Polarization in the ELAIS-N1 LOFAR deep field: Probing the sub-mJy regime of polarized extragalactic sources

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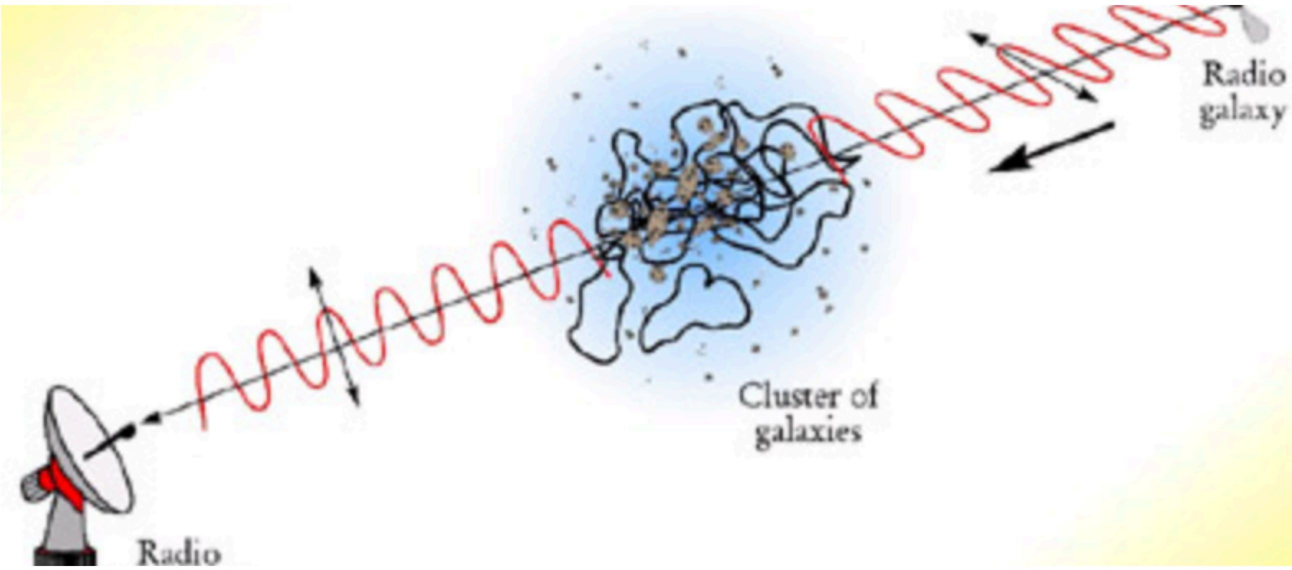
INTRODUCTION: FARADAY ROTATION



https://www.skatelescope.org/

$$\chi(\lambda^2) = \chi_0 + RM\lambda^2$$

RM = *Rotation Measure*

$$\mathscr{P} = Q + iU = pIe^{2i\chi} = pIe^{(\chi_0 + \mathrm{RM}\lambda^2)}$$

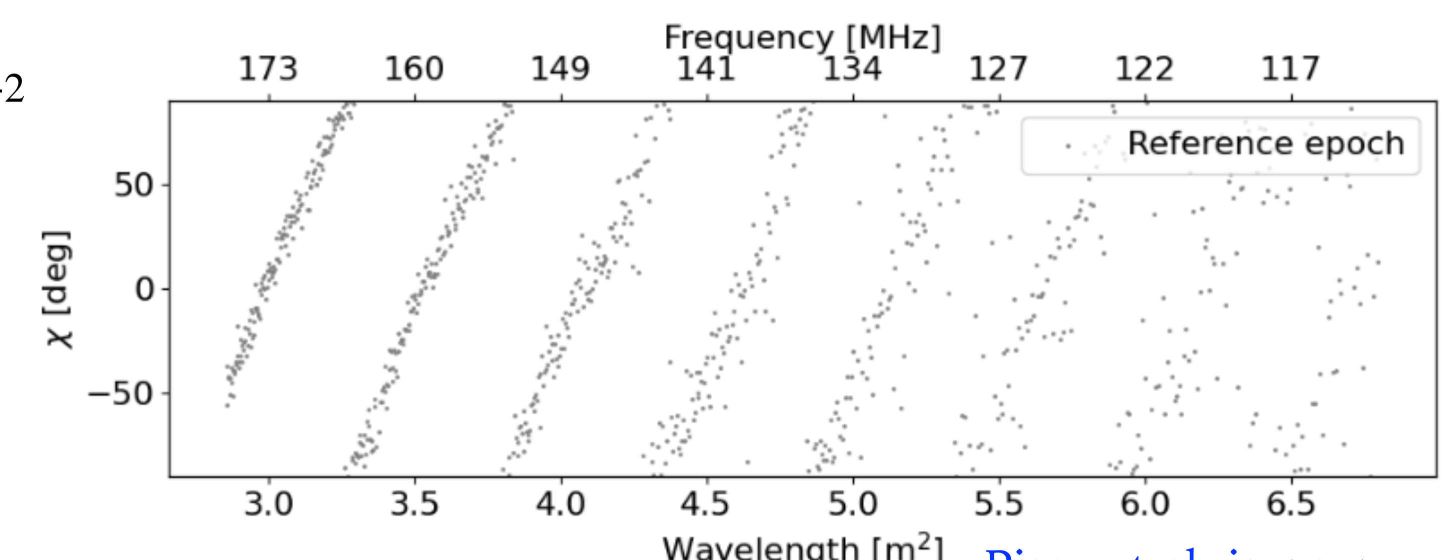
$$\chi = \frac{1}{2}\arctan\frac{U}{Q}$$

For a synchrotron-emitting source behind a magneto-ionic medium: $\mathrm{RM} = \phi$ *Faraday depth*

$$\phi(l) = 0.81\int_{source\,at\,l}^{observer} \frac{B_{\parallel}}{[\mu\mathrm{G}]}\frac{n_e}{[\mathrm{cm}^{-3}]}\frac{dl}{[\mathrm{pc}]}\ \mathrm{rad\,m^{-2}}$$

$$\mathscr{P}(\lambda^2) = \int_{-\infty}^{\infty} \mathscr{F}(\phi) e^{2i\phi\lambda^2} d\phi$$

Faraday dispersion function



Piras et al. in prep.

