Nathalie Ysard – IRAP, Toulouse, France

DUST GRAIN POLARISATION MODELS

What could we learn about grain properties from AtLAST?

Contents

- **Introduction**
  → Why is the emission from the grains polarised?
  → What quantities are important to measure?

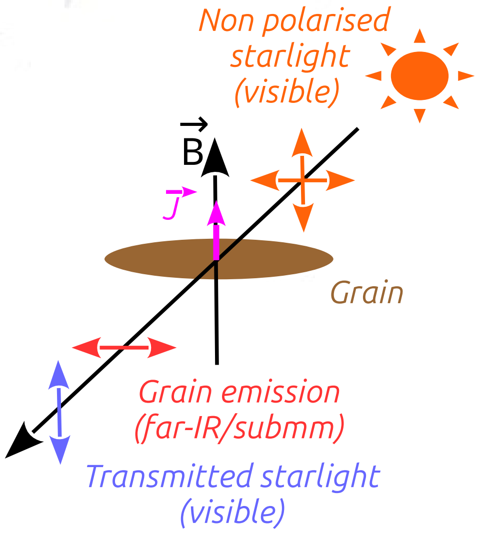
- **Where are we now? A few examples, not the state of the art**
  → Observations
  → Different options for modelling grains

- **Questions for AtLAST**
  → Grain size/composition based on the spectral index
  → 90° flip of the polarisation pattern around PPDs: link with grain size

- **Summary**

Why is the emission from the grains polarised in the ISM?

See for instance Hoang et al. (2023)



- **Paramagnetic material can align with the ambient B-field**

  → silicate grains with metallic inclusions, amorphous hydrocarbons
  → internal alignment: alignment of the grain's axis of maximal inertia with **J**
  external alignment: alignment of **J** with **B**

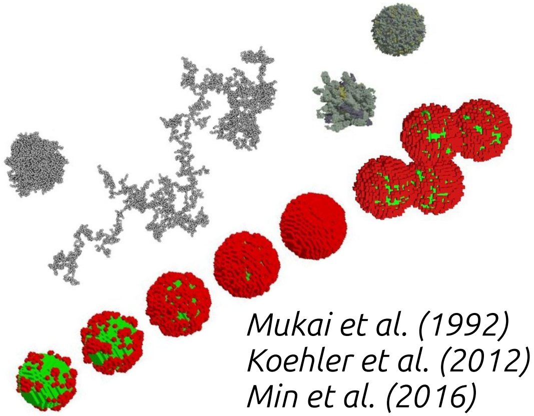
- **Polarised emission perpendicular to the B orientation**

  → grain's long axis = axis of maximum thermal emission

Dust polarised emission is a tracer of the orientation of the magnetic field

What quantities are important to measure ?

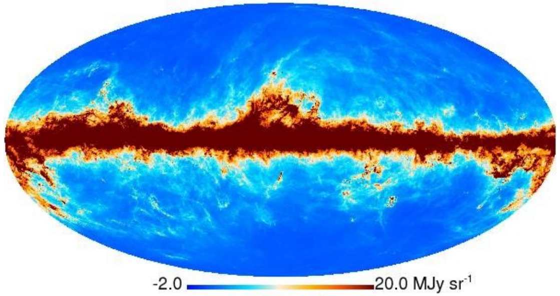
- Heating of the gas by photoelectic effect
  diffuse ISM ($A_V < 1$) & photon-dominated regions (PDRs)
- H_2 formation only possible on the grain surfaces
  intitiates all interstellar chemistry
- Determines if a cloud is optically thin or thick
  Molecules protected from photodissociation
  Reduced ionisation fraction
  Gas cooling through collisions
  } star formation
- Tracer for cloud masses & magnetic field



Mukai et al. (1992)
Koehler et al. (2012)
Min et al. (2016)

➡ ***All the above processes depend upon the exact grain size, structure, composition, shape and mass***

Observations: submillimetre spectral index
See Planck Collaboration XI (2014) + Planck Collaboration XI (2020)

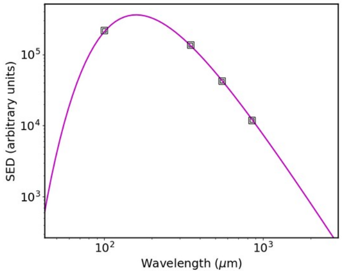


Total SED

IRAS - 100 μm
Planck-HFI - 350 μm
- 550 μm
- 850 μm

Polarised SED

Planck-HFI - 850 μm
- 1.3 mm
- 2 mm
- 3 mm



- Fit of each pixel of the sky

$$I_\nu = N_H \, \sigma_{\nu 0} \, B_\nu(T) \, (\nu/\nu_0)^\beta$$

column density → N_H; opacity → $\sigma_{\nu 0}$; Planck function → B_ν; temperature → T; spectral index → β

- Spectral index of the total SED: $\beta \sim 1.48$
  of the polarised SED: $\beta \sim 1.53$
  $\Delta\beta = 0.05 \pm 0.03$

Very close spectral indices at large scale
What does this tell us about grain properties?
Does it still hold true at small scales?
And what about shorter wavelengths ?

