Understanding of Linear Dust Polarization

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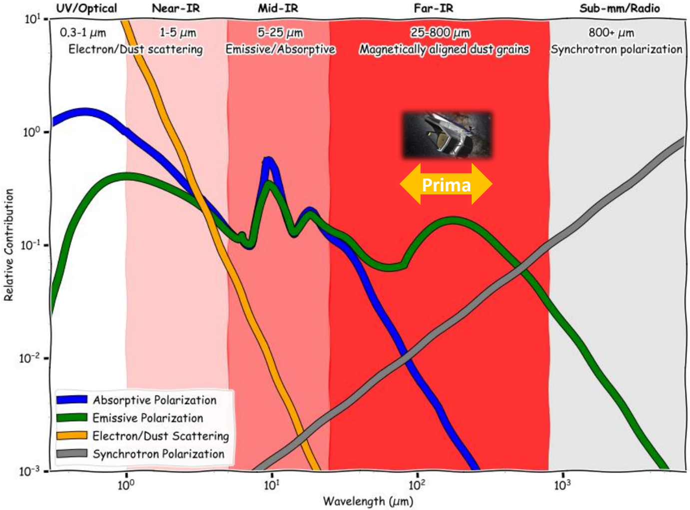
On behalf of

Grain Alignment and Dust Evolution Physics with Polarisation (GRADE-POL)

Le N. Tram (PI), Thiem Hoang (co-PI), Alex Lazarian, B-G Andersson, Enrique Lopez-Rodriguez, Thurshara Pillai, Archana Soam, Daniel Seifried, Brandon Hensley, Pham N. Diep, Nguyen C. Giang, Lapo Fanciullo, Nguyen B. Ngoc

PRIMA conference, Marseille, France

Polarization Spectrum (toy model)



Modification from E. Lopez-Rodriguez's toy model

Dust Polarization to Grain Properties + 3D-Bfield

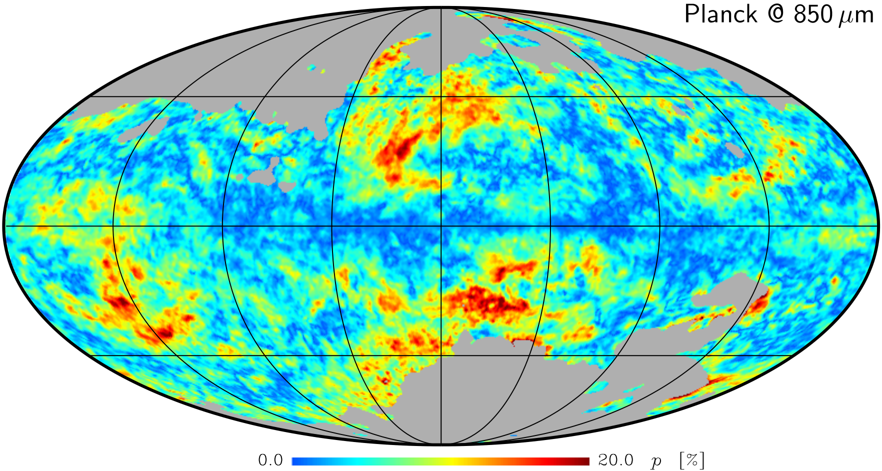
Degree of Dust Polarization = Intrinsic dust properties + Grain alignment Physics + Magnetic turbulence (2D) + 3D Magnetic Field (3D)

- Degree of Dust Polarization ← Observations
- Intrinsic dust properties ← Size, shape, composition, etc.
- Grain alignment Physics ← Theories of grain alignment
- Magnetic turbulence (2D) ← polarization angle dispersion (obs.)
- 3D Magnetic Field (3D) ← B-field incl. angle

- Dust Polarization provides insights into dust's physical properties and compositions
- Dust Polarization provides insights into 3D-magnetic fields

➡ Understanding of physics of alignment mechanisms is the key

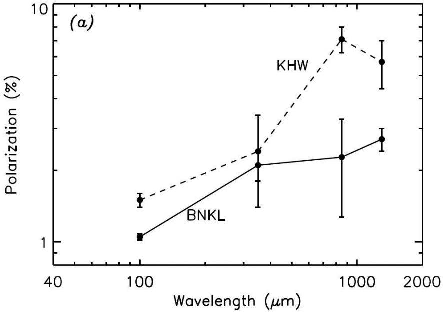
Polarized Thermal Dust Emission seen by Planck



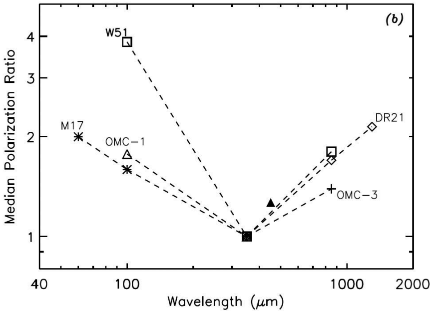
Planck collaboration XIX (2015)

