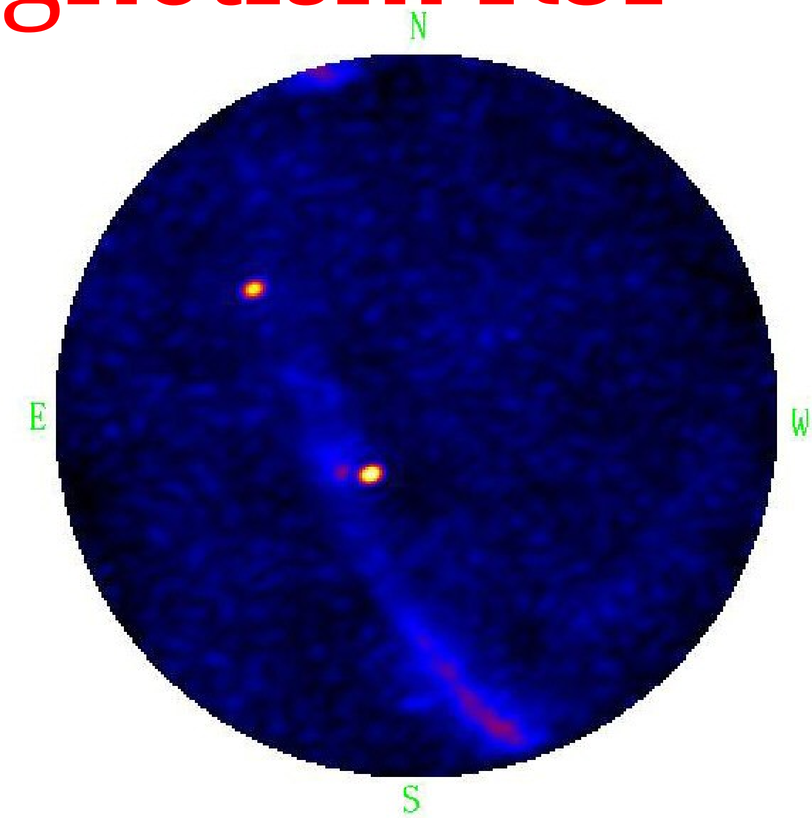
LOFAR
and the Cosmic Magnetism KSP



James M Anderson
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On behalf of the LOFAR collaboration and the LOFAR MKSP

Max-Planck-Institut für Radioastronomie

LOFAR

MAX-PLANCK-GESELLSCHAFT

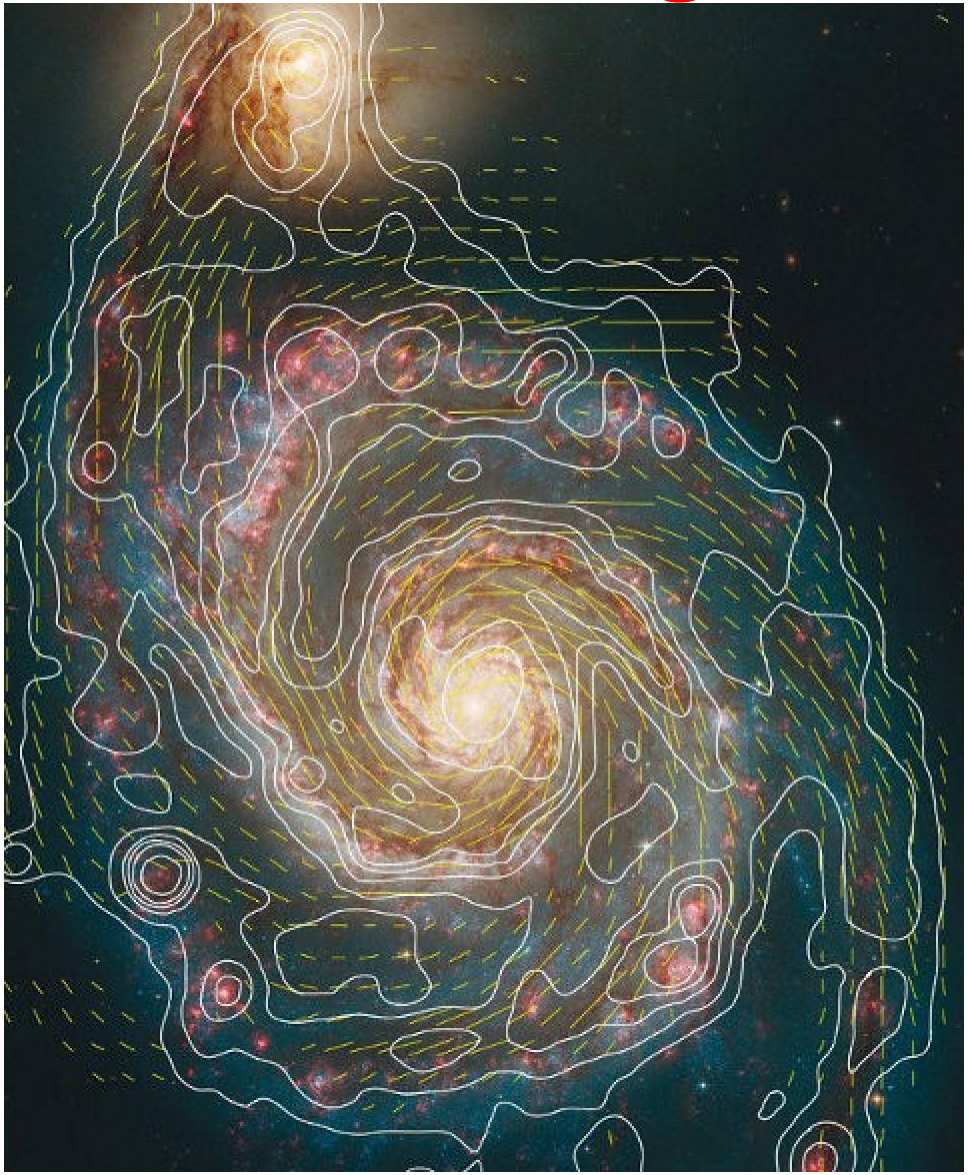
Terminology: The Term "Rotation Measure" Is Inadequate

- At low frequencies there are virtually no directions with only a single emission component along the line of sight
- Rotation measure synthesis (RM synthesis) is necessary
    - Insistence on capitalization of "RM Synthesis" by the LOFAR MKSP PI
- Frequency coverage and weighting determine the rotation measure spread function (RMSF)
    - Analogous to the PSF from imaging
        - But as the polarized emission is complex-valued (not real-valued), the analysis is, well, more complex
    - More appropriately it is related to the dirty beam from imaging
    - Similarly, one can have a clean beam or restoring RMSF for RM synthesis deconvolution
    - Gaps in frequency (λ^2) coverage are handled just like gaps in (u,v) coverage — they make your beam dirty and you need to deconvolve
    - Should have been called the FDSF, but unfortunately the original name has now become too embedded in the community
- RM synthesis transforms emission from frequency (or λ^2 space) to Faraday depth (FD) space
    - Term rotation measure (RM) reserved for trivial single component fits

Overview

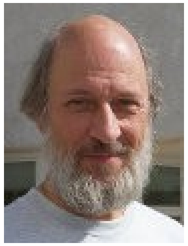
- The LOFAR Cosmic Magnetism KSP
- LOFAR, the instrument
- What LOFAR can do for measuring magnetic fields
- Status of commissioning LOFAR for magnetism

LOFAR Key Science Project on Cosmic Magnetism



Short form:
Magnetism Key Science Project (MKSP)

PI: Rainer Beck
(talk earlier today)



http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html

The LOFAR Cosmic Magnetism KSP

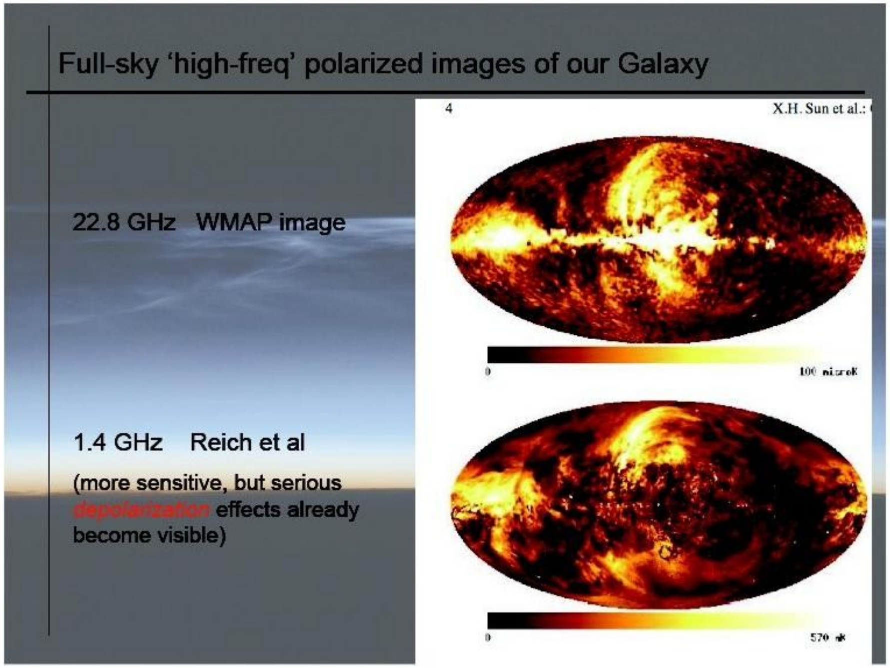
- **PI:** Rainer Beck, MPIfR Bonn
- **Management Team**
  - PI+
  - James Anderson, MPIfR Bonn
  - George Heald, ASTRON Dwingeloo
  - Anna Scaife, Dublin Inst. for Advanced Studies
- **Full Members (27)**
  - Paul Alexander, MRAO Cambridge
  - Michael Bell, MPA Garching
  - Michiel Brentjens, ASTRON Dwingeloo
  - Ger de Bruyn, ASTRON Dwingeloo
  - Chris Chyzy, Univ. Kraków
  - Ralf-Jürgen Dettmar, Univ. Bochum
  - Torsten Enßlin, MPA Garching
  - Andrew Fletcher, Univ. Newcastle
  - Jörn Geisbüsch, Dominion Radio Observatory
  - René Gießübel, MPIfR Bonn
  - Marijke Haverkorn, Univ. Nijmegen
  - Andreas Horneffer, MPIfR Bonn
  - Marco Iacobelli, Sterrewacht Leiden
  - Henrik Junklewitz, MPA Garching
  - Masaya Kuniyoshi, MPIfR Bonn
  - Enno Middelberg, Univ. Bochum
  - Arpad Miskolczi, Univ. Bochum
  - David Mulcahy, MPIfR Bonn
  - Aris Noutsos, MPIfR Bonn
  - Emanuela Orru, Univ. Nijmegen
  - Roberto Pizzo, ASTRON Dwingeloo
  - Wolfgang Reich, MPIfR Bonn
  - Thomas Riller, MPA Garching
  - Carl Shneider, Sterrewacht Leiden
  - Charlotte Sobey, MPIfR Bonn
  - Carlos Sotomayor, Univ. Bonn
  - Alice di Vincenzo, Tautenburg Obs.
- **Associate Members (42)**
  - Björn Adebahr, Univ. Bochum
  - Tigran Arshakian, MPIfR Bonn
  - Nadya Ben Bekhti, Univ. Bonn
  - Gianni Bernardi, CfA Cambridge
  - Dominik Bomans, Univ. Bochum
  - Jess Broderick, Univ. Southampton
  - Marcus Brüggen, Jacobs Univ. Bremen
  - Ettore Carretti, CSIRO Sydney
  - John Conway, Onsala Radio Obs.
  - Robert Drzazga, Univ. Kraków
  - Sven Duscha, ASTRON Dwingeloo
  - Jochen Eislöffel, Tautenburg Obs.
  - Jamie Farnes, MRAO Cambridge
  - Lauranne Fauvet, Univ. Nijmegen
  - Luigina Feretti, IRA Bologna
  - Katia Ferrière, Univ. Toulouse
  - Dave Green, MRAO Cambridge
  - Volker Heesen, Univ. Hertfordshire
  - Matthias Hoeft, Tautenburg Obs.
  - Cathy Horellou, Onsala Radio Obs.
  - Marek Jamrozy, Univ. Kraków
  - Jens Jasche, Univ. Bonn
  - Vibor Jelić, ASTRON Dwingeloo
  - Wojciech Jurusik, Univ. Kraków
  - Jongsoo Kim, Korea Astronomy & Space Science Institute
  - Ulrich Klein, Univ. Bonn
  - Michael Kramer, MPIfR Bonn
  - Marita Krause, MPIfR Bonn
  - Martin Krause, MPE Garching
  - Halime Miraghaei, Sharif Tech Univ
  - Katarzyna Otmianowska-Mazur, Univ. Kraków
  - Rosita Paladino, IRA Bologna
  - Amrita Purkayastha, Univ. Bonn
  - Julia Riley, MRAO Cambridge
  - Dominic Schnitzeler, ATNF Sydney
  - Anvar Shukurov, Univ. Newcastle
  - Marian Soida, Univ. Kraków
  - Ben Stappers, Univ. Manchester
  - Fatemeh Tabatabaei, MPIA Heidelberg
  - Monica Trasatti, Univ. Bonn
  - Marek Urbanik, Univ. Kraków
  - Marek Weżgowiec, Univ. Bochum

