Foregrounds

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on behalf of the Italian CMB community

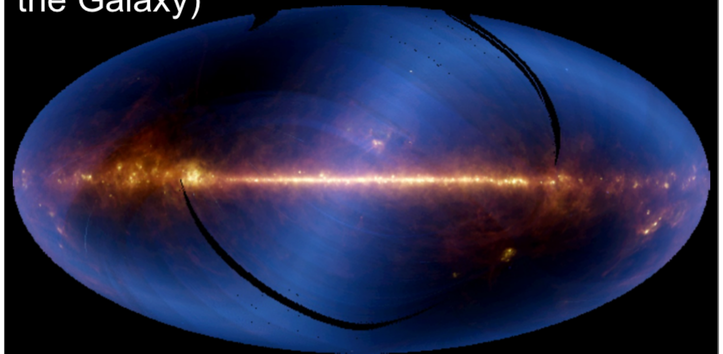
Overview

- Solar system diffuse emissions
  - Weak components?
- Galactic diffuse emissions
  - Microwave sky complexity in both temperature & polarization
  - Synchrotron emission
  - Dust emission
  - AME (spinning dust) and haze
- Extragalactic sources
  - Improvements in total intensity
  - Blazars
  - Dusty galaxies & high-z lensed sources
  - CIB
  - Proto-clusters
  - Improvements in polarization
- Conclusions

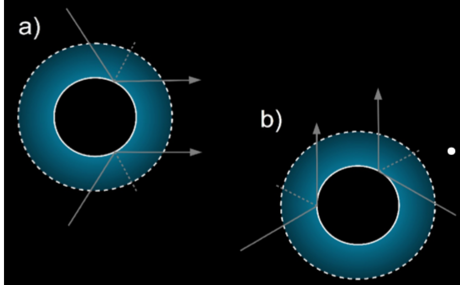
Classical ZLE - Separated in "time domain", for now simply exploiting differences in surveys & Secondary components? KBOE?

Zodiacal emission

...measured by IRAS (it's the white 'S', not the Galaxy)



How we do it

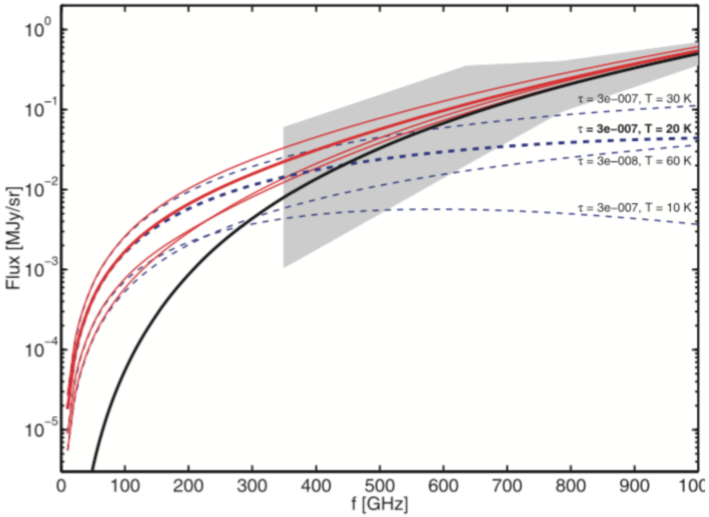


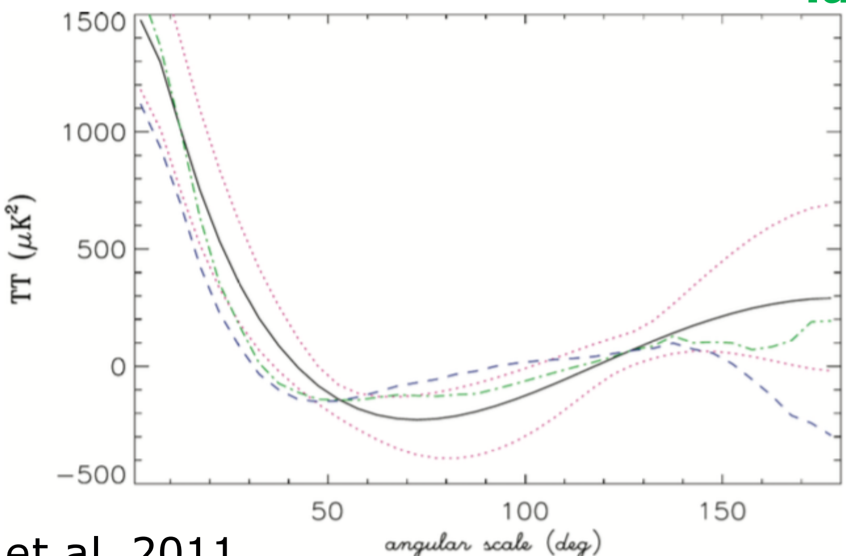
- In successive surveys we observe similar, but different total columns of interplanetary (local) dust (IPD)
- Making differences of successive surveys allows us to remove "contamination", but still be sensitive to the IPD

ZLE: first piece of the game

KBOE ?
far, cold, large dust grains

Imprints @ large scales?



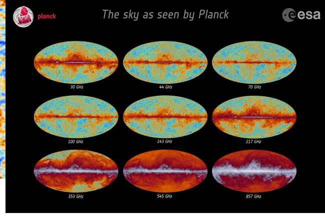


Maris et al. 2011

mm signal from KBOE?

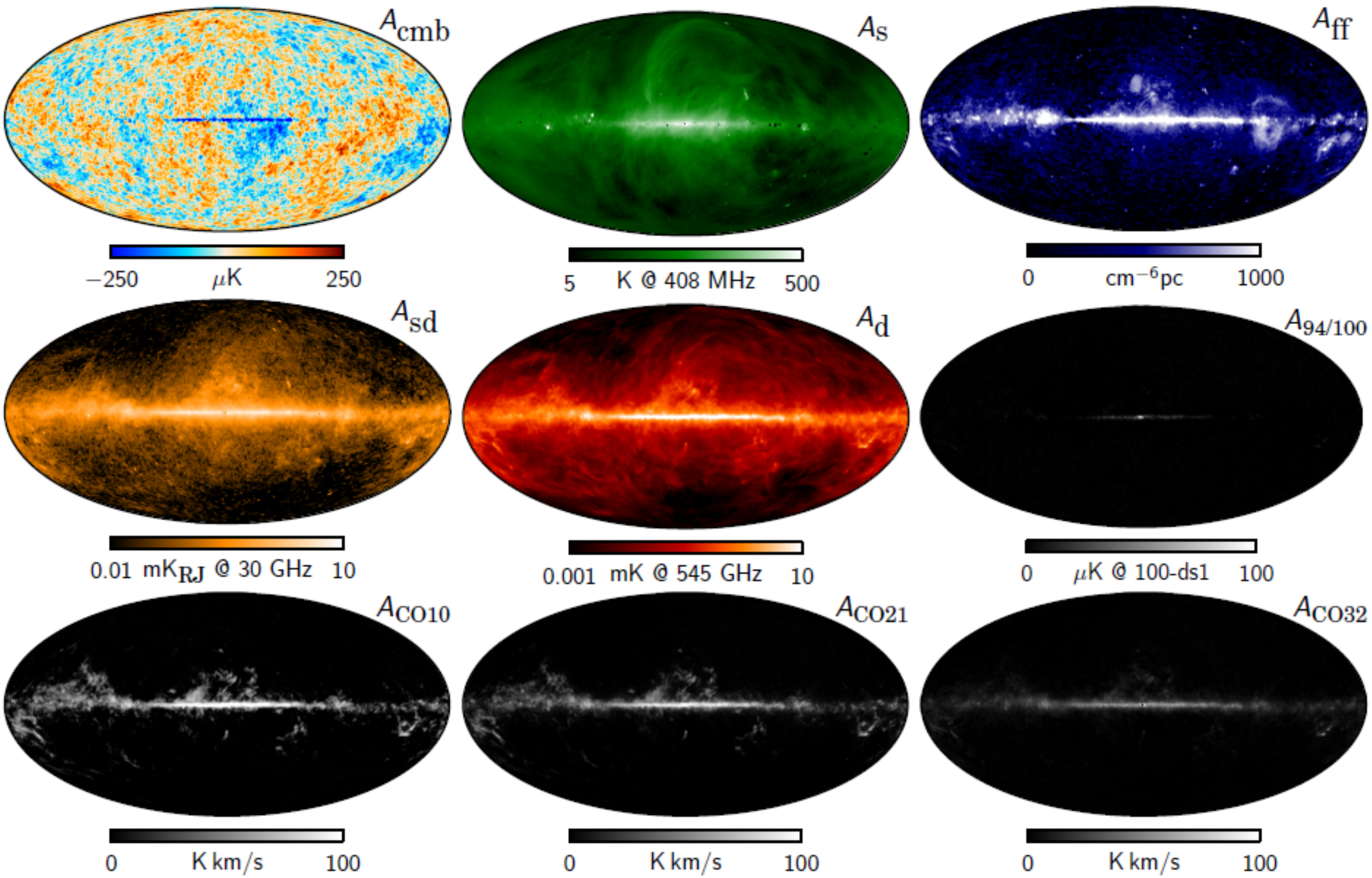
Low quadrupole?

