Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **478,** 2835–2849 (2018) doi:10.1093/mnras/sty1304
Advance Access publication 2018 May 18

An all-sky survey of circular polarization at 200 MHz

Emil Lenc,[1,2,3]★ Tara Murphy,[1,2] C. R. Lynch,[1,2] D. L. Kaplan[4] and S. N. Zhang[5]

[1]*Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia*
[2]*ARC Centre of Excellence for All-sky Astrophysics (CAASTRO), The University of Sydney, NSW 2006, Australia*
[3]*CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia*
[4]*Department of Physics, University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA*
[5]*School of Astronomy and Space Science, Nanjing University, 163 Xianlin Avenue, Nanjing 210023, China*

Accepted 2018 May 12. Received 2018 April 26; in original form 2018 February 28

ABSTRACT

We present results from the first all-sky radio survey in circular polarization. The survey uses the Murchison Widefield Array (MWA) to cover 30 900 sq deg, over declinations south of $+30^\circ$ and north of -86° centred at 200 MHz (over a 169–231 MHz band). We achieve a spatial resolution of $\sim$3 arcmin and a typical sensitivity of 3.0 mJy PSF^{-1} over most of the survey region. We demonstrate a new leakage mitigation technique that reduces the leakage from total intensity into circular polarization by an order of magnitude. In a blind survey of the imaged region, we detect 14 pulsars in circular polarization above a 6σ threshold. We also detect six transient sources associated with artificial satellites. A targeted survey of 2376 pulsars within the surveyed region yielded 33 detections above 4σ. Looking specifically at pulsars previously detected at 200 MHz in total intensity, this represents a 35 per cent detection rate. We also conducted a targeted survey of 2400 known flare stars, this resulted in two tentative detections above 4σ. A similar targeted search for 1506 known exoplanets in the field yielded no detections above 4σ. The success of the survey suggests that similar surveys at longer wavelength bands and of deeper fields are warranted.

Key words: radio continuum: planetary systems – (stars:) pulsars: general – plasmas.

GLEAM: GaLactic and Extragalactic All-sky MWA survey

(Wayth et al. 2015)

