

The Milky Way at Low Frequencies

Galactic work with LOFAR

Marijke Haverkorn, on behalf of:

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Galactic science with LOFAR

Interstellar medium in the Galactic plane

ISM-1) HII regions

ISM-2) Supernova remnants

ISM-3) Cold neutral medium → talk by Raymond Oonk

Magnetic fields in the Galaxy

Bfield-1) Large-scale field (pulsar rotation measures)

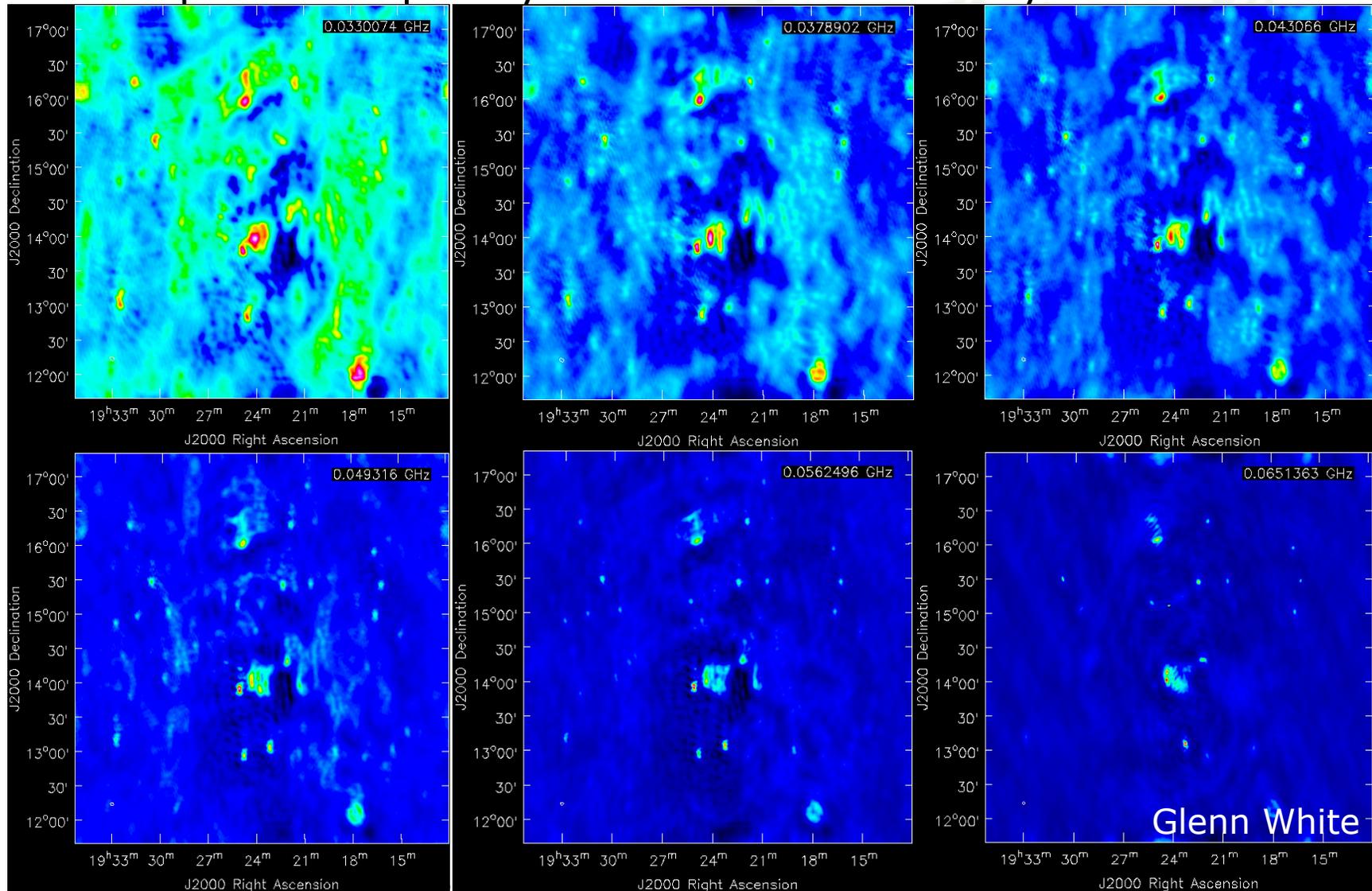
Bfield-2) Small-scale magnetized structure (diffuse polarimetry)

Imaging the Galactic plane: bright and extended emission throughout the field

- Many bright point and extended sources across the beam
- No useful sky models – no selfcal
- Highly structured bright diffuse background – source models tricky to make
- have to demix extended sources
- System temperatures depend on background – calibration difficult
- Lack of zero spacings: ringing/negative bowls around bright sources
- Spectral turnover in SNRs and HII regions: LBA and HBA may differ

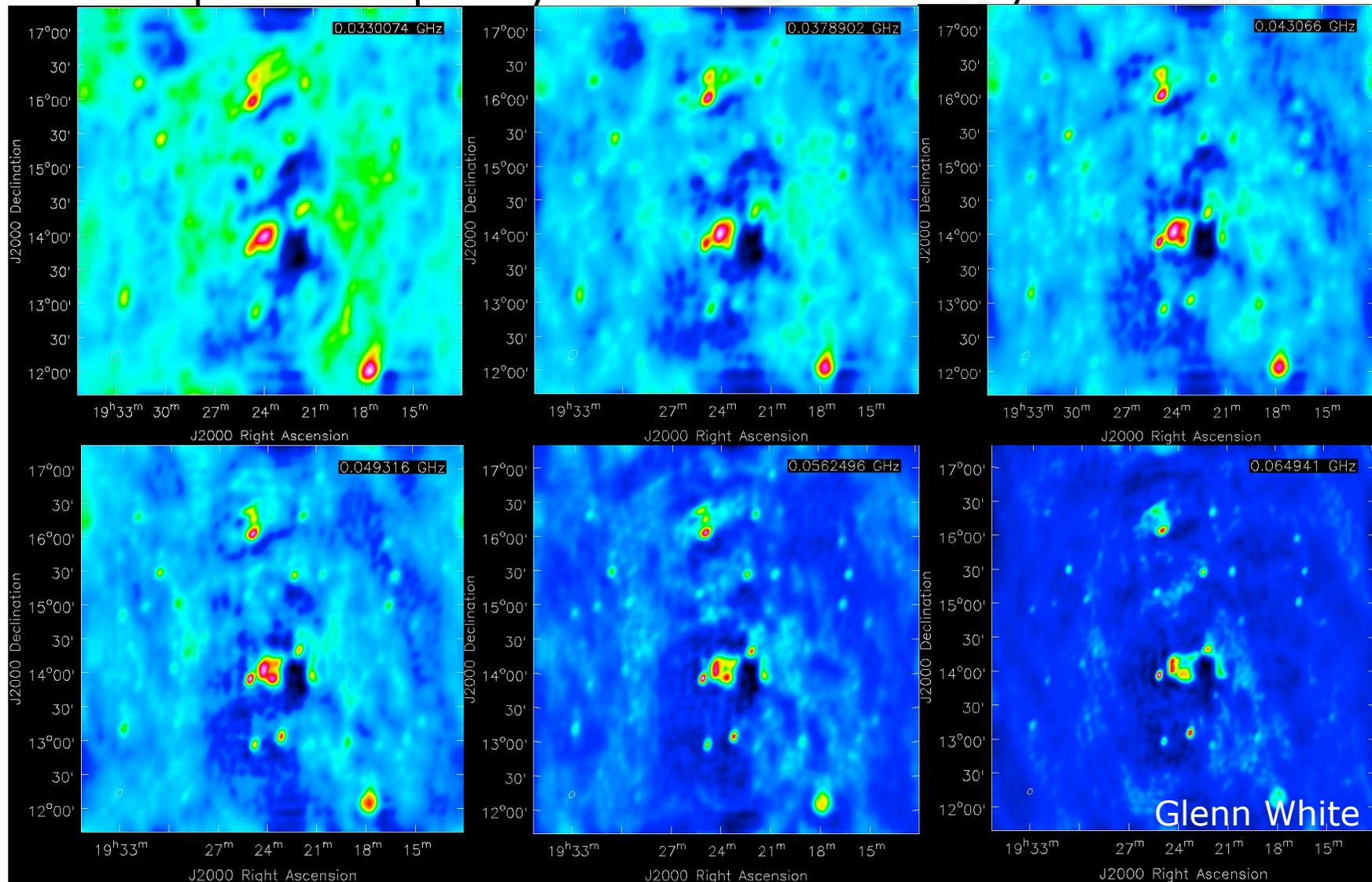
Imaging the Galactic plane: bright and extended emission throughout the field

Example of complexity: W51 LBA – selfcal skymodel



Imaging the Galactic plane: bright and extended emission throughout the field

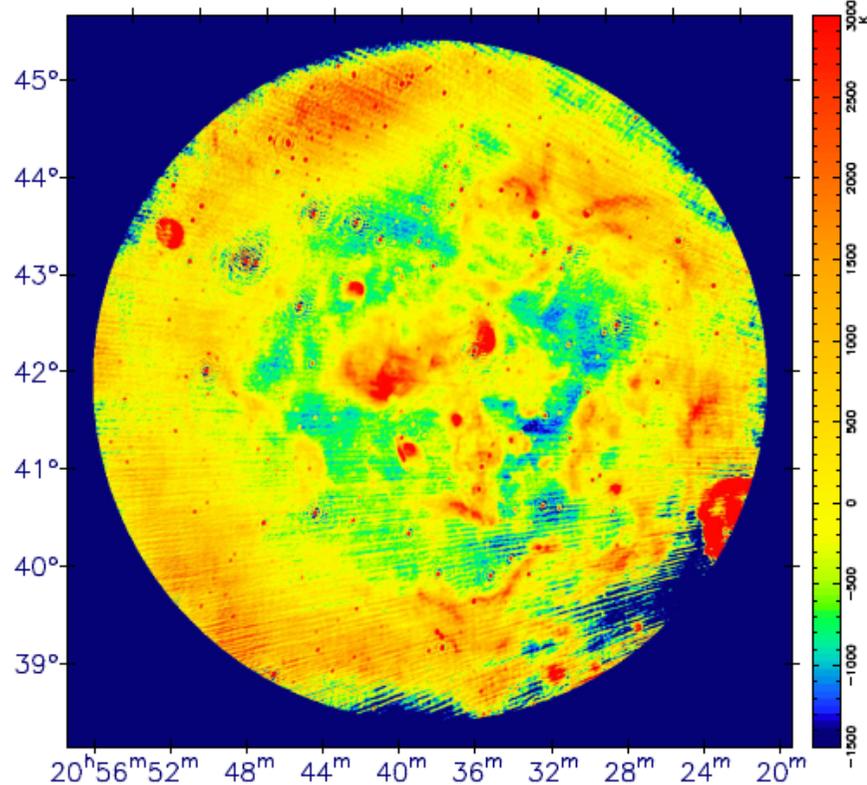
Example of complexity: W51 LBA – blank skymodel



