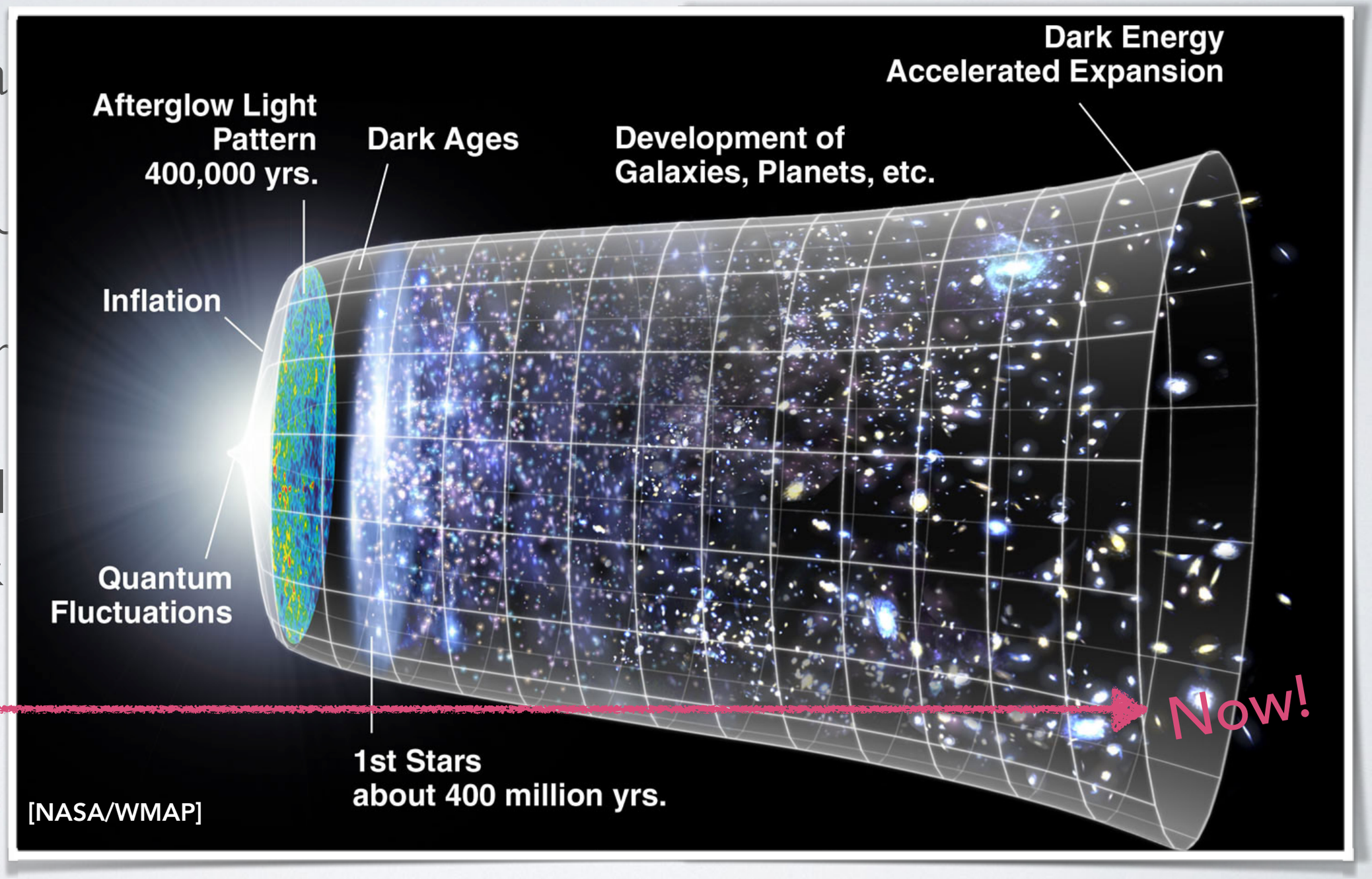
Using low-frequency pulsar observations *to study the* 3-D structure of the Galactic magnetic field

Charlotte Sobey
c.sobey@curtin.edu.au

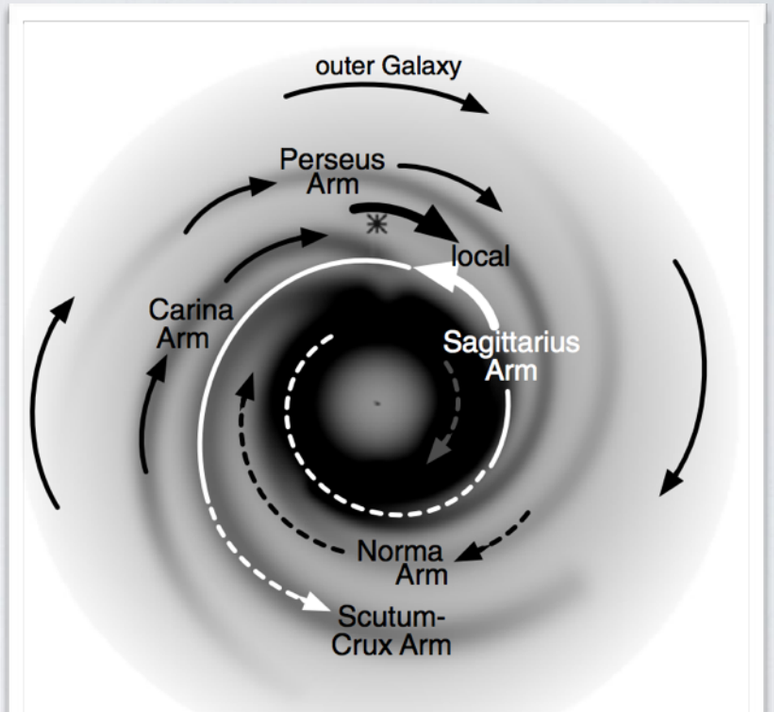
OVERVIEW

- **Why?** Ga
- **What?** pu
- **How?** Far
- **Where?** I
  LOFAR &
- **When?**

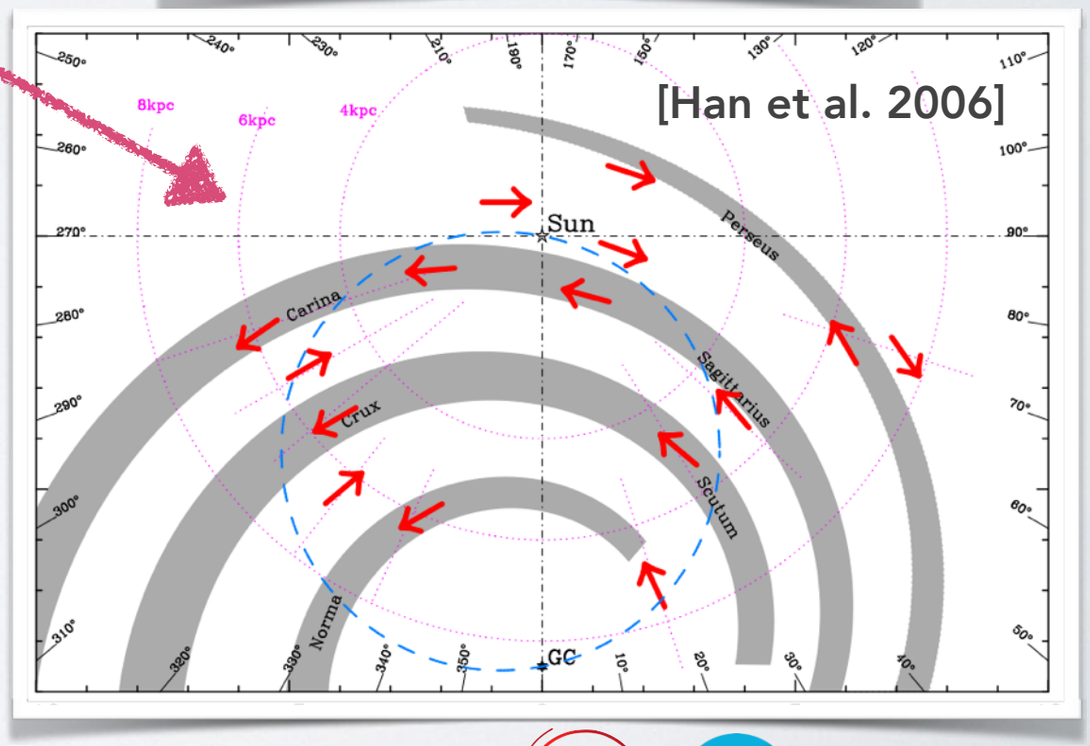


MOTIVATION

- GMF permeates the diffuse ISM
- Large-scale, ordered and…
- …Small-scale, random fields
- In the disk: data suggest overall clockwise direction, but number and location of field reversals debated
- In the halo: reversal across Galactic disk, but even less well studied in 3-D
- No reversals in other galaxies!
- As foreground to EoR: synchrotron, Faraday rotation…



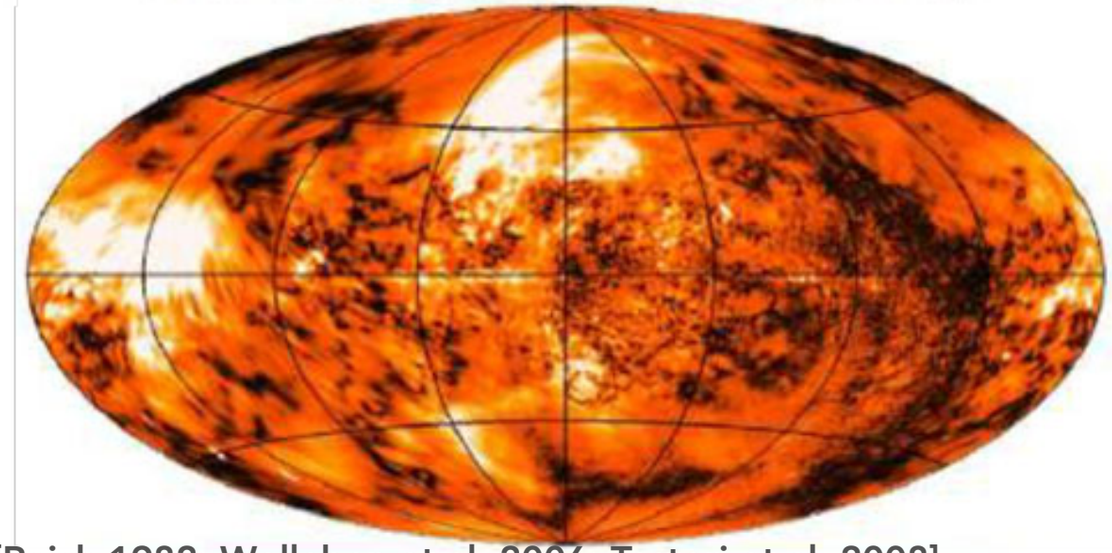
[van Eck et al. 2011]



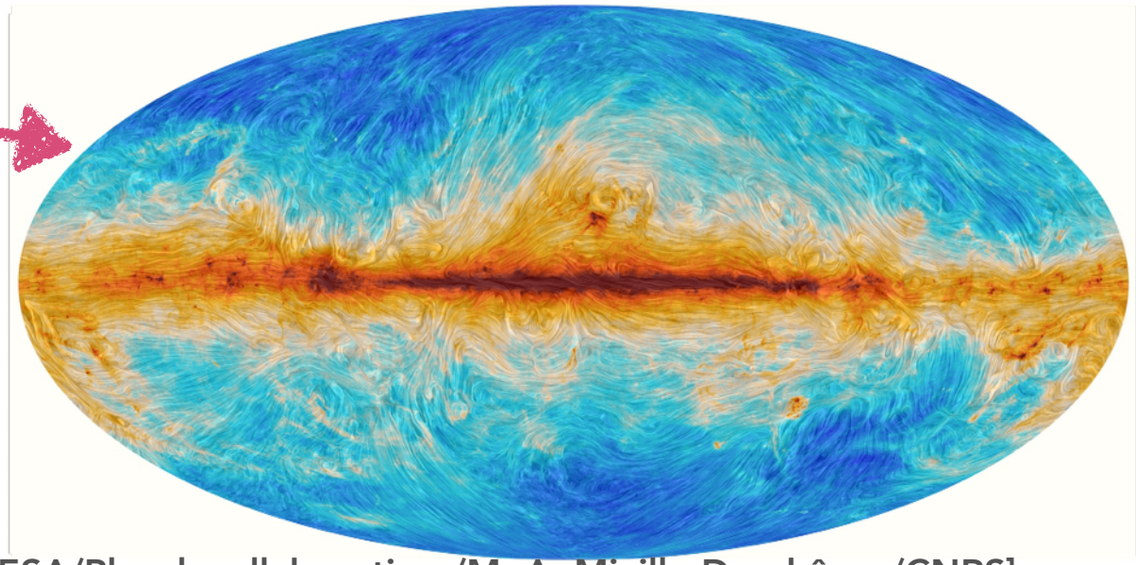
[Han et al. 2006]

OBSERVABLES INFER MAGNETIC FIELDS

- Observables (complementary):
  - Zeeman splitting
  - Synchrotron (I and P)
  - Starlight (P)
  - Thermal dust emission (P)
  - Ultra-High Energy Cosmic Rays
  - **Faraday rotation measures!**



[Reich 1982; Wolleben et al. 2006; Testori et al. 2008]

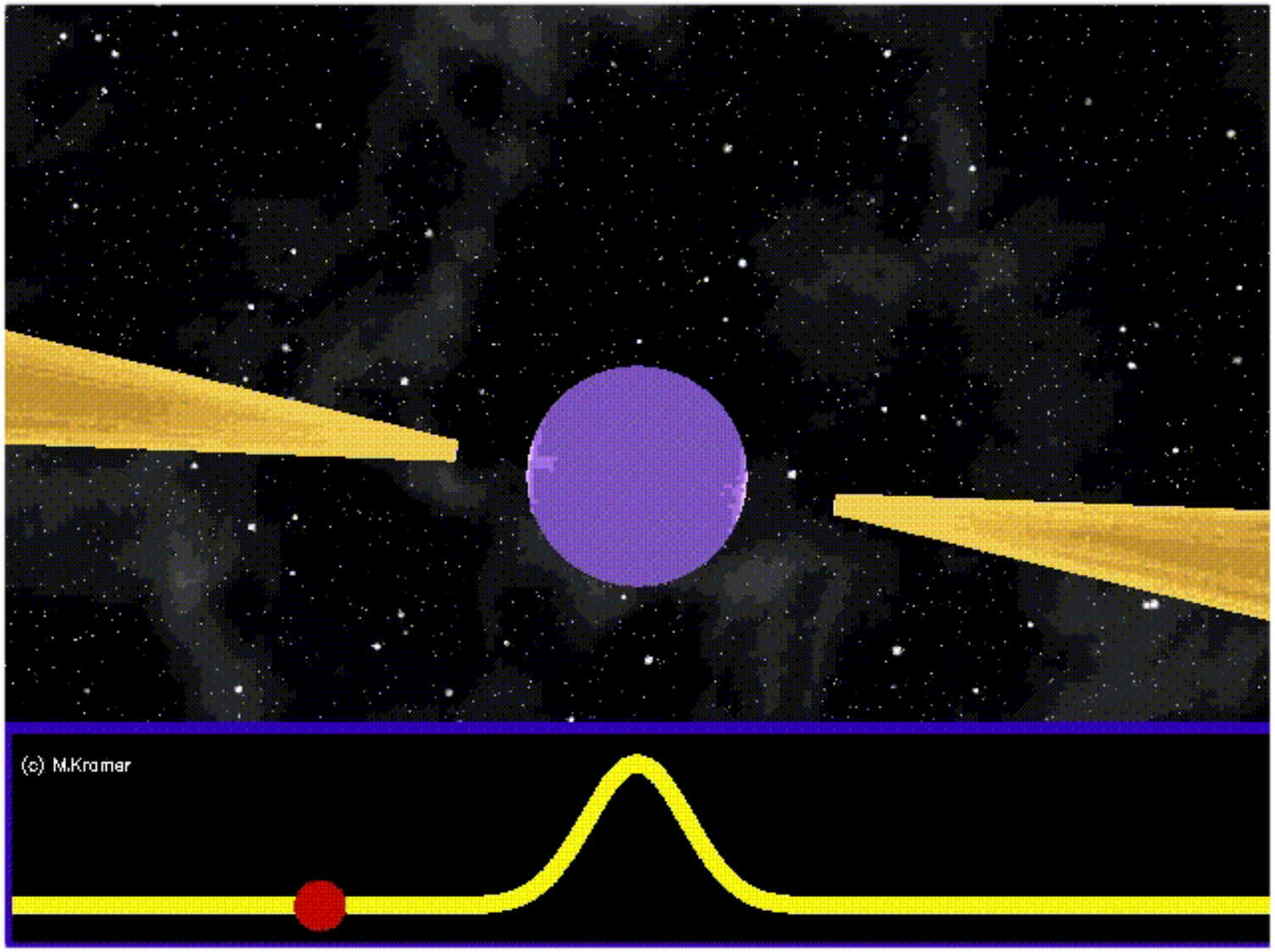


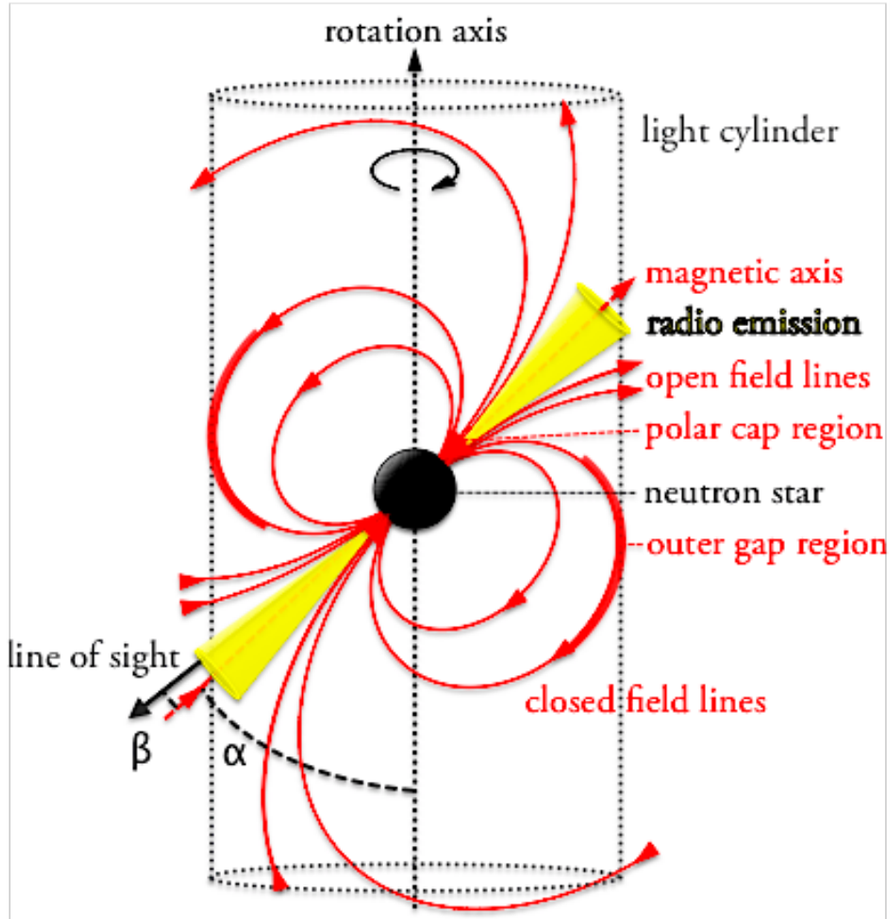
[ESA/Planck collaboration /M.-A. Miville-Deschênes/CNRS]

