The Milky Way at Low Frequencies

Galactic work with LOFAR

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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)

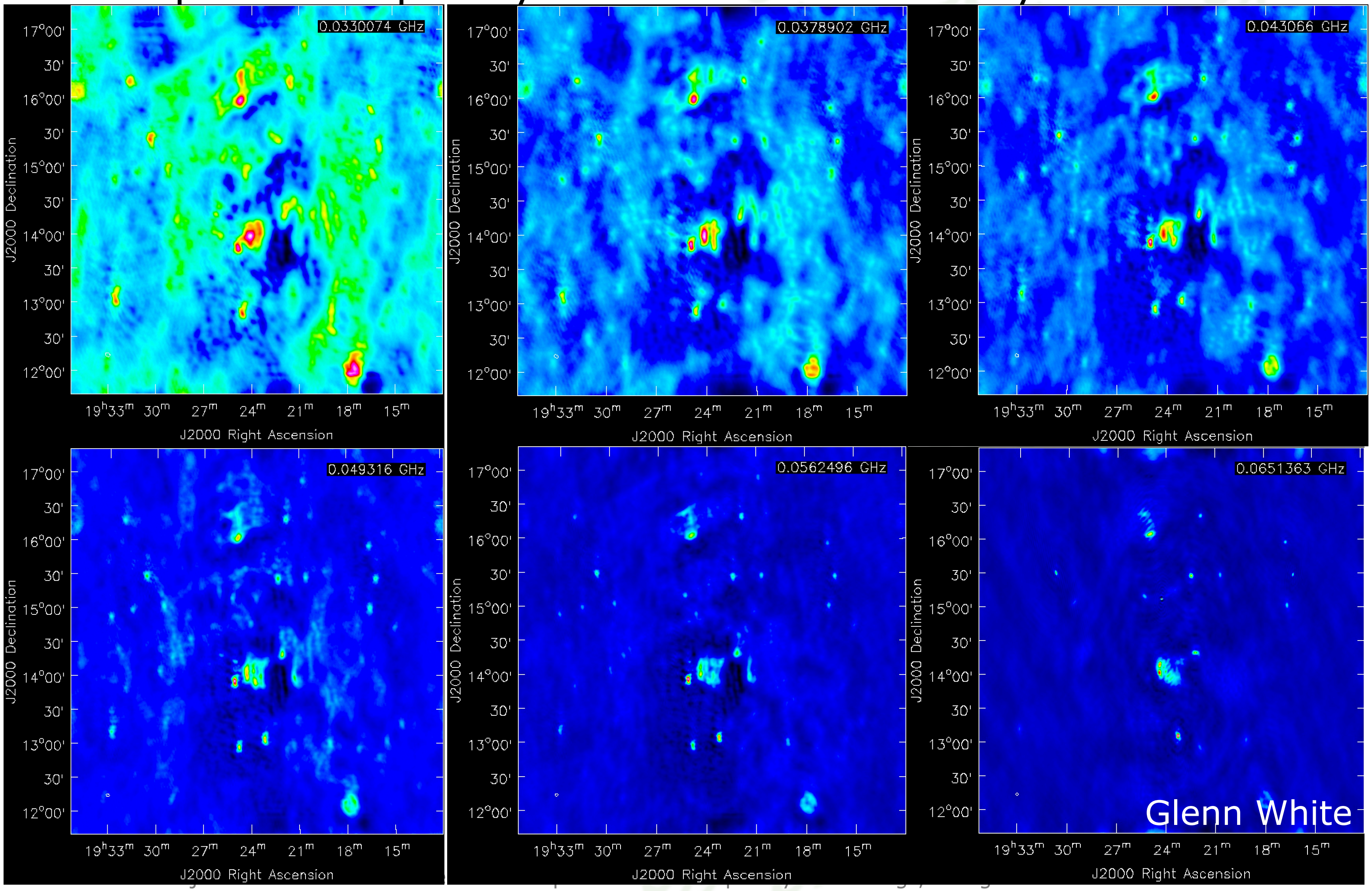
Bfield-2) Small-scale magnetized structure (diffuse polarimetry)

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

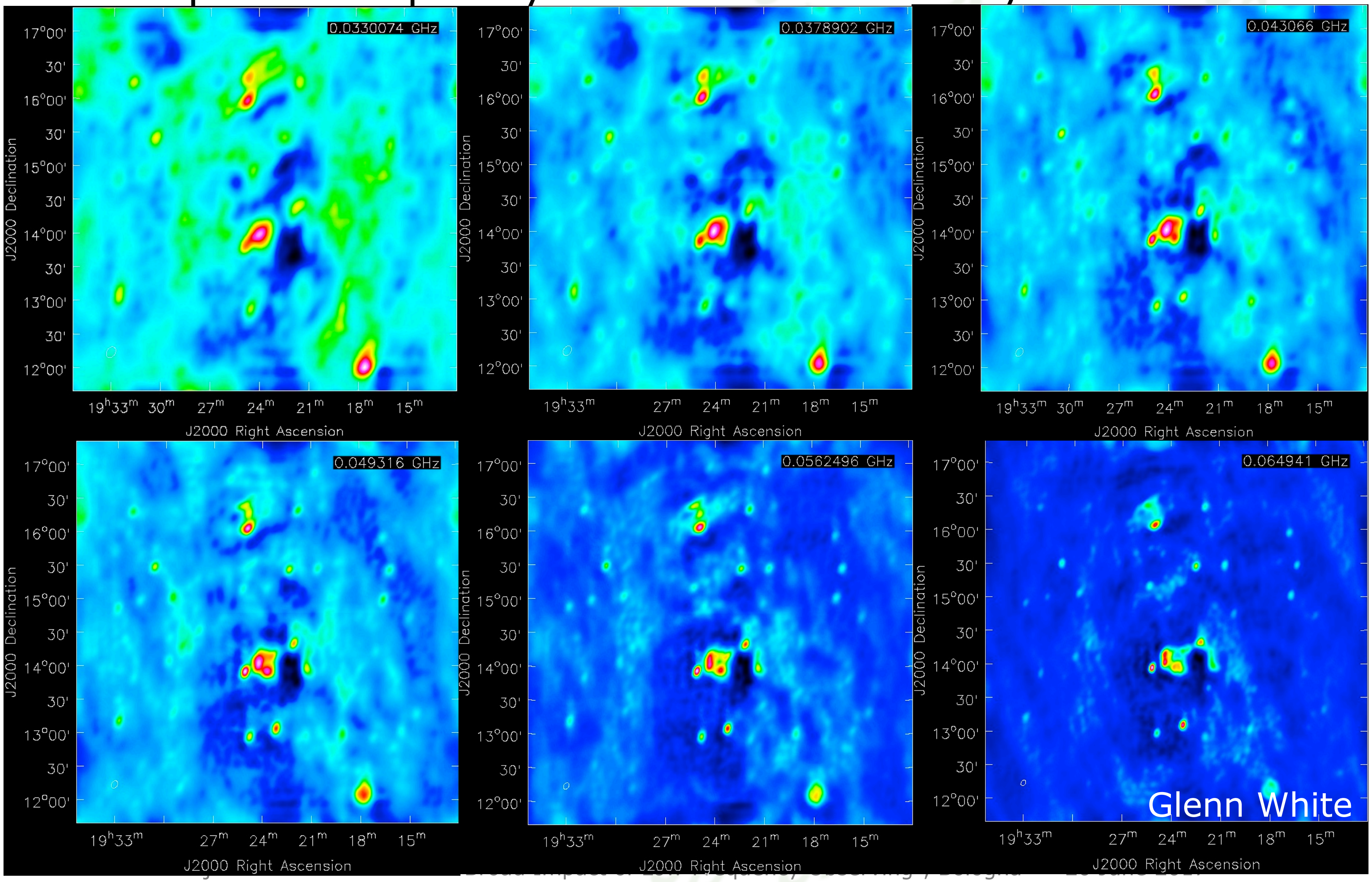
Imaging the Galactic plane:
bright and extended emission throughout the field

Example of complexity: W51 LBA – selfcal skymodel



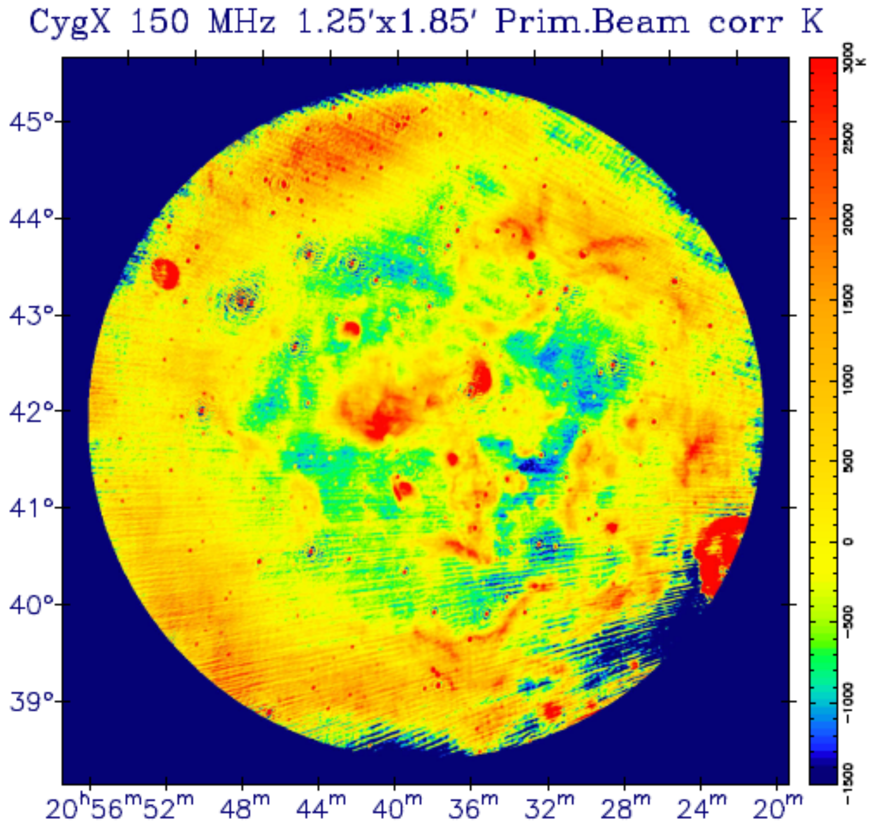
Imaging the Galactic plane: bright and extended emission throughout the field

