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The Far-Infrared Polarization Spectrum of OMC-1 using HAWC+/SOFIA Observations

(arXiv:2008.00310)

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Outline

- Introduction
  - Orion Molecular Cloud-1
  - Dust Grains and Polarization in the ISM
  - Grain Alignment via Radiative Torques
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  - Probing the Polarization Spectra with Ratios
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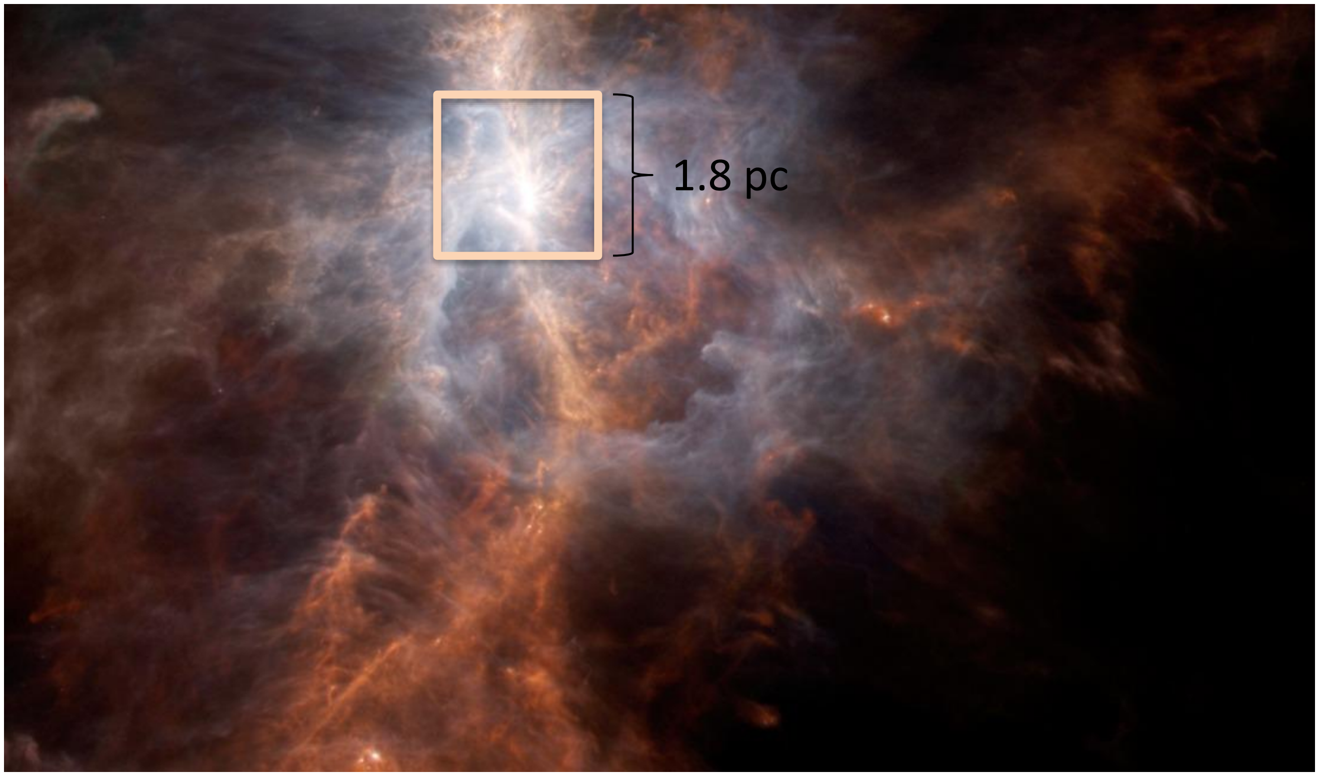
Orion Molecular Cloud-1 (OMC-1)



Credit: ESA/NASA/JPL-Caltech

- Closest region of massive star formation
- Distance: about 390 pc (Kounkel et al. 2017)

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Dust Grains and Polarization in the ISM

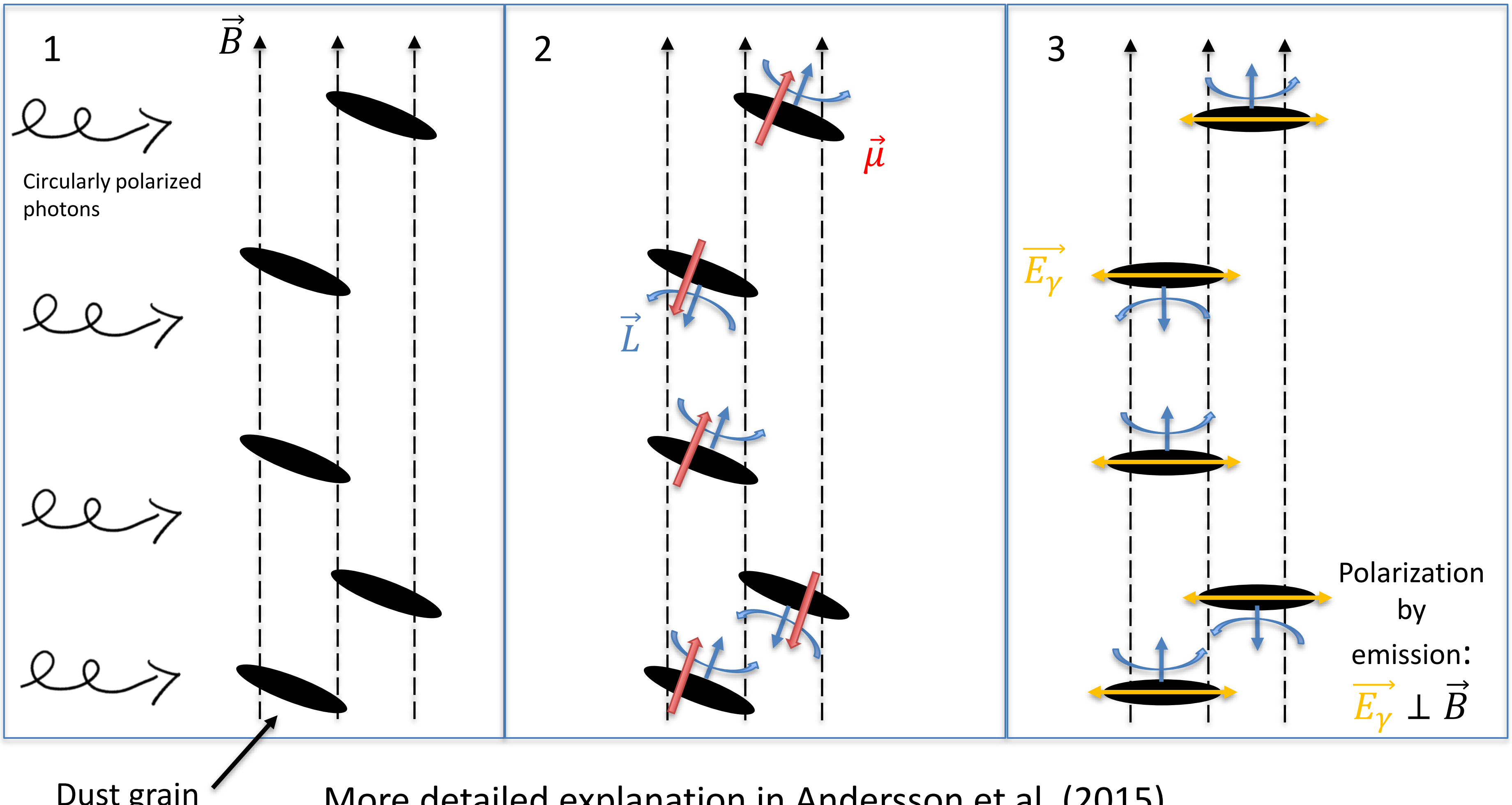
- Discovered by Trumpler in 1930
- Polarization from dust discovered in the optical in 1949 by Hall and Hiltner
- Stein (1966) predicted dust polarization in far-IR wavelengths, Cudlip et al. (1982) first detected it
- Understanding grain alignment leads to deeper understanding of characterizing magnetic fields in ISM and properties of dust

