Dust : from the Milky-Way to nearby galaxies

J.P. Bernard
on behalf of the Planck collaboration
and the Herschel Heritage & Higal Team

Dust : from the Milky-Way to nearby galaxies

J.P. Bernard
on behalf of the Planck collaboration
and the Herschel Heritage & Higal Team

Layout

Dust Physics (before Planck & Herschel)

Our Galaxy with Planck & Herschel

- The galactic halo
- The solar neighborhood
- Molecular clouds and Cold Cores
- The MW plane

The Neighbourhood (LMC/SMC) with Planck & Herschel:

- The LMC/SMC
- Nearby Galaxies

The polarization with Planck

Dust Physics

Dust:

Catalysis of molecule formation

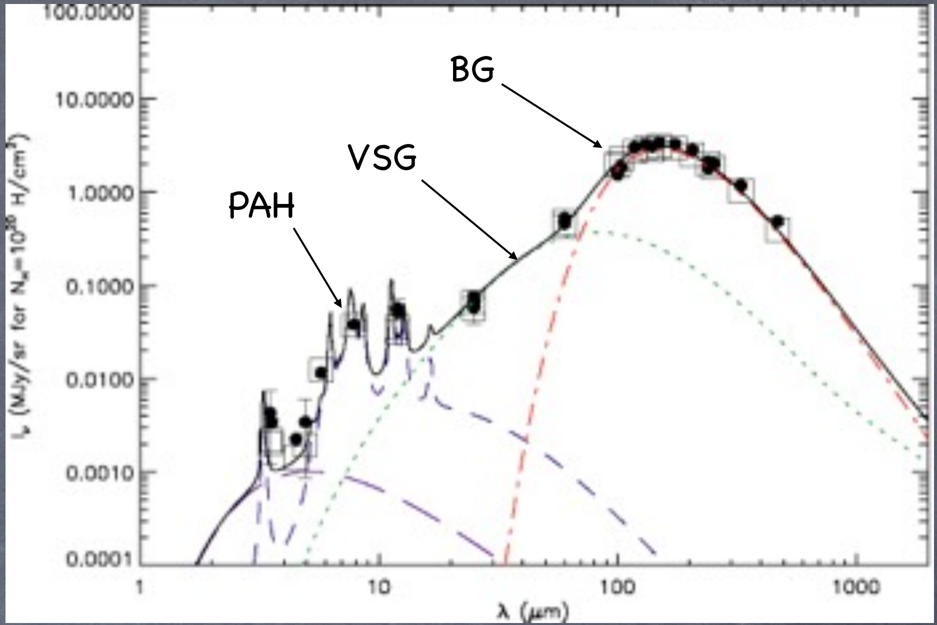
Gas heating (photo-electric effect)

Cooling in dense regions

"Universal" tracer of the ISM structure

FIR observations of distant galaxies

Foreground Emission / CMB Cosmology



Composition:

PAH = Polycyclic Aromatic Hydrocarbons

VSG = Very Small Grains

BG = "Big" grains Silicates + Graphite (≈ 0.1 μm)

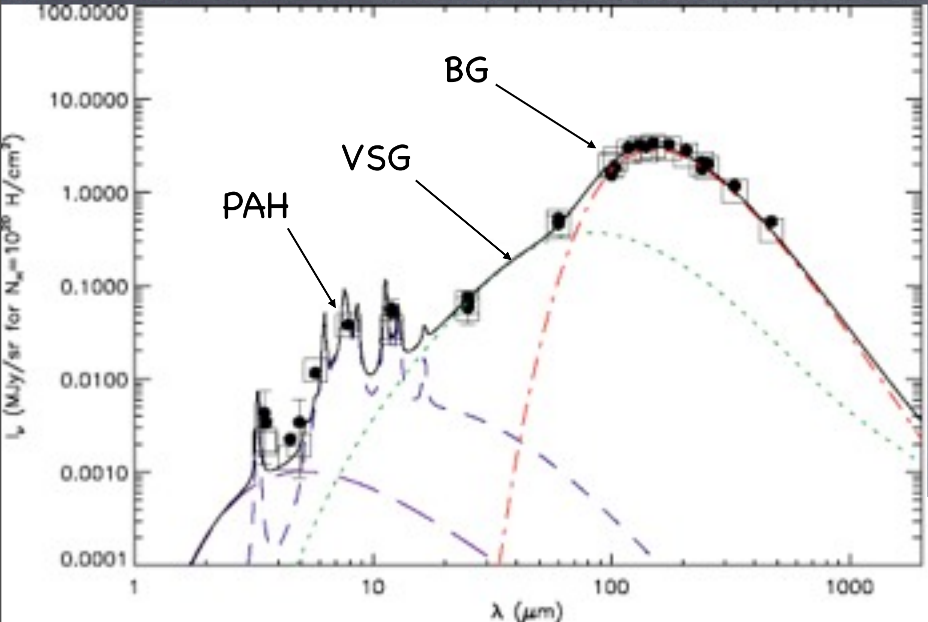
$$I_\nu = \tau_\nu B_\nu(T_D) = \pi a^2 Q_{abs}(\lambda) X_{dust} N_H \, B_\nu(T_D)$$

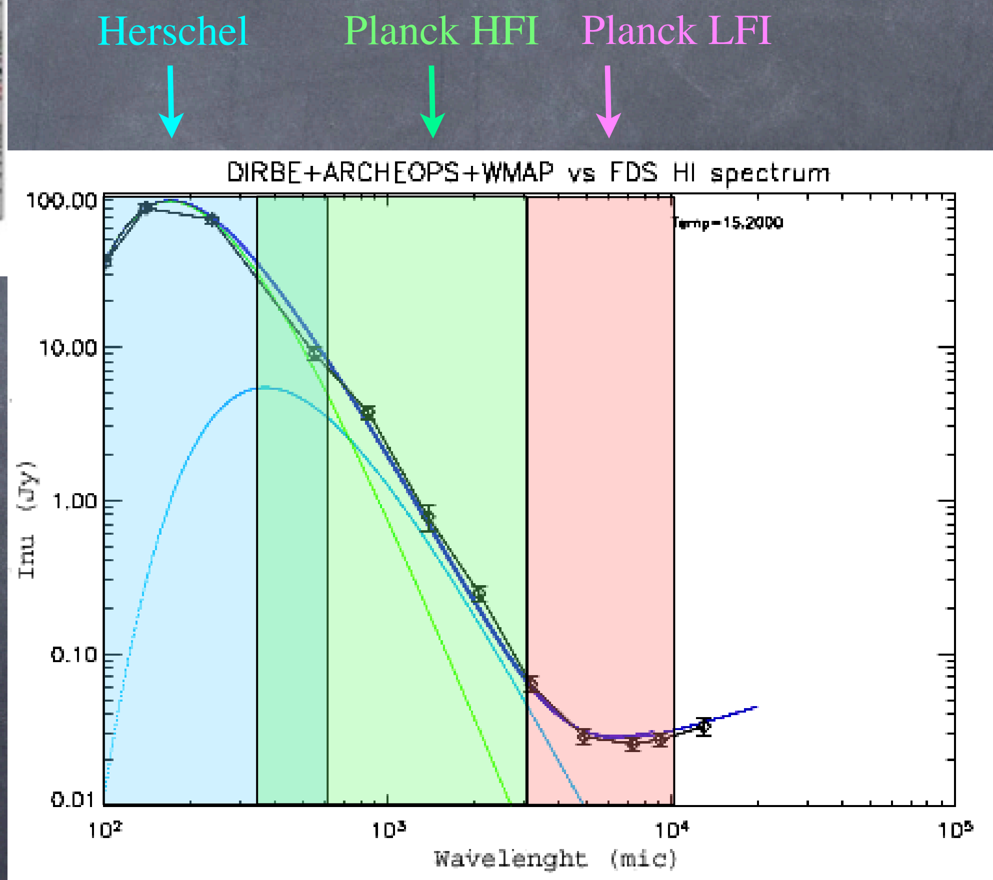
BG at thermal equilibrium -> dust temperature T_D measures radiation field intensity (G0)

It is usual to assume $Q_{abs}(\lambda)$ α $\lambda^{-\beta}$ with β=2 (Quadratic Law)

- In the FIR-mm optical depth are small (can account for the mass of a whole galaxy)
- In the Rayleigh-Jeans regime, I_ν α T_D, so mass determinations not very sensitive to temperature determination in Submm-mm ...

Herschel-Planck and Dust

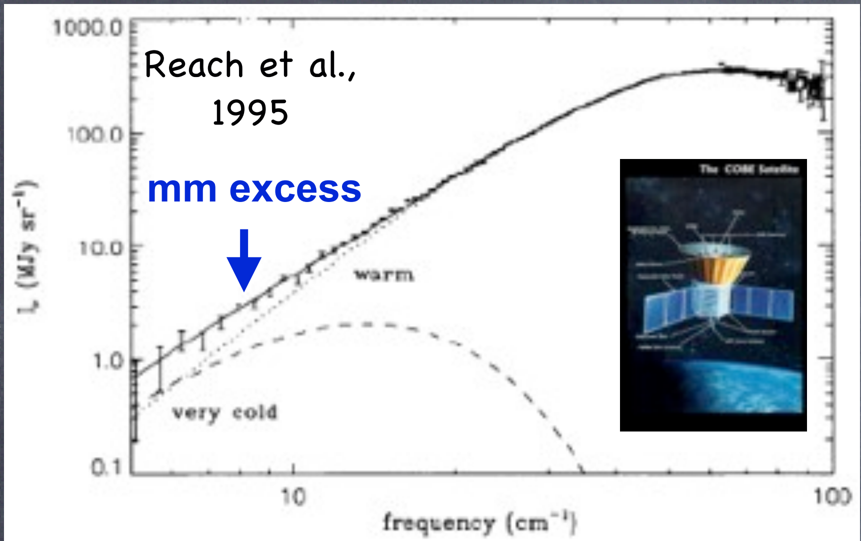




- Herschel and Planck-HFI are mostly sensitive to thermal emission by «large» dust grains (BG)
- At long wavelengths Planck-LFI is mostly sensitive to ionized gas (free-free, Synchrotron, spinning dust ...)

The flat MW SED

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



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 <u>reject</u> "very cold" dust.

Finkbeiner et al. 1999 (FSD)

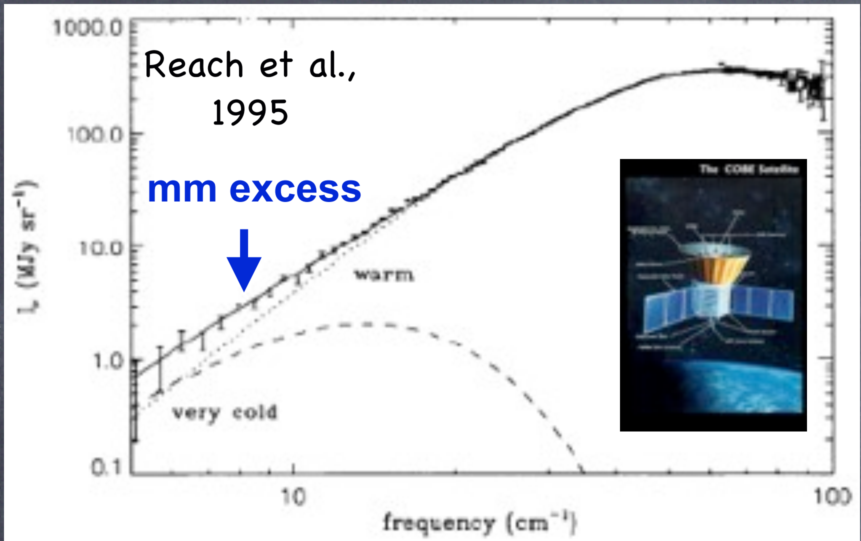
2 components= Graphite + Silicate

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

The flat MW SED

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



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)

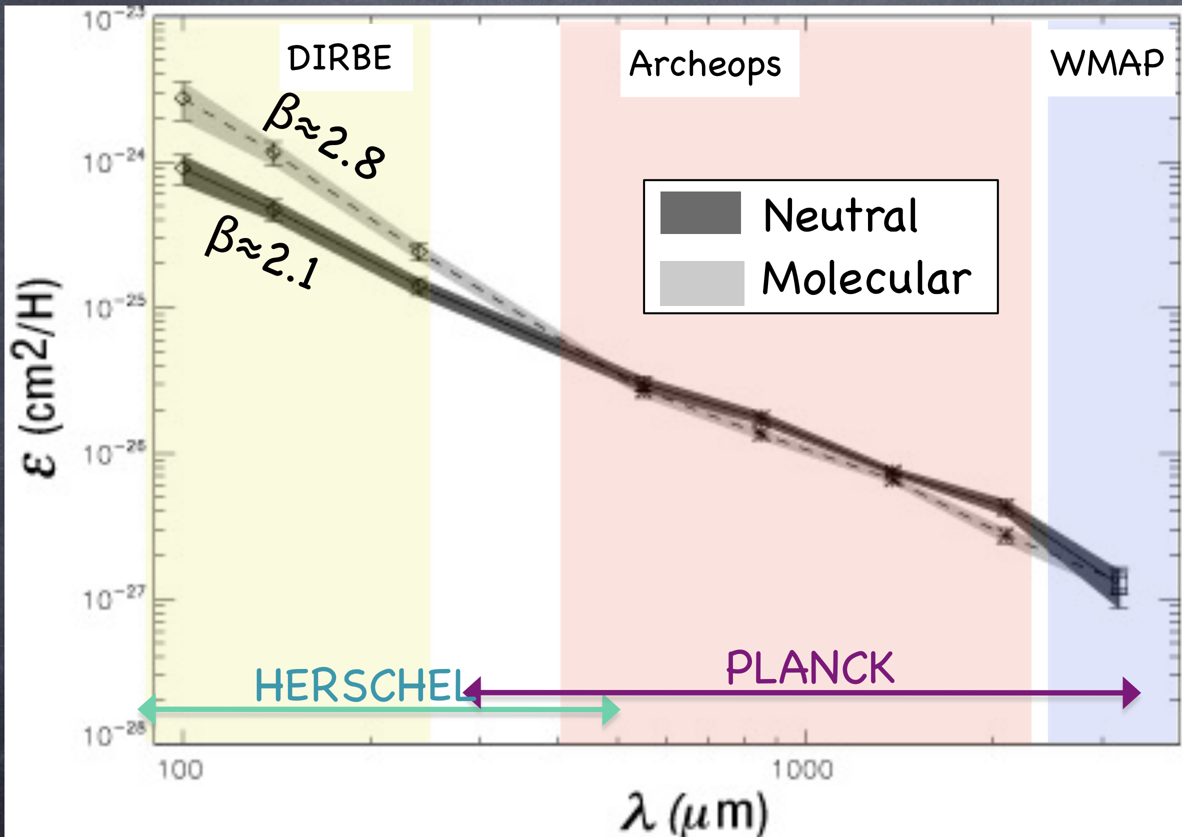
2 components= Graphite + Silicate

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

FIR-Submm dust emissivity

Early results from DIRBE, Archeops and WMAP towards cold molecular clouds



Show signs for emissivity variations :

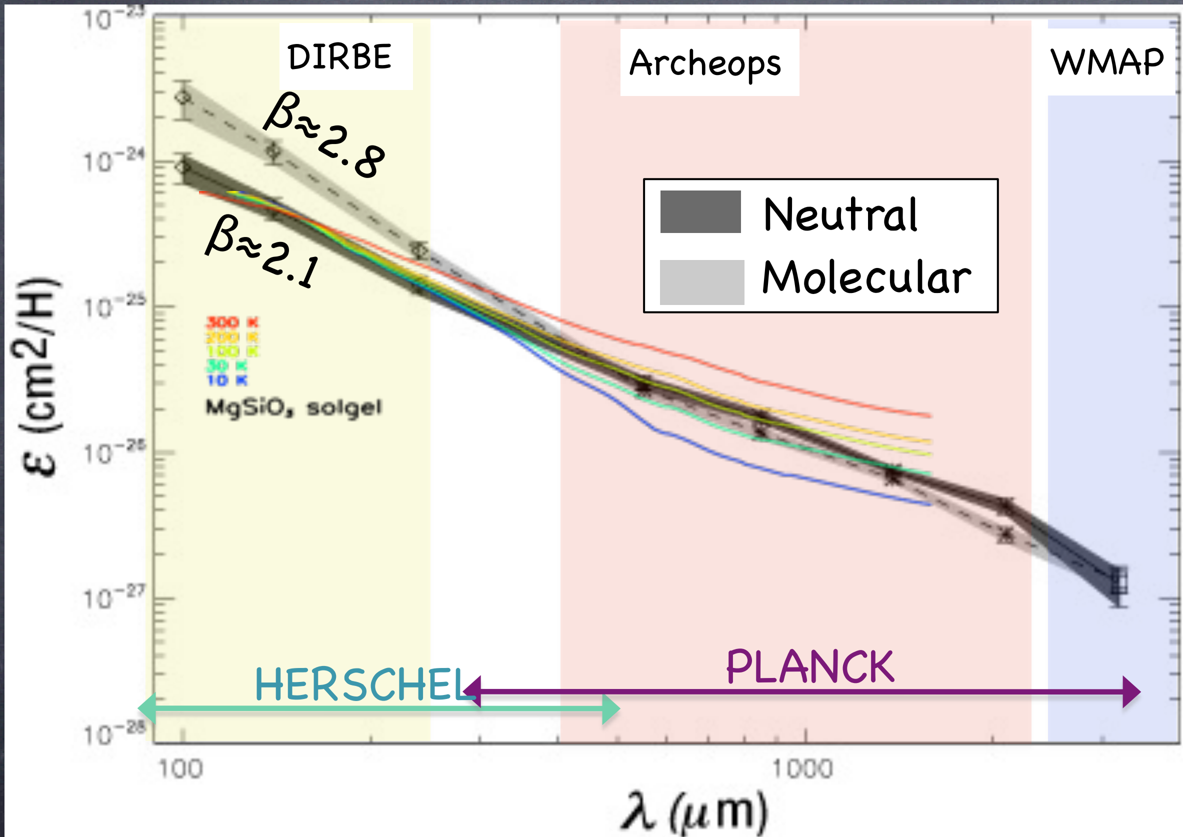
- Flattening of dust SED above 500 microns
- Increased emissivity in cold molecular clouds

