

LOW-FREQUENCY POLARISATION OBSERVATIONS OF PULSARS

to probe the

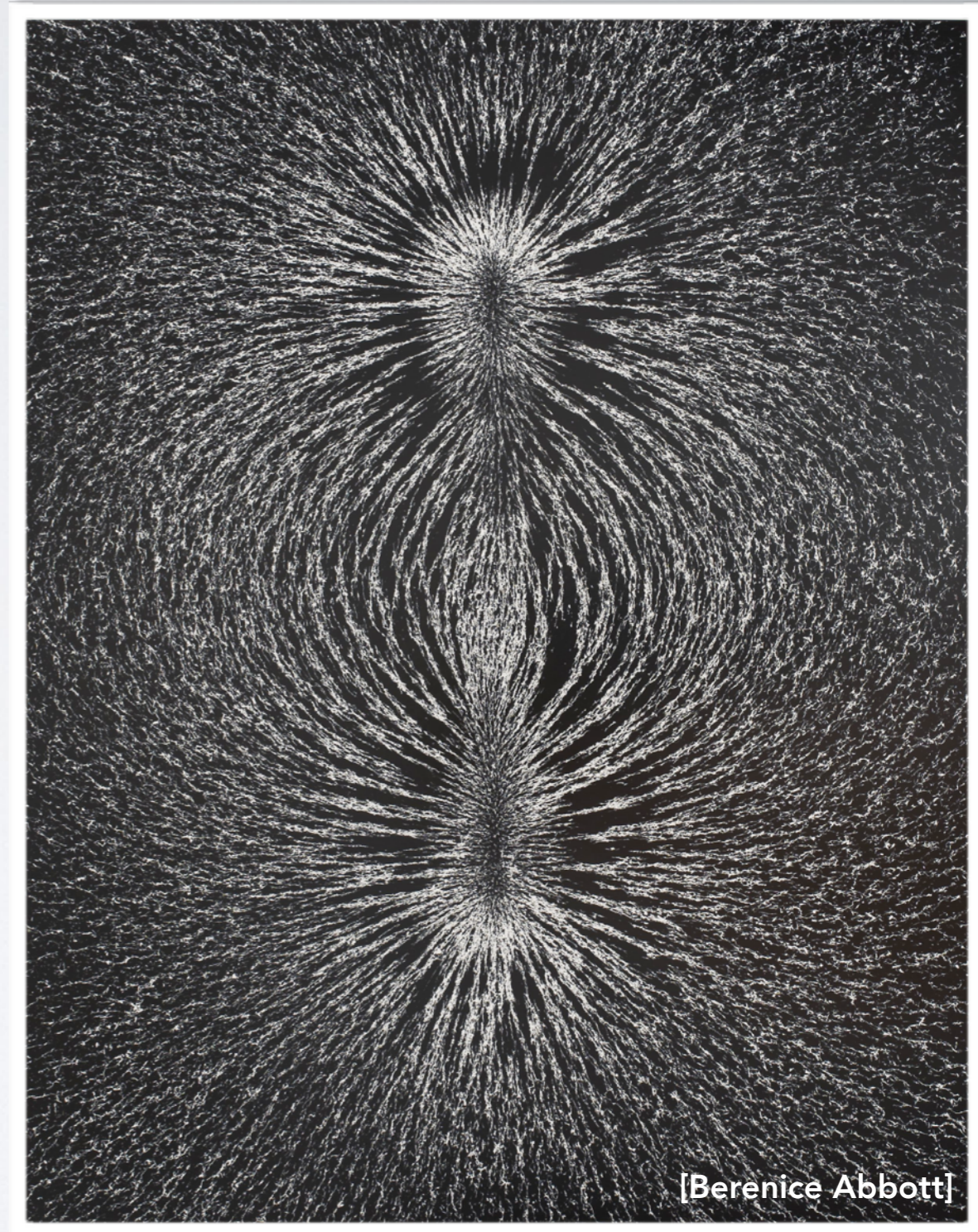
3-D STRUCTURE OF THE GALACTIC MAGNETIC FIELD

Charlotte Sobey
c.sobey@curtin.edu.au



OVERVIEW

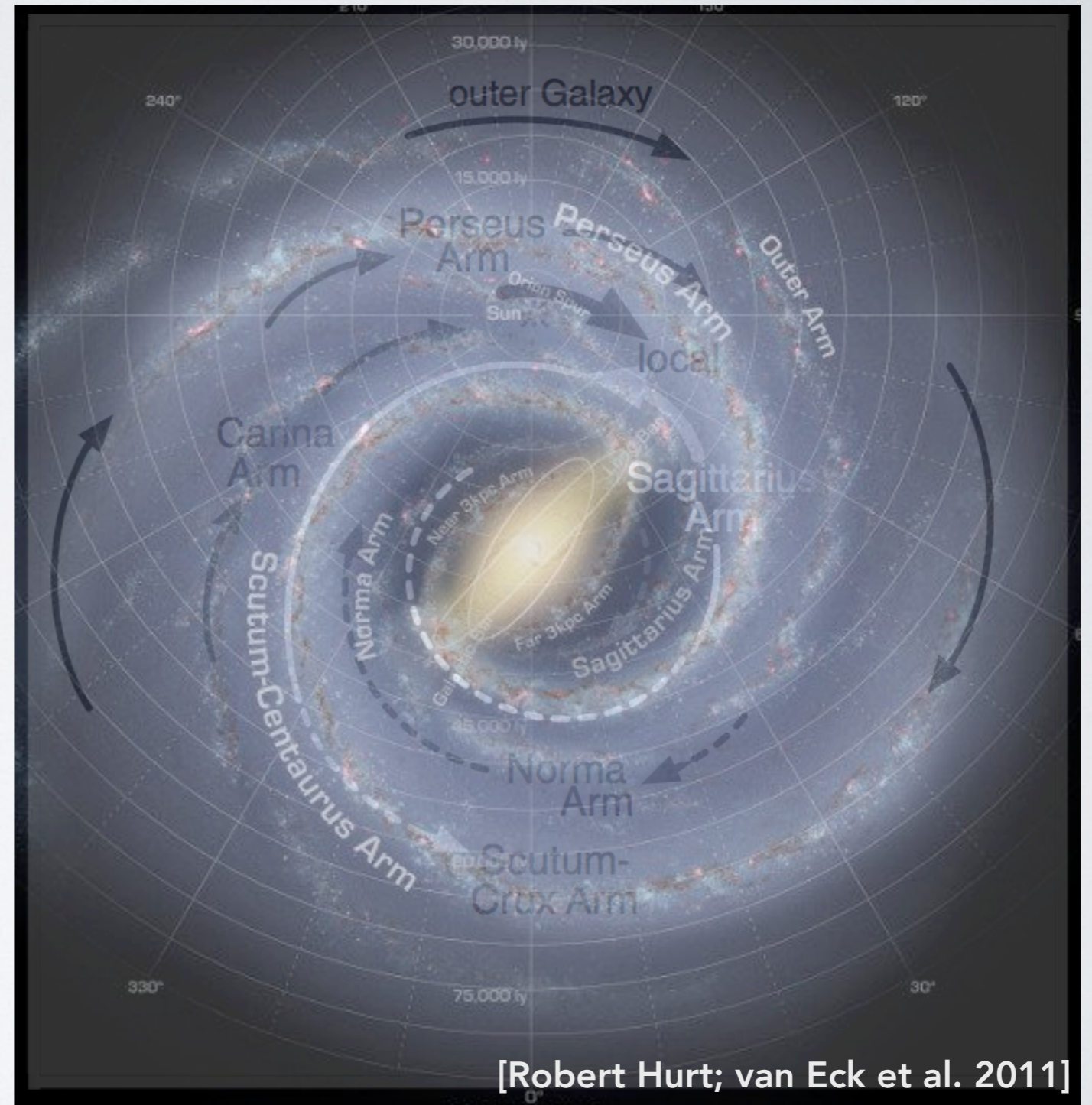
- **Motivation: GMF**
- **Methods: RMs towards pulsars**
- **LOFAR pulsar observations**
- **MWA pulsar observations**
- **Summary and future work**



CONTEXT/MOTIVATION

Galactic magnetic field:

- Permeates diffuse ISM
- Impacts many astrophysical processes
- Foreground to extragalactic & cosmological signals
- Structure (and origin) still debated
- No reversals in other galaxies!



OBSERVABLES INFER MAGNETIC FIELDS

- Observables (complementary):