Grain Alignment via Radiative Torques

Grains spun up by circular polarization

Grains obtain magnetic moment from Barnett Effect

Grains align perpendicular to field and emit polarized radiation



More detailed explanation in Andersson et al. (2015)

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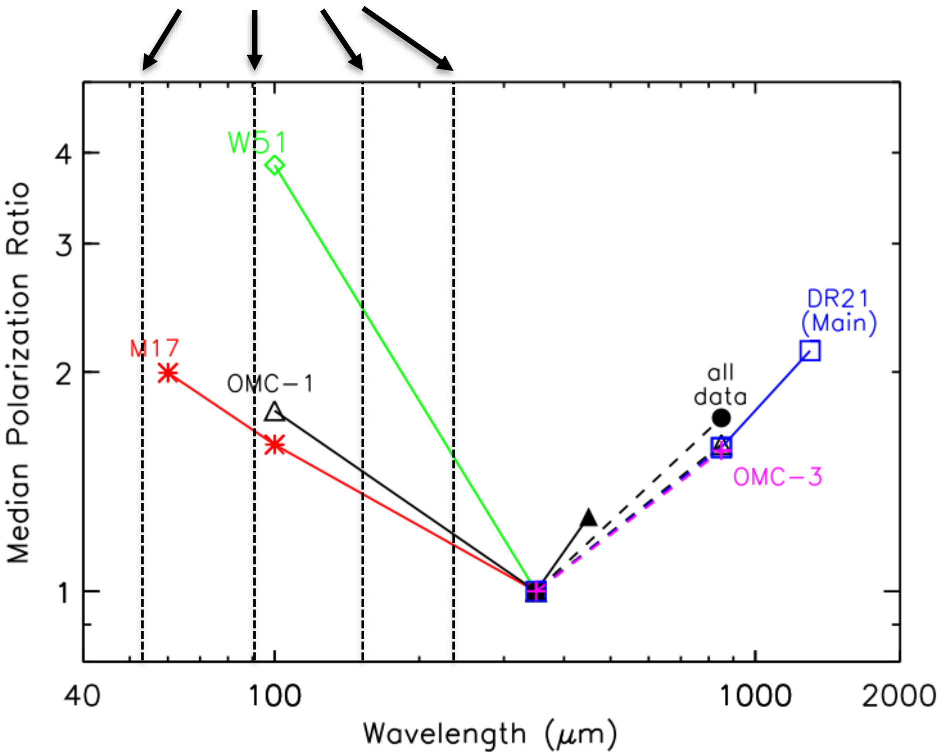
Polarization Spectra

HAWC+ Filters



Vaillancourt and Matthews (2012)

- Measures relative polarization fraction as a function of wavelength
- Probes systemic changes in dust polarization efficiency
- Three "eras":
  - Hildebrand + Vaillancourt
  - BLASTPol (+ Planck)
  - HAWC+ (+ POL-2 + TolTec + ALMA?)

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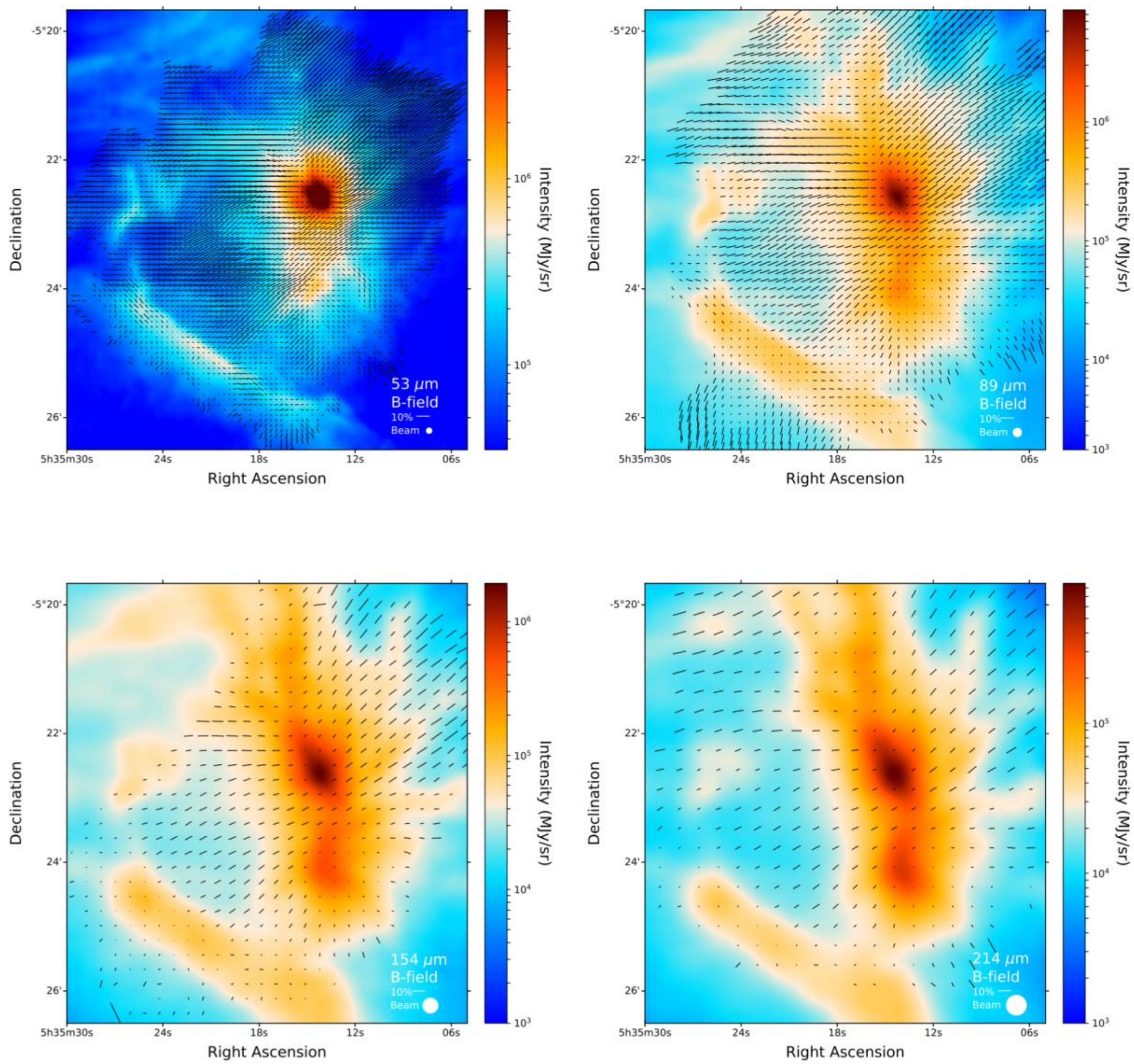
HAWC+ Data



Data originally published in Chuss et al. (2019)

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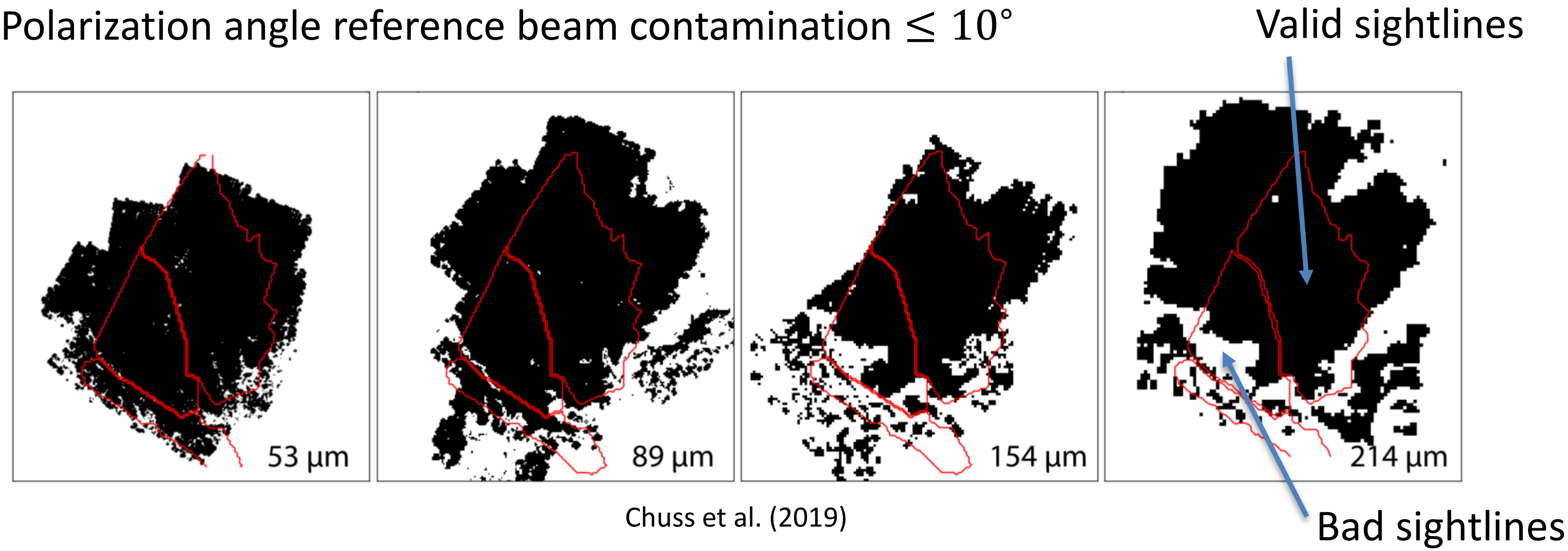
Data Cuts

