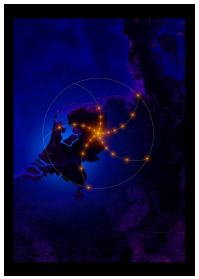
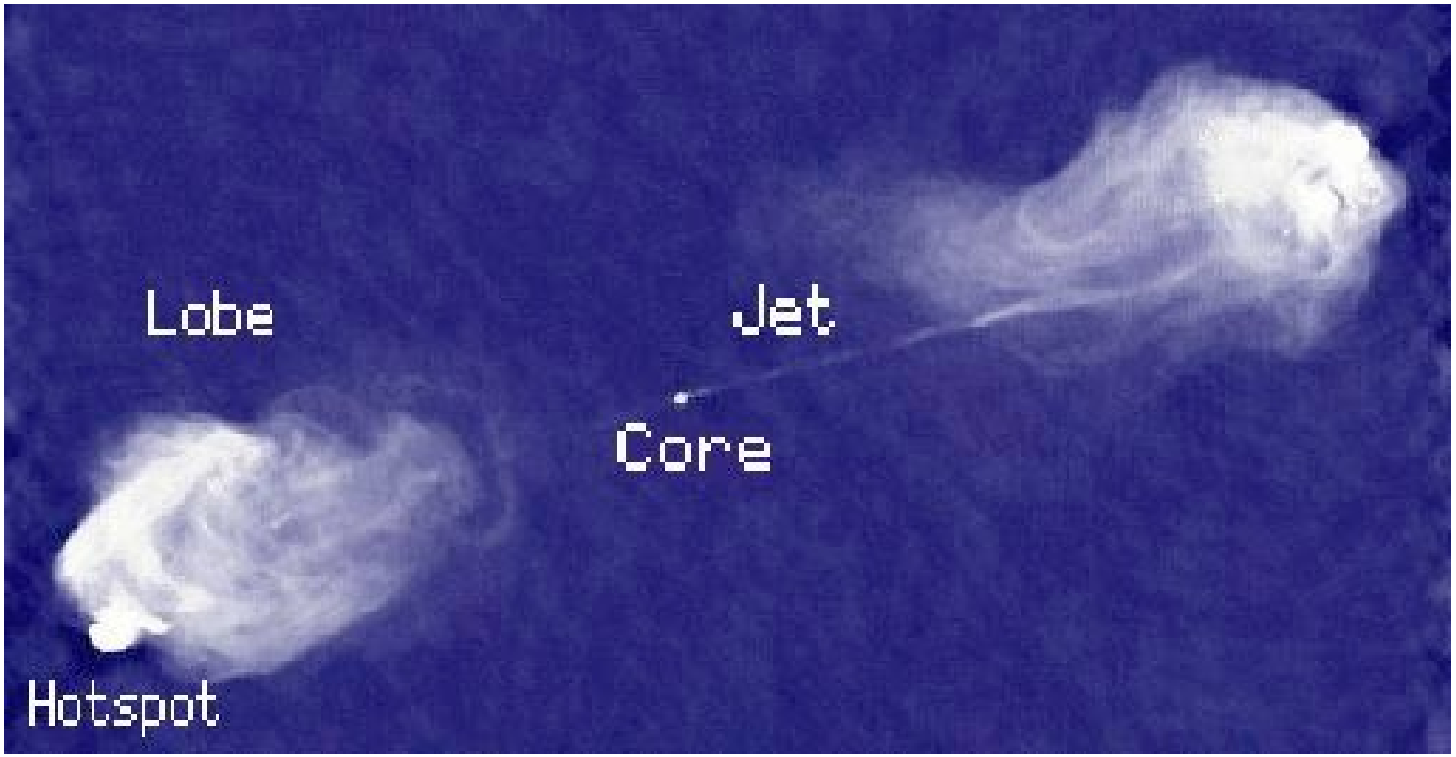


LOFAR surveys

Probing the formation and evolution of massive galaxies, AGN, and clusters

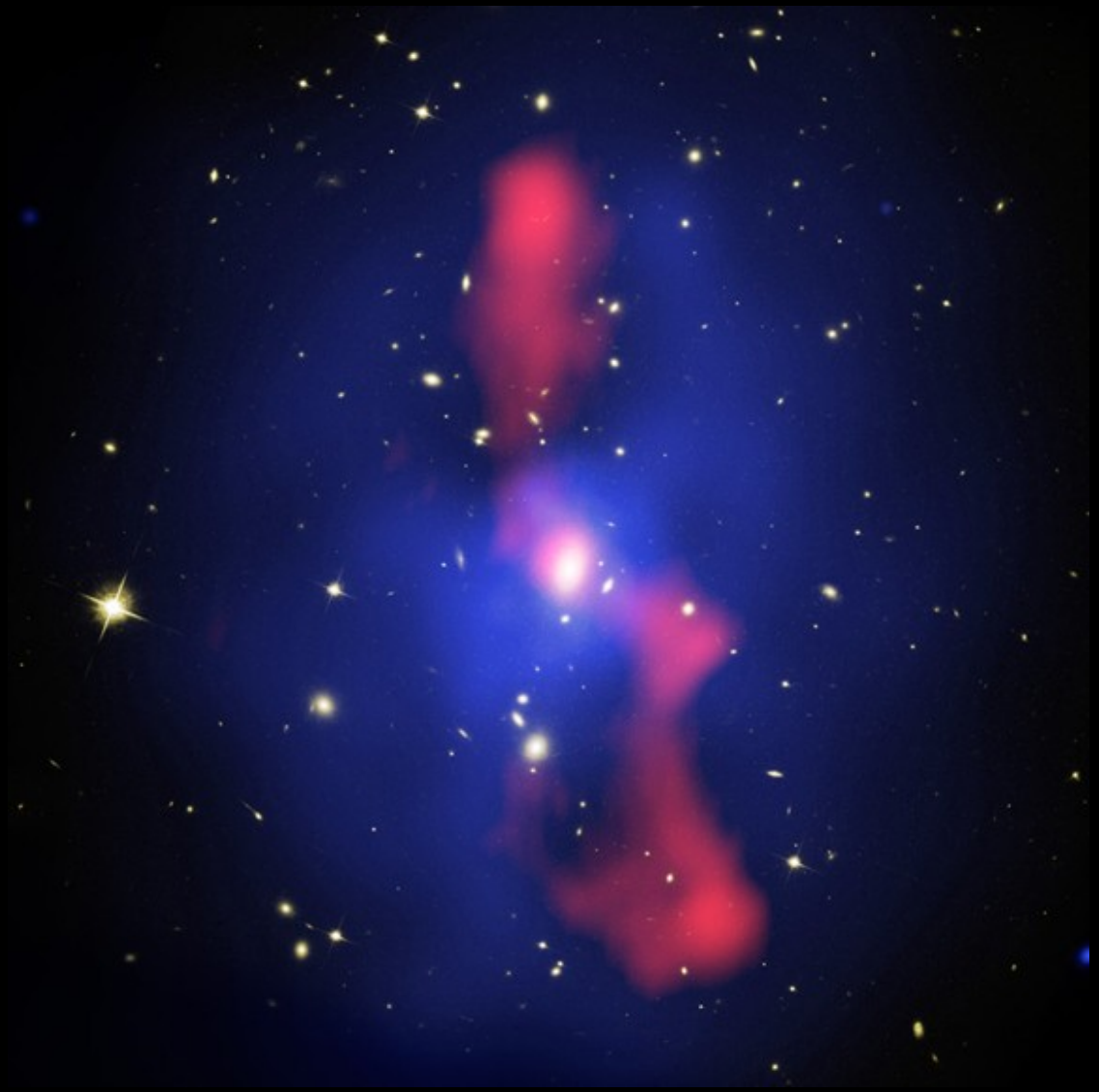
Huub Röttgering
Leiden Observatory

Radio Galaxies



Probes of formation of black holes and massive galaxies

Clusters of galaxies



Red: radio emitting synchrotron plasma

Blue: X-ray gas

White: galaxies

Questions

- Physics
- Formation and evolution

LOFAR's unique capabilities

- **Very Low Frequencies**
  - **Detection of highest redshift objects (z=10)**
- **High angular resolution**
  - **Physical processes**
  - **Identification with optical and IR observations**
- **Enormous Field of View**
  - **Detection of rare as well as large number of objects**
- **Sensitive polarization measurements**
  - **Magnetic fields**
- **Low-Frequency Radio Spectroscopy**
  - **Neutral gas in the early universe**

