Multi-frequency (and multi-epochs) polarimetry of a complete sample of “faint” PACO sources.

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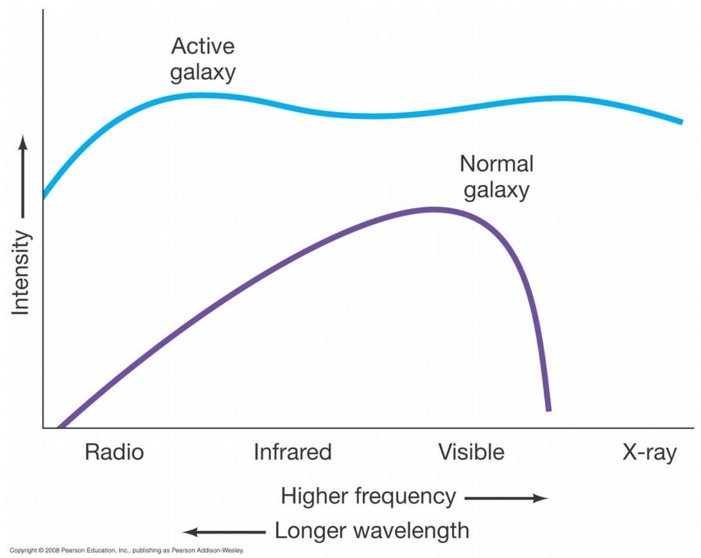
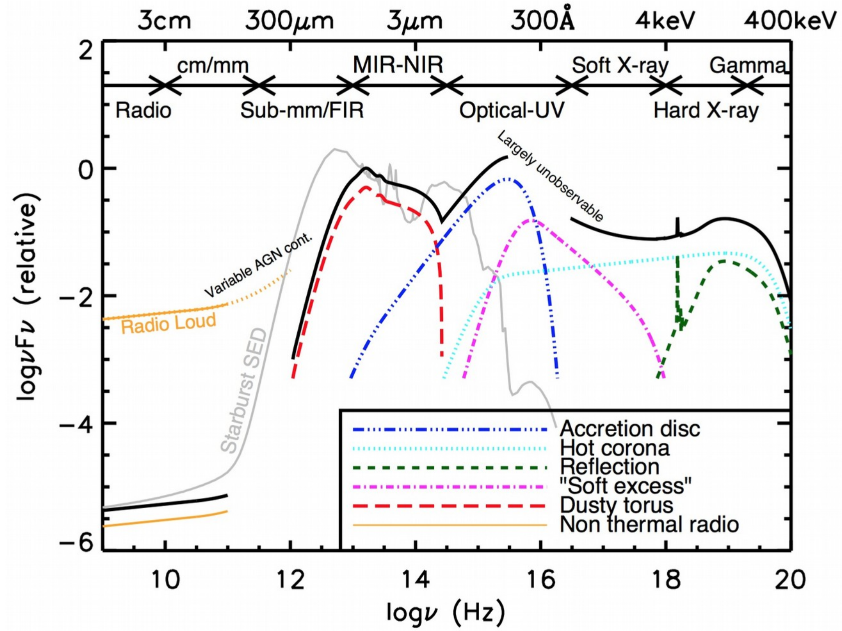
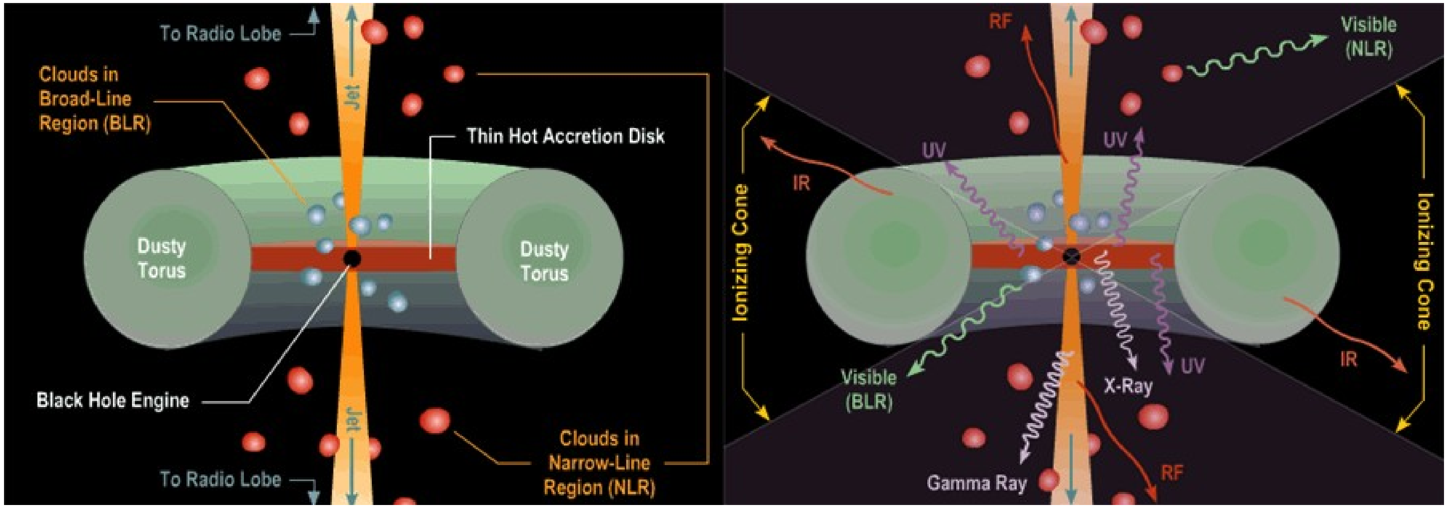
Active Galactic Nuclei

- About 1% of all the galaxies show bolometric luminosities greater than normal galaxies ones by a factor ~1000 (i.e. 10^{40}-10^{41}W)