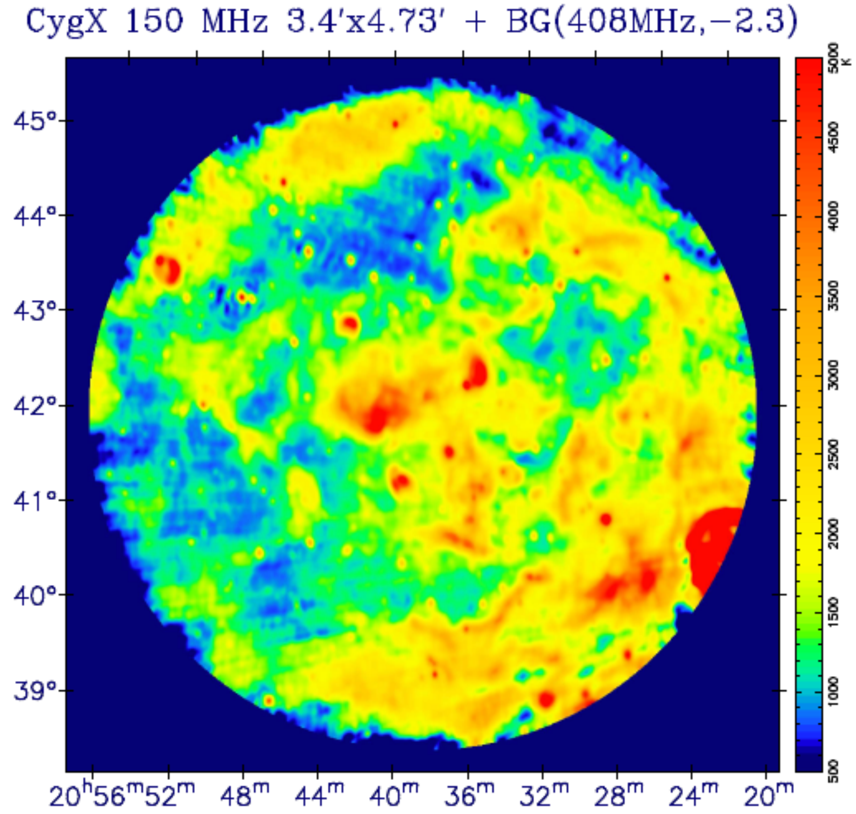
Example of complexity: W51 LBA – blank skymodel



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

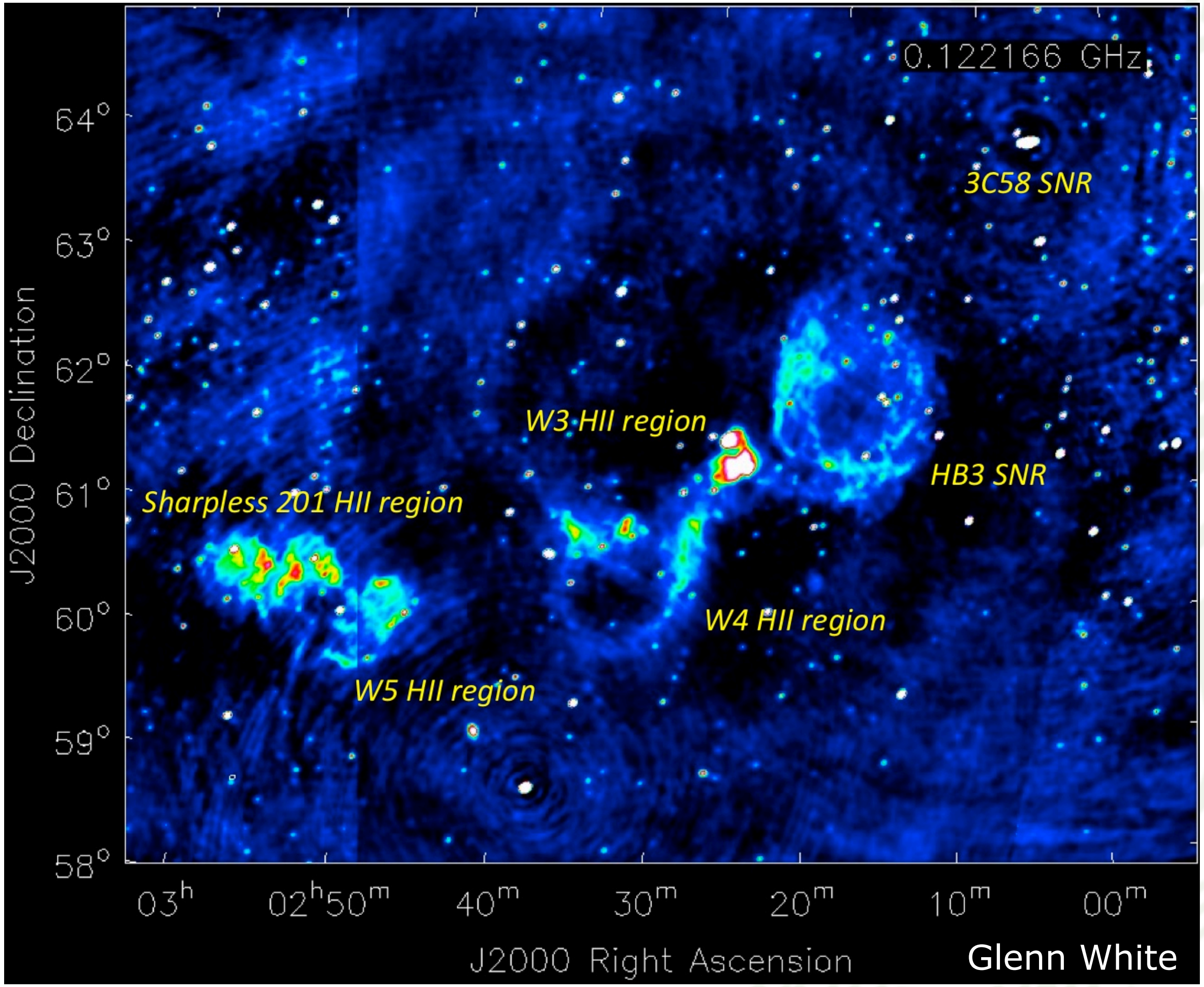
Cygnus X: filling in missing short spacings





