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Max-Planck-Institut für Radioastronomie

The Structure of the Large-scale Galactic Magnetic Field from Pulsar Rotation Measures

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Radioastronomische Fundamentalphysik

"Magnetisation of Interstellar and Intergalactic Media" — *Kloster Irsee, 5 October 2010*

Why is the Galactic Magnetic Field so Important?

- Contributes to the stability of the interstellar matter (via magnetic tension)

  — perhaps also to the dynamics of the Galactic disc

- Compressed fields in molecular clouds are amongst the most important agents for star formation

- The large-scale fields in the Galactic halo provide pathways through our Galaxy for the Ultra-High Energy Cosmic Rays

- Studies of the Cosmic Microwave Background require knowledge of the polarised, foreground radio emission: i.e. the Galactic magnetic fields are also important for extragalactic astronomy and even cosmology!

Observational Tracers of the G.M.F.

Starlight Polarisation
Polarised Thermal Dust Emission
Diffuse Synchrotron Emission
Zeeman Splitting

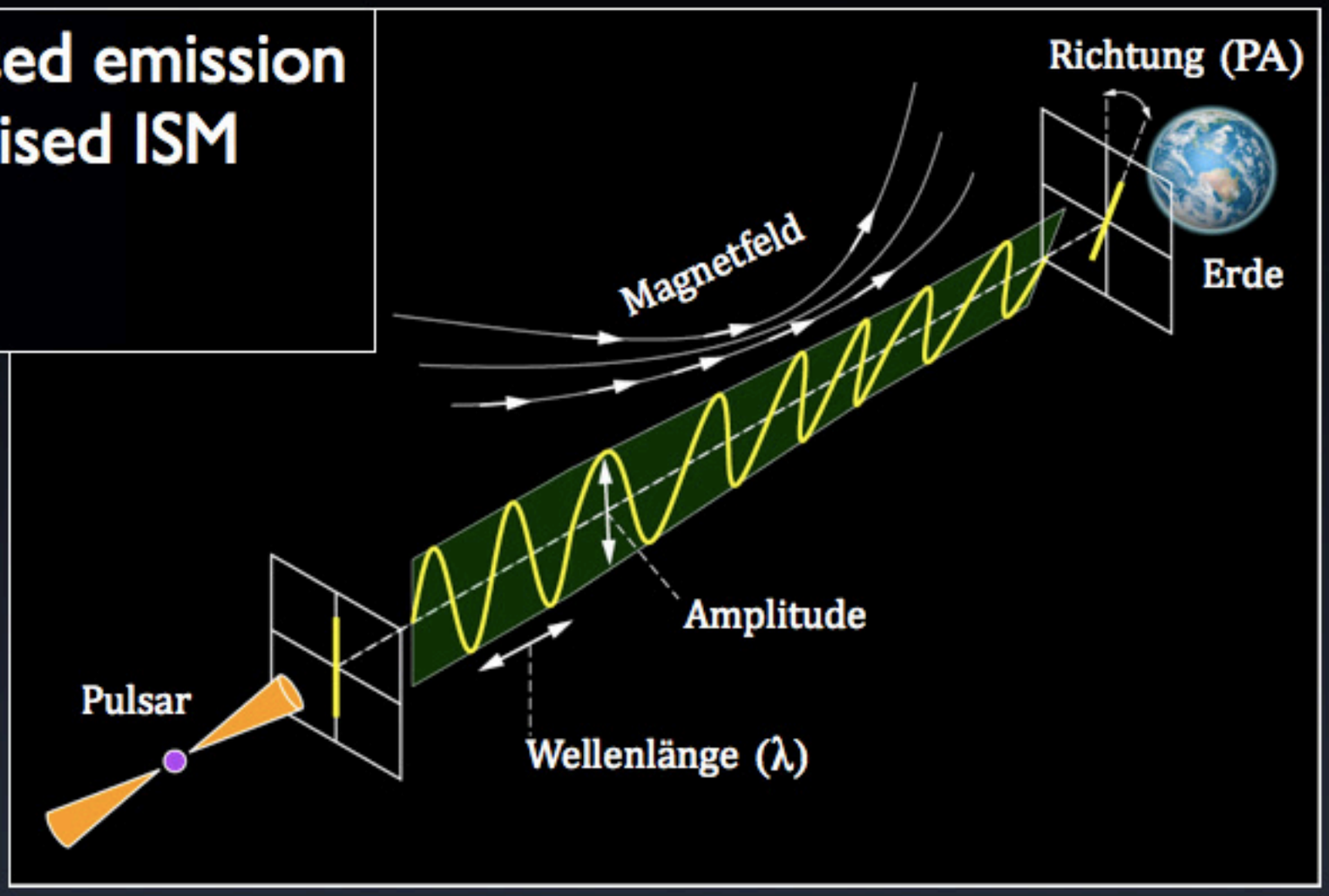
Faraday Rotation of Pulsars (and Extragalactic Sources)

The plane of linearly polarised emission rotates through the magnetised ISM

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

$$\mathrm{RM} = 0.812 \int_{\mathrm{PSR}}^{\oplus} n_e(l) B_{\parallel}(l) dl$$

This method traces the line-of-sight component of *B*

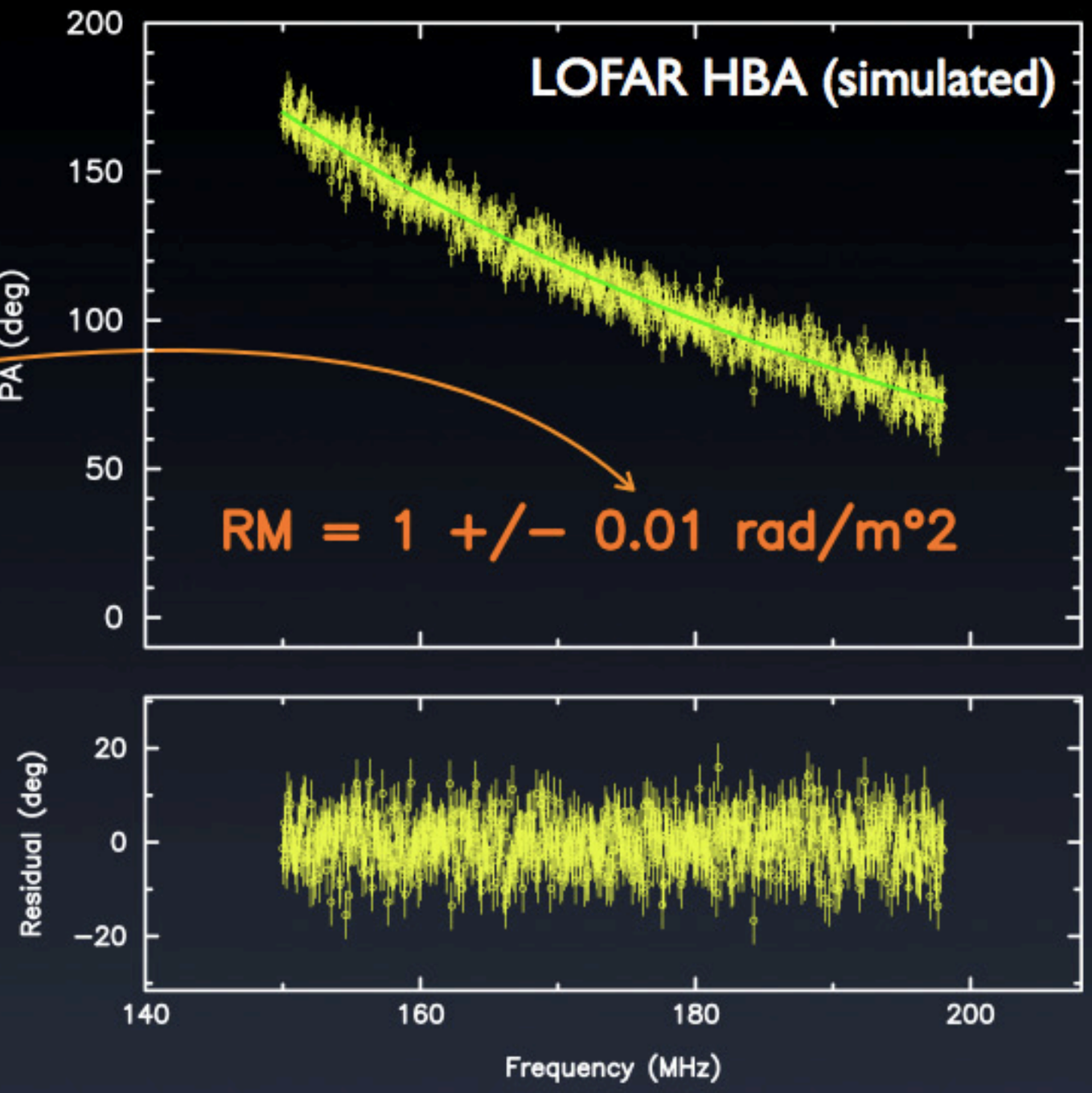


Observational Tracers of the G.M.F.

The amount of Faraday Rotation — and thus the RM — can be measured accurately using telescope back-ends with large bandwidths and high frequency resolutions

$$\sigma_{\mathrm{RM}} = \frac{1}{2\lambda^2(\mathrm{s/n})(\mathrm{BW}/f)}$$

Large fractional bandwidths at low frequencies, combined with high-s/n data, are optimal for accurate RM measurements.

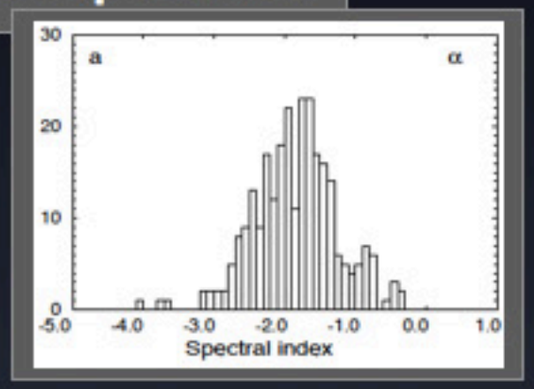


Advantages of Pulsars

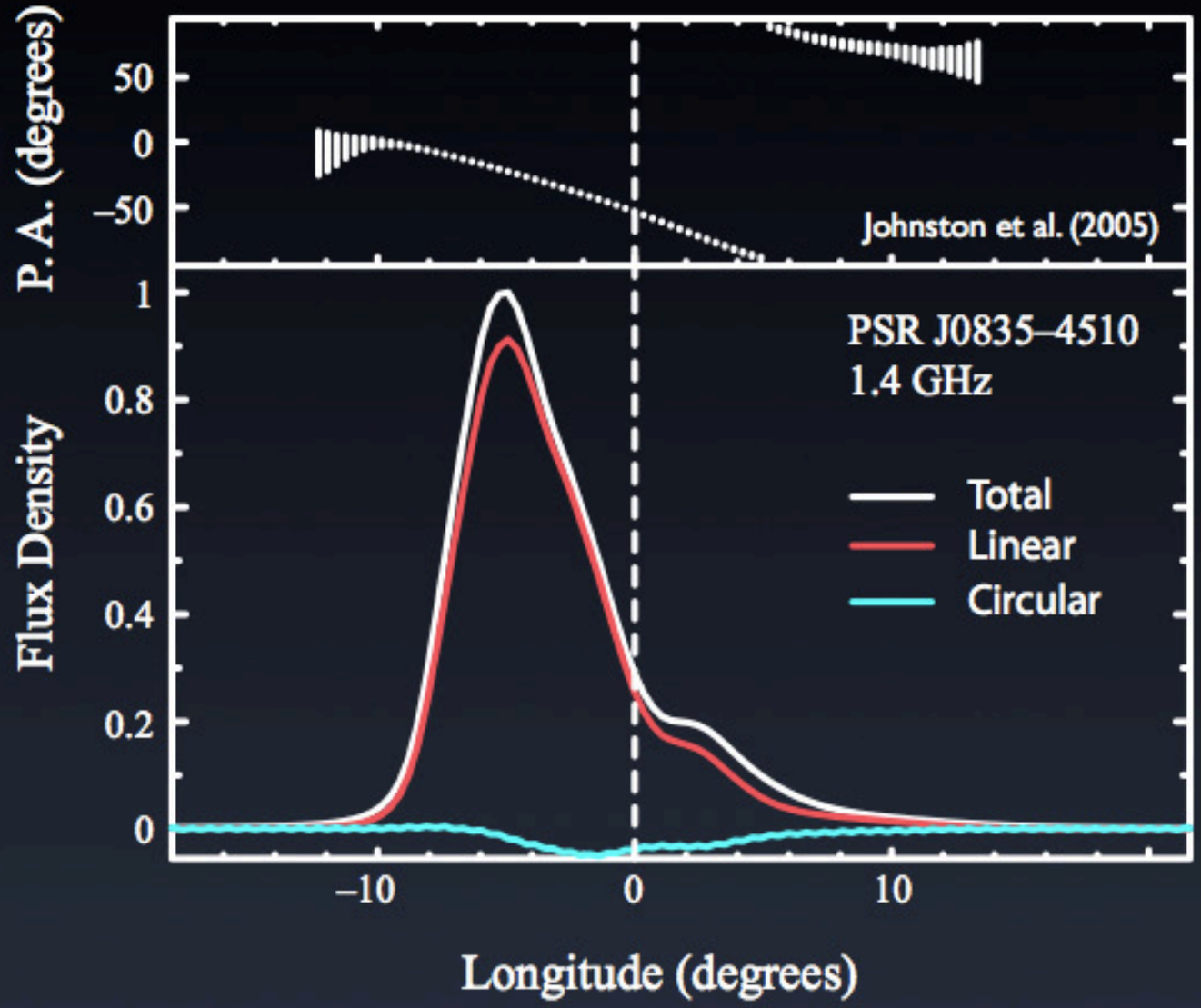
Faraday Rotation of pulsars is the best available method for mapping the GMF on large scales:

