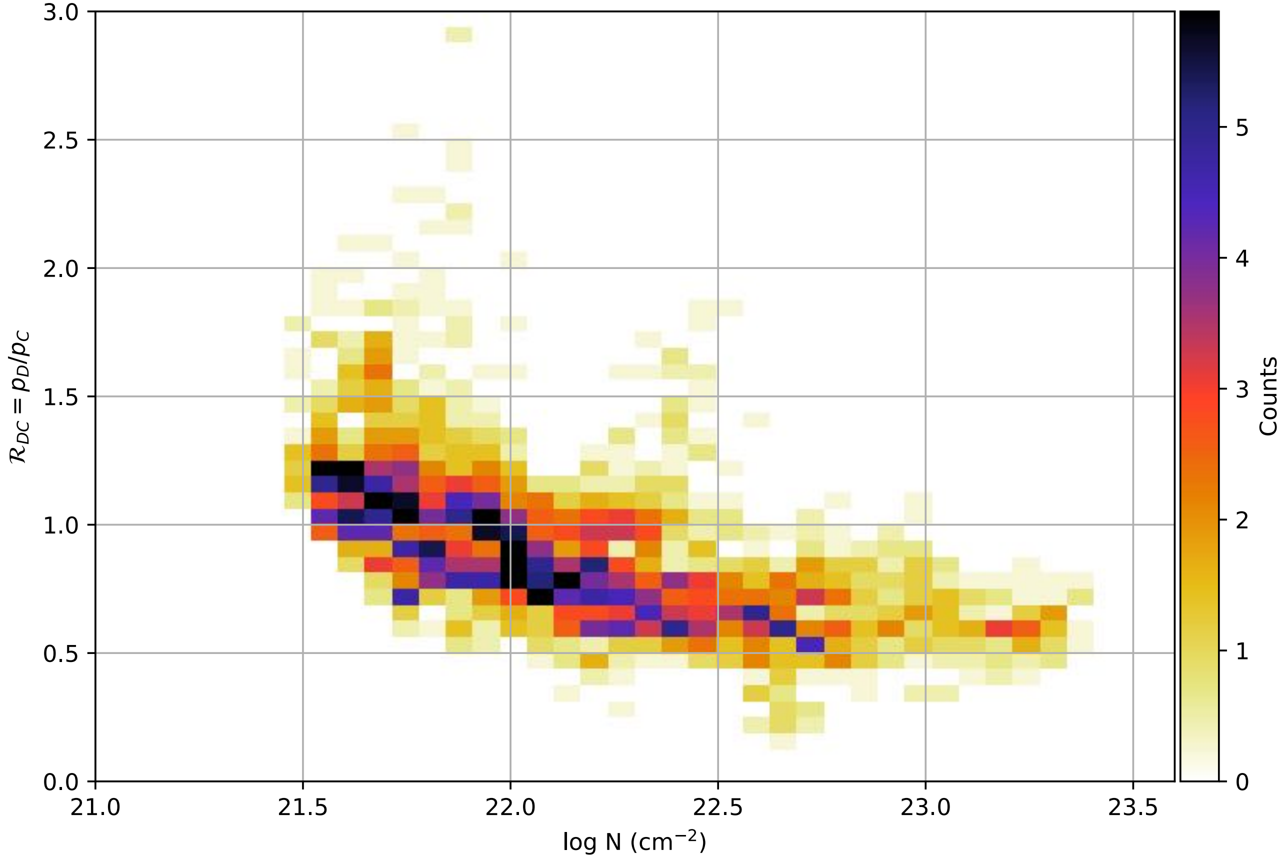
Santos et al. (2019, ApJ 882 2)

Far-IR pol. spectrum: model *vs.* observations

- Comparing model with observations:
  - Calculate R_{DC} *vs.* log N for different R_T values: 0.3 *R*, 0.6 *R* and 0.9 *R*