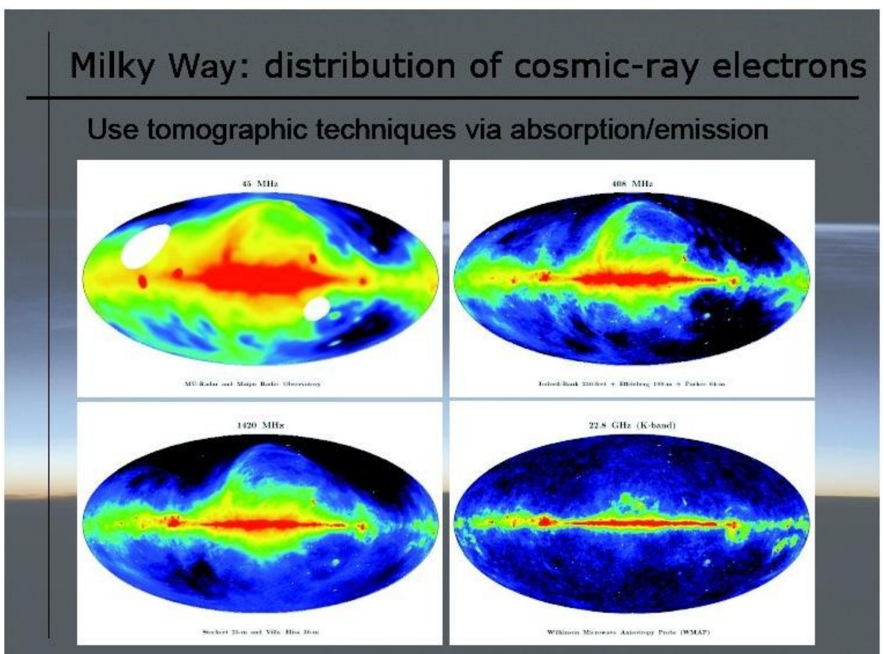
LOFAR Cosmic Magnetism KSP Working Groups

1. Milky Way
   - in collaboration with the Survey KSP
   - chair: Marijke Haverkorn (Nijmegen)
2. Pulsar RMs and the Galactic magnetic field
   - in collaboration with the Transients KSP
   - chair: Aris Noutsos (Bonn)
3. Nearby galaxies
   - in collaboration with the Survey KSP
   - chair: Chris Chyzy (Kraków)
4. Giant radio galaxies
   - in collaboration with the Survey KSP
   - chair: Ger de Bruyn (Groningen)
5. Intergalactic filaments
   - in collaboration with the Survey & EoR KSPs
   - chair: Thorsten Enßlin (Garching)
6. Stellar jets
   - in collaboration with the Transients KSP
   - chair: Jochen Eislöffel (Tautenburg)

Aim of the MKSP is to measure magnetic fields in the nearby universe

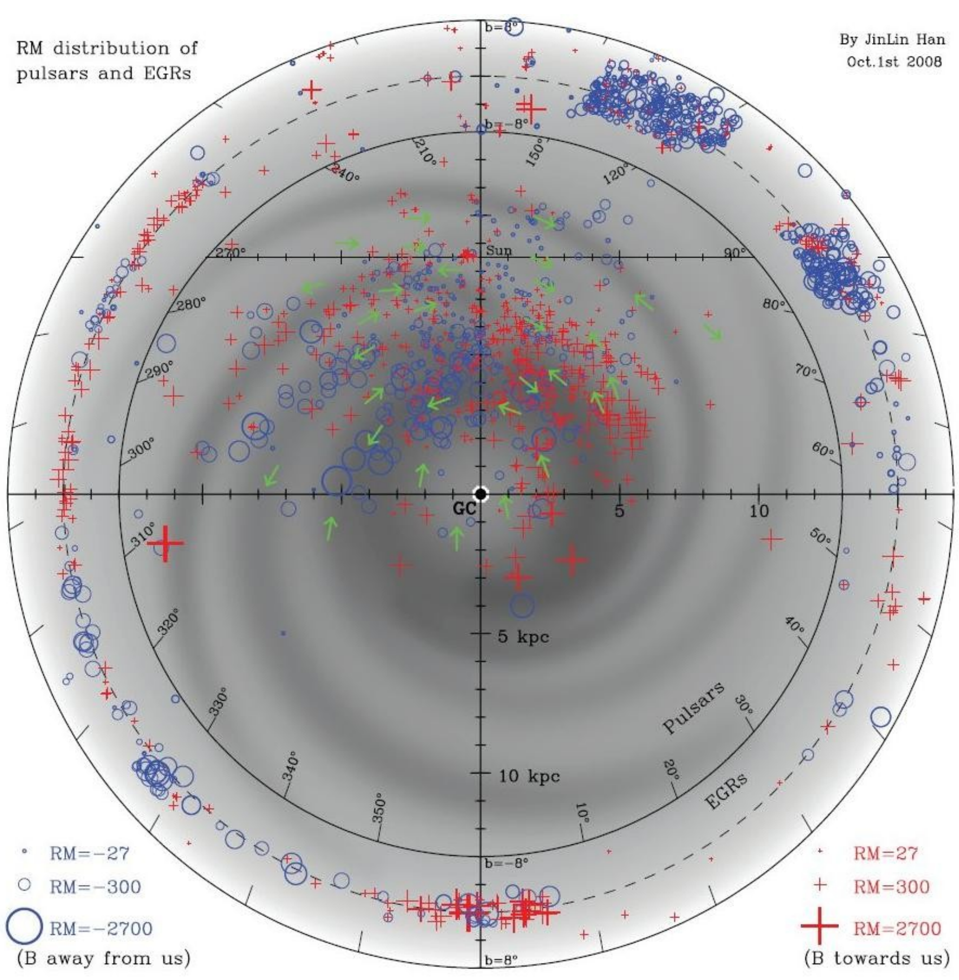
Milky Way





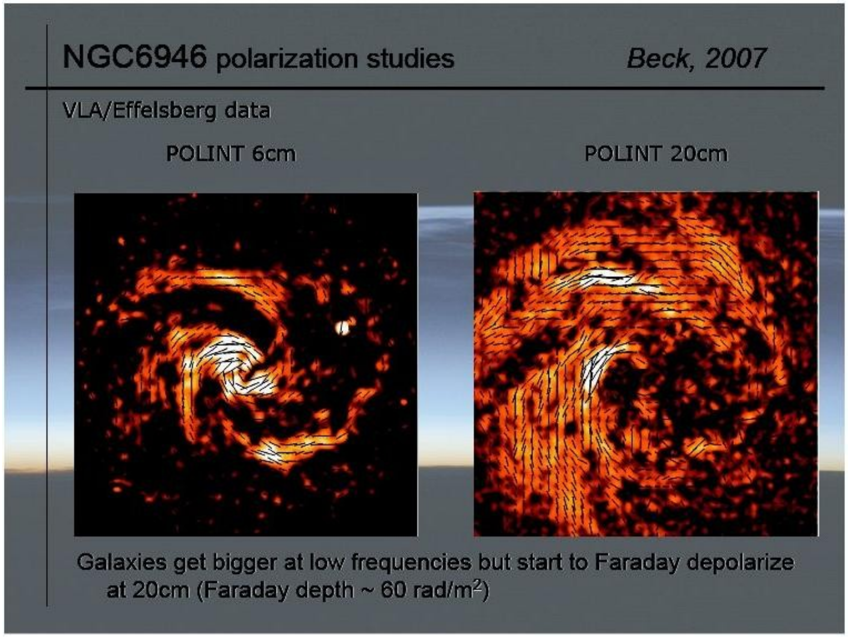
- Cosmic-ray electron distribution
- Magnetic field distribution
- Supernova remnants
- Halo gas and magnetic field
- Planetary nebulae, HII regions, etc.

