Synergies between ***Fermi*** and ***Radio Sky Surveys***

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Thanks to: George Heald, Tracy Clarke, Dale Frail, Jason Hessels, Joeri van Leeuwen, Tim Shimwell, and many others

Sixth International Fermi Symposium

9 November 2015

Initial Considerations

- Multi-wavelength studies crucial
- Radio observations = physics probes
  - Incoherent (synchrotron) emission
  - Coherent emission
- New era in radio astronomy
  - Bandwidth & sensitivity
  - Spatial, spectral & temporal resolution
  - Low-frequency radio sky
  - Wide field of view
- Many radio surveys

Conclusions

- Multi-wavelength studies crucial
- Radio observations = physics probes
  - Incoherent (synchrotron) emission
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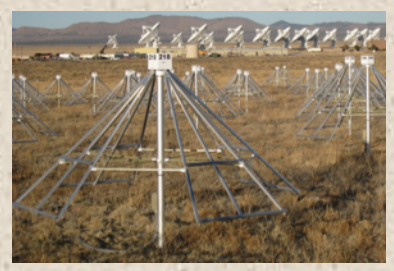
- New era in radio astronomy
  - Bandwidth & sensitivity
  - Spatial, spectral & temporal resolution
  - Low-frequency radio sky
  - Wide field of view
- Many radio surveys → many opportunities

Many Facilities Upgraded

- Jansky Very Large Array
- Westerbork Synthesis Radio Telescope
- Australian Telescope Compact Array
- Giant Metrewave Radio Telescope
- Arcminute Microkelvin Imager
- European VLBI Network
- Very Long Baseline Array
- Green Bank Telescope
- Parkes Radio Telescope

New Kids on the Block

- Low Frequency Array (LOFAR, *30-240 MHz*)
- Long Wavelength Array (LWA, *20-80 MHz*)
- Murchison Widefield Array (MWA, *80-300 MHz*)
- VLA Low-band Ionospheric & Transient Experiment (VLITE, *320-384 MHz*)
- Karoo Array Telescope (MeerKAT, *1-1.75 GHz*)
- Australian Square Kilometer Array Pathfinder (ASKAP, *0.7-1.8 GHz*)

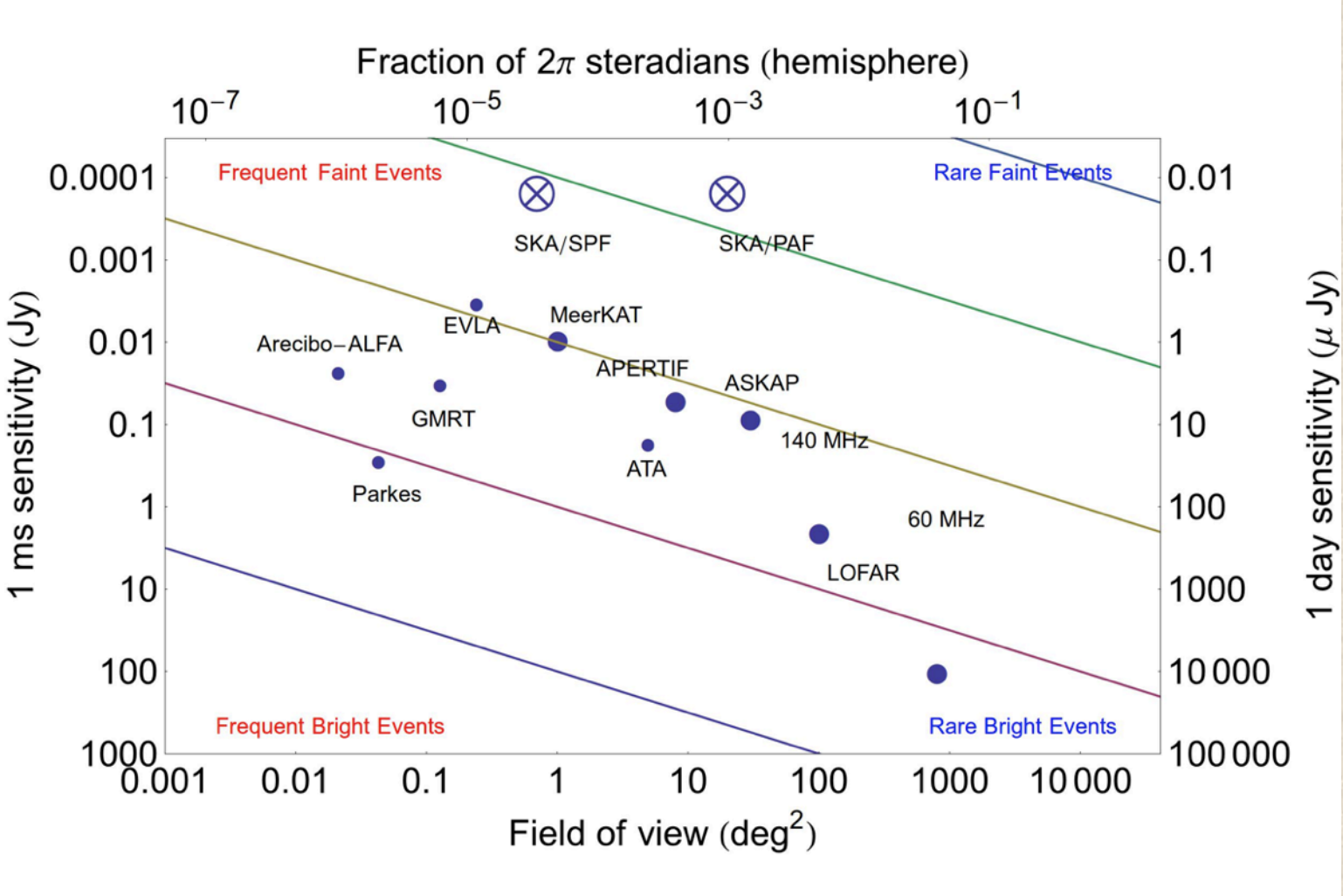


(Low-Frequency) Radio Sky

- Epoch of reionization (redshifted HI & CO)
  - First structure formation during dark ages
- Deep extragalactic surveys
  - High-z galaxies, clusters, star formation history
  - AGN physics & evolution
- Cosmic magnetism (polarization surveys)
  - Magnetic field evolution over cosmic time
- Transients & variable sources
- Ultra high energy cosmic rays
- Solar science & space weather

Imaging Survey Speed

Diagonal lines: equal survey speed



Fender & Bell (2011)

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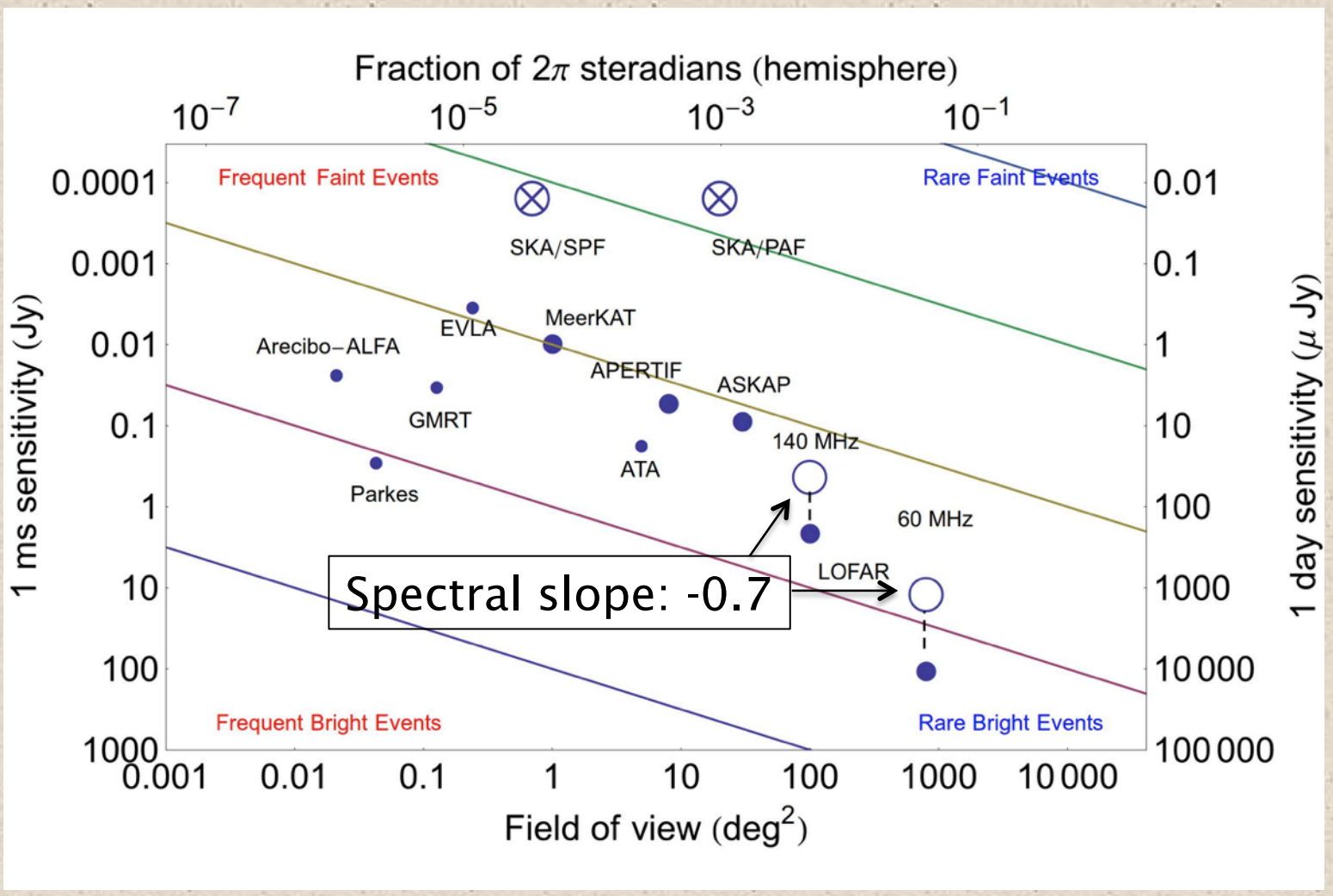

