Multi-frequency polarimetry of a complete sample of faint PACO sources.

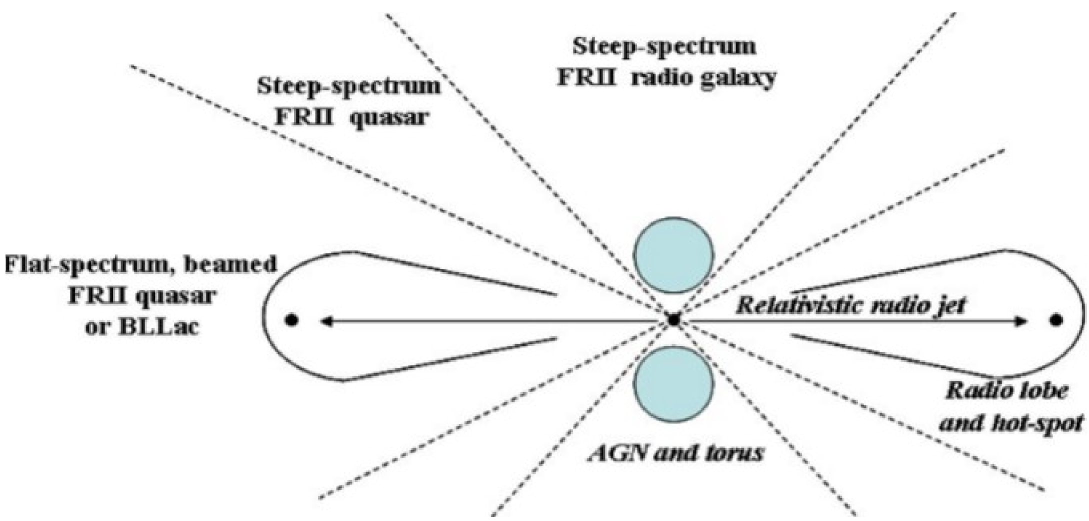
Vincenzo Galluzzi
DiFA (University of Bologna)
INAF-IRA (Bologna)

EUROPEAN ARC
ALMA Regional Centre || Italian

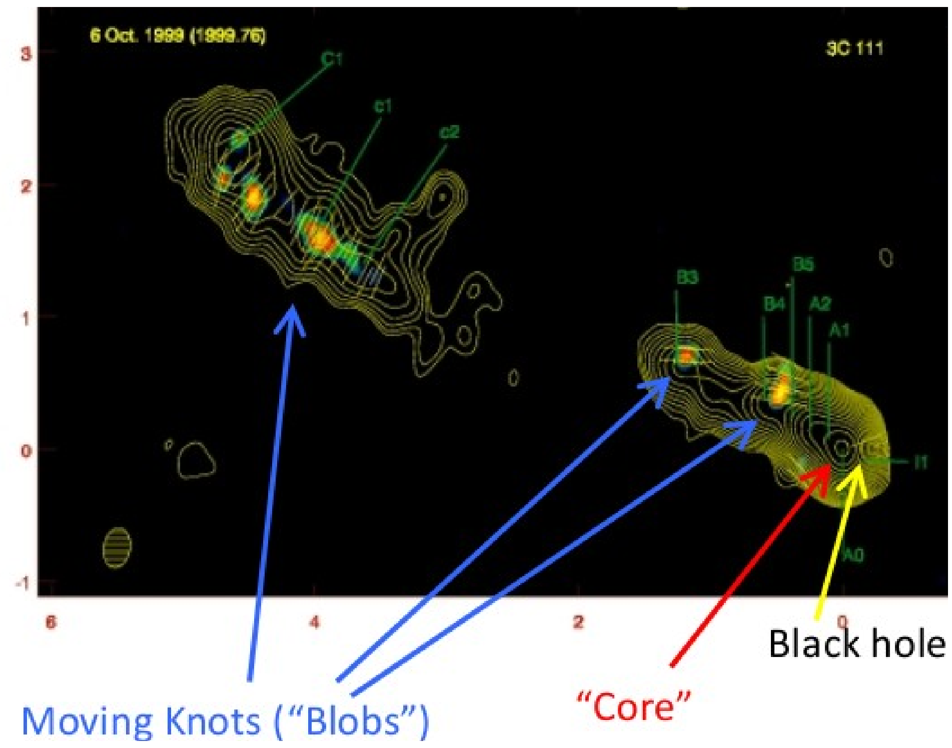
Marcella Massardi
INAF-IRA & Italian ARC

The state-of-the-art

- The high frequency bright flux density (> 0.1 Jy) population is dominated by compact Doppler-boosted sources.
- Self-absorbed synchrotron emissions from knot-like structures closer and closer to the AGN.
- Polarized signal typically is a few percent of the total intensity (~ 2.5 % at 20 GHz).
- Spectral indices in total intensity and polarization are similar on average.
- There are several sources for which the spectral behaviour is different in polarization.
- Polarization properties of extragalactic radio sources at high frequencies (> 20 GHz) are still poorly constrained.



$$1\,Jy = \frac{10^{-26}\,W}{m^2 \cdot Hz} = \frac{10^{-23}\,erg}{s \cdot cm^2 \cdot Hz}$$



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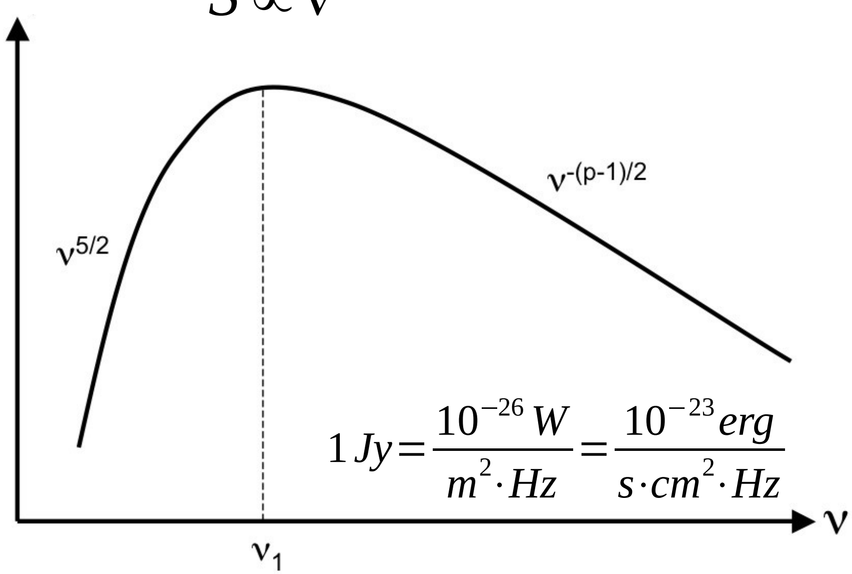
$$S \propto \nu^{\alpha}$$



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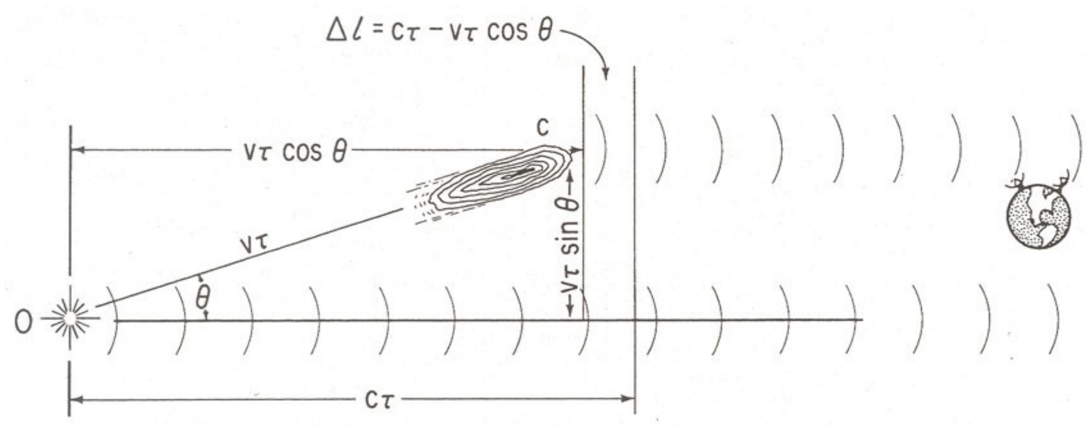
$$\mathcal{D} = \frac{1}{\gamma(1 \mp \beta \cos\theta_0)}$$



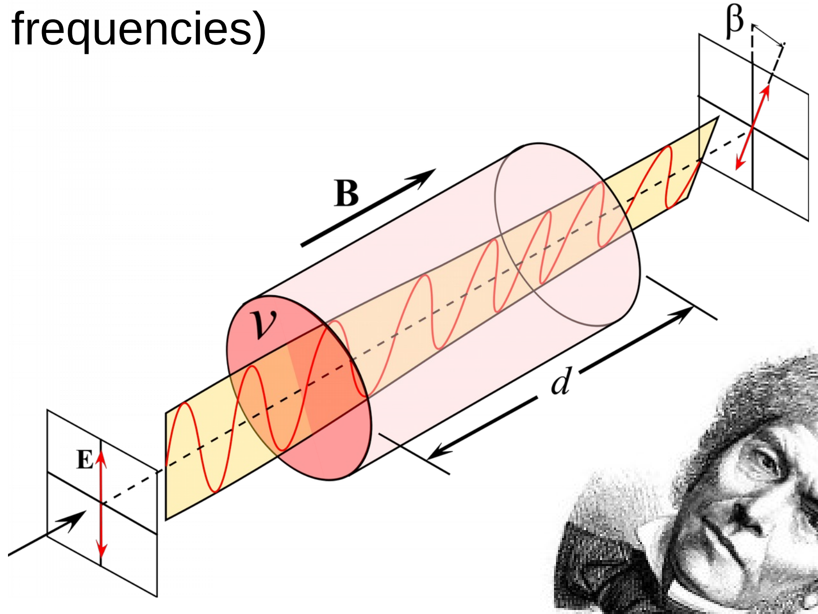
Polarimetric observations

- Polarized signal is a tiny fraction of total intensity emission (down to ≈ 1 mJy)

$$\sigma_{th} = \frac{2k_B T_{sys}}{A_{eff}\left[N(N-1)\Delta\nu\,\tau P\right]^{1/2}}$$

e.g., for a 2.5 % we need a factor ~2.0x10^3 more in τ!

