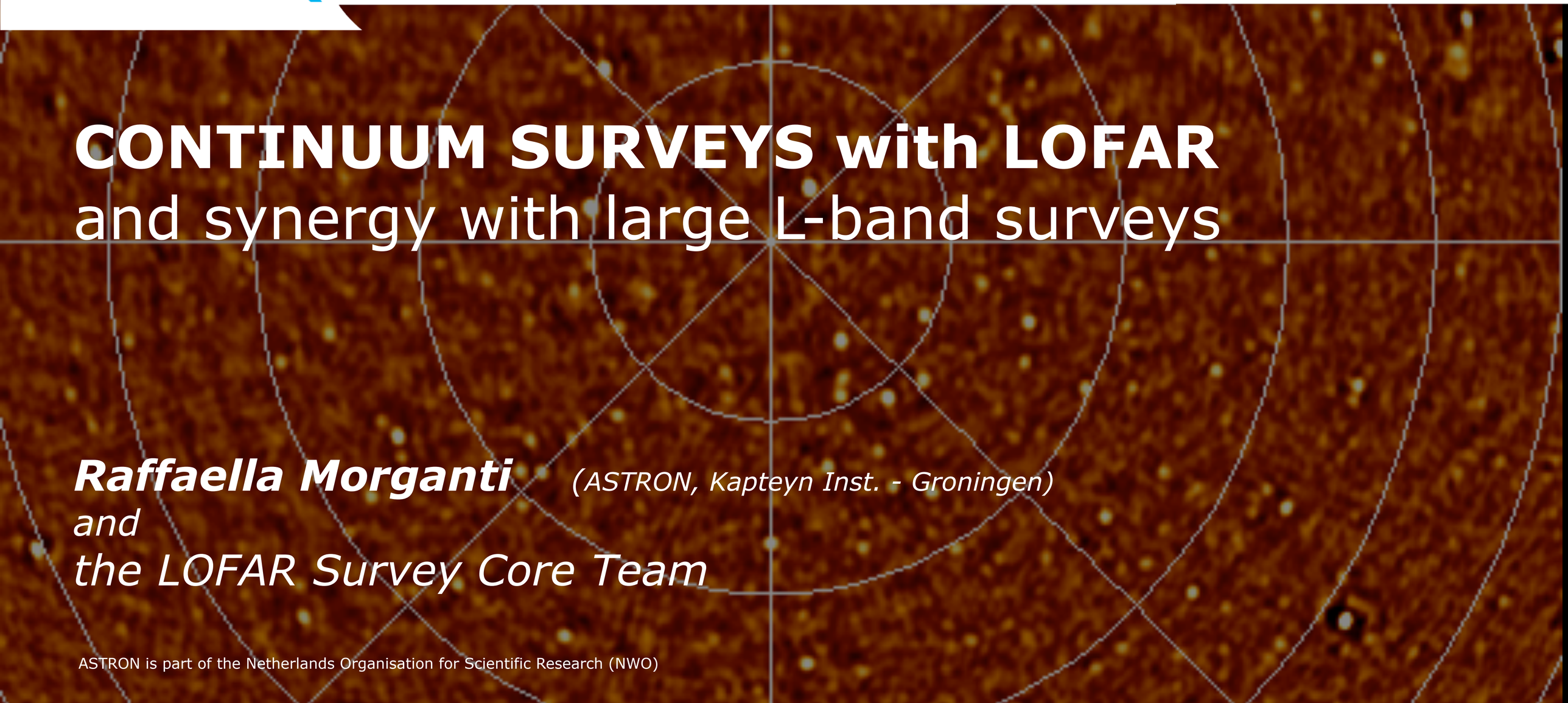
ASTRON

Netherlands Institute for Radio Astronomy



CONTINUUM SURVEYS with LOFAR
and synergy with large L-band surveys

Raffaella Morganti *(ASTRON, Kapteyn Inst. - Groningen)*

and

the LOFAR Survey Core Team

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

LOFAR - Low Frequency Array - phased array telescope

- Aperture array: replace dishes by many cheap dipoles: no moving parts - relies on digital signal processing + fibre-based network + high performance super computer

optimised for frequency range: **30 – 240 MHz**

Frequency ranges	LBA 30 - 80 MHz	HBA 115 - 240 MHz	
Two types of dipole antenna	Sparse dipoles	Tiles (4x4 dipoles)	
18+ NL Core Stations	96 dipoles	2x24 dipoles	~2 km
18+ NL Remote Stations	96 dipoles	48 dipoles	~80 km (~2 arcsec @200MHz)
8+ International Stations	96 dipoles	96 dipoles	>1000 km

Resolution subarcsec to degrees!

Sensitivity (after 4 h, 4 MHz bandwidth)

- @ 60 MHz ~ 3 mJy
- @ 150 MHz ~ 0.15 mJy

Up to 8 simultaneous 4 MHz beams possible

Roll out as we speak....

Low Band Antenna
- (10) 30MHz - 80 MHz
- 96 dipoles per station
- Within NL only 48 can be used at a time

High Band Antenna
- 120 MHz - 240 MHz
- 1 tile = 4 x 4 antennas
- 48 tiles per station (Within NL)

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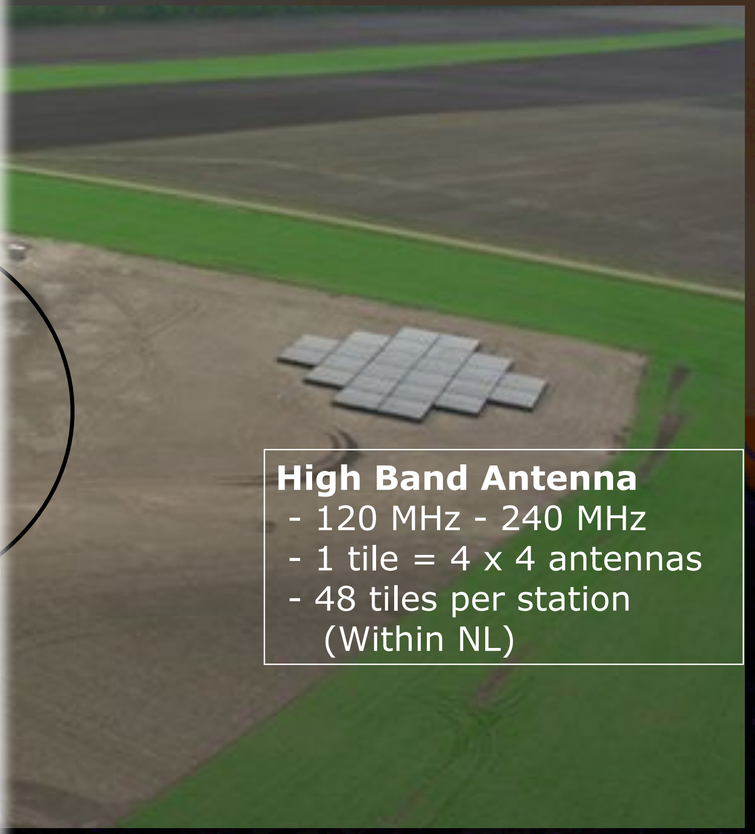

