Thermal Dust Observations and Theory

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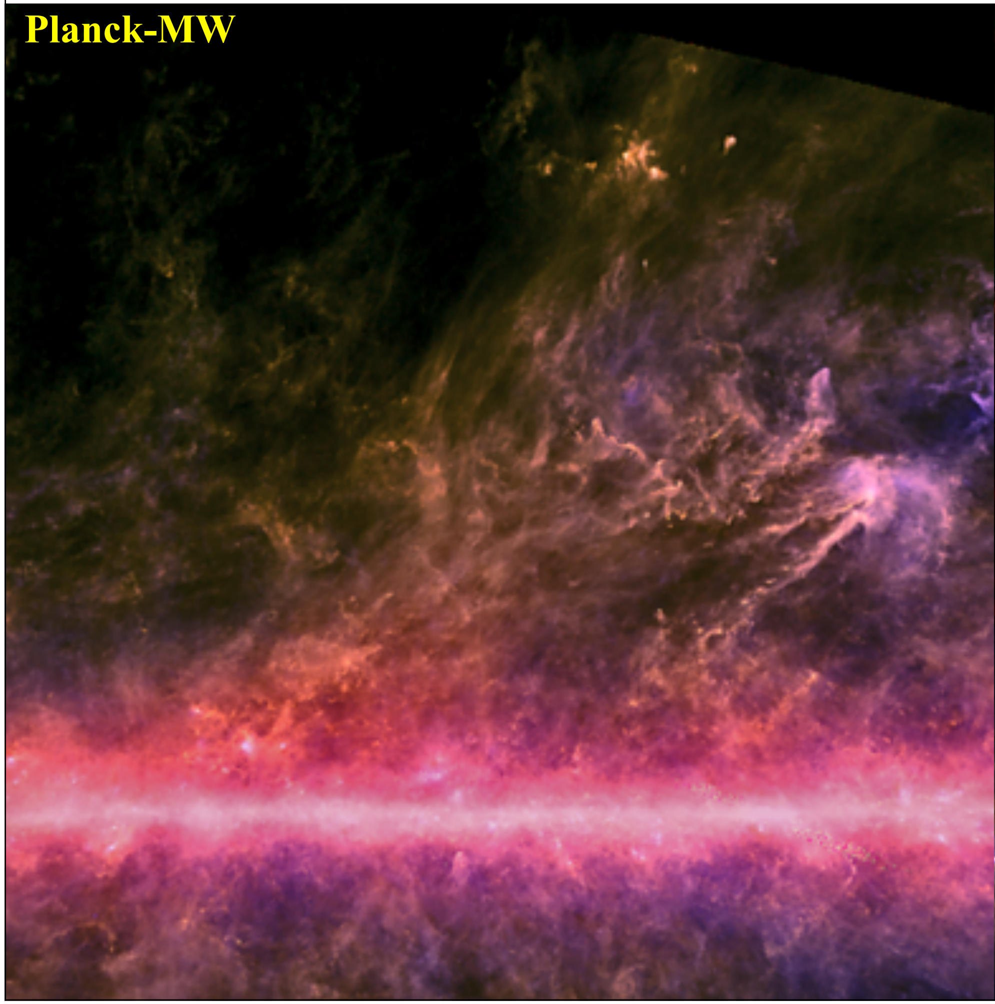
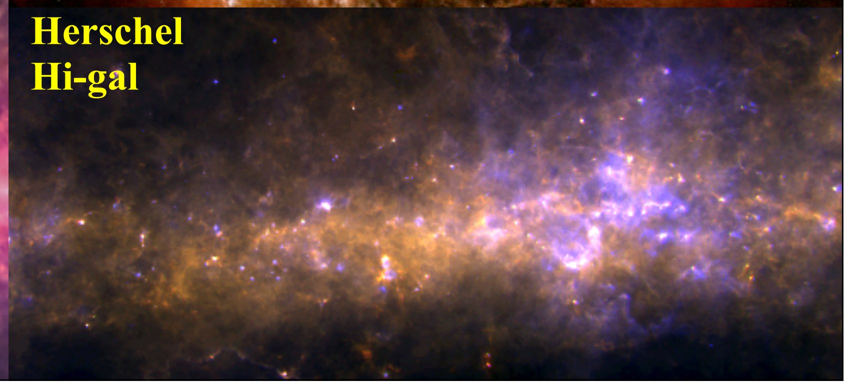
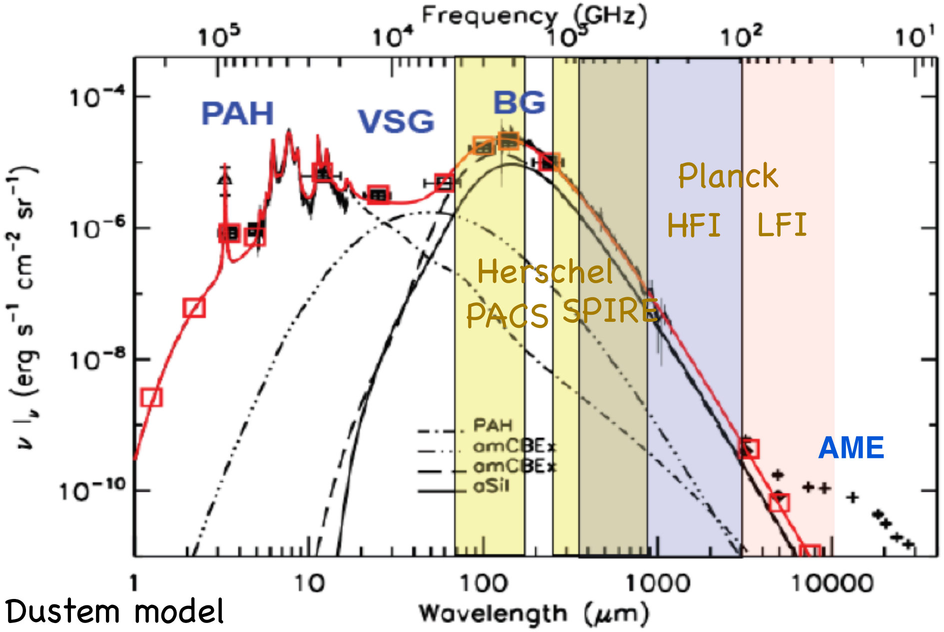
On behalf of a few large collaborations: Planck, Herschel Heritage, Herschel Higal





Dust Physics

<u>Composition</u>:
PAH = Polycyclic Aromatic Hydrocarbons
VSG = Very Small Grains
BG = "Big Grains"
Silicates + Graphite ($\approx 0.1\,\mu m$)



Dustem model

<u>Far-Infrared/millimeter continuum</u>:
Dominated by Big Grains
"Universal" tracer of the <u>ISM structure</u>
FIR observations of <u>distant galaxies</u>
Foreground Emission / CMB Cosmology

$$\boxed{I_\nu = \tau_\nu B_\nu(T_D) = \pi a^2 Q_{abs}(\lambda) X_{dust} N_H \; B_\nu(T_D)}$$

BG at thermal equilibrium -> dust temperature T_D measures radiation field intensity (G0)

It is usual to assume $Q_{abs}(\lambda) \propto \lambda^{-\beta}$ with β=2 (<u>Quadratic Law</u>)

- In the FIR-mm optical depth are small (can account for the mass of a whole galaxy)
- In the Rayleigh-Jeans regime, $I_\nu \propto T_D$, so mass determinations not very sensitive to temperature determination in Submm-mm …

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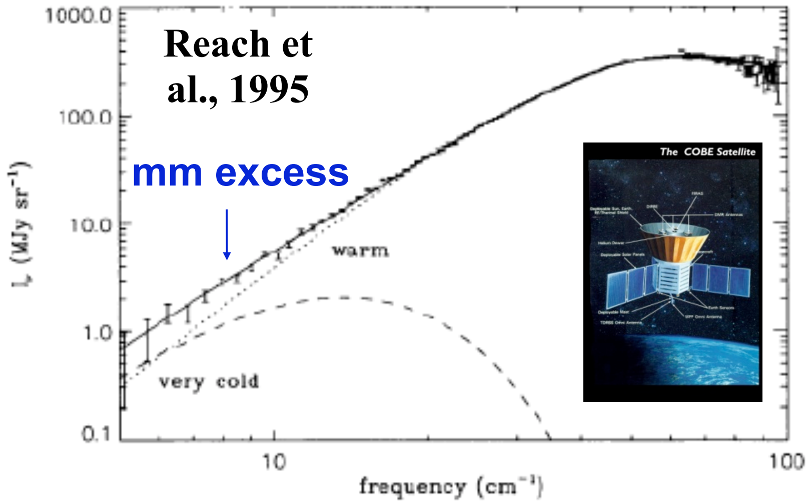
The flat MW SED

COBE/FIRAS : MW SED much flatter than predicted by the quadratic law (1.5<β<1.7)



mm excess :
Warm dust at ~17.5 K
Very cold dust (5-7K) ?

mm excess is strongly correlated to FIR emission at high |b|
This lead Reach et al. to reject "very cold" dust.

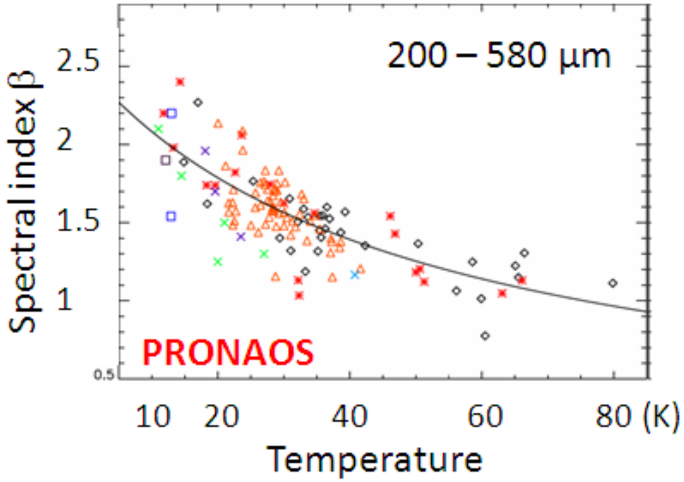
Finkbeiner et al. 1999 (FSD) 2 components= Graphite + Silicate

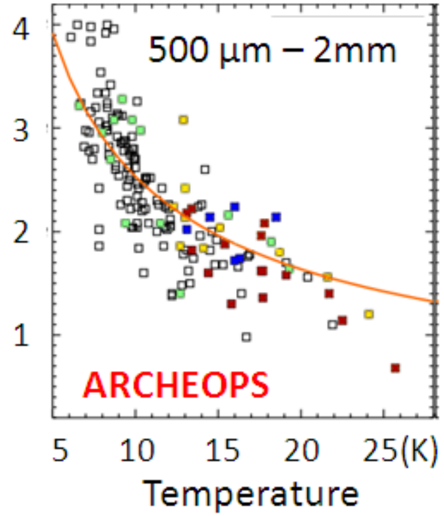
Number	Model	α_1	α_2	f_1	q_1/q_2	$\langle T_1 \rangle$	$\langle T_2 \rangle$	P_1/P_2	χ^2	χ^2_ν
1........	One-component: $\nu^{1.5}$ emis	1.5	...	1.0	1.0	20.0	...	...	24943	204
2........	One-component: $\nu^{1.7}$ emis	1.7	...	1.0	1.0	19.2	...	...	8935	73
3........	One-component: $\nu^{2.0}$ emis	2.0	...	1.0	1.0	18.1	...	...	3801	31
4........	One-component: $\nu^{2.2}$ emis	2.2	...	1.0	1.0	17.4	...	...	9587	79
5........	Pollack et al. two-component	1.5	2.6	0.25	0.61	17.0	17.0	0.33	1866	15.3
6........	Two-component: both ν^2	2.0	2.0	0.00261	2480	4.9	18.1	0.0026	1241	10.3
7........	Two-component: fit f, q	1.5	2.6	0.0309	11.2	9.6	16.4	0.0319	244	2.03
8........	Two-component: fit f, q, α_1, α_2	1.67	2.70	0.0363	13.0	9.4	16.2	0.0377	219	1.85

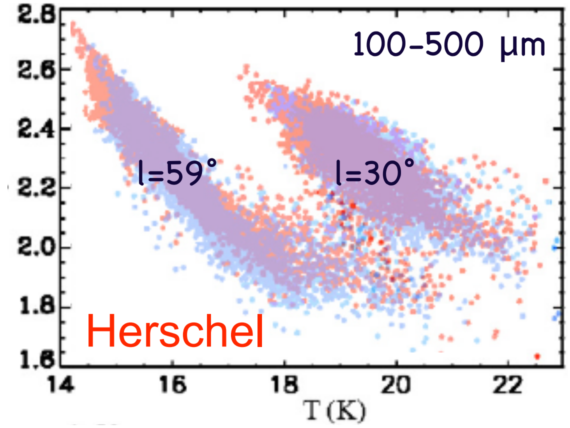
2 Temperature models can fit sky brightness distribution beautifully, but do not provide a physical explanation for the very cold dust at 9K
(No realistic grain material explains dust at 9 K in diffuse ISM)

T-β correlation ?

Variations of spectral index appear inversely correlated with dust temperature.

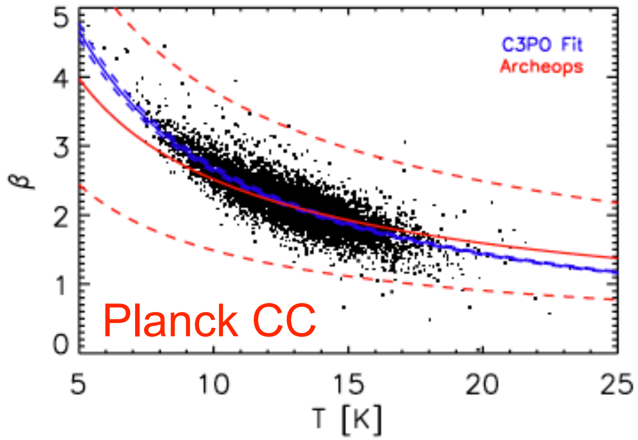






However T and β are degenerate in SED fits and naturally inversely correlated.
Demonstration that the effect is real requires taking errors into account.

The following studies concluded that the effect is not due to this degeneracy : Dupac et al. 2003, Désert et al. 2008, Paradis et al. 2010, Planck Collaboration 2011 XXIII



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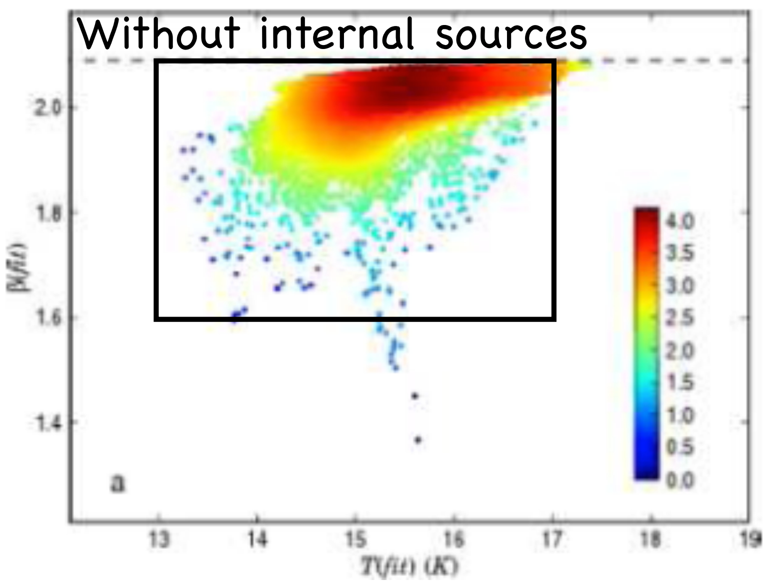
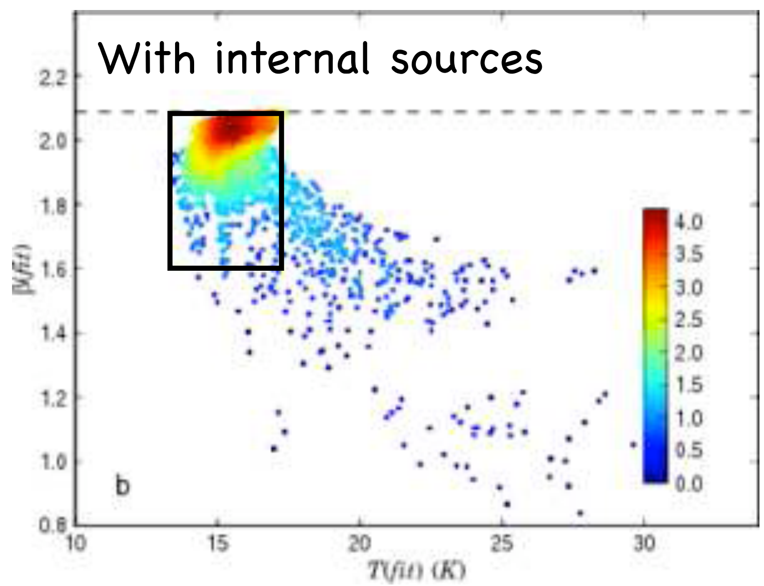
T mixing ?

Malinen et al. 2010 : 3D MHD simulation + full radiative transfer + realistic distribution of heating sources (stars) + Herschel noise.

- cases with no internal sources: no fake T-beta inverse correlation
  (in fact produces the opposite)
- cases with internal sources: fake T-beta inverse correlation for a minority of pixels, close to embedded sources.





Similar results in Ysard et al. 2012, in prep.