INTRODUCTION: POLARIZATION WITH LOFAR

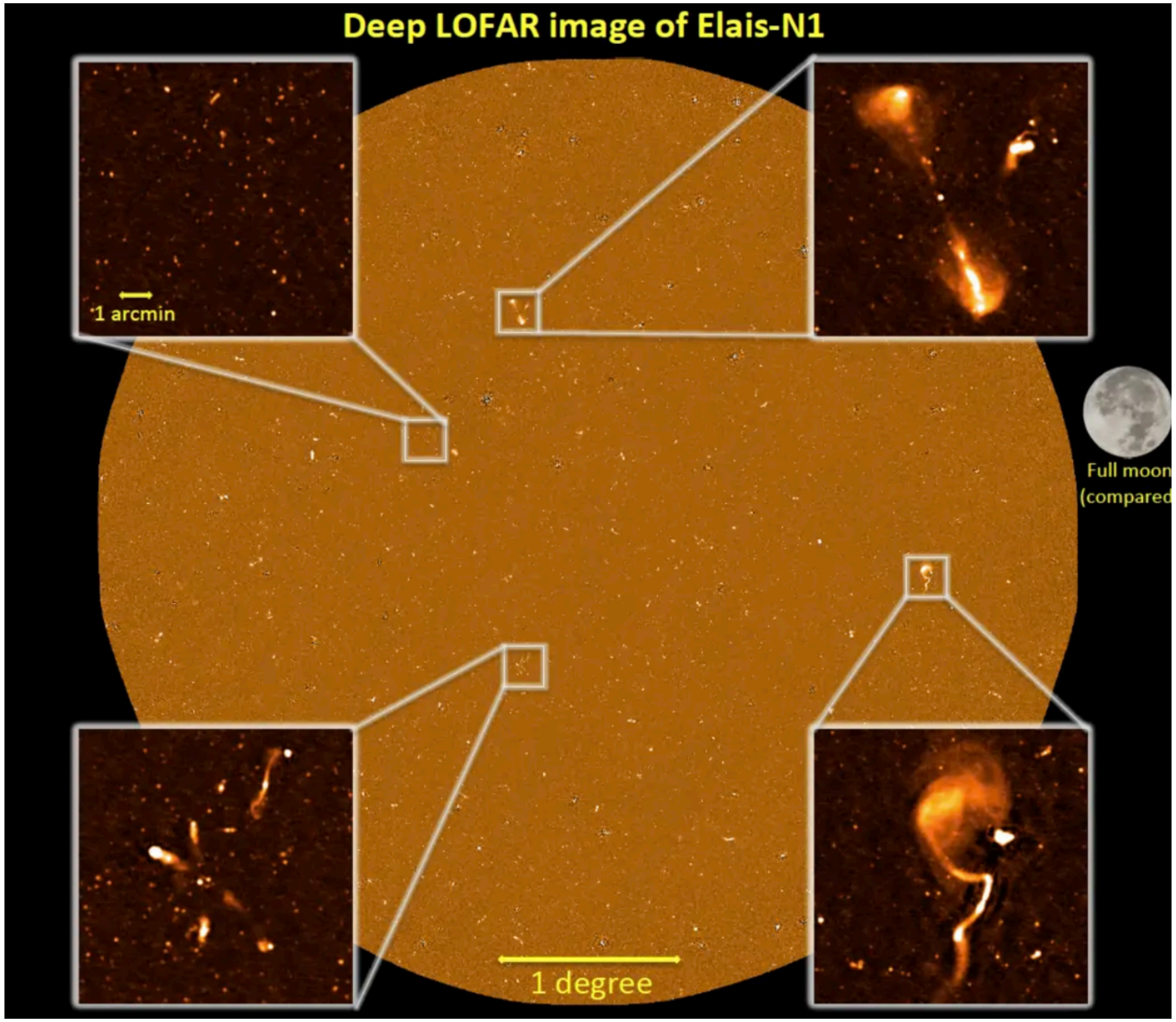
- Polarization with LOFAR:
- Frequency range of HBA: ≈115 - 177 MHz (wavelengths of 1.7 - 2.6 m)
- High precision on rotation measures: ~1 rad/m^2
- But stronger Faraday depolarization at long wavelengths
- Polarized counts are unknown at low frequencies

Polarized sources per square degree	Resolution	Sigma	Field
0.16	4.3'	1 mJy/beam	HETDEX DR1 (Van Eck et al. 2018)
0.3	20"	100 μJy/beam	M51 (Neld et al. 2018)
0.6	20"	26 μJy/beam	ELAIS-N1 (Herrera Ruiz et al. 2021)
0.48 0.29	20"	80 μJy/beam	LoTSS DR2 (O'Sullivan et al. 2023)

