# LOFAR Survey of Spatially Resolved Ultra-Steep Spectrum Sources

## (High-redshift Radio Galaxies at Low Frequencies)

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Adam Deller, Javier Moldon, Raymond Oonk, George Miley, Huub Röttgering, + LB working group

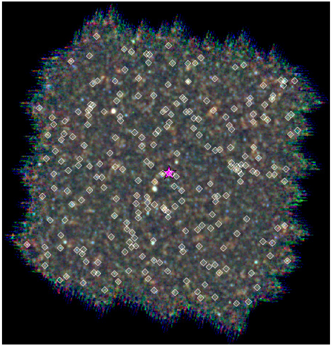
Sterrewacht Leiden

Leiden Observatory

The Many Facets of Extragalactic Radio Surveys
23 October 2015

# Why are HzRGs important?

protocluster
environments



False color Herschel/SPIRE, Rigby+ (2014)

radio galaxy
formation & evolution

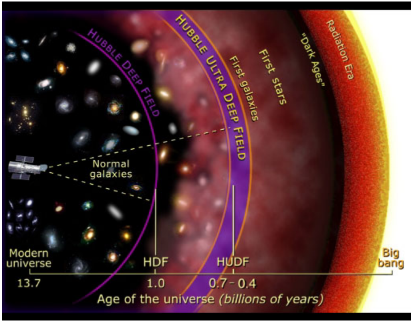
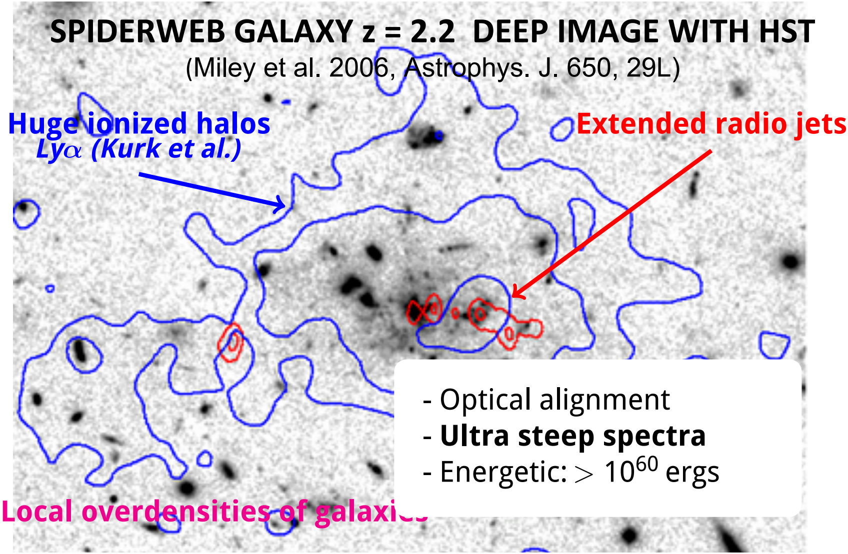



Image Credit: www.firstgalaxies.org

# HzRGs: Characteristics



# Open questions...

Selection from Miley & De Breuck (2008):

* What is the particle acceleration mechanism in the relativistic plasma and why do HzRGs have much steeper radio spectra than nearby radio sources?
* What are the detailed processes by which the radio jets interact with the gas and trigger starbursts and how important is jet-induced star formation for producing stars in the early Universe?
* What effect does feedback between the AGN and the galaxy have on the evolution of HzRGs and the general evolution of massive galaxies?
* What is the detailed mechanism by which the SMBHs produce quasars and luminous collimated jets?
* What is the size distribution of radio-selected protoclusters and what is is the topology of the cosmic web in the neighbourhood of the HzRGS?