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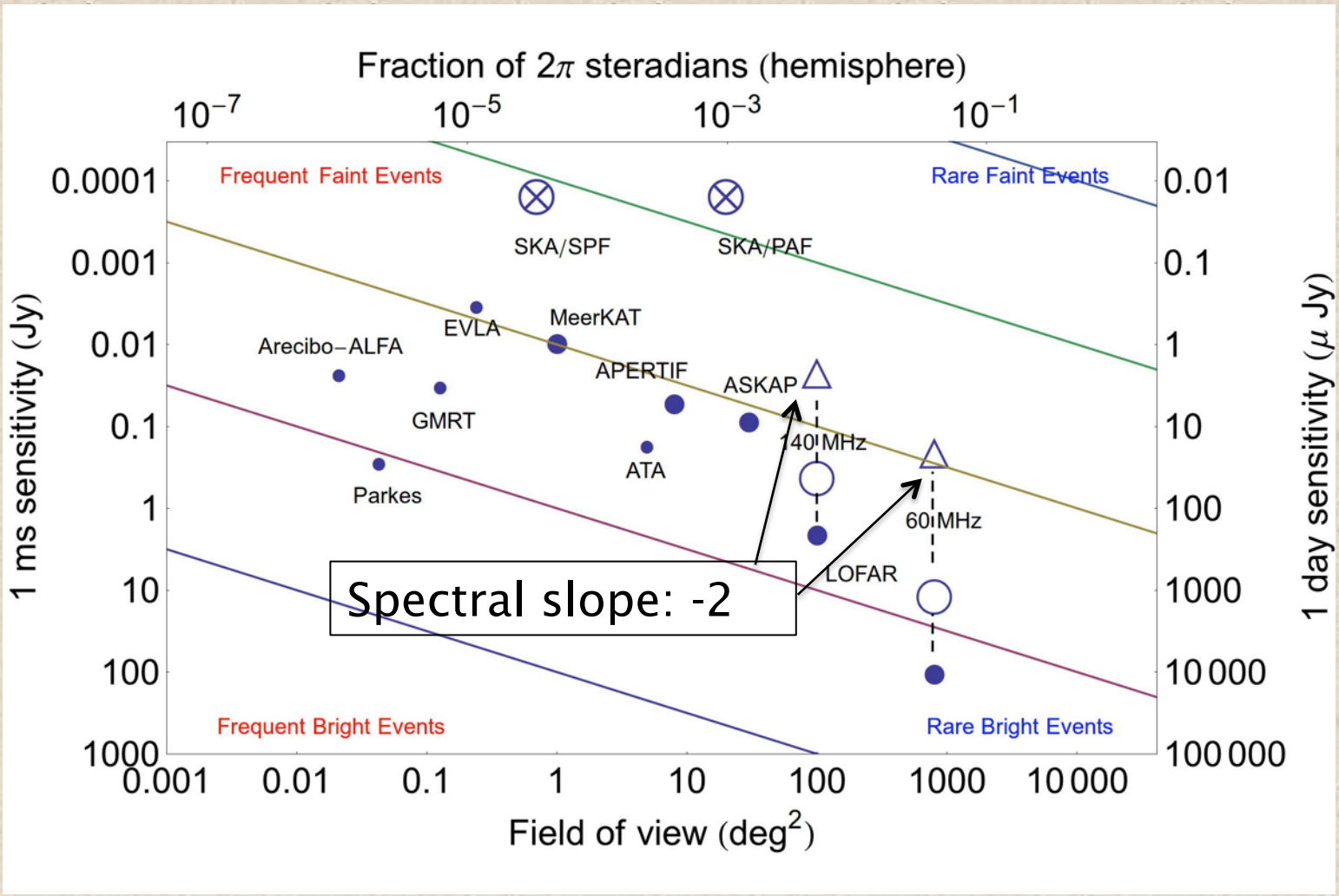
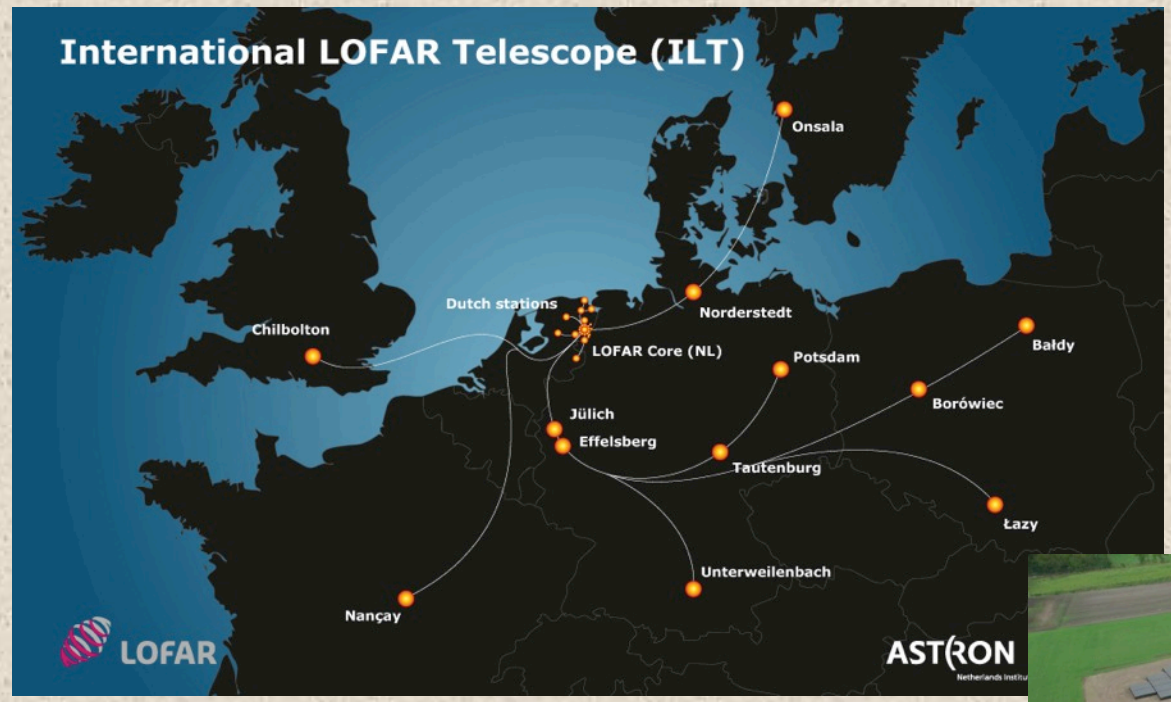


Fender & Bell (2011)

