LOFAR surveys of the radio sky: *probing shocks and magnetic fields in galaxy clusters*

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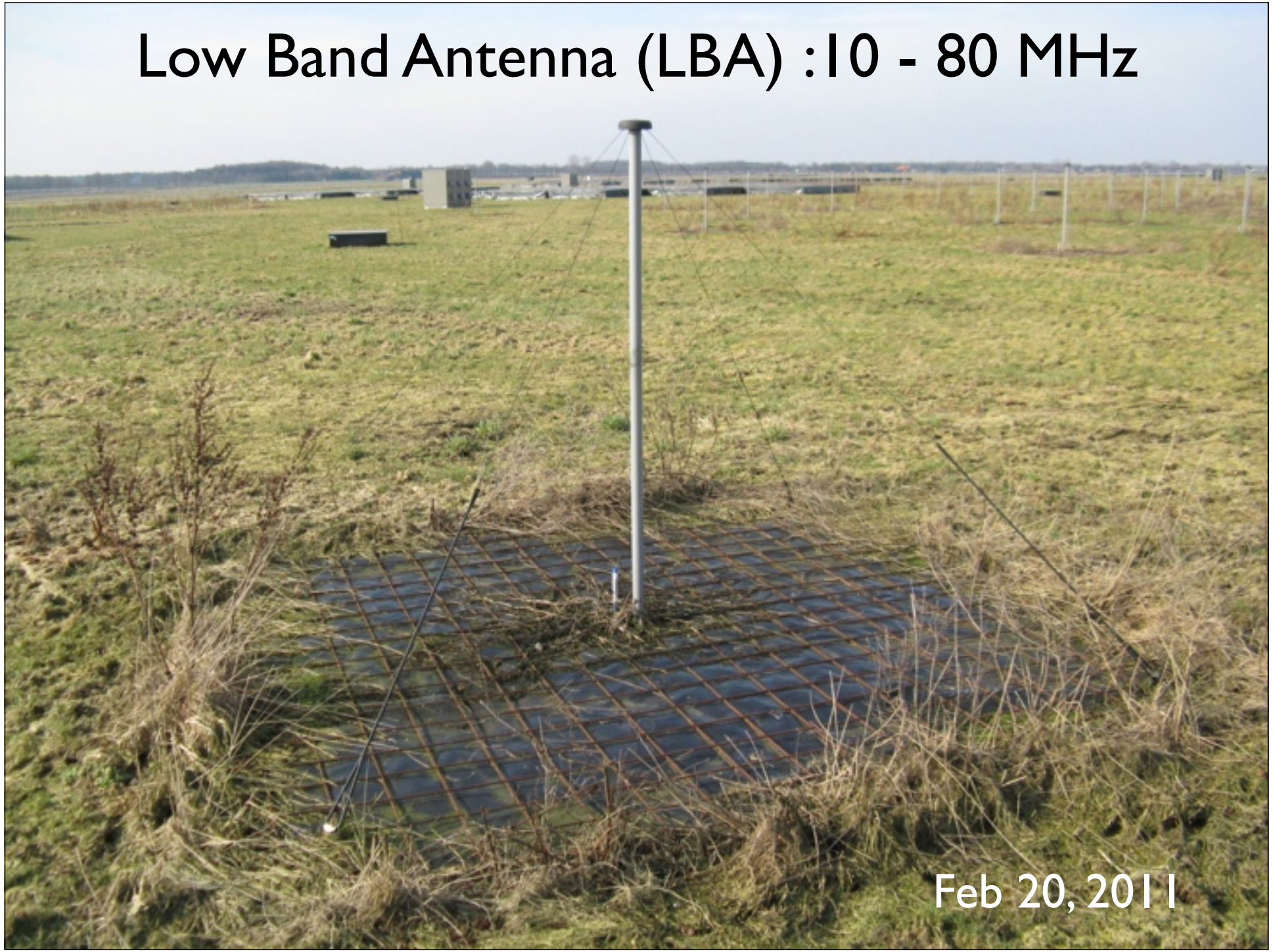
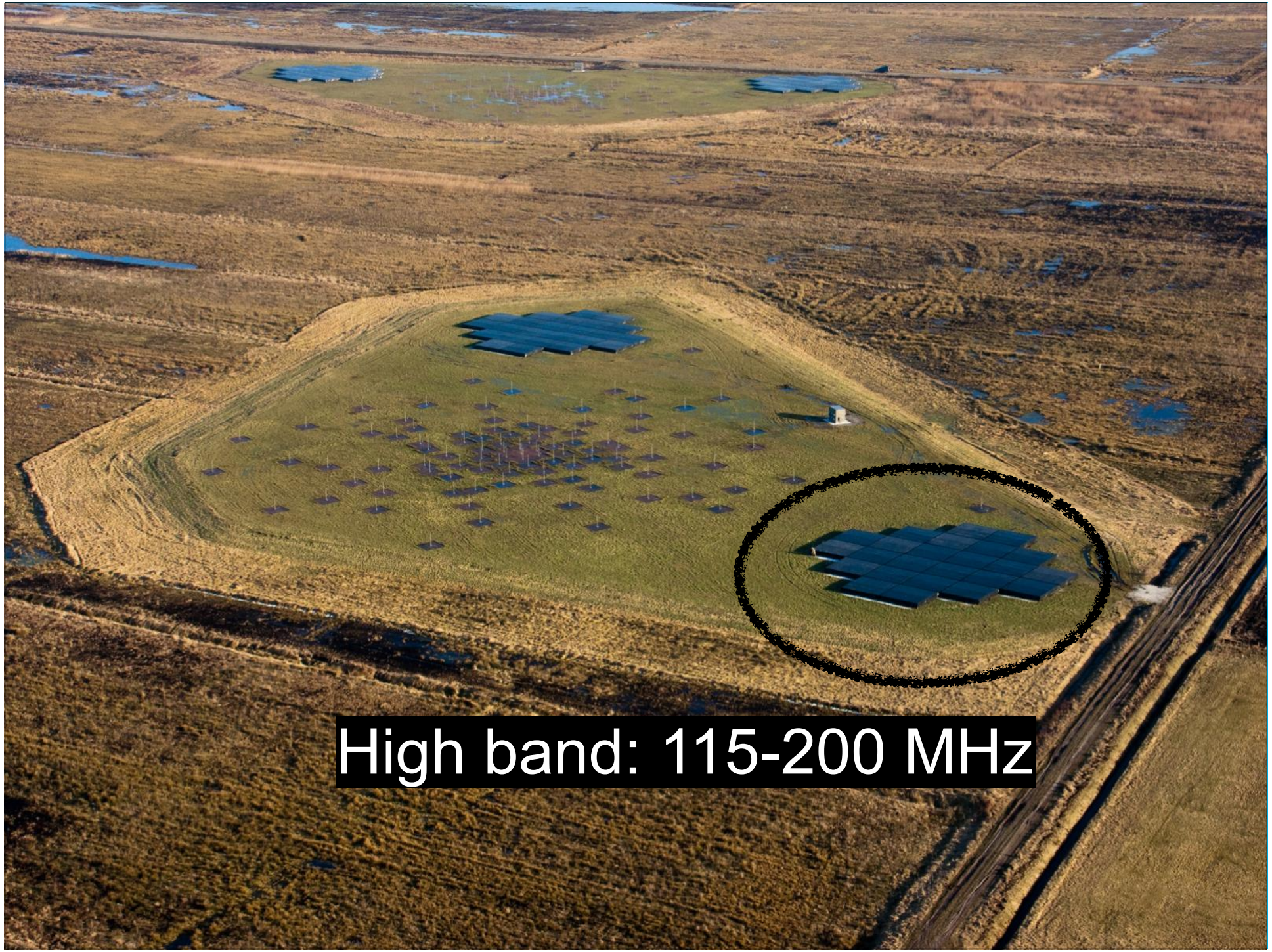
F. De Gasperin, C. Ferrari, S. van der Tol, J. van Zwieten, et al.

Overview

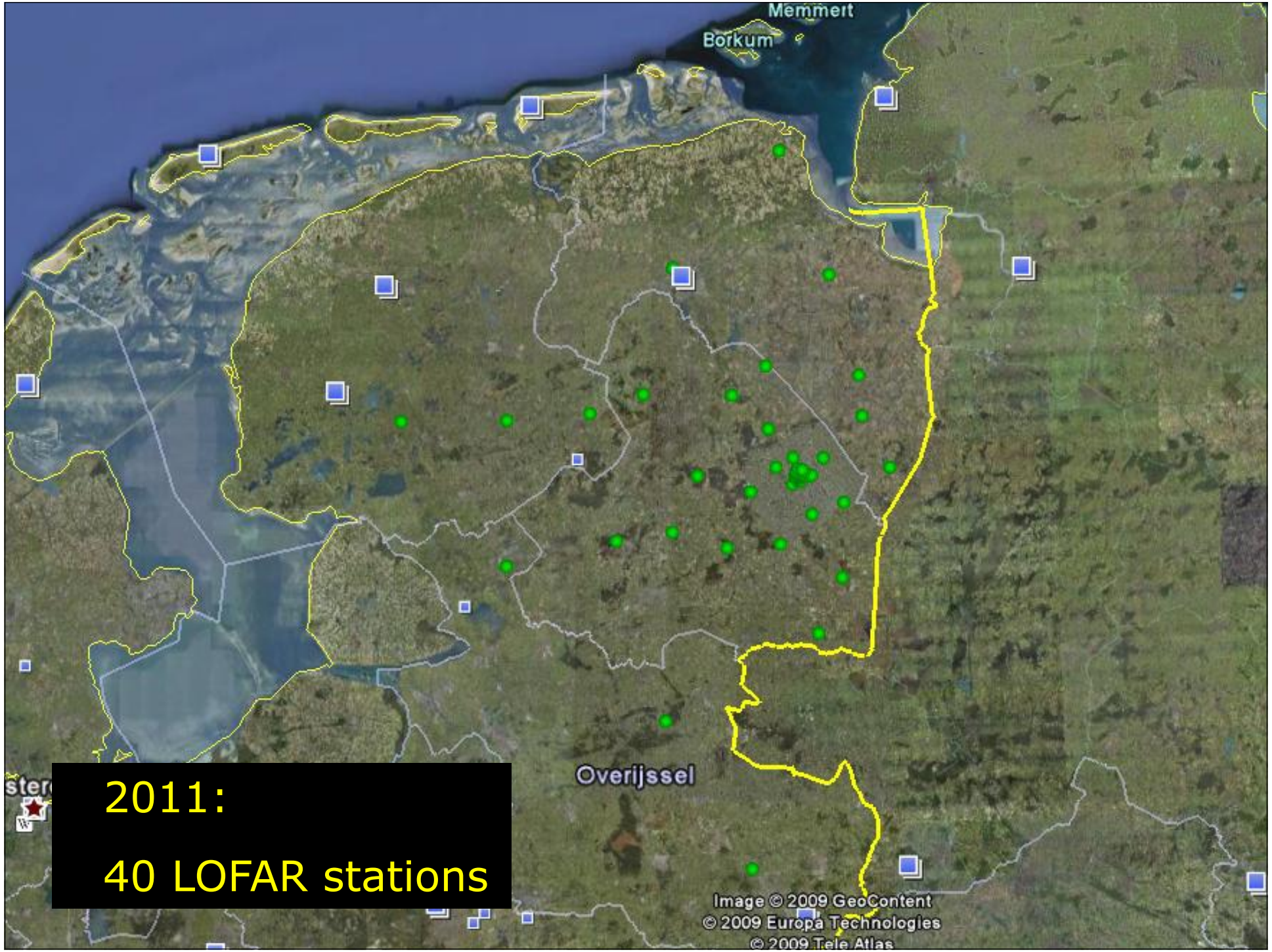
- LOFAR project
- LOFAR and WSRT surveys
- Relics and halos: an introduction
- ‘Sausage cluster’
- Recent LOFAR results on A2256
- The puzzle of the `Toothbrush relic’

Low Band Antenna (LBA) :10 - 80 MHz



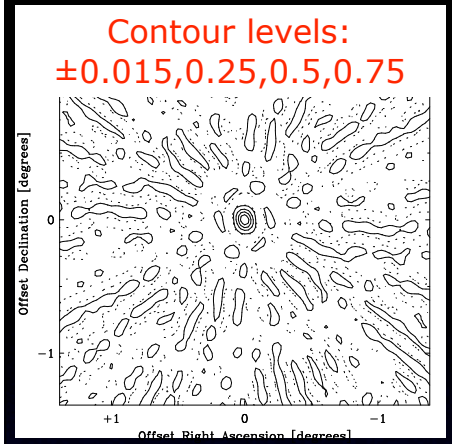

High band: 115-200 MHz

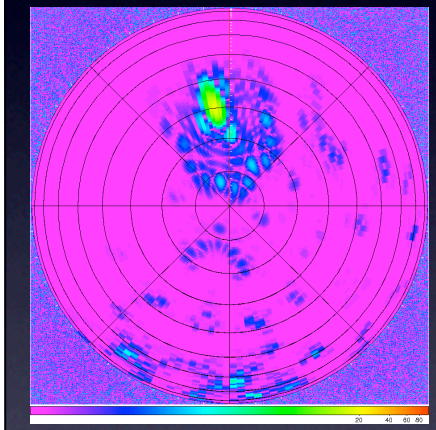

LOFAR Superterp
June 2010

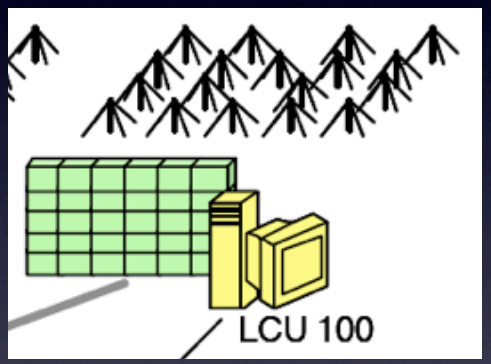

Memmert
Borkum
Overijssel
2011:
40 LOFAR stations
Image © 2009 GeoContent
© 2009 Europa Technologies
© 2009 Tele Atlas