Polarized Thermal Dust Emission in multiple wavelengths

Two cloud cores in OMC
(monotonic-increasing spectra)

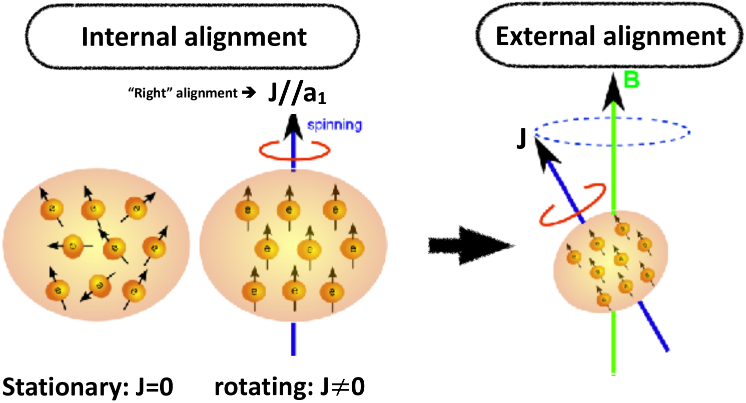


Different Clouds
(V-shape spectra)



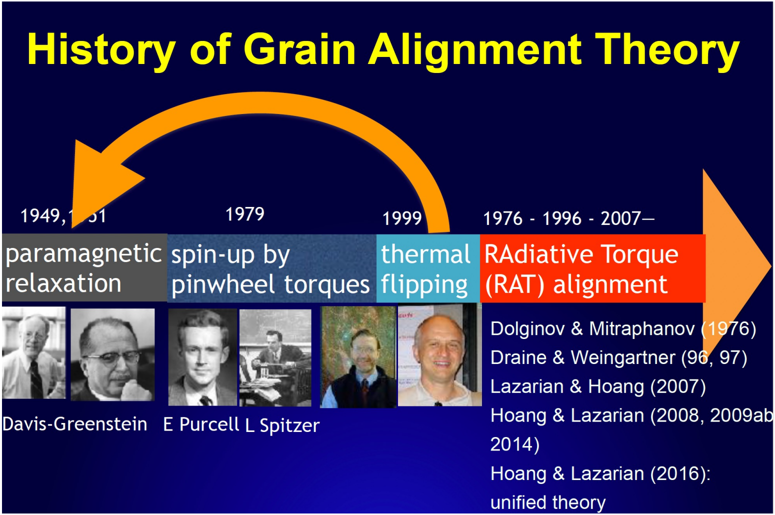
see Hilderbrand et al. 2000, Vaillancourt et al. 2008

Alignment Mechanisms[1] in a Nutshell (Ideal case)



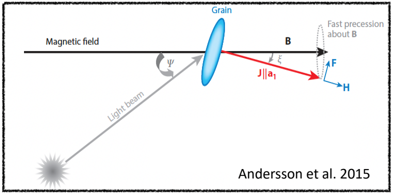
[1] Only considering paramagnetic grains (e.g., astrosilicate)
Disregarding diamagnetic grains (e.g., carbonaceous)

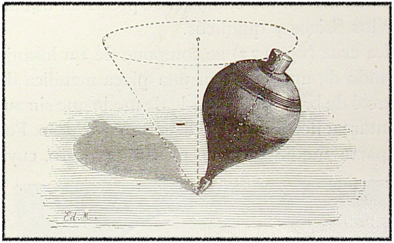
Alignment Mechanisms of Grains – What do we know?



Adopted from Thiem Hoang presentation

Radiative Torque Alignment (RAT-A) Theory

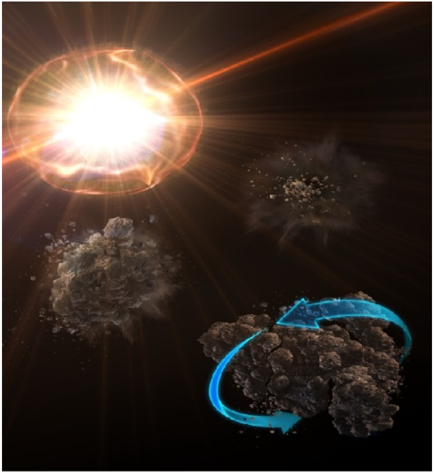




- Anisotropic radiation field causes irregular grains to rotate (Dolginov & Mitrofanov, 1976).
- Rotation damped by gas collisions and dust re-emission
- Internal alignment due to Barnett relaxation (Barnett, 1909)
- Alignment with external B-field due to DG mechanism and "F" component of RATs.