The majority of pulsars produce radio pulses with high degrees of linear polarisation

Most pulsars have negative ν : i.e. brighter at low frequencies

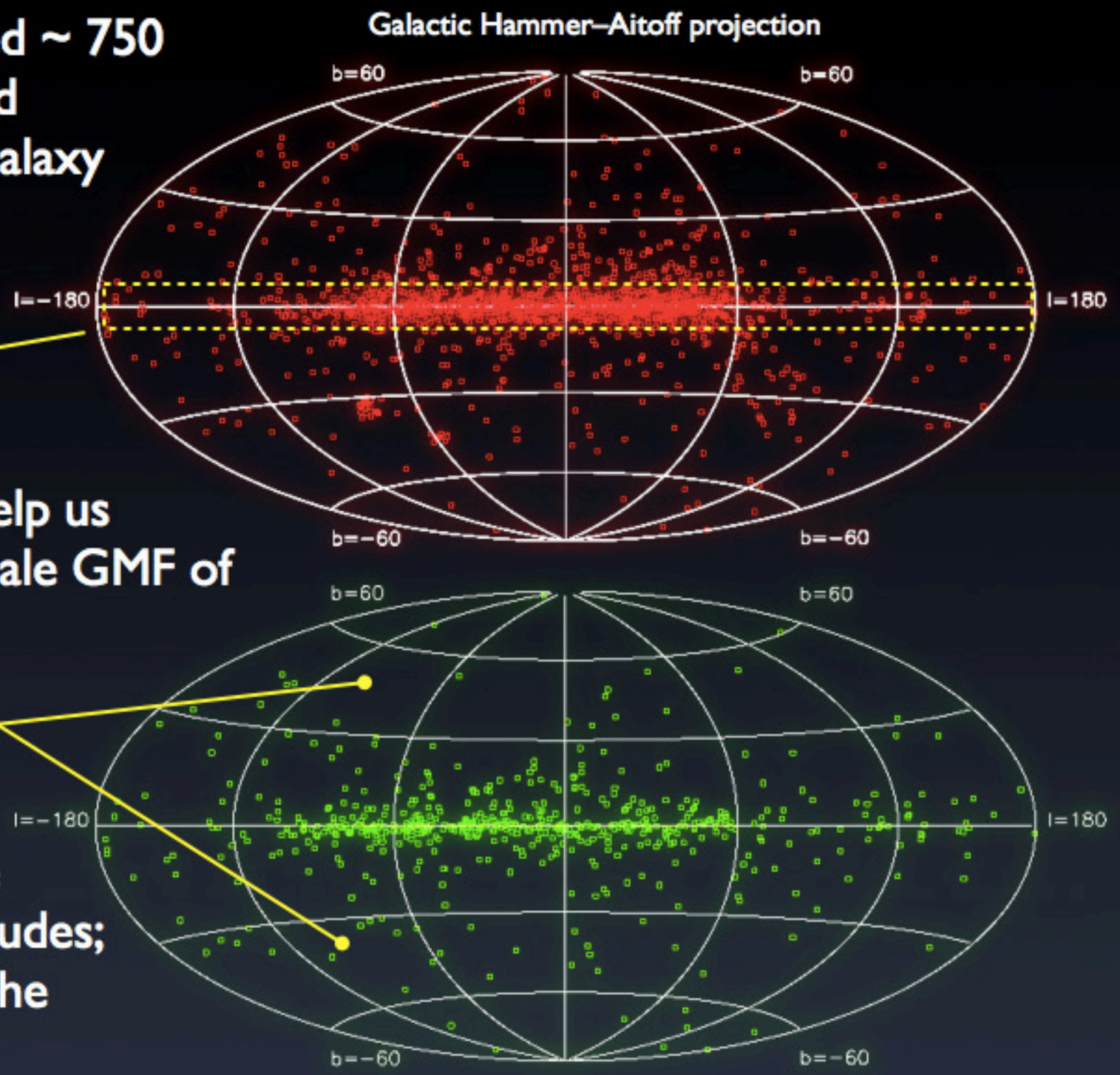


Accurate determination of RM is straightforward



Advantages of Pulsars

We have measured ~ 750 pulsar RMs, spread throughout the Galaxy



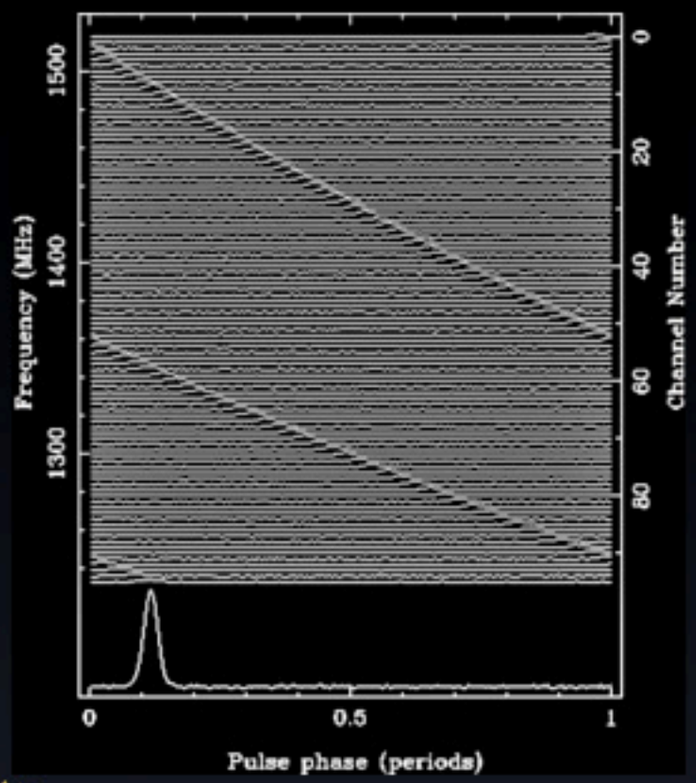
All pulsars (N_{PSR}~2000)

These RMs can help us study the large-scale GMF of the disc

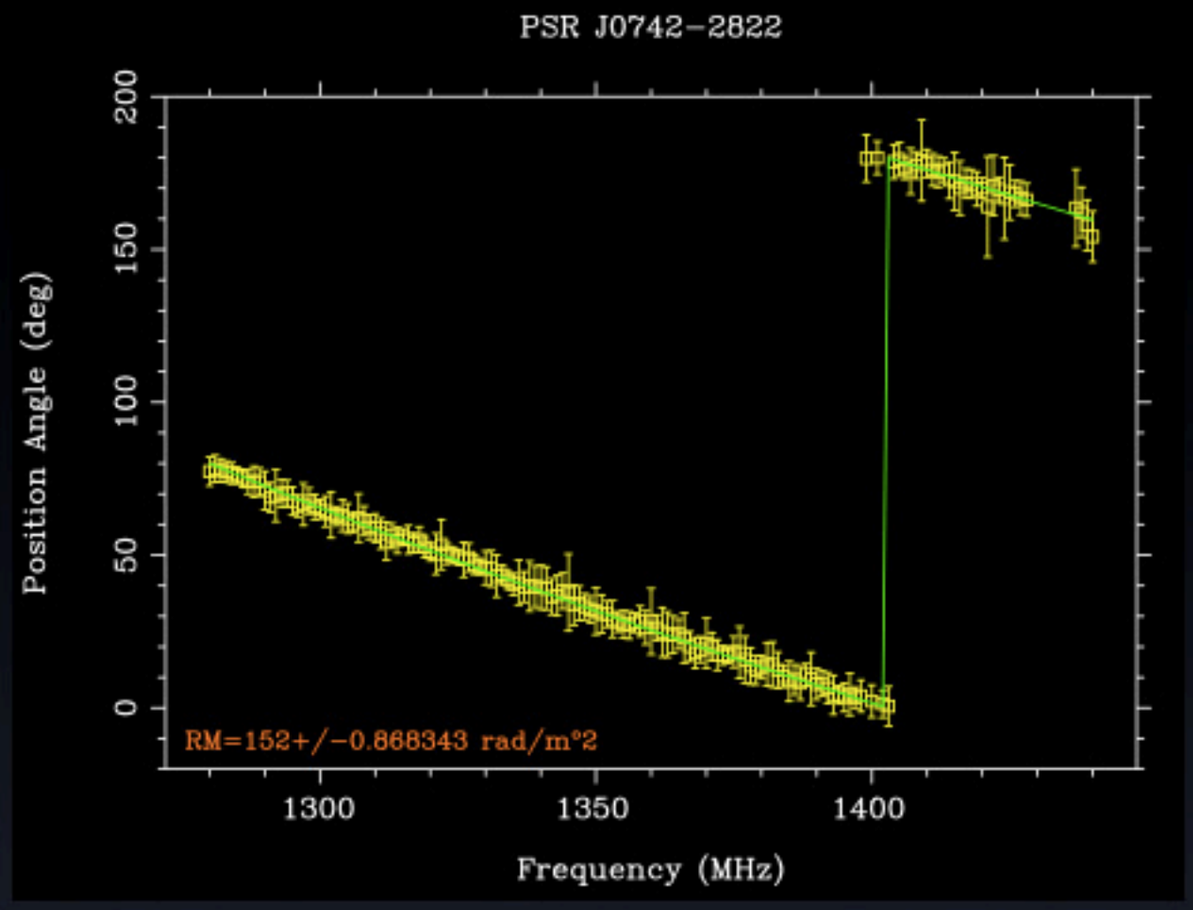
Fewer pulsars are found at high latitudes; these can reveal the field in the halo

All pulsar RMs (N_{RM}~750)

Advantages of Pulsars



+



1. The measurable dispersive delay of the pulses via the pulsar DM can be used with an ISM model to estimate the pulsar distance …

2. … and can also be combined with the measurable RM via the P.A. rotation …

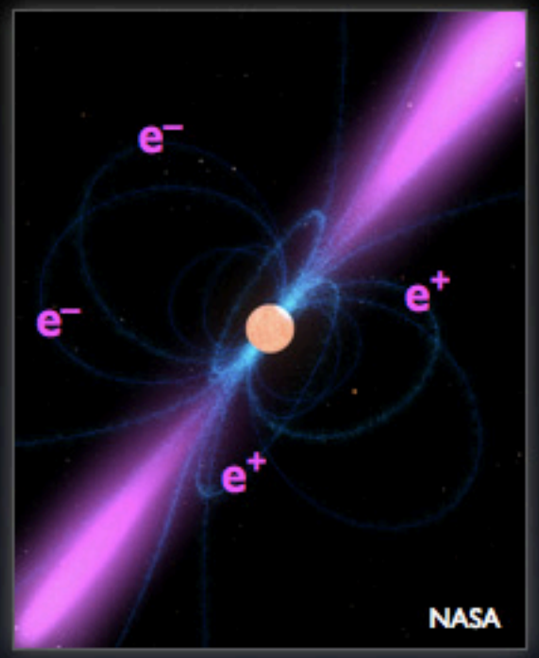
3. … to provide an estimate of the average $B_{\parallel}$ between the pulsar and the observer:

$$\langle B_{\parallel} \rangle = \frac{\int_{\rm PSR}^{\oplus} n_e(l) B_{\parallel} dl}{\int_{\rm PSR}^{\oplus} n_e(l) dl} = 1.232 \, \frac{\rm RM}{\rm DM}$$

Advantages of Pulsars

Pulsars are compact radio sources with no internal Faraday Rotation and Dispersion

↳ ultra-relativistic e^+–e^- pairs do not cause FR



Therefore DMs and RMs sample solely the ISM*

* An exception is PSRs in SNRs, which show DM and RM e.g. monthly variations due to the magnetised filaments

But these variations are small (~ a few rad m^{-2}) and <u>do not distort</u> the overall picture from a large pulsar sample