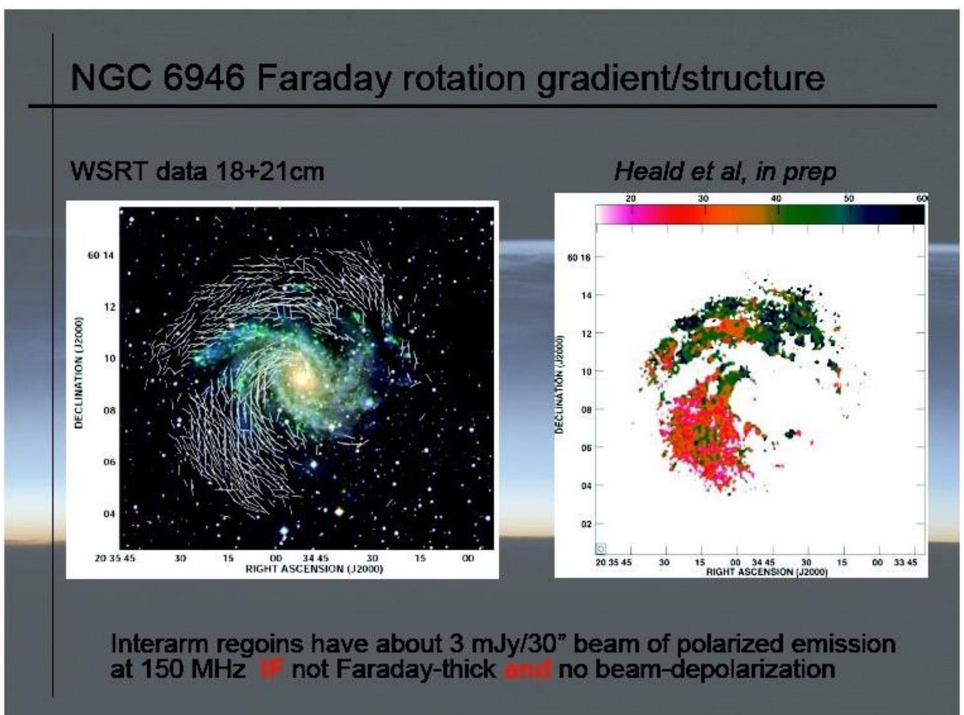
Pulsar FDs and the Galactic ISM



- Pulsars are usually highly polarized at low frequencies
- LOFAR is expected to discover ~1000 new pulsars
- For known and new pulsars, will measure the FD and DM to high precision
- Will have an order of magnitude more pulsar measurements of the Galactic magnetic field

Nearby Galaxies



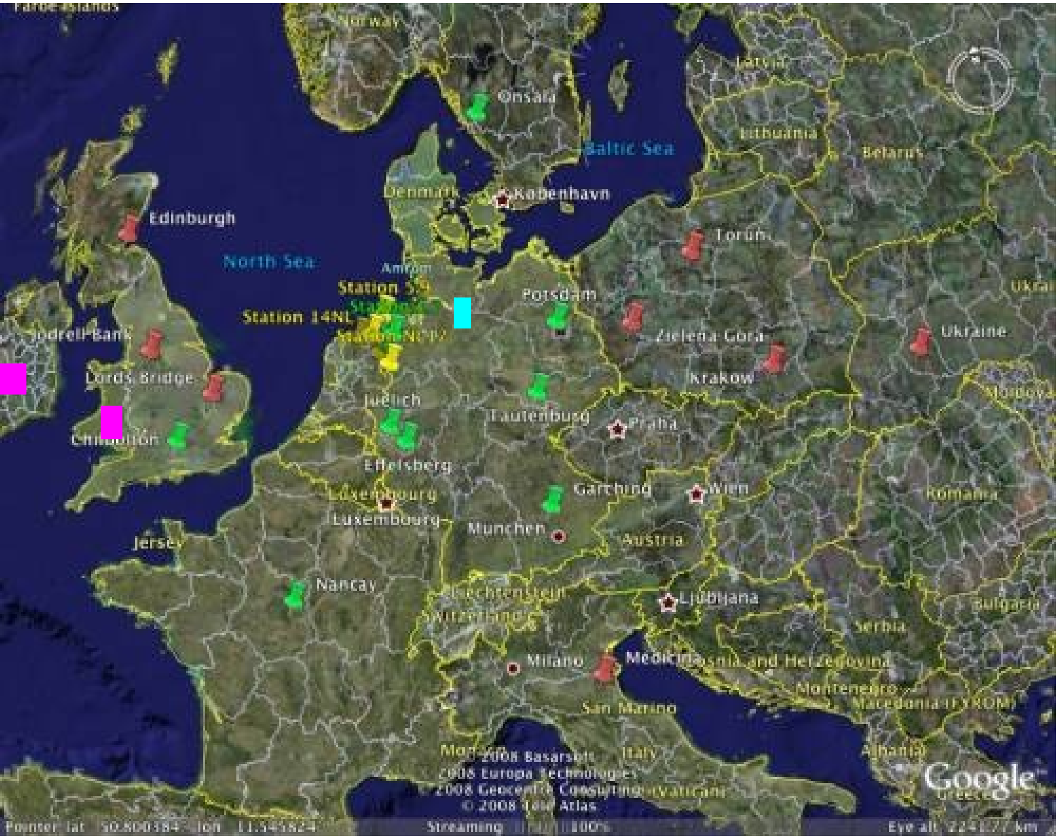


- Spiral galaxies
- Dwarf galaxies
- Relationship of magnetic fields to spiral arms
- Turbulent and coherent fields
- Magnetic fields in galaxy halos --- inflow or outflow?
- ...

Intergalactic Magnetic Fields

- Use high redshift AGNs (radio galaxies, radio loud quasars, etc.) as sources of polarized emission to probe magnetic fields in
  - Extended disks of nearby galaxies and the Milky Way
  - Cluster magnetic fields
  - Intercluster primordial magnetic fields
- Want to measure Faraday depth down to precision of 0.01 rad m^{-2}
  - Able to measure **nanogauss** field strengths in the IGM
  - Milky Way will introduce variations in FD much larger than this, so will need to do statistics over many sources
- Need <~ arcsecond resolution to avoid beam depolarization

LOFAR:
The Low Frequency Array



- Aperture array technology
  - digital processing
- Low Band (LBA)
  - normally 30 to 80 MHz
  - can do 10 to 80 MHz
- High Band (HBA)
  - 110 to 240 MHz
- 3rd input
  - open at International stations
  - extra LBA inputs for Dutch stations (better performance < 30 MHz)

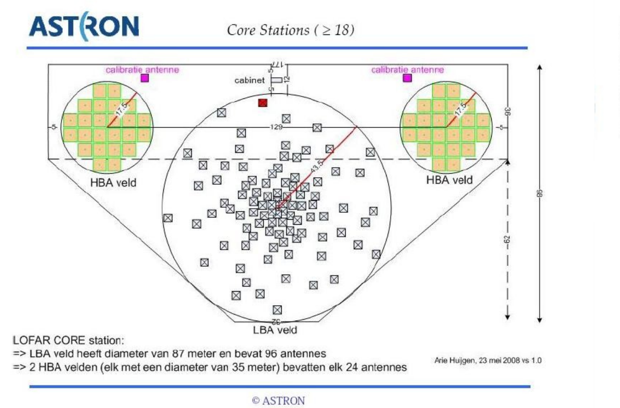
- Core (2 km diameter)
- Remote (inside NL)
- International (outside NL)

} International LOFAR Telescope (ILT)

Core

- 2 km diameter
- Micky Mouse design
- Station Beam FWHM
  - 8.7 6.6 5.3 2.6°
  - 30 75 120 240 MHz
- Synthesized beam
  - 800 300 200 100”
  - 30 75 120 240 MHz

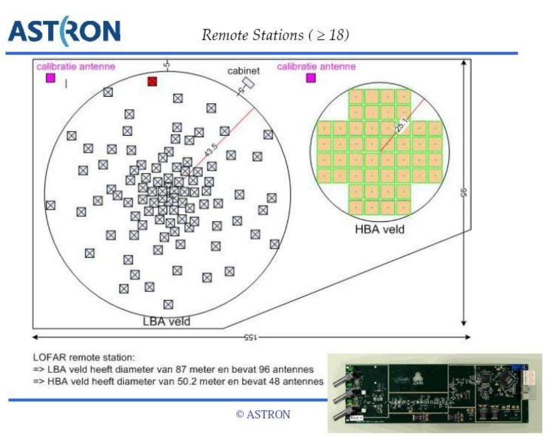
- Core area will be a nature reserve
- 96 LBA antennas (48 observing at a time) & 2 x 24 HBA tiles



Remote

- Up to 130 km baselines
- Circular-pair half-design
- Station Beam FWHM
  - 8.7 6.6 3.7 1.9°
  - 30 75 120 240 MHz
- Synthesized beam
  - 20 8 5 3”
  - 30 75 120 240 MHz

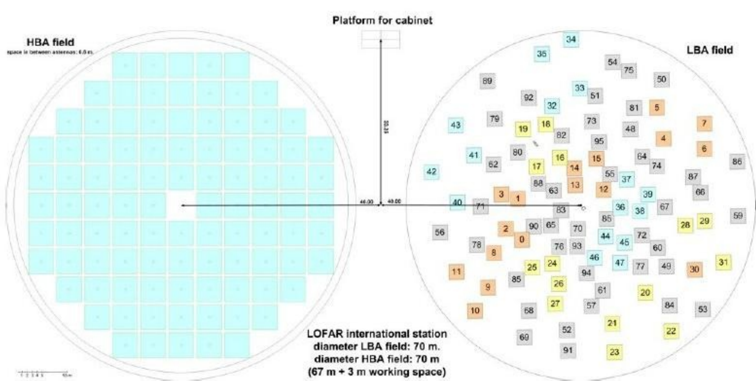
- 48 HBA tiles & 96 LBA (only 48 at a time used for observation)
- Station field rotation as well



International

- ~1000 km baselines
- Original station design
- Station Beam FWHM
  - 9.9 4.0 2.5 1.2°
  - 30 75 120 240 MHz
- Synthesized beam
  - 1.7 0.7 0.4 0.2”
  - 30 75 120 240 MHz

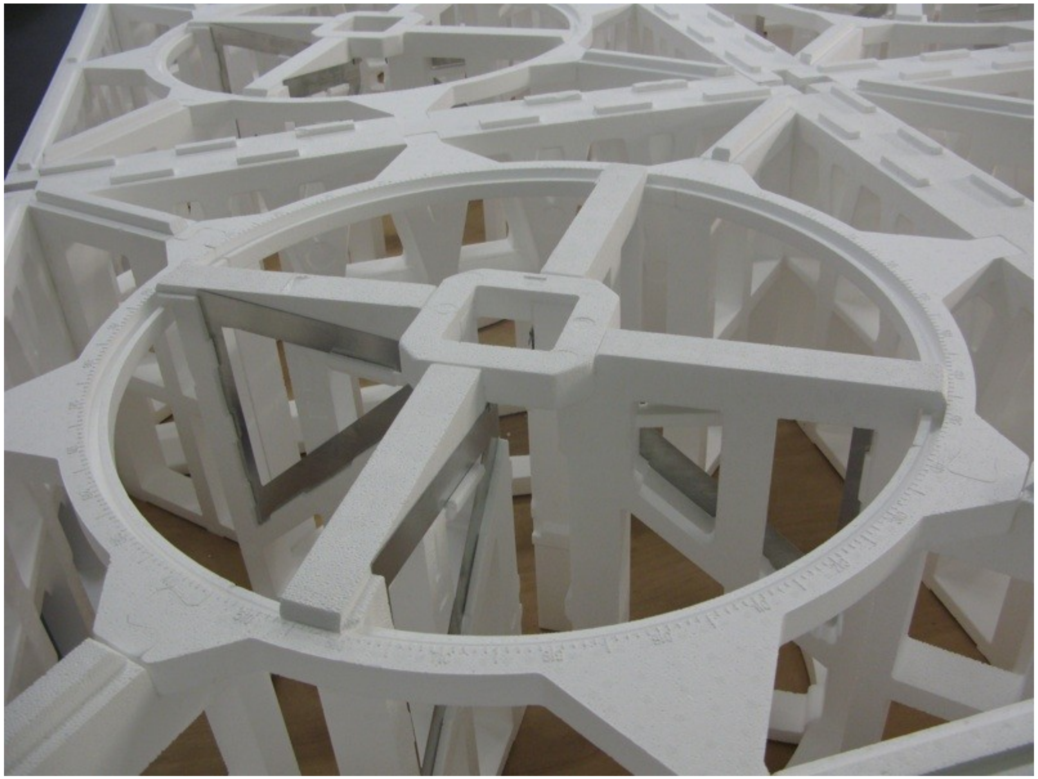
- 96 LBA and 96 HBA tiles
- Station rotation also applied