- Depolarizations: beam dep., intra-band dep., Faraday rot. by electrons plasma
- Leakage calibration
- Polarization angle calibration
- Source variability (greater at higher frequencies)



The state-of-the-art

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 $S_{5\,\mathrm{GHz}} > 1.3\,\mathrm{Jy}$
Okudaira *et al.* (1993)[24]	10	99	flat-spectrum sources with $S_{5\,\mathrm{GHz}} > 0.8\,\mathrm{Jy}$
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 $S_{1.4\,\mathrm{GHz}} > 2.5\,\mathrm{mJy}$
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 $S_{0.4\,\mathrm{GHz}} > 0.8\,\mathrm{Jy}$
Lister (2001)[29]	43	32	90% complete sample with $S_{5\,\mathrm{GHz}} > 1.3\,\mathrm{Jy}$
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 $S_{5\,\mathrm{GHz}} > 1\,\mathrm{Jy}$
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 $S_{20\,\mathrm{GHz}} > 40\,\mathrm{mJy}$
Tripp *et al.* (2010)[35]	[80, 267]	86	complete sample with $S_{90\,\mathrm{GHz}} > 0.2\,\mathrm{Jy}$
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 $S_{20\,\mathrm{GHz}} > 500\,\mathrm{mJy}$
Agudo *et al.* (2014)[38]	86, 229	211	complete sample of flat-spectrum sources with $S_{86\,\mathrm{GHz}} > 1\,\mathrm{Jy}$
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)

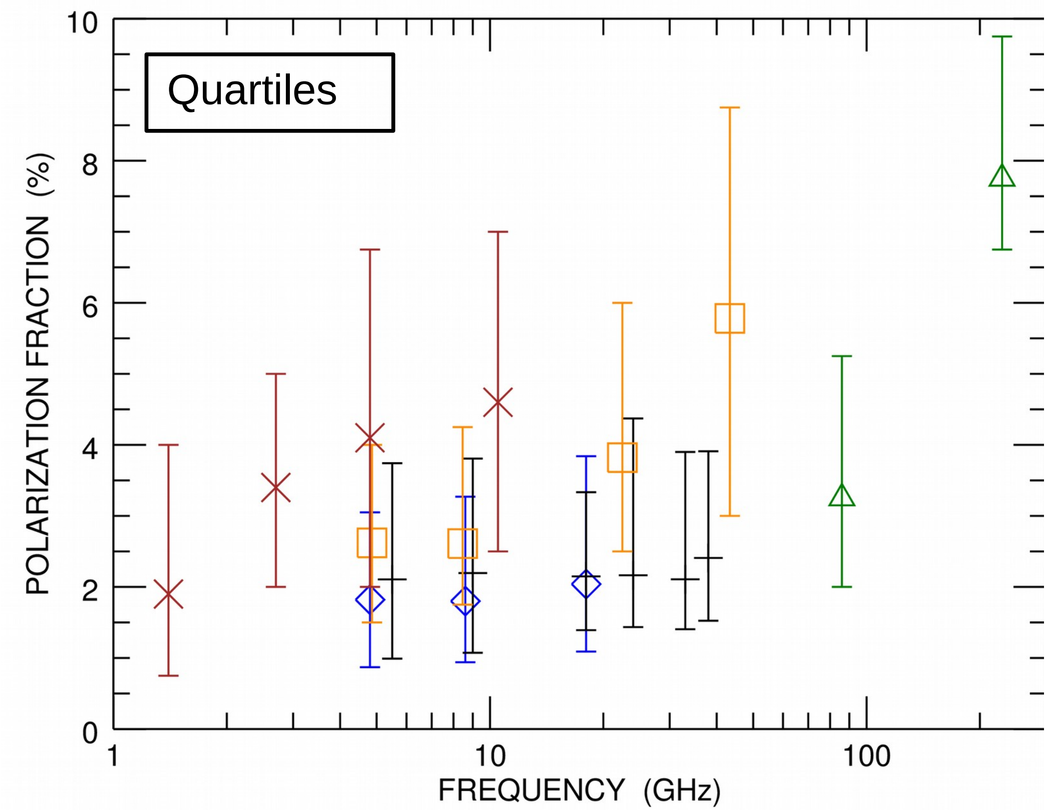
Compilations (no close observations at different frequencies, no completeness)

Spectral selection (no completeness)

High flux density treshold, i.e. ≈ 1 Jy (WMAP, PLANCK catalogues)

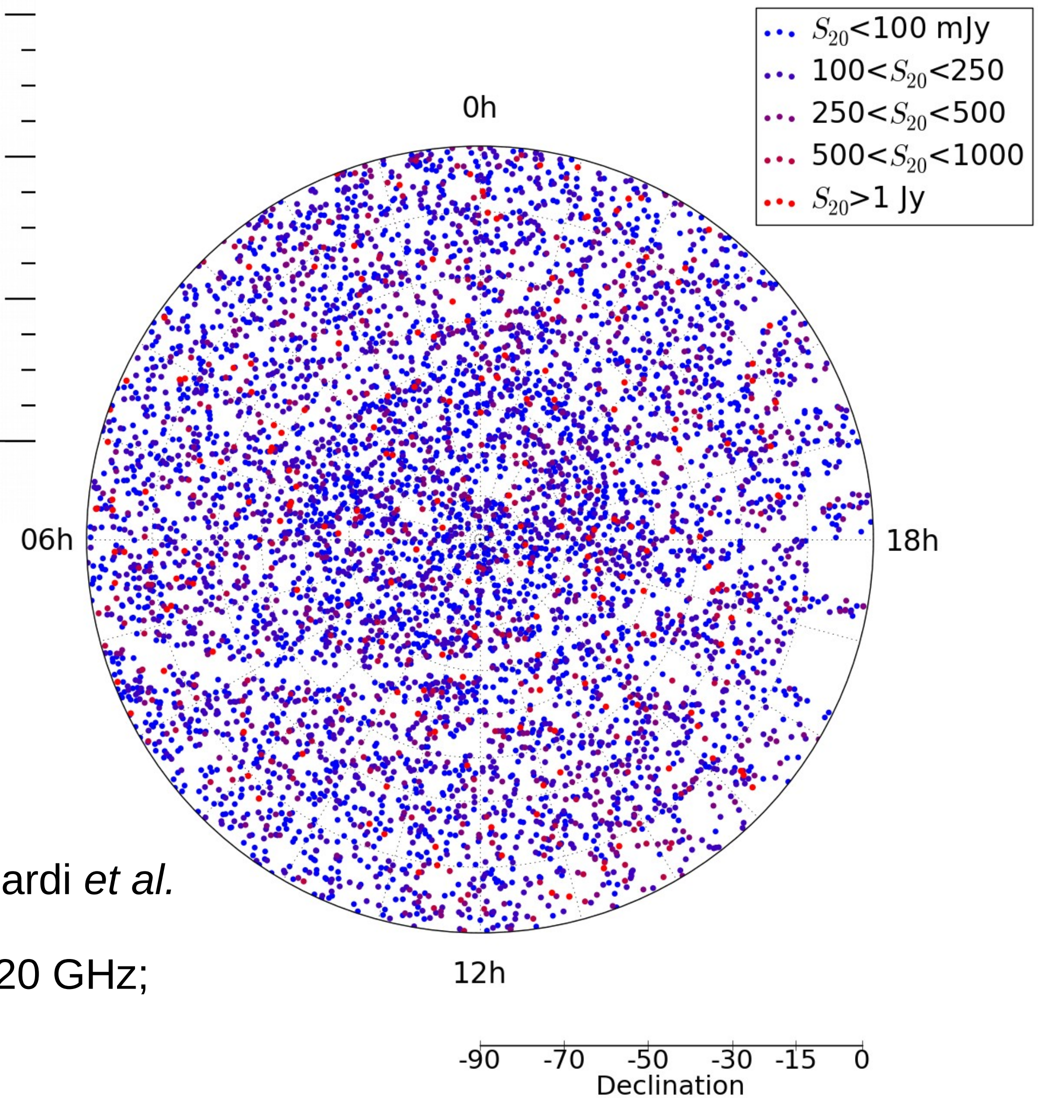
Complete sample with high frequency obs.

The state-of-the-art



x Klein et al. 2003 (# 192, B3-VLA)
□ Sajina et al. 2011 (# 159 from AT20G)
Δ Agudo et al. 2014 (# 211, $S_{86\ GHz}$ > 1 Jy)
◊ AT20G survey (# 467, $S_{20\ GHz}$ > 40 mJy)
– Sep 2014 obs. (# 53, $S_{20\ GHz}$ > 200 mJy)

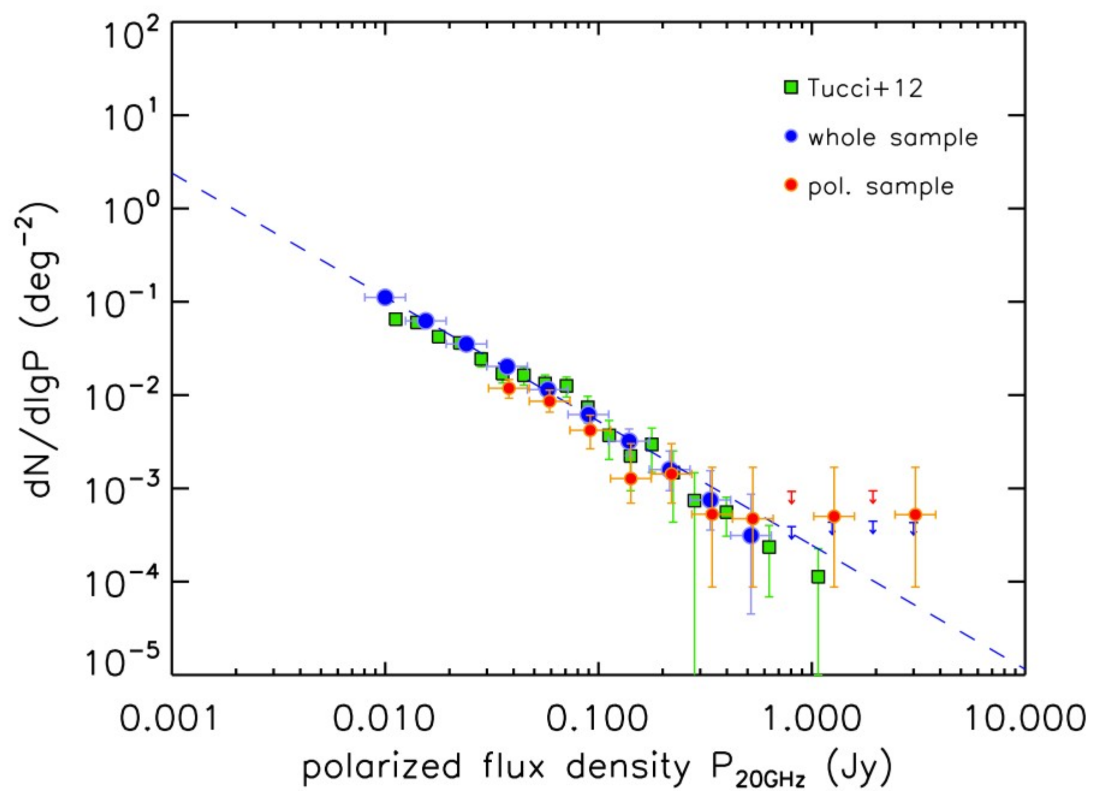
V. Galluzzi *et al.* 2016,
(Int. J. Mod. Phys. D 25, 11)



The AT20G survey (T. Murphy *et al.* 2010; M. Massardi *et al.* 2011):
5890 sources; only 768 detected in polarization at 20 GHz; only 467 have also detections at 5 and/or 8 GHz.