Wolfgang Reich

ISM-1) HII regions



LOTSS survey HBA

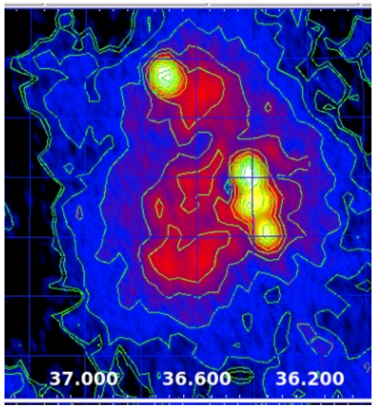
122 MHz, 20 subbands

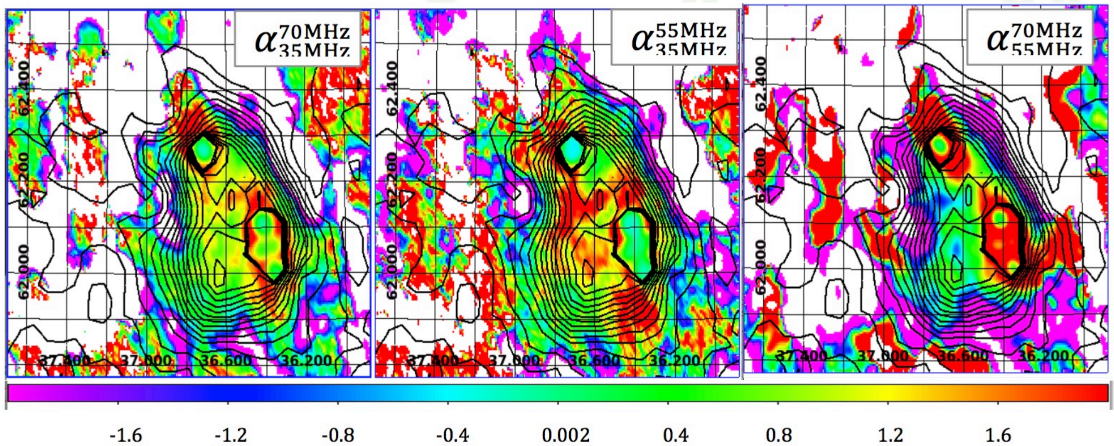
2 pointings

preliminary

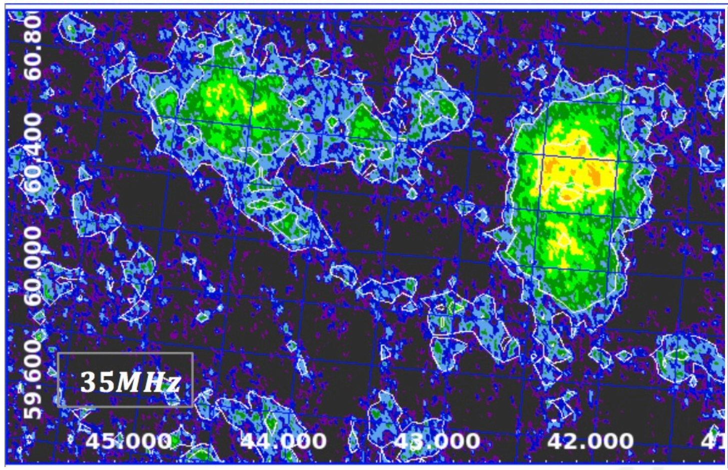
ISM-1) HII regions

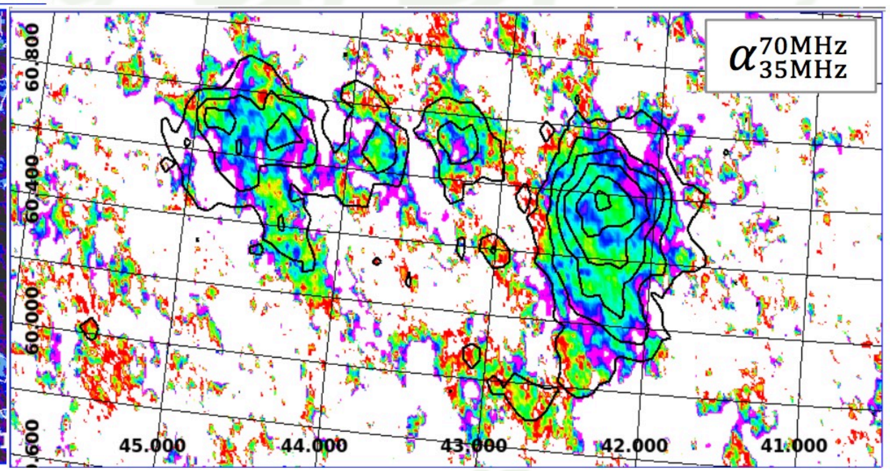
W3





W5

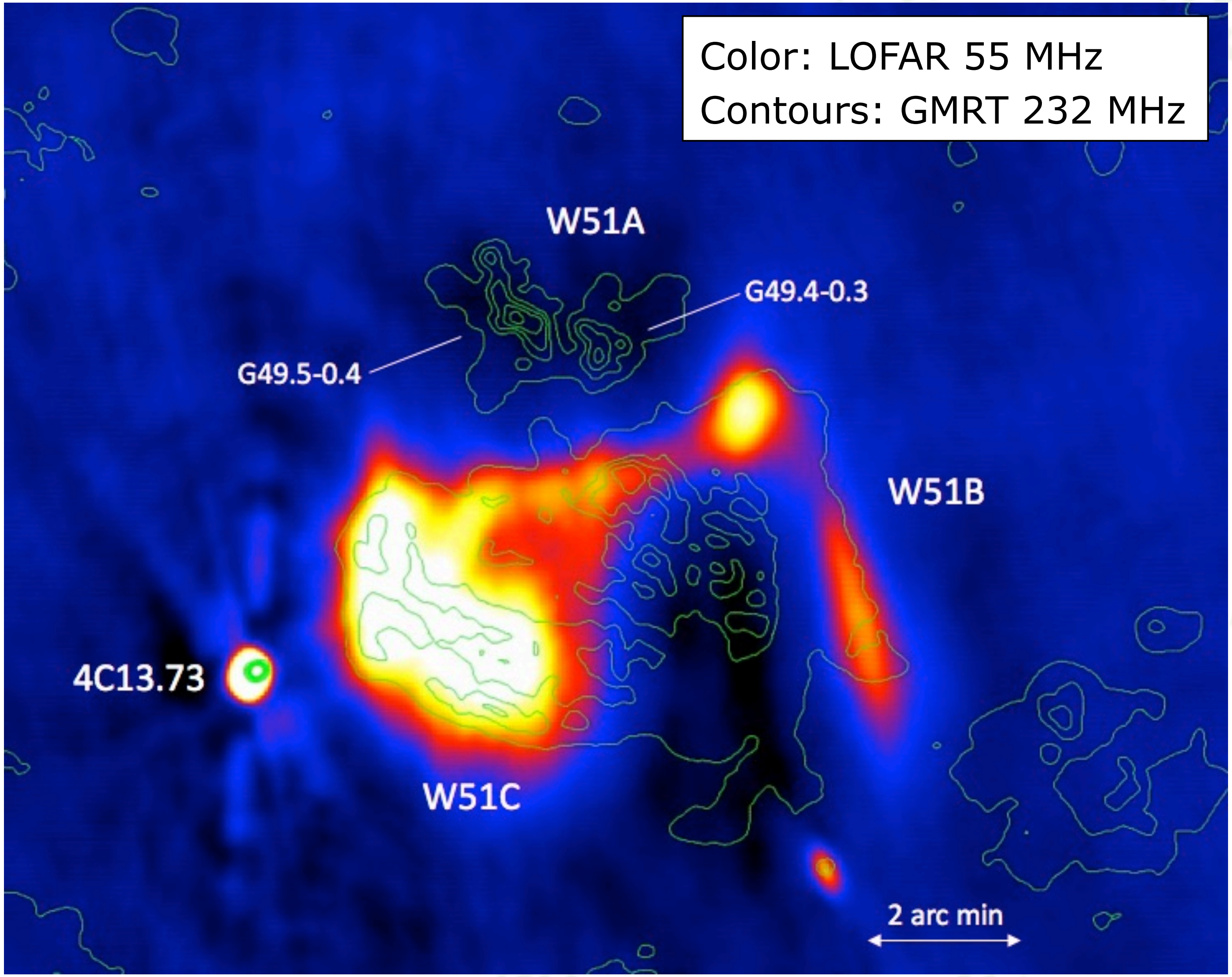




PhD thesis Kiz Natt

ISM-1) HII regions

W51

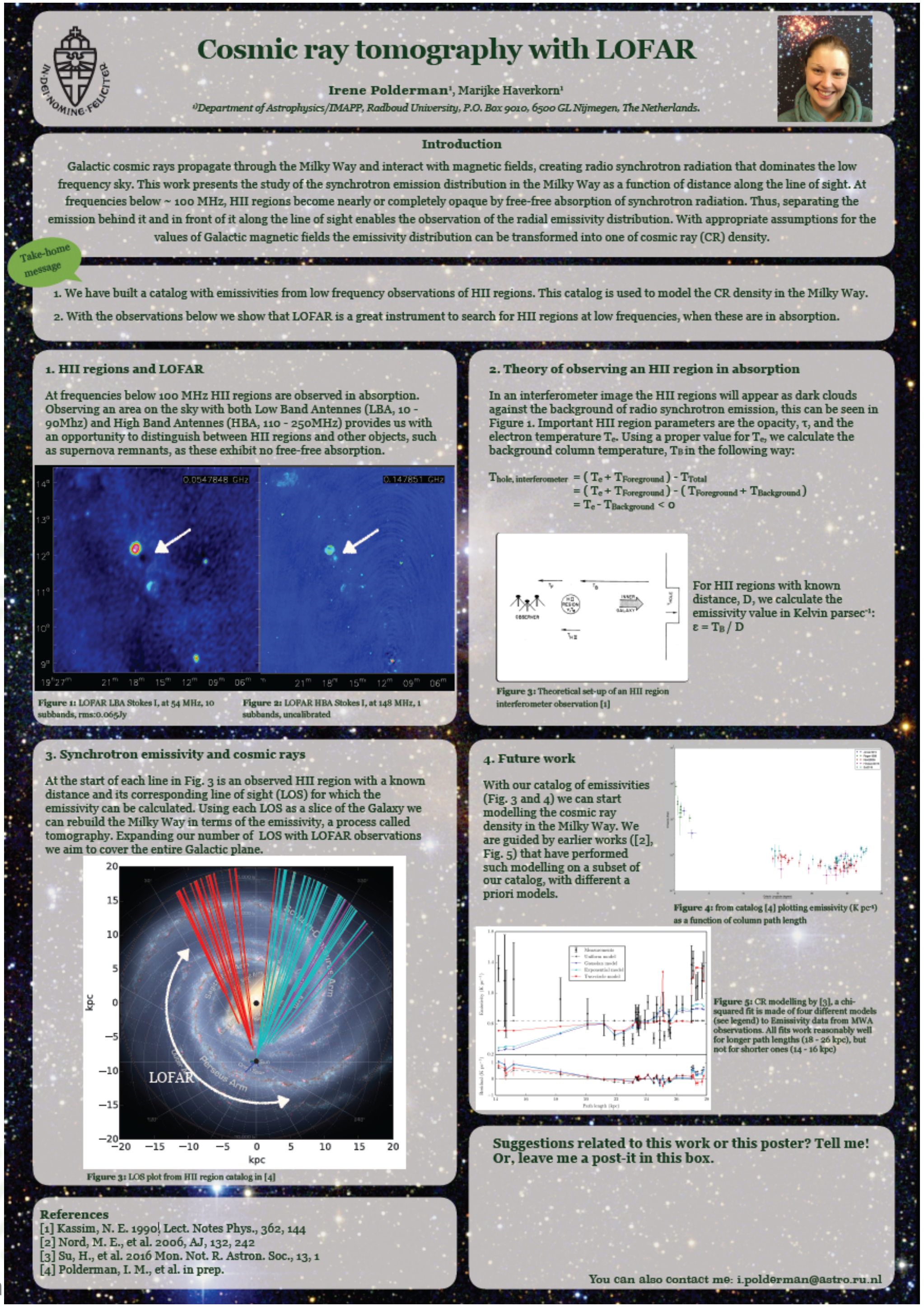


White et al, in prep

ISM-1) HII regions

LBA measurements show free-free absorption of HII regions.