➡ RAT's predictions are successfully tested by observations
(e.g., reviews in Andersson et al. 2015 Tram & Hoang 2022)

Radiative Torque Disruption (RAT-D) Mechanism



Hoang, Tram et al. 2019, Nature Astronomy
Hoang, 2020
Lazarian & Hoang, 2021
Tram & Hoang, 2022

Table 2 | Characteristic timescales of dust destruction by different mechanisms

Mechanisms	Timescales (yr)
RATD	$1.0 a_{-5}^{-0.7} \bar{\lambda}_{0.5}^{1.7} U_6^{-1} S_{\max,9}^{1/2}$
Thermal sputtering	$9.8\times10^{3} a_{-5} n_1^{-1} T_6^{-1/2} (0.1/Y_{sp})$
Non-thermal sputtering	$5.7\times10^{3} \hat{\rho} a_{-5} n_1^{-1} v_{\rm drift,3}^{-1} (0.1/Y_{sp})$
Grain–grain collision	$7.6\times10^{4} \hat{\rho} a_{-5} n_1^{-1} v_{\rm drift,3}^{-1}$

$a_{-5}=a/(10^{-5}\,{\rm cm})$, $U_6=U/10^6$ $S_{\max,9}=S_{\max}/(10^9\,{\rm erg\,cm^{-3}})$ $n_1=n_{\rm H}/(10\,{\rm cm^{-3}})$, $T_6=T_{\rm gas}/(10^6\,{\rm K})$ $v_{\rm drift,3}=v_{\rm drift}/(10^3\,{\rm km\,s^{-1}})$, and Y_{sp} is the sputtering yield.

- RAT-D: large grains $\rightarrow$ smaller species
- RAT-D is far more efficient for $a > 0.1\,\mu$m and $U \gg 1$
- Disruption efficiency depends on the gas density, radiation strength, and grain porosity
- Disruption affects on the largest grains $\rightarrow$ modification of the grain-size distribution

RAT paradigm = RAT-A + RAT-D

Novel Computational Models for Dust Polarization

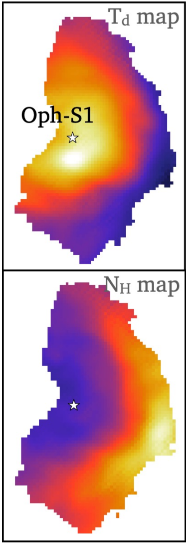
(First part)	(Second part)
DustPOL-py[2]	POLARIS+[3]
(0-D and 1-D and 2-D)	(2-D and 3-D)
(Tram et al. 2021,2024,2025)	(Giang, Hoang, Kim & Tram, 2023)
– B-RAT paradigm	– B-/k- RAT paradigm
//	– dust self-scattering
– multi-wavelength	– multi-wavelength
– perfect alignment (ideal)	– IA and EA physics (more realistic)
– uniform B-field (POS and inclined)	– arbitrary B-field (e.g., from MHD)
– (simple) radiative transfer	– (complex) radiative transfer
– pol. degree	– pol. degree & pol. angle
– single-dish obs.	– single-dish and interferometry obs.

[2] https://github.com/lengoctram/DustPOL-py

[3] Initially developed by Reissl et al. 2016, Update version: link

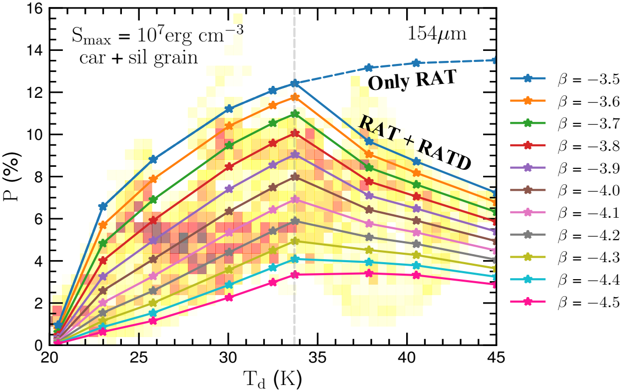
Dust Polarization in Ophiuchus: RAT-D effect