- Zeeman splitting

- Synchrotron (I and P) →

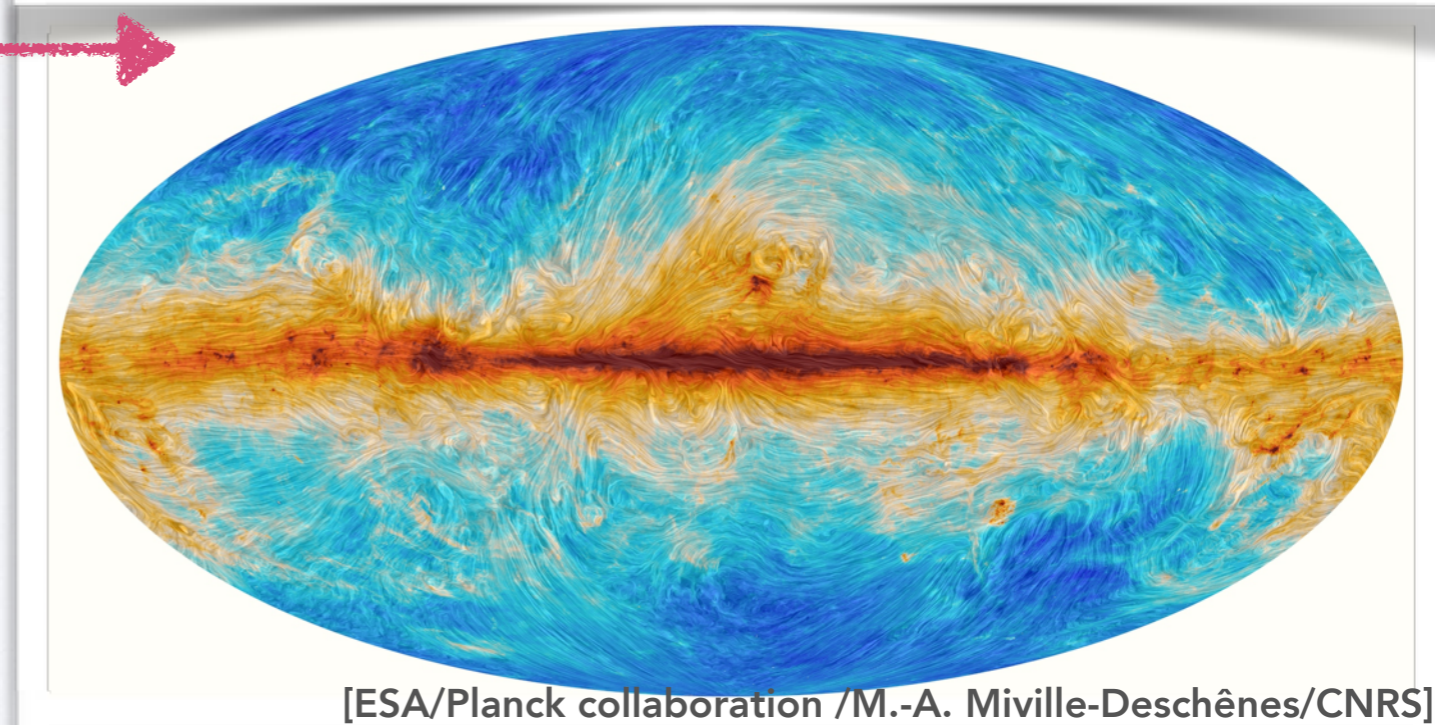
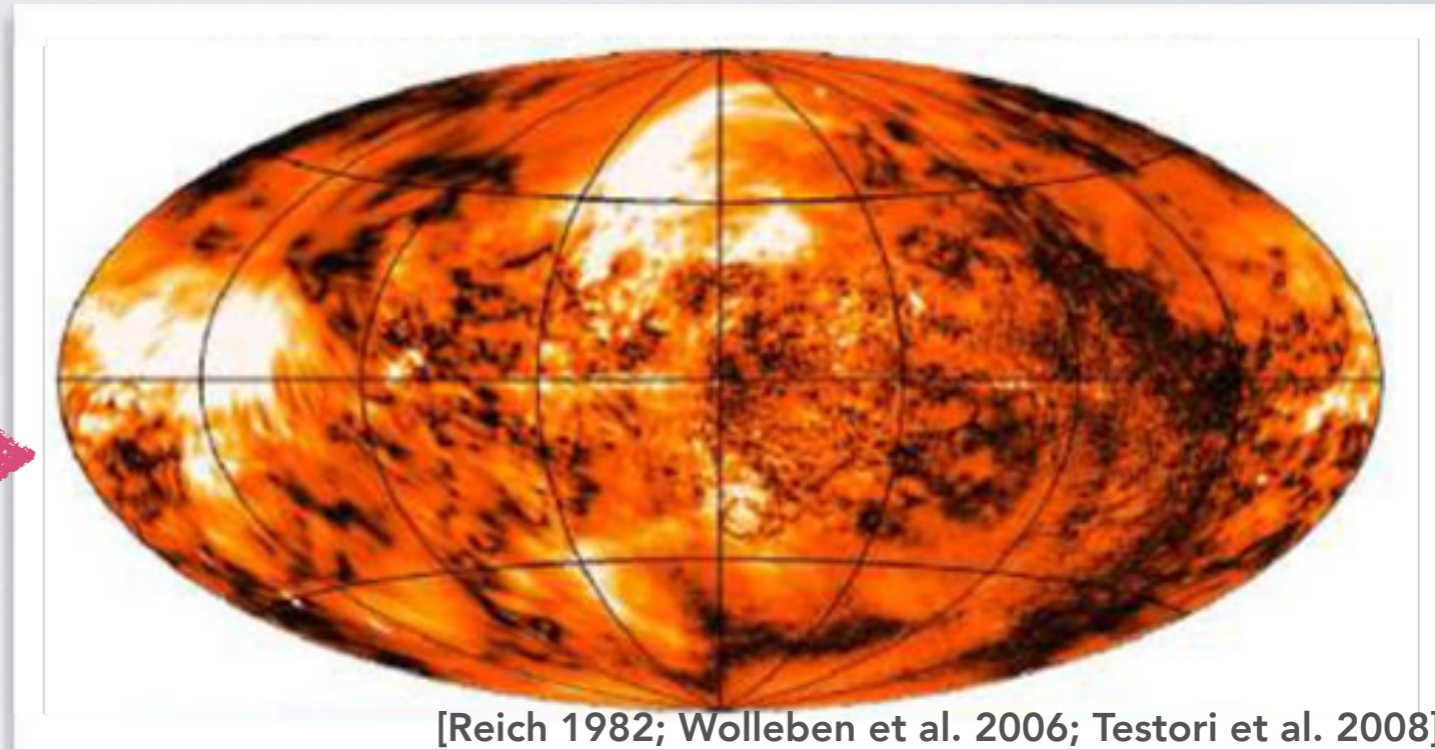
- Starlight (P)

- Thermal dust emission (P) →

- Ultra-High Energy Cosmic Rays

- **Focus: Faraday rotation measures!**

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

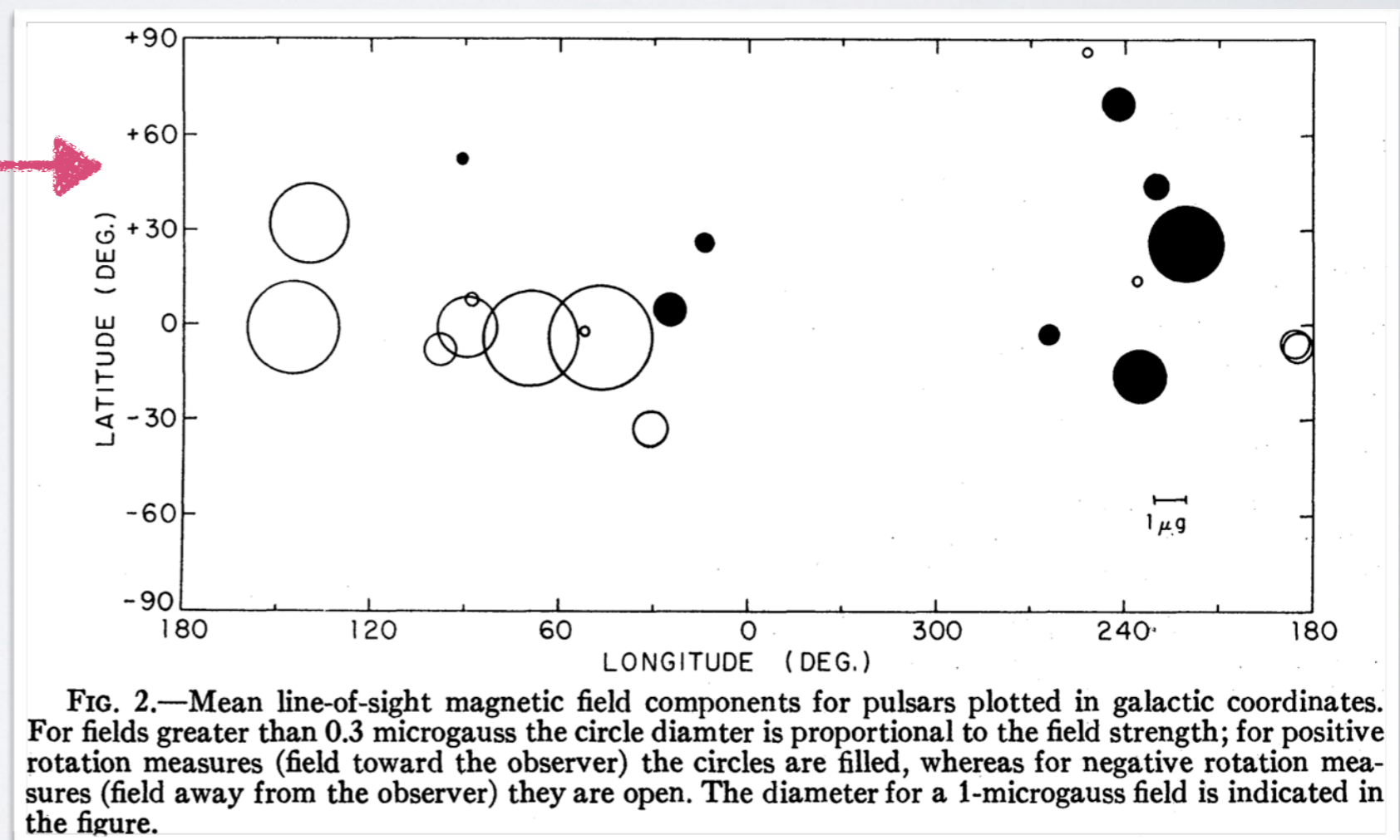


PULSARS... AS 3-D PROBES OF THE ISM

$$\langle B_{\parallel} \rangle = 1.232 \mu G \frac{\text{RM} = 0.81 \int_{\text{d}}^0 n_e \mathbf{B} \cdot d\mathbf{r} \text{ rad m}^{-2}}{\text{DM} = \int_0^{\text{d}} n_e dl \text{ pc cm}^{-3}}$$

- 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;
Manchester 1974;
Rand & Lyne 1994;
Han et al. 1999, 2006;
Noutsos et al. 2008,
van Eck et al. 2011



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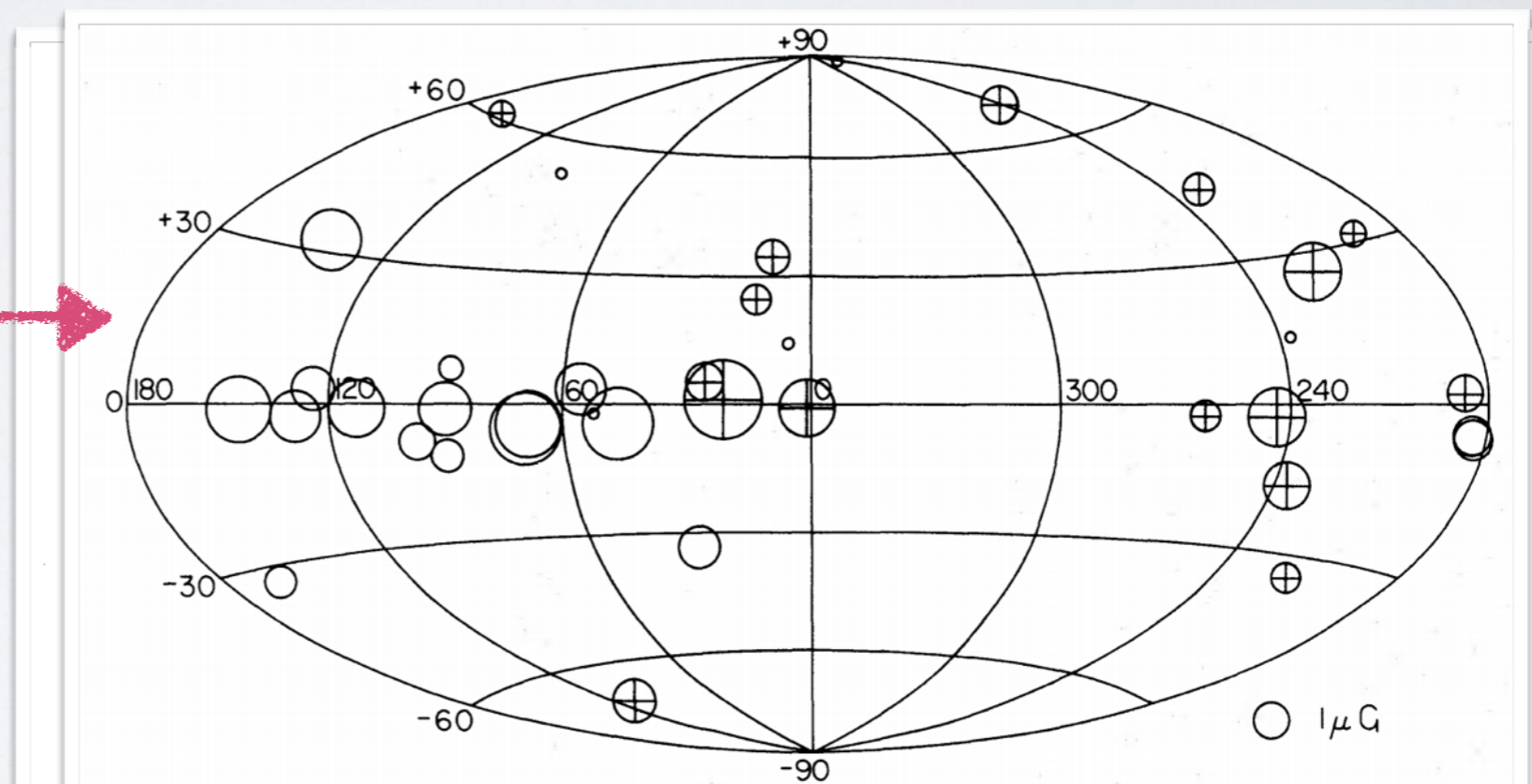