Observations: polarisation fraction

See Vaillancourt et al. (2008) + Ashton et al. (2018)

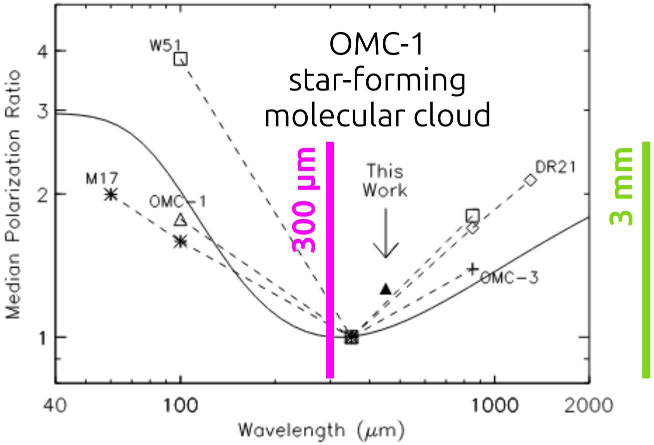


FIG. 3.— Far-infrared and submillimeter polarization spectrum, normalized at 350 μm. The 450/350 μm OMC-1 comparison from this work is shown as a solid triangle. The 850/350 μm comparison in W51 (open squares) is calculated from 850 μm data in Chrysostomou et al. (2002) and 350 μm data in Dotson et al. (2008). All other data are from Vaillancourt (2002). The solid curve is a 2-component dust model (see text).

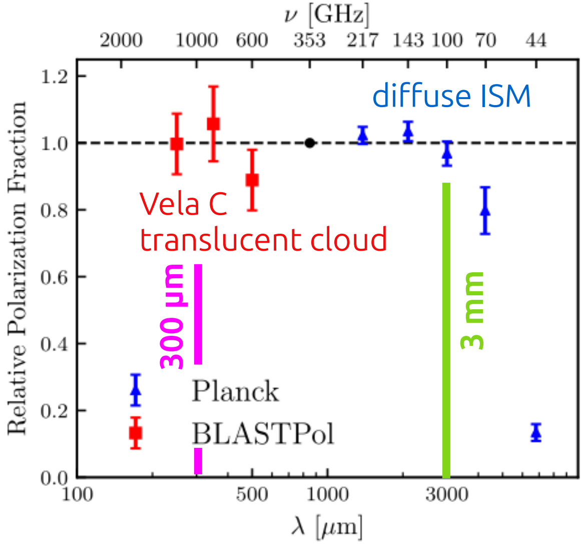


Figure 13. The polarization fraction of the dust emission relative to the 850 μm (353 GHz) polarization fraction as determined by BLASTPol and Planck observations. The BLASTPol data are from observations in the Vela Molecular Ridge (Ashton et al. 2018) while the Planck data are based on the total and polarized dust SEDs (Planck Collaboration Int. XVII 2014; Planck Collaboration Int. XXII 2015; Planck Collaboration XI 2020) compiled in Table 3. Little wavelength dependence is observed except at the longest wavelengths where AME becomes a significant fraction of the total dust emission.

easy to explain with a 2-component dust model → $T_1 \neq T_2$
(e.g. Hildebrand et al. 1999, Vaillancourt et al. 2002)

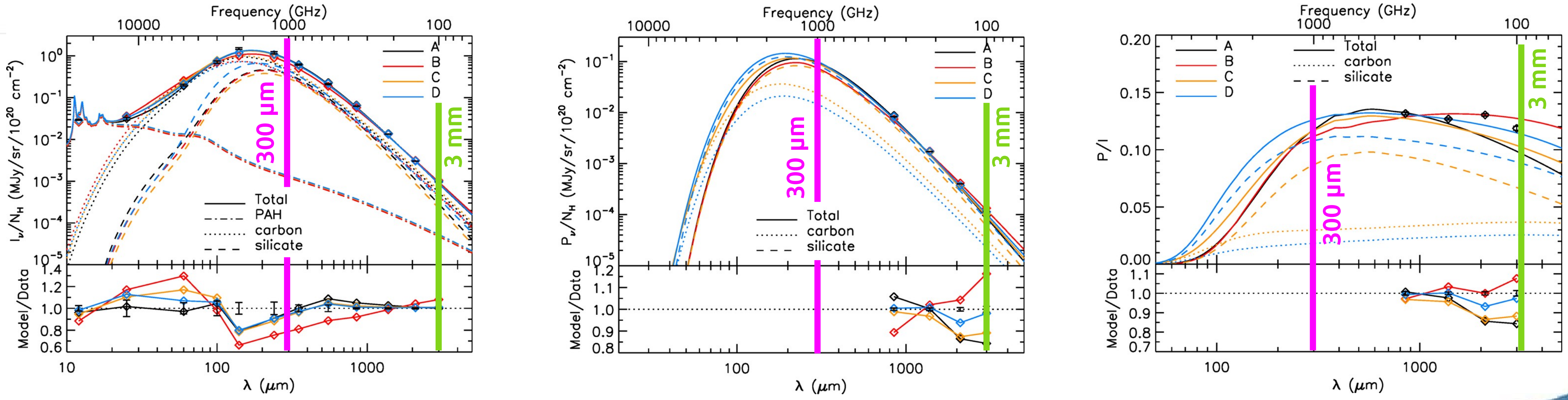
easy to explain with a 1-component dust model
but a 2-component model still possible

