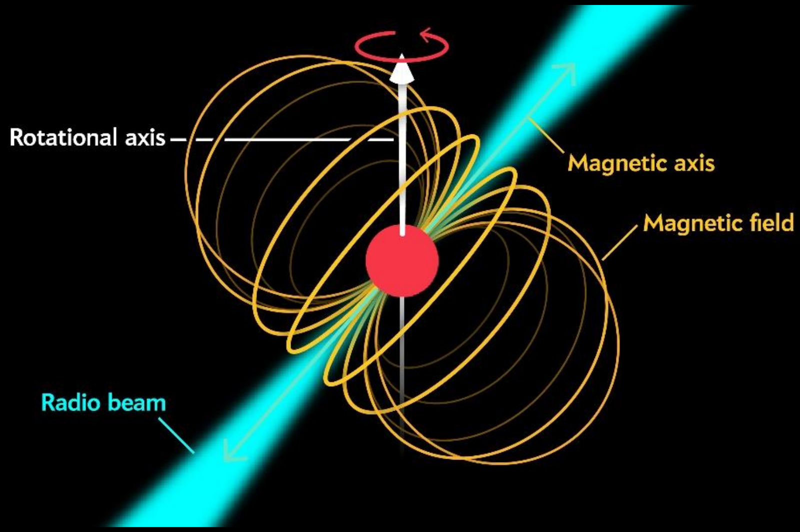
The polarisation leakage and correction for pulsar observation with the MWA

Mengyao Xue

Pulsars

- Neutron stars
- Rapidly rotating

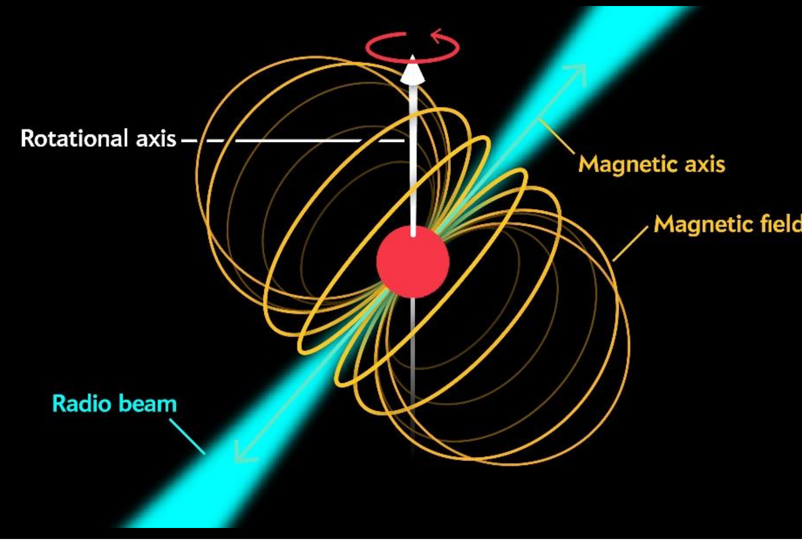
  (~ 1 ms to 10 s)
- Radius: ~ 10 km
- Mass: ~ 1.2 to 2.3 $M_\odot$
- Pulse:
  - Light house effect



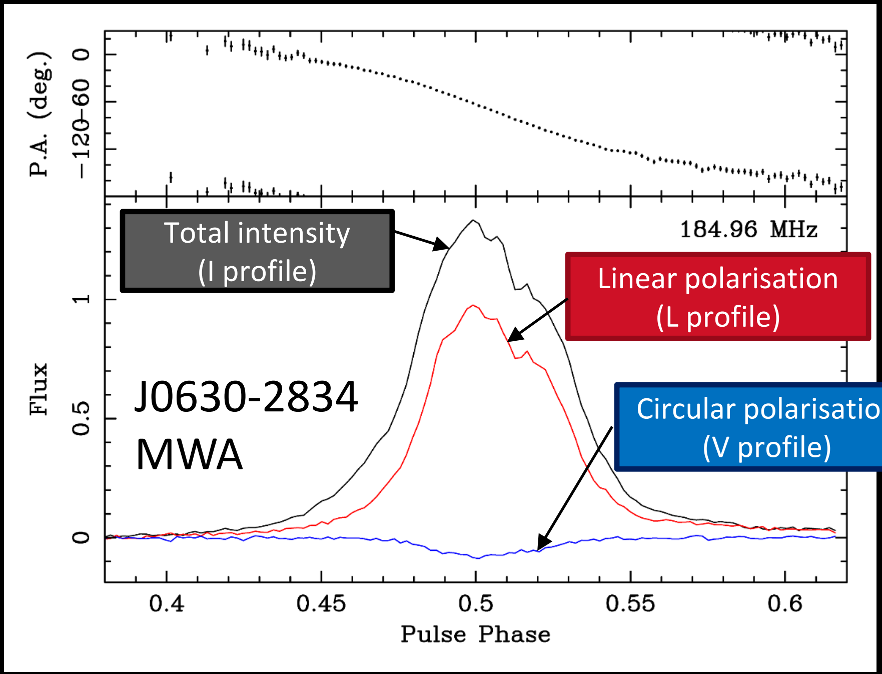
Credit: Jen Christiansen

Pulsar Polarisation

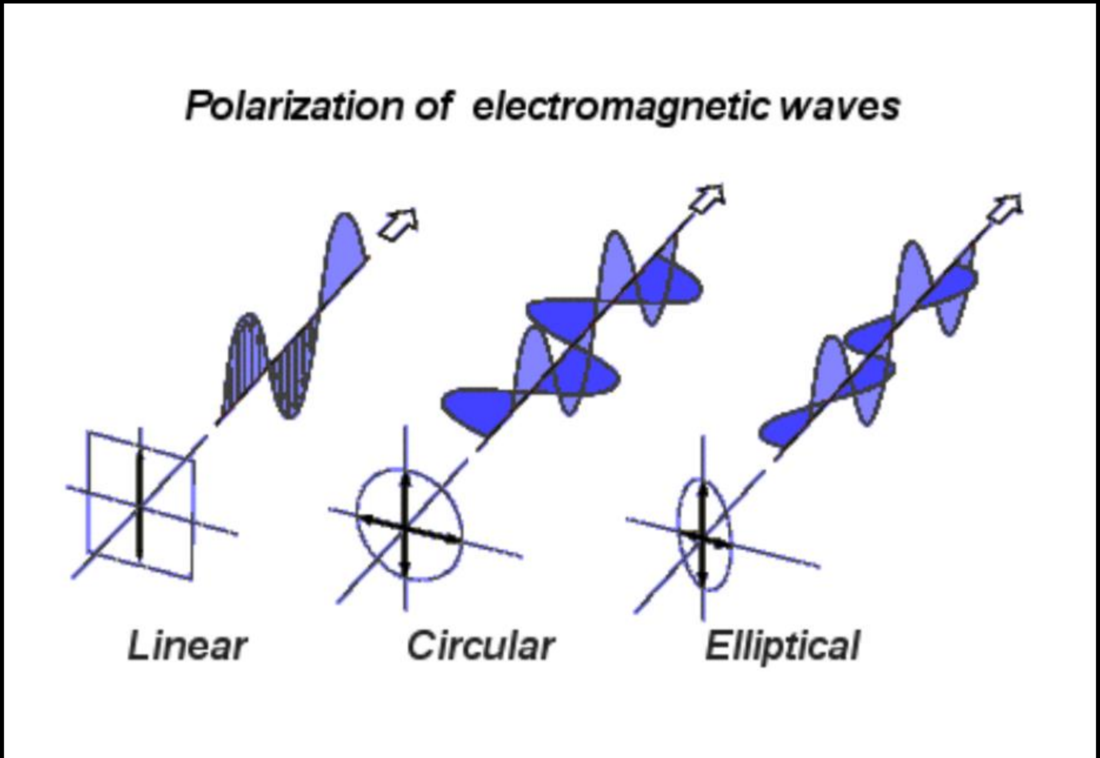
- Highly magnetised
  - (~10^8 - 10^{14} G)



- Highly polarised
- Linear:
  - Average ~20%, highest ~100%
  - Tends to ↓ with frequency ↑
- Circular :
  - Average ~10%



Polarisation



Linear: orthogonal components in phase with constant ratio of strengths giving constant direction of electric vector.
Circular: orthogonal components 90° out of phase with equal amplitudes – electric vector traces circle.

Stokes Parameters *I, Q, U, V*

I: total intensity

$L = \sqrt{Q^2 + U^2}$: linear polarisation

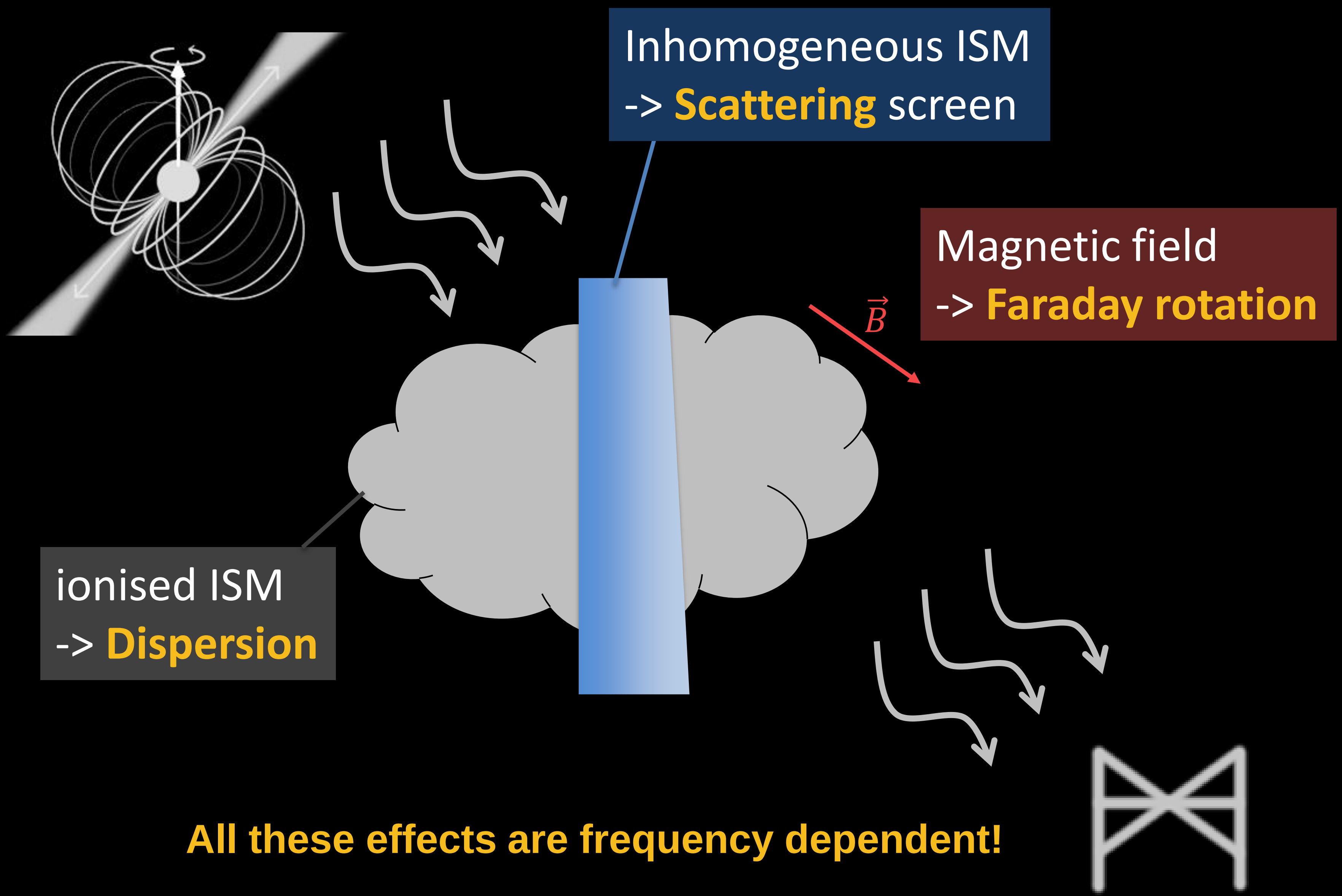
V: circular polarisation

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \equiv \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2\,\mathrm{Re}\left(E_x E_y^*\right) \\ -2\,\mathrm{Im}\left(E_x E_y^*\right) \end{bmatrix} = \begin{bmatrix} E_x^2 + E_y^2 \\ E_x^2 - E_y^2 \\ 2E_x E_y \cos\delta \\ 2E_x E_y \sin\delta \end{bmatrix}$$

Ex and Ey represent the electric field that can be obtained by orthogonal linear feeds in a radio antenna;

δ is the phase difference between the two orthogonal components, x and y, which are perpendicular to the wave propagation direction z.

Propagation effects due to ISM



All these effects are frequency dependent!

Propagation effects due to ISM

Dispersion

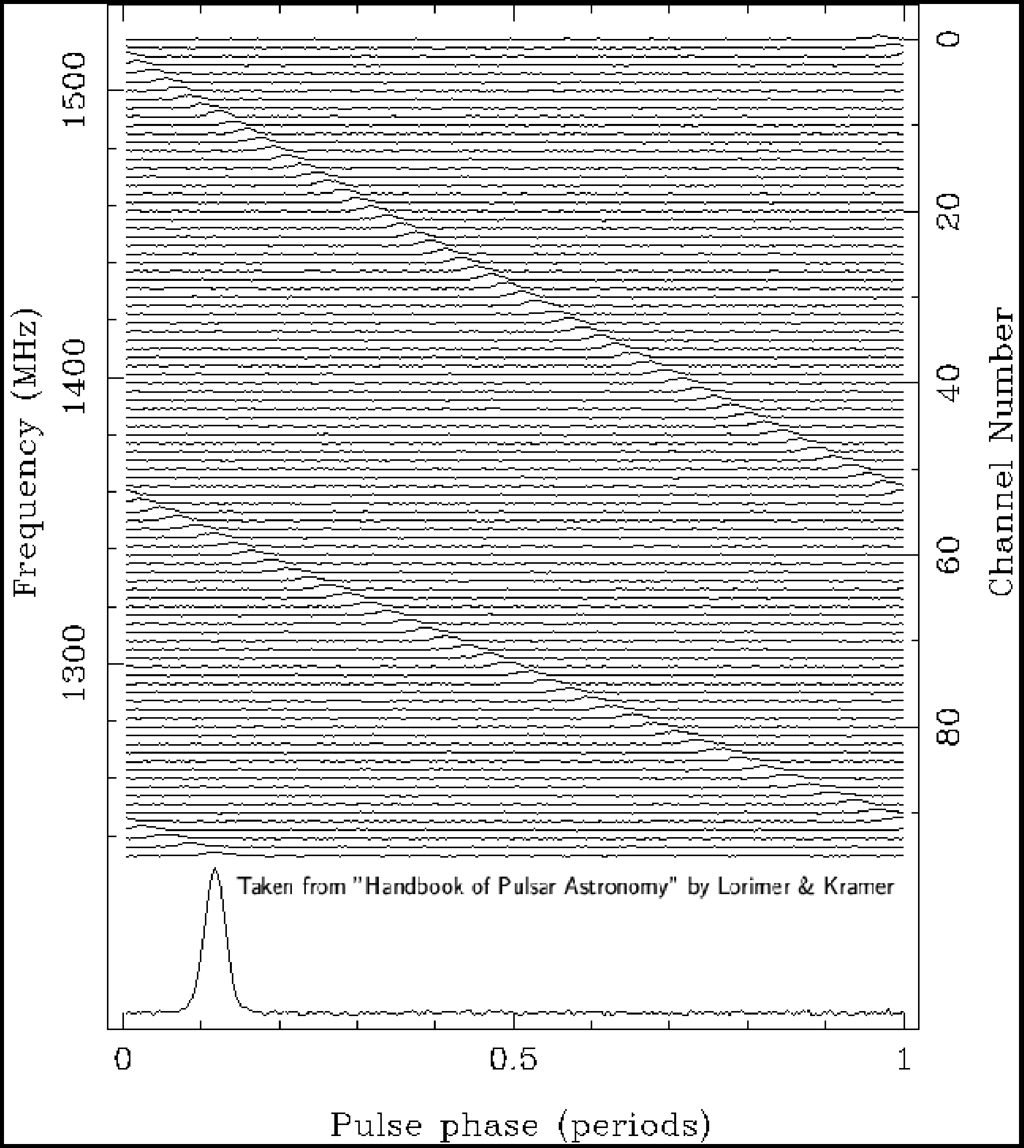
Different group velocity for different frequency wave in the ionised ISM