The TLS model of amorphous grains

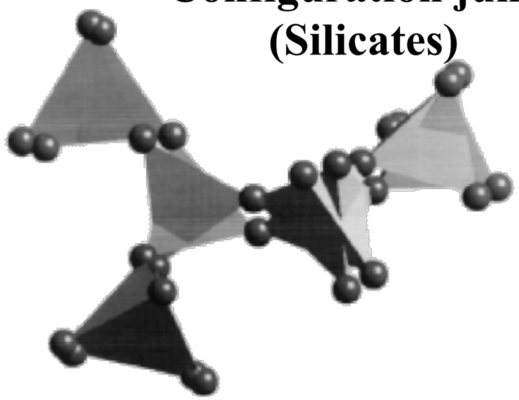
Most dust (98%) in ISM is amorphous (Kemper 2004)

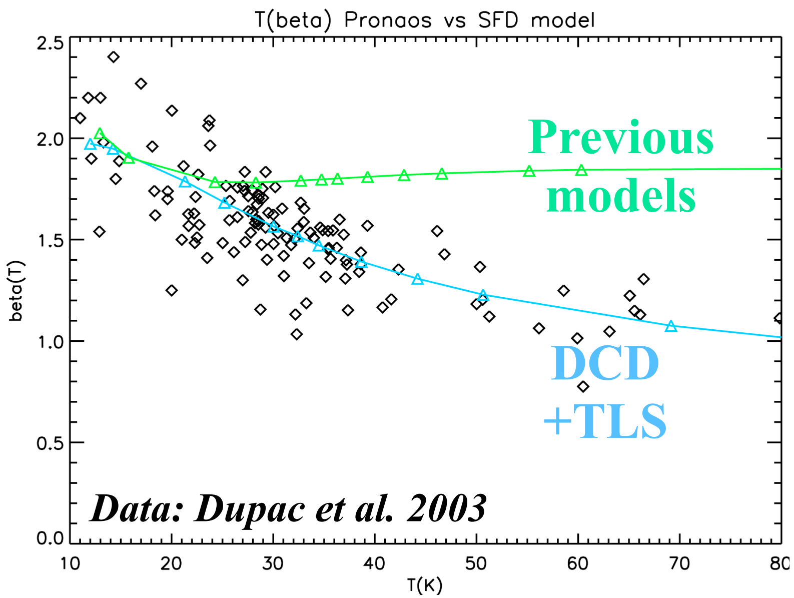
TLS Strongly inspired from solid-state physics : *Meny et al. 2007*
A double description of disorder in amorphous solids

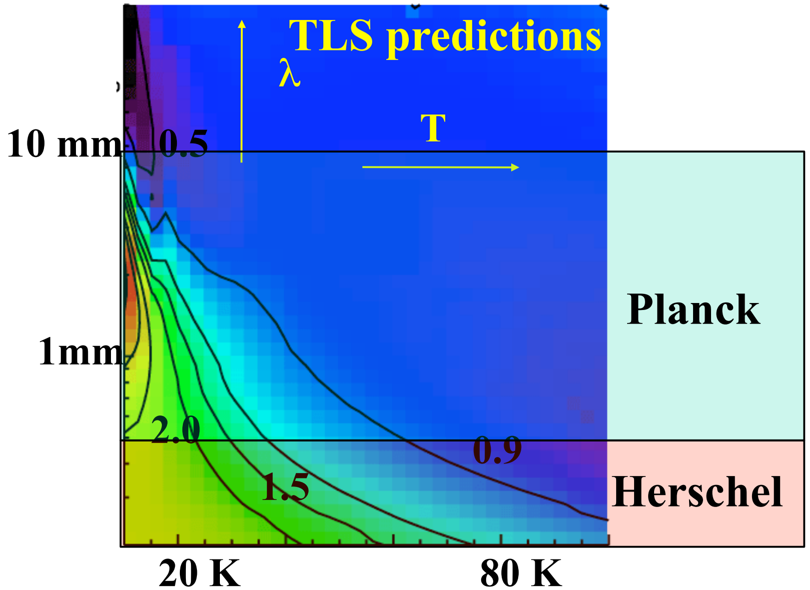
• A Disordered Charge Distribution (DCD)
⇒ Emission independent of temperature (FIR)

• A microscopic distribution of asymetrical <u>double potential wells</u> (Two Level Systems: TLS) with small ΔE:
⇒ Emission dependent on temperature (submm)

Configuration jump
(Silicates)







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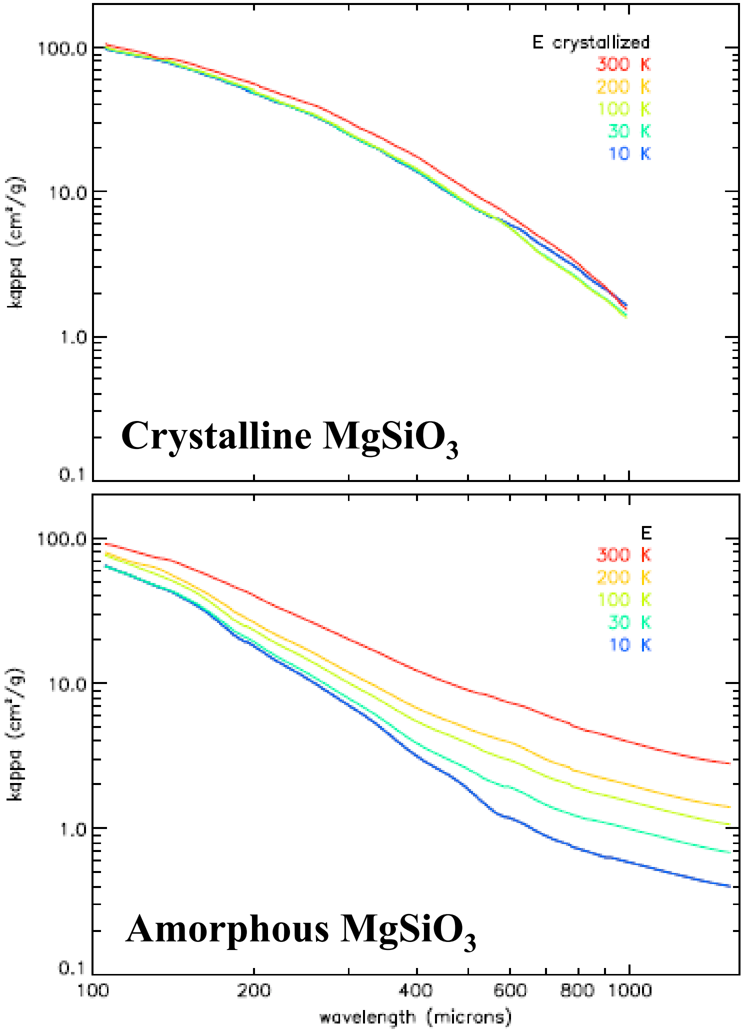
Laboratory data

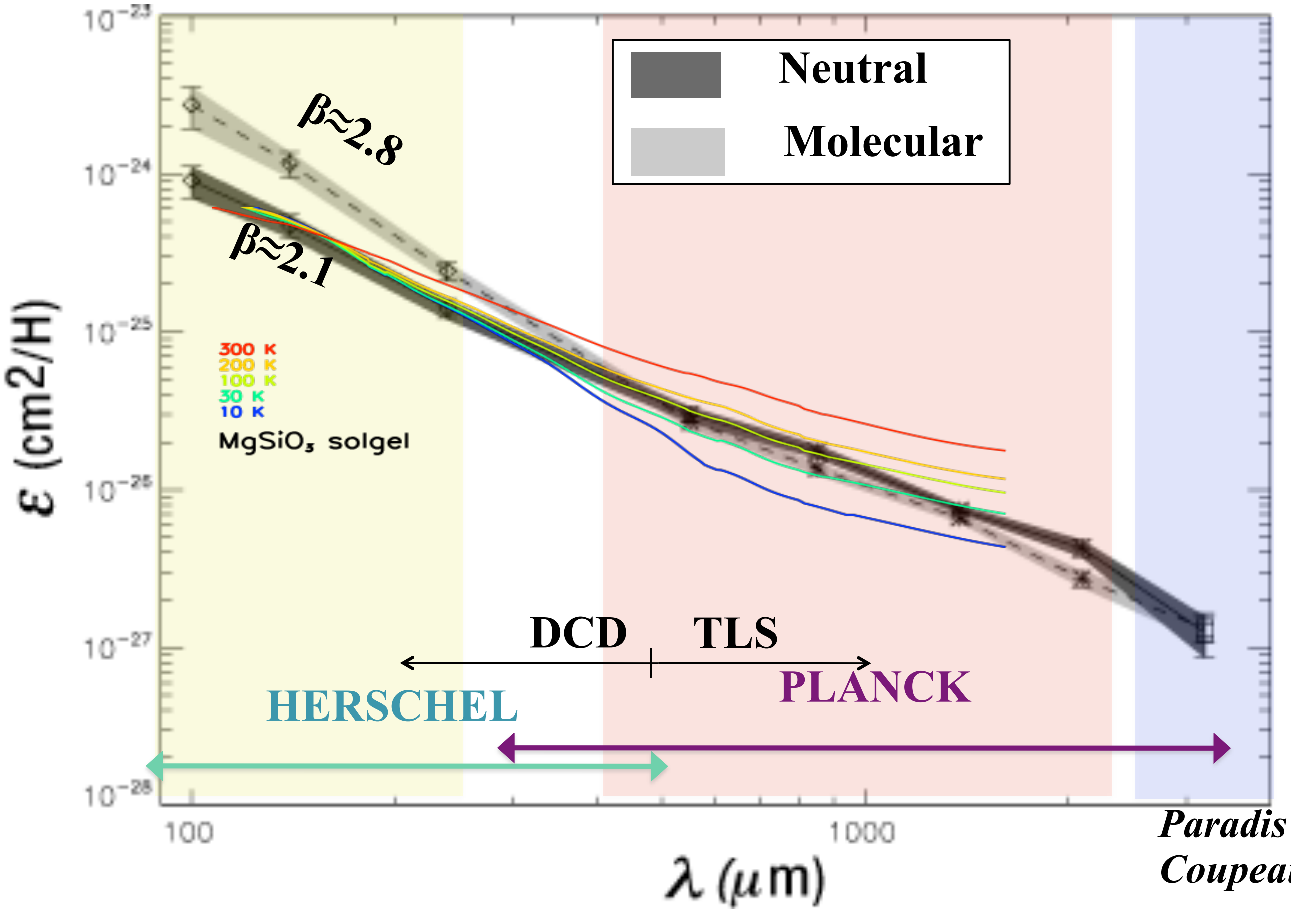


Coupeaud et al. 2011

Laboratory measurements of dust analog materials show (*Coupeaud et al. 2011*):
- Internal structure of the grain material (amorphous vs crystalline) affects both the emissivity shape and intensity
- Emissivity flattens at long wavelenghs
- Emissivity flattens at high temperature

A physical explanation may be provided by models including grain structure disorder (TLS model) :
Meny et al. 2007
Paradis et al. 2011

Laboratory vs Astronomical data

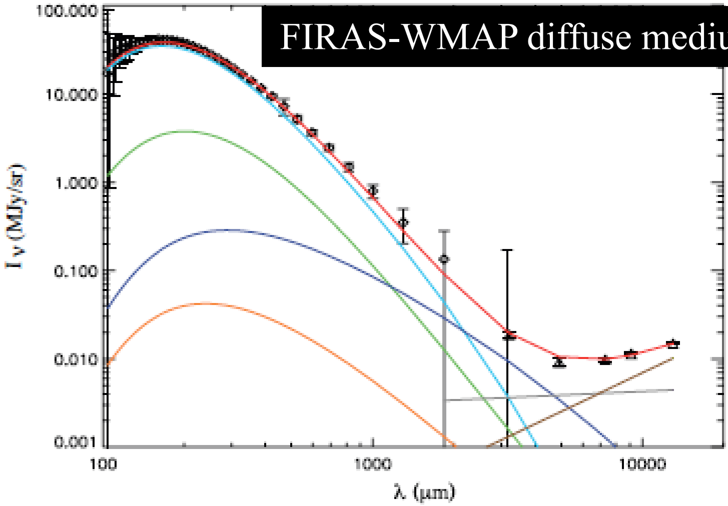


Paradis et al. 2009
Coupeaud et al. 2011

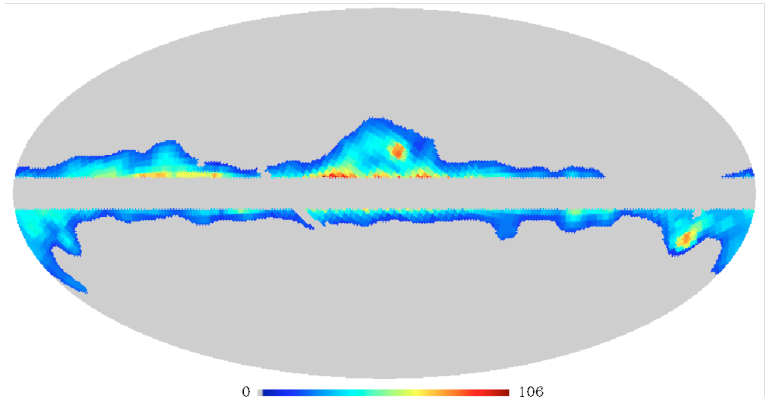
Some materials (here $MgSiO_3$) and mechanical structure certainly match the observed SED for the right temperature (here T=30 K). Not all do.

The TLS model of amorphous grains

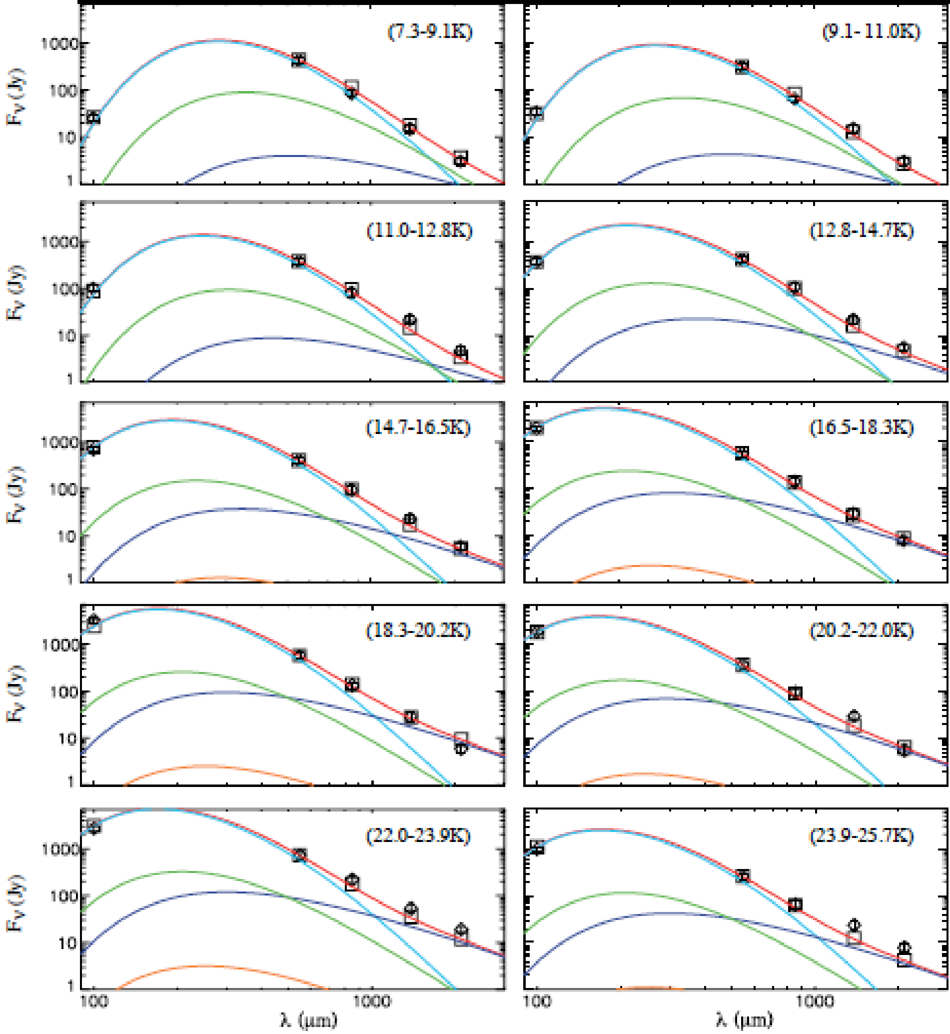
Paradis et al. 2012



Deriving standard parameters of the TLS model (5 parameters) to explain both FIRAS MW spectrum and Archeops observed SED flattening with increasing T_d.