Correlation function?



from freq. → maps

Planck Galactic foreground components in temperature



Planck polarization frequency maps: synchrotron & dust components

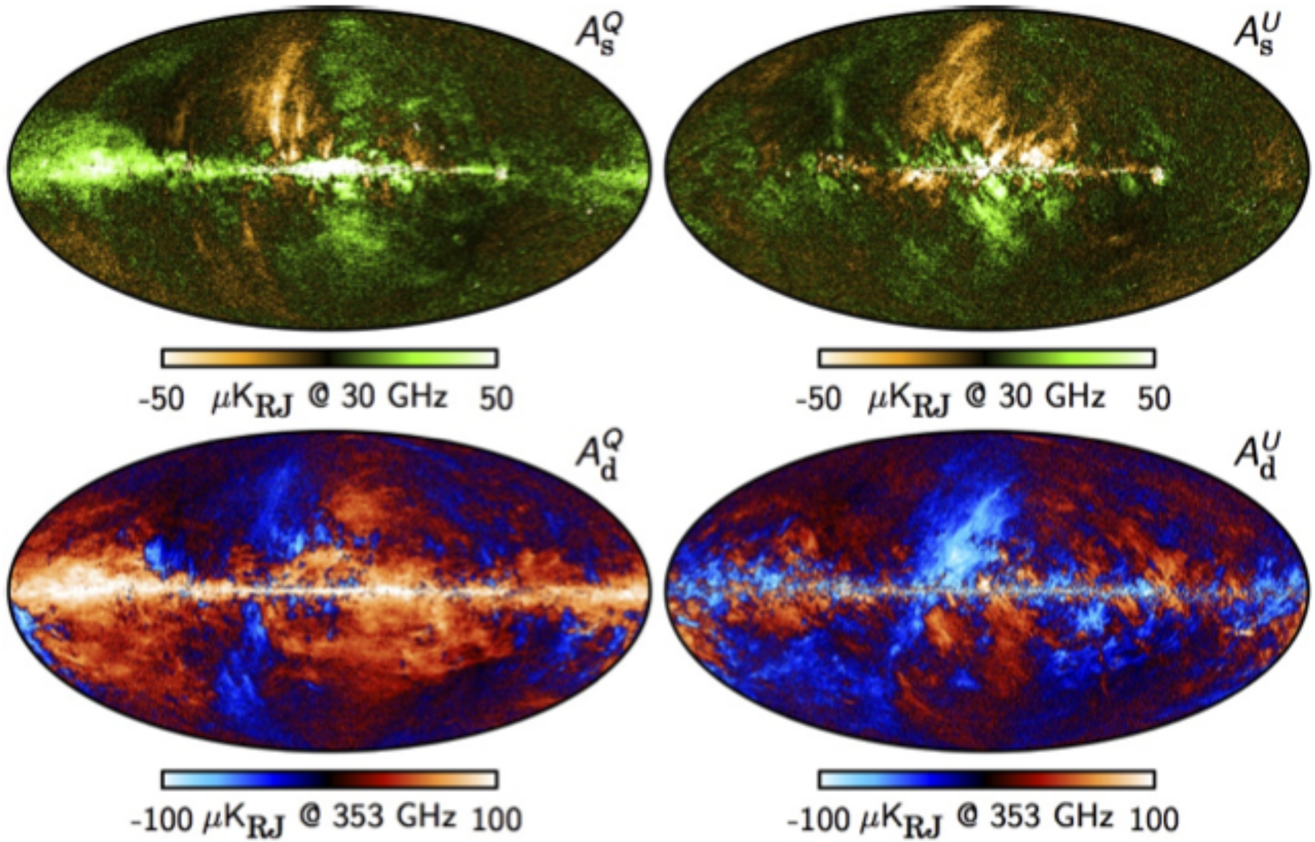
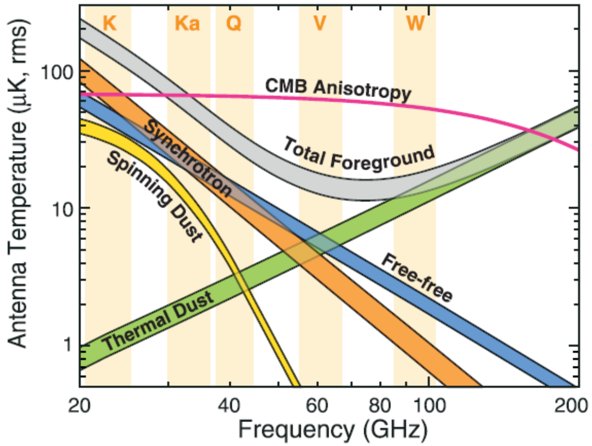


Fig. 15. Maximum posterior amplitude polarization maps derived from the *Planck* observations between 30 and 353 GHz (Planck Collaboration X 2015). The left and right columns show the Stokes Q and U parameters, respectively. Rows show, from top to bottom: CMB; synchrotron polarization at 30 GHz; and thermal dust polarization at 353 GHz. The CMB map has been highpass-filtered with a cosine-apodized filter between $\ell = 20$ and 40, and the Galactic plane (defined by the 17 % CPM83 mask) has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2015).

rms fluctuations in T & P: CMB vs foregrounds
Change of paradigm from *Planck* maps



WMAP 9

75-85% sky coverage

***Planck* in T: 81-93% sky coverage - 1° FWHM**

c.f. common mask 78%

Microwave sky complexity: more relevant components!

Many parameters!

Synch: 2 +

Dust: 3 (* 2 ?)

FF: 2 (EM,T_e)

Spinning dust: 3loc+1glob

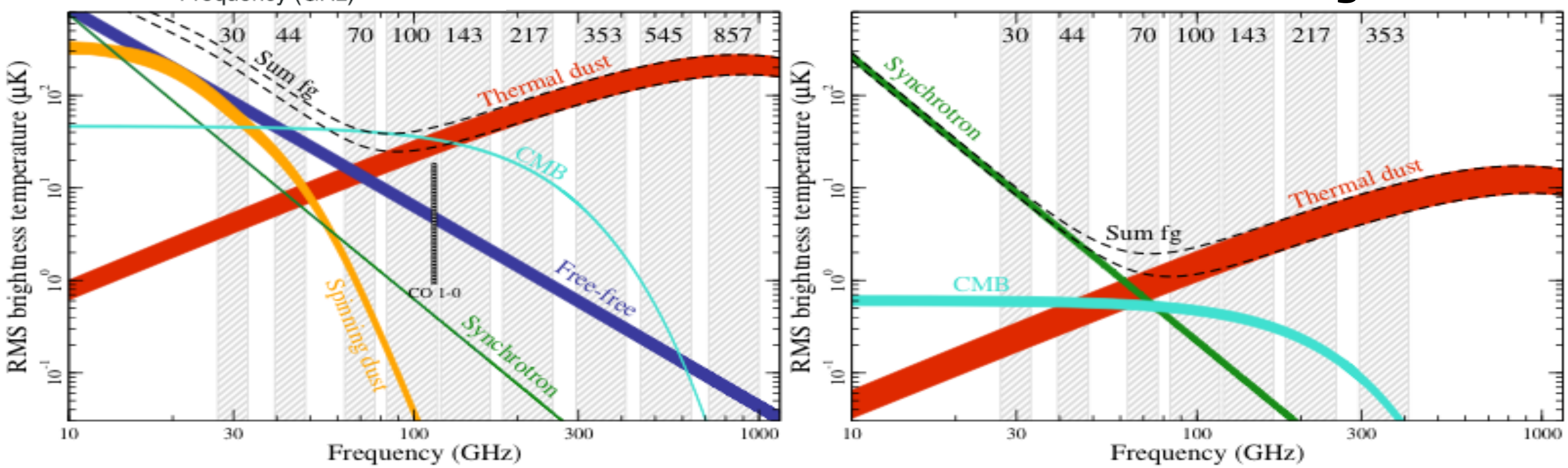
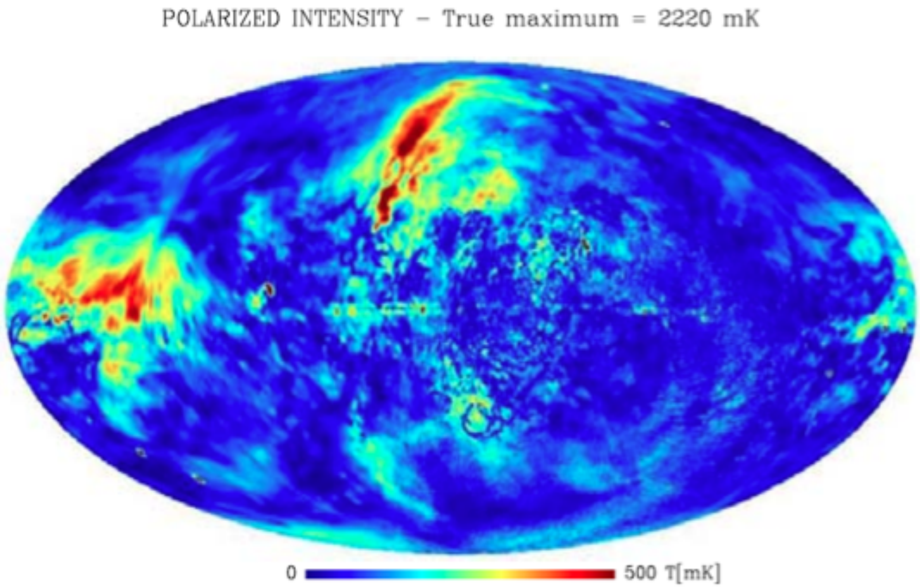
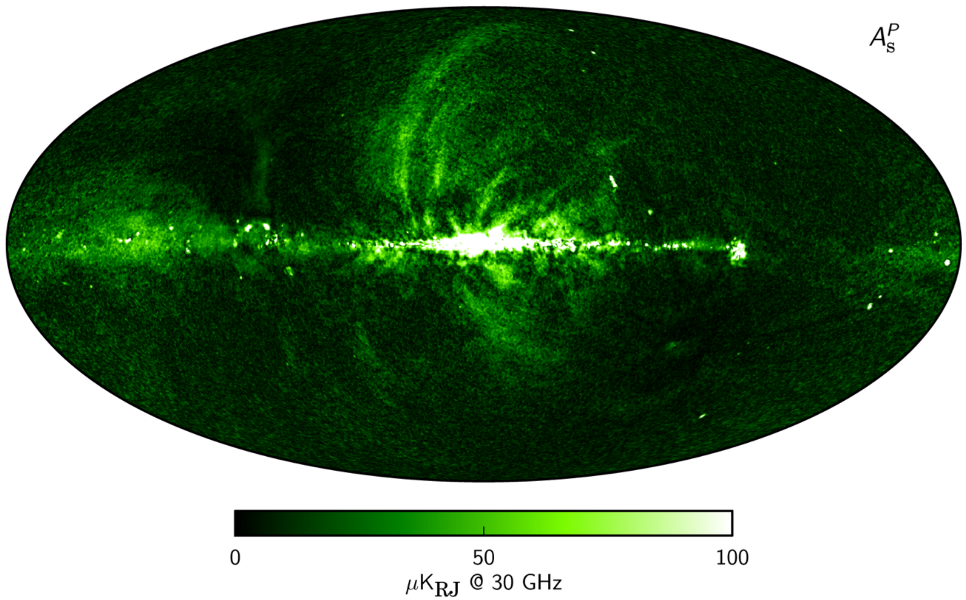


Fig. 16. Brightness temperature rms as a function of frequency and astrophysical component for temperature (*left*) and polarization (*right*). For temperature, each component is smoothed to an angular resolution of 1° FWHM, and the lower and upper edges of each line are defined by masks covering 81 and 93 % of the sky, respectively. For polarization, the corresponding smoothing scale is 40′, and the sky fractions are 73 and 93 %.

