Pulsar polarimetry

with

LOFAR

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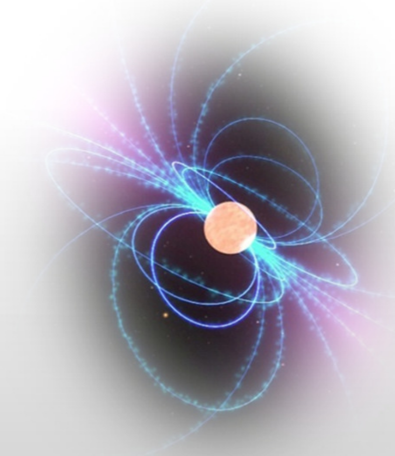
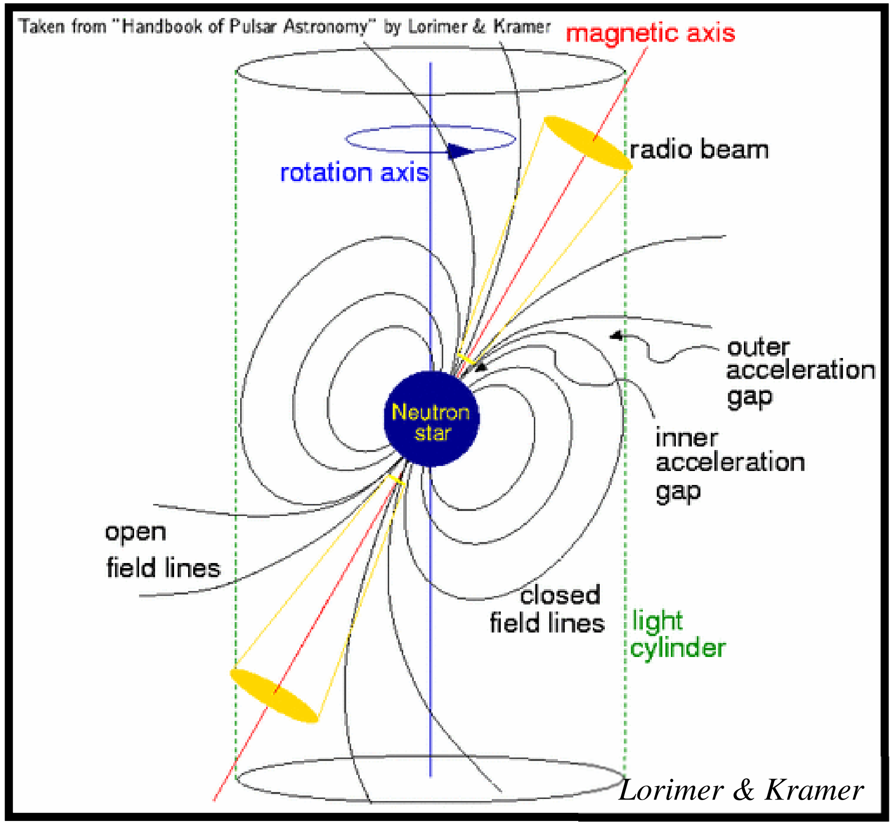
Outline

- Pulsars – as objects
- Pulsars – as probes of the ISM
- Faraday rotation using RM synthesis
- LOFAR observations
- Correcting for the ionosphere
- Measuring the structure of the GMF
- Summary



Pulsars I

- Rapidly rotating, highly magnetised neutron stars



- Diameter ~ 12 km
- Mass ~ 1.4 $M_{\odot}$
- Density ~ nuclear
- Magnetic field ~ 10^{10} T

(|B_{Earth}| ~ 5×10^{-5} T, |B_{fridge}|~ 10^{-2} T)

  - Inferred $\propto P\dot{P}$ (dipole)
  - Measured using X-ray obs
  - Created? Sustained?

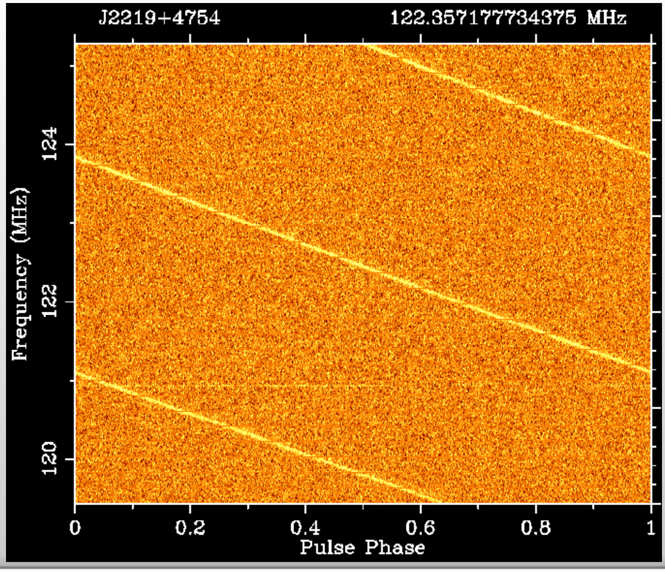
Pulsars II

- Natural accurate clocks emitting highly polarised coherent radiation

- Dispersion measure (DM):

  Observed: $DM \; \alpha \; \Delta t_{DM} \, \nu^2$

  $$DM = \int_0^d n_e \, dl \;\; (pc \; m^{-3})$$

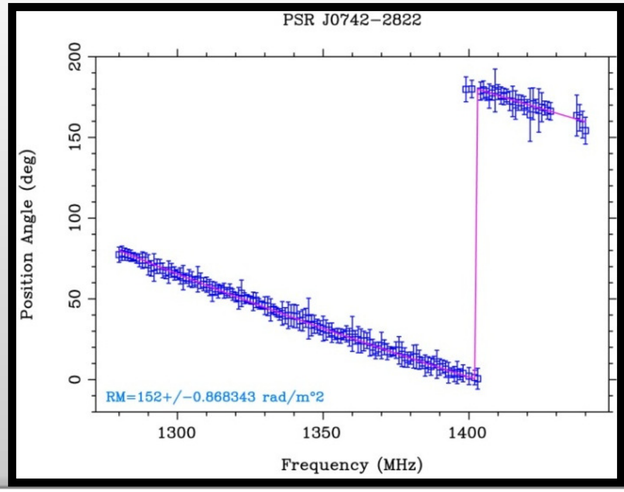


- Rotation measure (RM, ϕ):

  Observed: $\chi(\lambda^2) = \chi_0 + \phi \, \lambda^2$

  Where $\chi = {}^{1}/_{2} \tan^{-1} {}^{U}/_{Q}$

  $$\phi = 0.812 \int_{source}^{observer} n_e \, \boldsymbol{B} \cdot d\boldsymbol{l} \;\; (rad \; m^{-2})$$

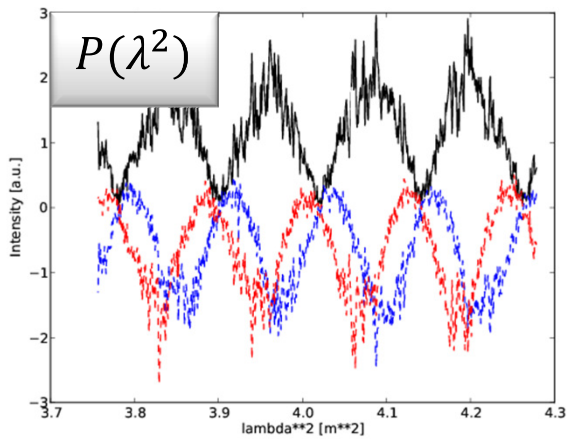


RM synthesis

- Measuring Faraday depth (Burn 1966, Brentjens & de Bruyn 2005)

