Spatially Resolved Studies of High-z Radio Galaxies (HzRGs) with LOFAR

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Sterrewacht Leiden

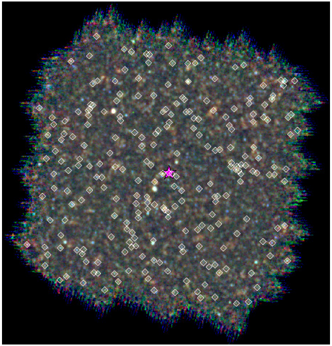
Leiden Observatory

LOFAR Community Science Workshop 2015

3 June 2015

Why are HzRGs important?

protocluster
environments



False color Herschel/SPIRE, Rigby+ (2014)

radio galaxy
formation & evolution

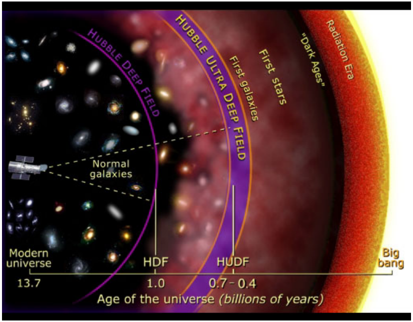
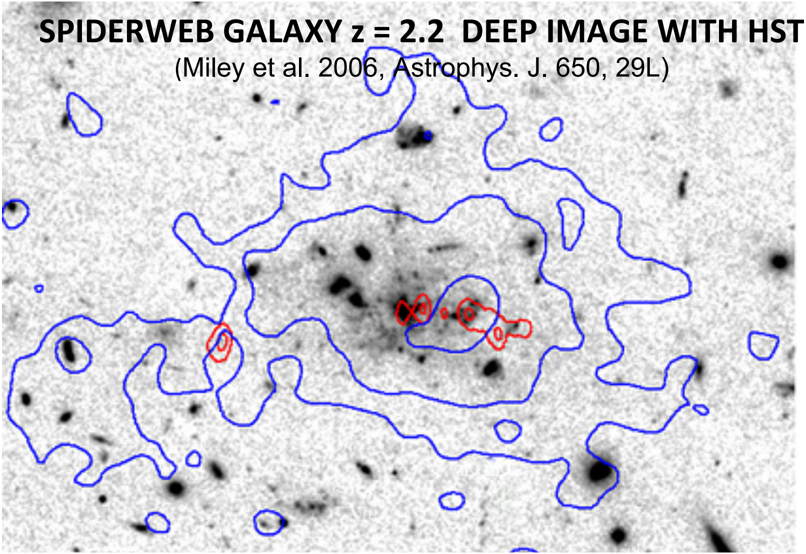


Image Credit: www.firstgalaxies.org

HzRGs: Characteristics



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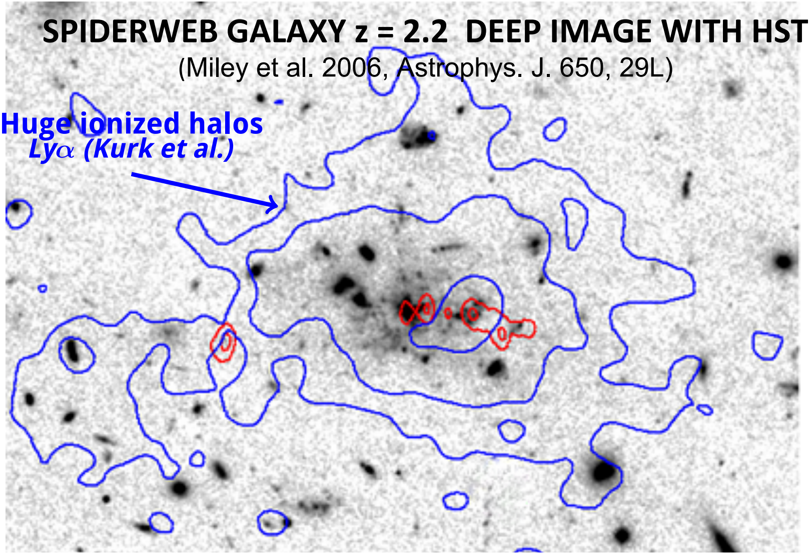