ρ Oph-A cloud



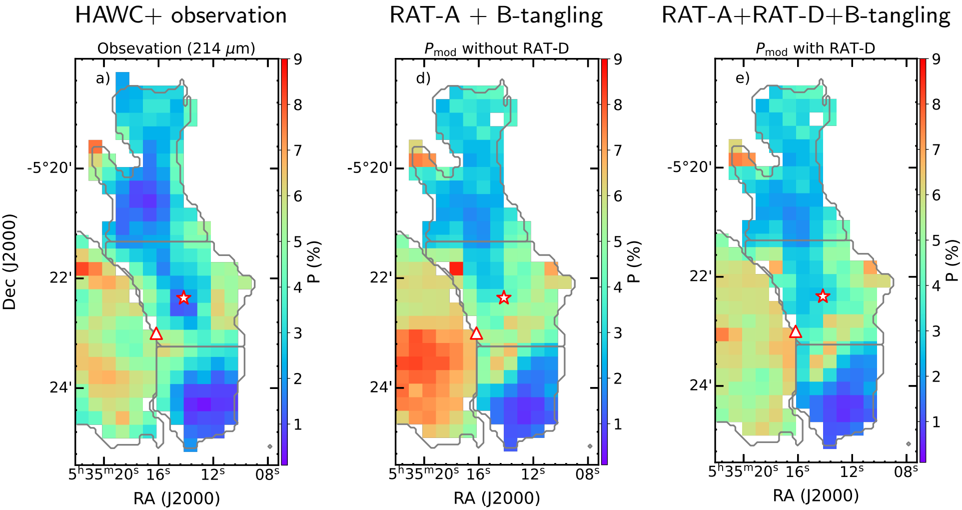
Santos et al. (2019)

SOFIA/HAWC+ @14”



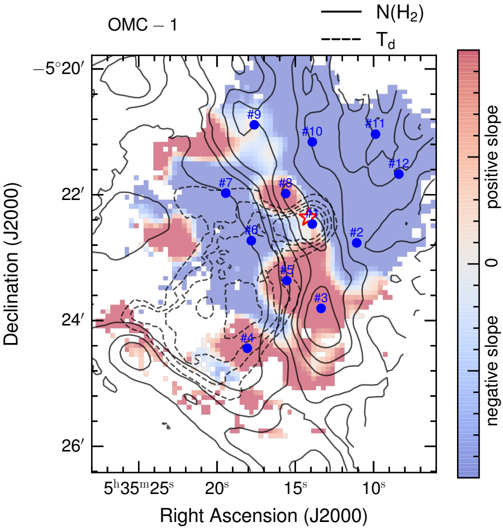
Tram et al. (2021a)

Dust Polarization in Orion: RAT-D and B-field tangling



Ngoc, Diep, Hoang & Tram (2024)

Multiple-wavelength Dust Polarization: OMC-1

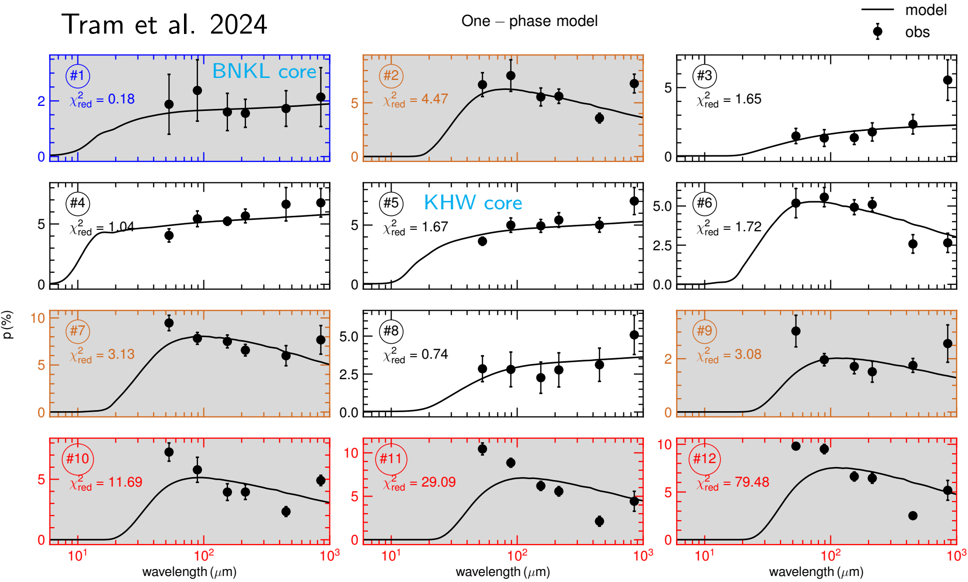


Tram et al. 2024

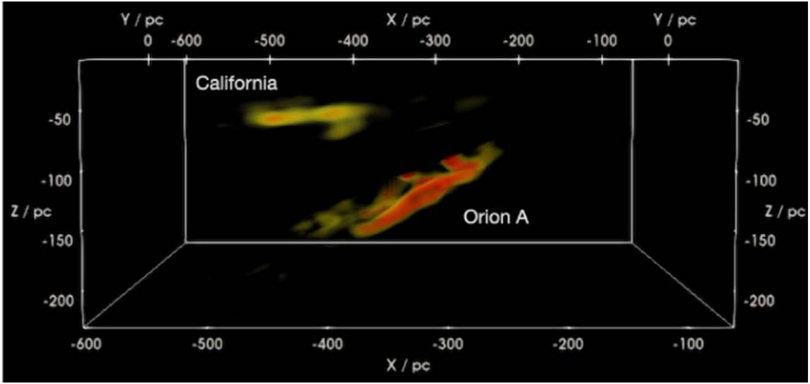
- pol. spectrum
  - 54, 89, 154, 214 μm with SOFIA/HAWC+ (Chuss+2019; Michail+2021)
  - 450, and 850 μm with JCMT/Pol-2 (Hwang+21)
- Spectrum slope: straight-line fitting ...
- Raising spectrum in dense region
- Falling spectrum in warm region