Different options for modelling grains
1) The ‘classic’: silicates and carbons separated, only silicates aligned
See for instance Guillet et al. (2018): models A & B

- Models A & B: only big silicates aligned
  → different silicate optical properties [astrosilicates from Weingartner & Draine 2001 or Li & Draine 2001]

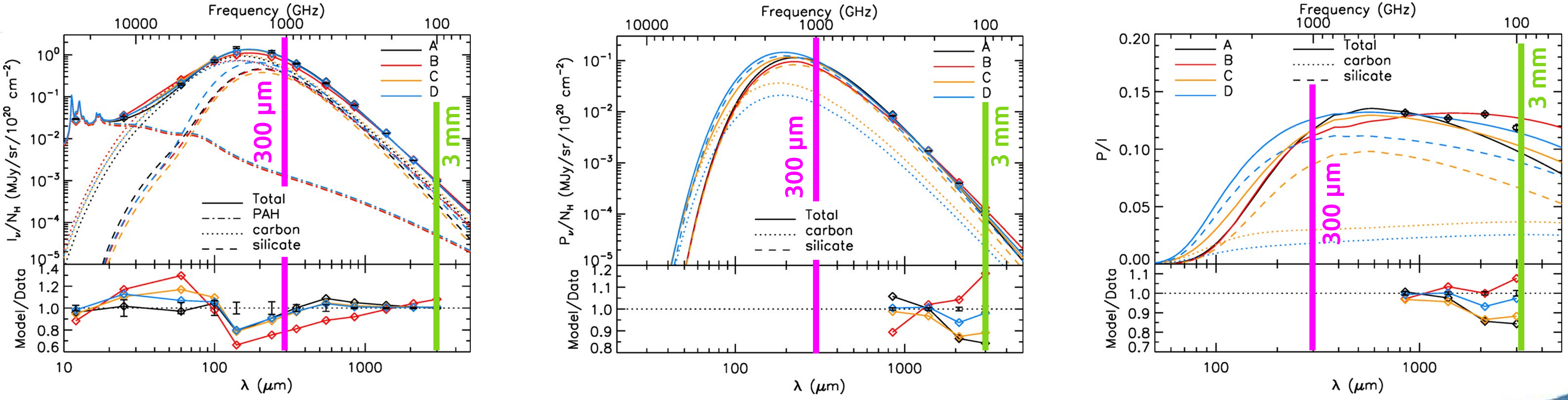
- Both compatible at ±20% with observations

- *P/I* at shorter wavelengths would help to discriminate between models



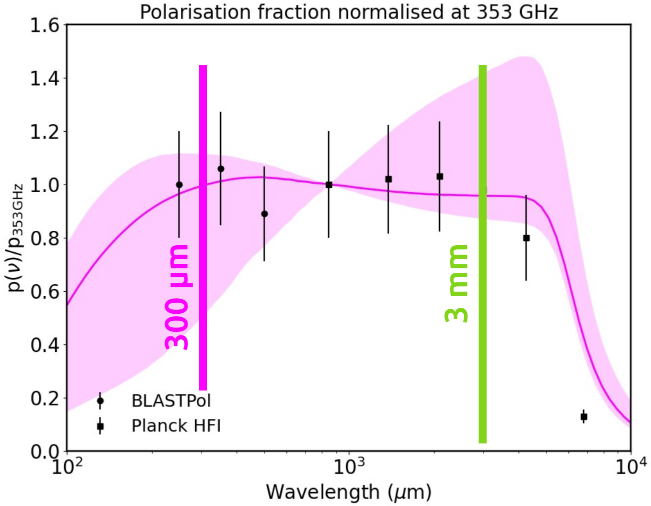
Different options for modelling grains
2) Silicates and carbons still separated, all grain types aligned
See for instance Guillet et al. (2018): models C & D

- Models C & D: all big grains aligned
  → different silicate optical properties [astrosilicates from Weingartner & Draine 2001 or same with carbon inclusions]
- Both compatible at ±20% with observations
- *P/I* at shorter wavelengths would help to discriminate between models



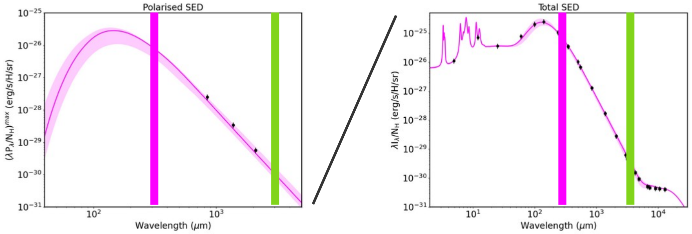
Different options for modelling grains
2) Silicates and carbons still separated, all grain types aligned
See for instance Ysard et al. (2024)

