LOFAR Survey Key Project

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

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Why surveys?

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

- 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 (Pannstars) etc.

- Data reduction is a real challenge and computer intense: delivering final data products is a real challenge

Note: there is also open time

The Exploration of the unknown
(Kellerman et al. Decadal White paper)

- The excitement of the next generation of astronomical facilities is not in the old questions which will be answered, but in the new questions that they will raise

- Major discoveries (AGN, pulsars masers, exo-planets etc.), were the results of building powerful new instrument and not the result of trying to test any particular model or trying to answer a previously posed question.

Overview

- Survey science

- Current survey plans

- Ionospheric calibration

    - 3-dimensional phase screens

    - Residual PSF variations

- Organisation
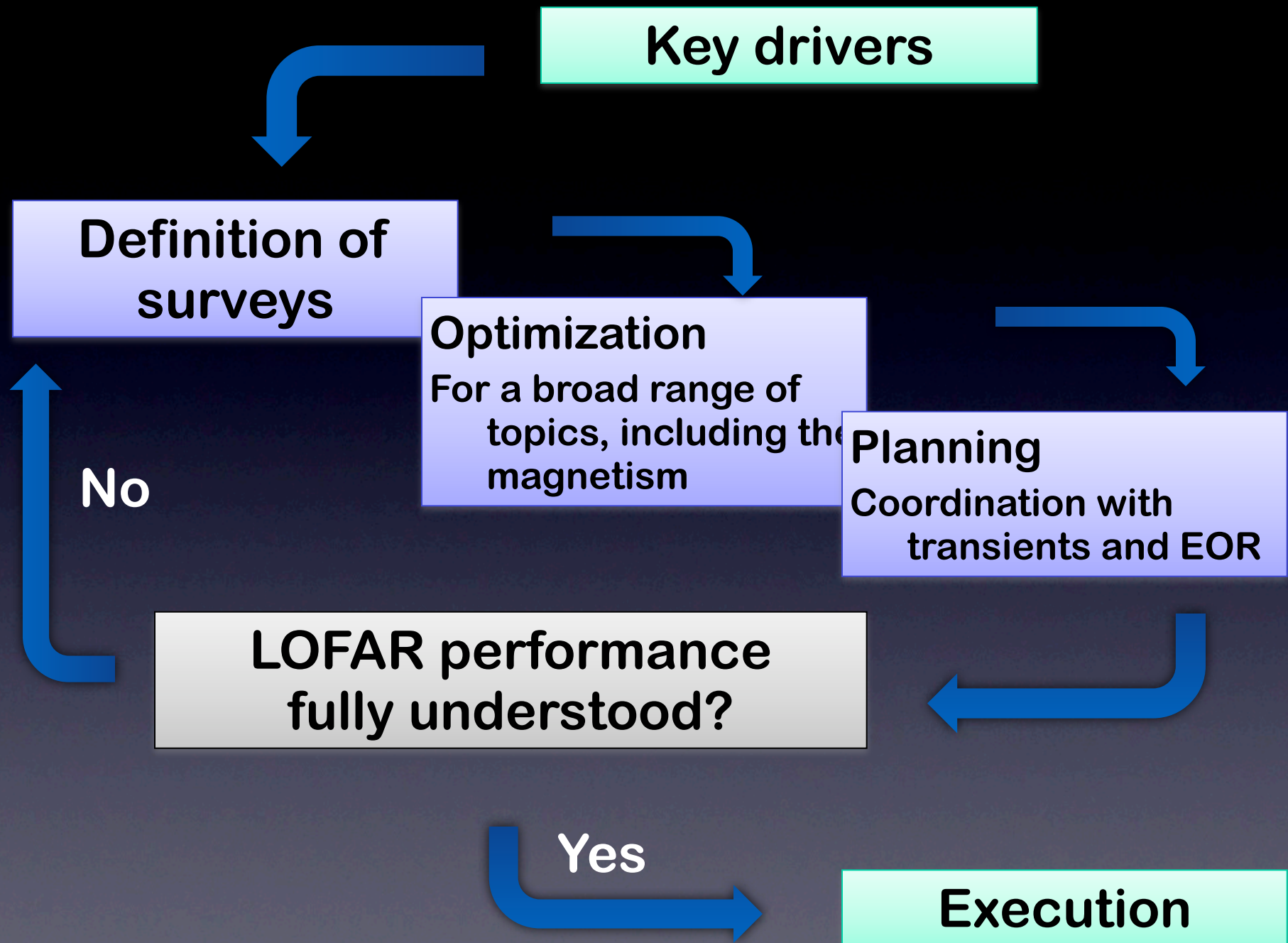
Main Drivers

- 100 z ~ 6 radio galaxies

  Formation and evolution of massive galaxies, black holes and clusters at/near the epoch of reionisation

- 100 cluster radio sources at z > 0.6

  Dynamics of cluster gas, evolution of cluster wide magnetic fields

- 10 clusters of starbursts starbursts at z>2

  SFR ~ 10 M0/yr at z=2-3

- Serendipity

  << 30 MHz

Other important topics

- AGN and radio source physics
  - Giant radio sources
  - Young radio sources
  - Feedback processes
- Nearby galaxies
  - Warm ISM
  - Halos
- Lensing
- Cosmological sudies
  - Baryonic oscillations
  - Integrated Sachs-Wolf effect
- Galactic radio sources
  - Supernova Remnants
  - HII regions
  - ``Diffuse structures''