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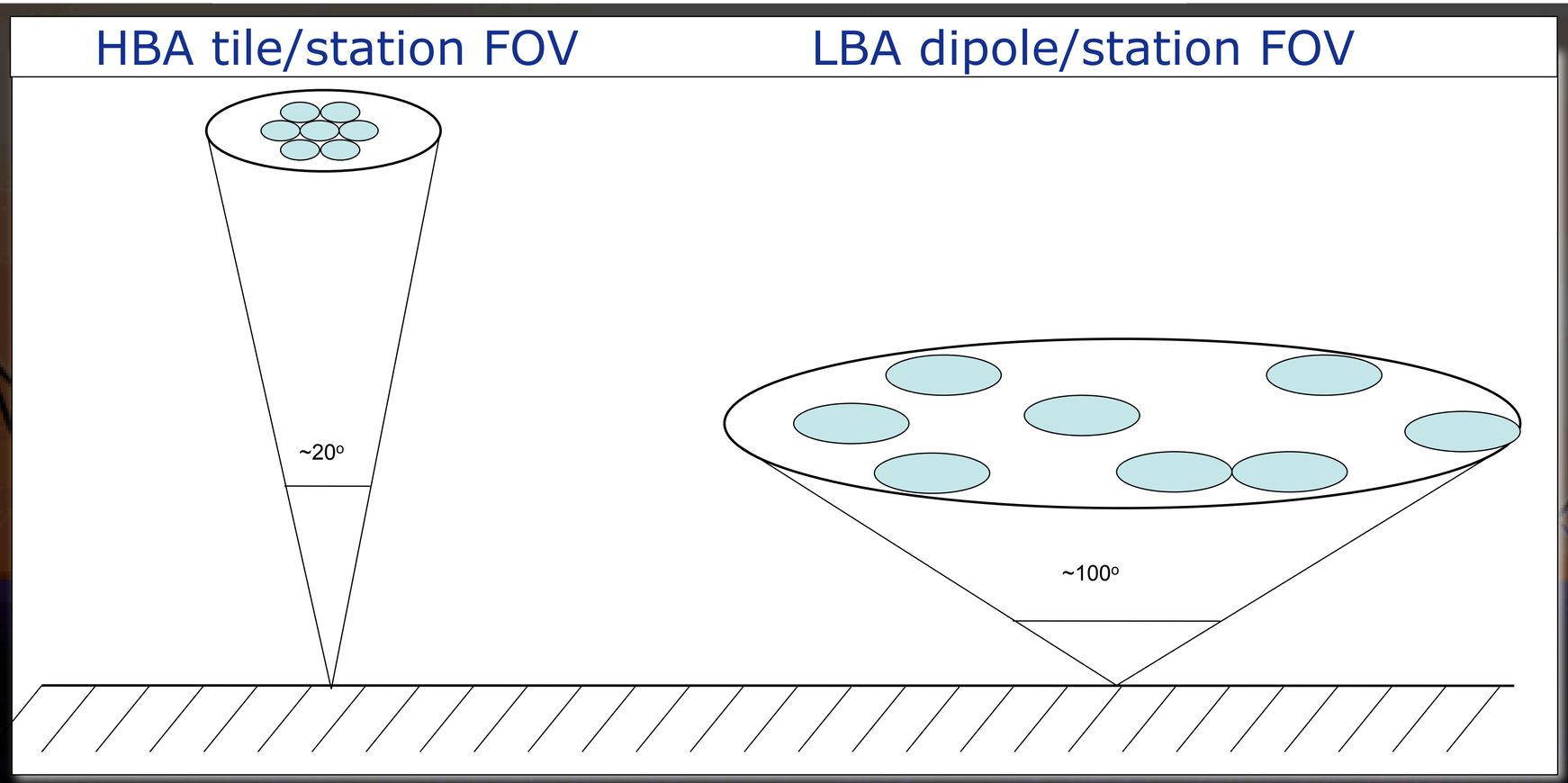
Ideal telescope for surveys



- dipoles sensitive to a large fraction of the sky ➔ beamforming at each station can be made to "look" in any direction on the sky
- data transport and correlator Blue Gene/P (Groningen) limit for the number of beams ➔ trade beams/bandwidth: 8 x 4 MHz or 1 x 32MHz (higher sensitivity) for 16-bit

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Continuum surveys: one of the LOFAR Key Science Projects

Core Team

★ Huub Röttgering (PI), Philip Best, Matt Jarvis, John Conway, Matt Lehnert, Marcus Brüggen, Peter Barthel, George Miley, Raffaella Morganti, Ignas Snellen, Gianfranco Brunetti, Krzysztof Chyzy

Members (45+)

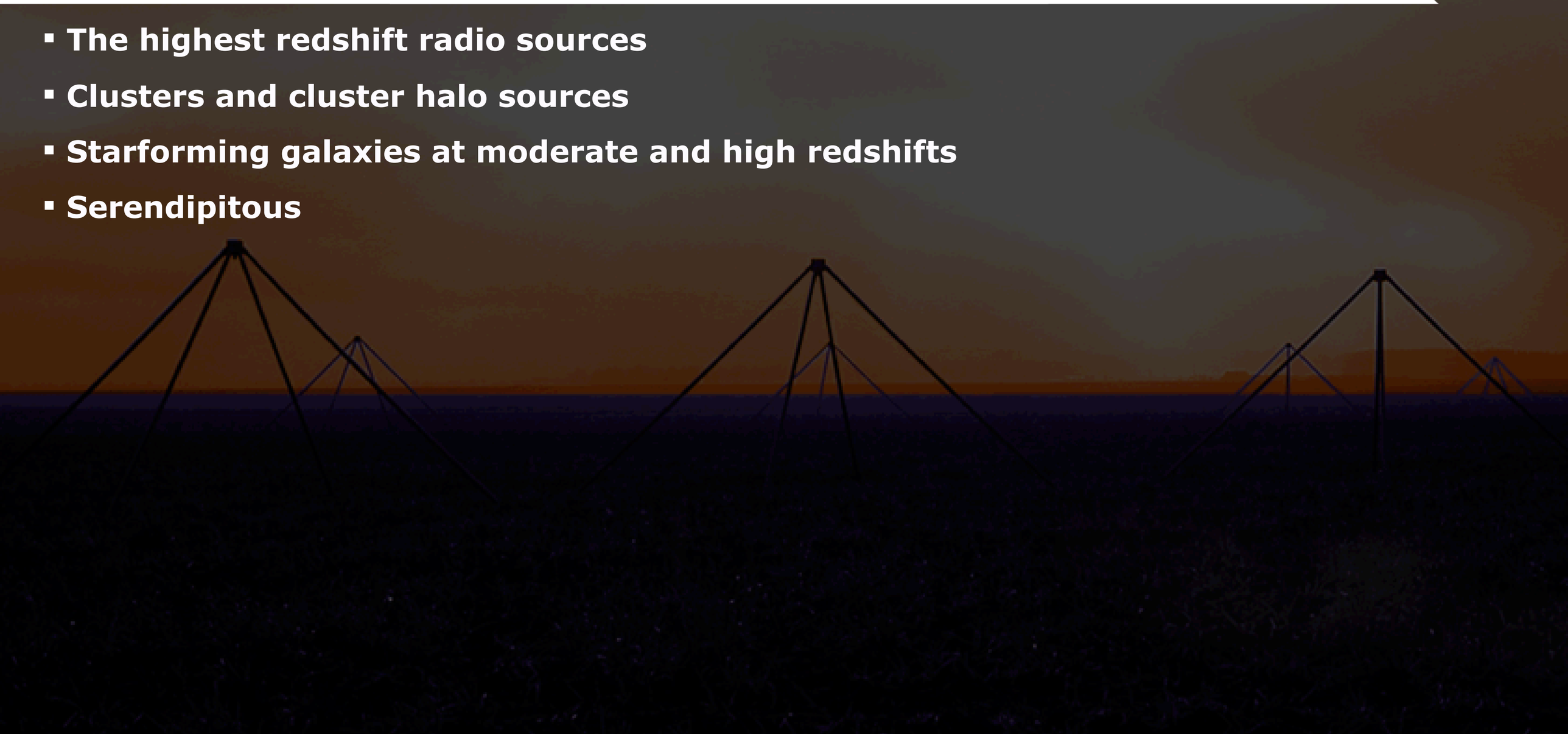
★ Proposed by the partaking countries

★ Specific expertise, specific access to data/telescopes

Main science topics for the LOFAR surveys

ASTRON

- **The highest redshift radio sources**
- **Clusters and cluster halo sources**
- **Starforming galaxies at moderate and high redshifts**
- **Serendipitous**



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- AGN at moderate redshift
- Gravitational lensing
- Detailed studies of low-redshift AGN
- Nearby galaxies
- Cosmological studies
- Galactic radio sources
- …

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Aim of the planned surveys: “general” enough to be a legacy product of LOFAR and enable a broad range of science

Proposed Radio Surveys: a wish list!

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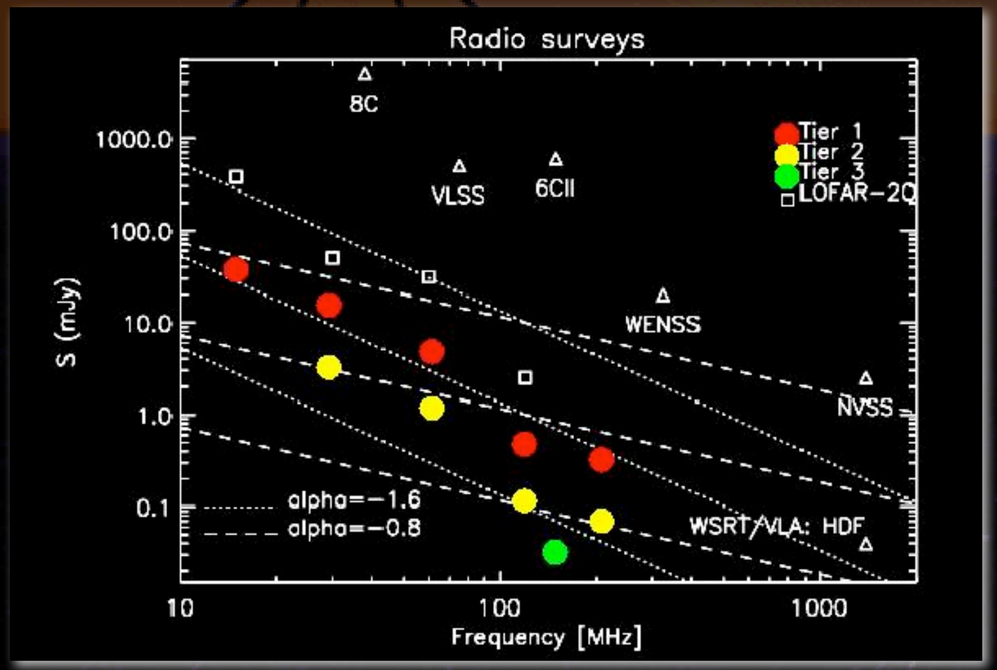
"Classical" set-up for the proposed surveys!

