ASTRON

Netherlands Institute for Radio Astronomy

Next Generation Radio Astronomy with LOFAR

Michael Wise
LOFAR Project Scientist
(ASTRON / UvA)

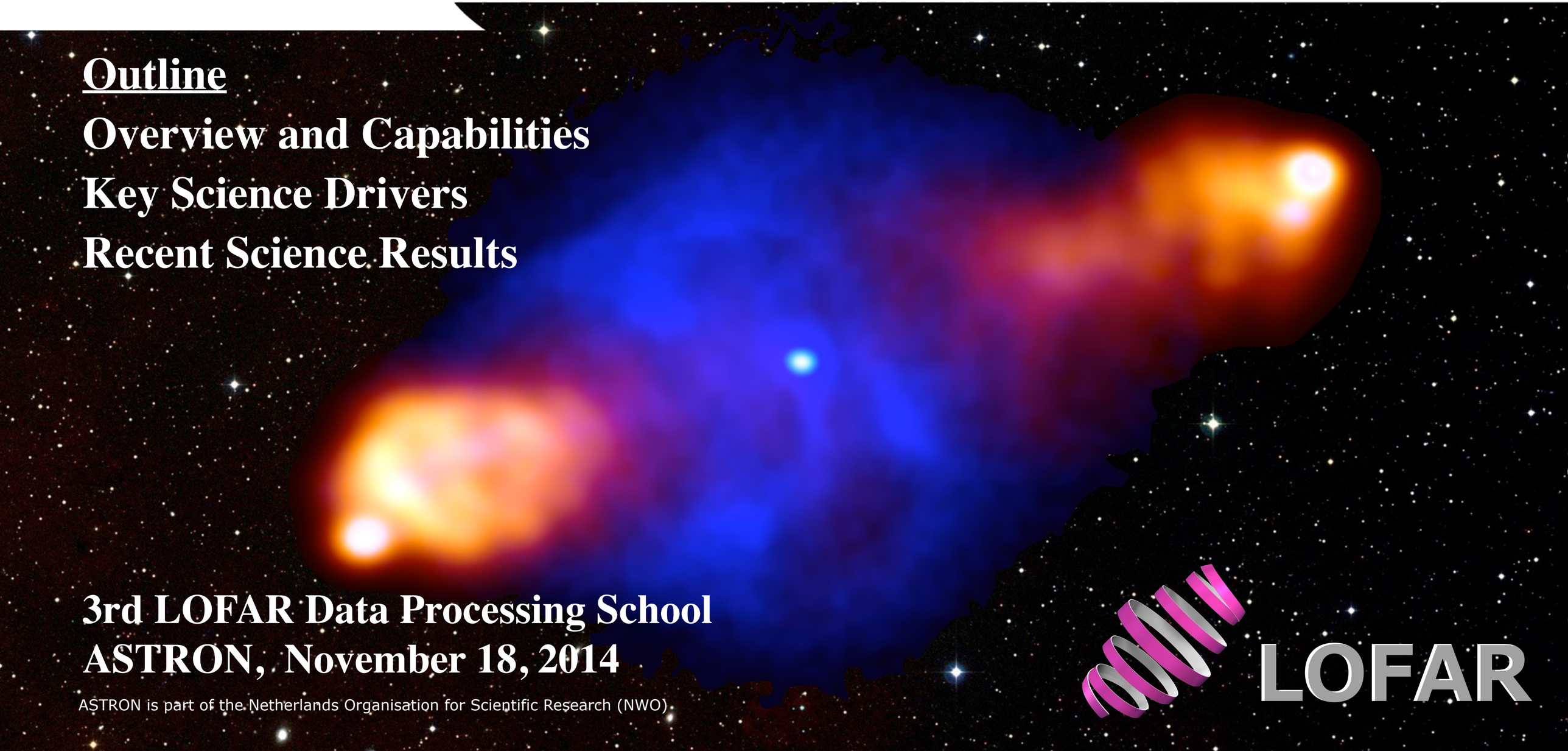
3rd LOFAR Data Processing School
ASTRON, November 18, 2014

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

LOFAR

ASTRON

Netherlands Institute for Radio Astronomy



Outline

Overview and Capabilities

Key Science Drivers

Recent Science Results

3rd LOFAR Data Processing School
ASTRON, November 18, 2014

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LOFAR

International LOFAR Telescope

Europe-wide radio interferometry array @ 10-270 MHz
Resolution: 2 arcmin - 0.3 arcsec

Onsala
Dutch stations
Norderstedt
Chilbolton
LOFAR Core (NL)
Potsdam
Bałdy
Borówiec
Jülich
Effelsberg
Tautenburg
Łazy
Unterweilenbach
Nançay

International LOFAR Telescope

Europe-wide radio interferometry array @ 10-270 MHz
Resolution: 2 arcmin - 0.3 arcsec

- *46 operational stations completed*
- *38 NL stations, 8 international*
- *4 new stations funded in: Germany (1), Poland (3),*
- *Proposed stations: Ireland (1), Italy (1), Finland (1) , NL (2+)*

Onsala
Dutch stations
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Nançay

LOFAR Core
"Superterp"


Effelsberg


Nançay


Unterweilenbach


Chilbolton


Onsala


Tautenburg


Potsdam

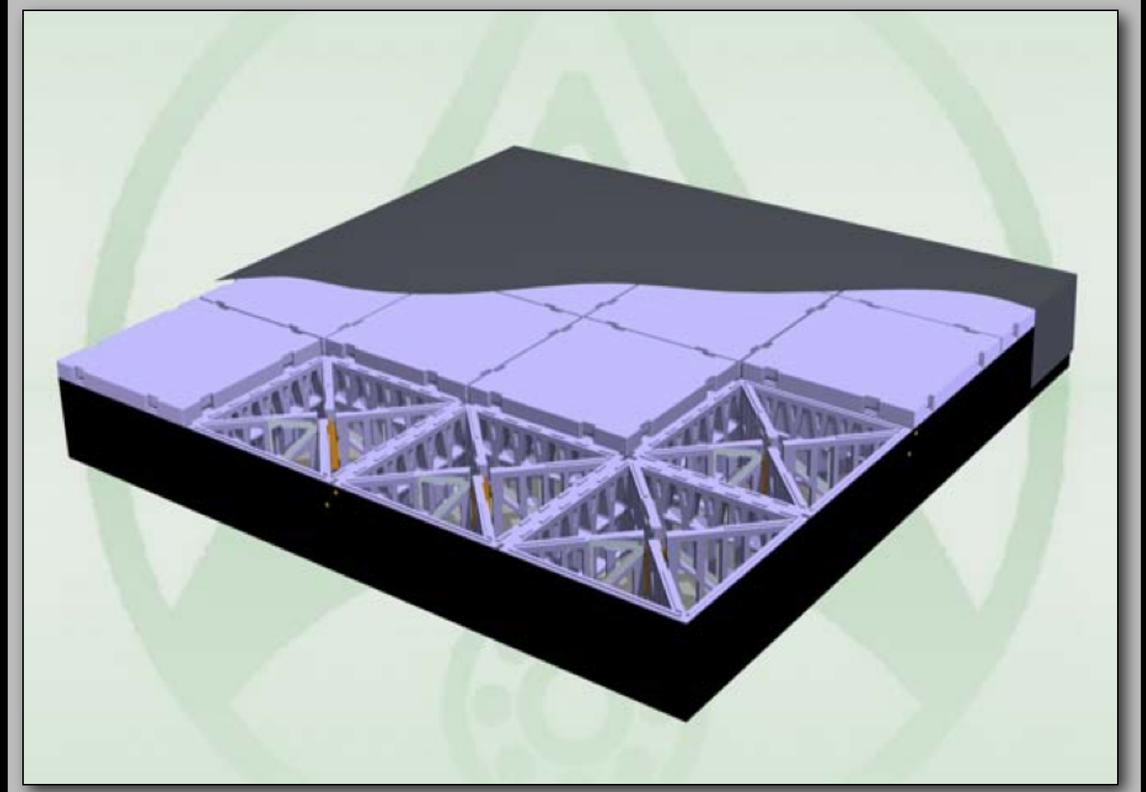

Jülich

LOFAR Antennas

Low band antenna: 30 – 80 MHz
48/96 antennas per station

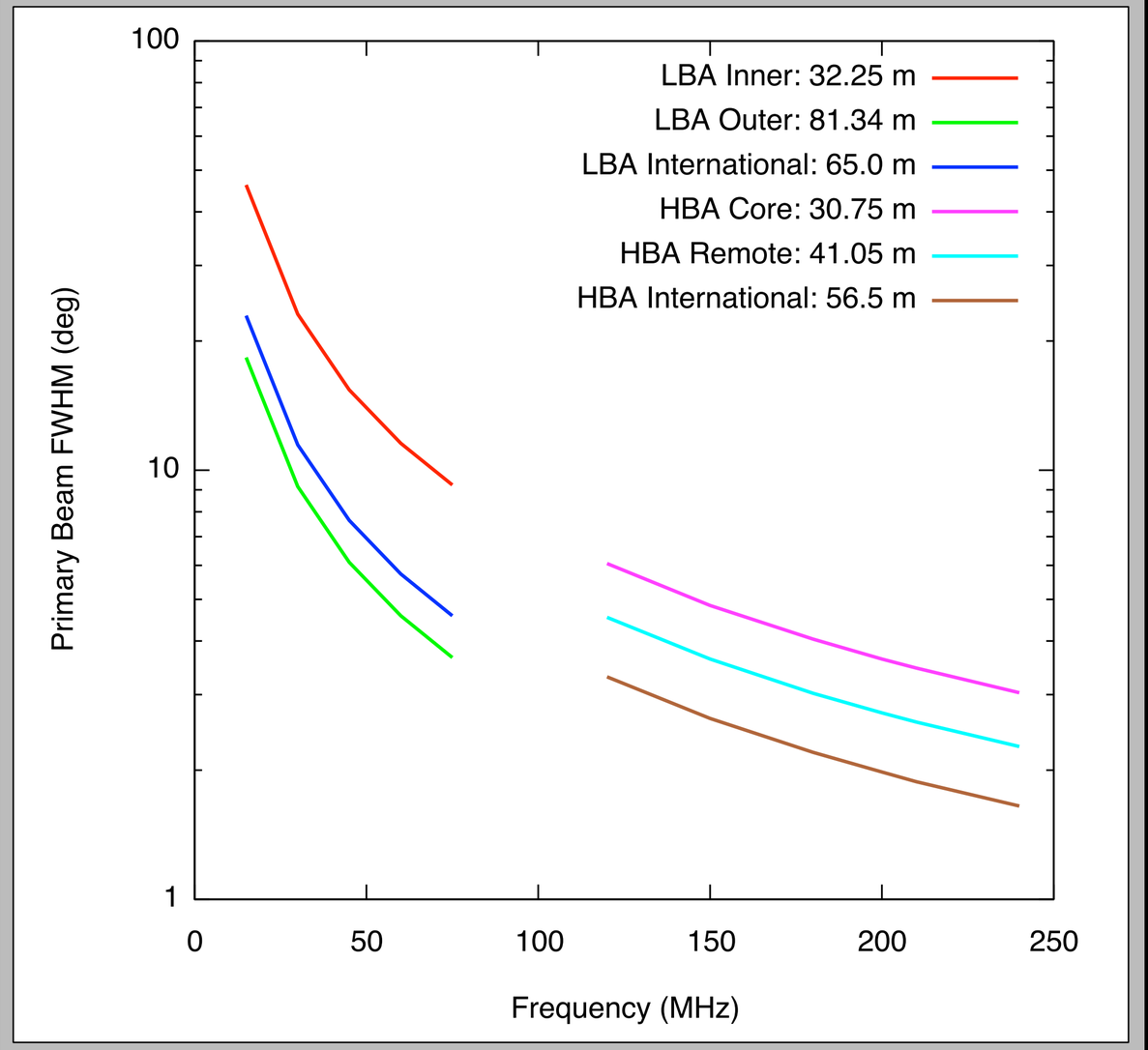
38 NL + 8 EU stations of dipoles
Replace big dishes by many cheap dipoles
No moving parts: electronic beam steering
Flexible digital beam forming

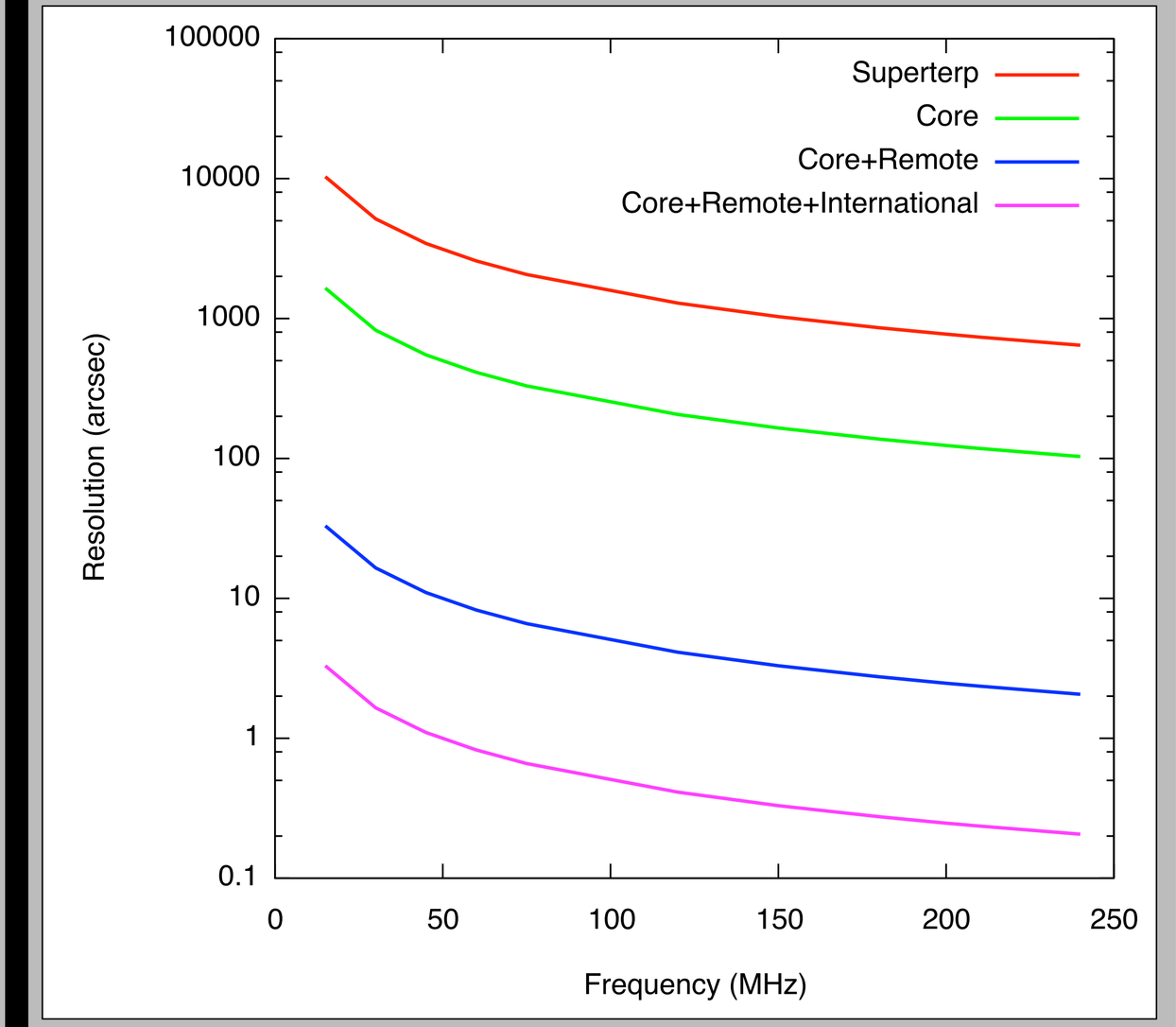
High band tiles:120 – 240 MHz
48/96 tiles/station, 4x4 antennas/tile



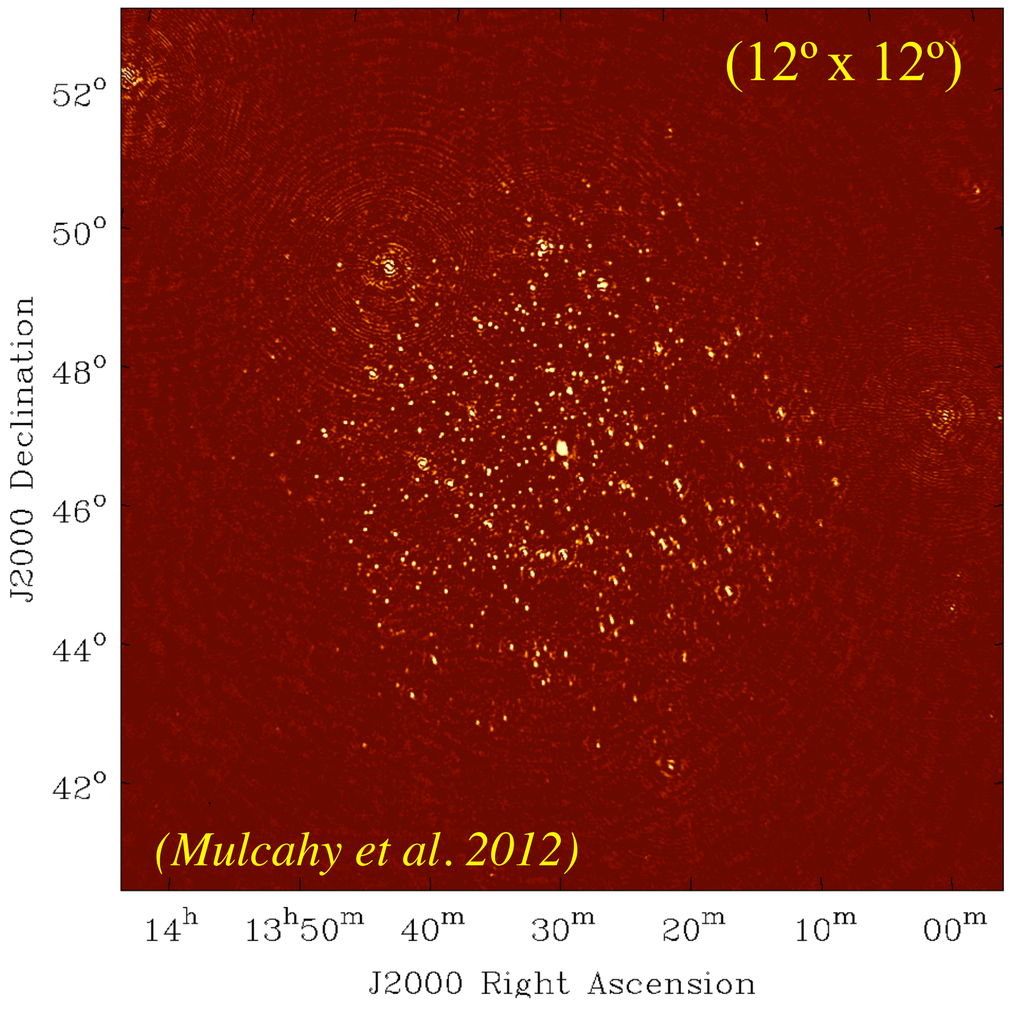
Relatively unexplored part of spectrum!