Considerations

- Survey speed

- Wide bandwidth

  - RM synthesis for the collaboration with the magnetism KSP

  - Calibration

  - Spectral properties

- Tiling of the beams

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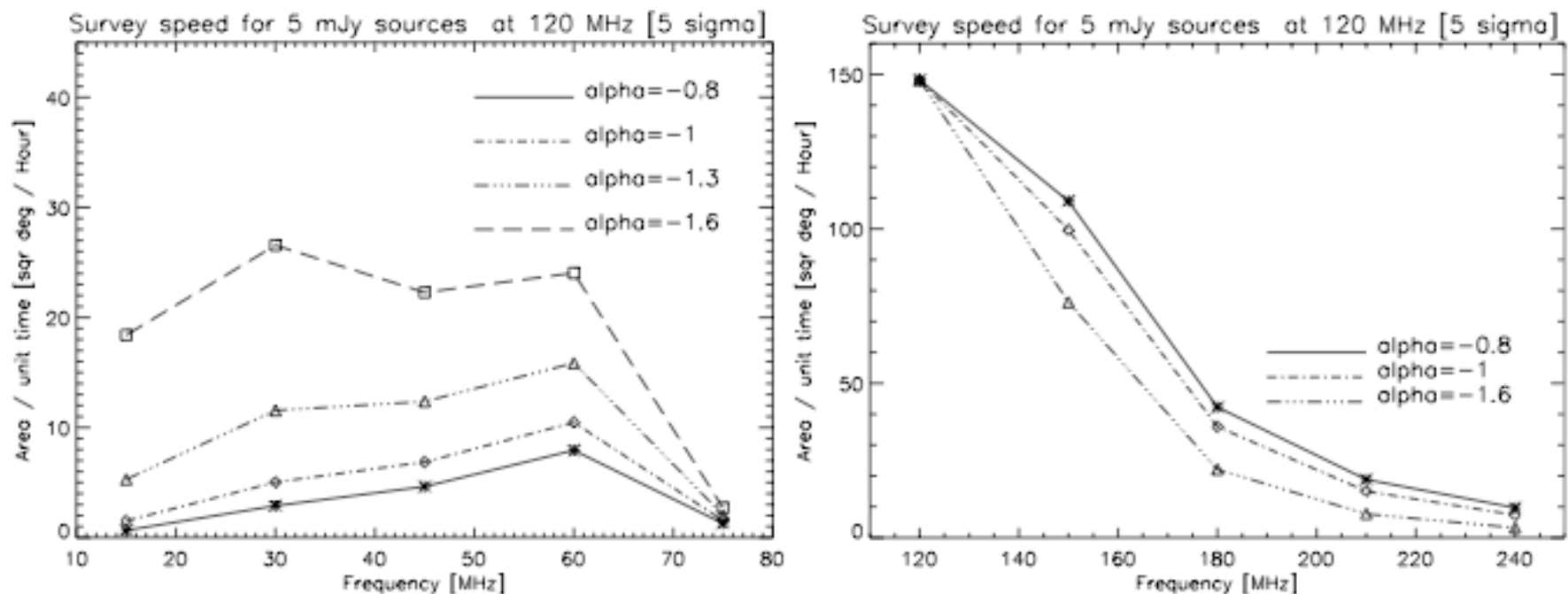## Sweet spots: 15-60 MHz (!) and 120 MHz

Figure 7: *Using one 4 MHz beam, the survey speed taken as the area on the sky covered per unit time deep using enough to detect a 5 mJy source at 120 MHz at the 5 sigma level as a function of frequency. (left) Low-band system, (right) High-band system.*

Wide bandwidth

Table 5: *LOFAR filter bandpasses*

Filter	LBA/HBA	Frequency range
1	LBA	10–90 MHz
2	LBA	30–90 MHz
3	HBA	110–190 MHz
4	HBA	170–230 MHz
5	HBA	210–270 MHz

