ASTRON

Netherlands Institute for Radio Astronomy

# Next Generation Radio Astronomy with LOFAR

**Michael Wise**
**LOFAR Project Scientist**
**(ASTRON / UvA)**

**Realising the Astronomy of the Future**
**June 07, 2012**

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

LOFAR

ASTRON

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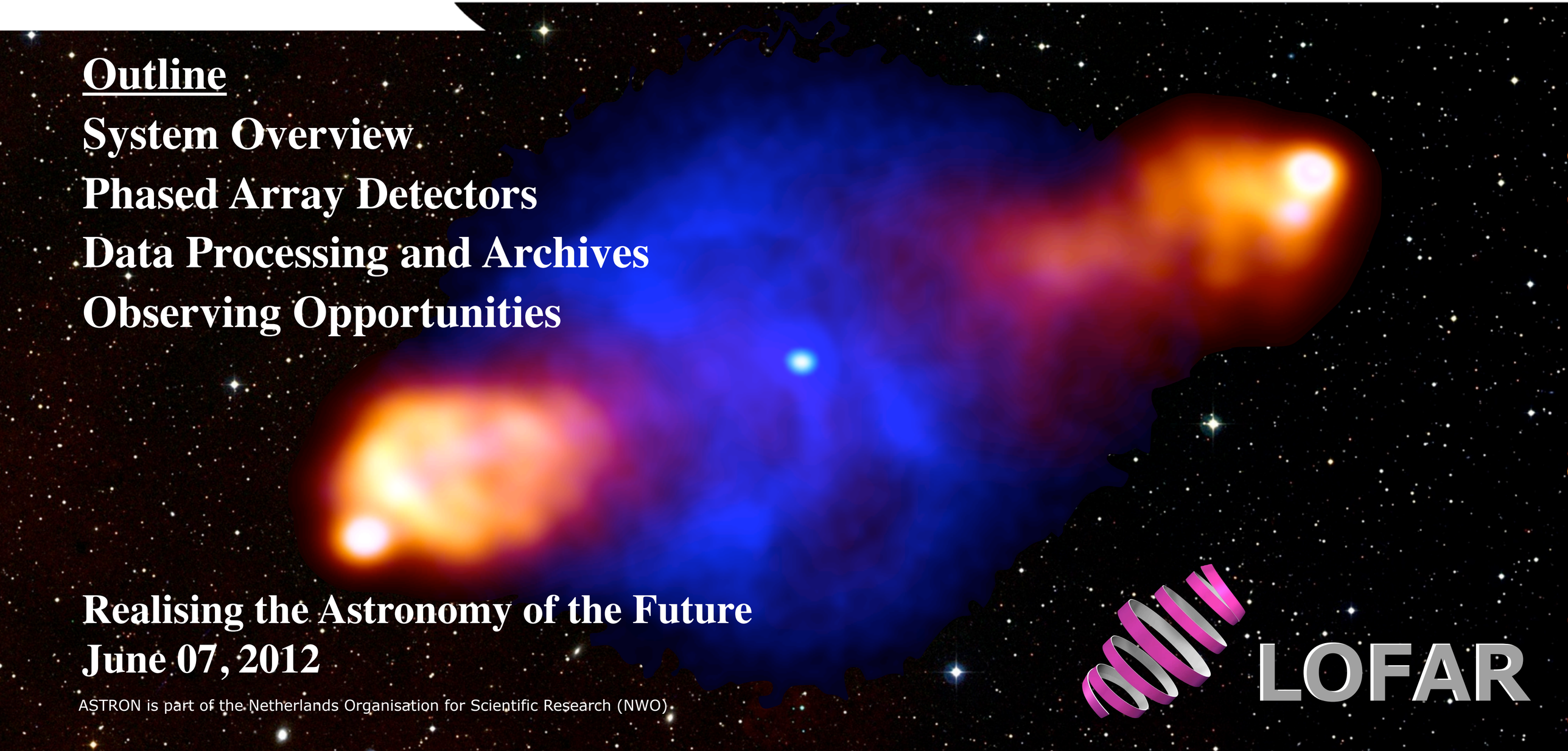

## Outline

## System Overview

## Phased Array Detectors

## Data Processing and Archives

## Observing Opportunities

**Realising the Astronomy of the Future**

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LOFAR

# LOFAR Core

*August 2011*


Effelsberg


Nançay


Unterweilenbach


Chilbolton


Onsala


Tautenburg


Potsdam


Jülich

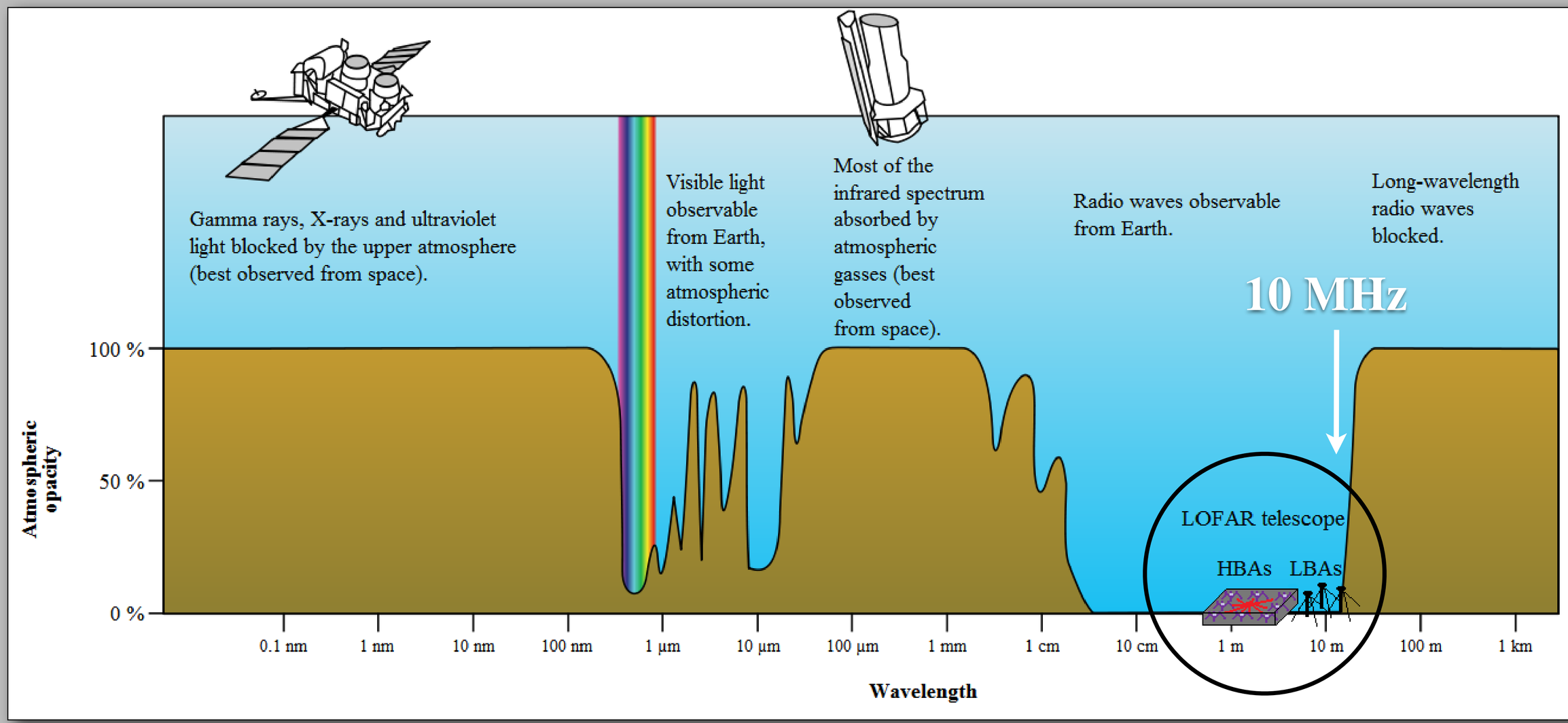
# Current Array Status

- 41 operational stations
  - *33 available in NL (7 more this year)*
  - *8 international stations online*
  - *Remaining stations complete mid-2012*
  - *Additional stations in Poland, Germany*

- IBM BlueGene/P supercomputer
  - *Correlation and online processing*
  - *42 TFLOPS and 640 Gbits/s I/O*

- Post-processing cluster
  - *Calibration, imaging, science pipelines*
  - *25 TFLOPS and 2 PB working storage*
  - *Holds roughly a week of operations*

# Low Frequency Radio

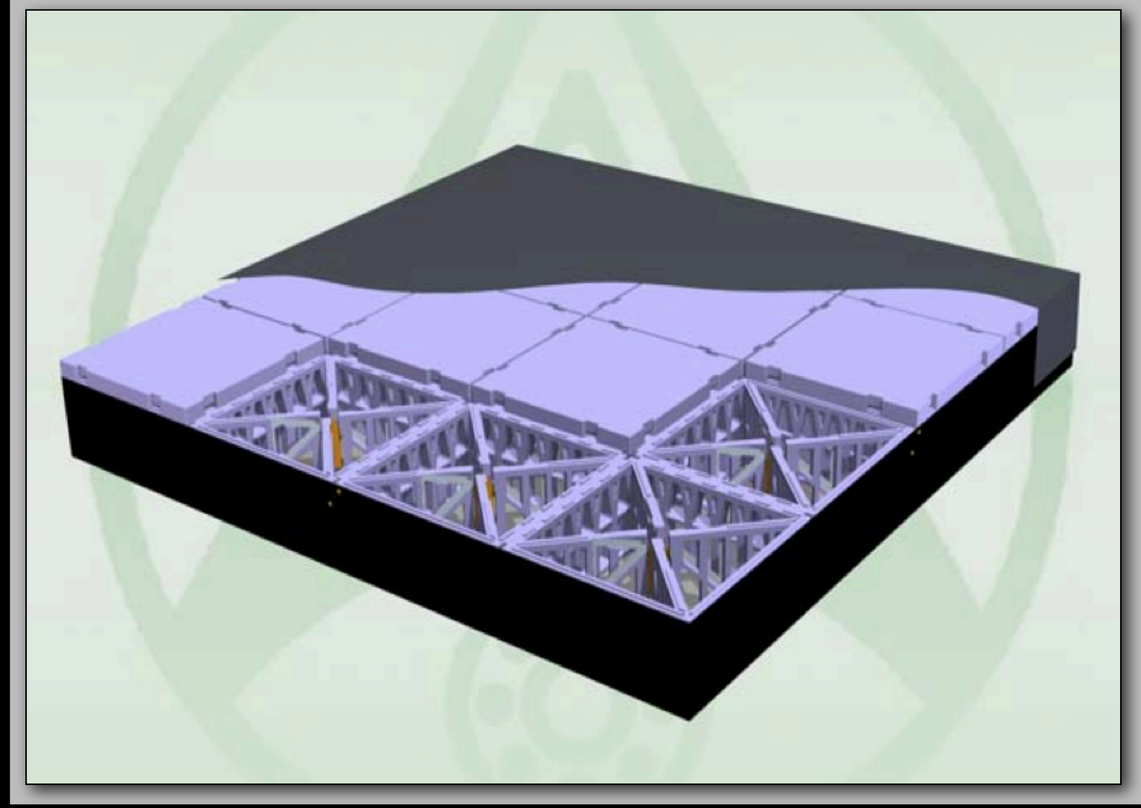



***Relatively unexplored part of spectrum***
***Enormous frequency range***

# LOFAR Antennas

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

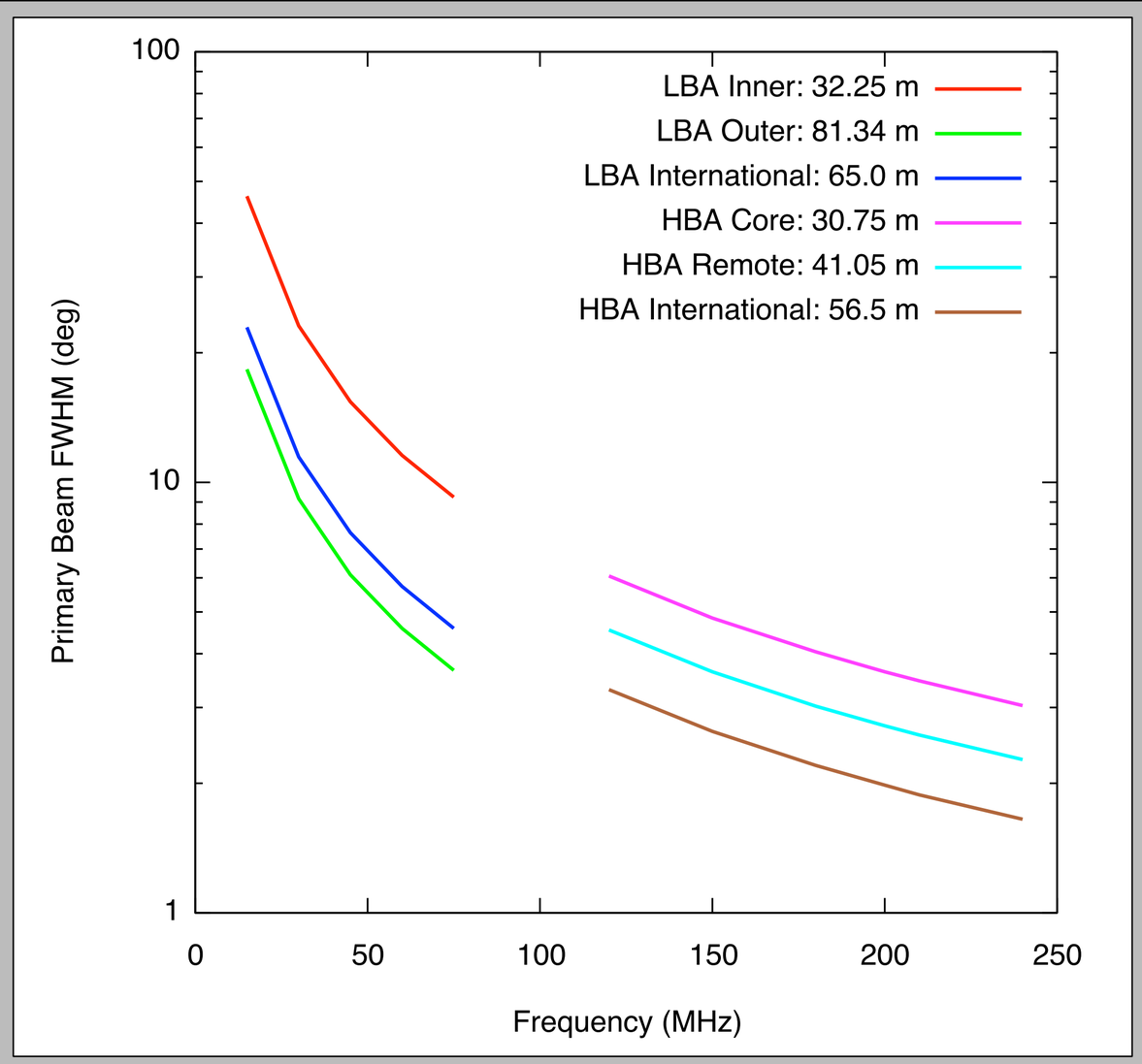
High band tiles:120 – 240 MHz
48/96 tiles/station, 4x4 antennas/tile