- Mostly 2-D tracers, strength/direction, requiring ancillary data

PULSARS…

Rapidly-rotating, highly-magnetised neutron stars



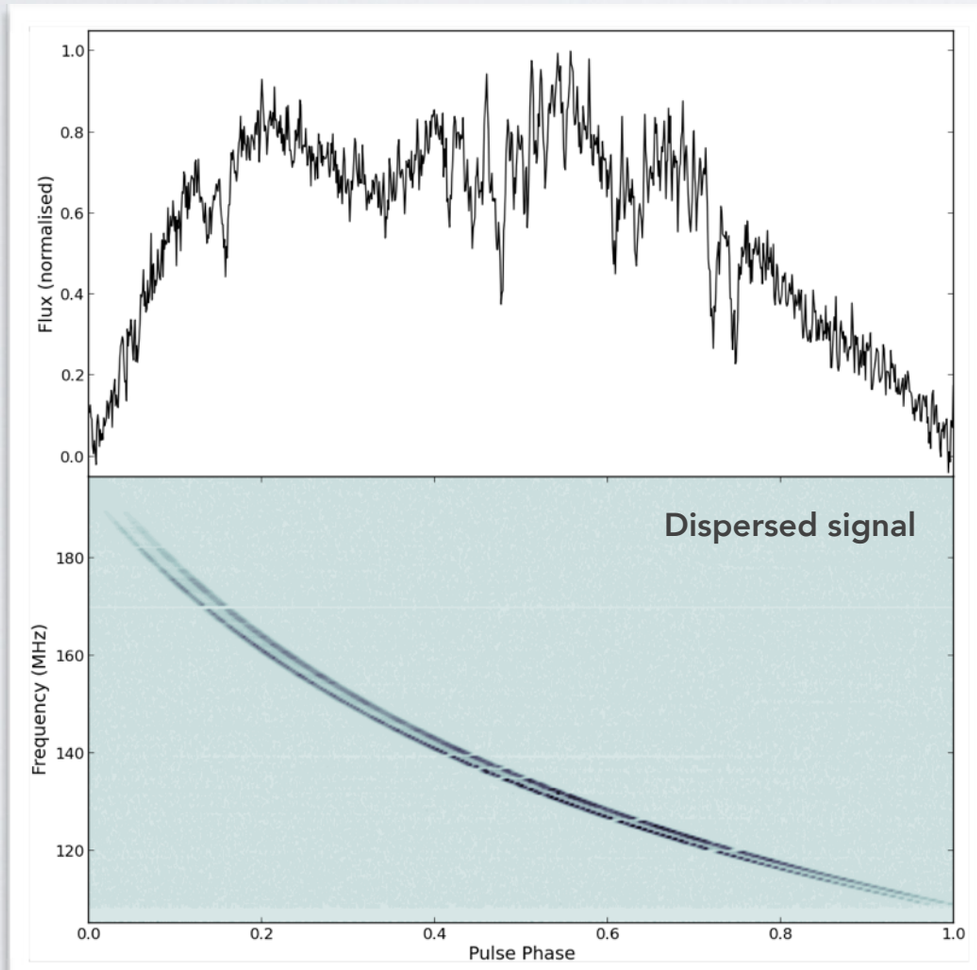


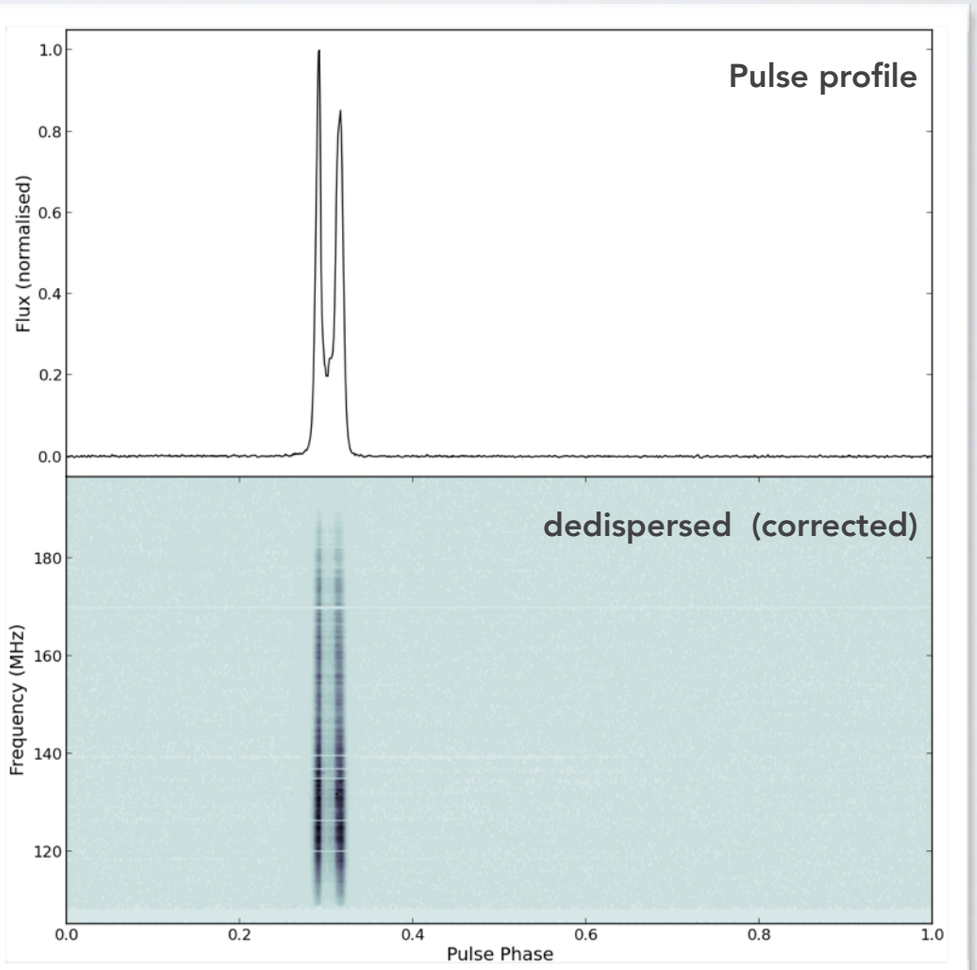
PULSARS… AS PROBES OF THE ISM

- Dispersed pulses measure electron density

$$\Delta t \simeq 4.15 \times 10^6 \text{ ms } \times (f_1^{-2} - f_2^{-2}) \times \text{DM}.$$

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





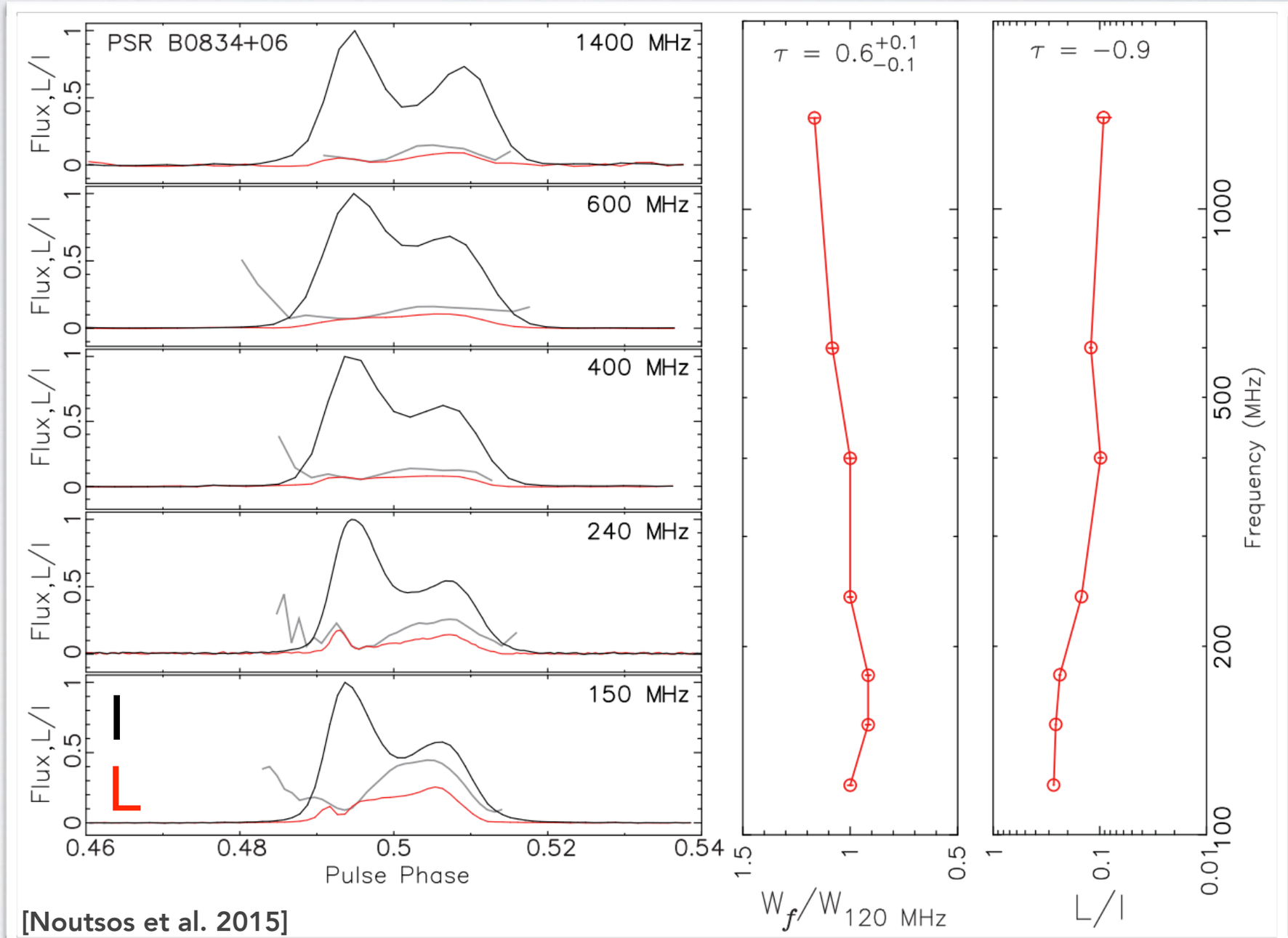
PULSARS… AS PROBES OF THE ISM

- Often highly (linearly) polarised - allows Faraday rotation measurements

$$\Delta PA = \mathrm{RM}\,\lambda^2$$

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

- Negligible 'internal' Faraday rotation especially at low-frequencies (e.g. Wang at al. 2011)



[Noutsos et al. 2015]

PULSARS… AS PROBES OF THE ISM

$$\langle B_{\parallel} \rangle = 1.232\ \mu G \frac{\mathrm{RM}=0.81 \int_{\mathrm{d}}^{0} n_{\mathrm{e}} \mathbf{B} \cdot \mathrm{d}\mathbf{r}\ \ \mathrm{rad\,m^{-2}}}{\mathrm{DM}=\int_{0}^{\mathrm{d}} n_{\mathrm{e}} \mathrm{dl}\ \ \mathrm{pc\,cm^{-3}}}$$

- Distributed throughout Milky Way (extragalactic sources provide entire LoS)
- Distances known (parallax) or estimated (DM distance with n_e model)

Previous work, e.g.:
Manchester 1972;
Manchester1974;
Rand & Lyne 1994;
Han et al. 1999, 2006;
Noutsos et al. 2008,
van Eck et al. 2011

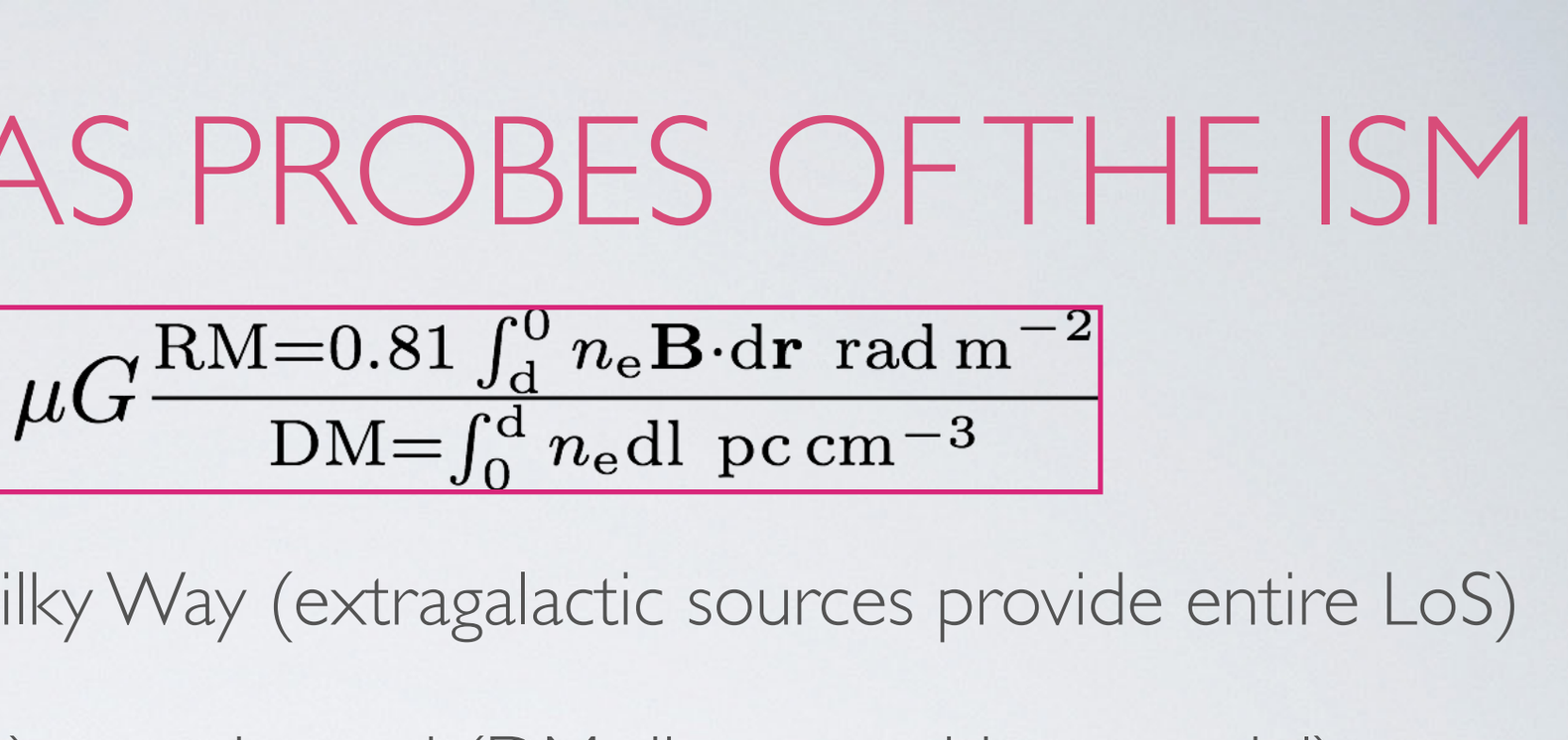


FIG. 2.—Mean line-of-sight magnetic field components for pulsars plotted in galactic coordinates. For fields greater than 0.3 microgauss the circle diamter is proportional to the field strength; for positive rotation measures (field toward the observer) the circles are filled, whereas for negative rotation measures (field away from the observer) they are open. The diameter for a 1-microgauss field is indicated in the figure.

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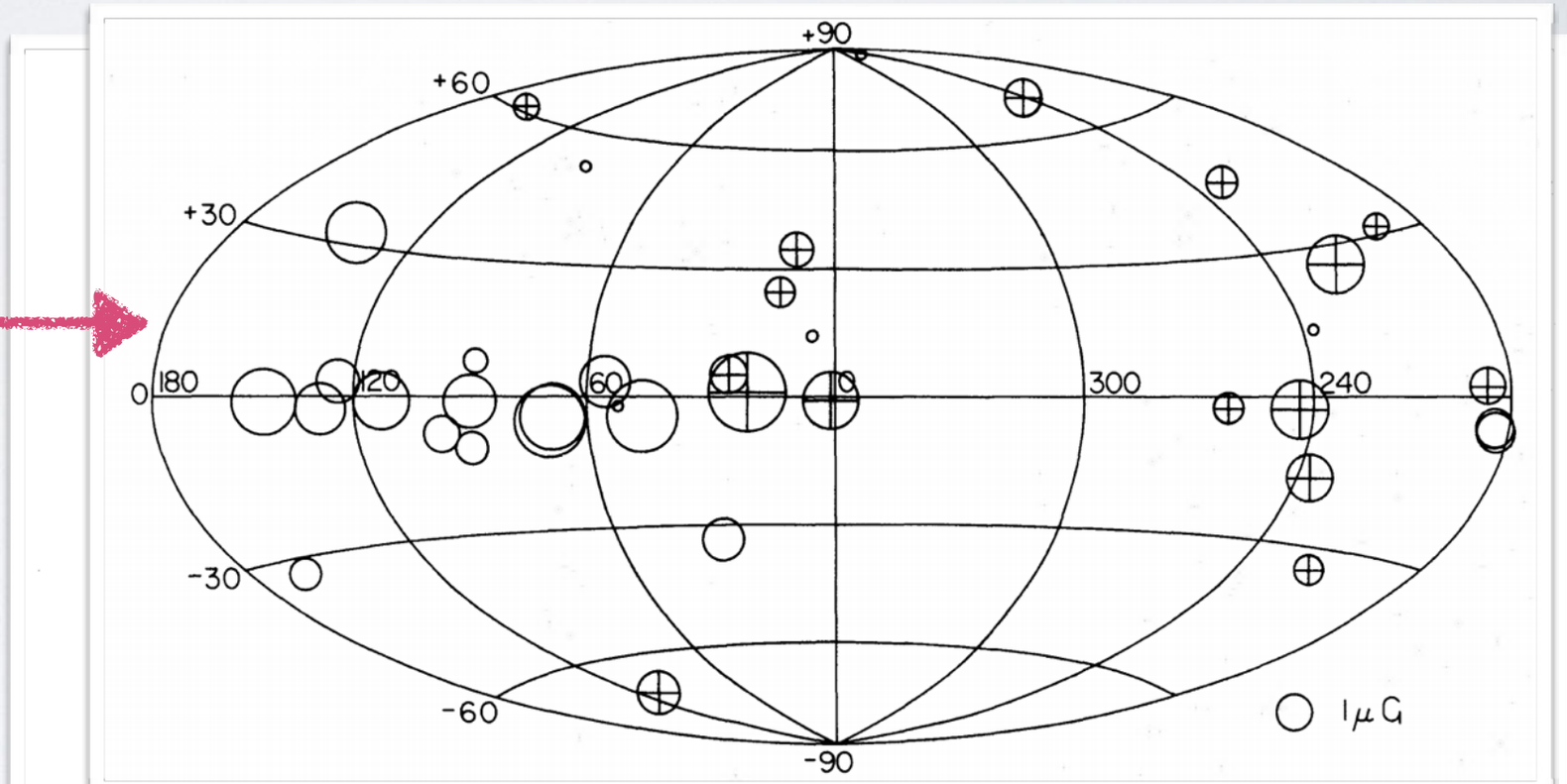

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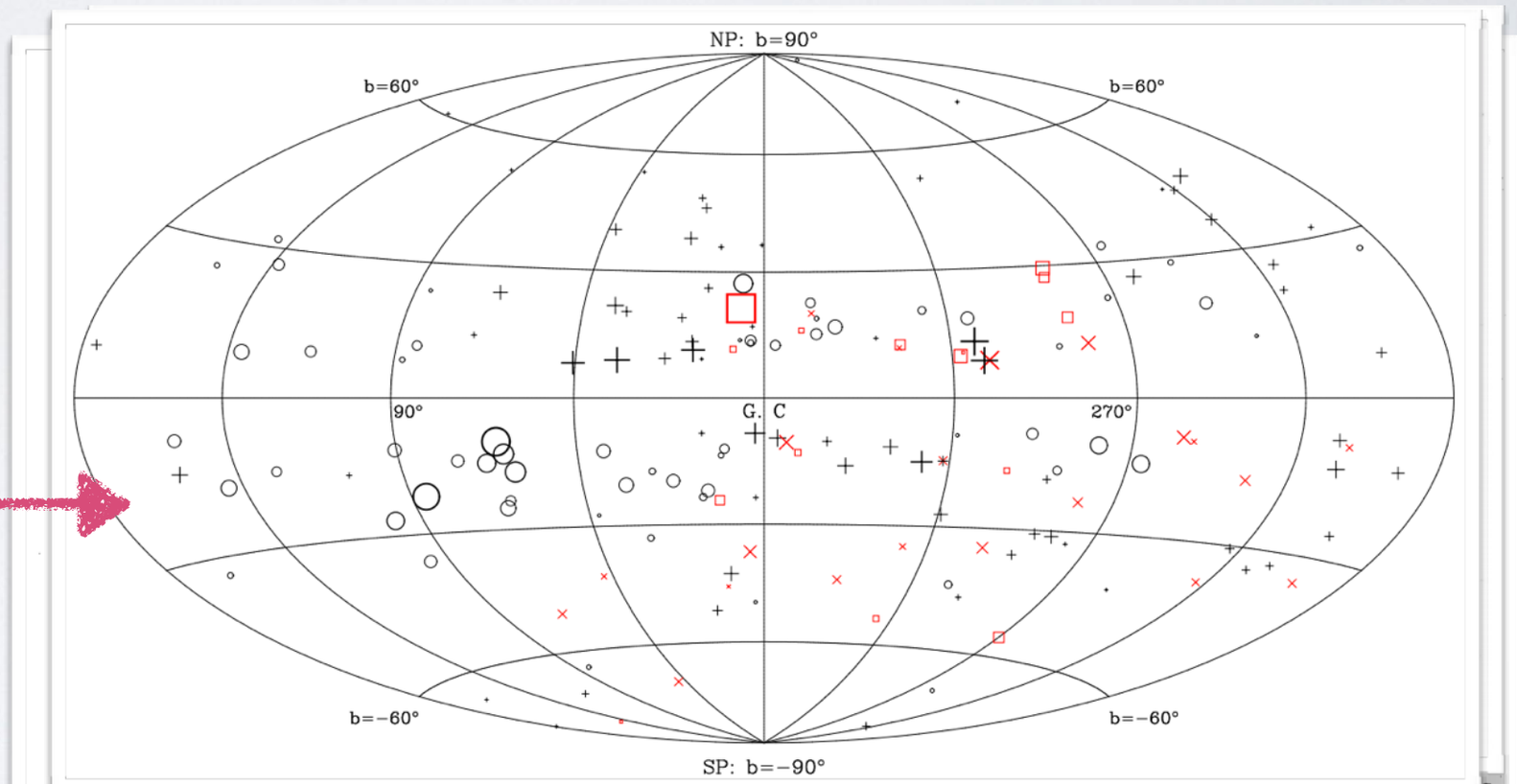