Paradis et al. 2009

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

FIR-Submm dust emissivity

Early results from DIRBE, Archeops and WMAP towards cold molecular clouds



Show signs for emissivity variations :

- Flattening of dust SED above 500 microns
- Increased emissivity in cold molecular clouds

Paradis et al. 2009

Laboratory measurements of some amorphous materials (here $MgSiO_3$) seem to match the observed SED for the right temperature (here T=30 K)

See presentation by K. Demyk

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

The TLS model of amorphous grains

Strongly inspired from solid-state physics : *Meny et al. 2007*

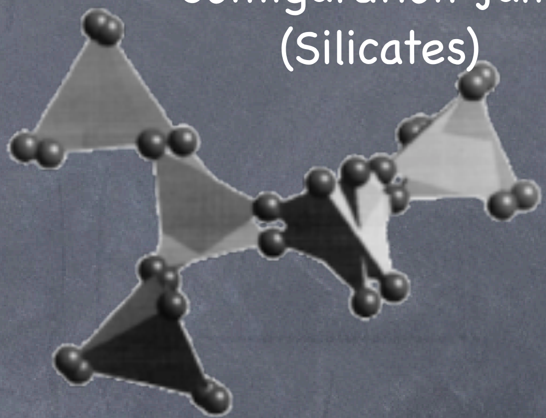
A double description of disorder in amorphous solids

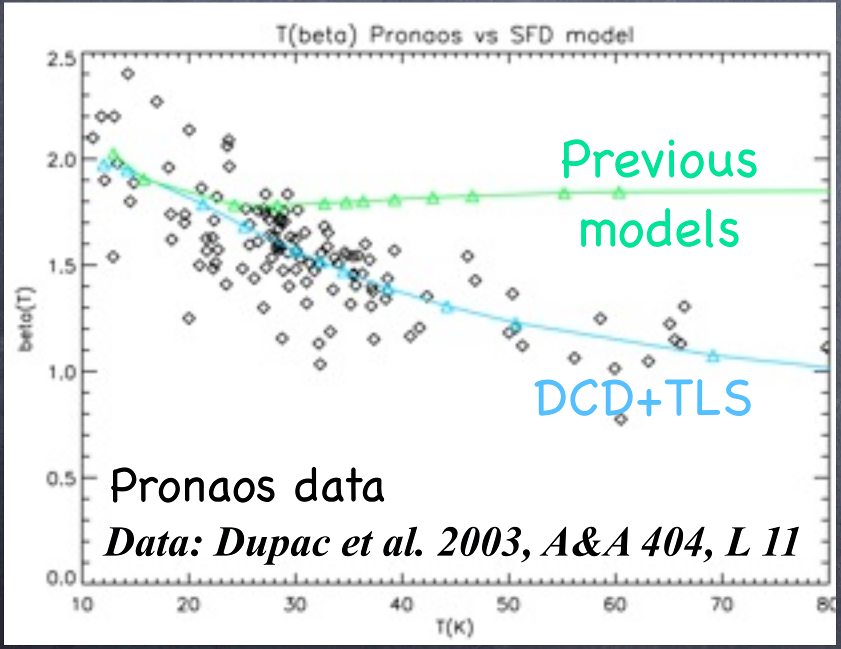
★A Disordered Charge Distribution (DCD)

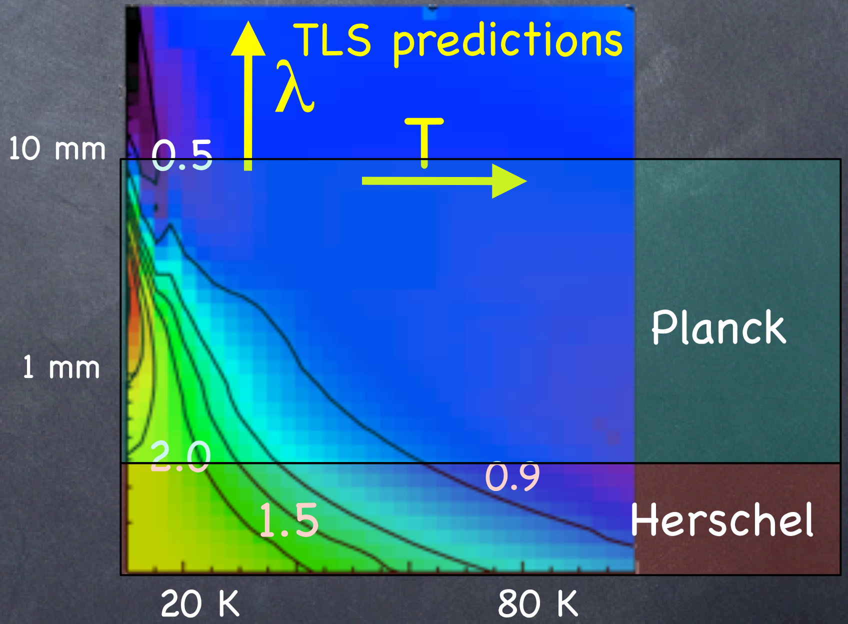
⇒ Emission independent of temperature (FIR)

★A microscopic distribution of asymetrical double potential wells (Two Level Systems: TLS) with small ΔE:

⇒ Emission dependent on temperature (submm)

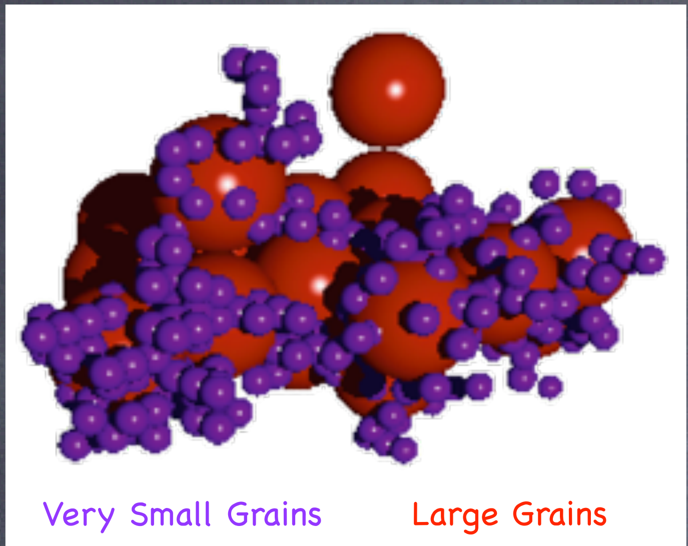




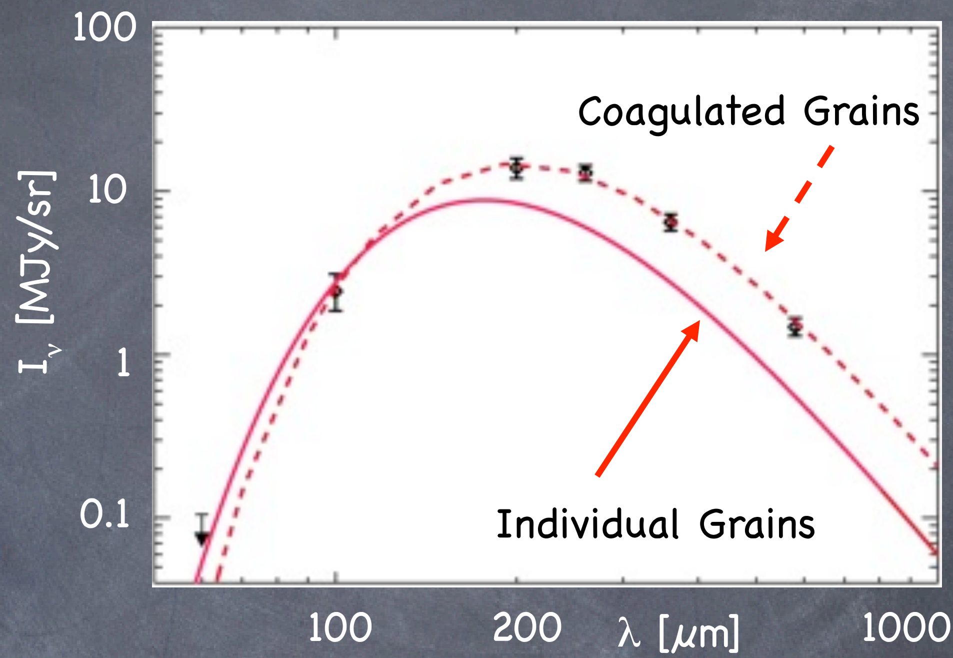


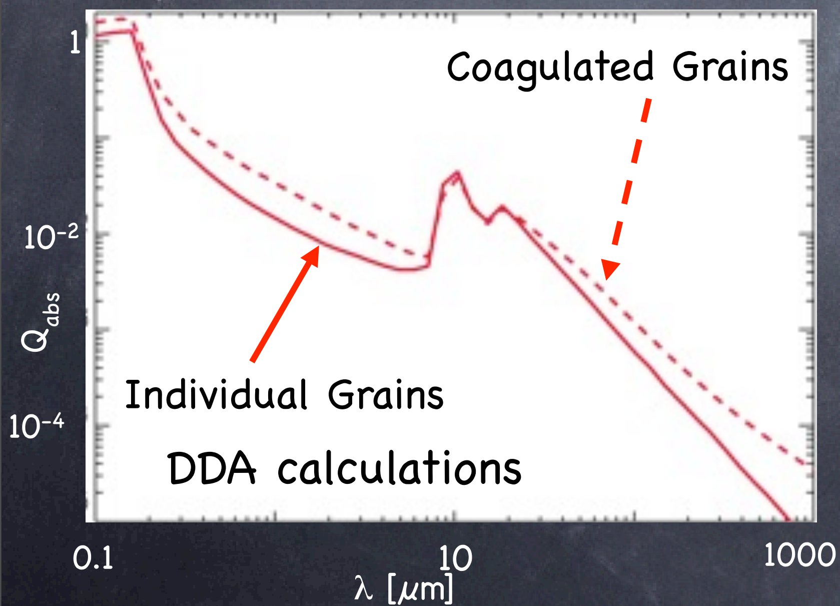
★Parameters optimized on ISM SED (Paradis et al. 2011)

grain-grain Coagulation



PhD Thesis B. Stepnik





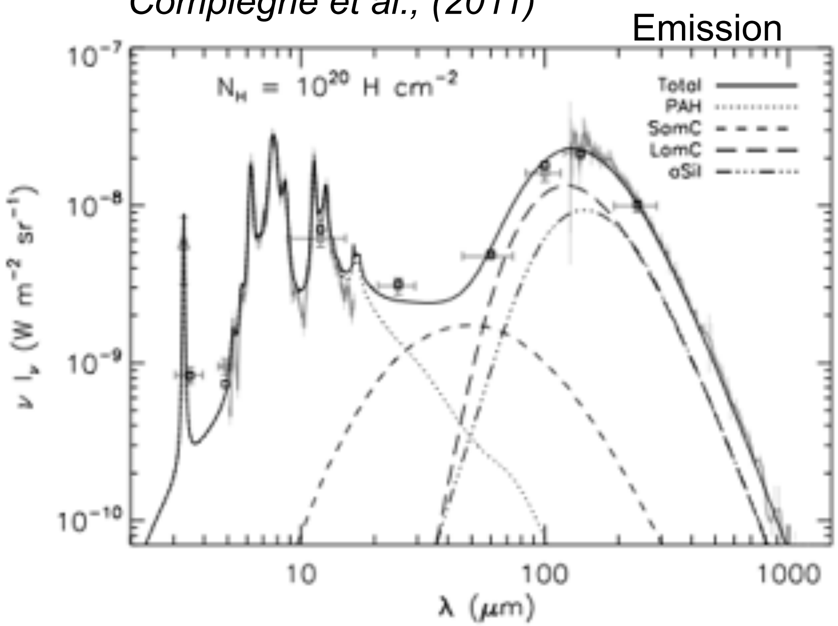
Bernard et al. 1999, A&A 347, 640
Stepnik et al. 2003, A&A 398, 551
Khöler et al. 2011, A&A 528, 96

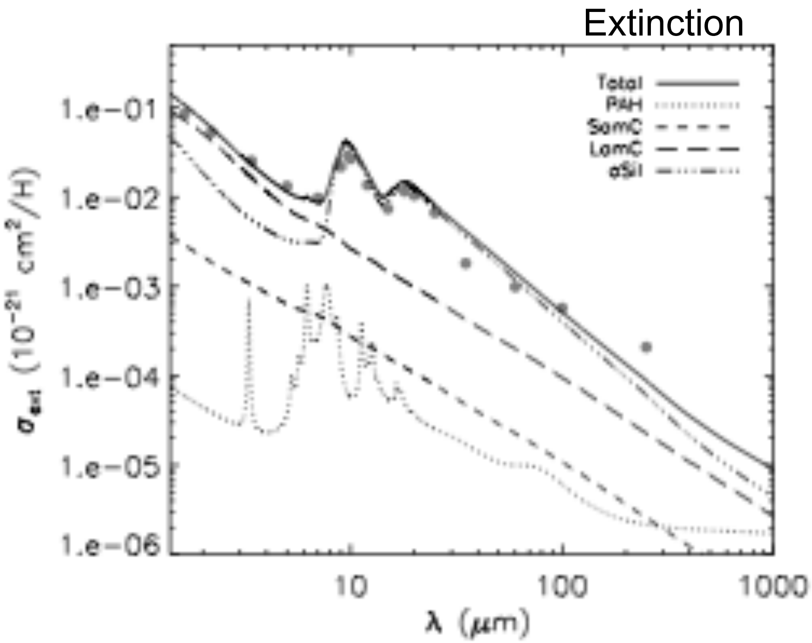
- Evidences in the Pronaos data (Polaris, Taureau)
- Coagulation of large and very small grains
- Fractal dimension ~2, N_{grains}>20
- 80-100% of small grains included in aggregates
- Fractal grains are more emissive (antena)
- Fractal grains are colder

DustEM

PCMI Collaborative work from Compiegne, Paradis, Flagey, Ysard, etc ...
Guided by the more experienced (LV, JPB, ...)

Compiegne et al., (2011)



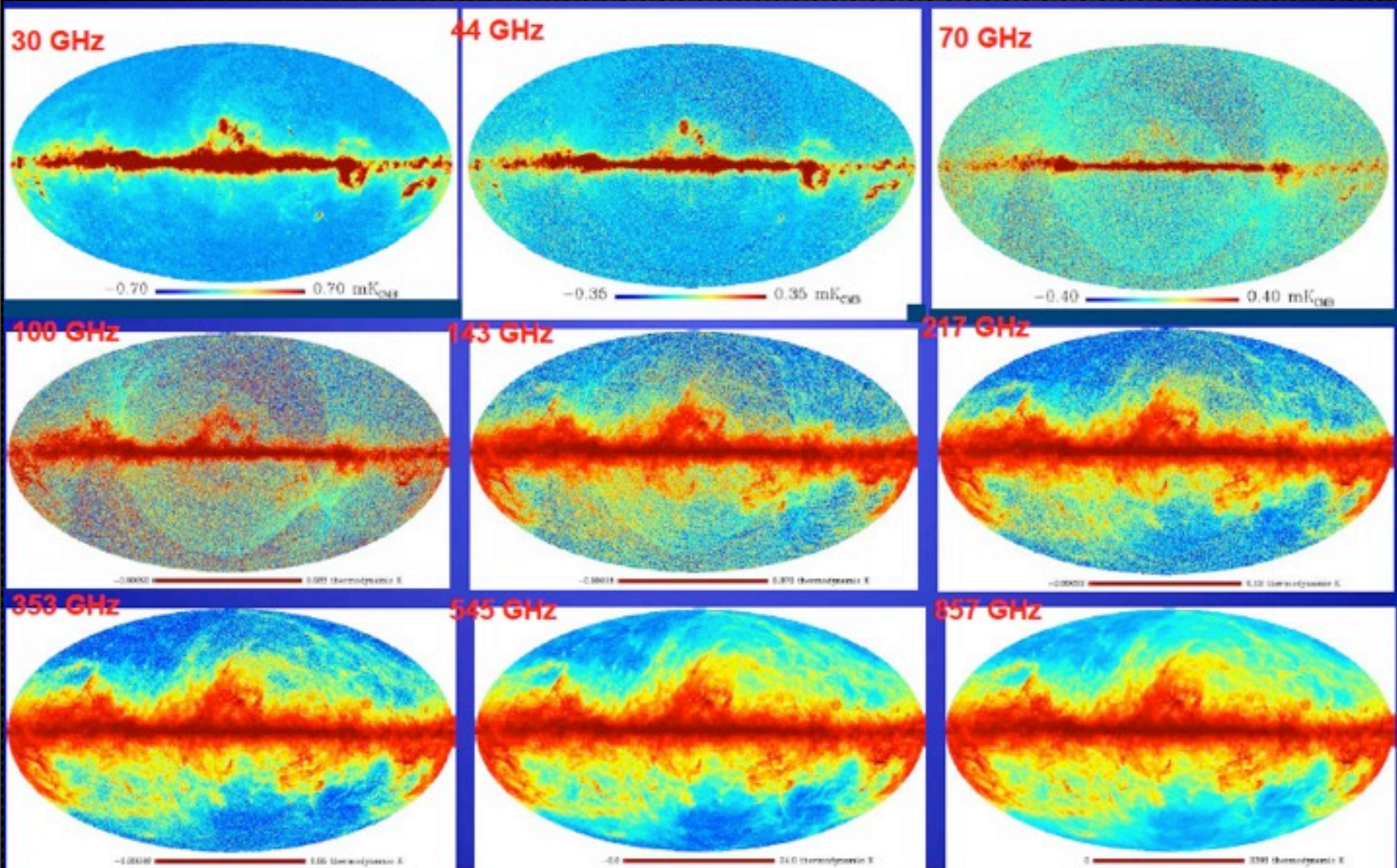


=> Fortran code available here: http://www.ias.u-psud.fr/DUSTEM/
now included in the Meudon PDR code + 3D radiative transfer codes