Telescope: MWA

Area: 30,900 deg^2

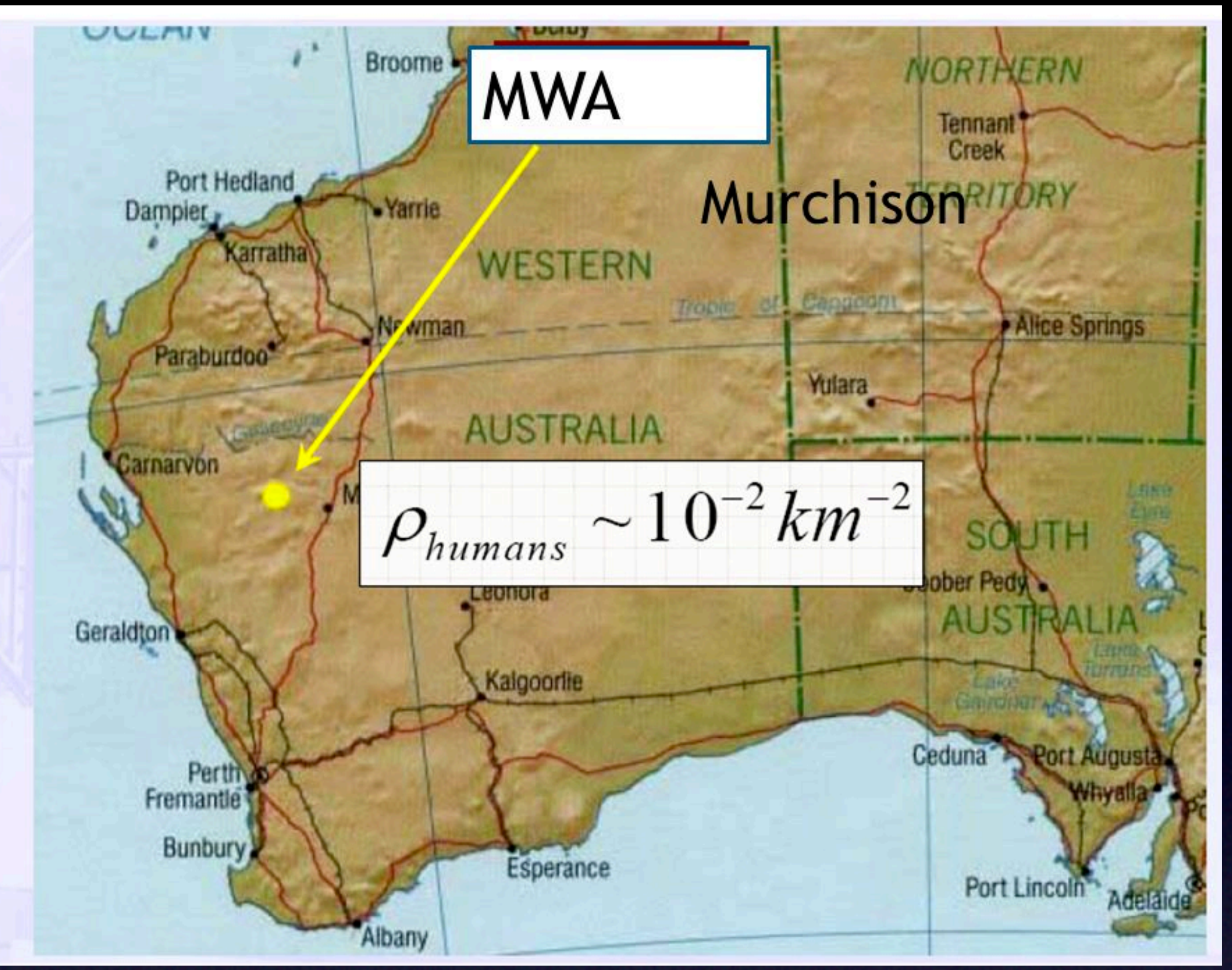
Dec: $-86° < \delta < +30°$

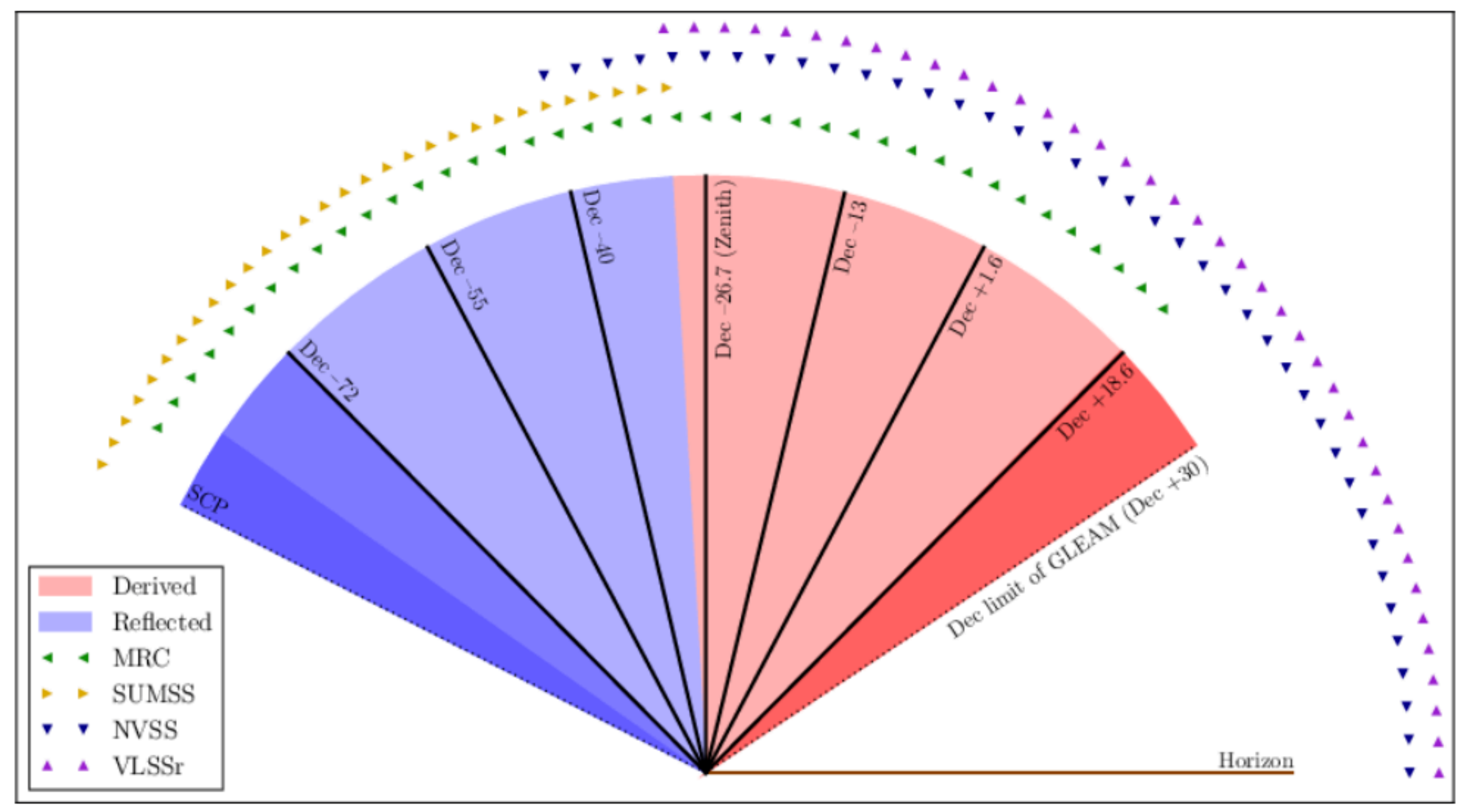
Frequency: 169 – 231 MHz (2 bands)

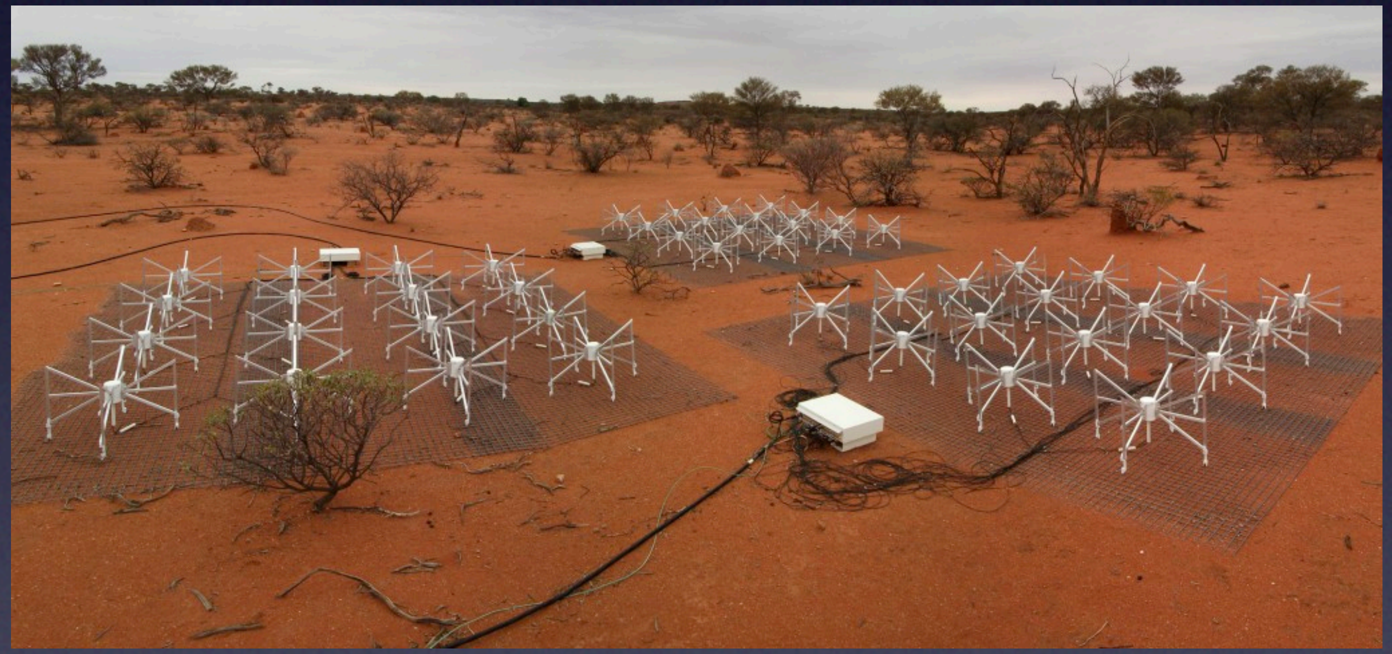
Resolution: 3′

$S_{min} \approx 3$ mJy PSF^{-1}

Drift-scan survey







Murchison Widefield Array

Data products:

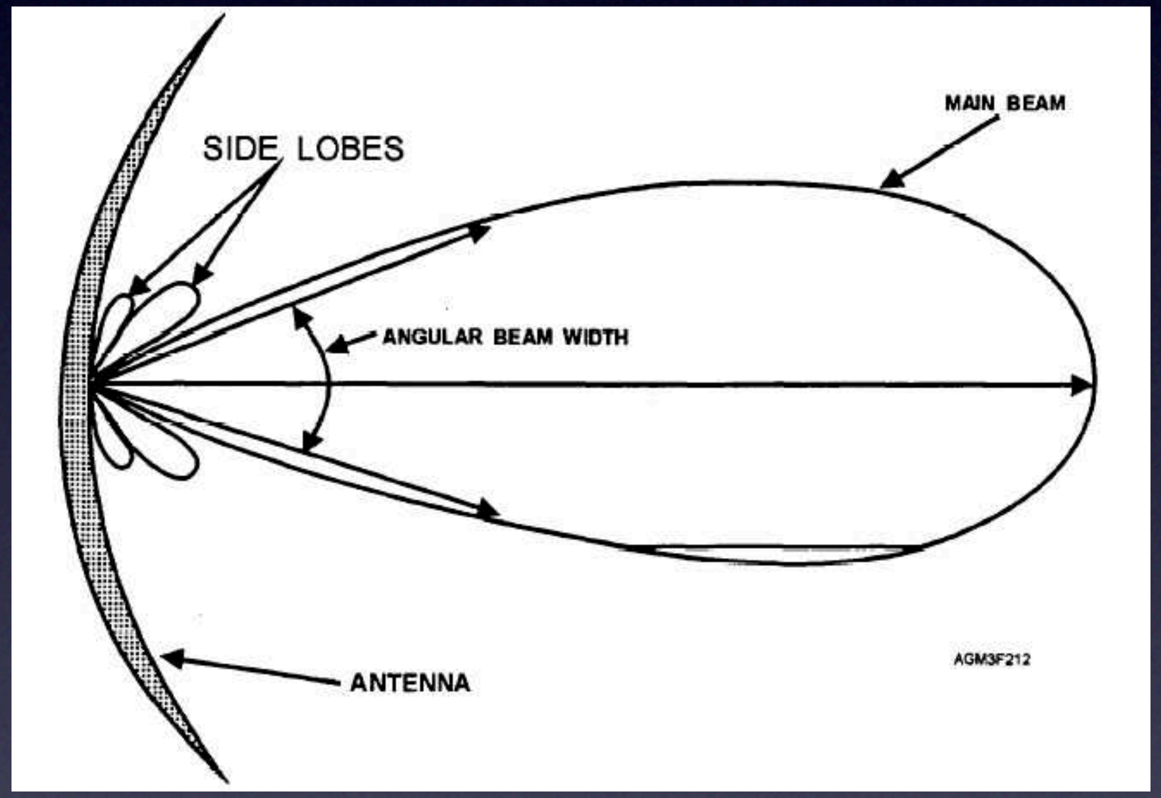
- 2-min snapshots (IQUV)
- 2187 x 2187px images (25° x 25° FoV)
- 40kHz spectral resolution
- frequency-averaged (centred on 200MHz)

History

To date, no all-sky surveys in Stokes V

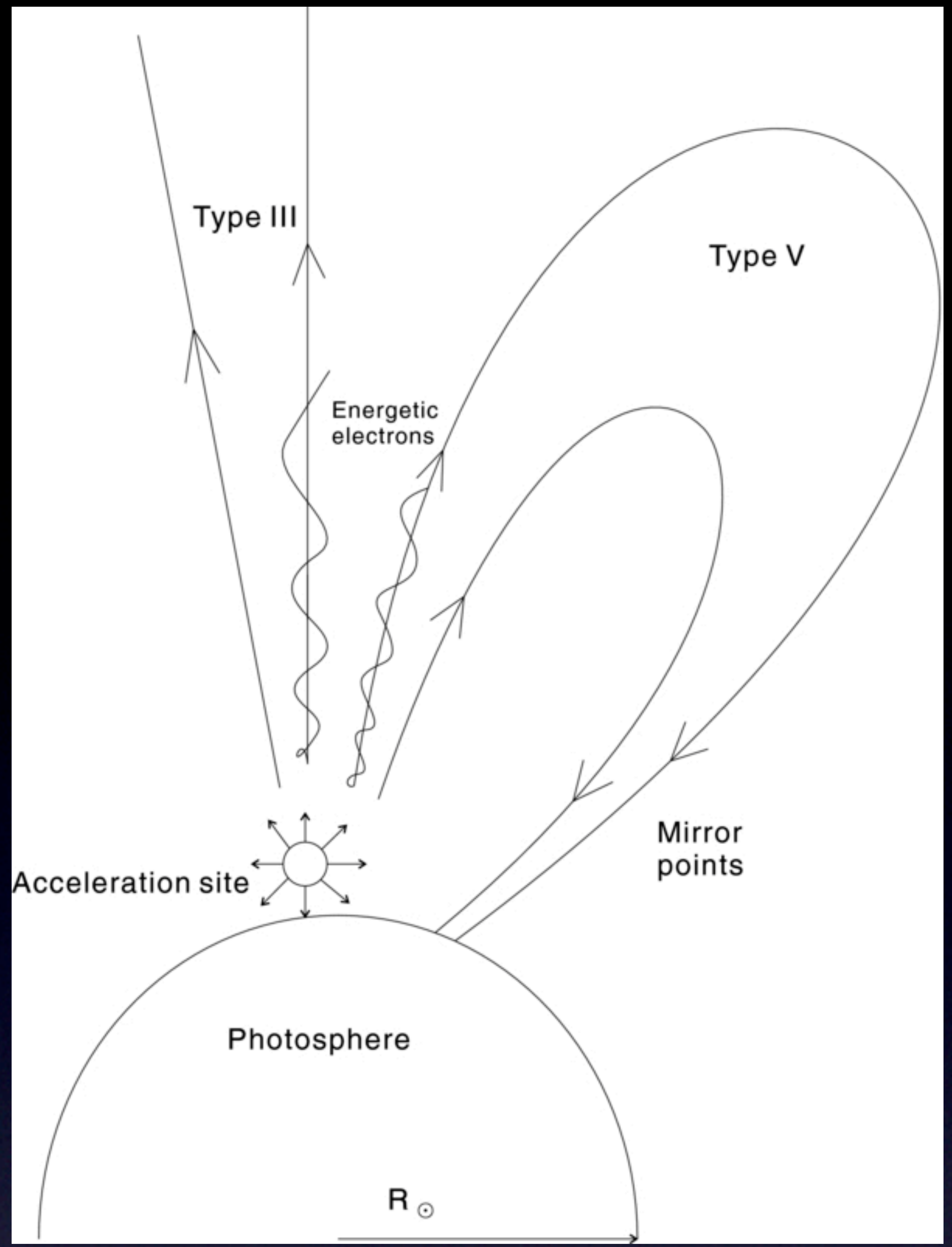
Advantages:

- Only a small fraction of sources emit in V → Lower confusion limit*
- Continuum observations in Stokes V can help detect pulsars missed due to:
  - complex orbits
  - sub-ms pulsars
  - pulse-broadened (scattered) pulsars
- If those pulsars have steep spectra, low-frequency imaging can help to detect them



* MWA is confusion-limited

Sources of V



Astrophysical processes that generate V:

- Synchrotron V is very weak
- Propagation effects:
  - scintillation
  - refraction near black holes
  - propagation of lin. pol. waves through relativistic plasma
- Pulsars
- AGN have <0.5% V
- CMI: electron–synchrotron maser instability (planets)

  e.g. Jupiter is known to have V/I ~ 1% @ 3.24 GHz (Seaquist 1969)

Leakage

All-sky observations in Stokes V suffer from instrumental leakage:

I → Q (strongest leakage)

I → U → V (~5% level)