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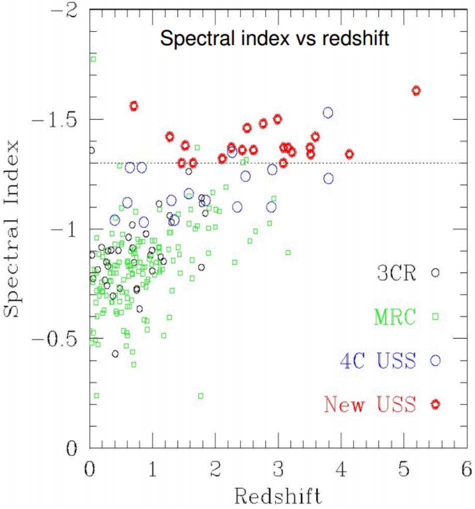
# Ultra Steep Spectra

## Why do high-$z$ sources have USS?

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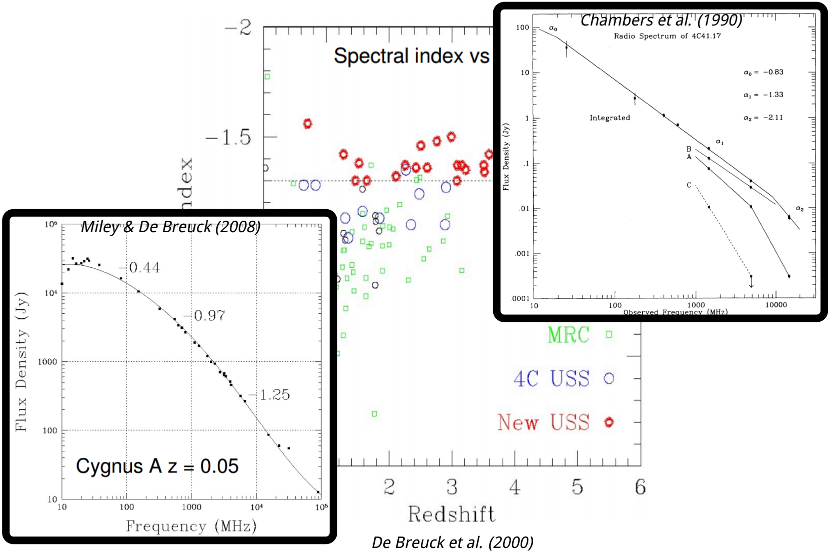


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# Ultra Steep Spectra (USS)

## Why do high-*z* sources have USS?

* Concavity at lower frequencies + K-correction
  - Higher redshift → probe higher rest frequencies

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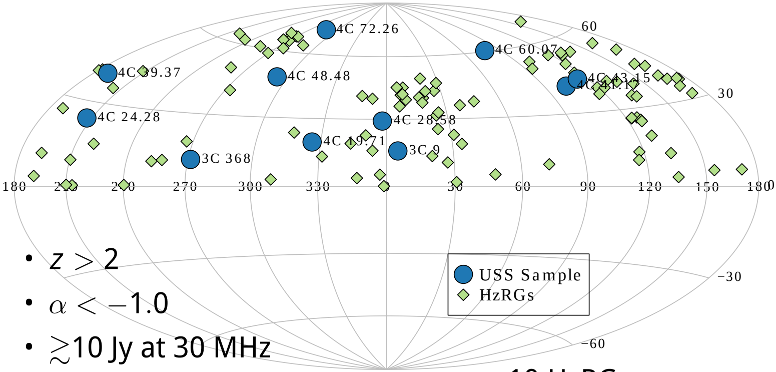
***To resolve: need low frequencies & high resolution***