★ **Tier 1: "Large Area": all northern sky at 15,30,60,120 MHz; 'substantial area' at 210MHz**

★ **Tier 2: "Deep": few x 100 sq. deg^2 to factor few deeper at 30,60,120,200 MHz**

★ **Tier 3: "Ultra-deep": Small number of pointings very deep in one frequency 150MHz**



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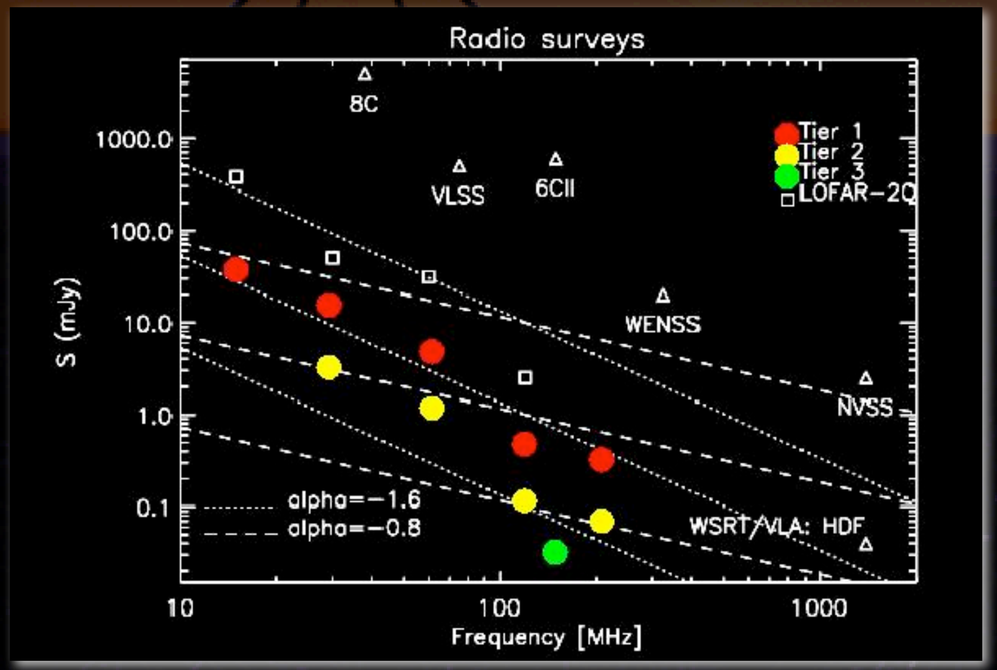
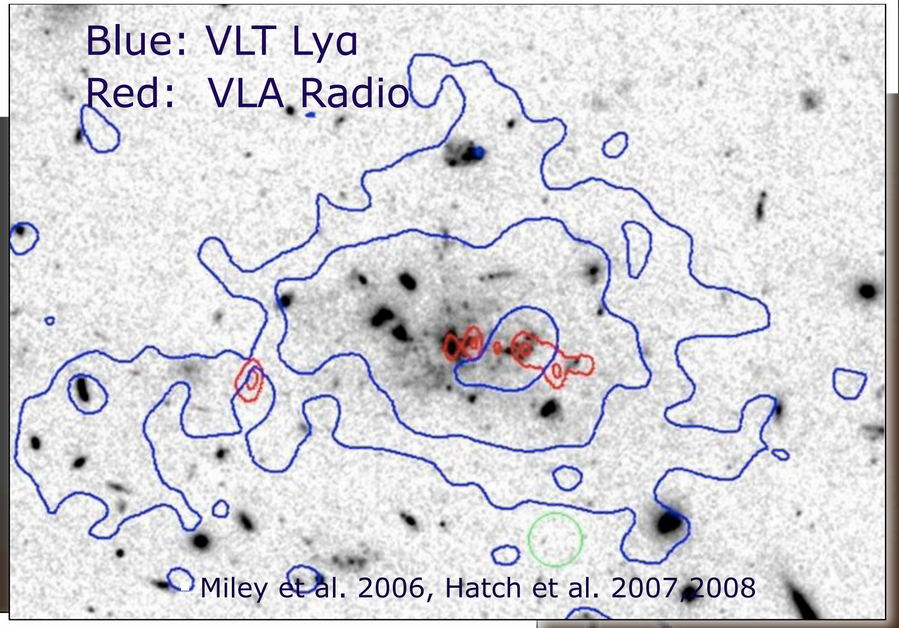


Strong connection to the magnetism Science Project (PI Beck) - choice of freq/bands for RM

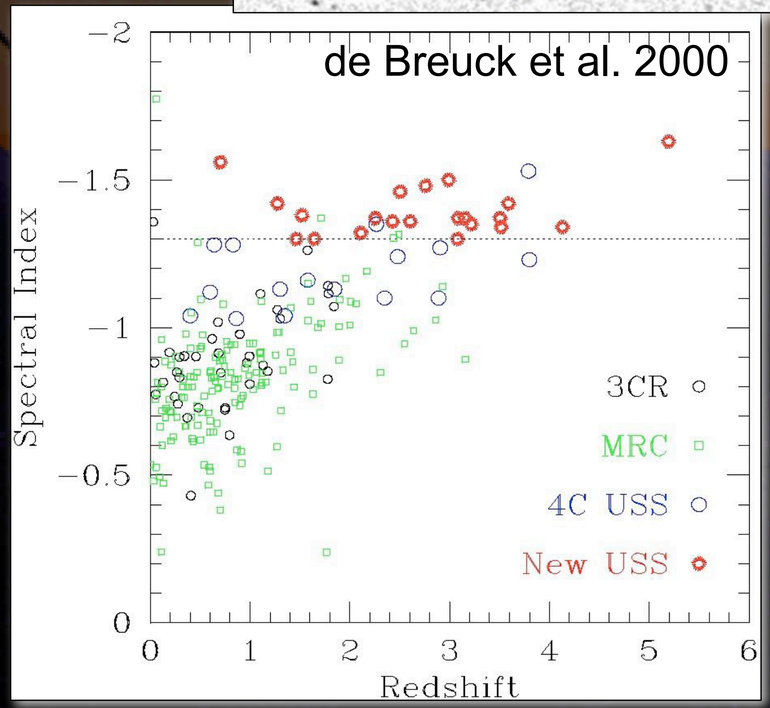
Connection to Transients - multi pass in the observation startegy

The quest for high-z radio galaxies!

- Distant radio galaxies: unique cosmic probes - high energy phenomena traced to the early Universe.
- Are there HzRG at z>6? Possibility of detecting these objects close or before the epoch of reionization
- Constraints on how/when massive black holes are formed
- Progenitors of dominant cluster galaxies?



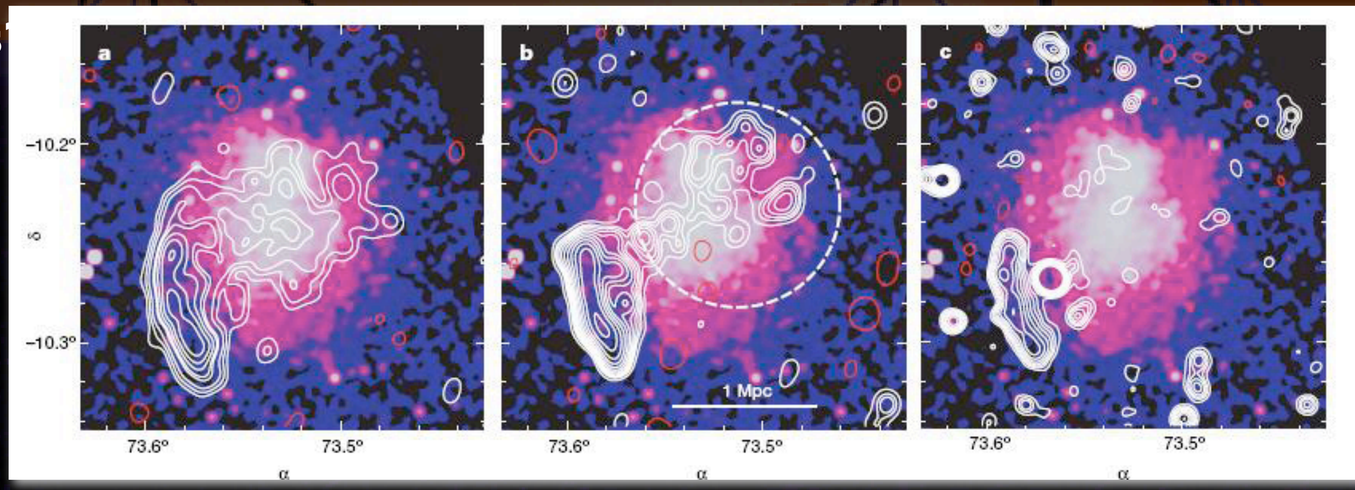
- Selection through spectral index:
  larger redshift ➔ steeper spectrum
  (Blumenthal & Miley, various papers de Breuck et al.)
- Physical explanation for the correlation? Radiation mechanism for producing the ultra-steep spectrum?
- Higher fraction of RG at high z located in dense environment (Klamer et al. 2005)? Radio emission probing the medium around? Search for HI absorption?



