Multi-frequency polarimetry of a complete sample of PACO radio sources

Vincenzo Galluzzi [1,2], Marcella Massardi 1 e Loretta Gregorini[1]
[1]INAF, Istituto di Radioastronomia, Via P. Gobetti 101, I-40129, Bologna
[2]INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo, 11, I-34143, Trieste
[vincenzo.galluzzi@inaf.it ; massardi@ira.it]

Co-I's list: A. Bonaldi, M. Bonato, C. M. Burigana, L. Bonavera, J. R. Callingham, V. Casasola, G. De Zotti, R. Ekers, E. Liuzzo, M. López-Caniego, A. Mignano, R. Paladino, G. Puglisi, R. Ricci, L. Toffolatti, T. Trombetti, M. Tucci, S. di Serego Alighieri.

Abstract. The high-frequency (> 20 GHz), bright flux density (> 200 mJy) radio population is dominated by blazars, i.e. compact Doppler-boosted objects, whose emission arises from knot-like synchrotron structures along the relativistic jet. Their polarization properties was so far poorly constrained at high frequency and results in literature are typically biased. Extending the characterization of polarization properties of radio sources to high frequencies provides invaluable information about magnetic fields and plasma in the inner and unresolved regions of relativistic jets. Furthermore, extragalactic radio sources are an important contaminant for the angular power spectrum of CMB (Cosmic Microwave Background) at multipoles l > 50 up to 150 GHz: their polarimetry is crucial to search for primordial B-modes, the footprint of inflation.
We present high sensitivity multi-frequency and multi-epoch polarimetric observations of a complete sample of 104 compact extragalactic radio sources drawn from the faint (> 200 mJy at 20 GHz in total intensity) Planck-ATCA Coeval Observations (PACO) catalogue, performed with the Australia Telescope Compact Array (ATCA) at 7 frequencies, between 2.1 and 38 GHz. We found that polarization spectra of single sources cannot be simply inferred from total intensity ones, as different synchrotron components dominate the different emissions. ALMA (Atacama Large Millimetre and sub-millimetre Array) observations extends the analysis up to 100 GHz for a (complete) sub-sample of 32 objects. We compute number counts in polarization at 20 and 100 GHz to a deeper level than available so far and provide forecasts for current and forthcoming CMB experiments.