Pulsar Distances

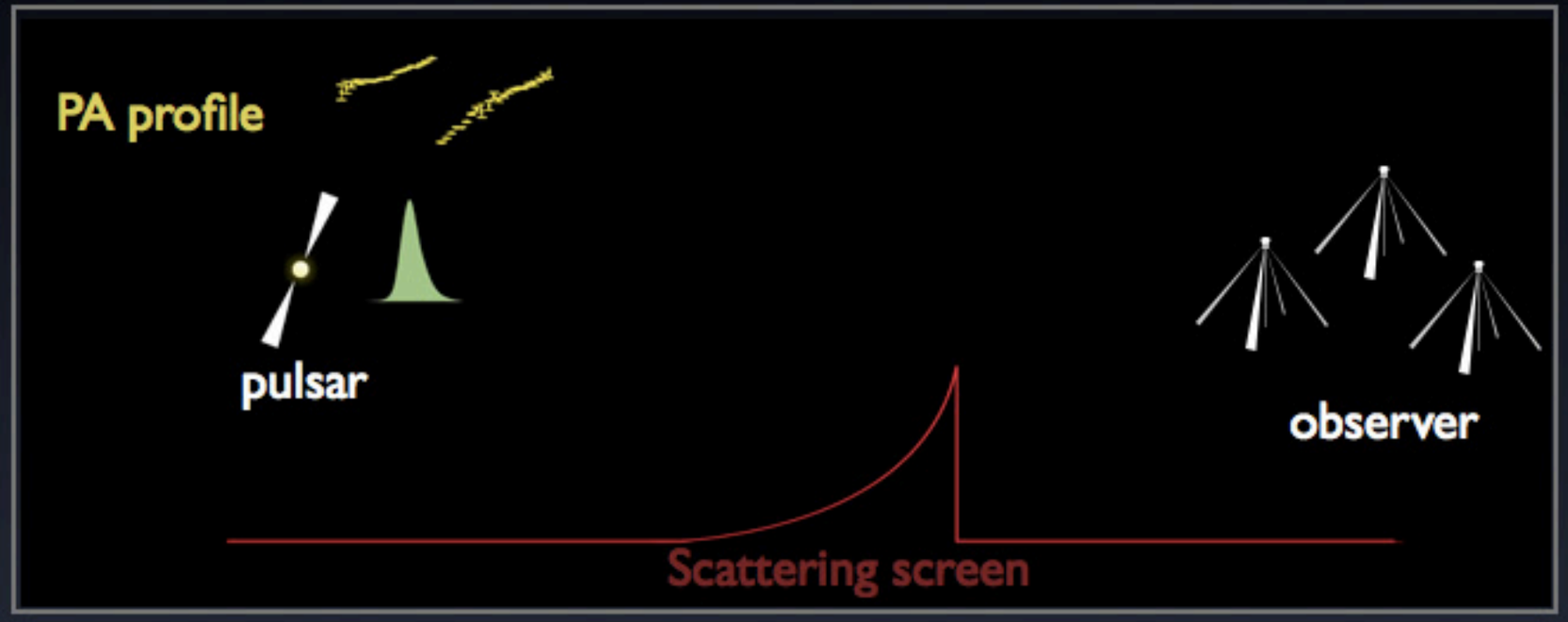
A **well-known problem** with pulsars is the uncertainty on the DM-based distances, which arise from partial knowledge of the n_e distribution

But we can use ISM scattering to our advantage …

Interstellar scattering distorts PA profiles with steep gradients:

the steep PA sweeps become flatter

Example animation (not to scale!)



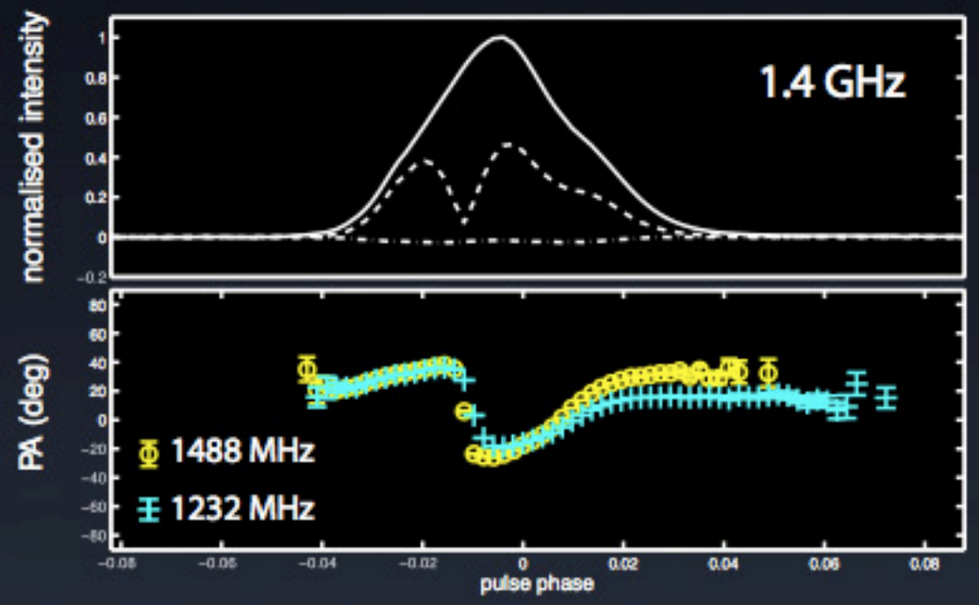
This is a well-known effect and scattering time-scales for a small number of pulsars can be found in the literature

Pulsar Distances

A **well-known problem** with pulsars is the uncertainty on the DM-based distances

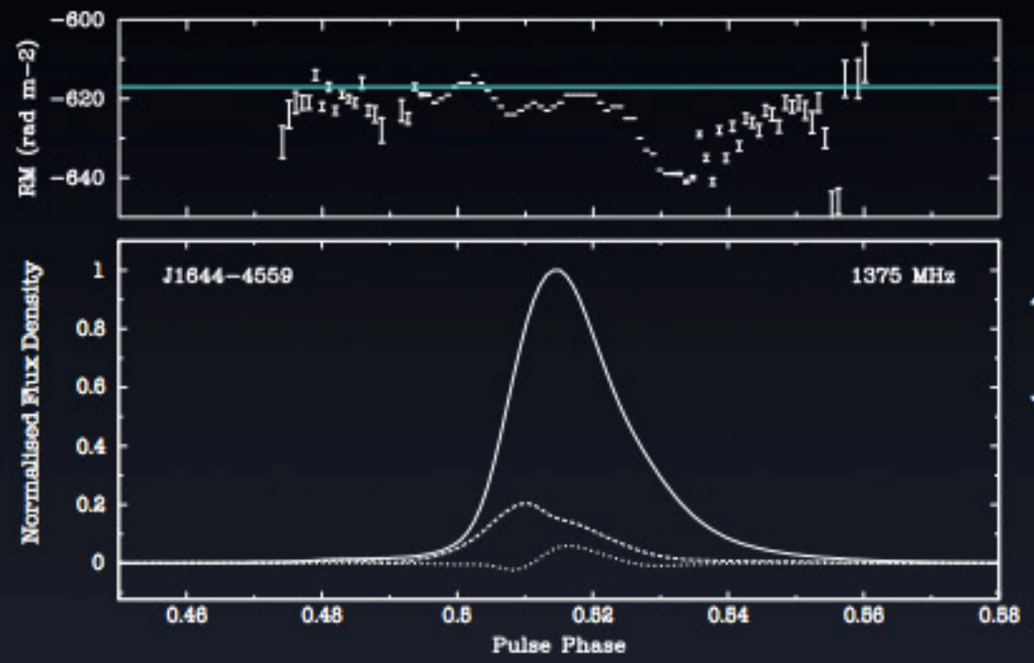
The changes in the PA profiles due to scattering are **frequency dependent**.

This impacts on the Faraday Rotation measured at a given pulse phase, as there is effectively a rotation of the PA as a function of frequency.



Karastergiou (2009)

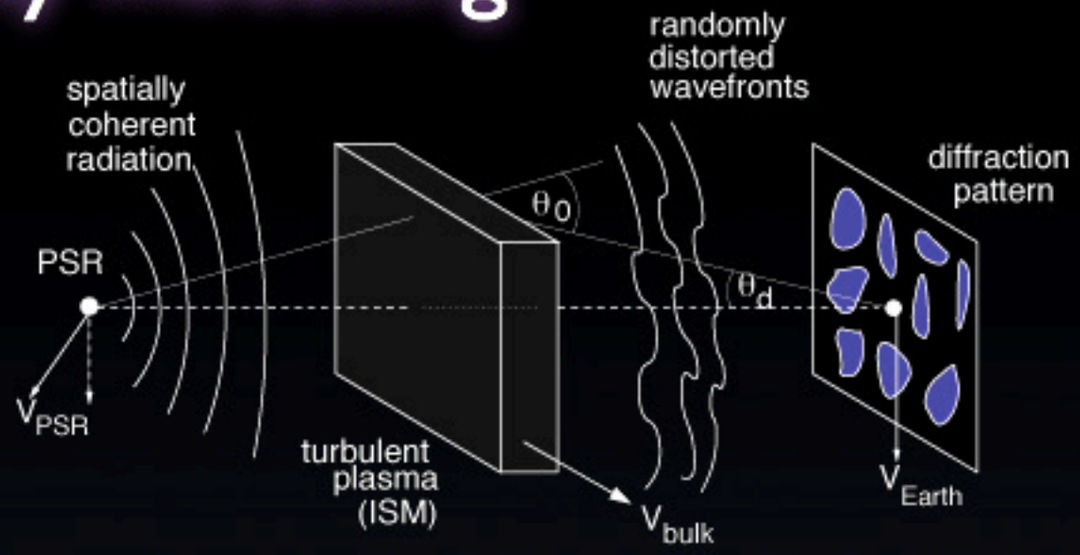
Δ(RM) ~25 rad m^{-2}

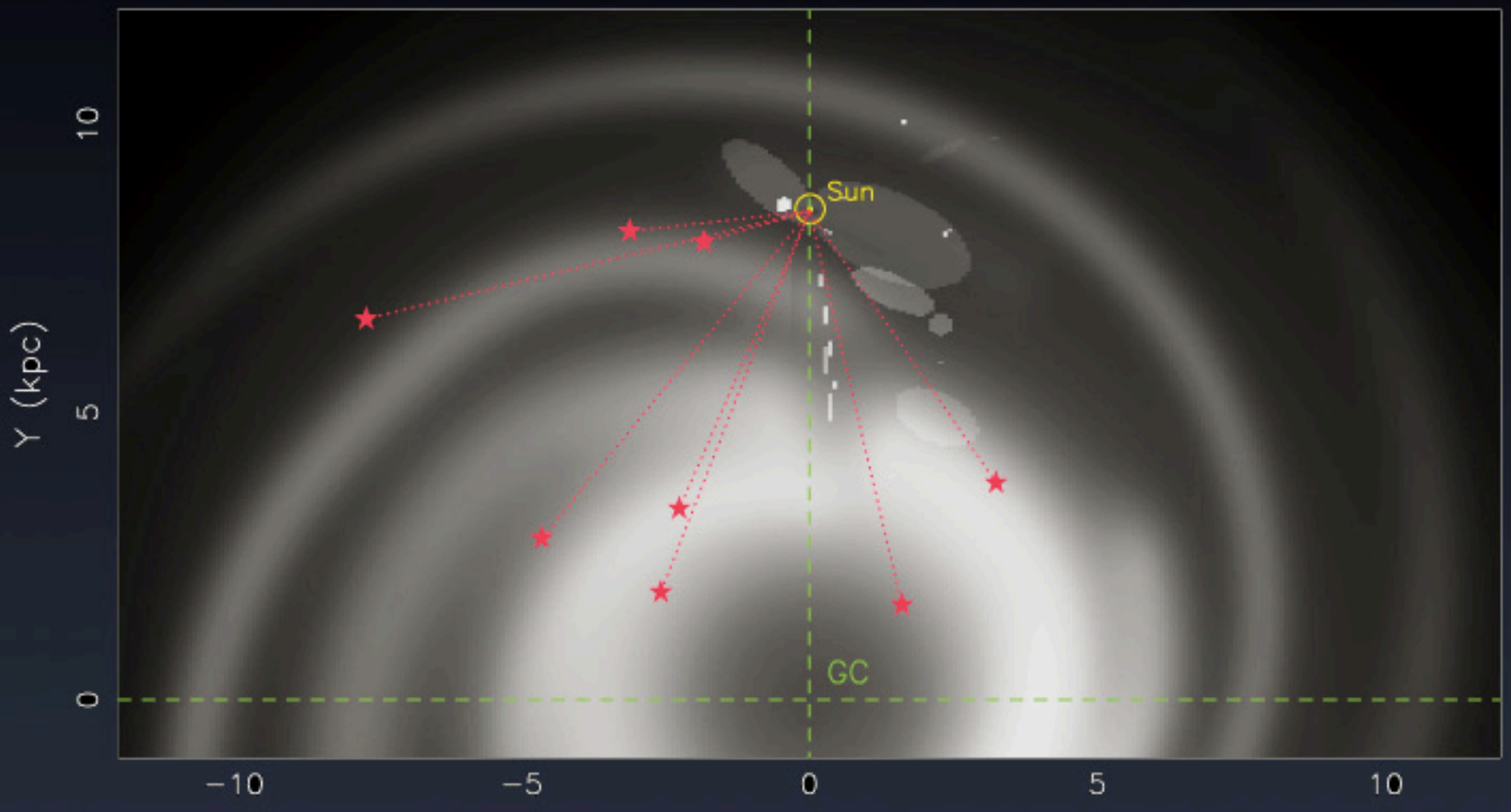


Hence, an **artificial** change in RM as a function of pulse phase is introduced by scattering

Free-electron density modelling

We plan to model the scattered RM profiles and independently estimate the distances to the pulsars, assuming Kolmogorov turbulence-scale spectrum.





