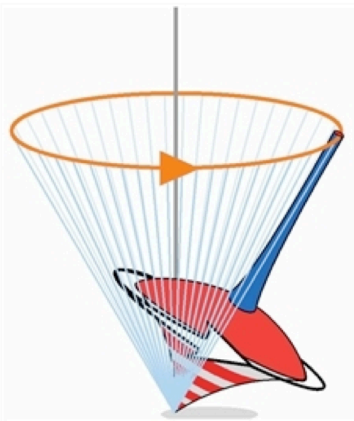
Constraing dust physics with NIKA2 : Road map avec *Planck*



V. Guillet (IAS,LUPM)

F. Levrier (ENS/LRA), F. Boulanger (ENS/LRA),
and the Planck Collaboration

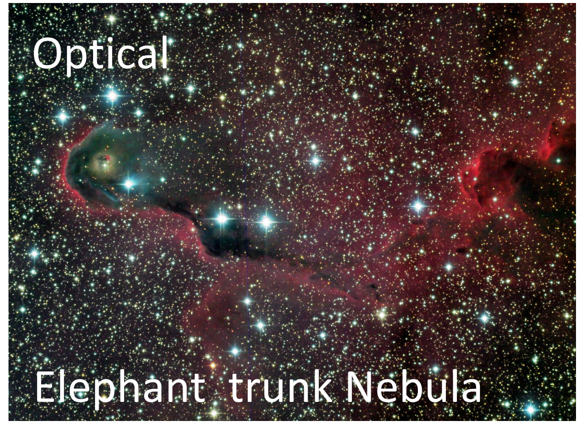
OUTLINE

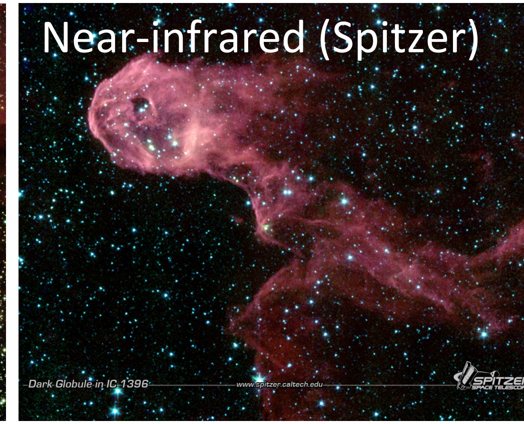
1. *Planck* results on the Diffuse InterStellar Medium (DISM) dust
   - Contraints on DISM dust optical properties
     - In total intensity
     - In polarization
   - New dust models needed for the DISM
   - Constraints on grain alignment in the DISM
2. Dust polarization at high resolution and high extinction
3. Grain growth in cores traced by self-scattered emission ?

Introduction on ISM dust : extinction and emission

Dust grains absorb and scatter starlight

… and then reemit this energy in the infrared

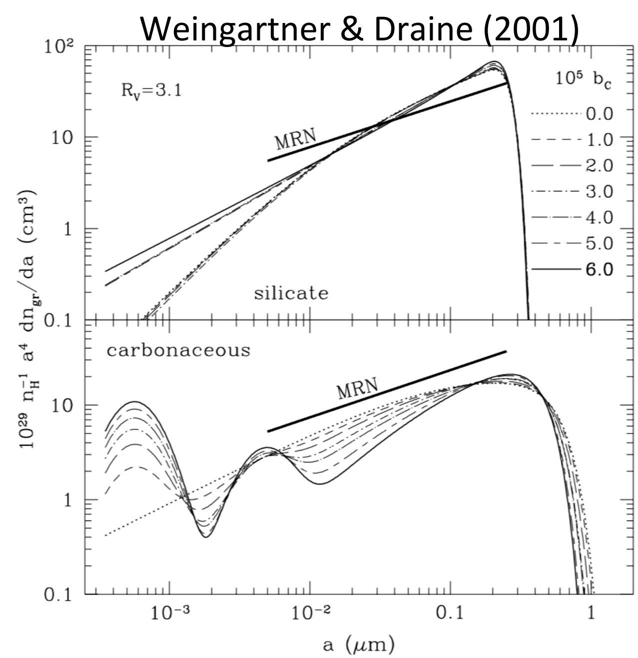




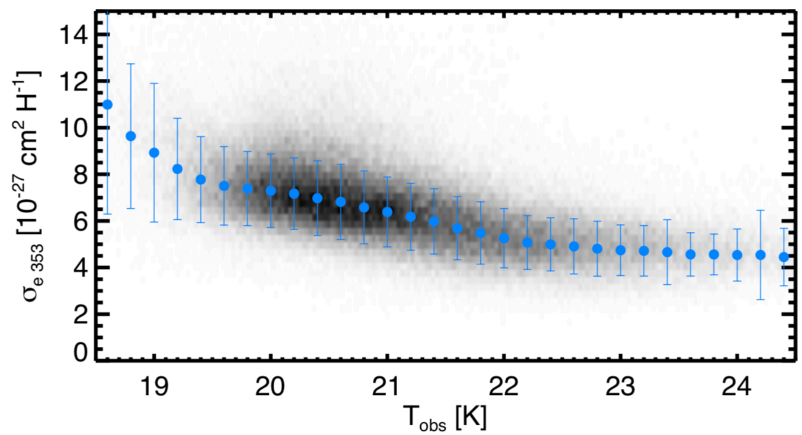
Which dust size distribution to explain this ?

- Very small aromatic grains (< nm)
- small grains (5 nm) for mid-IR stochastic emission
- Large grains (10-300 nm)
  - Silicate (mid-IR absorption polarized bands)
  - Carbonaceous
  - $\Rightarrow$ **No grains larger than a fraction of a micron**

    These are the grains observed by NIKA2



Planck results on DISM dust : dust emissivity



Planck 2013 results XI.

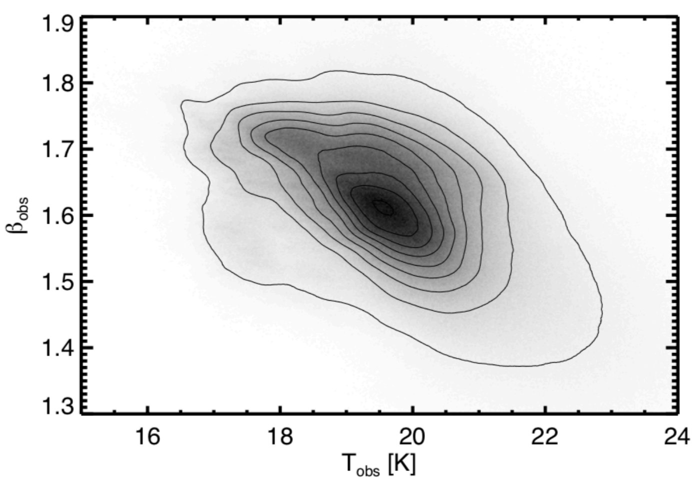
Method

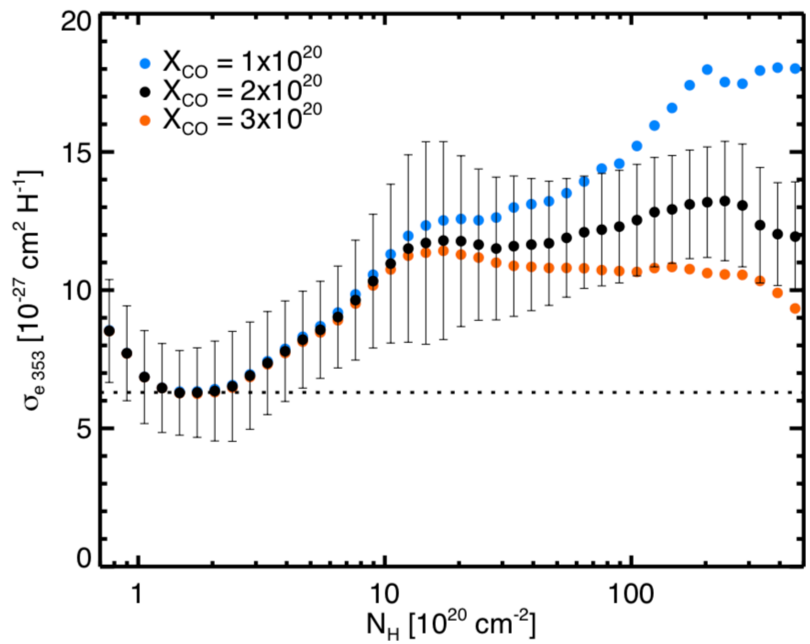
- Combine IRAS, DIRBE &*Planck* data : 100 µm – 3 mm.
- Use high-latitude sky, traced by H I.
- Modified black-body fit to the SED (3 parameters):

$$I_\nu = \tau_{353} (\nu/353\text{GHz})^\beta B_\nu(T)$$

Results:

- **Dust opacity $\sigma_e = \tau_{353}/N(HI)$** varies by a factor ~ 2: variations in dust optical properties
- Anticorrelation β - T