Multiple-wavelength Dust Polarization: One-layer Dust

Tram et al. 2024



Multiple Dust Layers toward Orion-A

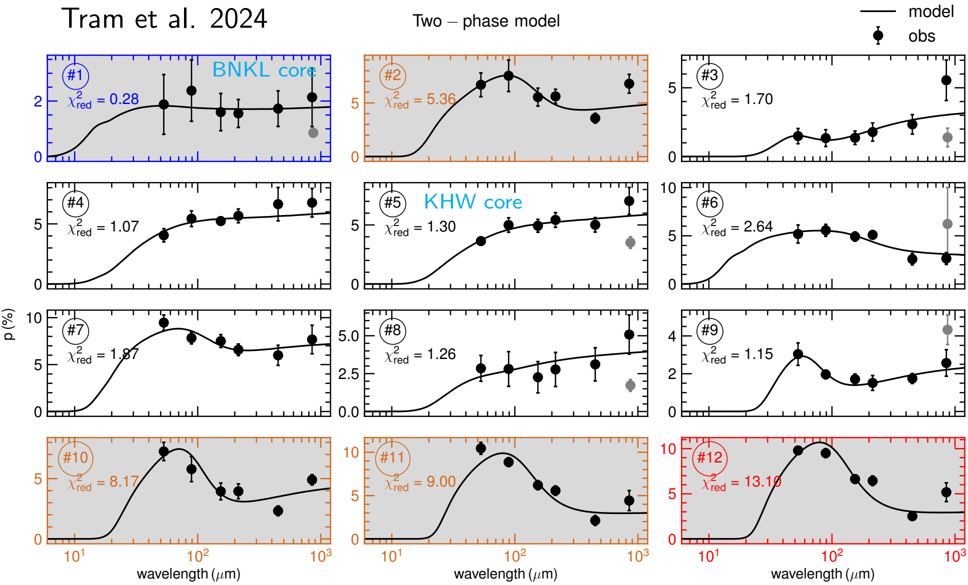


Rezaei & Kainulainen, 2022

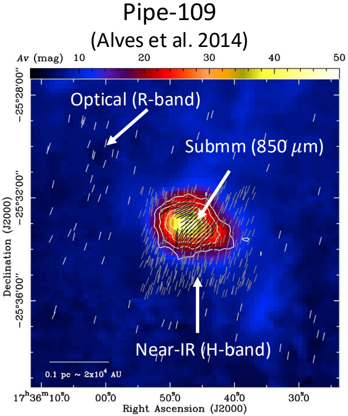
- 3D Structure of OMC-A in dust shows "two dust layers" (Rezaei & Kainulainen, 2022)
- Potential contribution of multiple-dust components in $p(\%)$!

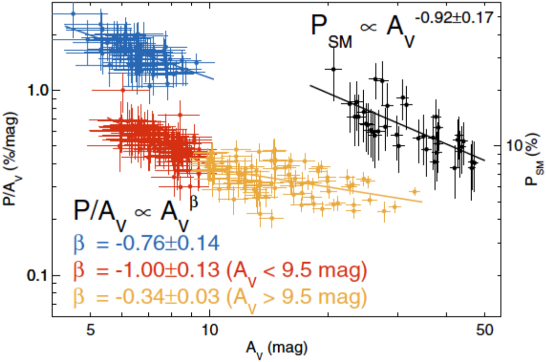
Multiple-wavelength Dust Polarization: Multi-layers Dust