→ imply Galactic cosmic ray distribution from many absorbed HII regions



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

Maria Arias[1], Jacco Vink[1] & Francesco de Gasperin[2]

[1]University of Amsterdam, [2] Leiden University

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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.

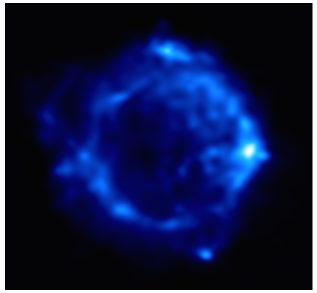


Figure 1: Cassiopeia A in the *LOFAR* LBA. Central frequency is 54 MHz, beam size is 10 arcsec, noise is 0.01 Jy/bm, and dynamic range is of 13,000.

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 $S_\nu = S_{1\mathrm{GHz}} \left(\frac{\nu}{1\mathrm{GHz}}\right)^{-\alpha}$, with $S_{1\mathrm{GHz}} = 2720$ Jy and $\alpha = 0.77$.

Fitting

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

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

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

We fitted for the equation:

$$S_\nu = \left(S_{\nu,front} + S_{\nu,back}\, e^{-\tau_{\nu,int}}\right) e^{-\tau_{\nu,ISM}} \qquad (2)$$

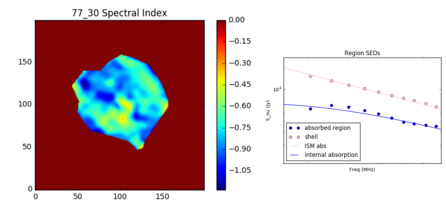


Figure 2: **Left.** Spectral index map made from 30 MHz and 77 MHz images. The images were made with a common $u - v$ range of 500 to 12,000 λs (scales of 7 arcmin to 17 arcsec, for a source of size ~ 5 arcmin). **Right.** Spectra for the shell (pink) and the absorbed region in the SE of the SNR (blue) 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: $Z_{ISM} = 1$, $T_{ISM} = 20$K, $Z_{int} = 3$, $T_{int} = 300$K, and $S_{\nu,front} = S_{\nu,back}$. The best-fit emission measures are EM$_{ISM} = 0.0085$ pc cm^{-6} and EM$_{int} = 1.44$ 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 EM $= n_e^2 l$, where l is a thickness element. In this case, the mass in the unshocked ejecta is:

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

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 $\sim 2\, M_\odot$.

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. Oonk, R. J. van Weeren, P. Salas, F. Salgado, L. K. Morabito, M. C. Toribio, A. G. G. M. Tielens, and H. J. A. Röttgering. Carbon and hydrogen radio recombination lines from the cold clouds towards Cassiopeia A. , 465:1066–1088, February 2017.

[3] Thomas L. Wilson, Kristen. Rohlfs, and Susanne. Httemeister. *Tools of Radio Astronomy*. Berlin, Heidelberg, 2009.

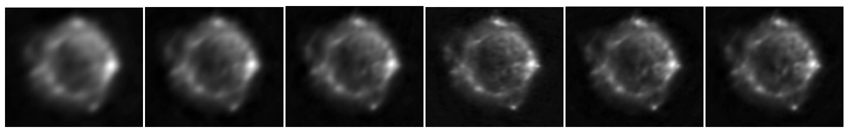
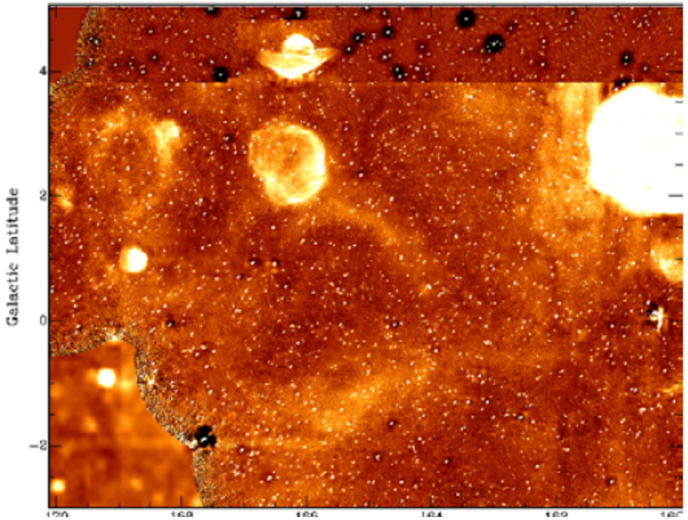
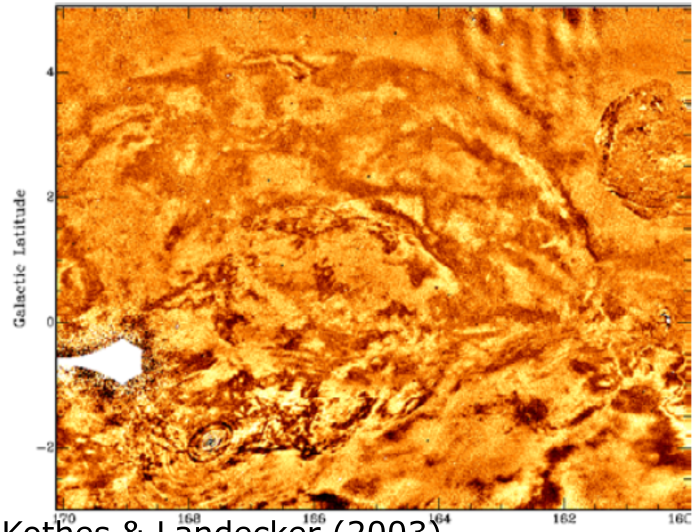


Figure 3: 1 MHz images of Cassiopeia A in the *LOFAR* LBA. From left to right, 30, 40, 50, 60, 70, and 77 MHz

ISM-2) Supernova remnants: VRO 42.05.01

María Arias, Jacco Vink,
Marco Iacobelli





Kothes & Landecker (2003)

UNPUBLISHED DATA

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

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

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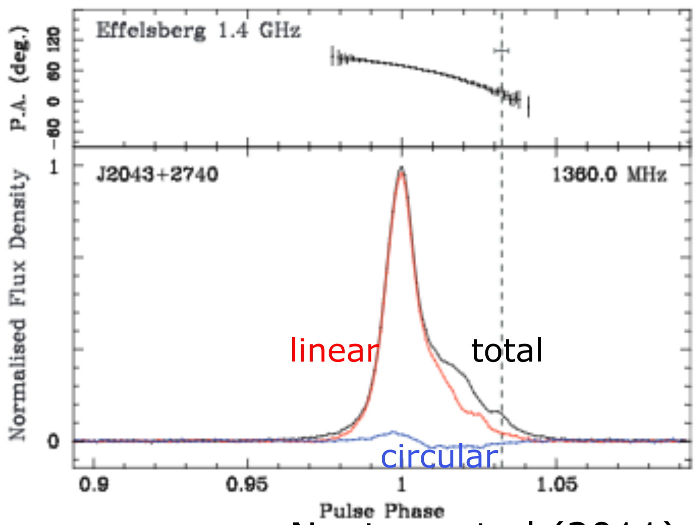
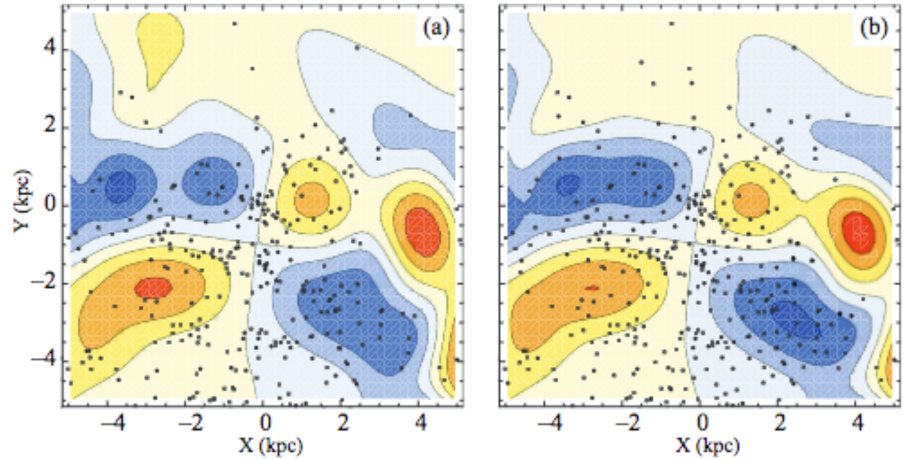
Bfield-1) Large-scale field (pulsar rotation measures)