# USS Survey




- $z > 2$
- $\alpha < -1.0$
- $\gtrsim$10 Jy at 30 MHz
- LAS $> 5''$

10 HzRGs
+ 1 low-z analog

# USS Survey: Goals

Low resolution Imaging

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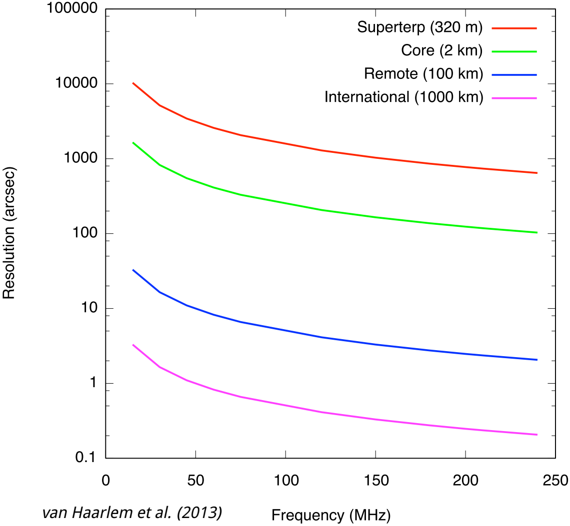
3. Search for carbon radio recombination lines
   - Probe of cold neutral medium

# USS Survey: Instruments

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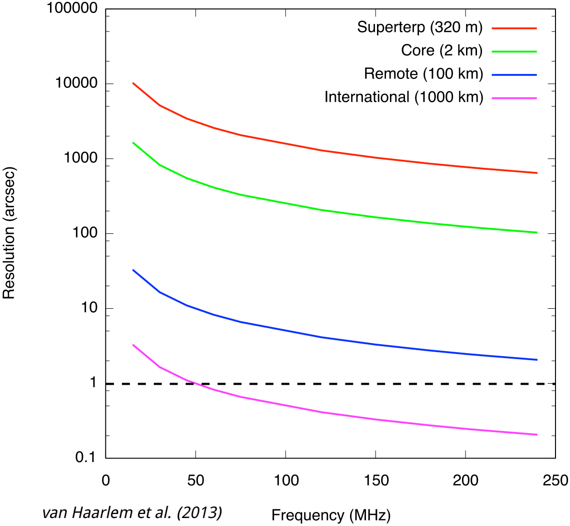


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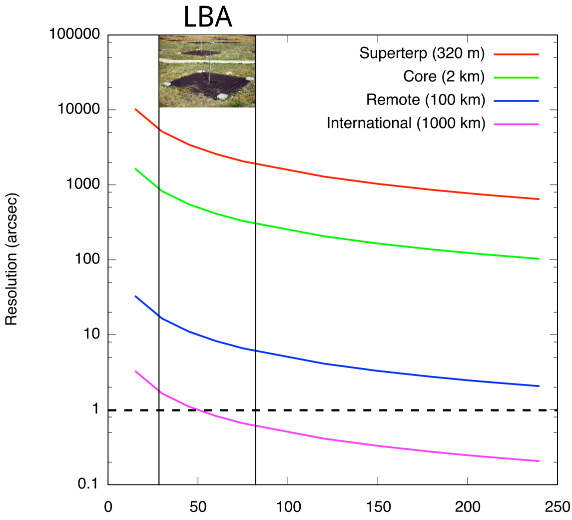


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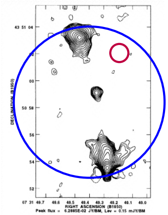

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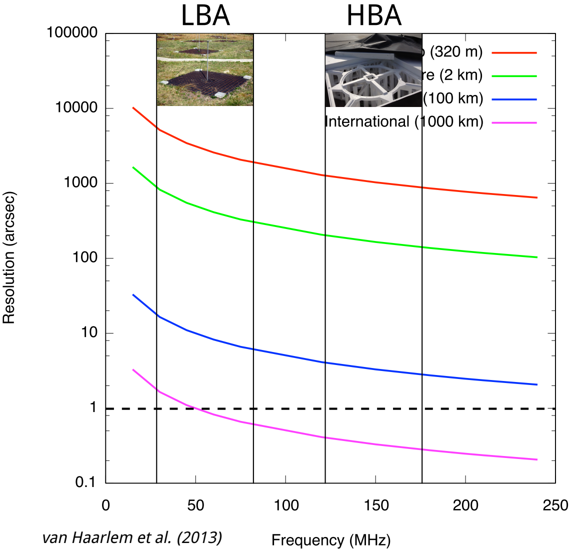


