The Planck-ATCA Co-eval Observations (PACO) project

Marcella Massardi (INAF-IRA)

in collaboration with **A. Bonaldi (JBCA, Manchester),**
L. Bonavera, M. Lopez-Caniego (Instituto de Fisica de Cantabria),
G. De Zotti (INAF-OAPD), R. Ekers (ATNF), V. Galluzzi (INAF-IRA, UniBO)

The simultaneous observations

The **knowledge of the extragalactic radio sources at submm frequencies (> 10 GHz) improved thanks to the wide area (full Southern sky) deep (~10mJy) AT20G survey and CMB satellite catalogues as WMAP & Planck**

Extragalactic radio sources constitute the major contaminant to CMB signal on scales smaller than 30 arcsec. **Extrapolation from low frequency is not reliable because of the many possible spectral behaviour** for extragalactic radio sources and their time **variability.**

Co-eval observations with Planck were collected in order to

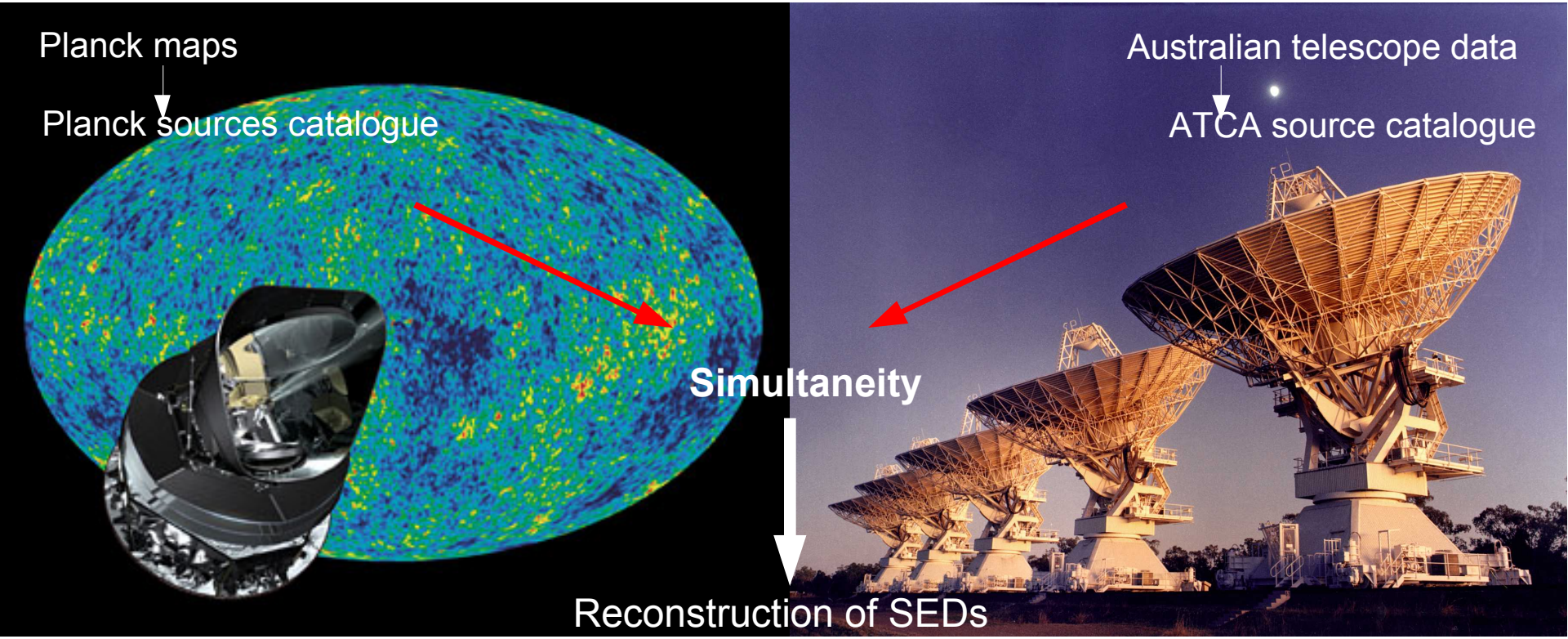
- **estimate the contribution** of sources to the CMB observations.
- **improve the knowledge** of the SEDs
- **assess quality** of detection techniques

With several ground based facilities:

- VLA (PI: Partridge; 5-43 GHz; 34 bright objects; typically simultaneously with Planck)
- APEX (PI: Tornikoski; LABOCA; 64 blazars, 2 epochs)
- Metsahovi (PI: Lahteenmaki; 37 GHz; 104 blazars, several epochs)
- Effelsberg, Ratan…
- Medicina Radiotelescope (PI: Massardi; 5, 8, 22 GHz; 264 objects: all the NEWPS catalogue in the North + few South for cross-calibrations)
- **ATCA (PI: Massardi; 4.5-40 GHz; 480 objects in the AT20G)**