=> IDL wrapper allows to fit photometric, spectroscopic, extinction data, proper color correction for many instruments, available here:
http://dustemwrap.irap.omp.eu/

⇒ Current developments :
- Spinning dust emission
- Polarized extinction/emission
- Physics of amorphous solids at low T (TLS model)

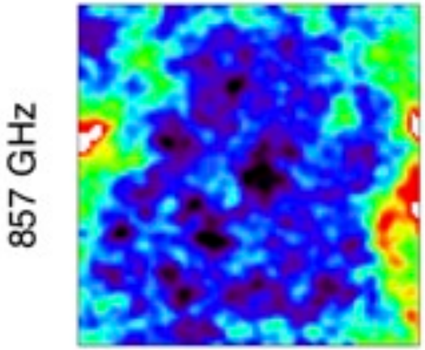
Planck data (DR2)

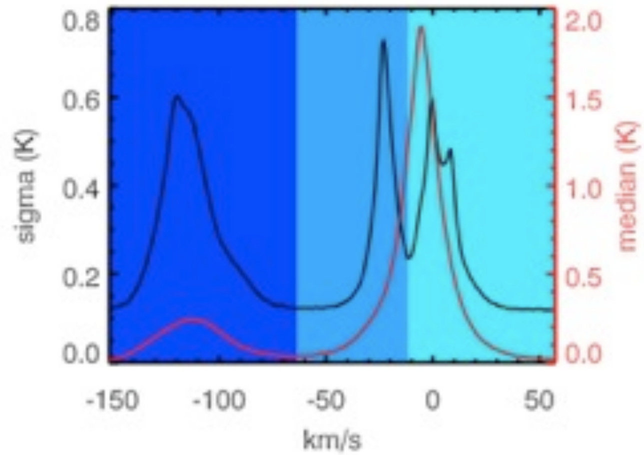


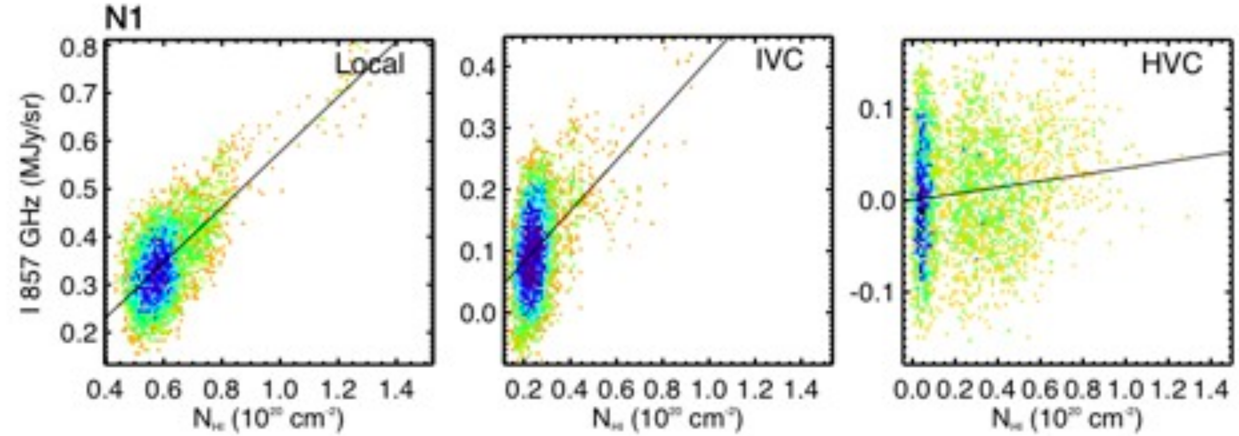
Dust-HI correlation in the Halo

Planck Collaboration 2011, A&A 536 XXIV C. author M.A. Miville-Deschenes

N1-Field :

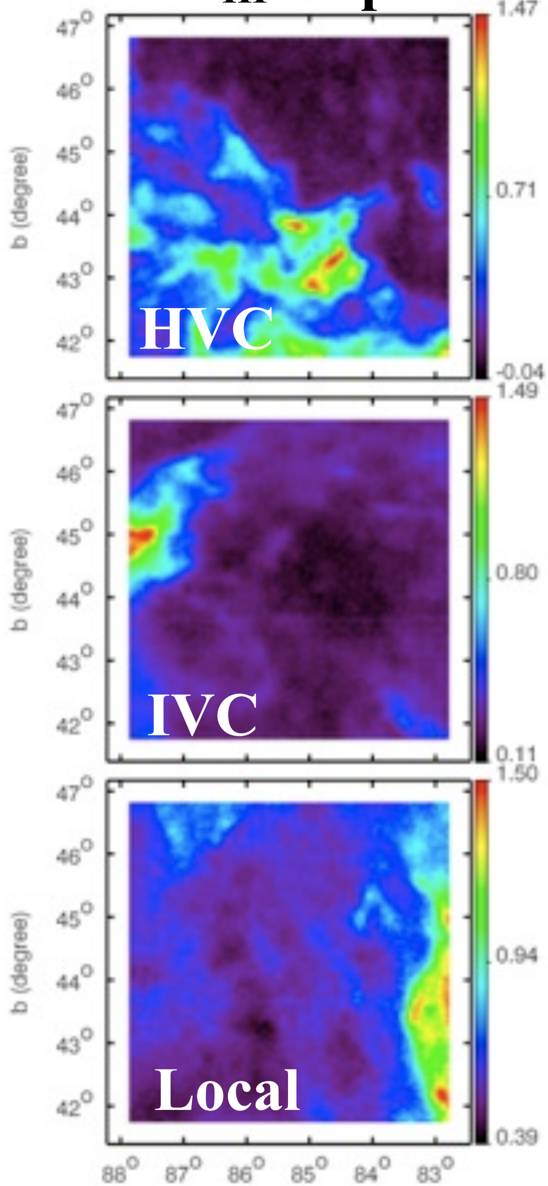






$$I_\nu(x,y) = \sum_{i=1}^{3} \epsilon_\nu^i N_{HI}^i(x,y) + R_\nu(x,y) + Z_\nu$$

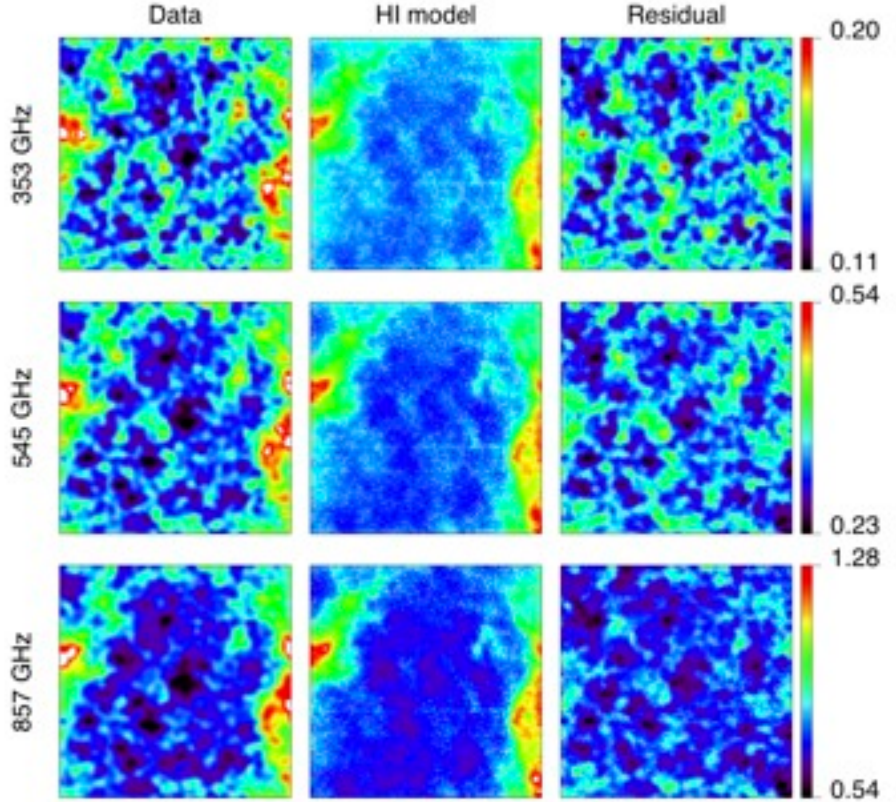
N_{HI} maps



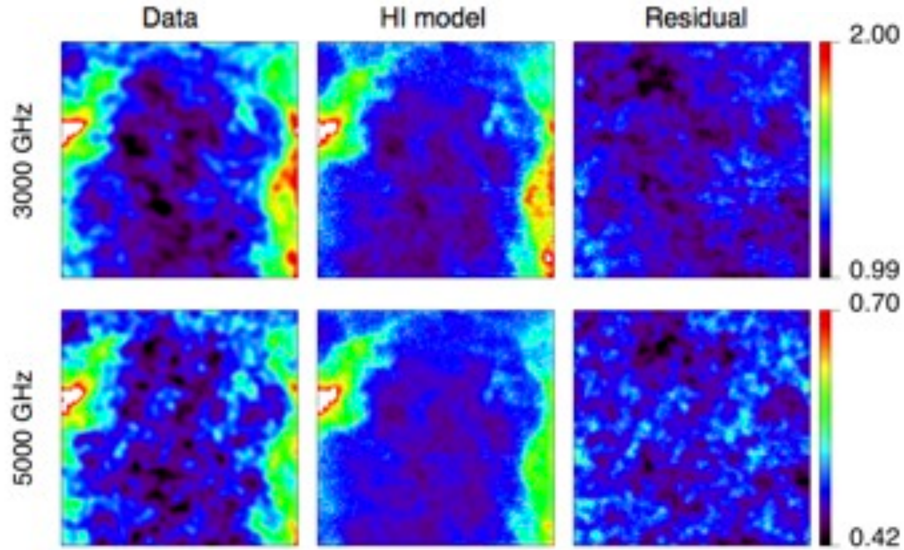
planck

Dust-HI correlation in the Halo

Planck



IRAS



$$R_\nu(x,y) \equiv I_\nu(x,y) - \sum_{i=1}^{3} \epsilon_\nu^i N_{HI}^i(x,y) - Z_\nu$$

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)

Faint fields ($N_{HI} < 2 \times 10^{20}$ cm^{-2}) : residual compatible with CIBA - no evidence for dust in the WIM

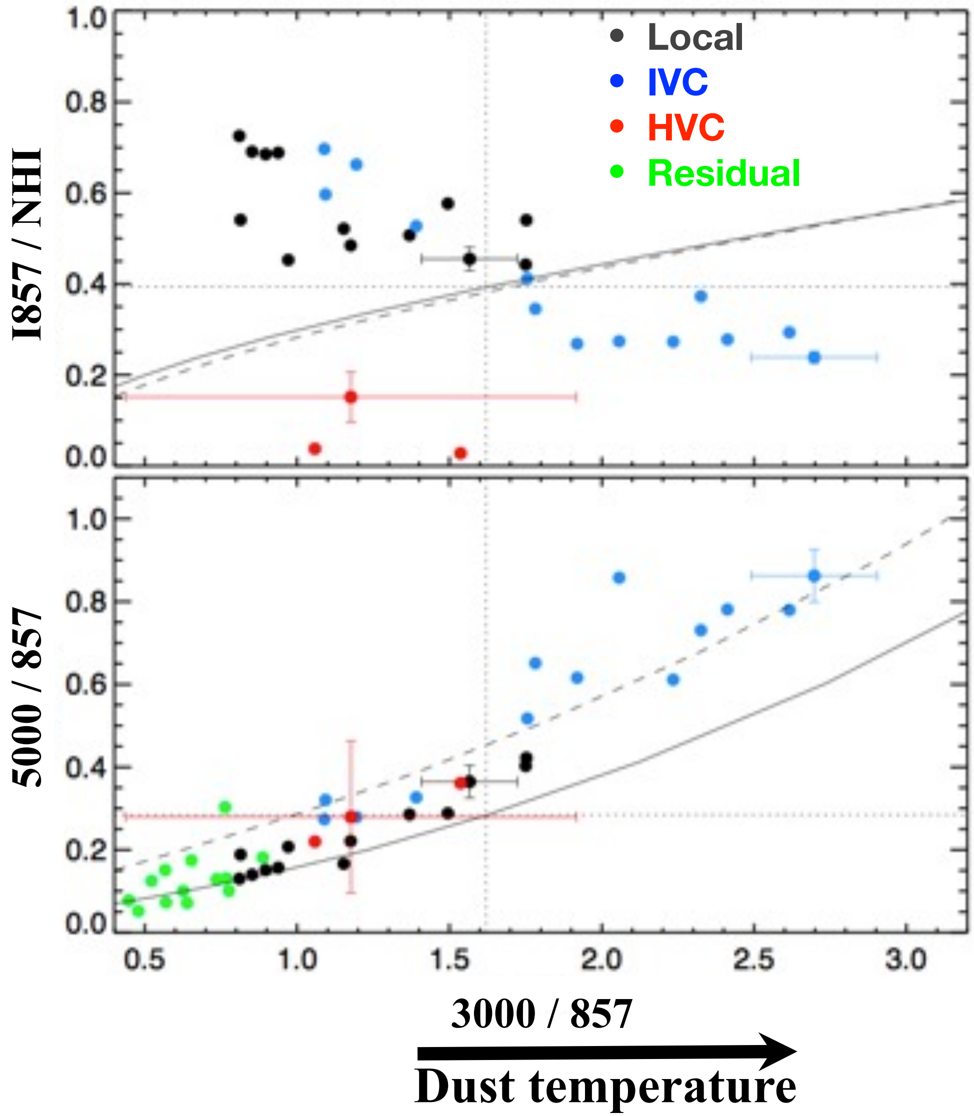
Excess emission for $N_{HI} > 3 \times 10^{20}$ cm^{-2} compatible with Dark-Gas (10% in mass)

planck

Dust-HI correlation in the Halo

Unexpected evidences for dust evolution in the diffuse ISM:

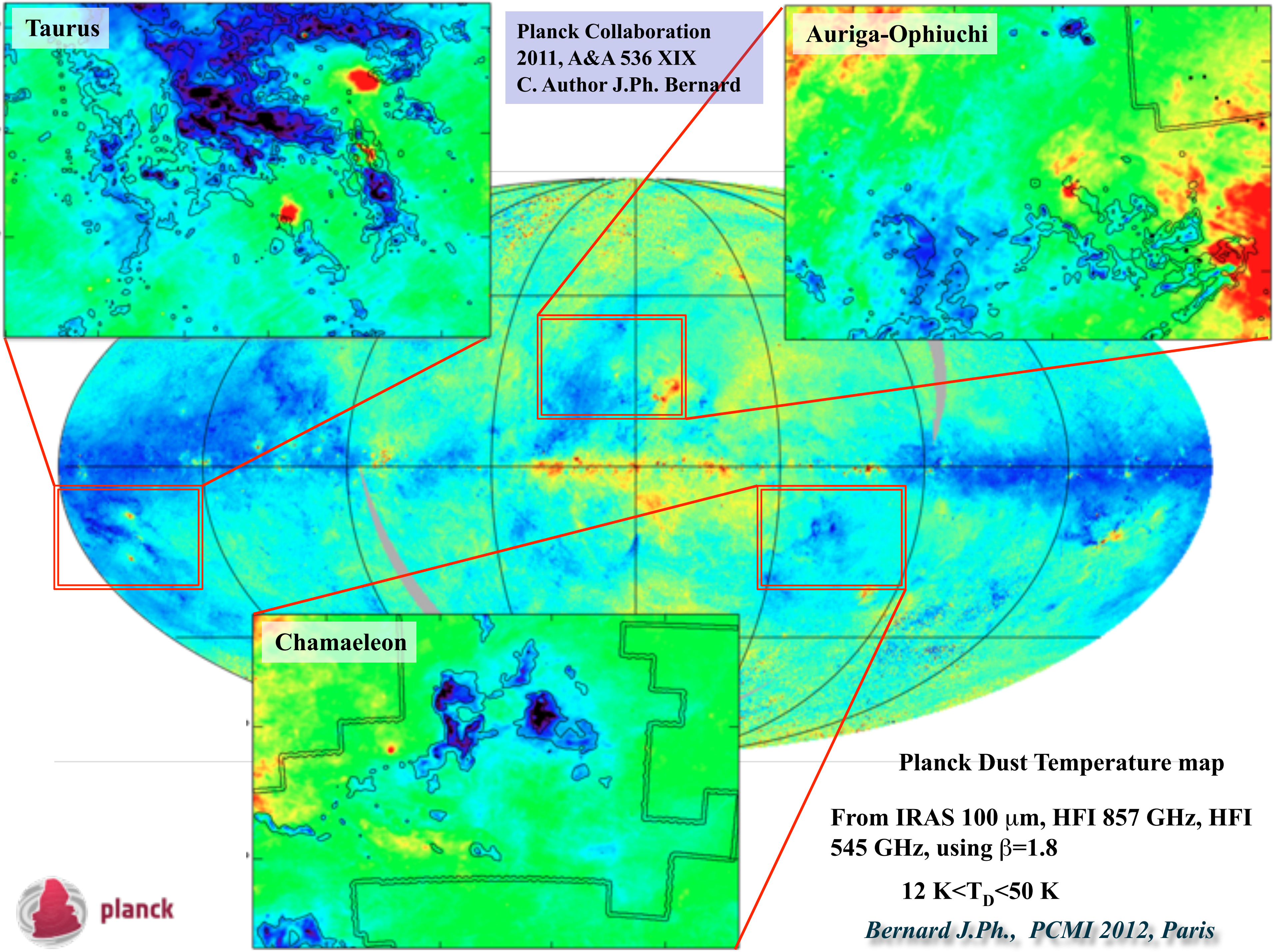
- IVC : 4 times larger VSG abundance, hotter dust (T~20K). Compatible with clouds part of the Galactic fountain (dust shattering)
- Temperature - emission cross-section anti-correlation suggesting modification of grain structure through coagulation
- Marginal detection of HVCs (1-3.8 σ) compatible with low metallicity (~0.1 solar)