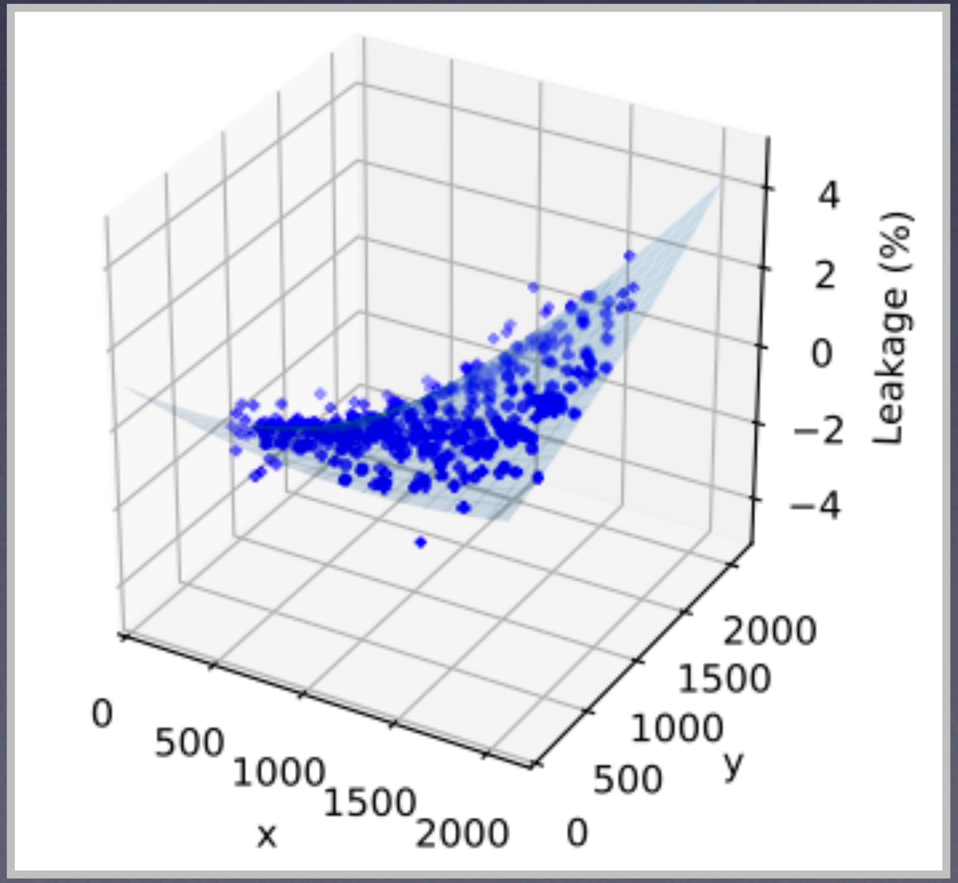
$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |X|^2 + |Y|^2 \\ |X|^2 - |Y|^2 \\ 2\,\mathrm{Re}(X^*\,Y) \\ 2\,\mathrm{Im}(X^*\,Y) \end{bmatrix}$$

X and Y are ideally ‘orthogonal’

Leakage from U to V results from uncorrected X–Y phase offsets

- Assume all sources are unpolarised
- Any measured polarisation is leakage

Leaked signal from I can result in false detections in V



To correct leakage in V:

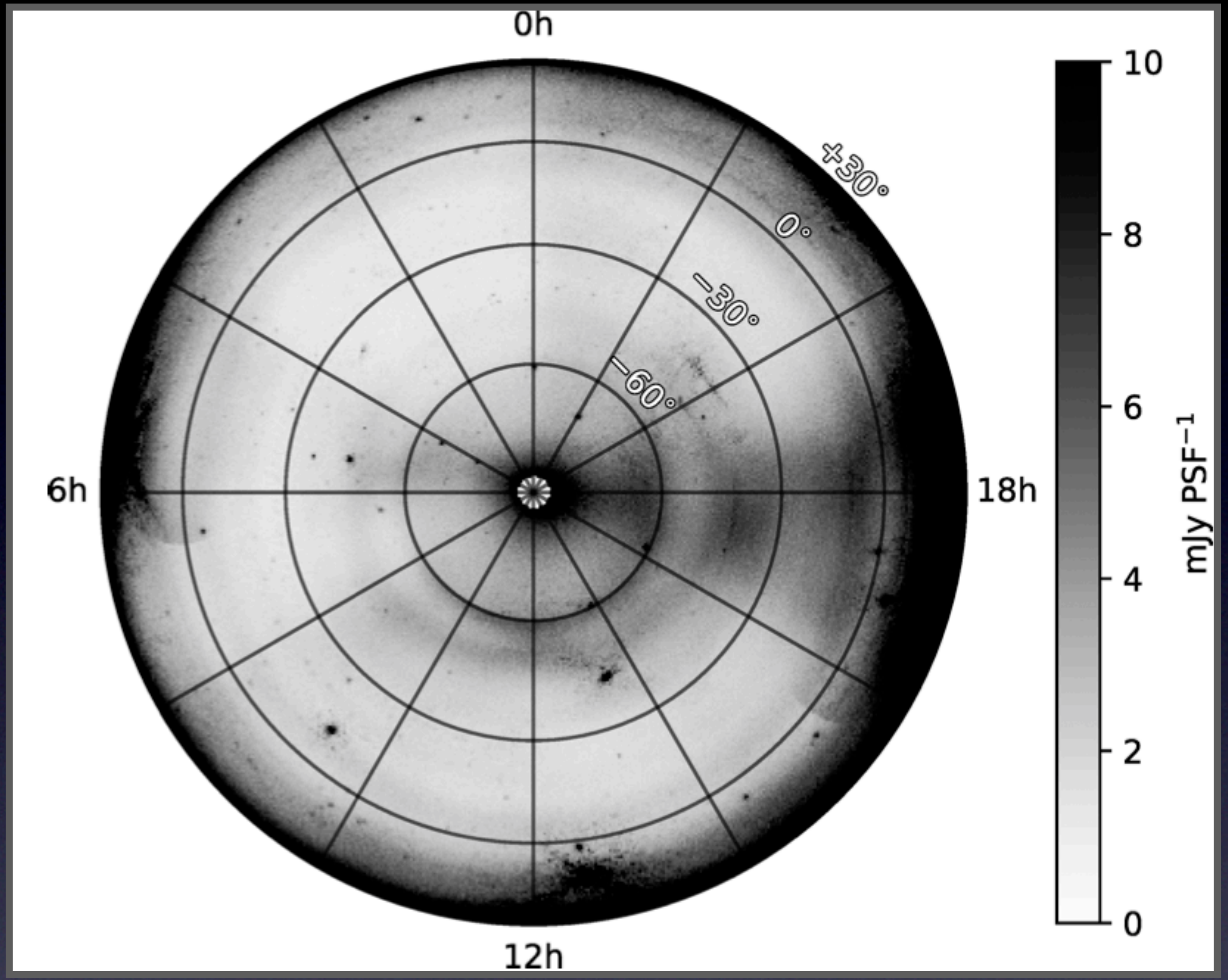
- The leakage was modelled with a quadratic surface across the beam
- Fitted surface was used to scale Stokes I map and subtract it from V map
- Based on lin. pol. sources, U → V leakage was estimated to be 20–30%*