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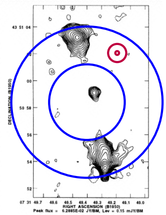

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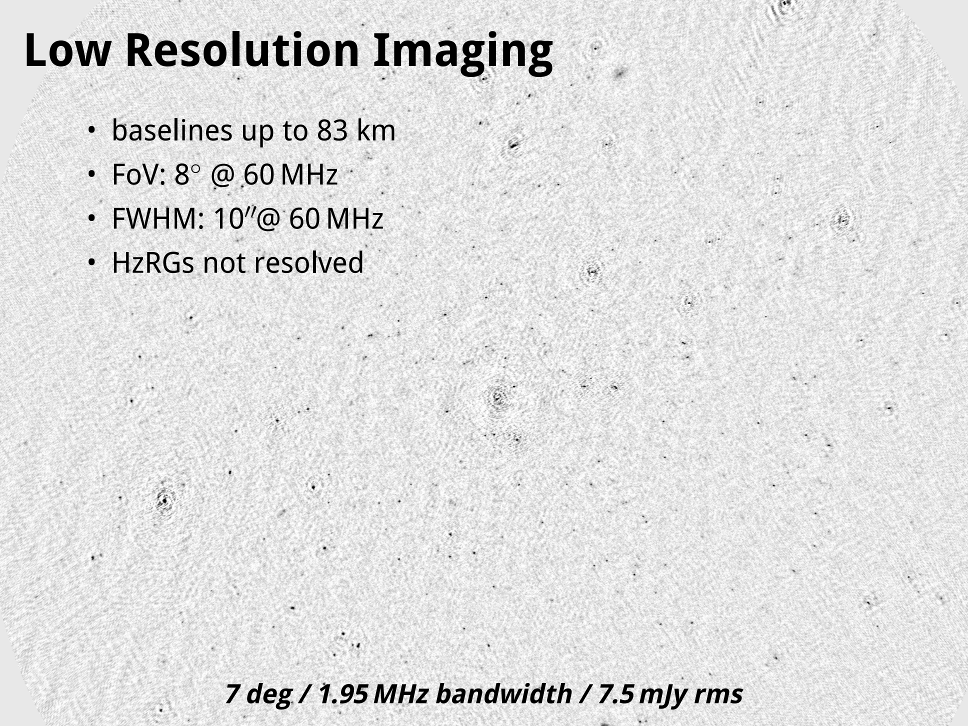
# Low Resolution Imaging

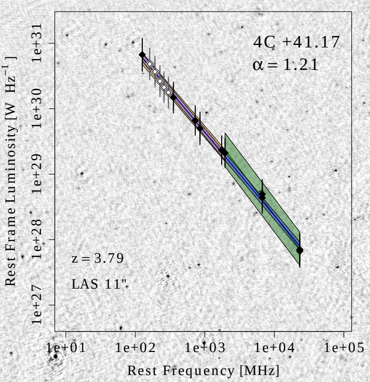
- baselines up to 83 km
- FoV: $8^\circ$ @ 60 MHz
- FWHM: $10''$@ 60 MHz
- HzRGs not resolved

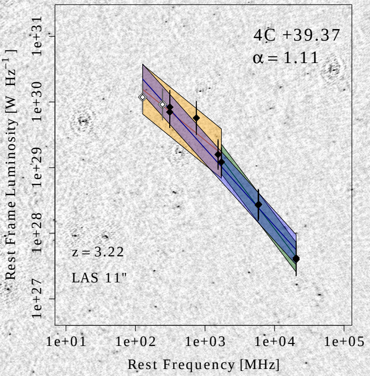


***7 deg / 1.95 MHz bandwidth / 7.5 mJy rms***

# Low Resolution Imaging

## Preliminary Results




Some ultra-steep spectra remain ultra steep. Others may be starting to turn over. Can spatially resolved images help solve this?