Planck Collaboration 2011, A&A 536 XXIV
C. author M.A. Miville-Deschenes

planck

Planck Collaboration 2011, A&A 536 XIX
C. Author J.Ph. Bernard



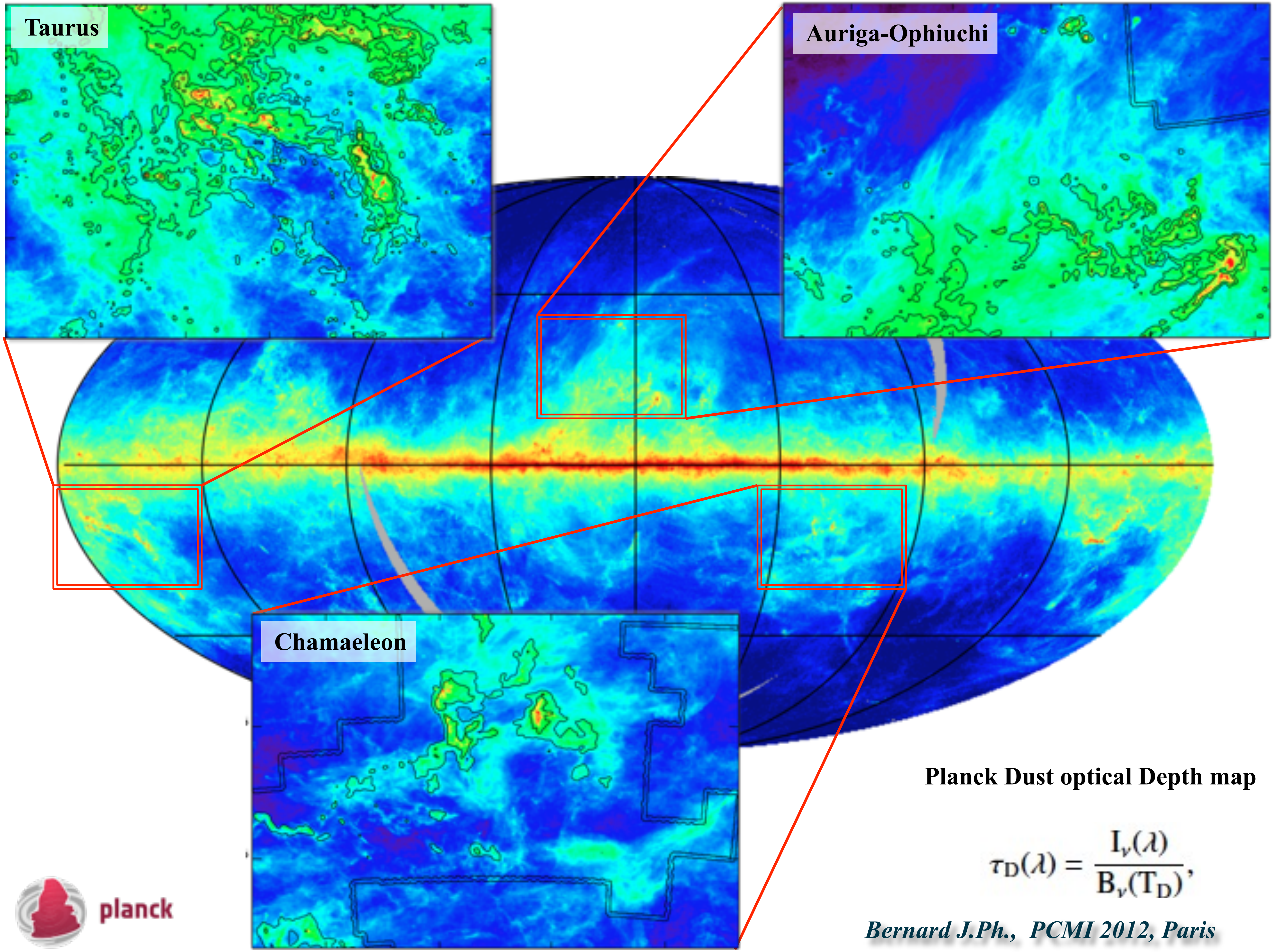
Planck Dust Temperature map

From IRAS 100 μm, HFI 857 GHz, HFI 545 GHz, using β=1.8

12 K<T_D<50 K

Bernard J.Ph., PCMI 2012, Paris

planck

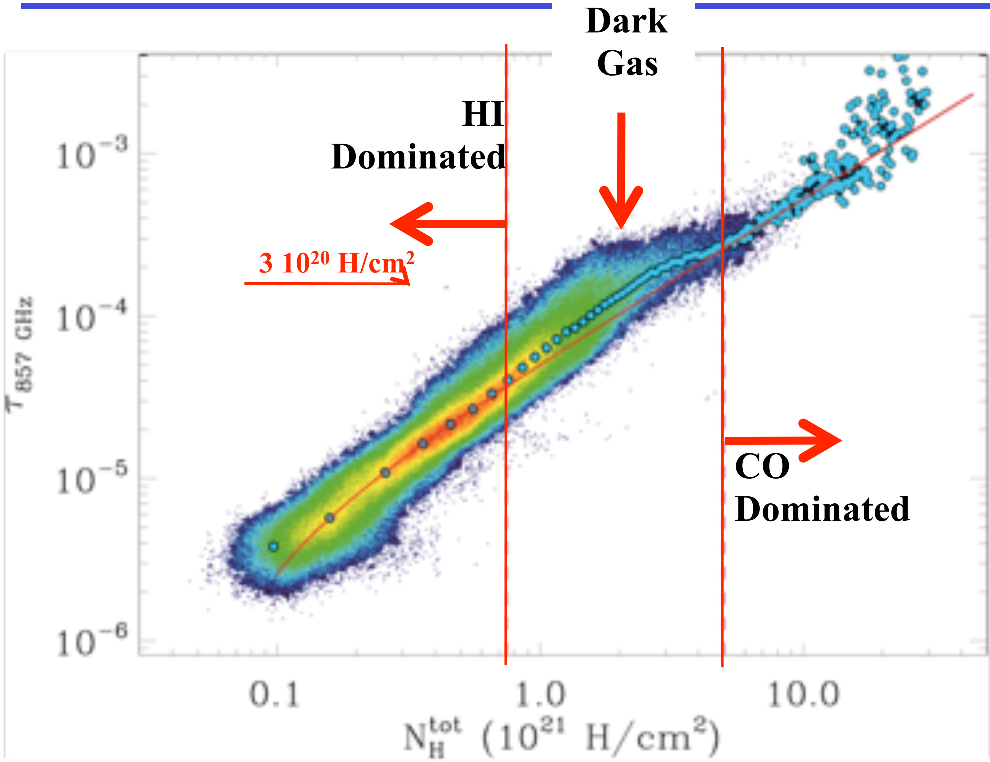


Planck Dust optical Depth map

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

Bernard J.Ph., PCMI 2012, Paris

Evidence for Dark Gas



Planck Collaboration 2011, A&A 536 XIX
C. Author J.Ph. Bernard

- LAB HI data (atomic gas). assumed optically thin
- 3 $^{12}CO(J=1-0)$ surveys: *Dame et al. 2001*, Dame unpublished, Nanten (unpublished)

68% of the sky

Very similar plots obtained from IRAS 100 μm, HFI 857, 545, 353 GHz

As computed in solar neighbourhood (|b|>10°) and assuming thin HI :

Transition between HI dominated and Dark Gas found at Av=0.4+-0.03 mag

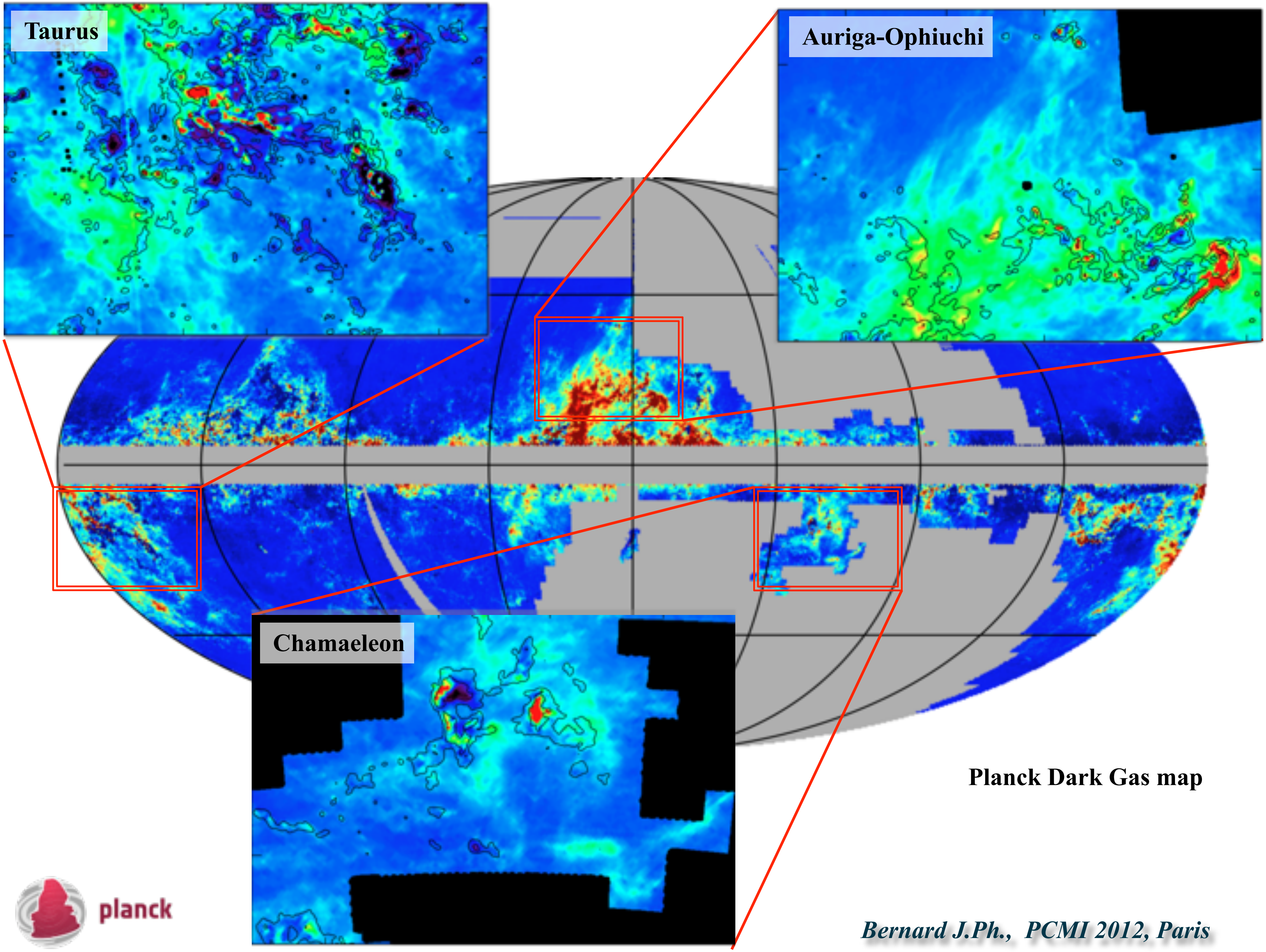
τ/N_H ~power law with β=1.8. Absolute value consistent with value at 250 μm (Boulanger et al 1996)

Average Xco factor Xco=2.54+-0.13 10^{20} $H_2/cm^2/(Kkm/s)$

Dark Gas mass fraction: 28%+-2.8% of HI gas, 118%+-1.2% of molecular gas

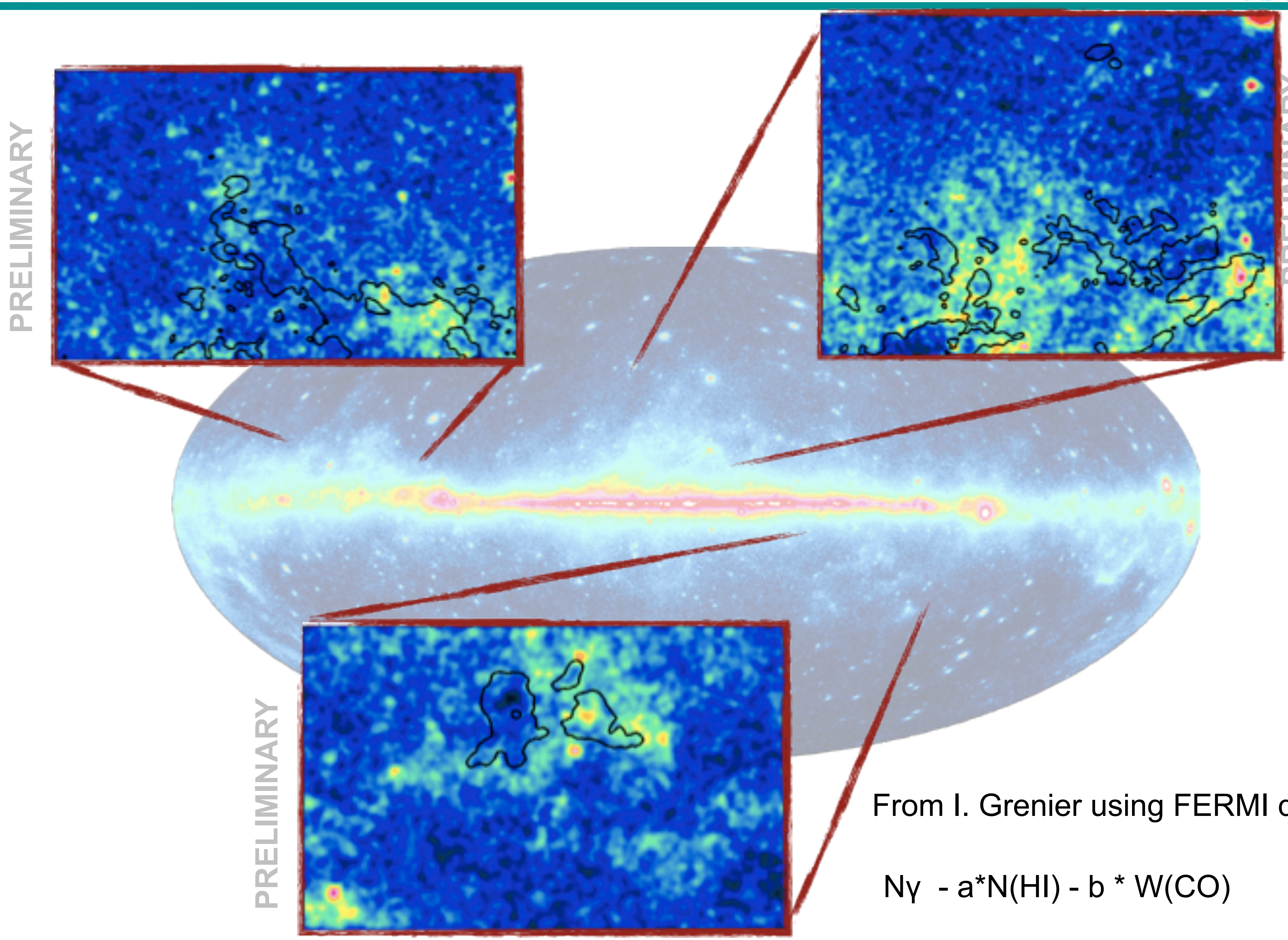
γ-ray observations find a similar "Dark-Gas" phase, with a similar mass fraction (*Grenier et al 2005, Abdo et al. 2010*)
Herschel GotC+ find similar Dark-Gas fractions in the MW plane (*Langer et al. 2010*)

planck



Bernard J.Ph., PCMI 2012, Paris

dark neutral gas map from γ rays



From I. Grenier using FERMI data

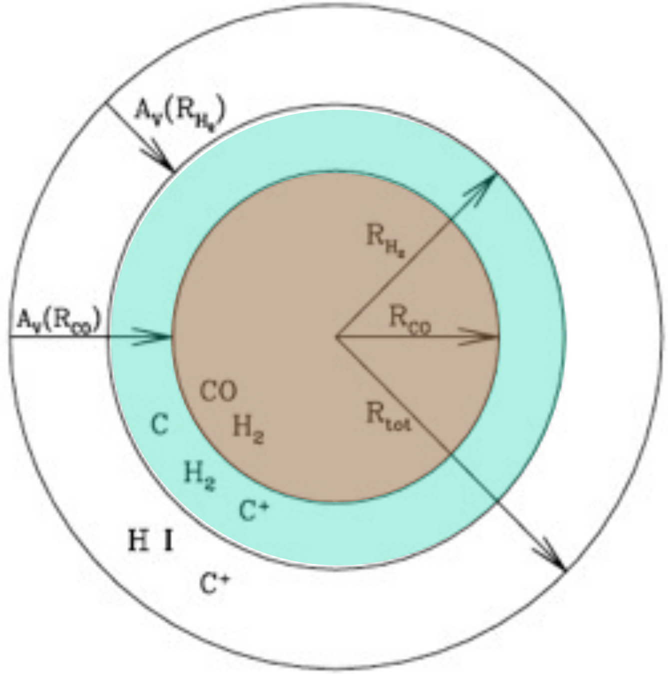
$N\gamma$ - a*N(HI) - b * W(CO)

Dark Gas origin ?