LOFAR Stations Across Europe

Three Beams

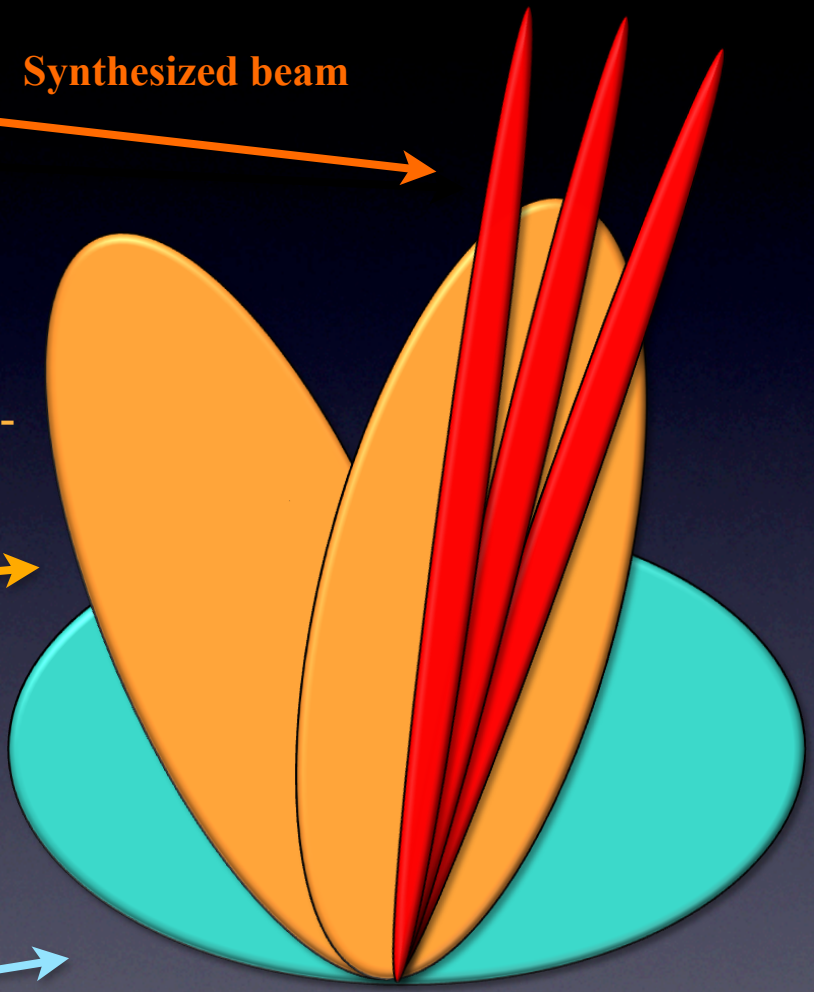


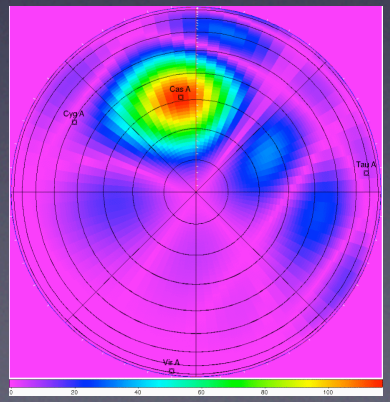




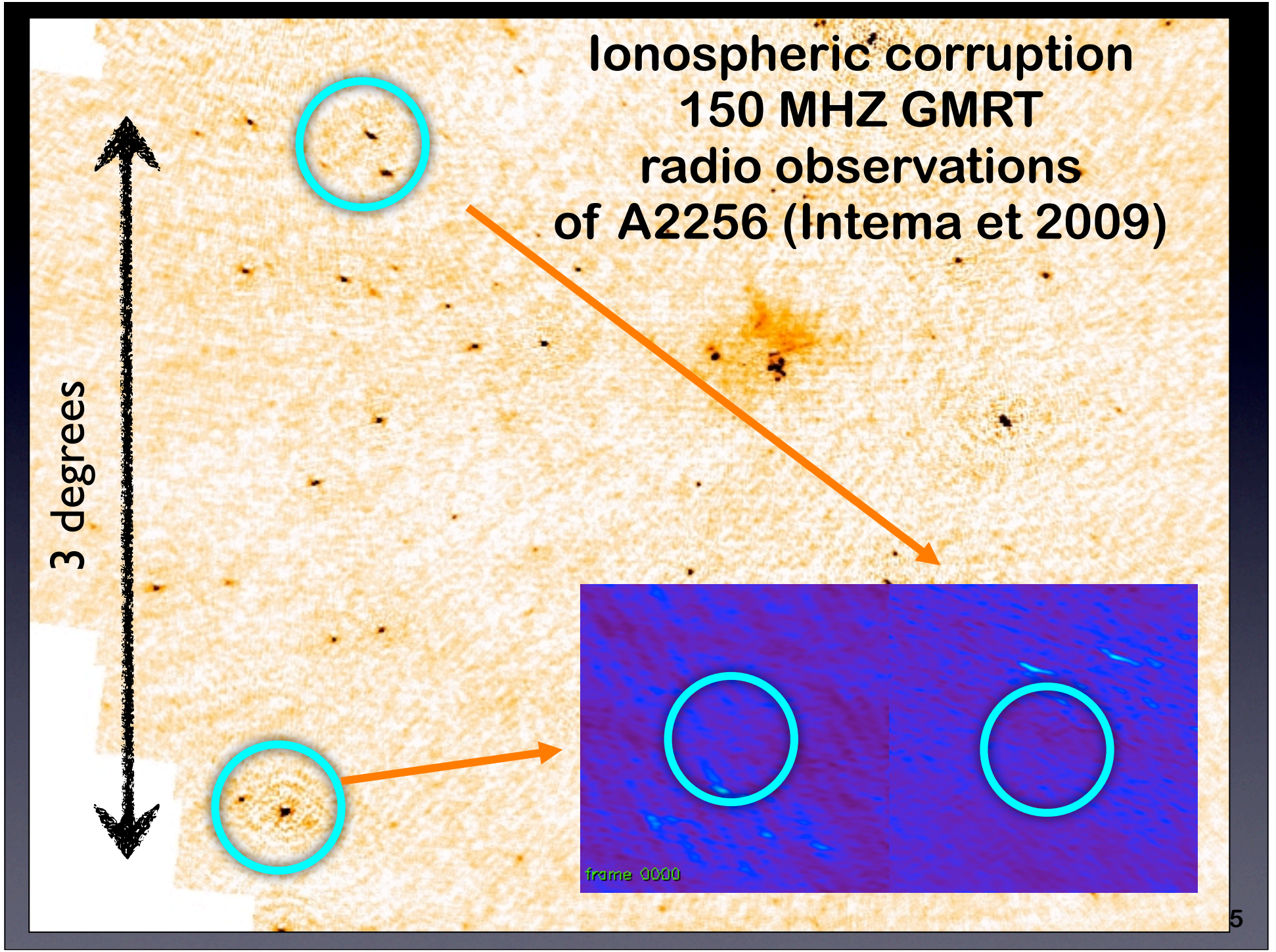
Station-
Beam

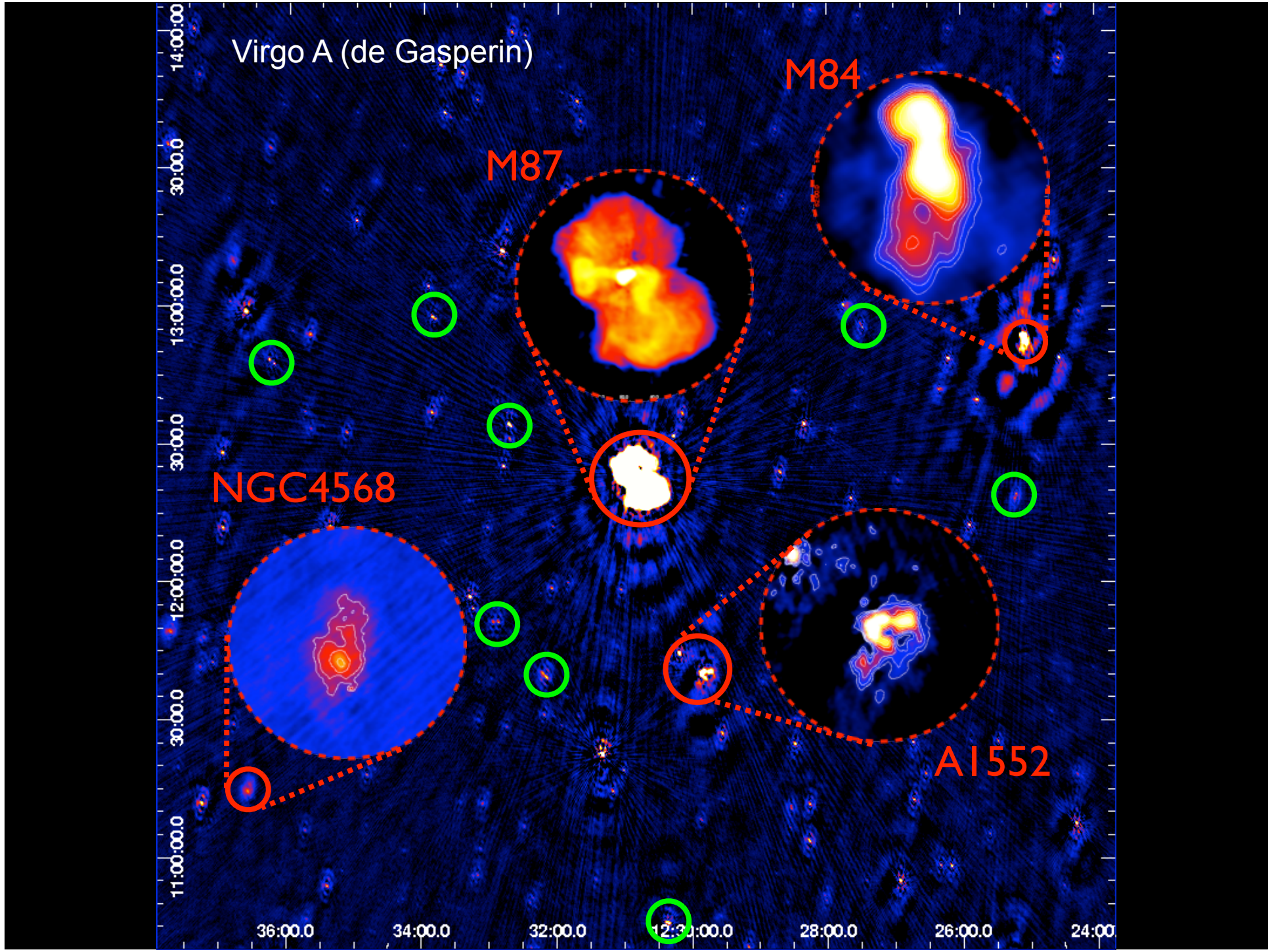
Synthesized beam



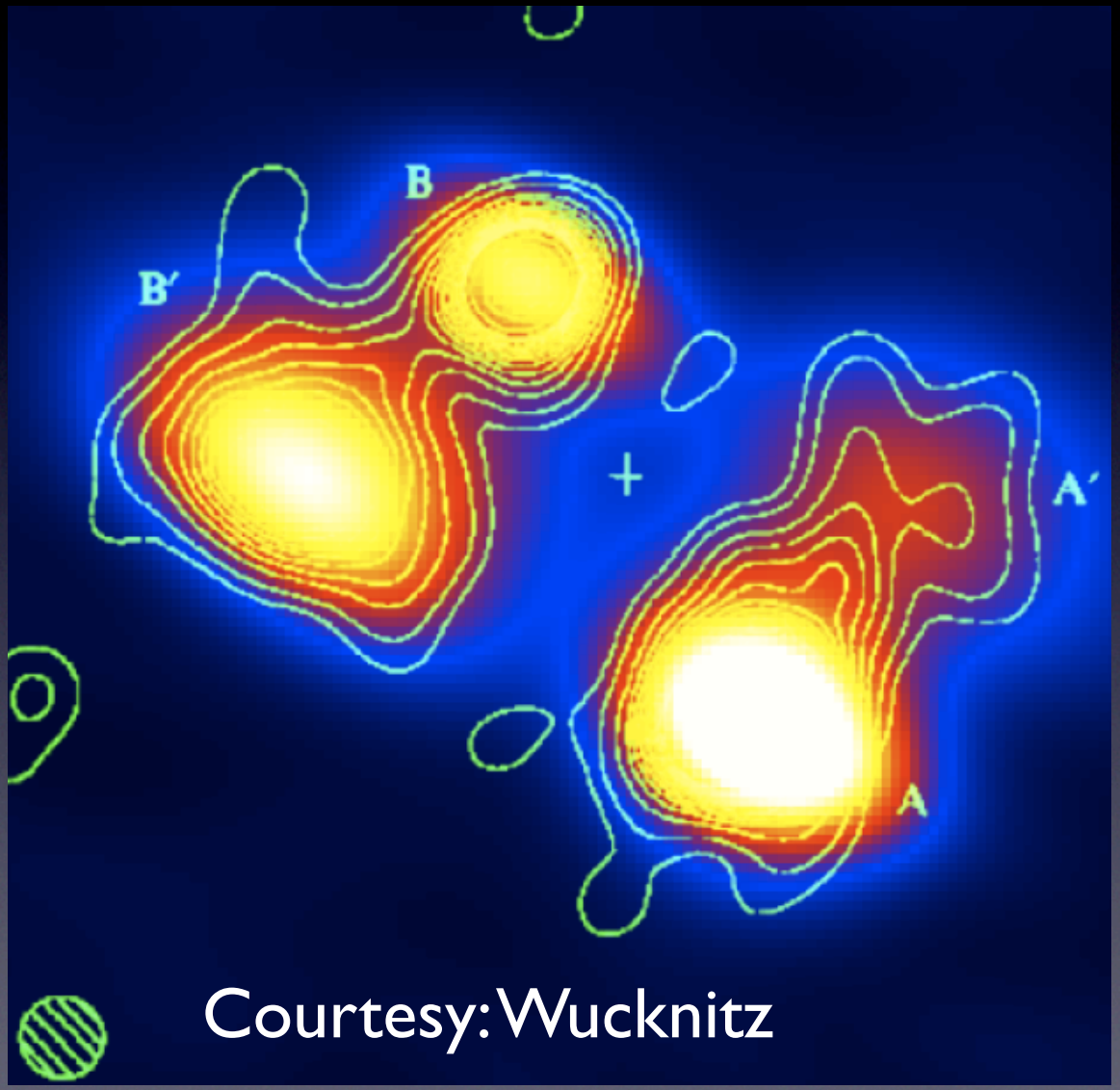


Antenna beam


Ionospheric corruption
150 MHZ GMRT
radio observations
of A2256 (Intema et 2009)
3 degrees
frame 0000


Virgo A (de Gasperin)
M84
M87
NGC4568
A1552
14:00:00
30:00.0
13:00:00.0
30:00.0
12:00:00.0
30:00.0
11:00:00.0
36:00.0
34:00.0
32:00.0
28:00.0
26:00.0
24:00

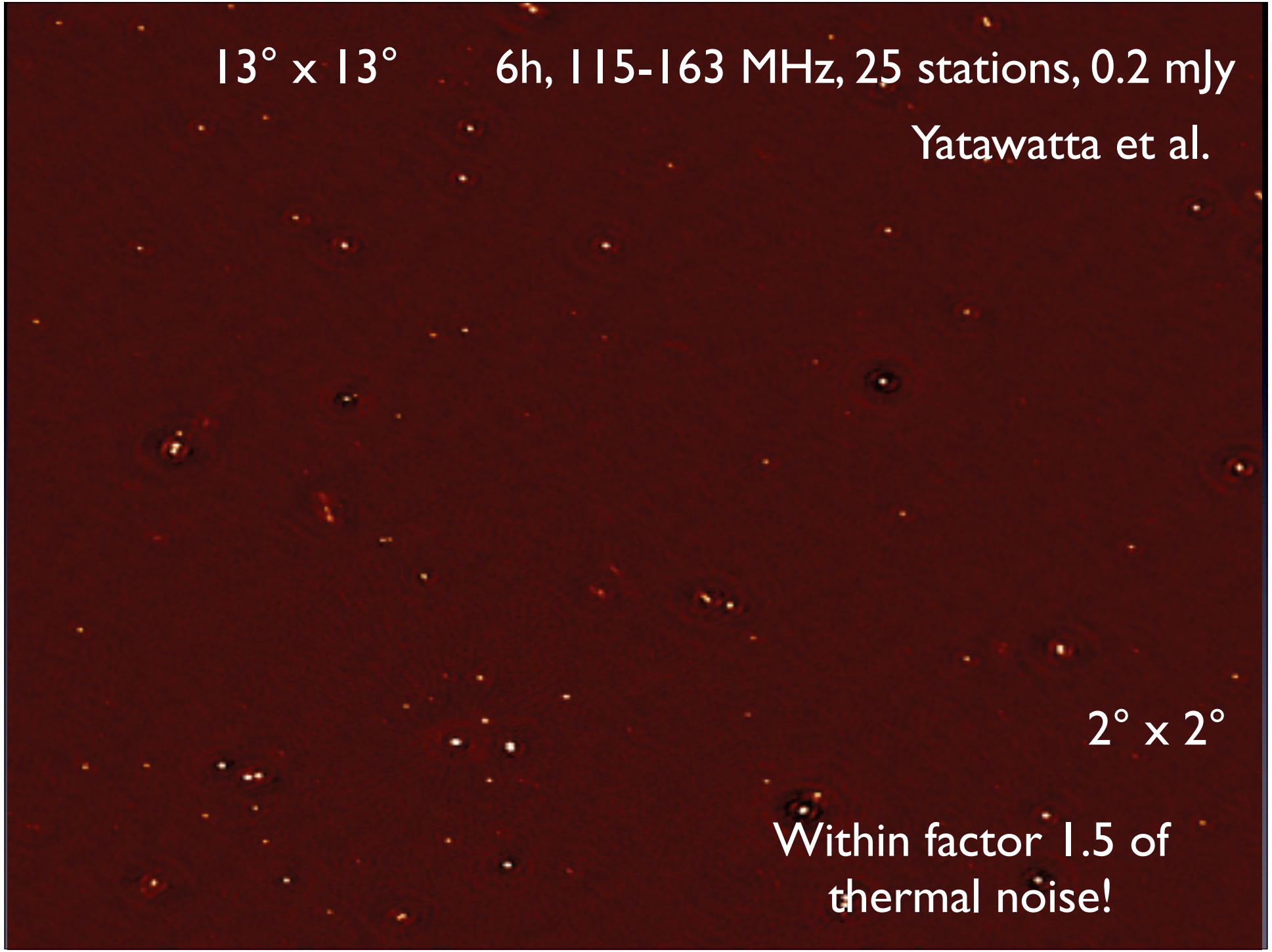
50 MHz LOFAR Observations of lensed quasar 3C196 resolution of 1 arcsec