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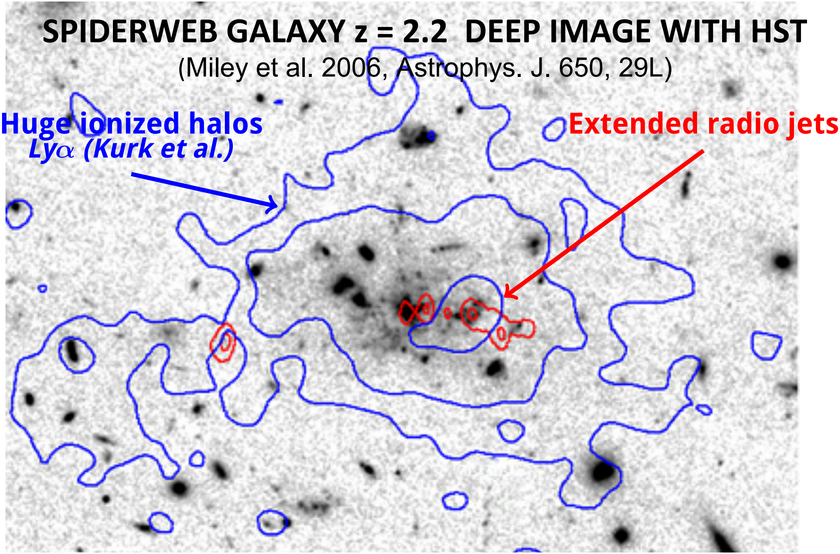

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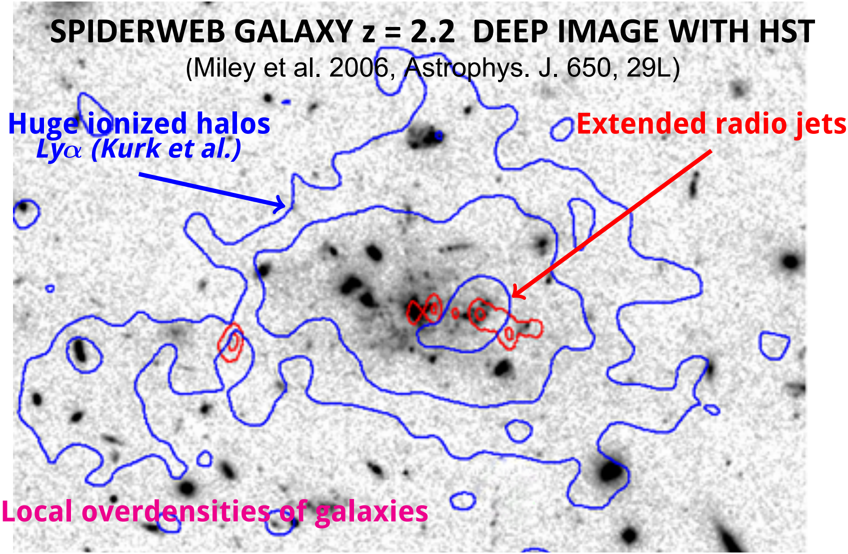

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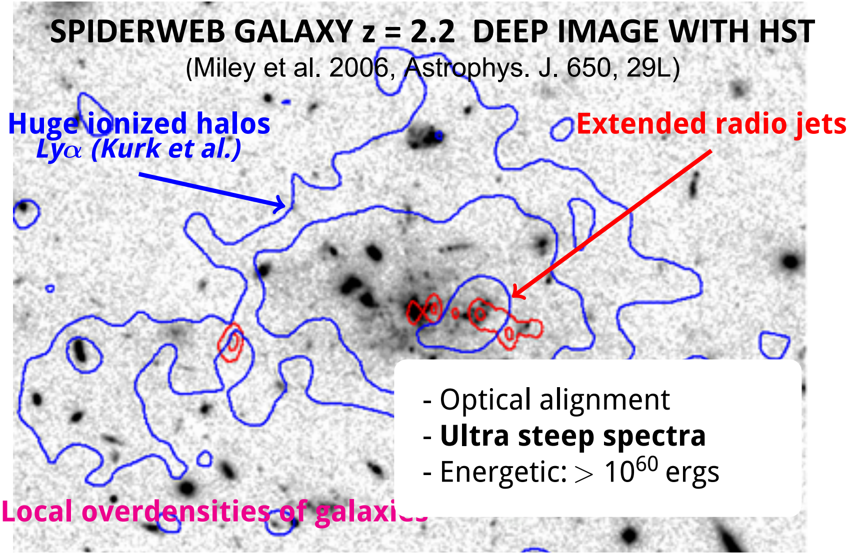

- Optical alignment
- **Ultra steep spectra**
- Energetic: $> 10^{60}$ ergs

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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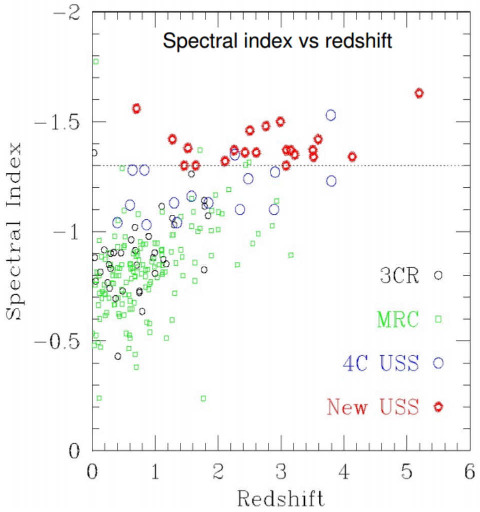
Ultra Steep Spectra (USS)

Why do high-*z* sources have USS?



