SOFIA School 2023

Far-IR dust polarization observations:
HAWC+ and the magnetic field in the ISM

Data Analysis techniques

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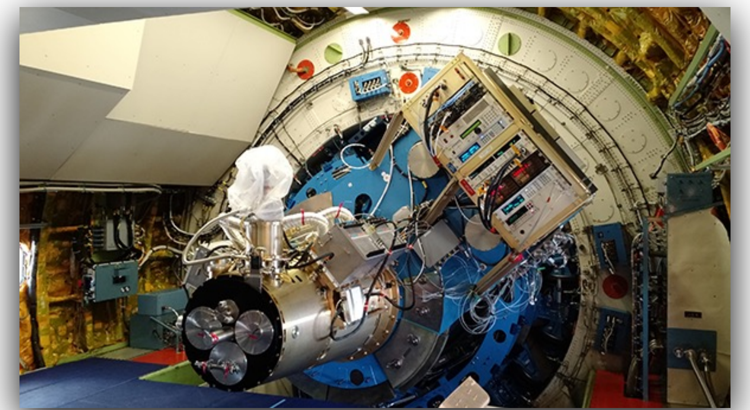
Introduction to HAWC+ observations

Instrument Parameters for Bands A–E

Band/ Wavelength	Δλ	Angular Resolution	Total Intensity FOV (arcmin)	Polarization FOV (arcmin)
A / 53 µm	8.70	4.85" FWHM	2.8 x 1.7	1.4 x 1.7
B[a] / 63 µm	8.90	10.5" FWHM	4.2 x 2.7	2.1 x 2.7
C / 89 µm	17.00	7.8" FWHM	4.2 x 2.7	2.1 x 2.7
D / 154 µm	34.00	13.6" FWHM	7.4 x 4.6	3.7 x 4.6
E / 214 µm	44.00	18.2" FWHM	8.4 x 6.2	4.2 x 6.2

HAWC+ instrument on board of SOFIA



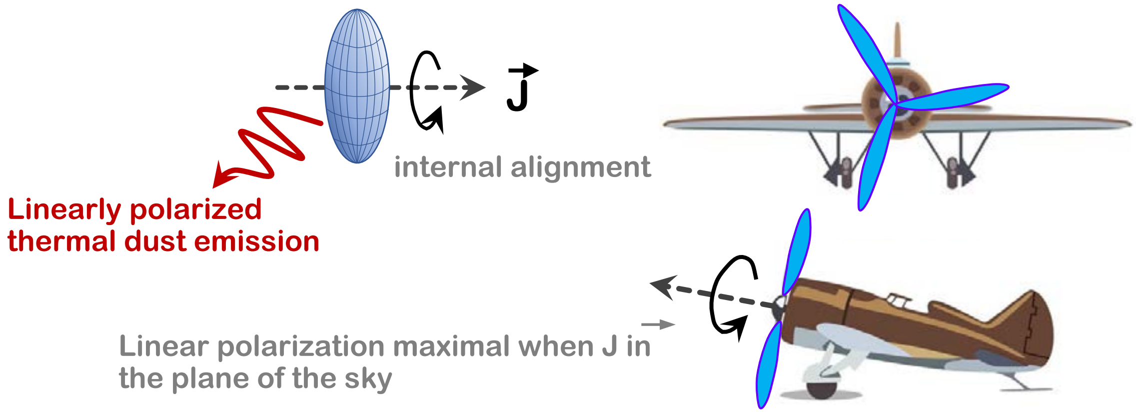
Pipeline products: Full Stokes parameters maps (*I, Q, U, V*), and full covariance matrix.

Polarized Intensity: $$P = \sqrt{Q^2 + U^2}$$

Polarization fraction: $$P_{\rm frac} = \frac{P}{I}$$

Polarization angle: $$\chi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right).$$

The origin of the FIR polarized dust emission



The polarization fraction results from an integration along the line-of-sight (LOS),…

… and is thus sensitive to distribution of the grain characteristics, grain (external and internal) alignment efficiency, alignment axis organization, along the LOS

Outline

Introduction to HAWC+ polarization observations

With HAWC+ polarization data we can …

1. Study the magnetic fields in the ISM with …

- the DCF method ; Davis (1951) and Chandrasekhar and Fermi (1953)
- the ADF method ; Hildebrand+2009, Houde+2009, Houde+2016
- the density gradients method ; Soler (2013)
- velocity structures and gradients
- multiscale magnetic field observations
- the polarization fraction and the dispersion of polarization angles
- the velocity gradients method ; González-Casanova & Lazarian (2017)
- the KTH method ; Koch (2012)

2. Study interstellar dust characteristics and grain alignment with …

- models of grain alignment
- evolution of polarization with local physical conditions
- polarization fraction spectra
- dust evolution models
- polarization radiative transfer

Part 1.

Studying magnetic fields in the ISM with SOFIA HAWC+ polarization observations

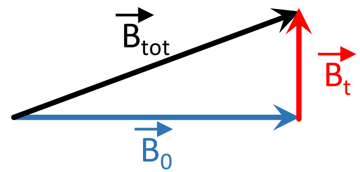
Studying magnetic fields in the ISM with …

the DCF method

Davis (1951) and Chandrasekhar and Fermi (1953)

Assumption of an equipartition between the transverse turbulent magnetic and kinetic energies (Alvén relation):

$$\frac{1}{2}\rho\delta v_{\perp}^{2} = \frac{\left(B_{\perp}^{t}\right)^{2}}{2\mu_{0}},$$



If $B_{t\perp}^{POS} / B_0^{POS} << 1$, then $B_{t\perp}^{POS} / B_0^{POS} \sim \delta\phi^{POS}$, the dispersion of position angles.

$$B_{tot}^{POS} \sim \sqrt{4\,\rho\pi}\,(\delta v_{NT}^{LOS} / \delta\phi^{POS})$$

caveats/assumptions:

- What about compressible modes ?
- Orientation of B_0 with the plane of the sky
- sub- vs super-alfvenic domains
- Isotropic turbulence ?
- Integration in the line-of-sight, beam averaging, filtering of the large-scale component

The validity of the classic DCF method in strongly sub-alvénic self-gravitating regions is questionable.

See recent work by Liu+2022a,b, Chen+2022

Studying magnetic fields in the ISM with …

the DCF method

Davis (1951) and Chandrasekhar and Fermi (1953)

Considering compressible modes,
Skalidis & Tassis 2021 proposed:

$$B_{tot}^{POS} \sim \sqrt{2\rho\pi}\,(\delta v_{NT}^{LOS} / \sqrt{\delta\phi^{POS}})$$

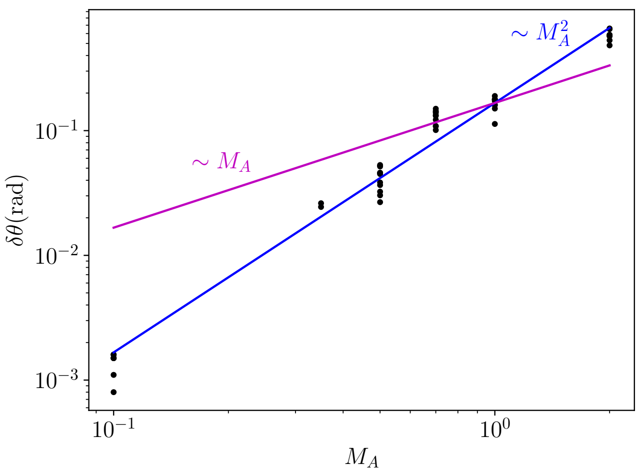
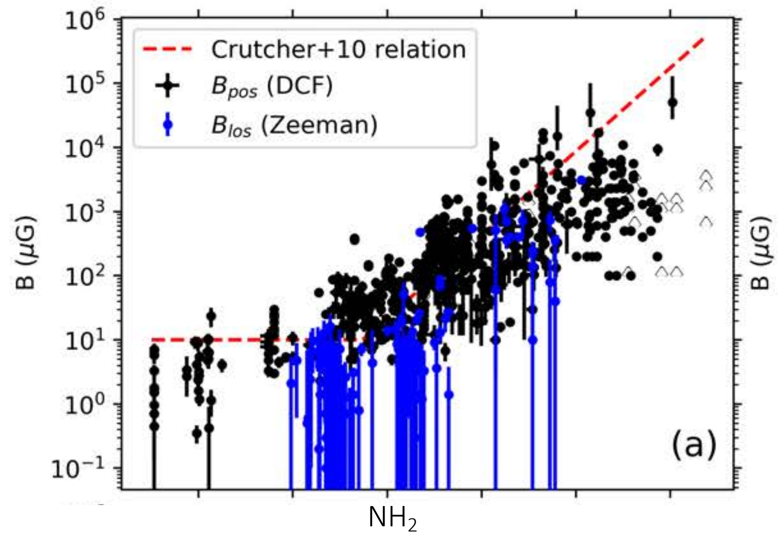


Fig. 1. Polarization angle dispersion as a function of the Alfvénic Mach number. Blue line: ST scaling; magenta line: DCF scaling. The two lines are normalized so that they pass through the data for $M_A = 1.0$.

Comparing magnetic field measurements done with Zeeman detections against DCF estimations:



Overestimation of the B-field with the DCF method ?

Pattle+2023

Studying magnetic fields in the ISM with ...

the ADF method

Hildebrand+2009, Houde+2009, Houde+2016

The Angular Dispersion Function (ADF):

analyzing the structure function of magnetic field position angles as a function of the spatial scales,...

Can take into account the large-scale field structure and small-scale, beam-integrated turbulence, and the effects of filtering

$$B_{\rm POS} \simeq \sqrt{4\pi\rho}\,\sigma_v \left[\frac{\langle B_t^2\rangle}{\langle B_0^2\rangle}\right]^{-1/2}$$

$$1 - \langle \cos[\Delta\phi(\ell)]\rangle = \frac{1}{1+\mathcal{N}\left[\frac{\langle B_t^2\rangle}{\langle B_0^2\rangle}\right]^{-1}} \times \left\{1 - \exp\left[-\frac{\ell^2}{2(\delta^2+2W^2)}\right]\right\} + a_2\ell^2$$

- $1 - \langle \cos[\Delta\phi(\ell)]\rangle$: two-point dispersion function of polarization vector difference
- $\mathcal{N}$: Number of turbulent cells
- δ: turbulence correlation length
- W: Beam width
- $a_2\ell^2$: Large scale component

The fit of the function $1 - \langle \cos[\Delta\phi(\ell)]\rangle$ as a function of the POS spatial scale ℓ constrains $\frac{\langle B_t^2\rangle}{\langle B_0^2\rangle}$

See also works by Pillai+2015, Pattle+2017, and the recent Differential Measure Approach by Lazarian+2022.