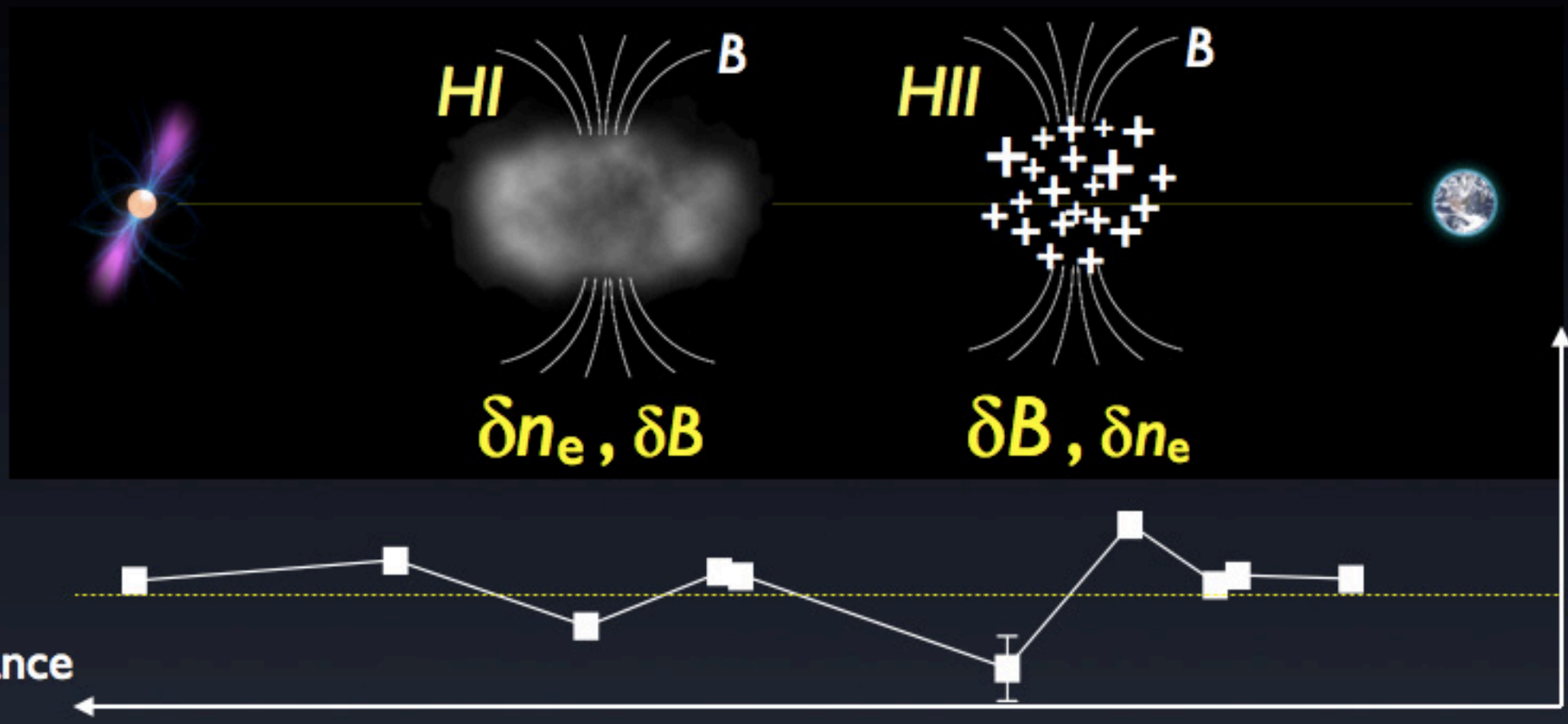
$$d^{2.2} \propto f^{4.4} \tau_s$$

A large sample of Ts measurements is required to fit a free-electron density model

Some Problems

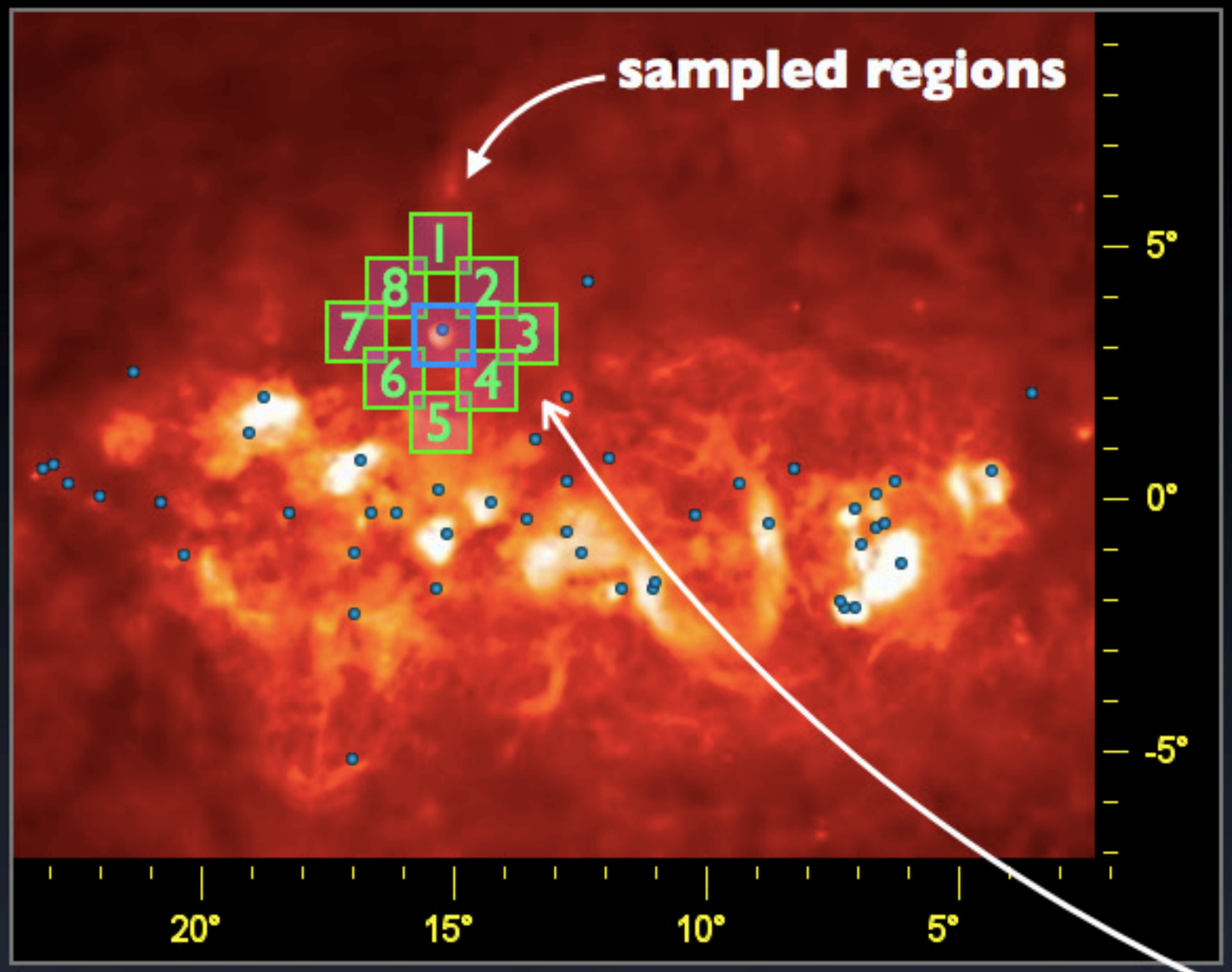
There are LOS to pulsars that pass through numerous highly magnetised (~ tens of μG or even higher) local regions:

the anomalous n_e and $\boldsymbol{B}$ fluctuations across those regions result in measured RMs that can distort our view of the regular, smoothly varying GMF



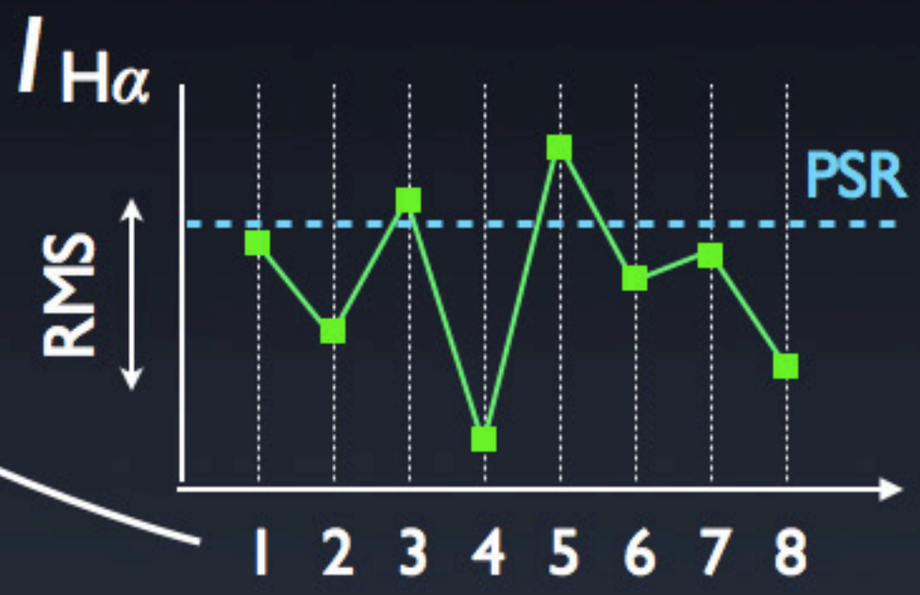
In mapping the regular field, it is imperative to omit LOS to anomalous regions. This has been noted and — to some degree — applied in recent work (Han et al. 2006; Noutsos et al. 2008; Nota & Katgert 2010).

The Clumpy Foreground



$$I_{\mathrm{H}_\alpha} \propto \int_{\infty}^{\oplus} n_e^2 dl$$

We will compare the Hα emission from the direction of the PSR to that of the surroundings



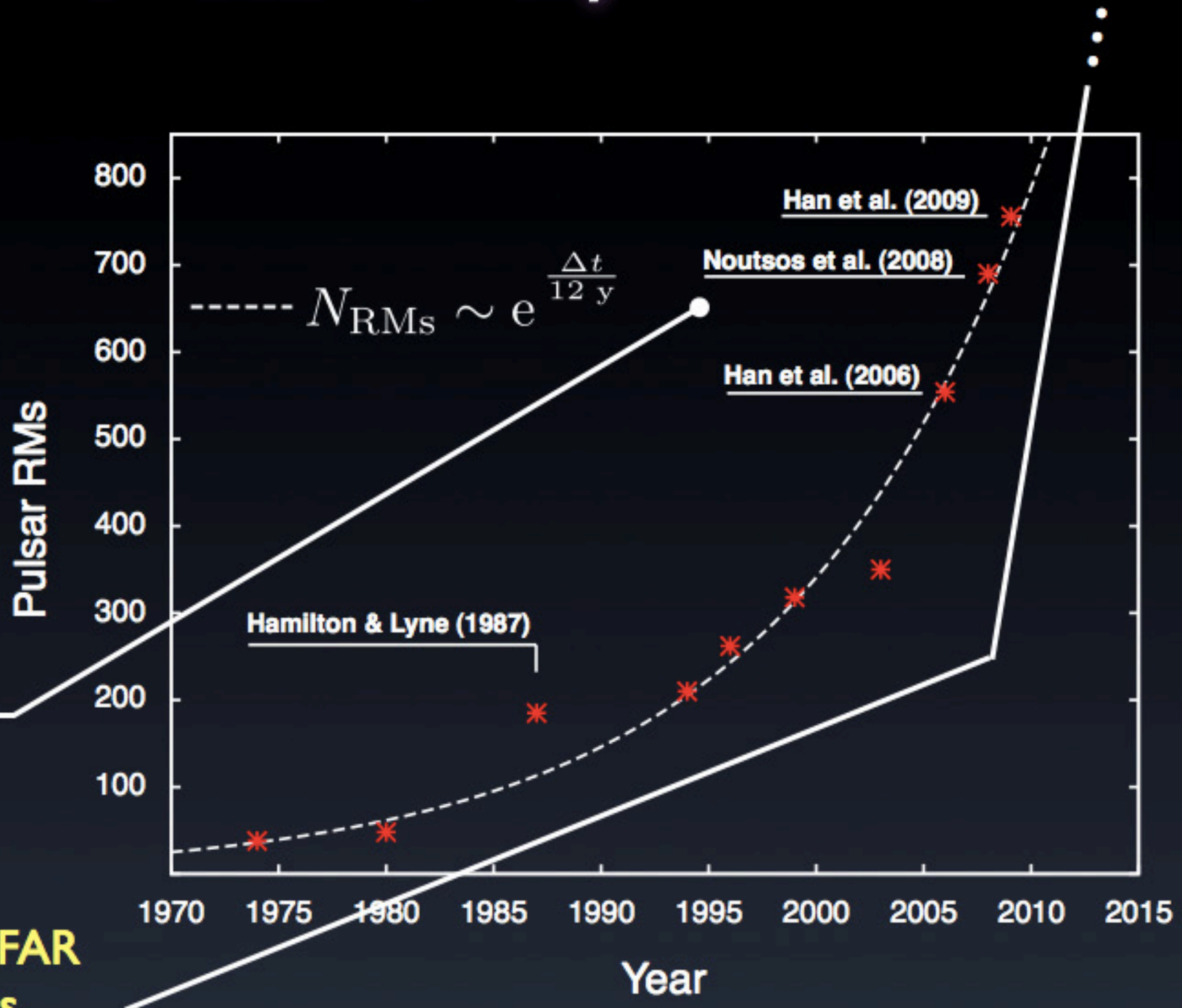
If the emission in the pulsar direction exceeds a certain threshold above the neighbouring emission, we will reject the associated pulsar RM

