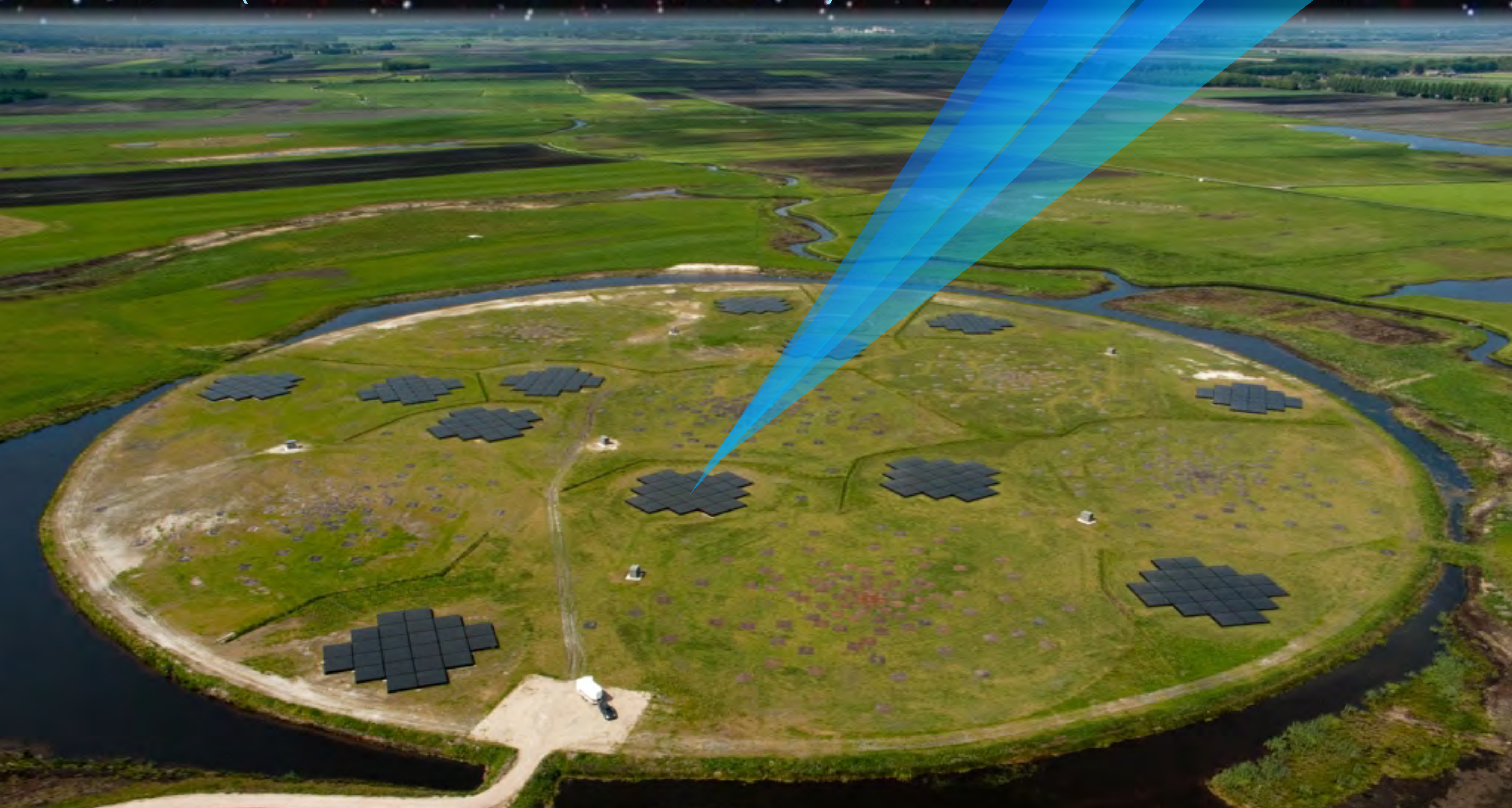
# Pulsars and Fast Transients with LOFAR

Jason Hessels
(ASTRON/U of Amsterdam)

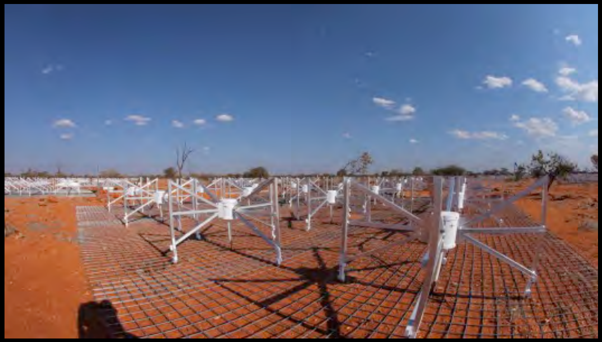


# LOFAR

# Rebirth of Low-Frequency Radio Astronomy

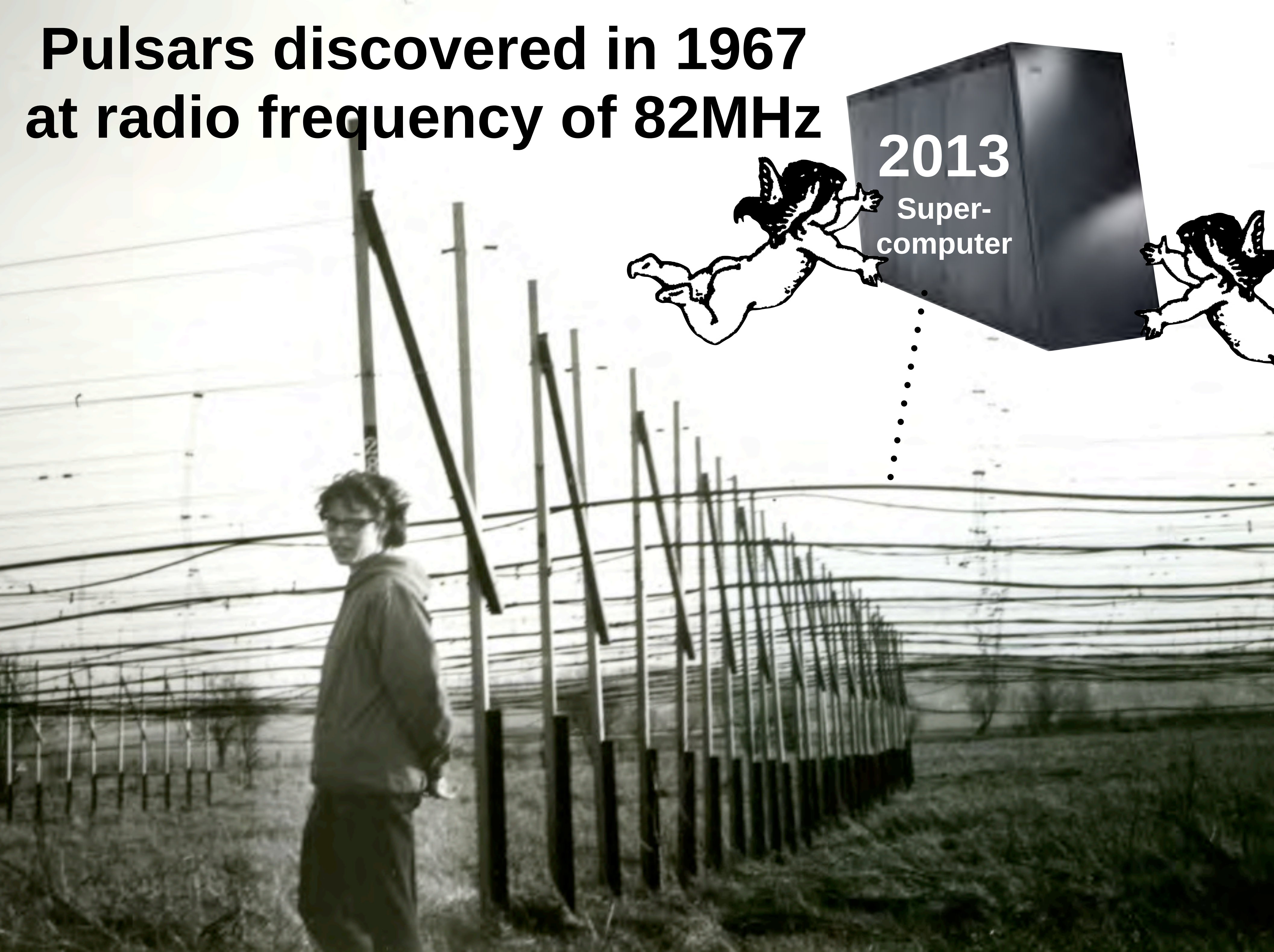
**LOFAR**
**LOw-Frequency ARray**

**LWA**
**Long-Wavelength Array**

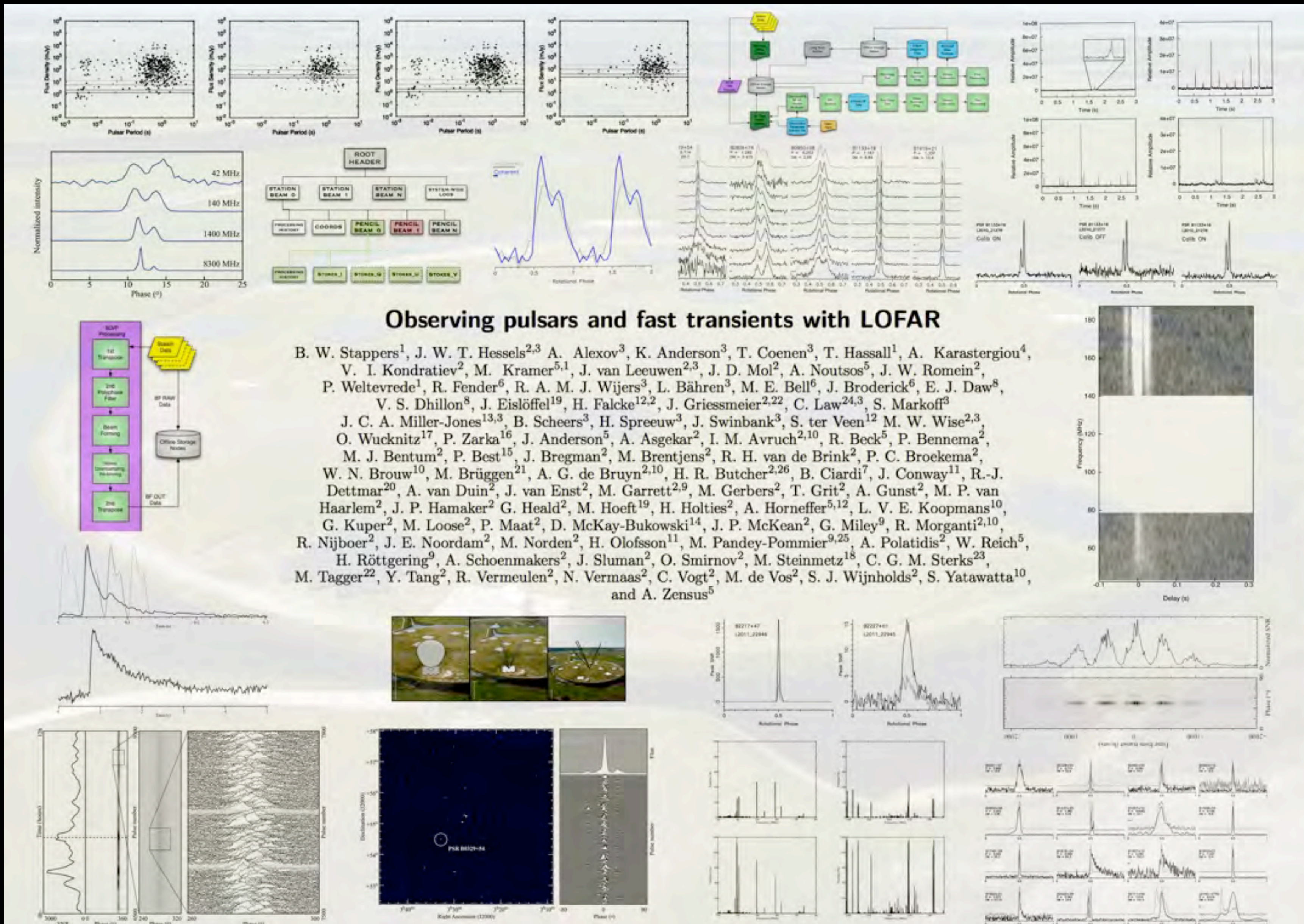


**MWA**
**Murchison Widefield Array**

**It's not a competition; it's a community**


Pulsars discovered in 1967
at radio frequency of 82MHz
2013
Super-
computer

# LOFAR Pulsar Reference Paper




Stappers, Hessels, Alexov et al. 2011

# LOFAR Reference Paper Online!

## http://arxiv.org/abs/1305.3550

### LOFAR: The LOw-Frequency ARray

M. P. van Haarlem, M. W. Wise, A. W. Gunst, G. Heald, J. P. McKean, J. W. T. Hessels, A. G. de Bruyn, R. Nijboer, J. Swinbank, R. Fallows, M. Brentjens, A. Nelles, R. Beck, H. Falcke, R. Fender, J. Hörandel, L. V. E. Koopmans G. Mann, G. Miley, H. Röttgering, B. W. Stappers, R. A. M. J. Wijers, S. Zaroubi, M. van den Akker, A. Alexov, J. Anderson, K. Anderson, A. van Ardenne, M. Arts, A. Asgekar, I. M. Avruch, F. Batejat, L. Bähren, M. E. Bell, M. R. Bell, I. van Bemmel, P. Bennema, M. J. Bentum, G. Bernardi, P. Best, L. Bîrzan, A. Bonafede, A.-J. Boonstra, R. Braun, J. Bregman, F. Breitling, R. H. van de Brink, J. Broderick, P. C. Broekema, W. N. Brouw, M. Brüggen, H. R. Butcher, W. van Cappellen, B. Ciardi, T. Coenen, J. Conway, A. Coolen, A. Corstanje, S. Damstra, et al. (139 additional authors not shown)

*(Submitted on 15 May 2013)*

LOFAR, the LOw-Frequency ARray, is a new-generation radio interferometer constructed in the north of the Netherlands and across europe. Utilizing a novel phased-array design, LOFAR covers the largely unexplored low-frequency range from 10-240 MHz and provides a number of unique observing capabilities. Spreading out from a core located near the village of Exloo in the northeast of the Netherlands, a total of 40 LOFAR stations are nearing completion. A further five stations have been deployed throughout Germany, and one station has been built in each of France, Sweden, and the UK. Digital beam-forming techniques make the LOFAR system agile and allow for rapid repointing of the telescope as well as the potential for multiple simultaneous observations. With its dense core array and long interferometric baselines, LOFAR achieves unparalleled sensitivity and angular resolution in the low-frequency radio regime. The LOFAR facilities are jointly operated by the International LOFAR Telescope (ILT) foundation, as an observatory open to the global astronomical community. LOFAR is one of the first radio observatories to feature automated processing pipelines to deliver fully calibrated science products to its user community. LOFAR's new capabilities, techniques and modus operandi make it an important pathfinder for the Square Kilometre Array (SKA). We give an overview of the LOFAR instrument, its major hardware and software components, and the core science objectives that have driven its design. In addition, we present a selection of new results from the commissioning phase of this new radio observatory.

