EUROPEAN ARC
ALMA Regional Centre || Italian

Ground based observations of Extragalactic Radiosources for CMB polarimetric experiments

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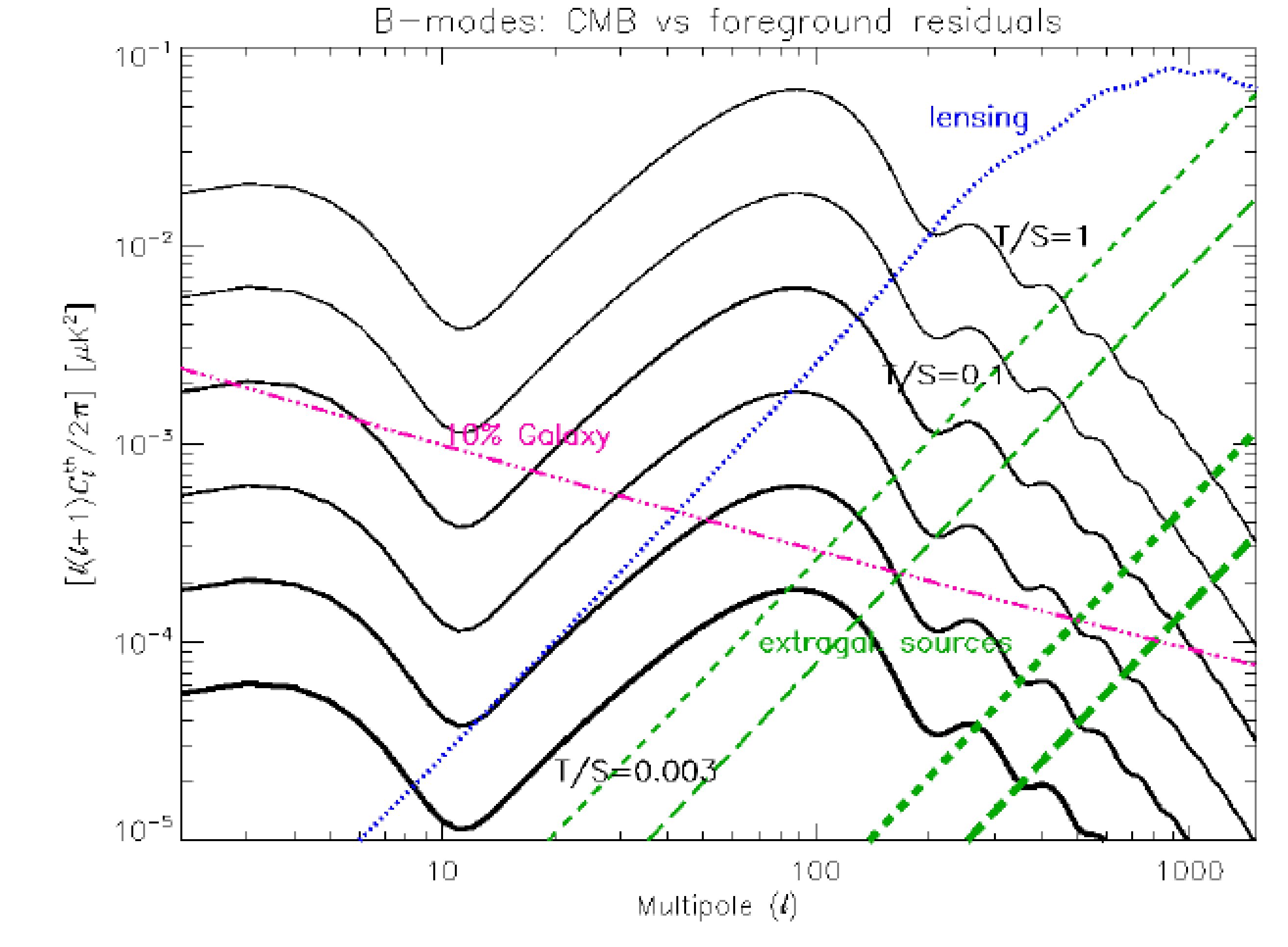
(with contributes by
V. Galluzzi and E. Liuzzo)

La Laguna – CMB foregrounds - 15-19 october 2018

Extragalactic radio sources for cosmology: 1) FOREGROUNDS

Extragalactic radio sources are one of the dominant contaminant to the microwave sky in total intensity and in polarization at scales smaller than 30 arcmin up to 100 GHz.



B-mode signal from polarized radio sources at 100 GHz (thin green lines) assuming the detection thresholds of 200 mJy (dashes) and 60 mJy (long dashes) in total intensity.

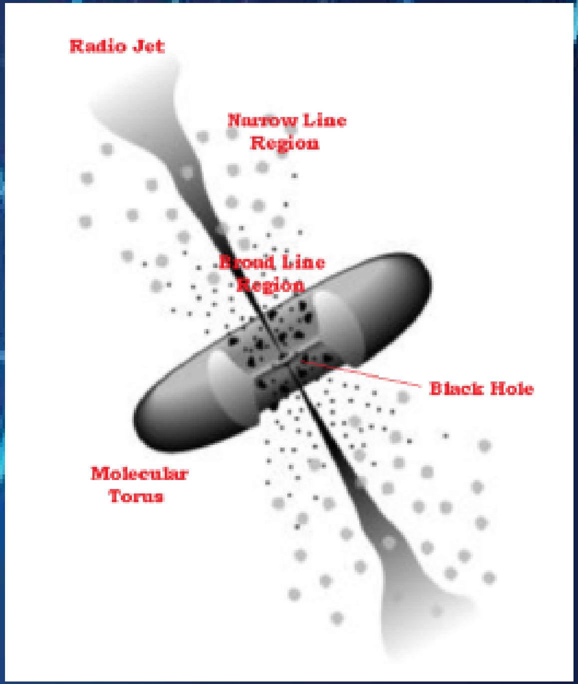
Thick lines show the radio source contribution due to the uncertainty in the statistical knowledge of their polarization degree assuming a substantial improvement, i.e. an error reduced down to 1%, achievable with recent radio observations.

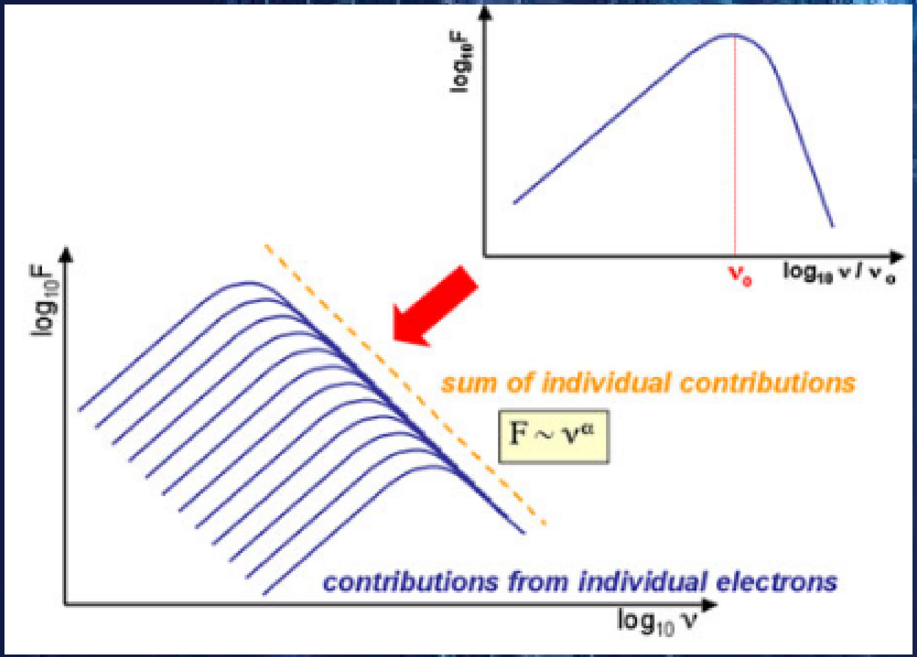
(Massardi et al. 2017, Remazeilles et al. 2017)

Extragalactic radio sources for cosmology: 2) CALIBRATORS

Cosmology experiment so far shallow resolution (~arcmin) and sensitivity (~few hundreds of mJy) allow for detection only of the brightest or most polarized sources.

While faintest objects constitute the major contaminant to CMB power spectrum, brightest object characterization is needed for validation of the detections and of the fotometry



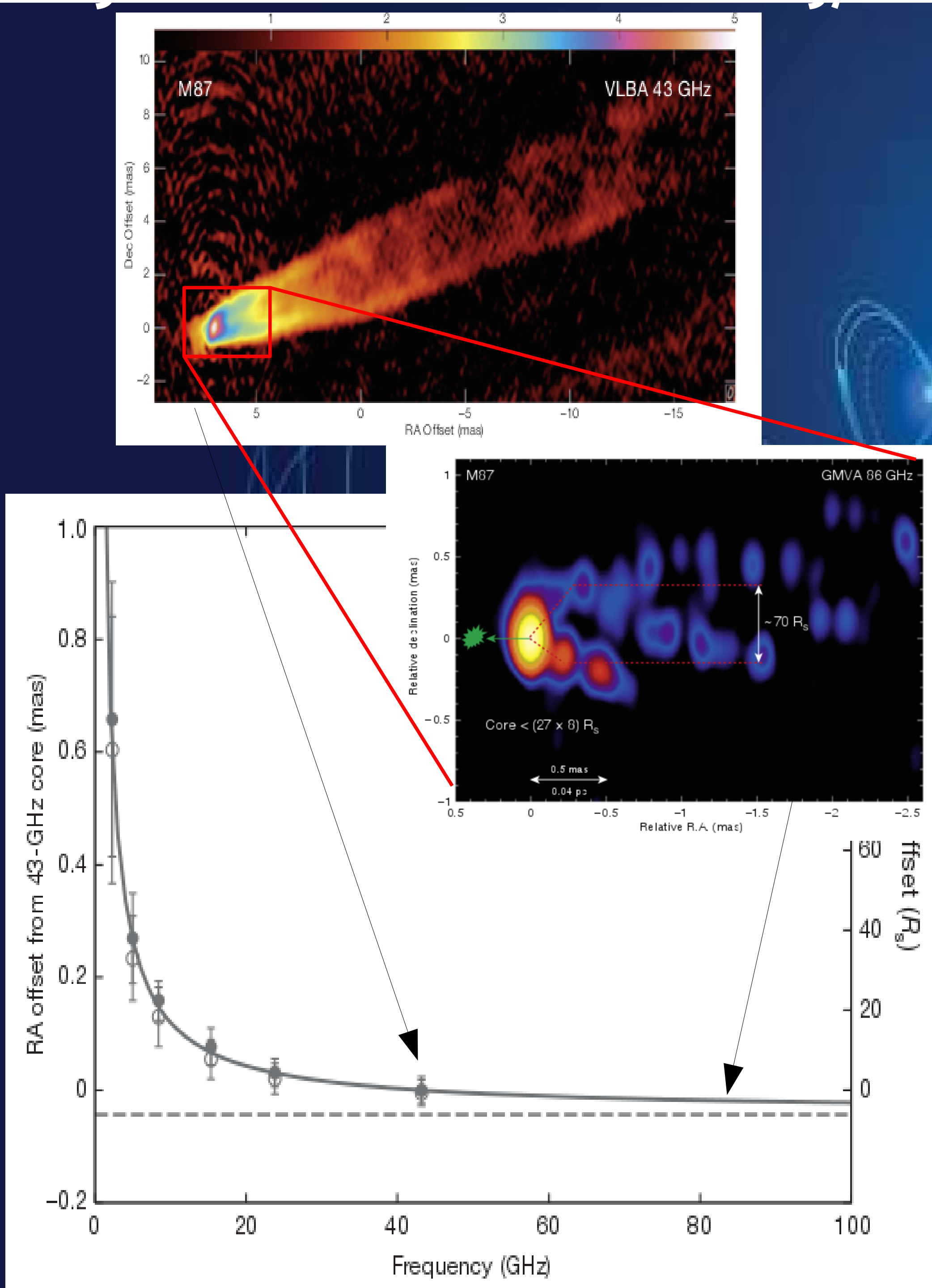


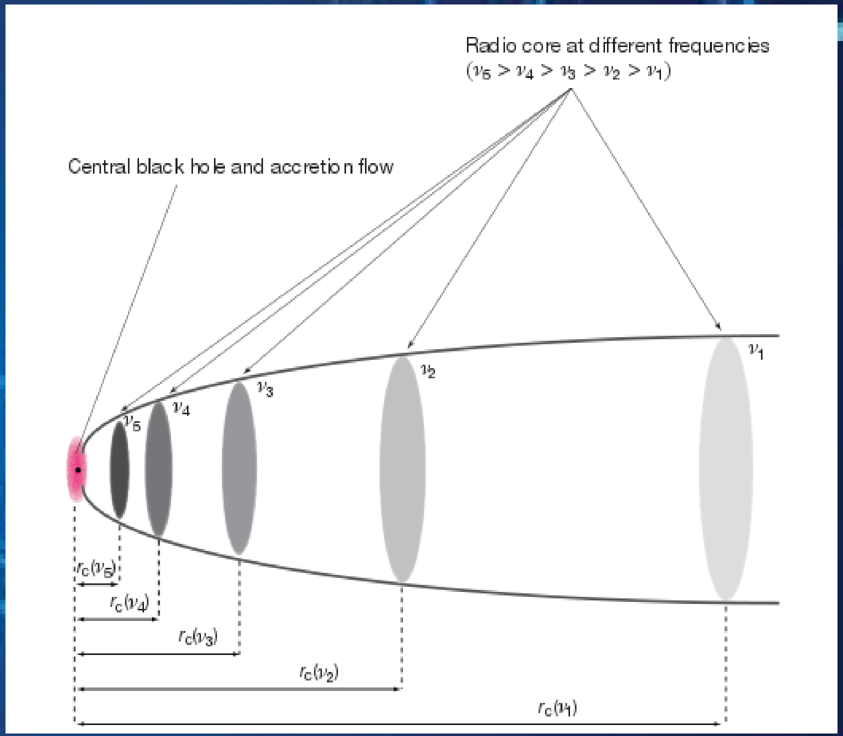
The high-frequency, bright flux density population is dominated by compact, Doppler-boosted sources, whose emission at higher and higher frequency mostly arises from self-absorbed, knot-like synchrotron structures in the relativistic jet closer and closer to the active nucleus