FIG. 2.— Mean line-of-sight magnetic field components for pulsars plotted in galactic coordinates. For fields greater than 0.3 microgauss the circle diameter is proportional to the field strength; for positive rotation measures (field toward the observer) the circles are filled, whereas for negative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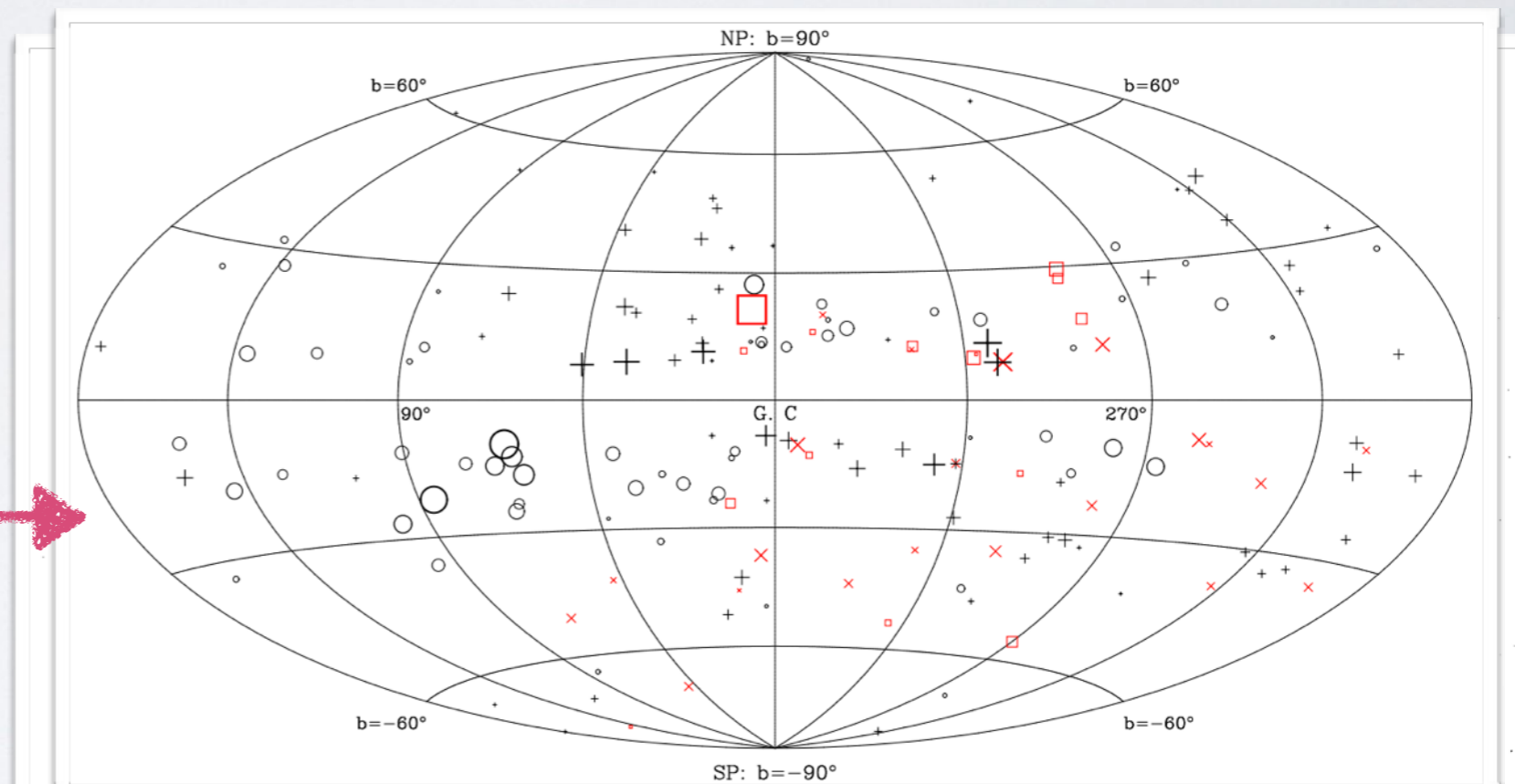
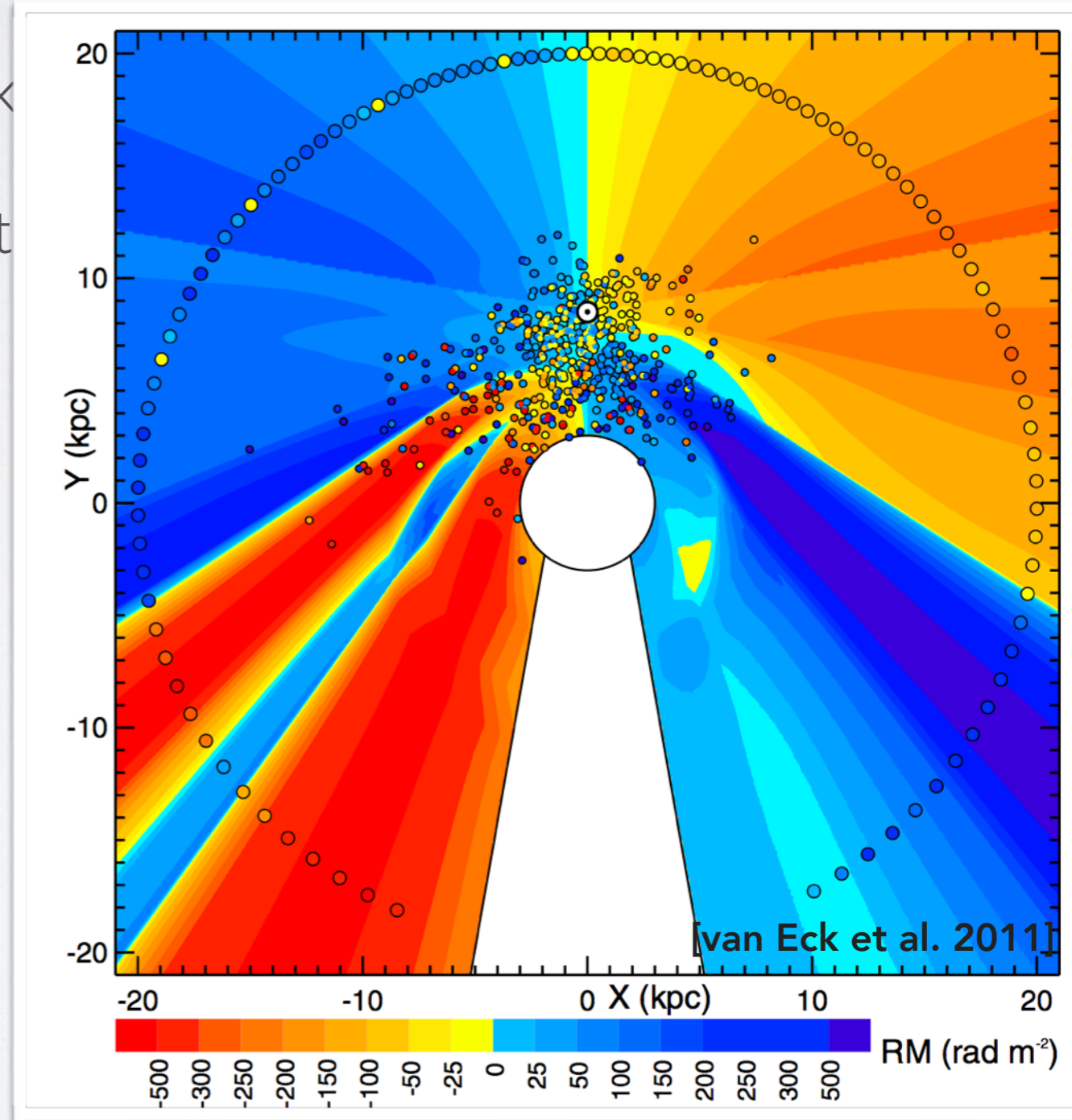


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- Distributed throughout Milky Way (ex
- Distances known (parallax) or estimat
- Currently: 2627 known pulsars; 734 (28%) have published RMs
- Complementary extragalactic RMs 41,632 (e.g. Oppermann et al. 2015)



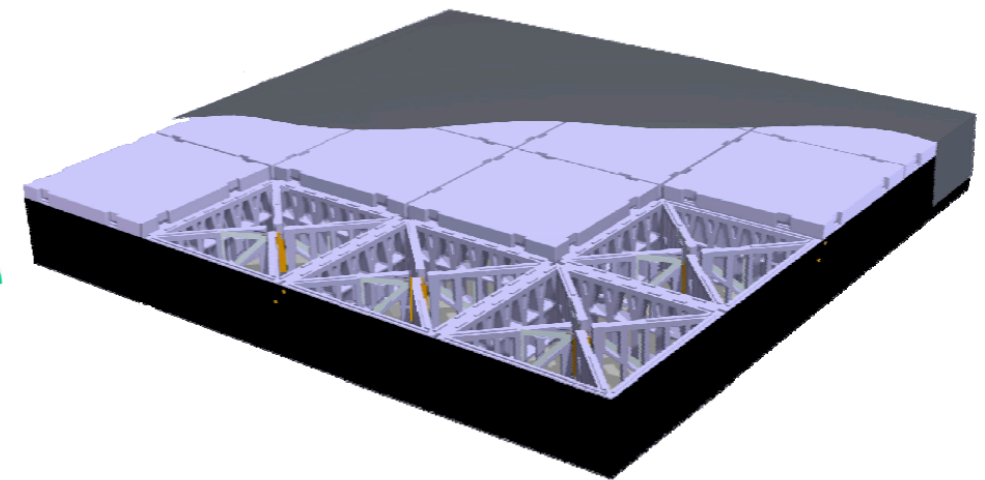
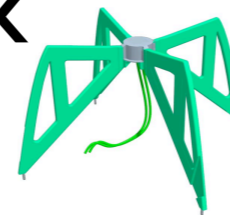
LOFAR



HBAs

100-250MHz

(2x)24x



van Haarlem et al. 2013
Stappers et al. 2011

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 (Cagliari)
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)