Polarimetric observations: goals

- **Characterize the polarization properties (e.g. the fractional polarization trend with frequency and Faraday depolarization at lower frequencies) of radio source populations.**
- **Statistically study the geometry of the emission regions, i.e. properties of magnetic fields and matter distributions of the surrounding and outflowing matter.**
- Estimate and remove foreground contamination from the polarised CMB angular power spectrum.



Massardi *et al.*
MNRAS 436, 2915–2928 (2013)

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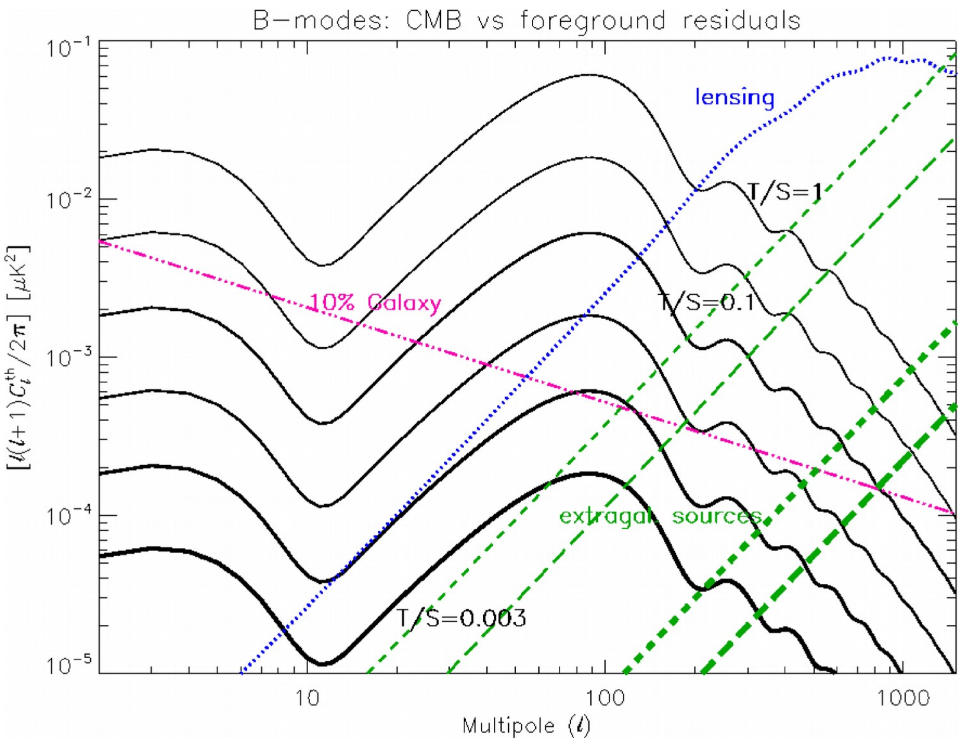
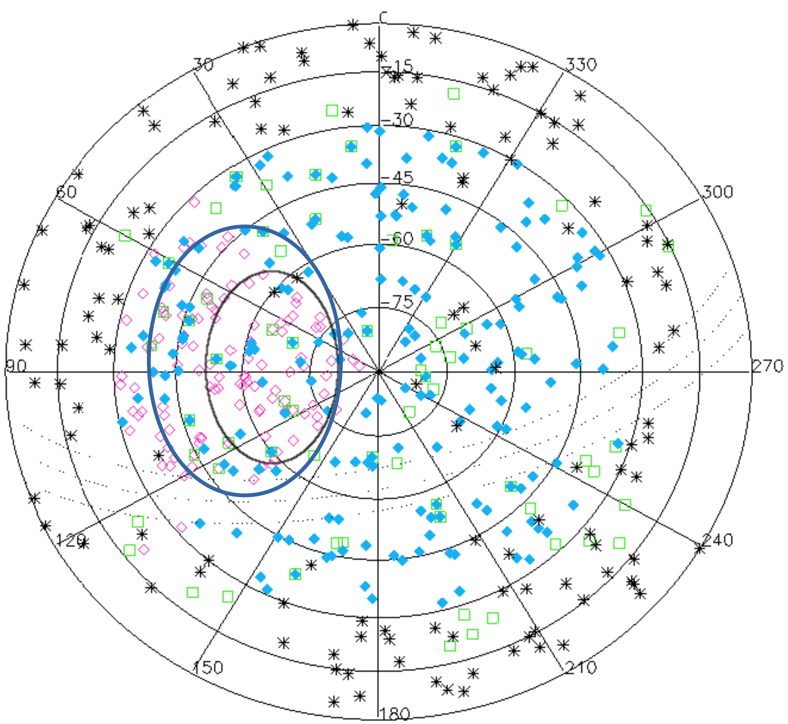


From Massardi, Galluzzi, Paladino and Burigana, Int. J. Mod. Phys. D 25 (2016) 1640009

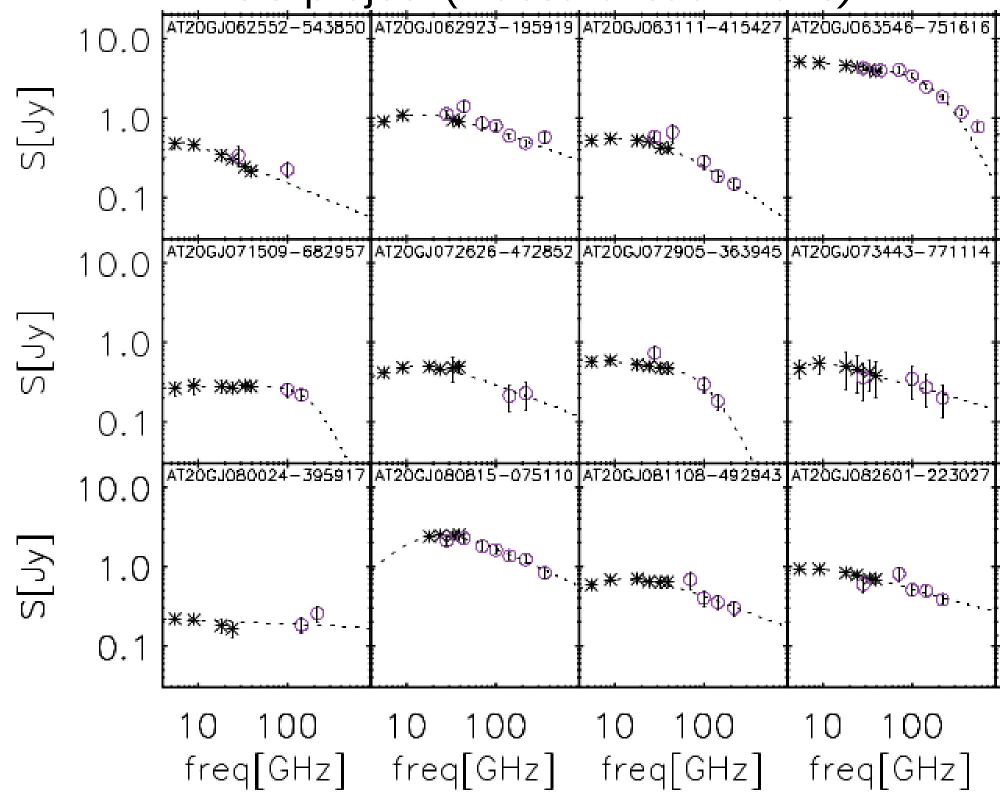
ATCA observations

Epoch	Time allocated	frequencies	# objects	region
Sep. 2014	21 h	[5.5;38] GHz	53	b < - 75°
Mar.-Apr. 2016	26 h	[5.5;38] GHz	54	-75° ≤ b < -65°
	14 h	2.1 GHz	107	b < - 65°

- Spatial configuration: H214 (hybrid and compact). Resolution $\lambda/b_{max} \approx 5 \div 36$ arcsec (without CA06); $0.5 \div 4$ arcsec (with CA06).
- Integration on source: at least 3 min (e.g. 2X1.5 min, at least 2 cuts at different hour angles).
- Sensitivity: ≈ 0.7 mJy (≈ 1 mJy for 2.1 GHz).



PACO project (Massardi *et al. 2015)*



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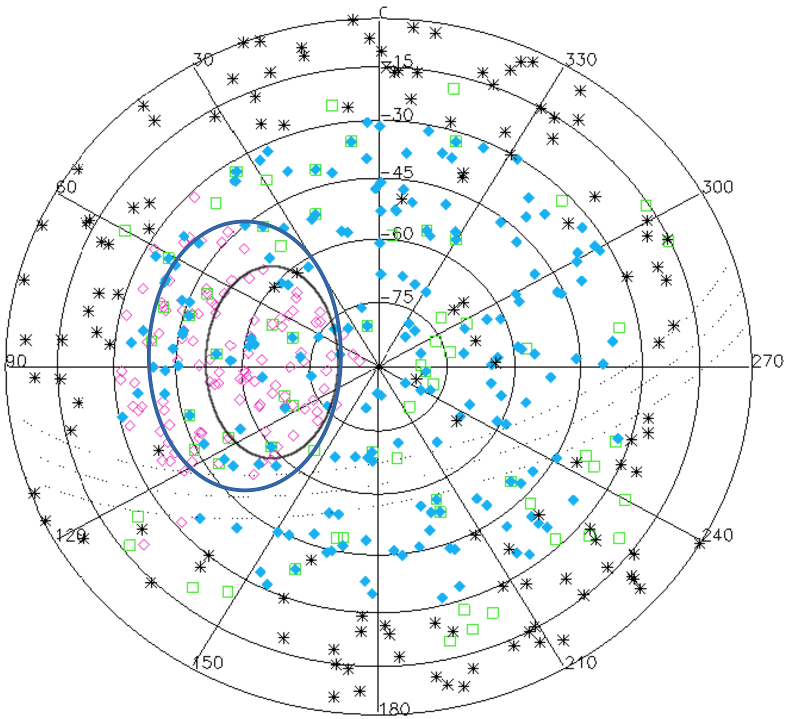
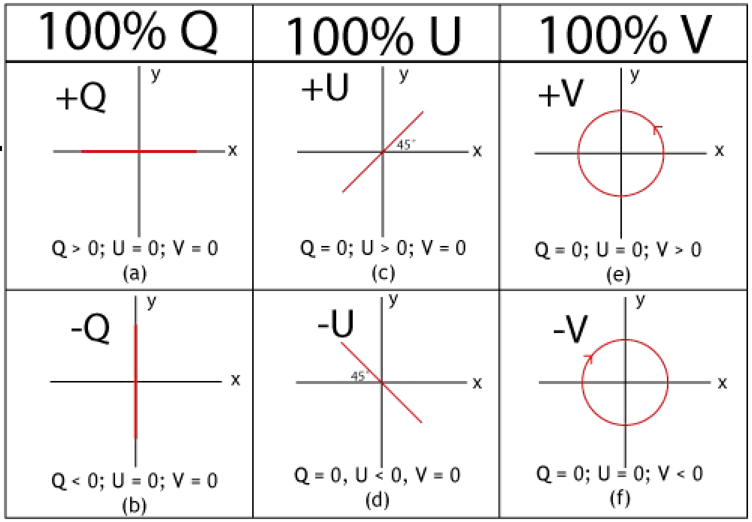