Table 6: *LOFAR survey frequency setups*

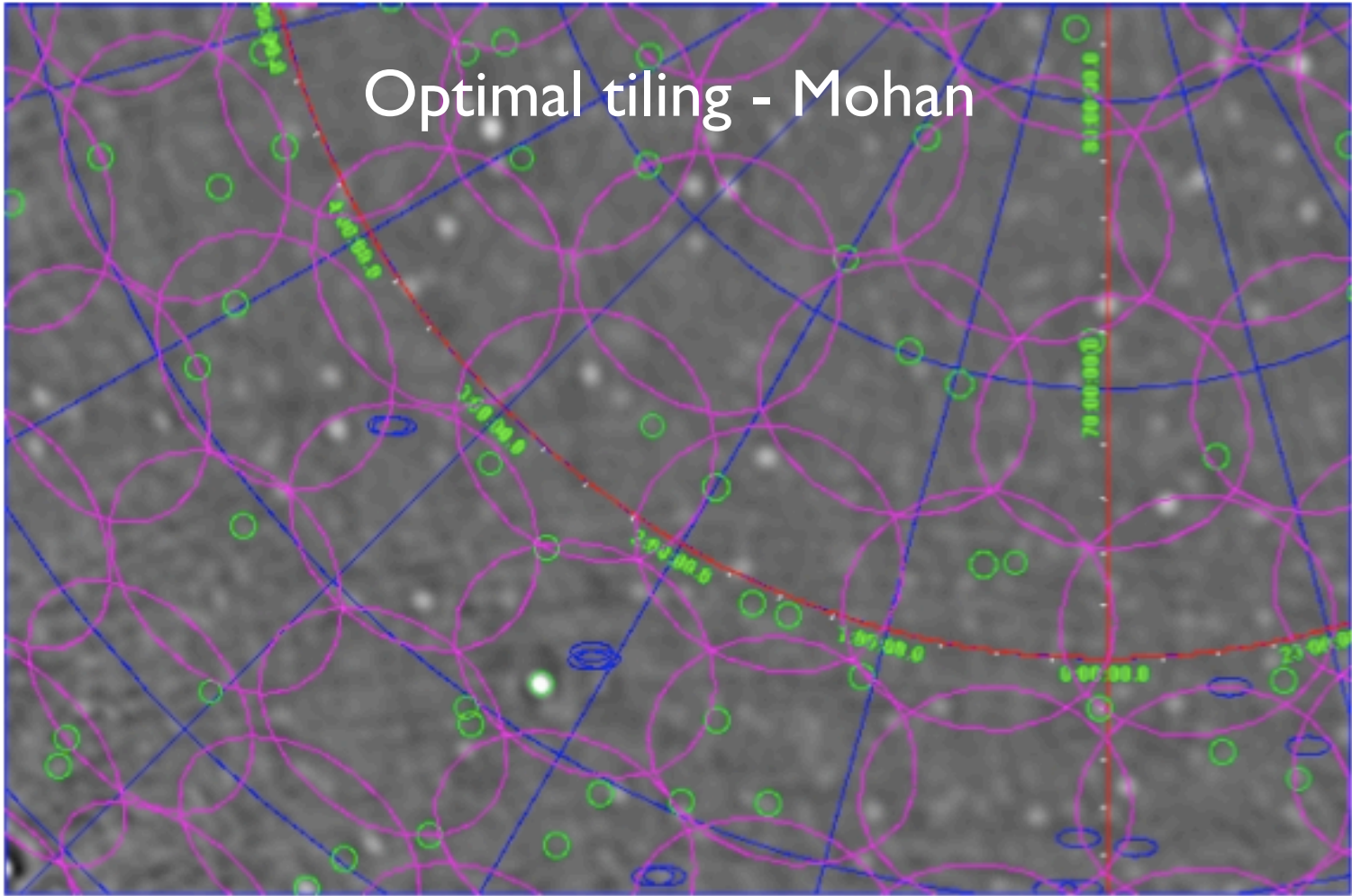| Nominal survey frequency (MHz)	Frequency range (MHz)	Total bandwidth MHz	LOFAR band pass
15	15 - 23	4	10 - 90
30	30 - 50	16	30 - 90
60	60 - 80	16	30 - 90
120	120 - 150 (90 %)	14.5	110 - 190
	150 - 190 (10 %)	1.5	
150	126 - 174	48	110 - 190
200	180 - 210	16	170 - 230

Figure 5: *A blow-up of figure 4. Also indicated are in green galaxies from the list in the Appendix and in blue clusters of galaxies also from the list in the Appendix.*

Proposed LOFAR Survey Specifications

H. J. A. Röttgering[1], P.N. Best[2], M.J. Jarvis[3] P. N. Barthel[4],
M. Brüggen[5], G. Brunetti,[6] K.T. Chyży[7], J. Conway[8], M. Lehnert[9],
G. K. Miley[1], R. Morganti[4,10], I. Snellen[1]
for the LOFAR survey team

Table 7: *Tier 1: The "Large Area" survey*

f[1] MHz	Area deg[2]	rms mJy	BW MHz	Sources[2] /beam	Integration time[3] hrs	Number pointings	Days[4]	Total[2] sources
15	20626	10	4	17811	100	100	21	1.4e+06
30	20626	2	16	19106	22.3	218	42	3.5e+06
60	20626	0.75	16	30124	20.6	203	36	5.1e+06
120	20626	0.1	16	30016	3.8	1021	33	2.8e+07
200	20626	0.2	16	2472	1.0	3021	25	7.0e+06
200	1088	0.065	16	9373	9.3	150	12	1.4e+06

- 120 MHz: workhorse survey:
    - <u>depth and area</u> (50% of the sky!) driven by ~100 radio halos at z~0.6
- 15, 30, 60 MHz:
    - <u>depth and area</u> driven by ~ 100 hzrgs at z~6,
    - α^{30}_{60}=-1.6, α^{15}_{30}=-1.3

Fudge factor = 2.5

- 200 MHz
    - 150 pointings/1000 deg^2: matching 60 MHz with α=-0.75
        - 13 famous blank-field regions with superb degree-scale multi-wavelength data.
        - 60 nearby clusters or superclusters;
        - 60 nearby galaxies.
    - Shallow all sky