IRAS-Archeops compact sources (outer Galaxy) from Désert et al., 2008)



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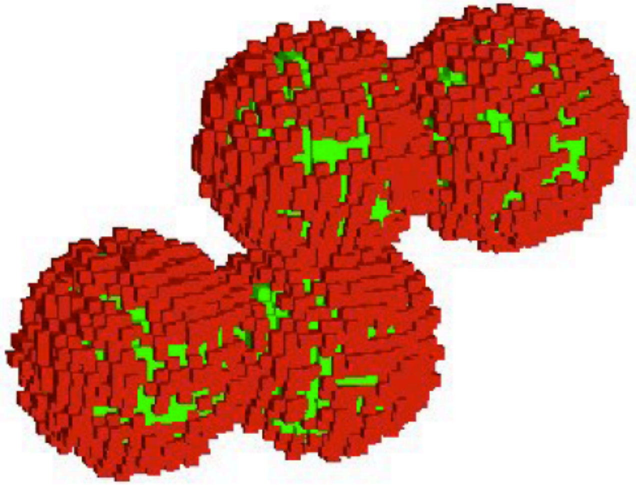
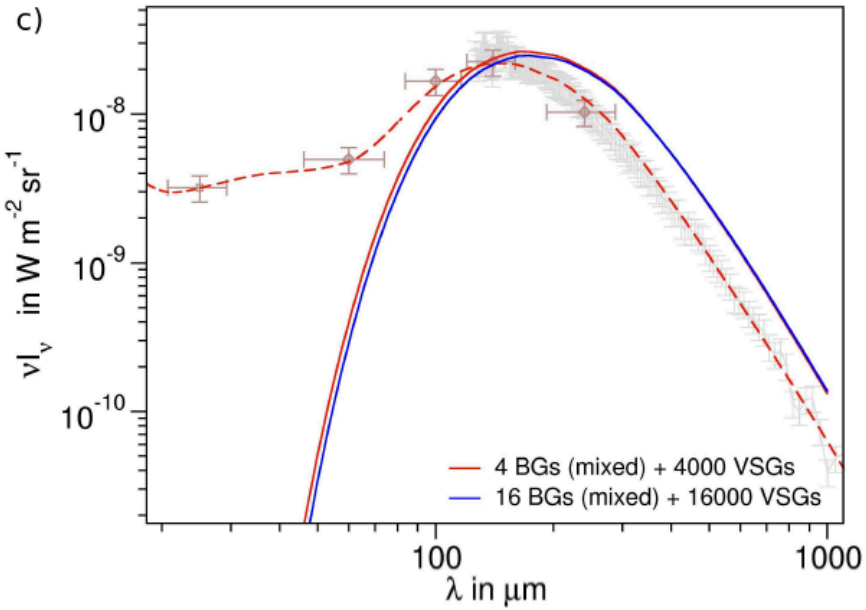
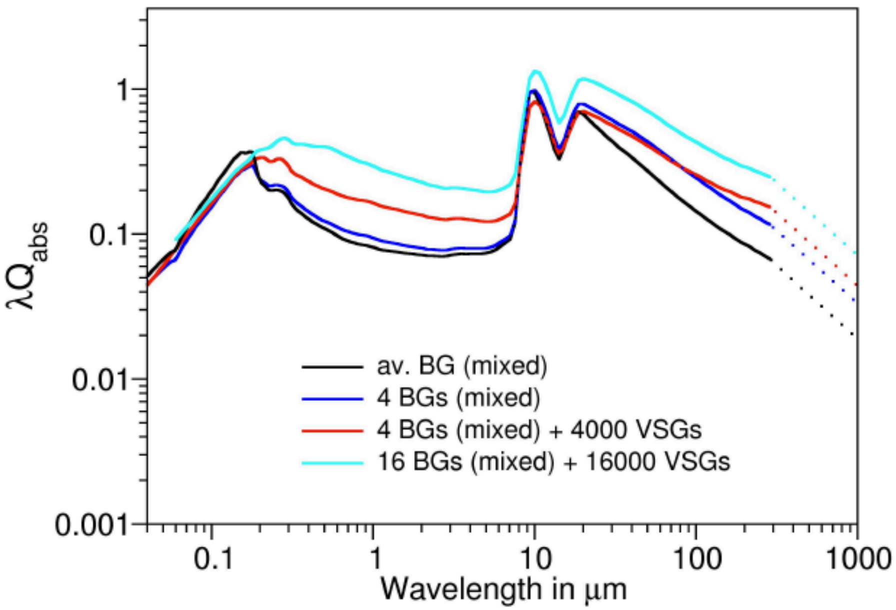
grain-grain Coagulation



Observational evidences:
Bernard et al 1999, Stepnik et al. 2003





Kohler et al. 2012, in prep.

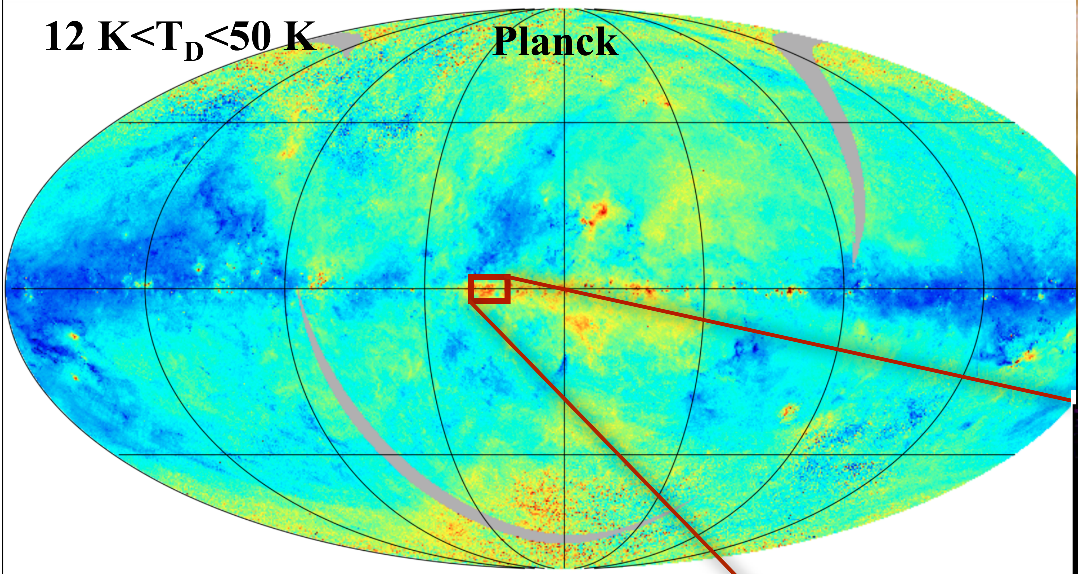
Discrete Dipole Approximation (DDA) calculations of dust aggregates show:
- Increase of emission cross section
- Little variation in absoprtion
- Resulting in higher dust emissivity and lower dust temperature for same radiation field

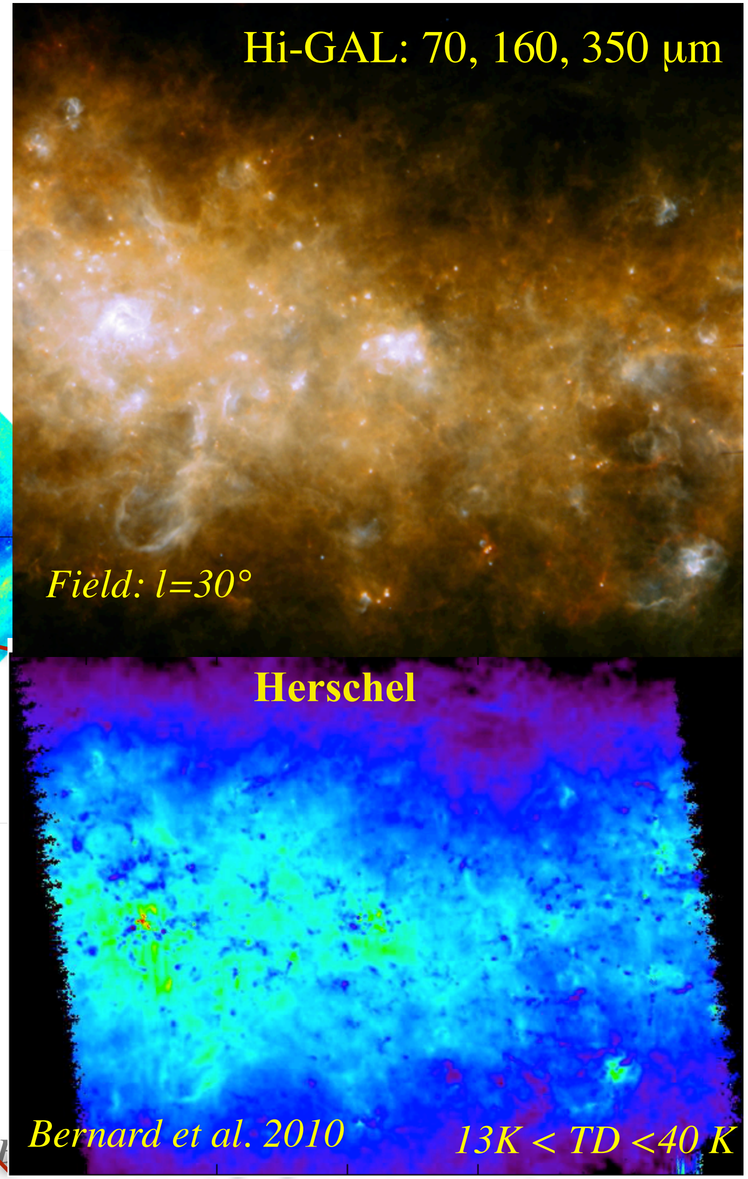

The Planck & Herschel revolution
ESA press-release (March 2010)
PLANCK Data
Blue : IRAS 100 μm
Green : Planck-HFI 350 μm
Red : Planck-HFI 550 μm
Herschel Hi-Gal Data
Blue : Herschel-PACS 70 μm
Green : Herschel-SPIRE 250 μm
Red : Herschel-SPIRE 500 μm

Dust Temperature

A critical parameter to measure dust masses

Dust Temperature computed from IRAS 100 μm, Planck-HFI 857 GHz, Planck- HFI 545 GHz, using β=1.8 (median value derived fromT-β fit)





- **Traces the intensity of the radiation field**
- **External Galaxy colder than inner Galaxy**
- **Warm regions are star forming**
- **Cold regions are molecular clouds**

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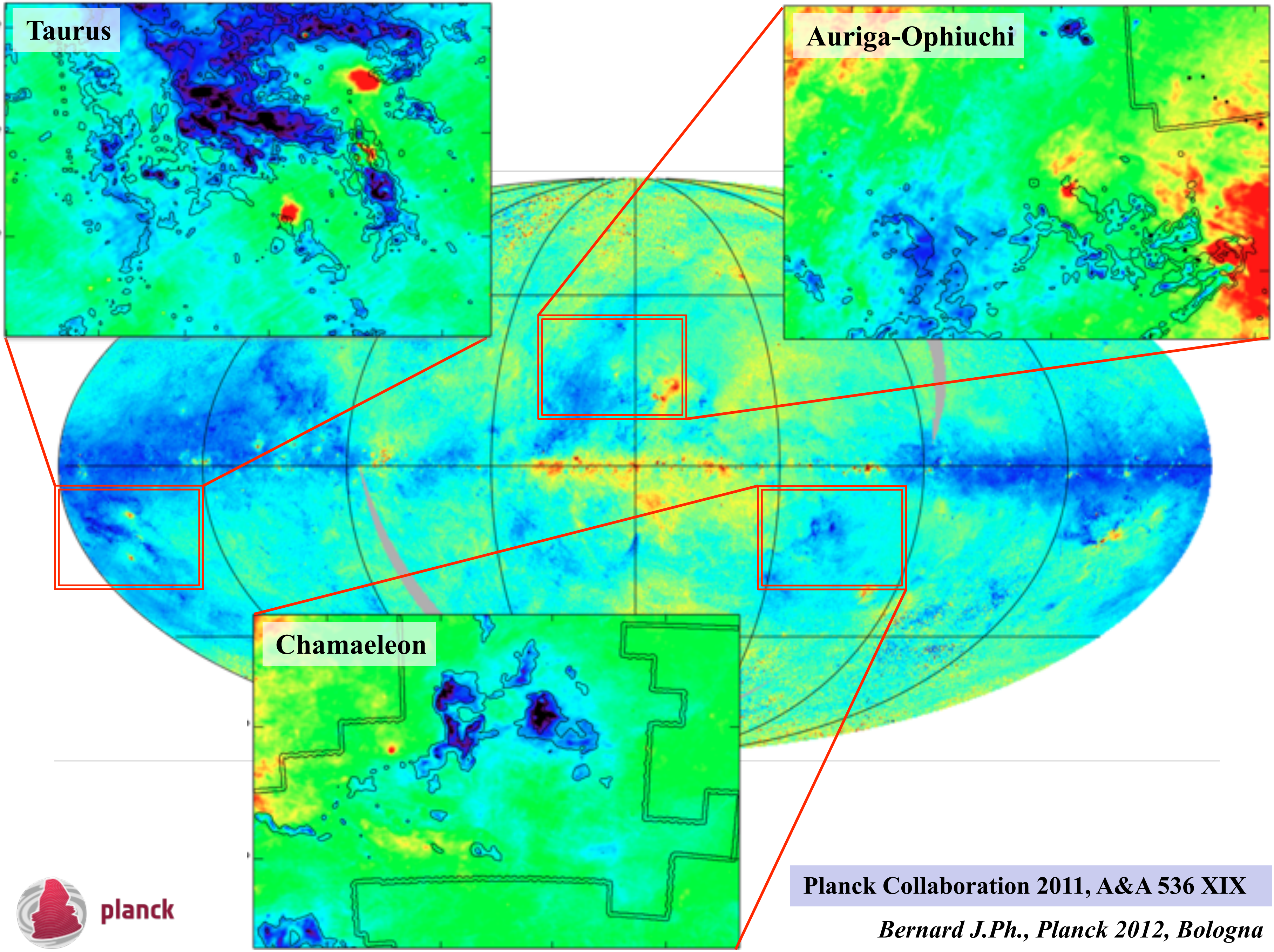
Planck Collaboration 2011, A&A 536 XIX



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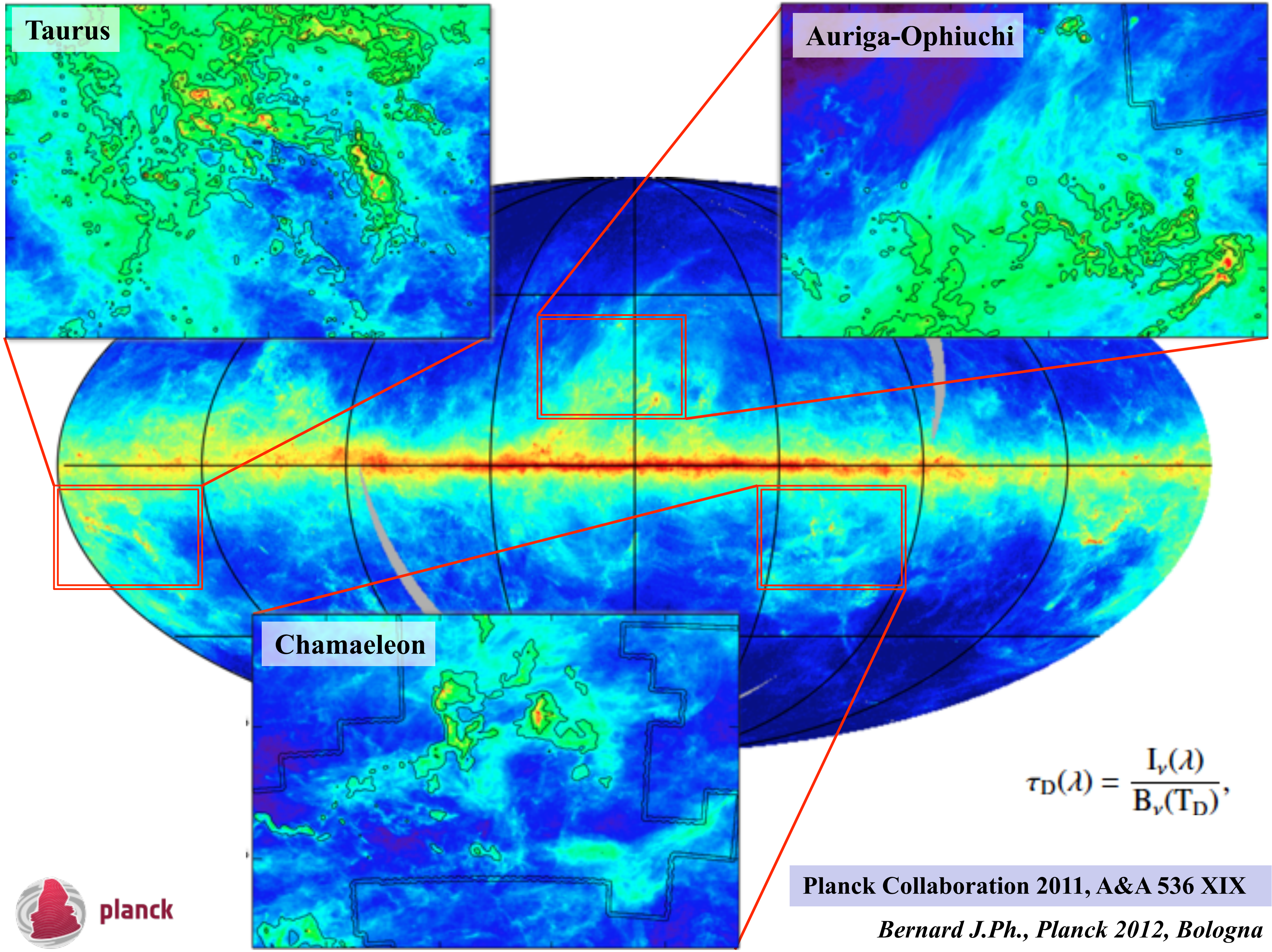

$$\tau_D(\lambda) = \frac{I_\nu(\lambda)}{B_\nu(T_D)},$$

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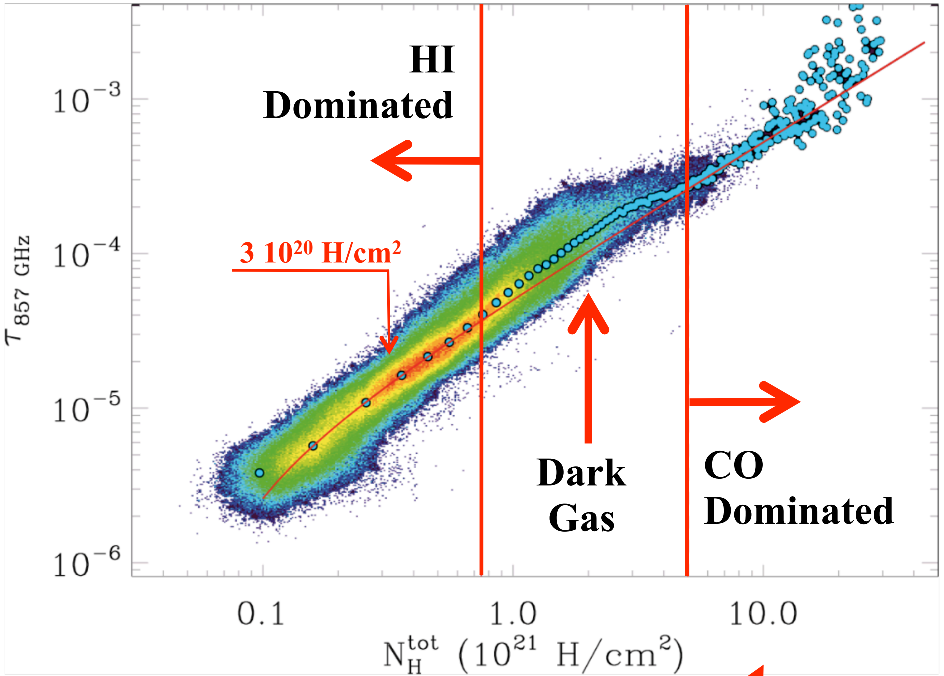
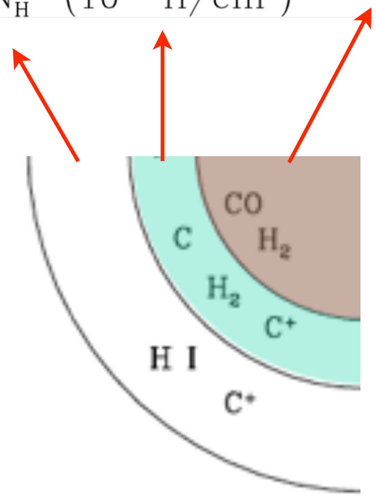
Evidence for Dark Gas



