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Netherlands Institute for Radio Astronomy

Radio surveys: an overview

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ASTRON (NL) and Kapteyn Institute

Turning points for radio surveys!

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Surveys (and deep fields) have played also in radio astronomy an important role

.....now we are at a turning point:

entering a new era of surveys !

- new technology (e.g. wide field of view, broad bandwidth, high data rate etc.)

  => larger+deeper surveys can be done (line, continuum, polarisation, transients, serendipitous!...)

- delivering a broader variety of products

  => revolutionise the field: amazing databases for the community

These changes have already started!

This talk:

- radio surveys so far:

Radio continuum, line (HI)

- what is coming up now/soon

One survey fits all - challenges in handling the many products from new radio surveys.....

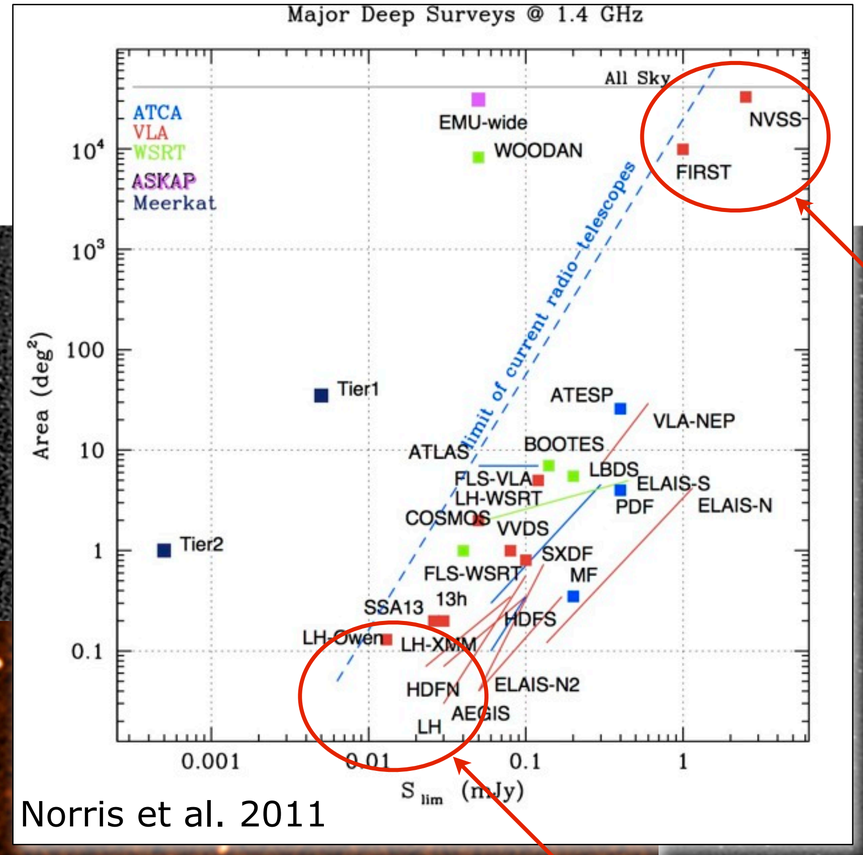
See also talks from R. Taylor, M. Wise and J. van Leeuwen

Radio surveys key ingredients

Limitations up to now:

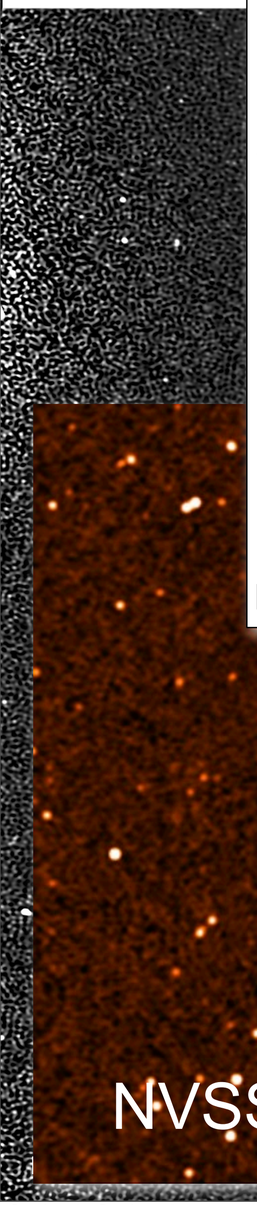
- ➡ spatial resolution often low/poor
- ➡ compromise in sensitivity => field of view => observing time
- ➡ limited frequency coverage & bandwidth => *penalised* magnetism, RM synthesis, spectral index...
- ➡ no multi-epoch => *penalised* transients