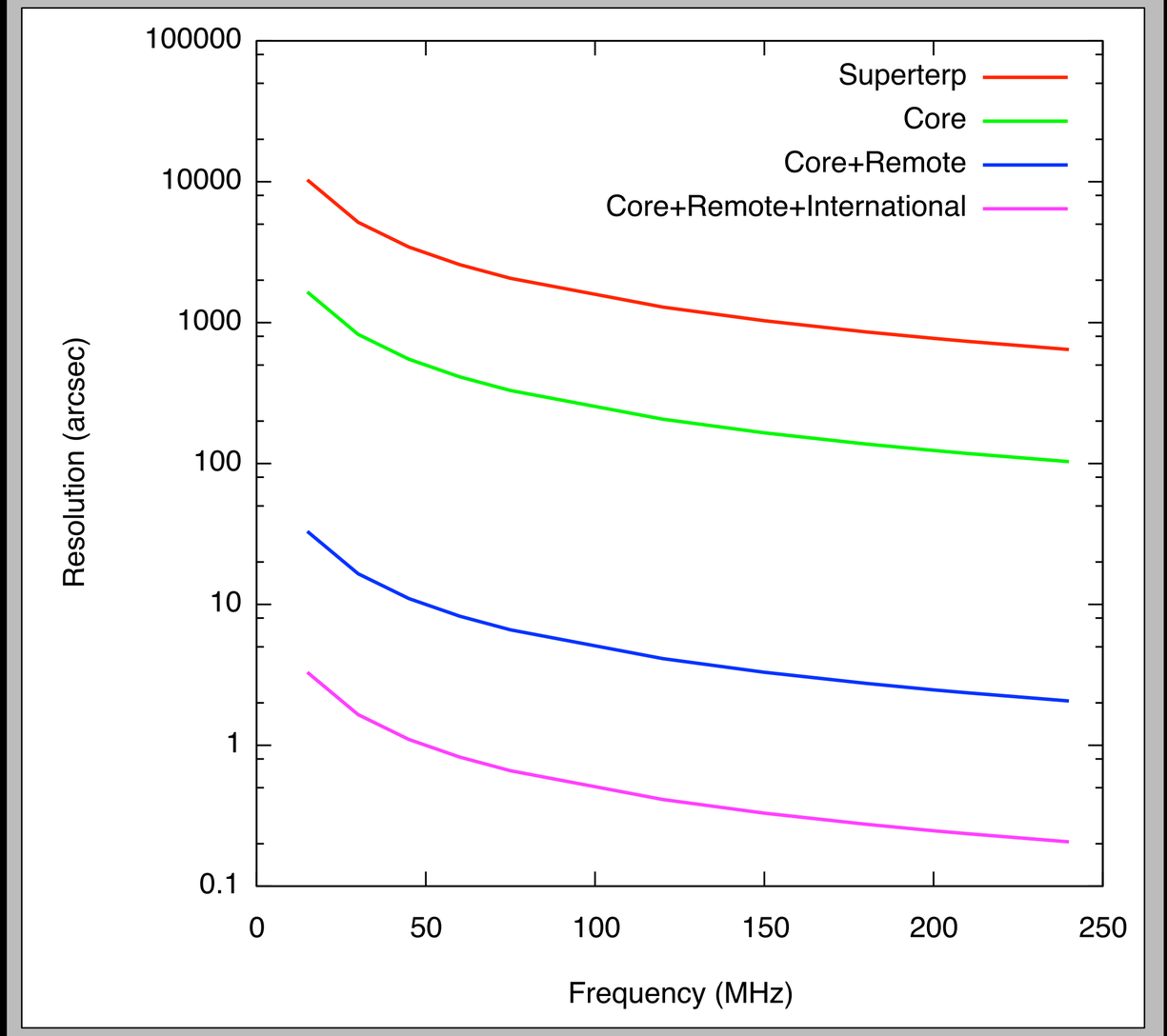


40 NL + 8 EU stations of dipoles
Replace big dishes by many cheap dipoles
No moving parts: electronic beam steering
Flexible digital beam forming

***Technology pathfinder for SKA Low***

# Resolution and Field-of-View



# High Resolution Imaging

## 3C196 at 30-80 MHz

NL stations only (35” x 22”)

Full array (1.5” x 0.9”)

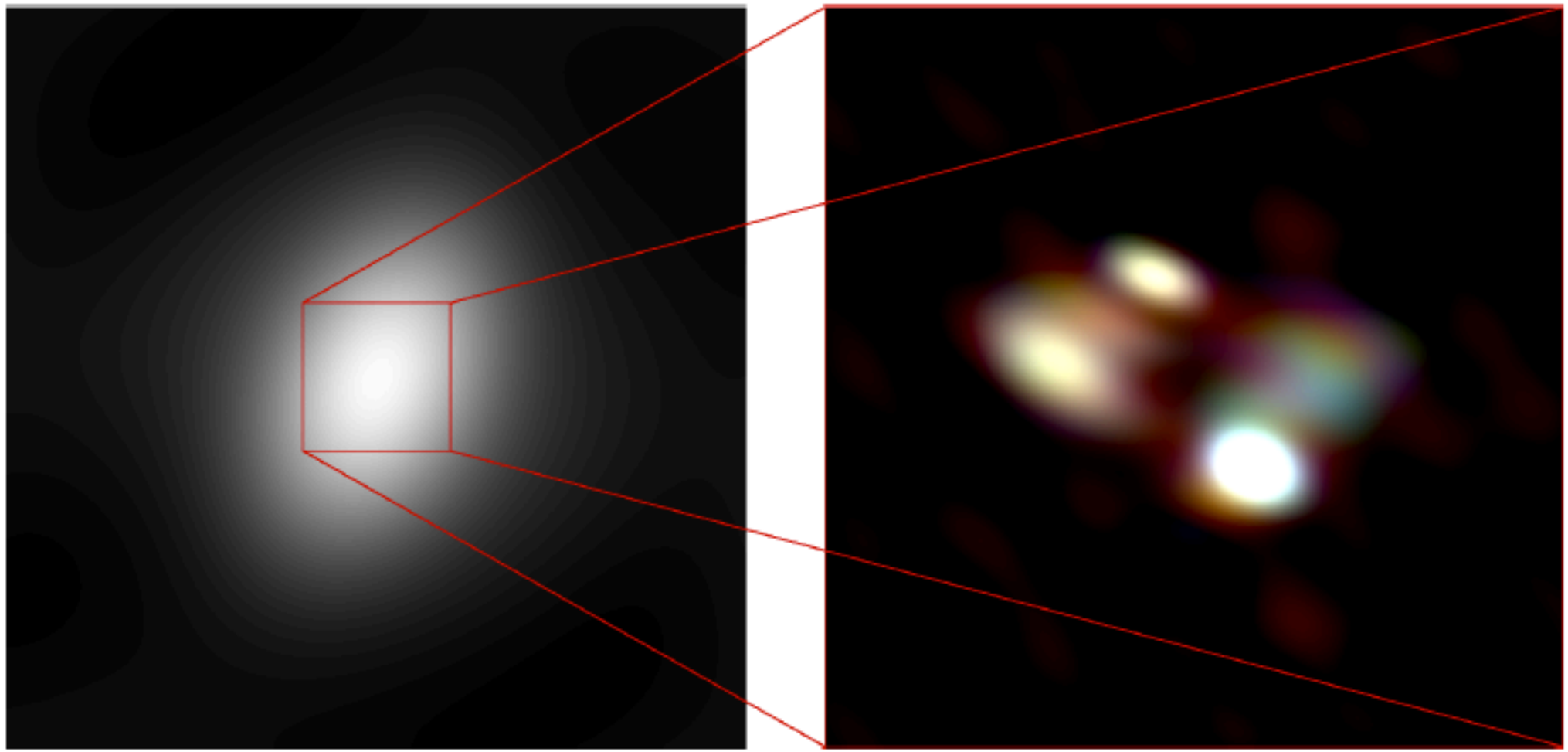
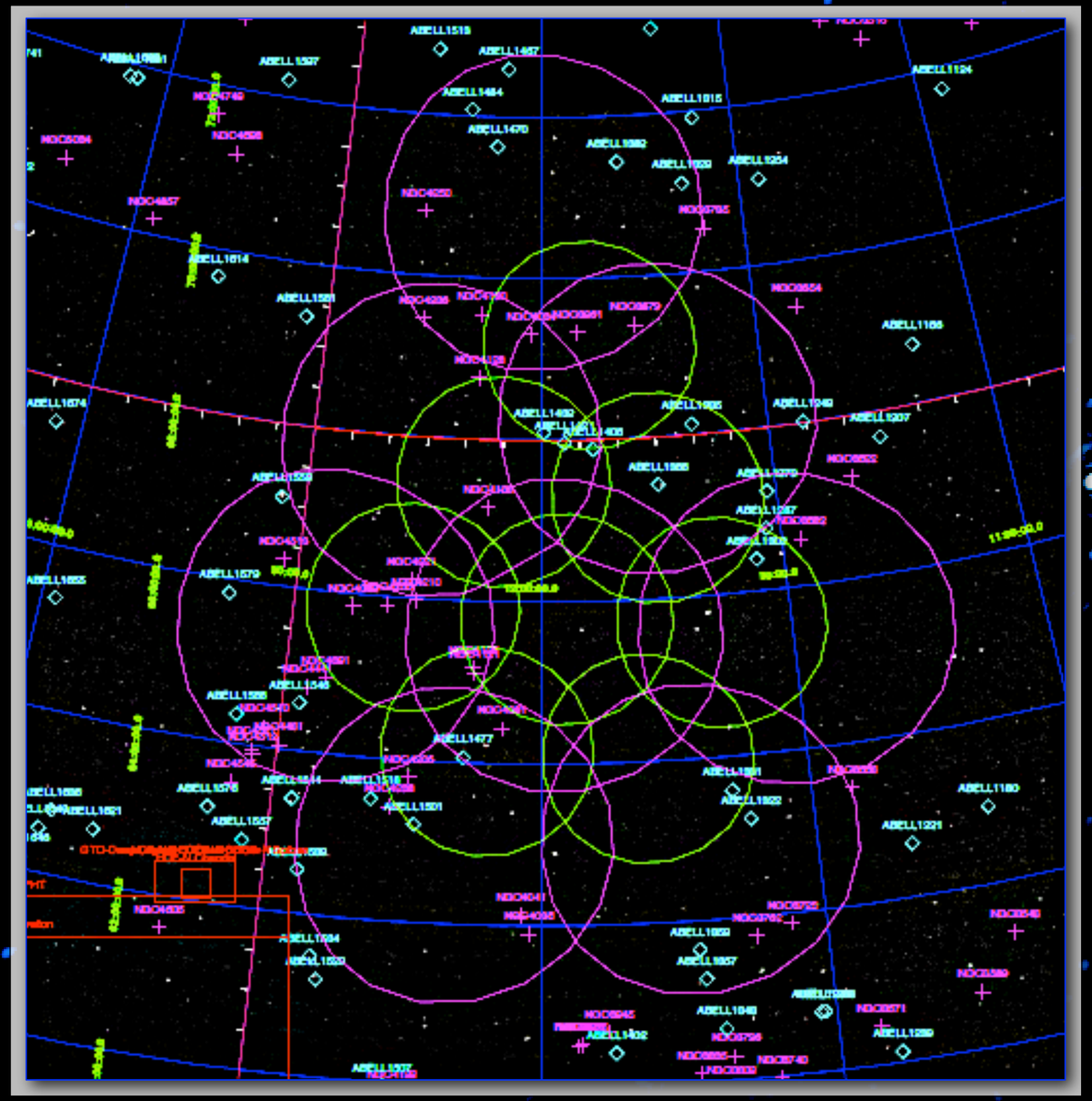
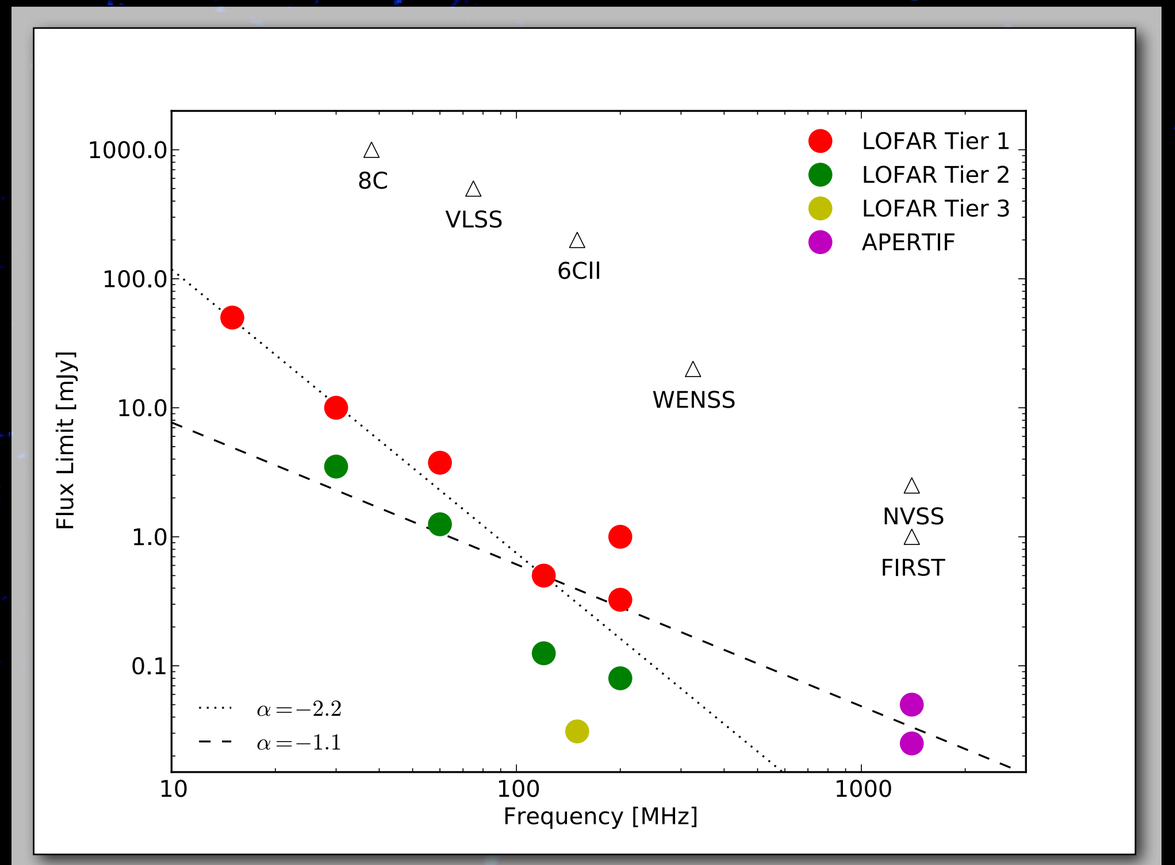