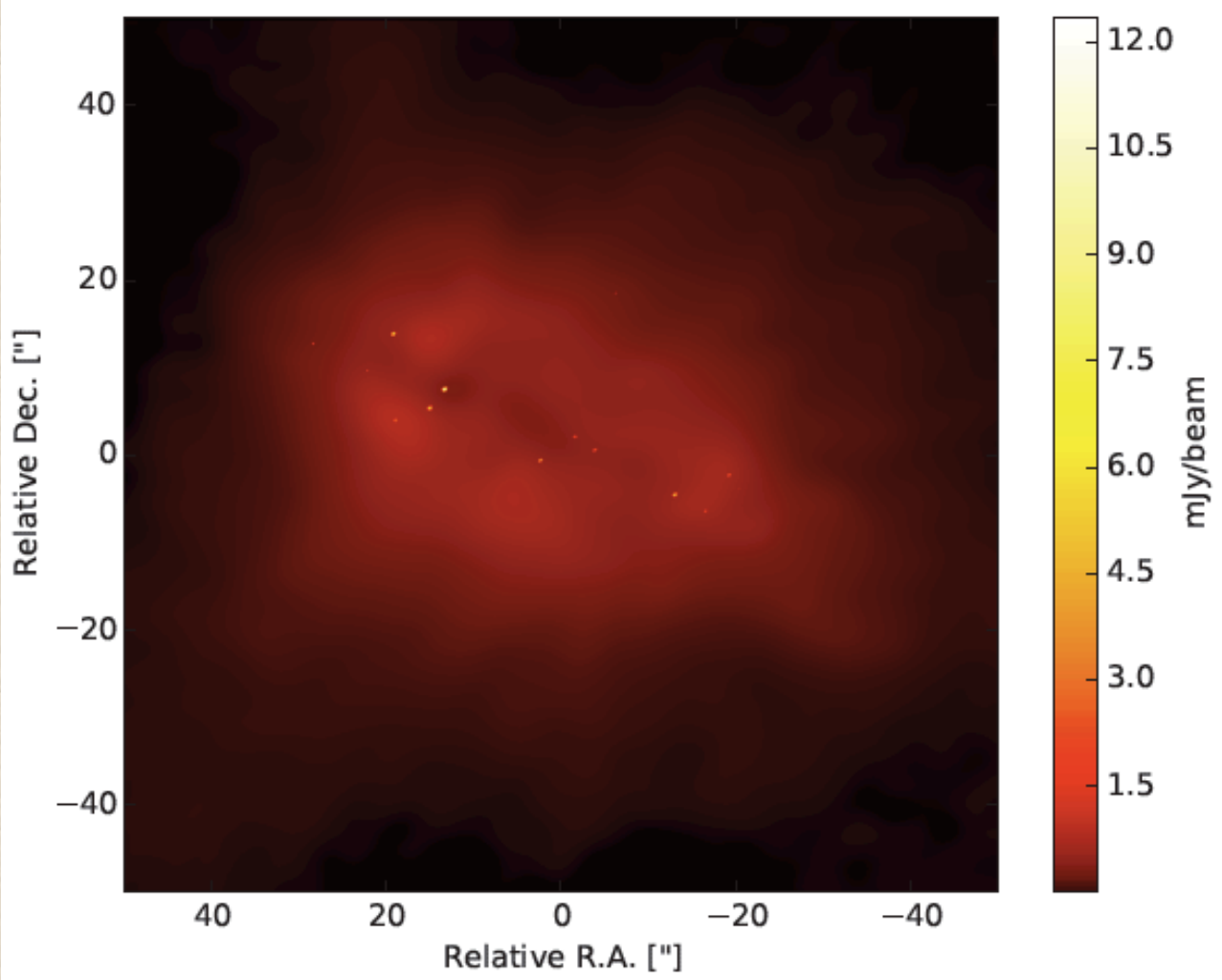
Low Frequency Array



- Software telescope
- LBA: 30-80 MHz
- HBA: 120-240 MHz

International LOFAR Telescope

M82: 146-162 MHz, 0.3”, 0.15 mJy/beam

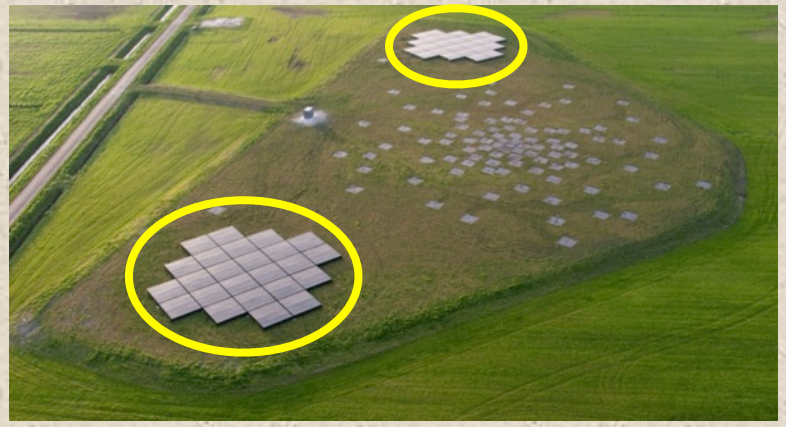


Varenius et al. (2015)

Multifrequency Snapshot Sky Survey

MSSS: LOFAR's first imaging survey

MSSS-HBA



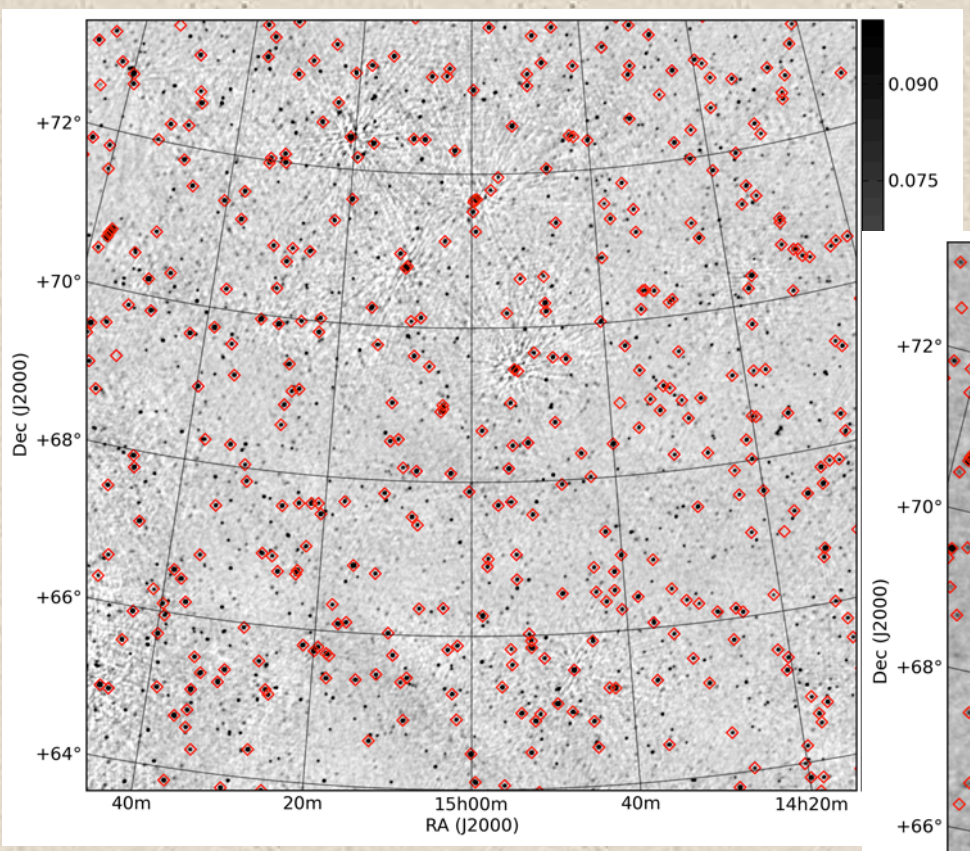
- 120-160 MHz (8 x 2 MHz)
- Resolution < 120"
- Sensitivity < 5 mJy/beam
- 3616 fields
- 6 x ~4° beams
- Obs. 100% complete

MSSS-LBA

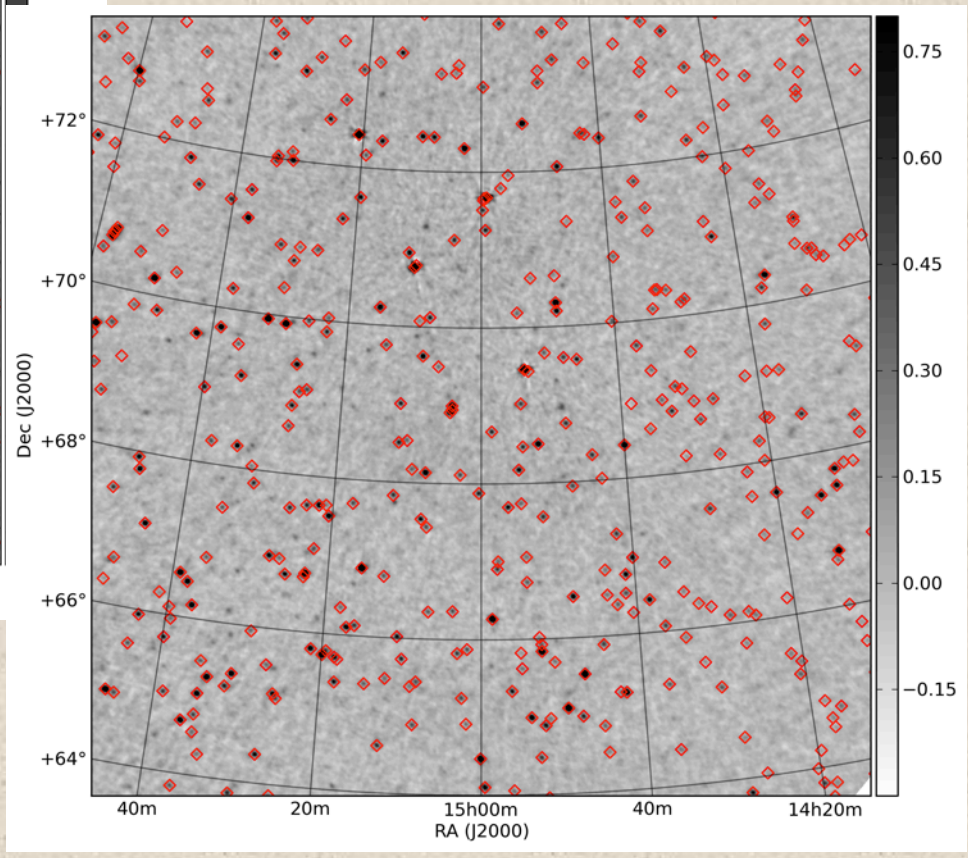
- 30-75 MHz (8 x 2 MHz)
- Resolution < 100"
- Sensitivity < 15 mJy/beam
- 660 fields
- 5 x ~10° beams
- Test obs. resuming

