LOFAR

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

The polarisation properties of pulsars below 200 MHz

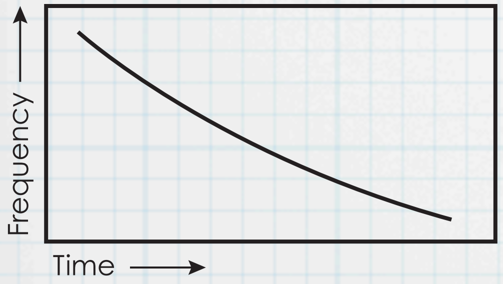
Aristeidis Noutsos
and the
Pulsar Working Group and *Magnetism Key Science Project*
of LOFAR

Pulsar Radio Emission

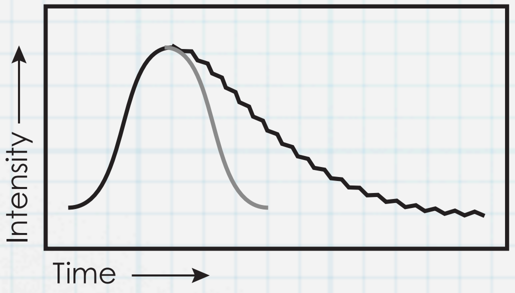
One of the biggest challenges in pulsar astronomy is to understand the magnetospheric processes that generate pulsar radio emission and its polarisation.

In order to study magnetospheric emission one needs to understand the distorting effects of the intervening medium.

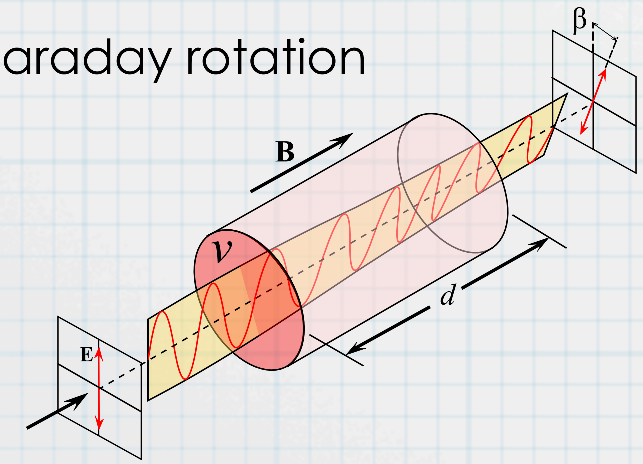
pulse dispersion

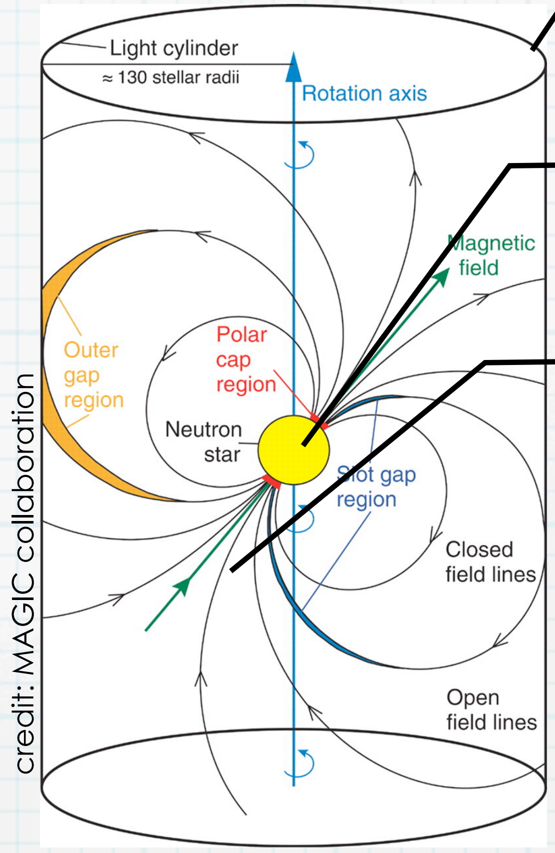


pulse scattering



Faraday rotation



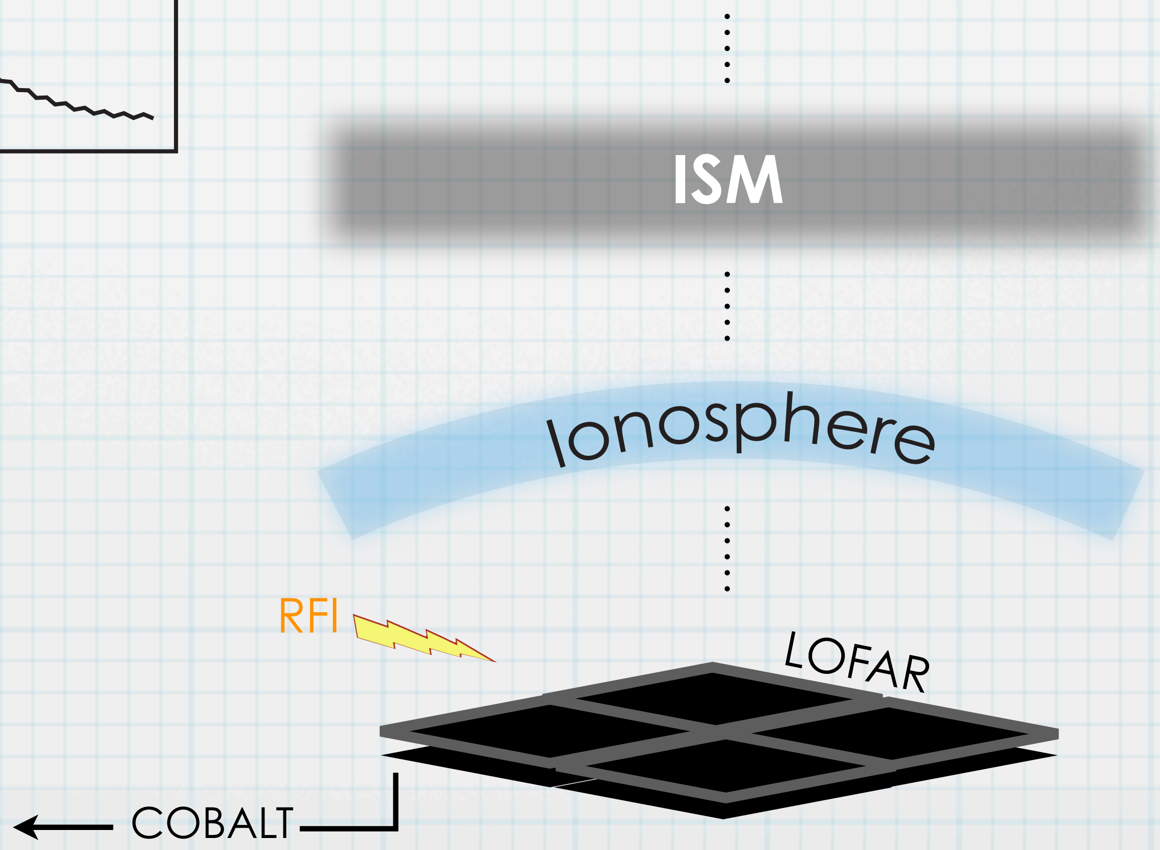


credit: MAGIC collaboration

light cylinder ($R_{LC} = c/\Omega$)

Quantum-mechanical effects

Magnetospheric effects:
– Relativistic effects (e.g. A/R)
– Propagation effects (e.g. birefringence)



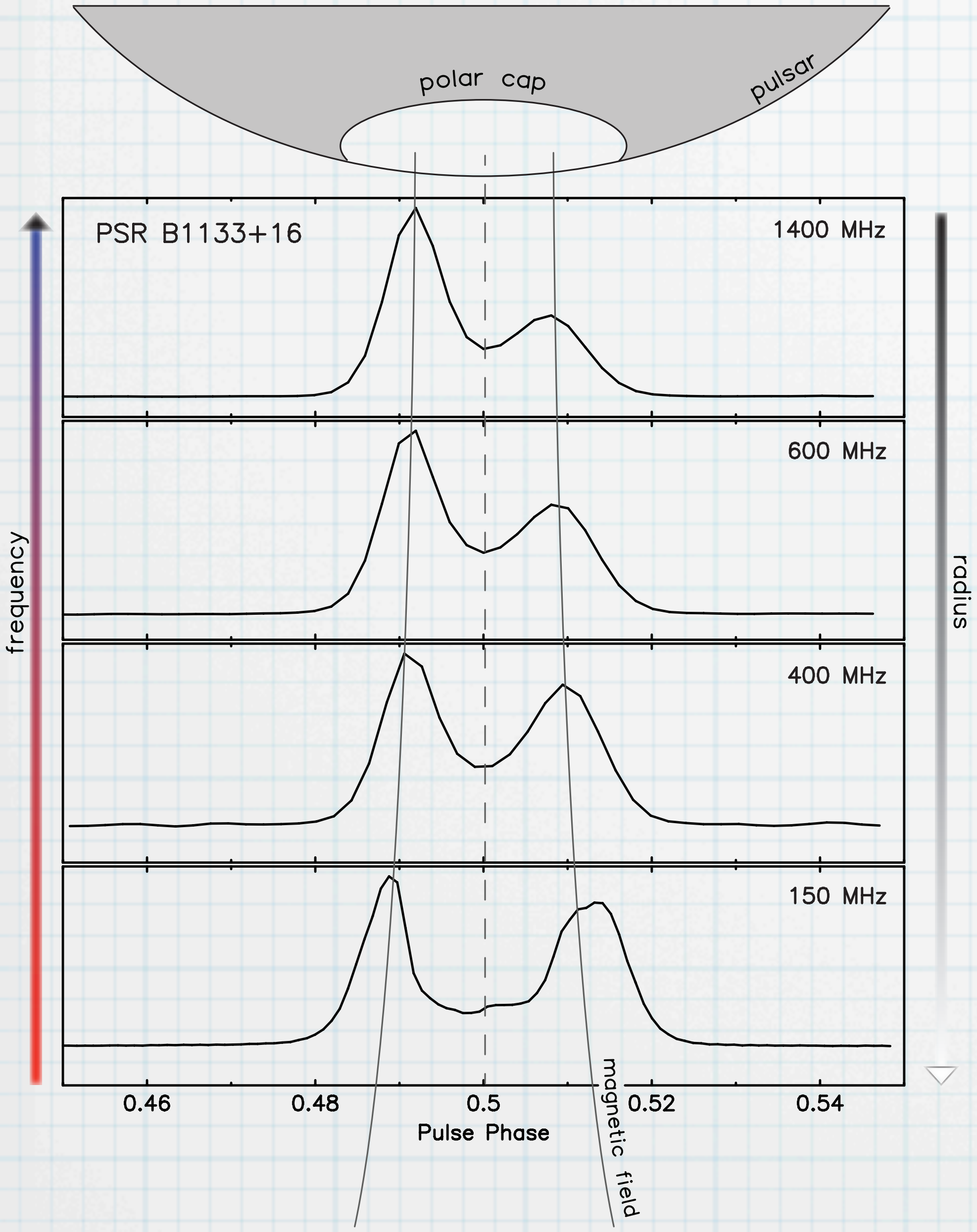
dispersion
scattering
Faraday rotation

Faraday rotation

Station calibration
Polarisation calibration

Multi-frequency Observations

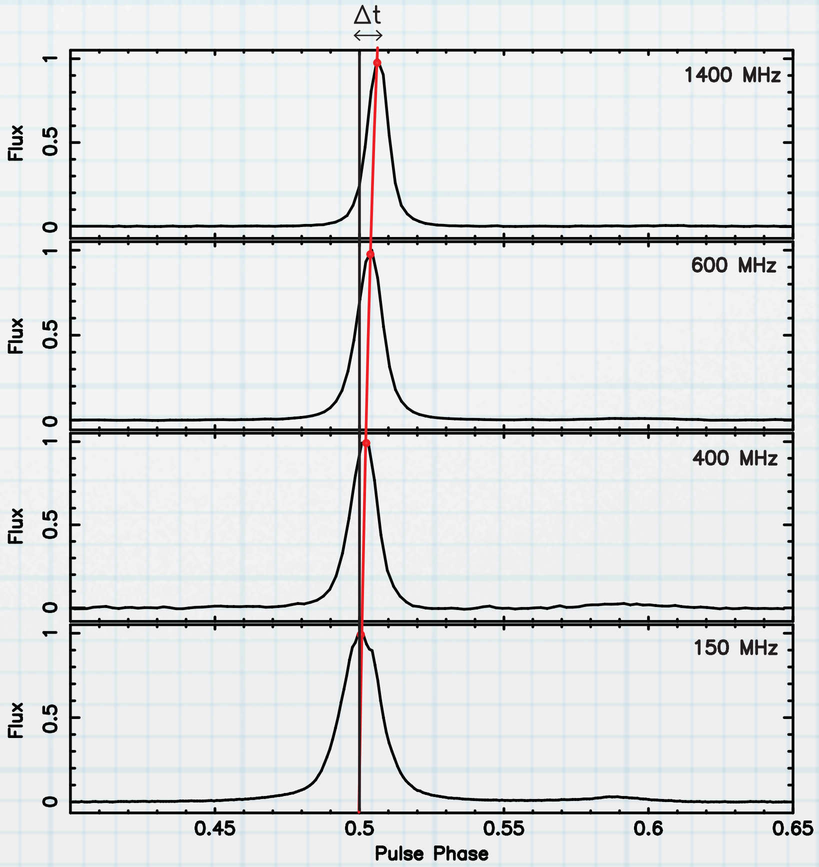
The usefulness of combining multi-frequency pulsar data has been recently shown in LOFAR observations of bright pulsars (Hassall et al. 2012; Hassall et al. 2013).

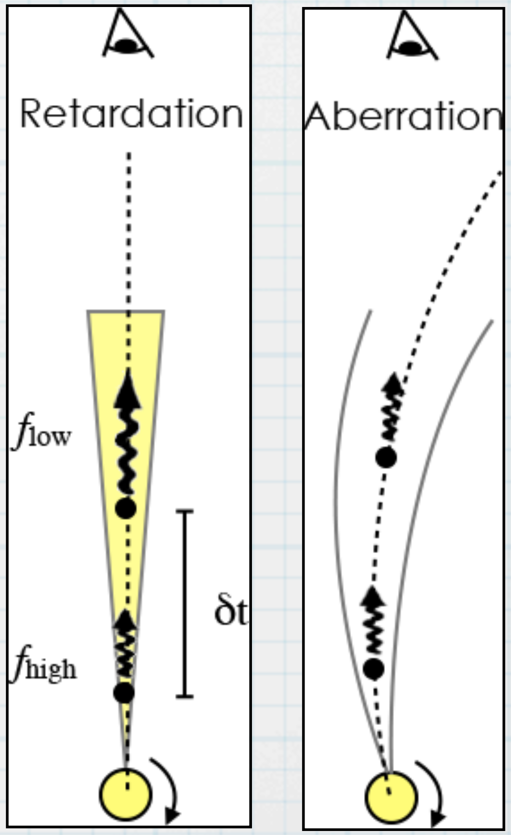


Radius-to-frequency mapping (RFM)

Assuming RFM emission heights can be estimated by measuring the peak separation

In addition, aberration and retardation effects cause phase lags between the arrival time of pulses at different frequencies.