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

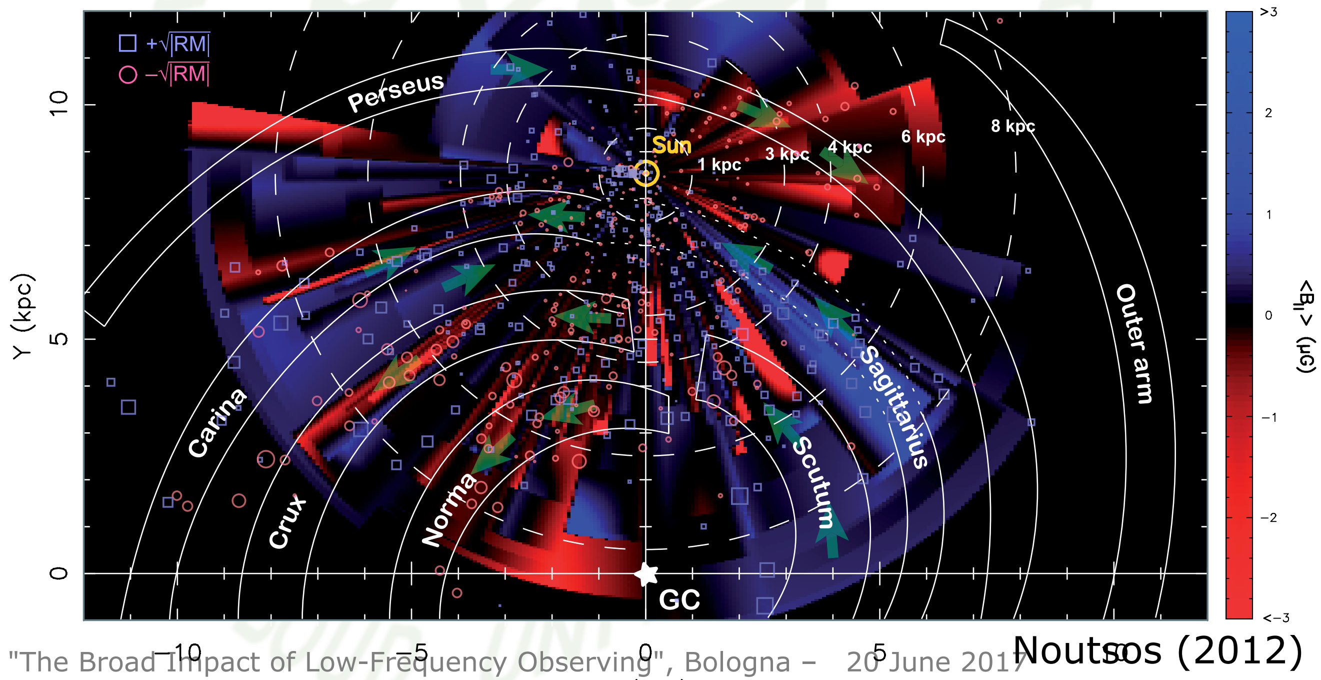
Large-scale magnetic field through pulsars



Noutsos et al (2011)



Sobey et al (2010)



Noutsos (2012)

Large-scale magnetic field through pulsars

Charlotte Sobey, Aris Noutsos + TKP Pulsar working group

UNPUBLISHED DATA

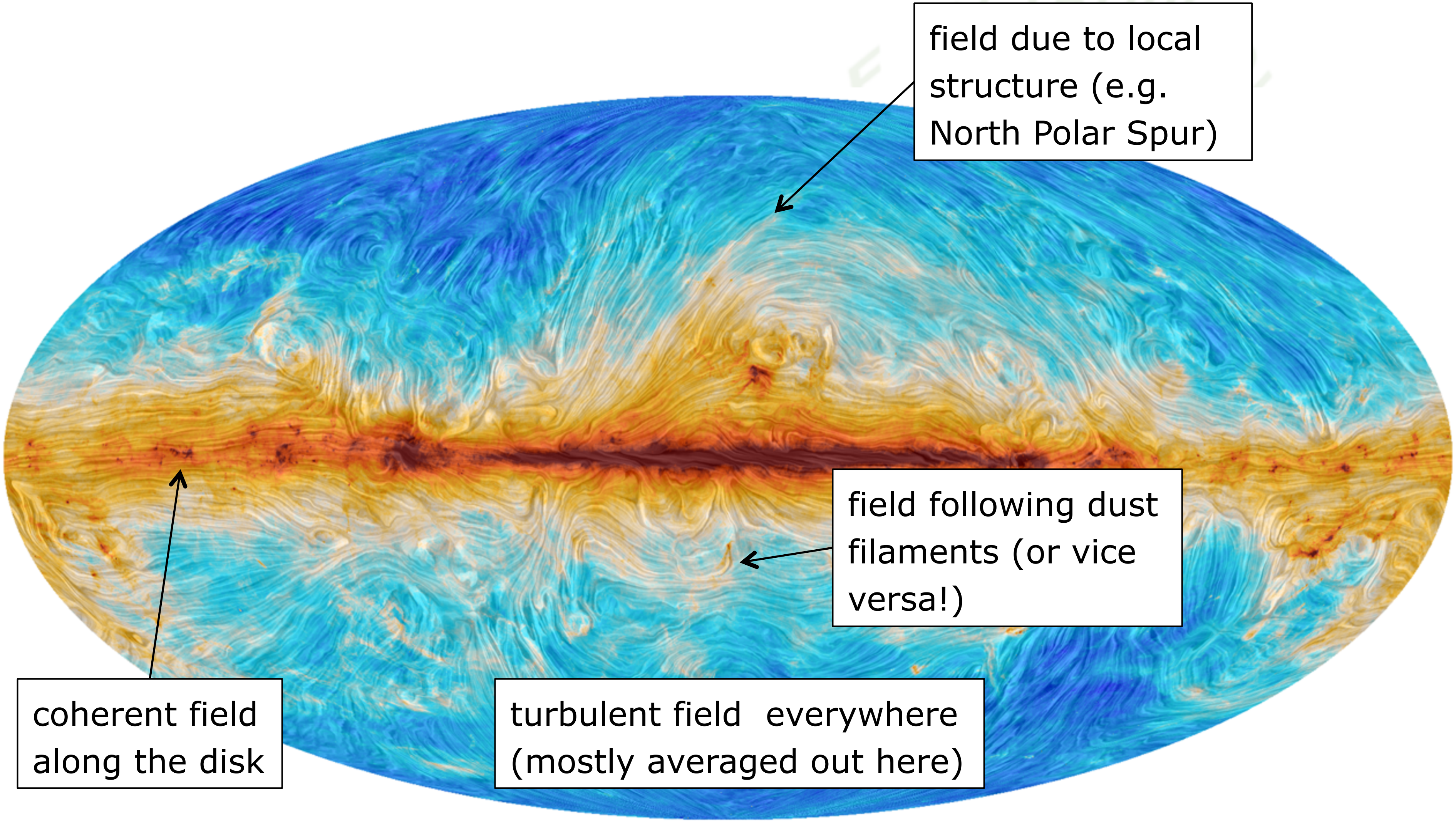
- existing pulsar catalog
- ■ LOFAR pulsar catalog (Sobey+, in prep)

Large-scale magnetic field through pulsars

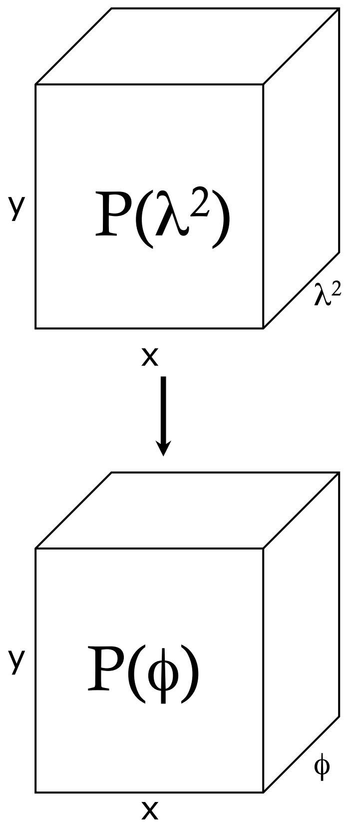
Charlotte Sobey, Aris Noutsos + TKP Pulsar working group

