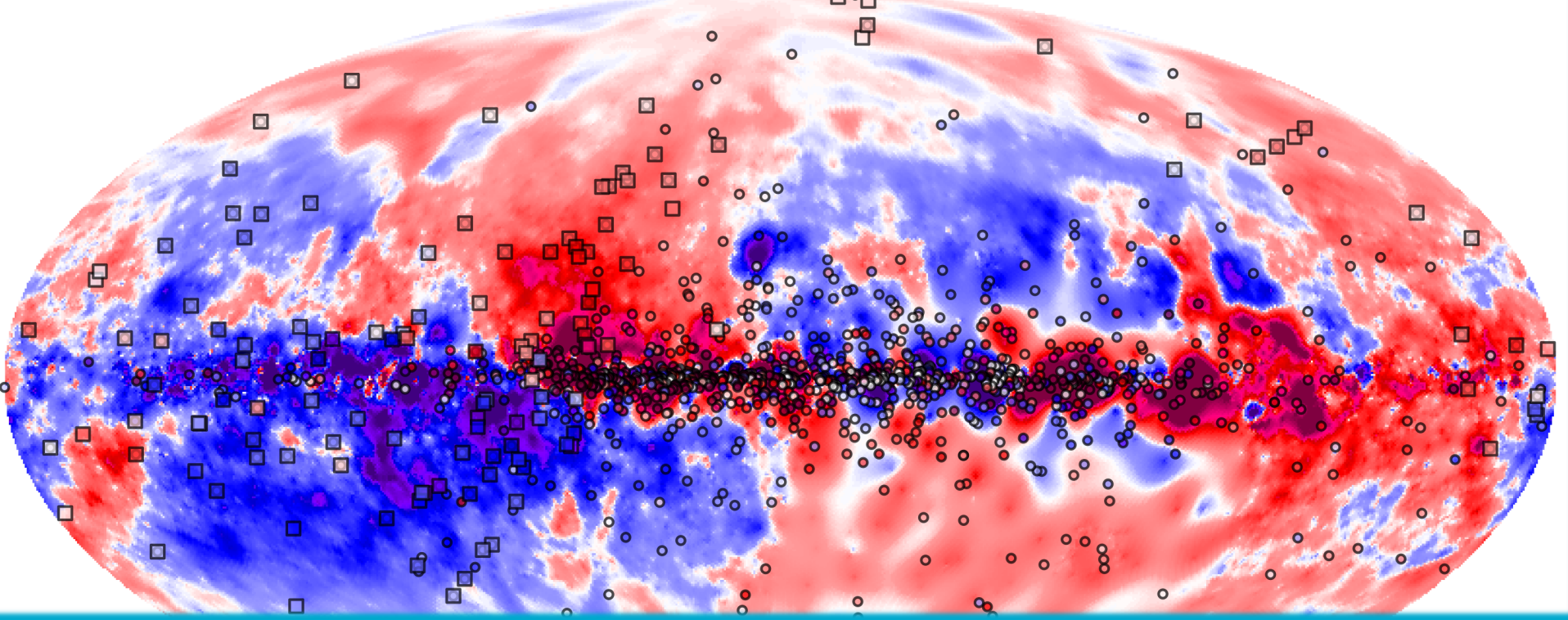

Faraday rotation measures towards pulsars using LOFAR: probing the 3-D Galactic halo magnetic field

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21 May 2019

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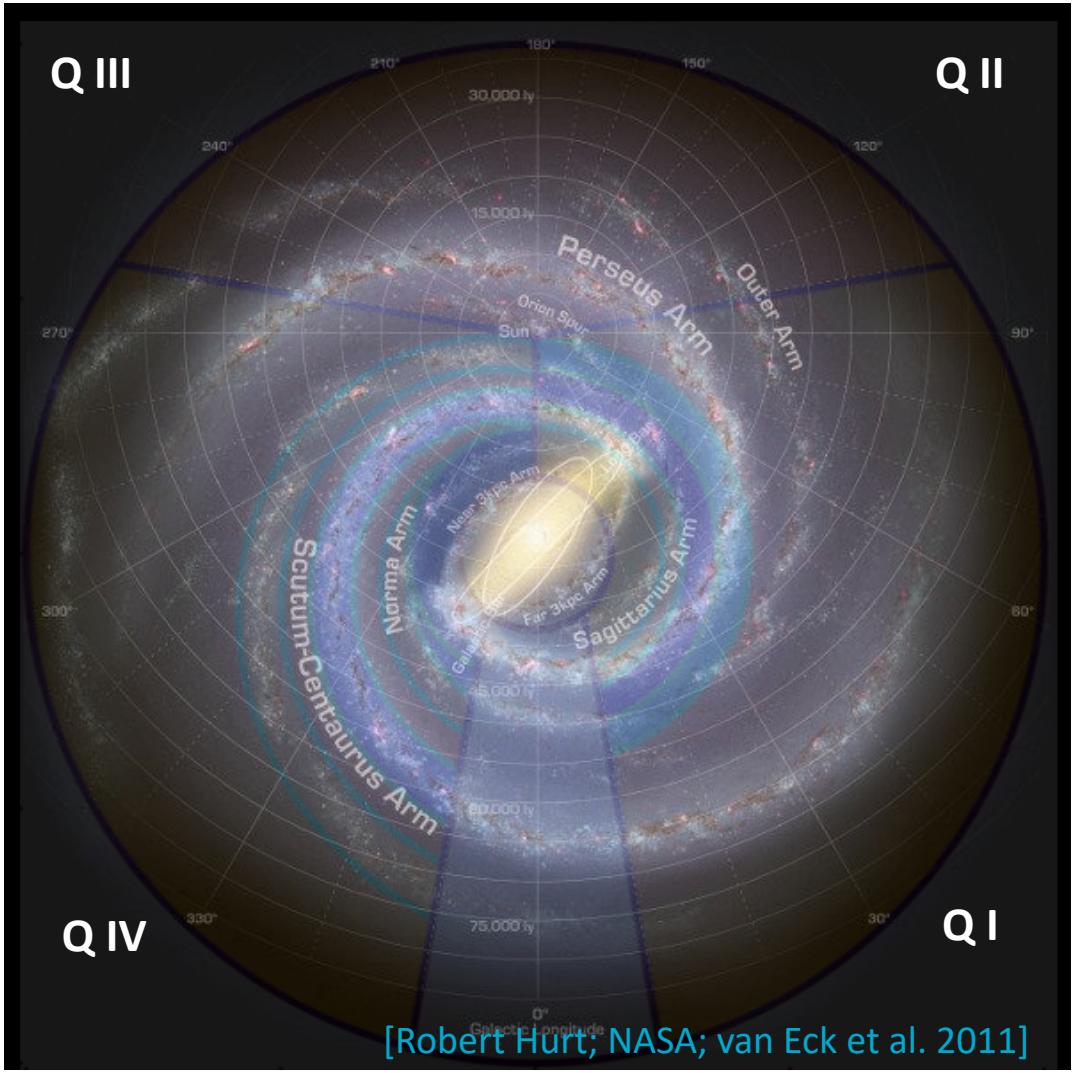
LOFAR