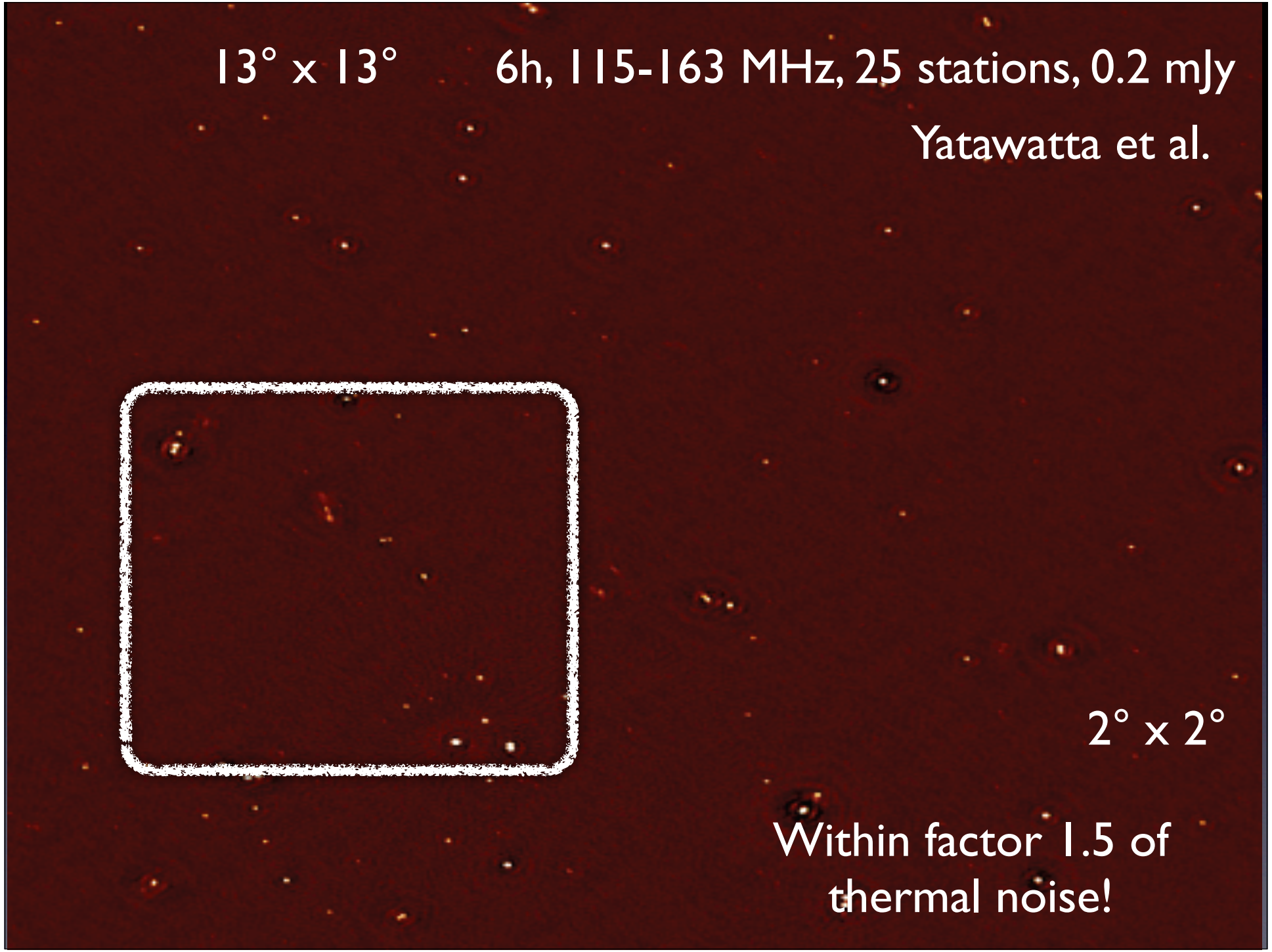


Courtesy: Wucknitz

5 NL + 3 DE stations (Effelsberg, Unterweilenbach, Tautenburg)

Green contours: 408 MHz Merlin maps


13° x 13°
6h, 115-163 MHz, 25 stations, 0.2 mJy
Yatawatta et al.
2° x 2°
Within factor 1.5 of
thermal noise!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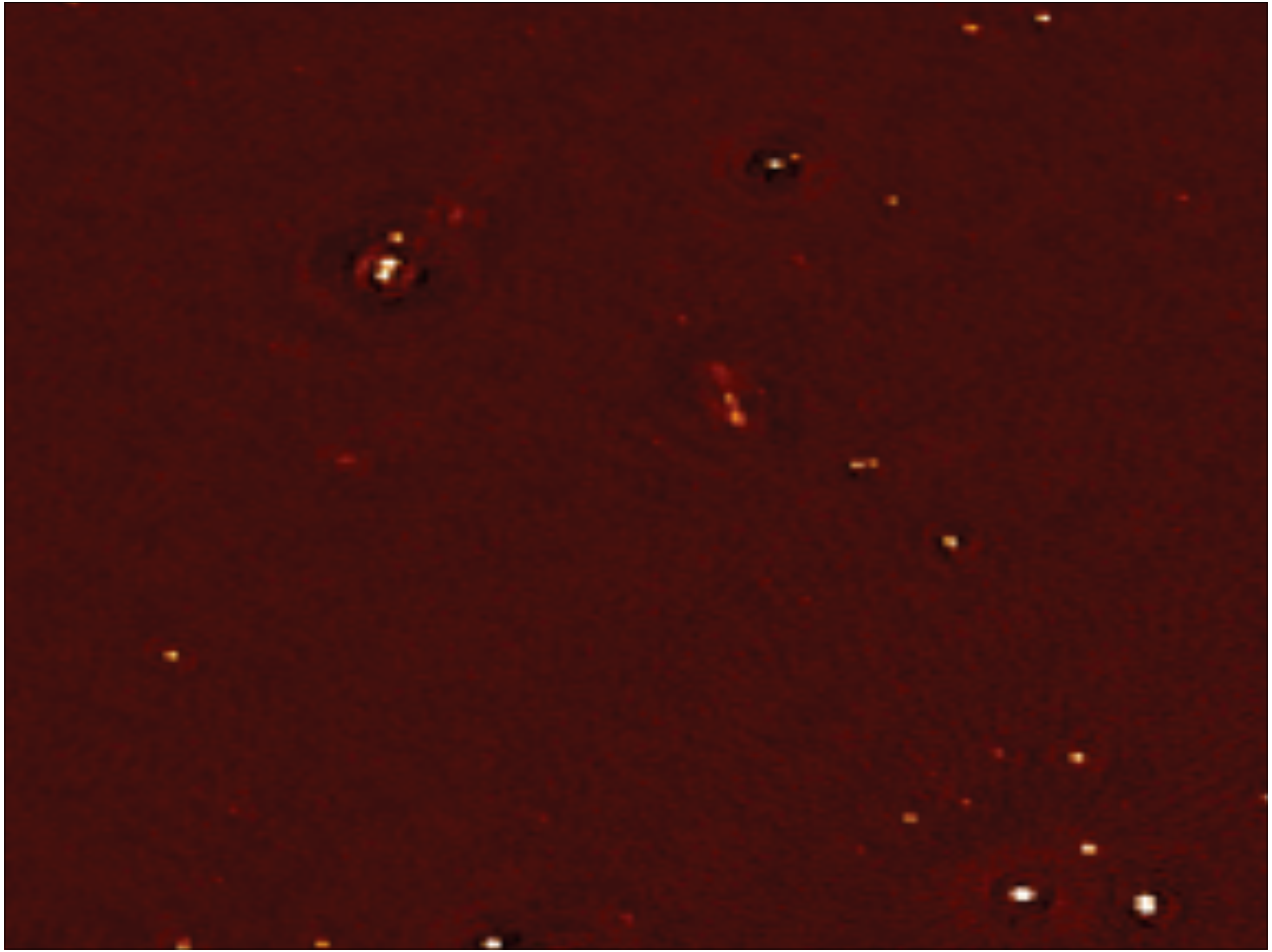
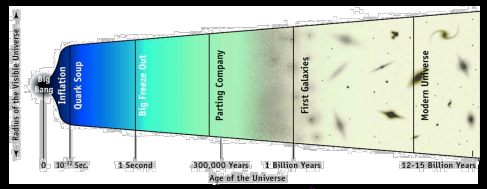
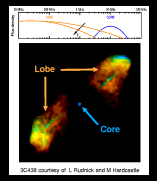
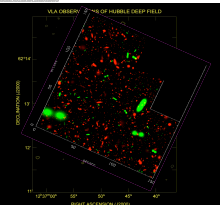


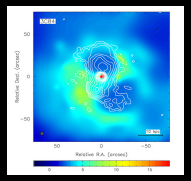
LOFAR- The Key Science

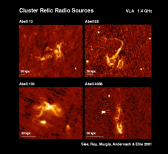
- Epoch of Reionisation
- Surveys
- Transients
- Cosmic Rays
- Magnetism
- Sun, Space Weather

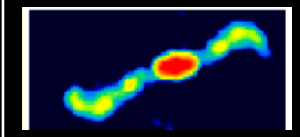


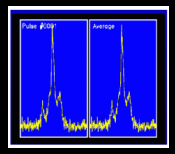


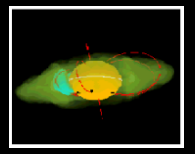


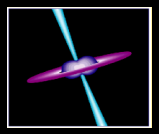


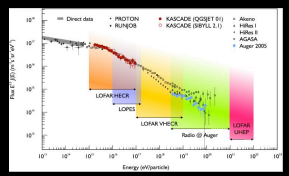


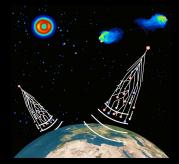


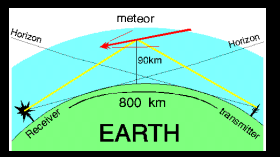


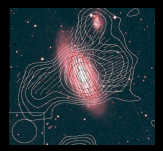


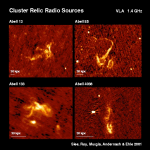


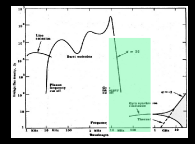


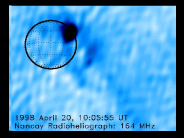


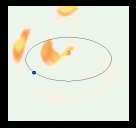


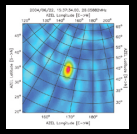








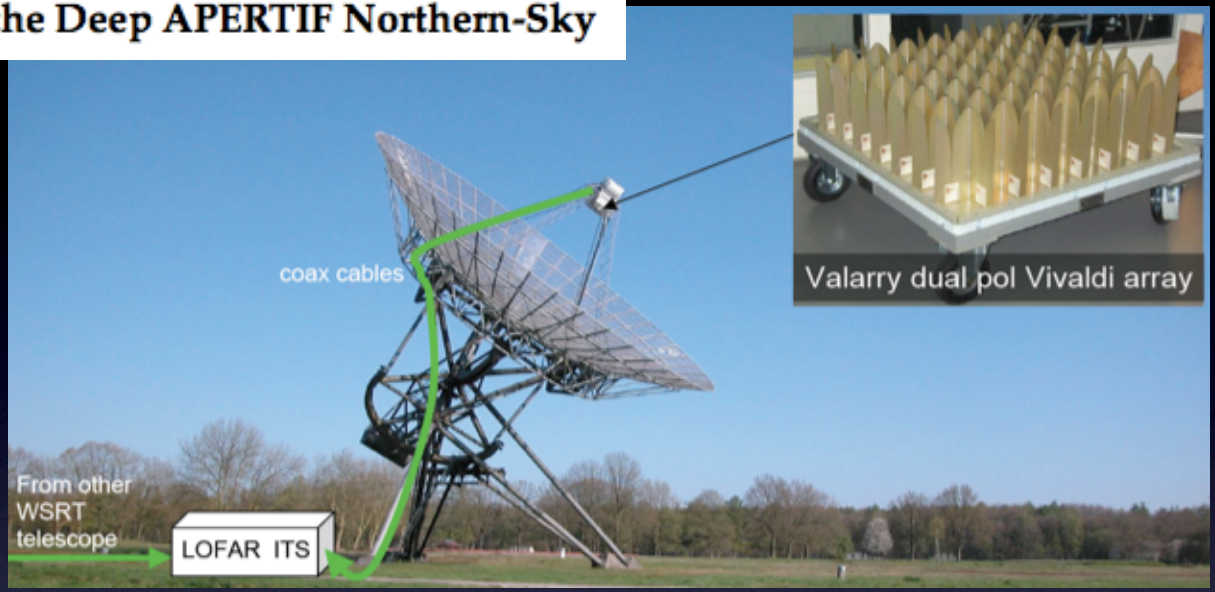




Wodan

Westerbork Observations of the Deep APERTIF Northern-Sky

10 microJy rms, delta > 30



Lead Team: Huub Röttgering, Jose Afonso, Philip Best, Marcus Brüggen, Tom Oosterloo.

Co-I's: James Anderson, Ashish Asgekar, David Bacon, Peter Barthel, Rainer Beck, Werner Becker, Rob Beswick, Laura Birzan, Annalisa Bonafede, Michael Brown, Gianfranco Brunetti, Krzysztof Chyzy, Tracy Clarke, John Conway, Catherine Cress, Judith Croston, Ralf-Jürgen Dettmar, Loretta Dunne, Tom Dwelly, Alastair Edge, Bjorn Emonts, Torsten Ensslin, Heino Falcke, Ilana Feain, Luigina Feretti, Chiara Ferrari, Bryan Gaensler, Michael Garrett, Gabriele Giovannini, Martin Hardcastle, Marijke Haverkorn, George Heald, Matthias Hoeft, Andrew Hopkins, Rob Ivison, Neal Jackson, Marek Jamrozy, Matt Jarvis, Melanie Johnston-Hollitt, Henrik Junkelwitz, Amy Kimball, Hans-Rainer Kloeckner, Anton Koekemoer, Leon Koopmans, Baerbel Koribalski, Joe Lazio, Matt Lehnert, Ashish Mahabal, John McKean, George Miley, Raffaella Morganti, Matteo Murgia, Eric Murphy, Tom Muxlow, Kiz Natt, Bob Nichol, Peder Norberg, Ray Norris, Paul Nulsen, Seb Oliver, Emanuela Orru, Paola Padovani, Laura Pentericci, Wendy Peters, Kevin Pimbblet, Roberto Pizzo, Antonis Polatidis, Isabella Prandoni, David Rafferty, Somak Raychaudhury, Thomas Reiprich, Larry Rudnick, Mario Santos, Richard Schilizzi, Paoblo Serra, Nick Seymour, Chris Simpson, Dan Smith, Cyril Tasse, Russ Taylor, Mark Thompson, Corrado Trigilio, Grazia Umana, Mattia Vaccari, Ed Valentijn, Ilse van Bemmel, Kurt van der Heyden, Paul van der Werf, Sjoerd van Velzen, Reinout van Weeren, Jacco Vink, Glenn White, Michael Wise.

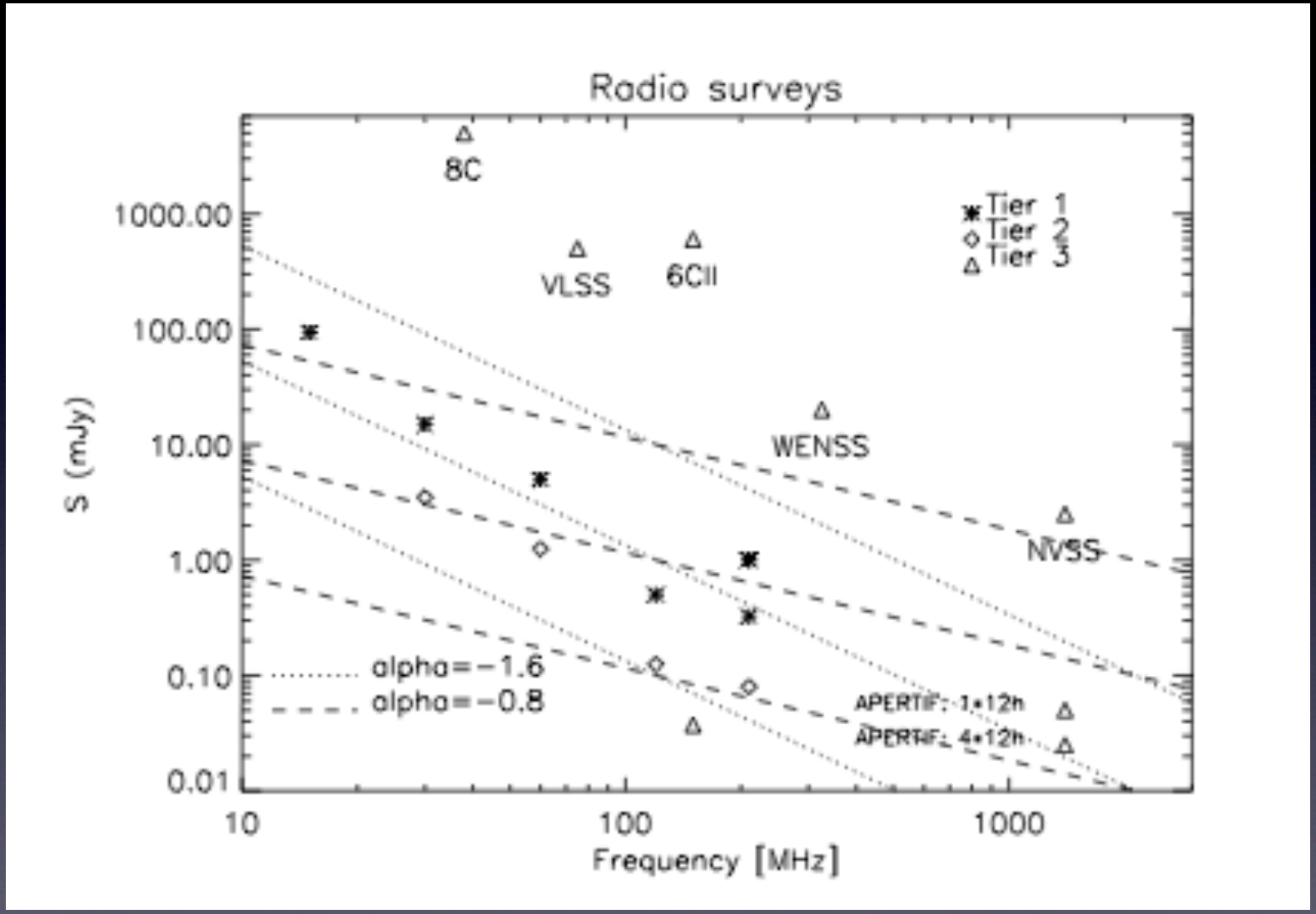
LOFAR+WSRT
Three tiered surveys

Key frequencies:
15, 30, 60, 120, 150,
200, 1400 MHz

1. The highest redshift radio sources - George Miley: ~100 at z>6
2. Starforming galaxies at moderate and high redshifts- Lehnert/Barthel: 100 protoclusters at z>2
3. Clusters and cluster halo sources - Brüggen/Brunetti: 100 @ z>0.6; 60 nearby clusters
4. AGN at moderate redshifts - Philip Best
5. Gravitational lensing - Neal Jackson
6. Detailed studies of low-redshift AGN - Raffaella Morganti
7. Nearby galaxies - John Conway/Krzysztof Chyzy
8. Cosmological studies - Matt Jarvis/David Bacon
9. Galactic radio sources – Glenn White