Solar neighbourhood (|b|>10°) using thin HI :
HI/Dark Gas transition at Av=0.4 mag
τ/N_H ~power law with β=1.8. Absolute value consistent with value of Boulanger et al. 1996
Average Xco=2.54 H_2/cm^2/(Kkm/s)
DG mass fraction: 28% of HI, 118% of CO

Possible origins :
- Molecular Dark-Gas (most likely)
- Optically thick HI 21 cm
Assuming Ts=80 K reduces DG by ~1/2
- Weak CO below detection:
contribute <20% of DG



γ-ray : a similar "Dark-Gas" phase (*Grenier et al 2005, Abdo et al. 2010*)
Herschel GotC+ find similar Dark-Gas fractions in the MW plane (*Langer et al. 2010*)
Extinction also sees Dark-Gas (*Paradis et al 2012, submitted*)

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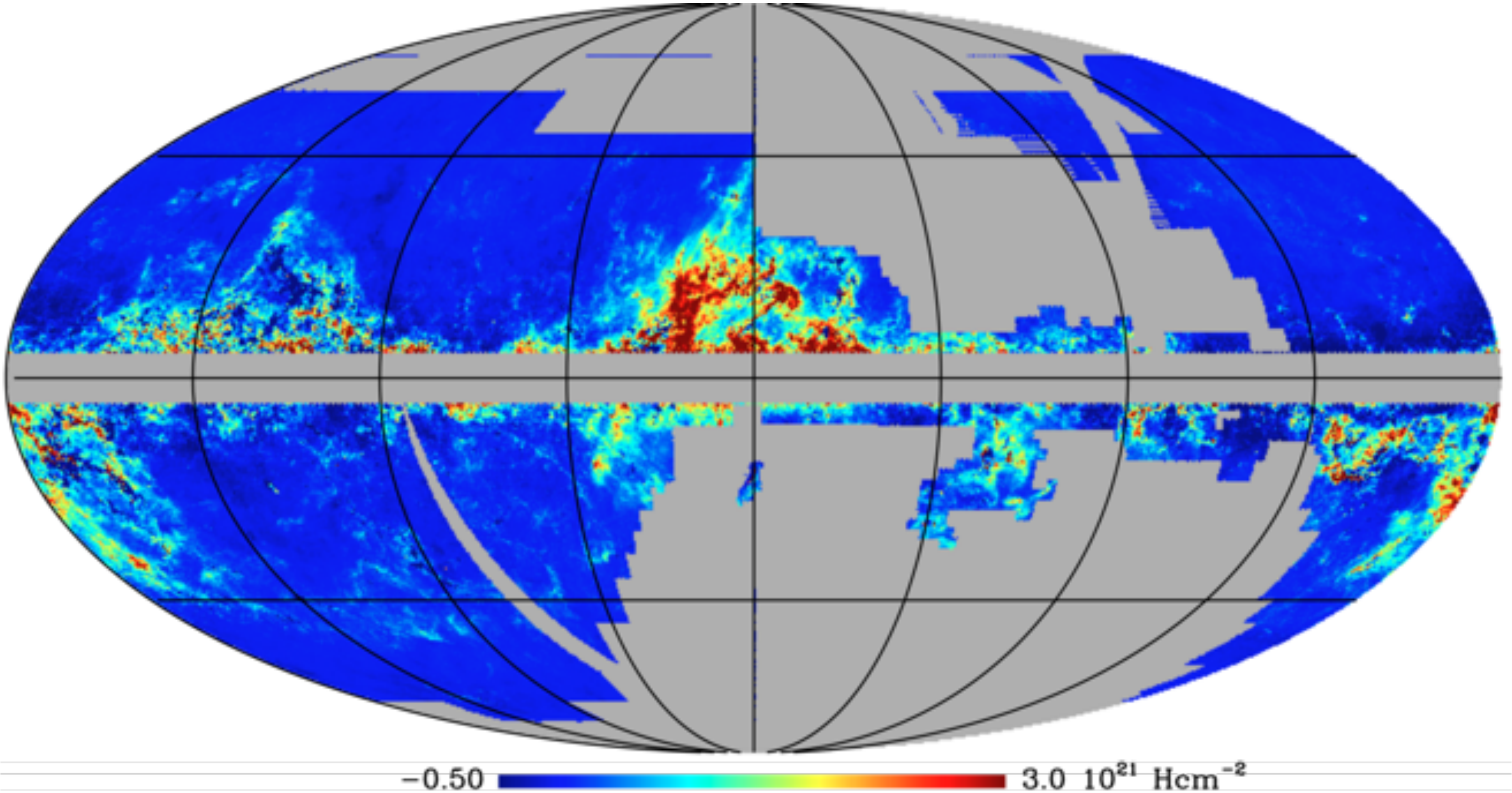
Dark Gas distribution



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Dust-HI correlation in the Halo

HI - dust correlation over 825 square degrees at high latitudes, N_{HI} from 0.6×10^{20} to 10×10^{20} cm^{-2}

Dust in the diffuse local ISM: good fit to grey body (T=17.9 K, β=1.8) from 3000 to 353 GHz (100 to 850 μm)

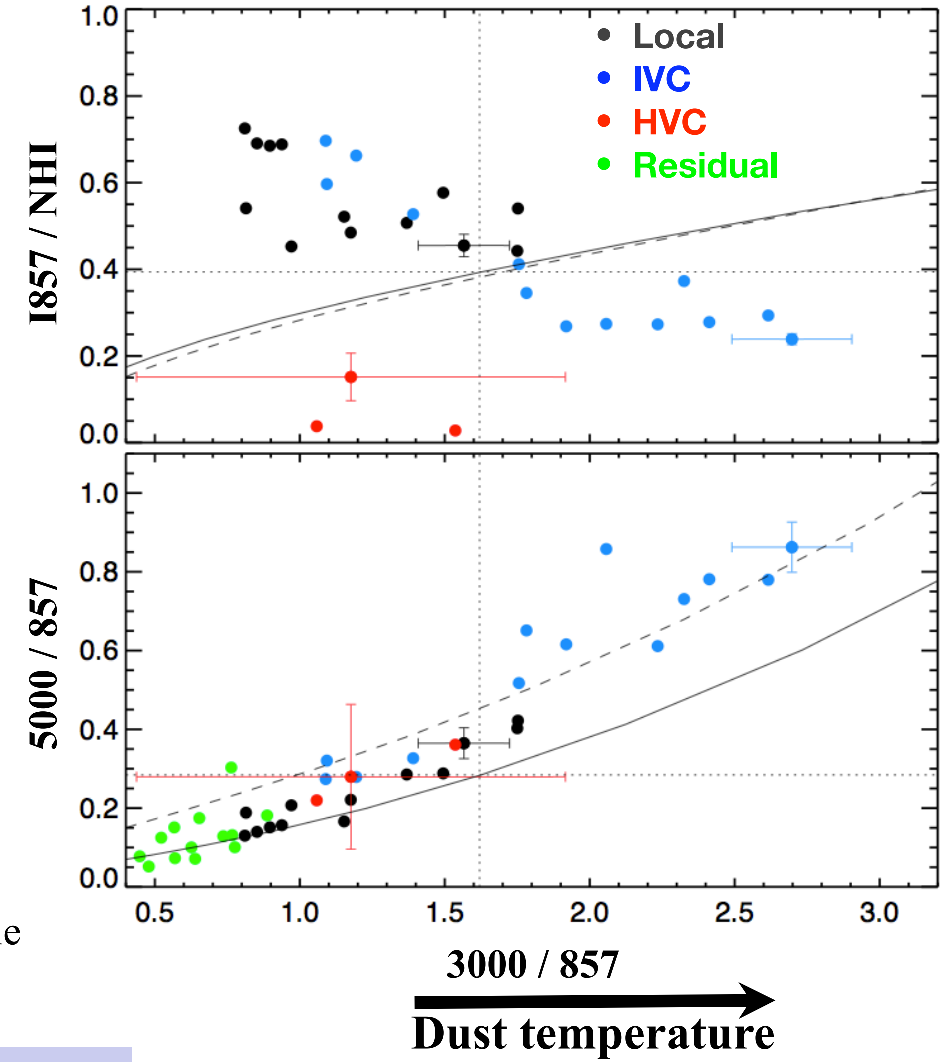
Unexpected evidences for dust evolution in the diffuse ISM:

- IVC : 4 times larger VSG abundance, hotter dust (T~20K). Compatible with clouds part of the Galactic fountain (dust shattering)

- Temperature - emission cross-section anti-correlation suggesting modification of grain structure through coagulation.

Marginal detection of HVCs (1-3.8 sigma) compatible with low metallicity (~0.1 solar)

Excess emission for $N_{HI} > 3 \times 10^{20}$ cm^{-2} compatible with Dark-Gas (10% in mass)



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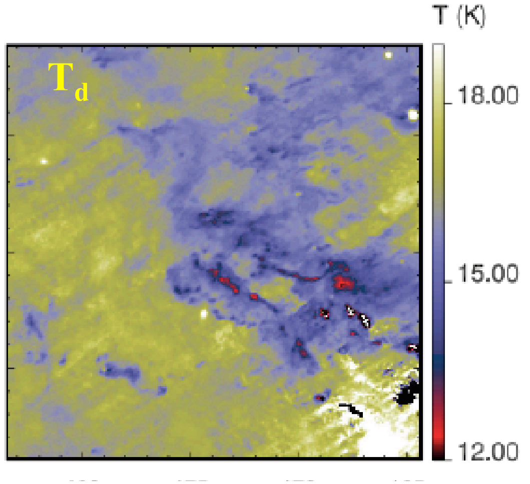
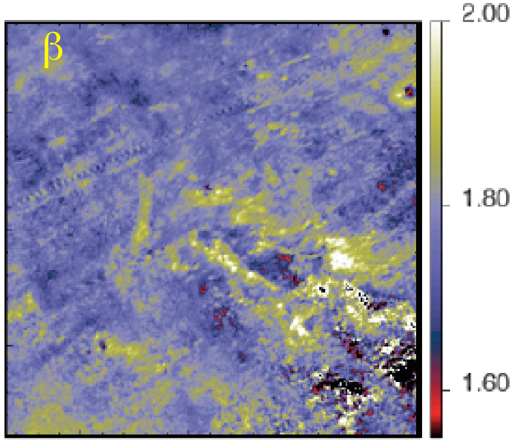
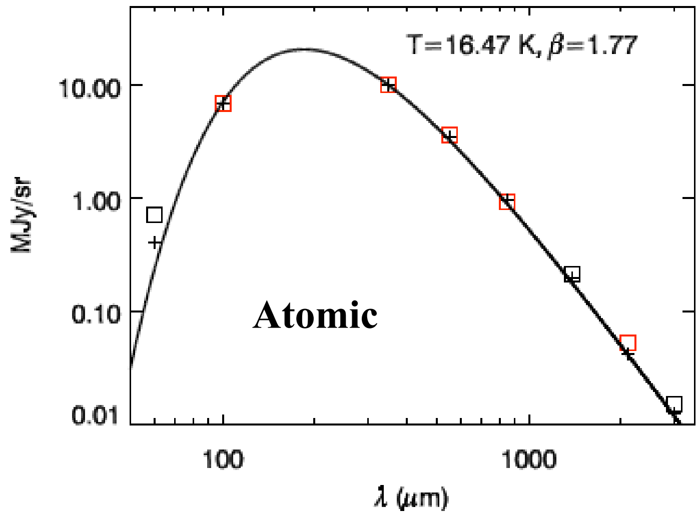
Dust in Molecular Clouds (Taurus)

Temperature and spectral index maps







- Narrow β distribution: 1.78 +- 0.08 (rms) +- 0.07 absolute

- Systematic residuals at 353 GHz (-7%) and 143 GHz (+13%) indicate spectrum more complex than a simple modified black-body

- Dust temperature maps from 16–17 K (diffuse regions) to 13–14 K (dense regions)

- Emissivity increase in dense regions :

τ/N_H @ 250 μm from ~ 10^{-25} cm^2 (diffuse) to ~2×10^{-25} cm^2 (dense)

-Such variations of τ/N_H have an impact on the equilibrium temperature of the dust particles

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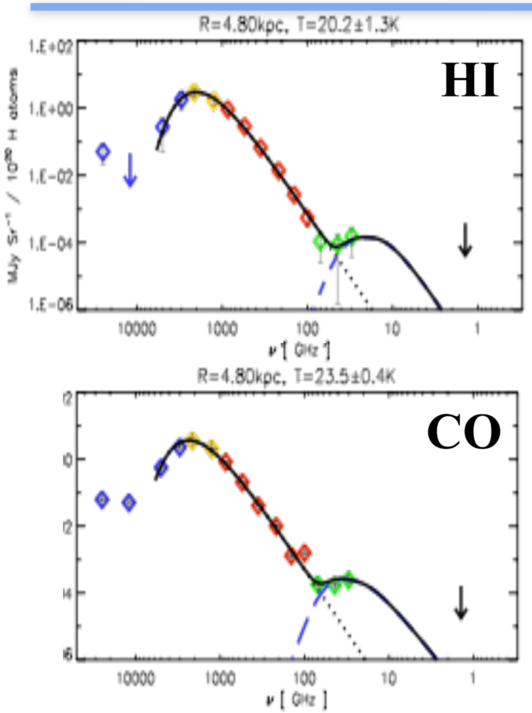
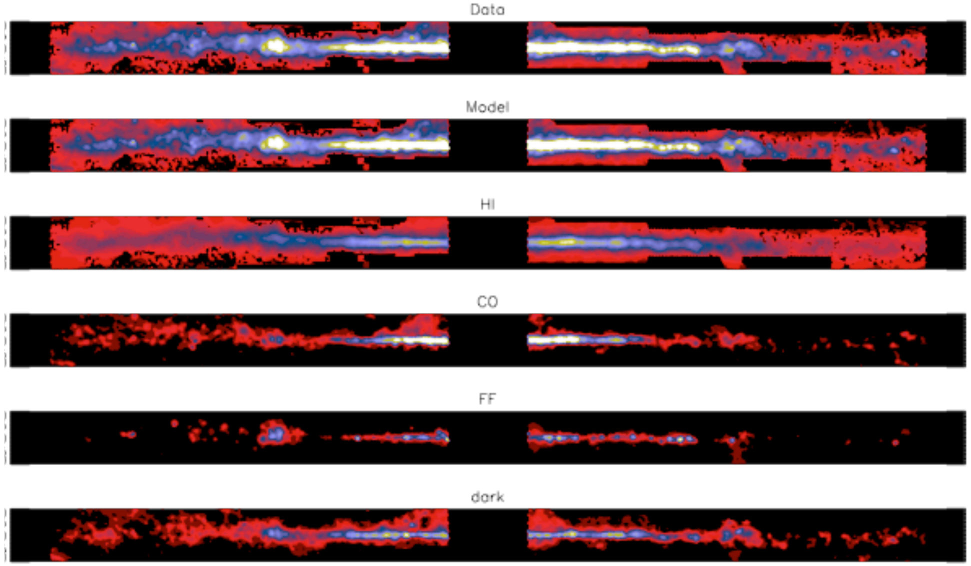
Galactic plane decomposition





Planck Data

Model

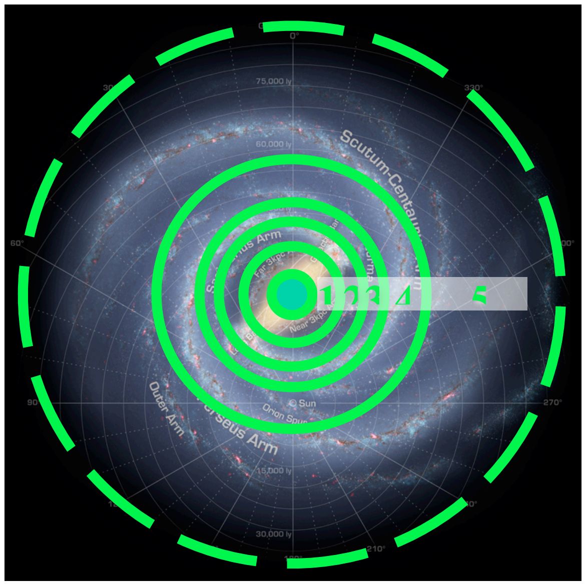
Neutral (HI)

Molecular (H_2)

Dark Gas

Ionized (HII)