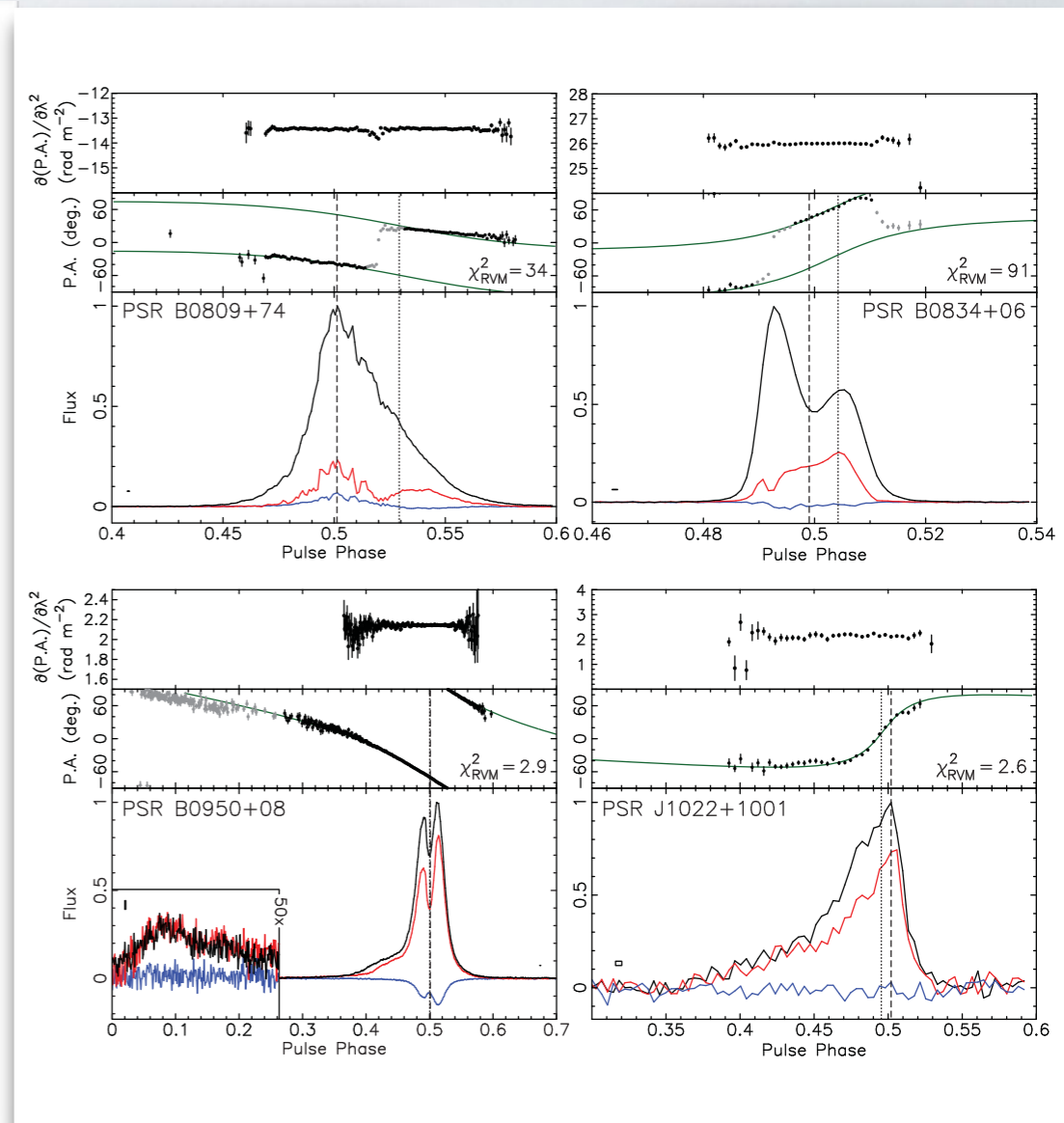
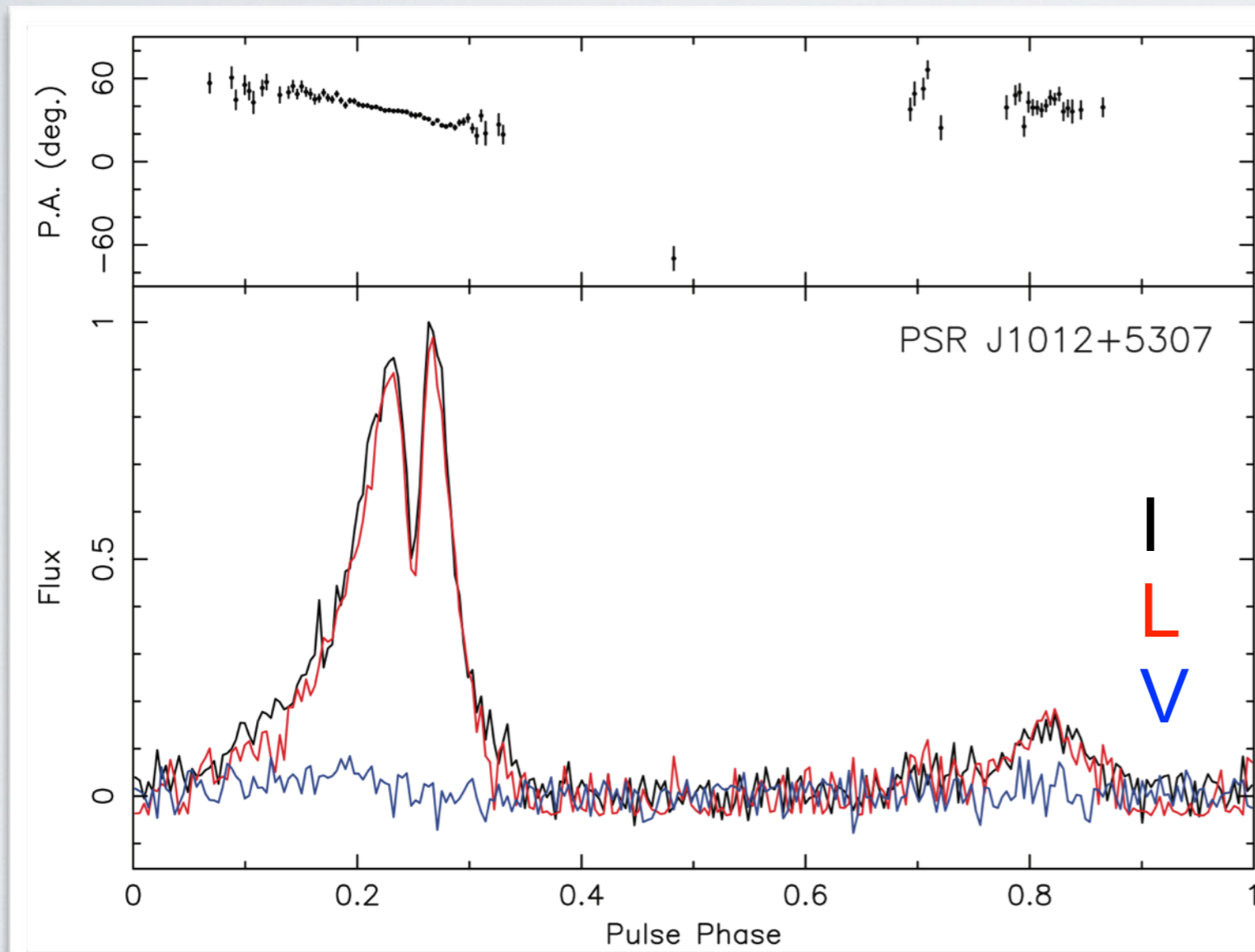
Marco Iacobelli (ASTRON)
Henrik Junklewitz (Bonn)
Wojciech Jurusik (Kraków)
Jana Köhler (MPIfR)
David Mulcahy (Manchester)
Blazej Nikiel-Wroczyński (Kraków)
Aris Noutsos (MPIfR)
Emanuela Orru (ASTRON)
Rosita Paladino (IRA Bologna)
Roberto Pizzo (ASTRON)
Wolfgang Reich (MPIfR)
Katharina Sendlinger (Bochum)
Charlotte Sobey (ICRAR-Curtin & CASS)
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)

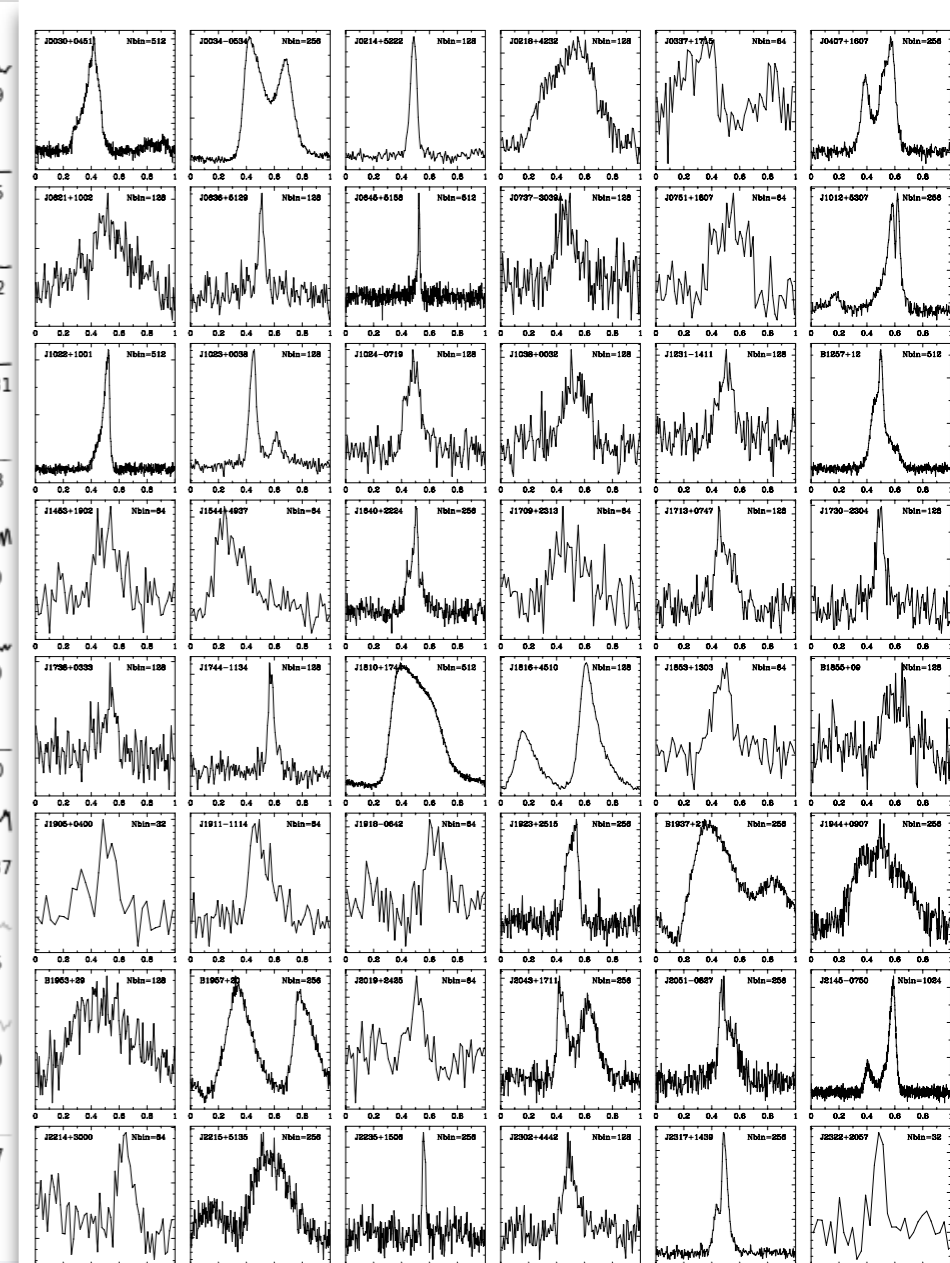
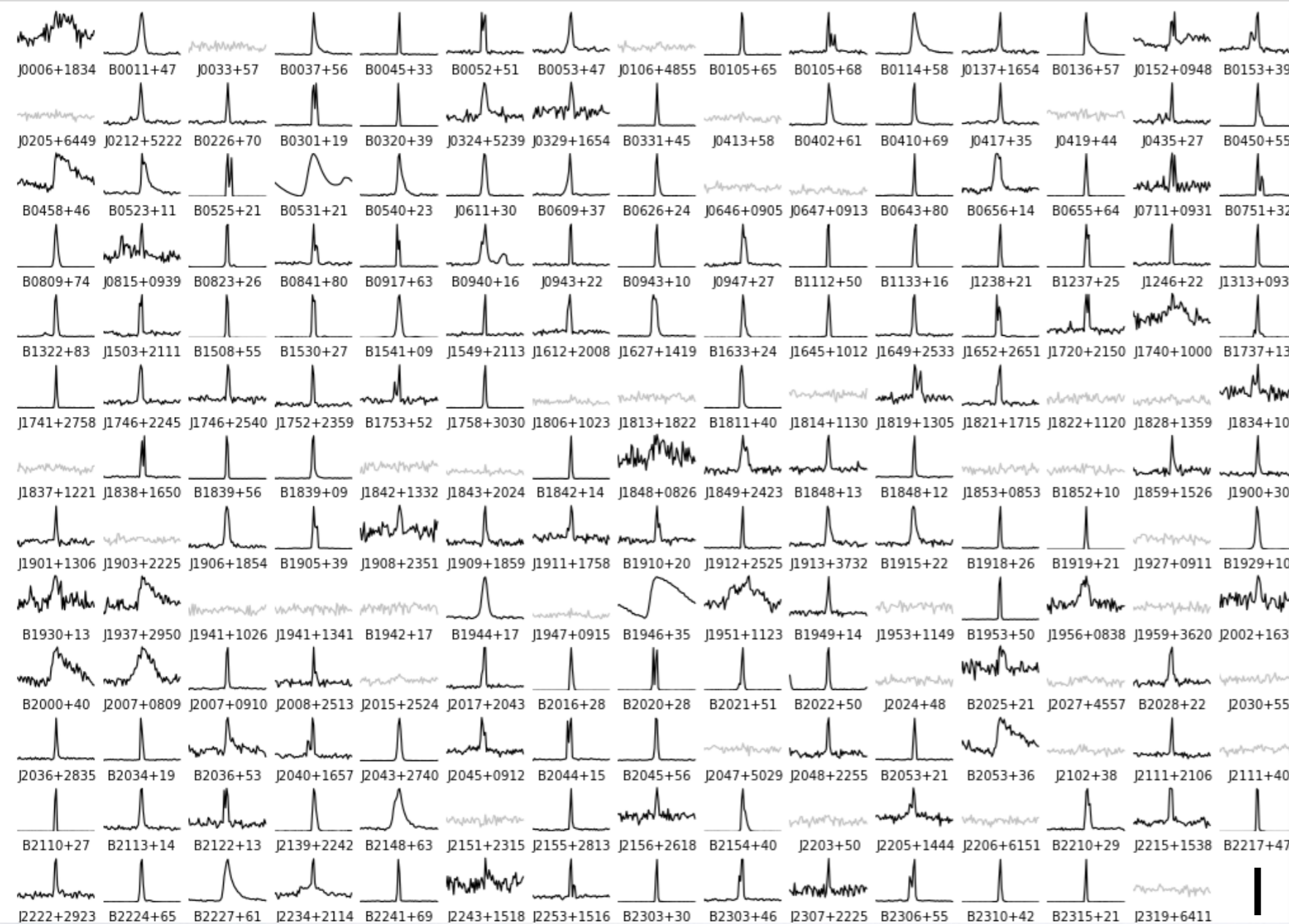


