



LOFAR

and
clusters/starburst galaxies

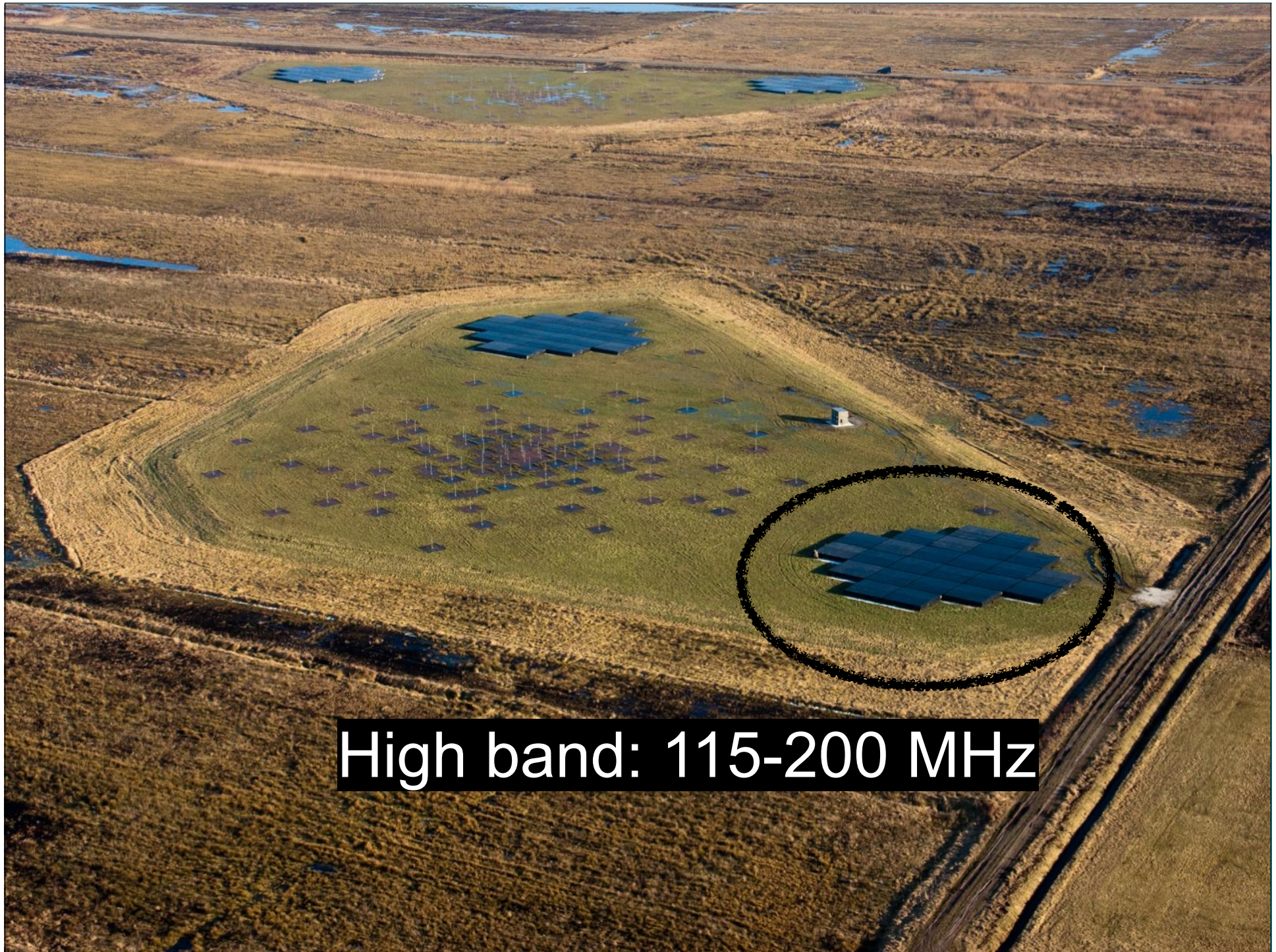
Huib Röttgering
Leiden Observatory
Q: Peter Barthel

Low Band Antenna (LBA) : 10 - 80 MHz



Feb 20, 2011

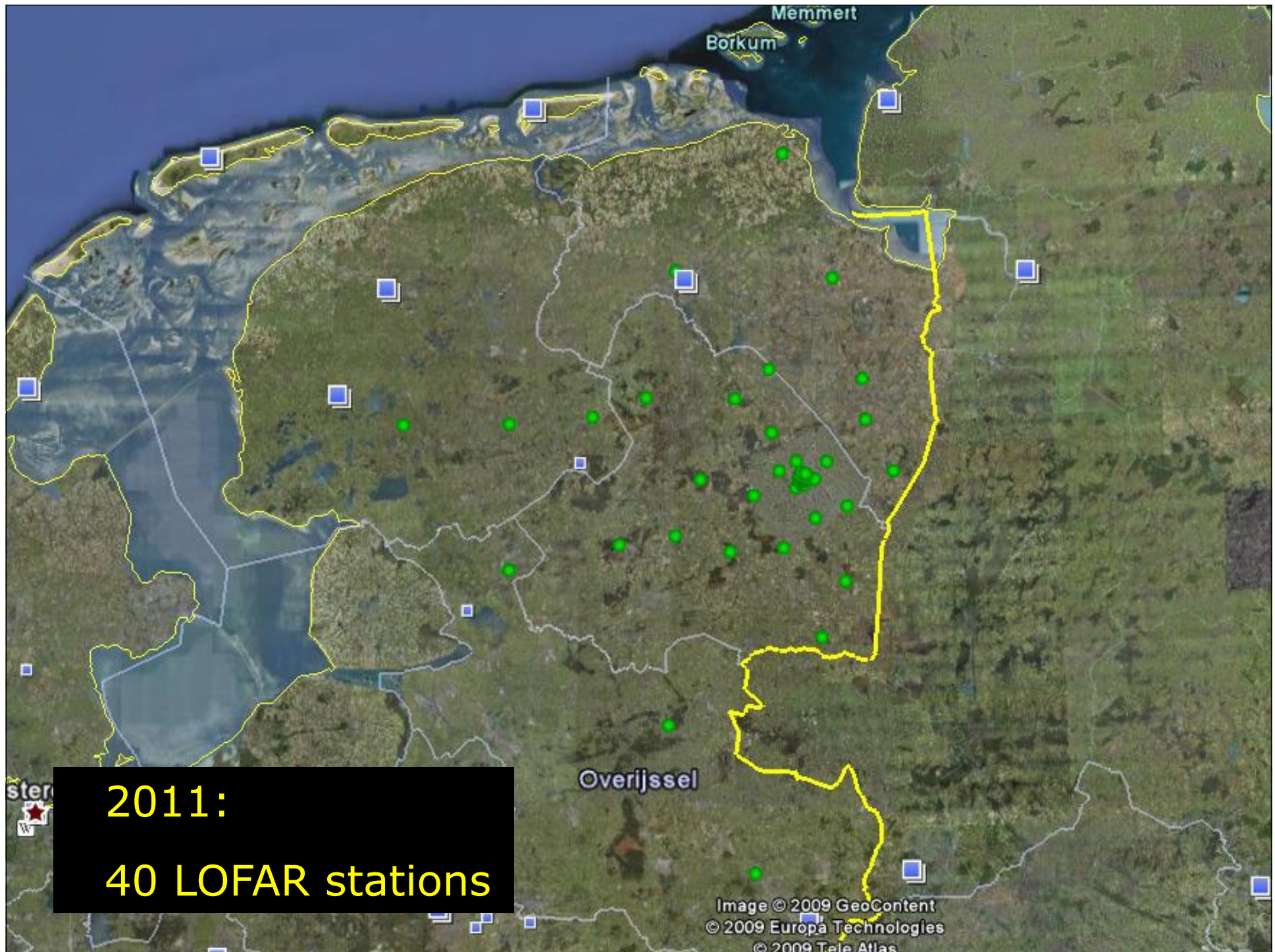




High band: 115-200 MHz



LOFAR Superterp
June 2010

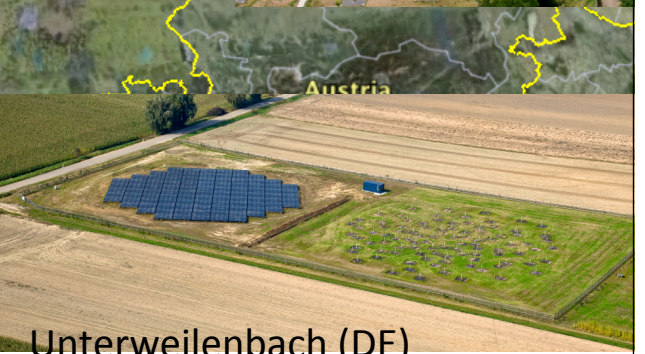
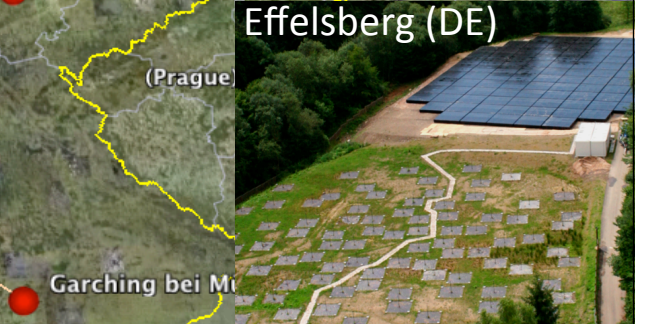
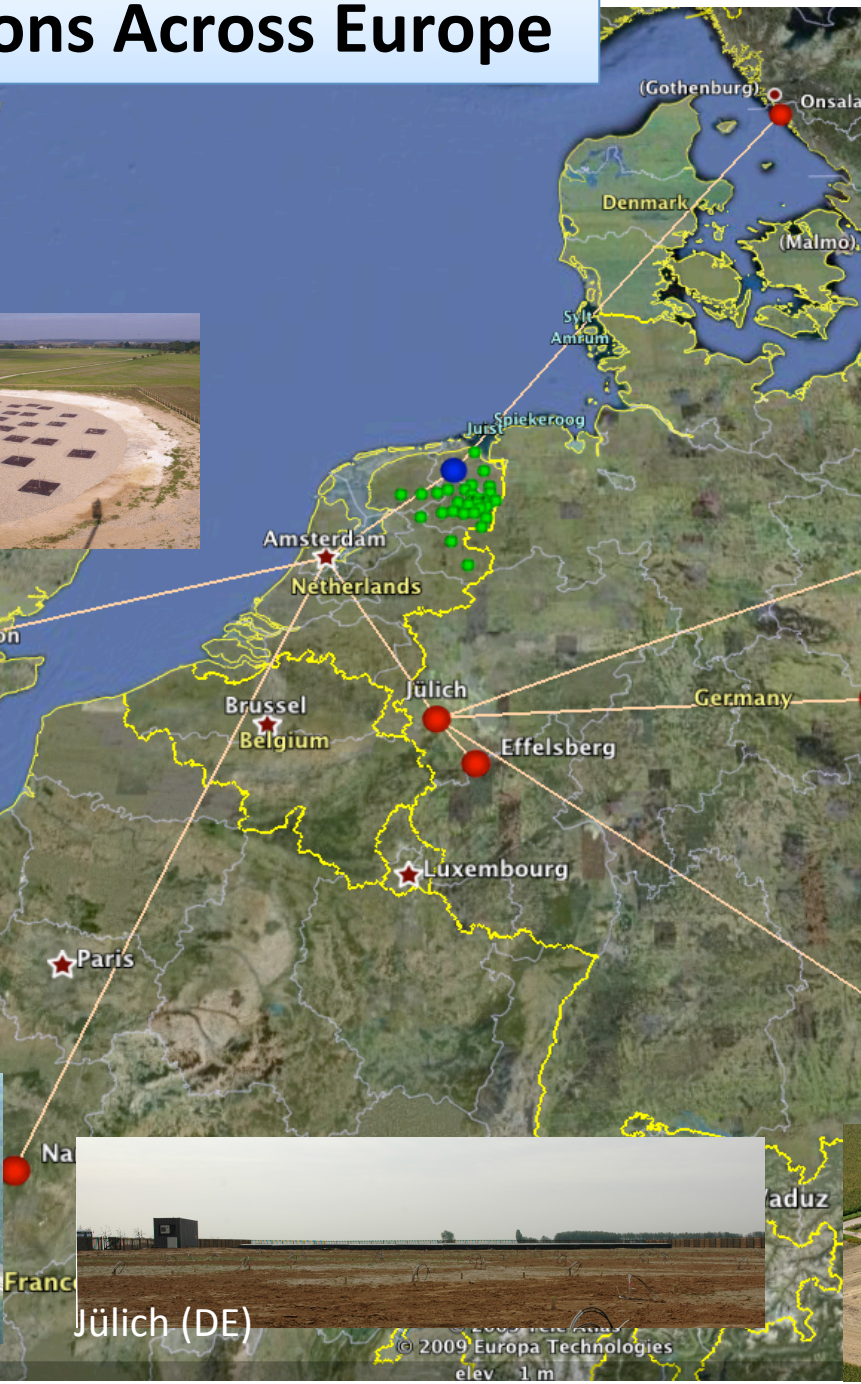