1. >3σ de-biased polarization fractions

2. Polarization angle reference beam contamination $\leq 10^{\circ}$

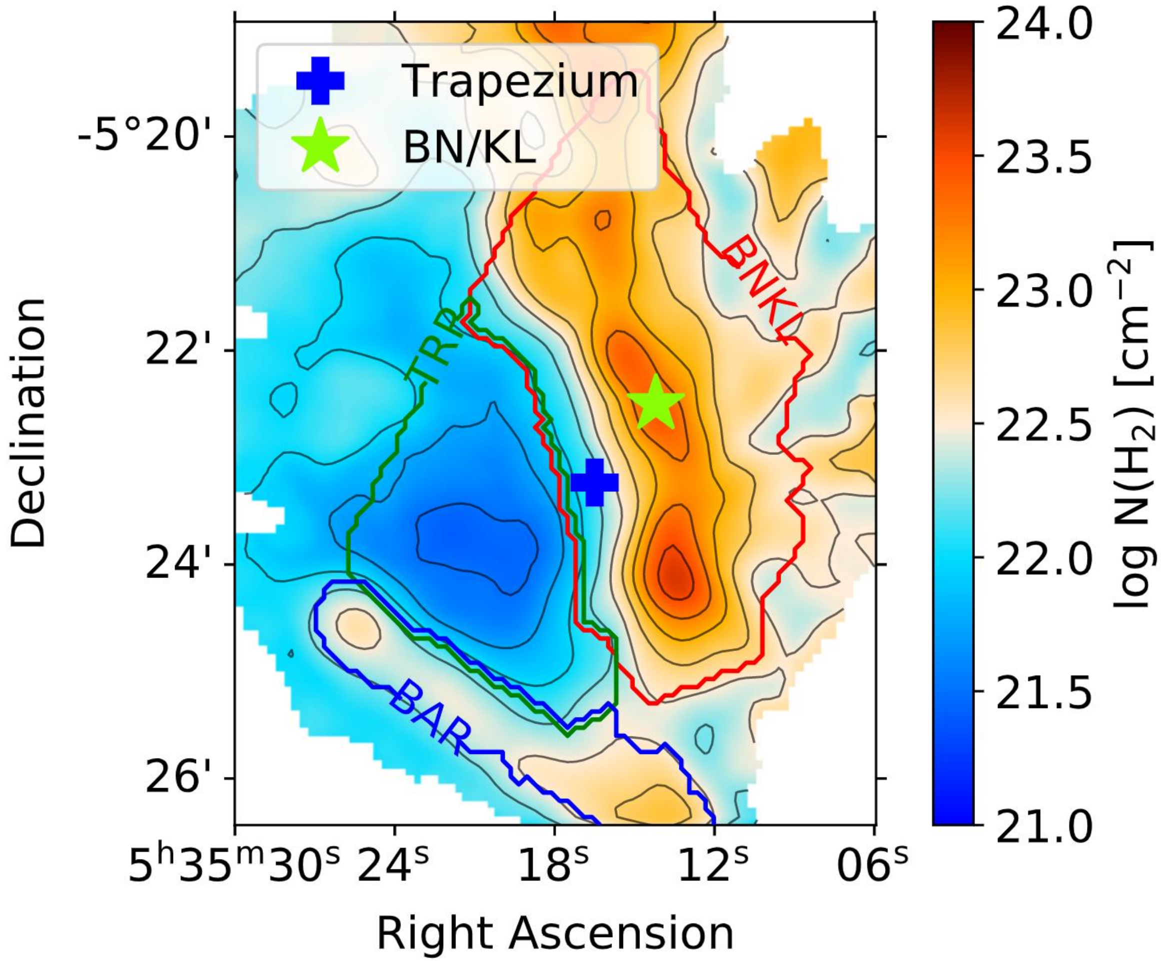


Chuss et al. (2019)

3. Polarization angle range across all wavelength $\leq 15^{\circ}$

4. Sightlines where data from all 4 wavelengths are present

Regional Masks



- BNKL: High-density region with sites of massive star formation (i.e. BN/KL, OMC-1S)
- TRP: HII region formed by the massive OB Trapezium stars
- Bar: Photodissociation region (PDR) formed from Trapezium stars

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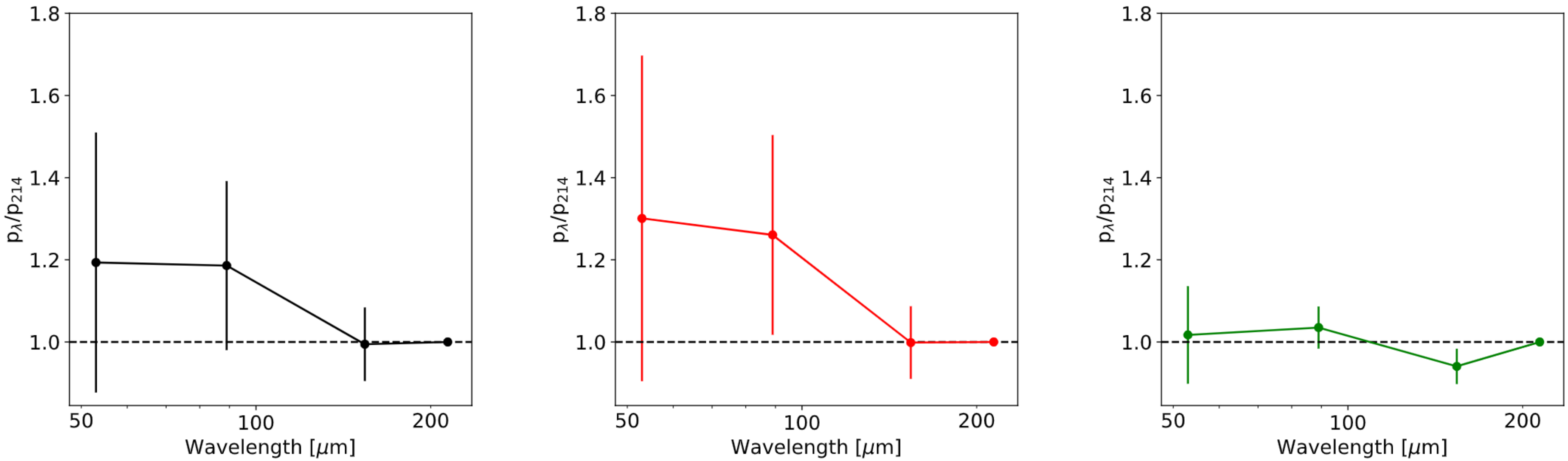
Polarization Spectra By Region



(a) Overall Cloud Spectrum (b) BNKL Region Spectrum (c) Trapezium Region Spectrum

One additional cut for the regional spectra: At least 3 valid pixels per region

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Pixel-By-Pixel Polarization Spectra