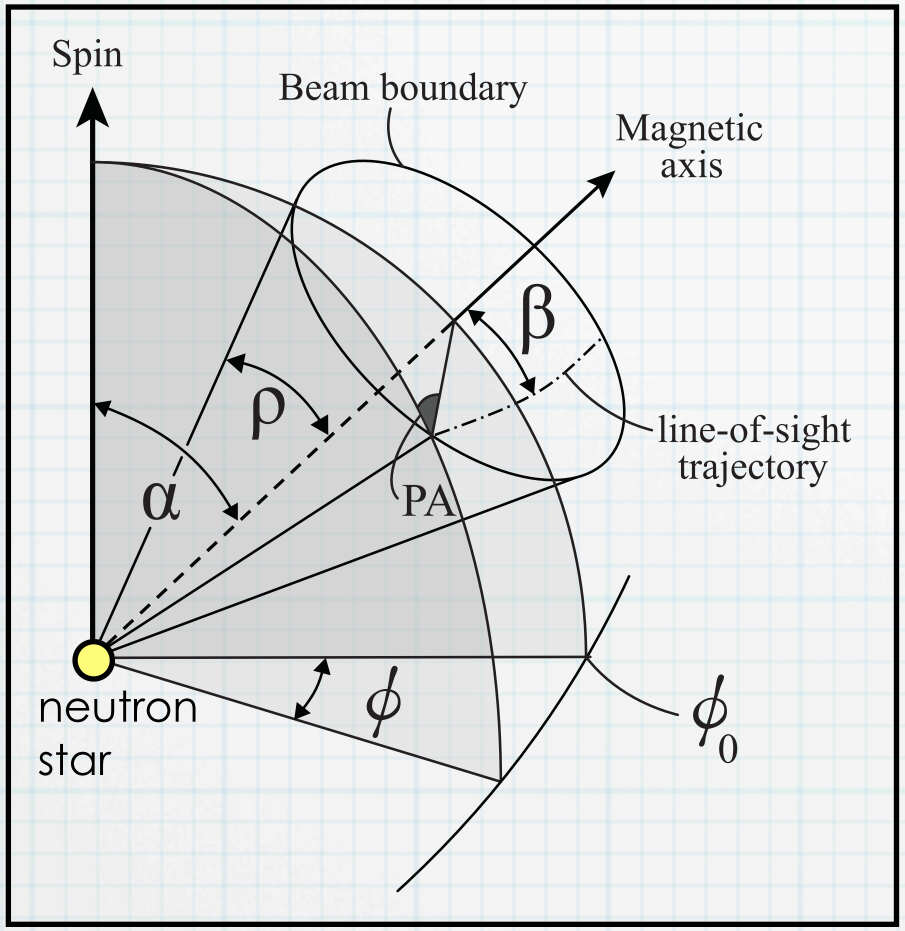


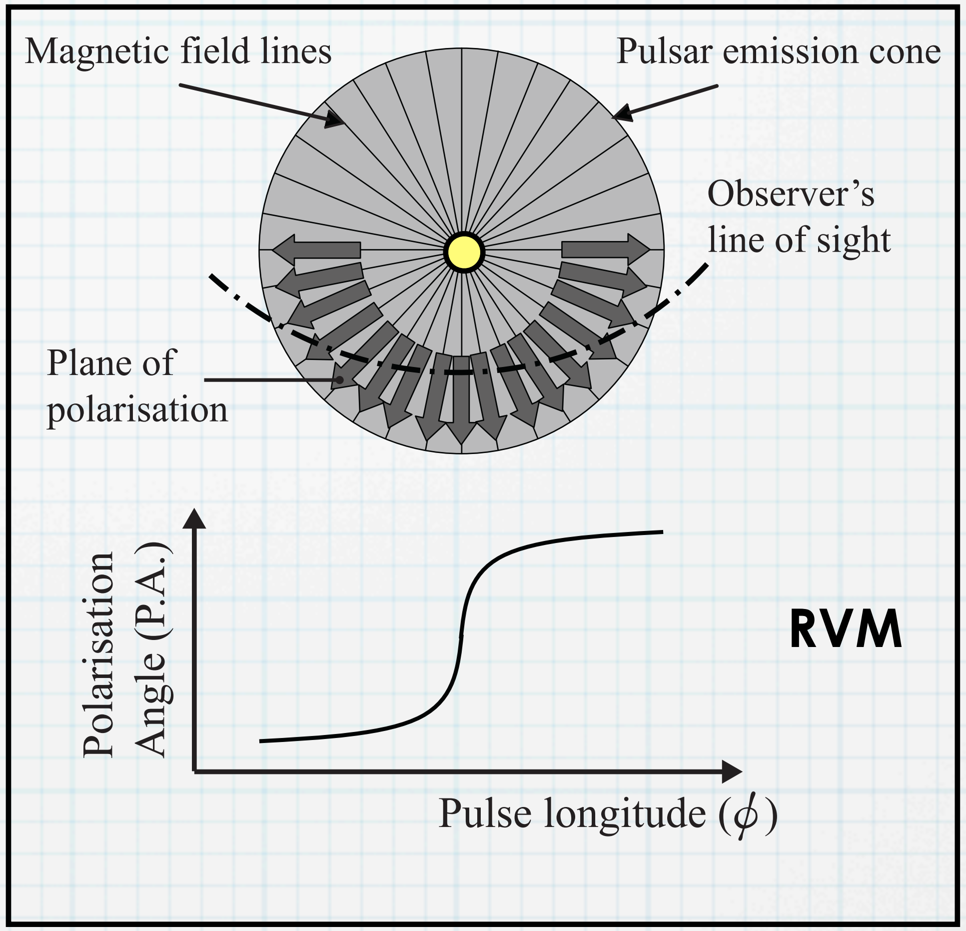
$$\Delta t_{\mathrm{A/R}} = (1+\sin\alpha)\frac{\Delta r_{\mathrm{em}}}{c}$$

It was suggested that radio emission is generated within a narrow altitude range of ~100 km (compare with R_{LC}~10,000 km)

Pulsar Polarisation Phenomenology

Polarisation reflects the geometry of pulsar magnetospheric emission.





Noutsos et al. (2012)

In the open field-line region, radio emission is produced by magnetospheric currents running along the magnetic-field lines.

The emission is polarised in the planes defined by the dipolar magnetic-field geometry.

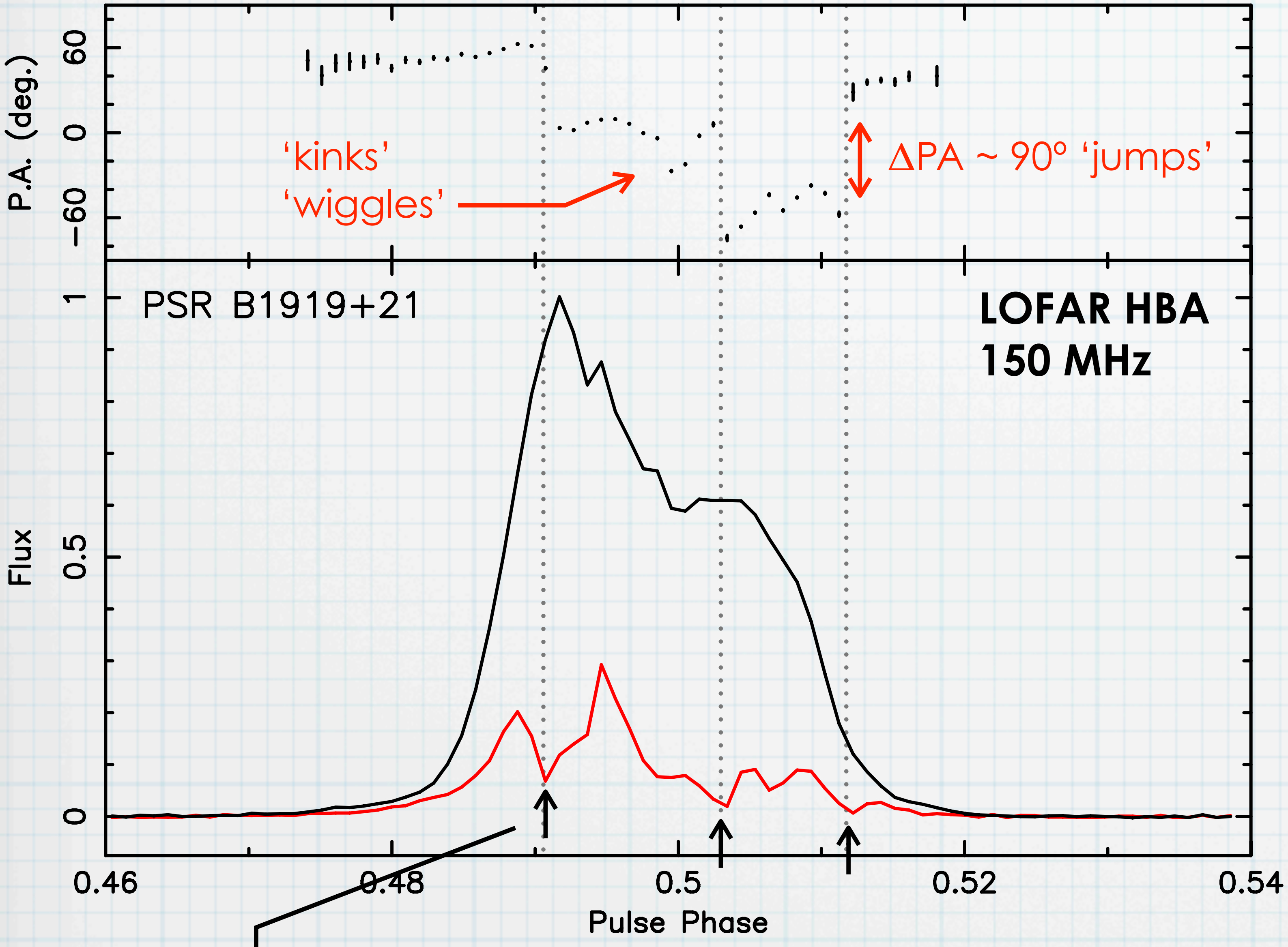
Rotating Vector Model (RVM):

The parallactic rotation of the tangent to the dipolar magnetic-field lines, as the emission cone sweeps across the observers line of sight, is observable as a Polarisation Position Angle (PA) sweep across the pulse (an 'S' curve).

Pulsar Polarisation Phenomenology

The simple, geometric representation of pulsar polarisation fails to explain observations in several cases.

Noutsos et al. (in preparation)

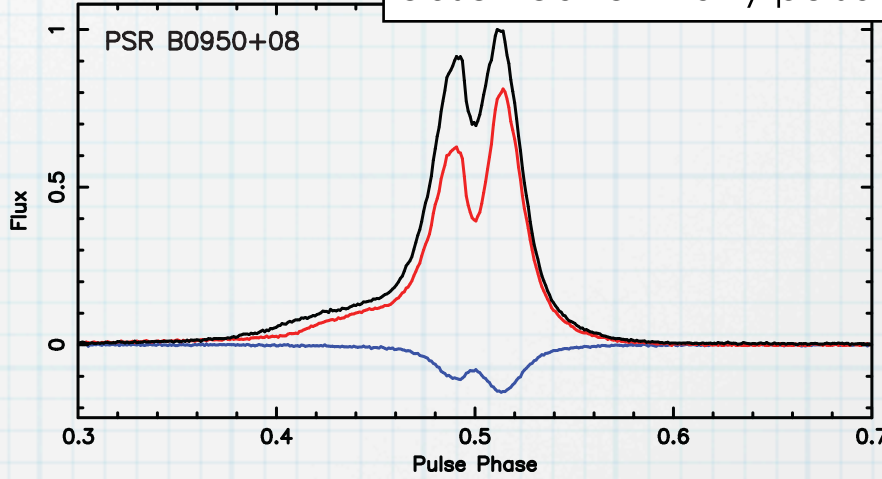


sharp local minima can be seen in *L* that do not correspond to changes in the total intensity

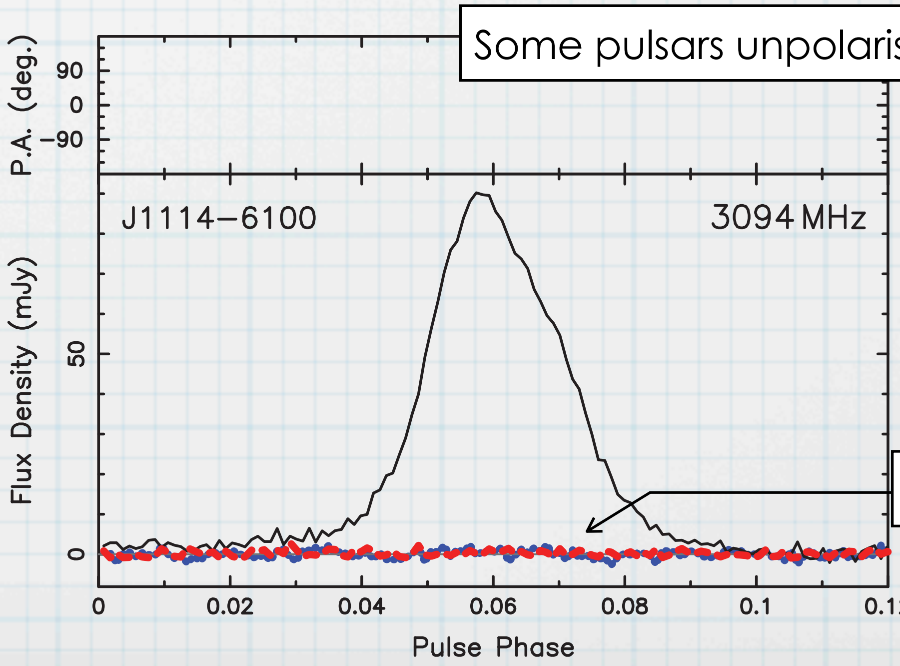
they almost always appear coincident with steep PA gradients.

Several PA profiles do not resemble the expected 'S' shape predicted by the RVM.

Significant fractions of circular polarisation can be observed for many pulsars



Some pulsars unpolarised.



zilch!

Multi-frequency Polarisation

As with the total intensity, multifrequency polarisation data are necessary for understanding not only magnetospheric processes but also how ISM affects polarisation.

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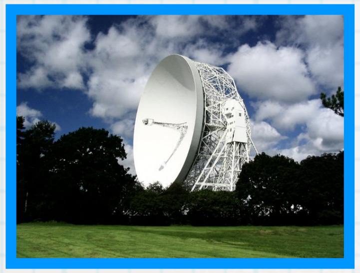
lovell



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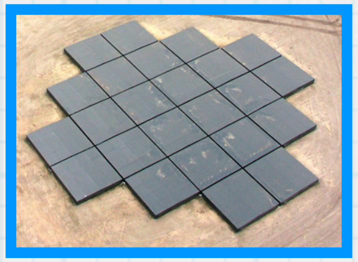
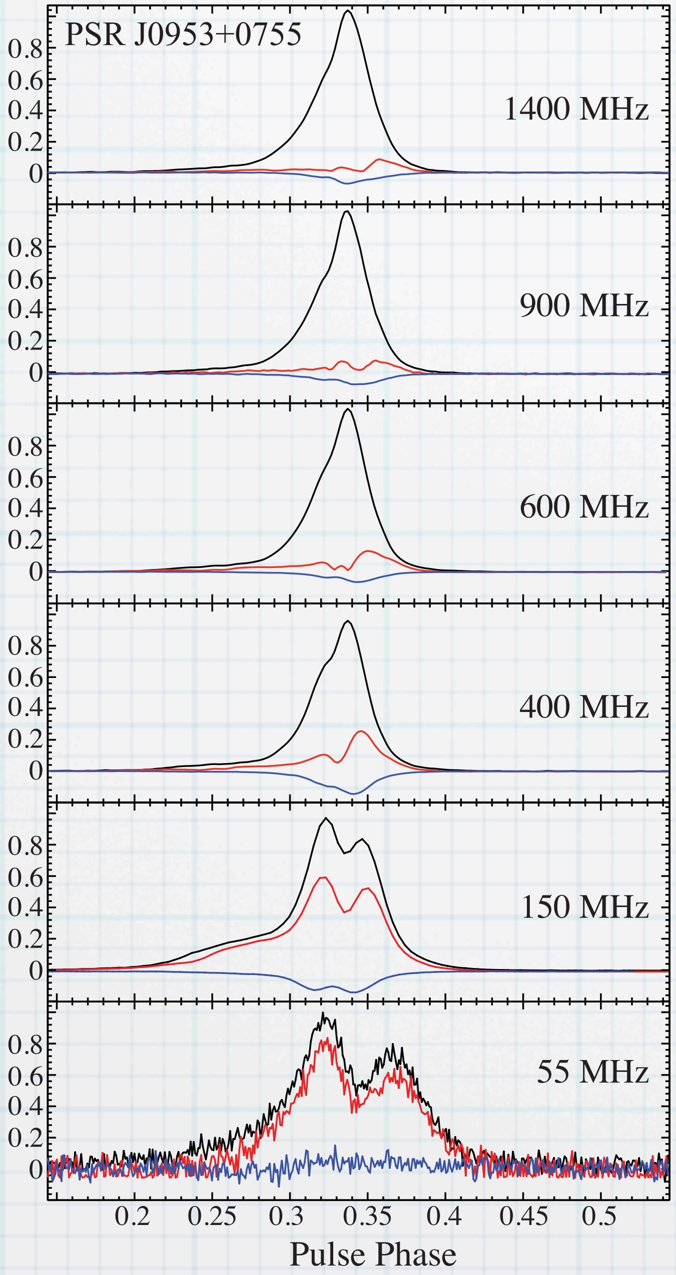
HBA