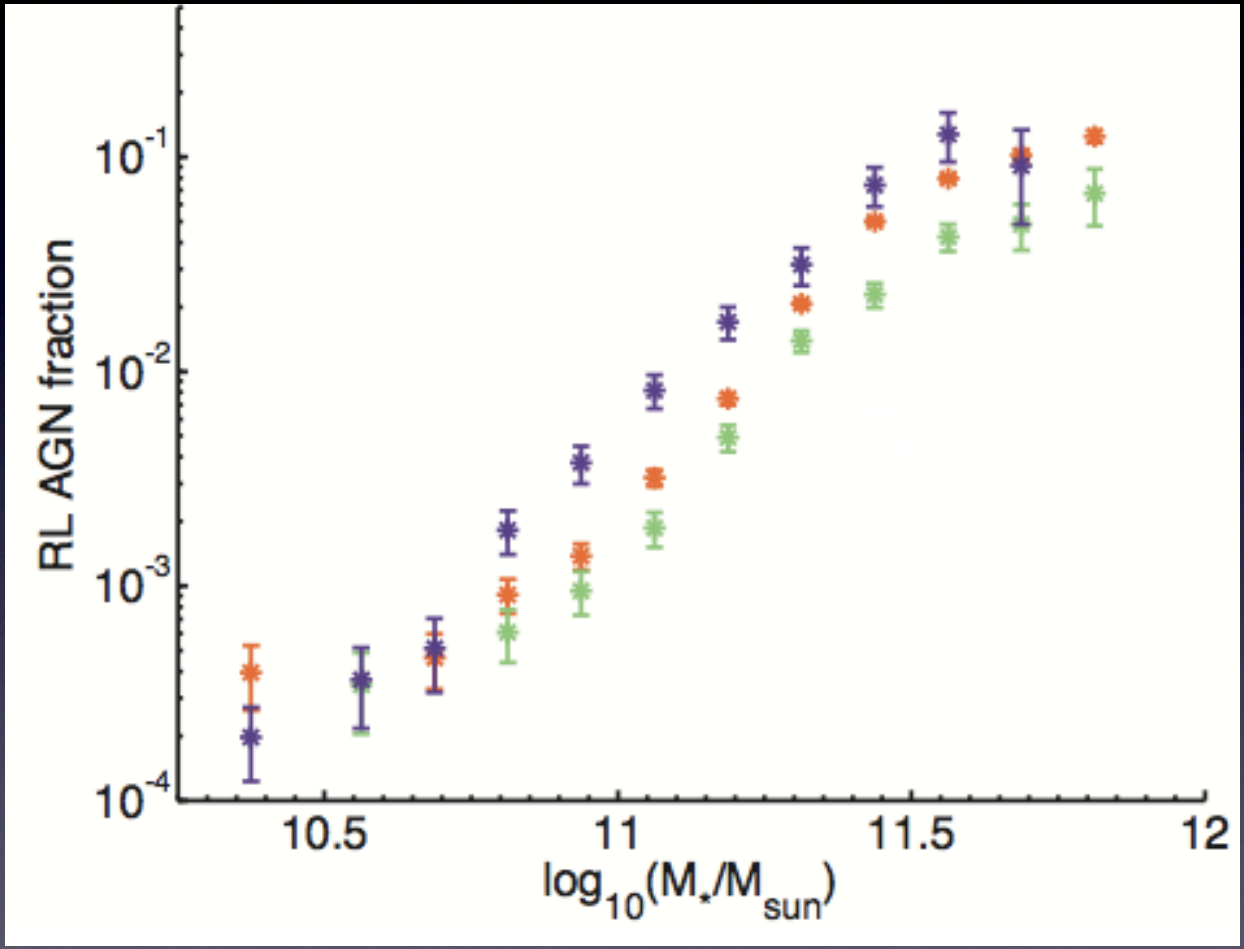
f[1] MHz	Area deg^2	thermal rms mJy	BW MHz	Sources[2] /beam	Int. time[3] hrs	Number pointings	Days[4]	Total[2] sources	Key[6] Topic	Main[6] Topic
Tier 1: The "Large Area" survey										
15	20626	10	4	17811	100	100	21	1.4e+06	4	10
30	20626	2	16	19106	22.3	218	42	3.5e+06	1,2	5,7,10
60	20626	0.75	16	30124	20.6	203	36	5.1e+06	1,2	5,7,10
120	20626	0.1	16	30016	3.8	1021	33	2.8e+07	1,2	5,7,8,9,10
200	20626	0.2	16	2472	1.0	3021	25	7.0e+06	1,2	5,7,10
200	1088	0.065	16	9373	9.3	150	12	1.4e+06	1,2	5,7,8,9,10
Tier 2: The "Deep" survey										
30[5]	2806	0.7	16	53523	204	25	44	1.6e+06	2,3	5,6,7
60	3025	0.25	16	96763	207	25	44	2.9e+06,	2,3	5,6,7
120	555	0.025	16	204070	67	25	14	5.6e+06	2,3	5,6,7
200	362	0.016	16	66635	172	50	74	3.5e+06	2,3	5,6,7
Tier 3: The "Ultra Deep" survey										
150	71	0.0062	48	543798	221	5	28	2.9e+06	3	5,6

Surveying the radio sky
15, 30, 60, 120, 150, 200, 1400 MHz



50 million sources

Fraction of blue massive galaxies (rare!) that are radio loud 2-3 higher then red galaxies



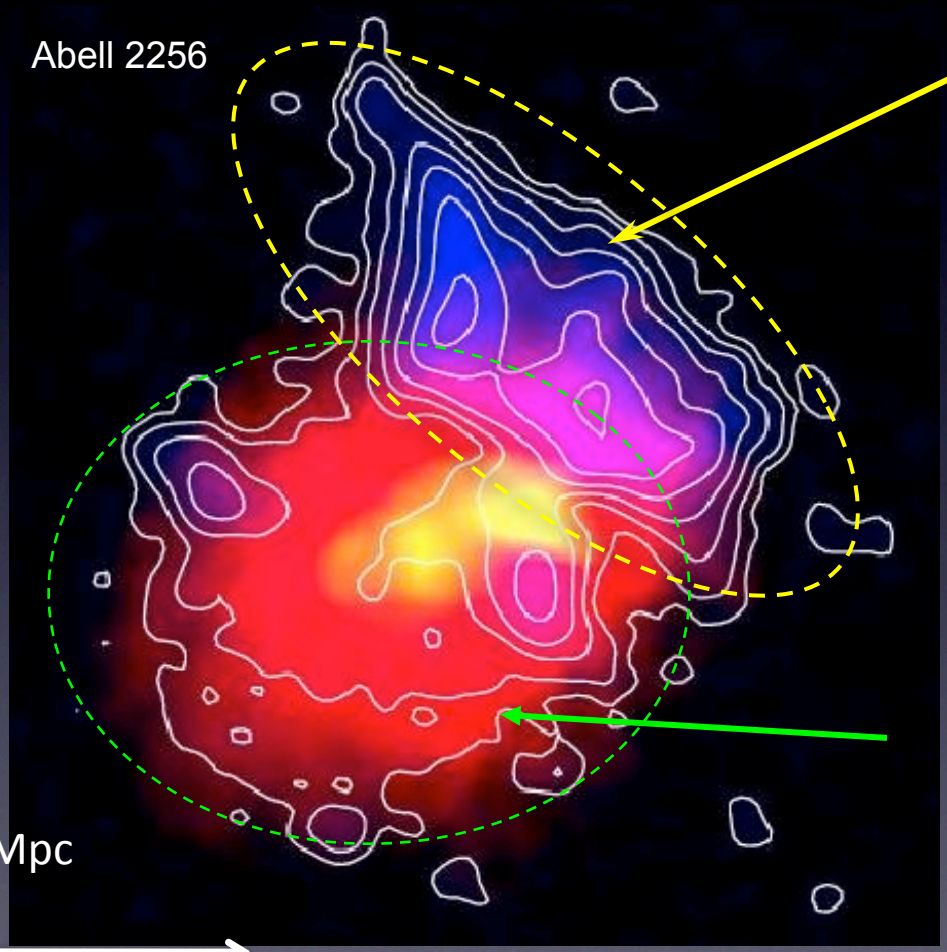
NVSS radio/SDSS
$0<z<0.3$
$P_{1.4GHz} > 10^{24}$ W/Hz

Red: $D_n4000>1.7$
Blue: $D_n4000<1.4$

Janssen, HR, Best, Brinchman

Relics and halos: an introduction

Diffuse cluster radio sources



VLA 1.4 GHz (contours and blue) on Chandra (red & yellow)

Clarke & Ensslin 2006

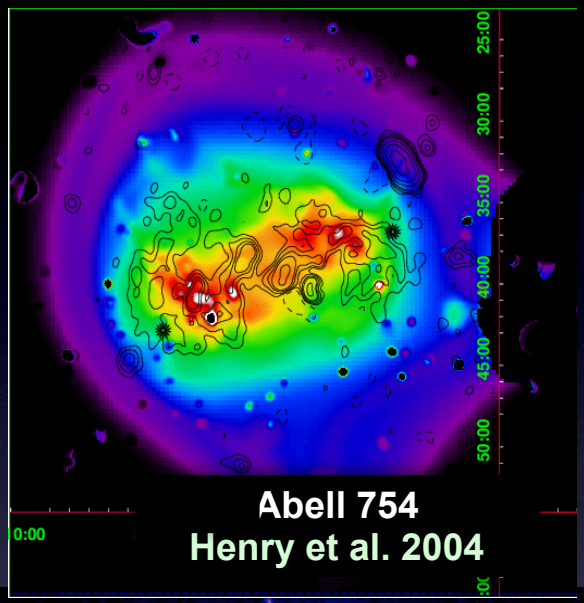
RADIO RELICS:

~ Mpc size
cluster outskirts
elongated morphology
polarized (up to 30%)

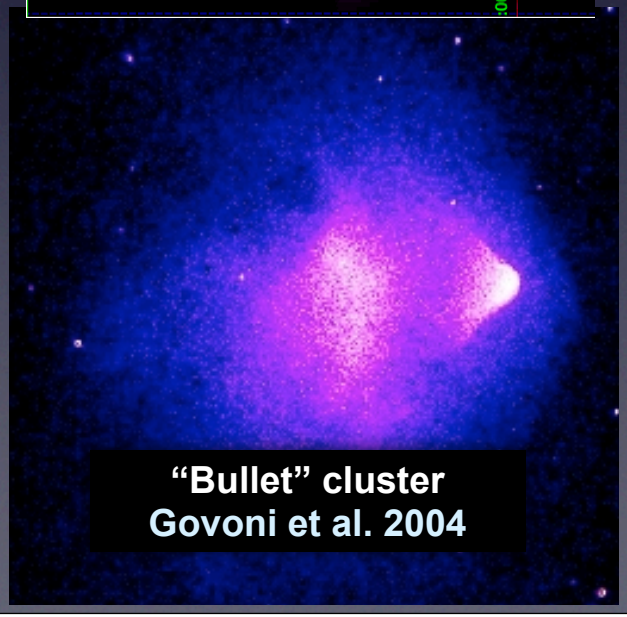
RADIO HALOS:

~ Mpc size
Cluster center
Unpolarized

Radio Halos massive merging clusters

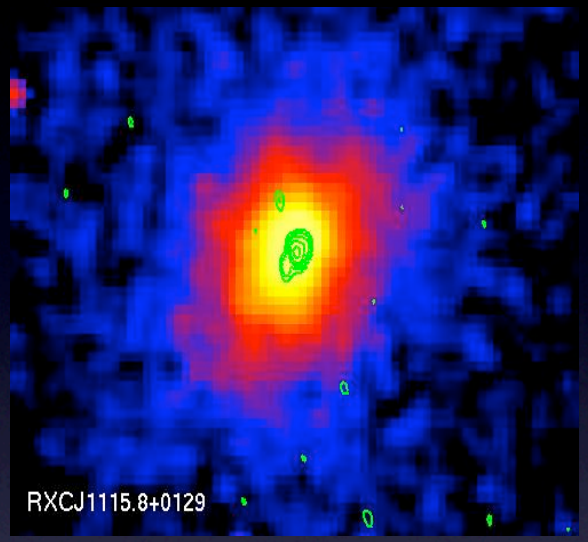


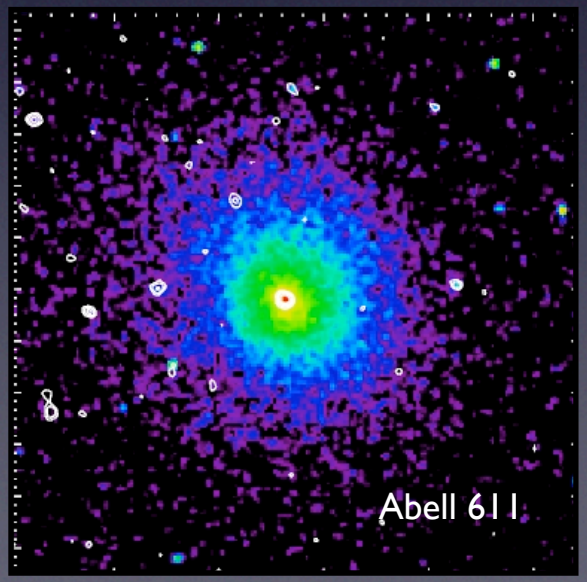
Abell 754
Henry et al. 2004



"Bullet" cluster
Govoni et al. 2004

Radio Quiet clusters are less massive and/or have relaxed dynamical status





Brunetti et al 2007
Cassano et al. 2010

The `Great Debate'
(Brunetti versus Keshet)