Outline

- Motivation:
  - The structure of the **Galactic magnetic field**
- LOFAR pulsar observations:
  - Collaborations: LOFAR Pulsar Working Group & Magnetism Key Science Project
- Methods
- Results
  - Catalogue of **137 low-frequency RMs**
  - Scale height of the Galactic halo magnetic field estimate
- Ongoing and future work

Galactic magnetic field structure

- Pervades diffuse ISM
- Affects processes across range of physical scales and field strengths
- Large-scale (kpc) and small-scale (1-100 pc) components
- Challenging to reconstruct model of Galaxy's structure
  - Magnetic field not directly observed (but inferred)
- MW accesses smaller-scale studies, for comparison to nearby galaxies



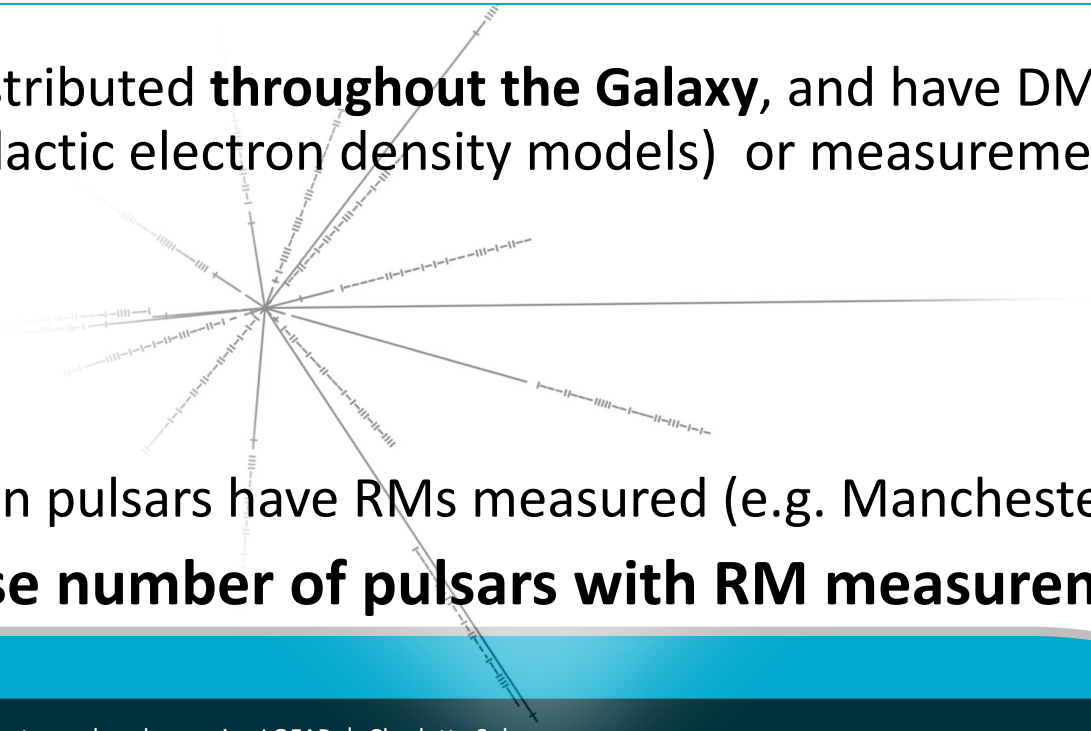
[Robert Hurt; NASA; van Eck et al. 2011]

Pulsars are efficient 3-D probes of the Galaxy

- Dispersion and Faraday rotation measure (DM, RM) for each pulsar provides
  - Electron-density-weighted **average magnetic field** parallel to LoS:

$$\langle B_{\parallel} \rangle = \frac{\int_0^d n_e B_{\parallel} \mathrm{d}l}{\int_0^d n_e \mathrm{d}l} = 1.232\ \mu\mathrm{G} \left(\frac{\mathrm{RM}}{\mathrm{rad\ m^{-2}}} \right) \left(\frac{\mathrm{DM}}{\mathrm{pc\ cm^{-3}}} \right)^{-1}$$

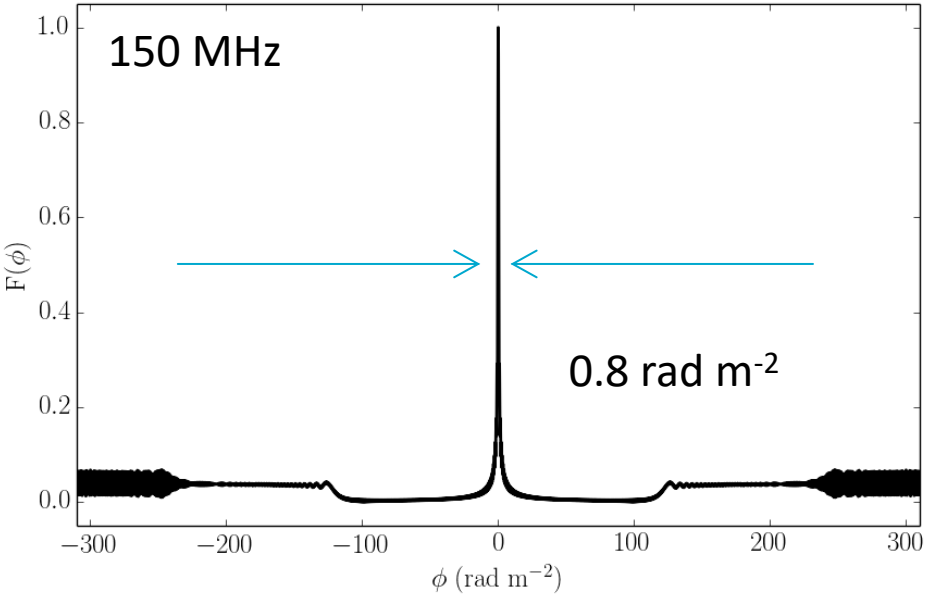
- Pulsars are distributed **throughout the Galaxy**, and have DM distance estimates (Galactic electron density models) or measurements (e.g. parallax)