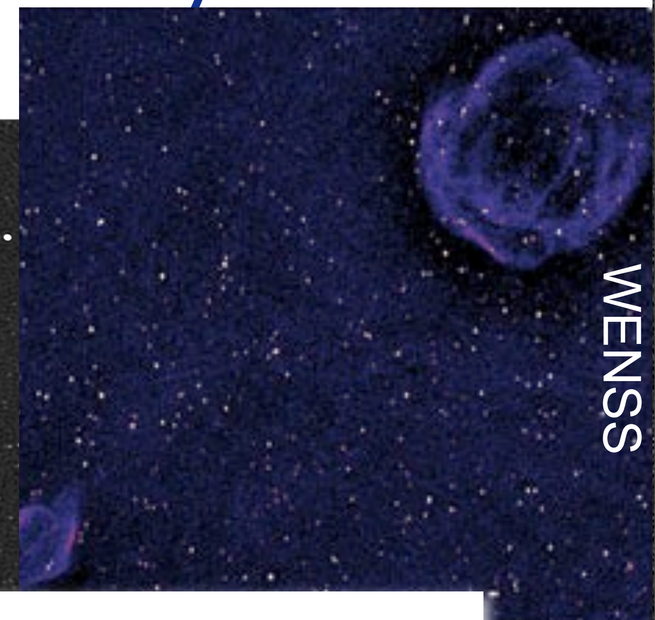
Radio continuum surveys

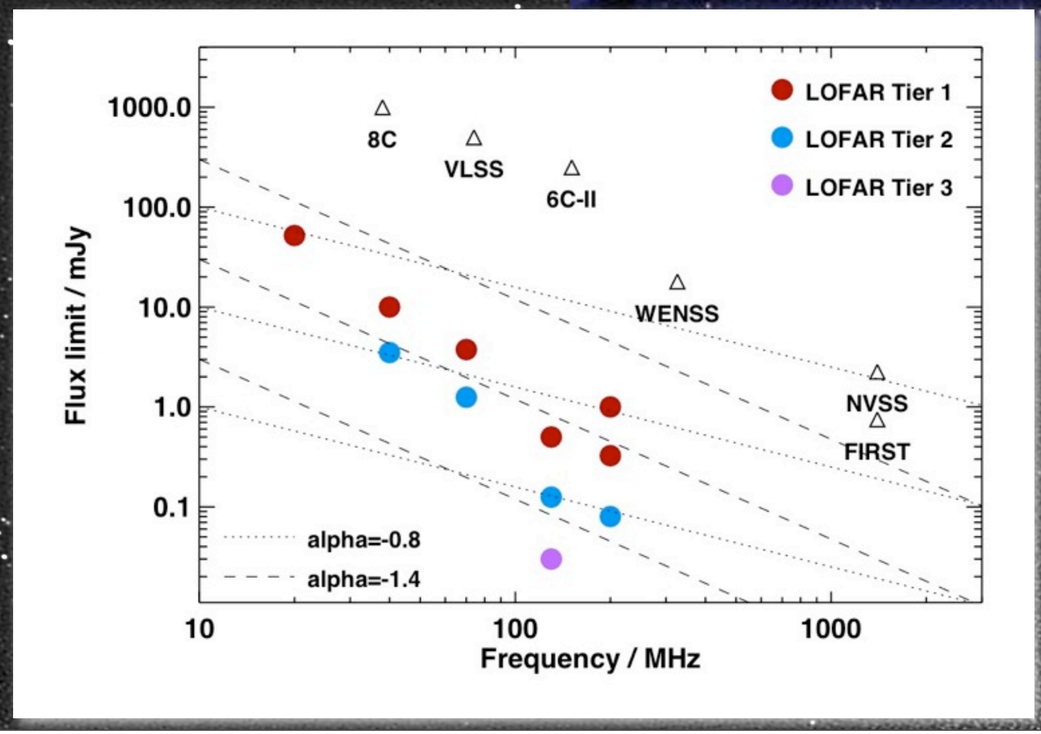


Largest radio surveys @ 1.4GHz

Deepest radio fields @ 1.4GHz







Radio continuum surveys (an incomplete list)

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Survey	Freq.	Area	Spatial resol.	5sigma
NVSS (NRAO VLA Sky Survey)	1.4 GHz	δ>-40deg	45 arcsec	2.5 mJy
FIRST (Faint Images of the Radio Sky at Twenty-cm)	1.4 GHz		5 arcsec	1mJy
WENSS (Westerbork Northern Sky Survey)	325 MHz	3.14 sr, δ>+30deg	54 arcsec *cosec(dec)	18 mJy
VLSS	74 MHz	δ> -30deg	80 arcsec	100 mJy
SUMSS (Molonglo Sky Survey)	843 MHz	δ< -30 deg	43 arcsec *cosec(dec)	5 mJy
Cambridge 7C	151 MHz	δ> +20 deg	70 arcsec	125 mJy
PMN (Parkes-MIT-NRAO)	4850 MHz	~all sky	5 arcmin	150 mJy

see also Condon 2010 for a review...

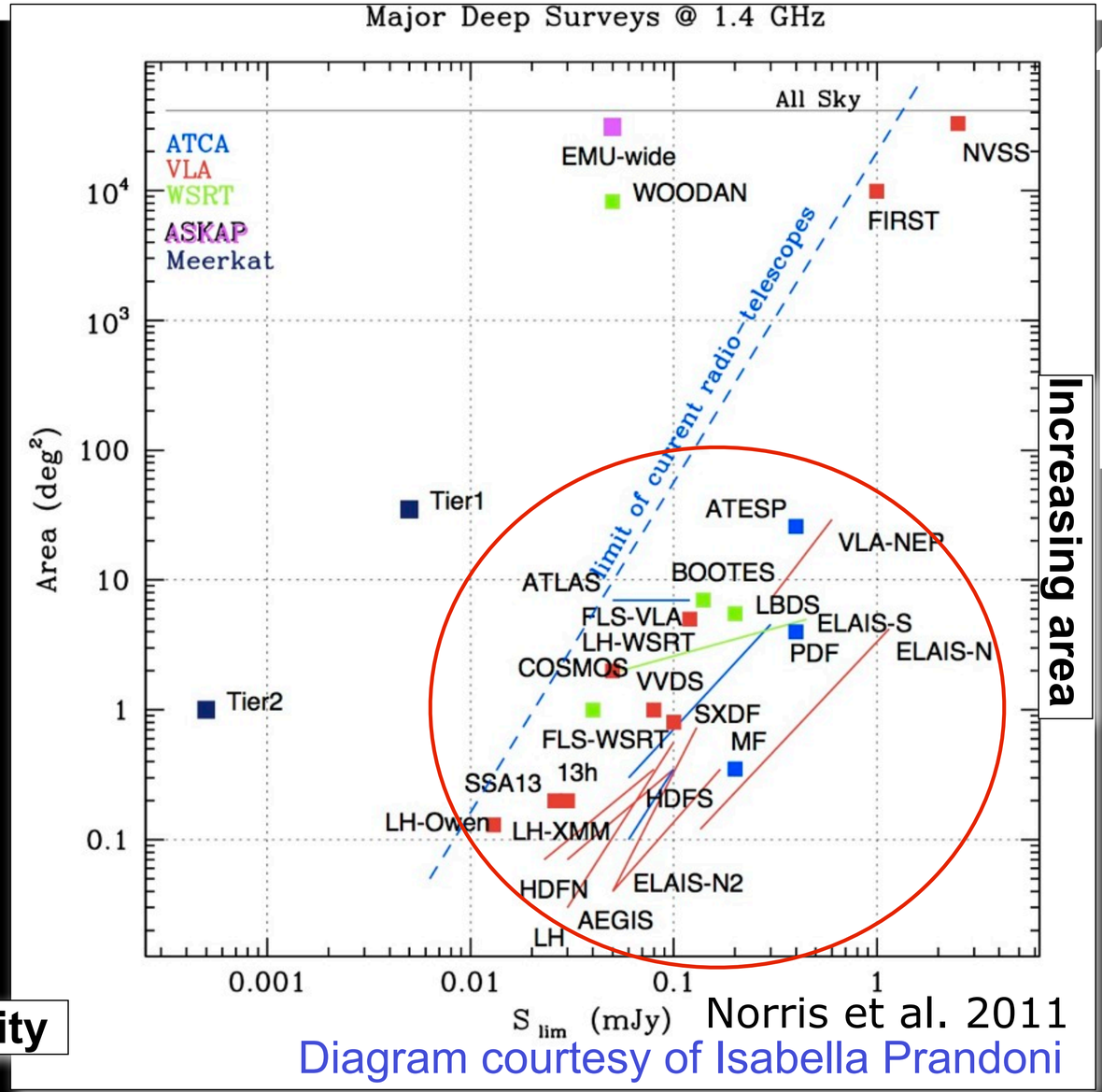
Most of the surveys at low frequencies, up to 1.4 GHz (compromise between area, observing time, spatial resolution and sensitivity => future surveys will also concentrate on this frequency range