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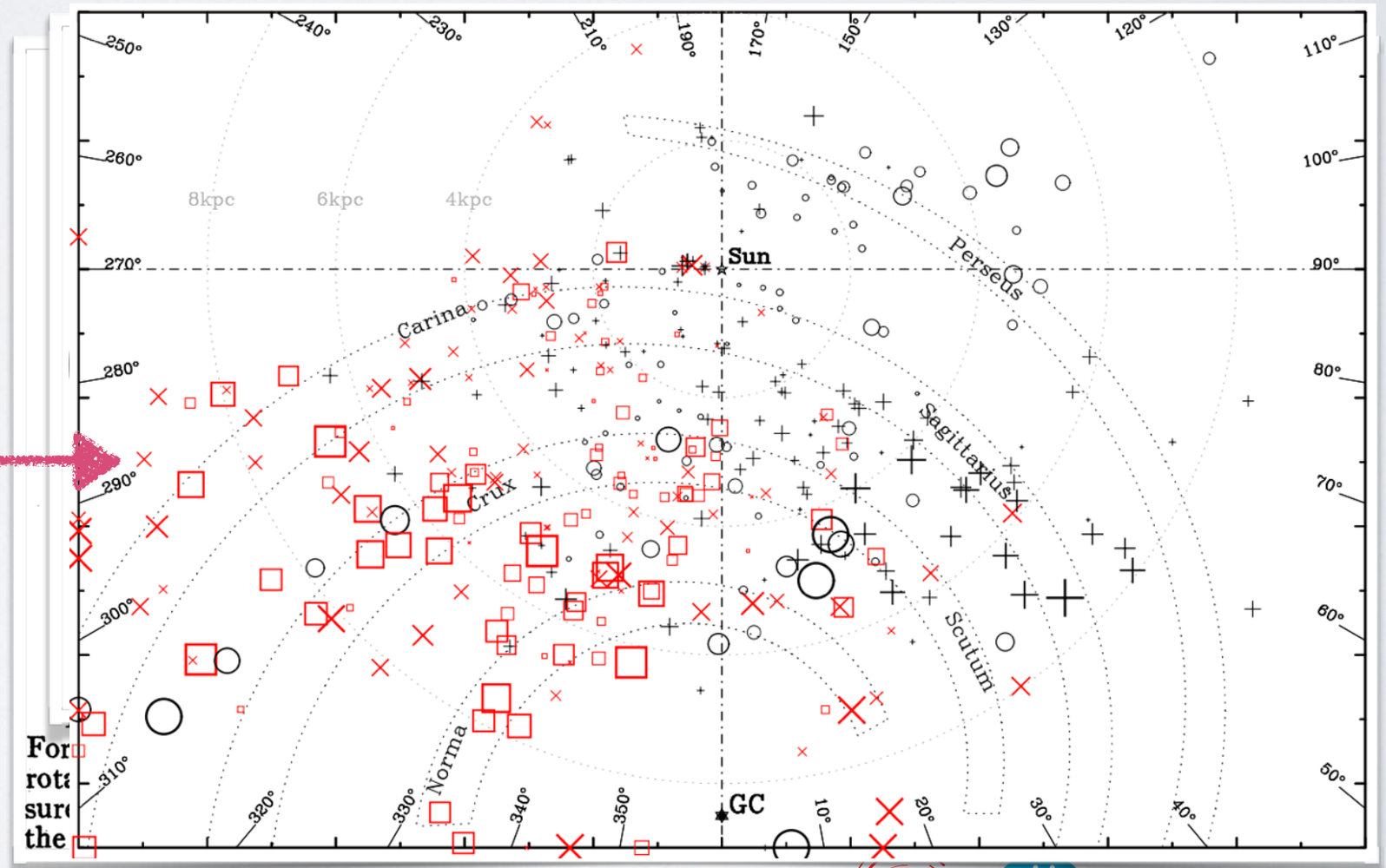

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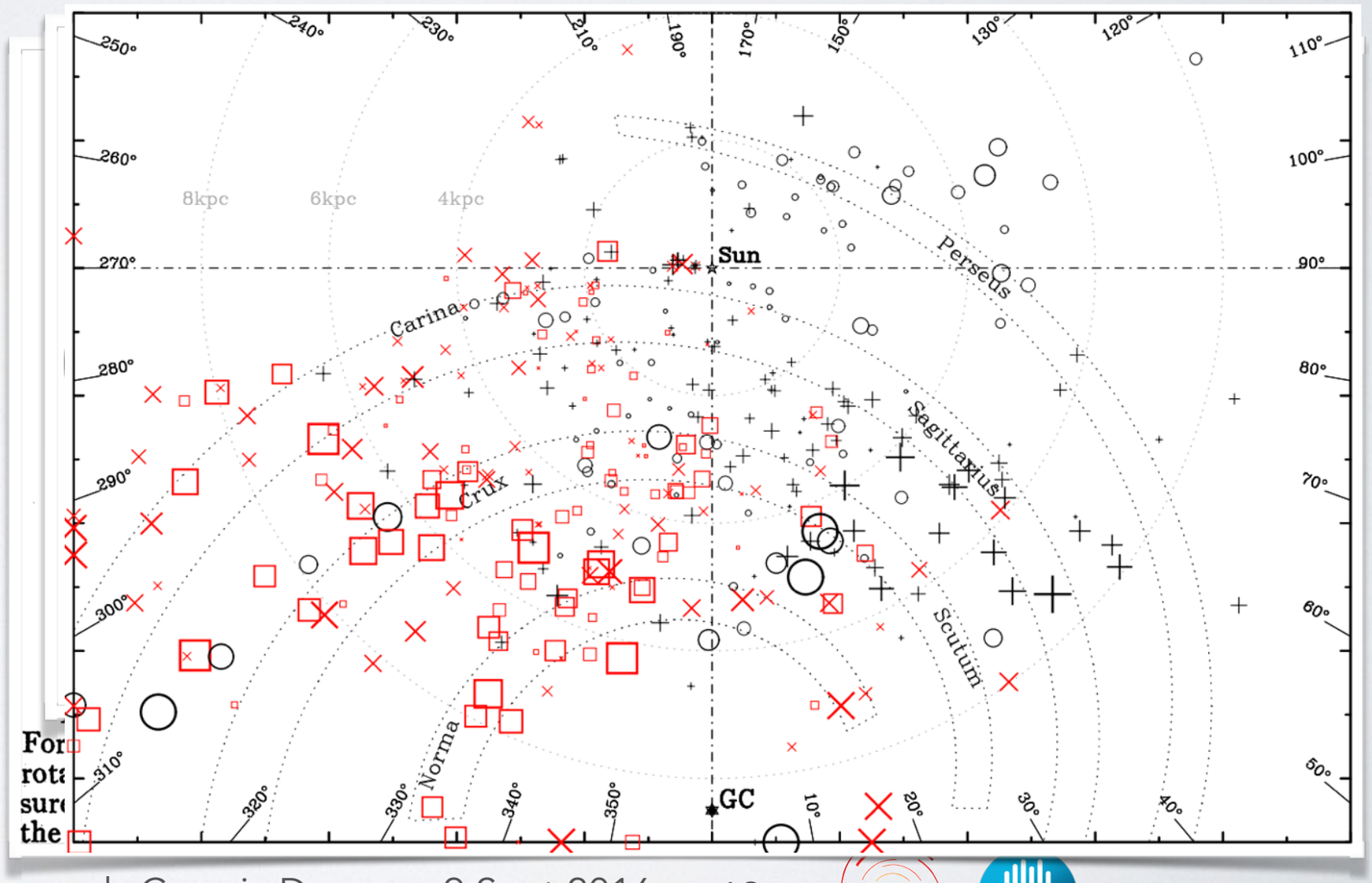
- Distributed throughout Milky Way (extragalactic sources provide entire LoS)
- Distances known (parallax) or estimated (DM distance with n_e model)
- Currently:
  2613 known pulsars,
  732 (28%) have
  published RMs



RECENT LOW-FREQUENCY RENAISSANCE

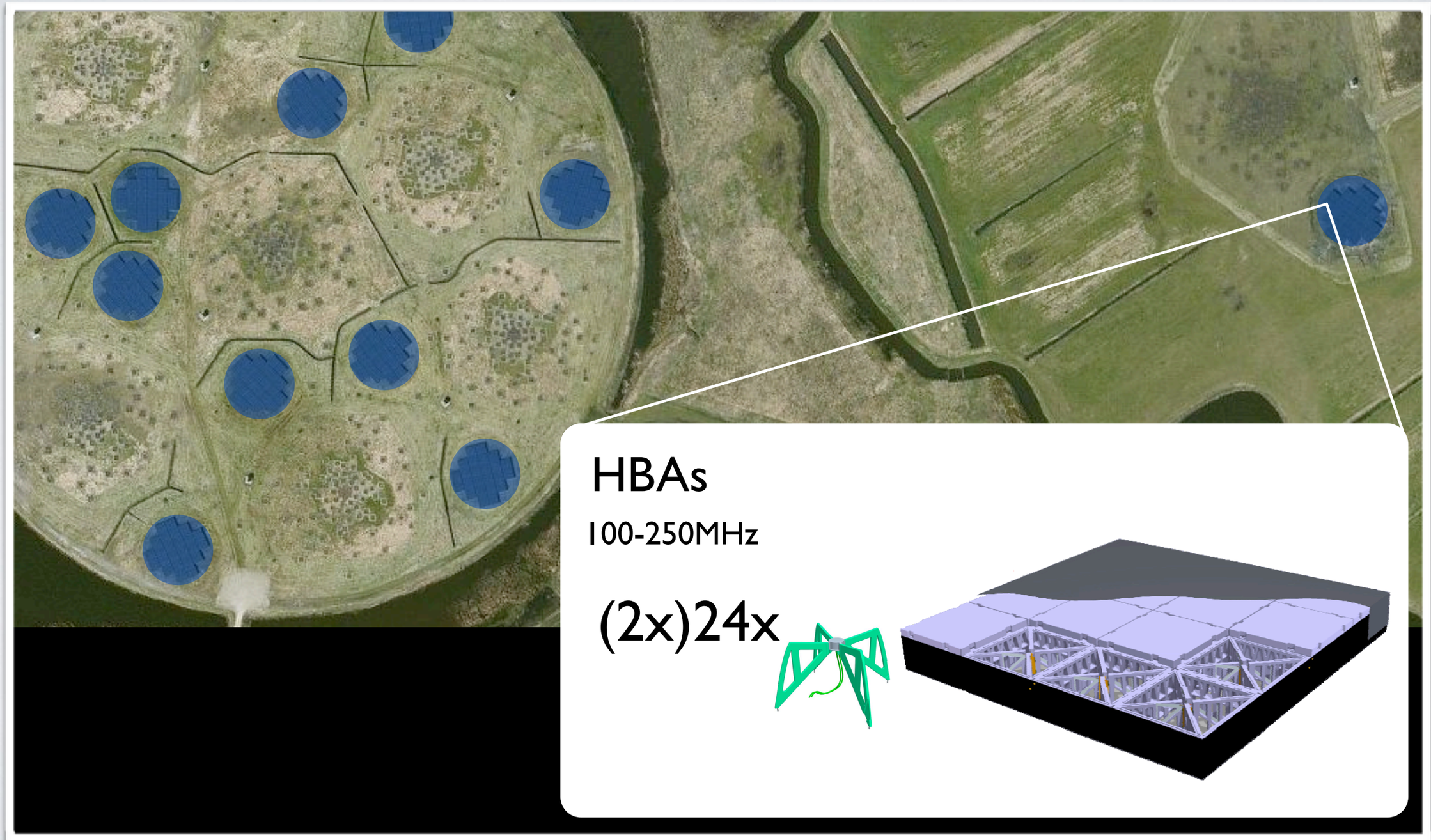
LOFAR
Low-frequency Array
10-90, 110-240 MHz
van Haarlem et al. 2013
Stappers et al. 2011

MWA
Murchison Widefield Array
80-300 MHz
Tingay et al. 2013
Tremblay et al. 2015

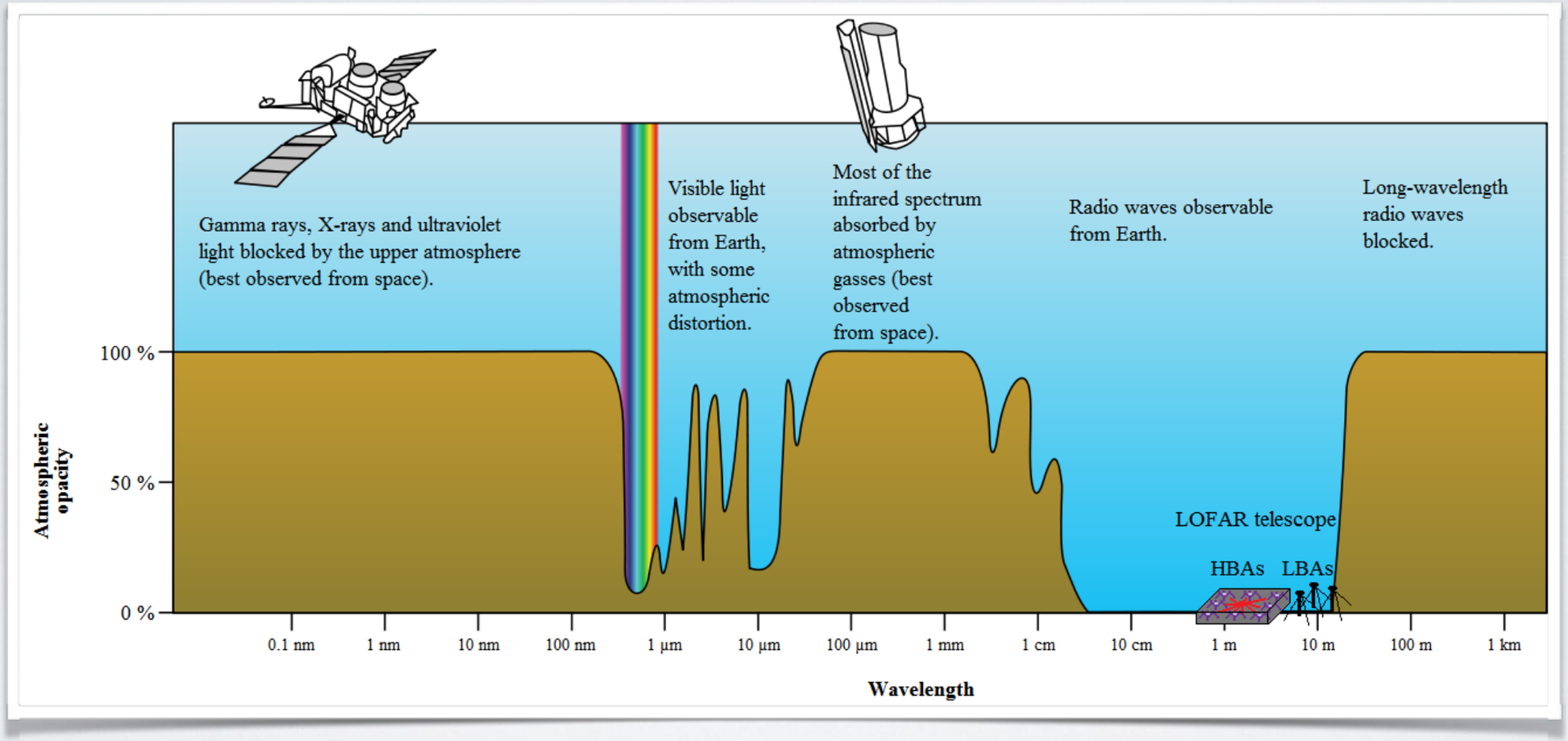
LWA
Long Wavelength Array
20-80 MHz
Kassim et al. 2010
Stovall et al. 2015

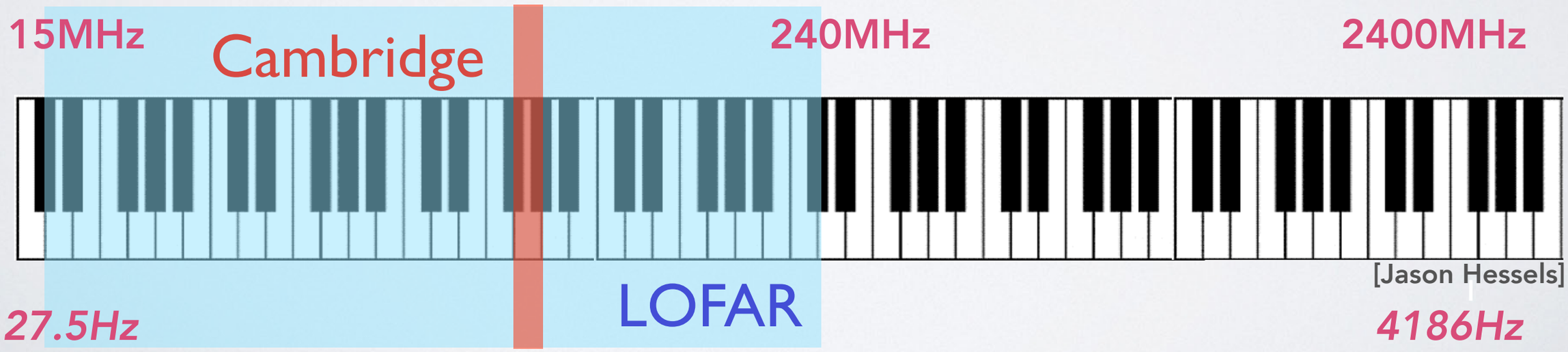
LOFAR (LOW-FREQUENCY ARRAY)

The High-Band Antennas (HBAs)



LOFAR'S WIDE BAND (2.0)

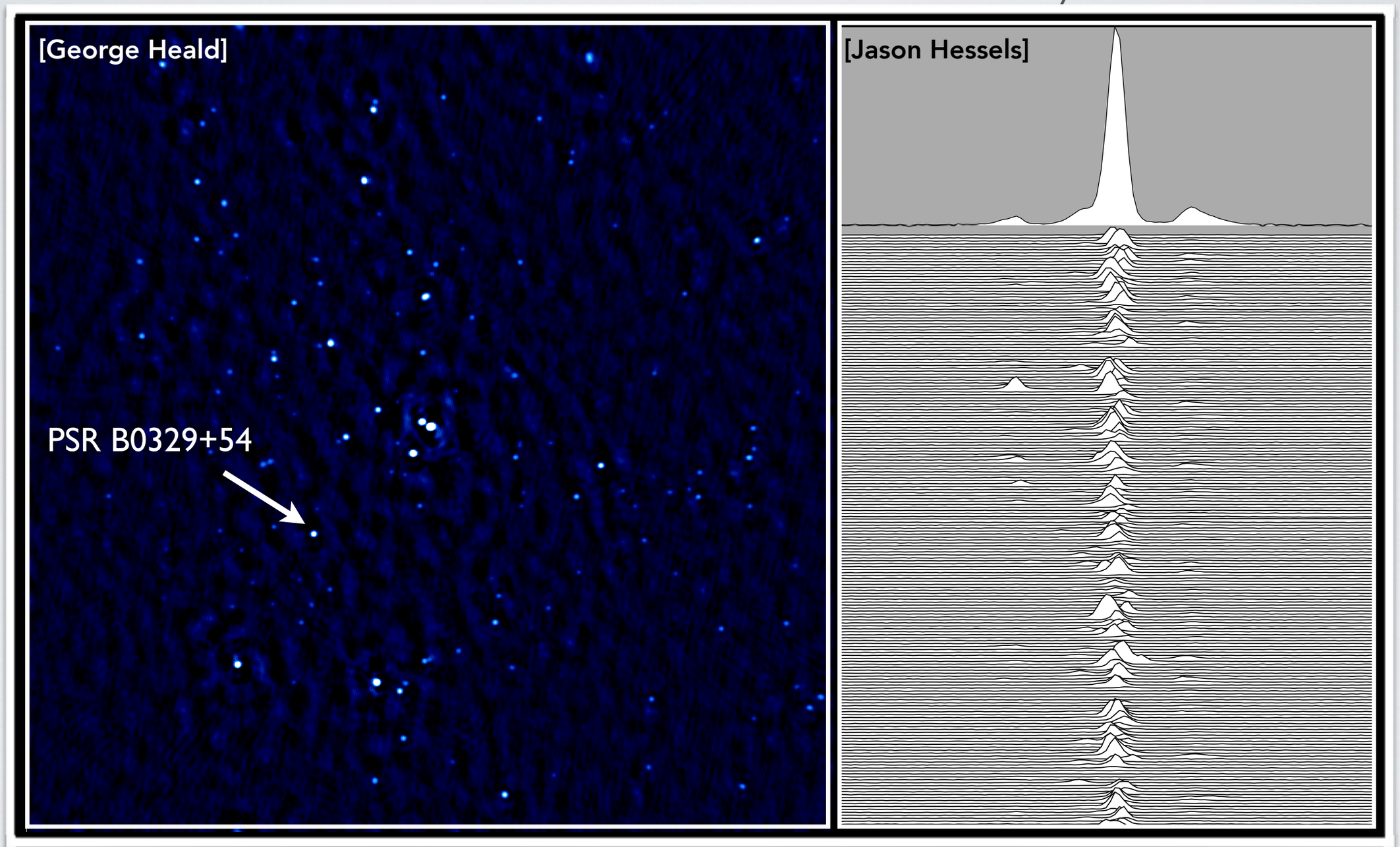




CSIRO Curtin University

LOFAR'S INSTRUMENT MODES

Interferometer **and**/or tied-array beamformer



1 s time resolution

1 ms time res.