Overview

- Why?
- LOFAR performance
  - Ionospheric issues
- Key science
- Additional science
- Resulting surveys
- Organization

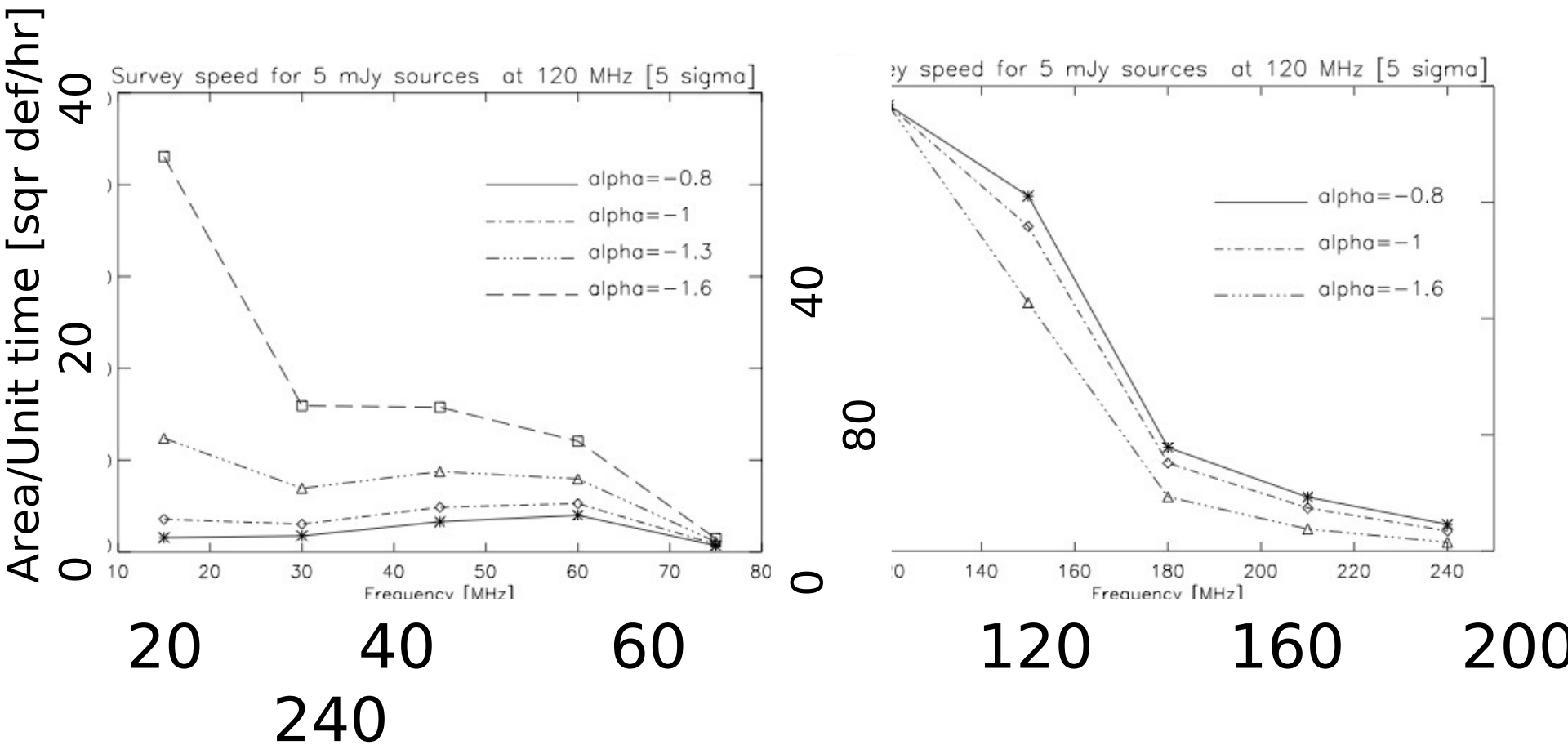
Why surveys?

- LOFAR is a natural survey instrument
  - Large field of view: 30 MHz : ~10 degrees
  - Every pointing contains a number of Abell and NGC galaxies
- Low radio frequency imaging is all sky imaging
  - Cf Hipparcos, Gaia
  - Need information from a large fraction of the sky for proper calibration of for example the ionosphere
- A natural compliment
  - to other LOFAR key programs (Reionisation, transient surveys)
  - to IR missions (Spitzer, Herschel), dark energy missions (Euclid etc.), Planck, JCMT+SCUBA2, optical/IR surveys etc.
- Data reduction is a real challenge and computer intense: delivering final data products is a real challenge

A well defined set of surveys will maximize the scientific usage of LOFAR (cf. Sloan)