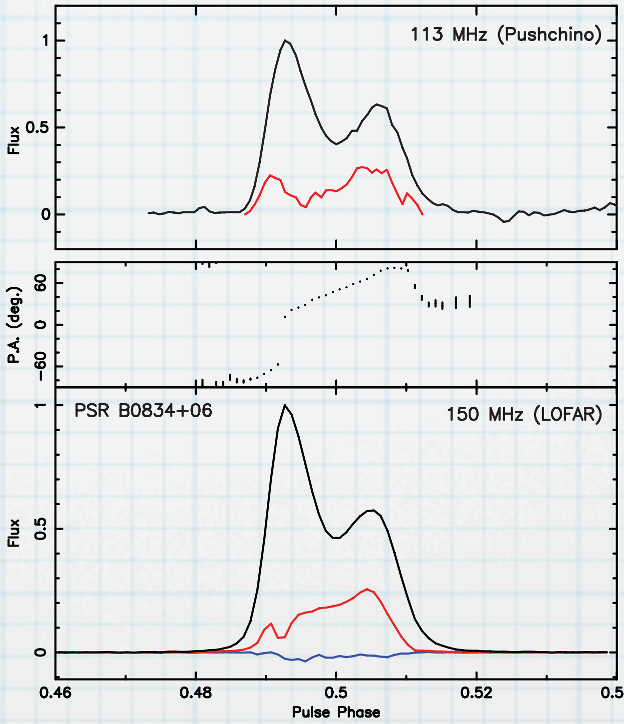
LBA

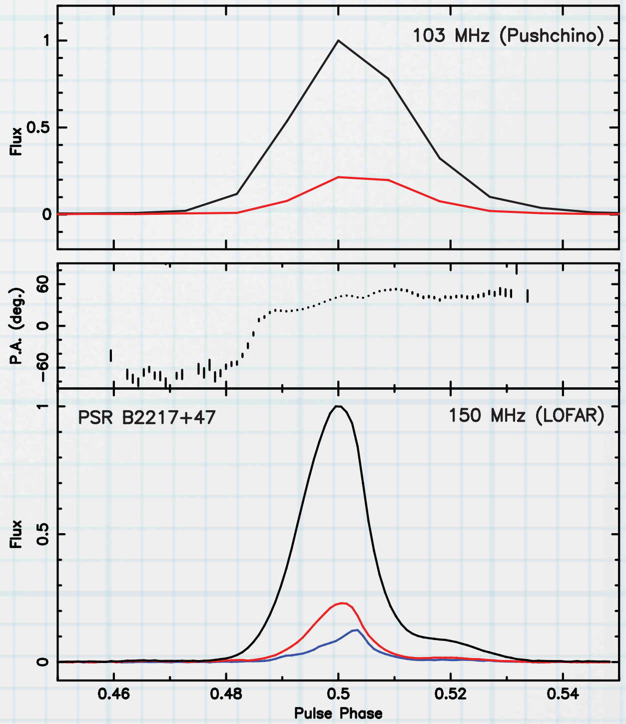
Commissioning data (early 2012)



Until LOFAR, most polarisation profiles below 200 MHz have been mostly the product of targeted work on individual sources.

In many cases the profile quality is much lower than that from LOFAR.





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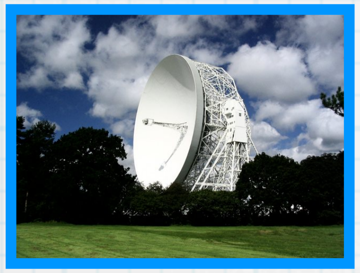

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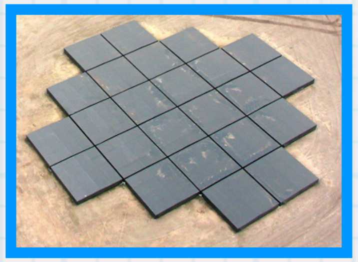

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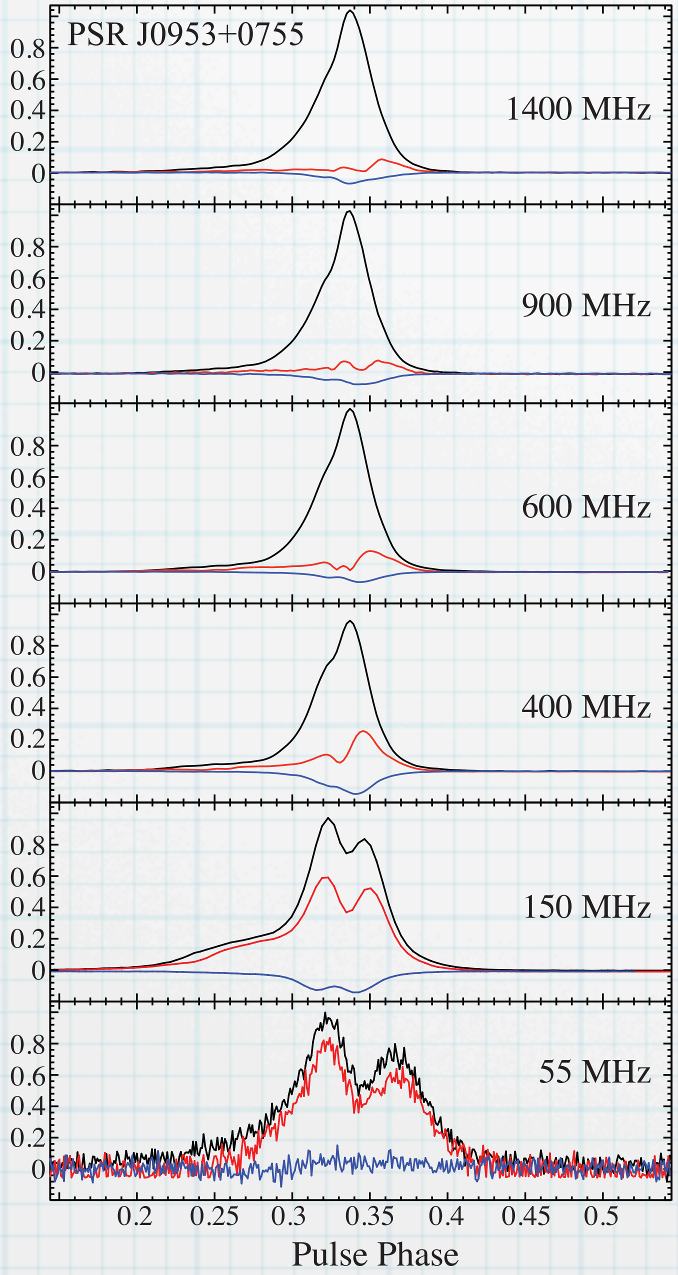

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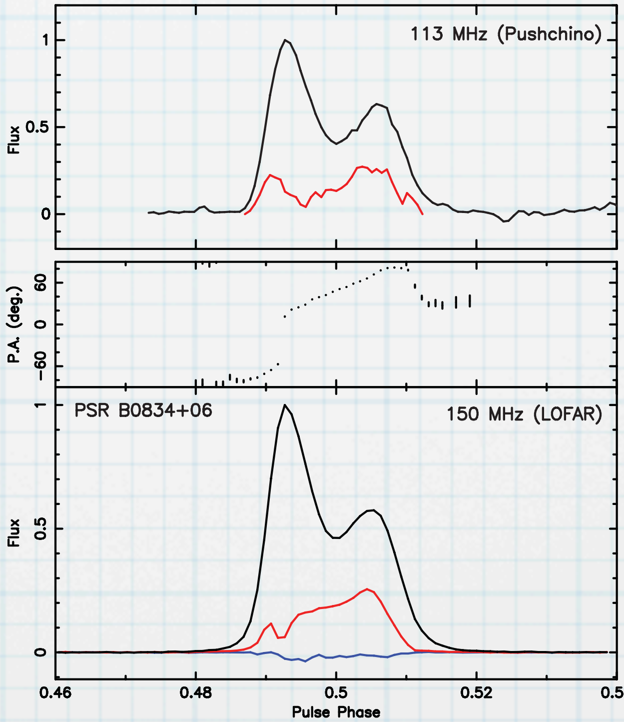
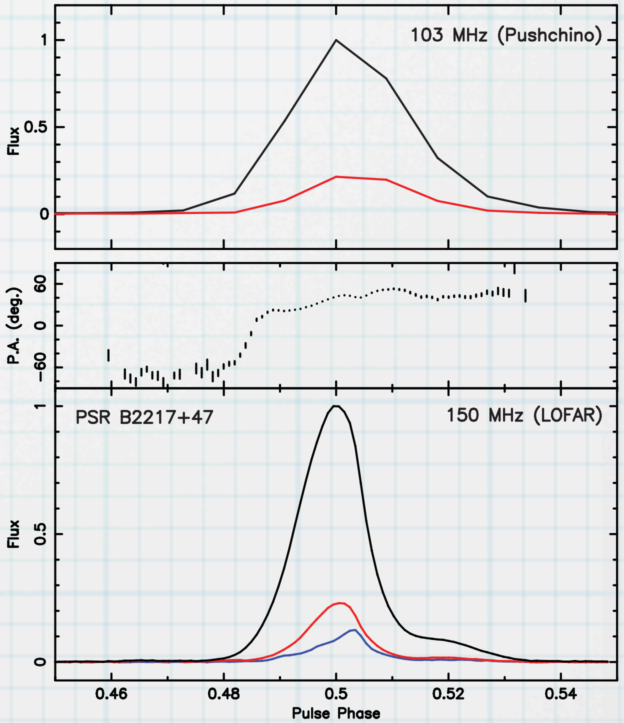




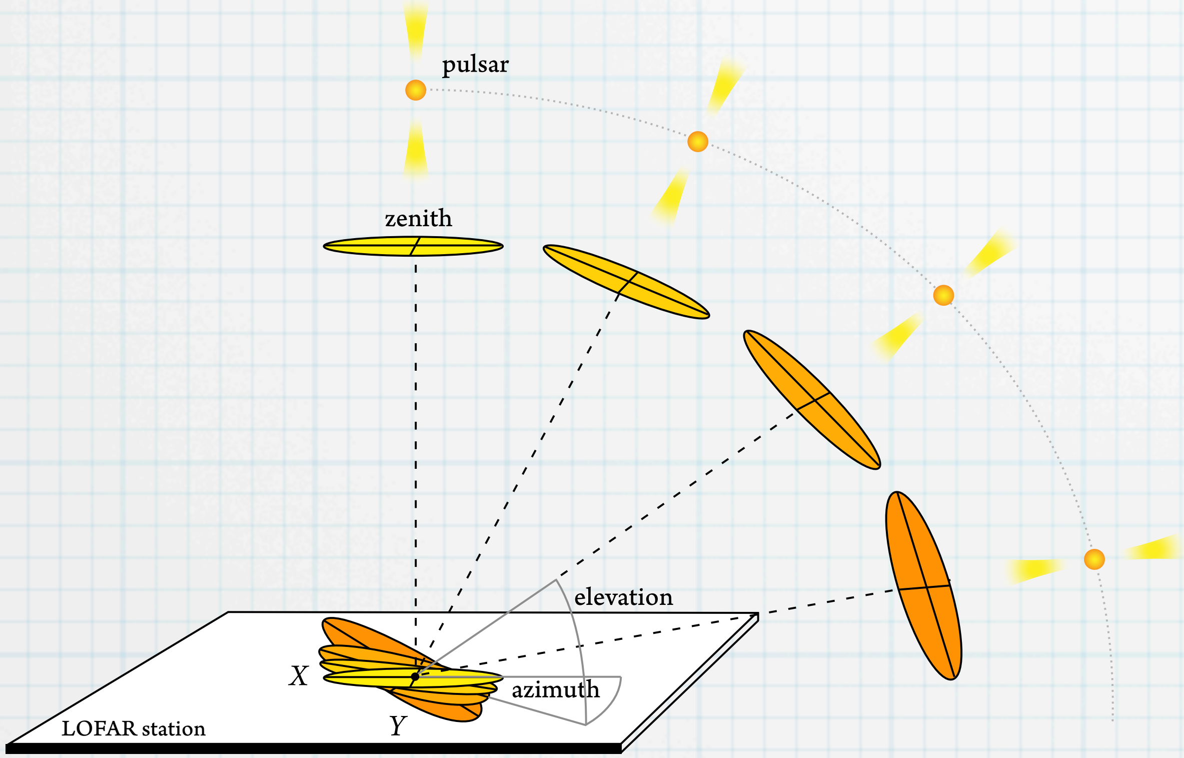
Our LOFAR polarisation survey (221 pulsars; |b|>10°) will extend to lower frequencies the high-quality polarisation information that is available from higher-frequency polarisation surveys (Cycles 1 & 2).

Polarisation Calibration

Polarisation calibration – Instrument

Before we can detect polarisation of astrophysical origin, we need to make sure that the instrumental effects are corrected for.

Parallactic source rotation



As the LOFAR beam tracks the pulsar across the sky, it is distorted due to the non-uniform sensitivity of the dipoles as a function of azimuth and altitude.

The signal is projected onto the ground screen. At any elevation other than 90°, the signal is projected onto a non-orthogonal frame containing the polarisation feeds.

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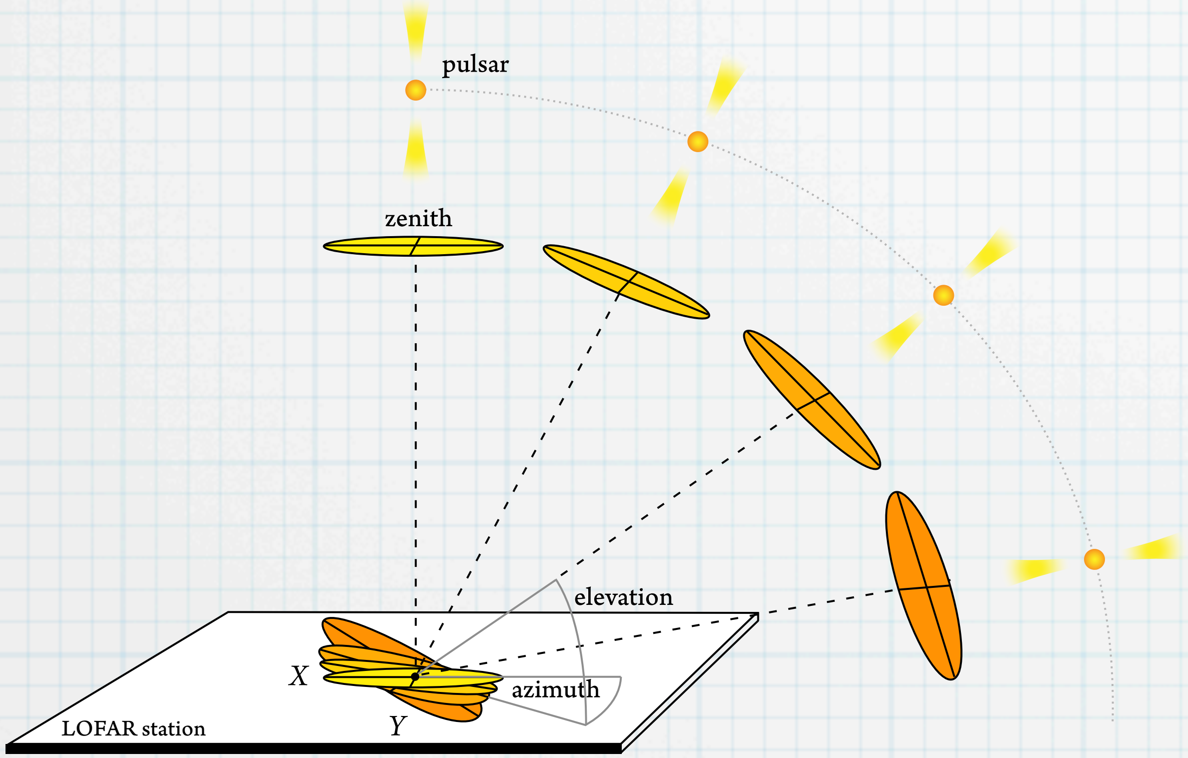

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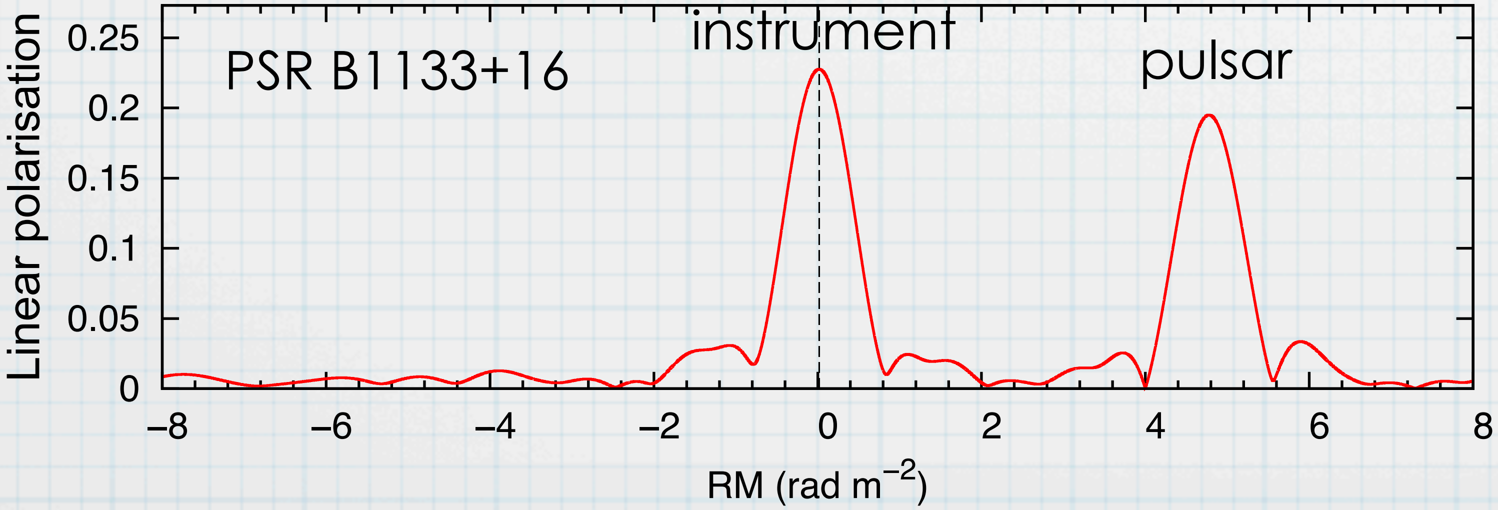
Leakage



Leakages due to system imperfections (feeds, electronics, etc.) can convert Total power to Linear and Linear to Circular.

