Synthetic Polarization of Central Molecular Zone-like Environments

Linking Dust Grain Alignment to Magnetic Field Morphology

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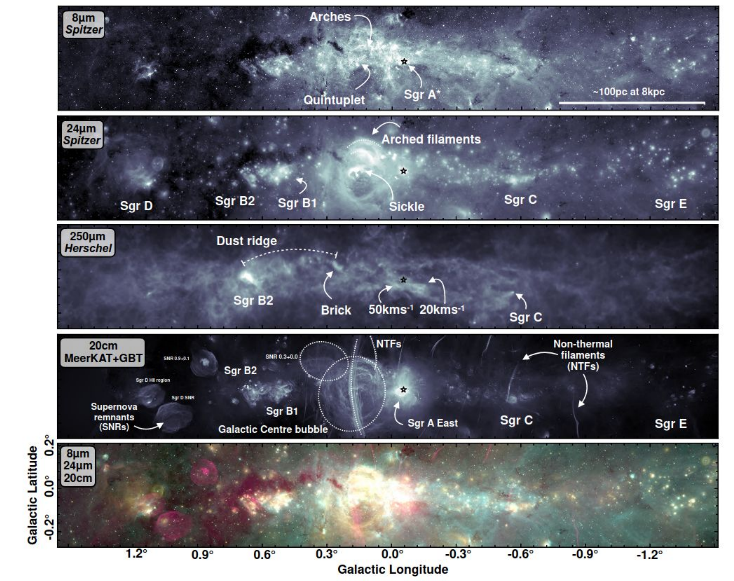
Role B-field in the Central Molecular Zone (CMZ)

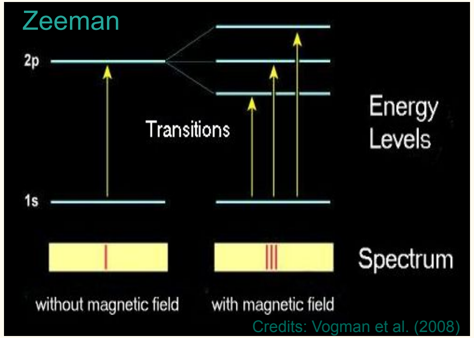
- Observations reveal a poloidal and toroidal B-field component, but the 3D structure remains unknown.
- B-field is largely ordered but the transition to turbulent field is not well understood.
- B-field measured from various techniques do not agree well with each other.
- How the B-field scales with density? Important to understand its role in cloud collapse and star formation.
- Role of B-field in bar driven inflows and accretion of matter towards the Galactic centre is not well understood.



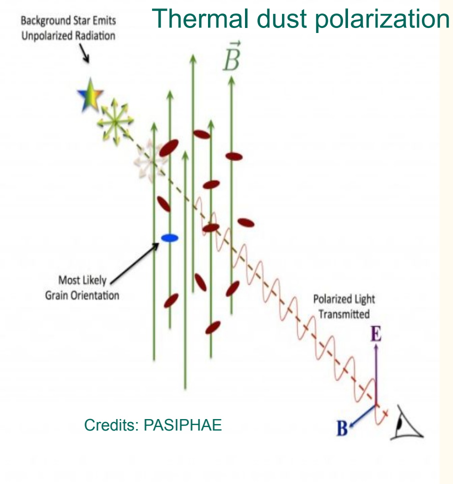
Henshaw et. al (2023)

Synthetic Polarization: Bridging Gaps in Astronomical Data Interpretation

- Derive 3D map of the magnetic field
- Influence of multiple components on the observed plane-of-sky dust polarization
- Understand the dust grain alignment mechanism which affects the interpretation of polarization observations
- Energy balance between magnetic fields and turbulence that play a role in the accretion of matter into the Galactic centre

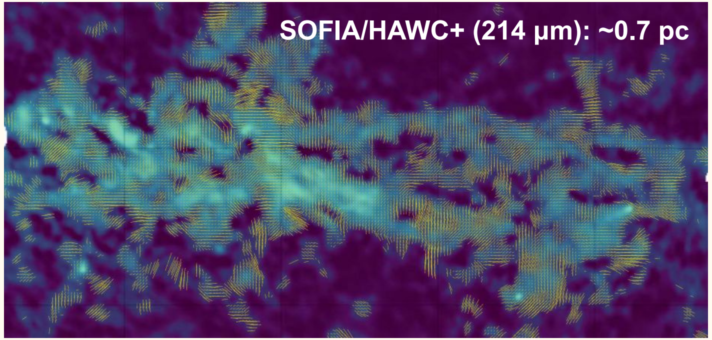


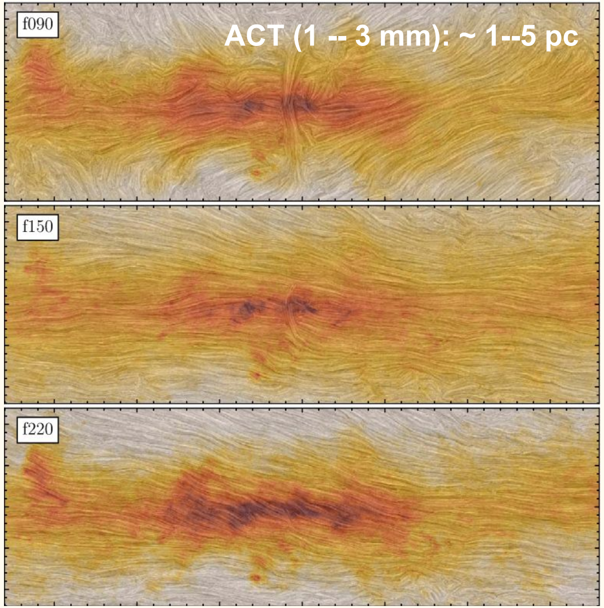
Credits: Vogman et al. (2008)

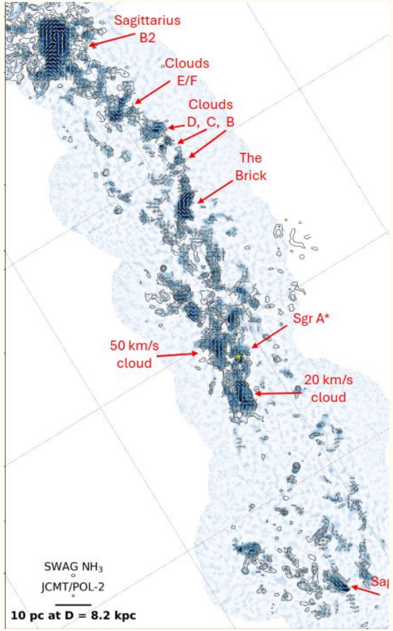


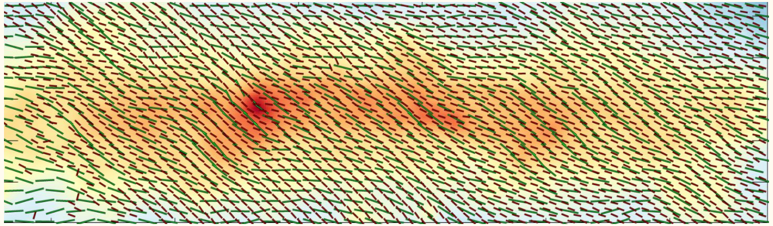
Credits: PASIPHAE

Available multiscale data of the CMZ









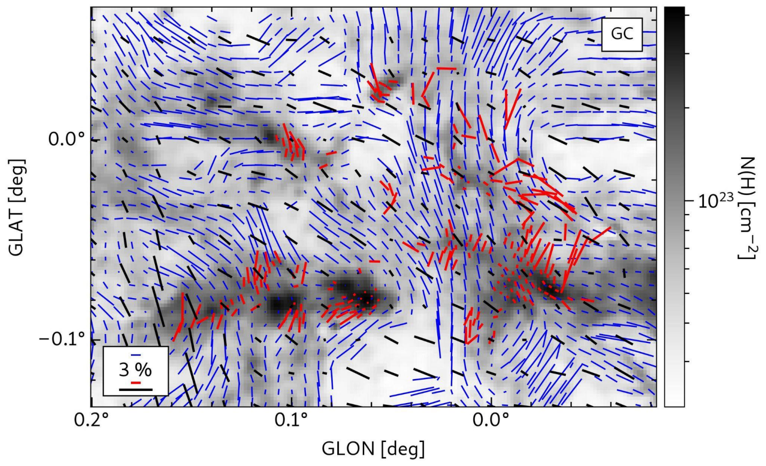
Planck (353 GHz) & PILOT (240 µm): ~ 5--10 pc

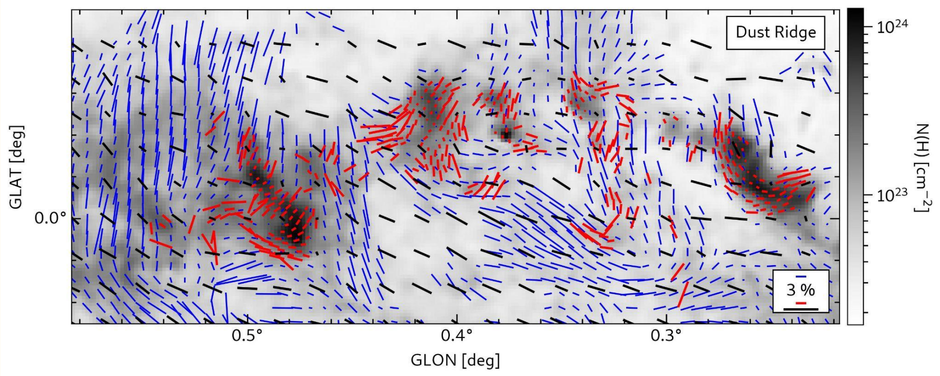
JCMT/ POL-2 (850 µm): ~0.6 pc

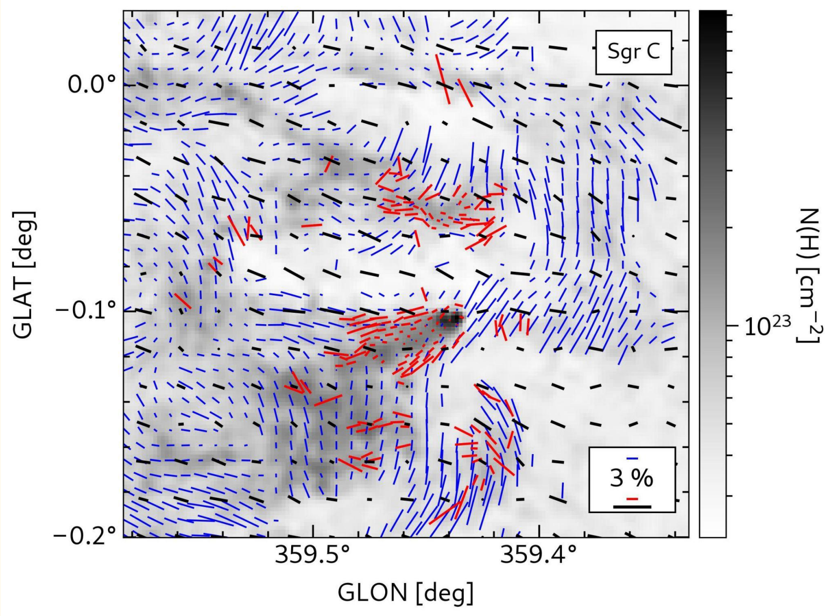
Data summaries

Instrument	Band / Wavelength	Resolution (arcmin/arcsec)	Resolution (parsec, at 8.3 kpc)	Spatial Scales Traced
ACT (Guan et al. 2021)	1 mm	~1 arcmin	~2.4 pc	Diffuse ISM.
JCMT POL-2 (Lu et al. 2020)	850 μm	14 arcsec	~0.55 pc	Dense molecular clouds ($n \sim 10^3$ - 10^4 cm^{-3}); filaments; star-forming cores.
SOFIA HAWC+ (Pare et al. 2024)	214 μm	18.9 arcsec	~0.76 pc	Warm dust ($T_d \sim 41K$); intermediate-density regions; magnetized rings and compressed zones.