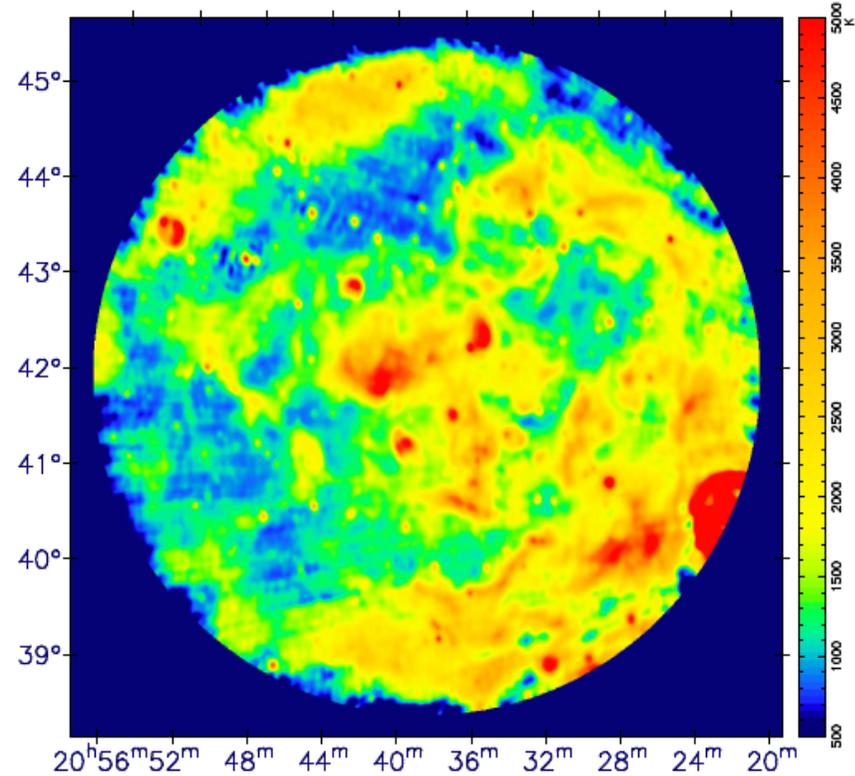
Imaging the Galactic plane: bright and extended emission throughout the field

Cygnus X: filling in missing short spacings

CygX 150 MHz 1.25'x1.85' Prim.Beam corr K

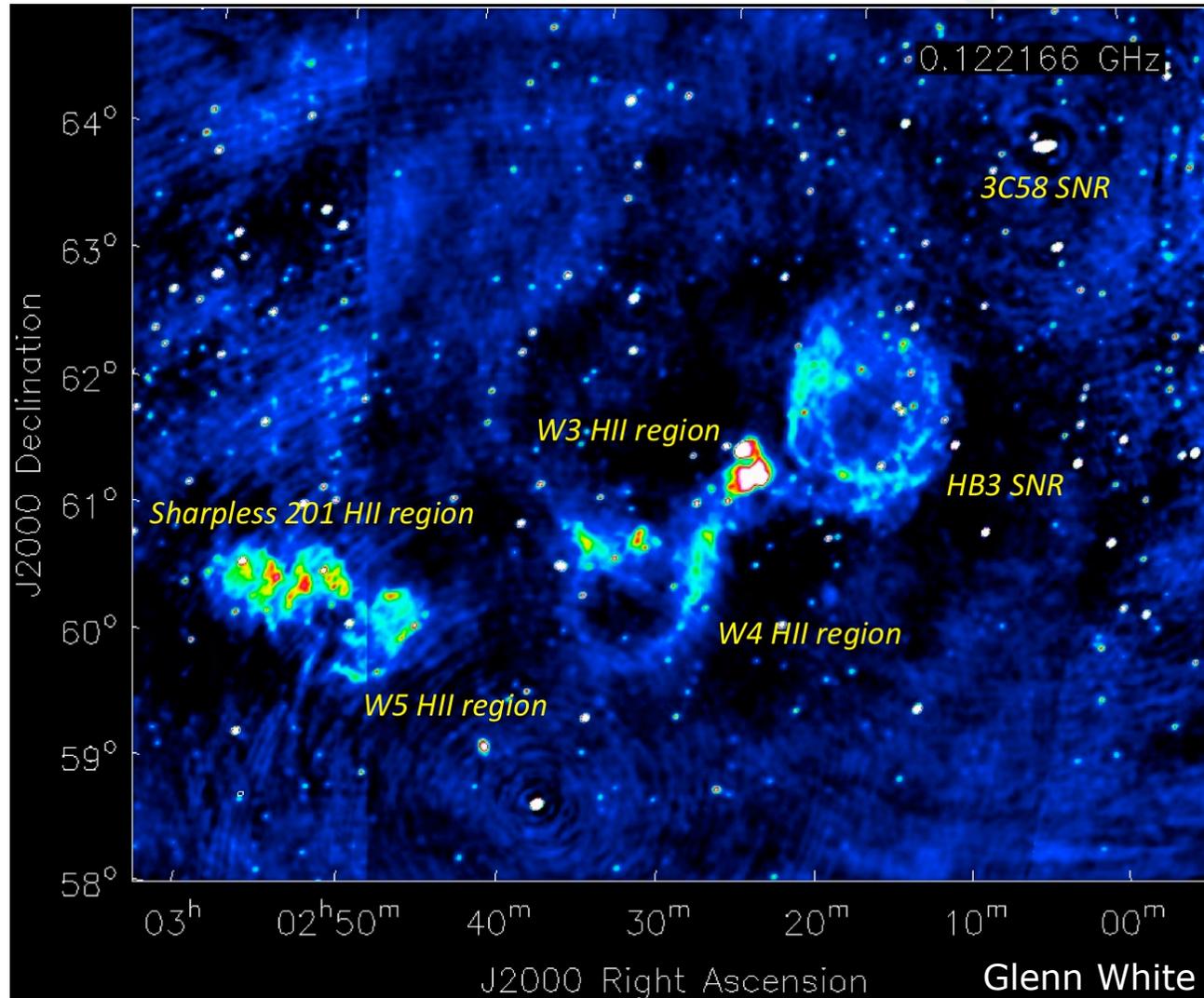


CygX 150 MHz 3.4'x4.73' + BG(408MHz,-2.3)



Wolfgang Reich

ISM-1) HII regions



LOTSS survey HBA

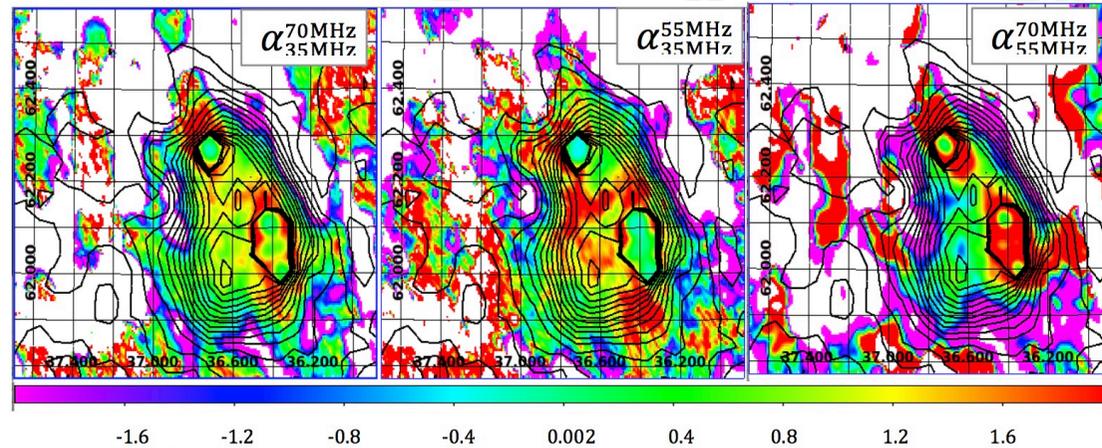
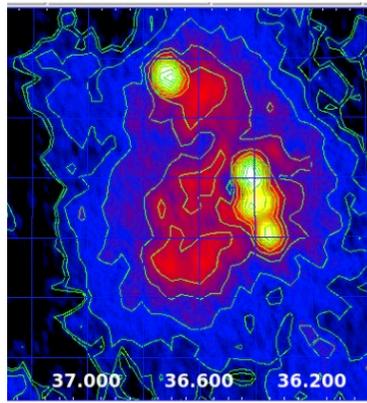
122 MHz, 20 subbands

2 pointings

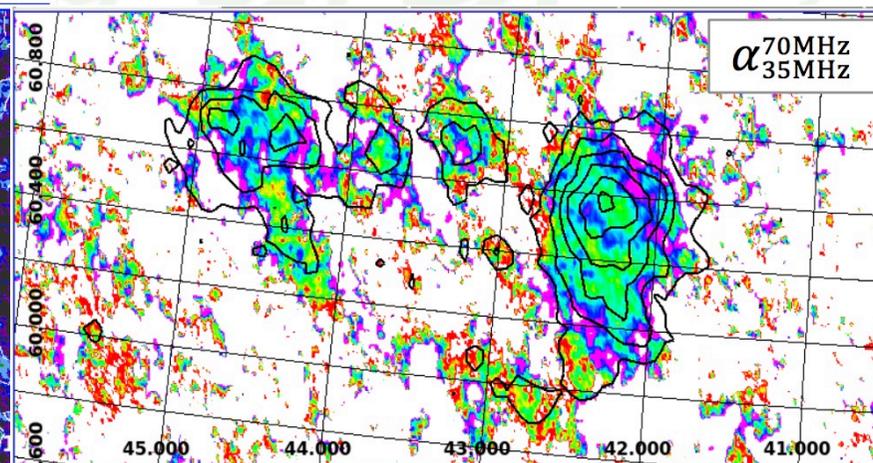
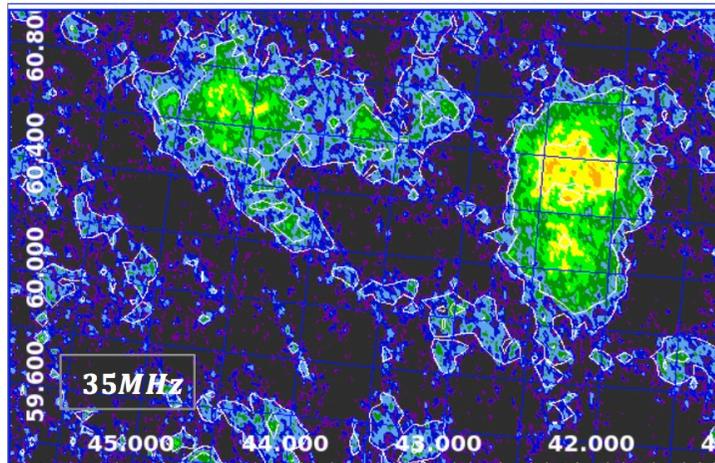
preliminary