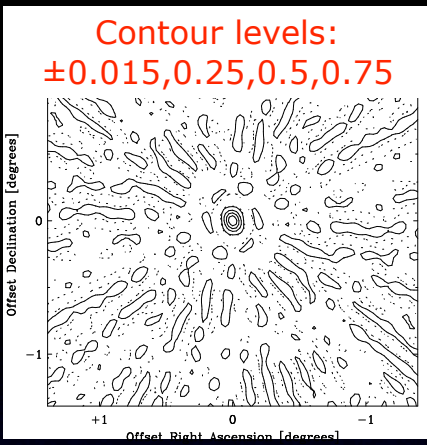
2011:
40 LOFAR stations

LOFAR Stations Across Europe

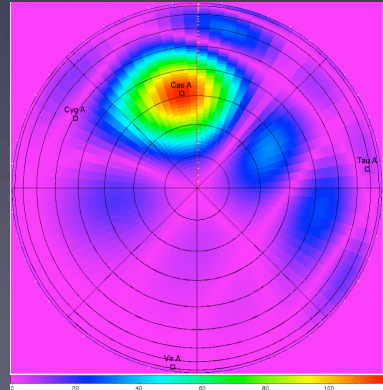
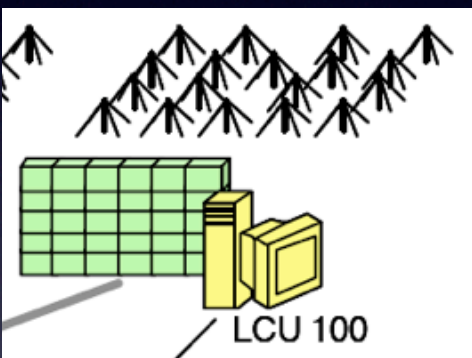
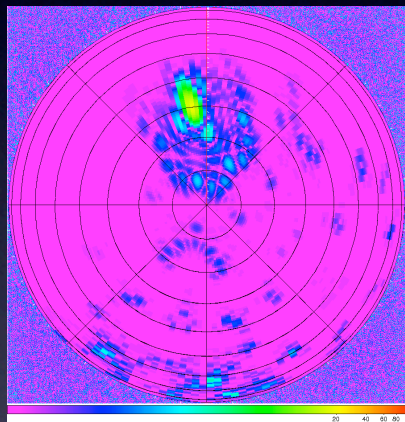


51°57.06" N 2°03'50.68" W





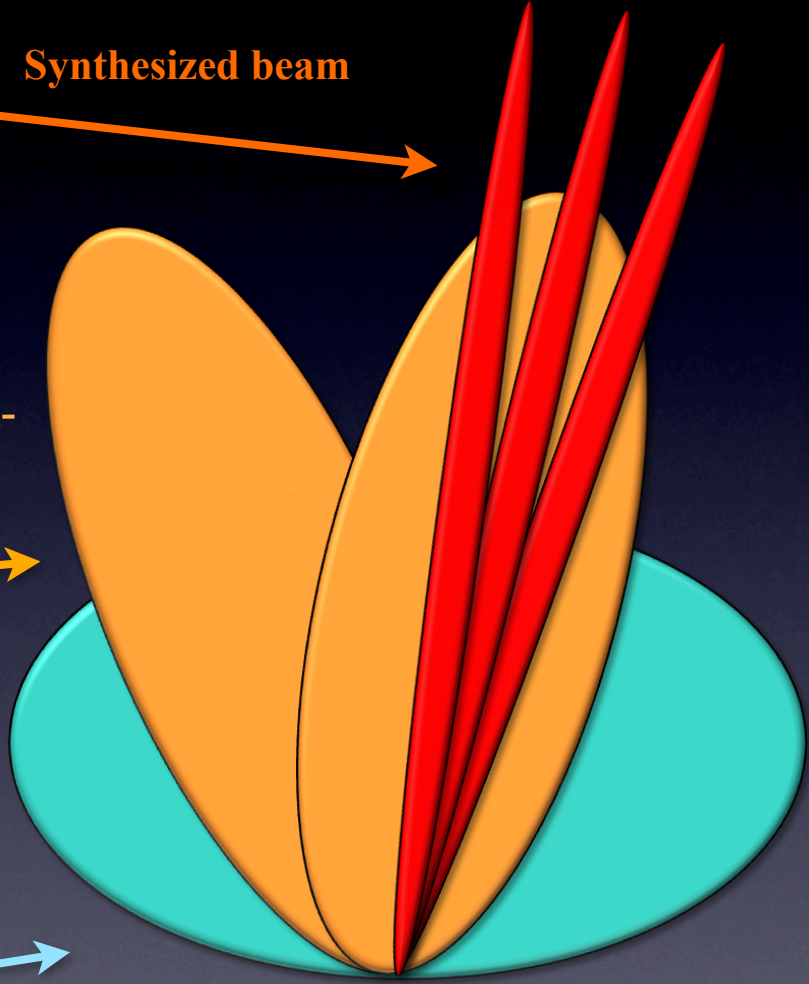
Beam forming: Three Beams



Synthesized beam

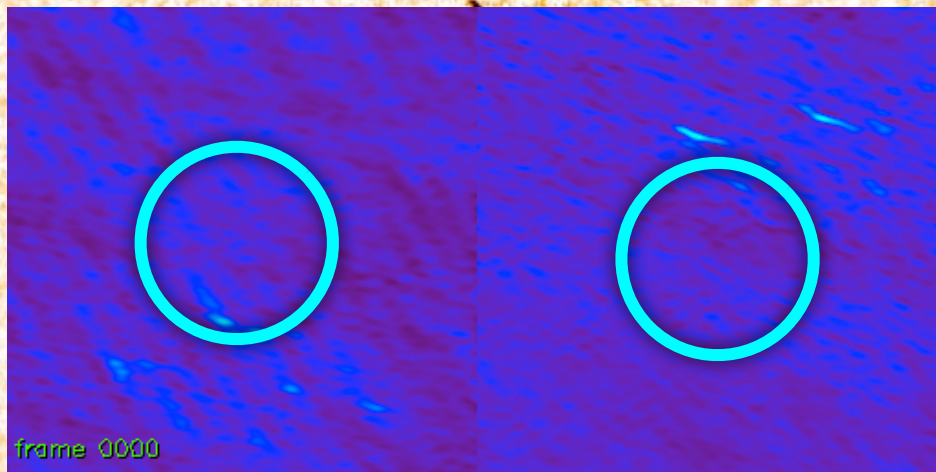
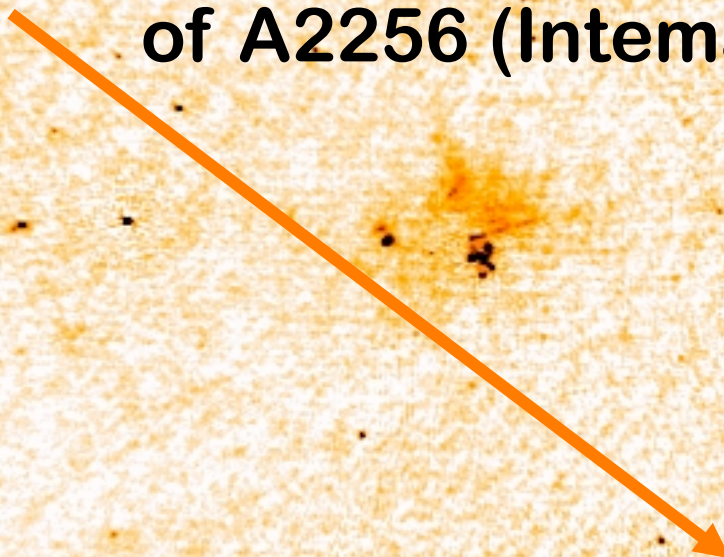
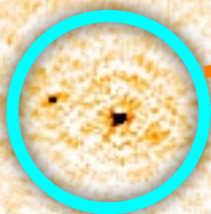
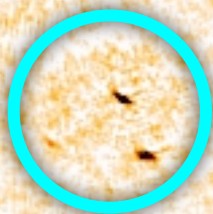
Station-Beam