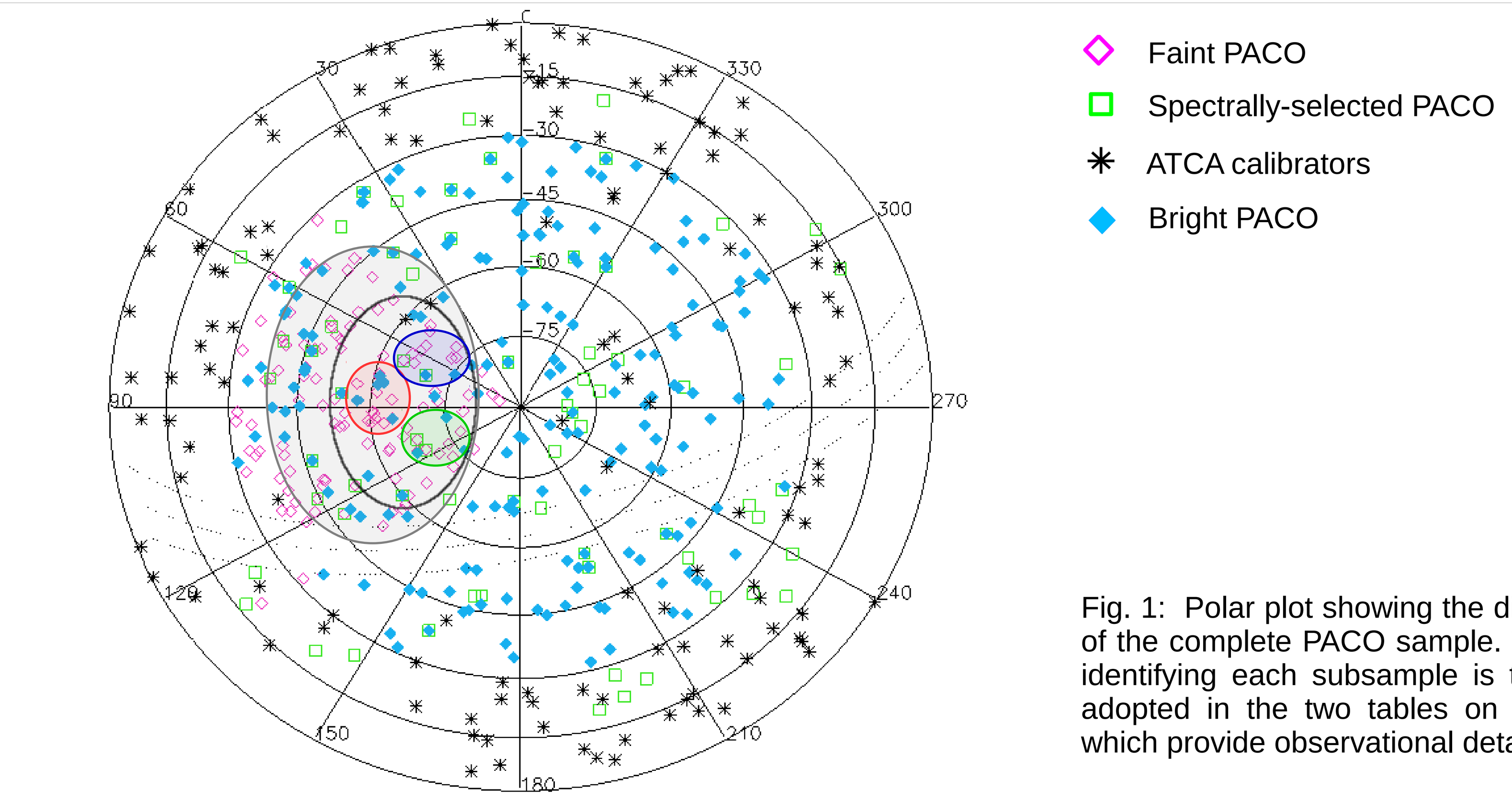


Fig. 1: Polar plot showing the distribution of the complete PACO sample. The color identifying each subsample is the same adopted in the two tables on the right, which provide observational details.