The Pulsar-RM Sky

The value of pulsars in studies of the GMF has encouraged the accumulation of pulsar RMs

Pulsar polarisation surveys with the Parkes 64m and the GBT 100m radio telescopes have contributed 100s of new RMs

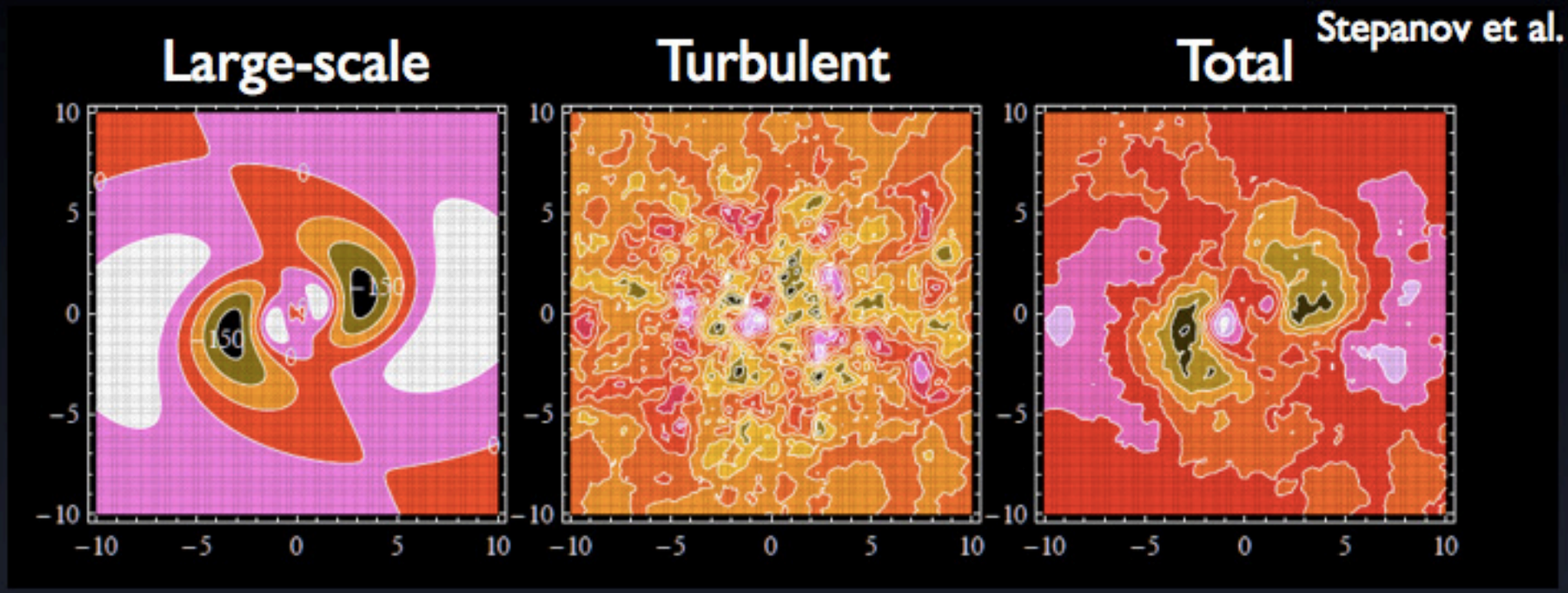
Upcoming surveys with LOFAR will return 100s of new RMs, especially from pulsars in the halo



Methodology

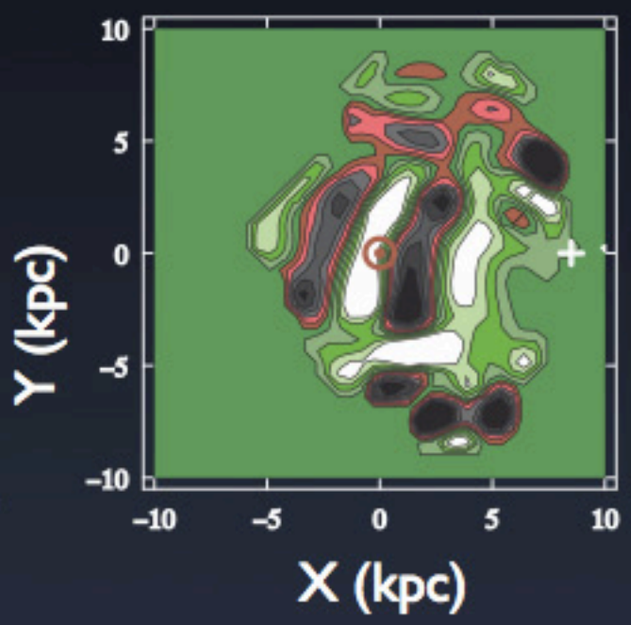
Modern techniques, like wavelet decomposition of the RM data, can filter out the small scales (noise) in the data and reveal the GMF on scales relevant to the regular field (~ kpc)

Stepanov et al.



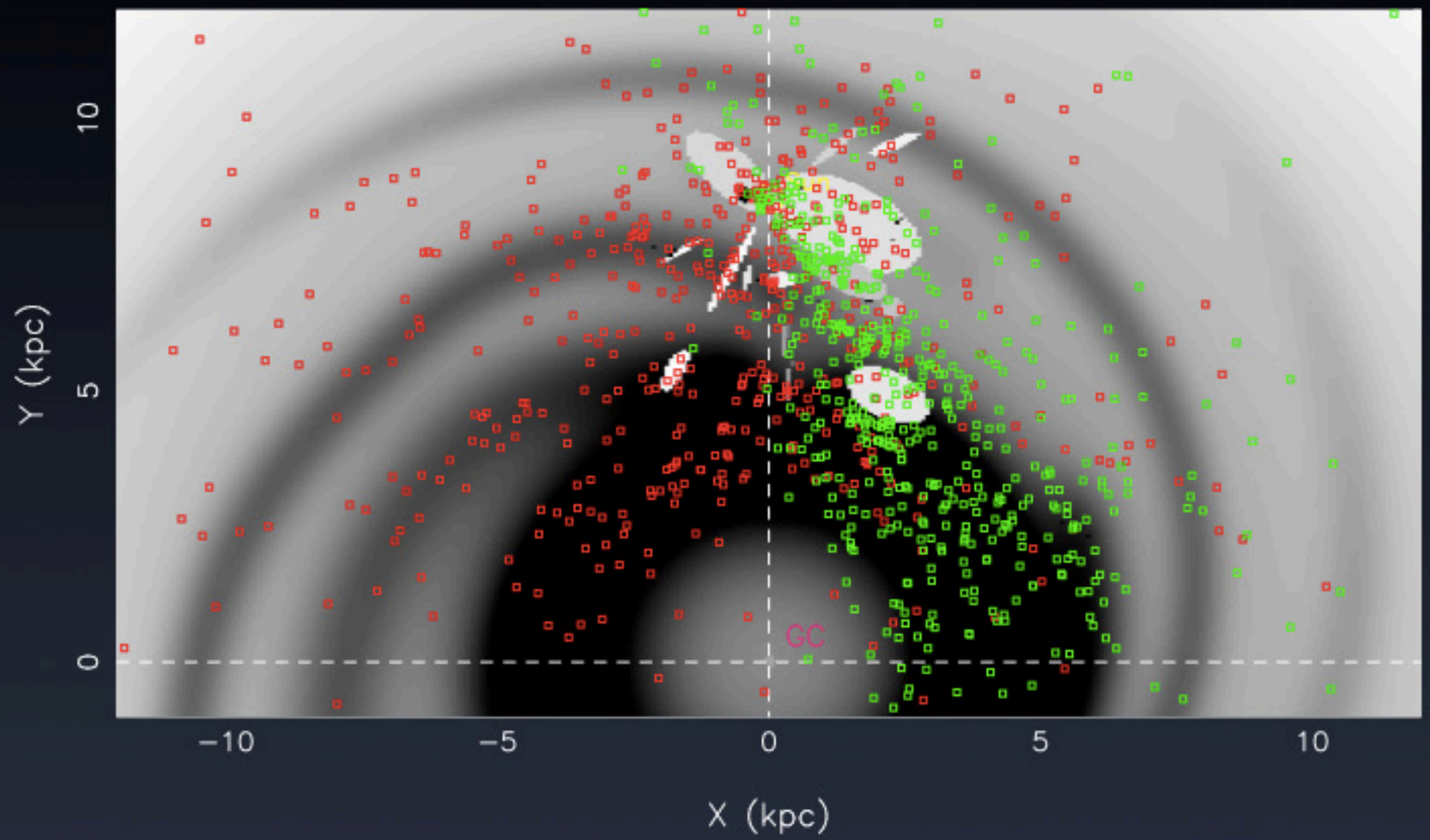
However, the RM-density requirement for this method is currently satisfied only up to ~2–3 kpc

Wavelet transform of a real, irregular pulsar-RM grid



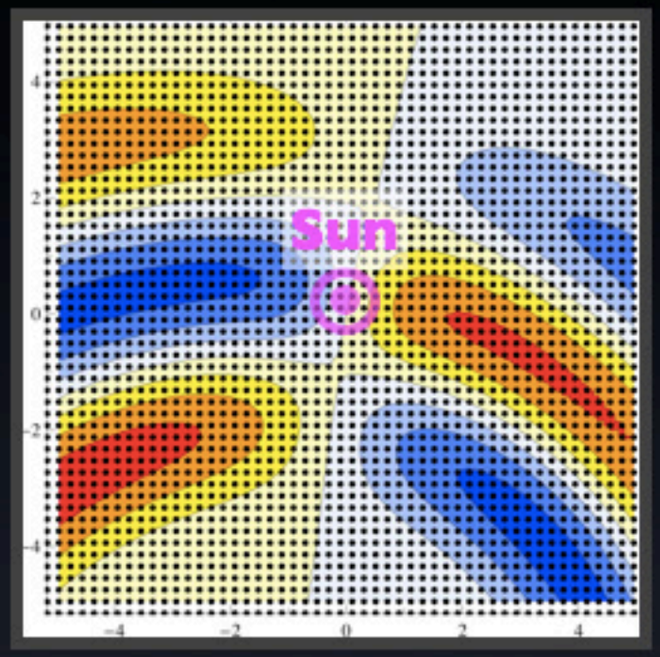
Wavelet Analysis

To assist GMF reconstruction using wavelets, we have identified poorly covered regions in the Galactic plane, and we will soon perform polarisation observations with the Effelsberg 100m, to obtain pulsar RMs from these regions

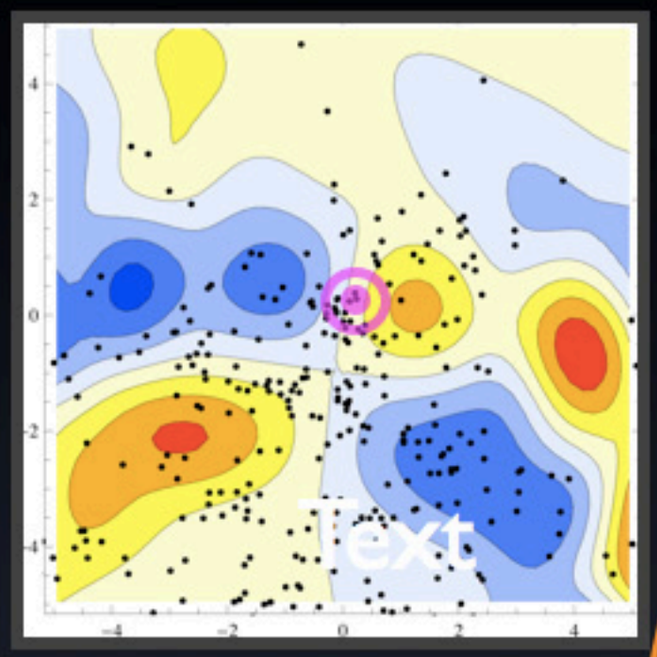


Wavelet Analysis

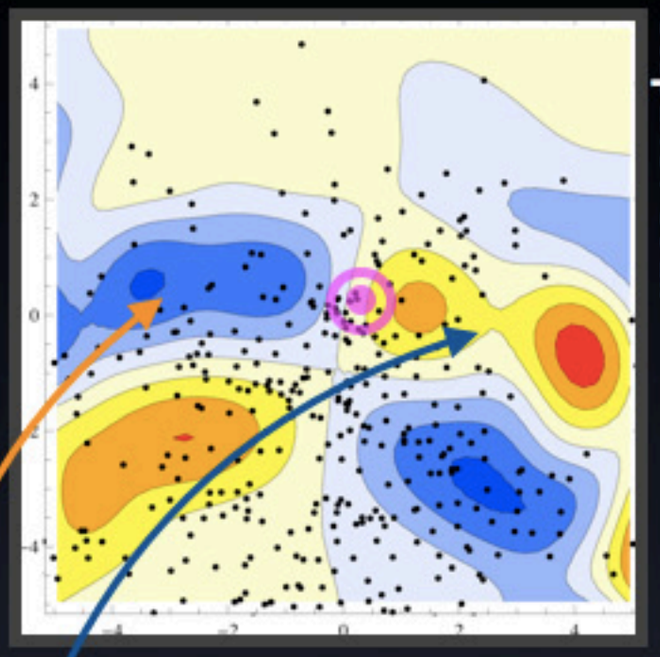
Wavelet-based reconstruction of the GMF is sensitive to the spatial coverage and regularity of the RM grid