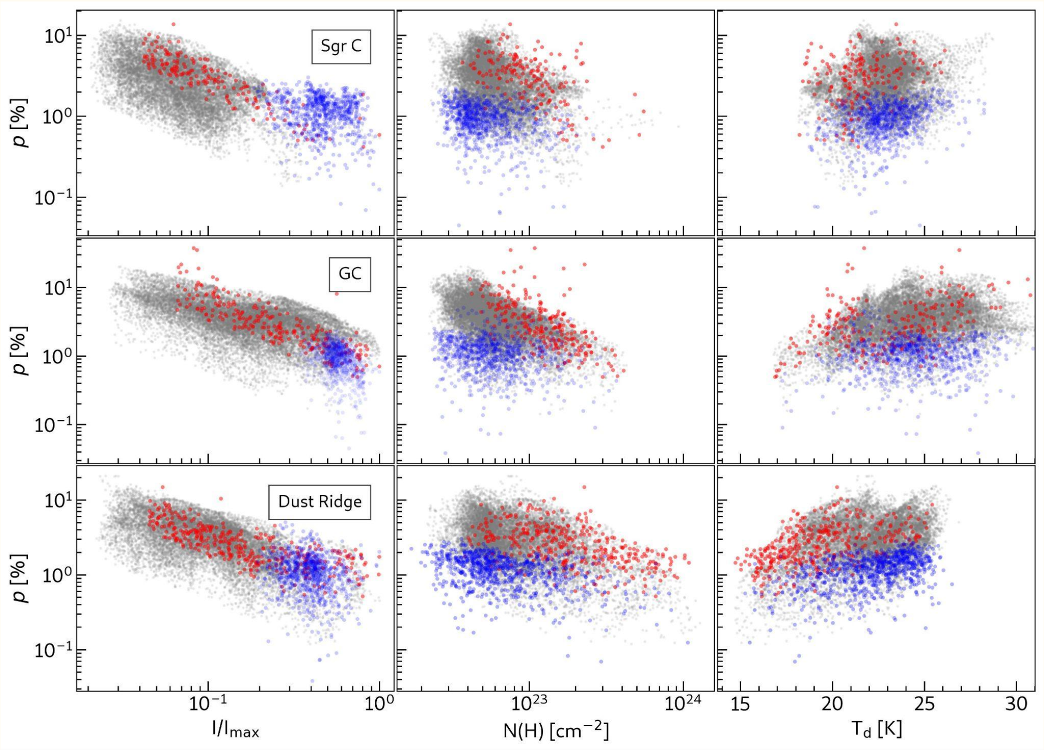
CMZ B-field from thermal dust polarization







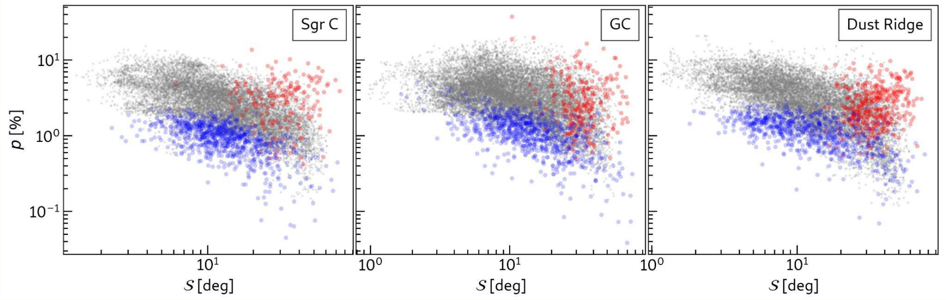
Dust Polarization vs. Local Environment

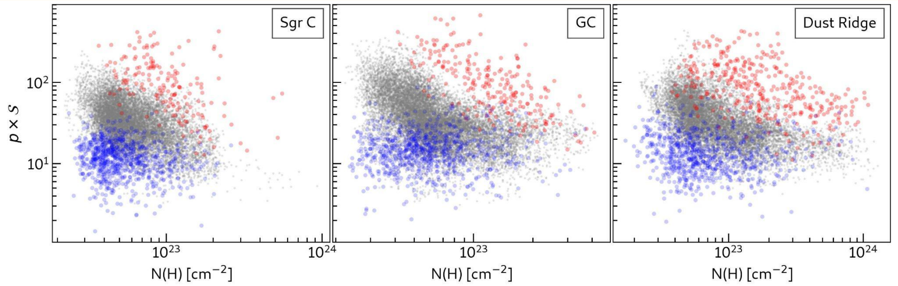


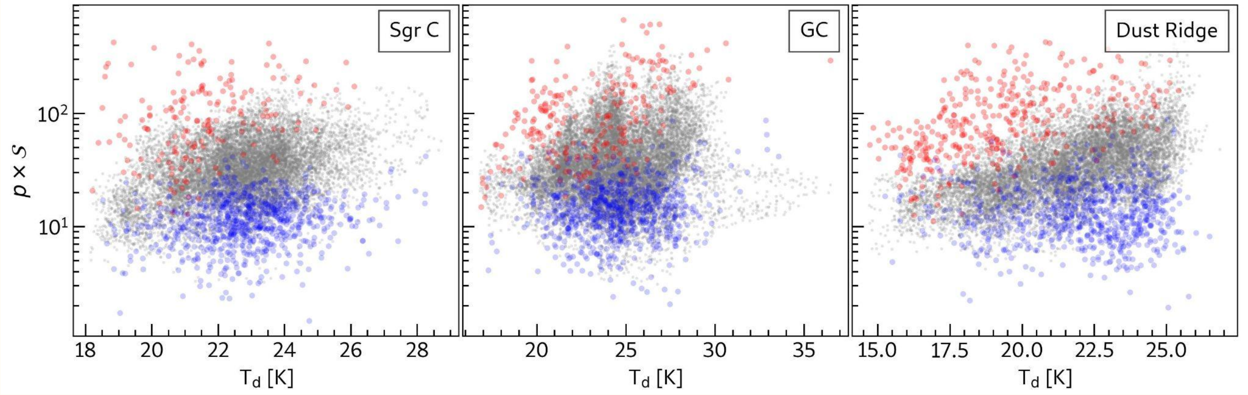
General trend follows the predictions of RAT alignment.

Column density and dust temperature maps from Marsh et al. (2017).

Tracing Magnetic Field: Order and Turbulence



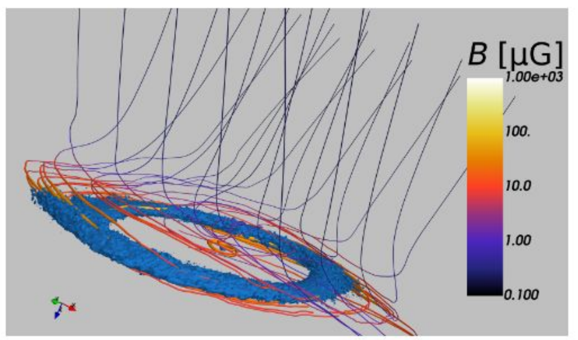


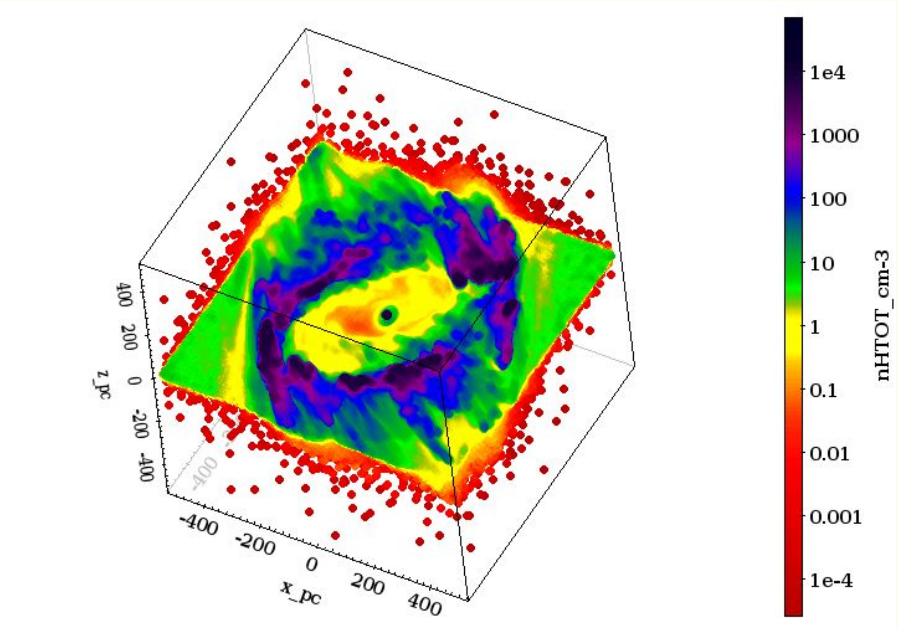


The observed B-field is mostly well ordered.

High dispersion only observed at higher densities.

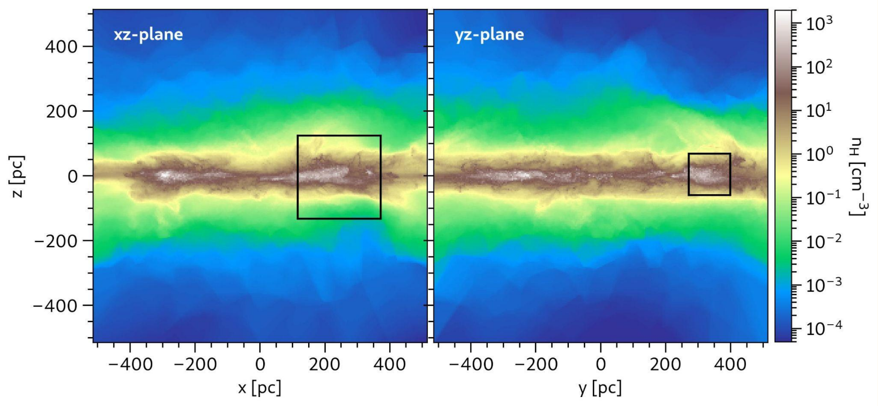
MHD Simulation of the Central Molecular Zone [Tress et al. 2023]

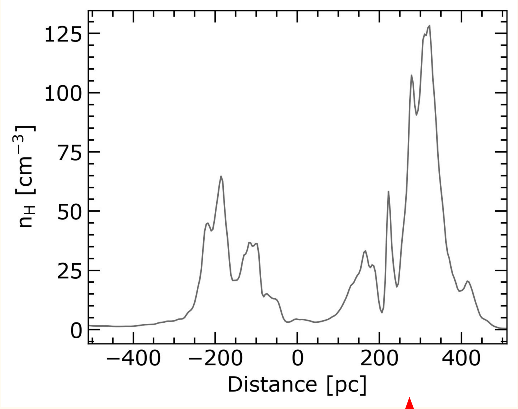




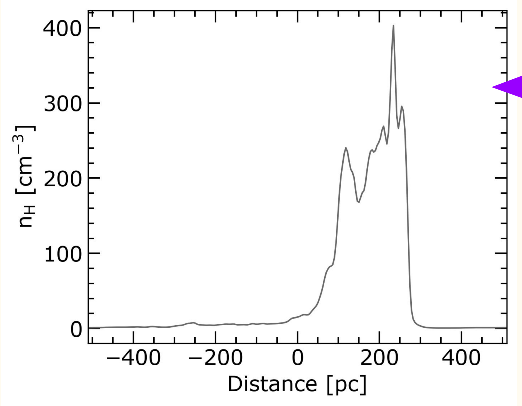
- **Global 3D magnetohydrodynamic (MHD)** simulation of gas flow in the **Milky Way's barred potential**, performed with **AREPO.**
- Models the **inner 5 kpc** region, focusing on the **100 pc CMZ ring and nuclear inflow**.
- **No self-gravity** or stellar feedback; isolates **magnetic and dynamical processes**.
- Provides self-consistent **3D magnetic field and density cubes** ideal for **polarized radiative transfer calculations**.