[Noutsos et al. 2015]

'NORMAL' & MSP CENSUS PROFILES

- 158 'slow' pulsars

- 48 MSPs



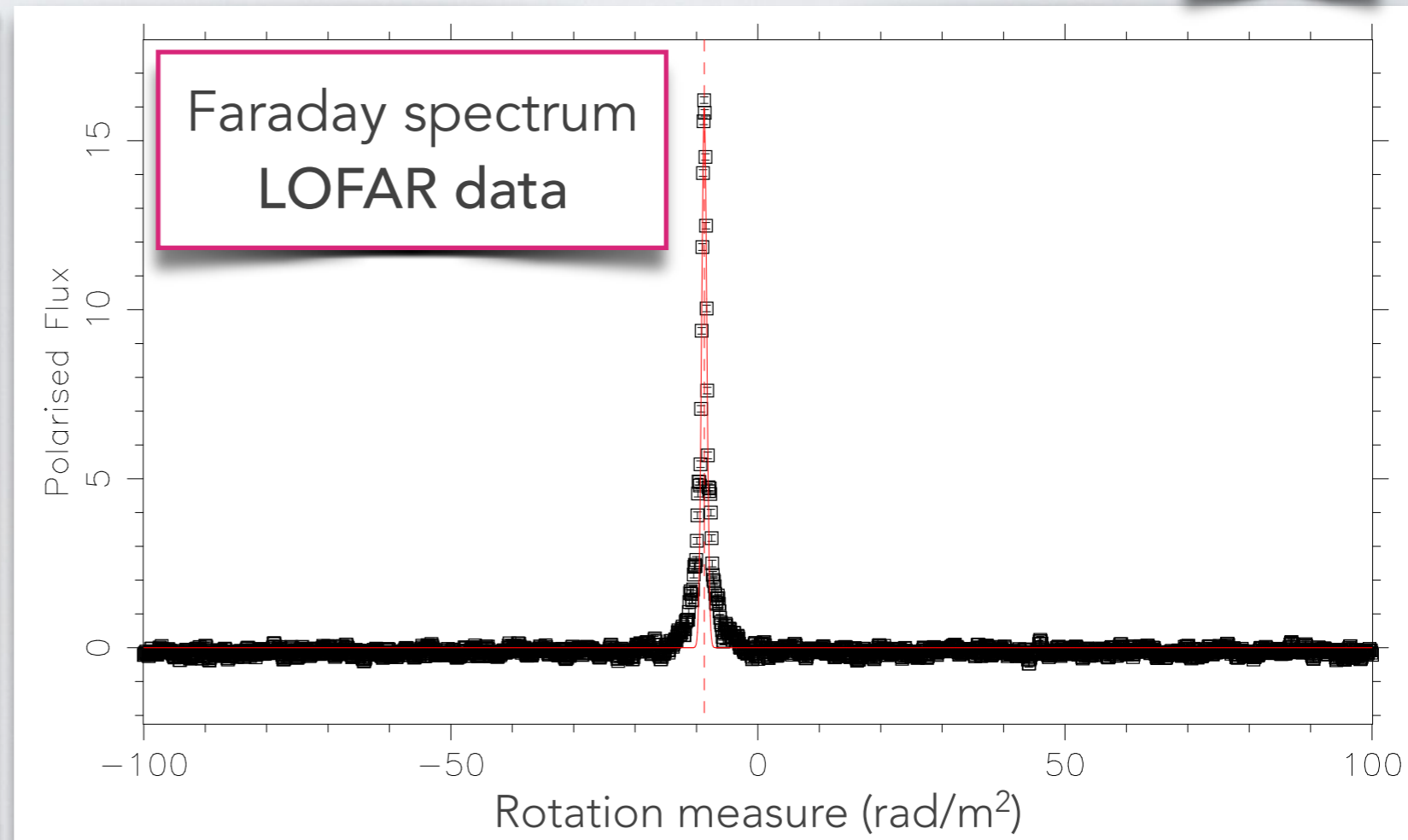
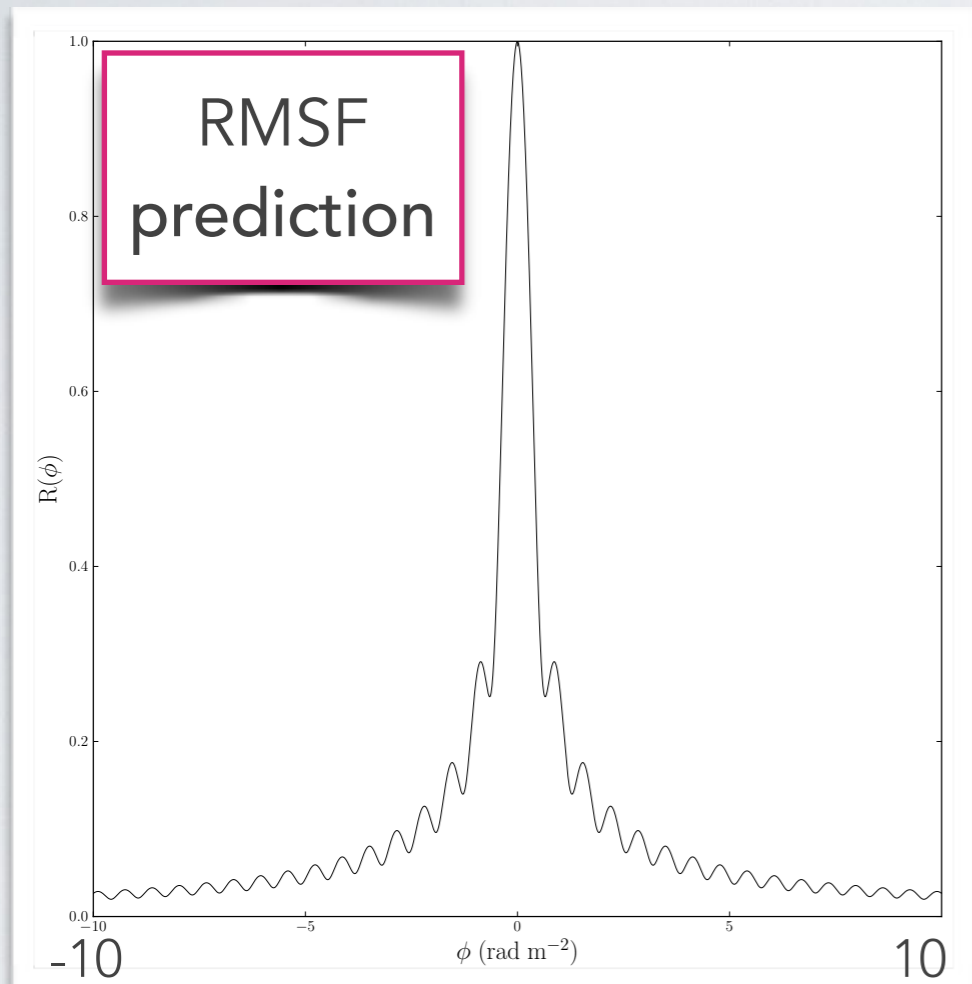
[Bilous et al. 2016]

[Kondratiev et al. 2016]

MEASURING RMs USING RM-SYNTHESIS

- Burn 1966; Brentjens & de Bruyn 2005
- LOFAR HBA data noiseless RMSF $\text{FWHM}_{150\text{MHz}} \sim 0.8 \text{ rad/m}^2$