LOFAR PULSAR WORKING GROUP

Jason Hessels (co-lead; ASTRON/UvA)
Ben Stappers (co-lead; Manchester)

Anya Bilous (Amsterdam)
Rene Breton (Manchester)
Thijs Coenen (UvA)
Sally Cooper (Manchester)
Heino Falcke (Nijmegen)
Jean-Mathias Grießmeier (LPC2E & CNRS)
Tom Hassall (Southampton)
Aris Karastergiou (Oxford)
Evan Keane (SKA)
Vlad Kondratiev (ASTRON)
Michael Kramer (MPIfR)
Masaya Kuniyoshi (NAOJ)
Aris Noutsos (MPIfR)
Stefan Oslowski (MPIfR & Bielefeld)
Maura Pilia (Sardinia)
Maciej Serylak (Cape Town)
Charlotte Sobey (ICRAR-Curtin & CASS)
Sander ter Veen (ASTRON)
Joeri van Leeuwen (ASTRON)
Joris Verbiest (Bielefeld/MPIfR)
Patrick Weltevrede (Manchester)
Kimon Zagkouris (Oxford)

[See Stappers et al. 2011 for description of LOFAR's pulsar modes]

LOFAR MAGNETISM KEY SCIENCE PROJECT

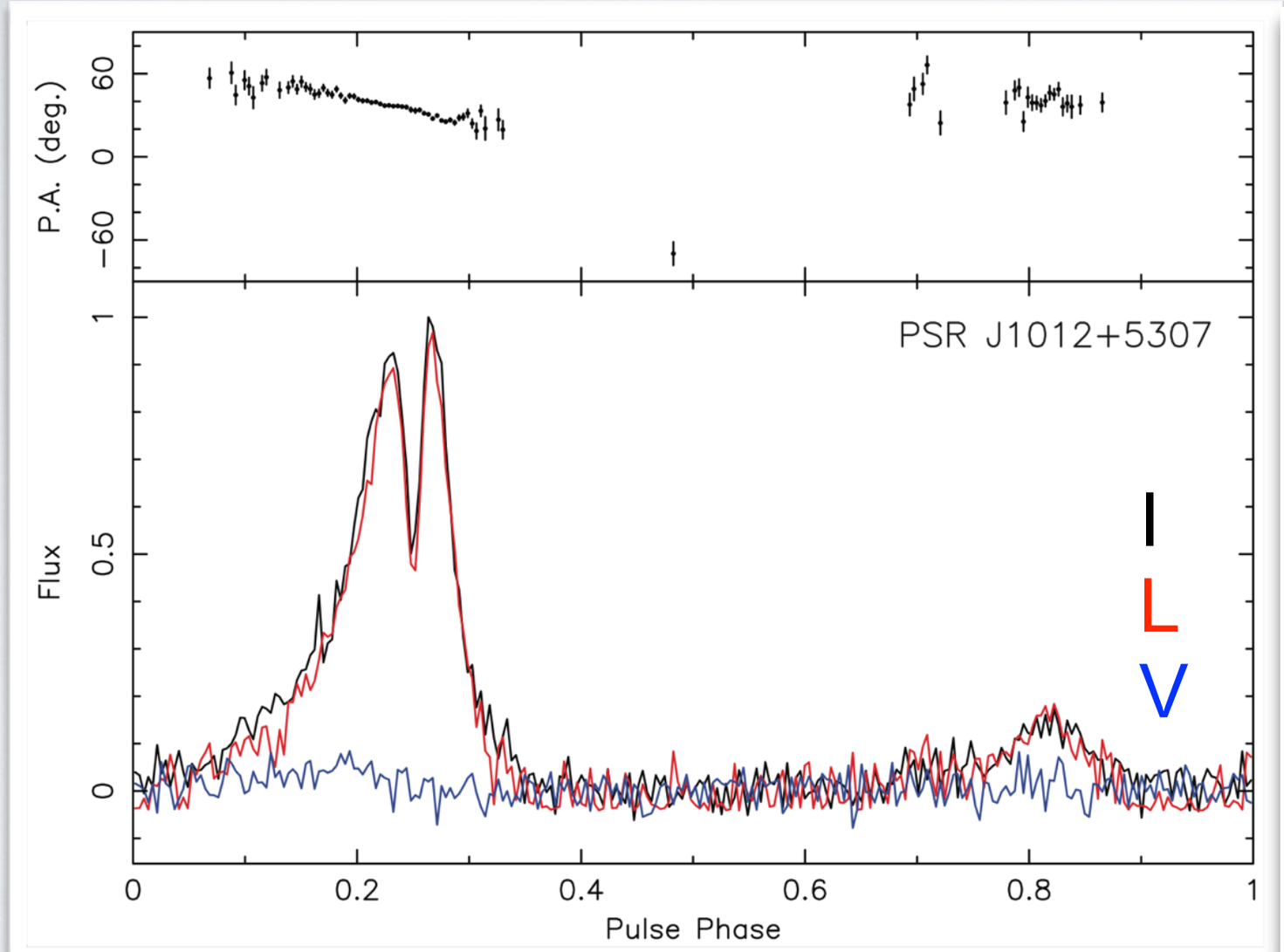
George Heald (co-lead; CSIRO)
Anna Scaife (co-lead; Manchester)

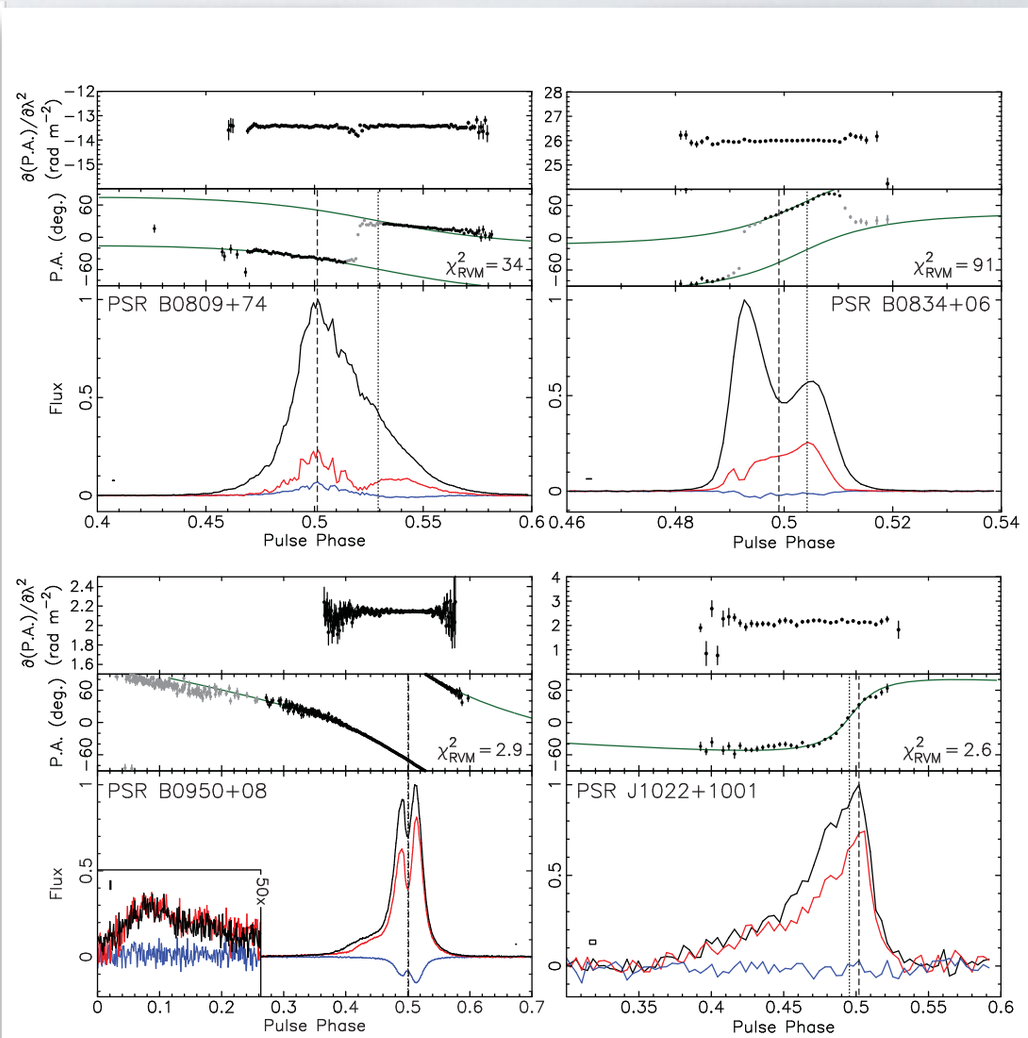
Full members:
Björn Adebahr (ASTRON)
James Anderson (GFZ Potsdam)
Rainer Beck (MPIfR)
Mike Bell
Annalisa Bonafede (Hamburg)
Michiel Brentjens (ASTRON)
Ger de Bruyn (ASTRON/Kapteyn)
Chris Chyzy (Kraków)
Alex Clarke (Manchester)
Ralf-Jürgen Dettmar (Bochum)
Torsten Enßlin (MPA)
Andrew Fletcher (Newcastle)
Marijke Haverkorn (Nijmegen)
Cathy Horellou (Onsala)
Andreas Horneffer (MPIfR)
Marco Iacobelli (ASTRON)
Henrik Junklewitz (Bonn)
Wojciech Jurusik (Kraków)
Jana Köhler (MPIfR)
David Mulcahy (Manchester)
Blazej Nikiel-Wroczynski (Kraków)
Aris Noutsos (MPIfR)
Emanuela Orru (ASTRON)
Rosita Paladino (IRA Bologna)
Roberto Pizzo (ASTRON)
Wolfgang Reich (MPIfR)
Katharina Sendlinger (Bochum)
Charlotte Sobey (ICRAR-Curtin & CSIRO)
Sarrvesh S. Sridhar (Groningen/Kapteyn)
Valentina Vacca (MPA Garching)
Cameron Van Eck (Nijmegen)

[See Beck et al. 2013 for LOFAR's view of cosmic magnetism]

LOFAR POLARISATION PROFILES

- LOFAR's large fractional bandwidth and collecting area produce high-quality polarisation profiles of pulsars below 200 MHz (105—197MHz)





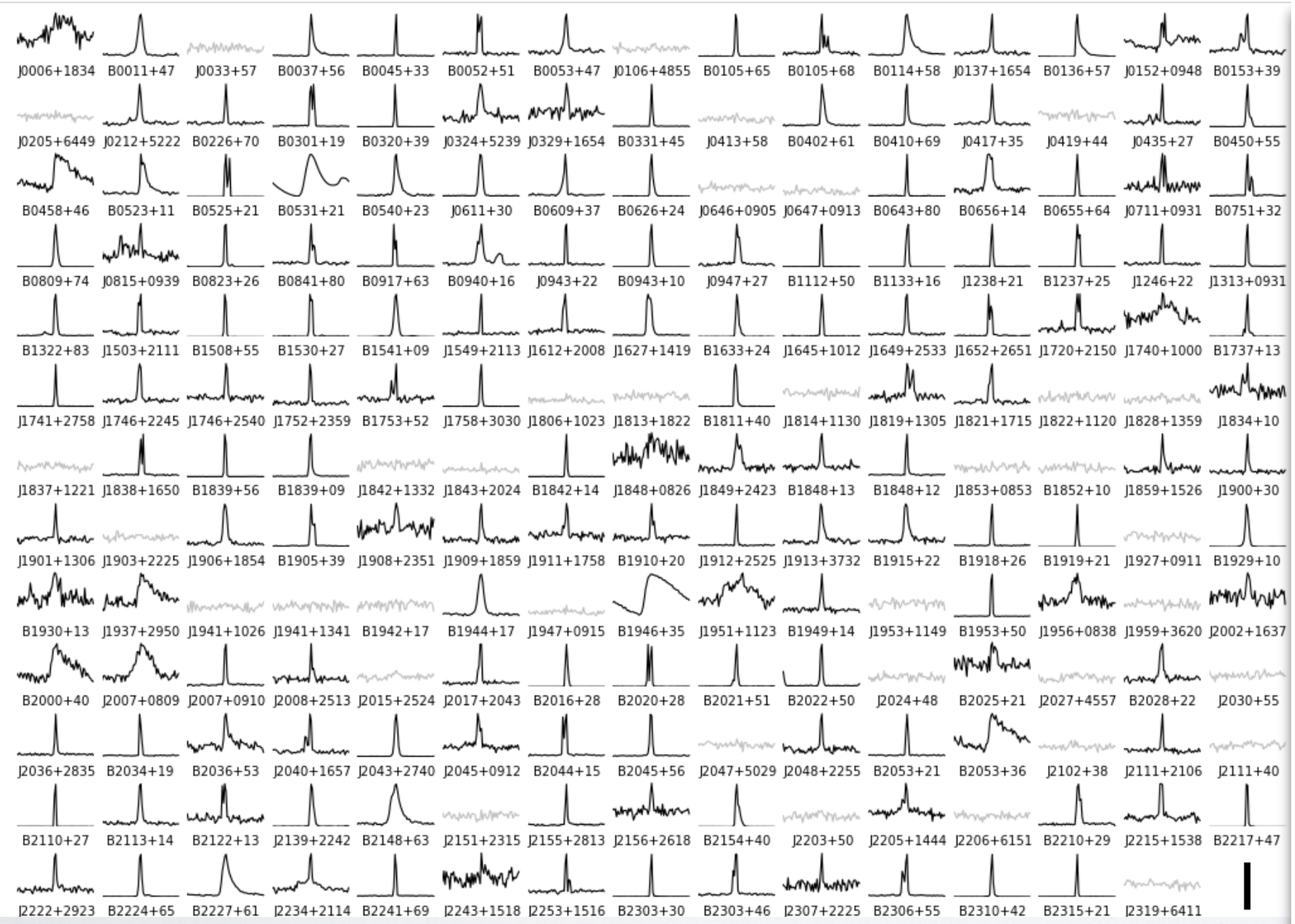
[Noutsos et al. 2015]

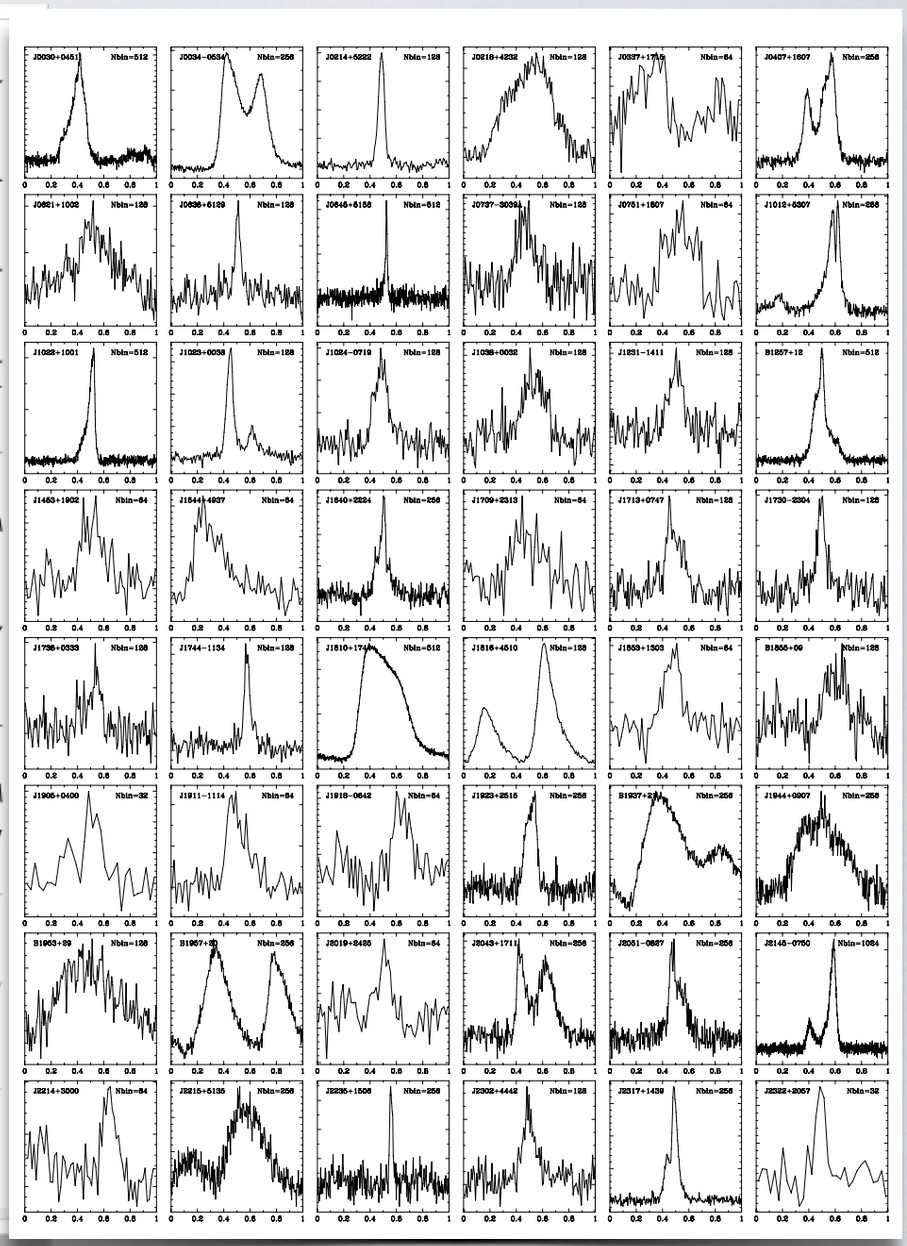
LOFAR OBSERVATIONS OVERVIEW

- HBA pulsar census (Bilous et al. 2016):
  - Large set of 195 pulsars (158 detected), |b|>3°, dec>+8°
  - 149 MHz, 78 MHz bandwidth, >= 20-minute integrations
- Millisecond pulsar (MSP) census (Kondratiev et al. 2016)
- Dedicated observations of pulsars with independent parallax distances
- Pulsar survey discoveries (~60; LOTAAS; Sanidas et al., in prep.)
- HBA timing (regular ~monthly observations)