Synchrotron emission in polarization: radio vs mm





All-sky maps of Galactic polarized synchrotron emission
at radio (1.4 GHz; from Burigana et al. '06) & mm (30 GHz) from *Planck*

Relativistic cosmic ray electrons spiralling in the Galactic magnetic field
→ Galactic synchrotron emission

Significant depolarization appearing in a wide region around the Galactic center in the radio, much less relevant in the microwaves

Synchrotron emission characterization

Relevance for e.g.:

- **cosmic ray physics**
- **Galaxy 3D models**
- **Galactic magnetic fields**

In frequency SED

From Planck Coll. 2015, XXV

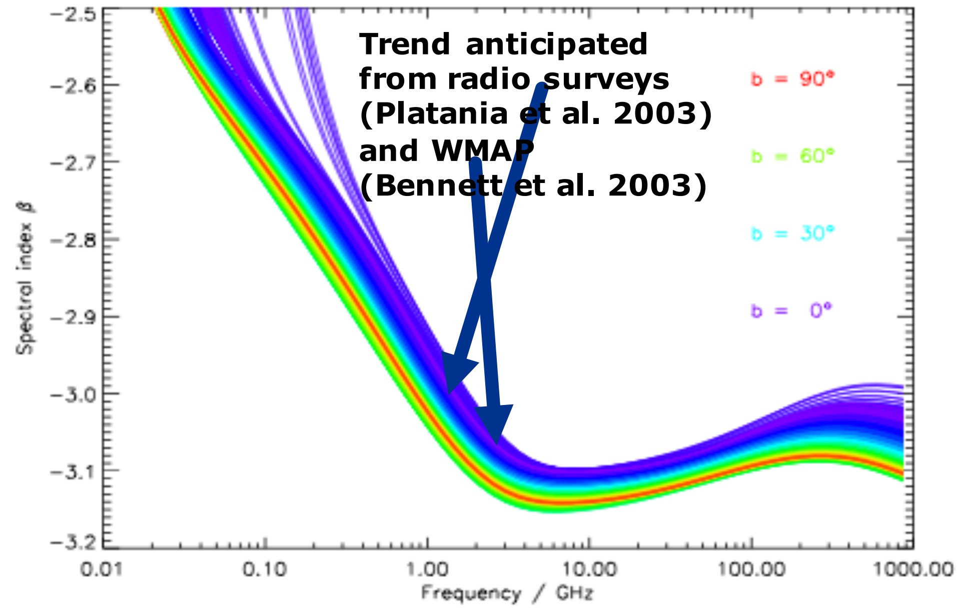


Fig. 15. Local spectral index of the synchrotron emission $\beta(\nu) = d\ln T/d\ln\nu$ vs. frequency for a sample of pixels (one per $N_{\rm side} = 8$ super-pixel), in the GALPROP z10LMPD_SUNfE model from Orlando & Strong (2013). The spectra are colour-coded by Galactic latitude: spectra at low latitudes show strong low-frequency curvature due to free-free absorption.

	Synchrotron		
	q [μK$^2_{\rm CMB}$]	α	q [
Common mask; apod = 1° FWHM; $f_{\rm sky}^{\rm eff}$ = 0.73			
EE	3.7 ± 0.2	-0.44 ± 0.07	
BB	1.3 ± 0.2	-0.31 ± 0.13	
BB/EE	0.36 ± 0.06		
Common mask; apod = 2° FWHM; $f_{\rm sky}^{\rm eff}$ = 0.68			
EE	3.2 ± 0.2	-0.49 ± 0.08	
BB	1.1 ± 0.2	-0.02 ± 0.17	
BB/EE	0.34 ± 0.07		

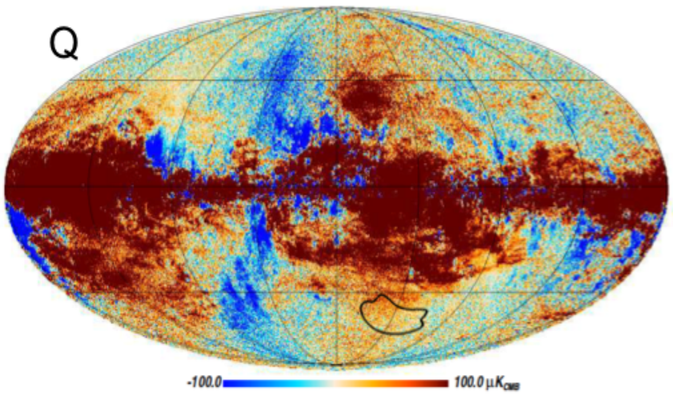
From Planck Coll. 2015, X

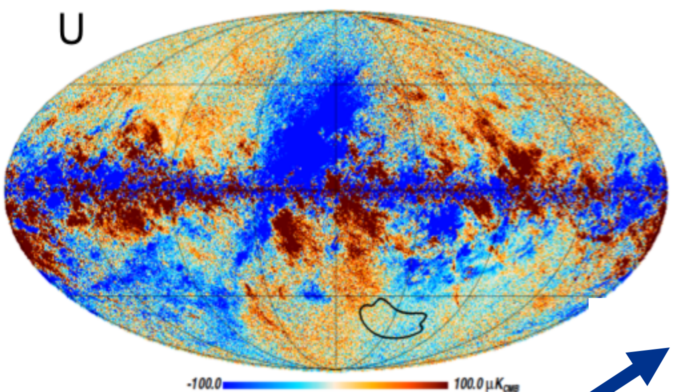
In angular correlation

EE & BB ← APS

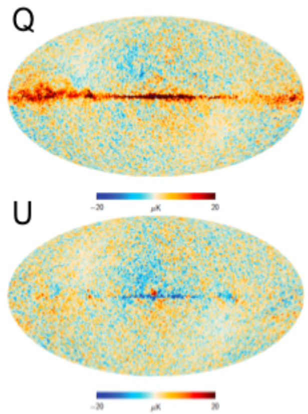
Planck 353 GHz full sky maps in polarization

- 353 GHz polarized maps are dominated by Galactic dust emission





For comparison, Planck 70 GHz is close to the minimum of Galactic foreground emission



Bicep2, Keck Array and Planck Collaboration

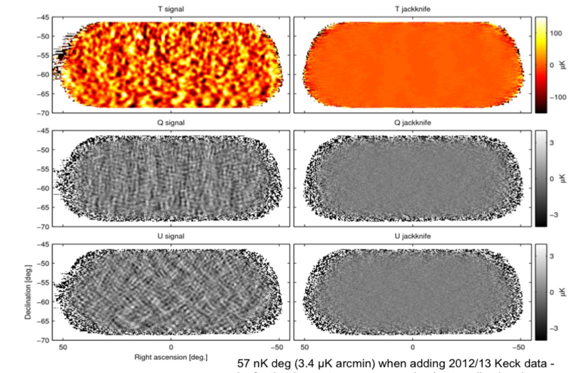
Dust essentially everywhere

Crucial for understanding the nature of B-mode polarization signal

Planck first results on dust polarized emission:

High observed degree of polarization (P/I)obs up to 18%

B2+Keck 150 GHz T/Q/U maps of small sky patch



57 nK deg (3.4 µK arcmin) when adding 2012/13 Keck data - by far the deepest maps ever made - but apodized and filtered...

Bicep2, Keck Array and Planck Collaboration

Planck Collaboration: Dust polarization at high latitudes

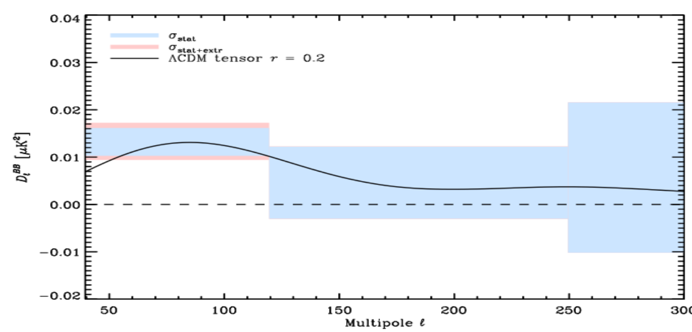
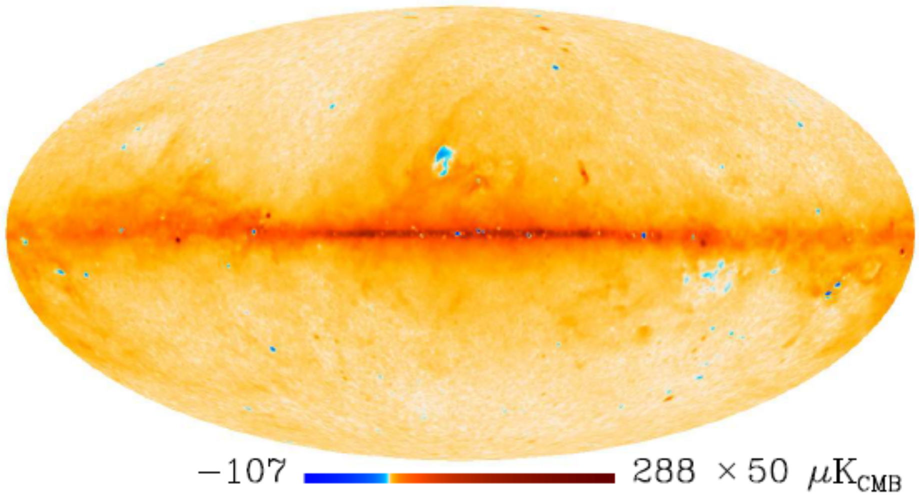


Fig. 9: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum computed on M_{B2} defined in Sect. 6.1 and extrapolated to 150 GHz (box centres). The shaded boxes represent the $\pm1\,\sigma$ uncertainties: blue for the statistical uncertainties from noise; and red adding in quadrature the uncertainty from the extrapolation to 150 GHz. The *Planck* 2013 best-fit ΛCDM $\mathcal{D}_\ell^{BB}$ CMB model based on temperature anisotropies, with a tensor amplitude fixed at $r = 0.2$, is overplotted as a black line.