Synchrotron is intrinsically highly polarized but radio source polarization fraction is rarely >3%

Spectral emission and polarimetric properties are the result of superposition of multiple components

Extragalactic radio sources for cosmology: 2) CALIBRATORS





As more energetic photons are also less absorbed (i..e. electron clouds are less thick) the inner and denser regions of the AGN become less optically thick and become more easily observable as the frequency of observation increases.

Hence, mm observations of AGN provide information on the jet structure and unveil the details of their basis getting closer to the black hole as the frequency increases.

But jet structure can be highly variable…

Observing radio source polarization: only for braves!!!

Observations of polarimetric properties of radio sources were (are?) a challenge because of a mixture of issues

IN THE SOURCE:

- Faint (Faraday depolarization, substructures and turbulence)
- Variable (new emitted components and flares)

INSTRUMENTAL:

- Calibration must be more accurate: solving for all the Stokes and calibrating leakages requires more information than total intensity (i.e. time consuming)
- Proper calibration requires knowledge of calibrators, but proper calibration sources (bright and not variable) are rare
- Instrumental beam and bandwidth reduces the polarization by smearing the polarized flux density of non resolved sources and mixes components for resolved Sources (Beam and bandwidth Depolarization)
- Interferometric observations filter only the scales of the observing baselines reducing the collected flux densities for resolved source

(Galluzzi et al. 2017)

Planck gave a burst to radio source investigation, also in polarimetry!!!

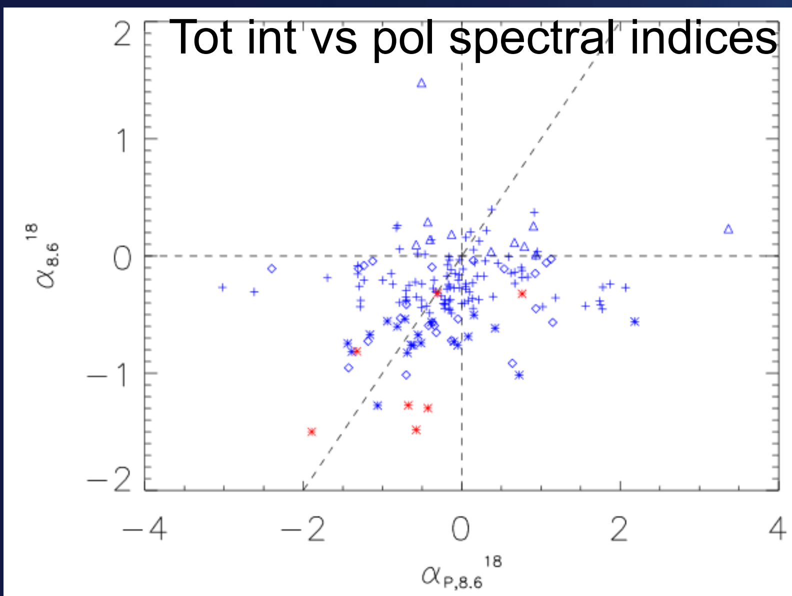
References	Frequency (GHz)	# sources	Notes
Eichendorf & Reinhardt (1979)[17]	[0.4, 15]	510	compilation of multi–frequency data
Tabara & Inoue (1980)[18]	[0.4, 10.7]	1510	compilation of multi–frequency data
Simard-Normandin *et al.* (1981)[19,20]	[1.6, 10.5]	555	compilation of multi–frequency data
Perley (1982)[21]	1.5, 4.9	404	compilation of multi–frequency data
Rudnick *et al.* (1985)[22]	[1.4, 90]	20	compilation of multi–frequency data
Aller *et al.* (1992)[23]	4.8, 8.0, 14.5	62	90% complete sample with $S_{5\,GHz} > 1.3$ Jy
Okudaira *et al.* (1993)[24]	10	99	flat-spectrum sources with $S_{5\,GHz} > 0.8$ Jy
Nartallo *et al.* (1998)[25]	273	26	compilation of flat-spectrum radio sources
Condon *et al.* (1998) - NVSS[26]	1.4	$\sim 2 \times 10^6$	100% complete survey down to $S_{1.4\,GHz} > 2.5$ mJy
Aller *et al.* (1999)[27]	4.8, 8.0, 14.5	41	BLLac sources
Fanti *et al.* (2001)[28]	4.9, 8.5	87	CSS sample with $S_{0.4\,GHz} > 0.8$ Jy
Lister (2001)[29]	43	32	90% complete sample with $S_{5\,GHz} > 1.3$ Jy
Klein et al (2003)[30]	1.4, 2.7, 4.8, 10.5	192	compilation of detections of the B3-VLA survey
Ricci *et al.* (2004)[31]	18.5	250	complete sample with $S_{5\,GHz} > 1$ Jy
Jackson *et al.* (2007)[32]	8.4	~ 16000	JVAS-CLASS surveys
Massardi *et al.* (2008) AT20G-BSS[11]	4.8, 8.6, 20	320	AT20G bright sample
Lopez-Caniego *et al.* (2009)[33]	23, 33, 41	22	polarization detections in WMAP maps
Jackson *et al.* (2010)[34]	8.4, 22, 43	230	WMAP sources follow-up
Murphy *et al.* (2010) AT20G[9]	4.8, 8.6, 20	5890	93% complete survey with $S_{20\,GHz} > 40$ mJy
Trippe *et al.* (2010)[35]	[80, 267]	86	complete sample with $S_{90\,GHz} > 0.2$ Jy
Battye *et al.* (2011)[36]	8.4, 22, 43	230	WMAP sources follow-up
Sajina *et al.* (2011)[12]	4.8, 8.4, 22, 43	159	AT20G sources follow-up
Massardi *et al.* (2013)[37]	4.8, 8.6, 18	193	complete sample with $S_{20\,GHz} > 500$ mJy
Agudo *et al.* (2014)[38]	86, 229	211	complete sample of flat-spectrum sources with $S_{86\,GHz} > 1$ Jy
Farnes *et al.* (2014)[39]	[0.4, 100]	951	Compilation of multi–frequency data
Planck Collaboration (2015)[8]	30, 44, 70	122, 30, 34	polarization detections in Planck LFI maps (PCCS2)
	100, 143, 217, 353	20, 25, 11, 1	polarization detections in Planck HFI maps (PCCS2)

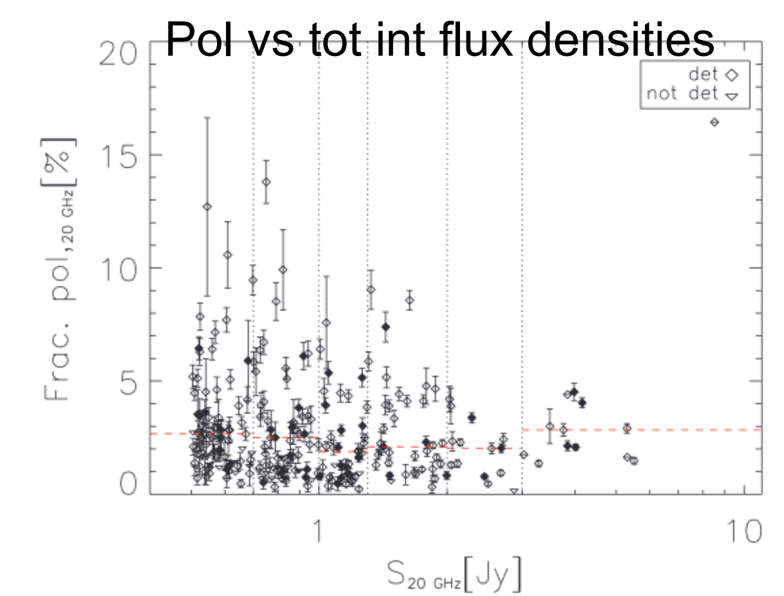
Compilations (no close observations at different frequencies, no completeness)
Spectral selection (no completeness)
High flux density treshold, i.e. ≈ 1 Jy (WMAP, PLANCK cat.)
Complete sample with high frequency obs.

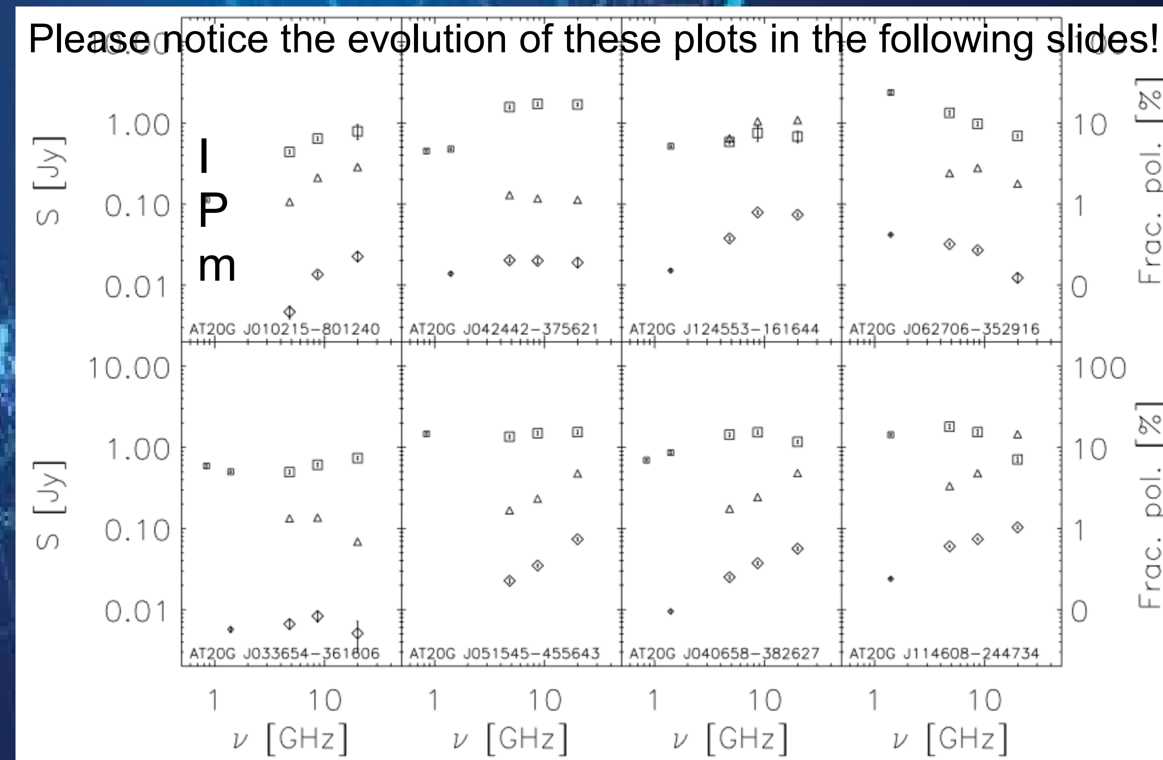
AT20G		PLANCK			ATCA		ALMA	
2004		2009	2010	2013		2016	2017	...