De Breuck et al. (2000)

Ultra Steep Spectra (USS)

Why do high-*z* sources have USS?

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

    Afonso et al. (2011), Miley & De Breuck (2008), Klamer et al. (2006), Athreya et al. (1998)

* Ambient density
  - Denser environment → 1st-order Fermi acceleration

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* Luminosity–α relation + observational flux limits
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External: environmental, observational

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Internal: particle acceleration processes

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External: environmental, observational

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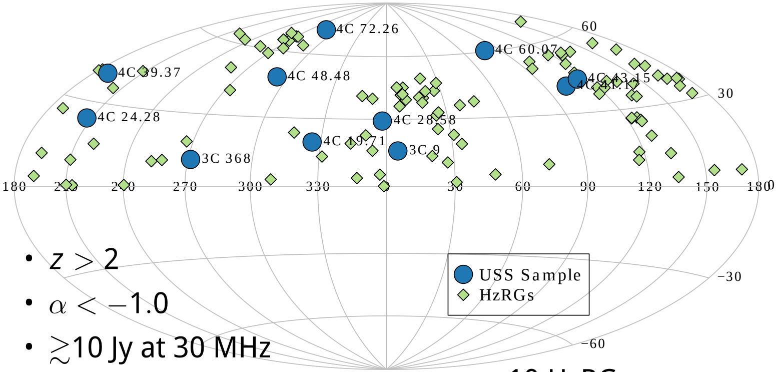
Internal: particle acceleration processes

To resolve: need <u>low frequencies</u> & <u>high resolution</u>

USS Survey

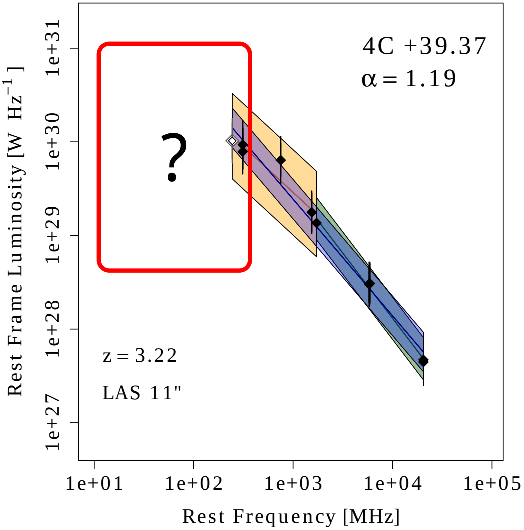


- $z > 2$
- $\alpha < -1.0$
- $\gtrsim$10 Jy at 30 MHz
- LAS $> 5''$

10 HzRGs
+ 1 low-z analog

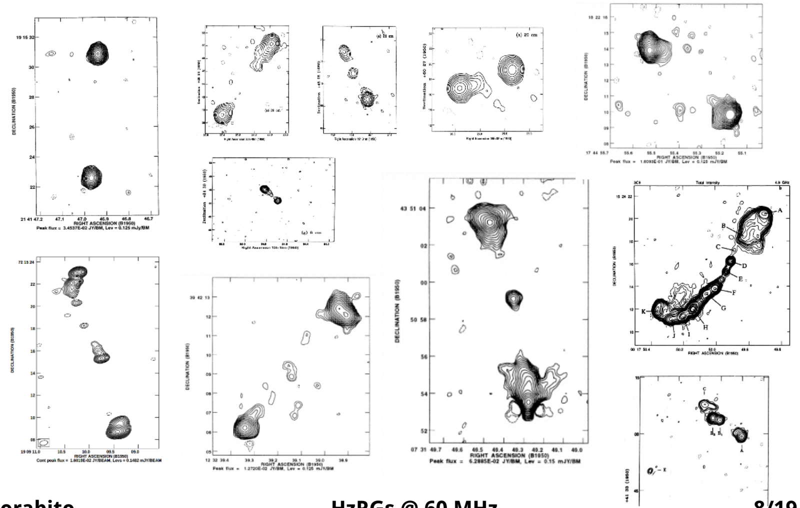
Using the LBA

Allows us to probe most relevant rest frequencies



Using the Long Baselines

HzRGs are unresolved with Dutch Array
Resolved with International Array



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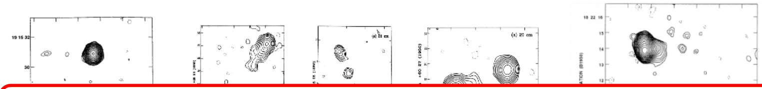
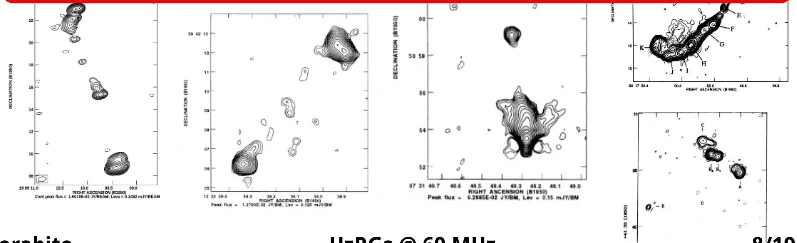