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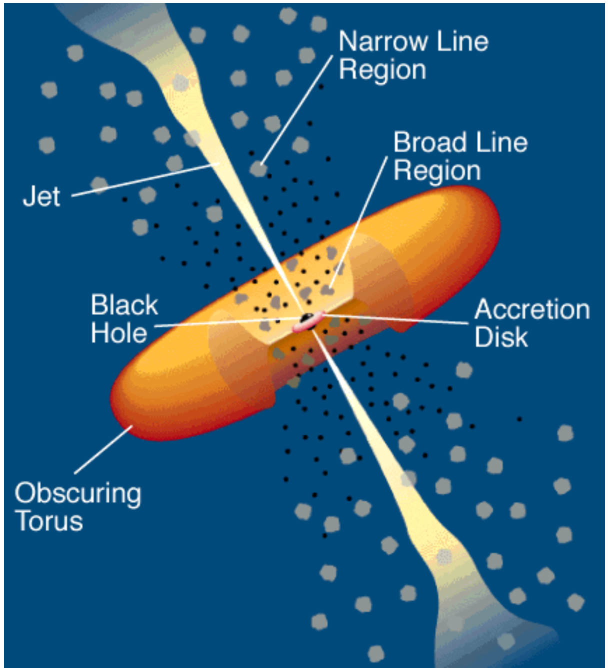
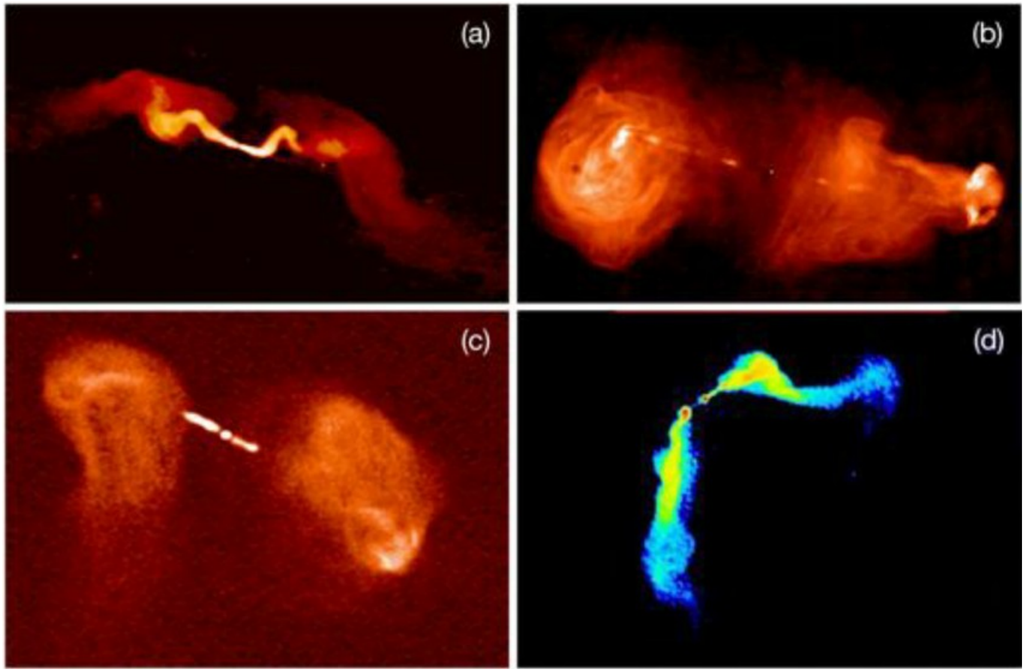
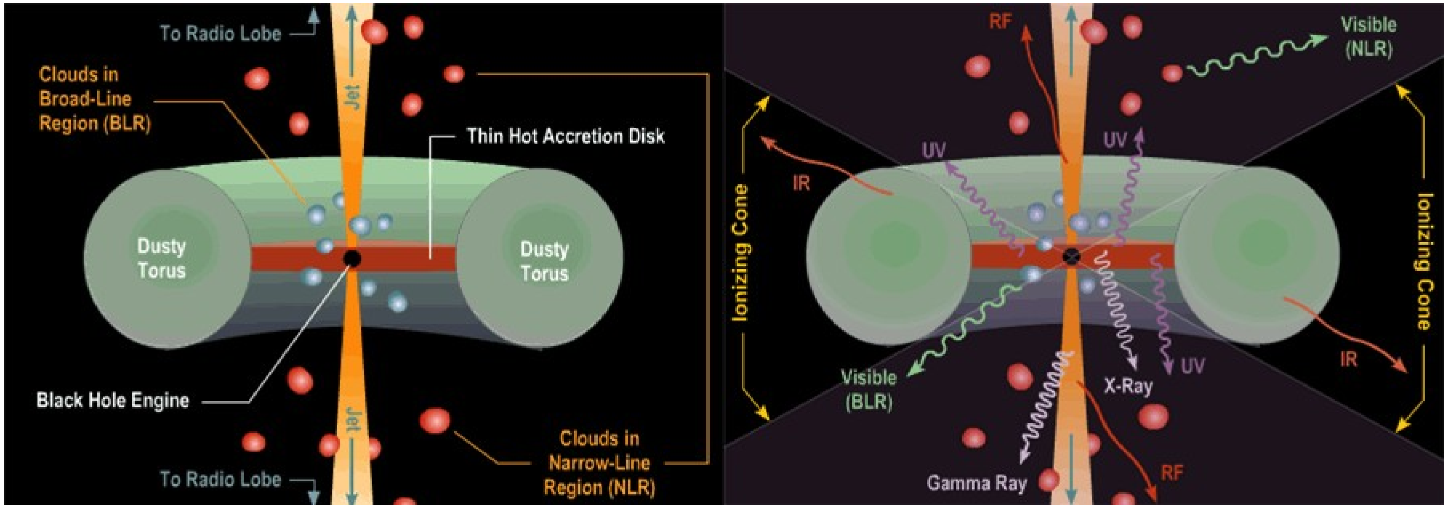
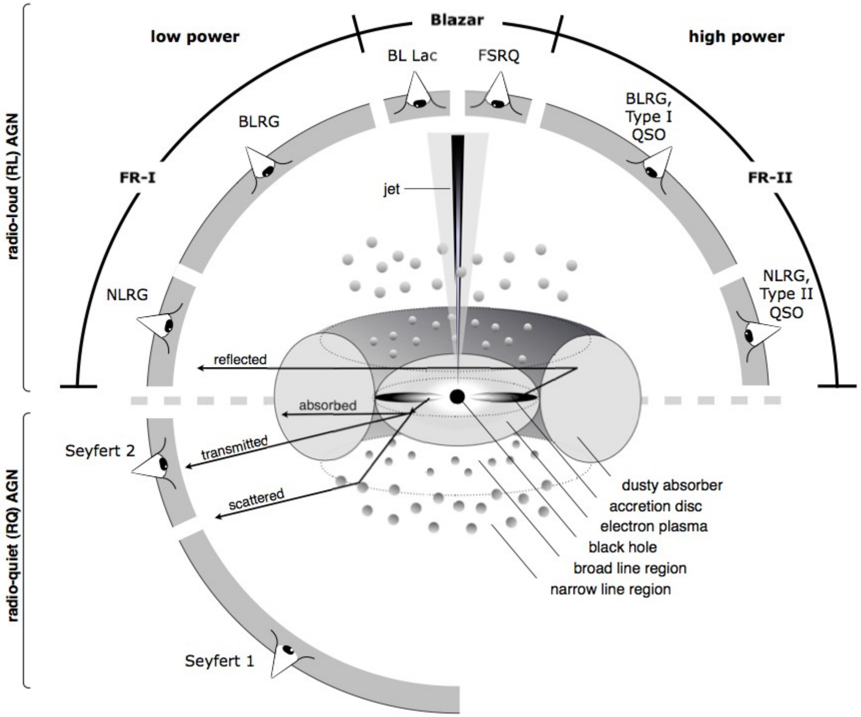
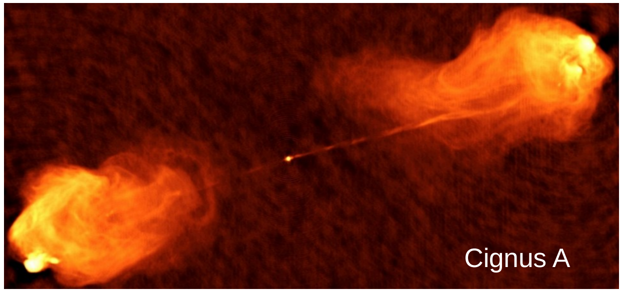


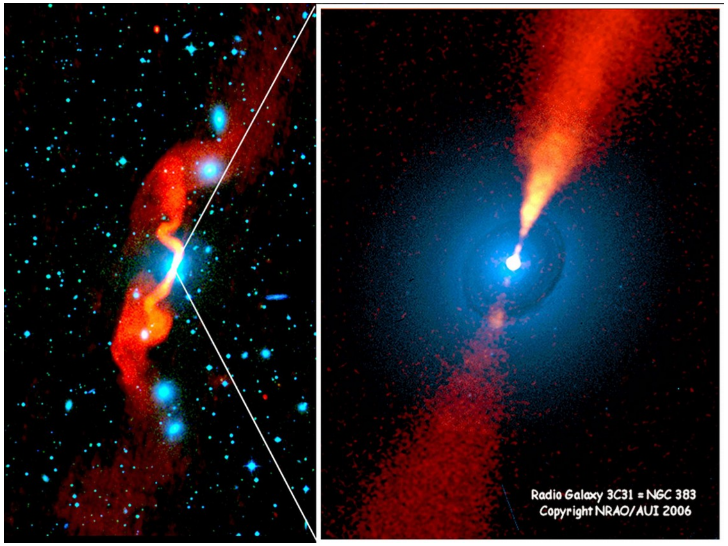




Active Galactic Nuclei





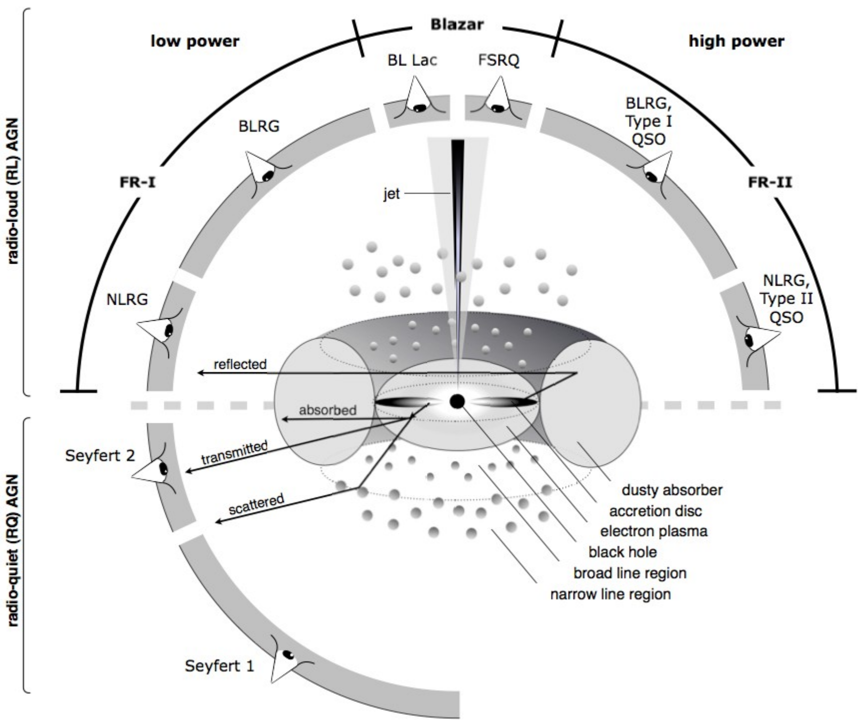


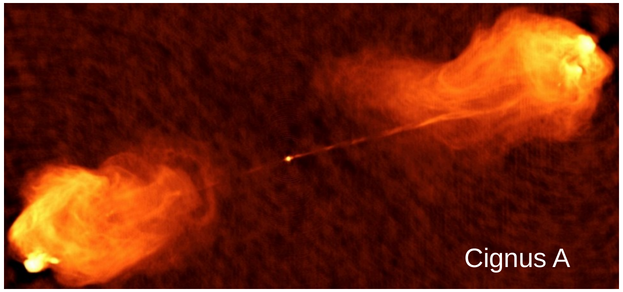
FRI	FRII
$P_{1.4} < 10^{24.5}$ Watt Hz^{-1}	$P_{1.4} > 10^{24.5}$ Watt Hz^{-1}
diffuse jets	highly collimated jets
no hot spots	bright hot spots
edge-darkened	edge-brightened
weak optical emission lines	strong optical emission lines

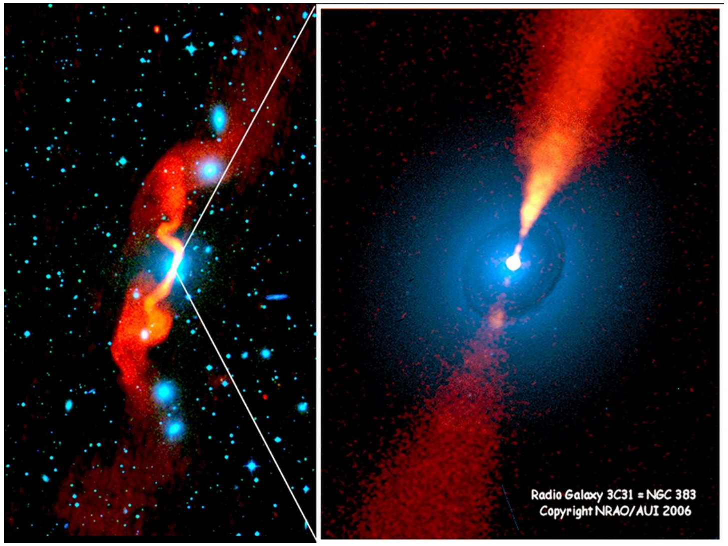
- Physical parameters:
  M, J, dM/dt, L, θ
  jet/no jet,
  jet composition
  B topology,
  host galaxy/environment