Antennabeam



**Ionospheric corruption
150 MHz GMRT
radio observations
of A2256 (Intema et 2009)**

3 degrees



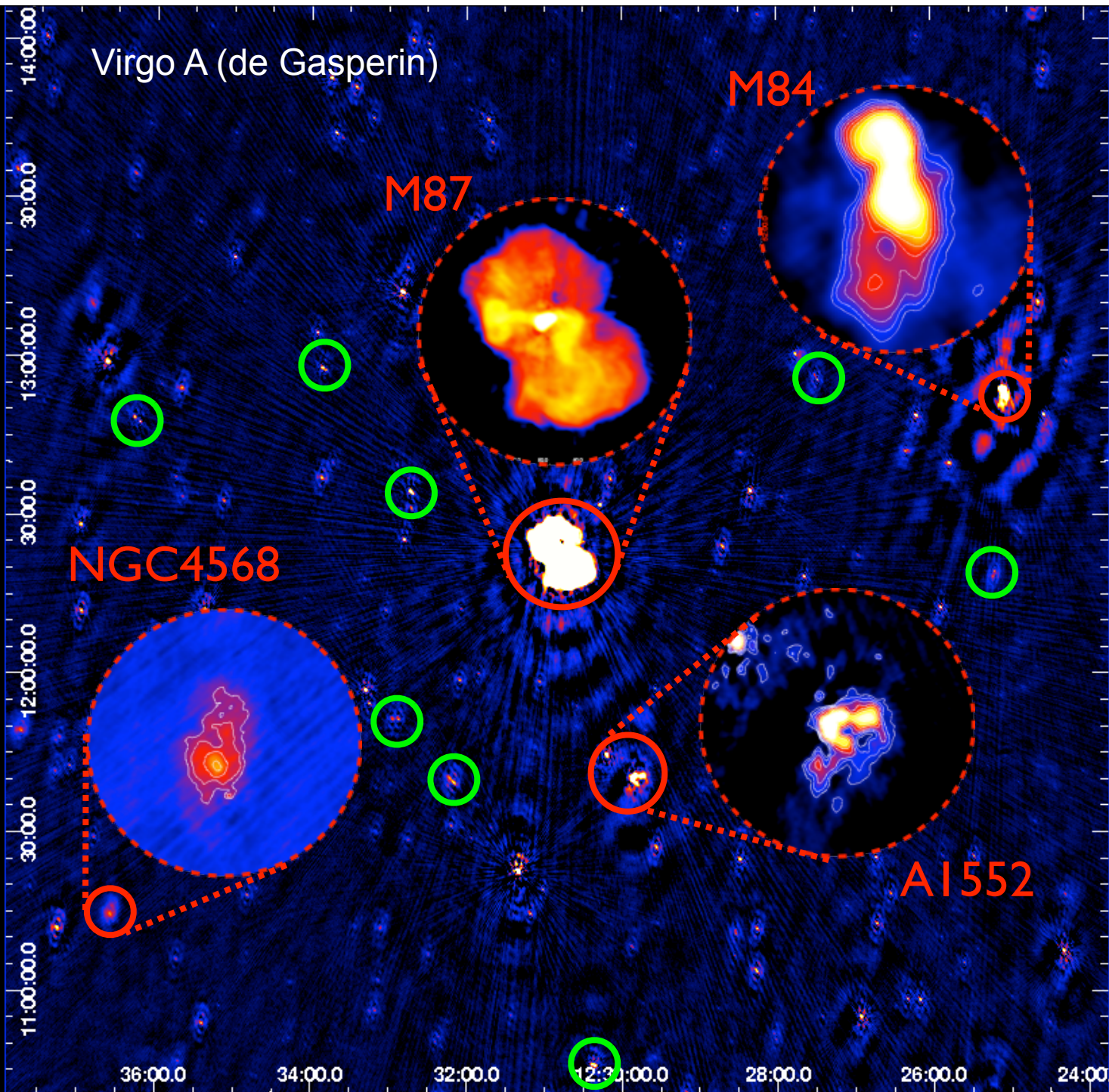
Virgo A (de Gasperin)

