Precise Faraday rotation measures from LOFAR pulsar observations… …towards reconstructing the 3-D Galactic magnetic field

Charlotte Sobey

(ASTRON)

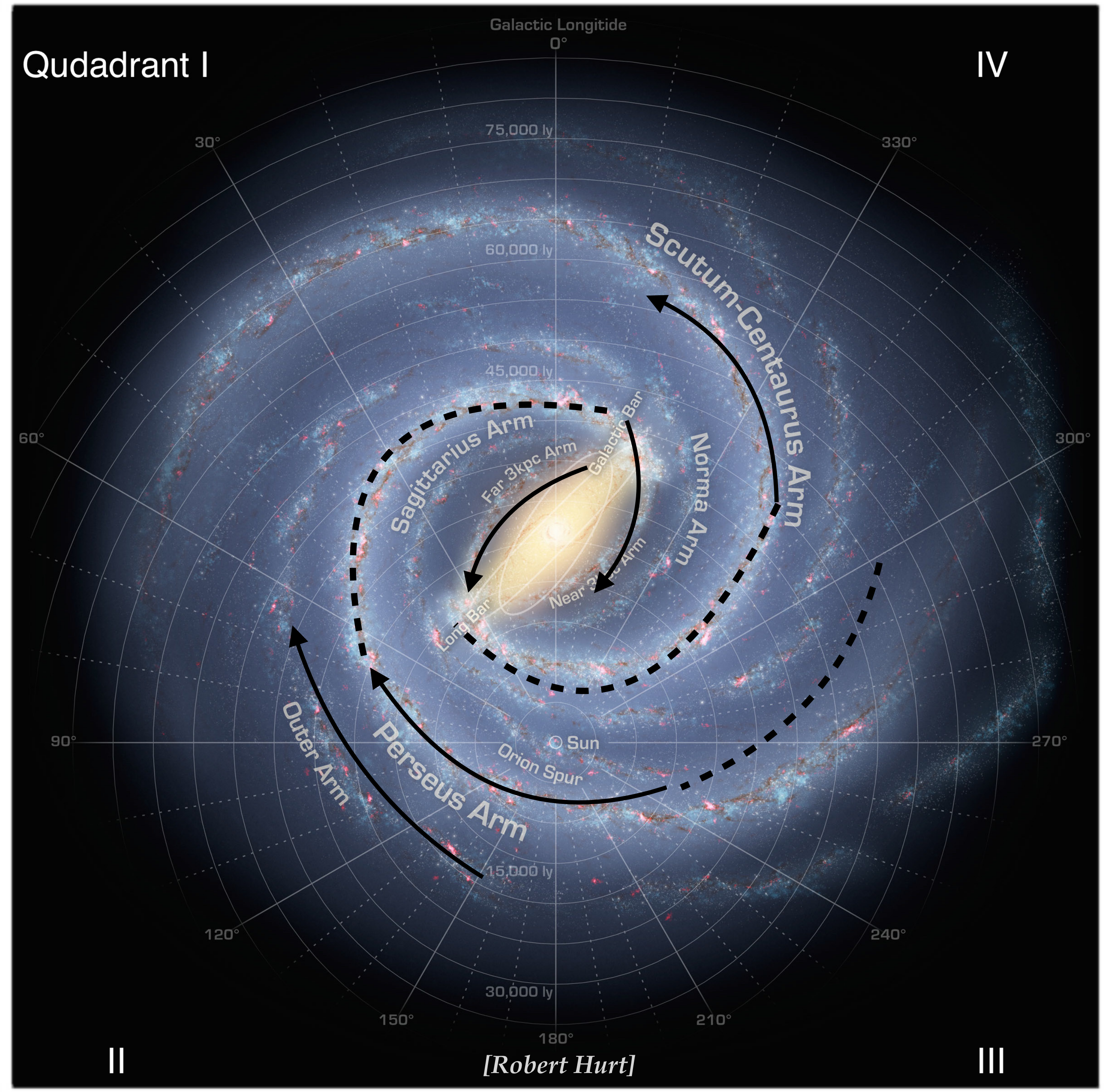
LOFAR *PWG & MKSP*

Overview

- Motivation
  - Galactic magnetic field 3-D structure
- Data
  - LOFAR pulsar observations
- Methods
  - Faraday RM-synthesis
- Results
  - >165 precise LOFAR RMs towards pulsars… so far!
- Summary and future outlook

Motivation: Galactic magnetic field

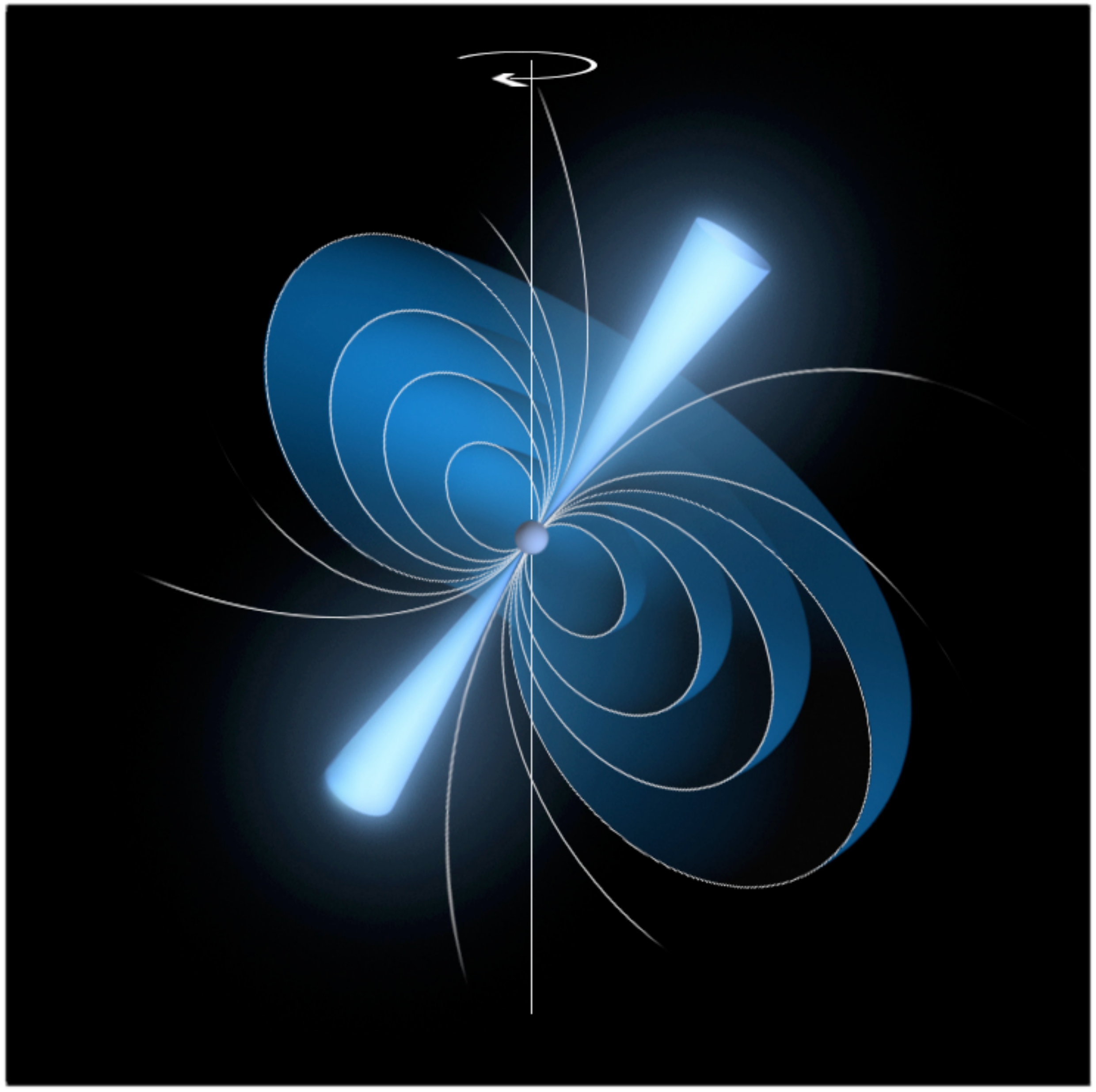
- Permeates diffuse ISM
- Large-scale, ordered & …
- Small-scale, random fields
- Observations suggest overall clockwise direction, with one field reversal in Scutum-Centaurus arm
- No reversals in other galaxies!