-Temperature follows the general ISRF decrease with R
- Solar circle values (T, τ/N_H) in agreement with high latitude studies
- No significant emissivity variation with R
- Dust not significantly colder in CO phase (more sensitive to local star formation)
- Warmer grains in ionized gas
- Spinning dust seen everywhere but the ionized ISM (25+/-5% (stat.) of 30 GHz signal)



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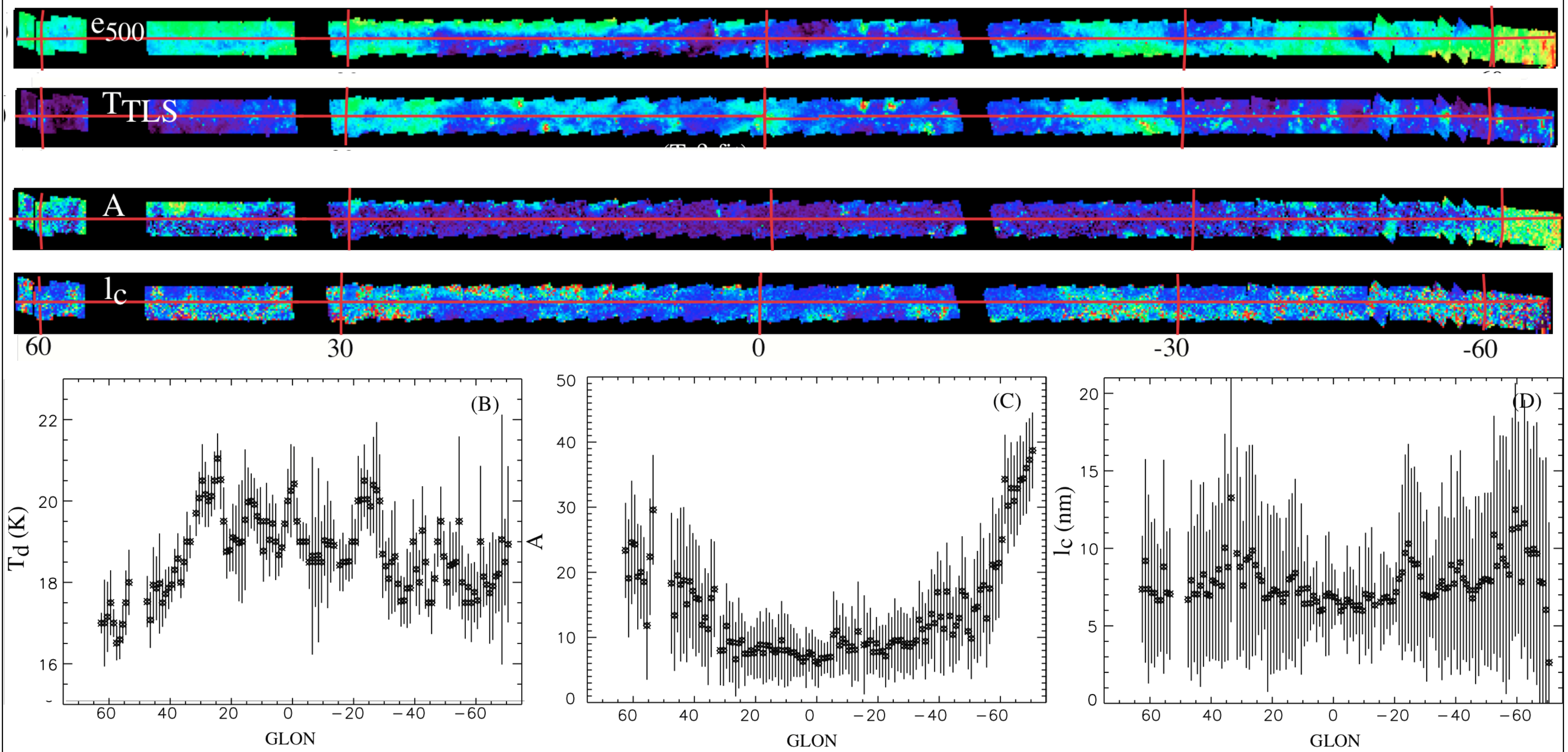
Herschel 500 mic excess

Paradis et al. 2012, usingthe available Hi-gal data (-60°<l<60°, |b|<1°)



Excess at 500 mic (e500) above a power law extrapolation
Relative importance of excess increases with galactic longitude
Interpreted as more amorphous dust away from internal MW regions

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Dust in other galaxies
Red: Herschel SPIRE 250 microns
Green:Herschel PACS 100 & 160 microns
Blue: Spitzer 24 & 70 microns
LMC has seen with Herschel & Spitzer
(Courtesy SAGE and Heritage Consortium)
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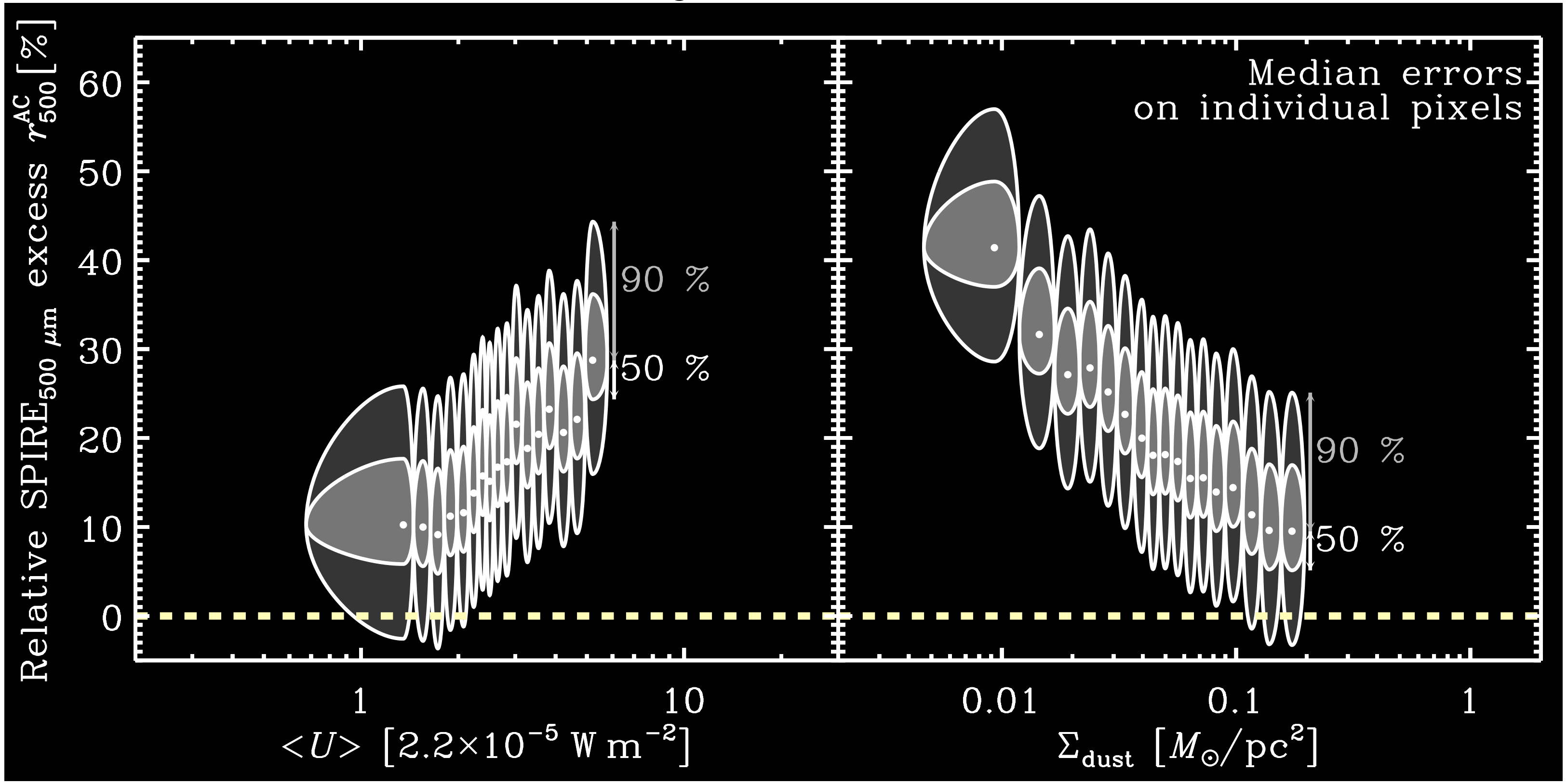
Herschel 500 mic excess in LMC

500 mic excess is ≈15% on average



Excess is correlated with dust temperature:

=> consistent with TLS model expectations

Excess is anticorrelated with dust column density:

=> cannot be due to contamination by high J CO lines;

=> no significant bias of the general dust mass estimate.

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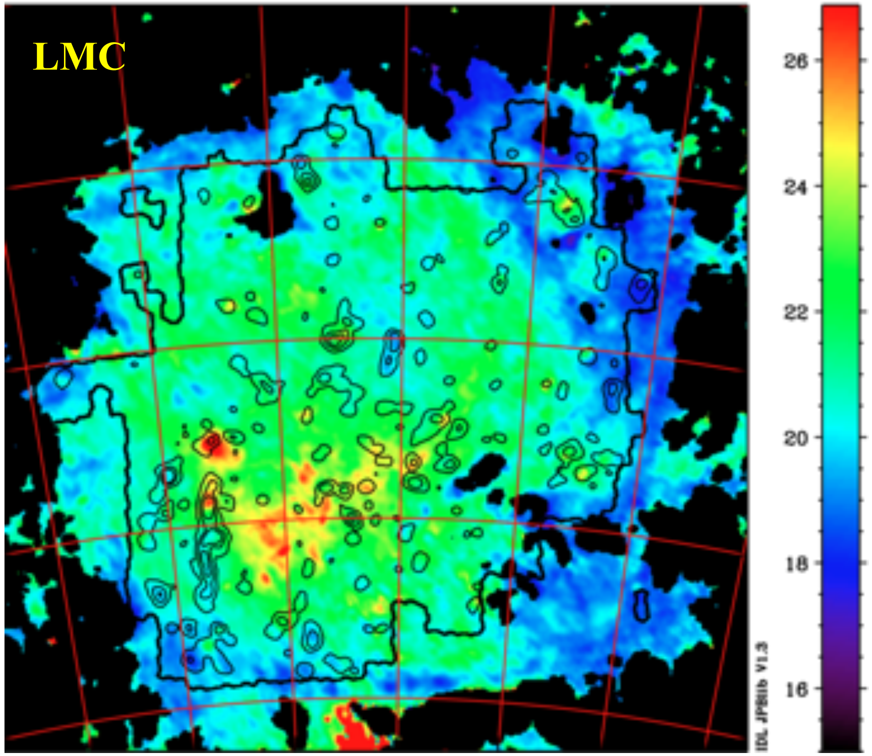
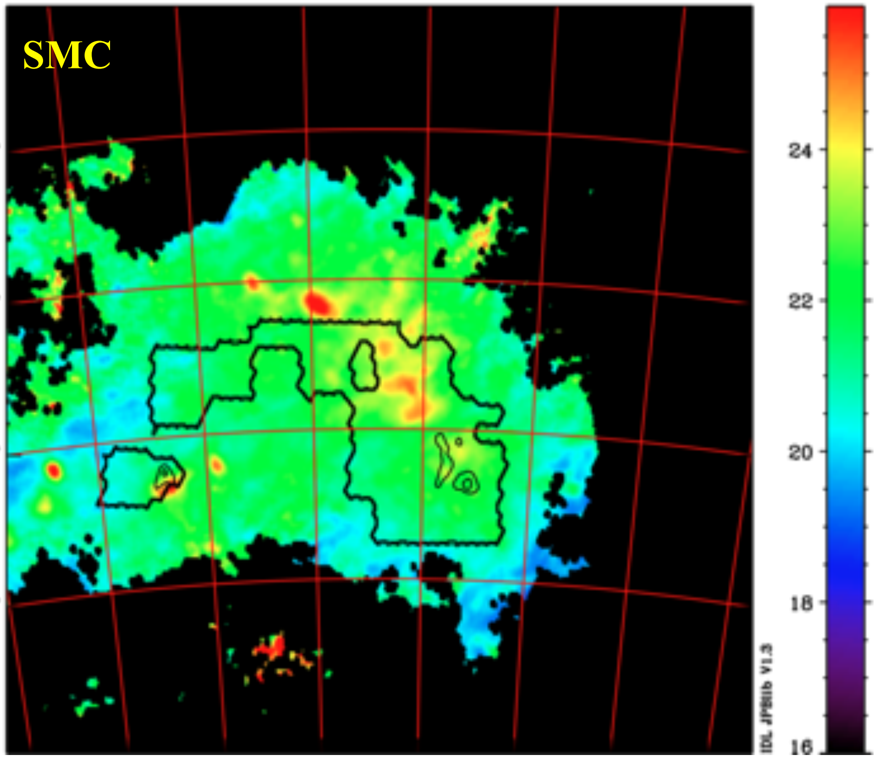
Dust Temperature (LMC/SMC)





- Temperature (T_D) from IRAS 100 µm, HFI 857,545 GHz, β=1.5 (median value derived from T-β fit)
- Foreground subtraction using MW emissivity measured around galaxies and MW HI emission
- (T_D) correlates with Hα emission (star formation)

LMC : Warm inner arm (already known). Cold outer arm (South and West) revealed by Planck.
SMC : Strong submm excess (similar to other low Z galaxies) ?

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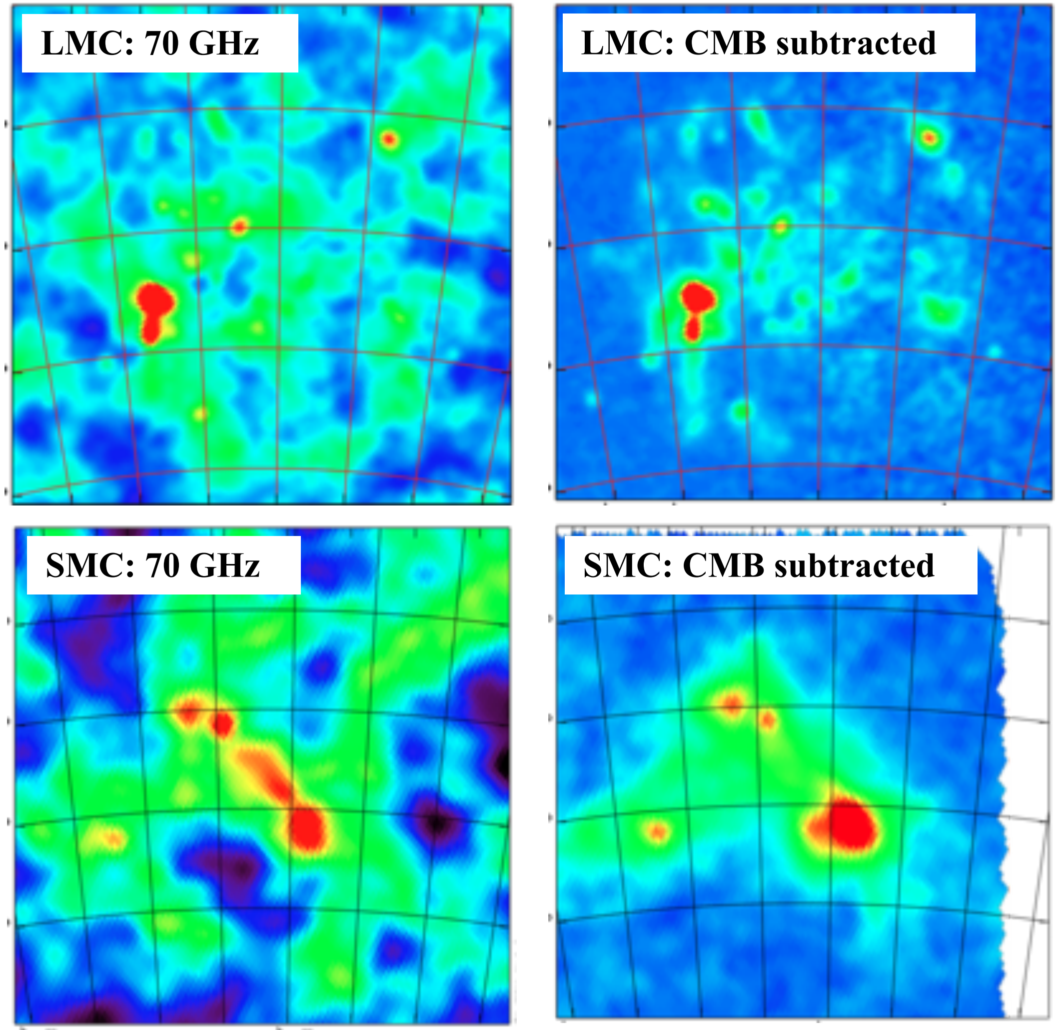
CMB Subtraction



CMB is a serious problem to study dust emission at low frequencies !! (will be even more true of smaller galaxies)

Internal Linear Combination (ILC) with patch size optimized to minimize CMB residuals, based on Monte-Carlo simulations
Uncertainties on CMB subtraction derived from Monte-Carlo simulations