M84

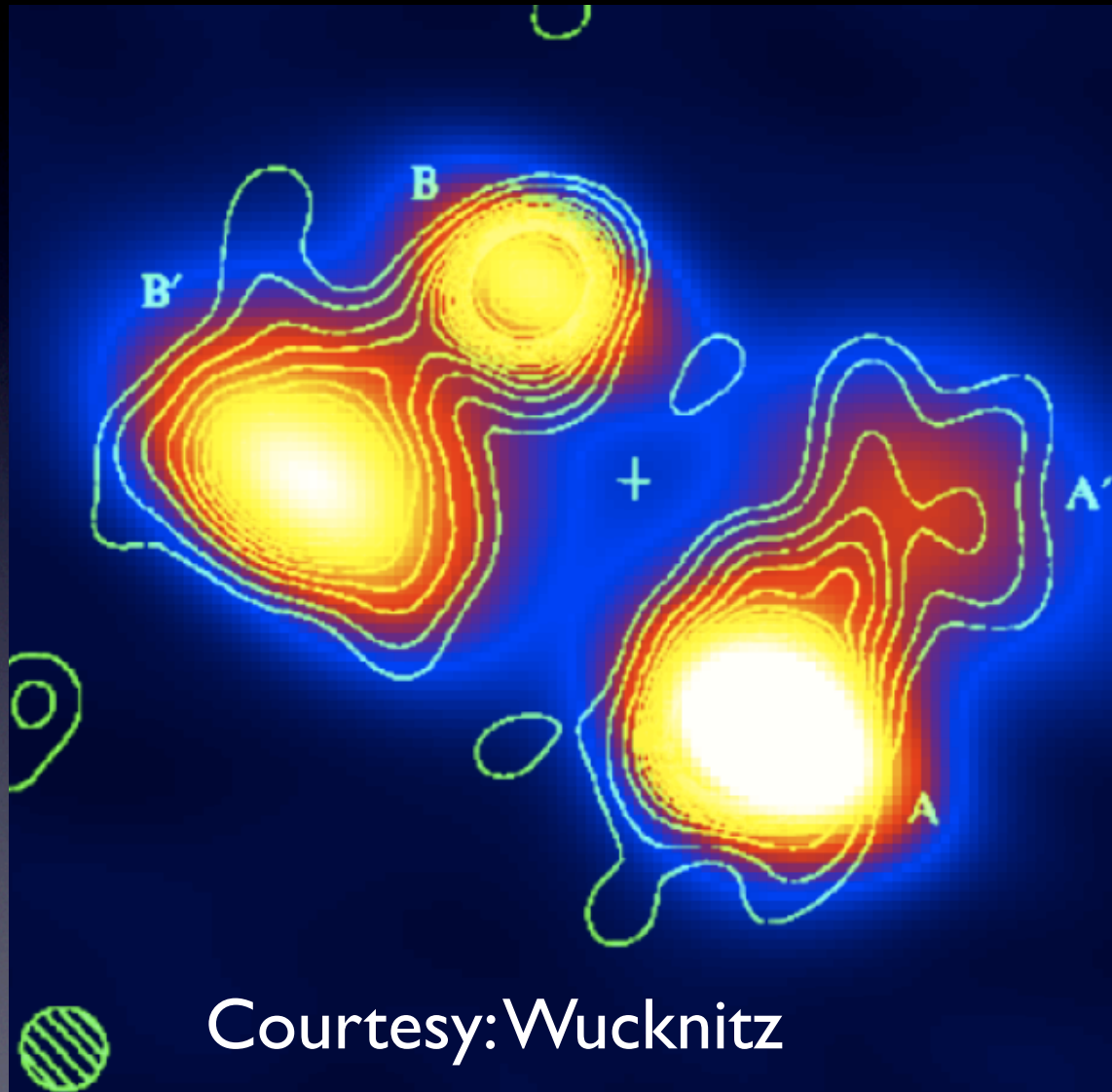
M87

NGC4568

A1552



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

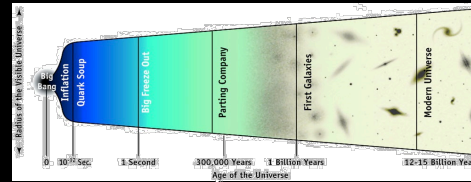


5 NL + 3 DE stations
(Effelsberg,
Unterweilenbach,
Tautenburg)

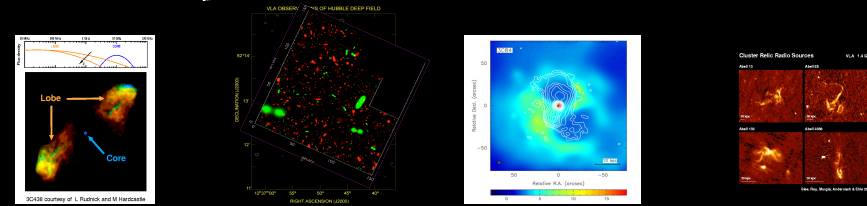
Green contours:
408 MHz Merlin maps

LOFAR- The Key Science

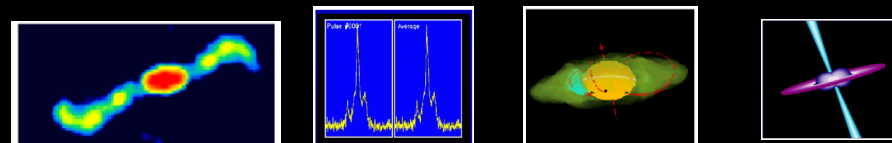
Epoch of Reionisation



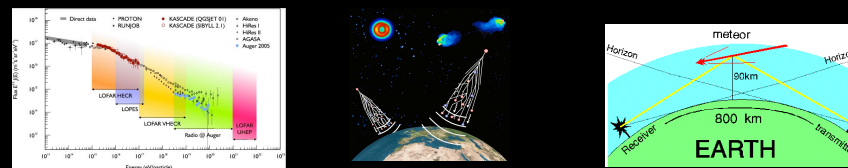
Surveys



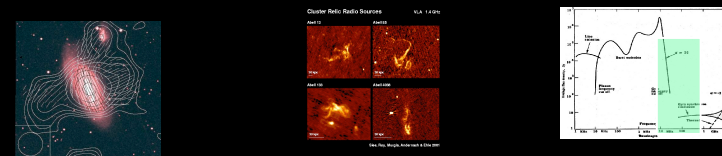
Transients



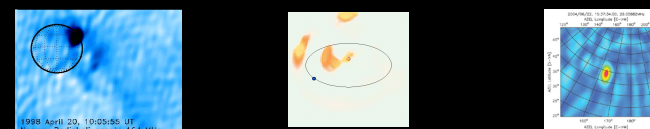
Cosmic Rays



Magnetism



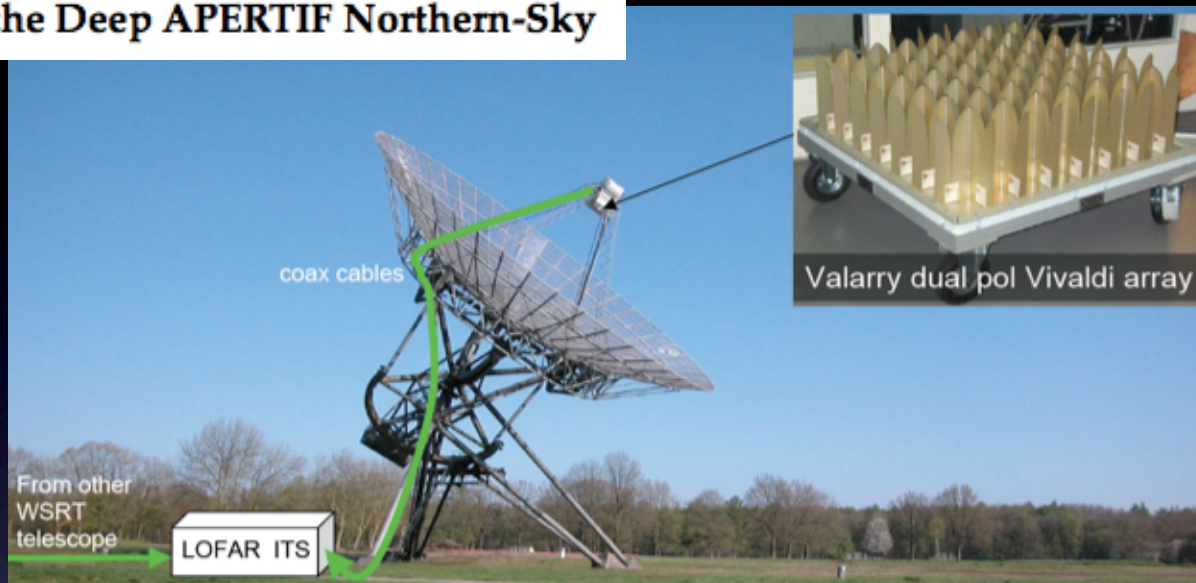
Sun, Space Weather



Wodan

Westerbork Observations of the Deep APERTIF Northern-Sky

10 microJy
rms, $\Delta > 30$



Lead Team: Huub Röttgering, Jose Afonso, Philip Best, Marcus Brüggem, 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 Jamrozny, 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 Pimblet, 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 Umara, Mattia Vaccari, Ed Valentijn, Ilse van Bemmelen, 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

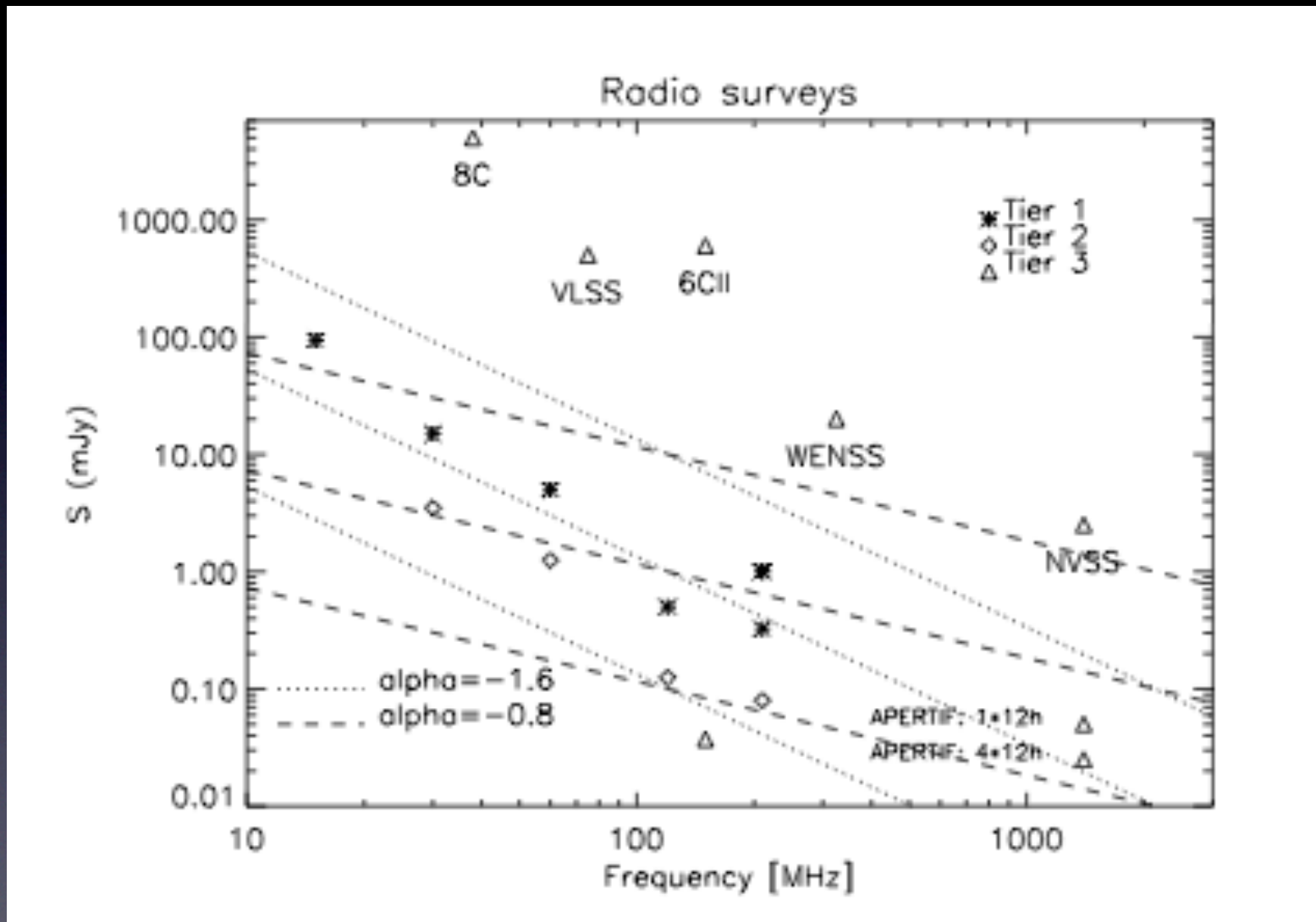
Key frequencies:
15, 30, 60, 120, 150,
200, 1400 MHz

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
<i>Tier 1: The "Large Area" survey</i>										
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
<i>Tier 2: The "Deep" survey</i>										
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
<i>Tier 3: The "Ultra Deep" survey</i>										
150	71	0.0062	48	543798	221	5	28	2.9e+06	3	5,6

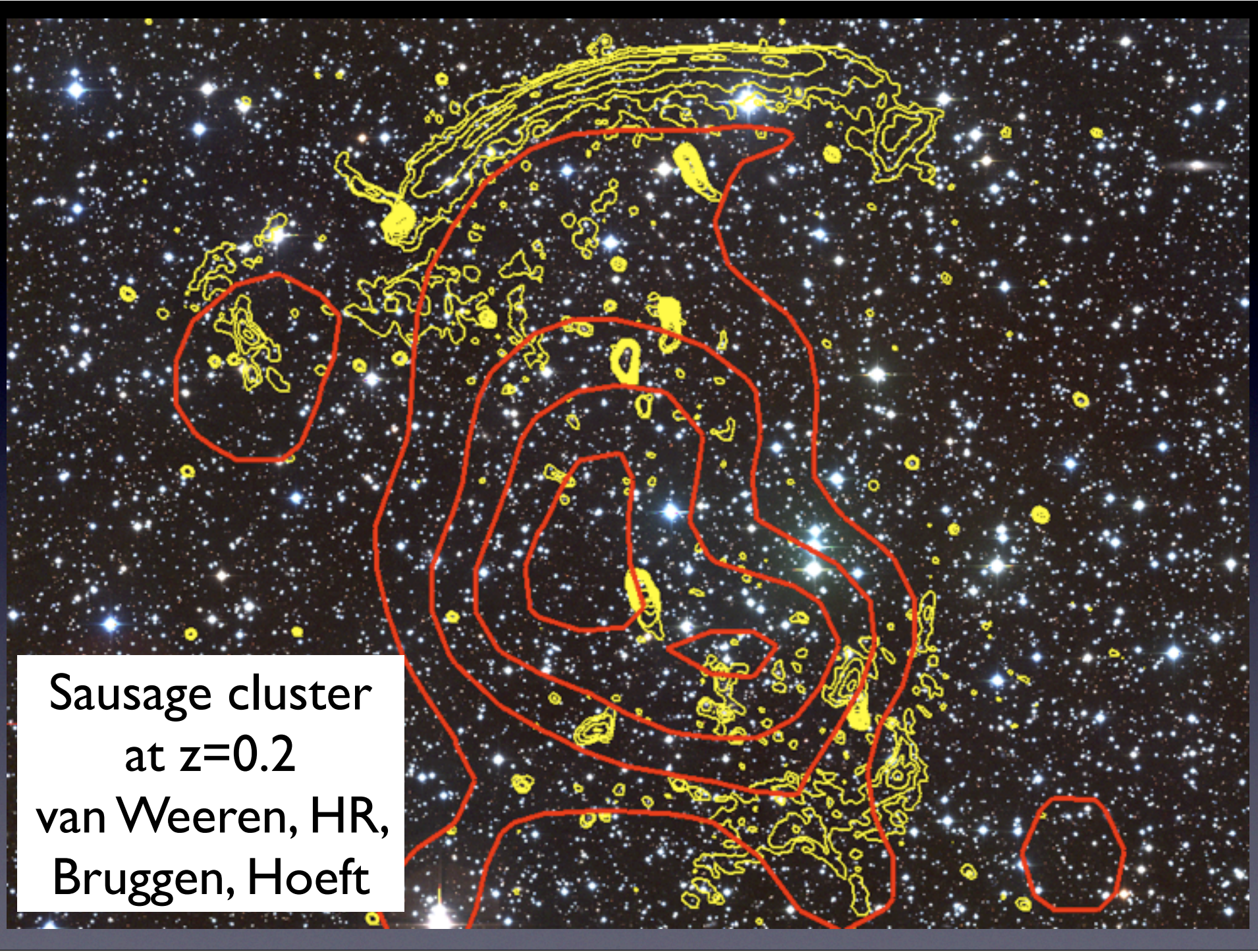
1. The highest redshift radio sources - George Miley: ~100 at $z > 6$
2. Starforming galaxies at moderate and high redshifts- Lehnert/Barthel: 100 protoclusters at $z > 2$
3. Clusters and cluster halo sources - Brüggem/Brunetti: 100 @ $z > 0.6$ @ 60 nearby clusters
4. AGN at moderate redshifts - Philip 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