What is the spatially resolved picture?

LBA can achieve $\theta = 1''$ at 60 MHz
Using the full international array



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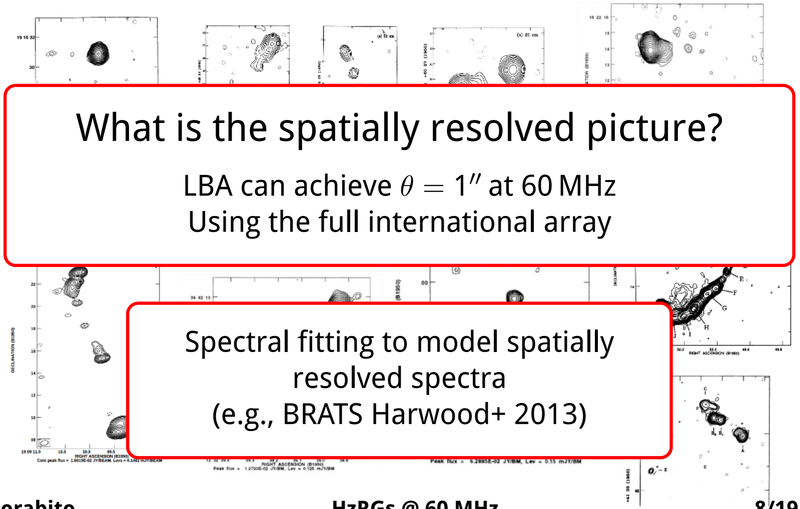

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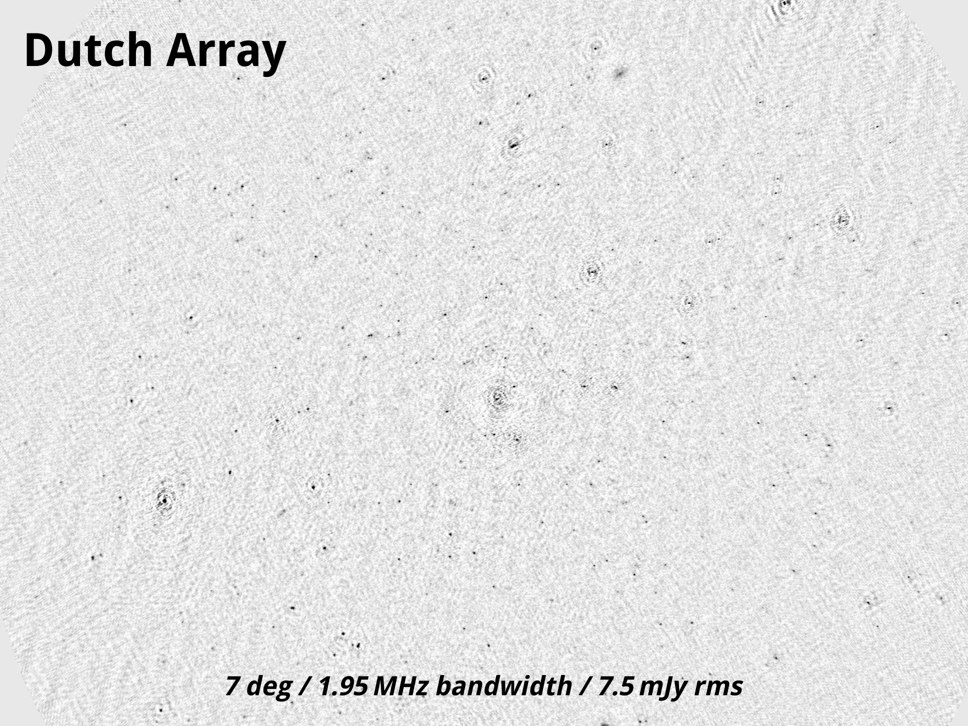
Spectral fitting to model spatially resolved spectra
(e.g., BRATS Harwood+ 2013)