LBA

- Low Band Antenna
- 10 to 80 MHz
- Peak response ~56 MHz
- Normally filter out RFI below 30 MHz
- Bent dipole design

HBA



- High Band Antenna
- 120—240 MHz
- Roughly uniform gain across band
- 4x4 dipole “tiles”

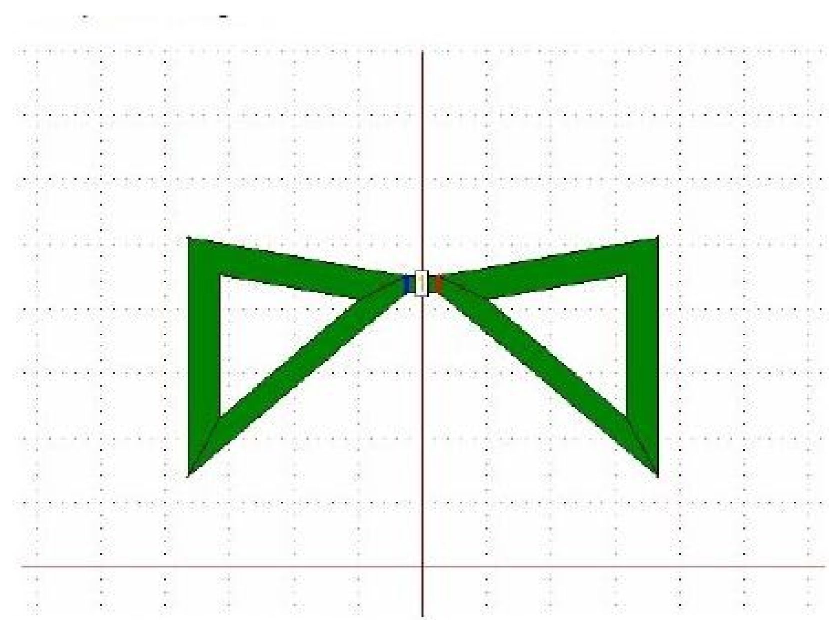


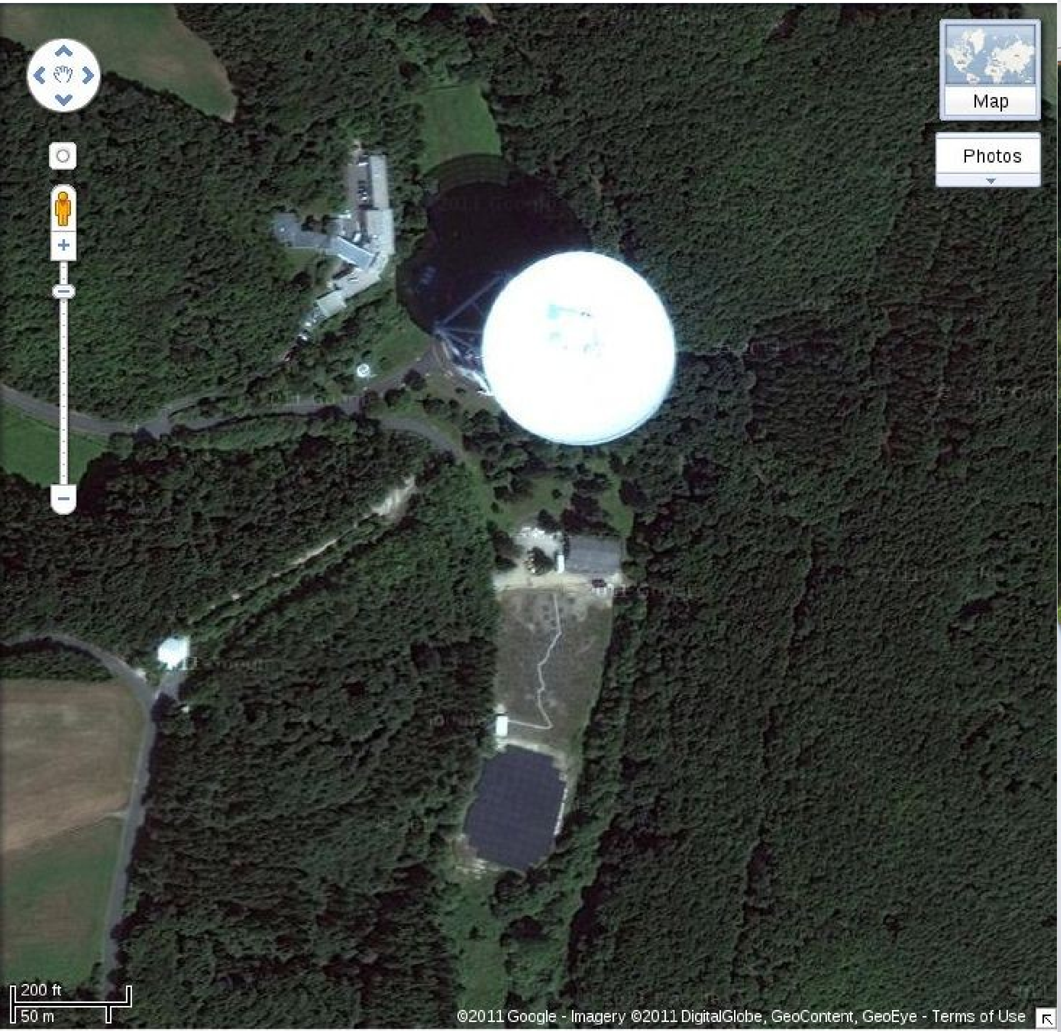
Figure 17 *A sketch of a HBA antenna element*

Example LOFAR Stations

Thueringer Landessternwarte/Eisloeffel

Thueringer Landessternwarte/M Pluto

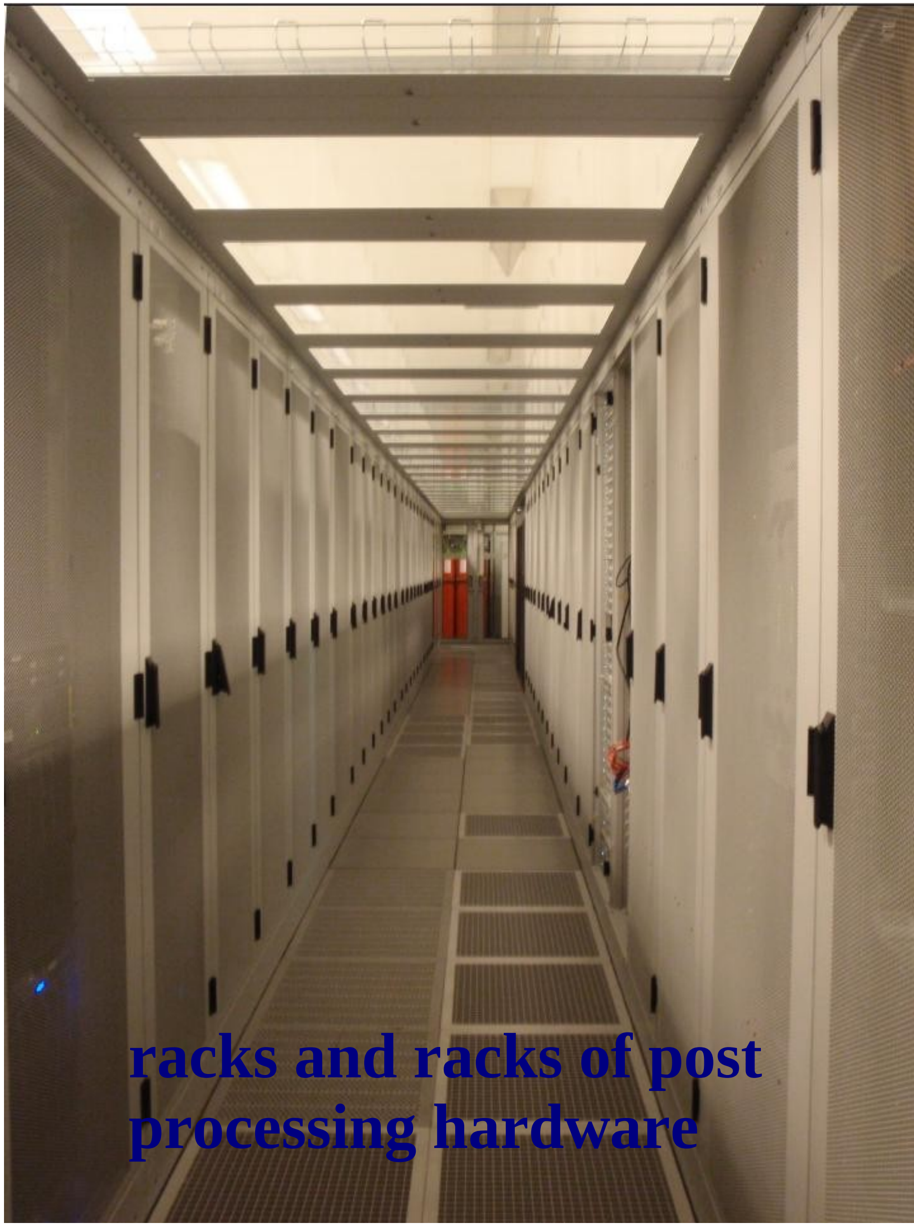
Scale


Map
Photos
200 ft
50 m
©2011 Google - Imagery ©2011 DigitalGlobe, GeoContent, GeoEye - Terms of Use