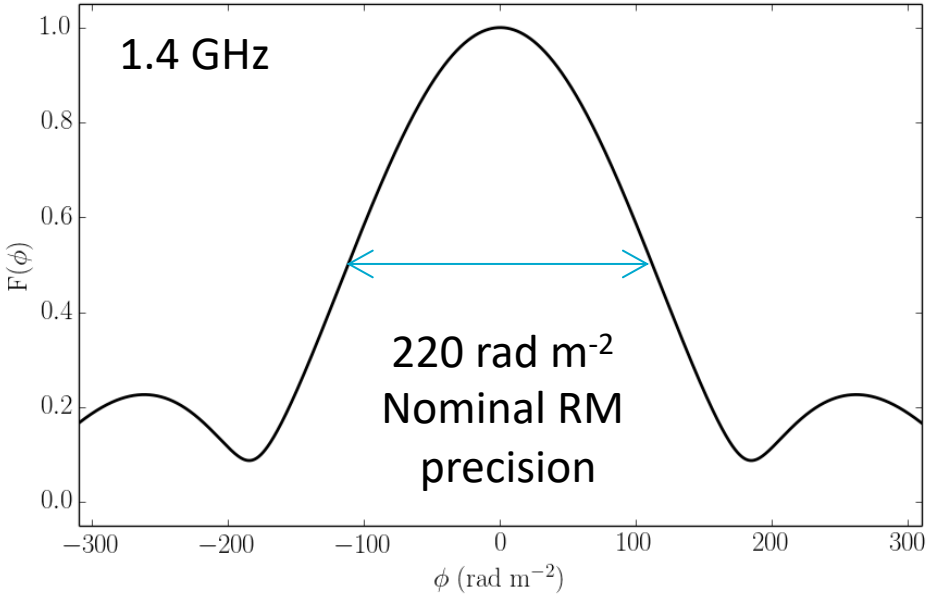


- <45% of known pulsars have RMs measured (e.g. Manchester et al. 2005)
- **Aim: Increase number of pulsars with RM measurements**

Why low-frequencies? Precise measurements…

- Dispersion and Faraday rotation measures (DMs, RMs):
  - **wavelength-squared** dependencies
- Using RM-synthesis (Burn 1966; Brentjens & de Bruyn 2005)
  - RM spread functions (RMSF) for LOFAR (150 MHz) and 1.4 GHz



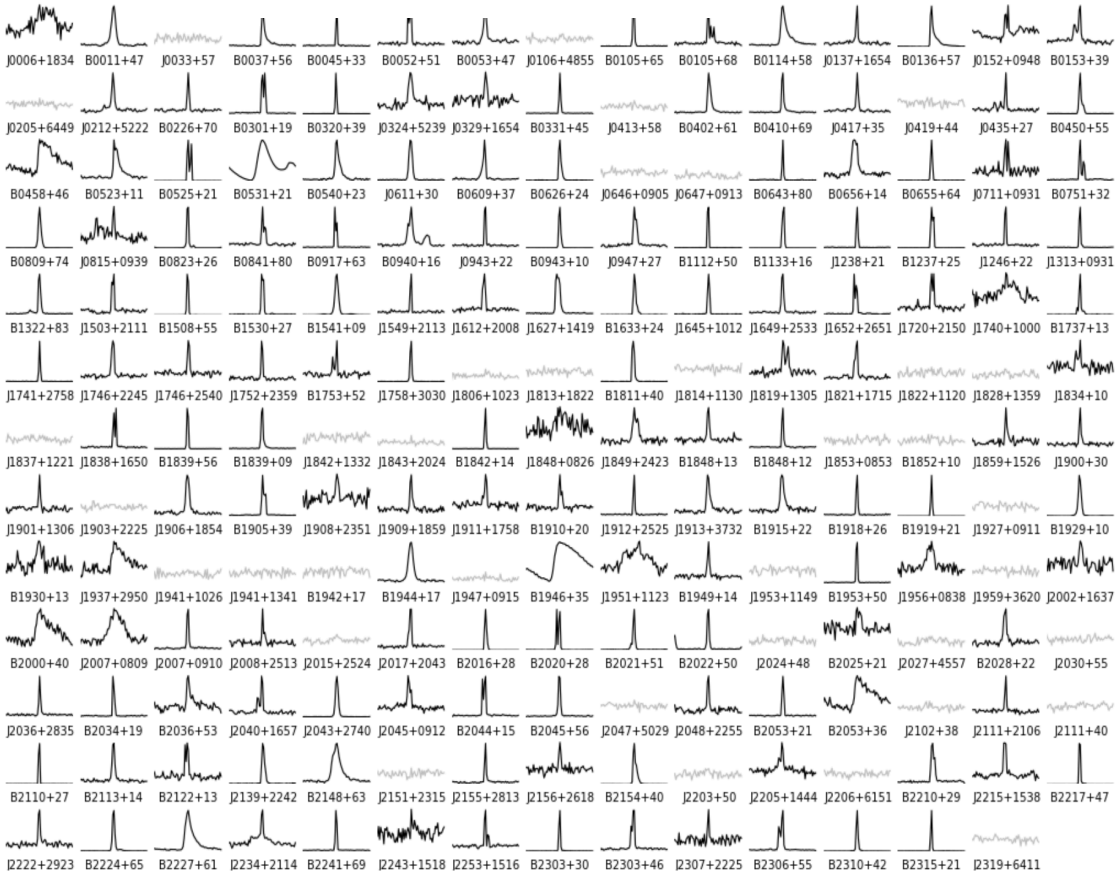


- **Aim: Reduce RM uncertainties for literature RMs**

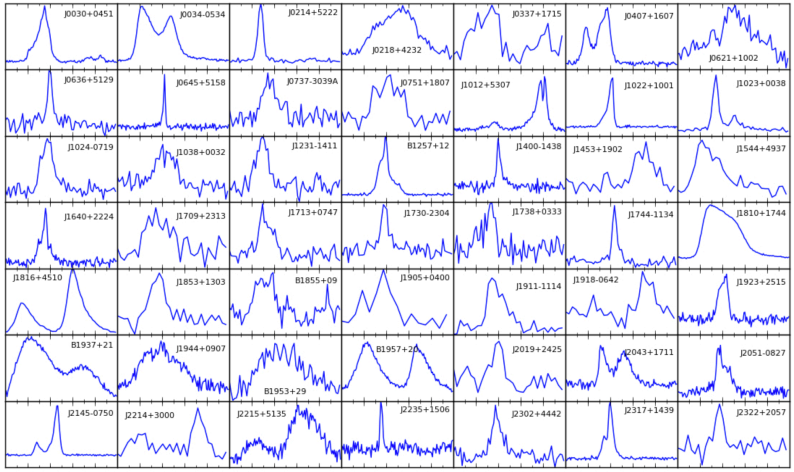
LOFAR observations at 150 MHz (HBA)

- LOFAR census of non-recycled pulsars (Bilous et al. 2016)
- LOFAR census of millisecond pulsars (Kondratiev et al. 2016)

158 ‘slow’