Note: there is also open time

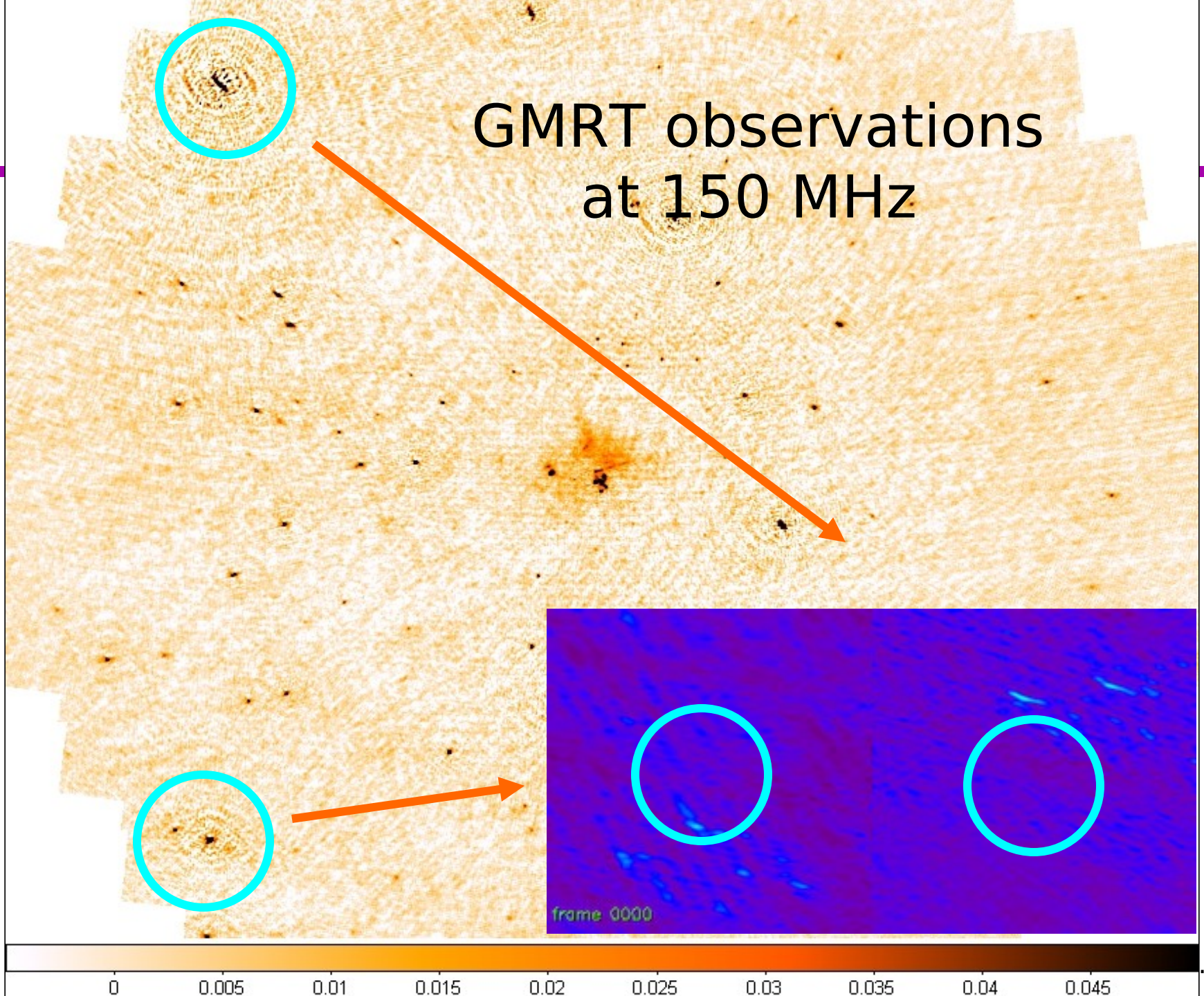
Survey speed (100 km; 1 beam 8MHz)
Sweet spots: 15-60 MHz (!) and 120 MHz



Based on Pandey, Nijboer et al. 2008

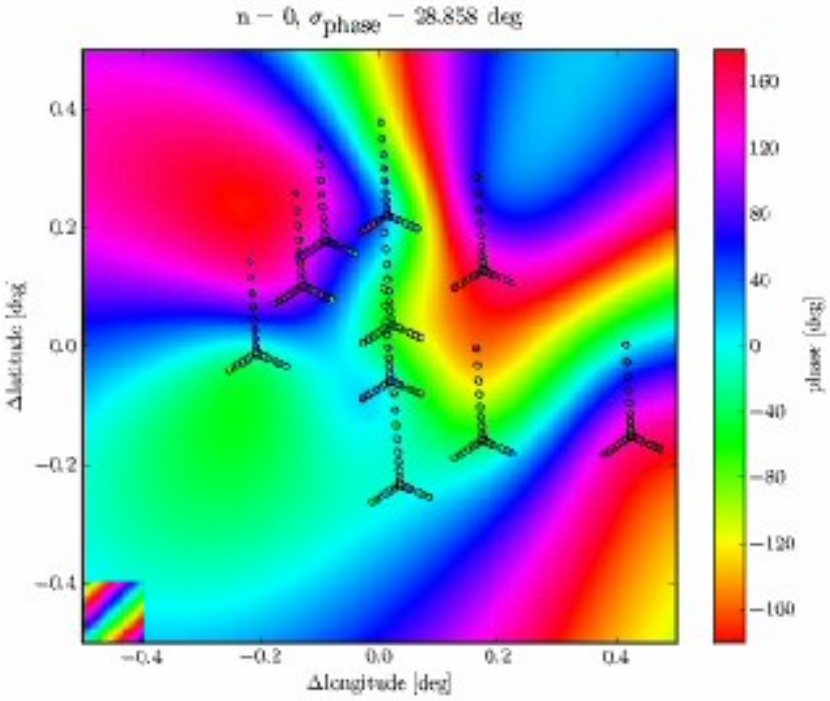
Cautionary notes

- Variation of sky brightness
- Tapering of the station beam to reduce side lobe levels
- Low elevation operations
- RFI
- Ionospheric calibration

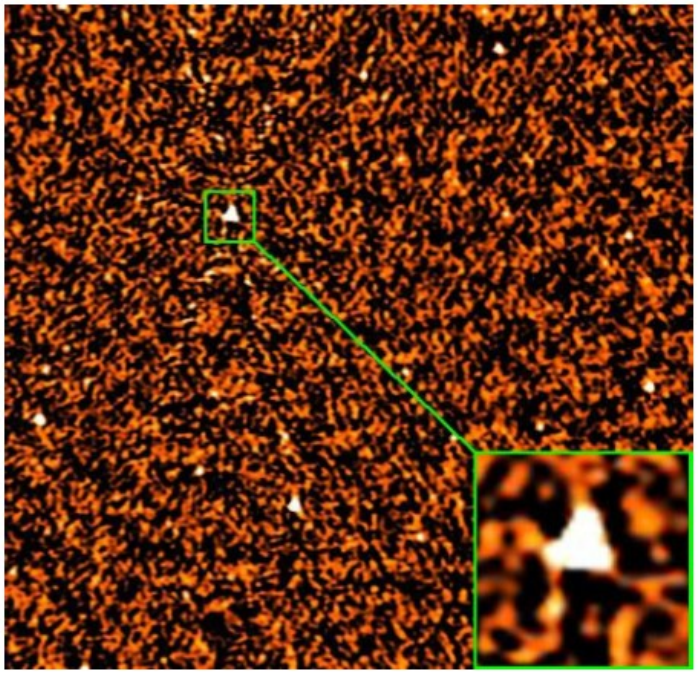

GMRT observations
at 150 MHz
frame 0000
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045

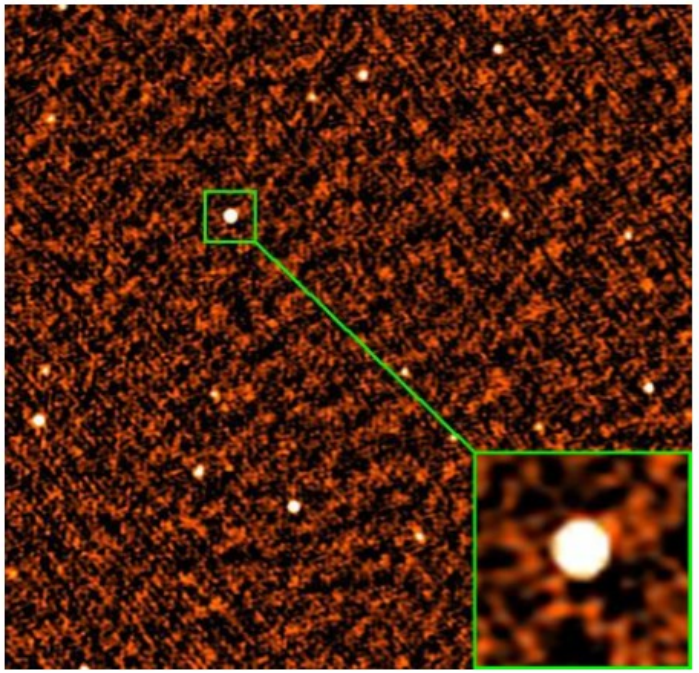
Ionospheric model fit (thesis Intema)