The Australia Telescope 20GHz (AT20G) survey

Observations in 2004-2008 with ATCA
All the Southern sky at 20 GHz with full-Stokes almost simultaneous follow-up at 5-8-20 GHz
A dedicated high sensitivity (σ=1mJy) polarimetric follow-up in 2006 at 20 GHz







- Polarimetric and total intensity behaviour are different
- No clear trend of polarization with S or ν
- PictorA and 0635-752 good polarization calibrators

(Massardi et al. 2008 and 2013)

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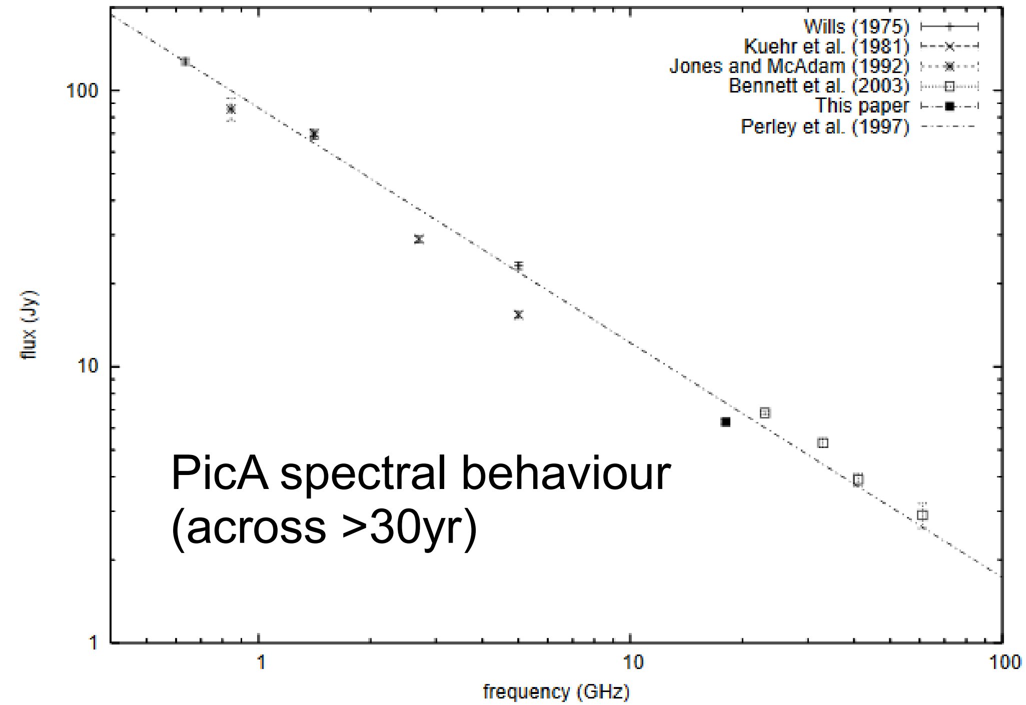

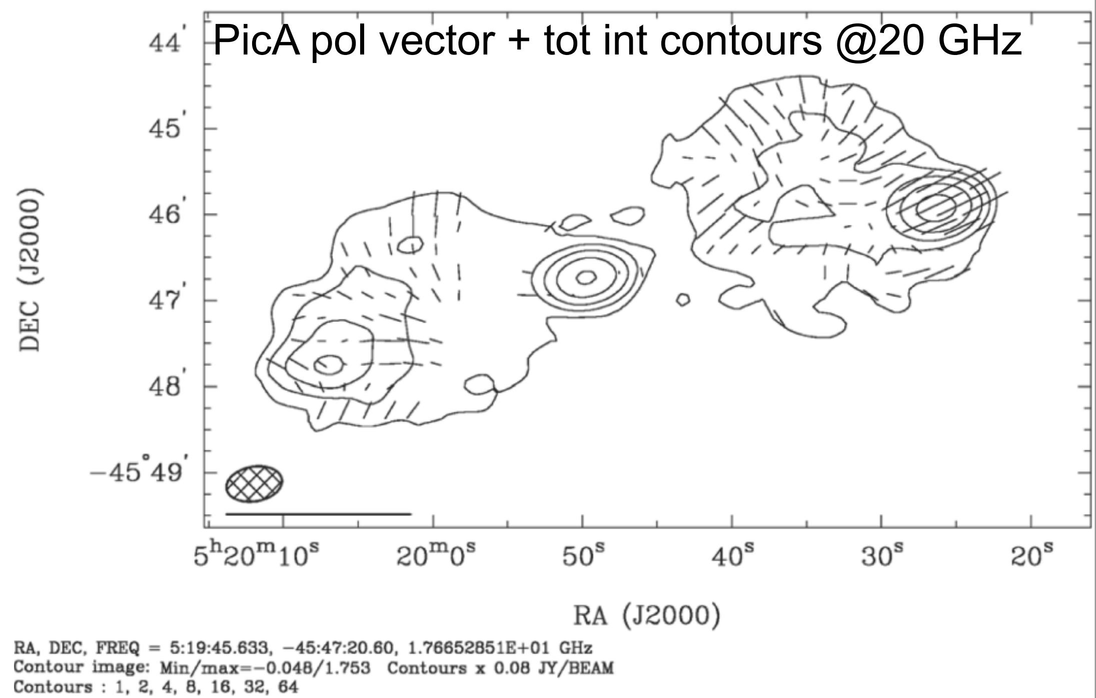

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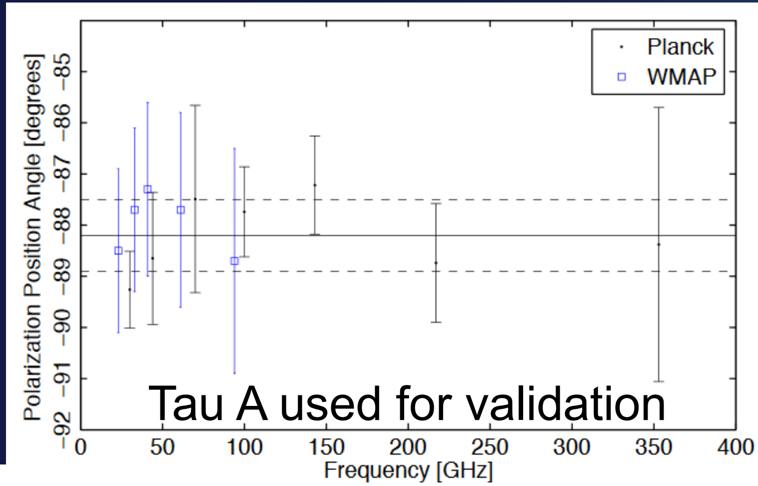
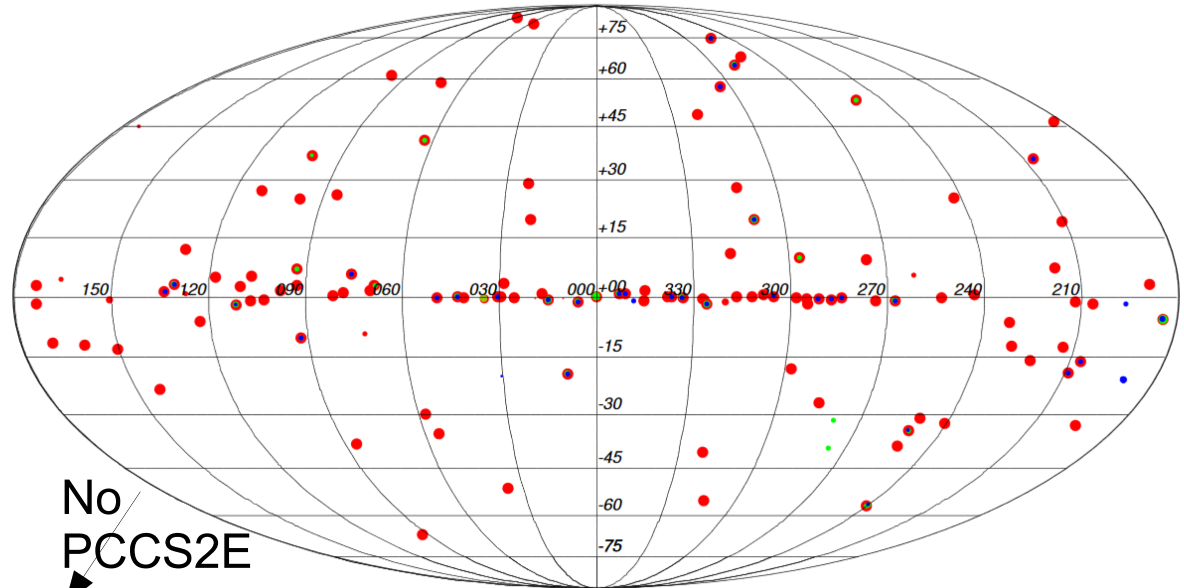
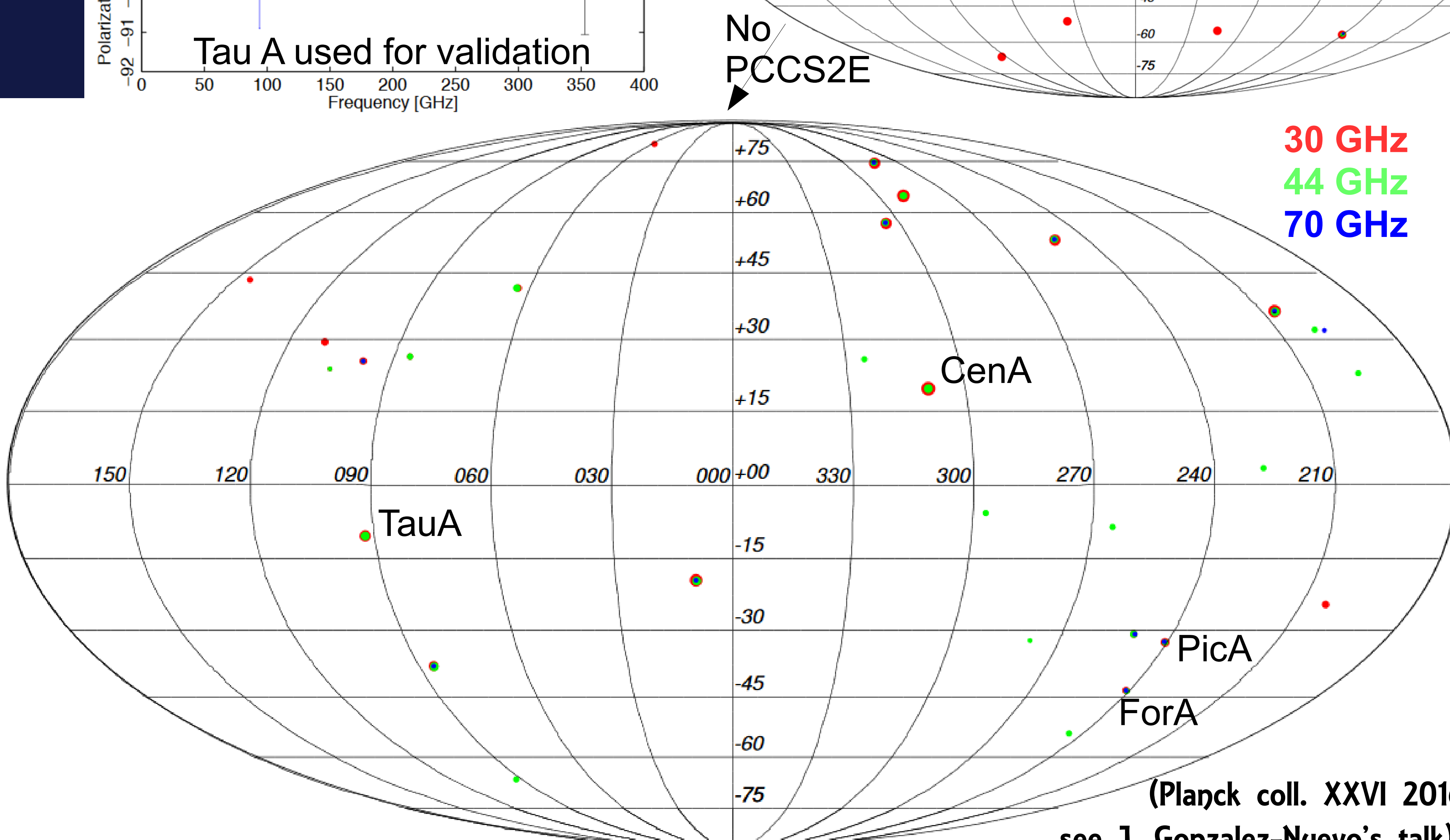
(Burke-Spolaor et al. 2009)