Table 8: *Tier 2. The "Deep" survey*

f[1] MHz	Area deg^2	rms mJy	BW MHz	Sources[2] /beam	Integration time[3] hrs	Number pointings	Days[4]	Total[2] sources
30	2806	0.7	16	53523	204	25	44	1.6e+06
60	3025	0.25	16	96763	207	25	44	2.9e+06
120	555	0.025	16	204070	67	25	14	5.6e+06
210	362	0.016	16	66635	172	50	74	3.5e+06

- 120 MHz: starburst galaxies (z=0.5: 10 M/yr; z=2.5: 100Mhz);
- 25 regions:
  - 13 famous blank-field regions with superb degree-scale multi-wavelength data.
  - 6 nearby clusters or superclusters;
  - 6 nearby galaxies.
- 30 and 60 MHz matches all sky with α = -1.4
- 200 MHz matches 120 MHz with α = -0.8

Table 9: *Tier 3. The "Ultra Deep" survey*

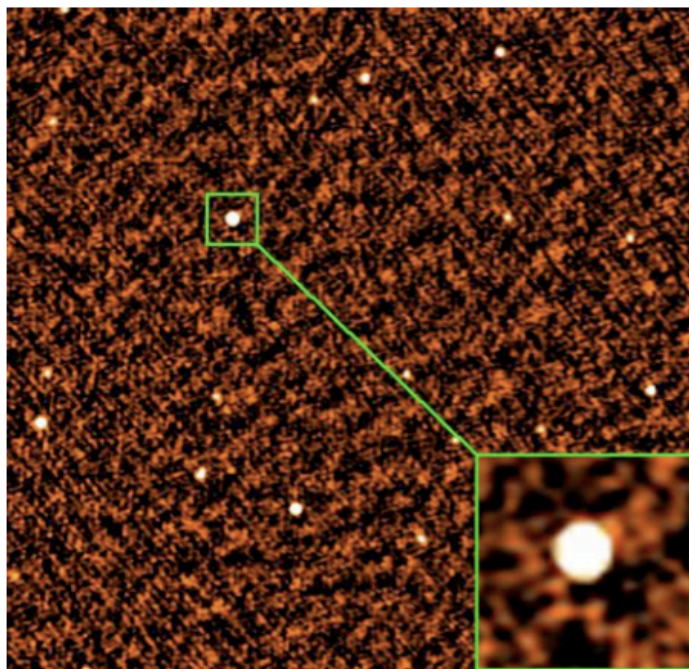| f[1] MHz	Area deg[2]	thermal rms mJy	BW MHz	Sources[2] /beam	Integr, time hrs	Number pointings	Days[3]	Total[2] sources
150	71	0.0062	48	543798	221	5	28	2.9e+06