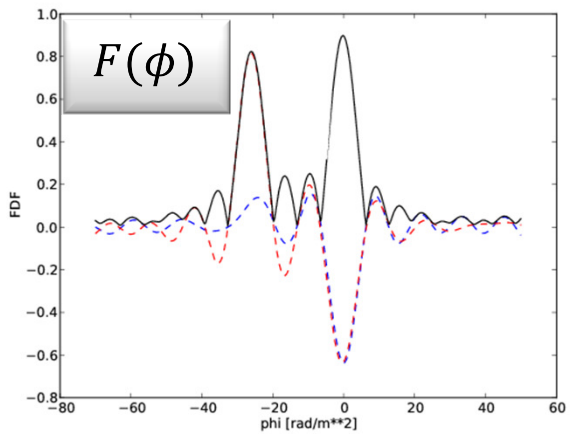
- Fourier transform-like observed complex polarisation vector can be inverted to give the intrinsic polarisation property of source as a function of Faraday depth:

$$F(\phi) = \int_{-\infty}^{\infty} P(\lambda^2)\exp(-2i\phi\lambda^2)\, d\lambda^2$$



$\mathcal{F}$

Finite sampling in λ^2:
$$FWHM = \frac{3.8}{\lambda^2{}_{max} - \lambda^2{}_{min}}$$



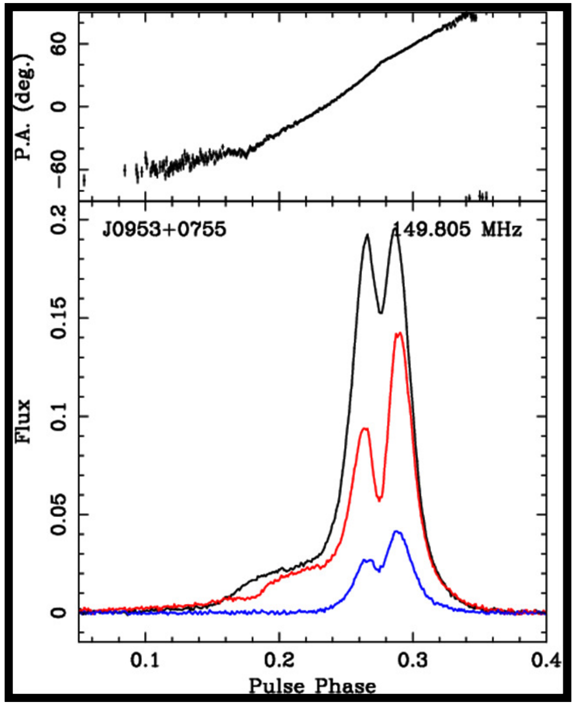
- LOFAR: Long-wavelength & large fractional bandwidth allows more accurate ϕ

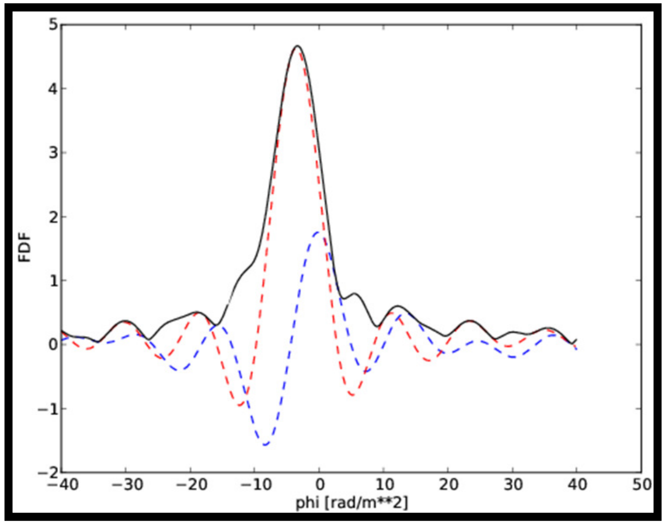
LOFAR HBA Observation

- Six Superterp High-Band-Antenna (HBA) stations coherently added in tied-array mode, Nyquist sampled with 80 us time resolution, coherent dedispersion

PSR B0950+08: t_{obs}=30 mins, ν=150 MHz, $\Delta\nu$=6 MHz, $FWHM_{RMSF}$ = 7 rad m^{-2}

Profile:
Total __
Linear __
Circular __



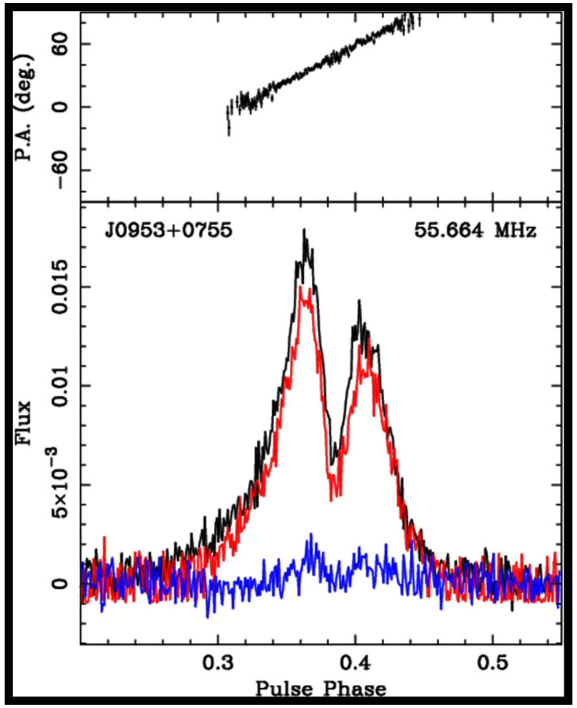


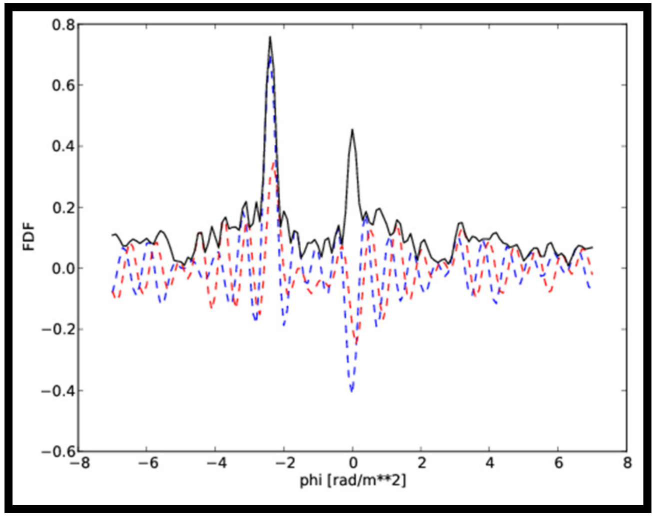
LOFAR LBA Observation

- Six Superterp Low-Band-Antenna (LBA) stations coherently added in tied-array mode, Nyquist sampled with 80 us time resolution, coherent dedispersion

PSR B0950+08: t_{obs}=30 mins, ν =56 MHz, $\Delta\nu$=6 MHz, $FWHM_{RMSF}$ = 0.4 rad m^{-2}