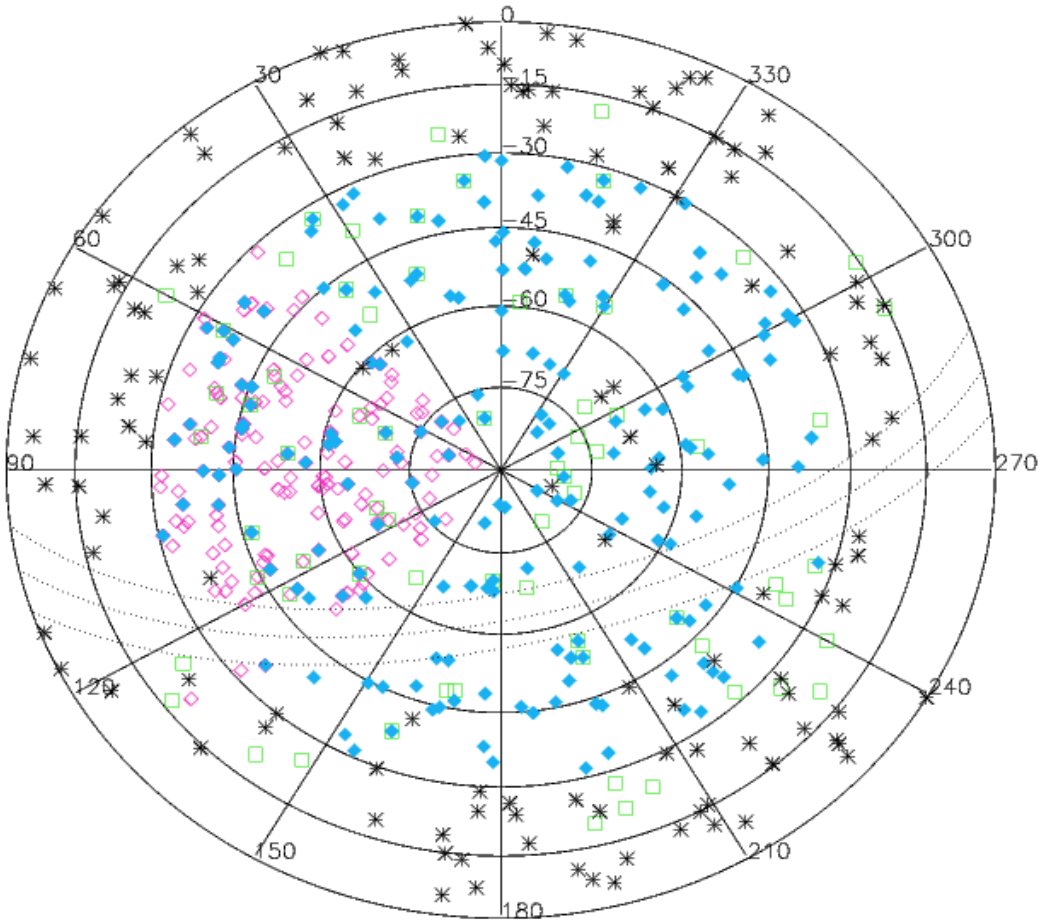
The Planck ATCA Co-eval Observations (PACO)

Nearly simultaneous (within a week from Planck observations) with ATCA multi-frequency observations (from 4.5 to 40 GHz) in total intensity and polarisation.



PACO observations and samples

- Observations **07 July 2009 – 23 August 2010**
- **Time allocated: >450h**
- **66 epochs**
- On average **35 sources per epoch @ 3 freqs**
- **Data lost: <15%**



-Bright sample:
189 S_{20GHz}>500mJy
dec<-30°
(MM et al. 2011)

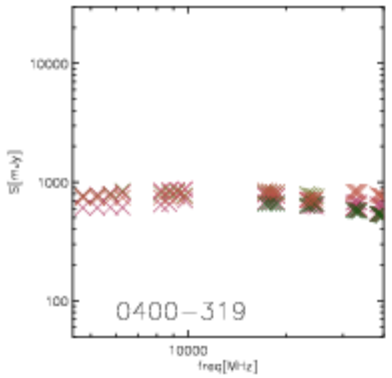
-Faint sample:
162 S_{20GHz}>200mJy
dec<-30°
(Bonavera et al. 2012)

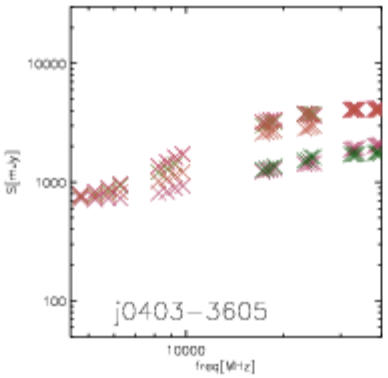
-Inverted sample:
69 S_{20GHz}>200mJy
(Bonaldi et al. 2013)

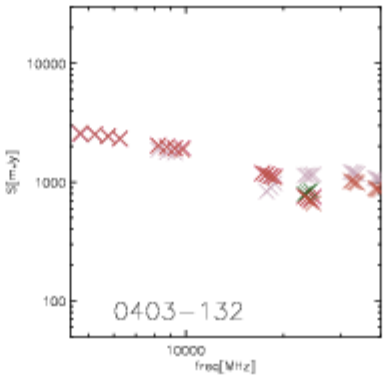
-ATCA calibrators:
197 (incomplete)

