# First results from pulsar observations with the full LOFAR core and the pulsar polarisation calibration pipeline

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## LOFAR Pulsars

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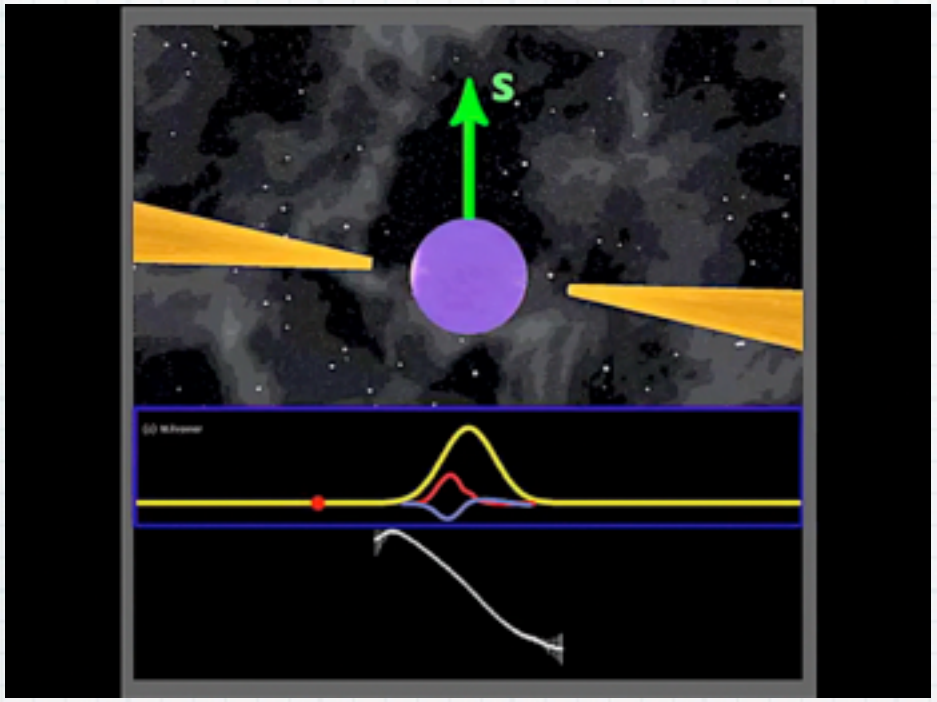
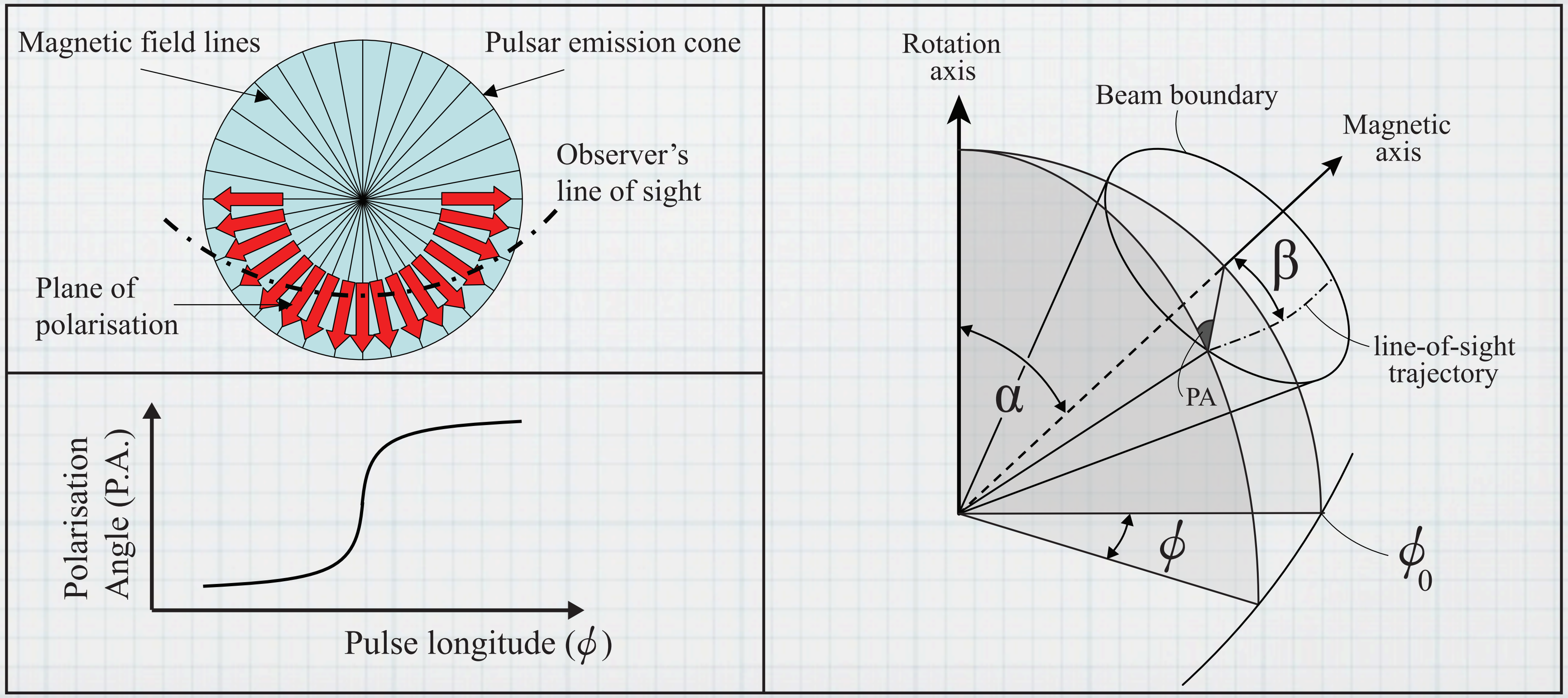
… and many, many more!

# Why study pulsar polarisation?

Pulsar polarisation reflects the geometry of pulsar beamed emission



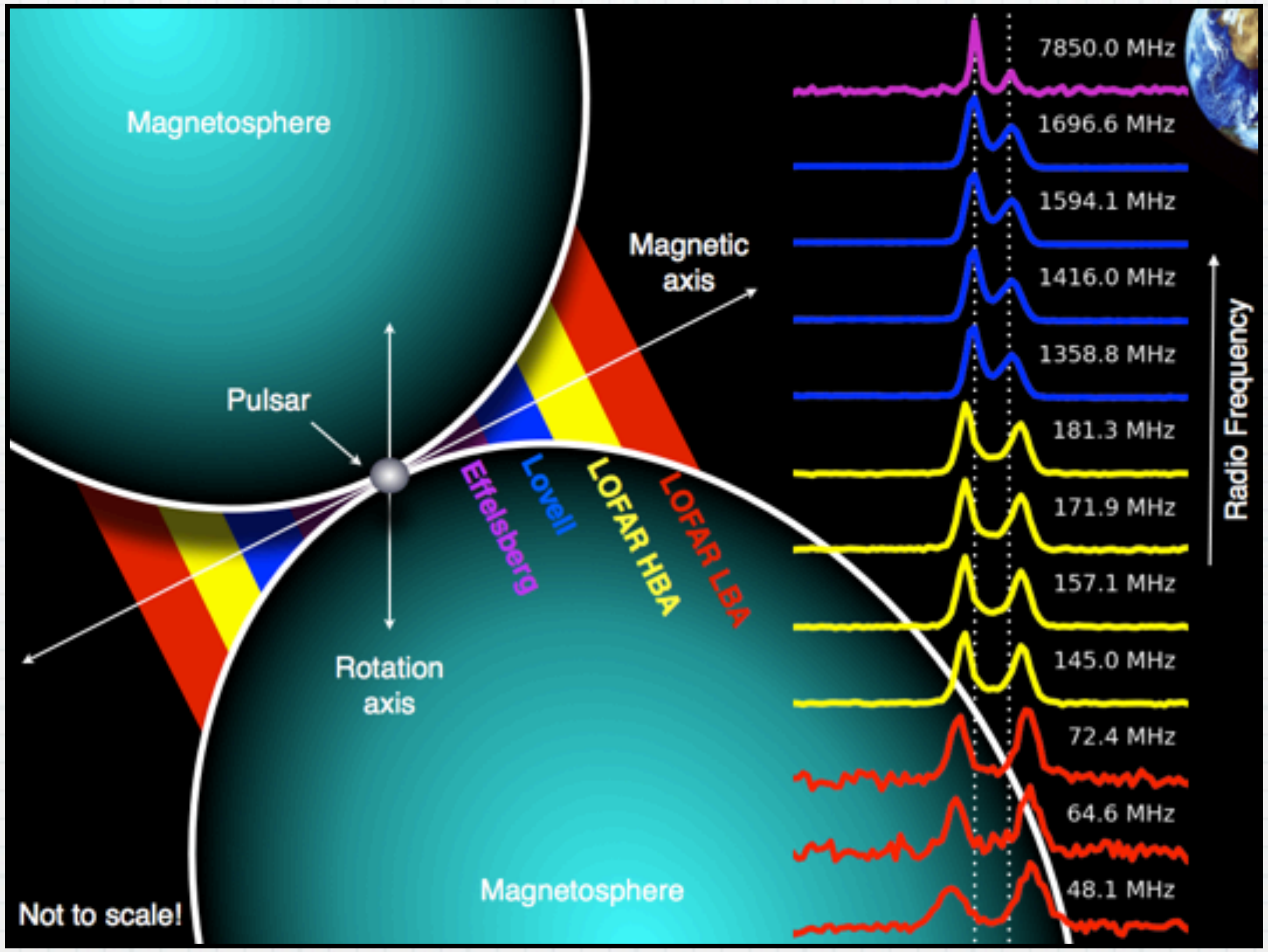

**The Rotating Vector Model (RVM)** parametrises the Polarisation Angle (PA) profile as a function of $\alpha$ and $\beta$



# Why study pulsar polarisation?

According to one of the theoretical models of pulsar radio emission, **different observing frequencies probe different altitudes of emission**:

*The highest frequencies originate from near the pulsar surface and the lowest frequencies, from higher altitudes*