ATCA obs (Sep 2014, Mar-Apr 2016)



- Observations consider all the Stokes parameters I,Q,U,V.
- Total intensity flux I with associated error $\sigma_I = \sigma_V$ (+ 2.5% I).
- Polarized flux density:

$$P = \sqrt{Q^2 + U^2 - \sigma_V^2} \qquad \sigma_P = \sqrt{\frac{Q^2\sigma_Q^2 + U^2\sigma_U^2}{Q^2 + U^2}} \text{ (+10\% P)}$$

  – Overall detection rate in polarimetry is about **90% at 5 σ.**

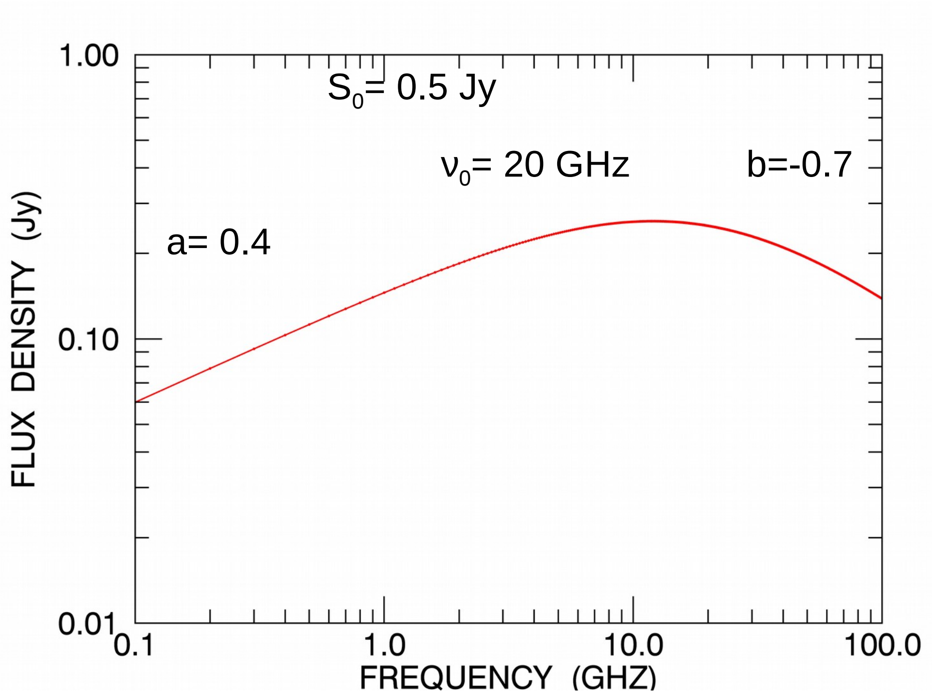
- Double power law for fitting spectra both in total intensity and in polarization:
  – Total intensity: 4X512 MHz chuncks;
  – Polarization: 2X1 GHz chuncks.

$$S(\nu) = \frac{S_0}{\left(\frac{\nu}{\nu_0}\right)^{-a} + \left(\frac{\nu}{\nu_0}\right)^{-b}}$$

  – Success rates:

  85% total intensity ($\chi^2 \approx 1.15$);

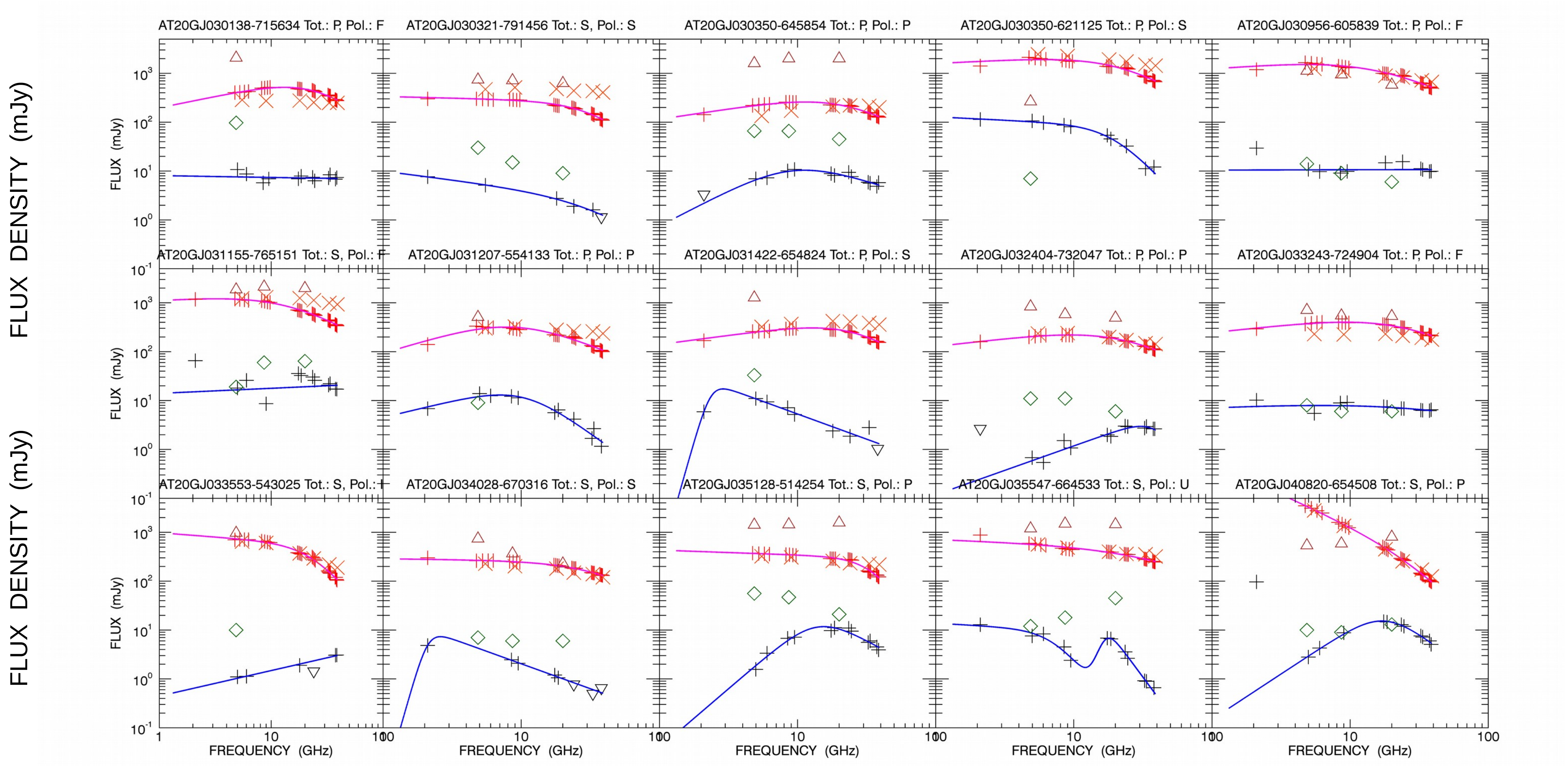
  70% polarization ($\chi^2 \approx 1.86$).



ATCA obs (Sep 2014, Mar-Apr 2016)

Spectra in total intensity and polarization

(error bars are smaller than plot symbols)



+ Tot. int. Sep2014

Δ Tot. int. AT20G (best epoch in 2004-2008)

x Tot. int. PACO (Jul 2009-Aug 2010)

– Tot. int. fitting curve

+ Pol. Sep2014

◊ Pol. AT20G (best epoch in 2004-2008)

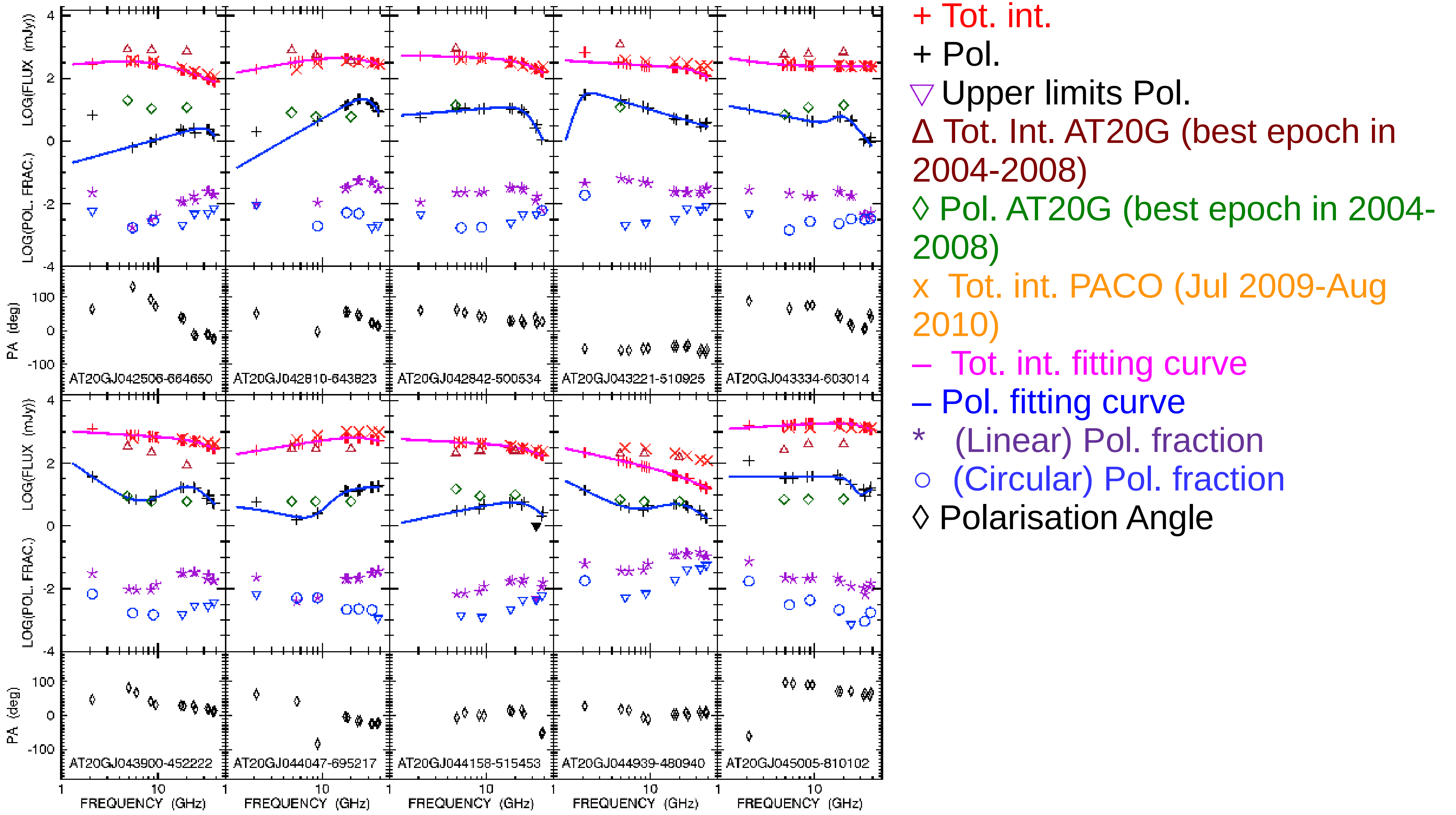
▽ Upper limits Pol.