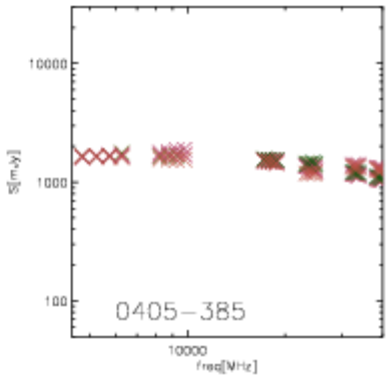
Whole sample to appear in MM et al. (in preparation)
with analysis of spectra
for 445 point sources including
Planck data

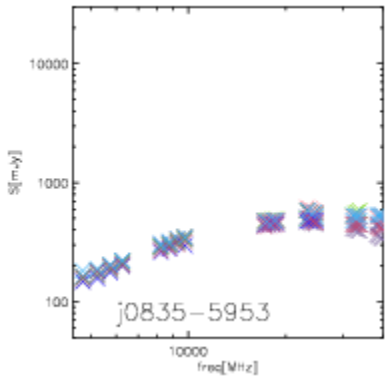
Multi-epoch PACO Spectra

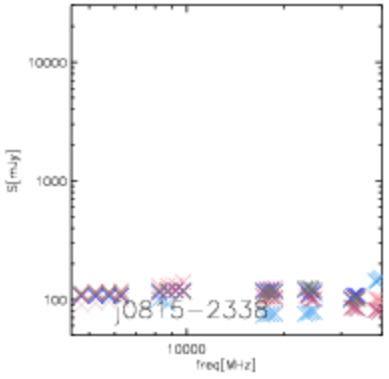


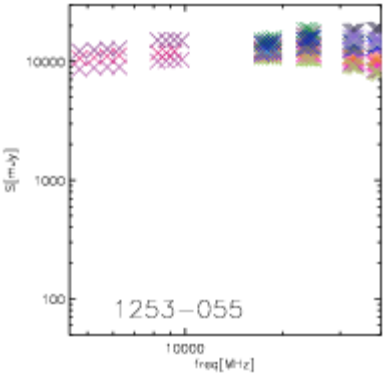


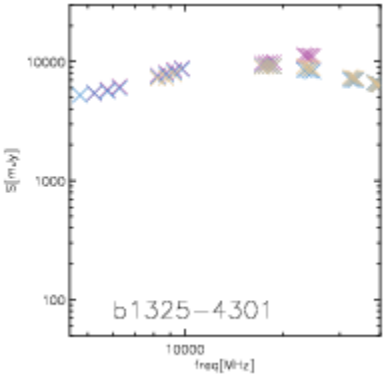


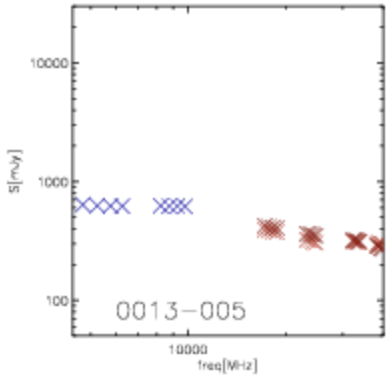


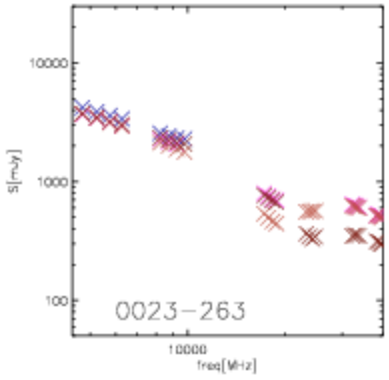


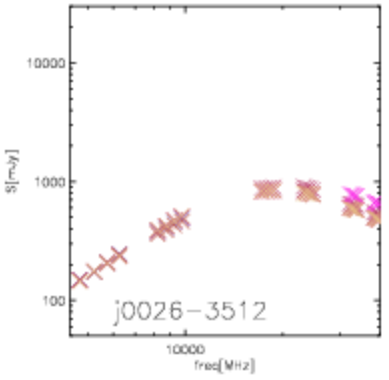


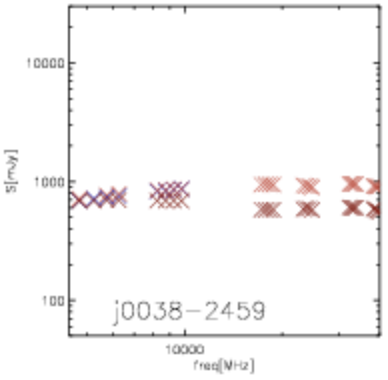












PACO results

Type	$200 \leq S_{20\,\mathrm{GHz}} < 500$ mJy (per cent)	$S_{20\,\mathrm{GHz}} \geq 500$ mJy (per cent)
Flat	5.1	10.3
Steep	13.3	3.6
Inverted	0	0.6
Peaked	11.2	14.5
Downturning	65.3	66
Self-absorbed	5.1	4.8
Upturning	0	0

Down-turning spectra dominate the population in the frequency range 5-40 GHz,
with an increasing fraction of steep spectra as the flux decreases.