Credit: Tom Hassall, *Univ. of Southampton*

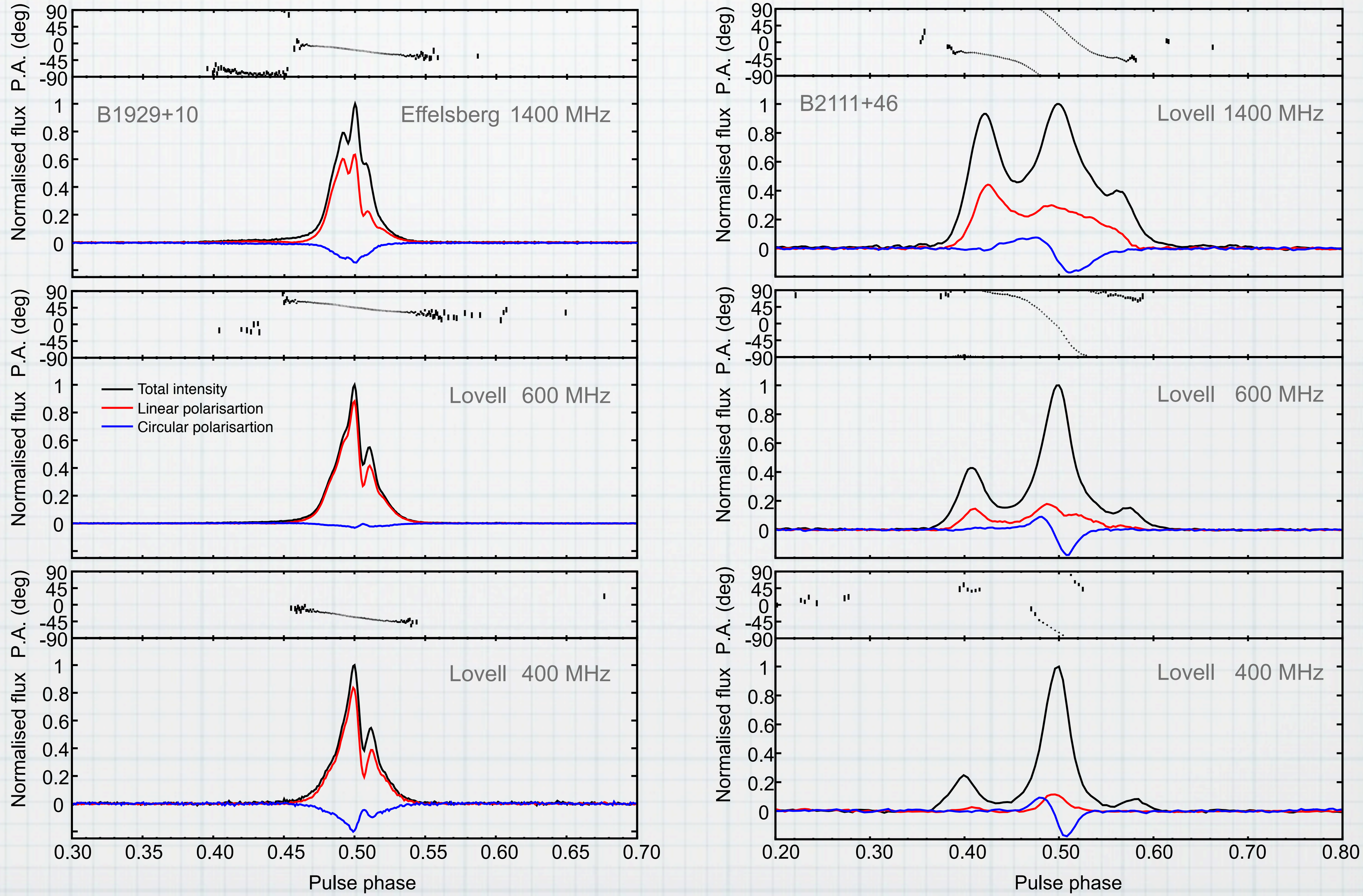
# Why study pulsar polarisation?

**The polarisation properties of pulsars are poorly known below ~300 MHz**

Above 300 MHz, there are high-quality observations of polarised pulsars with single dishes (Effelsberg, Lovell, Arecibo, GBT, *etc.*)

Sobey et al., *in preparation*

Gould & Lyne (1998)

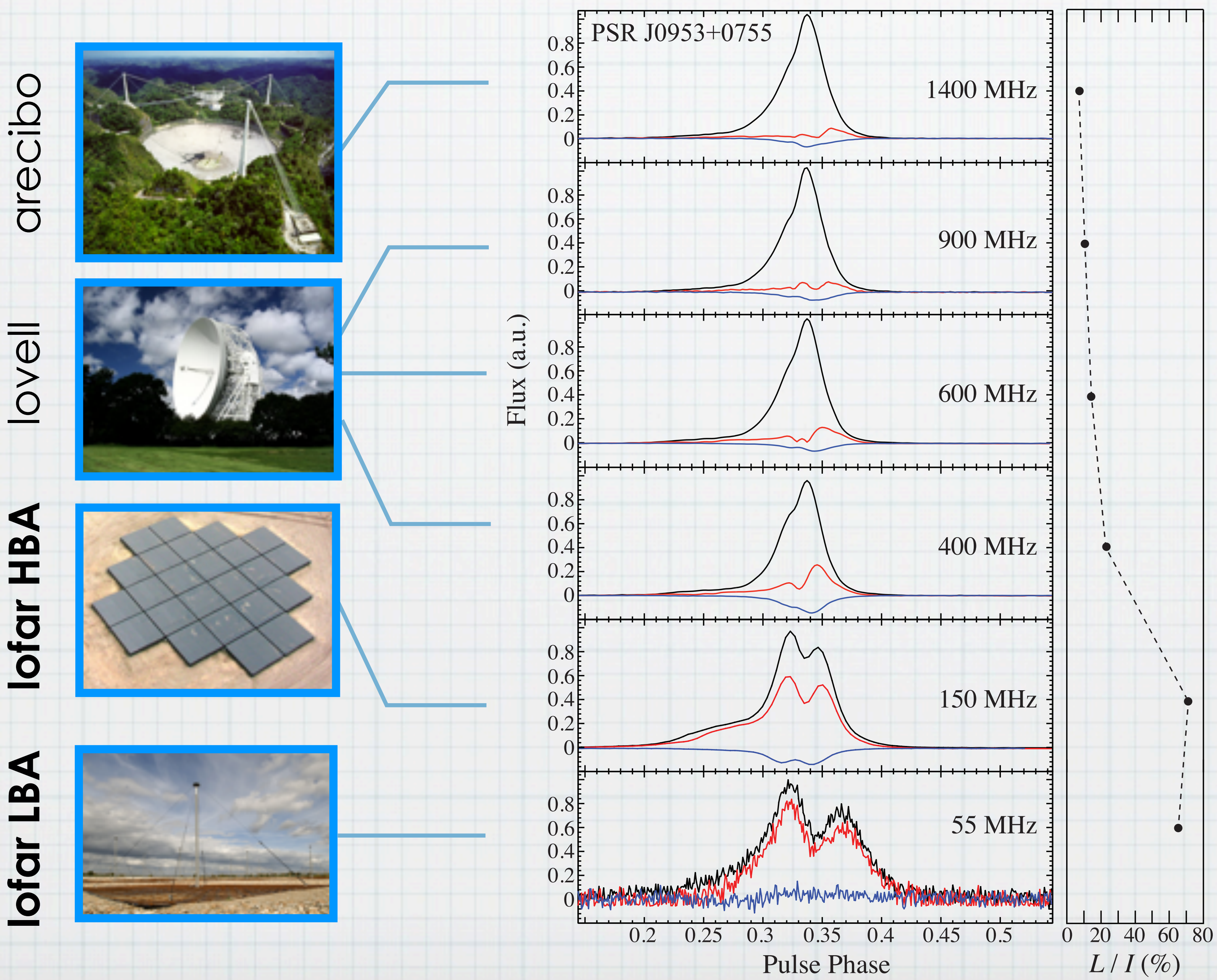


# Why study pulsar polarisation?

**Conclusion:**

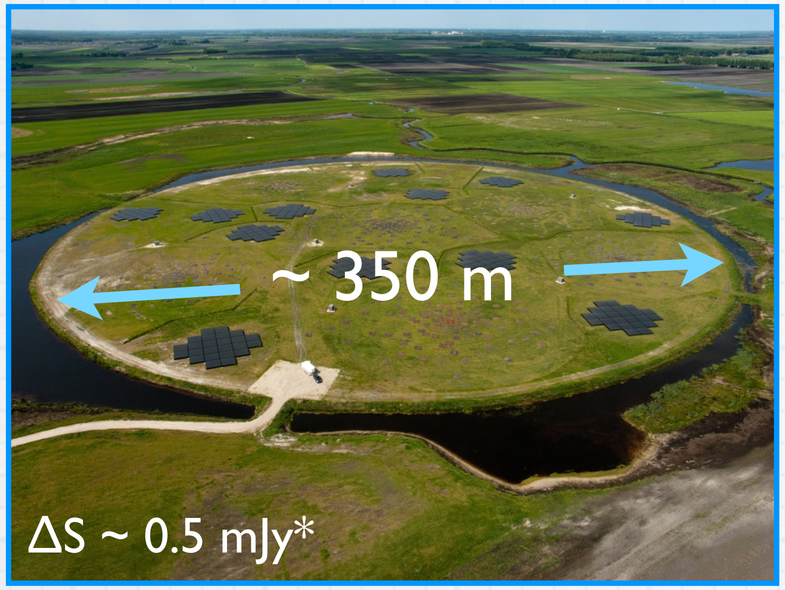
We need to cover the low-frequency part of the radio spectrum, in order to form a complete picture of the 3D geometry of the pulsar emission

LOFAR can provide high-quality polarisation below 200 MHz




Commissioning data (early 2012)

# LOFAR observations




*150 MHz
48 MHz
1 hr

+ LOFAR Dutch <u>core stations</u> = 40 HBA stations coherently summed

under a
single clock

**Scheduling:**

40 HBA CS

21 bright, polarised pulsars

10 min / pulsar

**Set-up:**

Signal Nyquist-sampled at δt ~ 5 $\mu$s – ($\tilde{V}_x$ , $\tilde{V}_y$)

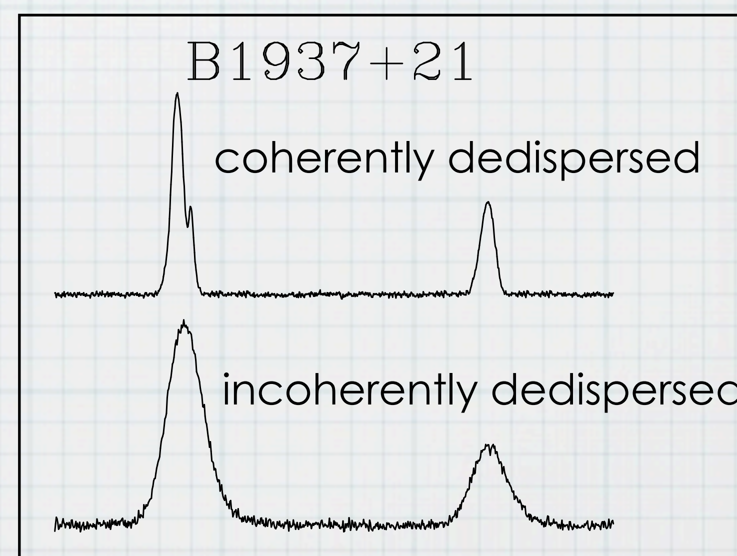
8-bit mode → bandwidth doubled to 96 MHz (470 sub-bands)

**Post-processing:**

Signal de-dispersed coherently [ $\tilde{V}(f_0 + f) = \tilde{V}_{\rm int}(f_0 + f)\tilde{H}(f_0 + f)$ ]