Cluster radio emission

- Diffuse radio sources in clusters ➔ tracers of the intercluster magnetic fields ➔ radio sources are **shaped by the dynamics of the gas** in which are embedded
- Probe the effects on the dynamics of cluster gas due to shocks waves produced by cluster mergers - **turbulent re-acceleration by merging of sub-clusters** - leakage from cluster radio galaxies
- Determine the origin of cluster magnetic fields
- Occurrence and characteristics of diffuse radio sources as a **function of redshift** - How did cluster relics (and magnetic field) evolve since cluster formation? Were relics more common at earlier epoch?
- **Relation low-z cluster ➔ high-z protoclusters**

ABELL 521 HALO
White contours radio superimposed on Chandra X-rays
Turbulent reacceleration?
Laboratories for intraclustermagnetic fields, interaction with gas and cluster evolution



GMRT 240 MHz GMRT 610 MHz VLA 1.4 GHz

Brunetti et al. Nature 2008

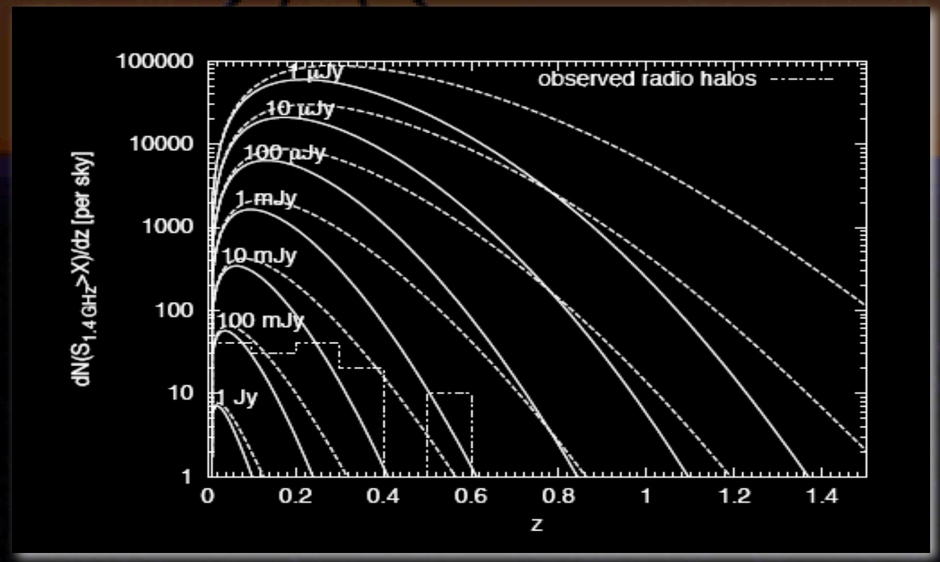
Tier 1: The “large-area” survey

- 120 MHz (2π survey) ➔ aiming to detect 100 cluster halo sources beyond z~0.6 ➔ this requires to reach 2 mJy. S/N=20 needed for these sources => rms limit 0.1mJy/b

- Lower frequencies less sensitive but exciting new territory. 30MHz (2π survey) ➔ Set limit to detect >100 FR1s and FR2s at z>7, with S/N>5. This requires rms of 3mJy/b

- Steep spectrum sources ➔ set 60MHz limit deep enough to detect α=-1.6 ($f_\nu \propto \nu^\alpha$)

- 210 MHz observations ➔ likely a limited area to same effective depth as 120MHz data for “typical” sources (α≈-0.8, $f_\nu \propto \nu^\alpha$), larger area ➔ match sensitivity 60MHz?



Expected redshift distribution of radio halos above a given flux density. Solid lines more realist model (Enslin & Rottgering, 2002)

Table 3: *Tier 1: The “All sky” survey*

f MHz	Area deg^2	rms mJy	BW MHz	Sources/[1] beam	Integration time[2] hrs	Number pointings	Days[3]	Total[1] sources
15	20626	7.5	8	19026	42.0	97	14	1.8e+06
30	20626	3.0	8	6506	19	388	26	2.5e+06
60	20626	1.0	8	9301	22	435	33	4.0e+06
120	20626	0.1	8	12953	7.7	2149	57	2.8e+07
210	783	0.065	8	4045	20	250	17	1.0e+06

[1] Number of sources in the beam with a signal to noise ratio larger than 5. [2] The integration time is quoted for 1 beam of 8 MHz. [3] The total number of days needed to complete the survey assuming the availability of 12 beams of 8 MHz.

Number of beams and bandwidth to be finalised - also depending on co-ordination with magnetism KSP!

Starforming galaxies - what do we learn?

- High sensitivity → growing number of starburst (decreasing radio-loud AGN)
- Aim: detecting SFR 10$M_\odot$/yr at z~1.5 - close to the epoch where the star formation history is believed to have peaked ....

- More extreme SFR (100 $M_\odot$/yr) detectable high z (z~5)
- How the relationship between star formation rate and galaxy mass evolves with z ("downsizing"?)

Follow-up far-IR and sub-mm very important

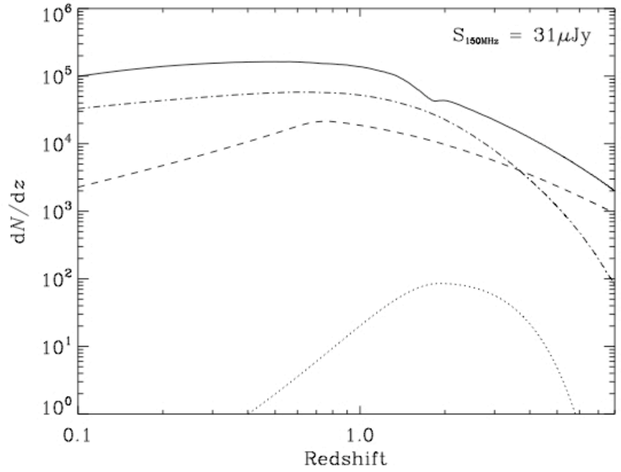


Figure 6: *Number of expected FRII radio sources (dotted), FRI radio sources (dashed), radio-quiet quasars (dot-dashed) and star-forming galaxies (solid) as a function of redshift for the 150 MHz ultra deep LOFAR surveys.*

Wilman et al. 2008
The SKADS simulated sky - http://s-cubed.physics.ox.ac.uk/

Tier 2 and 3: The “deep” and “ultra-deep” surveys

“Deep survey” - Aim is ~25 pointing at each frequency: 30,60,120 and 200MHz.