Image Credits: O. Wucknitz (Univ. of Bonn)

# Surveys with LOFAR

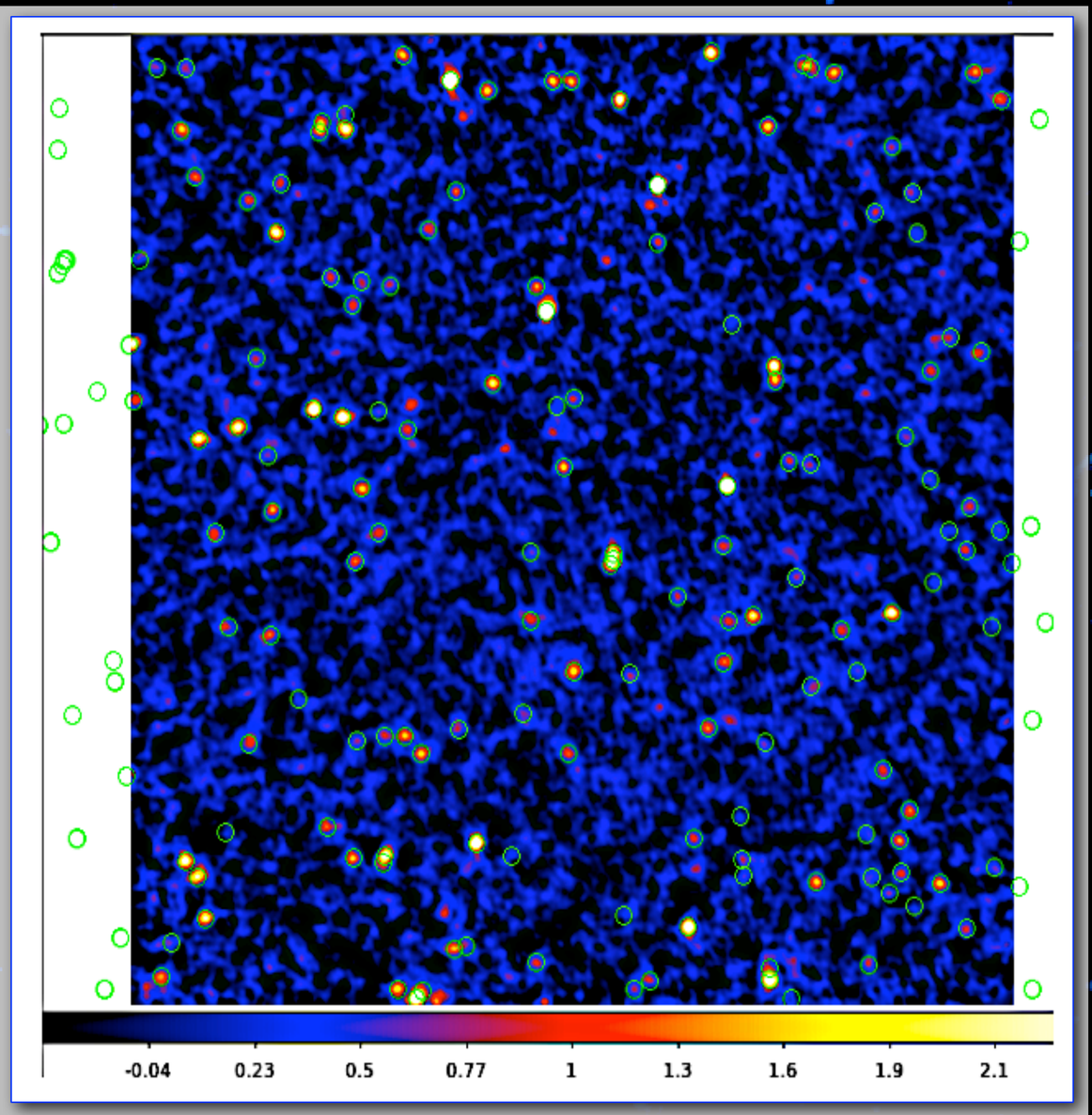





LBA 30–34 MHz ( ~30 mJy/beam, ~80 arcsec resolution)

100's supernova remnants,
100-1000's of clusters z< 0.6,
Protoclusters at z~2,
Many z>2 radio galaxies,
Halos, relics, AGN, SF galaxies, etc...

# Surveys with LOFAR

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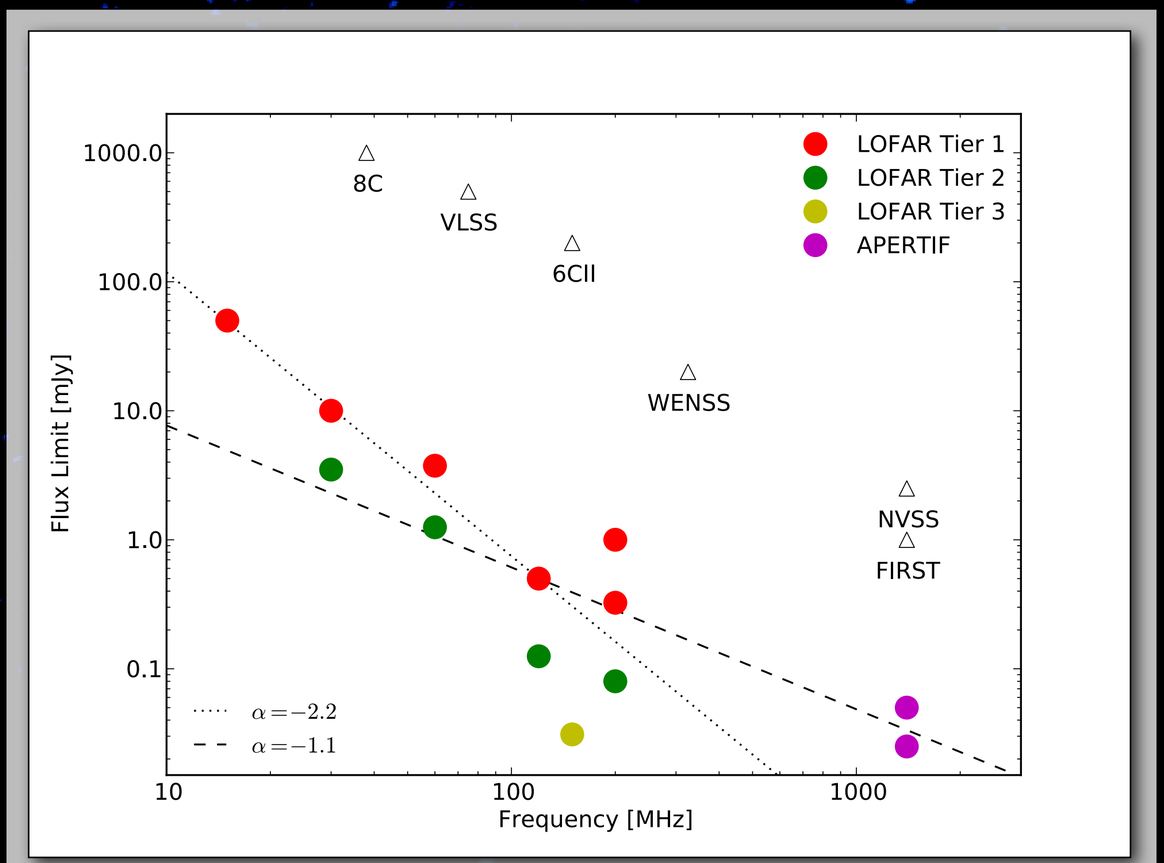


100's supernova remnants,
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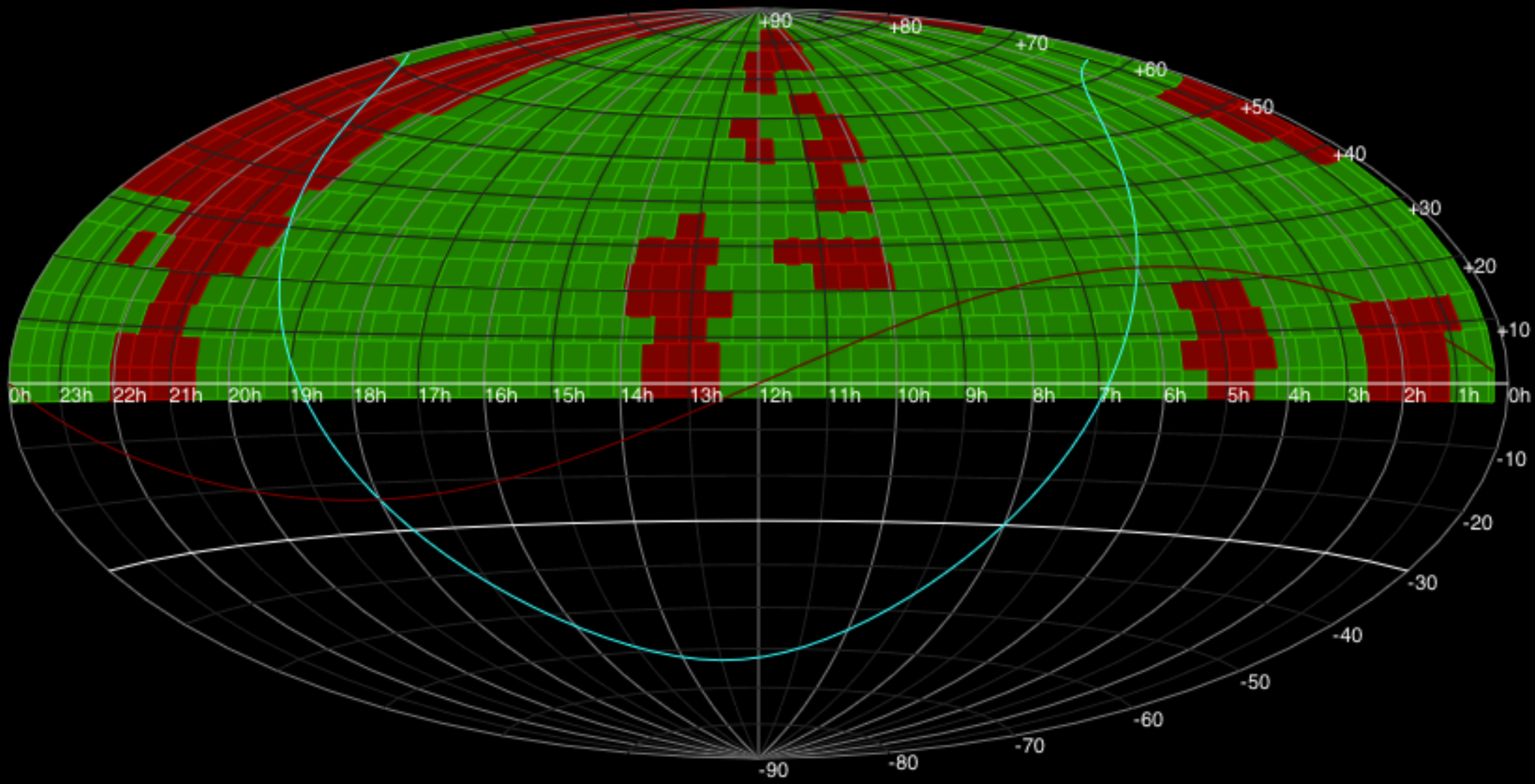
# MSSS: LOFAR's First Survey