Profile:
Total __
Linear __
Circular __

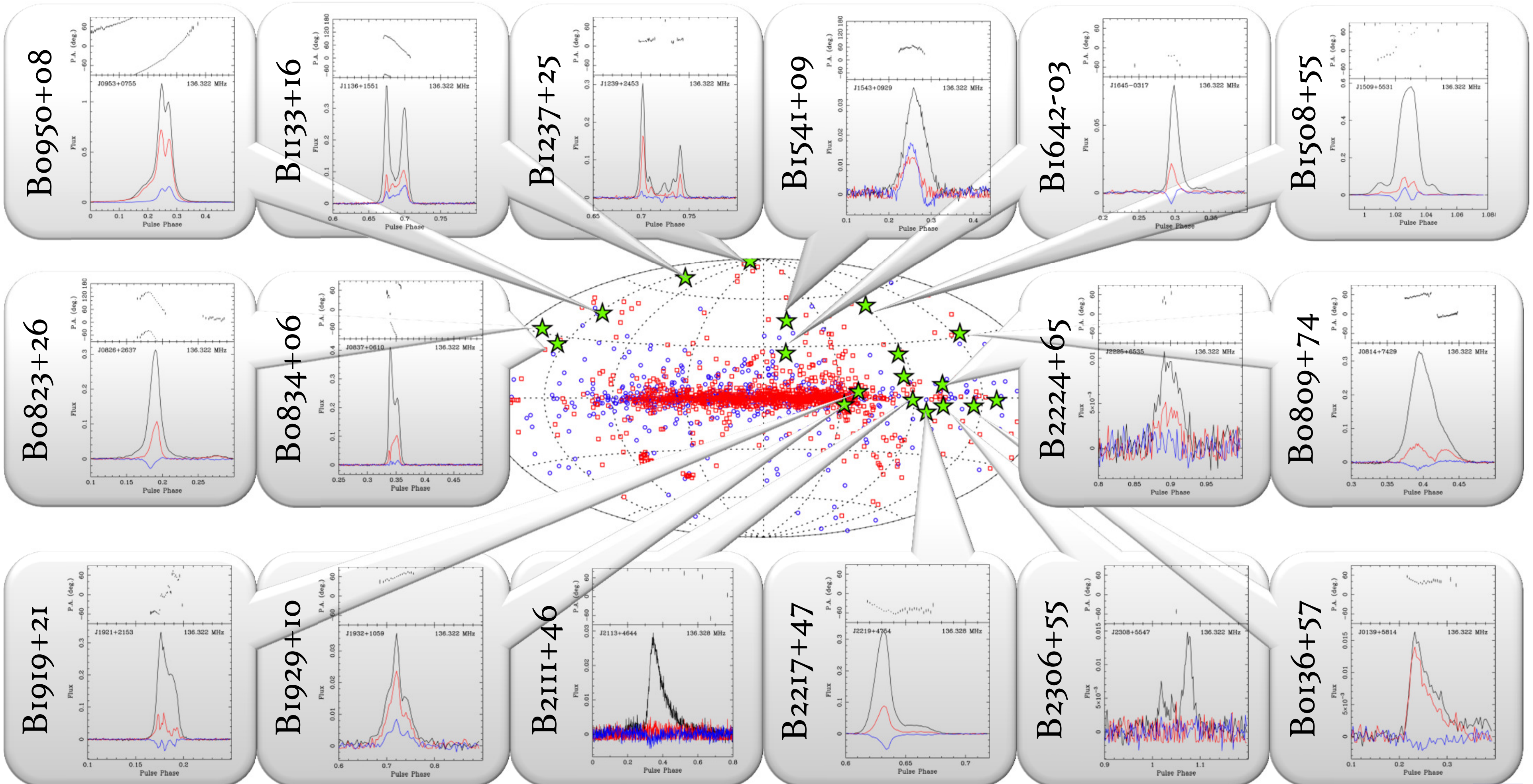




March 2011
20 psrs, 10 mins

More LOFAR HBA

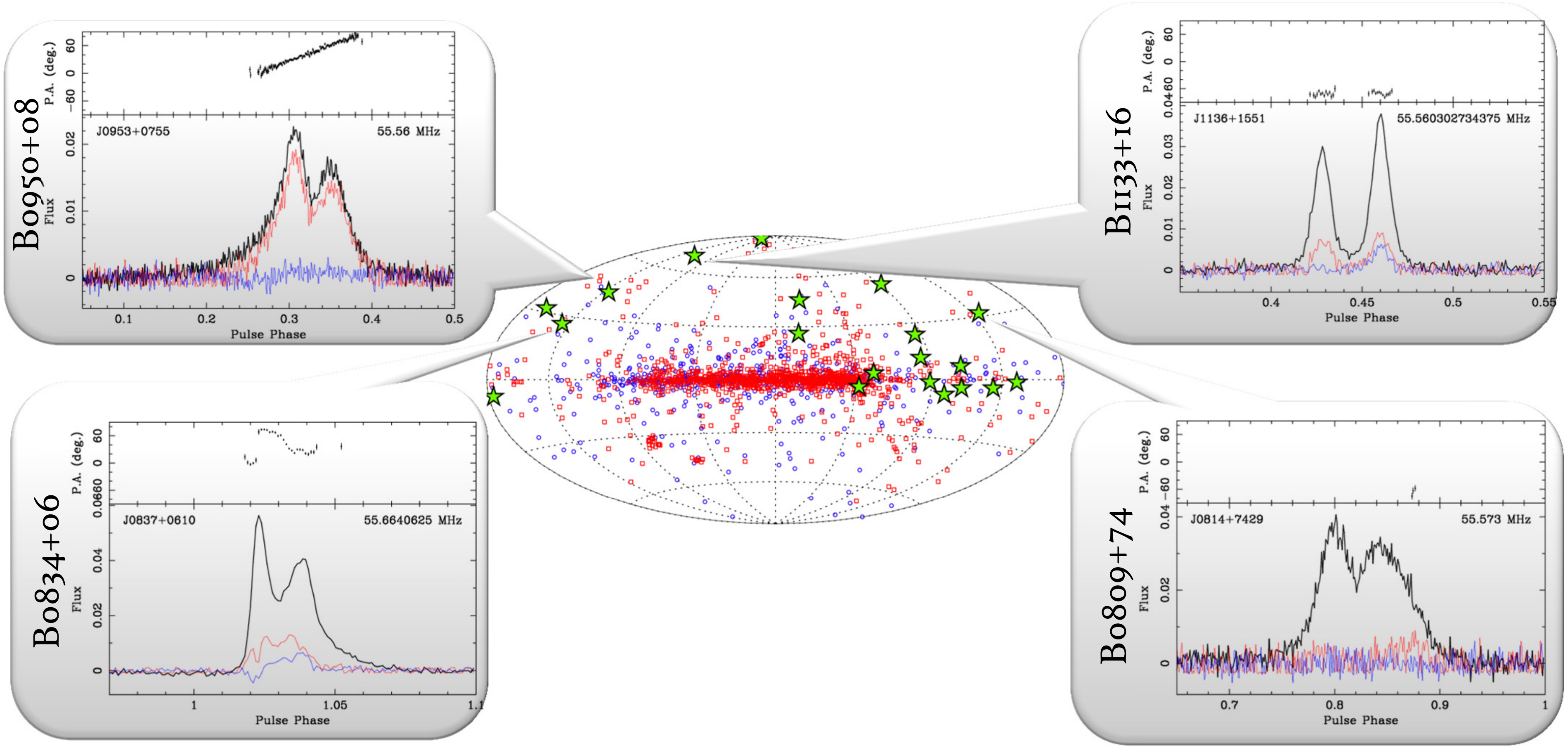
ν =136 MHz
$\Delta\nu$ =6 MHz



Dec 2011
5 psrs, 30 mins

More LOFAR LBA