# High Resolution Imaging

What are some of the issues?

| | |
|---|---|
| **Sensitivity** | LBA has poor signal to noise |
| **Clocks** | All stations are connected, only CS are on the same clock |
| **Correlator Model** | Baselines up to 1300 km lead to geometric errors/delays |
| **Ionosphere** | Can be wildly varying, larger differential impact on long baselines |
| **Calibrators** | Need compact, bright sources at low-$\nu$ ... very few known |

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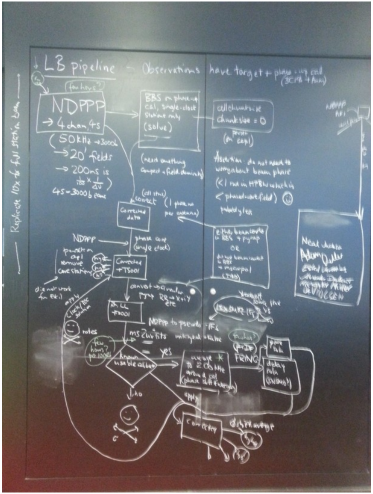
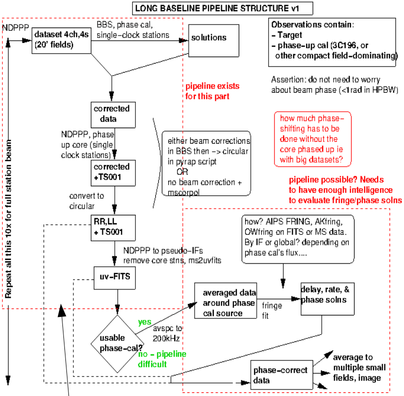
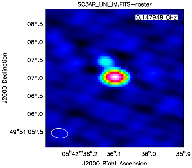
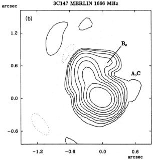
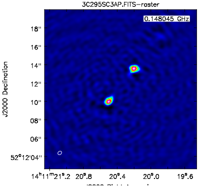
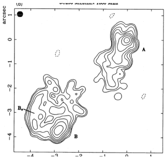


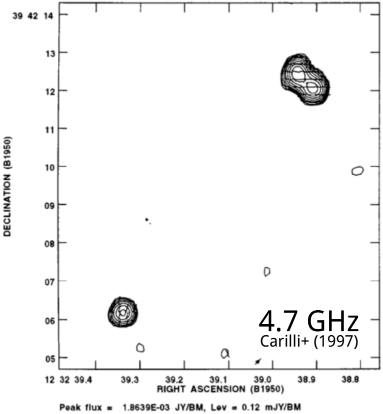

Now in official pipeline

# High Resolution Imaging: HBA

| | 145 MHz<br>LOFAR HBA | 1.6 GHz<br>MERLIN<br>Akujor et al. (1990) |
|---|---|---|
| 3C 147 |  |  |
| 3C 295 |  |  |

# High Resolution Imaging: HBA

4C +39.37



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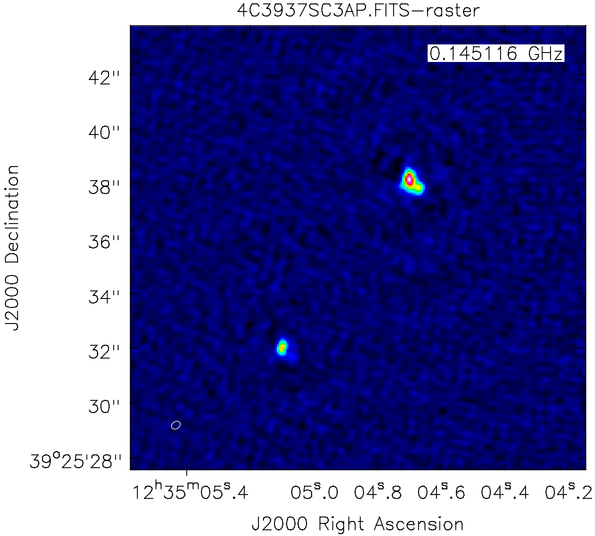