AME – spinning dust *all-sky* diffuse component

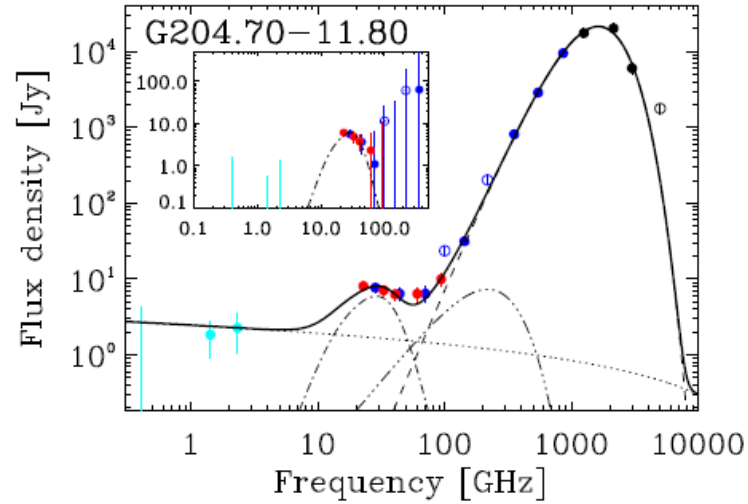
Planck Commander model has 2 AME components:

Planck Int. XV (2014)



- ✓ **Main component has variable peak with prior centred on 19 GHz**
- ✓ **"High frequency" component with peak 30 GHz**
  - ➢ **Still too low for some regions (Oph, California Nebula)**

- ❑ **AME flexibility forces us to use fixed template for synchrotron spectrum, despite plausible evidence for spectral variability**



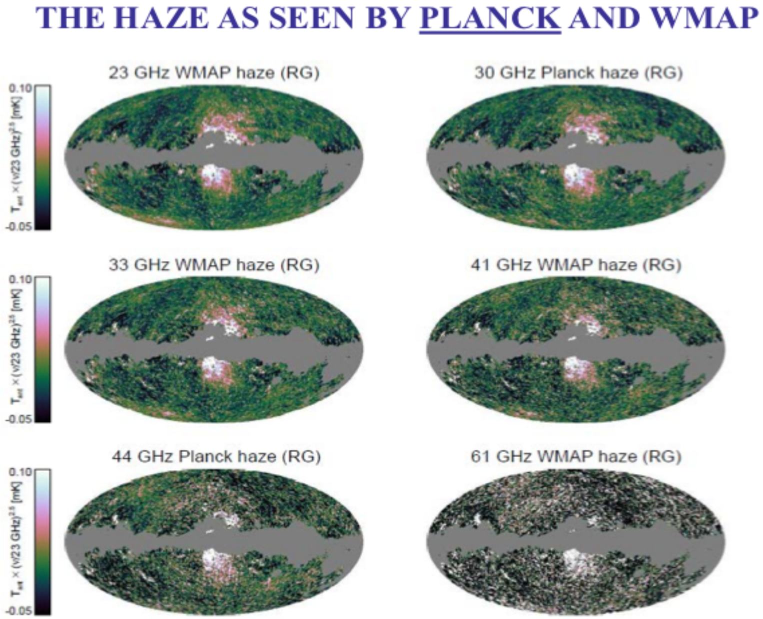
CMB, dust and free-free killed ILC combination

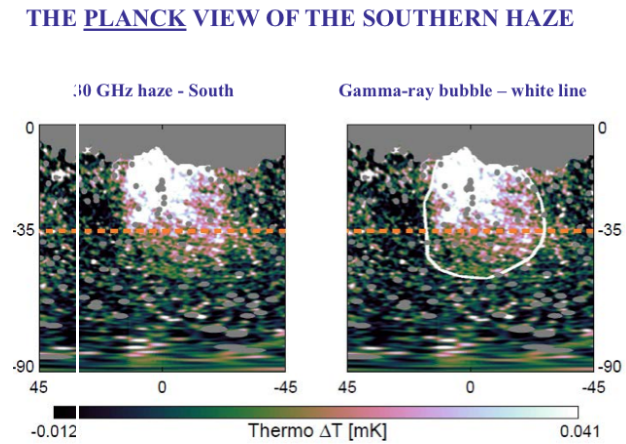
Rising spectrum between 30 & 44 GHz

AME with high-frequency peak

QUIJOTE (10-18 GHz), C-BASS (5 GHz)
S-PASS (2.3 GHz)
GMIMS (300 -1800 MHz) for synchrotron

Haze with *Planck*





Galactic Haze at 30 and 44 GHz, from *Planck*

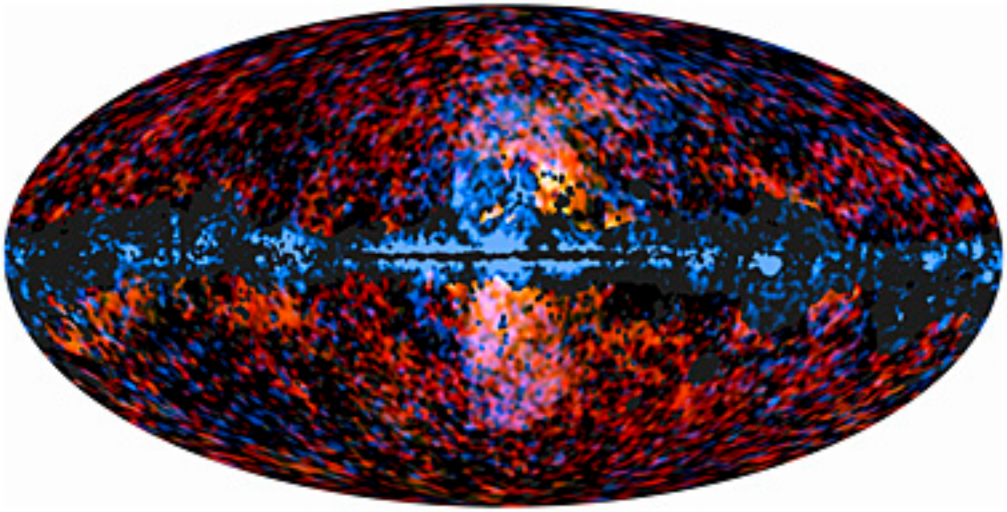
❖ The **Galactic Haze** is seen to be distributed **around the Galactic Centre**

❖ Its **spectrum is similar to that of synchrotron emission**

❖ However, compared to the synchrotron emission seen elsewhere in the Milky Way, the Galactic **Haze has a 'harder' spectrum**, meaning that its emission **does not decline as rapidly with increasing frequency**

❖ Diffuse synchrotron emission is interpreted as **radiation from highly energetic electrons** that have been accelerated in shocks created by supernova explosions

Haze with *Planck & Fermi*



← **Distribution of the Galactic Haze seen by ESA's *Planck* (red & yellow: 30 & 44 GHz) superimposed over the high-energy sky as seen by NASA's *Fermi* Gamma-ray Space Telescope (blue)**

❖ ***Fermi*** **data at (10-100) GeV reveal two bubble-shaped, gamma-ray emitting structures extending from the Galactic Centre**

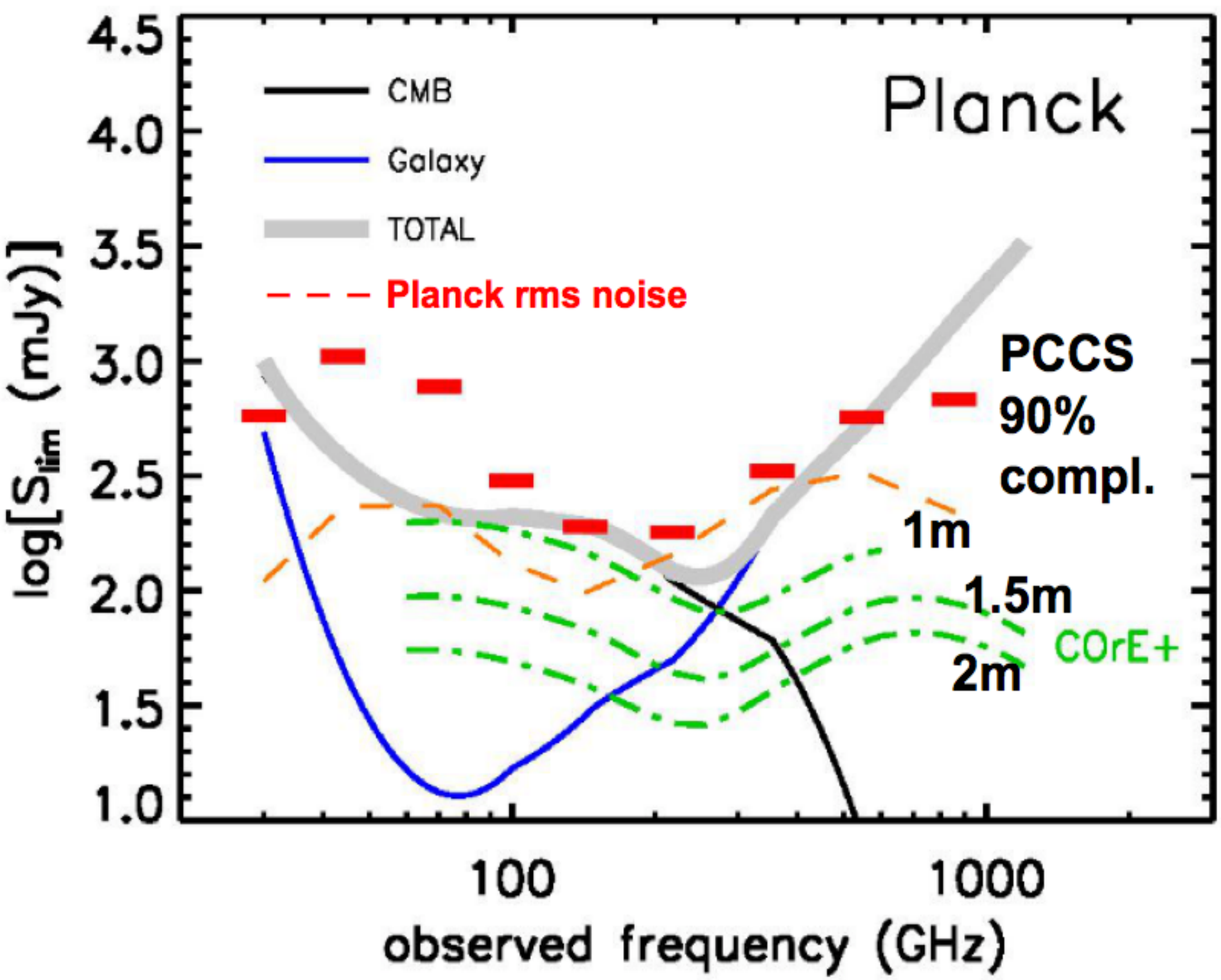
❖ **The two emission regions seen by *Planck* and *Fermi* at two opposite ends of the electromagnetic spectrum correlate spatially quite well**