Tram et al. 2024



Dust Polarization in Starless Cores: Grain growth effect

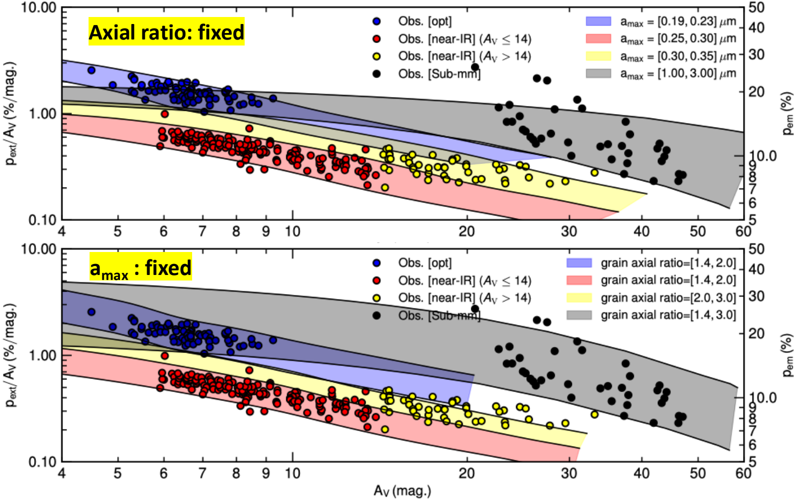




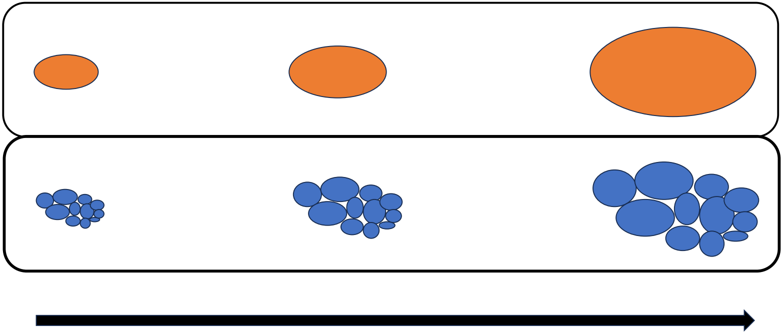
- R-band and H-band: OPD/LNA (in Brazil)
- 850 μm: APEX/PolKa (in Chile)

Dust Polarization in Starless Cores: Grain growth effect

DustPOL-py in 3D (Tram et al. 2025)



Anisotropic grain growth !? (first evidence – biased speaking)

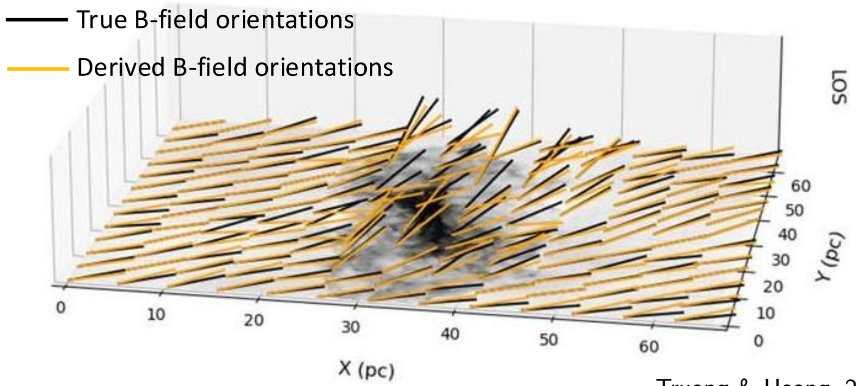


Visual extinctions (Av)

Universal?

- Anisotropic grain growth induced by magnetic grain alignment
- Icy mental?
- Compact vs. Porous vs. Composition: PRIMA + JWST

Dust Polarization to Characterizations 3D Magnetic Field



Truong & Hoang, 2025

- pol. angle → plane-of-sky B-field (2D)
- pol. degree → B-field's incl. angle (3D)
  (starlight + thermal pol.)

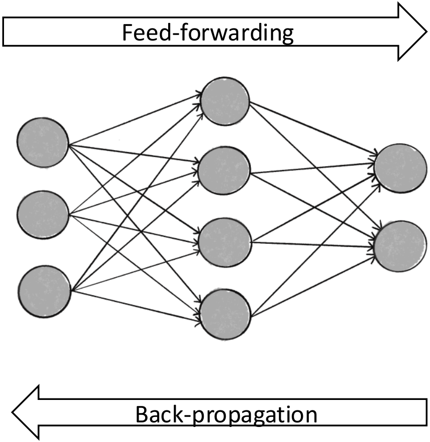
Dust Polarization to Dust Properties and 3D B-fields

Input

DustPOL-py

Deep learning models
(Neural network, CNN, Vision transformer)

Predictive Output



3D B-fields
($\gamma_{\rm obs}$)

at once

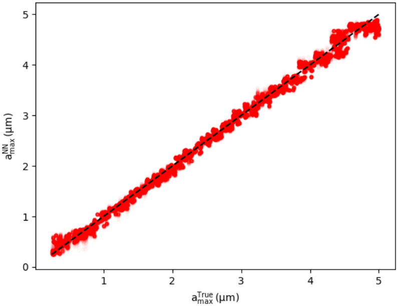
Dust
properties
($a_{\rm max}$, s)