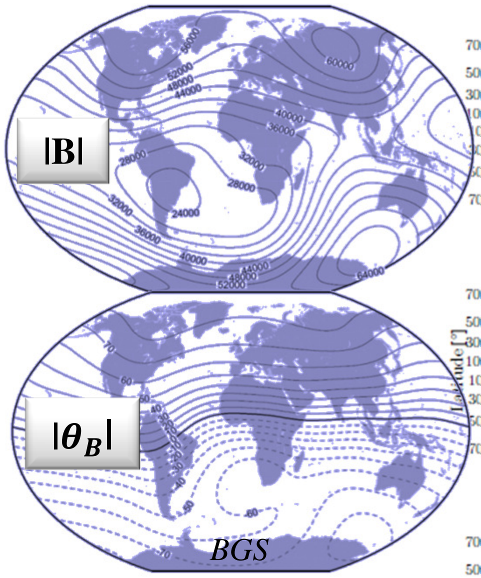
ν =56 MHz
$\Delta\nu$ =9 MHz



Ionosphere

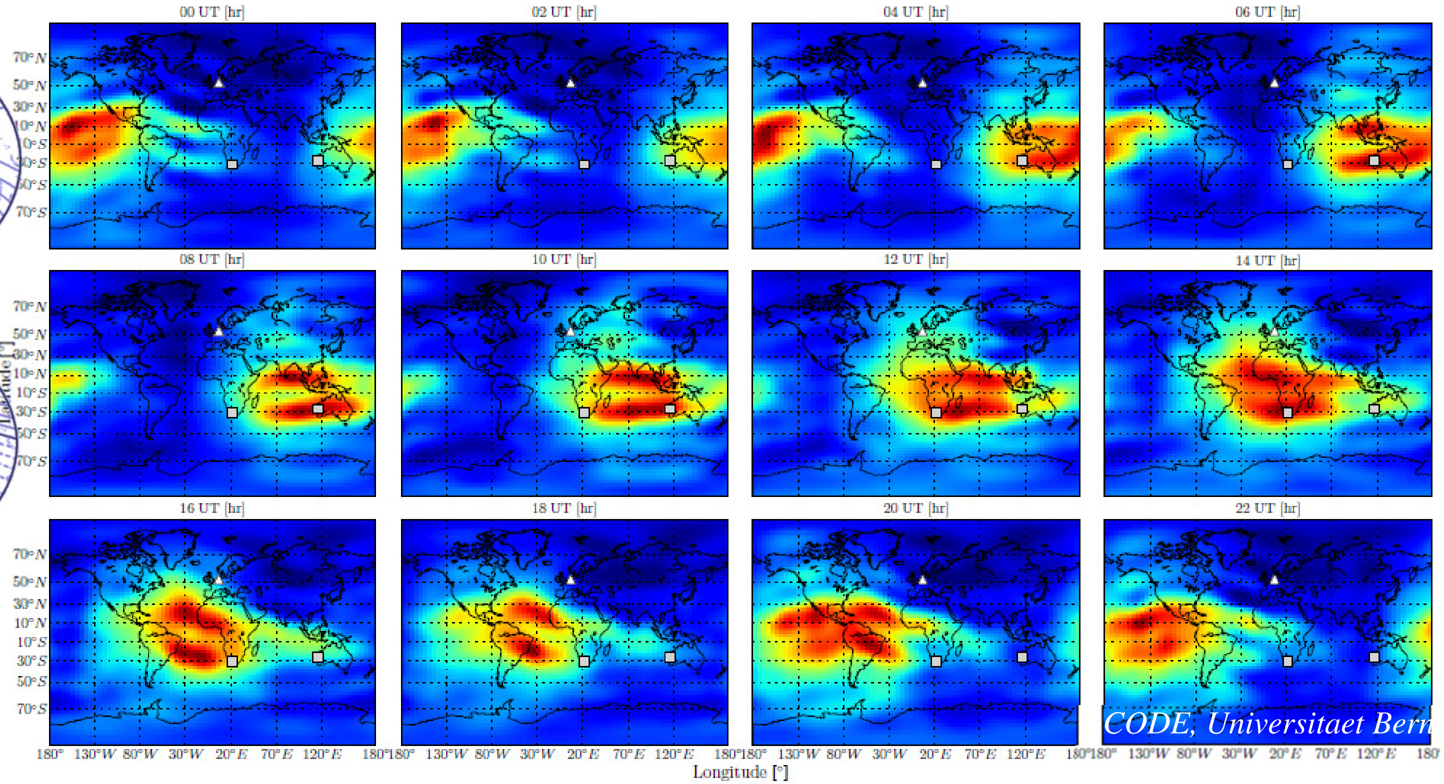
- The ionosphere is also an ionised plasma:

$$\chi(\lambda^2) = \chi_0 + (\phi_{ion} + \phi_{ISM} + [\phi_{IGM} + \phi_{int}])\,\lambda^2$$