Coherence parameters (xx*,xy*,yx*,yy*) converted to Stokes

Polarisation calibration

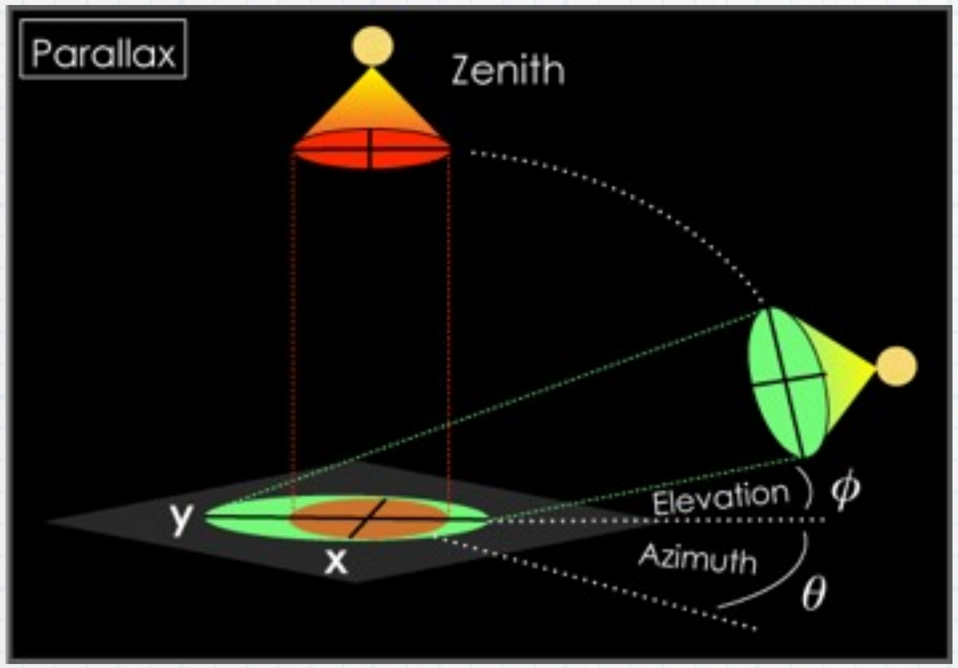


# Polarisation calibration

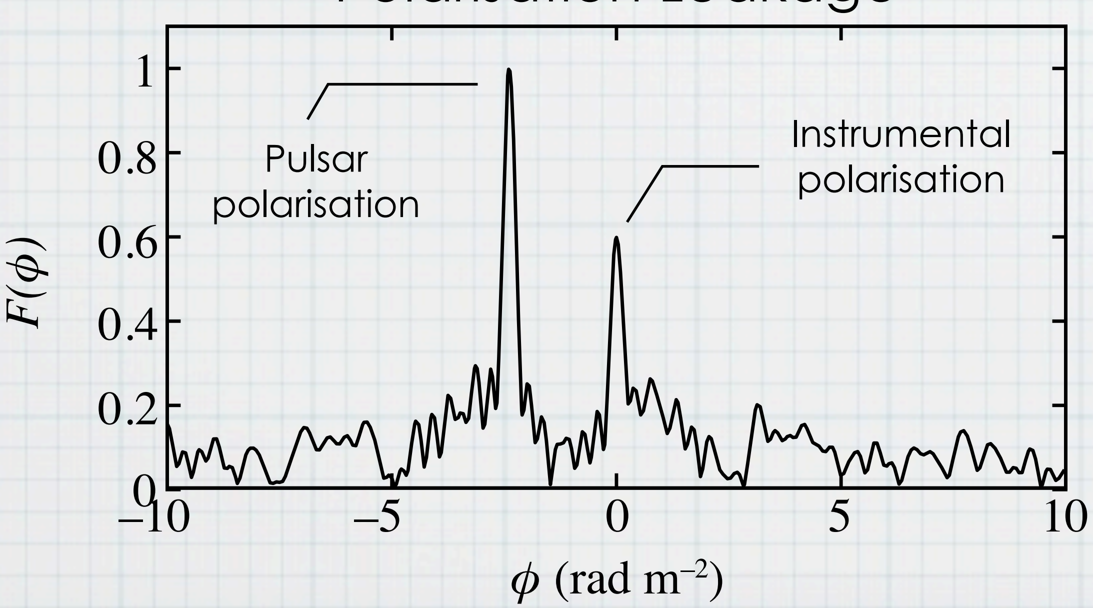
## Generalised *E*-Jones matrix

$$\begin{bmatrix} \tilde{V}_x \\ \tilde{V}_y \end{bmatrix} = \begin{bmatrix} E_\theta(\gamma,\beta) & E_\phi(\gamma,\beta) \\ E_\theta(\gamma,\beta-\pi/2) & E_\phi(\gamma,\beta-\pi/2) \end{bmatrix} \times \begin{bmatrix} \tilde{\Lambda}_1 \\ \tilde{\Lambda}_2 \end{bmatrix}$$

### Geometric corrections



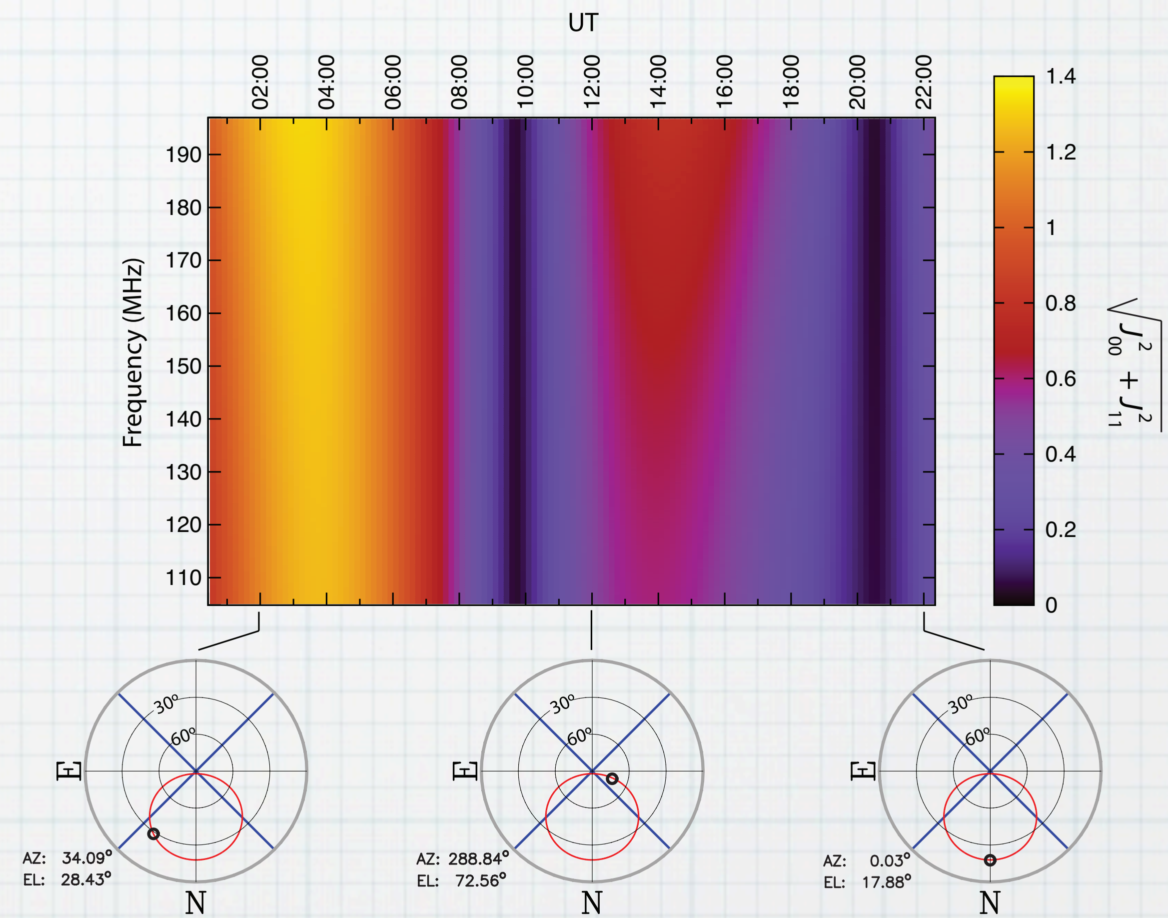

### Polarisation Leakage




## J. Hamaker's antenna response model

(part of LOFAR's standard BBS calibration pipeline)

### Python implementation by Tobia




### Complete description

$$\boxed{\boldsymbol{J}_i(\mathbf{r}, f, t) = \boldsymbol{B}_i\boldsymbol{G}_i\boldsymbol{D}_i\boldsymbol{E}_i\boldsymbol{P}_i\boldsymbol{T}_i\boldsymbol{F}_i}$$

bandpass
gain
beam
Faraday

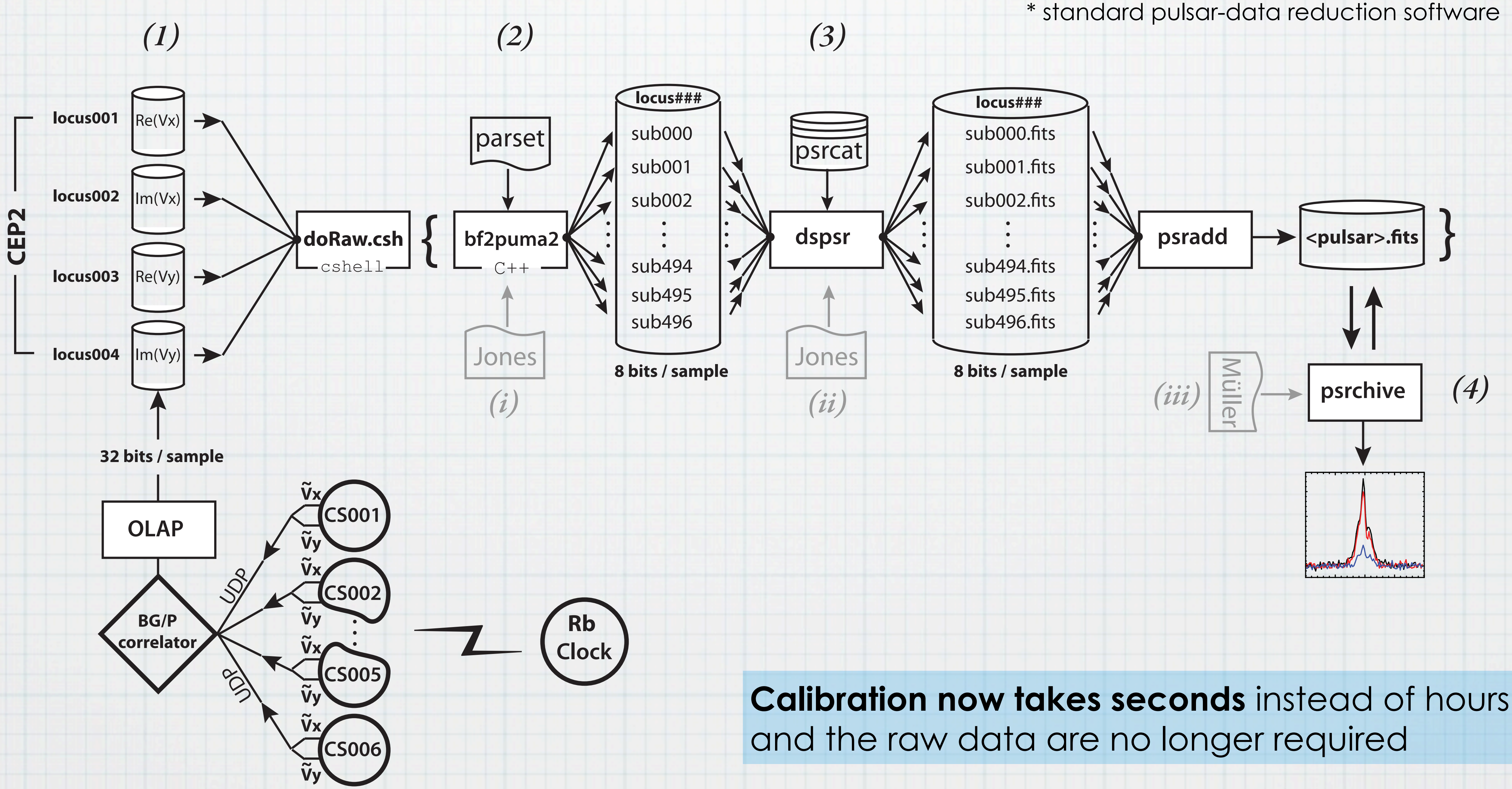
# Calibration pipeline

*(i),(ii)* Until recently, **polarisation calibration has required reading the raw data each time**