Rocco Lico,
PhD thesis

Active Galactic Nuclei





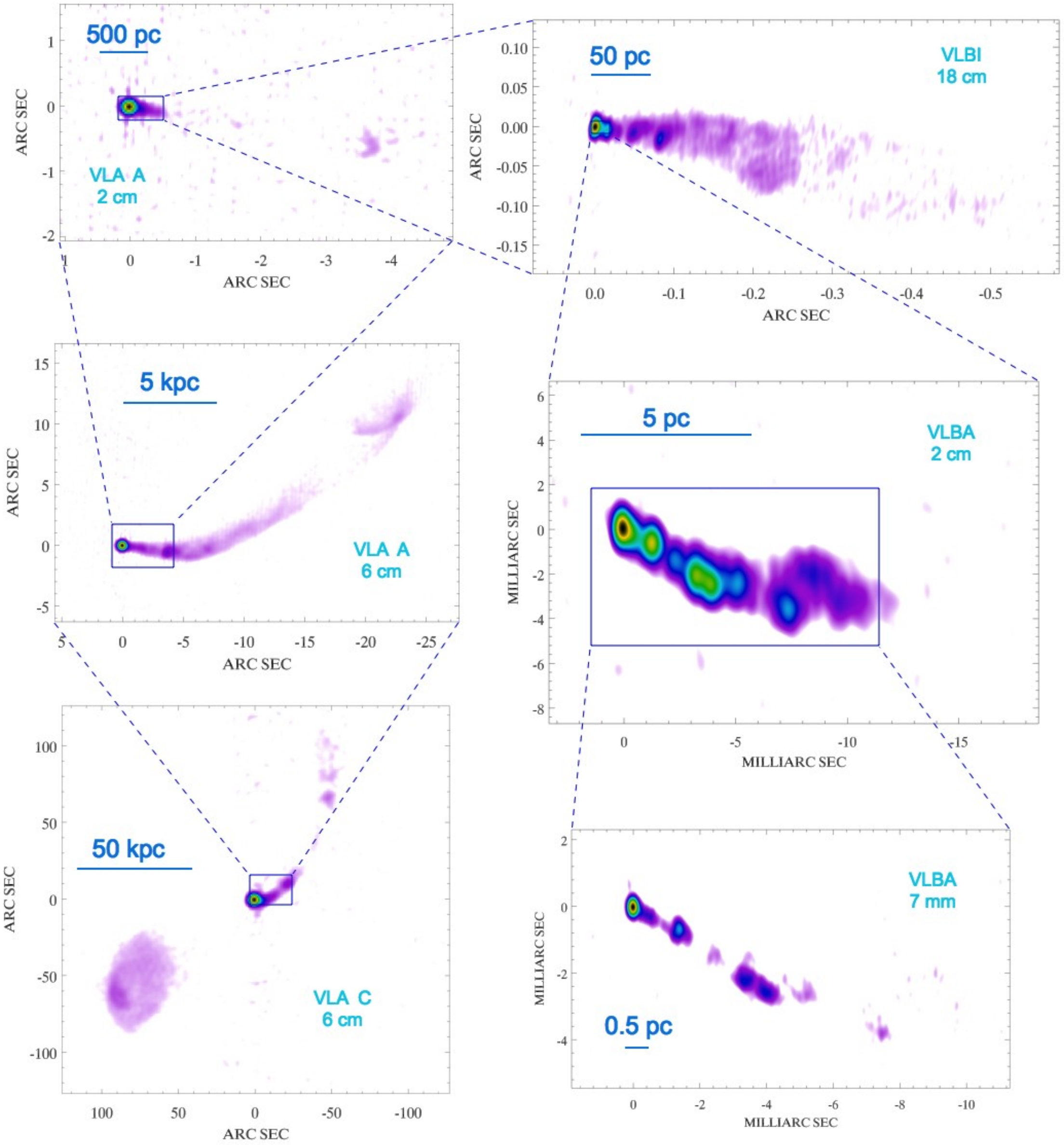


Property	BL Lacs	FSRQs
Optical spectrum	no or weak emission lines	strong emission lines
Typical redshift	$z < 0.6$	$z > 1$
Cosmological evolution	weak or negative	strong and positive
Integrated power	$L \lesssim 10^{46}$ erg s^{-1}	$L \sim 10^{46-48}$ erg s^{-1}
Synchrotron SED peak	$> 10^{15}$ Hz	$\lesssim 10^{14.5}$ Hz
Extended radio emission	FRI like	FRII like
SED photon energy	GeV/TeV	MeV/GeV
γ-ray photon index	$\Gamma_\gamma < 2$	$\Gamma_\gamma > 2$

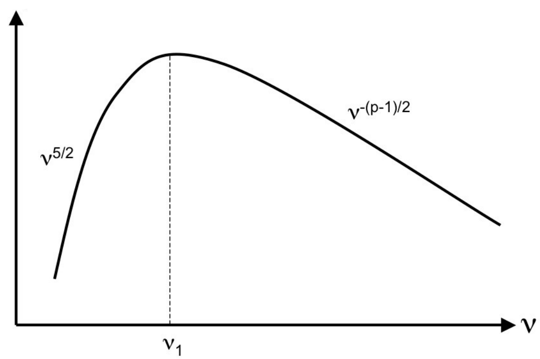
Rocco Lico,
PhD thesis

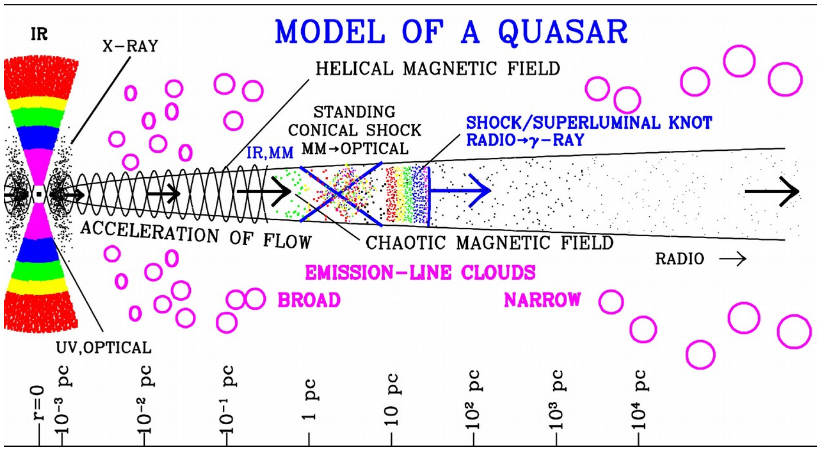
- Physical parameters:
  M, J, dM/dt, L, θ
  jet/no jet,
  jet composition
  B topology,
  host galaxy/environment

Knot structures along the jet



- Acceleration of particles occurs in situ via DSA (Fermi I) or magnetic reconnection (Lazarian et al. 2015)
- Multi-zone models are needed to explain jet features
- Leptonic models seems to be sufficient for describing blazars.





(Marscher et al. 2005)

The state-of-the-art

- Polarization properties of extragalactic radio sources at high frequencies (> 20 GHz) are still poorly constrained.

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 $S_{20\,\mathrm{GHz}} > 40\,\mathrm{mJy}$
Trippe *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)

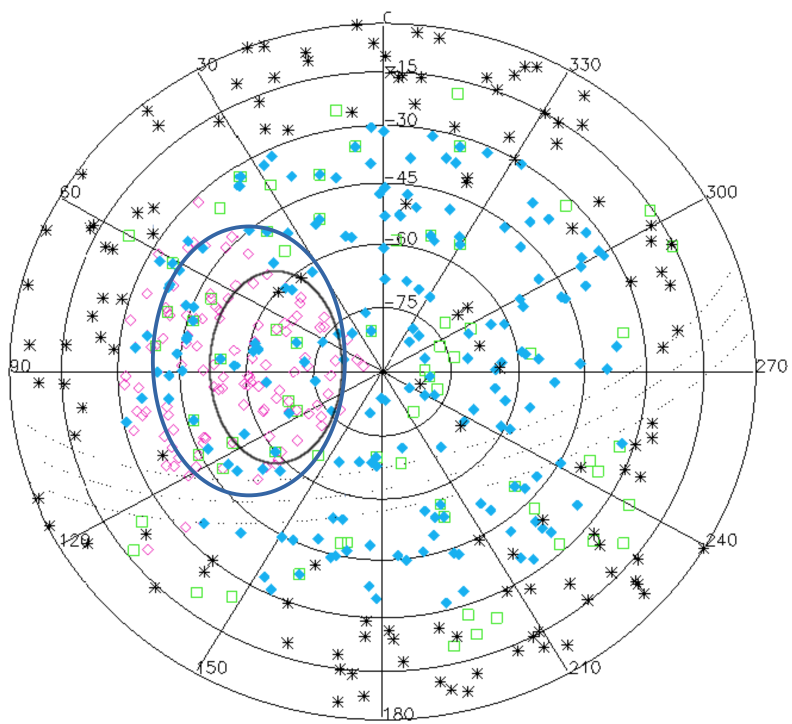
High flux density treshold, i.e. ≈ 1 Jy (WMAP, PLANCK catalogues)

Complete sample with high frequency obs.