Anderson/MPIfR

LOFAR Data Processing

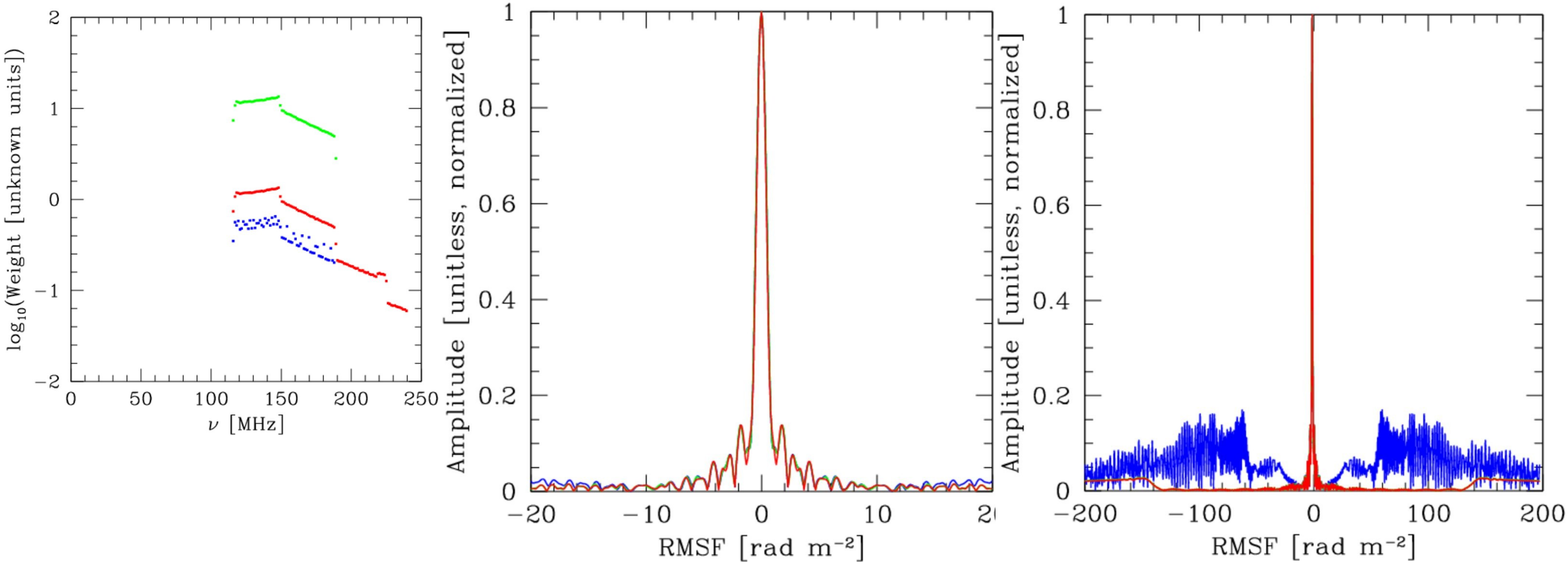
Blue Gene/P correlator



racks and racks of post processing hardware

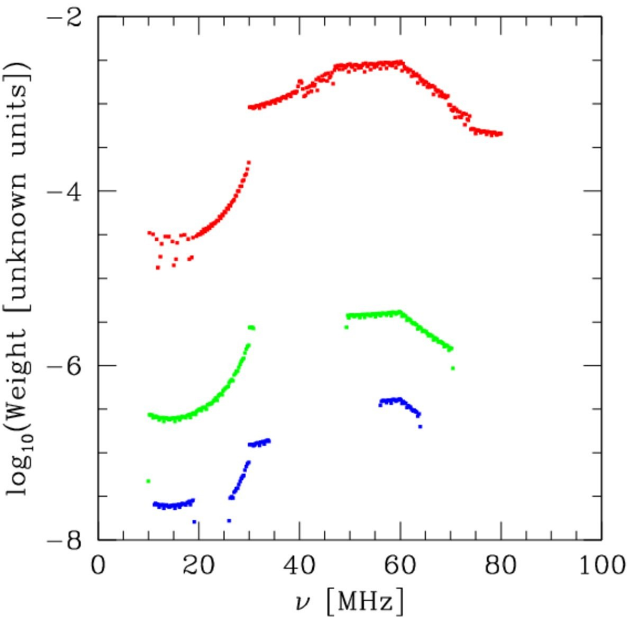
Broekema, 2011 Apr 20 LOFAR Status Meeting

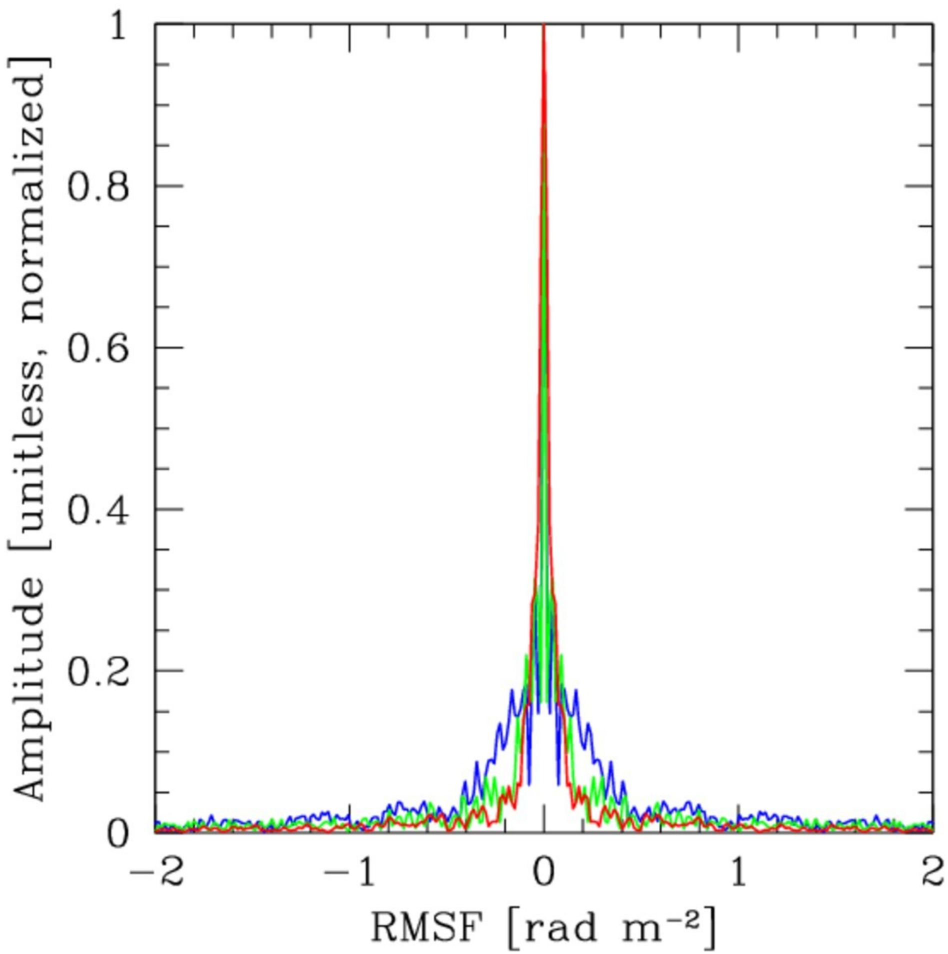
RMSF: High Band



- **Width of the RMSF ~ 1 rad m^{-2}**
- Frequency coverage and RMSF shown for MKSP comb proposal for a single RCU mode 5 comb, the combined RCU mode 5 combs, and the combined HBA combs
- Combined frequency combs greatly reduce RMSF sidelobes at high FDs

RMSF: Low Band



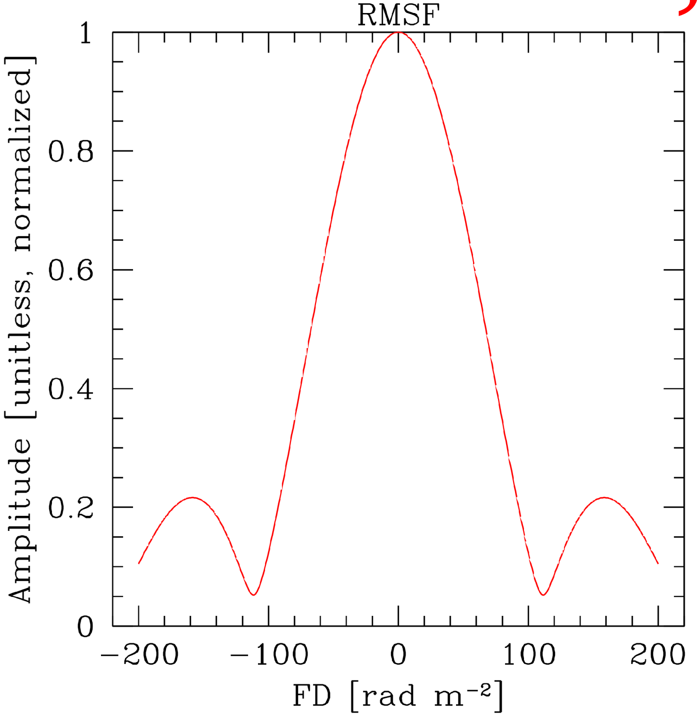


- **Width of the RMSF < 0.1 rad m^{-2}**
- Frequency coverage and RMSF shown for 15, 30, and 60 MHz bands of 8 MHz and 16 MHz bandwidth, and the MKSP frequency comb proposal

Comparison With Other Instruments

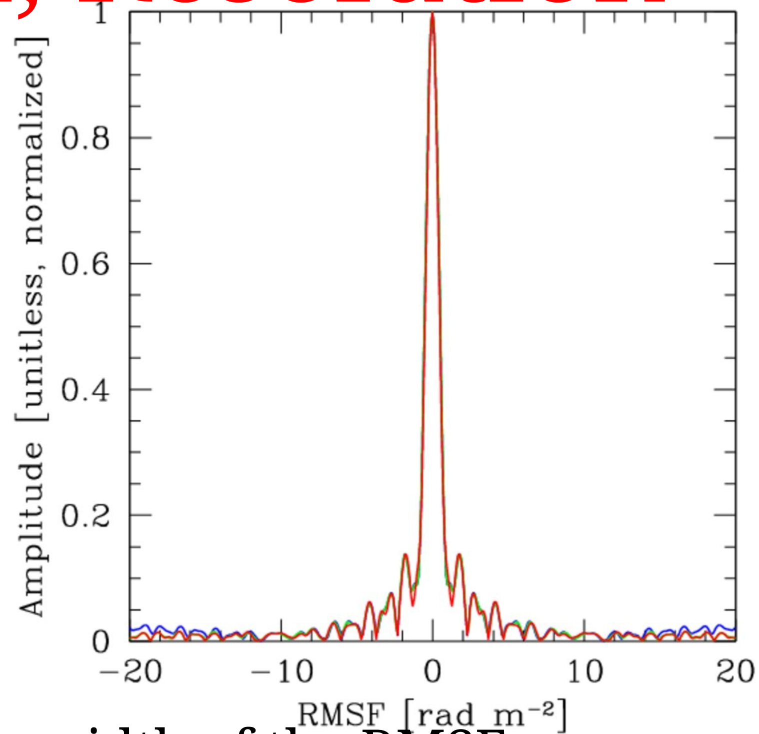
- LOFAR is the best instrument in the foreseeable future for high accuracy measurements of weak fields
  - LOFAR will be far better than even the SKA in this respect
  - This results from the combination of LOFAR's high FD resolution and its relatively high angular resolution
  - LOFAR is probably the best instrument for measuring intergalactic magnetic fields
- LOFAR is insensitive to large-scale features in FD-space
  - LOFAR does not on its own go to high enough frequencies to see large-scale features.
- Although the FD precision of LOFAR is excellent (and accuracy will be too once the calibration is good), it will be difficult for LOFAR to achieve high accuracy in position angle
  - Need higher frequency instruments for that