R_{DC} as a function of column density log N

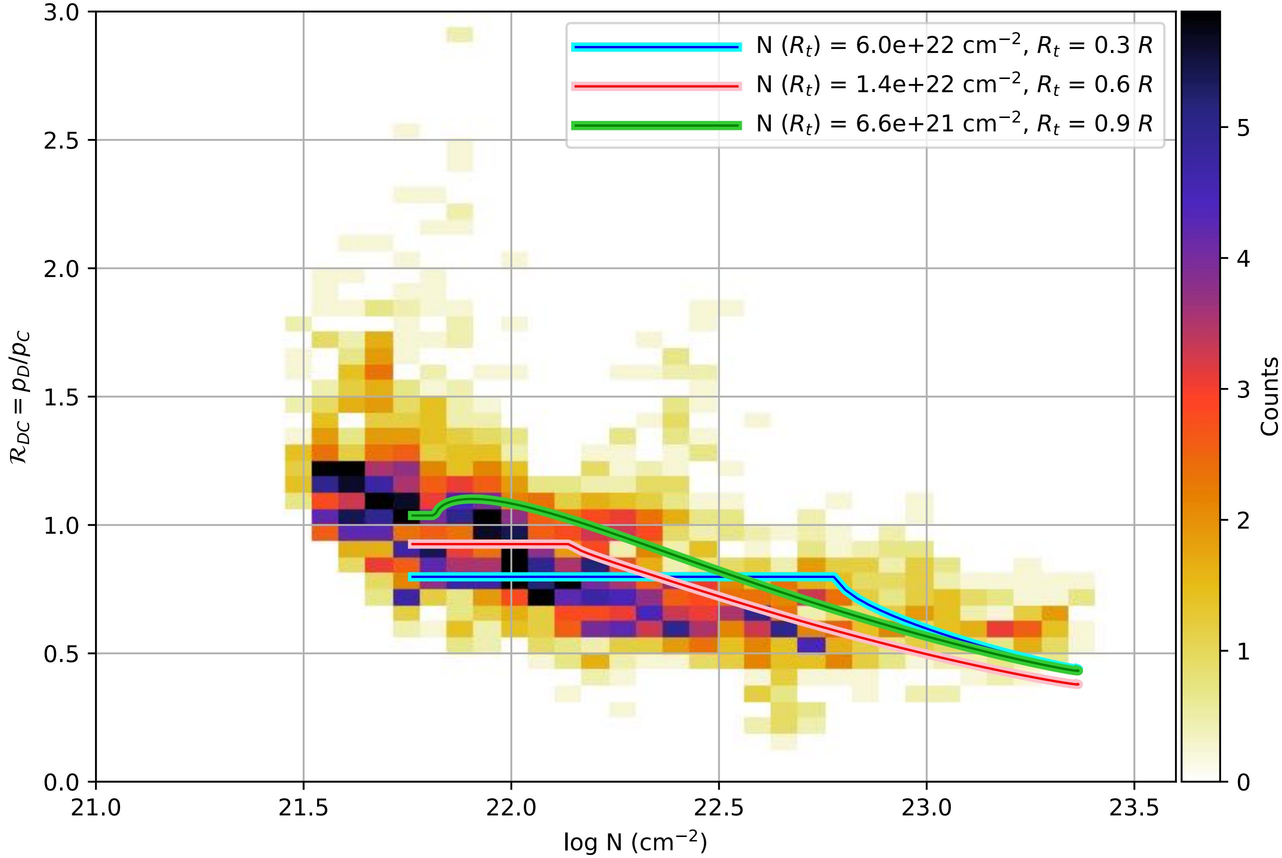


Santos et al. (2019, ApJ 882 2)

Far-IR pol. spectrum: model *vs.* observations

- The observed decrease of ~50% in R_{DC} can be reproduced with the simple model

R_{DC} as a function of column density log N

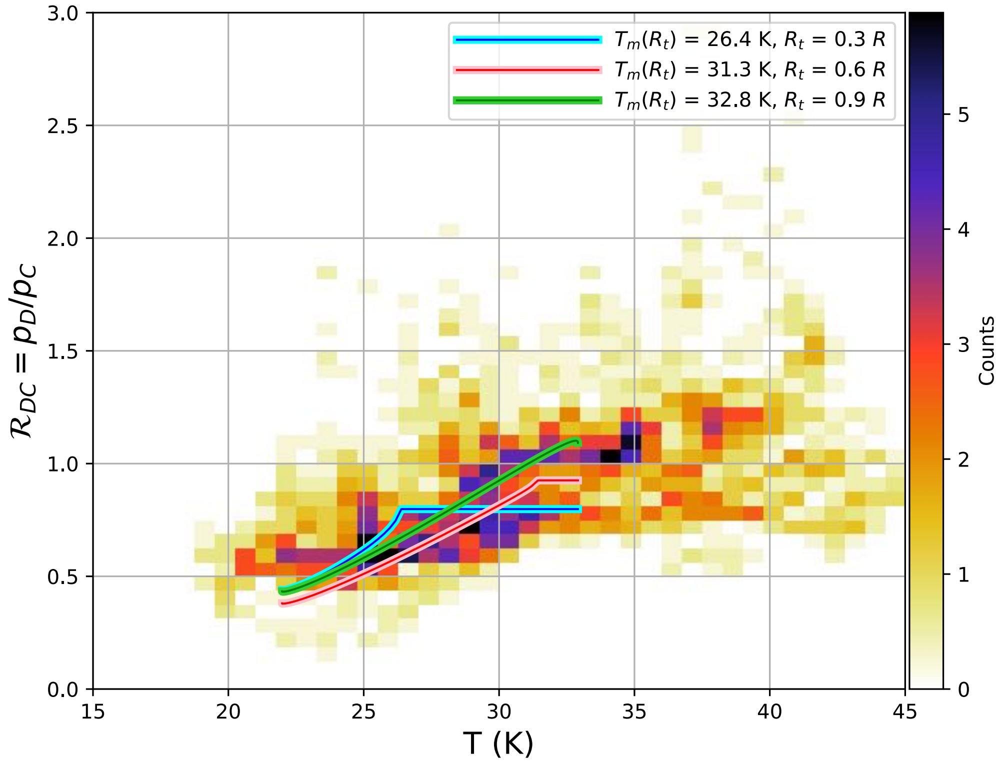


- Decrease in grain alignment efficiency likely responsible for trends in polarization spectrum slope – support for RATs

Santos et al. (2019, ApJ 882 2)