Low frequency signals will arrive later than higher ones

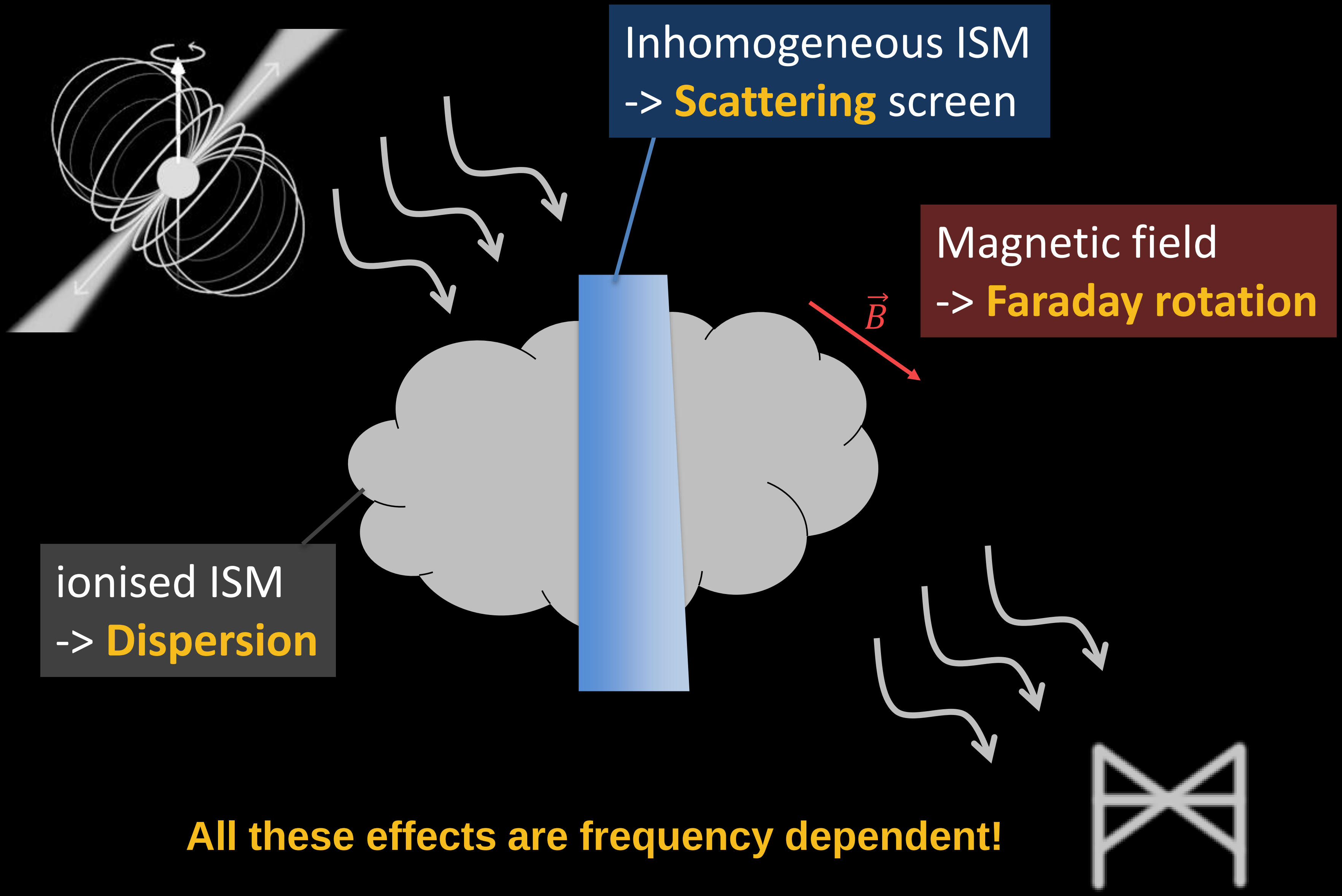
Dispersion Measure (DM)

$$t = \left(\int_0^d \frac{\mathrm{d}l}{v_\mathrm{g}} \right) - \frac{d}{c} = \frac{e^2}{2\pi m_\mathrm{e} c} \times \frac{\mathrm{DM}}{f^2}$$

$$\mathrm{DM} = \int_0^d n_\mathrm{e}\, \mathrm{d}l$$



Propagation effects due to ISM



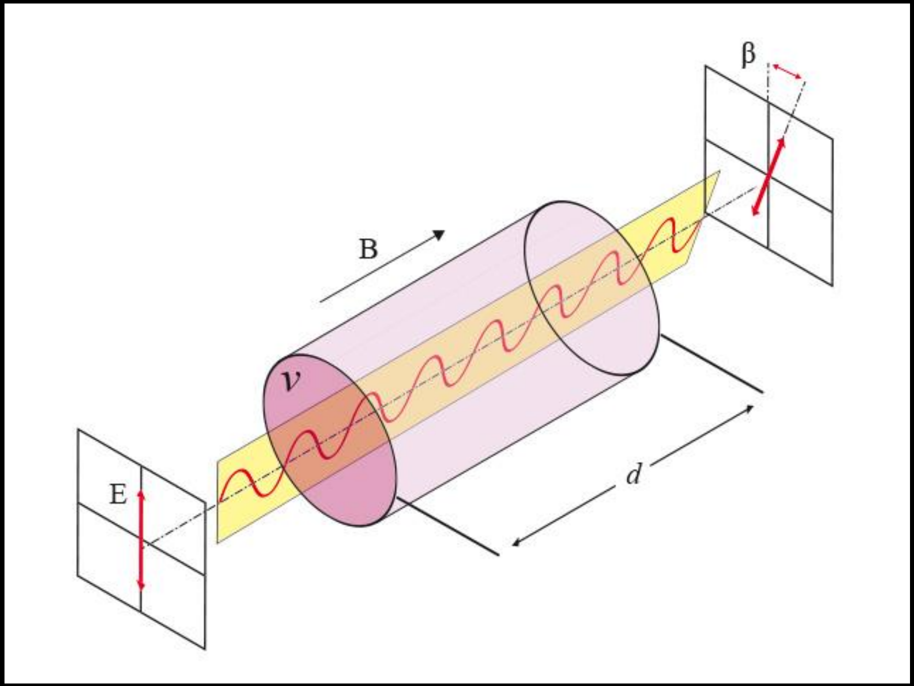
All these effects are frequency dependent!

Propagation effects due to ISM

Faraday Rotation Measurements (RM)

$$\Delta\Psi_{\mathrm{PPA}} \equiv \lambda^2 \times \mathrm{RM}$$

$$\mathrm{RM} = \frac{e^3}{2\pi m_{\mathrm{e}}^2 c^4} \int_0^d n_{\mathrm{e}} B_{||}\, \mathrm{d}l$$

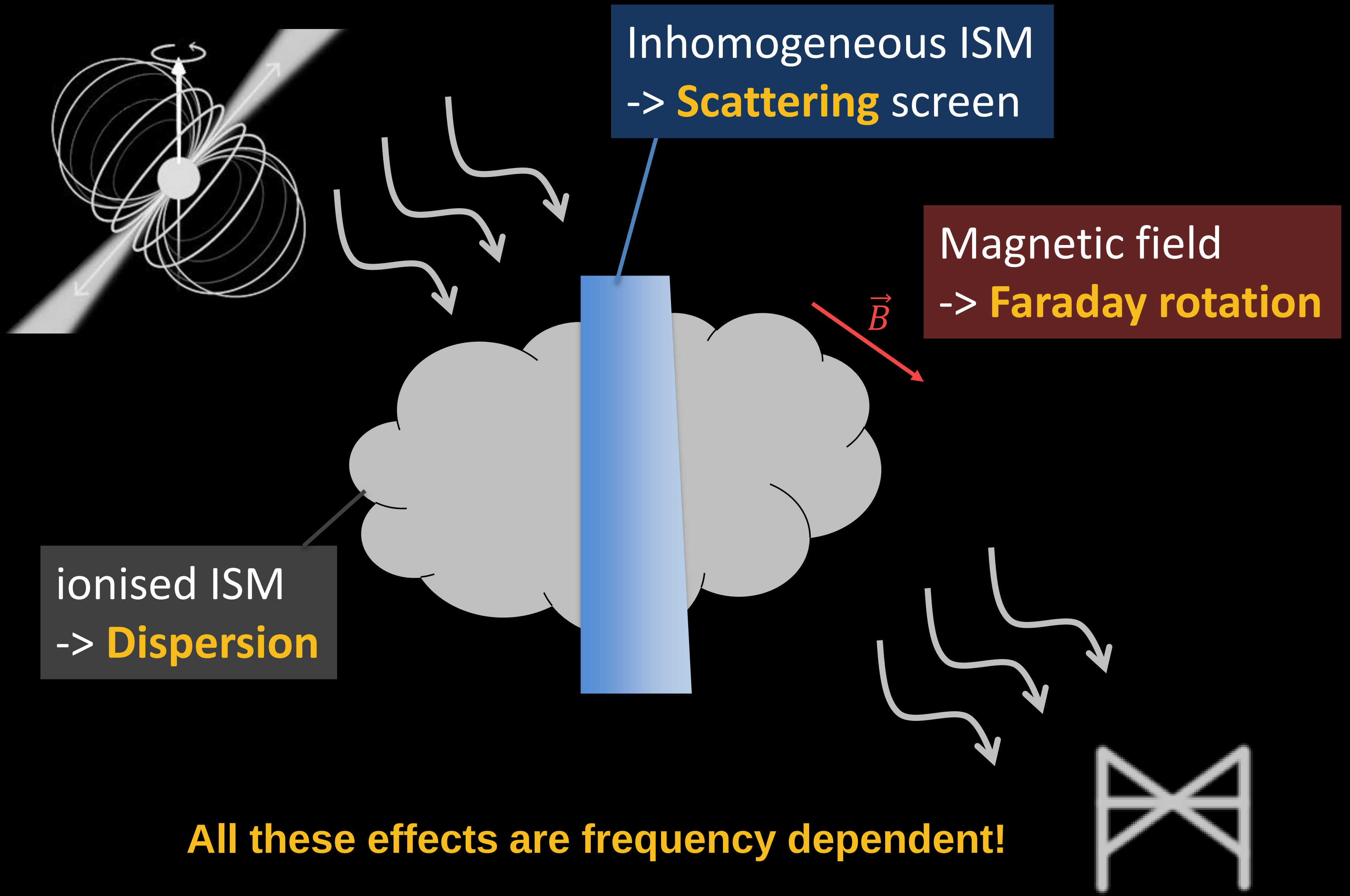


$$\langle B_{||} \rangle \equiv \frac{\int_0^d n_{\mathrm{e}} B_{||}\, \mathrm{d}l}{\int_0^d n_{\mathrm{e}}\, \mathrm{d}l} = 1.23\,\mu\mathrm{G} \left(\frac{\mathrm{RM}}{\mathrm{rad\,m^{-2}}}\right) \left(\frac{\mathrm{DM}}{\mathrm{cm^{-3}\,pc}}\right)^{-1}$$

Credit: wikipedia.org

Can be used to probe the galactic magnetic field

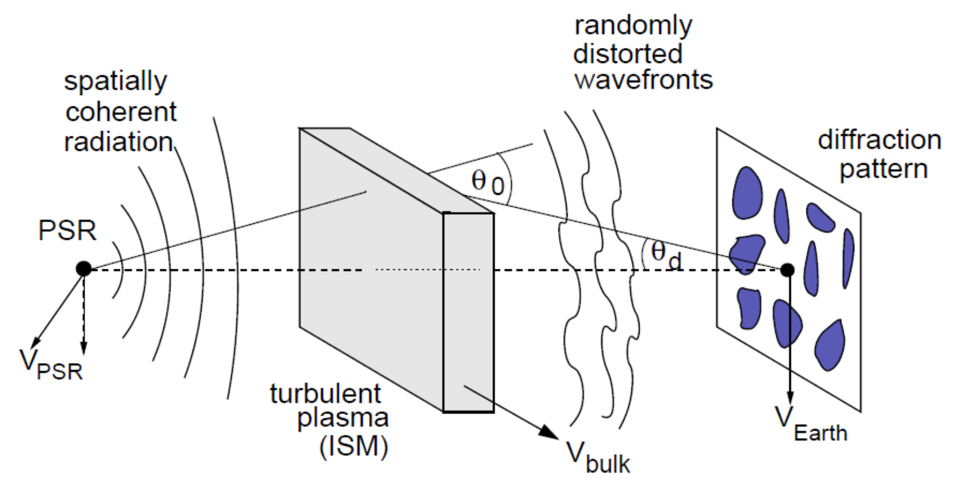
Propagation effects due to ISM

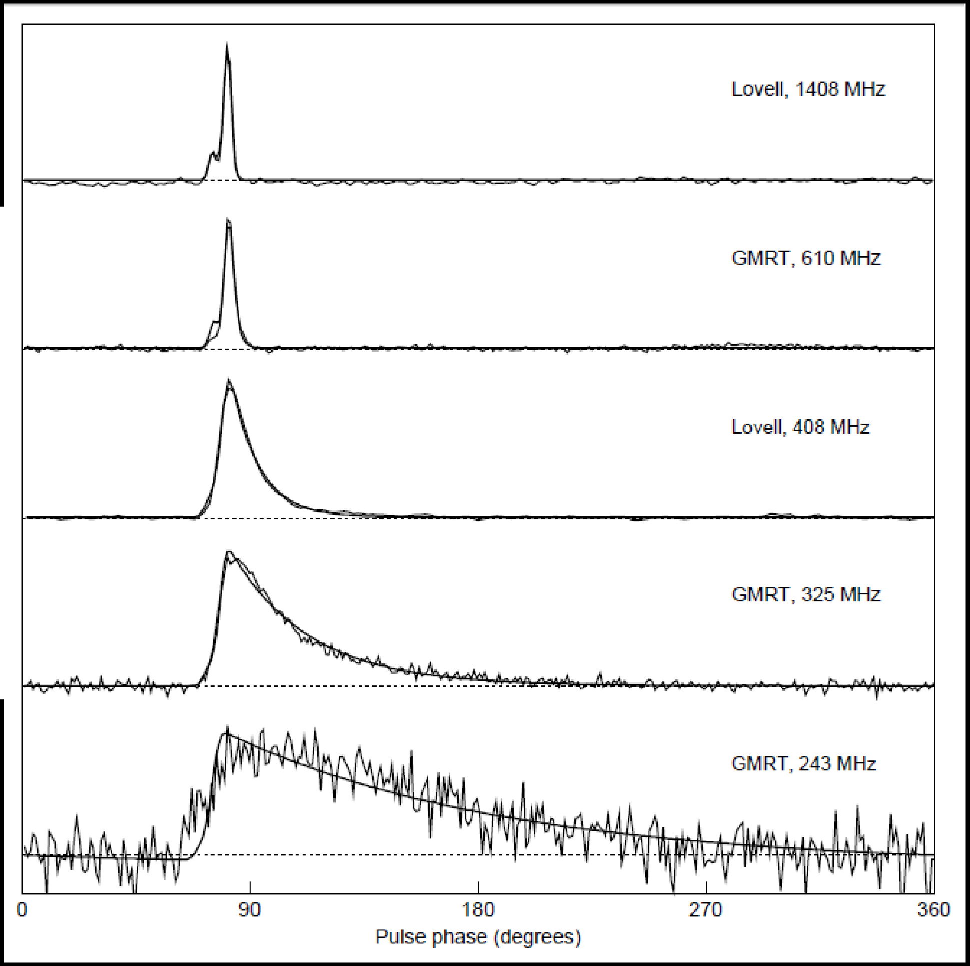


All these effects are frequency dependent!