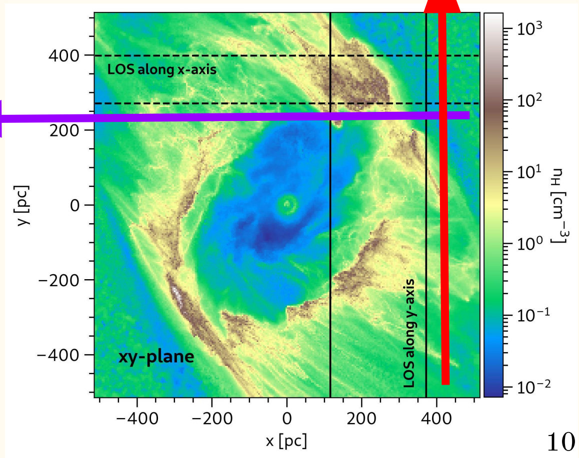
CMZ cross-sections for different components





Synthetic observations helps in understanding the effect of component integration along the line of sight.





POLARIS: Polarized Radiation Simulator

- **3D Monte Carlo radiative transfer code** for simulating **intensity and polarization** from astrophysical environments.

- Originally developed by **Reissl et al. (2016)** with **grain alignment physics upgrades** by **Giang et al. (2023).**

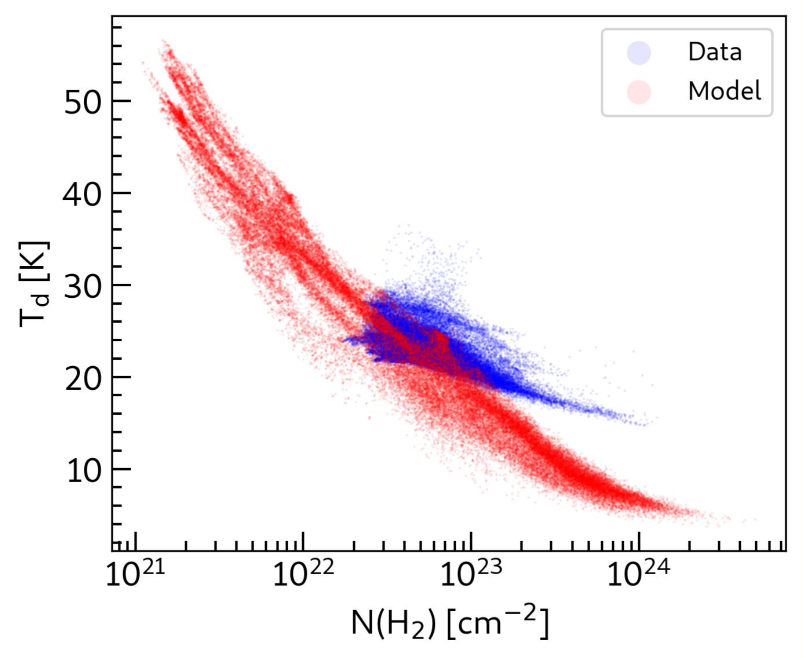
- **Radiative Alignment Torque (RAT)** physics for **grain alignment** with magnetic fields.

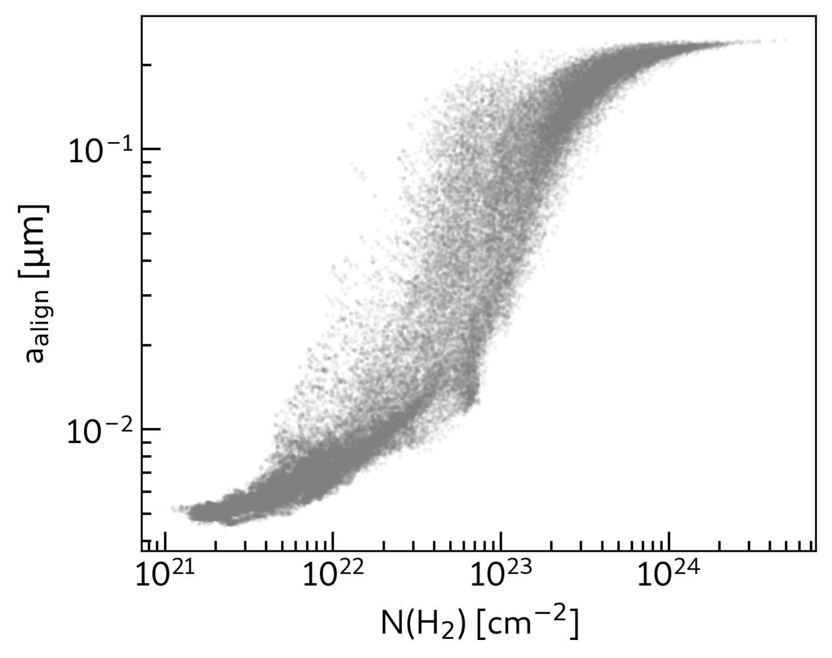
- **Magnetically enhanced RAT (MRAT)** mechanism for grains with **iron inclusions**.

- **Detailed grain size distributions** and **temperature dependent alignment**.

- Tests **depolarization mechanisms**: grain growth, magnetic field disorder, optical depth effects.

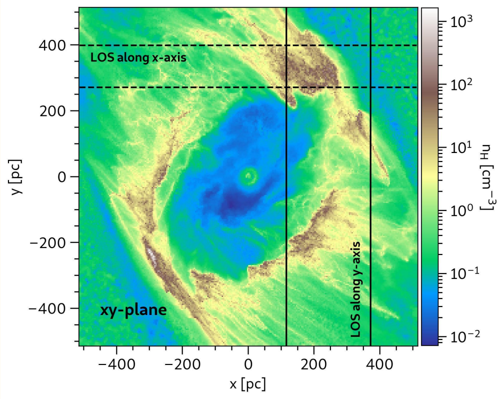
Dust environment and alignment sizes



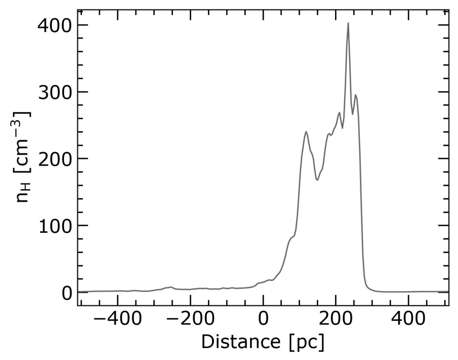


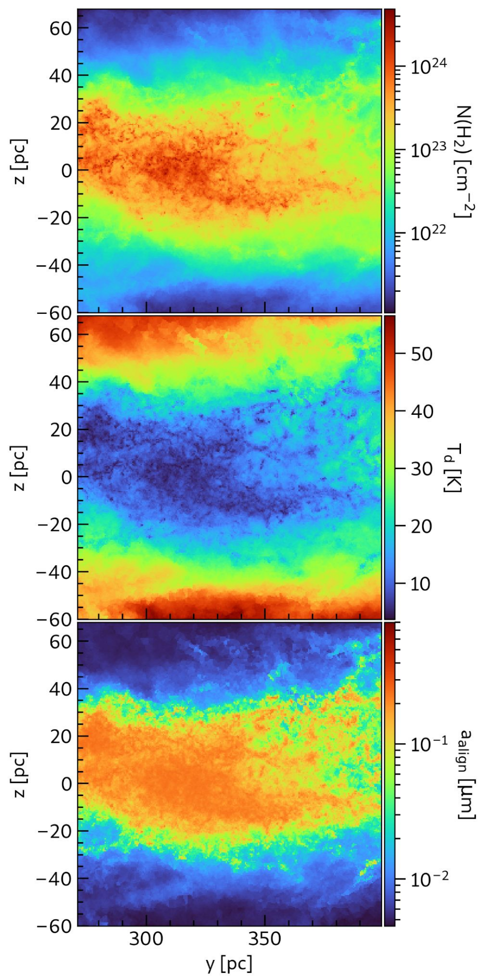
Radiation field of the MCRT adjusted to match the observed dust temperature of the CMZ

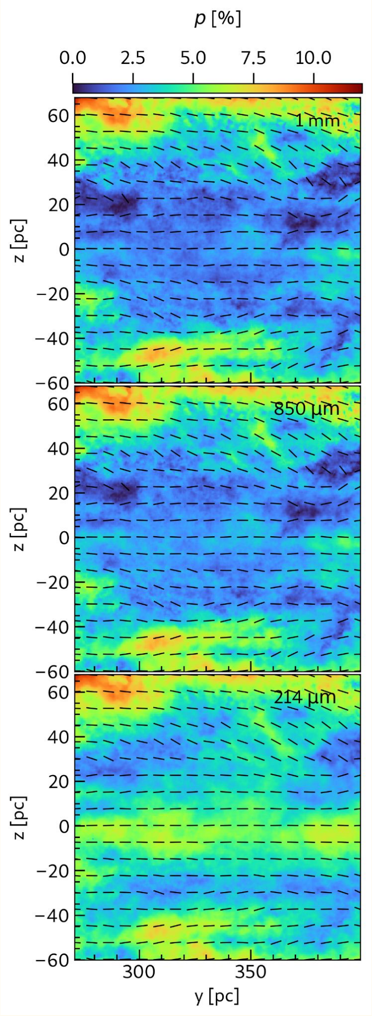
Synthetic maps of single component region



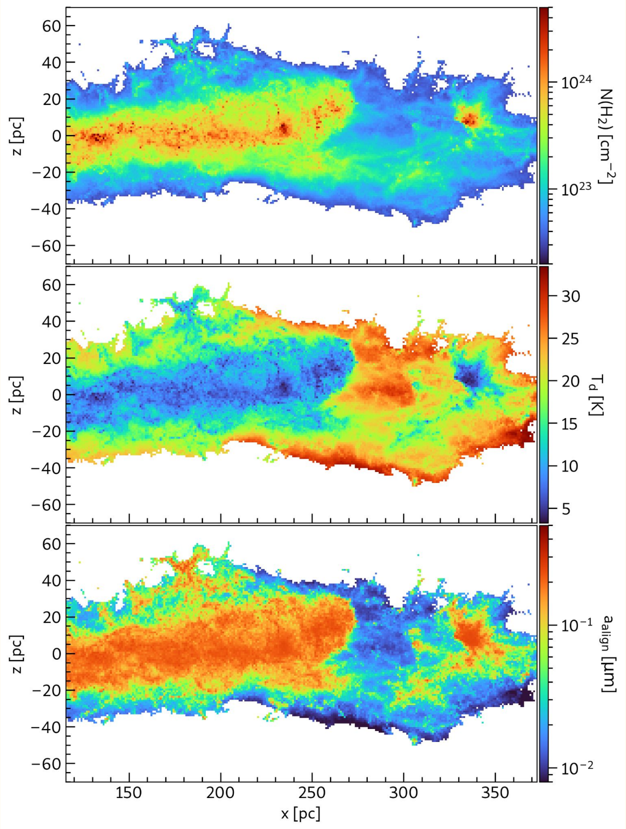
Higher polarization at shorter wavelength.