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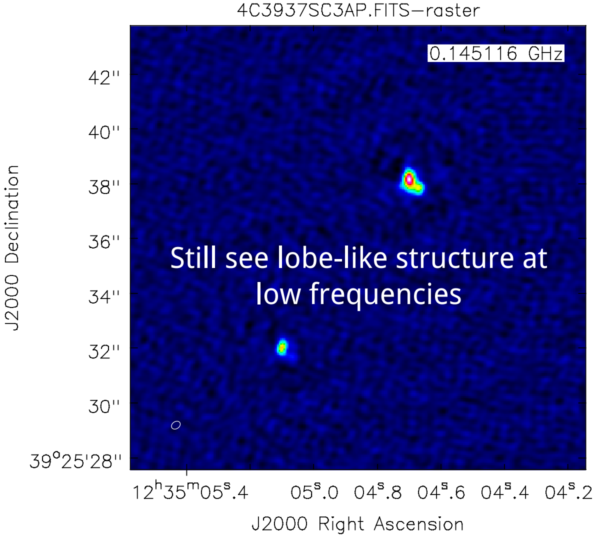

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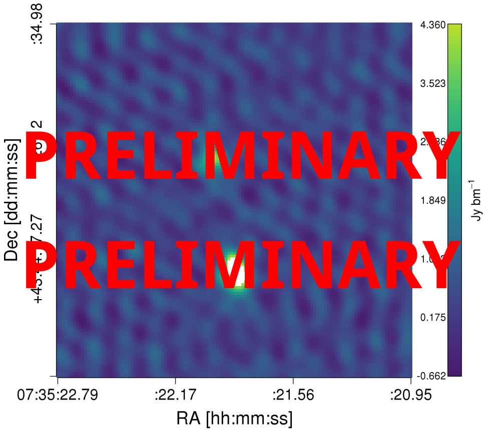


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rms = 150 mJy bm$^{-1}$

4.25 hr

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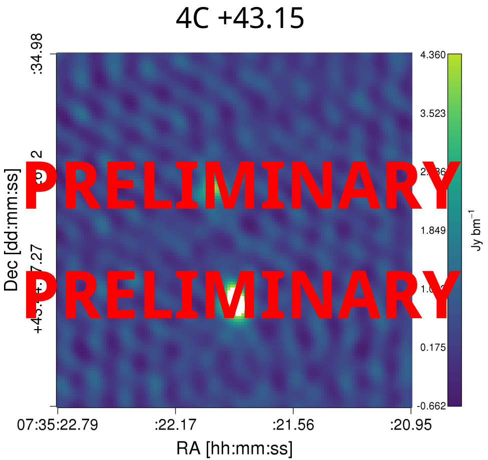


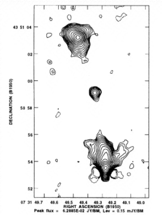

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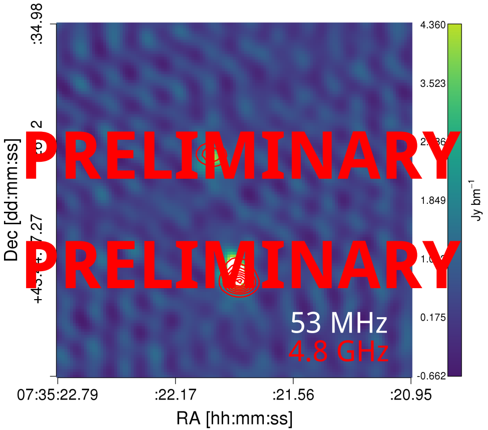