Planck detections in PCCS2



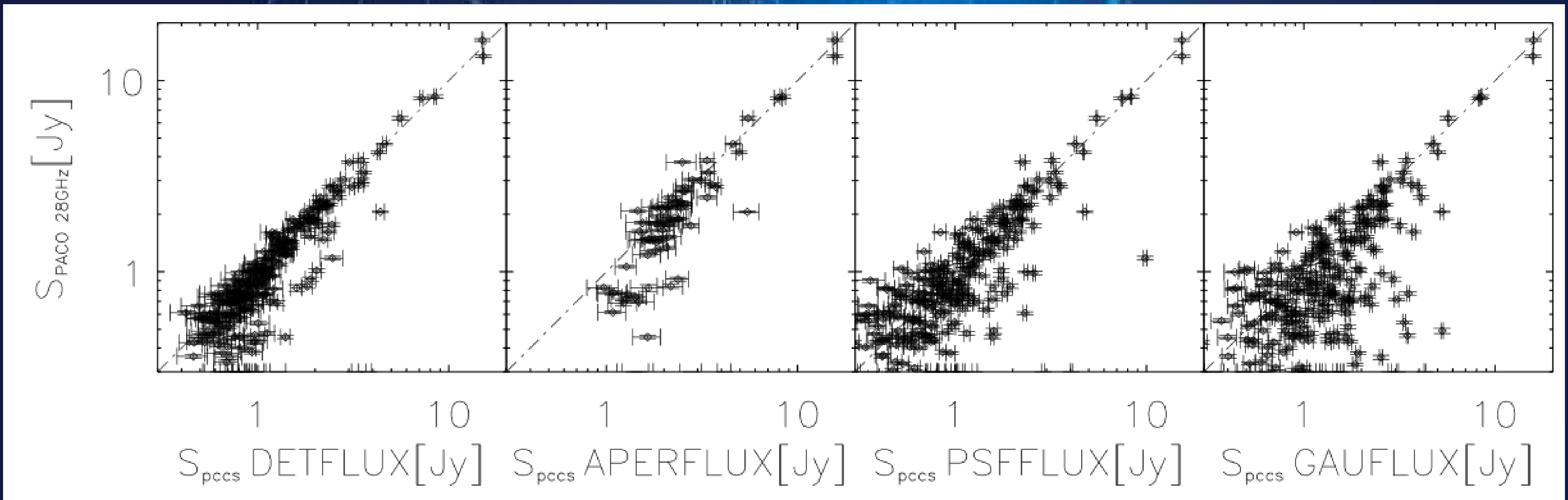




(Planck coll. XXVI 2016
see J. Gonzalez-Nuevo's talk)

The Planck ATCA Co-eval Observations

Observations in 2009-2010 with ATCA
>400 sources in Southern sky simultaneous to Planck
At 5-8-18-24-33-39 GHz
Including bright, faint and spectrally selected complete samples
Polarization calibration was not possible



PACO was one of several Pre-emptive Planck ground-based follow-up
Simultaneous observations allowed validation of detection methods and photometry

(Massardi et al. 2016)

The Planck ATCA Co-eval Observations

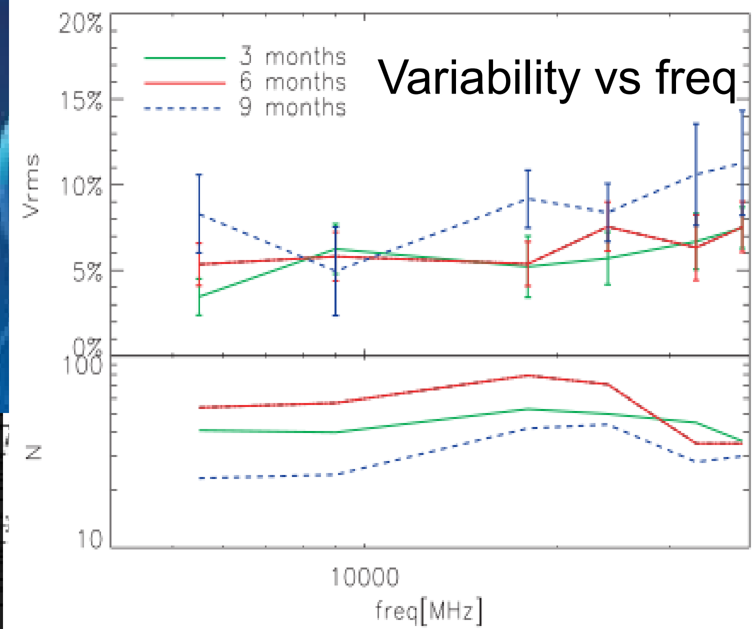
Observations in 2009-2010 with ATCA

>400 sources in Southern sky simultaneous to Planck

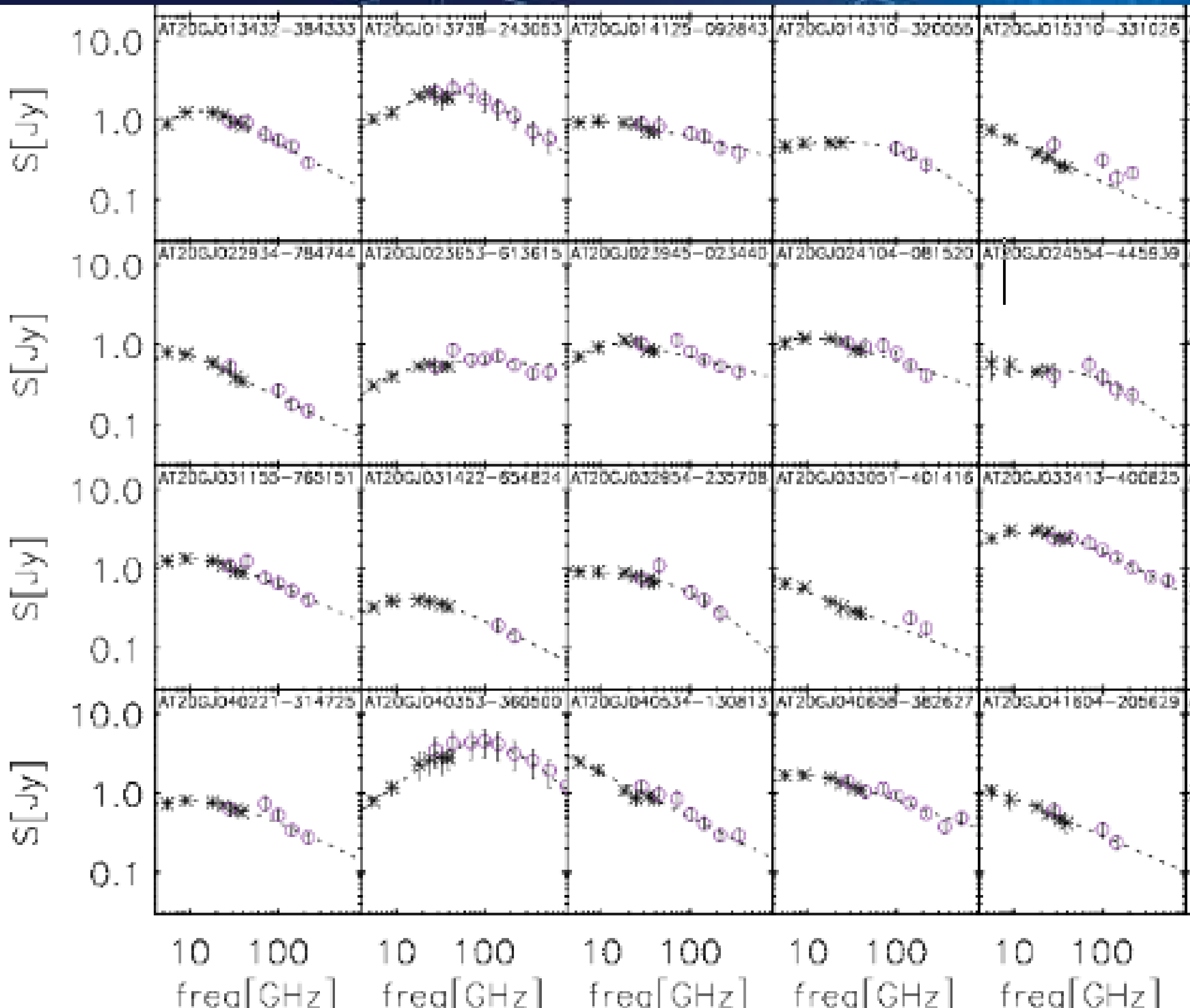
At 5-8-18-24-33-39 Ghz (6 points in spectra)

Including bright, faint and spectrally selected complete samples

Polarization calibration was not possible



Type	$200 \le S_{20\,\mathrm{GHz}} < 500$ mJy (per cent)	$S_{20\,\mathrm{GHz}} \ge 500$ 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

(Massardi et al. 2017)

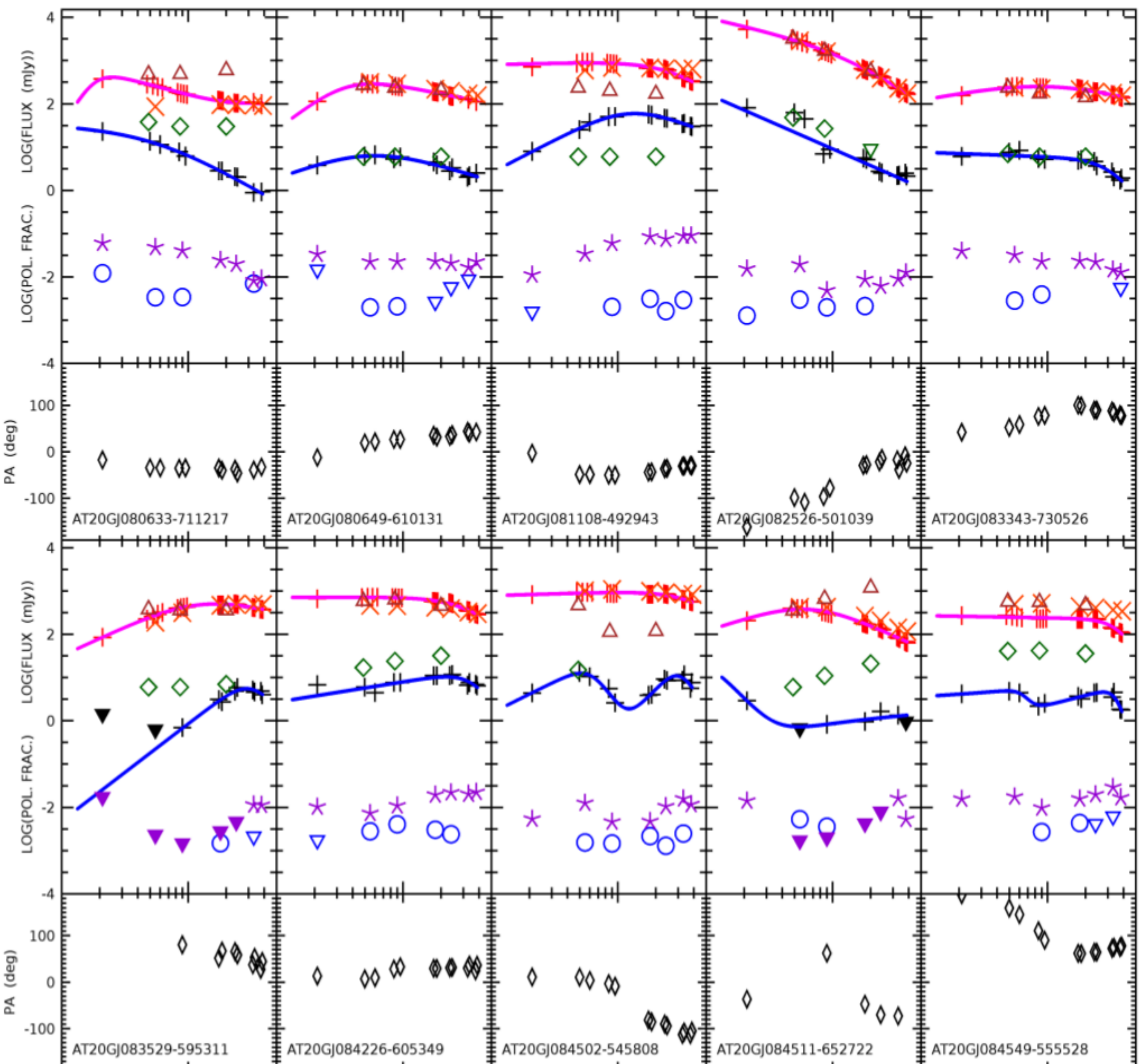
The PACO polarimetric follow-up

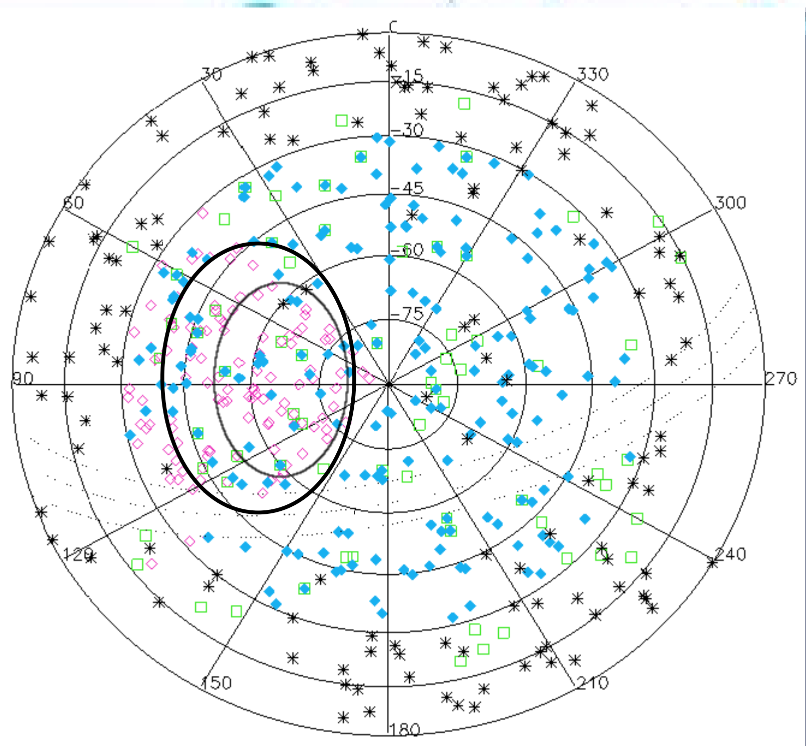
Observations in 2014-2016 with ATCA

104 sources brighter than 200mJy in AT20G

at 2.1-5-8-18-24-33-39 GHz

Sensitivity at 0.6mJy (splitted bands: up to 25 points in spectra)





+ Tot. int.