Possible origins :
- Dust abundance variations (unlikely in solar neighbourhood, DG seen in γ-ray)
- Dust property variations (unlikely as DG seen in γ-ray, confirmed with dust extinction)
- HI 21 cm can be optically thick: Assuming Ts=80 K reduces the DG fraction by about half
- Weak CO below the threshold of the surveys: (Wco~ 0.5 Kkm/s): can contribute <20% of DG

<u>**Planck in solar neighbourhood (|b|>10°):**</u>

Mass fraction of Dark Gas: 28% of HI (118% of CO)
Av(DG)=0.4 mag
Xco=2.54 10^{20} $H_2cm^{-2}/(Kkm/s)$



<u>**Predictions by Wolfire et al. 2010:**</u>

H_I/H_2 transition at $Av(R_{H2})$=0.2 mag
H_2/CO transition at $Av(R_{CO})$=1 mag
f_{DG} ~ 30% of CO gas

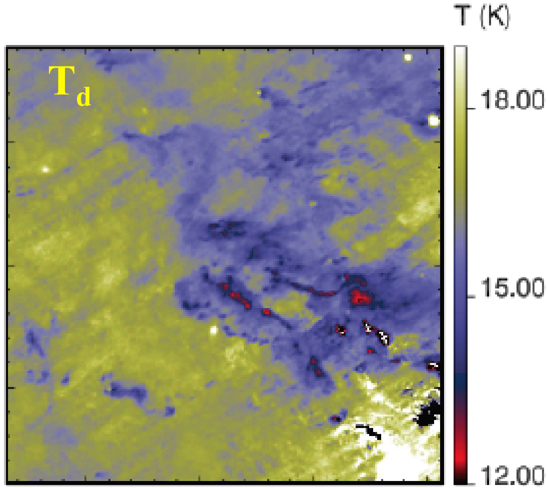
Clouds in theoretical study much more massive than in solar neigbourhood
Unclear if difference in f_{DG} due to assumed cloud mass …

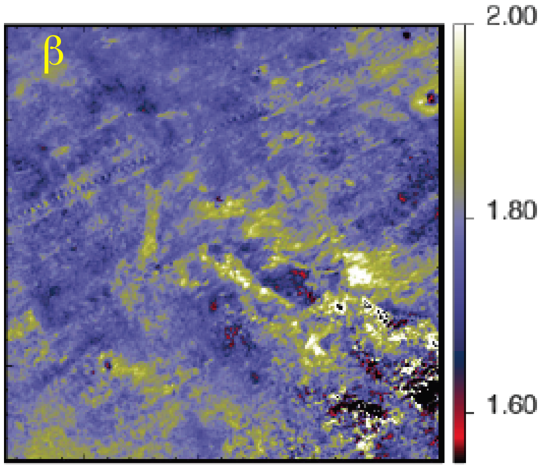
planck

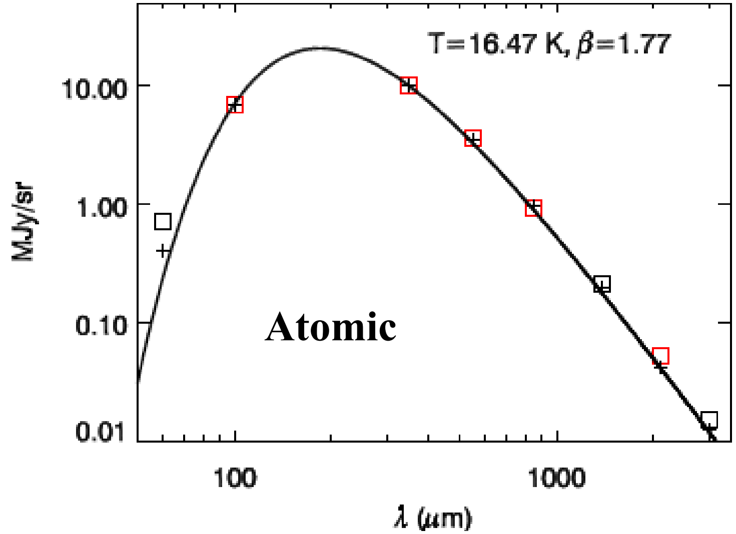
Bernard J.Ph., PCMI 2012, Paris

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} cm² (diffuse) to ~2×10^{-25} cm² (dense)

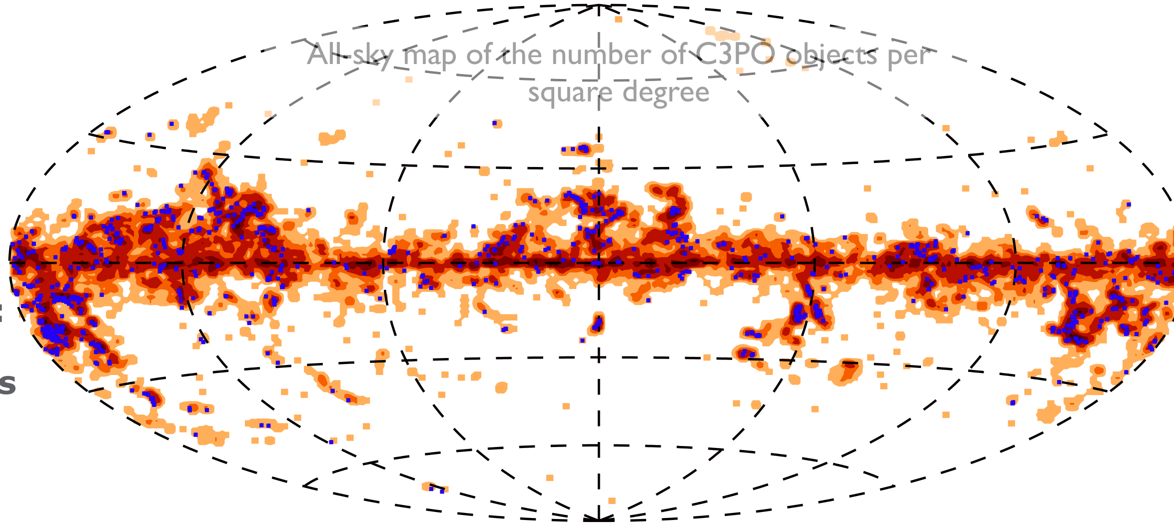
-Such variations of τ/N_H have an impact on the equilibrium temperature of the dust particles. They are likely due to dust aggregation.

planck

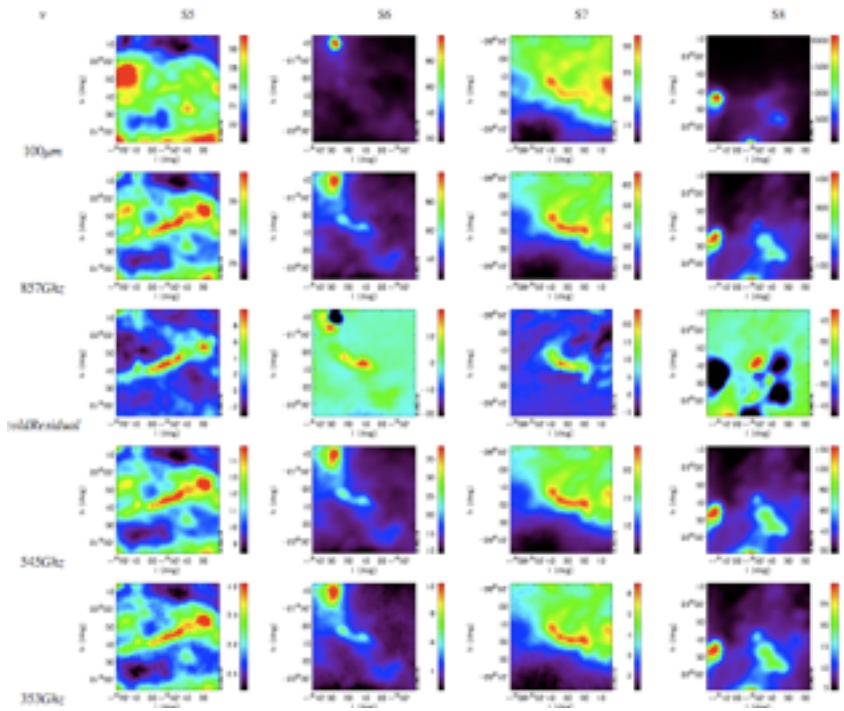
Planck Collaboration 2011, A&A 536 XXV
C. Author A. Abergel

Planck Cold-Clumps

Planck Collaboration 2011, A&A 536, A22
(C. Author I. Ristorcelli)



- Dedicated detection algorithm (cococodet)
- The Early Cold Core (ECC) catalogue : 915 objects highly reliable
- Cold Core Catalogue of Planck Objects (C3PO) 10783 objects over whole sky.
- Dense and cold molecular clouds potentially prestellar.
- organized in groups, filaments and aligned on large-scale loops.
- Unprecedented statistical view to the properties
- Unique opportunity for their classification in terms of their intrinsic properties and lifetime.



- Dust Temperature: 8K < T < 16 K
- Sizes: 0.2 < size < 10 pc
- Dust masses: 1 $M_\odot$ < Mass < 10^5 $M_\odot$

Planck Collaboration 2011, A&A 536, A23
(C. Author L. Montier)

PCCs follow-up

In the MW:

Herschel open time program + many ground obs.

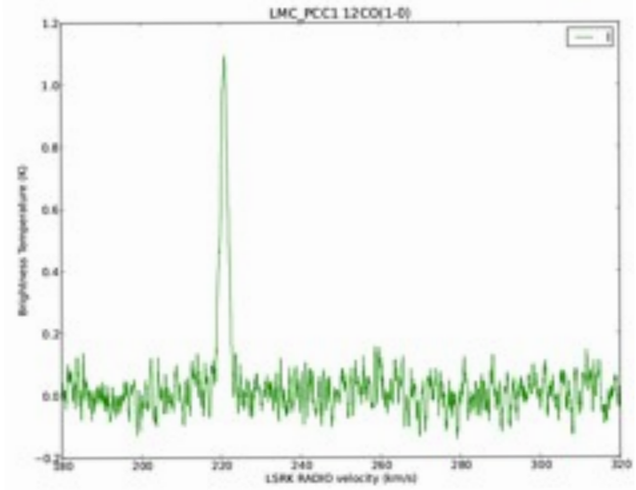
(see Poster by I. Ristorcelli)

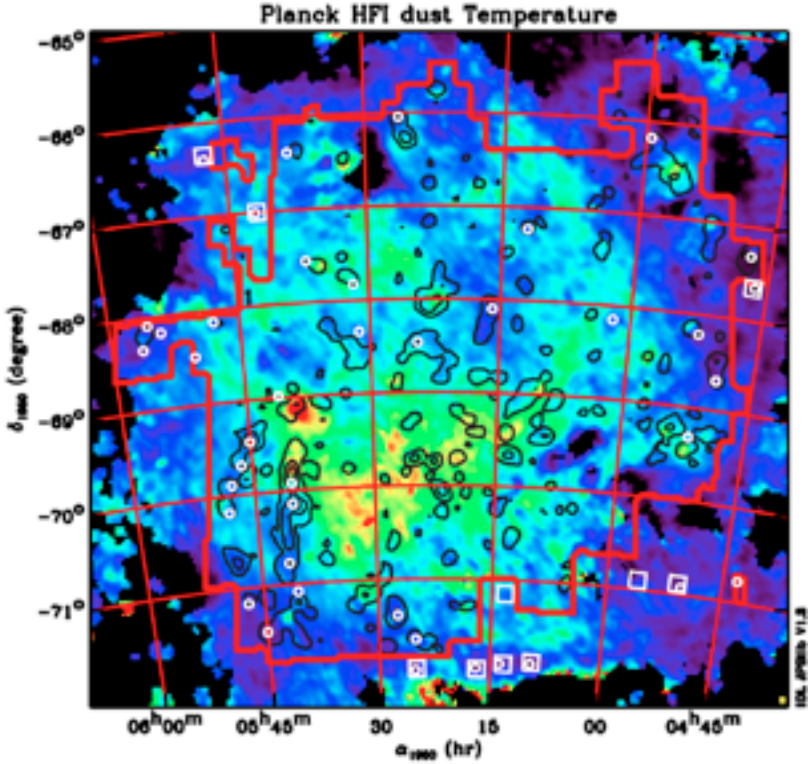
In the LMC :

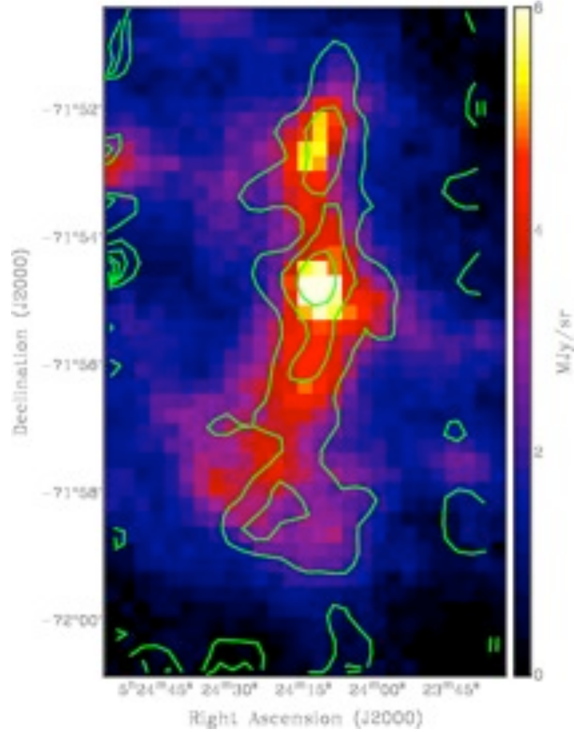
10 Planck cold cores outside NANTEN FoV

MOPRA: CO detected in 7 out of 8. Mapped 5

Quiescent non star forming GMCs





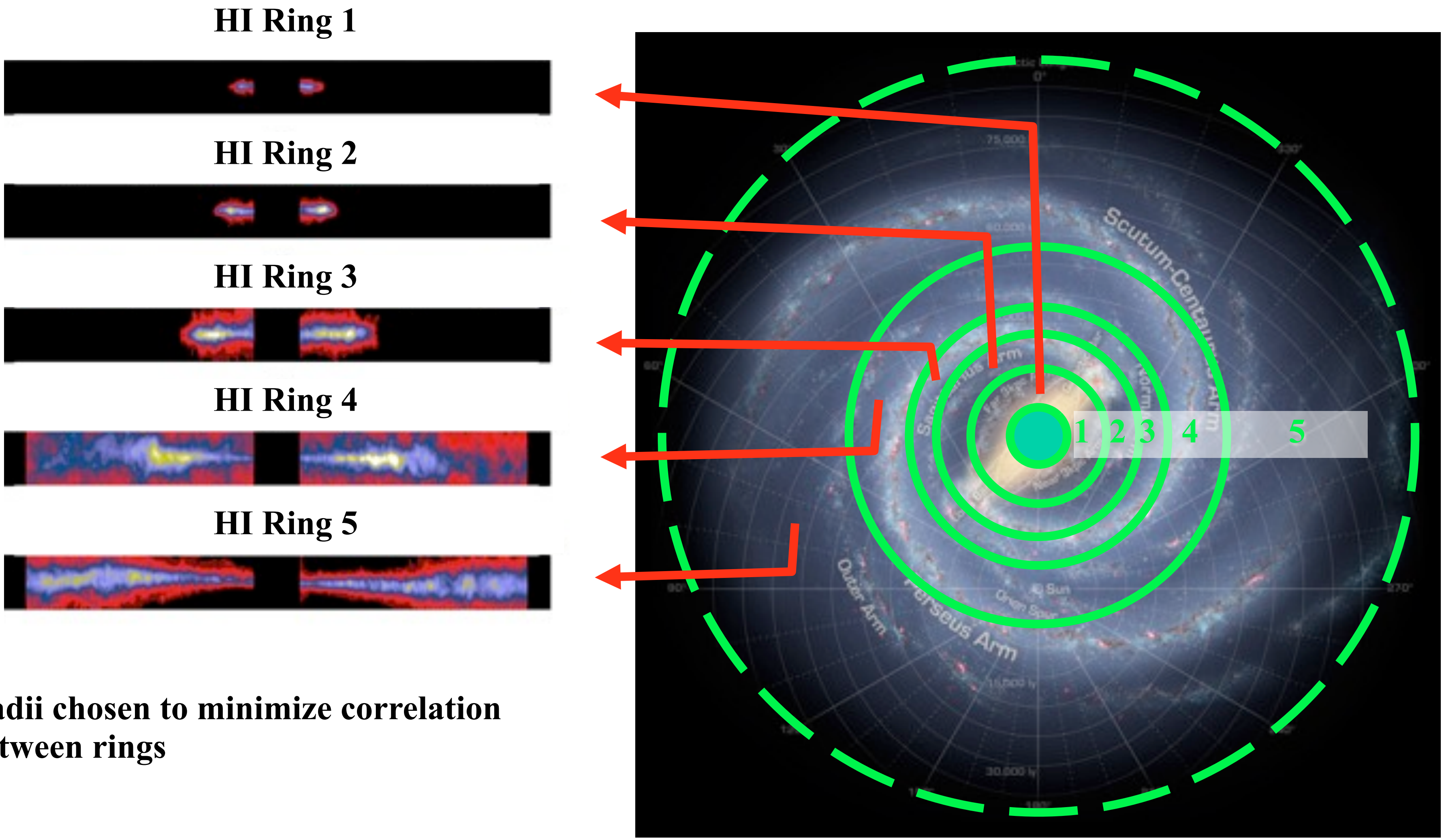


Hughes et al. in prep

Contours:
MOPRA CO(1-0)
Colors:
Herschel 500 µm

Bernard J.Ph., PCMI 2012, Paris

Galactic plane decomposition



Radii chosen to minimize correlation between rings

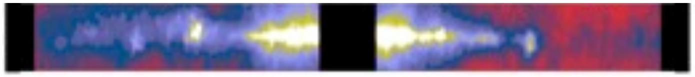
Planck Collaboration 2011, A&A 536, A21 (C. author D. Marshall)

planck

Galactic plane decomposition

HII (WMAP free-free)

Synchrotron (Haslam 408 MHz)

