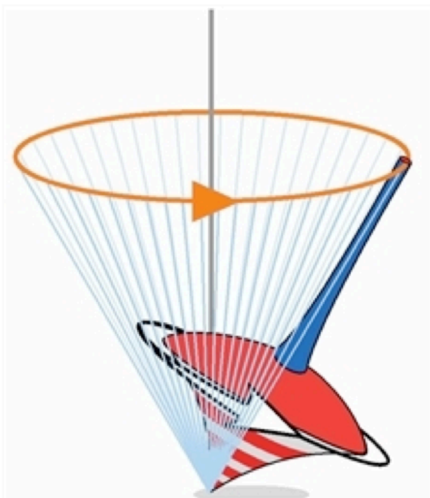
Galactic dust as a nuisance for cosmological studies



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Outline

1. Introduction : generalities on Galactic dust

2. Interaction of light with a solid particle

3. Planck results on dust polarized and unpolarized emission

4. Dust observables versus dust models

5. Spectral fluctuations of dust emission, polarized and unpolarized

Introduction

Generalities on interstellar dust

The Interstellar Medium (ISM): a turbulent, magnetized medium, with phases

3 phases approximately in pressure equilibrium

Phase	Volume	n (cm^{-3})	T (K)	Masse	Hydrogène
HIM (chaude)	60-70 %	0,0065	$\sim 10^6$	$\sim$ 0,1 %	H^+
WIM (tiède)	30-40 %	0,2 - 0,5	$6.10^3 - 10^4$	$\sim$ 10 %	H, H^+
CNM (froide)	2 %	50-100	20-50	$\sim$ 90 %	H

Clouds, cirrus, of gas and dust (1% of gas mass)

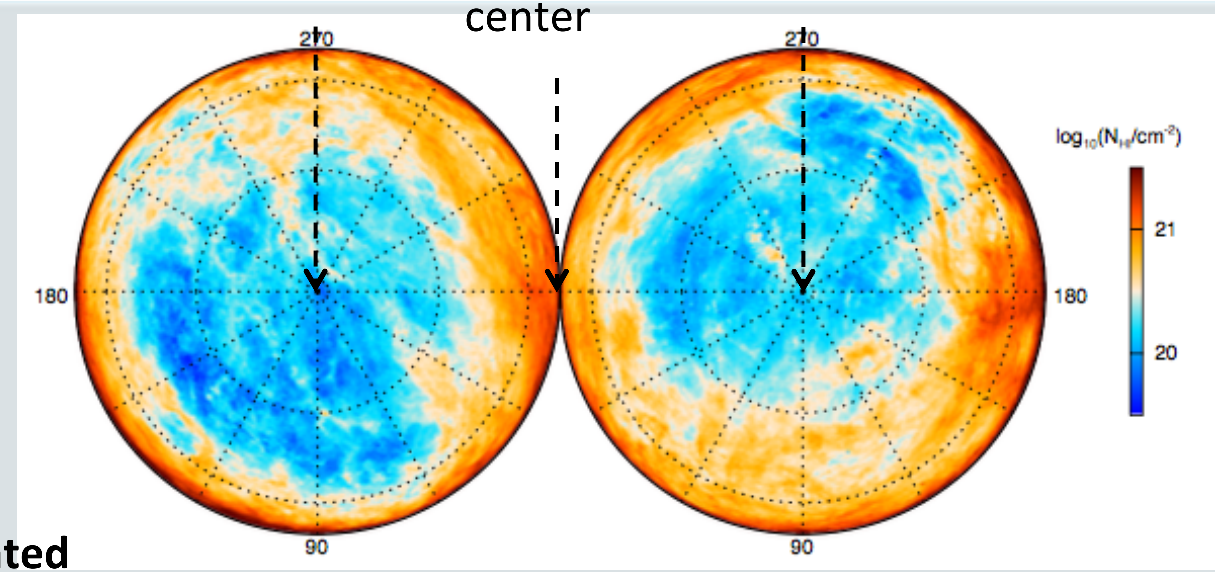
There is no line of sight free of Galactic dust

North pole

Galactic center

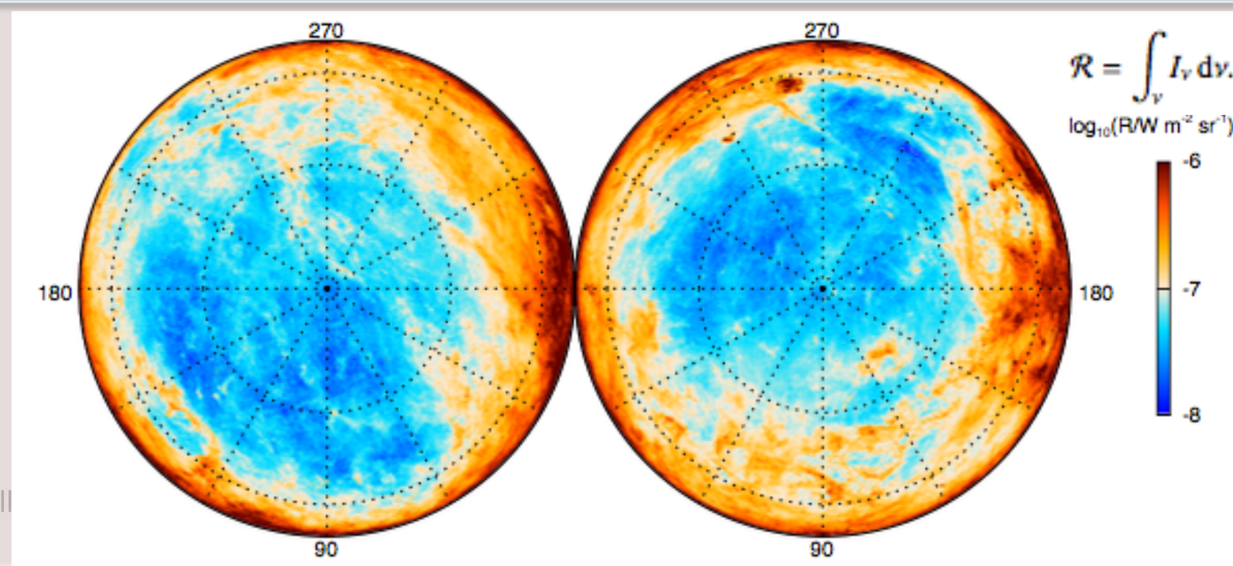
South pole

H I (neutral hydrogen)
(21 cm emission)



Dust and gas are well correlated

Dust ~ 1% of gas mass



Planck 2013 Results XI

Dust Thermal radiance R
(Planck)

An actor, a tracer, a nuisance

- **A physico-chemical actor of the Interstellar medium (ISM)**
  - Acts as a **catalyst** for molecule formation (H_2 formation, which releases 4.5 eV, is too slow in the gas phase)
  - Responsible for the **heating of the gas** in the diffuse ISM via the photolectric-effect (UV on dust => energetic electrons which collisionnaly heats the gas)
  - Charged particles => **couples the gas with the magnetic field** when the ionization is low (in dense clouds)
  - Dust extinction **protects molecules** from dissociation by UV photons

- **A tracer of galactic structures**
  - Of the **gas column density** : via dust extinction/thermal emission (cf. previous slide)
  - Of the **magnetic field orientation** : via dust polarized extinction/thermal emission

- **A nuisance for extra-galactic studies (unpolarized and polarized)**
  - Dust **hides** (extinction: from UV to NIR) or **contaminates** (emission: from Mid-IR to mm) extragalactic emission
  - Dust properties (spectral index, temperature, optical depth per H) are **not uniform** through the ISM
  - Variations in the dust properties combine with those of the **turbulent** Galactic magnetic field in polarized observables

Dust is the solid phase of the ISM

Major components : C, Si, Fe, Mg, O

- **sand (silicate) : olivine $MgFeSiO_4$, pyroxene $(MgFe(SiO_3)_2$**
- **soot (amorphous carbon a-C, hydrogenated amorphous carbon a-CH)**

Minor components : Na, Al, Ca, Ni

Trace components : Ti, K, Cr, Mn, Co

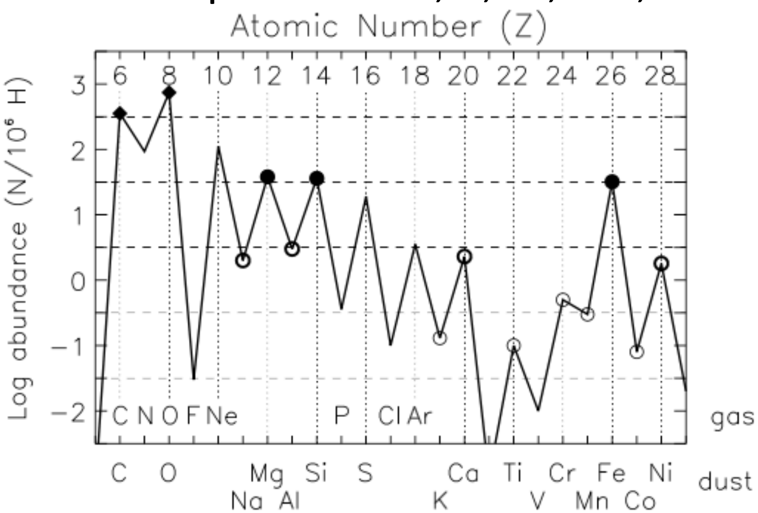


Figure 1. Solar abundances in parts per million (ppm $\equiv N/10^6$ H) *vs.* atomic number [Anders & Grevesse 1989; with C, N and O data from Grevesse and Noels 1993], (*solid line*). The elements labelled above (below) the x-axis indicate those elements with a 'preference' for the gas (solid) phase. The 'sawtooth' pattern, with peaks at even Z values, arises from the nucleosynthetic formation of the elements from He nuclei, $^4_2He^{++}$. The dust-forming elements can be grouped into primary (C and O with abundances ≥ 300 ppm, *filled diamonds*), major (Mg, Si and Fe with abundances ~ 30 ppm, *filled circles*), minor (Na, Al, Ca and Ni with abundances ~ 3 ppm, *heavy circles*), and trace (K, Ti, Cr, Mn and Co with abundances ~ 0.1 − 0.3 ppm, *light circles*) dust constituents.

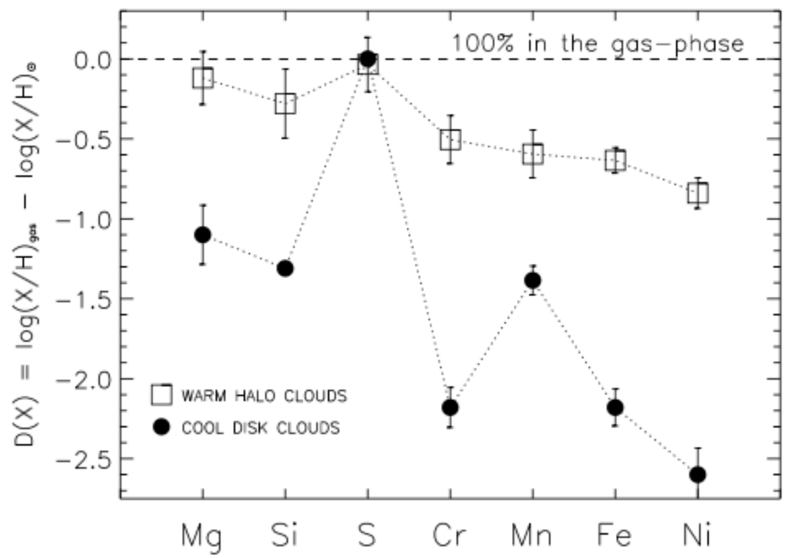


Figure 3. Gas phase abundances for the major (Mg, Si and Fe), minor (Ni) and trace (Cr and Mn) dust-forming elements and S for diffuse lines of sight lines through cool clouds in the Galactic disk (*filled circles*) and warm clouds in the Galactic halo (*open squares*) for Solar reference abundances. The vertical bars indicate the ranges of the observed values; data taken from Savage and Sembach [1996]. For the Mg data we have adopted the current best estimate for the Mg^+ oscillator strength from Fitzpatrick [1997].