❖ **and might indeed be a manifestation of the same population of electrons via different radiation processes**

❖ **Several explanations** have been proposed for this unusual behaviour, including ***enhanced supernova rates, galactic winds and even annihilation of dark-matter particles.***

❖ Thus far, **none** of them have been **confirmed** and the issue remains open. **Room for more** data especially in polarization.

Detection limits for a diffraction-limited survey



In total intensity:

Given current sensitivities, confusion dominates detection limits

→ **Angular resolution critical**

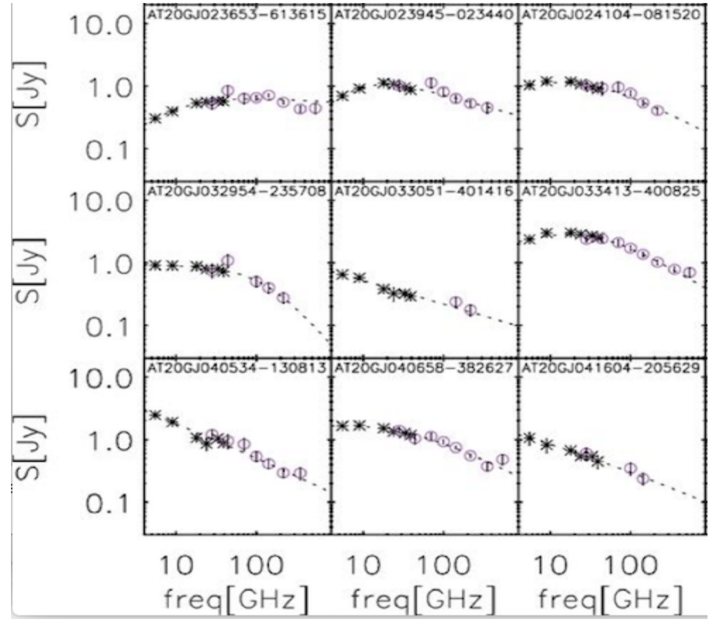
Planck HFI worse than diffraction limited

Improvements expected even with *smaller telescope* but *diffraction-limited*

Effect of COrE++ detection limit for extragalactic source counts

- Extragalactic **radio-sources** almost dominated by **blazars**, that is also dominating population in gamma-rays

- ***Planck*** data crucial to characterize their **synchrotron peak** and understanding their physics (Giommi et al. 2012)

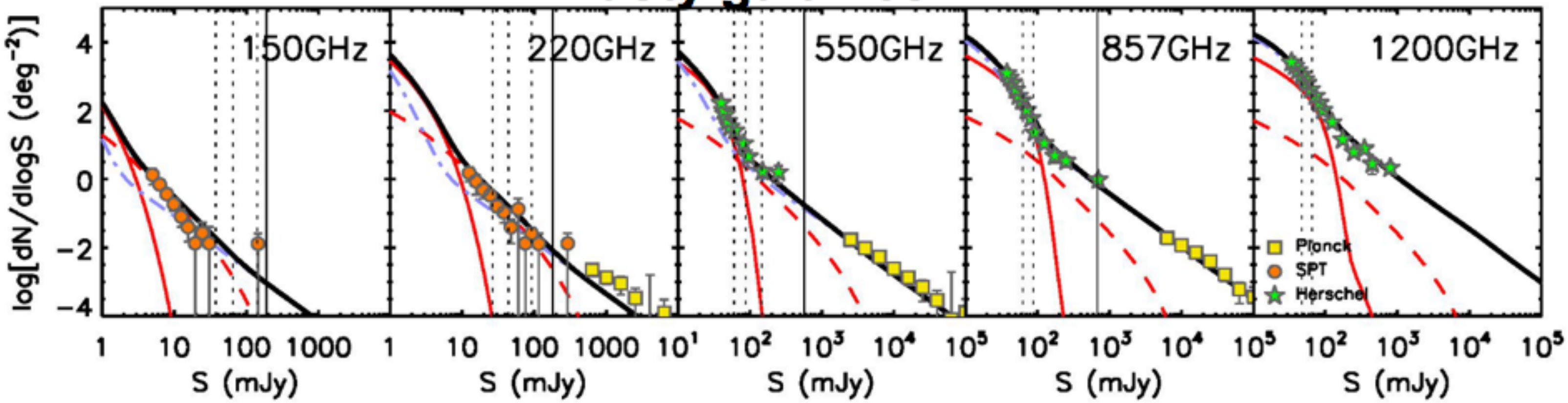


Extracted from
Massardi et al. 2016

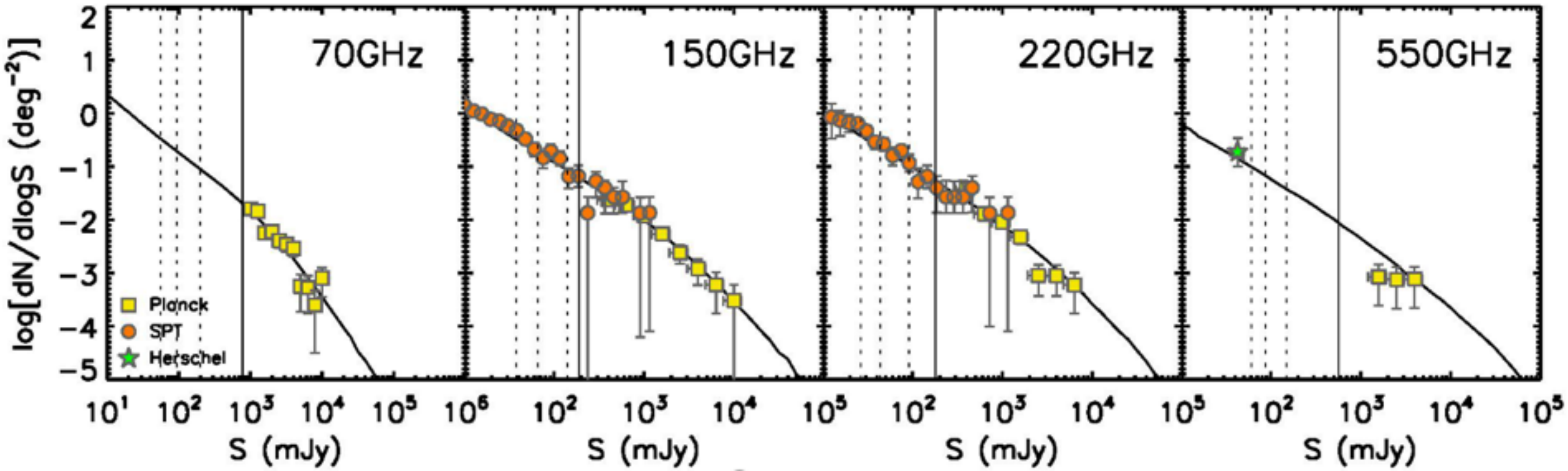
- **Galaxies with active star formation**
  - starlight absorbed by circumstellar dust grains and re-emitted in far-IR/sub-mm
  - **COrE-M5 will fill gap** between Planck flux limit and Herschel flux range, a gap where
    - ✓ **cosmological evolution** appears and thus particularly important for evolutionary models
    - ✓ it is easier to identify extreme cases of flux **gravitational amplification**