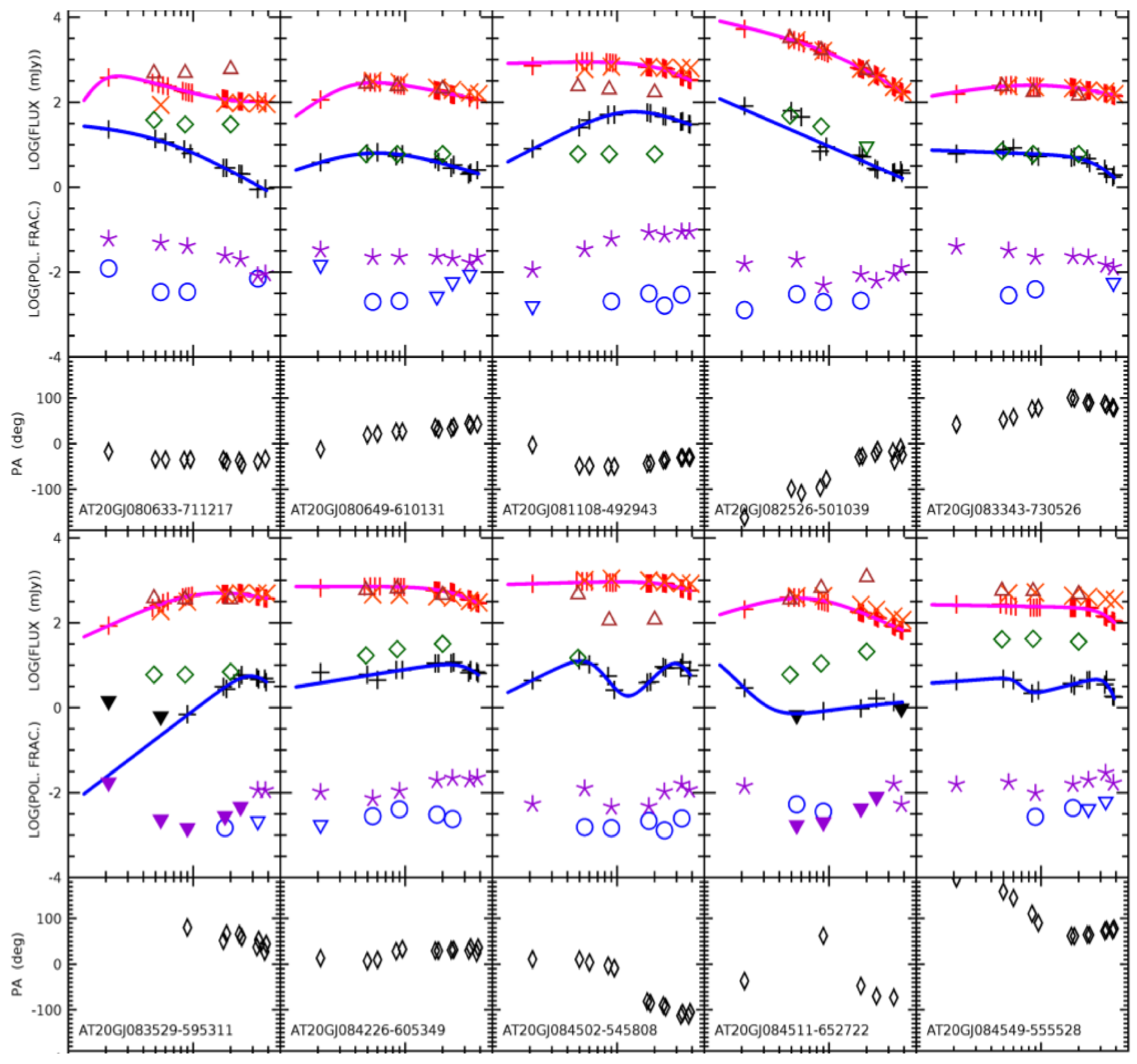


Fig. 2: Spectra in total intensity and polarization, (linear and circular) polarization fractions and polarization angles for some objects selected from our sample.

- **+ Tot. int.**
- **+ Pol.**
- **▼ Upper limits pol.**
- **Δ Tot. Int. AT20G (best epoch in 2004-2008)**
- **◊ Pol. AT20G (best epoch in 2004-2008)**
- **x Tot. int. PACO (Jul 2009-Aug 2010)**
- **– Tot. int. fit**
- **– Pol. fit**
- *** (Linear) pol. fraction**
- **▼ Upp. lim. pol. fraction**
- **○ (Circular) pol. fraction**
- **▽ Upp. lim. pol. fraction**
- **◊ Polarisation Angle**