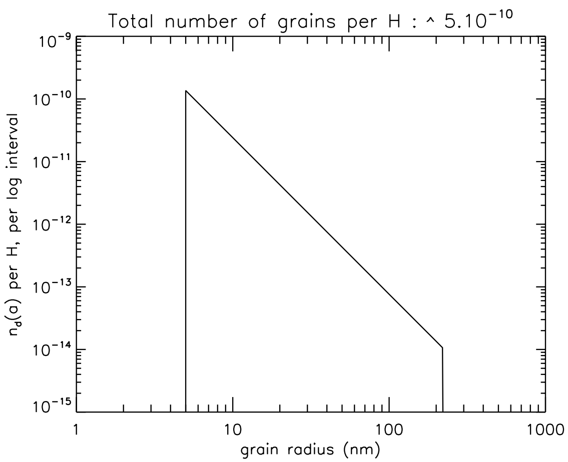
Jones, A. P. (2000). Depletion patterns and dust evolution in the interstellar medium. *Journal of Geophysical Research*, *105*, 10257–10268. http://doi.org/10.1029/1999JA900264

Dust grains are tiny particles << 1 µm

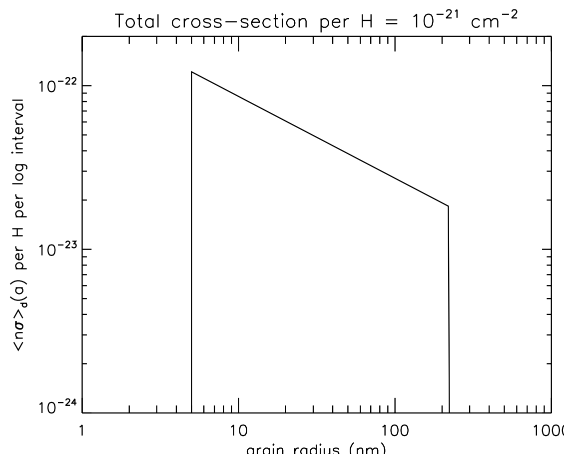
Example of the MRN size distribution for the diffuse ISM (Mathis, Rumpl, Nordsieck, 1977):

- power-law from 5 to 250 nm : $dn(a)/da = K\, a^{-3.5}$

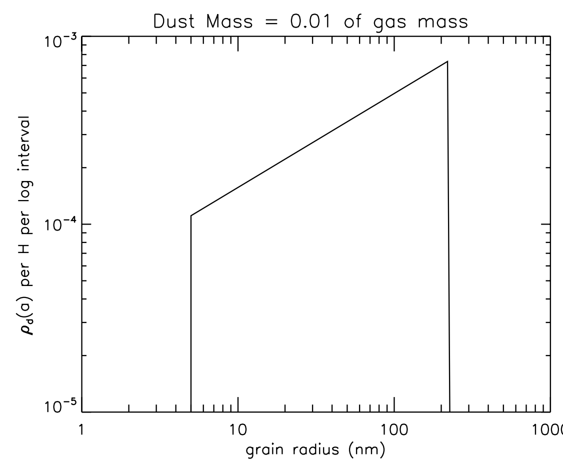
Number of grains



Cross-section of grains



Mass of grains



Grain size (nm)

- **Small grains (< 10 nm) dominate the charge carried by grains, and the surface for gas heating (photoelectric effect) and molecule formation.**
- **Large grains (> 10 nm) carry the mass, and dominate dust emission (∝ volume)**

Shape, alignment, optical properties, porosity

- Dust grains are non spherical (starlight polarization, Hall 1949)
- Dust grains are aligned along magnetic field lines (Davis & Greenstein, 1951)

- Silicate and a-C optical properties fromlab measures :
  - well-constrained from the UV to the NIR
    - Heidelberg − Jena − St Petersburg Database of Optical Constants : http://www.mpia.de/HJPDOC/
    - See also Jones et al 2013: The evolution of amorphous hydrocarbons in the ISM: dust modelling from a new vantage point, *558*, 62. http://doi.org/10.1051/0004-6361/201321686)
  - Only recently in the FIR and submm (Demyk et al. (2017). Low temperature MIR to submillimeter mass absorption coefficient of interstellar dust analogues. A&A, *600*, A123. http://doi.org/10.1051/0004-6361/201629711)

- Iron inclusions embedded in the silicate matrix ?
  - Davoisne, et al 2006. The origin of GEMS in IDPs as deduced from microstructural evolution of amorphous silicates with annealing. *A&A*, *448*, L1. http://doi.org/10.1051/0004-6361:200600002

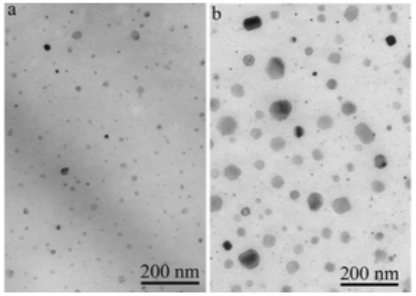
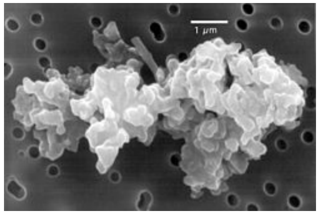


Fig. 1. TEM micrograph of annealed sample **a)** at 870 K for 780
and **b)** at 1020 K for 3 h. Rounded metallic nano-particles enclose
in the amorphous silicate. They formed by a reduction reaction an
further precipitation since metallic Fe is immiscible in silicates. Th
microstructure closely ressembles to those to GEMS found in IDPs.

- Dust grains are not very porous (P < 0.5 from X-ray scattering on dust grains)
  - Heng, K., & Draine, B. T. (2009). Constraining the Porosities of Interstellar Dust Grains.)



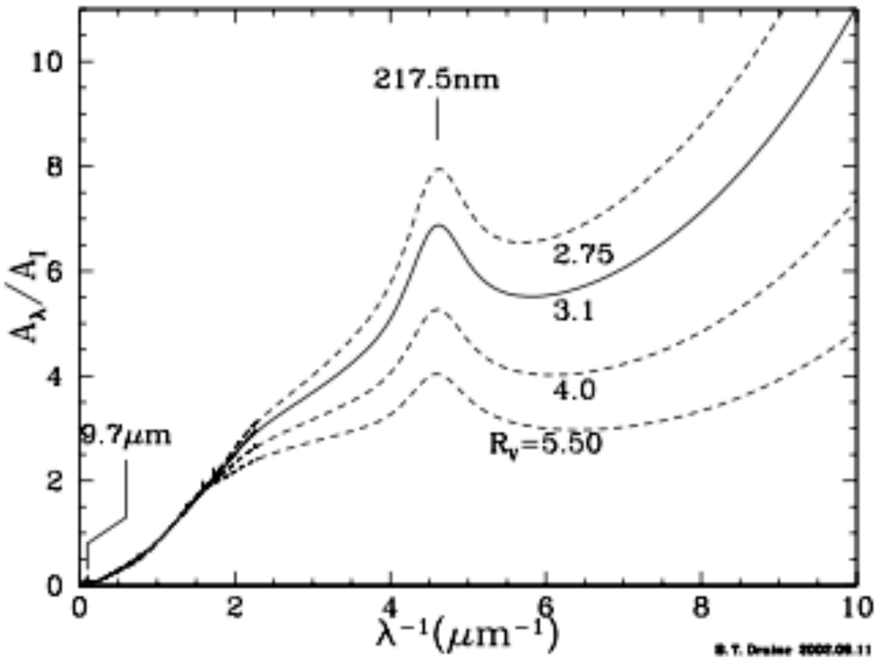
Interplanetary Dust Particle

Interaction of light with a solid particle

Extinction, emission, polarization

Extinction = absorption + scattering by dust grains => starlight reddening

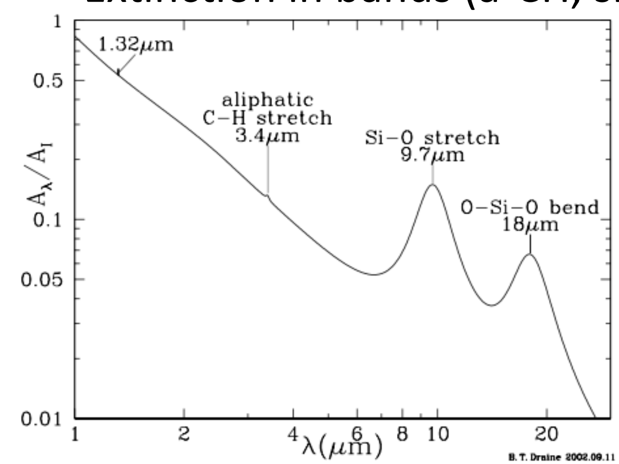
Reddening E(B-V)



Draine, B. T. (2004). Astrophysics of Dust in Cold Clouds. *The Cold Universe*, 213.

Dense core Barnard 68

Extinction in bands (a-CH, silicate)



Reddening E(B-V) correlates well with NH

$NH = 5.87\ 10^{21}\ E(B-V)$ (Rachford+09)

Interaction of an electromagnetic wave with a particle

We define $x = 2\pi a / \lambda$, a the radius of the sphere of the same volume as the grain.

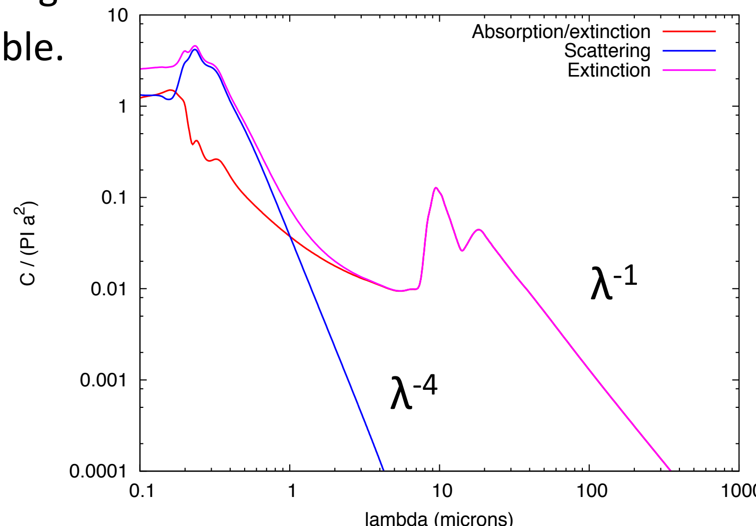
The dust optical property is described by the complex refractive index $m = n + ik$.

The grain cross-section (absorption, scattering) only depend on m and x.