Radio emission

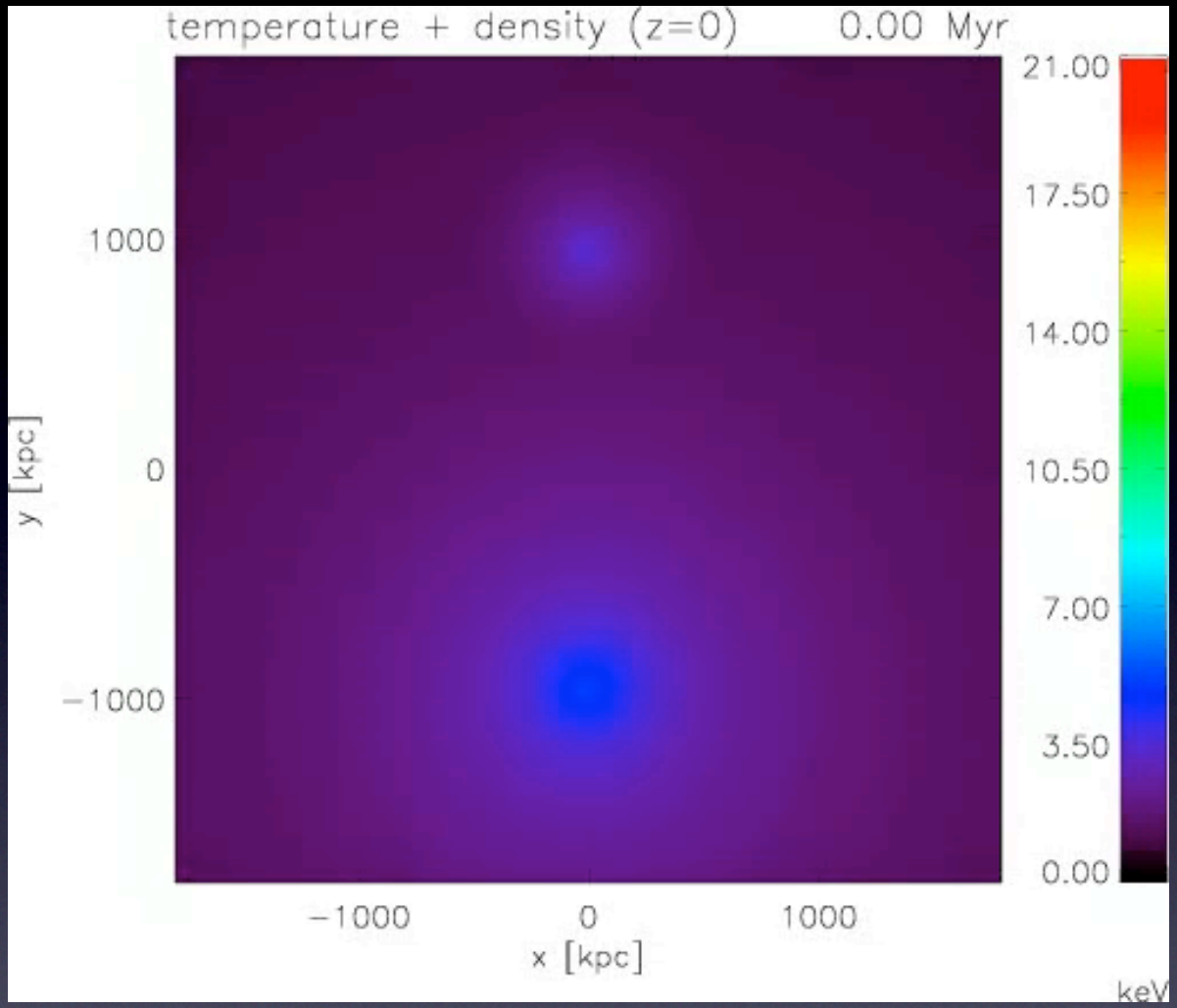
1. trace regions of particle acceleration (*primary electron scenario*) due to turbulence and/or shocks

or

2. regions with enhanced magnetic field with electrons originate from proton-proton collisions (*secondary electron scenario*)

As the magnetic field strengths seems similar in clusters with and without radio halos scenario 1. seems favored
(Govoni et al 2010 AA 522, 105, Brunetti, Cassano 2010)

Scenario



- FLASH with adaptive mesh refinement (AMR) code
- including hydro + gravity
- particle acceleration within the shock
- synchrotron emission and cooling: Hoeft & Brüggen 2007

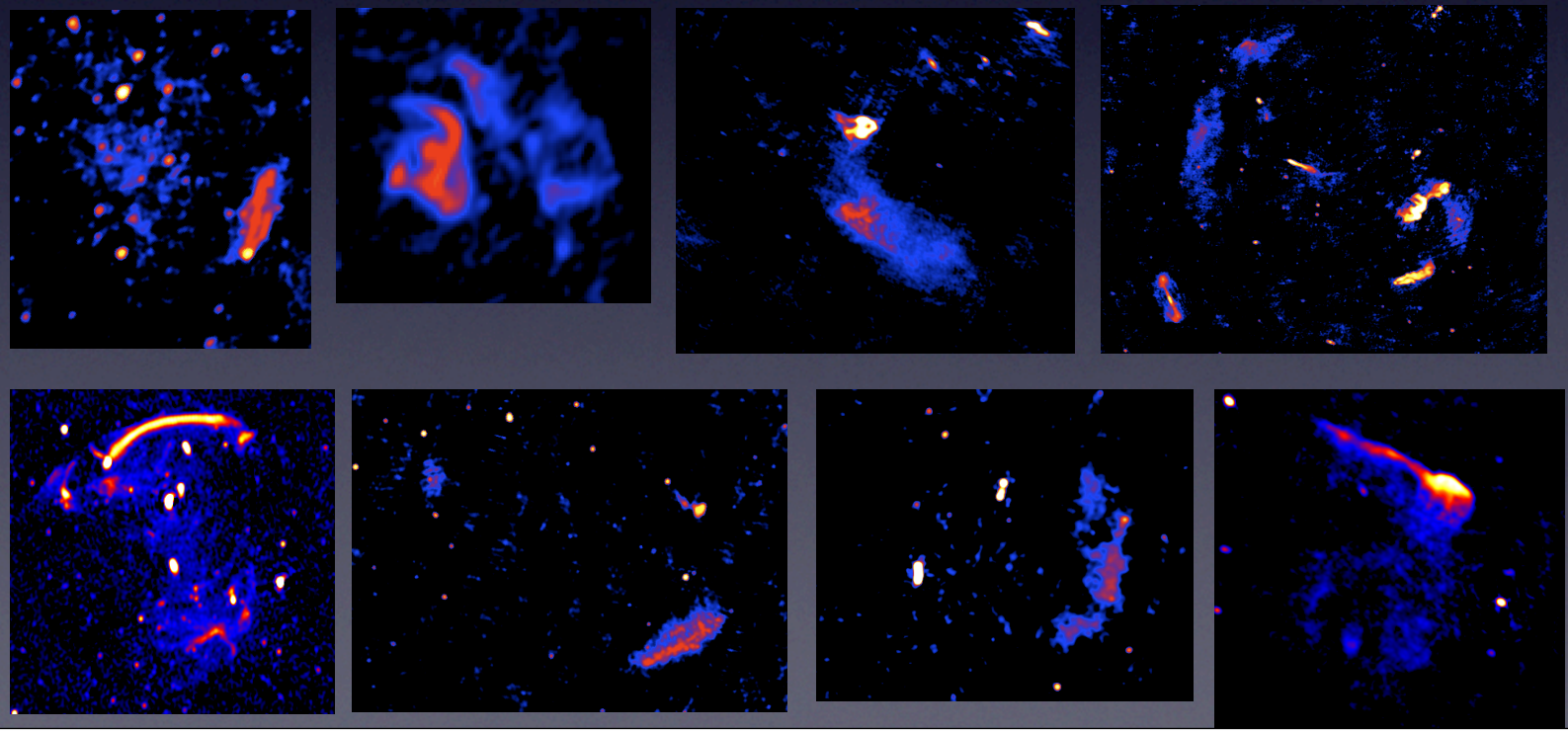
Questions

- Physics of shocks
  - Mach-number, magnetic fields strengths
  - B-field generation
  - Particle acceleration
- Merging clusters
  - mass ratios, impact parameters, substructure
- Cluster X-ray gas
  - Overall energy balance, magnetic field content
- Total masses and redshift evolution -> link to cosmology

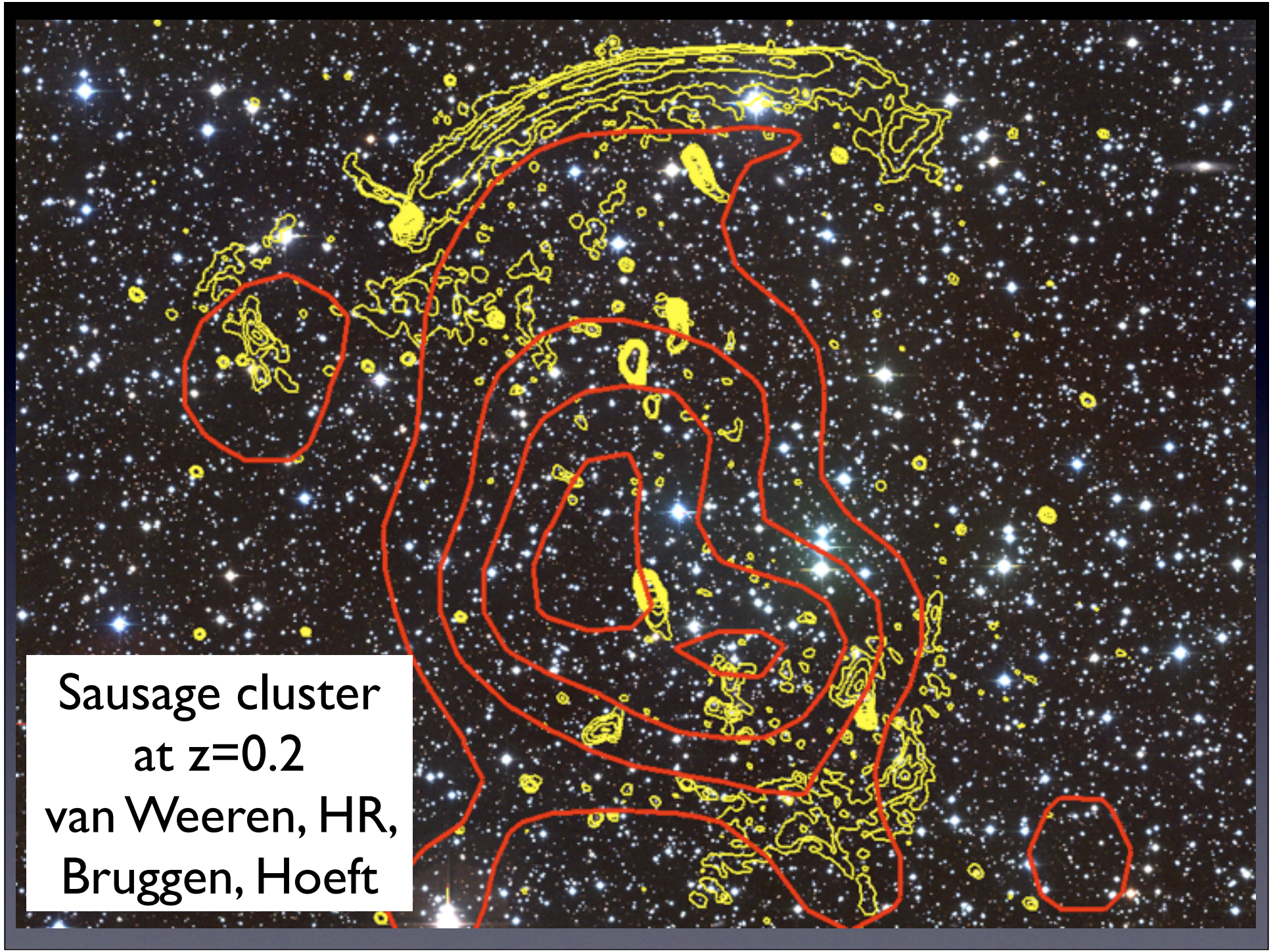
A new sample of relics

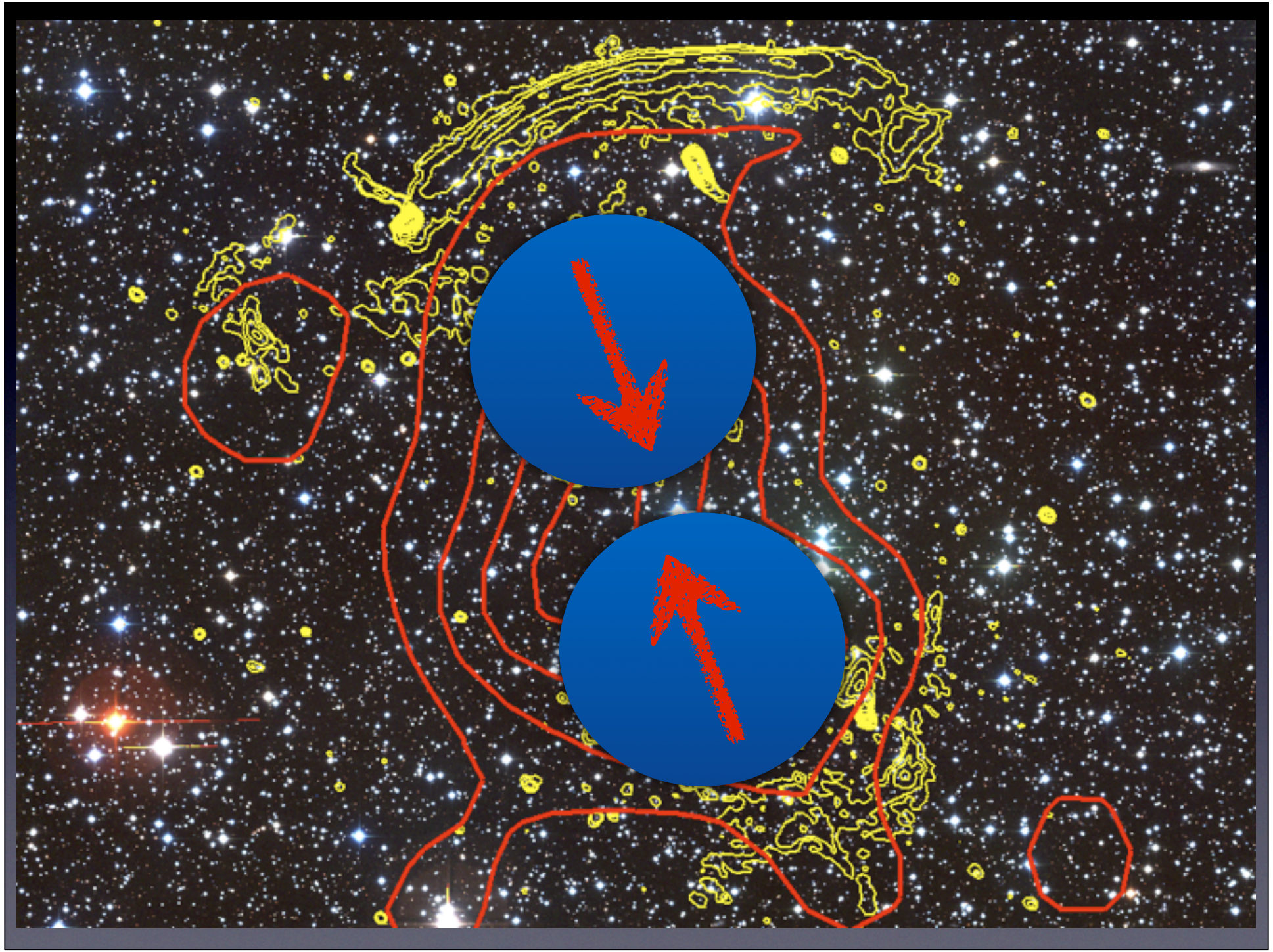
- GMRT, WSRT, GMRT observations of 26 diffuse sources from the 74 MHz VLSS survey with alpha < -1.7
  - 5 relics, 1 halo, 1 mini-halo,
  - rest FR-I/USS/"head-tails"
- 5 new relics from NVSS/WENSS/ROSAT comparisons
- 17 relics from the literature