Surveying the radio sky

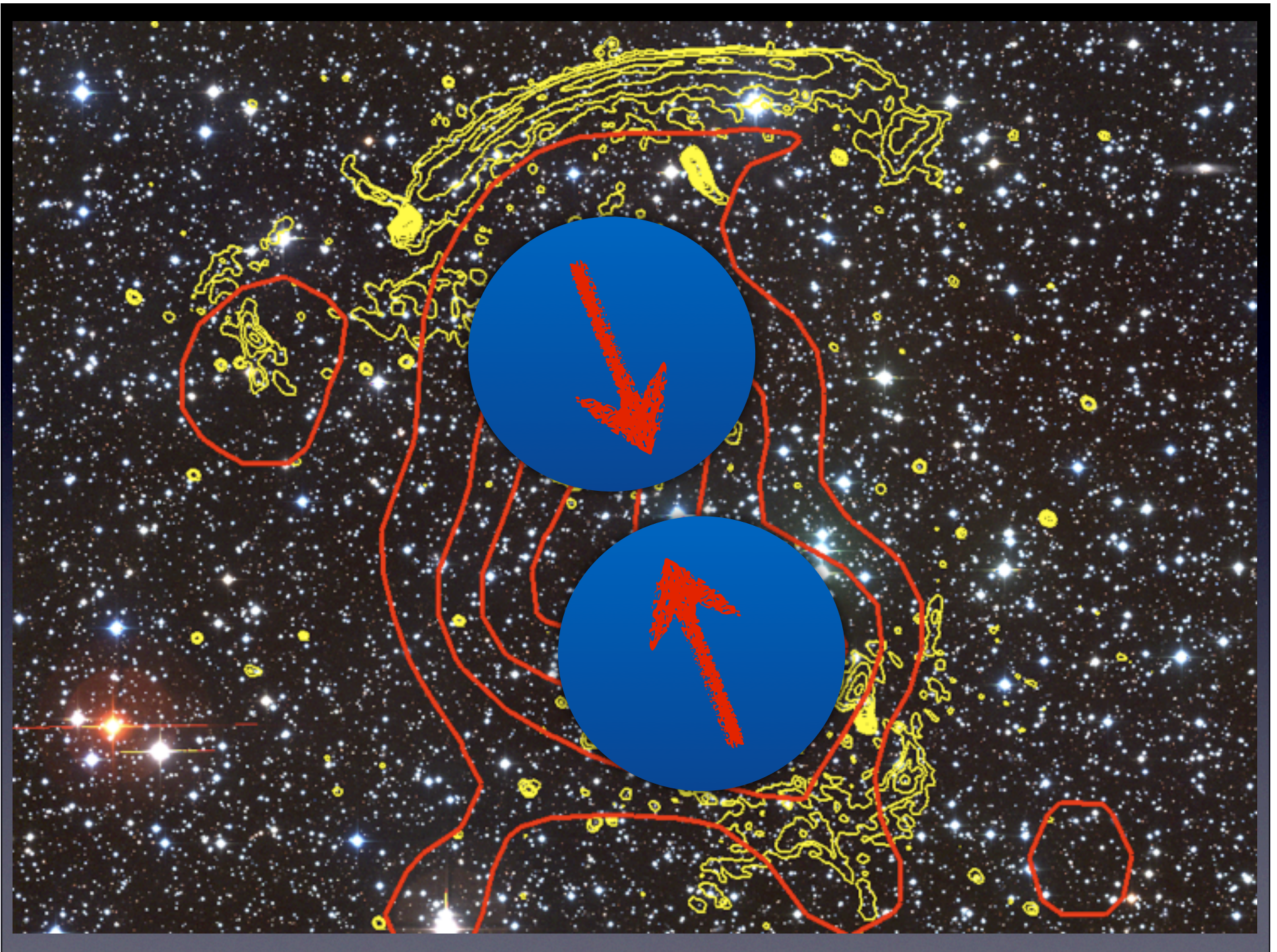
15, 30, 60, 120, 150, 200, 1400 MHz



50 million sources



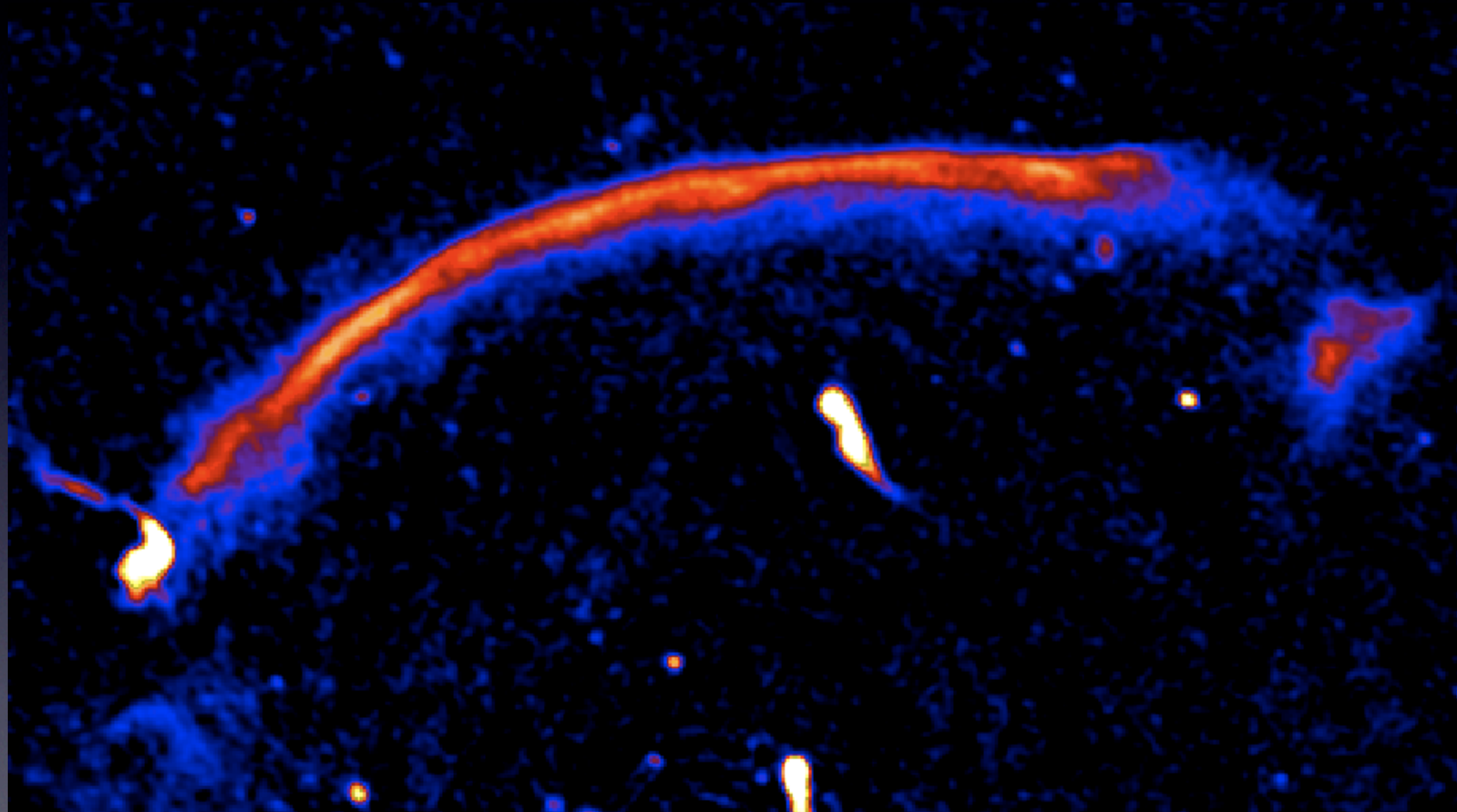
Sausage cluster
at $z=0.2$
van Weeren, HR,
Bruggen, Hoeft

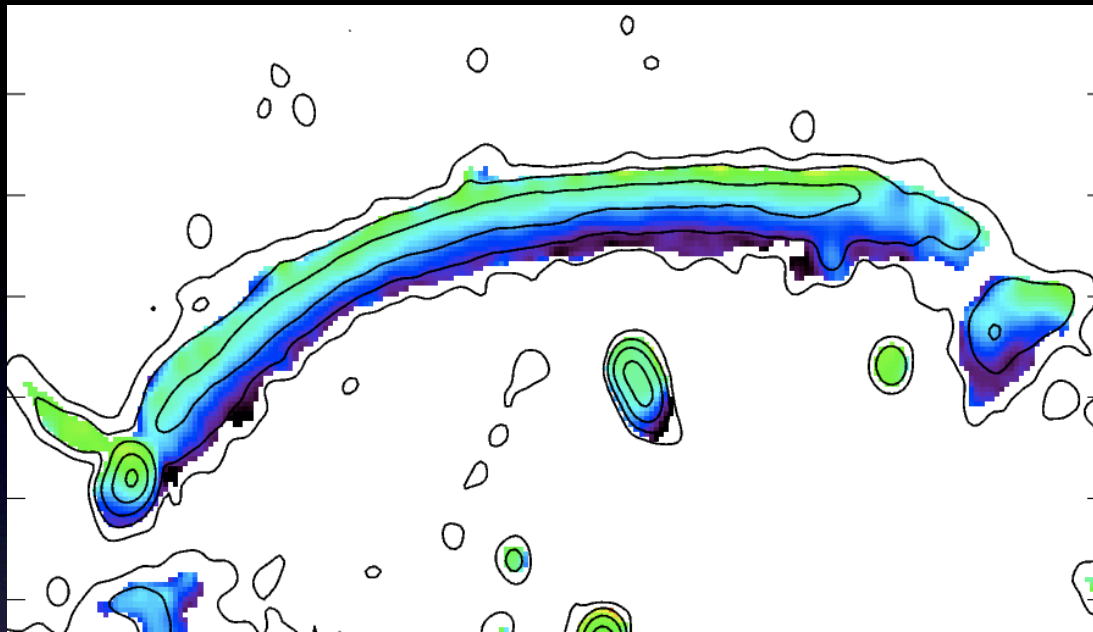




GMRT at 610 MHz

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

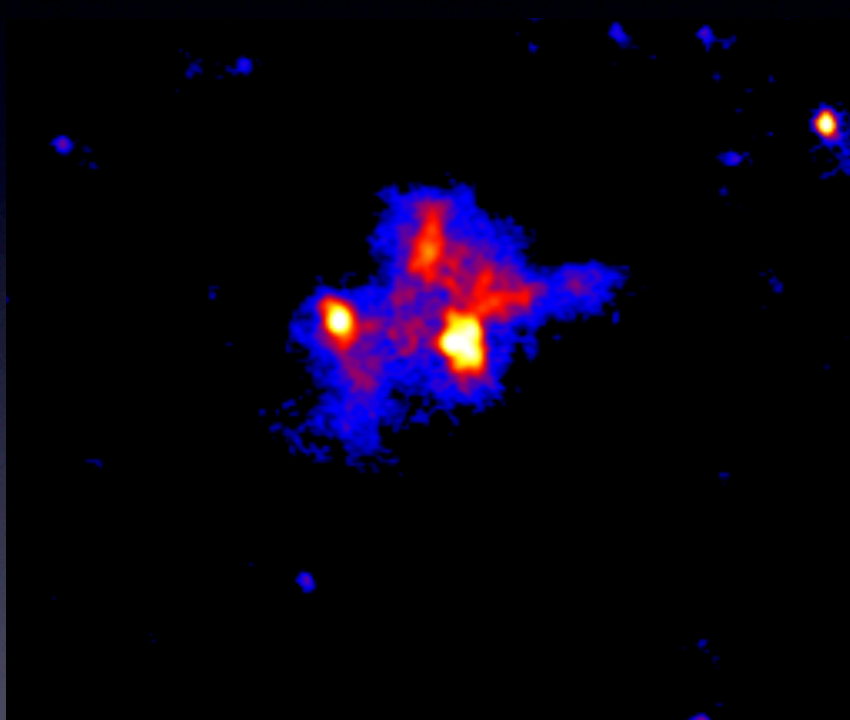
- radio spectral index \rightarrow Mach number 4.6 ± 1
- width \rightarrow downstream velocity ~ 1000 km/s
- aging analysis $\rightarrow B = 5$ microGauss