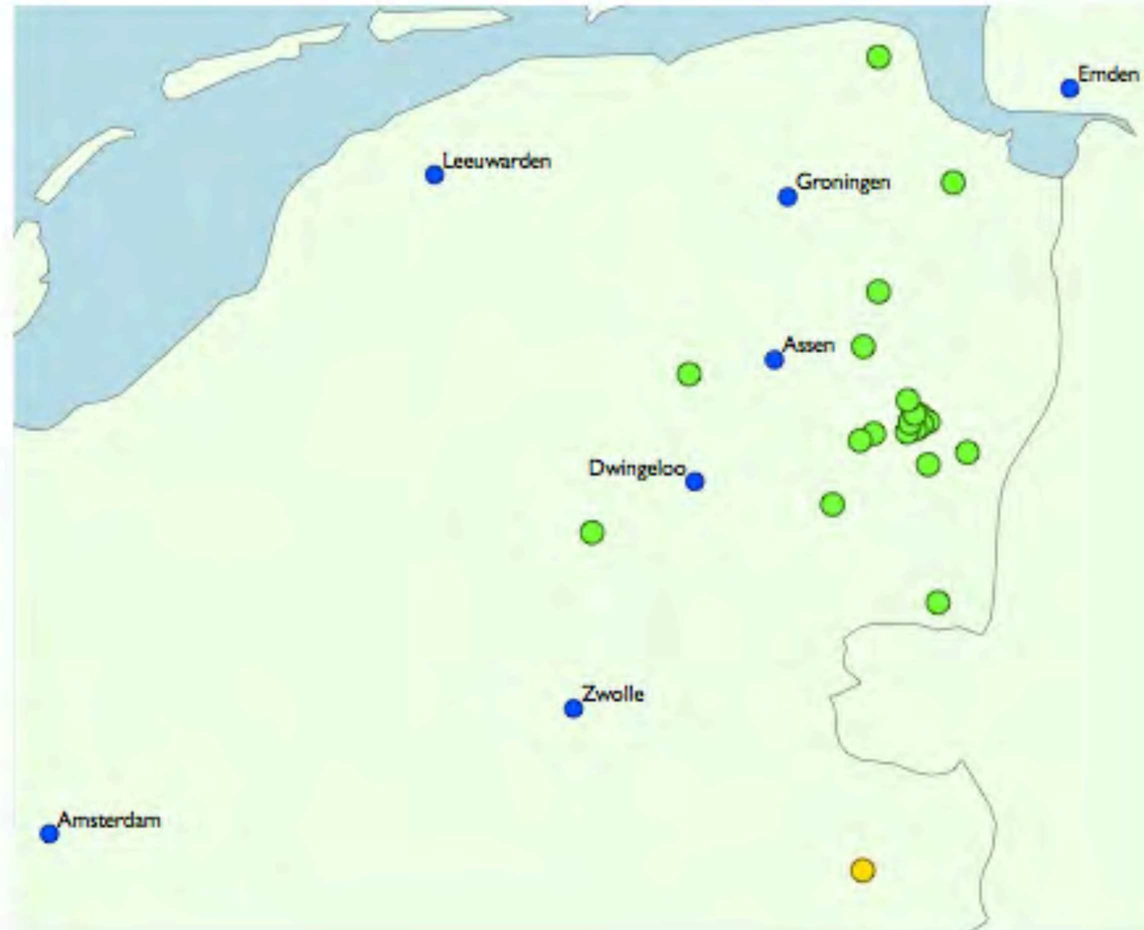
**van Haarlem et al. 2013**

# LOFAR “Superterp”

# LOFAR Across Europe


## 40 Dutch + 9 Intl. Stations

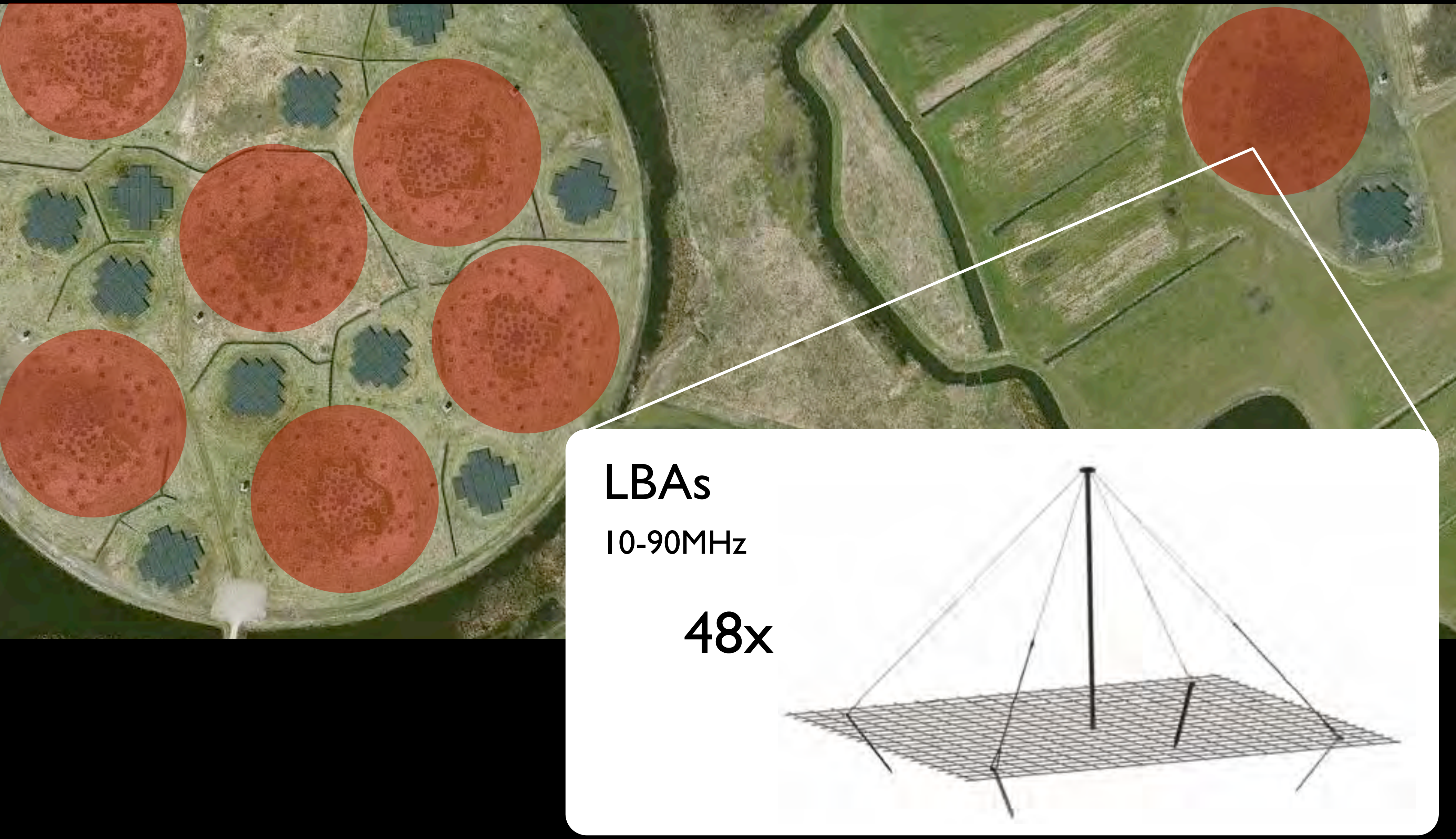
# LOFAR in NL



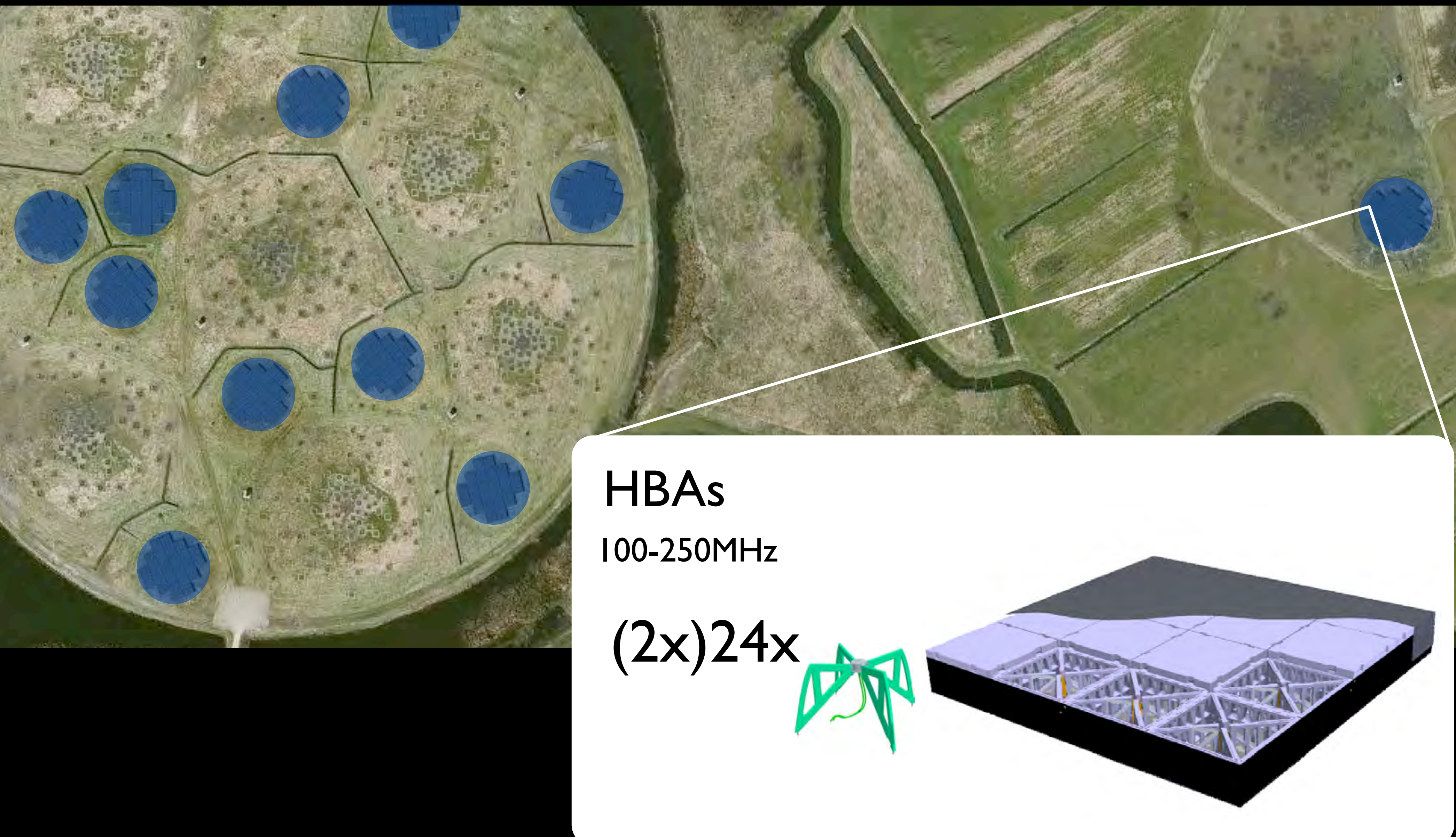

**24 Core + 16 Remote Stations**

# LOFAR

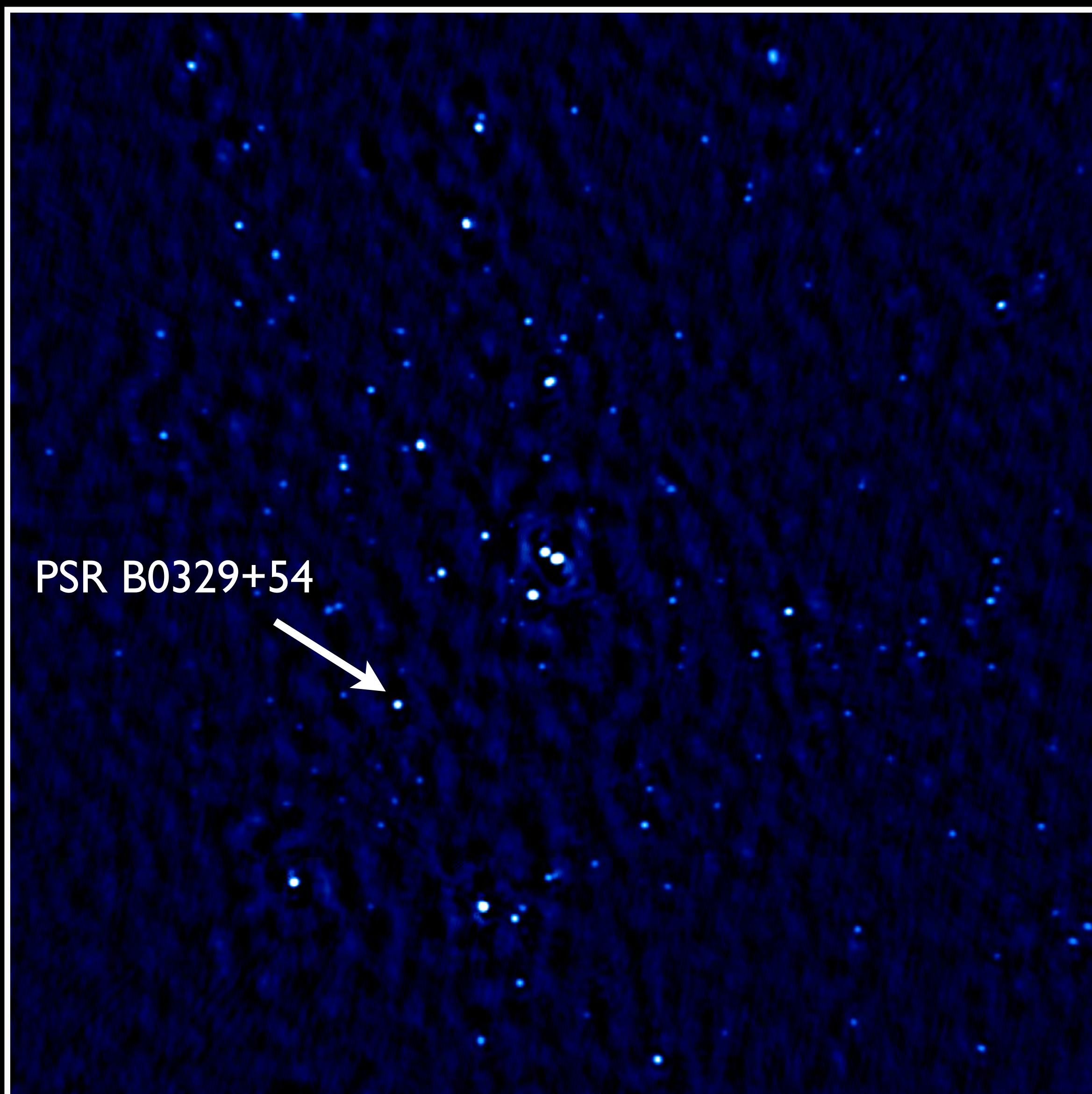
# LOFAR

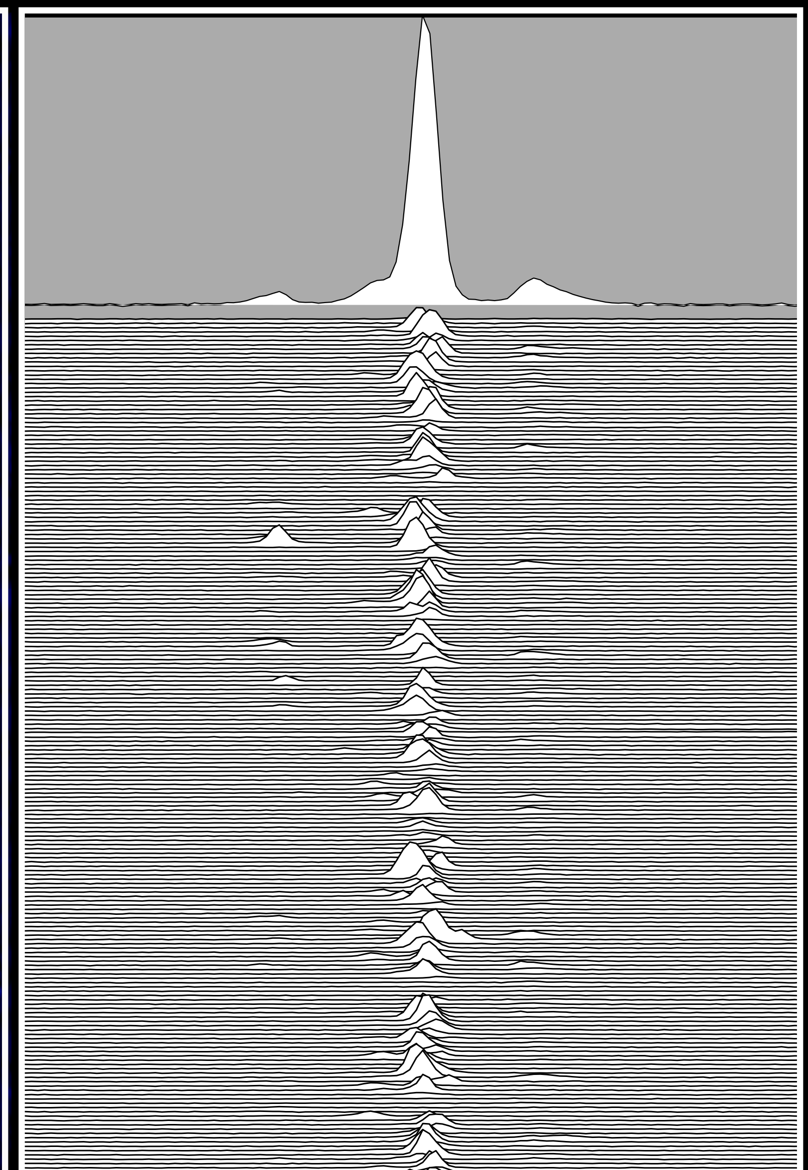


# LOFAR



# Basics of Pulsar Timing
## Instrumentation

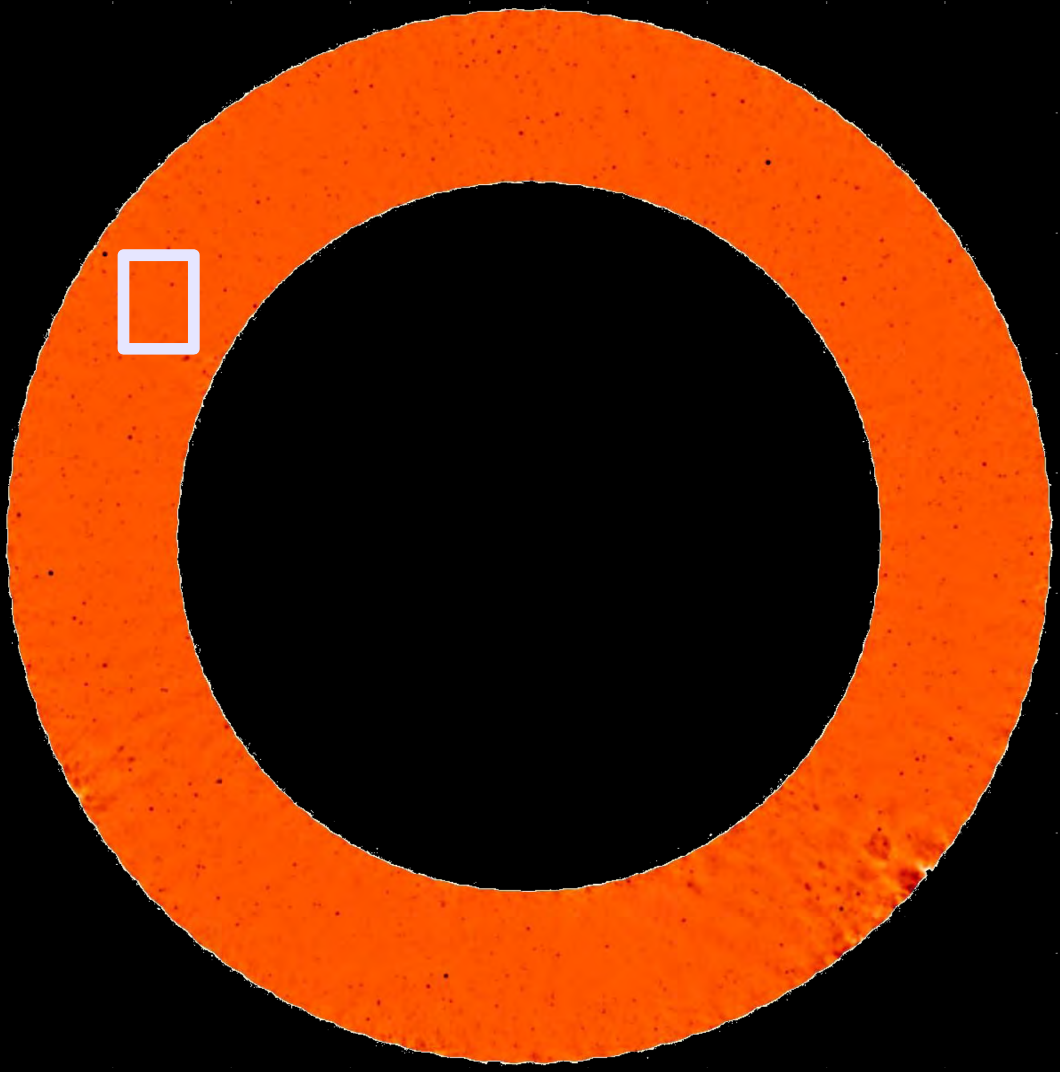


**1-s time res.** **1-ms time res.**

# LOFAR Radio Sky Monitor

Full Zenith strip session



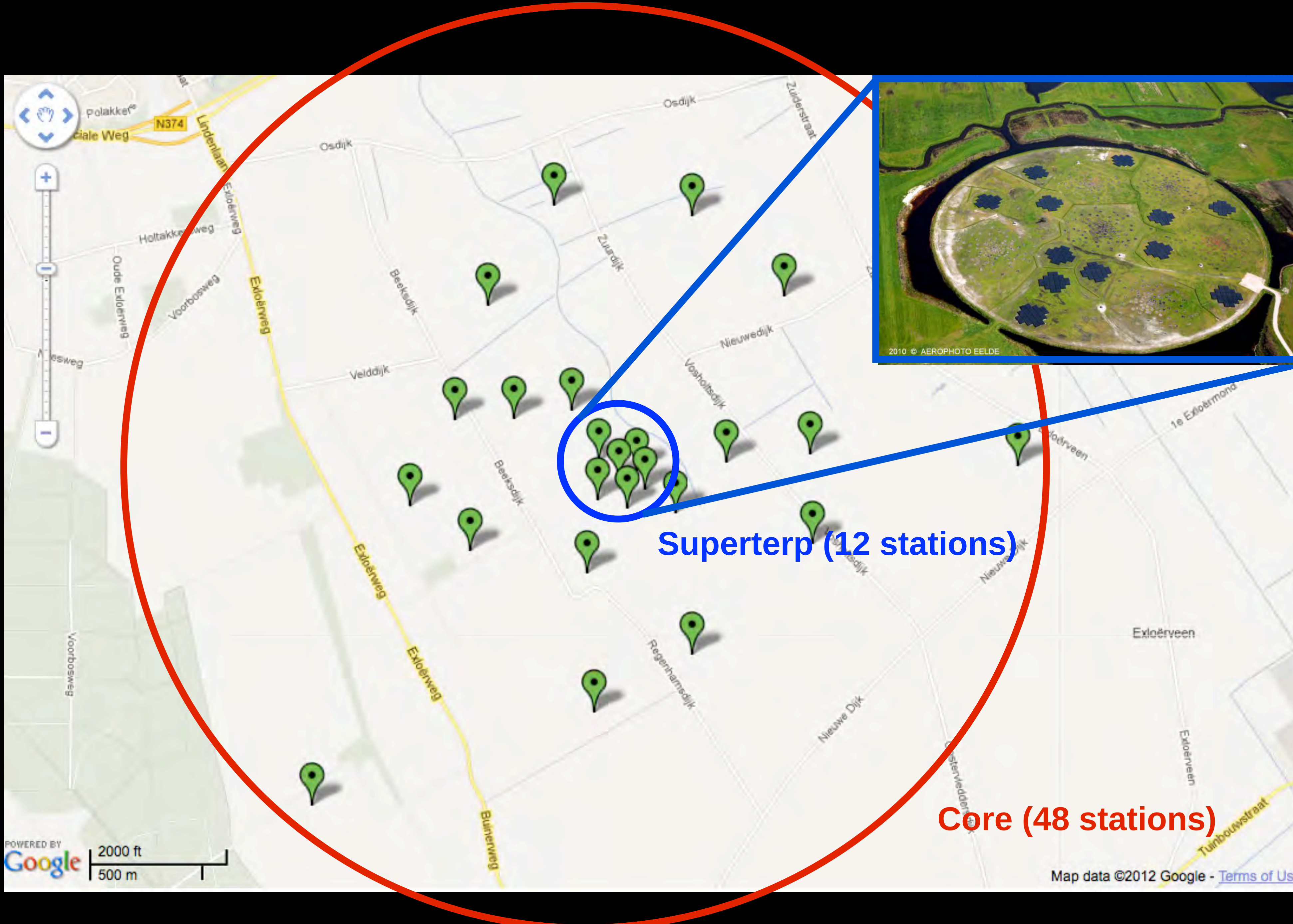
- ~12mJy/beam RMS noise.
- ~5x confusion limit for the 6-km baselines used so far.