- Models C & D: all big grains aligned
  → different silicate optical properties [astrosilicates from Weingartner & Draine 2001 or same with carbon inclusions]
- Both compatible at ±20% with observations
- *P/I* at shorter wavelengths would help to discriminate between models



Example from THEMIS 2

Two other ways of changing the shape of *P/I*
→ vary the efficiency of grain alignment
→ take into account the distinctive optical properties of amorphous carbons

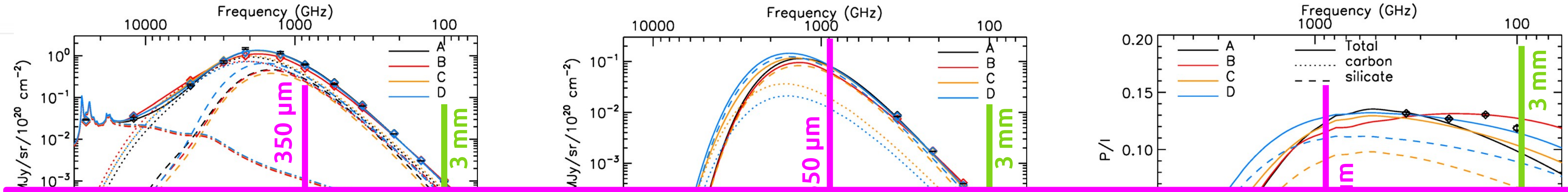


Different options for modelling grains
2) Silicates and carbons still separated, all grain types aligned
See for instance Guillet et al. (2018): models C & D

- Models C & D: all big grains aligned
  → different silicate optical properties [astrosilicates from Weingartner & Draine 2001 or same with carbon inclusions]

- Both compatible at ±20% with observations

- *P/I* at shorter wavelengths would help to discriminate between models



And many more subtleties if you are interested:

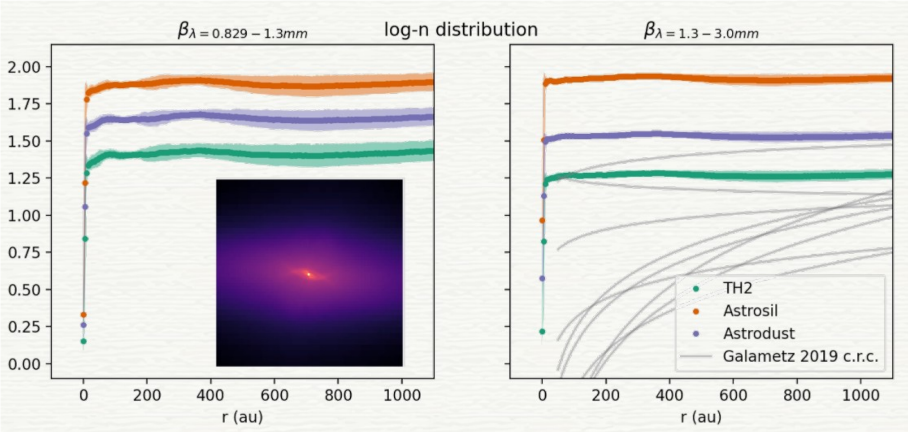
→ Astrodust (Hensley & Draine 2023): the empirical one, a single grain type in which silicates and carbons are completely mixed
→ Dark dust (Siebenmorgen 2022): addition of a dark and cold component to make part of the extinction, implication in the submm
→ THEMIS 2 (Ysard et al. 2024): the lab-based one, carbons and silicates separated but both aligned, explanation of β variations at large scale

Grain composition based on the spectral index

- What's behind aligning or not aligning carbonaceous grains?
  → graphite vs. amorphous carbon = diamagnetic vs. paramagnetic
  → strong impact on the carbon dust survival, chemistry (formation of PAHs and H_2 for instance), charge (link with dynamics)

- Impact of variations in composition on the β of the total intensity
  → lower β-values usually attributed to grain growth up to millimetre sizes
  → example of a MHD model of the envelope of a Class 0 protostar (Carpine et al. 2025 + Carpine et al. in prep)