Current major 20cm continuum surveys

- In addition to surveys: deep fields => situation so far
  - ***COSMOS***
  - ***HDF-N/S***
  - ***Bootes***
  - ***Lockman Hole***
  - ***Spitzer First Look***
  - ***ATLAS***
  - ***etc.***

only ≤10deg² of sky covered so far in such a depth (~10-50 μJy)

Increasing sensitivity



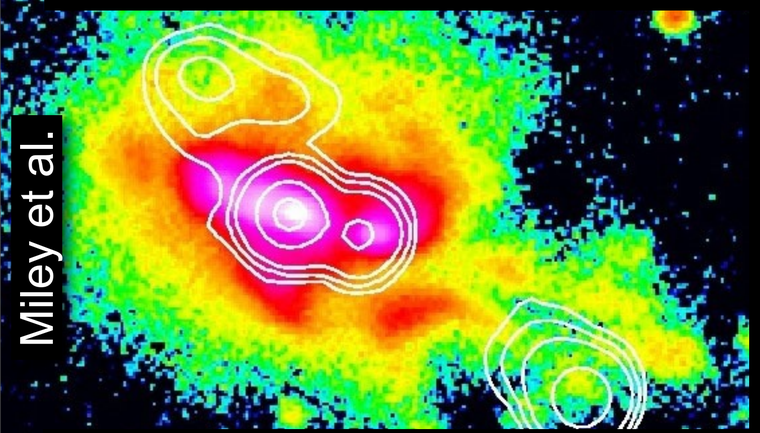
Norris et al. 2011

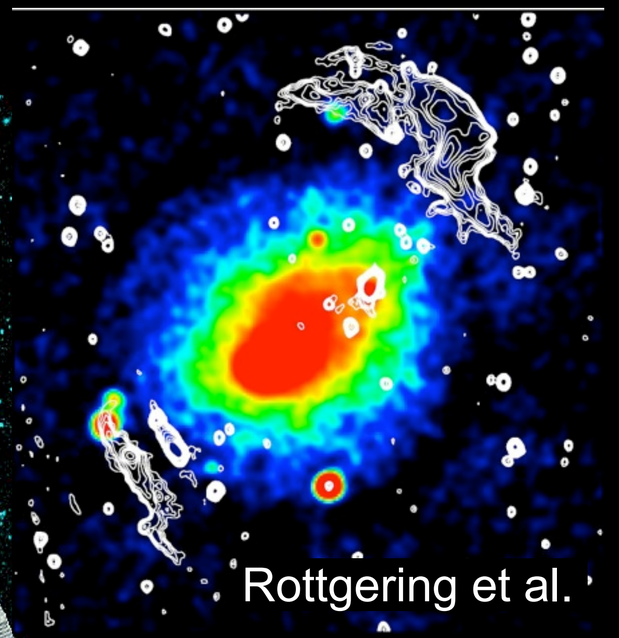
Diagram courtesy of Isabella Prandoni

Why continuum surveys? ....

Earliest radio surveys => major impact on understanding radio-loud AGN (radio galaxies and quasars)

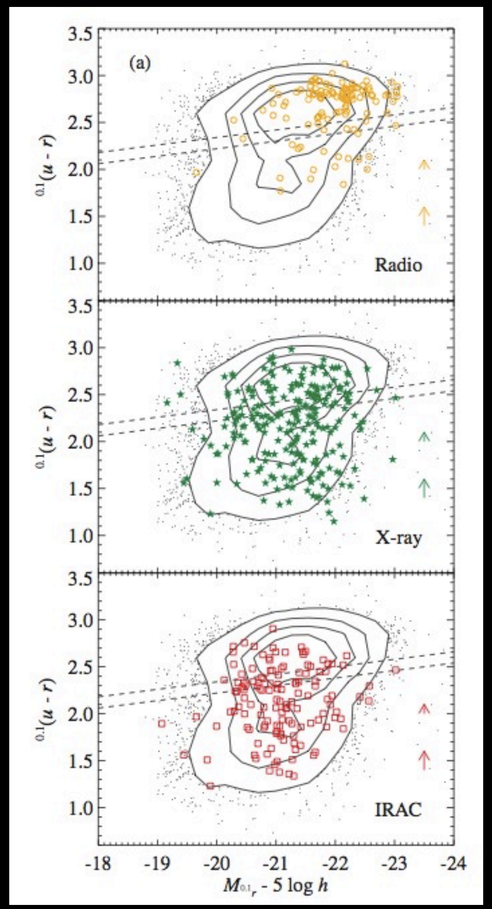
Radio sources stronger than ~1 mJy @ 1.4 GHz are typically powered by an AGN





- Identify high-z AGN via steep spectrum => TN J0924-2201 at z=5.2, the HzRG with the highest redshift known to date.
- Life cycle of AGN
- Radio halo in clusters
- ....too many to list all....

Radio AGN different from others: evolutionary sequence?



Selected radio power > $10^{23.8}$ W/Hz
Hickox et al. 2011

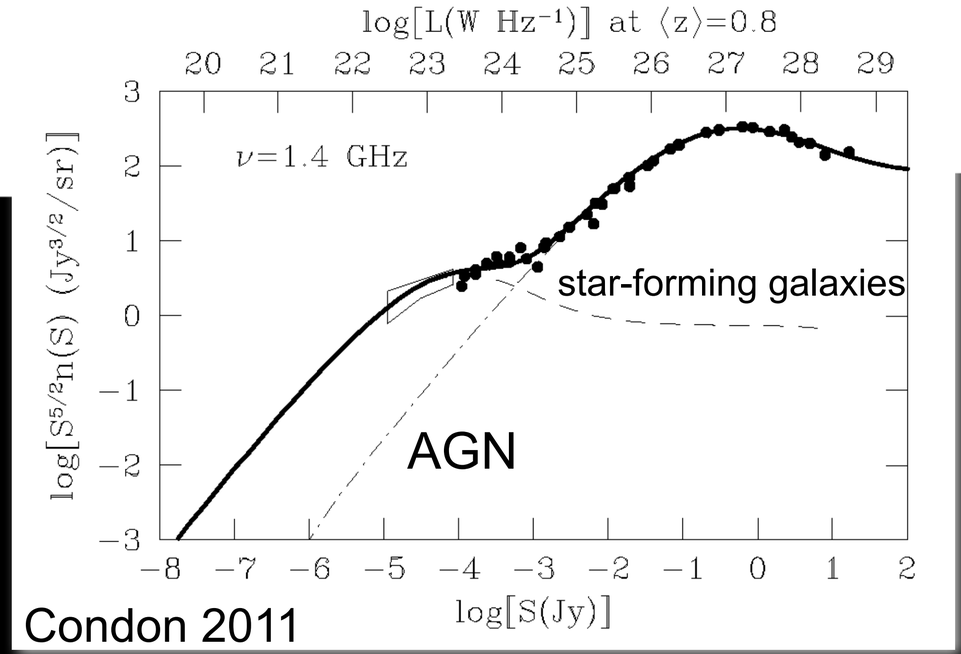
Why continuum surveys? ....