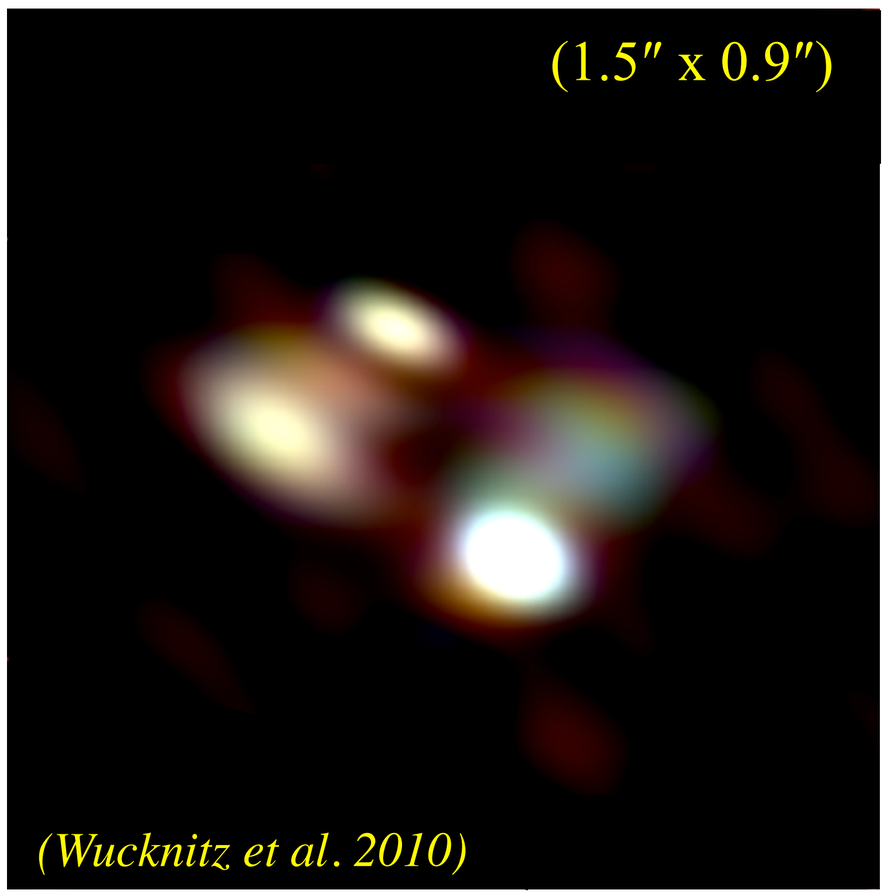
Resolution and Field-of-View



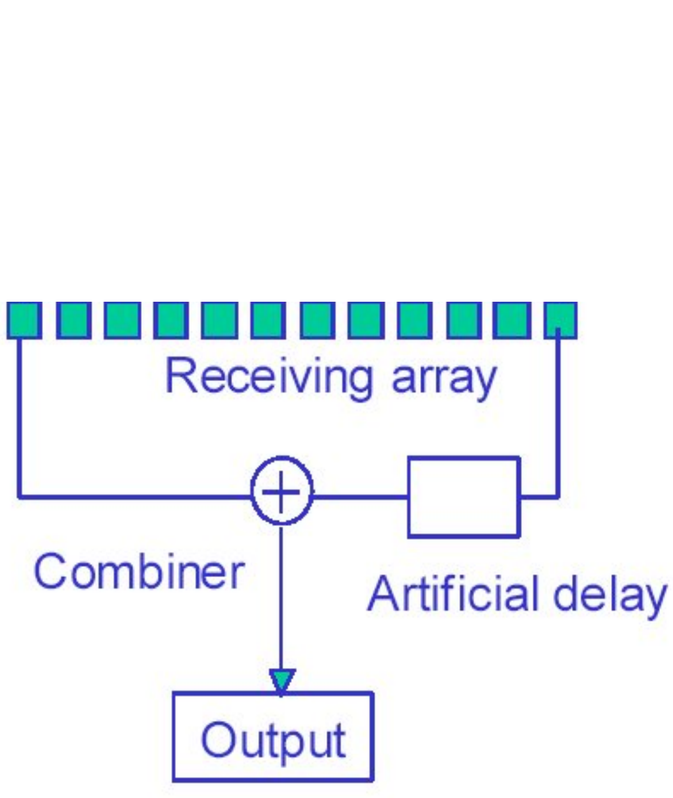


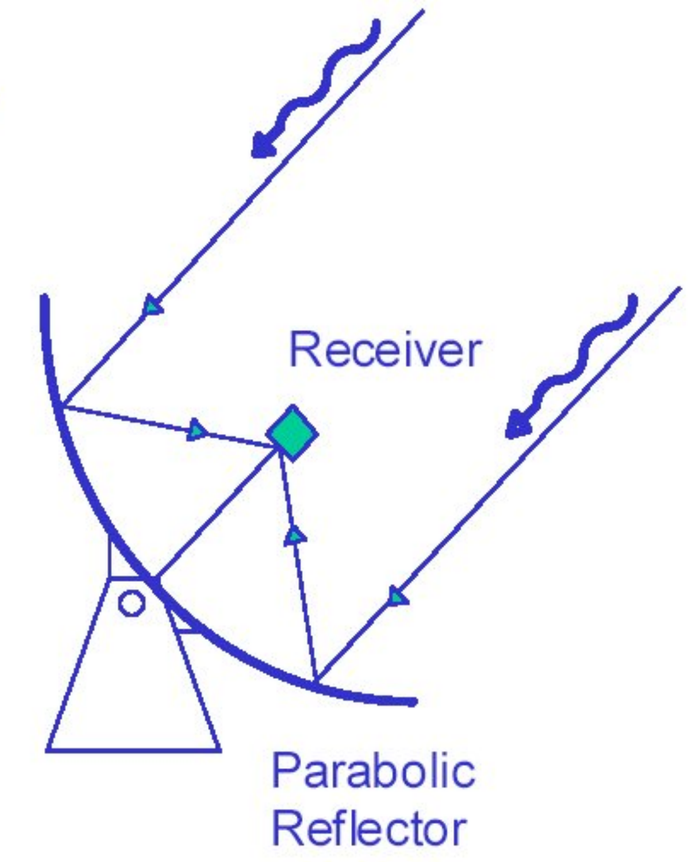
Resolution and Field-of-View





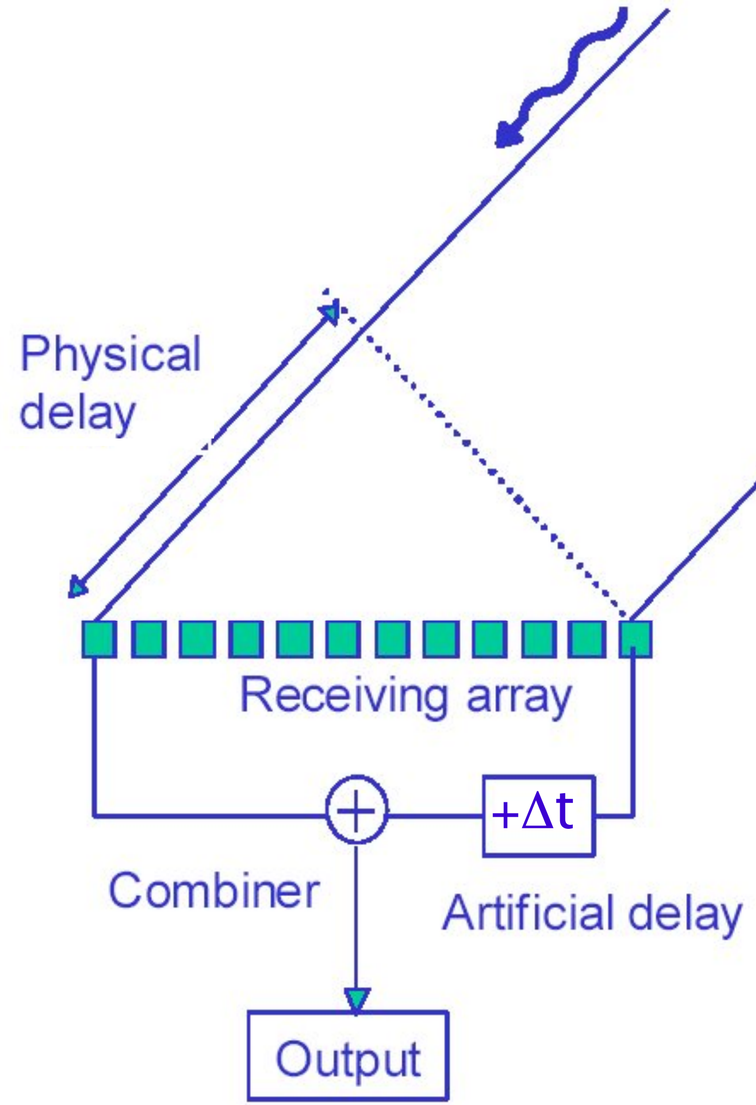
Phased Array Detectors

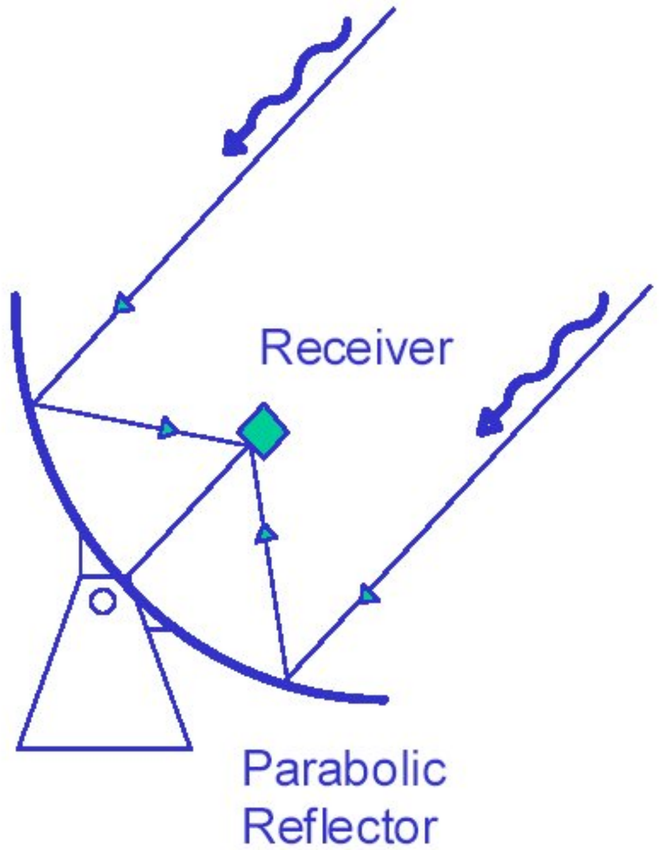




Electronic beam steering

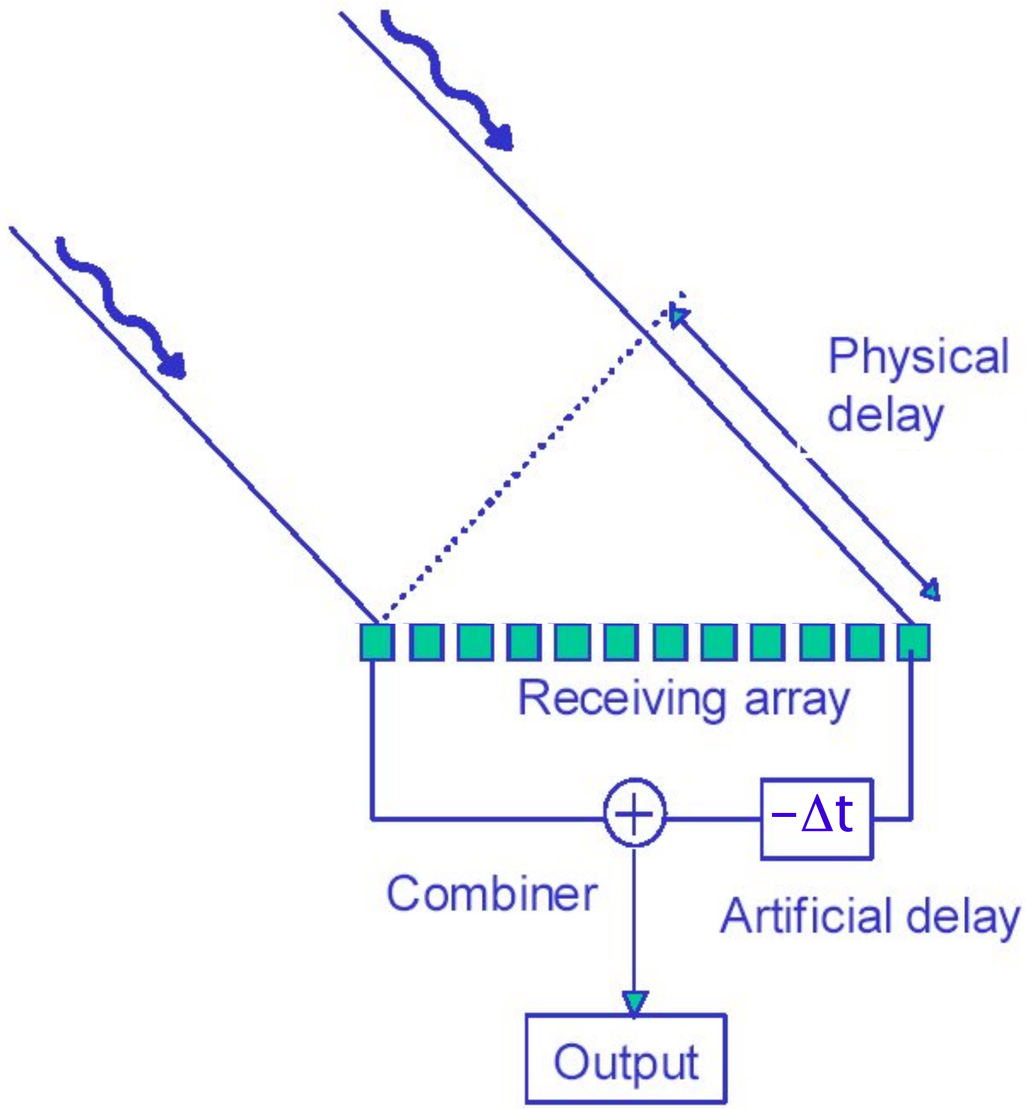
Phased Array Detectors

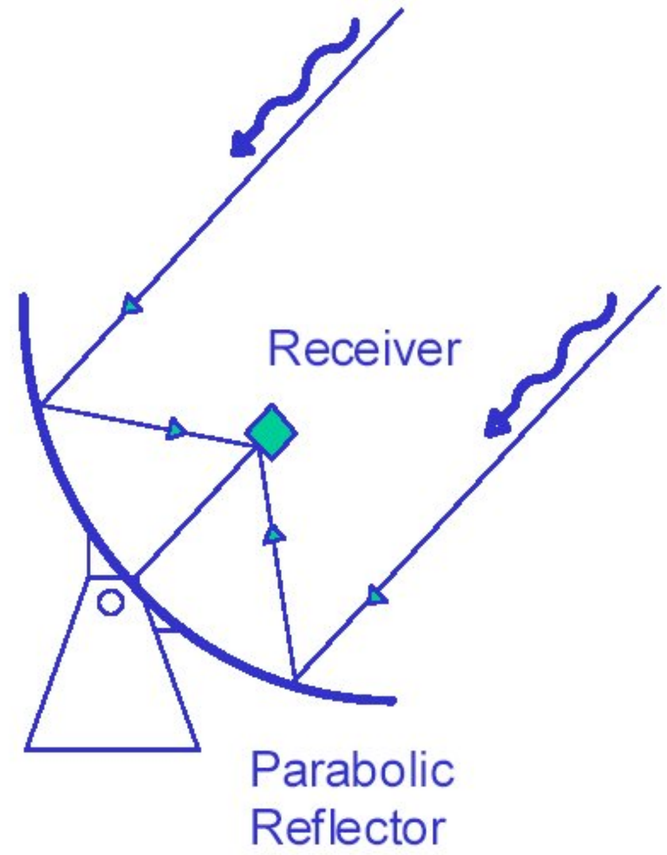




Electronic beam steering

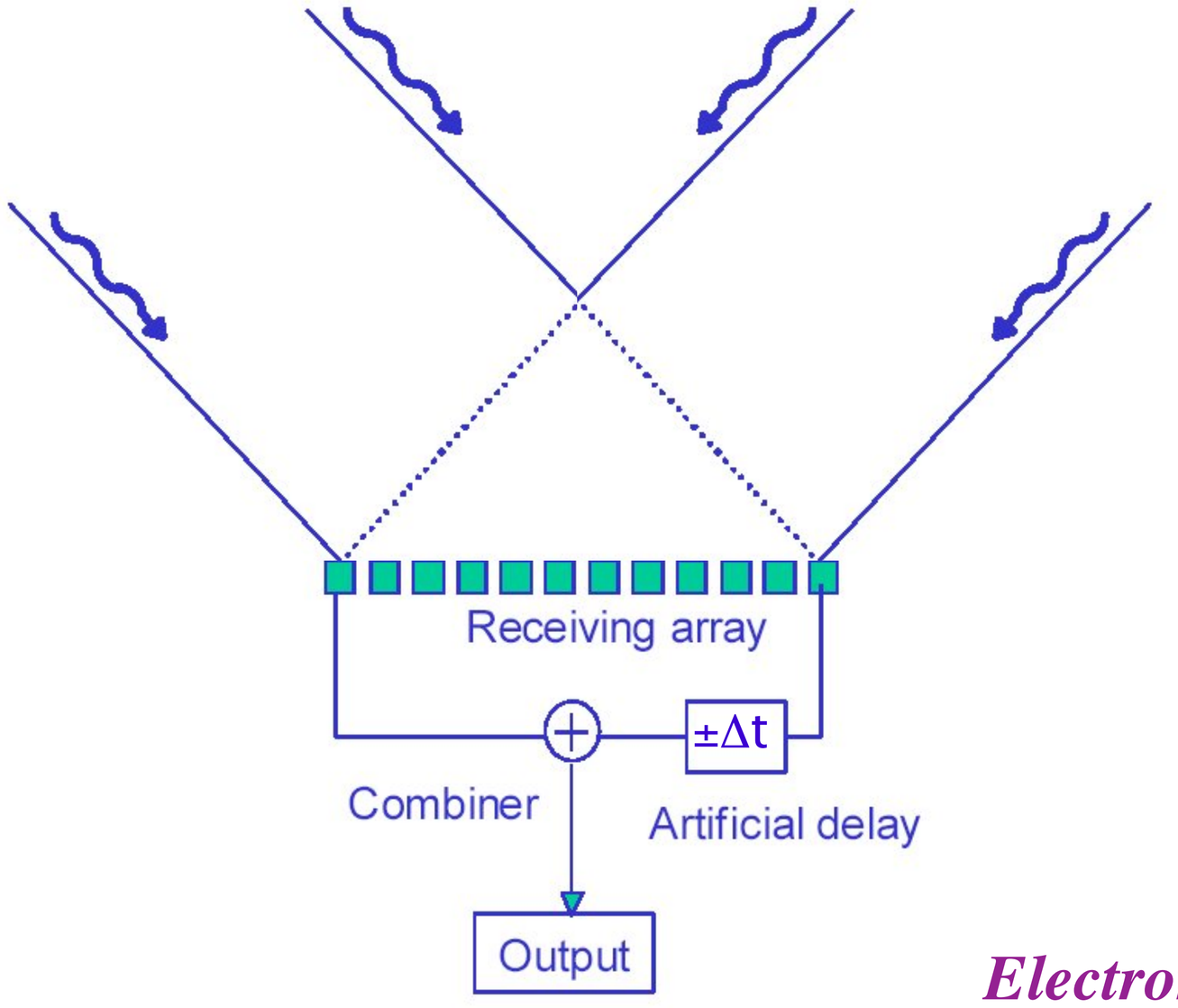
Phased Array Detectors

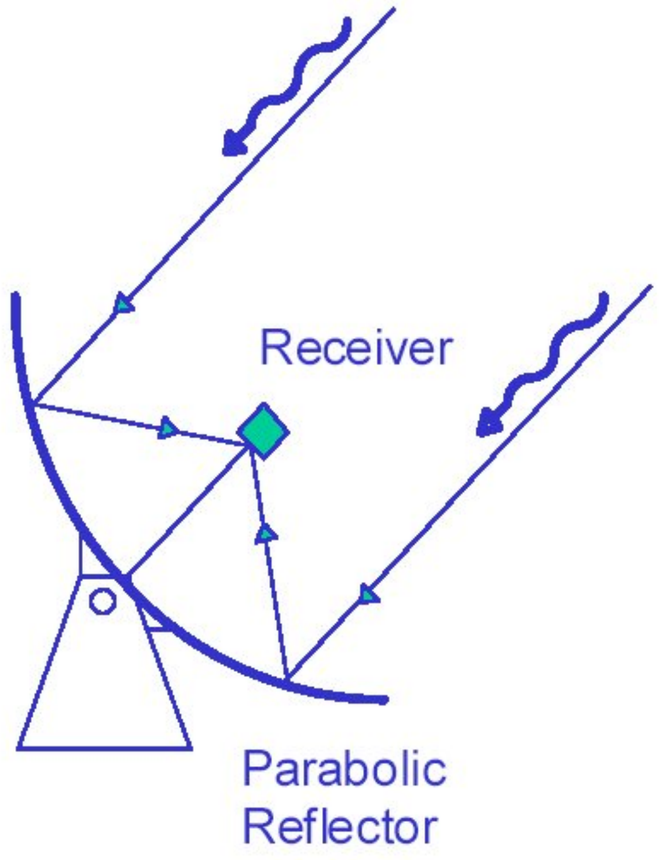




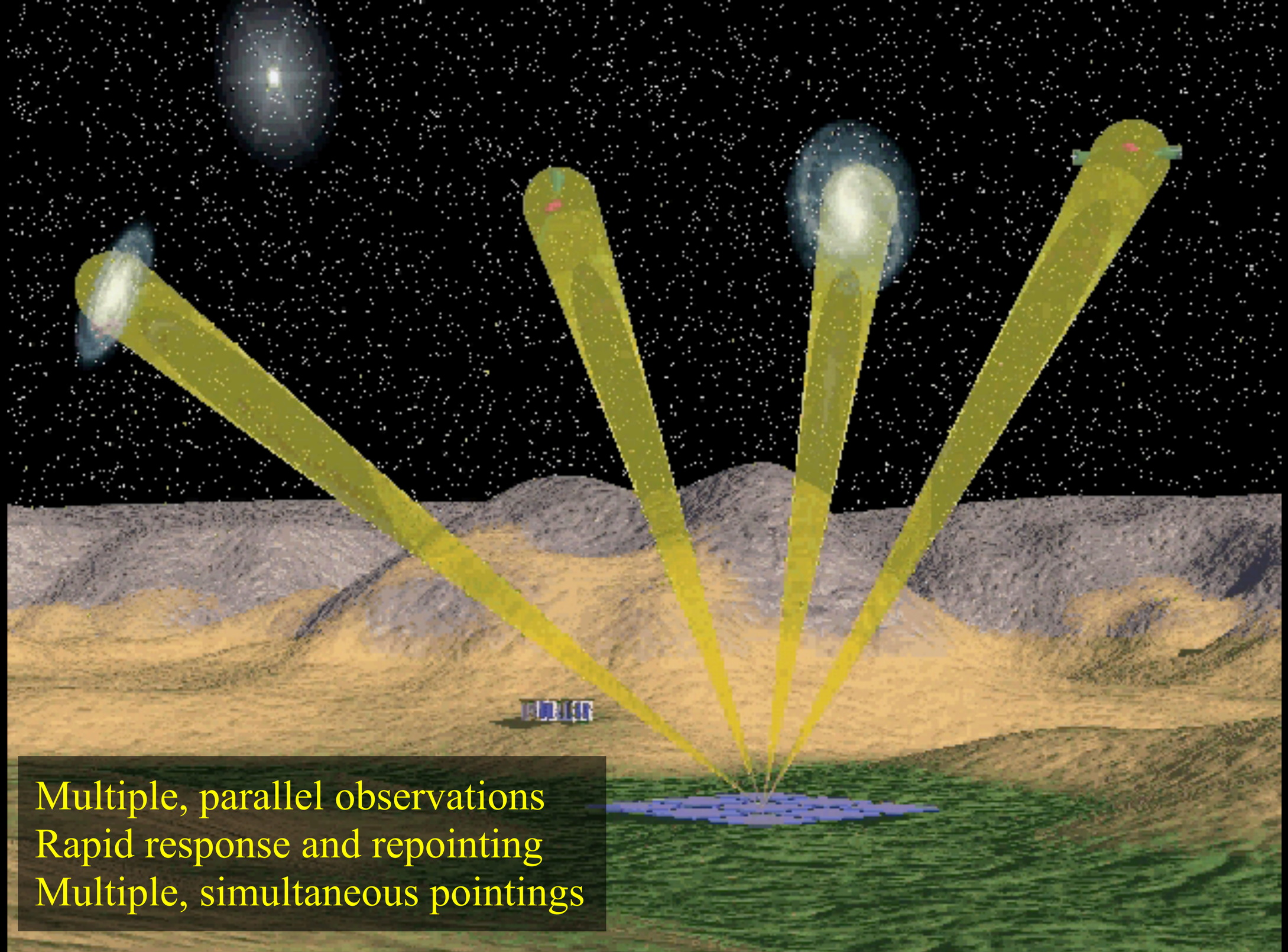
Electronic beam steering

Phased Array Detectors

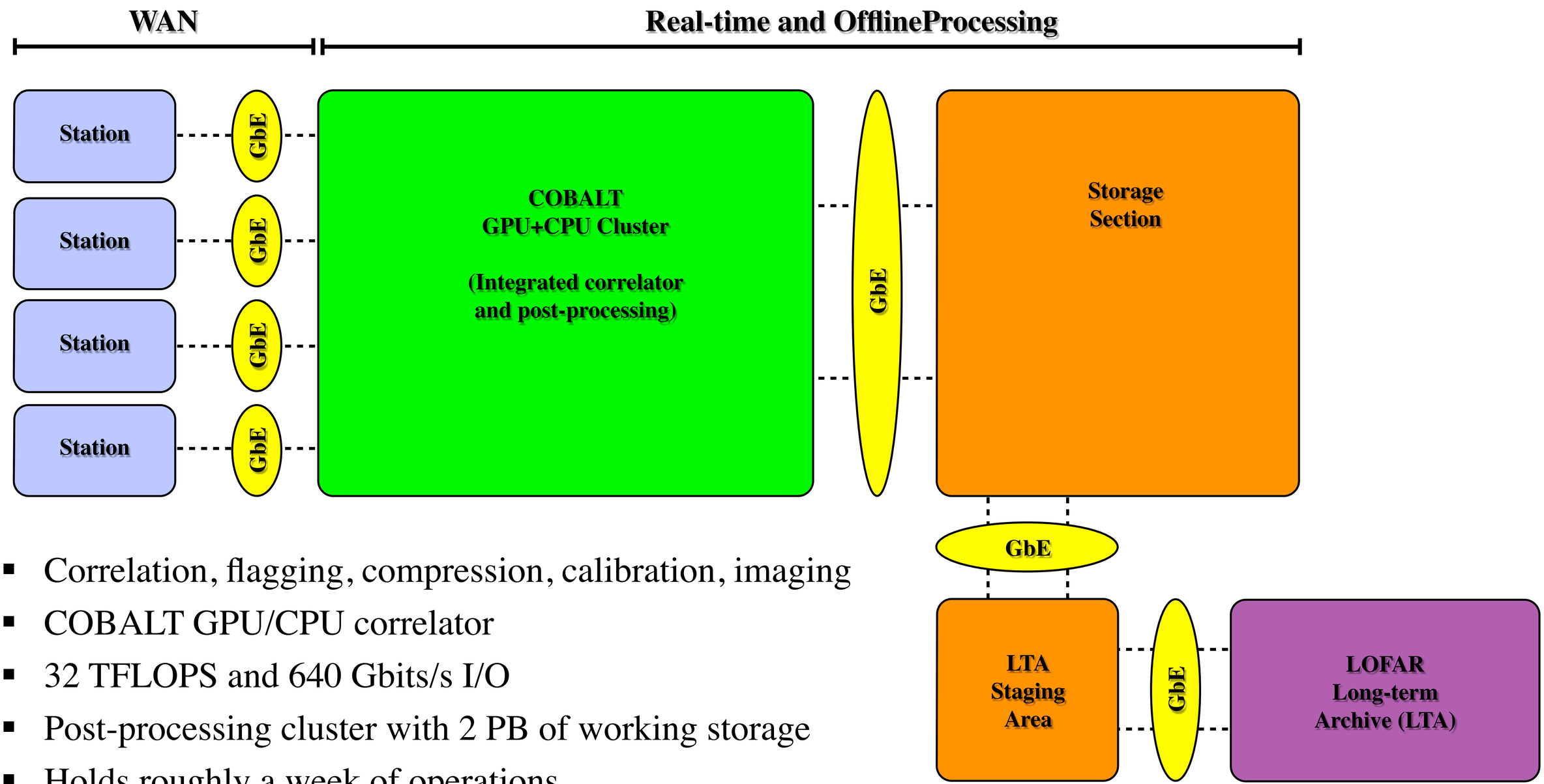




Electronic beam steering


Multiple, parallel observations
Rapid response and repointing
Multiple, simultaneous pointings

