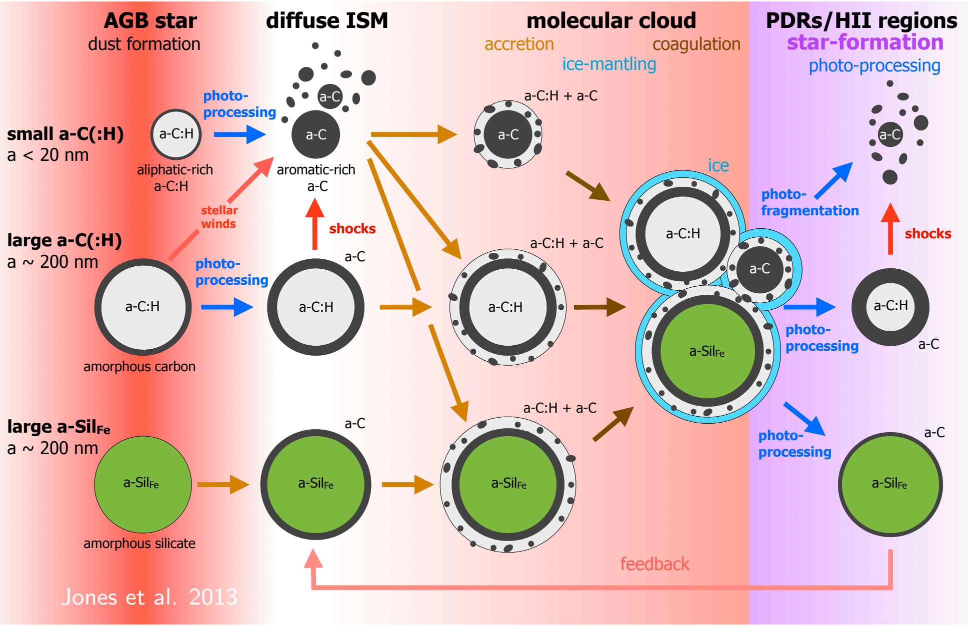
Dust Polarization and Radiative Torque Paradigm: Observations meet Theories

Le Ngoc Tram

Max-Planck-Institute for Radio Astronomy, Bonn, Germany
nle@mpifr-bonn.mpg.de

In collaboration with Thiem Hoang (KASI, Korea)
Pham Ngoc Diep (VNSC, Vietnam)
Nguyen Bich Ngoc (VNSC, Vietnam)
Ngan Le (SAGI, Vietnam)
Nguyen Chau Giang (KASI, Korea)
Nguyen Tat Thang (VNSC/USTH, Vietnam)


AGB star
dust formation
diffuse ISM
molecular cloud
accretion
coagulation
ice-mantling
PDRs/HII regions
star-formation
photo-processing
small a-C(:H)
a < 20 nm
a-C:H
aliphatic-rich
a-C:H
photo-
processing
a-C
a-C
aromatic-rich
a-C
a-C:H + a-C
a-C
stellar
winds
large a-C(:H)
a ~ 200 nm
a-C:H
amorphous carbon
photo-
processing
shocks
a-C
a-C:H
a-C:H + a-C
a-C:H
ice
a-C:H
a-C
a-SilFe
photo-
fragmentation
shocks
photo-
processing
a-C:H
a-C
large a-SilFe
a ~ 200 nm
a-SilFe
amorphous silicate
a-C
a-SilFe
a-C:H + a-C
a-SilFe
photo-
processing
a-C
a-SilFe
feedback
Jones et al. 2013

Galactic Starlight Polarization

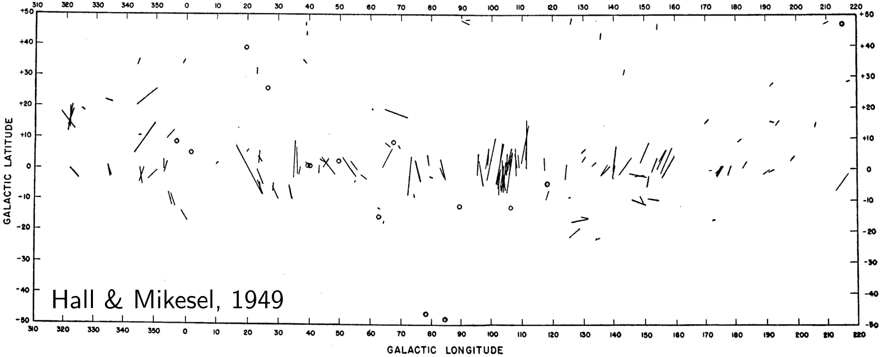
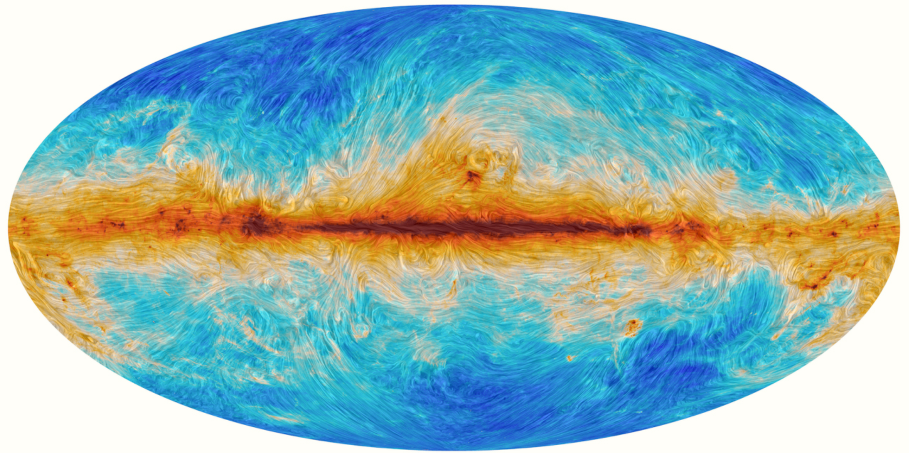


Figure 1. Vector diagram showing polarization of individual stars.