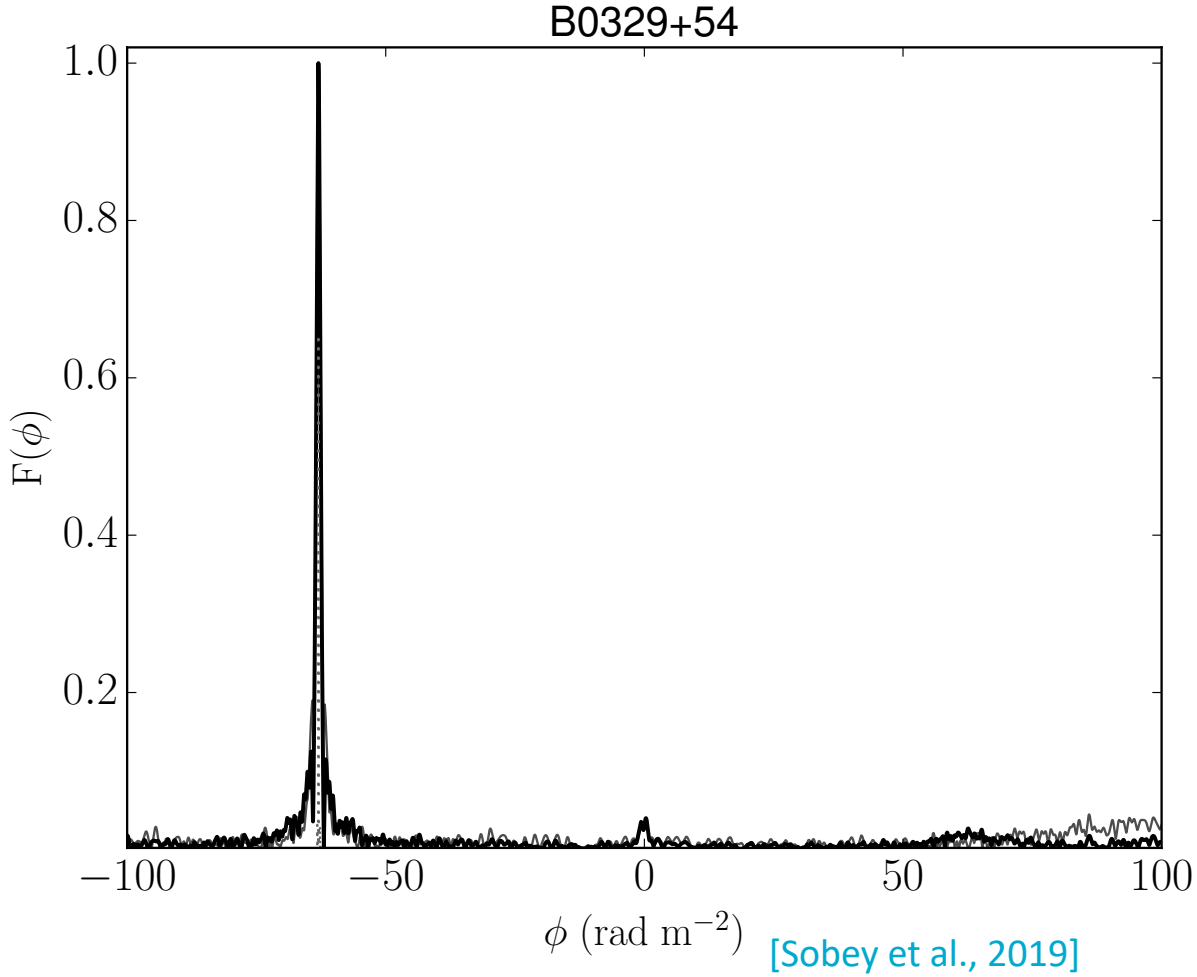


48 MSPs



RM synthesis

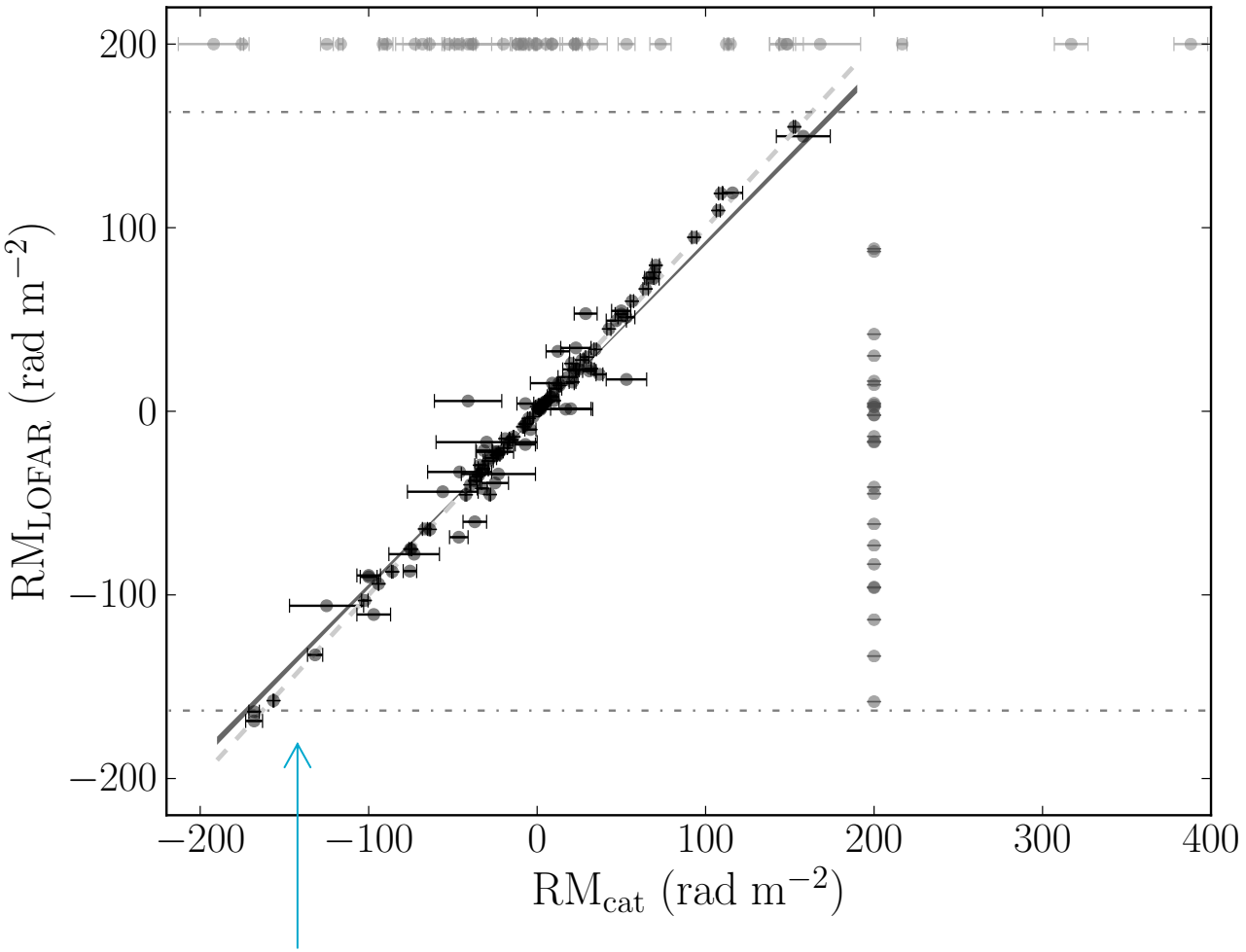
- Example Faraday spectrum (FDF) using LOFAR (110-190 MHz)