First: Calibrate Dutch Array

Direction independent calibration

1. Calibrator source (simultaneous beam)
   - Inspect amplitude solutions, smooth if necessary
2. Transfer amplitude + phase to target field
   - Avoids problems with solving for clock separately
3. Phase-only calibration against GSM
   - Include at least 5° around phase center
4. Further processing: Self-calibration
   - 3 phase only, 1 amp+phase calibration
   - Subtraction of sources in different directions is possible

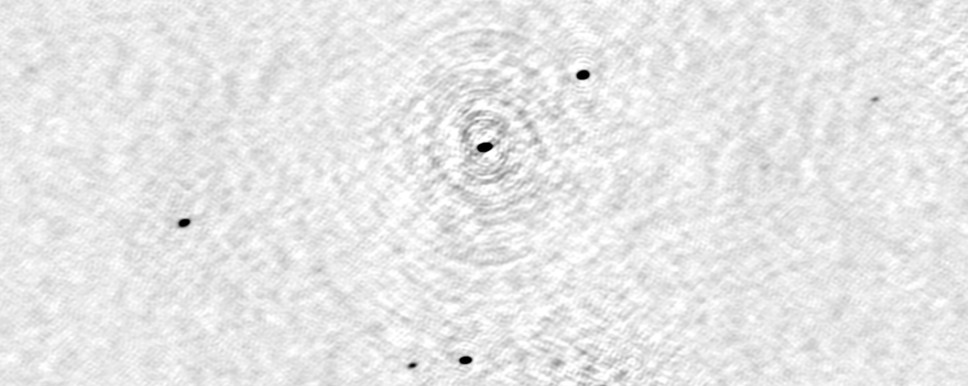
Dutch Array



7 deg / 1.95 MHz bandwidth / 7.5 mJy rms

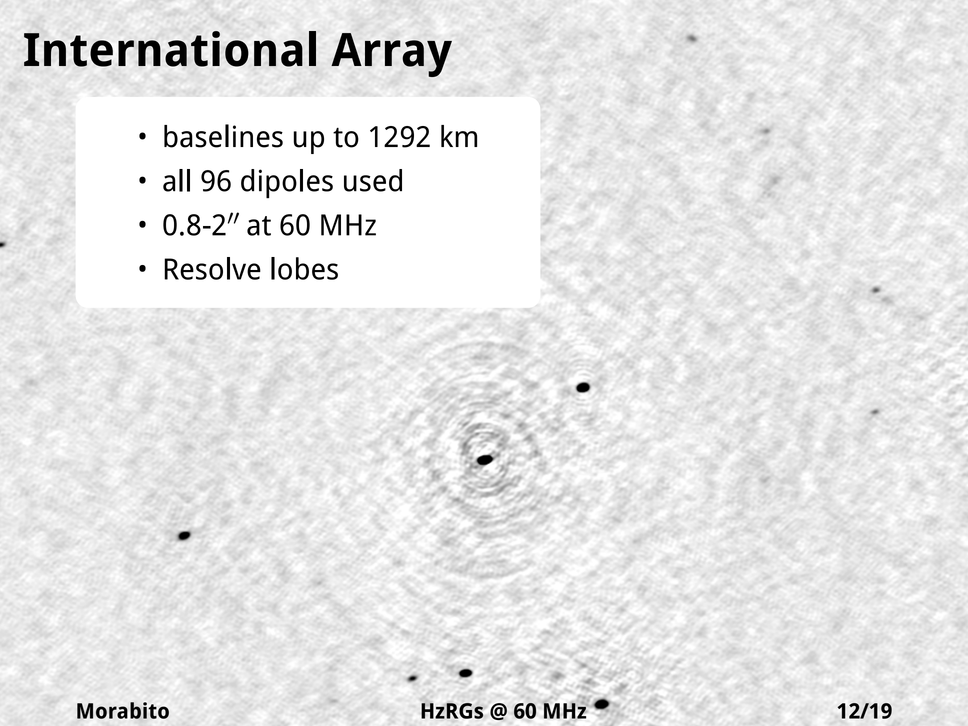
Dutch Array

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



International Array

- baselines up to 1292 km
- all 96 dipoles used
- 0.8-2″ at 60 MHz
- Resolve lobes



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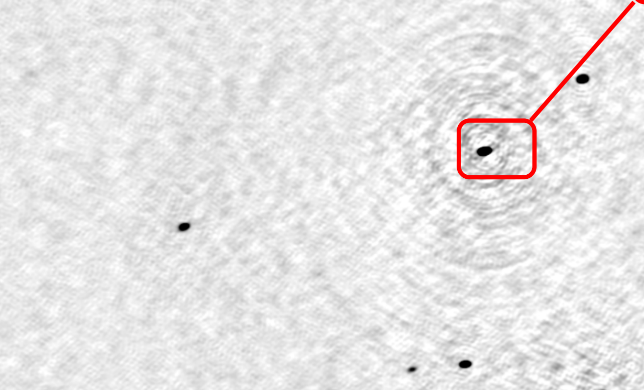
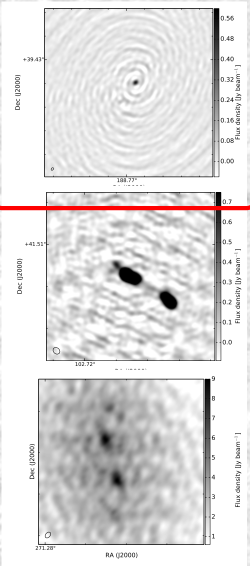