MSSS Verification Field

100 deg², ~1200 sources, ~2’ resolution



HBA mosaic:
Complete >100 mJy

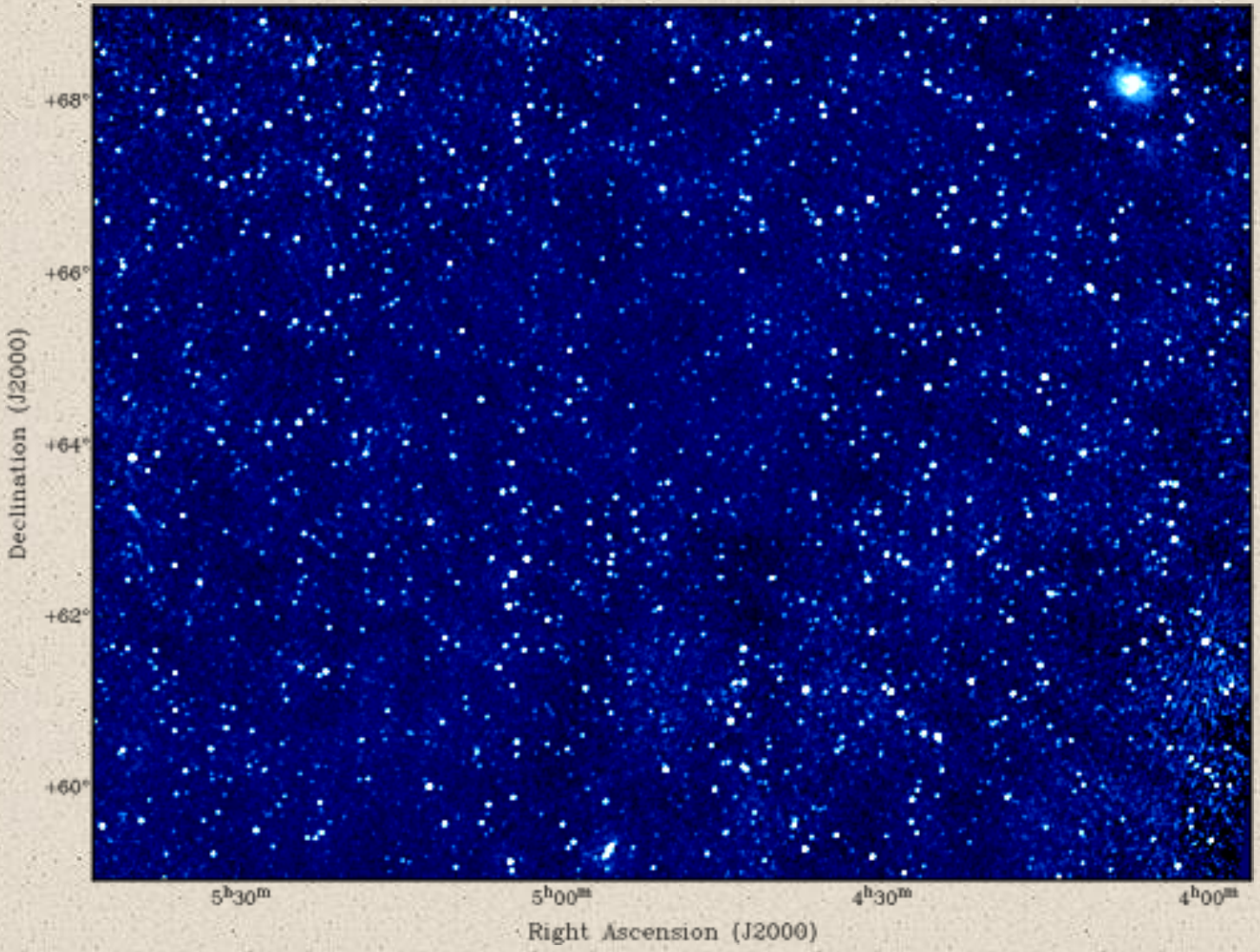


Heald et al. (2015)

LBA: Complete >550 mJy

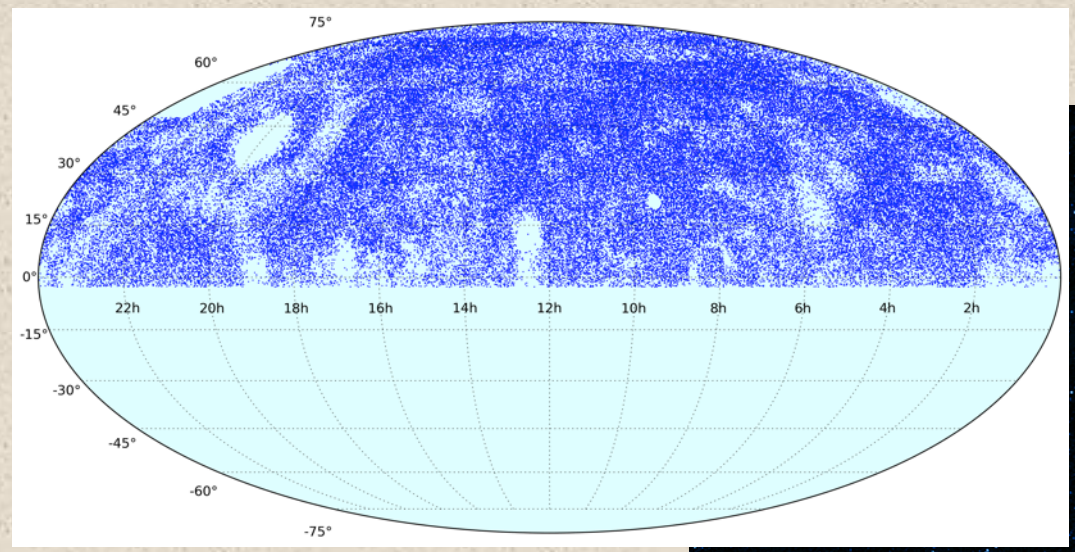
MSSS-HBA Mosaics

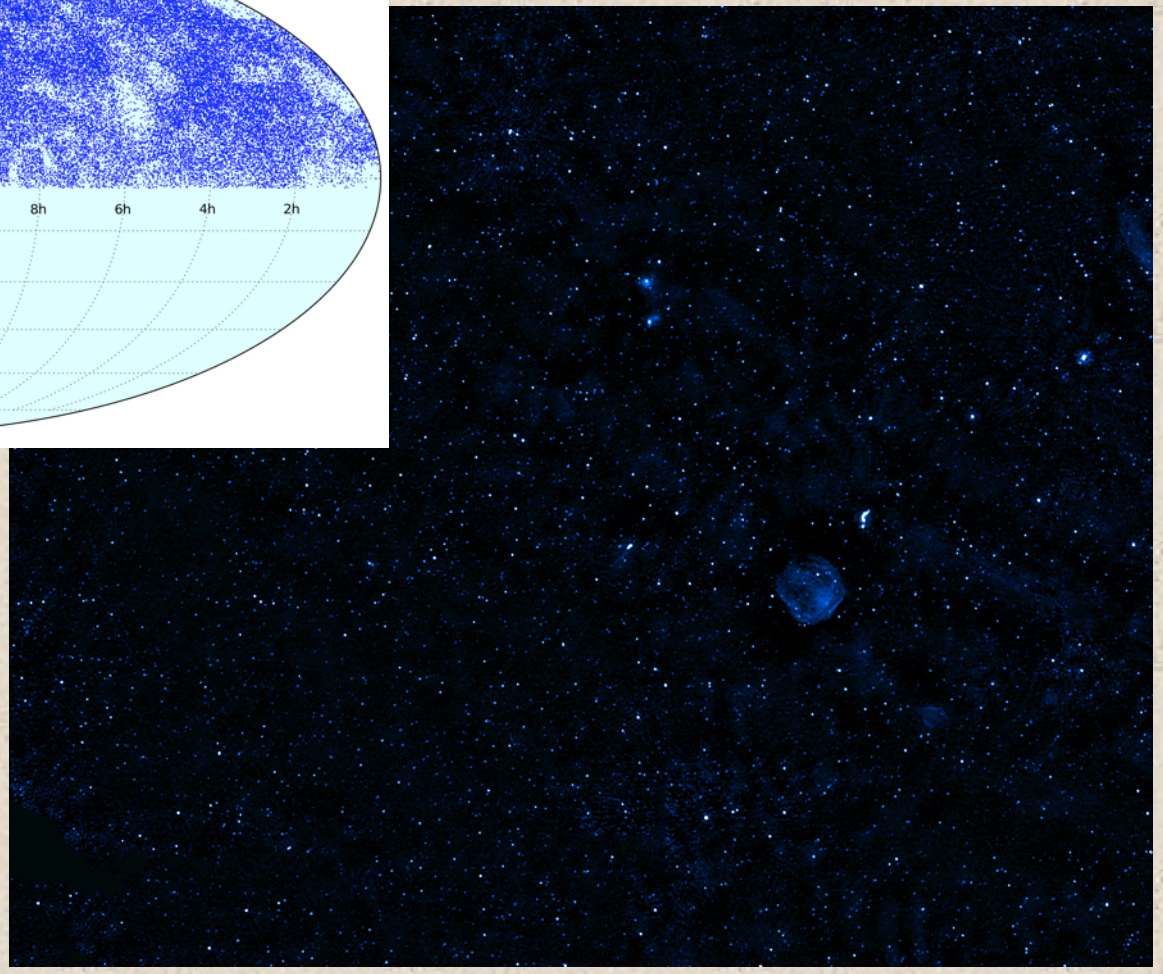
Standard imaging product: 100 deg^2 mosaics