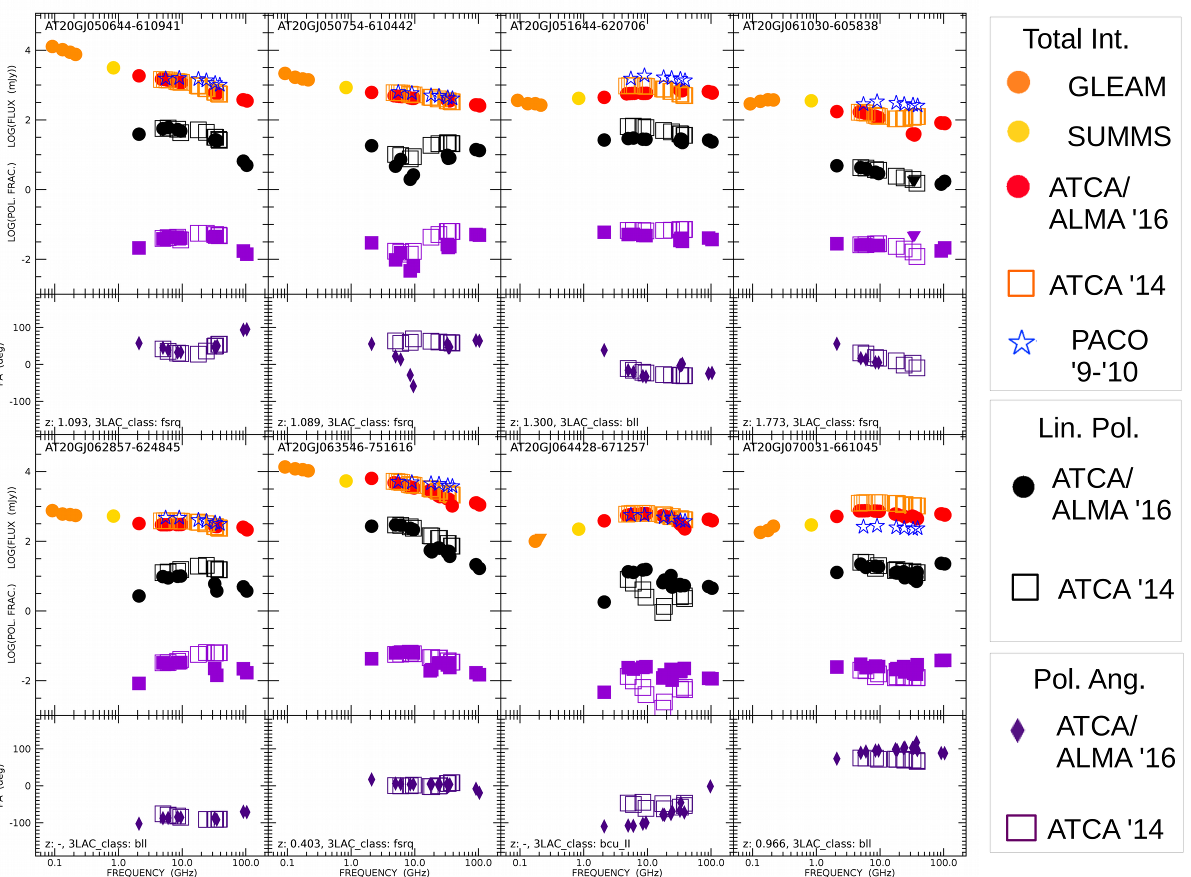


Fig. 3: Spectra in total intensity and polarization, (linear and circular) polarization fractions and polarization angles for some objects selected from our sample.

ATCA (Australia Telescope Compact Array) observations

Epoch	allocated time	frequencies	# objects	region
Sep. 2014	21 h	[5.5;38] GHz	53	b < - 75°
Mar.-Apr. 2016	26 h	[5.5;38] GHz	51	-75° ≤ b < -65°
	14 h	2.1 GHz	104	b < - 65°
July 2016*	5 h	33-35 GHz	35	b < -75°

- Spatial configuration: H214 (*H75, hybrid and compact).
- Resolution λ/b_{max} ≈ 5÷36 arcsec (without CA06)
- Integration on source: at least 3 min (e.g. 2X1.5 min, at least 2 cuts at different hour angles)
- Sensitivity: ≈ 0.6 mJy (≈ 1 mJy for 2.1 GHz)
- Detection rates linear pol. (5 σ): ≈ 91%
- Detection rates circular pol. (3 σ): ≈ 53%

ALMA-Cycle 3 (Atacama Large Millimeter & submillimiter Array) observations

SG – Epoch	Time allocated	Frequencies	# objects	Region (J2000)
1 – 24/08/2016	3.0 h	97.5 GHz (4 spw)	14	(05:06:44 , -61:09:41)
2 – 22/09/2016	3.5 h	97.5 GHz (4 spw)	9	(06:35:46 , -75:16:16)
3 – 27/09/2016	3.5 h	97.5 GHz (4 spw)	9	(03:24:04 , -73:20:47)