Breton

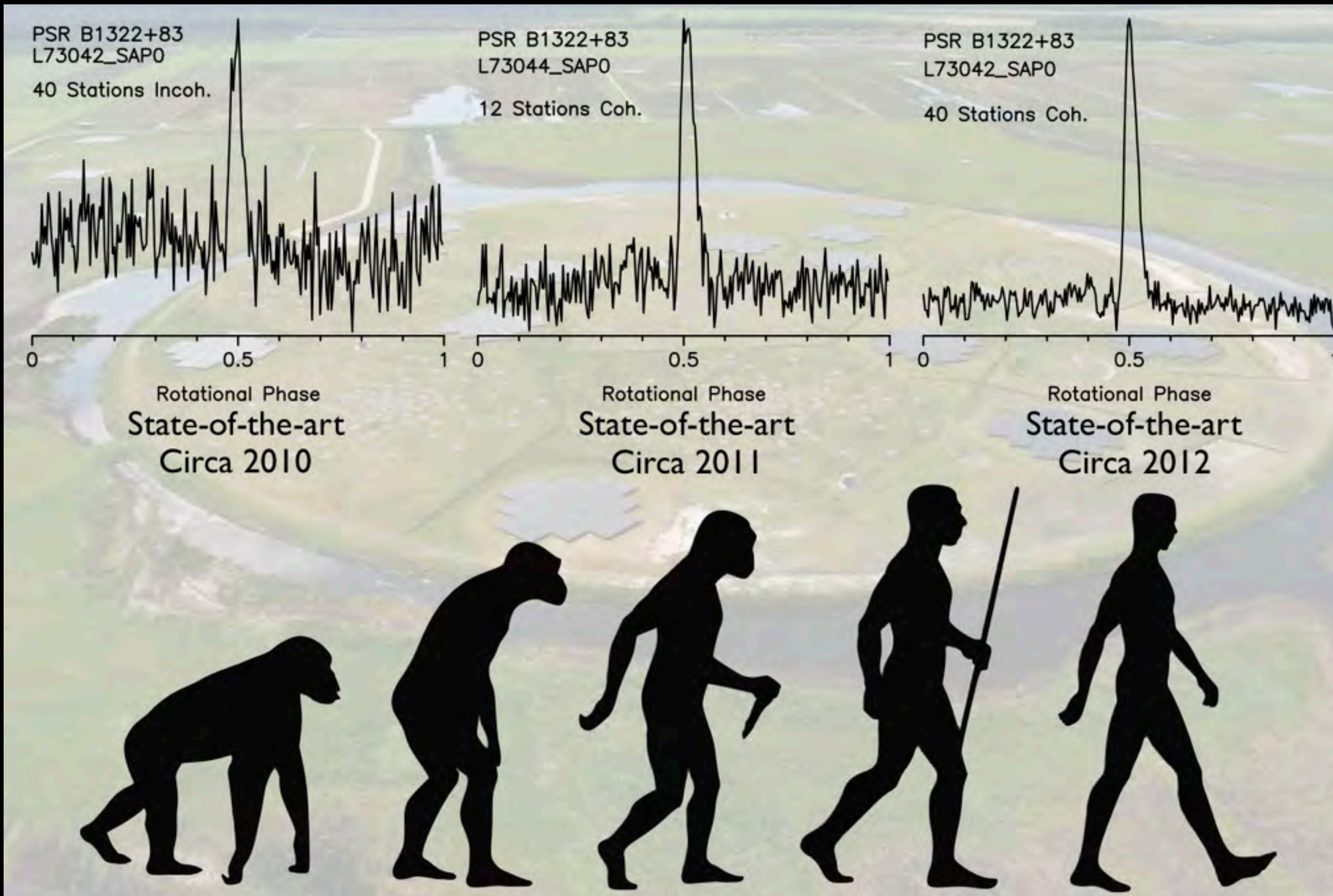
# LOFAR Pulsar Working Group

| | |
|---|---|
| Jason Hessels (co-lead) | ASTRON / Universiteit van Amsterdam |
| Ben Stappers (co-lead) | University of Manchester |
| Anya Bilous | Radboud Universiteit Nijmegen |
| Thijs Coenen | Universiteit van Amsterdam |
| Sally Cooper | University of Manchester |
| Heino Falcke | Radboud Universiteit Nijmegen |
| Jean-Mathias Griessmeier | LPC2E/CNRS |
| Tom Hassall | University of Southampton |
| Aris Karastergiou | University of Oxford |
| Evan Keane | MPI für Radioastronomie |
| Vlad Kondratiev | ASTRON |
| Michael Kramer | MPI für Radioastronomie |
| Masaya Kuniyoshi | MPI für Radioastronomie |
| Joeri van Leeuwen | ASTRON / Universiteit van Amsterdam |
| Aris Noutsos | MPI für Radioastronomie |
| Maura Pilia | ASTRON |
| Maciej Serylak | LPC2E/CNRS |
| Charlotte Sobey | MPI für Radioastronomie |
| Sander ter Veen | Radboud Universiteit Nijmegen |
| Joris Verbiest | MPI für Radioastronomie |
| Patrick Weltevrede | University of Manchester |
| Kimon Zagkouris | University of Oxford |

# The LOFAR Core



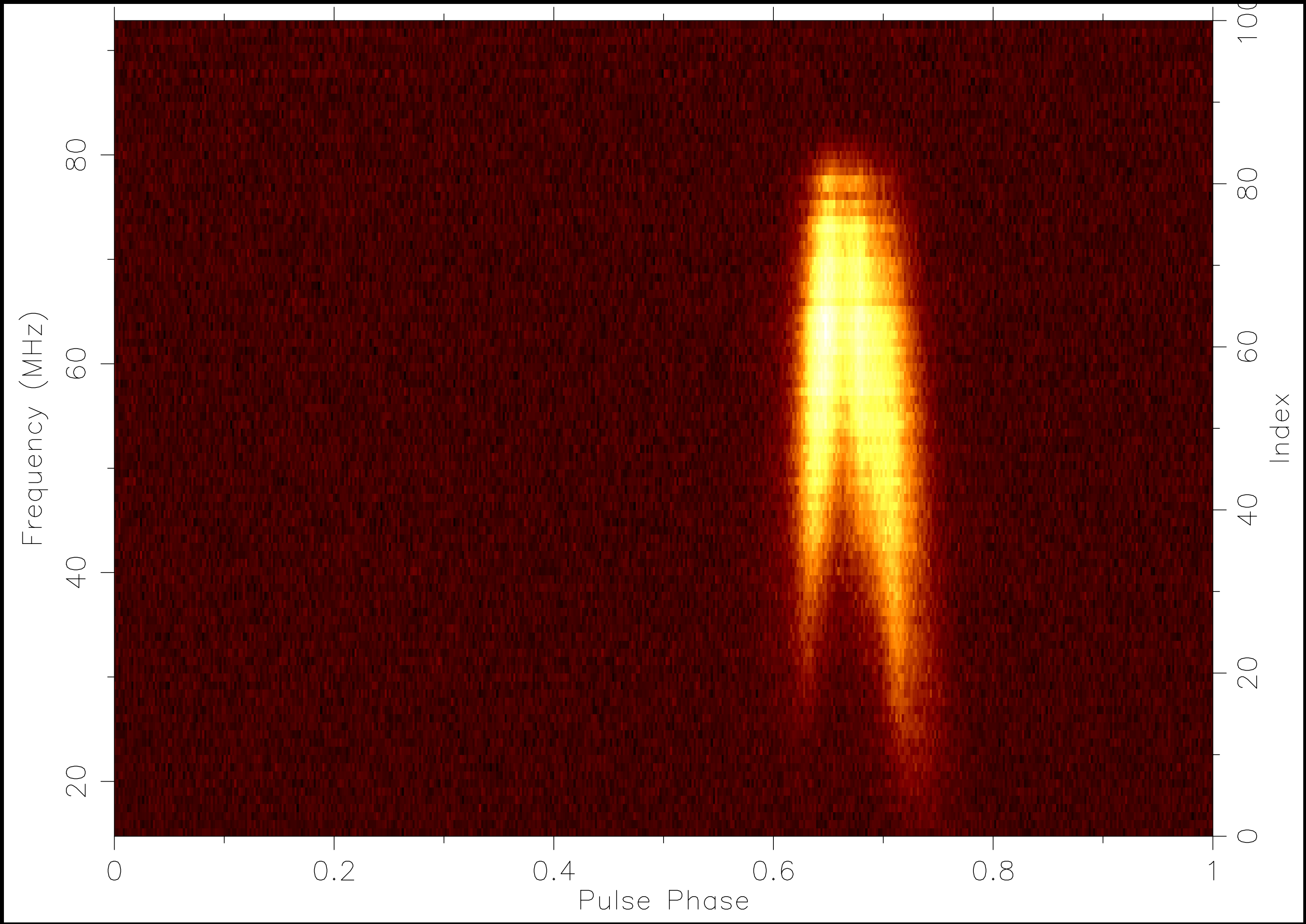
# Evolution of LOFAR's Sensitivity




Hessels

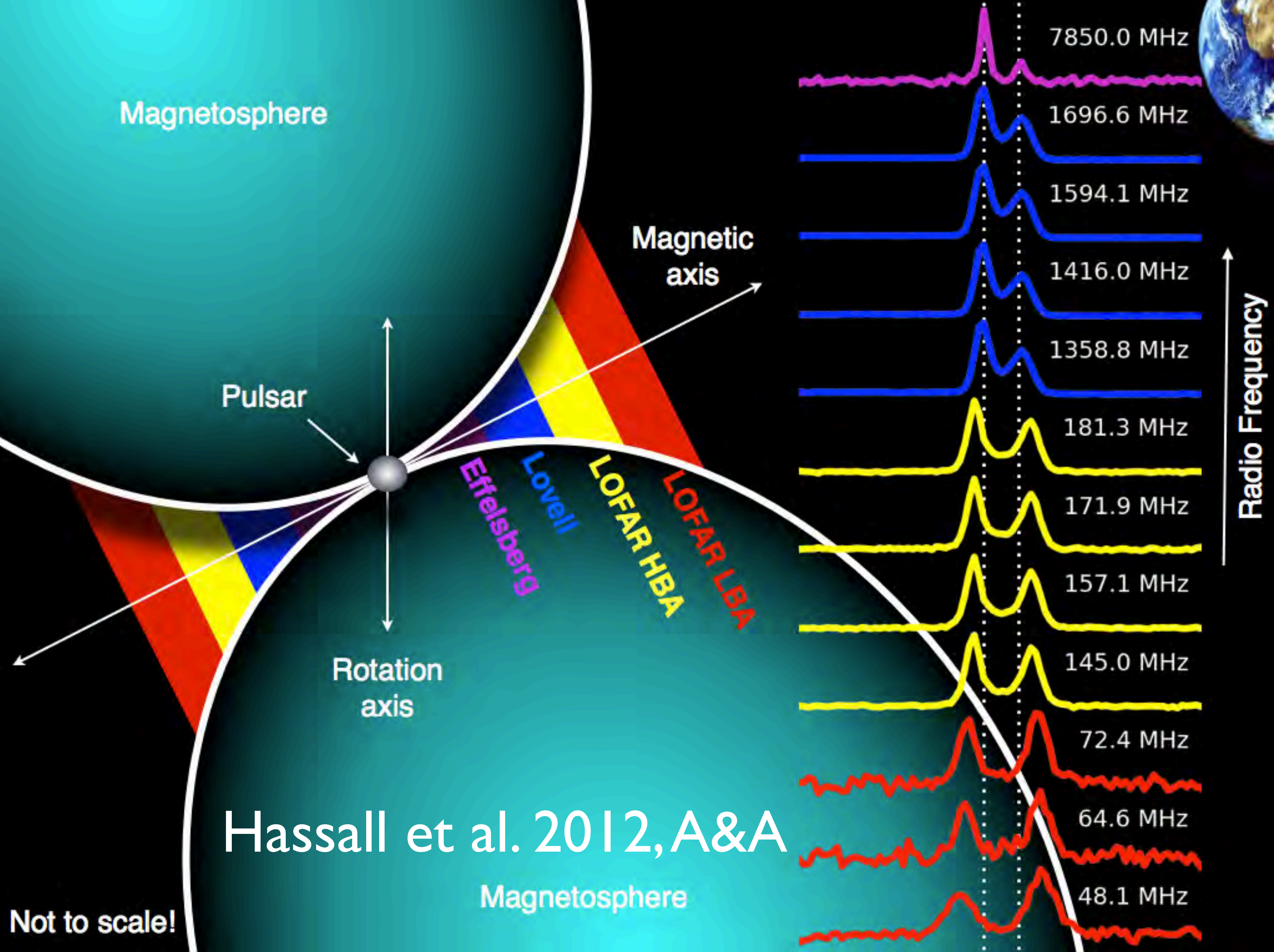
# LOFAR's Enormous Frequency Range

93MHz




15MHz

**PSR B0809+74 detected down to 15MHz**



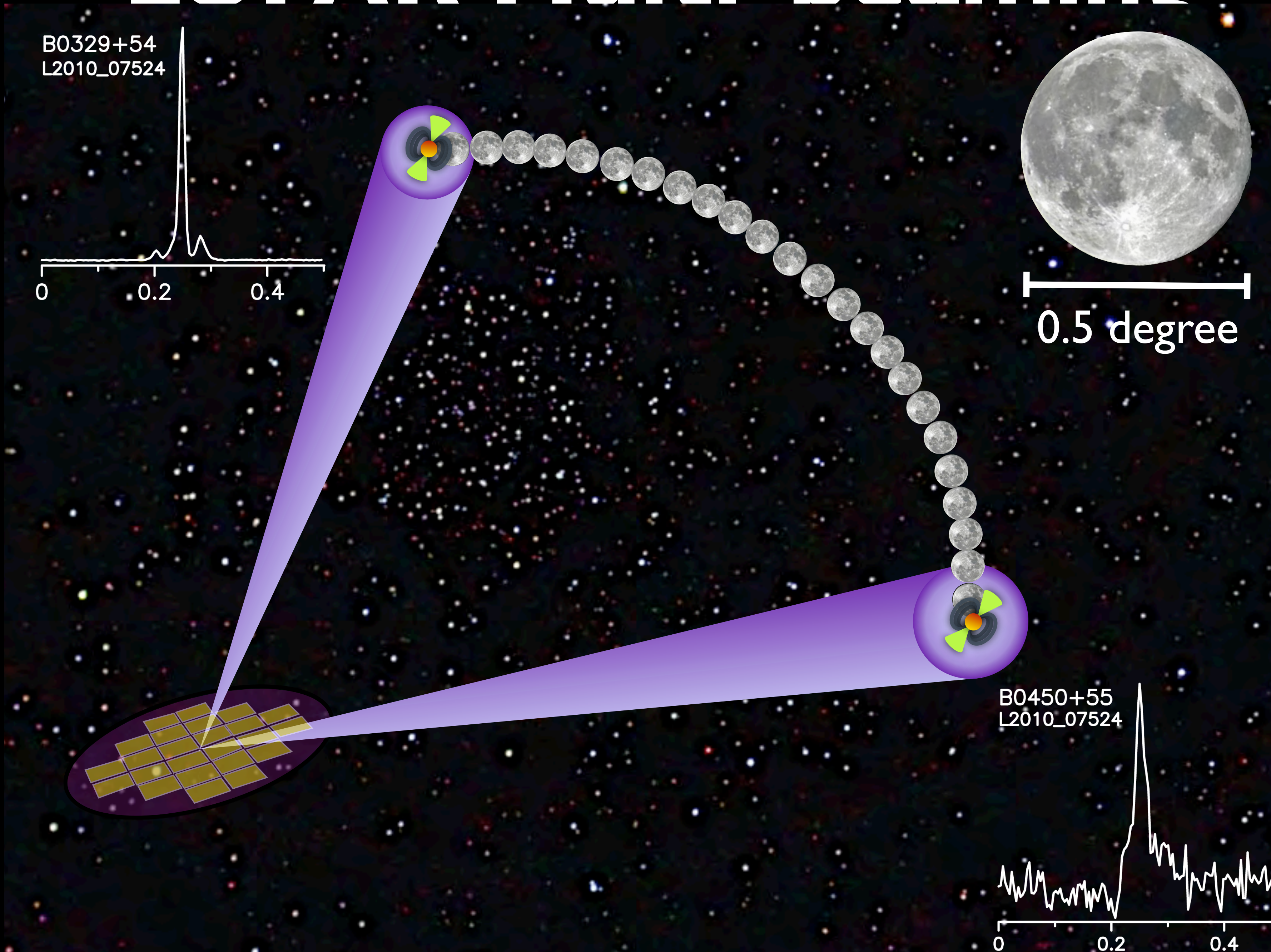

Hassall et al. 2012, A&A

# Flexible Beam-forming

(sparse aperture array)

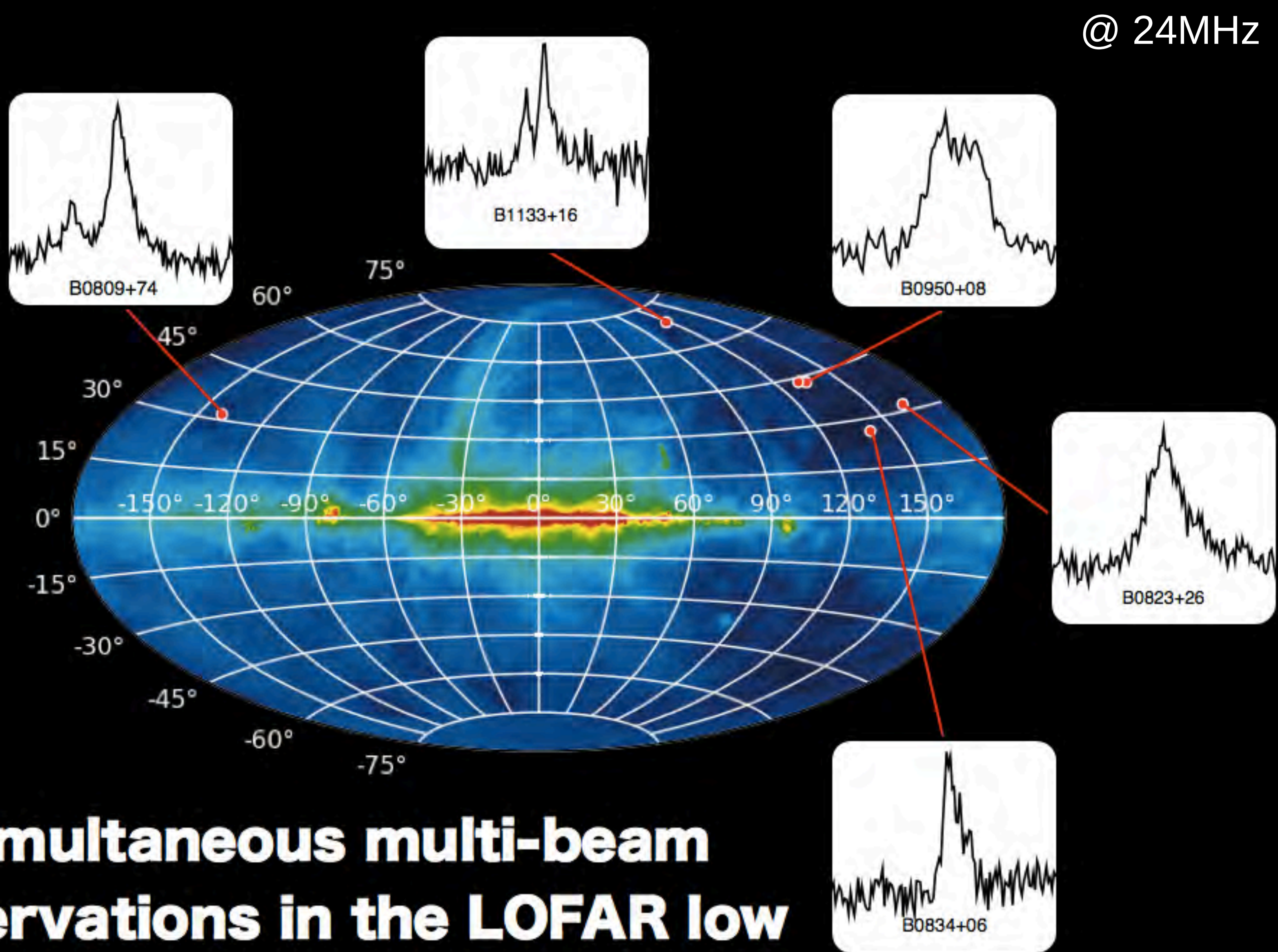

Element beam    Stations beam(s)    Tied-array beam(s)