Far-IR pol. spectrum: model *vs.* observations

- Temperature dependence of R_{DC}

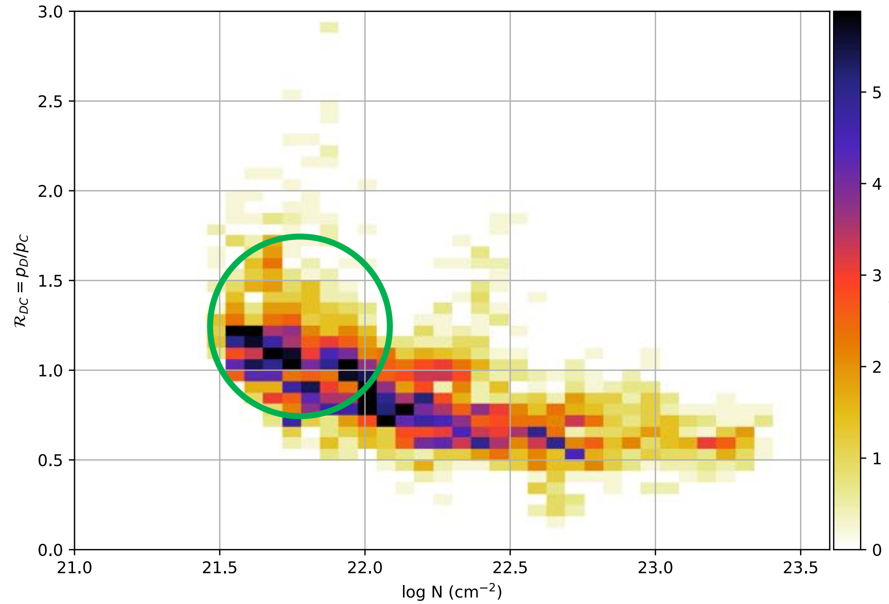


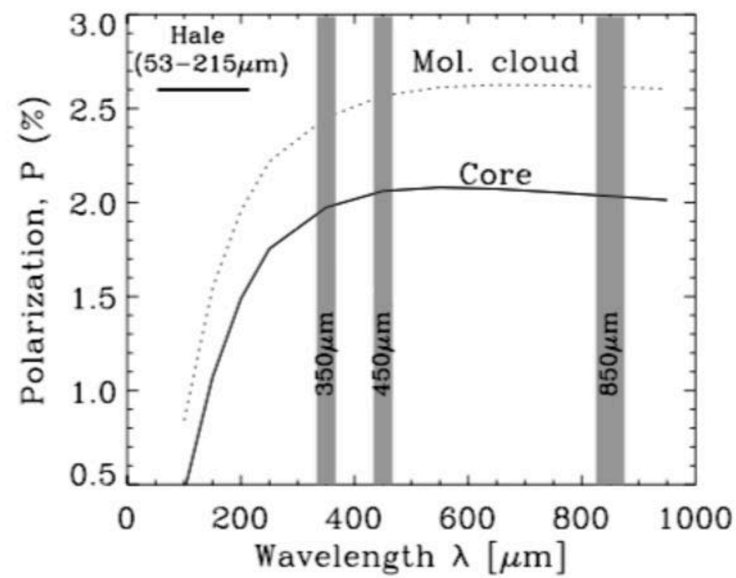
- The local temperature (from model) can serve as a proxy for the radiation intensity and can thereby be related to grain alignment efficiency.

Pol. spectrum comparison with dust grain models

- Lower column density end: $10^{21.5} < N\ (\mathrm{cm}^{-2}) < \approx 10^{22.0}$, mean $R_{DC} \approx 1.1$

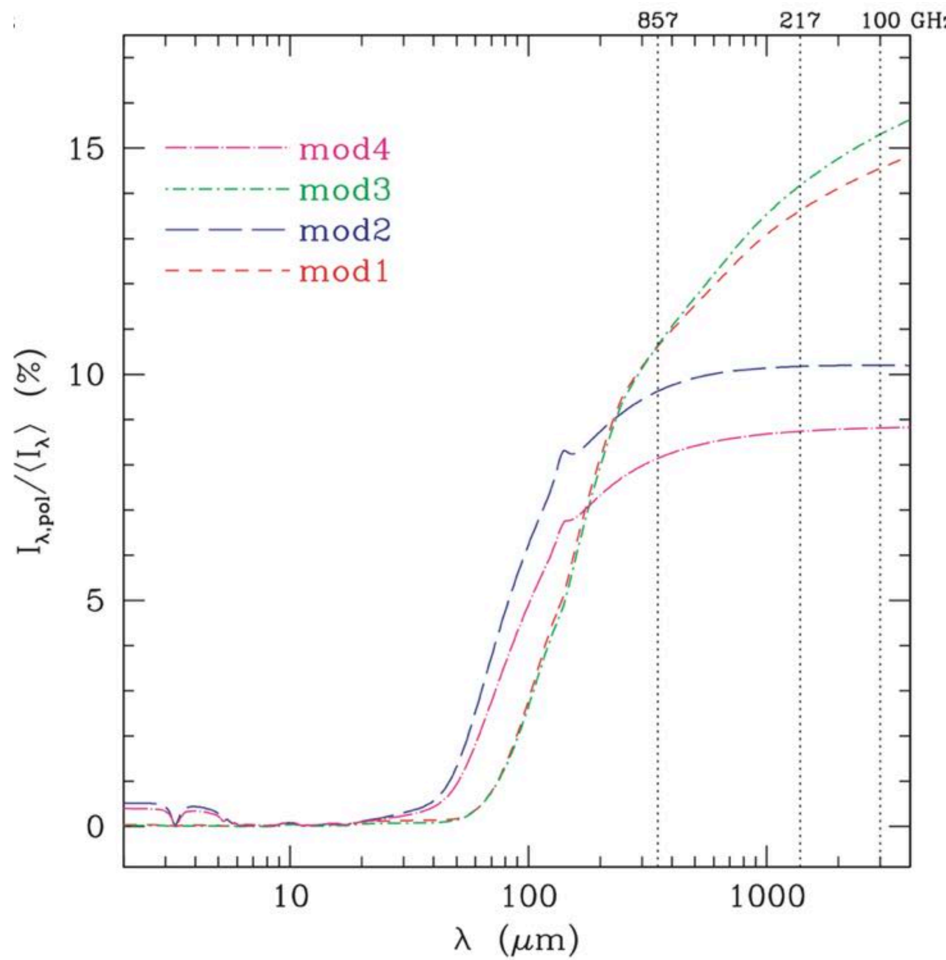
- From **Bethell et al. (2007)** model (which probes similar column densities): $1.75 < R_{DC} < 2.0$
  - But model temperatures (≈5–17 K) are much smaller than the observed around Rho Oph A (≈30–40 K)





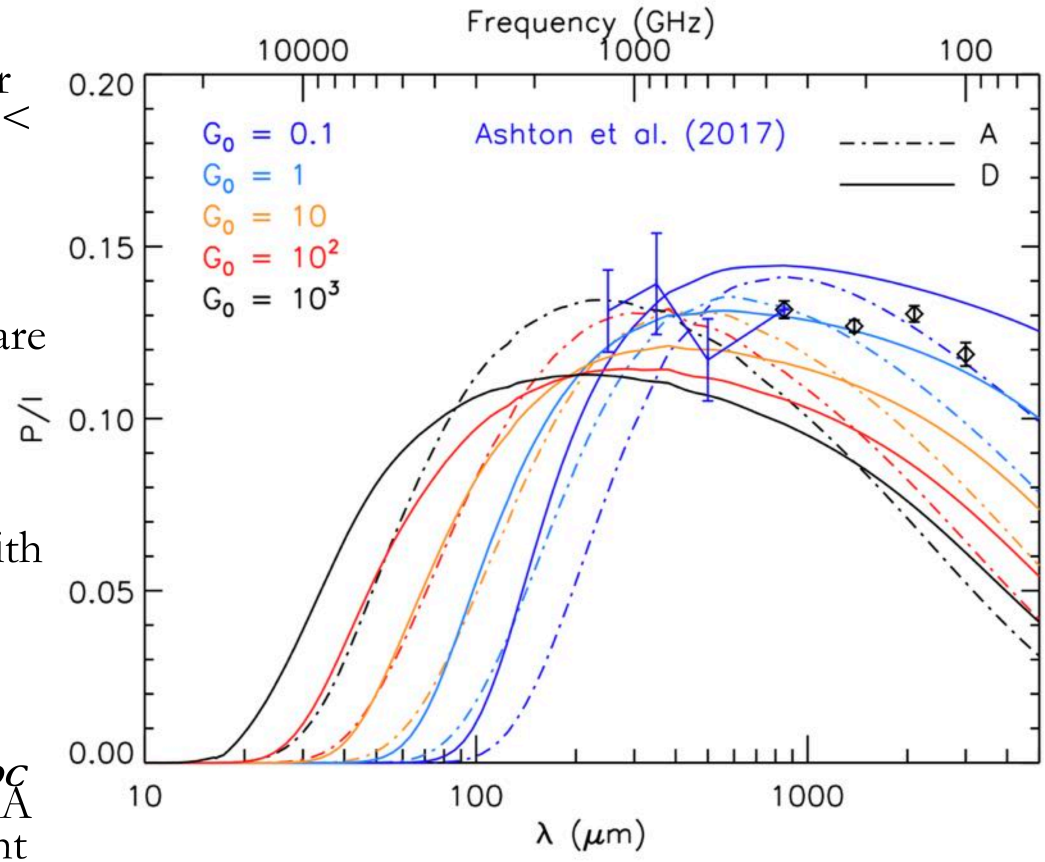
Pol. spectrum comparison with dust grain models