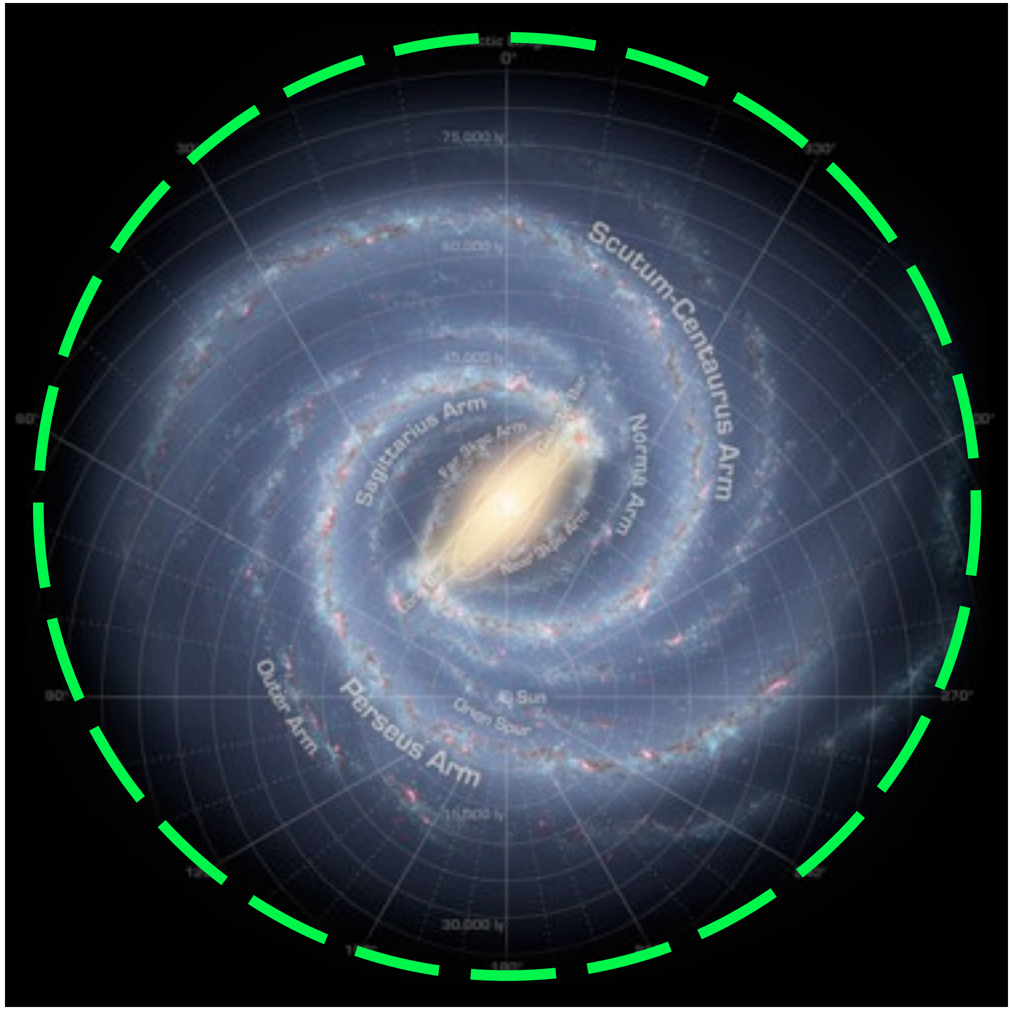


Dark gas

Result is 13 spatial templates (HI, CO, HII, Synchrotron & Dark gas)

- **Frequency maps can be expressed as a linear combination of the spatial templates**
- **Correlation coefficients measure the spectrum of dust associated to each component**

All templates and data are smoothed to 1° FWHM



Example at 857 GHz

Data

Model

HI

H_2

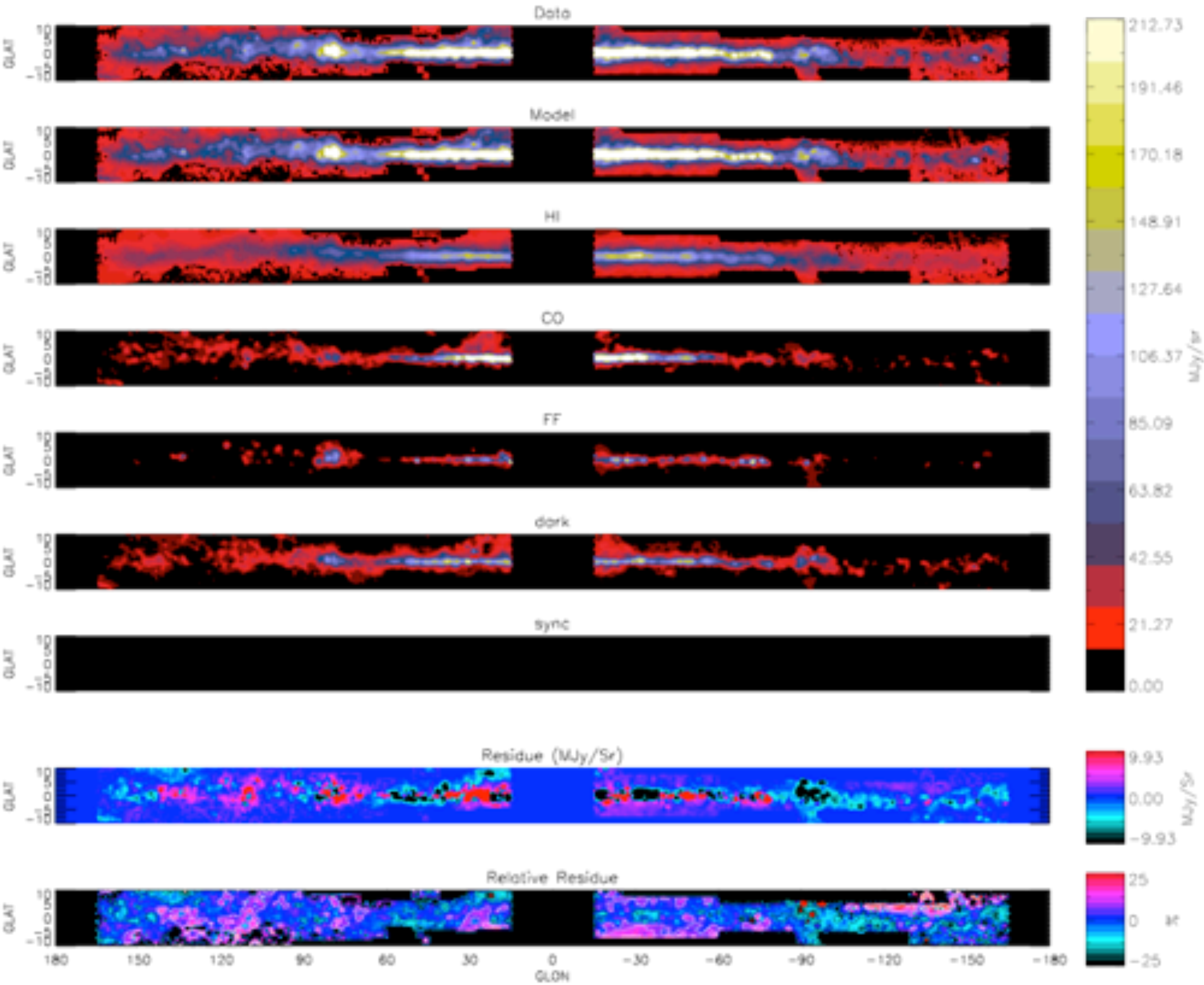
HII

Dark

Sync.

Residue

Relative Residue



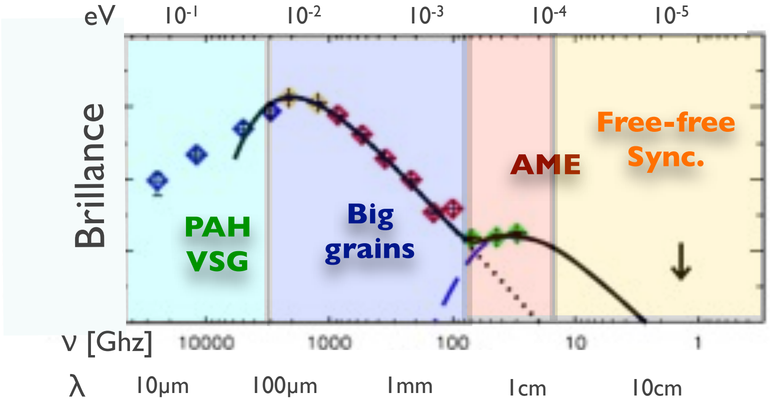
planck

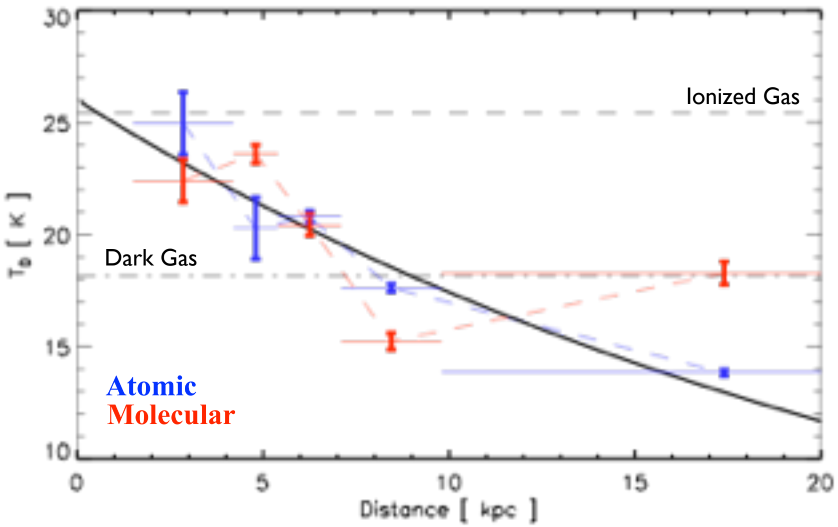
Bernard J.Ph., PCMI 2012, Paris

ISM properties in the Planck with Planck

Separation of different Galactic components :

- Gas phases
- Galactic distances

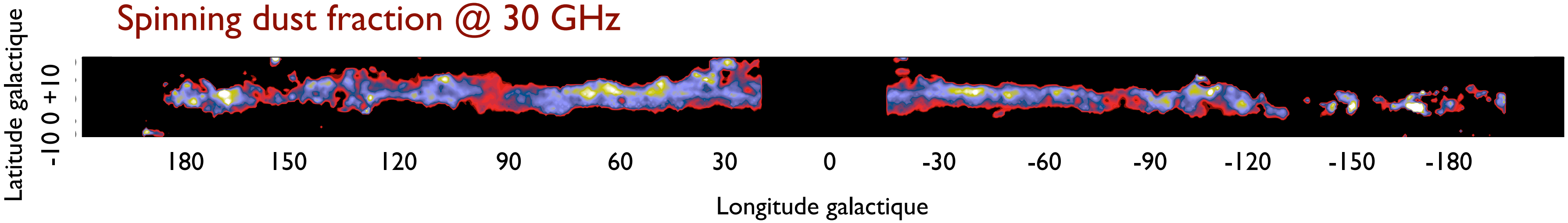




Dust in dark gas SED similar to atomic and molecular phases

AME is present throughout the Galactic plane

Spinning dust fraction @ 30 GHz

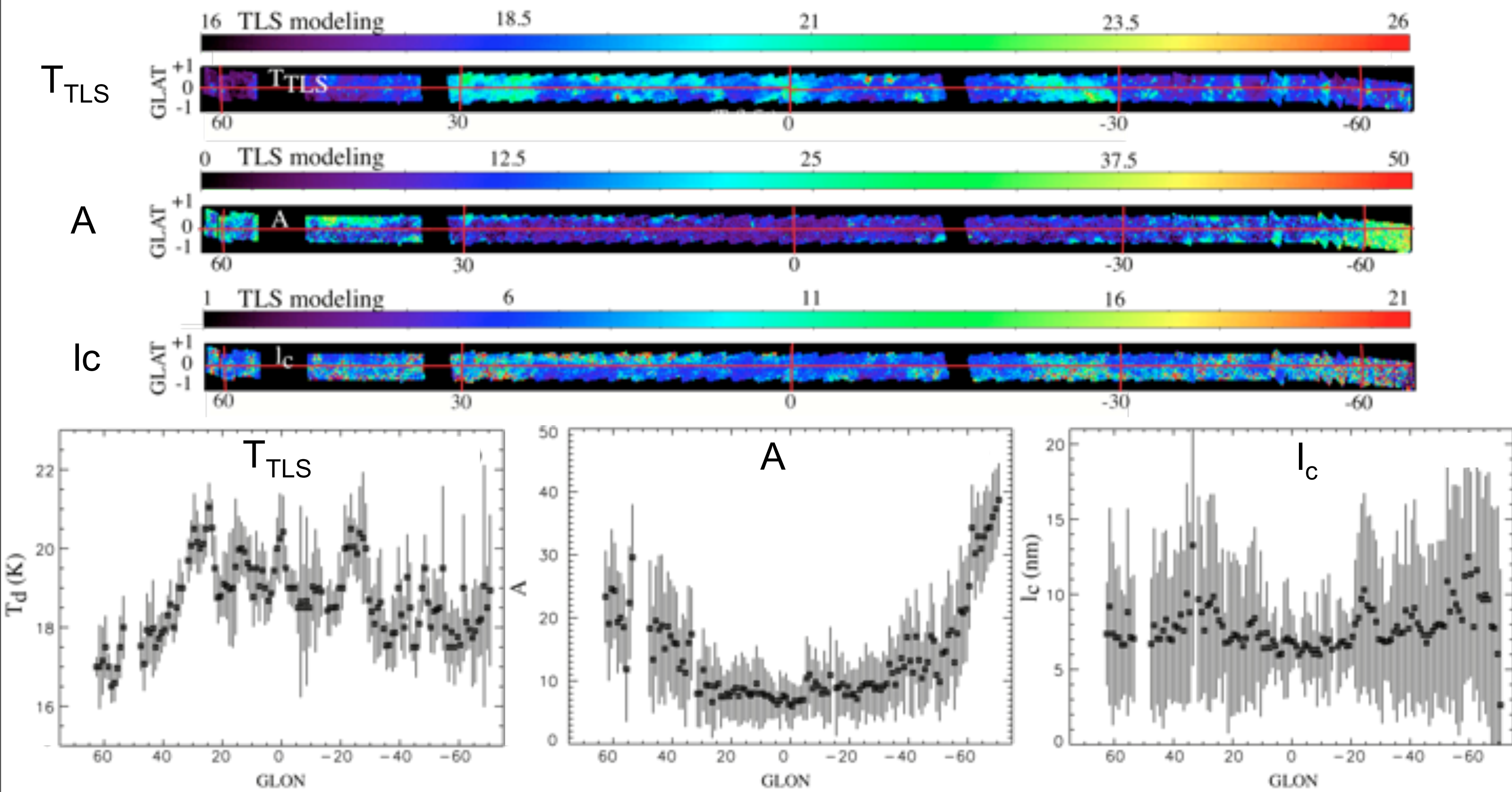


Planck Collaboration 2011, A&A 536, A21 (C. author D. Marshall)

Bernard J.Ph., PCMI 2012, Paris

Submm excess

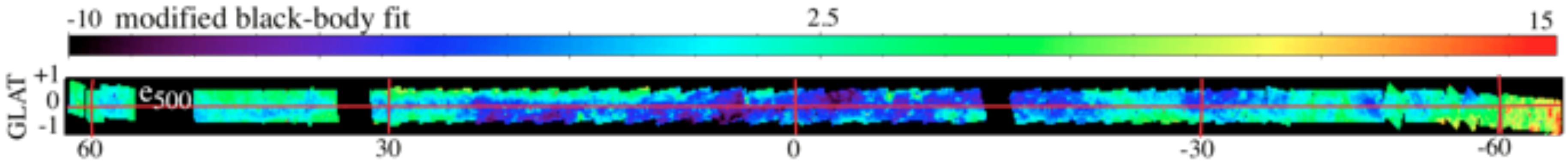
Paradis et al., (2012), Herschel Higal data



=> Variations in the dust properties from the central to peripheral parts of the inner GP: grains more amorphous in the peripheral parts
=> Comparison to solar neighborhood : either an atypical place or not a simple galactic gradient

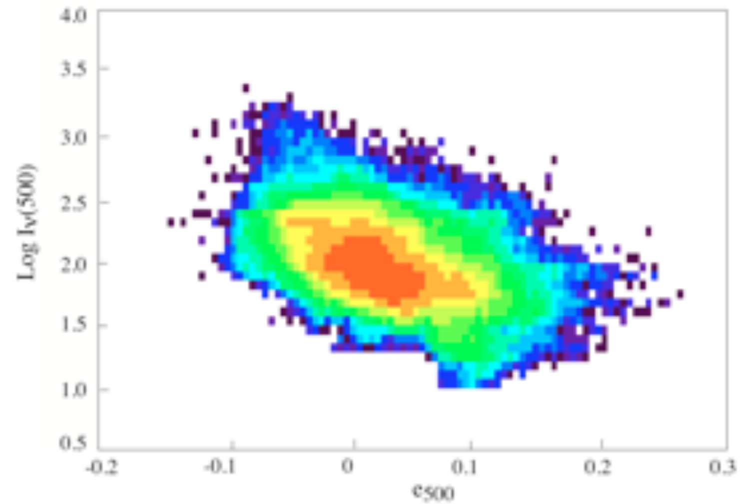
Bernard J.Ph., PCMI 2012, Paris

Submm excess



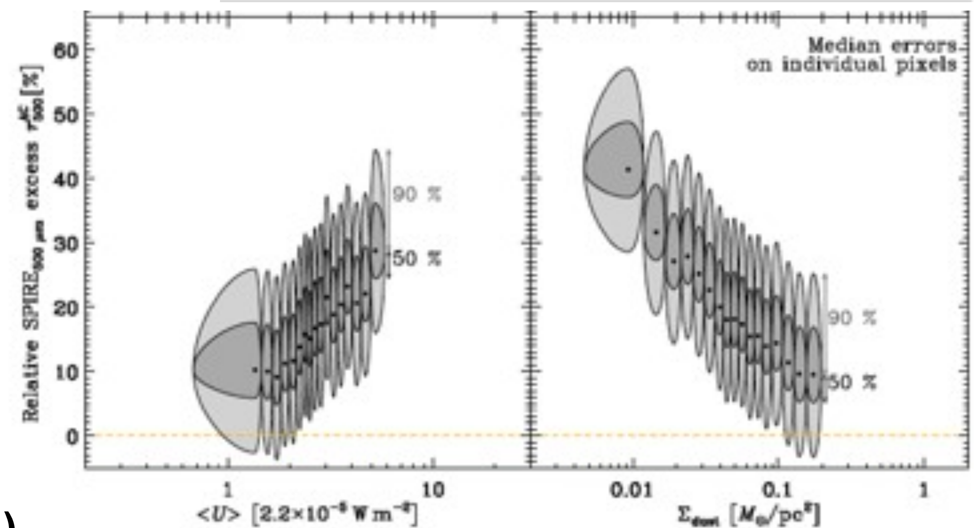
<u>Milky Way :</u>

==> Paradis et al. (2012) β ≈ 1.8 (entire Galaxy)
Hi-Gal Herschel data
- β decreases (spectrum flattens) from the inner to the peripheral parts of the Galactic plane
- 500 μm excess near |l|=60° is up to 16-20%
- little excess in the inner Galaxy