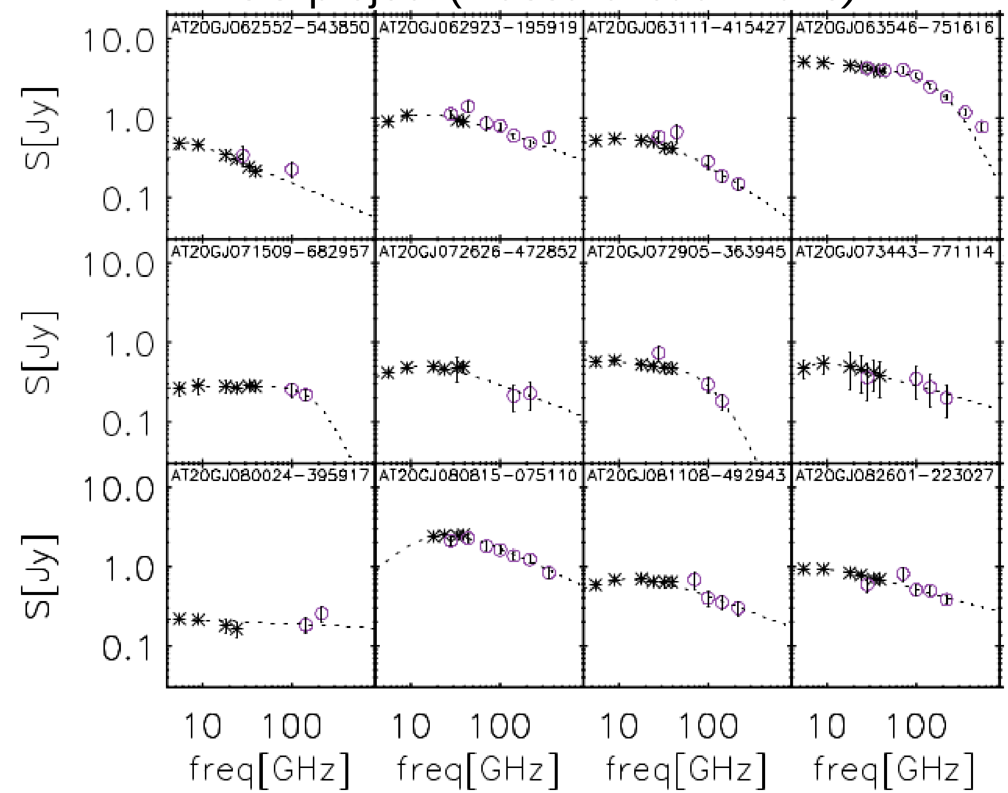
ATCA observations

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	51	-75° ≤ b < -65°
	14 h	2.1 GHz	104	b < - 65°

- Spatial configuration: H214 (hybrid and compact). Resolution $\lambda/b_{max} \approx 5 \div 36$ 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).



PACO project (Massardi *et al. 2015)*



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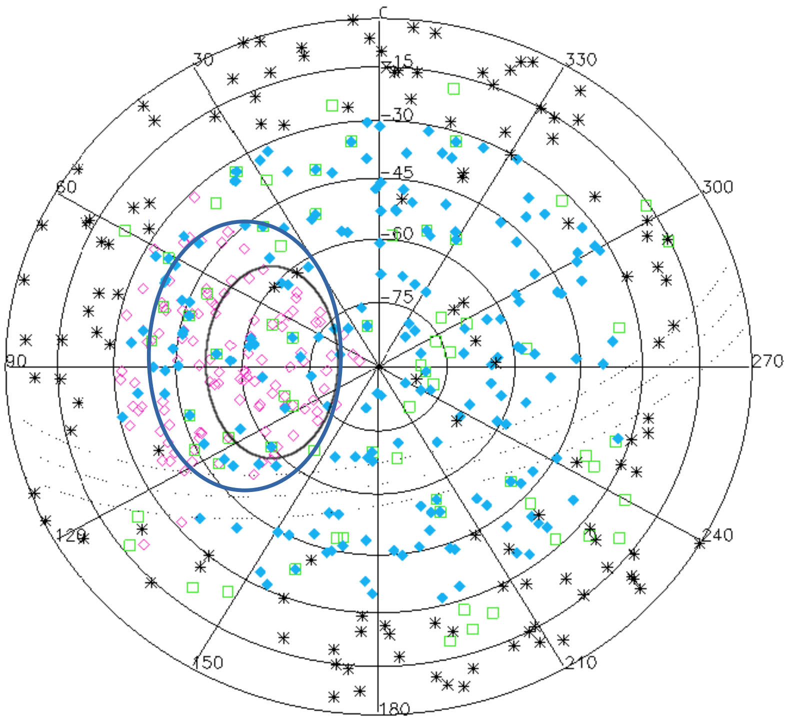
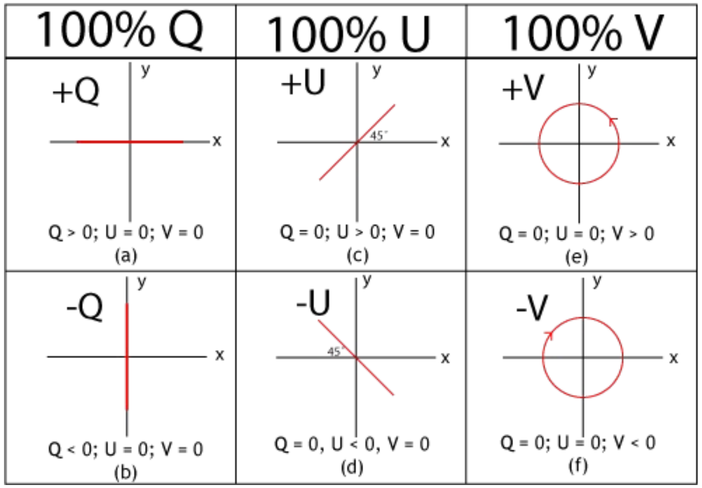


ATCA obs (Sep 2014, Mar-Apr 2016)

- 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:

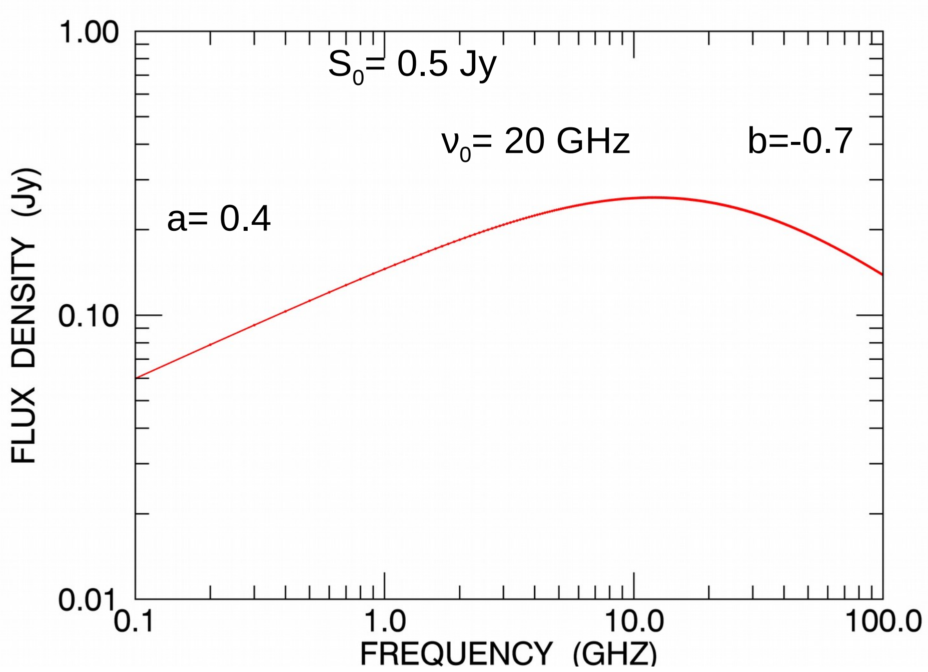
$$P = \sqrt{Q^2 + U^2 - \sigma_V^2} \qquad \sigma_P = \sqrt{\frac{Q^2\sigma_Q^2 + U^2\sigma_U^2}{Q^2 + U^2}} \text{ (+10\% P)}$$

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



- Double/triple power law models for fitting spectra both in I and P:
  - 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:

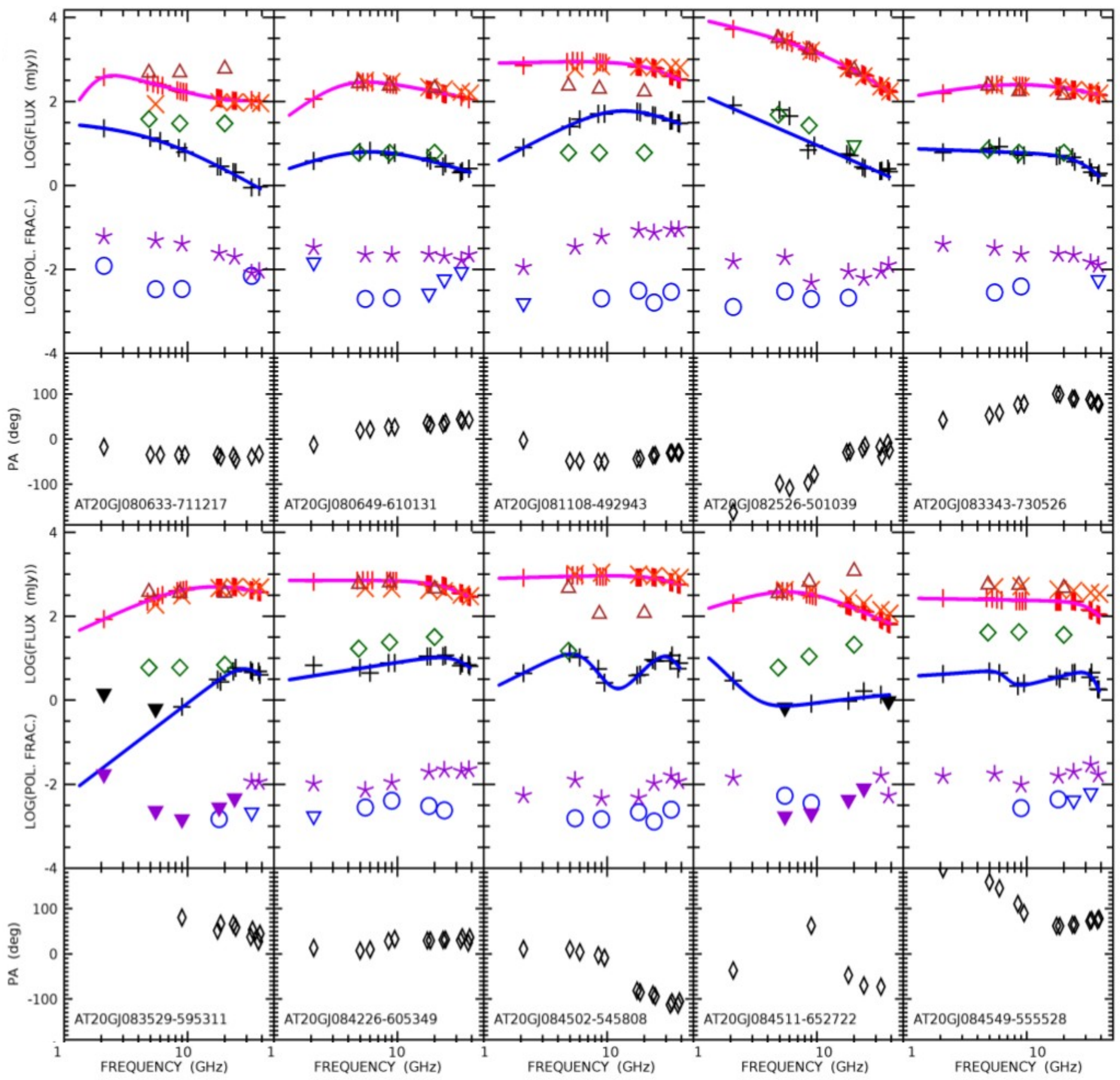
    94% total intensity ($\chi^2 \approx 1.12$);