Bao Truong (PhD at KASI, South Korea)

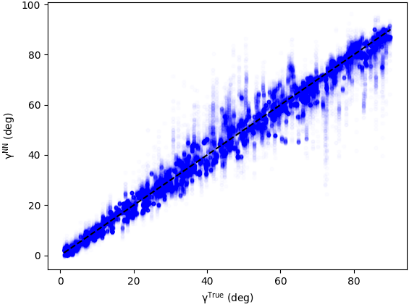
Dust Polarization to Dust Properties and 3D B-fields

Preliminary

$a_{\rm max}^{\rm output}$ vs. $a_{\rm max}^{\rm input}$ @ 850 μm



$\gamma_{\rm 3D-Bfield}^{\rm output}$ vs. $\gamma_{\rm 3D-Bfield}^{\rm input}$ @ 850 μm

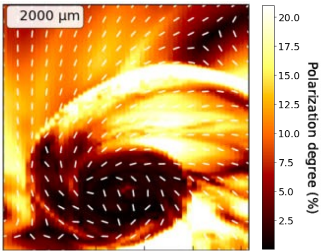


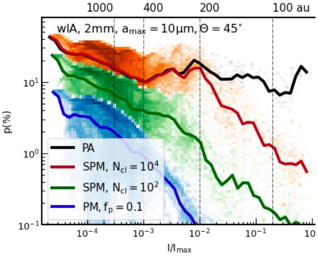
Bao Truong (PhD at KASI, South Korea)

Dust Polarization in YSOs

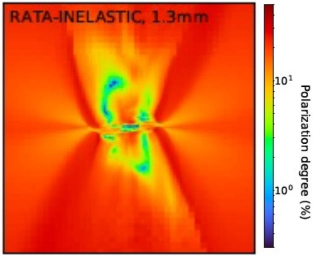
Giang & Hoang, 2024

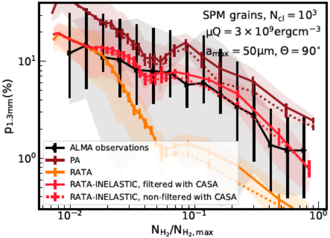
Low-mass YSOs





Intermediate-mass YSOs





Giang et al. 2024

→ SPM grains

(ion inclusions!)

→ Complex alignment

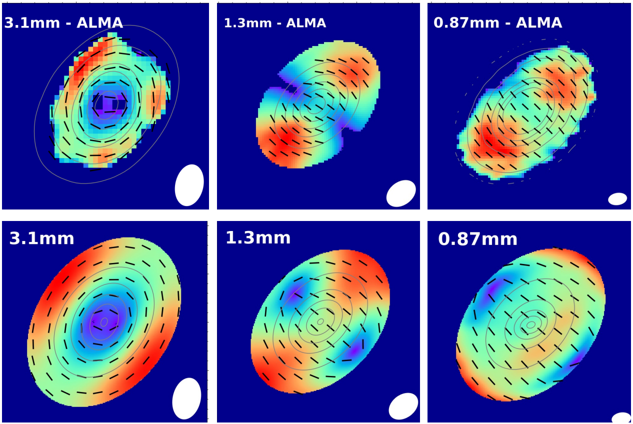
→ Large size

Dust Polarization in PPDs

Smooth physical profiles for disk

Observations (ALMA)

Simulations (POLARIS+)

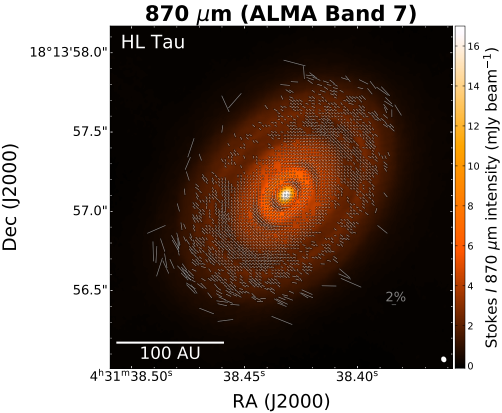


Combination of RATs and self-scattering

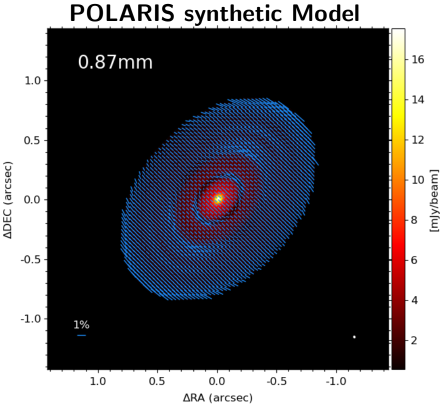
Nguyen Tat (incl. Tram) et al. 2024

Dust Polarization in PPDs

Ring/Grap physical profiles for disk



Stephens et al. 2023



Nguyen Tat (incl. Tram) et al. 2024

Do we completely understand dust polarization?