*This has been **slow** and requires **large amounts of storage***

*(iii)* **We have modified PSRCHIVE* to** accept any instrument response (Jones) and **directly operate on the Stokes PSRFITS data**

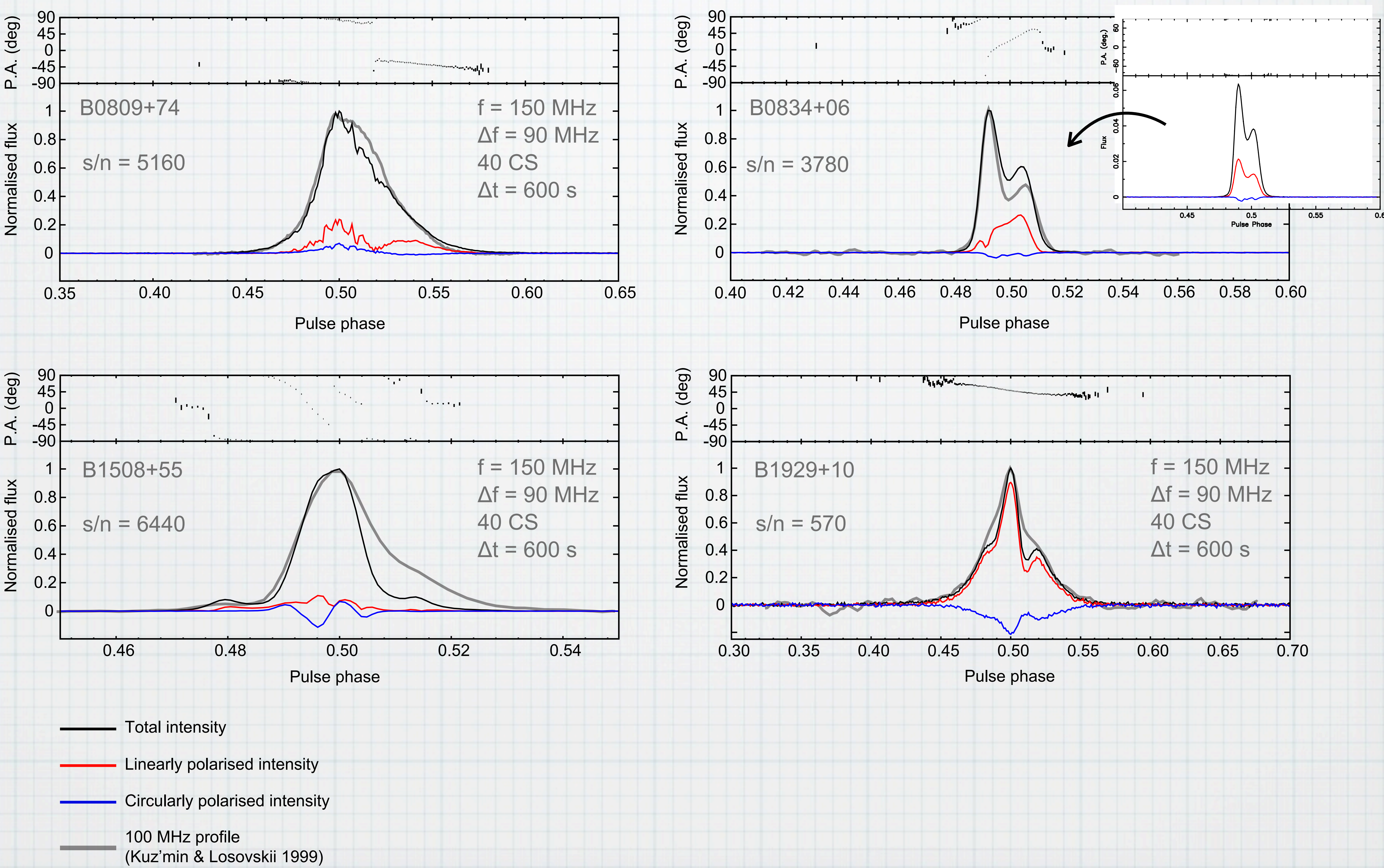
* standard pulsar-data reduction software




**Calibration now takes seconds** instead of hours and the raw data are no longer required

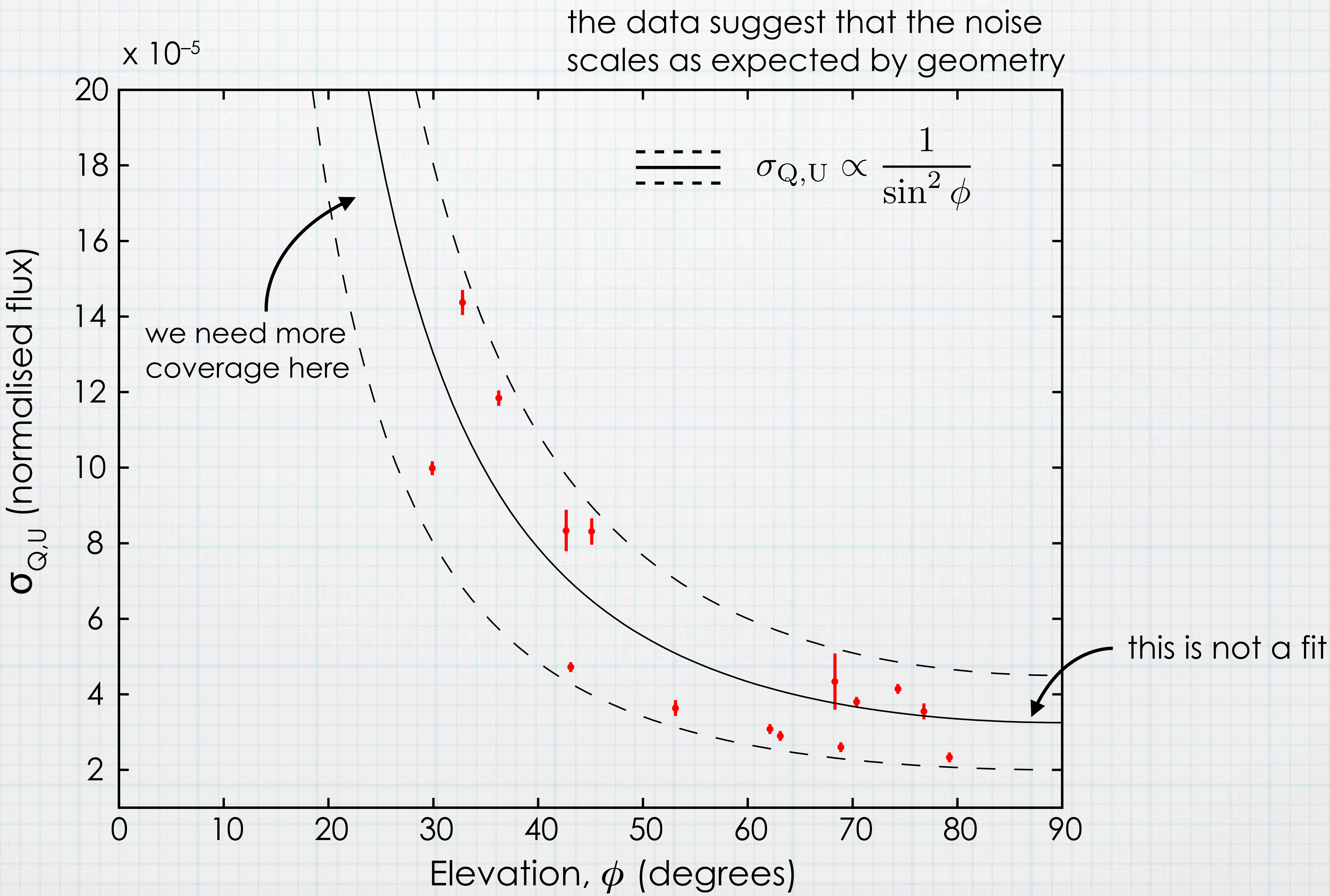
# Pulsar profiles

**These polarisation profiles from LOFAR are the best ever produced at these frequencies** and, in several cases, the only polarisation profiles available below 200 MHz