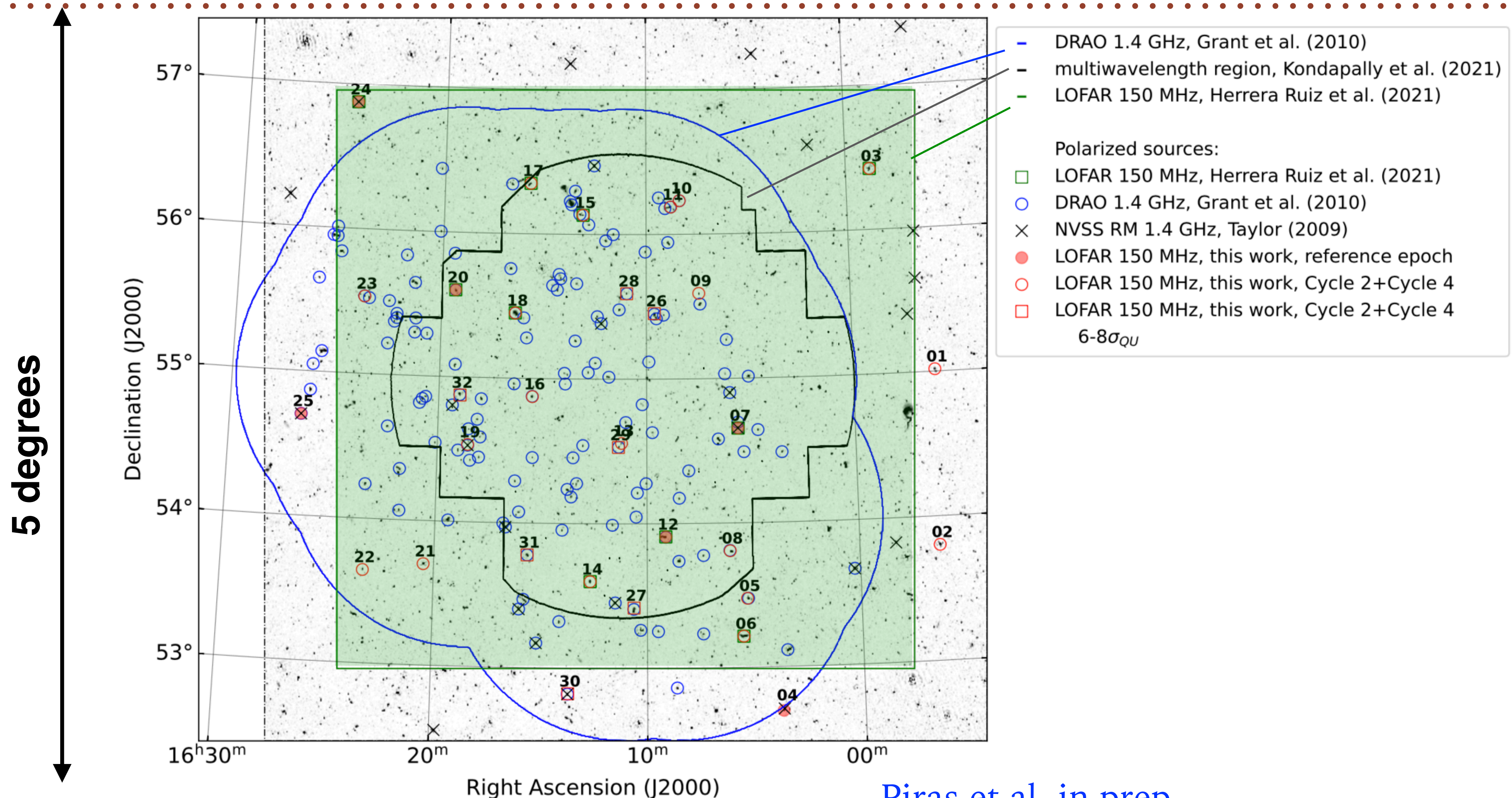
- RM grid

LOFAR SURVEYS DEEP FIELD: ELAIS-N1

- European Large Area ISO Survey-North 1
- Multiwavelength coverage: optical, infrared, radio
- With LOFAR (HBA at 114.9-177.4 MHz, 1.69-2.61 m) (Sabater et al. 2021):
  - 22 available epochs of 8 h each = 176 h
  - In Stokes I: final sensitivity of ~20 μJy/beam (central region), resolution of 6”, 68 deg^2
  - ~80 000 sources detected in continuum (~3 000 above 1 mJy/beam)
    - ~30 000 host-galaxies in ~7.15 deg^2 (Kondapally et al. 2021)
    - Redshifts (Duncan et al. 2021)



POLARIZATION IN ELAIS-N1



Piras et al. in prep.

Catalog	Reference	Frequency	Sensitivity in Q and U (μJy beam^{-1})	Resolution (arcsec)	Area (deg^2)	Number of polarized sources	
NVSS RM	(1)	1.4 GHz	290	45	25	25	Taylor et al. 2009
DRAO ELAIS-N1	(2)	1.4 GHz	78	49×59	7.43	83	Taylor et al. 2007
DRAO ELAIS-N1	(3)	1.4 GHz	45	42×62	15.16	136	Grant et al. 2009
LOFAR	(4)	150 MHz	26	20	16	10	Herrera Ruiz et al. 2021
LOFAR	(5)	150 MHz	22	6	25	32	This work

THIS WORK

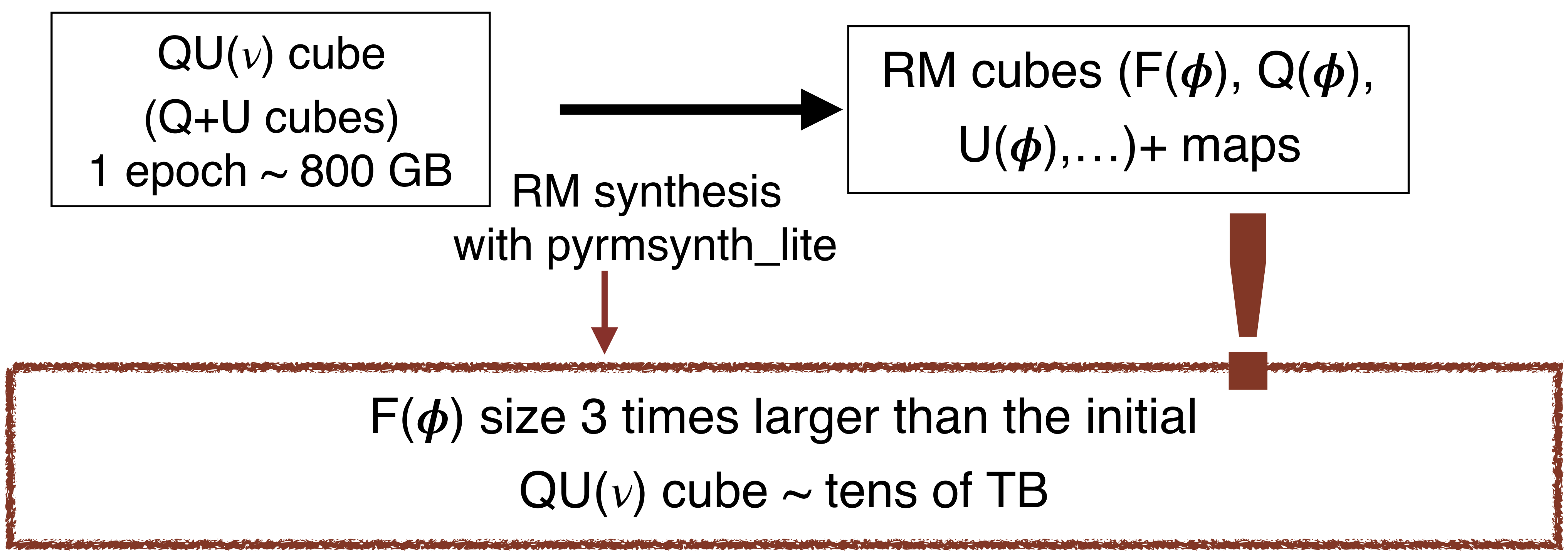
- 25 deg^2 region
- 19 epochs out of 22 epochs imaged at **6 arcsec resolution**
  - Align polarization angles
  - Stack the data
- Search in field → threshold = $8\sigma_{QU}$
- Search for polarization of radio sources known to be polarized at 1.4 GHz (Grant et al. 2010; NVSS RM catalog, Taylor et al. 2009) → threshold = $6\sigma_{QU}$

- Epochs
  - 10 with 800 frequency channels (Cycle 2)
  - 9 with 640 frequency channels (Cycle 4)
    - 4 epochs in common with Herrera Ruiz et al. (2021)

THE DATA

For each of the 19 epochs:

- 1 Q cube → ~50 GB compressed, >400 GB uncompressed
- 1 U cube → ~50 GB compressed, >400 GB uncompressed
- For a QU cube: 12005 pix (RA) x12005 pix (Dec)x 2 (Stokes) x 640 or 800 channels = (1.8 or 2.3) x10e11 pix
- Pixel size = 1.5 arcsec



STACKING TECHNIQUE

Polarization angles can be different in different observing runs : it's crucial to adopt a method to align polarization angles from different epochs before stacking

Alignment in frequency space for epochs with same number of frequency channels

(Herrera Ruiz et al. 2021)

→

Reference source as calibrator: we align the polarization angle, coherently band-averaged, of the reference source of epoch to be correct with the reference polarization angle

$$\mathscr{P}^{\mathrm{corr}}_{\mathrm{Ep}}(i,j,\nu) = \mathscr{P}_{\mathrm{Ep}}(i,j,\nu)\, e^{2\mathrm{i}\Delta\chi_{\mathrm{Ep}}}$$