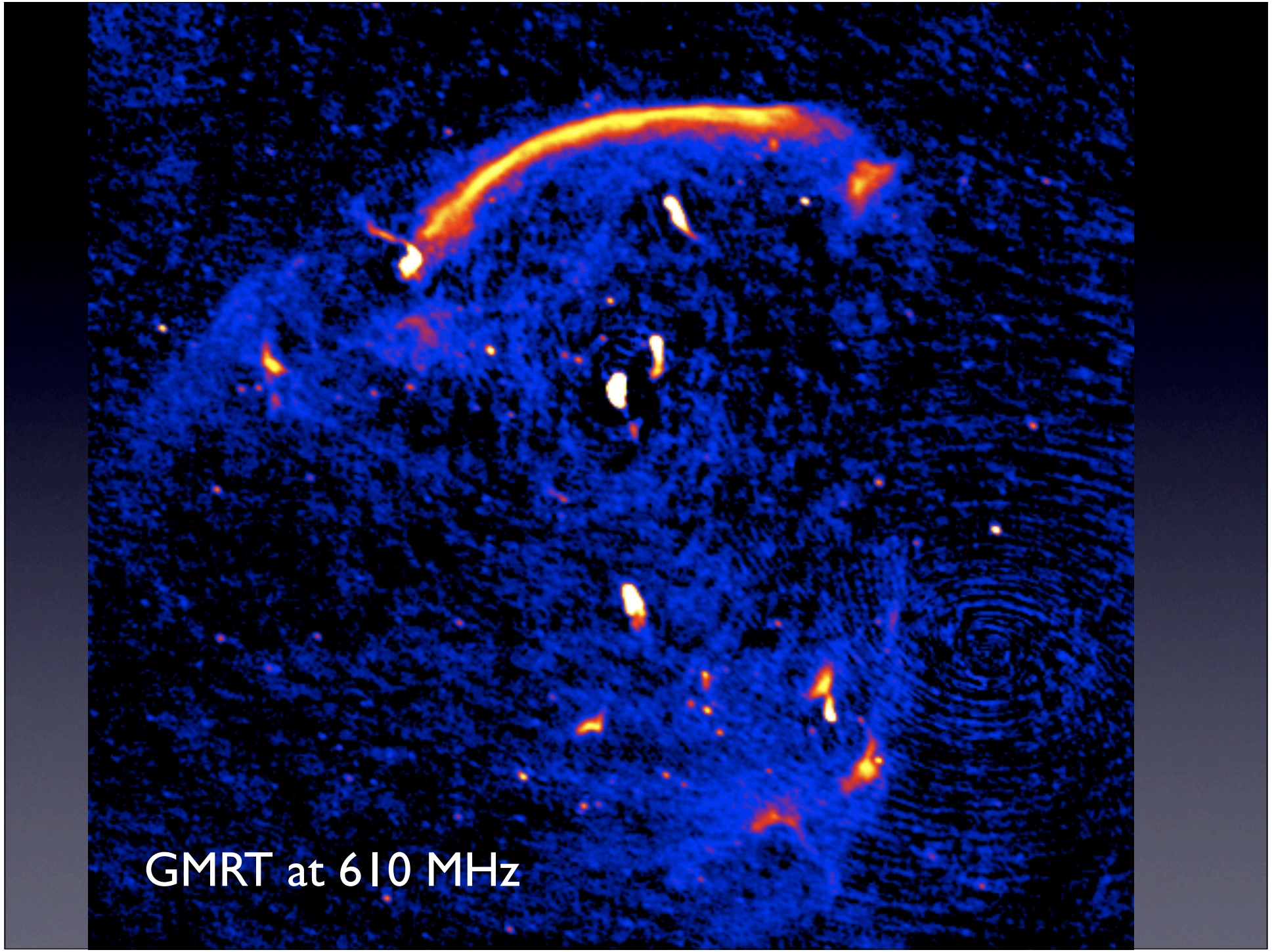
van Weeren, HR, Bruggen, Cohen 2009



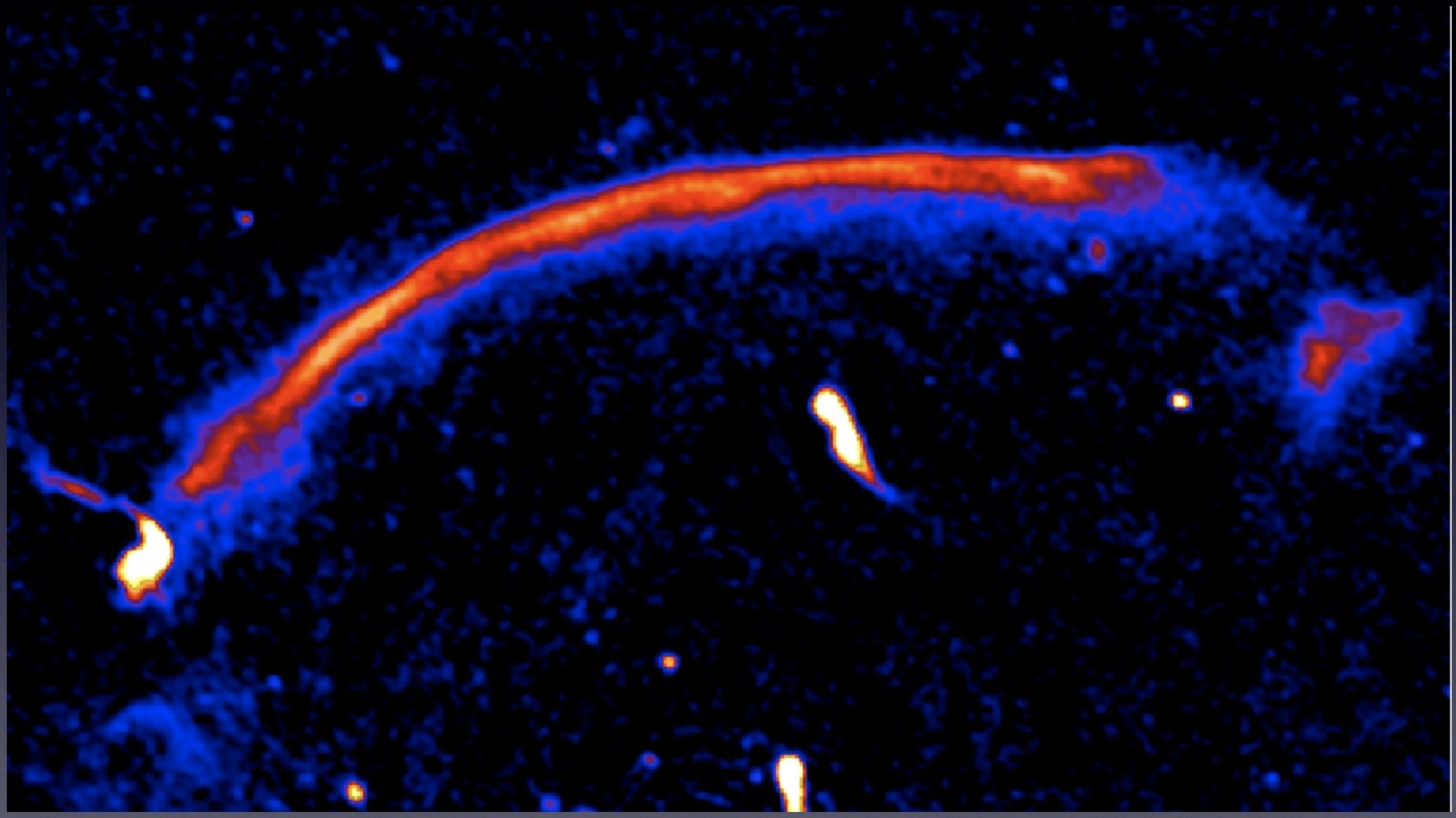
`Sausage cluster’

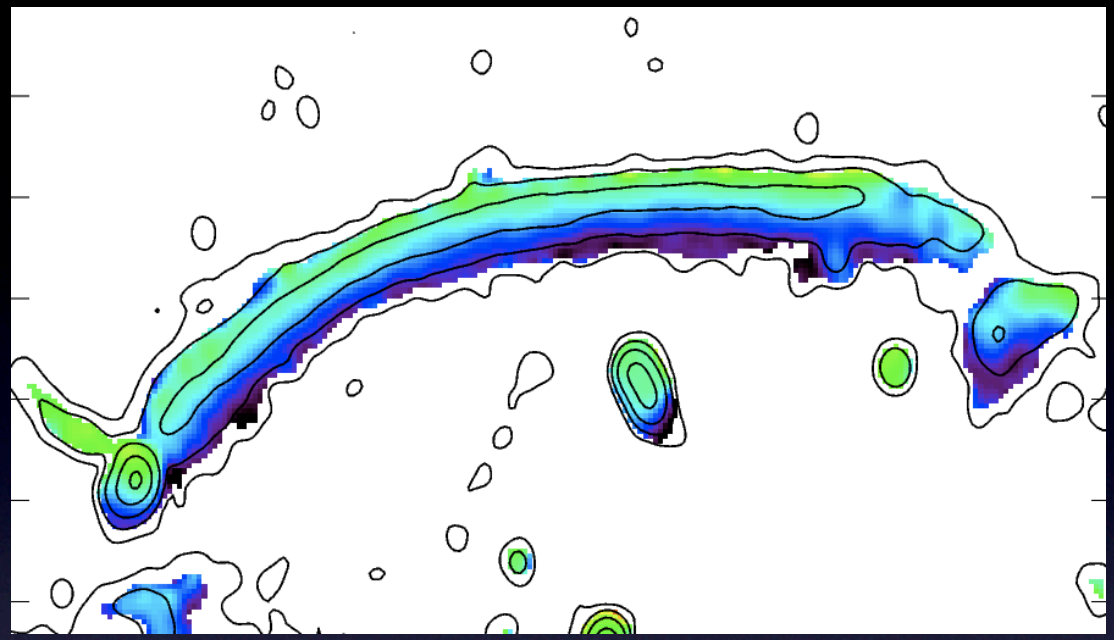

Sausage cluster
at z=0.2
van Weeren, HR,
Bruggen, Hoeft



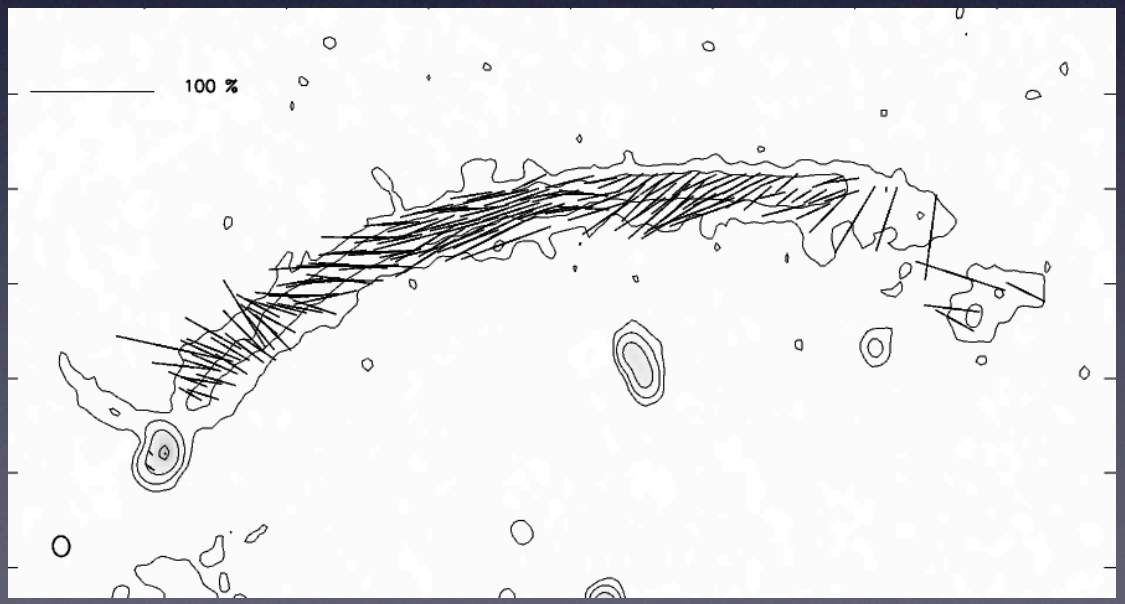

GMRT at 610 MHz

2 Mpc * 50 kpc!





The spectral index alpha =-0.6 - 2.0 from fit to matched GMRT and WSRT observations at 2.3, 1.7, 1.4, 1.2, and 0.61 GHz Resolution: 16.7 * 12.7 arcsec.



Highly polarized, up to 50 %

Conclusive evidence for shock induced particle acceleration in merging clusters

- radio spectral index → Mach number 4.6 ±1
- width → downstream velocity ~1000 km/s
- aging analysis → B = 5 microGauss

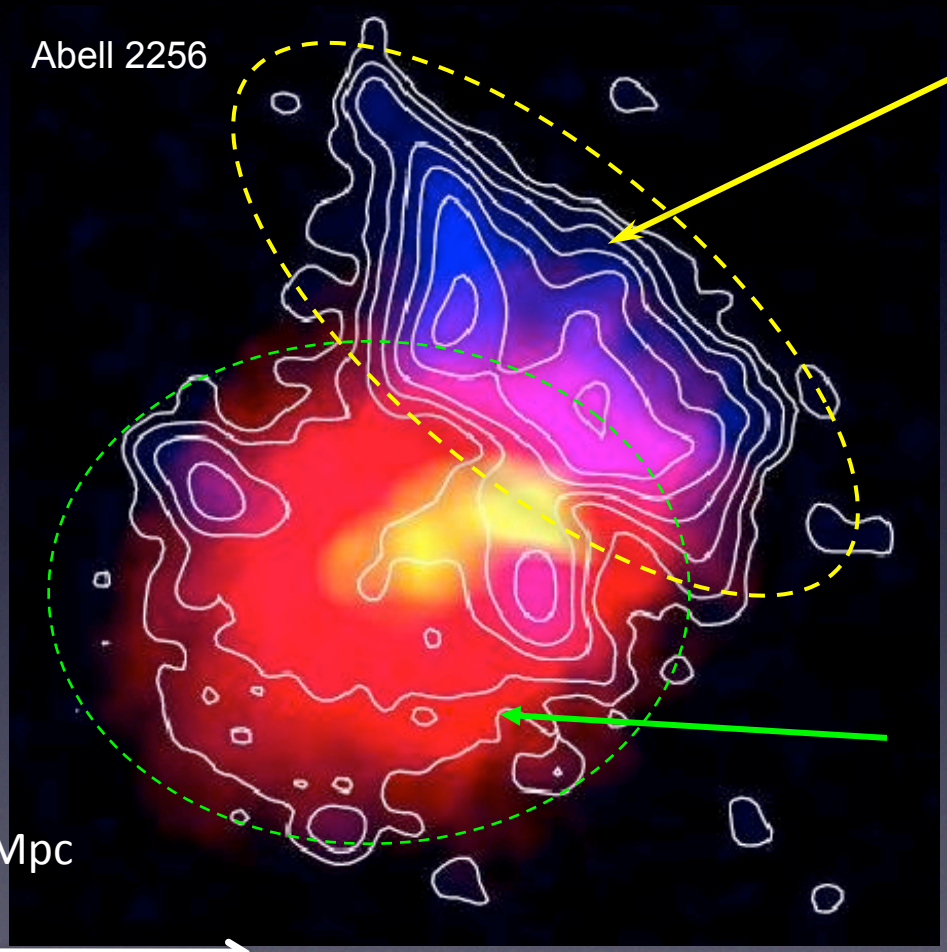
Van Weeren, HR, Bruggen, Hoeft, 2010, Science, 330,

Simulations → constrain cluster properties

- mass ratio 2 clusters ~2:1
- impact parameter ≤ 500 kpc
- time since core passage: ~1 Gyr
- shock waves seen close to edge-on (< 10°)
- ICM not very clumpy at relic location

A2256: bright prototype cluster with a relic and halo

shocked system viewed at ~45 deg



VLA 1.4 GHz (contours and blue) on Chandra (red & yellow)