Resolution, Resolution, Resolution



← POSSUM RMSF for ASKAP

LOFAR High Band RMSF →



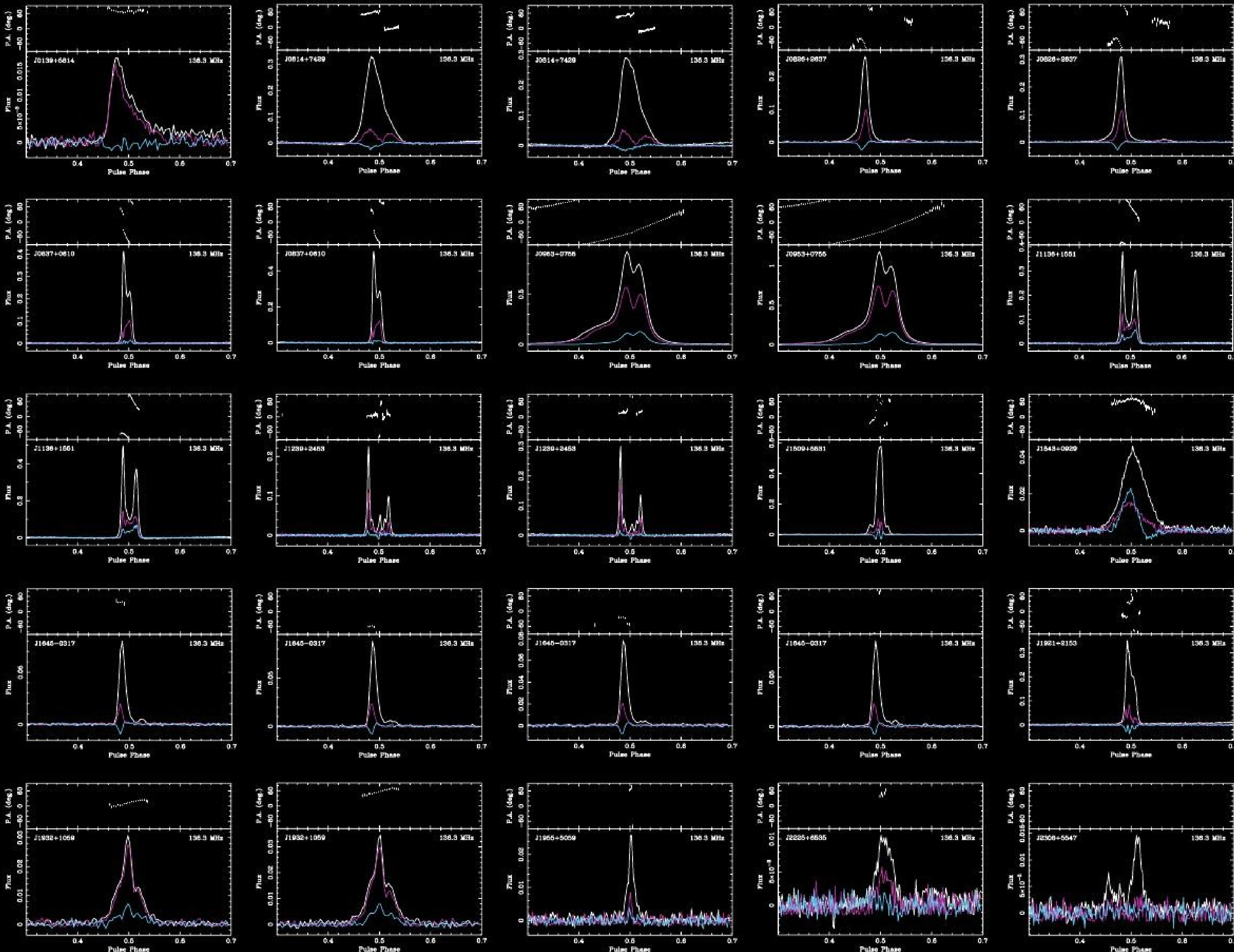
- The **precision** in FD-space goes as 1/SNR times the width of the RMSF
- But the **accuracy** in FD-space is usually limited by the width of the RMSF itself and the emission structure on FD scales smaller than the RMSF
- Simulations by Brentjens with zero instrumental noise shows that likely emission structures, based on simple, realistic models of source physical properties, lead to measurement errors of the RM that are larger than the width of the RMSF
  - Only by reducing the width of the RMSF can you get around this
- High angular resolution is also required to minimize beam depolarization and source confusion within the RMSF beam
  - International LOFAR stations are crucial for obtaining good results; hopefully Poland will join LOFAR

Time Variability

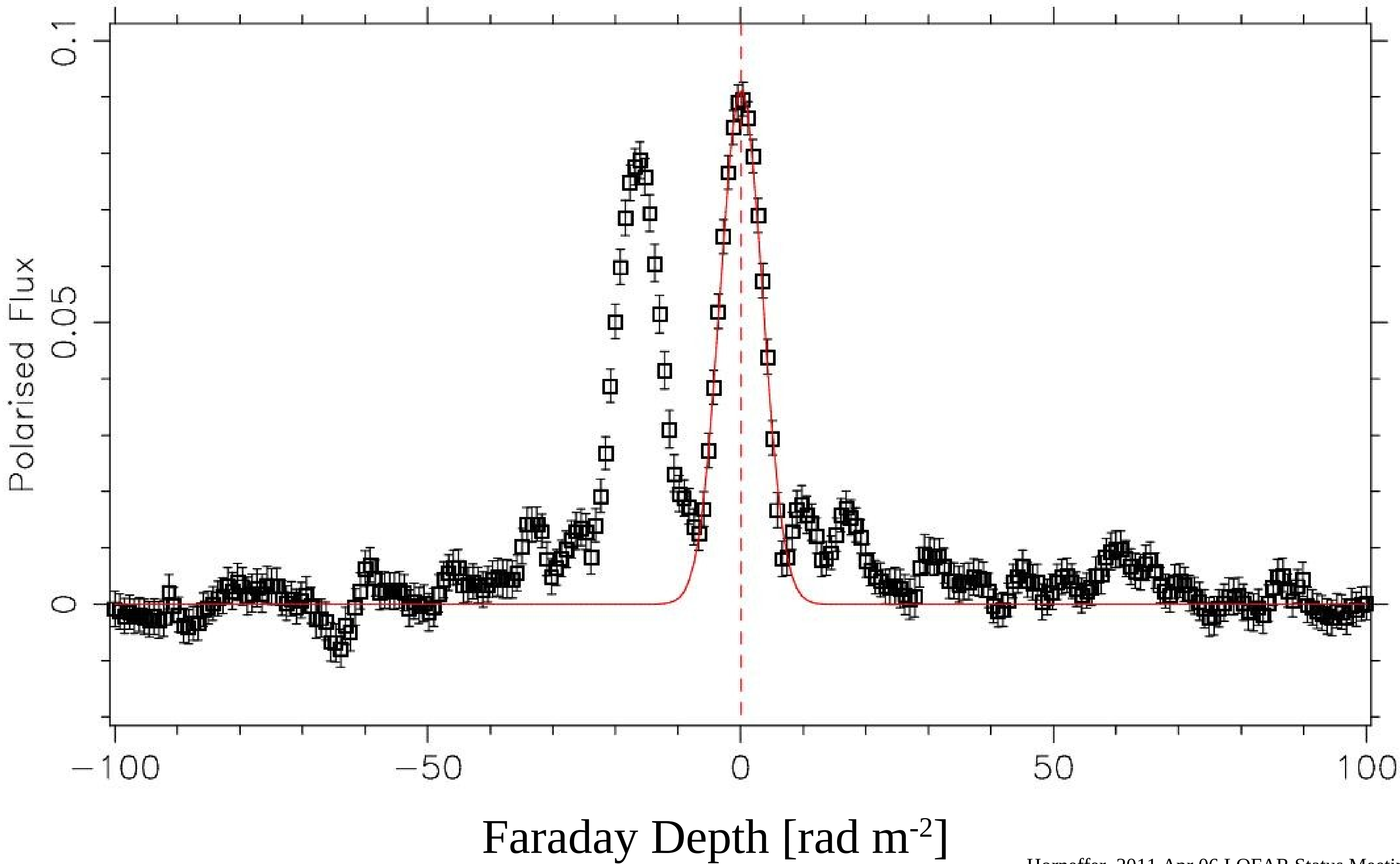
- Because the RMSF width for LOFAR is only ~1 rad m^{-2} for the high band, and down to below 0.1 rad m^{-2} for the low band, the precision of LOFAR measurements will often be 0.01 rad m^{-2} or smaller
- This is much smaller than the Faraday depth imposed by the intervening material
- We expect that for many sources, especially pulsars in the Galactic plane, we will be able to measure the time variability of the Faraday depth, and learn about the turbulent magnetic field structure along the lines of sight

LOFAR Commissioning Status

- Pulsars are relatively easy to measure
- Imaging is more difficult, but progress is being made

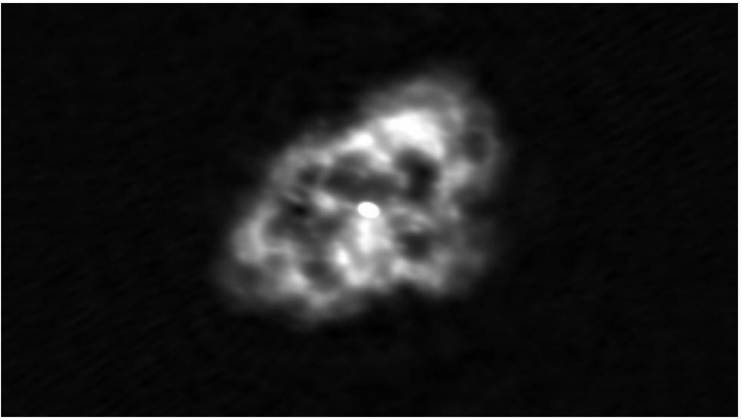

P.A. (deg.)
Flux
Pulse Phase
136.3 MHz
J0139+5814
J0814+7429
J0826+2637
J0837+0610
J0953+0755
J1136+1551
J1239+2453
J1509+5531
J1543+0929
J1645-0317
J1921+2153
J1932+1059
J1955+5059
J2225+6535