ISM-1) HII regions

W3

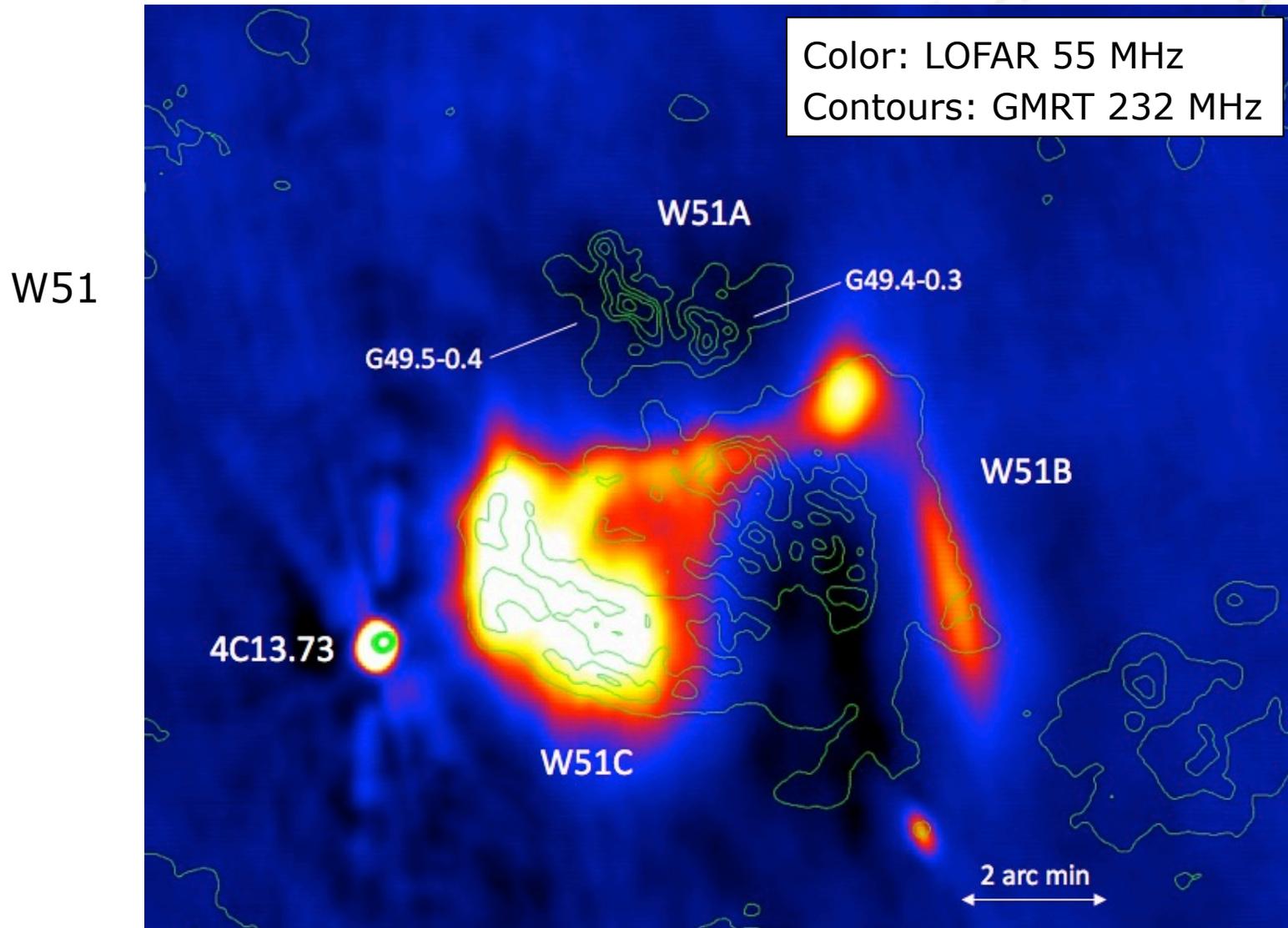


W5



PhD thesis Kiz Natt

ISM-1) HII regions



White et al, in prep

ISM-1) HII regions

LBA measurements show free-free absorption of HII regions.

→ imply Galactic cosmic ray distribution from many absorbed HII regions



Cosmic ray tomography with LOFAR

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Introduction

Galactic cosmic rays propagate through the Milky Way and interact with magnetic fields, creating radio synchrotron radiation that dominates the low frequency sky. This work presents the study of the synchrotron emission distribution in the Milky Way as a function of distance along the line of sight. At frequencies below ~ 100 MHz, HII regions become nearly or completely opaque by free-free absorption of synchrotron radiation. Thus, separating the emission behind it and in front of it along the line of sight enables the observation of the radial emissivity distribution. With appropriate assumptions for the values of Galactic magnetic fields the emissivity distribution can be transformed into one of cosmic ray (CR) density.

1. HII regions and LOFAR

At frequencies below 100 MHz HII regions are observed in absorption. Observing an area on the sky with both Low Band Antennas (LBA, 10 - 90MHz) and High Band Antennas (HBA, 110 - 250MHz) provides us with an opportunity to distinguish between HII regions and other objects, such as supernova remnants, as these exhibit no free-free absorption.

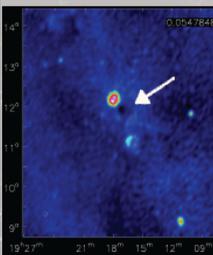
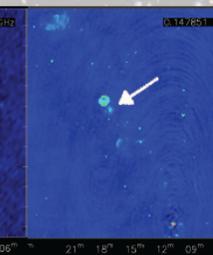



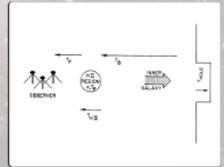
Figure 1: LOFAR LBA Stokes I, at 54 MHz, 10 subbands, rms=0.065 Jy Figure 2: LOFAR HBA Stokes I, at 148 MHz, 1 subband, uncalibrated

2. Theory of observing an HII region in absorption

In an interferometer image the HII regions will appear as dark clouds against the background of radio synchrotron emission, this can be seen in Figure 1. Important HII region parameters are the opacity, τ , and the electron temperature T_e . Using a proper value for T_e , we calculate the background column temperature, T_b in the following way:

$$T_{\text{hole, interferometer}} = (T_e + T_{\text{foreground}}) - T_{\text{total}}$$

$$= (T_e + T_{\text{foreground}}) - (T_{\text{foreground}} + T_{\text{background}})$$

$$= T_e - T_{\text{background}} < 0$$


For HII regions with known distance, D , we calculate the emissivity value in Kelvin parsec⁻³: $\epsilon = T_b / D$

3. Synchrotron emissivity and cosmic rays

At the start of each line in Fig. 3 is an observed HII region with a known distance and its corresponding line of sight (LOS) for which the emissivity can be calculated. Using each LOS as a slice of the Galaxy we can rebuild the Milky Way in terms of the emissivity, a process called tomography. Expanding our number of LOS with LOFAR observations we aim to cover the entire Galactic plane.

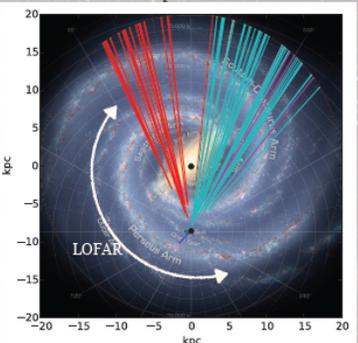


Figure 3: LOS plot from HII region catalog in [4]

4. Future work

With our catalog of emissivities (Fig. 3 and 4) we can start modelling the cosmic ray density in the Milky Way. We are guided by earlier works ([2], Fig. 5) that have performed such modelling on a subset of our catalog, with different a priori models.

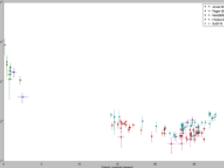


Figure 4: from catalog [4] plotting emissivity (K pc⁻³) as a function of column path length

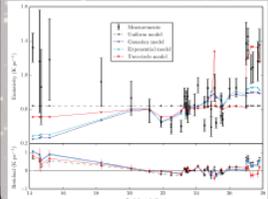


Figure 5: CR modelling by [3], a chi-squared fit is made of four different models (see legend) to Emissivity data from MWA observations. All fits work reasonably well for longer path lengths (10 - 20 kpc), but not for shorter ones (14 - 16 kpc)

References

[1] Kassim, N. E. 1990| Lect. Notes Phys., 362, 144
 [2] Nord, M. E., et al. 2006, AJ, 132, 242
 [3] Su, H., et al. 2016 Mon. Not. R. Astron. Soc., 13, 1
 [4] Polderman, I. M., et al. in prep.

Suggestions related to this work or this poster? Tell me! Or, leave me a post-it in this box.

You can also contact me: i.polderman@astro.ru.nl

ISM-2) Supernova remnants: Cas A

SNRs dominate at low radio frequencies because of their **steep spectral indices**.

Provide information on sites of **particle acceleration**.

E.g. mixed-morphology remnants: for radiative shocks with high compression ratios expect a flat spectral index

Cassiopeia A in the LOFAR LBA

An estimate of mass in the unshocked ejecta from low frequency absorption

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¹University of Amsterdam, ²Leiden University



Introduction

The brightest radio source in the sky, Cassiopeia A, is one of our Galaxy's youngest (~ 330 years) and best studied supernova remnants (SNRs). The bright radio shell marks the location of hot, shocked supernova ejecta, whereas unshocked ejecta is still freely expanding interior to the shell. These ejecta were originally shocked in the passage of the blast wave through the star, adiabatically cooled during the expansion of the SNR, and now are being heated again as they interact with the reverse shock. Since the unshocked ejecta is ionized, the interior cold gas can free-free absorb the synchrotron emission from the shell behind it. This happens preferentially at lower frequencies. In this work, we use LOFAR LBA images to fit for the effect of this absorption, and estimate the mass of the unshocked ejecta.