Source counts

Dusty galaxies

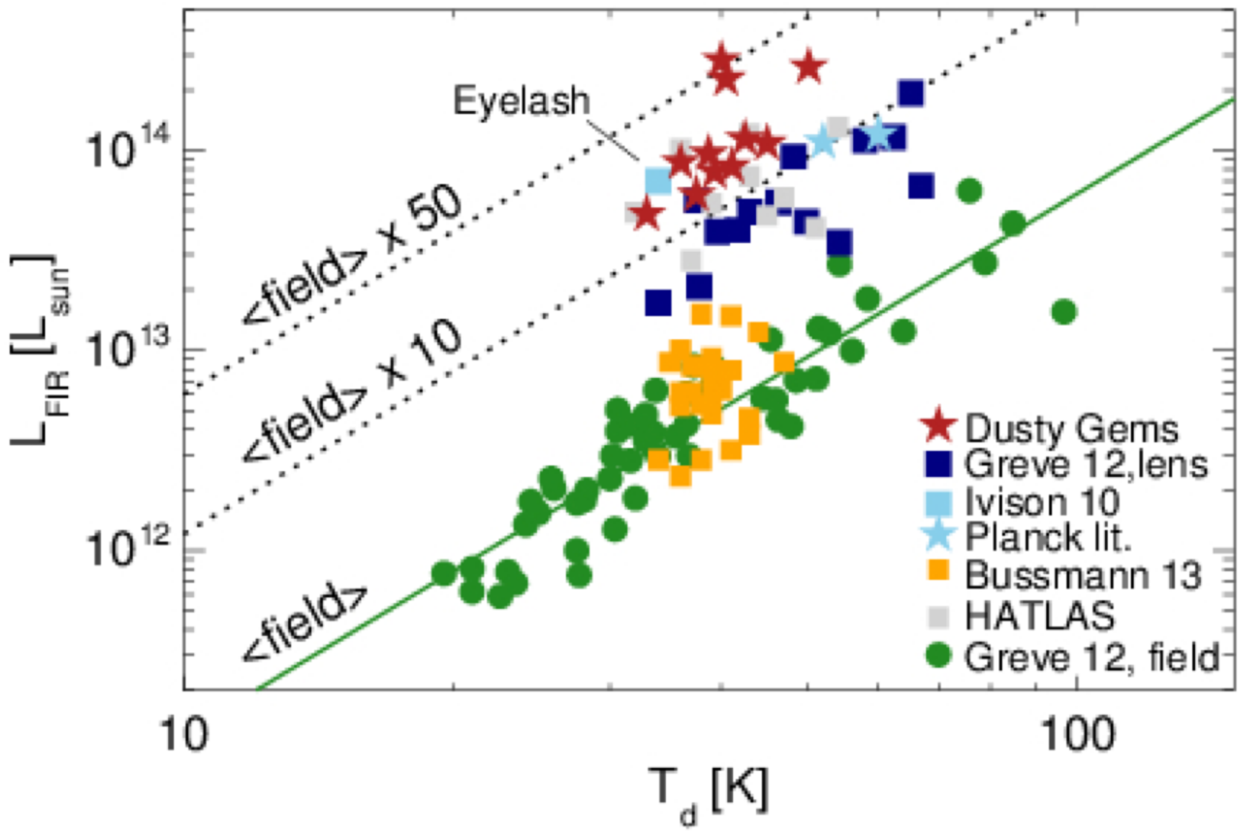


Radio sources



Negrello et al. (2013)

Follow-up with Herschel



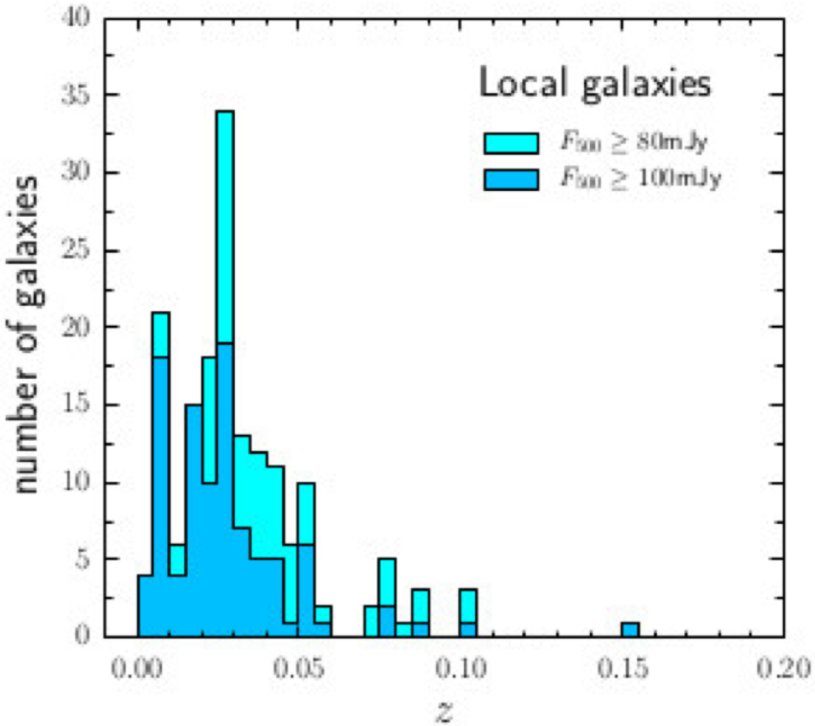
Dusty Gems: 11 strongly gravitationally lensed galaxies at z= 2.2 – 3.6 detected by *Planck*

(Cañameras et al. 2015)

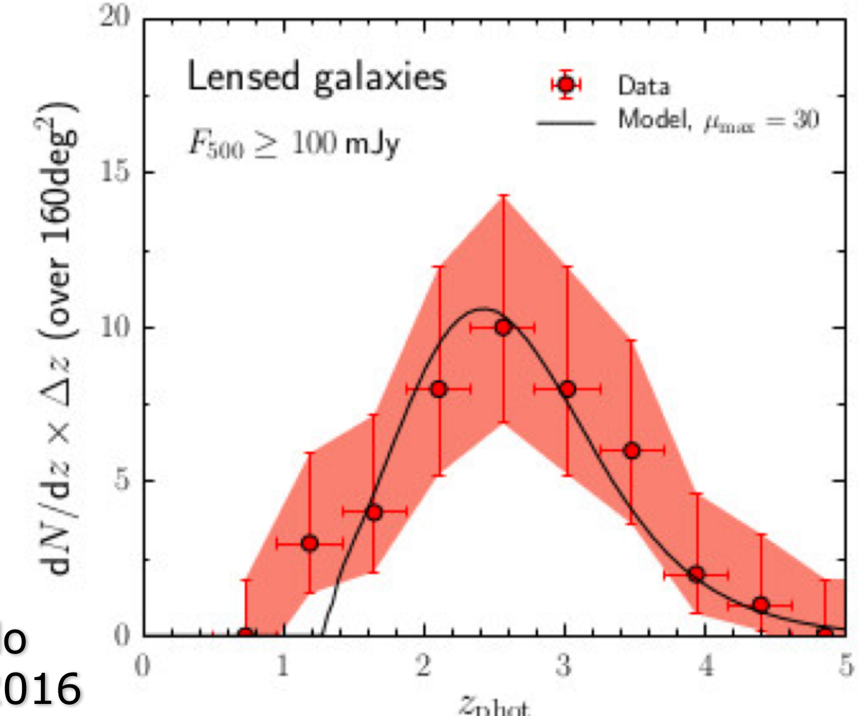
Extreme gravitational amplification of flux density (up to 50 times)
Most luminous galaxies in the Universe. Apparent luminosity & size enhancement → unique opportunity to study high-z galaxy physics

Distribution of intensities in *Planck* 545 GHz map in a ``clean'' region

Strongly lensed galaxies detection through these surveys has extremely high efficiency, close to 100%, since they are the high-z dominant population at high fluxes.
Other sources at these flux levels are local galaxies, appearing in optical catalogs, and a small number of blazars, easy to recognize

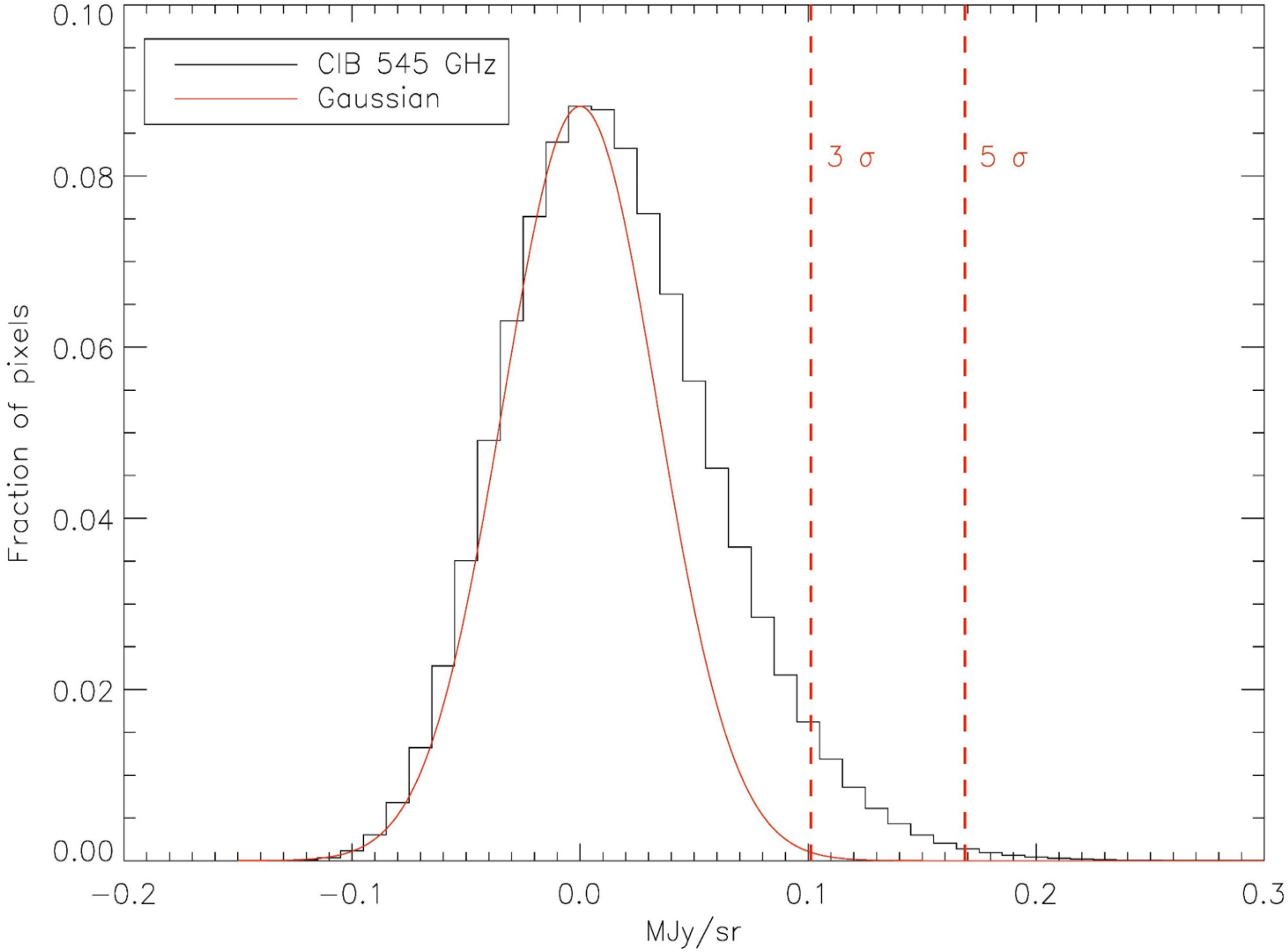


Negrello et al. 2016



Separation of strongly lensed from local galaxies very easy: local galaxies immediately recognized in shallow optical images.