LOFAR Central Processing



- Correlation, flagging, compression, calibration, imaging
- COBALT GPU/CPU correlator
- 32 TFLOPS and 640 Gbits/s I/O
- Post-processing cluster with 2 PB of working storage
- Holds roughly a week of operations

LOFAR Science Drivers

Key Science Projects

Epoch of Reionization

Transients and Pulsars

High Energy Cosmic Rays

Surveys and the Distant Universe

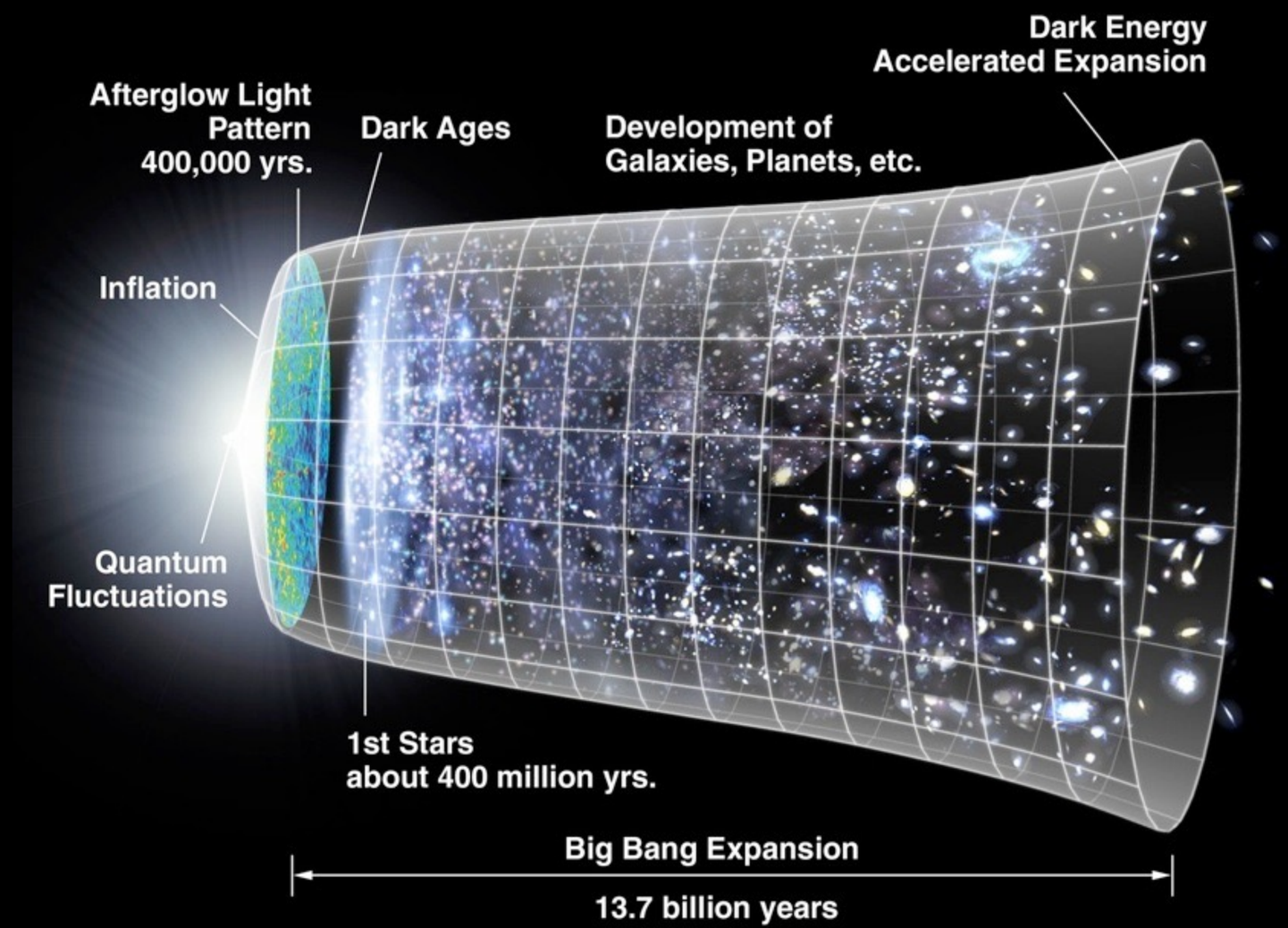
Cosmic Magnetism

Solar Physics and Space Weather

⇒ International membership from countries all over world

Contribute development and commissioning resources

The LOFAR Epoch of Reionization Key Science Project



- When was the Universe reionized ?
- How (fast) did reionization proceed ?
- Which objects were responsible ?
  stars/galaxies , QSOs, or …

<u>Redshifted HI to frequency mapping</u>

z =6.7 ⇒ 185 MHz

z = 8.5 ⇒ 150 MHz

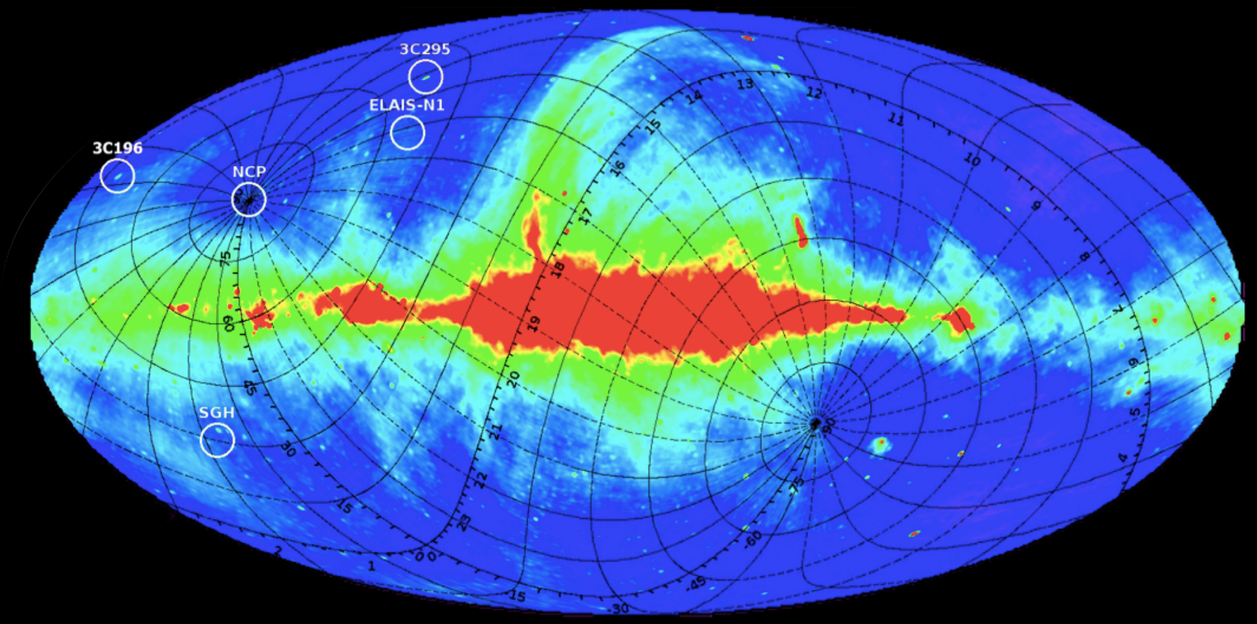
z = 11.4 ⇒ 115 MHz

$$\delta T_b \approx 28mK$$

Goal: Detect cosmological 21cm signal (z~6-10) from the Epoch of Reionization

⇒ 1.5 Pbytes and 10^{21}-10^{22} FLOP to extract signal!

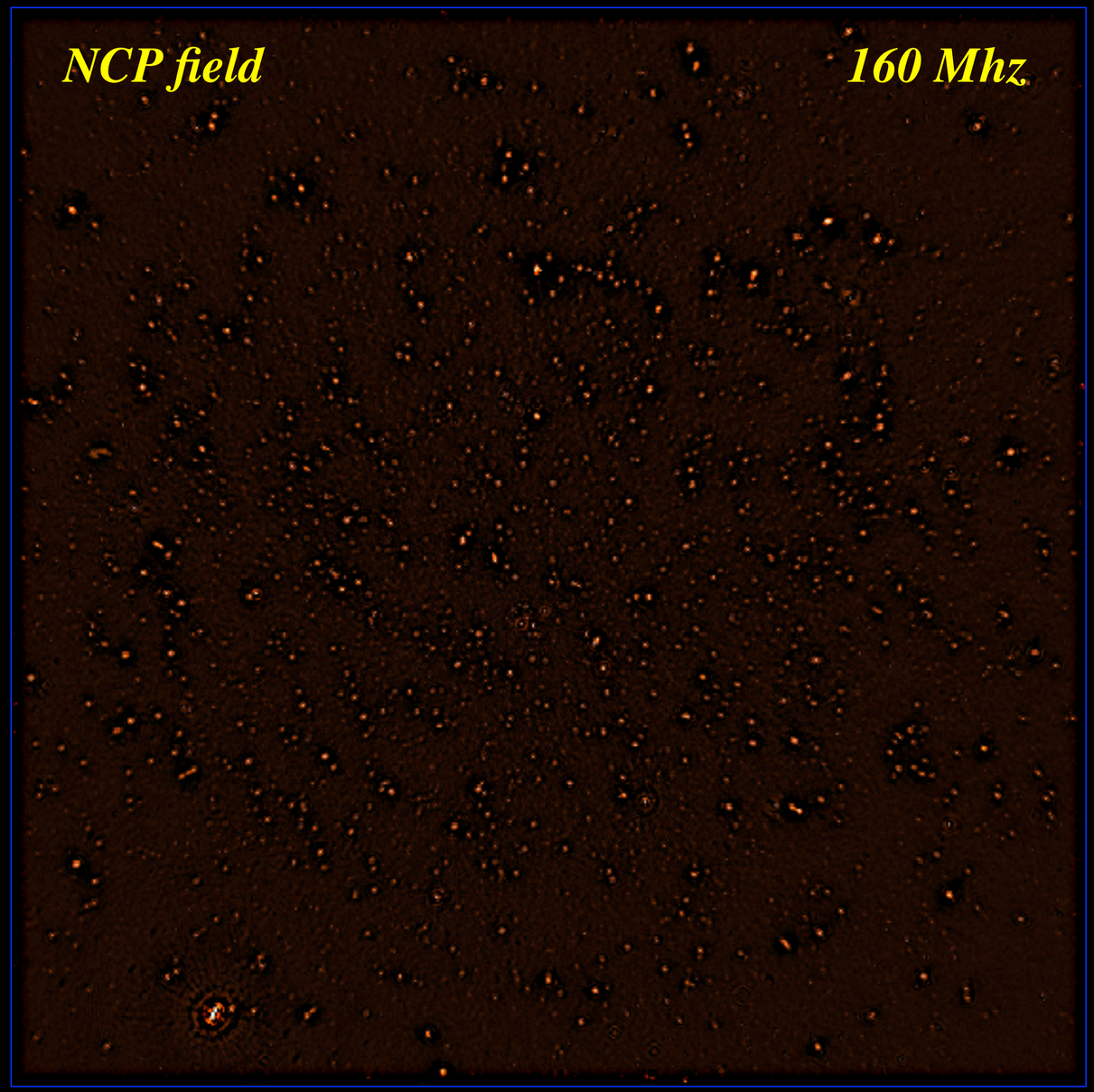
Initial Results on EoR Deep Fields



- Total 40 observations, 500 hours (NCP)
- Concentrating on 3 distinct fields
- Custom processing on EoR cluster

$\sigma \sim 30\ \mu Jy \qquad \theta \sim 6''$

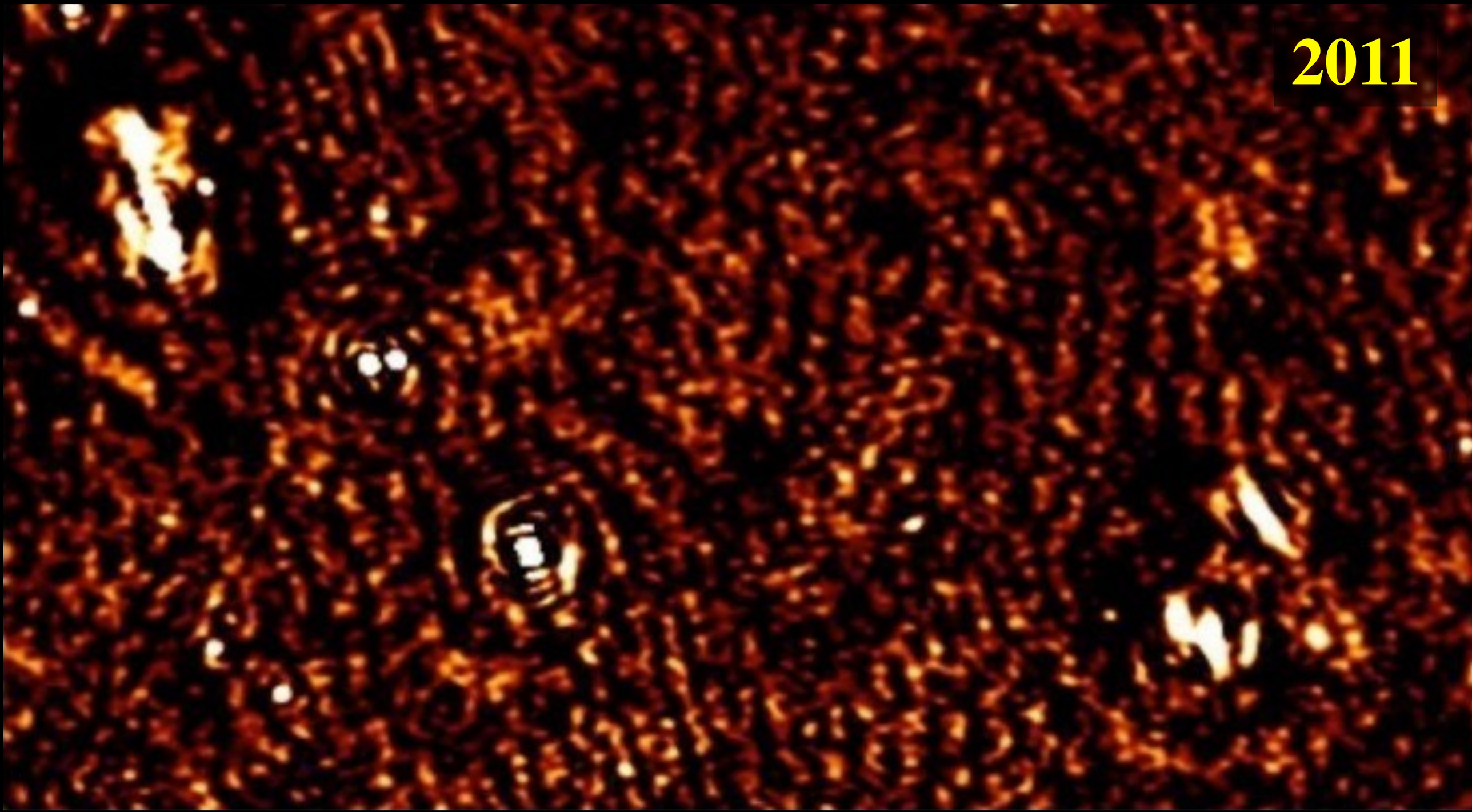
70 hrs, 96 MHz bandwidth
8^o x 8^o, 15000x15000 pixels, 2" pixels



(courtesy S. Yatawatta and the EoR KSP Team)

NCP field ≈ 180 μJy / beam

(image courtesy S. Yatawatta)



NCP field ≈ 30 μJy / beam

(image courtesy S. Yatawatta)

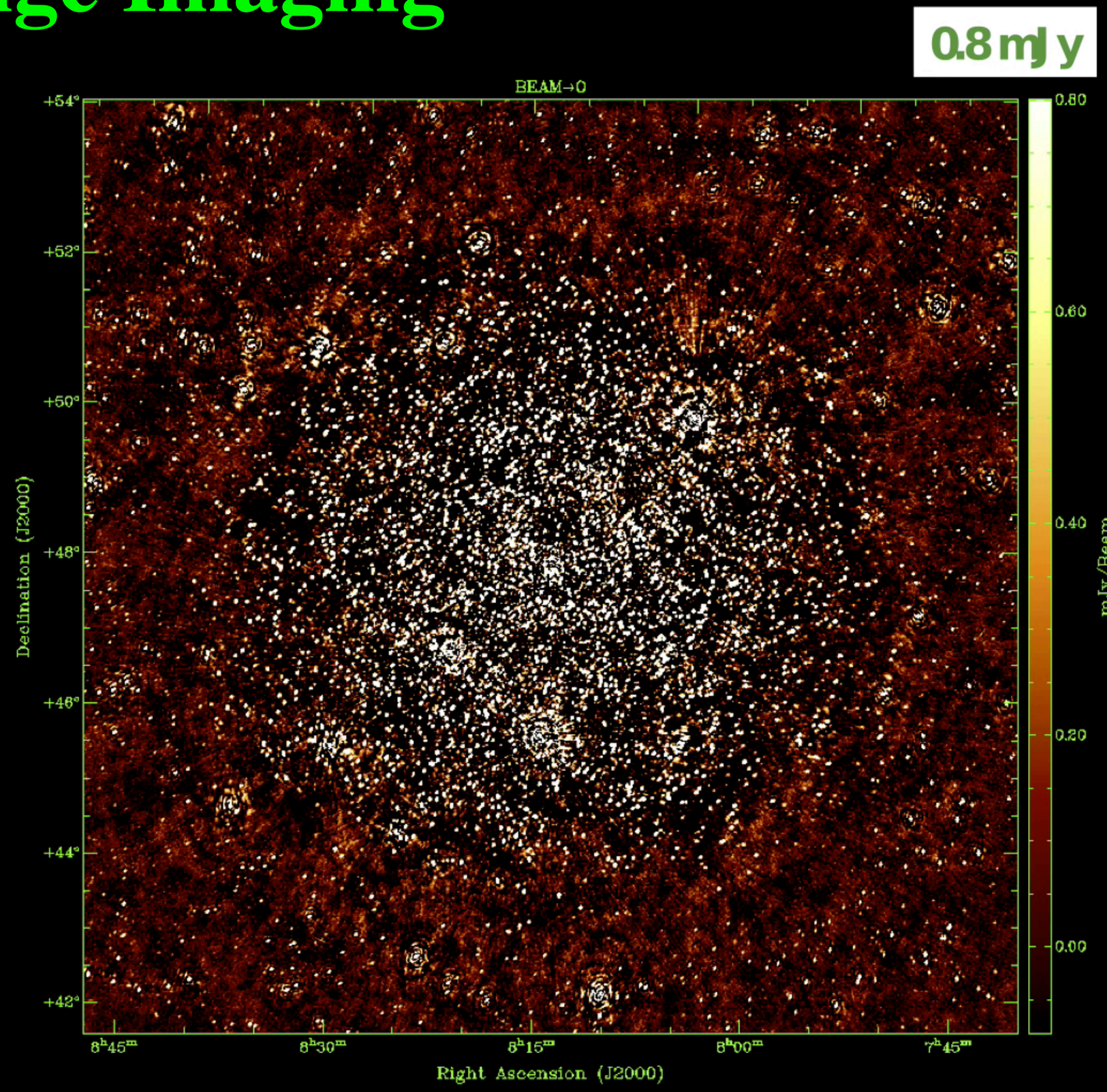
High Dynamic Range Imaging

(images courtesy V. Pandey)