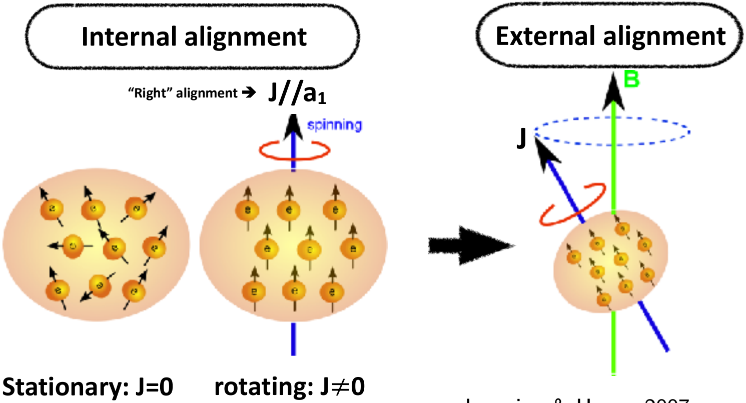
Galactic Thermal Dust Polarization



Planck Whole Sky Survey

https://www.ias.u-psud.fr/soler/planckhighlights.html

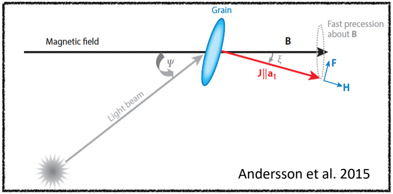
Grain Rotation and Alignment Physics of Dust Grains[1]

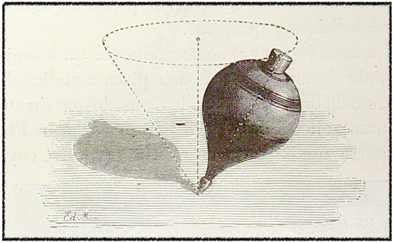


Lazarian & Hoang 2007
Andersson et al. 2015
Lazarian & Hoang, 2021
Tram & Hoang, 2022
Hoang, Tram et al. 2022

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

Radiative Torque Alignment (RAT-A) Theory

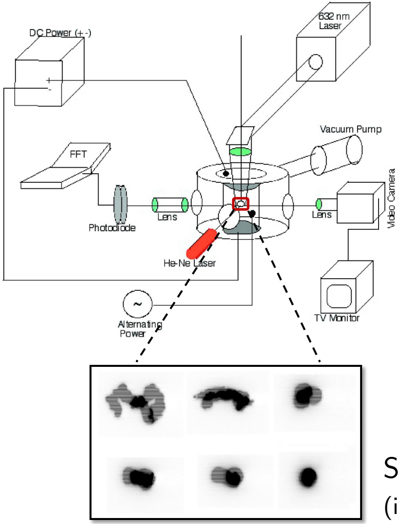


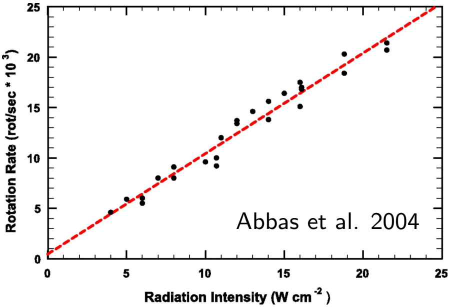


- Anisotropic radiation field causes irregular grains to rotate (Dolginov & Mitrofanov, 1976).
- Rotation damped by gas collisions and dust re-emission
- Internal alignment due to Barnett relaxation (Barnett, 1909)
- Alignment with external B-field due to DG mechanism and "F" component of RATs.

➡ RAT's predictions are successfully tested by observations (e.g., Andersson et al. 2015)

Laboratory Experiments on Rotation of Interstellar Dust Grains by Radiation

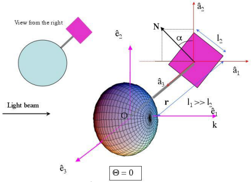




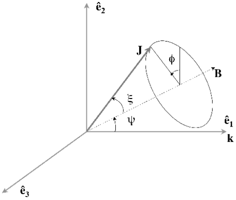
Snapshots of grain rotation
(in 40s with 8s interval)

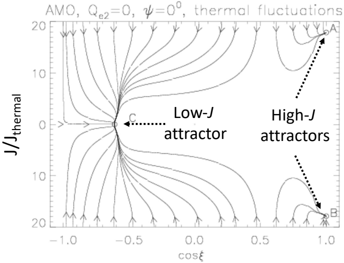
Modelings on Rotation of Interstellar Dust Grains by Radiation

Analytical model (AMO)

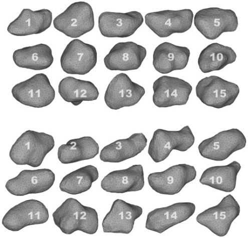


Lazarian & Hoang, 2007a



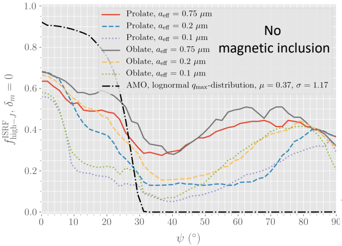


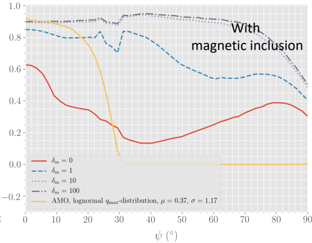
Numerical model



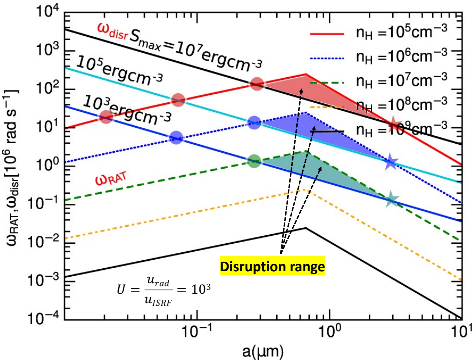
Herranen et al. 2021

Fraction at high-J





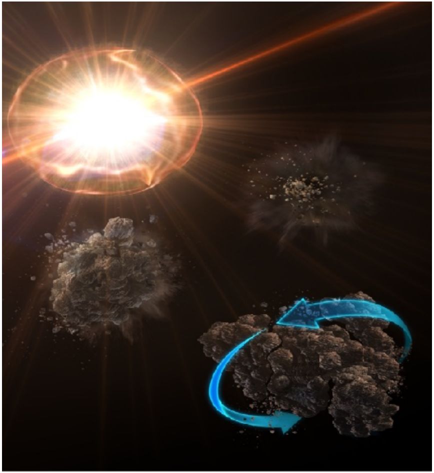
Large Grains' Angular Velocity and Disruption of Size



Hoang & Tram, 2020

- Angular velocity by RATs
  - $\omega_{\rm RAT} \sim a^{1/7}$ for $a < \bar{\lambda}/1.8$
  - $\omega_{\rm RAT} \sim a^{-1}$ for $a > \bar{\lambda}/1.8$
- Induced centrifugal stress
  - $S \sim \omega^2 a^2 \rightarrow \omega_{\rm crit} \sim S_{\rm max}^{1/2}/a$
- Rotational Disruption occurs
  - $\omega_{\rm RAT} \geq \omega_{\rm crit}$
- Grain's Internal Structure
  - $S_{\rm max} \simeq 10^6 - 10^8$: composite
  - $S_{\rm max} \simeq 10^9 - 10^{10}$: compact
  - $S_{\rm max} \simeq 10^{11}$: ideal material