Earliest radio surveys => major impact on understanding radio-loud AGN (radio galaxies and quasars)

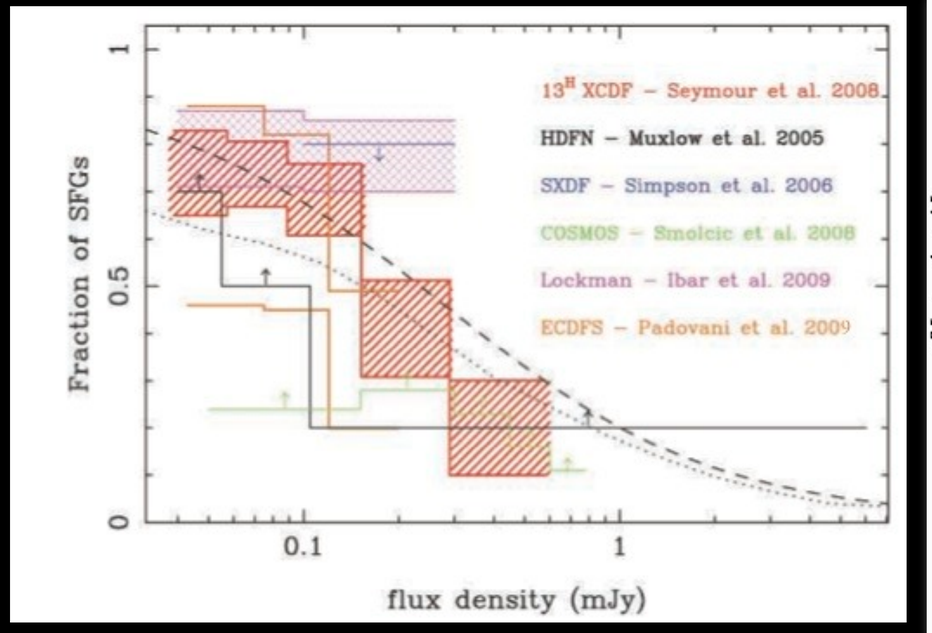
Radio sources stronger than ~1 mJy @ 1.4 GHz are typically powered by an AGN

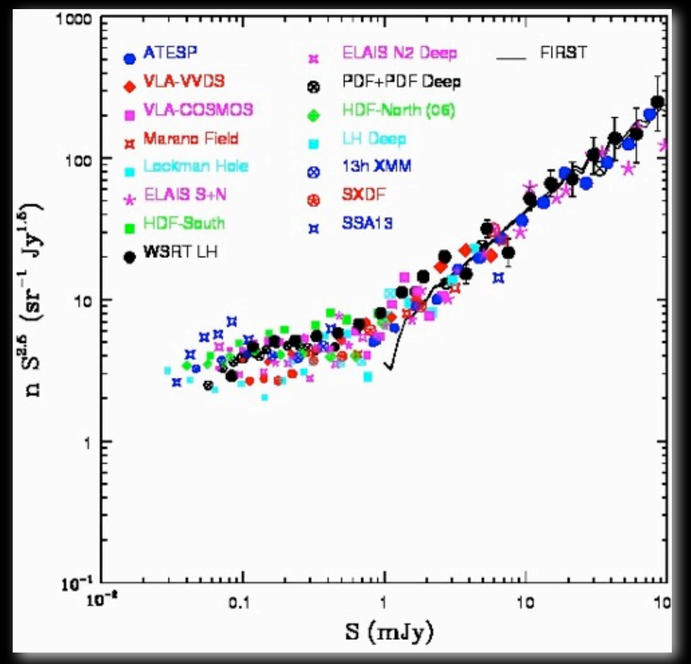
As the surveys probe the fainter end, the nature of the detected radio sources changes: **starforming galaxies** (change in the counts slope) together with **radio-quiet AGN**
=> evolution of star formation can be studied

Padovani et al 2009, Prandoni et al. 2009, Seymour et al. 2008



Condon 2011





Limited possibilities for polarisation studies

Galactic *B* poorly known but is important in most processes in the interstellar medium $\int B_{\parallel} n_e \, dl$

Measure rotation measure against many extragalactic sources
so one can reconstruct Galactic magnetic field
("The Rotation-Measure Grid")