‘NORMAL’ & MSP CENSUS PROFILES

- 158 ‘slow’ pulsars detected
- 48 MSPs detected

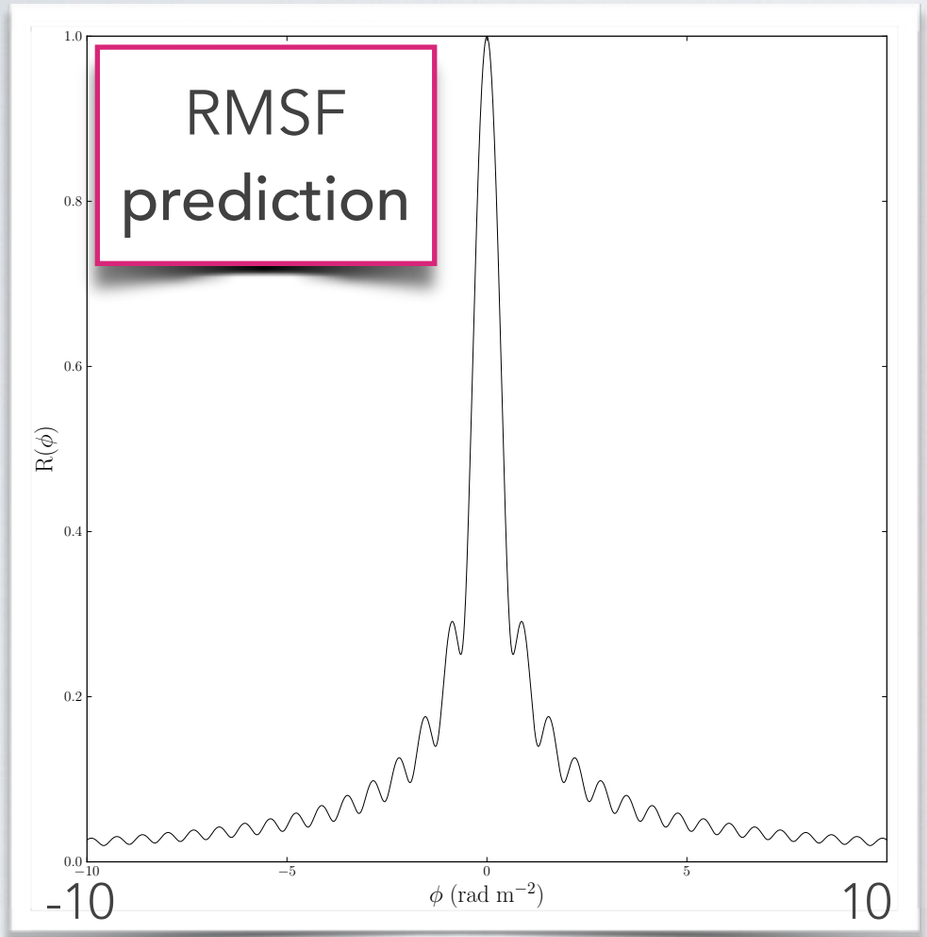


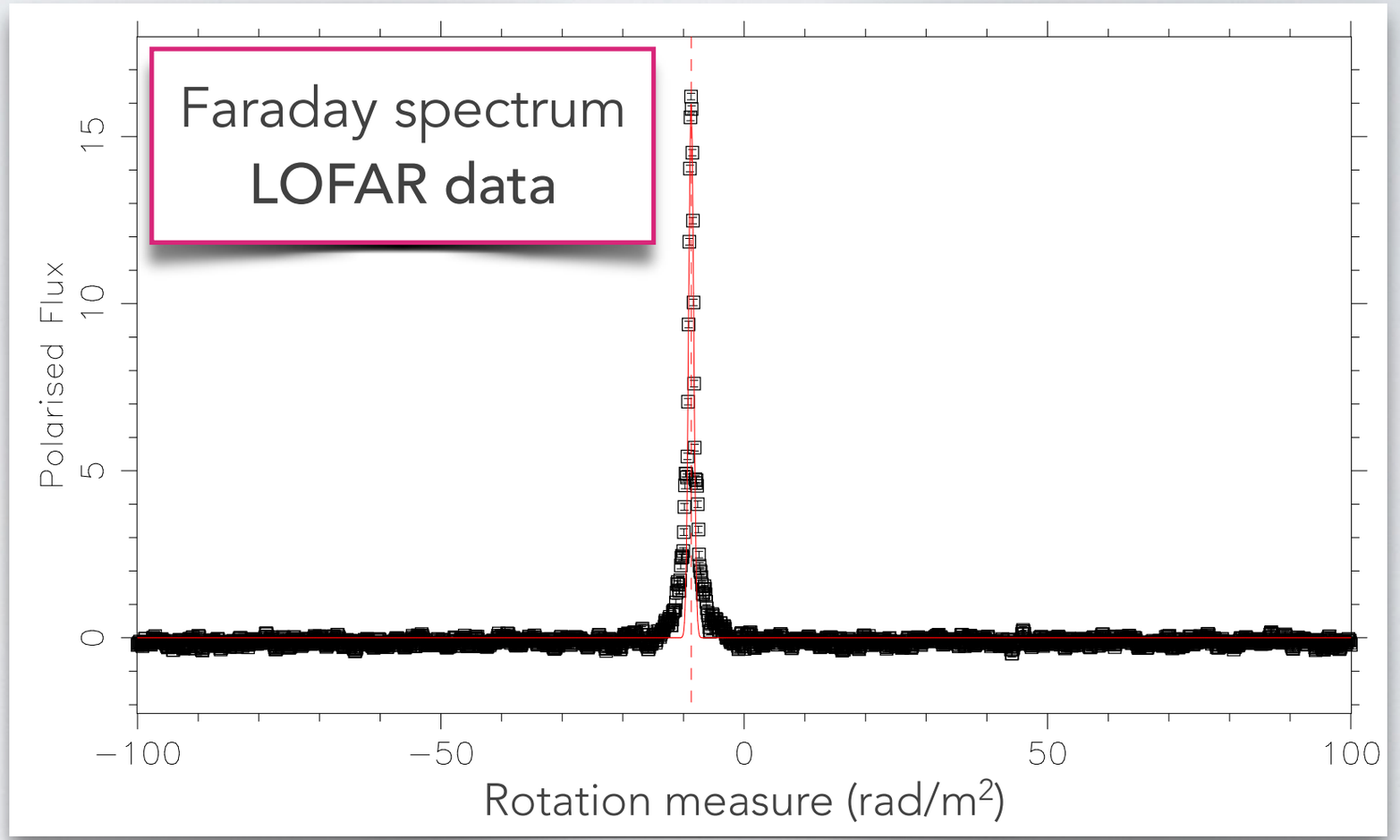


[Bilous et al. 2016] [Kondratiev et al. 2016]

MEASURING RMs USING RM-SYNTHESIS

- Using Stokes Q,U(λ^2) (Burn 1966; Brentjens & de Bruyn 2005) $\delta\phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2}$
- LOFAR HBA data gives noiseless RMSF FWHM$_{150MHz}$ ~ 0.8 rad/m^2

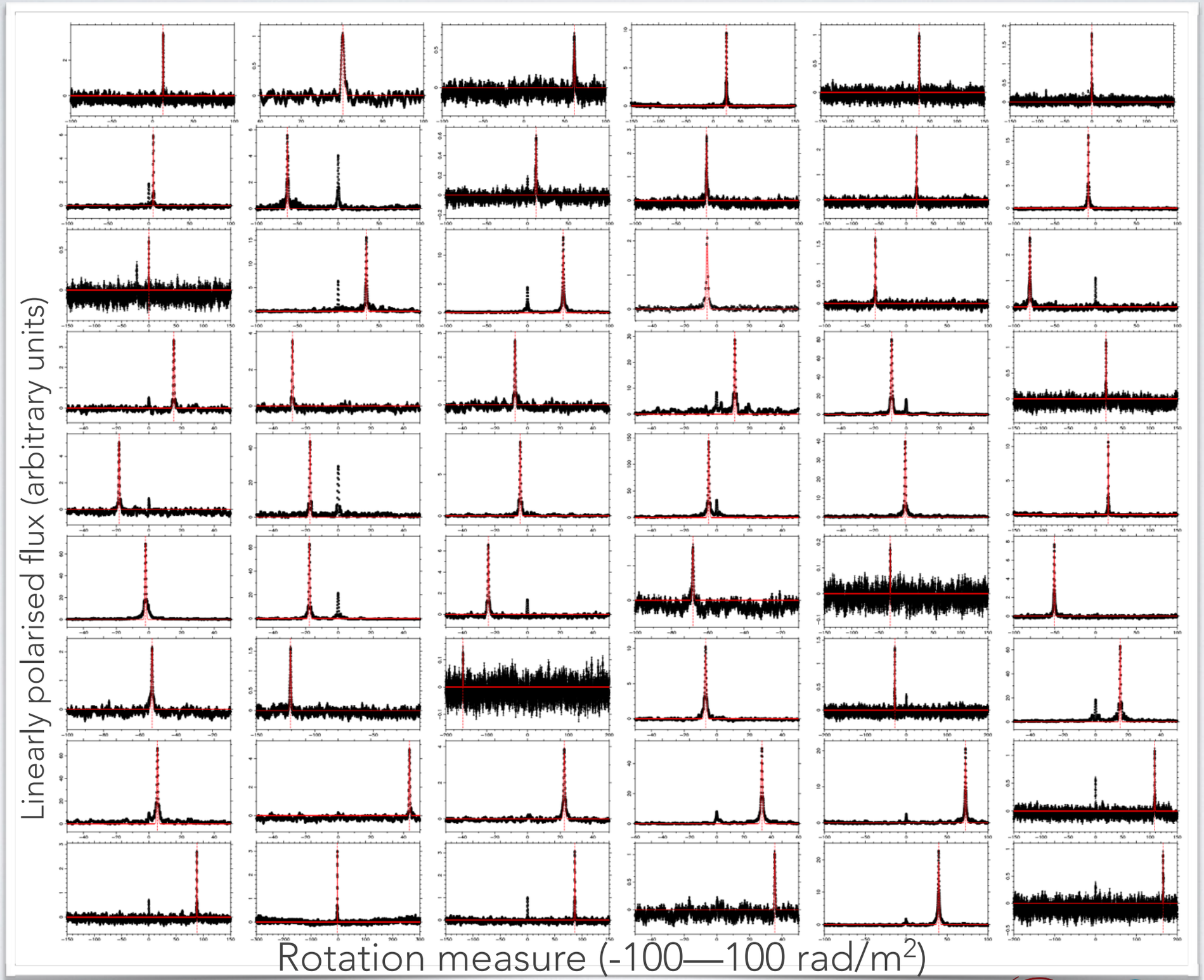




- cf.: FWHM$_{1.4GHz}$ ~ 300 rad/m^2 | FWHM$_{350MHz}$ ~10 rad/m^2

10x lower frequency: ~100x more precise!

FARADAY SPECTRA EXAMPLES

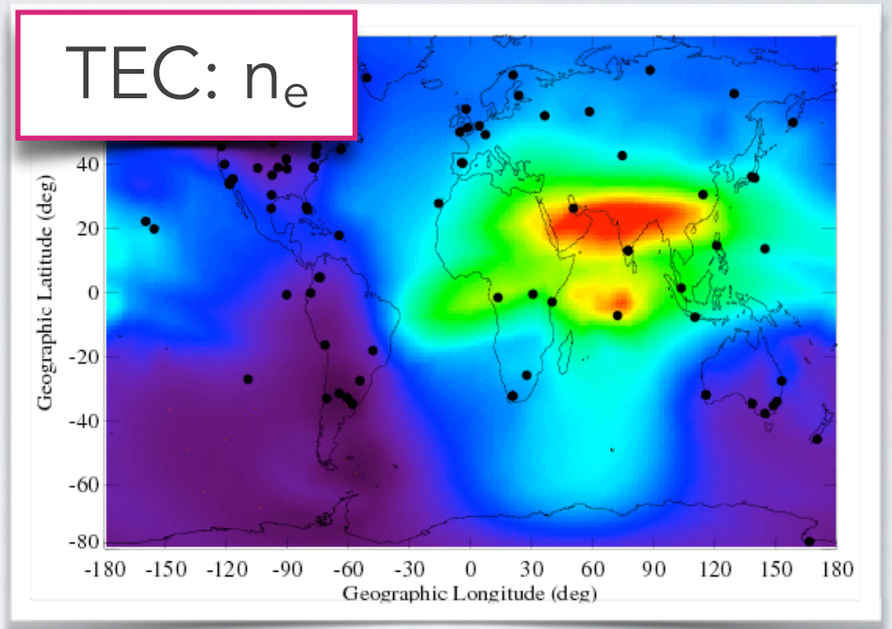


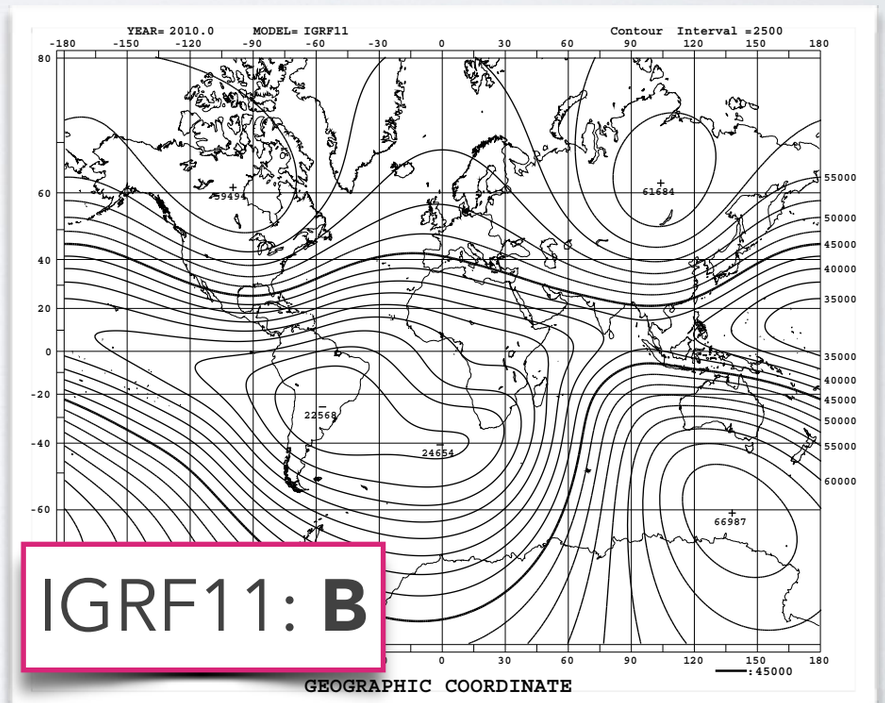
IONOSPHERIC RM CORRECTIONS

- Also a magneto-ionic medium
- Introduces time & position dependence to the RM

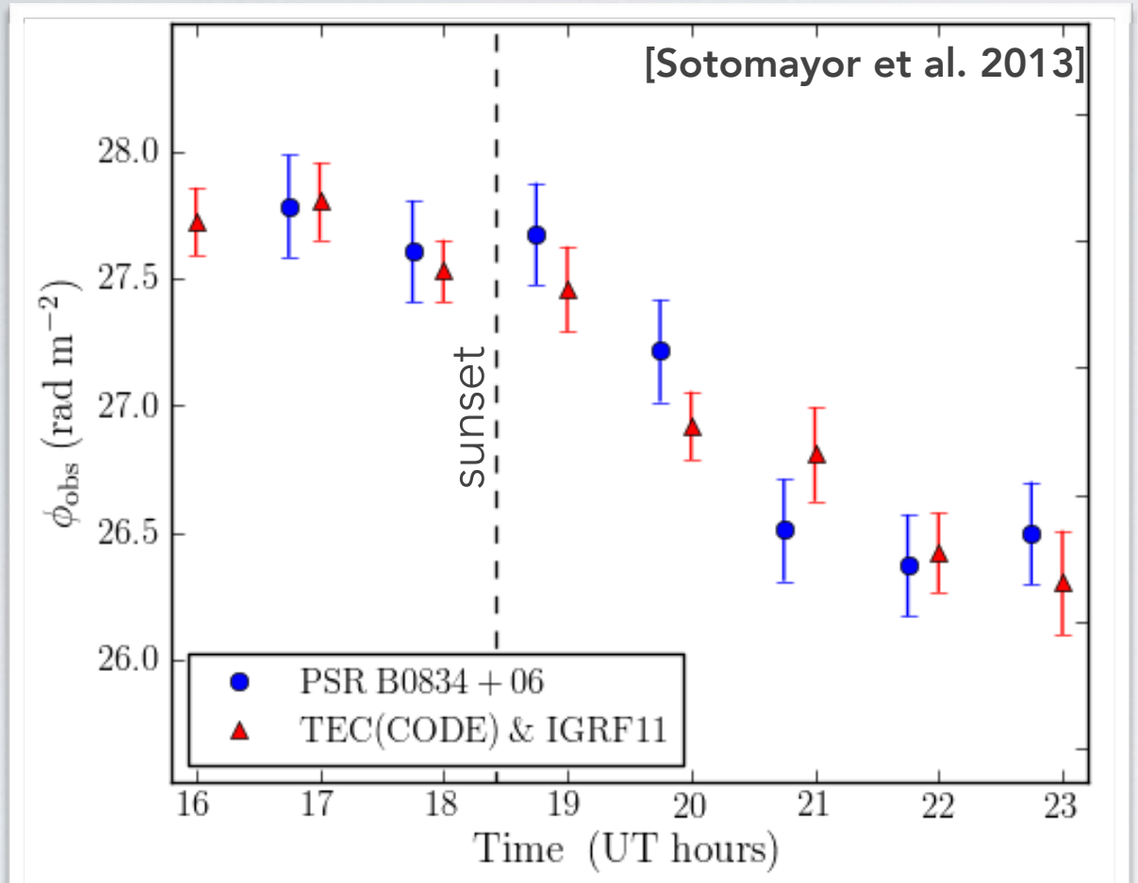
$$\mathrm{RM_{obs}} = \mathrm{RM_{ISM}} + \mathrm{RM_{ion}}$$

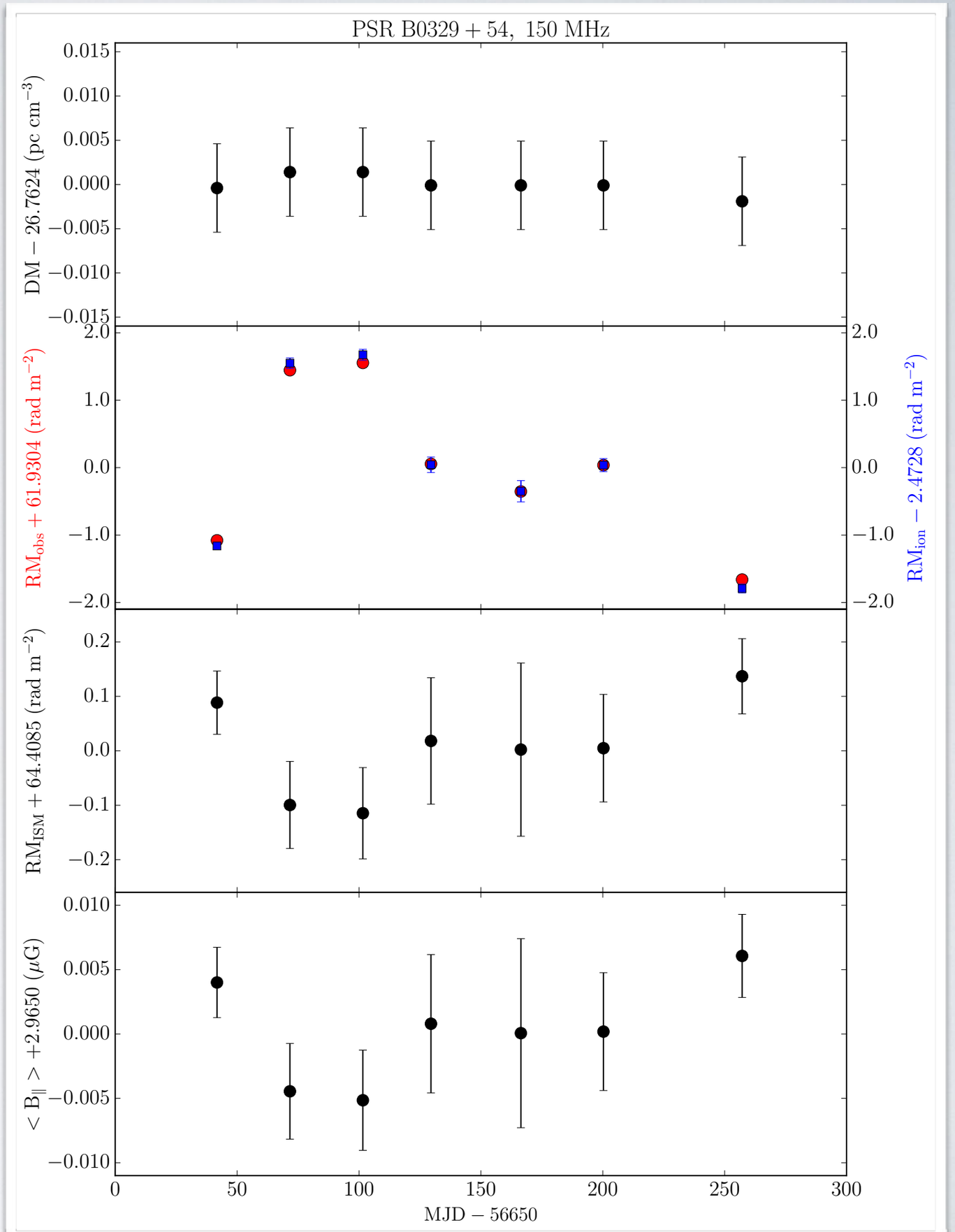
- ionFR (Sotomayor-Beltran et al. 2013) calculates ionospheric RM(LoS) using publicly available:
  - Total electron content (TEC) maps
  - International Geomagnetic Reference Field (IGRF)