VLA@74 MHz, 80'' res.,12 deg. FOV



Old

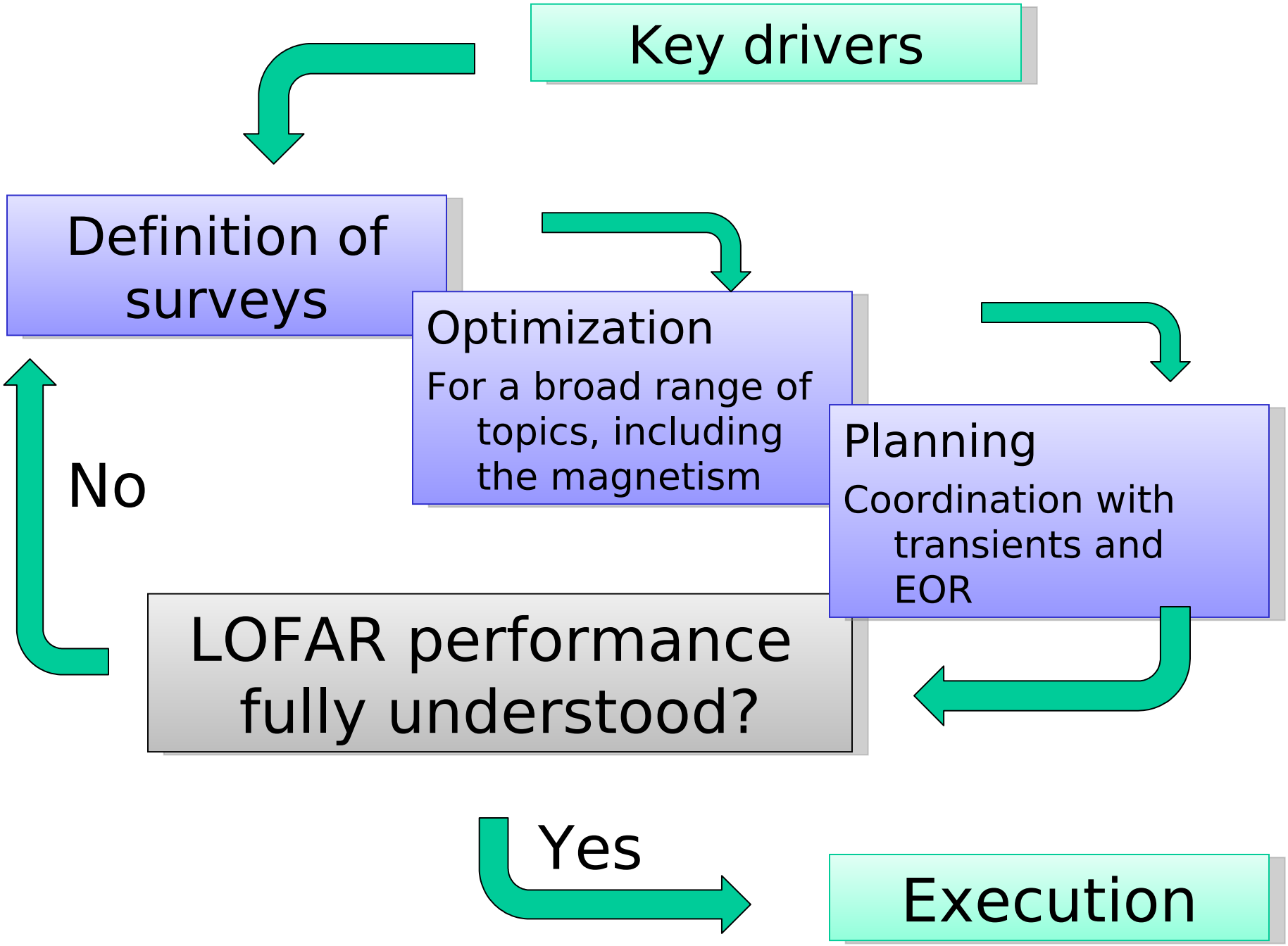




new

Ionospheric work in progress

- 2-d screen paper: Intema et al. submitted
  - Being implemented in BSS
- Observed ionospheric statistics from the 74 MHz - Cohen & HR)
- Analytic fitting of disturbances - van der Tol et al.
- Statistics of derived physical ionospheric parameters
- VLA 74 MHz ultra deep field – 36 hours
- Next steps:
  - 3-D screens
  - Time evolution

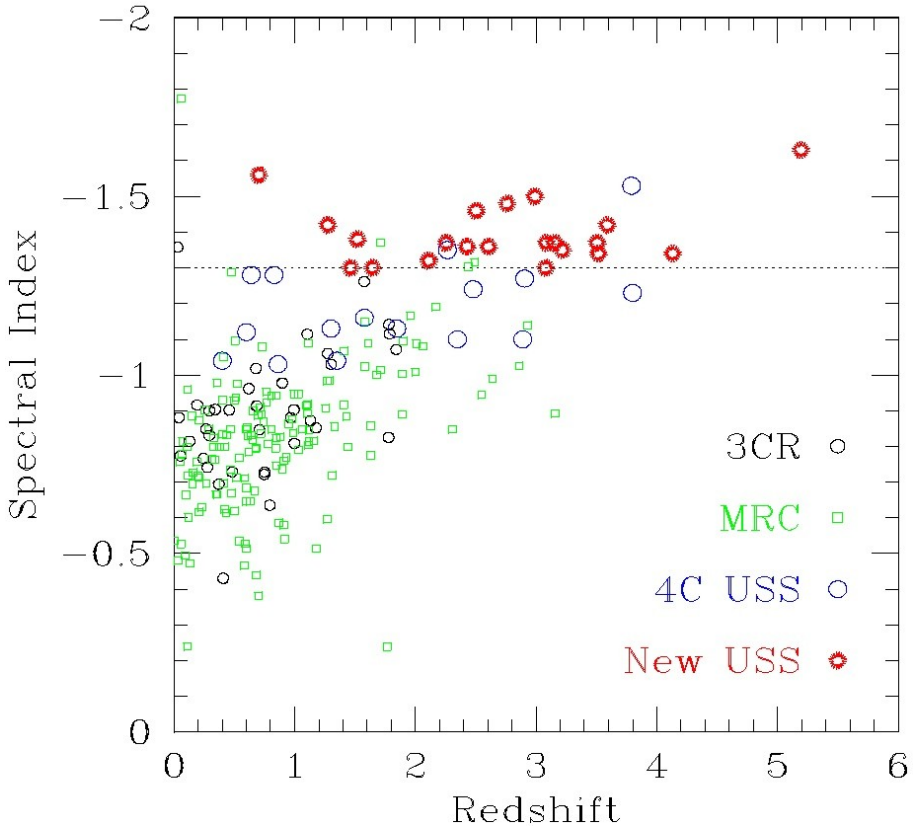

Key drivers
Definition of surveys
Optimization
For a broad range of topics, including the magnetism
Planning
Coordination with transients and EOR
LOFAR performance fully understood?
No
Yes
Execution