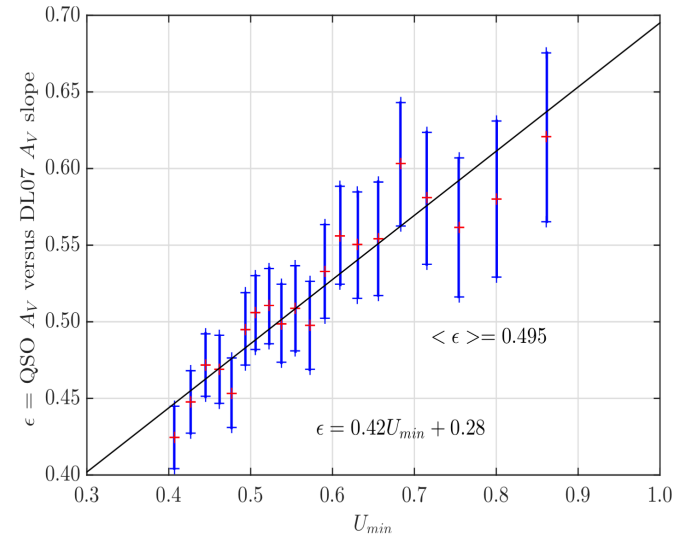


Planck results on ISM dust : emissivity per A_v

Planck int. results XXIX (2016)

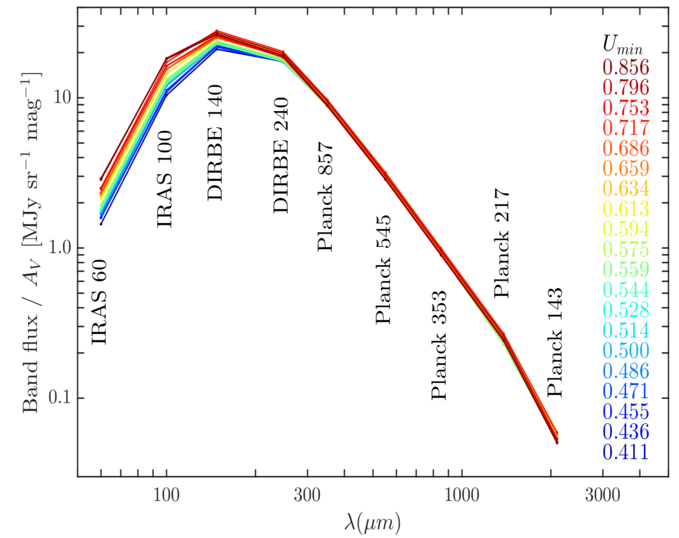
Method:

- Fit to the SED with a physical dust model : Draine & Li (2007) : PAHs, graphite, astrosilicate
  - Column density : Av
  - Radiation field intensity : U_{min}
  - Fraction of PDRs on the line of sight : f_{PDR}
- Correlation of resulting A_v with extinction toward 200,000 QSOs at high Galactic latitude.



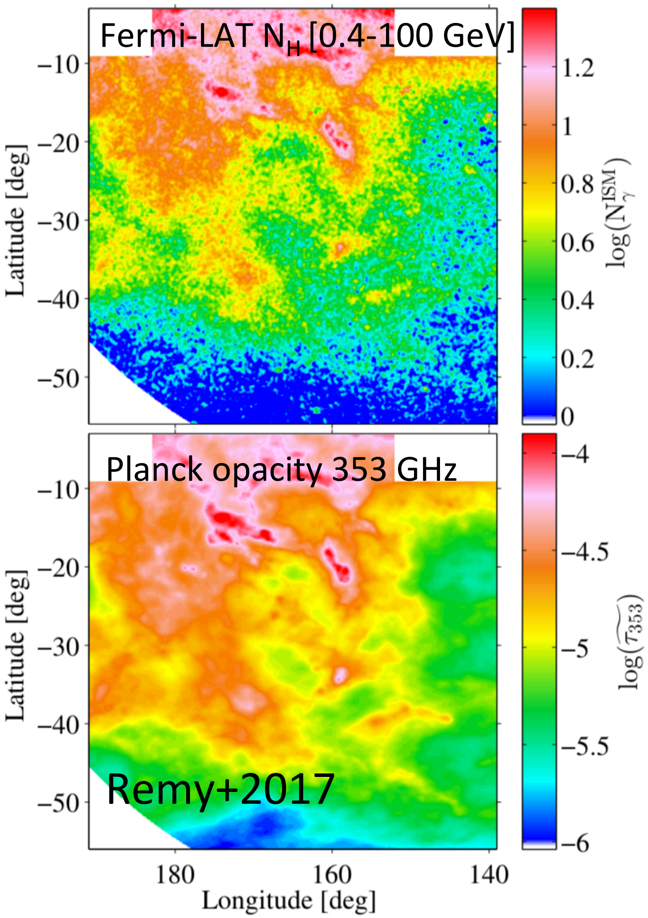
Results

- All SEDs are well fitted by the model: $\chi^2 \sim 1$
- The fitted A_v is too high by a factor 1.9 with respect to measured Av to QSOs: DL07 dust is not emissive enough.
- This systematic error depends on U_{min} : dust opacity per H is not uniform.
- Family of 20 SEDs per A_v ordered by their temperature



Dust properties from *Planck*-Fermi results

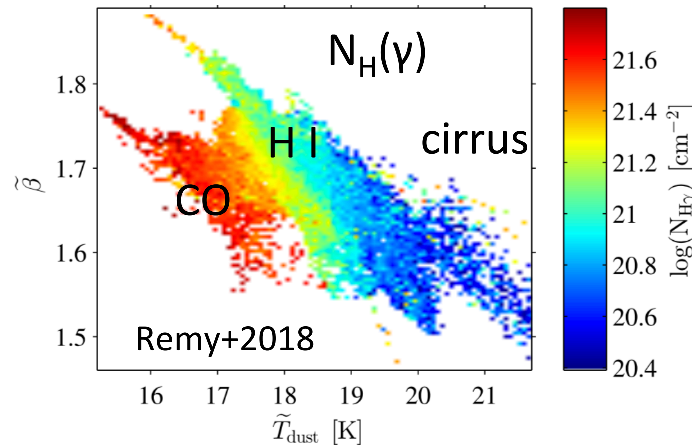
Planck and Fermi correlate very well

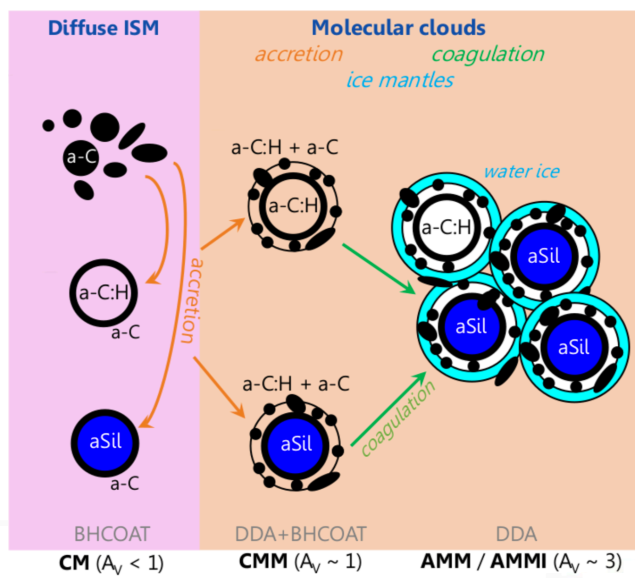


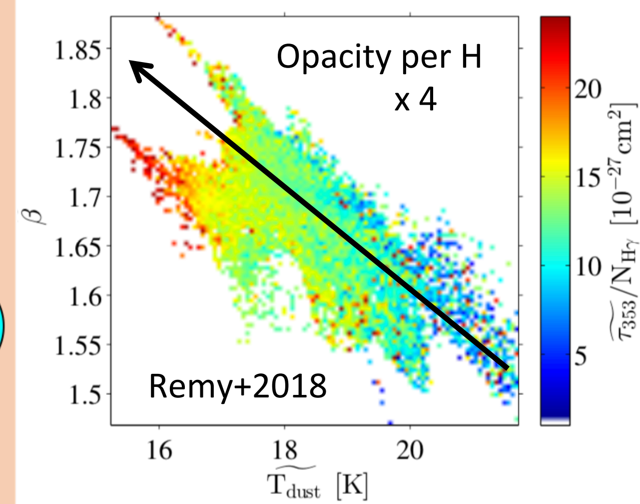
T/β anticorrelation follows the increase in N_H and in τ/N_H

Similar variations in extinction (E(B-V)/NH, Rv), but of smaller amplitude

Variations compatible with the THEMIS model (Jones+2013, Koehler+2015)

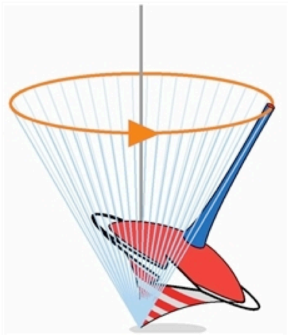






Introduction on ISM dust : grain alignment

Dust grains are **spinning tops**. Grain physics is that of gyroscopes. Owing to their magnetic properties, dust grains spin axis **precess around magnetic field lines.**



Some torques must rapidly (τ < 1 Myr) align interstellar grains.
« Dust grains are aligned along magnetic field lines»: **what does it mean ?**

or

?