Radiative Torque Disruption Efficiency



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

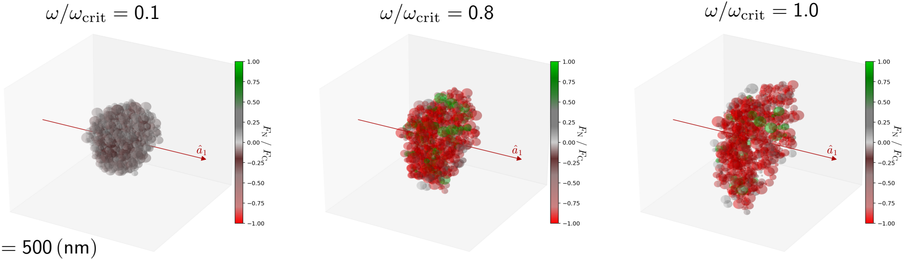
Mechanisms	Timescales (yr)
RATD	$1.0a_{-5}^{-0.7}\bar{\lambda}_{0.5}^{1.7}U_6^{-1}S_{\max,9}^{1/2}$
Thermal sputtering	$9.8\times10^{3}a_{-5}n_1^{-1}T_6^{-1/2}(0.1/Y_{sp})$
Non-thermal sputtering	$5.7\times10^{3}\hat{\rho}a_{-5}n_1^{-1}v_{\rm drift,3}^{-1}(0.1/Y_{sp})$
Grain–grain collision	$7.6\times10^{4}\hat{\rho}a_{-5}n_1^{-1}v_{\rm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

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

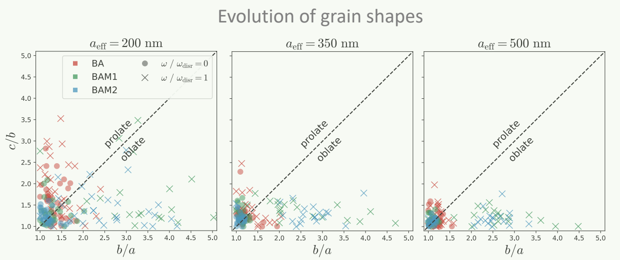
- RAT-D: large grains $\rightarrow$ smaller species
- RAT-D is far more efficient for $a > 0.1\ \mu$m and $U \gg 1$
- Disruption efficiency depends on the gas density, radiation strength, and grain porosity
- Disruption affects on the largest grains $\rightarrow$ modification of the grain-size distribution

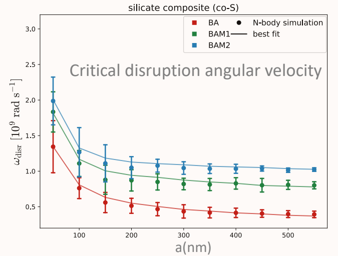
Simulations on Disruption of Porous Dust

Reissl et al. 2023

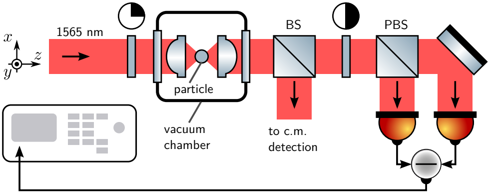


a = 500 (nm)

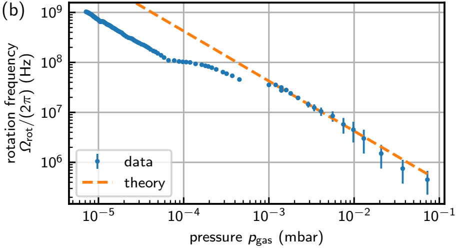




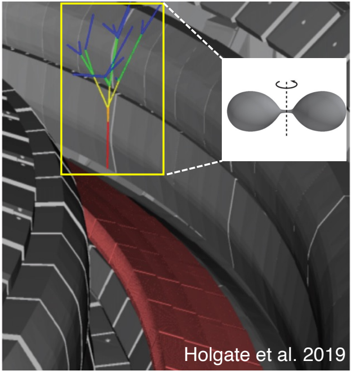
Laboratory Experiments on Disruption of Dust



Ahn et al. 2018
Reimann et al. 2018



Grain angular momentum gained by interaction with the laser field



<u>To disrupt: 10 µm tungsten droplet</u>
(surface tension 2.5N m^{-1} and density 17600 kg m^{-3})
<u>Least angular velocity: 6 x 10^5 s^{-1}</u>

Gain angular momentum from gyrating particles in the surrounding plasma

Dust Polarization Observations to Magnetic Fields

Abstract

Polarization Angle (Polarization Orientation) $\rightarrow$ B-field orientation

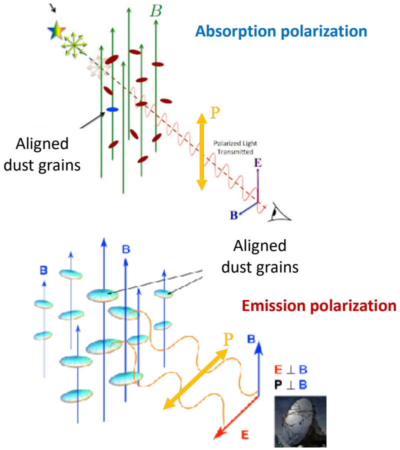
$$\theta = \frac{90}{\pi}\mathrm{arctan2}\left(\frac{\mathrm{U}}{\mathrm{Q}}\right) \quad \text{(degree)}$$

- Stokes Q and U are observed quantities

Polarization Angle + non-thermal broadening $\rightarrow$ B-field strength

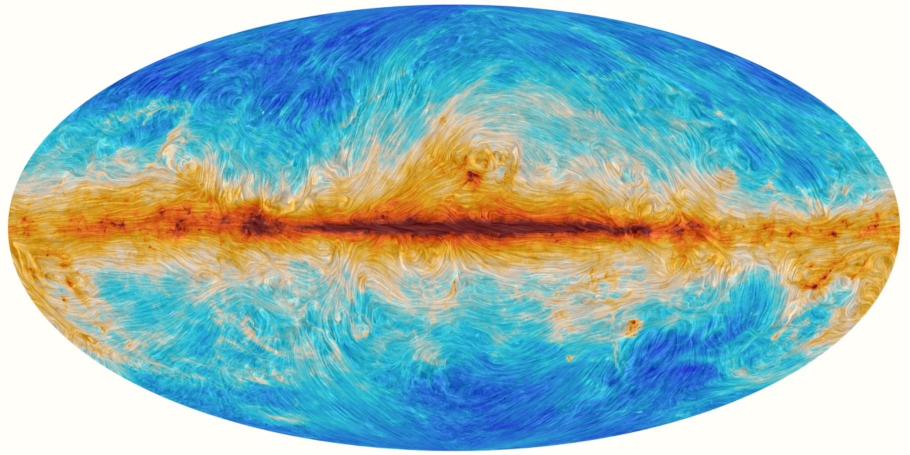
- resolved velocity profile is required (spectroscopic observations)

"Ideal" Grain Alignment → Dust Polarization → Magnetic Fields



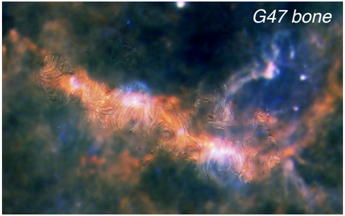
- Absorption pol. is parallel to B-fields
  - Pol. vectors → B_{POS} morphology
  - Observable at UV-NIR wavelengths
- Emission pol. is perp. to B-fields
  - Rotating the pol. vectors by 90^o → $B_{\rm POS}$ morphology
  - Observable at FIR-Submm wavelengths
- B-strength:
  - "Tradition"
    - Davis 1951; Chandrasekhar-Fermi 1953
  - "Improvement"
    - Falceta-Gonçalves et al. 2008
    - Hildebrand et al. 2009; Houde et al. 2009
    - Skalidis & Tassis 2021
    - Lazarian et al. 2022