$\phi_{ion} \geq 0$ North

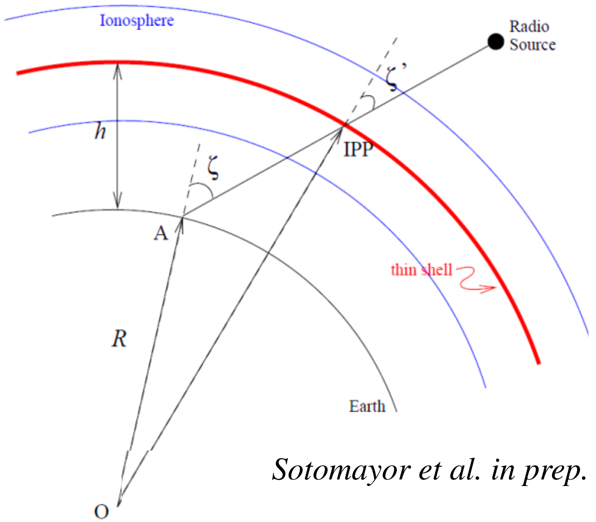
$\phi_{ion} \leq 0$ South



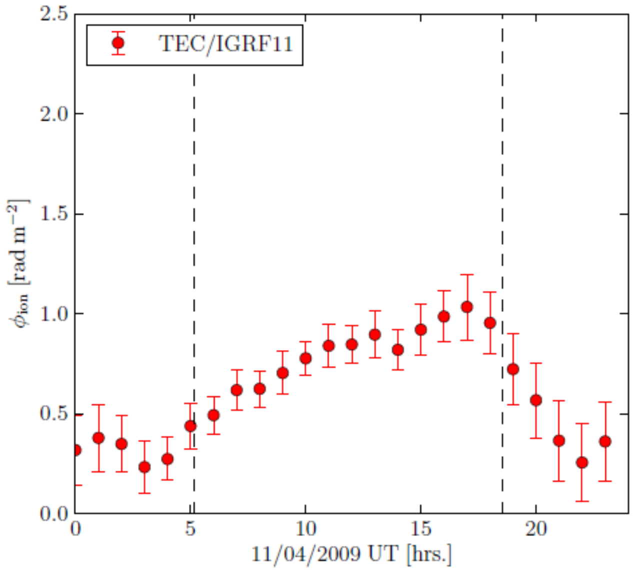
Ionosphere model: `IonFR`

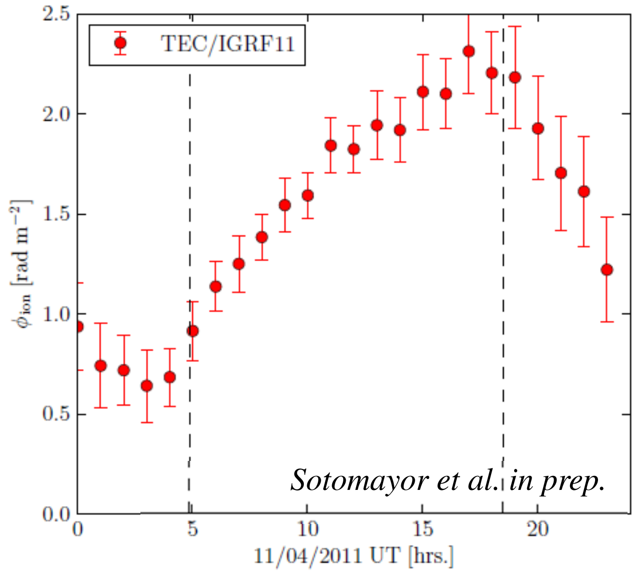
- Ionospheric Faraday depth is predicted by IonFR, written by C. Sotomayor
- Inputs include:
  - TEC maps from Centre for Orbital Determination in Europe (CODE)
  - Eleventh generation International Geomagnetic Reference Field (IGRF11)
  - RA & DEC of source, lat & long of telescope, date of observation
- Outputs ionospheric Faraday depth +error for given LOS every hour for the day specified:

$$\phi_{ion} = 2.6 \times 10^{-17}\, TEC_{LOS} B_{LOS}\ \ rad\ m^{-2}$$



Sotomayor et al. in prep.

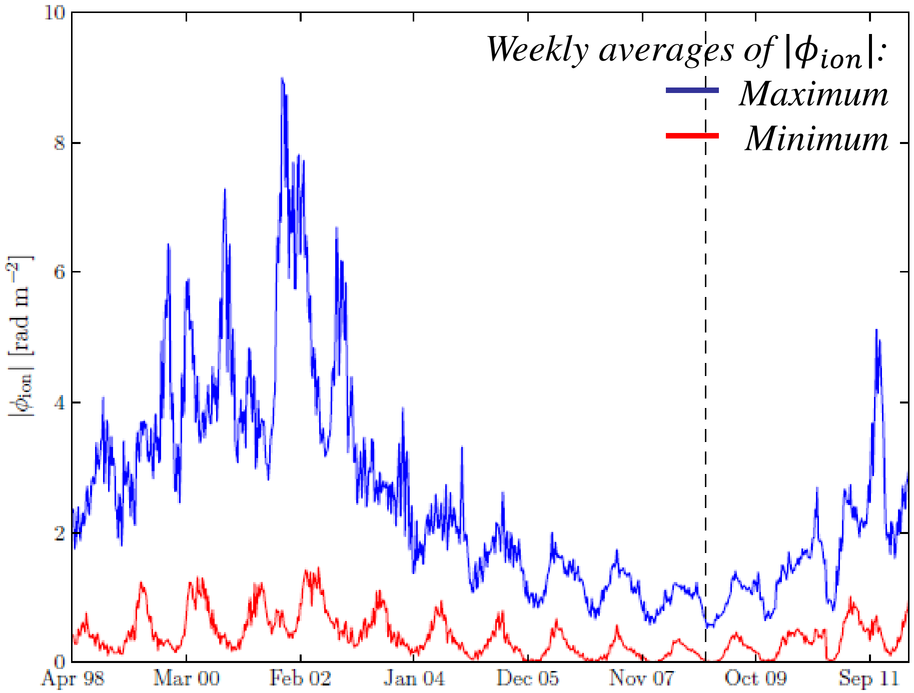




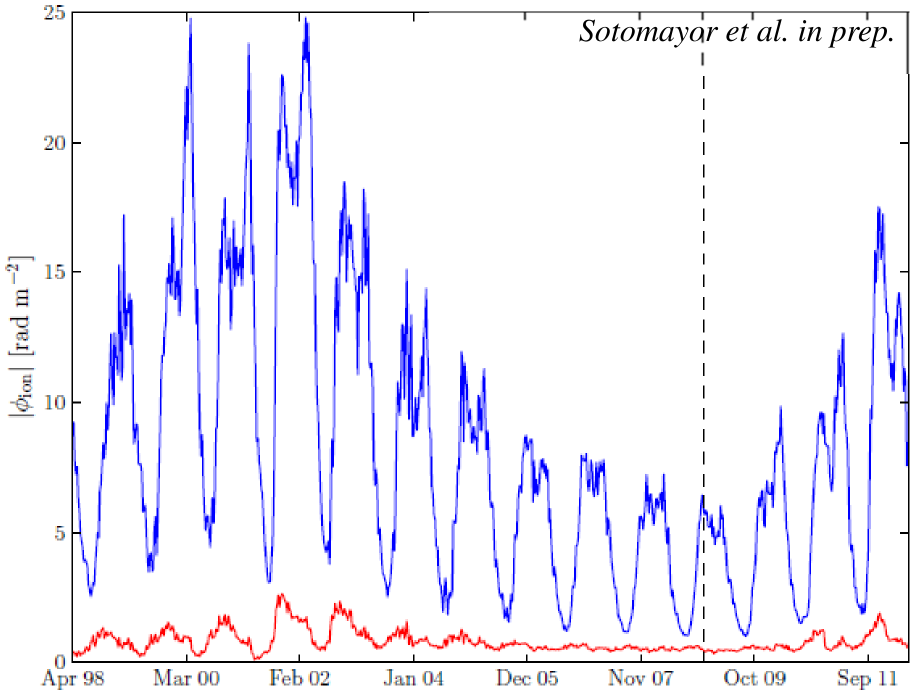
Sotomayor et al. in prep.

Ionospheric variations

- The ionospheric TEC varies depending on the time of day, season, solar activity
- Most important to correct for when measuring changes in Faraday depths