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

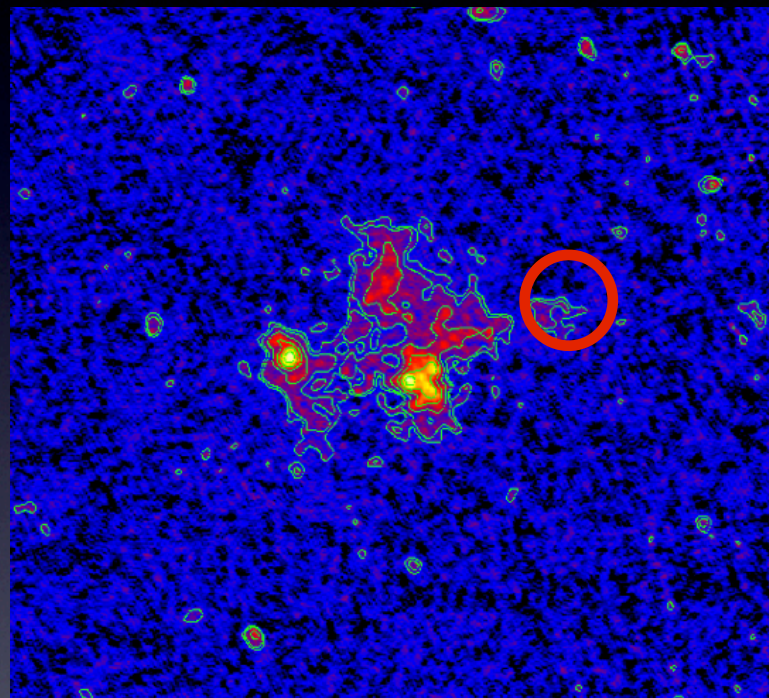
Derived cluster properties

- mass ratio 1.5 : 1 to 2.5 : 1
- impact parameter ≤ 500 kpc
- time since core passage: ~ 1 Gyr
- shock waves seen close to edge-on ($< 10^\circ$)
- ICM not very clumpy at relic location

LOFAR observations of A2256
60-64 MHz, August 2011 (longest baseline 80 km)
A2256: shocked system viewed at ~ 45 deg



30" x 30", noise 15 mJy/beam



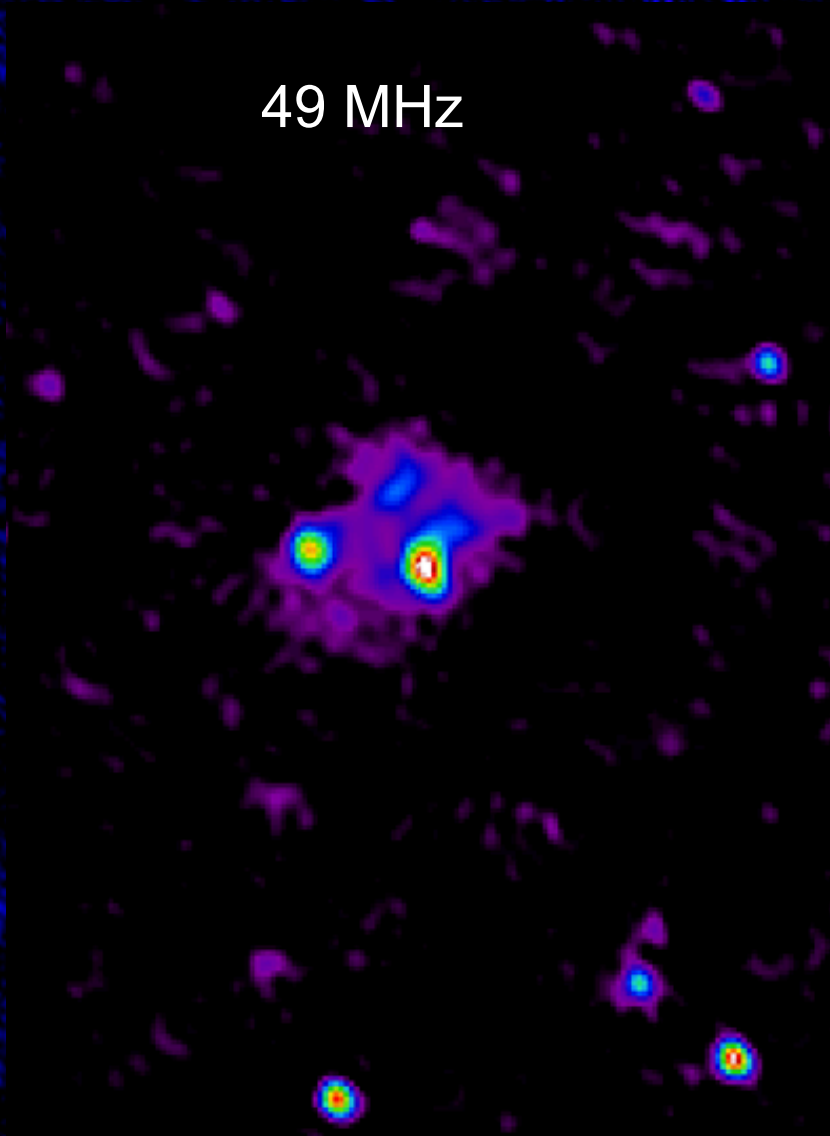
20" x 20", noise 8 mJy/beam

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

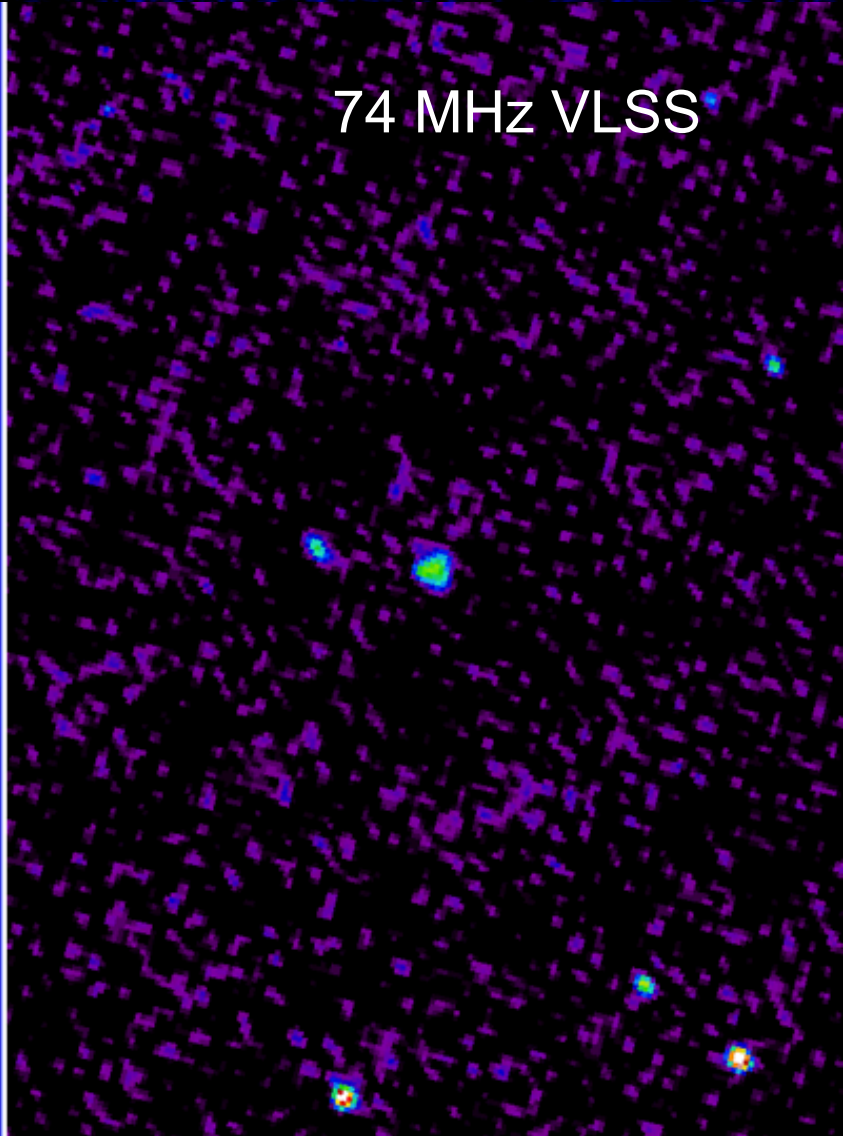
3° 49 MHz (longest baseline 25 km)