# LOFAR Multi-beaming




Hessels

# LOFAR Multi-beaming

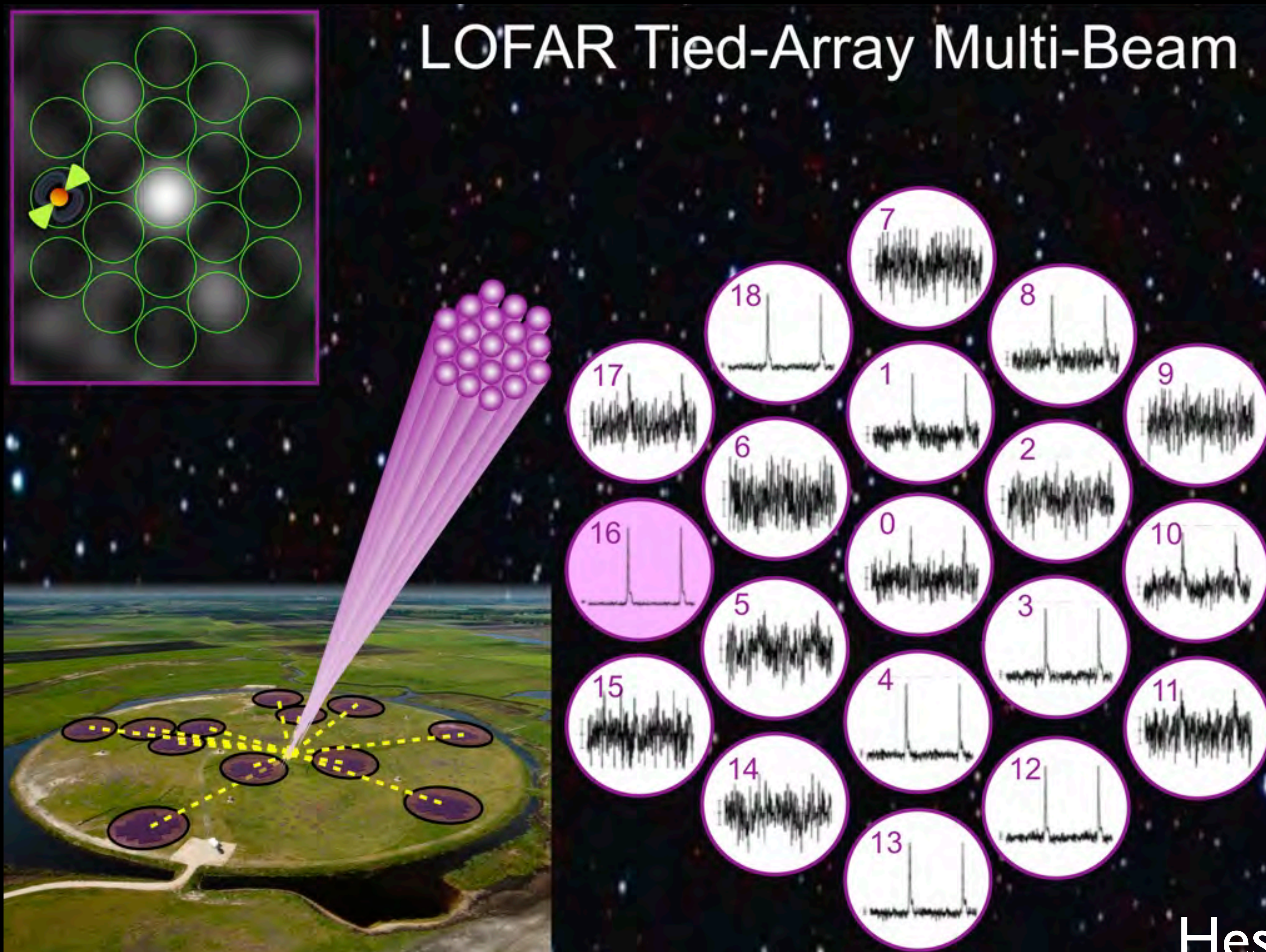



**simultaneous multi-beam observations in the LOFAR low band**

Hassall & Hessels

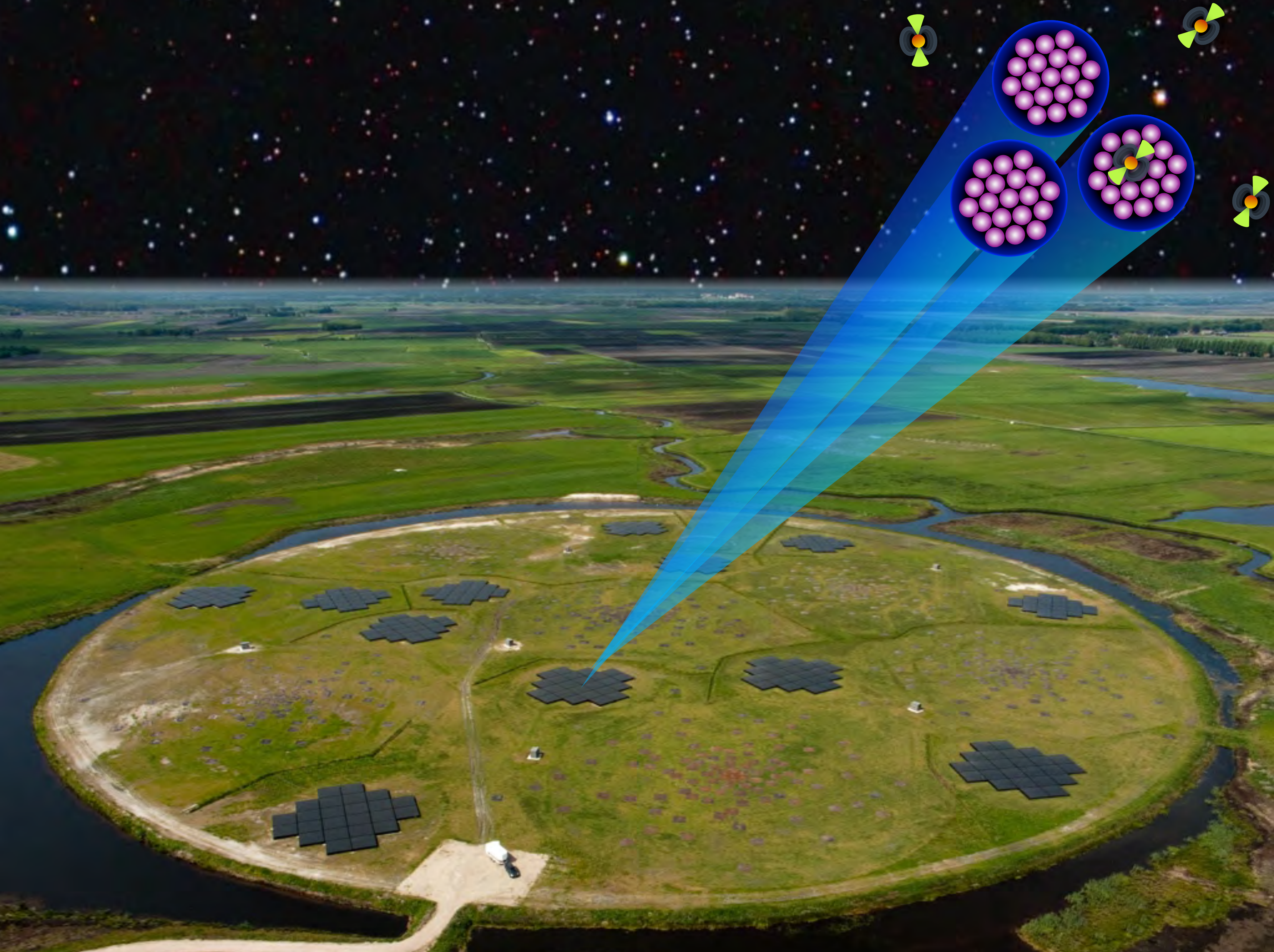
Haslam 408 MHz map courtesy of LAMBDA

# LOFAR Multi-beaming




Hessels

# LOTAAS - LOFAR Tied-Array All-Sky Survey



# LOTAAS

## LOFAR Tied-Array All-Sky Survey

## Survey Specs

- 3 SAPs of 32MHz each (119-151MHz).
- 1hr per pointing (1.5hr all-sky by end... new param. space).
- 0.49ms time resolution, 12kHz frequency channels.
- Find millisecond pulsars out to DM ~ 50 pc cm-3.
- **219 tied-array beams**, 3 incoherent beams.
- 12 sq deg. total per ptg. from tied-array beams.
- 60 sq deg. total per ptg. from incoherent beams.
- Smin ~ 6mJy at 135MHz.

**High-time-resolution version of MSSS, LOFAR's first imaging survey**

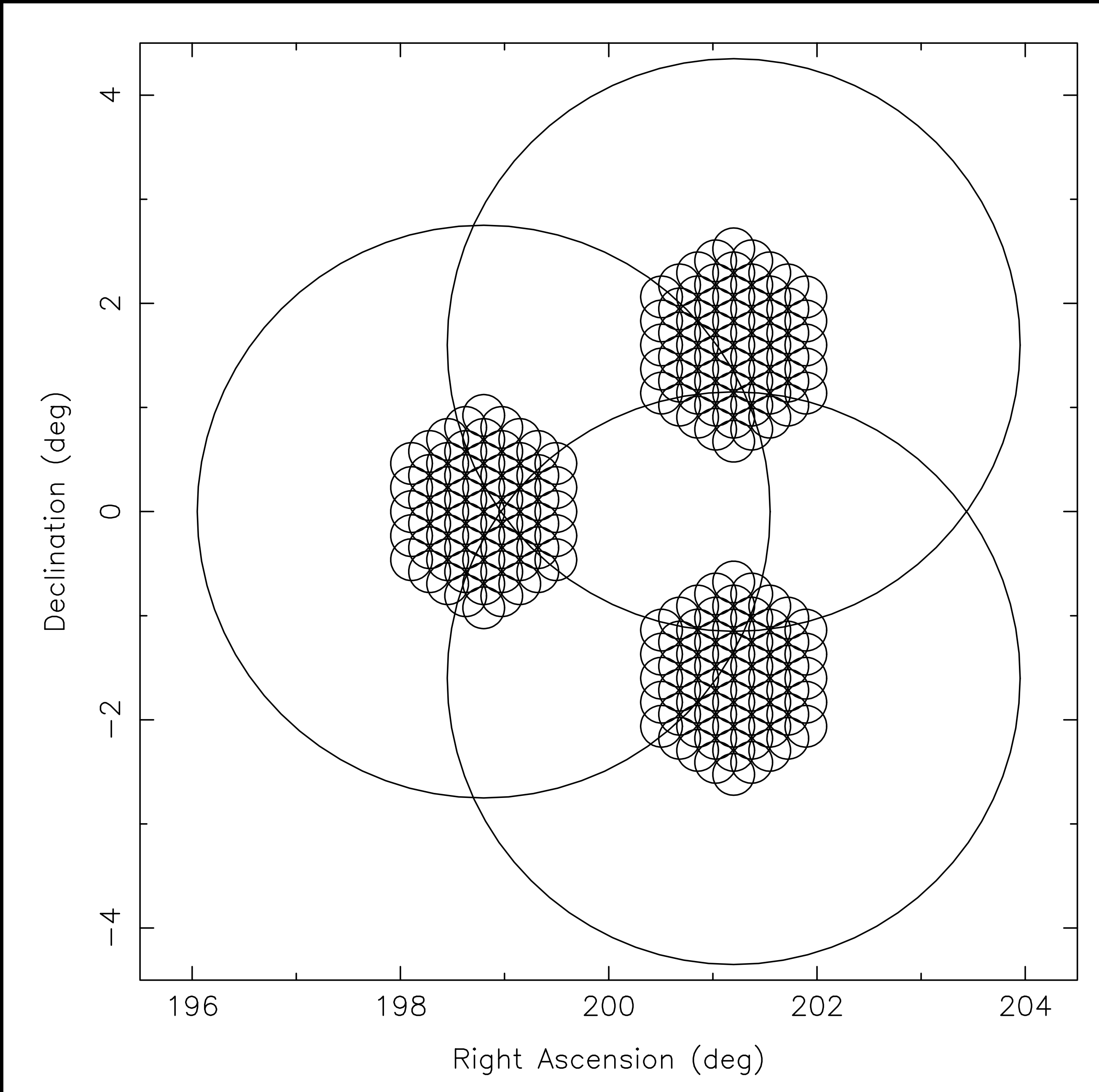
# LOTAAS vs. GBNCC

## (GBNCC = GBT Northern Celestial Cap Survey at 350MHz)

## Compare with state-of-the-art

- LOTAAS at 135MHz vs. GBNCC at 350MHz.
- LOTAAS ~25x the data rate vs. GBNCC
- LOTAAS > 60x the field-of view of GBNCC.
- LOTAAS 24x the dwell time of GBNCC.
- LOTAAS ~2x the cumulative sensitivity of GBNCC.
- LOTAAS lower time resolution and significantly worse at finding millisecond pulsars.
- LOTAAS likely better at finding RRATs (etc.) though instantaneous sensitivity is ~2.5x lower than GBNCC.

Hessels et al., in prep.