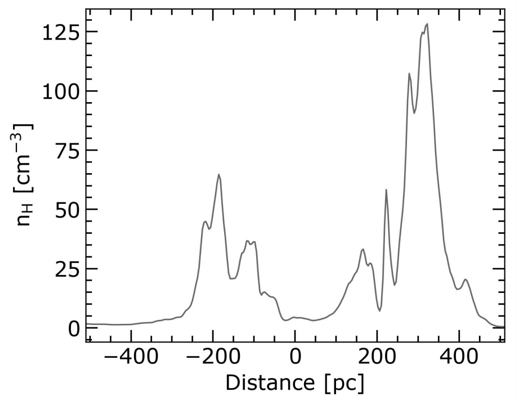


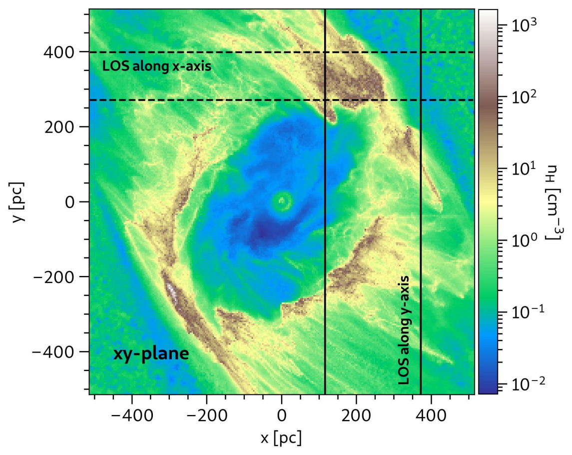


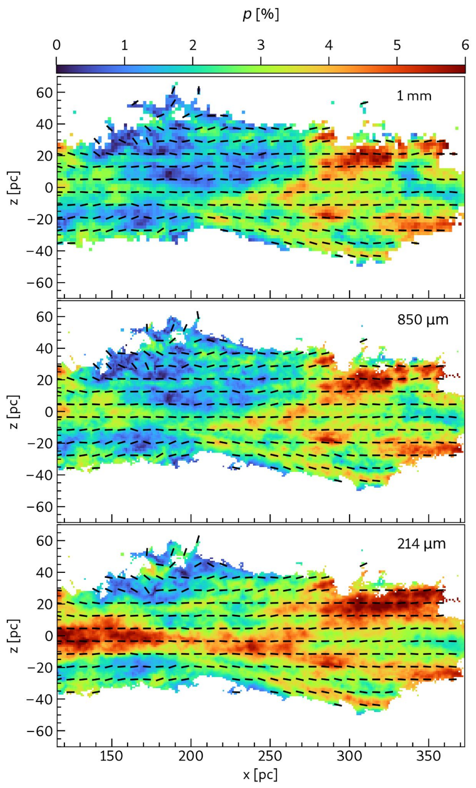


Synthetic maps of two component region







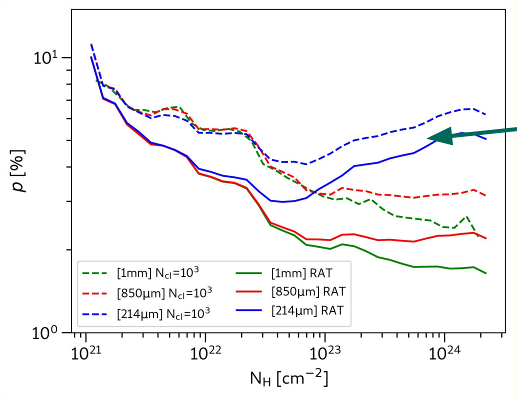


Longer wavelengths show similar levels of polarization degree.

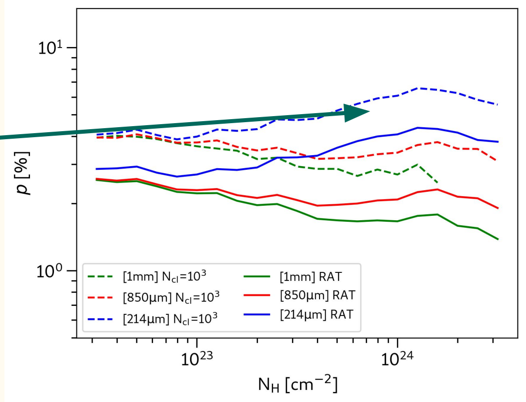
Can we reproduce the observed level of the polarization fraction

How well the magnetic field is traced at different wavelengths

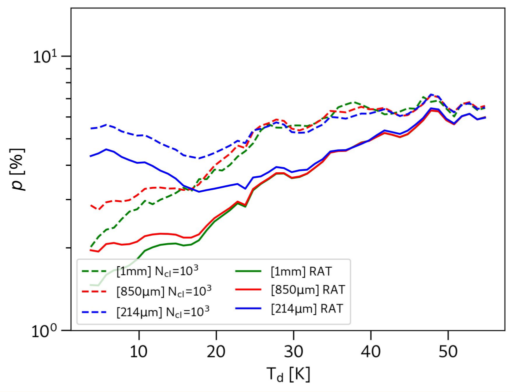
Polarization fraction for RAT and M-RAT alignment



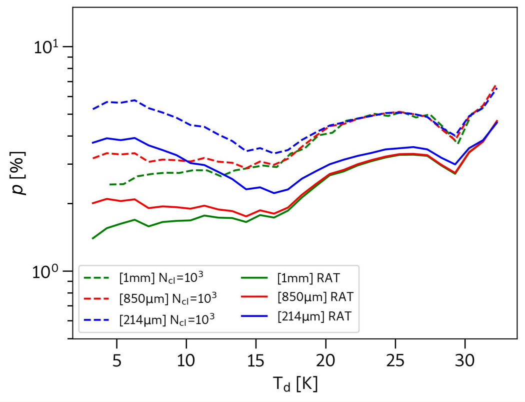
unexpected



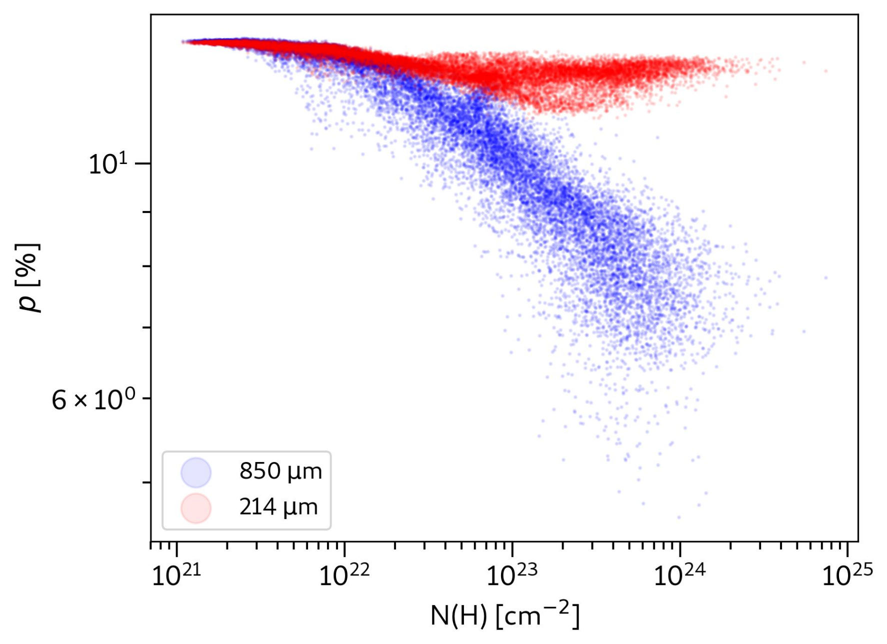
Single component



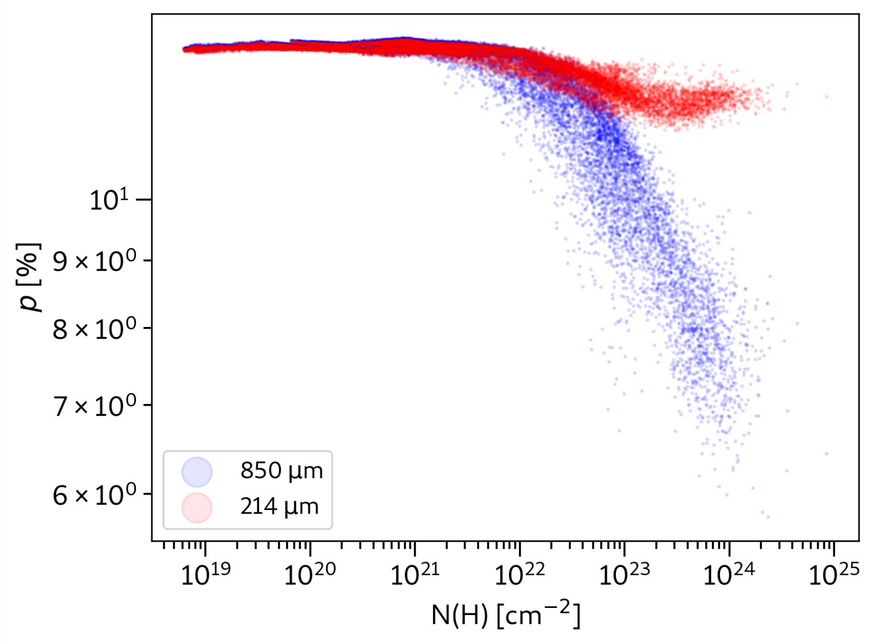
Two component



Depolarization assuming uniform magnetic field of 20μG (Test)

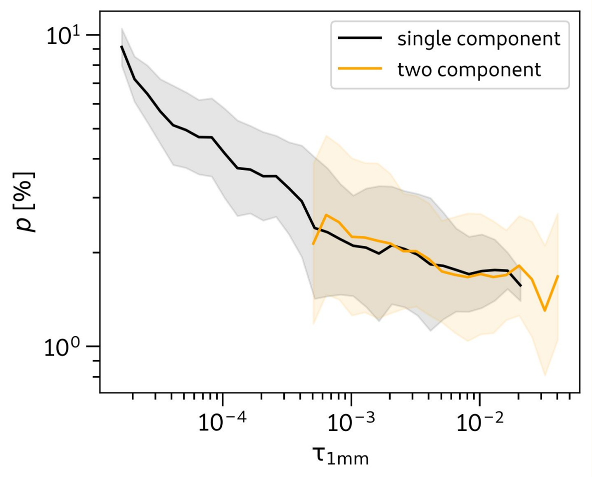


Single component

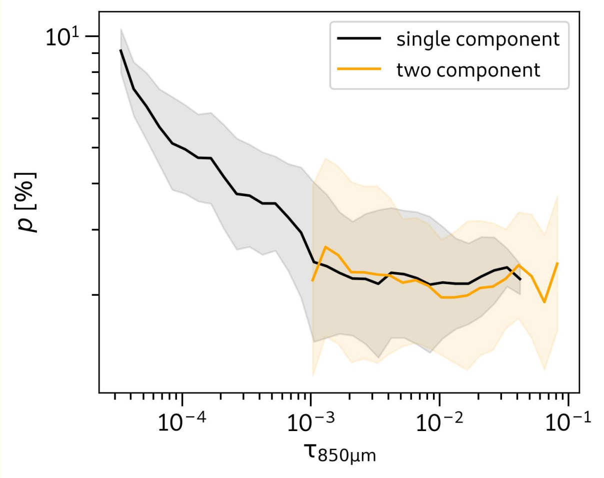


Two component

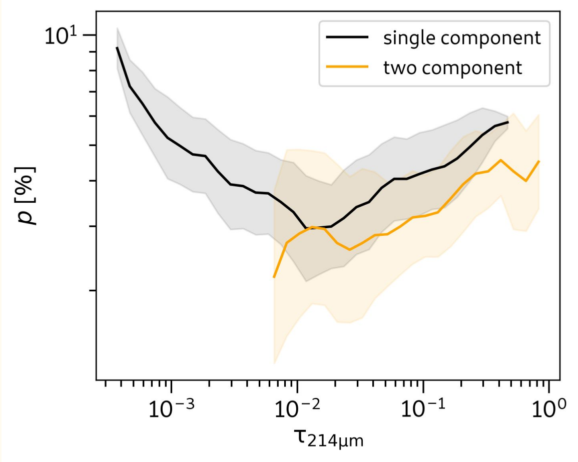
Optical depth of the region at different wavelengths