The grains spin axis are, on average, directed along the magnetic field lines.

Grain alignment processes

Grains can be aligned by different processes:

1. Magnetic alignment (Davis & Greenstein 1951) : not para-magnetic (ineffective) but super-paramagnetic (grains with ferro-mangnetic domains). Alignment along B.
2. Mechanical alignment : Gold (1951) supersonic mechanism, or subsonic mechanical torques (Hoang+2018) . Alignment along or perpendicular to the gas flow.
3. Radiative alignment (Draine & Weingartner 1996, 1997, Hoang & Lazarian 2007, 2014, 2016). Alignment along B or along the radiation field.

The radiative torque theory (e.g. Hoang & Lazarian 2014) is, **<u>in practice for modellers</u>**, more a theory of grain spin-up than a theory of grain alignment :

- **grains are aligned if they rotate suprathermally (w/r dust, not gas, temperature)**
- Spin-up torque (Hoang & Lazarian 2014) : $\Gamma_\lambda = \gamma_{\rm rad}\pi a^2 u_\lambda \left(\frac{\lambda}{2\pi}\right) Q_\Gamma,$

  => spin-up is dominated by the most numerous photons : NIR, not UV photons.
- The larger the grain, the faster it rotates

  => only grains larger than a certain size a_{alig} are aligned.
- a_{alig} depends on the local radiation field, its direction, anisotropy, & intensity.
- **a_{alig} also increases with the gas pressure *nT* (Hoang & Lazarian 2014)**

- To date, observational évidence favouring RATs have been mostly qualitative (trends), not quantitative.

Planck results on ISM dust : polarization

Planck Int. Results. XXI (2015)

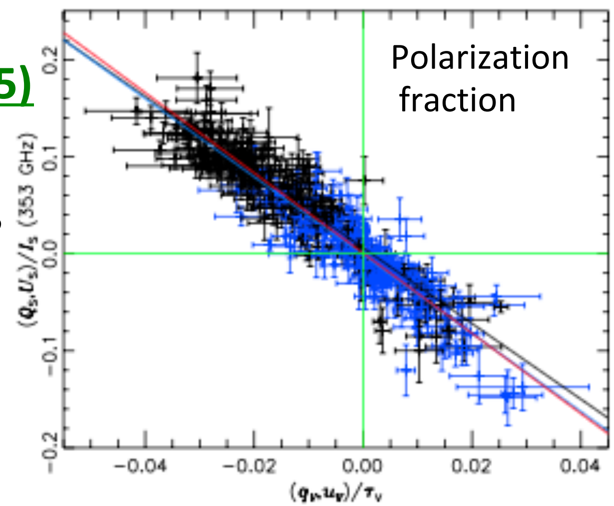
Method

- Correlate (Q,U) between 353 GHz and the optical.

Results:

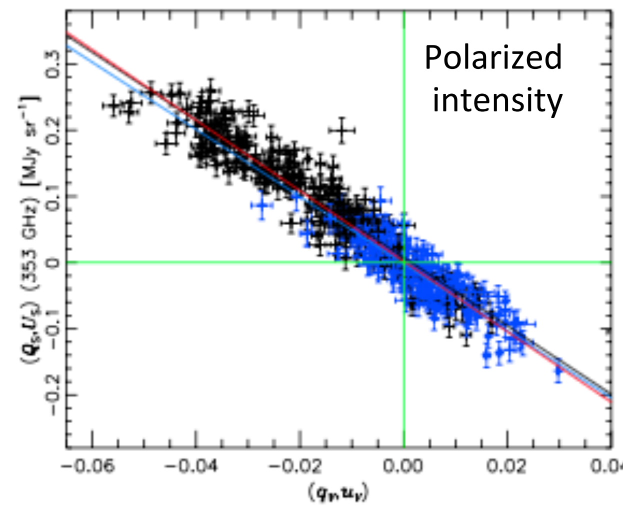
- $P_{353}/\ p_V = 5.4$ MJy/sr
- $(P_{353}/I_{353})\ /\ (p_V/\tau_V) = 4.2$

353GHz



Optical

353GHz



Optical

Planck Int. Results. XXII (2015)

Method

- Correlation analysis in intensity and polarization (brown mask)

Results

- P/I is slightly decreasing with the wavelength : $\beta_P - \beta_I \sim 0.09$

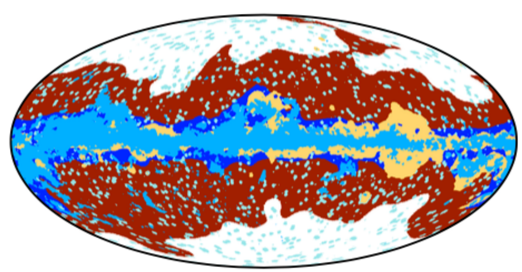
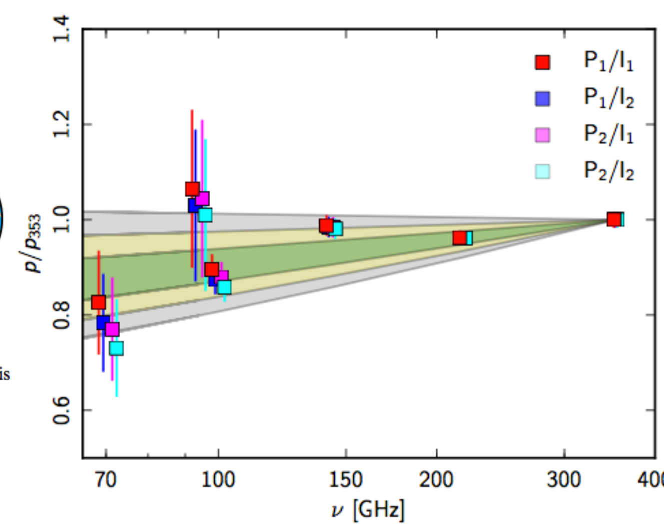


Fig. 1. Global mask used in the cross-correlation (CC) analysis



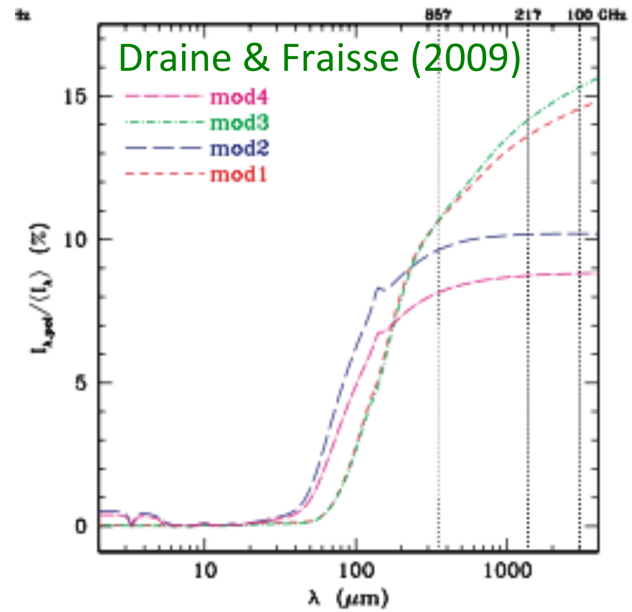
Need for new dust models

Pre-Planck models

Polarized emission: Draine & Fraisse (2009)

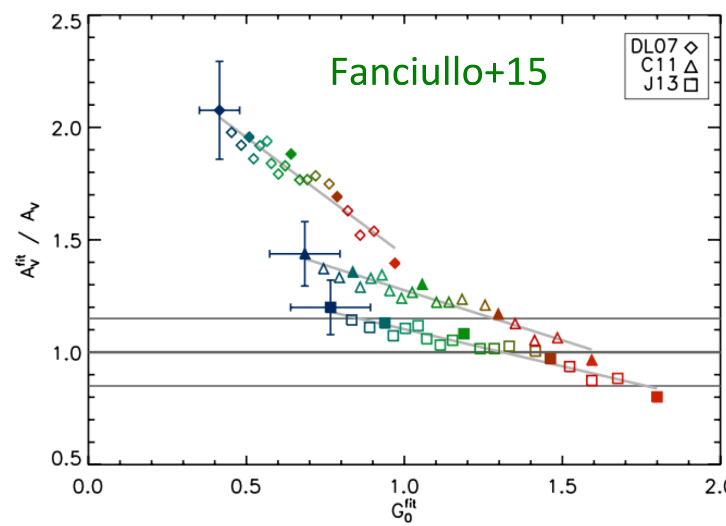
- Based on Draine & Li (2007): graphite & silicate
- P_{353}/ p_v = 2.2 MJy/sr << 5.4 MJy/sr
- $(P_{353}/I_{353}) / (p_v/\tau_v)$ = 3.3 ~ 4.2

- $P/I(\lambda)$ flat or increasing (actually, flat)



Total emission:

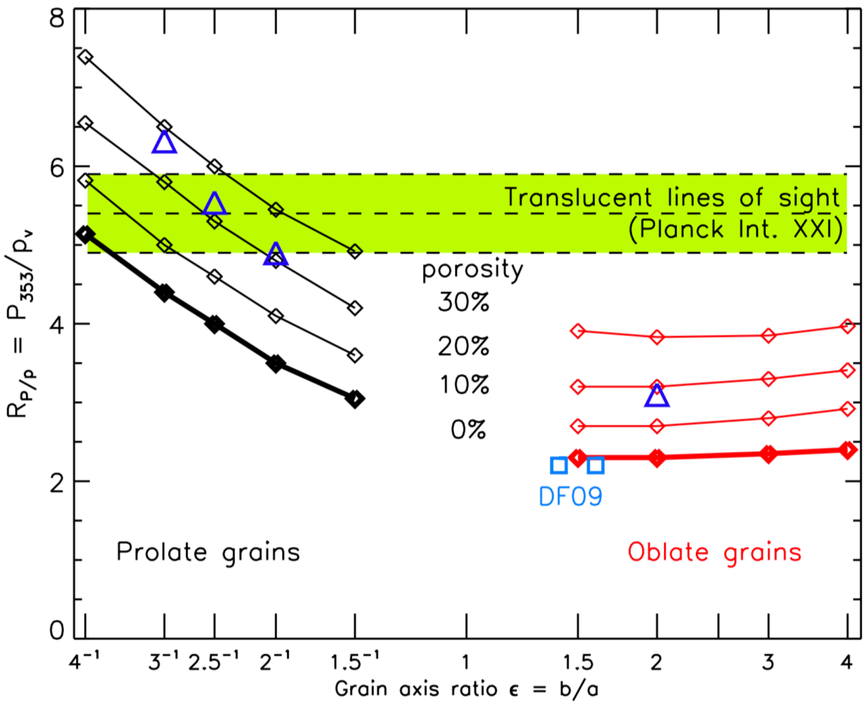
- Draine & Li (2007) dust is not emissive enough.
- Compiegne+11 almost ok : graphite replaced by more emissive a-C carbon
- Jones+13 (based on an evolution scenario) fit the data :
  - Silicate is core-mante (0.5 nm a-C mantle)
  - Carbon is core mantle (core : a-CH, mantle: a-C)

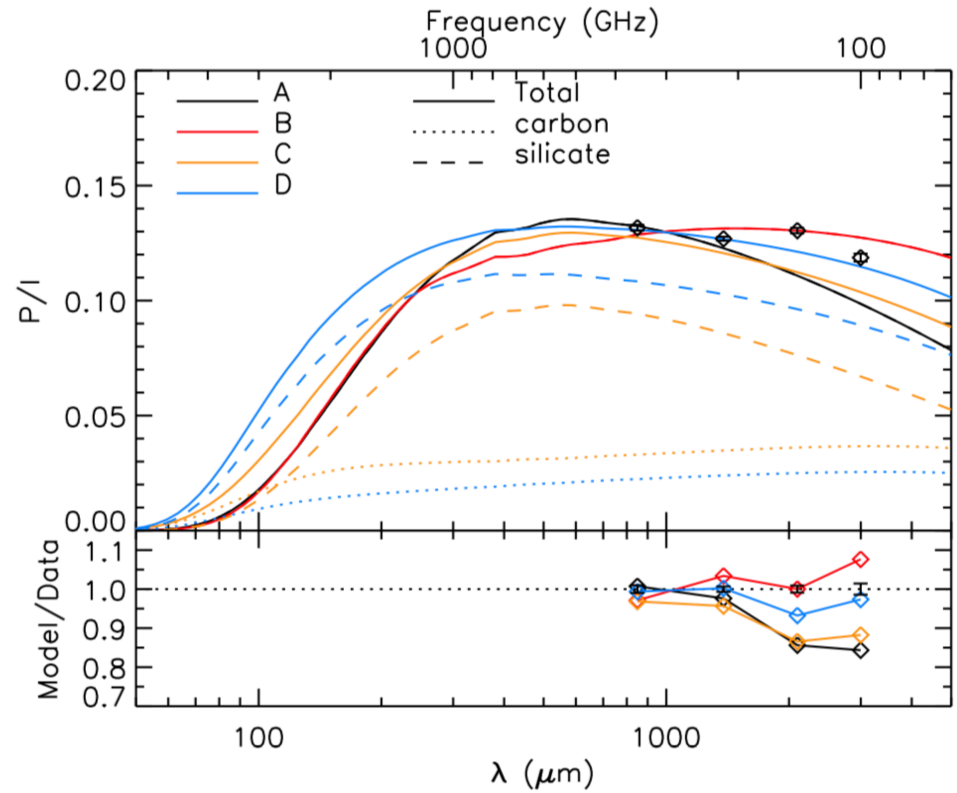


New dust model for the diffuse ISM (Guillet+2018)

Post-*Planck* dust model Guillet+2018, derived from Compiegne+2011

- Based on the `DustEM` tool : https://www.ias.u-psud/DUSTEM/





Planck 2018 XI : spectral index almost the same in intensity and polarization

$$\beta_P - \beta_I = 0.05 \pm 0.03$$

Planck results on grain alignment

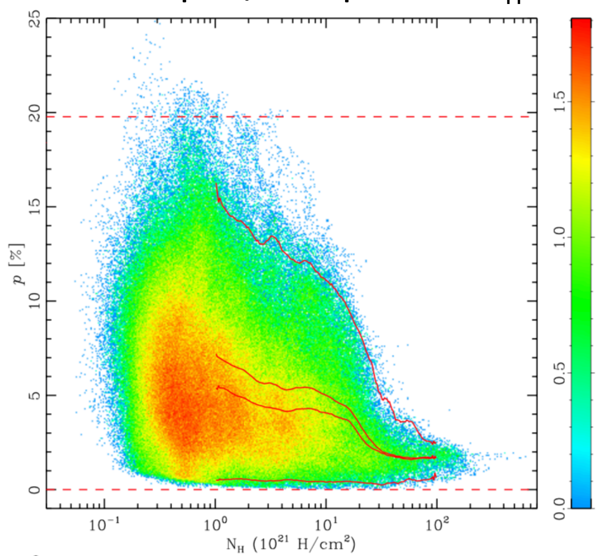
Planck int. results. XIX (2015)

- The polarization fraction p = P/I and the local dispersion of position angles S

$$\mathcal{S}(\boldsymbol{r},\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\psi(\boldsymbol{r}+\boldsymbol{\delta}_i) - \psi(\boldsymbol{r})\right]^2}$$

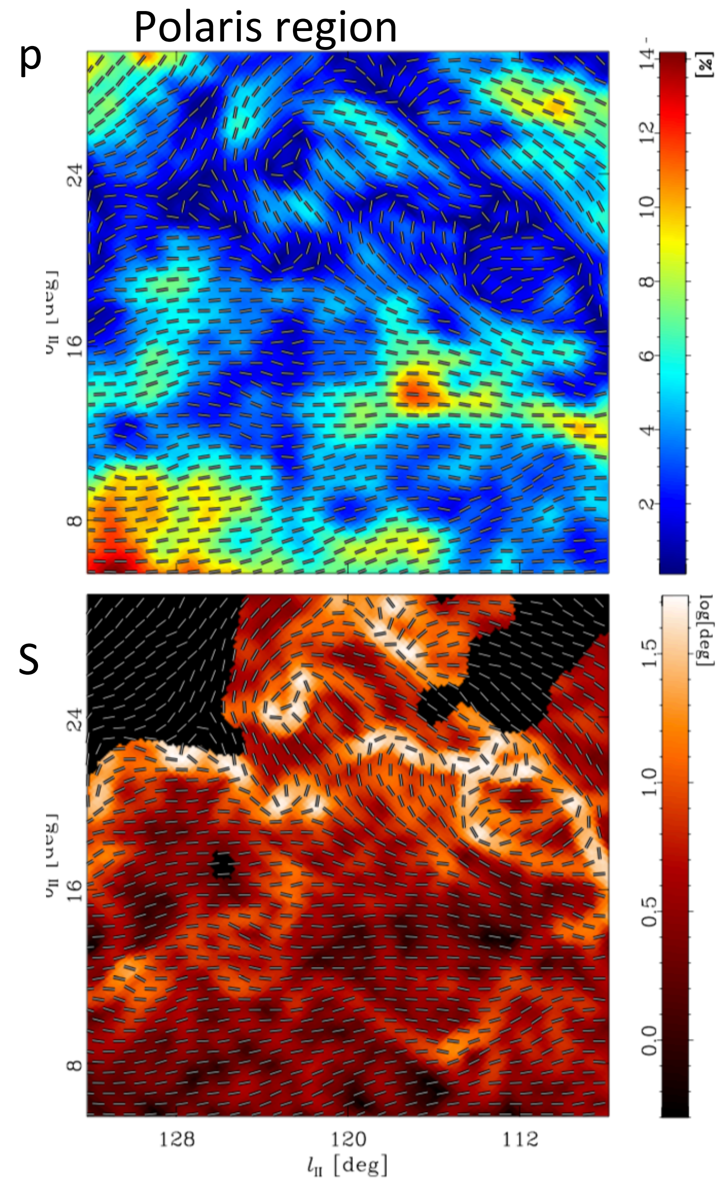
  are **anti**correlated

- The dust polarization fraction p=P/I drops with N_H



Planck int. results. XX (2015)