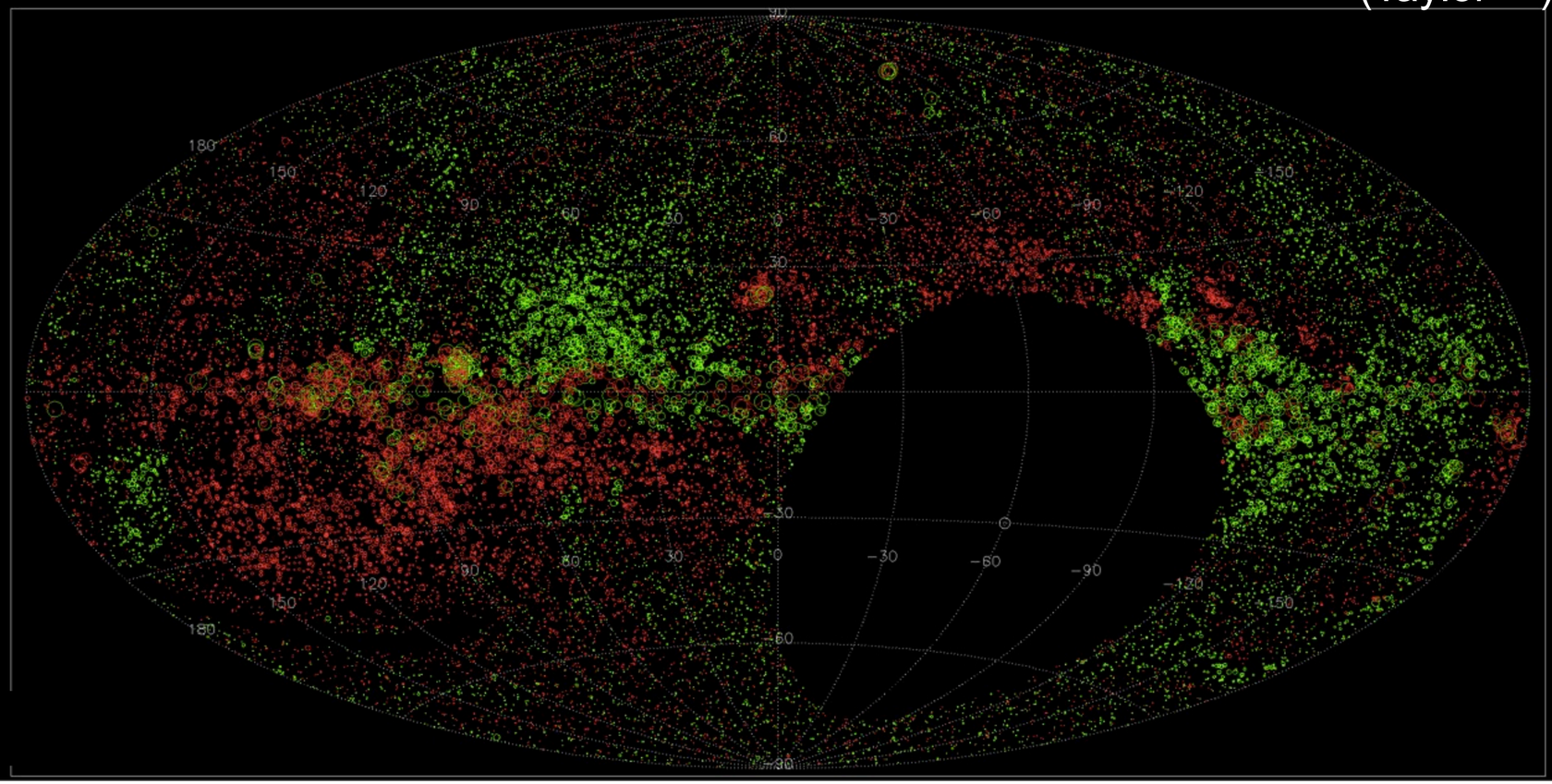
Studies so far done using the two bands available in the NVSS (Taylor et al.)

More frequencies and broad band needed will be provided by the new radio telescopes/surveys:

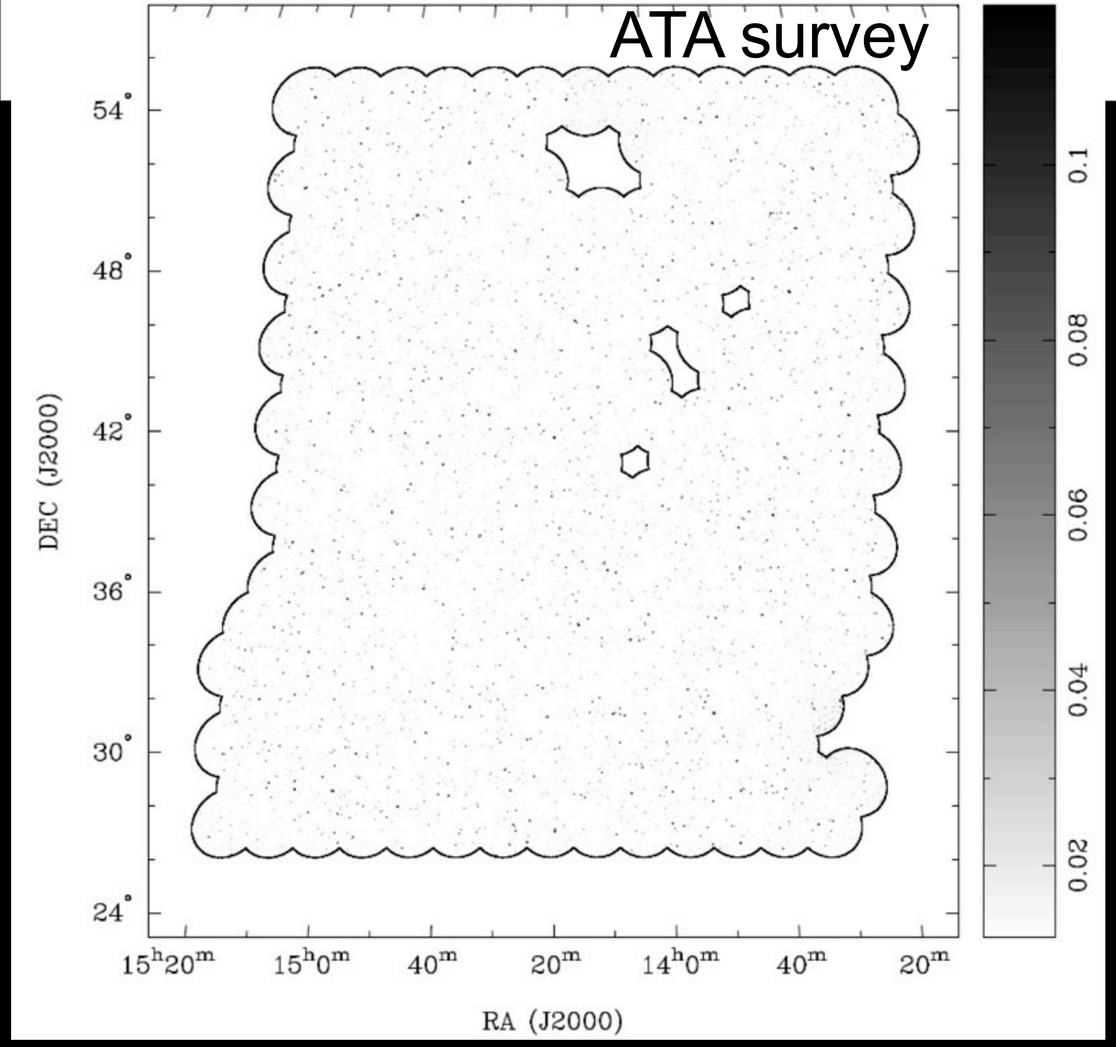
accurate determination
of rotation of polarisation vector over the band due
to magnetised plasma

Rotation measures derived from the NVSS. RMs below 450 in magnitude plotted.