LBA Long Baseline Issues

Issue 1: Amplitude calib. of International Stations

Need to know what standard flux calibrators look like at high resolution, low frequencies

Issue 2: Degeneracy in fringe fitting

Need better starting models to work out why self-calibration isn't helping

Better calibration will also help

Fortunately, the HBA can give a good starting point

* Starting model closer in frequency
* Efficient searching for nearby calibrator sources

Help from the HBA

Commissioning project: 4C +39.37

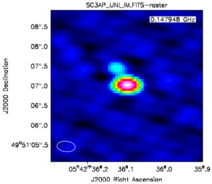
- 8.75 hr observation
- 120-268 MHz
- Flux calibrator: 3C 147
- Simultaneous beams: 3C 295 (LBA cal), 4C +39.37
    - Both targets have suitable nearby check sources

Two Goals:

* A high-resolution model of 3C 295 for use as an amplitude calibrator
* A high resolution model of the target 4C +39.37

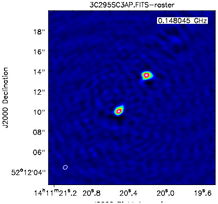
Help from the HBA

3C 147



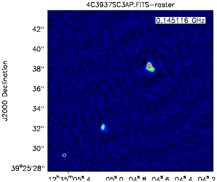
amplitude
calibrator

3C 295



LBA calibrator

4C +39.37



HzRG

Preliminary HBA results

Fringe fitting: NOT model dependent!
Start with point source model → able to self-calibrate!

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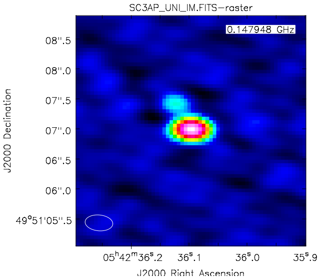
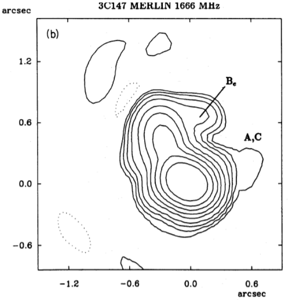


amplitude calibrator



1.6 GHz, Akujor+ (1990)

(LOFAR images made with uvrange $\geq 60k\lambda$)

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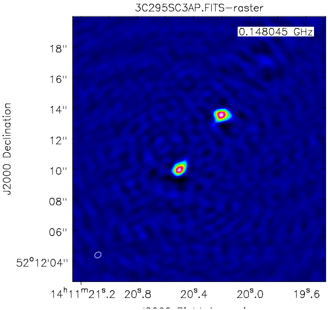
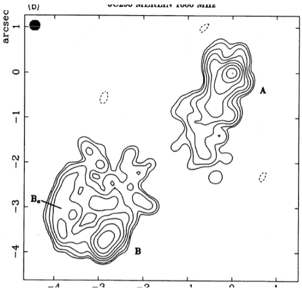
3C 295



LBA calibrator



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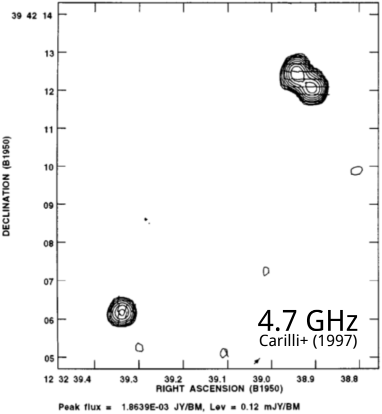
Preliminary HBA Results

4C +39.37



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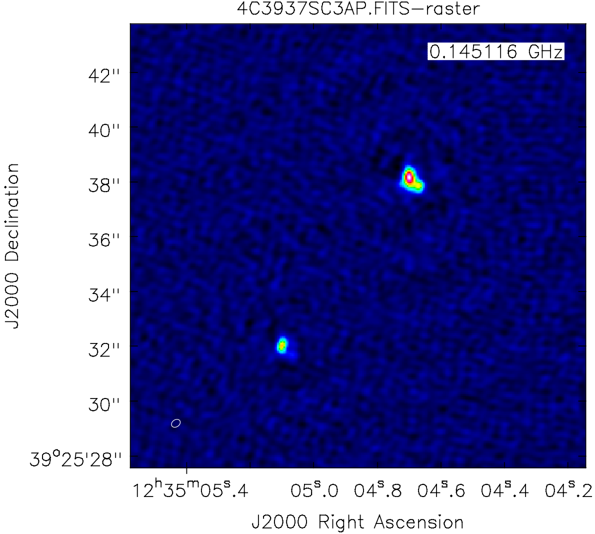