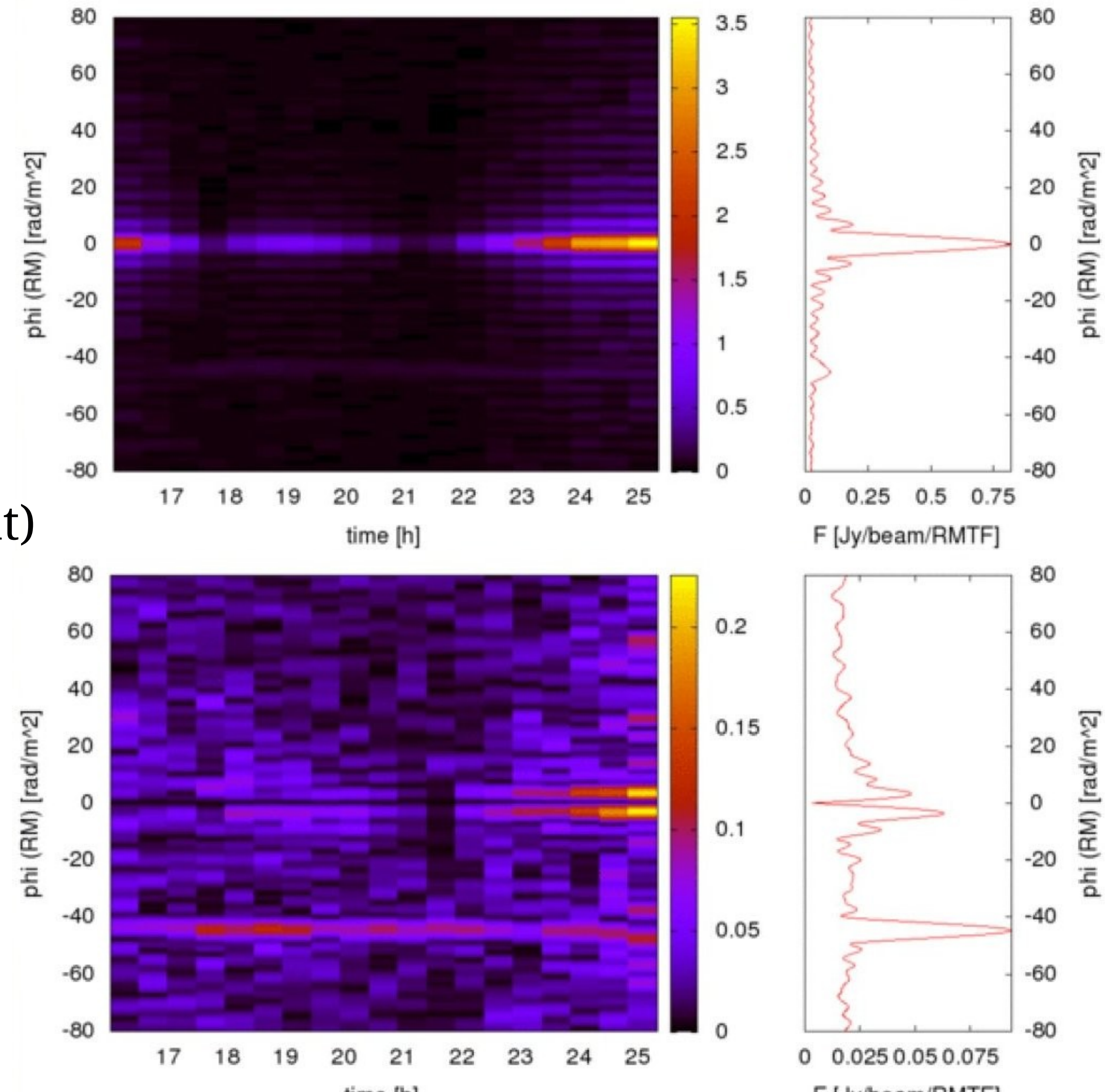
Pulsar RM Synthesis



Horneffer, 2011 Apr 06 LOFAR Status Meeting

Crab Pulsar Imaging for Polarization

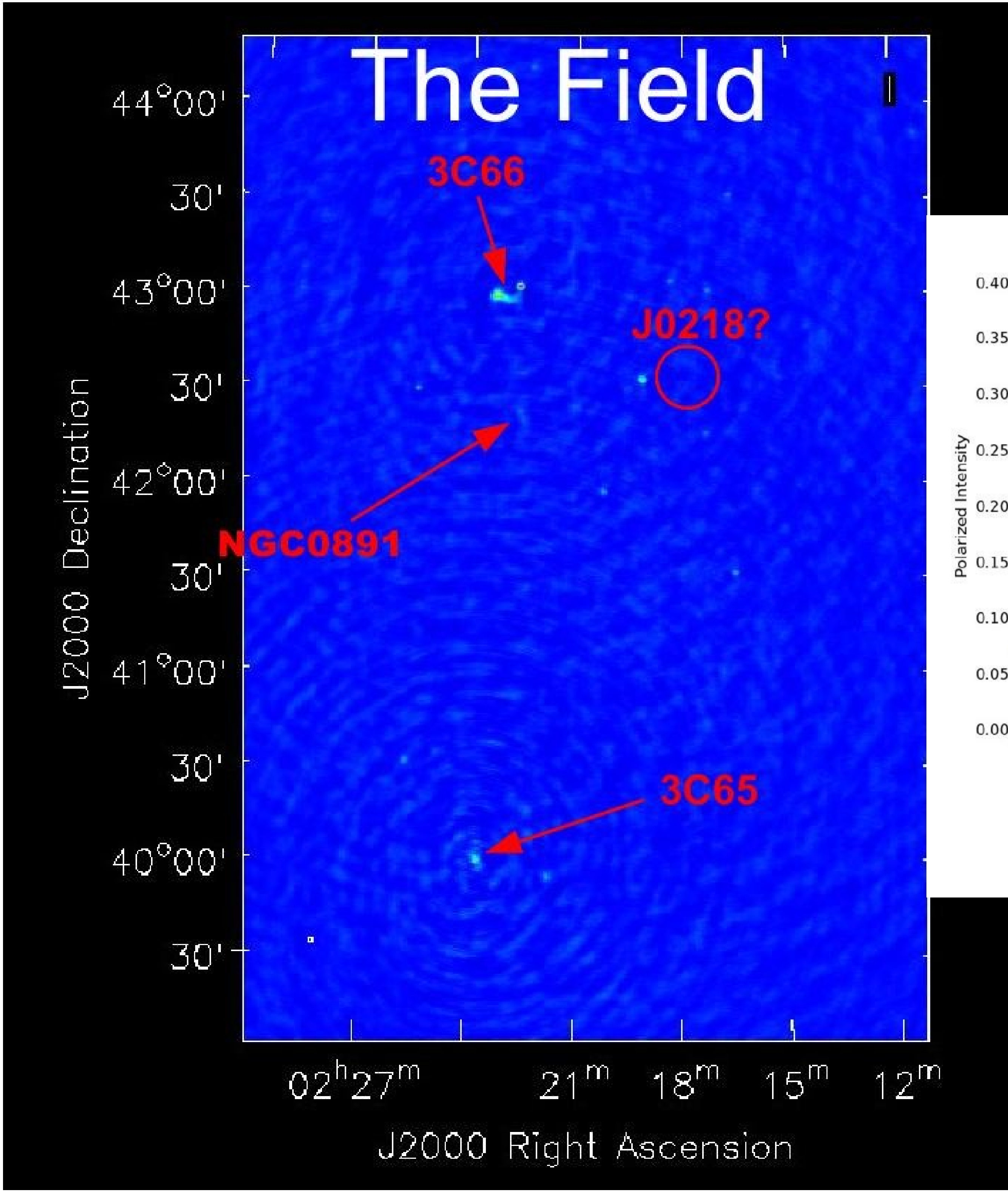


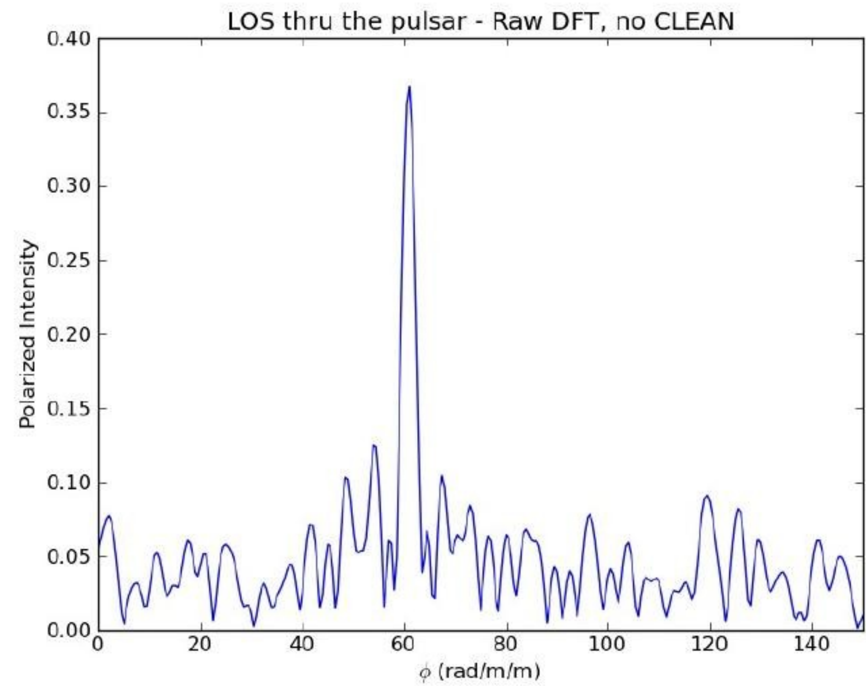


work by O Wucknitz, AIfA

- LOFAR Stokes I (left)
- FD versus time for pulsar direction, before (upper right) and after (lower right) one CLAEN iteration
- Only a priori correction for instrumental polarization applied
- The structure near FD=0 results from the remaining (large) instrumental polarization. This will be removed by proper calibration in the future