Data

The data were taken in August 2015 as a legacy dataset part of the LOFAR project to image all the A-team sources in the LBA.

Calibrator	Time Stations	Freq.	Resolution
3C380	8 hr CS, RS, int.	64 ch/sb	

Table 1: Observation details. * We removed the international baselines and kept the Dutch configuration.

The data were demixed, averaged, and calibrated against a 69 MHz model from 2011 observations of Cas A referenced in [2], which was provided by the authors. The visibilities were imaged with CASA's clean function, in multi-frequency synthesis mode and with a Briggs parameter of -0.5.

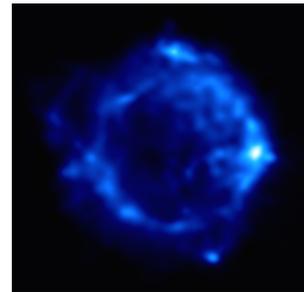


Figure 1: Cassiopeia A in the LOFAR LBA. Central frequency is 54 MHz, beam size is 10 arcsec, noise is 0.01 Jy/bm, and dynamic range is of 13,000.

Narrow bandwidth (i.e., ~ 1 MHz) images at 30, 35, 40, 45, 50, 55, 60, 65, 70, and 77 MHz were made in order to study the spectral behaviour of specific regions within the remnant. The narrow band images had their total flux (in a masked region containing Cas A) bootstrapped to $S_\nu = S_{\text{CMB}} \left(\frac{\nu}{\nu_{\text{CMB}}}\right)^{-\alpha}$, with $S_{\text{CMB}} = 2720$ Jy and $\alpha = 0.77$.

Fitting

The free-free optical depth in the Rayleigh-Jeans approximation [3] is:

$$\tau_\nu = 3.014 \times 10^4 Z \left(\frac{T}{\text{K}}\right)^{-3/2} \left(\frac{\nu}{\text{MHz}}\right)^{-2} \left(\frac{\text{EM}}{\text{pc cm}^{-6}}\right) g_{ff} \quad (1)$$

where Ze is the charge of the ion, $\text{EM} = \int_0^l n_e^2 ds'$ with n_e the number density of electrons, and g_{ff} is a Gaunt factor of order 1.

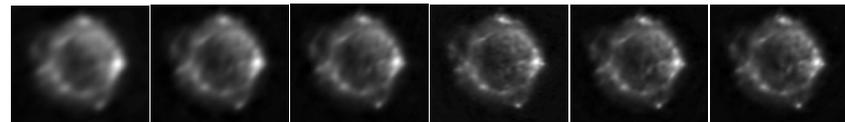


Figure 3: 1 MHz images of Cassiopeia A in the LOFAR LBA. From left to right, 30, 40, 50, 60, 70, and 77 MHz

We fitted for the equation:

$$S_\nu = (S_{\nu, \text{front}} + S_{\nu, \text{back}} e^{-\tau_{\text{ISM}}}) e^{-\tau_{\text{ISM}}} \quad (2)$$

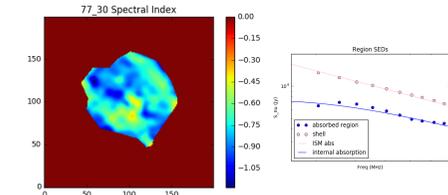


Figure 2: Left: Spectral index map made from 30 MHz and 77 MHz images. The images were made with a common $u-v$ range of 500 to 12,000 As (scales of 7 arcmin to 17 arcsec, for a source of size ~ 5 arcmin). Right: Spectra for the shell (pink) and the absorbed region in the SE of the SNR (blue) from our bootstrapped narrow frequency images. The data points in blue are multiplied by a factor of two for display. The shell is only fitted for free-free absorption from the ISM, and the absorbed region is also fit for free-free absorption from the unshocked ejecta. The parameters assumed for this plot are: $Z_{\text{ISM}} = 1$, $T_{\text{ISM}} = 20$ K, $T_{\text{int}} = 3$, $T_{\text{int}} = 30$ K, and $S_{\nu, \text{front}} = S_{\nu, \text{back}}$. The best-fit emission measures are $\text{EM}_{\text{ISM}} = 0.0085 \text{ pc cm}^{-6}$ and $\text{EM}_{\text{int}} = 1.44 \text{ pc cm}^{-6}$.

We chose a region encompassing the shell of the remnant to fit for the ISM contribution to the absorption (τ_{ISM}), and then the absorbed region in the south east of the remnant with a flatter spectral index (see the spectral index map) for τ_{int} . In each case we assumed a value of Z and of T , and the parameter that was fitted for was EM (see fig. 2).

Estimates of mass and density in the unshocked ejecta

If the electron density n_e is constant inside the reverse shock, then $\text{EM} = n_e^2 l$, where l is a thickness element. In this case, the mass in the unshocked ejecta is:

$$M = A m_p \frac{1}{Z} \sqrt{\frac{\text{EM}}{l}} V = 0.59 M_\odot \left(\frac{3}{Z}\right) \left(\frac{\text{EM}}{1.44 \text{ pc cm}^{-6}}\right)^{1/2} \left(\frac{1}{0.19 \text{ pc}}\right)^{-1/2} \left(\frac{V}{1.1 \text{ pc}^3}\right) \quad (3)$$

Here A is the average mass number of the ions, and m_p is the mass of the proton.

The mass estimate is dependent on the assumed geometry of the ejecta. Here we use a geometry where the unshocked ejecta is confined to two sheets interior to the reverse shock, as done in a similar study by [1]. For a homogeneously distributed ejecta, our best-fit value of EM implies a total mass in the absorbing plasma of ~ 2 M_\odot .

Conclusions

LOFAR's multifrequency capabilities allow for the study of local spectral variations in extended sources. This allows us to fit for frequency-dependent quantities with more detail than through a traditional spectral index map.

In this work we fit for the contribution of internal free-free absorption to the spectrum of a region in the south west of the SNR with a flat spectral index. Making reasonable assumptions about the geometry of the ejecta, we derive an estimate of 0.52 M_\odot of gas internal to the reverse shock.

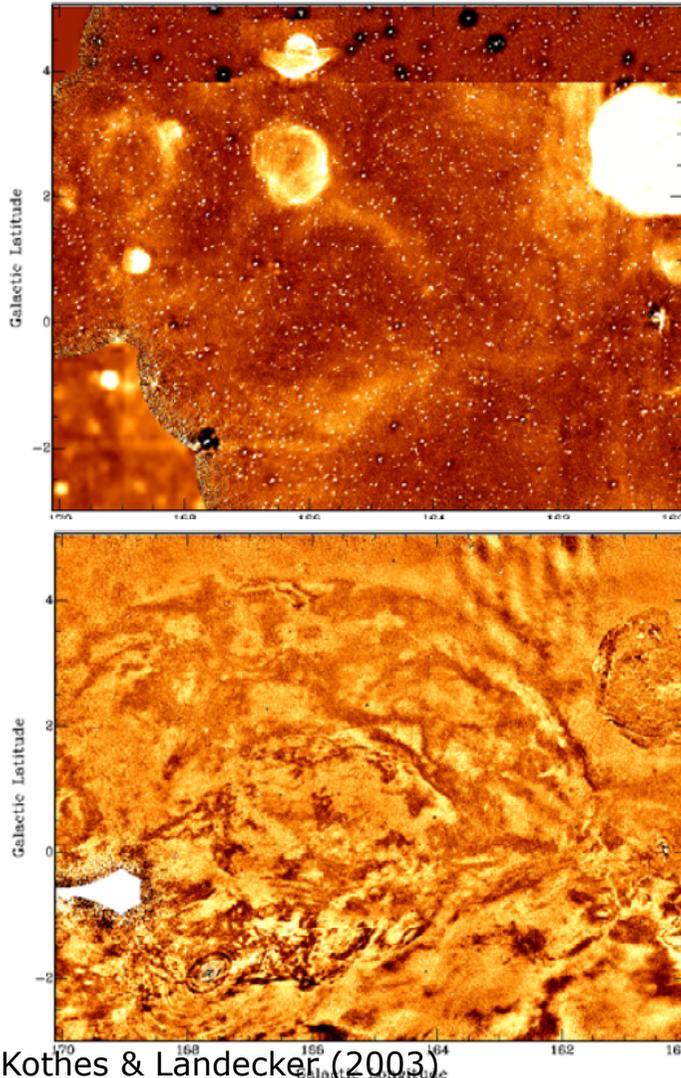
References

- [1] T. DeLaney, N.E. Kassim, L. Rudnick, and R.A. Perley. The density and mass of unshocked ejecta in Cassiopeia A through low-frequency radio absorption. *ApJ*, pages 59–69, 2014.
- [2] J. B. R. Oost, R. J. van Weeren, P. Salas, F. Salgado, L. K. Morillon, M. C. Tortello, A. G. G. M. Tielens, and H. J. A. Röttgering. Carbon and hydrogen radio recombination lines from the cold clouds towards Cassiopeia A. *A&AS*, 465:1066–1068, February 2017.
- [3] Thomas L. Wilson, Kristen Rohlf, and Susanne Hildebrandt. *Tools of Radio Astronomy*. Berlin, Heidelberg, 2009.