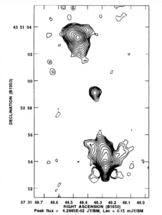


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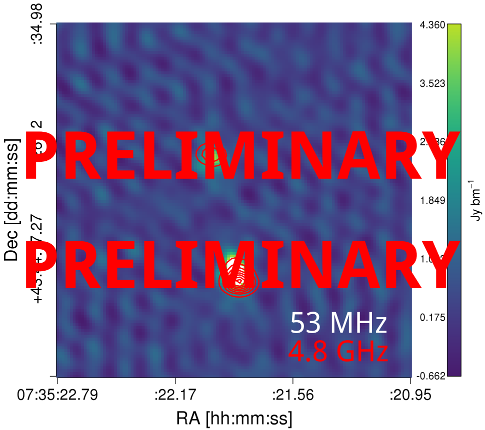


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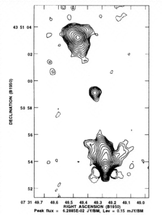

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First LBA image using full International LOFAR!

# Summary

High resolution imaging at low-$\nu$ is possible!

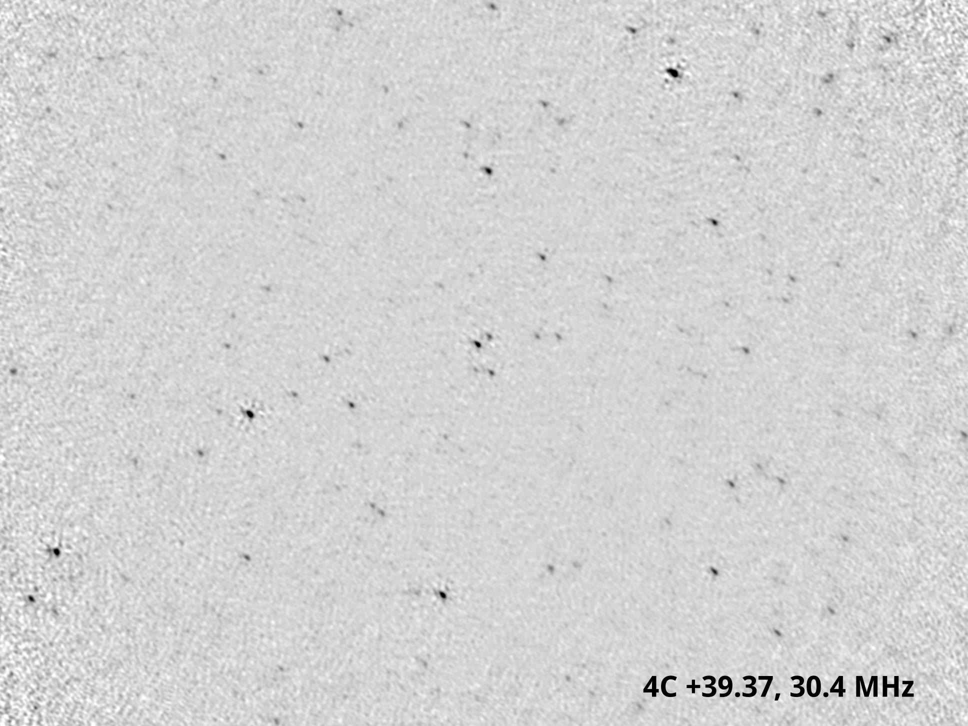
Low Frequency observations are revealing:

1. HzRG integrated spectra show variety
2. Spatial distribution is similar to higher frequencies

Future work:

- Calibration of intermediate baselines
- Tie together flux scale of longest & shortest baselines

Processing rest of survey ... stay tuned!


4C +39.37, 30.4 MHz