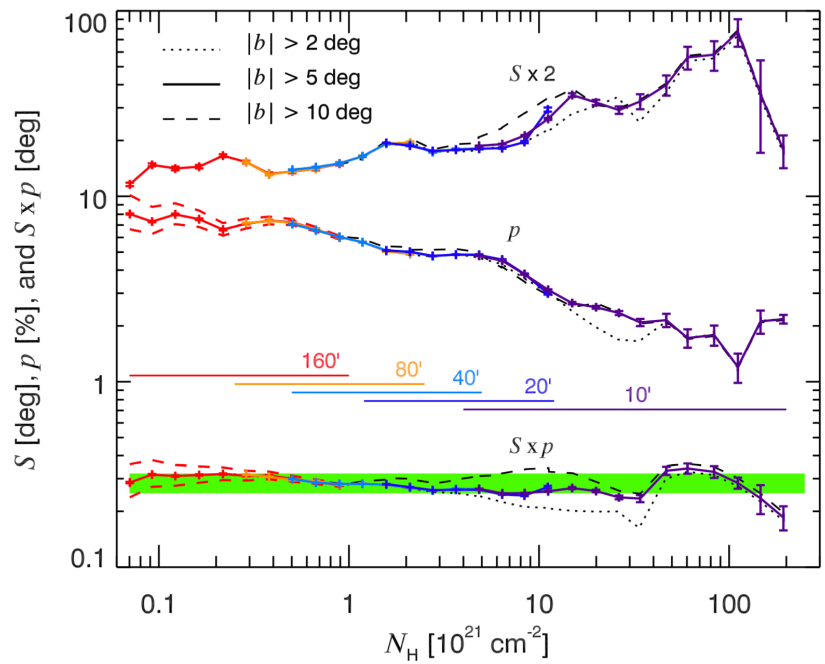
Both trends can be reproduced by computing polarization maps from MHD simulations (RAMSES, Hennebelle+2018), without any need for a variation in grain alignment.

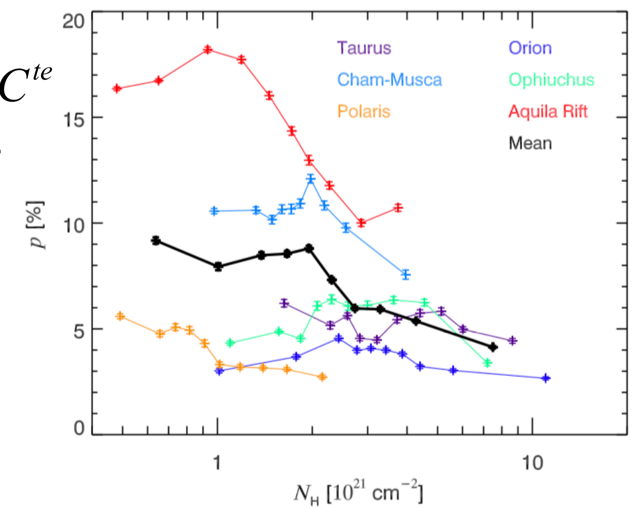


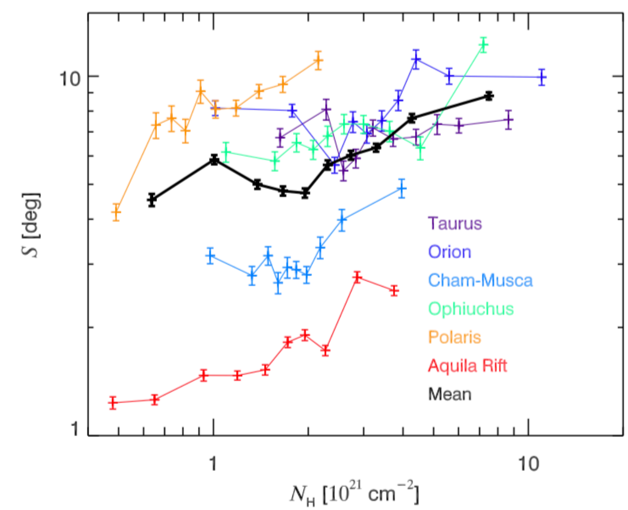
Planck results on grain alignment

Planck 2018 results. XII

- Reevaluated maximal polarization fraction : p = P/I: 22%
- Systematic **inverse**-correlation between S and p : $\left\langle S \times p \right\rangle_p = C^{te}$
- Variations in p are almost entirely due to variations in S, i.e. ar due to the variations of the magnetic field structure on the lin of sight and not to a drop of grain alignement.







S.p drops by less than 25% between $N_H=10^{20}$ and $N_H=2.10^{22}$ cm^{-2}.

Maximal polarization : emission vs extinction

Planck 2018 results. XII

353 GHz polarization correlates well very optical polarization :

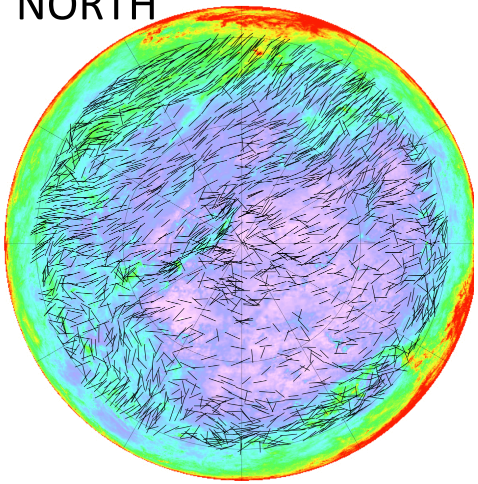
- Polarization angles agree well.
- 353GHz to optical ratios do not vary with N_H
- Similar decrease of p with $N_{H.}$

We use the correlation with *Planck* data to better estimate the maximal Polarization in the optical :

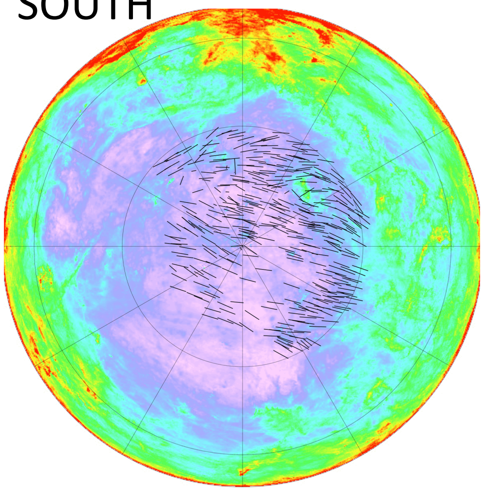
- 353GHz : P/I = 20%
- **Optical : p/E(B-V) = 13%**

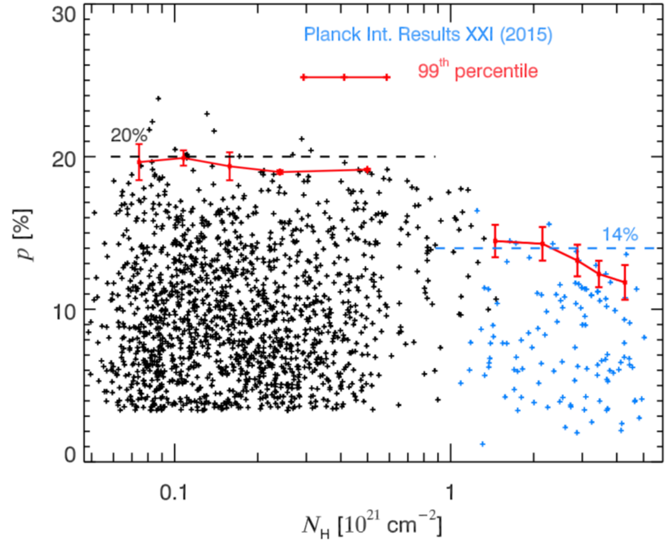
Well above the limit p/E(B-V) = 9 % (Serkowski+1975)