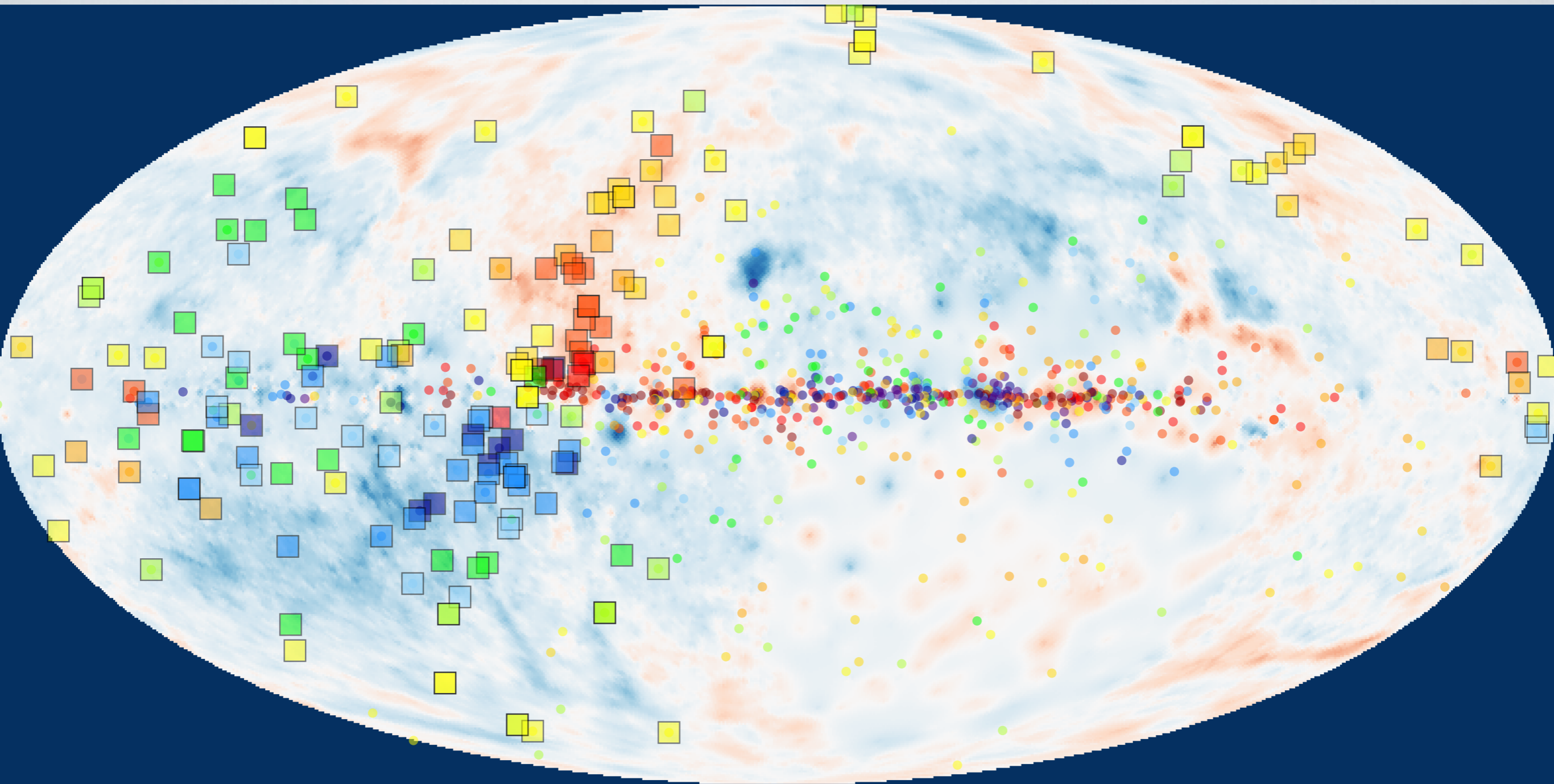
$$\approx \frac{2\sqrt{3}}{\Delta\lambda^2}$$



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

10x lower frequency: ~100x more precise!

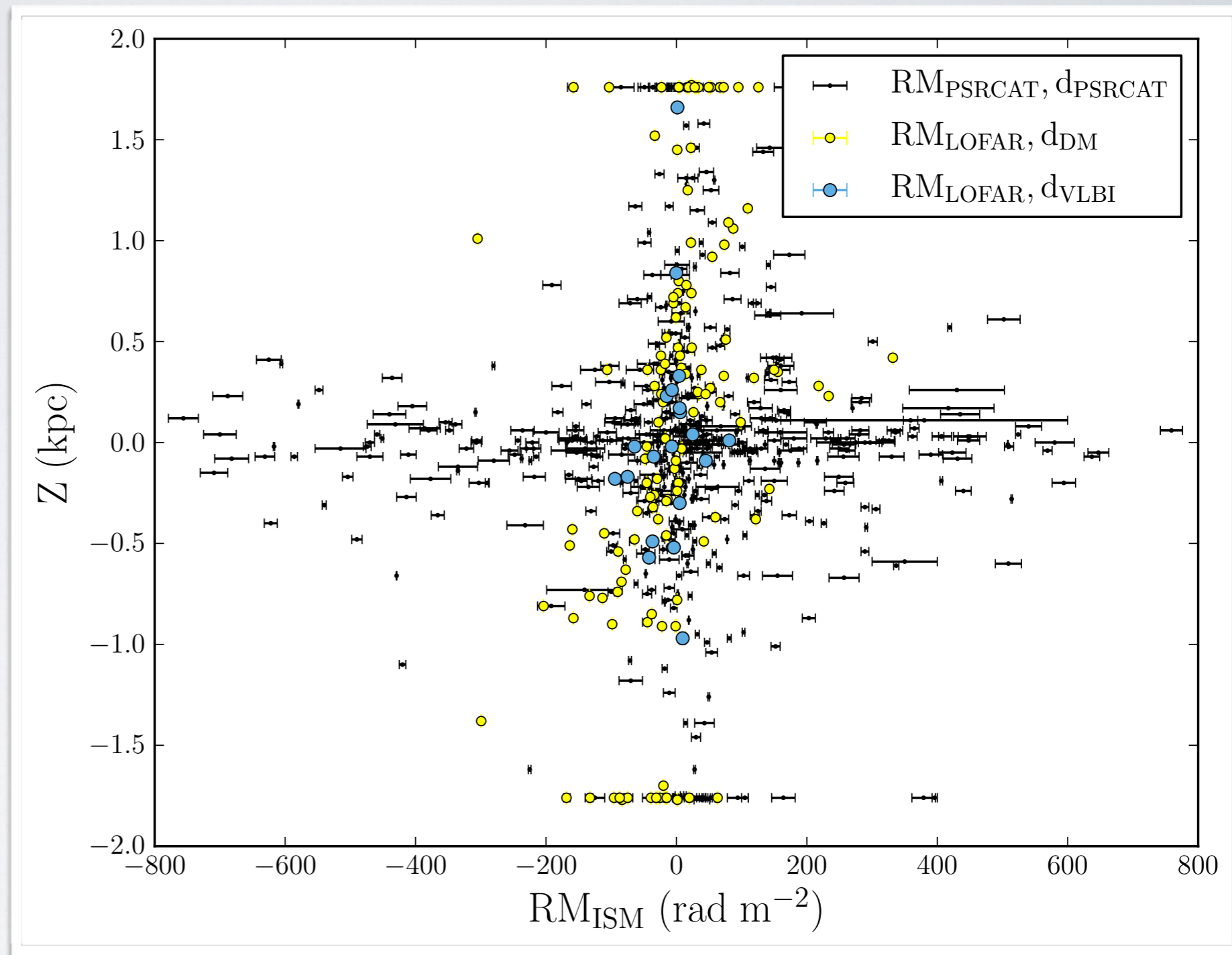
FARADAY ROTATION SKY



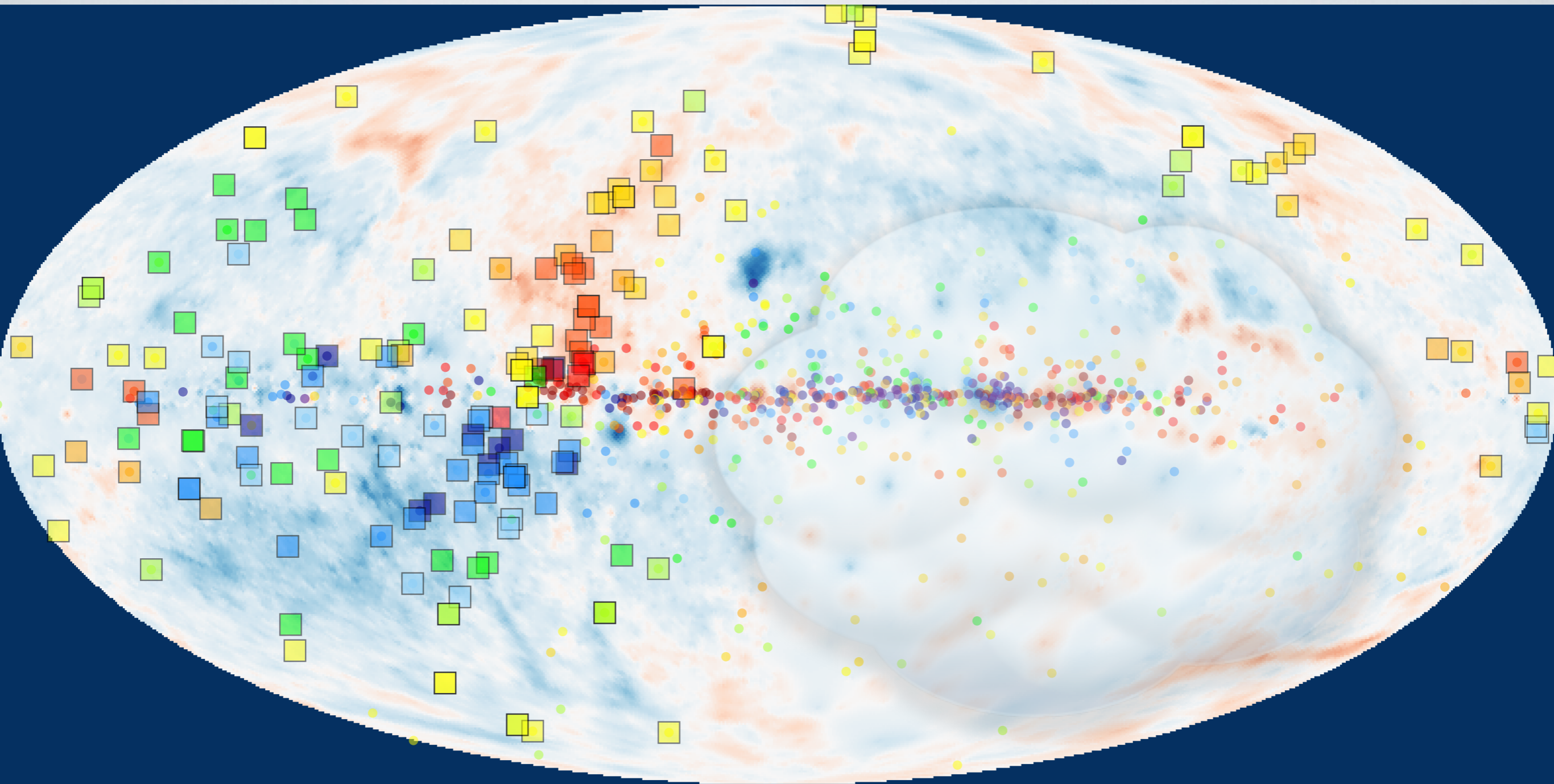
- LOFAR HBA pulsar RMs (Sobey et al. in prep., ~200 squares)
- Current pulsar RM catalogue (Manchester et al. 2005, 734 circles)
- Extragalactic sources (Oppermann et al. 2014, background)

LOFAR PULSAR RM RESULTS

- Catalogue of ~ 200 ionosphere-corrected RMs
- $\sim \pm 5 \mu\text{G}$ with $\sim 0.5\%$ fractional error
- ~ 90 new, others 30x more accurate
- Distance measurements (e.g. VLBI parallax) highly desirable for accurate 3-D GMF reconstruction



MEANWHILE... IN THE SOUTH



- LOFAR HBA pulsar RMs (Sobey et al. in prep., ~200 squares)
- Current pulsar RM catalogue (Manchester et al. 2005, 734 circles)
- Extragalactic sources (Oppermann et al. 2014, background)

MWA

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

MWA-VCS group includes:

Curtin:

Ramesh Bhat,
Steven Tremblay,
Dilpreet Kaur,
Sam McSweeney,
Bradley Meyers,
Mengyao Xue,
Nick Swainston

CSIRO:

Steve Ord

Swinburne:

Ryan Shannon

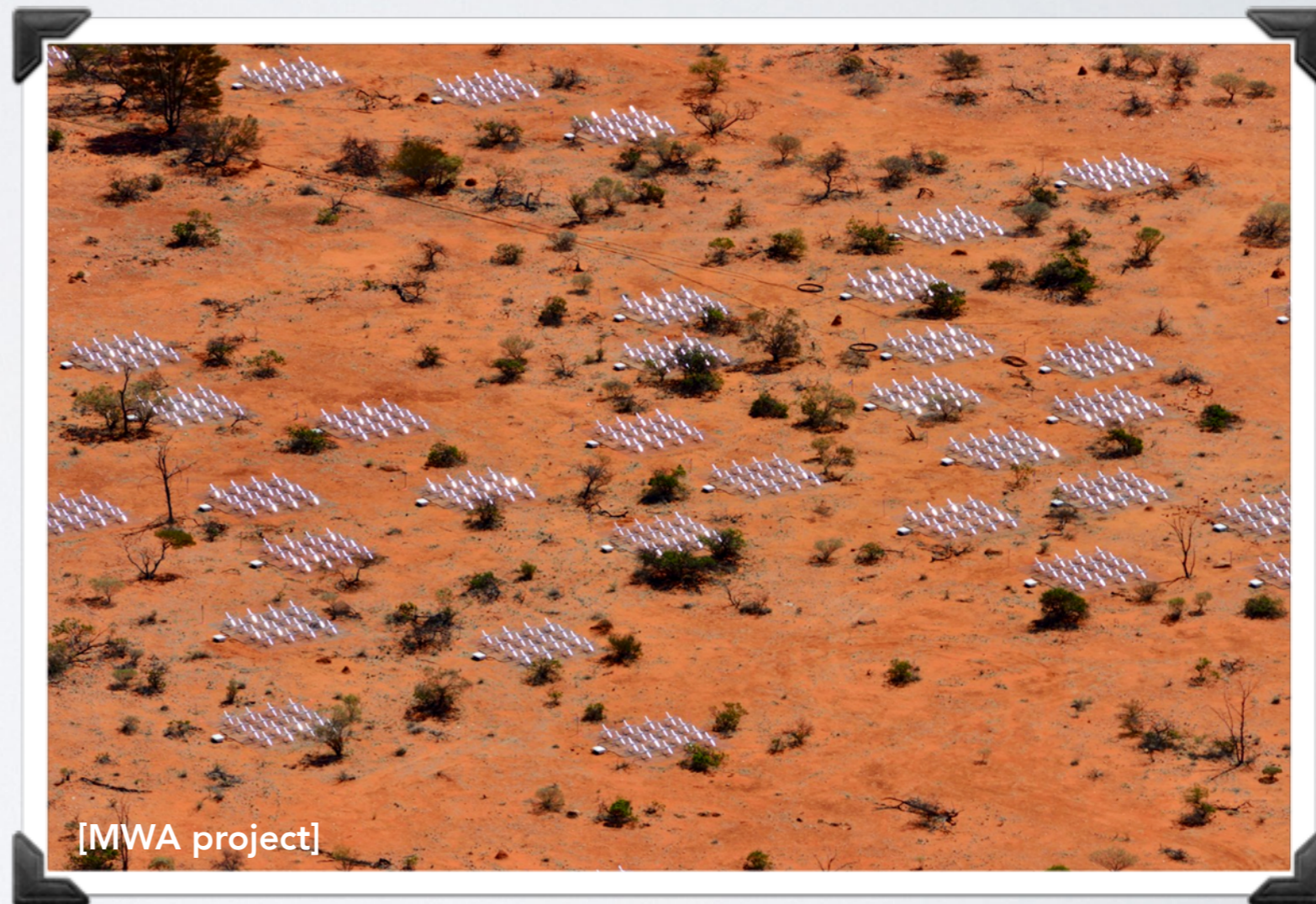
Onsala:

Franz Kirsten

UWM:

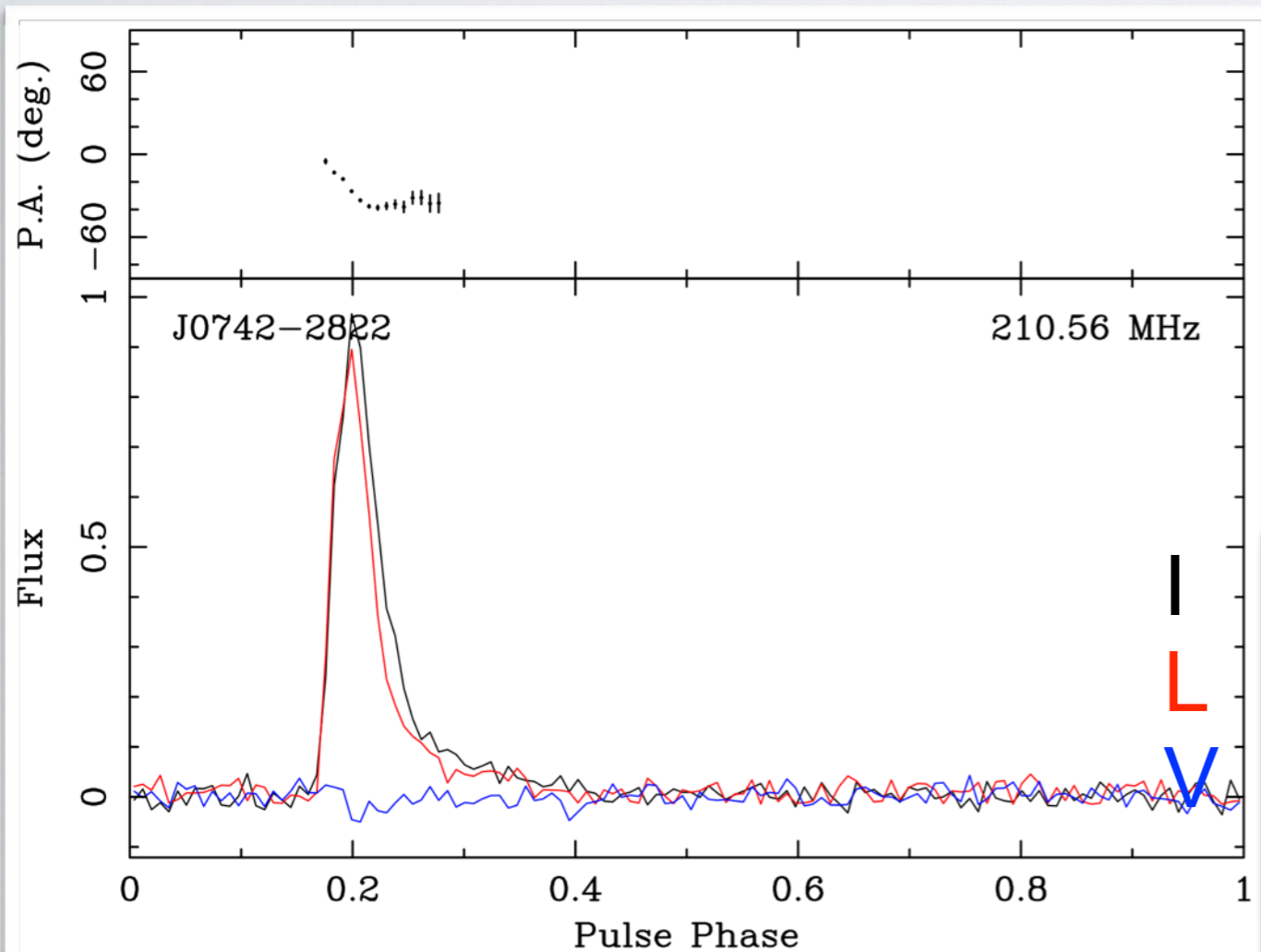
David Kaplan,
Joe Swiggum

...

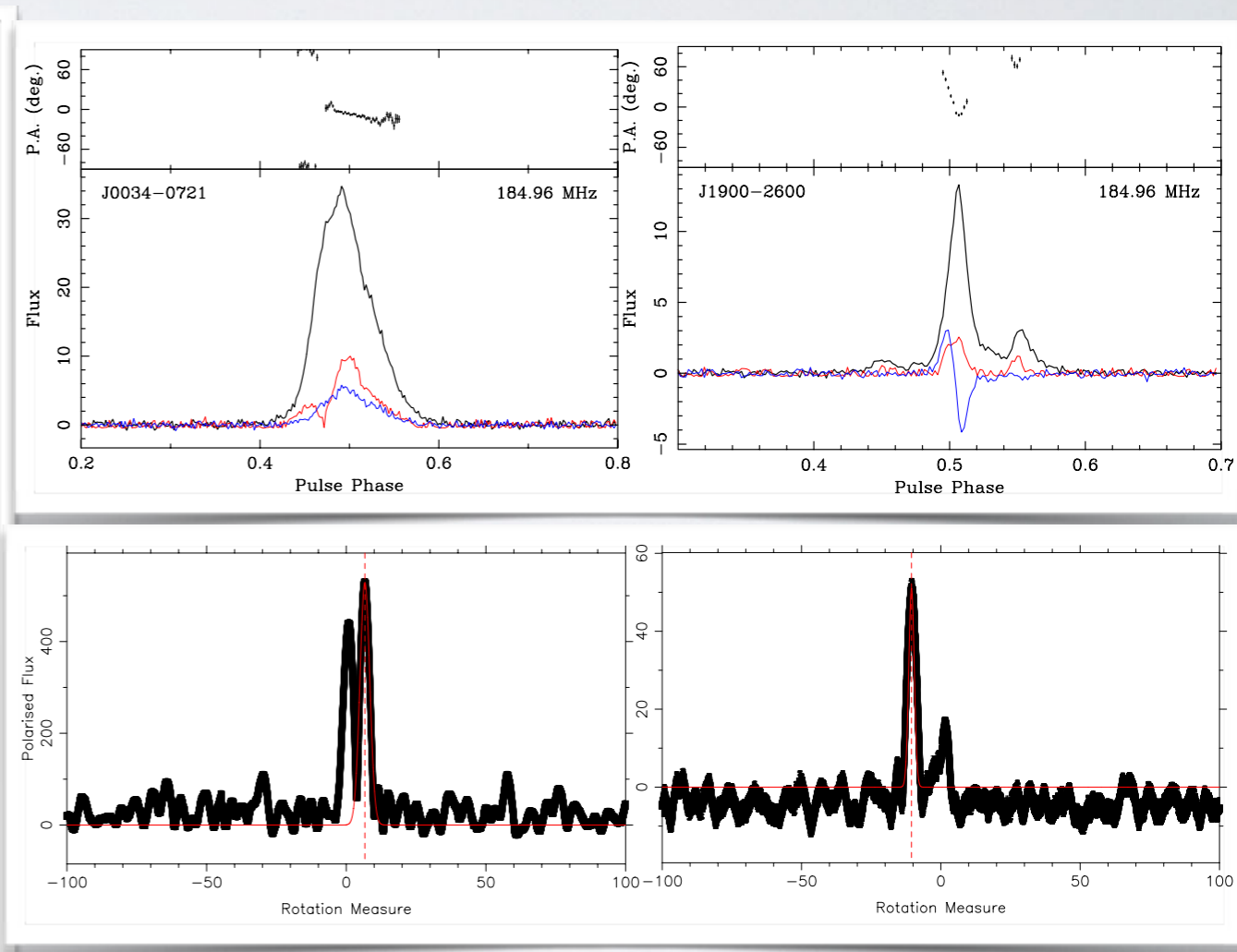


MWA PULSAR OBSERVATIONS

- Using 'voltage capture mode' with full polarisation
- Currently verifying multi-frequency polarisation profiles (128-312 MHz 'picket fence')
- RMs measured with complementary precision to LOFAR