3 regimes depending on x

- $x >> 1$: geometric optics : $C_{ext} = 2 \times \pi a^2$ (extinction paradox).
- $x \sim 1$: optical regime (Mie) : C_{abs} is of the order of πa^2, C_{sca} can be up to a few times πa^2
- $x << 1$: Rayleigh regime
  - $C_{abs} \propto V/\lambda$: proportional to the (total) volume of the grains
  - $C_{sca} \propto \lambda^{-4}$: decreases rapidly and becomes negligeable.

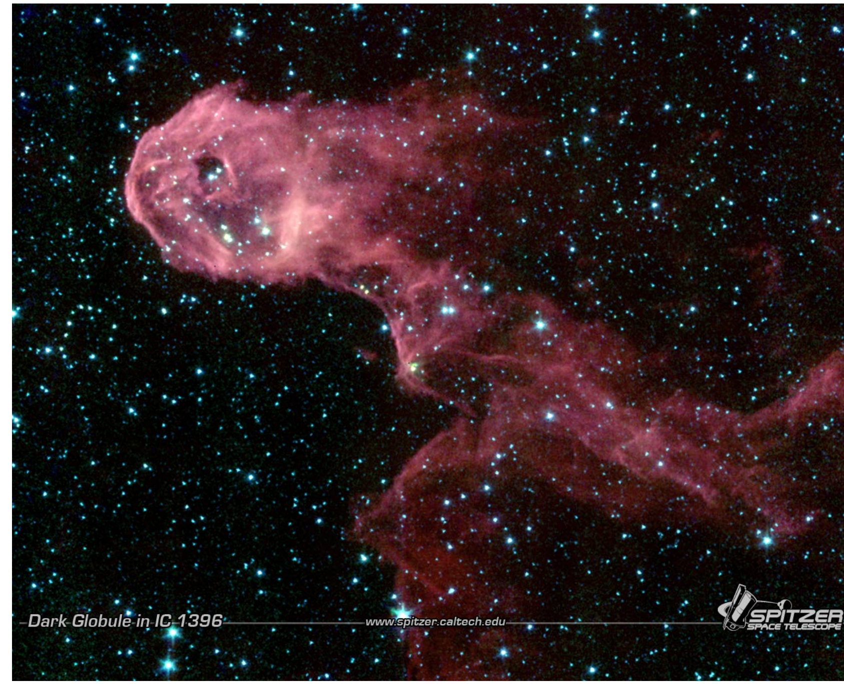
Exemple : sphere, a = 0.1 µm, astrosilicate



Energy balance between absorption & emission

The Elephant Trunk Nebula (Hubble, optical)

The Elephant Trunk Nebula (Spitzer, mid-IR)

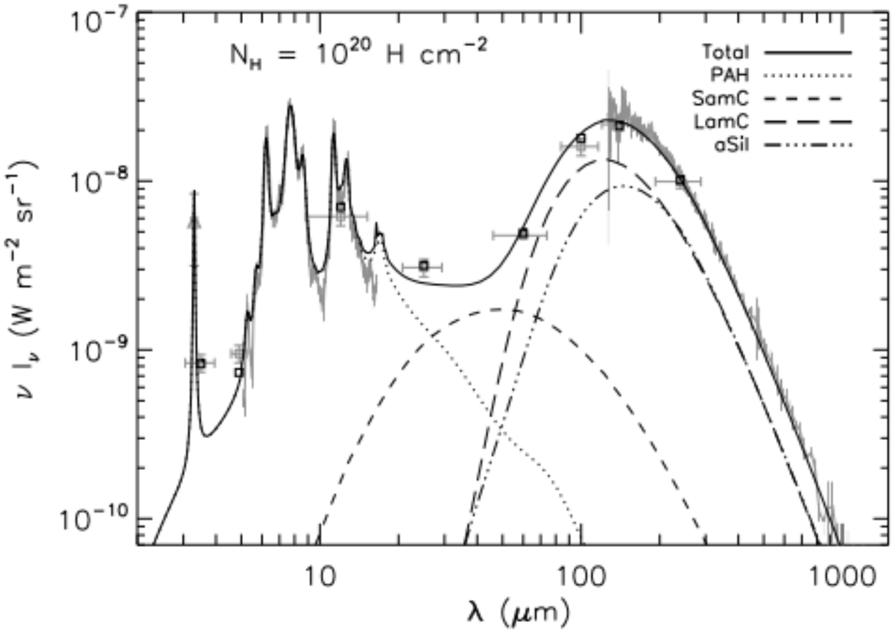


Dust extinction and dust emission trace the gas column density through the ISM:

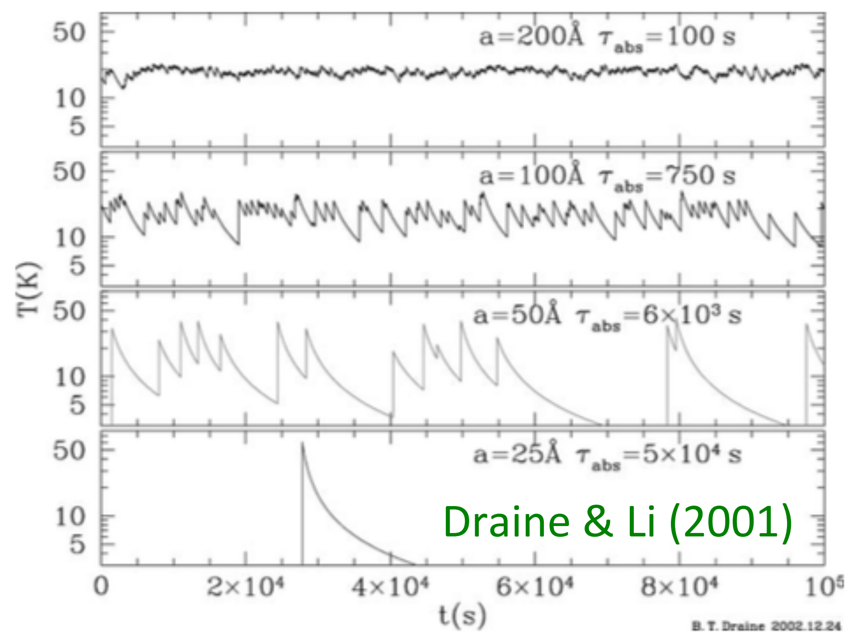
- Optical : becomes rapidly optically thick ($\tau \sim 1$) => use NIR to have $\tau < 1$
- Emission : almost always optically thin ($\tau \ll 1$)

Dust emission : at equilibrium or stochastic

Dust model (Compiegne+11)



Thermal fluctuations for different grains sizes



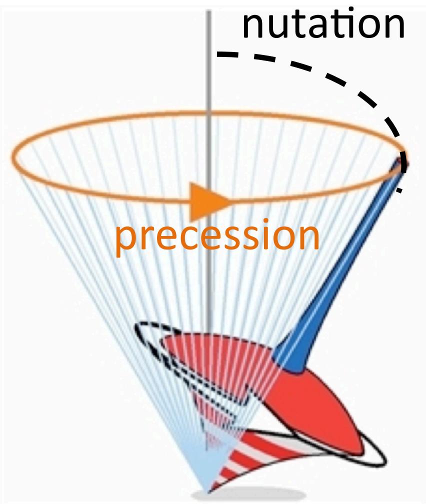
Emission can be :

- Thermal and at equilibrium (a > 10 nm) : modified black-body emission of spectral index $1 < \beta < 2$.
- Thermal and stochastic : fluctuation of dust temperature at each absorption of UV photons.
  - 5 < a < 20 nm: emission at 25 and 60 µm
  - PAHs : emission bands at 7.6, 8.6, 11.3, 12.7 µm due to in-plane and out-of-plane bending of C-H and C-C bounds from Polycyclic Aromatic Hydrocarbons (PAHs)
- Non thermal : spinning dust emission (may be) due to fast-rotating spinning grains (< 1 nm). Peaks at 30 GHz. Very Weakly polarized. See Planck Early Results XX.

Dust polarization : the top model

We think of grains like spinning tops :

- They spin around their axis of maximal inertia (small axis)
- Dust grains have an intrinsic magnetic moment (paramagnetic), or get it from their spinning (Barnett effect).
- Due to their magnetic moment, their spin axis precesses around magnetic field lines
- A torque can progressively align the spin axis along the magnetic field. This torque does not have to be magnetic



Review on grain alignment :
Andersson+15, Interstellar Dust Grain Alignment, ARAA, *53*, 501–539.
http://doi.org/10.1146/annurev-astro-082214-122414

What do we call « grain alignment » ?

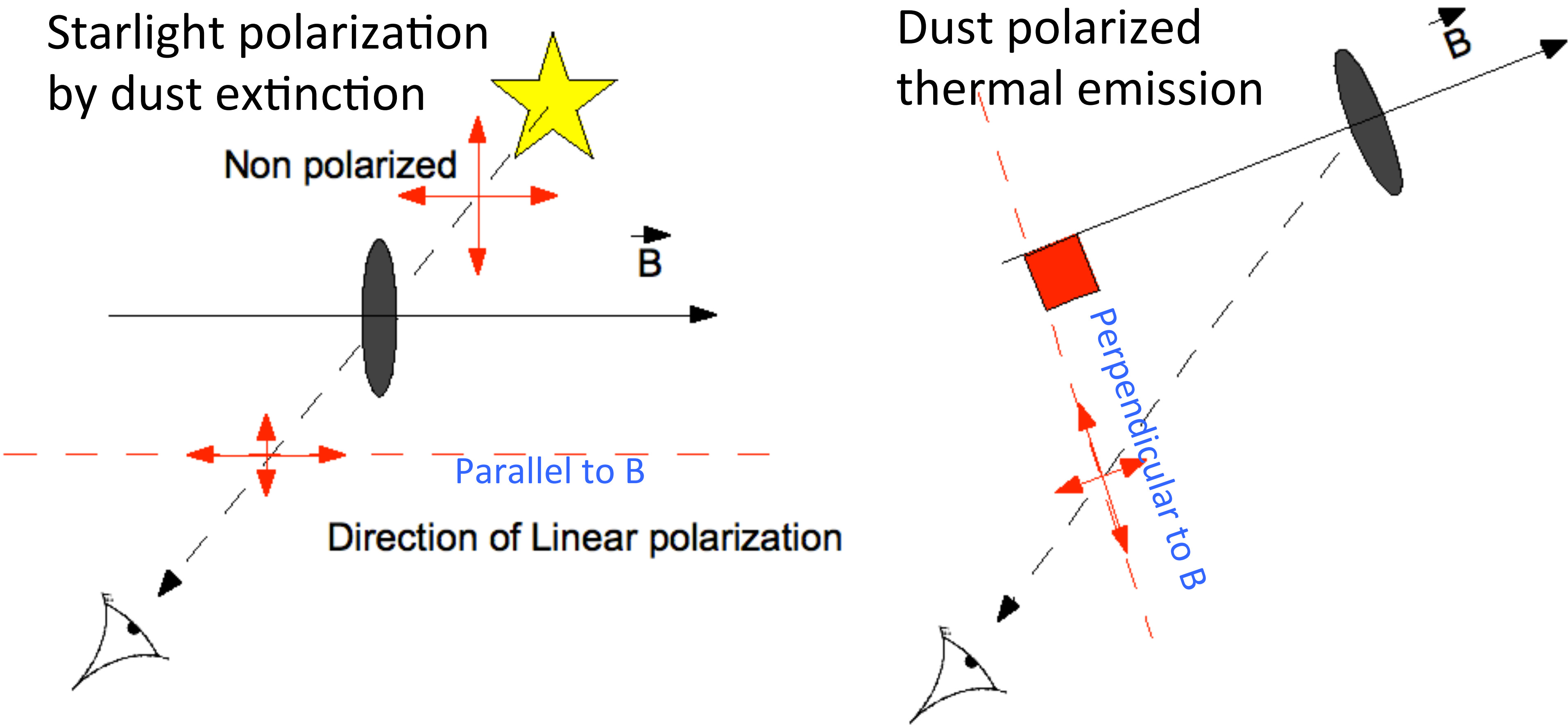
or

?