[Sobey et al., 2019]

Results

- **137** LOFAR RMs
  - 117 ‘slow’ pulsars: 86% of census
  - 19 MSPs: 60% of census with S/N>10
  - +PSR B0329+54
- After correction for ionospheric RM (Sotomayor-Beltran et al. 2013)
- **25 new** RMs
- **Factor of 20 reduction** in uncertainties

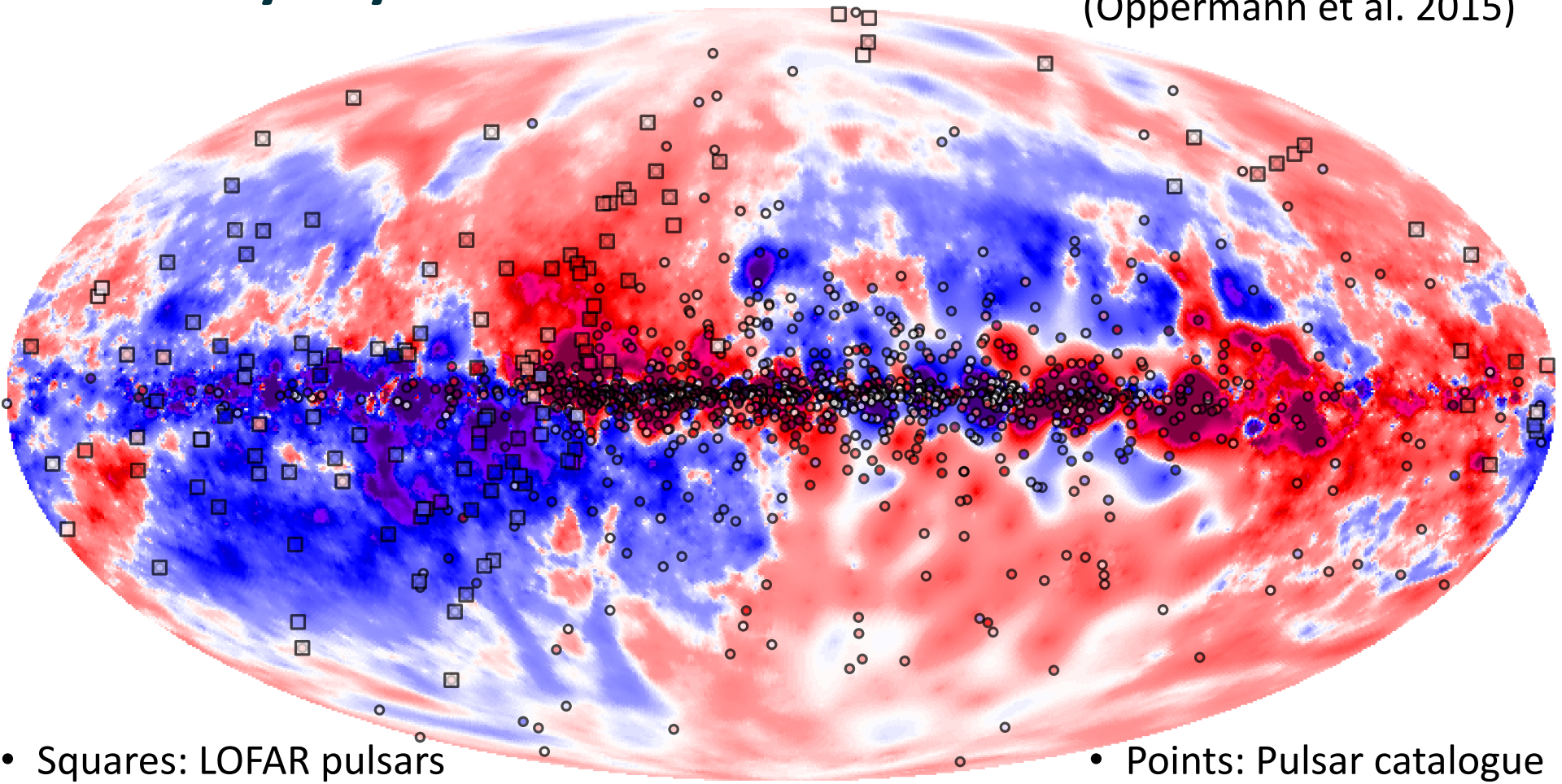


Max |RM|=168.7 rad m^{-2}

[Sobey et al., 2019]

Faraday sky

- Background: Extragalactic (Oppermann et al. 2015)