1 mm



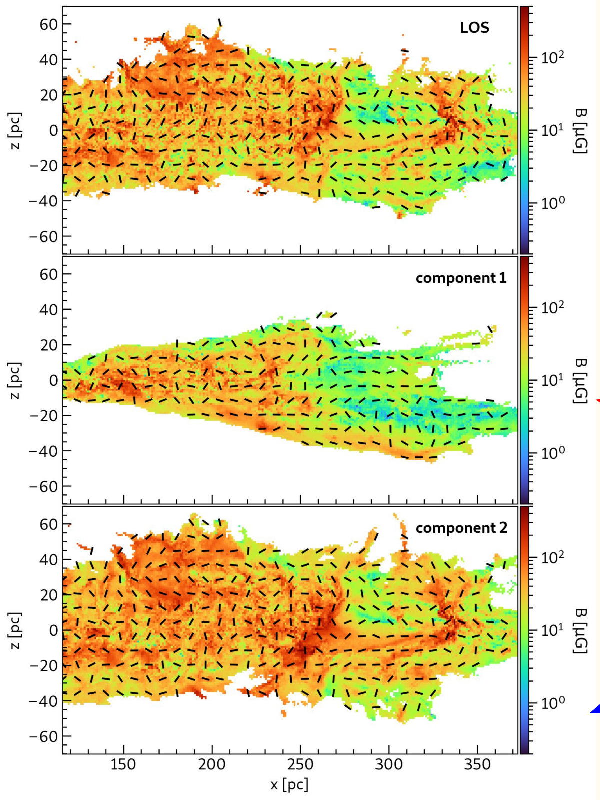
850 μm



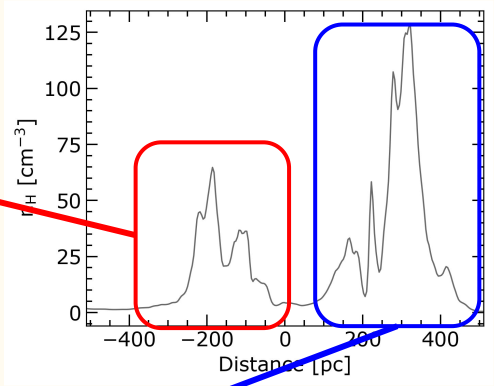
214 μm

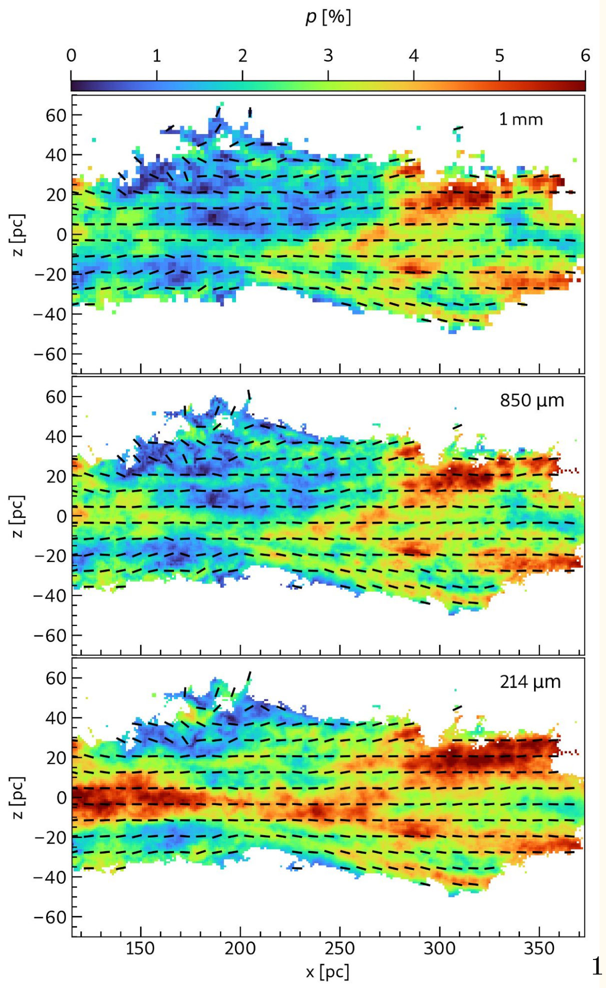
Unexpected trend at shorter wavelength even at low optical depth

Individual Component Analysis



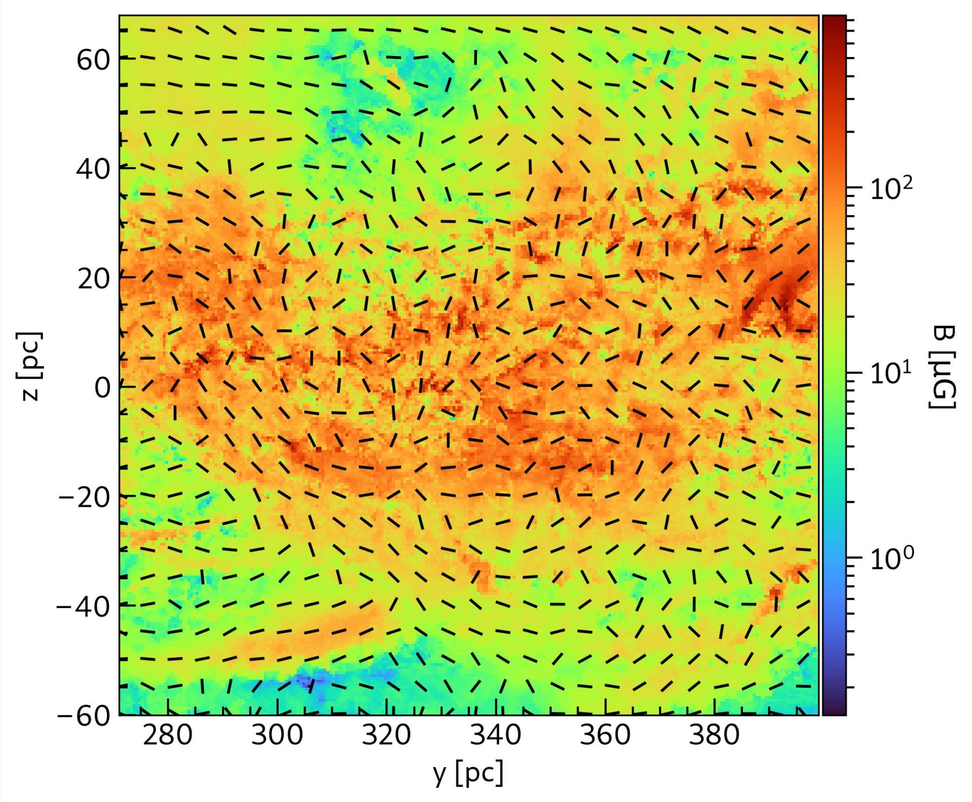
Polarization pattern at different wavelengths does not follow any one component in particular.

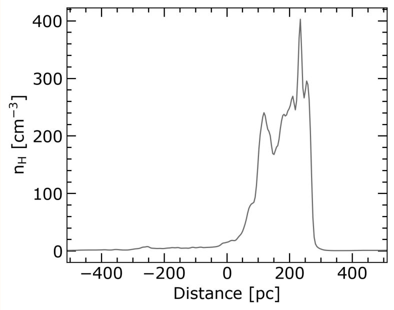




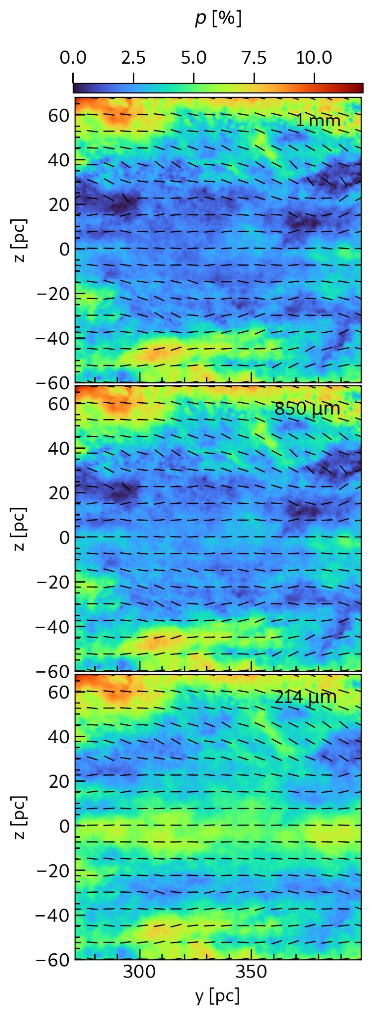
Normalized density weighted B-field vectors in the POS

Single component region density-weighted B-field map

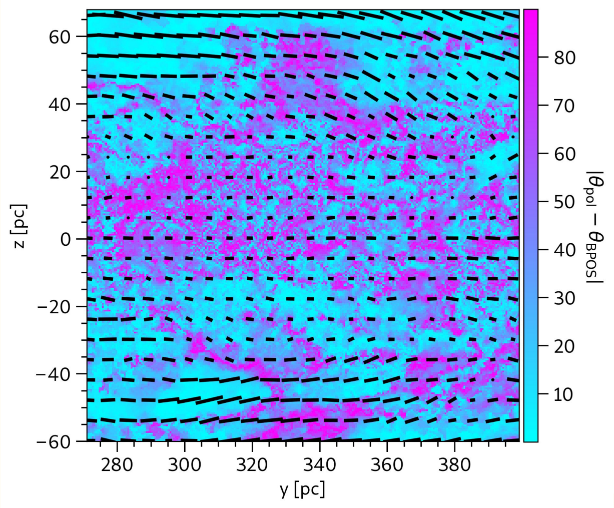




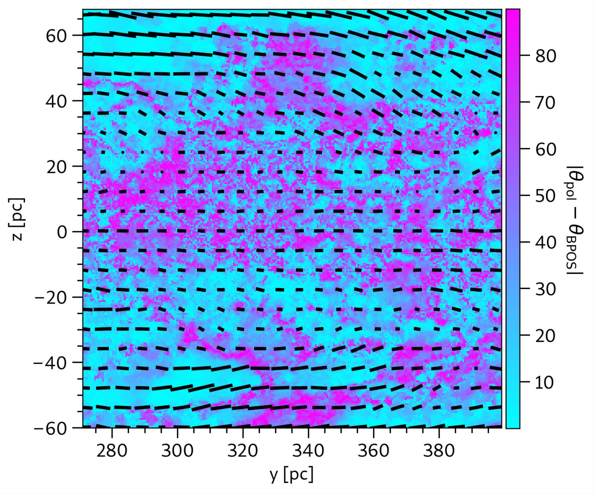
Uniform B-field pattern across wavelengths



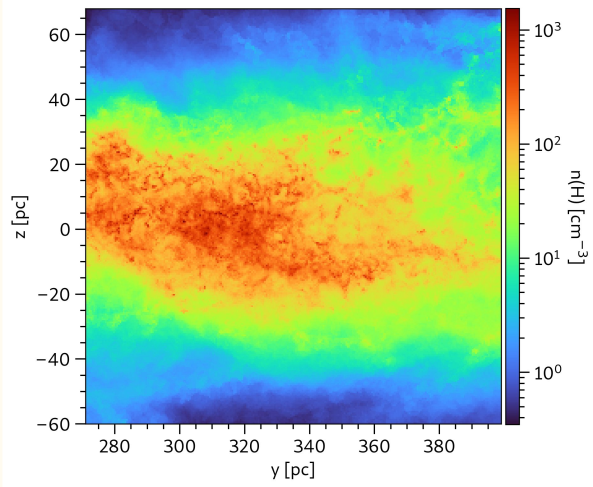
Comparing Magnetic Field Morphology: MHD vs Synthetic Polarization Maps