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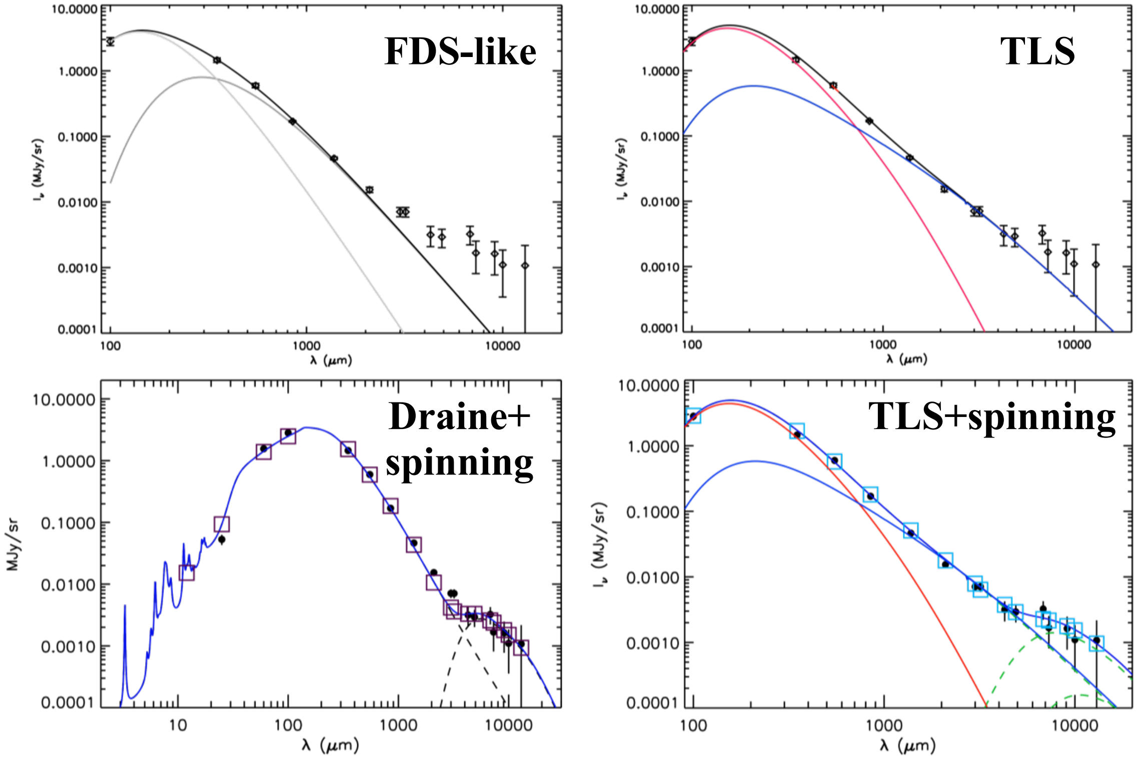
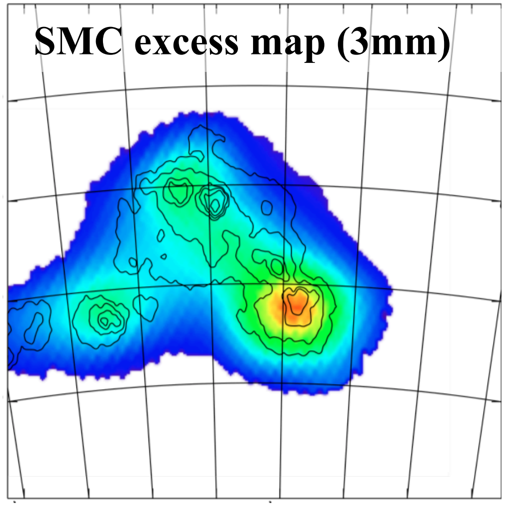
Submm excess of the SMC





Submm excess follows the spatial distribution of thermal dust at high frequencies

- Free-Free contribution subtracted, extrapolated from Hα emission, assuming no extinction
- Very Cold dust (Finkbeiner model) provides poor fit. Requires IR/optical opacity ratio 15 times larger than MW. Unlikely given spatial distribution.
- Best fit obtained for a combination of the Two-Level System (TLS) model and spinning dust
- Amorphous grains with similar parameters as MW, but more amorphous than in MW
- Spinning dust parameters compatible with PAH emission in the SMC

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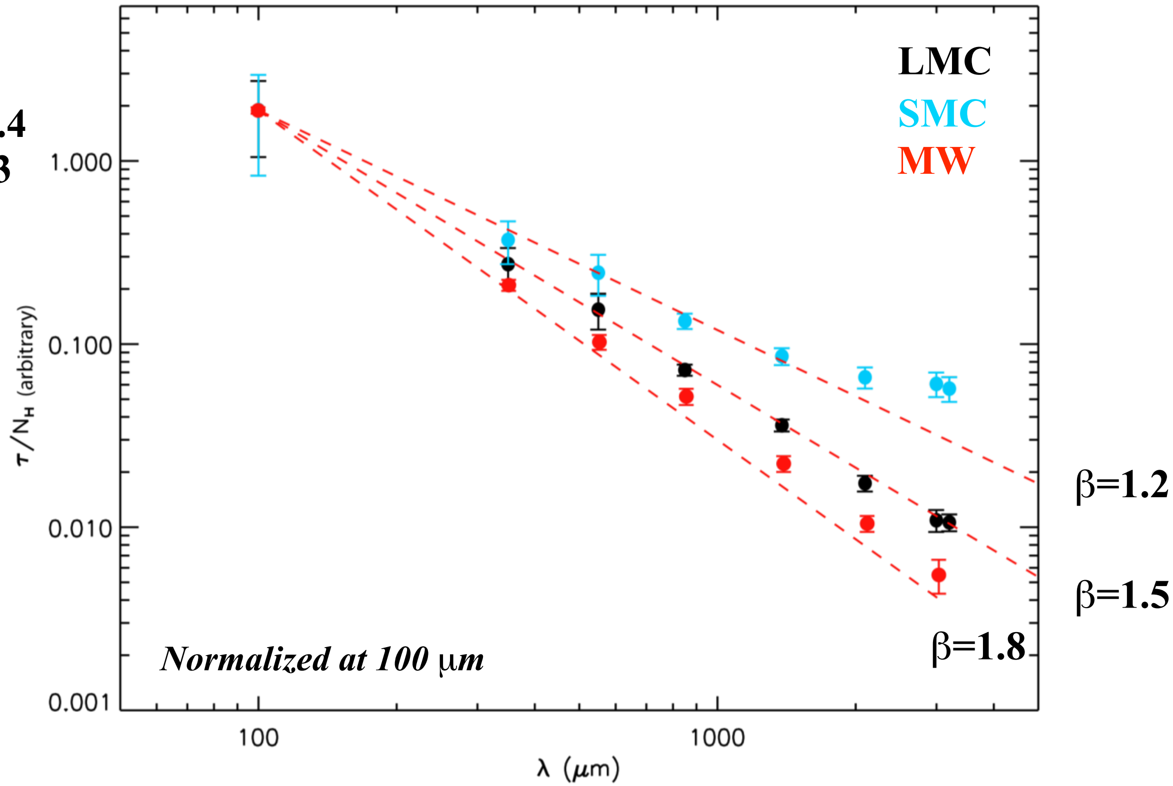
Submmm emissivity of MW, LMC, SMC

Large variations of the sub-mm emissivity are observed between the MW, the LMC and the SMC
MW ($Z=Z_\odot$) : β (FIR)=1.8
LMC ($Z=Z_\odot/2$): β (FIR)=1.5 (consistent with Gordon et al. 2010)
SMC ($Z=Z_\odot/6$): β (FIR)=1.2

Absolute value in the FIR :
MW: consistent with accepted value
LMC: consistent with Dust/Gas=1/2.4
SMC: consistent with Dust/Gas=1/13

MW emissivity flattens above λ~500 μm
SMC emissivity flattens above λ~700 μm
LMC emissivity seems constant



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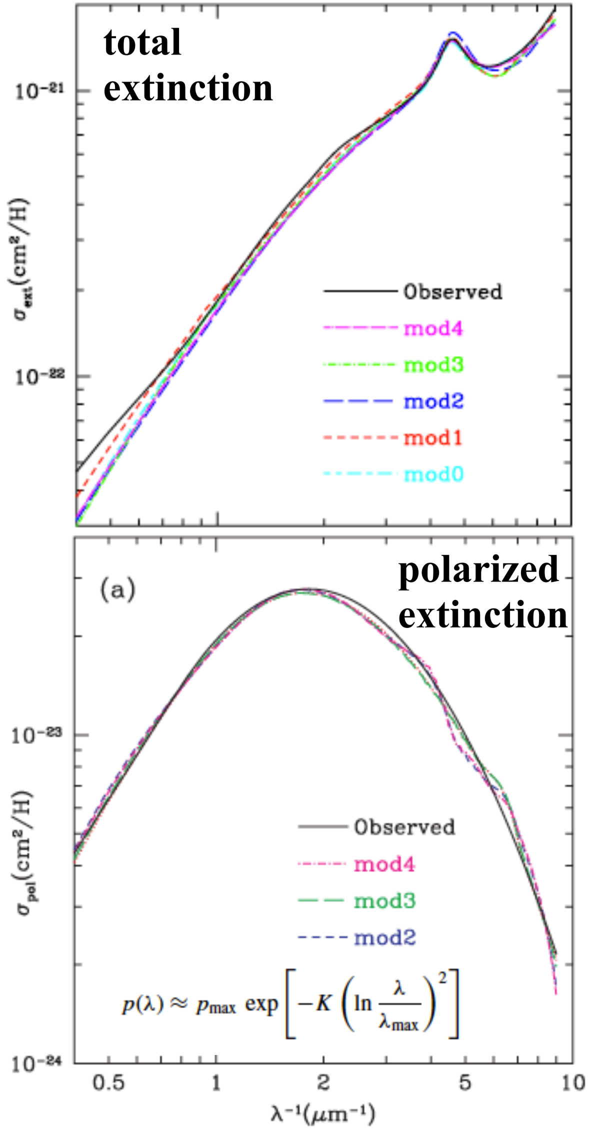
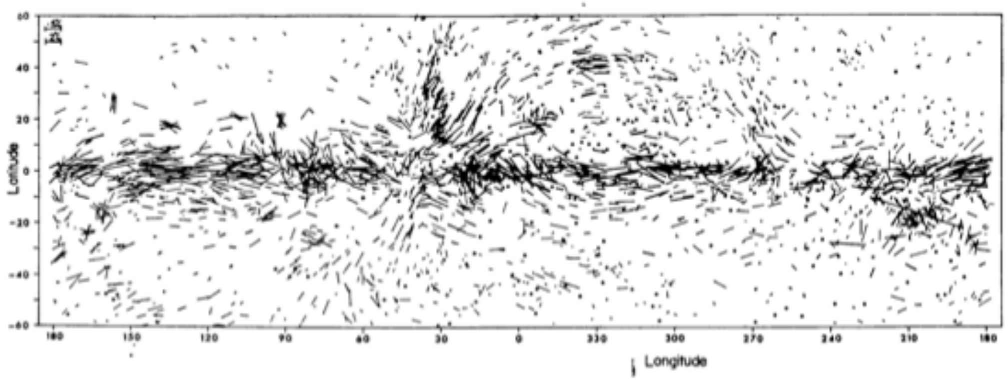
Bernard J.Ph., Planck 2012, Bologna

Polarization & dust properties

Draine & Fraisse 2009

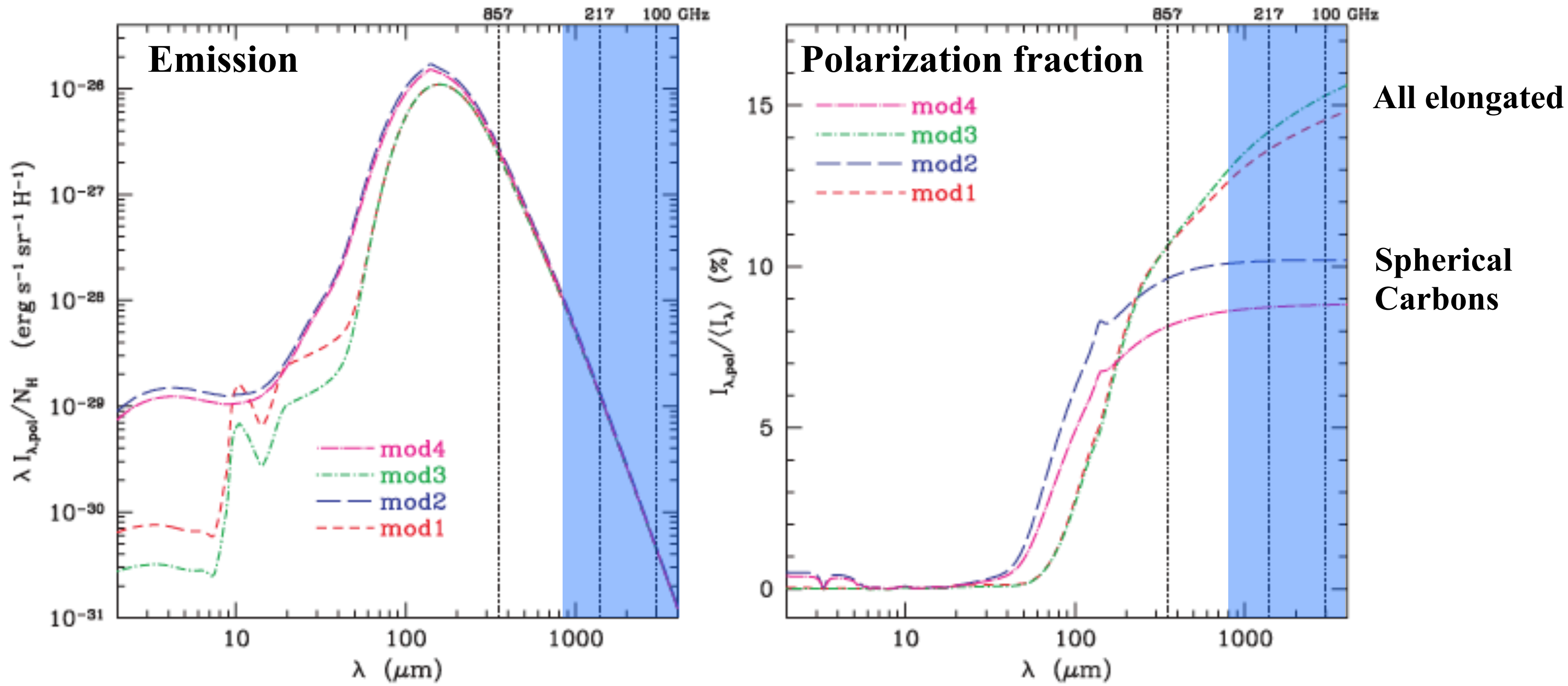




- Dust polarization is produced by elongated dust grains rotating and aligning with B
- Stellar polarization is produced by the same grains that produce submm polarization
- Polarized extinction indicate that the smallest dust particles do not polarize
- This is likely because small dust particles do not align with B (low inertia)

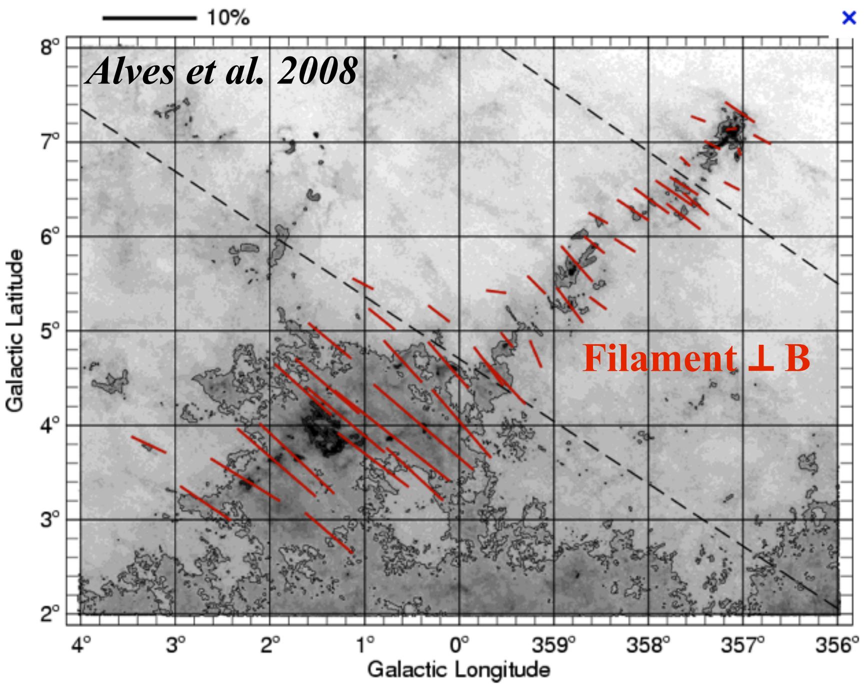
Polarization & dust properties

Draine & Fraisse 2009



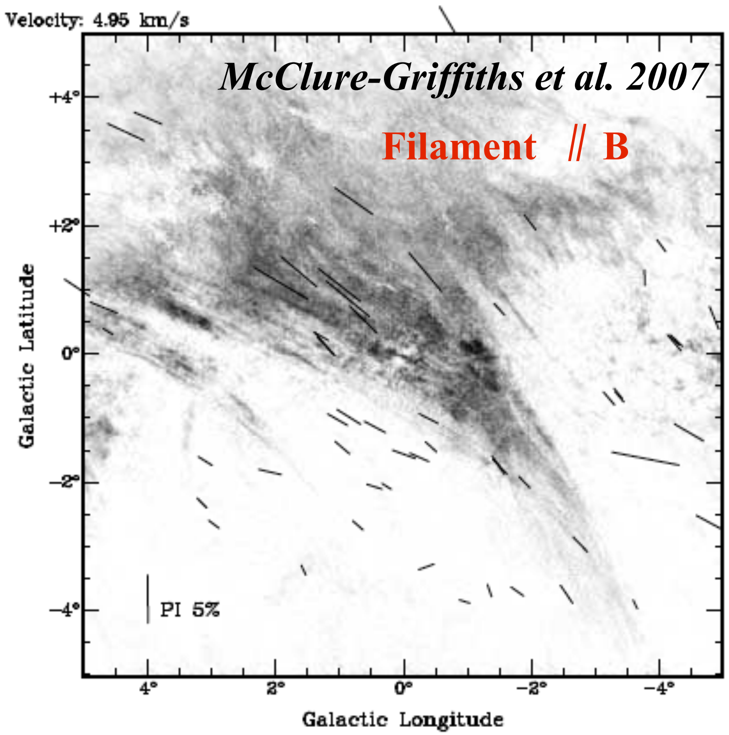
- Models with several dust components predict variations of p(λ) if some of these components do not polarize (e.g. spherical particles or poor alignment properties)
- Models with single dust components predict no variations of p(λ)
- Variations of p with column density (τ_D) and/or radiation field (T_D) may provide clues about alignment processes, but will often require radiative transfer modeling.