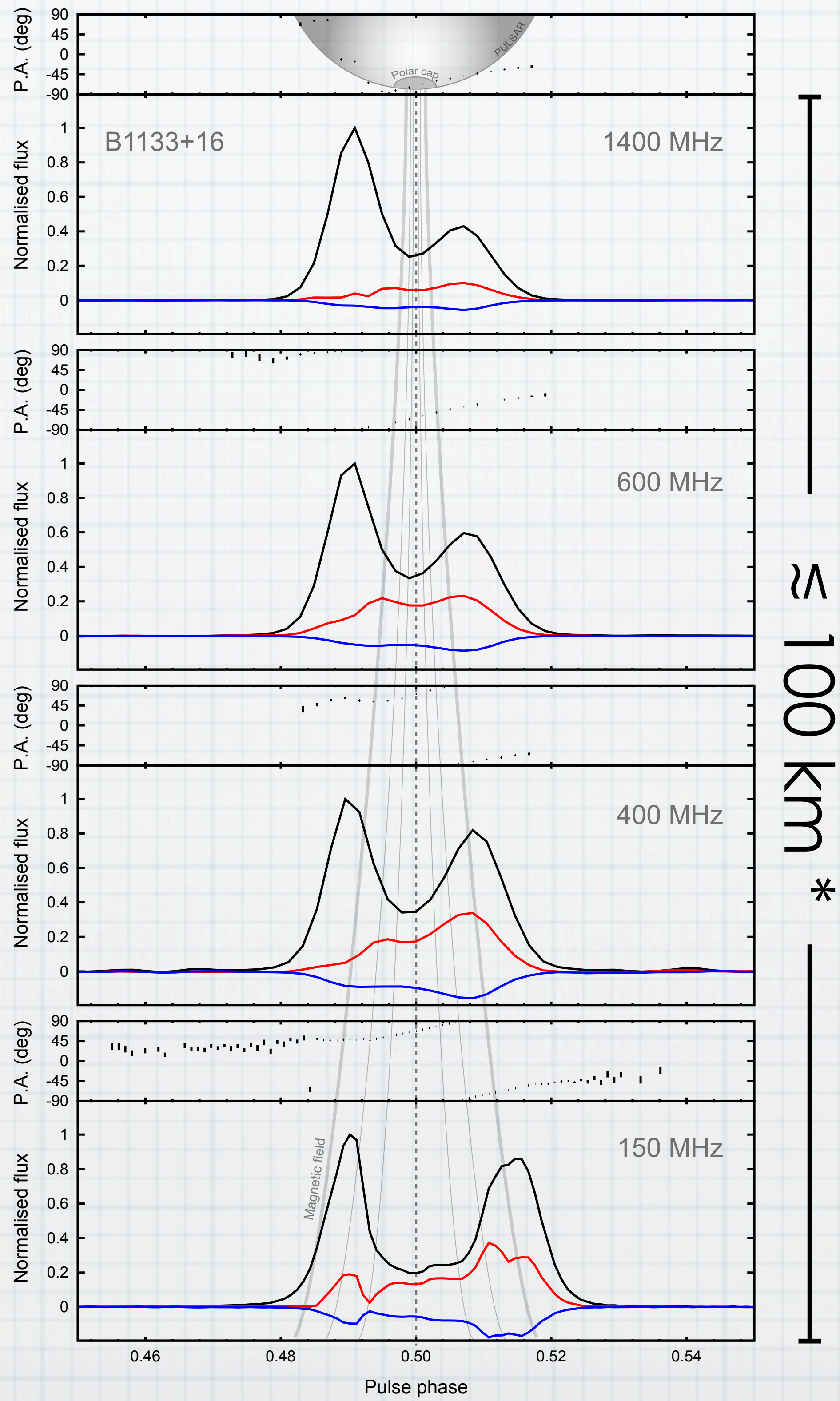
# Polarisation noise

**We used the calibrated profiles to measure the off-pulse polarisation noise as a function of elevation**



# Multi-frequency polarisation studies

LOFAR observations complement those at higher frequencies. All together, **multi-frequency polarisation data give us a complete view of the geometry of the active regions of pulsar magnetospheres**

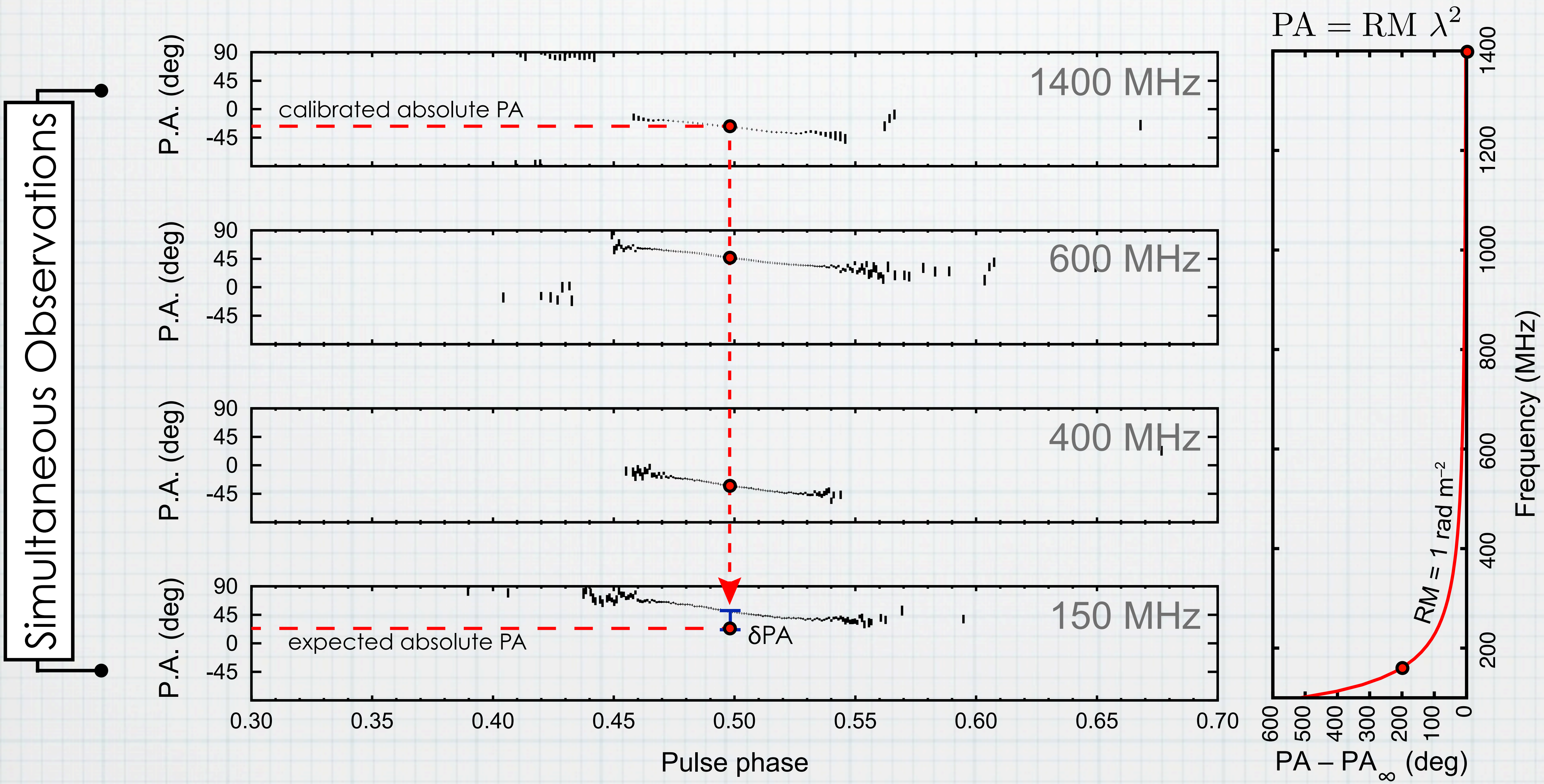



* from retardation between frequencies
(Hassall et al. 2012)

# Multi-frequency cross-calibration?

**Hassall et al. (2012) showed that the dispersion law ($\propto \lambda^2$) holds across 7 octaves in frequency** (accuracy: 1 part in $10^5$)

**If we assume that this is true for Faraday rotation**, it may be possible to **determine absolute PAs** by extrapolating from higher frequencies down to LOFAR data




**This could provide the much needed absolute polarisation calibrators for LOFAR**

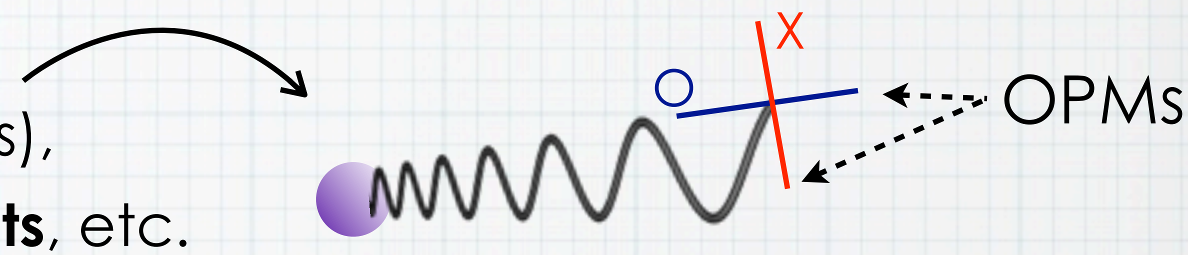
# Multi-frequency polarisation studies

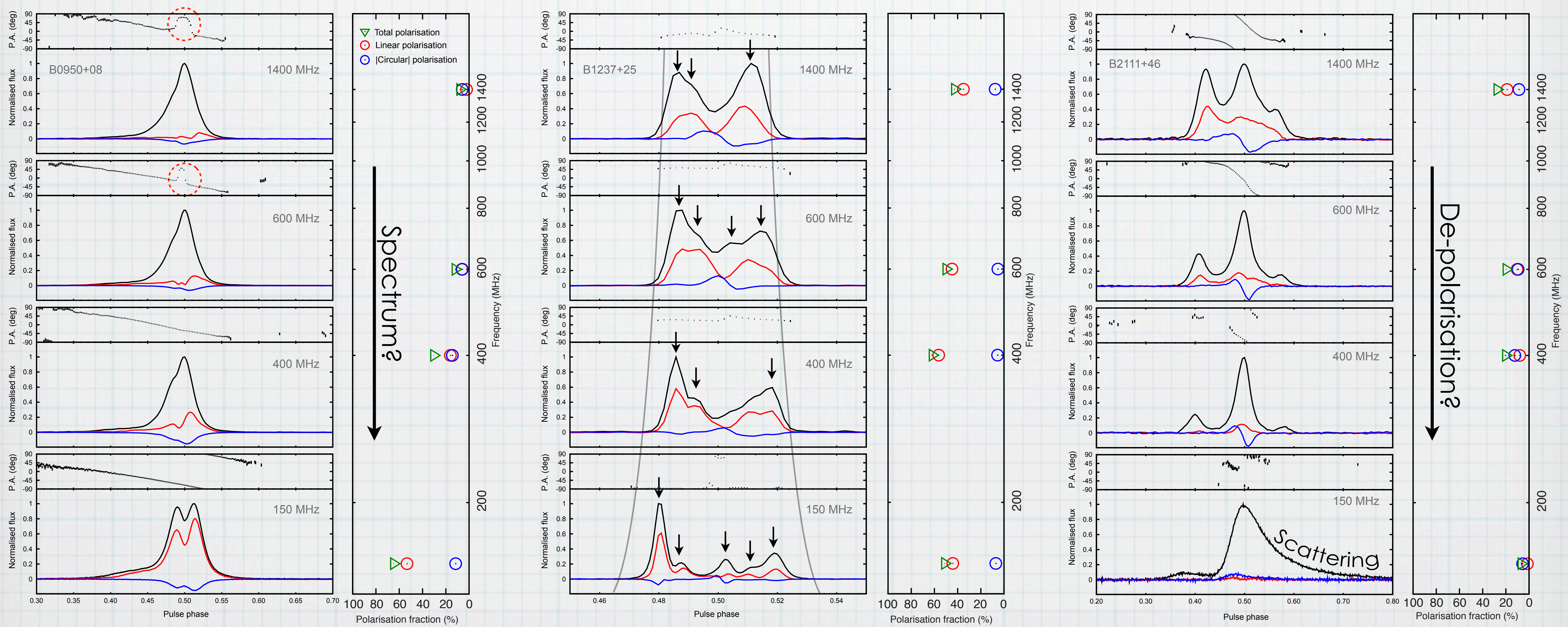
Changes in

- the **polarisation fraction**,
- the **polarisation state** (e.g. orthogonal modes),
- the **relative intensity of the profile components**, etc.

are key to understanding, e.g.