+ Pol.

▼ Upper limits Pol.

Δ Tot. Int. AT20G (2004-2008)

◊ Pol. AT20G (2004-2008)

x Tot. int. PACO (2009-2010)

– Tot. int. fit curve

– Pol. fit curve

* (Linear) Pol. fraction

○ (Circular) Pol. fraction

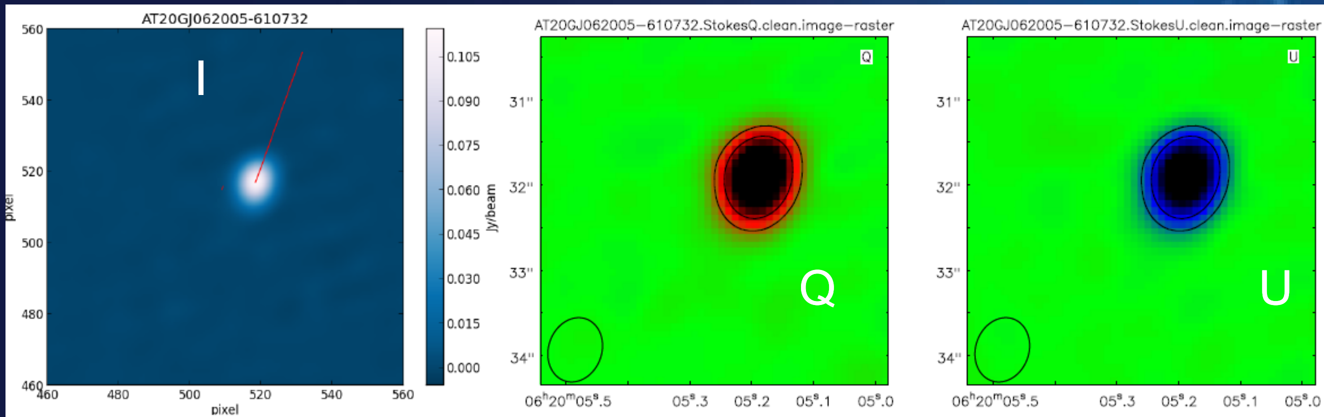
◊ Polarization Angle

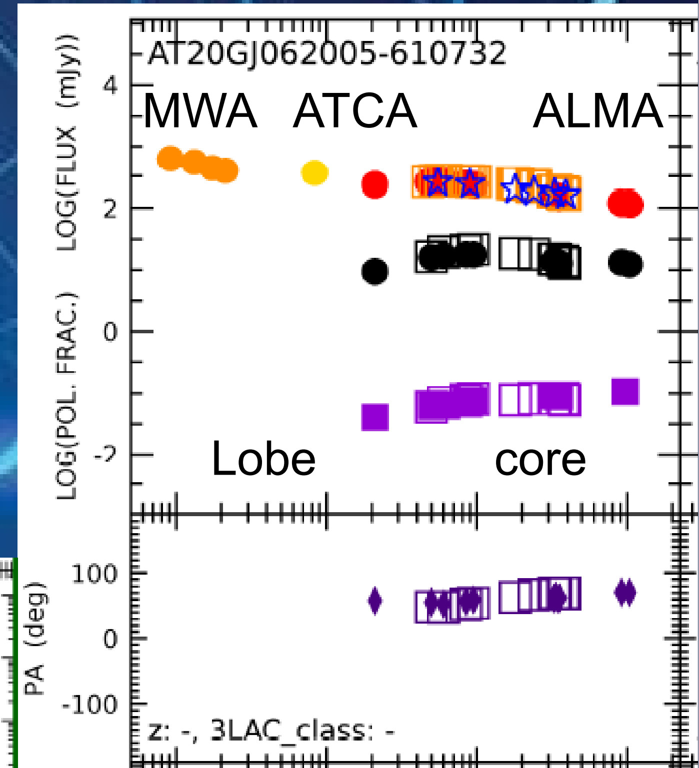
(Galluzzi et al. 2018)

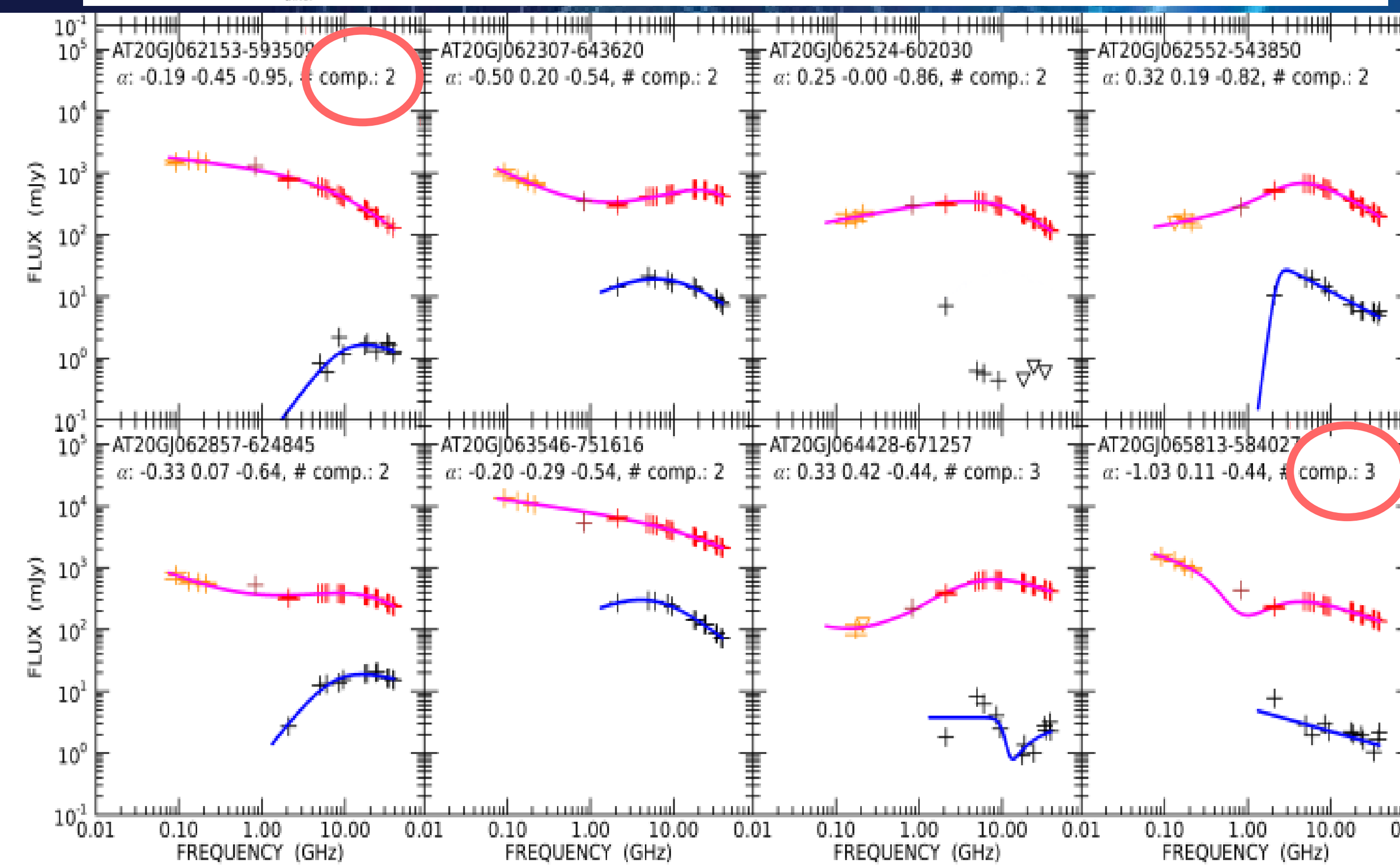
Up to 100 GHz from the ground: ALMA observations

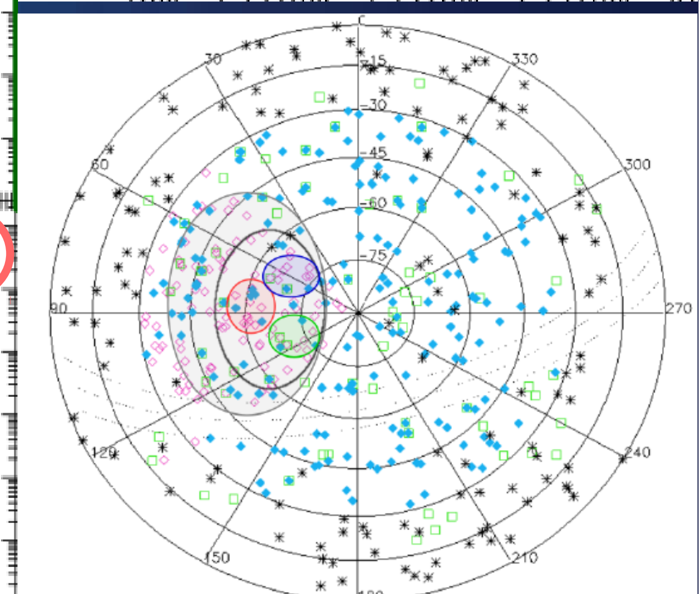
Follow-up of 32 PACO sources in 2016 with ALMA at 100GHz