[Robert Hurt]

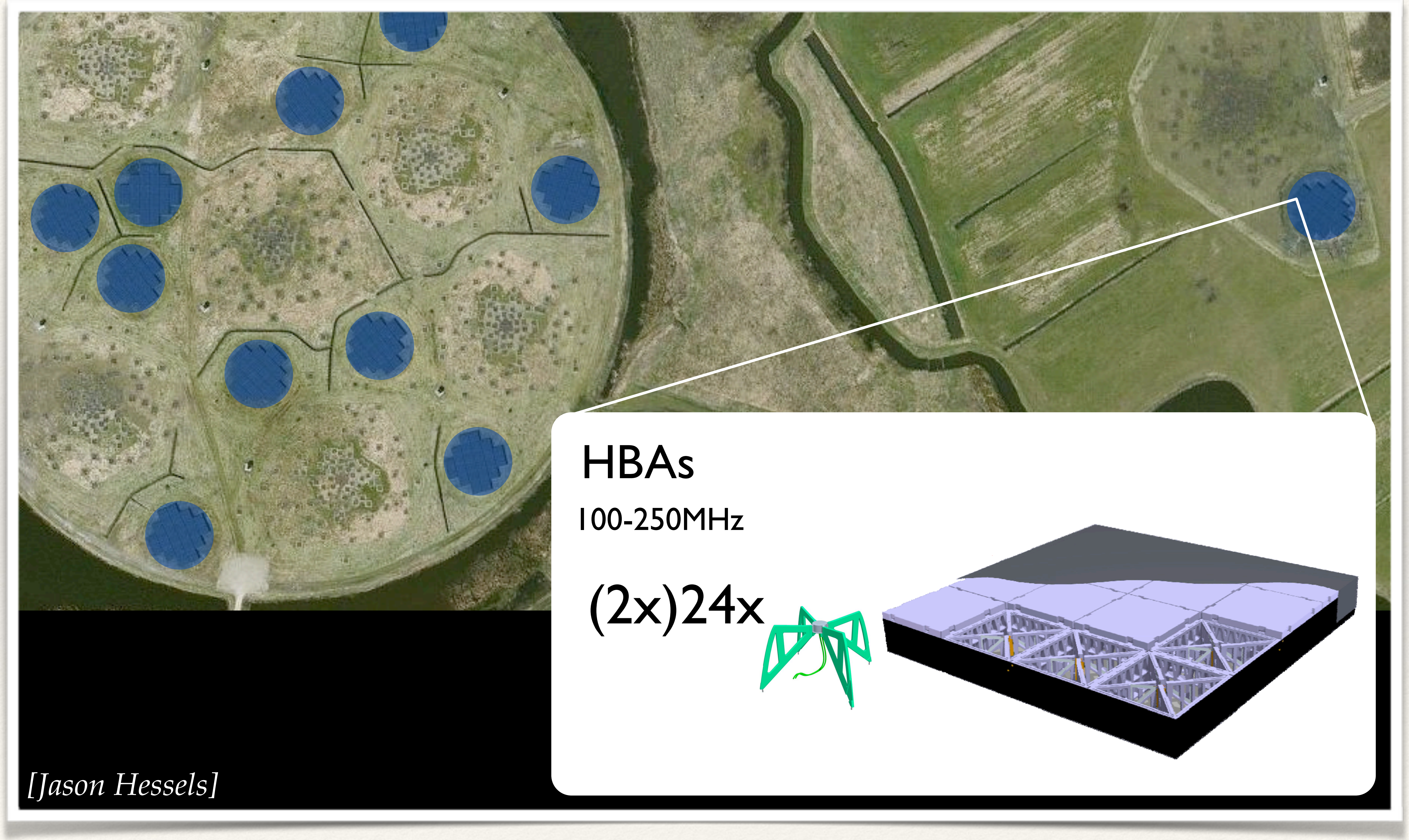
Why study pulsars at low-frequency?

- Emission mechanism:
  - Spectral index/turn-over
  - Profile evolution
  - Single-pulse properties
- Probes of the ISM:
  - Dispersion (n_e)
  - Faraday rotation ($n_e B$)
  - Scattering (Δn_e^2)
  - Scintillation (turbulence)
- Surveys:
  - Large FOV, distinguish RFI



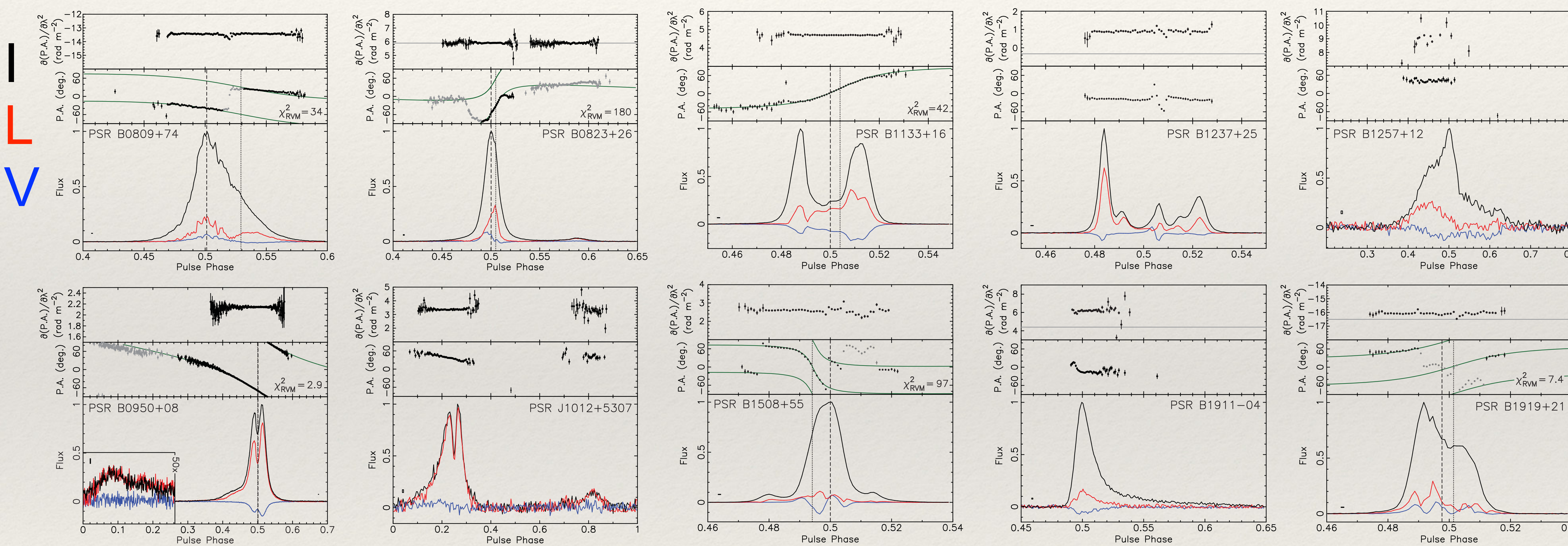
[See Stappers et al. 2011 re LOFAR's pulsar modes]

LOFAR high-band antennas (HBAs)



LOFAR HBA pulsar data

- LOFAR's large fractional bandwidth and collecting area combine to produce the highest-quality polarisation profiles of pulsars below 200 MHz to date.