ϕ_{ion} from LOFAR Superterp toward Cas A

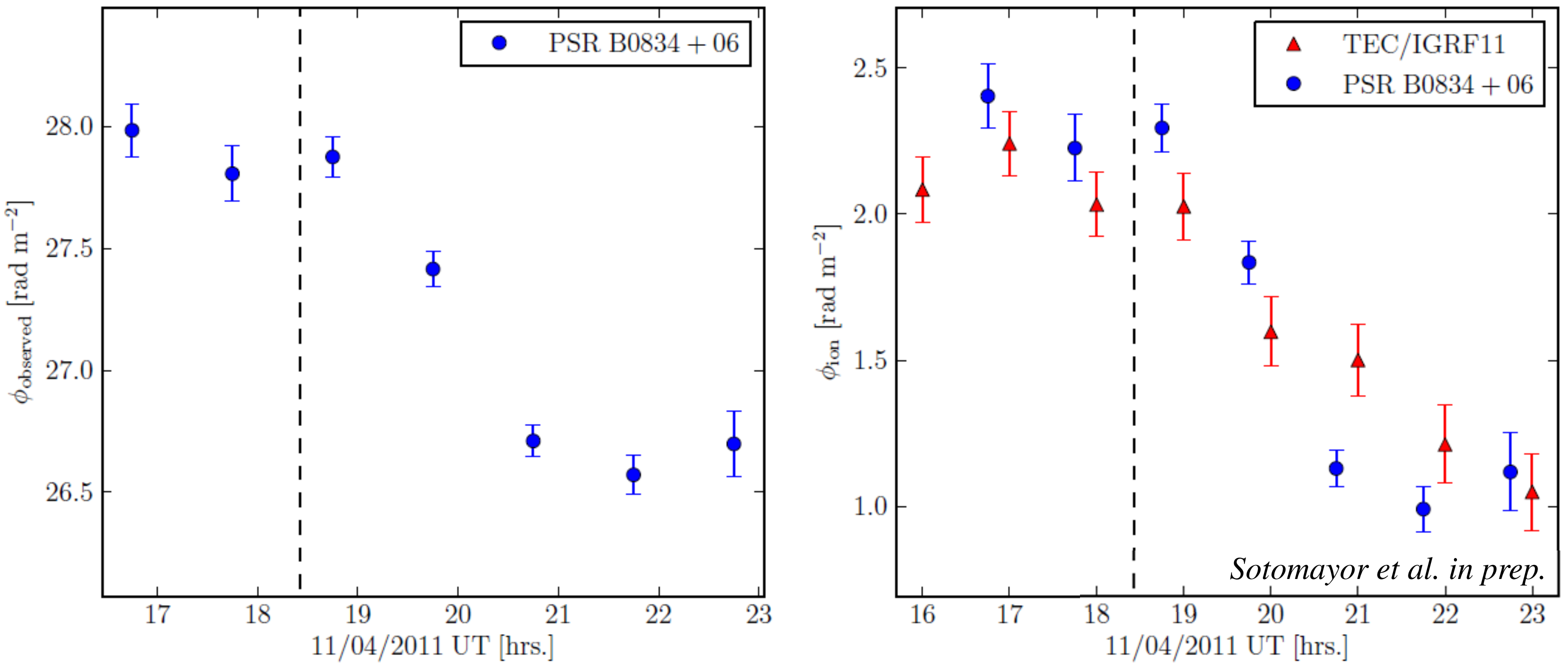


ϕ_{ion} averaged for SKA core sites toward Eta Carinae

Comparison with LOFAR obs I

- LOFAR Superterp HBA 7 x 10 min obs of PSR B0834+06, ν =120-126 MHz

- $\phi_{ISM} + \phi_{ion}(t)$
- $\phi_{ion}(t)$

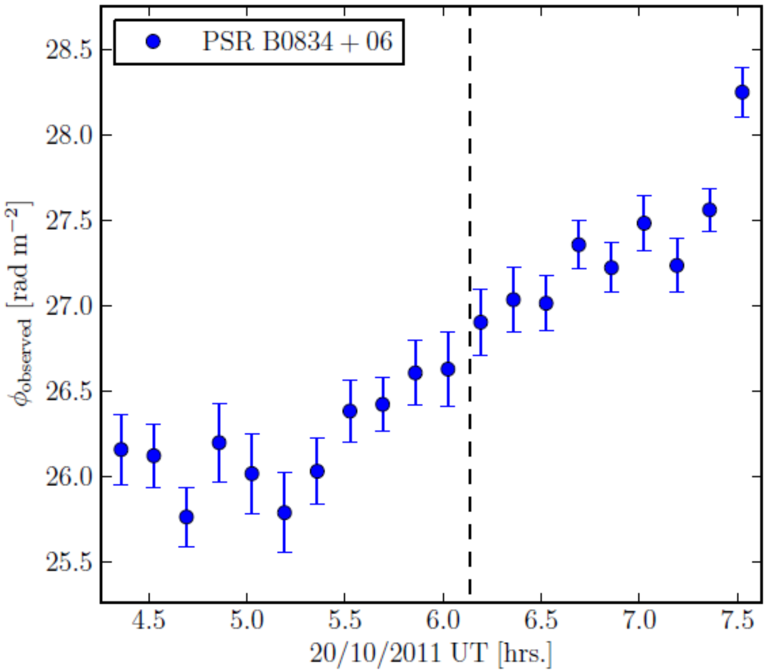


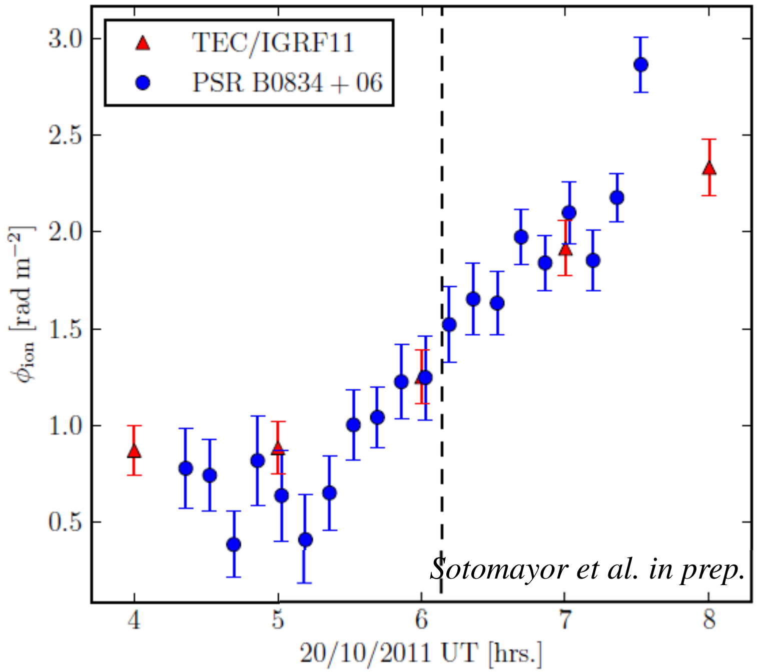
- $\phi_{ISM} = 25.58 \pm 0.18\, rad\, m^{-2}$ (agreement with WSRT obs $\phi_{ISM} = 25.6 \pm 1.8\, rad\, m^{-2}$)