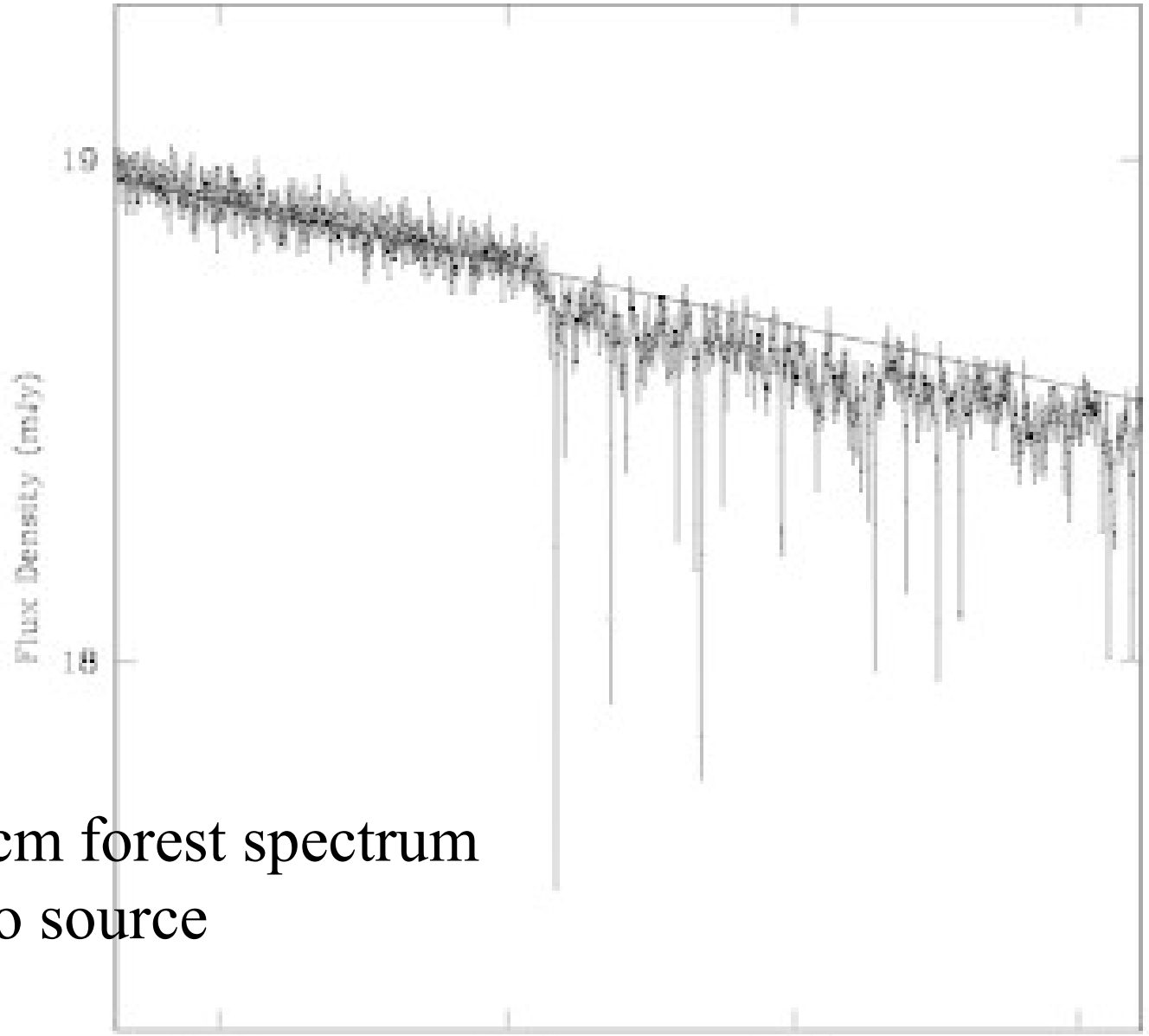
Key Drivers

1. 100 z ~ 6 radio galaxies
   - Formation and evolution of massive galaxies, black holes and clusters
2. 100 cluster radio sources at z ~ 0.6
   - Dynamics of cluster gas, evolution of cluster wide magnetic fields
3. 10 clusters of starbursts starbursts at z>2
   - SFR ~ 10 M_0/yr at z=2-3
4. Serendipity
   - << 30 MHz

1. Locating z>6 radio galaxies

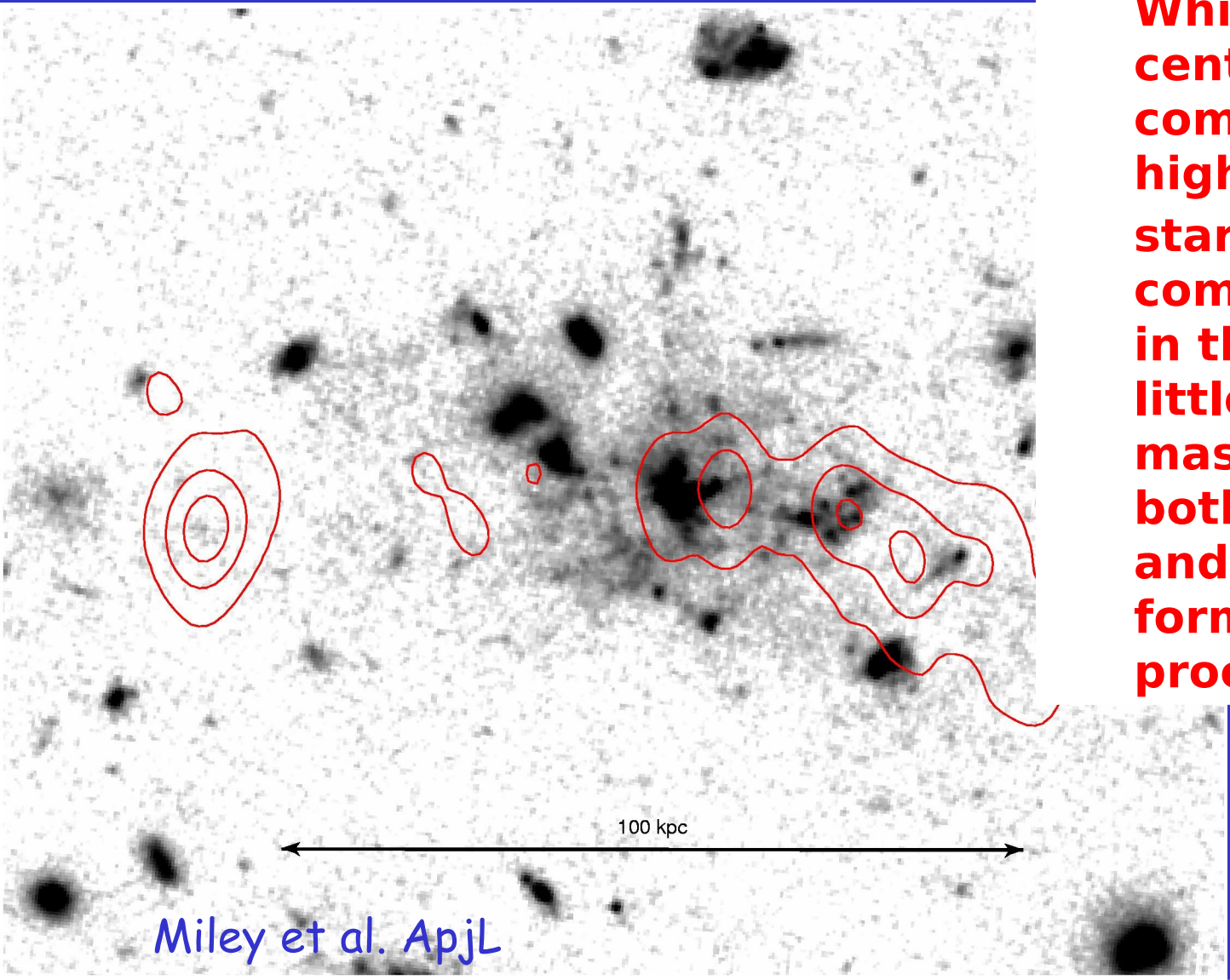
- Basis
  - Redshift ~ spectral index
  - Most distant radio sources luminous at low frequencies
- Science
  - Formation and evolution of massive blackholes, galaxies and clusters
  - As probes of epoch before reionisation to study HI absorption