- Clusters of starbursting galaxies with 20-30 M/yr at z=2.5: 100M/yr at z=8

- Targetting famous extra-galactic fields

Ionospheric model fit
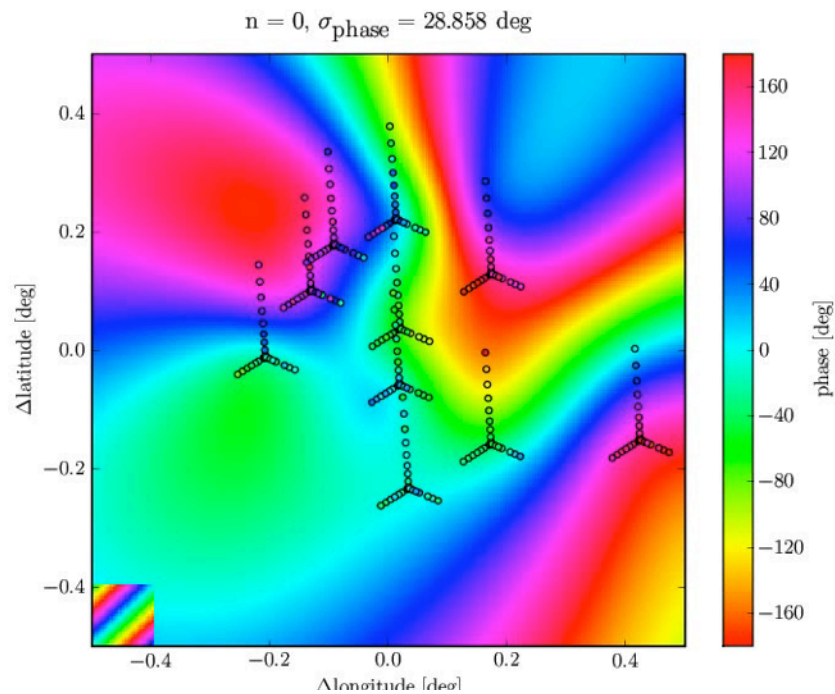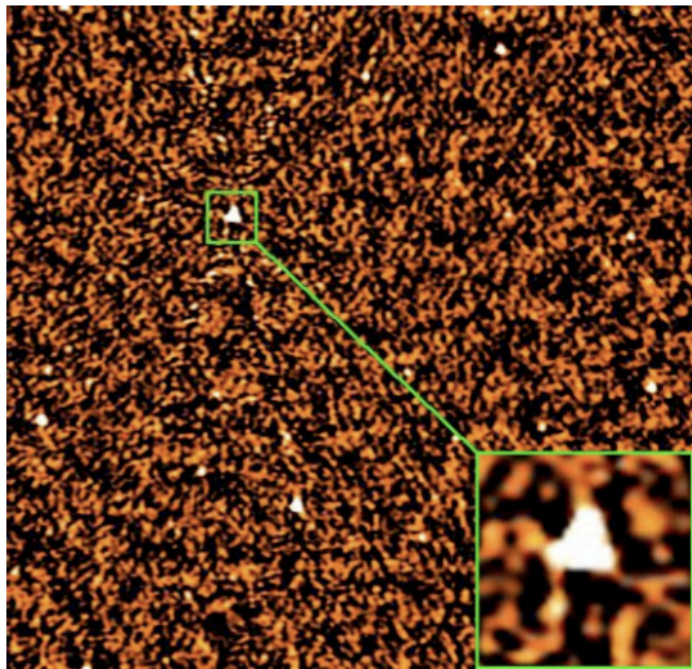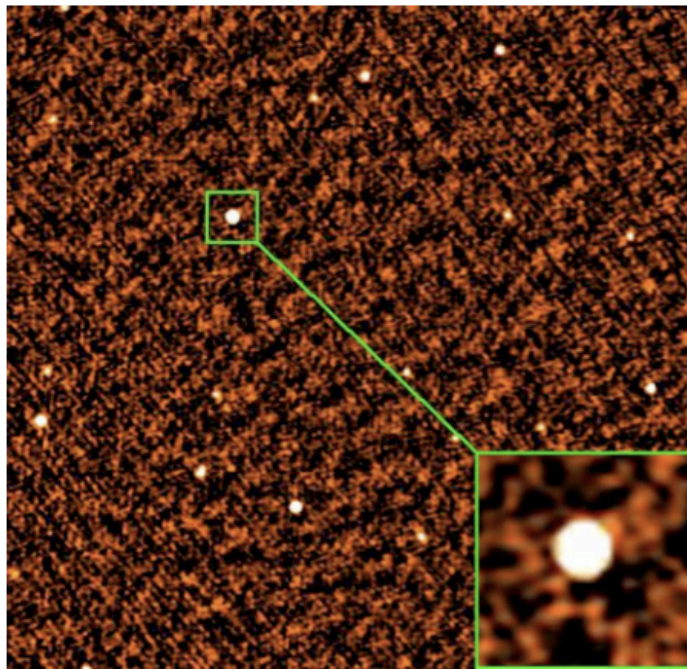## (PhD Intema)
VLA@74 MHz, 80'' res.,
2 deg. FOV

Old
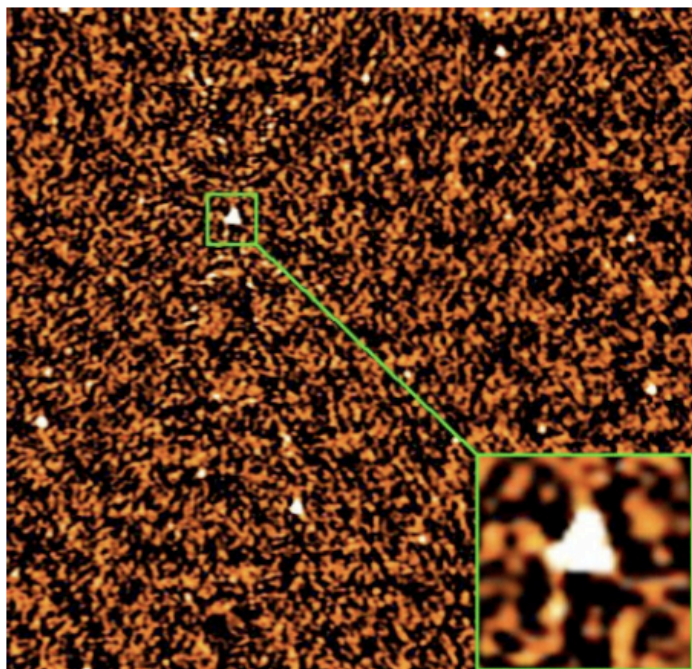
new

Ionospheric model fit (PhD Intema) VLA@74 MHz, 80" res., 2 deg. FOV

$n = 0$, $\sigma_{phase} = 28.858$ deg

Old

new

Ionospheric calibration

- Ionospheric obervations from the VLSS 74 MHz survey

  - Statistics: Cohen & HR, 2009arXiv0905.4501C

  - Analytic fitting of disturbances - van der Tol et al. thesis chapter

- Calibration using phase screens

  - 2-d screen: Intema et al. 2009arXiv0904.3975 and being implemented in BSS

  - 3-D screen paper: Intema et al.: thesis chapter

- Next steps:

  - Testing 2D model in BBS

  - BSS implementation of the 3D model

  - Time evolution
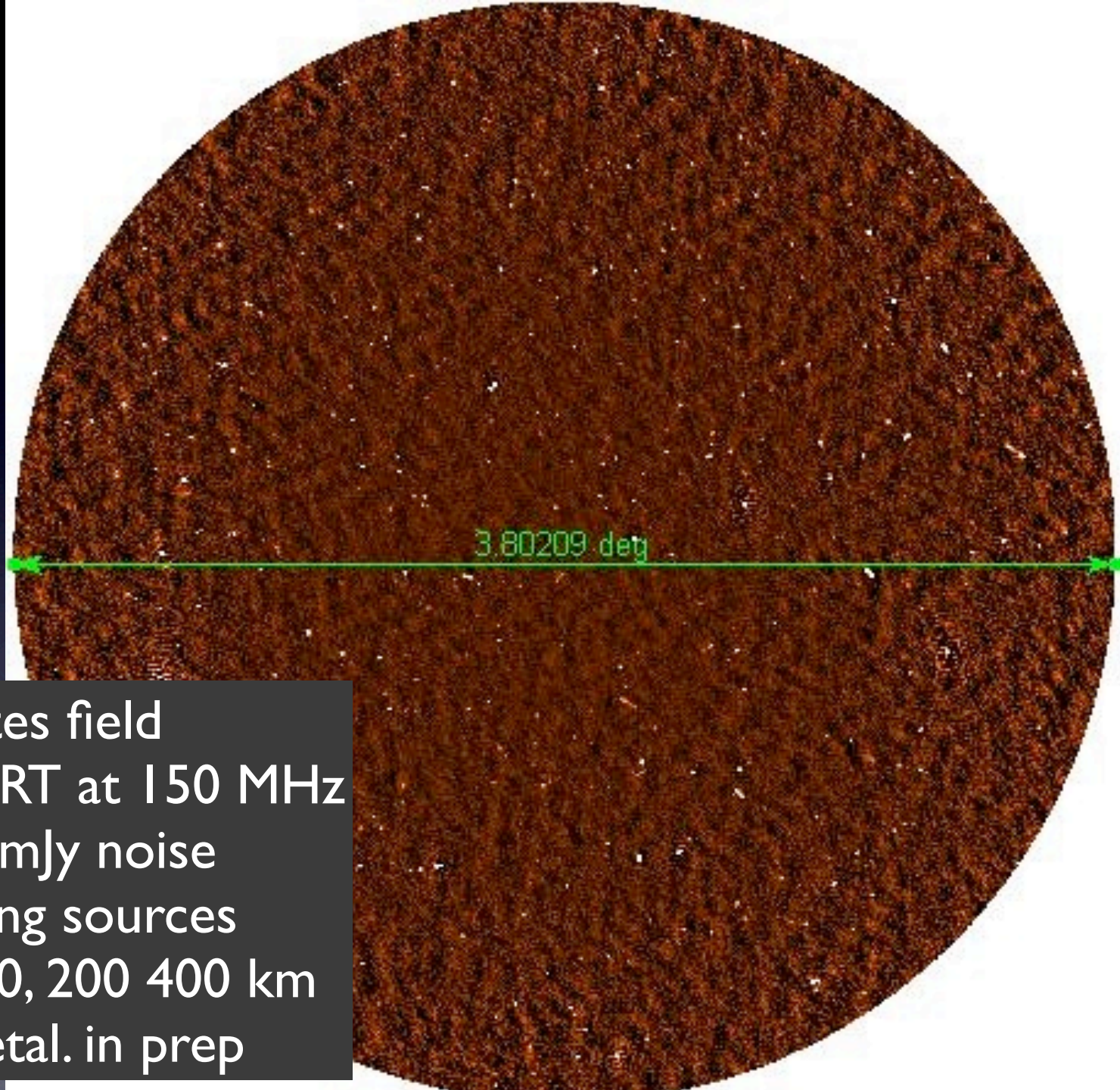
Bootes field
with the GMRT at 150 MHz
0.7 - 1 mJy noise
24 peeling sources
layers at 100, 200 400 km
Intema etal. in prep

PSF variations due to imperfect calibration - Mohan

Organisation

- Executive body: Core team

  - Huub Rottgering, Peter Barthel, Philip Best, Marcus Brüggen, Gianfranco Brunetti, Krzysztof Chyzy, John Conway, Matt Jarvis, Matt Lehnert, George Miley, Raffaella Morganti, Ignas Snellen

- Members

  - appointed by national consortia

  - Selected for specific expertise

- Rules and regulations document

  - www.strw.leidenuniv.nl/lofar/

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 ...
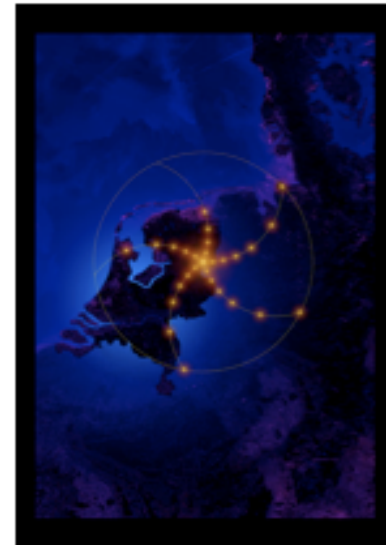
Commissioning