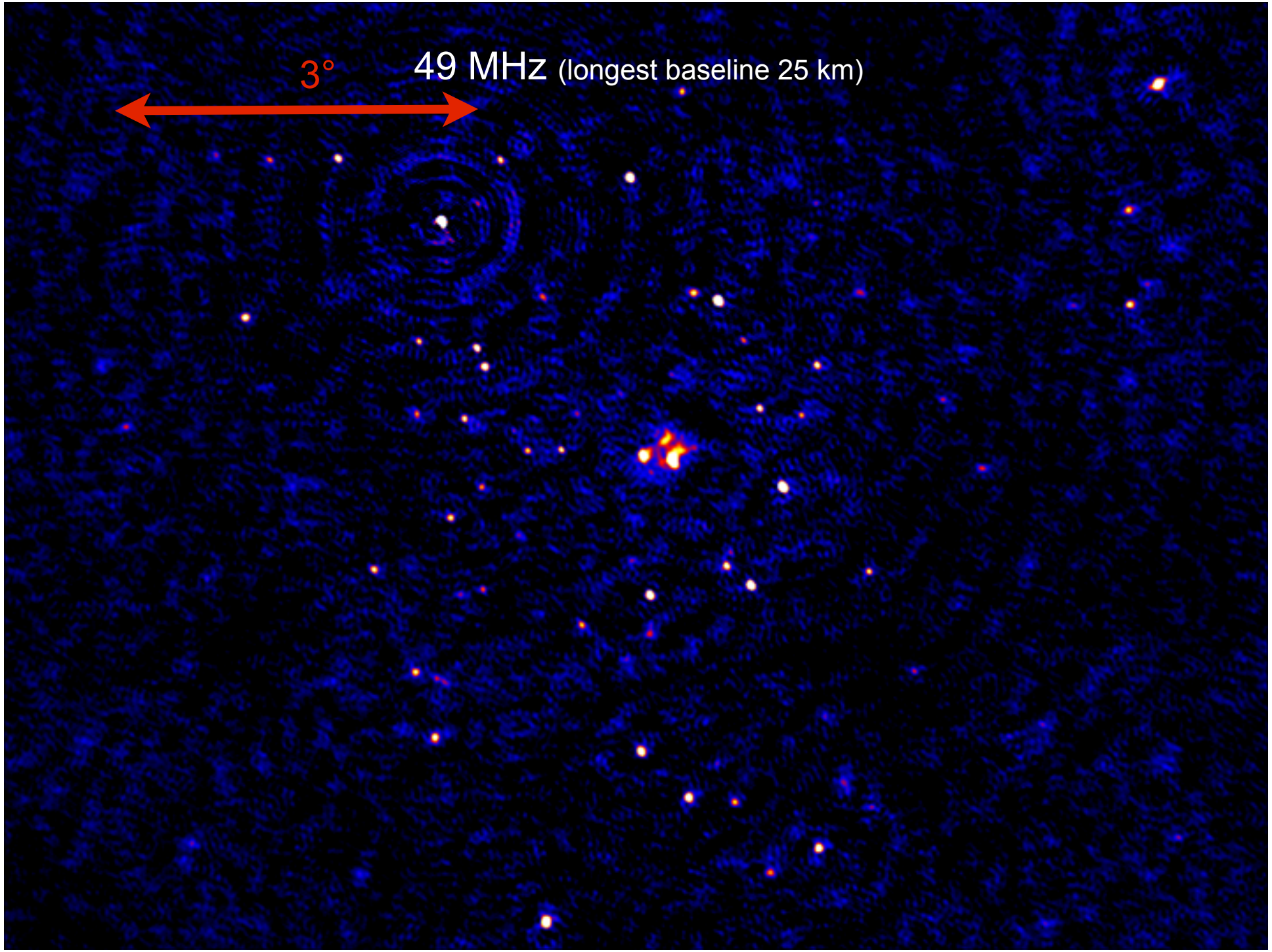
Clarke & Ensslin 2006

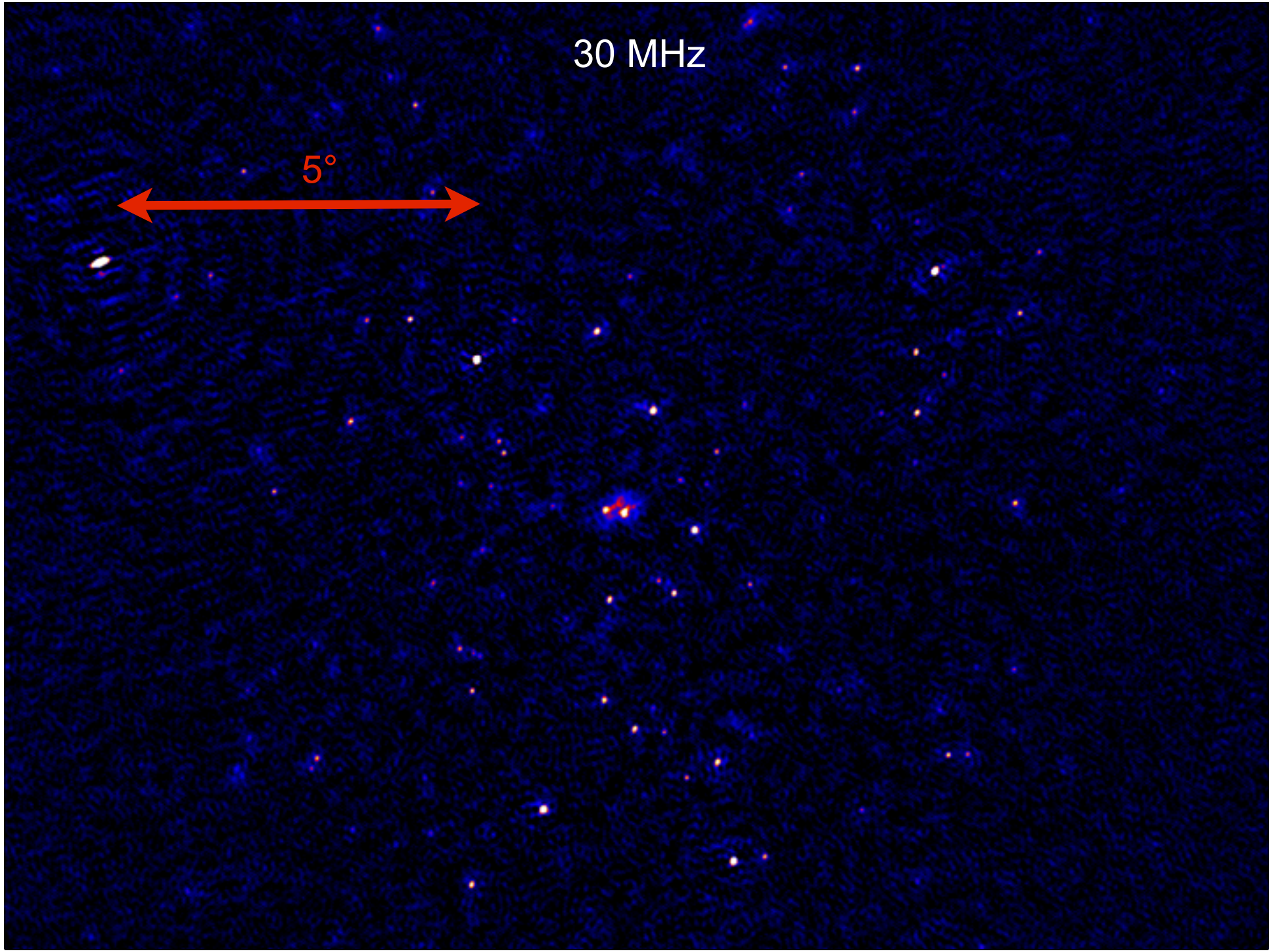
RADIO RELICS:

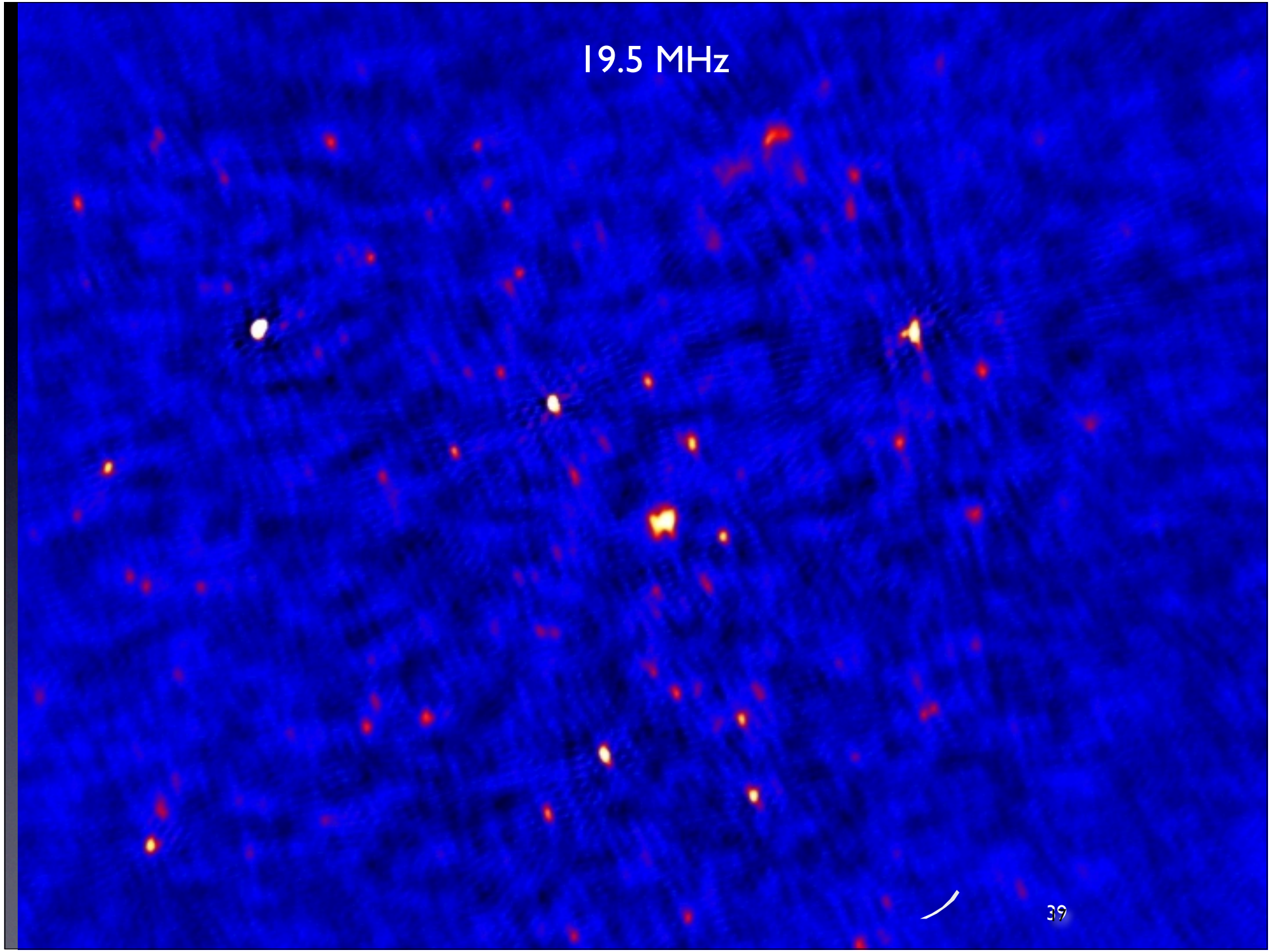
~ Mpc size
cluster outskirts
elongated morphology
polarized (up to 30%)

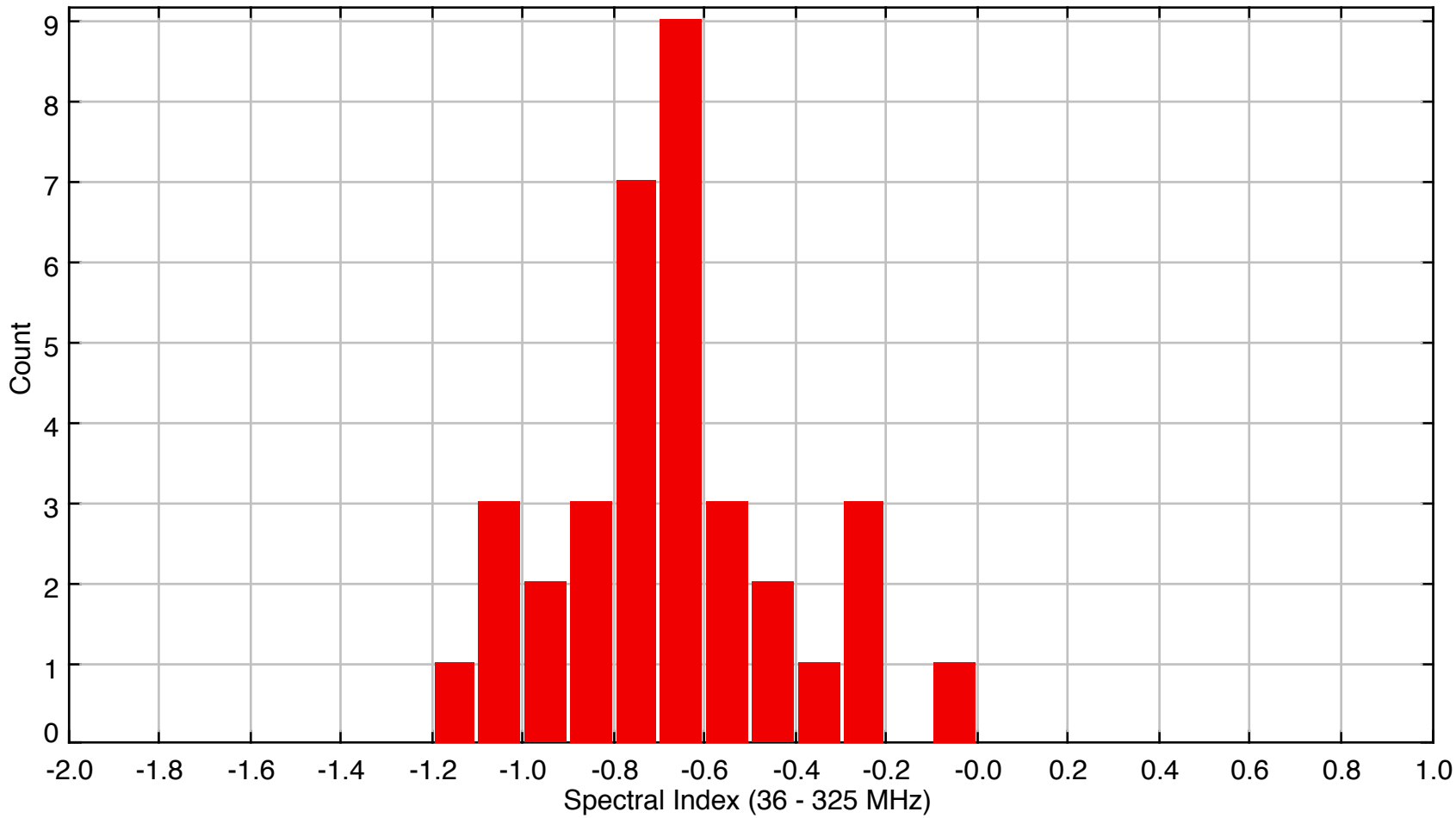
RADIO HALOS:

~ Mpc size
Cluster center
Unpolarized

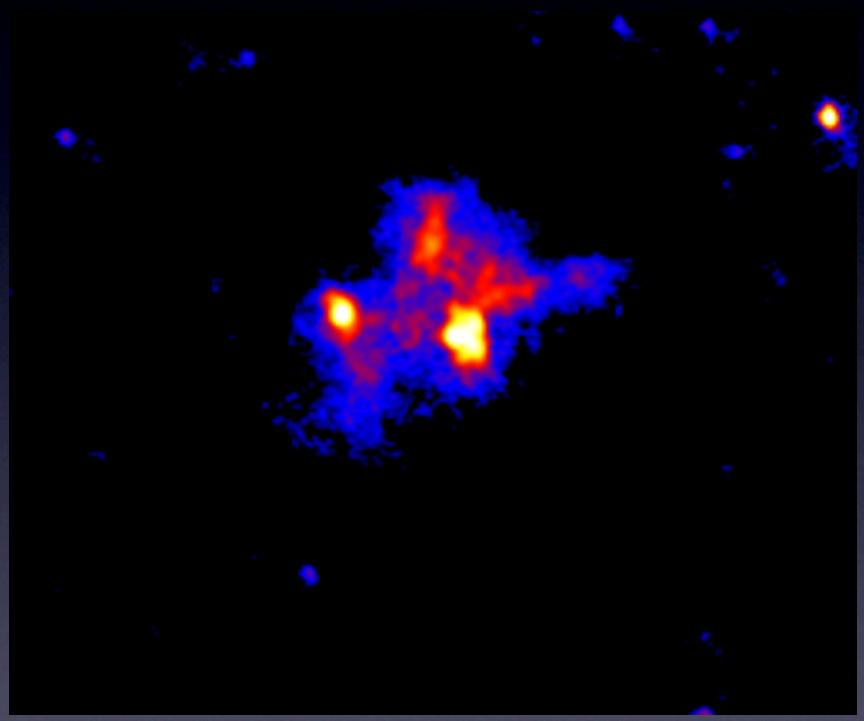

3°
49 MHz (longest baseline 25 km)


30 MHz
5°

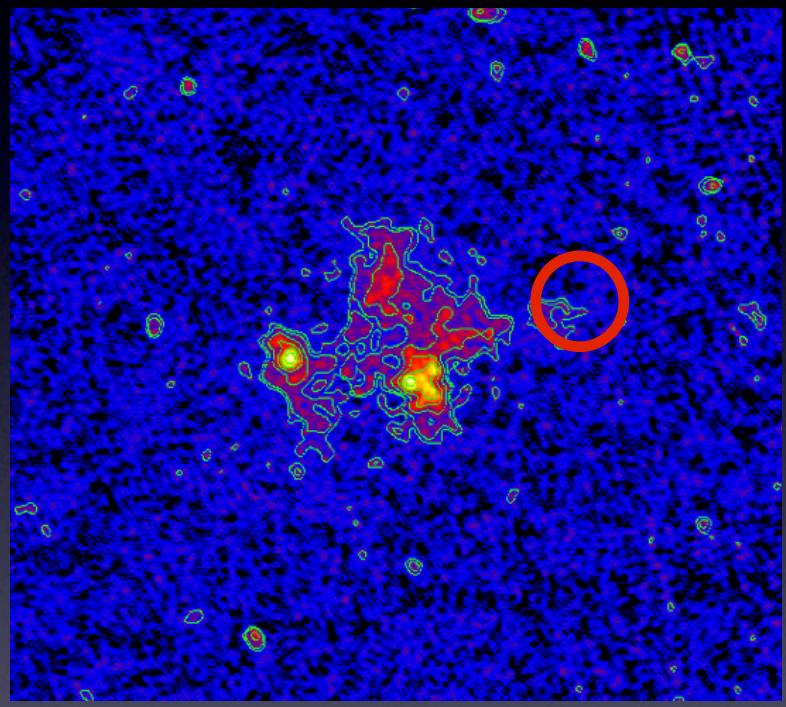

19.5 MHz


Count
0
1
2
3
4
5
6
7
8
9
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0
Spectral Index (36 - 325 MHz)

LOFAR observations of A2256
60-64 MHz, August 2011 (longest baseline 80 km)