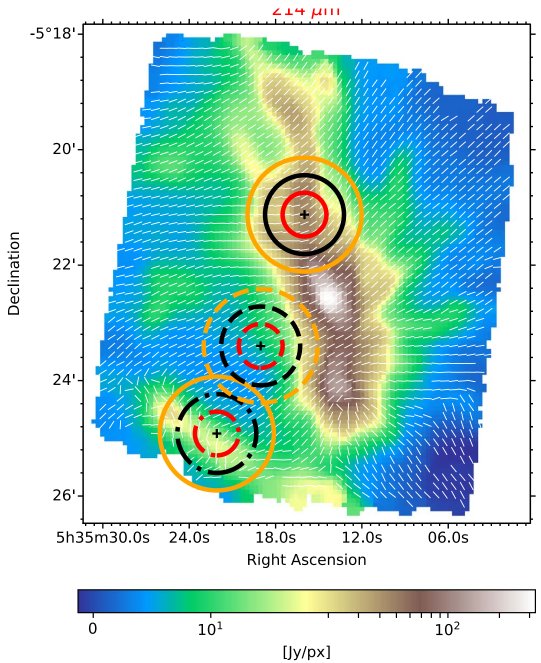
Studying magnetic fields in the ISM with …

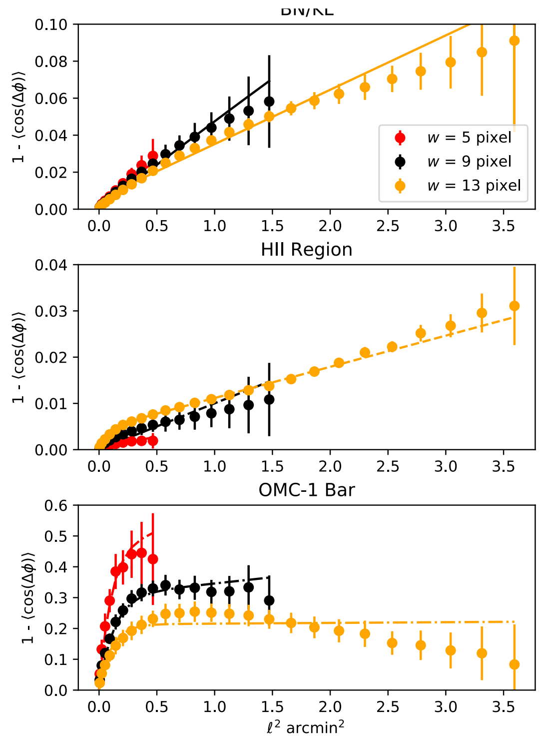
the ADF method

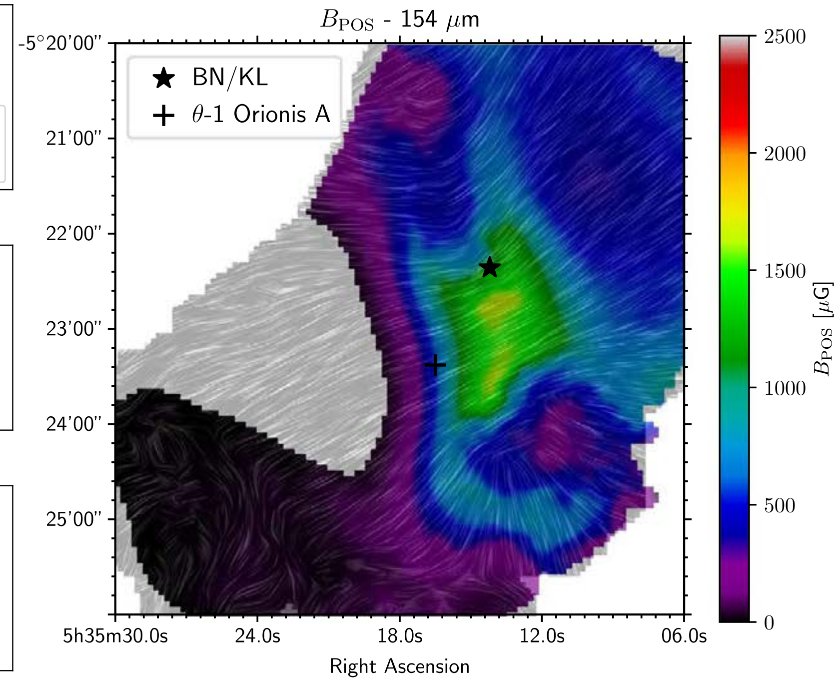
Hildebrand+2009, Houde+2009, Houde+2016

Example in the Orion KL region

Generally, HAWC+ polarization observation resolve the typical scales of local star forming clouds structures (~ 0.01 – 0.1 pc)







Chuss+2019, Guerra+2021

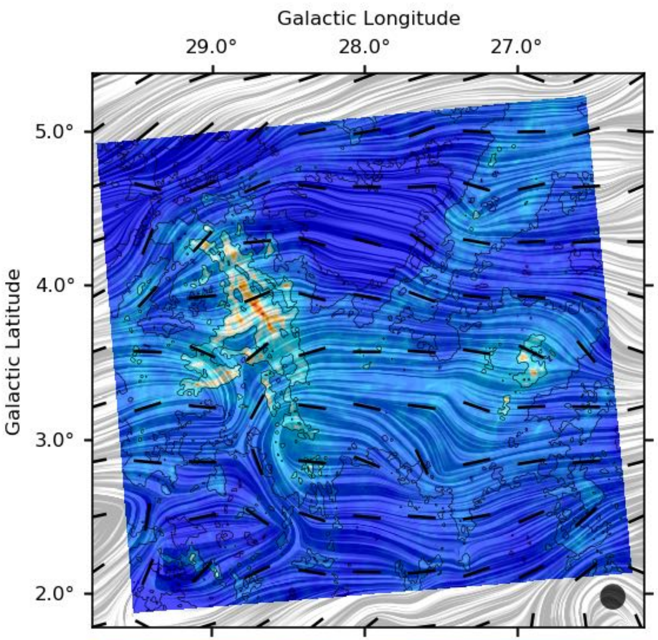
In fine, one can study B - n relation, compare magnetic field and turbulence, calculate the mass-to-flux-ratio to critical value, the virial state of dense structures, etc…

Studying magnetic fields in the ISM with … density gradients

1-10 pc
Molecular clouds and filaments (Planck)

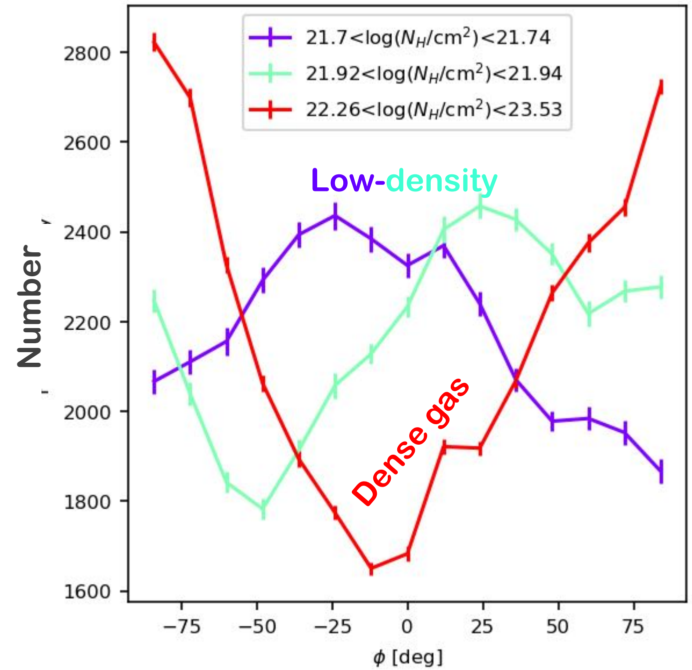
Densification (e.g. filaments) governed by turbulence, and magnetic fields

~ 0.1- 1 pc
Star-forming cores association (SOFIA)



Planck view of the Aquila rift

Histograms of relative orientations (HRO)



$\vec{B} \perp \vec{G}$ $\vec{B} \parallel \vec{G}$ $\vec{B} \perp \vec{G}$

Angle between $\vec{B}$ and density gradient $\vec{G}$

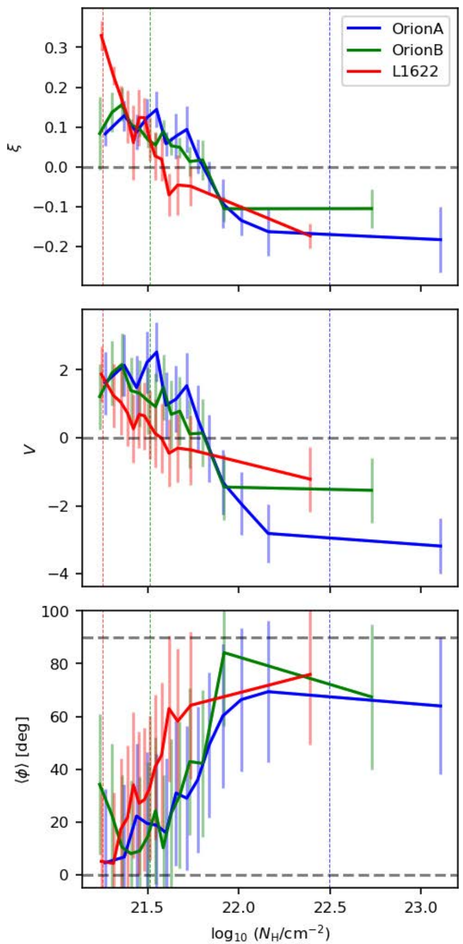
Soler+2019

Studying magnetic fields in the ISM with ...

1-10 pc
Molecular clouds and filaments (Planck)

~ 0.1- 1 pc
Star-forming cores association (SOFIA)

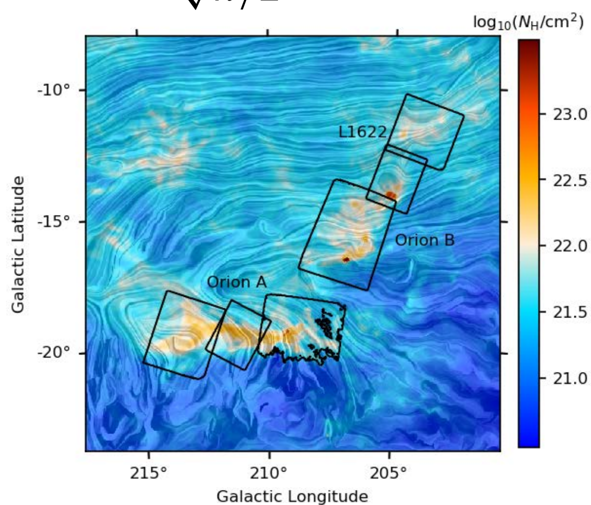
density gradients

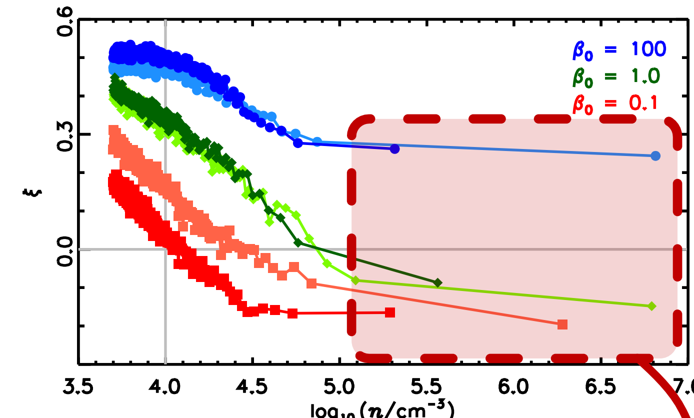


$$\zeta \equiv \frac{A_c - A_e}{A_c + A_e}.$$

Projected Raileigh statistics (Jow+2018):