No source shows upturning or inverted spectra

Variability trend seems to increase with frequency and time lag but not with flux density

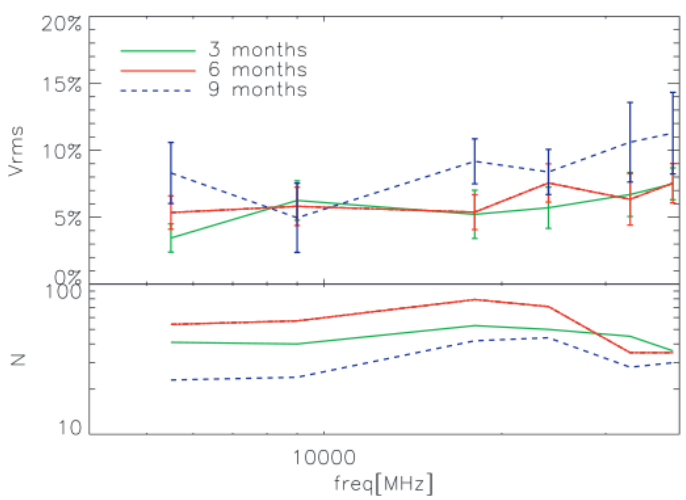


Figure 11. Top: median variability index of the sample as a function of frequency; error bars are $1.25\sigma/\sqrt{N-1}$. Bottom: number of sources.

Table 1. Variability index as a function of time lag and frequency for the PACO brigh sample (BS), faint sample (FS) and spectrally-selected sample (SS). The time lag of 2–4yr refers to the comparison between PACO and AT20G.

Sample	Time lag	5	9	18	24	33	39
FS	90 days	5.8	7.2	7.4	7.9	8.6	8.9
FS	180 days	6.9	9.6	9.9	9.4	11.4	8.0
FS	270 days	6.0	9.2	8.2	8.5	15.8	19.5
FS	360 days	9.3	20.9	5.2	8.2	11.3	13.0
FS	2–4yr	24.9	25.0	27.2			
BS	90 days	4.9	6.6	7.3	6.8	9.2	9.3
BS	180 days	5.8	7.2	8.3	8.0	6.7	7.3
BS	270 days	7.2	7.0	8.2	8.5	14.0	17.4
BS	360 days	6.6	12.3	9.0	9.6	10.2	11.2
BS	2–4yr	18.1	19.4	19.9			
SS	90 days	6.2	7.0	6.9	9.7	7.1	7.6
SS	180 days	7.7	7.4	9.1	10.7	8.8	10.8
SS	270 days	7.0	7.4	11.4	13.0	11.0	15.1
SS	360 days	6.7	8.7	10.8	12.1	15.1	15.7
SS	2–4yr	15.4	17.3	23.2			

Bonavera et al. (2012), MM et al. (2010 et in prep)

Source variability

To analyze the spectrally selected sample we used the variability between AT20G (2004–2007) and PACO (2009–2010) epochs

- candidate **High-Frequency Peakers (spectral peaks > 10 GHz in the observer frame) are < 0.5 per cent** of the S20GHz >200 mJy sources, consistent with the short duration of this phase implied by the 'youth' scenario

-≃ **89 per cent blazar candidates have smooth spectra,** well described by a double power law, suggesting that **the emission in the PACO frequency range is dominated by a single emitting region.**

- Sources with **peaked PACO spectra show a decrease of the peak frequency with time at a mean rate of ∼ 3 ± 2 GHz yr−1 on an average time-scale of τ = 2.1 ± 0.5 yr.**

- **At frequencies >20GHz spectral indices steepen**: the median spectral index between 30 and 40 GHz is steeper than the one between 5 and 20 GHz **by δα = 0.6.**

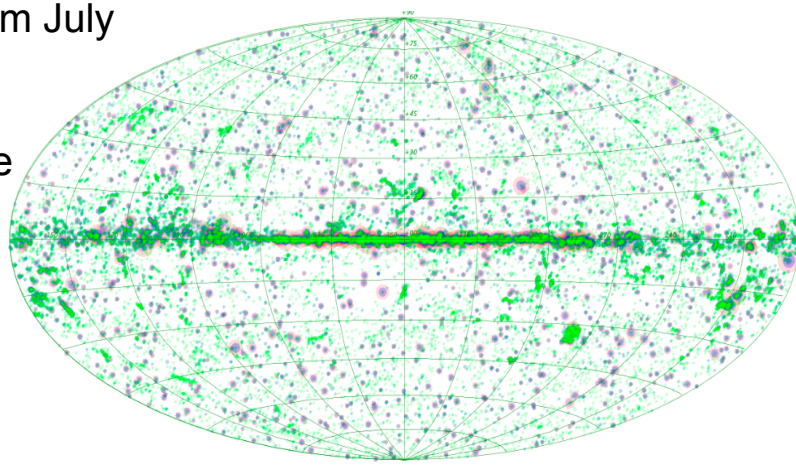
Table 1. Median variability indices (per cent) of the SS sources and associated errors ($1.25\sigma/\sqrt{N-1}$, where N and σ are the number of the variability indices and the standard deviation of their distribution, respectively).