Simulated 21 cm forest spectrum
For a z=8 radio source
Carilli 2005

ACS / HST imaging of MRC1138: a brightest cluster galaxy assembly at z=2.2



Miley et al. ApjL

While mass of central stellar component is very high (>10^{11} M_0), star-forming companions seen in the UV add little additional mass: Elements of both `hierarchical' and `monolithical' formation processes

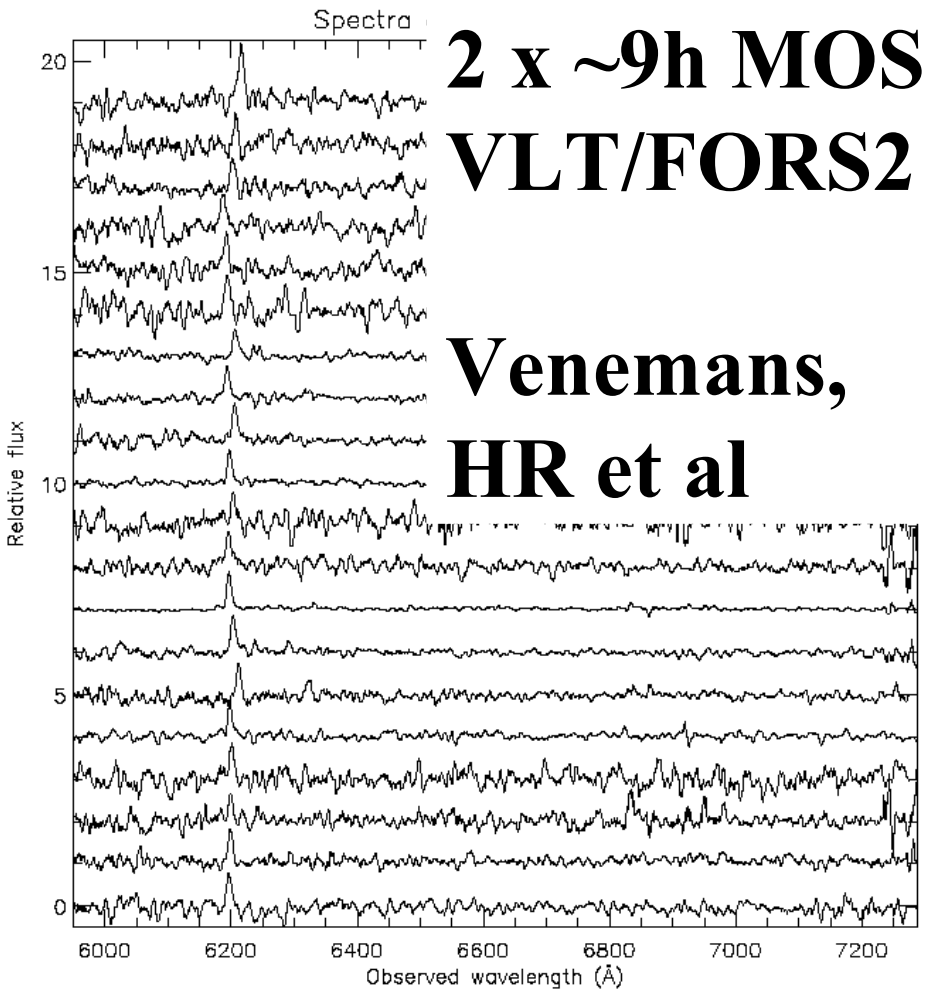
Radio galaxies as probes of Proto-clusters with mass 10^15 M0

20 Ly□ galaxies at z=4.1

Radio galaxy at z=4.1

2 x ~9h MOS VLT/FORS2

Venemans, HR et al



7’ * 7’ FORS/VLT field broad band image

Clusters and LOFAR

Low-z

- AGN feedback and studies of cavities on long time scales (>10^8) yr
- Magnetic field strength and configuration, energetics of radio halos
- Cluster weather through morphologies of
  extremely old tailed radio sources and starburst galaxies
- Inventory of shocks traced by radio emission in (merging) clusters and even the cosmic web

Intermediate-z

- **key driver: ample of ~ 100 clusters at z~0.6 with diffuse emission**
  ~ 100 at z~0.6
- Cluster lensing studies
- Location of radio sources wrt to LSS