MSSS-HBA Catalog

~140,000 sources; eventually 150,000-200,000

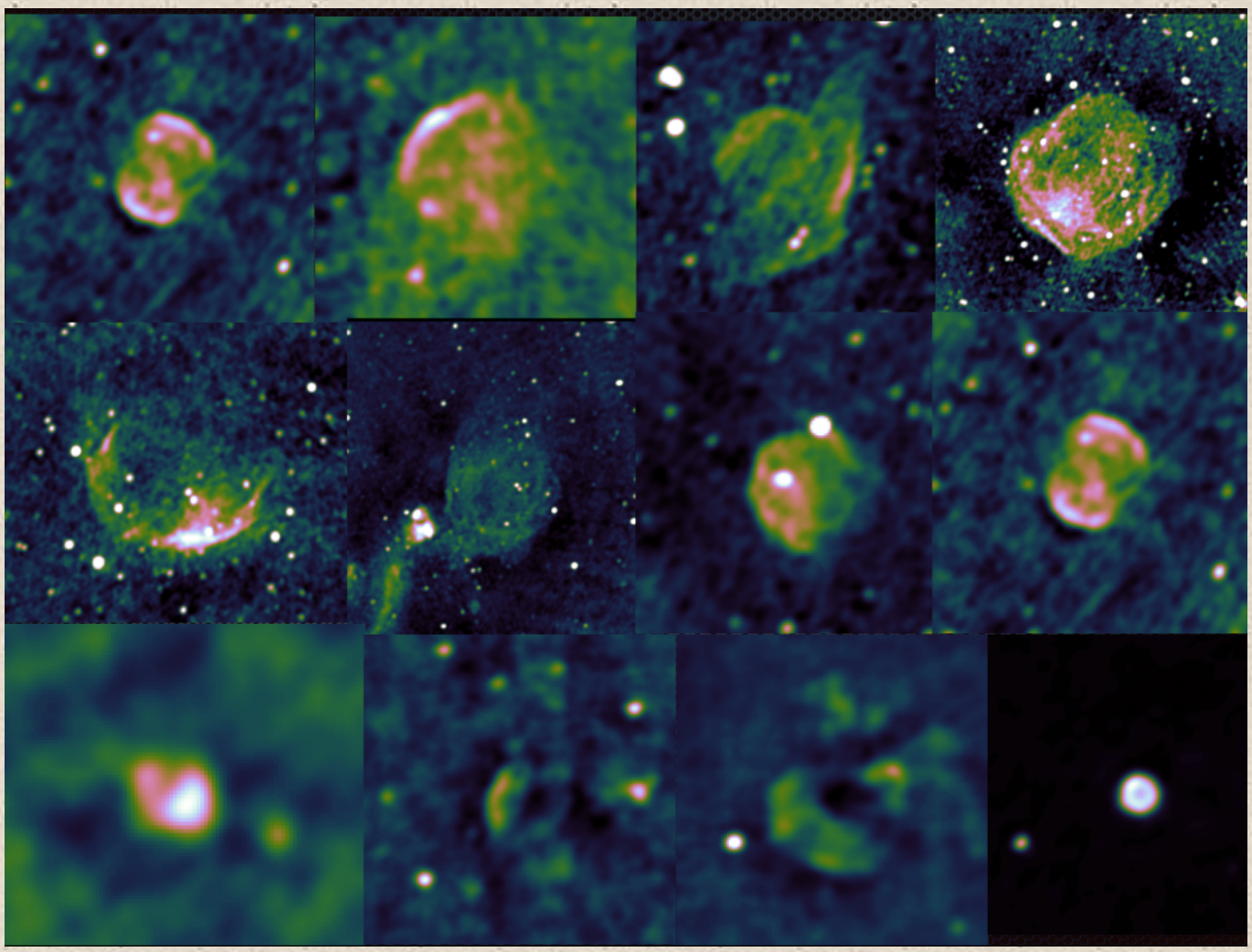




- On-line catalog
- Release in 2016
- Complementary to MWA's GLEAM

MSSS Supernova Remnant Hunt

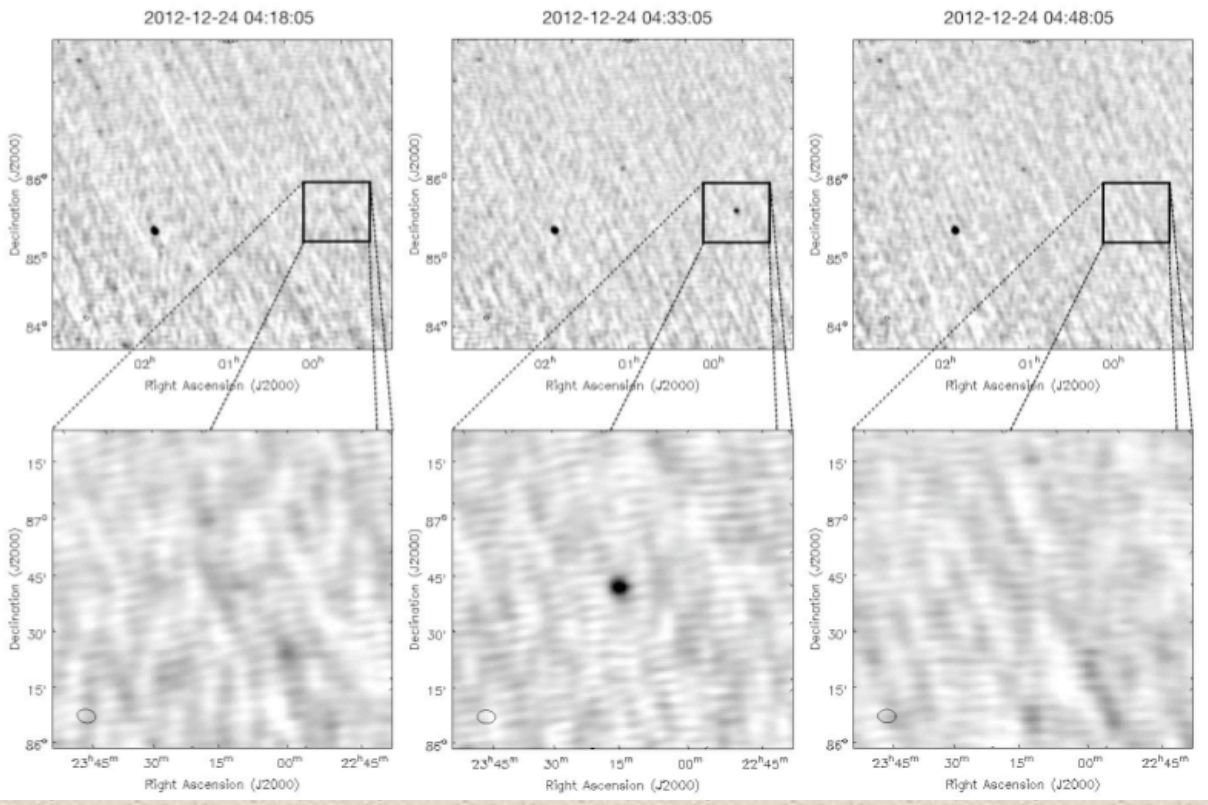
Challenge: new remnants in Galactic plane



Mulcahy et al. (in prep.)