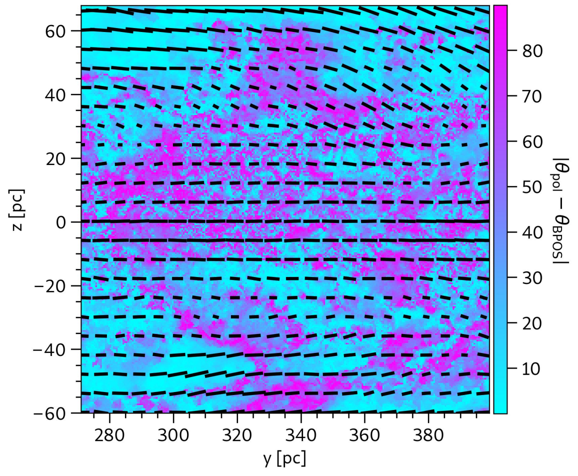


1 mm



850 µm



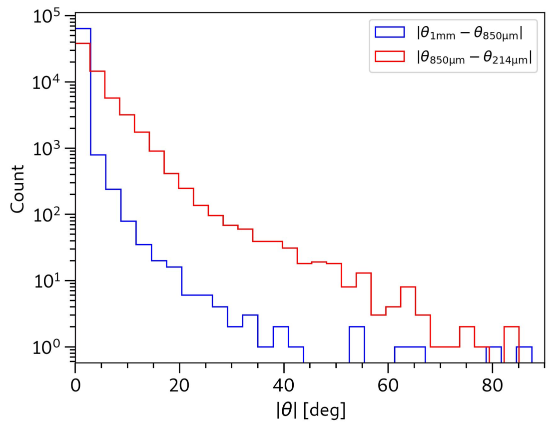


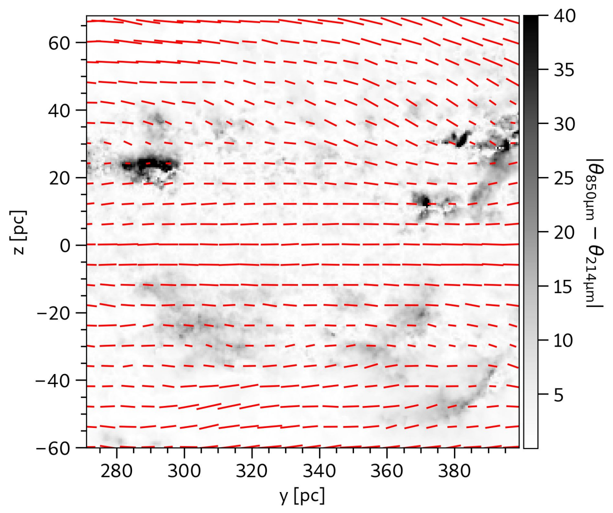
214 µm

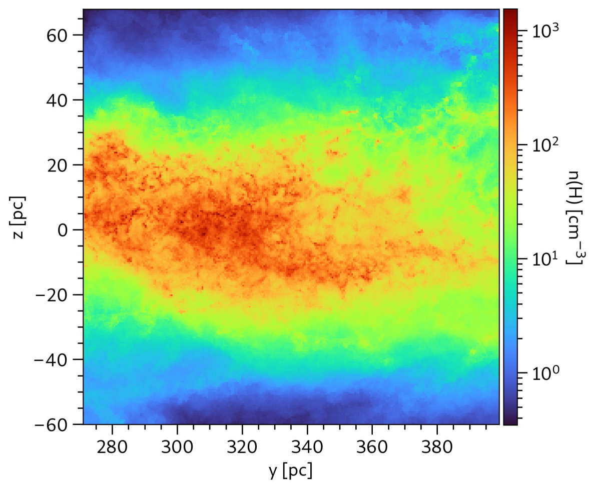
B-field orientation similar in all the maps with the only change observed in the fraction of aligned grains emitting in different wavebands.

Lower polarization in regions with larger angle difference at longer wavelength.

Differences in Polarization Angle Across Wavelengths



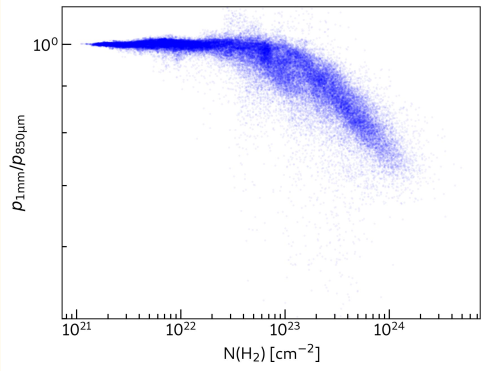


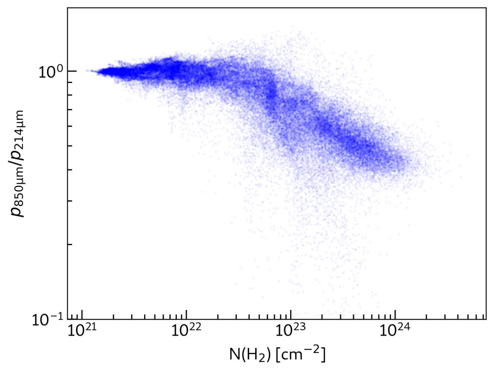


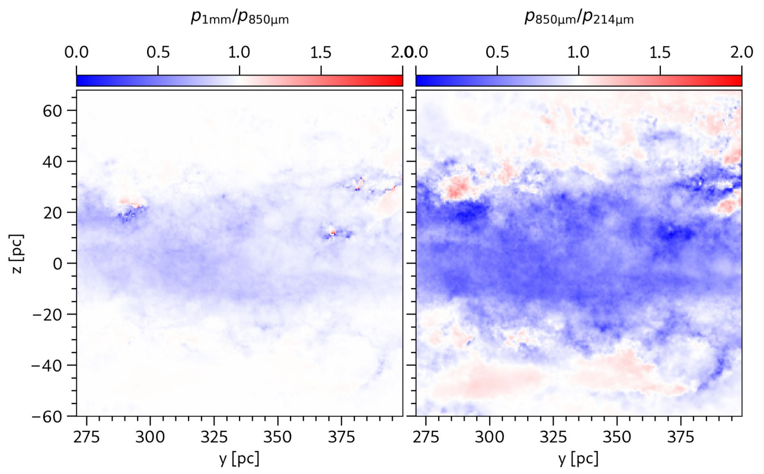
850 µm and 1mm observations show similar polarization vectors

Greater difference in polarization angle observed for 214 µm synthetic observations at moderate densities [n(H) ~ 10 - 10^2 cm^{-3}]

Polarization degree ratio with column density







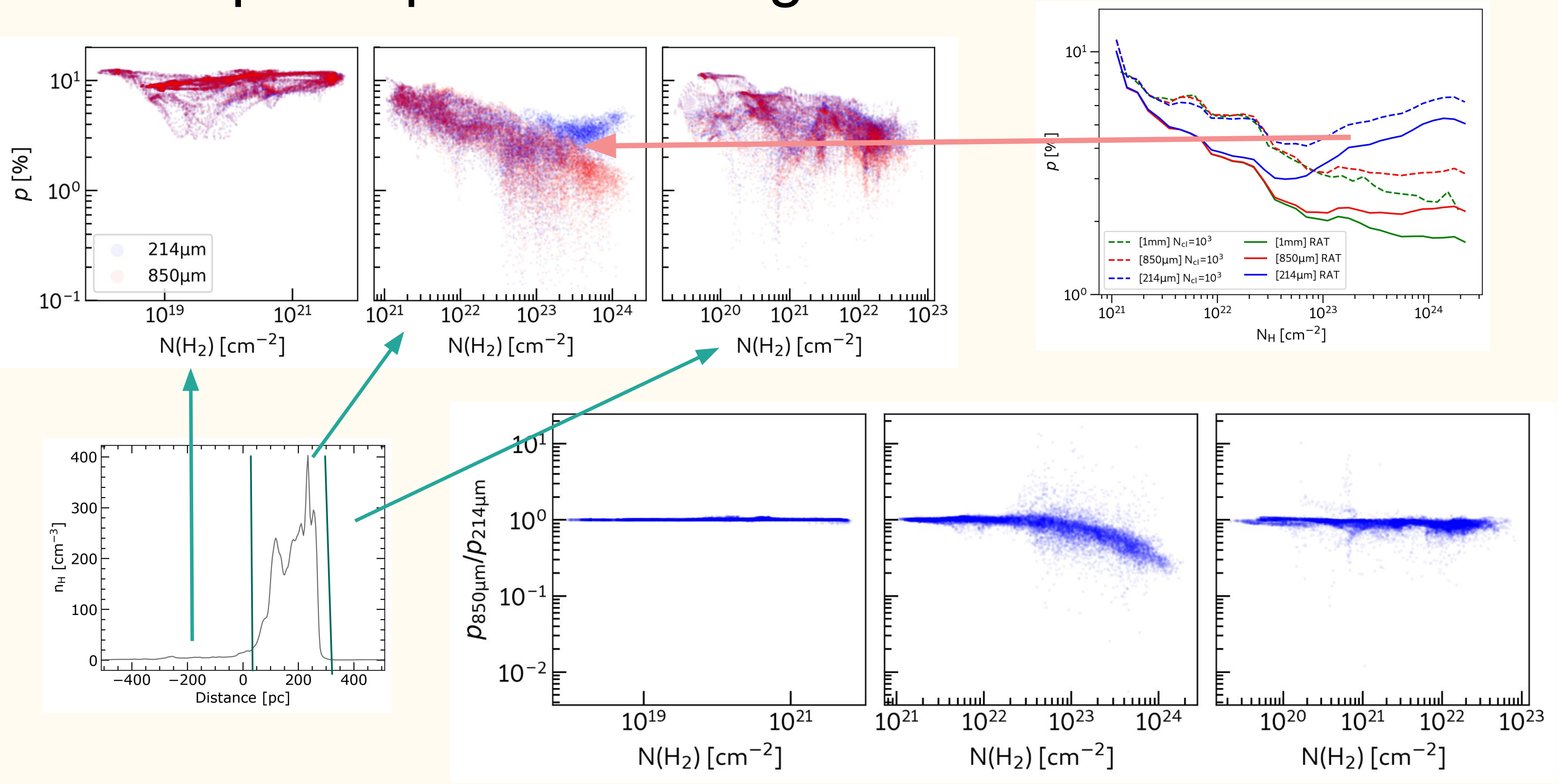
Constant ratio with column density: Similar alignment efficiency for grains traced at both wavelengths, or no significant change in grain size/composition.

Grain alignment is more strongly suppressed for smaller grains (traced at shorter wavelengths) as regions become denser.

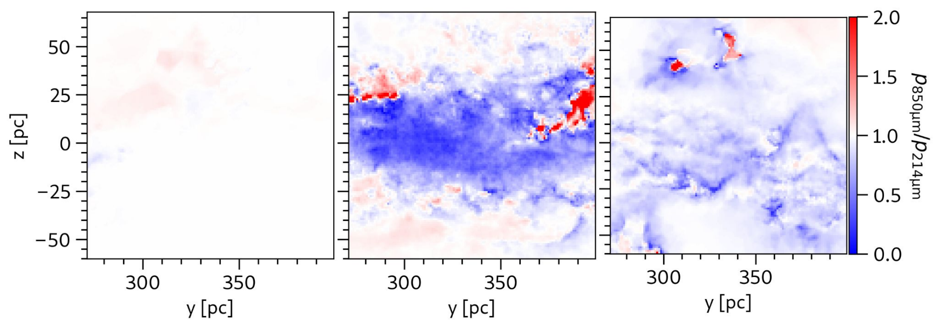
Less radiation penetrates dense clouds, reducing alignment especially for smaller grains [large a_{align} at high N(H_2)].
Ideally the ratio must **rise with column density** as RATs shut down for the small grains first.