ISM-2) Supernova remnants: VRO 42.05.01

María Arias, Jacco Vink,
Marco Iacobelli

HBA full band
prefactor
CS only
FWHM 152"
S/N 0.9 mJy/bm



UNPUBLISHED DATA

Images courtesy
Marco Iacobelli

ISM-2) Supernova remnants

Laura Driessen, Jason Hessels, Jacco Vink



NEW

UNPUBLISHED DATA

keep an eye on Driessen et al
on arXiv soon

Galactic science with LOFAR

Interstellar medium in the Galactic plane

ISM-1) HII regions

ISM-2) Supernova remnants

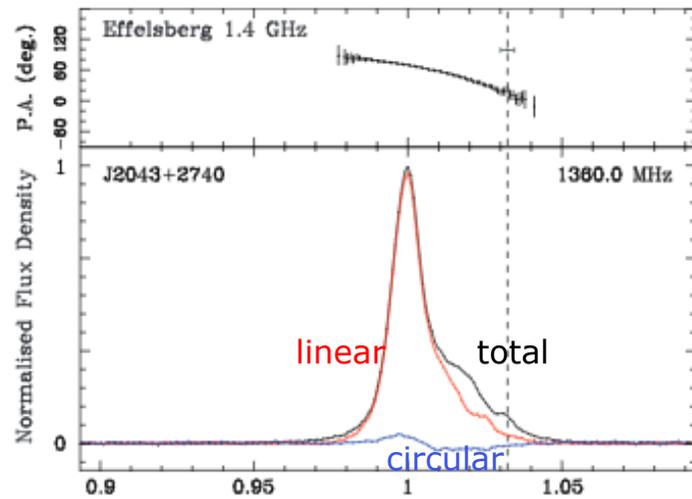
ISM-3) Cold neutral medium → talk by Raymond Oonk

Magnetic fields in the Galaxy

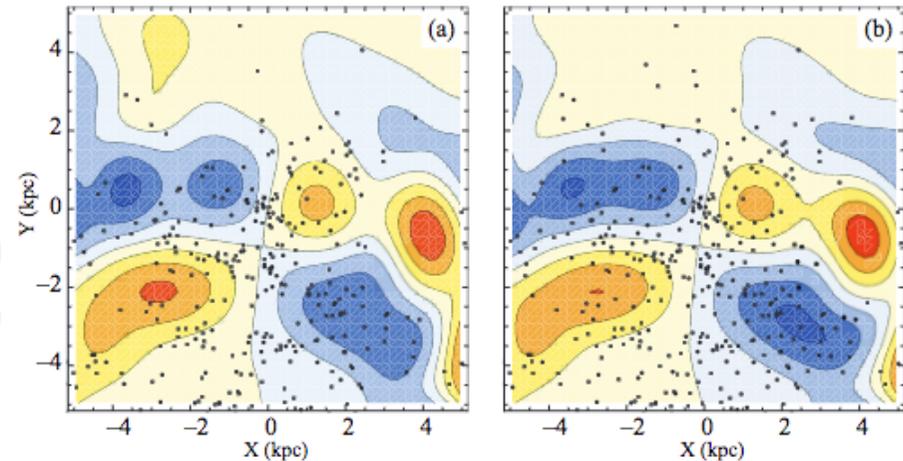
Bfield-1) Large-scale field (pulsar rotation measures)

Bfield-2) Small-scale magnetized structure (diffuse polarimetry)

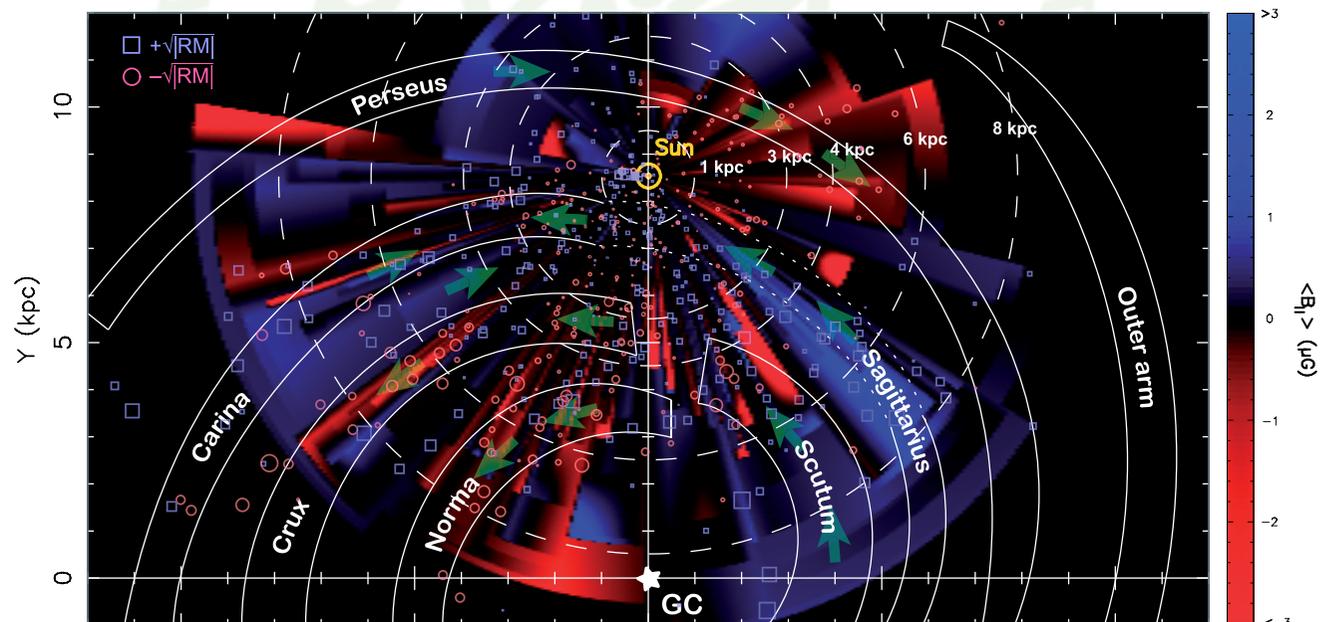
Large-scale magnetic field through pulsars



Noutsos et al (2011)



Sobey et al (2010)



Large-scale magnetic field through pulsars

Charlotte Sobey, Aris Noutsos + TKP Pulsar working group

UNPUBLISHED DATA

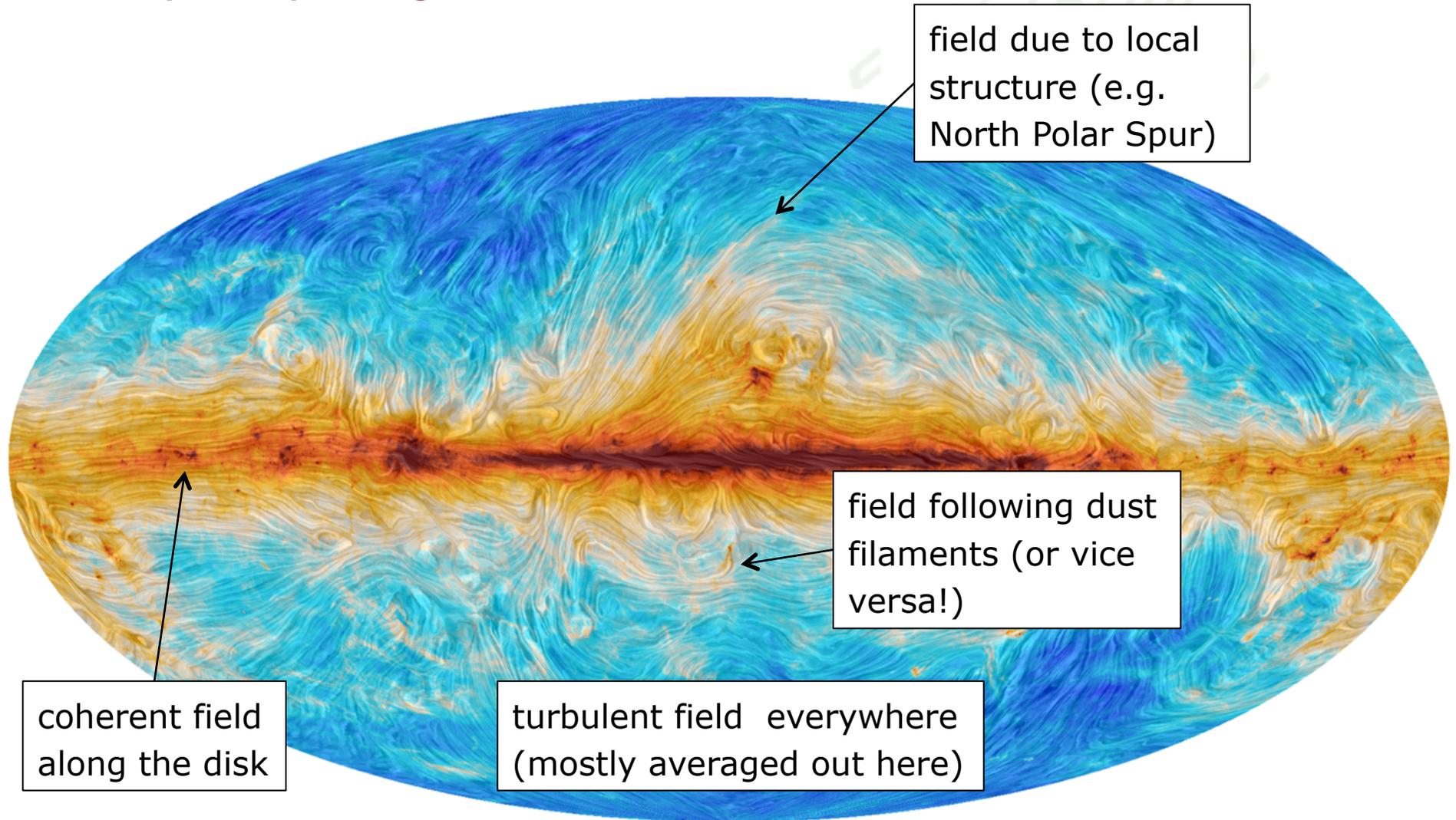
- existing pulsar catalog
- LOFAR pulsar catalog
(Sobey+, in prep)

Large-scale magnetic field through pulsars

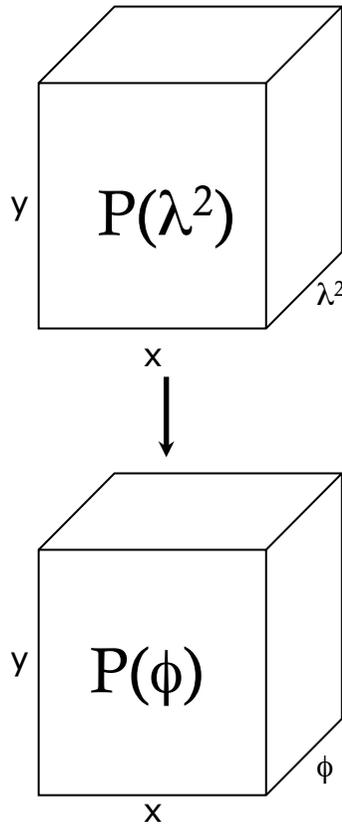
Charlotte Sobey, Aris Noutsos + TKP Pulsar working group