- See http://www.astron.nl/~heald/msss/msssmap_lba_obs.html




**MSSS-LBA: 516/660 fields = 78% complete**

**LBA component expected to complete early June**
**HBA component to begin June and run till September**

# LOFAR Science Drivers

## Key Science Projects

*Epoch of Reionization*

*Transients and Pulsars*

*High Energy Cosmic Rays*

*Surveys and the Distant Universe*

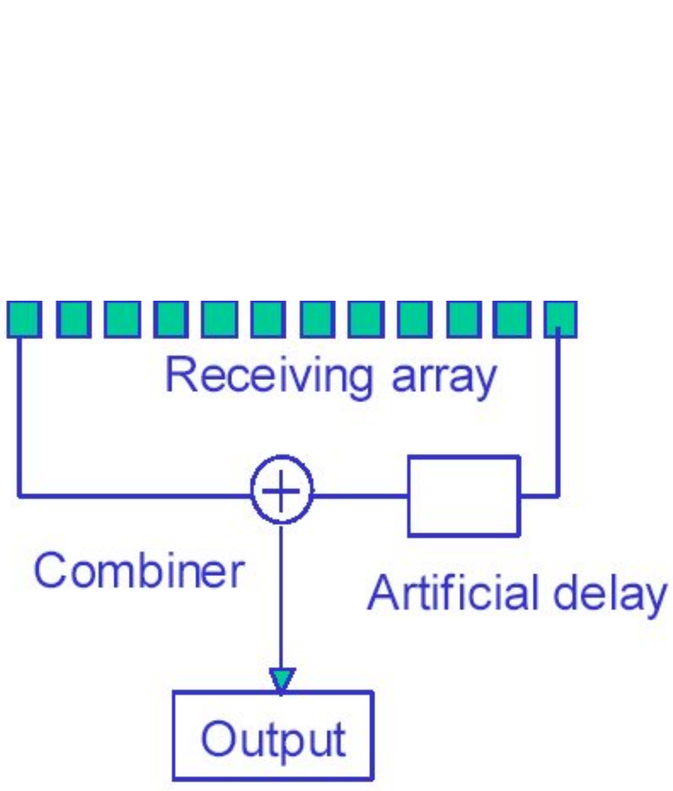
*Cosmic Magnetism*

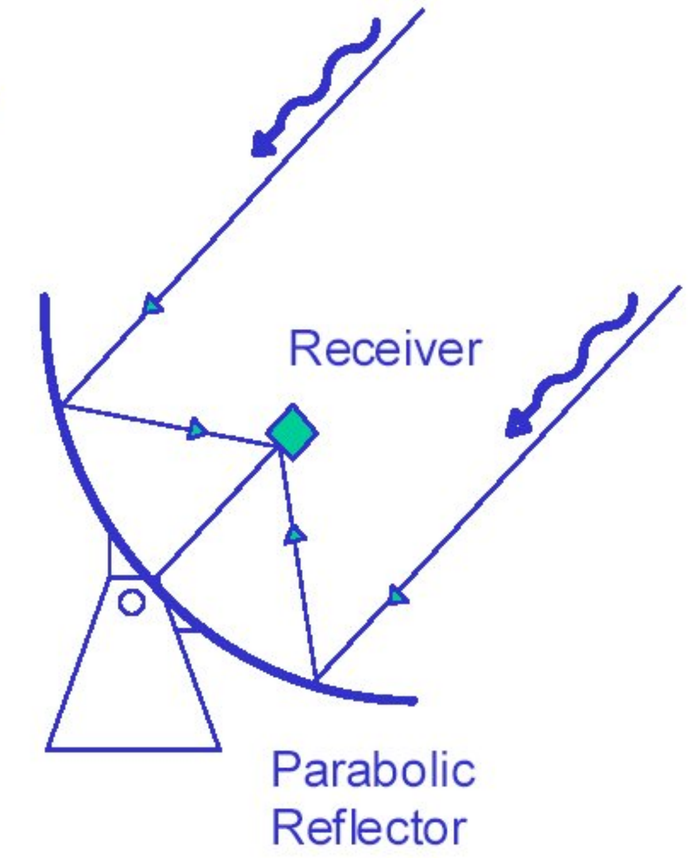
*Solar Physics and Space Weather*

⇒ International membership from countries all over world

Contribute development and commissioning resources

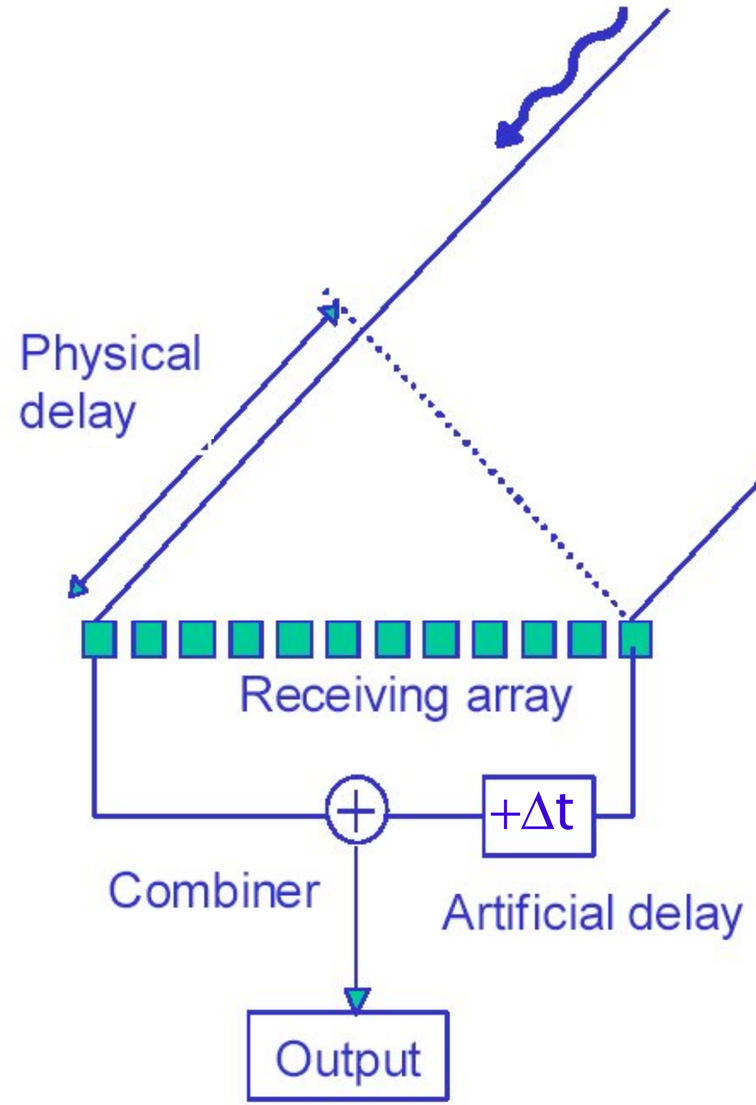
# Phased Array Detectors

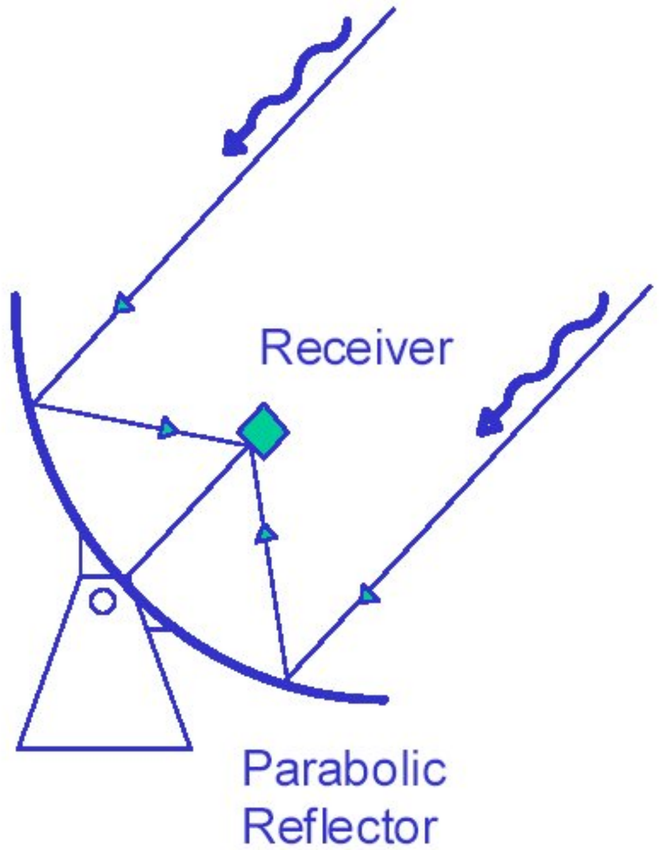



***Electronic beam steering***

# Phased Array Detectors




***Electronic beam steering***

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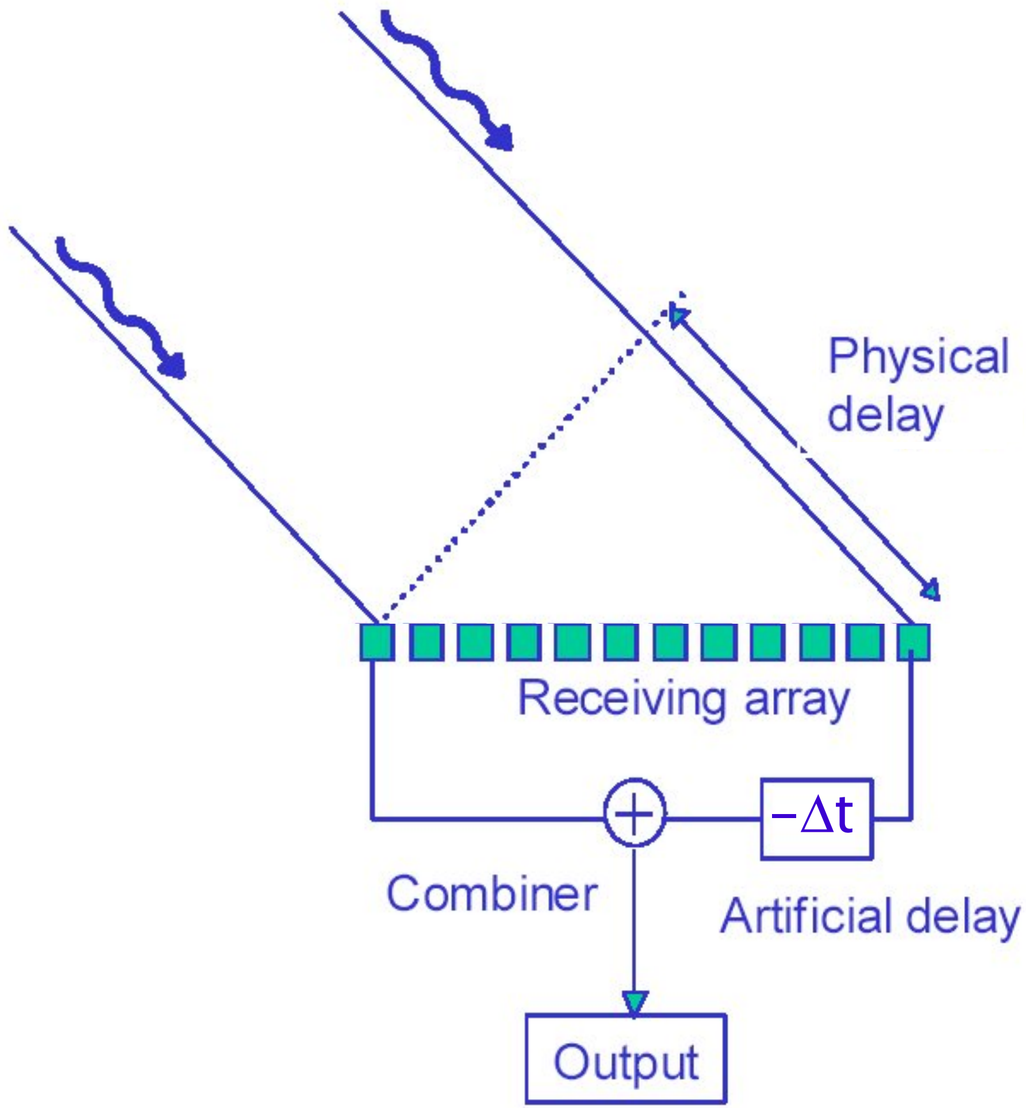