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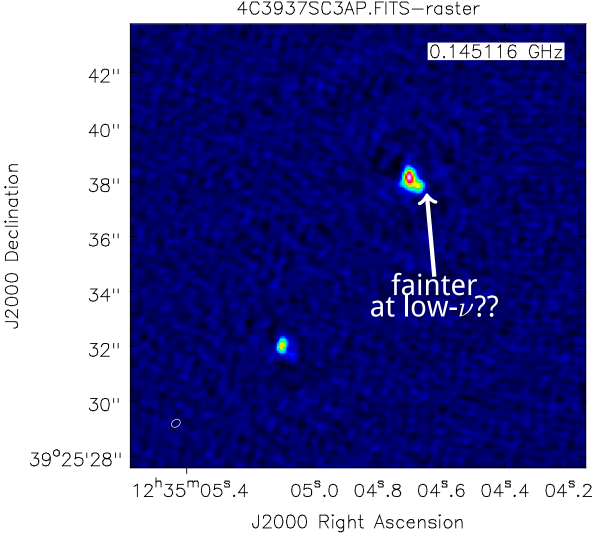
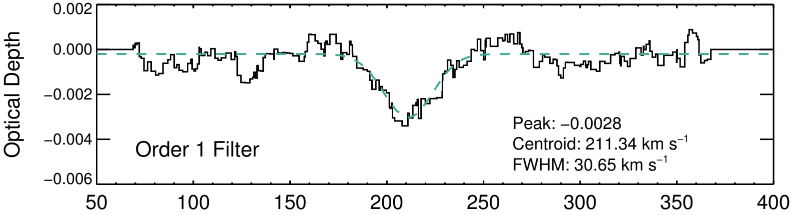


As a bonus!

HzRGs are known to have gas and dust reservoirs, and observing them with LOFAR allows us to search for carbon radio recombination lines that trace the cold, diffuse medium

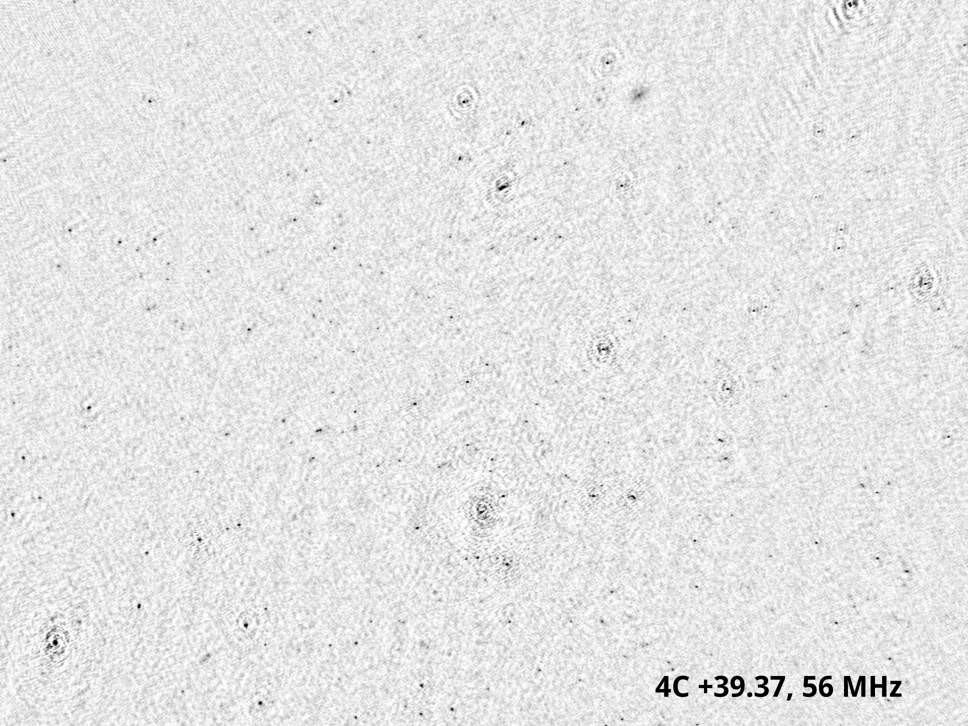


First extragalactic detection! M82, Morabito et al. 2014

Are HzRGS next?