$$Z_x = \frac{\sum_i^n \cos\theta_i}{\sqrt{n/2}}.$$





Soler+2013, Soler & Hennebelle 2017

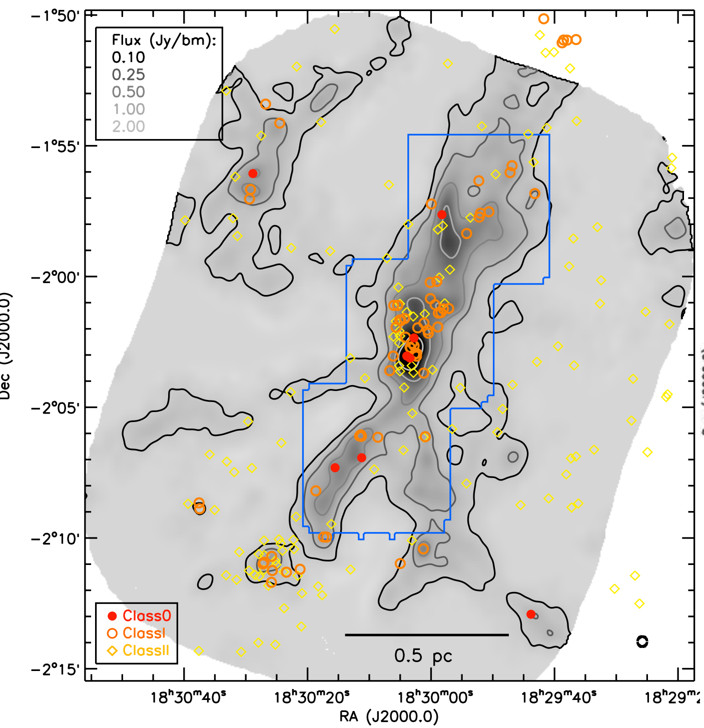
SOFIA regime in observations of SFRs.

Multiscale observations (covering different regimes of gas density) allows HRO to study converging flows, magnetic field measurement via the evolution of the transition density.

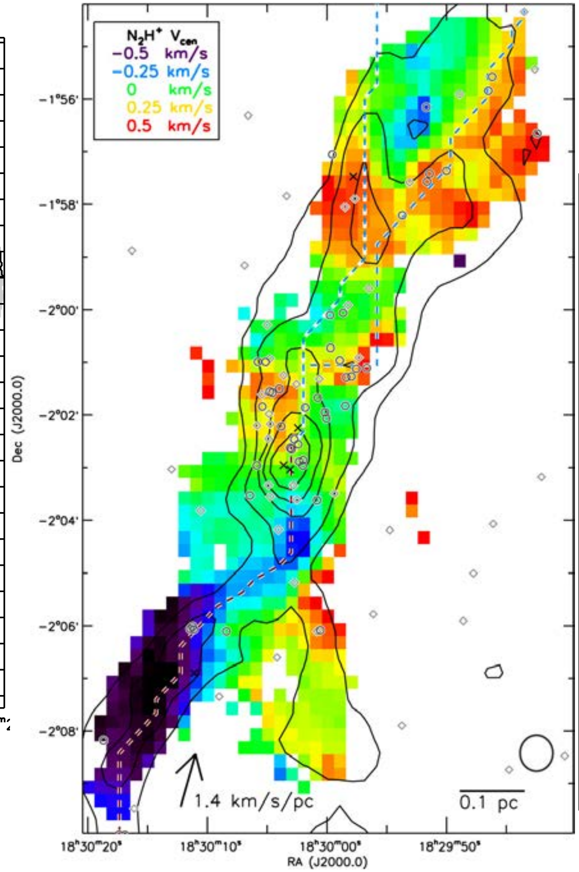
See the work of Lee, D. +2021 in Ophiuchus

Studying magnetic fields in the ISM with … velocity structures and gradients

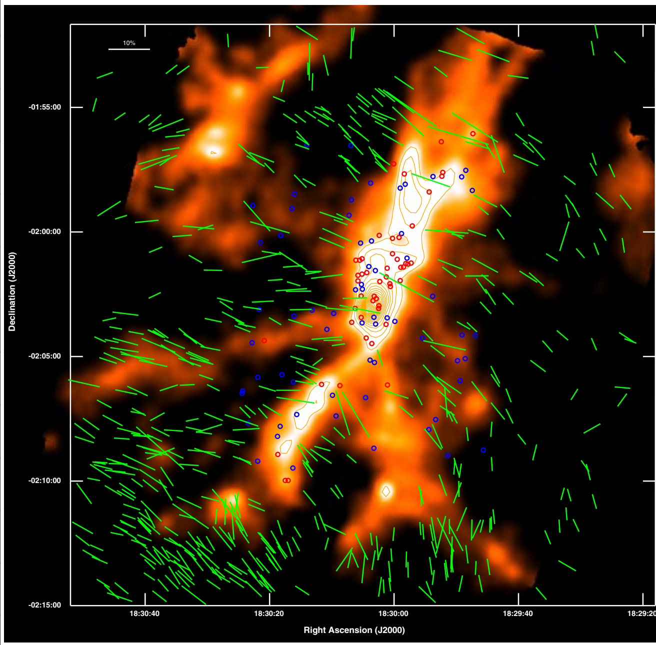
The example of Serpens South, a local hub-filament system harboring low-mass star forming cores



A clear velocity gradient along the filament: infalling material?



A large-scale magnetic field perpendicular to the main filament orientation

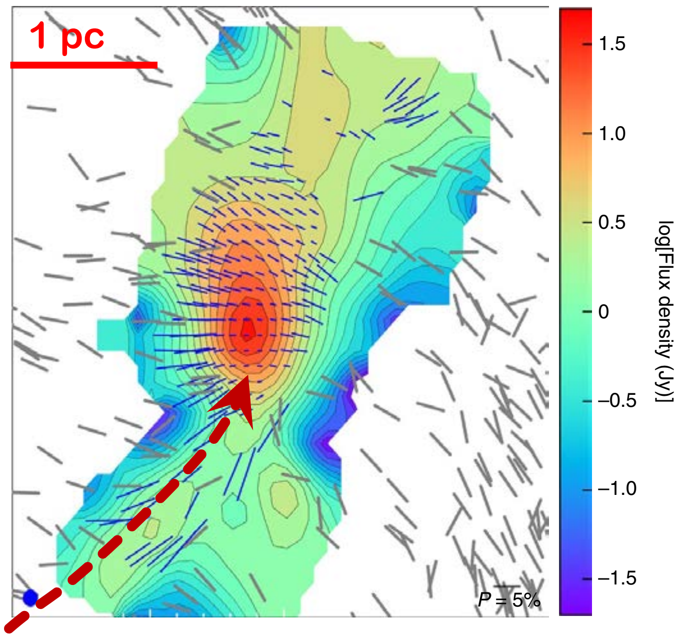


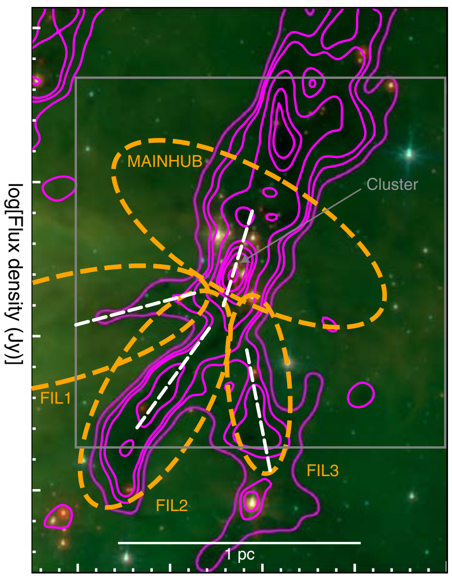
Sugitani+2011,Kirk+2013

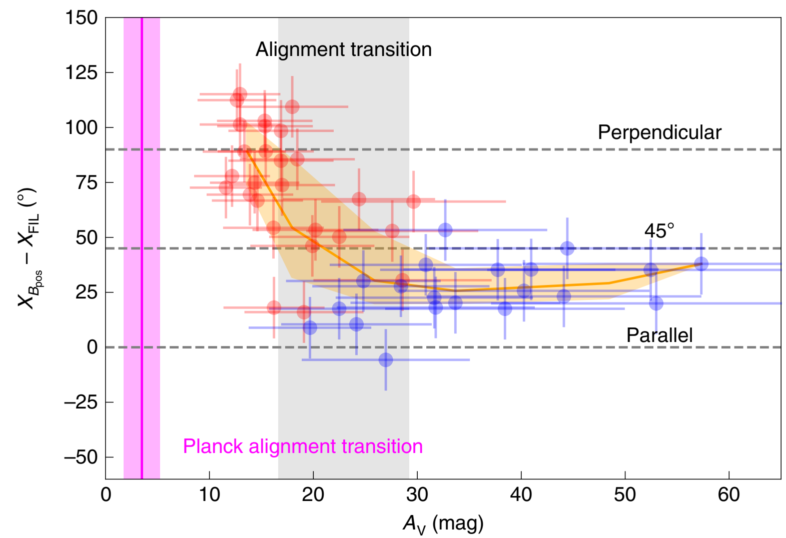
Studying magnetic fields in the ISM with …
velocity structures and gradients

The example of Serpens South.

SOFIA revealed a transition of magnetic field orientation toward the main filament. The magnetic field gets re-oriented toward the direction of major anisotropic infall.