a ~ 0.1 µm



Weingartner et al. (2001): empirical silicates

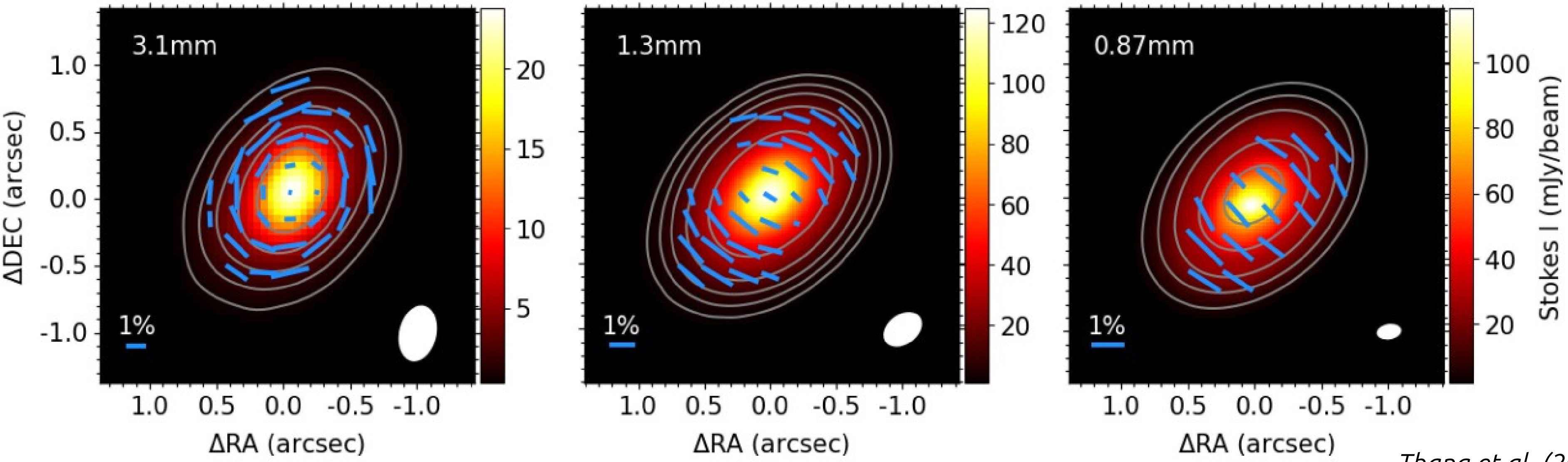
Hensley & Draine (2023, Astrodust): empirical silicates

Ysard et al. (2024, THEMIS 2): lab-based silicates

Radiative transfer with POLARIS
Brauer et al. (2017), Reissl et al. (2016)

Strong impact of the dust composition on the retrieved β values for both total and polarised emissions
Are the grains really that big around Class 0 protostars ?

90° flip of the polarisation pattern around PPDs: relation with grain size

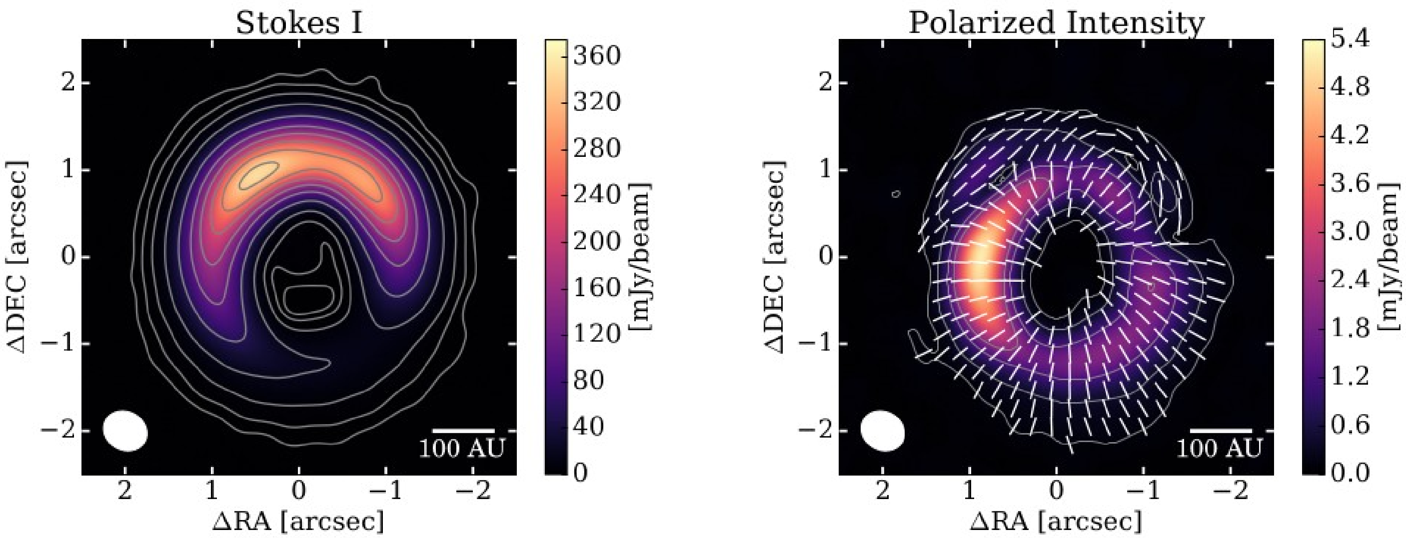


Thang et al. (2024)
Stephens et al. (2014)

- ALMA+CARMA+SMA observations of the HL Tau protoplanetary disk
  → 1st explanation: complex magnetic fields dominated by toroidal components (Matsakos et al. 2016)
  → 2nd explanation: dust peculiarities

- Three ways of interpreting polarised emission = three (very) different grain size estimates
  → self-scattering $a_{max} \lesssim 100$ μm
  → thermal emission in the Mie regime $a_{max} \lesssim 1$ mm
  [→ alignment mechanisms: wIA, k-RAT, v-MET] [$a_{max} \lesssim 90$ μm]