- Aims

- List of observations

- Organisation

  - Manpower

    - PhD students /postdocs

  - Busy week

  - List of science projects/papers

  - Proposals

- Some input for proposals

Aims of Commissioning

- Which dipoles to use to optimize survey speed?
  - What tapering?
  - Trade-off between sensitivity, FOV and low side-lobe levels
  - Station beam stability, pointing accuracy
- Which frequency setups are best for our purpose?
  - RFI
  - spectral index, polarization and RM determination
- How to deal with the ionosphere
  - 2D / 3D models?
  - Time resolution?
- Quality of the final maps: uniformity of noise, detectibility of extended structure, stability of the psf and sensitivity
  - all as a function of declination
- Overall issue: what limits the dynamic range?
- Long baseline to be included in any observations

First list of commissioning observations

- 1. At the full range of frequencies: a low and high elevation field (Bootes and the XMM-LSS?)
  - Especially
    - at 30 MHz: different selections of dipoles, also combined with 60 Mhz observations
    - at 120 MHz: range of bandwidths
    - how low can we go (in frequency and declination)?
    - how well at zero declination?
- At the survey frequencies
  - two deep fields
    - 5 pointings in a hexagonal grid
    - At a depth comparable to the proposed 'tier-1' all sky surveys
      - ~100 hours for the high declination and ~200 hours for low declination field
  - Lenc field
  - Coma cluster
  - A giant radio source
  - Deep observations at a very bright source
  - A simple galactic field (CTA-1 ?)
  - Galactic center
  - All the observations with long baselines at 0.25 sec.

Busy week

- One week with hand on reducing LOFAR data with the aim of debugging the system

- (a bit of science)

- end of September/beginning of october?

Fabien	Batejat	c	John Conway	phd
Annalisa	Bonafede	c	Luigina Feretti	phd
Francesco	de gasperin	c	Merloni	phd
Robert	Drzazga	c	Krzysztof Chyzy	phd
Louise	Ker	c	Philip Best	phd
Elzbieta	Kuligowska	c	Marek Jamrozy	phd
Giulia	Macario	c	Gianfranco Brunetti	phd
Hanifa	Temourian	c	Matt Jarvis	phd
Reinout	van Weeren	c	Huub Rottgering	phd
Laura	Birzan	c	Huub Rottgering	post
Rossella	Cassano	c	Gianfranco Brunetti	post
Sven	Duscha	c	Torsten Ensslin	post
Tom	Dwelly	c	Judith Croston?	post
Tim	Garn	c	Philip Best	post
Annette	Haas	c	Marcus Bruggen	post
George	Heald	c	Raffaella Morganti	post
John	McKean	c	Raffaella Morganti	post
Niruj	Mohan	c	Huub Rottgering	post
Emanuela	Orru	c		post
David	Rafferty	c	Huub Rottgering	post
Nick	Seymour	c	Matthew Page	post
Bas	van der Tol	c	Huub Rottgering	post

Busy weekers/
commissioners

2 co-organisers?

Philip	Best	c?
Marcus	Brüggen	c?
John	Conway	c?
Huub	Röttgering	c
Marijke	Haverkorn	c
Neal	Jackson	c
James	Anderson	c?
Rob	Beswick	c?
Aaron	Cohen	c?
Chiara	Ferrari	c
Matthias	Hoeft	c
Enno	Middelberg	c
Isabella	Prandoni	c?

Busy weekers/
commissioners

Commissioning proposal input

- General science case

- List of specific projects and related papers

  - Names!

- Main issues for commissioning

- Specification of observations

  - area, depth, frequencies ...

  - long baselines

- Data reduction plan

  - Names, (also for the busy week)

Science working groups

1. Commissioning
   - Fill-out a 3-D matrix
     - 9 science working groups
     - 6 major commissioning aims
     - ~10 different observations
   - Sketch a commissioning proposal
   - Make a planning
2. Comment overall survey plan
   - depth, areas, frequencies
   - source and field lists
   - priorities/schedules
3. Comment on MS^3
   - depth, area, frequencies

Table 1: *Sensitivity table for 1h integration time, 2 polarizations and 3.57 MHz bandwidth*

Freq (MHz)	wavelength (m)	ΔS_{20} (mJy)	ΔS_{18+18} (mJy)	ΔS_{25+25} (mJy)
15	20	198	110	79.2
30	10	36	20	14.4
45	6.7	19.8	11	7.9
60	5.0	13.0	7.2	5.2
75	4.0	21.60	12	8.6
120	2.5	0.74	0.41	0.30
150	2.0	0.58	0.32	0.23
180	1.7	0.67	0.37	0.27
210	1.4	0.76	0.42	0.30
240	1.2	0.83	0.46	0.33