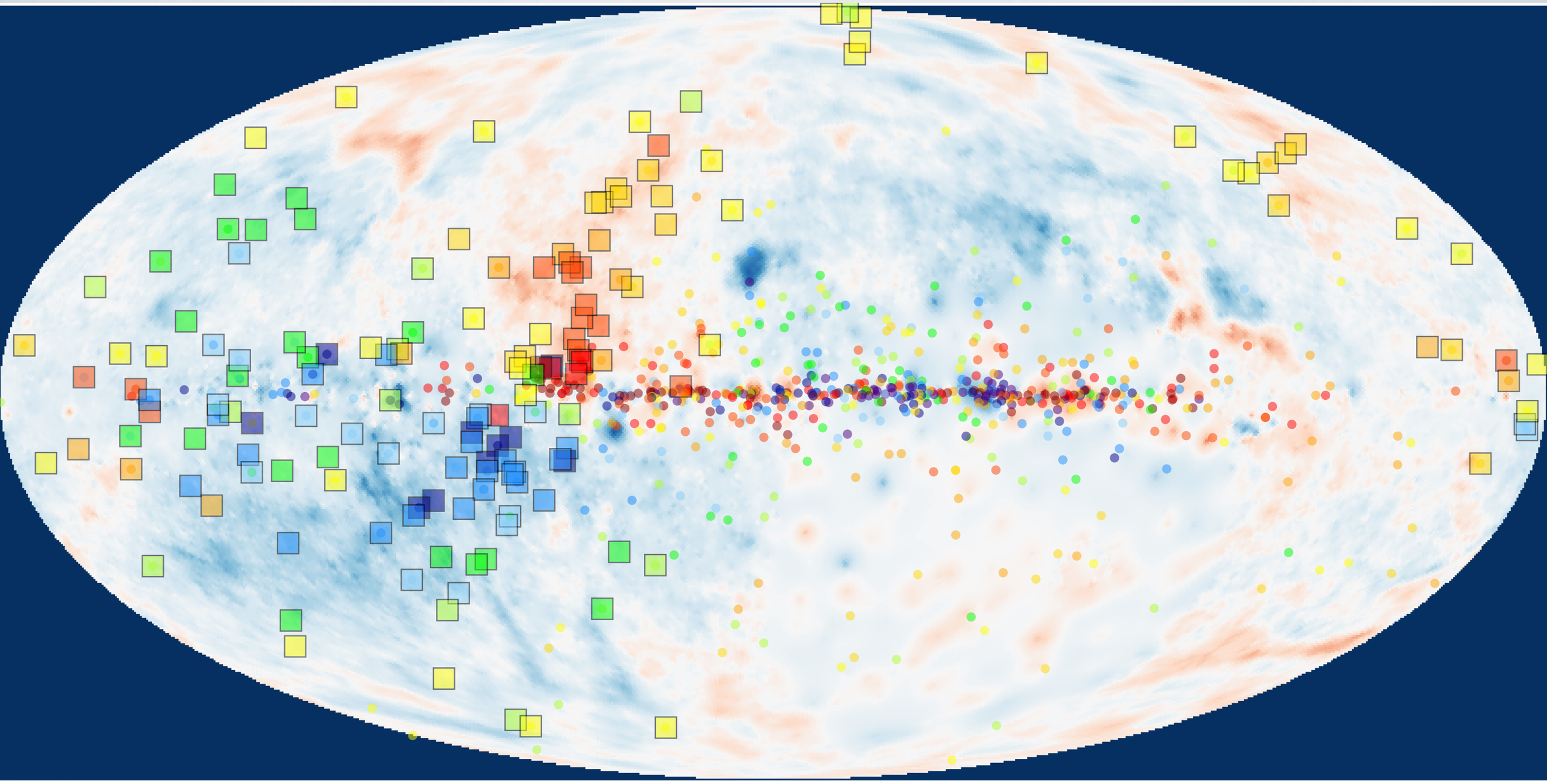
IONOSPHERE





- LOFAR RMs and ionospheric RM comparison
- Accuracy ~0.1 rad/m^2 or 0.005uG (now limited by ionospheric RM subtraction)

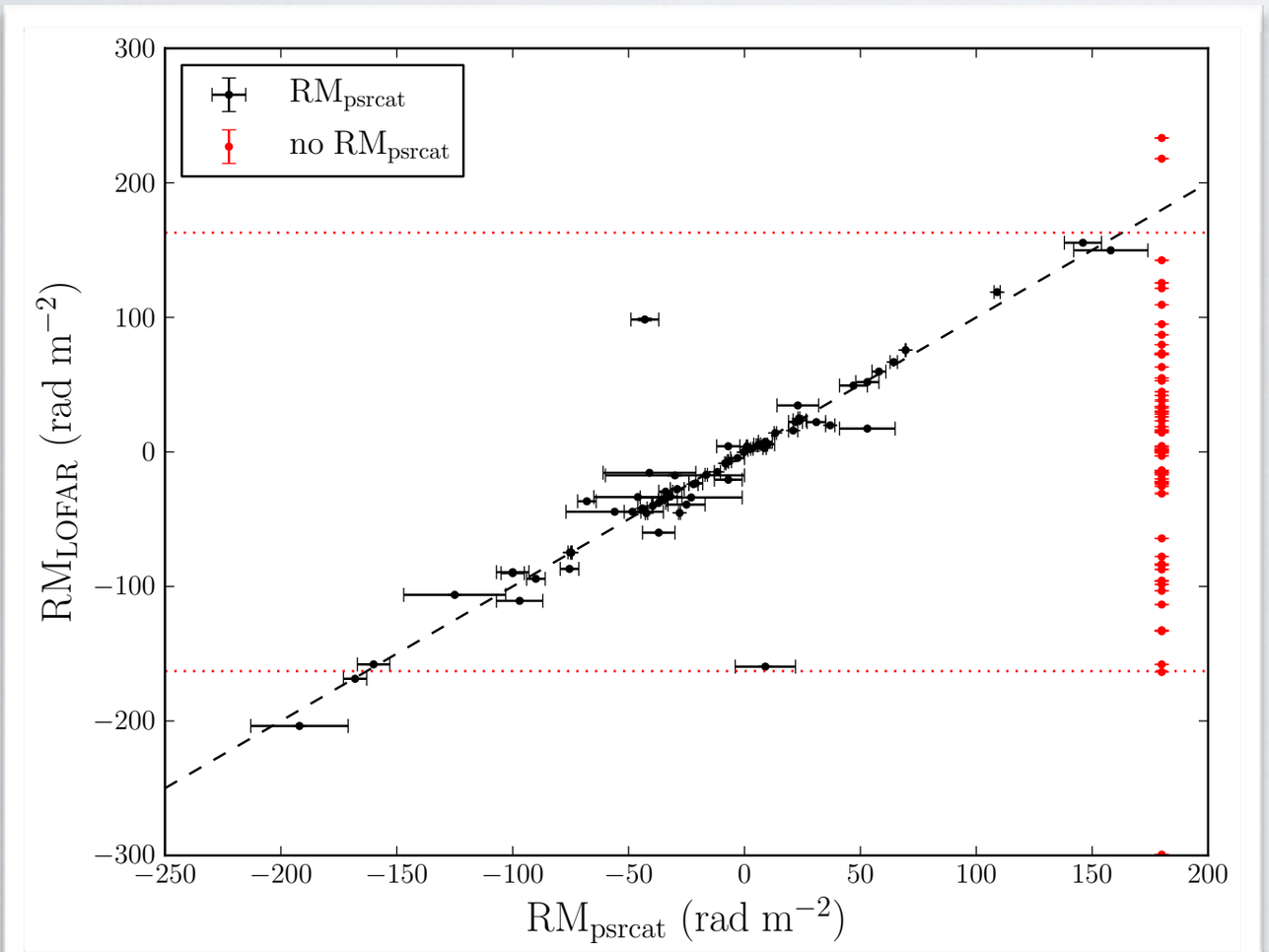
FARADAY ROTATION SKY

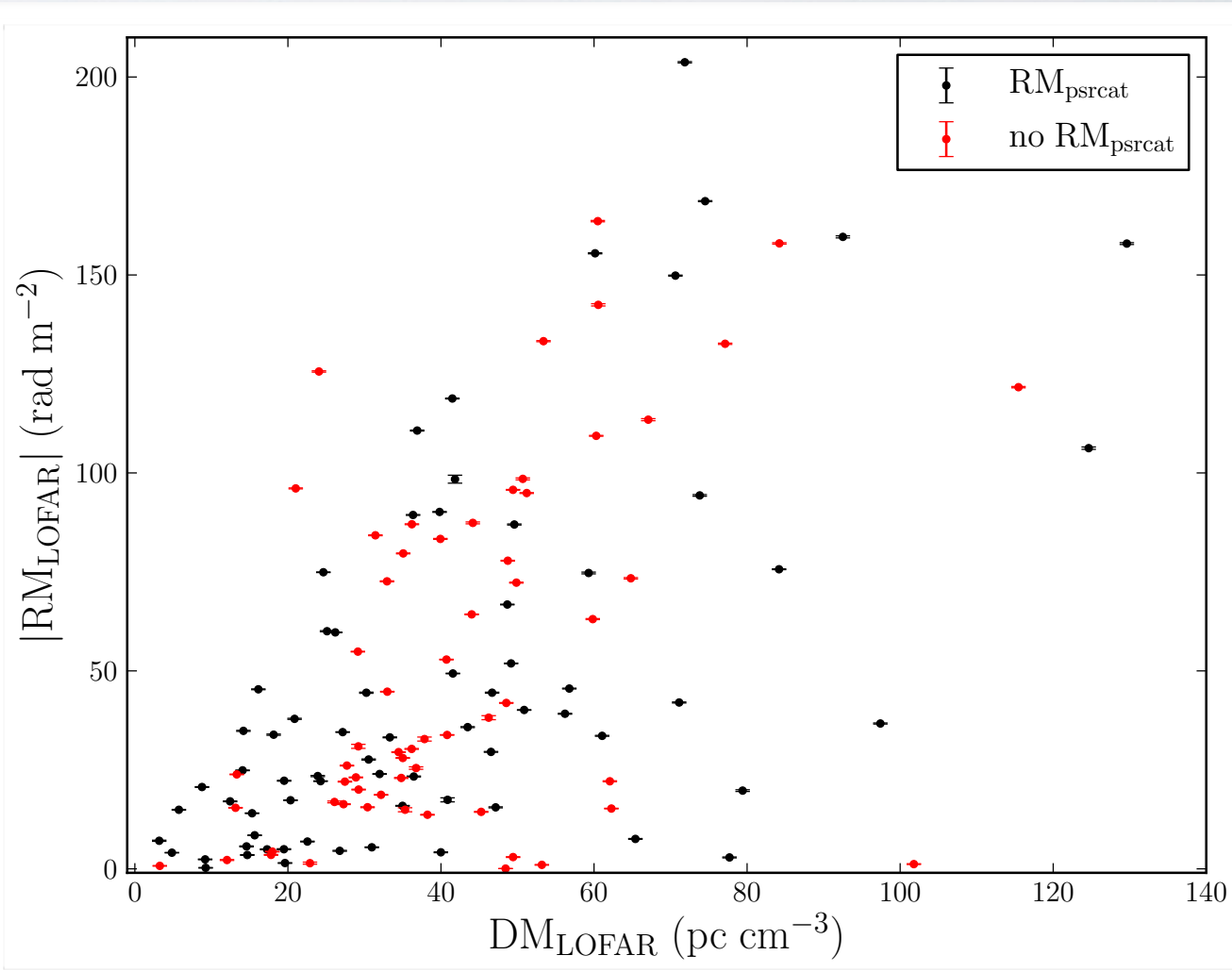


- LOFAR HBA RMs (Sobey et al. in prep., ~200 squares)
- Current pulsar RM catalogue (Manchester et al. 2005, 680 circles)
- Extragalactic sources (Oppermann et al. 2014, background)

LOFAR PULSAR RM RESULTS

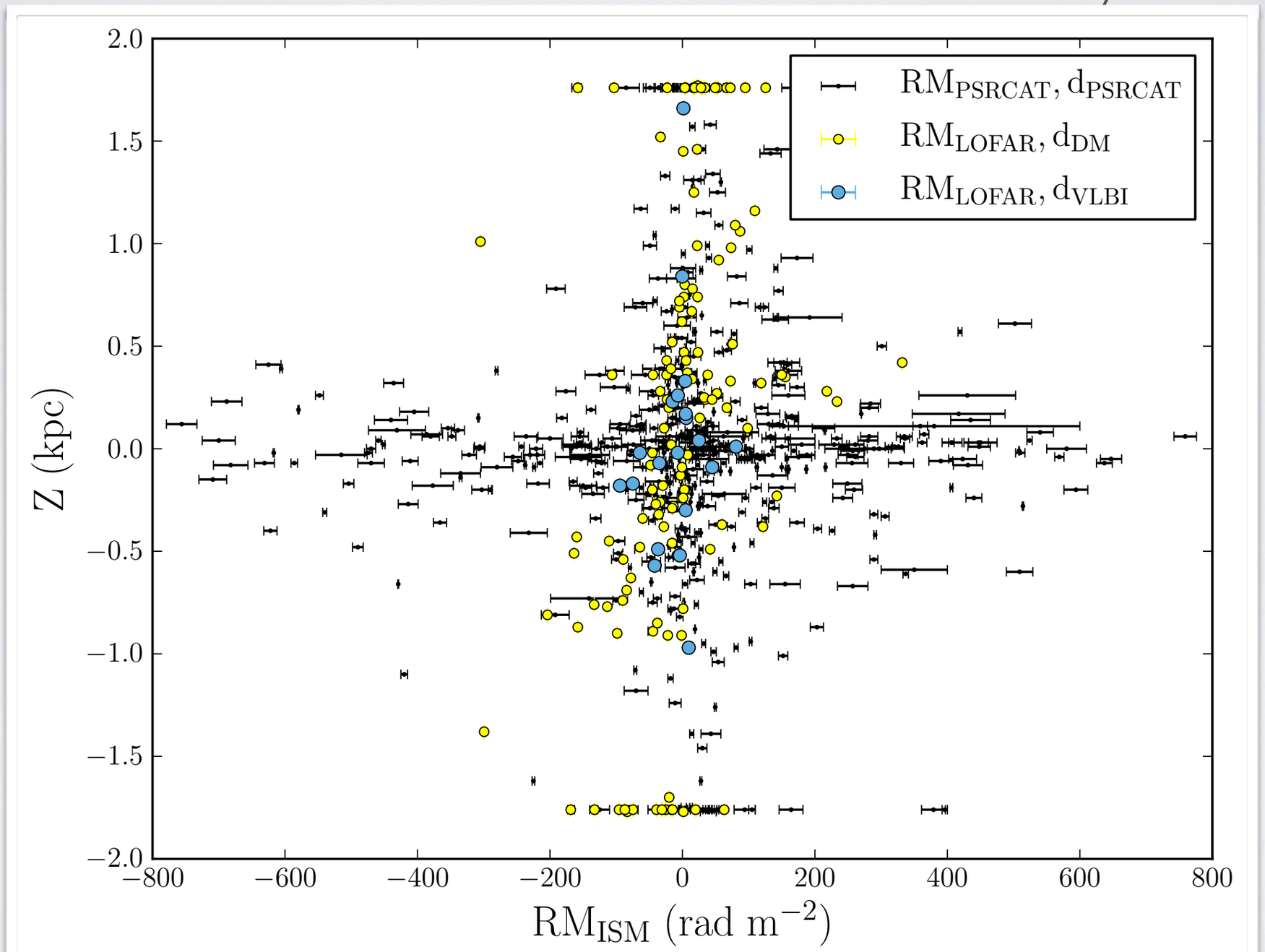
- Catalogue of ~200 RMs: between ±5uG with <**σ**>=0.5% fractional error
- ~90 new, others 30x more accurate



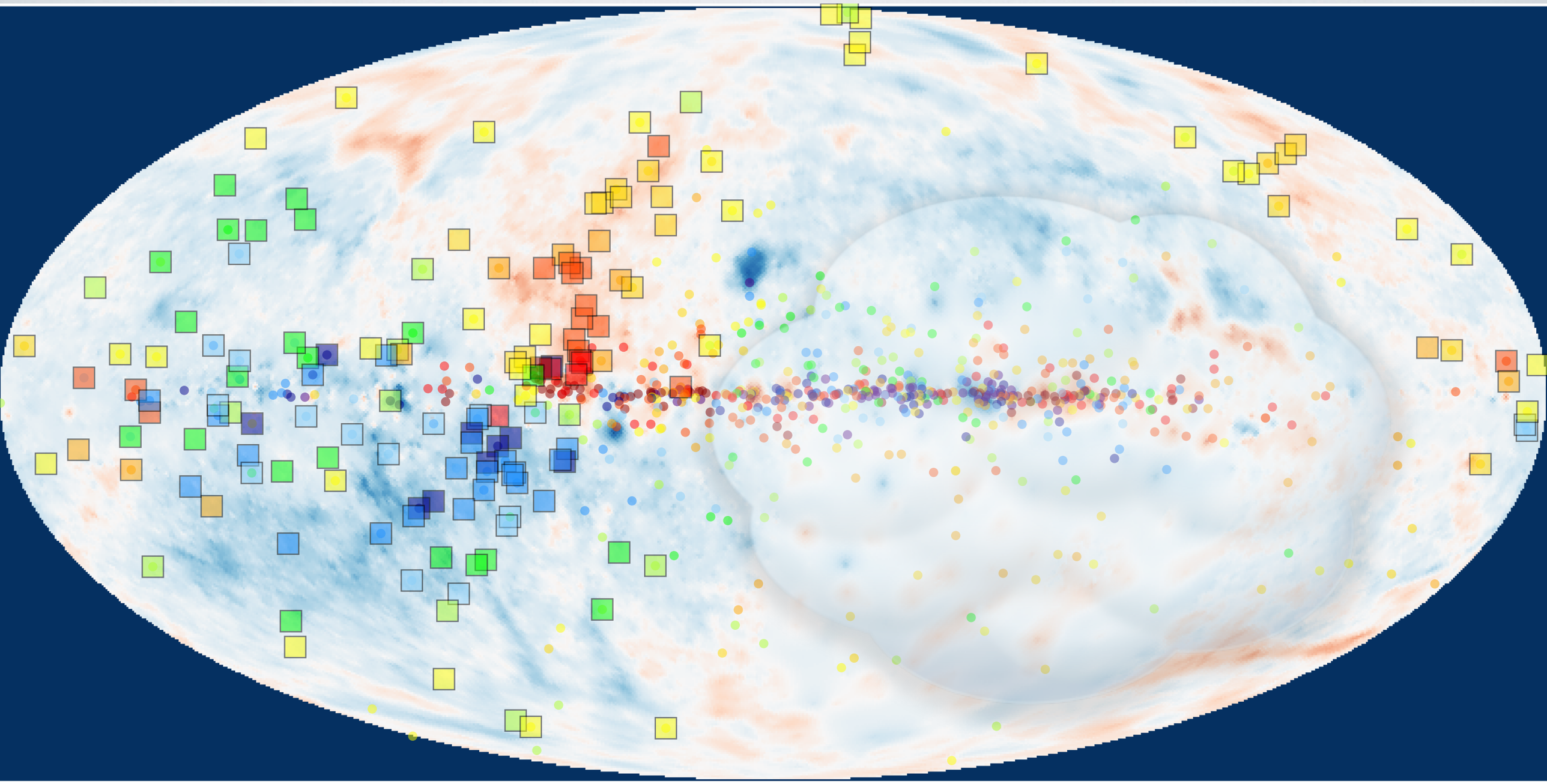


WANTED: INDEPENDENT DISTANCES!