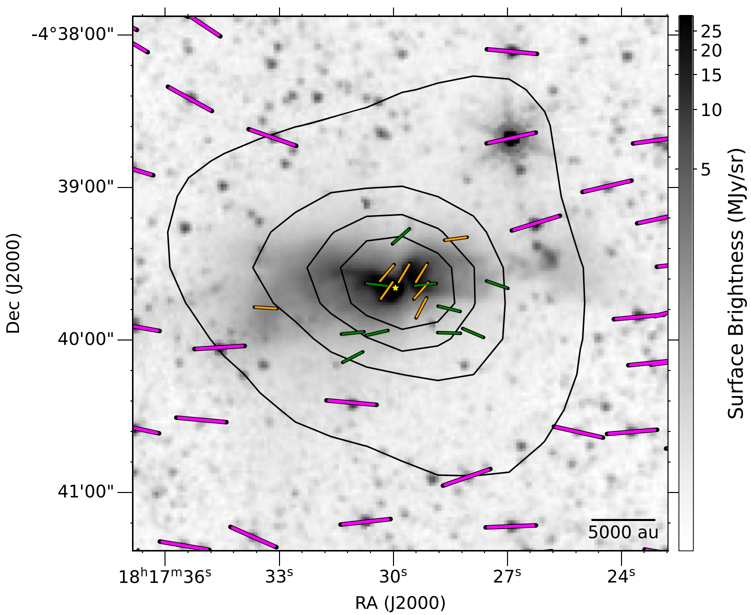




Pillai+2020

Studying magnetic fields in the ISM with …
multiscale polarization observations

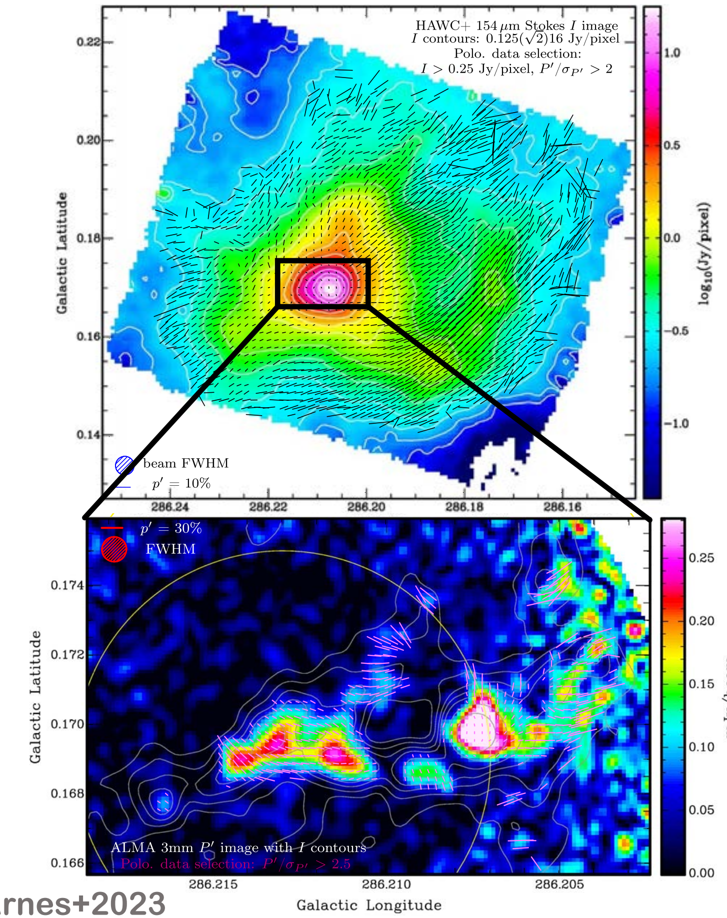
L483 Class 0 protostellar core
Large-scale (10 000 au): Starlight polarization
Intermediate-scale (5000 au): 350 microns SHARP
Small-scale (1000 au): 154 microns SOFIA



Evolution of the magnetic field morphology with scale in the protostellar binary system L483

Cox+2022

HAWC+ and ALMA polarization observations of the BYF 73 high-mass star forming dense core



HAWC+ Stokes I (colorscale) + B-field vectors

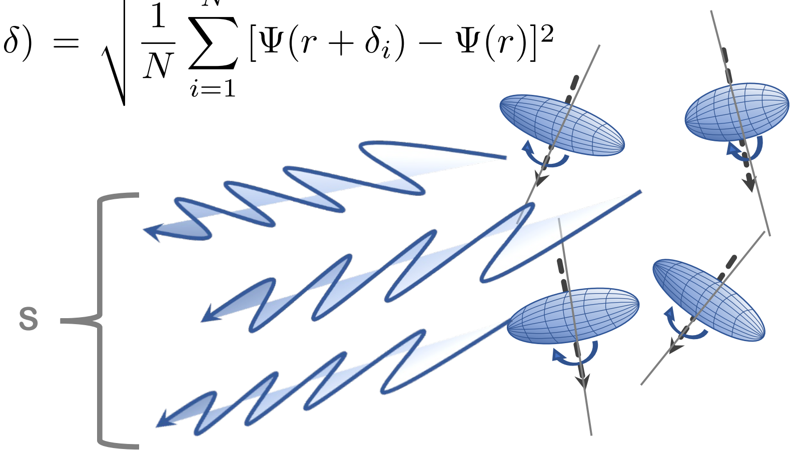
ALMA Stokes I (contours) + ALMA polarized intensity (colorscale) + B-field vectors

Barnes+2023

Studying magnetic fields in the ISM with …
the polarization fraction and polarization dispersion angle

Dispersion of polarization angle

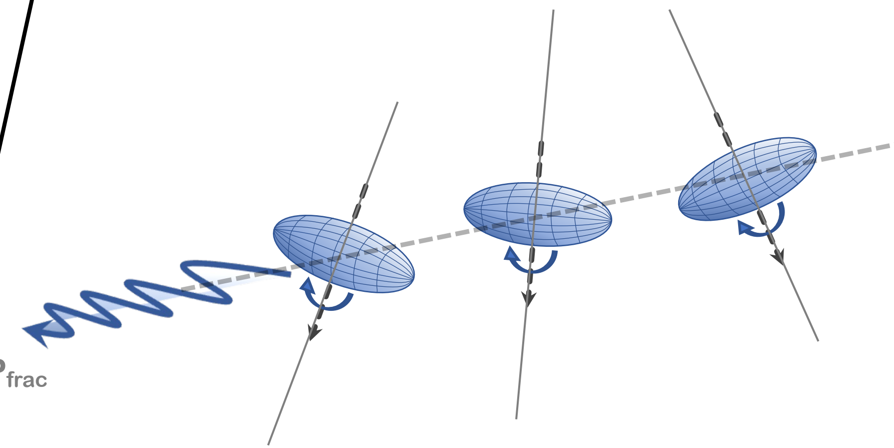
$$S(r,\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[\Psi(r+\delta_i)-\Psi(r)]^2}$$

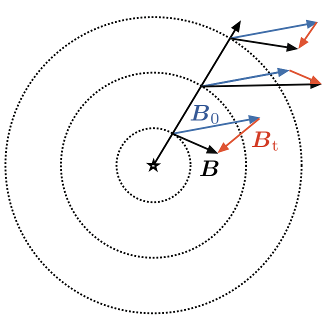


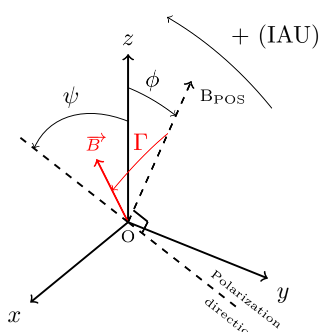
disorganized component of the B-field in the plane of the sky

Polarization fraction

Grain alignment efficiency + disorganized component of the B-field in the line of sight







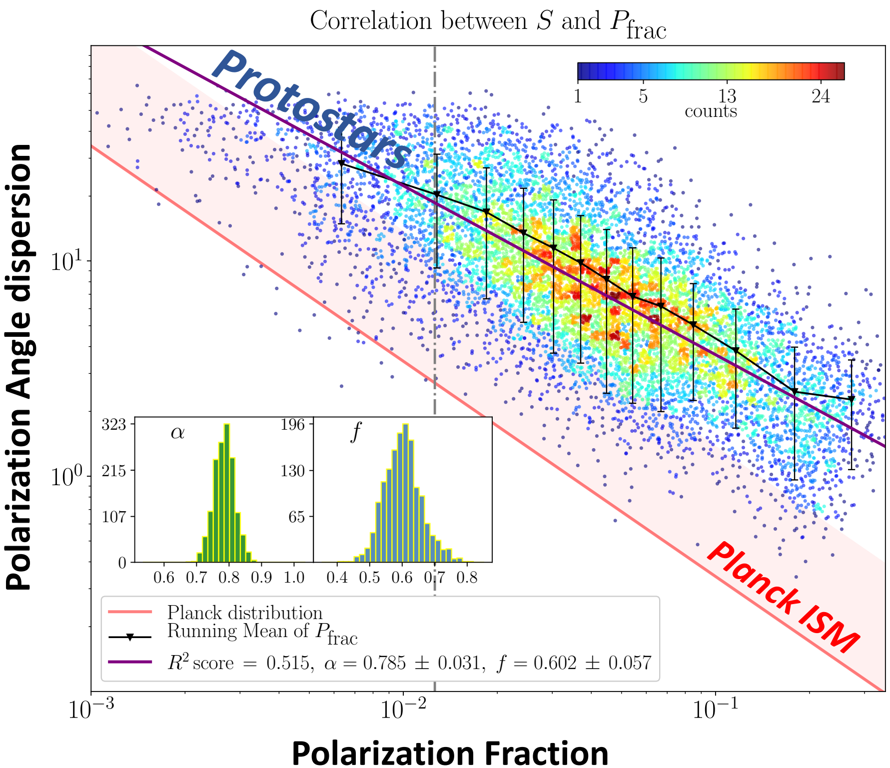
Planck 2020

$$\langle \mathcal{S}(\delta)\rangle_{\mathcal{P}_{frac}} \approx \frac{f_m(\delta)}{\sqrt{6N}}\frac{\mathcal{P}_{frac,max}}{\mathcal{P}_{frac}},$$

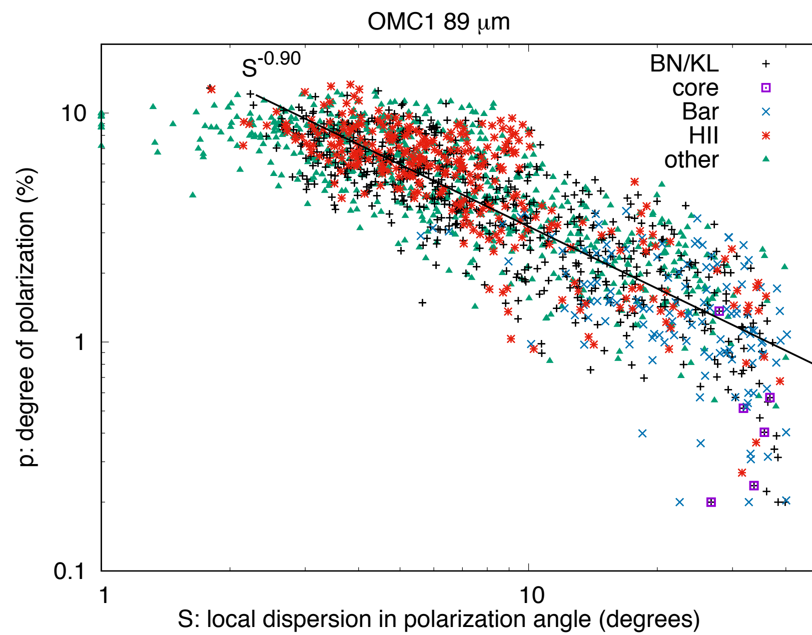
- The 3D magnetic field structure governs the correlation between S and P_{frac}

Studying magnetic fields in the ISM with …
the polarization fraction and polarization dispersion angle