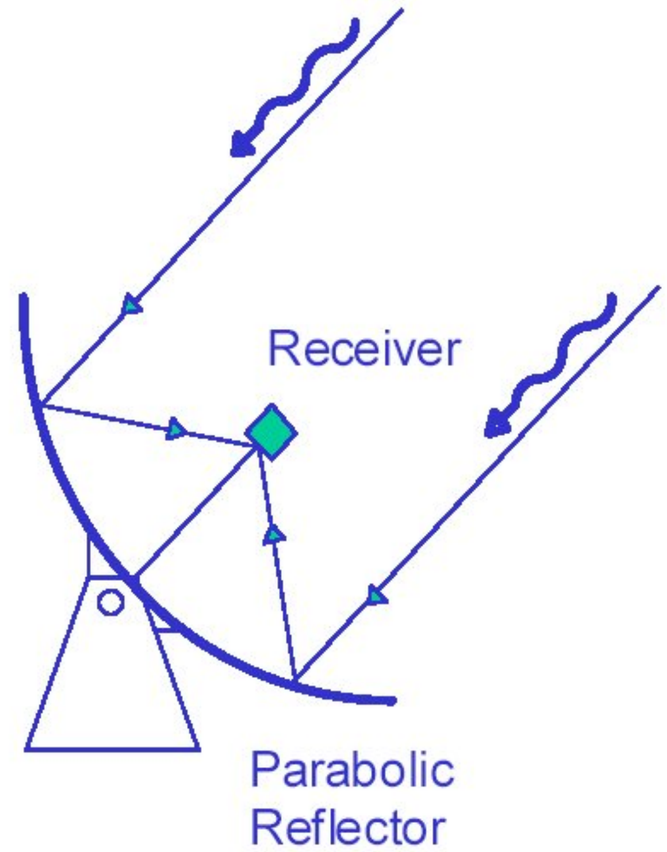


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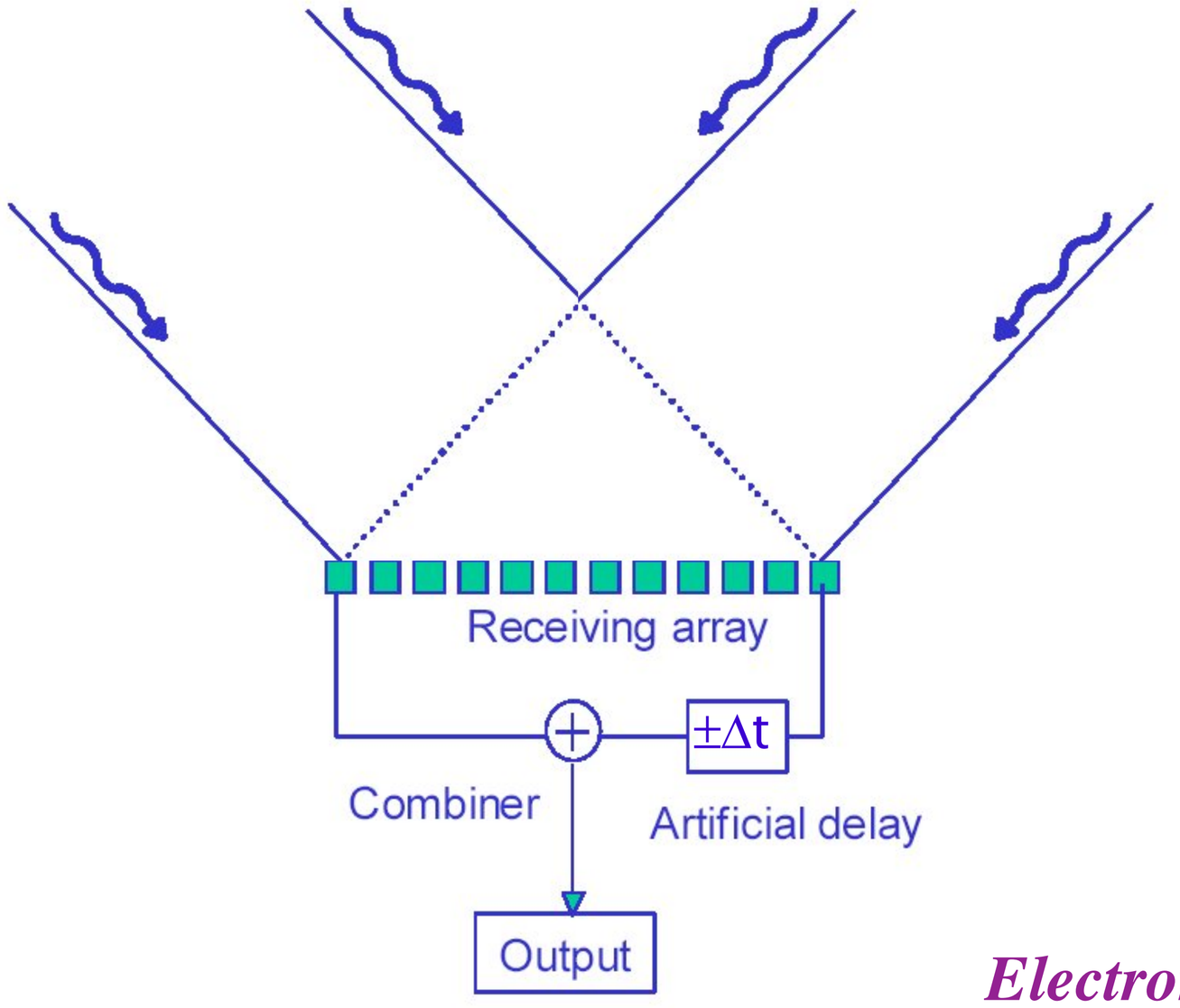
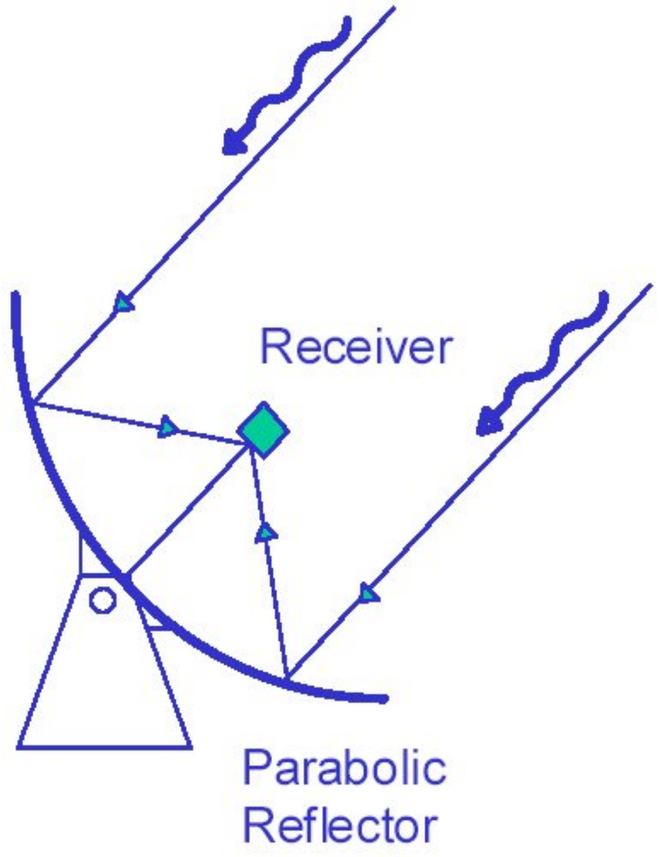
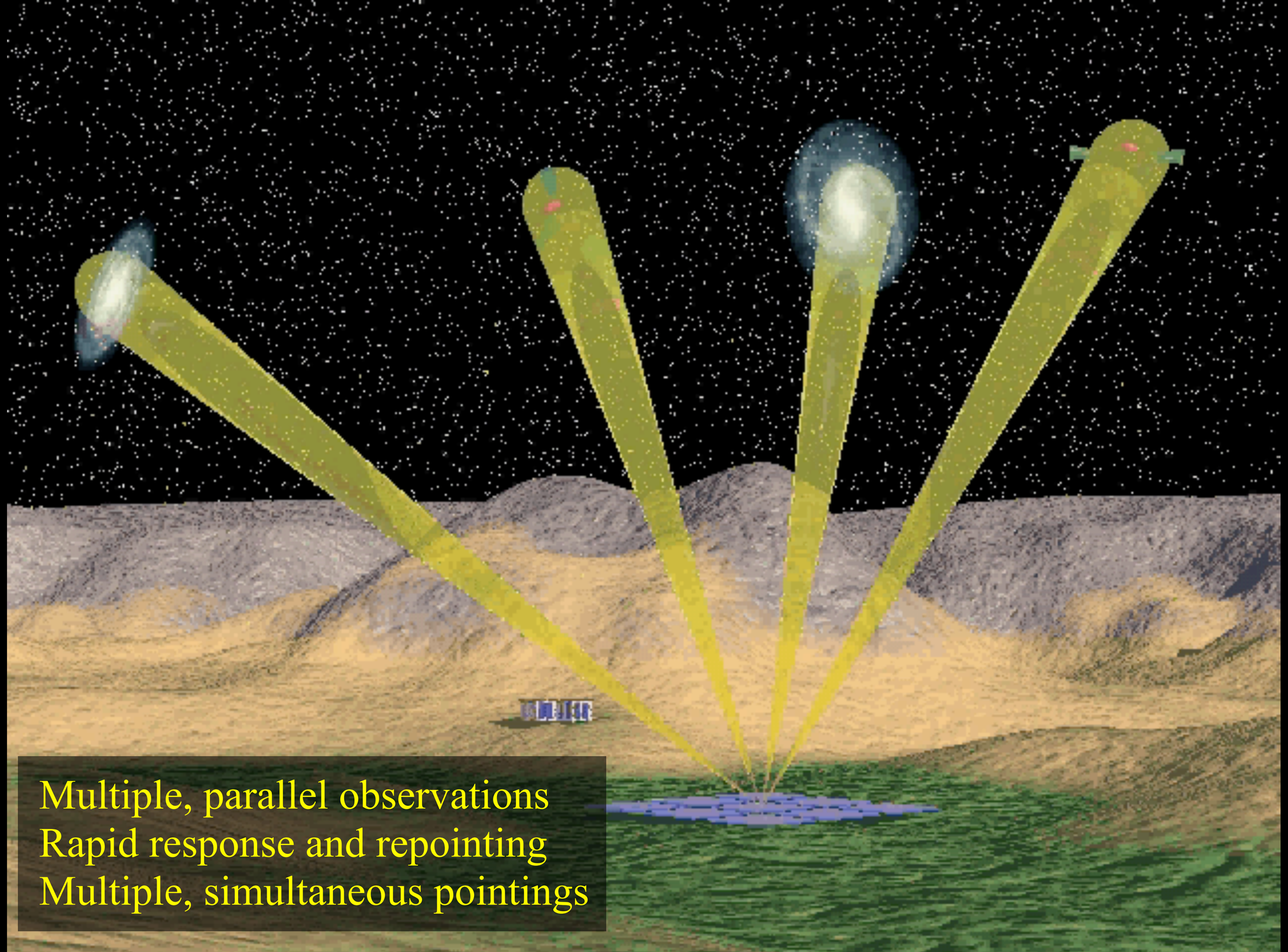


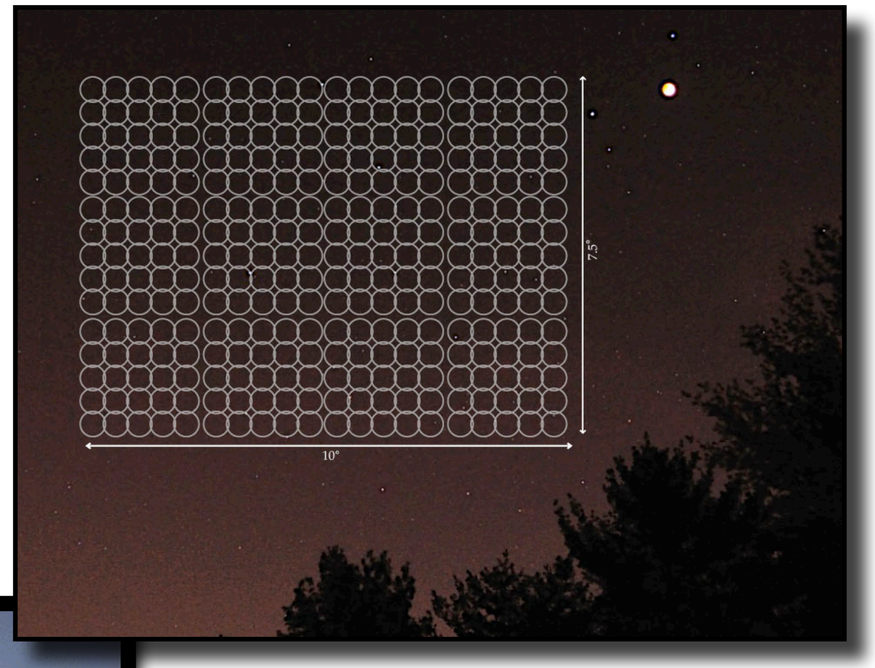




***Electronic beam steering***

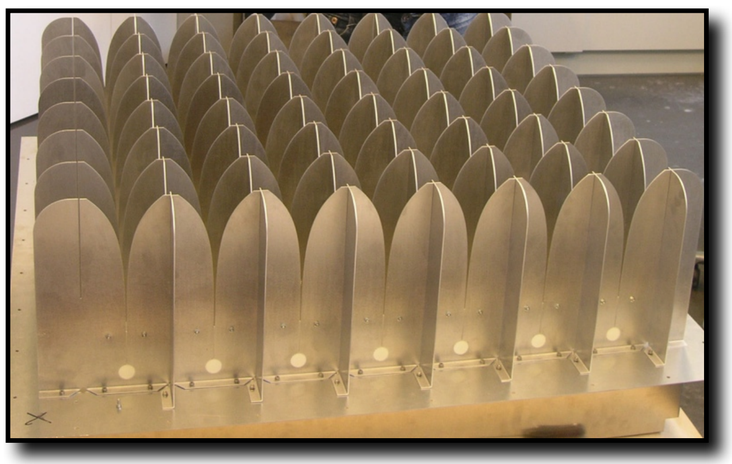

Multiple, parallel observations
Rapid response and repointing
Multiple, simultaneous pointings

# Focal Plane Arrays

- Replace single-pixel detector with array of detectors and turn single dish into a camera
- Survey speed increases by factor 20-40
- Can do in a day what now takes a month!
- Commissioning with 6-8 dishes to begin mid 2013