Grain alignment means alignment of the grain spin axis with the local magnetic field

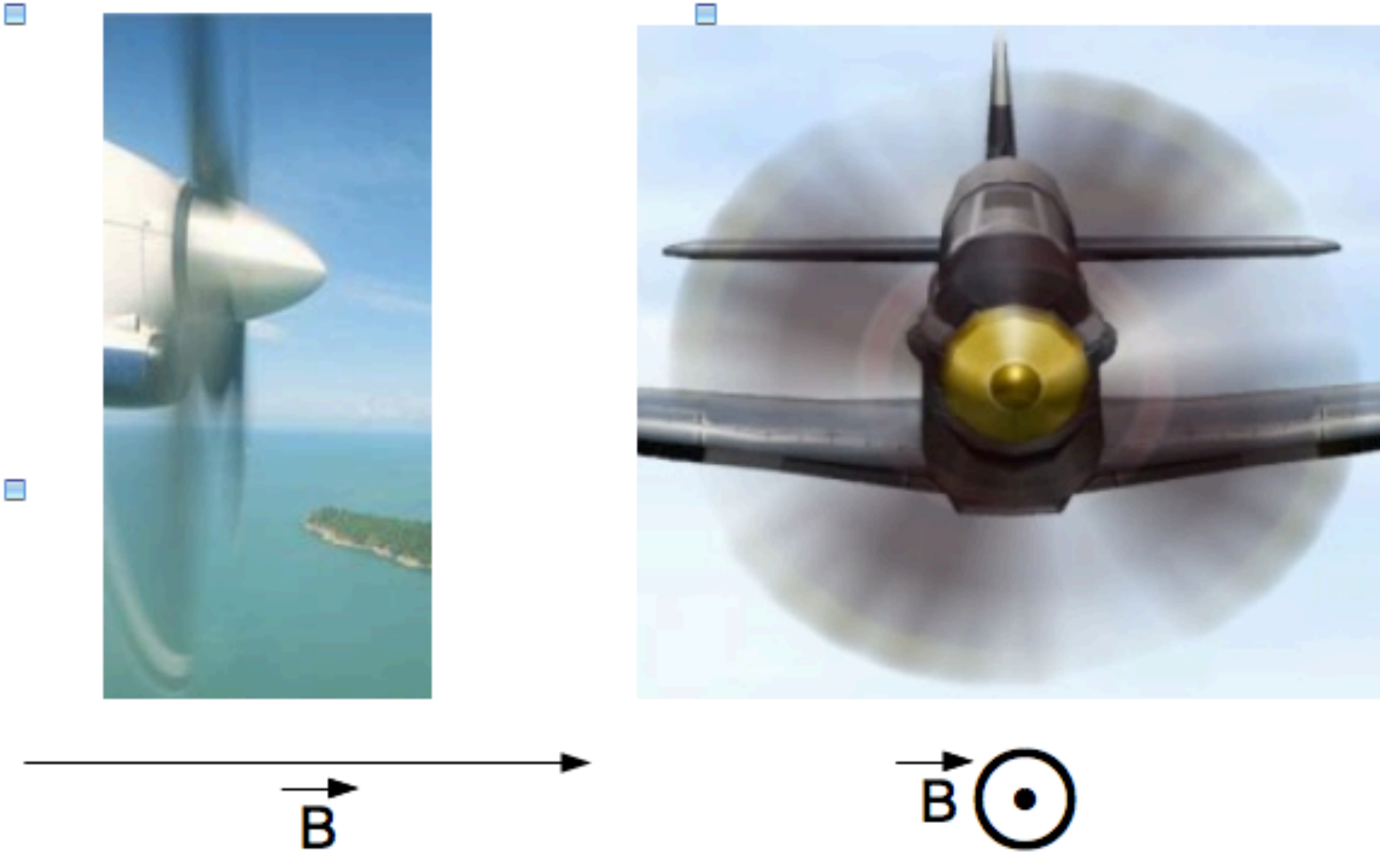
It is an alignment of the direction of the spin axis, not of the position of the grain.

Dust linear polarization
dichroic absorption & scattering



Scattering and absorption (=emission, Kirchoff's Law) cross-sections are larger when the oscillating electric field is along the longer axis than along the smaller axis

Projection effects due to the mean magnetic field orientation



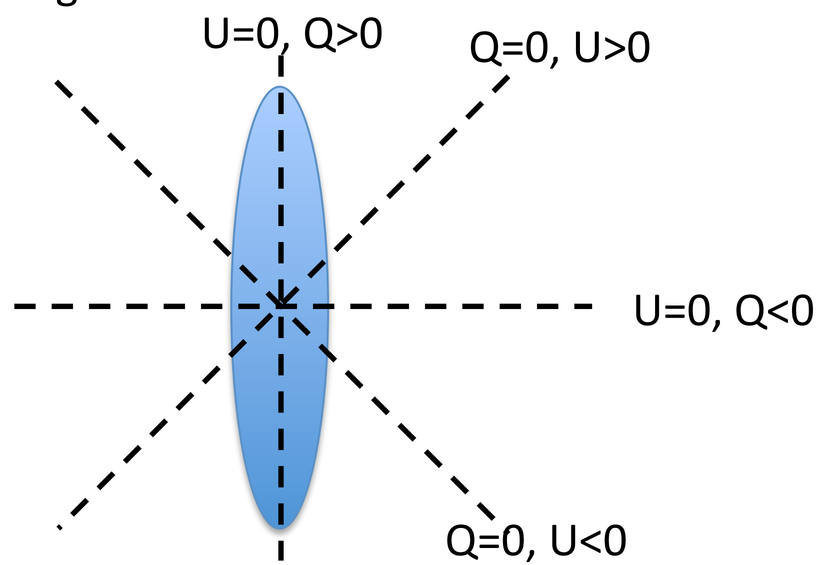
Polarization is maximal

Polarization is zero

Circular polarization

- Starlight is also circularly polarized by dust extinction.
- Aligned dust grains are a birefringent medium
- Circularly polarized light is created by dust extinction when incoming light has a U component in the polarization frame of the grain

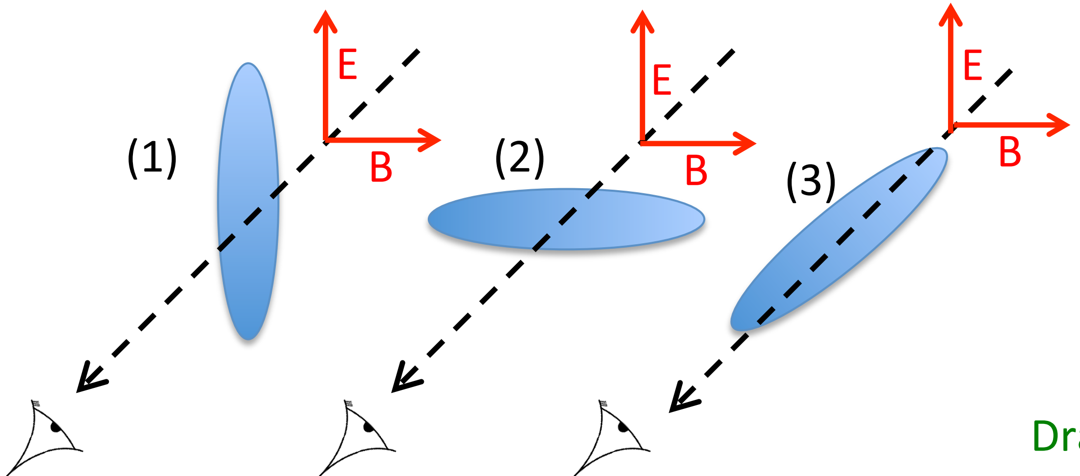
To measure polarization, 4 measures are needed:
- *2 measures at 90° : Stokes Q*
- *The same rotated by 45° : Stokes U*



- Circularly polarization is created when direction of alignment (the magnetic field) projected onto the plane-of-the-sky rotates.
- Dust emission should not be polarized ($\tau << 1$)

Rayleigh approximations for polarized emission

- In the Rayleigh regime (x << 1), the grain absorption/emission cross-section does not depend on the orientation of the oscillating magnetic field with the symmetry axis.



Draine & Fraisse 2009
Guillet+17

Case 1 : E parallel to the symmetry axis
Case 2 and 3: E perpendicular to the symmetry axis : same cross-section.

This leads to some simplification : $C_{pol} = (C_E - C_B)/2\ R\ F\ \cos^2\gamma$

- C_E (resp. C_B) is the grain cross-section when E is parallel to the grain symmetry axis
- R is the Rayleigh alignment Reduction Factor : $R = 3/2\ (\langle\cos^2\beta\rangle - 1/3)$, and β the nutation angle (angle between the spin axis and the magnetic field). Average is done over the grain dynamics.
- Gamma (γ) is the angle of the magnetic field with the plane-of-the-sky
- $F = 3/2(\cos^2\theta - 1/3)$ is the reduction factor due to magnetic field disorder on the line of sight

These simplifications are not strictly valid in the optical, and sometimes wrong.

Planck results on dust polarized and unpolarized emission

- Total Emission: Planck 2013 Results XI, Planck Int. Results XXIX
- Polarized emission: Planck Int. Results XIX, XX, XXI, XXII

Dust emission properties

Planck 2013 Results. XI

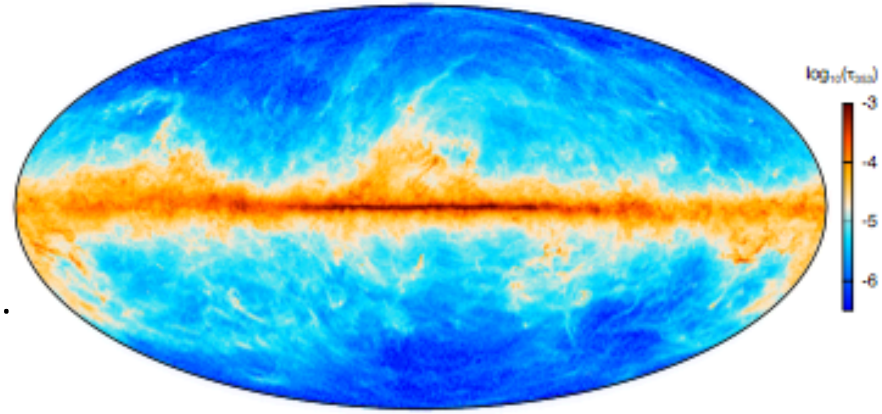
Combine IRAS, DIRBE and *Planck* data : 100 µm − 3 mm.