Propagation effects due to ISM

Scattering





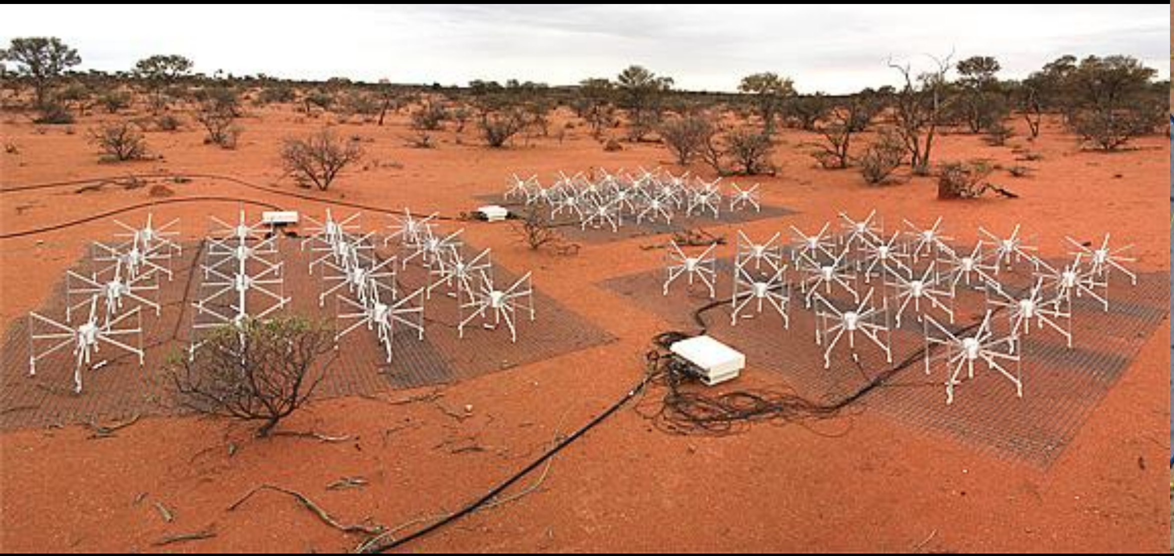
For a thin-screen model

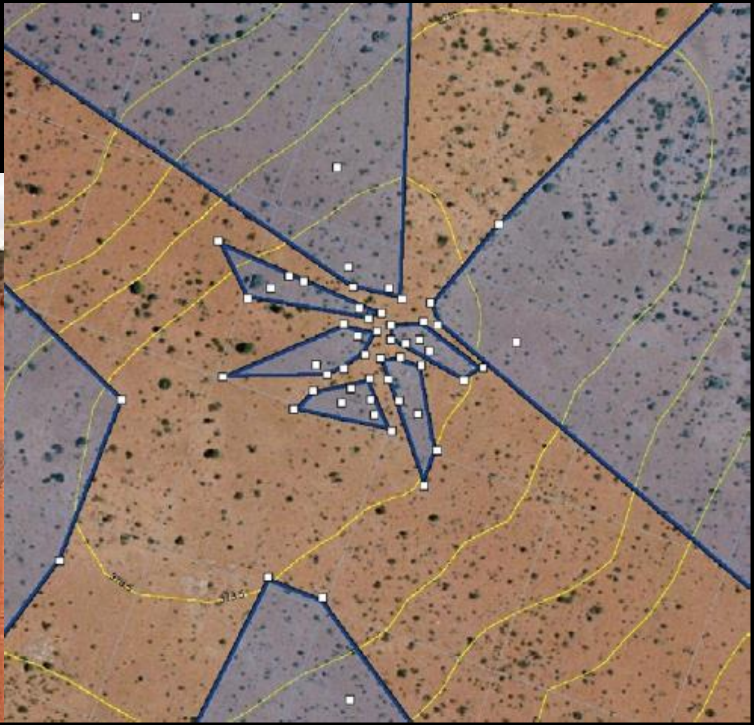
$$\tau_s \propto \nu^{-4}$$

Murchison Widefield Array (MWA)

Phase I (2012 -- 2016)

- 128 tiles, distributed in ~ 3 km diameter region
  - each tile contains 16 dipoles, 4×4 dual polarisation array
- Low-frequency phased array
- Working frequency: 80-300 MHz
- Bandwidth: 30.72 MHz (24*1.28 MHz)



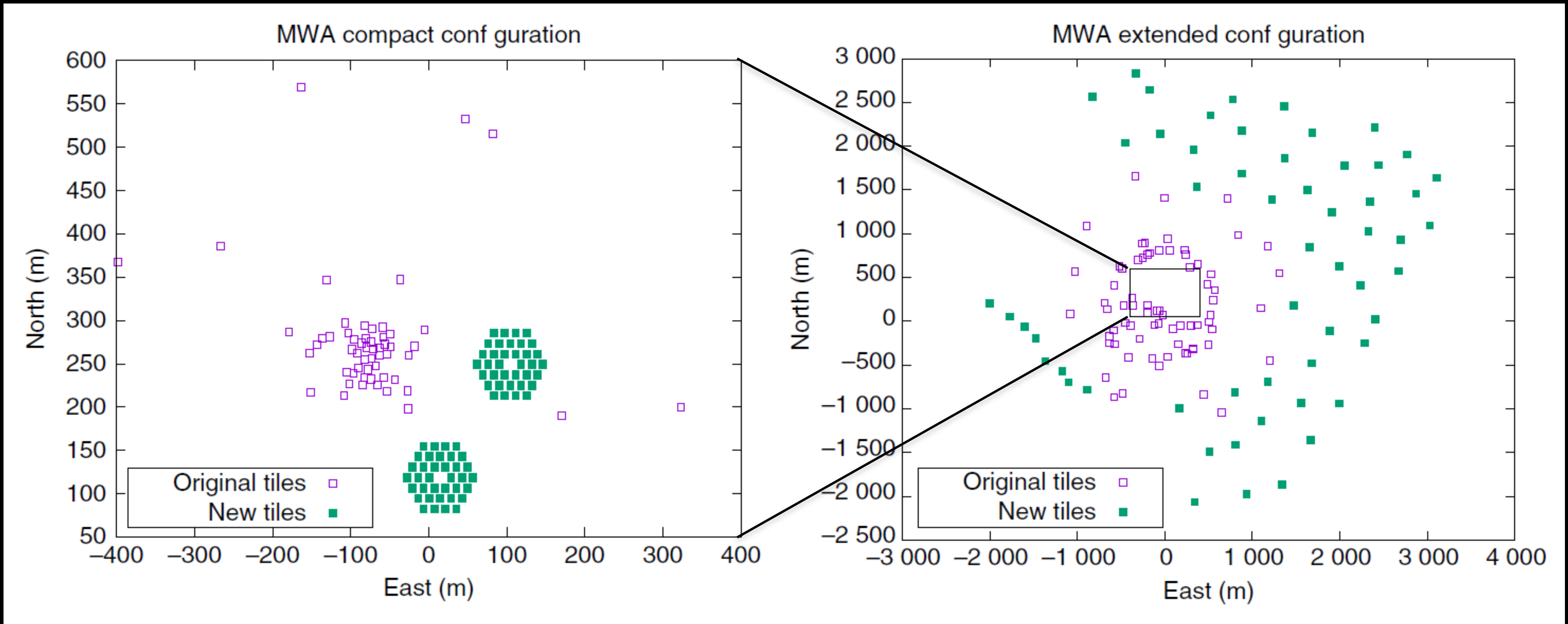


Tingay et al. (2013)

Murchison Widefield Array (MWA)

Phase II (2016 -- 2021)

- 256 tiles in total, but can only use 128 tiles at a time
  (because of the maximum signal throughput of the MWA hardware)
- Two type of configuration:
  compact and extended for different science goal



Wayth et al. (2018)

MWA Phase II Configuration

May 2021 -

- MWAX commissioning

Apr 2020 - Jan 2021

- Extended configuration

Sep 2019 - Feb 2020

- Compact configuration

Feb 2019 - Jul 2019

- Extended configuration

Jul 2018 - Dec 2018

- Compact configuration

Oct 2017 - Jun 2018

- Extended configuration

Oct 2016 - Sep 2017

- Compact configuration

Observing pulsars with the MWA

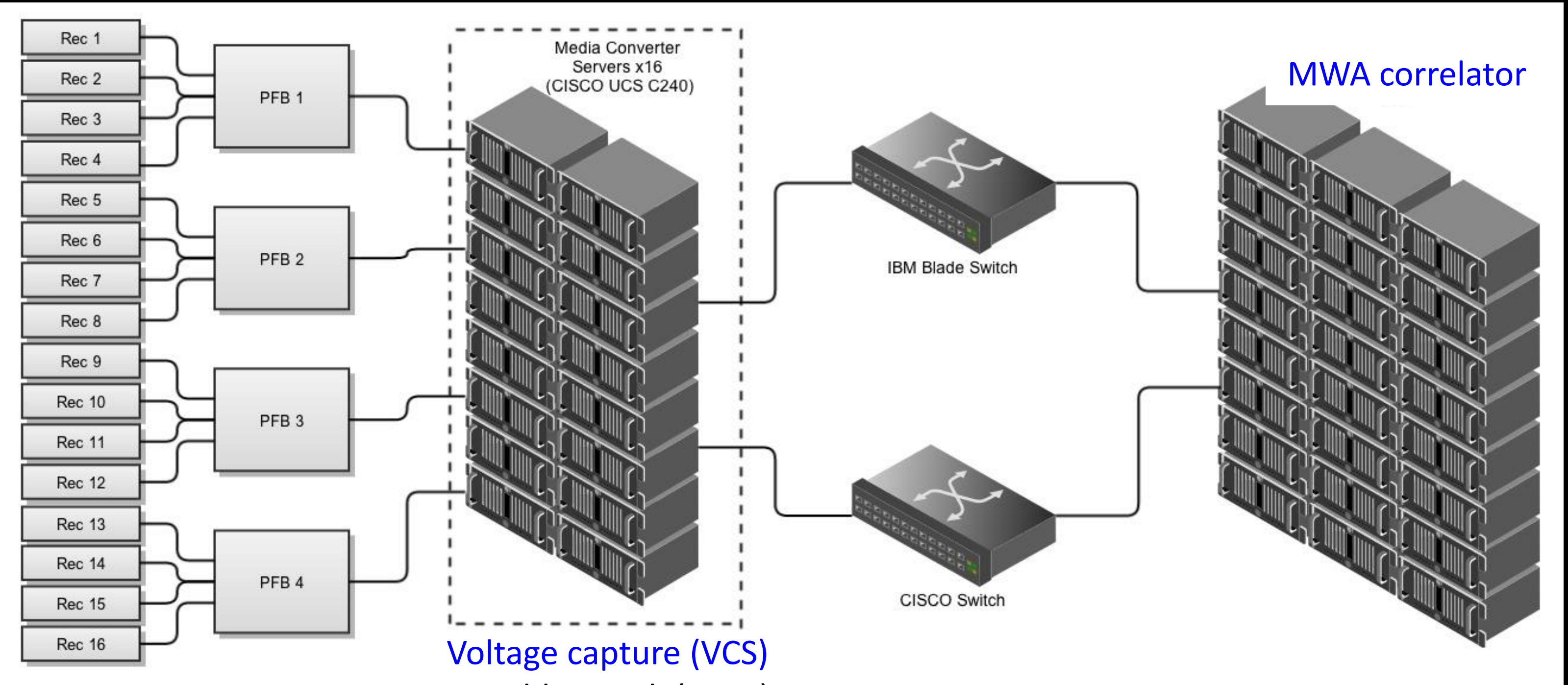
the “voltage capture” (VCS) way

Record all channelised voltage streams from each tile

Bandwidth: 30.72 MHz (24 coarse channels, 1.28 MHz each)

Time resolution: 100 μs   Frequency resolution: 10 kHz

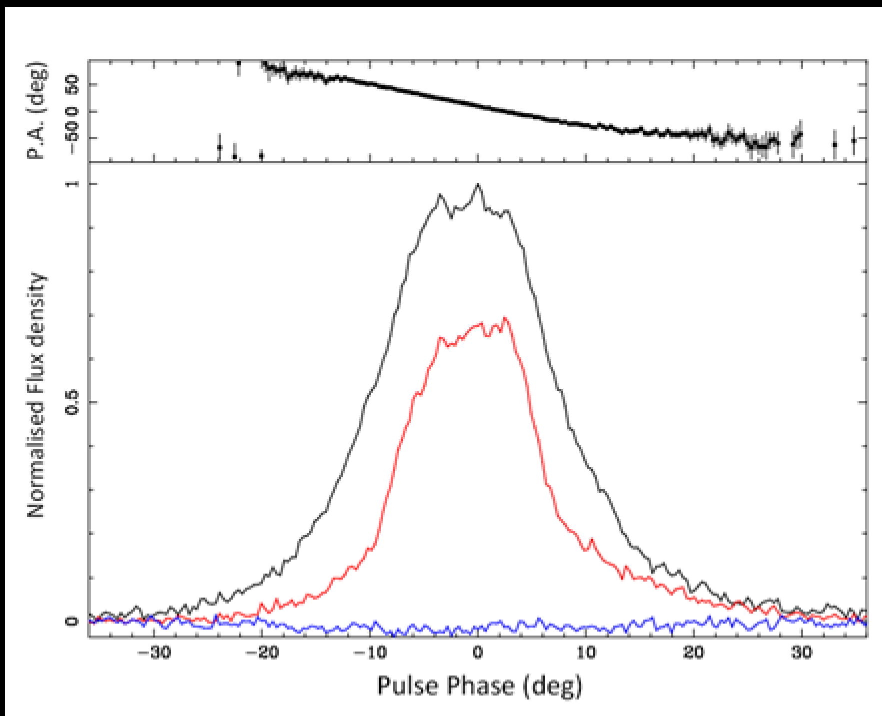
Data rate: 28 TB per hour   Maximum recording: 1.5 hour