The 3D magnetic field structure governs the correlation between S and P_{frac}



Combining ALMA data of protostellar cores, Le Gouellec + 2020

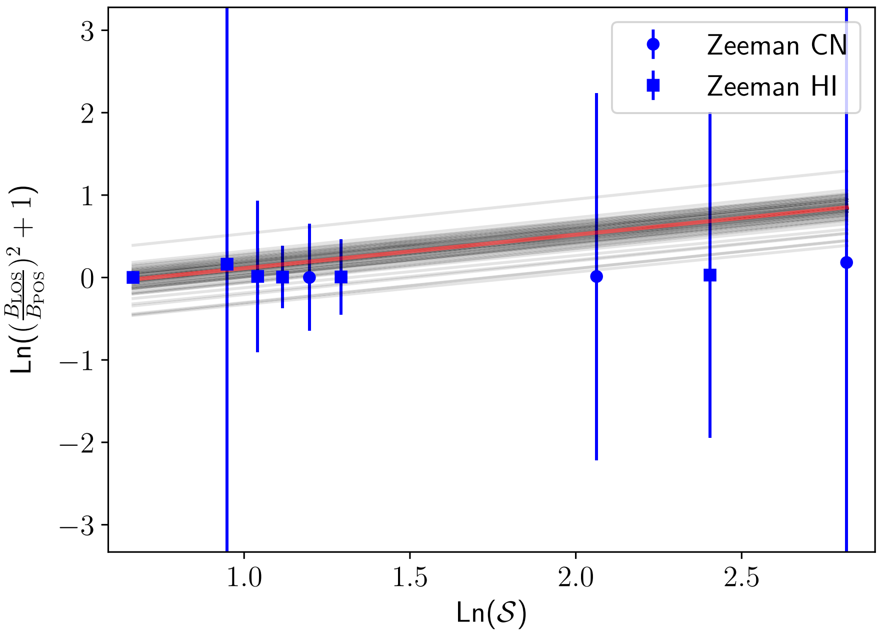


HAWC+ data of the Orion-KL region, Chuss+2019

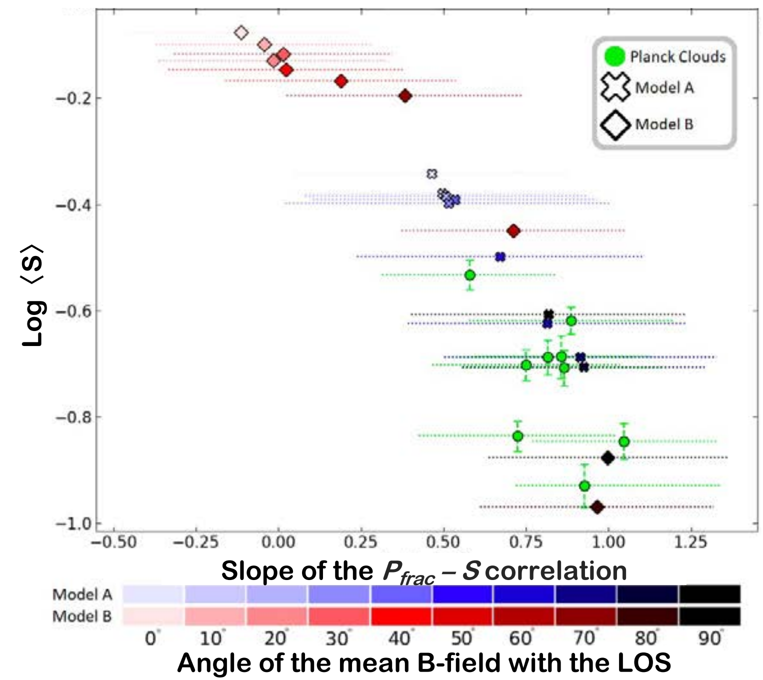
Studying magnetic fields in the ISM with …
the polarization fraction and polarization dispersion angle

The 3D magnetic field structure govern the correlation between S and P_{frac}

The $P_{frac} - S$ correlation is also sensitive to the orientation of the magnetic field with respect to the line-of-sight.



Comparing B_{LOS} (Zeeman detections) / B_{POS} (ADF with HAWC+ data) versus S, in Orion-KL (Guerra+2021)



Evolution of the $P_{frac} - S$ correlation with the orientation of the mean B-field with the LOS in MHD simulations (Sullivan+2021)

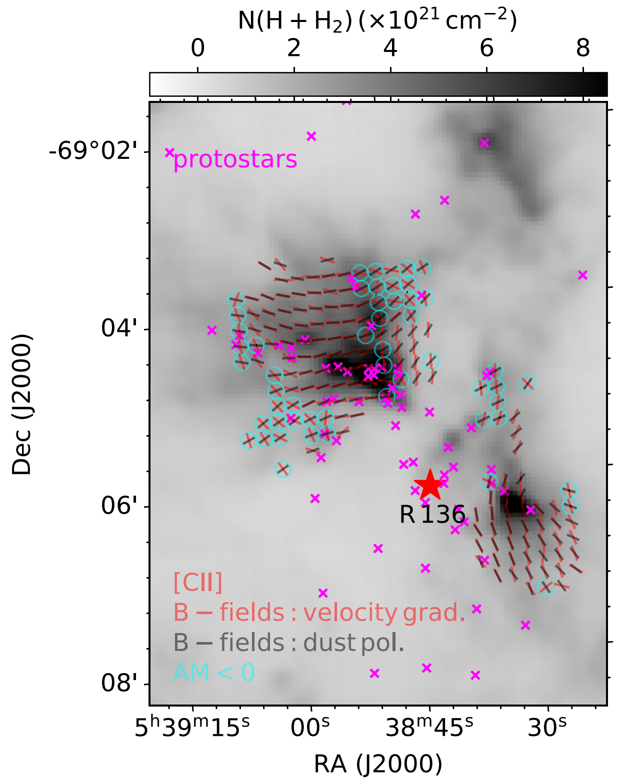
Studying magnetic fields in the ISM with …
the velocity gradients method

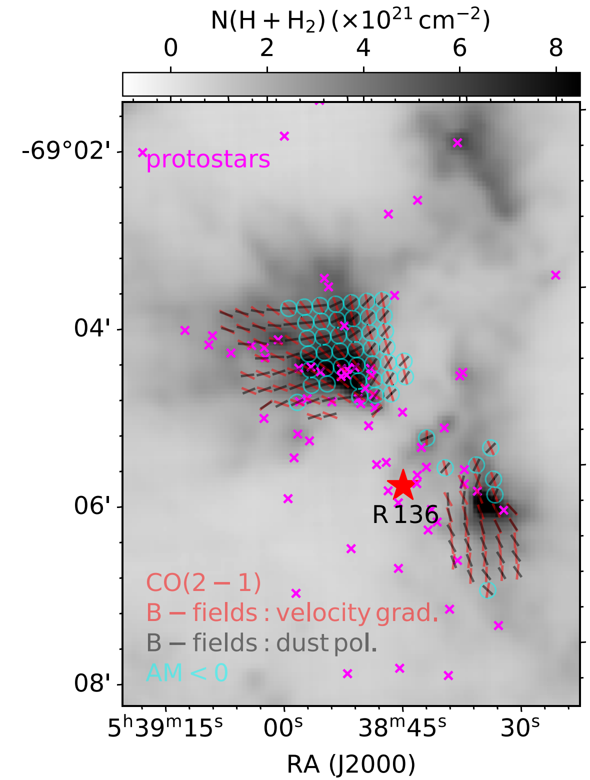
González-Casanova & Lazarian (2017)

Method: - Building PPV datacube
- building raw gradient map
- ``integrating'' along the LOS

Dust emitting environment and the environment traced by the gas specie (and transition must coincide)

VGs departing from being perpendicular to B-field lines can indicates gravitational collapse





The example of 30 Dor in the LMC, HAWC+ data (polarization), APEX (CO) and GREAT (CII). Tram+2023

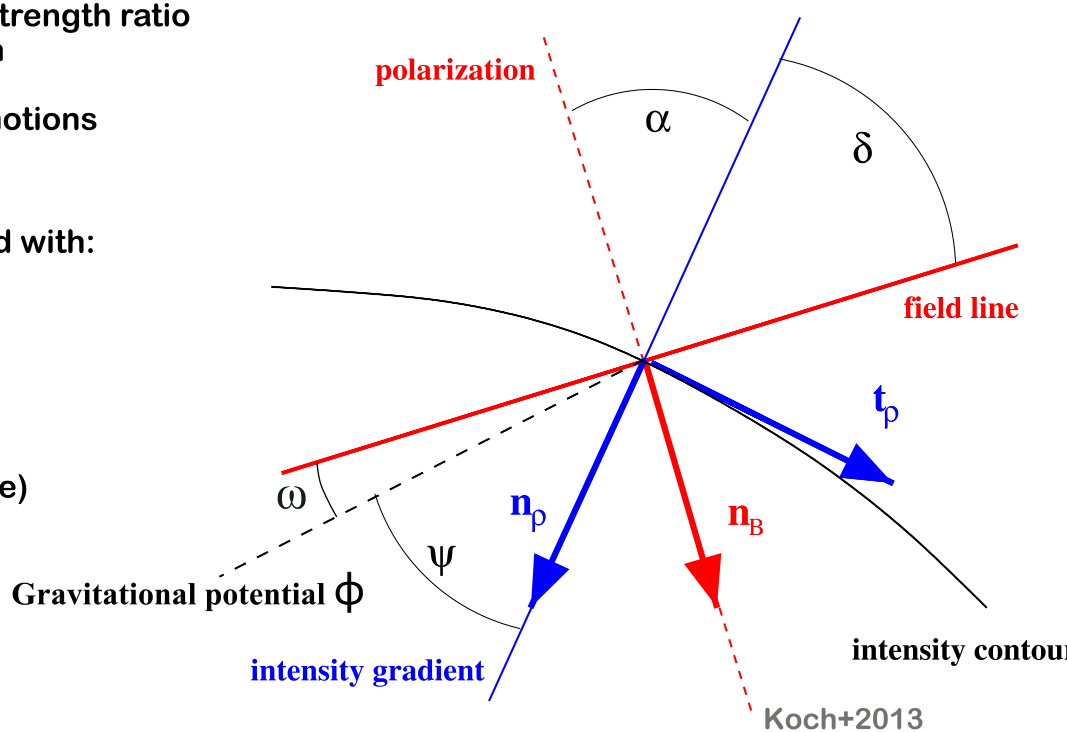
For further explanations see Yen & Lazarian 2017, Lazarian & Yuen 2018, Hu+2018, Hu+2021

Studying magnetic fields in the ISM with ...

the KTH method

Koch+2012

Assumptions: - negligible viscosity
- infinite conductivity (ideal MHD)
- isotropic magnetic field pressure
- small turbulent-to-ordered field strength ratio
- small variation of B-field strength
- stationarity
- Stokes I gradient = direction of motions



Then, the local B-field strength can be expressed with:

$$B = \sqrt{\frac{\sin\psi}{\sin\alpha}\left(\nabla P + \rho\nabla\phi\right)4\pi R},$$

(valid in strong field case --- negligible turbulence)

Method to be investigated in SOFIA data ! (see examples in Koch+2018, Liu+2020, Añez-López+2020)