Sensitivity at 0.04mJy







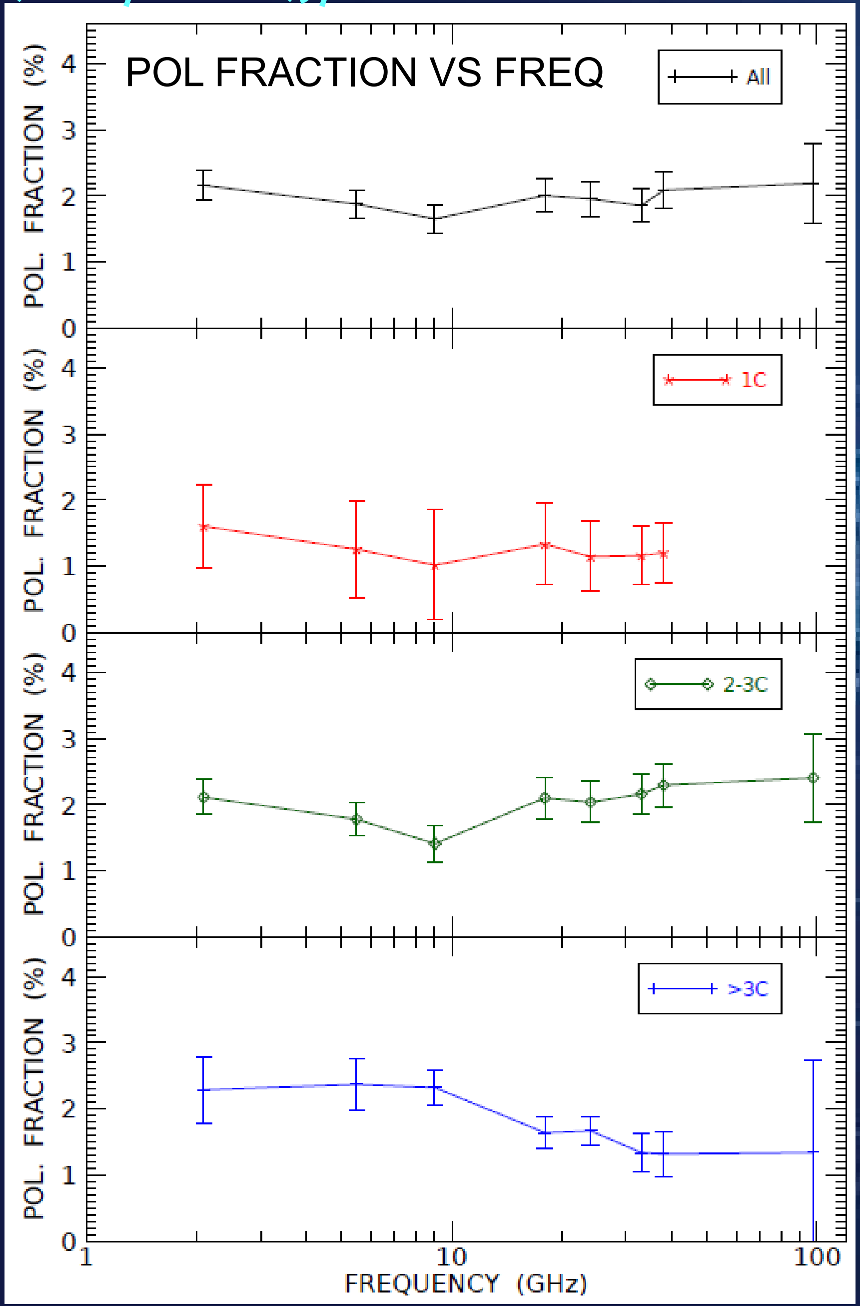


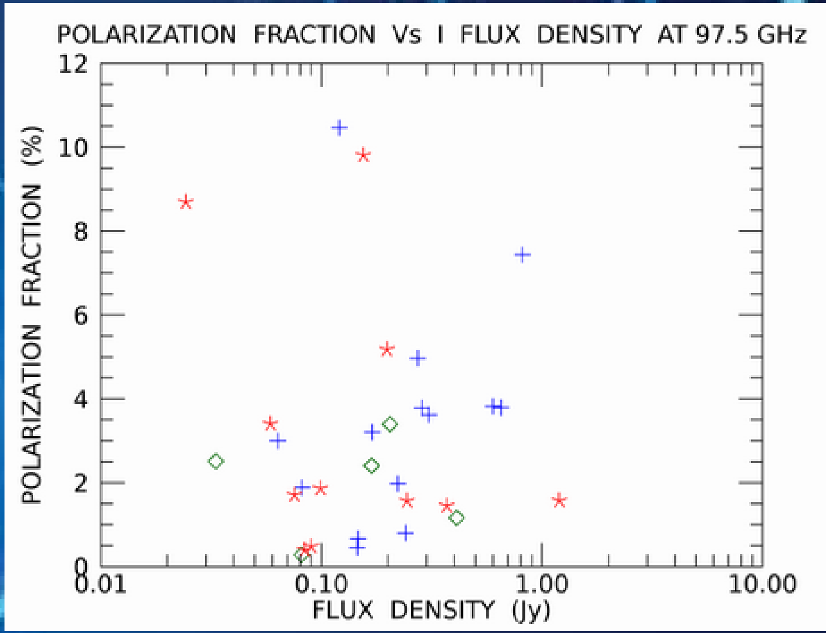
(Galluzzi et al. in press)

Up to 100 GHz from the ground: ALMA observations

Follow-up of 32 PACO sources in 2016 with ALMA at 100GHz

Sensitivity at 0.4mJy





Thanks to multi-band almost simultaneous polarimetric observations we could characterize the structure of the sources

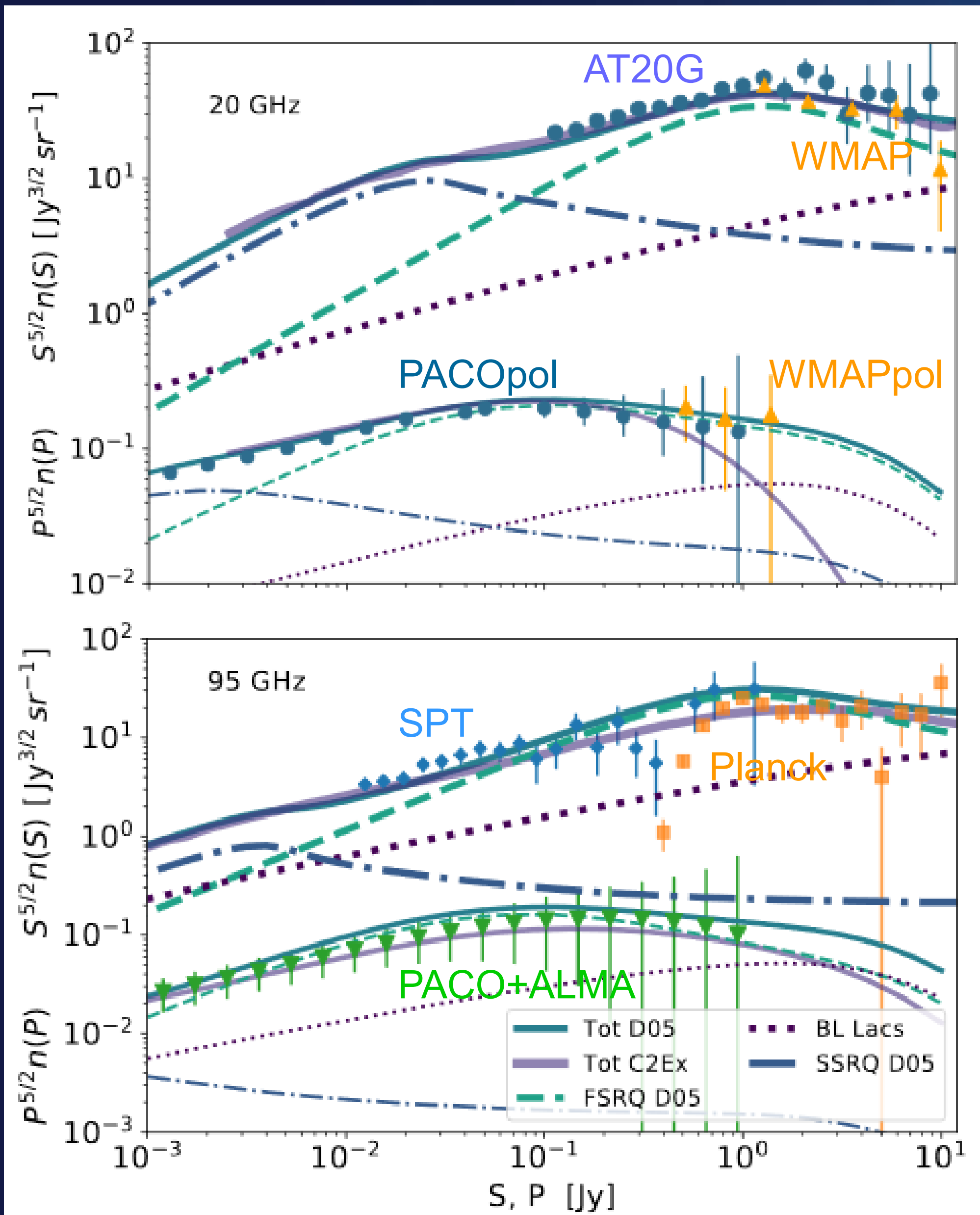
There are no clear trends of polarization fraction with frequency or flux density

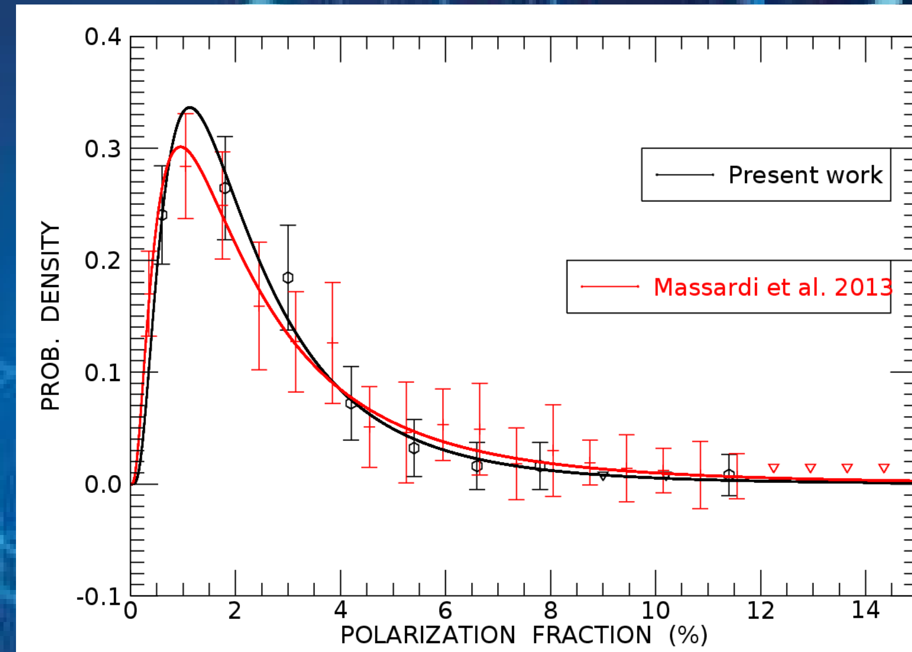
Median frac pol is 2.2+-0.6 at 100GHz

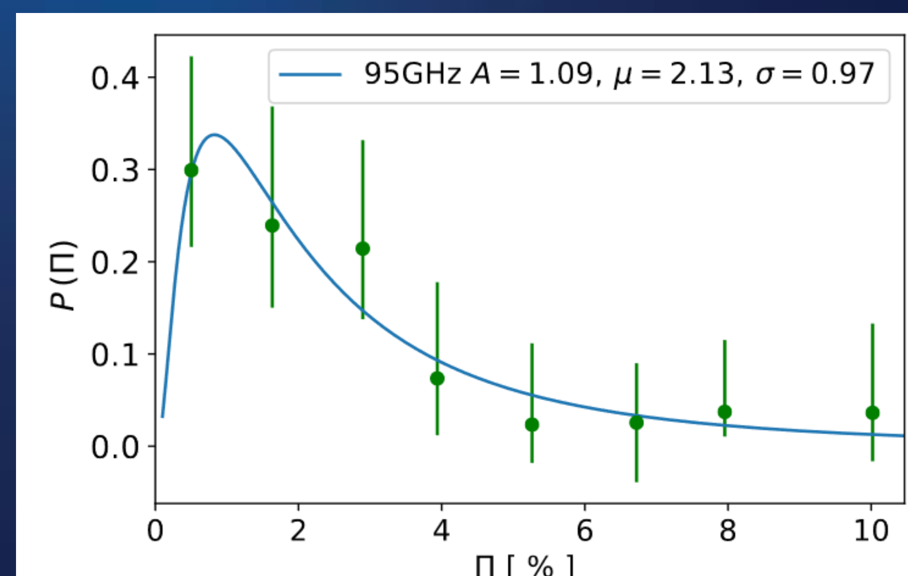
No time to discuss about V Stokes or RM,
Stay tuned for the paper!