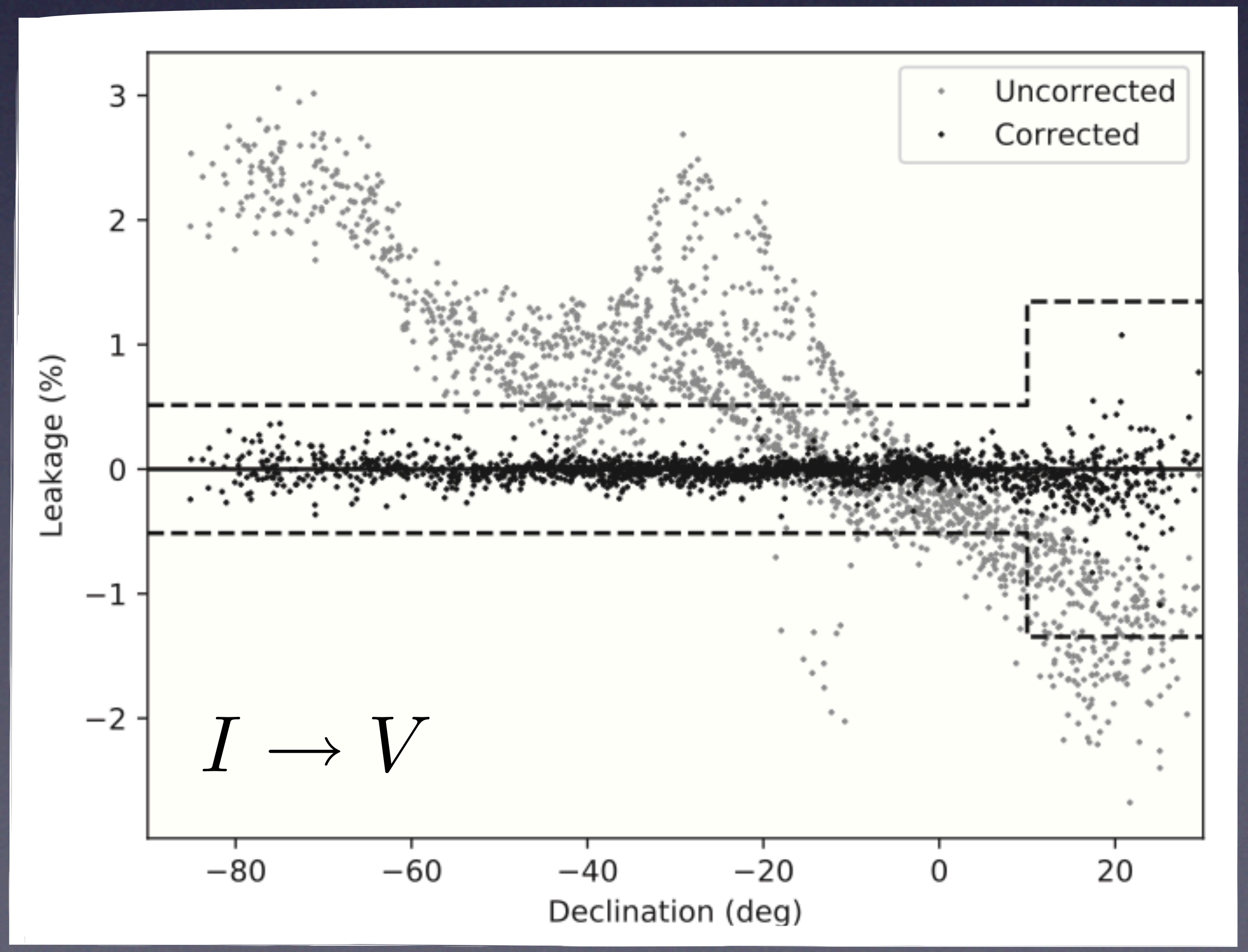
* this is not a problem for high-RM sources (FR depolarisation)

Leakage

1,779 GLEAM sources were used to check flux scale and directional leakage @ 200 MHz:

- Largest errors on the corrected flux towards high δ and towards GC
- RMS of leakage (I → V) after correction ~ 0.12%
- Leakage reduced by factor ~10, after correction