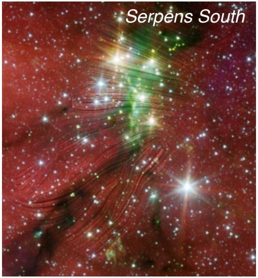
Galactic Magnetic Fields @5' with Planck

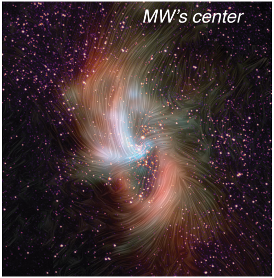


https://www.ias.u-psud.fr/soler/planckhighlights.html

Galactic Magnetic Fields with SOFIA/HAWC+

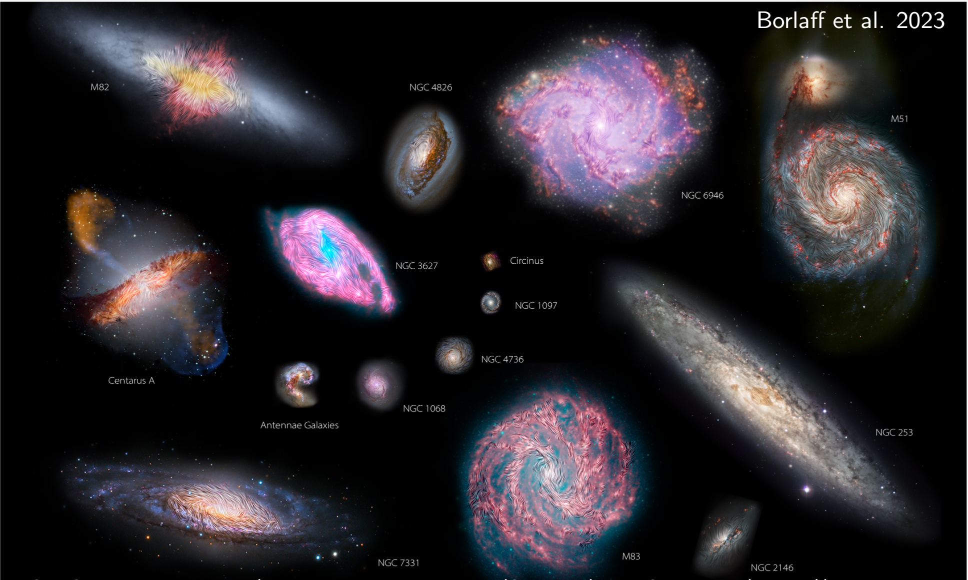






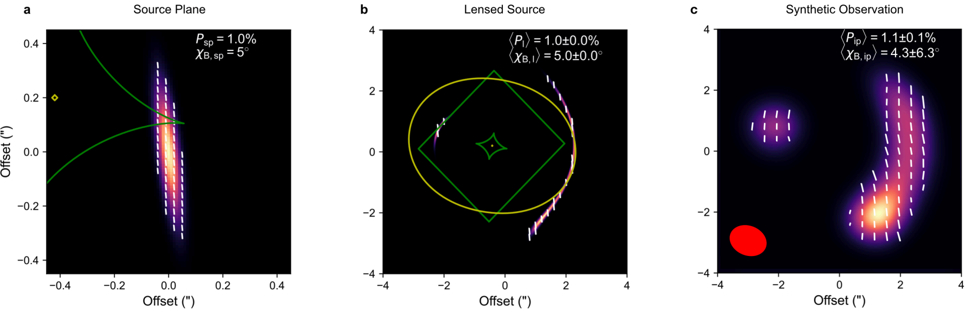
Credit: NASA/SOFIA

Extra-Galactic Magnetic Fields with SOFIA/HAWC+



SALSA Large Program (PIs: E. Lopez-Rodriguez (Stanford) and S.A. Mao (MPIfR))

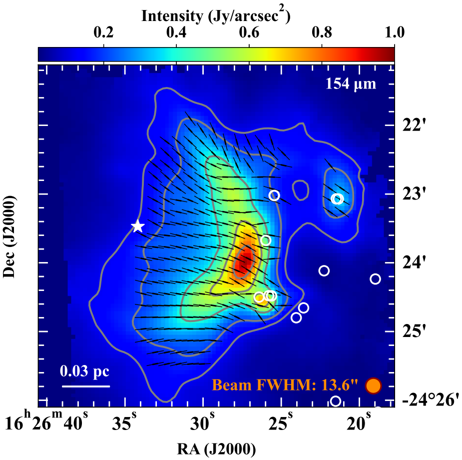
High-redshifted Galactic Magnetic Fields with ALMA



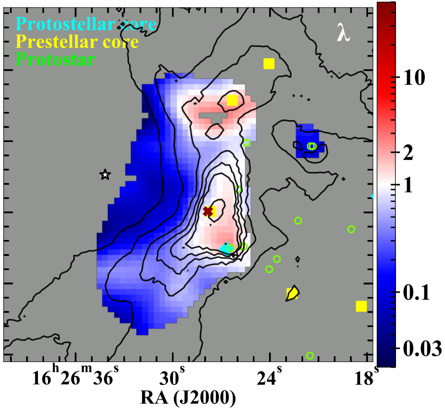
Geach et al. 2023, Nature

- Gravitationally lensed galaxy 9io9 at z=2.553,
- The polarized emission arises from the alignment of dust grains with the local magnetic field,
- 5kpc-scale ordered magnetic field with strength of $\simeq 500\mu$G.

A Case Study of Ophiuchus-A cloud



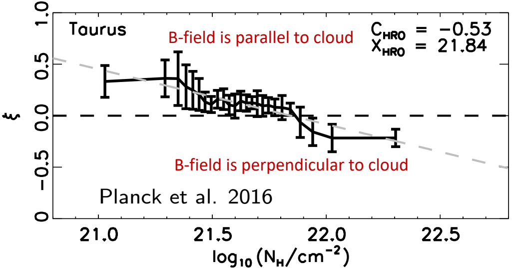
$[\lambda] = [\text{gravity}]/[\text{B} - \text{field}]$

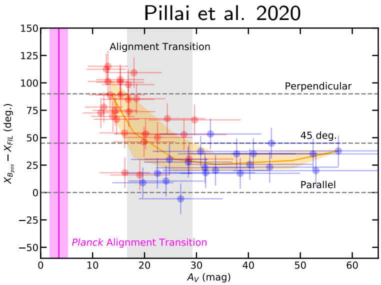


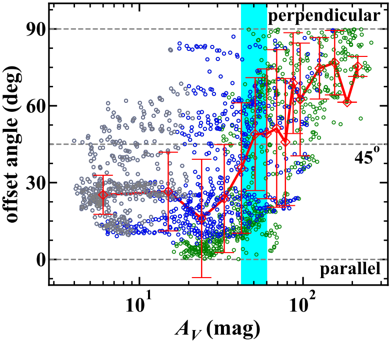
- B-field morphology → the MC's flat-shape
- Star formation occurs in $\lambda > 1$

Santos et al. 2019
Lê, Tram et al. (sub.)