– Pol. fitting curve

ATCA obs (Sep 2014, Mar-Apr 2016)

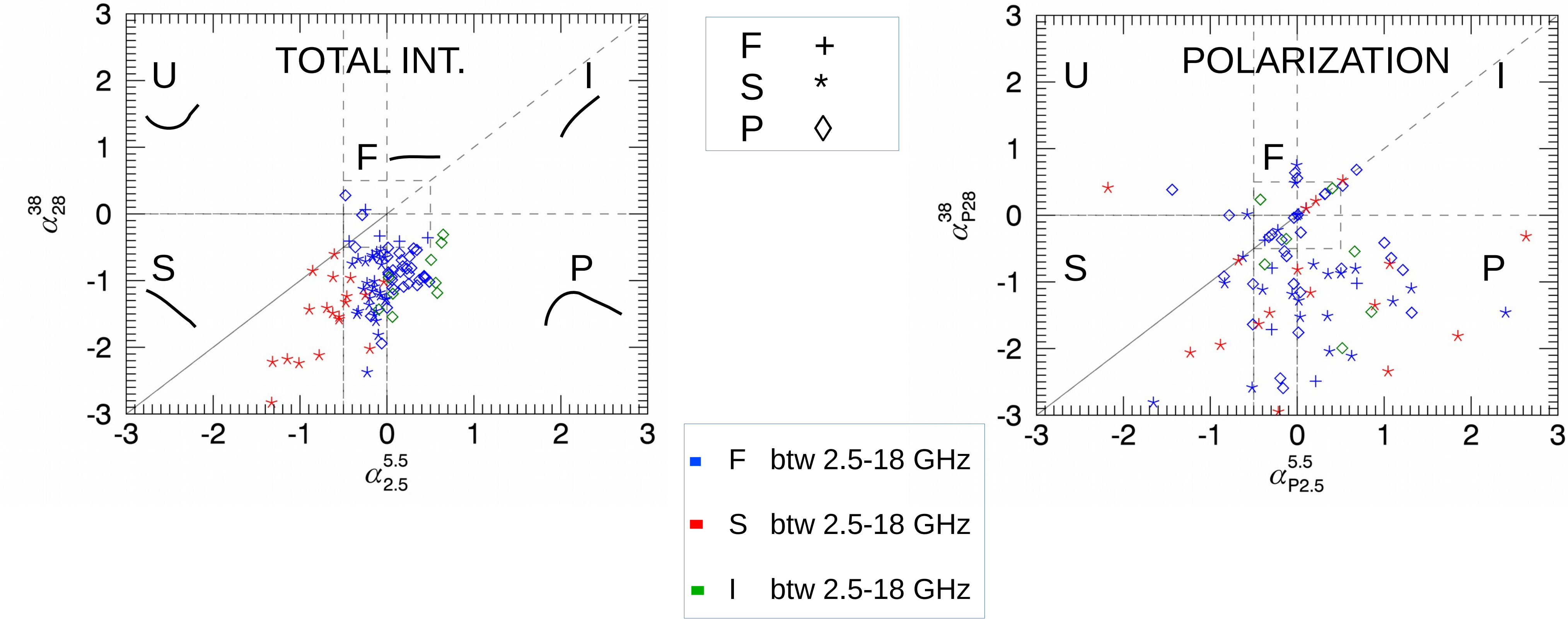
Spectra in total intensity and polarization; pol. fraction and PA

(error bars are smaller than plot symbols)



Color-color plots

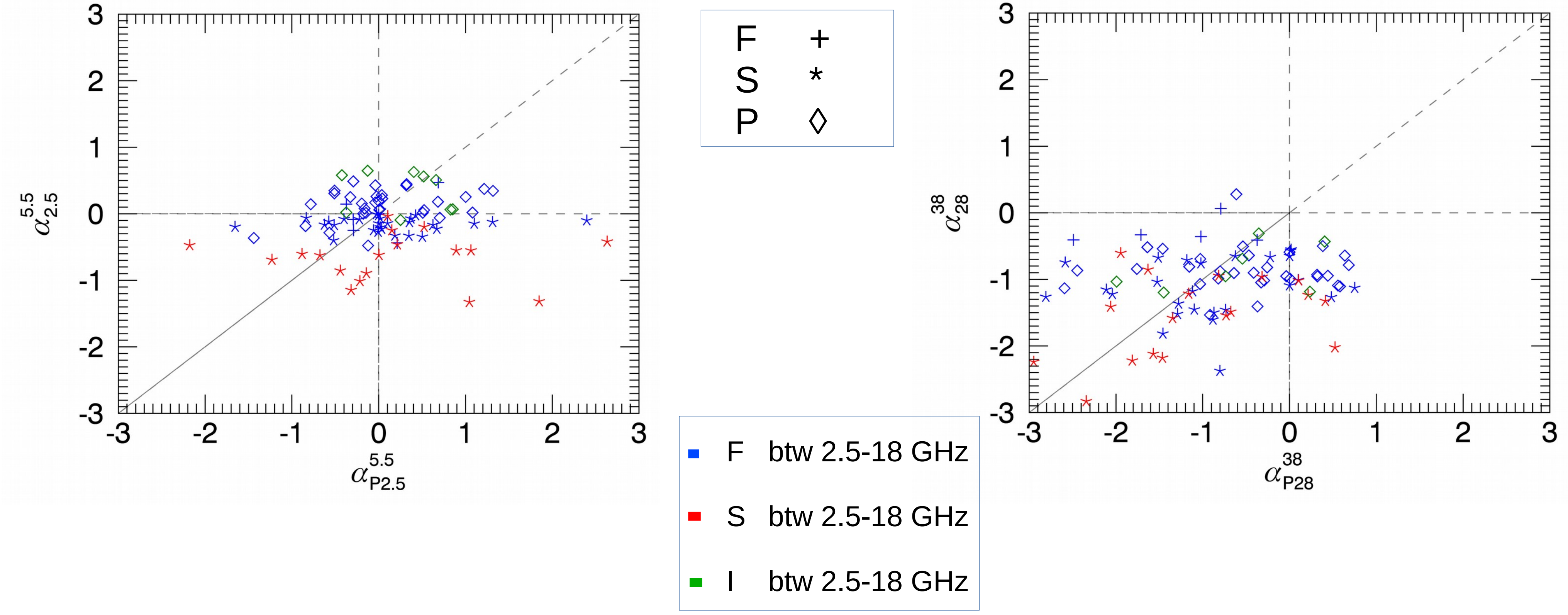
(error bars are smaller than plot symbols)



Tot. Int. → Pol. Int. ↓	(I)	(P)	(F)	(S)	(U)	
(I)	0	4	0	1	0	5
(P)	0	17	3	21	0	41
(F)	0	14	1	6	0	21
(S)	0	10	2	13	0	25
(U)	0	5	0	4	0	9
(NA)	0	1	0	2	0	3
	0	41	6	46	0	

Colour-colour plots

(error bars are smaller than plot symbols)



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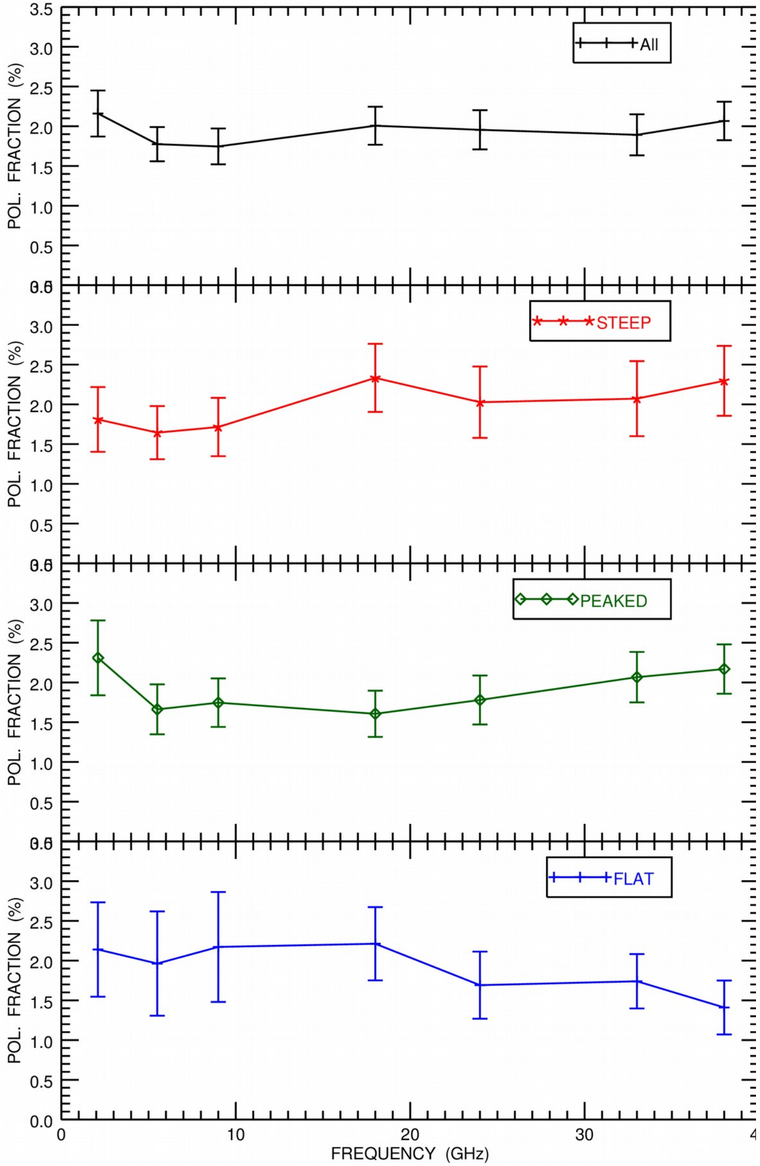
(S)	0	10	2	13	0	25
(U)	0	5	0	4	0	9
(NA)	0	1	0	2	0	3
	0	41	6	46	0	