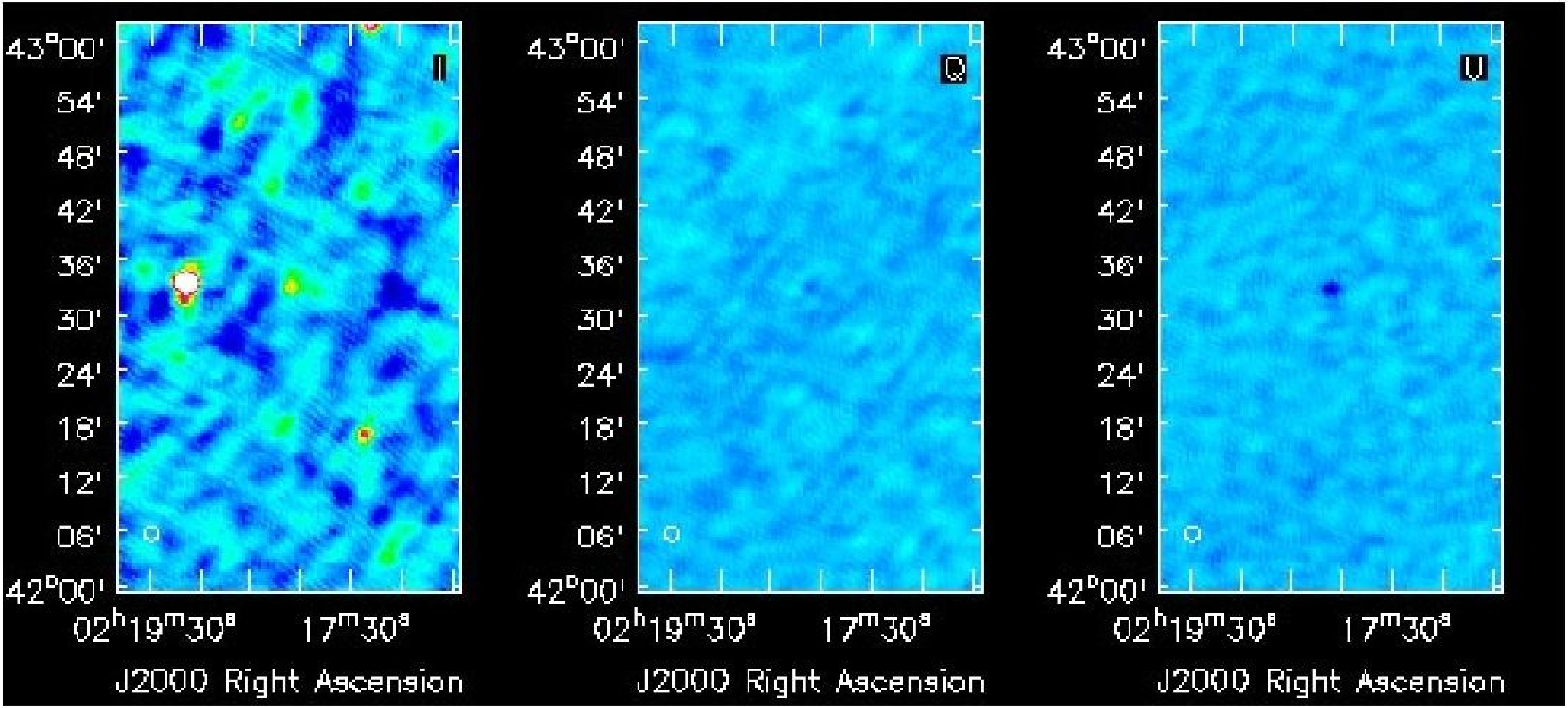
Pulsar J0218





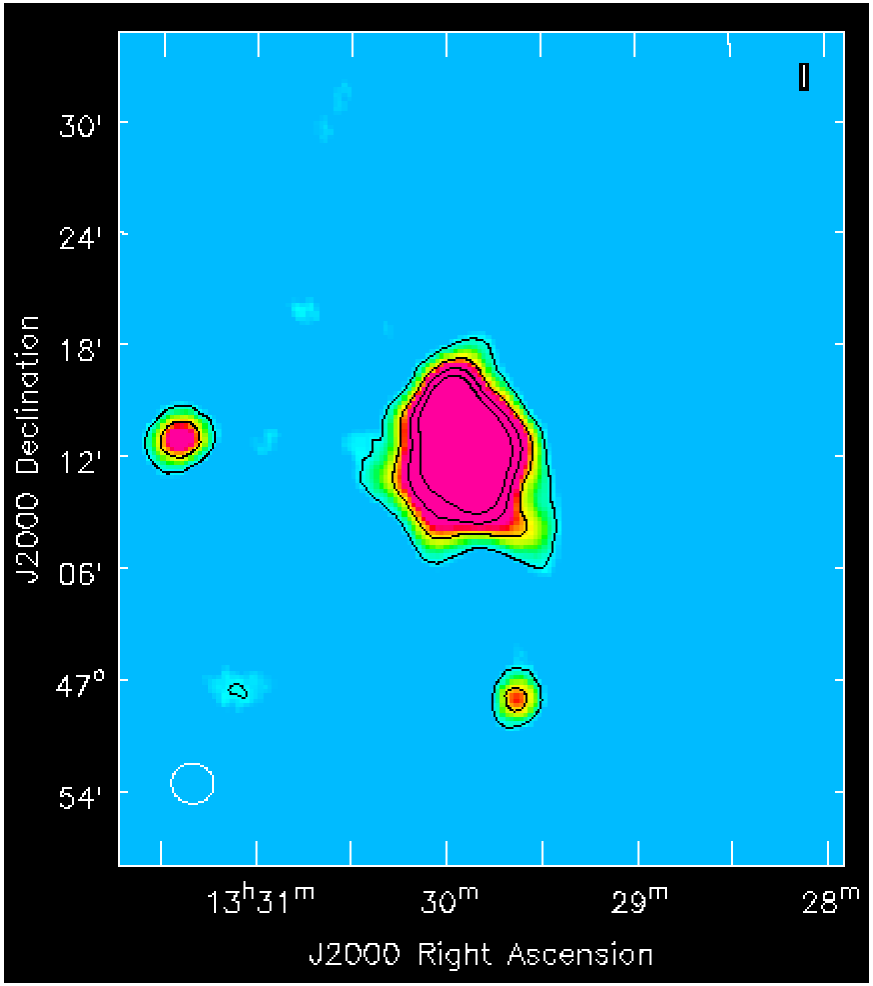
Work by the MKSP commissioners, lead by A Horneffer, MKSP RM synthesis development lead by M Bell

Closeup Of Pulsar Region

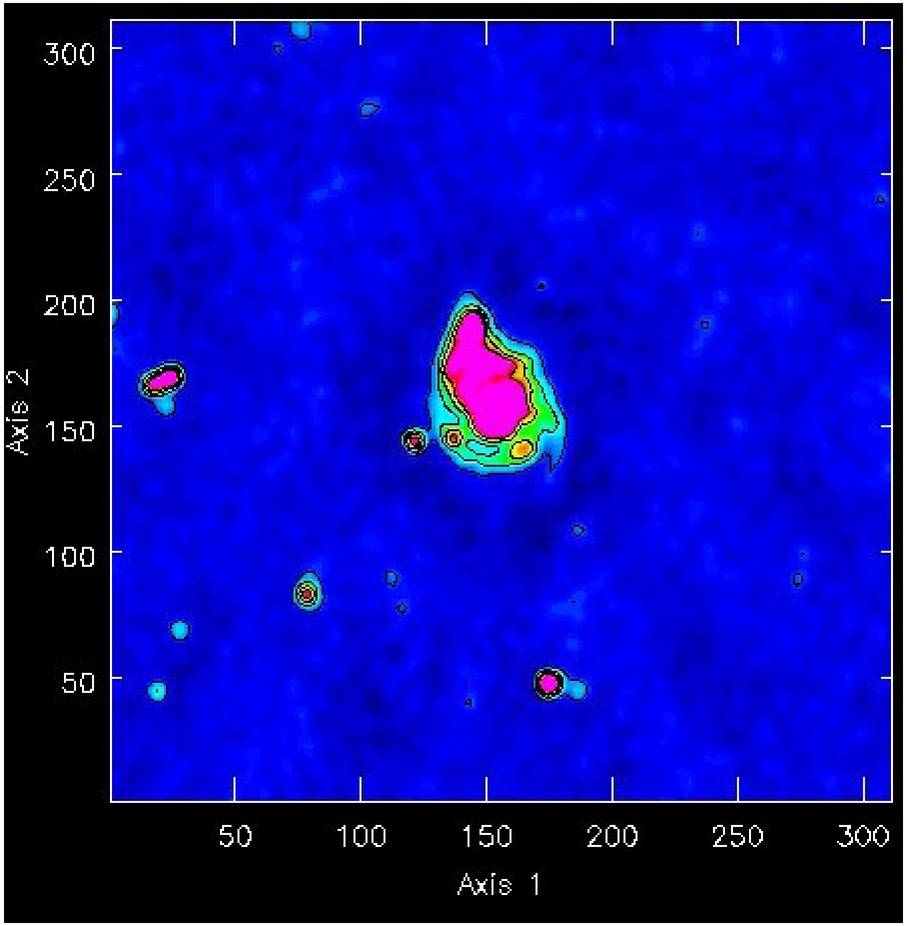


146.898 MHz Image courtesy Andreas Horneffer

M51 Stokes I



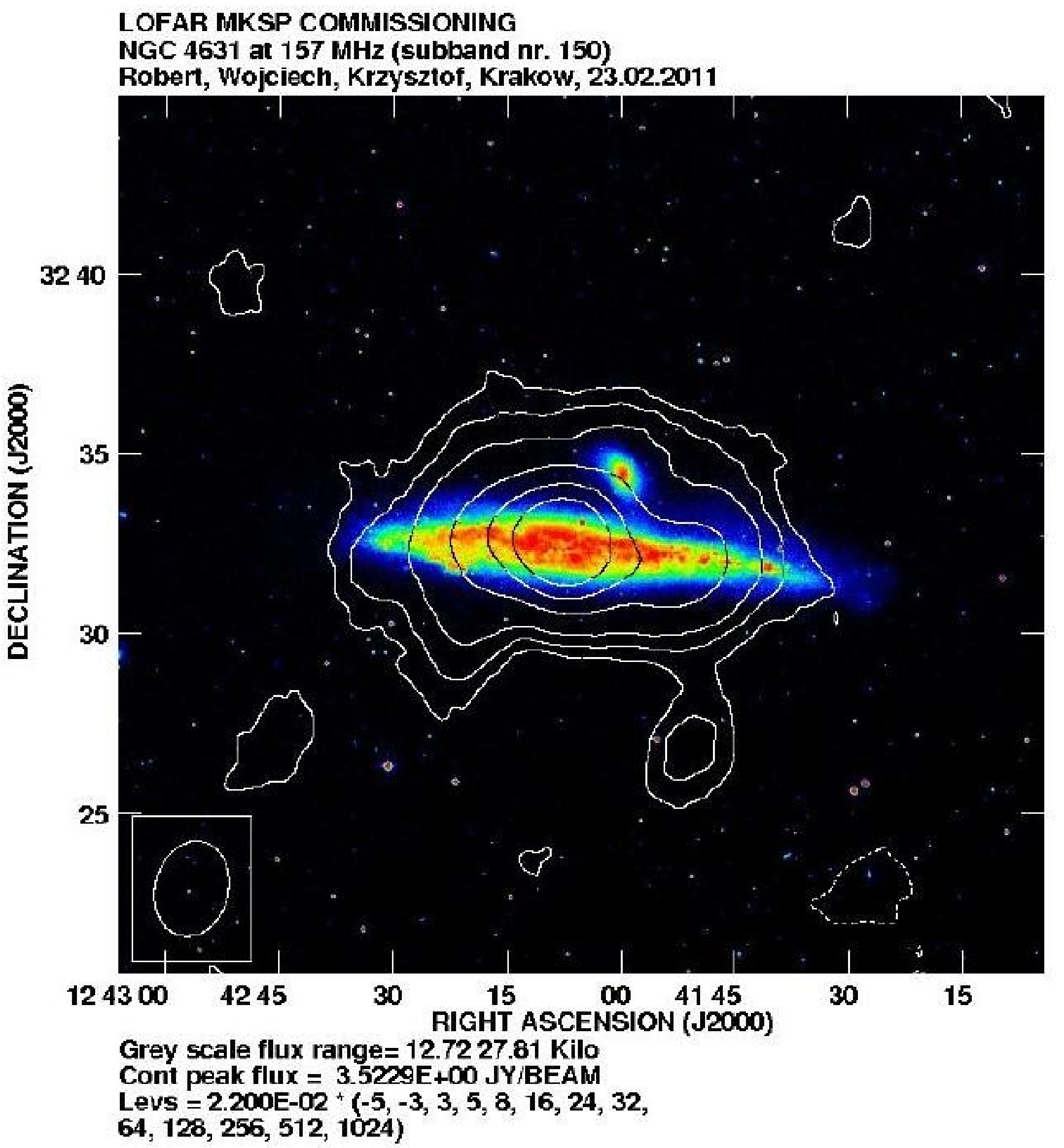
NVSS



LOFAR

work by D Mulcahy, see next talk

NGC 4631 Stokes *I*



R. Drzazga

Conclusions

- LOFAR will be a fantastic instrument for accurate, precision measurements of weak magnetic fields
- Combined with RM synthesis, LOFAR will open up a new era in measuring the *distribution* of magnetic fields and electron densities, not just a single number for the integrated path length
- The Cosmic Magnetism KSP of LOFAR is responsible for developing and commissioning of LOFAR to enable polarization measurements and RM synthesis

The End