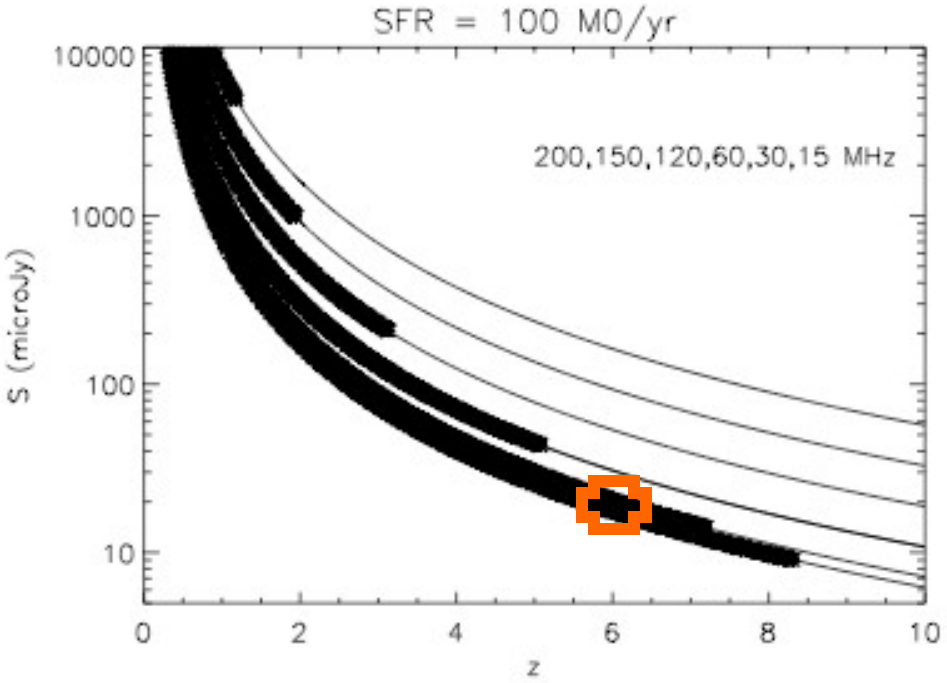
High-z

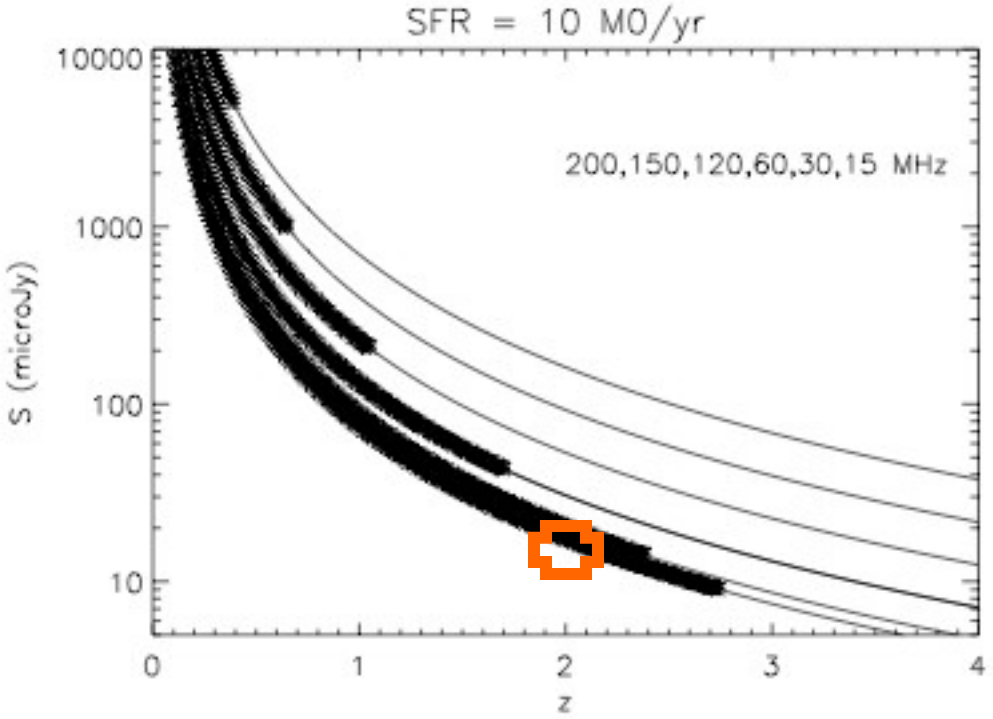
- Sample of z>2 proto-clusters
  through the study of high RM sources
  in combination with Herschel