- **Draine & Fraisse (2009)** found R_{DC} values between 1.4 and 2.6, which are also slightly higher than the mean values found in Rho Oph A for the lower column density areas.
  - But this model is valid for the **diffuse ISM**.



Pol. spectrum comparison with dust grain models

- **Guillet et al. (2018)** presents models for translucent clouds of $10^{21.0} < N\ (\mathrm{cm}{-2}) < \approx 10^{21.5}$, i.e., somewhat smaller than Rho Oph A column density levels.
- Predicted polarization spectrum curves are significantly affected by the ISRF level.
- Models with higher ISRF levels show $R_{DC} \approx 1.1$ (black curves), while models with lower ISRF intensities show $R_{DC} \approx 20.0$ (blue curves).
- Somewhat **small positive values of R_{DC}** for the diffuse component of Rho Oph A (as compared to dust grain models) might be due to the **strong exposure to radiation from Oph S1**.



Guillet et al. (2018) polarization spectrum models for a translucent cloud considering different levels of the **interstellar radiation field** (IRSF).

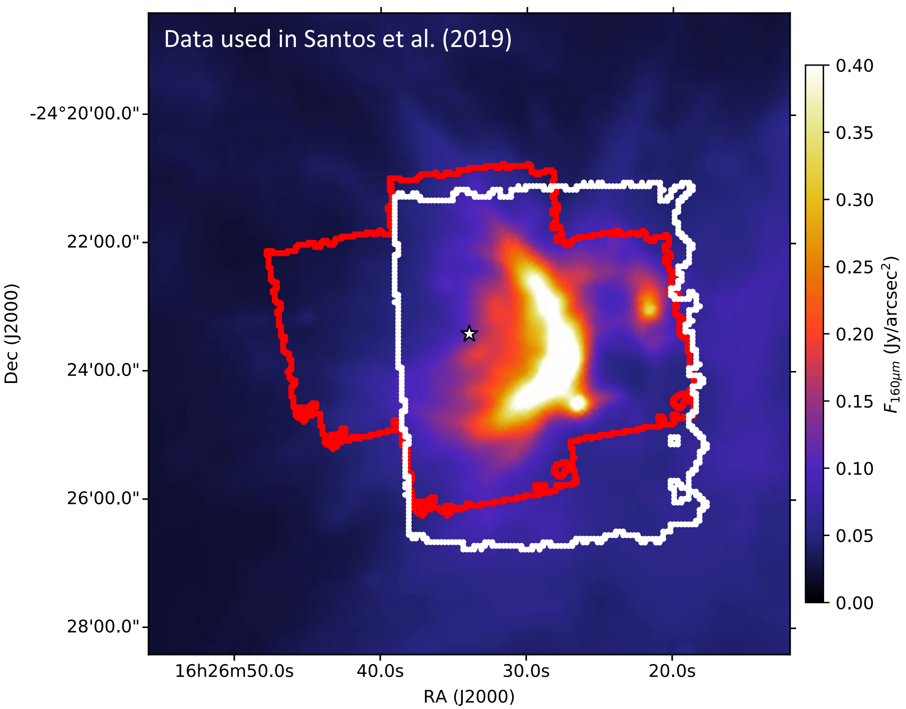
Far-IR pol. spectrum: model *vs.* observations

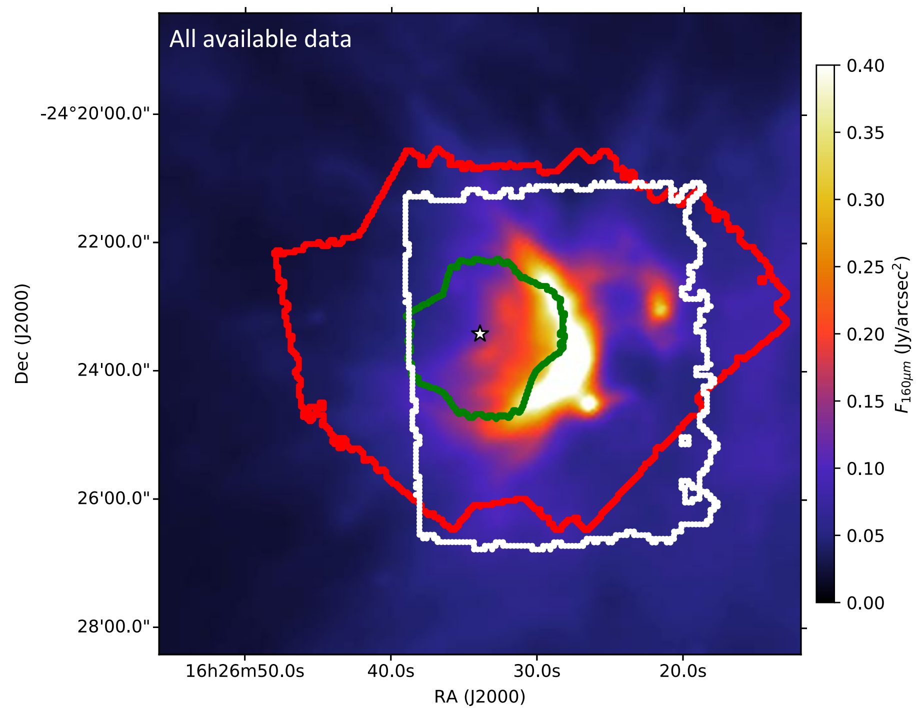
- Main conclusions and take-away points:
  - This analysis introduces a **new method** to probe the grain alignment efficiency in molecular clouds;
  - Provided that a model is given for the studied cloud, **one may test** beyond which core depth, or below which local temperature, the **grain alignment is no longer efficient, with no LOS inclination effects.**
  - Comparison between simple cloud model and observations provides **support to the radiative-driven grain alignment mechanism (RATs)**
  - **Connection between dust models and observations**: first direct observation of positive inclinations in the FIR polarization spectrum