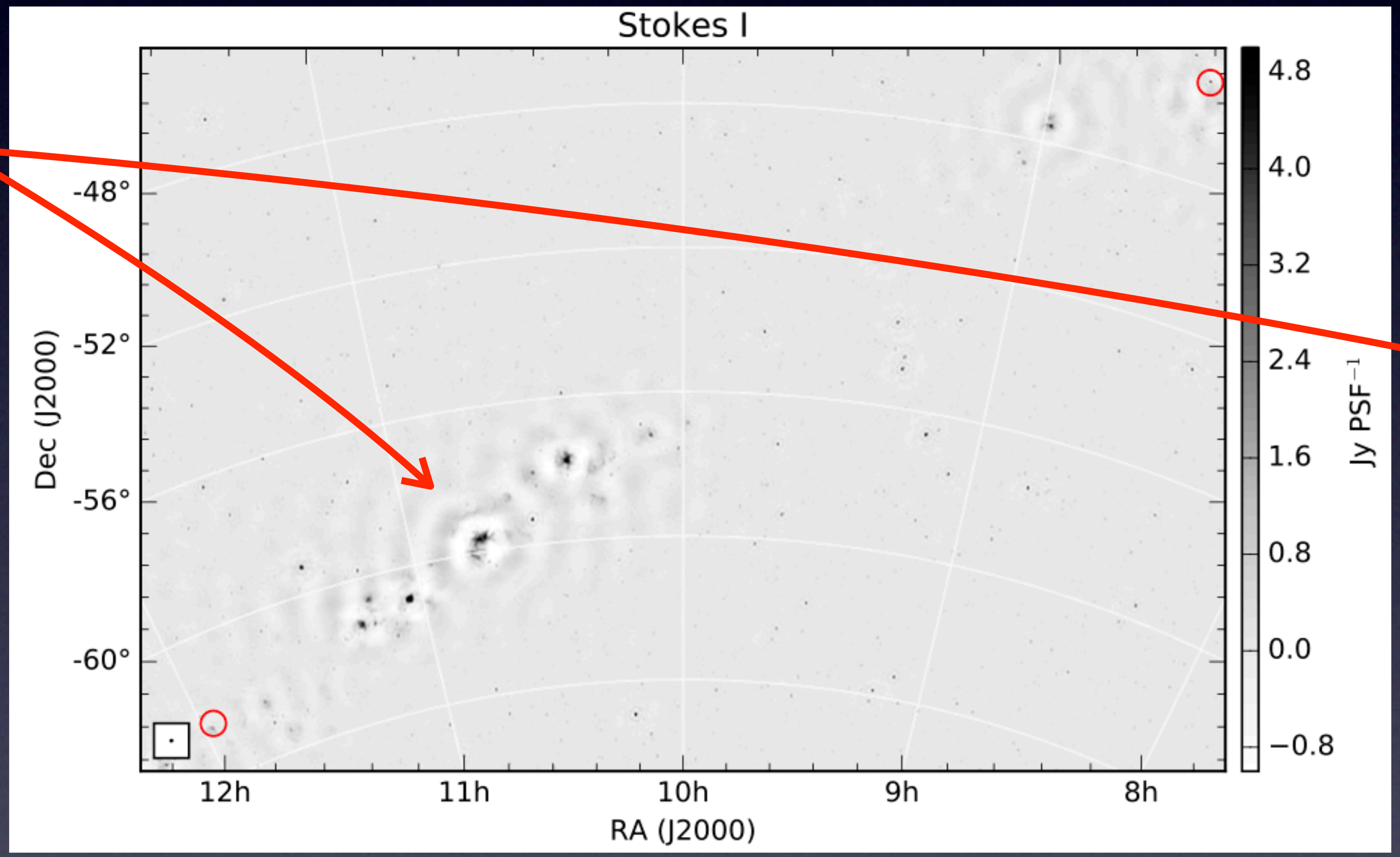


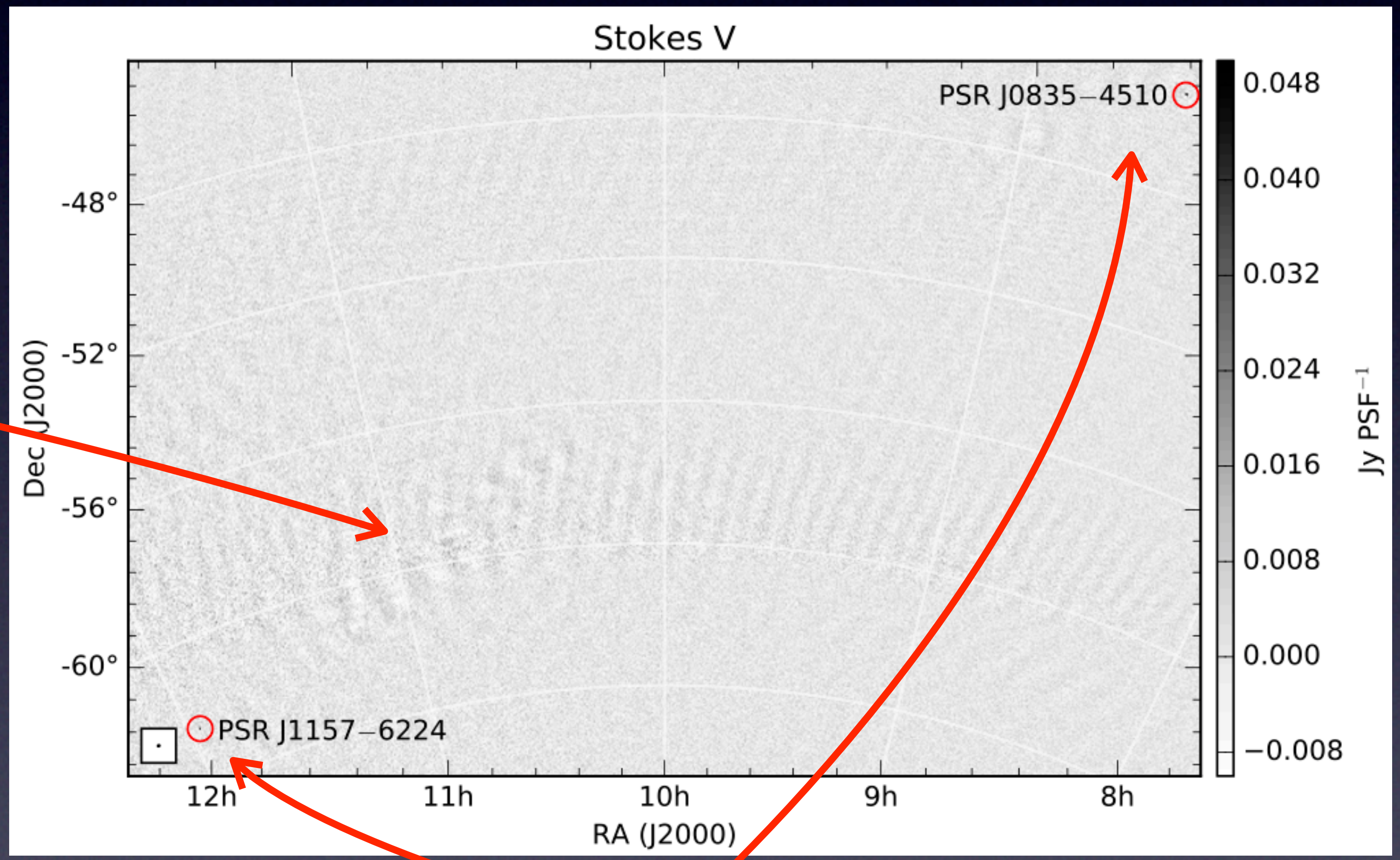


Mosaics

- Used SWARP to create mosaics from the 2-min snapshots
- ZEA (zenith-equal-angle projection)
- Averaged all frequencies to create Stokes I,V maps (uncorrected & corrected)

We expect higher Stokes V noise around bright sources (due to higher leakage)

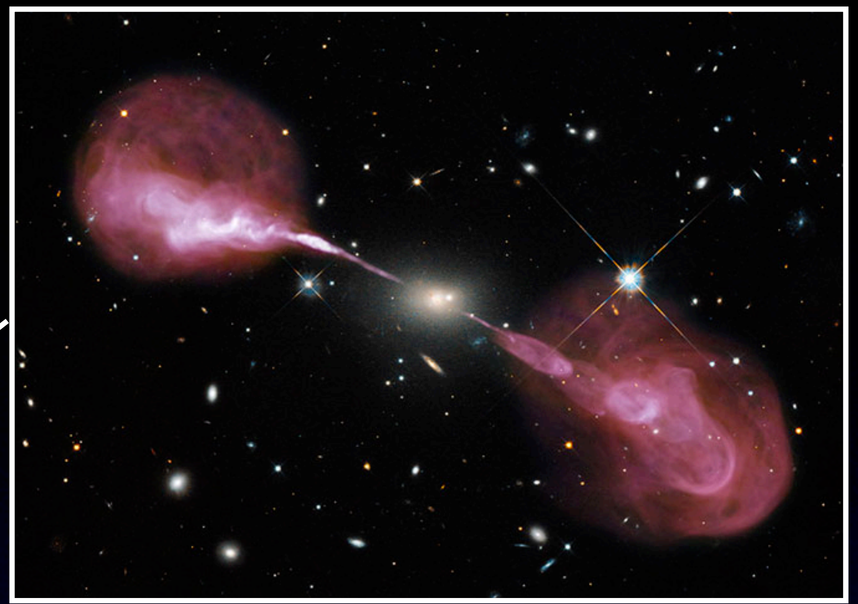




PSRs J1157–6224 & Vela were detected in both maps

Survey noise: $\langle\sigma_V\rangle \sim 3$ mJy/PSF (2x–5x better than GLEAM)