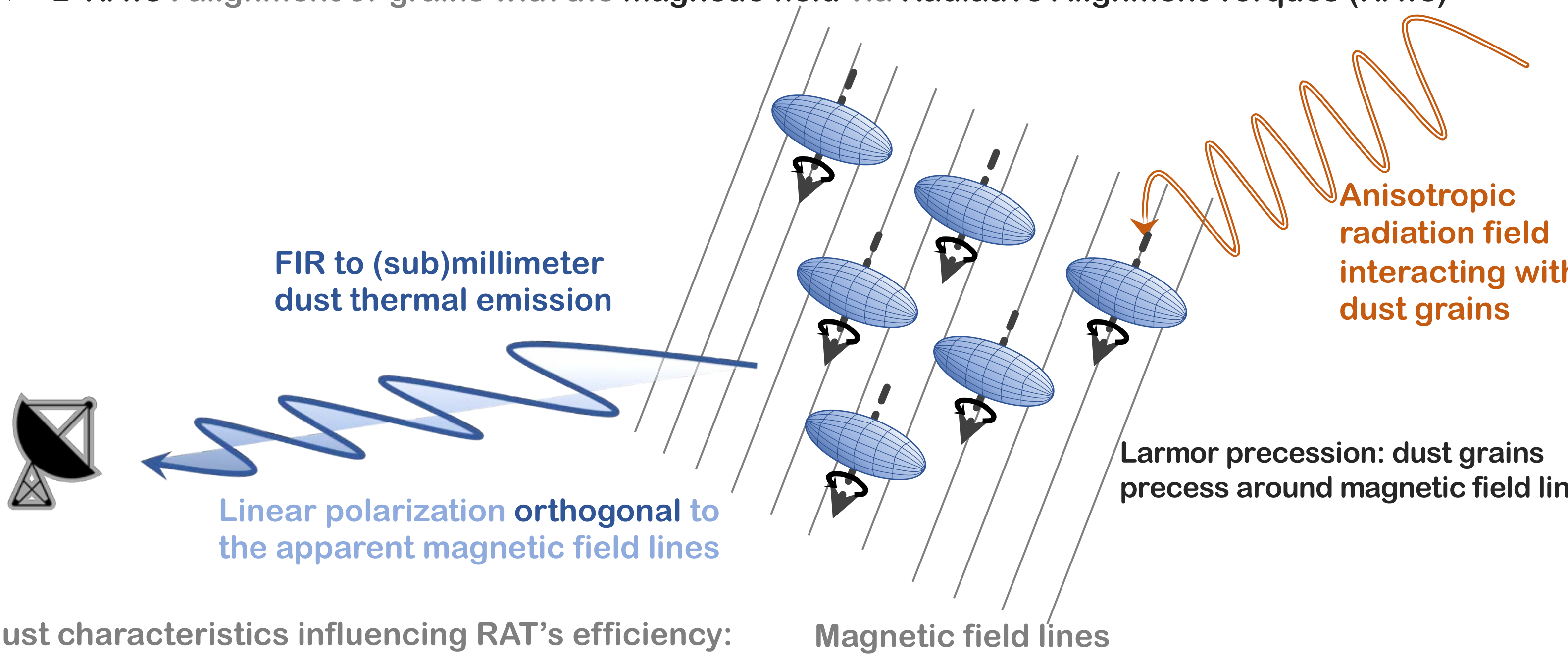
Part 2.

Study interstellar dust characteristics and grain alignment

Study interstellar dust characteristics and grain alignment with … grain alignment models

What **grain alignment mechanisms**?

- **B-RATs** : alignment of grains with the **magnetic field** via **Radiative Alignment Torques (RATs)**



Dust characteristics influencing RAT's efficiency:

- Size
- Shape
- Composition

What we assumed so far in this presentation!

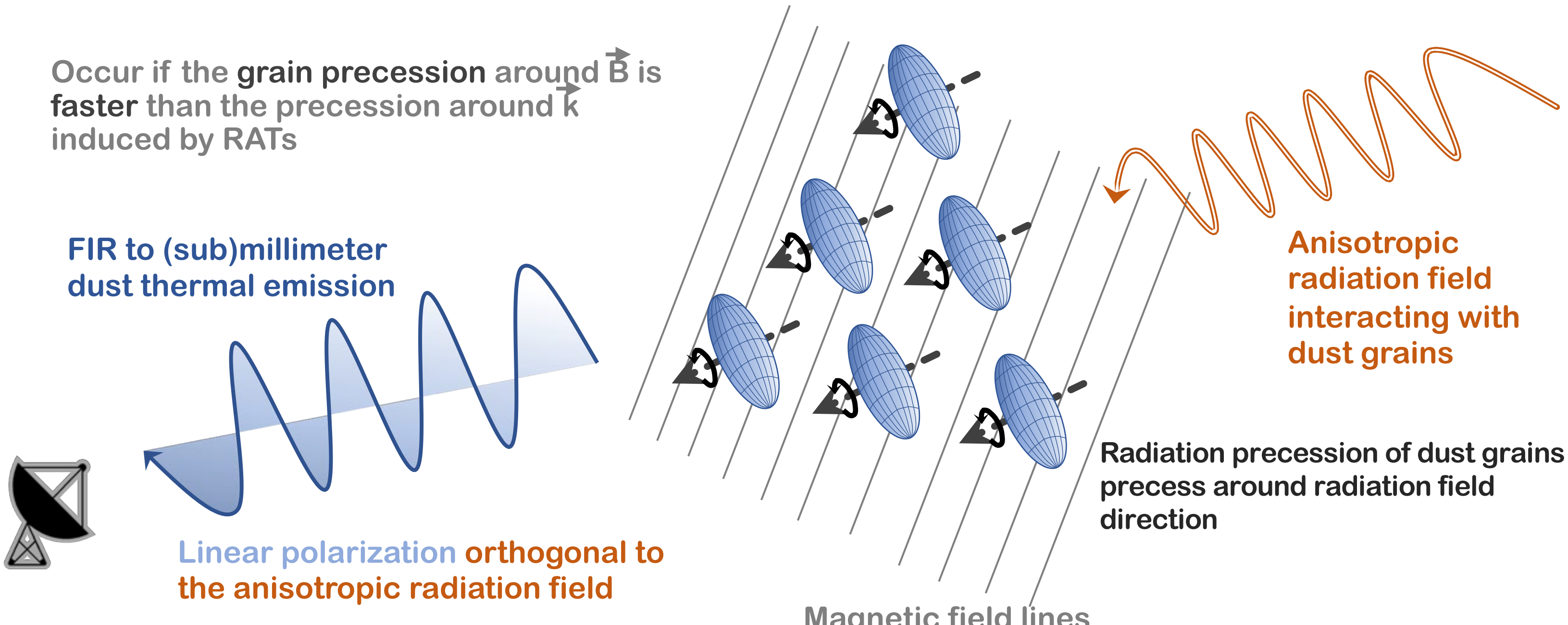
Dolginov & Mitranov 1976, Draine+1996, Draine+1997, Lazarian & Hoang 2007

Study interstellar dust characteristics and grain alignment with …
grain alignment models

What **grain alignment mechanisms?**

- B-RATs : alignment of grains with the magnetic field via Radiative Alignment Torques (RATs)
- **k-RATs :** alignment of grains with the **radiation field** via **Radiative Alignment Torques (RATs)**

Occur if the **grain precession** around $\vec{B}$ is **faster** than the precession around $\vec{k}$ induced by RATs



Possible to compare SOFIA FIR polarization (sensitive to hot dust) with radiation field direction in irradiated region

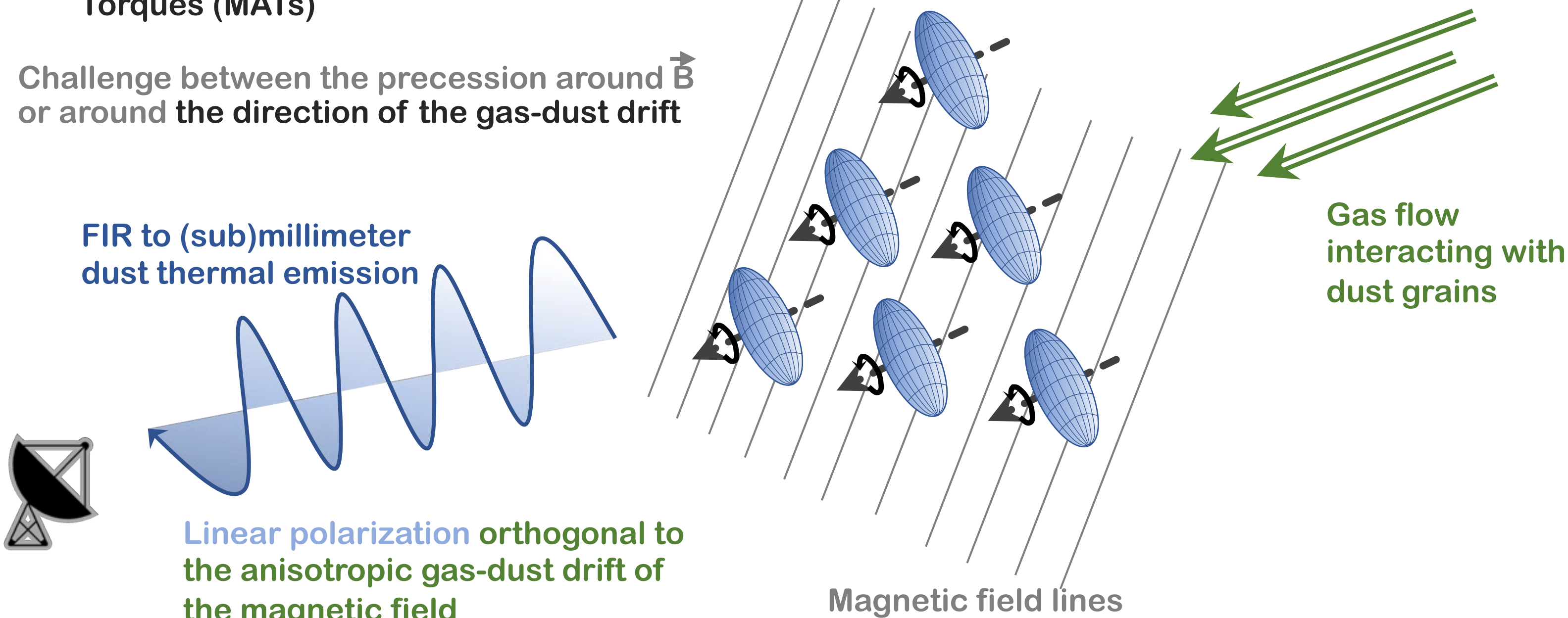
Lazarian & Hoang 2007

Study interstellar dust characteristics and grain alignment with … grain alignment models

What **grain alignment mechanisms?**

- B-RATs : alignment of grains with the magnetic field via Radiative Alignment Torques (RATs)
- k-RATs : alignment of grains with the radiation field via Radiative Alignment Torques (RATs)
- **MATs:** alignment of grains with the **gas flow** or **the magnetic field** via **Mechanical Alignment Torques (MATs)**

Challenge between the precession around $\vec{B}$ or around **the direction of the gas-dust drift**



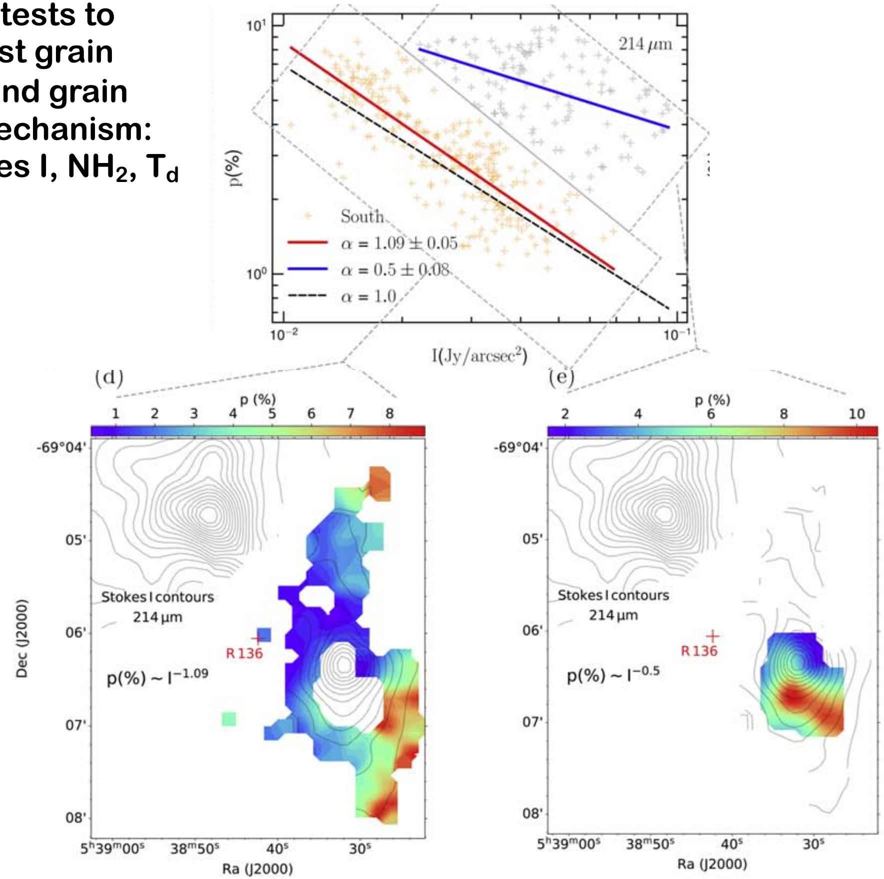
Possible to investigate in region with high gas-dust drift like AGB envelopes