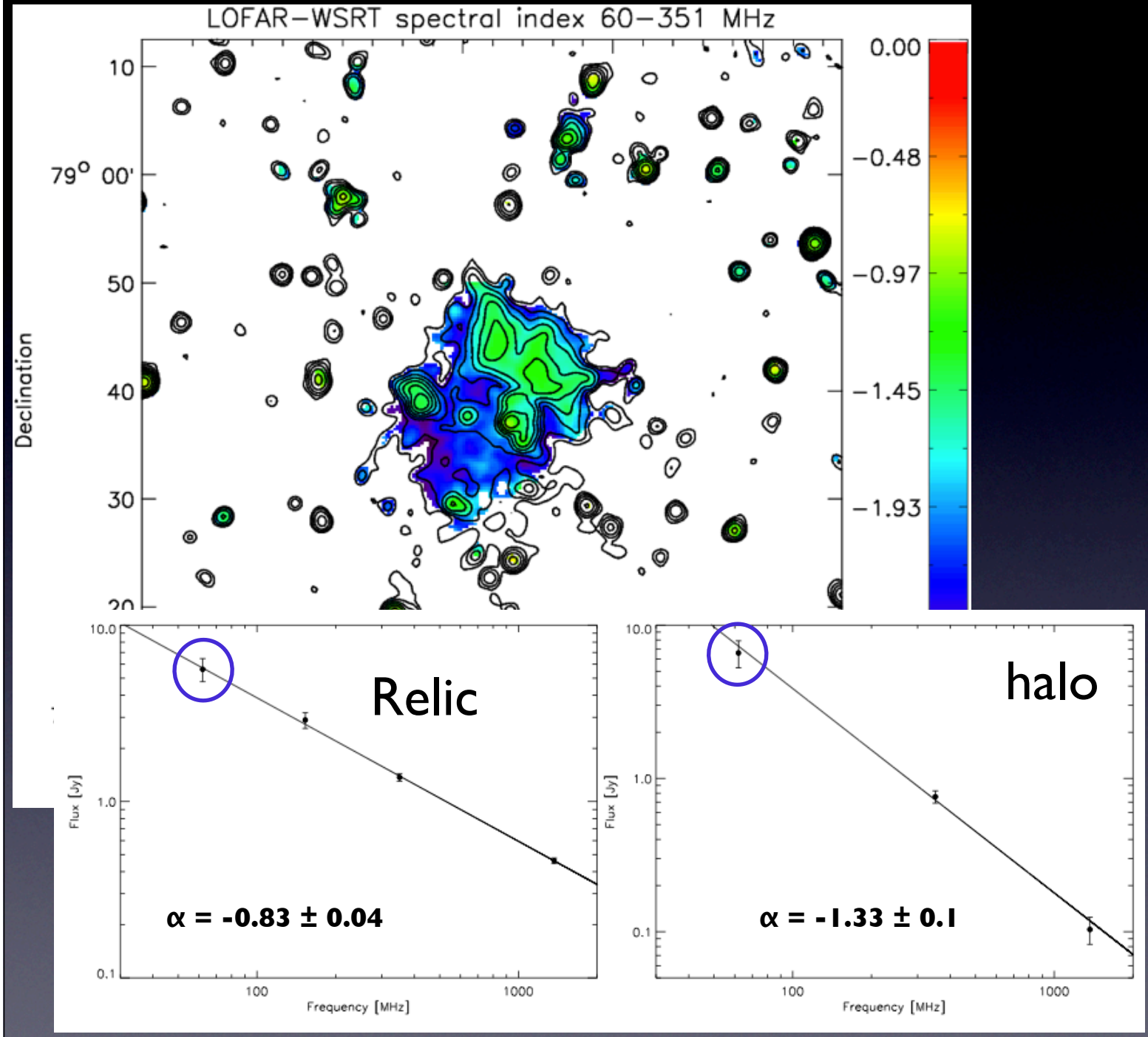


30″ x 30″, noise 15 mJy/beam

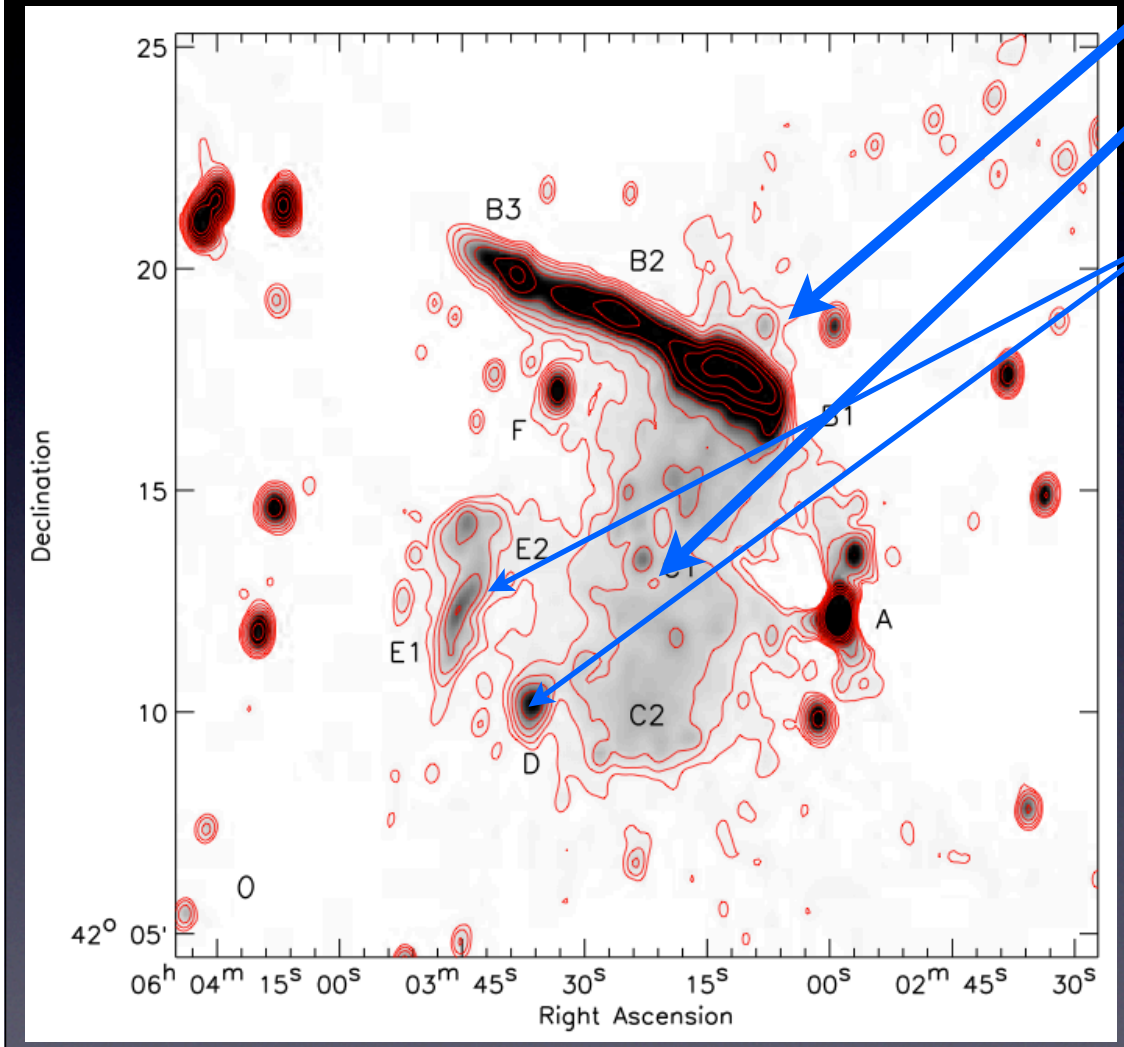


20″ x 20″, noise 8 mJy/beam

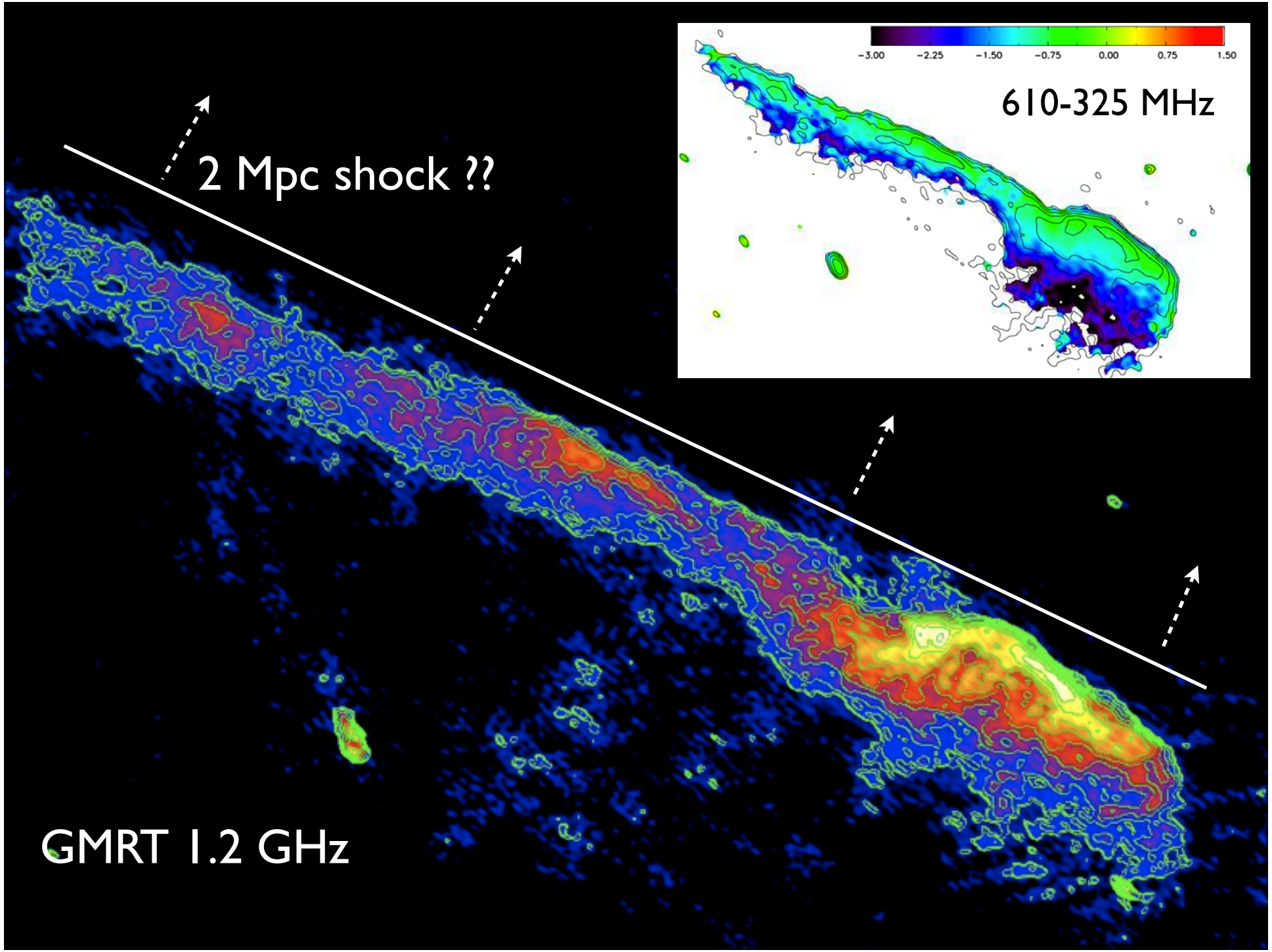
note: deepest VLA 74 MHz image (25" x 25") has a noise of 20 mJy/beam


LOFAR–WSRT spectral index 60–351 MHz
Declination
10
79° 00'
50
40
30
20
0.00
−0.48
−0.97
−1.45
−1.93
Relic
α = -0.83 ± 0.04
Flux [Jy]
Frequency [MHz]
10.0
1.0
0.1
100
1000
halo
α = -1.33 ± 0.1

‘toothbrush’ cluster



- 2 Mpc radio relic
- 2 Mpc radio halo
- polarized up to 60% at 4.9 GHz
- additional fainter relics
- WHT spectra: z = 0.225
- $L_X \sim 1 \times 10^{45}$ erg/s

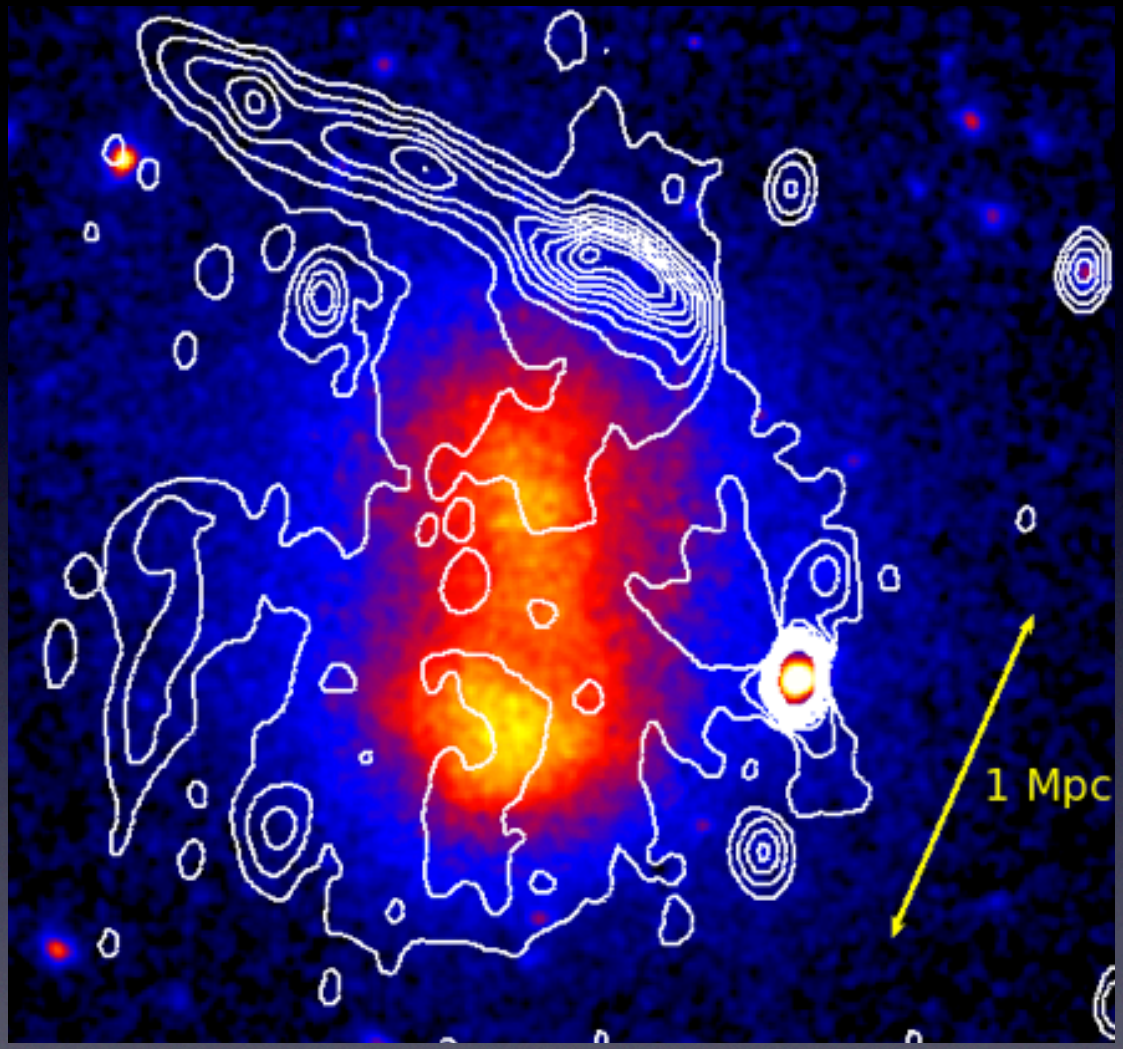

2 Mpc shock ??
610-325 MHz
−3.00
−2.25
−1.50
−0.75
0.00
0.75
1.50
GMRT 1.2 GHz

XMM observations

```
Date: Tue, 11 Oct 2011 12:46:01 GMT
From: XMM-Newton SOC <xmmhelp@xmm.esac.esa.int>
To: rottgering@strw.leidenuniv.nl
Cc: usg_xsa@sciops.esa.int
Subject: XSA notification: XMM-Newton ODF data available (Observation '0675060101')

Dear Dr Huub Rottgering,

XMM-Newton Observation Data Files (ODF) for one of your observations
have been made available for you.

XMM-Newton Observation Id : 0675060101
Observed in Revolution    : 2164
ODF version number        : 001
```

+ van Weeren, Croston, Bruggen, Hoeft

Tooth-brush puzzle:



How to produce a linear shock during a merger?

Conclusion

- LOFAR works,
- will be a great tool for studies of distant clusters and galaxies,
- and an excellent compliment to eROSITA