90° flip of the polarisation pattern around PPDs: relation with grain size

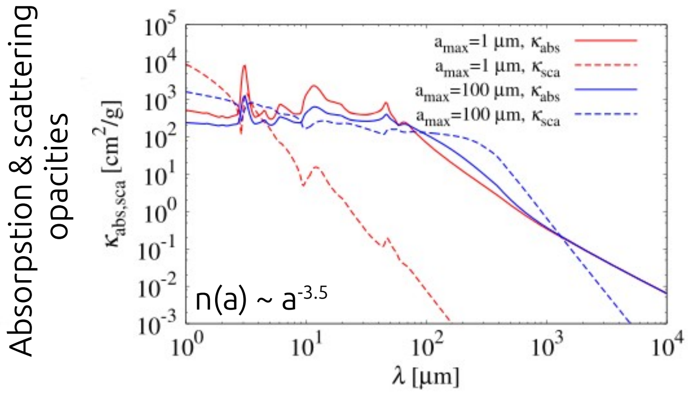


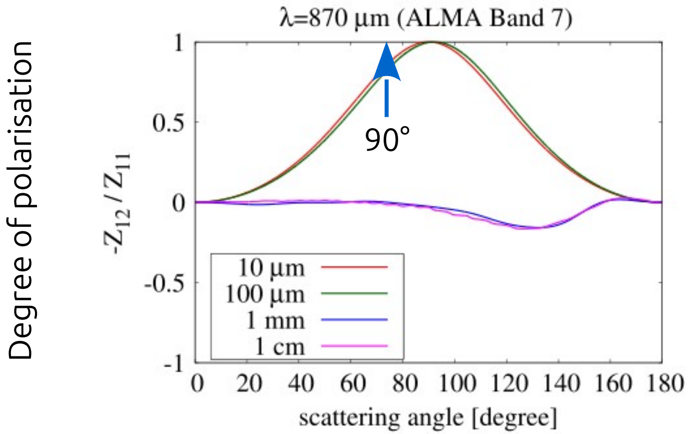
Kataoka et al. (2016)

- ALMA observations of the protoplanetary disk around HD 142527 at 870 μm

- Three ways of interpreting polarised emission = three (very) different grain size estimates
  - → self-scattering $a_{max} \lesssim 100$ μm
  - → thermal emission in the Mie regime $a_{max} \lesssim 1$ mm
  - [→ alignment mechanisms: wIA, k-RAT, v-MET] [$a_{max} \lesssim 90$ μm]

90° flip of the polarisation pattern around PPDs → self-scattering (Kataoka et al. 2015, 2016, 2017)





- Grains are efficient scatterers when $x = 2\pi a / \lambda \sim 1$ (Rayleigh limit)
  $\mathcal{A} = \kappa_{sca} / (\kappa_{abs} + \kappa_{sca})$
  → grains can scatter their own thermal emission
- Scattered light polarised if anisotropic radiation field
  → protoplanetary disks with ring-like or lopsided surface brightness
- Detectable grain size depends on the observed wavelength
  → 60 µm ≤ a_{max} ≤ 1 mm for 60 µm ≤ λ ≤ 1 mm
  → non-spherical grains allow higher polarisation degree
  can increase the inferred grain sizes
  (Kirchschlager & Bertrang 2020)

90° flip of the polarisation pattern around PPDs → self-scattering (Kataoka et al. 2015, 2016, 2017)

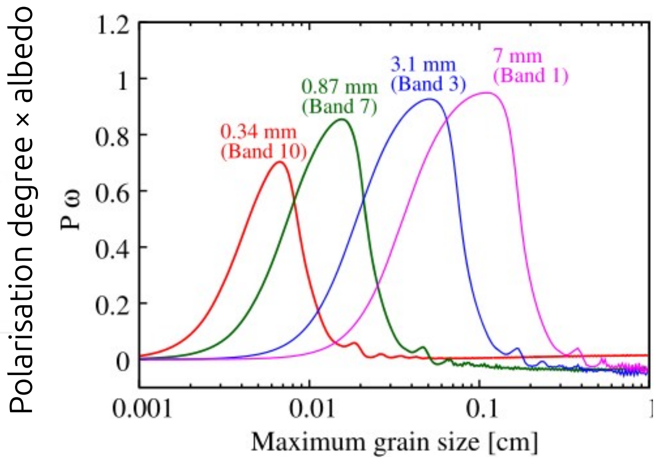
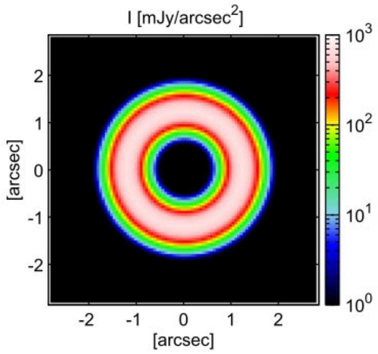