## *Apertif system on WSRT*



# LOFAR Raw Data Volumes

- 2688 dipoles (LBA), 200 MHz sampling, 2 polarizations, 12 bit digitization

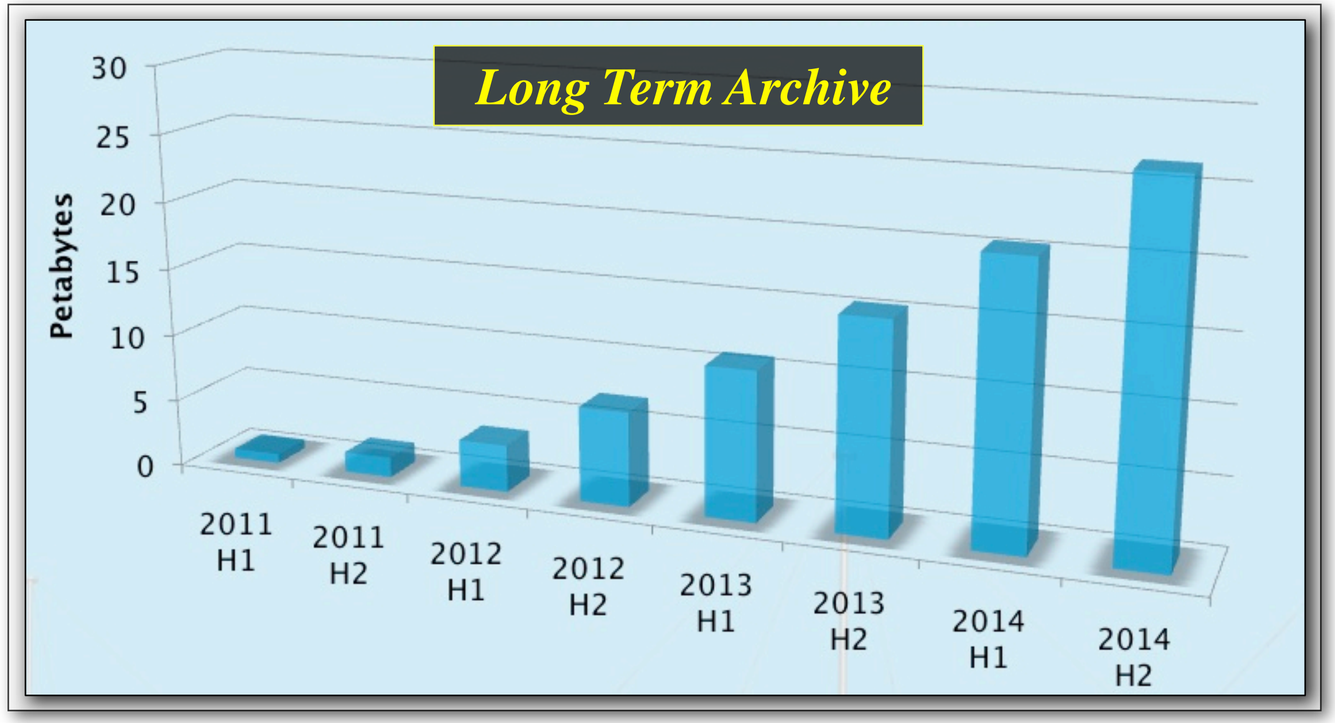
  $\Rightarrow$ 13 Tbits/s ~ 1.6 TB/s ~ 138 PB/day

- 48 stations, 48 MHz total bandwidth, 8 independent beams (up to 244)
- 1128 baselines, 242 sub-bands, 256 channels, 4 polarizations, 1 sec correlator dump-time

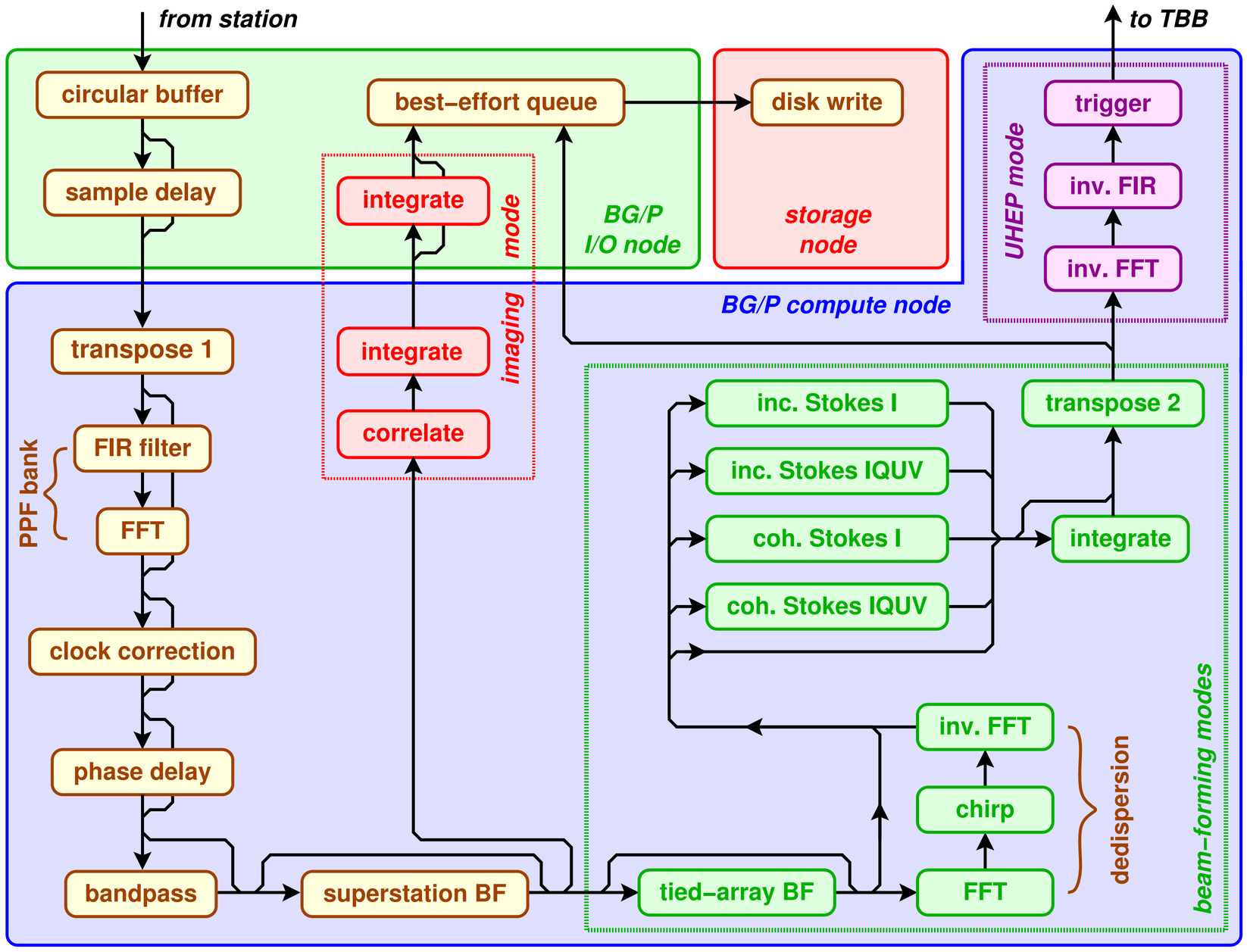
  $\Rightarrow$ ~ 10 TB/hr ~ 240 TB/day ~ 0.1 EB/yr