(Taylor++)

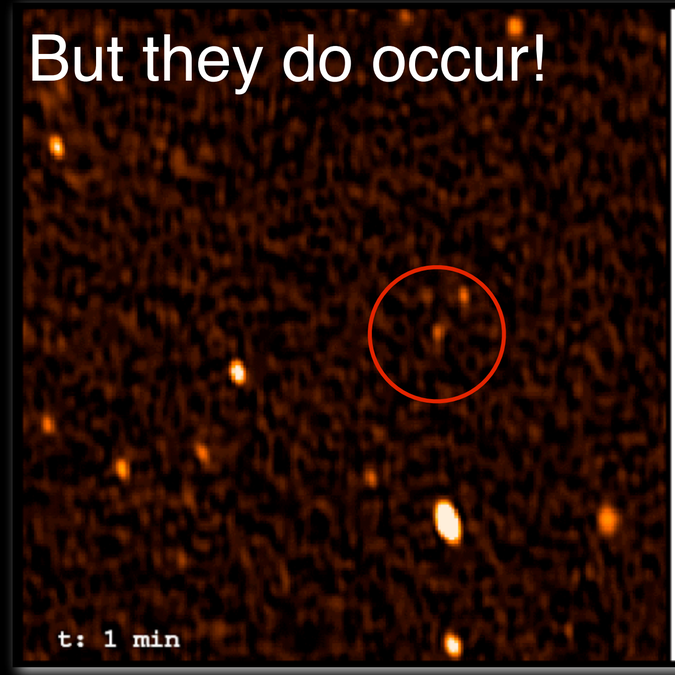


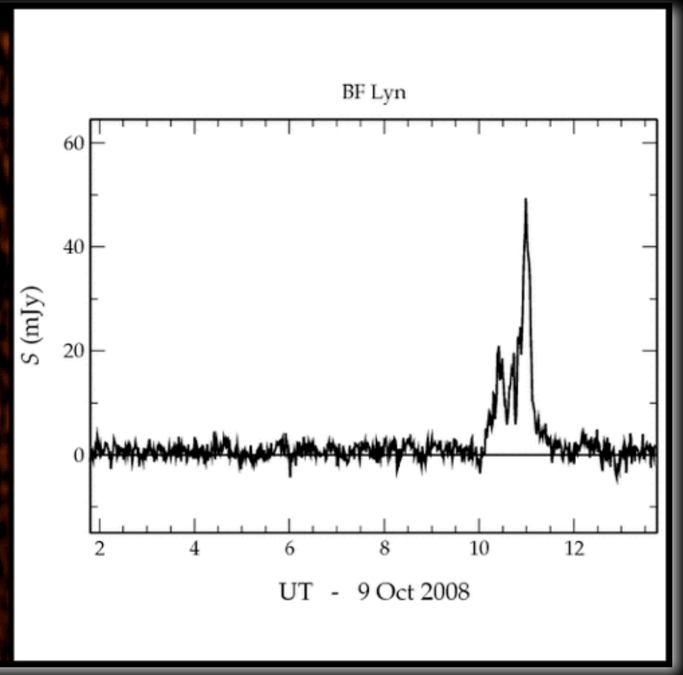
Limited possibilities for radio transients



Allen Telescope Array: 11-epoch deep field observations 700 sq deg (Croft+ 2010).

No transients > 40 mJy

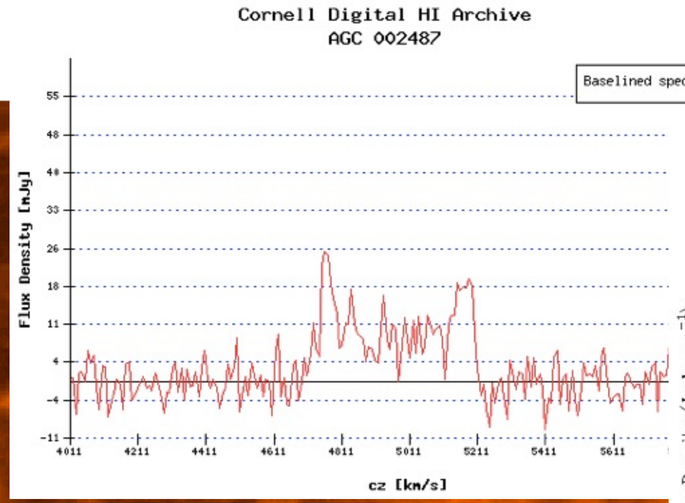


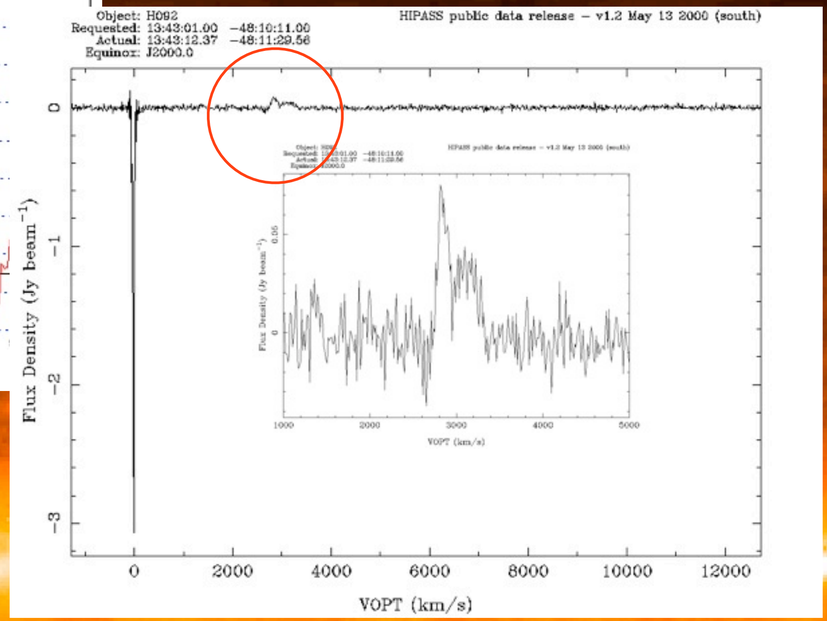


Serendipitous detection of flare star with WSRT

Need for more sensitivity, cover larger area and sample different time domain.
e.g. ASKAP can do NVSS every day….