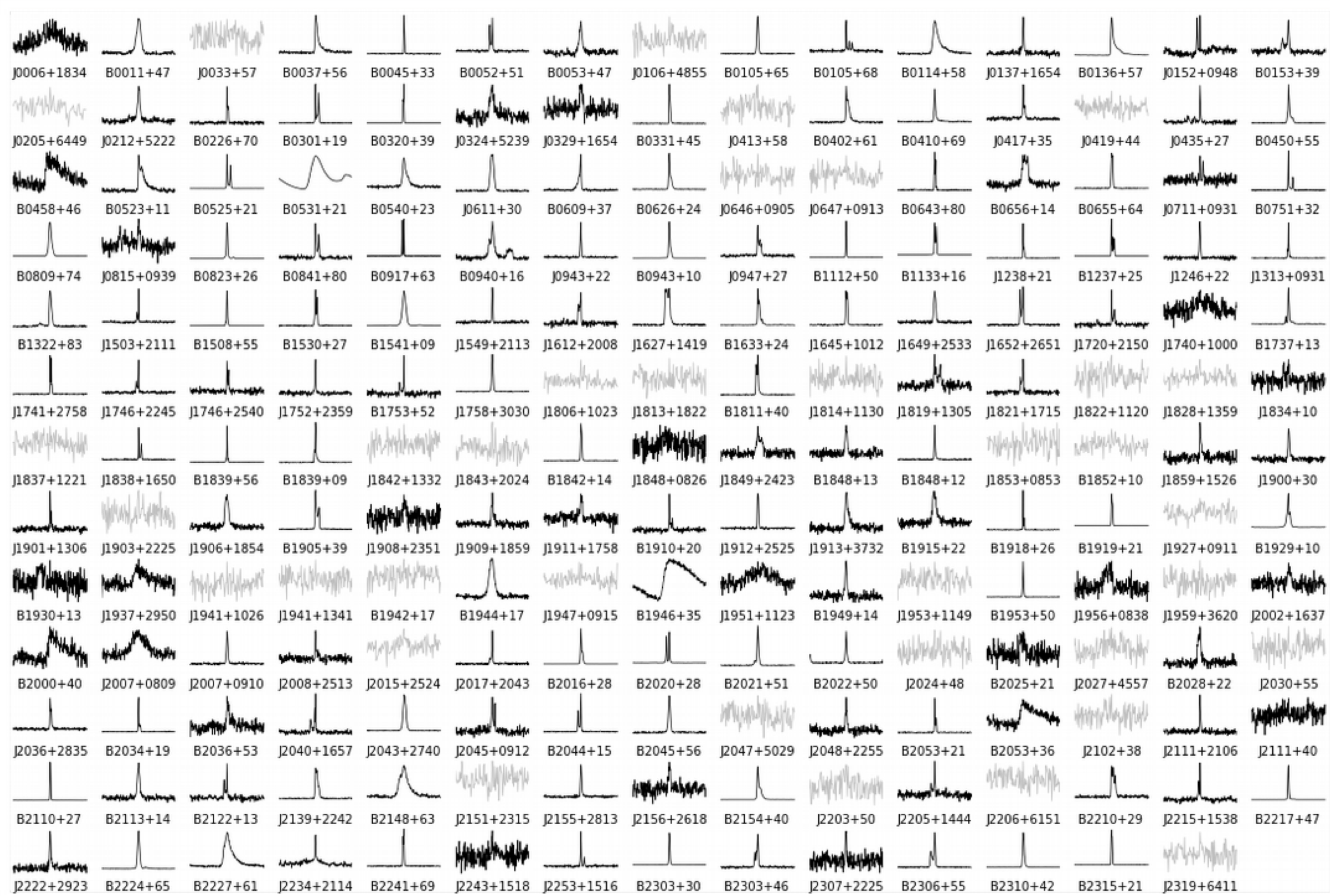
[see Noutsos et al. 2015]

Data: HBA pulsar census +

- HBA pulsar census:
  - Large sample of 195 pulsars (158 detected), $|b| > 3°$, dec>+8°
  - 149 MHz, 78 MHz bandwidth, >= 20-minute integrations
- HBA timing
- MSP census (c.f. Vlad Kondratiev's talk)
- LOTAAS confirmation observations (c.f. Daniele Michilli's talk)

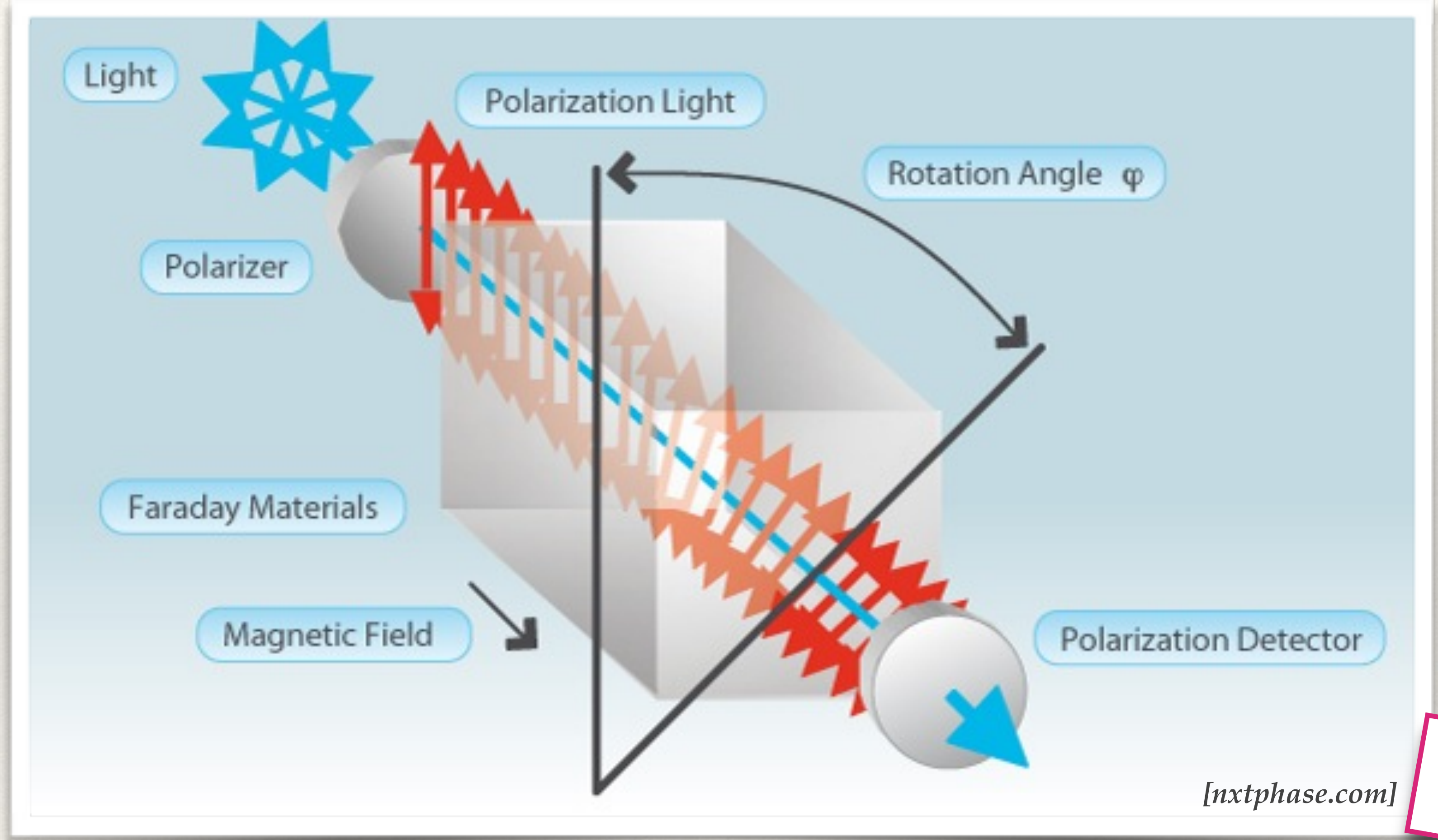
Data: HBA pulsar census profiles

[Anya Bilous et al., submitted]



Method: Faraday rotation measures

- Faraday rotation effect: rotation of the plane of polarisation through magneto-ionic medium



[nxtphase.com]