Variation in B-field Orientation







Relative orientation between B-field and cloud

- Planck era: $B_{||}$ $(A_V \leq 3) \leftrightarrow B_{\perp}$ $(A_V > 3)$
- Serpens South: $B_{||}$ $(A_V \geq 21)$
- Oph-A: $B_{\perp}$ $(A_V > 40)$

Dust Polarization to Dust Properties

Abstract

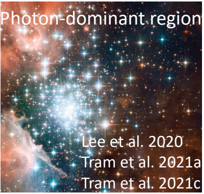
Polarization degree = Dust's intrinsic properties + ISM properties

Polarization degree : $p(\%) = 100 \times \frac{\sqrt{U^2+Q^2}}{I}$ (observable quantity)

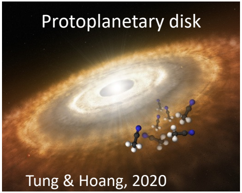
- Dust's intrinsic properties : shape, size-distribution, composition, magnetic properties
- ISM properties : density, temperature, radiation, B-field, etc.

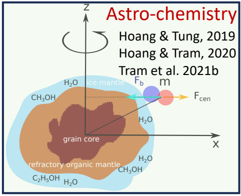
a "complete understanding" of grain alignment physics is required!

Applications in Astrophysics and Astrochemistry



Rotational Disruption



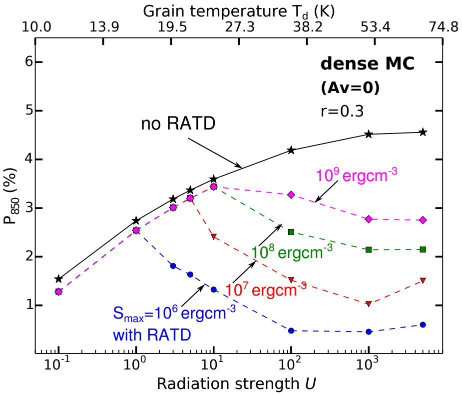


Novel Computational Models

(This talk)	(Other SAGI seminar!?)
DustPOL-py[2]	POLARIS+[3]
(0-D and 1-D)	(2-D and 3-D)
(Lee et al. 2019, Tram et al. 2021)	(Giang, Hoang, Kim & Tram, 2023)
– RAT-A, MRAT and RAT-D	– RAT-A, MRAT and RAT-D
//	– dust self-scattering
– multi-wavelength	– multi-wavelength
– perfect alignment (ideal)	– IA and EA physics (more realistic)
– uniform B-field (on POS and inclined)	– arbitrary B-field (e.g., from MHD)
– optically thin emission	– radiative transfer
– single-dish obs.	– single-dish and interferometry obs.

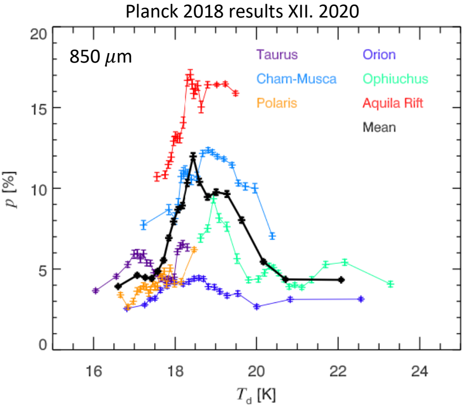
[2]https://github.com/lengoctram/DustPOL-py
[3]Initially developed by Reissl et al. 2016

Dust Polarization in Star-forming Regions: RAT-D effect



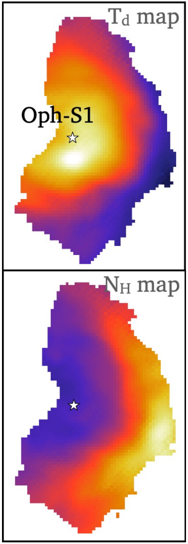
Lee et al. 2020

Planck data @40$'$



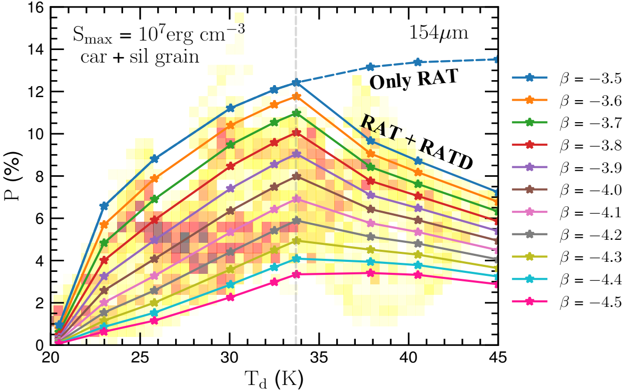
Dust Polarization in Ophiuchus: RAT-D effect

ρ Oph-A cloud



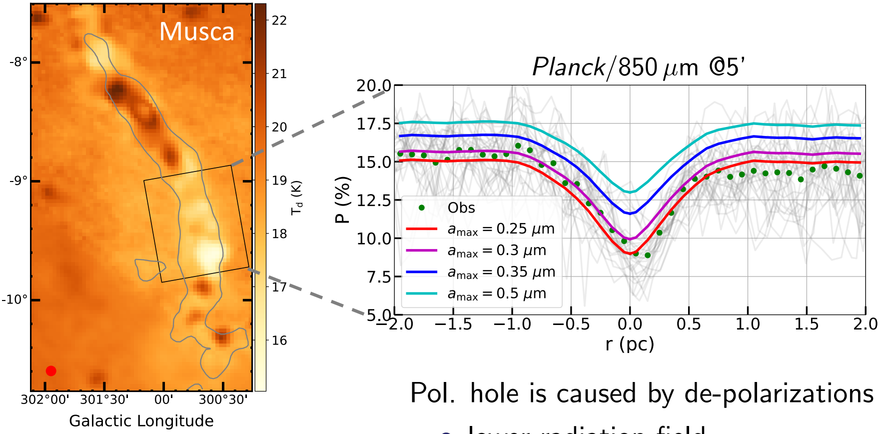
Santos et al. (2019)

SOFIA/HAWC+ @14''



Tram et al. (2021a)