- 2155 valid pixels (sampled at 4 pixels per beamwidth)
- Regress a linear model per pixel of the form:

$$\frac{p(\lambda)}{p(\lambda_0)} = a_l(b_l[\lambda - \lambda_0] + 1)$$

(Gandilo et al. 2016; Shariff et al. 2019)

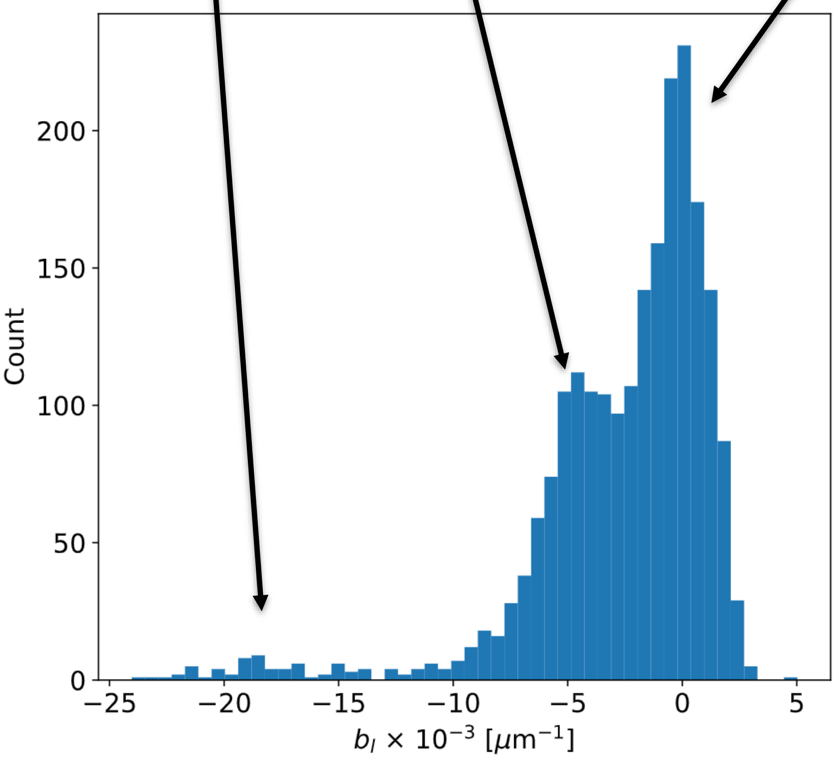
“Falling” spectrum: $b_l < 0$
“Rising” spectrum: $b_l > 0$
“Flat” spectrum: $b_l \approx 0$

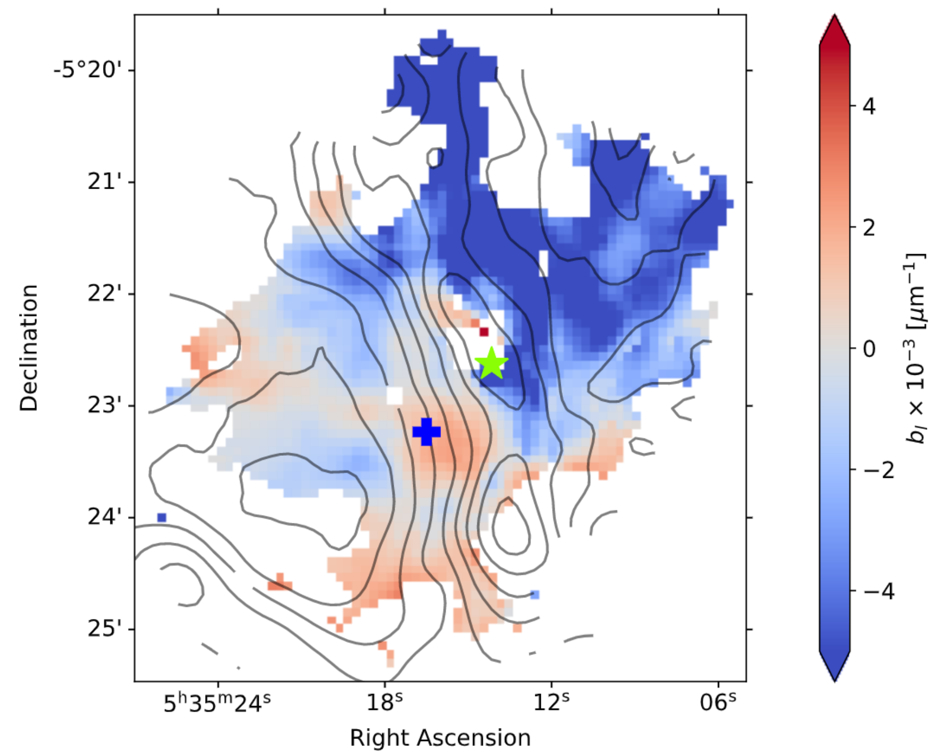
Pixel-By-Pixel Polarization Spectra

Bad spectra fits

Falling spectra

Rising and flat spectra





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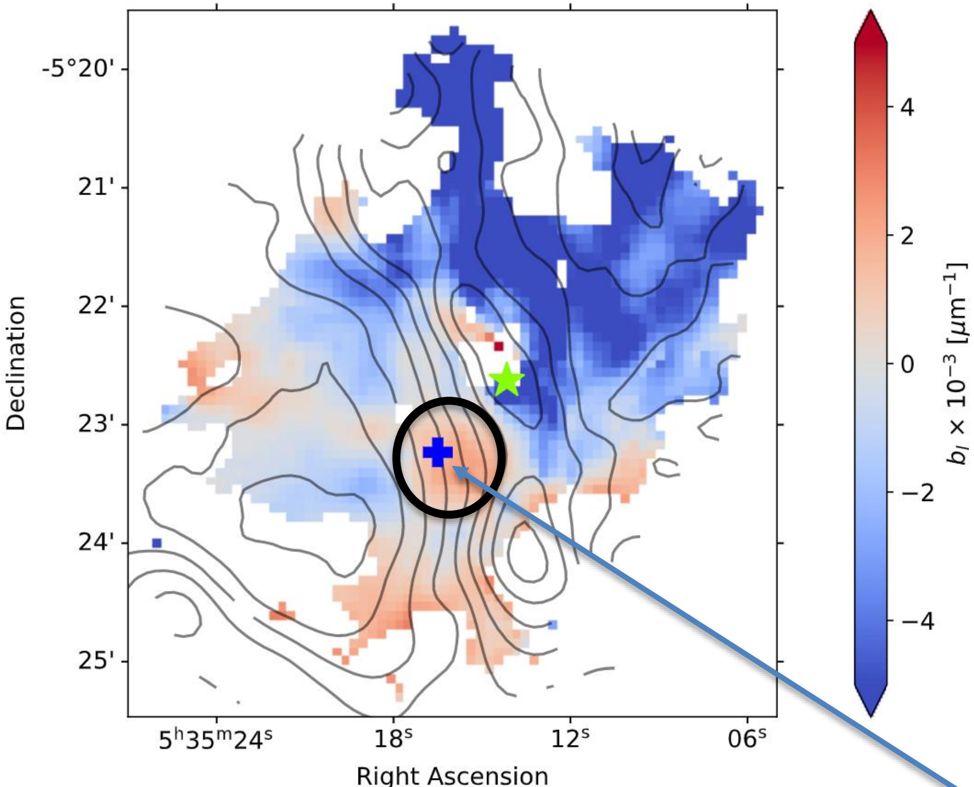
Pixel-By-Pixel Polarization Spectra