My answer: **NOT YET**

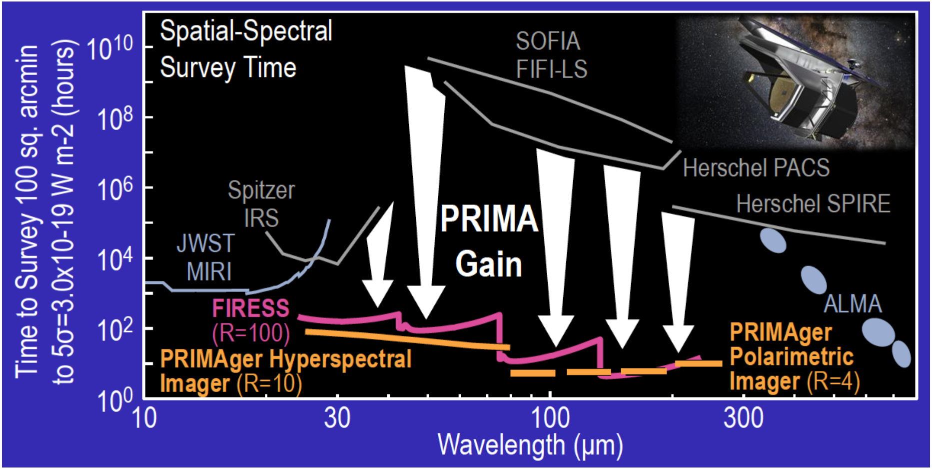
1. Simple DustPOL-py as a promising tool for understanding single-dish observations
2. Sophisticated POLARIS+ as a promising tool for interferometric observations

More works ...

1. More FIR-polarization observations in syns. with
   UV (PUFFINS, POLLUX), NIR (Keck, ...), Sub-mm (POL-2), MM (NIKA-2, ATLast, ...)
2. Dust polarization spectrum, extinction curve and SED
3. Grain properties in extra-galaxies?
4. Dynamics and alignment of fluffy/aggregated grains (Tram et al., in progress...)
5. Rotation and Disruption by Mechanical Torque (MET) (Tram et al., in progress ...)
6. Alignment of carbonaceous grains (Hoang, Minh & Tram 2023, , more works required ...)
7. Complex grain compositions proposed from lab experiments (Demyk et al. 2017a,b)

   ...

∞ Not known yet!

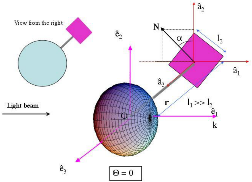


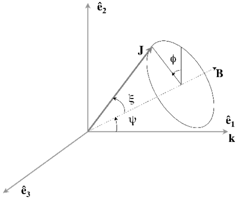
Thank you for your attention!

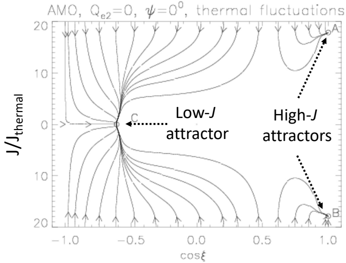
Back ups

Modelings on Rotation of Interstellar Dust Grains by Radiation

Analytical model (AMO)

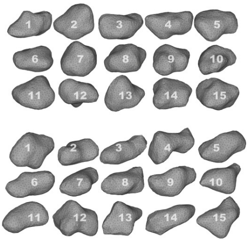






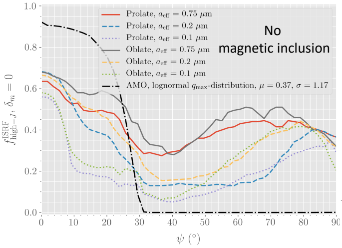
Lazarian & Hoang, 2007a

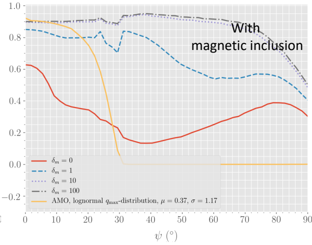
Numerical model



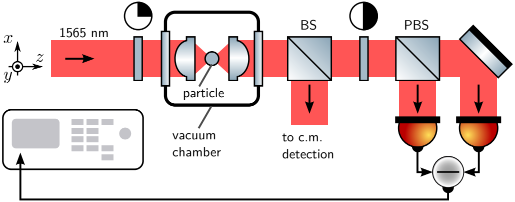
Herranen et al. 2021

Fraction at high-J





Lab. Experiments on Supra-thermal Rotation of Grains



Ahn et al. 2018
Reimann et al. 2018