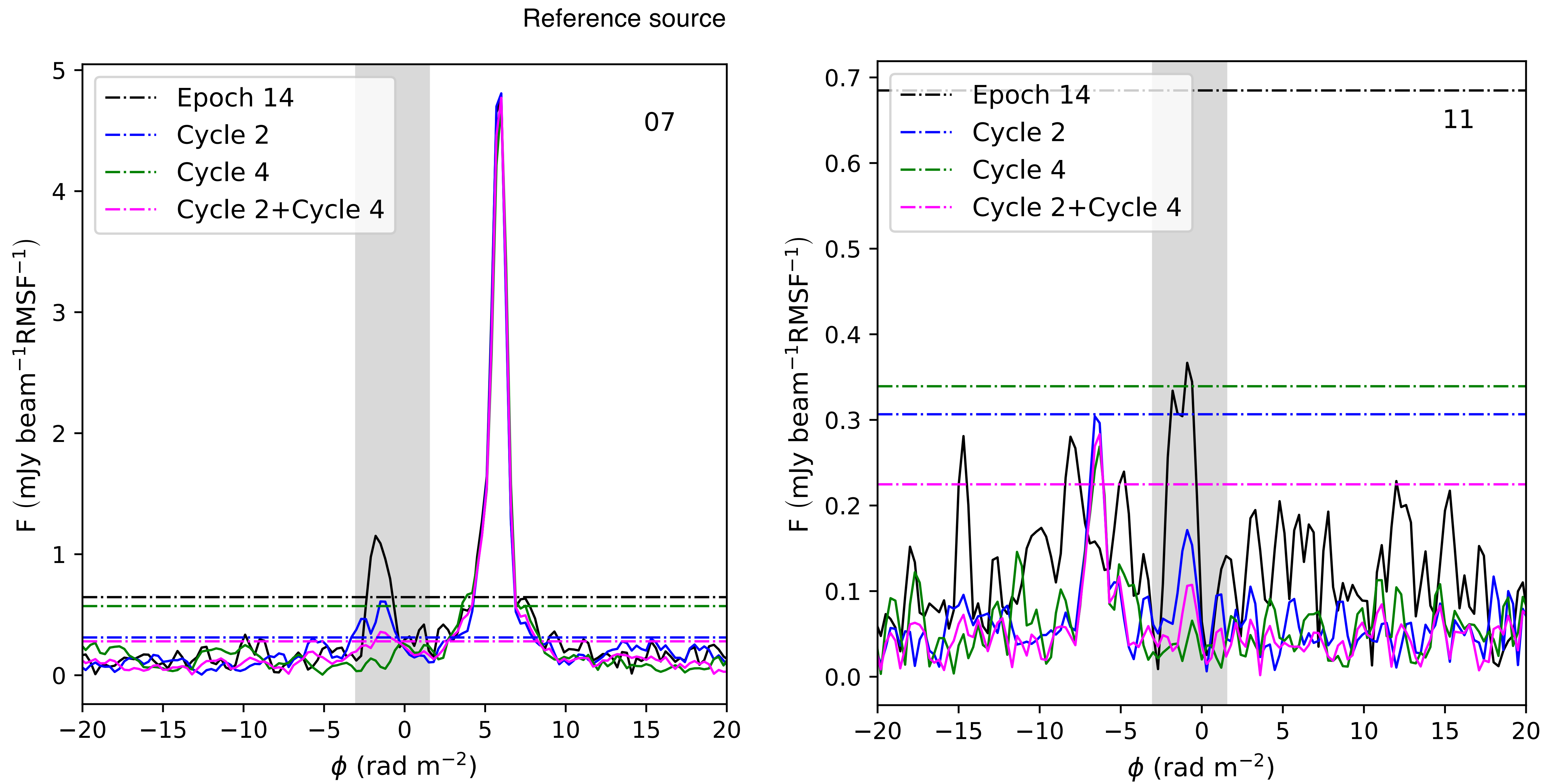
Alignment in Faraday depth space for cycles with different number of frequency channels

→

$$\mathscr{F}^{\mathrm{corr}}_{\mathrm{Cycle\ 4}}(i,j,\phi) = \mathscr{F}_{\mathrm{Cycle\ 4}}(i,j,\phi) e^{2\mathrm{i}\phi\Delta\lambda_0^2}$$

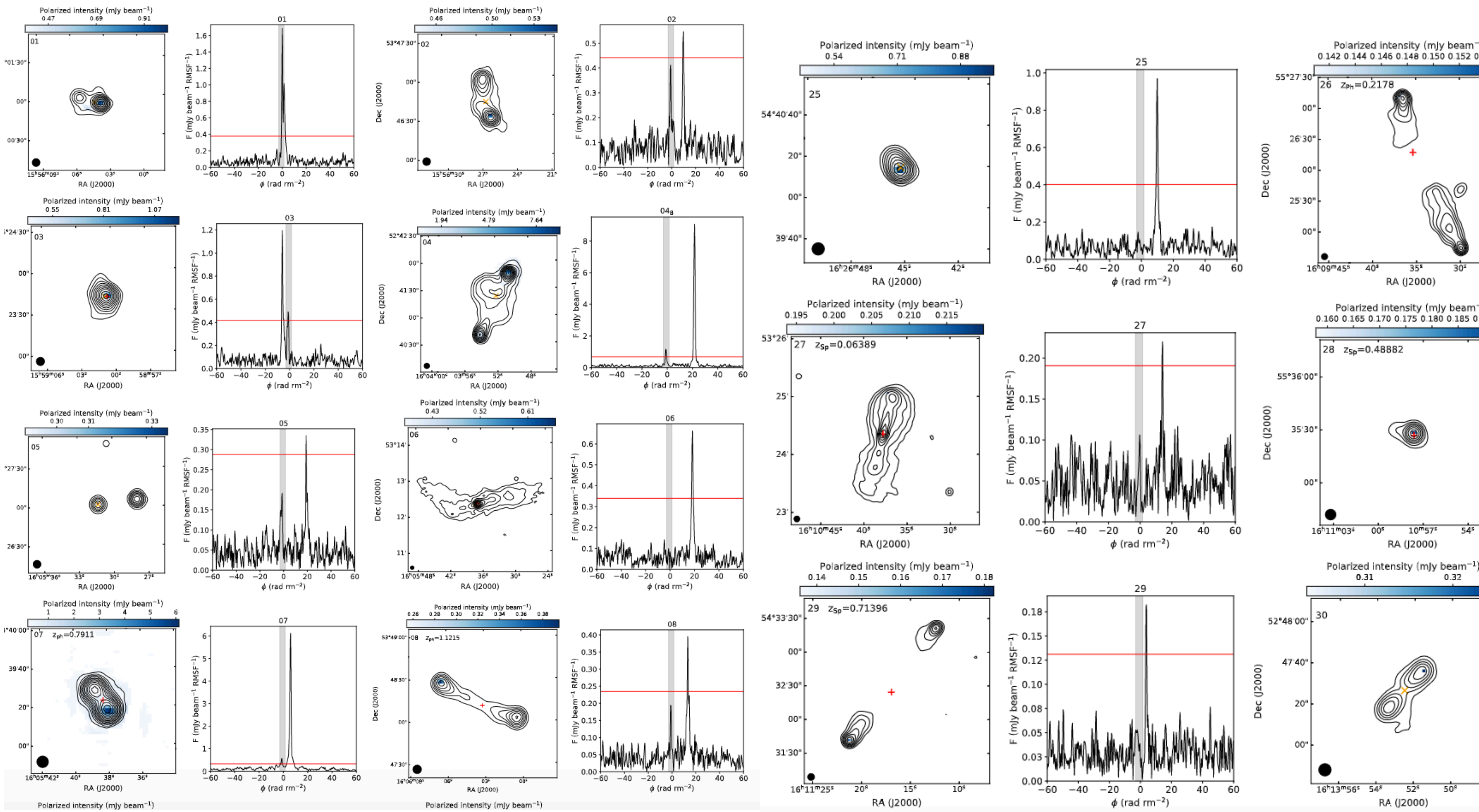
See also Šnidarić et al. (subm.)