MSSS Transient Searches

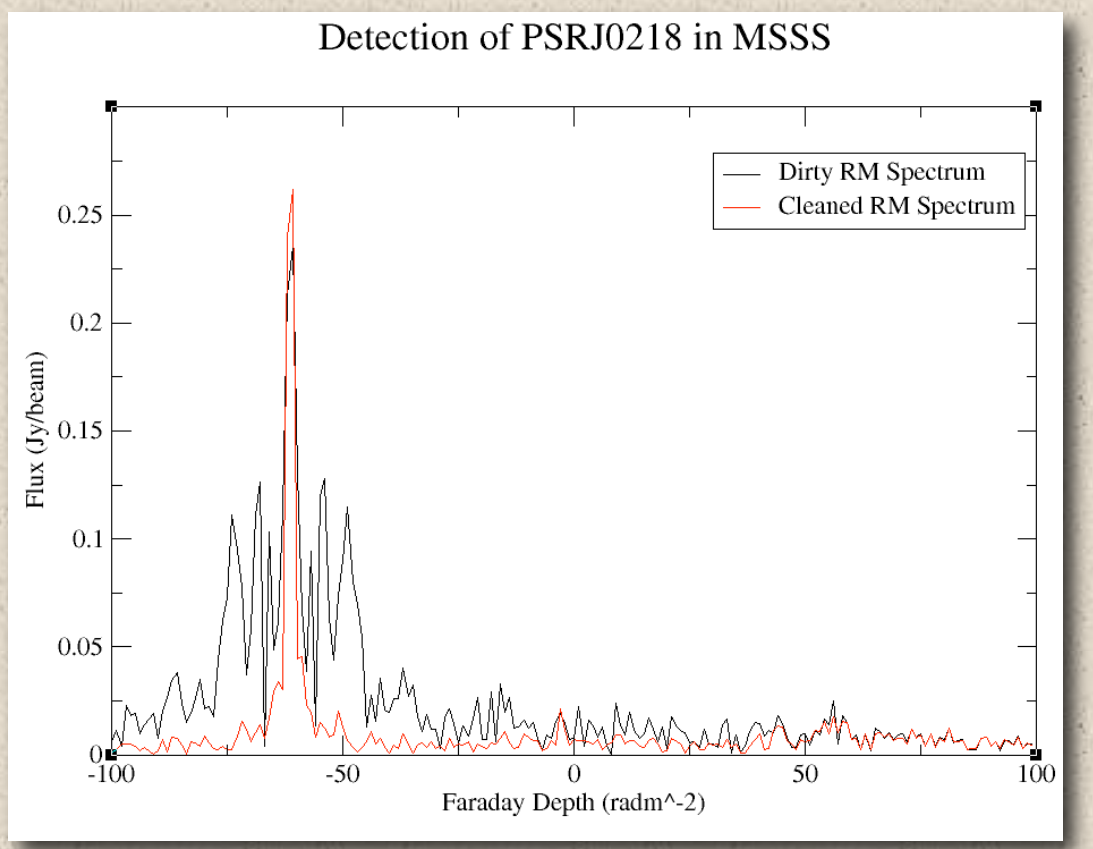
- MSSS-LBA: 1 subband (60 MHz) always on NCP
- First MSSS transient, only in one 11-min snapshot
- MSSS-HBA: started systematic transient search

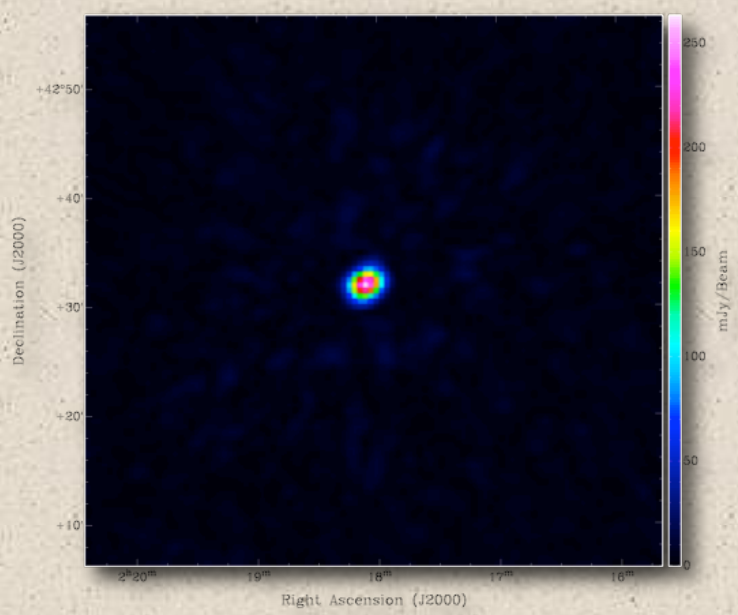


Stewart et al. (2015)

MSSS-HBA Polarization

Polarized pulsar detected with MSSS imaging data

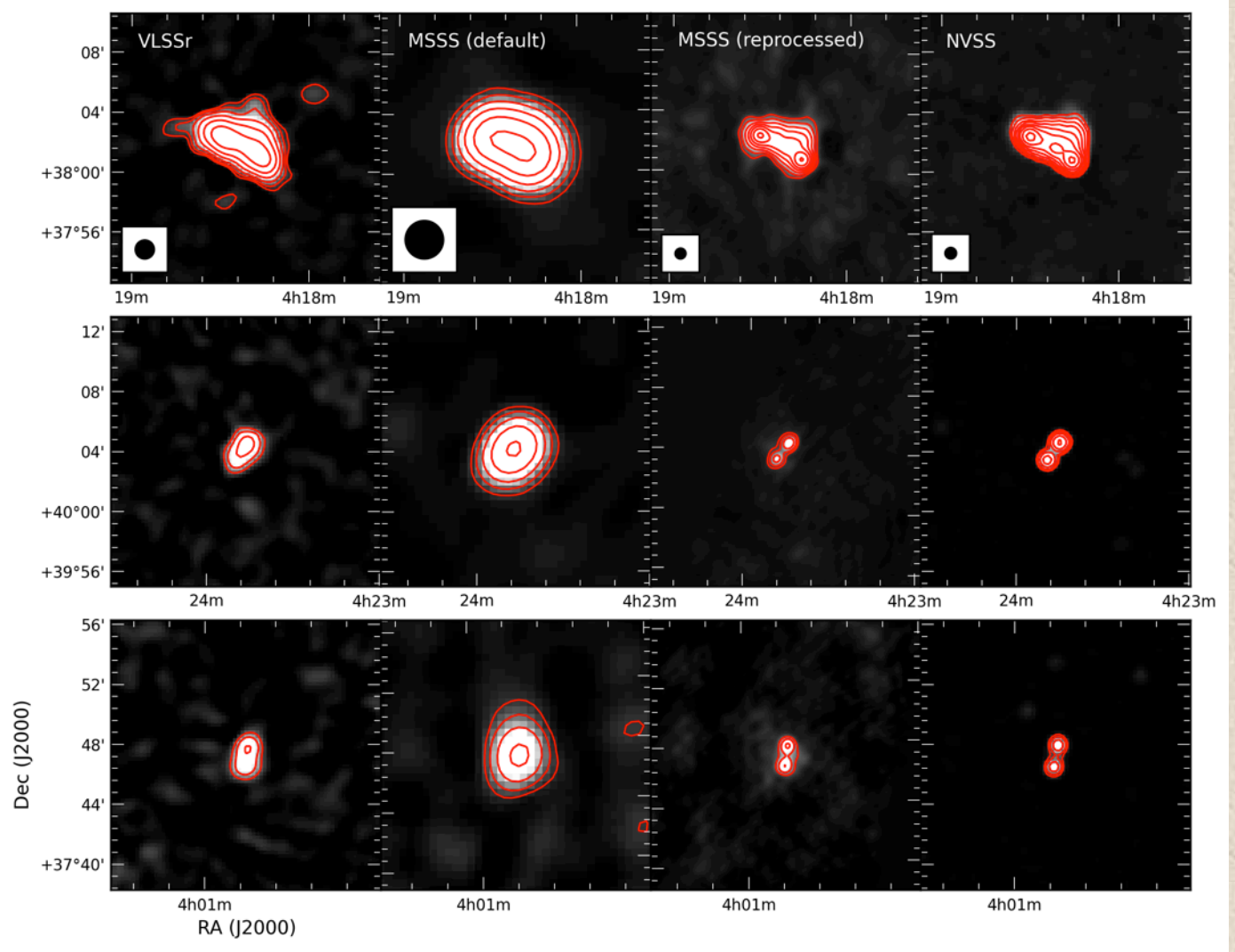




Mulcahy et al. (in prep.)