Polarization : B field direction



Some ISM filamentary structure show apparent connection with magnetic field ...

... although the two examples shown here (only a few degrees apart on the sky) give opposite filament orientation w.r.t. B field



The planck data will allow to test this with much more statistics than stellar absorption measurements allow

Bernard J.Ph., Planck 2012, Bologna

Conclusions

Herschel and Planck have brought wonderful data about thermal dust emission in the MW and nearby galaxies

So far, these observations seem to confirm some previous findings, such as :

- **Ability of thermal dust to trace radiation field**
- **Large variations of small dust abundance**
- **Dust coagulation**
- **Presence of cold cores**
- **Ability of thermal dust to trace Dark Gas.**

They also bring somewhat surprising new pieces of evidence, such as :

- **Dark Gas in MW and nearby galaxies**
- **Large D/G variations in MW halo**
- **Variations of dust emissivity in MW, LMC, SMC**

There are still important questions to be answered, such as :

- **Variations of beta with wavelengths ?**
- **Variations of beta with temperature ?**
- **What is the impact of D/G variations, ISRF mixing ?**

This is just a beginning ...
the Planck Polarization data will also bring a lot to the study of thermal dust & magnetic structure of the ISM.

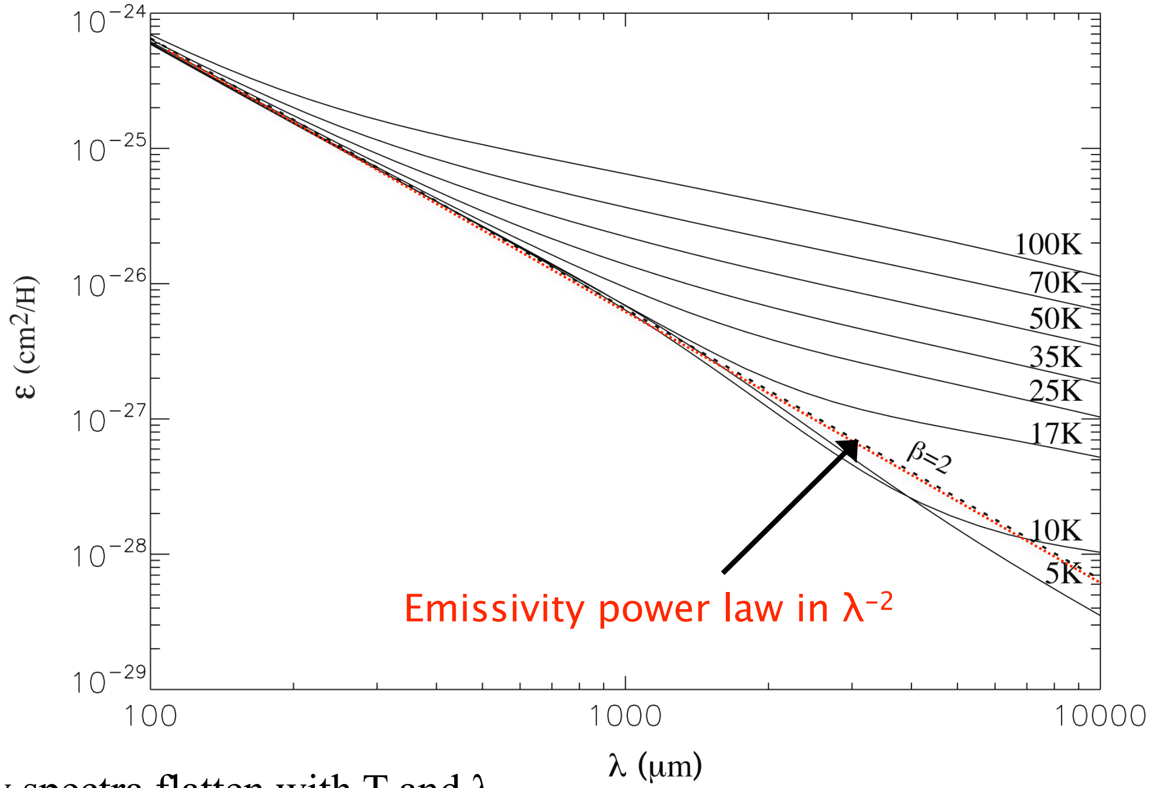
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Planck 2012, Bologna

A model of amorphous dust: the TLS model

Dust emissivity predictions

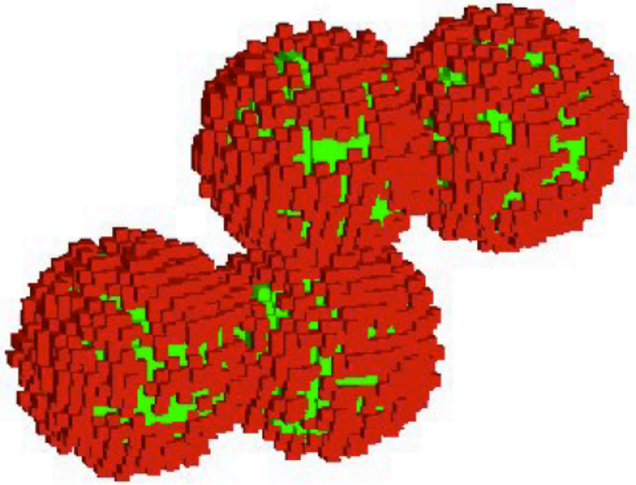


Emissivity spectra flatten with T and λ

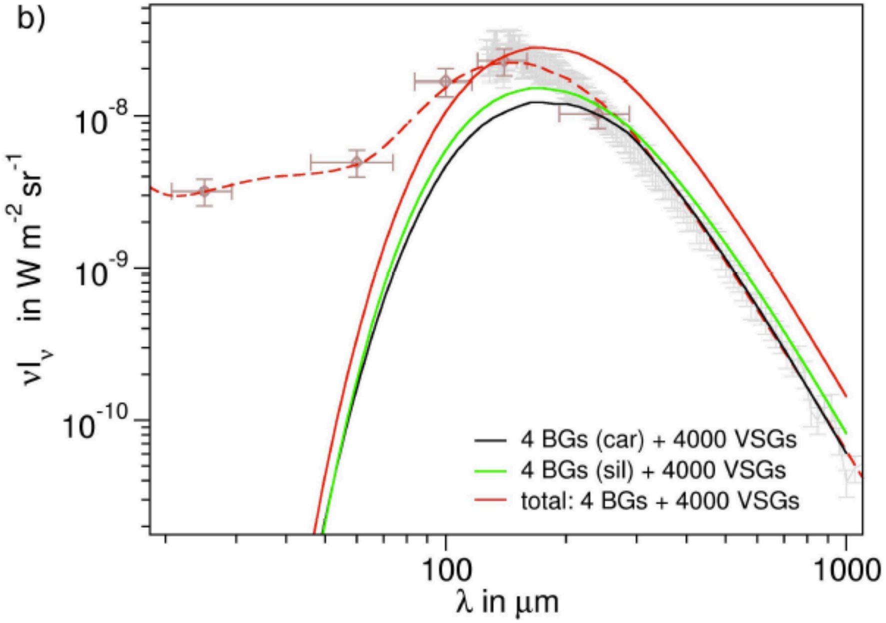
=> Therefore, when assuming no dependency of the emissivity spectrum with λ nor T, one can significantly bias the mass estimate, especially when derived from submm/mm data and extrapolated to shorter wavelengths.

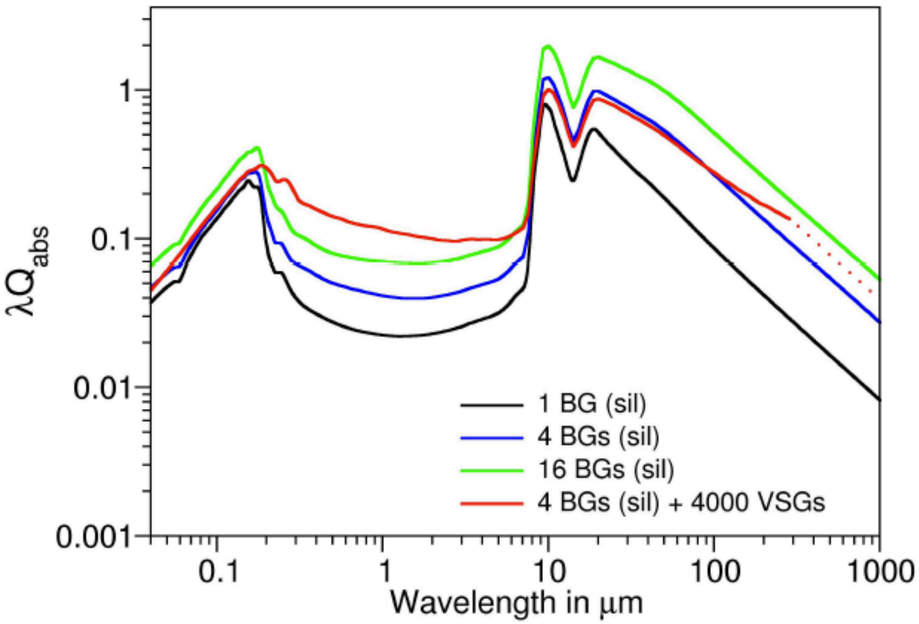
Paradis, Bernard, Mény, & Gromov, 2011a, A&A in press, arXiv1107.5179

grain-grain Coagulation



Observational evidences:
Bernard et al 1999, Stepnik et al. 2003

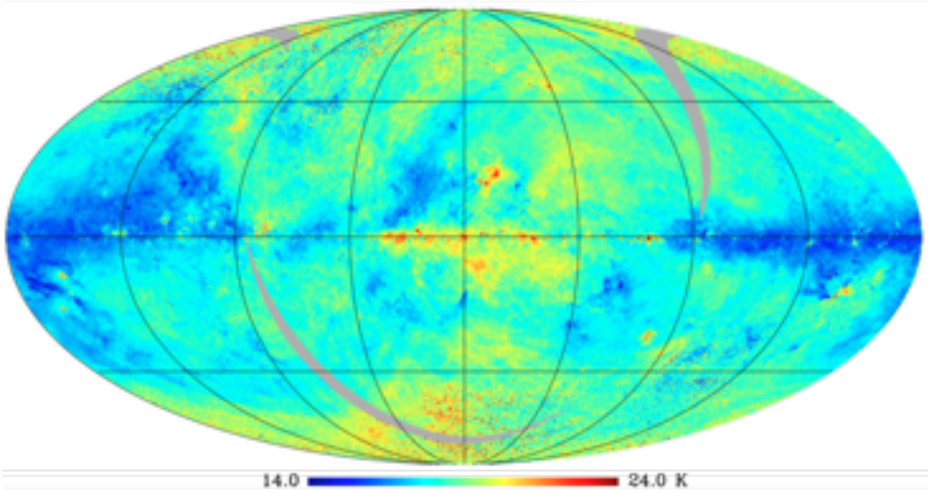




Kohler et al. 2012, in prep.

Discrete Dipole Approximation (DDA) calculations of dust aggregates show:
- Increase of emission cross section
- Little variation in absoprtion
- Resulting in higher dust emissivity and lower dust temperature for same radiation field

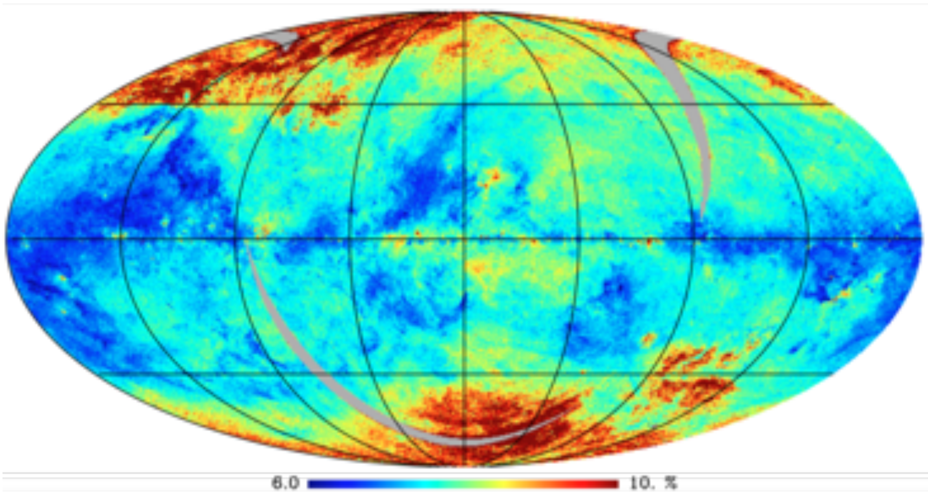
Dust Temperature



Temperature (T_D) computed from IRAS 100 μm, HFI 857 GHz, HFI 545 GHz, using β=1.8 (median value derived fromT-β fit)

12 K<T_D<50 K

- Dust temperature clearly traces the intensity of the radiation field:
- External galaxy is colder than inner Galaxy (was already known from COBE data)
- Molecular clouds are colder than surrounding
- Warm regions are star forming regions, HII regions, etc ..



Uncertainty on dust temperature from X^2 minimization using relative and absolute error. $\Delta T_D/T_D$<10% except at high latitudes (low brightness)

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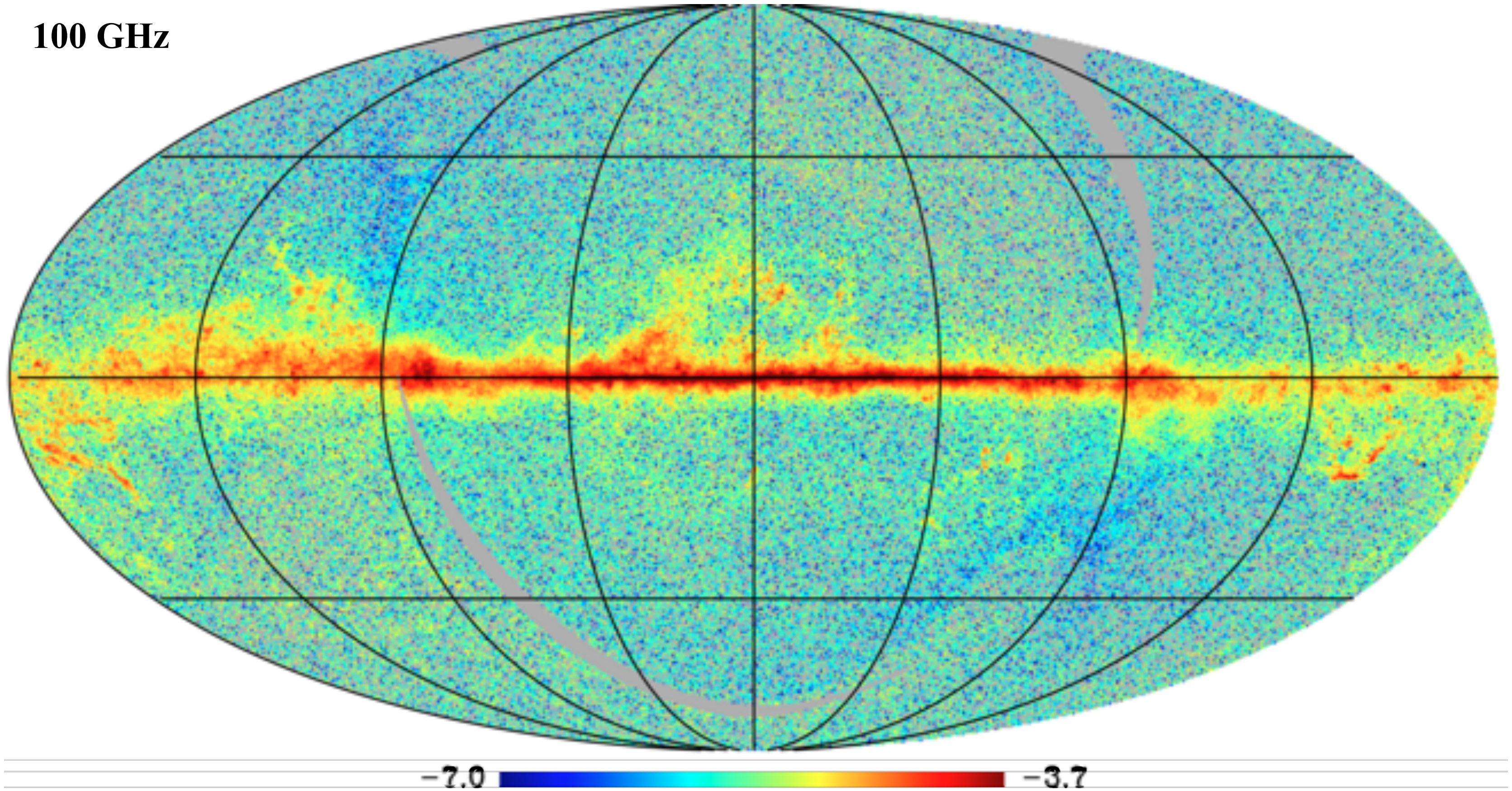
Planck Collaboration 2011, A&A 536 XIX

Bernard J.Ph., Planck 2012, Bologna

Dust Optical Depth (MW)