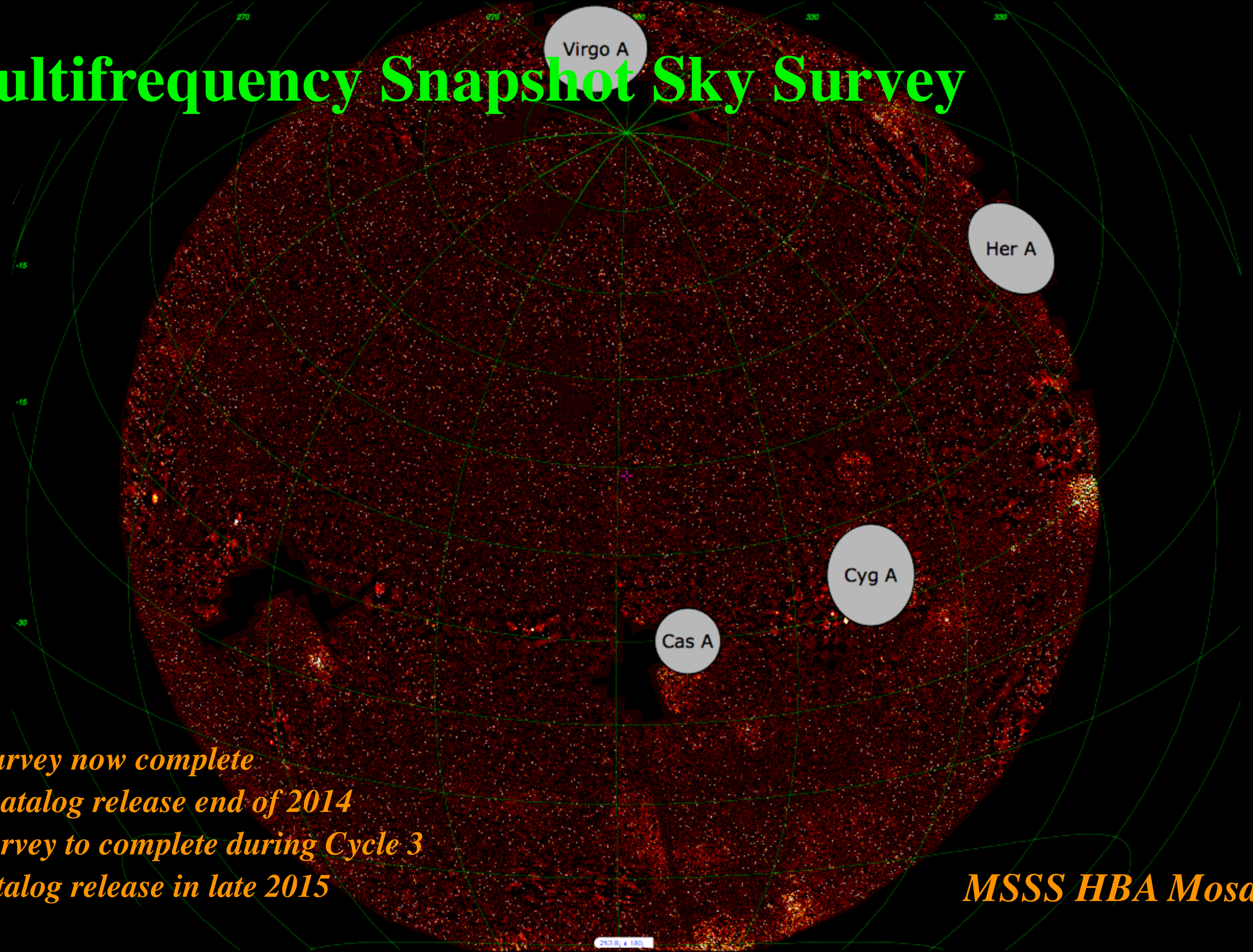
3C196 field

160 MHz, 32 hrs, 96 MHz bandwidth

DR ~ 1,000,000:1!



Multifrequency Snapshot Sky Survey



HBA Survey now complete
Initial catalog release end of 2014
LBA Survey to complete during Cycle 3
LBA catalog release in late 2015

MSSS HBA Mosaic

Multifrequency Snapshot Sky Survey

Project Leader: George Heald

MSSS-LBA

Frequency: 30-75 MHz (8 x 2 MHz bands)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660

MSSS-HBA

Frequency: 115-180 MHz (8 x 2 MHz bands)
Resolution: ≤120 arcsec
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616

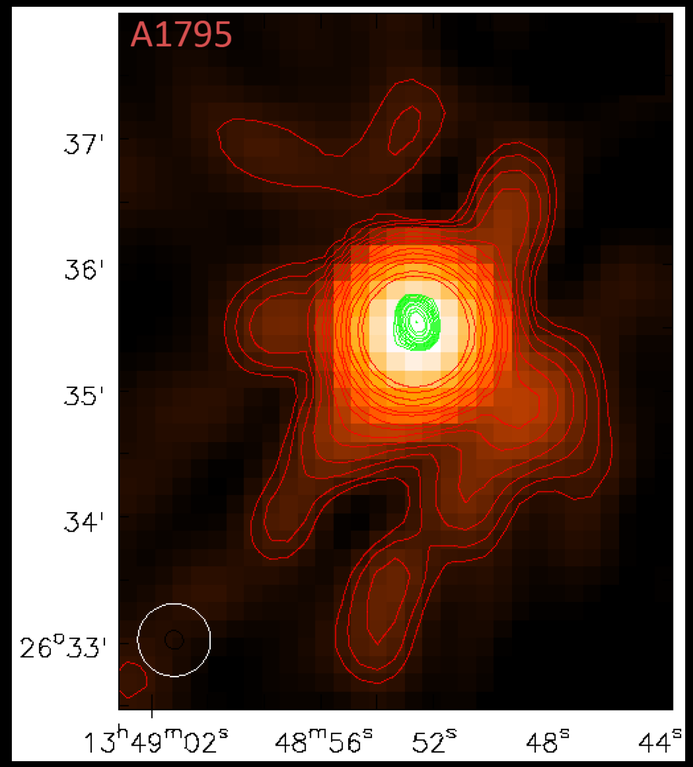
Goals: Obtain broadband sky model, test LOFAR operations

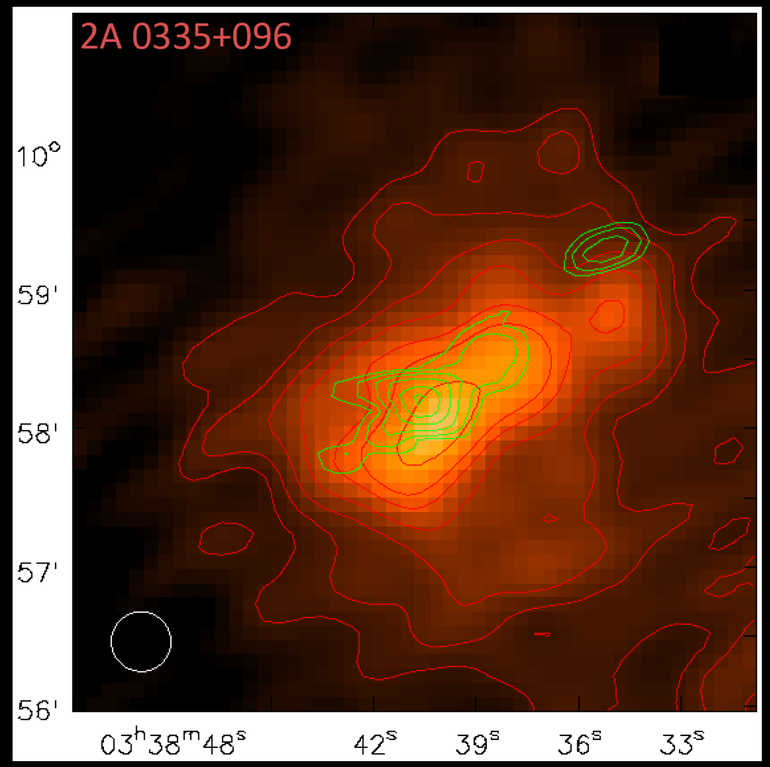
MSSS HBA mosaic M073+43

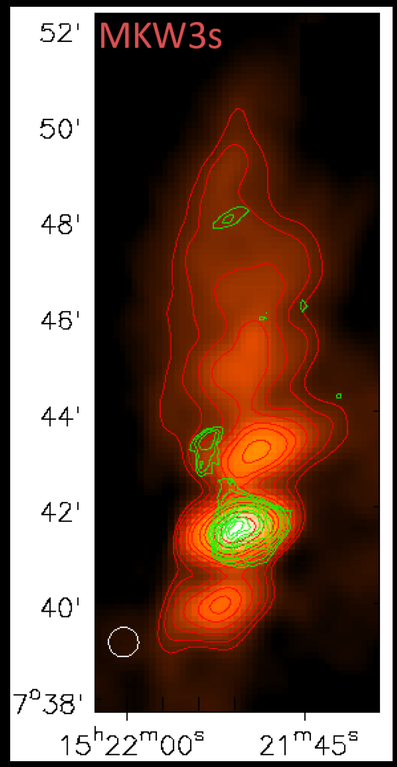
(SNR G160.4+02.8 and 3C129)

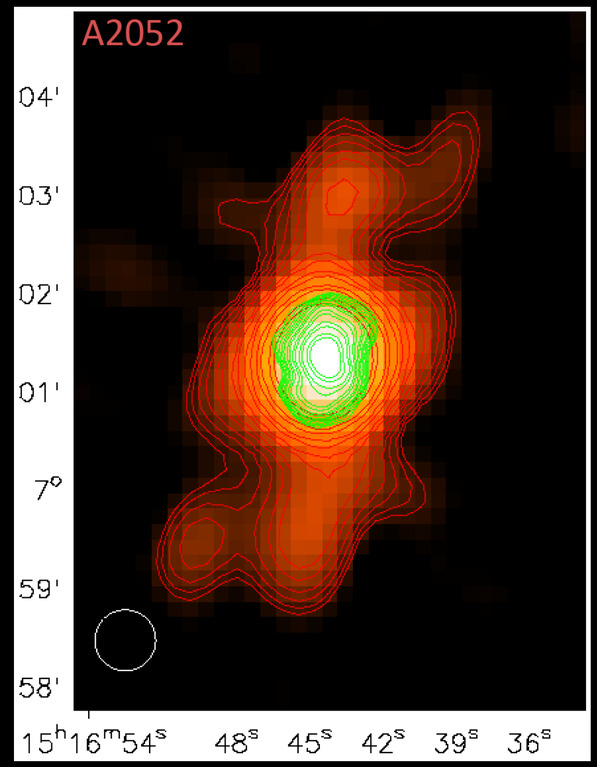
Heald & the MSSS Team

Feedback Systems in MSSS









VLA 330 MHz from Bîrzan et al. (2008)

Reprocessed LOFAR MSSS 140 MHz

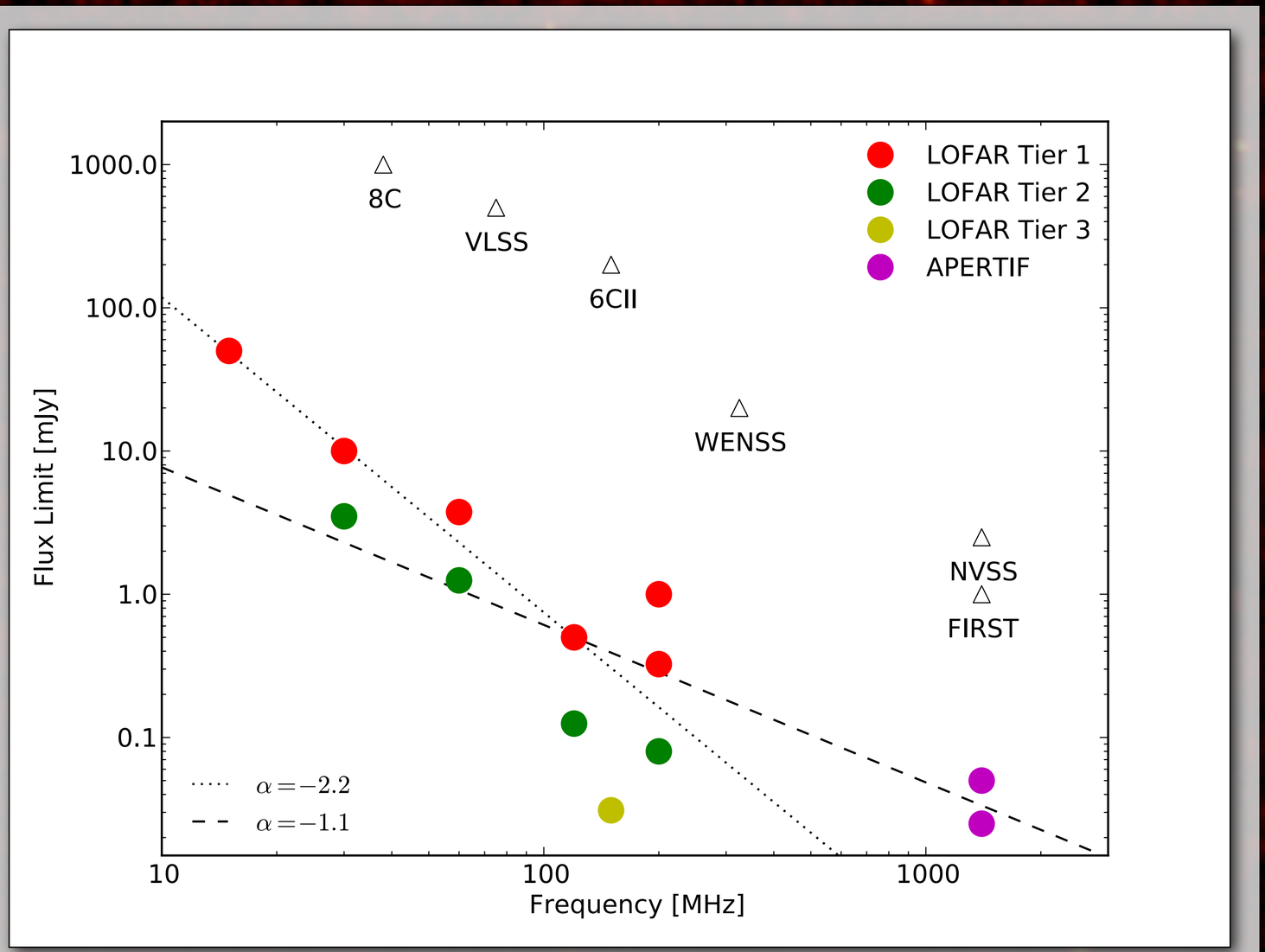
Roughly 2/3 of Bîrzan et al. sample detected

Check calibration of P_{cav} relationship

Distinguish between fossil outbursts and mini-halos

Kokotanekov et al. (in prep.)

LOFAR Deep Extragalactic Surveys



Few x10^8 unique sources
100's of clusters z < 0.6
Protoclusters at z~2
Many z > 2 radio galaxies
Halos, relics, etc...

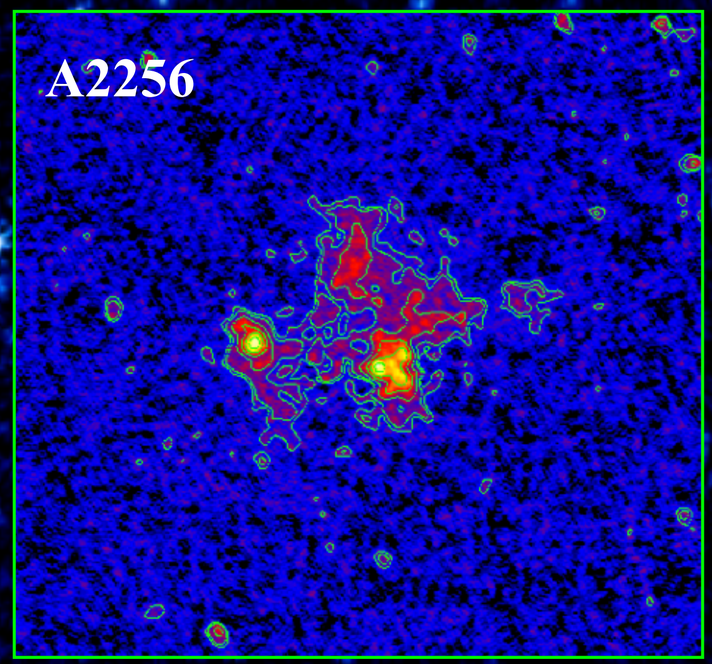
NCP field
(~ 30 μJy / beam)

Yatawatta & the EoR KSP Team

Cluster Radio Halos and Relics

- **Increase the sample size of halos and relics**
- **Constrain re-acceleration models for halos**
- **Calibrate energy input from mergers**

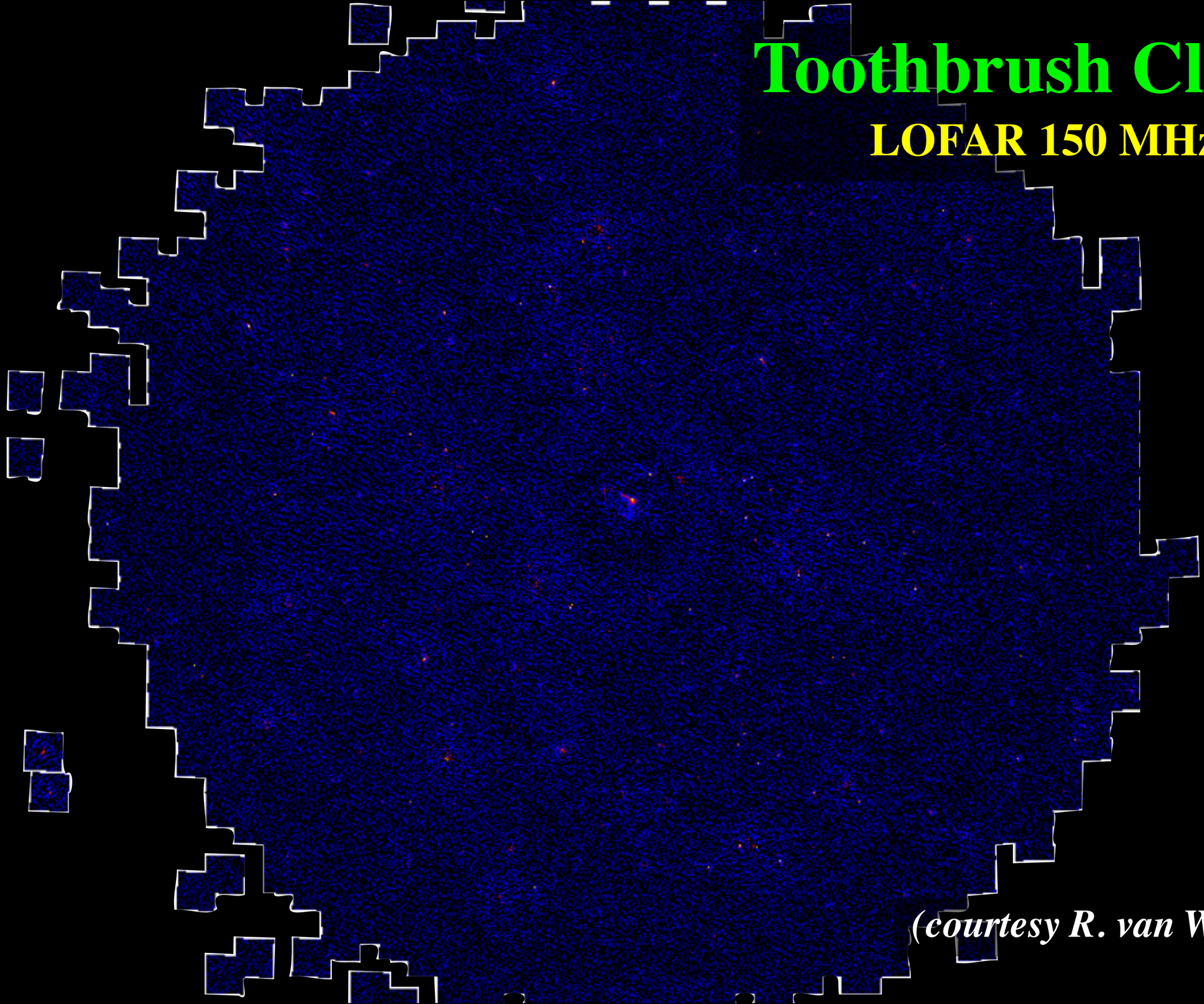
The Toothbrush Cluster (van Weeren et al. in prep.)