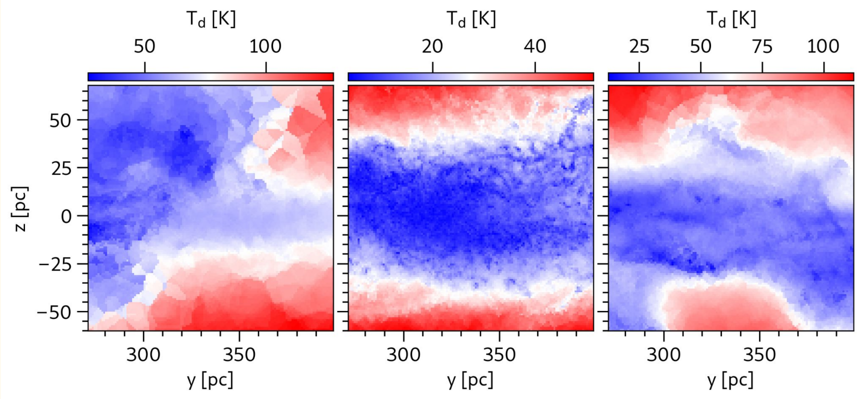
The **absolute polarized emission** (not just alignment efficiency) is intrinsically higher at the shorter wavelength.

Break up components along the LOS



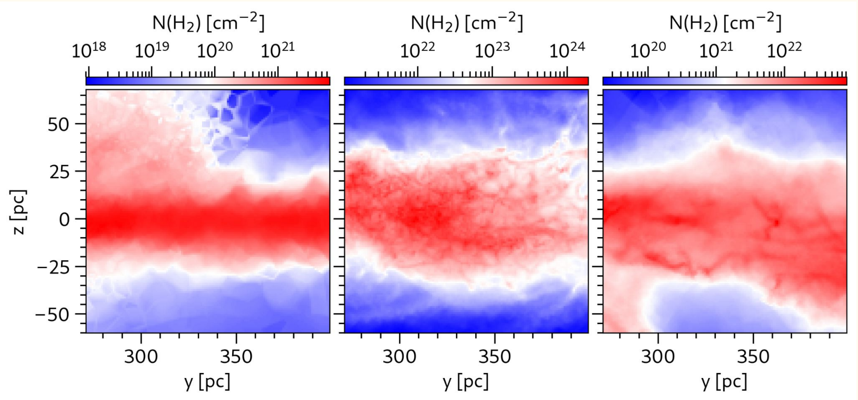
Local environment of individual components



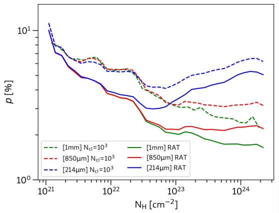


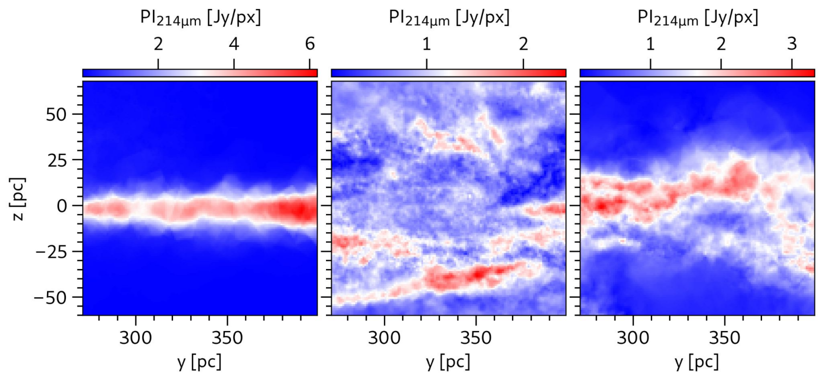
High polarization observed at 214μm coming from the surface of the high density region.

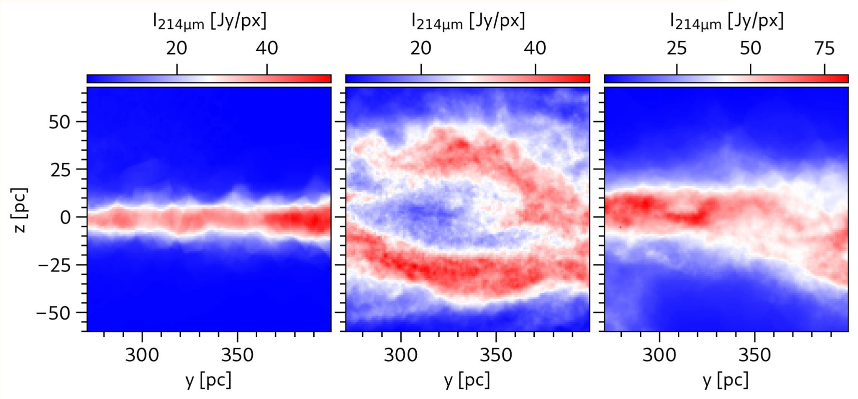
Since it is not tracing the emission from low temperature regions, the integrated polarization is much higher.

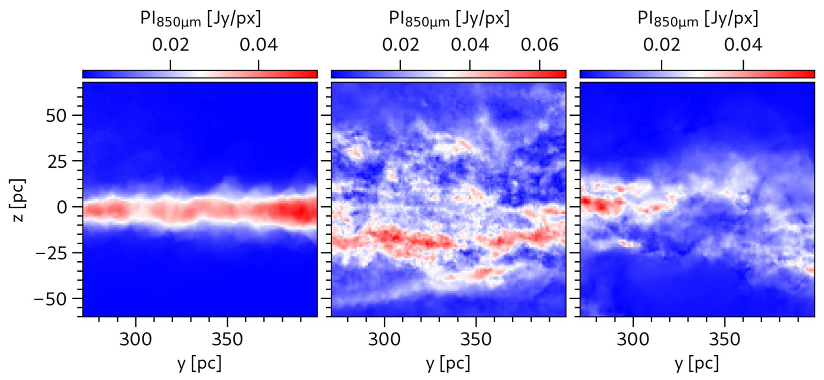


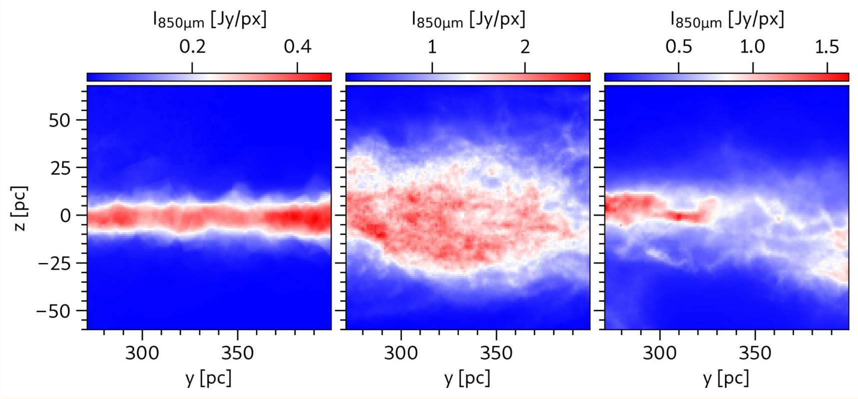
Polarized intensity at different wavelengths