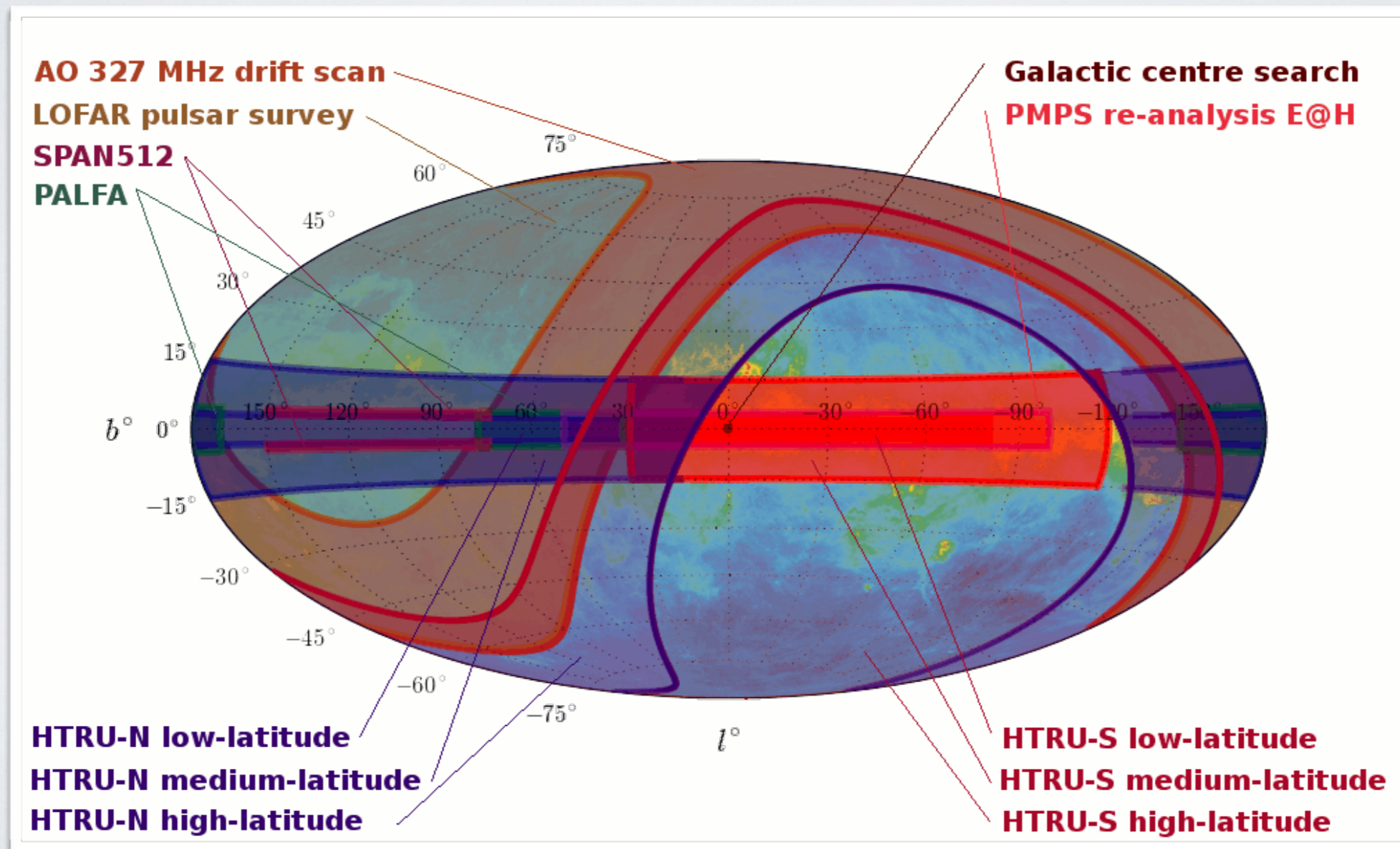
[Mengyao Xue]



[C. Sobey]

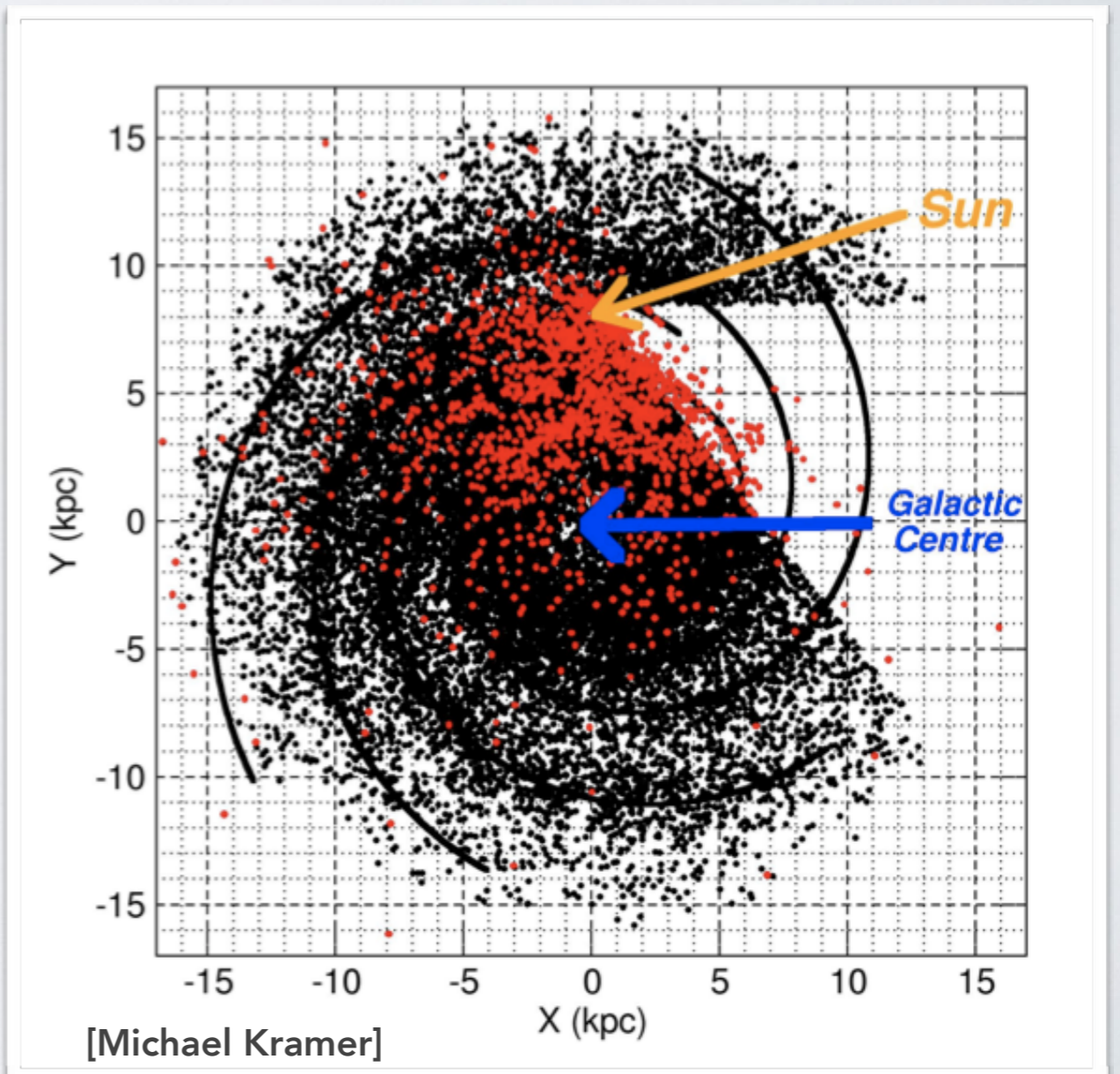
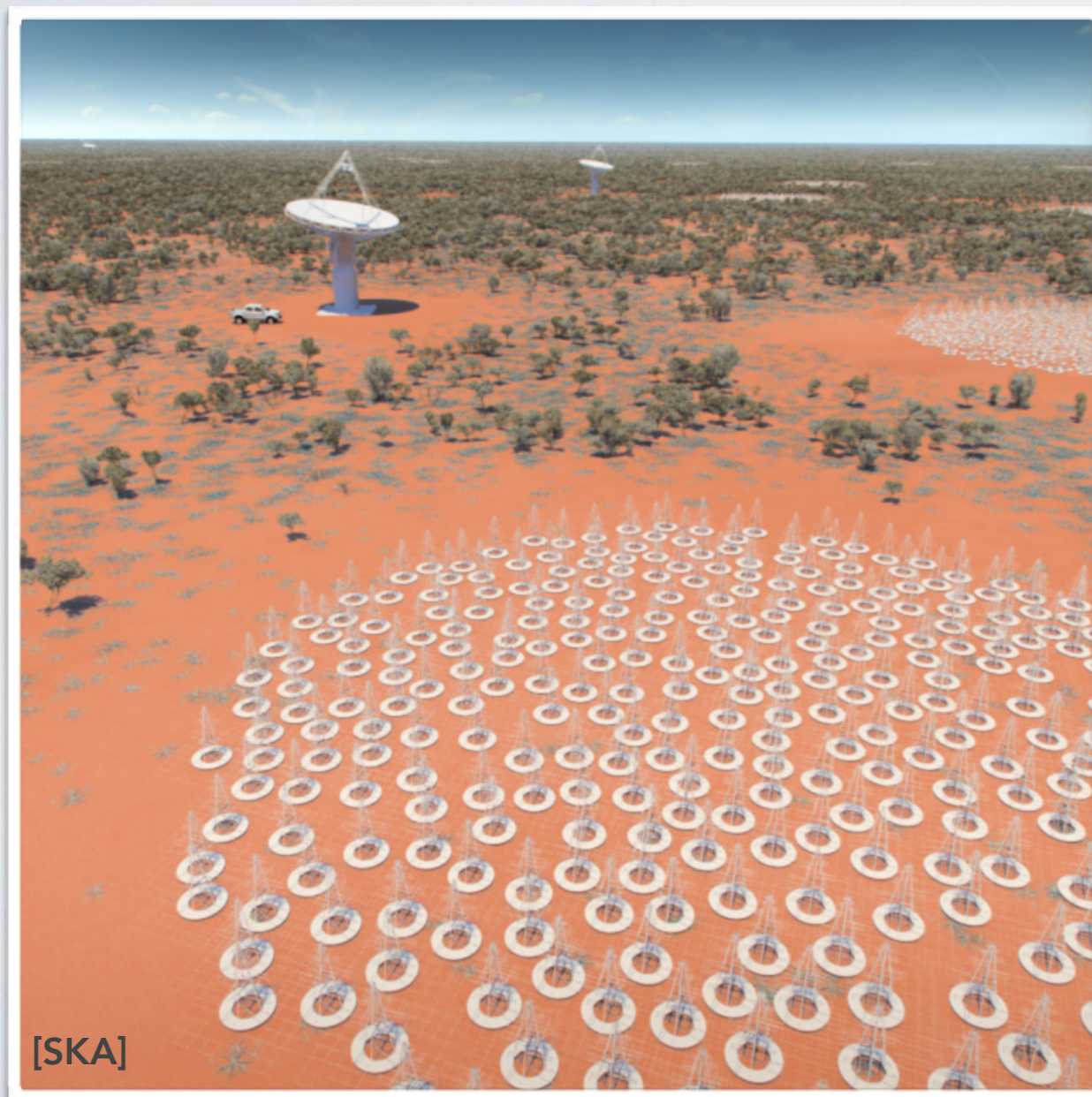
FUTURE PROSPECTS...

- Precision measurements enable 'monitoring' era (and investigation of smaller scales, e.g., turbulence and heliosphere)
- Many ongoing (time/image-domain) pulsar surveys: increasing pulsar RM catalogue and therefore numbers of 3-D probes of the GMF



...TOWARDS THE SKA

- SKA will discover thousands more pulsars - 3-D tomography (Han+2015)
 - Highly desirable: well-understood polarisation characteristics and accurate ionospheric (RM) monitoring



SUMMARY

- Low-frequency RMs towards pulsars — precise 3-D probes of the GMF
- LOFAR & MWA facilitate all-sky low-frequency RMs
- Towards DM/RM monitoring era, e.g., small-scale/turbulent structures

Thank you for listening!