<u>Magellanic Clouds :</u>

==> Galliano et al. (2011), Gordon et al. (2010) β ≈ 1.5 (LMC) 1.2 (SMC)
Heritage Herschel data
- 500 μm excess correlated with T
- 500 μm excess anti-correlated with N_H
- 500 μm excess not due to very cold dust



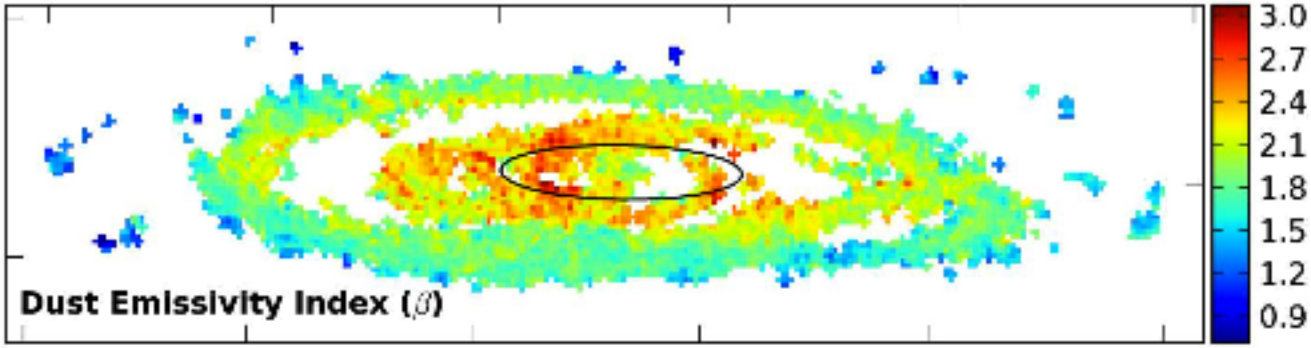
500 μm excess is correlated with dust T and anti-correlated with column density (!)

Dust emissivity and Submm excess in External Galaxies

Andromeda:

==> Smith et al. (2012)

β decreases from the center to the outer galaxy



Nearby galaxies from the KINGFISH sample:

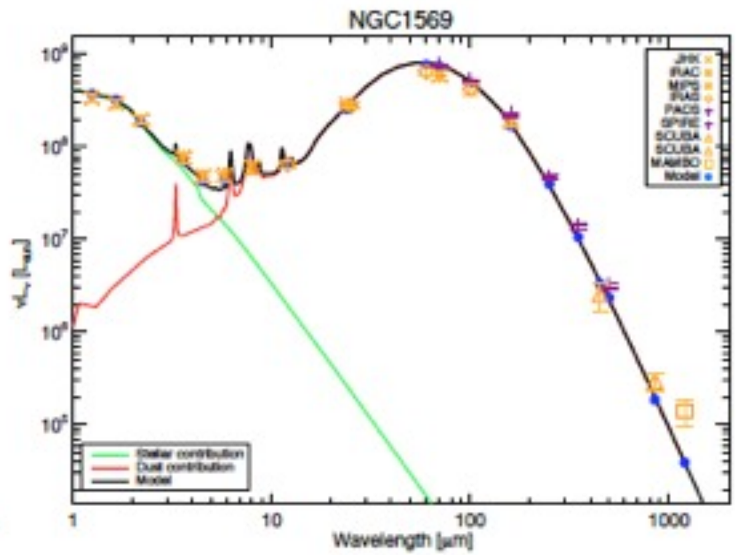
==> Dale et al. (2012): 8/9 dwarf/irregular/Magellanic galaxies with detection at 500 μm show evidence for significant excess of emission at this wavelength compared to the Draine & Li (2007) model fits.

Low metallicity galaxies:

==> Galliano et al. (2003, 2005): strong sbmm excess in Dwarf low Z galaxies (very cold dust ?)

==> Madden et al. (2011) : 50% of the DGS (dwarf galaxy survey) galaxies detected at 500 μm show a submm excess of 7% to 100%.

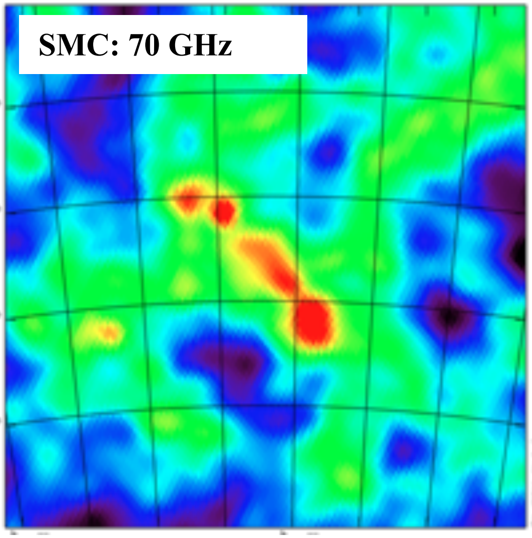
==> Dwarf Galaxy Survey (DGS) is confirming the flater submm slope, indicative of the submm excess, in most dwarf galaxies (Rémy et al. in preparation)

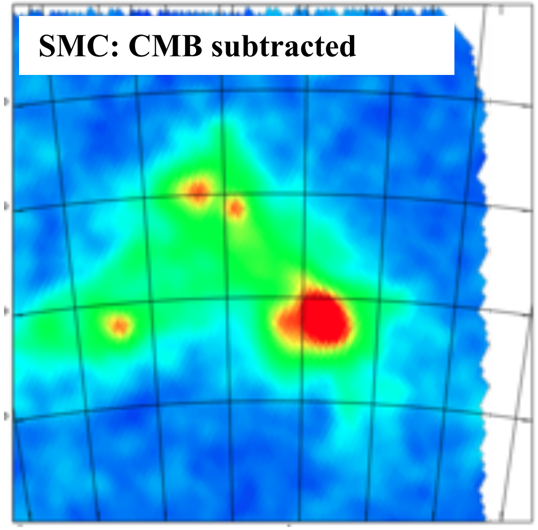


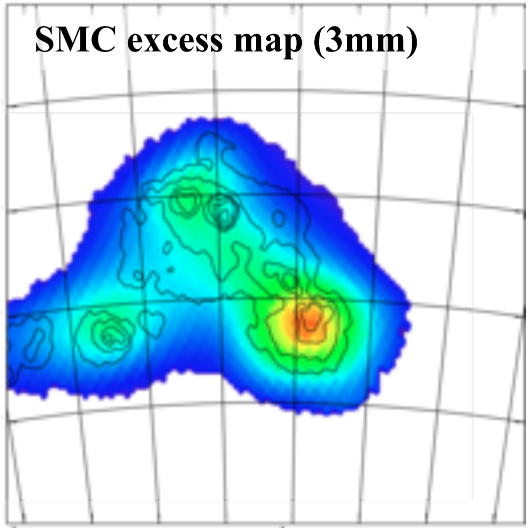
Madden et al 2012, in prep. DGS: 48 Low Z galaxies

Bernard J.Ph., PCMI 2012, Paris

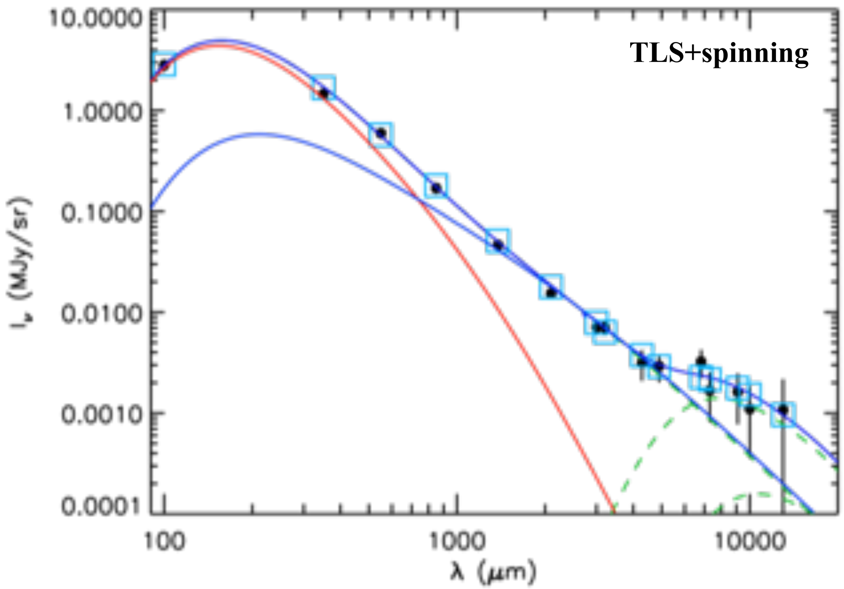
Submm excess of the SMC







- Free-Free contribution subtracted, extrapolated from Hα emission, assuming no extinction
- Submm excess follows the spatial distribution of thermal dust at high frequencies
- 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

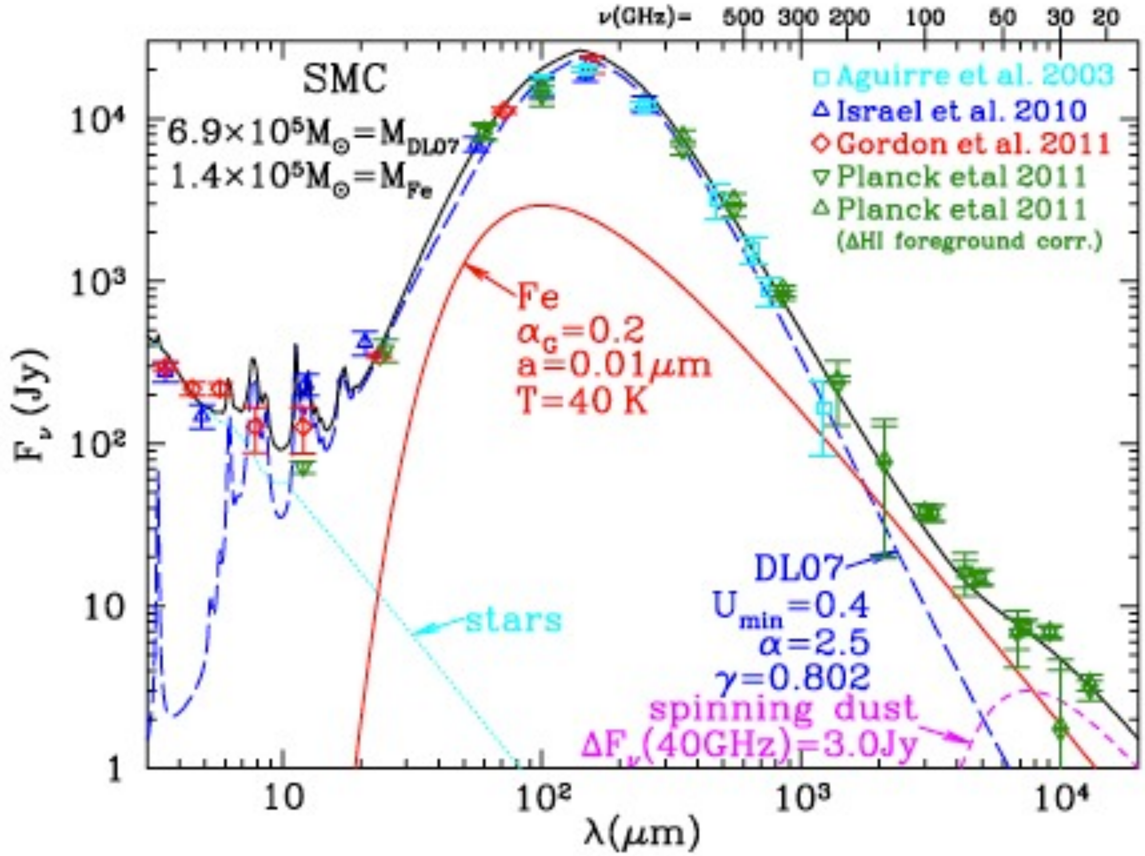


Planck Collaboration 2011, A&A 536, A17
(C. Author J.-Ph. Bernard)

Bernard J.Ph., PCMI 2012, Paris

Magnetic nanoparticles ?

==> Draine et al. 2011, 2012: Explaining diffuse ISM and SMC Planck SED with magnetic nanoparticles



Makes predictions about polarization variation with frequency

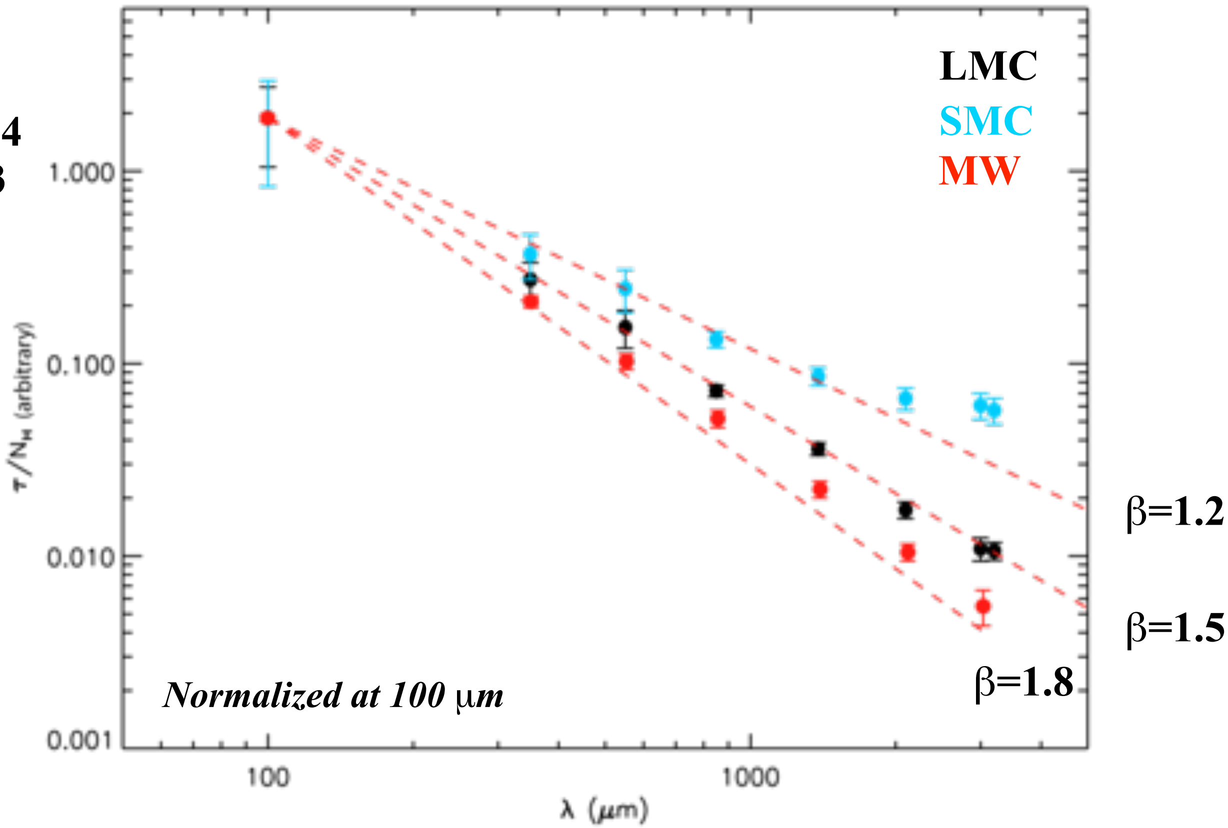
Bernard J.Ph., PCMI 2012, Paris

Submm emissivity of MW, LMC, SMC

Large variations of the sub-mm emissivity are observed between the MW, the LMC and the SMC
MW: β (FIR)=1.8
LMC: β (FIR)=1.5 (consistent with Gordon et al. 2010)
SMC: 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

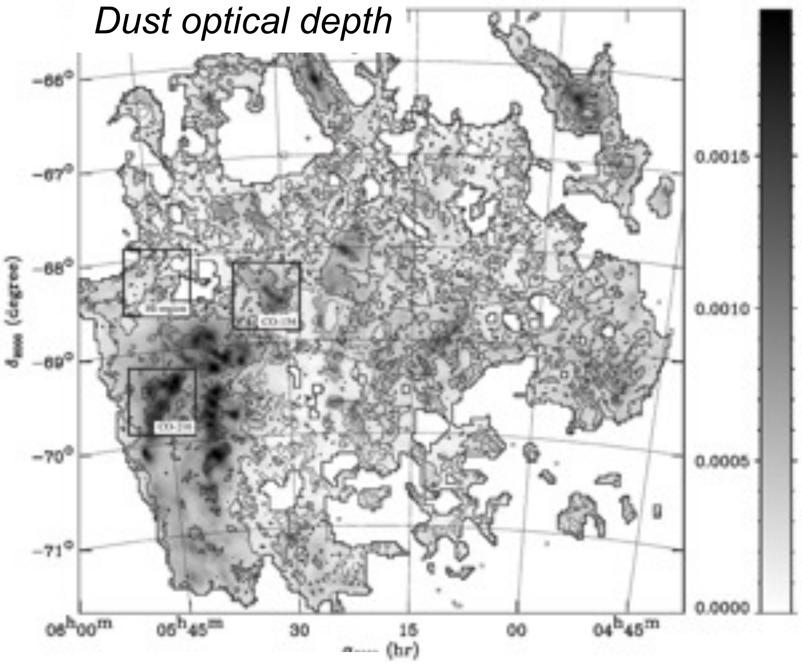


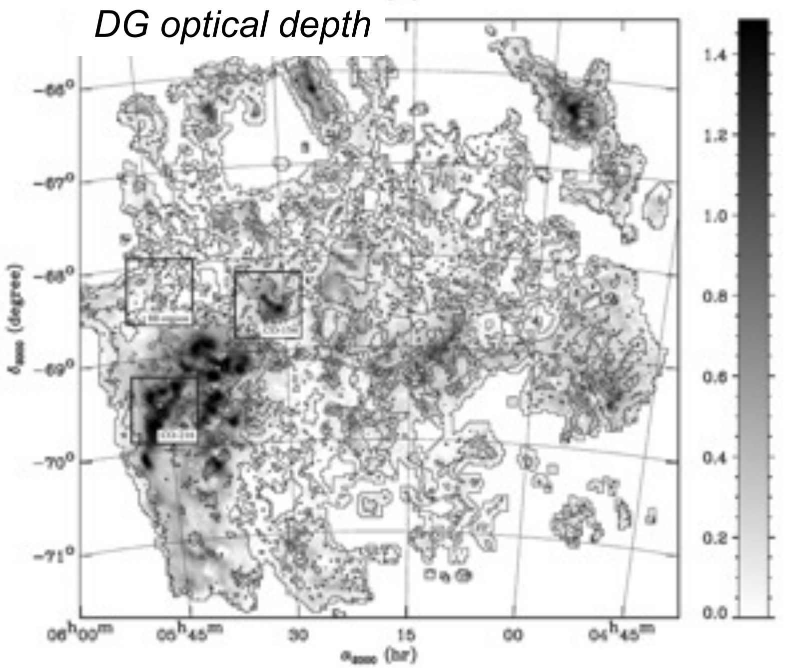
Dark Gas in external Galaxies ?