Distribution of intensities in *Planck* 545 GHz map in a ``clean'' region



Given the low noise level, fluctuation field is dominated by signal.

Signal shows up with a strong super-Gaussian tail of positive fluctuations.

LSS provides the major contribution to these fluctuations, related to galaxy over-density in the resolution element.

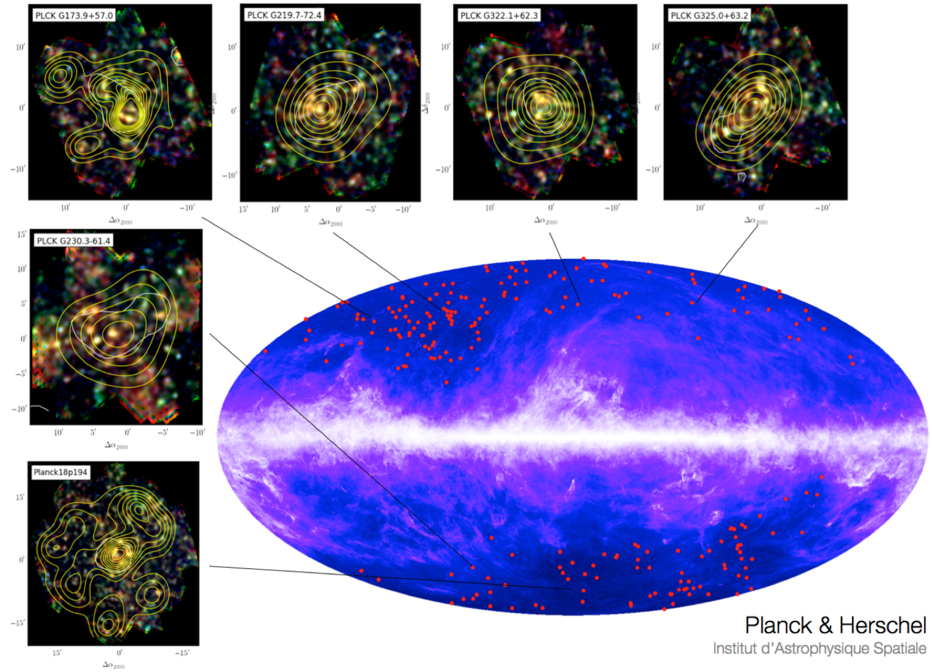
From proto-clusters to Gamma-rays?

Fluctuation analysis → identification of more than 2000 proto-cluster candidates, more than 200 confirmed by higher resolution *Herschel* observations

Still unclear how many proto-cluster candidates are really gravitational bounded systems that

are observed when star formation was active in their galaxies and IGM was still to be heated at virial temperature

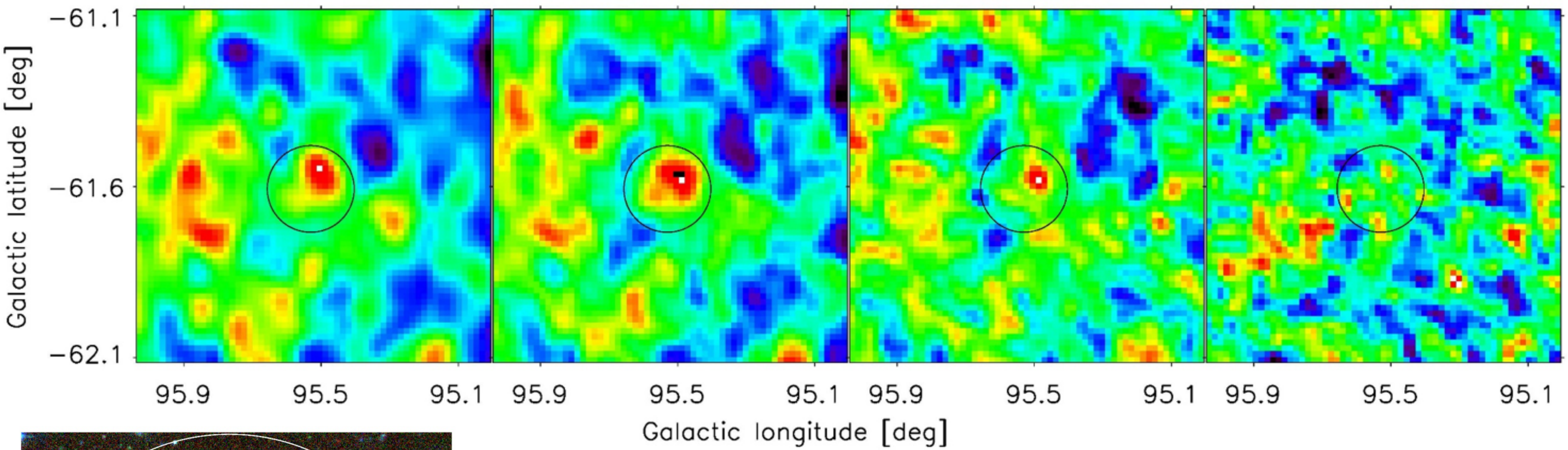
Planck intermediate results. XXVII, 2015

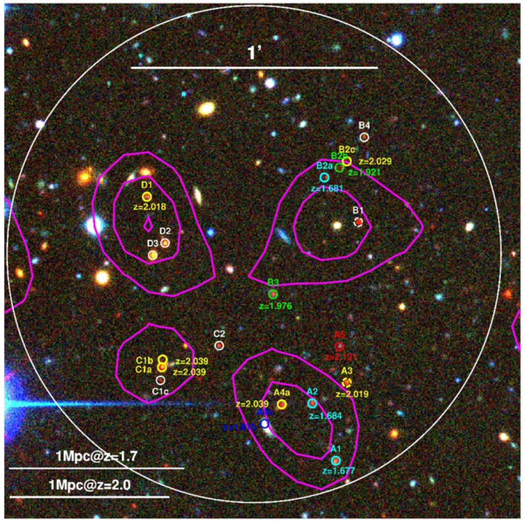


- → **Objects not detectable through usual optical/near-IR, X, SZ methods**
- → **Far-IR/mm surveys provide unique information on this LSS evolutionary phase**

Furthermore, intense star formation → high cosmic ray production → in the presence of abundant ISM and IGM → likely these objects are relevant Gamma-ray emitters

Multi-frequency follow up of a *Planck* candidate proto-cluster





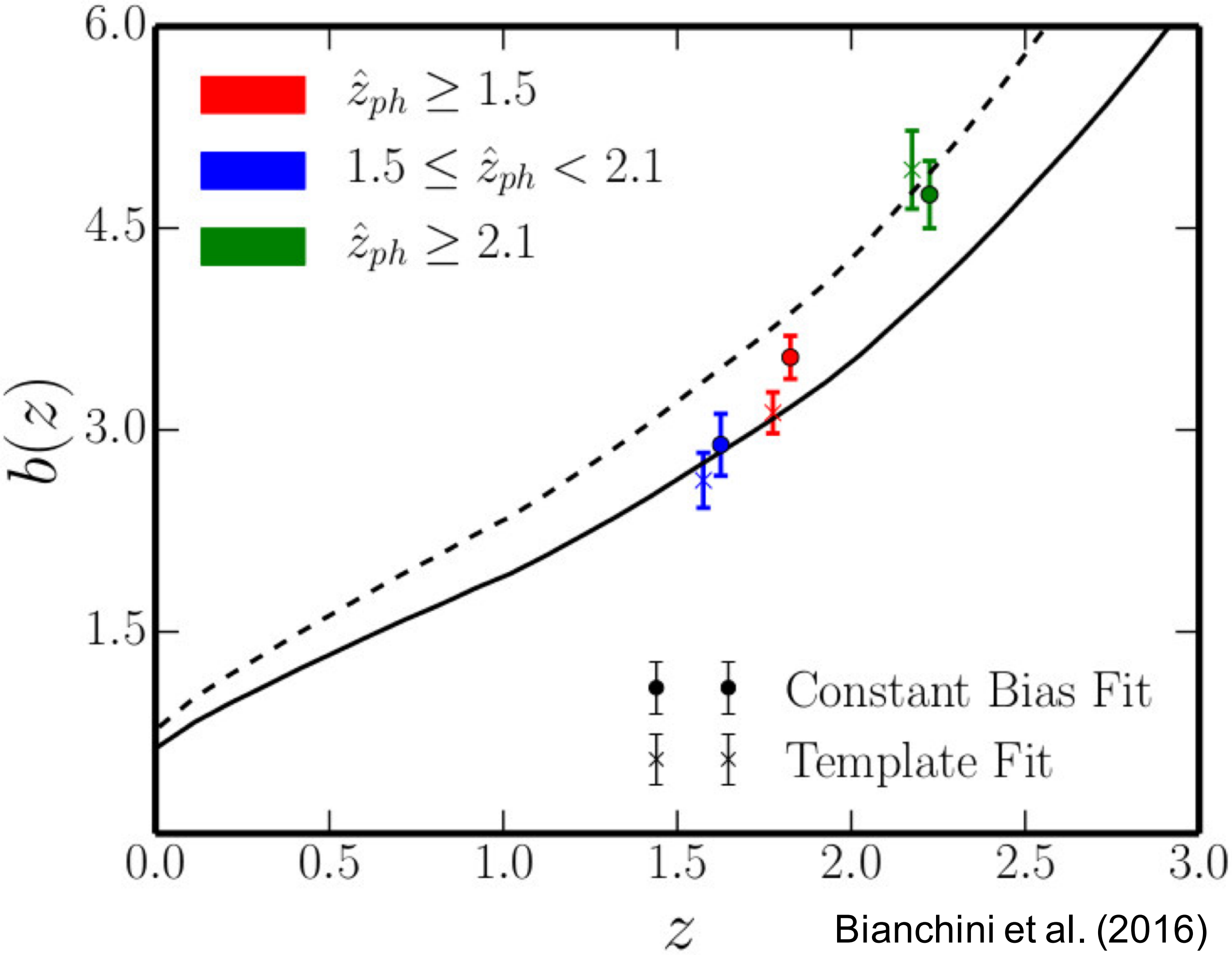
The only object widely observed at many frequencies, including optical spectroscopy, has revealed that it is made of

two structures at $z \simeq 1.7$ and at $z \simeq 2.0$.