Table 1
The Detectable Grain Size for Observed Wavelengths

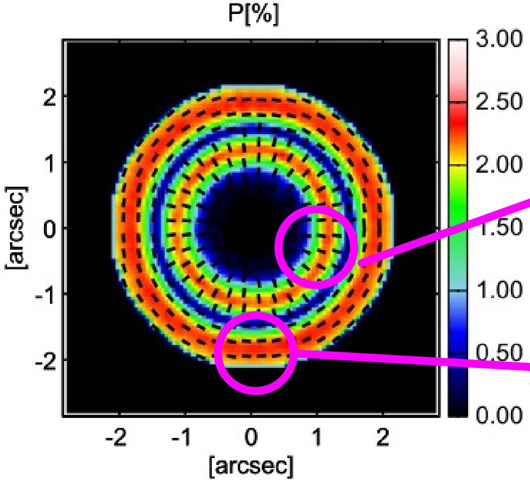
Wavelengths λ	The Detectable Grain Size a_{max}
7 mm	1 mm
3.1 mm	500 μm
870 μm	150 μm
340 μm	70 μm

- Grains are efficient scatterers when $x = 2\pi a / \lambda \sim 1$ (Rayleigh limit)
  $\mathcal{A} = \kappa_{sca} / (\kappa_{abs} + \kappa_{sca})$
  → grains can scatter their own thermal emission
- Scattered light polarised if anisotropic radiation field
  → protoplanetary disks with ring-like or lopsided surface brightness
- Detectable grain size depends on the observed wavelength
  → 60 μm ≤ a_{max} ≤ 1 mm for 60 μm ≤ λ ≤ 1 mm
  → non-spherical grains allow higher polarisation degree
  can increase the inferred grain sizes
  (Kirchschlager & Bertrang 2020)

90° flip of the polarisation pattern around PPDs → self-scattering (Kataoka et al. 2015, 2016, 2017)

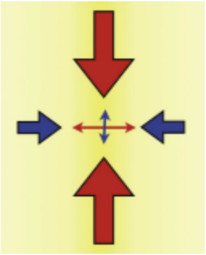


ring-shaped protoplanetary disk

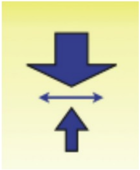


- Grains are efficient scatterers when $x = 2\pi a / \lambda \sim 1$ (Rayleigh limit)
  $\mathcal{A} = \kappa_{sca} / (\kappa_{abs} + \kappa_{sca})$
  → grains can scatter their own thermal emission
- Scattered light polarised if anisotropic radiation field
  → protoplanetary disks with ring-like or lopsided surface brightness
- Detectable grain size depends on the observed wavelength
  → 60 µm $\leq a_{max} \leq$ 1 mm for 60 µm $\leq \lambda \leq$ 1 mm
  → non-spherical grains allow higher polarisation degree
  can increase the inferred grain sizes
  (Kirchschlager & Bertrang 2020)

net flux from the azimuthal direction larger than in the radial direction



strong radial gradient



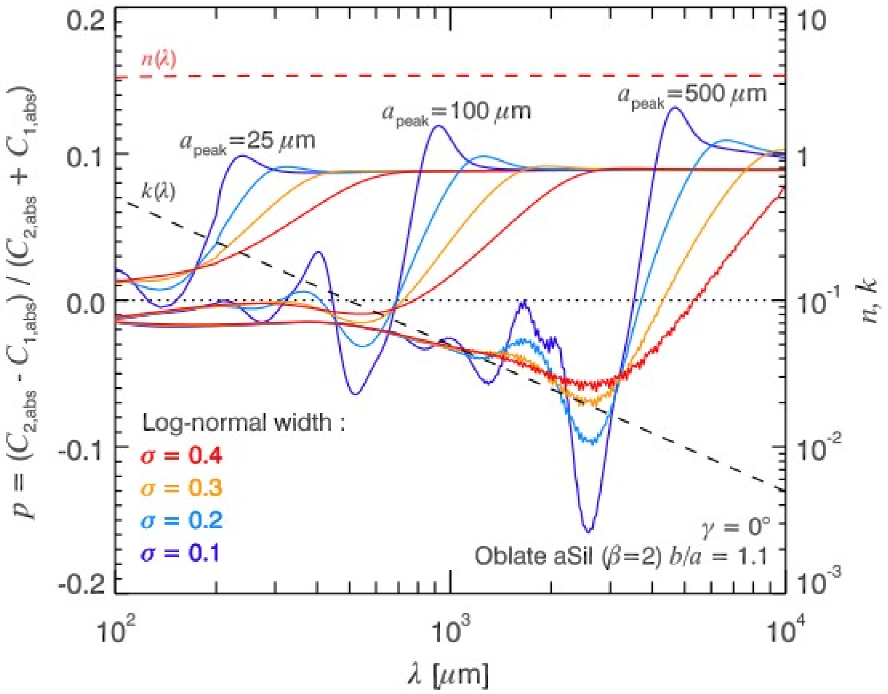
90° flip of the polarisation pattern around PPDs → polarised emission in the Mie regime (Guillet et al. 2020)

- Common in the ISM → the Rayleigh regime
  grains with sizes of $a \sim 0.1$ μm
  observations in the (sub)mm: $x = 2\pi a / \lambda \ll 1$