***Storage limits give a ~1 week processing window***

***LOFAR is a pathfinder for data-intensive astronomy!***



# Real-time Processing



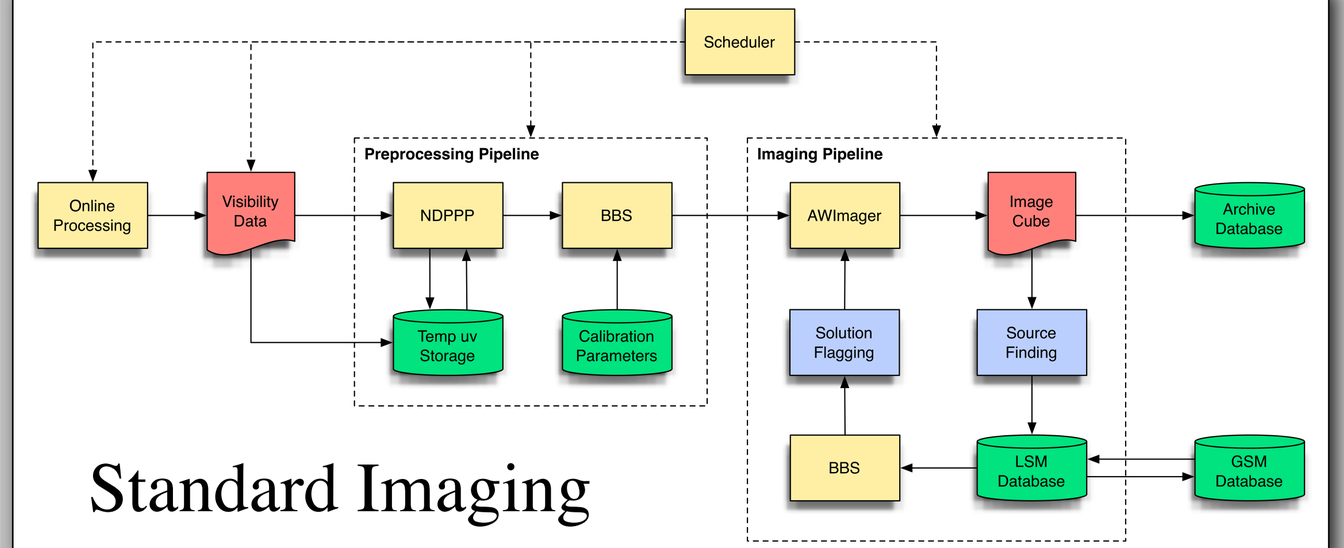

*BG/P supercomputer*
*45 TFLOPS*

*Data reception*
*Correlation*
*Beam-forming*
*De-dispersion*
*Triggering*

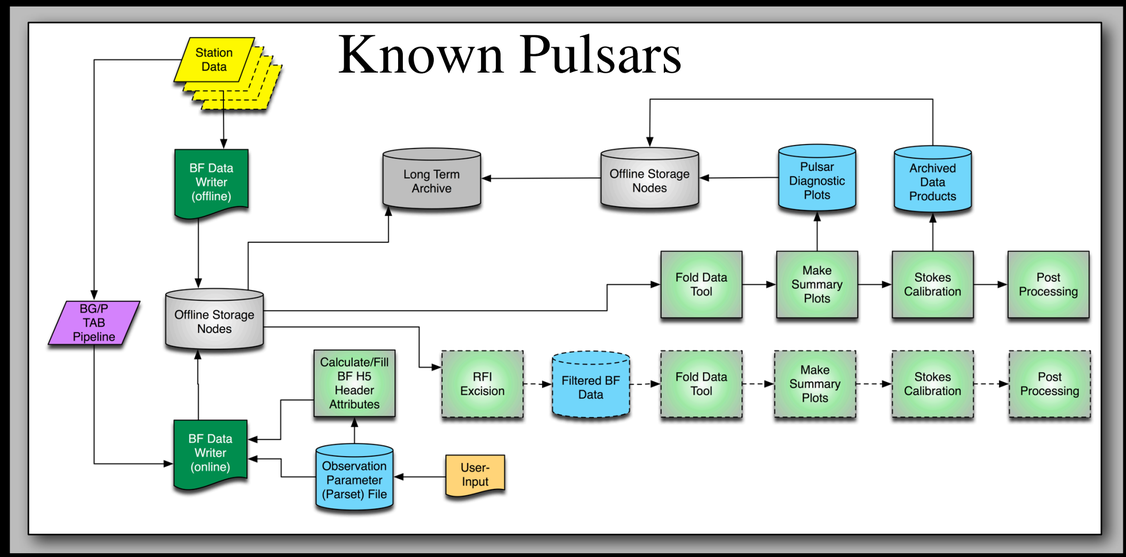
*Multiple parallel processing streams*

*Multiple simultaneous observing programs*

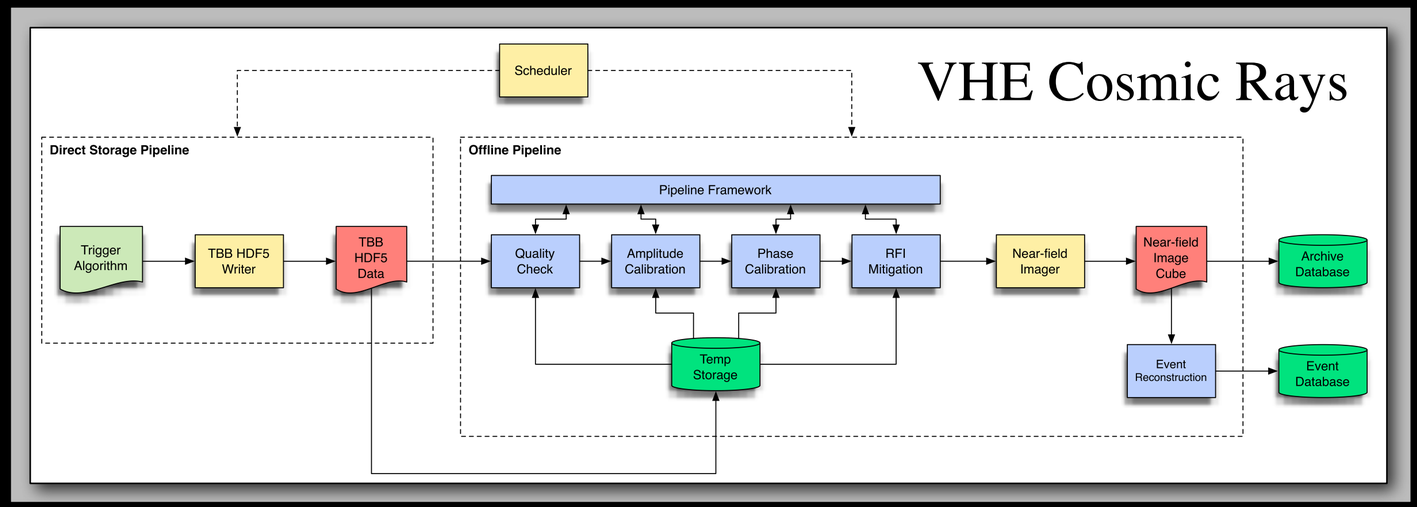
# Automated Science Pipelines




## Standard Imaging

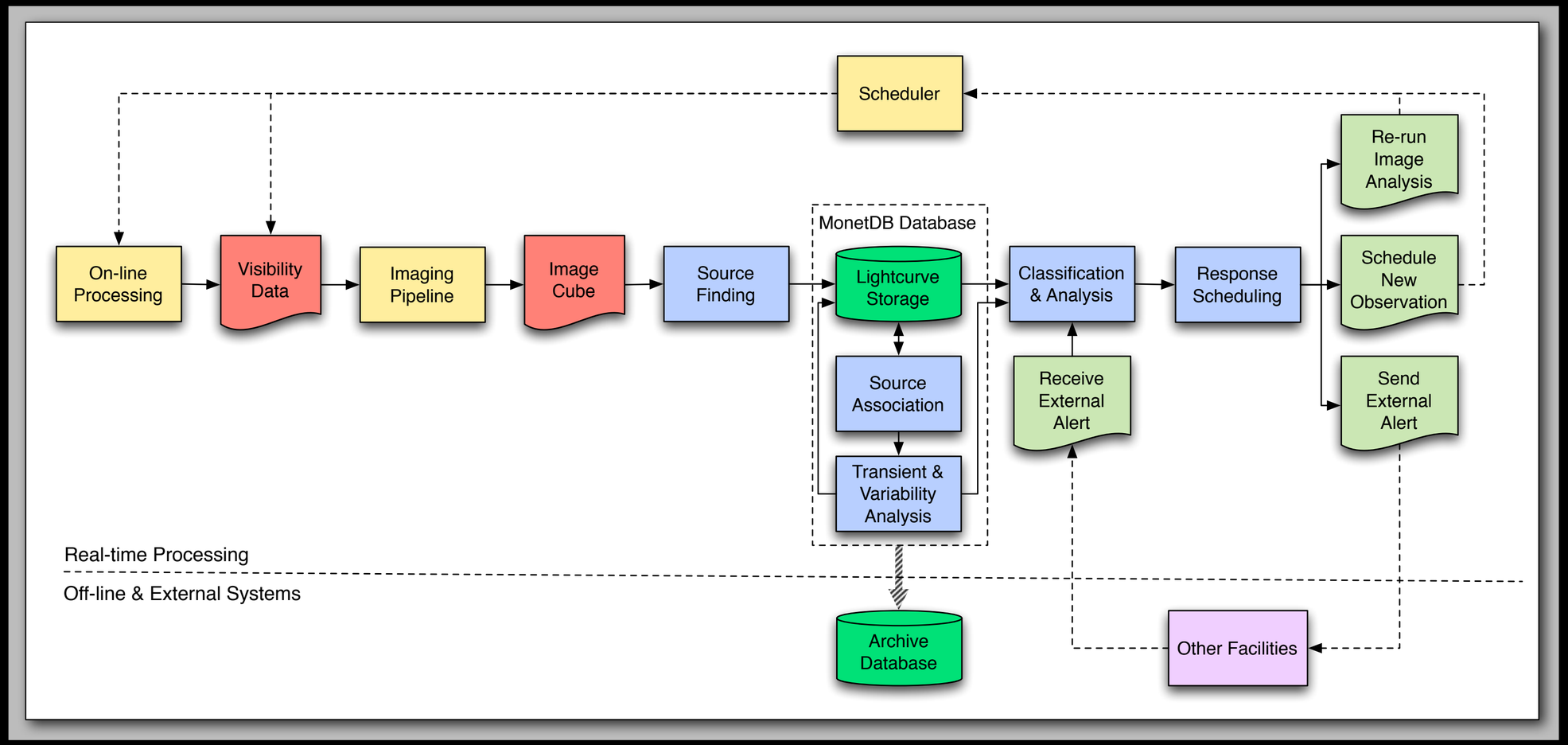



- Current set of pipelines under development for initial system
- Additional pipelines to be rolled out steadily in subsequent releases
- Primarily driven by KSP science
- Transient detection, magnetism, solar imaging, planets, etc.



# Responsive Telescope

***Fast Transient Pipeline will be next major pipeline development***




***Developed in cooperation with Transients KSP***

- Implement trigger generation and response first
- Generate and respond to triggers (internal + VOEvent)
- Major modifications to achieve real-time imaging

# LOFAR Surveys in Context

2000 - 2014  Sloan Digital Sky Survey (SDSS)

120 Mpixel camera, (0.08 PB in 10 yrs)

$3x10^8$ unique sources (4 TB)

2018 - 2028  Large Synoptic Survey Telescope (LSST)

3.2 Gpixel camera (6 PB per year)

1000 observations of every source

few $x10^9$ sources, few $x10^{12}$ rows (2 PB)

2013 - 2018  LOFAR Low-Frequency Sky Survey (LFSS)

~100 $deg^2$ FOV  (~5.2 Gpixel)  (~0.1 EB per year)

10-$10^3$ freqs, $10^2$-$10^4$ observations of every source

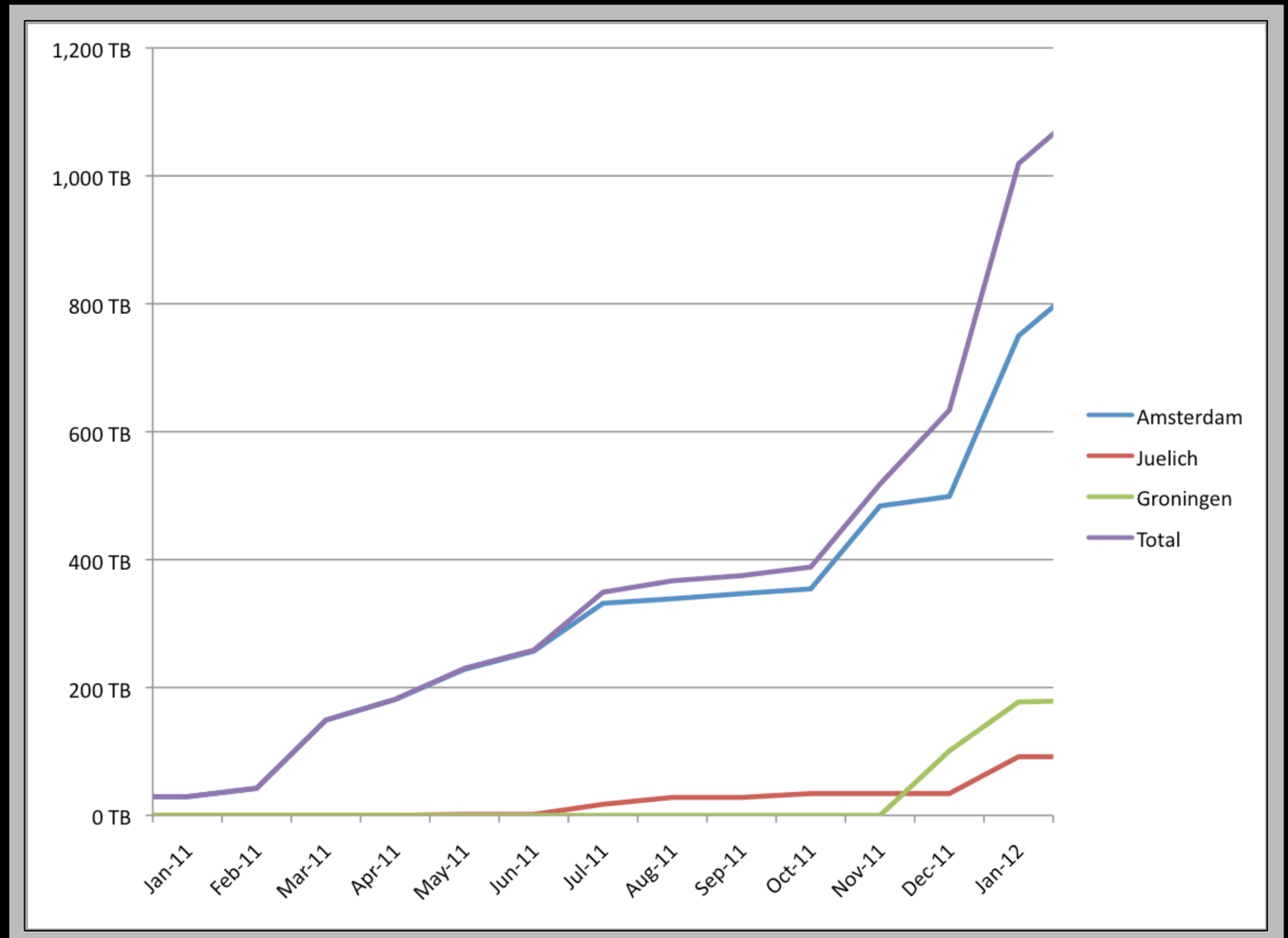
few $x10^8$ sources, few $x10^{12}$-$10^{13}$ rows (~1-5 PB)

LBA 30–34 MHz  ( ~30 mJy/beam,  ~80 arcsec resolution)

# Integrated Long Term Archive

- **H2 - 2012**
  - Initial source catalog (as generated by MSSS)
  - Support for TBB dataproducts
  - Support for single station data products
  - Manually operated pulsar processing
  - Manually operated image processing
  - Extend LTA datamodel (quality related) metadata
  - Extending/enhancing the user interface
- **H1 - 2013**
  - Extend support as needed for LOFAR operations
  - User initiated processing using LTA pipeline framework
  - Support for new observing modes/pipelines and associated data products/formats as released
  - Virtual Observatory integration
- **2013+**
  - Further operational enhancements as required
  - Improve automation, scalability, usability, etc.

***LTA data volumes through January 2012***



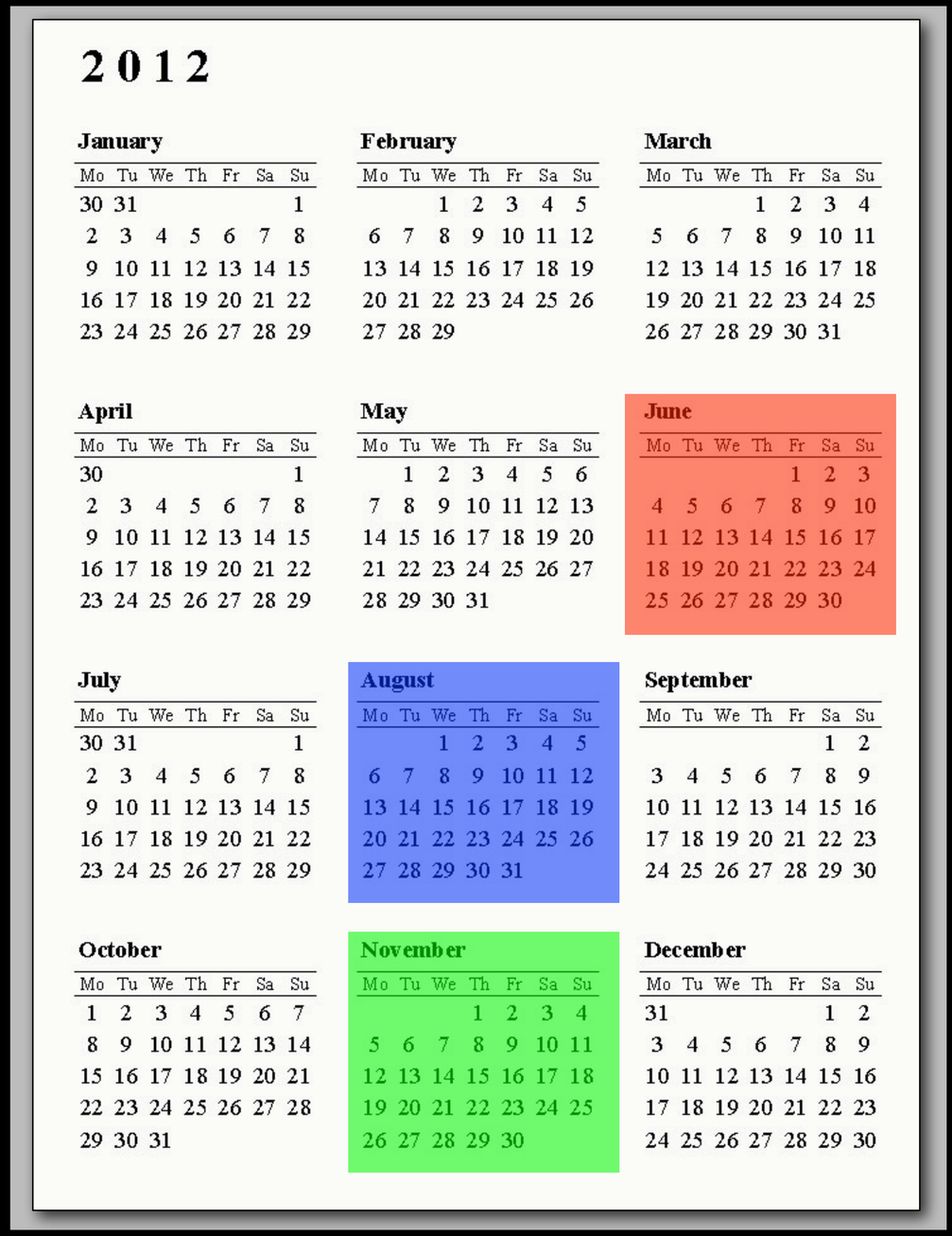

***Sustained transfer bandwidth to SARA (8.6 Gbps) and Juelich (9.6 Gbps)***

# How to get LOFAR Data

- **Commissioning Proposals**
  - *Open to qualified commissioning teams*
  - *Rolling proposal cycle and review*
  - *Reporting requirements*
  - *Must follow publication policies*