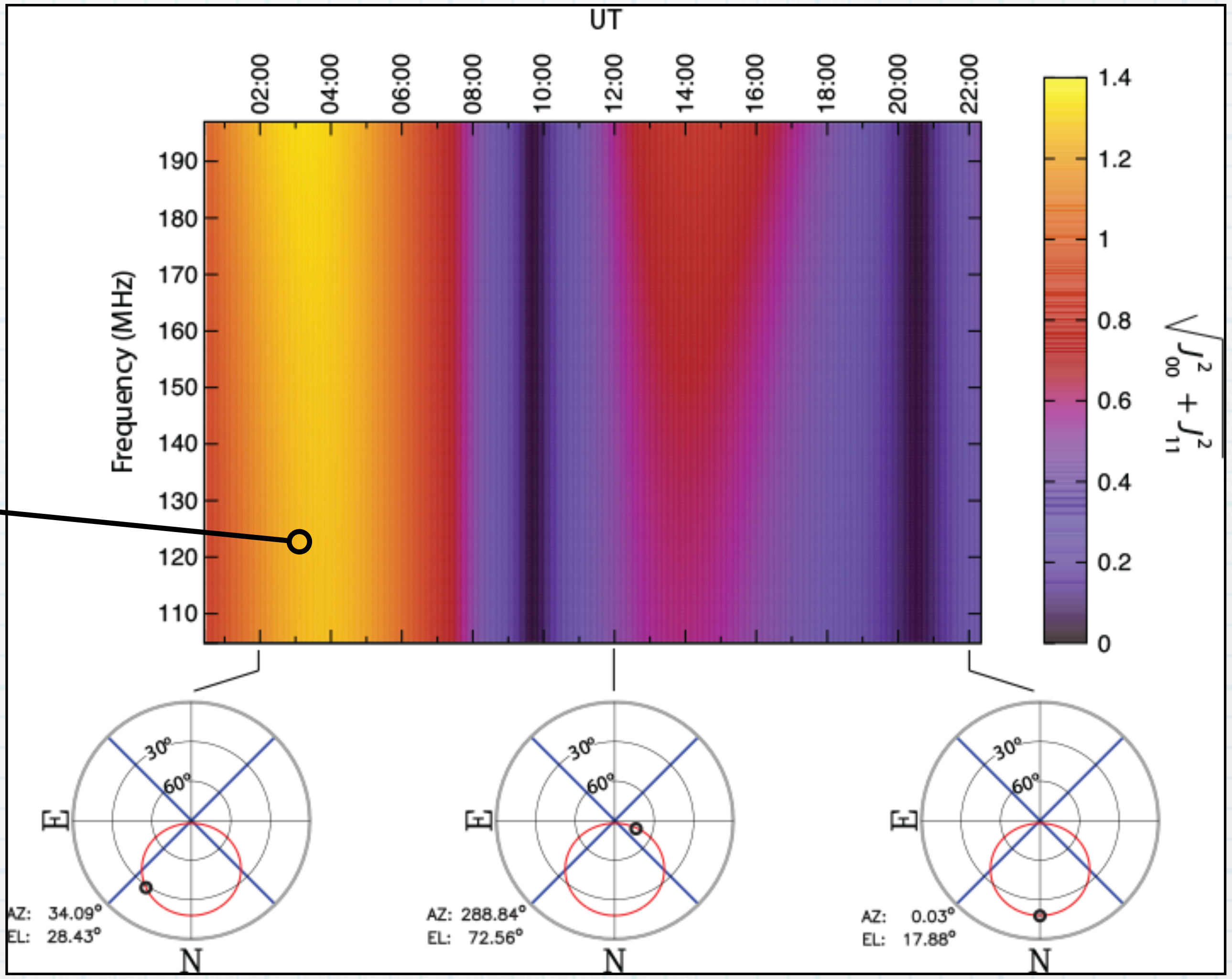
Also, differences between the feed gains can cause leakage between L and V.

Polarisation calibration – Instrument

Beam calibration is performed using the Hamaker formalism + EM simulation software.

For a certain direction (azimuth,altitude) and observing frequency, the Hamaker model can be described as a 2x2 complex Jones matrix.

Jones matrices describing the Beam (E) and Gain (G) response can be derived for any direction and frequency.



Complete description

$$\boxed{\boldsymbol{J}_i(\mathbf{r}, f, t) = \underbrace{\boldsymbol{B}_i}_{\text{bandpass}}\underbrace{\boldsymbol{G}_i}_{\text{gain}}\boldsymbol{D}_i\underbrace{\boldsymbol{E}_i}_{\text{beam}}\boldsymbol{P}_i\boldsymbol{T}_i\underbrace{\boldsymbol{F}_i}_{\text{Faraday}}}$$

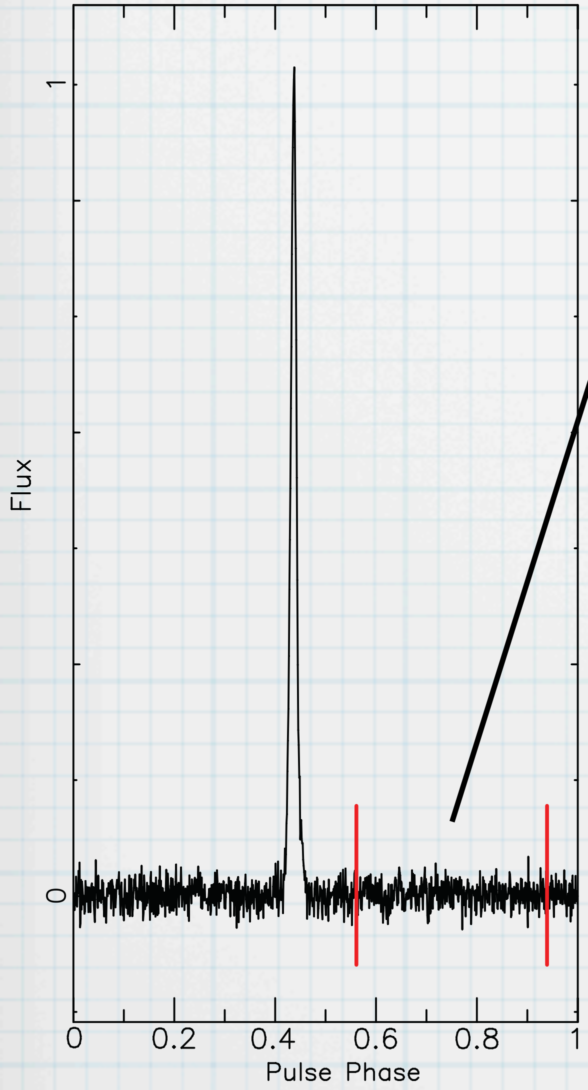
Finally, the inverse response is then applied to the measured complex voltages, to recover the original polarisation signal.

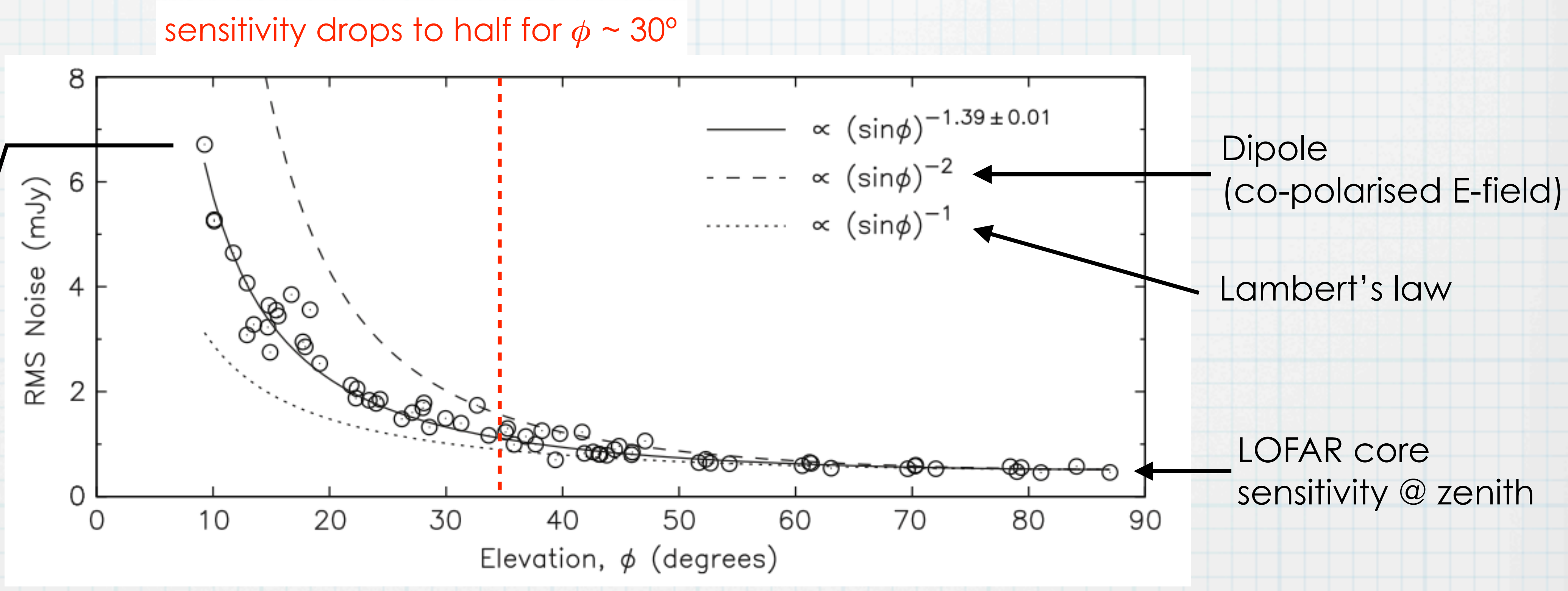
$$\begin{pmatrix} \tilde{J}_{00} & \tilde{J}_{01} \\ \tilde{J}_{10} & \tilde{J}_{11} \end{pmatrix}^{-1} \times \begin{pmatrix} \tilde{V}_1 \\ \tilde{V}_2 \end{pmatrix} = \begin{pmatrix} \tilde{\Lambda}_1 \\ \tilde{\Lambda}_2 \end{pmatrix}$$

Polarisation calibration – Instrument

Sensitivity as a function of (α, δ):

We observed 4 bright pulsars, PSRs B0834+06, B1929+10, B1953+50 and B2217+47, at various HA with the LOFAR core. The sensitivity was expressed as the RMS value of the off-pulse flux density, which was measured after calibrating with the model.





sensitivity drops to half for ϕ ~ 30°

Dipole
(co-polarised E-field)

Lambert's law

LOFAR core
sensitivity @ zenith

Conclusions:

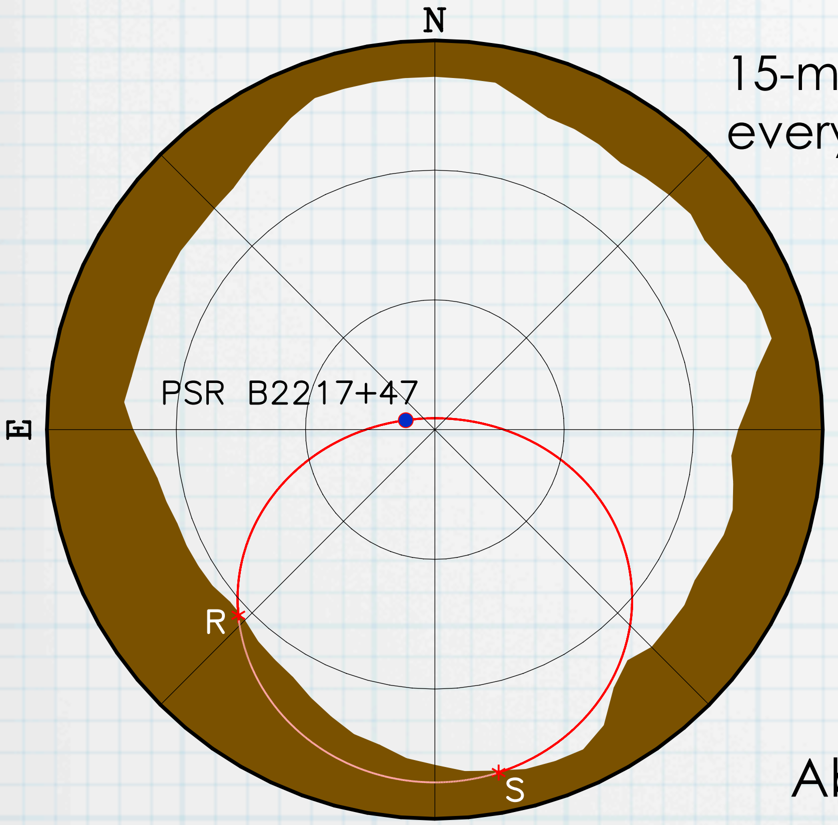
- The sensitivity increases with elevation as ~$\sin^{-1.4}$(elevation).
- Above 30° elevation the sensitivity remains >50% of its zenith value.

Calibration Tests

Polarisation stability as a function of (α, δ):

We observed a bright pulsar for 17 hours across transit, with DE601.