Frequency (GHz)	PACO–AT20G (2–4 yr)	PACO–PACO (6 months)
5	13.1 ± 1.9	5.5 ± 1.5
9	15.0 ± 2.2	4.9 ± 1.7
18	20.3 ± 2.5	5.7 ± 1.7
24		8.2 ± 2.0
33		4.8 ± 3.0
39		5.3 ± 3.2

Bonaldi et al. (2013)

Combination with the Planck Catalogue of Compact Sources

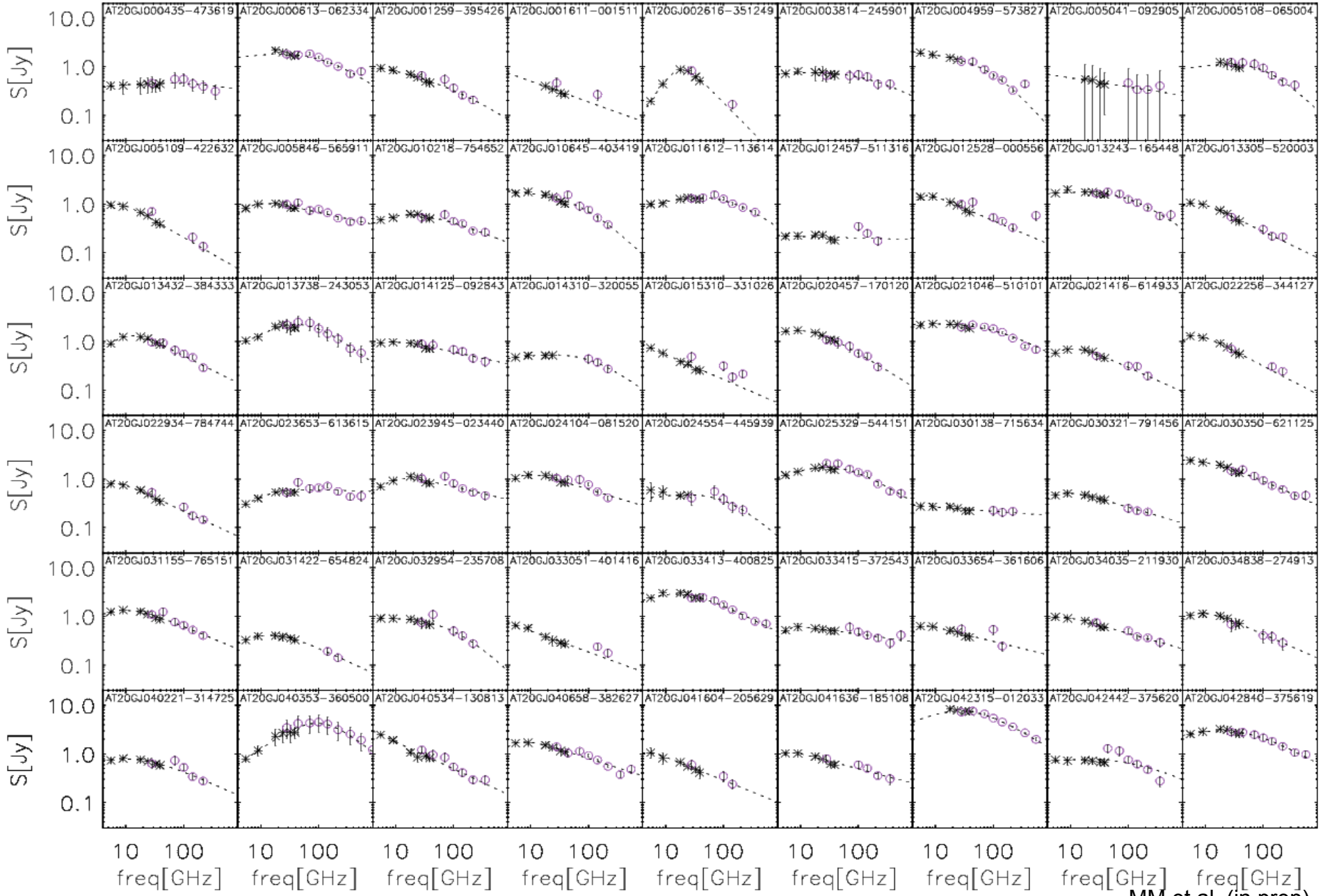
The PCCS flux densities are the result of **repeated observations of the same source within the Planck nominal mission** (from July 2009 to November 2010).
The number of observations per source is a function of the source position, with a peak close to the Ecliptic pole, where sources are observed continuously for about three months for each survey, and a minimum at the equator, where observations last for few days every 6 months



PACO has been used for quality assessment of various extraction and photometric methods.

	Channel								
	30	44	70	100	143	217	353	545	857
Frequency [GHz]	28.4	44.1	70.4	100.0	143.0	217.0	353.0	545.0	857.0
Wavelength, λ [μm]	10 561	6807	4260	3000	2098	1382	850	550	350
Beam *FWHM*[a] [arcmin]	32.38	27.10	13.30	9.65	7.25	4.99	4.82	4.68	4.33
Pixel size [arcmin]	3.44	3.44	3.44	1.72	1.72	1.72	1.72	1.72	1.72
S/N thresholds:									
Full sky	4.0	4.0	4.0	4.6	4.7	4.8	...	...	...
Extragalactic zone[b]	...	...	...	...	...	...	4.9	4.7	4.9
Galactic zone[b]	...	...	...	...	...	...	6.0	7.0	7.0
Number of sources:									
Full sky	1256	731	939	3850	5675	16 070	13 613	16 933	24 381
$\|b\| > 30°$	572	258	332	845	1051	1901	1862	3738	7536
$N(>S)$[c]:									
Full sky	934	535	689	3425	5229	15 107	13 184	15 781	23 561
$\|b\| > 30°$	373	151	191	629	857	1409	1491	2769	6773
$\|b\| \leq 30°$	561	384	498	2796	4422	13 698	11 693	13 012	16 788
Flux densities:									
Minimum[d] [mJy]	461	825	566	266	169	149	289	457	658
90% completeness [mJy]	575	1047	776	300	190	180	330	570	680
Uncertainty [mJy]	109	198	149	61	38	35	69	118	166
Position uncertainty[e] [arcmin]	1.8	2.1	1.4	1.0	0.7	0.7	0.8	0.5	0.4