Radio surveys: line (HI)

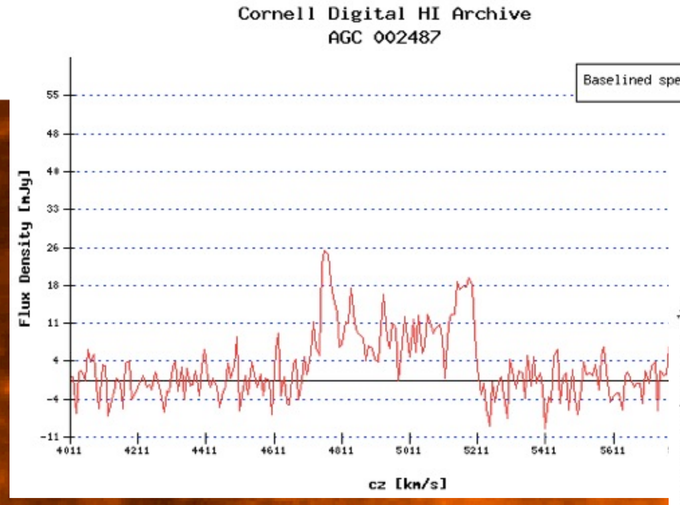


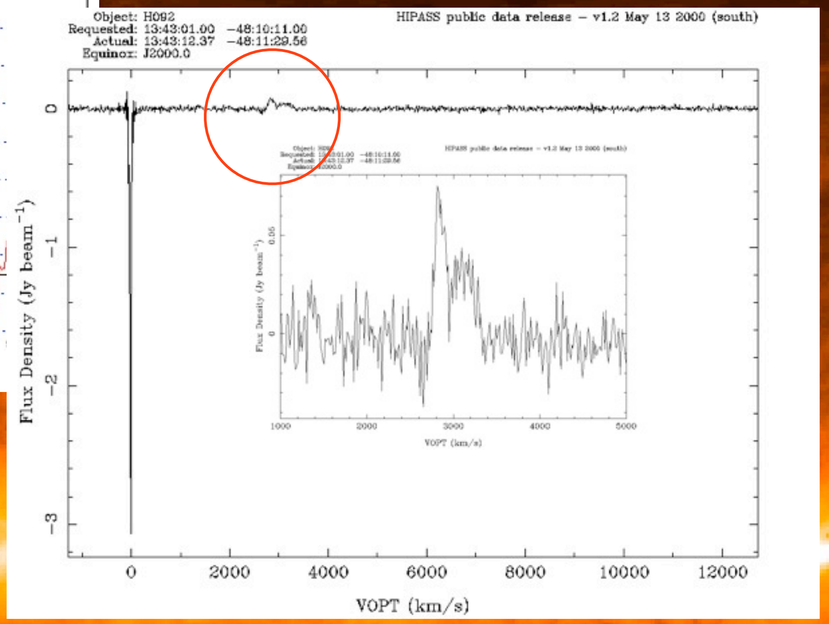


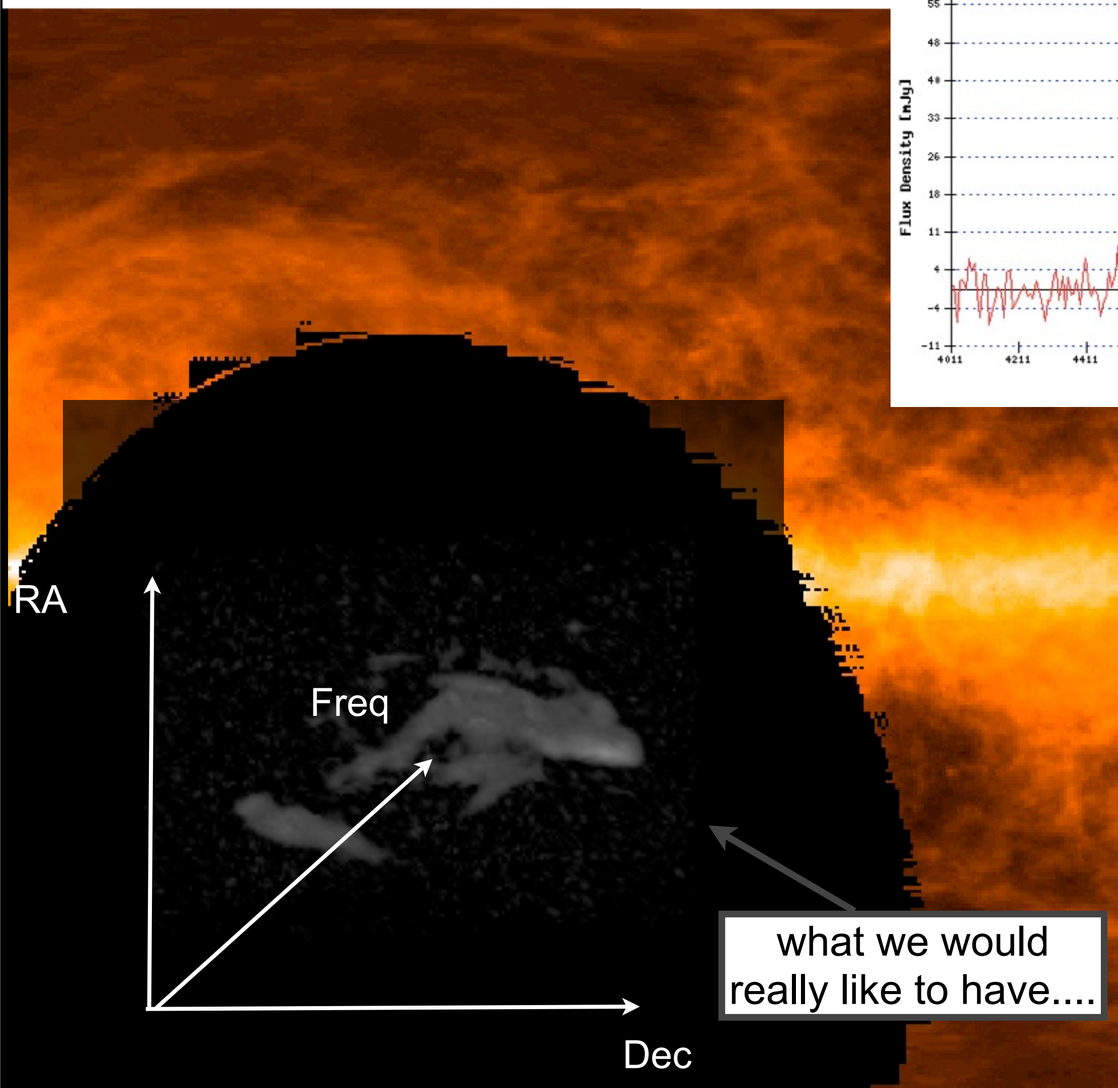
Blind line (HI) surveys

- largest HI surveys are single dish => no spatial information
- Limited/No morphological information
- Limited sensitivity
- Only ‘local’ Universe, no evolution