49 MHz



74 MHz VLSS

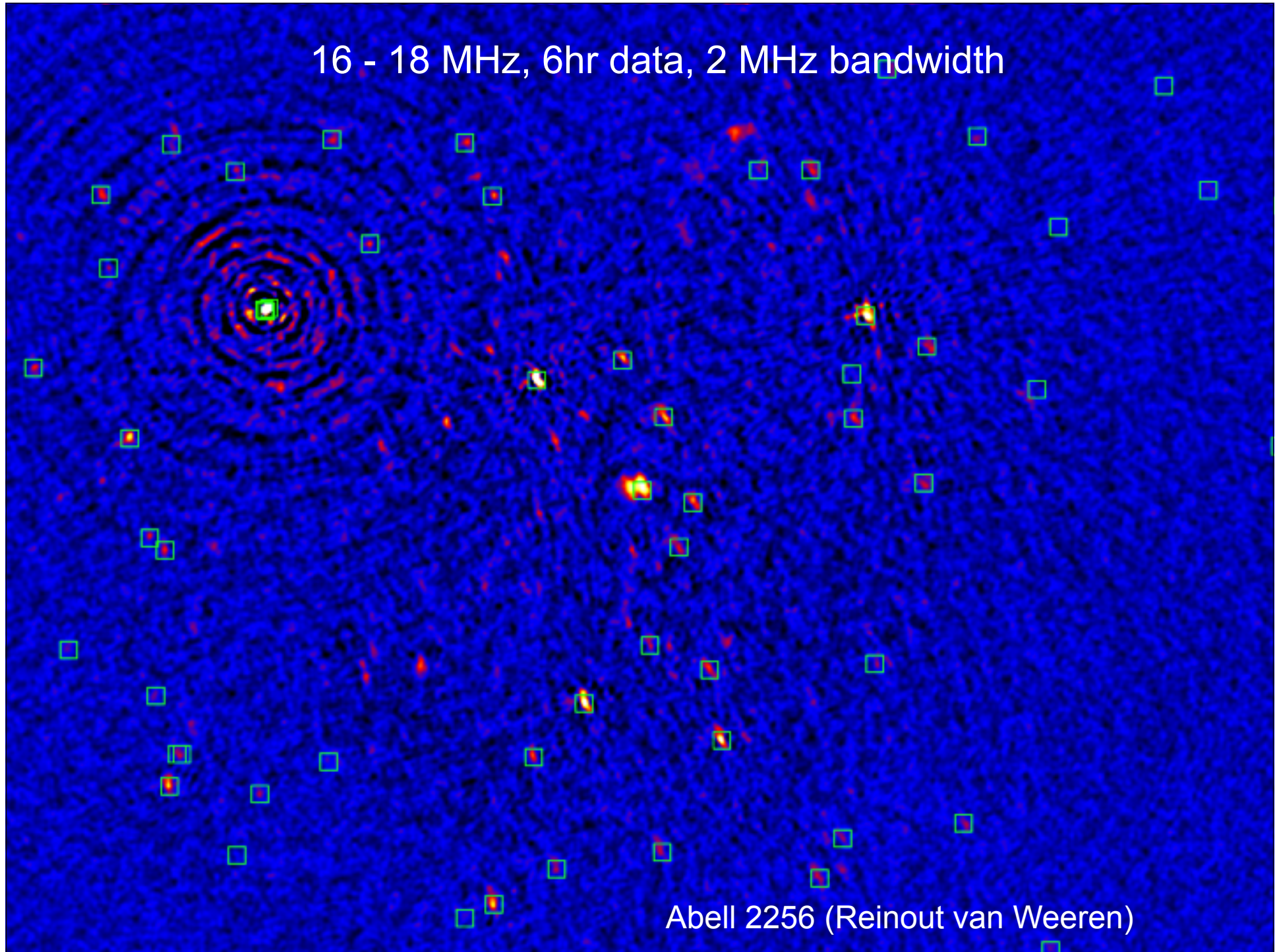


30 MHz

5°

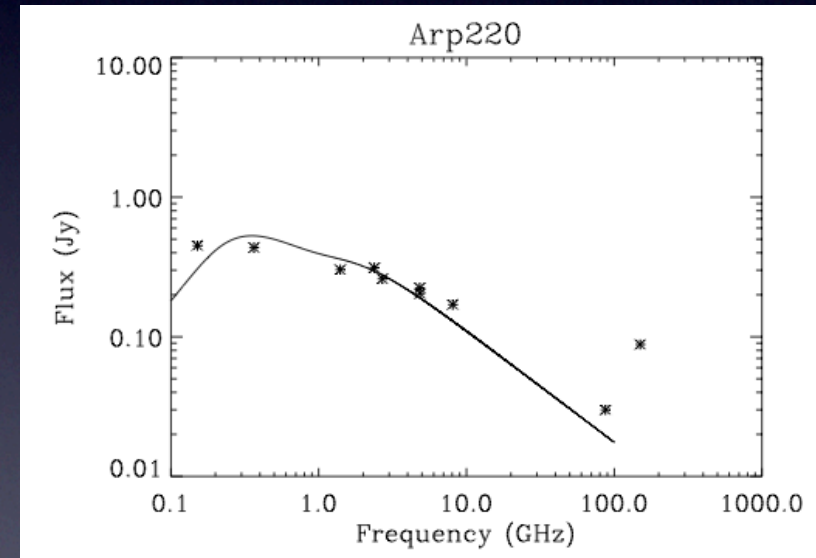
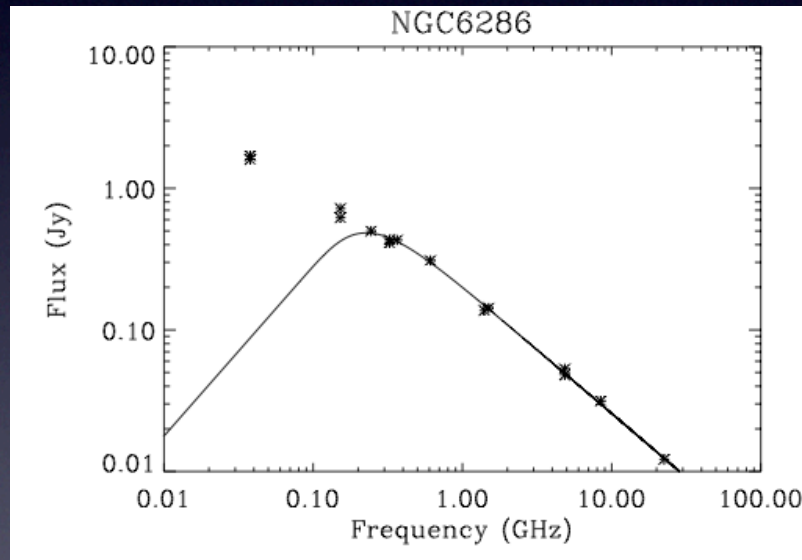


16 - 18 MHz, 6hr data, 2 MHz bandwidth



Abell 2256 (Reinout van Weeren)

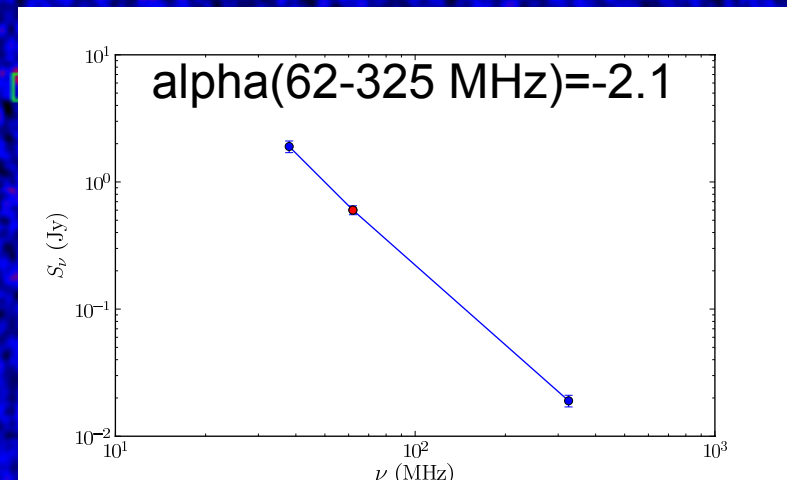
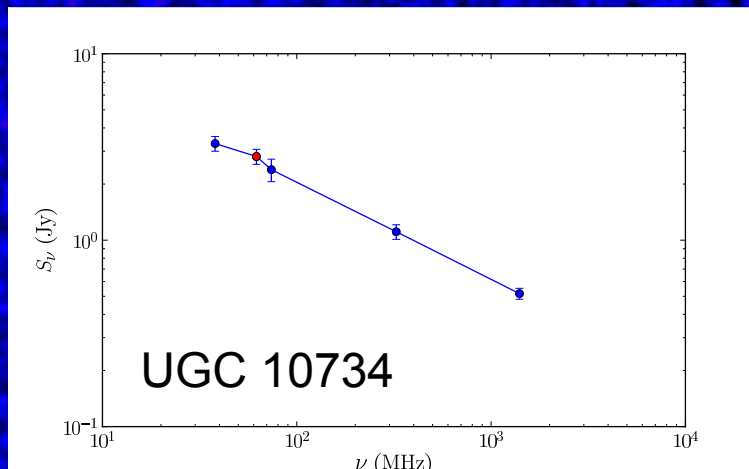
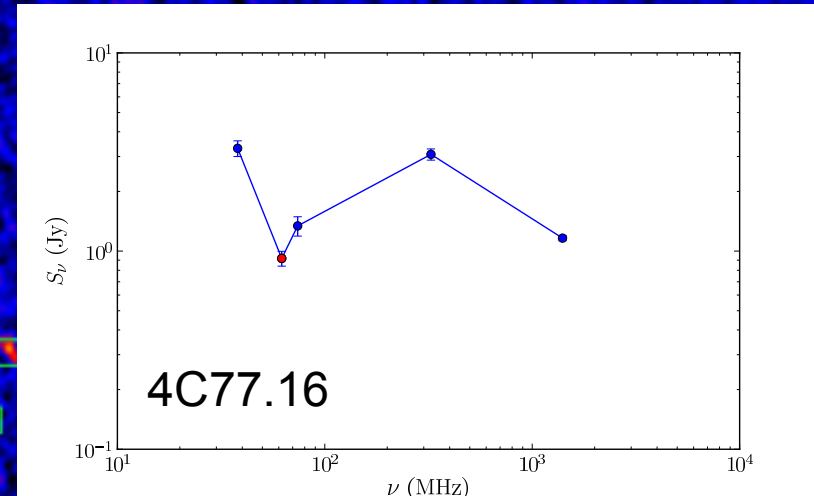
LOFAR and starbursts



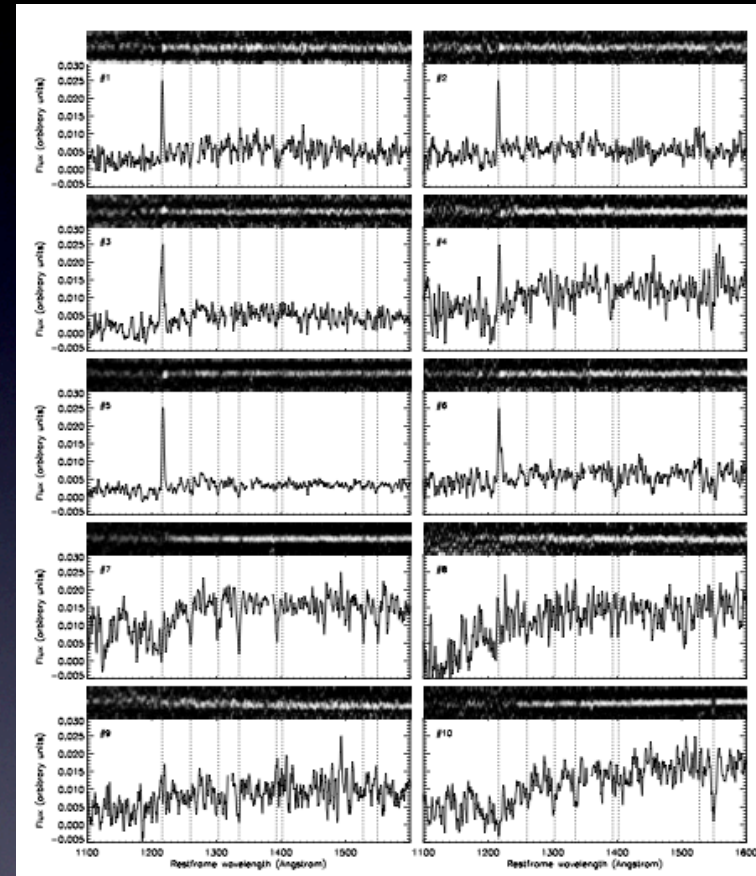
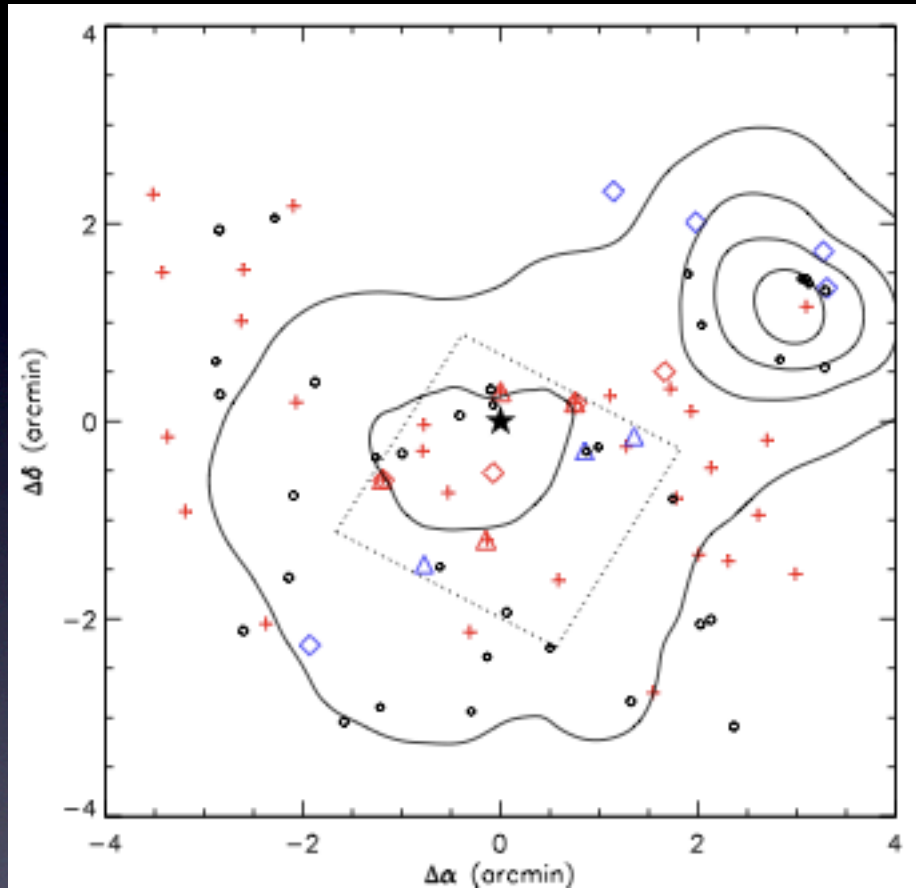
Free-free absorption models by Clemens et al., 2010
overlayed with low-frequency radio data