5-857GHz spectral behaviour



MM et al. (in prep)

Source populations results (on going)

-Spectra fitted with double power laws up to 217 GHz
(with the only exception of 5% of objects)

$$S(\nu) = S_0/[(\nu/\nu_0)^{-a} + (\nu/\nu_0)^{-b}]$$

- Spectra are smooth in the full range:
→ emission comes from a unique component in most of the cases

- The vast majority are steep above 30GHz → optically thin synchrotron
→ at mm wavelength spectral properties does not identify compact and extended?

- There is no evidence of steepening at higher frequencies
(break due to electron ageing) → sources are young?
→ Planck bias?
→ Needs to know the magnetic field properties

- No raising of dust emission signals associated to sources at high frequencies
→ compensating the electron ageing?

→ Needs of mm wavelength high resolution and sensitivity follow-up (ALMA)

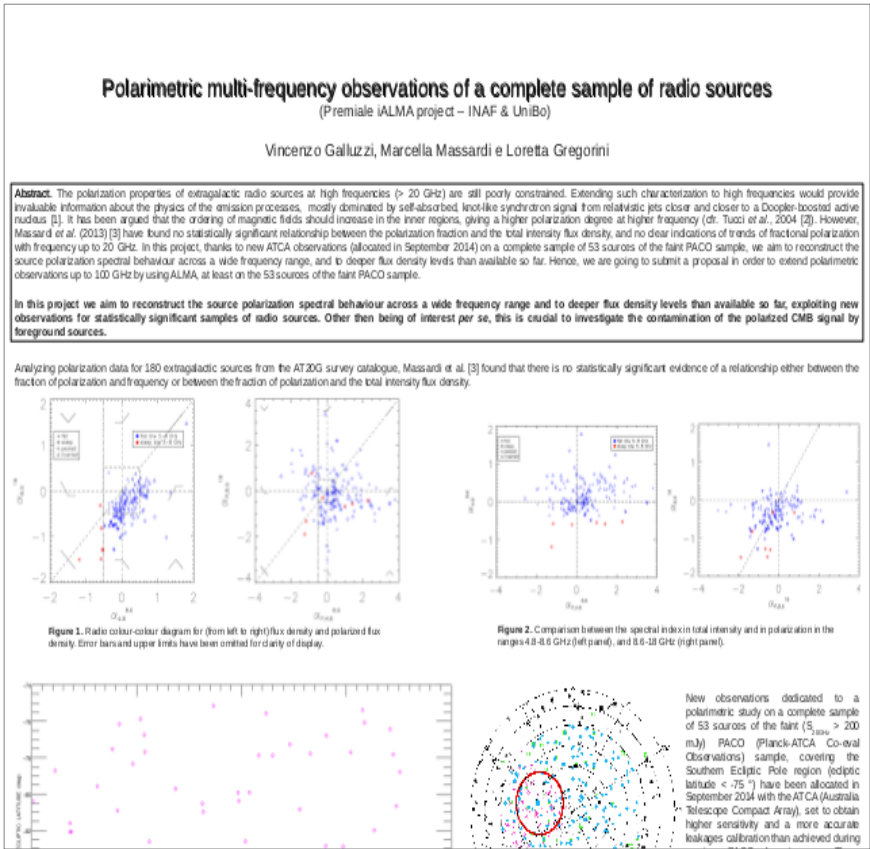
MM et al. (in prep)

PACO source polarisation (& ALMA)

53 faint sample point sources with b<-75° were observed in polarisation in September 2014 with ATCA at PACO frequencies.
Data reduction is on-going with Miriad and CASA.

The project is part of the activities to investigate radio sources polarisation properties down to mm wavelength and exploit them for ALMA commissioning capabilities in the framework of the iALMA project.

See the poster Vincenzo Galluzzi's poster.



Polarimetric multi-frequency observations of a complete sample of radio sources

(Premiale iALMA project – INAF & UniBo)

Vincenzo Galluzzi, Marcella Massardi e Loretta Gregorini

Abstract. The polarization properties of extragalactic radio sources at high frequencies (> 20 GHz) are still poorly constrained. Extending such characterization to high frequencies would provide invaluable information about the physics of the emission processes, mostly dominated by self-absorbed, knot-like synchrotron signal from relativistic jets closer and closer to a Doppler-boosted active nucleus [1]. It has been argued that the ordering of magnetic fields should increase in the inner regions, giving a higher polarization degree at higher frequency (cfr. Tucci *et al.*, 2004 [2]). However, Massardi *et al.* (2013) [3] have found no statistically significant relationship between the polarization fraction and the total intensity flux density, and no clear indications of trends of fractional polarization with frequency up to 20 GHz. In this project, thanks to new ATCA observations (allocated in September 2014) on a complete sample of 53 sources of the faint PACO sample, we aim to reconstruct the source polarization spectral behaviour across a wide frequency range, and to deeper flux density levels than available so far. Hence, we are going to submit a proposal in order to extend polarimetric observations up to 100 GHz by using ALMA, at least on the 53 sources of the faint PACO sample.