(van Weeren et al. 2011)

Toothbrush Cluster

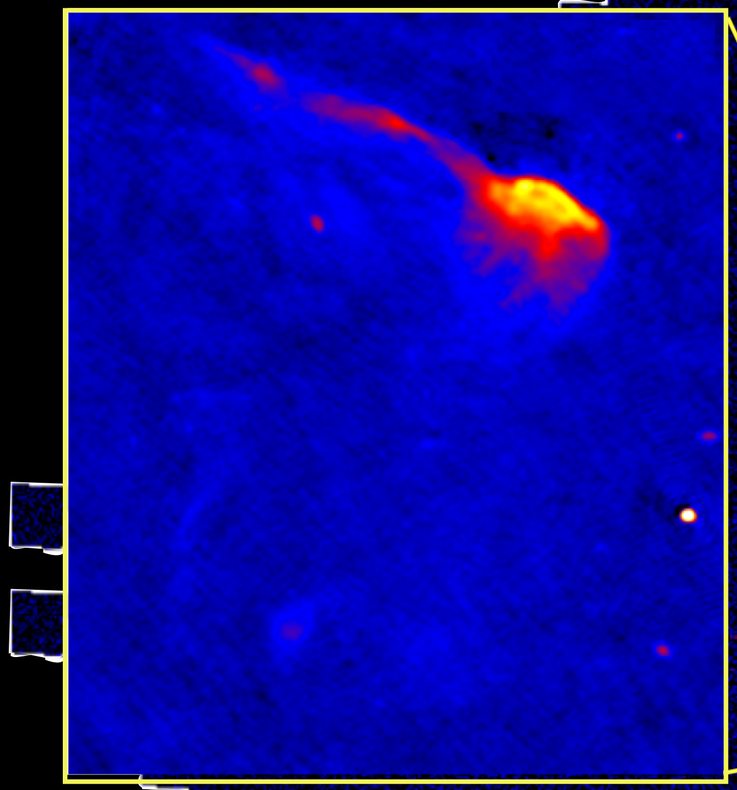
LOFAR 150 MHz

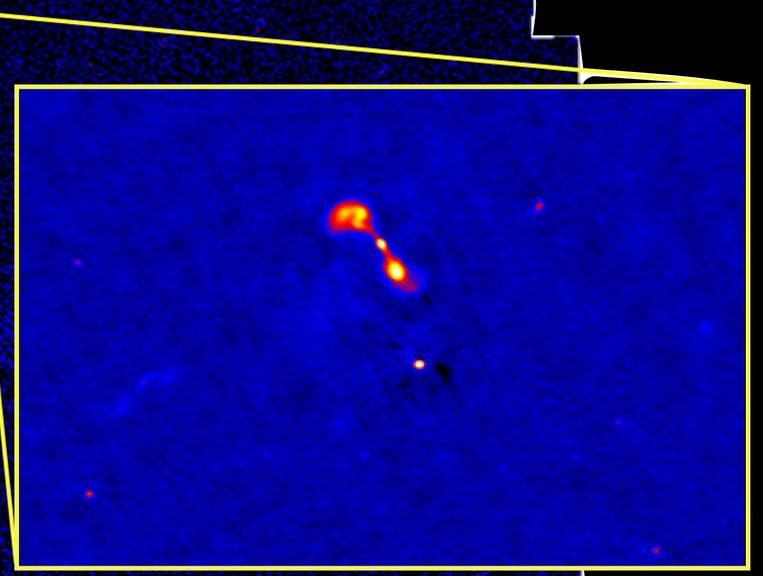


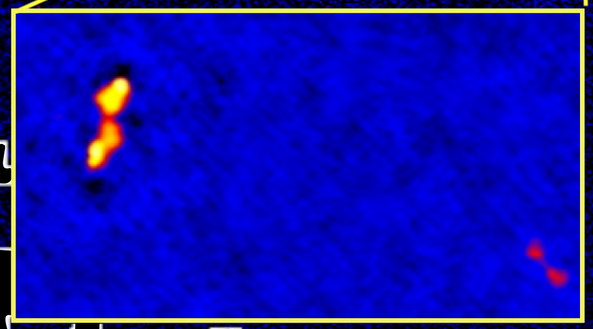
(courtesy R. van Weeren)

Toothbrush Cluster

LOFAR 150 MHz







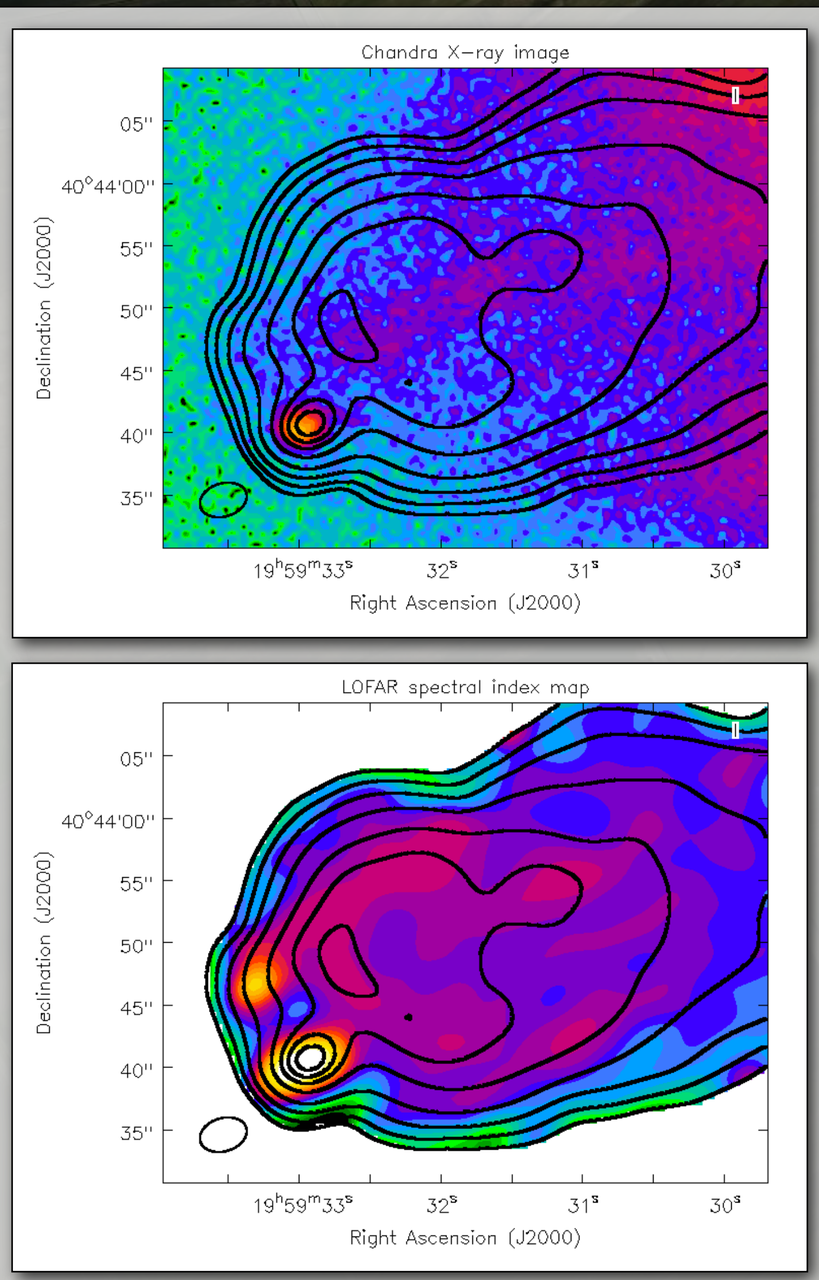
(courtesy R. van Weeren)

Cygnus A Radio Galaxy

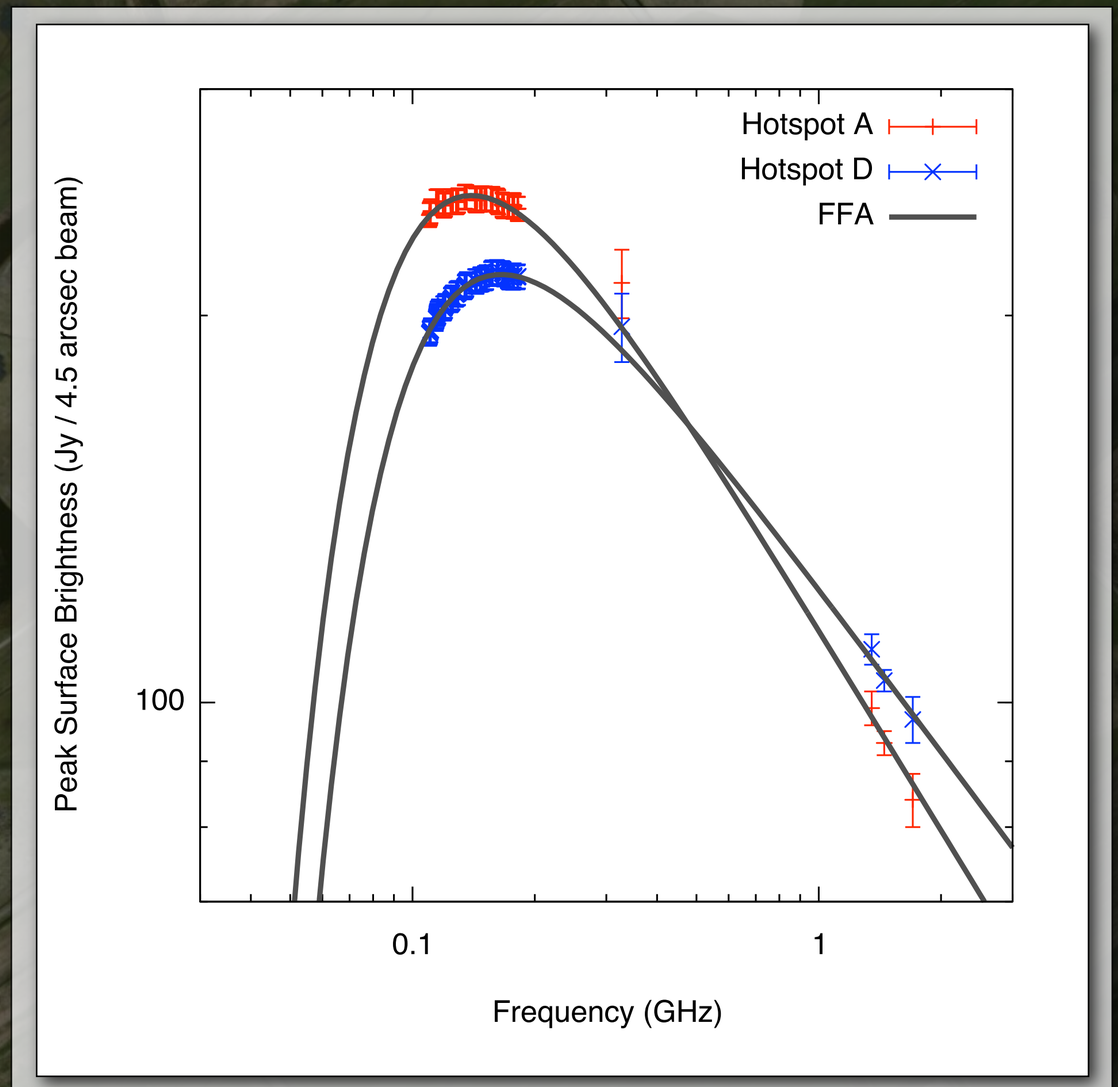
Interaction between the powerful radio jet in Cygnus A and the surrounding intracluster medium

Image Credits: J. McKean and M. Wise (ASTRON)

Cygnus A Hotspot Spectral Analysis

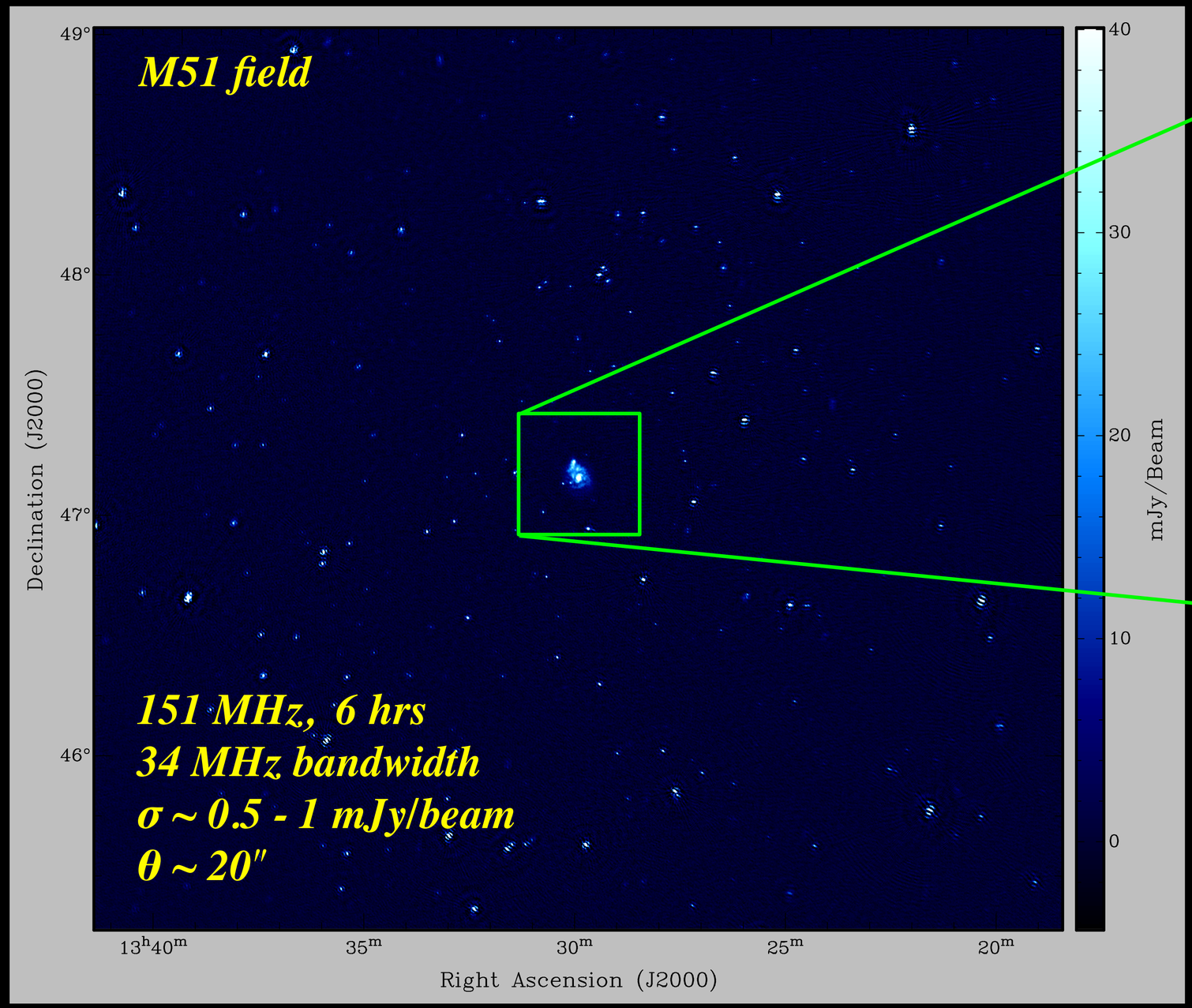


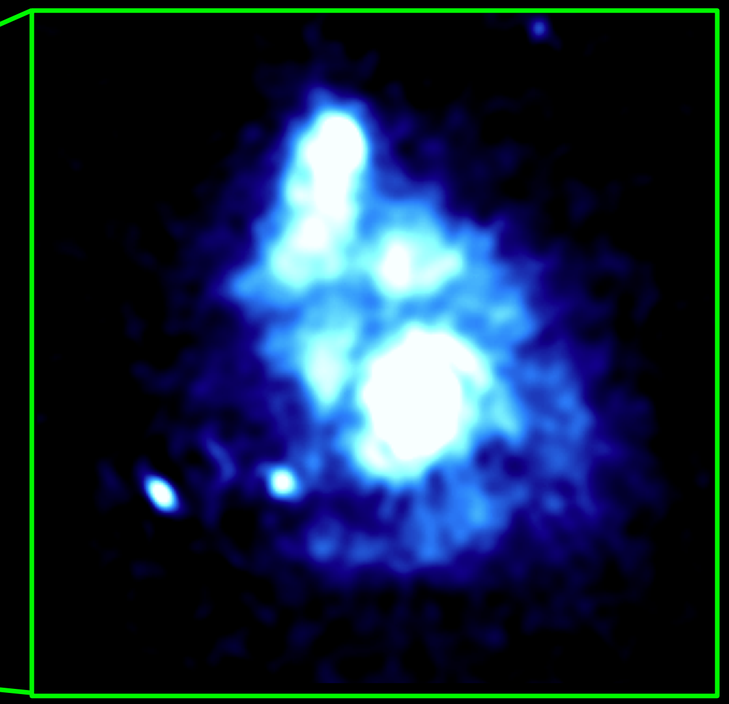
- **High resolution at low frequency**
- **Resolve hotspots and constrain emission physics**
- **Unique LOFAR capability!**

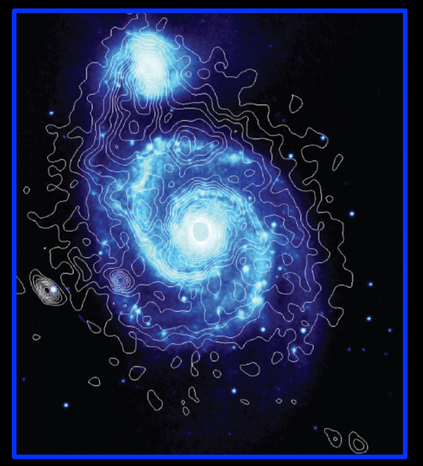


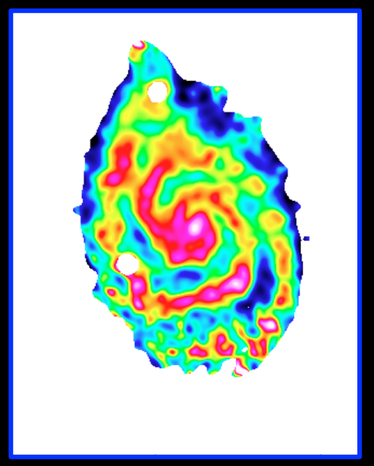
McKean et al. (2014)

Nearby Galaxies with LOFAR



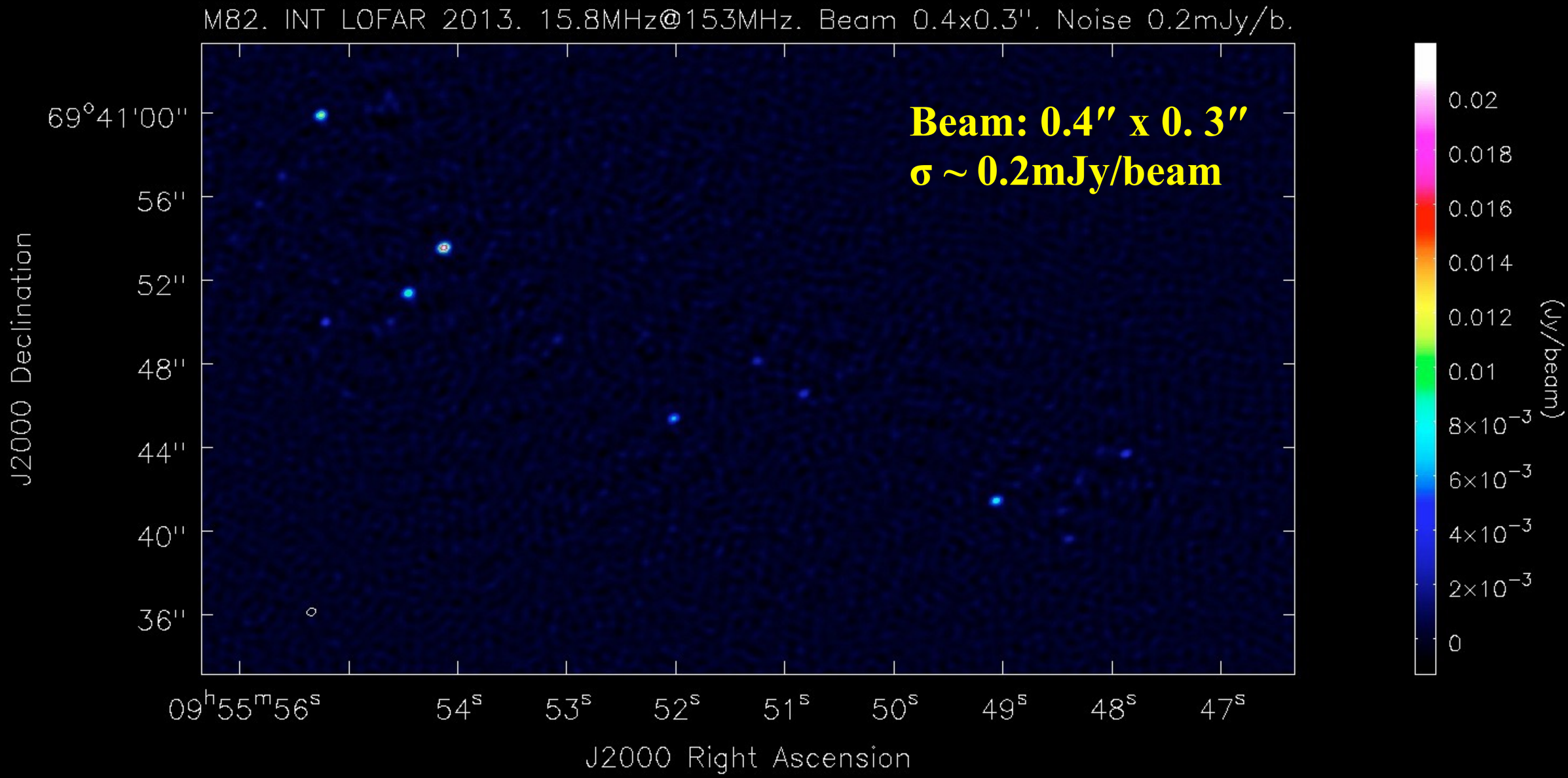






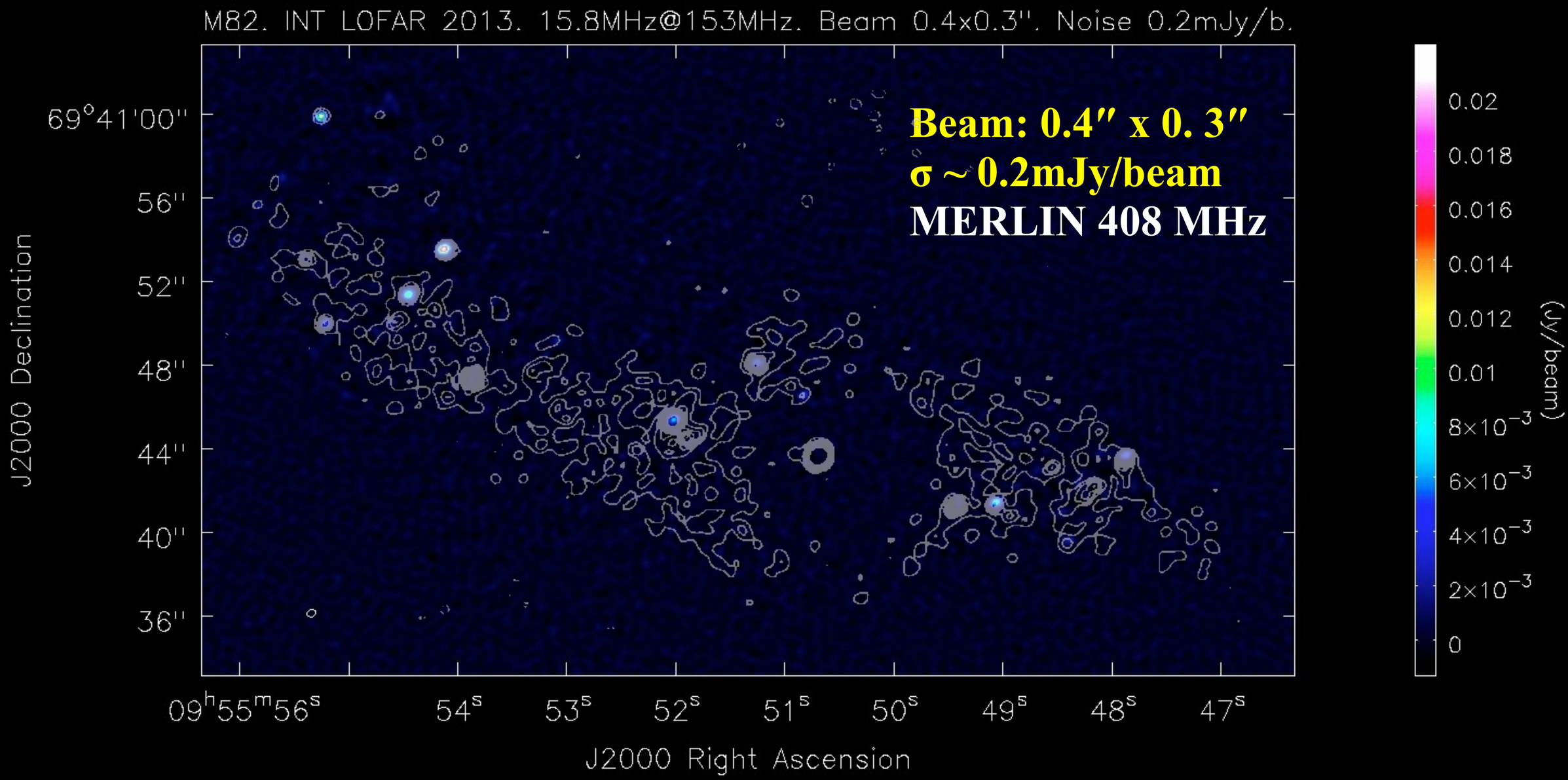
(courtesy D. Mulcahy and the Magnetism KSP)

M82 with International Baselines



(Varenius, Conway, et al. 2014, in prep.)