- **the process of coherent radio emission in pulsars**
- **why some pulsars appear strongly polarised while others do not**

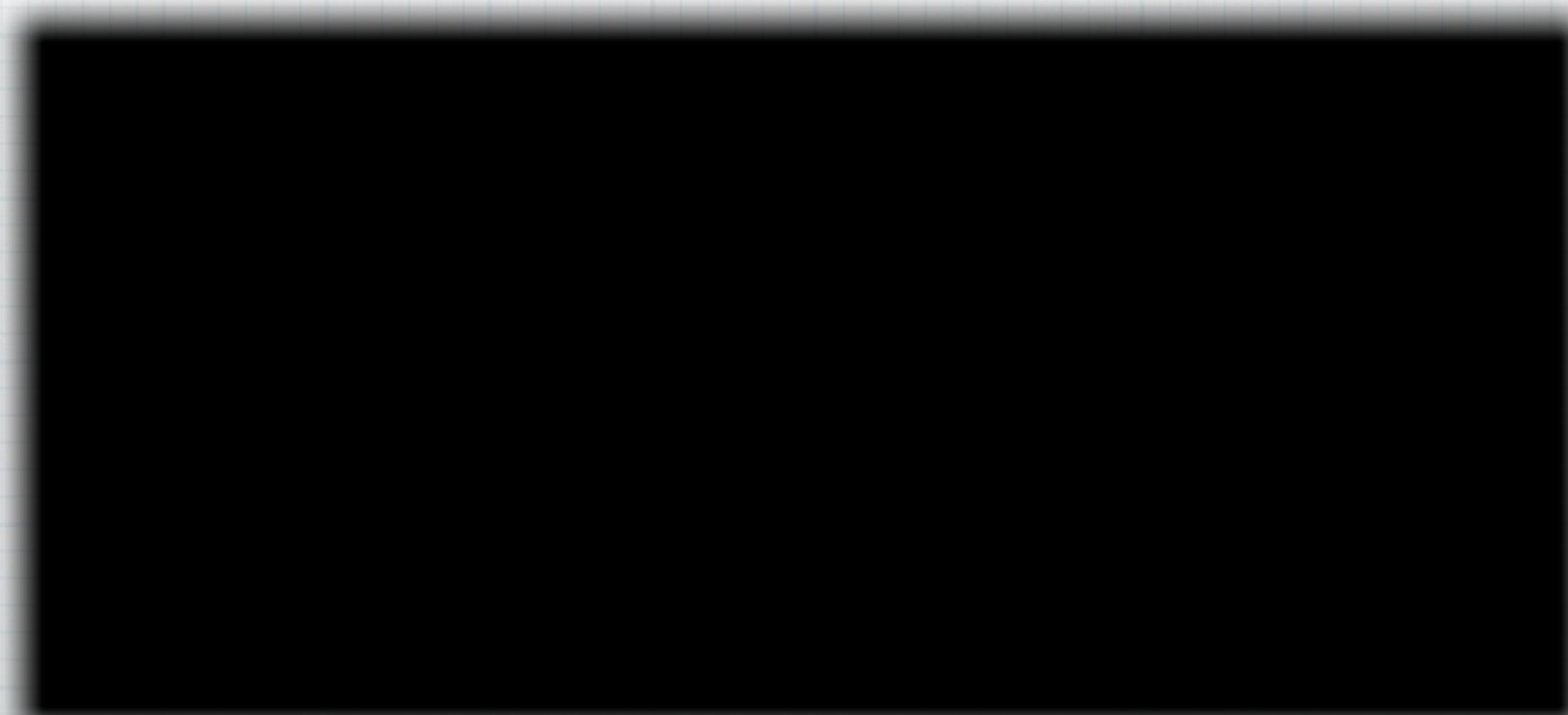


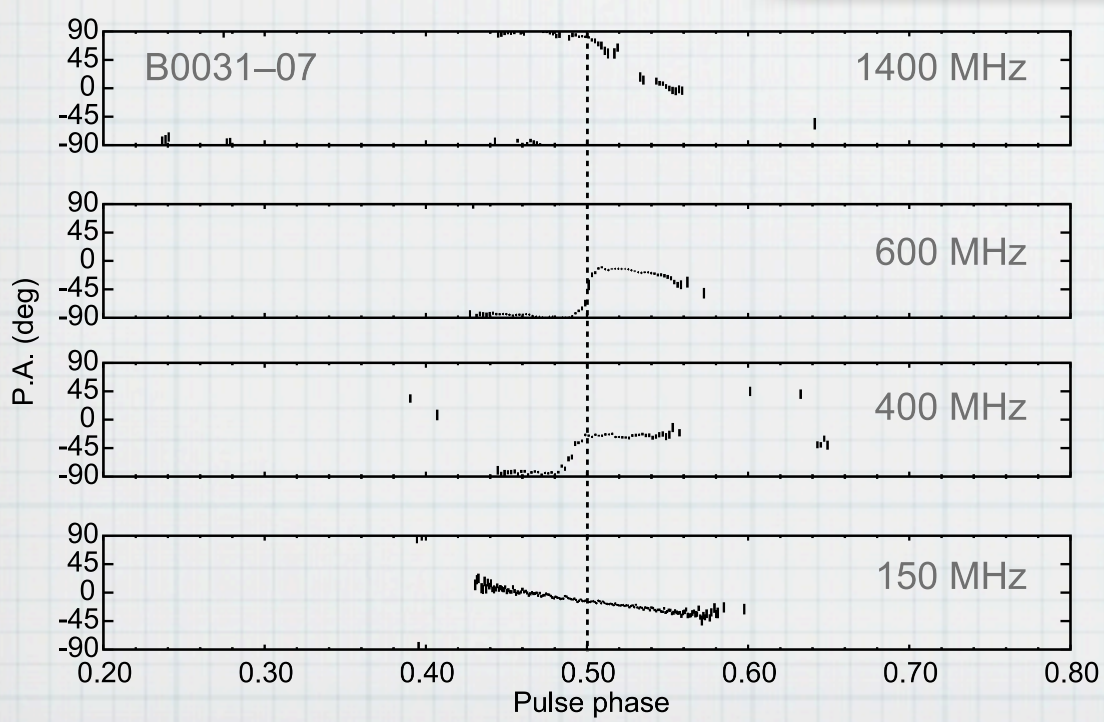



# Polarisation & Scattering

**Scattering becomes very important at low frequencies**, as it scales with $\lambda^4$

**Scattering flattens steep PA profiles**, as polarised intensity from earlier pulse phases is mixed with that from later phases






This is evident in multi-frequency data

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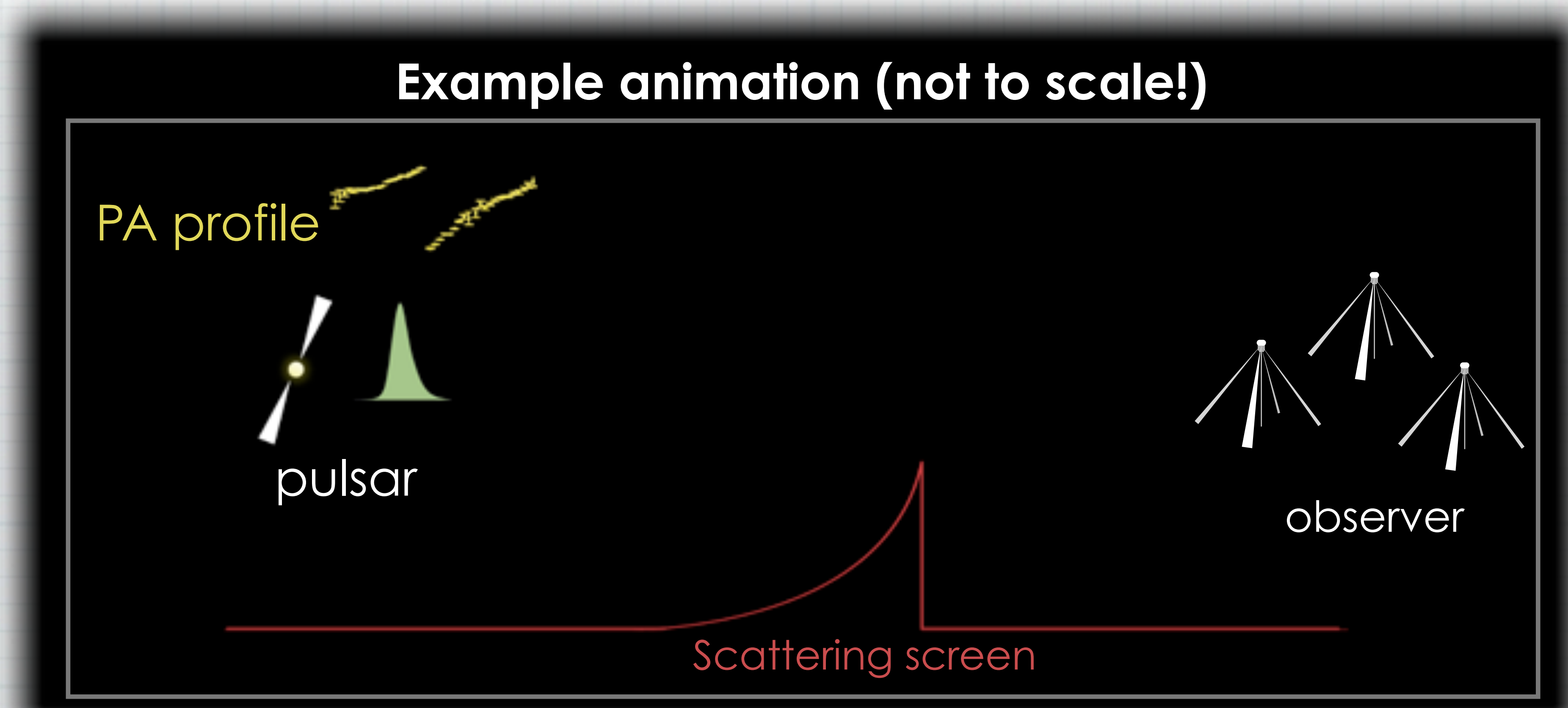