100 GHz



Planck Collaboration 2011, A&A 536 XIX

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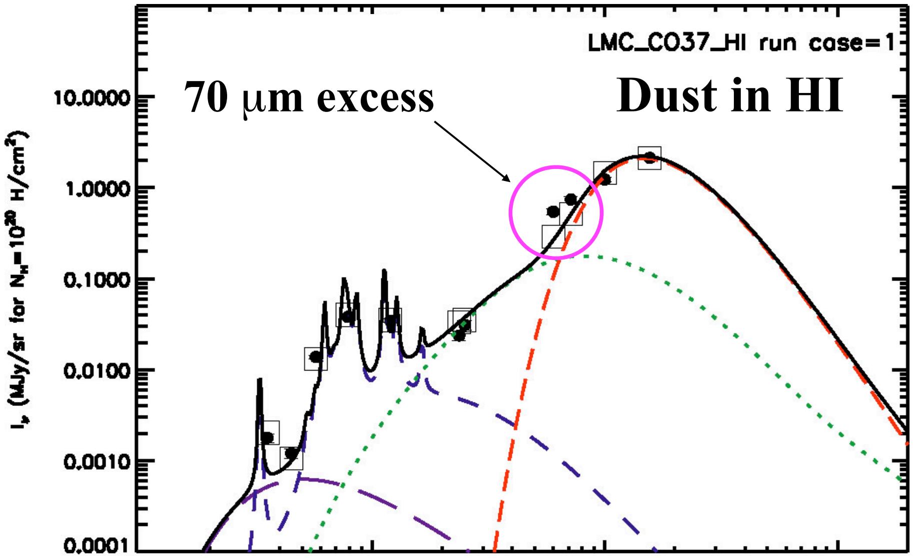
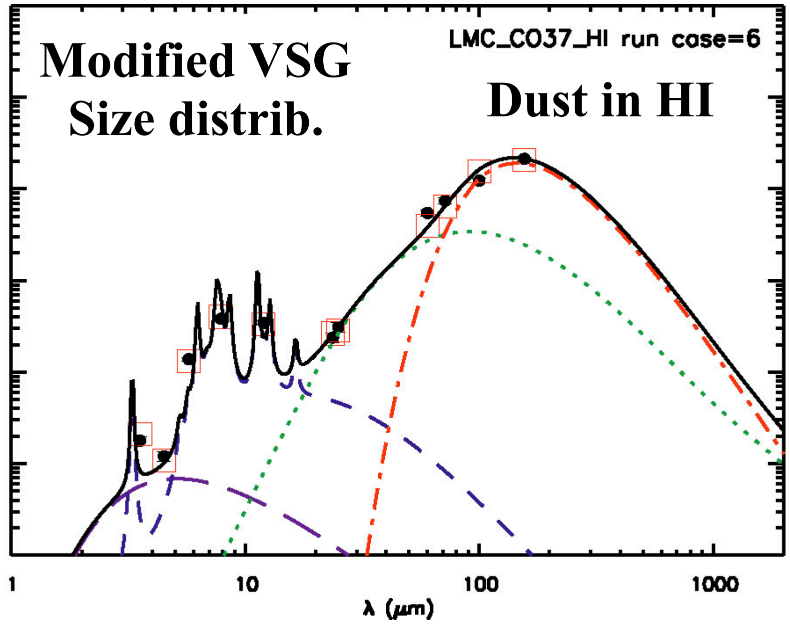
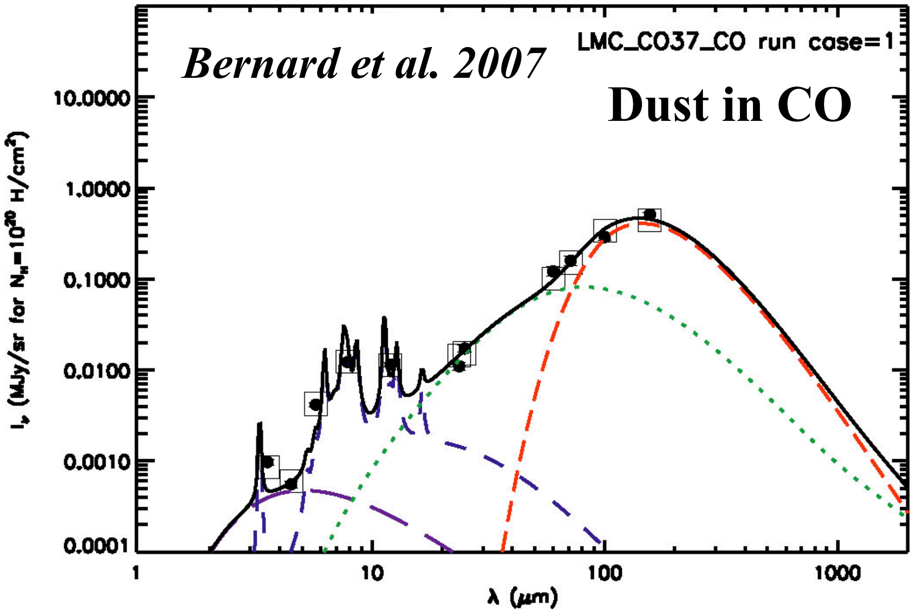
The magellanic Clouds

- Some of the most **nearby** galaxies: LMC ~50kpc, SMC ~60kpc
- High resolution observations
- **Low metallicity** galaxies (LMC~1/2 and SMC ~1/6 solar)
- Perfect laboratories for dust studies in a very different environment than our Galaxy with access to relatively small scales

Origin of 70 μm excess





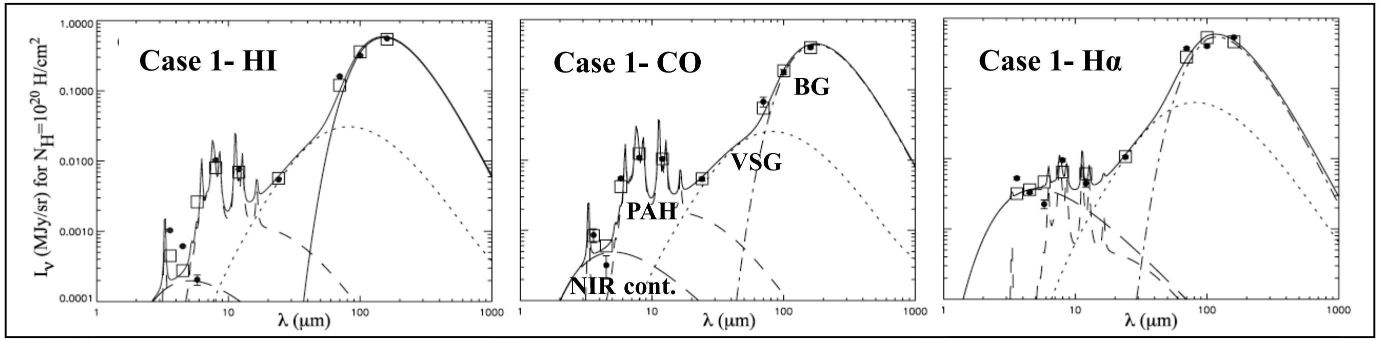


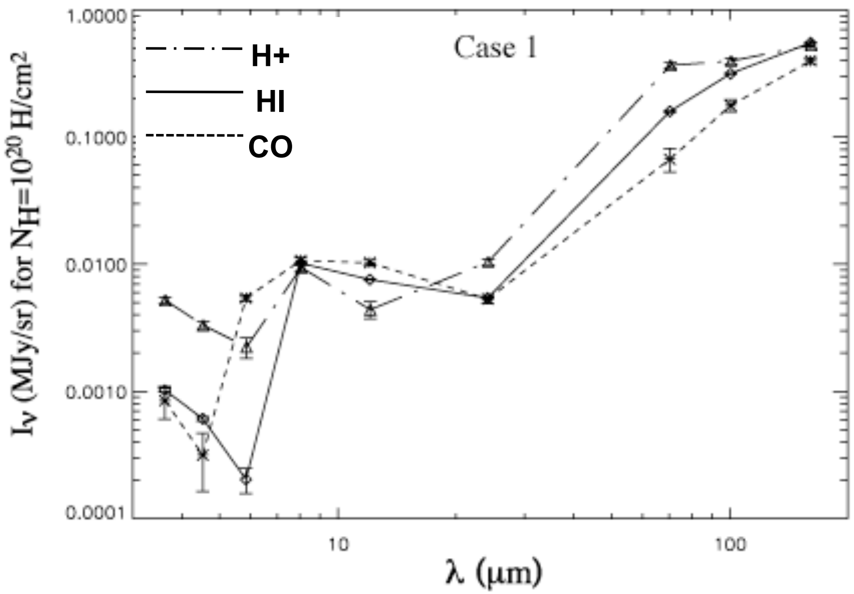
- **70 μm excess found mainly in HI**
- **Can be explained by modifying the grain size distribution.**
- **Requires an increase abundance of the large VSGs (or of the small BGs).**
- **corresponds to ~13 % of the total dust mass**
- **Grain erosion processes in the diffuse medium ?**

Bernard J.Ph., Lorentz Center workshop 2011, Leiden

Dust in the diffuse ionized gas (LMC)

Modeling with a single RF





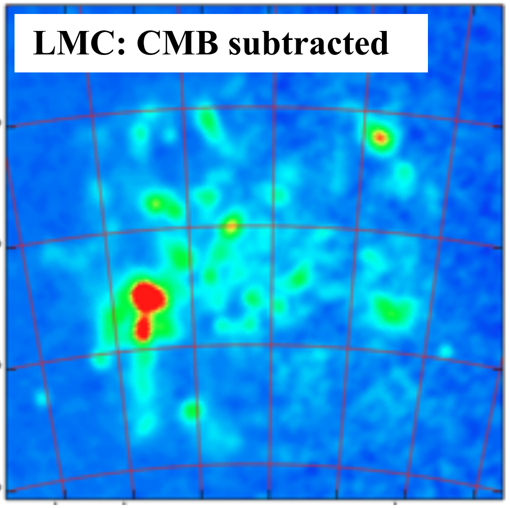
- ✓ Dust emission in H+ dominant in the FIR
- ✓ T_d^{H+}=23.9 K, T_d^{HI}=18.7 K and T_d^{CO}=16.1 K
- ✓ ε_{160}^{H+}= 2.3x10^{-26} cm^2/H

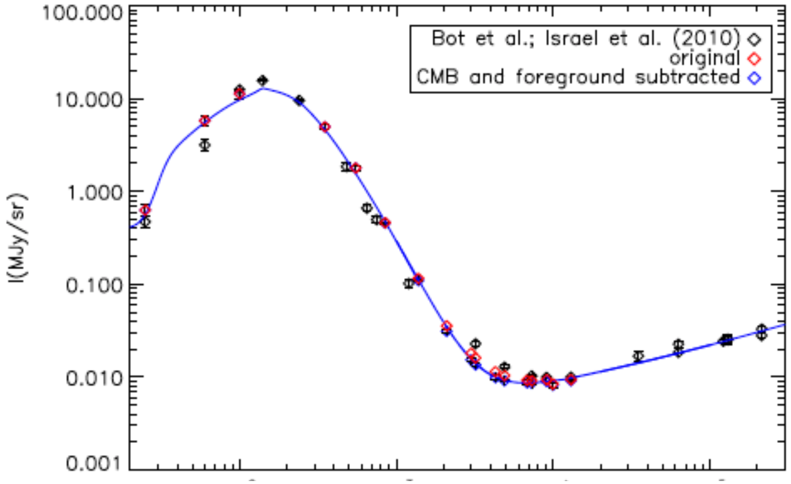
  => ε_{LMC}=1/10 $\varepsilon_{[illegible]}$= 1/40 ε_{GAL}
- ✓$(Y_{PAH}/Y_{BG})^{H+}$ =1/3 $(Y_{PAH}/Y_{BG})^{HI}$

  =1/6 $(Y_{PAH}/Y_{BG})_{CO}$
- ✓ [illegible] of the NIR continuum in the H+ phase

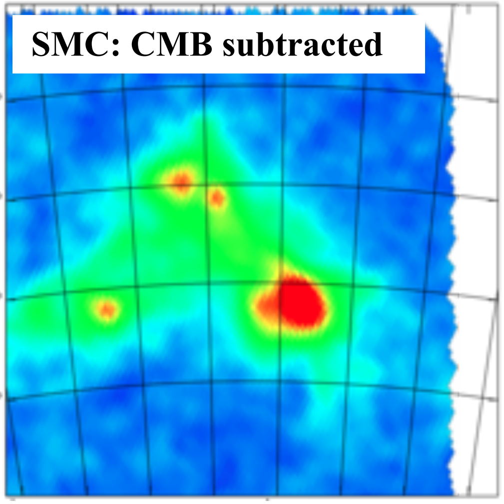
Paradis et al. 2011, accepted

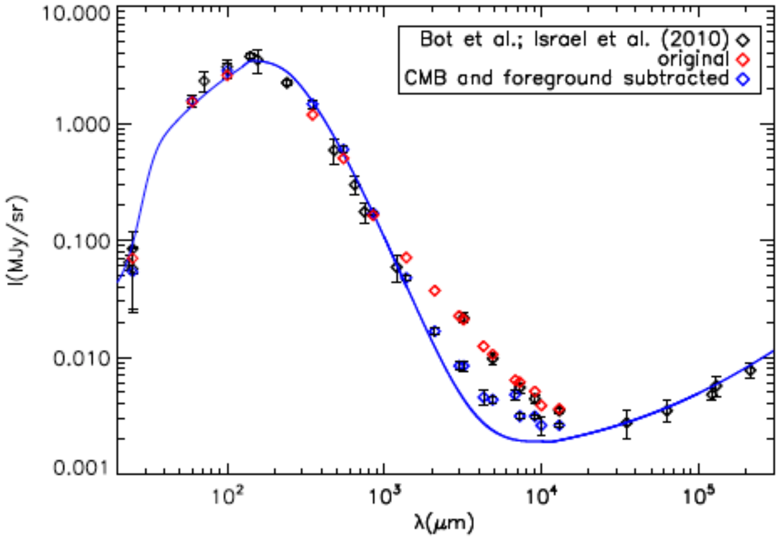
Integrated SEDs





The submm excess in the LMC goes away with CMB subtraction





The submm excess in the SMC remains after CMB subtraction

Model Draine & Li 2007 (see Bot et al. 2010)

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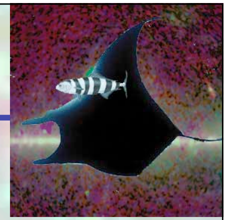
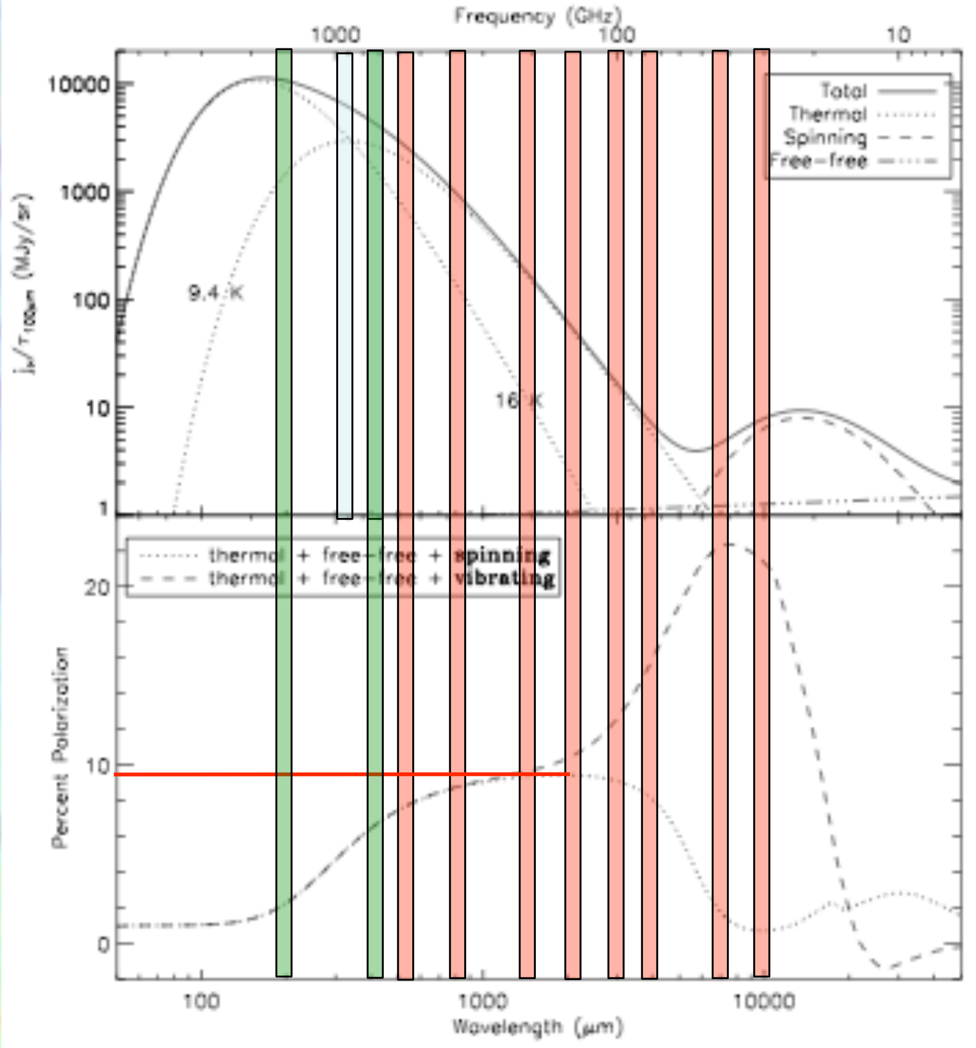
Planck Collaboration 2011, A&A 536 XVII

PILOT vs Planck λ-coverage





Planck: polarized

Planck: unpolarized

PILOT

Phot. Channels:	240/450 μm
M1 diam:	700 mm
Resolution:	1.4'/3.3'
S(3-σ)	0.3/0.4 MJy/sr
FOV:	46'*23'
Gondola mass:	~ 700 kg
Flight altitude:	~ 40 km

Toy model by Vaillancourt, based on a two-temperature model, with emission from graphite grains assumed unpolarized