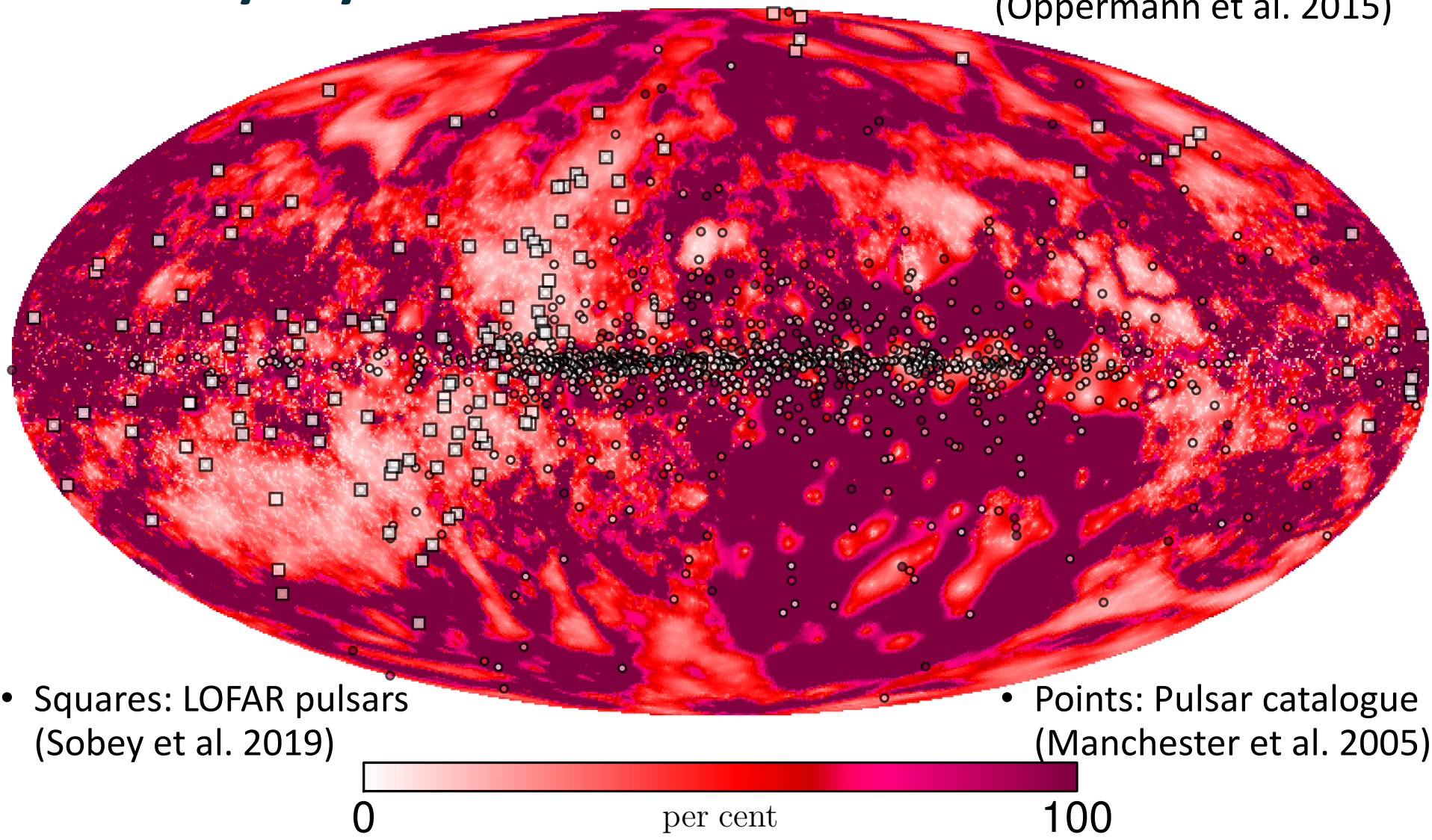


- Squares: LOFAR pulsars (Sobey et al. 2019)
- Points: Pulsar catalogue (Manchester et al. 2005)

-204 $\mathrm{rad\ m^{-2}}$ 204

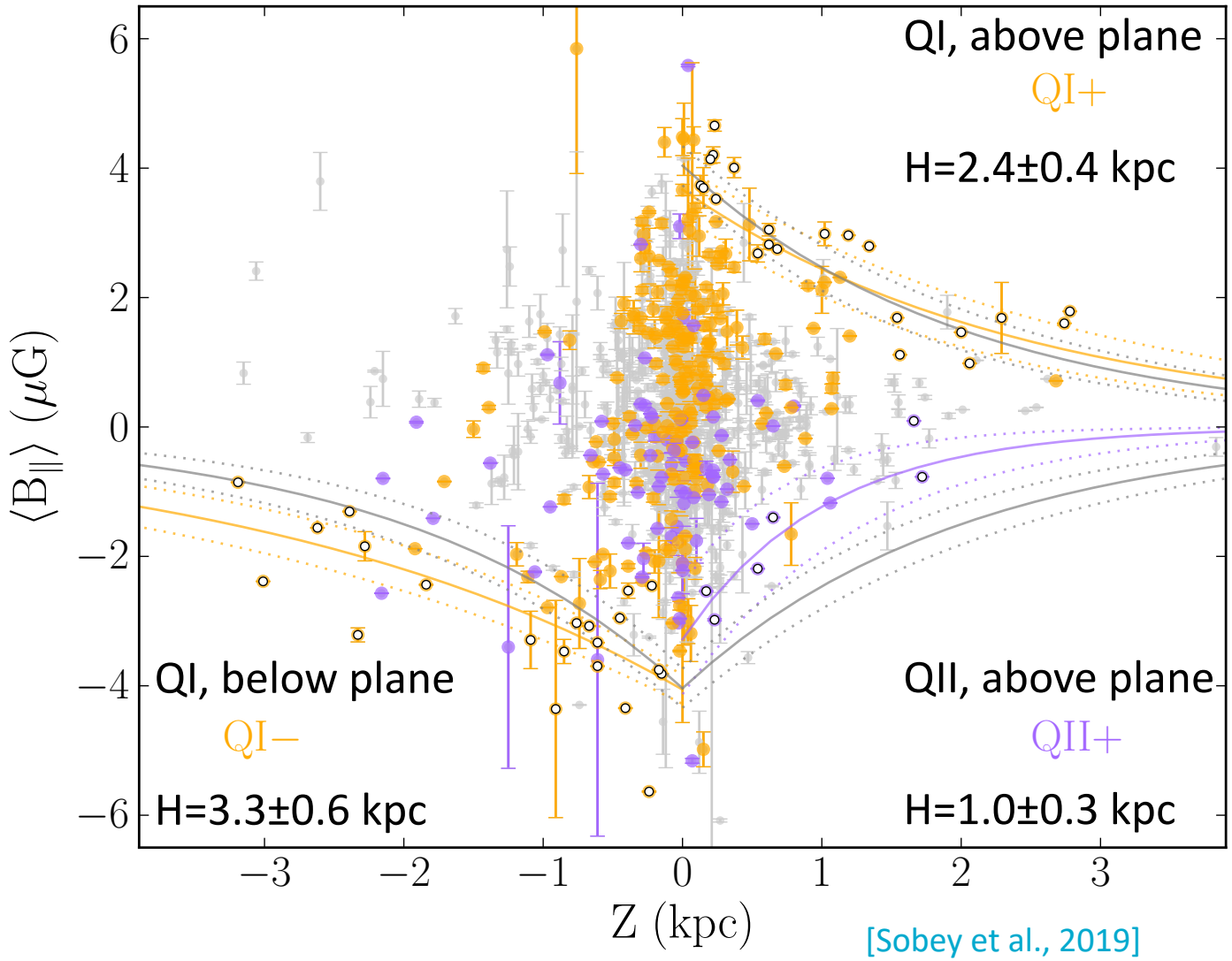
Faraday sky uncertainties

- Background: Extragalactic (Oppermann et al. 2015)



- Squares: LOFAR pulsars (Sobey et al. 2019)
- Points: Pulsar catalogue (Manchester et al. 2005)