radio spectra down to 15 MHz

- free absorption
- evolution K-corrected radio-IR



Progenitors of clusters: Protoclusters



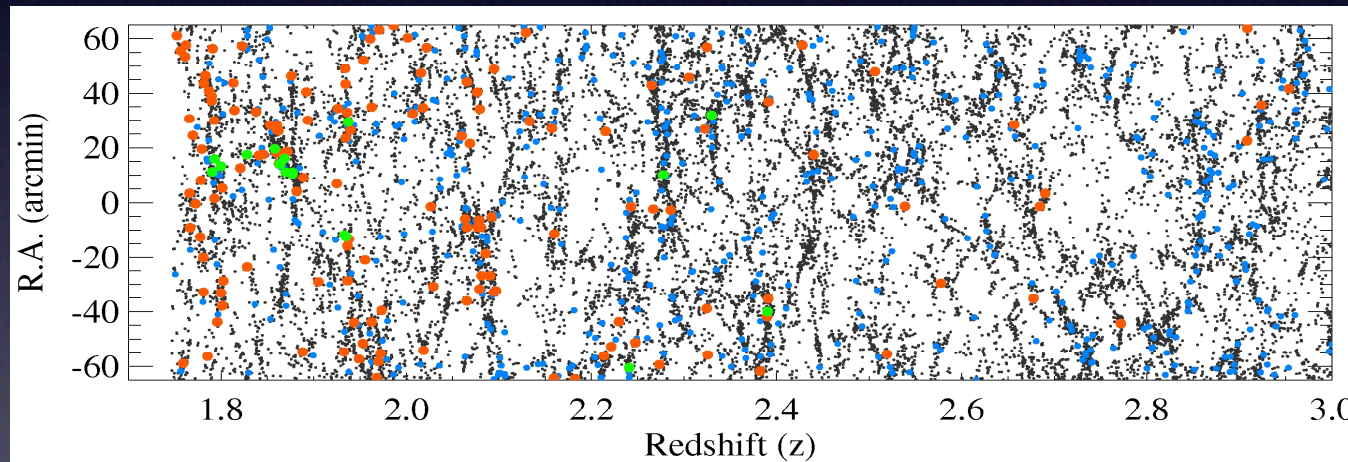
0316-262 ($z=3.1$) two protoclusters at $z=3.10$ and 3.13
contours: confirmed and unconfirmed LBGs using the VLT
Kuiper et al. 2011, in prep.

Using the radio - IR correlation to locate and study proto-clusters

Aim: 50 proto-clusters of starbursts with SFR $\sim 10 M_{\odot}/\text{yr}$ at $z=2-3$

Science: evolution of the cosmic star formation history in high and low density environments

Survey: 5 Deep pointings at 150 MHz



Simulations of LOFAR and Herschel observations of distant galaxies based on the simulations of the Virgo Consortium. Green are the proto-cluster galaxies detectable by LOFAR and Herschel, orange detectable both by Herschel and LOFAR, blue are the LOFAR only detections (with Overzier and Groves)

$13^\circ \times 13^\circ$

6h, 115-163 MHz, 25 stations, 0.2 mJy

Yatawatta et al.

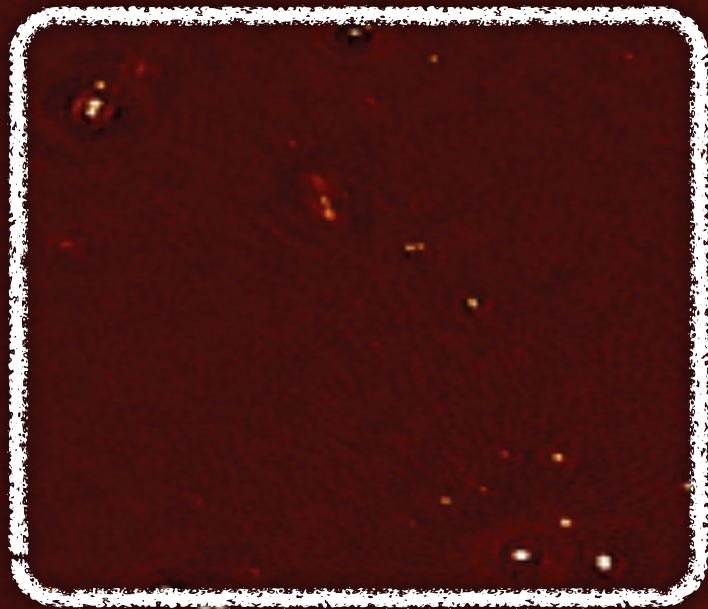
$2^\circ \times 2^\circ$

Within factor 1.5 of
thermal noise!

$13^\circ \times 13^\circ$

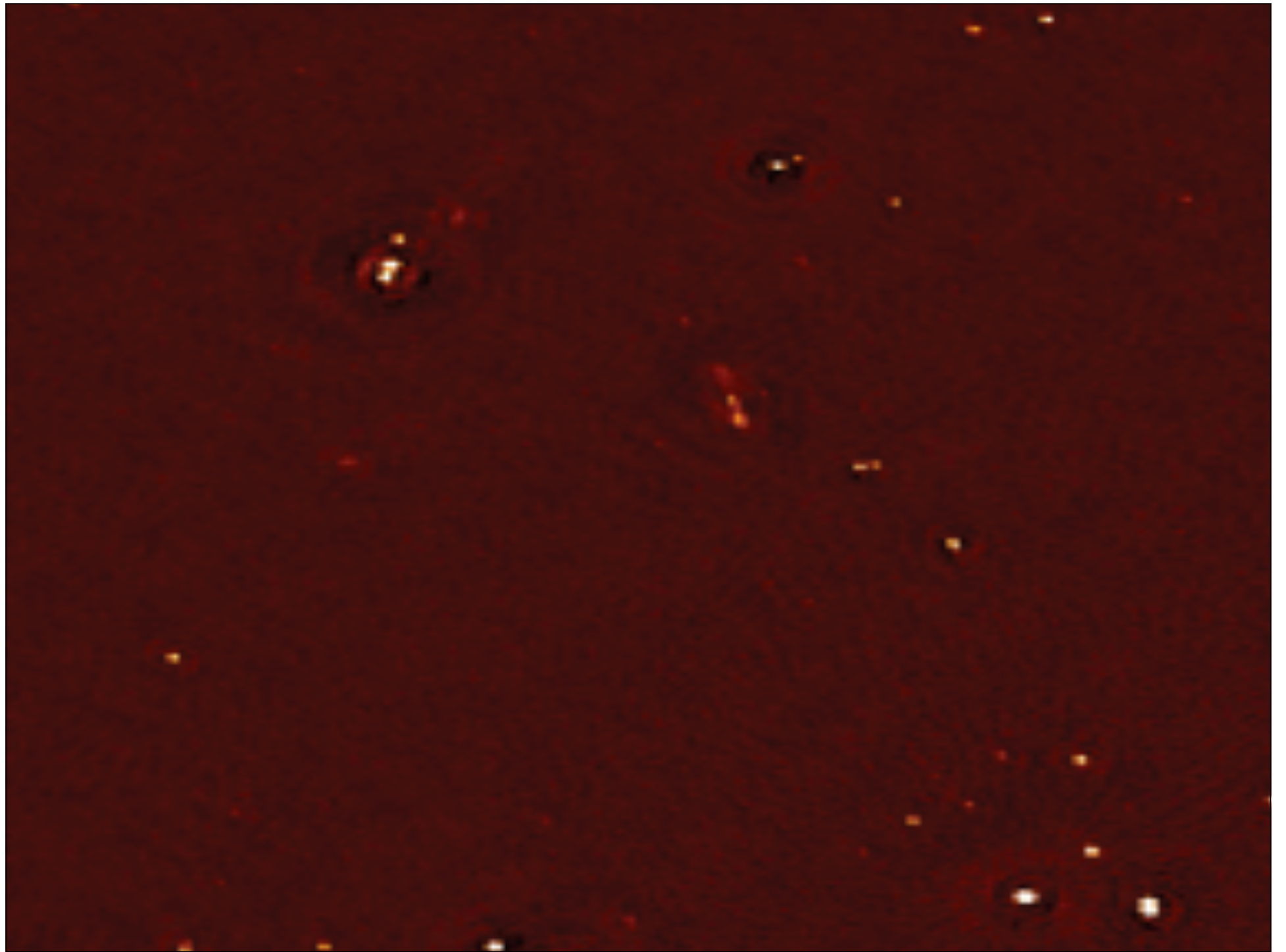
6h, 115-163 MHz, 25 stations, 0.2 mJy

Yatawatta et al.



$2^\circ \times 2^\circ$

Within factor 1.5 of
thermal noise!



Conclusion

- LOFAR works!
- and will be a great tool for studies of distant clusters and galaxies