(Galluzzi et al. in press)

Source counts and estimates for cosmology





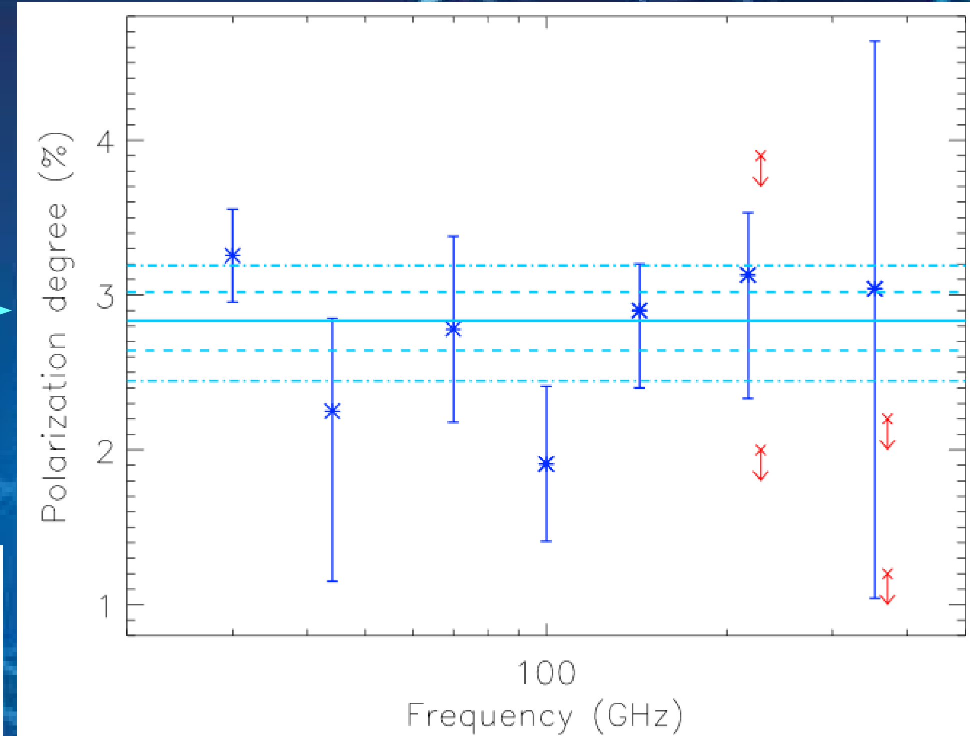


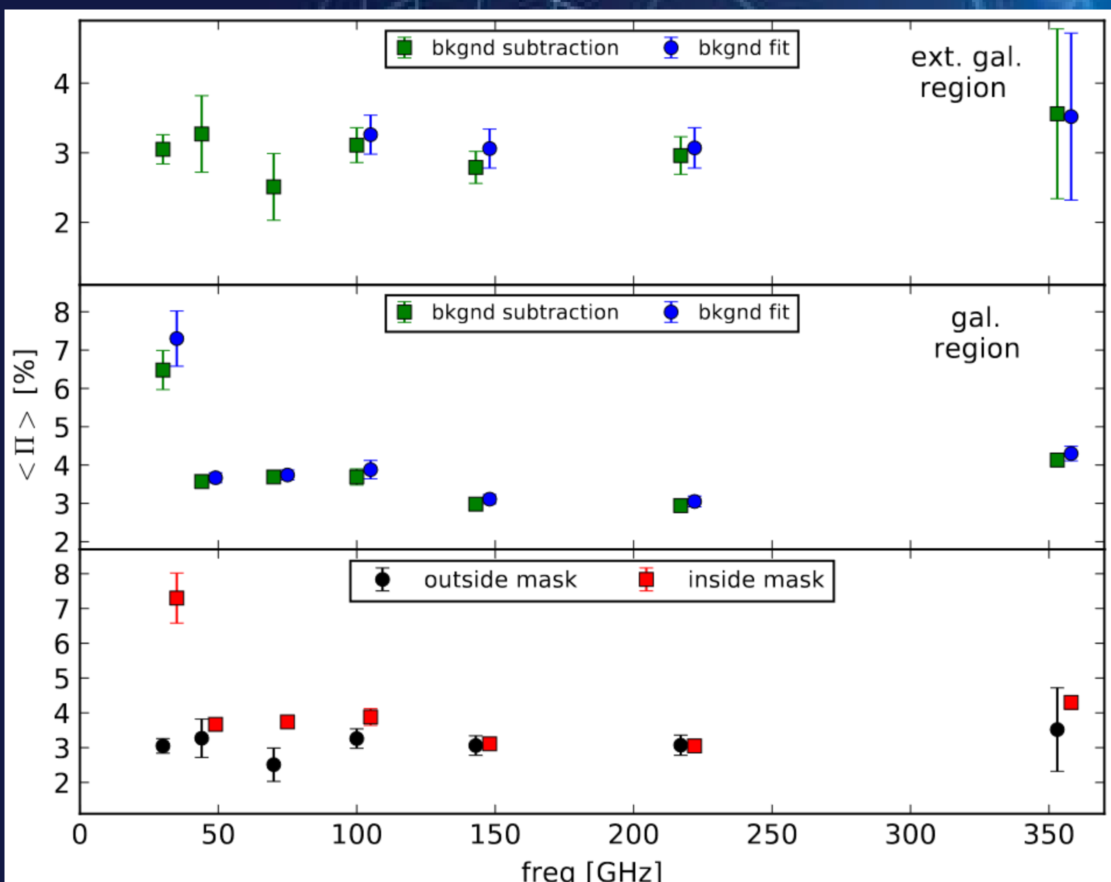
(Galluzzi et al. in press, Puglisi et al. 2018)

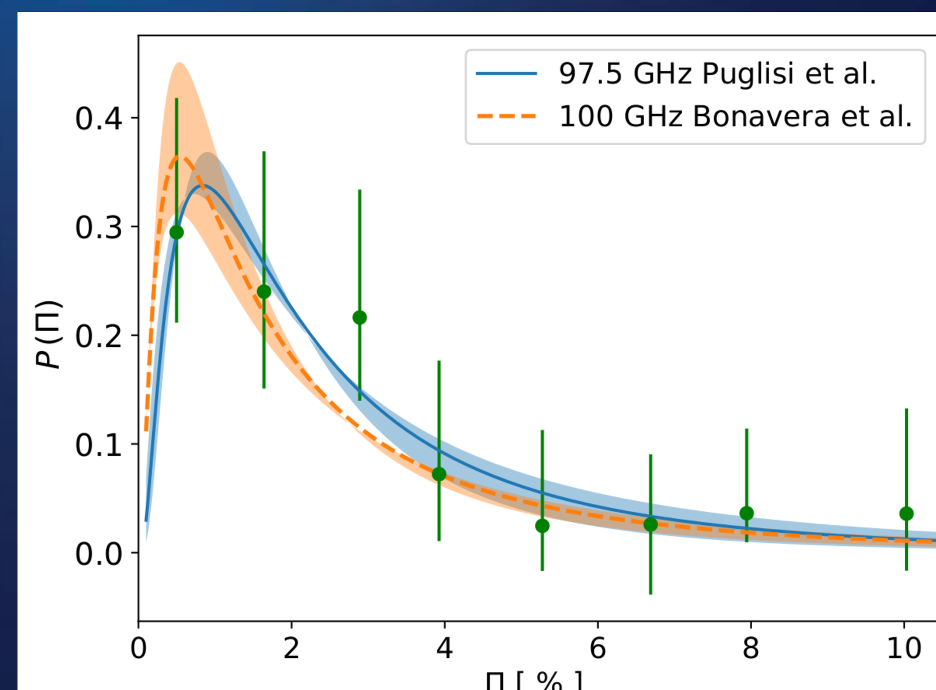
Going fainter in CMB projects

Different statistical techniques have been applied to going deeper in detections on Planck maps

- intensity distribution analysis (Trombetti et al. 2018)
  Median pol frac 1.8+-0.5%
- stacking (Bonavera et al. 2018)
  Median pol frac 1.8+0.4-0.3%



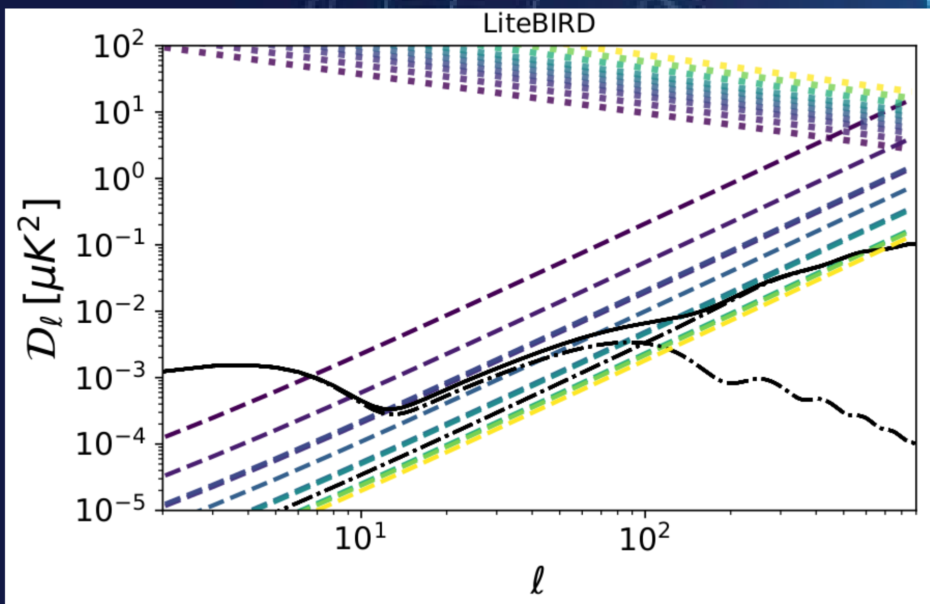


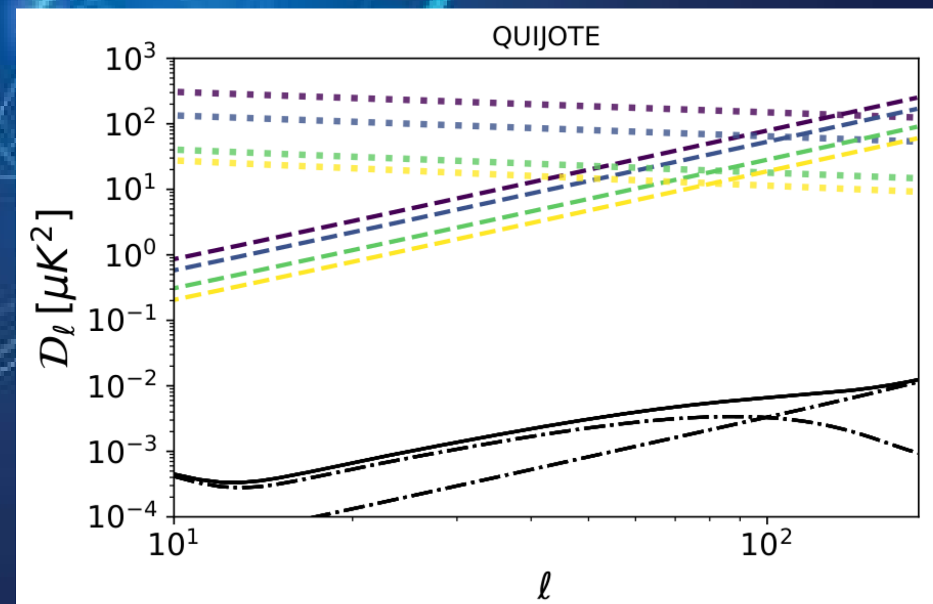


(ALMA Median pol frac 2.2+-0.6%)

Source counts and estimates for cosmology

	Frequency [GHz]	Sensitivity [μK arcmin]	FWHM	f_{sky}
QUIJOTE	11,13,17,19	1800	1°	50%
CMB-S2	95, 150	25,30	3.5′	5%
CMB-S3 SA	30, 40, 95,150	8, 6, 1, 2	1°	20%
CMB-S3 LA	30, 40, 95,150	8, 6, 1, 2	10′, 7′, 3′, 2′	20%
LiteBIRD	40, 50, 60, 68, 78	53, 32, 25, 19, 15	1°	100%
	89, 100,119, 140,166	12, 15.6, 12.6, 8.3, 8.7	1°	100%
CORE150	60, 100, 145	10.6, 7.1, 5.1	14′, 8′, 6′	100%





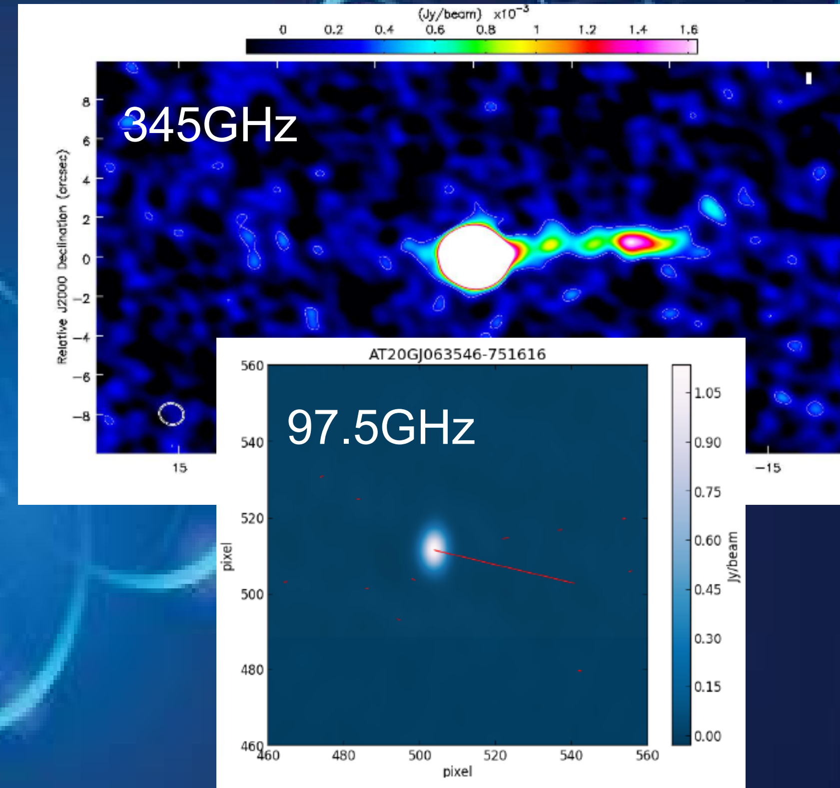
— - B-modes (primordial and lensed E separately)
—— Total B-modes
· · · · Galactic synchrotron foreground
-------- ERS foreground
Purple to *yellow* ⟶ *increasing frequency*