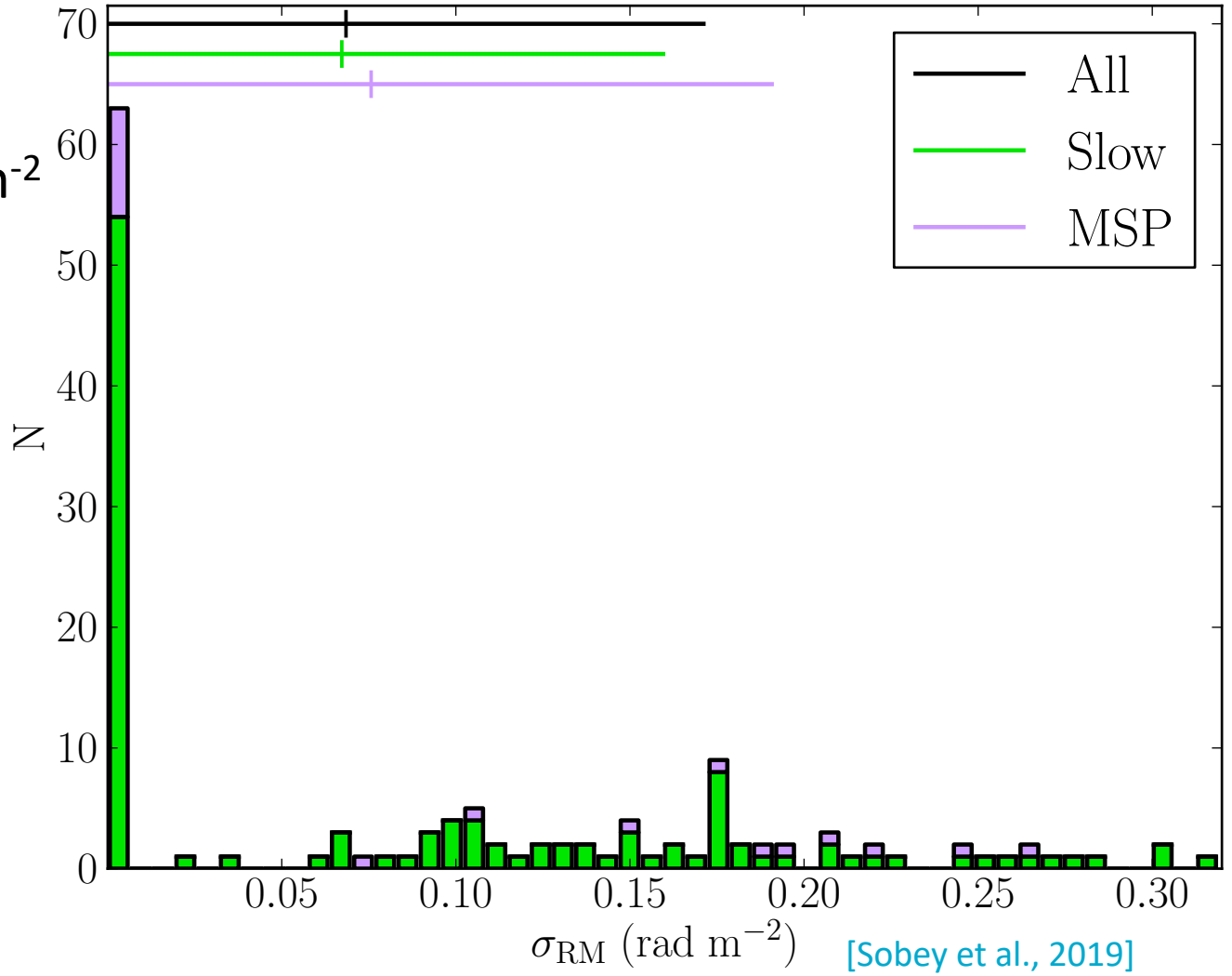
Magnetic scale height estimate



[Sobey et al., 2019]

In addition: RM dispersions…

- **137** RM dispersions
  - Using RM CLEAN
- Mostly <0.001 rad m^{-2}
- Very Faraday thin



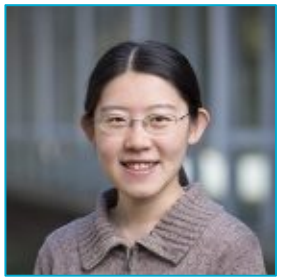
[Sobey et al., 2019]

Ongoing and future work…

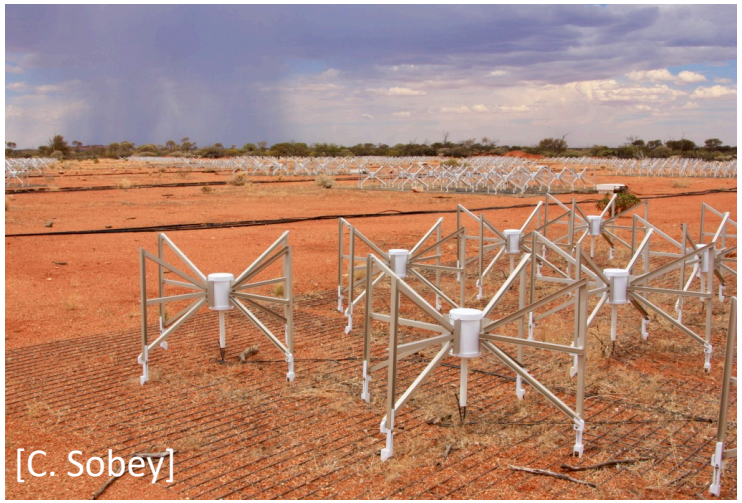
- An initial sample of precise RMs using LOFAR
  - Being expanded by using LOFAR observations of more pulsars
- Baseline for future observations to monitor RMs over time
  - Increasing accuracy for timing/monitoring data set (multiple observations, multiple ionospheric RM corrections)
- Improving ionospheric RM correction accuracy (largest contributor to uncertainties ~0.1 rad m^{-2} using current method)
- Publishing polarisation profiles

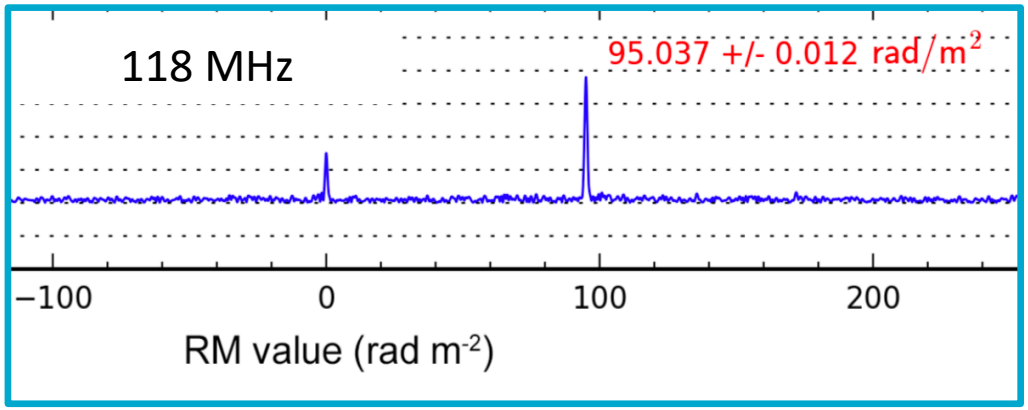
[LOFAR Superterp and nearby Core Stations]