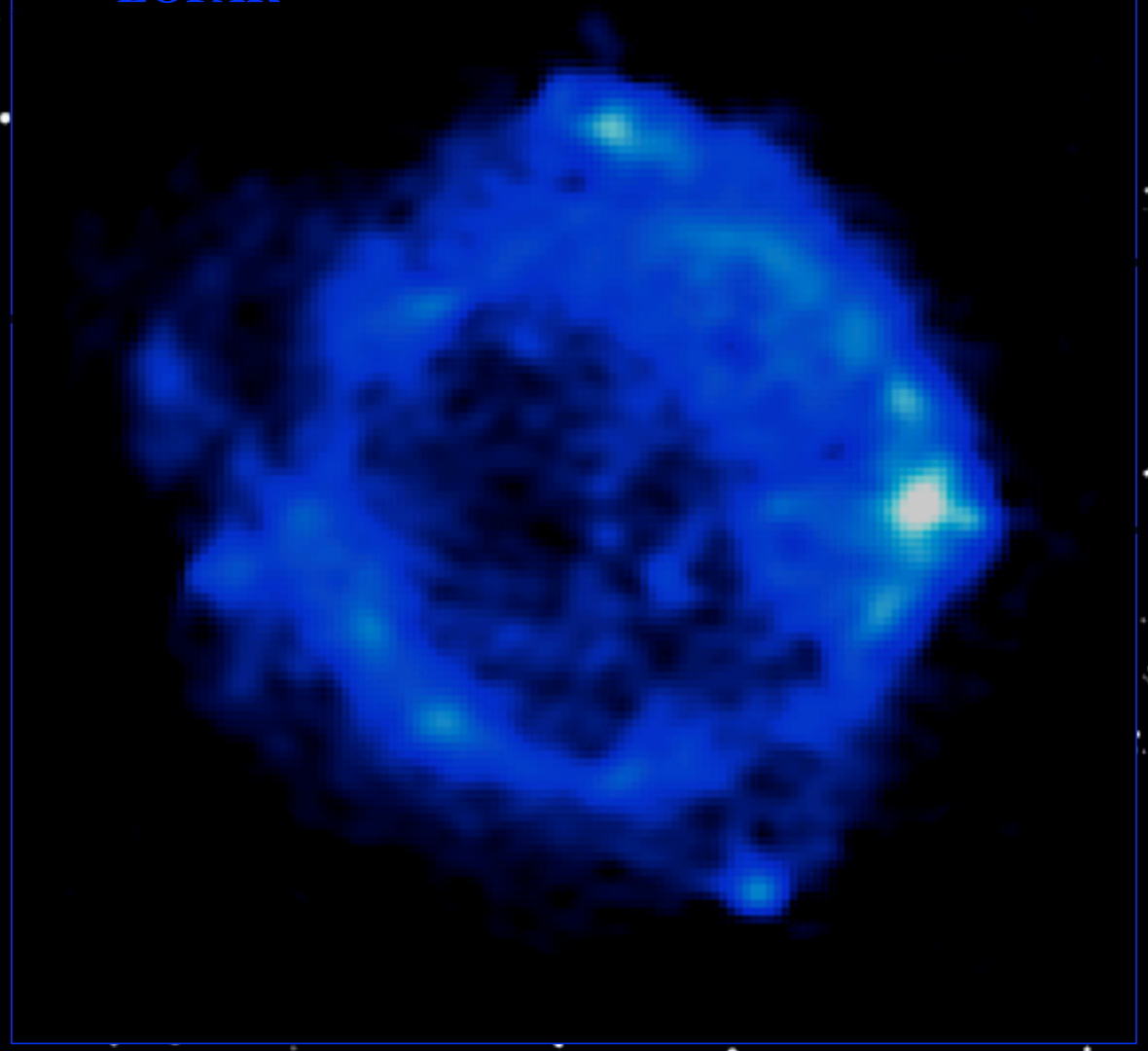
- **Open Access Proposals**
  - *Open to entire international community*
  - *Dominated initially by KSP projects*
  - *Year one open time fraction ~10%*
  - *Ramping up steadily in coming years*
  - *Final allocations decided by TAC*

***Announcement of Opportunity expected to be released June 2012***

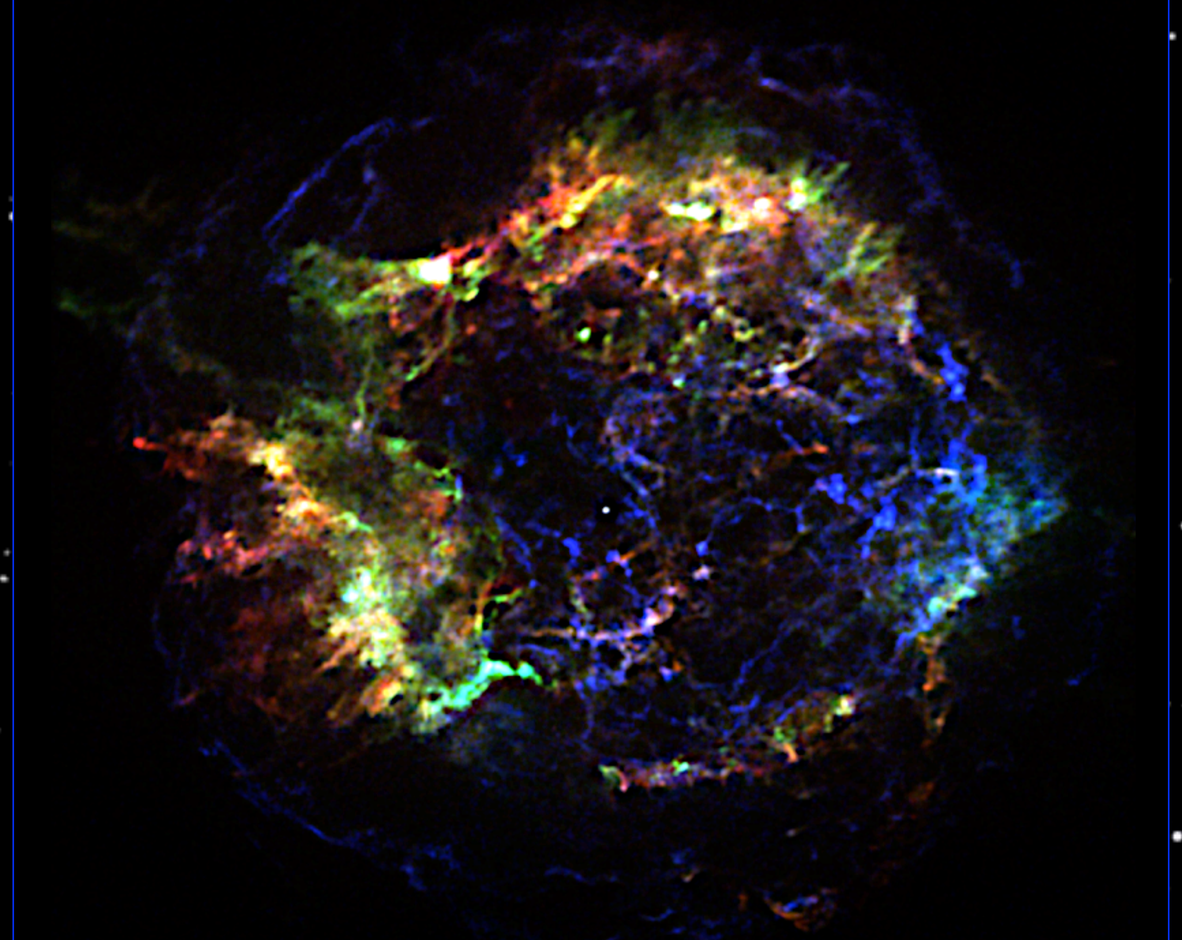


# Cassiopeia A

**LOFAR**



**Chandra**



*(van Weeren et al. 2012)*

# 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)

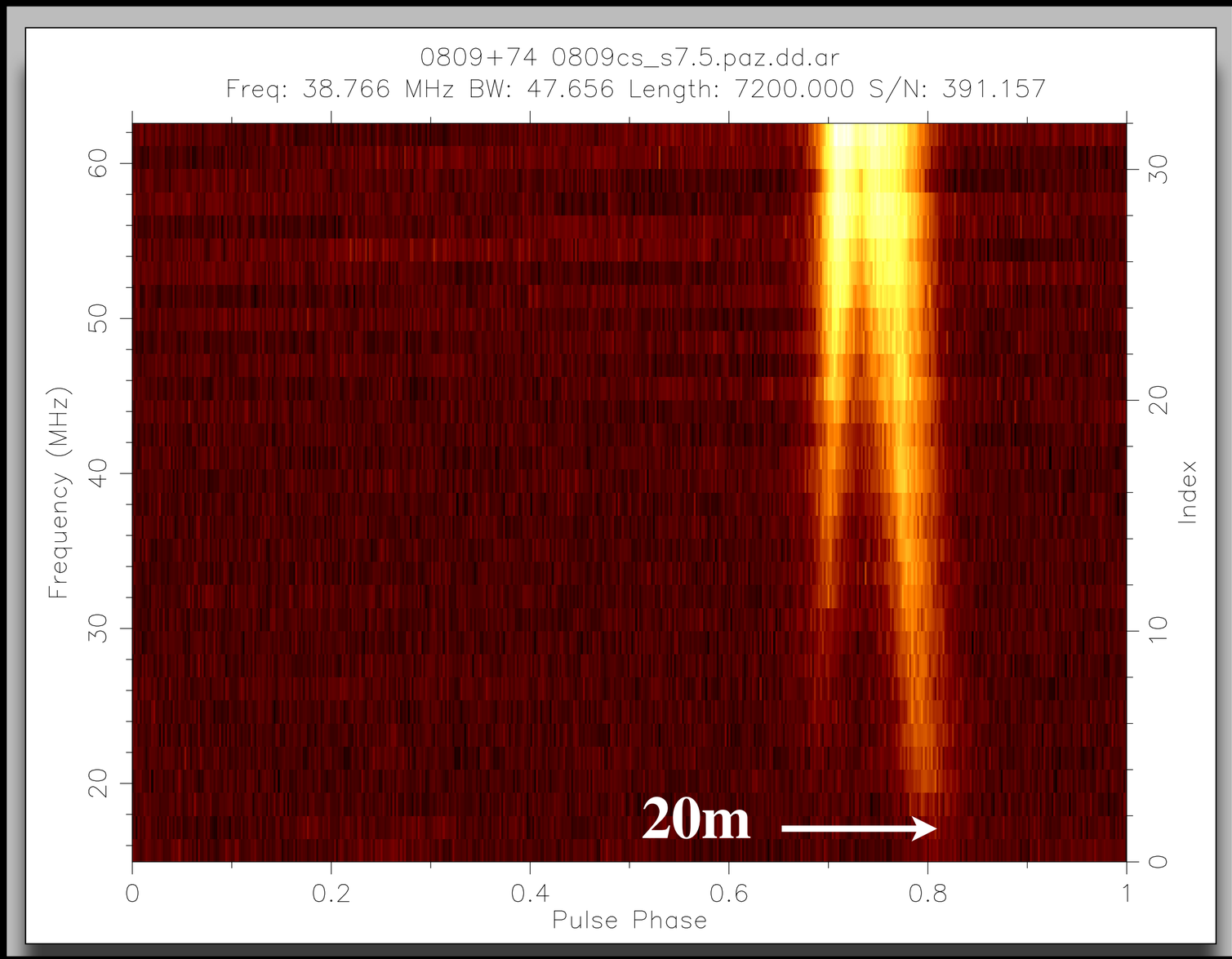
# Wide-band Pulsar Monitoring

## 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***

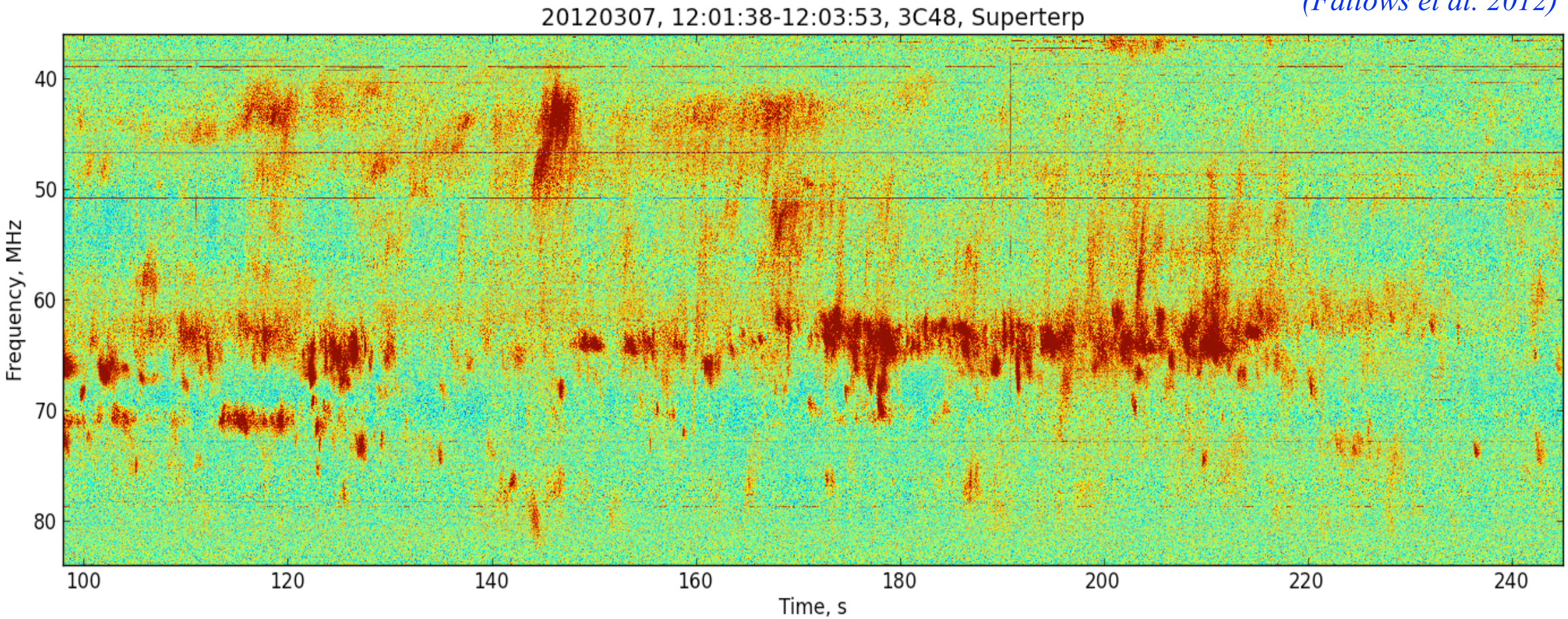
15 - 63 MHz Observing Frequency




*(Kondratiev et al. 2012)*

# Solar Wind Observations

*(Fallows et al. 2012)*




***Dynamic spectrum IPS observation of 3C48 using all Superterp stations***

# LOFAR as an SKA Pathfinder

- **Instrumentation:**
  *LF antenna design, phased arrays, networking, digital processing*

- **Computation:**
  *Calibration, imaging, HPC processing, science pipelines, analysis algorithms*

- **Operations:**
  *Distributed system administration, dynamic scheduling, automated processing, multiple parallel observing programs*

- **Data Managment:**
  *Large-scale data storage, curation, distribution, in-archive processing, data-intensive analysis*

- **Community:**
  *International science collaborations, student training, potential SKA work force*

# LOFAR

The End