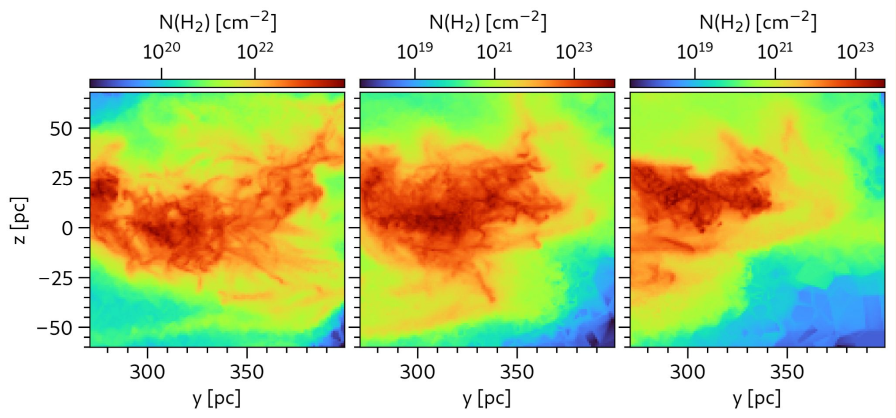


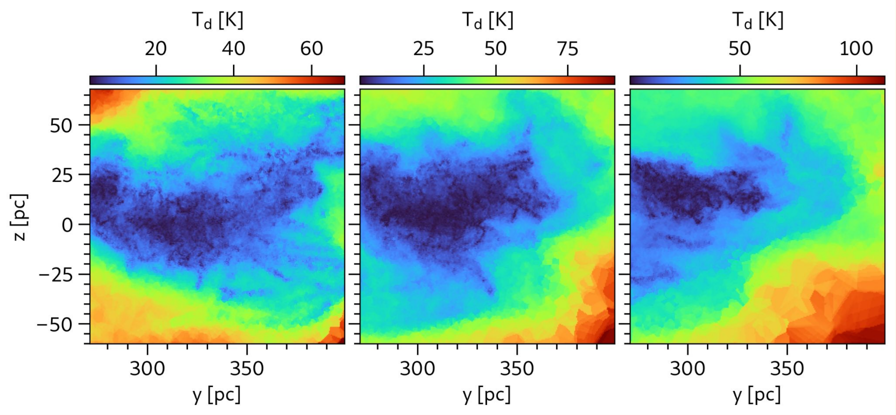


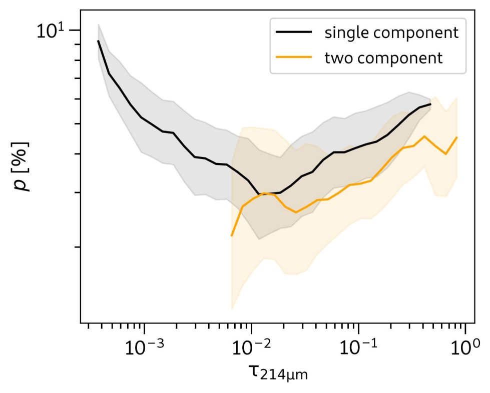




Interstellar Radiation Field: The radiation source

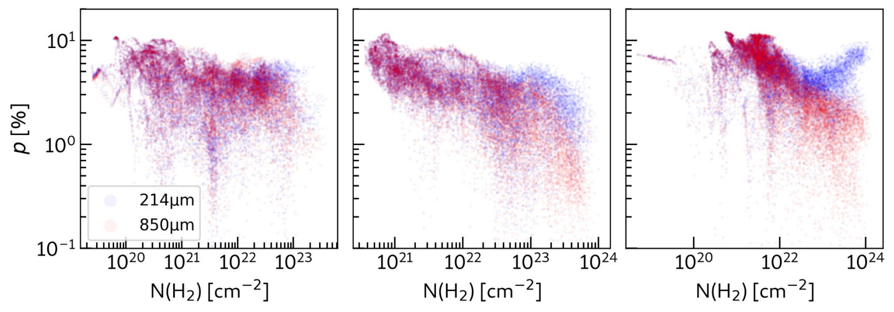




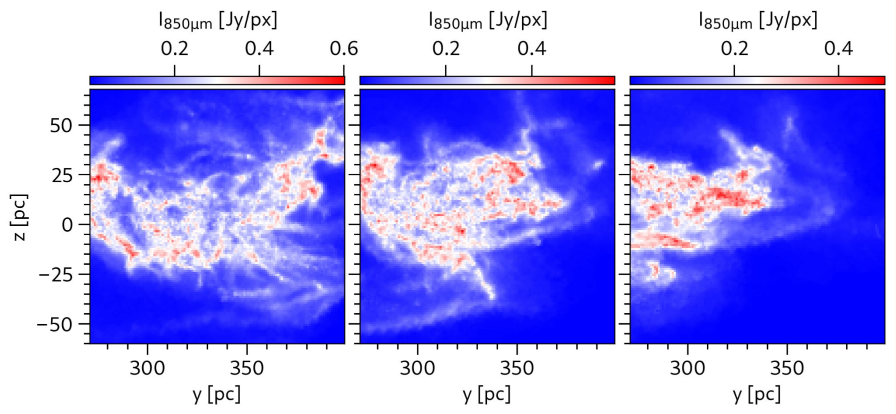


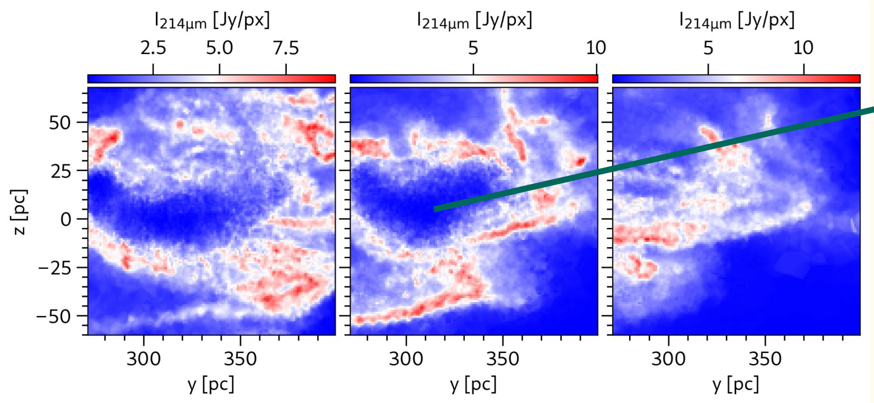
Even at low optical depth the shorter wavelength does not trace the completed column along the LOS.

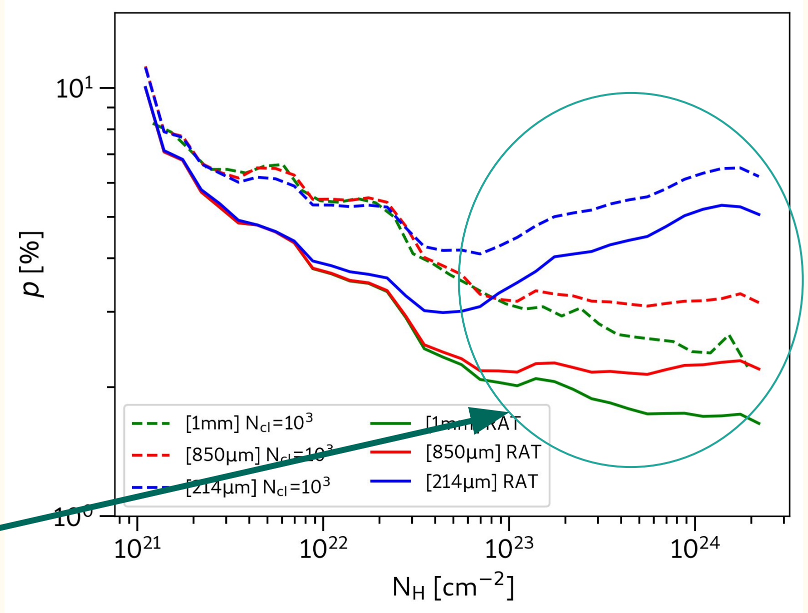
Limitation of using only ISRF as the radiation source.



Polarization well traced at lower column densities



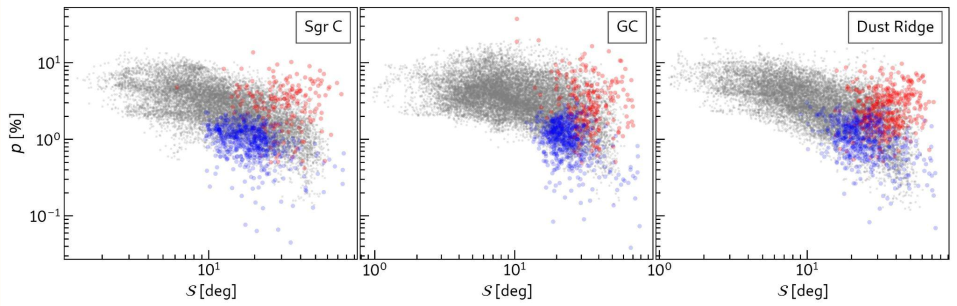


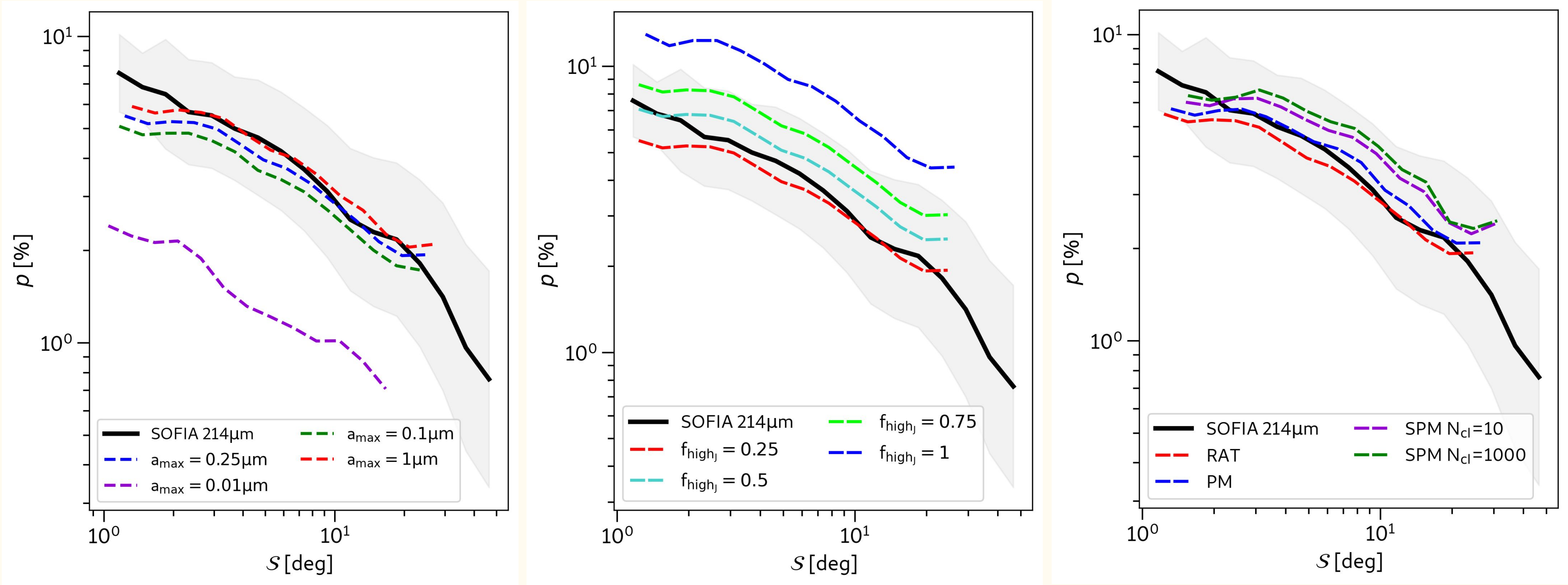


Our synthetic models at first glance, can reproduce the level of polarization observed at low column densities [$N(H_2) < 10^{23}$ cm^{-2}] in CMZ like environments.

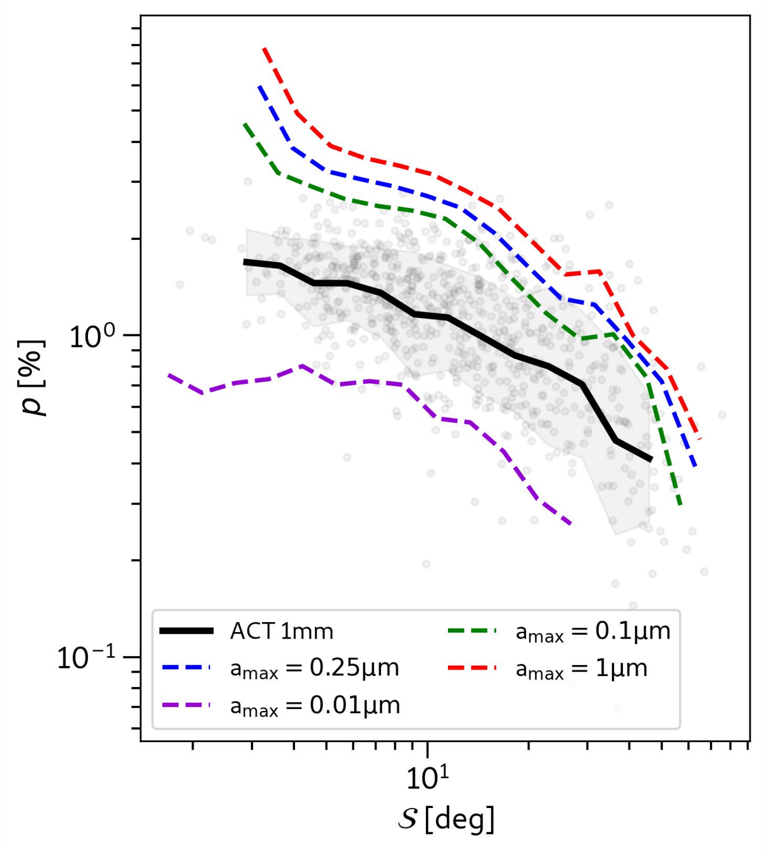
Polarization degree: Data vs Synthetic observations

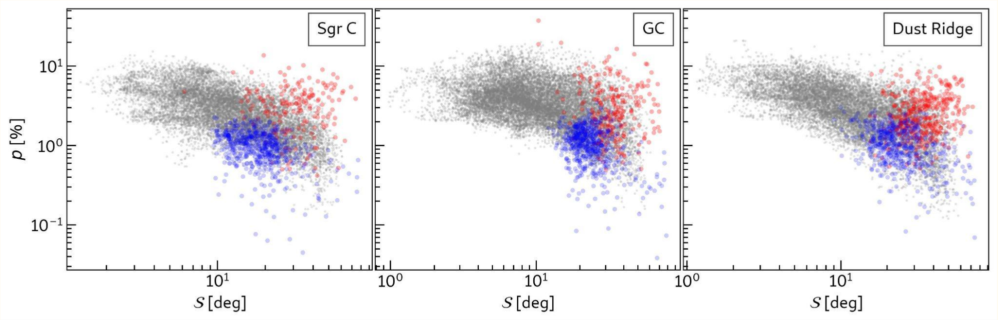
Observed polarization degree can be reproduced with RATs with grain sizes of about 0.25 - 1μm.





Low polarization observed at 1mm





Might suggest the absence of larger grains that primarily emit at longer wavelengths

Conclusions

- Observed level of polarization at 214μm can be explained through RAT with dust grains of size 0.25 - 1μm.
- 1mm dust polarization too low compared to model predictions, could indicate absence of large dust grains.
- Polarization pattern shows uniform magnetic field, does not match the B-fields very well in dense regions.
- No change in polarization pattern with wavelength.

Next steps:

- Improve radiation field for MCRT calculation.
- Reconstruct 3D B-field from polarization maps.
- Test validity of DCF in multi-component complex environments.

Thank you