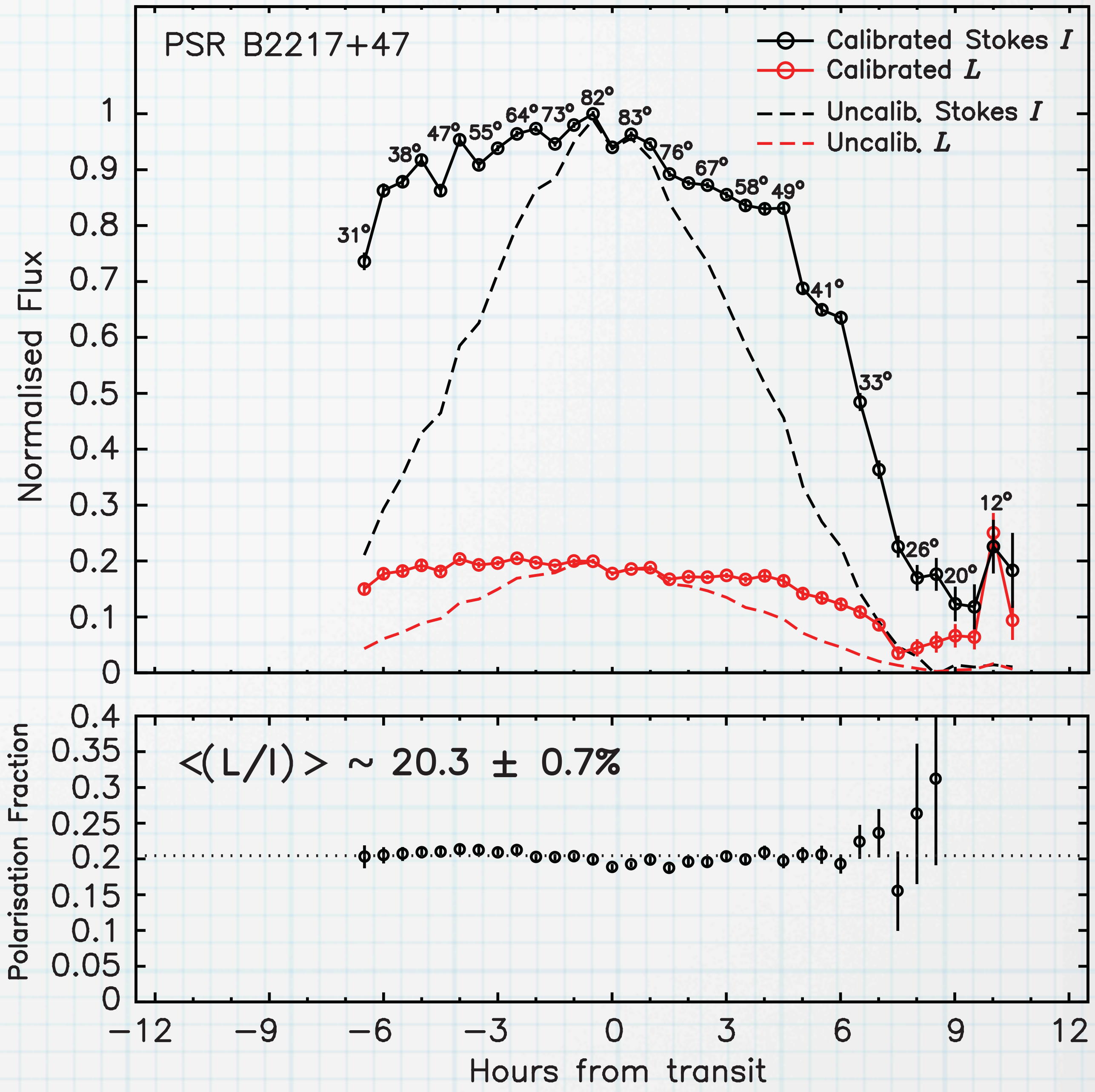
(PSR B2217+47; typically ~20% linearly polarised)

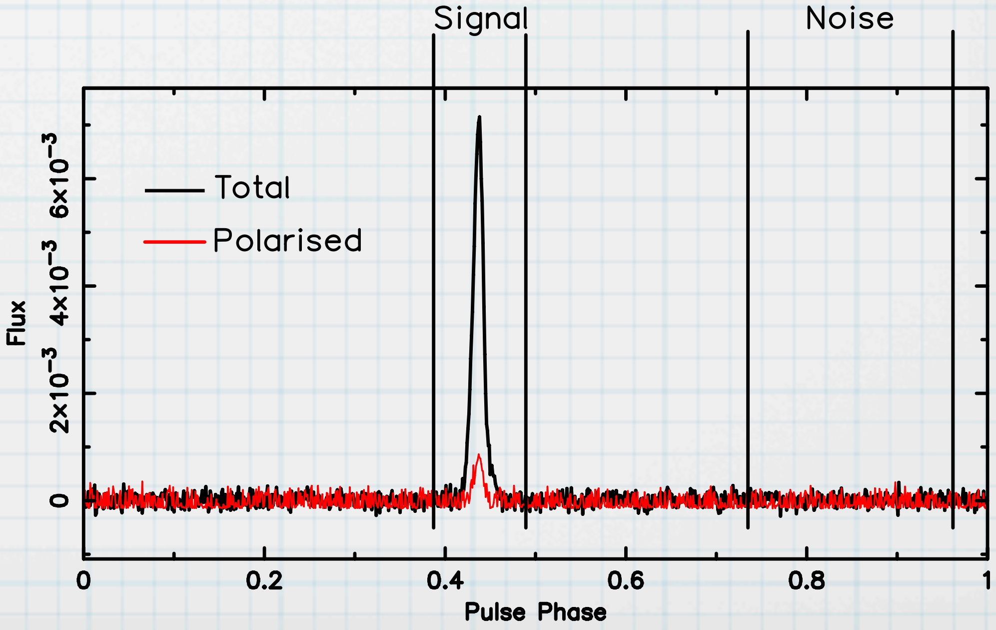


15-min pointing
every 30 min for 17 hours

Above 30° elevation

- <L/I> ~ 20.3 ± 0.7%
- <δL/L_0> ~ 6.0 ± 0.7%





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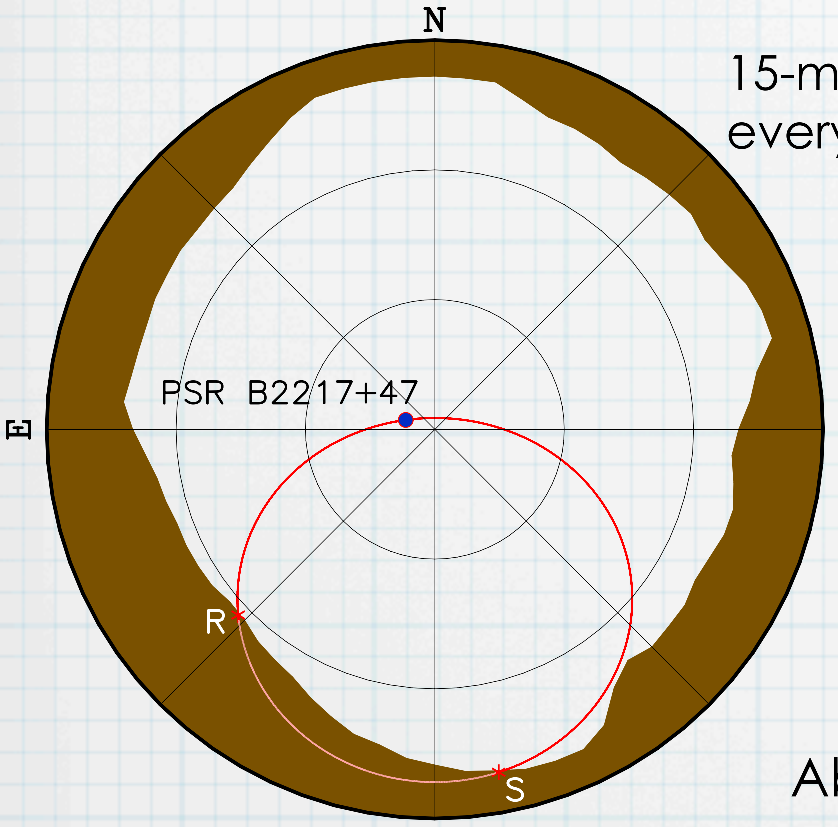

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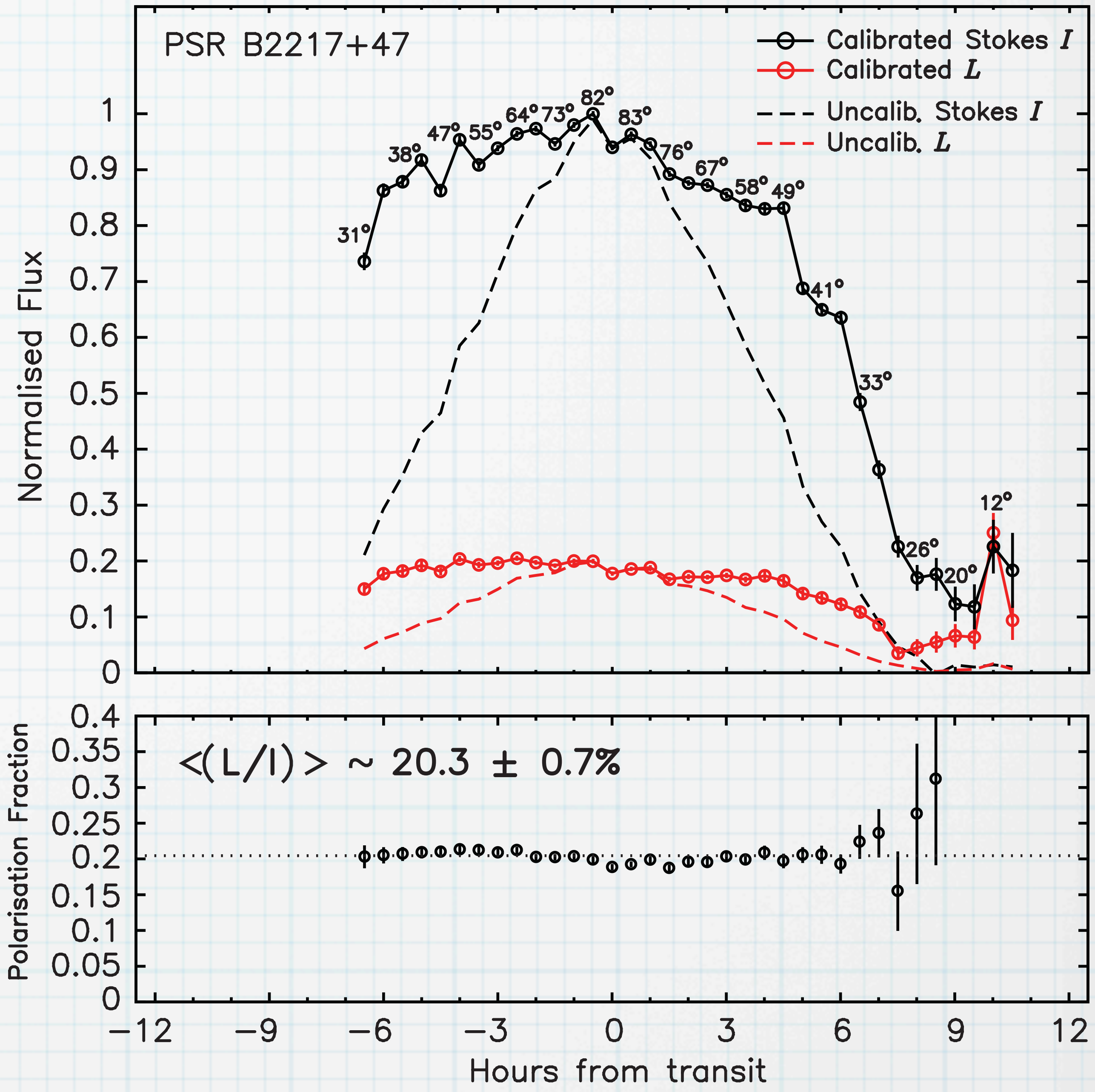
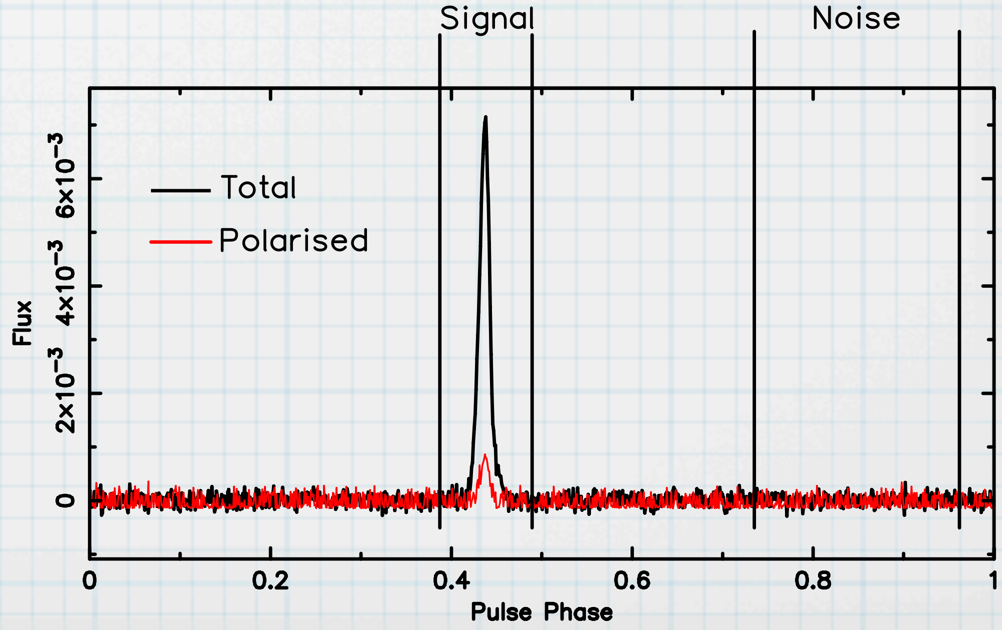




Conclusion:

Above 30° elevation, the model is reliable to within 5–10% systematic uncertainty.

Polarisation Profiles & Data Analysis

HBA Core Observations

Sample*

16 non-recycled PSRs

PSR B0031–07
PSR B0136+57
PSR B0809+74
PSR B0823+26
PSR B0834+06
PSR B0950+08
PSR B1133+16
PSR B1237+25
PSR B1508+55
PSR B1911–04
PSR B1919+21
PSR B1929+10
PSR B1953+50
PSR B2111+46
PSR B2217+47
PSR B2224+65

4 MSPs

PSR J0034–0534
PSR J1012+5307
PSR J1022+1001
PSR B1257+12

* Pulsars chosen for their high polarisation fractions, based on 230 –1600 MHz data (Gould & Lyne 1998)

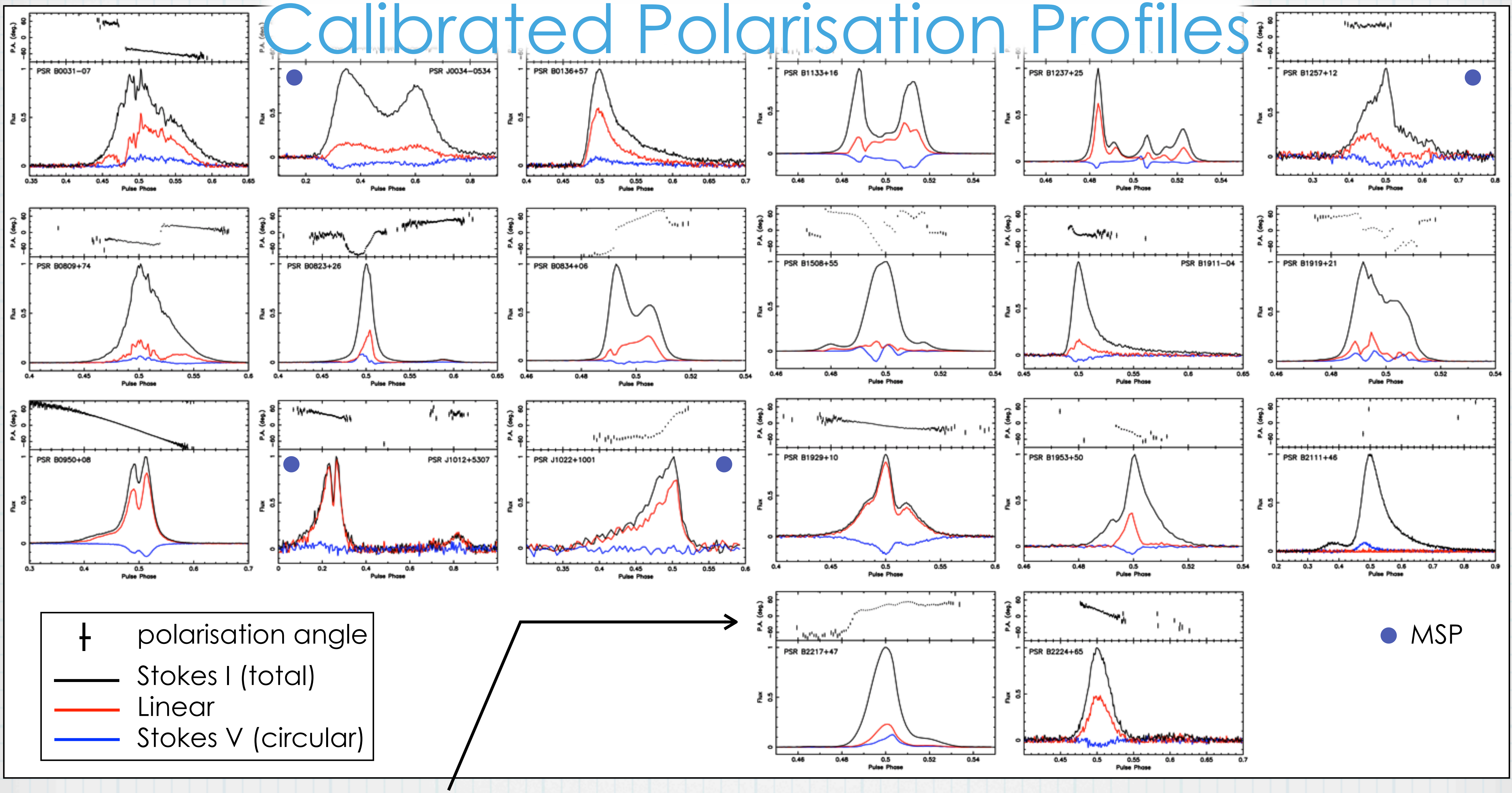
Setup

- Full HBA core: 24 stations coherently summed
- 8-bit mode; 96 MHz bandwidth
- All pulsars observed near transit
- Elevations: 15 PSRs ($\phi > 45°$), 5 PSRs ($\phi > 30°$)

Pre-processing

- Coherent dedispersion
- Polarisation calibration
- RFI excision (no more than 5% of the data was zero-weighted)
- Faraday correction
- Time/Frequency-averaged full-Stokes profiles were produced.