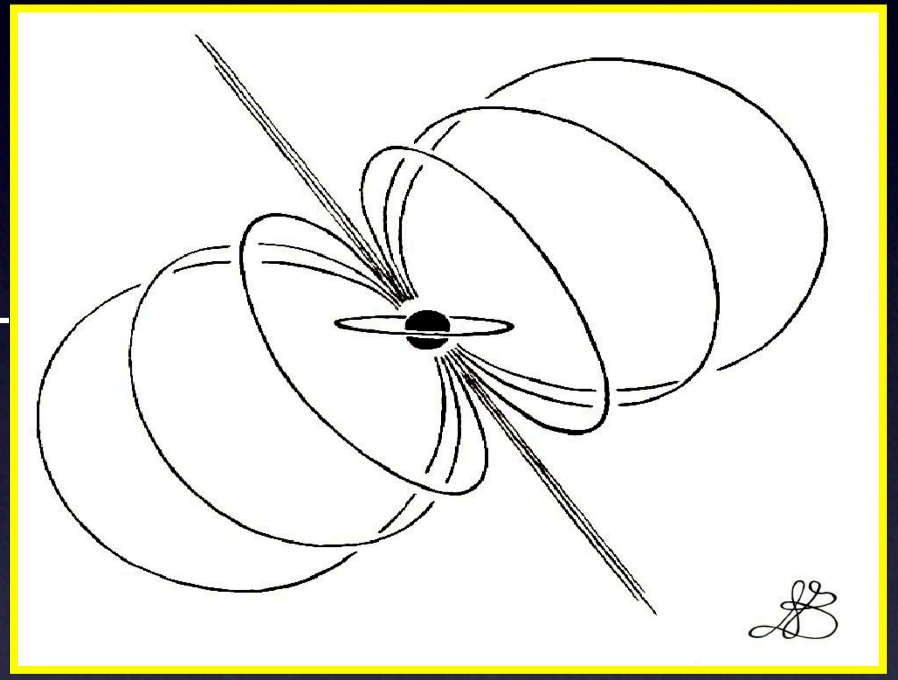
Results (Blind Search)



Flagged all pixels with $S_{200} \geq 6\ \sigma_{noise}$ (σ from noise map)

– 63 detections ($\geq 6\sigma$):

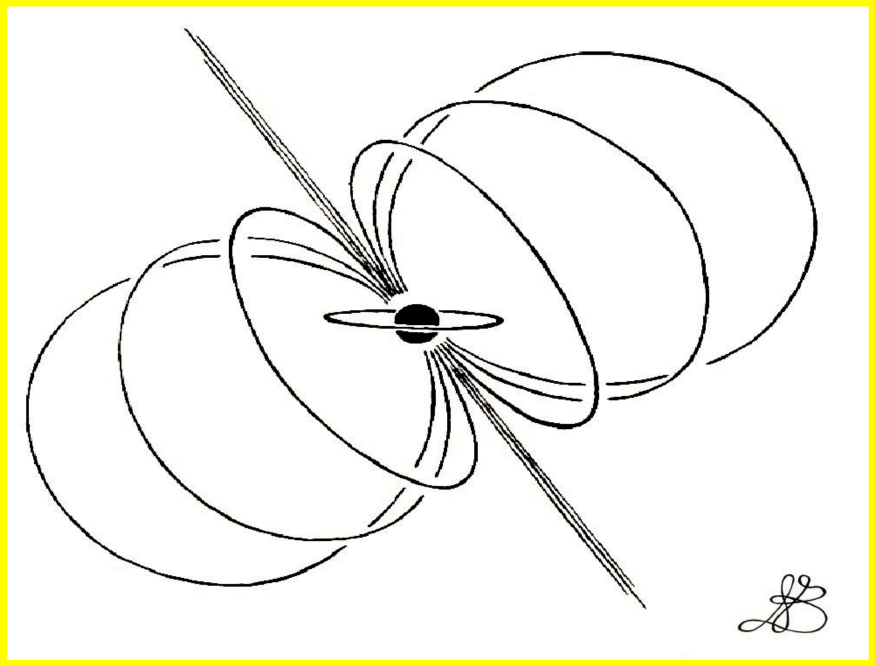
- 41 bright radio galaxies
- 15 known pulsars (incl. Crab)
- 1 Jupiter
- 15 trannies – which turned out to be artificial satellites



– Rejected the Crab nebula and all but 3 AGN due to enhanced brightness/leakage

Astrometric uncertainties:
- $0'.3$, for 6σ sources
- $1'$, for ionosphere

Pulsars (Blind Search)



14 PSRs

Source	V_{200} (mJy)	SNR
PSR J0034−0721	+30.5	13.9
PSR J0437−4715	+135.4	24.6
PSR J0630−2834	− 20.7	12.9
PSR J0738−4042	+14.0	7.4
PSR J0742−2822	− 15.3	9.0
PSR J0745−5353	− 18.7	9.2
PSR J0835−4510	+243.6	32.7
PSR J1136+1551	− 159.7	18.7
PSR J1157−6224	+50.8	11.3
PSR J1327−6222	− 33.8	7.2
PSR J1453−6413	+57.0	11.2
PSR J1651−4246	− 213.9	22.0
PSR J1932+1059	− 58.3	8.3
PSR J2048−1616	+17.6	9.8

incl. some classical ones

nearest
(& dearest?) MSP

Vela (+V)

B1133+16 (–V)

B1929+10

Properties:

- V / I > 3% – for overlapping sample, LOFAR shows similar V/I and signof(V) to MWA
- N_{+V} / N_{-V} ~ 1
- Vela SNR > 30σ
- PSR J0745–5353 was detected in V but not in I

AGN (Blind Search)

3C 139.2 : Detected in region with poor sensitivity: likely a false detection

PMN J0257–2433, PKS J0006–4235 :

- offset from their Stokes I positions by >2′ –
- likely associated with AGN hotspot that are

  (i) linearly polarised and

  (ii) have low RM

  → they leak U into V

Jupit*R* (Blind Search)

- Known to exhibit V/I ~ 1% @ 3.24 GHz
- MWA measured V/I ~ 3.1% @ 200 MHz (7.3σ significance)