222 beams per pointing

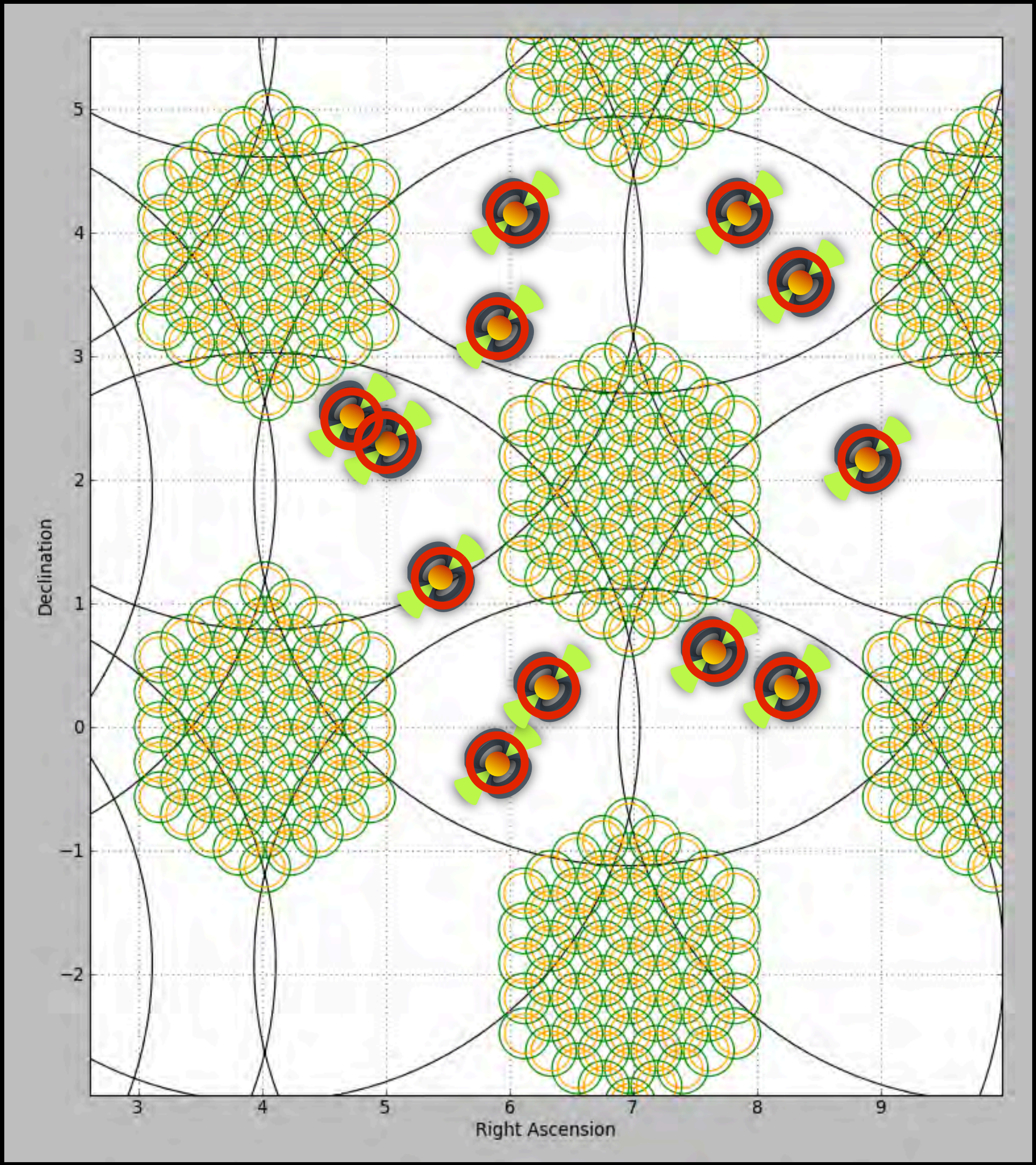
# LOTAAS Single Pointing

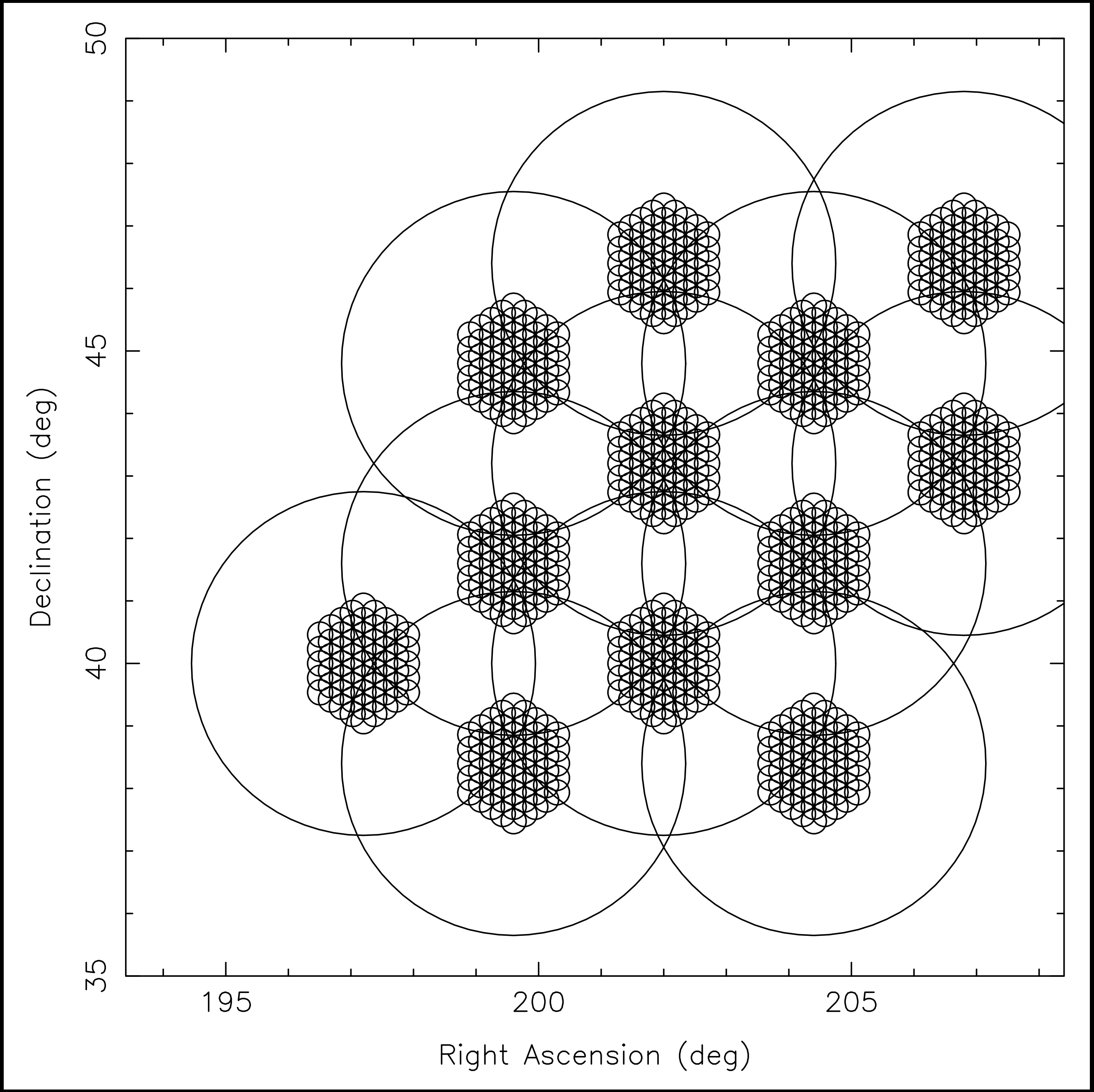
**First SKA-like pulsar survey**

**1 Extra-galactic burst per 10hr observing?**

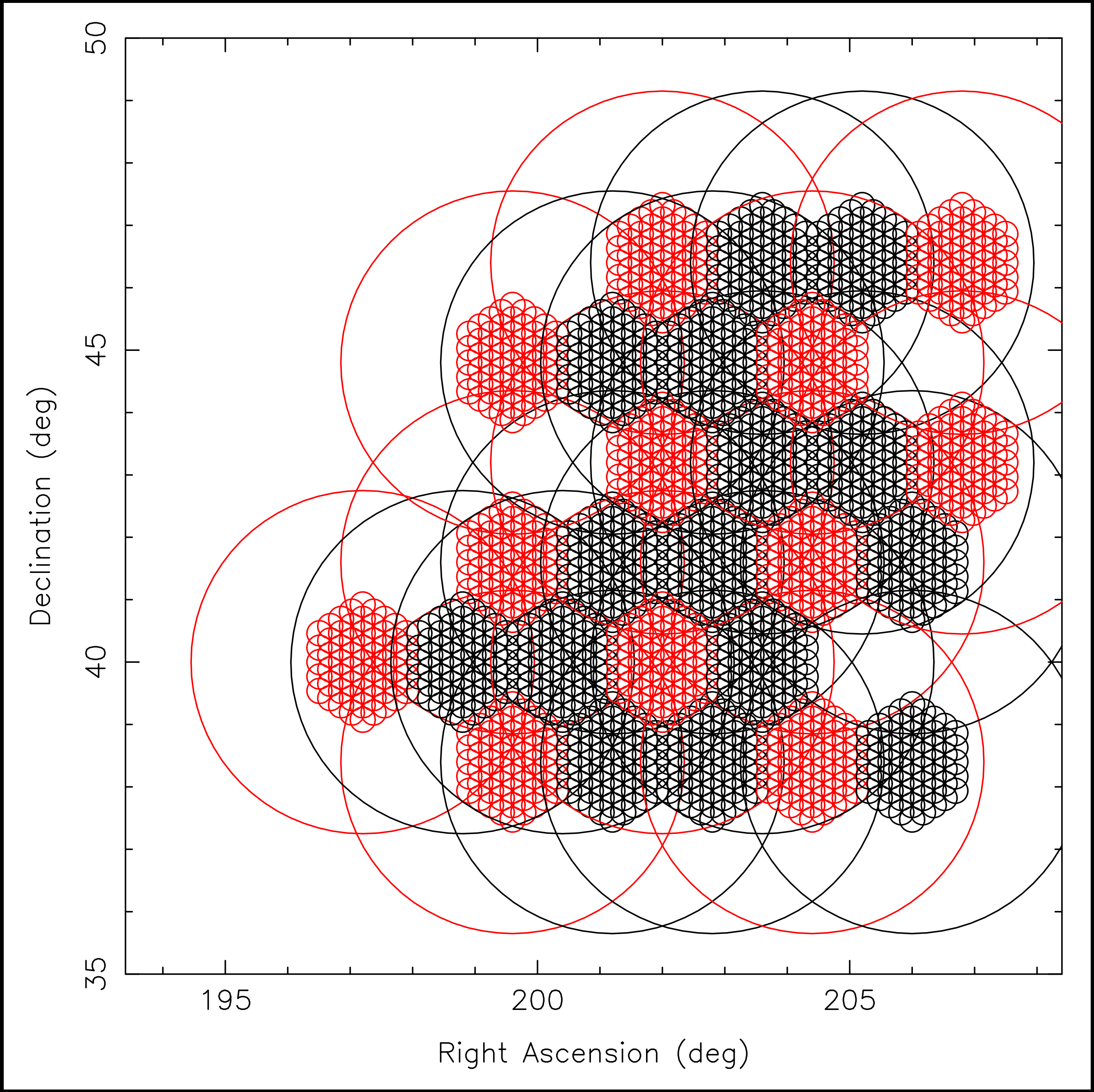
# LOTAAS

## LOFAR Tied-Array All-Sky Survey





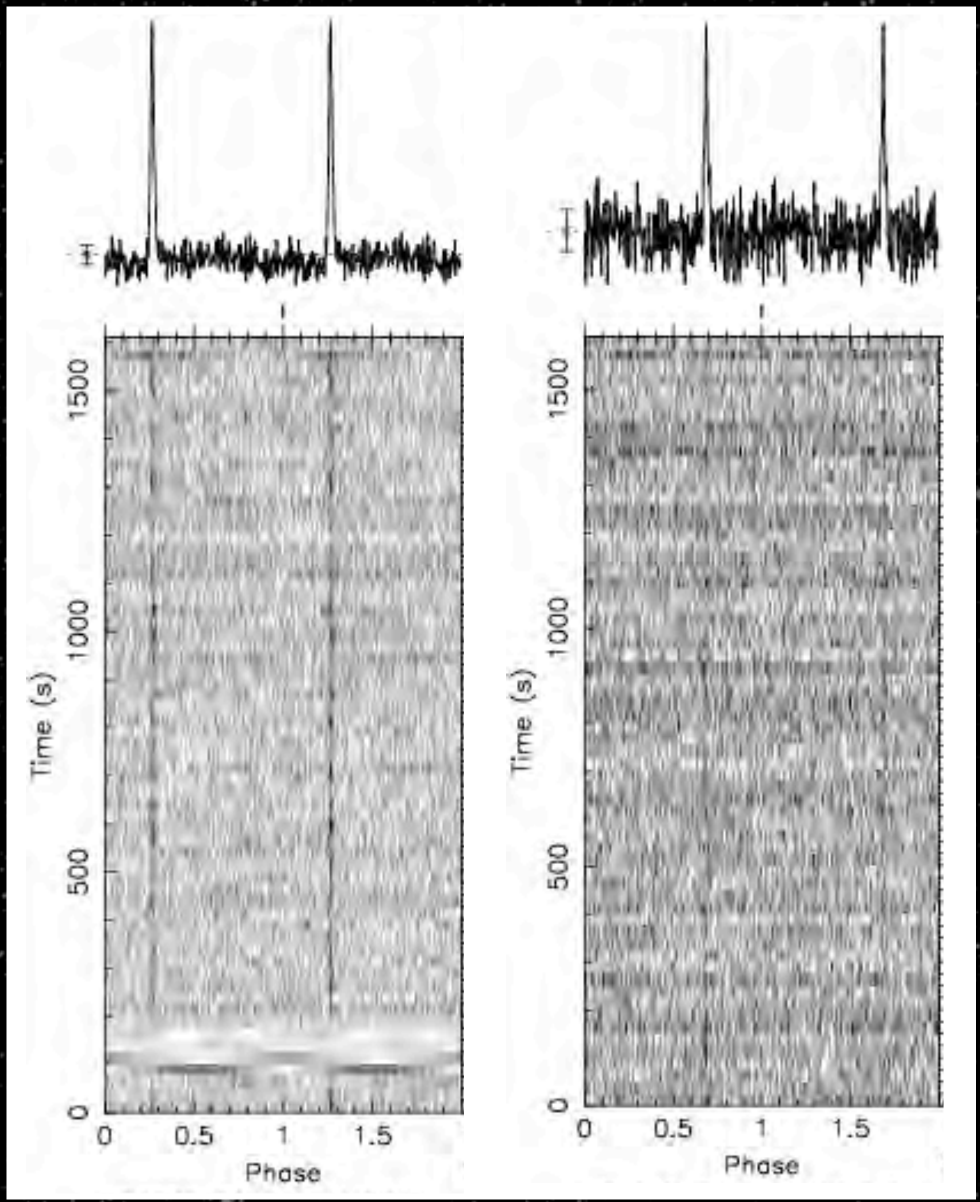

# LOTAAS Sparse Sampling




# LOTAAS Sparse Sampling

# First LOFAR Pulsar Discoveries

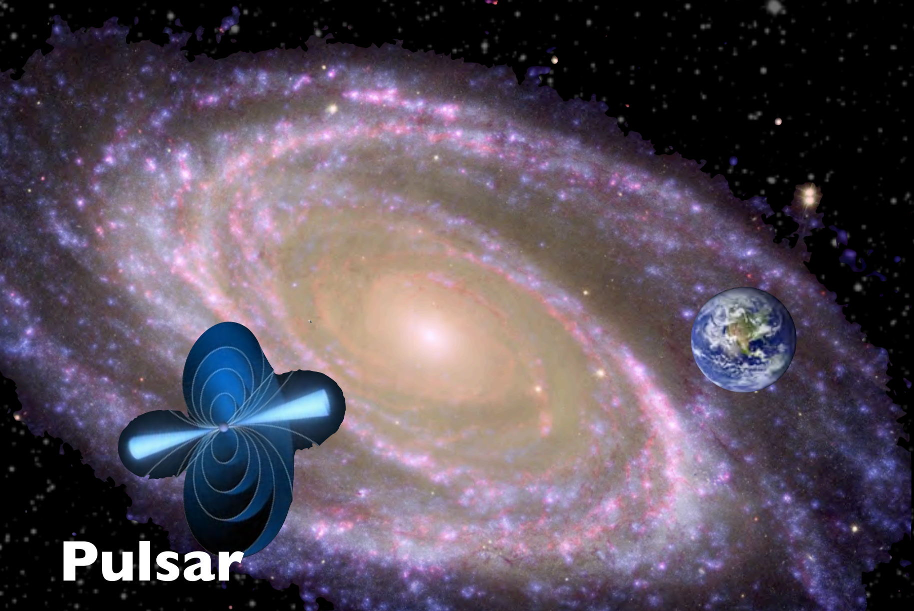
**Expect 1/100 sq. deg.**



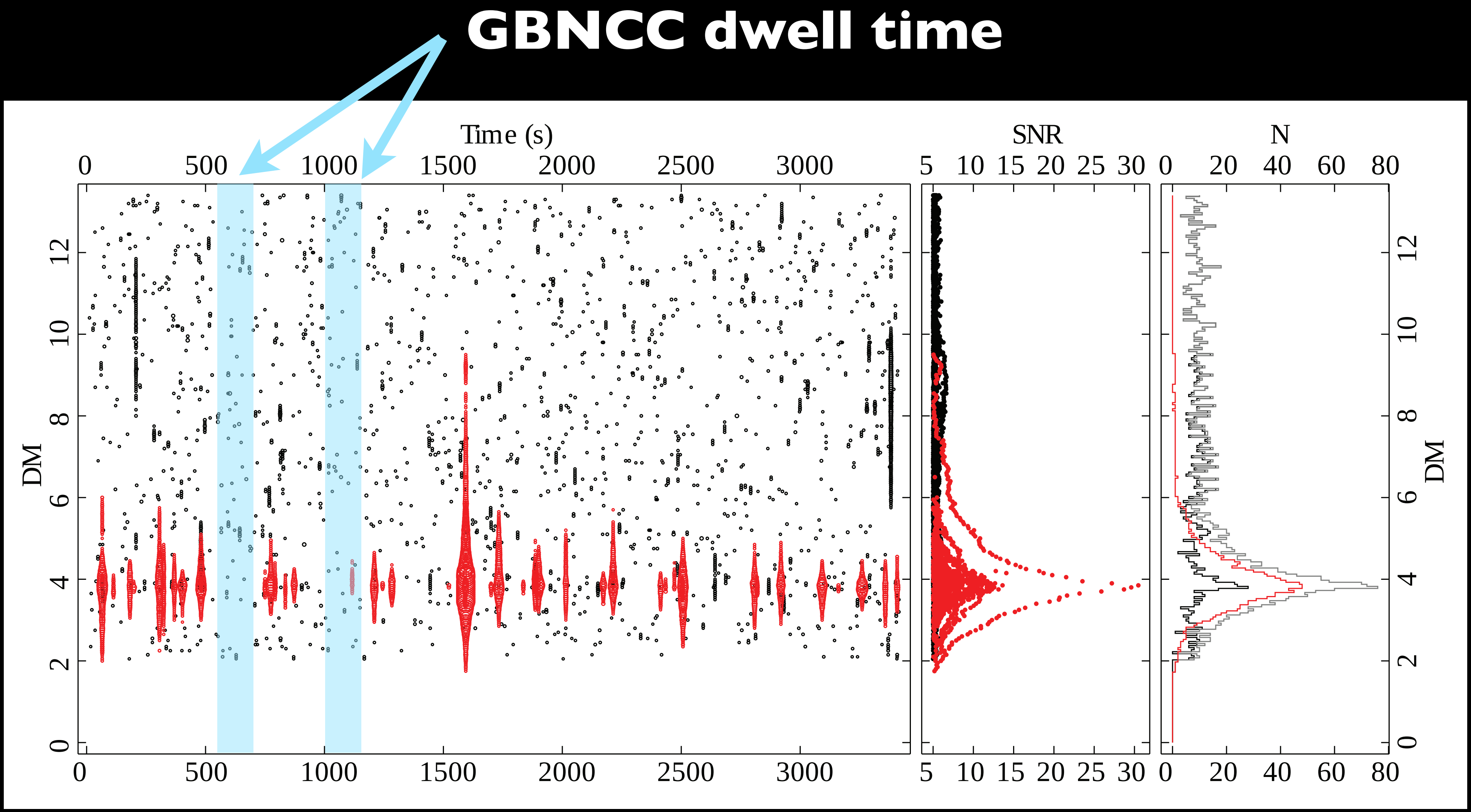

**Period = 1.8 sec** **Period = 0.6 sec**

**DM = 102 pc cm$^{-3}$** **DM = 19 pc cm$^{-3}$**

Coenen et al., almost submitted

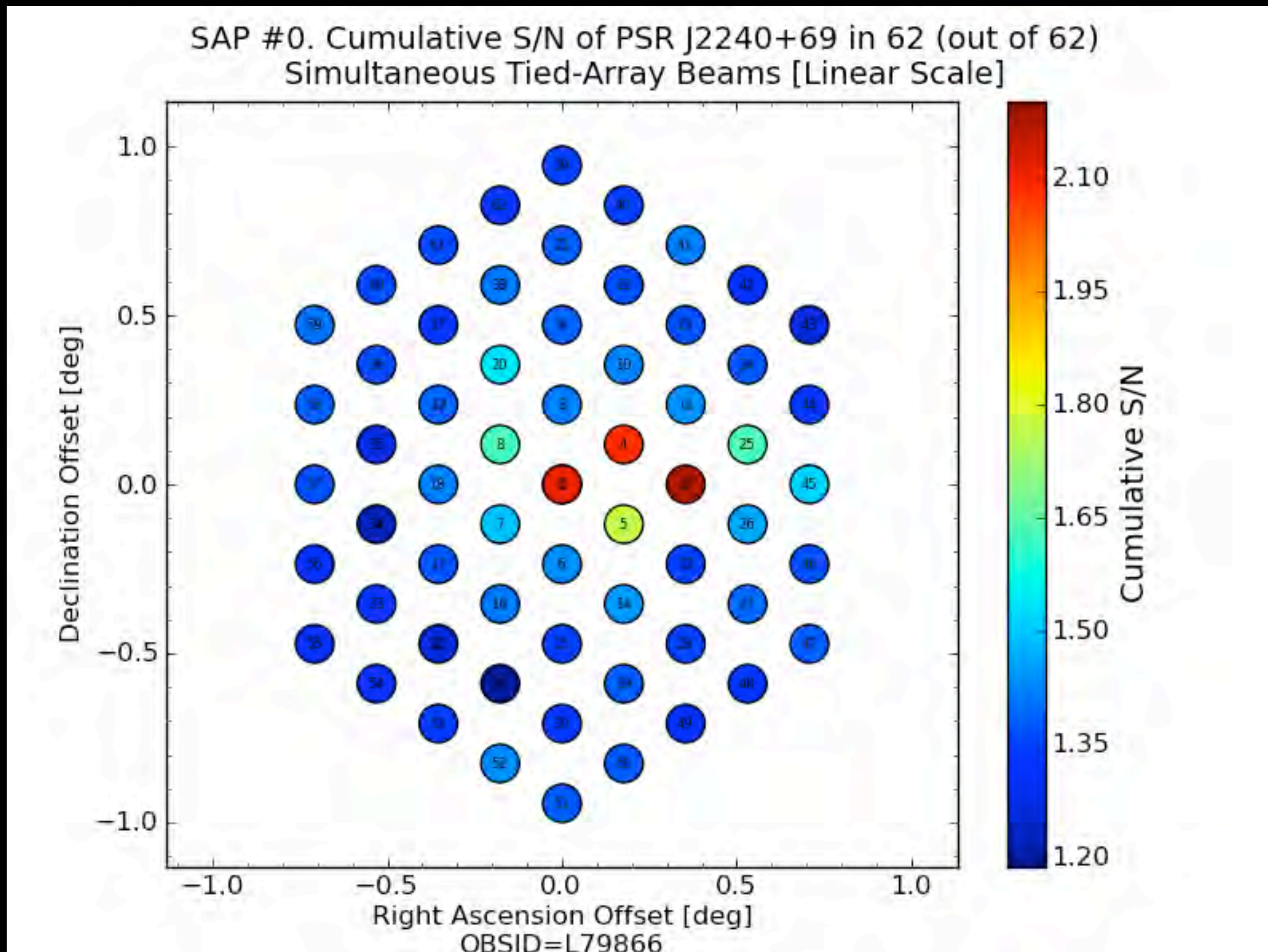


# LOTAS Blind Detections




**Highly sporadic emission from nearby source**

# Localizing LOTAAS Sources



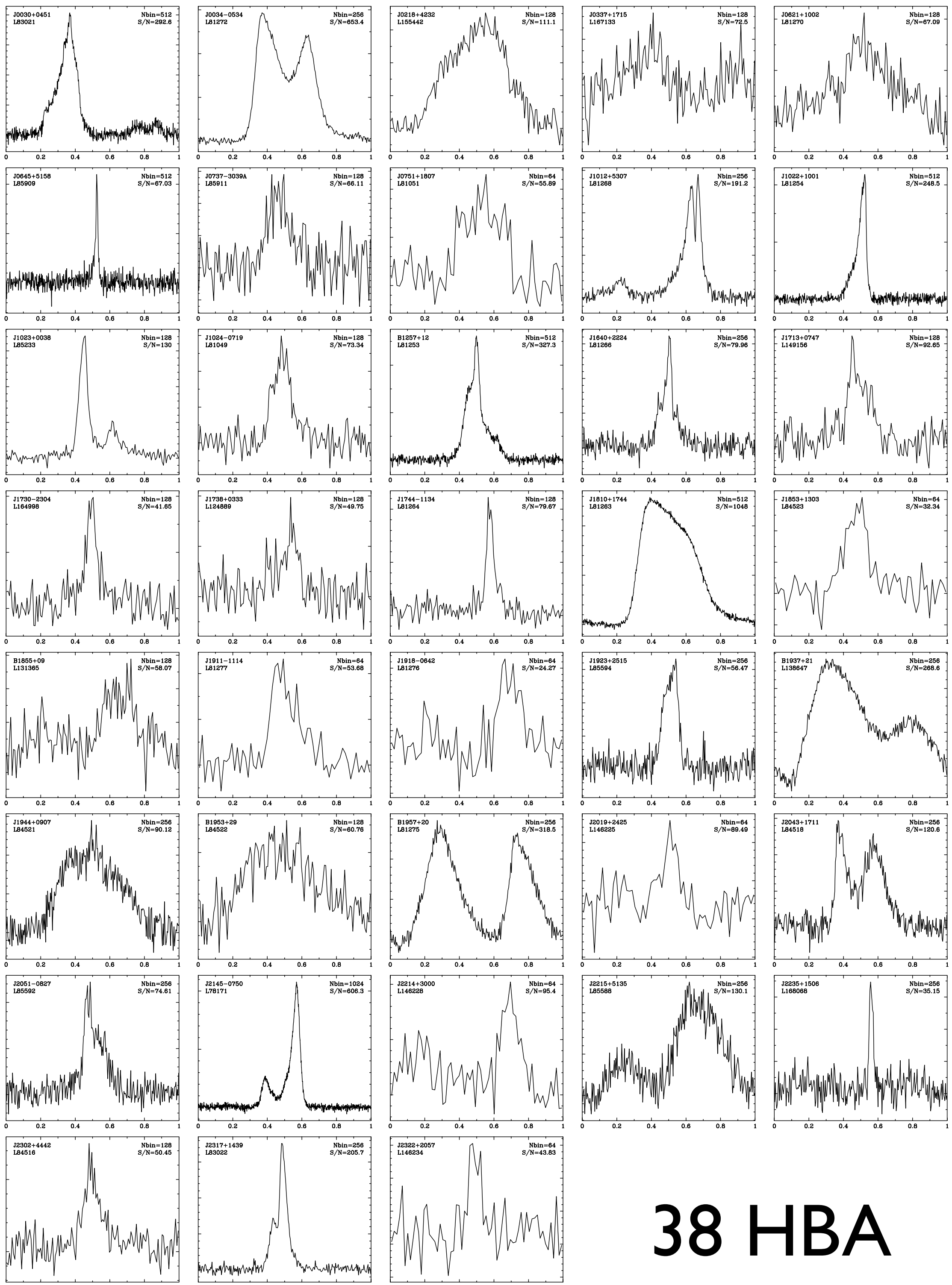