Improving MSSS Resolution

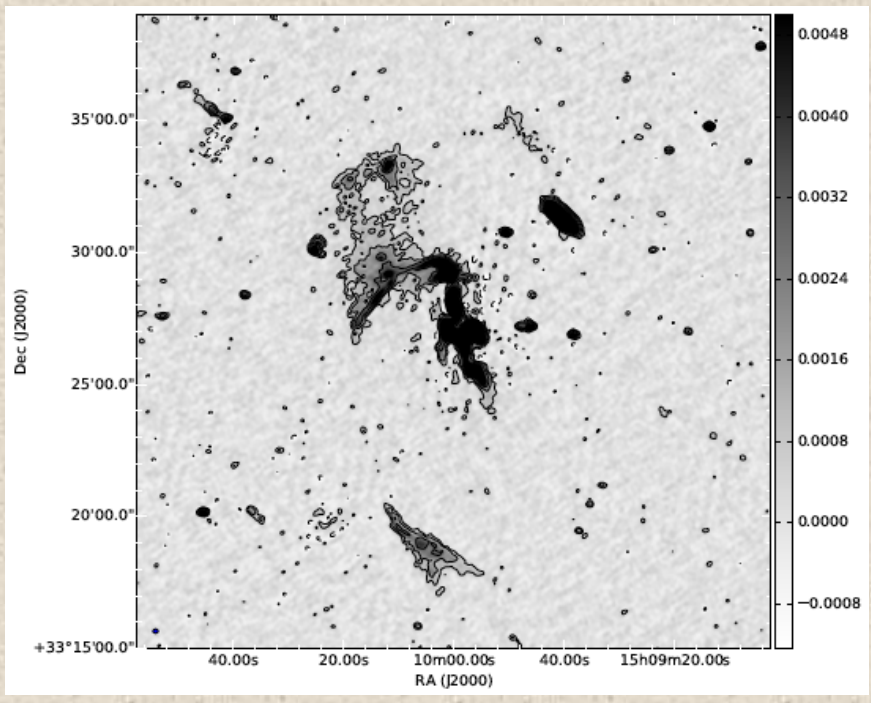
Catalog v2: imaging at 20-30” resolution



New LOFAR Imaging Surveys

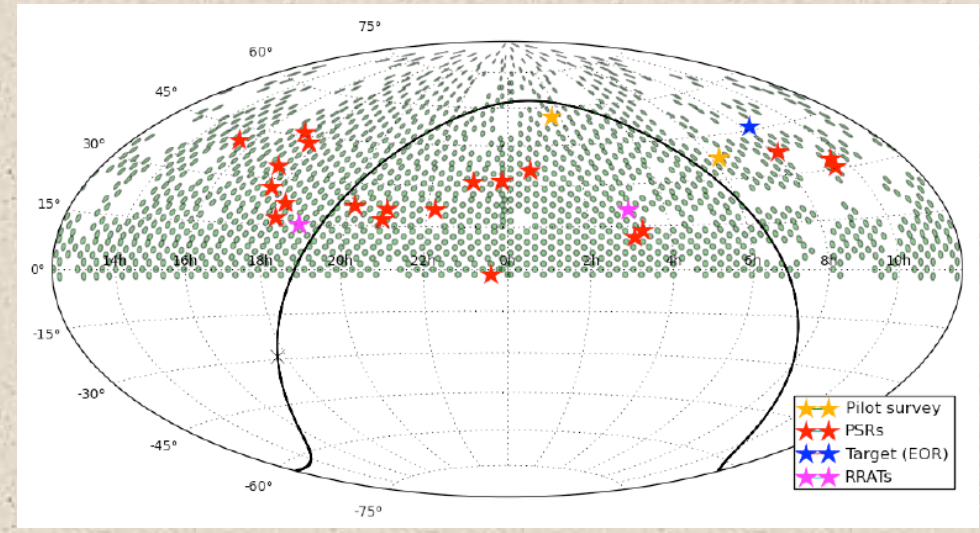
- 120-168 MHz, 5” resolution
- ~100 μJy/beam in 8 hours
- Tier-1 Survey:
  - Cover entire Northern sky
  - 3200 8-hour pointings
  - 185 pointings so far
- Tier-2 & Tier-3:
  - Several deep fields
  - 50+ hours per field

160 μJy, 5”x7”



LOFAR Tied-Array All-Sky Survey

- LOTAAS: first SKA-like pulsar survey
- High-time resolution version of MSSS
- 119-151 MHz, 0.49 ms time resolution
- Millisecond pulsars out to DM ~ 50 pc cm^{-3}
- 25 pulsar discoveries (~1 per 100 deg^2)
- 2 RRAT discoveries (same pipeline for FRBs)



Kondratiev et al. (in prep.)

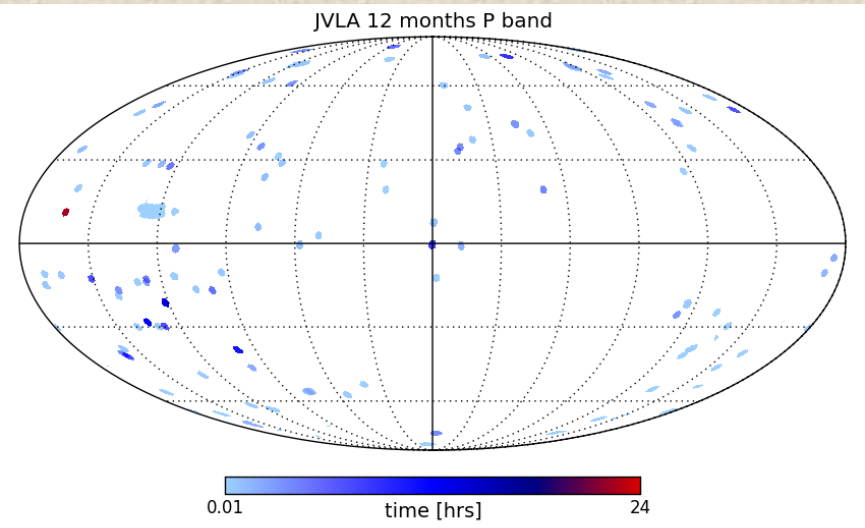
LOFAR Fast Transients

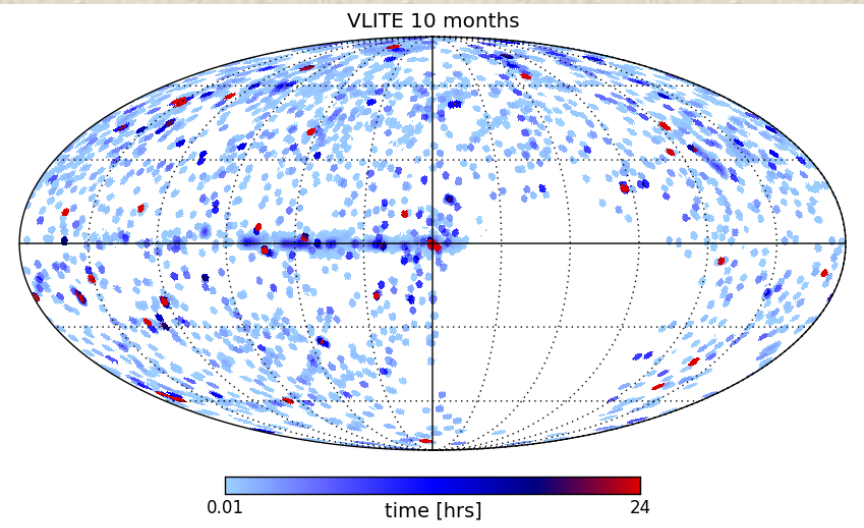
- DRAGNET (Hessels et al.)
  - Dynamic Radio Astronomy of Galactic Neutron Stars and Extragalactic Transients
  - Substantial hardware & software extension of current LOFAR abilities
- ALERT (van Leeuwen et al.)
  - Apertif-LOFAR Exploration of the Radio Transient Sky
  - Localization of extragalactic bursts
  - Synergy of LOFAR and Apertif on Westerbork
  - Apertif: full array in May 2016

VLITE

- VLA Low-band Ionospheric & Transient Experiment (Kassim, Clarke, Ray, et al.; NRL)
- Commensal observing system at ~330 MHz
- Field of view > 5 degrees
- No impact on primary observer programs
- Transient search → LOFAR Transients Pipeline
- Started 25 Nov 2014, 3-year lifetime
- VLITE on 10 antennas → possibly Low Band Observatory (LOBO) on all 27 antennas