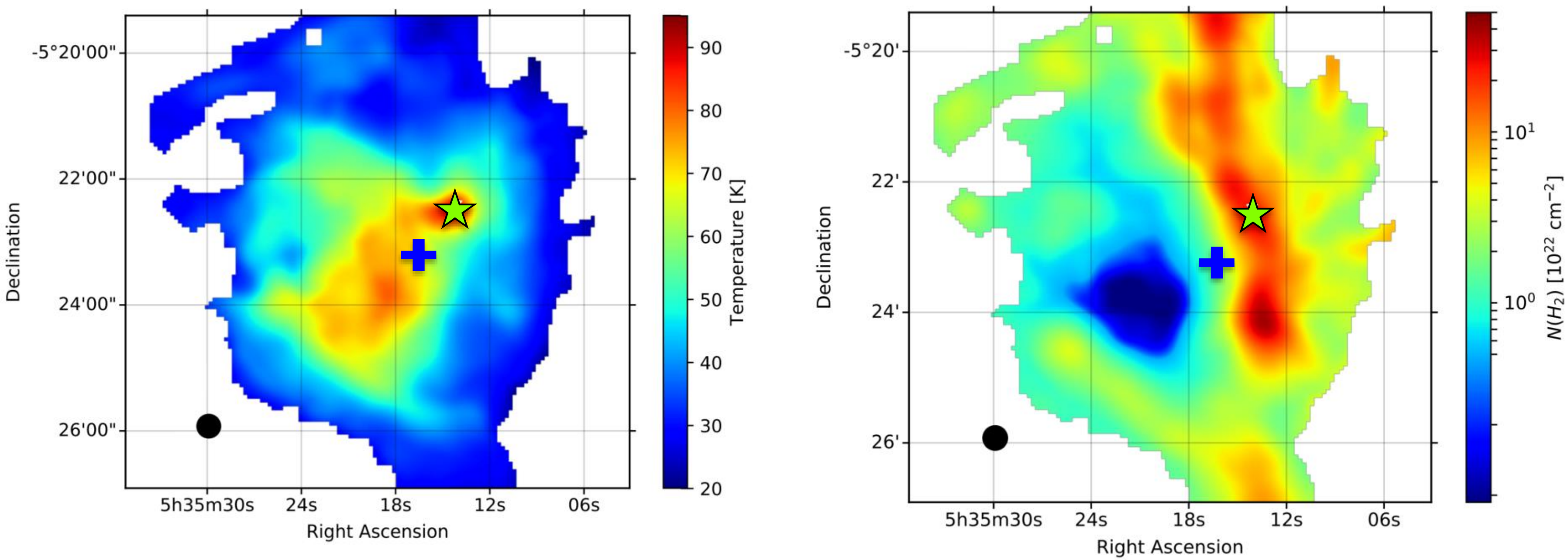


"…may indicate the presence of transiently-heated, unaligned, small dust grains in the vicinity of the OB stars."

Trapezium Cluster

Dependence of Polarization Spectra On Environment

Correlate b_l with temperature and column density



Chuss et al. (2019)

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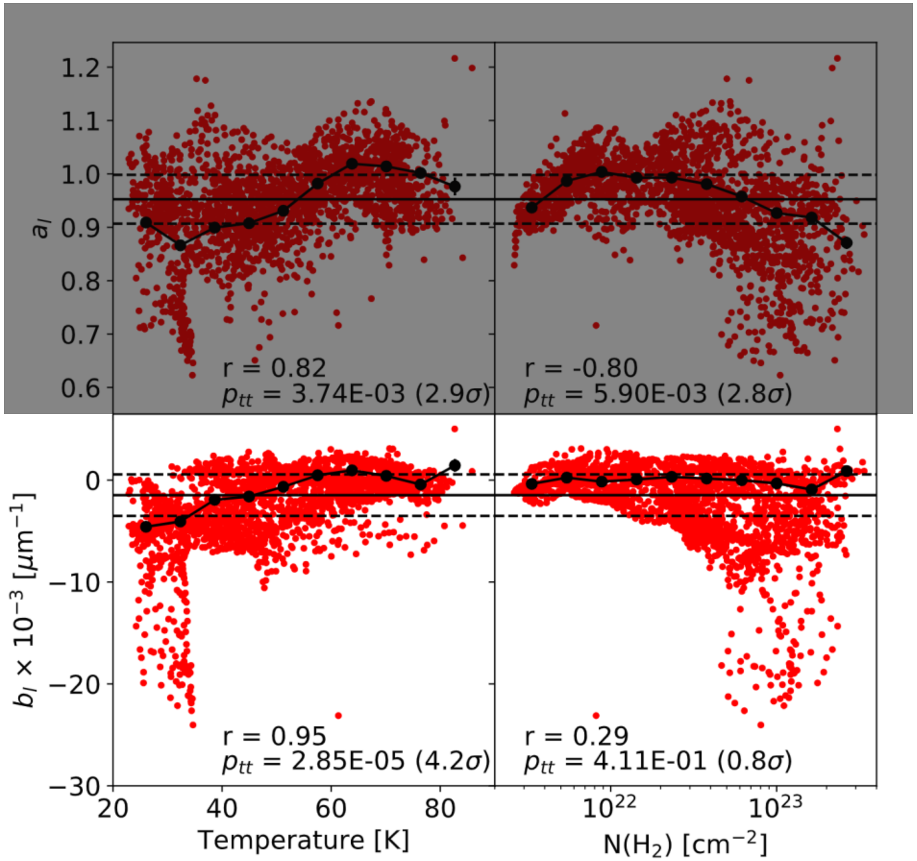
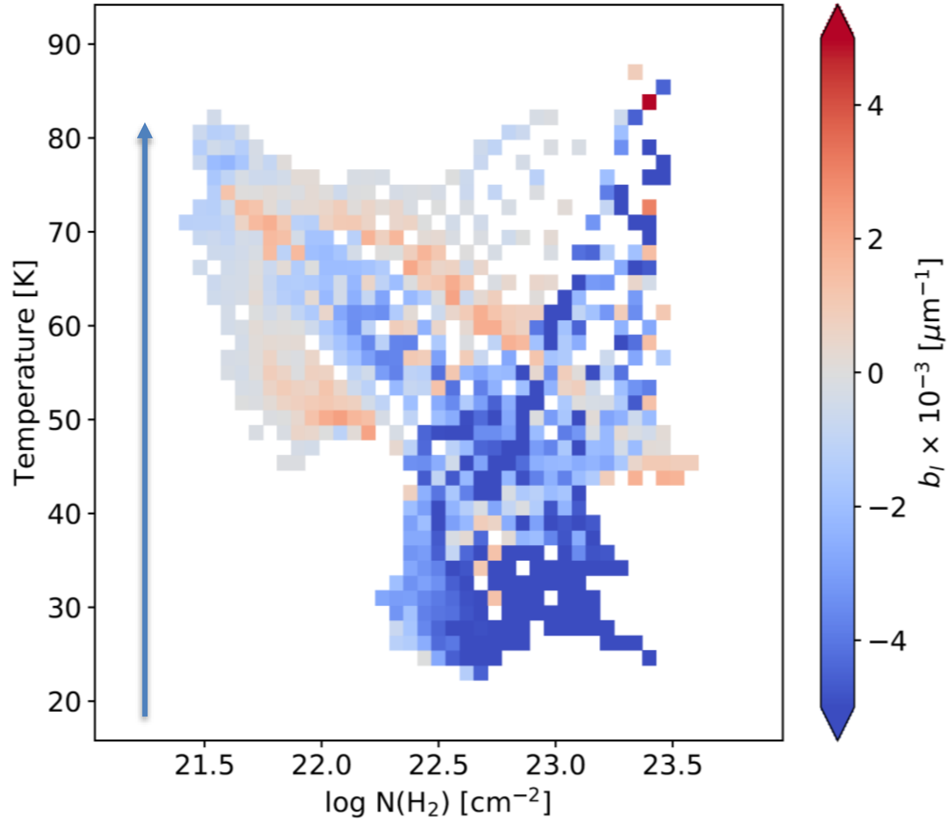
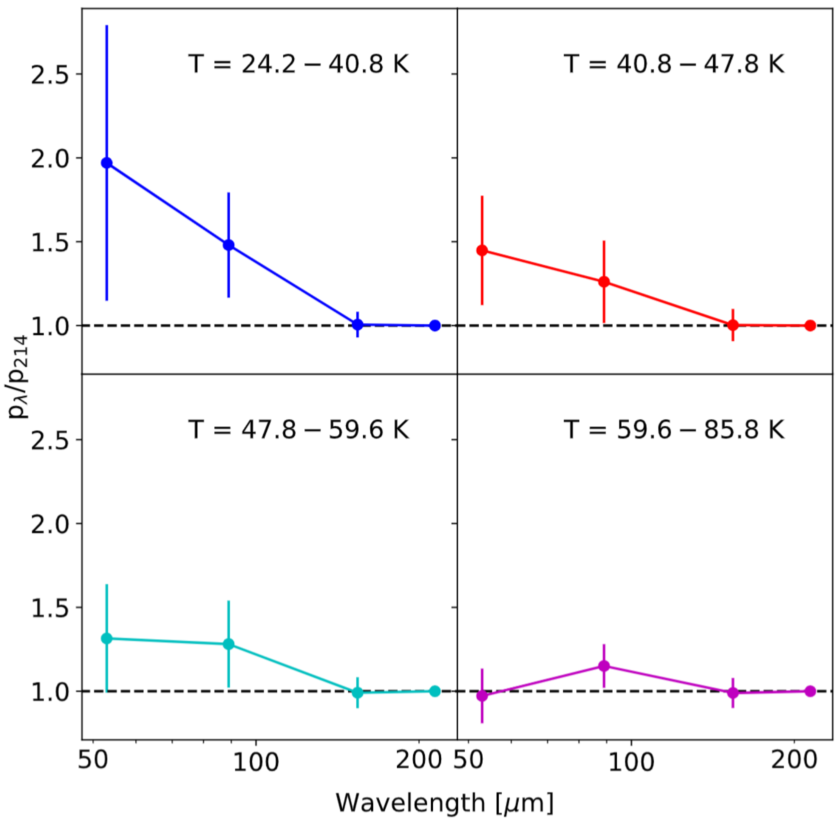
Dependence of Polarization Spectra On Environment