Continuing work: new polarimetric dataset

- Additional GTO dataset

Band A (53 μm) – green – new (centered on Oph S1)
Band C (89 μm) – red – more spatial coverage
Band D (154 μm) – white – same as before



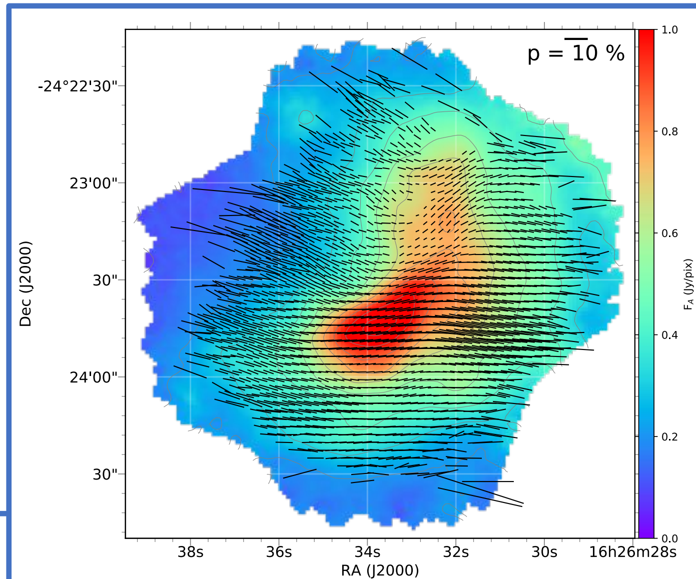


- More spectral coverage including band A, better angular resolution – B-fields near Oph S1

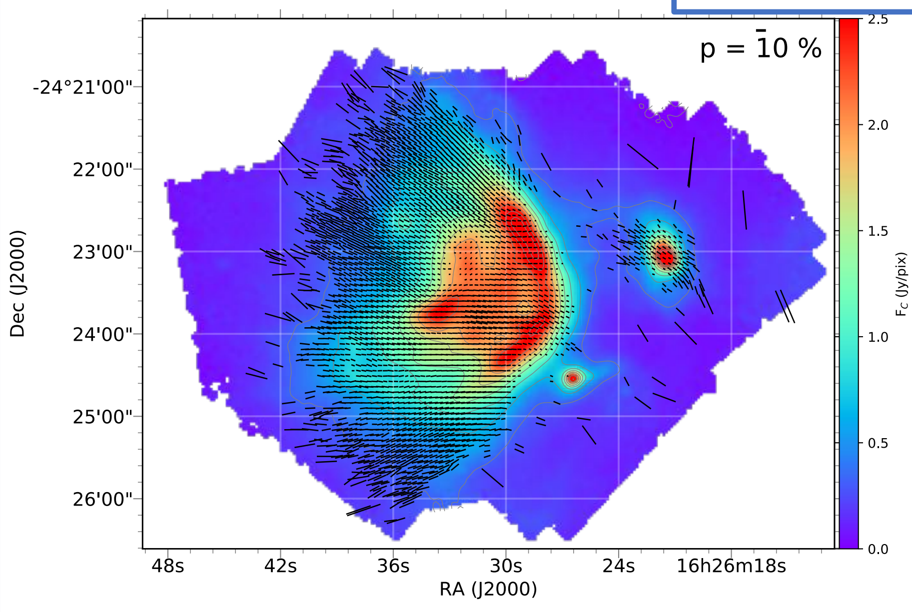
Continuing work: new polarimetric dataset

- Polarization maps (B-fields):