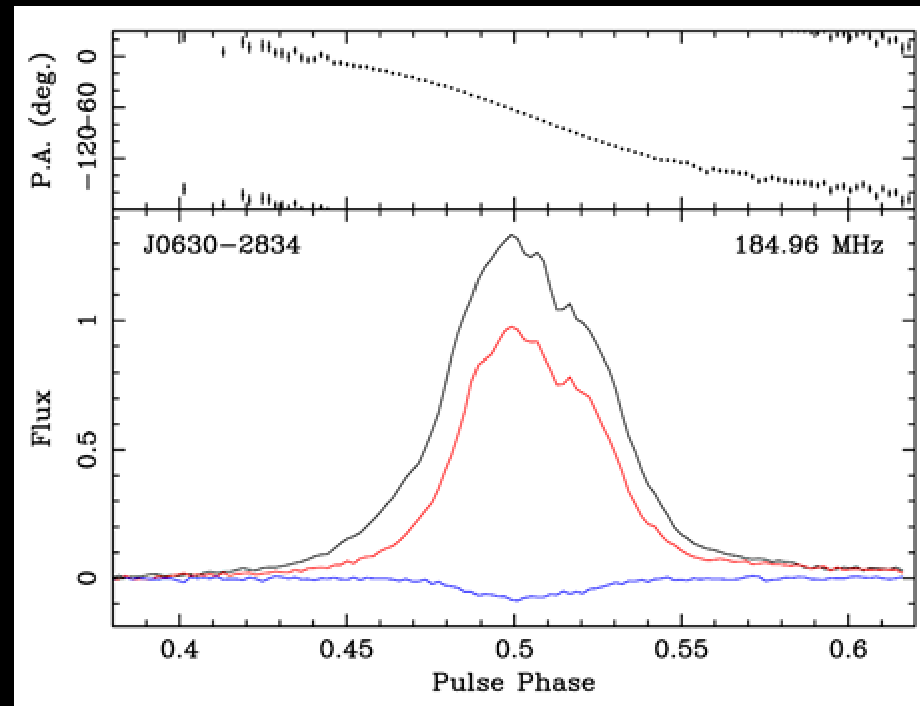
Tremblay et al. (2015)

Pulsar polarimetry with the MWA

J0630-2834 at 690 MHz   Parkes

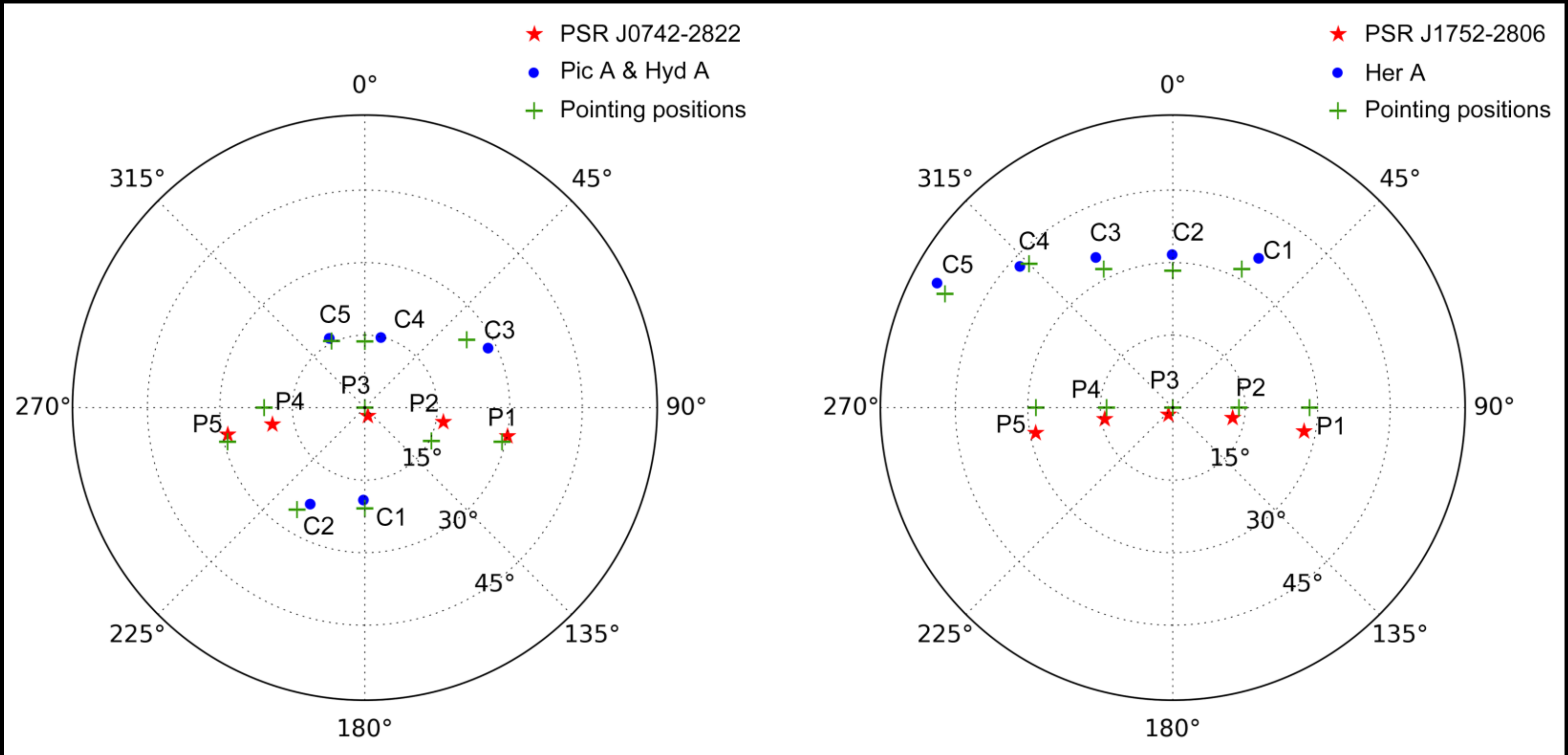


J0630-2834 at 185 MHz   MWA



MWA tied-array polarimetric response verification

J0742-2822 J1752-2806



Xue et al. (2019)

Different sky pointing position

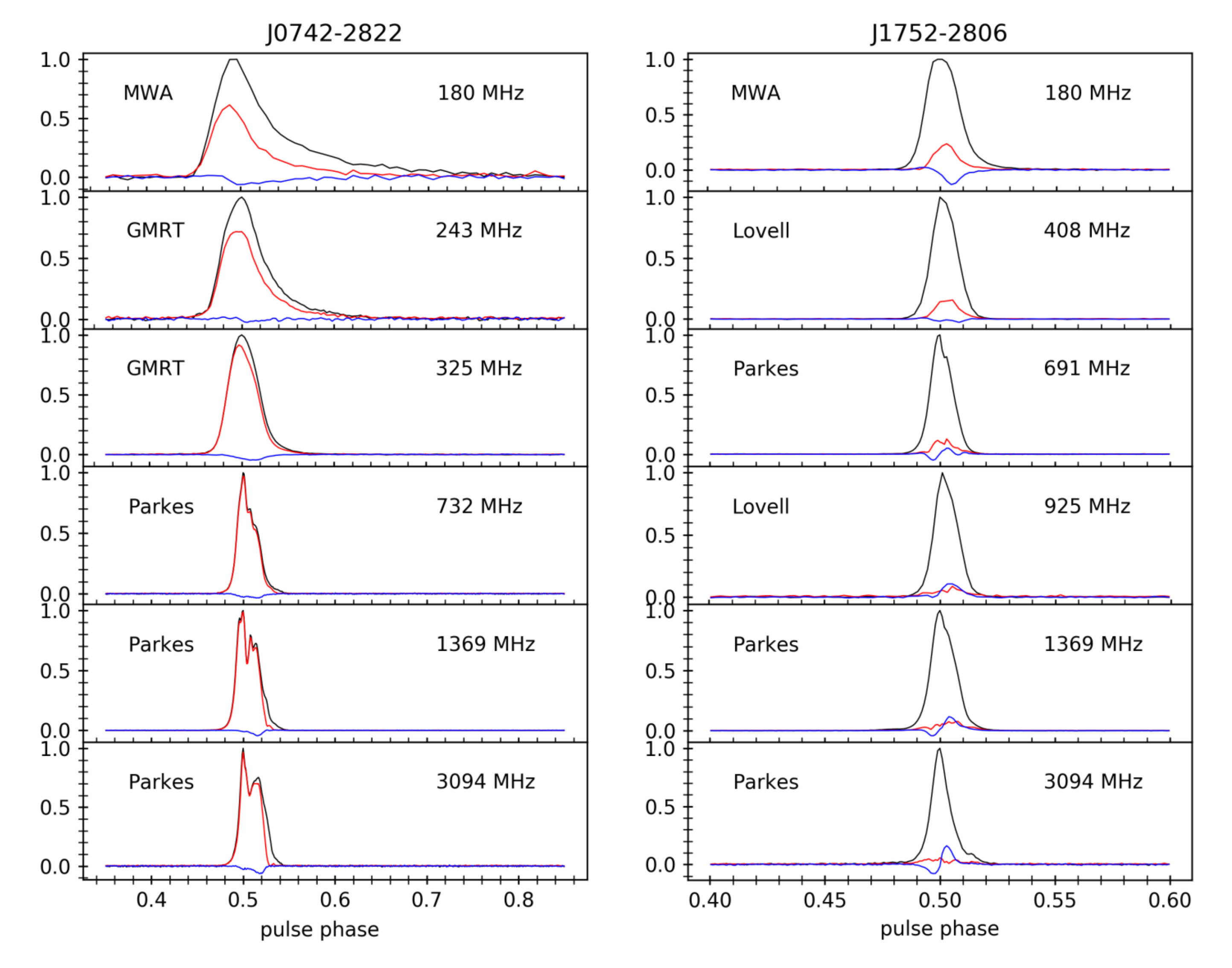
Large frequency range: 76.80 – 312.32 MHz

(24 × 1.28MHz non-contiguous channels simultaneously)

Frequency < 270 MHz & Zenith Angle < 45°

The polarimetric performance is reliable and stable

Polarimetric profiles evolution with frequency

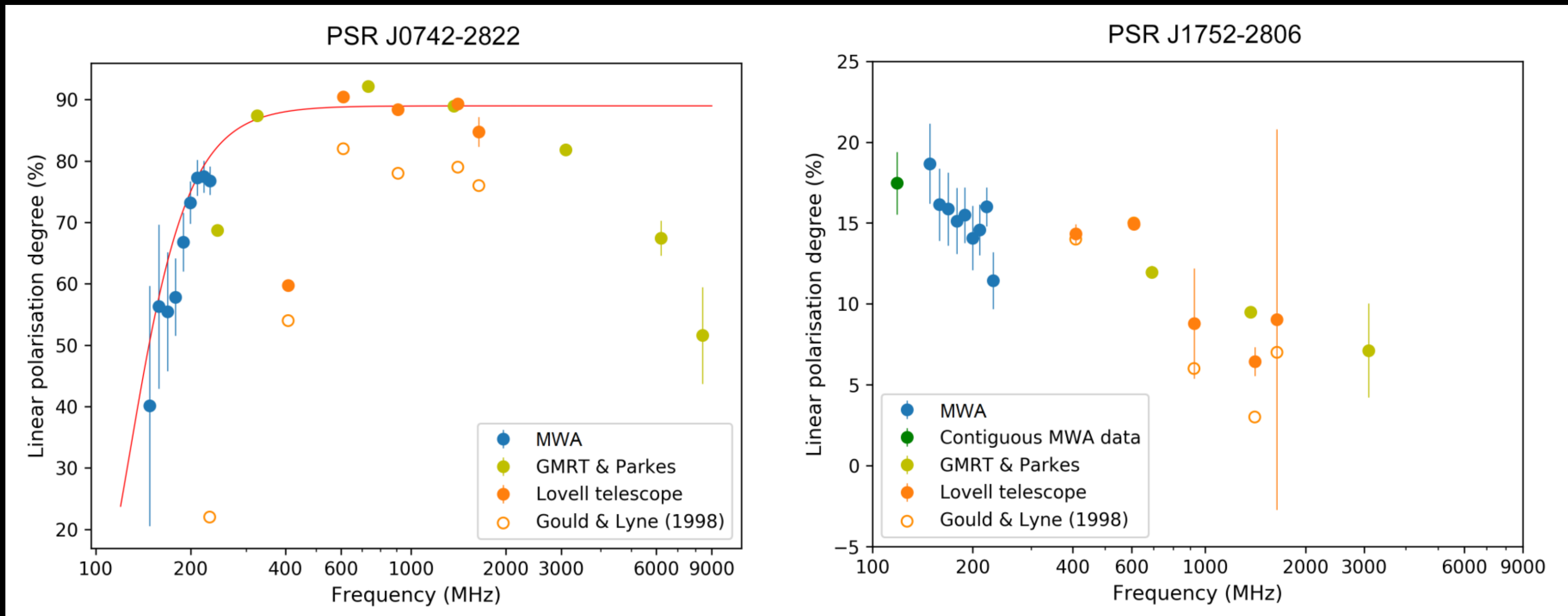


Xue et al. (2019)

Fraction of linear polarisation as a function of frequency

Xue et al. (2019)