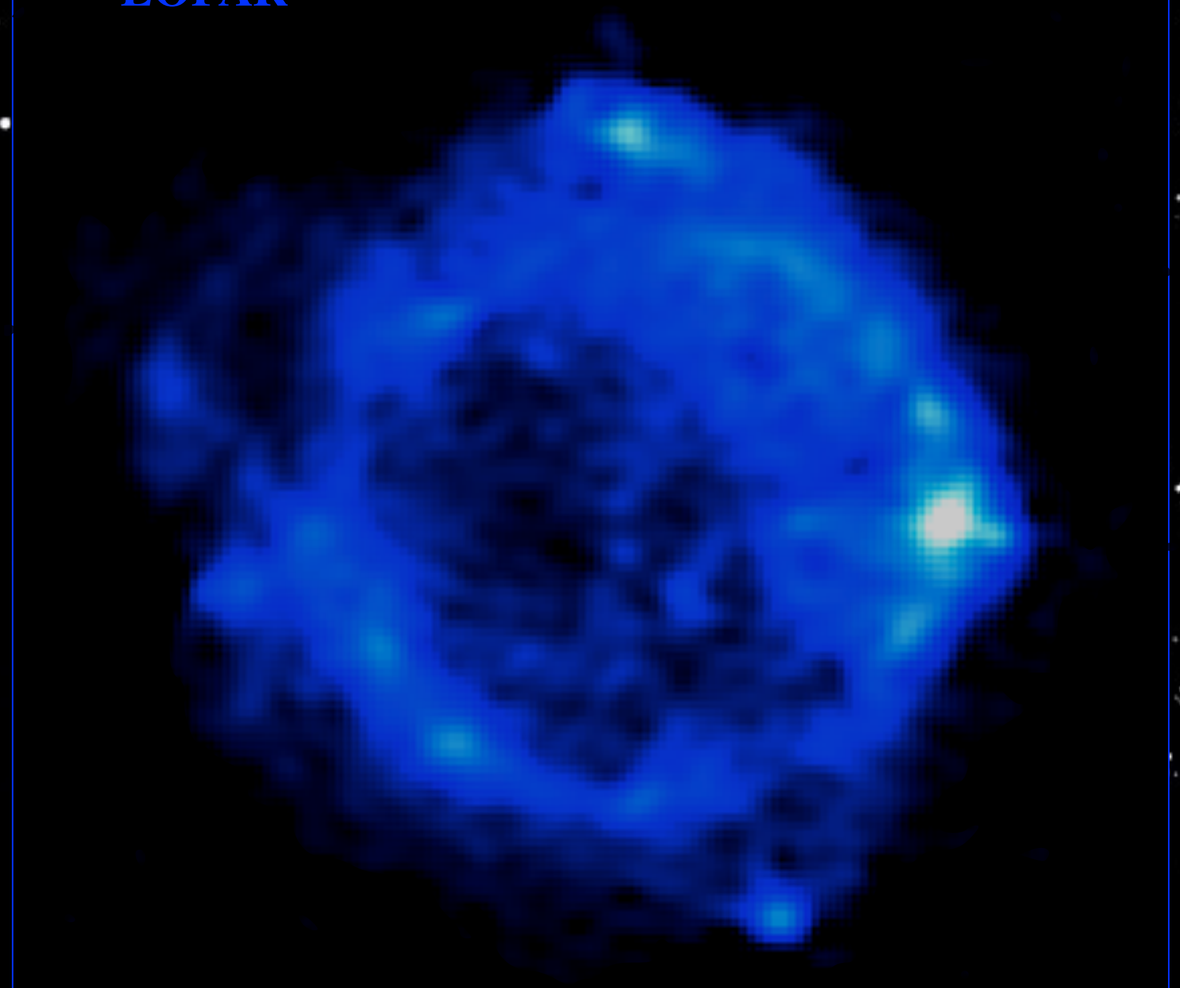
M82 with International Baselines



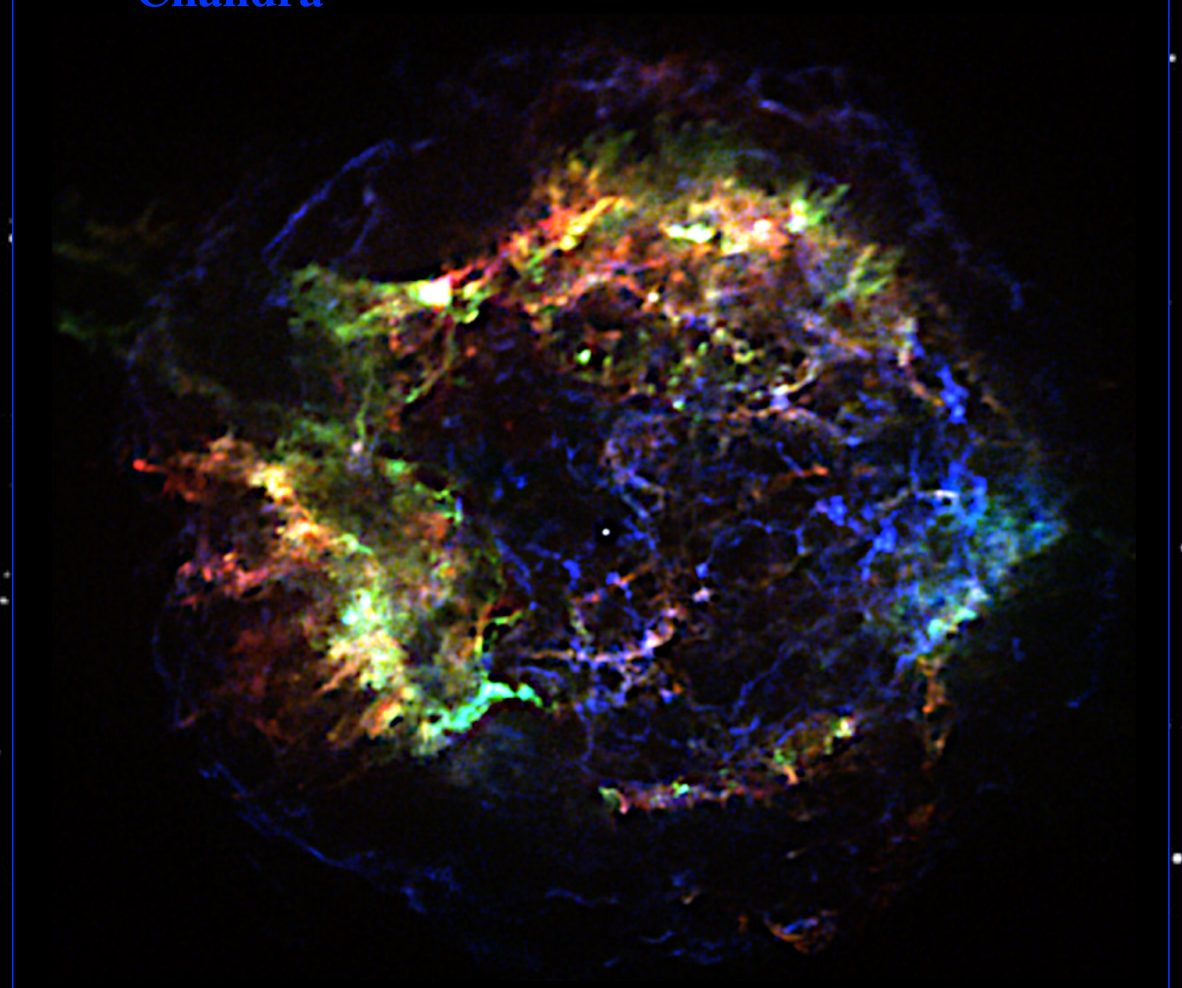
(Varenius, Conway, et al. 2014, in prep.)

Cassiopeia A

LOFAR

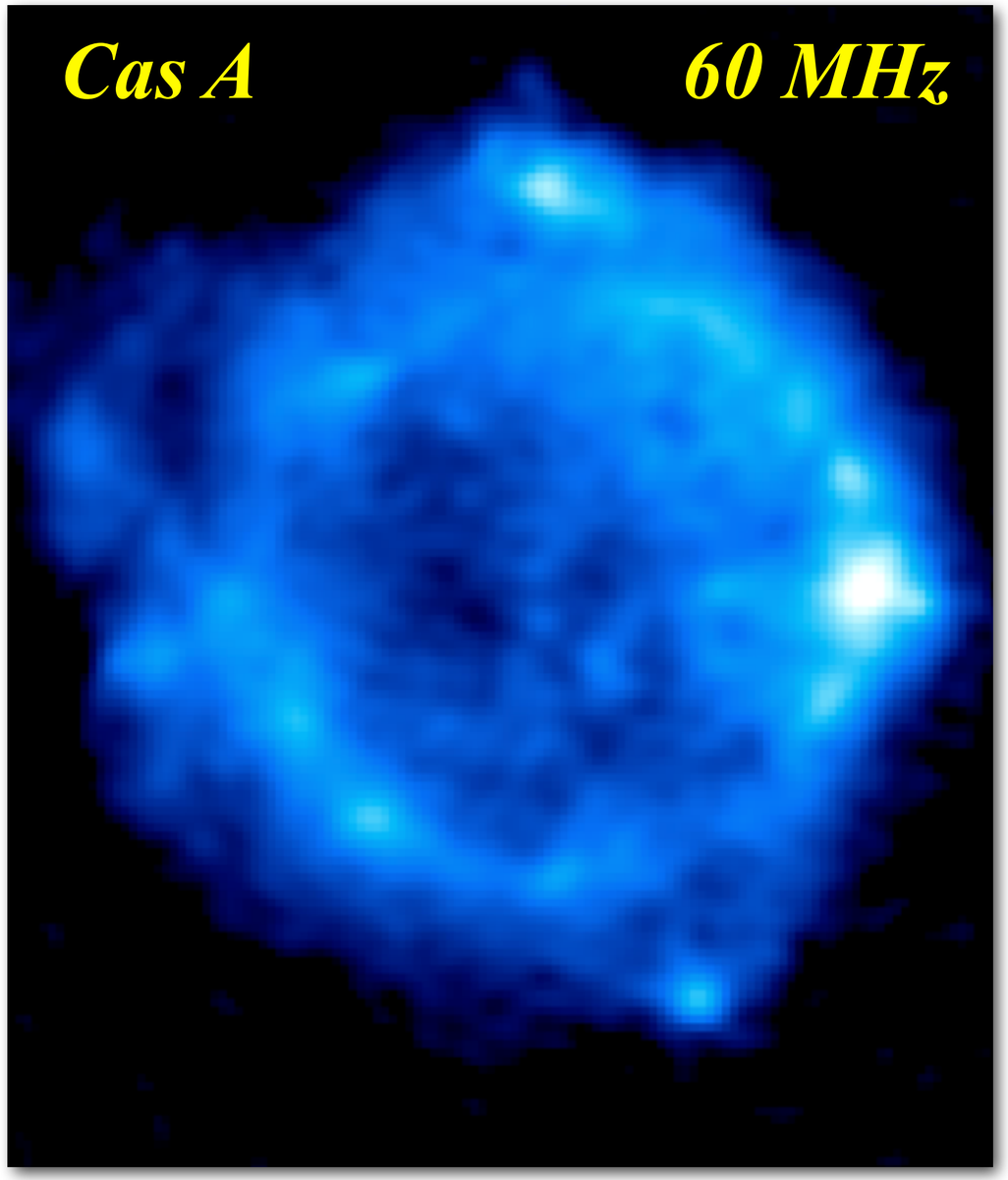


Chandra



(van Weeren et al. 2011)

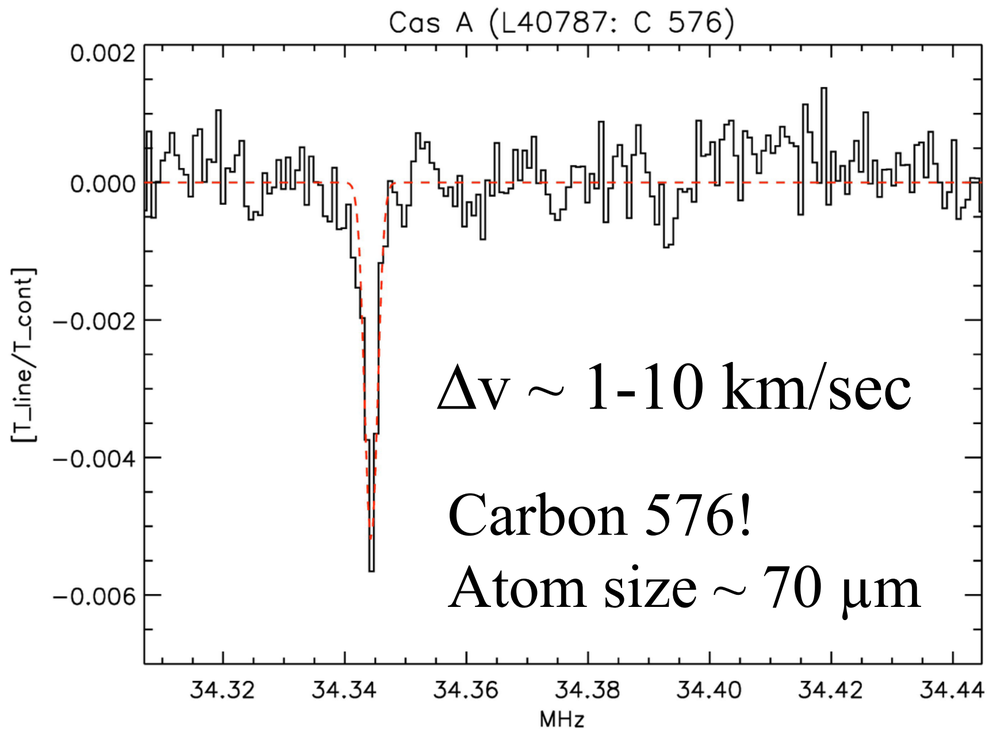
Radio Recombination Lines



(van Weeren et al. 2011)

RRLs probe the Cold Neutral Medium (CNM)

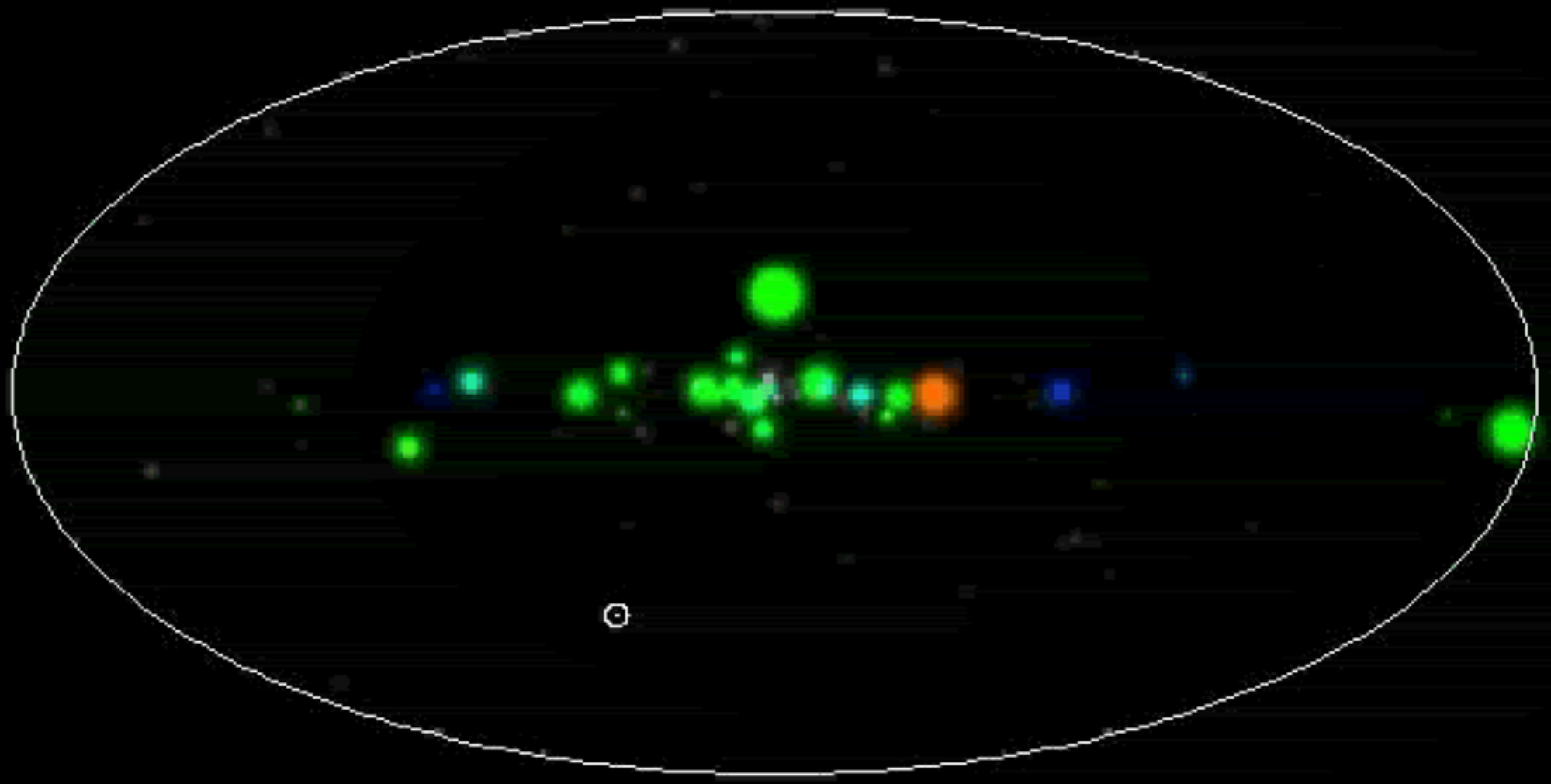
LOFAR spectrum towards Cas A



(Asgekar, Oonk, et al. 2013)

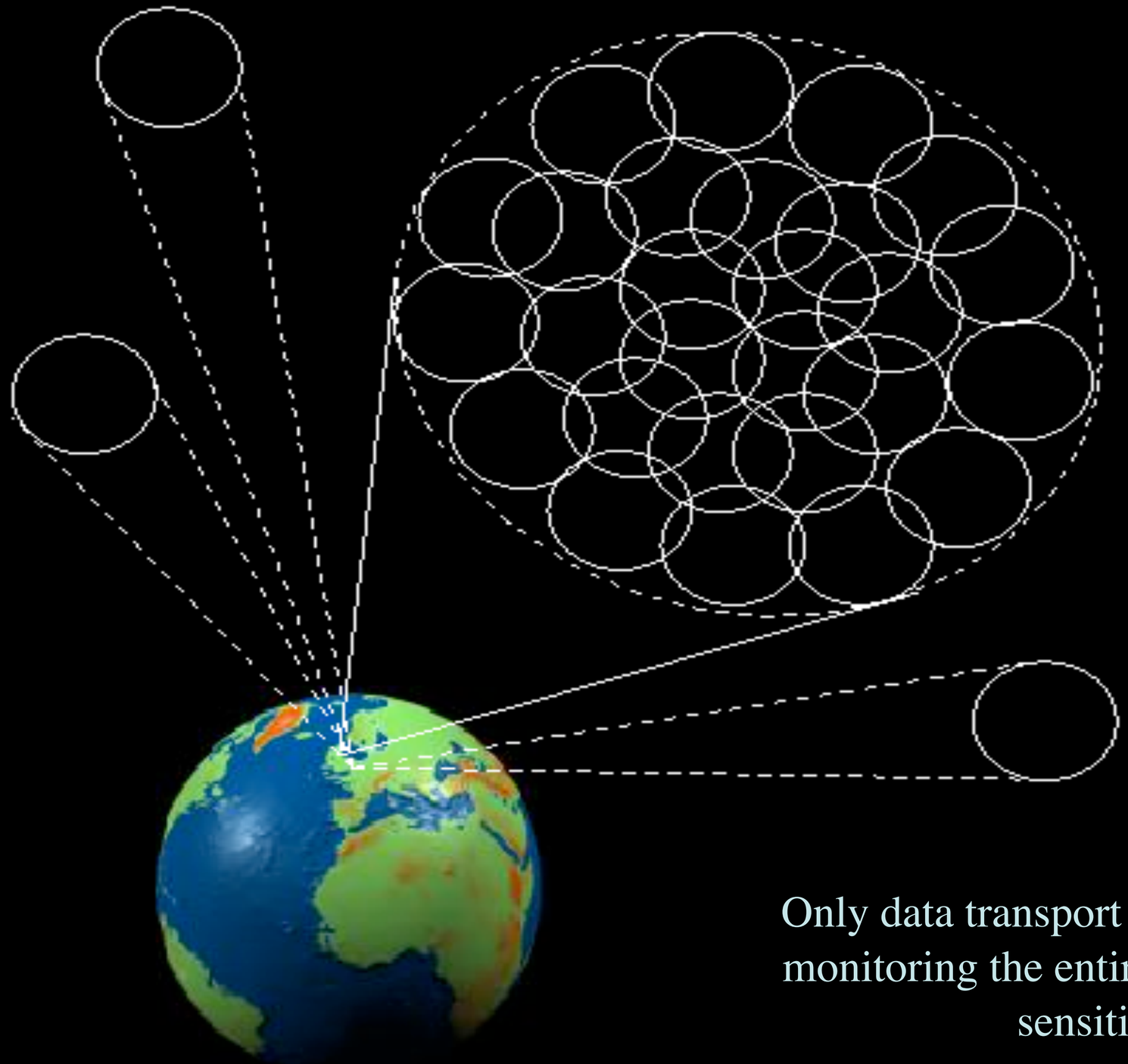
C-RRLs actually seen throughout Galaxy!

The RXTE All-Sky Monitor Movie



The sky is highly variable on a wide range of timescales!

Radio Sky Monitor: Multiple station beams tile out a significant fraction of the sky and detect transient sources on timescales down to 1 second



Multiple beams used to watch for new transients

Single beam(s) monitor known sources

Only data transport and processing power prevent us monitoring the entire visible sky continuously at full sensitivity and resolution!