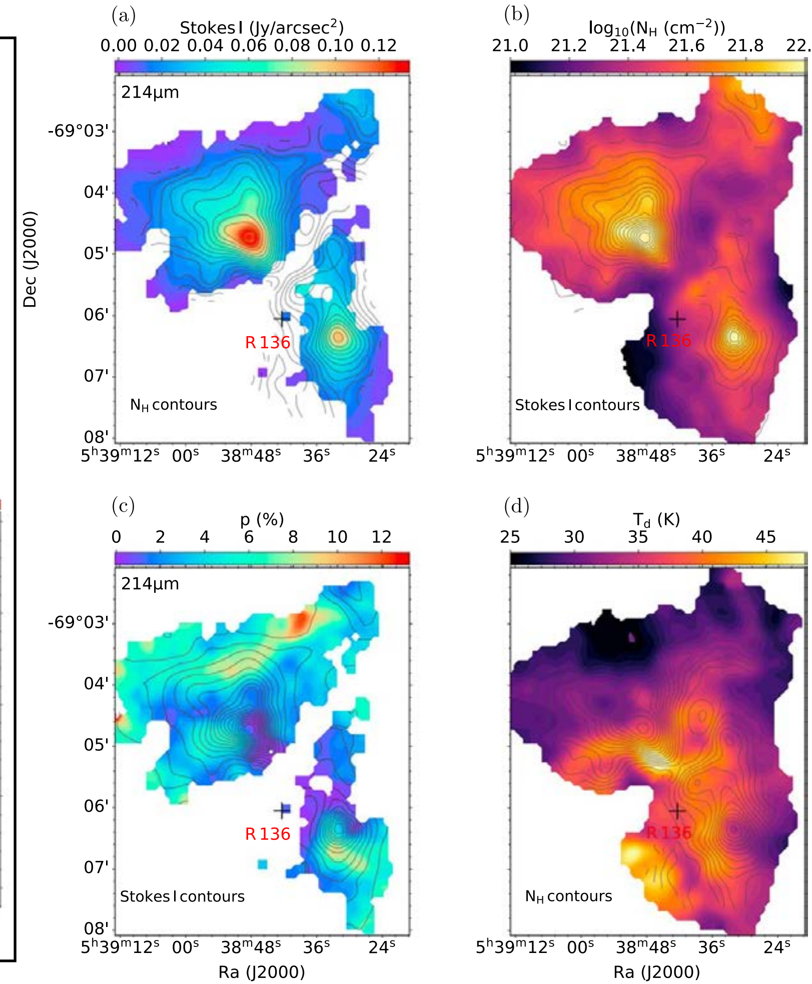
Lazarian & Hoang 2007, Hoang+2018, Reissl+2022

Study interstellar dust characteristics and grain alignment with …

the evolution of polarization with local physical conditions

Quantitative tests to constrain dust grain properties, and grain alignment mechanism: P_{frac} vs. Stokes I, NH_2, T_d

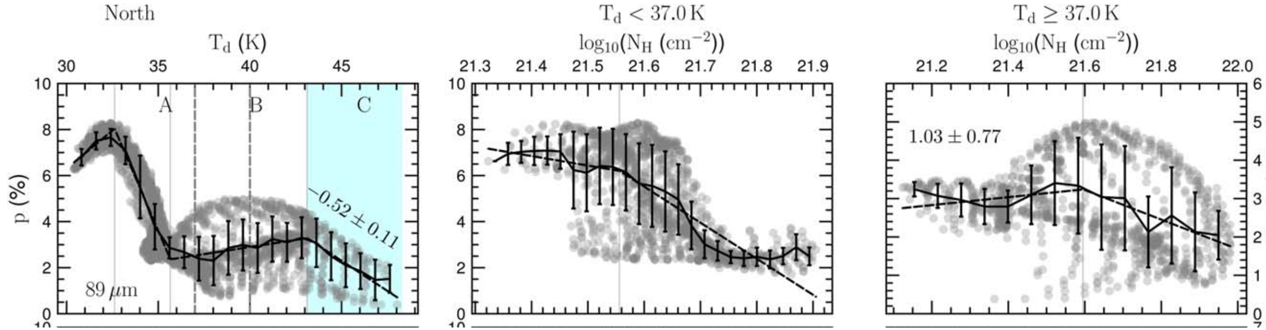




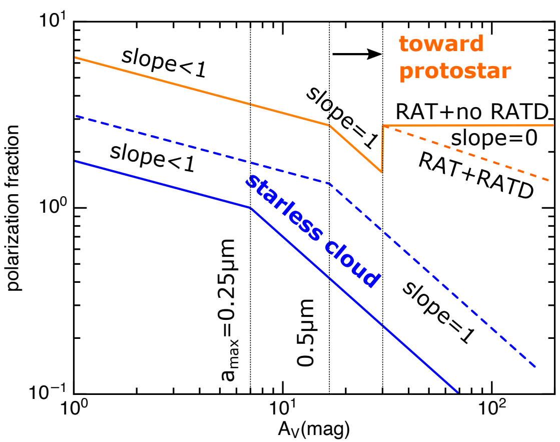
Tram+2021

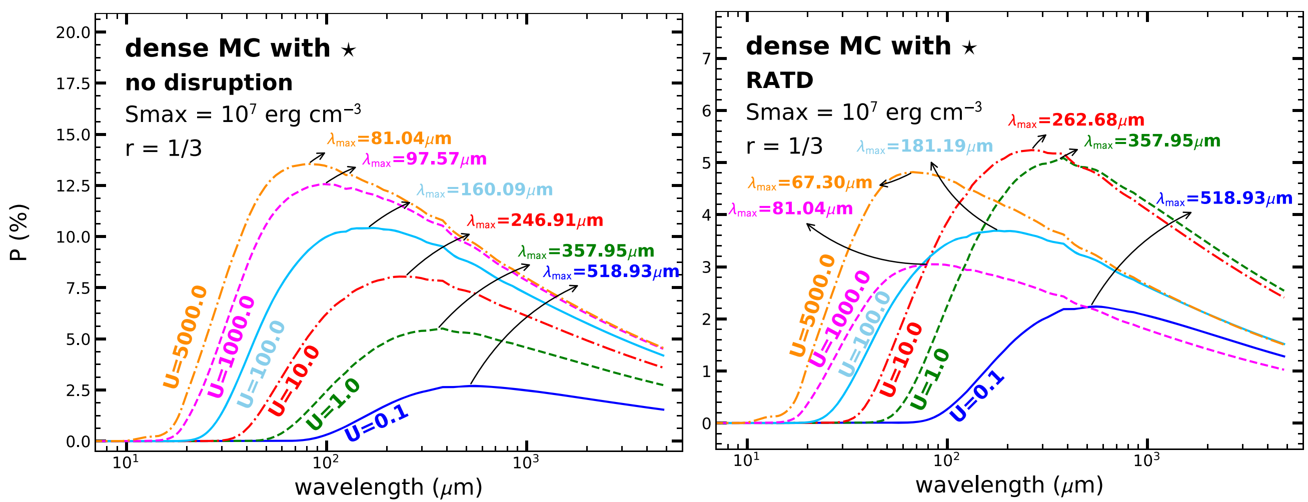
Study interstellar dust characteristics and grain alignment with …
the evolution of polarization with local physical conditions

RAT theory predict the grain alignment efficiency to increase with the dust temperature …



Radiative Torque Disruption theory: disruption of the largest aligned grains if the grain rotation speed exceeds the grain cohesion strength

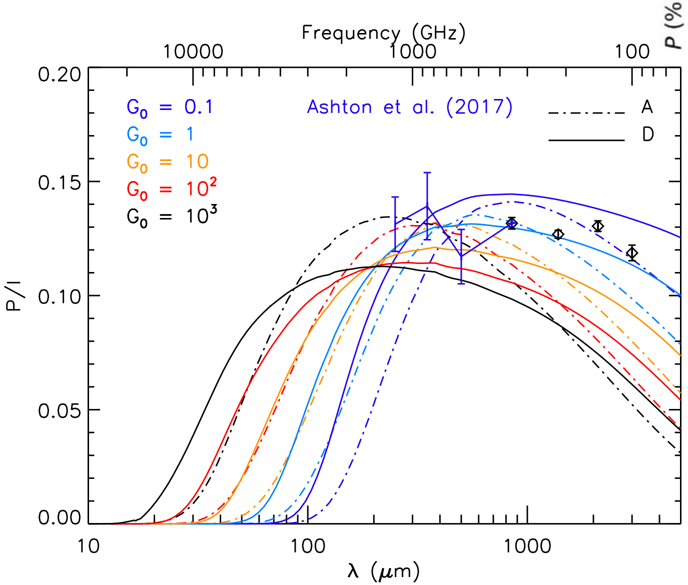


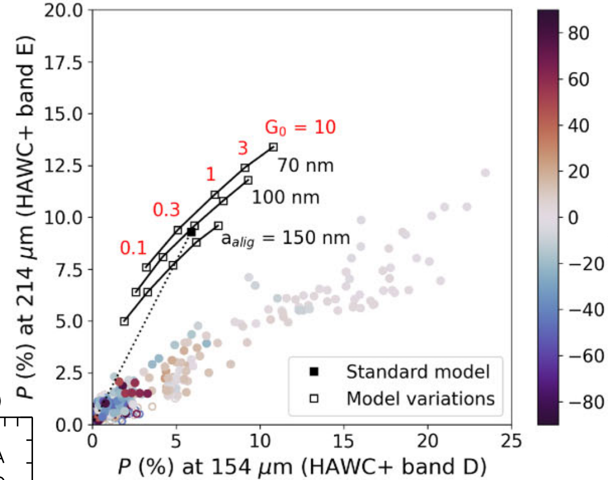


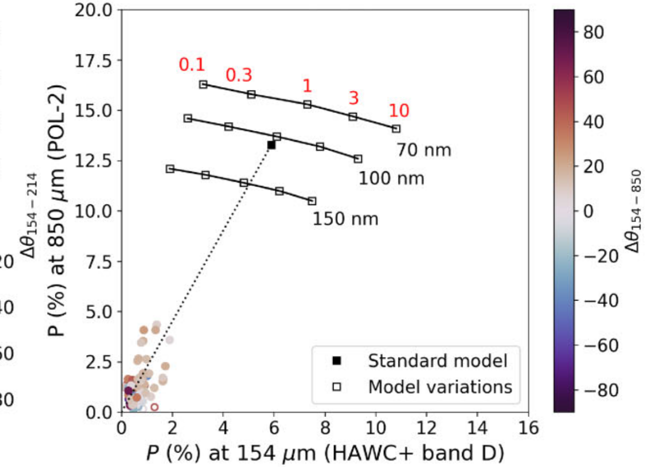
Hoang+2019, Lee+2019, Hoang+2020, Tram+2021