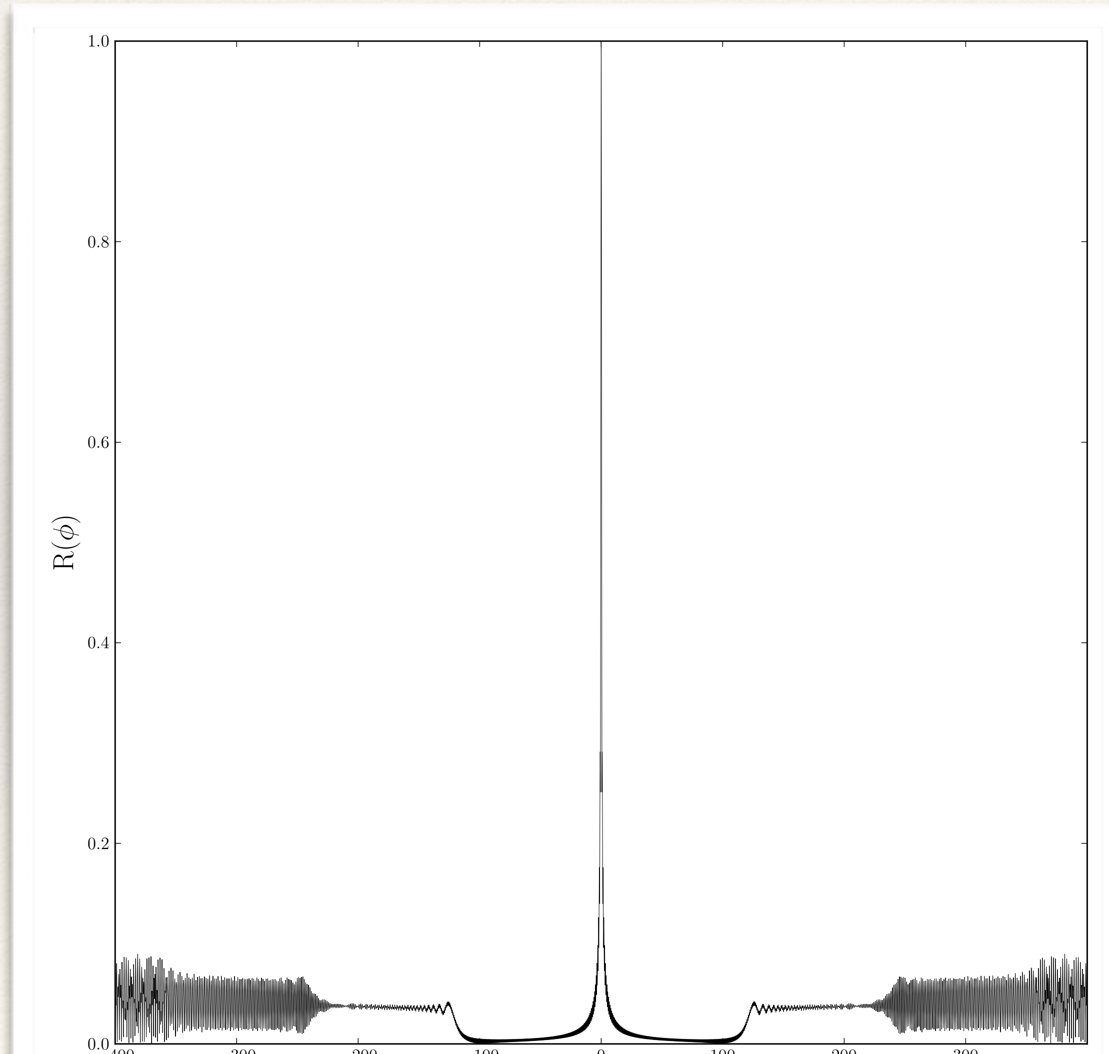
$\propto \Delta\lambda^2$

$$\langle B_{\|} \rangle = 1.232\ \mu G \frac{\mathrm{RM} = 0.81 \int_d^0 n_e \mathbf{B} \cdot d\mathbf{r}\ \ \mathrm{rad\,m^{-2}}}{\mathrm{DM} = \int_0^d n_e \mathrm{d}l\ \ \mathrm{pc\,cm^{-3}}}$$

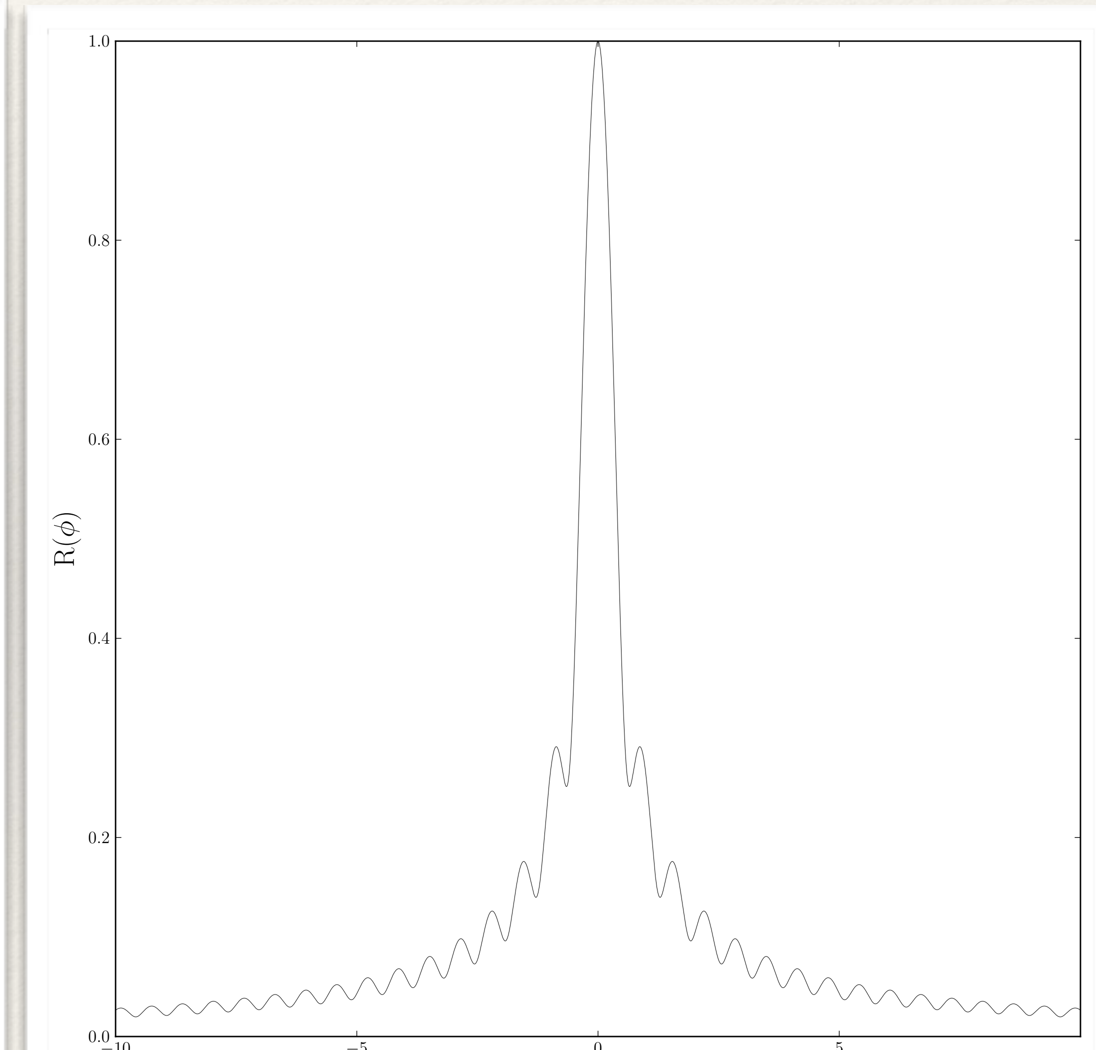
10x lower frequency:
~100x more precise!

Method: RM-synthesis

- Noiseless RMSF for HBA pulsar data: $FWHM_{150MHz}$ ~ 0.8 rad/m^2
- (For comparison: $FWHM_{1.4GHz}$ ~ 300 rad/m^2 & $FWHM_{350MHz}$ ~ 10 rad/m^2)