LOFAR-20 only a factor of ~4 'slower' than

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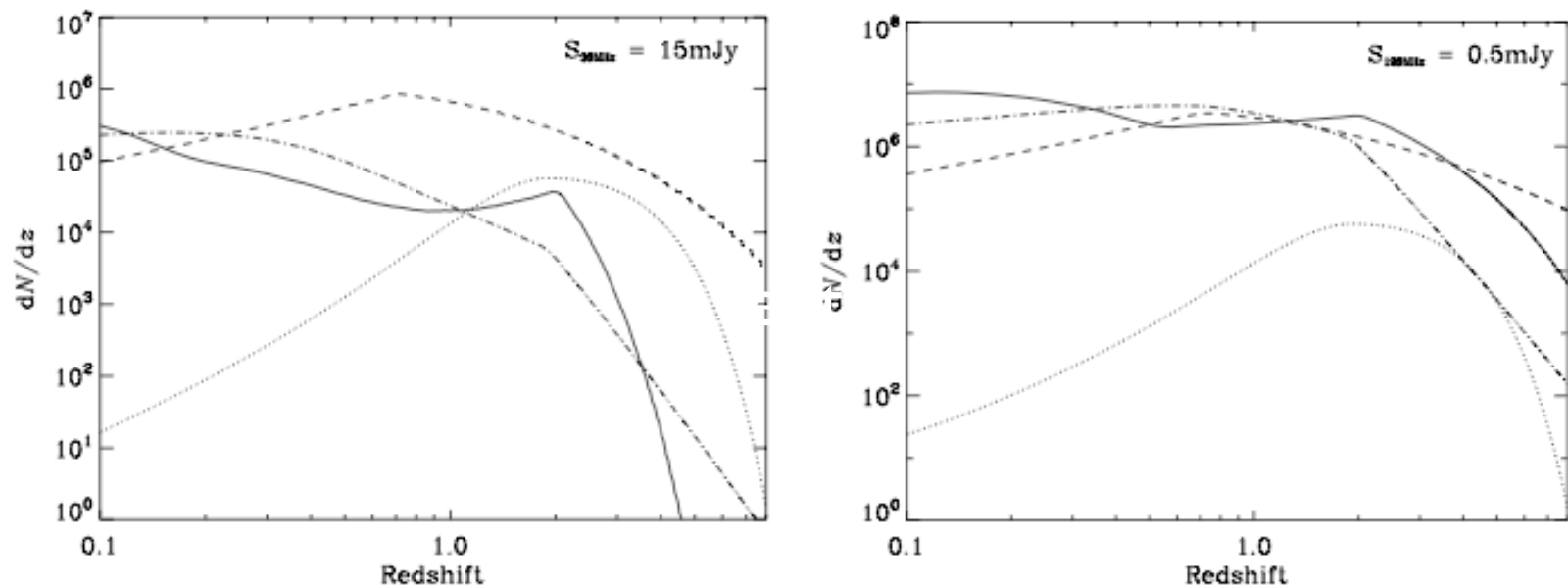| f[1] MHz	Area deg[2]	rms mJy	BW MHz	Sources[2] /beam	Integration time[3] hrs	Number pointings	Days[4]	Total[2] sources
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200	20626	0.2	16	2472	1.0	3021	25	7.0e+06
200	1088	0.065	16	9373	9.3	150	12	1.4e+06

30 MHz

120 MHz

Figure 9: *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 30 MHz (left) and 120 MHz (right, update) all sky LOFAR surveys.*

Busy week/ commissioners

- Clusters

  - Bonafeda, Macario, Birzan, Rafferty, Duscha, Orru, Bruggen, Ferrari, Hoeft, Edge

- Galaxies

  - Robert Drzaga, Tigran, Heald (?), Beswick (?), Batajat, Conway

- Milky Way

  - Marijke, ~2 PhD position with Marijke and Glenn

- input on comissioning

- input for the survey plan

- agenda

Commissioning

- chairs send me

  - their notes

  - list of commissioning observations

  - list of ms3 projects

  - names

    - busy weeks

    - projects/papers

Survey plans

- lists of sources/fields
  - galaxies
  - clusters
  - blank fields
- talk to potential collaborators

Next steps

- 2 small busy weeks

- Cluster meeting Oct - Bologna?

- Bremen Nov/Dec - decision in September on size

  - planning/priorities

  - first data

- Leiden LC March 8-12

  - ms3 data / commissioning data

Agenda

- chairs reporting

- select blank fields

  - info on Herschel/Atlas - Matt

- individual contribution

  - Nick on Askap

  - Merloni

C Deep extragalactic deep fields

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Suitable blank fields for LOFAR Deep Surveys
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XMM-LSS           02 25 00   -04 30 00    DXS  PS1  CFHTLS  Subaru
IFA/Lynx          08 43 00   +44 40 00         PS1
COSMOS            10 00 00   +02 12 00         PS1
Lockman Hole      10 57 00   +57 40 00    DXS  PS1
NGC4258-field     12 18 57   +47 18 14         PS1
HDF+HFFs ??       12 36 49   +62 12 58
VISTA-Video1      14 00 00   +05 00 00         PS1
Groth Strip       14 17 00   +52 30 00              CFHTLS
Bootes            14 32 00   +34 30 00                              NDWFS
Elais N1          16 10 00   +55 00 00    DXS  PS1
NEP               18 00 00   +66 33 00              (CFHT)
VIMOS 4/SA22      22 17 00   +00 20 00    DXS  PS1
DEEP2             23 30 00   +00 00 00         PS1
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fields prio

- prio1:

- xmm-lss

- cosmos

- bootes

- LH

- prio2

- EN1, NEP , FLS, SSA22

- prio3