Distance measurements (e.g. VLBI parallax) requires to reconstruct 3-D GMF more accurately



MEANWHILE… IN THE SOUTH



- LOFAR HBA RMs (Sobey et al. in prep., ~200 squares)
- Current pulsar RM catalogue (Manchester et al. 2005, 680 circles)
- Extragalactic sources (Oppermann et al. 2014, background)

MWA: MURCHISON WIDEFIELD ARRAY

- Starting work on low-frequency RMs in the southern sky
- Using Voltage Capture System (VCS; see Tremblay et al. 2015)

MWA-VCS collaborators include:

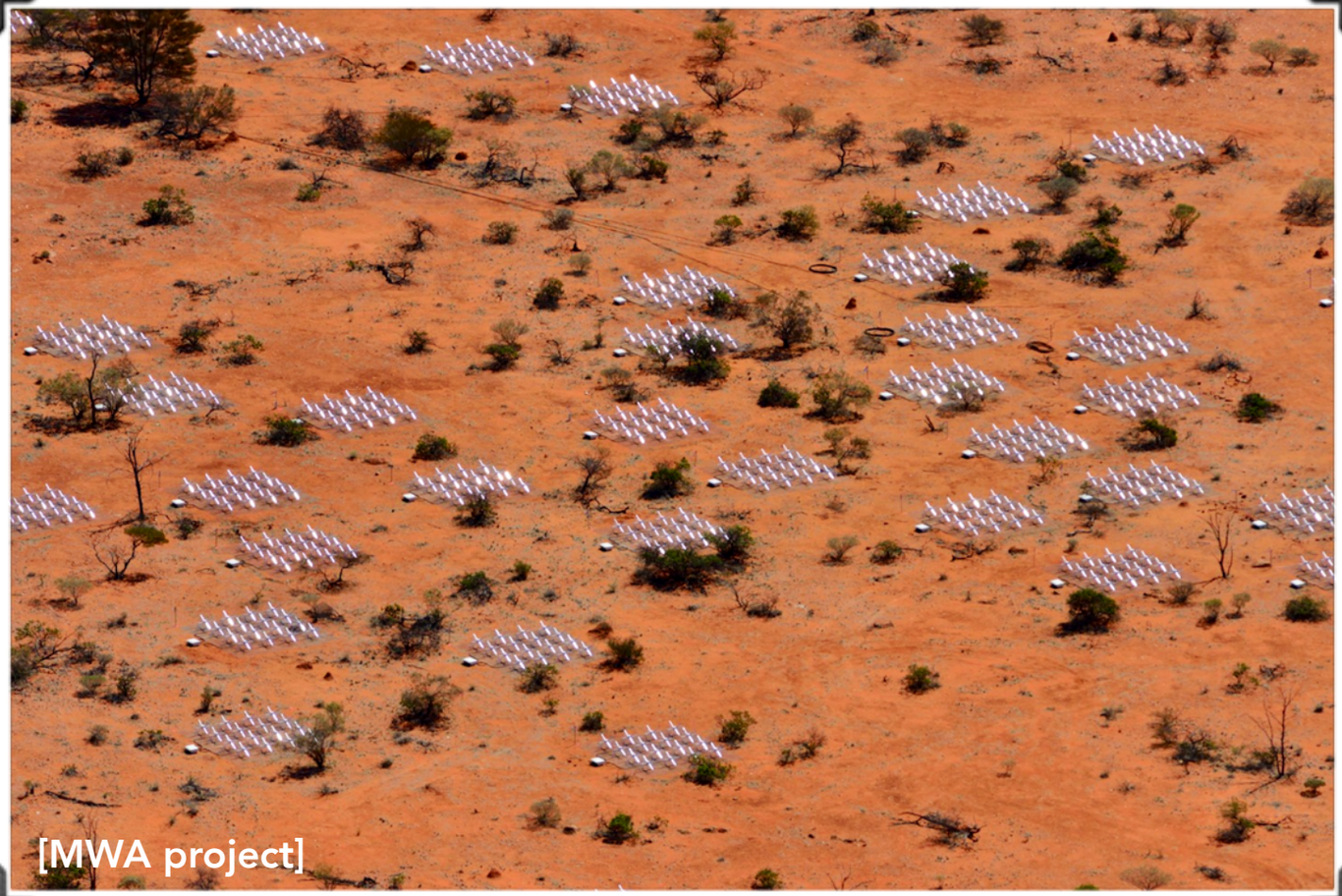
Curtin:
Ramesh Bhat,
Steven Tremblay,
Charlotte Sobey,
Dilpreet Kaur,
Sam McSweeney,
Bradley Meyers,
Mengyao Xue,
Nick Swainston

CSIRO:
Steve Ord,
Ryan Shannon

Onsala:
Franz Kirsten

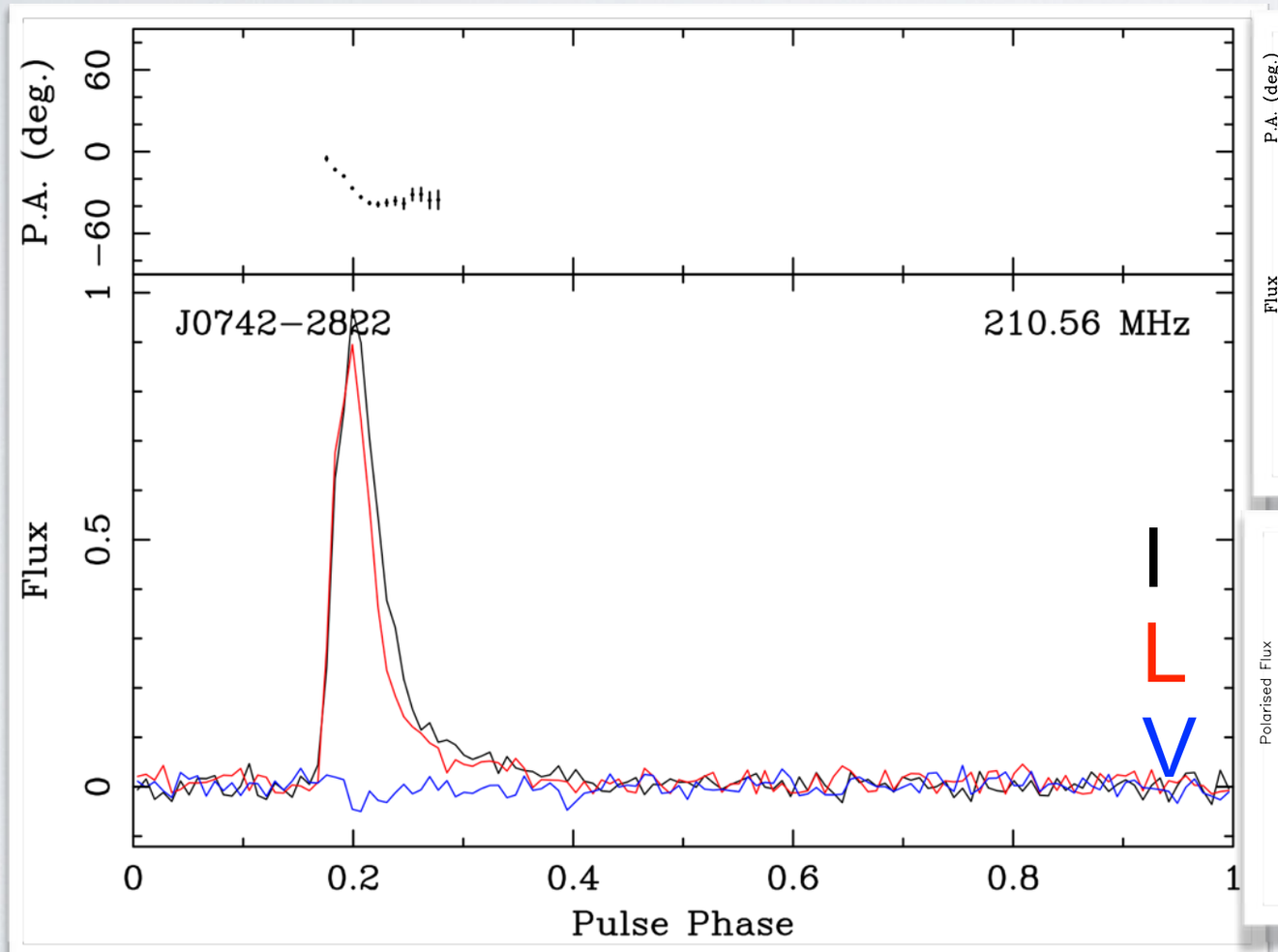
UWM:
David Kaplan,
Joe Swiggum

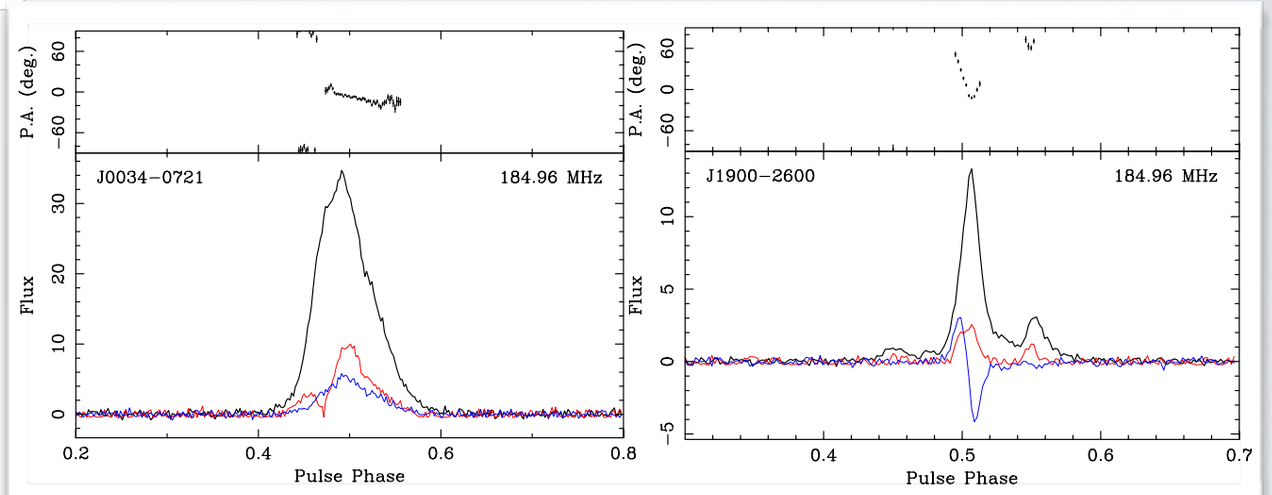
…

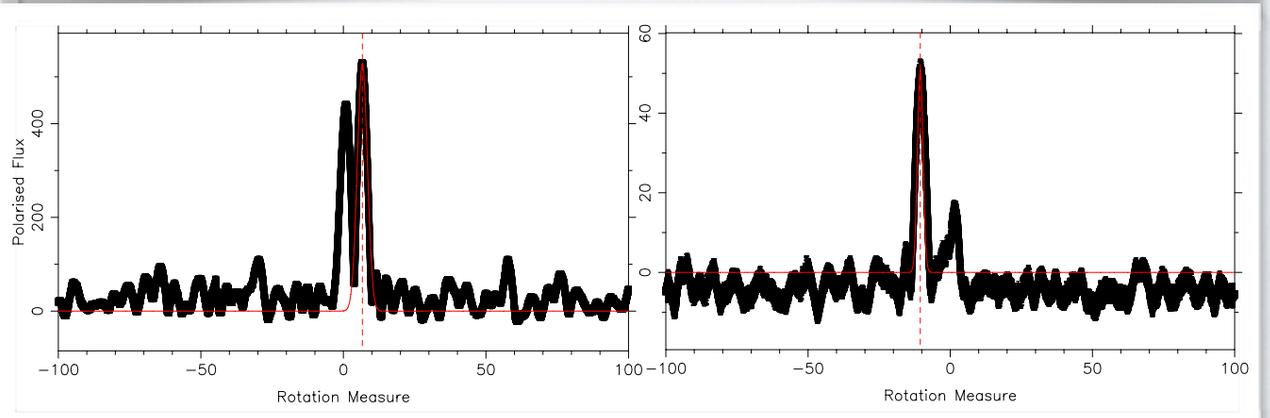

[MWA project]

MWA PULSAR OBSERVATIONS

- Using 'voltage capture mode' with full polarisation
- Currently verifying multi-frequency polarisation profiles (128-312 MHz 'picket fence')



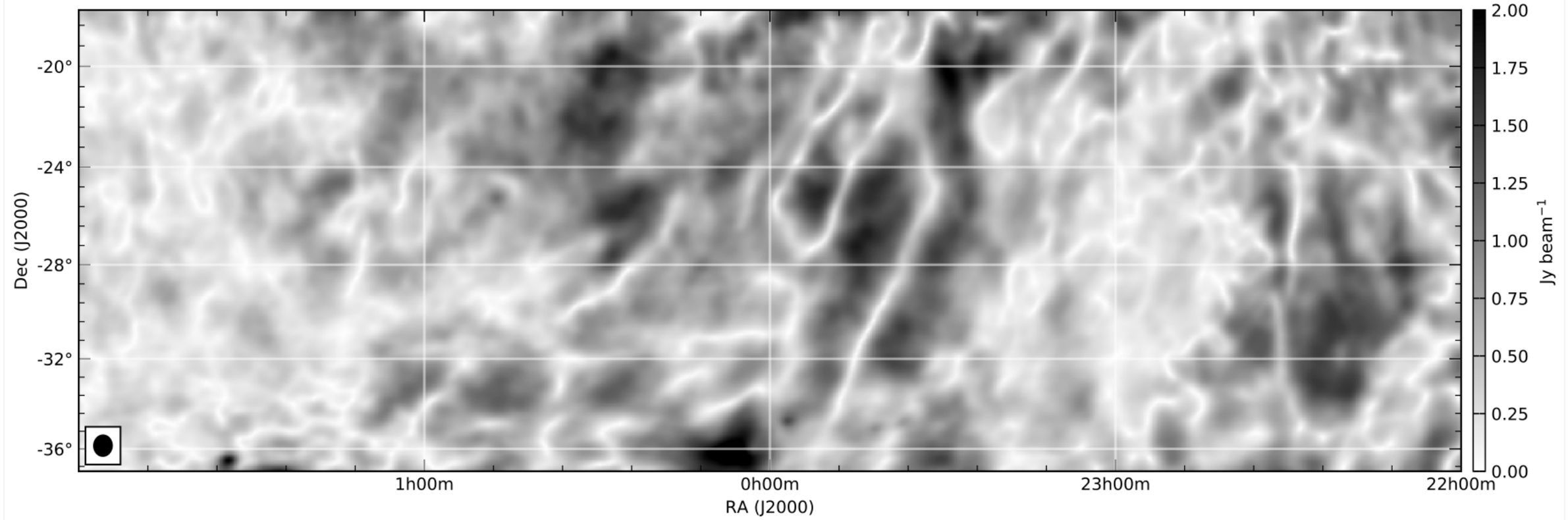




[M. Xue, C. Sobey]

PULSARS IN MWA IMAGES TOO!

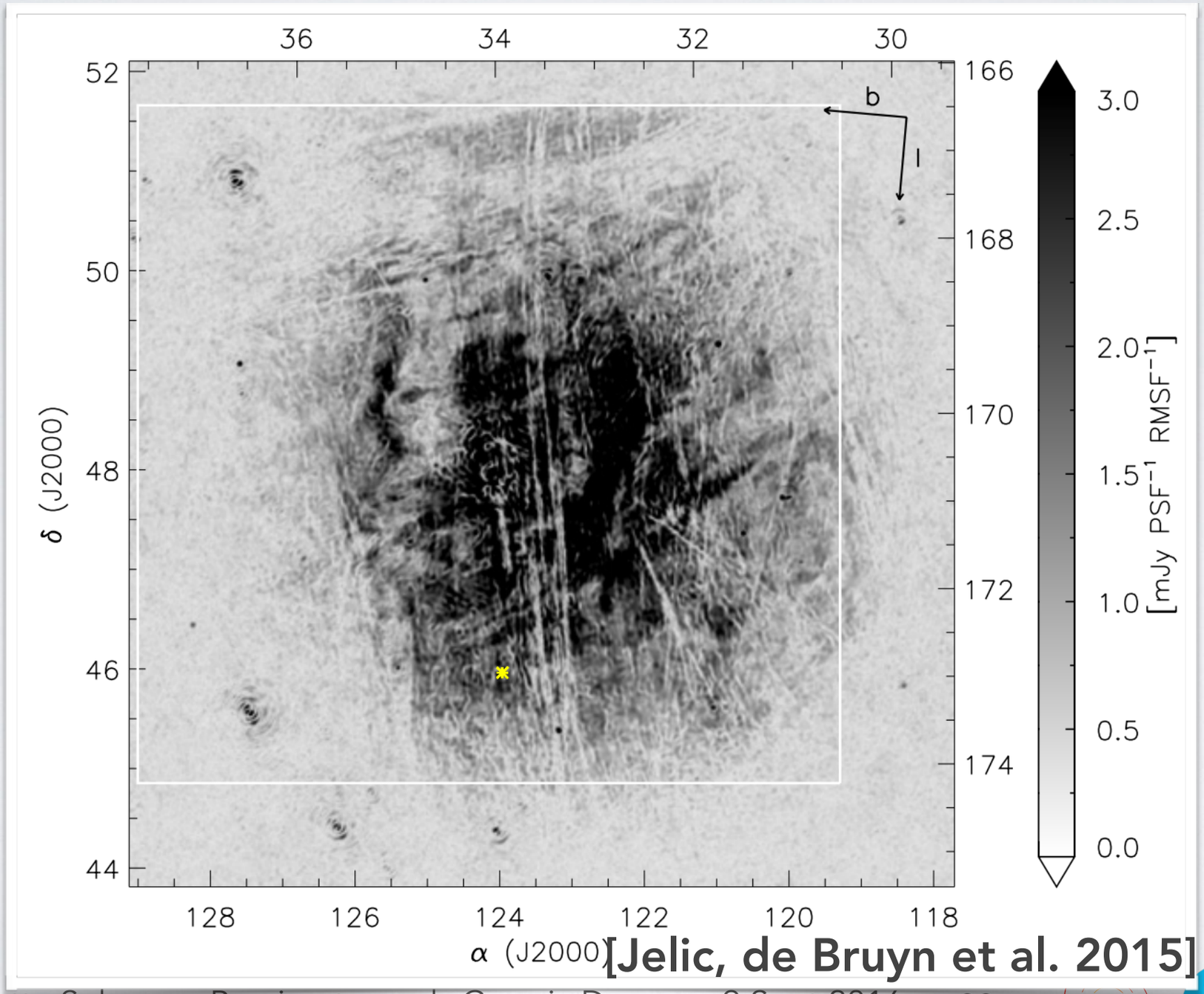
[Lenc et al. 2017]



Source name	Type	P_{MWA} (mJy)	RM_{MWA} (rad m^{-2})	RM_{lit} (rad m^{-2})	Reference
PMN J0351−2744 (E)	AGN Hot spot	637	+33.58±0.03	+34.7±5.5	Taylor et al. (2009)
PMN J0351−2744 (W)	AGN Hot spot	148	+34.9±0.2		
PSR J0437−4715	Pulsar	195	+2.2±0.1	+0.58±0.09	Dai et al. (2015)
PSR J0630−2834	Pulsar	151	+46.5±0.1	+46.53±0.12	Johnston et al. (2005)
PKS J0636−2036 (N)	AGN Hot spot	142	+36.1±0.3	+34.8±7.2	Taylor et al. (2009)
PKS J0636−2036 (S)	AGN Hot spot	1283	+50.18±0.05	+47.1±1.9	Taylor et al. (2009)
PSR J0742−2822	Pulsar	293	+150.6±0.1	+149.95±0.05	Johnston et al. (2005)
PSR J0835−4510	Pulsar	2234	+37.3±0.1	+31.38±0.01	Johnston et al. (2005)

PULSARS IN LOFAR IMAGES

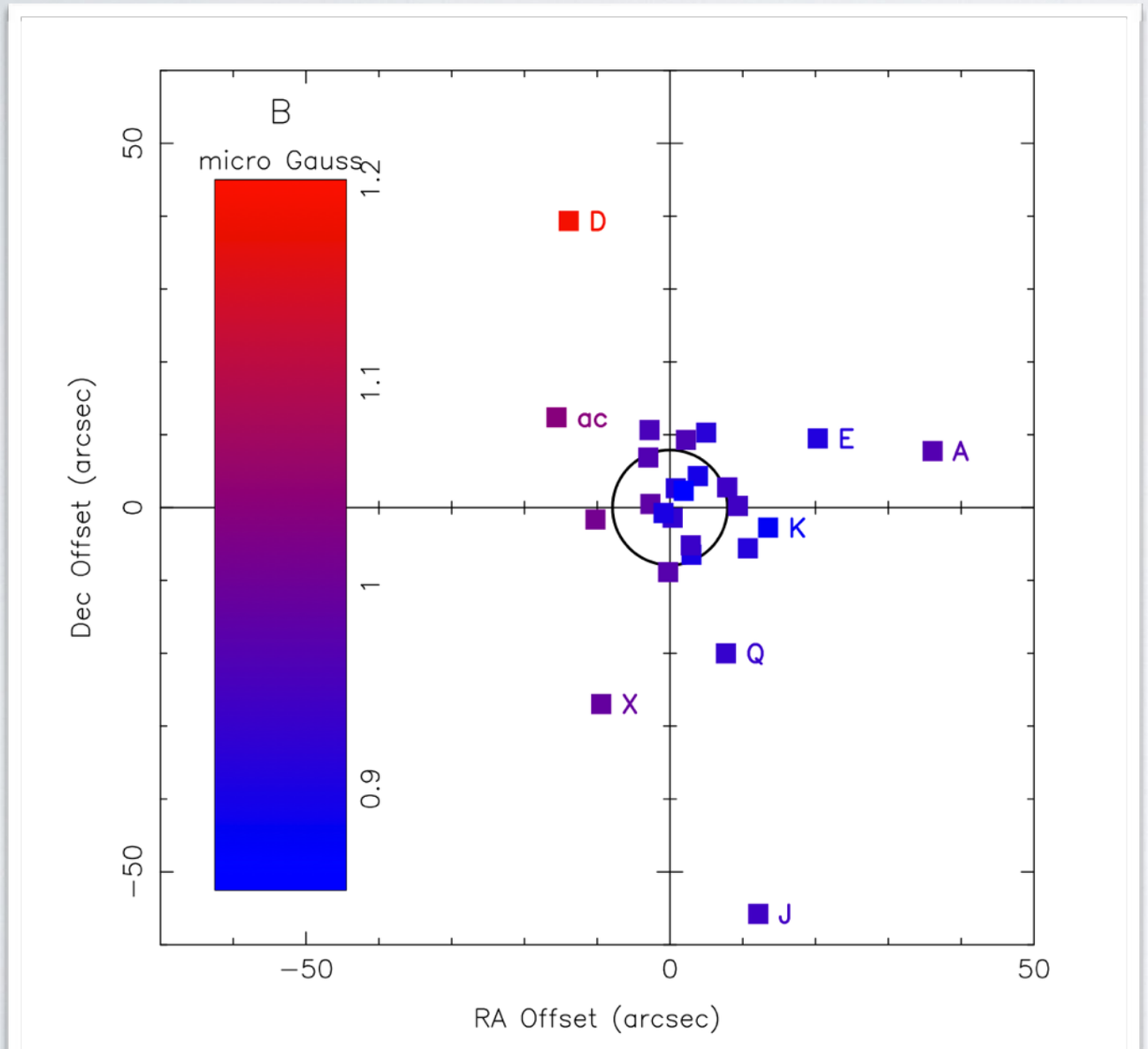
- Pulsars detected in images, and also **discovered** in LOFAR EoR 3C196 field
- DM = 11.28 pc cm^{-3} :: RM = +2.7 ± 0.1 rad m^{-2} :: $<B_{||}>$= 0.3 ± 0.1 μG :: D ~ 400 pc