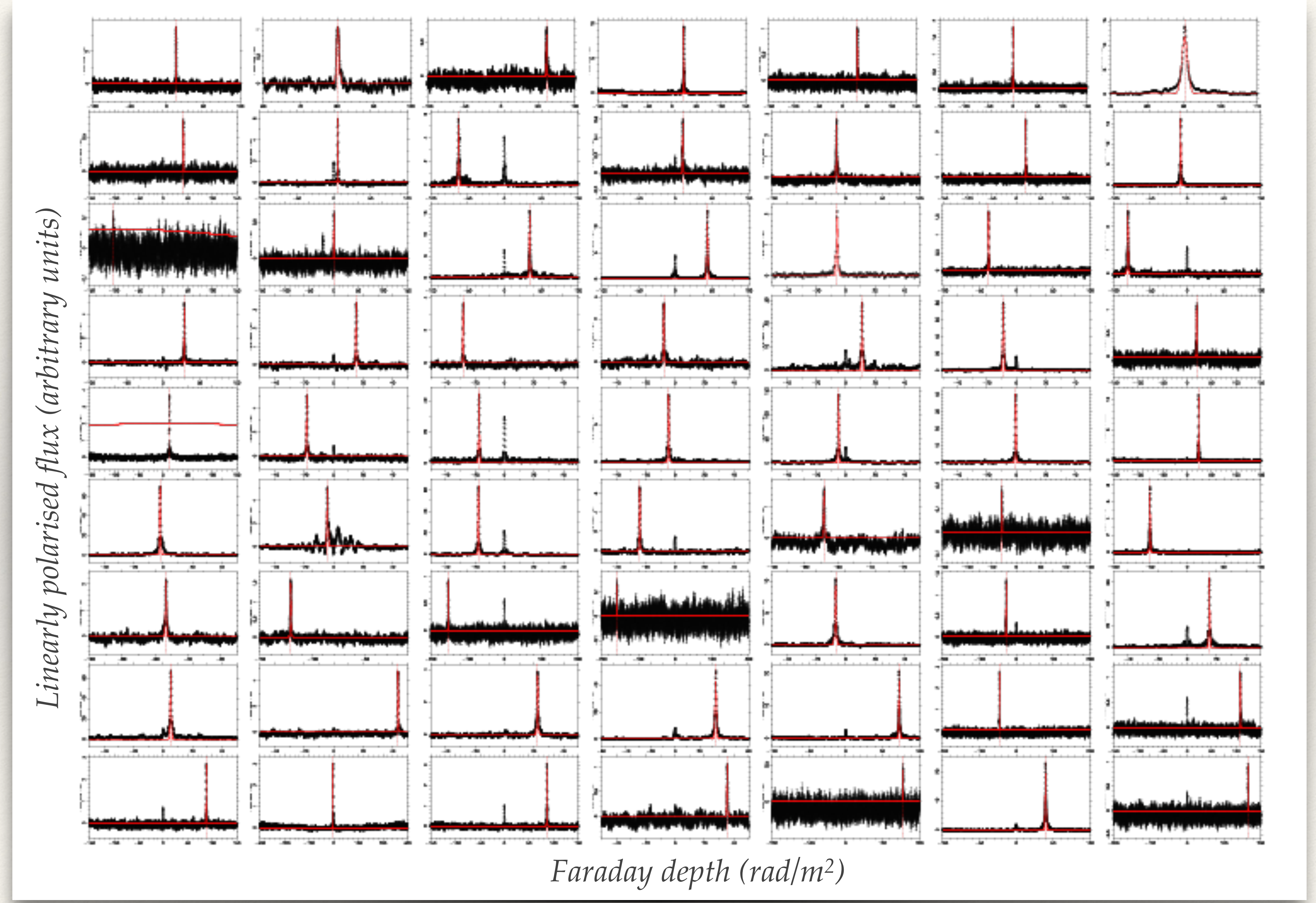


-400 Faraday depth (rad/m^2) +400



-10 Faraday depth +10

Results: Selection of Faraday spectra

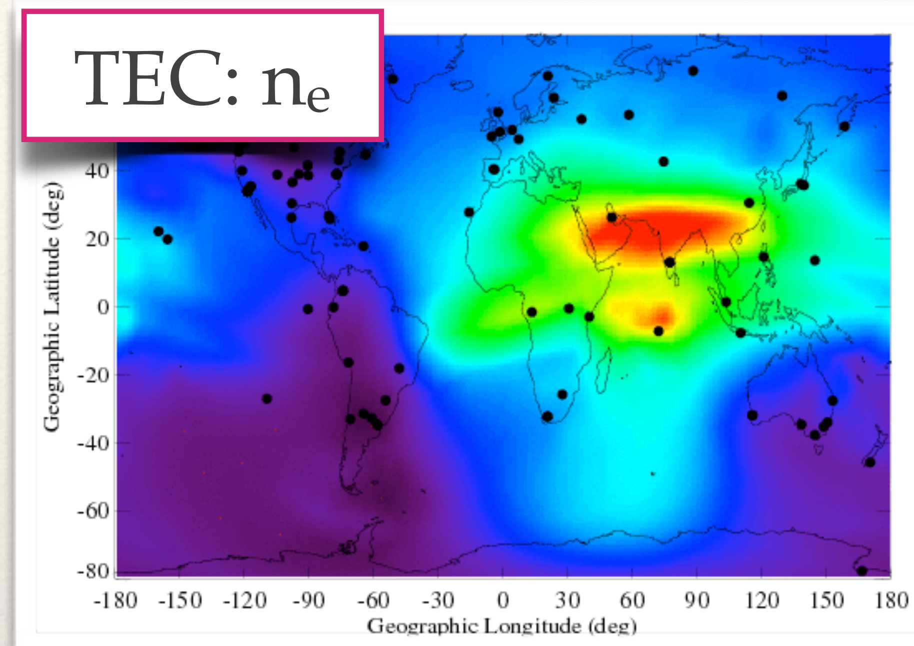


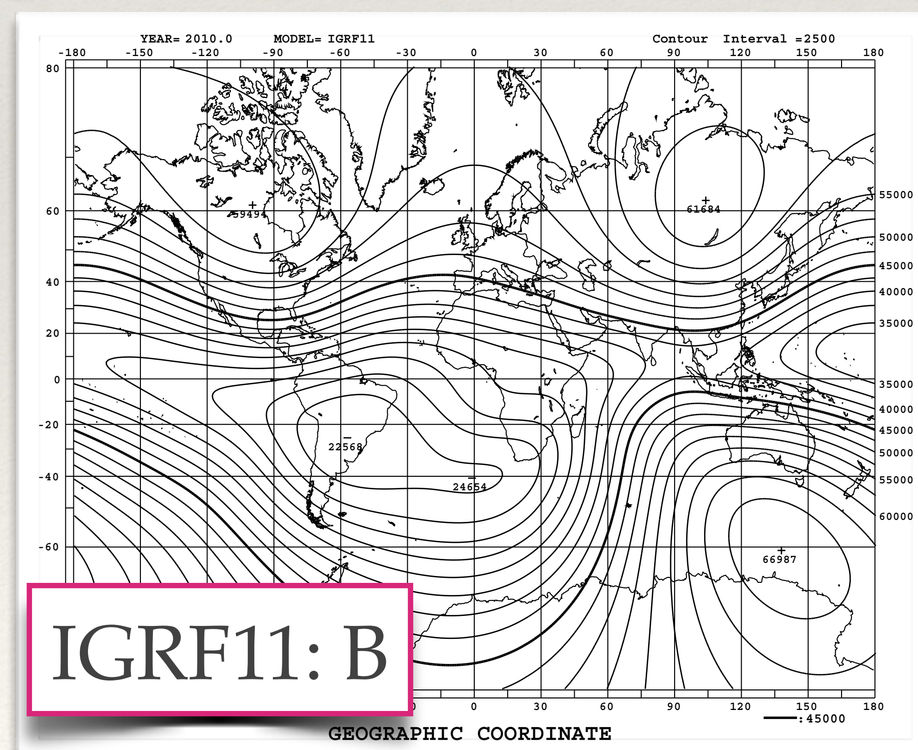
But wait!: Ionospheric Faraday rotation

- Magneto-ionic medium
- Introduces time & position dependence

$$\mathrm{RM_{obs}} = \mathrm{RM_{ISM}} + \mathrm{RM_{ion}}$$

- ionFR code (see Sotomayor et al. 2013) calculates ionospheric RM(LOS) using:
  - Total electron content (TEC) maps
  - International Geomagnetic Reference Field (IGRF)