Comparison with LOFAR obs II

- LOFAR Superterp HBA 20 x 3 min obs of PSR B0834+06, ν =129-140 MHz

- $\phi_{ISM} + \phi_{ion}(t)$
- $\phi_{ion}(t)$

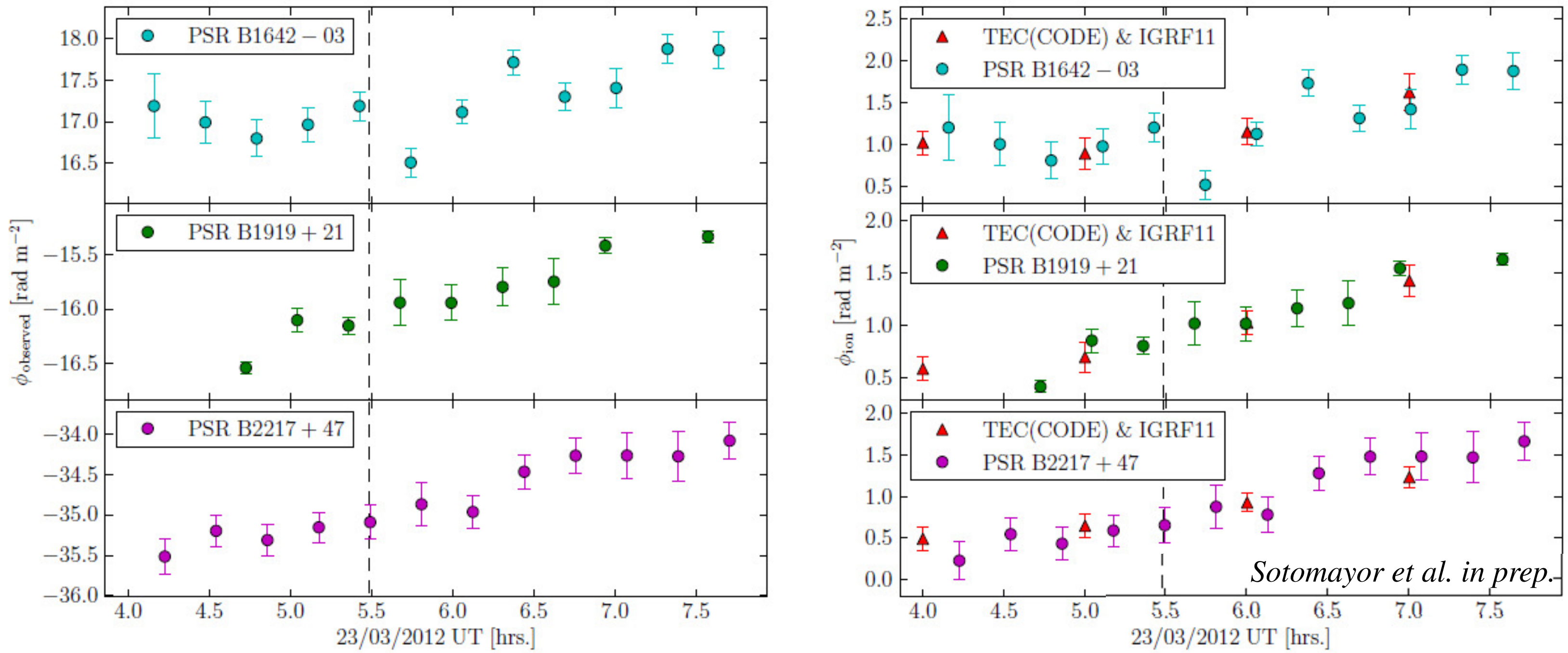




- $\phi_{ISM} = 25.38 \pm 0.19\, rad\ m^{-2}$ (agreement with WSRT obs $\phi_{ISM} = 25.6 \pm 1.8\, rad\ m^{-2}$)

Comparison with LOFAR obs III

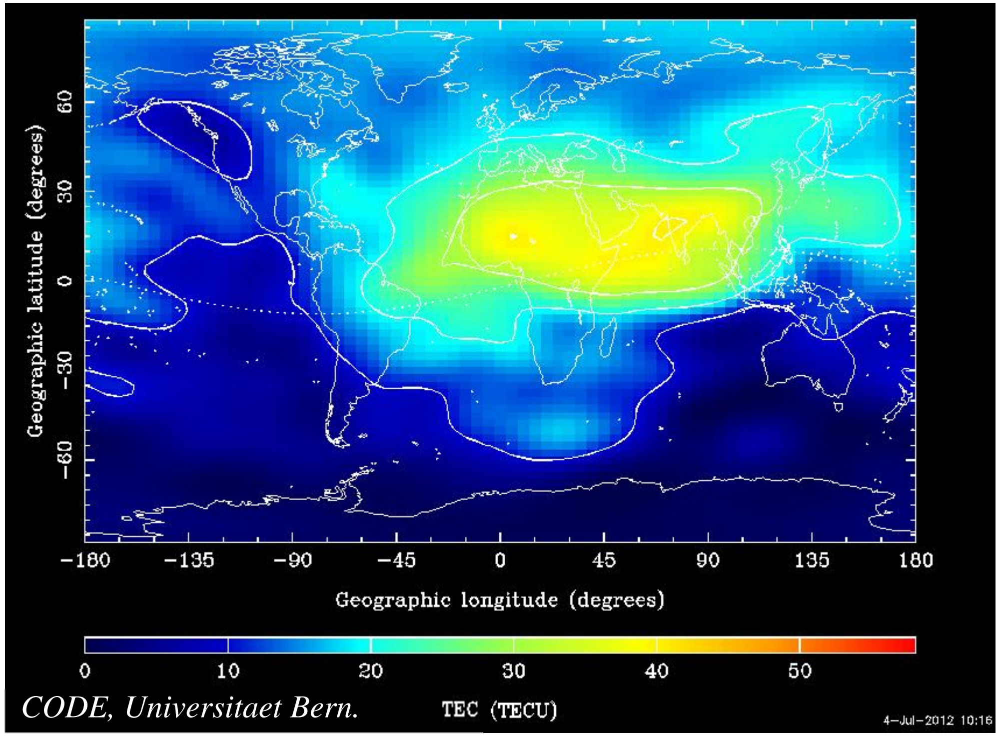
- LOFAR Superterp obs of PSRs B1642-03, B2217+47 (HBA ν =119-125 MHz) and PSR B1919+21 (LBA, ν =58-64 MHz) for 12 x 3 minutes each

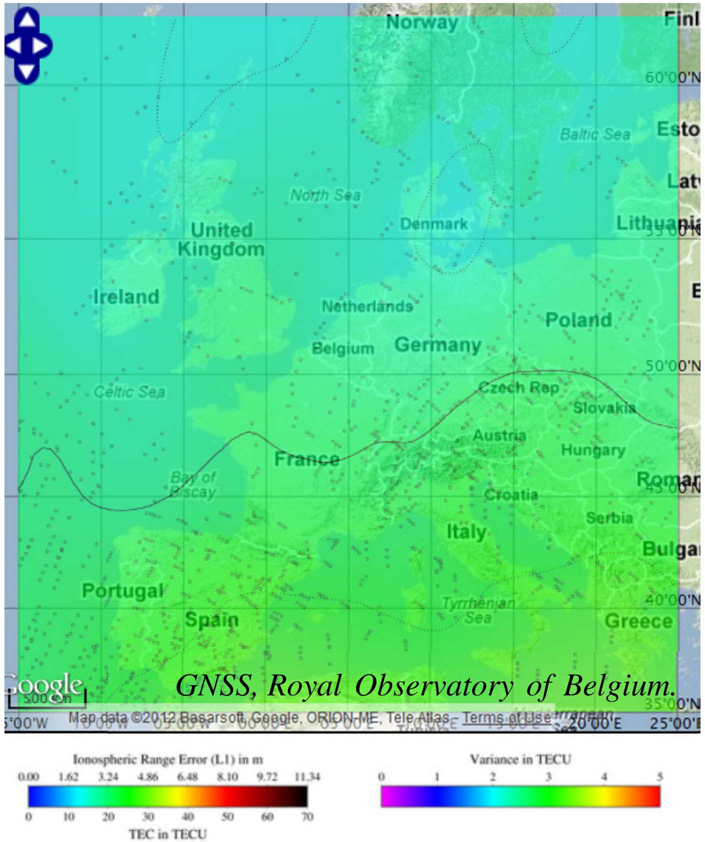


- $\phi_{ISM}{}^{B1642-03} = 15.98 \pm 0.28\, rad\ m^{-2}$ $\phi_{ISM}{}^{B1919+21} = -16.96 \pm 0.21\, rad\ m^{-2}$, $\phi_{ISM}{}^{B2217+47} = -35.74 \pm 0.40\, rad\ m^{-2}$