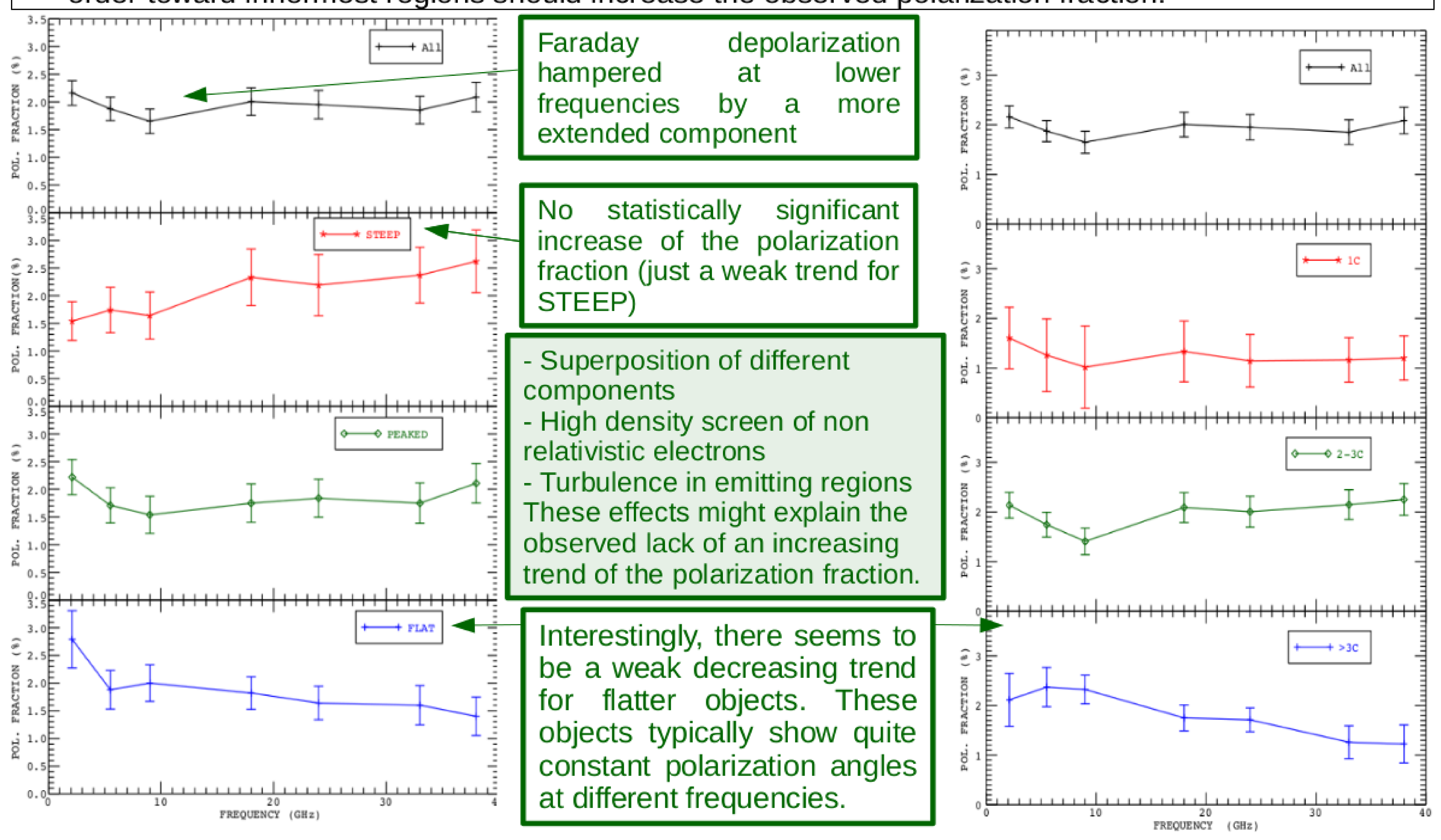
- Resolution λ/b_{max} ≈ 0.3 arcsec;
- Integration on source: at least 5 min (up to ≈ 12 min for SG2 and SG3 objects)
- Sensitivity: ≈ 0.04 mJy (down to ≈ 0.02 mJy for SG2 and SG3 objects).
- Detection rate: ≈ 97% (only 1 non-detection)

Goals of the observations:

- characterize the polarization properties of radio source populations in the 2.1-100 GHz frequency range with high polarization sensitivity;
- statistically study the physics of the synchrotron emission processes, the geometry of emission regions, the properties of magnetic fields, the matter distributions of the surrounding or outflowing matter;
- estimate the radio-source contribution to the CMB power spectrum up to 100 GHz in total intensity and polarization.

Linear polarization fractions

- Agudo et al. (2010) between 15 − 90 GHz and Sajina et al. (2011) between 5 − 40 GHz find indications of increasing polarization fraction with frequency.
- Faraday depolarization is expected to be efficient for ν < 10 GHz, while at ν > 10 GHz higher magnetic order toward innermost regions should increase the observed polarization fraction.