30 and 60 MHz depths **set to match “large area” 120MHz data** depth for typical spectral index sources (α=-0.8)

120 and 210 MHz data depths are set to detect SF galaxies with 10 M_{sun}/yr at z=0.5, and 100 M_{sun}/yr at z=2.5

f MHz	Area deg^2	rms mJy	BW MHz	Sources/[1] beam	Integration time[2] hrs	Number pointings	Days[3]	Total[1] sources
30[4]	1327	0.7	8	25322	355	25	30	6.3e+05
60	1184	0.25	8	37875	356	25	30	9.5e+05
120	239	0.025	8	88066	123	25	10	2.2e+06
210	78	0.016	8	28756	332	25	28	7.2e+05

“Ultra deep” survey - Although LOFAR is not competitive with eVLA for ultra-deep surveys, the low frequency still makes it interesting to carry out one (but at a single frequency) ➔ 10 M_{sun}/yr at z=1.5, and 100 M_{sun}/yr at z=5

150 MHz is optimal choice for single deep pointing ➔ ~30deg^2 0.0062 mJy/b

Synergy with large surveys at L-band

- most innovative part of LOFAR: ***wide field of view, set of low frequencies*** **possible and** ***high spatial resolution***
- however, most of the work done so far to understand/characterise the various groups of radio sources [e.g. faint sub-mJy radio sources] is at L-band → **crucial reference point**

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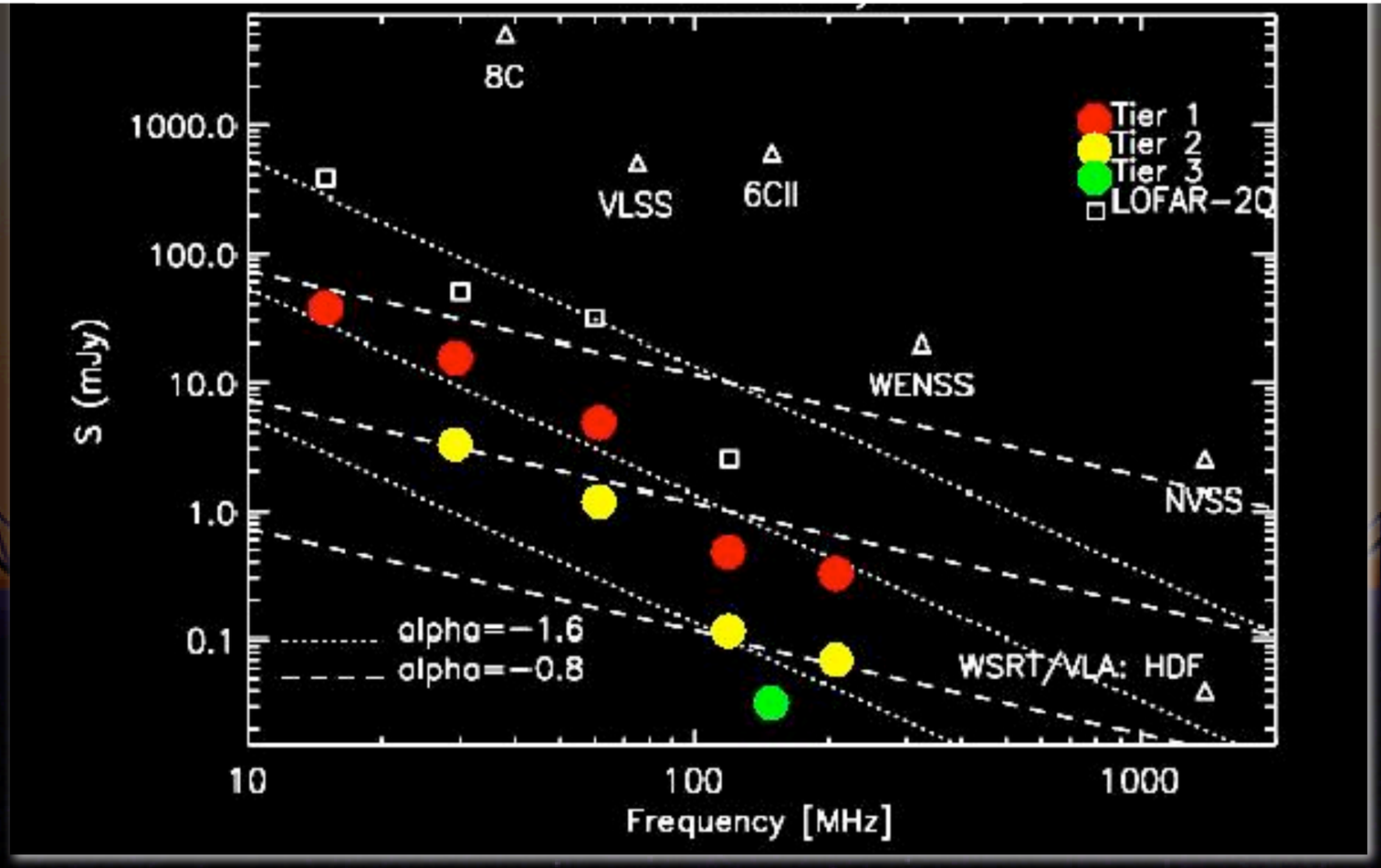
- most natural synergy is with large surveys at L-band
- large L-band surveys *on comparable time scales!* ➔ **Apertif & ASKAP**
  - Apertif: looking at the same sky!
  - LOFAR less efficient at low dec ➔ nevertheless effort to cover area observable by VLT and ALMA ➔ overlap with ASKAP (MeerKat?)

Comparison with other surveys



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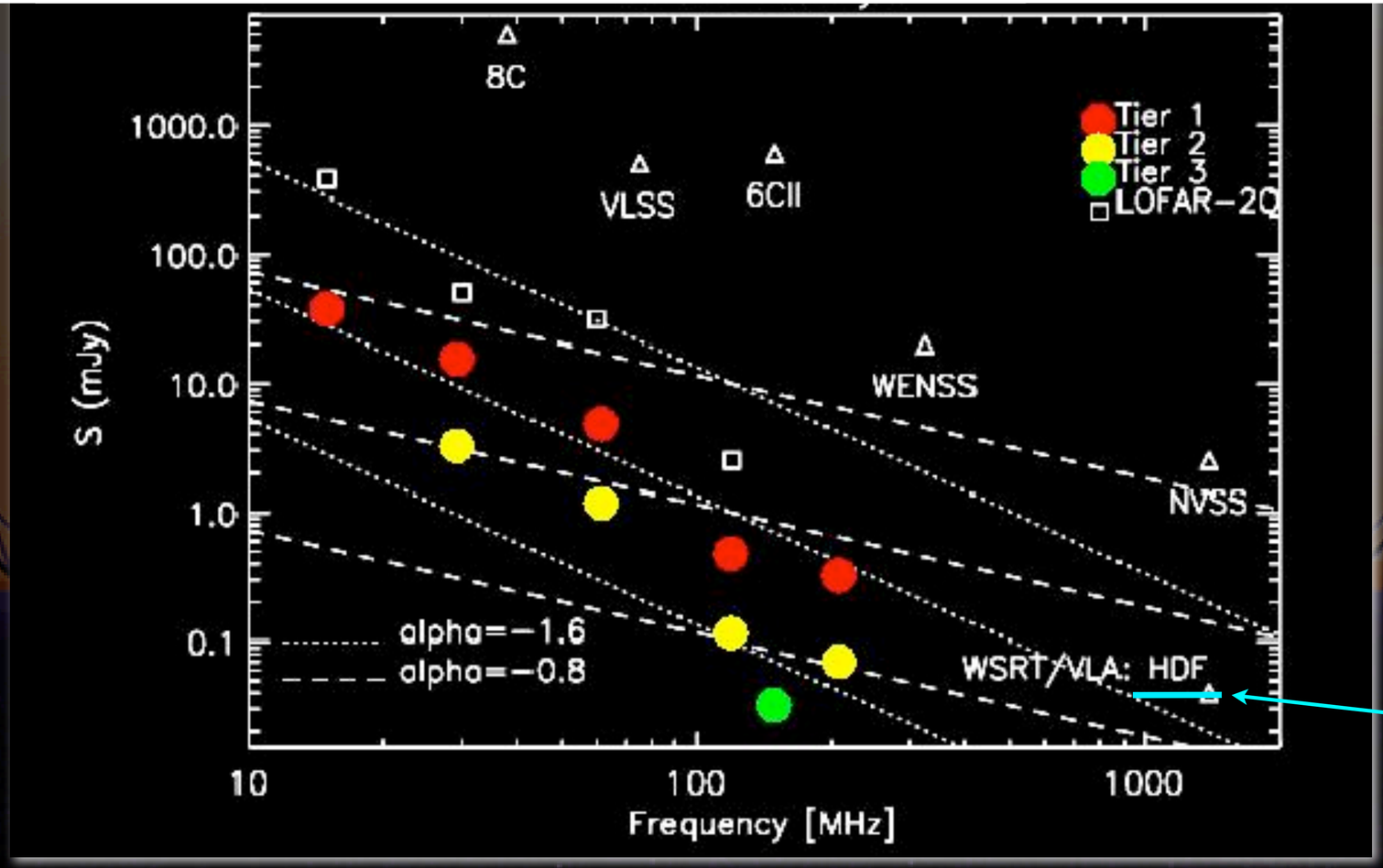