Modified black-body fit to the SED (3 parameters):

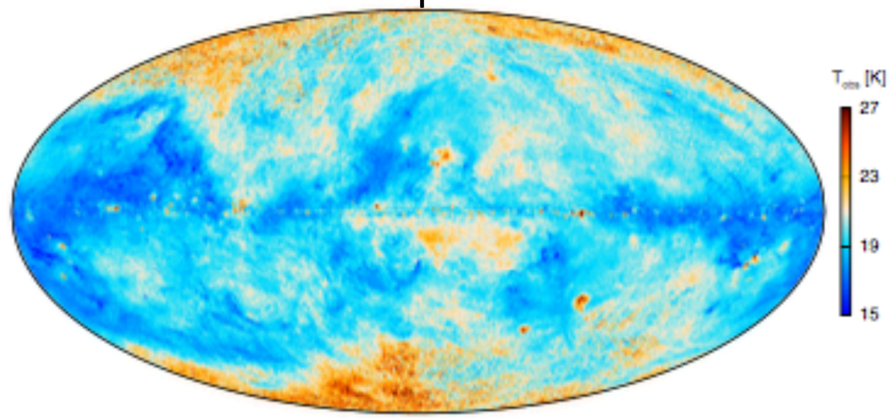
$$I_\nu = \tau_{353} \, (\nu/353\text{GHz})^\beta \, B_\nu(T)$$

- Dust opacity τ_{353}/N(HI) varies by a factor ~ 2: varitions in dust optical properties
  For an interpretation, see Fanciullo et al 2015, Dust models post-Planck: constraining the far-infrared opacity of dust in the diffuse interstellar medium, A&A, *580*, A136.
  http://doi.org/10.1051/0004-6361/201525677
- The Radiance per H, R/N(HI), is almost constant at high latitude = uniforme interstellar radiation field
- Anticorrelation β-T :
  Shetty et al 2009 (The Effect of Line-of-Sight Temperature Variation and Noise on Dust Continuum Observations, *ApJ*, *696*, 2234.
  http://doi.org/10.1088/0004-637X/696/2/2234)

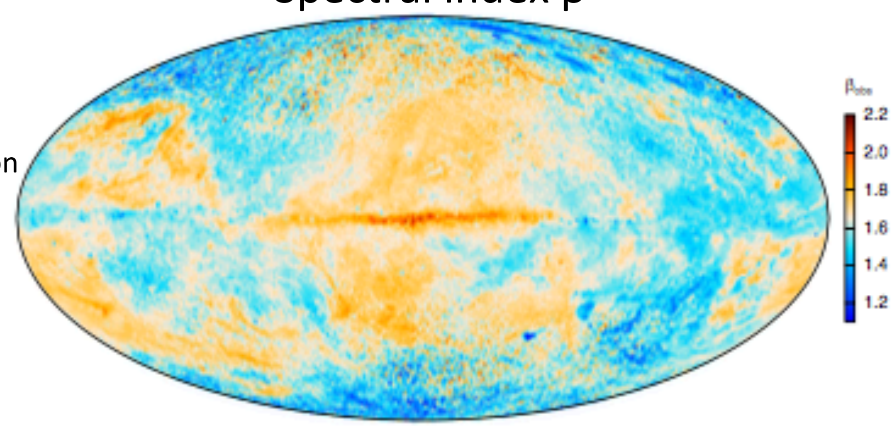
Optical depth τ_{353} at 353 GHz



Dust temperature T

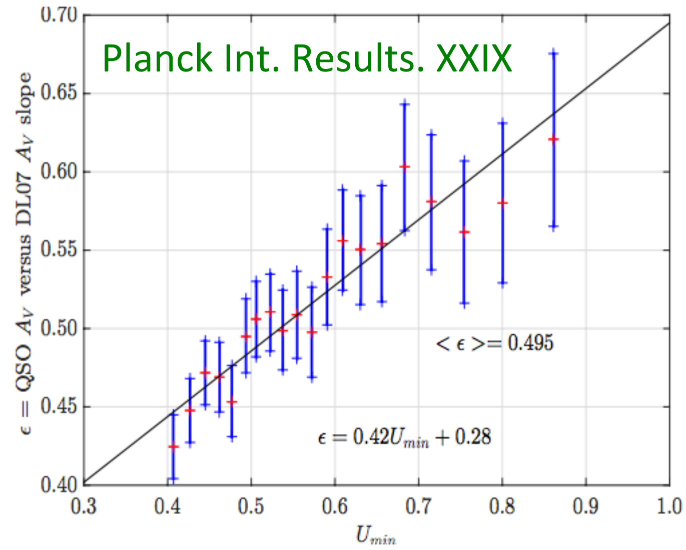


Spectral index β



Correlation between dust emission and extinction to QSOs

Planck Int. Results. XXIX



Fit to the SED with a physical dust model : Draine & Li (2007) : PAHs, graphite, astrosilicate

3 fitted parameters :

- Column density : Av
- Radiation field intensity : U_{min}
- Fraction of PDRs on the line of sight : f_{PDR}

Correlation of result Av with extinction toward 200,000 QSOs.

- All SEDs are well fitted by the model: $\chi^2 \sim 1$
- The Av fitted 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.

Dust polarized emission : Q_{353} & U_{353} maps

Planck Int. Results. XIX

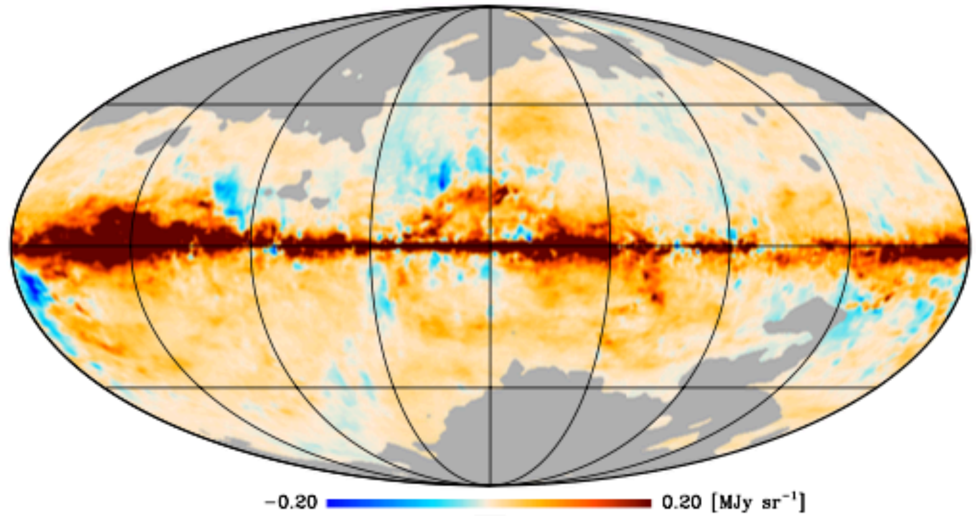
353GHz : Best S/N.

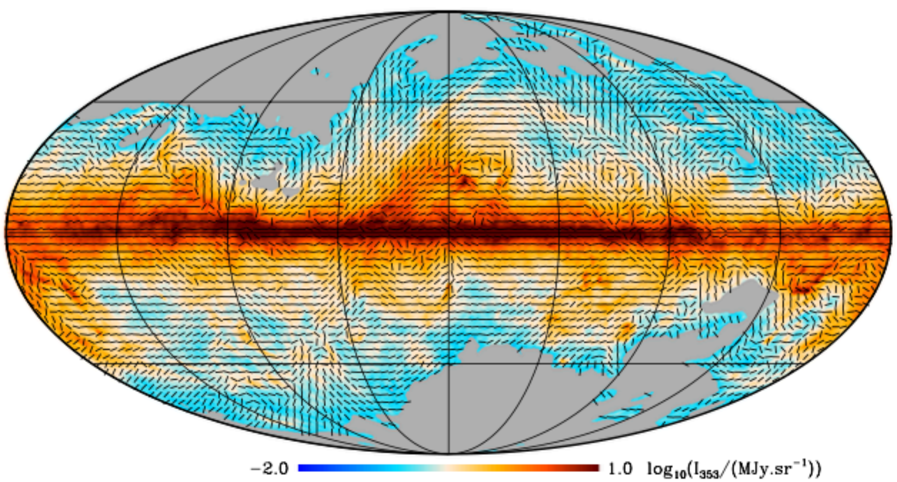
Pôles hidden : Systematics still present (2015)

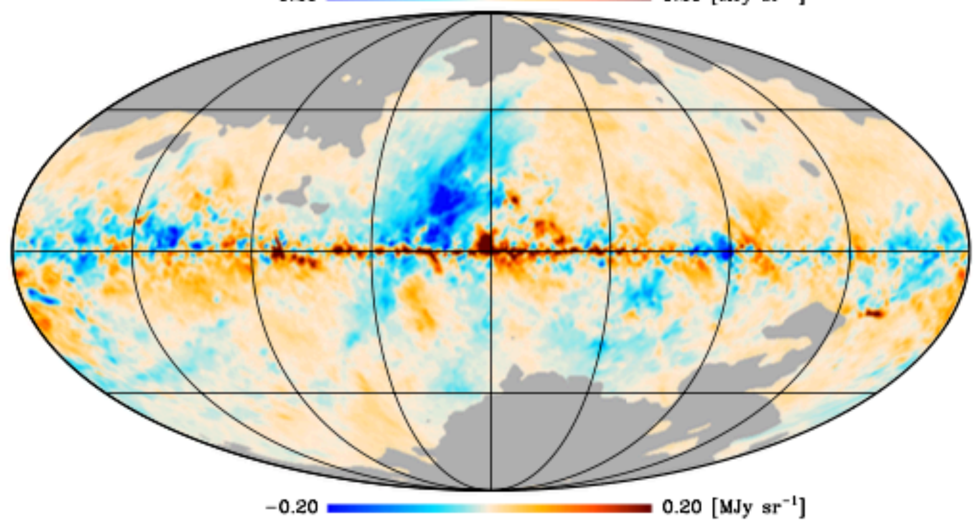
Polarization angle (Healpix convention)

$$\psi = 0.5 \times \arctan(U, Q).$$

Ψ-$\pi/2$ = magnetic field orientation.