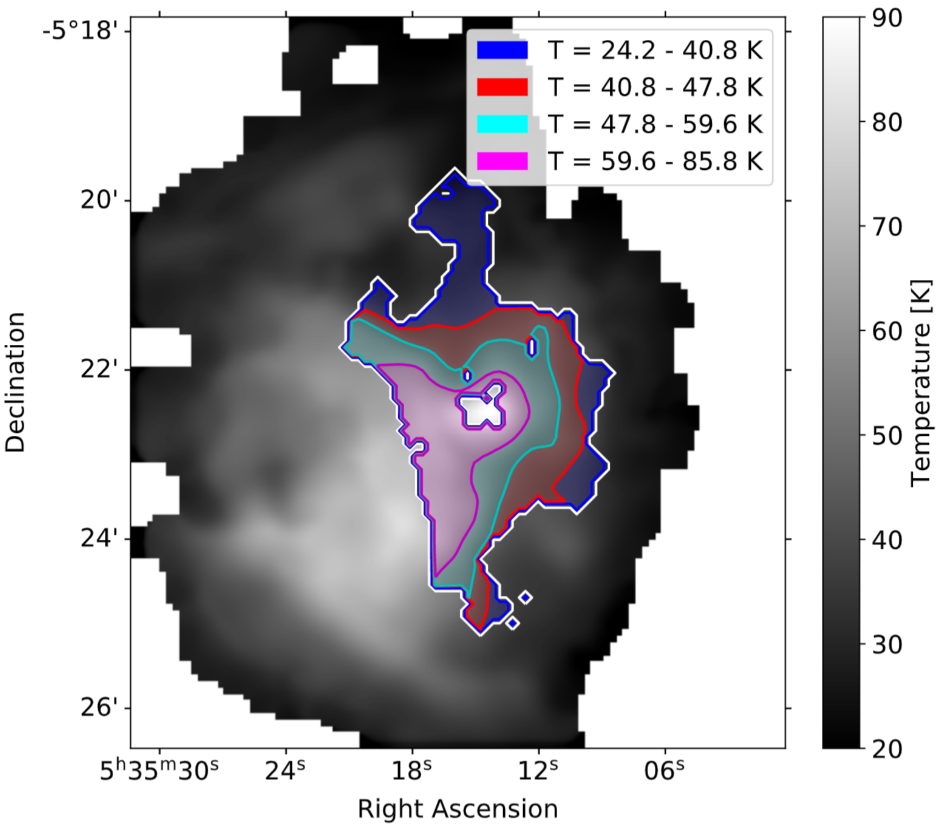




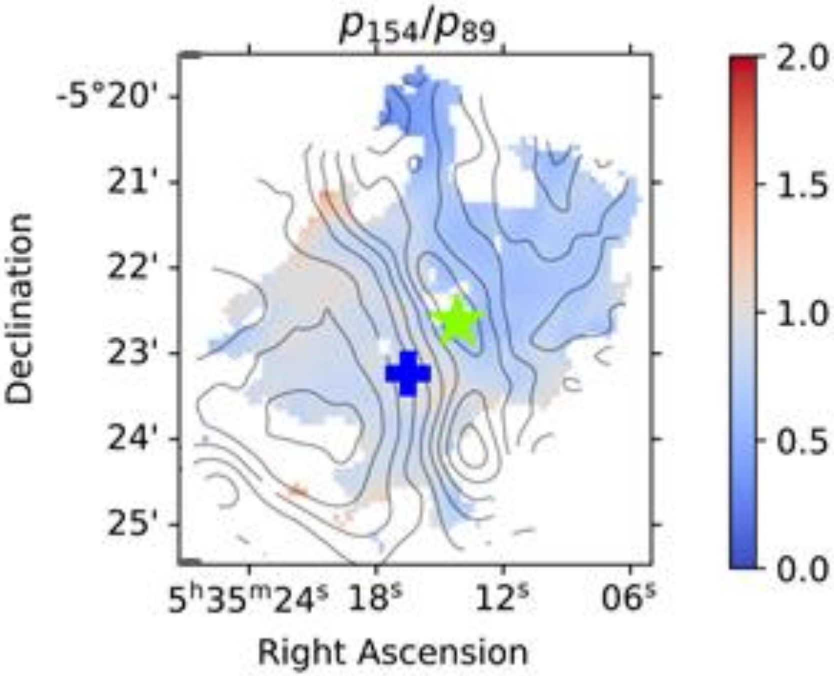
Clear correlation between slope and temperature

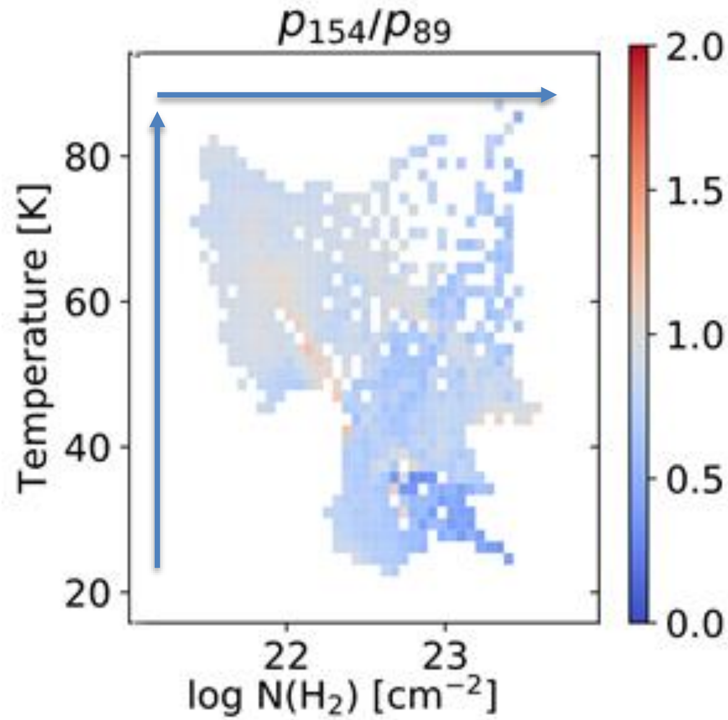
Dependence of Polarization Spectra On Environment





Probing the Polarization Spectra with Ratios





- Santos et al. (2019): Correlations between T, $N(H_2)$, and p_{154}/p_{89} in ρ Oph A
- > 1: "Positive" ratios
- < 1: "Negative" ratios
- ≈ 1: "Flat" ratios

- More positive ratios at higher temperatures
- More negative ratios at higher column density