RESULTS



Piras et al. in prep.

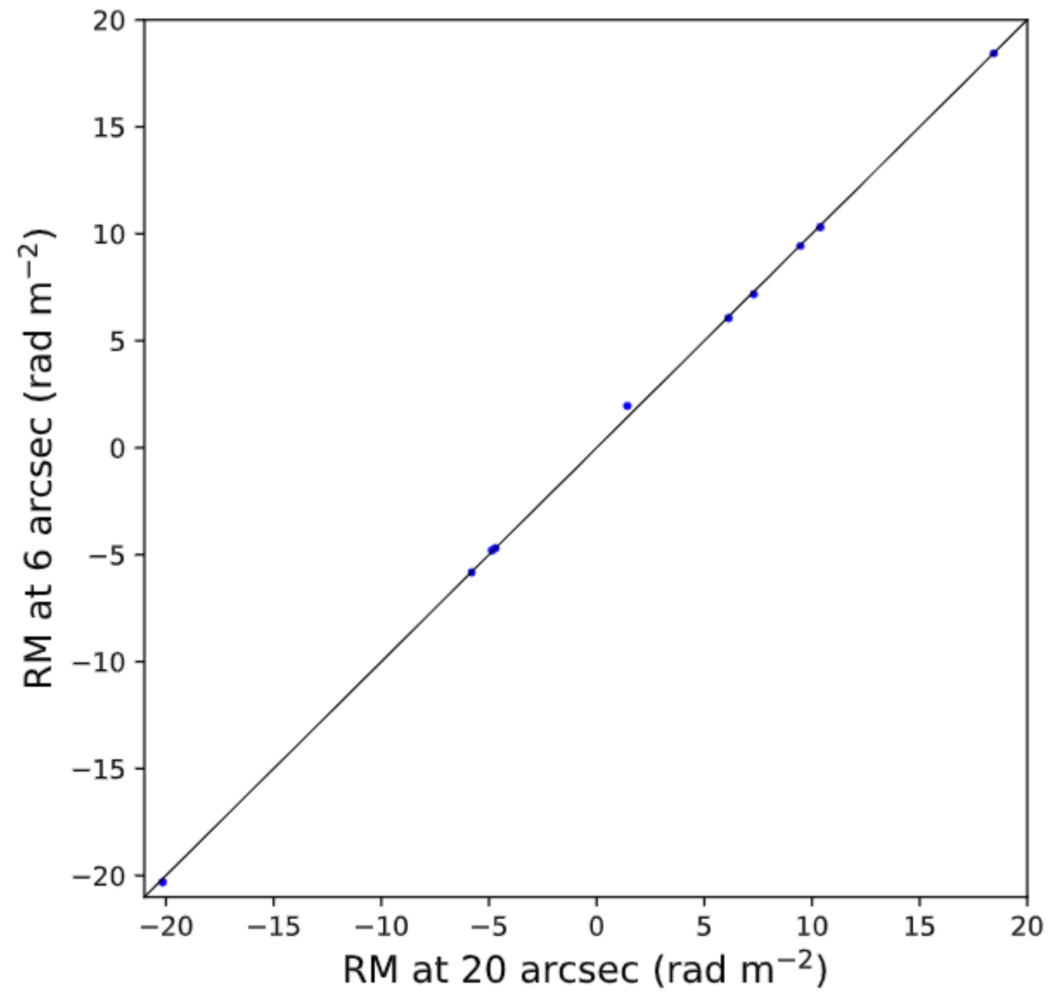
Found 32 polarized sources in 25deg^2
= 1.3 sources/deg^2
Lower noise level = 18 μJy/beam



Variety of source morphologies Piras et al. in prep.

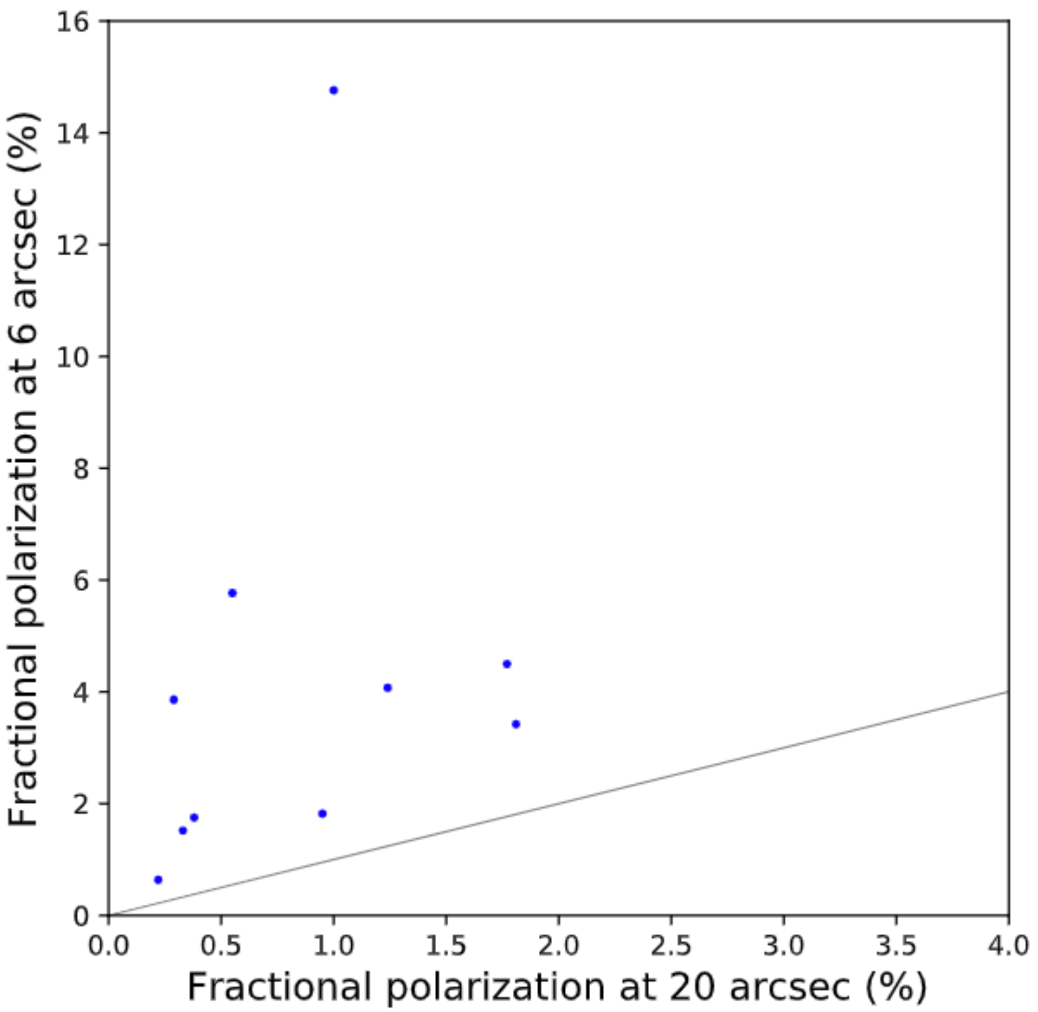
RESULTS: COMPARISON WITH THE 20" DATA (HERRERA RUIZ ET AL. 2021)

Piras et al. in prep.