Calibrated Polarisation Profiles



ⱡ polarisation angle
— Stokes I (total)
— Linear
— Stokes V (circular)

● MSP

The measured PA profiles are not absolutely calibrated, ***George!***

Each PA can be trusted with respect to the rest but not as the intrinsic angle of the generated linear polarisation.

Absolute calibration requires:

- A reference calibration signal (e.g. 100% polarised signal, injected at 45° between the linear feeds).

  … to calculate the gain and phase differences between the linear feeds.

- An observation of a reference source with a known PA

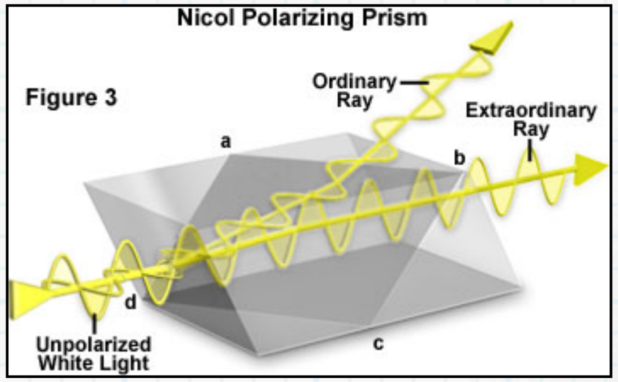
  … to estimate the PA rotation introduced by the different paths of the X and Y signals through the electronics chain.

Birefringence

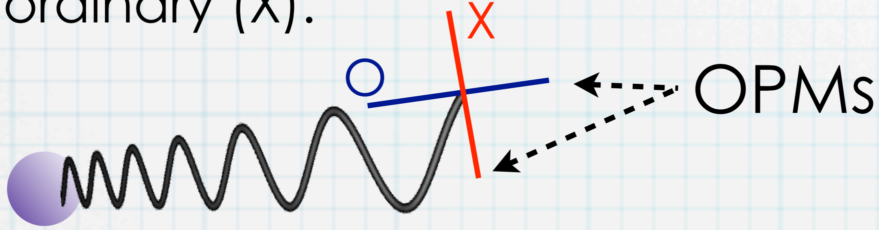
Birefringence has been put forward as an explanation for

- OPM jumps
- Intrinsic depolarisation and
- Pulse broadening

McKinnon 1997



It is assumed that pulsar polarisation is produced in two orthogonal propagation modes (OPMs), the Ordinary (O) and Extraordinary (X).

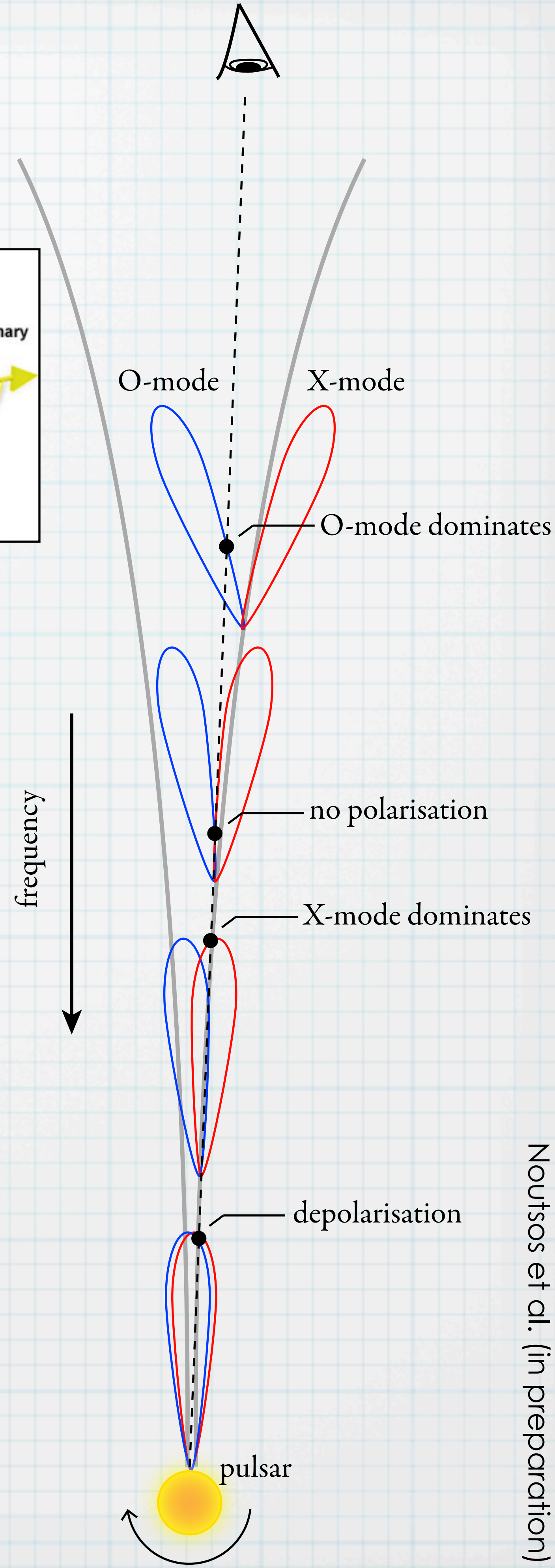


OPMs

At each pulse phase we observe the sum of those modes.
The PA corresponds to the orientation of the dominant mode.

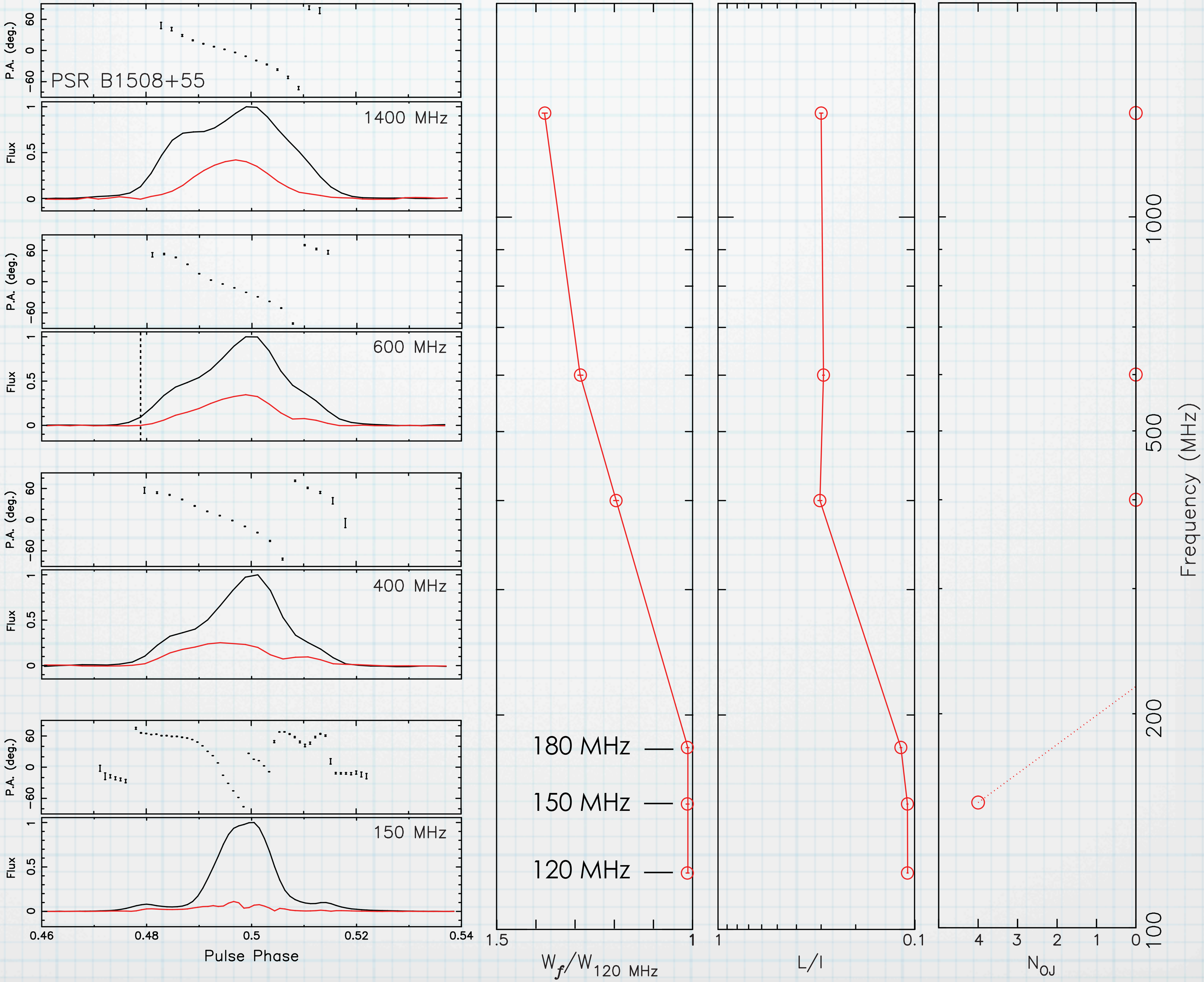
We have tested 3 predictions of birefringence:

- **Depolarisation** towards high frequencies, as the polarisation modes overlap.
- **Pulse broadening** towards low frequencies, as the polarisation modes' beams diverge.
- **Increasing number of OPM jumps** towards low frequencies, as the observer's line of sight traverses the divergent polarisation beams.



Noutsos et al. (in preparation)