- Bigger grains in star-forming regions → the Mie regime
  grains with sizes up to a ~ 100 μm or even 1 mm ???
  observations in the (sub)mm: $x = 2\pi a / \lambda \geq 1$

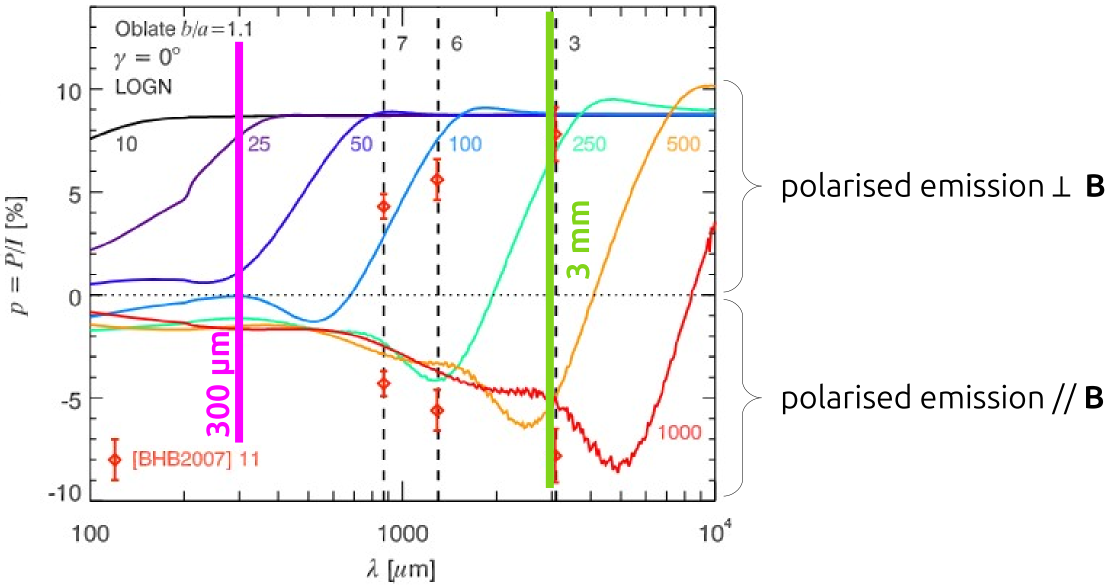
- Grains optical properties depend on x and on the material complex refractive index
  $m = n + ik$

- 25 μm grains in the Mie regime (far-IR) → high k-values
  500 μm grains in the Mie regime (mm) → low k-values
  positive to negative polarisation efficiency

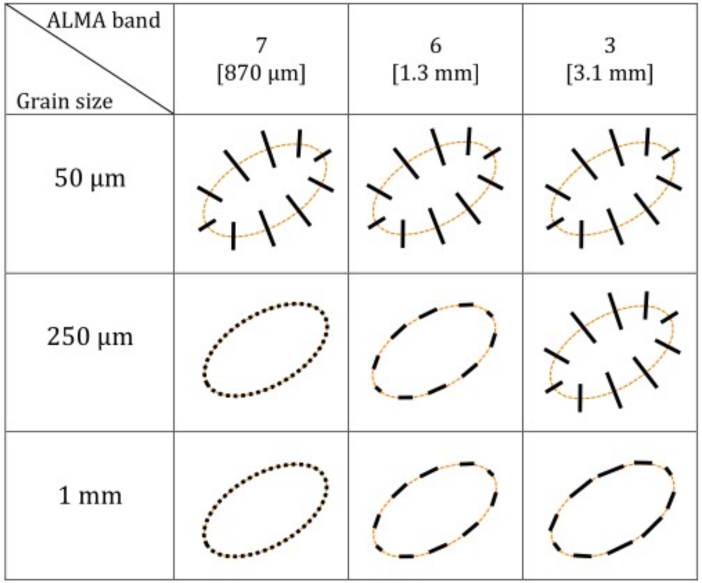


Large grains aligned with the magnetic field: polarised thermal emission parallel to the magnetic field
Valid for materials with low k-values at long wavelengths

90° flip of the polarisation pattern around PPDs
→ polarised emission in the Mie regime (Guillet et al. 2020)



polarisation fraction for grains perfectly aligned in the plane of the sky (ISRF + G_0 = 100)



polarisation vectors from aligned grain emission for a protoplanetary disk inclined by an angle of 45° with perfect azimuthal magnetic field (orange ellipses)

Summary

- Still a lot of uncertainty about the properties of the grains
  → nature of the carbonaceous component of the grains ?
  → separation of carbonaceous and silicate grains ?
  → grain sizes, in particular in star-forming regions
  → alignment mechanisms

  → strong impact on the ISM/disks chemistry and dynamics

- Submm/mm polarisation appears to be a great tool for making progress on theses issues
  → models available
  → multiwavelength observations

- Importance of lab inputs for improving the dust models
  → e.g. spectral index variations with wavelength and temperature

  → need to reconcile sizes measured with flat β in disks and sizes measured with polarisation