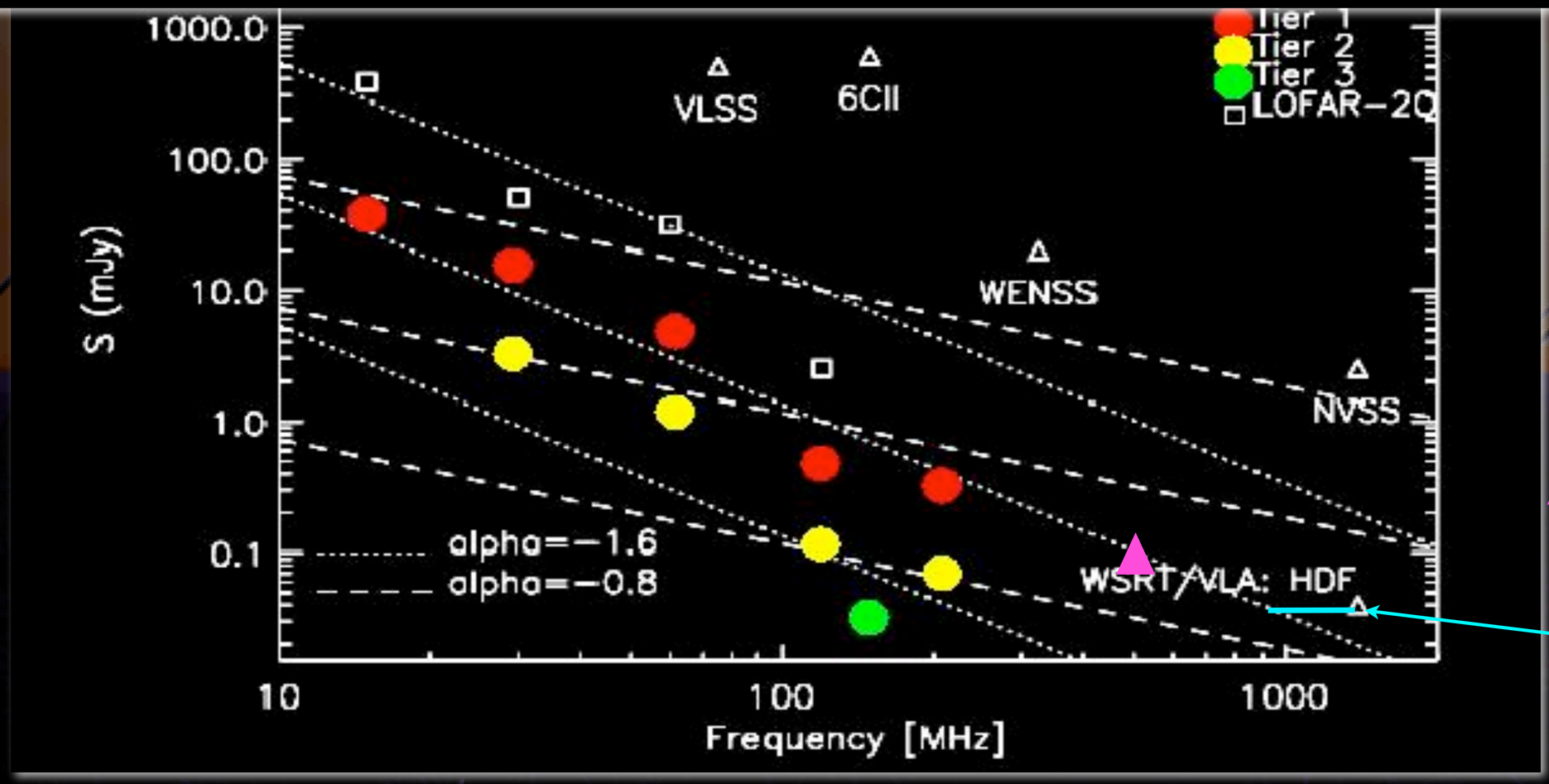
WSRT+Apertif
ASKAP

- plenty of science possible - only two mentioned here:

  sub-mJy radio sources and nearby radio AGN

Combining low frequency and L-band wide surveys

- many studies (see previous presentations) are already connecting L-band and low freq. deep field observations ➔ e.g. GMRT 610 MHz



GMRT Lockman Hole
Ibar et al. 2009
(inner 100 arcmin^2)

WSRT+Apertif
ASKAP

The sub-mJy population

- below 1 mJy ~ 50% AGN (Padovani et al.) ➔ 25% FRI-like

  ➔ 23% radio-quiet
- below 0.1 mJy radio-loud fraction drops *vs* radio-quiet counts ~costant (Ibar et al.)

  ➔ radio-quiet do not represent the faint end of radio power?
- SFG dominate @50 μJy (1.4GHz) but AGN still ~25% (Seymont et al., Ibar et al.)

AGN make up a significant fraction but ➔ **what kind of AGN? what is the nature of radio-quiet - not radio silent! (low accretion rate/low efficiency? interesting for feedback?)**

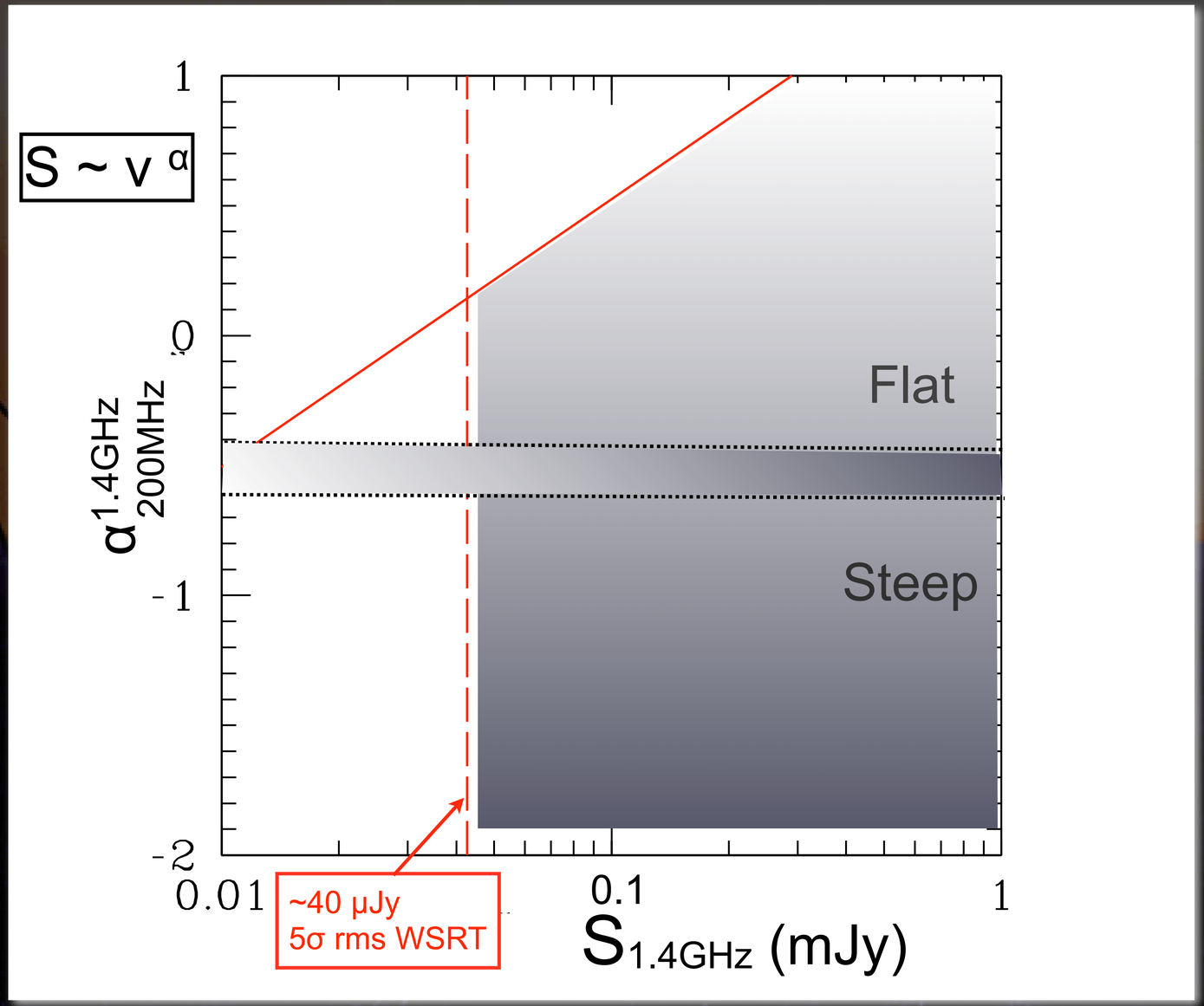
- no evolution for the median spectral index for faint radio sources - most prevalent emission mechanism in sub-mJy regime is optically thin synchrotron (Ibar et al.)
- dominant flat-spectrum or ultra-steep ruled out?
- BUT flattening of the spectral index seen in other studies (especially @high freq, Prandoni et al.): origin?

Combining surveys

Combined L-band with LOFAR tier1 - all sky selection of **steep spectrum** sources
➔ ~50 microJy @1.4GHz with steep spectrum (~-1 for 200 MHz) ➔ **SFG and AGN**

Combined L-band with LOFAR tier 2&3 - exploring the dependence of the spectrum index with flux? source population down to micro Jy -> nature of this population - beamed?