Regular RM grid (ideal)



Current RM grid



Expected RM grid from our survey (simulated)

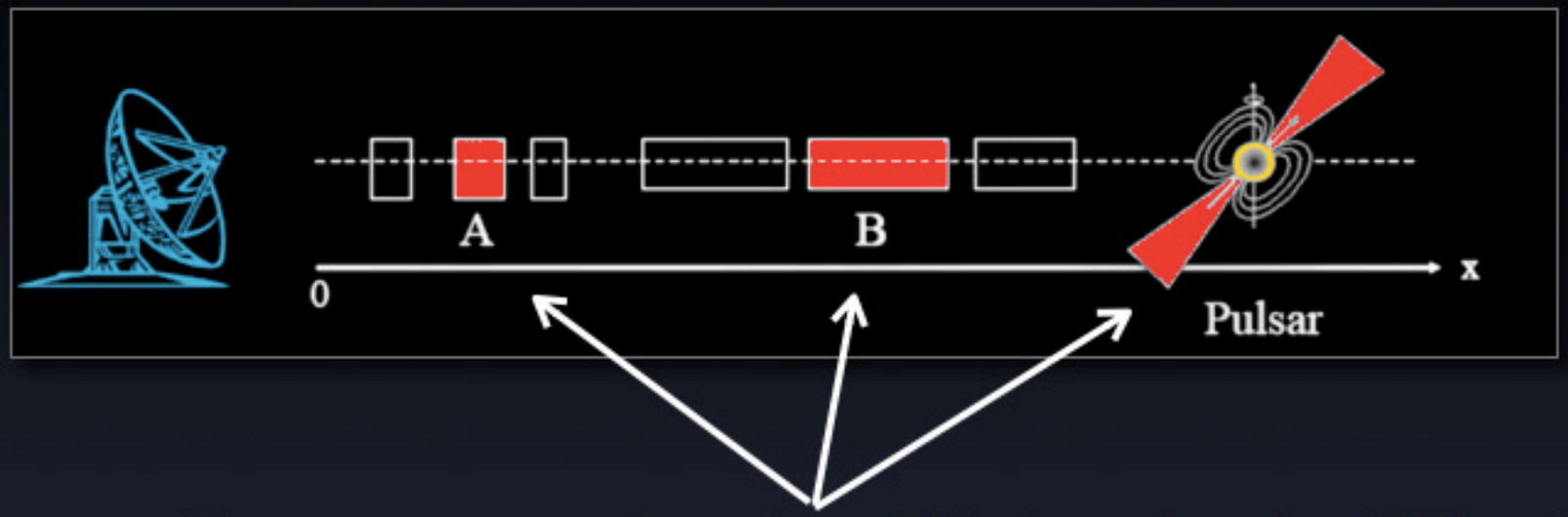
Stepanov et al.

Elongated features of the B-field are becoming prominent

Methodology

Polarisation surveys at low frequencies (e.g. MS^3 with LOFAR) will greatly contribute to GMF mapping:

Wavelet-based RM Synthesis can be applied to high-frequency-resolution data at low frequencies



These surveys will return not only pulsar RMs but also the RMs of all intervening polarised sources that cause Faraday Rotation: e.g. HI and HII regions

Upon determination of the distance to those sources — with other methods — we will have thousands more RMs to our disposal, for GMF mapping

Recent Studies of the Large-scale Field from Faraday Rotation of Pulsars and EGS

"Magnetisation of Interstellar and Intergalactic Media" *Kloster Irsee, 5 October 2010*

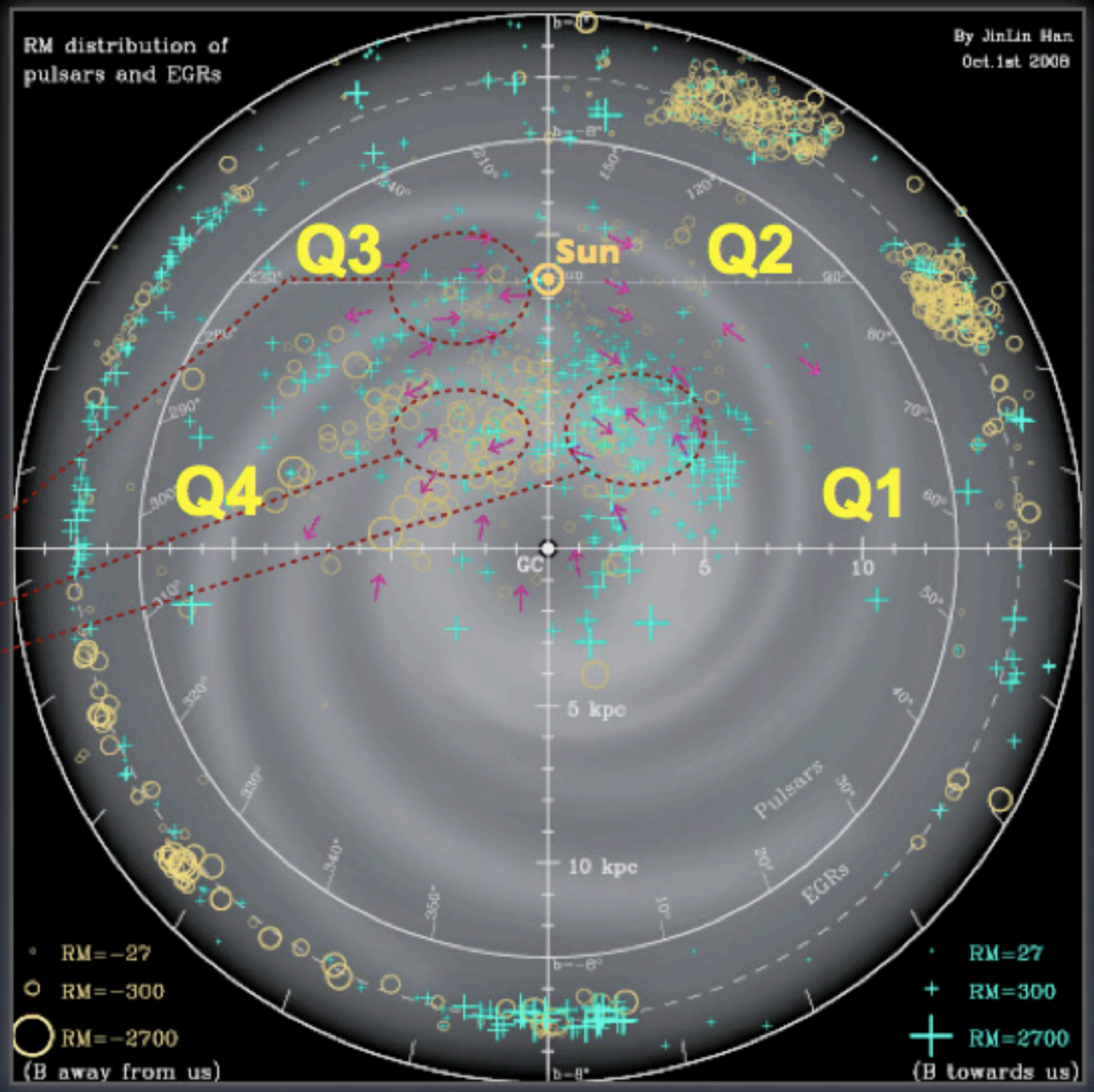
Field Reversals

Map of the derived large-scale field from all pulsar RMs[1] with $b < 8°$

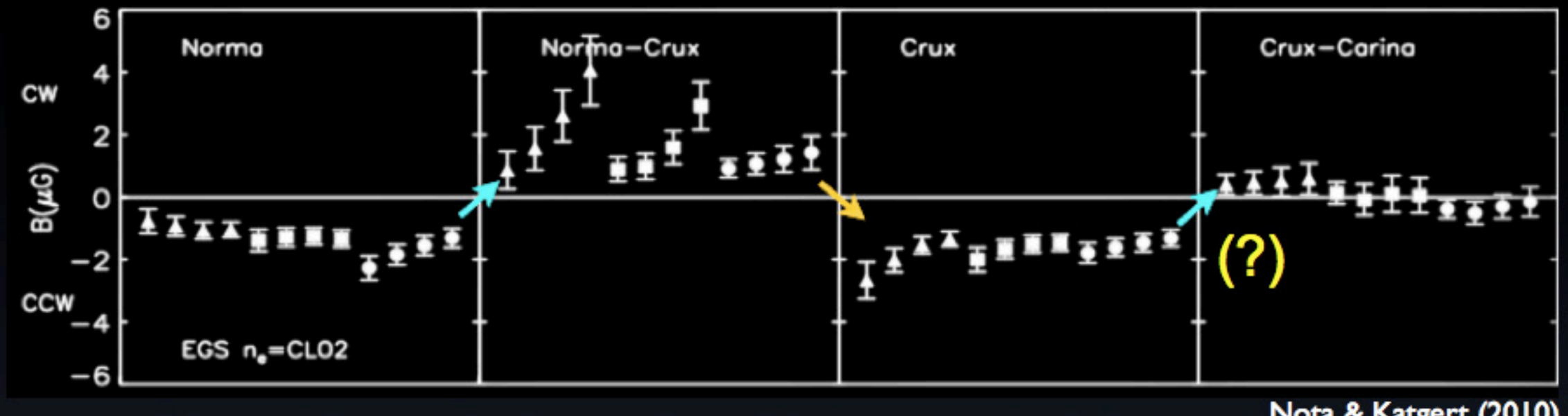
[1] from Han (2008); includes new, unpublished RMs from GBT survey

In this map, several[2], radial field reversals (many in Q4) can be seen between spiral arms

[2] no radial reversals have been found in external galaxies!



Field Reversals



Nota & Katgert (2010)

Nota & Katgert (2010) examined RMs in **Q4** with |b|<3°

They excluded all LOS to pulsars that showed strong n_e fluctuations
(this is recommended for all future analyses!)

The authors find that the field reverses
(1) in the Norma and Crux arms and (2) the Norma–Crux interarm region

Instrumentation & Pulsar Surveys

"Magnetisation of Interstellar and Intergalactic Media"