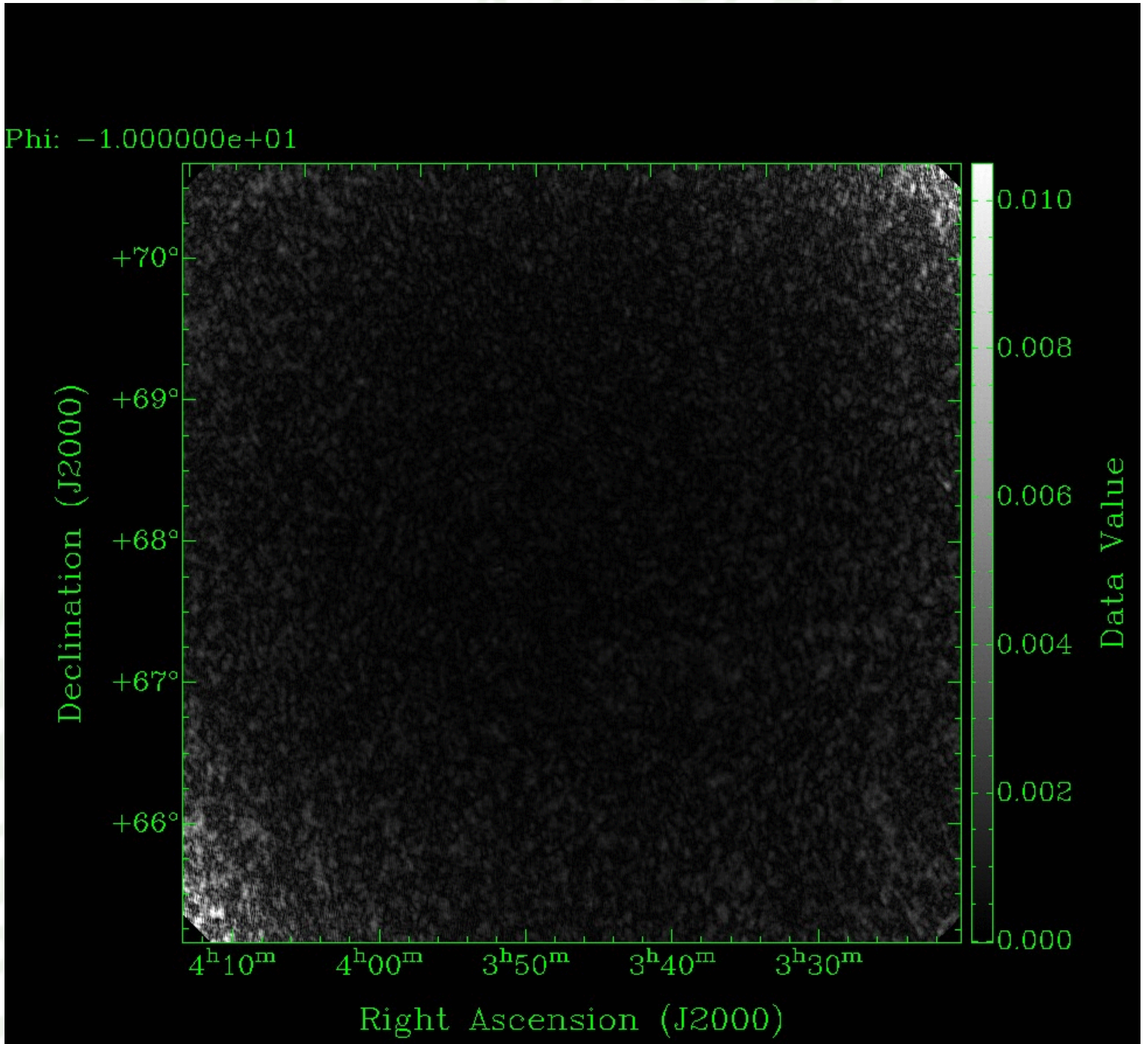
UNPUBLISHED DATA

Milky Way magnetic field



Use Rotation Measure synthesis:

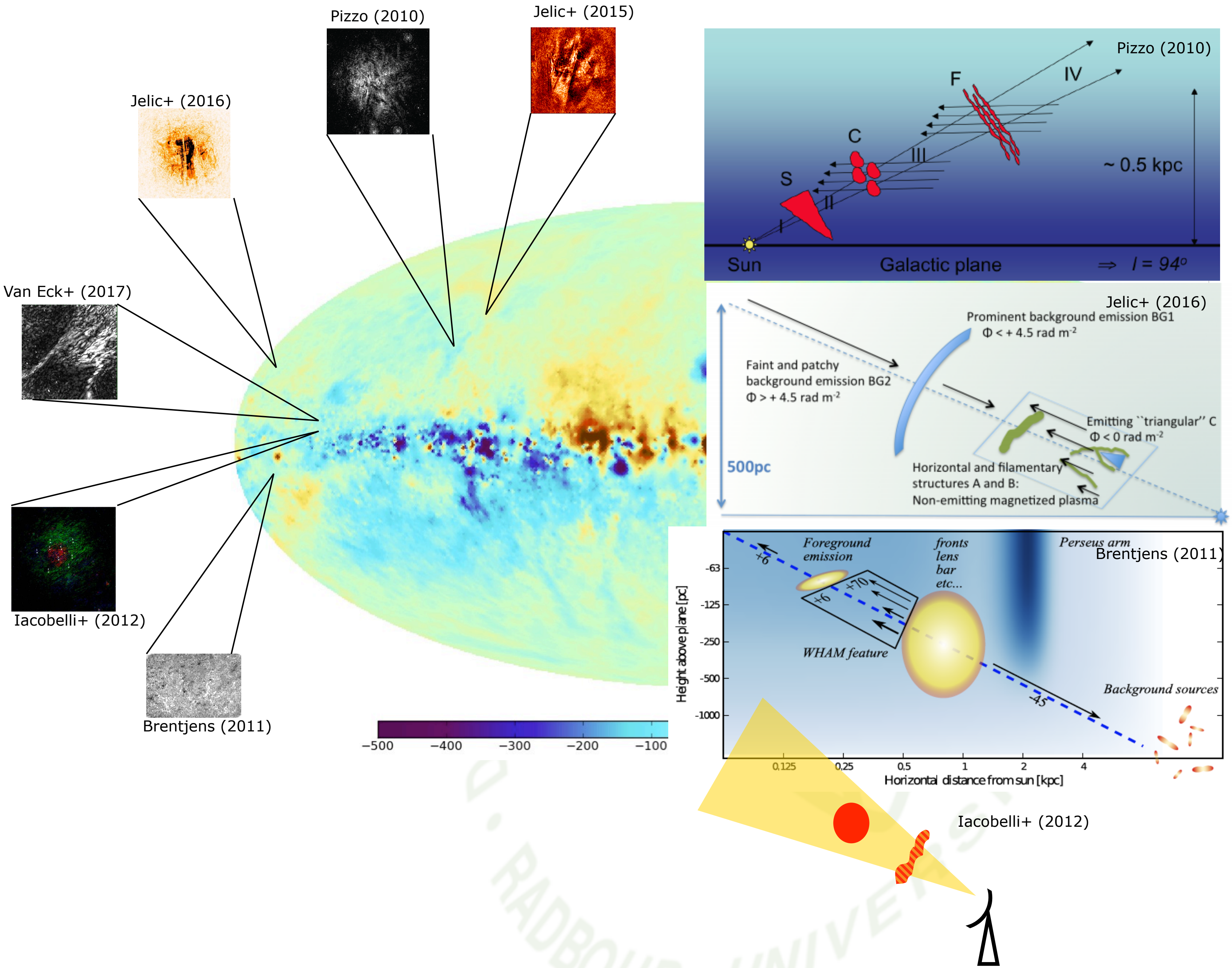




Van Eck et al (2017)