    75% polarization ($\chi^2 \approx 1.89$).

ATCA obs (Sep 2014, Mar-Apr 2016)

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

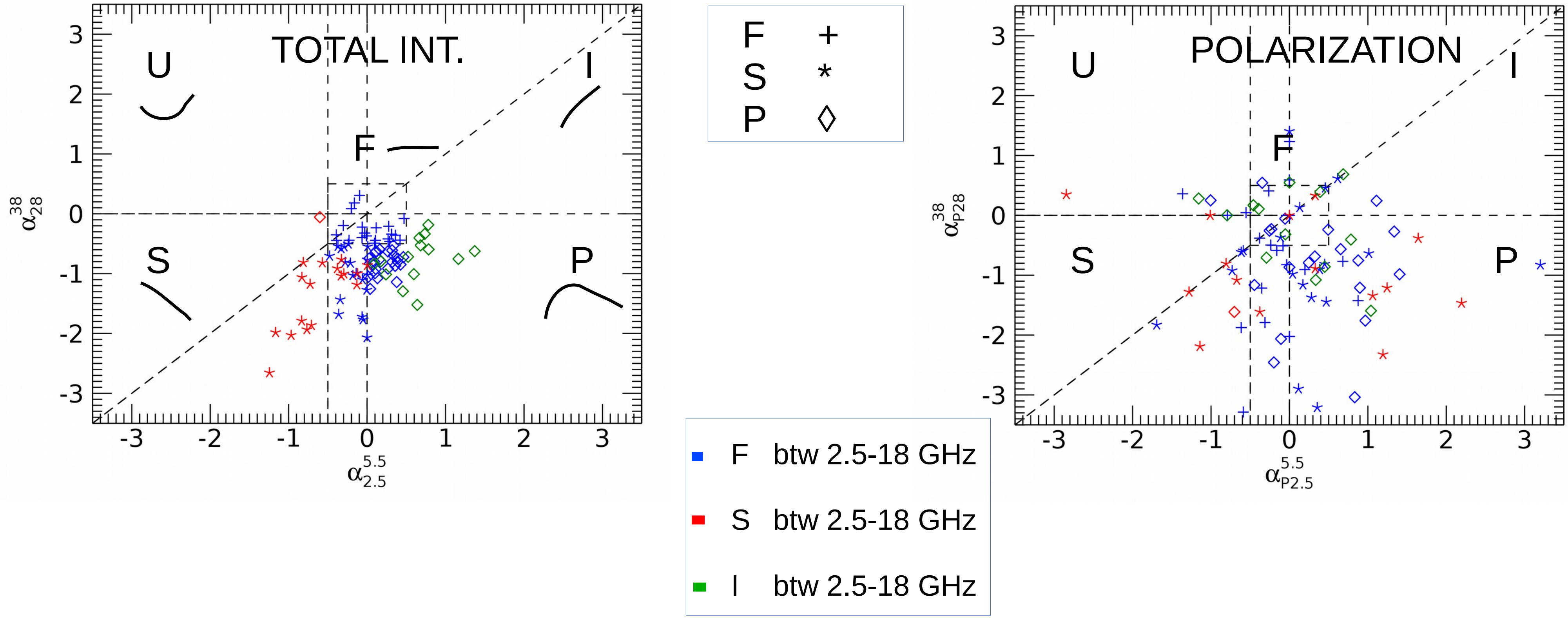
(error bars are smaller than plot symbols)



+ 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 curve
– Pol. fit curve
* (Linear) Pol. fraction
○ (Circular) Pol. fraction
◊ Polarization Angle

Color-color plots

(error bars are smaller than plot symbols)



Tot. Int. → Pol. Int. ↓	(I)	(P)	(F)	(S)	(U)	
(I)	0	3	0	1	0	4
(P)	0	24	4	20	0	48
(F)	0	5	4	4	0	13
(S)	0	5	8	7	0	20
(U)	0	8	5	3	0	16
(NA)	0	1	1	1	0	3
	0	46	22	36	0	

TOT. Int.	2.5 – 5.5 GHz	5.5 – 10 GHz	10 – 18 GHz	18 – 28 GHz	28 – 38 GHz
All	−0.02	−0.11	−0.24	−0.46	−0.75
Steep	−0.33	−0.37	−0.46	−0.76	−1.02
Peaked	0.32	0.06	−0.14	−0.42	−0.74
Flat	−0.01	−0.12	−0.14	−0.26	−0.34

POL. Int.	2.5 – 5.5 GHz	5.5 – 10 GHz	10 – 18 GHz	18 – 28 GHz	28 – 38 GHz
All	0.15	−0.06	−0.15	−0.53	−0.80
Steep	0.33	−0.06	−0.24	−0.76	−0.92
Peaked	0.49	−0.01	−0.06	−0.32	−0.73
Flat	−0.21	−0.29	−0.33	−0.54	−0.68

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.