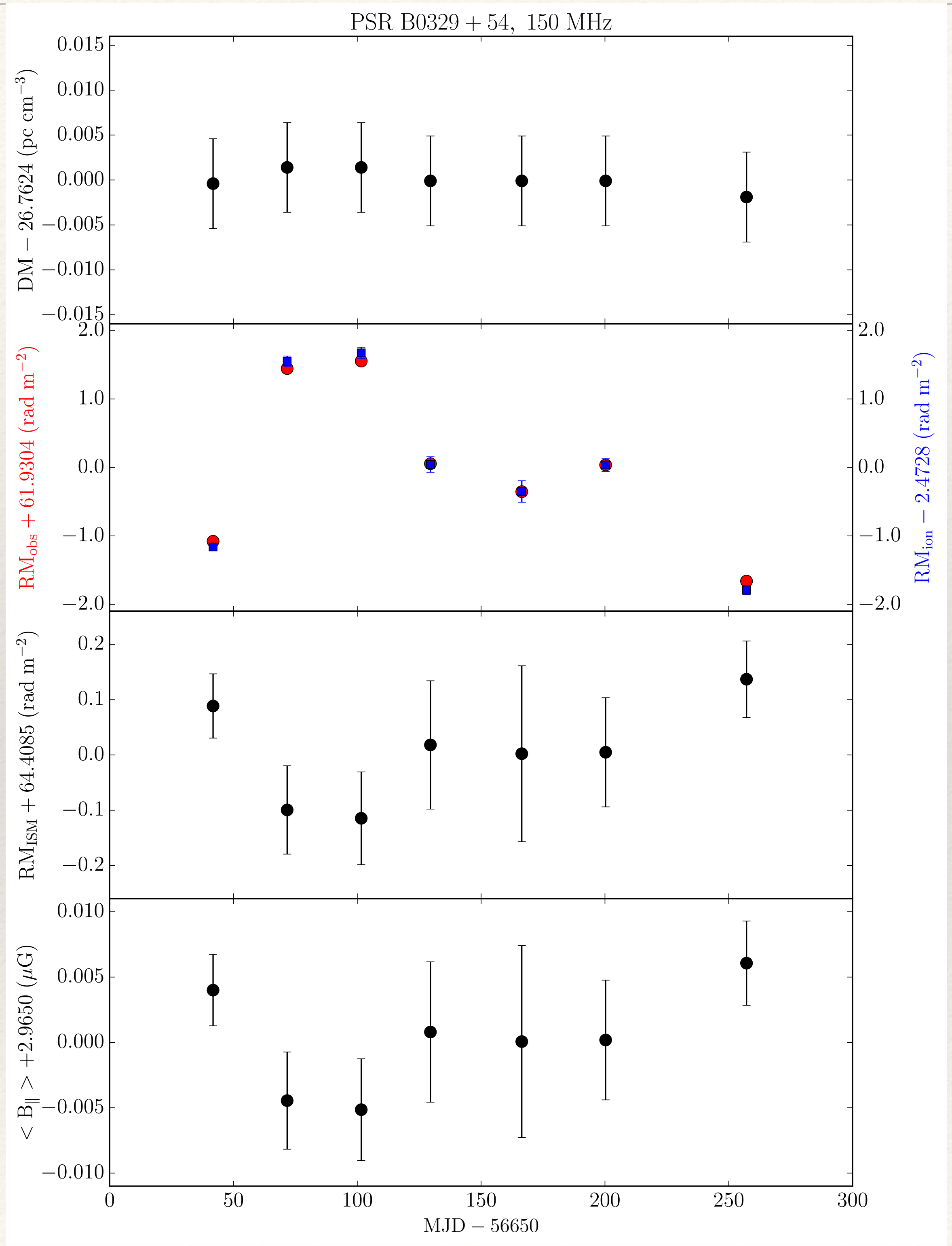


Comparison to LOFAR observations

- Pulsar timing data for PSR B0329+54
- 3 Feb - 3 Nov '14
- 149(78) MHz

Accuracy ~ 0.1 rad m^{-2}

Accuracy ~ 0.005 uG



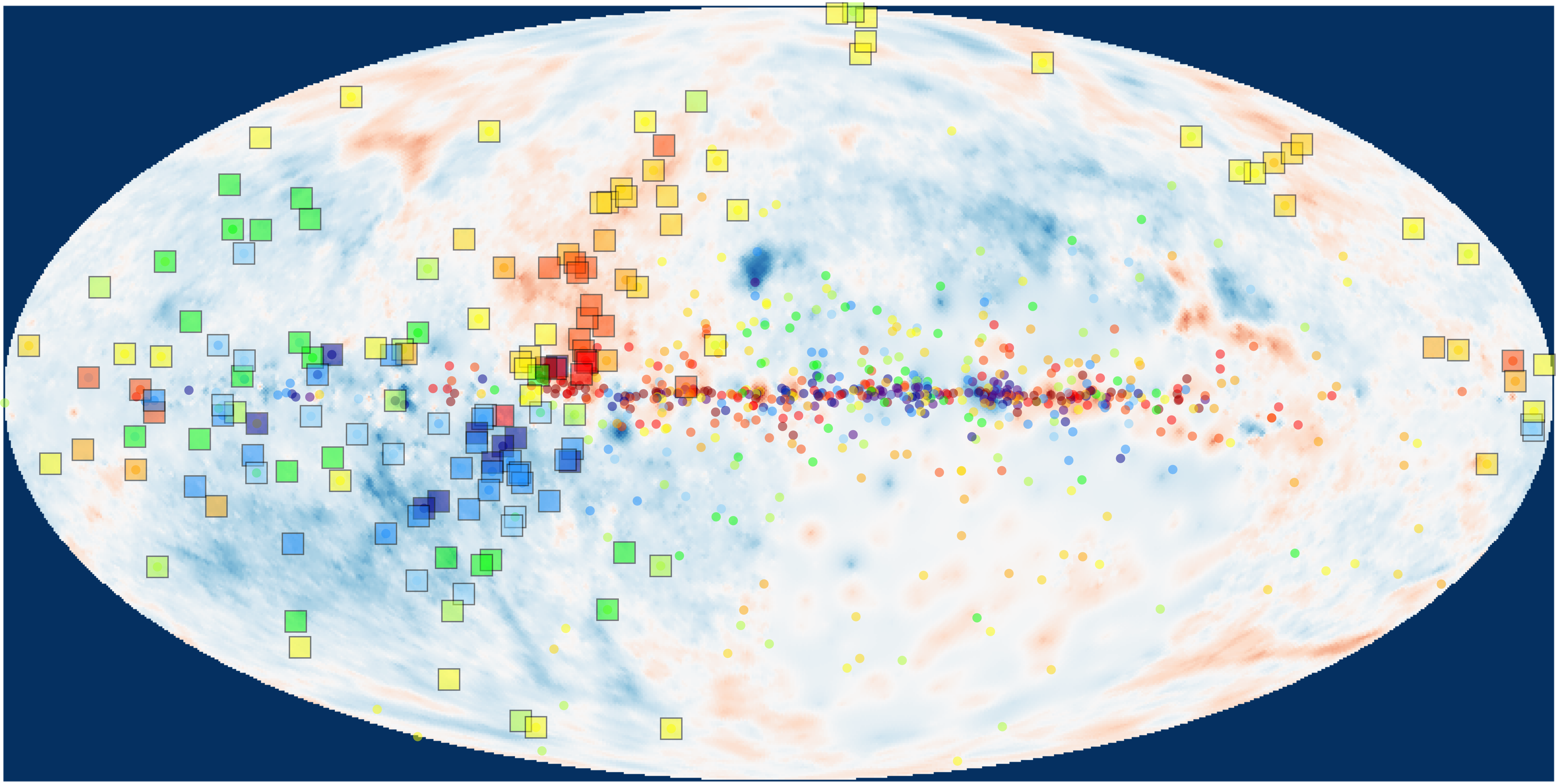
Results

- 165 precise & ionosphere-corrected RMs (so far!)
  - 75 without previous RM measurements
  - 90 with ^ (LOFAR uncertainties 30x smaller, on average)

Table 1: LOFAR observations centred at 148.925 MHz, using 78.125 MHz bandwidth and 400 channels, included in this summary. Note: nd = no convincing detection yet! * = check (low S/N or high instrumental).

PSR (name)	**OBSID**	**Date** (dd.mm.yy)	**Time** (UT)	τ_{int} (min)	**DM**$_{psrcat}$ (pc cm^{-3})	**RM**$_{psrcat}$ (rad m^{-2})	**DM**$_{LOFAR}$ (pc cm^{-3})	**RM**$_{LOFAR}$ (rad m^{-2})
J0006+1834	L204692	15.02.2014	13:47	20	12.0(6)	–	11.406696	nd
B0011+47	L221897	26.04.14	10:57	21	30.85(7)	–	30.404790	−13.06(5)
B0037+56	L215805	06.04.14	09:58	20	92.595(9)	9(13)	92.514581	−155.71(20)
B0045+33	L204694	15.02.14	14:29	21	39.94(4)	–	39.922037	−80.22(7)
B0052+51	L222340	29.04.14	07:24	36	44.125(15)	–	44.012725	−61.84(5)
B0053+47	L204693	15.02.14	14:08	20	18.09(4)	−23(22)	18.135353	−42.56(10)
B0105+65	L227584	07.05.14	09:30	22	30.46(5)	−29(3)	30.548183	−24.37(5)
B0105+68	L204695	15.02.14	14:51	20	61.092(16)	−46(19)	61.061654	−30.51(5)
B0114+58	L227167	03.05.14	11:08	20	49.423(4)	–	49.420675	−0.27(5)*
J0137+1654	L204696	15.02.14	15:18	20	26.6(4)	–	26.083760	−13.4(2)
B0136+57	L215807	06.04.14	10:40	20	73.779(6)	−90(4)	73.811406	−90.26(5)
J0152+0948	L227585	07.05.14	10:02	46	21.87(2)	–	22.881164	5.55(18)
B0153+39	L221899	26.04.14	11:40	31	60.0(6)	–	59.833422	65.8(1)
J0212+5222	L221900	26.04.14	12:12	20	38	–	38.235546	−11.14(5)
B0226+70	L204697	15.02.14	15:58	25	46.64(3)	−56(21)	46.679440	−41.6(1)
B0301+19	L204698	15.02.14	16:24	24	15.737(9)	−8.3(3)	15.656766	−5.47(3)
B0320+39	L204699	15.02.14	16:49	51	26.01(3)	58(3)	26.189752	62.24(4)
J0324+5239	L227168	03.05.14	11:39	20	119	–	115.463559	244.19(20)