Dust Polarization in Musca Filament

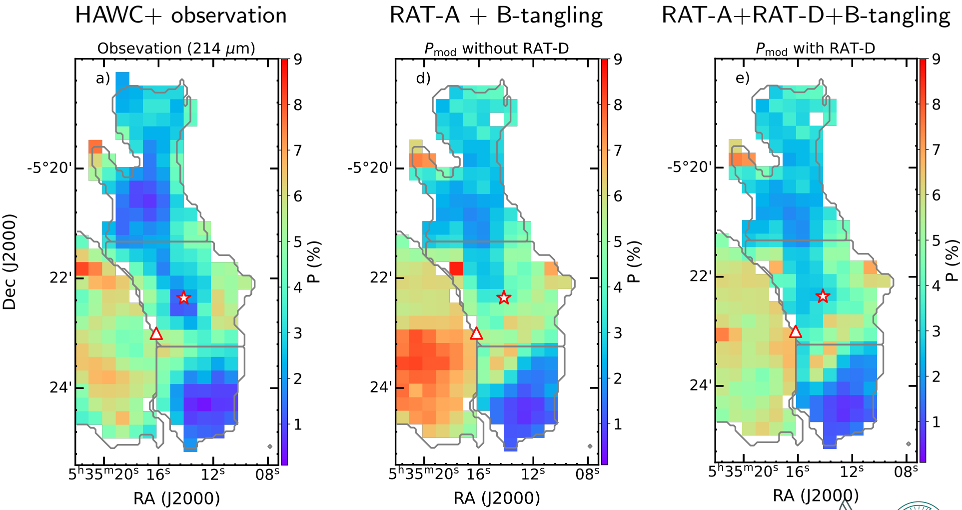


Ngoc, Diep, Hoang & Tram (submitted)

Pol. hole is caused by de-polarizations

- lower radiation field
- higher gas density

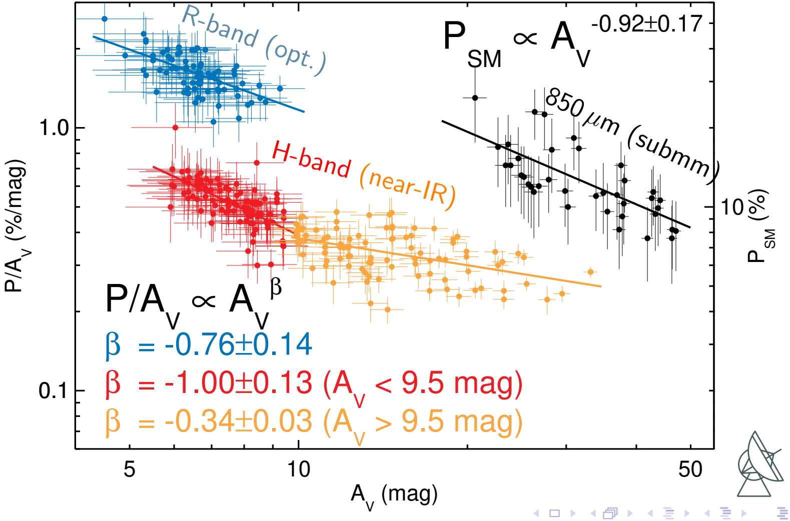
Dust Polarization in Orion: RAT-D and B-field tangling



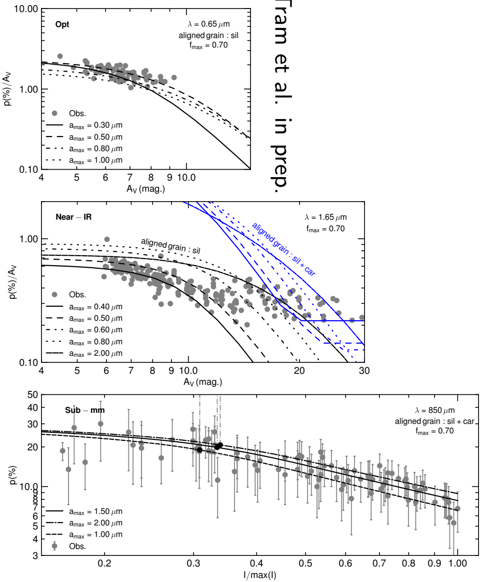
Ngoc, Diep, Hoang & Tram (submitted)

Dust Polarization in Starless Cores: Effect of grain growth

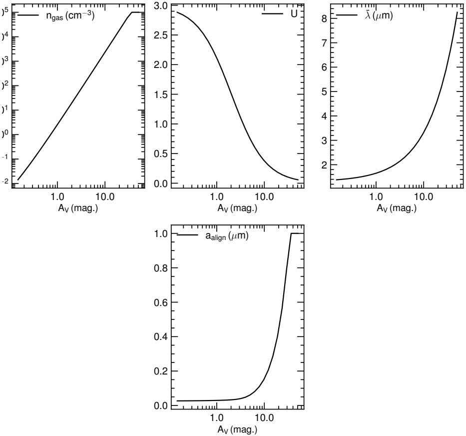
Pipe-109 starless core (Alves et al. 2014)



Dust Polarization in Starless Cores: Effect of grain growth

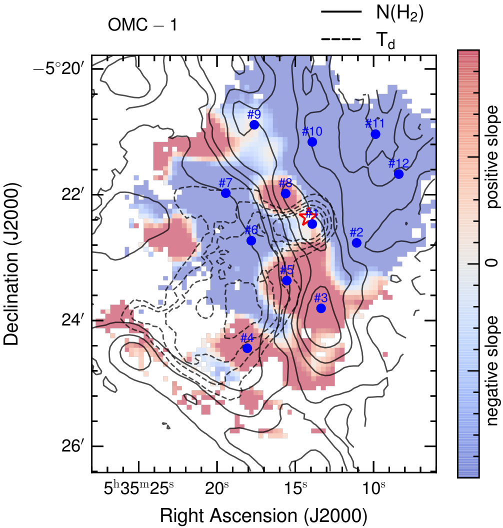


Tram et al. in prep.