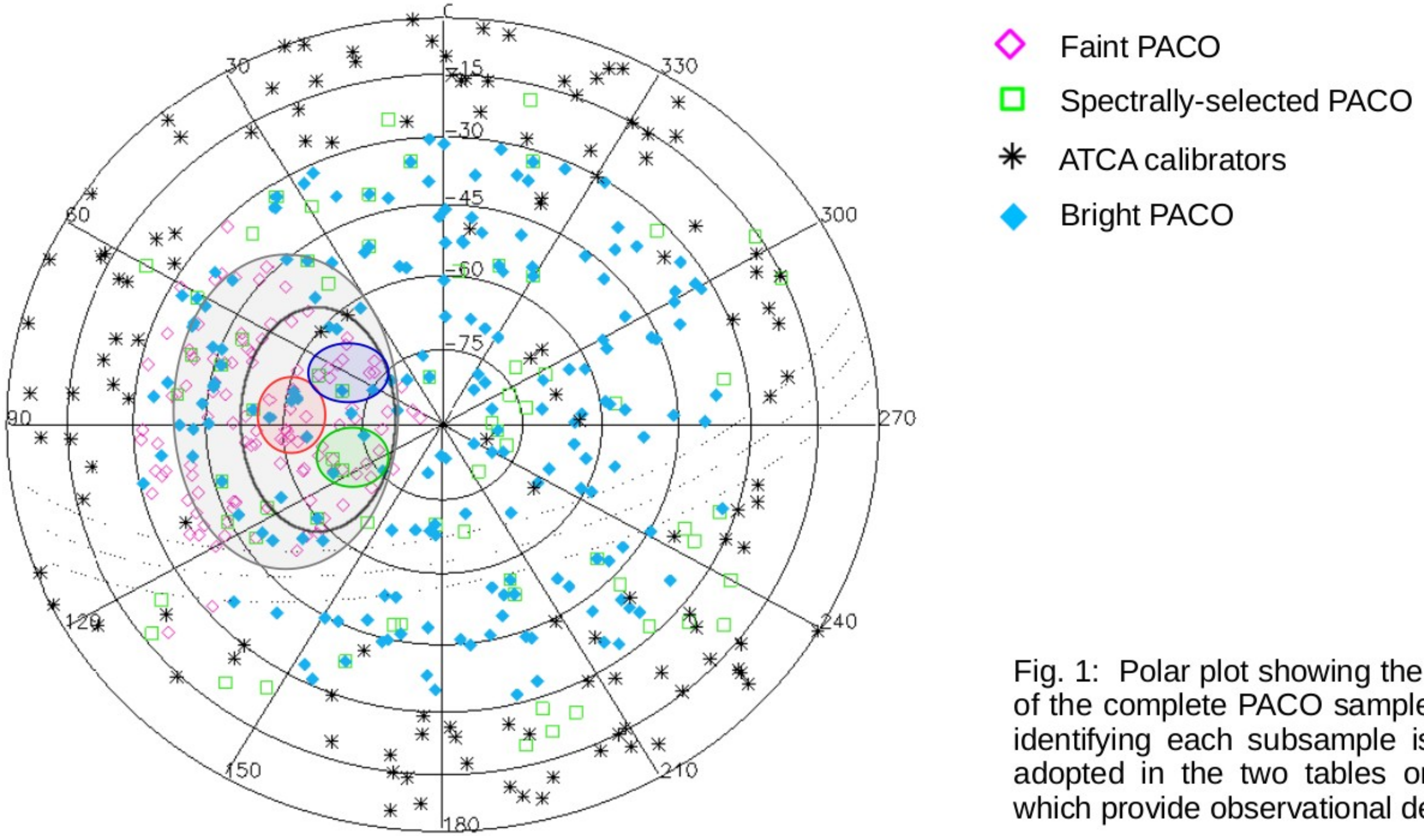
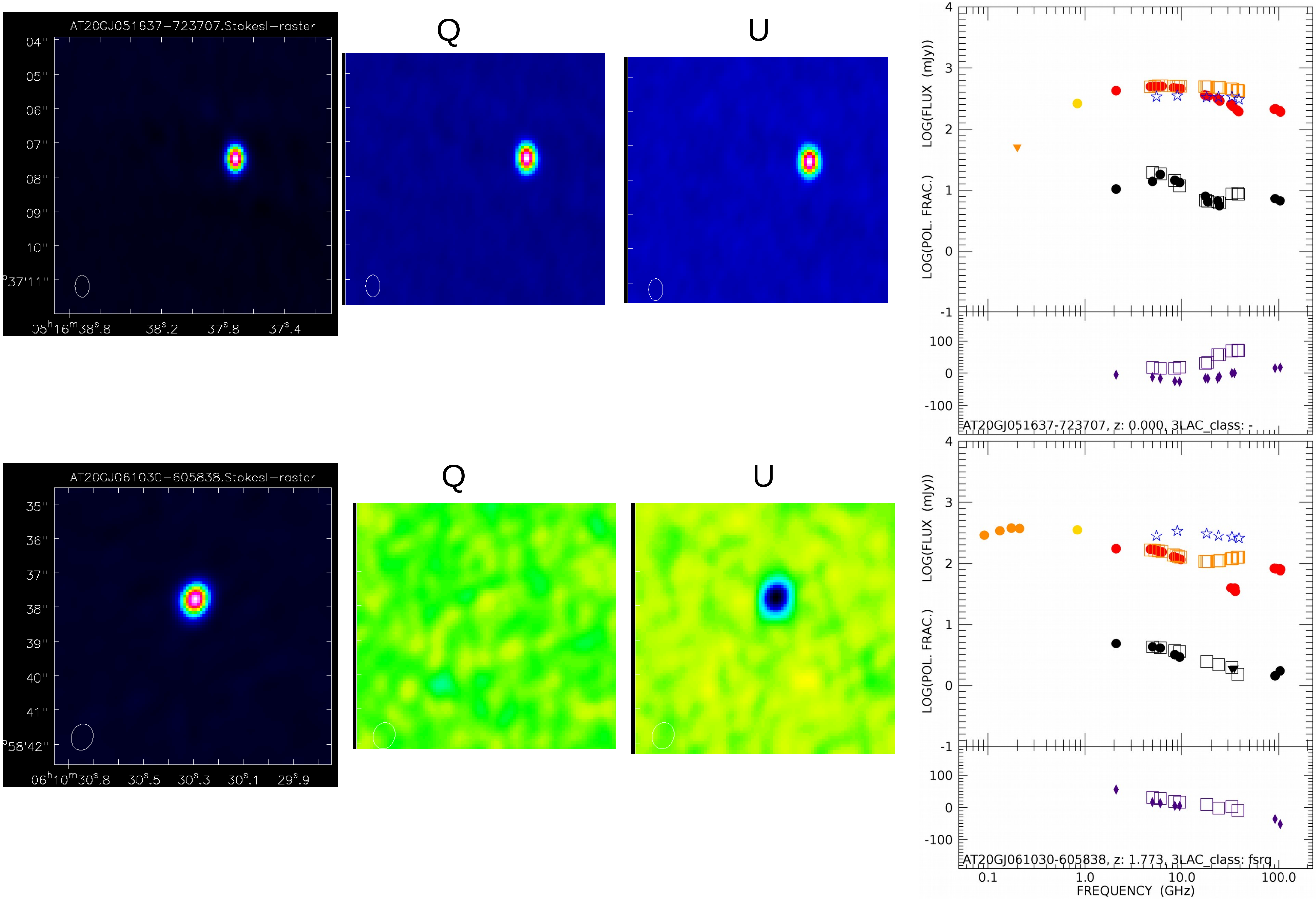


Fig. 1: Polar plot showing the distribution of the complete PACO sample. The color identifying each subsample is the same adopted in the two tables on the right, which provide observational details.

MWA + ATCA +ALMA

(Galluzzi et al. 2017 MNRAS accepted, Hurley-Walker et al. 2016)



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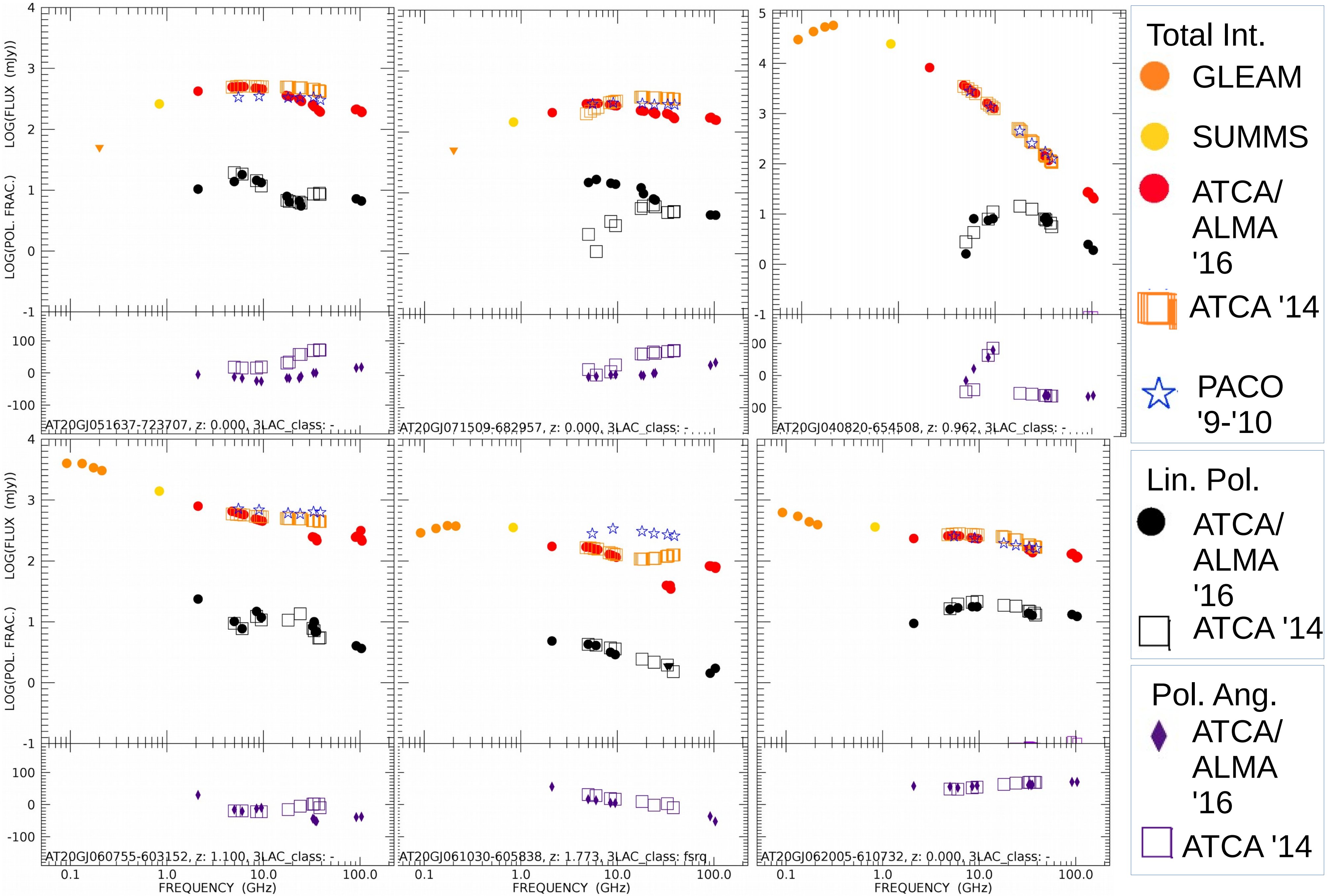
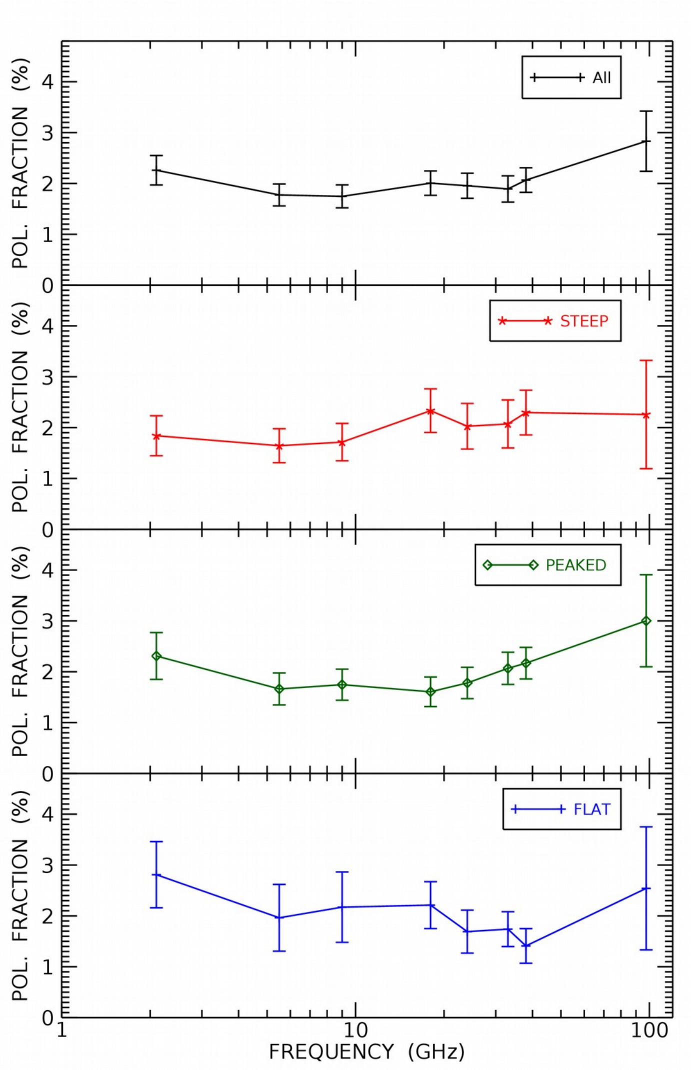
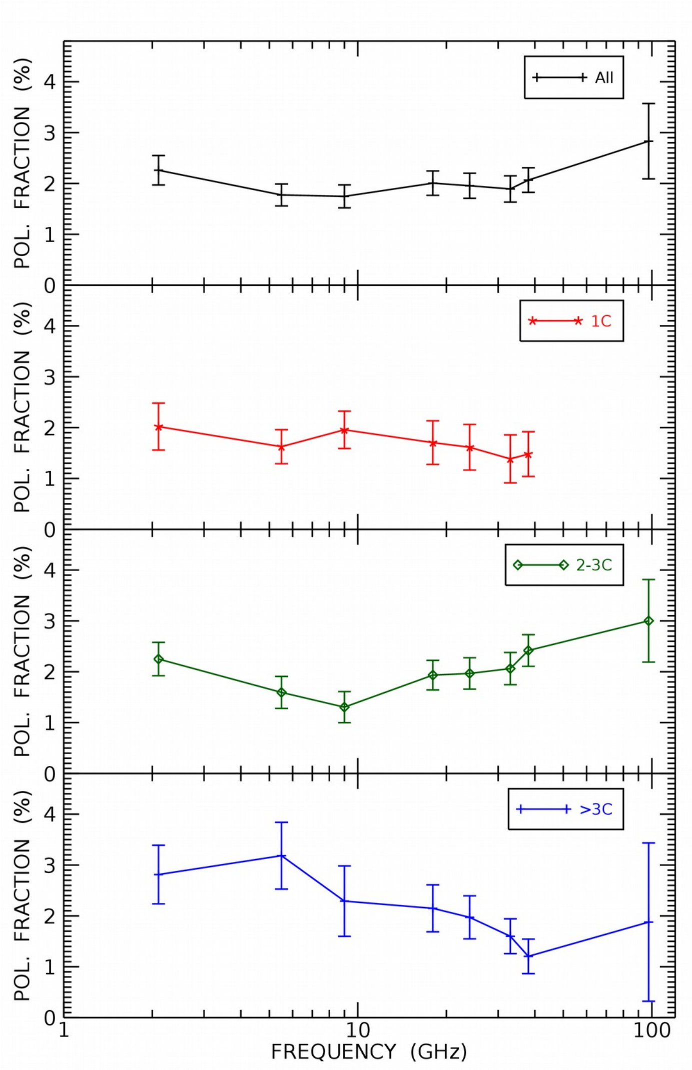