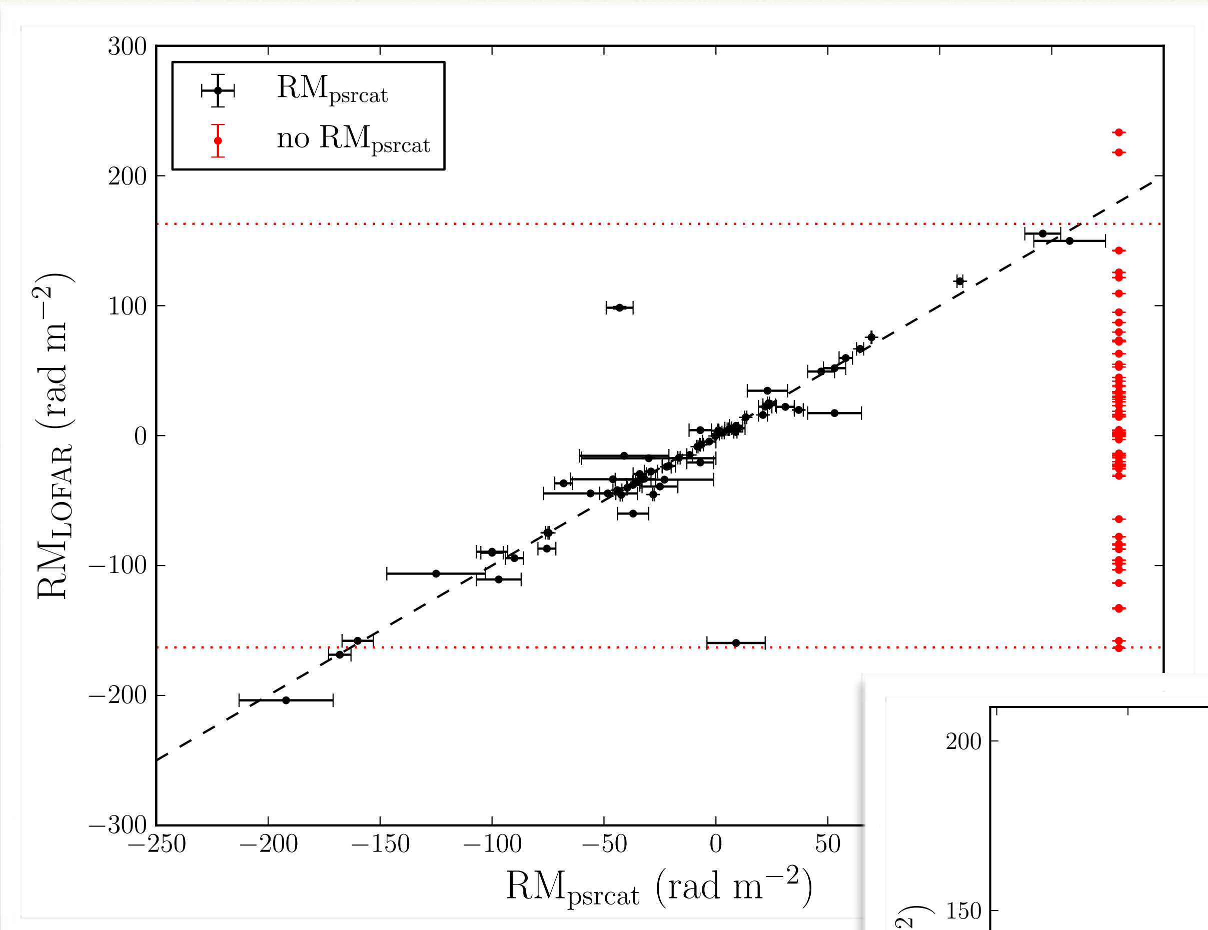
⋮

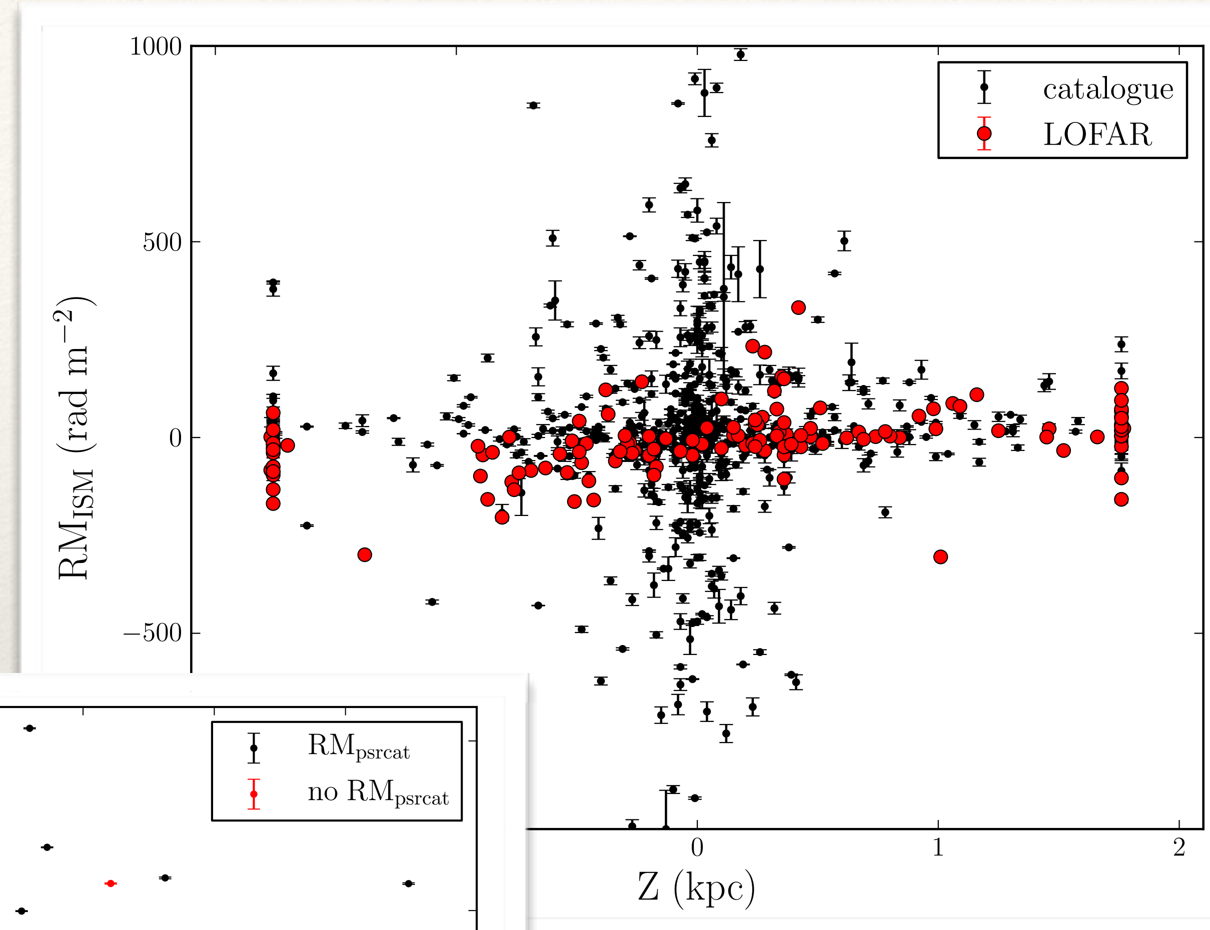


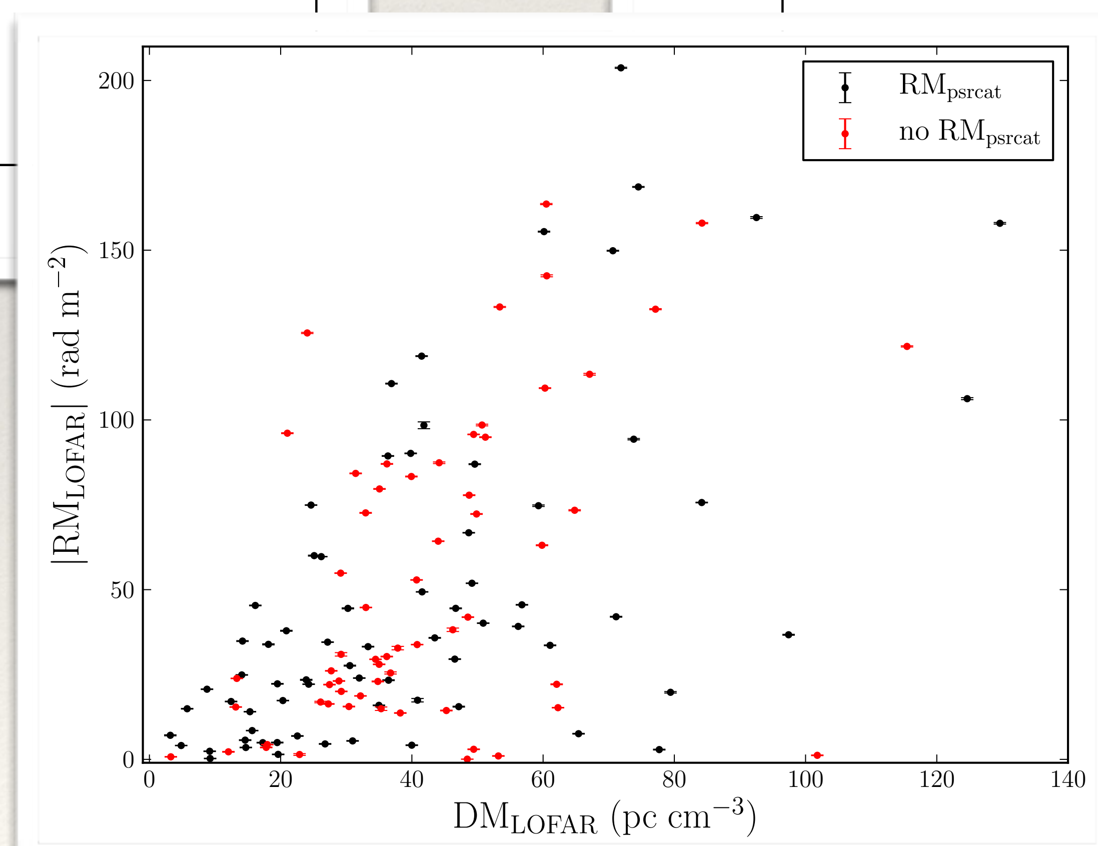
New precise pulsar RMs using LOFAR

LOFAR HBA RMs
(165 so far, squares)
+
Current pulsar RM catalogue
(Manchester + 2005, 680 circles)
+
Oppermann + 2014 (background)

RM & DM Results

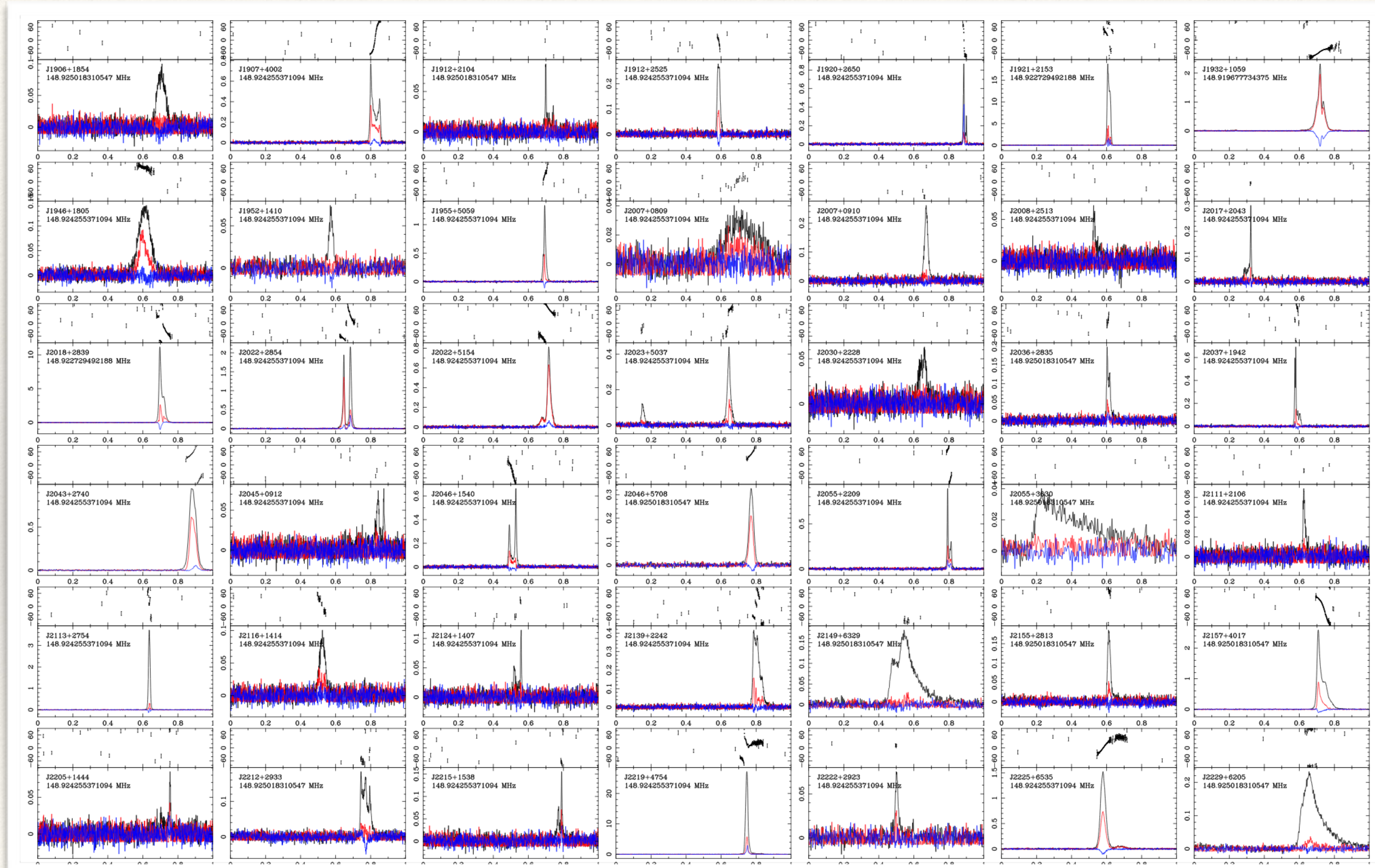






Data: Selection of polarisation profiles

I
L
V



Summary & Future Work

- LOFAR data provide precise (& accurate) RMs for nearby pulsars (165 so far, 75 new)
- Provide much improved information about GMF in northern sky
- Ongoing:
  - Obtaining more RMs, including for further ~40 pulsars with parallax
  - Further analysis
- Technique can also be applied for further investigations of B-fields:
  - Targeted search of globular clusters for polarised pulsars
  - Heliosphere

Thank you for listening!

…more interesting pulsar papers using LOFAR data:

- Stappers et al. 2011: Observing pulsars and fast transients with LOFAR
- Hassall et al. 2012: Wide-band simultaneous observations of pulsars:…
- Hermsen et al. 2013: Synchronous X-ray and Radio Mode Switches:…
- Sotomayor-Beltran et al. 2013: Calibrating high-precision Faraday rotation measurements for LOFAR and…