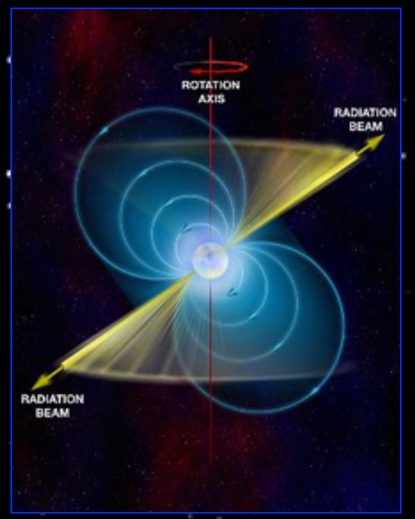
Transient and Pulsar Science Case

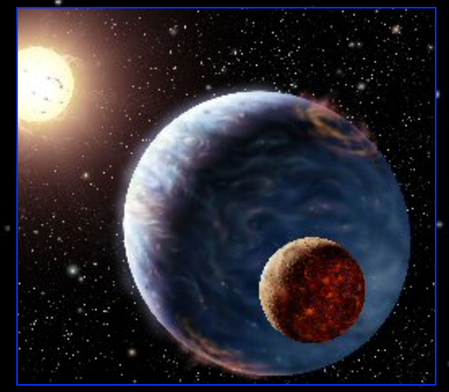
- Time variability of most extreme objects - e.g. accreting black-holes and neutron stars, gamma-ray bursts, and supernovae

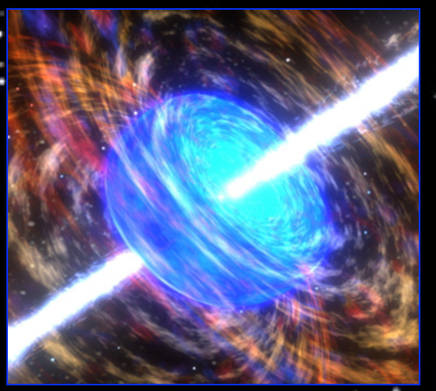
- Radio provides an important complement to X-ray and γ-ray observations

- LOFAR's FoV is critical to catch up with high-energy monitoring for rare events

- Probe timescales from secs to years

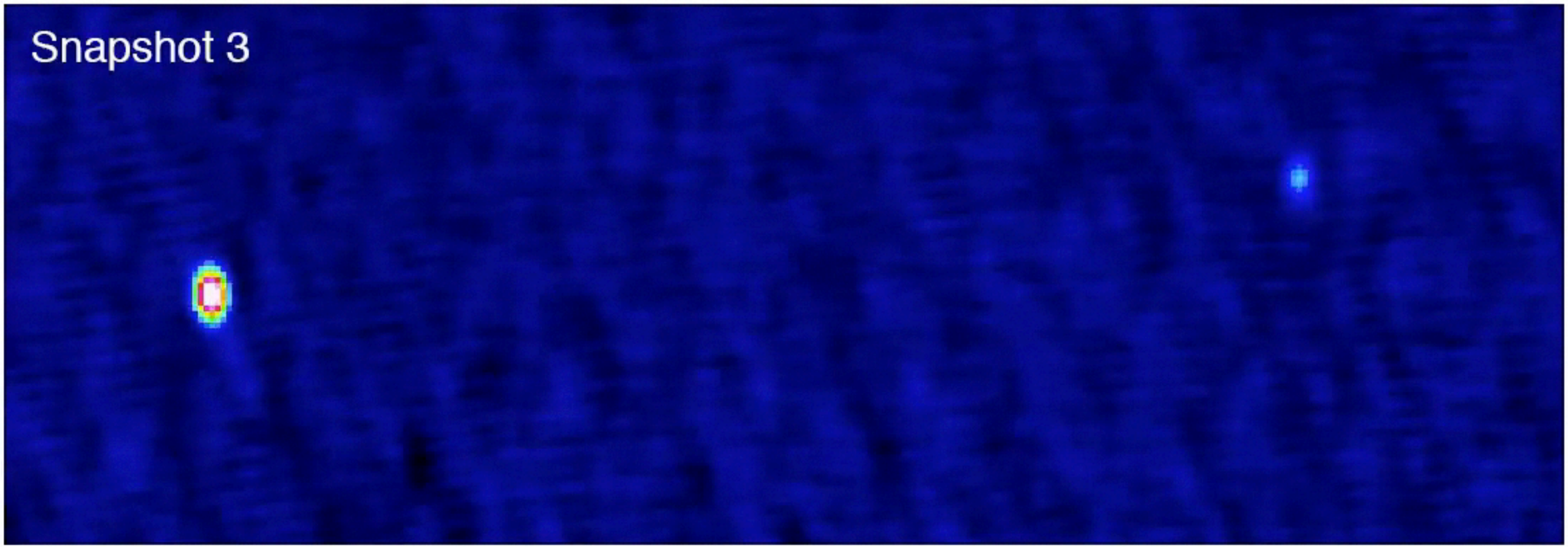






Transients with MSSS

First MSSS(-LBA) transient candidate (Stewart et al, in prep)



- Appears in one 11-min snapshot, using 10σ threshold of 4 Jy
- Implied rate for Δt=11min is 1/2537 transients day^{-1} deg^{-2} (~1 transient per square degree per 7 years!)

In MSSS-LBA, 1 subband always monitoring NCP

Pulsar Surveys with LOFAR

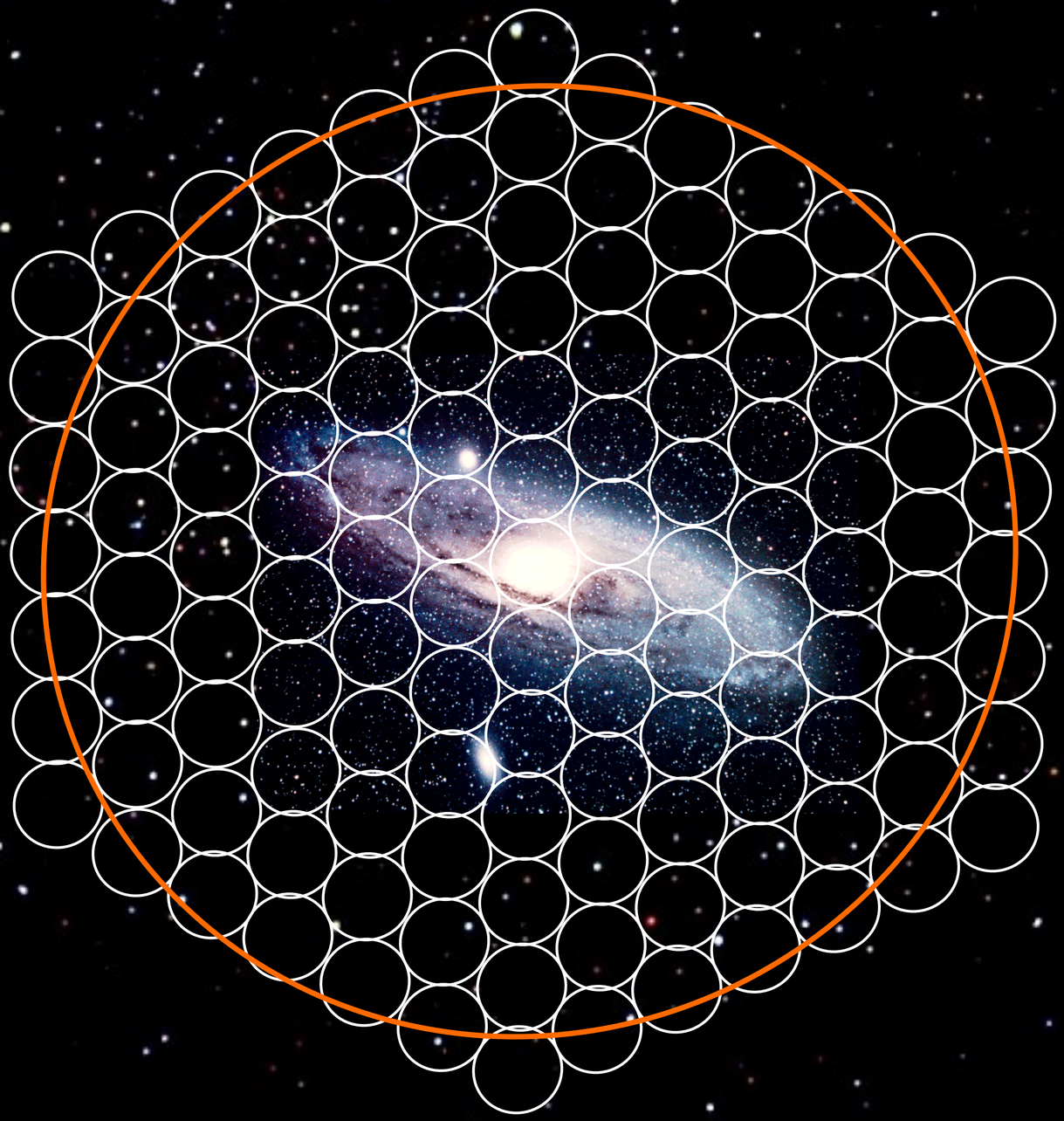
Flexible beam-forming

Element beam | Stations beams | Tied-array beams

⇒ ***Roughly speaking, beam-formed modes trade spatial resolution for time resolution***

Andromeda

Andromeda

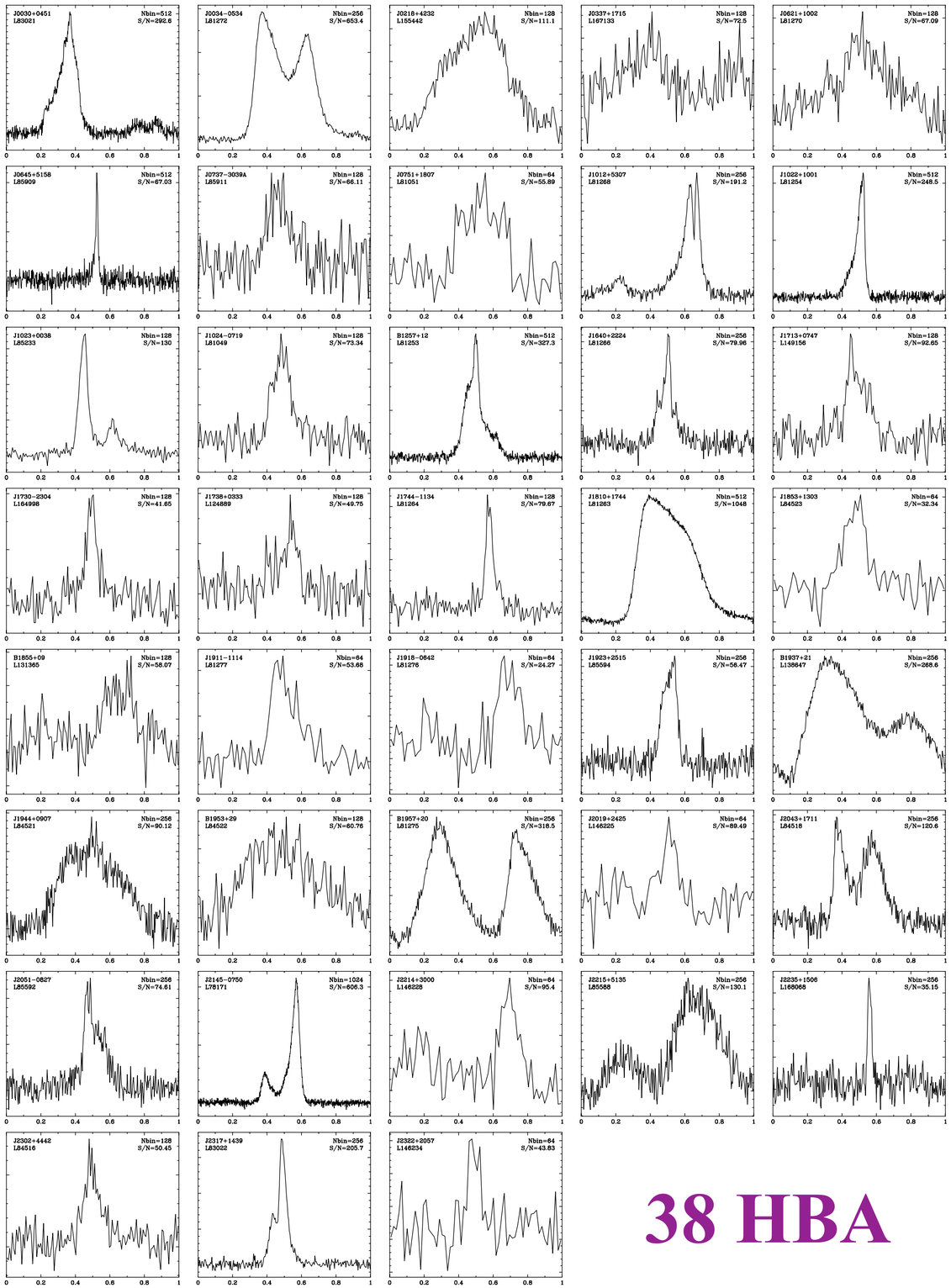


Virgo Cluster

Millisecond Pulsars

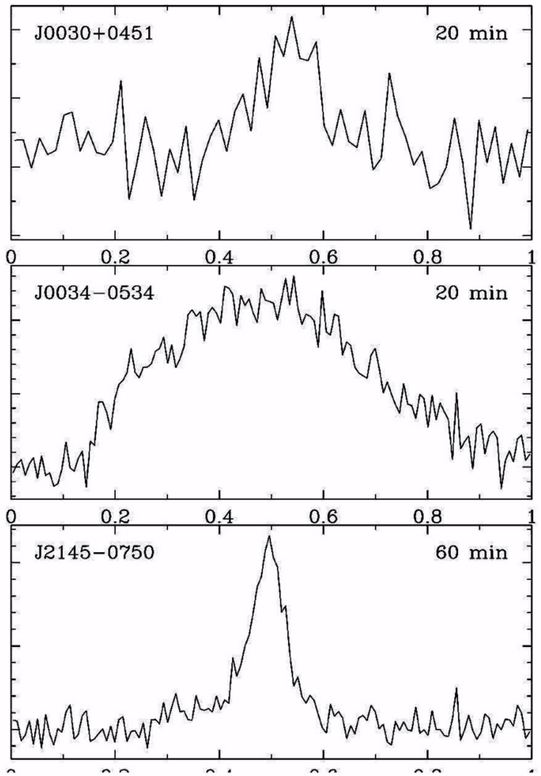
The premier low-frequency MSP census

(Kondratiev, Hessels et al. 2014)



38 HBA

3 LBA



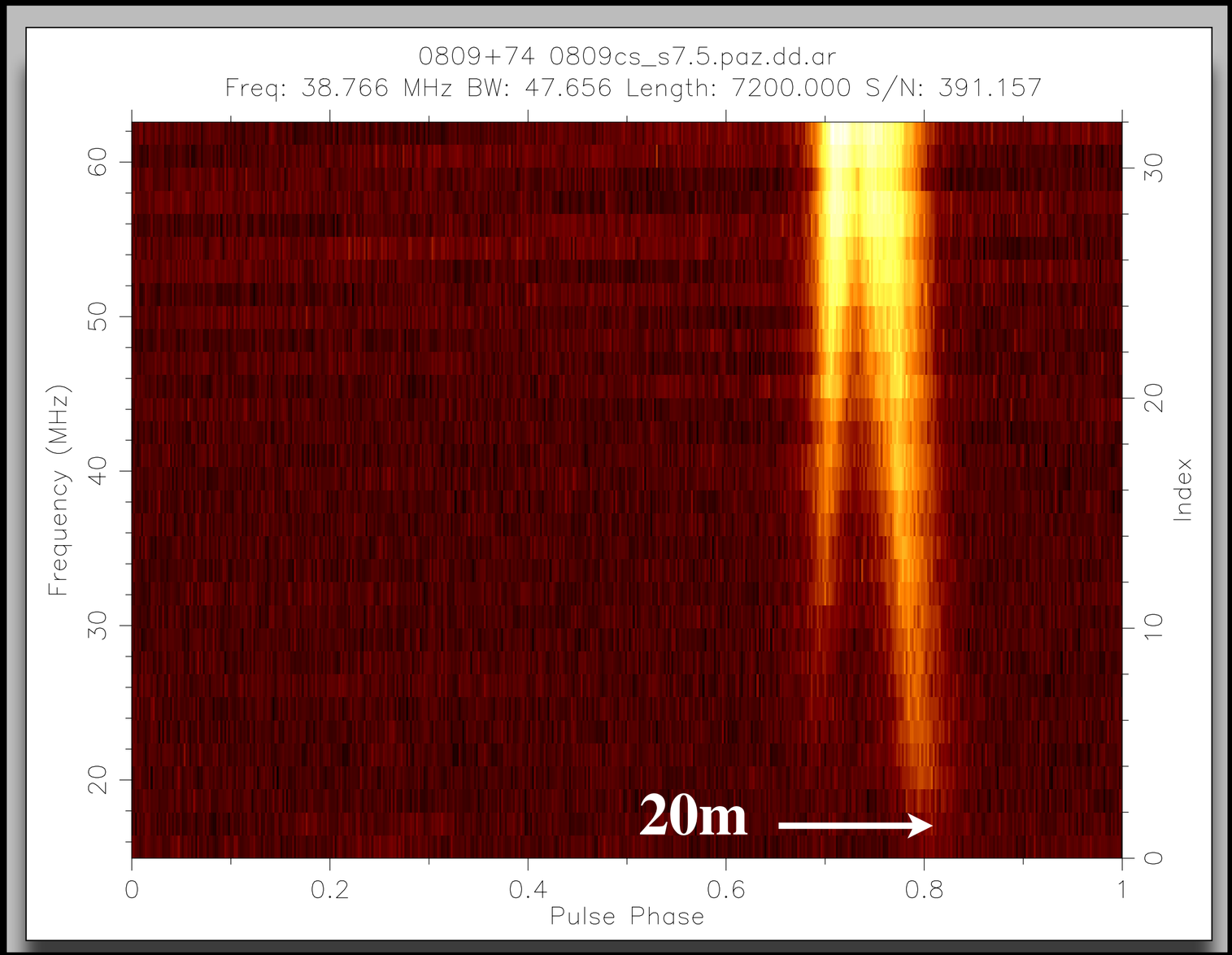
Wide-band Pulsar Monitoring

PSR B0809+74 detected all the way down to 16MHz!

Superterp stations in sync to ~1ns

Single clock for the entire core on the way

15 - 63 MHz Observing Frequency



(Kondratiev et al. 2012)

Magnetosphere

Magnetic axis

Rotation axis

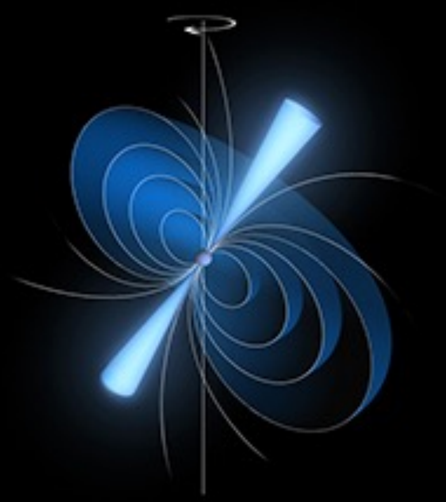
Pulsar

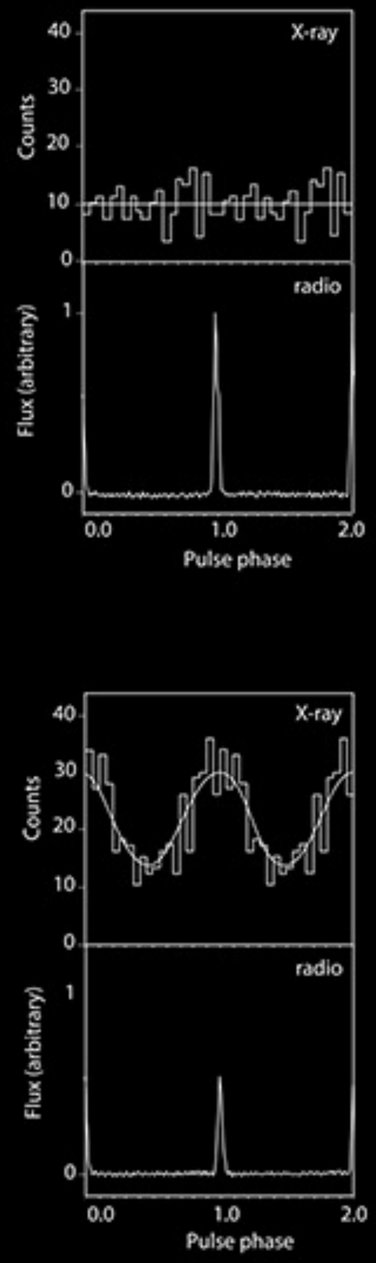
Magnetosphere

Not to scale!