# Also *localize* transients

# LOFAR - Millisecond Pulsars

# MSPs

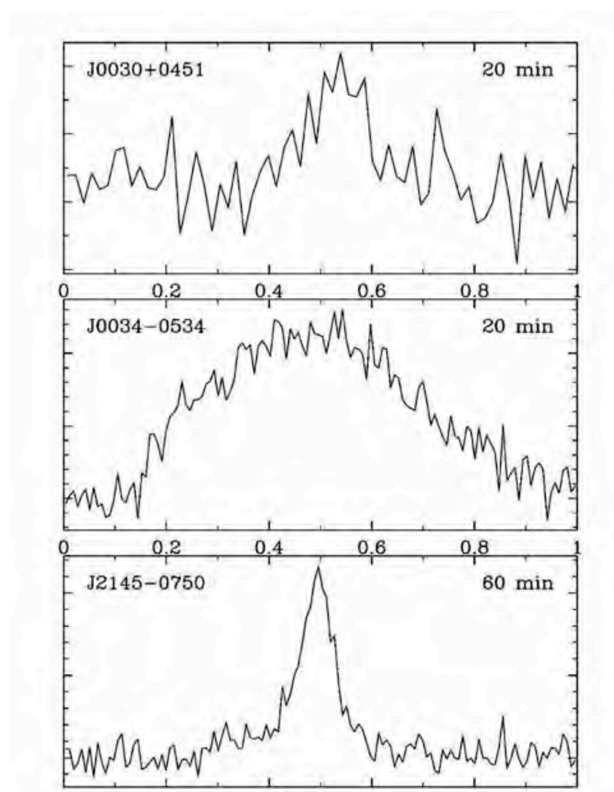
## The premier low-frequency census

Kondratiev, Hessels et al. 2013, almost submitted



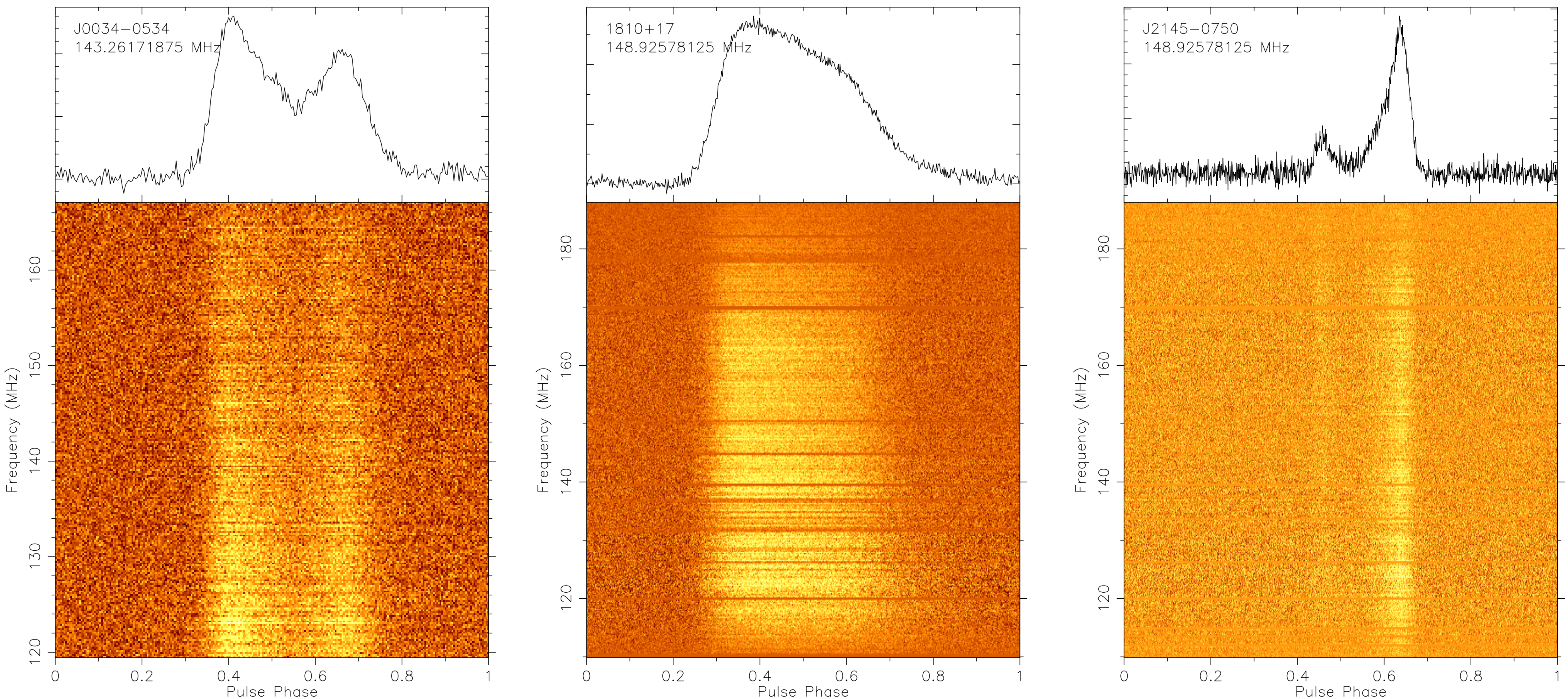
38 HBA

3 LBA



# LOFAR MSP Detections

## (110-190MHz)




Verbiest

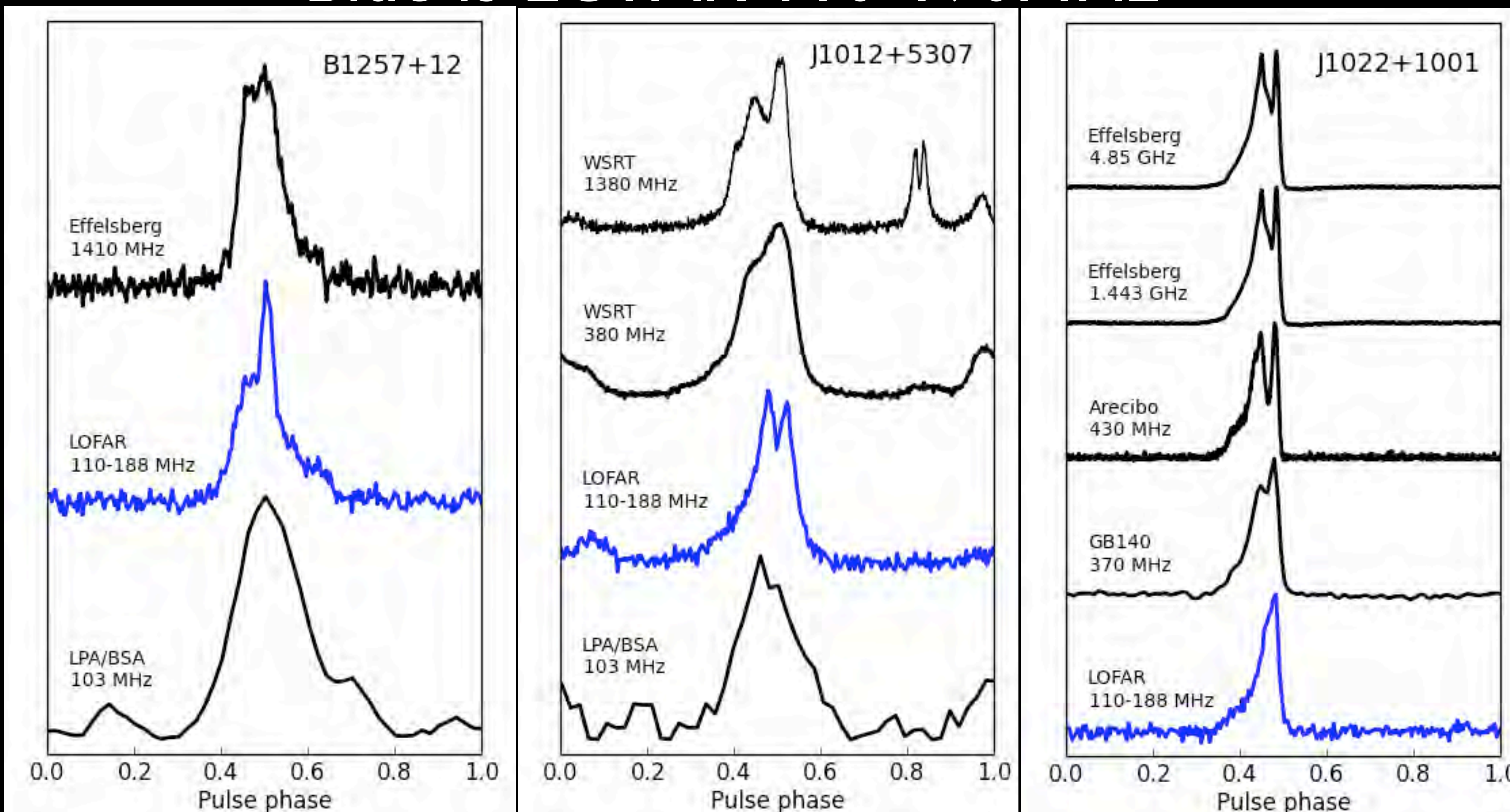
J0034-0534 J1810+1744 J2145-0750

Scintellometry

# LOFAR MSP Detections

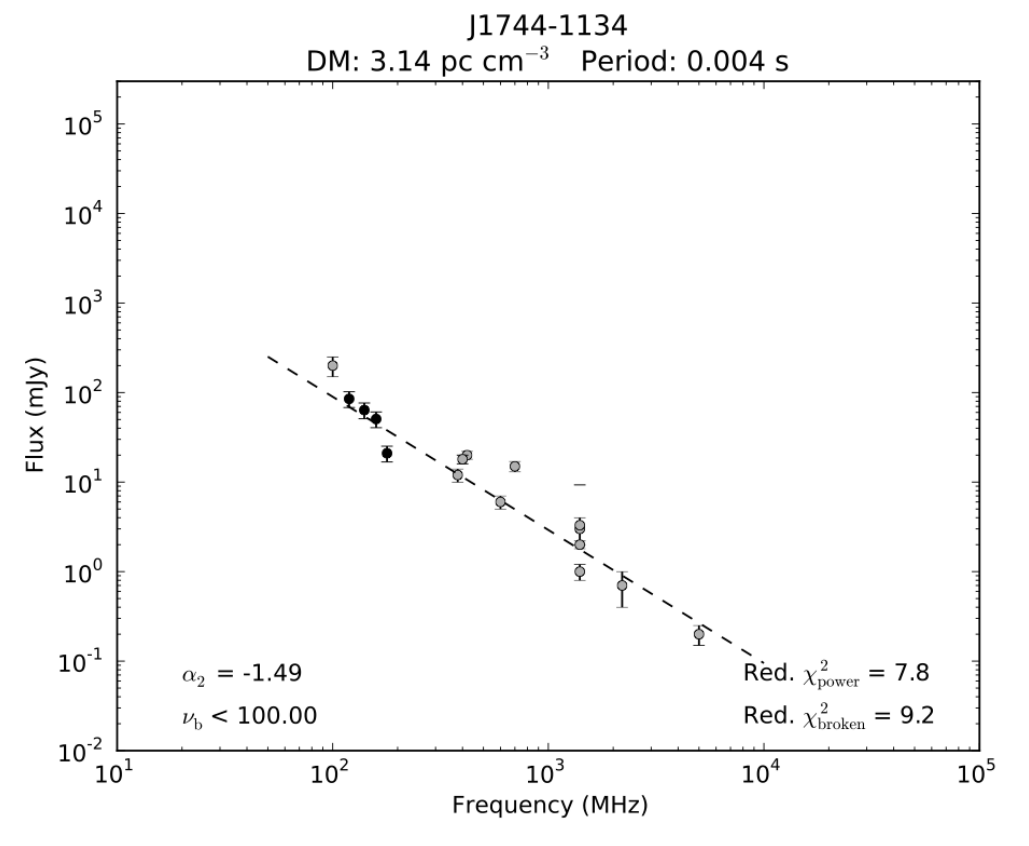
Blue is LOFAR 110-190MHz

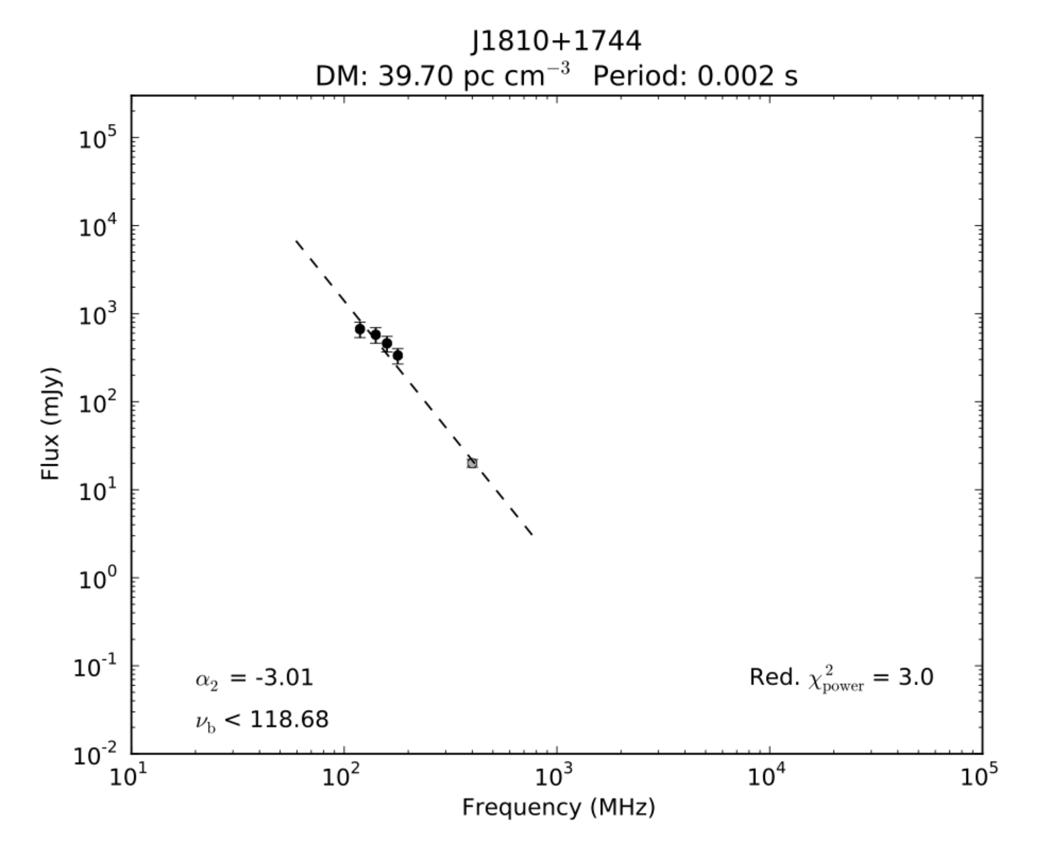
Kondratiev, using EPN




Some profiles getting narrower?

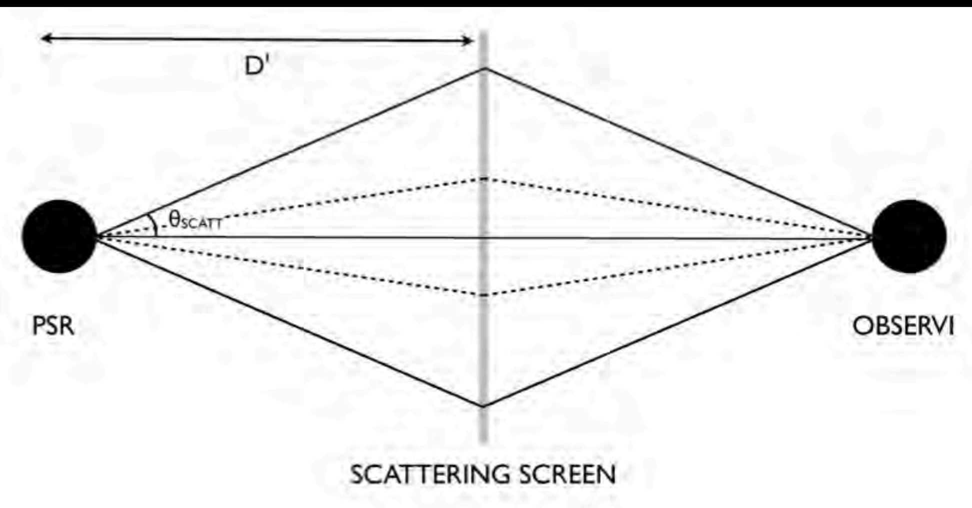
# MSP Spectra

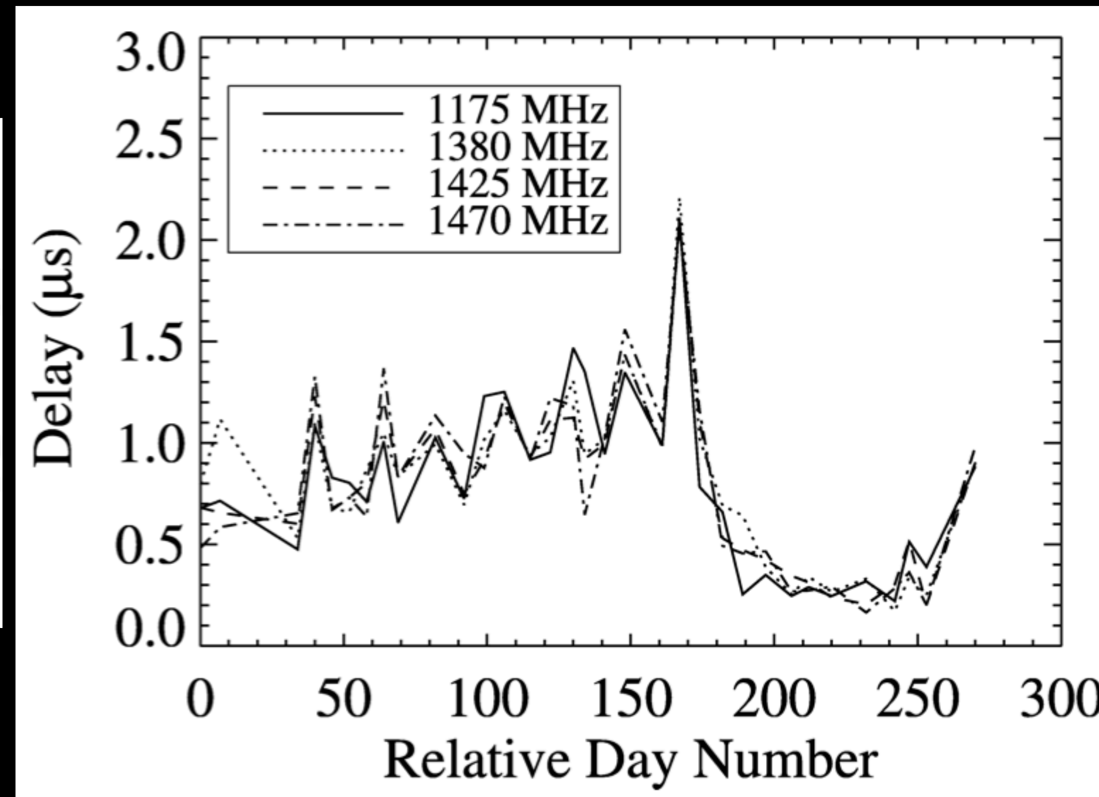



Hassall et al. 2013, in prep

# The LOFAR Weather Report



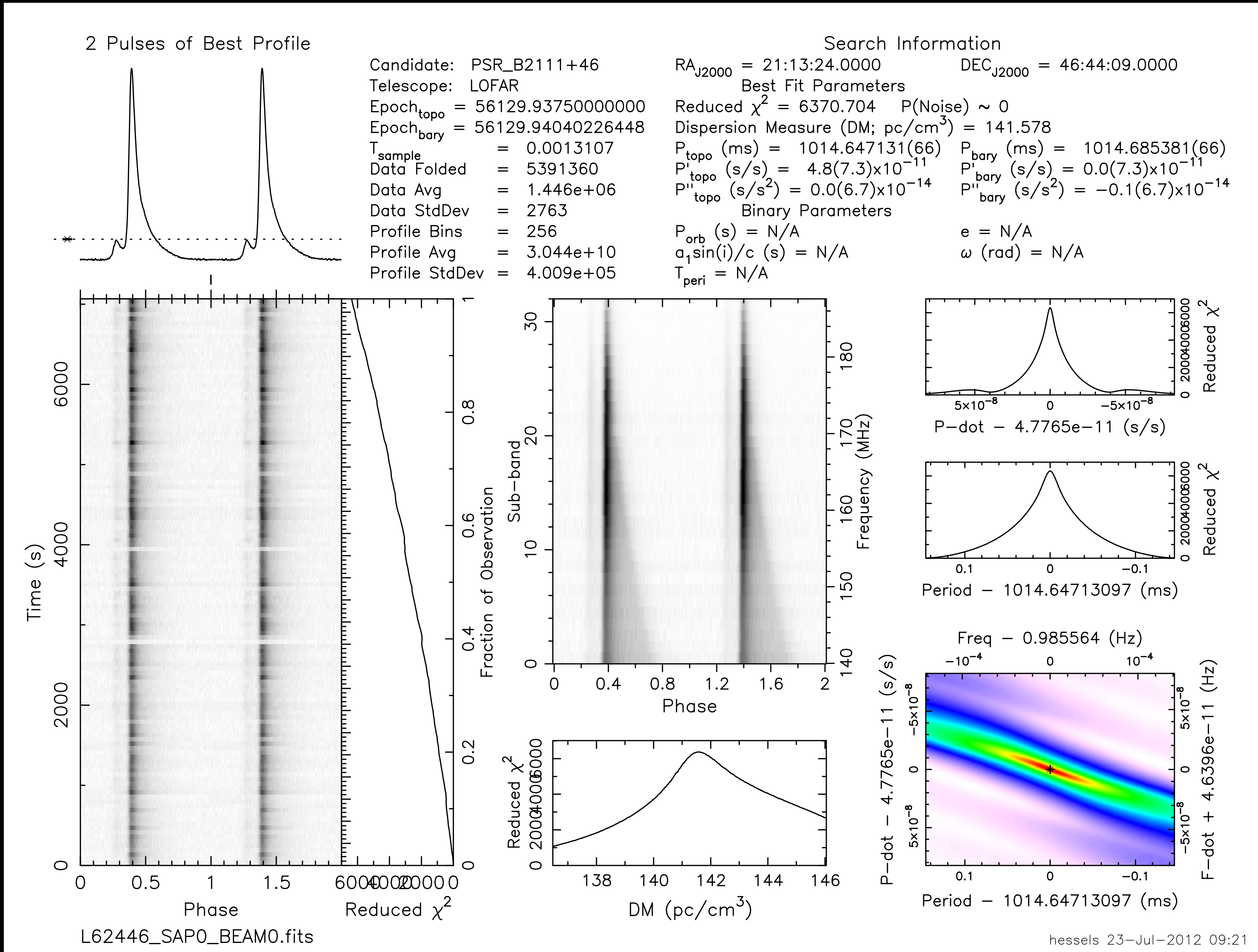

Hemberger & Stinebring 2008

1 us scatt. at 1400MHz is 10 ms scatt. at 140MHz

1 ms scatt. at 140MHz is 100 ns scatt. at 1400MHz

Do LOFAR DMs/Scatt. agree with those at high-freq.?