Frequency Evolution of Polarisation



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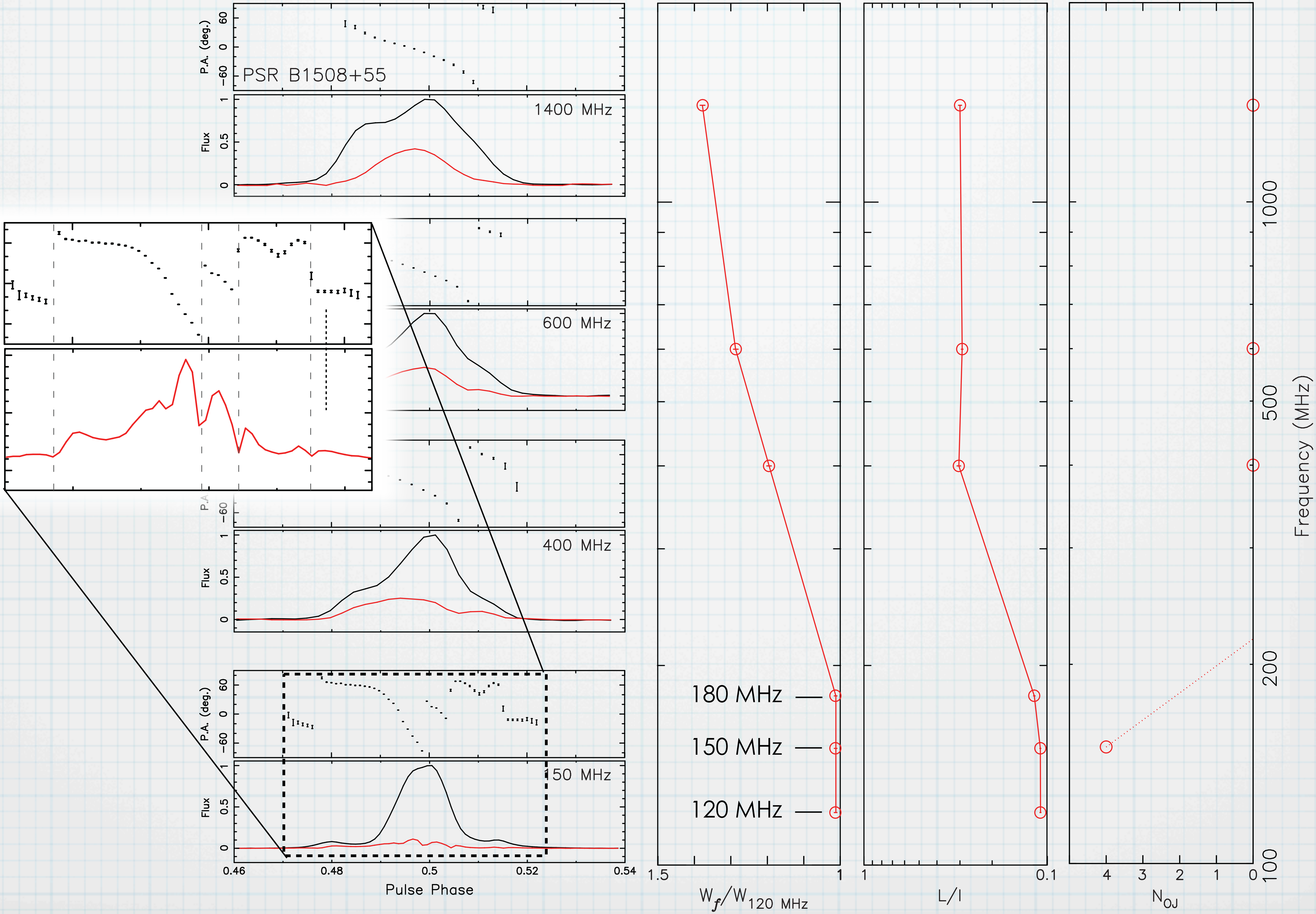
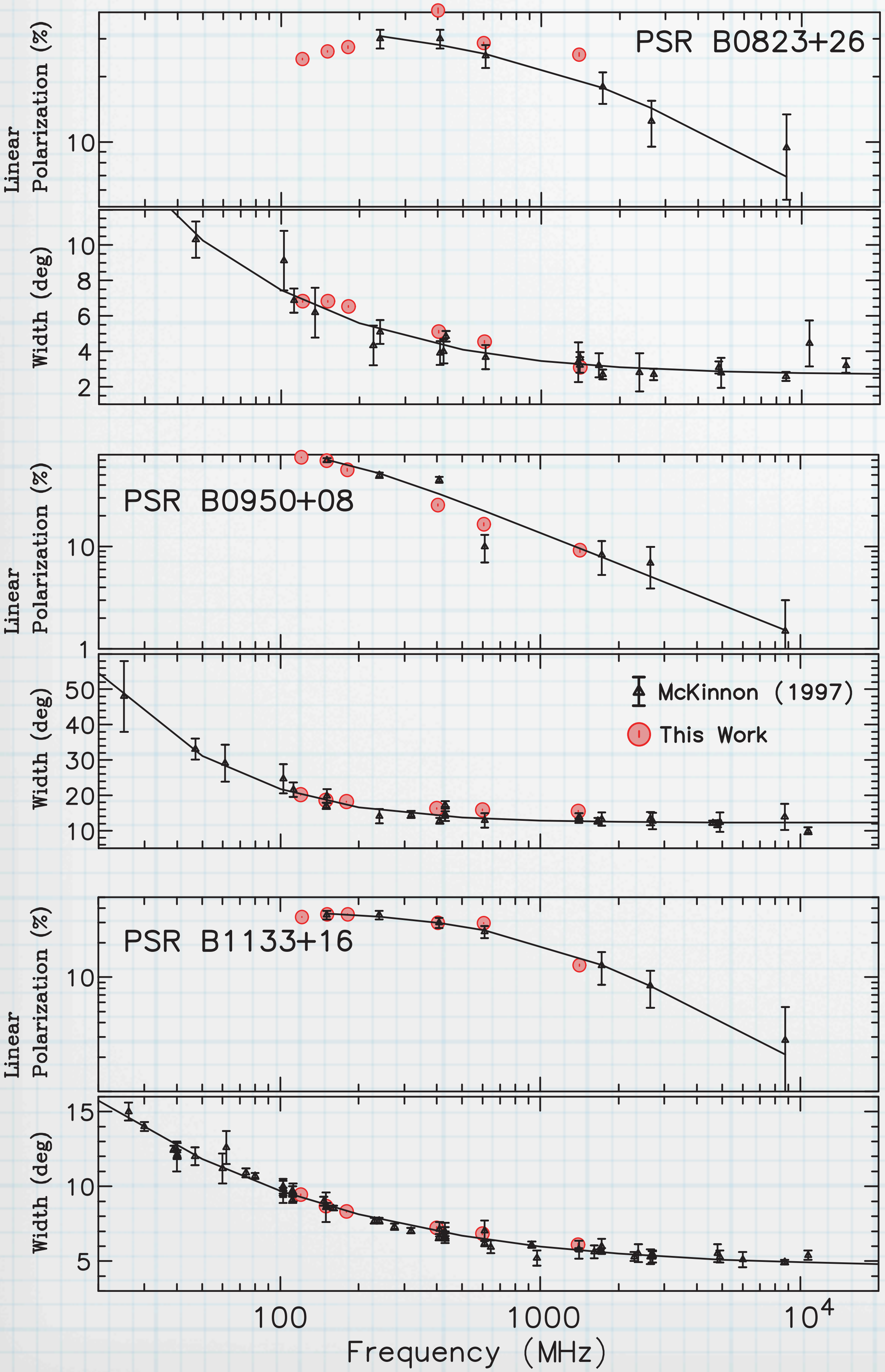
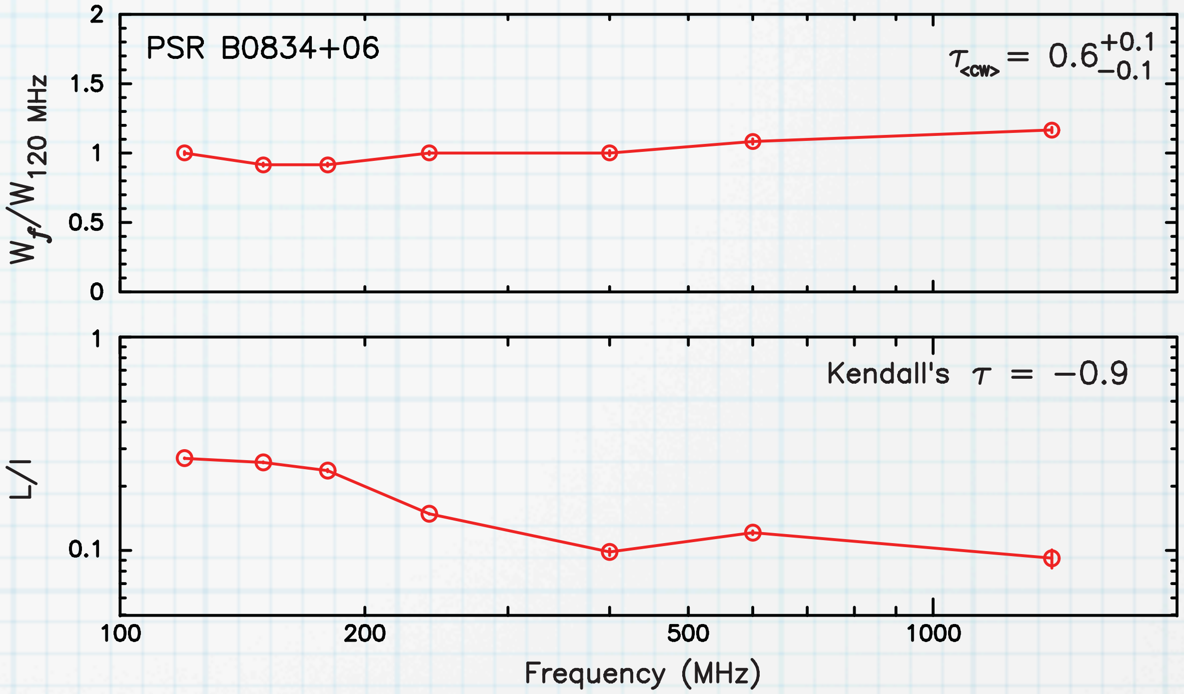
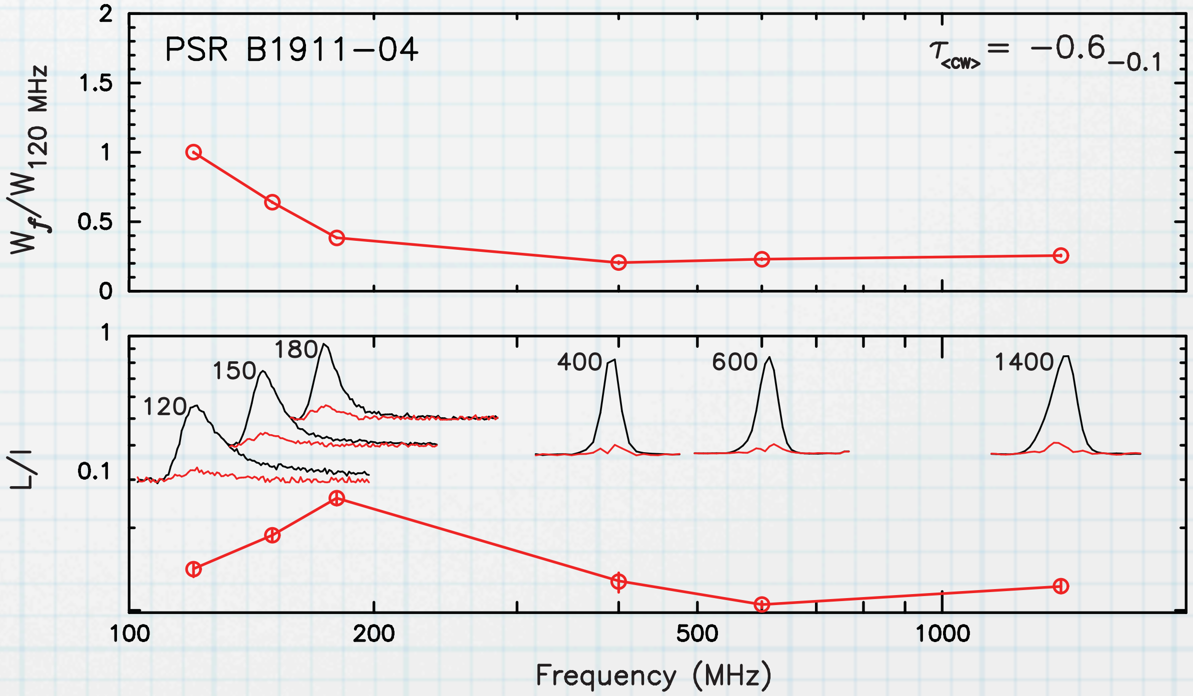


Birefringence







60% show pulse broadening towards low frequencies.

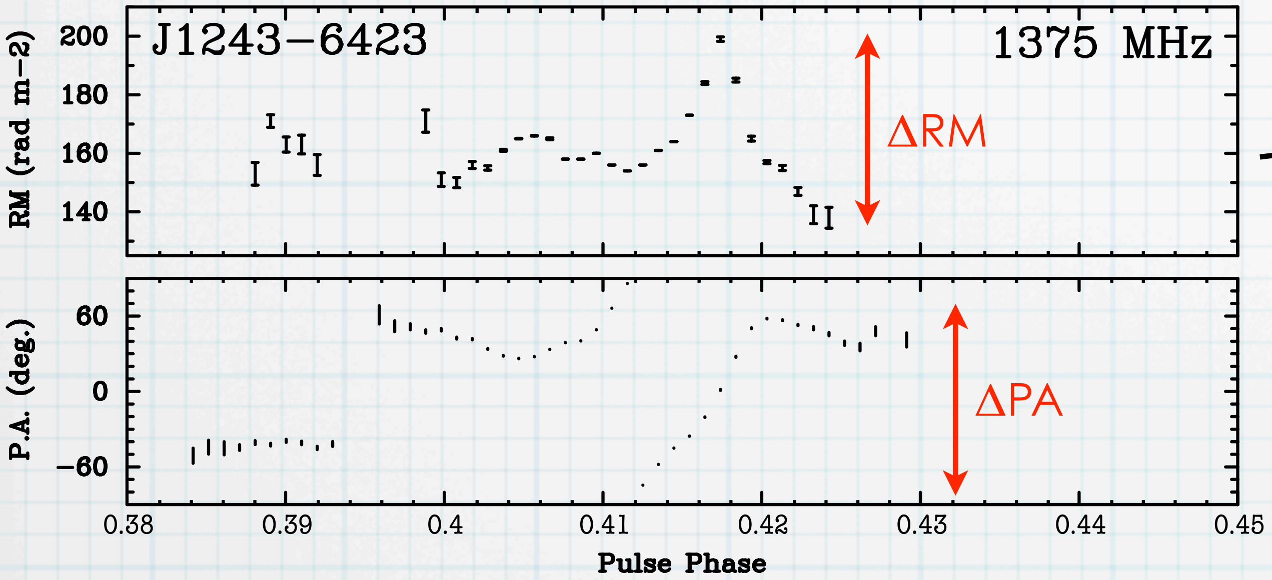
40% show depolarisation towards high frequencies.

50% show more OPM jumps towards low frequencies.

Scattering

ISM scattering **depolarises** the pulsar profiles and **flattens** PA profiles.

e.g. Komesaroff, Hamilton & Ables 1972; Li & Han 2003; Noutsos et al. 2009; Karastergiou 2009



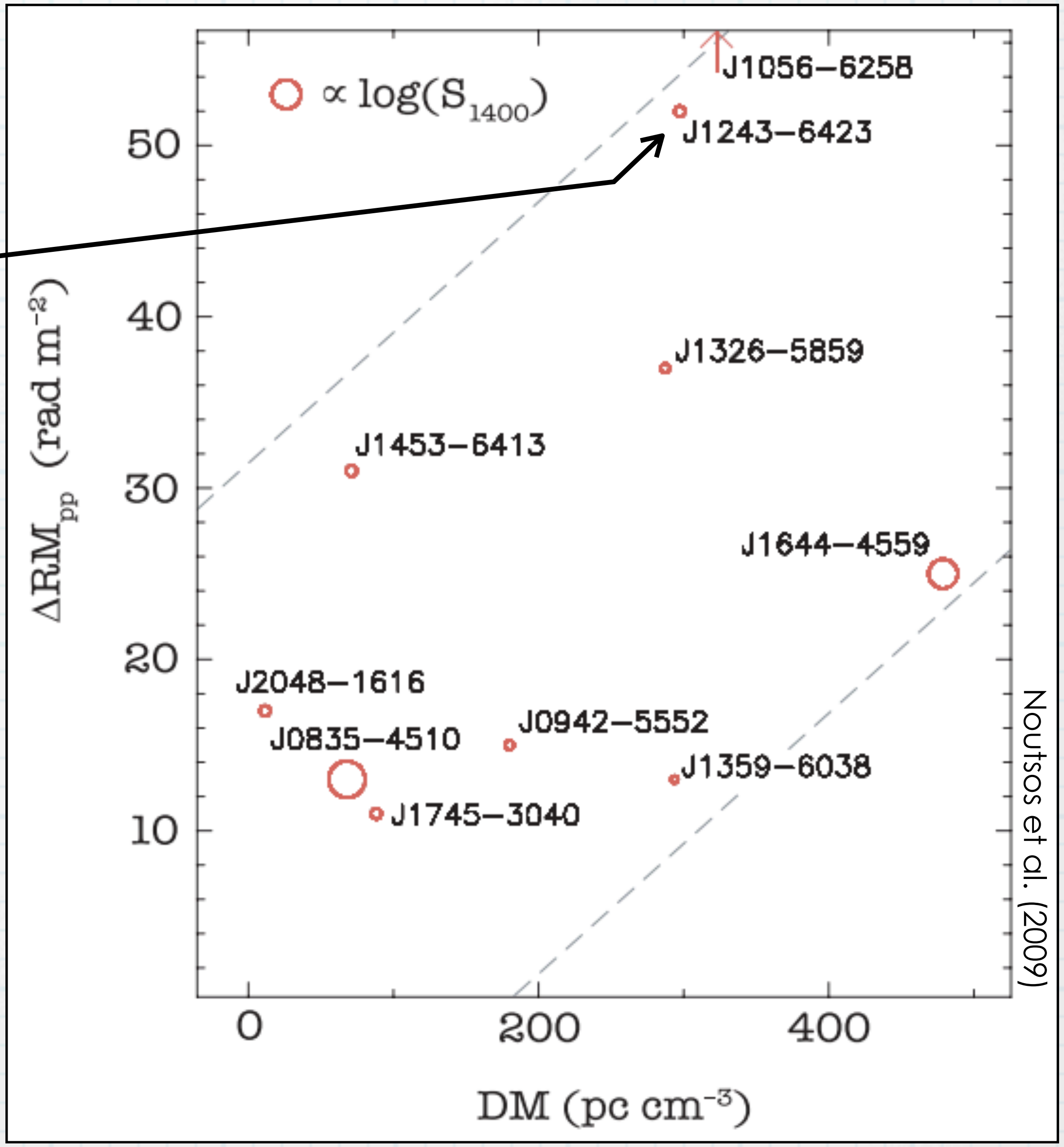
Variations of RM as a function of pulse phase has been associated with scattering.

Noutsos et al. 2009; Karastergiou 2009

ΔRM has been qualitatively associated with the ΔPA across the profile.

simulations by Karastergiou

Scattering causes a differential PA rotation as a function of frequency and phase that is indistinguishable from Faraday rotation.



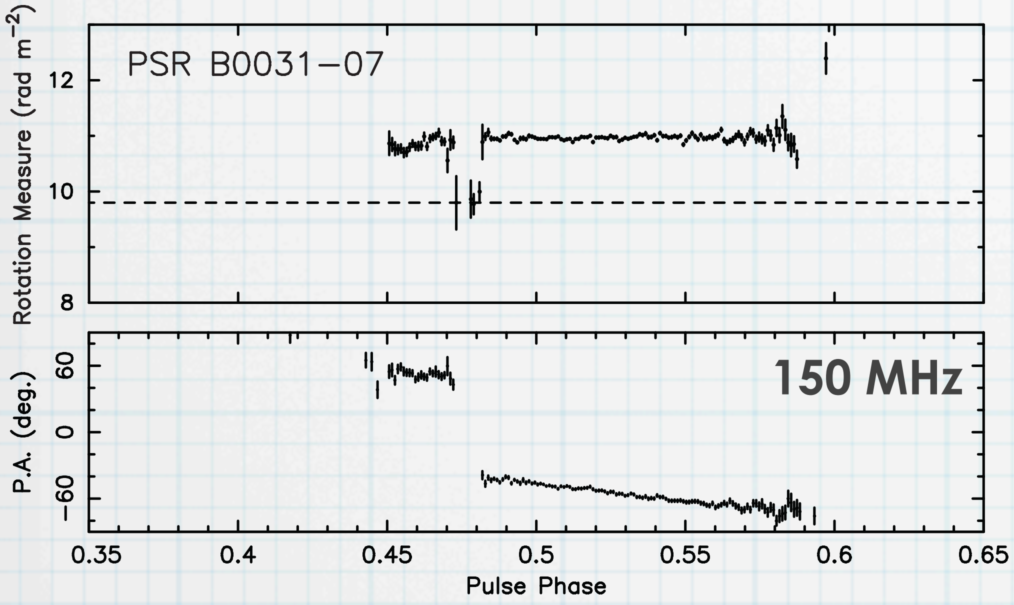
Noutsos et al. (2009)

A qualitative trend between DM and ΔRM is seen in 1.4-GHz Parkes data.