Mixing source counts obtained from observations with telescope capabilities we get an estimate of what we should expect from the future…

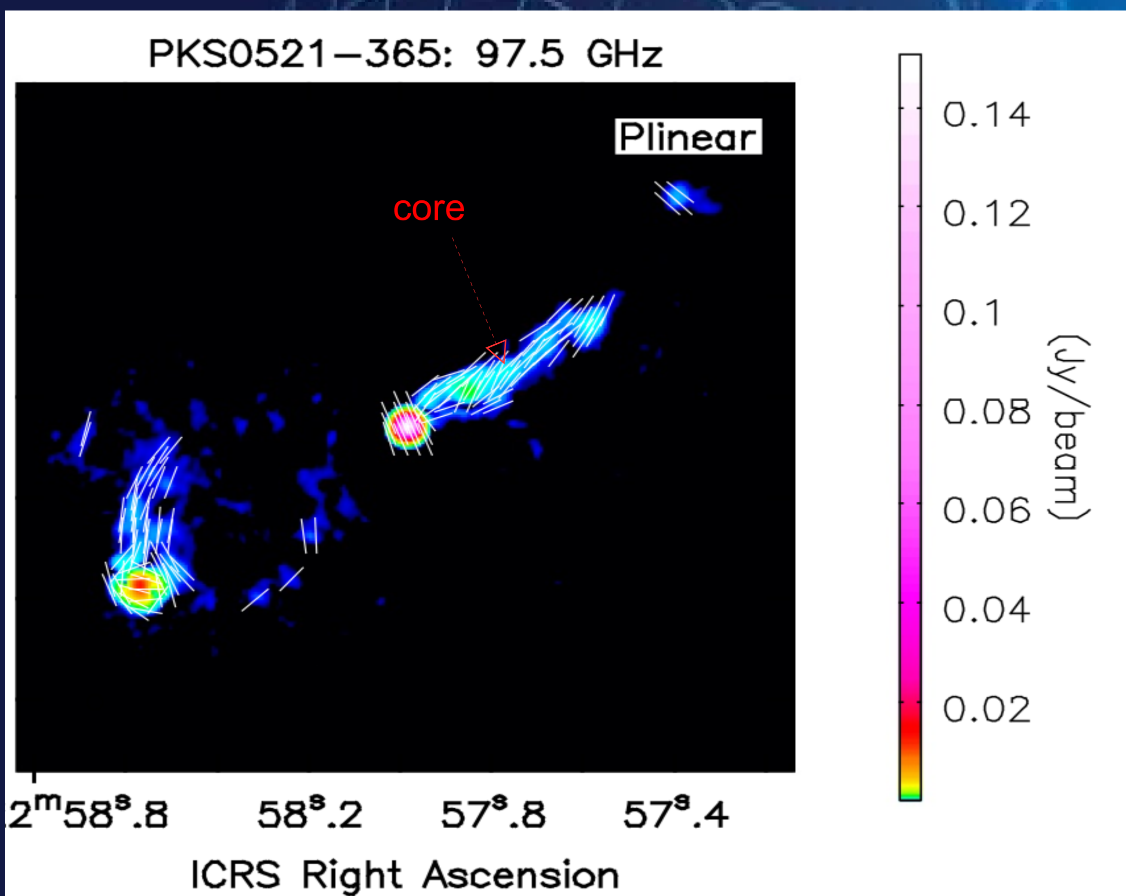
(selection of the examples is only indicative
See G. Puglisi's talk for more details)

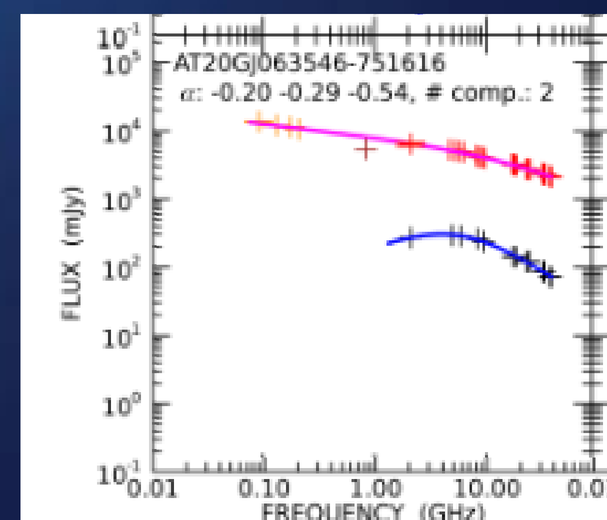
Looking for calibrators: 0521-365 and 0637-752

Both the sources are ALMA polarization calibrators thanks to their compact bright core that dominate the emission… but to a deeper analysis, possible with archival ALMA data they reveal their complex structure



0637-752 is at ~1 Jy and ~1.6% polarized at 97.5 GHz.





(Liuzzo et al. in prep, Massardi et al. In prep., Agliozzo et al. 2016, Galluzzi et al. In press)

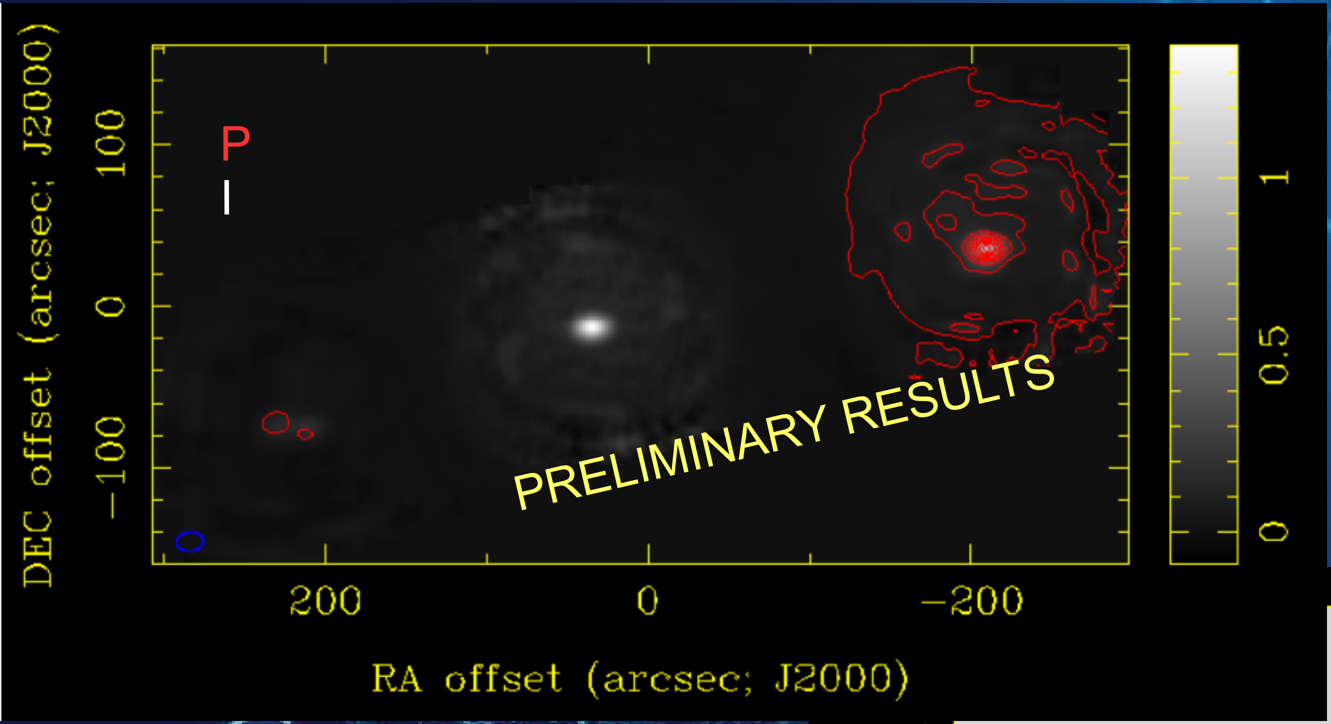
Looking for calibrators: PictorA

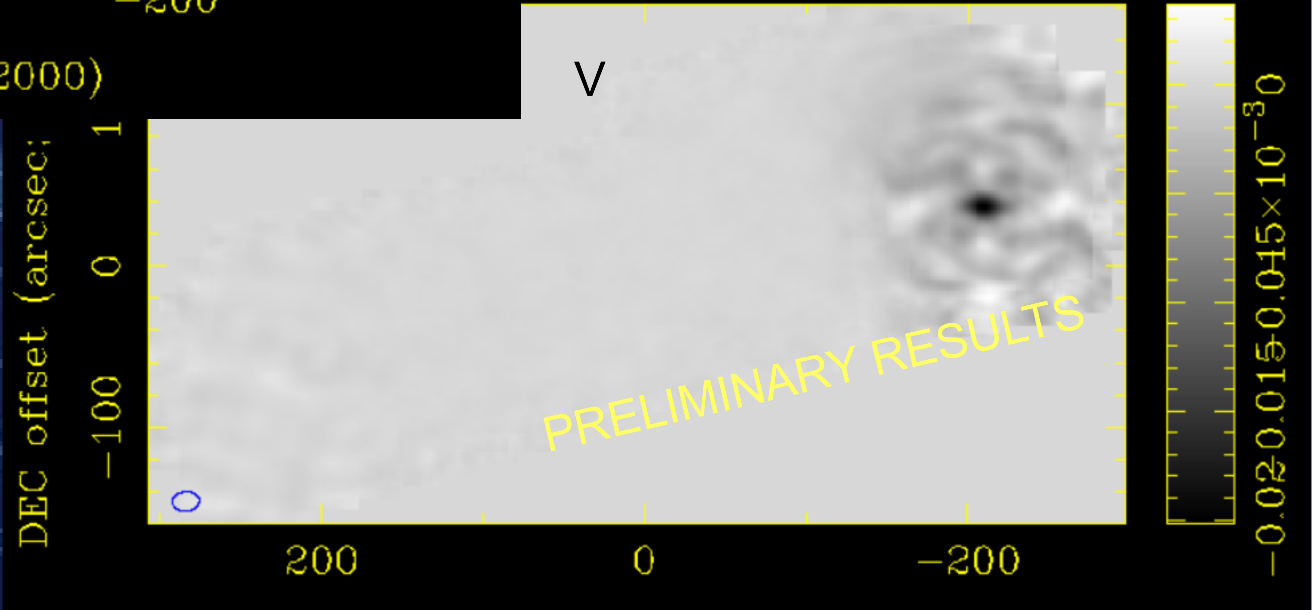
Polarimetric observations at 33 GHz of Pictor A with ATCA in July 2016

Imaging issues: 120 pointing mosaic (use CASA TCLEAN)

Too high dynamic range

Attempting peeling, multiscale, selfcal … IN FULL STOKES!!!





(Galluzzi et al. In prep.)

Next to come: ALMA Cycle 7 and beyond

ALMA in next cycle (Cy7) will allow
for the first time mosaic polarimetric observations
→ it will be possible to map the calibrators
to high resolution and at cosmologically
suitable frequencies

Analysis of large samples are still limited by instrumental issues but new approaches to calibration will allow to take advantage of current and future capabilities:

- enlarged basebands
  (more instantaneous sensitivity and spectral coverage)
- single dish capabilities and PAF
  (larger sky coverage and survey modes)
- Band 1 around 30 Ghz
- Band 2 (or 2+3) between 64 and 116 GHz

Can you see chances for cosmology with ALMA?

Summary of the learnt lessons

- Radio sources are faint, variable and with many possible behaviours
  But can help cosmological studies if properly characterized
  (for all the Stokes!!!)

- Radio sources are contaminants, validation tools and calibrators

- Do not rely on extrapolation from low frequency

- Always prefer simultaneous observations possibly at your observing frequency, or in multibands

- For validation at high frequencies choose complete samples selected on flux density basis,
  not on spectral classes: sources may change class with time

- Polarization properties and spectral behaviour can describe
  the source emitting structure

- High resolution polarimetric mapping of sources is
  necessary to unveil the mechanisms of emission
  and verify if is a suitable calibrator for cosmology

- Do not hesitate to mix different telescopes, but be
  aware of the calibration issues, in particular in pol