RMs in excellent agreement

150 MHz

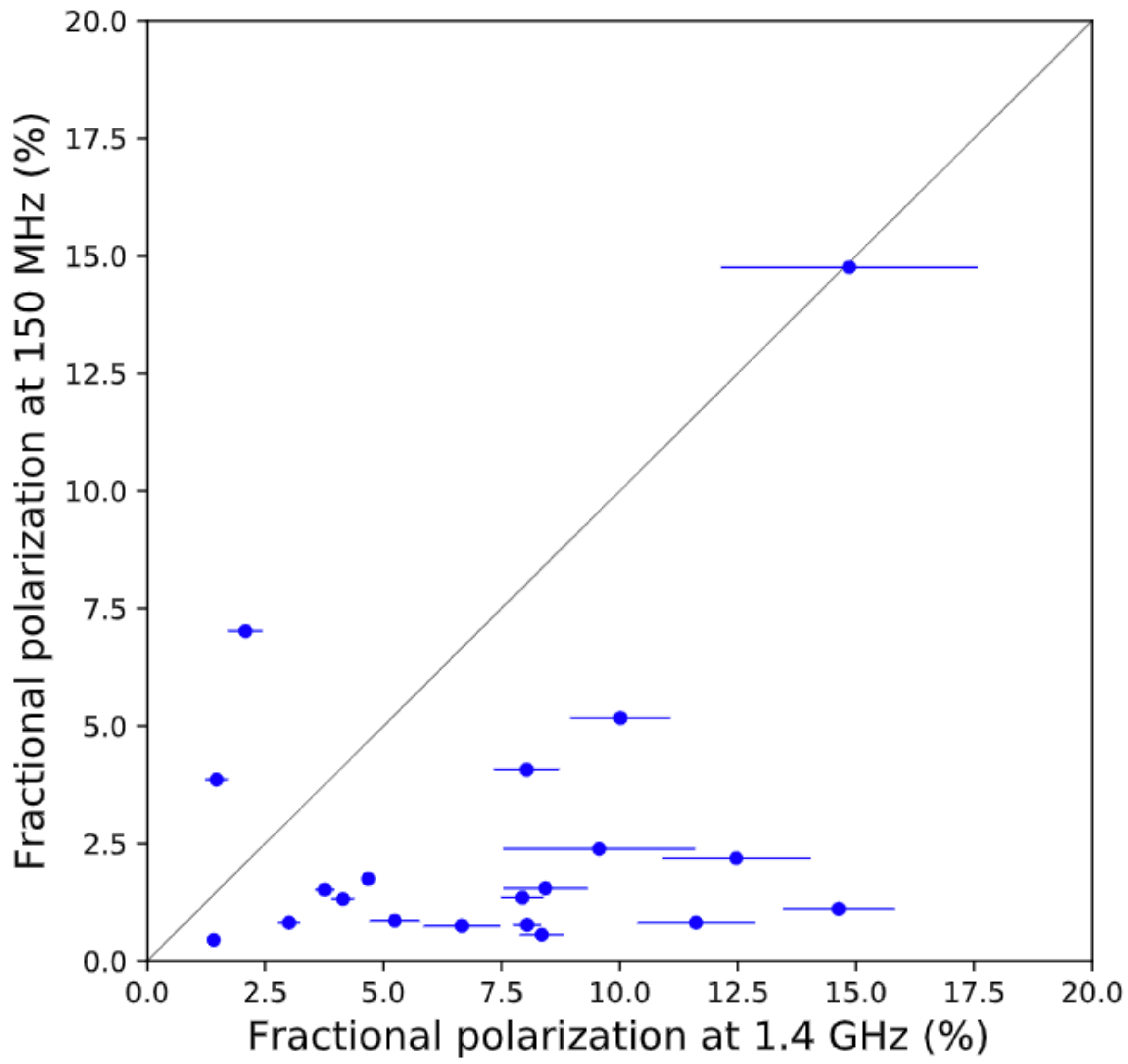


Evidence for
beam depolarization at 20"

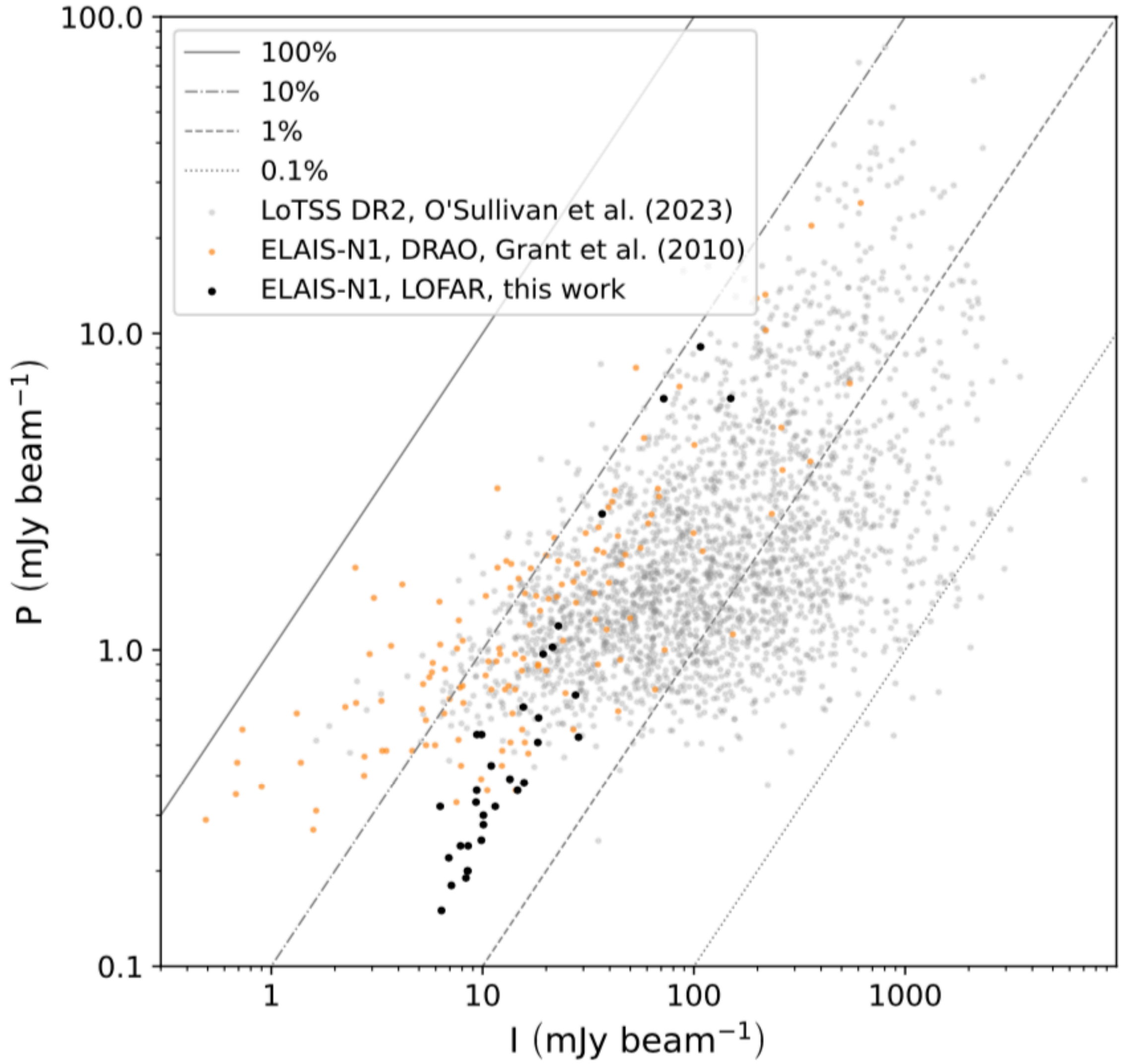
RESULTS: COMPARISON WITH THE 1.4 GHZ DATA FROM GRANT ET AL. (2010)