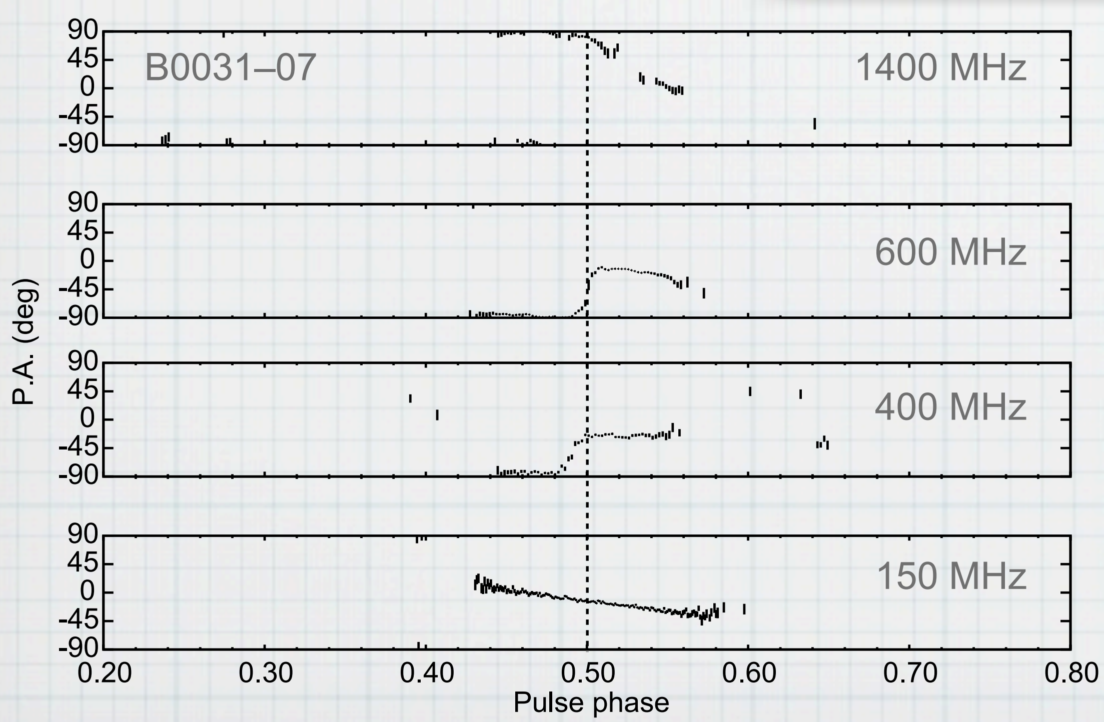


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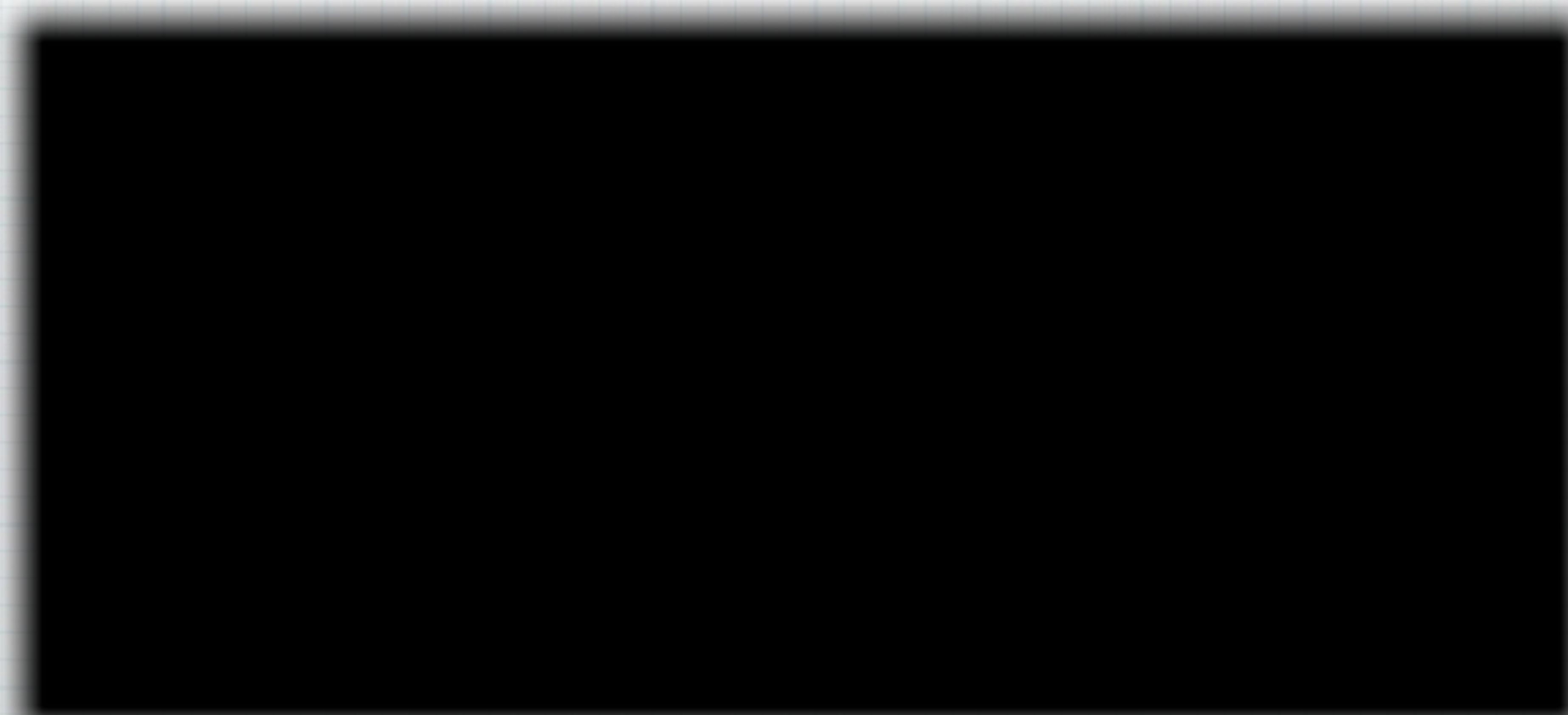
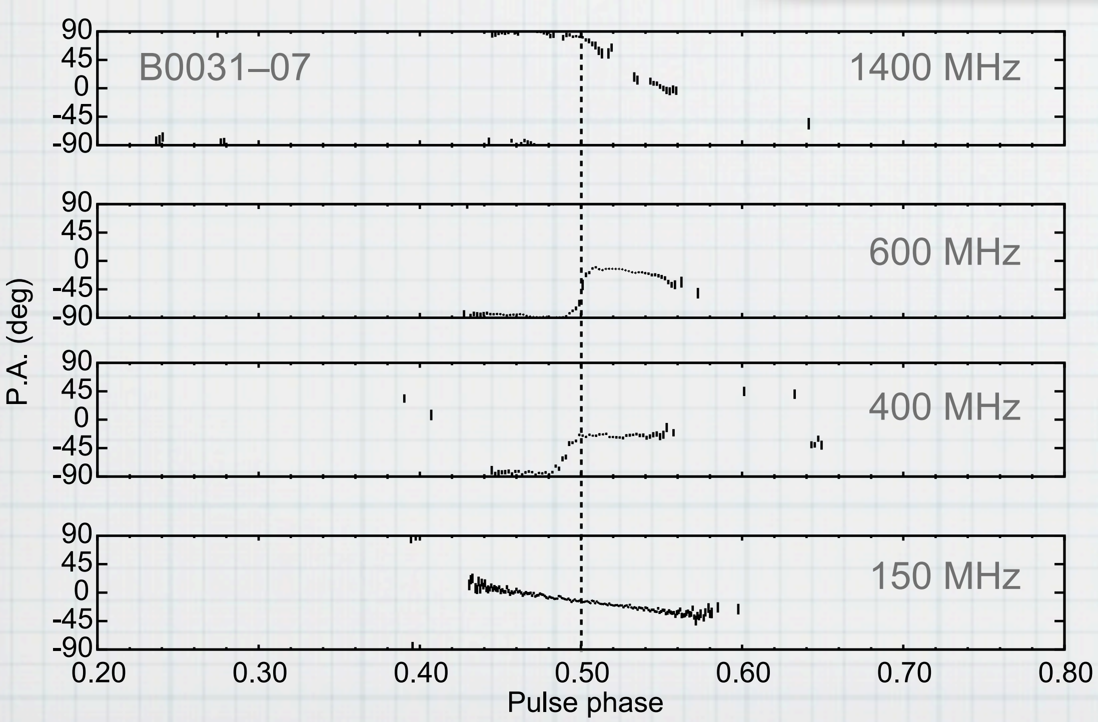





This is evident in multi-frequency data

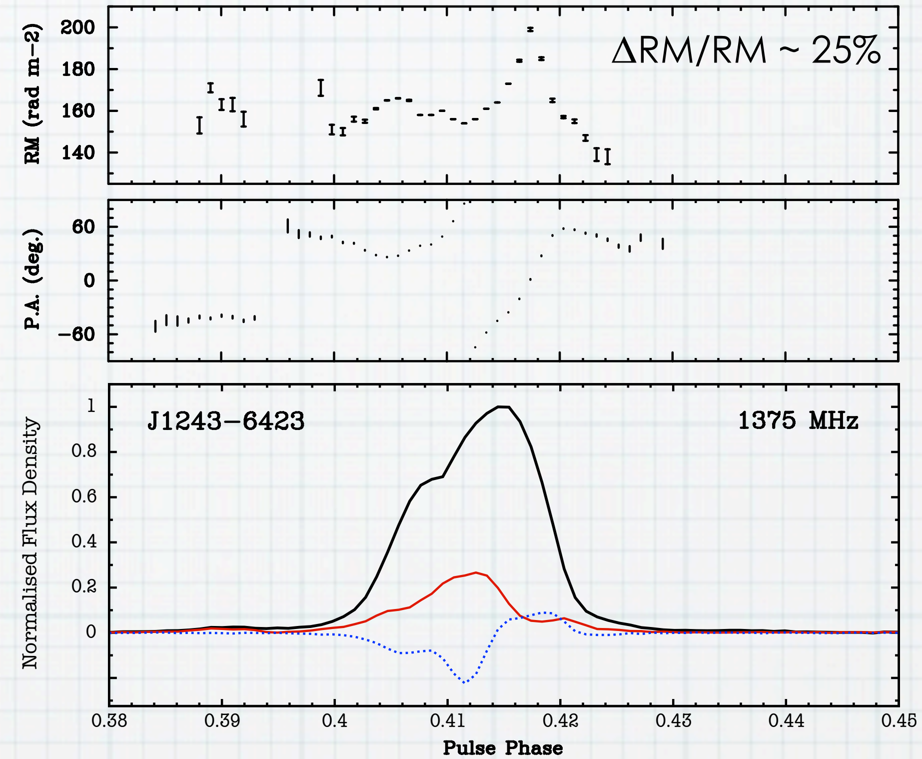
# Polarisation & Scattering

## Scattering becomes very important at low frequencies, as it scales with $\lambda^4$

The amount of scattered intensity depends strongly on frequency.