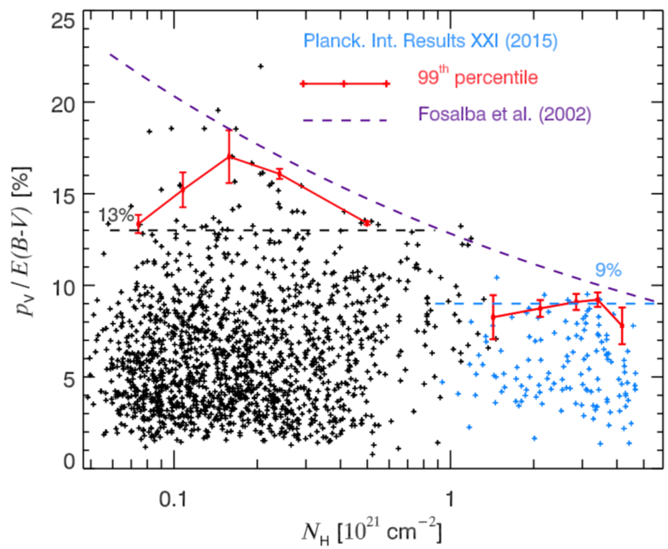
NORTH



SOUTH

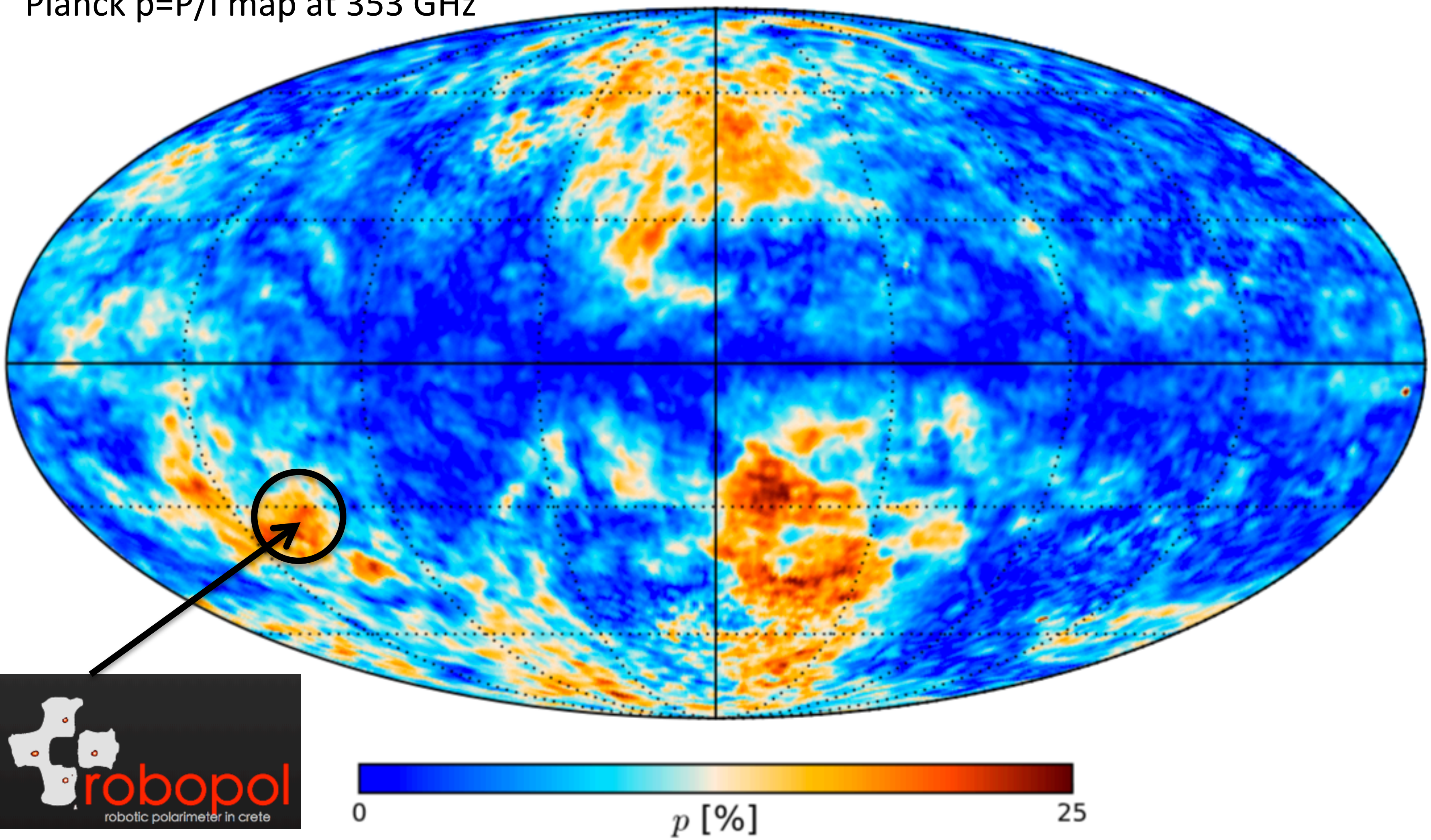






Follow-up in the optical of a *Planck* polarization peak

Planck p=P/I map at 353 GHz

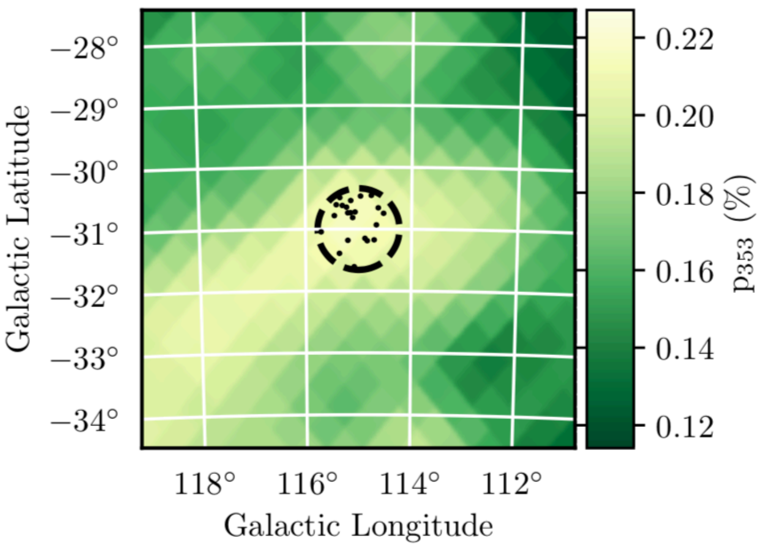


robopol
robotic polarimeter in crete

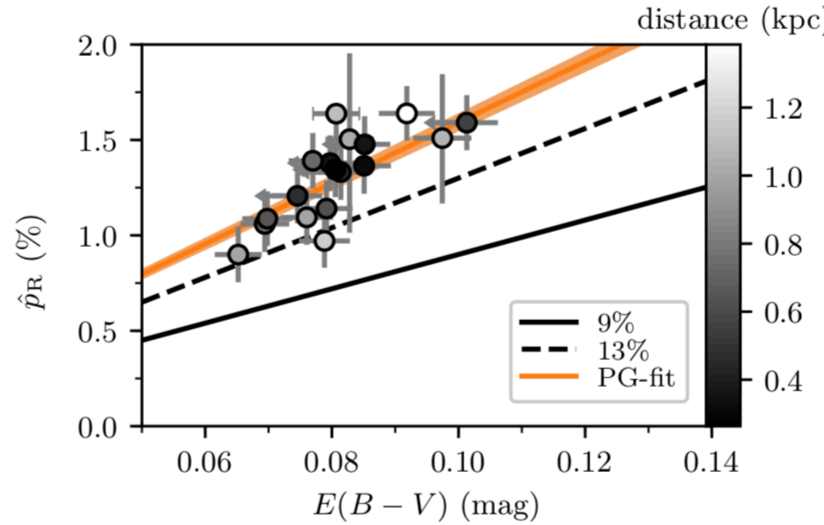
Follow-up in the optical of a *Planck* polarization peak

Panopoulou+2019

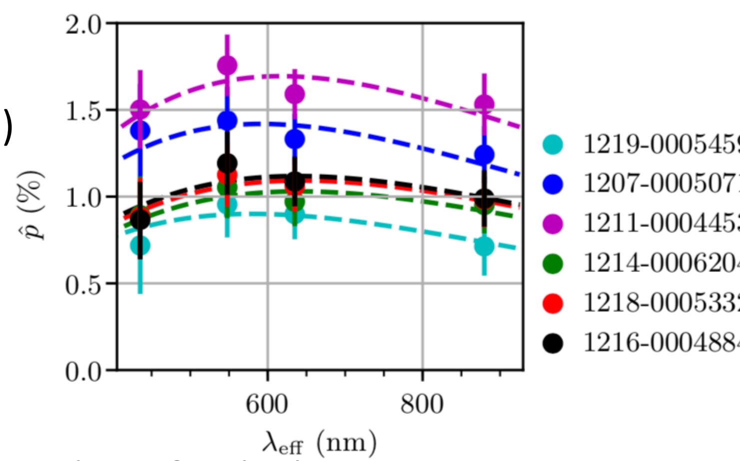
Planck polarization fraction : 20-22%



Very high polarization fraction in the optical (**R-band**):
p/E(B-V) = 13-18%, depending on the *E(B-V)* map.



Peak of polarization normal (close to diffuse ISM mean value)
⇒ **Is NOT to a peak of the alignment efficiency**



First summary and perspectives

***Planck* results on dust physics**

- Dust properties (emissivity, spectral index) vary in the diffuse ISM, and systematically in the transition from the diffuse to the dense ISM
- Dust models based on compact astrosilicate (Draine & Li 2007, Siebenmorgen+2014, some of Zubko+2004) are not emissive enough by a factor 2 in intensity and 2.5 in polarization.
- Dust maximal polarization fraction is ~1.5 higher than usually assumed : 22% in emission, > 13% in extinction.
- Grain alignment is high and uniform in the diffuse ISM (up to $N_H \sim 10^{22}$ cm-2).

Some open questions on dust polarization :

- **Is dust a reliable tracer of the magnetic field in dense cores ? Where ?**
- How fast do grains lose their alignment by RATs when entering dense cores ?
- What is the shape and structure of dust grains in the diffuse ISM ?
- How does dust evolution, namely dust coagulation in dense cores, affect the capability of dust grains to emit polarized emission ?