%L

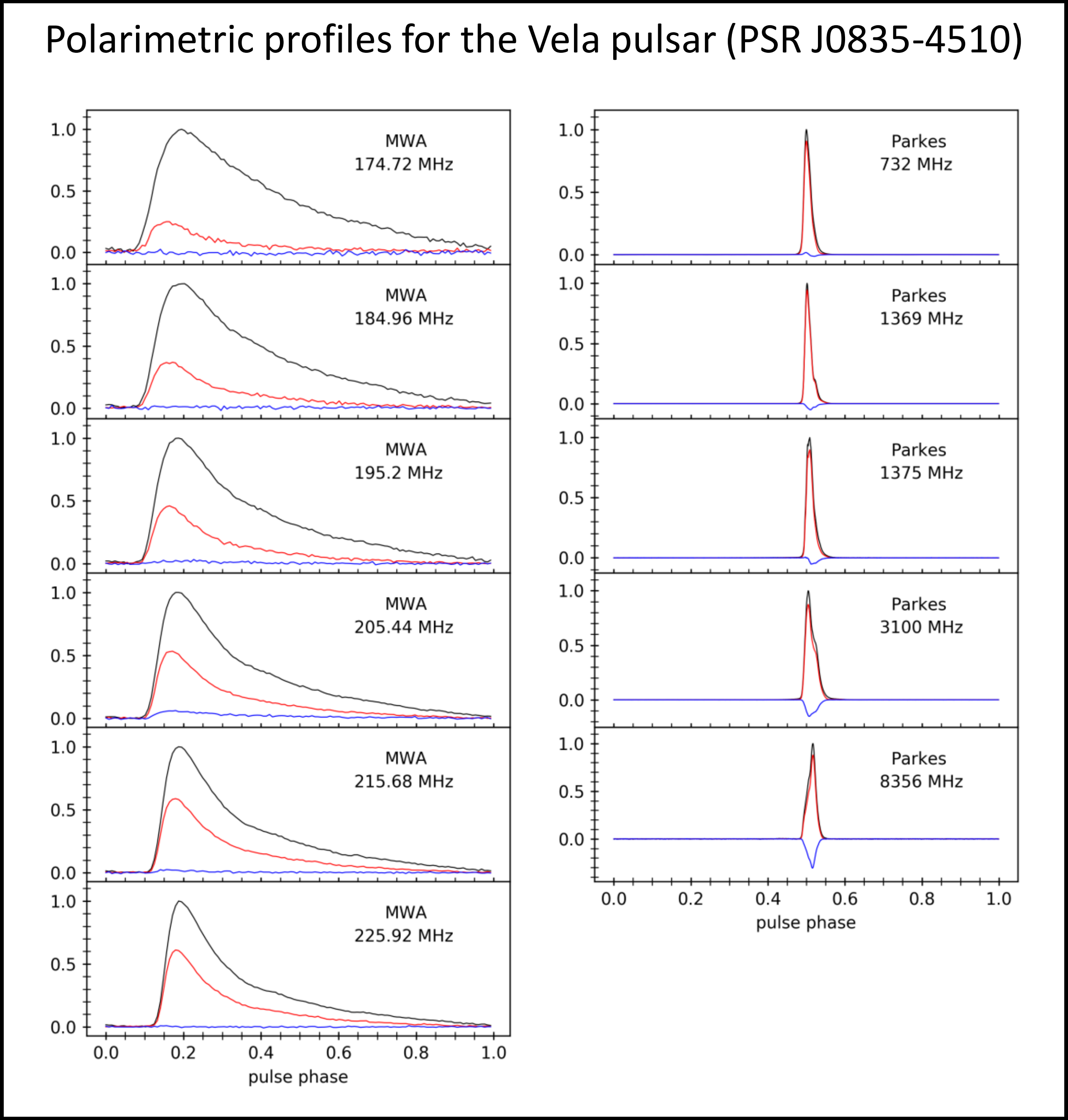


An interesting rapid **depolarisation** at low radio frequency for PSR J0742-2822
Potential causation: irregular RM variation (ionosphere, ISM, etc.)

$\%L \propto \exp(-2\lambda^4\, \delta RM^2)$ <- Macquart & Melrose (2000)

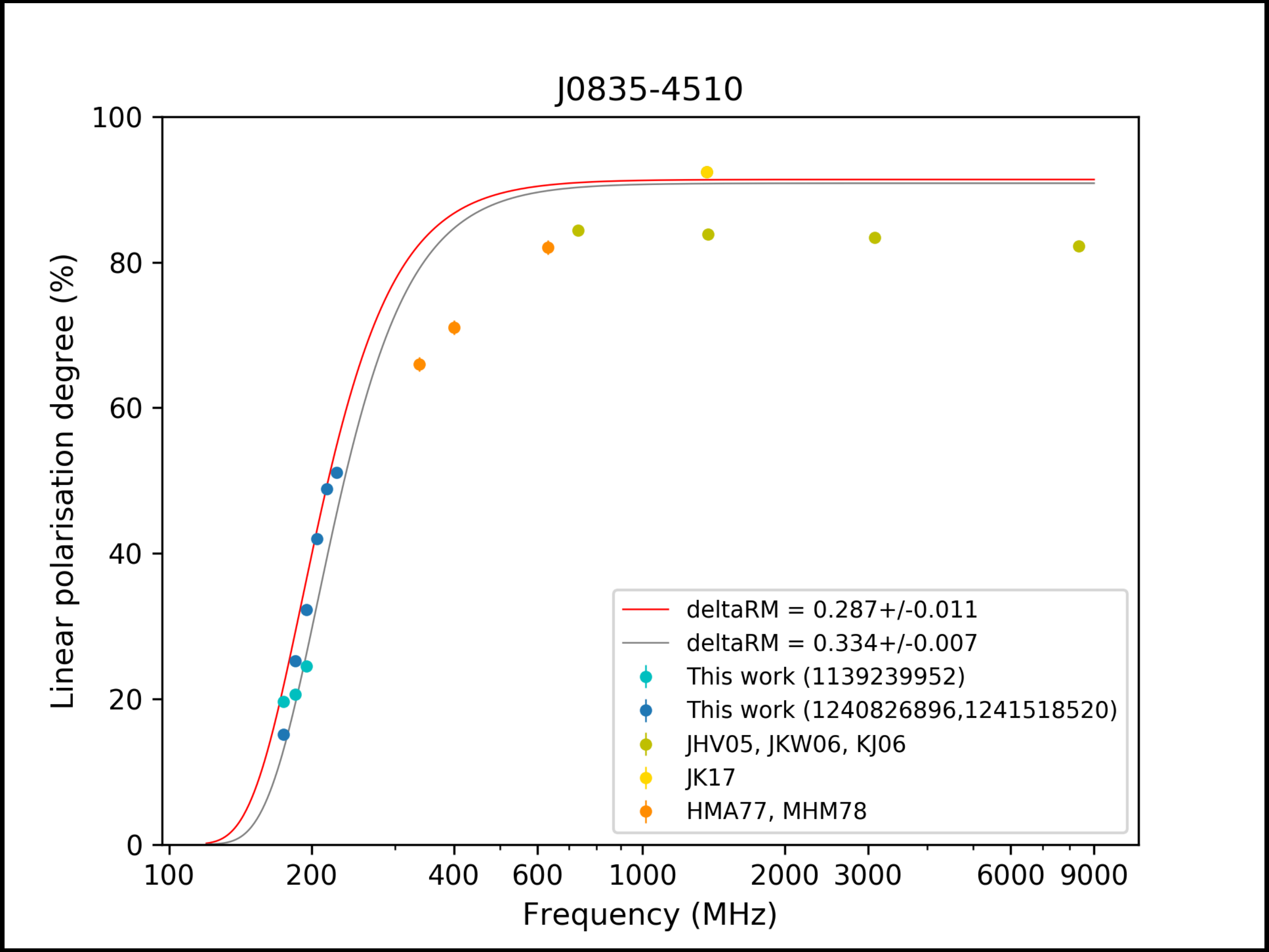
Best fit δRM=0.13

Got the same trend of %L vs. freq. in the Vela pulsar!



the %L vs. freq. for the Vela pulsar

%L

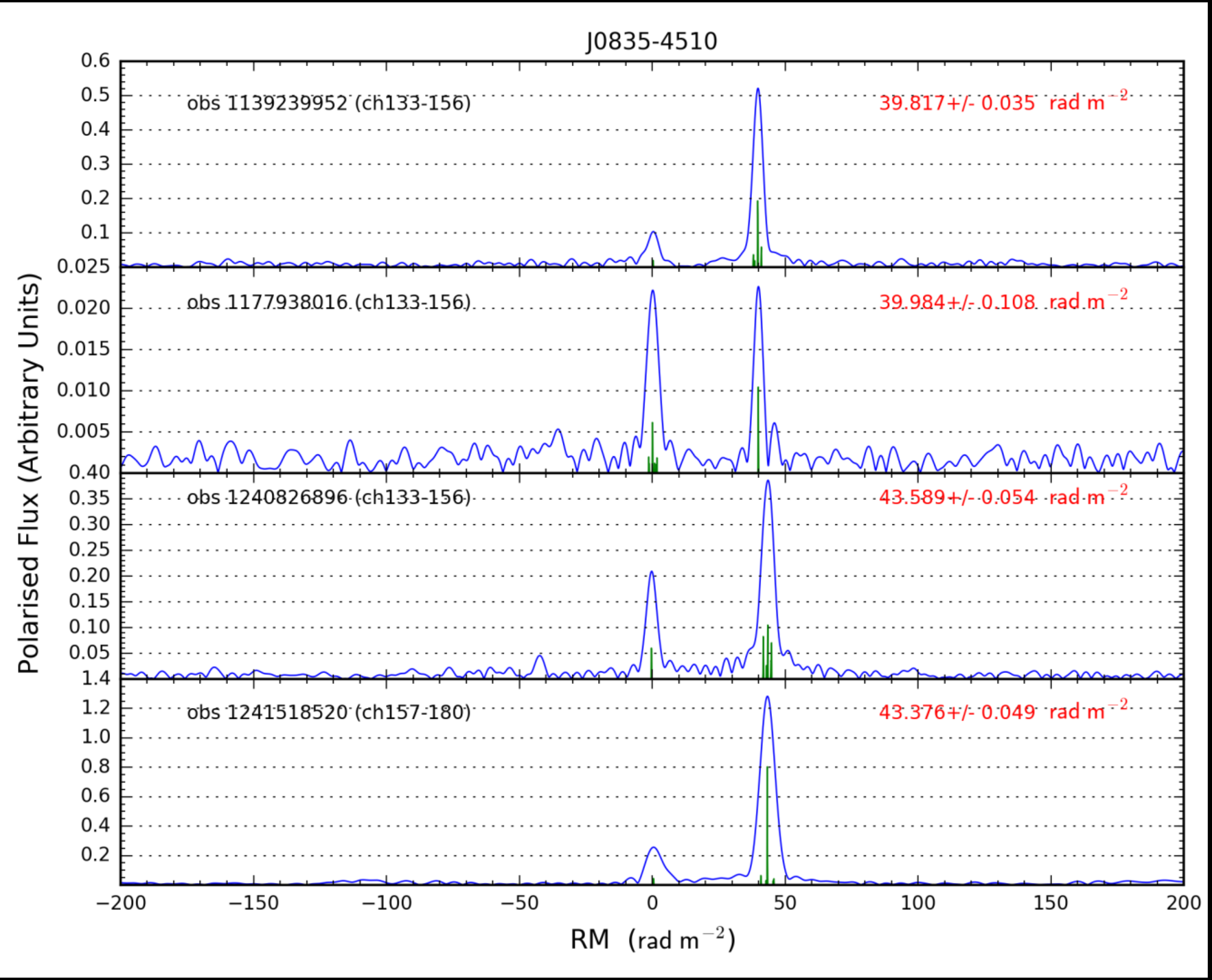


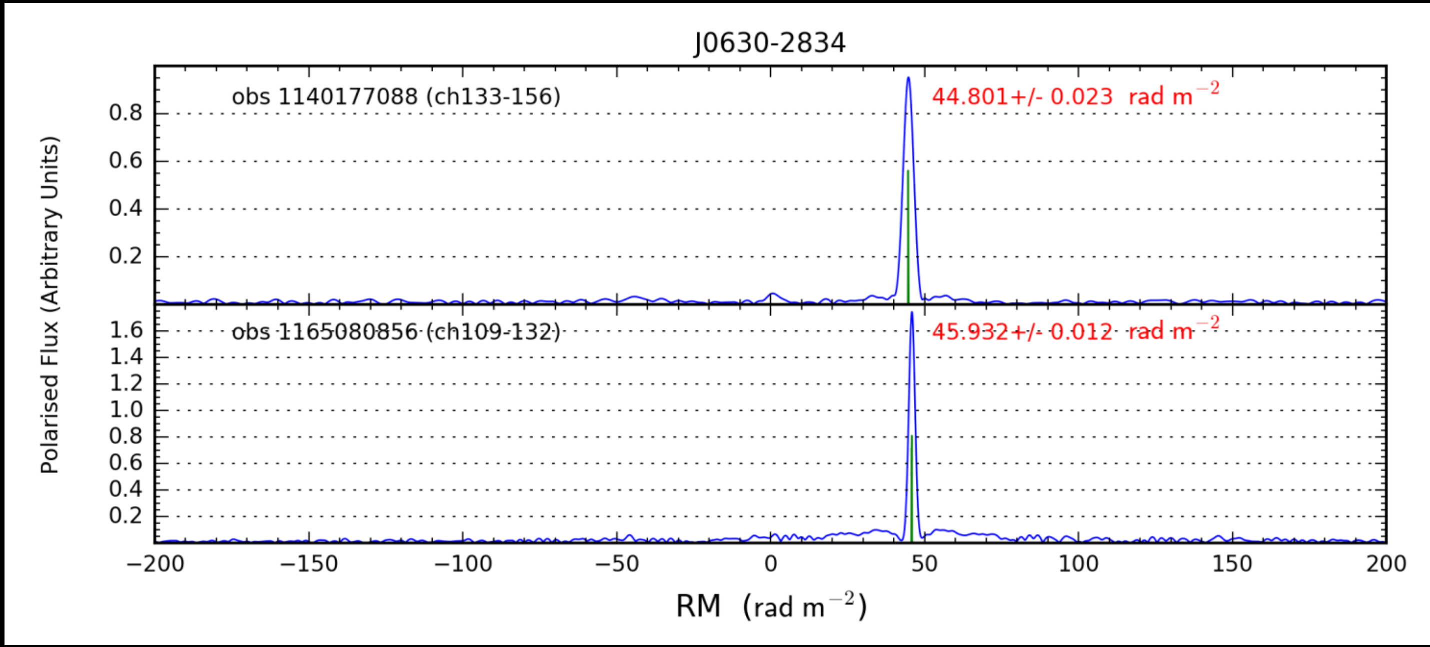
RM spectra of the Vela pulsar from different MWA observation