In this project we aim to reconstruct the source polarization spectral behaviour across a wide frequency range and to deeper flux density levels than available so far, exploiting new observations for statistically significant samples of radio sources. Other then being of interest *per se*, this is crucial to investigate the contamination of the polarized CMB signal by foreground sources.

Analyzing polarization data for 180 extragalactic sources from the AT20G survey catalogue, Massardi et al. [3] found that there is no statistically significant evidence of a relationship either between the fraction of polarization and frequency or between the fraction of polarization and the total intensity flux density.

Figure 1. Radio colour-colour diagram for (from left to right) flux density and polarized flux density. Error bars and upper limits have been omitted for clarity of display.

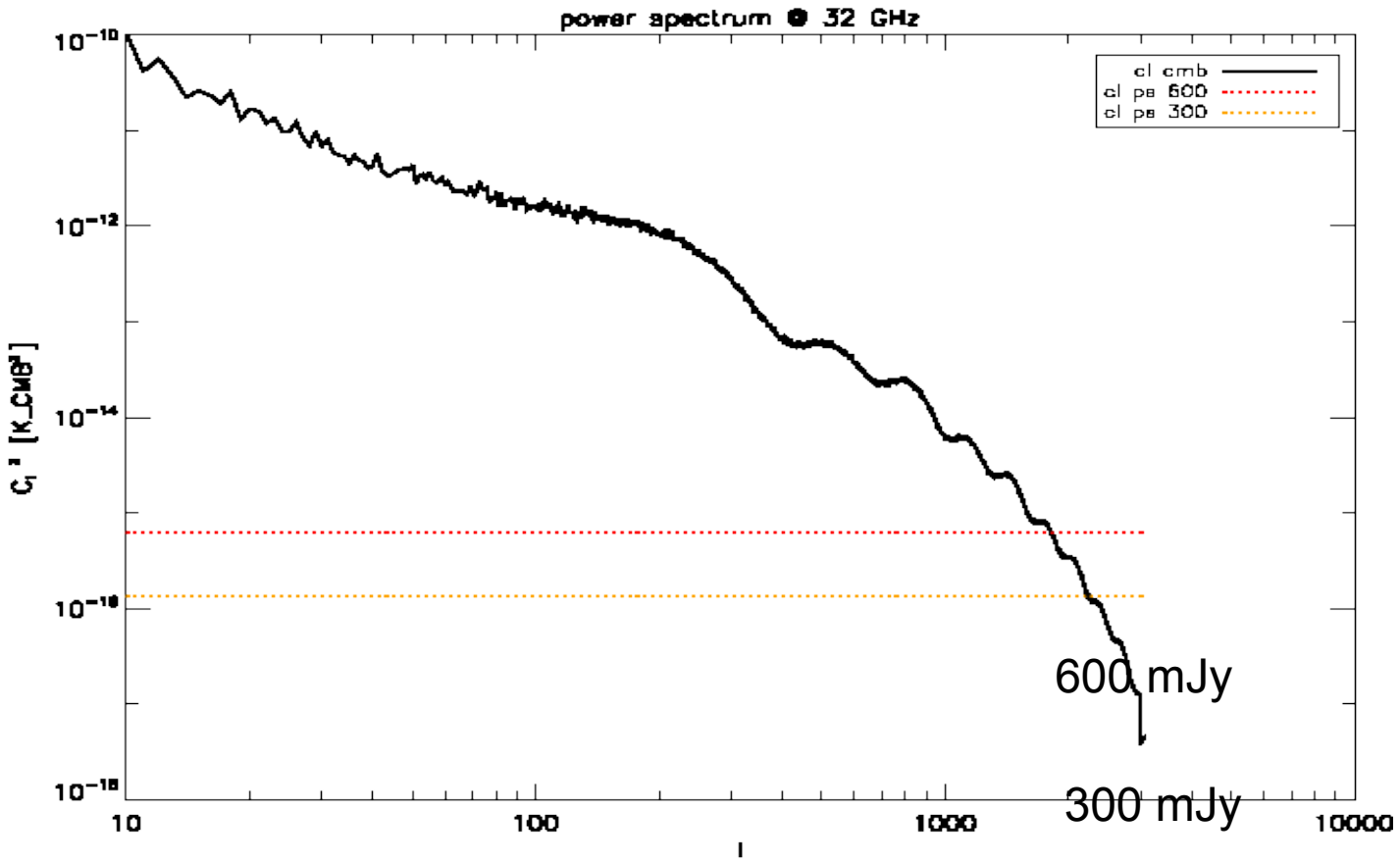
Figure 2. Comparison between the spectral index in total intensity and in polarization in the ranges 4.8–8.6 GHz (left panel), and 8.6–18 GHz (right panel).

New observations dedicated to a polarimetric study on a complete sample of 53 sources of the faint ($S_{20\,GHz}$ > 200 mJy) PACO (Planck-ATCA Co-eval Observations) sample, covering the Southern Ecliptic Pole region (ecliptic latitude < -75 °) have been allocated in September 2014 with the AT CA (Australia Telescope Compact Array), set to obtain higher sensitivity and a more accurate leakages calibration than achieved during

Selections of AT20G and PACO sources have been included in ALMA calibrator lists.