Sources of TEC maps

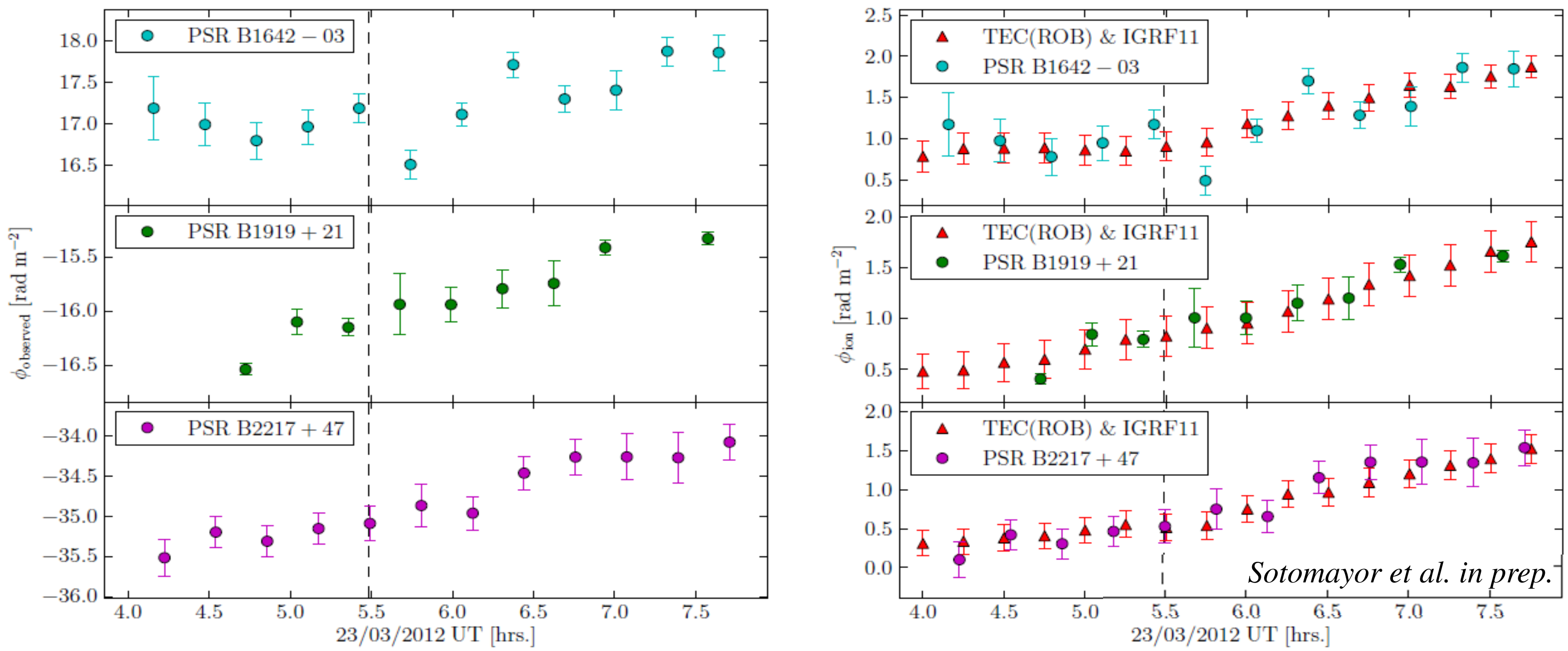
- CODE: global, 2h 5°x2.5° resolution
- ROB: Europe, 15m 0.5°x0.5° resolution





Comparison with LOFAR obs IIIa

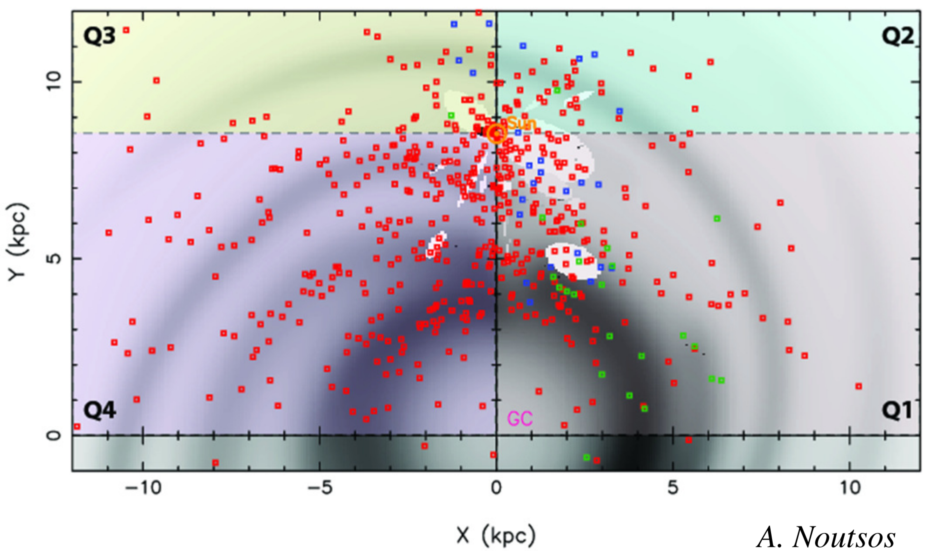
- LOFAR obs as shown previously, except with comparison to ROB TEC data



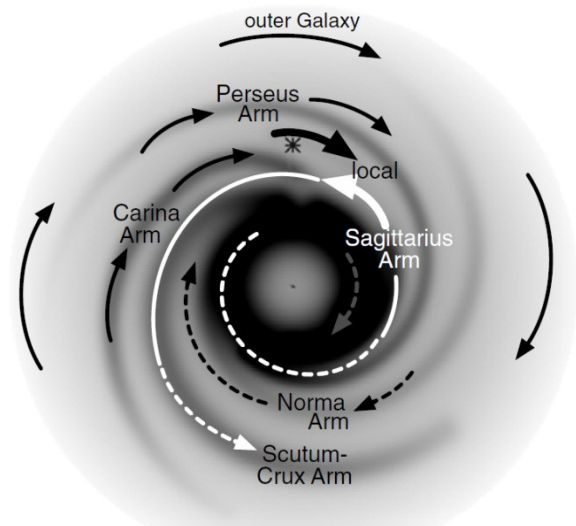
- $\phi_{ISM}{}^{B1642-03} = 16.01 \pm 0.26\, rad\ m^{-2}$ $\quad \phi_{ISM}{}^{B1919+21} = -16.94 \pm 0.10\, rad\ m^{-2}$, $\phi_{ISM}{}^{B2217+47} = -35.62 \pm 0.30\, rad\ m^{-2}$

Future Work

- Now the ionosphere's contribution to Faraday depth can be subtracted…
- Observations are go!
- 1800 known pulsars, only ~40% have measured Faraday depths
- At low frequency: spectral index, fractional polarisation, RM synthesis



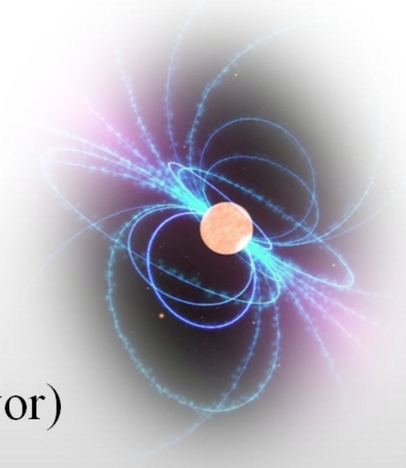
A. Noutsos



Van Eck et al. 2011

Summary

- Pulsars great astrophysical laboratories…
- Including as probes of the ISM, i.e. magnetic fields
- RM synthesis very useful for determining Faraday depths
- LOFAR observations of pulsars so far
- Correcting for the ionosphere using `IonFR` (C. Sotomayor)
- Ongoing work measuring pulsar Faraday depths to measure GMF
- Plus… interesting studies of pulsars along the way!



Thanks for listening!