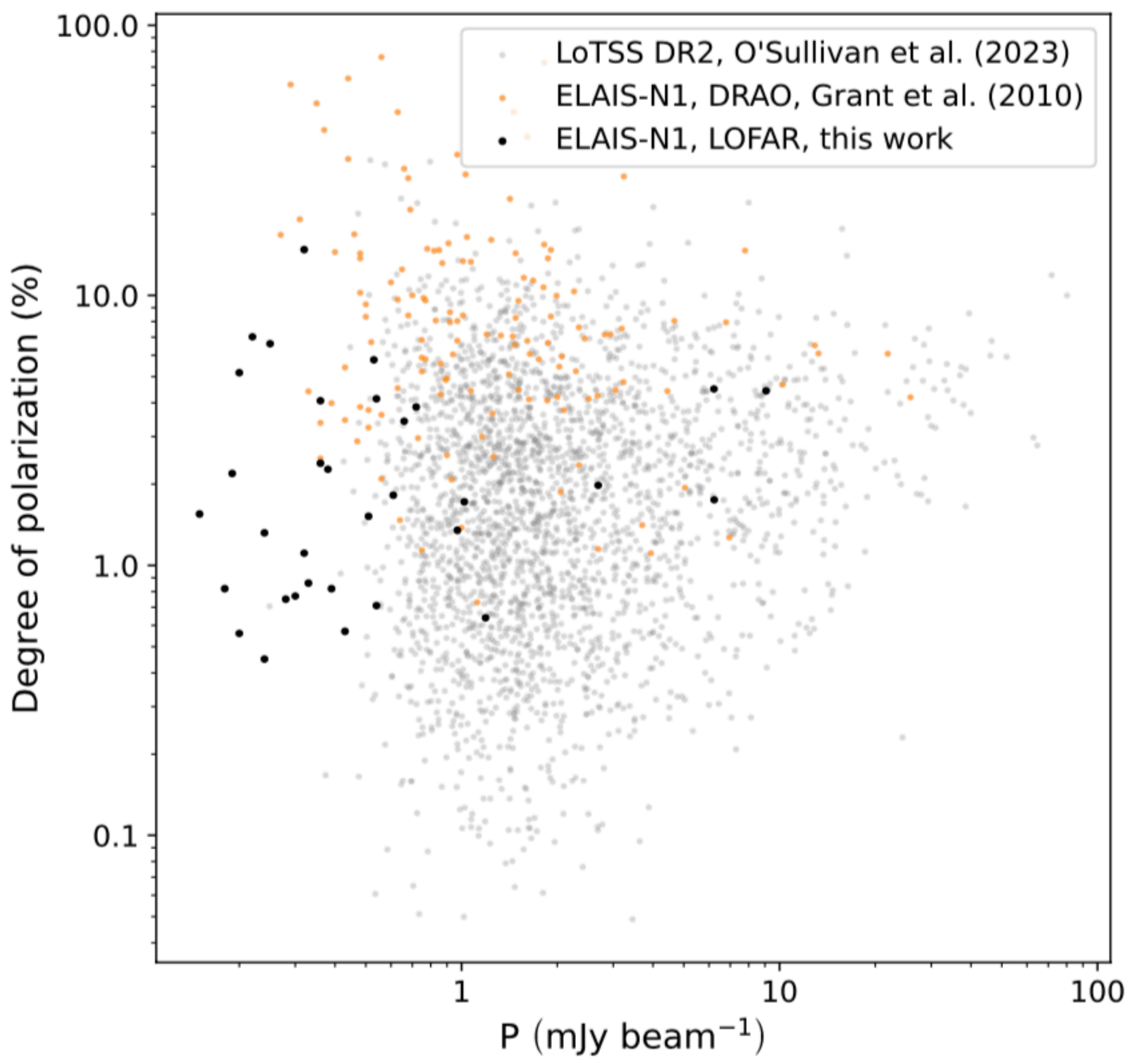
Frequency	Π_{med}
1.4 GHz	7.06 %
150 MHz, this work (∩ 1.4 GHz)	1.43 %
150 MHz, this work	1.75 %

Piras et al. in prep.



RESULTS: WIDE (LOTSS DR2) VS DEEP (THIS WORK)



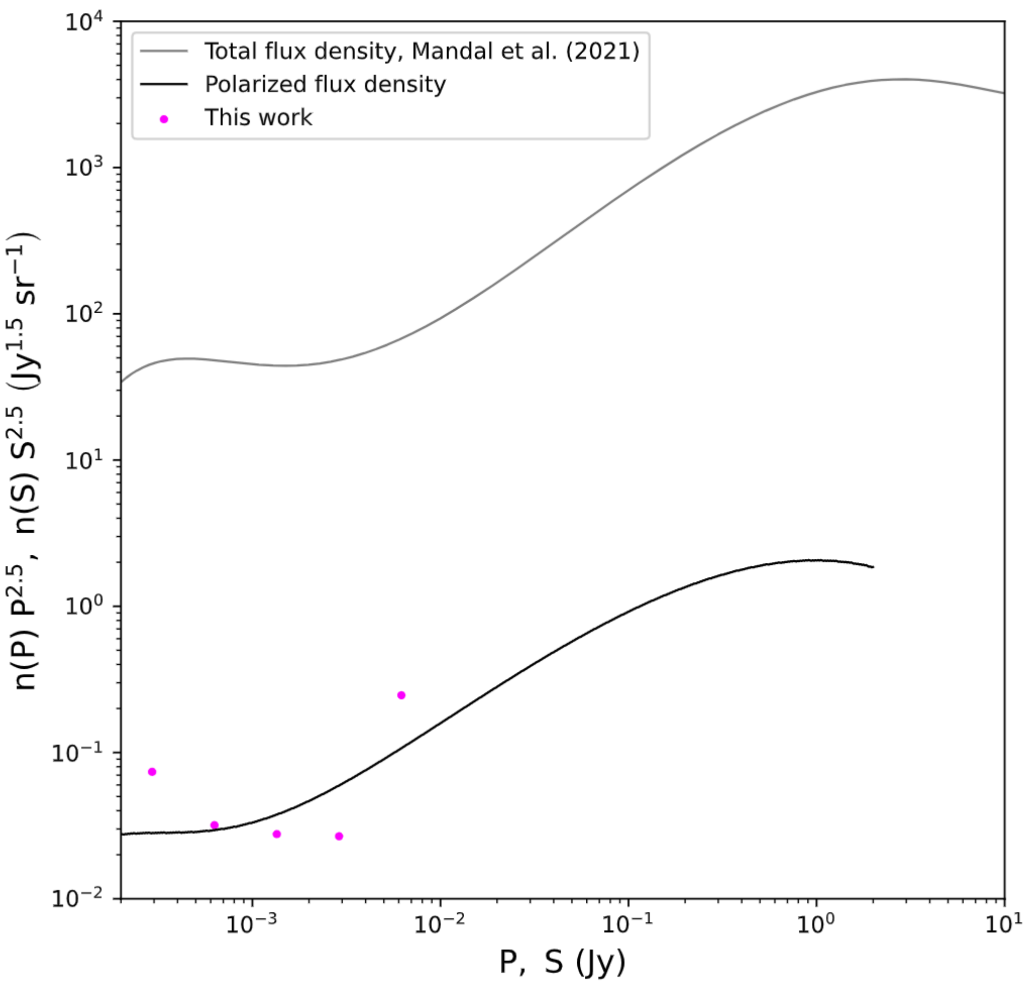


Piras et al. in prep.