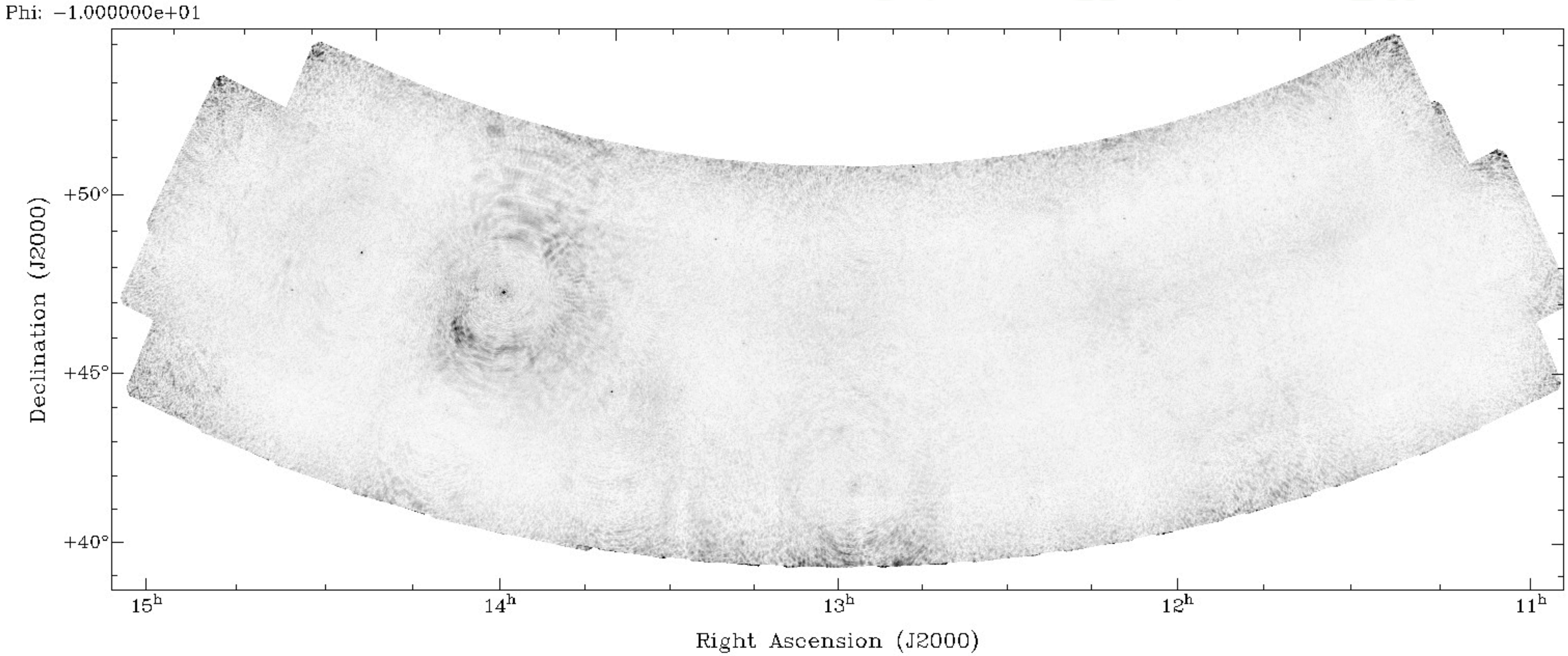
Faraday depth

$\phi = 0.81 \int n_e \, \mathbf{B \cdot dl}$



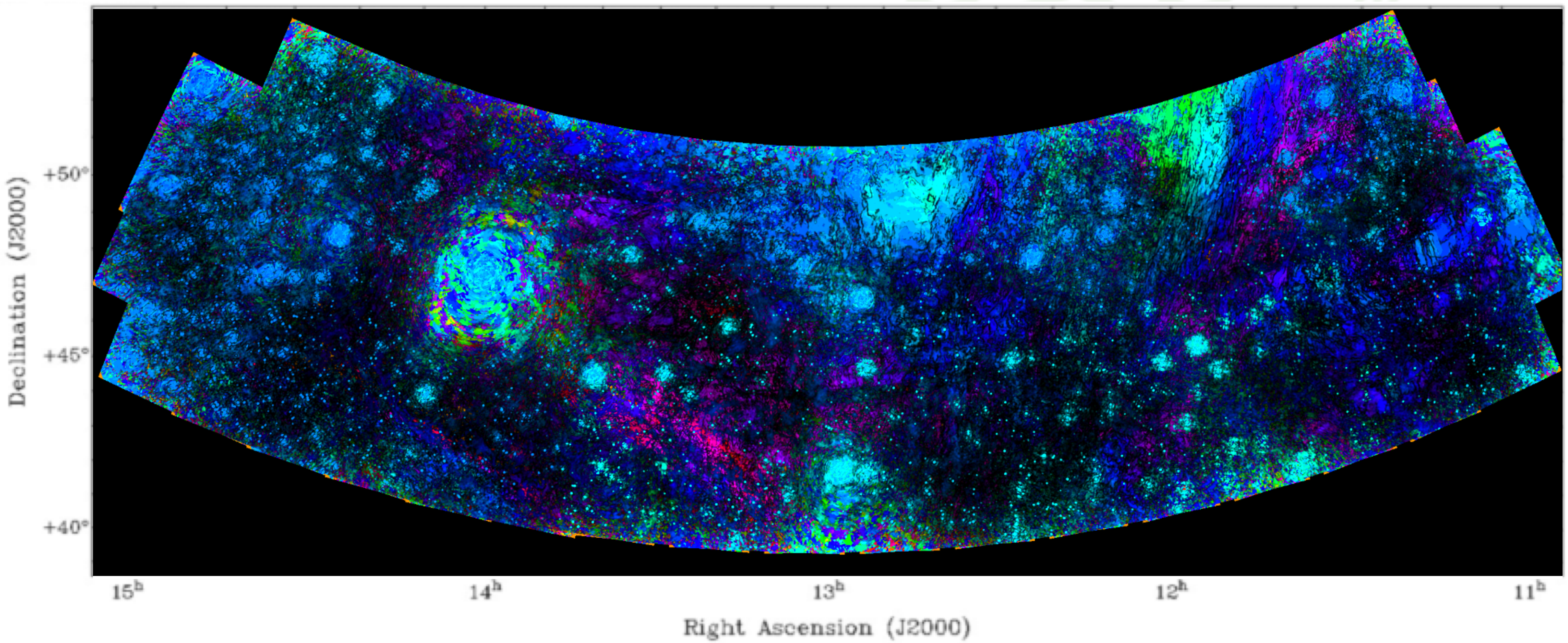
Pizzo (2010)
Jelic+ (2015)
Jelic+ (2016)
Van Eck+ (2017)
Iacobelli+ (2012)
Brentjens (2011)
−500
−400
−300
−200
−100
Pizzo (2010)
F
IV
C
III
S
II
I
~ 0.5 kpc
Sun
Galactic plane
l = 94°
Jelic+ (2016)
Prominent background emission BG1
Φ < + 4.5 rad m-2
Faint and patchy
background emission BG2
Φ > + 4.5 rad m-2
Emitting ``triangular'' C
Φ < 0 rad m-2
500pc
Horizontal and filamentary
structures A and B:
Non-emitting magnetized plasma
Foreground
emission
fronts
lens
bar
etc...
Perseus arm
Brentjens (2011)
WHAM feature
Background sources
Height above plane [pc]
Horizontal distance from sun [kpc]
Iacobelli+ (2012)

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



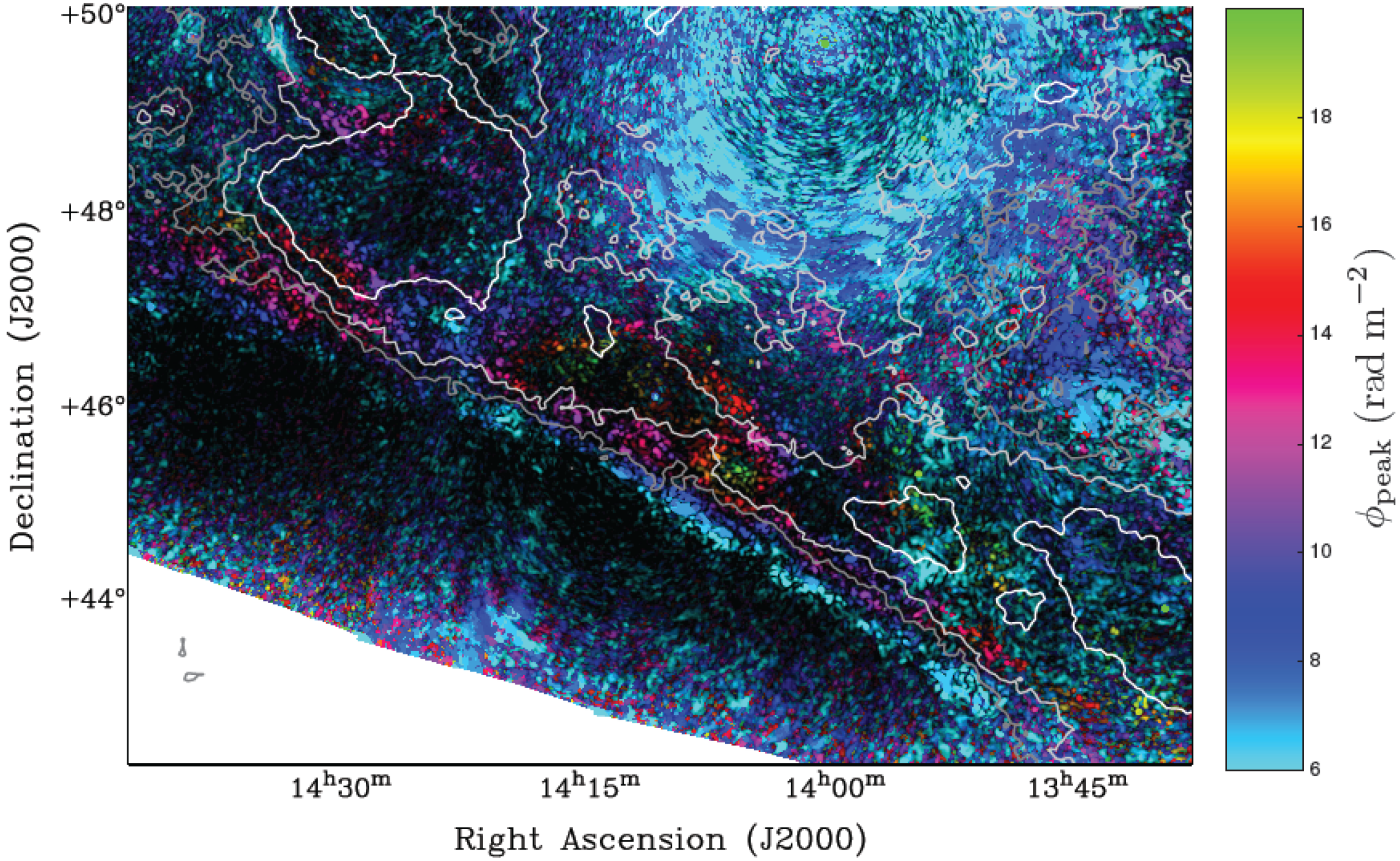
Van Eck et al (2017b,c)