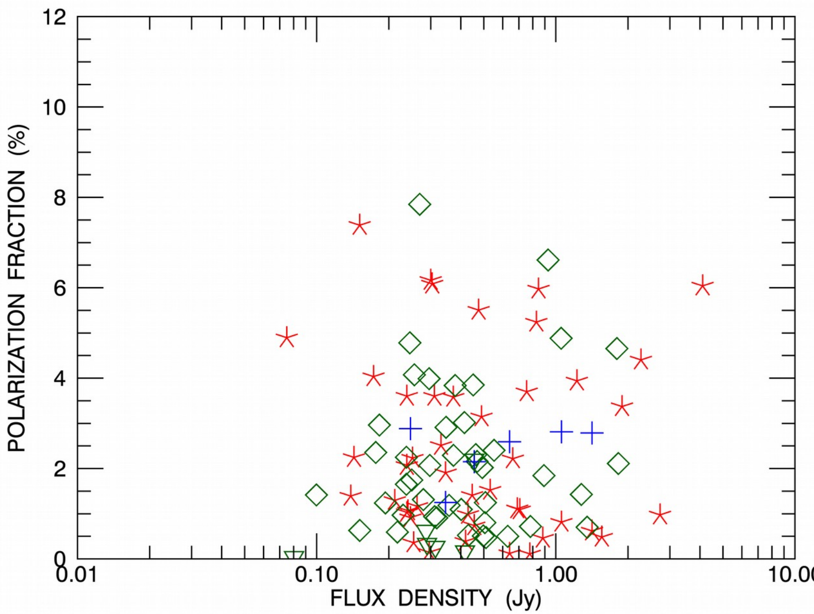
Tot. Int.	2.5 – 5.5	5.5 – 10	10 – 18	18 – 28	28 – 38 GHz
All	−0.06	−0.13	−0.23	−0.55	−0.95
Steep	−0.23	−0.31	−0.43	−0.75	−1.24
Peaked	0.23	0.07	−0.08	−0.42	−0.88
Flat	0.00	−0.05	−0.15	−0.21	−0.30
Pol. Int.	**2.5 – 5.5**	**5.5 – 10**	**10 – 18**	**18 – 28**	**28 – 38 GHz**
All	0.04	−0.03	−0.08	−0.54	−0.82
Steep	0.03	−0.13	−0.18	−0.81	−1.16
Peaked	0.04	0.01	0.01	−0.18	−0.81
Flat	−0.04	−0.04	−0.34	−0.46	−1.04

(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.



F	+
S	*
P	◊



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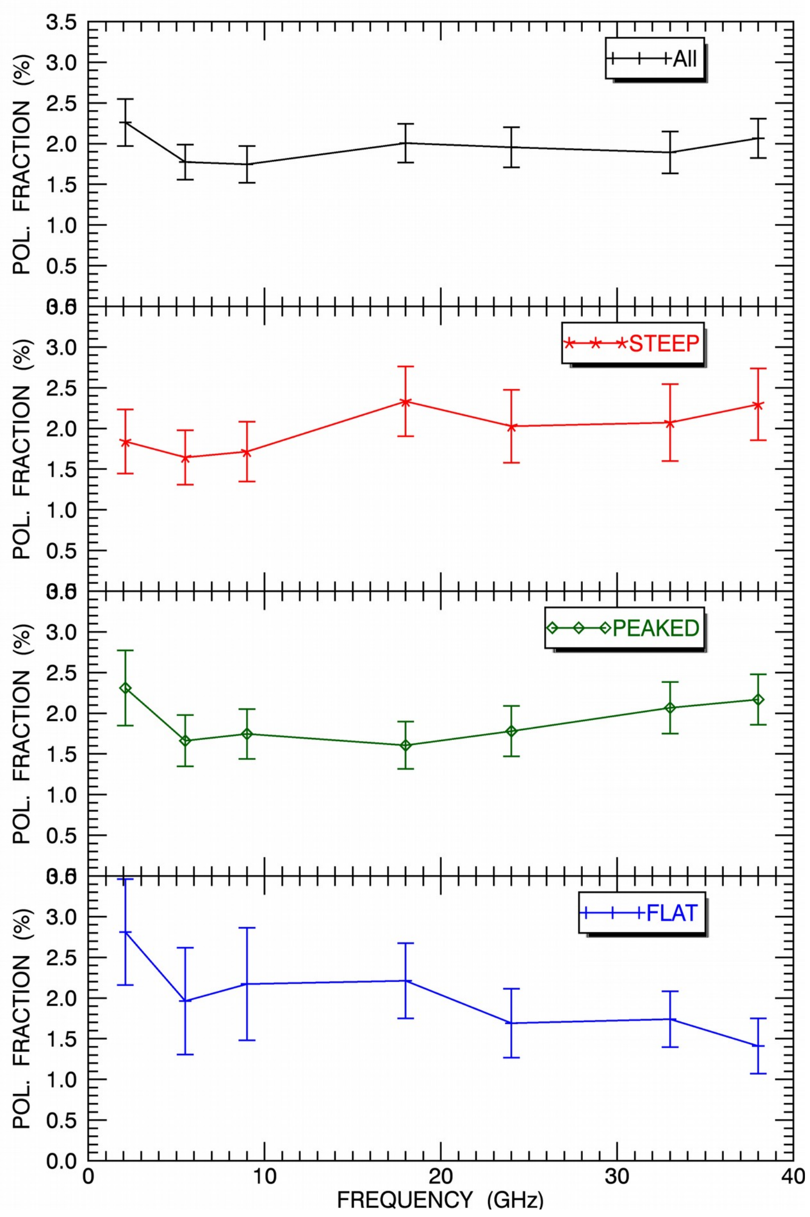
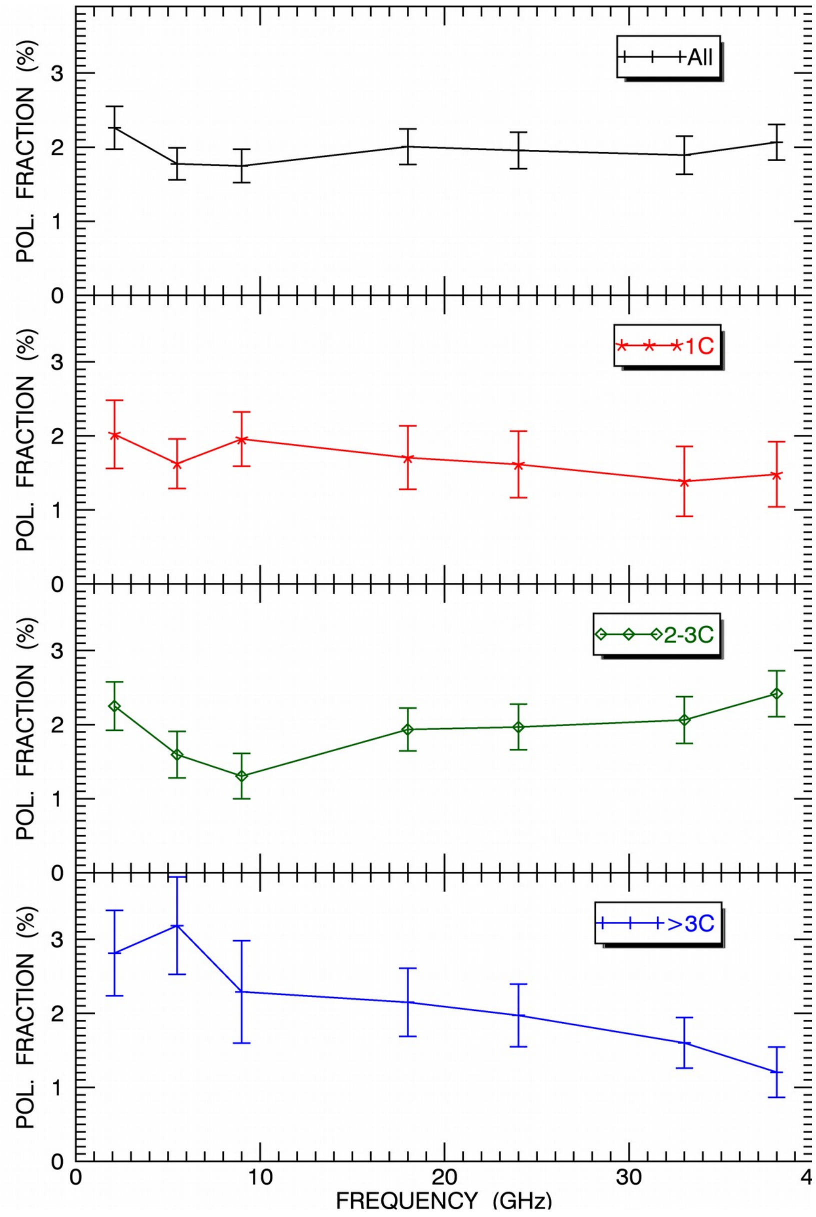
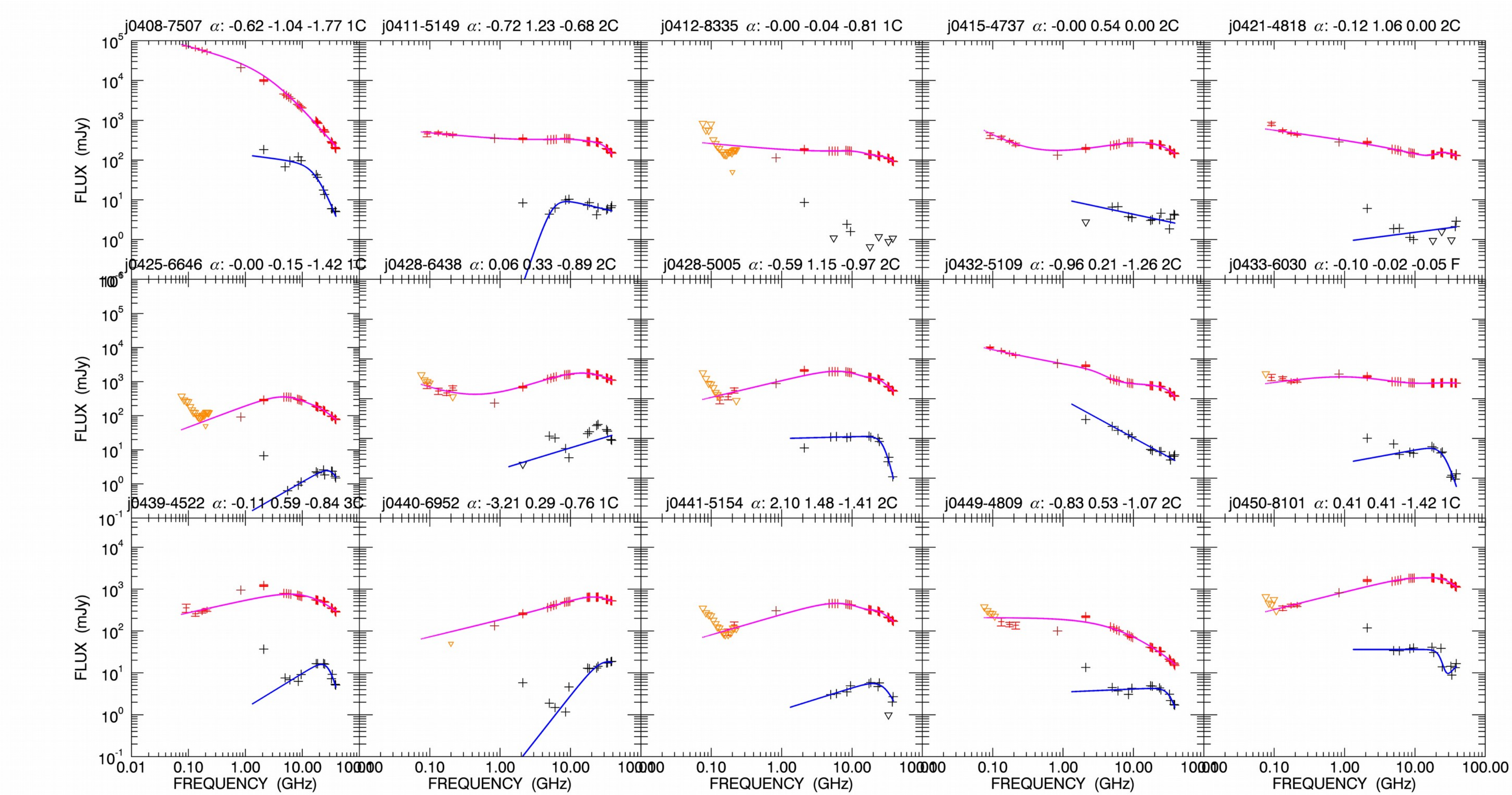