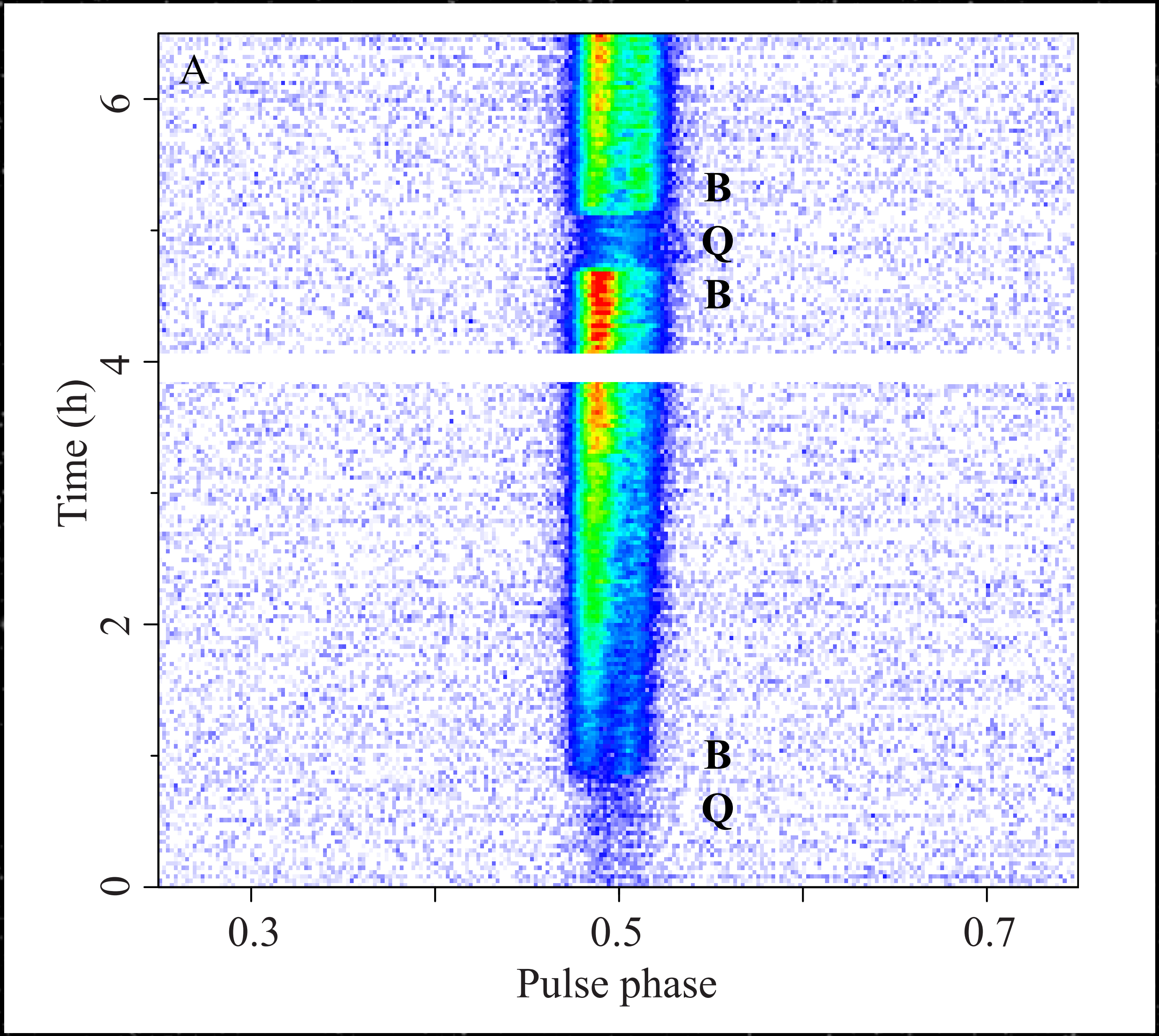
# Scattering




Hessels

# LOFAR - Pulsar Mode Switching

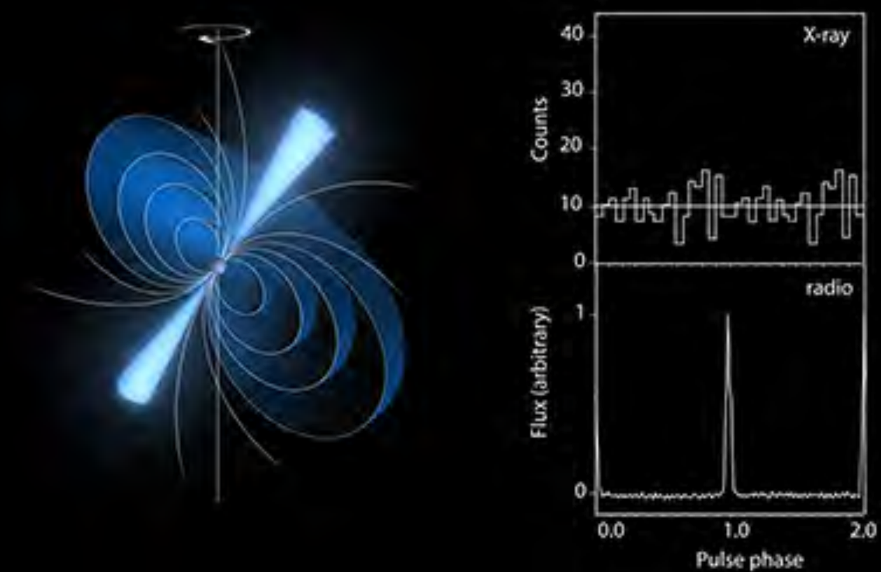
# PSR B0943+10 Switching Modes




Hermsen, Hessels, Kuiper et al. 2013, *Science*

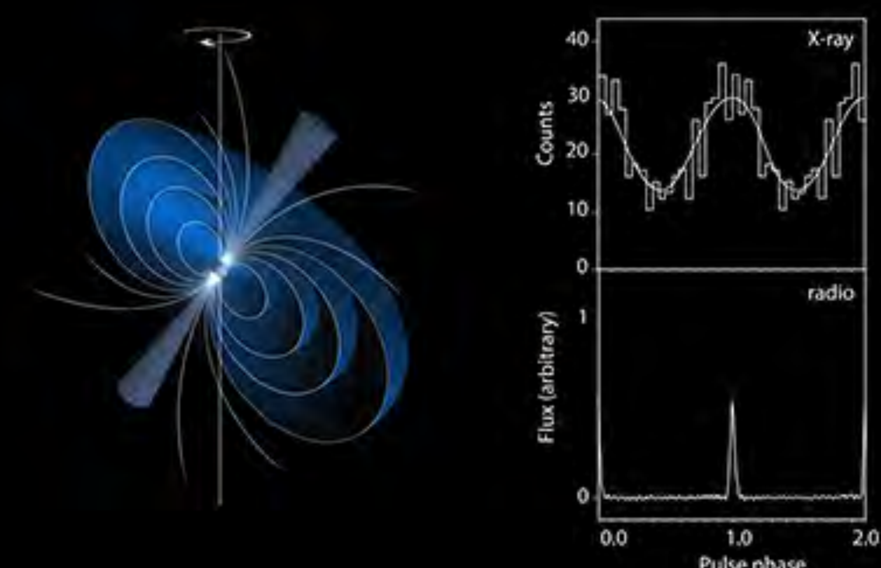
# Global magnetospheric mode switching

Hermsen et al. 2013, *Science*




X-ray dim

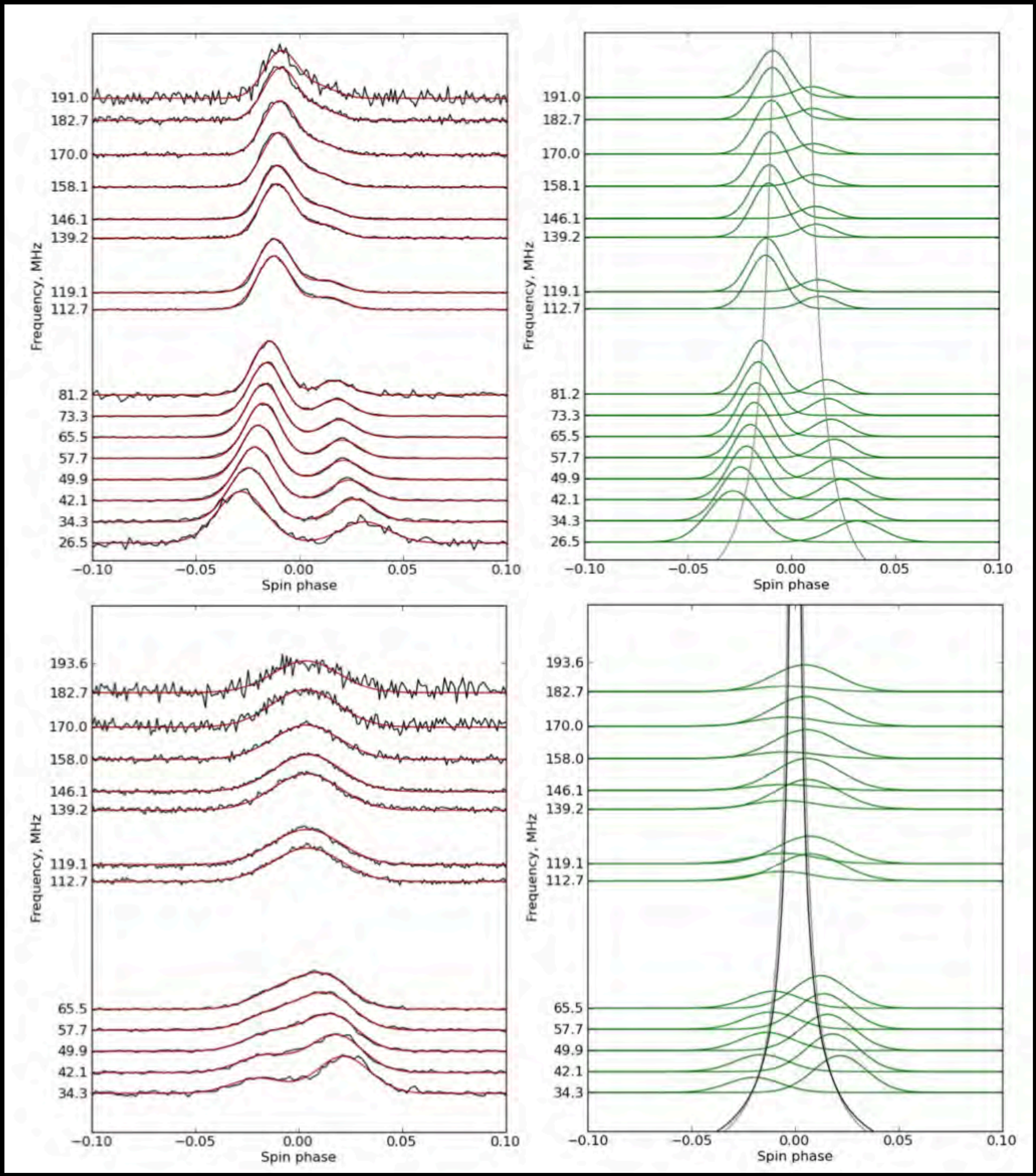
Radio bright




X-ray bright

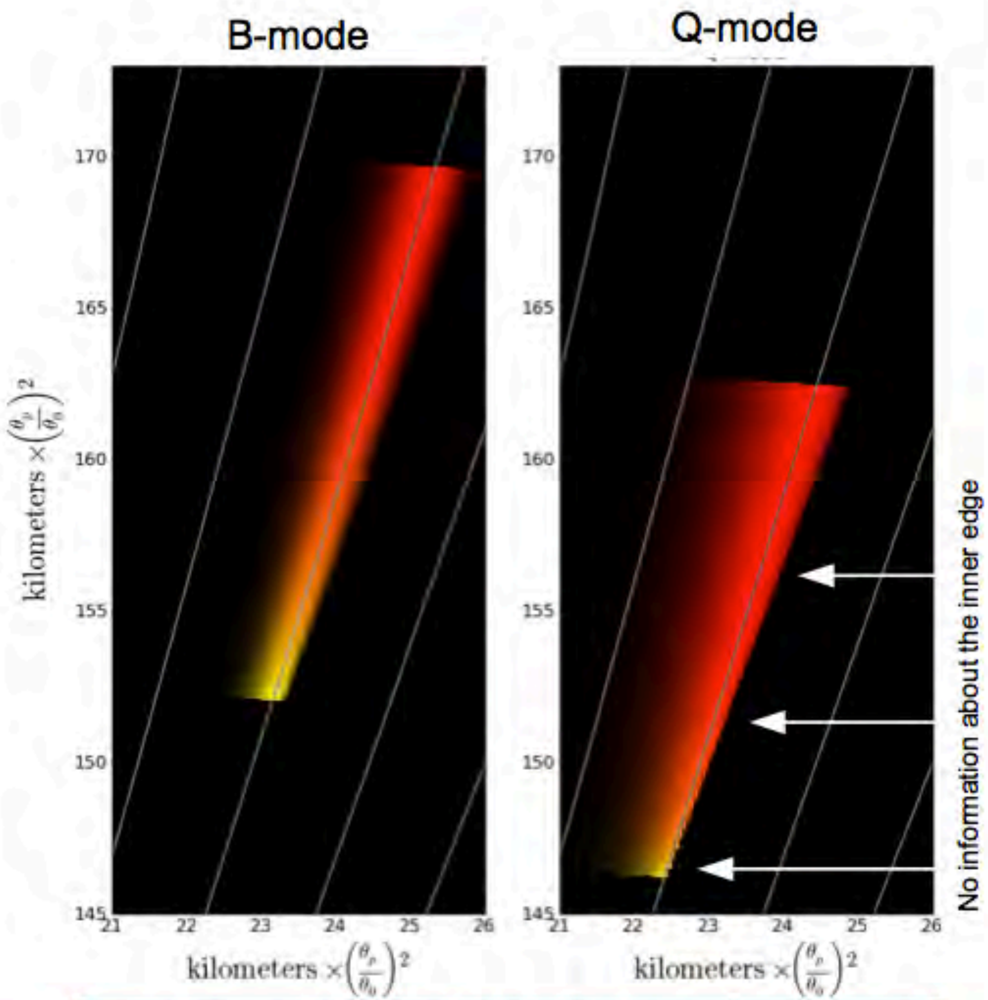
Radio dim

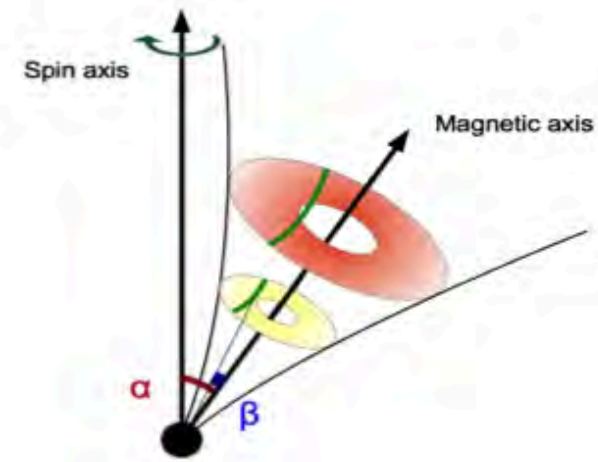
# PSR B0943+10 from 10-200MHz

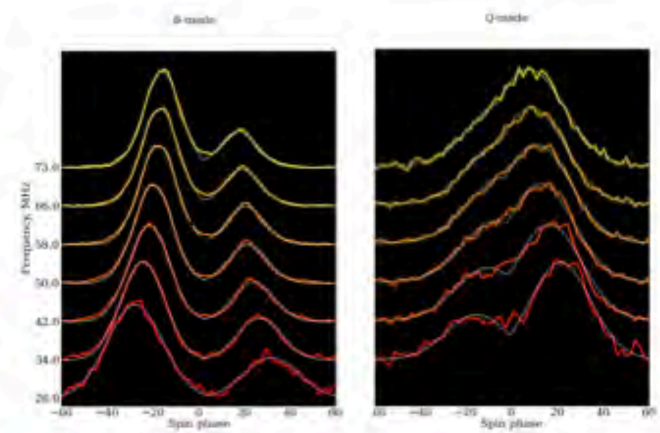



Bilous, Hessels et al. 2013, in prep.

# PSR B0943+10's Emission Geometry




The difference in average profiles in B and Q modes at 25-80 MHz can be explained by shifting emitting region by few km along the field line.