Zero peak on RM spectra due to Stokes I leak into Q

↑

Amplitude difference between pol-X and pol-Y

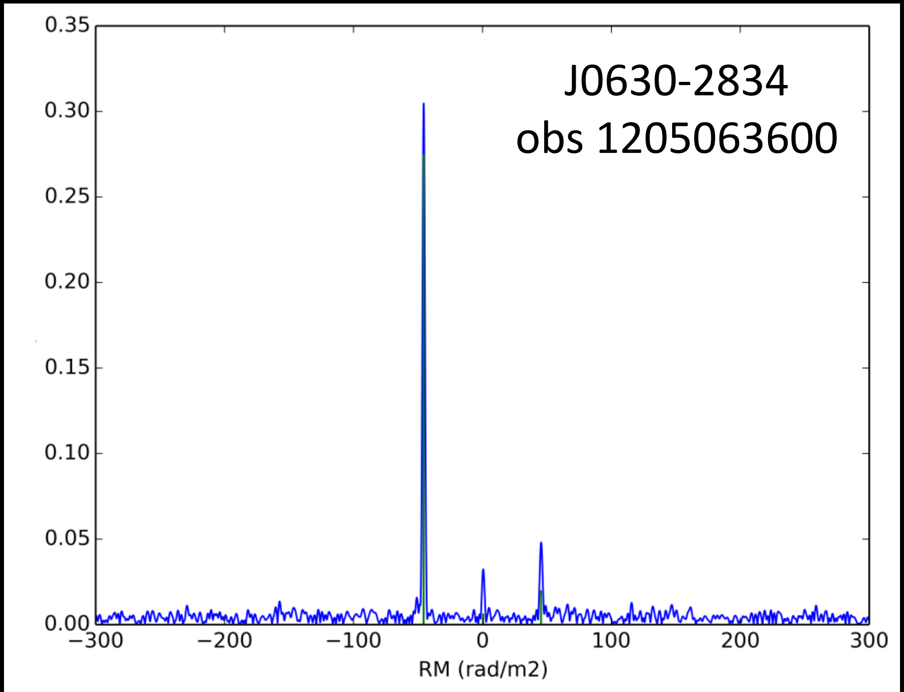




Mirror peak on RM spectra due to Stokes U leak into V

↑

Phase misalign between pol-X and pol-Y

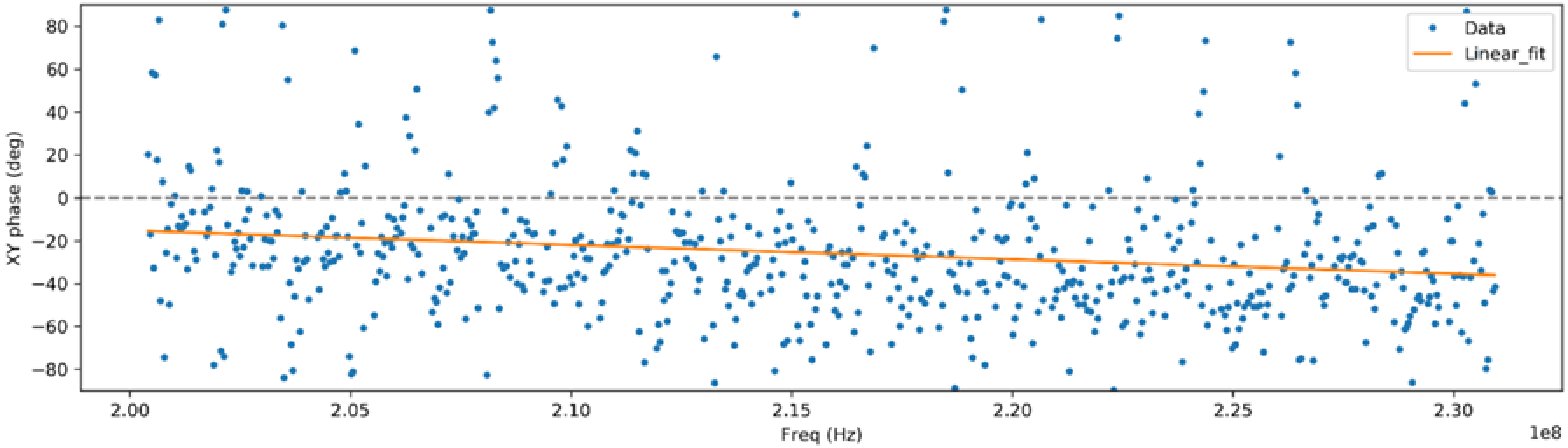


Xiang Zhang

XY phase correction: use a linearly polarized source

$$M = \begin{bmatrix} m_{II} & m_{IQ} & m_{IU} & m_{IV} \\ m_{QI} & m_{QQ} & m_{QU} & m_{QV} \\ m_{UI} & m_{UQ} & m_{UU} & m_{UV} \\ m_{VI} & m_{VQ} & m_{VU} & m_{VV} \end{bmatrix}$$

<- Mueller matrix



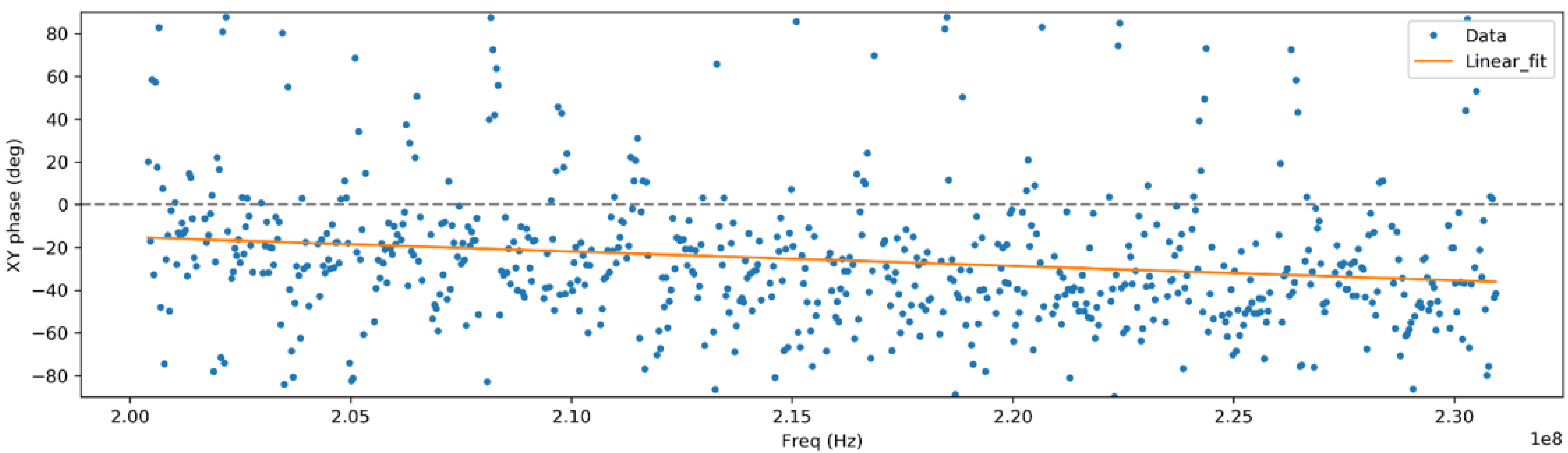
Xiang Zhang

XY phase correction: use a linearly polarized source

$$\mathbf{M_A} = \begin{bmatrix} 1 & \frac{\Delta G}{2} & 0 & 0 \\ \frac{\Delta G}{2} & 1 & 0 & 0 \\ 0 & 0 & \cos\psi & -\sin\psi \\ 0 & 0 & \sin\psi & \cos\psi \end{bmatrix}. \quad (34)$$

Amp diff in X/Y, Stokes I leak into Stokes Q

Phase diff in X/Y , Stokes U leak into Stokes V



Xiang Zhang

Dashboard / ... / Galactic and Extragalactic (GEG)   Save for later   Watch   Share   ...

Polarimetry

Created by Gulay Gurkan Uygun GGU, last modified by Xiang Zhang on May 20, 2021

Team Lead: Dr Xiang Zhang

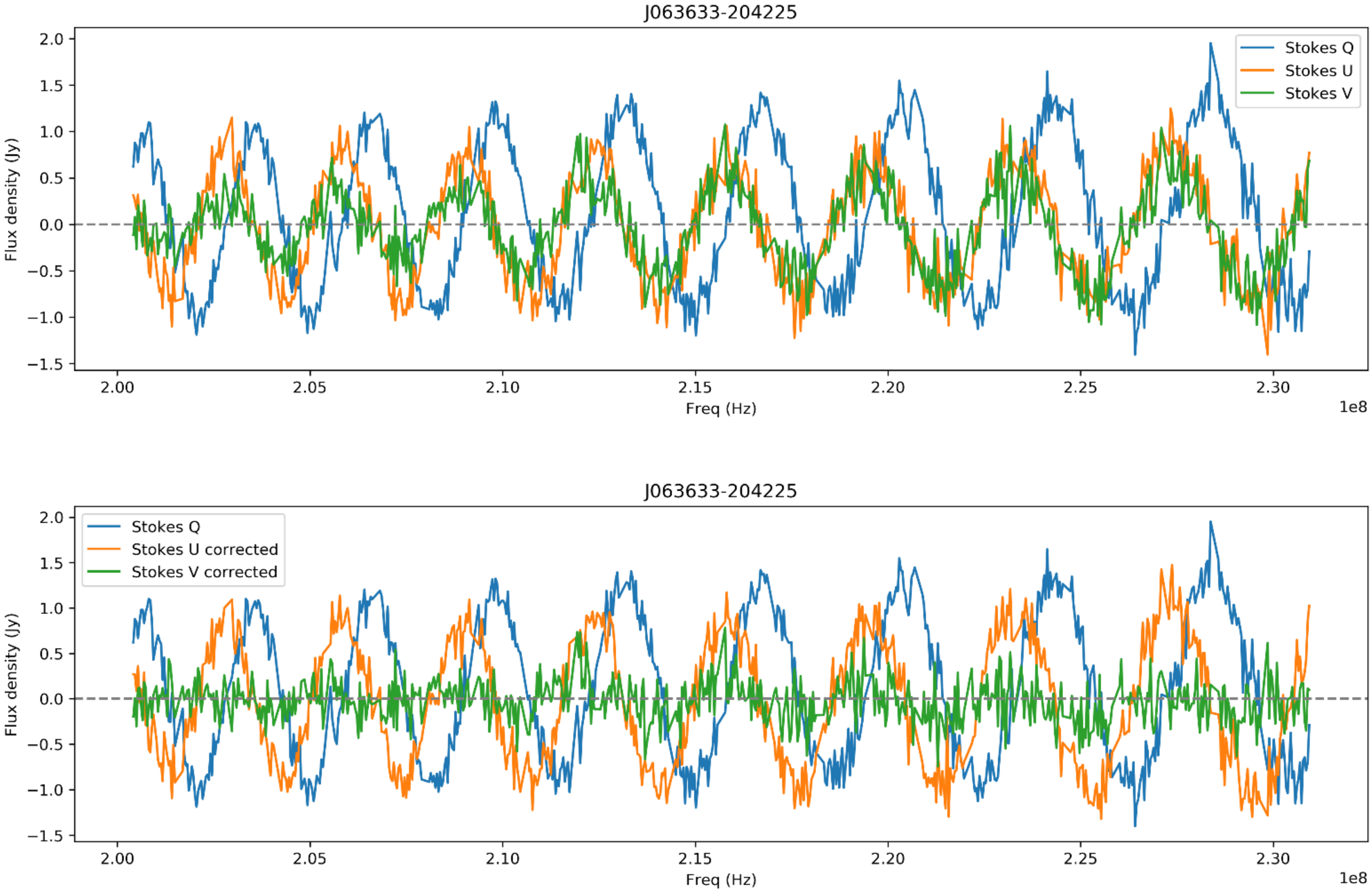
Members: Chris Riseley (Uni. Bologna), Takuya Akahori (NAOJ), Bryan Gaensler (Uni. Toronto), George Heald (CSIRO), Melanie Johnston-Hollitt (ICRAR/Curtin), Nick Seymour (ICRAR/Curtin), Keitaro Takahashi (Kumamoto Uni.), Tessa Vernstrom (CSIRO), Jennifer West (Uni. Toronto), Xiaohui Sun (Yunnan Uni.).

Polarisation calibrators: selected from POGS-II_ExGal catalogue

data_id	ra	dec	polint	rm
GLEAM J063633-204225	99.14097	-20.70861	1.104038	50.286
GLEAM J121834-101851	184.64228	-10.31118	0.711955	-8.159
GLEAM J035140-274354	57.94213	-27.71584	0.519881	33.59
GLEAM J041340+111209	63.44819	11.19557	0.389896	-13.351
GLEAM J153150+240244	232.96013	24.0331	0.363536	11.731

Estimated XY phase for 2018-2020 observations: Phase = 4.426533296449057023e-07 * Freq + 2.806338586067941065e+01, where Freq is in Hz and Phase is in deg.

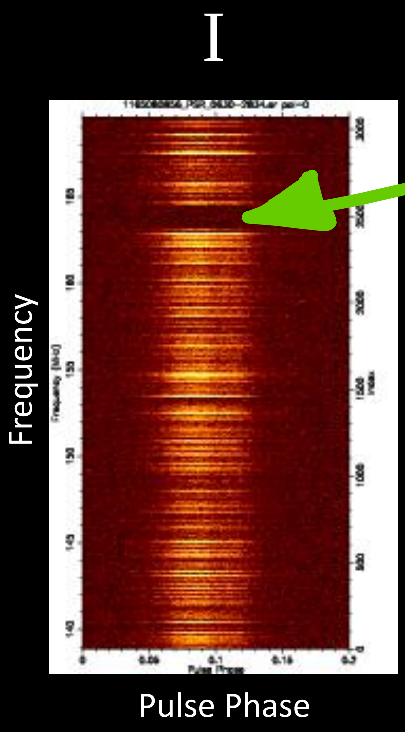
Xiang Zhang



J063633-204225
Stokes Q
Stokes U
Stokes V
Flux density (Jy)
Freq (Hz)
1e8
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
2.00
2.05
2.10
2.15
2.20
2.25
2.30
J063633-204225
Stokes Q
Stokes U corrected
Stokes V corrected
Flux density (Jy)
Freq (Hz)
1e8