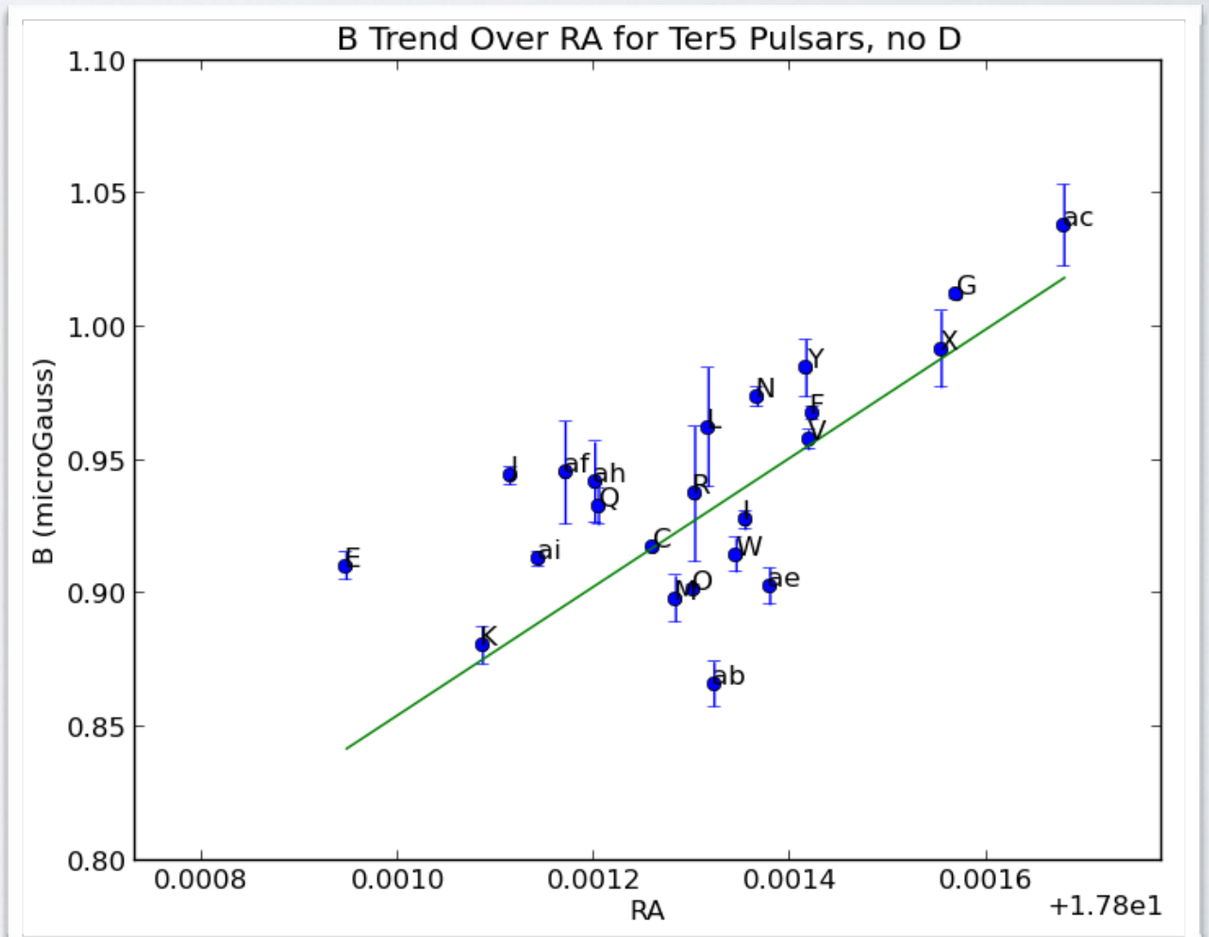
[Jelic, de Bruyn et al. 2015]

TOWARDS SMALL-SCALES

- Denser RM grids, e.g., investigating magnetic field in globular clusters
- Gradient in Galactic magnetic field measured towards Terzan 5 pulsars using the GBT



[Anna Ho, Ransom, Demorest, in prep.]



TOWARDS SMALL-SCALES

- Precision measurements: now enable 'monitoring' era of RM(time)
  - Probing small scale turbulence and other foregrounds (e.g. heliosphere)

LWA pulsar data [Howard et al. 2016]

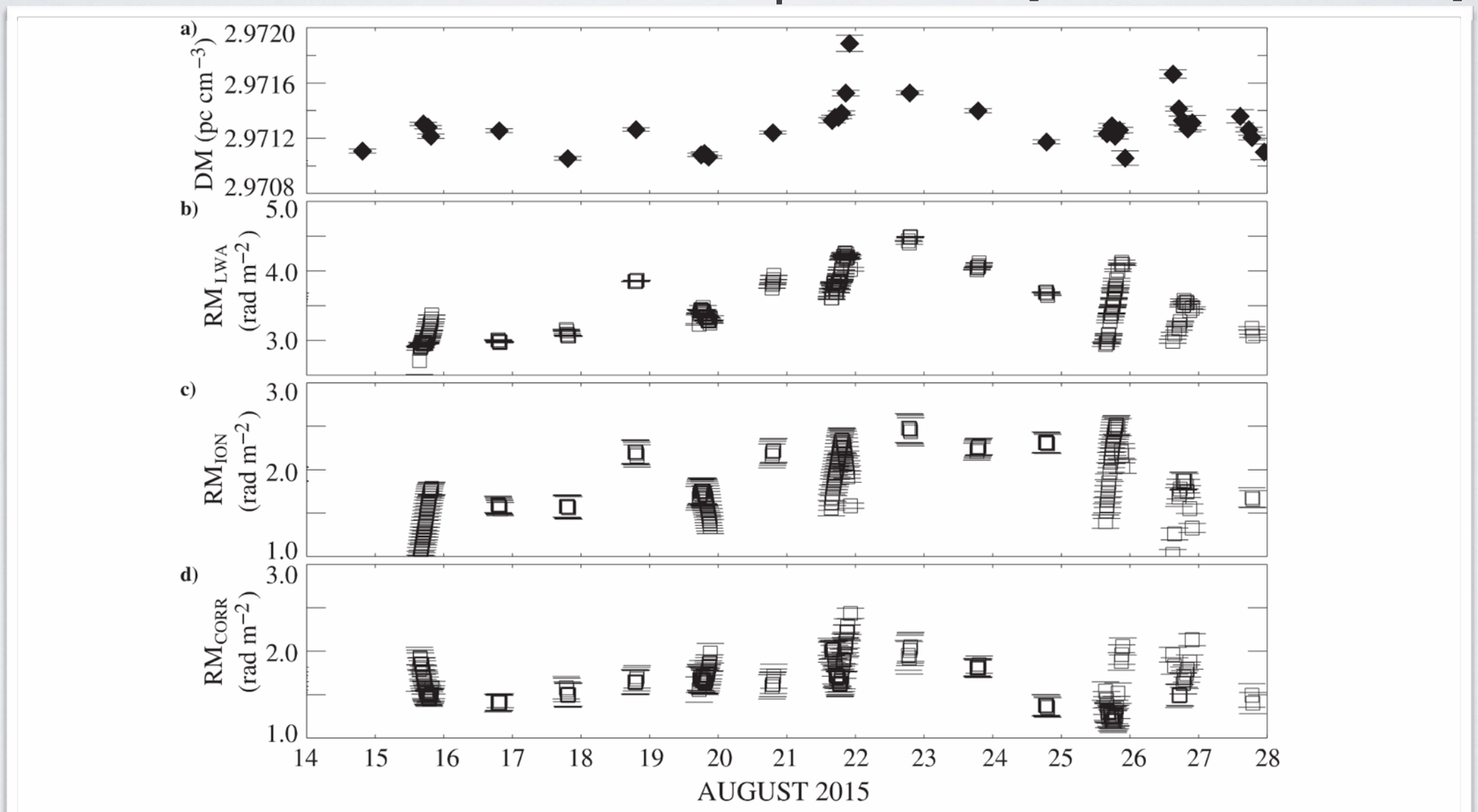
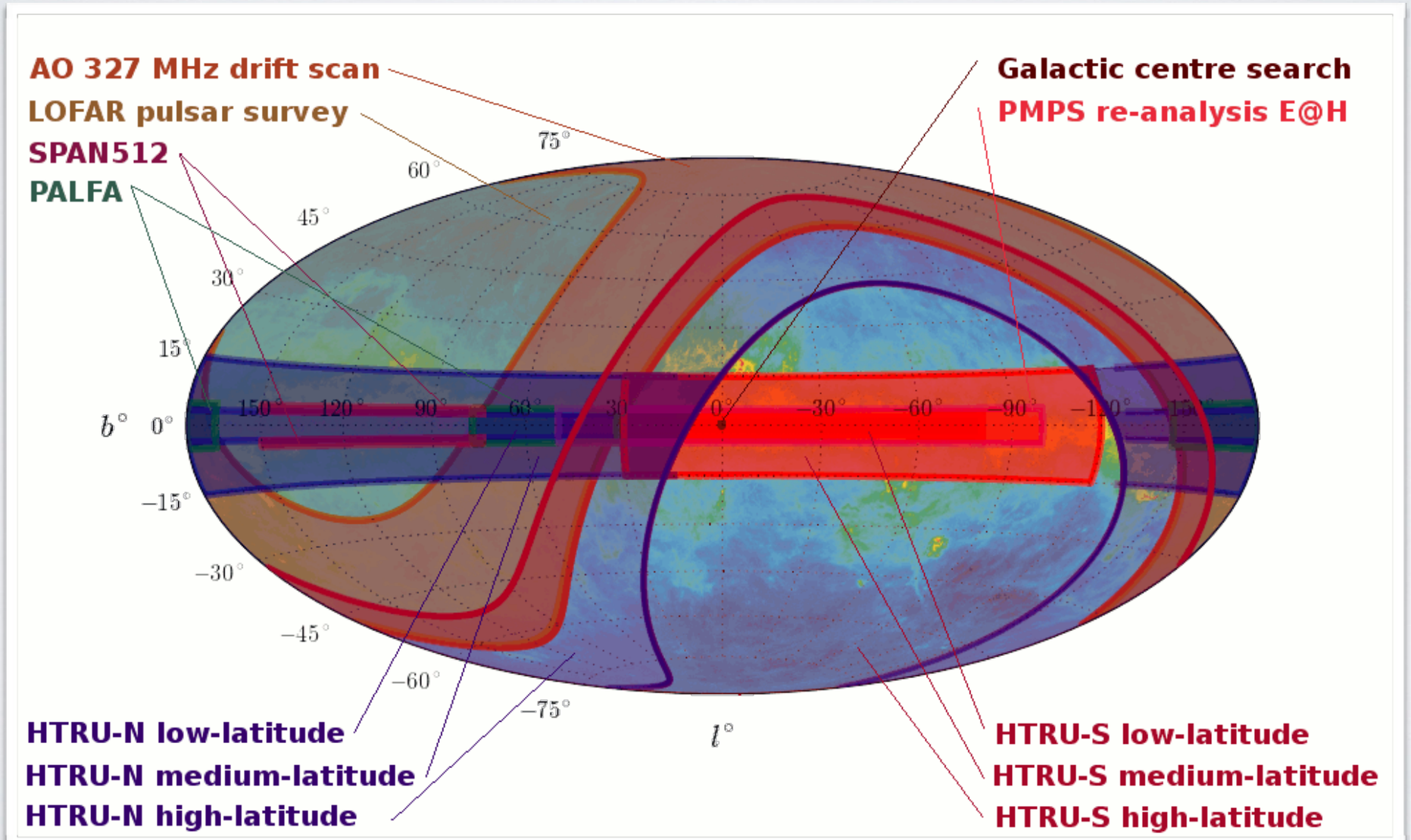


Figure 4. RM and DM values of the pulsar from LWA-1 for every observing run in our campaign. The panels are as follows: (a) total DM, (b) total RM, (c) estimated RM contribution from the ionosphere, and (d) RM with the ionosphere removed.

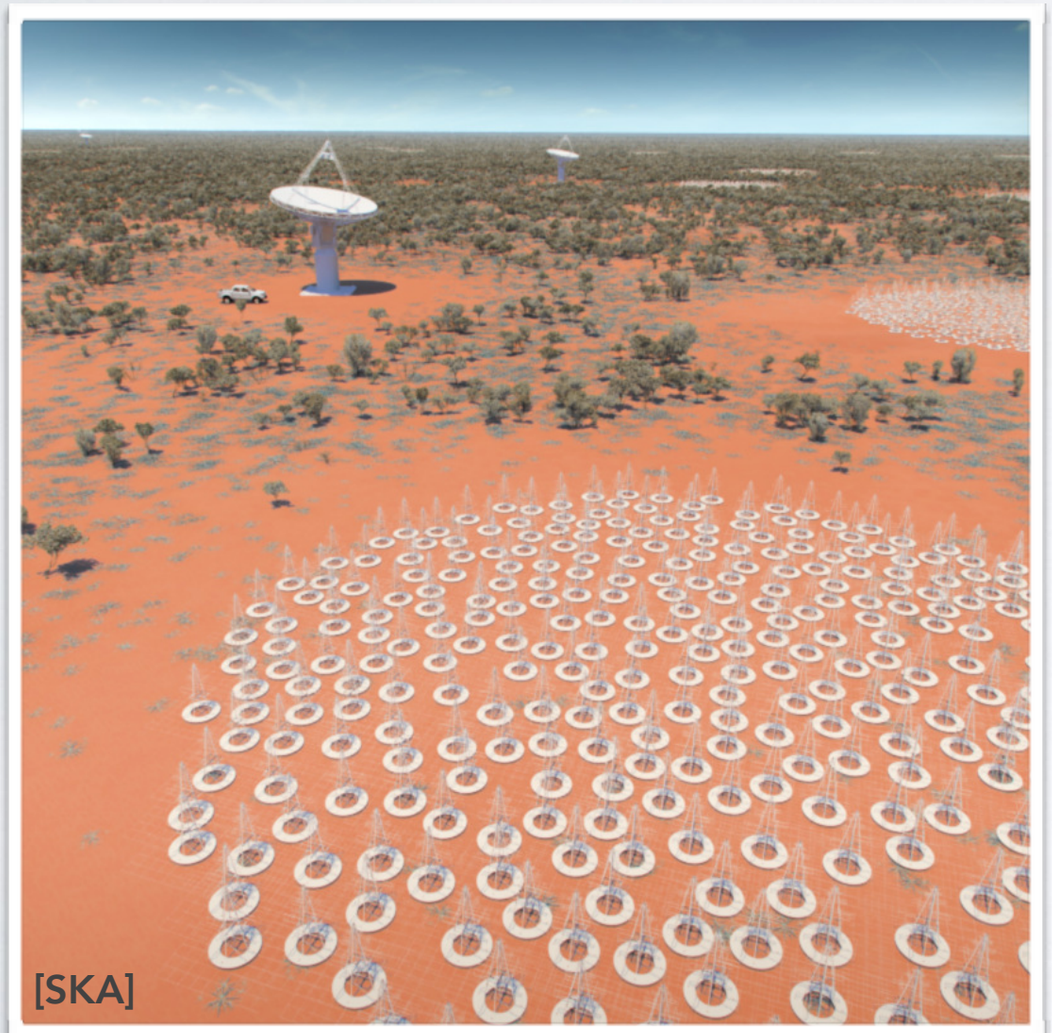
FUTURE PULSAR DISCOVERIES

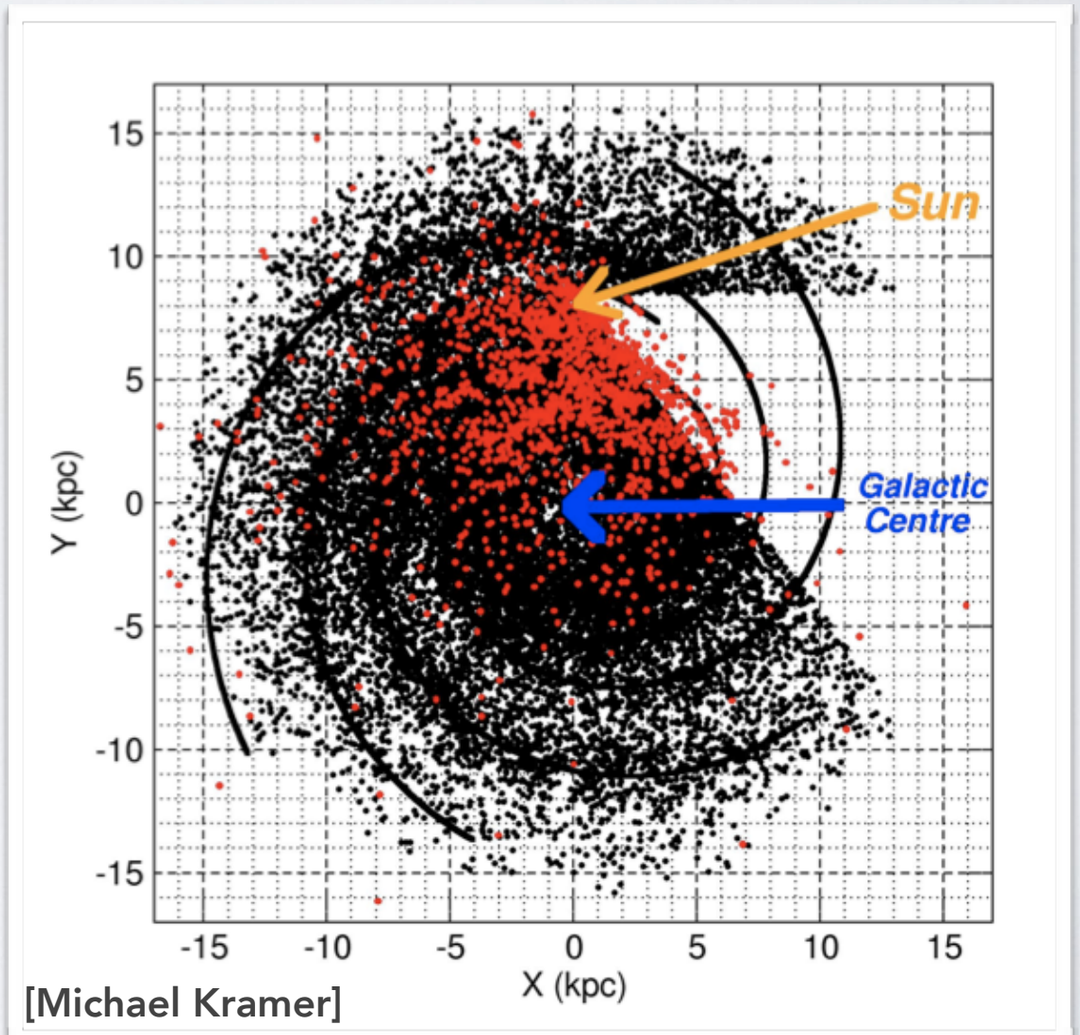
- Many ongoing time-domain pulsar surveys
- Important for (at least!) increasing RM catalogue and therefore LoS
- New techniques being developed e.g. variance imaging using MWA / ASKAP



TOWARDS THE SKA…

- SKA will discover thousands more pulsars - 3-D tomography (Han+2014)
  - Highly desirable: well-understood polarisation characteristics and accurate ionospheric (RM) monitoring
- A lot of synergy with EoR requirements (probably less stringent constraints)





SUMMARY

- Low-frequency RMs towards pulsars — precise 3-D probes of the GMF
  - LOFAR & MWA facilitate this and provide all-sky coverage
  - Towards DM/RM monitoring, e.g., small-scale/turbulent structures
- Question: what would you like to obtain from (3-D) foreground models?

Thank you for listening…Hvala!

AND NOW FOR SOMETHING COMPLETELY DIFFERENT
TOMORROW, THURSDAY 5 OCTOBER…