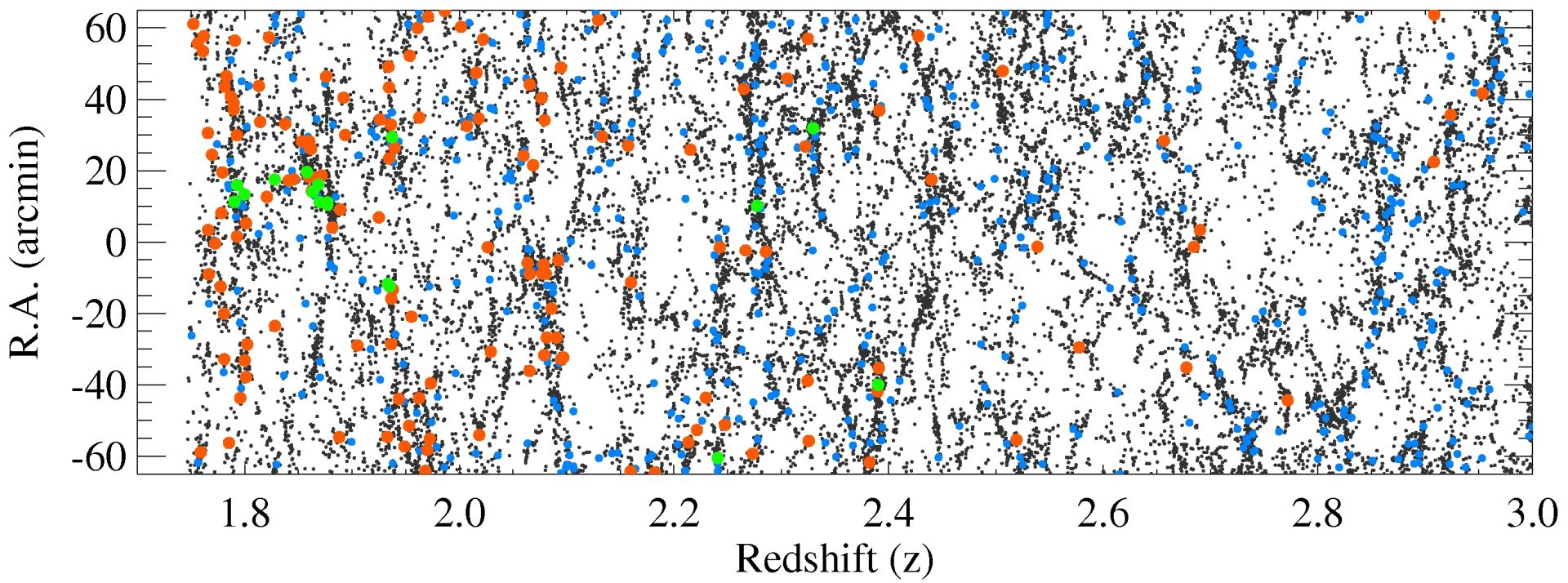
Very High-z

- **_Environment of z>6 radio galaxies**

3. Distant starbursts

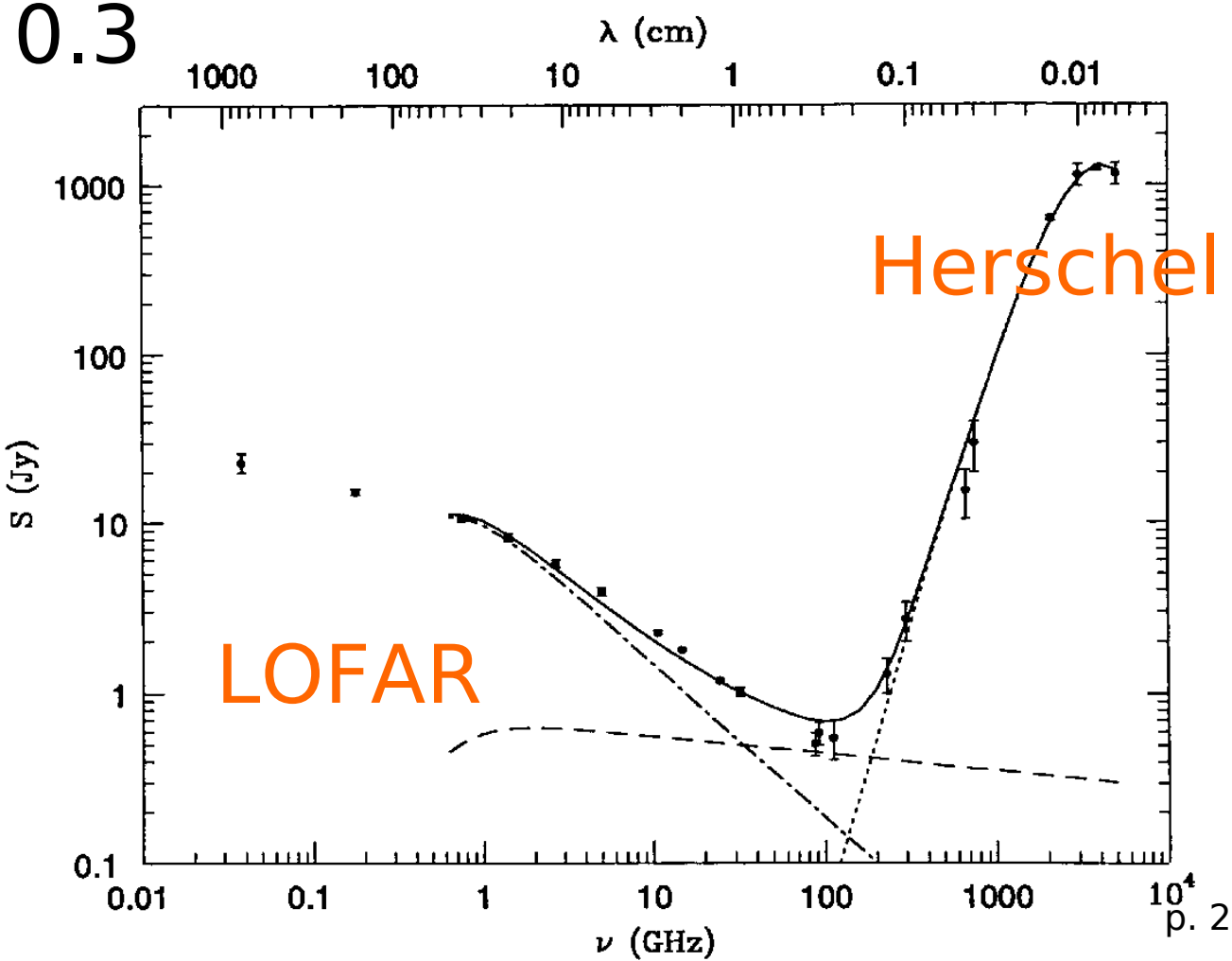






- ***Simulations of combined LOFAR and*** *Herschel observations of distant galaxies on the basis of semi-analytical galaxy formation models as developed by the Virgo Consortium. The part of the simulations that is shown is a 120 * 20 arcmin projected slice centred on a progenitor of a nearby massive cluster at z=1.8 with a mass of 10^{15} solar masses. Green are the proto-cluster galaxies detectable by LOFAR and Herschel, orange are field galaxies detectable both by Herschel and LOFAR, blue are the LOFAR only detections and the grey dots trace the dark matter particle distribution (with Overzier and Groves)*

- Proto-cluster searches around HzRgs are biased
- Combine deep Herschel and LOFAR surveys to get a large sample with $\Delta z\_phot = 0.3$



Other important topics

- AGN at moderate redshifts
  - Feedback, clustering
  - AGN activity as function of redshift, mass, environment etc.
- Gravitational lensing
  - Strong lensing by clusters and galaxies
- Detailed studies of low-redshift AGN
  - Giant radio sources
  - Young radio sources
- Nearby galaxies
  - Nearby normal galaxies/dwarf galaxies/starburst galaxies
  - Warm ism
  - Halo
- Galactic
  - Supernova Remnants
  - HII regions
  - Exo-planets
  - Pulsars

LOFAR surveys
A three tier wedding cake

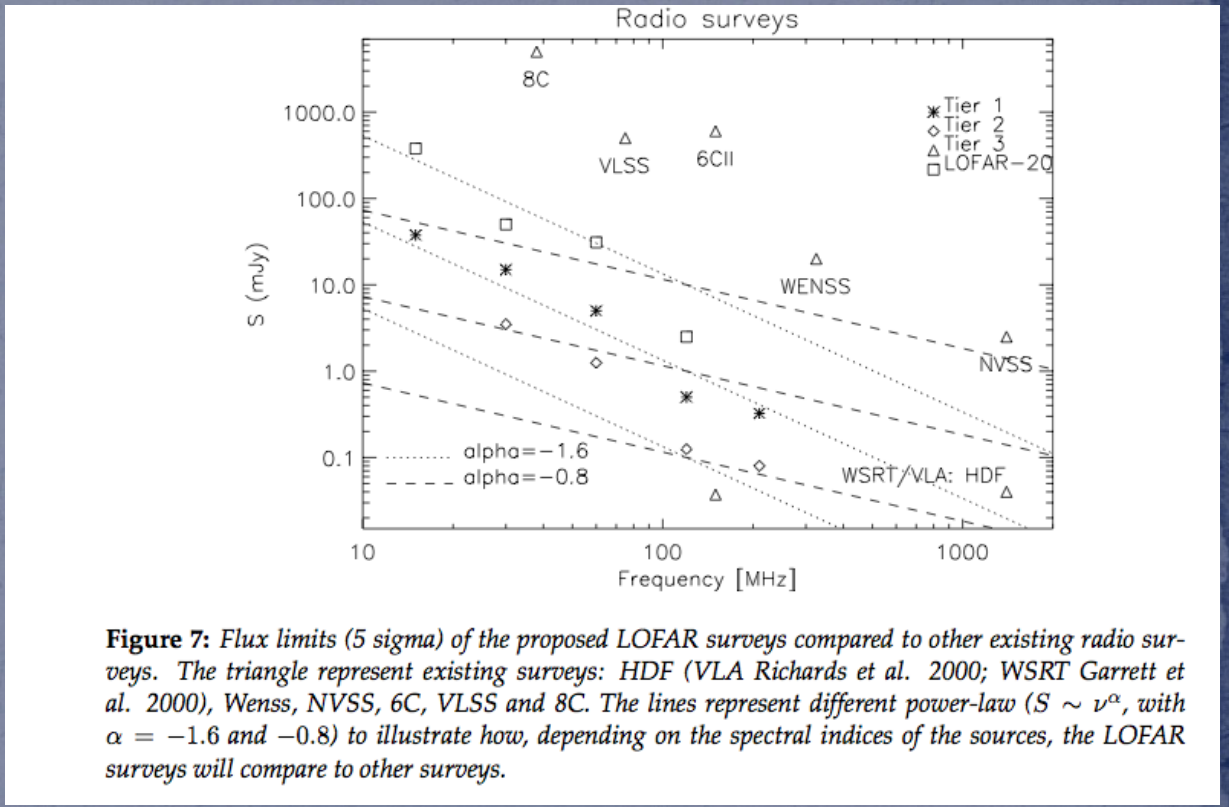


Figure 7: *Flux limits (5 sigma) of the proposed LOFAR surveys compared to other existing radio surveys. The triangle represent existing surveys: HDF (VLA Richards et al. 2000; WSRT Garrett et al. 2000), Wenss, NVSS, 6C, VLSS and 8C. The lines represent different power-law ($S \sim \nu^{\alpha}$, with $\alpha = -1.6$ and -0.8) to illustrate how, depending on the spectral indices of the sources, the LOFAR surveys will compare to other surveys.*

Core team

- Executive body
- Members
  - appointed by national consortia
  - Selected for specific expertise
- Current composition
  - Huub Rottgering, Philip Best, Peter Barthel, Philip Best, Marcus Brüggen, Gianfranco Brunetti, Krzysztof Chyzy, John Conway, Matt Jarvis, Matt Lehnert, George Miley, Raffaella Morganti, Ignas Snellen

Science group (SG) and chairs

- The highest redshift radio sources - George Miley
- Starforming galaxies at moderate and high redshifts- Matt Lehnert
- Clusters and cluster halo sources - Marcus Brüggen/Torsten Ensslin
- AGN at moderate redshifts - Philip Best
- Gravitational lensing - Neal Jackson
- Detailed studies of low-redshift AGN - Raffaella Morganti
- Nearby galaxies - John Conway
- Cosmological studies - Matt Jarvis
- Galactic radio sources – Marijke Haverkorn / Glenn White

LOFAR: 2011

- Reionisation detected and generally viewed as major breakthrough
- The nearby filamentary cosmic web is fully traced at low radio frequencies
- $>10^{21}$ cosmic rays are much more common that foreseen and theorist have great difficulties explaining this
- A new category of exo-planets detected through their radio emission.

and much more …