(Flores-Cacho et al. 2016)

Both structures occupy a circular region of comoving radius smaller than 1 Mpc, consistent with being physically bound.

Cross-correlation CMB lensing / source catalogs



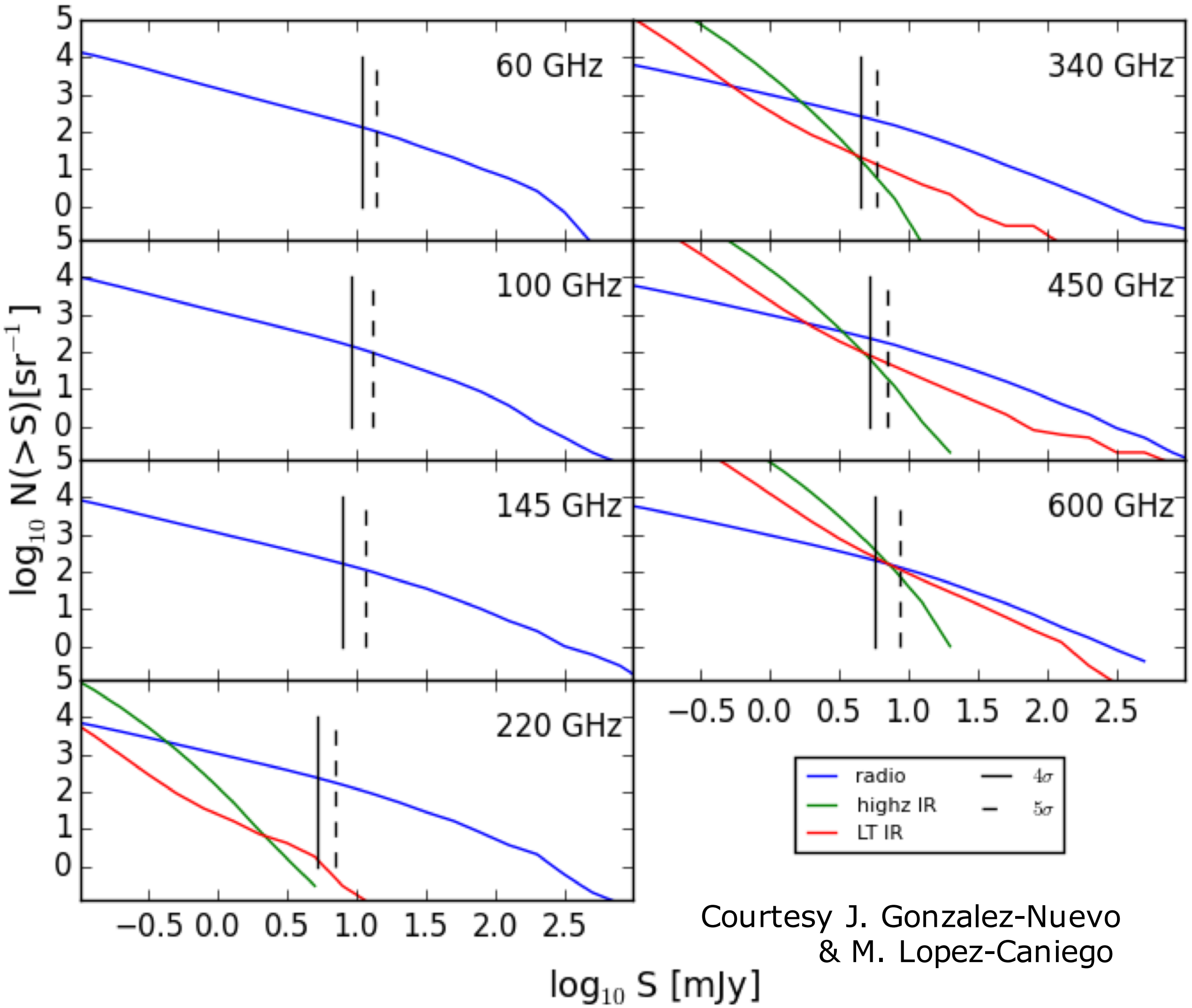
Bianchini et al. (2016)

Cross-correlation of accurate CMB lensing maps with samples of extragalactic sources in different z intervals

→ "tomography" of cosmic gravitational field and of its evolution

← Example: cross-correlation *Planck* lensing maps with *Herschel*/ATLAS source catalog over 1% f_{sky} provided interesting results

Predicted counts in polarization for a 1m telescope



Courtesy J. Gonzalez-Nuevo & M. Lopez-Caniego

Complete samples in polarization are currently limited to:

- ✓ **some tens of radio-sources (microwaves/mm)**
- ✓ **negligible number (sub-mm)**

COrE-M5 high sensitivity in polarization open a new window

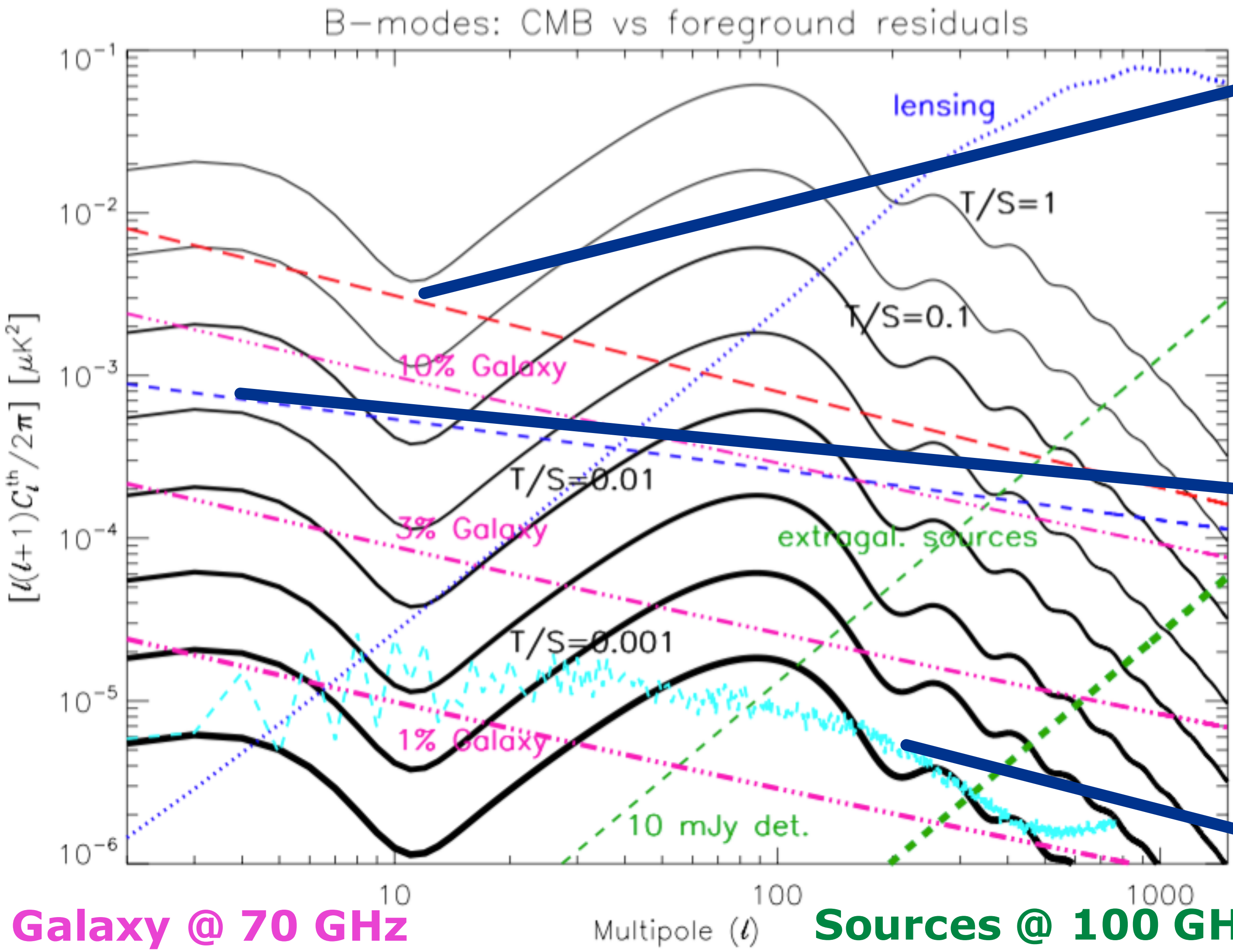
Simulations for COrE-M5 suggest:

- ❖ **detection of: thousands of sources in its whole frequency range**
- ❖ **for the first time: hundreds of galaxies with intense star formation with polarized signal by dust grains**

→ Unique information on:

- ➢ **their magnetic fields**
- ➢ **unknown origin of tight correlation between IR and radio luminosities of these objects**

Impact of residuals & subdominant components / features complexity in dominant components



Residual from dust starting from 353 GHz for an error in beta_dust of 0.01

Residual from synch starting from 30 GHz for an error in slope of 0.02

Estimate of AME, assuming pol. degree of 2%

Galaxy @ 70 GHz

Sources @ 100 GHz

Conclusion

- **Astrophysical foregrounds: *limitation* & *opportunity***
- **We need to map & understand them with high accuracy in order to properly extract CMB maps: this is even more crucial in polarization and for B-modes for low *r* values**
- **Microwave sky complexity calls for many frequency channels (15 or more), related to the global number of foreground parameters**
- **Legacy science of a future CMB mission potentially immense:**
  - **all-sky → essential for Galactic studies, extragalactic samples, high-z studies, rare phenomena**
  - **polarization: even *Planck* is only at the beginning**
    - **2 Galactic components, about 10^2 sources**
  - **products: mapping all Solar System & Galactic components, identify fine features, producing sample of thousands of galaxies**
  - **cross-product: "absolute" calibration → legacy data for calibrating ground observations**