Summary

- LBA can produce deep, wide images
- Directional calibration is possible
  - dependent on ionosphere?
- HzRG integrated spectra remain USS
- Preliminary HBA data is promising!
  - Already sorting out low-ν morphology

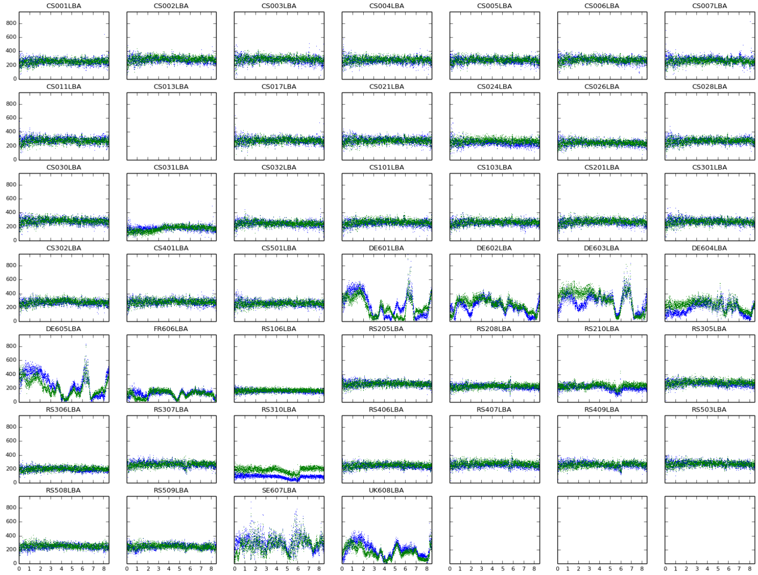

4C +39.37, 56 MHz

USS Survey

- Northern hemisphere, $z > 2$
- Ultra steep spectra, $\alpha < -1.0$
- Brighter than 10 Jy at 30 MHz
- LAS $> 5''$, simple morphology

Source	z	S_{178} [Jy]	α_{178}^{1400}	S_{30} [Jy]	LAS
4C 41.17	3.792	2.7	-1.12	19.84	$13''$
3C 9	2.02	19.4	-1.06	128.09	$9.6''$
3C 368*	1.131	15	-1.2	127.07	$11''$
4C 39.37	3.221	5.3	-1.47	72.52	$8''$
4C 60.07	3.791	3.1	-1.45	40.72	$9''$
4C 72.26	3.537	3.2	-1.15	24.91	$15.4''$
4C 28.58	2.905	2.9	-1.17	23.11	$14.5''$
4C 24.28	2.889	4.8	-1.05	30.87	$6''$
4C 43.15*	2.429	4.5	-0.95	20.61	$10.8''$
4C 48.48	2.343	3	-1.02	18.44	$14''$
4C 19.71	3.592	2.5	-0.96	13.89	$8.9''$

A note on differential FR



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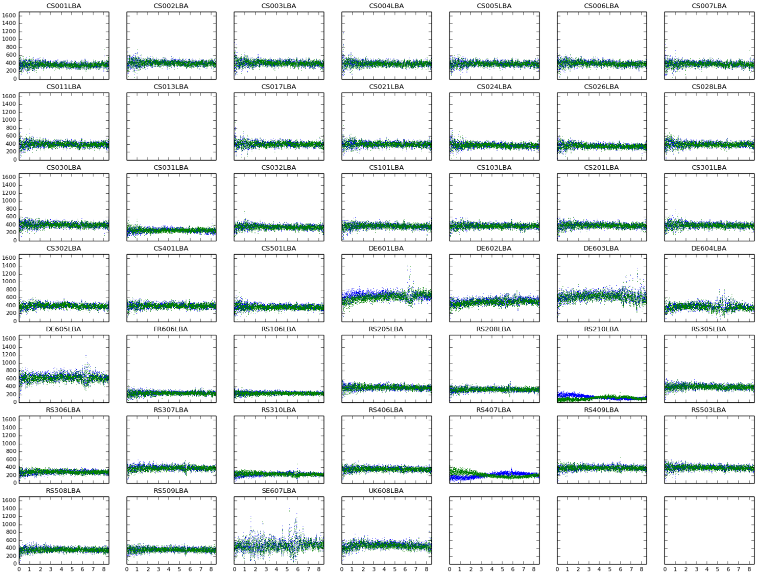

Delays

Table 4. Approximate delay contributions at 140 MHz to a 700 km baseline.

Effect	Delay	Timescale
Non-dispersive		
Correlator model error	~75 ns	24 h (periodic)
Station clocks	~20 ns	~20 min
Source position offset (1.5″)	~ 15 ns	–
Dispersive		
Slowly varying ionosphere	~300 ns	~h
Rapidly varying ionosphere	$\gtrsim$10 ns	~10 min
Differential ionosphere (source elevation 60 deg)	5 ns/deg sep.	–

Moldon et al. (2015)