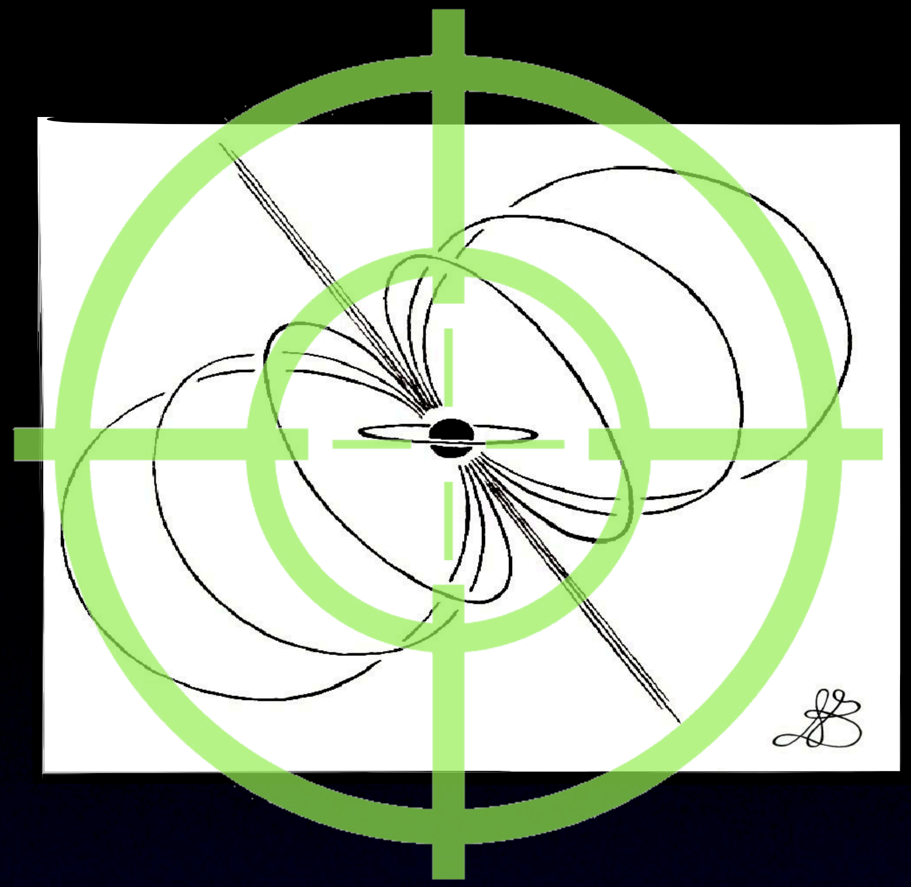
perhaps an overestimate

Artificial Satellites

- Satellites can reflect FM-radio signals
- However, the detections were at 200 MHz » FM (87.5 – 108 MHz)

Conclusion: the signals were direct satellite transmissions

Pulsars (Targeted Search)



- 2,376 PSRs within surveyed sky (total = 2,659)
- A lower 4σ threshold was used for the targeted search

Results:

- Total number of detections: 32 PSRs
- 18/32 not seen in the Blind Search
- 3 PSRs (J0206-4028, J0828–3417 and J1900–2600) opposite signof(V) compared to higher frequencies
- 21 of the 60 pulsars detected by Murphy et al. (2017) in Stokes I (>100–200 mJy) were detected in V
- 11 PSRs were detected in V but not I → Stokes V surveys can help discover PSRs

Exoplanets (Targeted Search)

- Planetary auroras can generate bright CMI emission
- CMI frequency tied to B-field strength

  ⇒ we can measure B-field* and probe planet's interior composition

  ⇒ time/frequency variations of the radio emission can constrain B-field geometry and planet's orbit

* To date, no unambiguous detections of exoplanetary B-fields

CMI emission: $f_c = \frac{eB_\mathrm{p}}{2\pi m_\mathrm{e}} \approx (2.8\,\mathrm{MHz})B_\mathrm{p}$

e.g. B_p for Proxima Cen b ~ 1 G ⇒ f_c ~ 3 MHz (ionosphere absorbs <10 MHz)

Exoplanets (Targeted Search)

- Planetary auroras can generate bright CMI emission
- CMI frequency tied to B-field strength

  ⇒ we can measure B-field* and probe planet's interior composition

  ⇒ time/frequency variations of the radio emission can constrain B-field geometry and planet's orbit

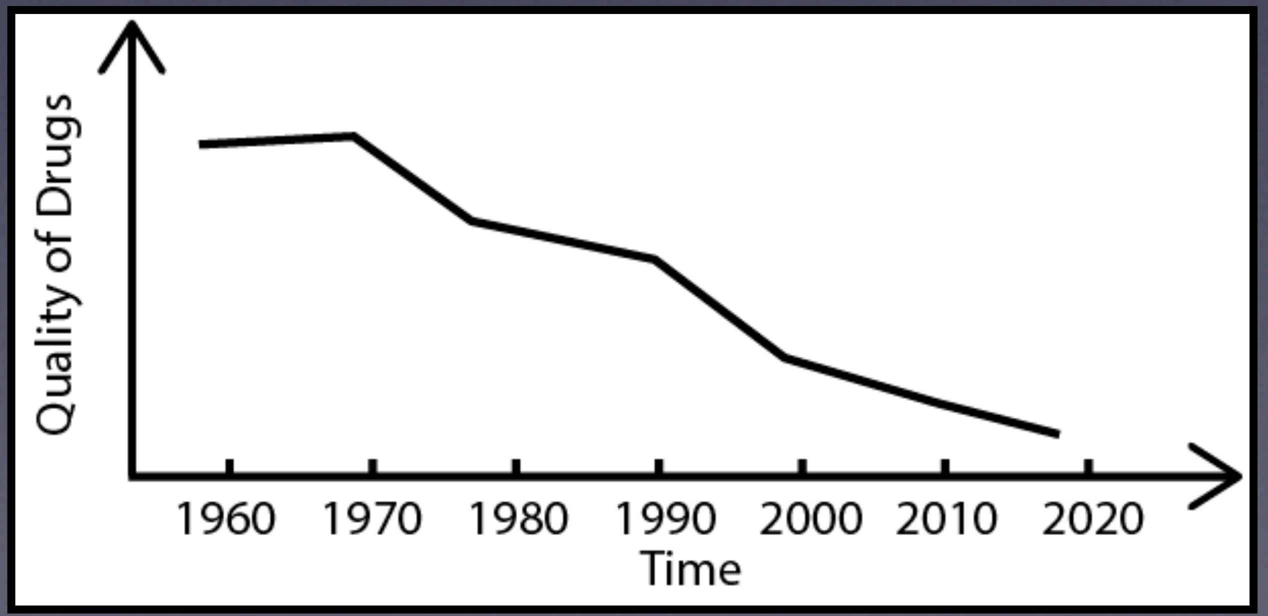
* To date, no unambiguous detections of exoplanetary B-fields

CMI emission: $f_c = \frac{eB_\mathrm{p}}{2\pi m_\mathrm{e}} \approx (2.8\,\mathrm{MHz})B_\mathrm{p}$

e.g. B_p for Proxima Cen b ~ 1 G ⇒ f_c ~ 3 MHz (ionosphere absorbs <10 MHz)

In the 1960s and 1970s,

- Several magnetically active M stars were observed with single-dish telescopes to produce 0.03–0.8 flares/hr @ 90–300 MHz with S=0.8 –20 Jy
- No detections since (see figure for possible explanation)



Exoplanets (Targeted Search)

Targeted search of 1,506 exos:

- **Proxima Cen b** and **HD 34445** were found to have 4σ Stokes V emission

- The emission is real, but probably associated with the host stars

Summary

- All-sky Stokes V survey with the MWA (using GLEAM data)
- Polarisation-leakage mitigation for MWA (leakage reduced by factor 10 = 0.72%)
- Detection of 32 PSRs, 6 satellites, 2 flare stars
- 35% of PSRs were detected in both V and I
- 11 PSRs detected in V but not in I (due to sensitivity / confusion)
- Detection of transients whose signof(V) flips will require integrations shorter that the flippin' time-scale
- In future, the extended MWA will have reduced sidelobes
- The leakage mitigation should be applicable in the SKA: it will require that

  (i) the leakage is constant with time

  (ii) good images over short integrations can be made