MWA Polarisation Leakage – J0630-2834

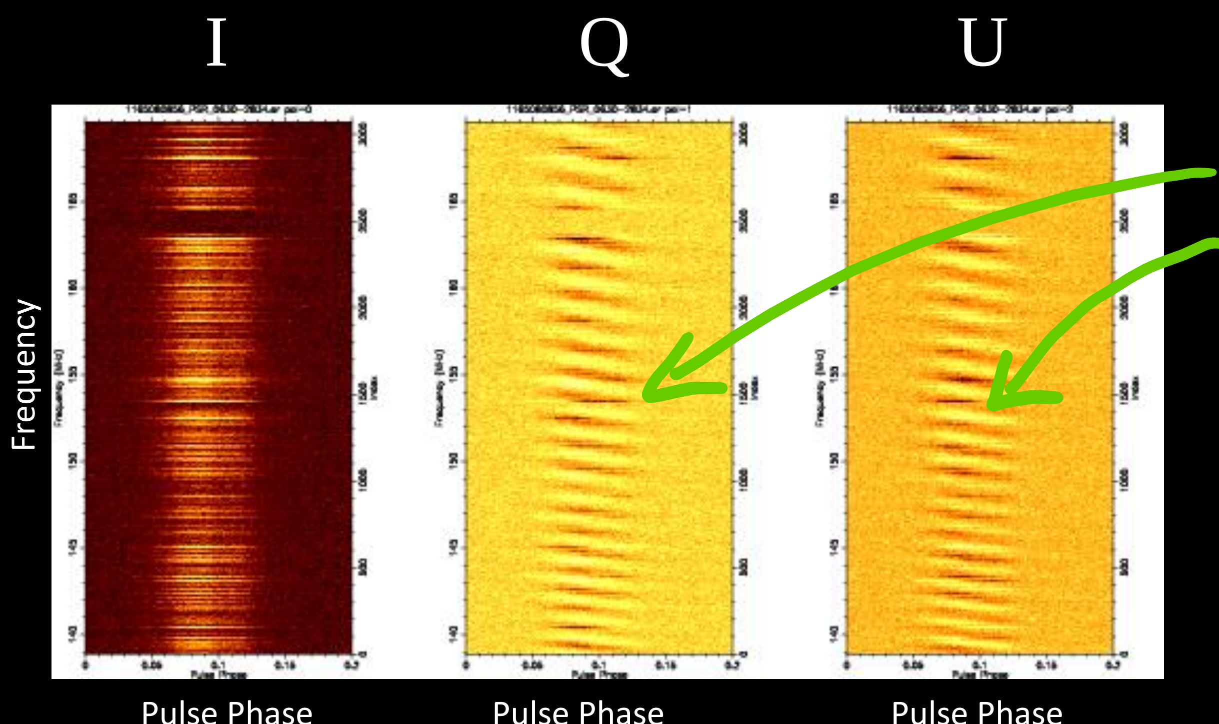
Sammy McSweeney



Bad channel during calibration, removed

MWA Polarisation Leakage – J0630-2834

Sammy McSweeney

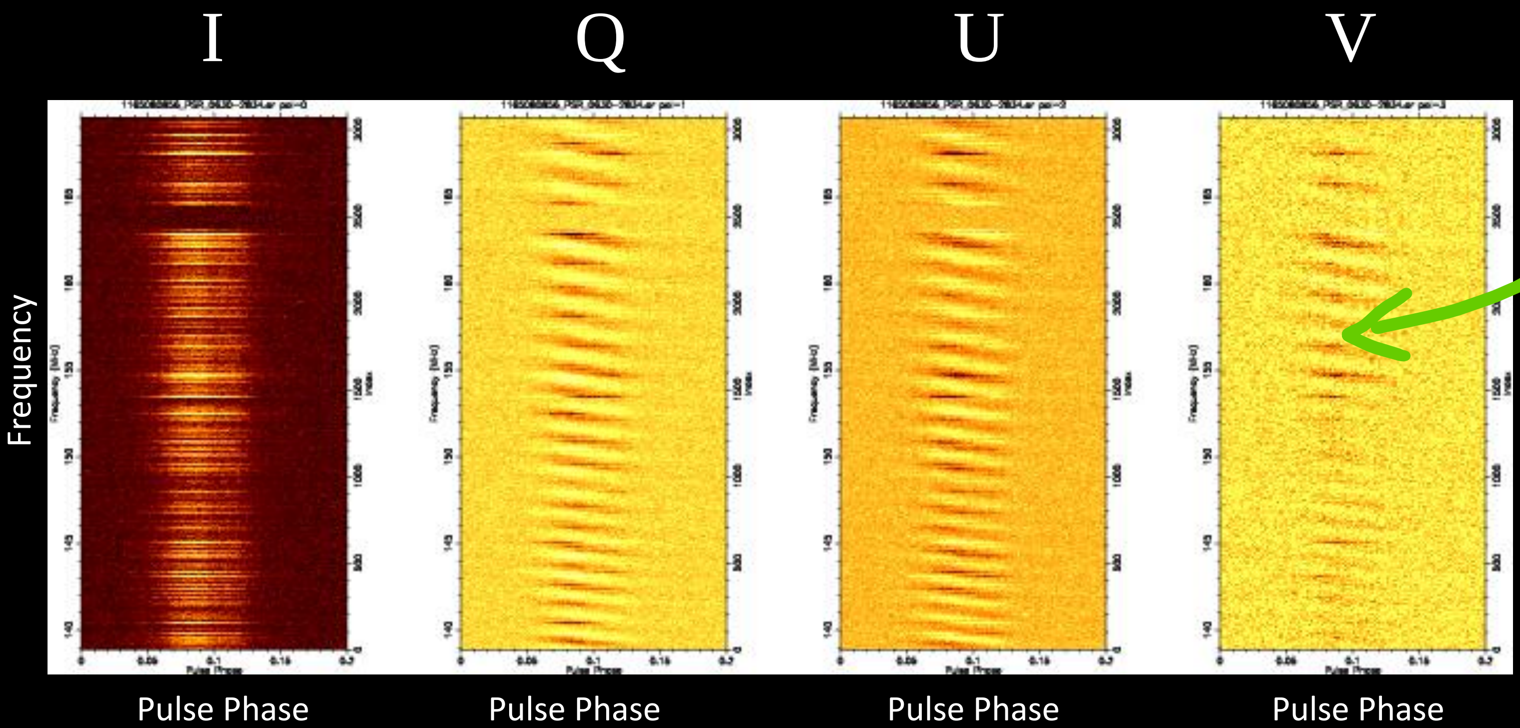


ISM Faraday rotation

(So far, everything looks as expected…)

MWA Polarisation Leakage – J0630-2834

Sammy McSweeney

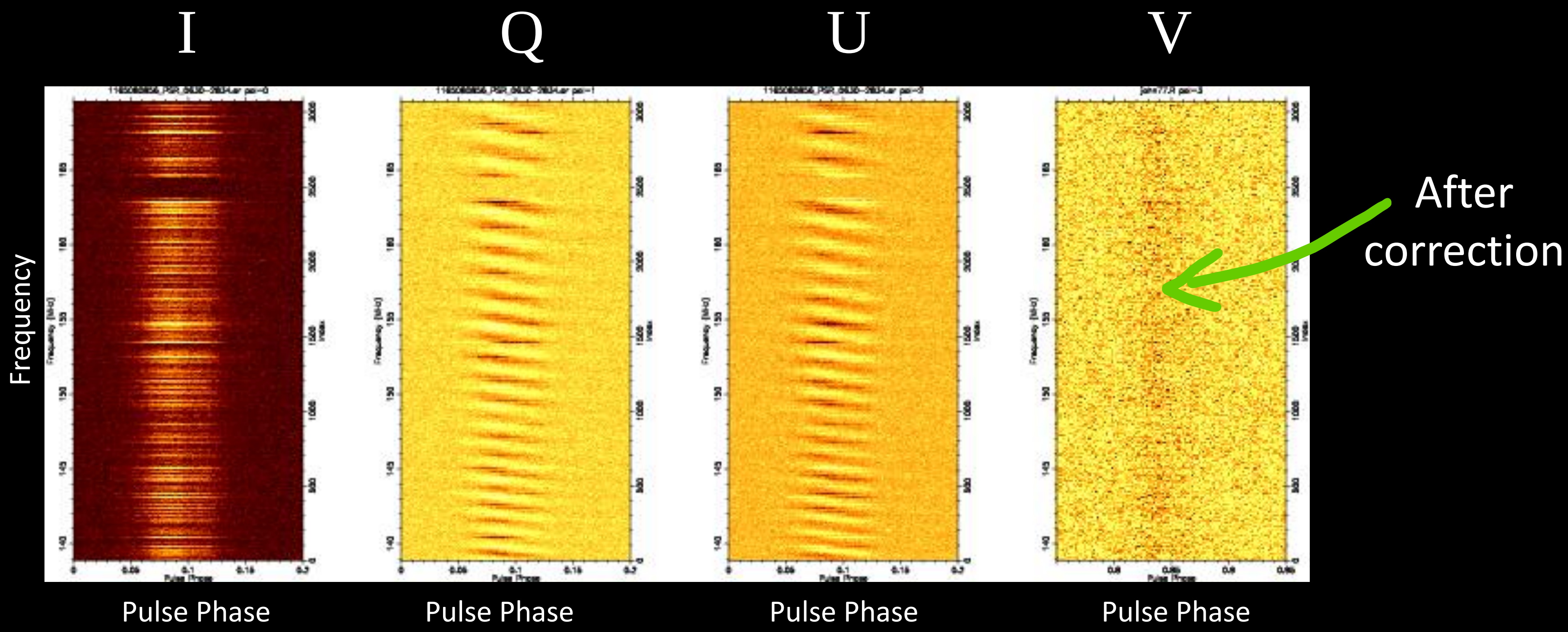


Leakage!

(…because Stokes V is unaffected by Faraday rotation)