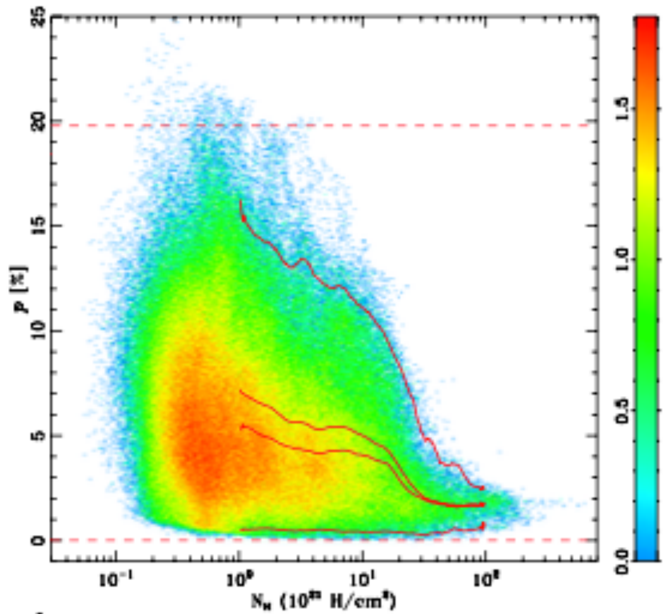
Dust polarized emission : P_{353} and P_{353}/I_{353}

Planck Int. Results. XIX

Polarization fraction must be debiased

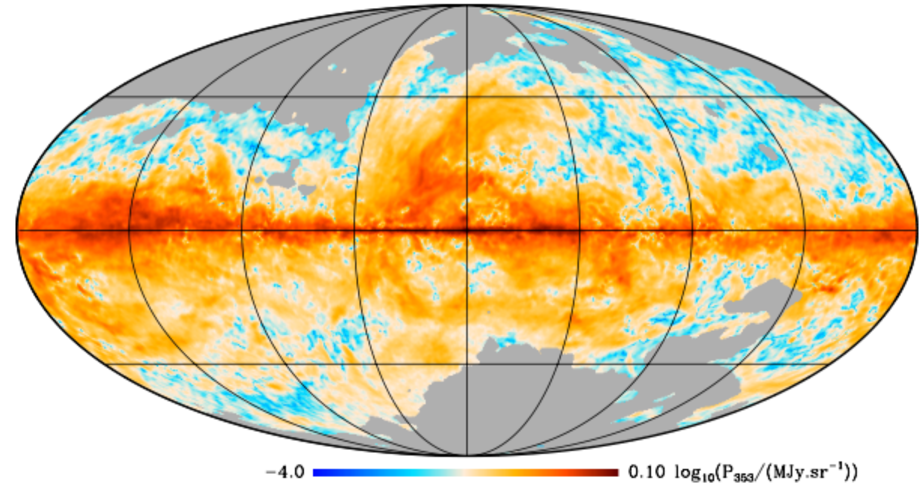
(We recommend the MAS estimator : Plaszczynski+13: A novel estimator of the polarization amplitude from normally distributed Stokes parameters.)

P/I decreases with the column density

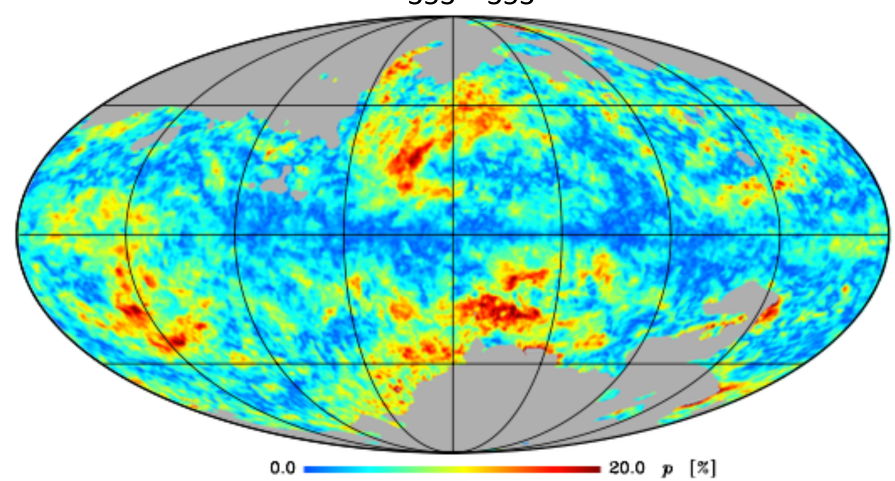


- Loss of alignment ?
- Line of sight effect ?
- Dust evolution ?

P_{353} (MJy/sr) (= 287.45 x K_CMB)



P_{353}/I_{353}



Dust polarized emission

Planck Int. Results. XIX

New tool : the polarization angle structure function

$$S(\mathbf{x},\delta) = \left(\frac{1}{N}\sum_{i=1}^{N}(\Delta\psi_{xi})^2\right)^{1/2}$$

Random vectors : S = 52°
Uniform vectors : S = 0°
Maximal : 90°

S anticorrelates with P/I everywhere

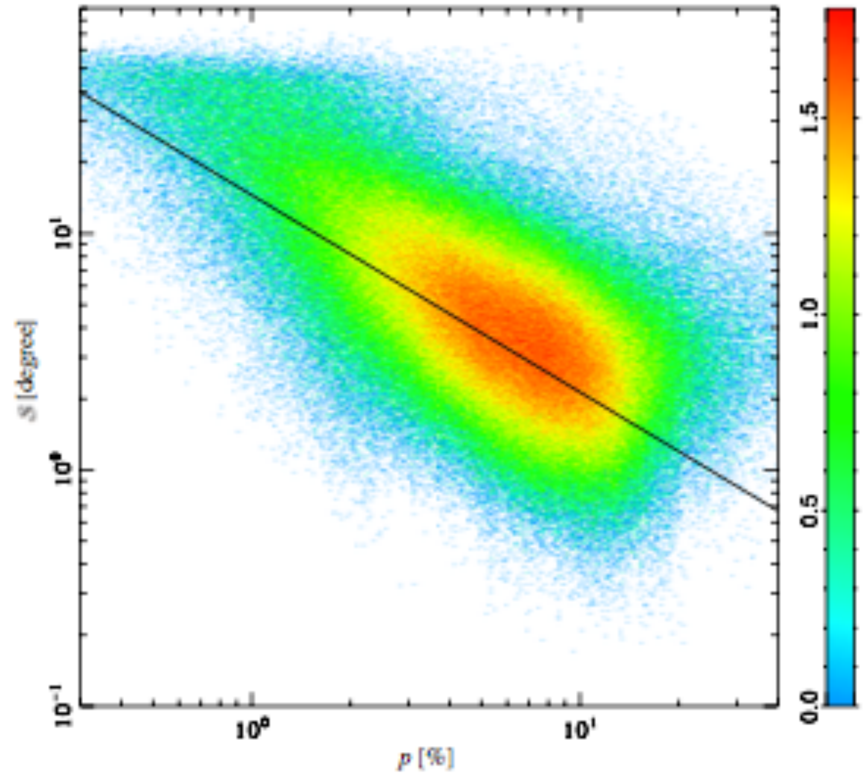
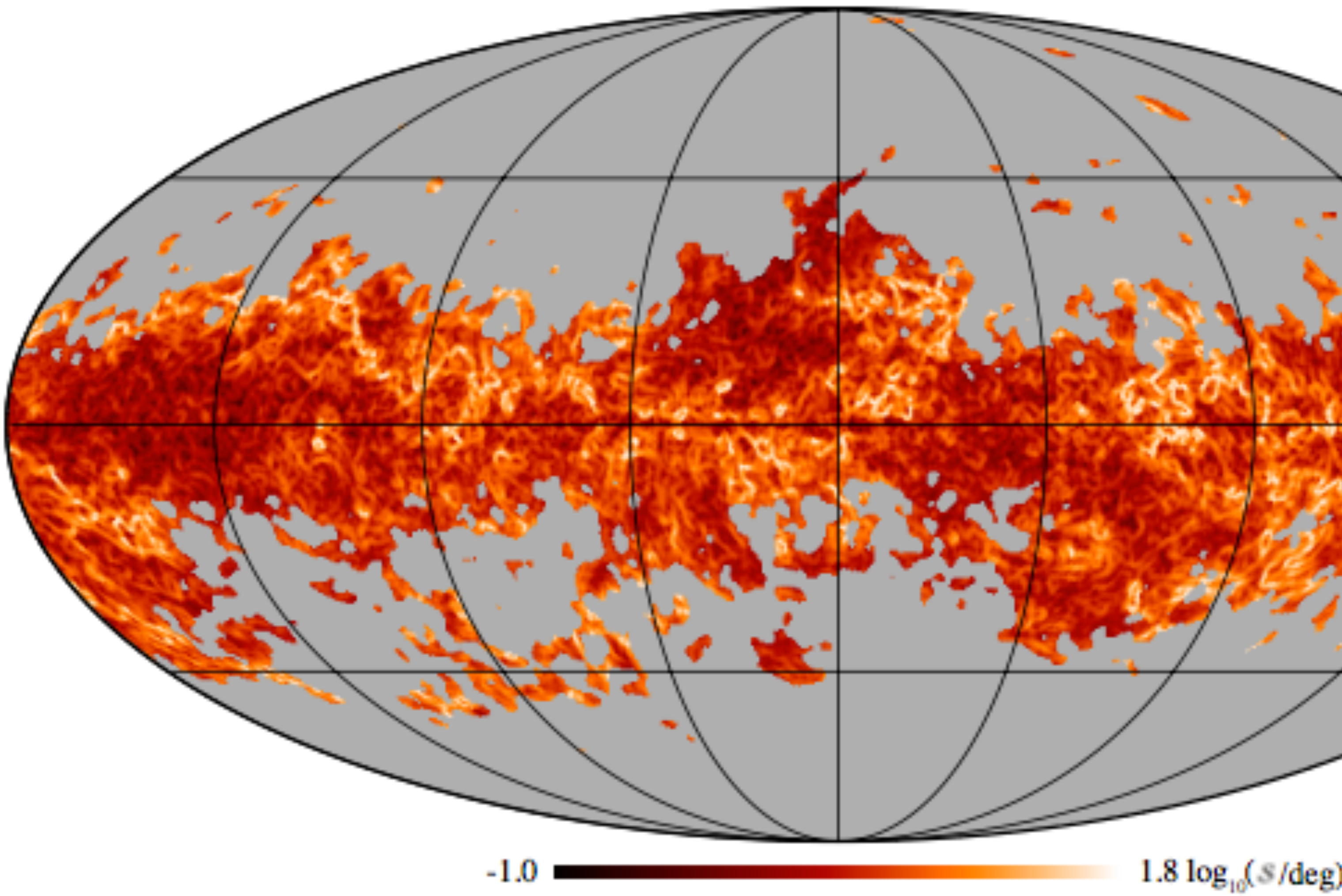
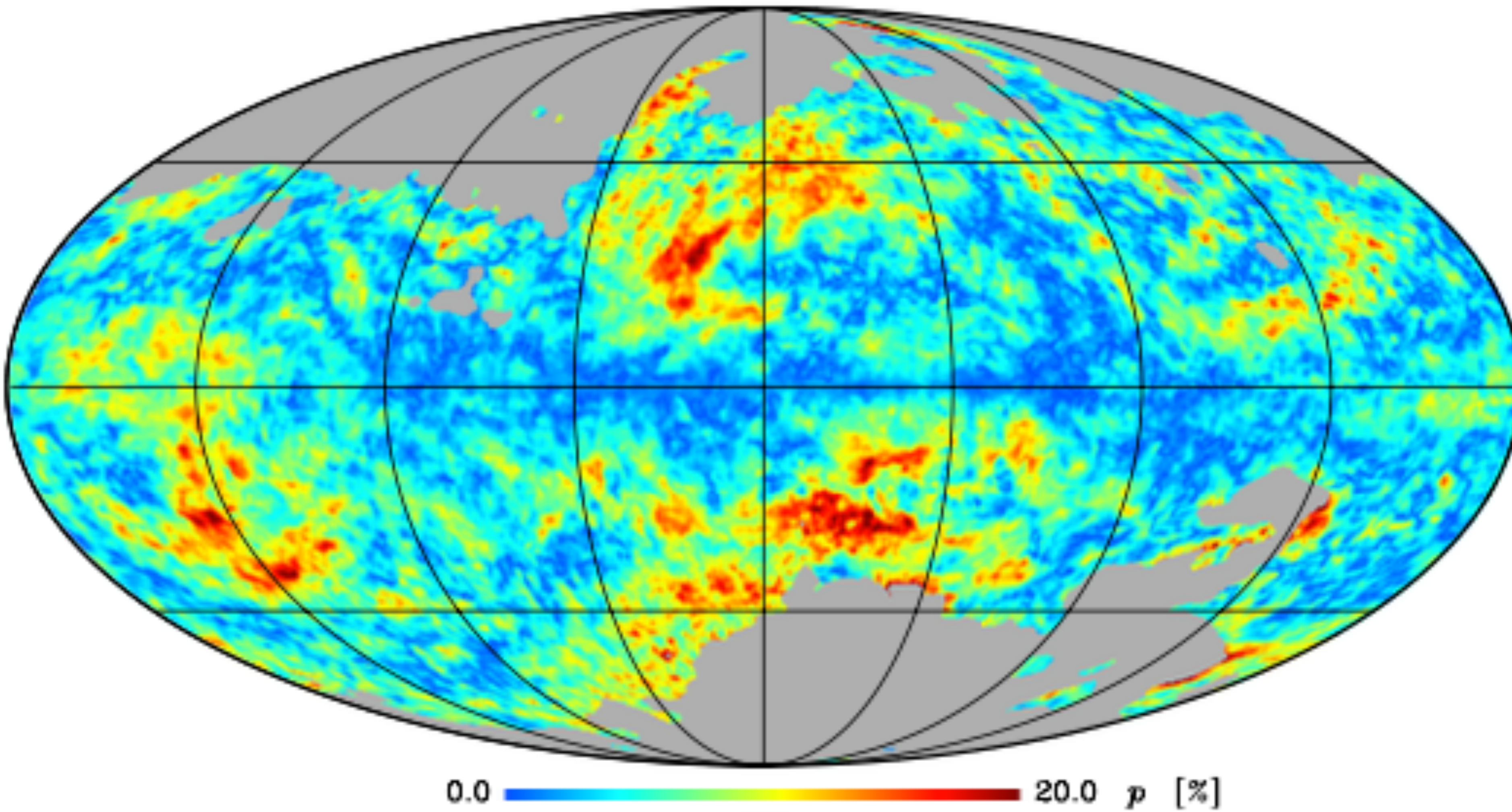