Possibility of identifying the self-absorbed sources! e.g. disappearing @ low freq?
Compact/young: exploring the properties for radio faint samples and/or evolution with z? relation peak vs size, high-z expected free-free due to gas around?


S ~ ν α
1
0
-1
-2
$\alpha^{1.4GHz}_{200MHz}$
Flat
Steep
0.01
0.1
1
~40 μJy
5σ rms WSRT
$S_{1.4GHz}$ (mJy)

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- Spectral index not enough to distinguish e.g. SFG and low power AGN ➔ still we will learn about the **spectral properties of the radio sources** ➔ L-band +LOFAR can provide new insights
- Radio morphology can be use as a extra parameter ➔ arcsec resolution NL-LOFAR, sub-arcsec E-LOFAR (very important!) +VLBI follow-up (e.g. Klockner et al. 2009, Chi et al. poster)

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➡ **data at other wavebands crucial !!**
optical imaging/spectroscopy, mid/far IR, X-ray ...

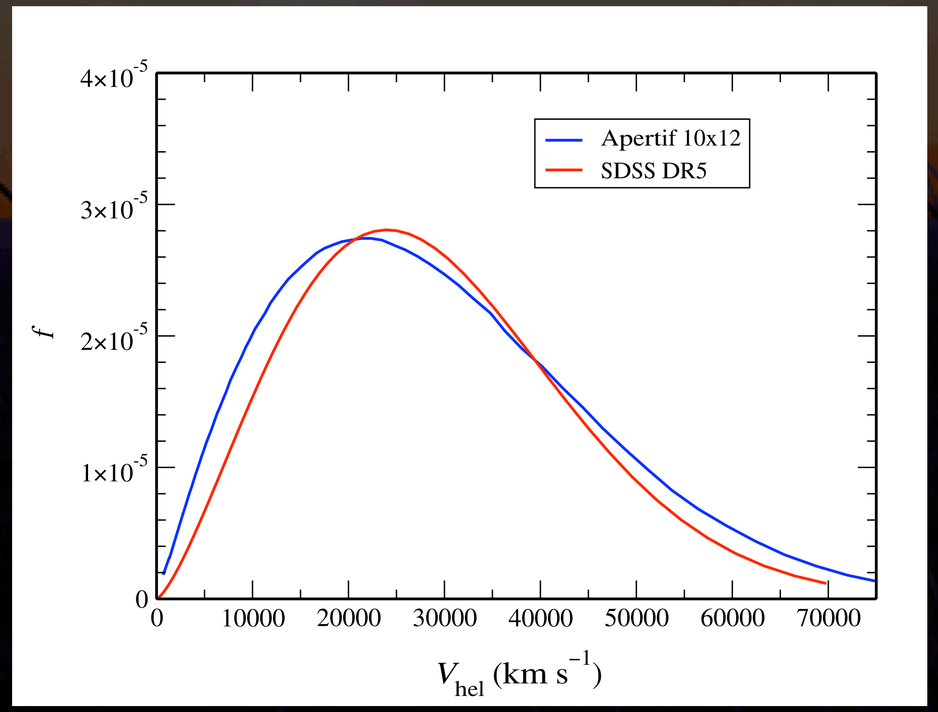
Nearby radio sources - the role of gas

- for the nearby sources Apertif/ASKAP will provide information on the gas: deep HI (z<0.3) and OH (z<0.6-0.7!) observations

➔ possibility of studying the gas content for the most nearby radio sources

➔ e.g. **relation gas ➔ AGN properties**

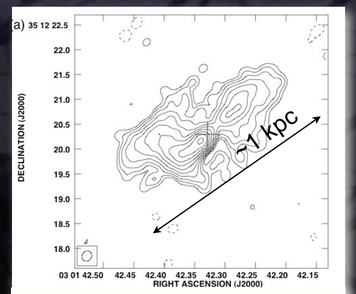
➔ **duty-cycle activity**



Gas, nuclear activity & duty-cycle

B2 0258+35 z= 0.0165

Struve et al. in prep



Giroletti et al. 2005

Young radio galaxy (compact steep spectrum)

Gas, nuclear activity & duty-cycle

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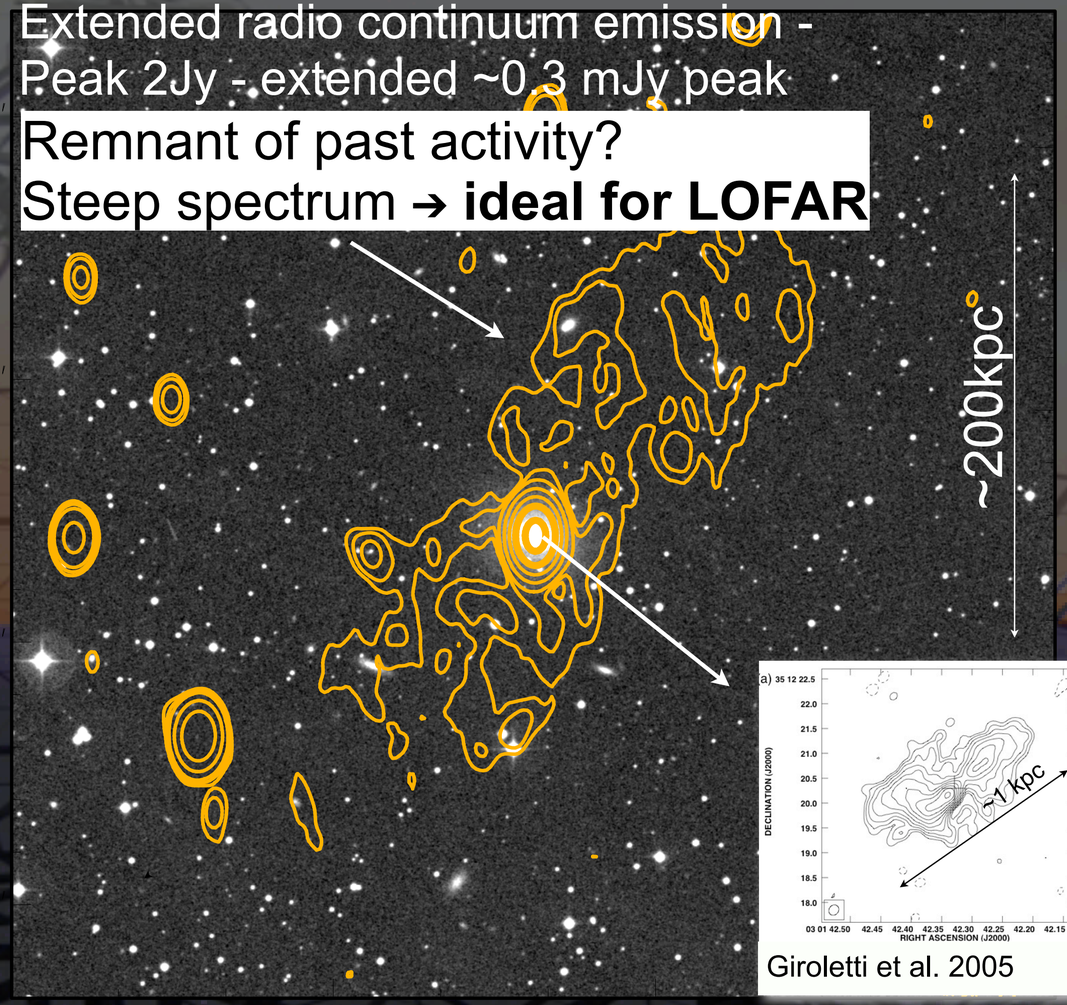