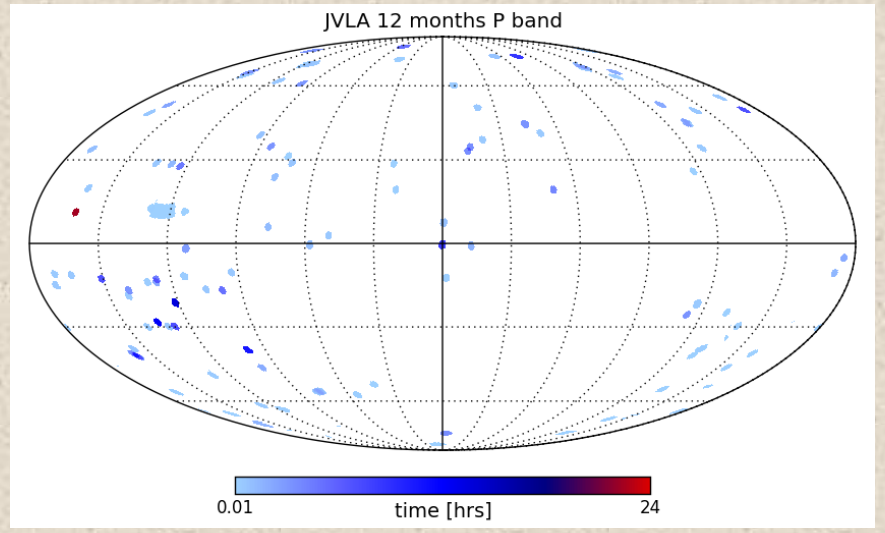
VLITE Sky Coverage

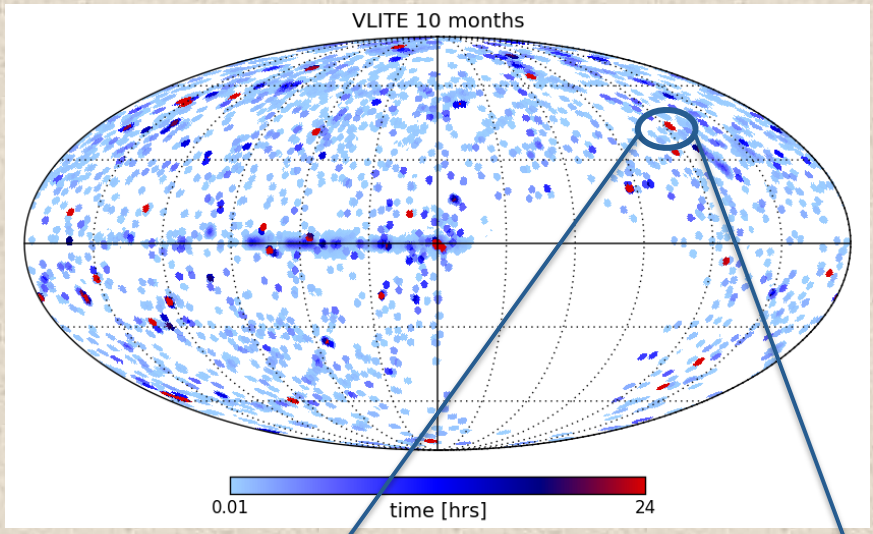




- WIDAR 12 months:
  - Deepest P band field: 22h
- VLITE 10 months:
  - ~5400h total (68% wall time)
  - Deepest P band field: > 290h

VLITE Sky Coverage





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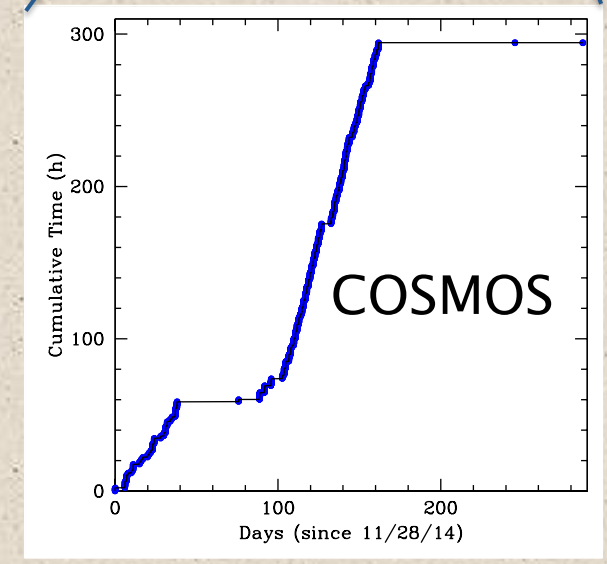
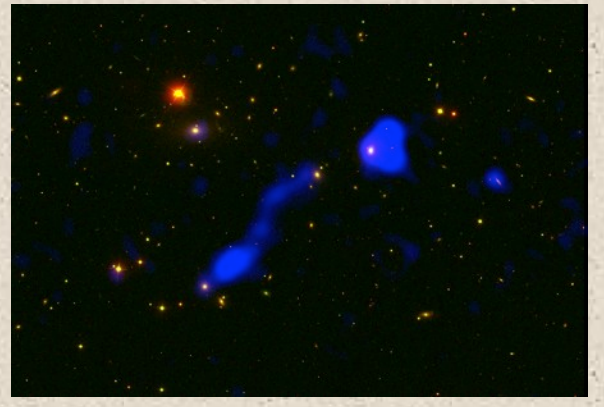
    → transient searches



VLITE Archive Products

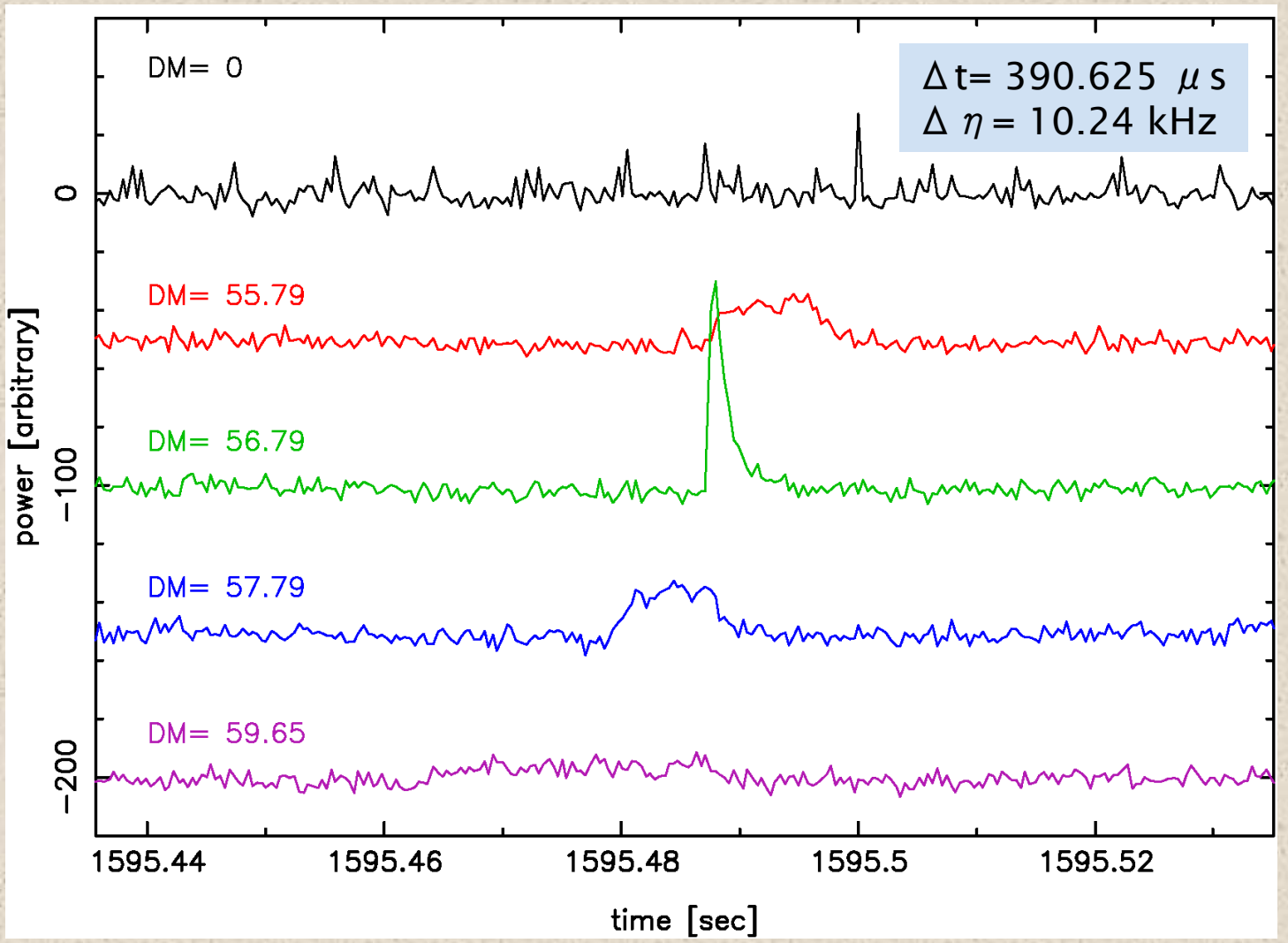
- Pipeline: real-time + 1 day lag post processing
- Wide-band, full-field images
- Narrow-band spectral window images
- Combining images on bi-monthly basis
- Spectral index maps
- Calibrated UV data
- Sky catalog
- Light curves
- Possible addition of polarization products



http://vlite.nrao.edu

VLITE FAST Transients

Crab Giant Pulses



Jansky VLA Sky Survey (VLASS)

- New radio sky survey with upgraded JVLA
  - ~20 years after NVSS & FIRST (1993-2002)
- All-sky ($\delta > -40^{o}$): ~34,000 square degree
- High spatial resolution: 2.5”
- Wide bandwidth: 2-4 GHz
- 5400 hours over 7 years (13% of time)
- 3 epochs with 32 month cadence
- 69 μJy/beam (each epoch: 120 μJy/beam)

→ 10 million sources!

VLASS Data & Science

- NRAO provides basic data products:
  - Raw & calibrated UV data
  - Full Stokes images (single-epoch & cumulative)
- Community-led science effort:
  - Enhanced data products
  - Source catalogs
  - Multi-wavelength & multi-messenger studies
  - RM synthesis maps → Faraday tomography
  - Real-time & long-term transient searches
- Design reviews + Pilot Project in 2016

https://science.nrao.edu/science/surveys/vlass

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