RESULTS ON NUMBER COUNTS

- Polarized source counts as convolution of **source counts in total flux density** with a **probability function of fractional polarization** Π

$$\frac{dN}{dP} = \int_{S_0}^{\infty} F \mathscr{P}\left(\Pi = \frac{P}{S}\right) \frac{dN}{dS} \frac{dS}{S}$$



Piras et al. in prep.

- F : Fraction of sources polarized

$$F = \frac{N\,\text{polarized components}}{N\,\text{components}} = 2\,\%$$

- $\frac{dN}{dS}$: source counts in total flux density from Mandal et al. (2021)

$$\log\left(\frac{dN}{dS} S^{2.5}\right) = \sum_{i=0}^{k} a_k (\log S)^k$$

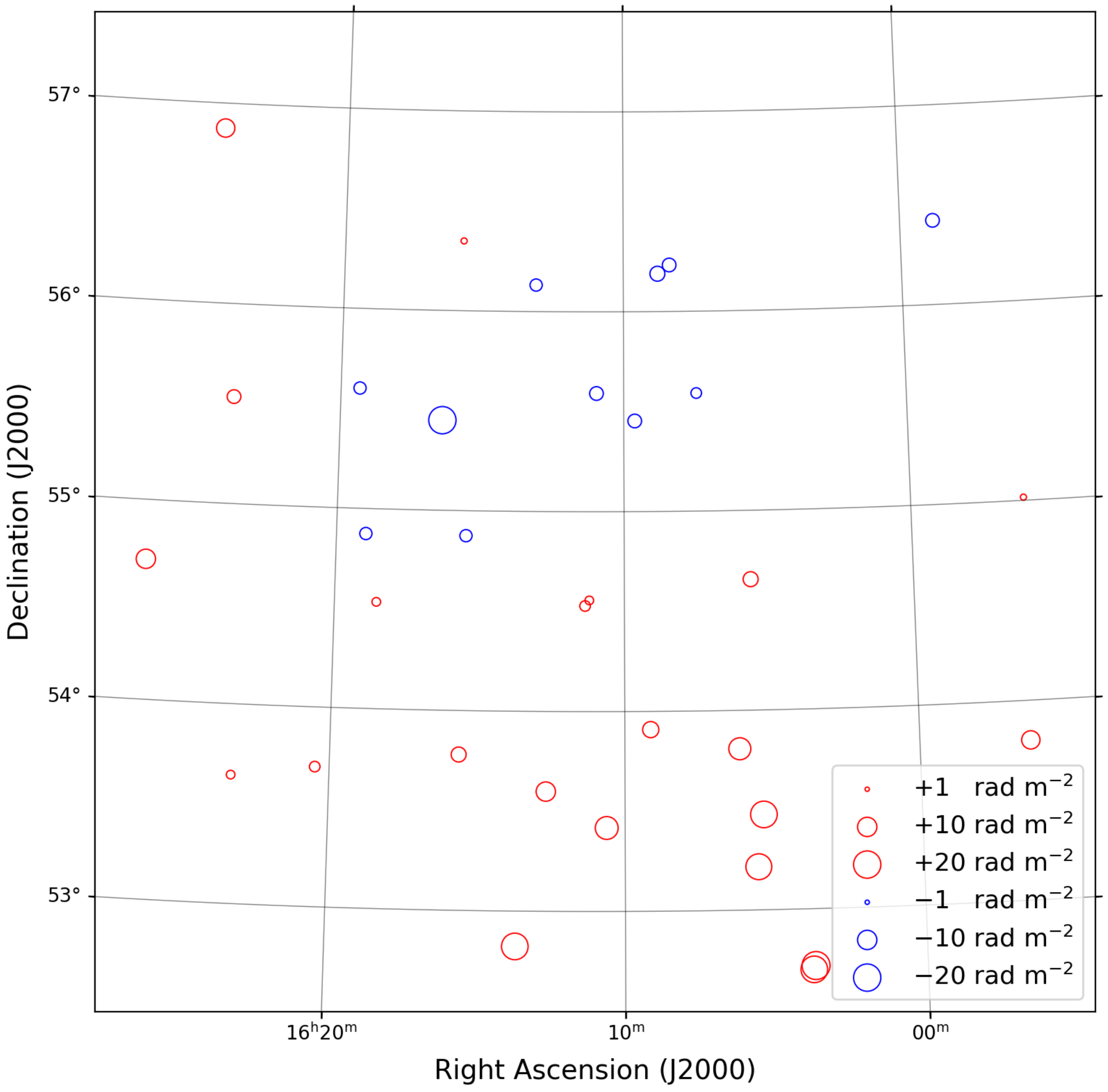
- $\mathscr{P}$: probability function

$$\mathscr{P}(\Pi) = \frac{1}{\sqrt{2\pi}\sigma\Pi} \exp\left\{ -[\log(\Pi/\Pi_{med})]^2/2\sigma^2 \right\}$$

$$\sigma = 5$$

$$\Pi_{med} = 1.82\,\%$$

RESULTS: ELAIS-N1 DEEP FIELD RM GRID



Piras et al. in prep.

CONCLUSIONS

- Not much is known about how the fractional polarization behaves (increase/decrease toward lower flux densities? implications for future RM grid)
- We have developed new methods to stack polarization and probe the faint (sub-mJy) regime in polarization and applied them to data from ELAIS-N1.
- Deepest LOFAR polarization data so far: noise level at the center of the field of 18 μJy/beam
- We confidently detected polarization in 32 radio galaxies (1.3 polarized sources per deg2) in the ELAIS-N1 LOFAR deep field (25 deg^2), after stacking data from 19 epochs
- Detected polarized sources show a variety of morphologies
- Still low number statistics

WORK IN PROGRESS AND FUTURE WORK:

- Further optimize the algorithm for searching for polarized sources
- Characterize the sources (morphology, redshift, etc)
- Comparison with other frequencies ➞ depolarization properties
- Source counts modelling
    - Taking account of depolarization
- Apply the analysis to other fields (LoTSS and LOFAR deep fields: GOODS-North, Boötes and Lockman Hole)
- International baselines provide a resolution of 0.4”. Unknown territory in polarization but likely reduced depolarization.