Fig. 23. Scatter plot of the polarization angle dispersion function S as a function of polarization fraction p at 353 GHz. The colour scale shows the pixel density on a $\log_{10}$ scale. The line indicates the best fit (see text).

Anticorrelation S versus P/I



Anticorrelation S versus P/I

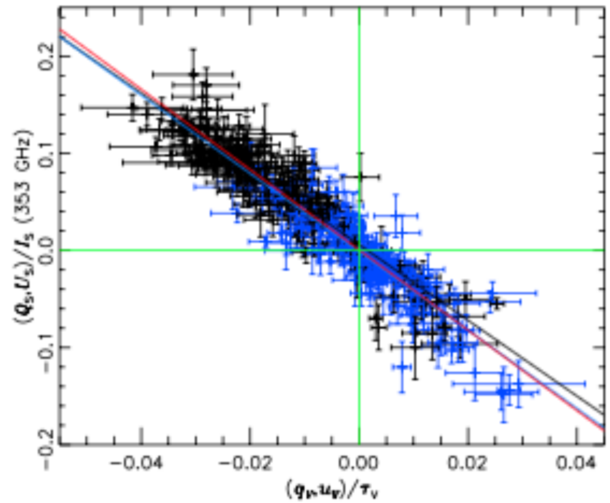


Mean dust spectral properties in polarization

Planck Int. Results. XXI

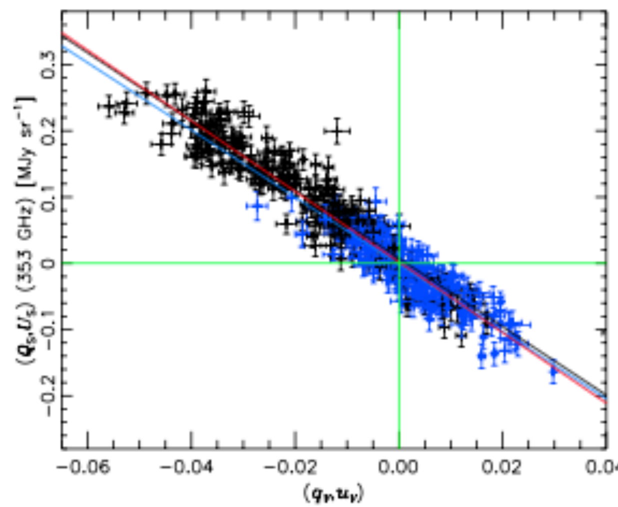
- Correlate (Q,U) between 353 GHz and the optical.
- $P_{353}/\ p_v = 5.4$ MJy/sr
- $(P_{353}/I_{353})\ /\ (p_v/\tau_v) = 4.2$

353GHz



Optical

353GHz



Optical

Planck Int. Results. XXII

- Mask = brown
- P/I is slightly decreasing with the wavelength : β_P-β_I~ 0.09

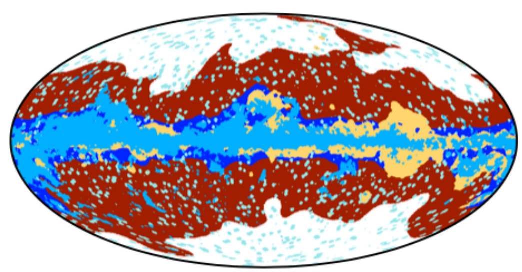
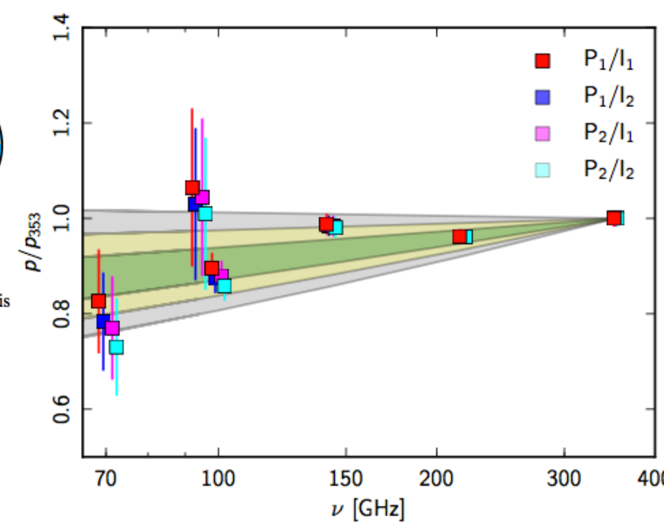


Fig. 1. Global mask used in the cross-correlation (CC) analysis



⇒ Dust models must be updated

Dust observables versus dust models

- Draine & Li (2007)
- Compiegne et al (2011)
- Guillet et al (2017)

Pre-Planck models

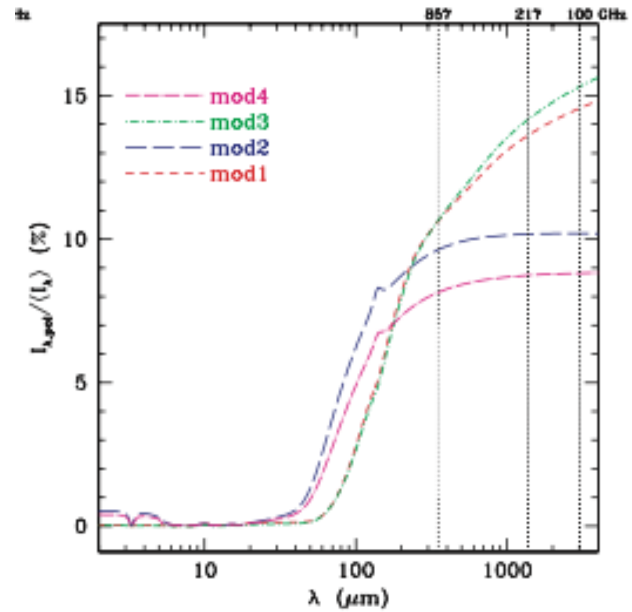
Polarized emission: Draine & Fraisse (2009)

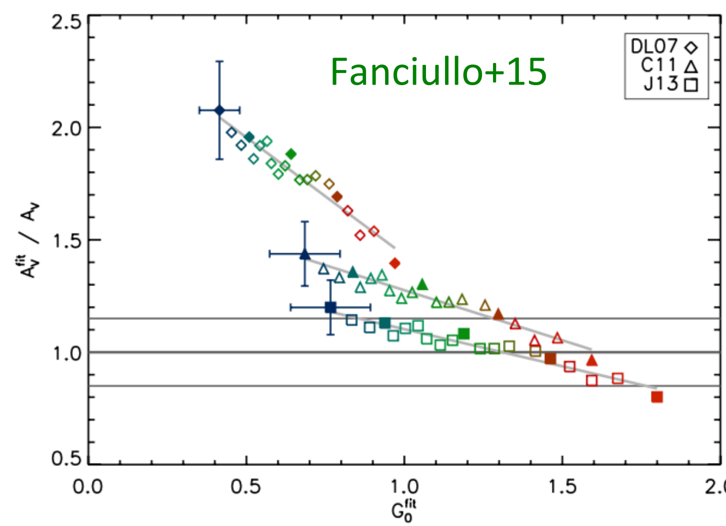
- Based on Draine & Li (2007): graphite & silicate
- $P_{353}/\ p_v = 2.2$ MJy/sr << 5.4 MJy/sr
- $(P_{353}/I_{353})\ /\ (p_v/\tau_v) = 3.3 \sim 4.2$
- $P/I(\lambda)$ flat or increasing (actually, flat)

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)

Draine & Fraisse (2009)



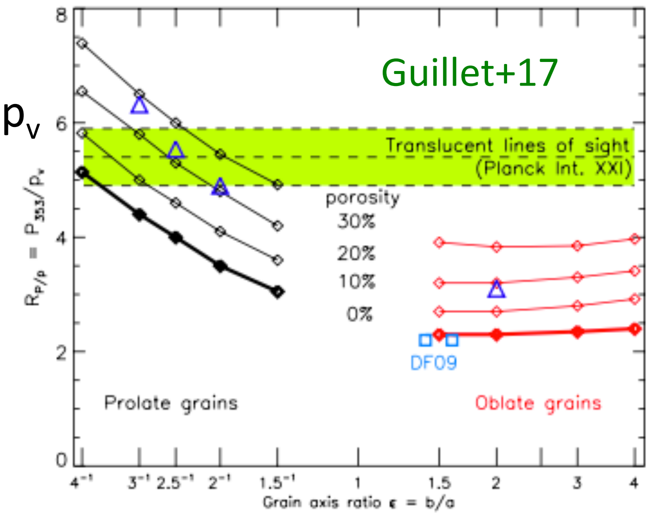


New dust model compatible with Planck data in translucent lines of sight

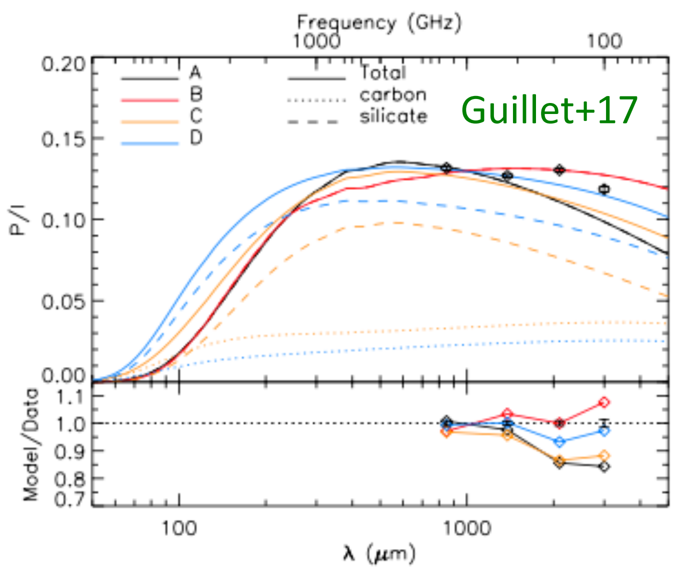
Guillet+17, derived from Compiegne+13

- Valid for translucent lines of sight (0.5 < Av < 2.5).
- Dust properties are adapted to fit Planck polarization ratios:
  - $P_{353}/p_v = 5.4$ MJy/sr, $(P_{353}/I_{353}) / (p_v/\tau_v) = 4.2$.
  - Max(p/Av)= 3%, max(P/I) = 13%
- With the optical properties from astrosilicates, only elongated prolate shape, with porosity, succeed.
- 2 kind of models
  - A & B : only silicate aligned
  - C & D : silicate and a-C grains aligned
- Silicate of model D have a-C inclusions (6% in volume)
- **Not adapted to the high-latitude ISM**