MWA Polarisation Leakage – J0630-2834

Sammy McSweeney

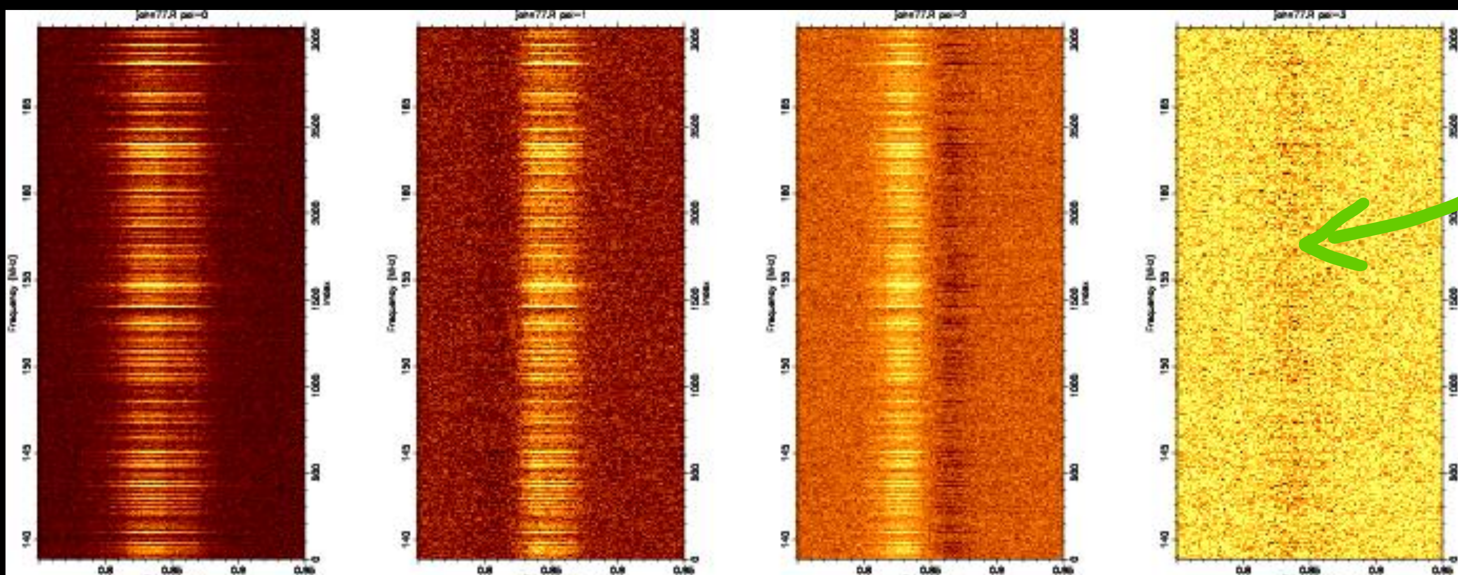


MWA Polarisation Leakage – J0630-2834

Sammy McSweeney

I Q U V

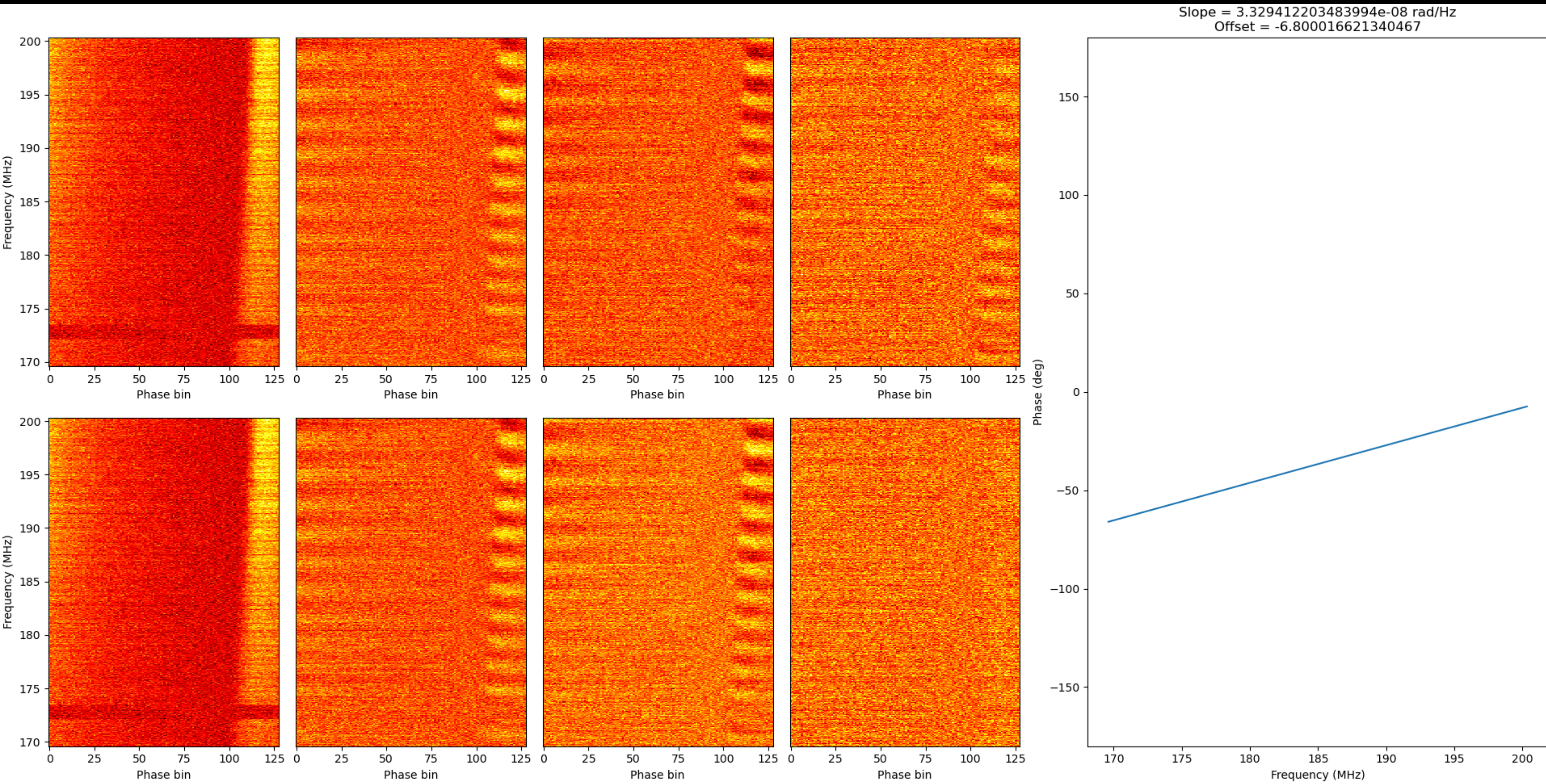
Frequency



Pulse Phase Pulse Phase Pulse Phase Pulse Phase

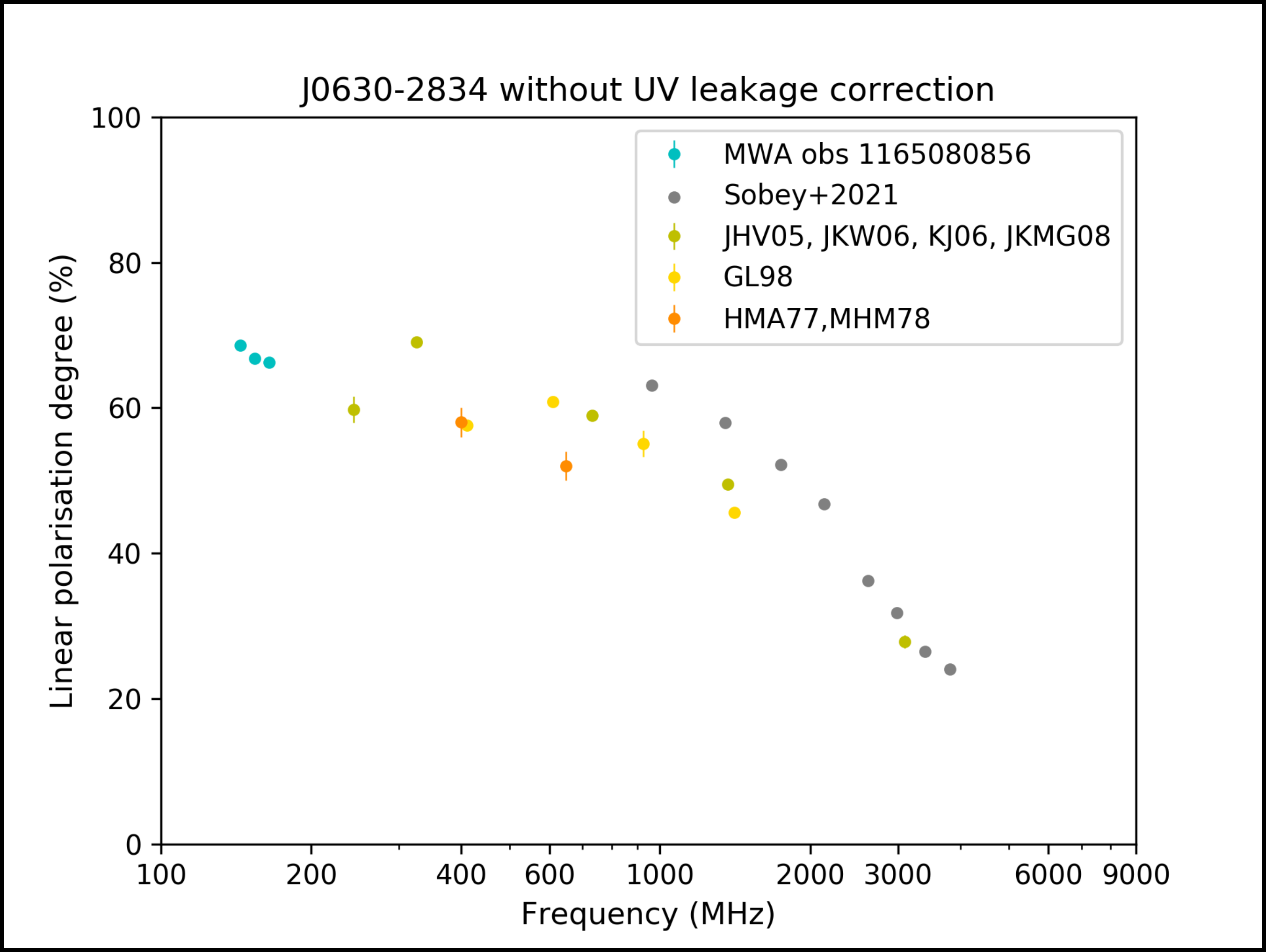
After correction *and* De-Faraday rotation

Sammy McSweeney

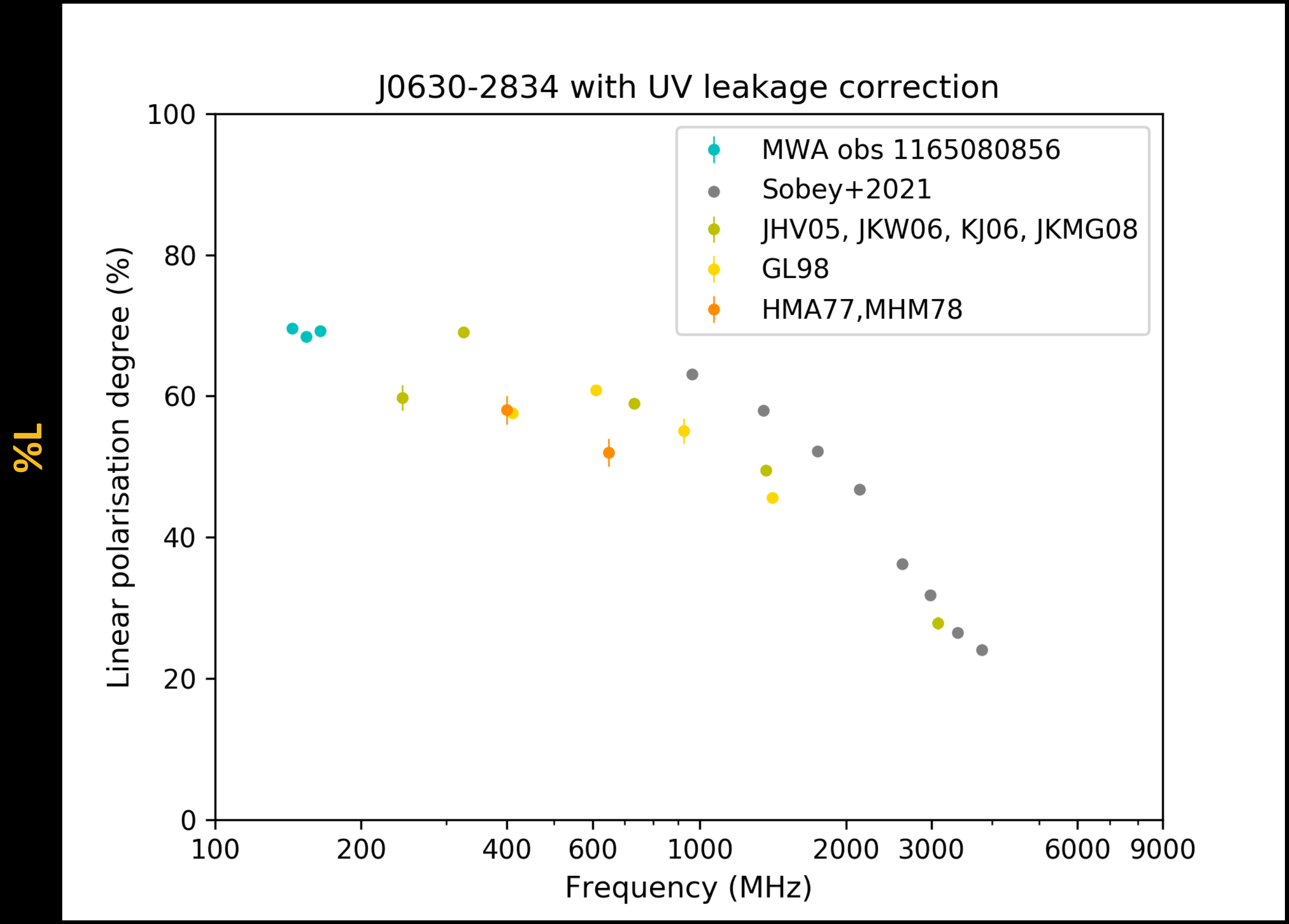


Revisiting the %L vs. freq. for J0742

%L

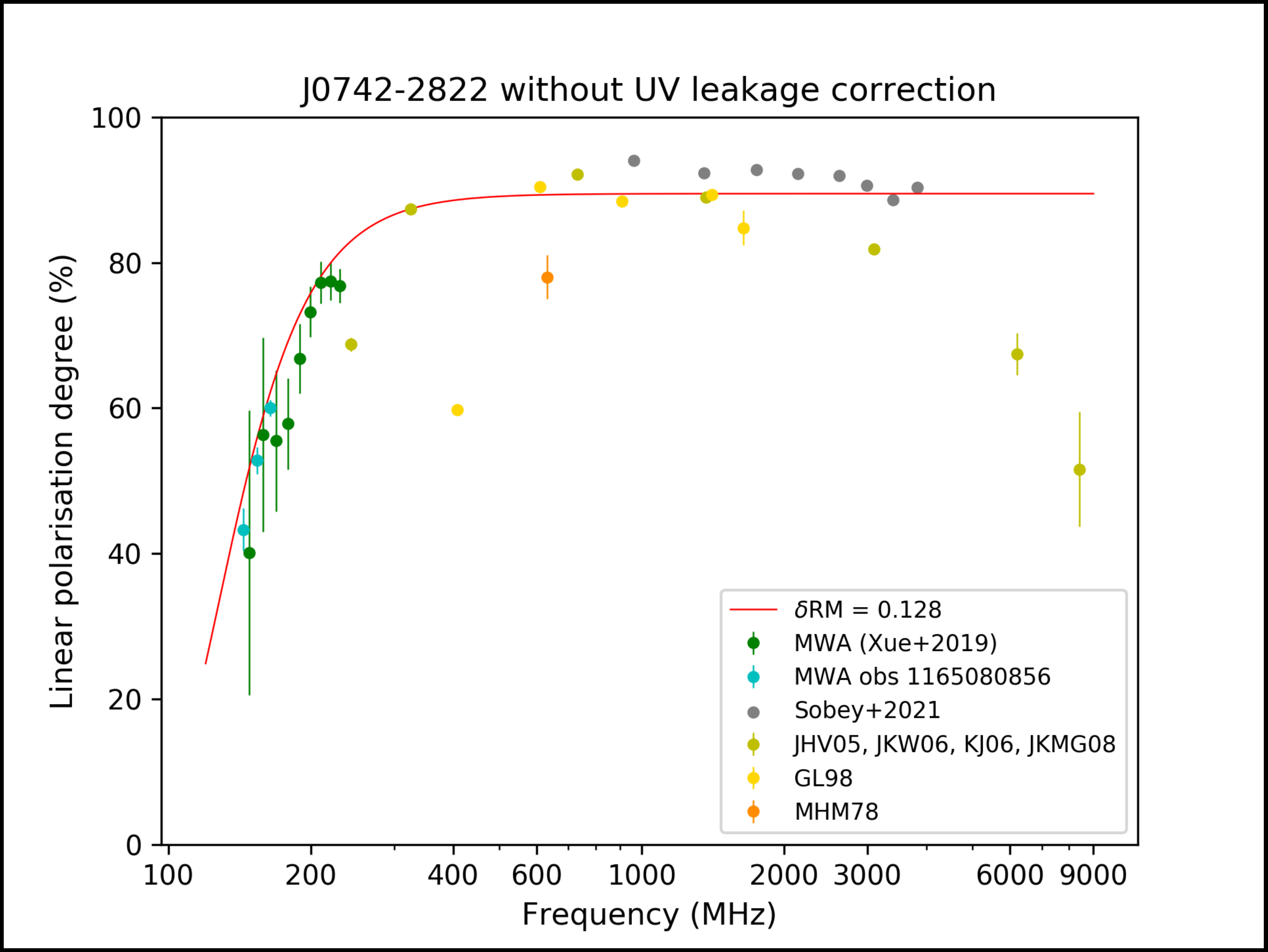


Revisiting the %L vs. freq. for J0742

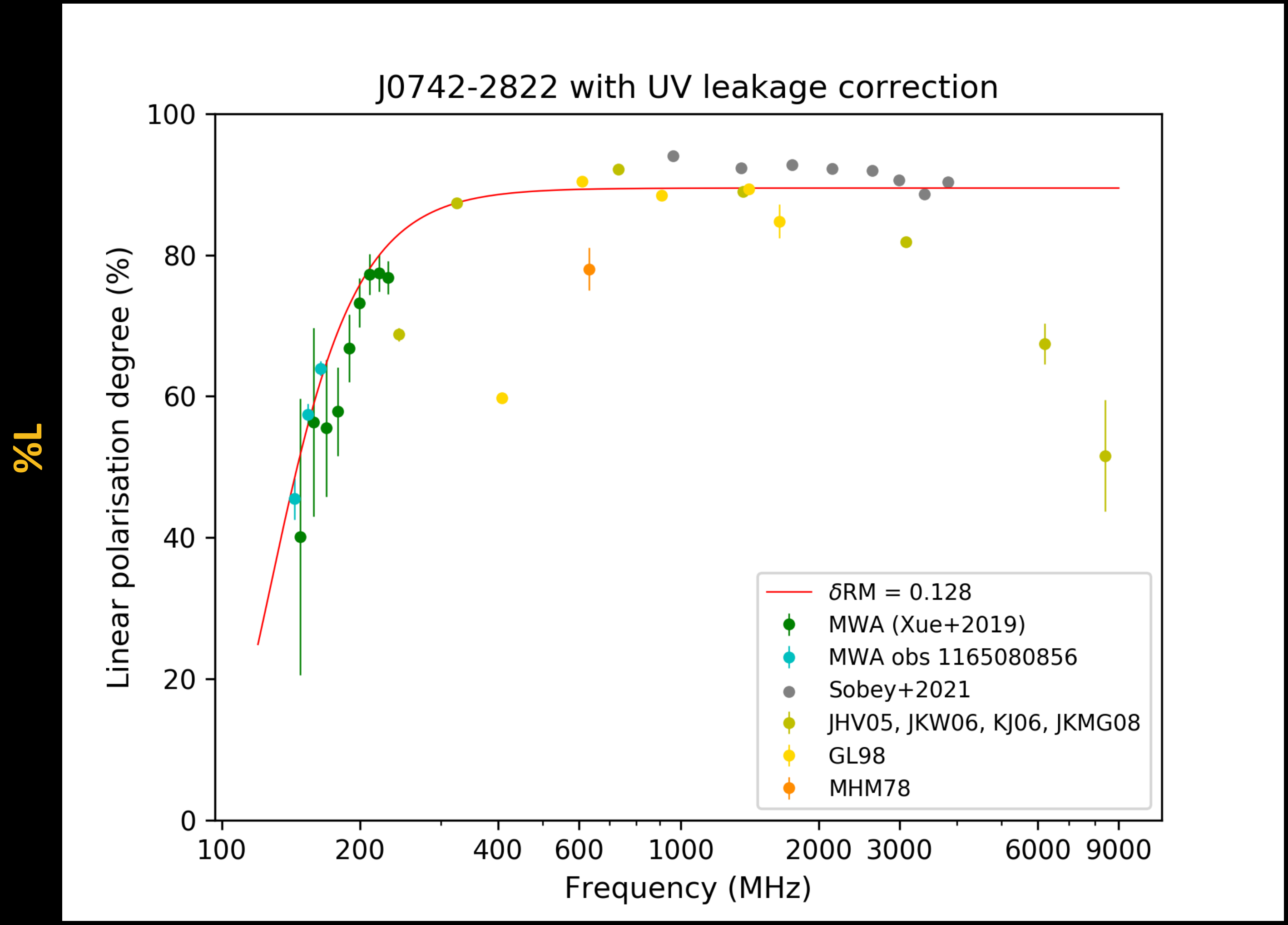


Revisiting the %L vs. freq. for J0742

%L



Revisiting the %L vs. freq. for J0742



Summary

Polarimetric performance of the MWA:

- At Frequency < 270 MHz & Zenith Angle < 45°
  reliable and stable to the first order

- Compensate polarisation leakage is still an on going work

- The XY phase correction value for MWA is generally stable for several month, but have significant variation when Phase or configuration changed.

Despite the instrumental leakage from U -> V which will affect the liner polarisation degree (%L), the rapid decrease trend of %L we saw in significantly scattered pulsars such as J0742 and the Vela pulsar should still be real.