F +
S *
P ◊



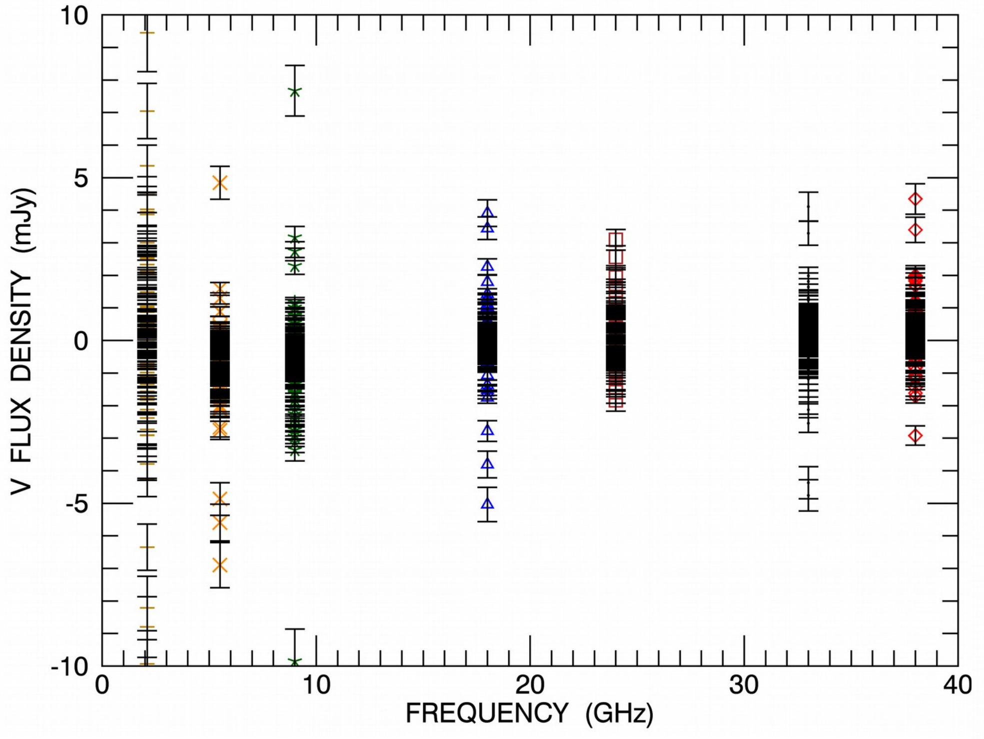
GLEAM (MWA) + C2922 (ATCA)

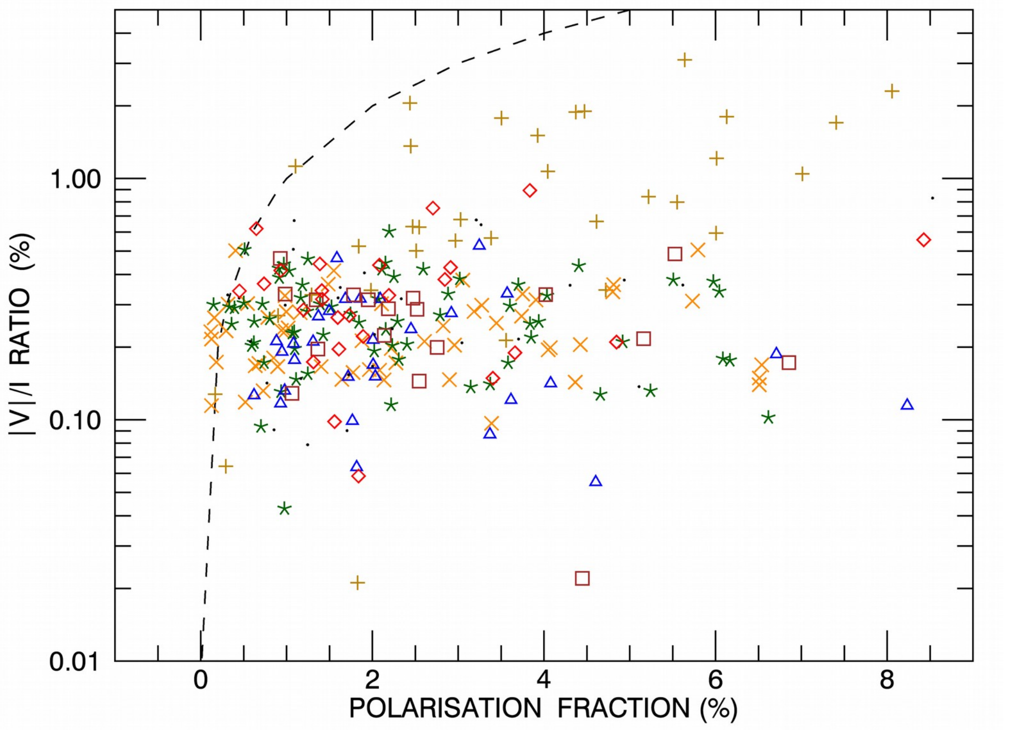
- 69% of C2922 objects are in GLEAM (GaLactic and Extragalactic All-sky Murchinson Widefield Array) survey at 200 MHz (Hurley-Walker et al. 2017)



(Circular) Polarization fractions

- Intrinsic circular polarization is typically very weak, i.e. ≤ 0.1 %, a direct proxy for magnetic field strenght.
- Detection rate at ≈ 35% at all the observed frequencies, with peaks of more than 50% at 5.5 and 9 GHz:
- 5.5 GHz → (0.17+-0.02)%   9 GHz → (0.20+-0.02)%
- These higher values probably due to Faraday conversion.





Polarization angle

- Measure of the relative polarization angle from Q and U flux densities:

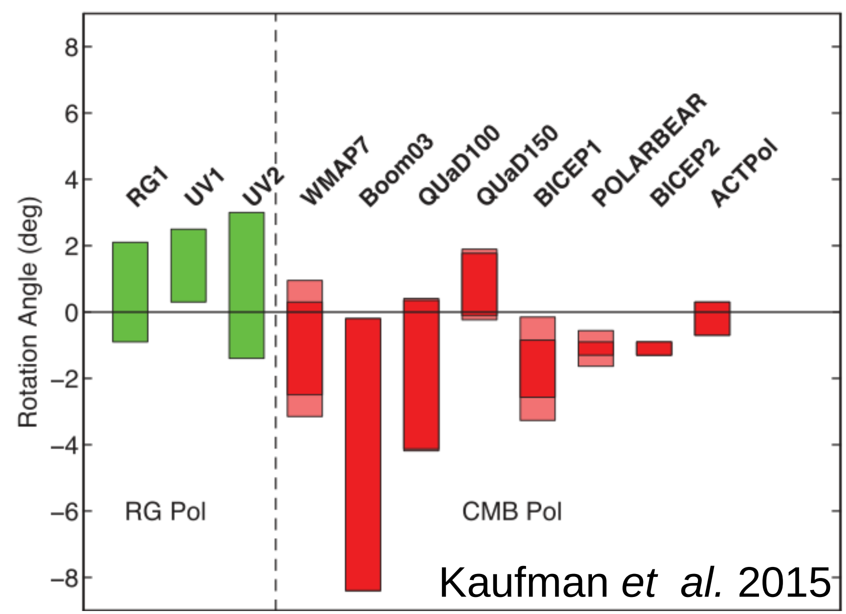
$$\phi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right) \qquad \sigma_\phi^2 = \frac{Q^2\sigma_U^2 + U^2\sigma_Q^2}{4(Q^2+U^2)^2} + \sigma_{\phi,\,cal}^2.$$

- Statistical error associated to PA is ≈1-2% at all frequencies.
- Calibration procedures are expected to contribute for an additional ≈ 3 deg to the global error (the latter is an order of magnitude higher).