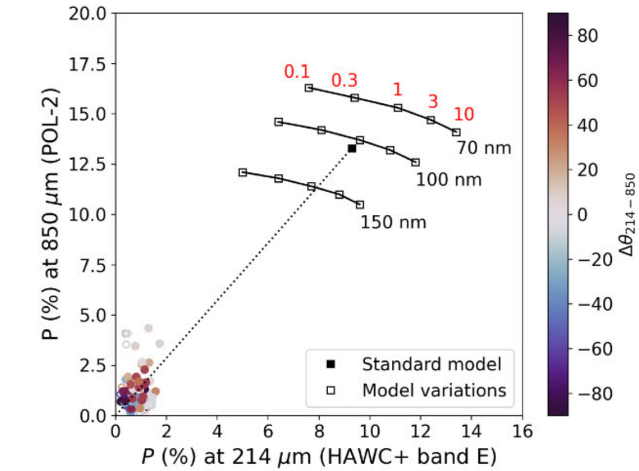
Study interstellar dust characteristics and grain alignment with ... polarization fraction spectra

Constraining models of polarization fraction spectra with SOFIA HAWC+ and JCMT POL2 data of NGC2071 in Orion



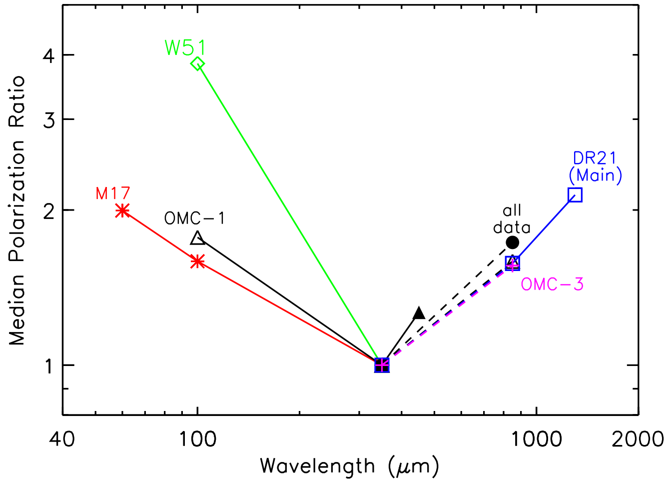






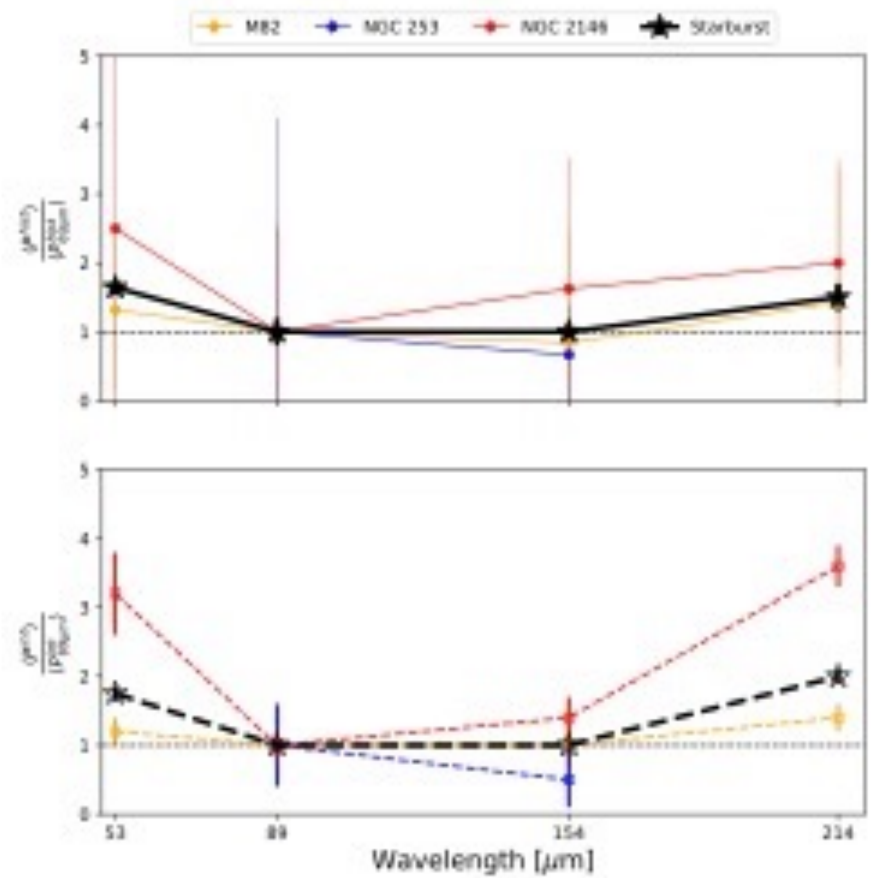
Guillet+2018, Fanciullo+2022

Study interstellar dust characteristics and grain alignment with …
polarization fraction spectra



Polarization fraction spectra of massive clouds
Vaillancour+2012

- HAWC+ multiwavelength polarization of archival data allows such science
- Synergies with current and future instruments : ALMA, JCMT POL2 , IRAM30m NIKA2pol, LMT Toltec,



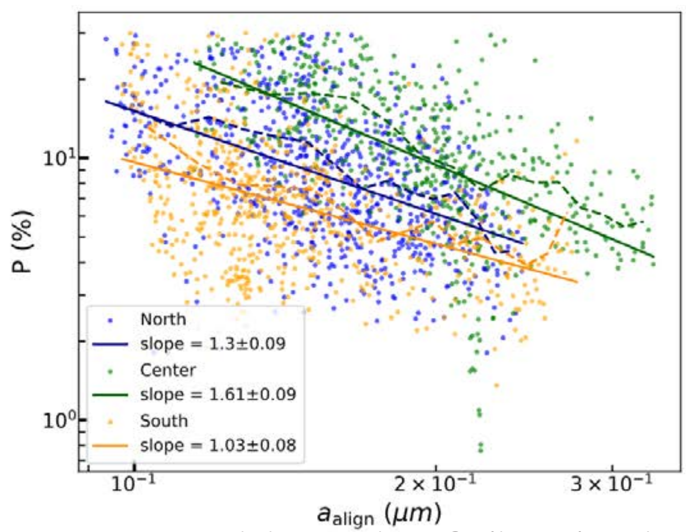
Polarization fraction spectra of nearby galaxies, HAWC+ 4 bands data, Lopez-Rodriguez+2022

Study interstellar dust characteristics and grain alignment with … dust evolution models

Dust formation (AGB) — Diverse processing (ISM) — **Growth (molecular clouds)** — Destruction (PDRs, HII regions)

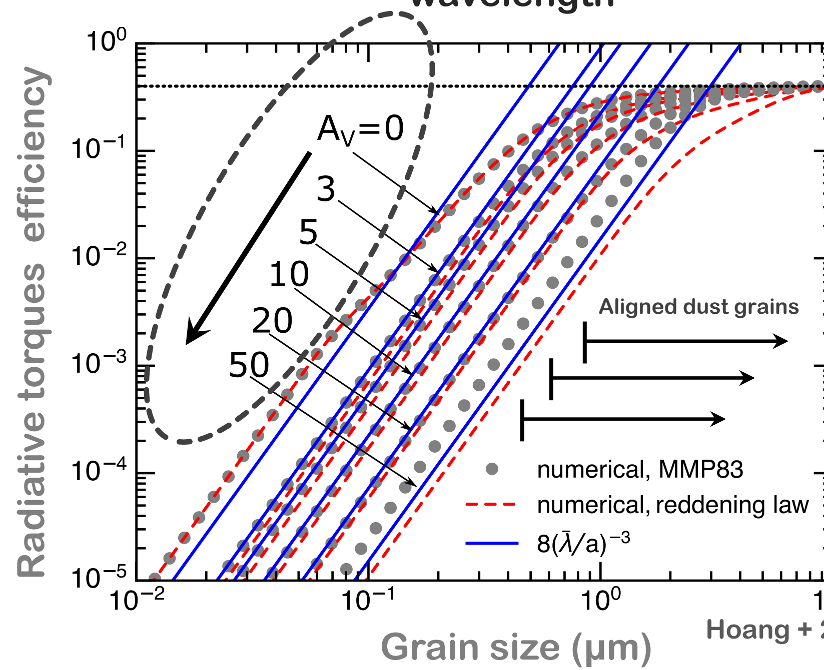
Dust evolutionary track

Increasing extinction A_v
=>
Increasing of the radiation field wavelength



a_{align} = minimum size of aligned grains

Grain growth in an Infrared dark cloud with HAWC+ data



Hoang + 2020

Hoang+2020, Bich Ngoc+2023

Study interstellar dust characteristics and grain alignment with … polarization radiative transfer

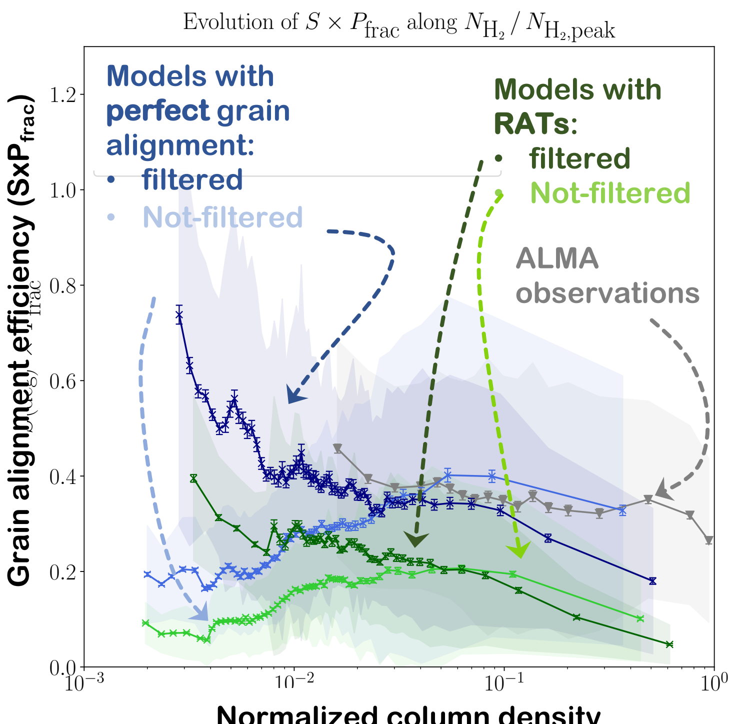
Polarization Radiative Transfer Code

POLARIS

… onto MHD simulation

⟷ **SOFIA HAWC+ data, and others…**

Different grain alignment hypotheses



How?

Comparing:

- Max P_{frac}
- $S \times P_{frac}$
- polarization spectra
- Correlation with NH_2, T_d

To constrain:

- Grain evolution (growth, disruption)
- Grain composition, shape
- Alignment properties

Reissl+2016, Le Gouellec+2020, Chau Giang+2023
See also Li, P.-S.+2021,2022

Fin