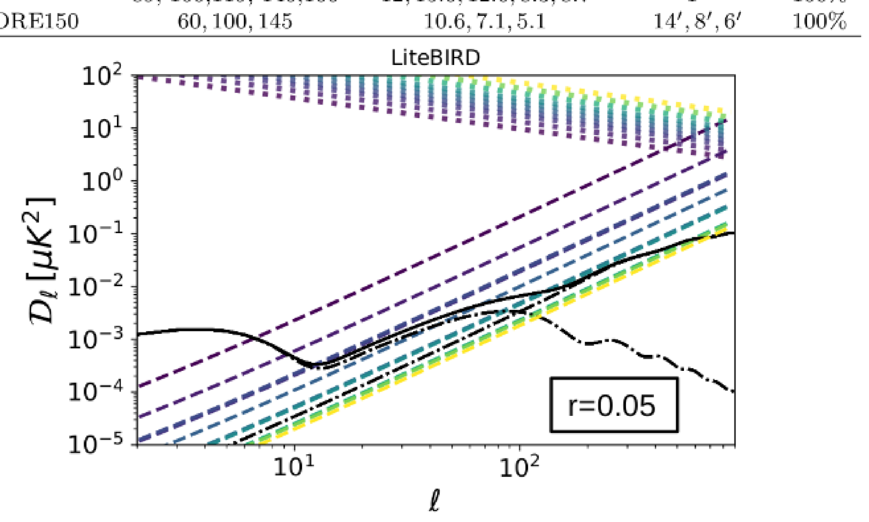
Forecast for ERS foreground

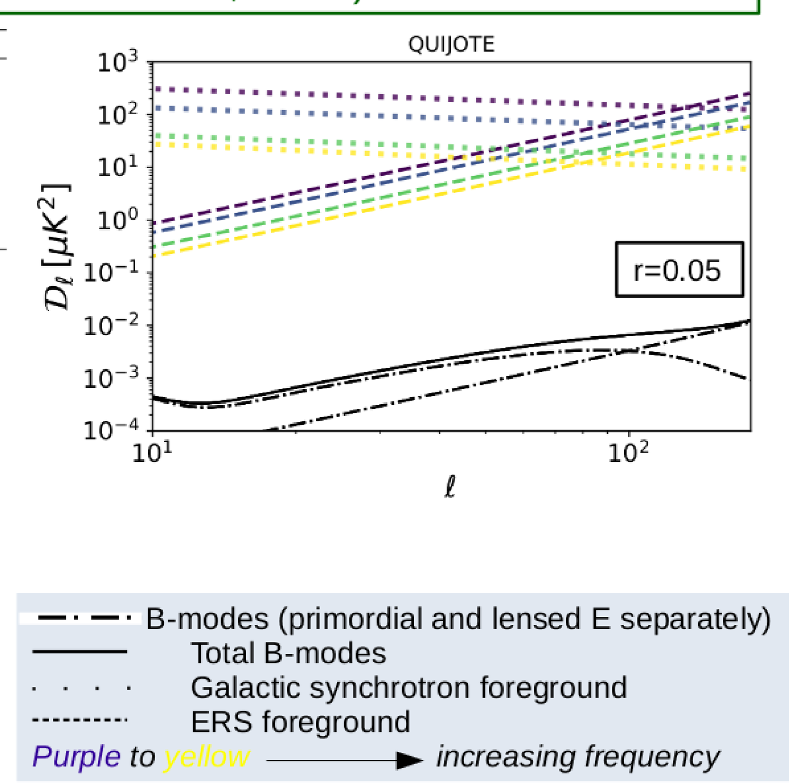
(in collaboration with G. Puglisi, SISSA, [Puglisi, Galluzzi et al. 2018])

- The stockastic background of GW induced by inflation is expected to leave its footprint in CMB angular power spectrum (primordial B modes), still undetected.
- Current upper limit on r is 0.07 at 95% c.l. (BICEP 2/Keck and Planck Collaboration 2015)
- For r down to 0.001, Extragalactic Radio Sources (ERS) are important contaminant for the CMB angular power spectrum for l > 50 up to 150 GHz

- Given current and next-coming CMB experiments we forecast ERS contamination to the CMB B-mode angular power spetrum (Point Source ForeCast, PS4C)*

	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%





* *Available at: https://gitlab.com/giuse.puglisi/PS4C*

Polarization angle

Some authors (Pasetto et al. 2018) report intrinsic RMs up to 1000 rad/m² in wideband observations up to 15 GHz. Departure from λ² probably due to turbulent medium.