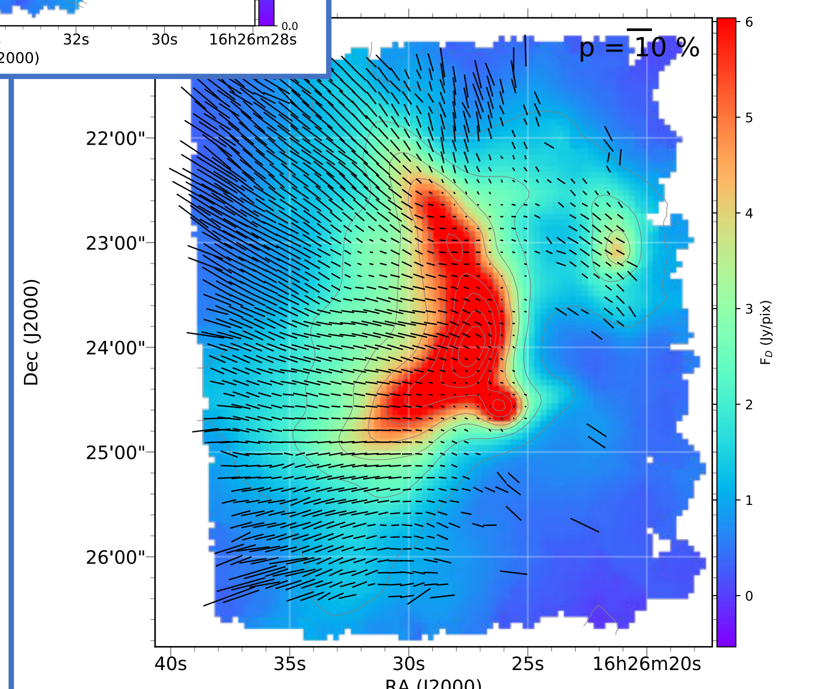
Band A



Band C



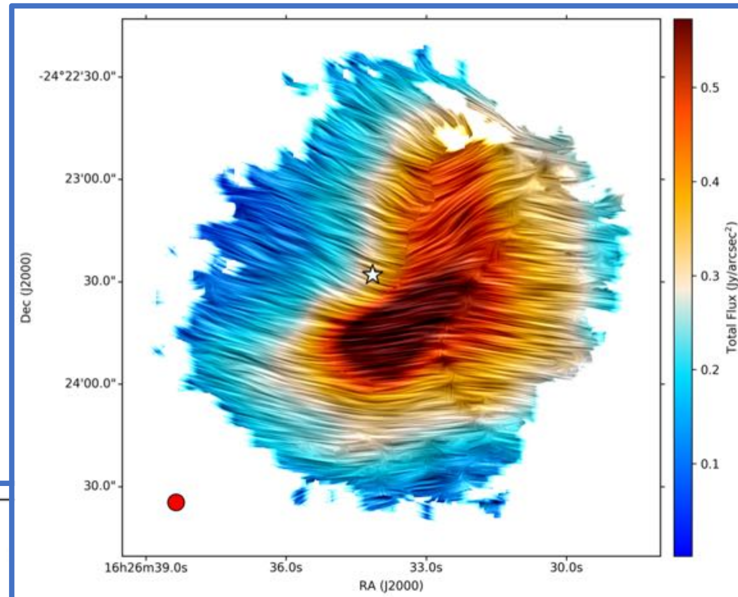
Band D



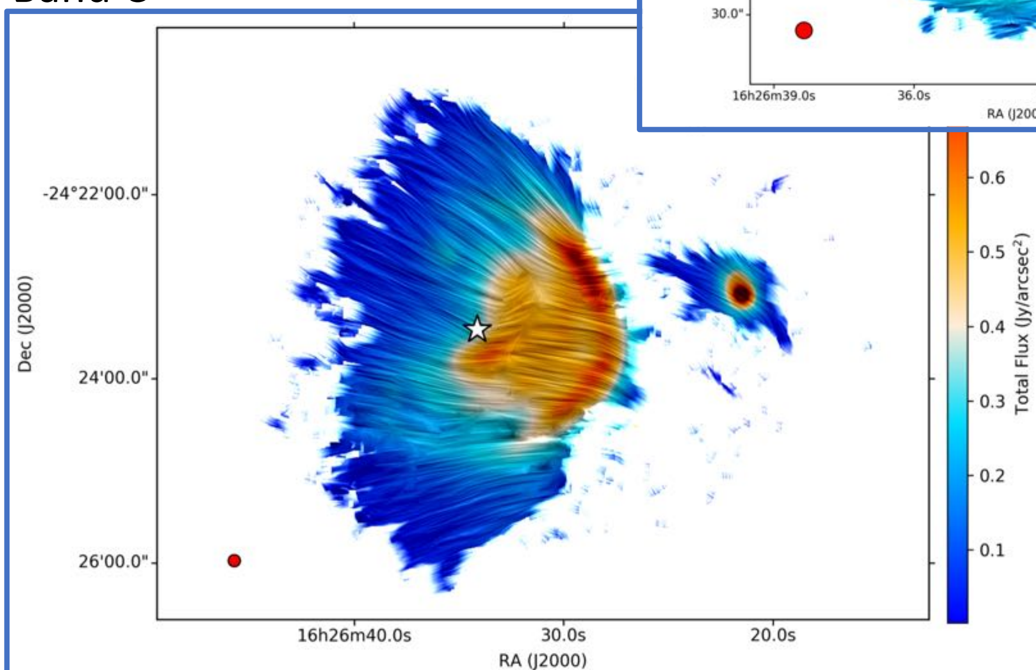
Continuing work: new polarimetric dataset

- Line-integral-convolution maps:

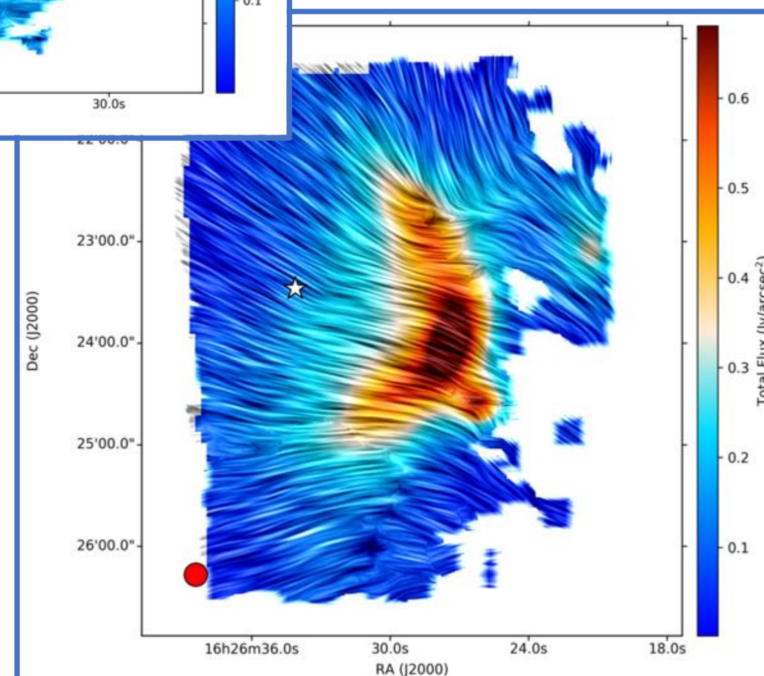
Band A



Band C

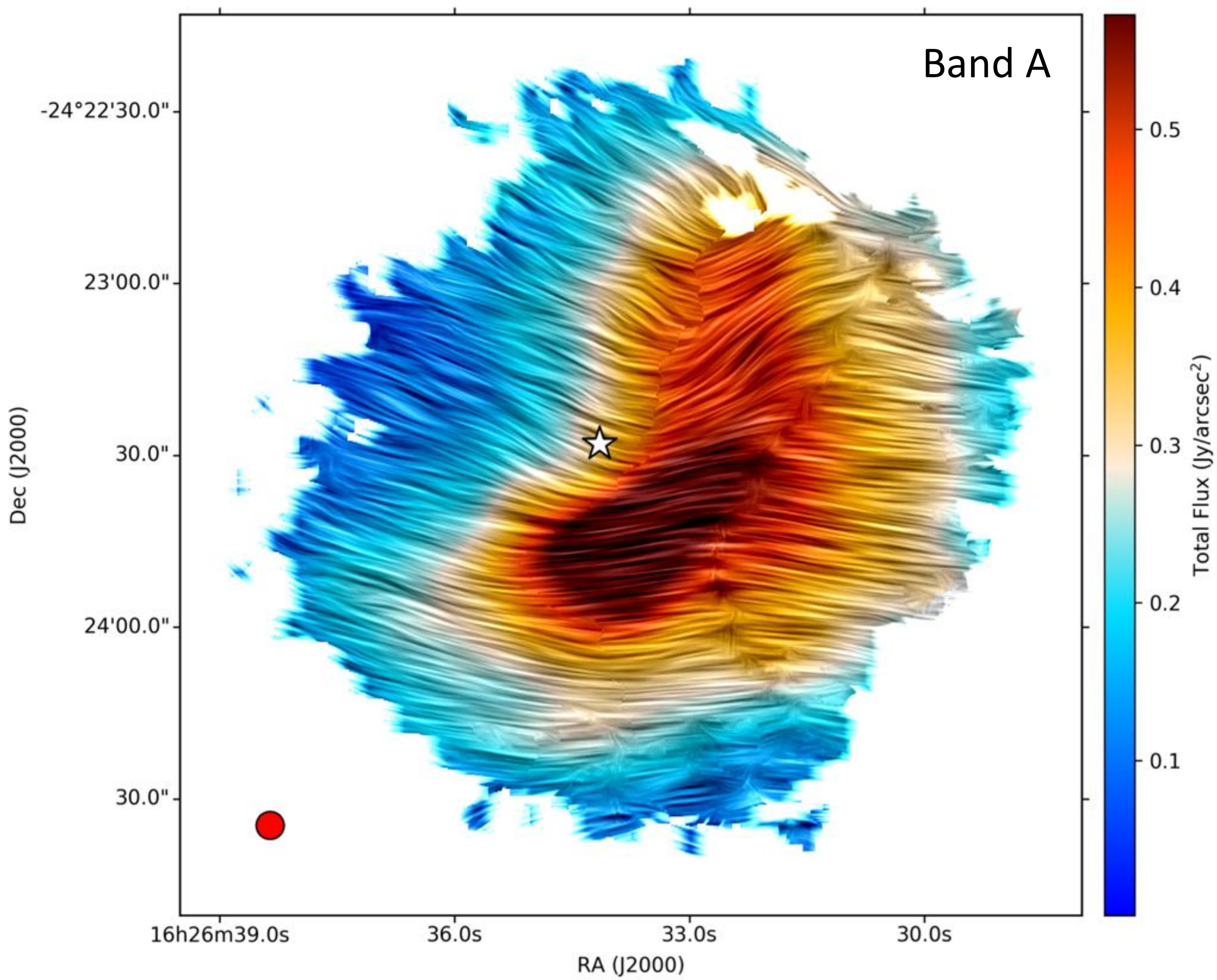


Band D



Continuing work: new polarimetric dataset

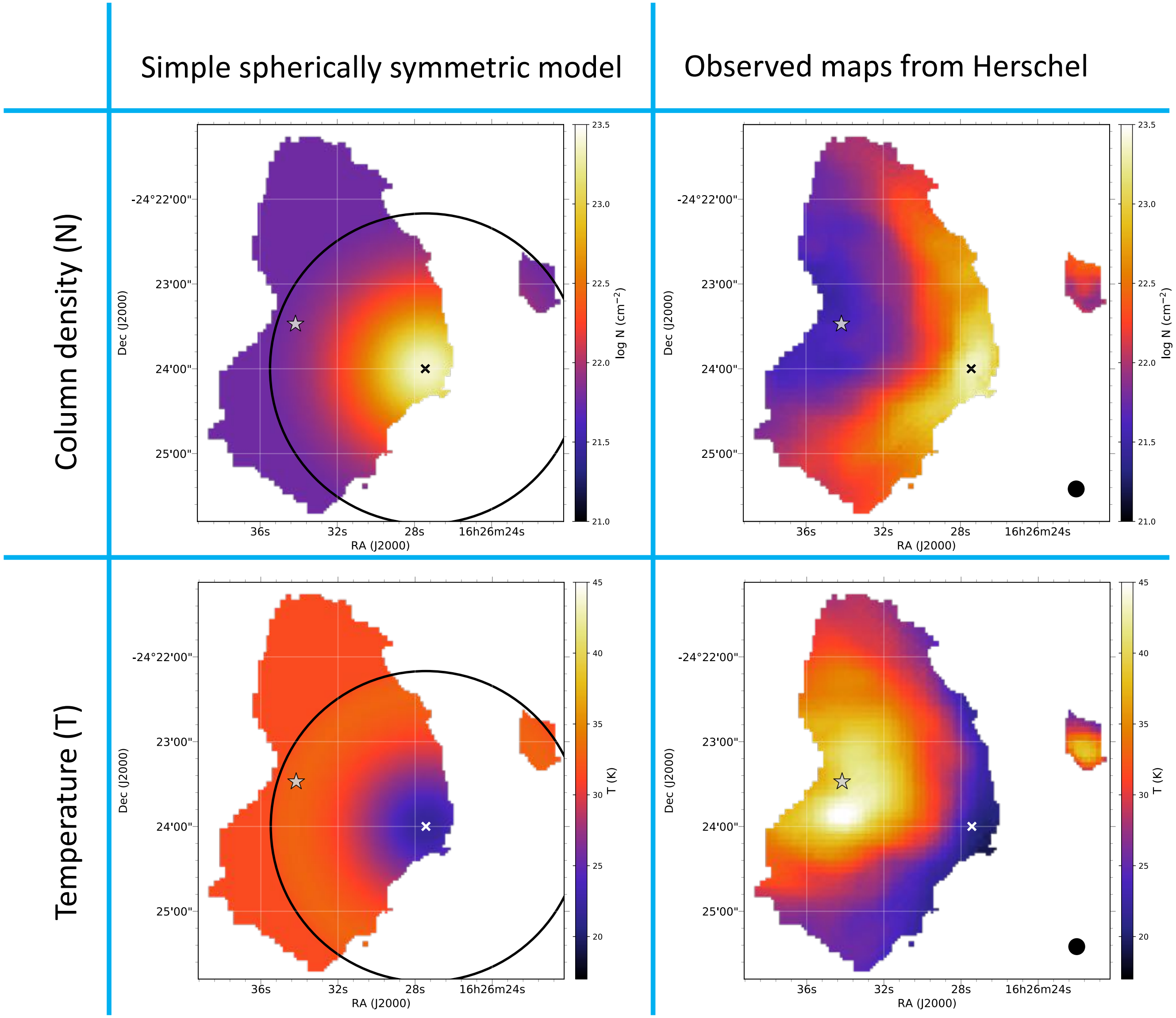
- Distortion of B-fields around Oph S1
- Possibly due to expansion of UC HII region around the massive star