Scattering

LOFAR data gives us the opportunity to investigate the effect of phase-resolved RM variations at low frequencies, where scattering is much stronger (~f^4).

At LOFAR frequencies, the increased RM precision provides higher sensitivity to small RM variations ($\sigma_{\mathrm{RM}} \sim 1/\Delta\lambda^2$).



1.4 GHz

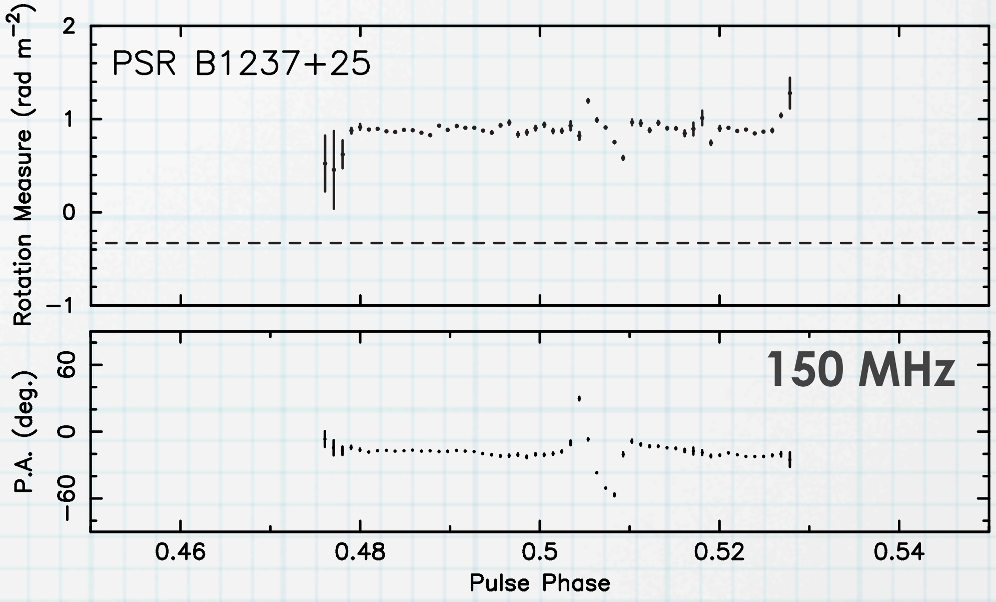
$\Delta\mathrm{RM}_{\mathrm{pp}} \sim 10 - 100$ rad m^{-2}

$\Delta\mathrm{RM}/\mathrm{RM} \sim 1 - 100\%$

150 MHz

$\Delta\mathrm{RM}_{\mathrm{pp}} < 1$ rad m^{-2}

$\Delta\mathrm{RM}/\mathrm{RM} < 40\%$



From first principles:

$$\Psi = \mathrm{RM} \cdot \lambda^2 \quad \text{(Faraday rotation)}$$

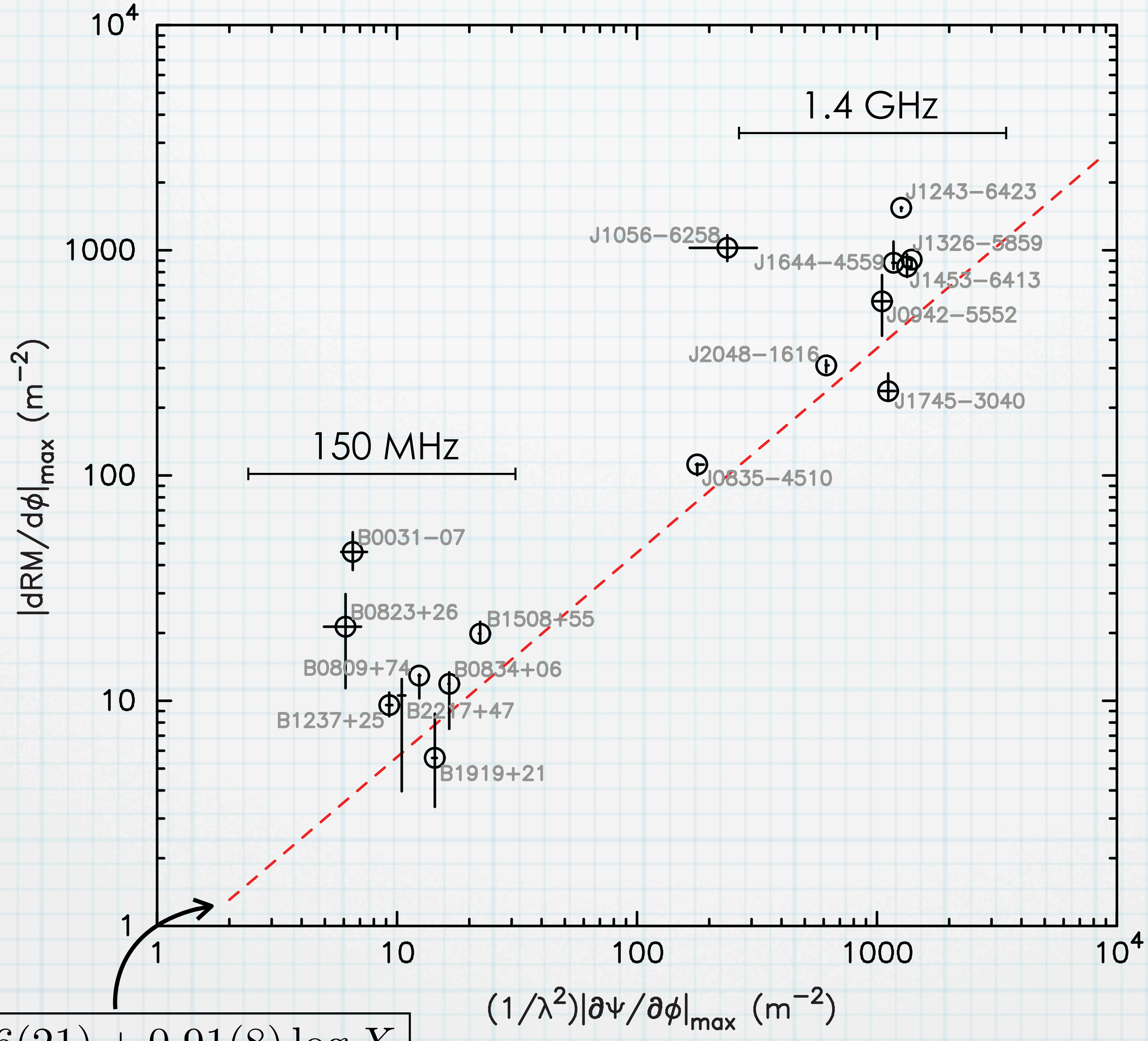
$$\phi(\lambda^2) \sim \tau_{\mathrm{s}} \sim \lambda^4 d^2 \quad \text{(thin-screen scattering)}$$

$$\frac{\partial}{\partial \lambda^2}\left(\frac{\partial \Psi}{\partial \phi}\right) = \frac{\mathrm{dRM}}{\mathrm{d}\phi} \Rightarrow \boxed{\left|\frac{\mathrm{dRM}}{\mathrm{d}\phi}\right| \sim \frac{|\mathrm{RM}|}{2\tau_{\mathrm{s}}} \sim \left|\frac{\partial \Psi}{\partial \phi}\right| \frac{1}{\lambda^2}}$$

So, contrary to expectation the magnitude of the RM variations does not scale with the amount of scattering.

Scattering

We tested these calculations with 1.4 GHz and 150 MHz data.



$$\boxed{\log Y = -0.16(21) + 0.91(8) \log X}$$

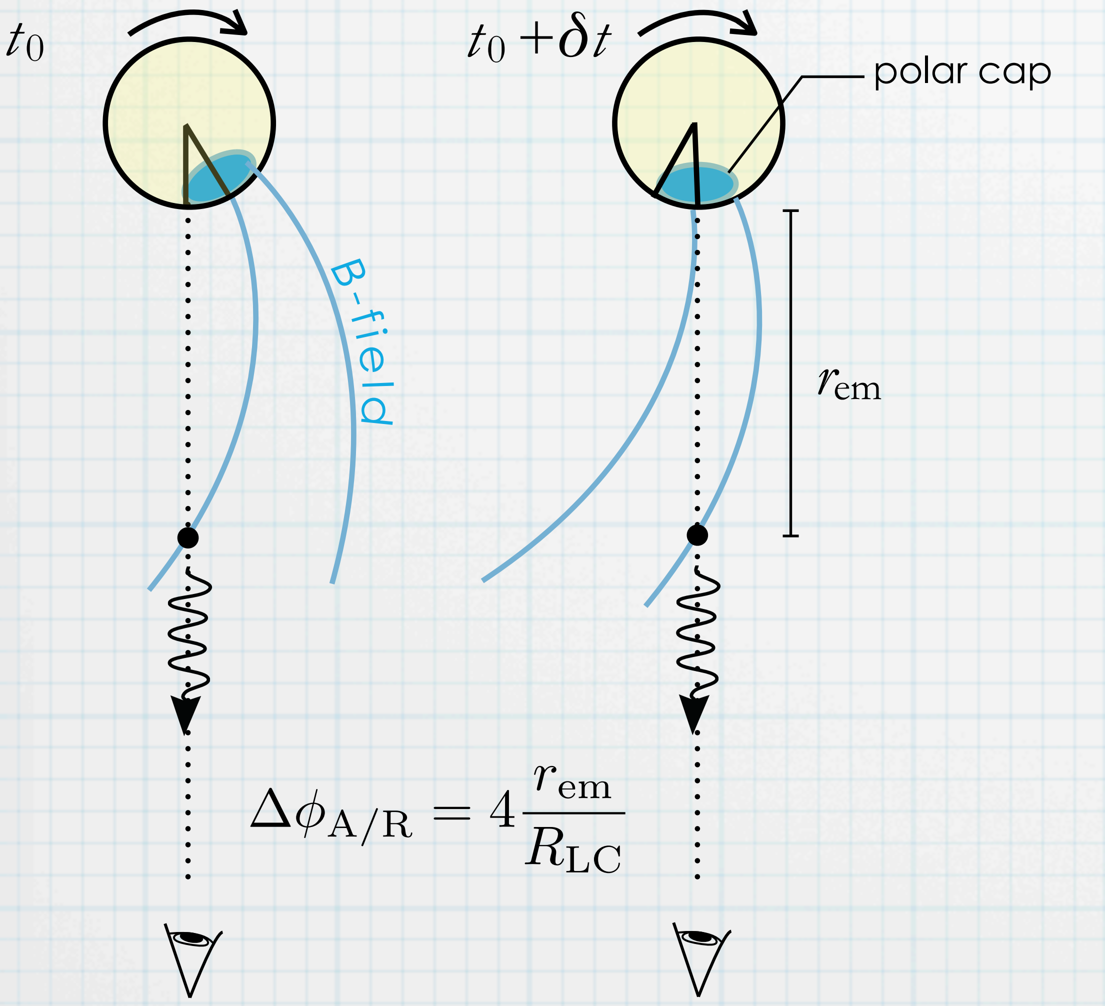
The data appear to confirm the relation between RM and PA gradients between 150 MHz and 1.4 GHz.

An appreciable scatter can be seen.

Emission Altitudes

In the framework of aberration/retardation (A/R), the field lines are bent forward due to relativistic effects (Blaskiewicz, Cordes & Wasserman 1991).

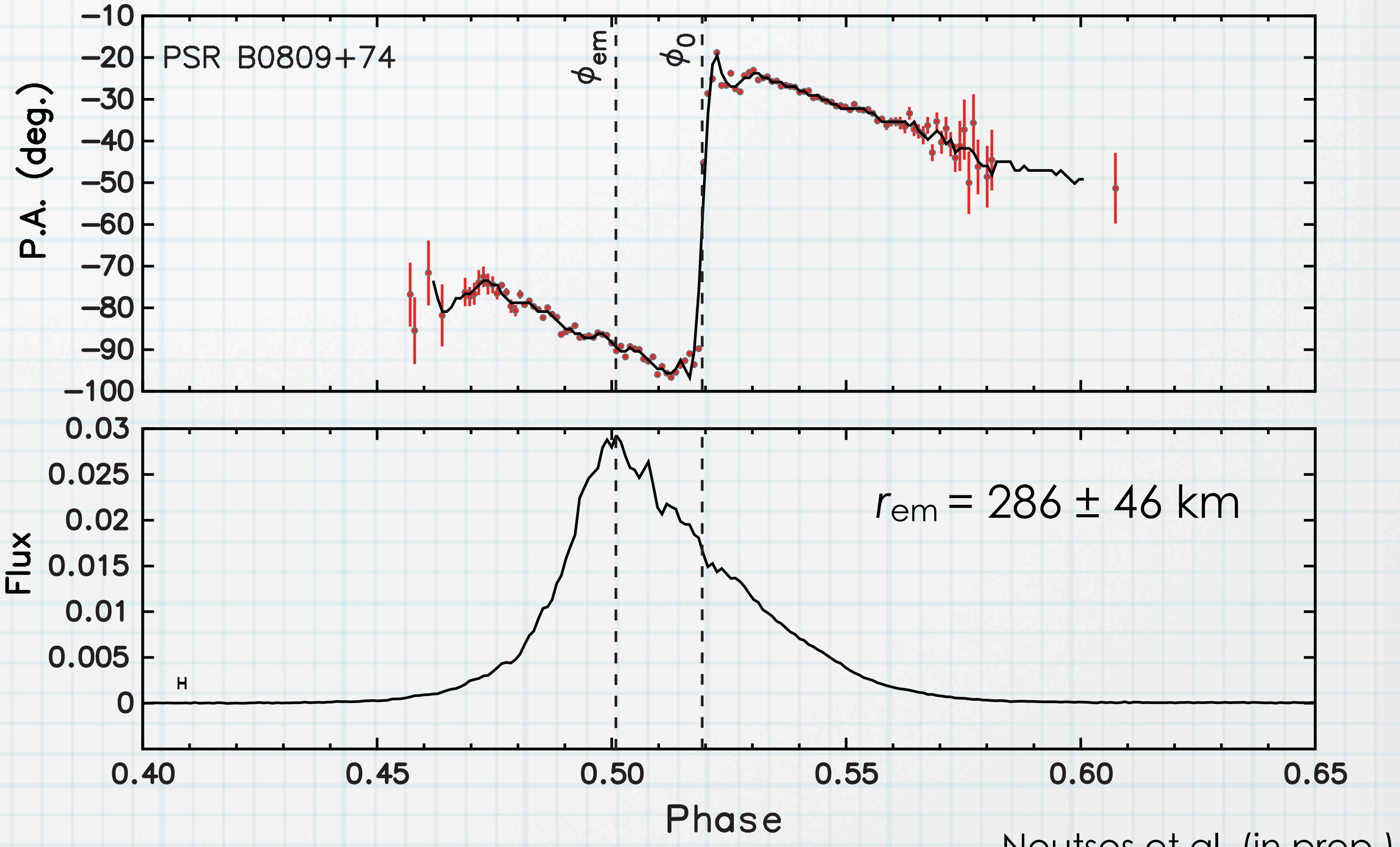
The **maximum of the emission** — generated at a finite altitude — precedes the closest approach to the magnetic pole, i.e. **the steepest PA gradient**.



$$\Delta\phi_{\rm A/R} = 4\frac{r_{\rm em}}{R_{\rm LC}}$$

Max. emission: corresponds to magnetic field originating nearest to the magnetic pole ($\phi_{\rm em}$)

Steepest PA gradient: corresponds to the observer's closest approach to the magnetic pole (ϕ_0)



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PSR	$r^{\rm a}_{\rm em}$ [km]	$r^{\rm b}_{\rm em}$ [km]	$r^{\rm c}_{\rm em}$ [km]	$r^{\rm d}_{\rm em}$ [km]
B0136+57	3(10)	–	–	–
B0809+74	286(46)	–	–	–
B0823+26	4(19)	43(19)	282(19)*	235(20)*
B0834+06	8(46)	282(46)	120(46)*	170(46)
B1133+16	236(43)	–	63(43)	–
B1237+25	–	–	16(50)*	49(50)
B1919+21	15(48)	179(48)	106(48)	89(48)
B1929+10	83(22)*	–	108(22)*	–
B1953+50	0(19)	–	–	–
B2217+47	97(19)*	–	–	–

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- **Emission altitudes based on A/R effects on polarisation** are consistent with previous claims that pulsar emission is generally produced over a ~100 km altitude range above the polar caps.