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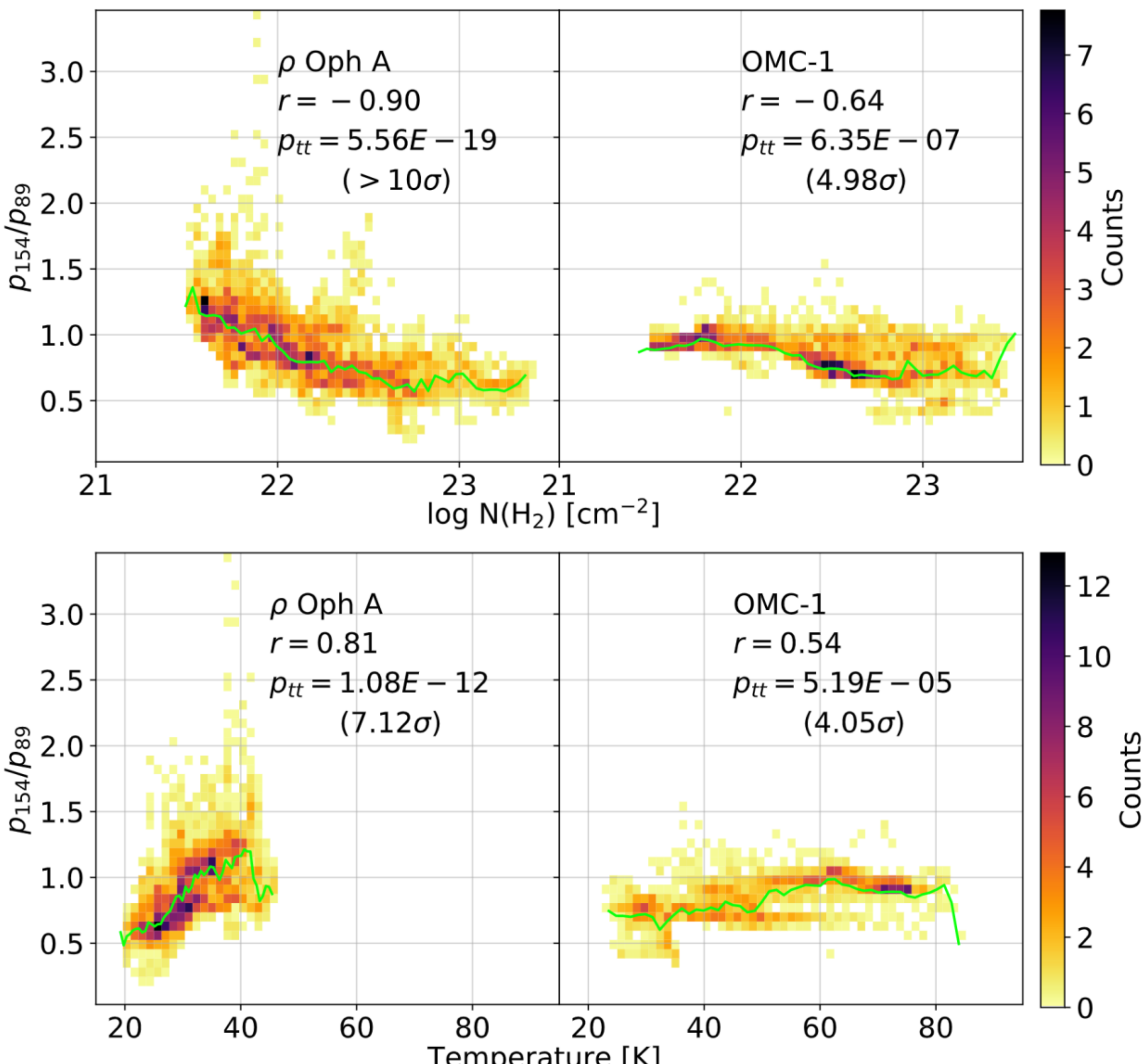
Probing the Polarization Spectra with Ratios: Comparison with ρ Oph A



- We see a negative correlation between $N(H_2)$ and p_{154}/p_{89} in both clouds (NB: no correlation between b_l and $N(H_2)$)
- Trends between SED parameters and p_{154}/p_{89} are much stronger in ρ Oph A: why?

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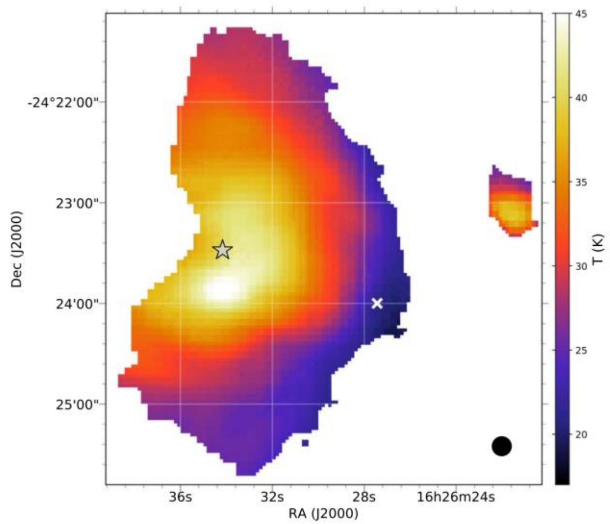
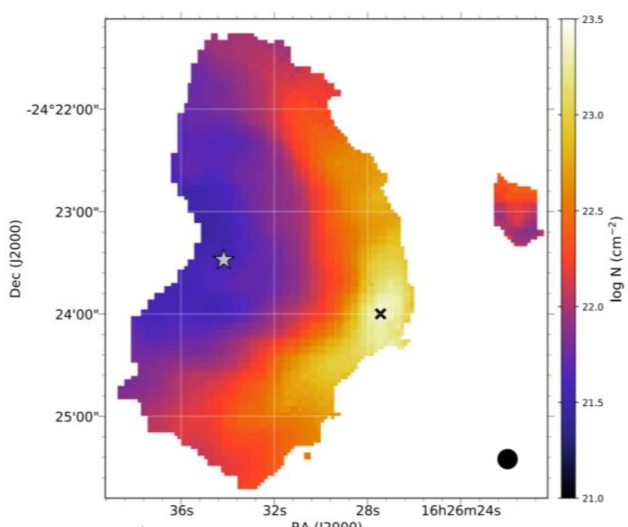
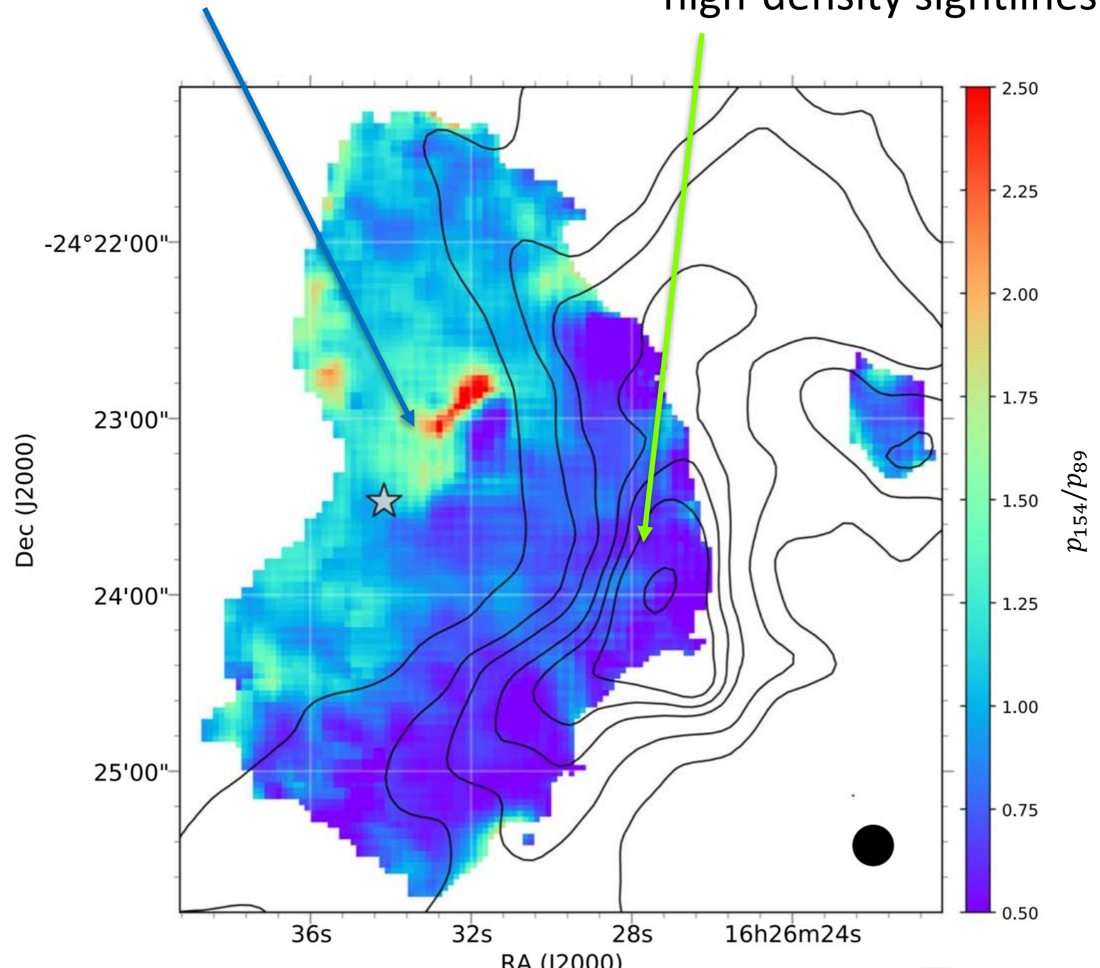
The Heterogeneous Cloud Effect