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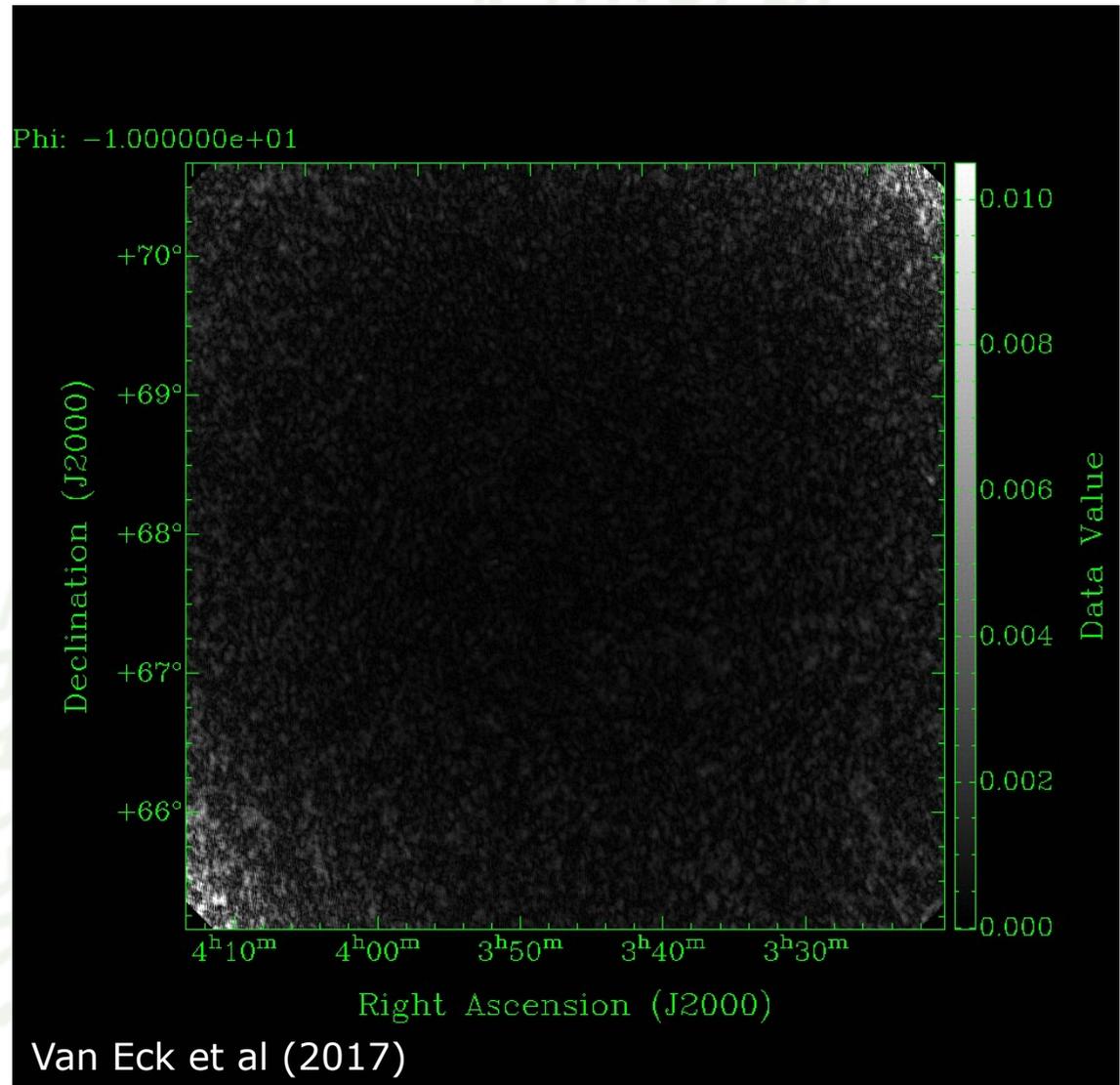
Milky Way magnetic field

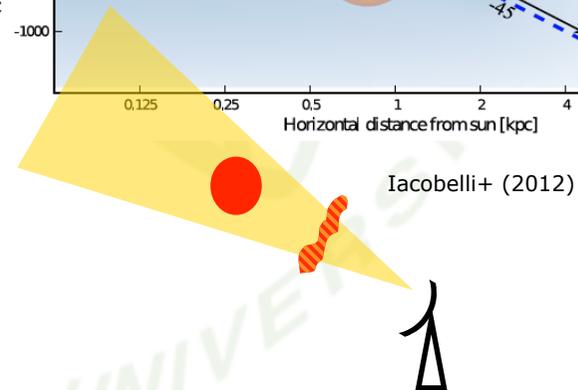
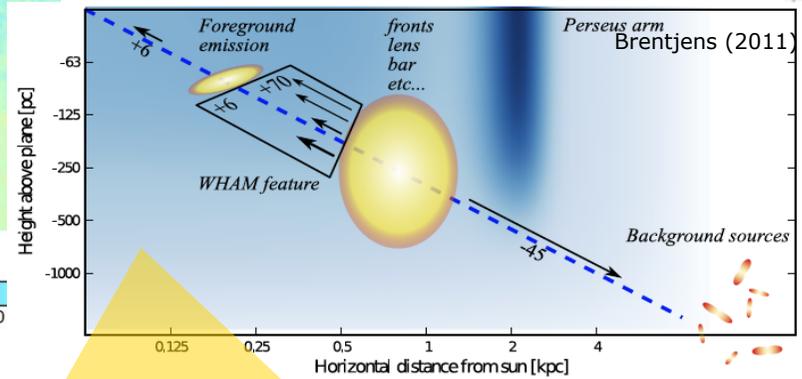
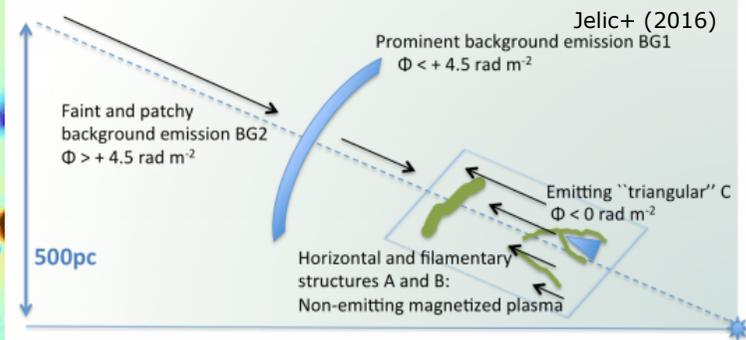
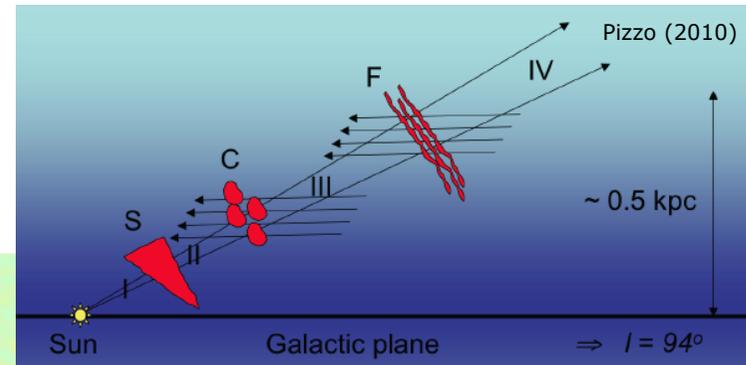
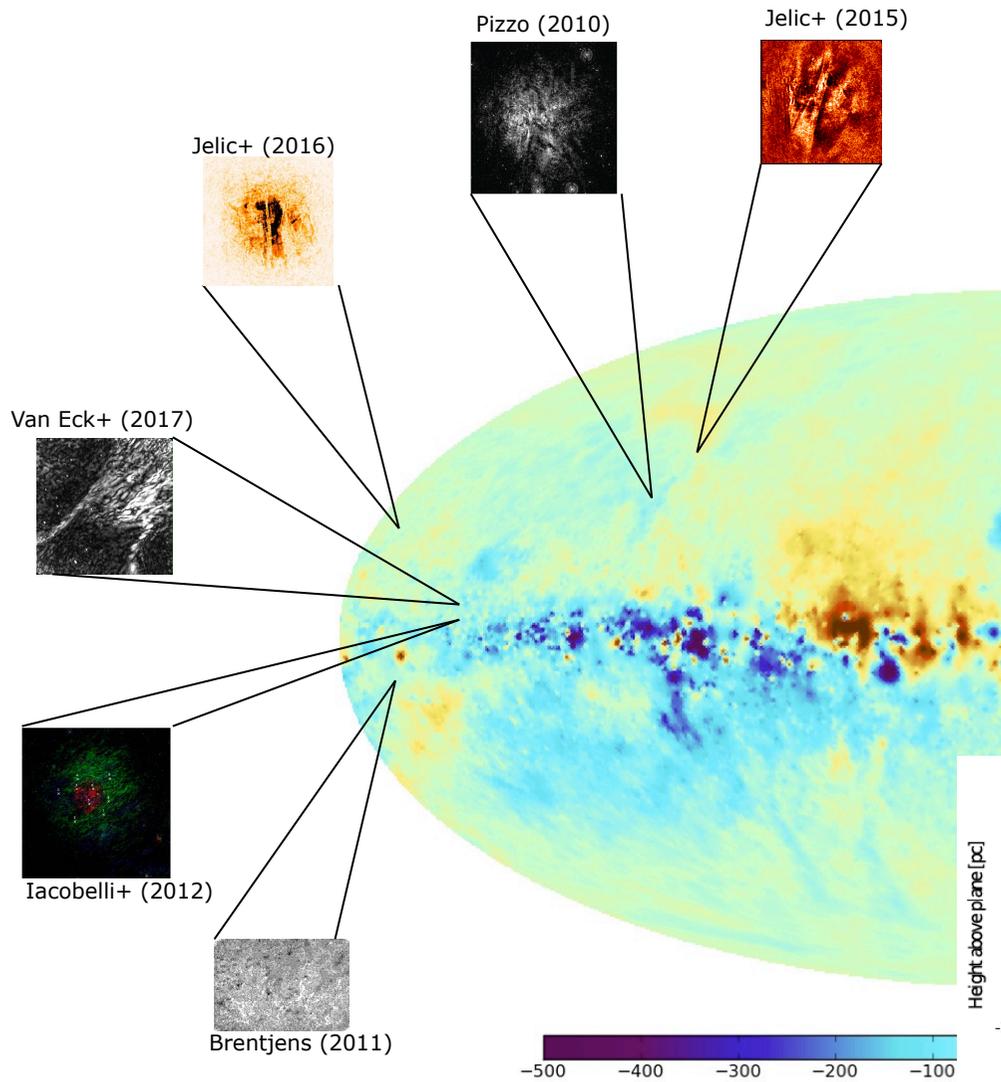