Continuing work: problems with current model

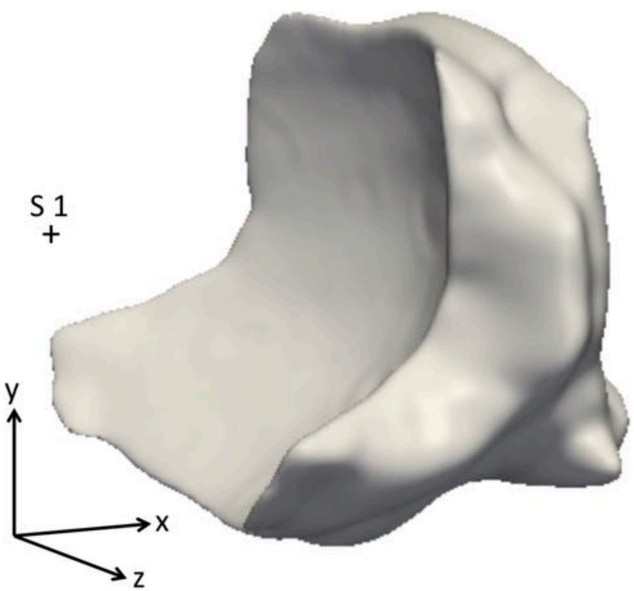
- Comparison between synthetic maps from spherical model and observations

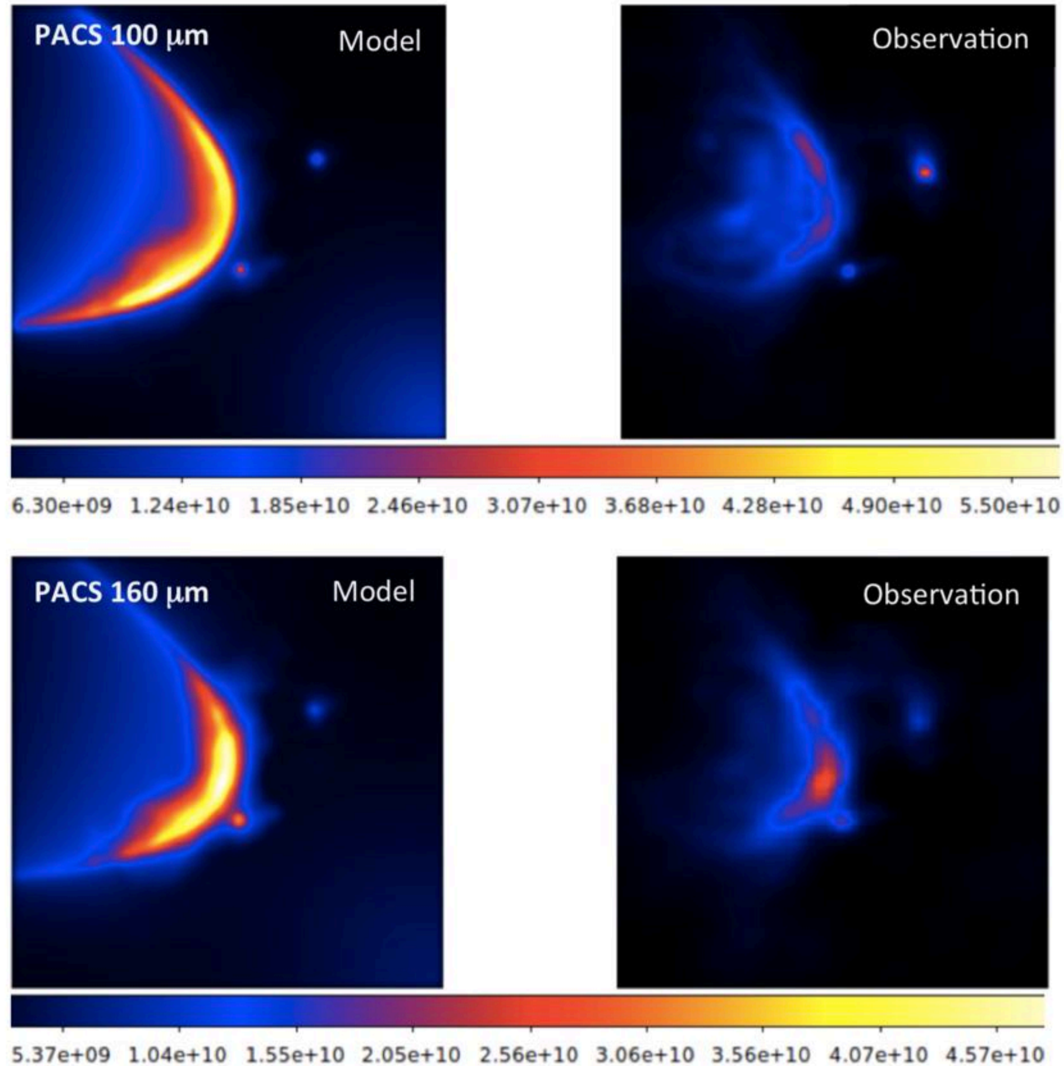
- Best possible *spherical* model, but clear differences exist



Continuing work: new model

- New model, more realistic, by Liseau et al. (2015)





Final remarks

- First conclusive observation of systematic variations of the far-infrared polarization spectrum within an interstellar cloud.

- Consistent with reduced grain alignment efficiency in the core, based on very simple modeling of the cloud.

- New method to probe grain alignment efficiency. Grain alignment theory: critical connection between interstellar polarization and magnetic fields – crucial to understand star formation.

Thank you!