- First introduced by Hildebrand et al. (1999)
- Explains negatively sloped polarization spectra via RAT theory
- Thought process:
  - Warmer sightlines (which are polarized) are brighter at short wavelengths
  - Cooler sightlines (which are not polarized) are brighter at long wavelengths
  - The superposition of warm and cool sightlines causes negatively-sloped spectra
- "HCE" is the more general case of the Extinction-Temperature Alignment Correlation (ETAC)

The Heterogeneous Cloud Effect







Santos et al. (2019)

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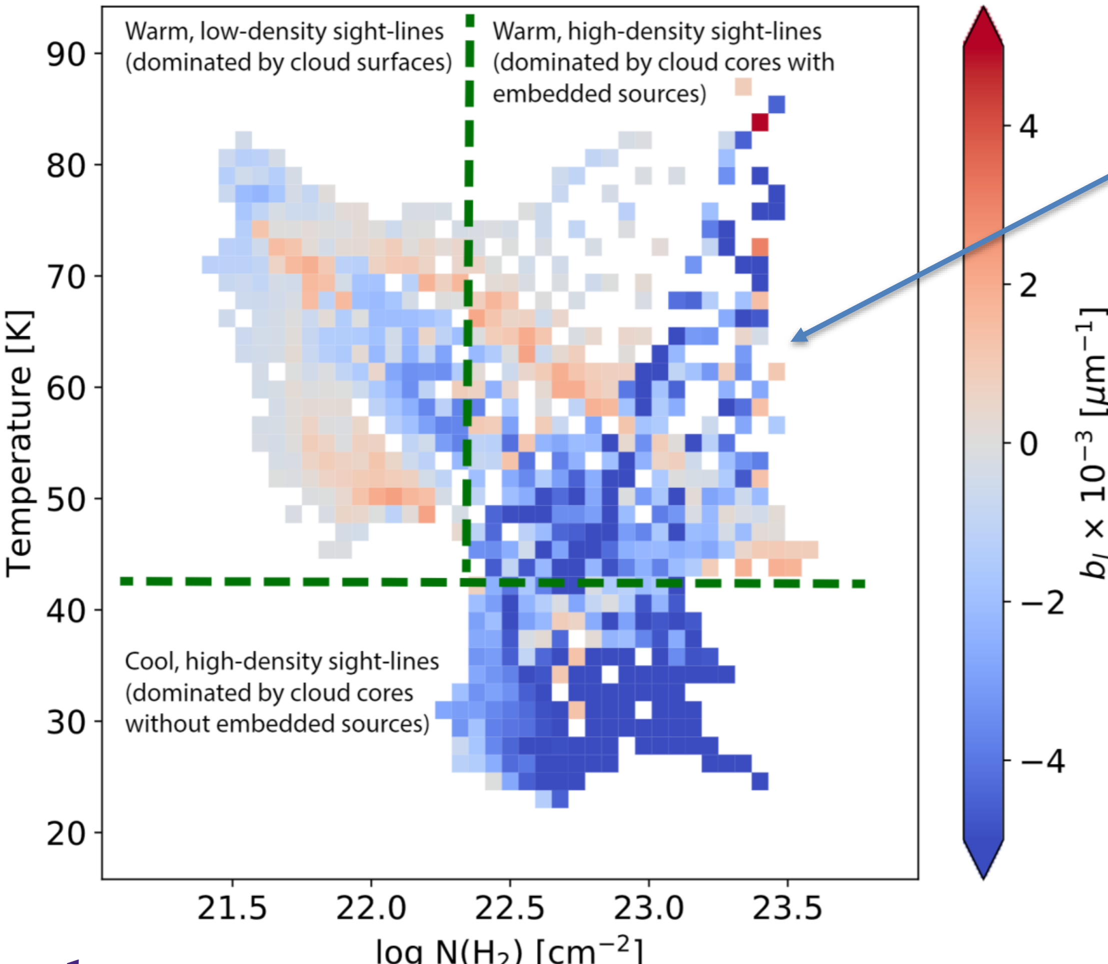
The Heterogeneous Cloud Effect

Why don't we see a slope-column density anti-correlation in OMC-1?



These warm, high-density sightlines (embedded sources) are not present in ρ Oph A

High-mass star formation may drive grain alignment deep in OMC-1 due to high-luminosity sources

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The Heterogeneous Cloud Effect

Then, why do we see an anticorrelation between p_{154}/p_{89} and column density in OMC-1?

- p_{154}/p_{89} is not a good probe for the entire far-IR polarization spectrum in OMC-1
- p_{154}/p_{89} might be probing a "transition" region between the warm (89 μm) and cold (154 μm) material

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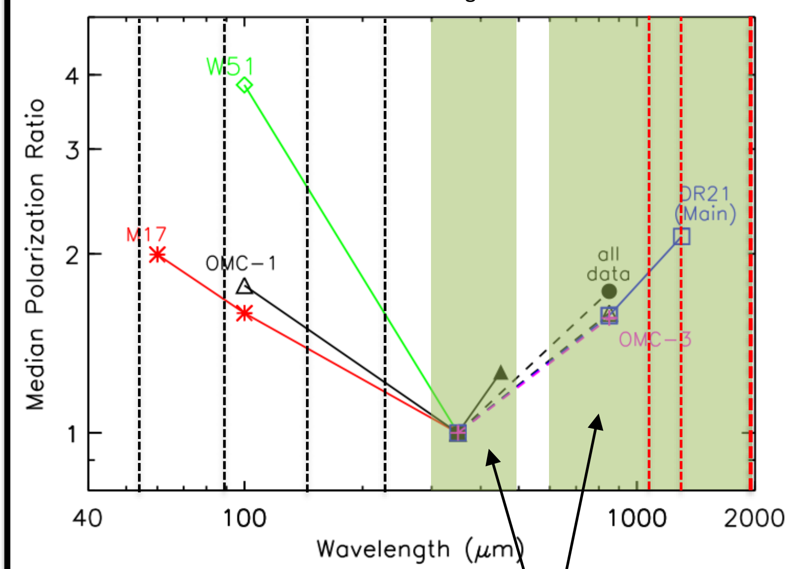
The Future of Polarization Spectra Analysis with HAWC+/SOFIA

- B-BOP/SPICA: Cancelled
- Origins Space Telescope: Launch in 2035?
- HAWC+ is the ONLY far-IR polarimeter for (at least) the next 15 years

- Scan-mode polarimetry is coming (soon?)
- Large maps can be made without possible reference beam contamination

HAWC+/TolTec/ALMA Synergy

Near-continuous ALMA coverage between 0.6 and 3.6 mm



Current (or future) ALMA polarization capability

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Summary and Conclusions

- We find a positive correlation between polarization spectra slope and dust temperature
- We find no correlation between polarization spectra slope and column density
- Our results favor that HCE is explained via RAT theory (i.e., via intensity/temperature) rather than changes in dust shape or alignment efficiency due purely to density

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