- larger grain size toward core
- mixture composition toward core

Multiple-wavelength Dust Polarization: OMC-1

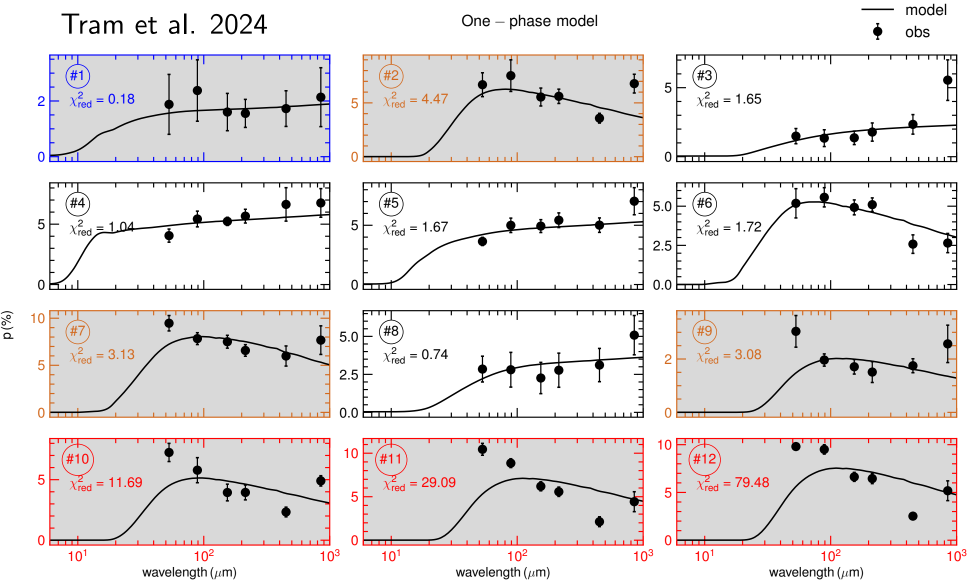


Tram et al. 2024

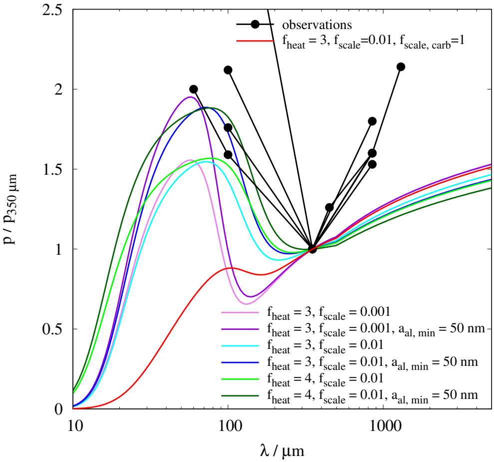
- pol. spectrum
  - 54, 89, 154, 214 μm with SOFIA/HAWC+ (Chuss+2019; Michail+2021)
  - 450, and 850 μm with JCMT/Pol-2 (Hwang+21)
- Spectrum slope: straight-line fitting ...
- Raising spectrum in dense region
- Falling spectrum in warm region

Pol. Spectrum in Orion: One-phase DustPOL-py

Tram et al. 2024



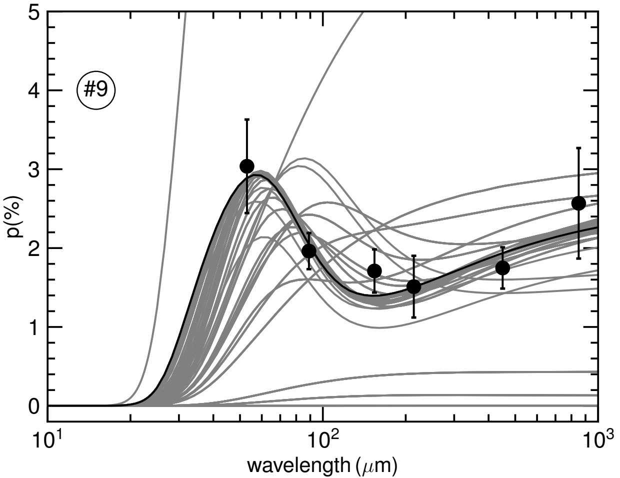
Multiple-wavelength Dust Polarization: Multiple Dust Component as a Potential Solver



- Two dust phases (dense and cold, warm and dilute) along the LOS!
- In warm and dilute phase: the destruction of carbon grains (by UV radiation) leads to a significantly pronounced V-shape!
- In dense and cold phase: the reduction in the alignment efficiency can pronounce more V-shape!

see Hilderbrand et al. 2000, Vaillancourt et al. 2008, Seifried et al. 2023

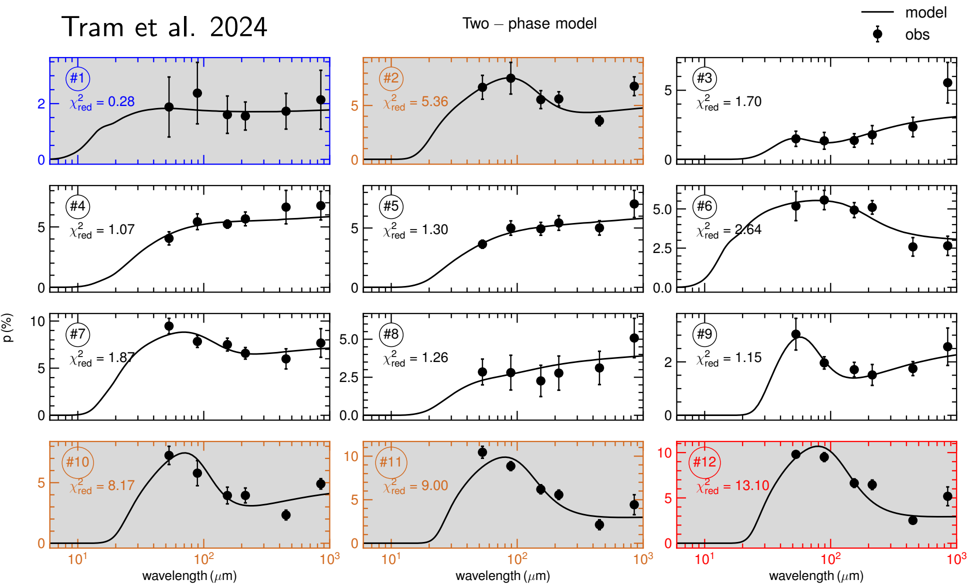
Example of Two-phase (two-layer dust) DustPOL-py



Two-phase DustPOL fits better than the one-phase

Pol. Spectrum in Orion: Two-phase DustPOL-py

Tram et al. 2024

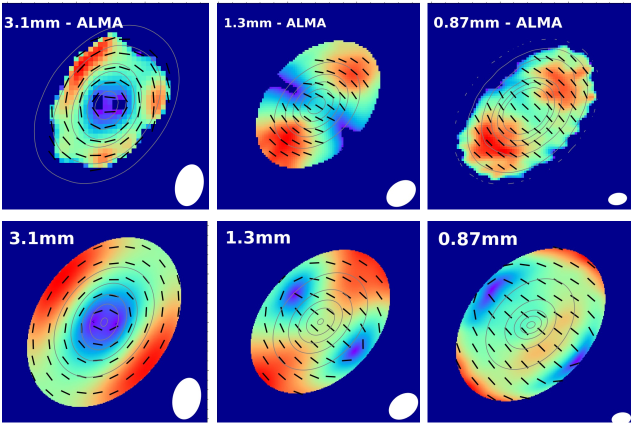


Dust Polarization in Era of ALMA: HLTau PPD

Smooth physical profiles for disk

Observations (ALMA)

Simulations (POLARIS+)