==> LMC (Bernard et al. 2008): Spitzer
up to 200% of known mass could be DG (!!)
==> LMC (Roman-Duval 2010): Heritage
Local study, not consistent with above, ...
==> SMC (Leroy et al. 2007: 10% of mass
in DG).
==> SMC : Bot private communication finds
same as LMC with same hypothesis.

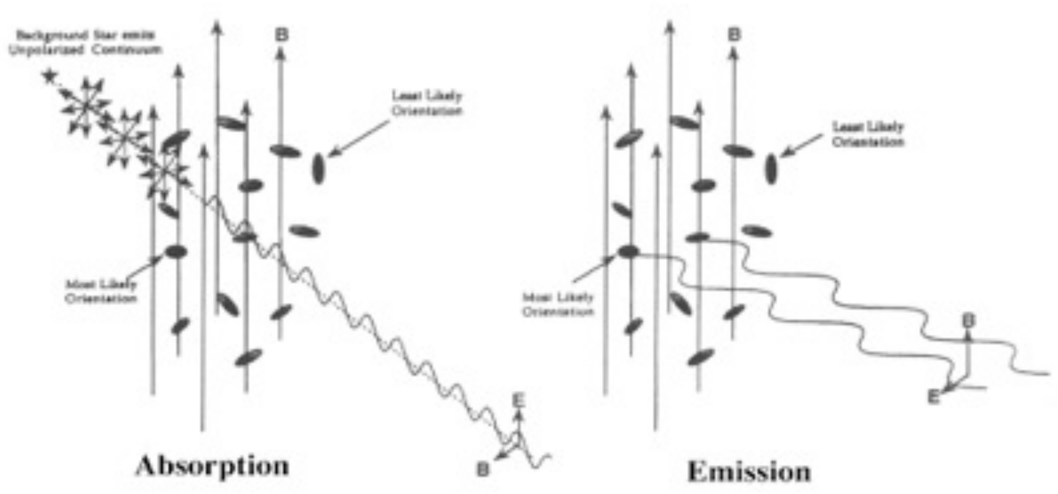
$$\frac{I_{160}}{B_{160}(T)} = \left(\frac{\tau_{160}}{N_H}\right)\left(X_{HI} W_{HI} + 2\,Xco\,W_{co}\right) + cste$$

==> Main problems are :
- D/G variations (linked to metallicity variations)
- HI can be optically thick
- Xco factor varies (and not everyone has the same definition ...)



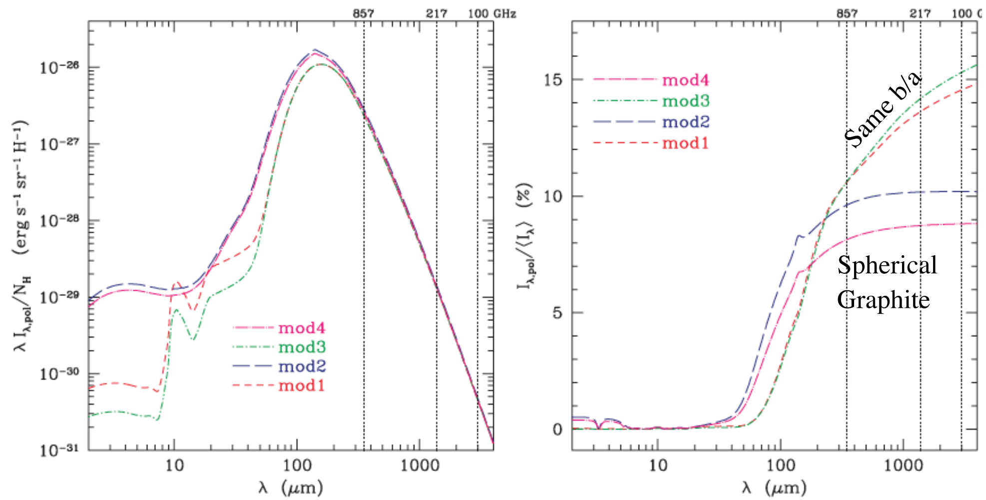


Dust Polarization



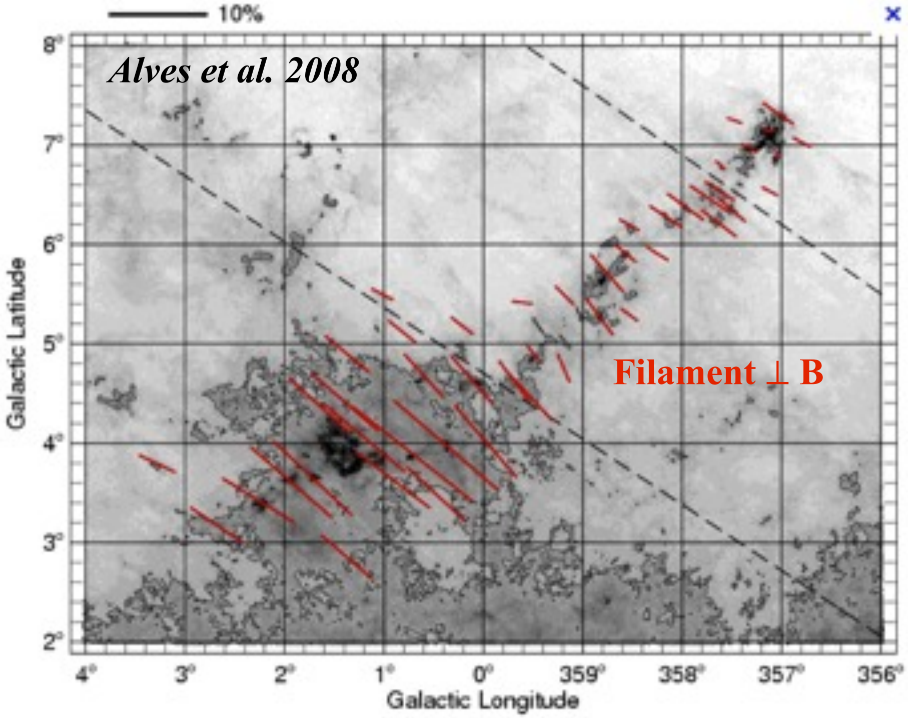
- Elongated grains rotate and relax to rotation // to magnetic field B
- polarized extinction // to B, polarized emission orth to B
- p=polarization degree (p~few %) Ψ=polarization angle ([-90°, 90°])
- If same LOS, Ψ should not vary with λ (great to assess noise)

- Models predict mild to no variations of p with λ in the Submm
- This is because only large grains rotate (and therefore align). Transition ~0.1 μm
- so, p(λ) in submm sensitive to grain composition and size distribution



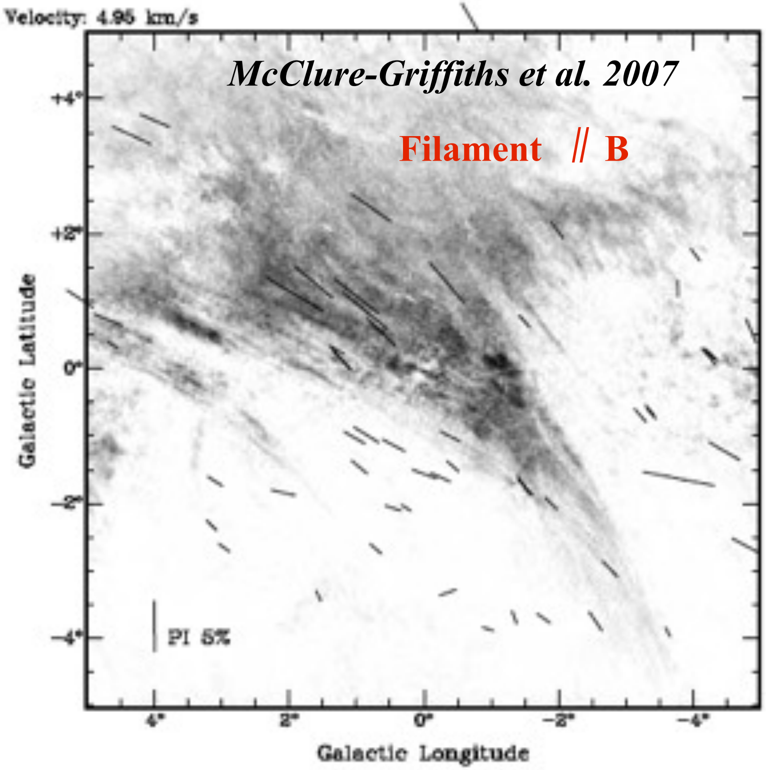
Draine & Fraisse 2009

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



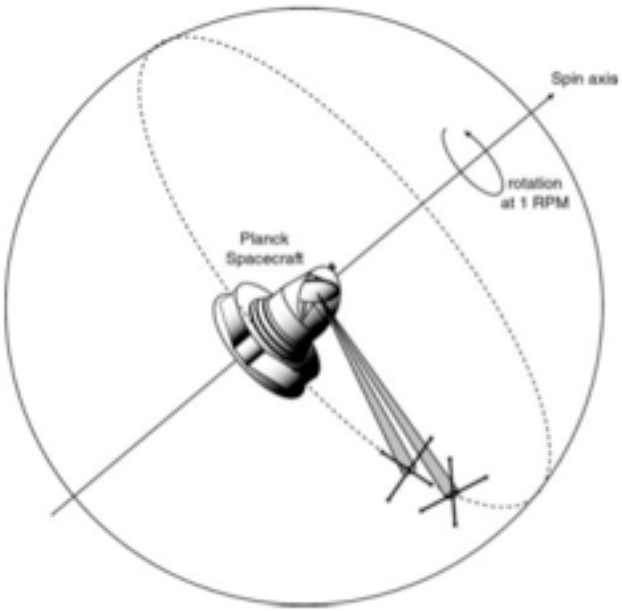
The planck data will allow to test this with much more statistics than stellar absorption measurements allow.

Expect a very significant step forward in our understanding of the magnetic field geometry and dust alignment properties in the next future.

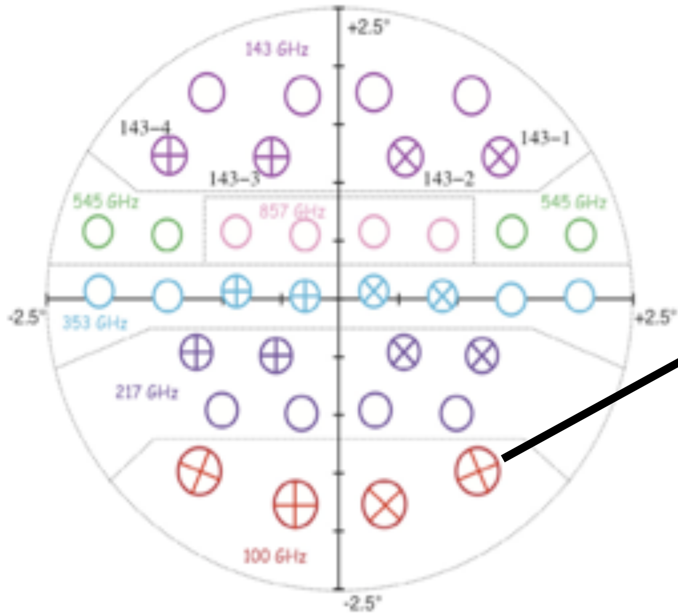
Bernard J.Ph., PCMI 2012, Paris

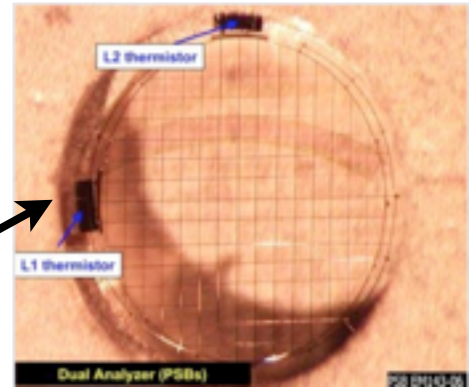
From data to Stokes parameters

Planck scanning the sky



Planck/HFI focal plane





Derivation of Stokes parameters (I, Q and U) involves the combination of two pairs of PSB bolometers that observe the same sky positions within a few seconds. The polarizers of the second pair are rotated by 45° with respect to the first pair.

$$s_1 - s_2 = Q\ cos(2\alpha) + U\ sin(2\alpha)$$
$$s_3 - s_4 = Q\ sin(2\alpha) - U\ cos(2\alpha)$$

Measuring differences at the % level

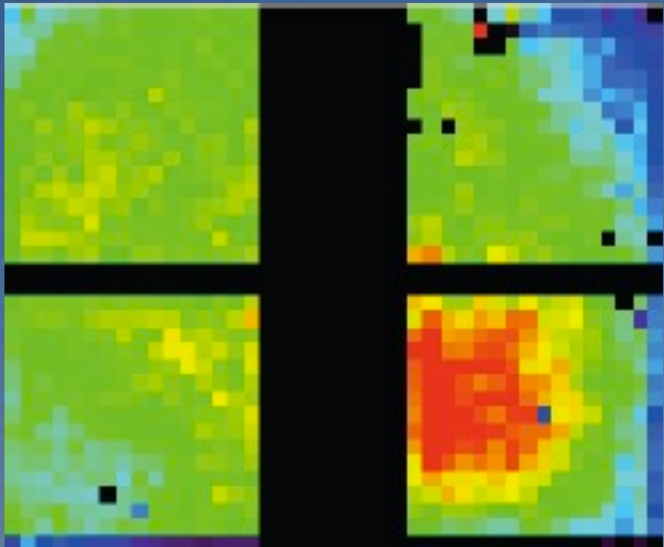
Multiple scans and multiple surveys provide Q and U measurements with different α orientation. Maps of Q and U and their standard deviations are inferred from the multiple measurements.

Bernard J.Ph., PCMI 2012, Paris

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.

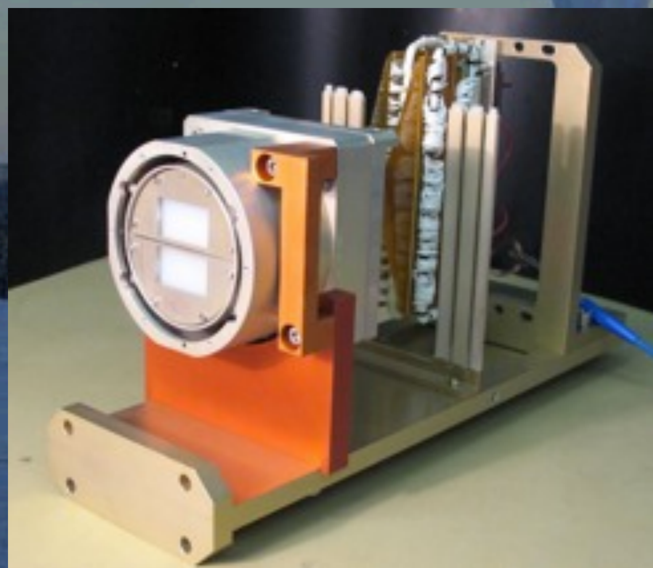
Coming soon : Pilot



Dust emission polarization at 240 and 500 microns

First launch forseen in 2014

http://pilot.irap.omp.eu



Conclusions/Perspectives

Planck and Herschel bring wonderful data about dust in our Galaxy and nearby galaxies

The French PCMI representants have played a major role

So far, these observations confirm previous findings, such as :

- Dust coagulation
- Presence of cold cores

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 :

- How widespread is spinning dust ?
- Variations of emissivity with wavelengths, temperature ?
- How well can we measure the total mass of galaxies from dust emission ?

This is just a beginning ...
The co-analysis of Planck and Herschel data could bring even more answers.
Planck Polarization data is the next step forward in our understanding of dust (and magnetic field) ...