Is dust a reliable tracer of the magnetic field ?

Polarization fraction : a highly degenerate observable

In emission (Rayleigh approximation when *a* << *λ*) :

$$p = p_{max} R F \cos^2 \gamma$$

Magnetic field inclination

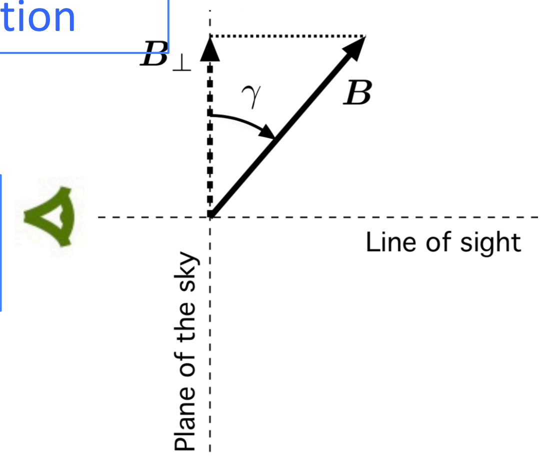
B field

Magnetic field disorder (line of sight, beam)

dust

Grain shape & composition

Grain alignment (Rayleigh reduction factor)



We want to determine under which physical conditions dust polarized emission is a reliable tracer of the magnetic field.

If p decreases because grains are less aligned (R) or less polarizing (p_{max}), then no matter the resolution, we will not be able to probe the magnetic field at high extinction.

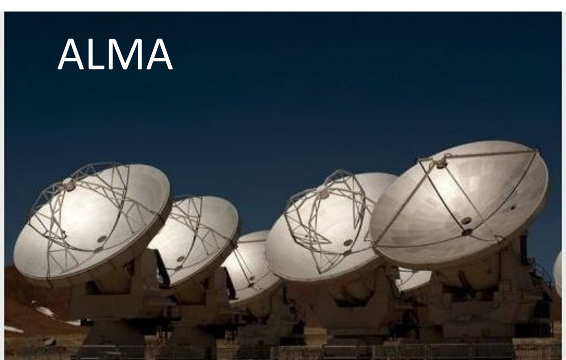
But if p decreases because the magnetic field is tanglin (F), then higher resolution observations will recover some polarization, that had disappeared at lower resolution, thereby allowing to trace the magnetic field.

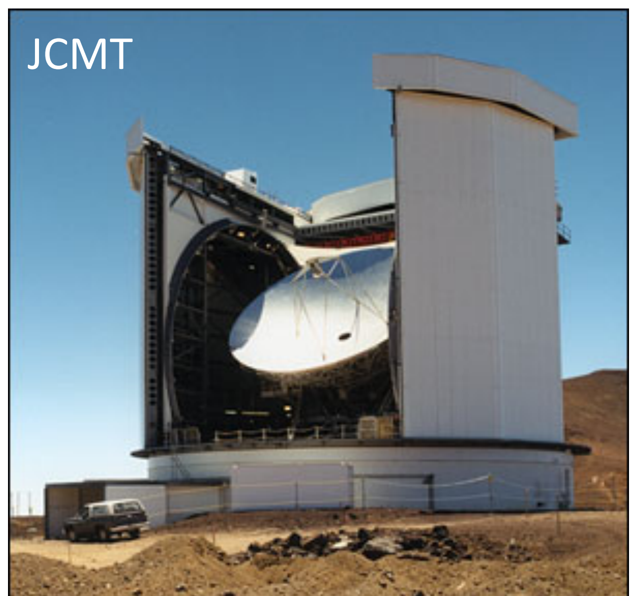
Therefore, we need to study how the ability of dust grains to polarize light, i.e. **the product $R\ p_{max}$** which combines dust properties (composition, shape and size) and grain alignment efficency, vary with the local conditions. How can we do that (simulation, data analysis) ?

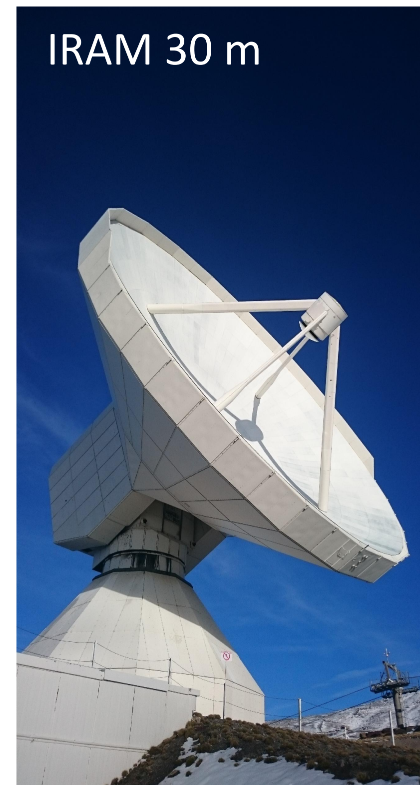
Dust polarization at high resolution and extinction

Present and upcoming instruments for polarization measures at high resolution

	wavelength (µm)	*Beam (arcsec)*	*FOV (arcmin)*
SOFIA/HAWC+	53, 89, 154, 214	5’’, 8’’, 14’’,19’’	1.3’ x 1.7’, 2.1’ x 2.6’, 3.6’ x 4.5’, 4’ x 6.1’
JCMT/SCUBA-2/POL-2	450, 850	10’’, 14’’	12’
IRAM 30m/NIKA2	1150	12’’	1.8’
ALMA	870, 1300, 3100	0.4’’, 0.3’’, 0.5’’	
SPICA/B-BOP	100, 250, 350	9’’, 18’’, 32’’	2.7’ x 2.7’







Results from HR observations: 1) SOFIA/HAWC+

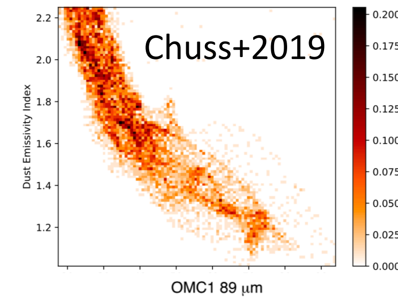
<u>*Lopez-Rodriguez+2018*</u>: 10% coherent dust polarized emission at 53 and 89 µm in AGN Cygnus A

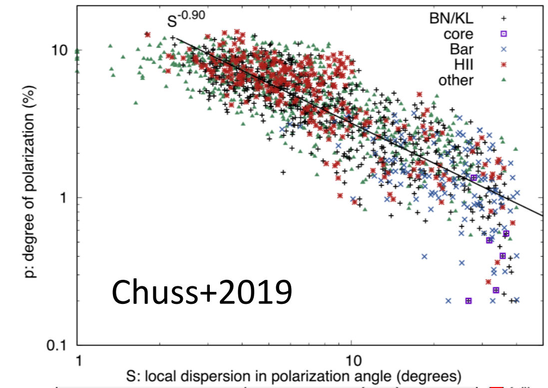
<u>*Chuss+2019*</u> : OMC-1 at 53, 89, 154, and 214 µm

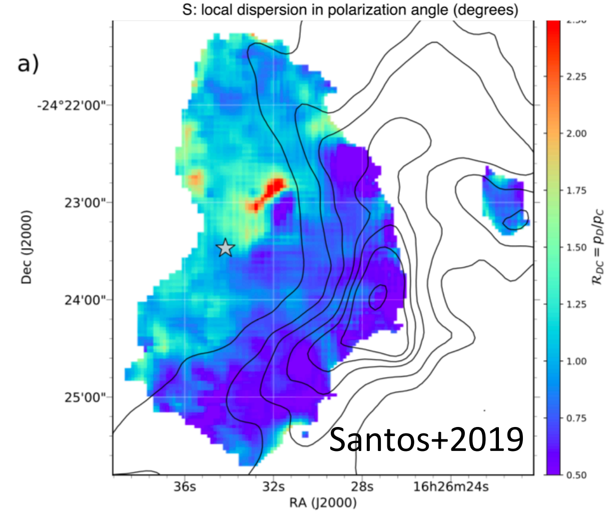
- Anticorrelation T-β, of « physical origin »
- « the depolarization as a function of unpolarized intensity is a result of intrinsic field geometry as opposed to decreases in grain alignment efficiency in denser regions. »

<u>*Santos+2019*</u>: ρ Oph-A at 89 and 154 µm.