(Linear) Polarization fractions

- 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.





Polarization angle

- Only 9 objects can be fit by the linear RM relation over the 2.1-38GHz range (4 compatible with very low or null rotation < 10 rad/m^2.
- We identify two regimes, i.e. cm and mm-wavelenghts and perform separate linear fit

  (~40% cm, ~57% mm)

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 (23)			1C (2)			2-3C (18)			>3C (3)		
I	med	III	I	med	III	I	med	III	I	med	III
40	94	244	-	335	-	46	84	220	-	122	-

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 (27)			1C (2)			2-3C (22)			>3C (3)		
I	med	III	I	med	III	I	med	III	I	med	III
679	2300	5252	-	742	-	716	2351	5191	-	4022	-

$$\Delta\phi = \mathrm{RM}\lambda^2$$

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

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

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

$\mathrm{RM_{Gal}}$ ~ +20 rad/m^2

$\mathrm{RM_{ion}}$ < 5 rad/m^2

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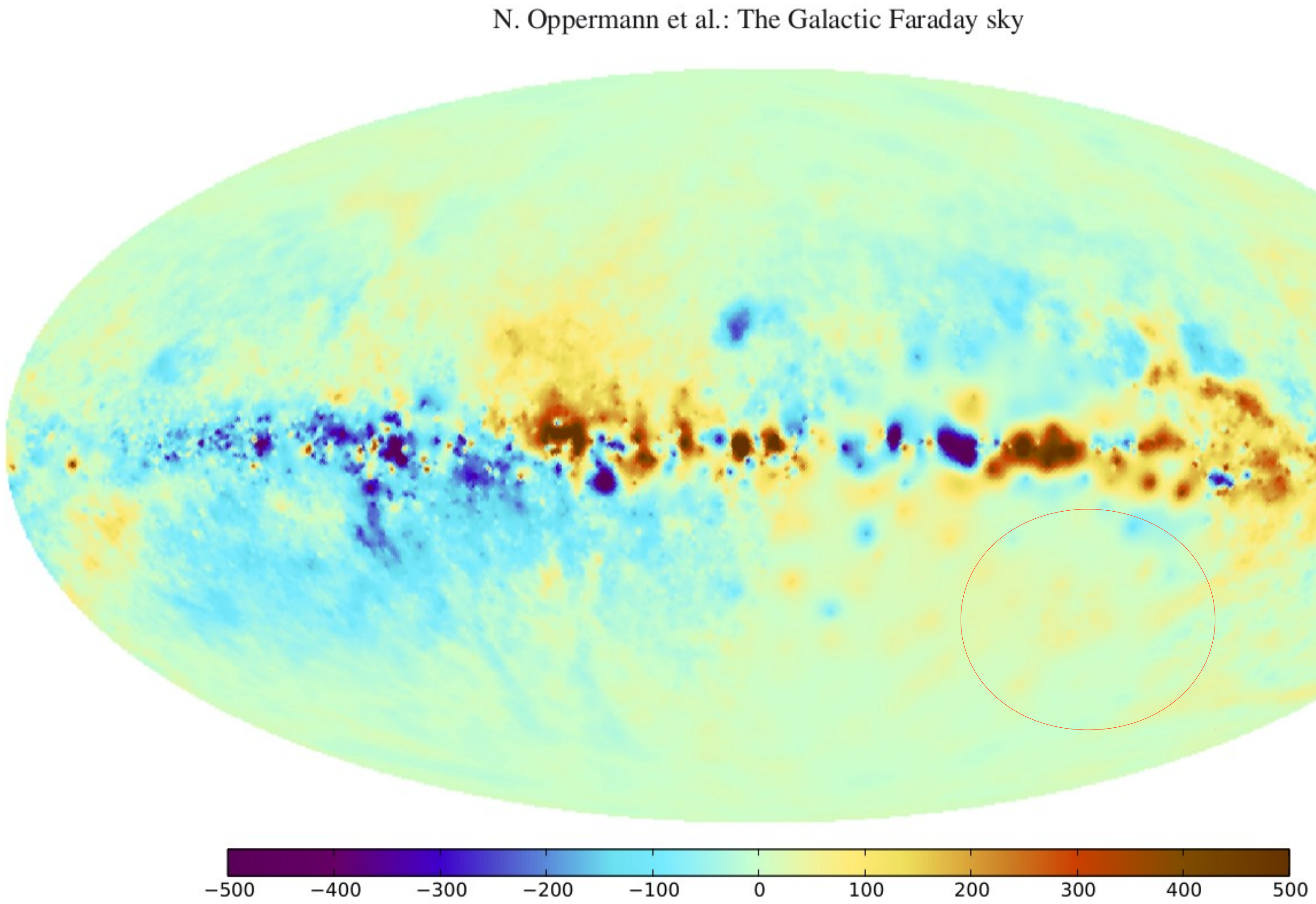
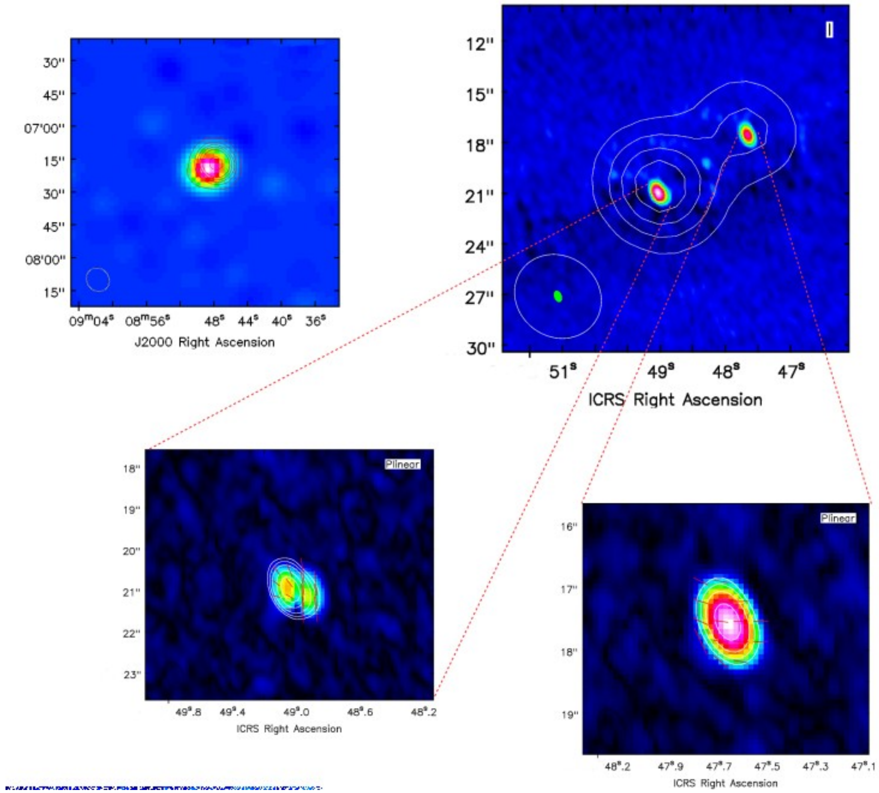
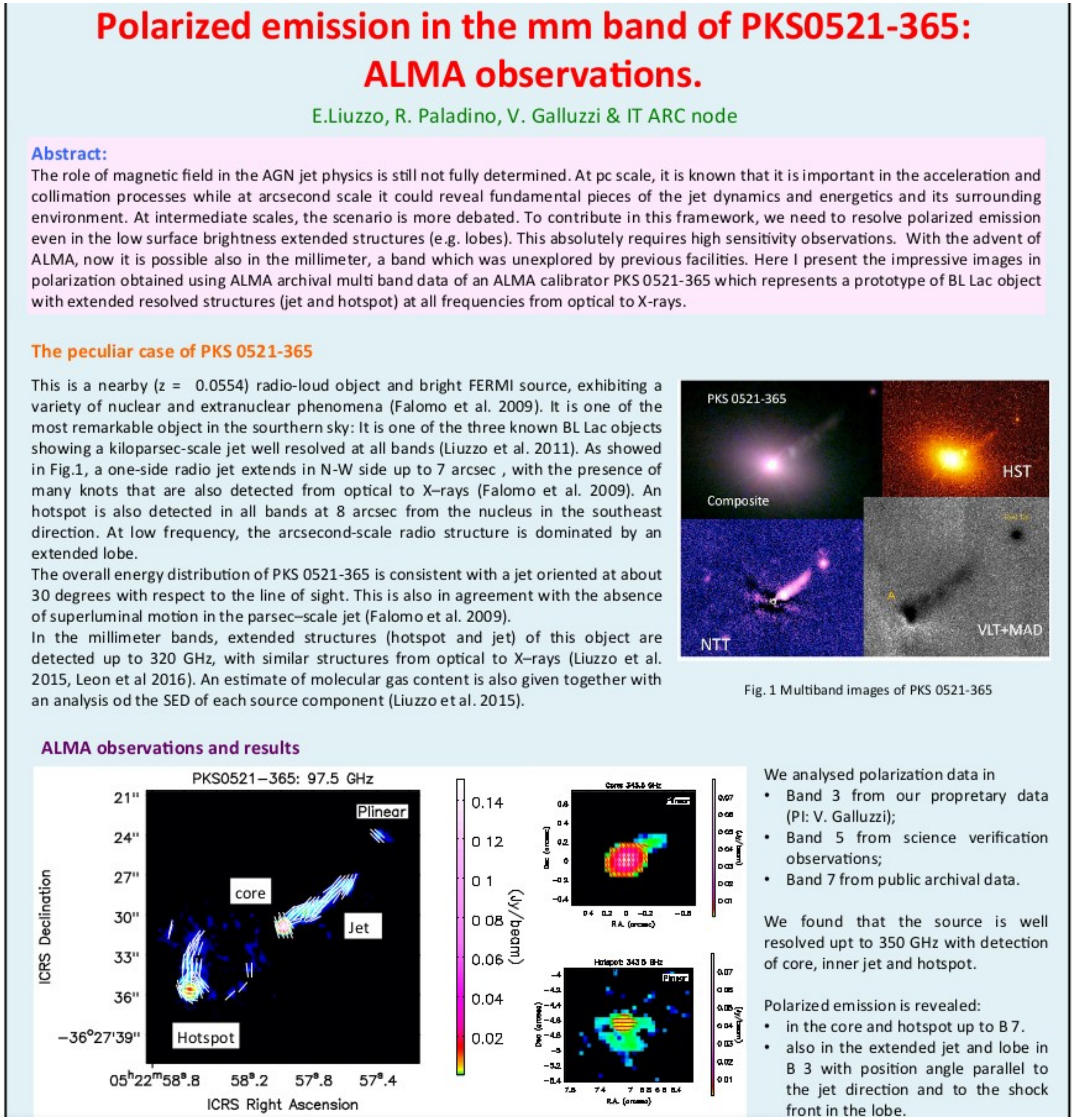