Knowledge of source calibration properties in the mm bands is crucial to optimize the calibration procedures and assess the instrumental capabilities. For CMB mission It is needed for proper source removal ad power spectra reconstruction in B and E modes.

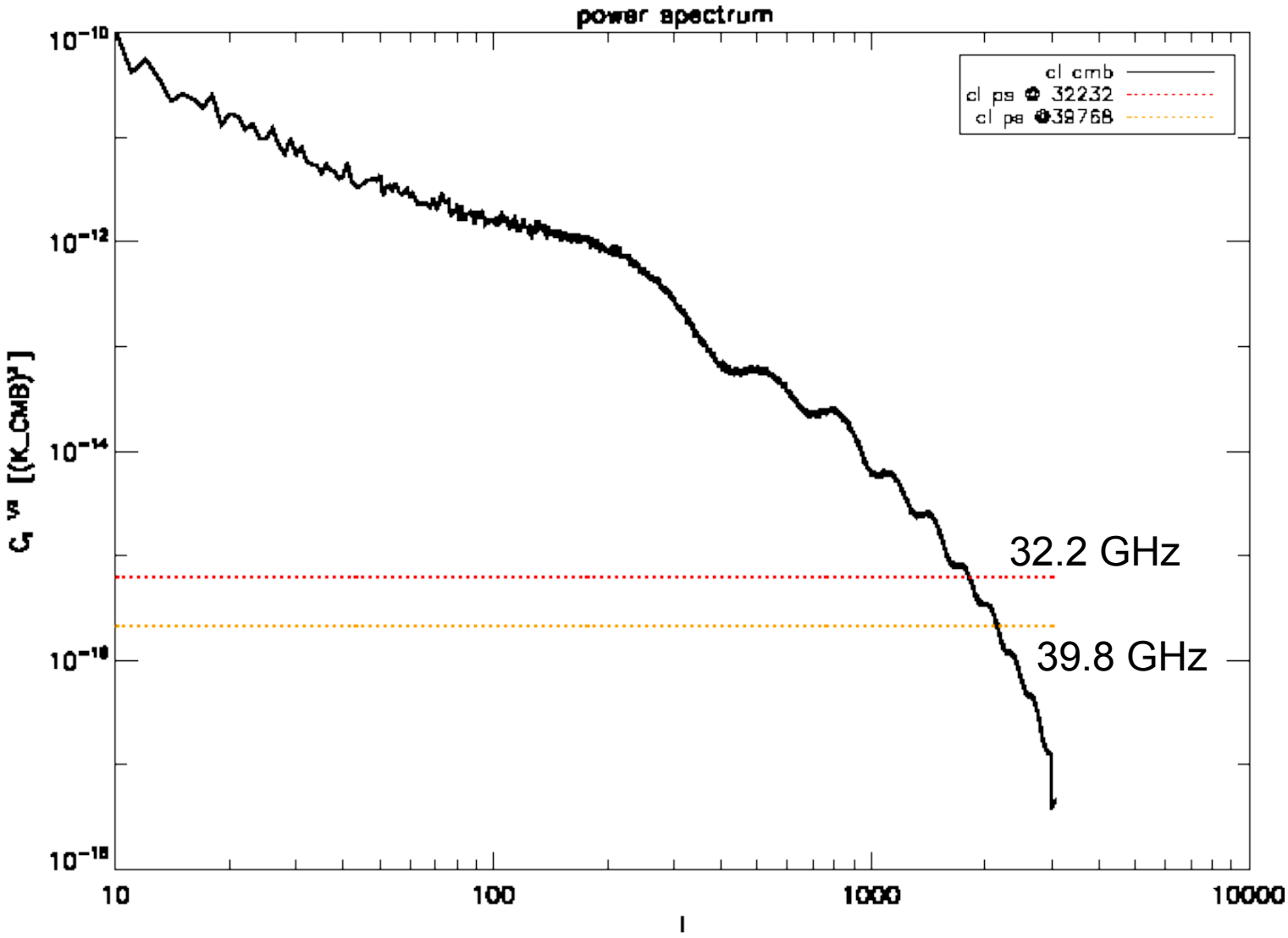
Contribution of sources at varying flux limit



The faint sample has been successfully used to confirm the quality assessment for the Planck Catalogues (Planck collaboration 2011, 2013)
and to **estimate the radio source contribution to CMB power spectra down to ~ 200 mJy at 30 and 44 GHz.**

Bonavera et al. (2012)

Contribution of sources at varying frequency



Flux limit 600 mJy

Bonavera et al. 2012)

Conclusions

The PACO project exploited the simultaneity with Planck to minimize source variability and investigate radio source polarization in the mm-wavelength range

PACO data between 5-40GHz showed that **down-turning spectra dominate the population in the frequency range 5-40 GHz, with an increasing fraction of steep spectra as the flux decreases. No source shows upturning or inverted spectra.**

The same was confirmed up to 217 GHz.
Spectra look smooth, down-turning or steep with no further steepening or raising due to dust emission.

Emission come from unique component, source look young and dominated by the AGN component up to high frequencies

Faint sample have been followed up in polarization

→ Needs of mm wavelength high resolution and sensitivity follow-up (with ALMA) to disentangle the effects of Planck biases and confirm the findings and characterize polarization properties.