Radio Frequency

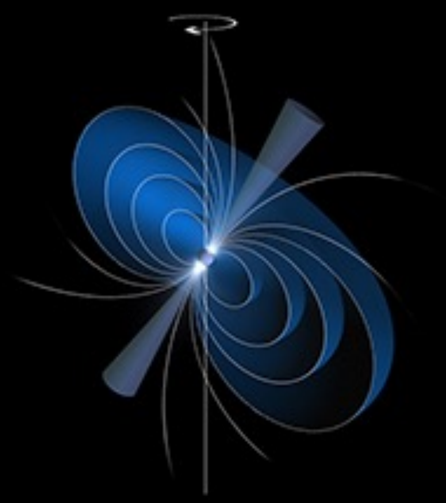
Joint X-ray and Radio Pulsar Monitoring





X-ray dim

Radio bright



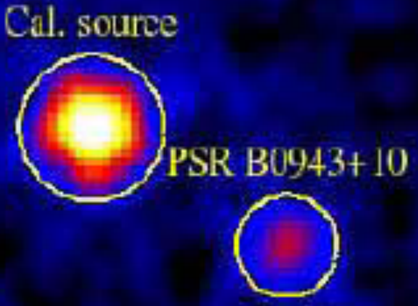
X-ray bright

Radio dim

PSR B1931+24

XMM EPIC 1-2 keV

Simultaneous monitoring of transitions between bright and quiet states

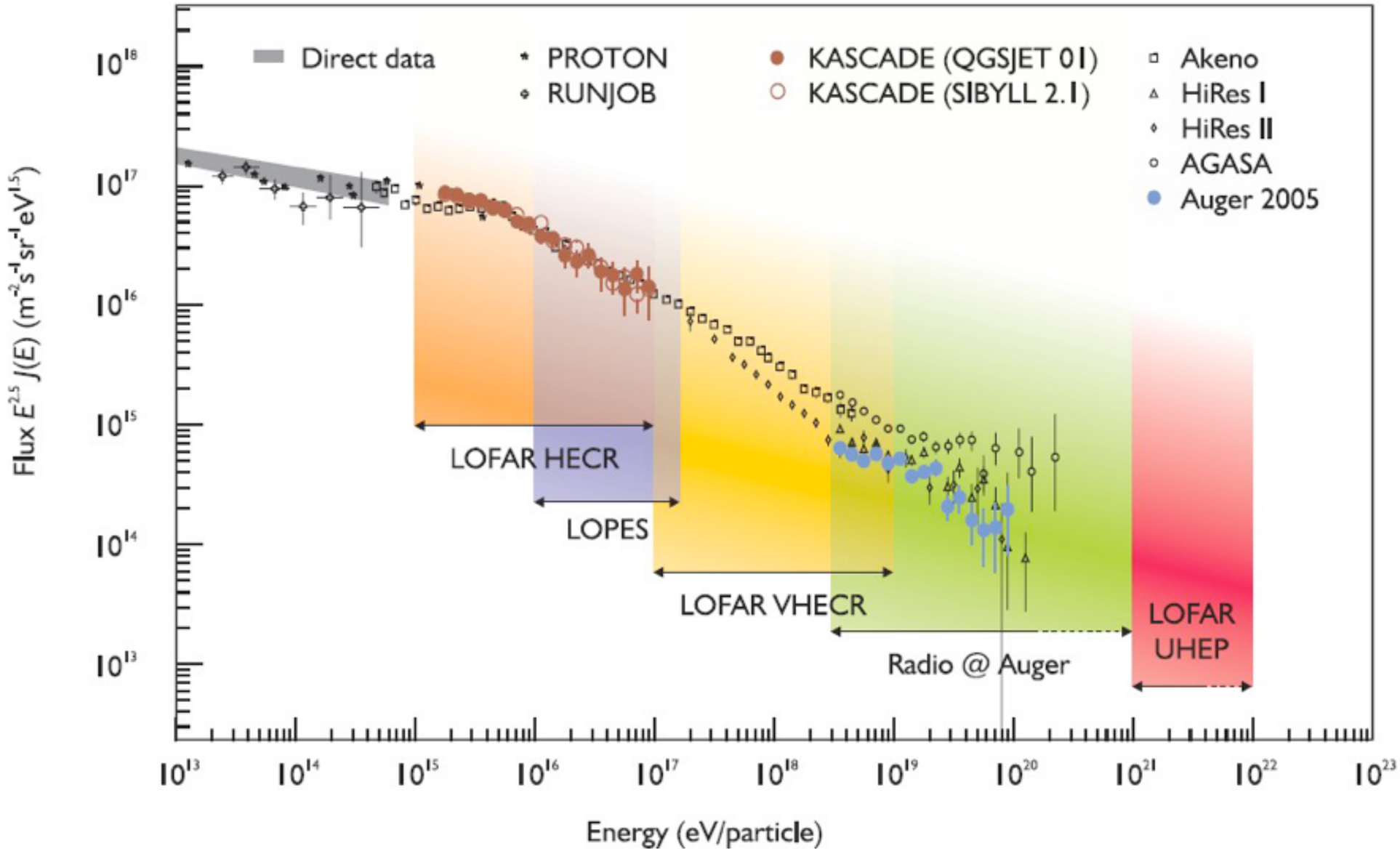


6 x 6 hrs with XMM, LOFAR, GMRT

(Hermsen et al., Science 2013)

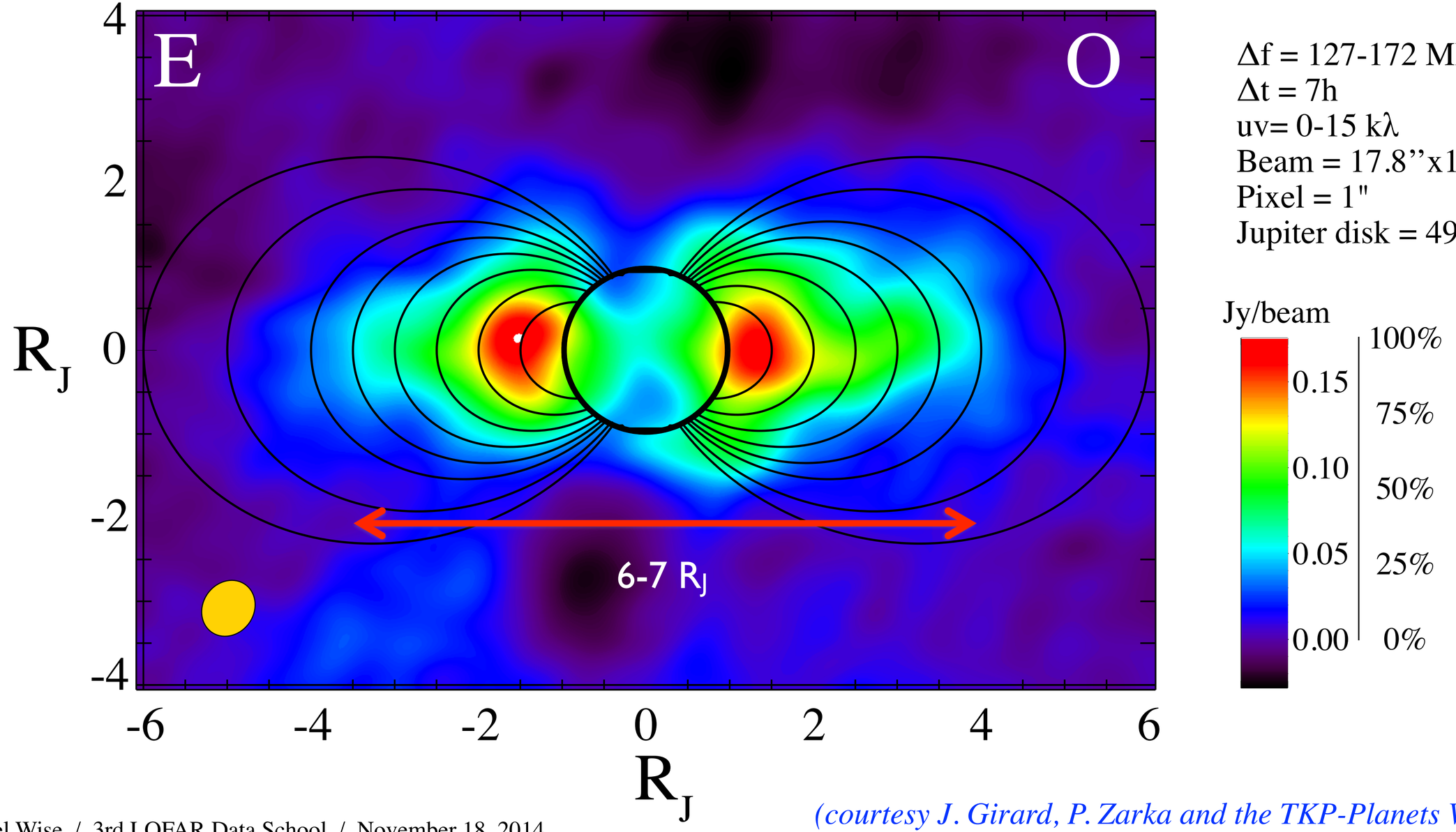
Detection of Particle Showers from Cosmic Rays

Cosmic Ray Energy Spectrum



Low-Frequency Planetary Emission

Radio emission from Jovian radiation belts

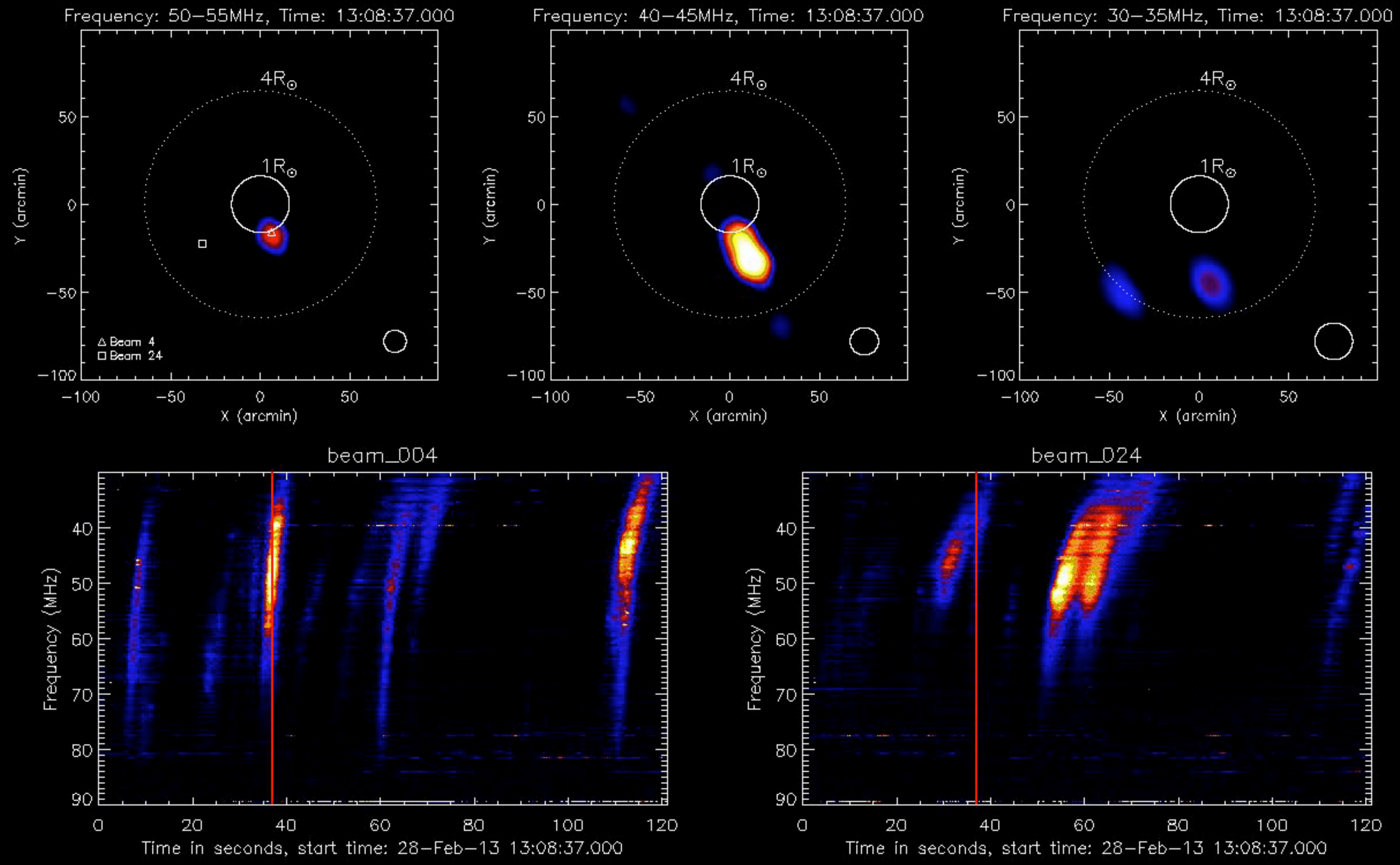


Rotation & frequency averaged image:

Δf = 127-172 MHz,
Δt = 7h
uv= 0-15 kλ
Beam = 17.8”x15.5”
Pixel = 1"
Jupiter disk = 49”

(courtesy J. Girard, P. Zarka and the TKP-Planets WG)

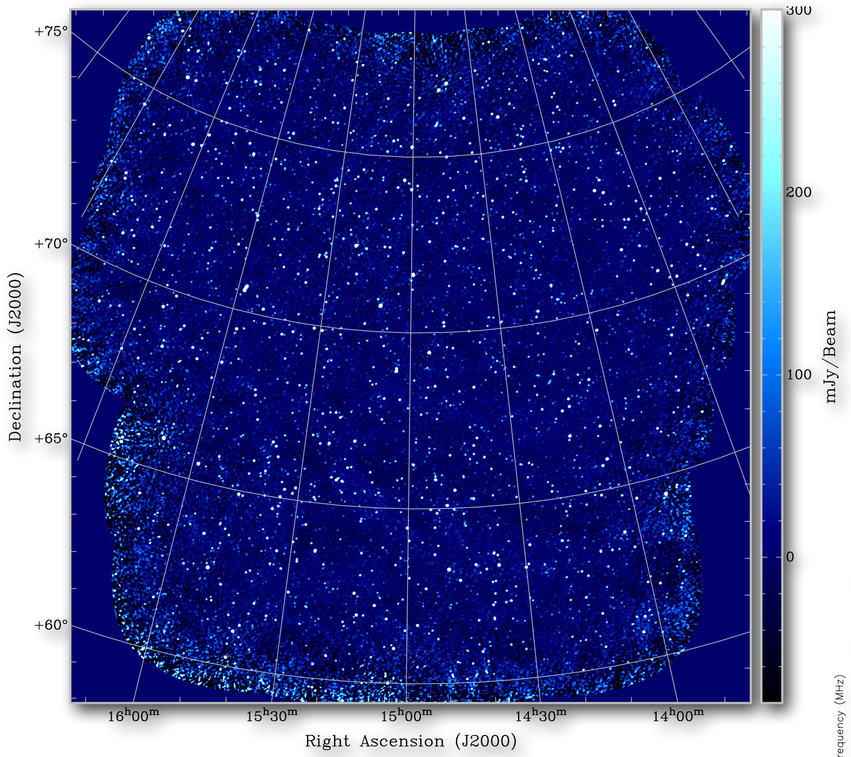
Solar Flares with LOFAR

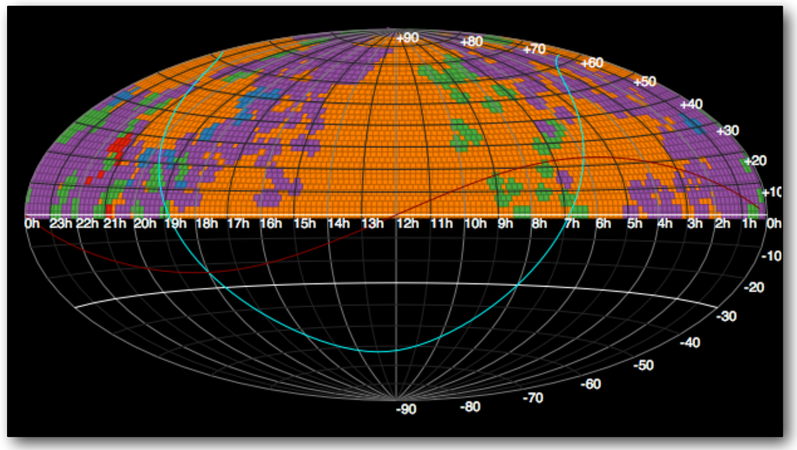


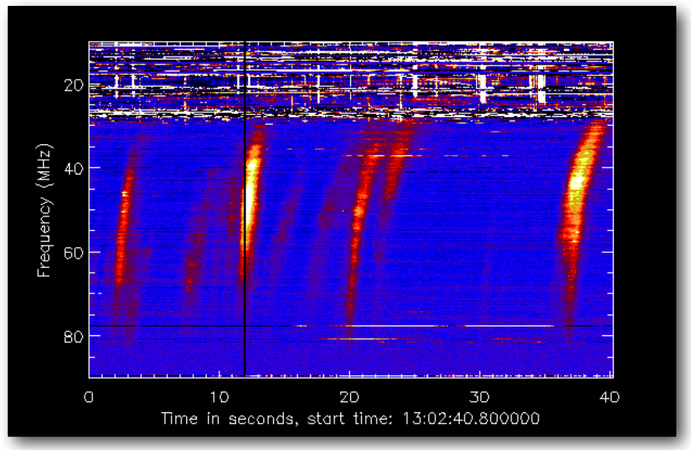
(courtesy D. Morosan, P. Zucca, P. Gallagher and the Solar KSP)

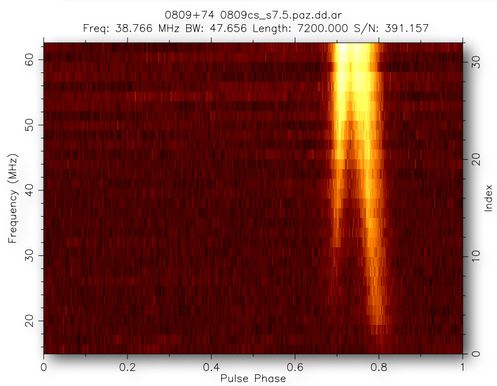
LOFAR Science Products

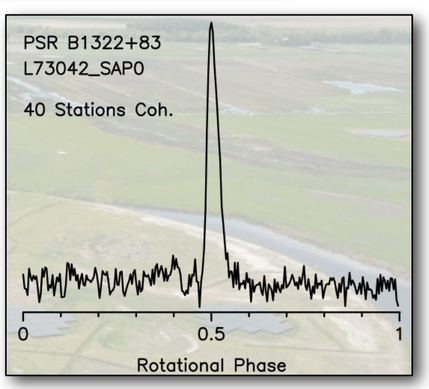
- Velocity *(Raw data rates of ~13 Tbits/s, correlated ~10 TB/hr)*
- Volume (*100 TB visibilities, 1 TB cubes, 1 PB catalogues*)
- Variety *(raw telemetry, uv data, beam-formed data, 2D-3D-4D-5D cubes, RM cubes, light-curves, catalogues, etc.)*

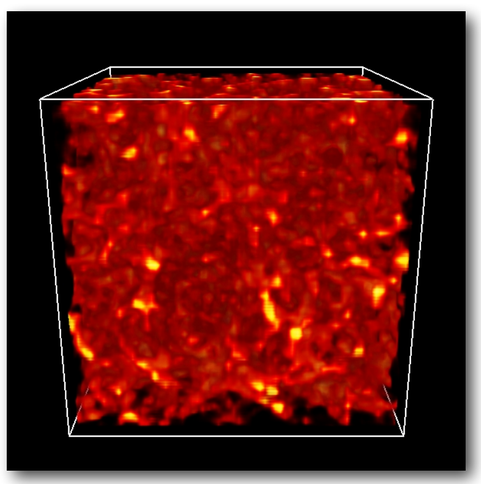




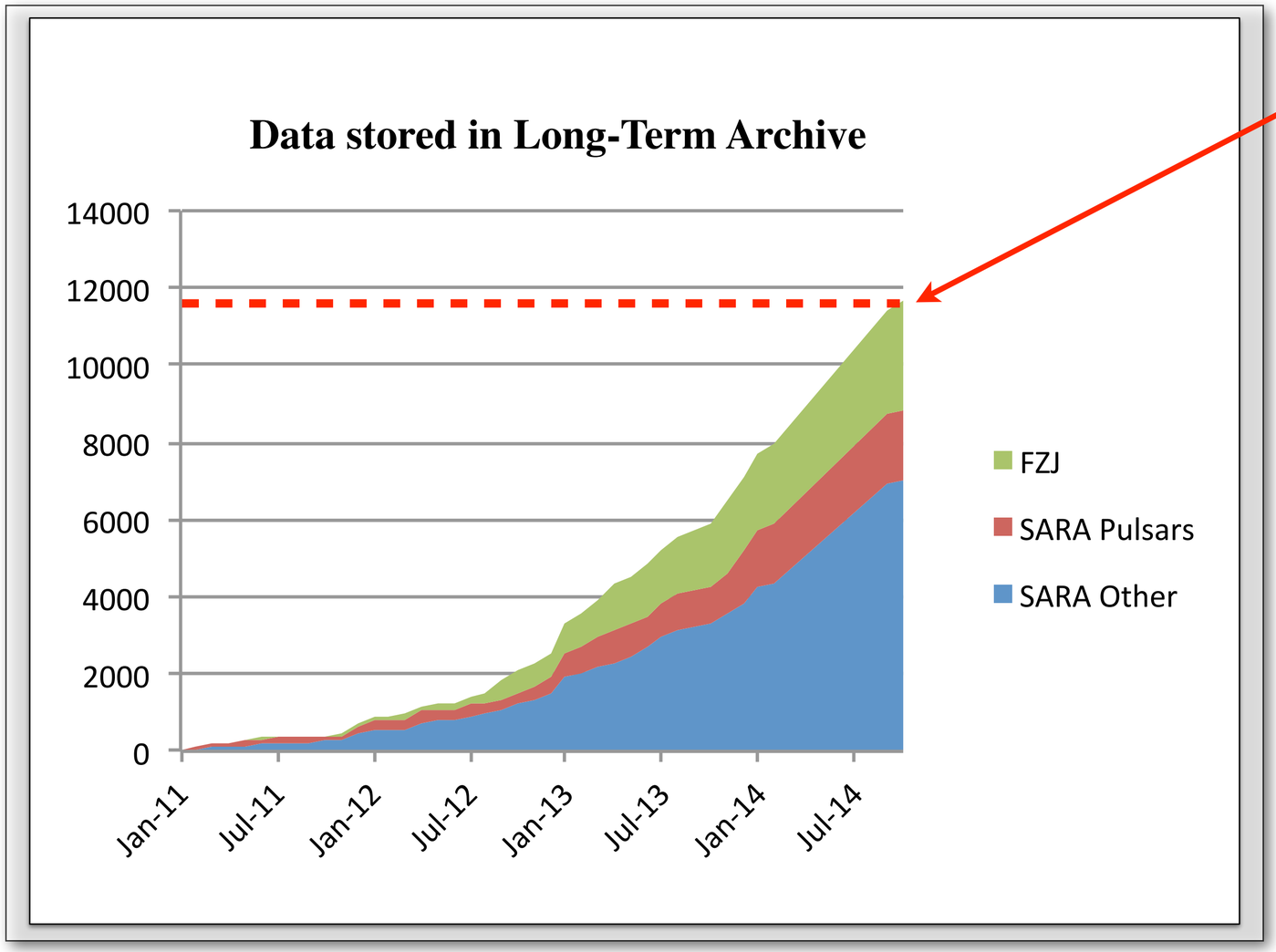








LOFAR Data Accumulation



11.9 PBytes as of Q3 2014

Total today: ~13 PB

Visibilities, images, and BF data
Does not include raw visibility data
Does not include derived products

- 3 million data products
- 600 million files
- 11.3 Petabytes stored (5 sites, 2 countries)
- 500 TB per month archived
- 100 TB per month retrieved
- Eleven 10 Gb/s connections

LOFAR LTA team: W. Frieswijk, G.A.Renting, H.A.Holties, N.Vermaas, W.J.Vriend

Summary

Takeaway Points

- ***LOFAR is up and running and generating great data***
- ***Hardware status of the LOFAR array is excellent***
- ***LOFAR provides several unique scientific capabilities***
- ***MSSS HBA survey complete, LBA survey in 2015***
- ***LOFAR is great for a wide range of science***

LOFAR needs YOU!

LOFAR

The End