- Hassall et al. 2013: Differential frequency-dependent delay from the pulsar magnetosphere
- Coenen et al. 2014: The LOFAR pilot surveys for pulsars and fast radio transients
- Bilous et al. 2014: LOFAR observations of PSR B0943+10: profile evolution and…
- Archibald et al. 2014: Millisecond Pulsar Scintillation Studies with LOFAR: Initial Results
- Dolch et al. 2014: A 24 Hr Global Campaign to Assess Precision Timing of the Millisecond Pulsar J1713+0747
- Noutsos et al. 2015: Pulsar polarisation below 200 MHz: Average profiles and propagation effects
- Karako-Argaman et al. 2015: Discovery and Follow-up of Rotating Radio Transients with the Green Bank and LOFAR…
- Karastergiou et al. 2015: Limits on fast radio bursts at 145 MHz with ARTEMIS, a real-time software backend
- Sobey et al. 2015: LOFAR discovery of a quiet emission mode in PSR B0823+26
- Pilia et al. 2015: Wide-Band, Low-Frequency Pulse Profiles of 100 Radio Pulsars with LOFAR
- Kondratiev et al. 2015: A LOFAR Census of Millisecond Pulsars
- Bilous et al. 2016 (submitted to A&A): A LOFAR census of non-recycled pulsars: average profiles, dispersion measures…

ASTRON

LOFAR