If something dramatic happens to radio, it must be at higher frequencies

$1 < \vartheta_p/\vartheta_0 < 3.5$

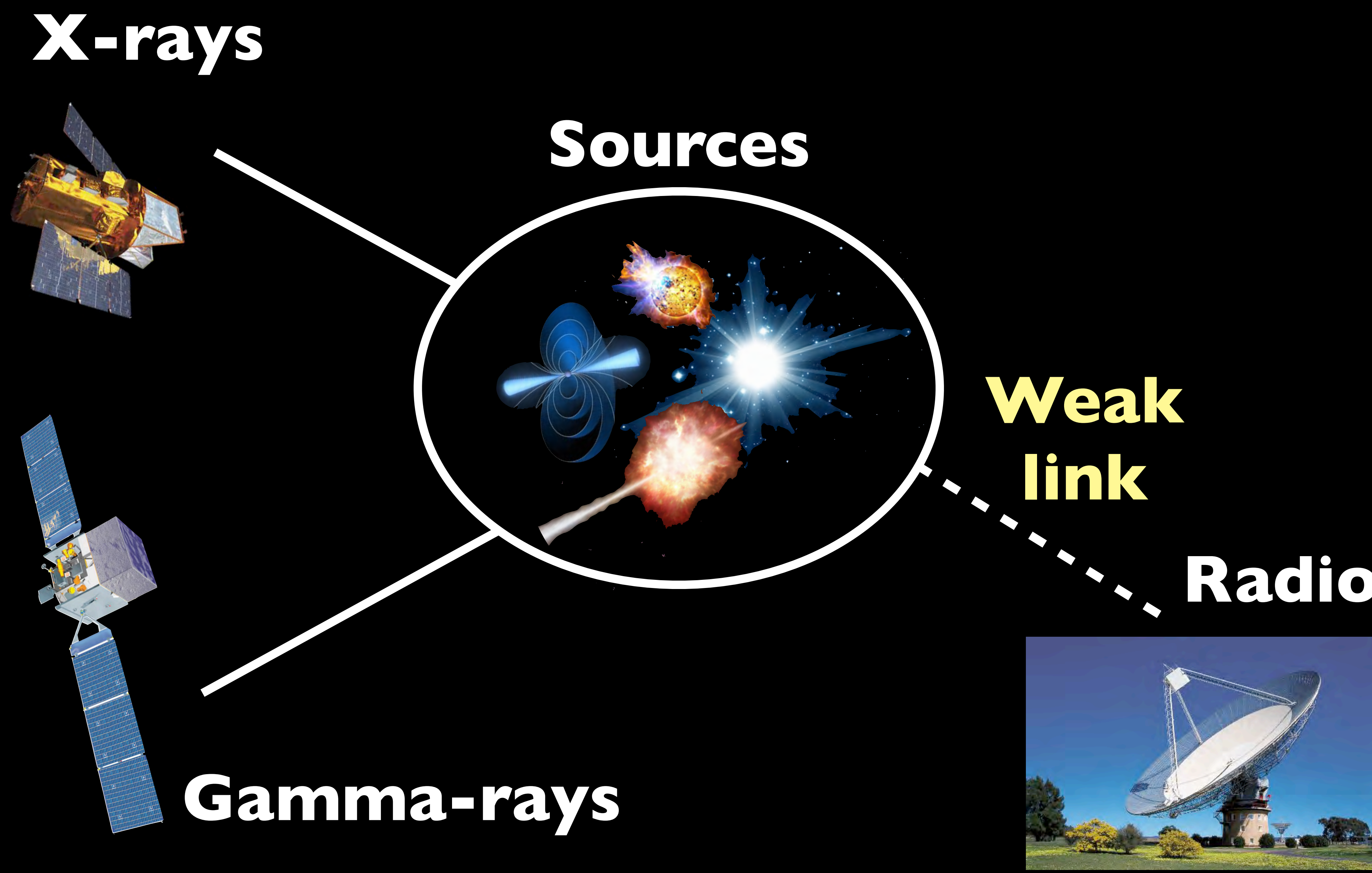
Radius of light cylinder : 52000 km

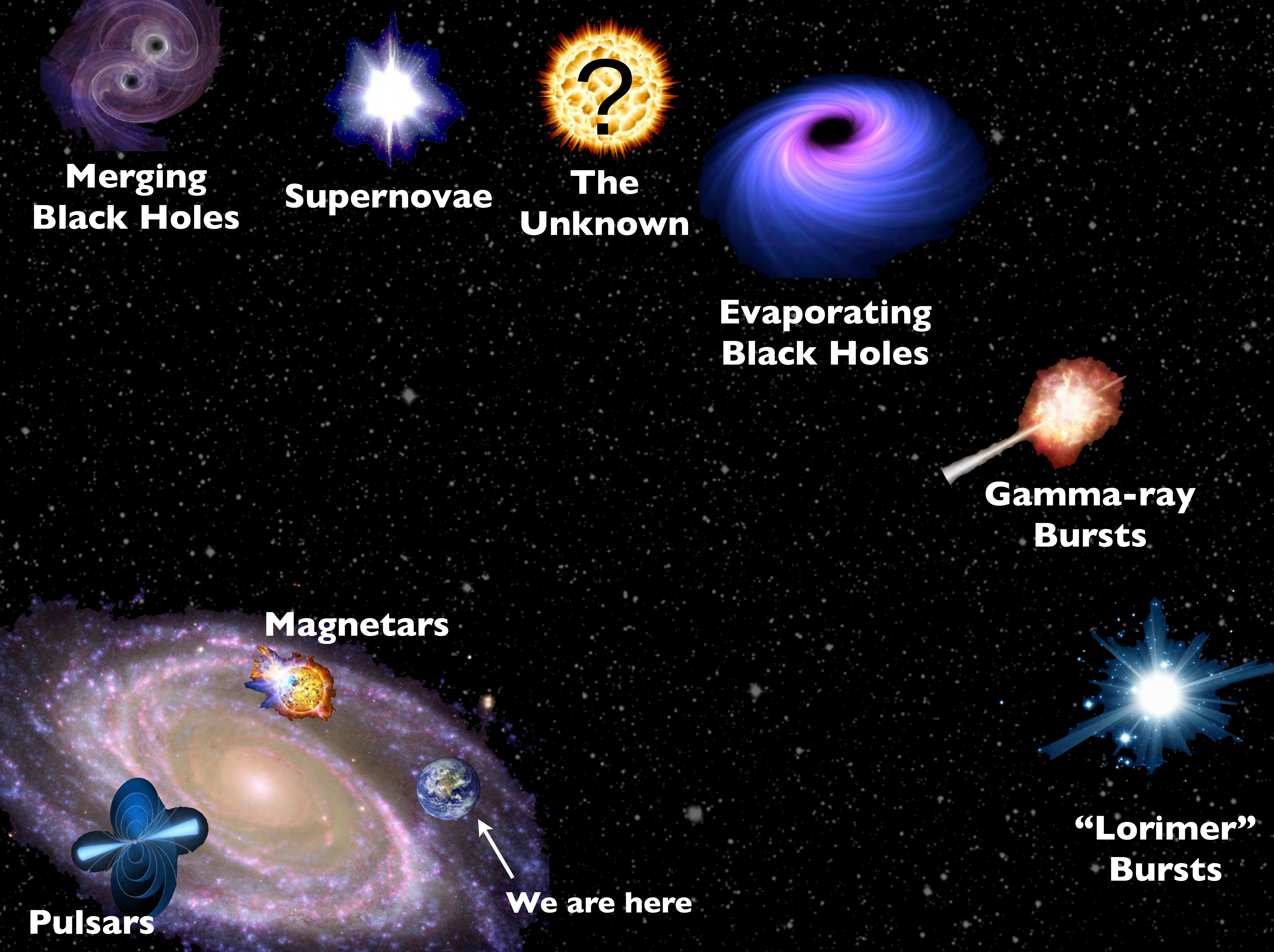
Radius of the star: 10 km

Bilous et al. 2013, in prep.


# Dynamic Radio Astronomy of Galactic Neutron Stars and Extragalactic Transients

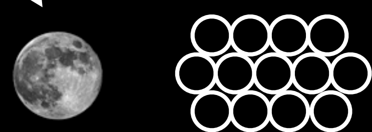
# All-sky monitoring




Merging Black Holes
Supernovae
The Unknown
Evaporating Black Holes
Gamma-ray Bursts
Magnetars
"Lorimer" Bursts
We are here
Pulsars

# Fast radio transient factories

**Moon** **Field-of-view**



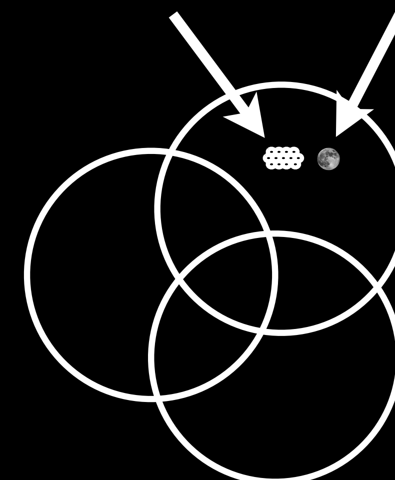
## Parkes

**0.6 sq. deg.**

## Current state-of-the-art

**100x**

**Parkes** **Moon**



## LOFAR

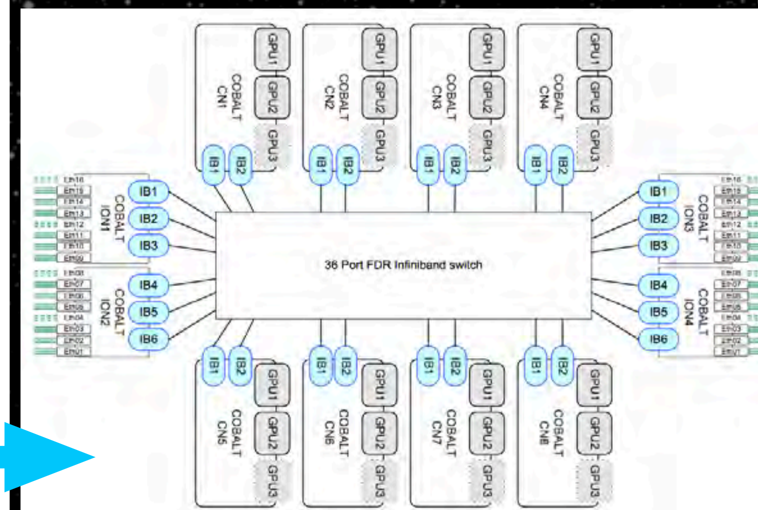
**Field-of-view**

**60 sq. deg.**

LOFAR

DRAGNET

Budget for GPU cluster




Raw data
1 - 72
stations

100 Fields-of-view

Offline processing

10hr / week
observing

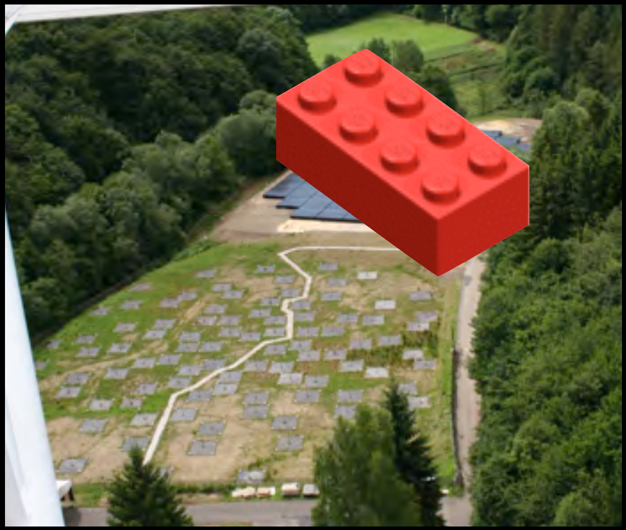
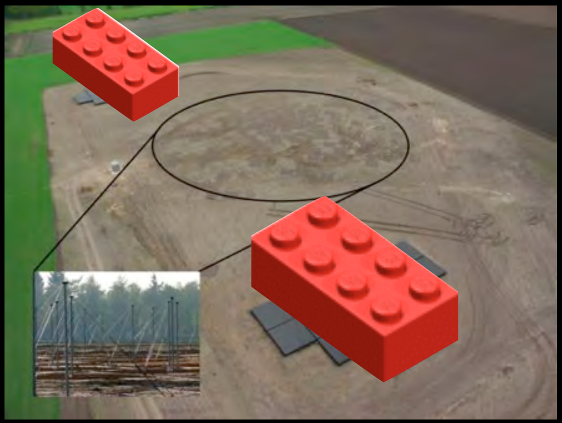
Sub-arraying

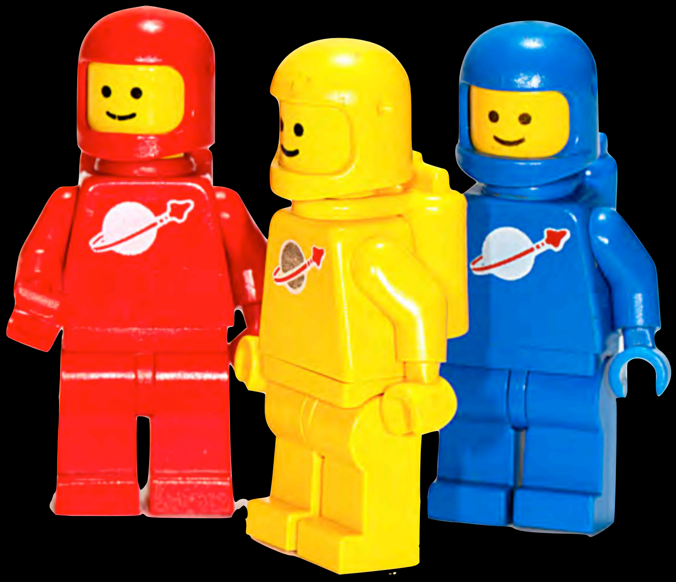
80x400 Fields-of-view

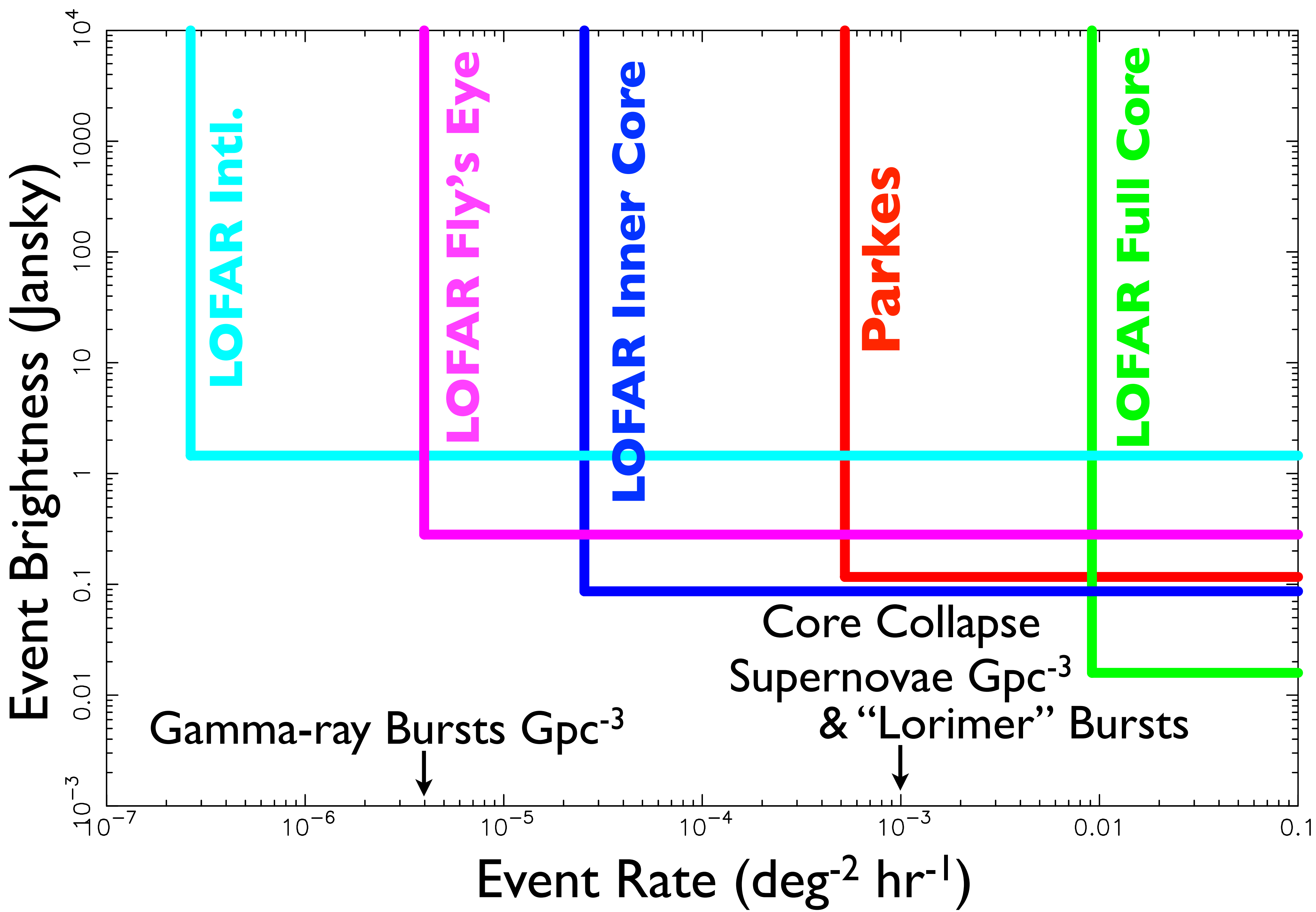
Realtime processing

Observe 24/7

Localize events

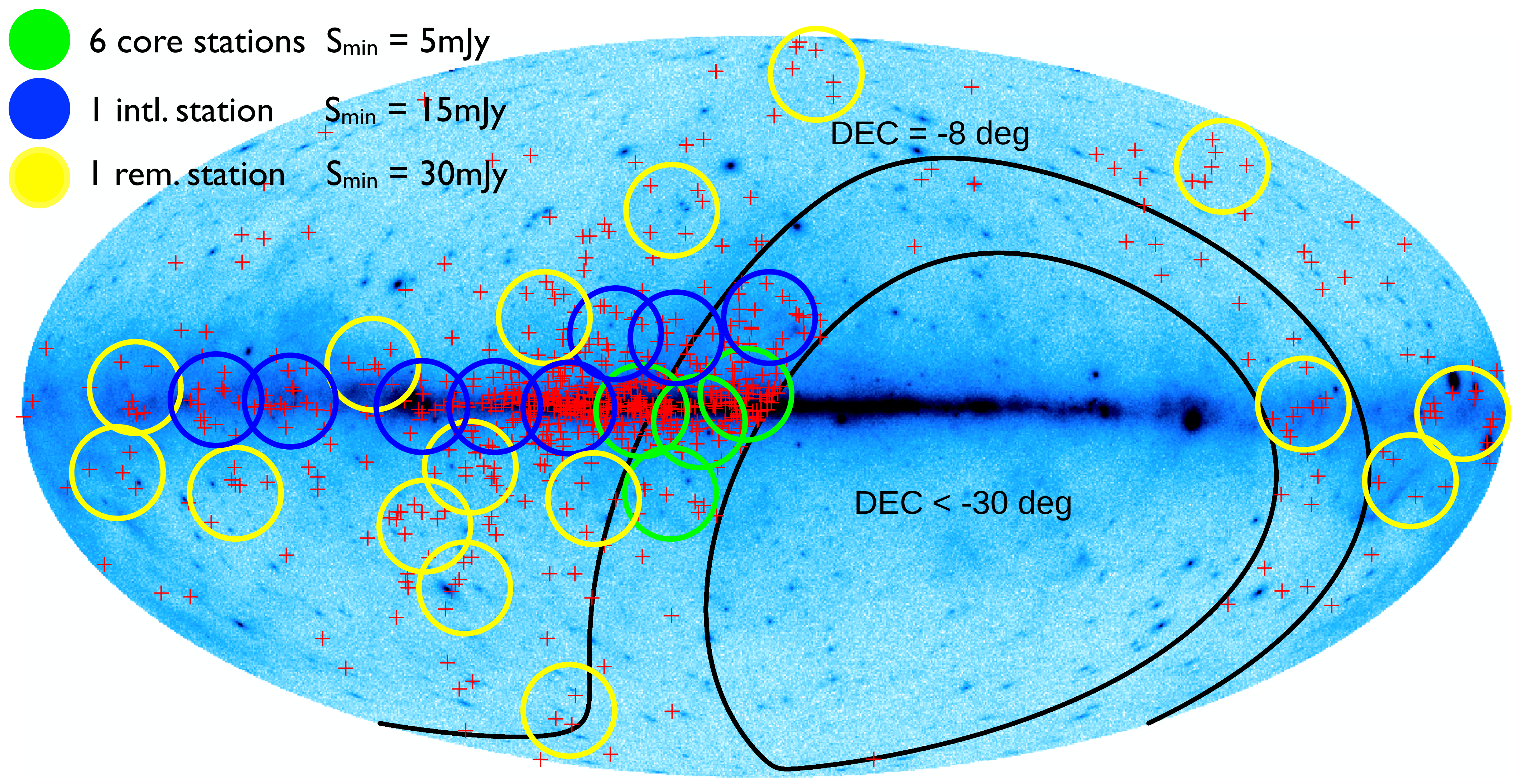





LOFAR Intl.
LOFAR Fly's Eye
LOFAR Inner Core
Parkes
LOFAR Full Core
Core Collapse
Supernovae Gpc-3
& "Lorimer" Bursts
Gamma-ray Bursts Gpc-3
Event Brightness (Jansky)
Event Rate (deg-2 hr-1)
10^4
1000
100
10
1
0.1
0.01
10^-3
10^-7
10^-6
10^-5
10^-4
10^-3
0.01
0.1

# Near Future




# Move towards a flexible LOFAR