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



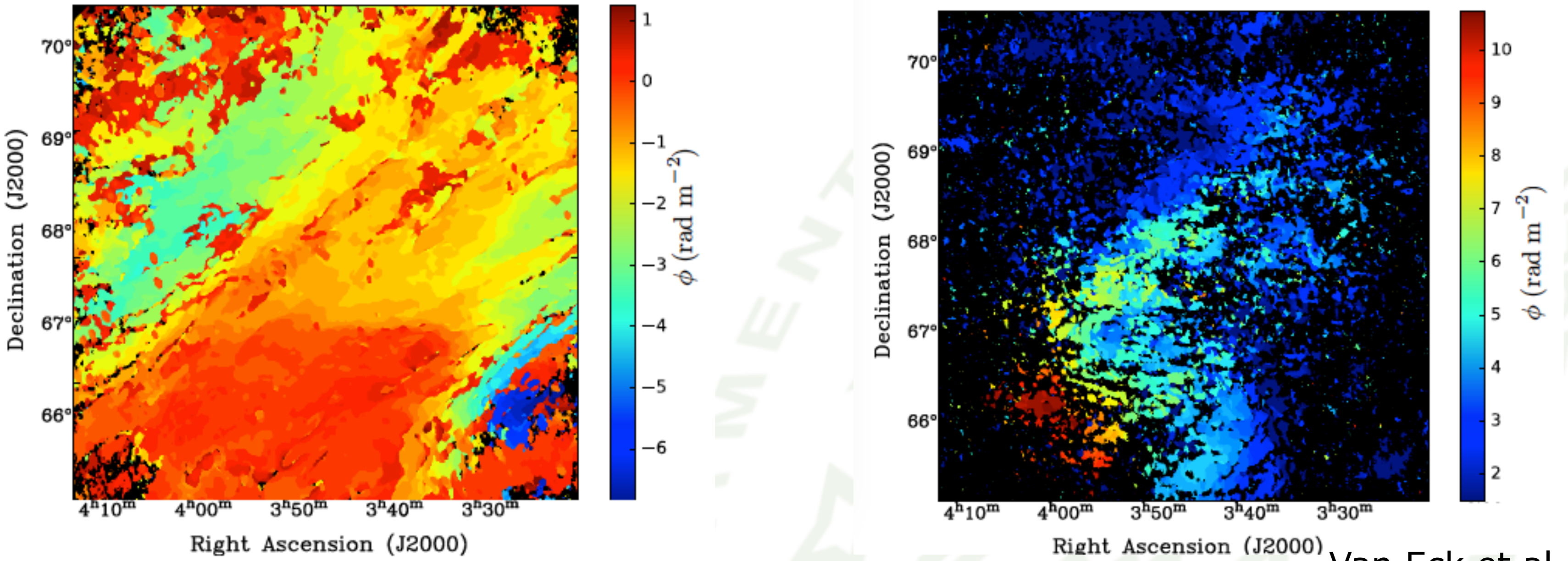
Van Eck et al (2017c)

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)

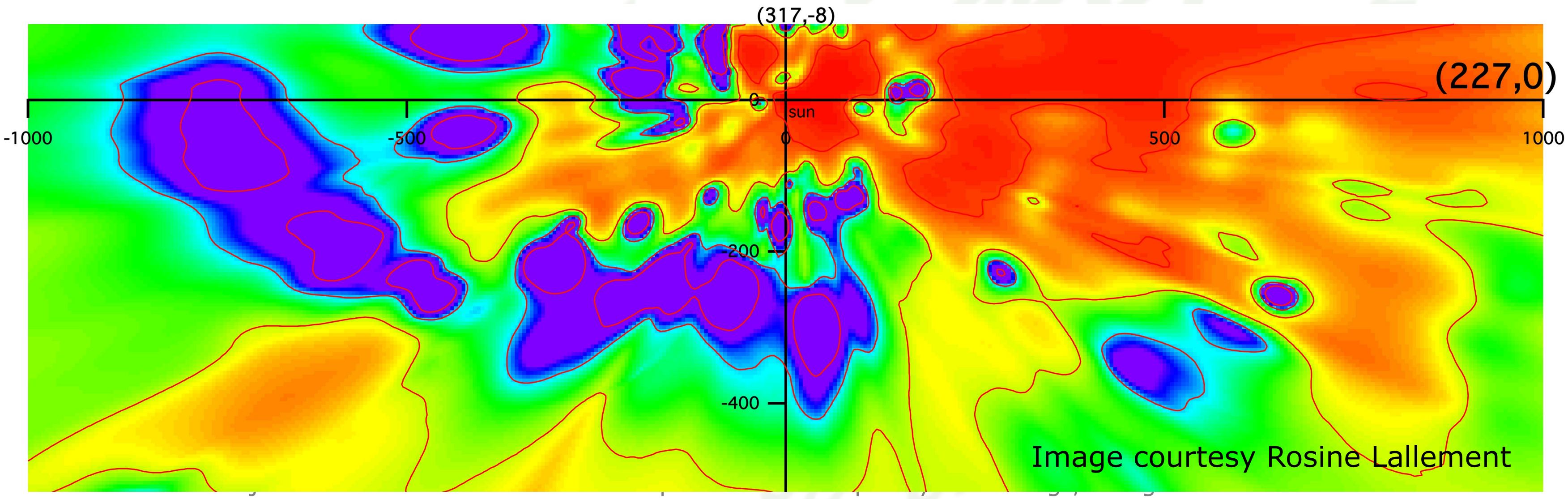
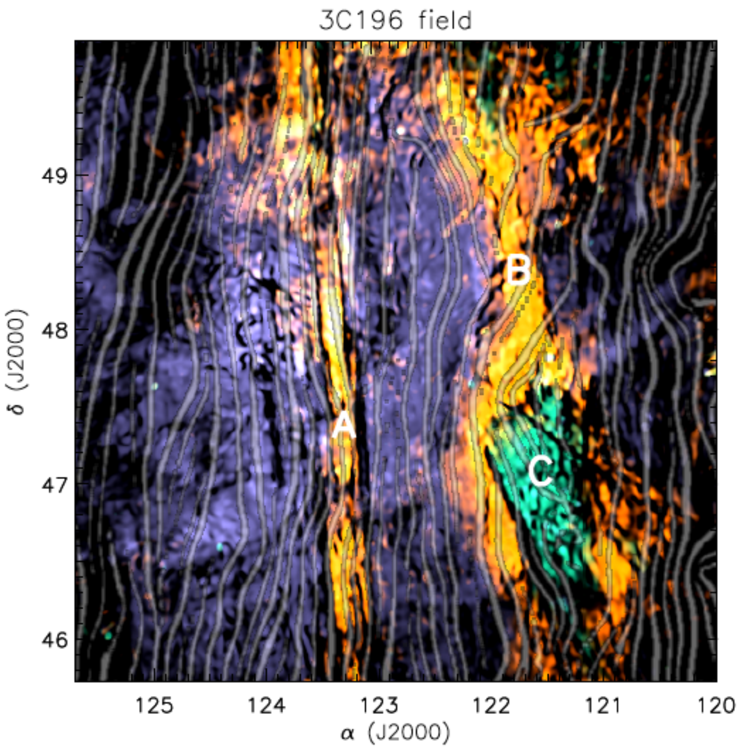
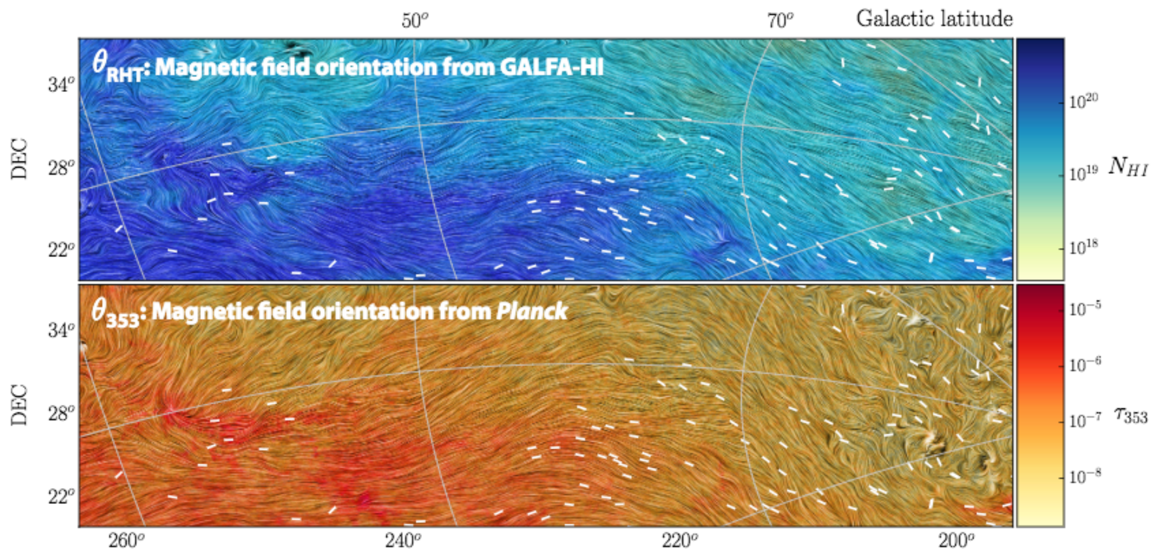


Image courtesy Rosine Lallement

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