Use Rotation Measure synthesis:



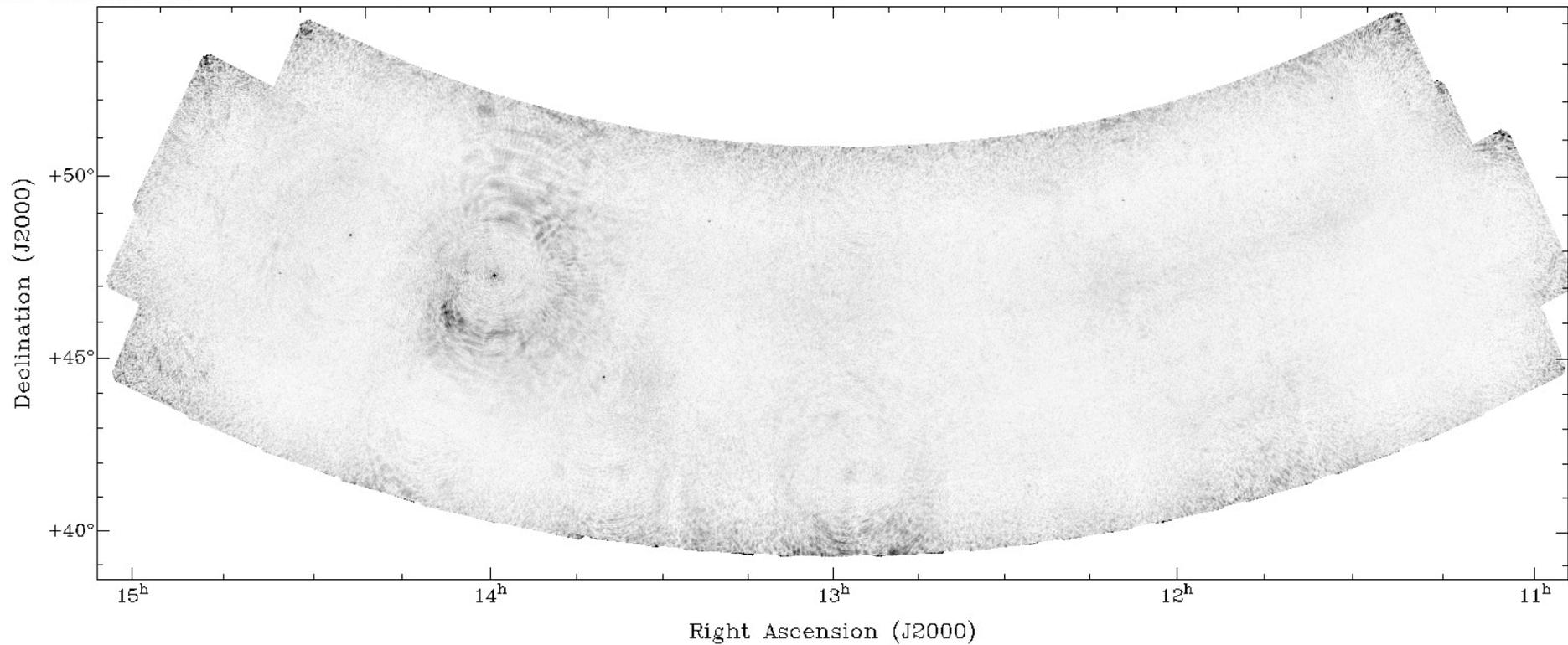
Faraday depth
 $\phi = 0.81 \int n_e \mathbf{B} \cdot d\mathbf{l}$





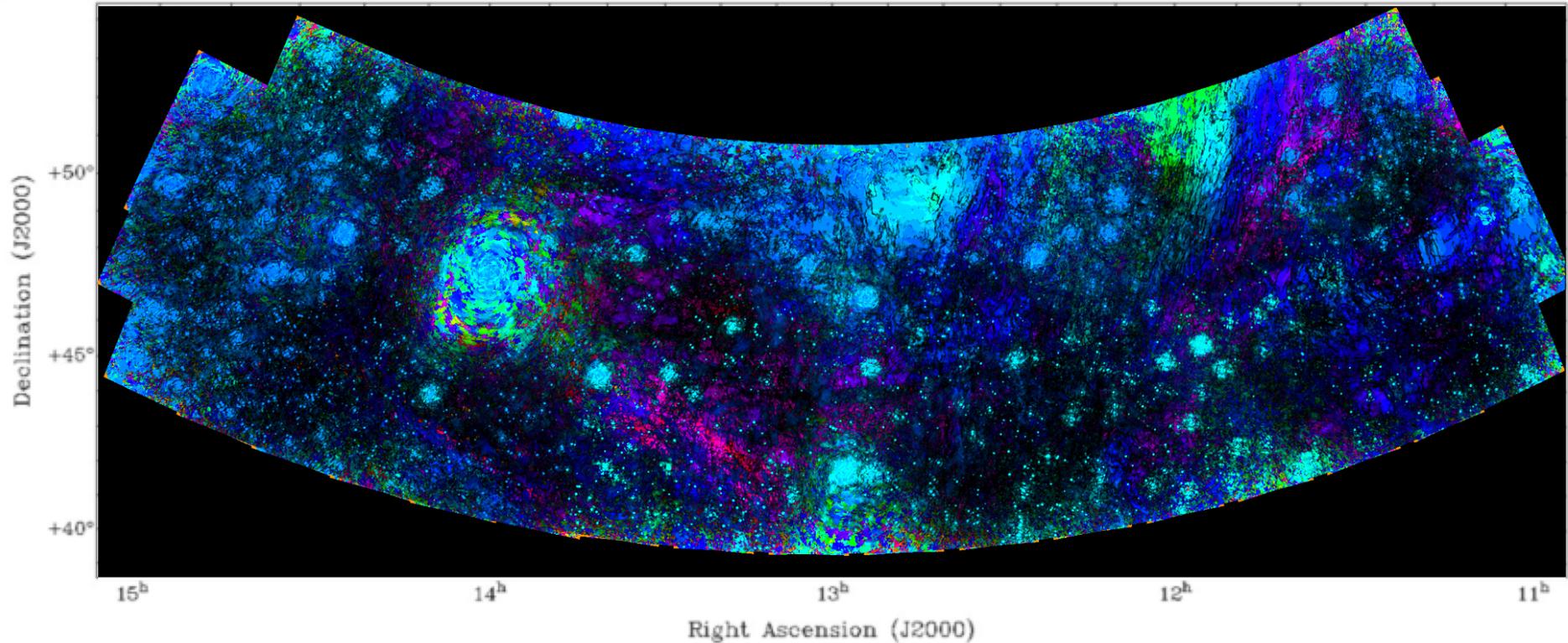
Get the global picture: spectro-polarimetry of the LOFAR Tier1 survey

Phi: $-1.000000e+01$



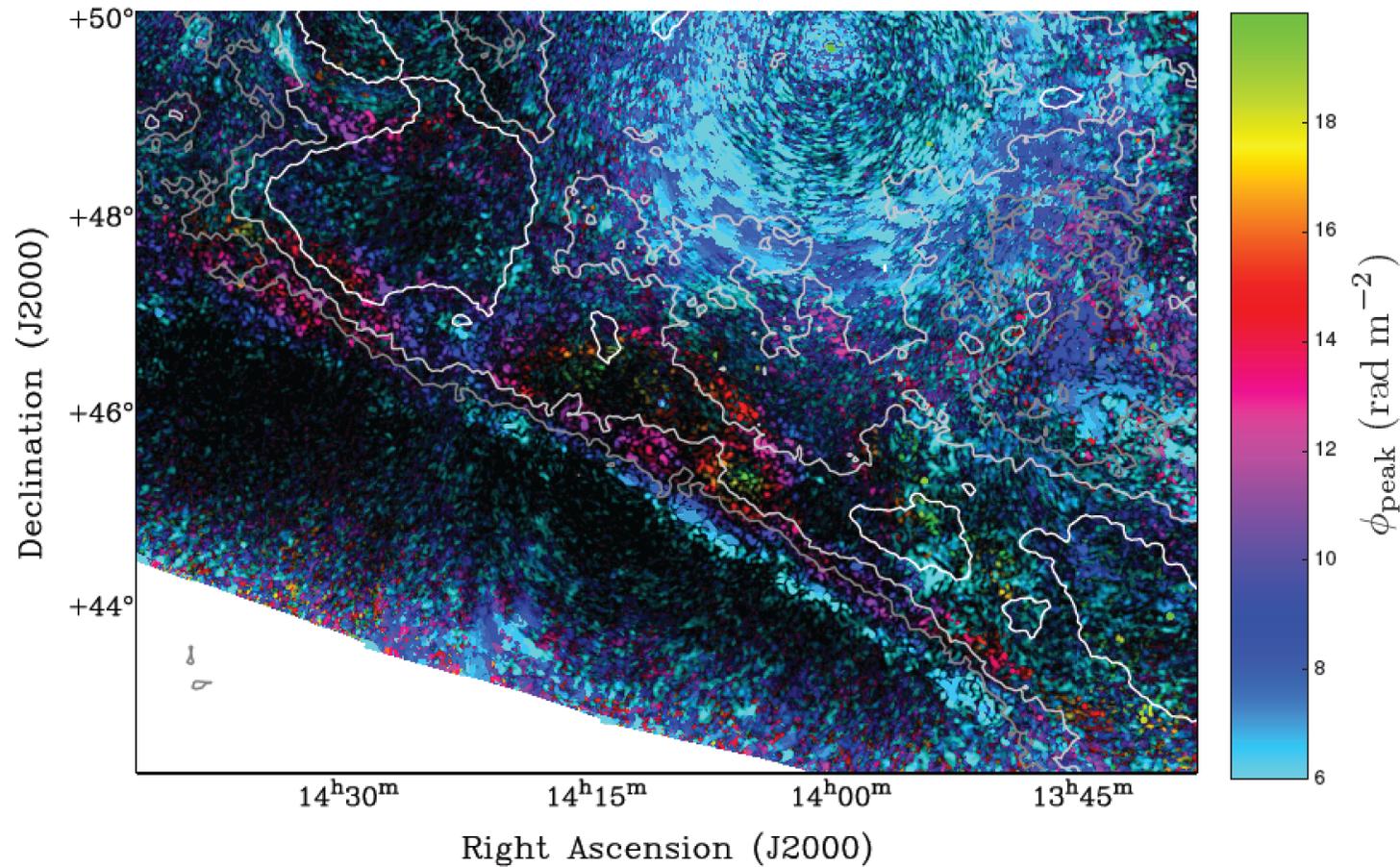
Van Eck et al (2017b,c)