Some peculiar objects...

- PKS B0409-752



- PKS0521-365 (Elisabetta Liuzzo's poster)



Polarized emission in the mm band of PKS0521-365: ALMA observations.

E.Liuzzo, R. Paladino, V. Galluzzi & IT ARC node

Abstract:
The role of magnetic field in the AGN jet physics is still not fully determined. At pc scale, it is known that it is important in the acceleration and collimation processes while at arcsecond scale it could reveal fundamental pieces of the jet dynamics and energetics and its surrounding environment. At intermediate scales, the scenario is more debated. To contribute in this framework, we need to resolve polarized emission even in the low surface brightness extended structures (e.g. lobes). This absolutely requires high sensitivity observations. With the advent of ALMA, now it is possible also in the millimeter, a band which was unexplored by previous facilities. Here I present the impressive images in polarization obtained using ALMA archival multi band data of an ALMA calibrator PKS 0521-365 which represents a prototype of BL Lac object with extended resolved structures (jet and hotspot) at all frequencies from optical to X-rays.

The peculiar case of PKS 0521-365

This is a nearby (z = 0.0554) radio-loud object and bright FERMI source, exhibiting a variety of nuclear and extranuclear phenomena (Falomo et al. 2009). It is one of the most remarkable object in the southern sky: It is one of the three known BL Lac objects showing a kiloparsec-scale jet well resolved at all bands (Liuzzo et al. 2011). As showed in Fig.1, a one-side radio jet extends in N-W side up to 7 arcsec , with the presence of many knots that are also detected from optical to X–rays (Falomo et al. 2009). An hotspot is also detected in all bands at 8 arcsec from the nucleus in the southeast direction. At low frequency, the arcsecond-scale radio structure is dominated by an extended lobe.
The overall energy distribution of PKS 0521-365 is consistent with a jet oriented at about 30 degrees with respect to the line of sight. This is also in agreement with the absence of superluminal motion in the parsec–scale jet (Falomo et al. 2009).
In the millimeter bands, extended structures (hotspot and jet) of this object are detected up to 320 GHz, with similar structures from optical to X–rays (Liuzzo et al. 2015, Leon et al 2016). An estimate of molecular gas content is also given together with an analysis od the SED of each source component (Liuzzo et al. 2015).

Fig. 1 Multiband images of PKS 0521-365

ALMA observations and results

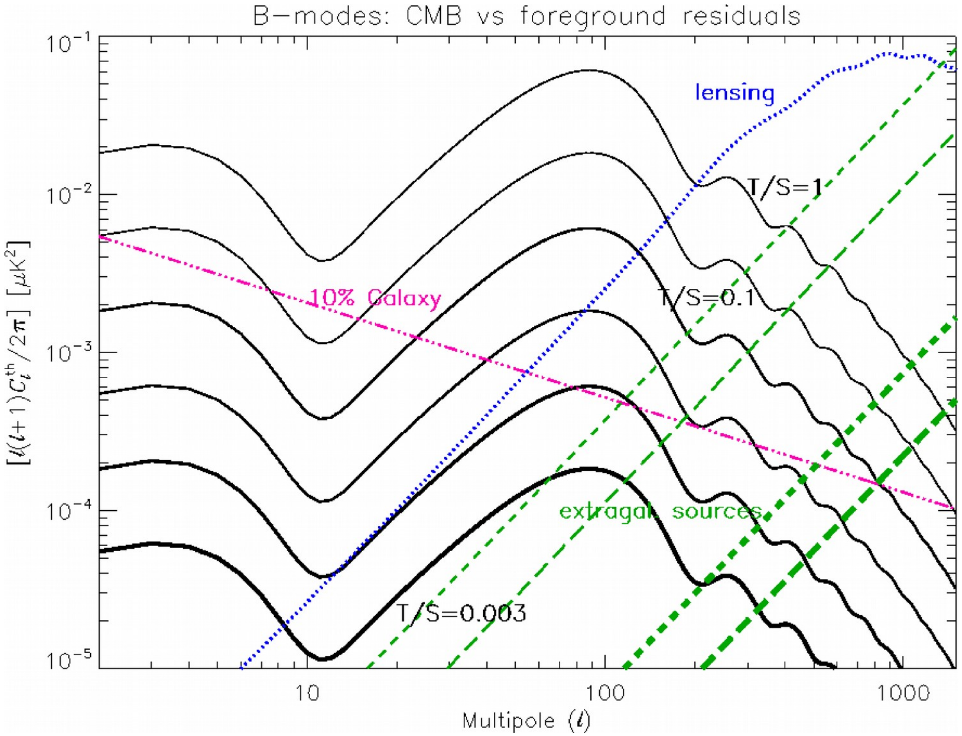
We analysed polarization data in
- Band 3 from our proprietary data (PI: V. Galluzzi);
- Band 5 from science verification observations;
- Band 7 from public archival data.

We found that the source is well resolved upt to 350 GHz with detection of core, inner jet and hotspot.

Polarized emission is revealed:
- in the core and hotspot up to B 7.
- also in the extended jet and lobe in B 3 with position angle parallel to the jet direction and to the shock front in the lobe.

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.**



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

Conclusions

- High sensitivity ($\sigma_P \approx$ 0.6 mJy/beam) polarimetric observations of a complete sample of 104 extragalactic radio sources (det. rate ≈ 90%).
- Continuum spectra of about 85 % of sources well fitted by a double/triple power laws, both in total intensity and polarization.
- Polarized emission cannot be simply inferred from total intensity for several sources.
- 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 9 cases over the whole 2.1-38 GHz range, usually two regimes with higher RM at higher frequencies.
- 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 polarization higher variability by a factor ≈ 1.5 wrt total intensity.