As a result, **the value of RM at each phase bin appears to vary across the pulse**

*this is not due to changes in $n_e$ or $B_{\|}$*

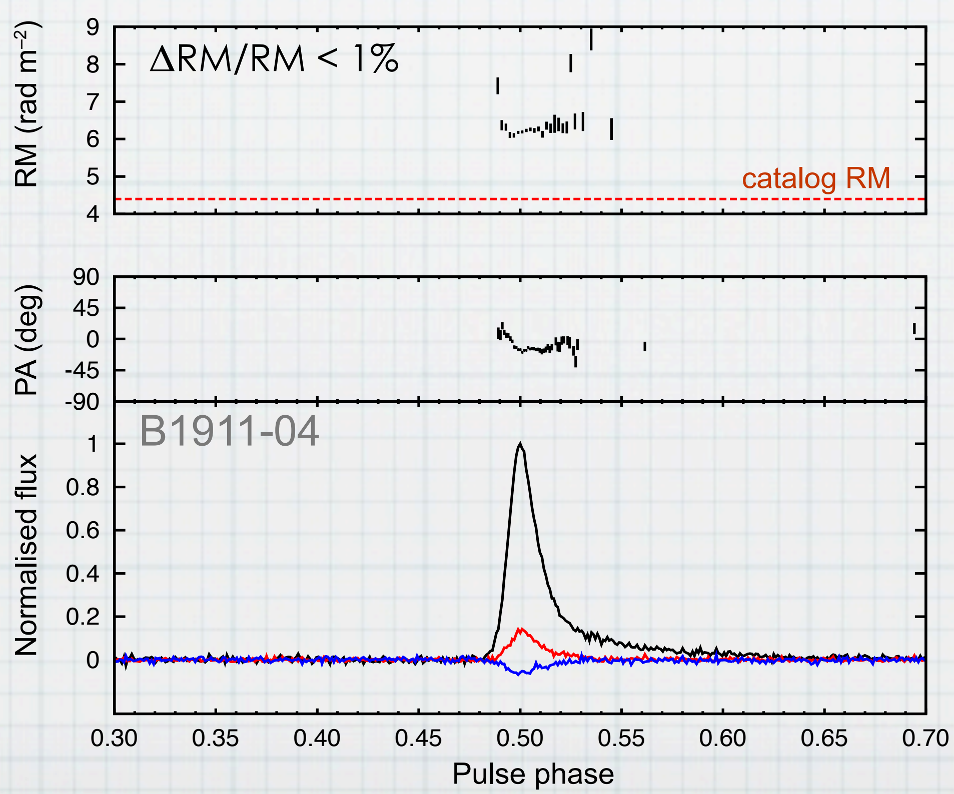


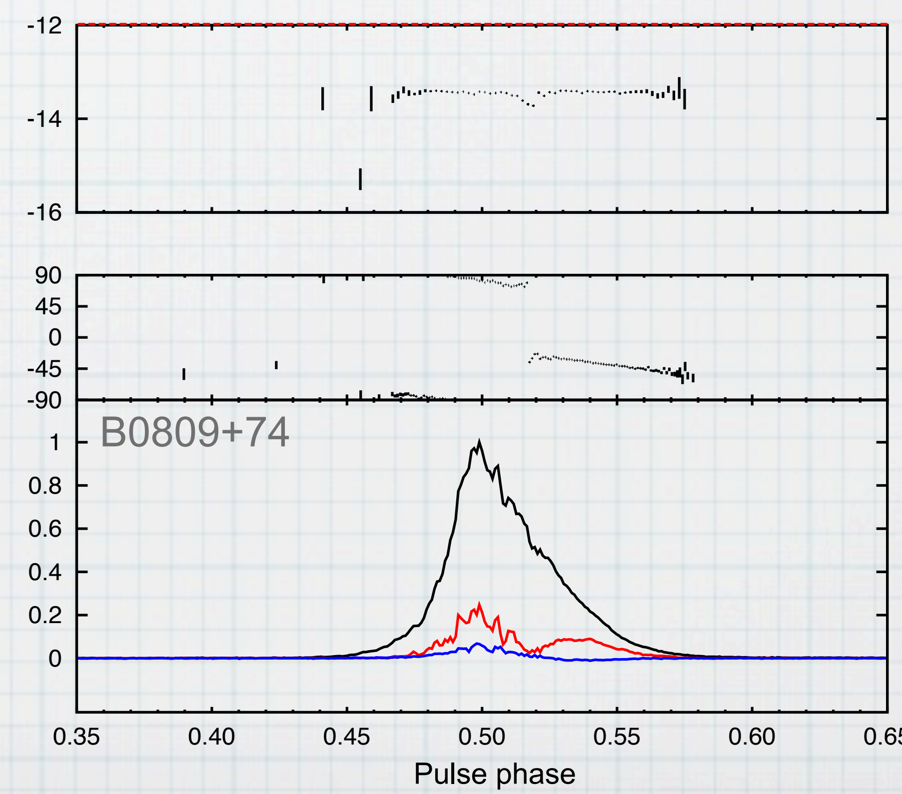

Noutsos et al. (2009)

## PRELIMINARY

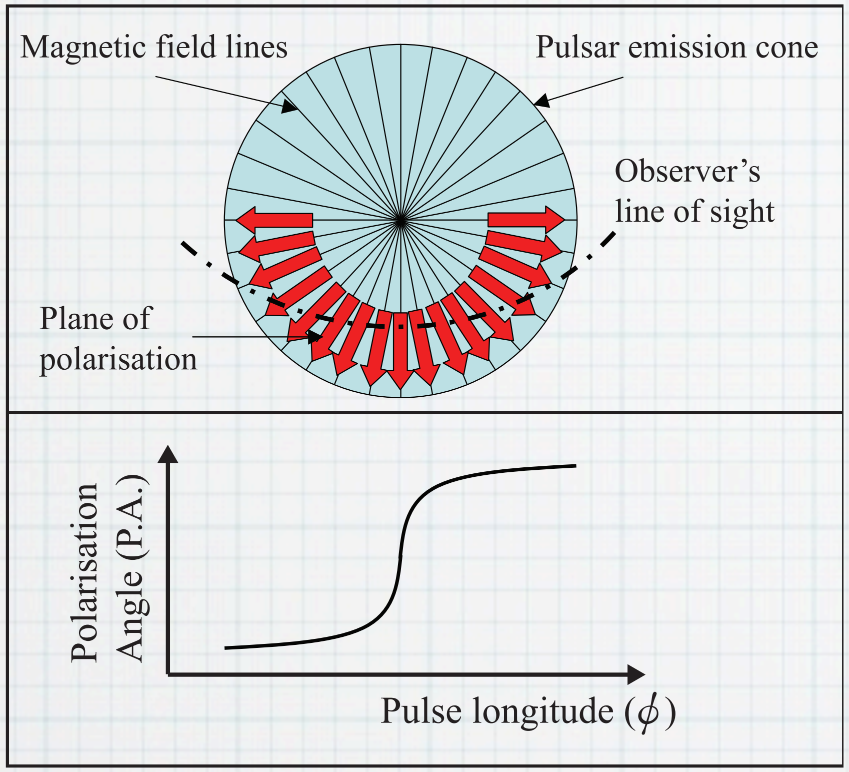
**Our LOFAR data do not confirm our expectations**, with < 1% variation of the measured RM across the pulse

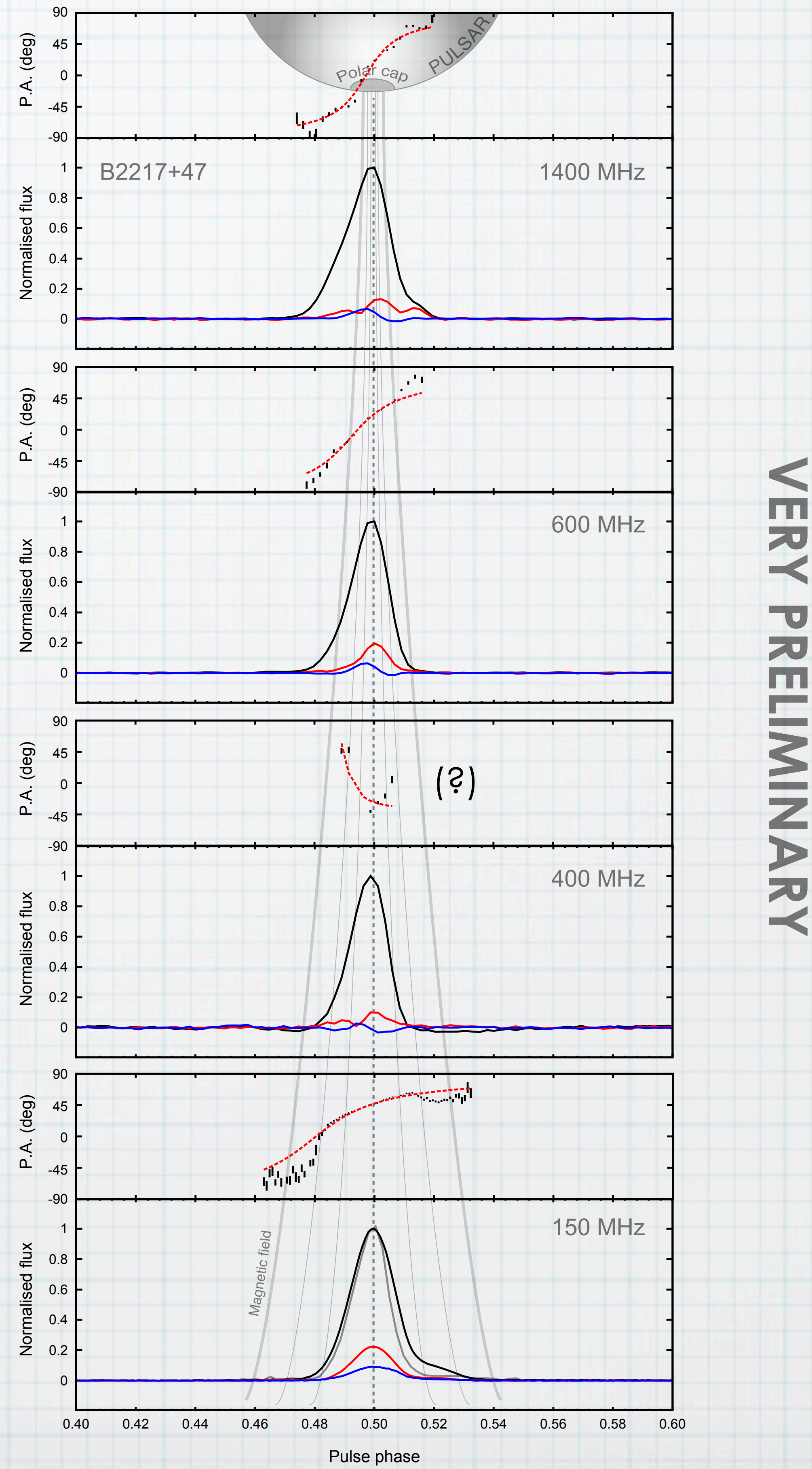
Perhaps scattering at ~100 MHz is severe enough to flatten RM profiles as well !



# Polarisation & Beam Geometry




At lower frequencies, the combination of

- **high-s/n profiles from LOFAR**,
- **larger polarisation fractions** and
- **larger solid angles of polarised emission**

could provide better constraining RVM fits

We could also **better constrain the altitudes of emission** by measuring aberration and retardation effects between 1.4 GHz and 100 MHz

# Things to follow

- The polarisation calibration will be tested with **long-track observations of a bright pulsar**

  *polarisation profile must remain constant with azimuth & elevation — polarisation-noise measurements come for free*

- **Calibration for the LBAs and the international stations** has not been tested, yet

- We need to complete the low-frequency end with **LBA observations of the pulsar sample**

  *we will begin observations in early June (cycle 0)*

- Work on the **polarisation calibration pipeline**:

  i. Develop a user-friendly PSRCHIVE calibration:

     *e.g improve the frequency matching between the Jones-matrix file and the data file*

  ii. Automate the calibration on the cluster

- **Extend the sample of calibrated pulsars** at 100 MHz (cycle 1):

  *We need a reference sample of polarised pulsars for checking the calibration of polarised fields (e.g. Fan region)*

- Do some science: **Measure the beam geometry and retardation effects** between 1.4 GHz and 100 MHz for more pulsars (link between radio and high-energy emission)

- … *finally, **our pulsar survey will keep finding new pulsars**. So watch this space!*