Get the global picture: spectro-polarimetry of the LOFAR Tier1 survey



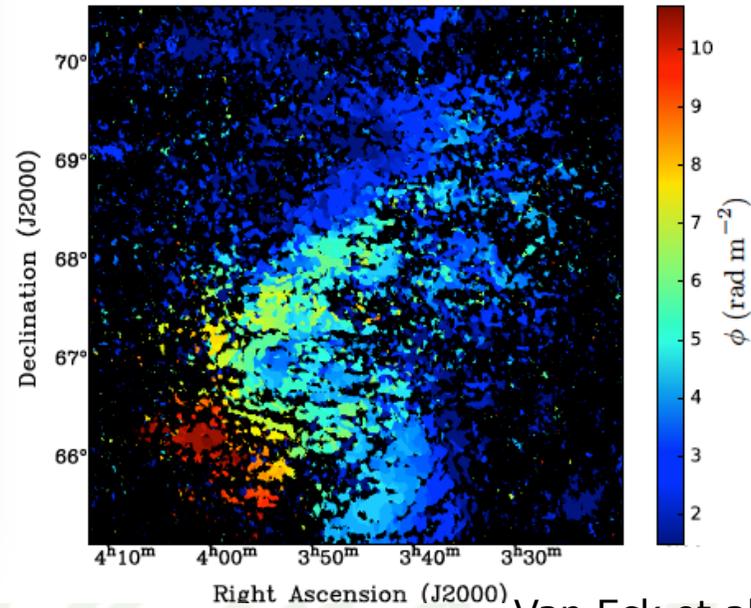
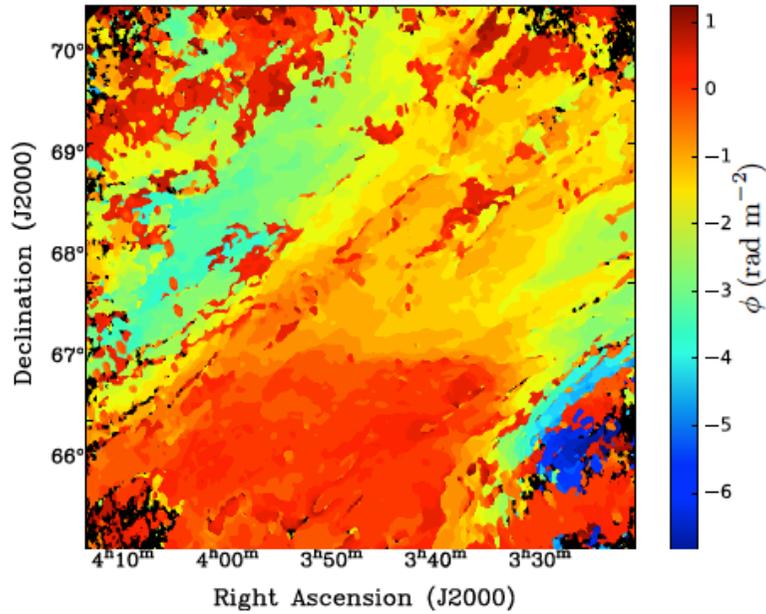
Van Eck et al (2017c)

Magnetized structures correspond to HI filaments

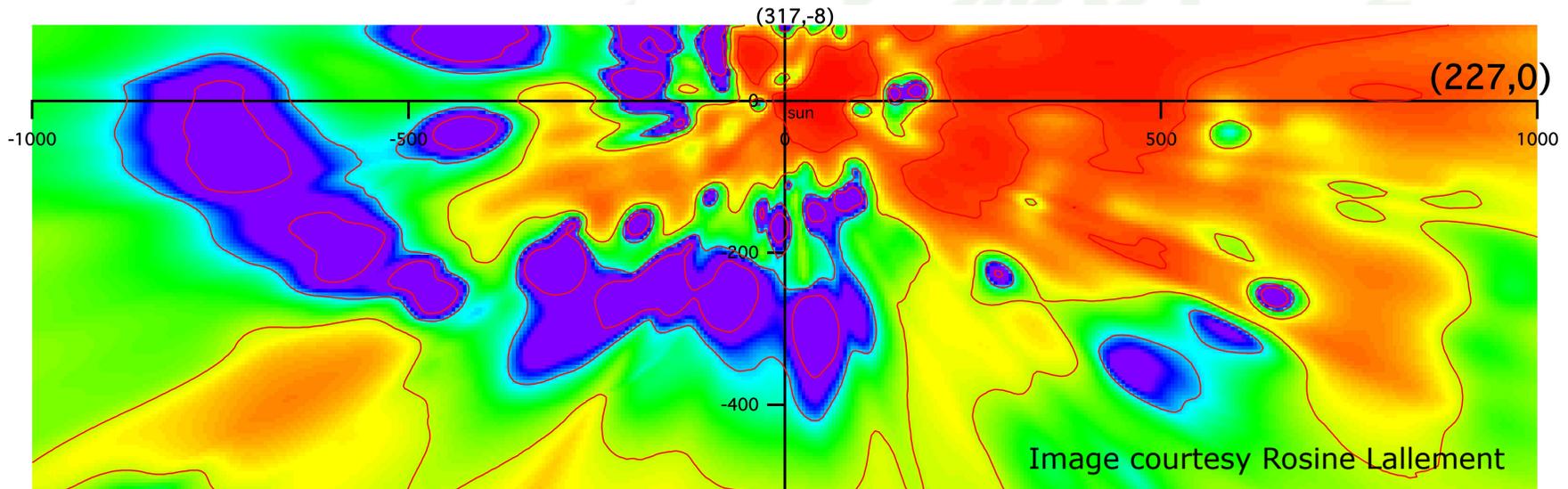


Van Eck et al (2017c)

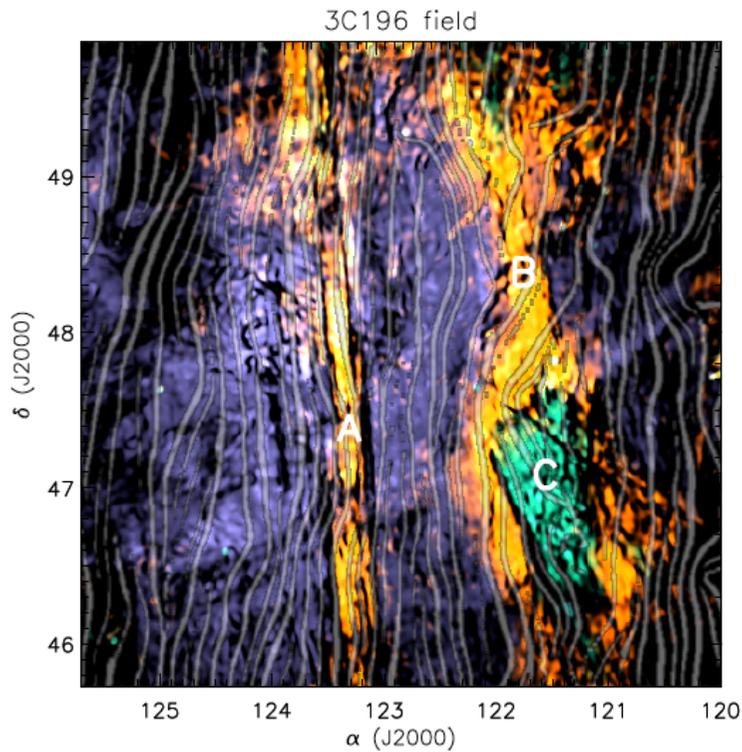
Associations with other tracers: synchrotron polarization traces neutral clouds



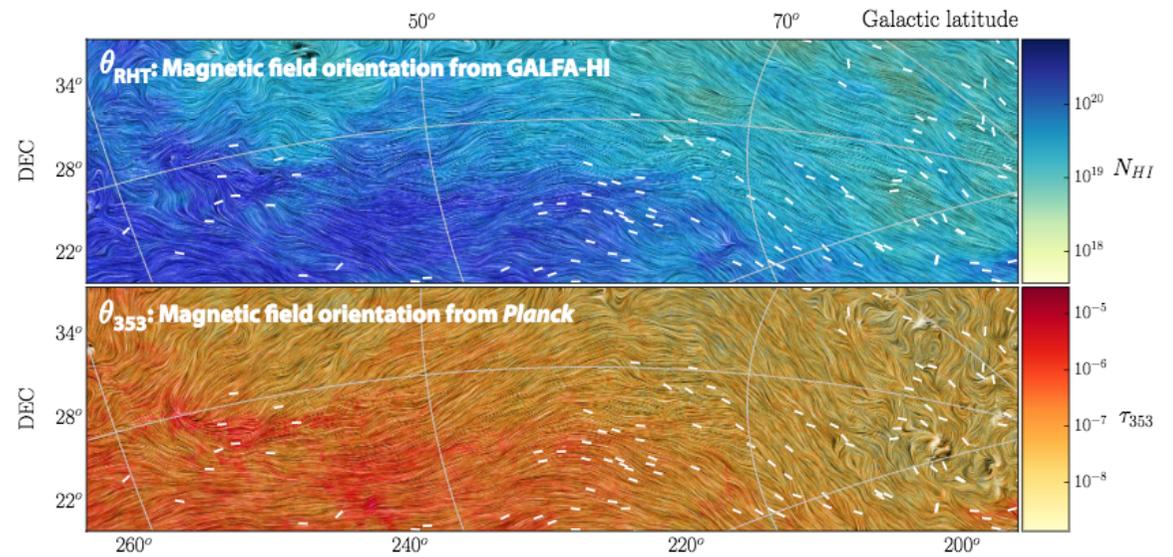
Van Eck et al (2017a)



Associations with other tracers: synchrotron polarization traces dust polarization, which traces HI filaments



Zaroubi et al (2015)



Clark et al (2015)

Summary

LOFAR imaging of the Galactic plane is tough but possible.

HII regions: physical properties, Galactic cosmic ray distribution

SNRs: properties, shock acceleration, distribution

Cold neutral clouds: unique information from LOFAR RRLs

LOFAR polarimetry gives unique magnetic field info

Small-scale field: coupled to dust, neutral clouds, HI filaments, ...

Large-scale field: low-freq pulsars give excellent model constraints