– Wideband polarimetric observations for a complete sample of 104 objects up to 39 GHz (+ 32 objects at 90-105 GHz)

– Only 9 objects can be fit by the linear RM relation over the 1.1-39 GHz range (4 compatible with very low or null rotation < 10 rad/m²).

– We identify two regimes, i.e. cm and mm-wavelenghts and perform separate linear fit

(~40% cm, ~57% mm) and find high RMs (up to 4000 rad/m²) matching the structural complexity we argued (also consistent with the linear polarization fraction behaviour). We again found several departures from the λ².

– ALMA data (although the big uncertainties ~ 1/λ²) reveal a bunch of objects with extreme intrinsic RMs, again consistent with structure, enforcing indications of NLR (or even BLR) clouds acting as external screens.

1.1-10 GHz

All sample (42)			1C (3)			2-3C (31)			>3C (8)		
I	med	III	I	med	III	I	med	III	I	med	III
18	37	58	-	60	-	15	34	53	-	37	-
All sample (34)			**1C (3)**			**2-3C (24)**			**>3C (7)**		
I	med	III	I	med	III	I	med	III	I	med	III
52	100	236	-	212	-	39	77	216	141	236	259

17-39 GHz

All sample (59)			1C (4)			2-3C (50)			>3C (5)		
I	med	III	I	med	III	I	med	III	I	med	III
225	635	1397	-	342	-	283	637	1397	-	1141	-
All sample (45)			**1C (3)**			**2-3C (37)**			**>3C (5)**		
I	med	III	I	med	III	I	med	III	I	med	III
900	2615	5429	-	814	-	942	2562	5495	4010	4076	8972

90-105 GHz

All sample (8)	2-3C (6)	>3C (2)
1.3×10^4	1.2×10^4	3.3×10^4
All sample (5)	**2-3C (3)**	**>3C (2)**
1.3×10^5	6.3×10^4	1.4×10^5

$$\Delta\phi = \mathrm{RM}\lambda^2$$
$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4}\int_0^d n_e(s) B_{||}(s)\,\mathrm{d}s$$

$$\mathrm{RM}_{\mathrm{obs}} = \frac{\mathrm{RM}_{\mathrm{AGN}}}{(1+z)^2} + \mathrm{RM}_{\mathrm{Gal}} + \mathrm{RM}_{\mathrm{ion}}$$

<z> ~ 0.94 (~70% with z)
$\mathrm{RM}_{\mathrm{Gal}}$ ~ +20 rad/m²
$\mathrm{RM}_{\mathrm{ion}}$ < 5 rad/m²

The second row in each table presents intrinsic RM values (the number of objects is in parenthesis)

References: • Agudo I., *et al.* 2010, ApJS, 189, 1 • Battye R. A., *et al.* 2011, MNRAS, 413, 132 • Blandford R. D., Königl A., 1979, ApJ, 232, 34 • Bonaldi A., *et al.*, 2013, MNRAS, 428, 1845 • Bonavera L., *et al.* 2011, MNRAS, 416, 559 • Galluzzi V., *et al.*, 2017, MNRAS, 465, 4085 • Massardi M., *et al.*, 2008, MNRAS, 384, 775 • Massardi M., *et al.*, 2011b, MNRAS, 415, 1597 • Massardi M., *et al.*, 2013, MNRAS, 436, 2915 • Massardi M., *et al.*, 2016, MNRAS, 455, 3249 • Pasetto A., *et al.*, 2018, arXiv:1801.09731, Sadler E.M., *et al.*, 2006, MNRAS, 371, 898 • Sajina A., *et al.* 2011, ApJ, 732, 45.

Acknowledgements. This poster makes use of the following ALMA data: ADS/JAO.ALMA\#2015.1.01522.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. We thank the staff at the Australia Telescope Compact Array site, Narrabri (NSW), for the valuable support they provide in running the telescope and in data reduction. The Australia Telescope Compact Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. We acknowledge financial support by the Italian Ministero dell'Istruzione, Università e Ricerca through the grant "Progetti Premiali 2012-iALMA".