→ **Hence, we can assess a resulting accuracy of 3 deg about relative PA measured.**

- Polarimetric studies on radio source population can provide potential calibrators for the PA to reduce the calibration error at sub-degree scale.
- They are useful for CMB experiments and for further studies constraining Cosmic Polarization Rotation (CPR) in radio and sub-mm bands.

Quijote CMB experiment (11-40 GHz)



Kaufman *et al.* 2015

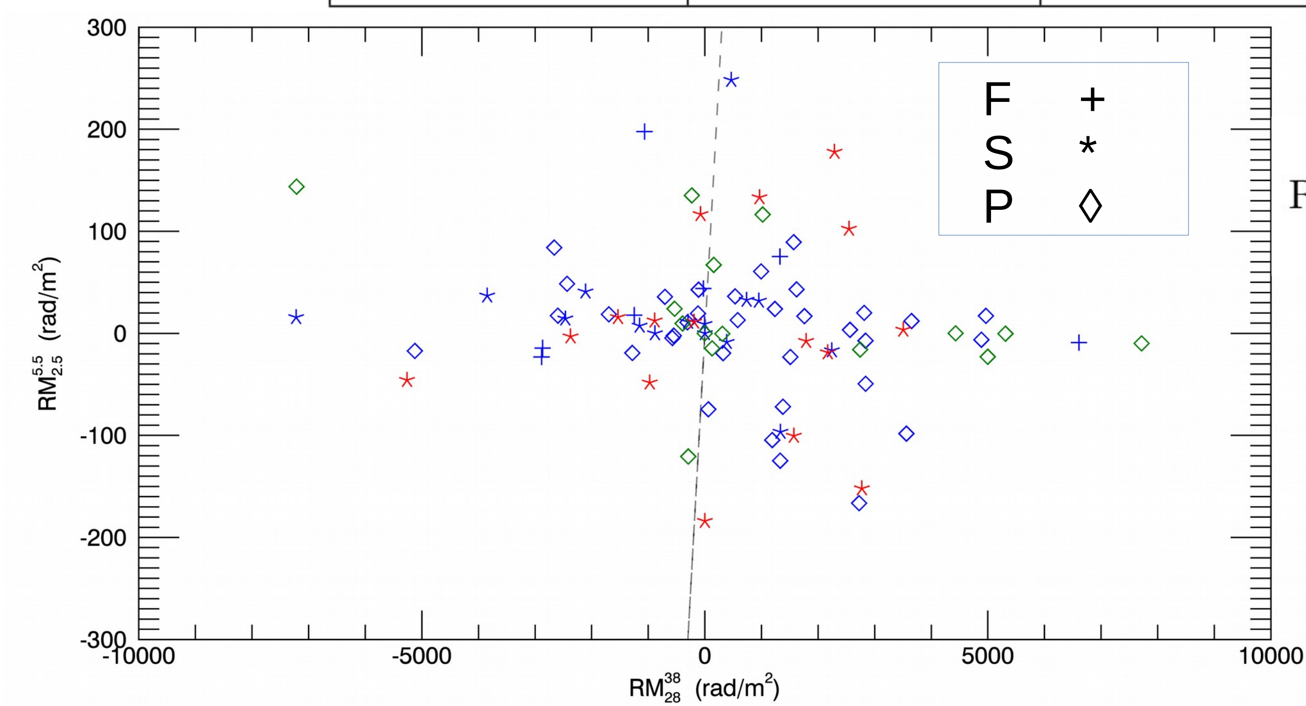
Polarization angle

- Only 6 objects can be fit by the linear RM relation over the 2.1-38GHz range
- We identify two regimes, i.e. cm and mm-wavelenghts and perform separate linear fit

(~57%   cm, ~69% mm)

All sample (58)			1C (15)			2-3C (34)			>3C (8)		
I	med	III	I	med	III	I	med	III	I	med	III
20	34	53	23	43	89	17	32	52	-	34	-
All sample (26)			1C (7)			2-3C (15)			>3C (4)		
I	med	III	I	med	III	I	med	III	I	med	III
217	362	719	-	310	-	160	354	648	-	755	-

All sample (72)			1C (15)			2-3C (47)			>3C (8)		
I	med	III	I	med	III	I	med	III	I	med	III
196	639	1439	283	689	1129	241	630	1359	-	1426	-
All sample (33)			1C (5)			2-3C (23)			>3C (4)		
I	med	III	I	med	III	I	med	III	I	med	III
415	2794	7601	-	293	-	526	2811	7522	-	8808	-



$$RM_{obs} = \frac{RM_{AGN}}{(1+z)^2} + RM_{gal} + RM_{ion}$$

<z> ~ 0.8 (~43% with z)

RM_{gal} ~ -100 rad/m^2

RM_{ion} < 5 rad/m^2

Variability

- Variability estimated via the index btw Sep 2014 – PACO (65 epochs in Jul 2009- Aug 2010) and Sep 2014-AT20G (best epoch in 2004-2008)

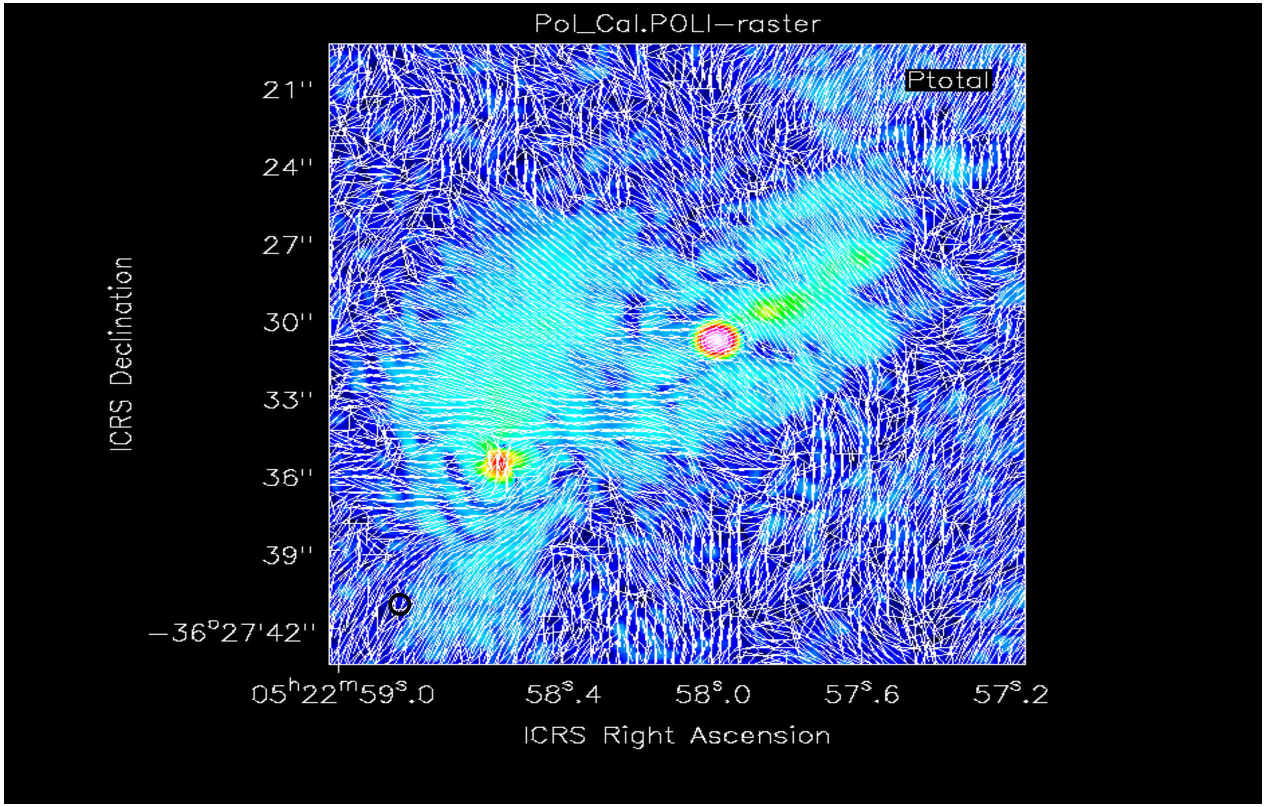
$$V.I. = \frac{100}{\langle S \rangle} \sqrt{\frac{\sum_{i=1}^{n} (S_i - \langle S \rangle)^2 - \sum_{i=1}^{n} \sigma_i^2}{n}}$$

- Increase of variability index both with frequency and time lag for total intensity.
- Given a time lag of 8 yr, the variability in polarization is greater by a factor ≈1.5 wrt total intensity.

Sel.	Time lag			Band	(GHz)		
	(yr)	5.5	9	18	24	33	38
All	4-5	14 ± 2	14 ± 2	15 ± 2	17 ± 2	21 ± 2	22 ± 2
	8	36 ± 3	32 ± 3	36 ± 3			
Steep	4-5	13 ± 3	14 ± 3	15 ± 2	17 ± 3	23 ± 3	25 ± 3
	8	35 ± 4	33 ± 5	38 ± 5			
Peaked	4-5	16 ± 2	15 ± 2	14 ± 2	16 ± 2	16 ± 3	17 ± 2
	8	38 ± 6	28 ± 6	28 ± 5			
All (pol.)	8	50 ± 7	57 ± 6	52 ± 6			

ALMA Data

- Observed proposal for ALMA-Cycle 3 to measure the polarization of the PACO faint sample at 100GHz to even higher sensitivity (down to 0.03 mJy) .
- Only 32 sources selected from the original 53 (obs. in Sep. 2014) drawn from the faint PACO sample.



Conclusions

- High sensitivity ($\sigma_P \approx$ 0.7 mJy) polarimetric observations of a complete sample of 107 extragalactic radio sources (det. rate ≈ 91%).
- Continuum spectra of over 70 % of sources well fitted by a double power law, both in total intensity and polarization.
- Polarized emission cannot be simply inferred from total intensity for several sources (bimodal behaviour for steep sources in polarization).
- Spectra both in total intensity and polarization generally steepen at $\nu \gtrsim 30$ GHz.
- No significant trend of the fractional polarization with either flux density or frequency was found.
- Polarization angle accuracy limited by calibration error at ≈ 3 deg.
- Evidence of Faraday rotation in only 6 cases over the whole 2.1-38 GHz range.
- Mean variability index in total intensity of steep-spectrum sources increases with frequency for 4-5 year lag, while no significant trend shows up for peaked-spectrum and for 8 year lag. In polarisation higher variability by a factor ≈ 1.5 wrt total intensity.