- Study of $R = p_{154}(\lambda)/p_{89}(\lambda)$ to constrain grain alignment.
- **R is observed to systematically decrease with N_{H2}**
- « We explain the dependence of R on N_{H2} as a consequence of the ETAC (extinction-temperature-alignment correlation), i.e., grains in the warm and diffuse outskirts of the core are well aligned due to better exposure to radiation, while the alignment efficiency gradually decreases toward the colder and denser shielded core. »







Results from HR observations: 2) JCMT/SCUBA-2/POL-2

Juvela+2018 : study of *Planck* cold clumps

- Submm β ~ 1.7
- **« Most of the observed *T* -β anticorrelation can be explained by noise. »**

Kwon+2018: BISTRO Observations of the ρ Oph-A core

- « The results are consistent with previous observations of the brightest regions of ρ Oph-A, where the degrees of polarization are at a level of a few percent, but our data reveal for the first time the magnetic field structures in the fainter regions surrounding the core where the degree of polarization is much higher (>5%). »

Wang+2018: Magnetic fields within the hub filament structure in IC 5146

- « We find a power-law dependence between the polarization fraction and total intensity with an index of 0.56 in **A_V ~ 20–300 mag** regions, suggesting that **the dust grains in these dense regions can still be aligned** with magnetic fields in the IC5146 regions. »

Liu+2019: The Magnetic Field In The Starless Core ρ Ophiuchus C

- « The polarization percentage (P) decreases with an increasing total intensity (I) with a power-law index of −1.03 ± 0.05. » => grains not aligned in dense cores

Different regions, but also different methodologies giving different results.

Disentangling between dust and B effects

To achieve this, we must be able to isolate the « magnetic field » terms F and $\cos^2(\gamma)$ from the dust terms R and p_{max}. This can not be done with the study of *p* alone.

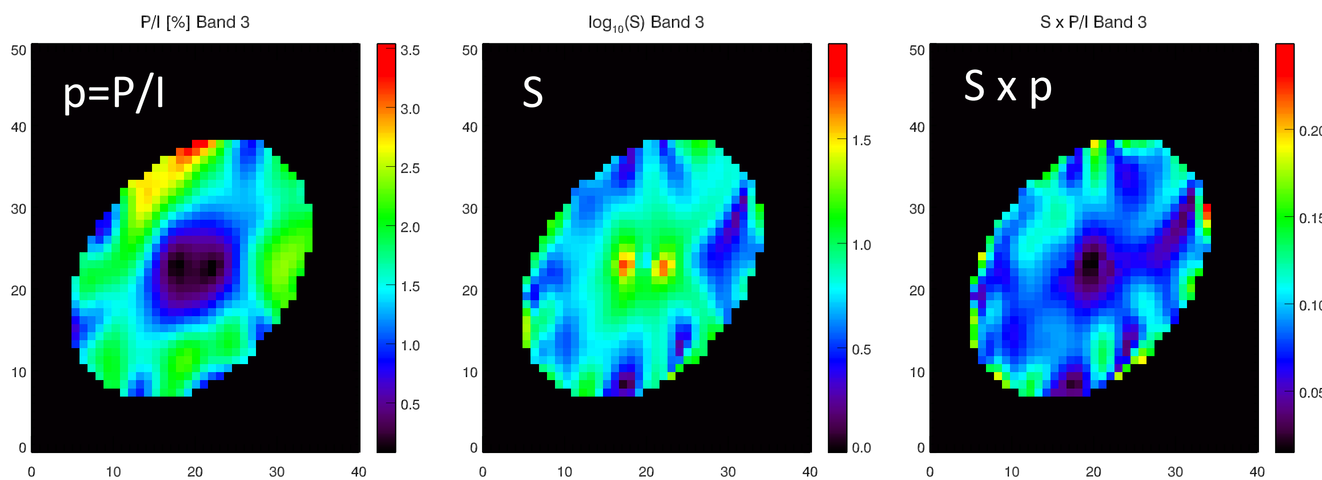
Results from Planck 2018 results XII: use the statistics of S and p together

In Planck 2018 results XII, we demonstrated that : $\langle S \times p \rangle \propto f_M \left(\frac{R p_{max}}{\sqrt{N}} \right) FWHM^{0.18}$

- N is the number of independent cells on the line of sight
- $f_M = \sigma_B / B$ is the typical ratio of turbulent to ordered magnetic field intensity.

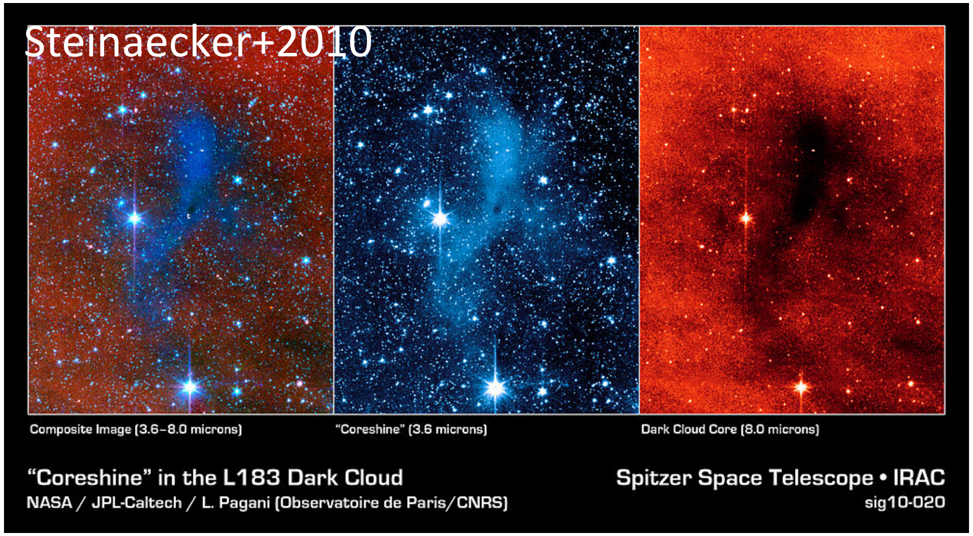
The mean value of S x p can serve as a proxy to study local variations of R p_{max}. Still, to obtain this, we have introduced new quantities that are unknown, N and f_M, that are not related to the detailed structure of the B field, but to its statistical properties.

Tentative example: HL Tau protoplanetary disk, observed at 3.1 mm (ALMA Band 3)

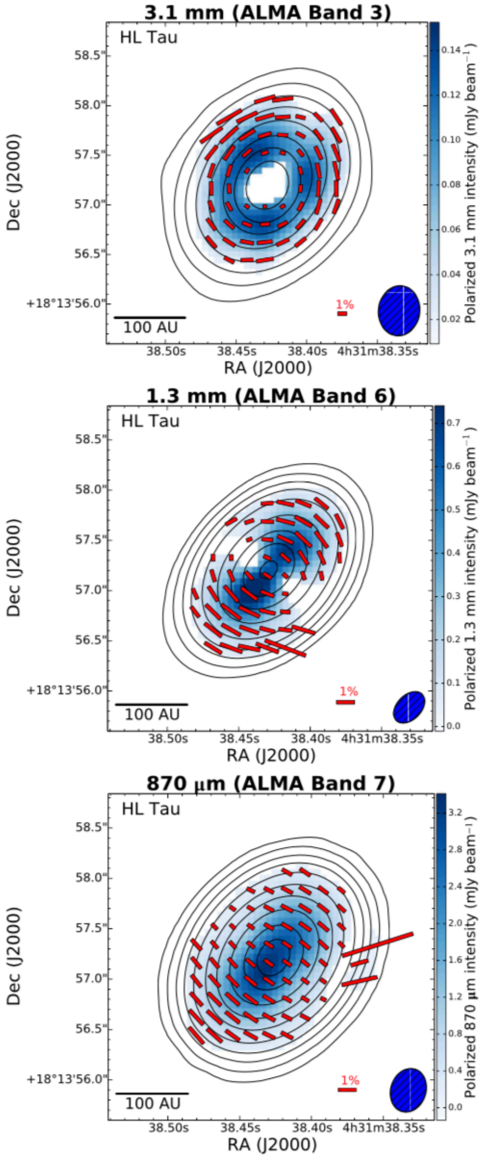


Grain growth through self-scattered emission ?

- CORES : « Coreshine » = scattering in the NIR
  - Inferred grain size : 1 µm or 0.5 µm depending on models



- DISKS : Self-scattered polarization : polarization by the scattering of dust emission by very large (2π a ~ λ) grains.
  - Observed in the majority of disks
  - **Unexpected**
  - Prevent from tracing the magnetic field by dust polarization
  - Inferred grain size : 100 µm − 1 mm
  - Polarization by aligned grains recovered at larger wavelengths



Conclusions and perspectives with NIKA2

- *Planck* observations have demonstrated that the traditional dust models based on astrosilicate and graphite (e.g. Draine & Li 2007) were off by a factor of ~ 2 in total emission and 2.5 in polarized emission, per unit extinction.

- New models compatible with *Planck* data exist
  - Jones+2013 for the diffuse ISM, and THEMIS in total intensity (pre-*Planck* model based on laboratory data)
  - Guillet+2018 in polarization (post-*Planck* model, fitted on *Planck* data)

  Both can be used with DUSTEM (https://www.ias.u-psud/DUSTEM/)

- Do dust grains trace the magnetic field in dense cores ?

- Study of grain alignment with NIKA2 and other FIR & submm polarization facilities
  - Framework : radiative + magnetic + mechanical alignment of superparamagnetic grains = MRATs (Hoang & Lazarian 2016, Hoang+2018)
  - Hard to disentangle between dust effects and magnetic field effects.
  - Use MHD simulations with tools like POLARIS (Reissl+2016) which incorporates all the detailed physics of dust alignment.

- Beware of potential polarization by self-scattering of dust emission (Kataoka+2015) in the FIR