P353/ pv



Grain axis ratio



Spectral fluctuations of dust emission

- unpolarized
- polarized

Variations in total emission

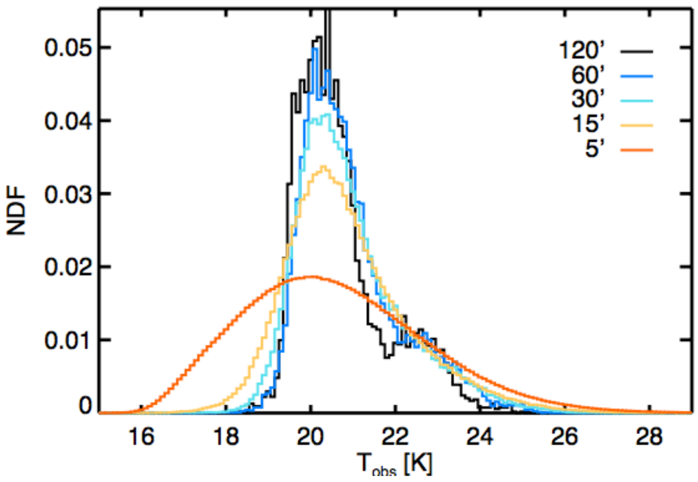
Planck 2013 Results XI + Planck Int. Results XXIX
Fanciullo+15 :

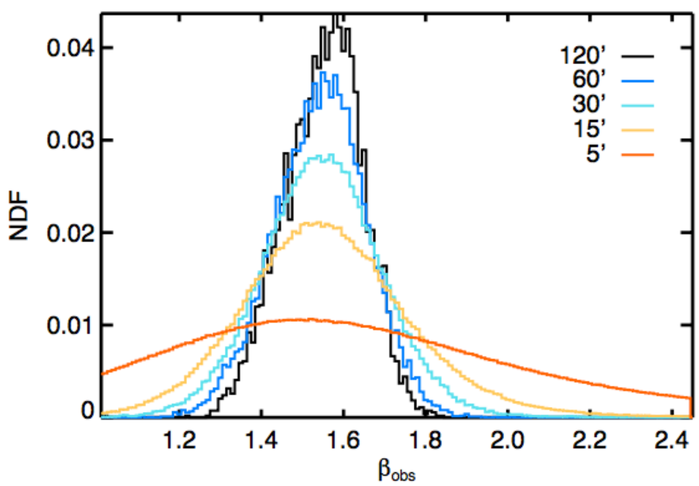
T does not only trace the heating via the radiation field, but also intrinsic variation in the dust emissivity.

WARNING : 100 μm IRAS, with its 13.6% of calibration uncertainty, limits our precision on T

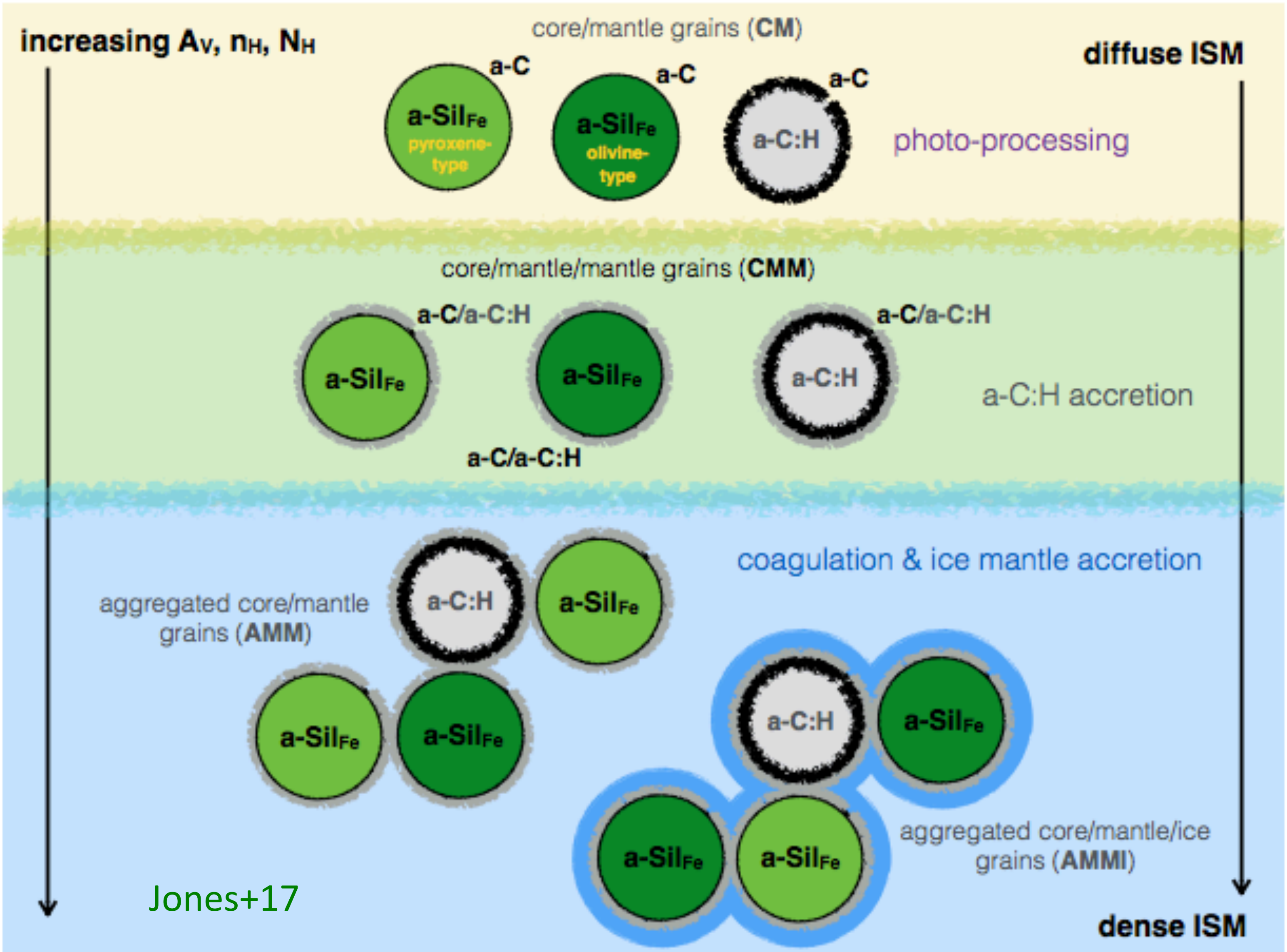
Dust optical properties vary in the diffuse ISM

- τ by a factor ~ 2
- FWHM(β) ~ 0.25 => σ_β ~ 0.1





Dust evolution : the THEMIS scenario



Variations in the spectral index of polarized emission, β_P

1) Limits of Planck HFI observations :

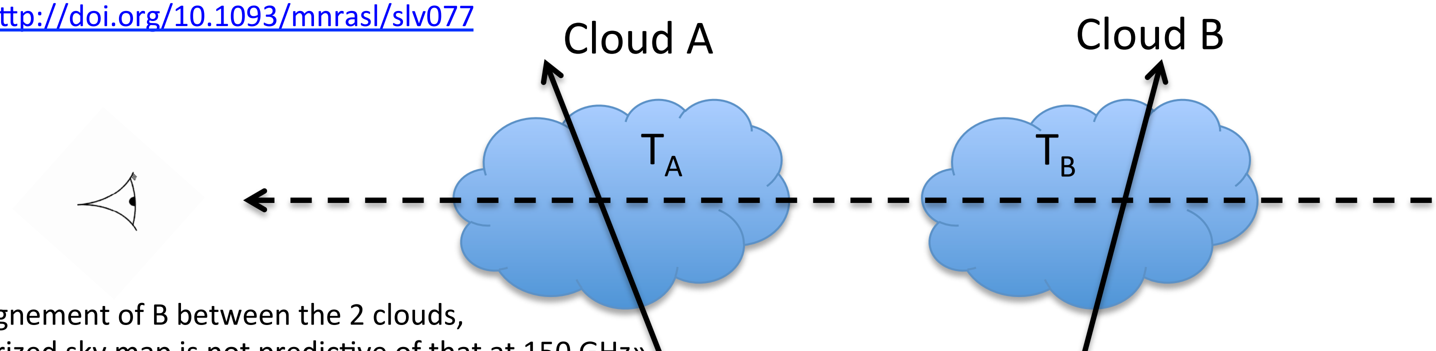
- Temperature of aligned grains not measured by Planck (no channel in the Wien part of the spectrum)
- Too much noise in Planck data to constrain the fluctuations of the spectral index of polarized emission β_P on each line of sight.

2) $C_{pol} = (C_E - C_B)/2\ R\ F\ \cos^2\gamma$ => at a first approximation, β_P does not depend on grain alignment and mean magnetific field orientation because these are achromatic processes.

3) Possibility to model variations in β_P using a dust model (Guillet+17, Draine & Fraisse 2009) based on our knowledge of β_I on each line of sight, or a least statistically.

4) Possibility of a **decorrelation** of submm channels by line of sight integration if the magnetic field direction varies a lot on the line of sight and the spectral index and temperature also.

Tassis, K. and Pavlidou, V, Searching for inflationary B modes: can dust emission properties be extrapolated from 350 GHz to 150 GHz, *451*(1), L90–L94. http://doi.org/10.1093/mnrasl/slv077



If there is a strong misalignement of B between the 2 clouds,
Then « the 350 GHz polarized sky map is not predictive of that at 150 GHz»

Questions, rather than conclusion

- What is mass of dust per mass of gas ?
- Is it correct to say that starlight polarization is due to grain absorption ?
- Which processes can change dust optical properties ?
- What is aligned when we say « grains are aligned along magnetic field lines » ?
- What are the dependences of the polarization fraction in the Rayleigh Regime ?

Thanks for your attention