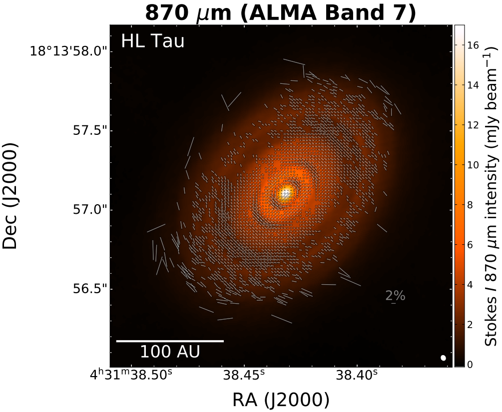


Combination of RATs and self-scattering

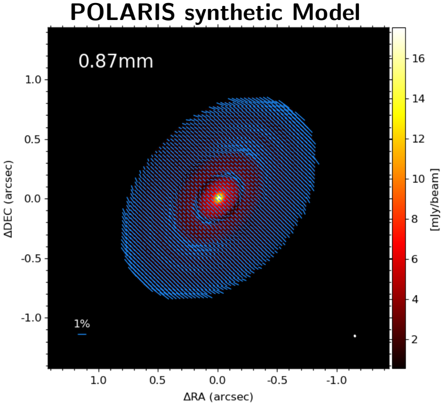
Nguyen Tat (incl. Tram) et al. 2024

Dust Polarization in Era of ALMA: HLTau PPD

Ring/Grap physical profiles for disk



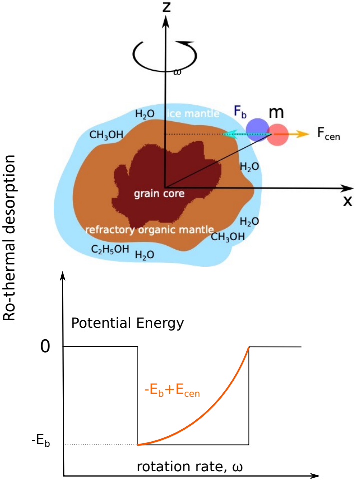
Stephens et al. 2023

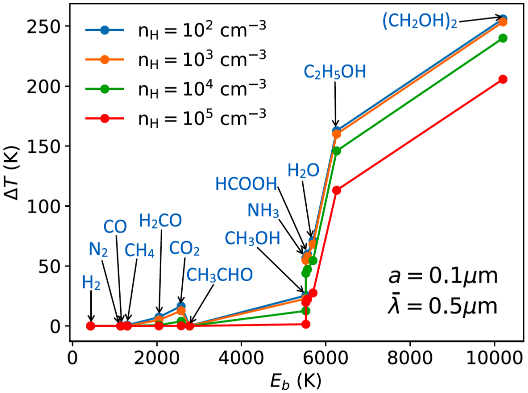


Nguyen Tat (incl. Tram) et al. 2024

Grain Rotation and Astrochemistry

Novel Ro-thermal Desorption

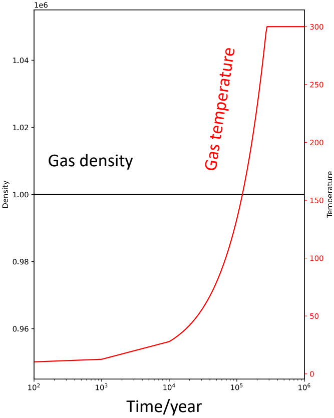




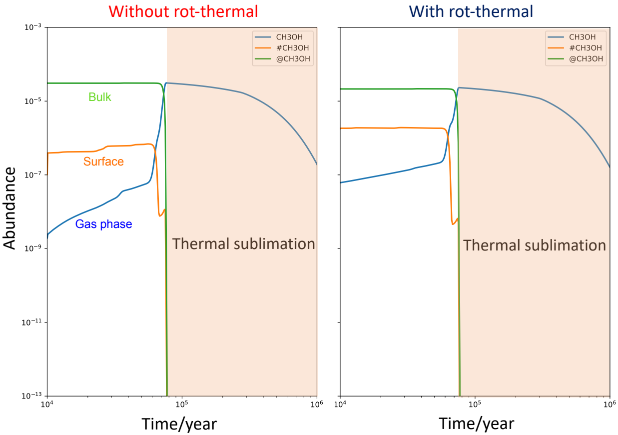
Hoang & Tung (2019)

Methanol (CH_3OH) in Hotcore

UCLChem Model[4]

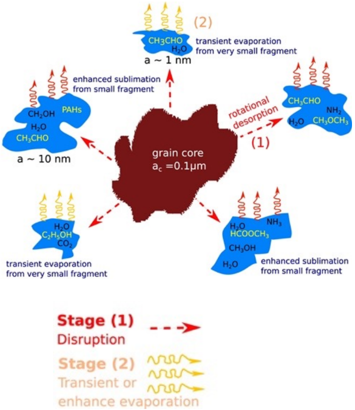


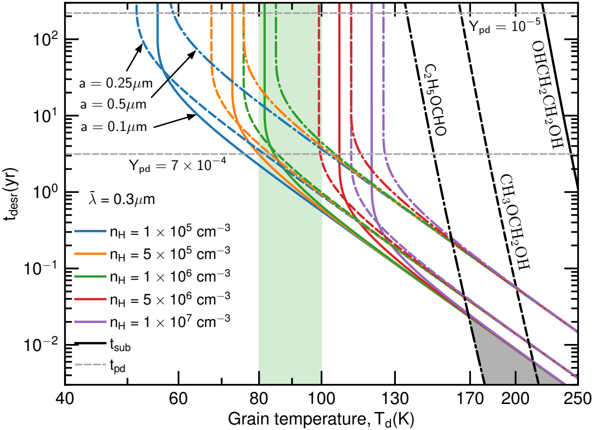
Thermal/Non-thermal desorption mechanisms and



[4]https://uclchem.github.io

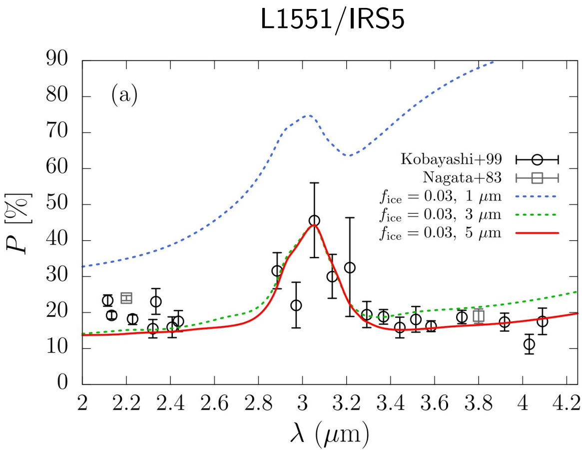
Novel Rotational Desorption





Hoang & Tram (2020), Tram et al. (2021b)

Water Ice Depletion in Protostar Envelope



- ❑ Micron-size ice-poor particles
  → grain growth
- ❑ Low ice abundance (f_{ice})
  → ice depletion of water ice
  → necessity of ice disruption

Tazaki et al. 2021
and references therein

Conclusion and perspective

Conclusions

1. Cosmic dust grains are seen to rotate, not stay at rest
2. Extremely fast rotation can break grain's structure and fragment it in smaller sizes
3. RAT-A + RAT-D is essential for dust polarization observation interpretations.
   - Numerical modeling: DustPOL-py (https://github.com/lengoctram/DustPOL-py)
   - Numerical simulation: POLARIS+ (publicly available soon)
4. Pol. spectrum of dust is important to comprehensively understand the physics of dust grain and improve the model's level of precision.
5. The Effect of grain rotation on surface chemistry must be considered.

Perspectives

1. More investigations on starlight polarization
2. Rotation and Disruption by RATs for fluffy/aggregated grains (Tram et al., in progress...)
3. Rotation and Disruption by Mechanical Torque (MET) (Tram et al., in progress ...)
4. Alignment of carbonaceous grains (Hoang, Minh & Tram 2023, , more works required ...)