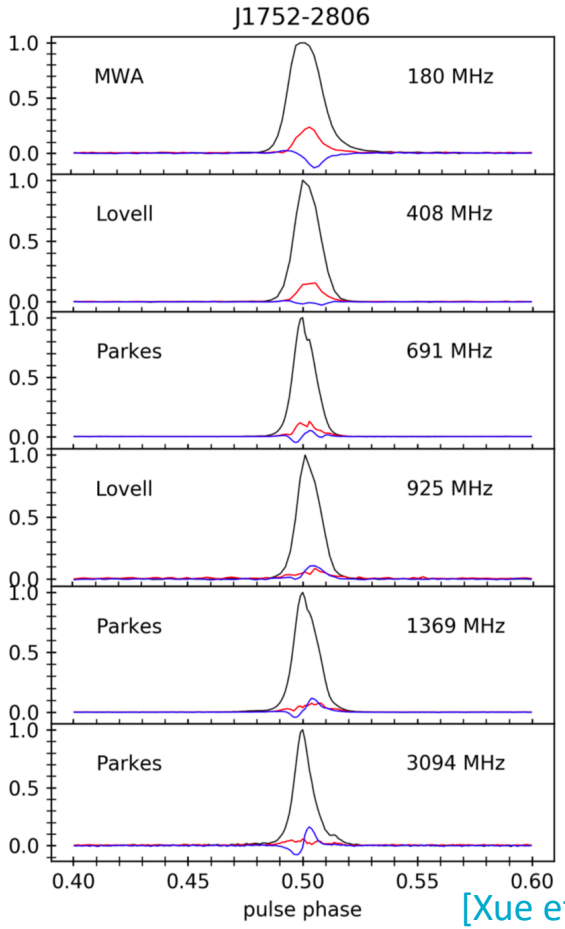
…MWA for low-frequency Southern sky…



- Towards an all-sky low-frequency RM catalogue towards pulsars
- Polarimetric observations verified; Xue, M., et al. 2019 (accepted)



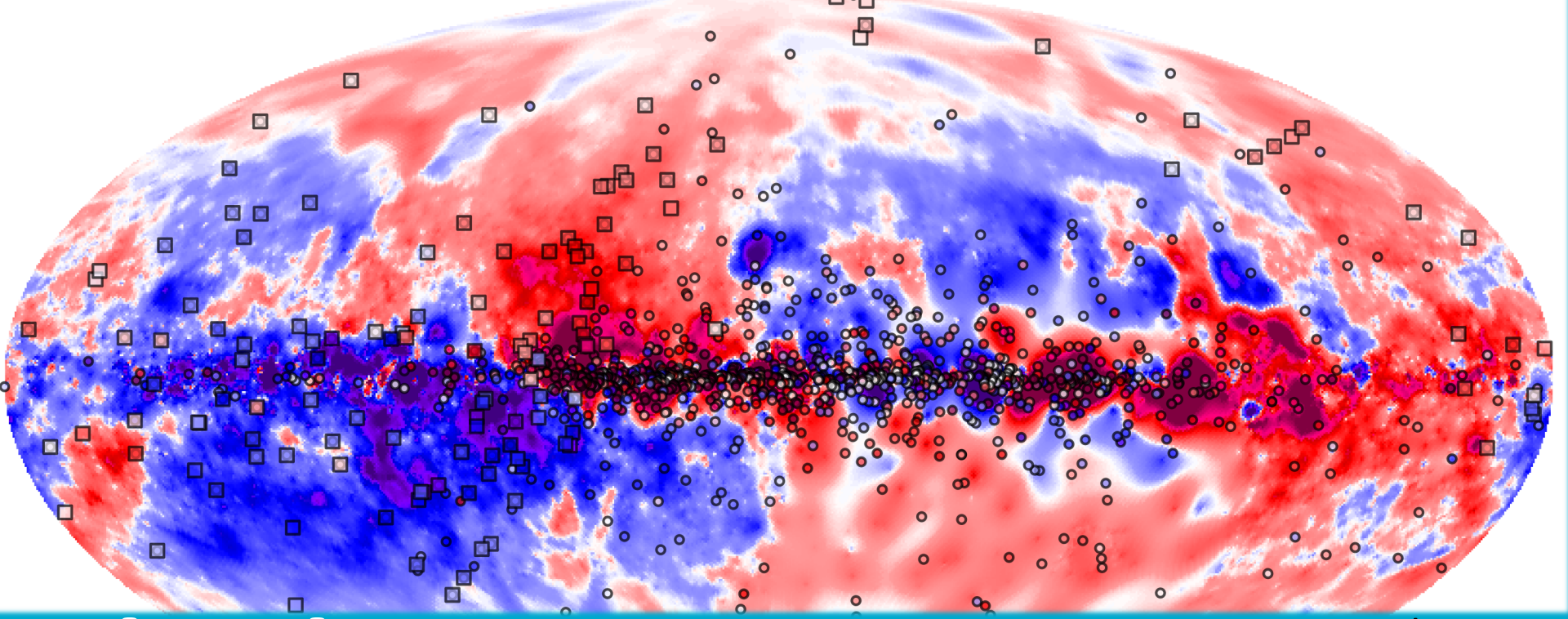




[Xue et al., 2019]

Complementary work & magnetic field tracers

- **New pulsars** being discovered at low (and higher) radio frequencies…
  - LOFAR Tied Array All-Sky (LOTAAS) Survey: Tan et al. 2018; Sanidas et al. accepted
- **Independent pulsar distance measurements** increasingly important
  - e.g. VLBA annual parallax measurements; Deller et al. 2018
- **Extragalactic source** RMs provide LoS through Galaxy (at least)
  - MKSP RM Grid effort using LoTSS DR2 (Shane O'Sullivan's talk)
- Towards a complete model of the **3-D Galactic magnetic field**
  - Galactic Synchrotron emission: field in the plane of the sky (Vibor Jelic's talk)
  - IMAGINE: Bayesian inference framework developing to reconcile multiple data sources and theoretical models to determine likely structure (Boulanger et al. 2018)
- In the future **SKA(-LOW)** will provide ground-breaking observations and revolutionise our understanding of the Galaxy's (magnetic) structure



Thank you

Squares: 137 LOFAR pulsar RMs
(Sobey et al. 2019)

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