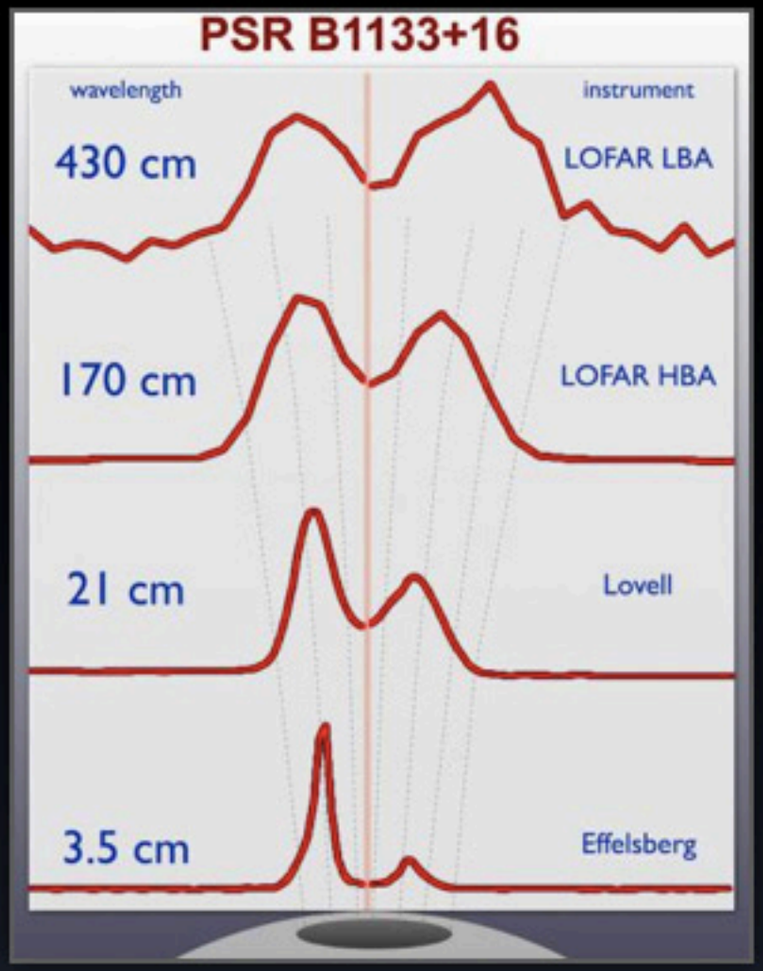
Kloster Irsee, 5 October 2010

LOFAR

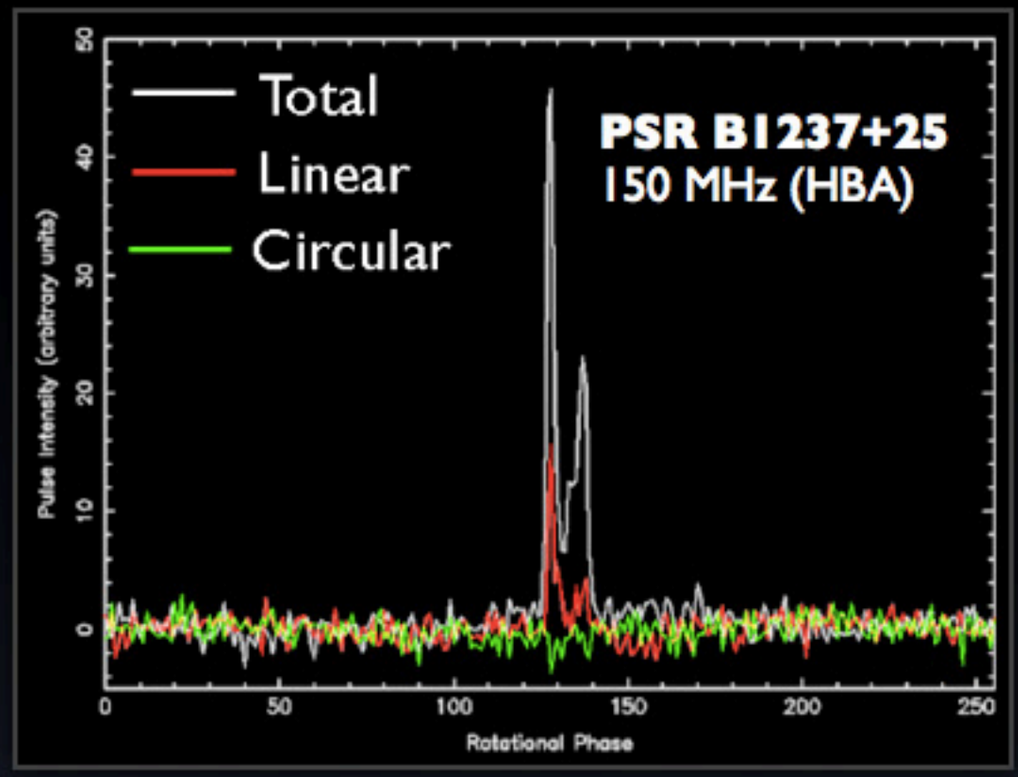
In Europe …

In Germany …

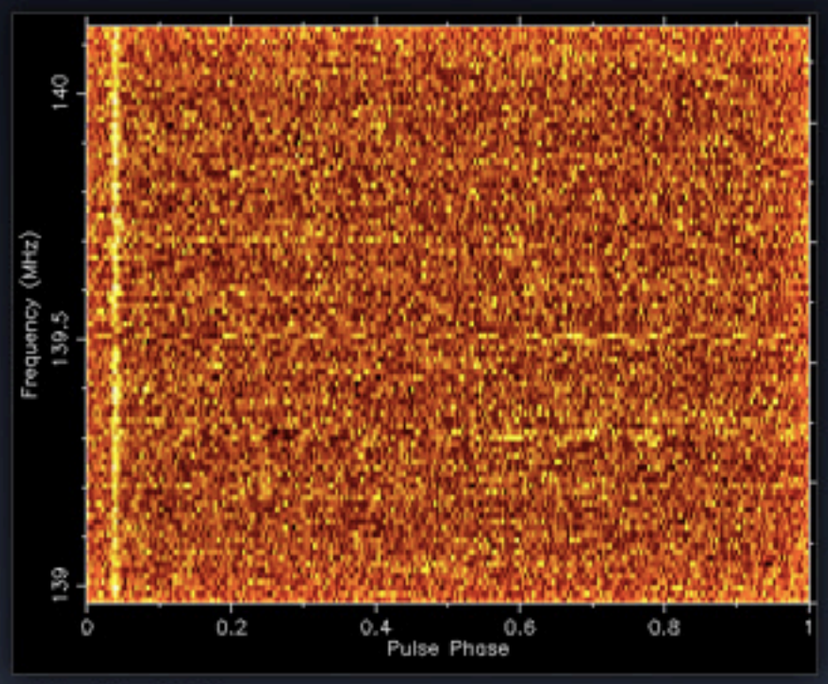
LOFAR Pulsar Observations



The LOFAR Pulsar Group has had 9 'Busy Weeks' pulsar-pipeline development



PSR B0329+54, coherently de-dispersed

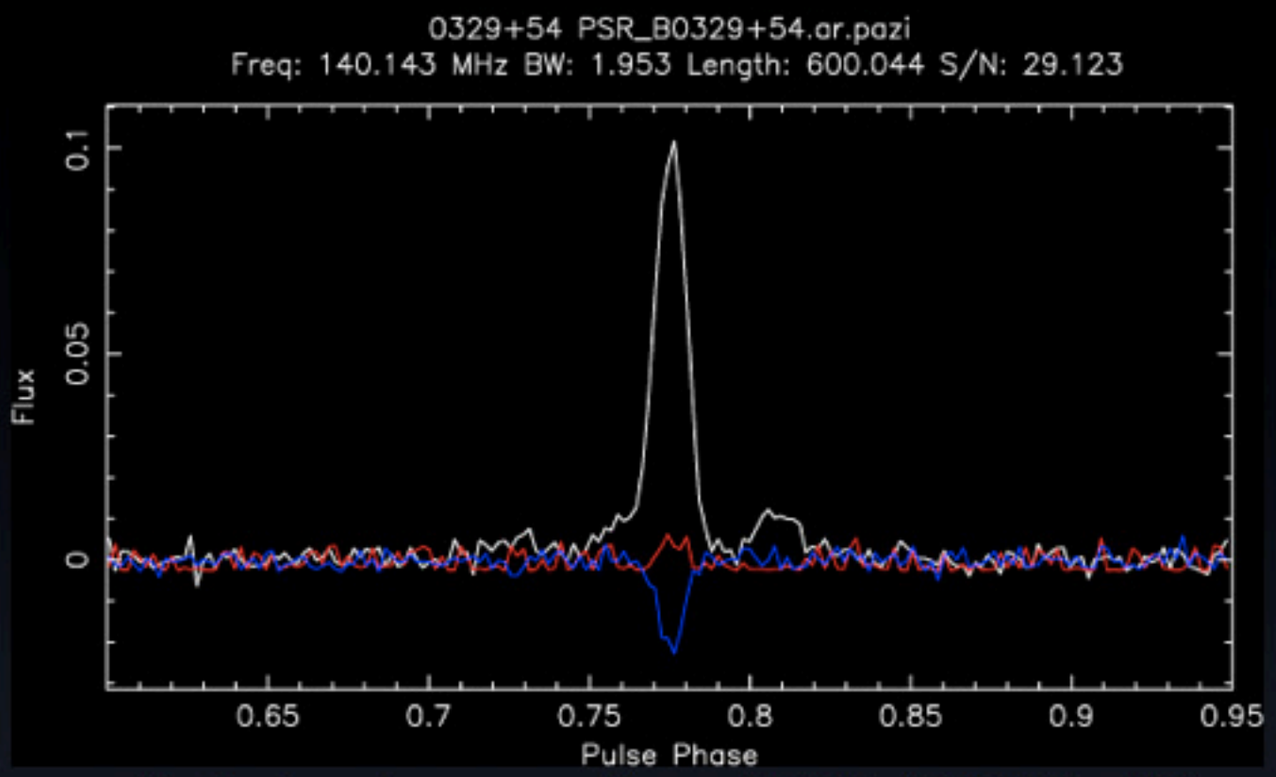


Incoherently de-dispersed polarisation profile (uncalibrated)

Simultaneous observations from 70 MHz to 8.5 GHz with **LOFAR** (LBA + HBA) and **Lovell 76m** and **Effelsberg 100m** dishes

!!! Our recent proposal to observe many more pulsars with LOFAR for commissioning and calibration has just been reviewed with many positive comments

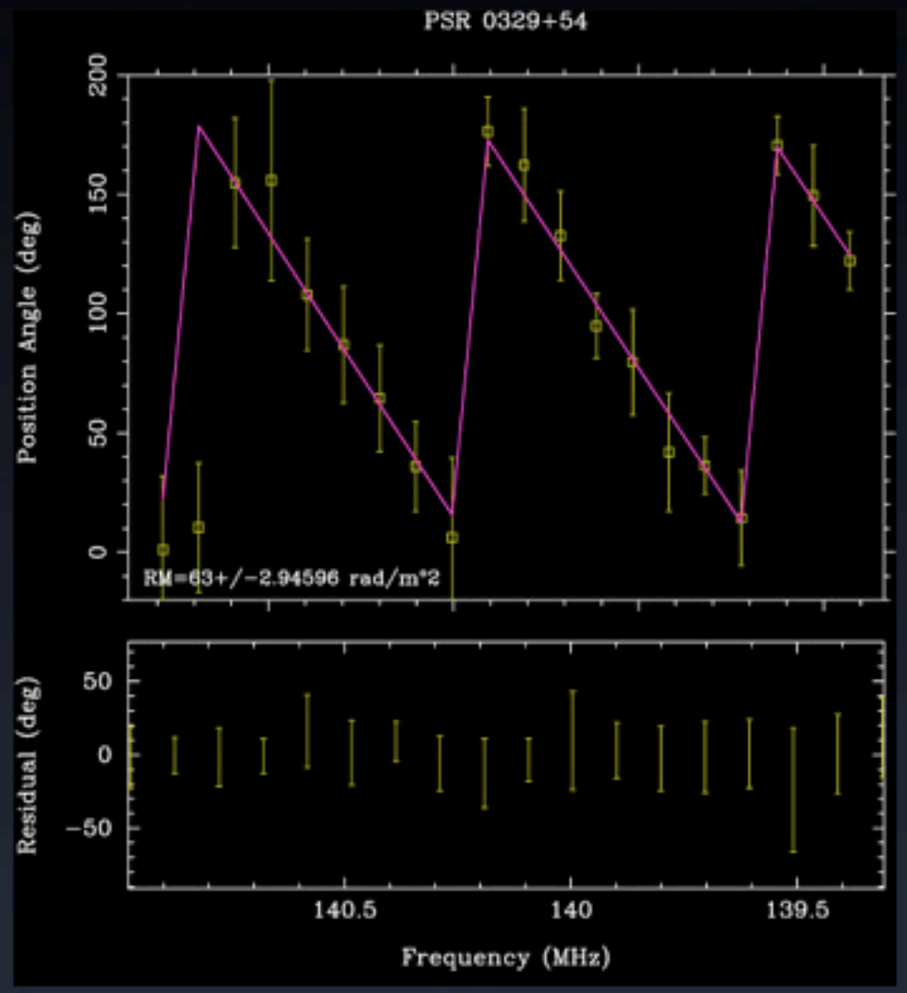
LOFAR Pulsar Observations



Polarisation profile of PSR B0329+54

The pulsar was observed with a single station, was overhead and only for 10 minutes: no calibration required

PA fit yielded the correct RM



LOFAR Pulsar Observations

The upcoming Million Source Shallow Survey (MS^3) will give us the opportunity to search for new pulsars in the disc and in the halo

Piggy-backing (*Pulsars* & *Transients* and *Magnetism* KSPs):

- Incoherent, beamformed (pulsar) data for pulsar searches
- Polarisation products will be possible
- RM determination from channelised Stokes data

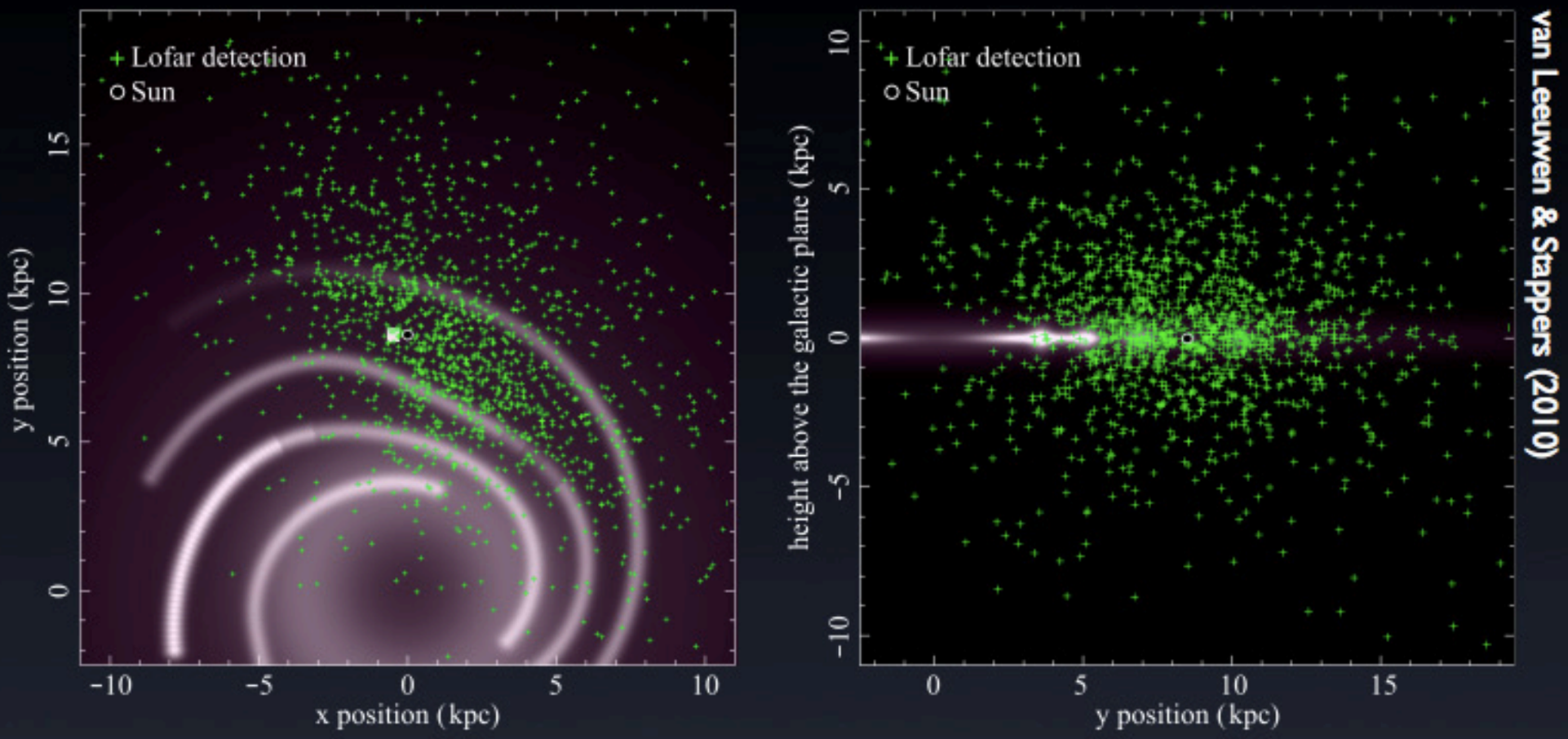
MS^3 products:

- Imaging data
- High frequency resolution (~ 1,000 – 10,000 channels)
- RM determination from RM Synthesis on images

The survey will provide a large data set from which we hope to measure thousands of new RMs

LOFAR Pulsar Observations

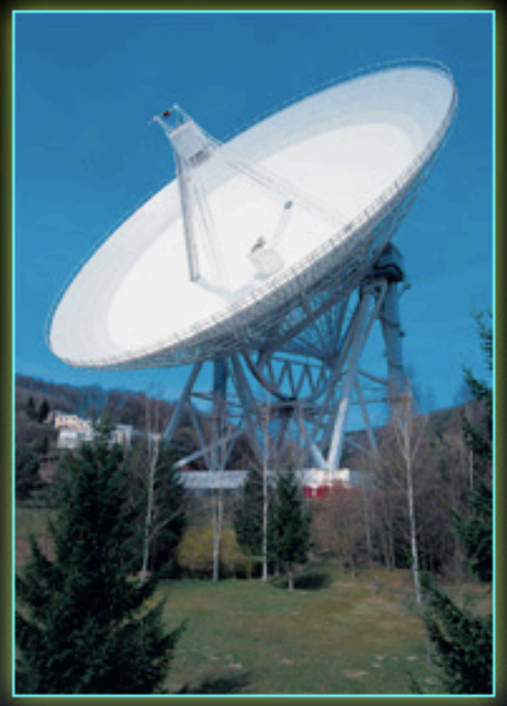
Based on current simulations, LOFAR will detect 1000+ new pulsars, in a 25-day survey (1h pointings)



In the plane, due to scattering limitations, LOFAR will detect pulsars up to 3 kpc; but many pulsars will be detected further out, at high latitudes

LOFAR's high sensitivity will allow us to detect all pulsars within a 3 kpc radius

Other Surveys



We are conducting a PSR survey of the northern sky and the Galactic plane with Effelsberg with the newly installed 7-beam, 21cm receiver

The survey promises to deliver 100s of new (and exciting) pulsars, buried deep in the plane

We will follow up on the detected pulsars with our new, wide-band receiver (300–900 MHz), that will be soon installed at Effelsberg, and the new high-resolution digital filterbank (DFB).

RMs for all polarised pulsars will be measured

A complementary survey, in the South, is being conducted with the Parkes 64m radio-telescope

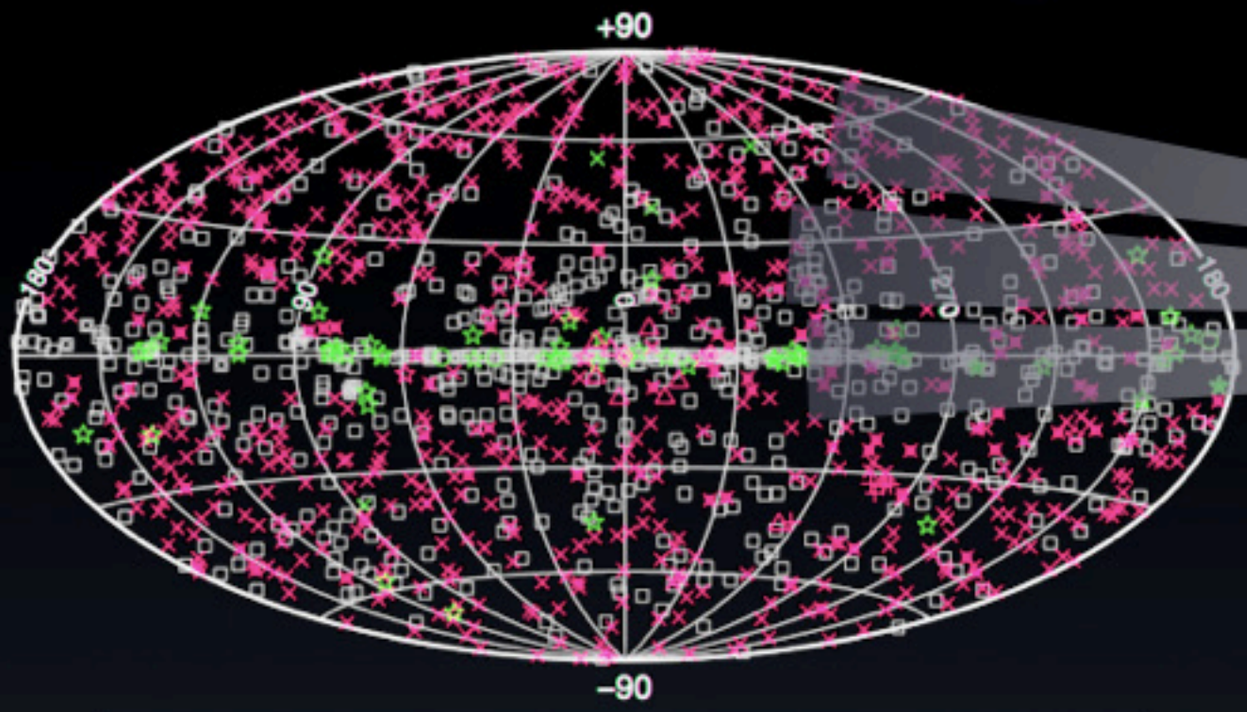
The survey has already returned 70 new PSRs

Complementary Surveys

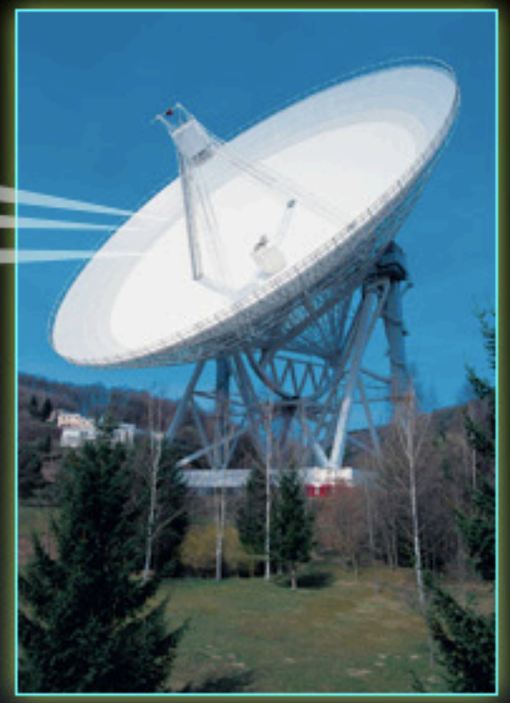
The Parkes and Effelsberg surveys complement each other at high frequencies
(**North** + **South**)

The Effelsberg and LOFAR surveys complement each other in sensitivity and Galactic volume
(**Weak** & **Near** + **Bright** & **Far**)

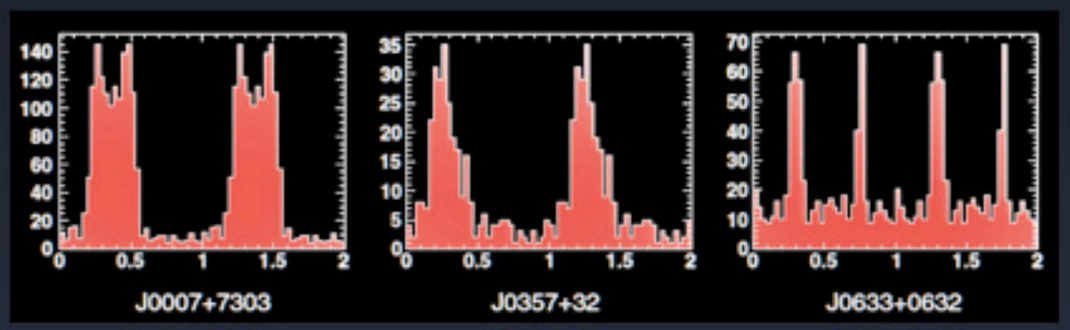
High Energies



□ No association	▫ Possible association with nearby SNR or PWN		
× AGN – blazar	✷ Starburst Gal	☆ Pulsar	★ Pulsar w/PWN
✖ AGN – unknown	+ Galaxy	◈ PWN	△ Globular cluster
× AGN – non blazar		○ SNR	⊠ XRB or MQO



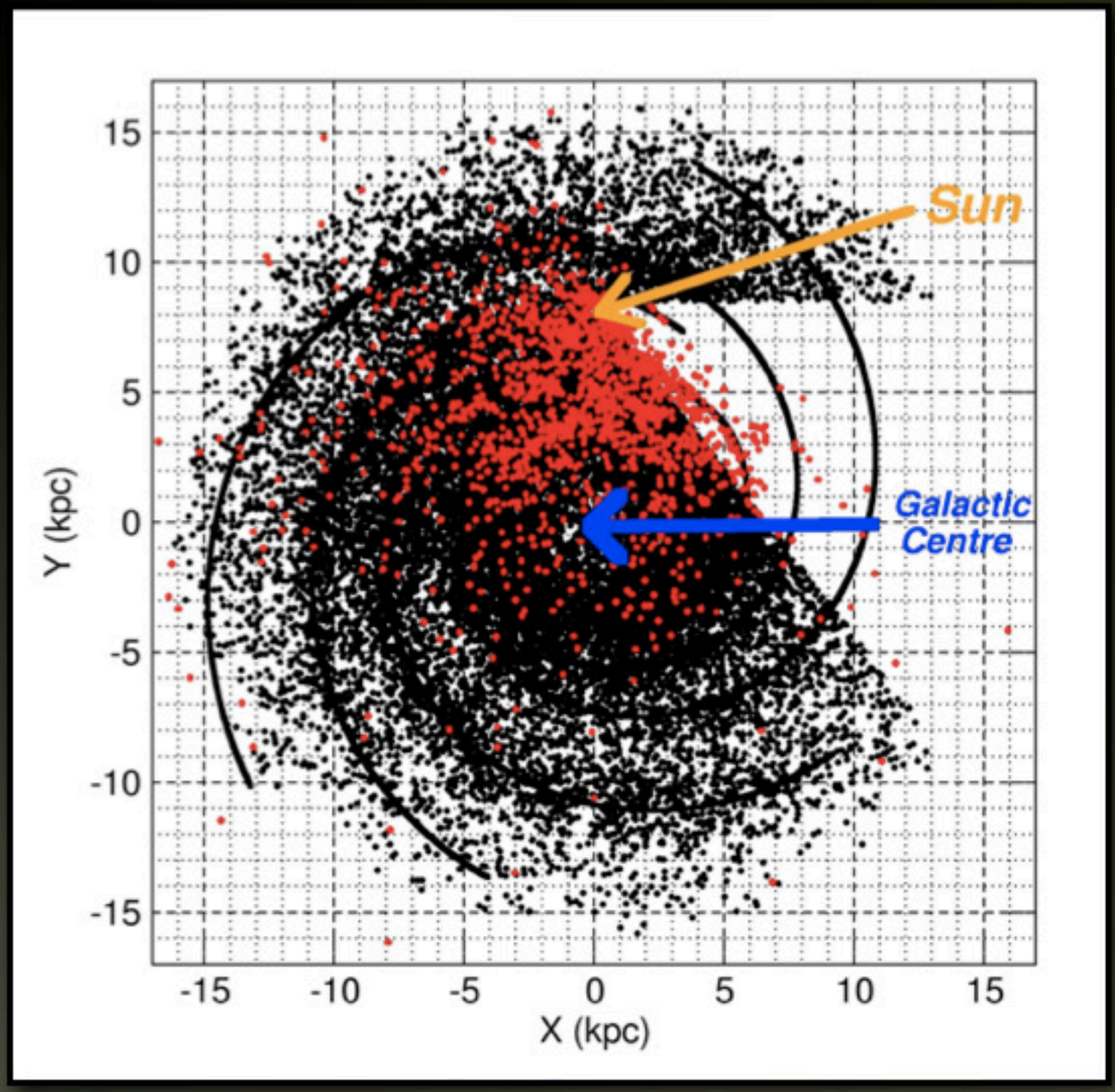
We are also searching the unidentified FERMI sources for radio-pulsar counterparts



If these γ-ray pulsars are polarised in the radio, they will be added to the RM grid

SKA

Simulation: M. Kramer



- All currently known PSRs
- PSRs expected from the SKA