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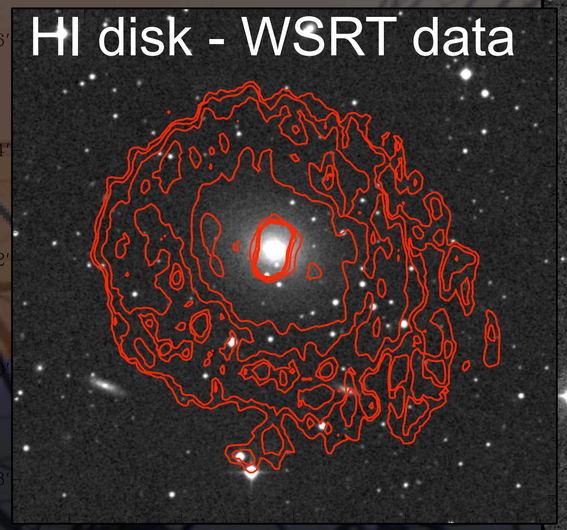
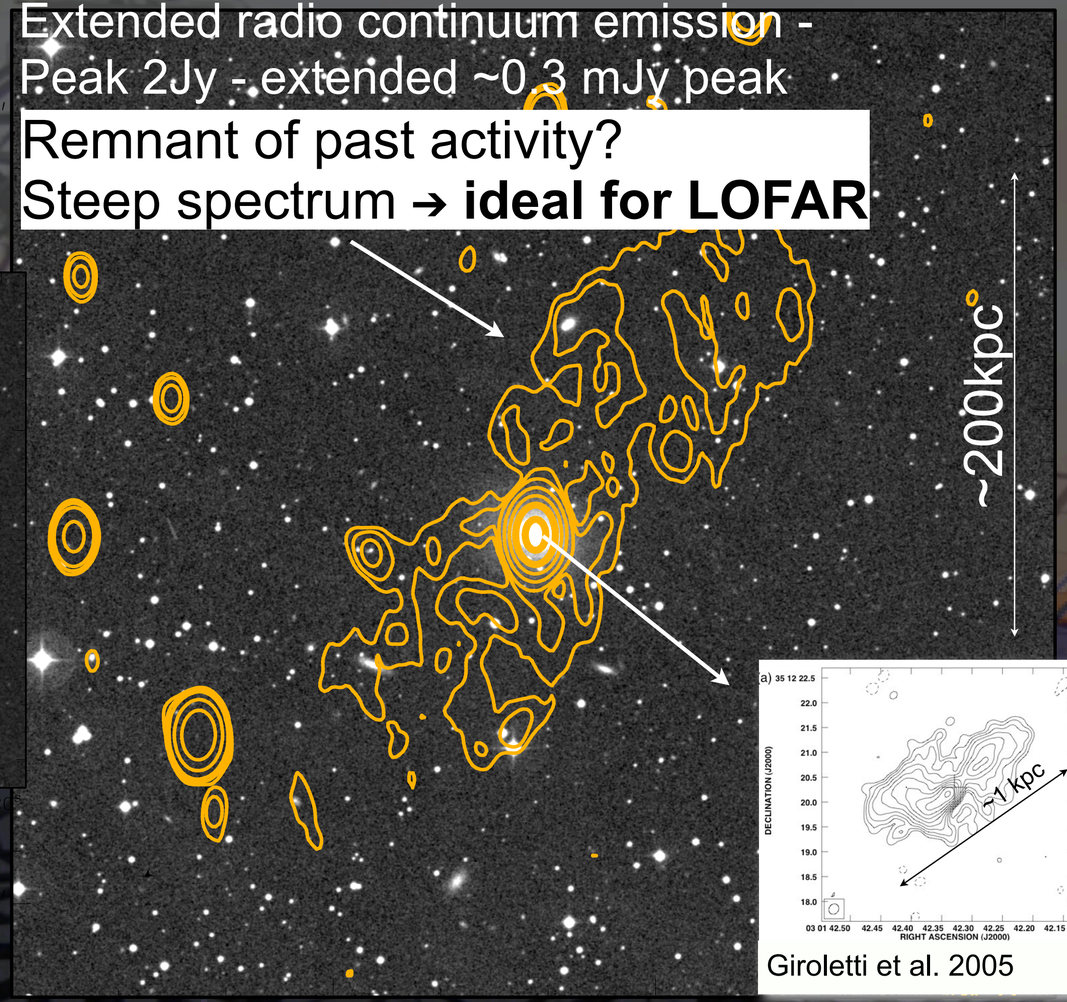
HI disk - WSRT data



Extended radio continuum emission -
Peak 2Jy - extended ~0.3 mJy peak

Remnant of past activity?

Steep spectrum → **ideal for LOFAR**



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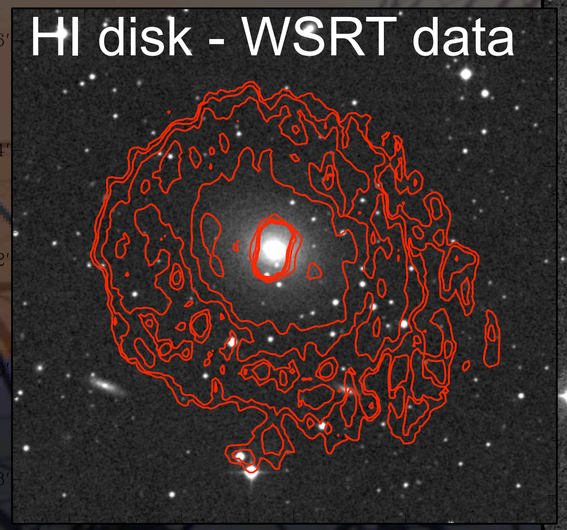

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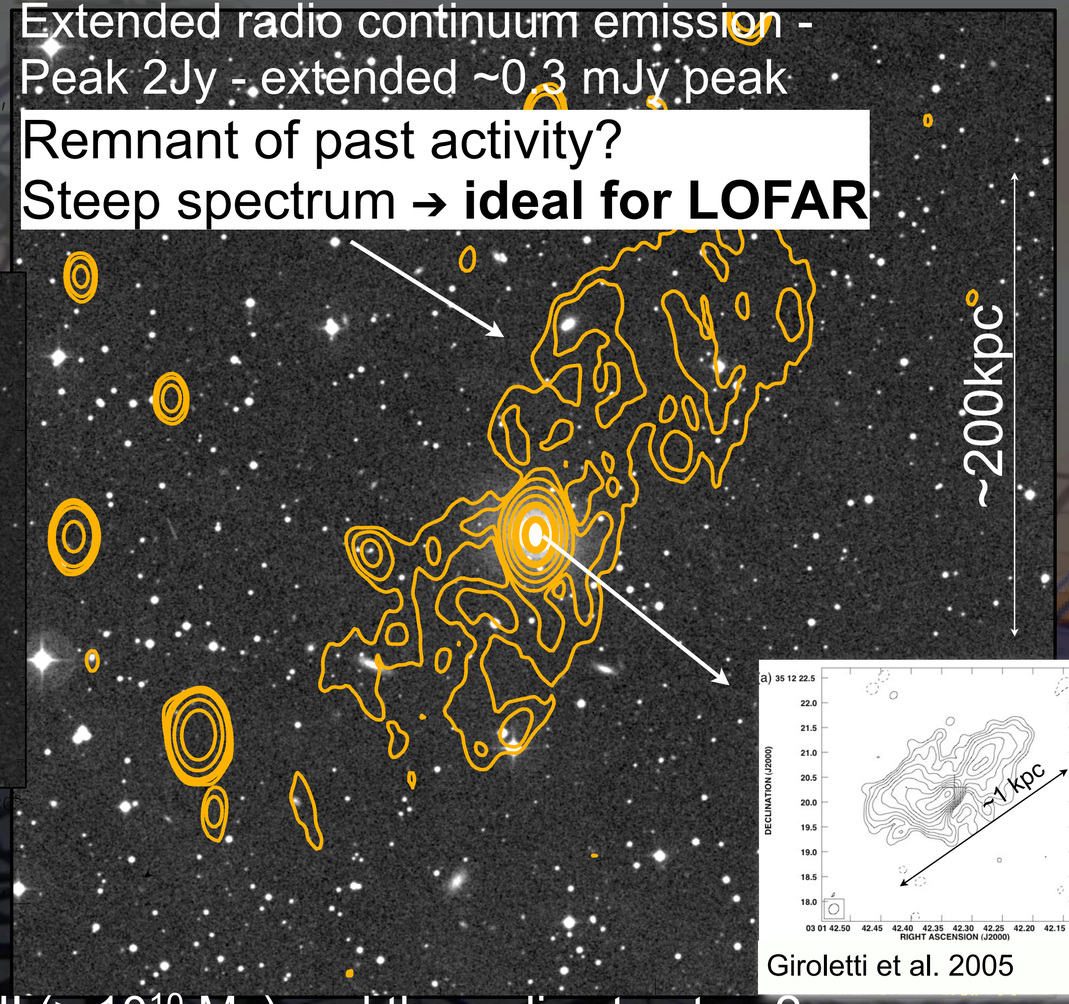

Giroletti et al. 2005

Young radio galaxy (compact steep spectrum)

➔ Any relation between the large amount of HI (> 10^{10} $M_\odot$) and the radio structure?

➔ First phase of radio activity “stopped or disturbed” by the merger (assuming the HI comes from a merger....)?

Conclusions

- LOFAR ideal telescope for surveys: roll out now, soon fun will start!
- Plans for large surveys at various depth and different frequencies (from 30 to 200 MHz)
- Aiming at finding rare, steep spectrum objects -> high-z radio galaxies, diffuse radio sources in cluster, high-z starforming galaxies.
- BUT also enabling plenty of other exciting science !!!
-
- Important synergy with L-band large surveys: sub-mJy population, nearby AGN: duty-cycle of the activity, spectral characteristics of radio sources....