Radio surveys: line (HI)







Blind line (HI) surveys

- largest HI surveys are single dish => no spatial information
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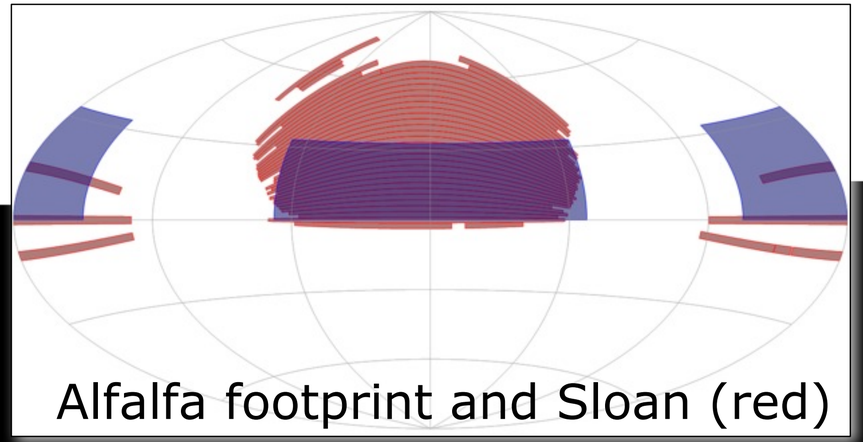
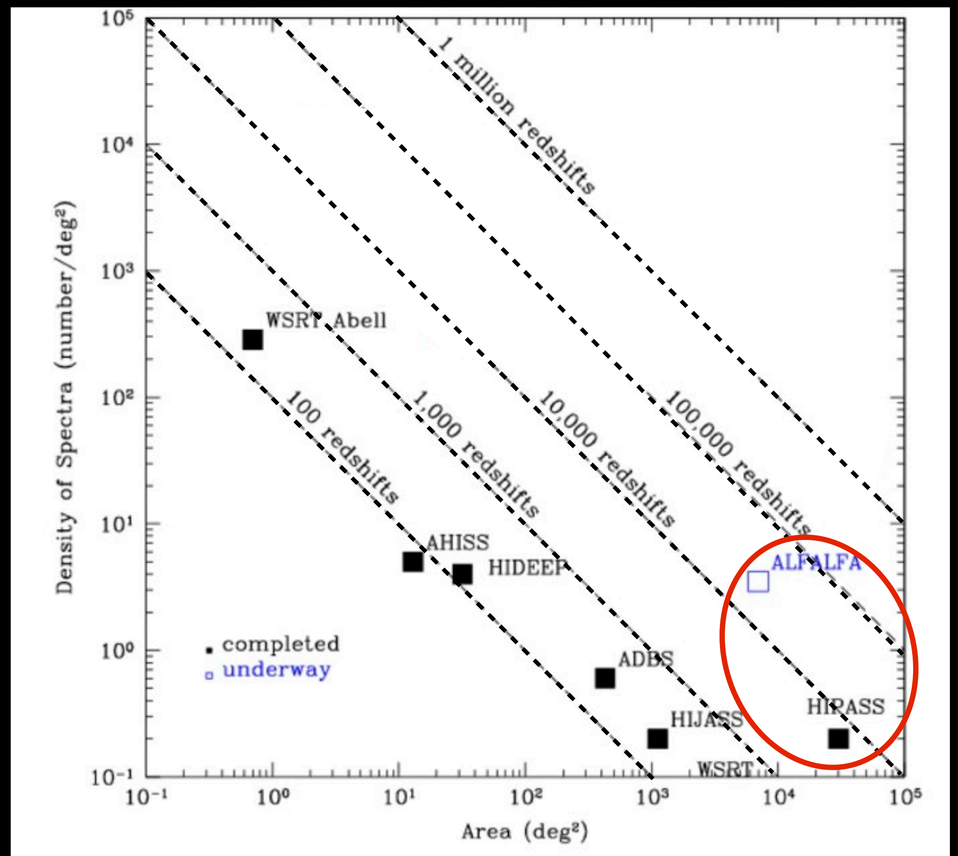
Main blind HI surveys

Recent HI surveys have large field of view provided by multibeam systems but very limited spatial resolution - all single-dish:

- **HIPASS (Parkes)** - 2/3 of the sky, out to 12700 km/s (z~0.04; velocity resol. ~ 13 km/s) spatial res.~15 arcmin, rms noise 13mJy
  => **5317 extragalactic detections HI emission**
- **AlfAlfa (Arecibo):** 7000 deg^2 z~0.06, spatial resolution ~ 3 arcmin, rms 1.6 mJy/ch
  => **expected 30000 extragalactic detections HI emission** (15000 so far, 40% release; Haynes et al.)
- **HIJASS (Jodrell)**
- **Effelsberg Bonn HI survey**

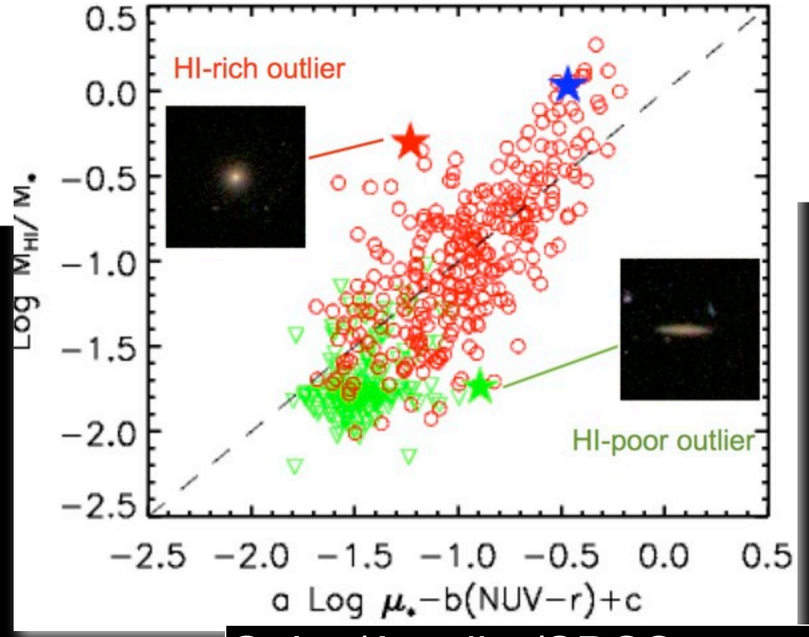


Alfalfa footprint and Sloan (red)

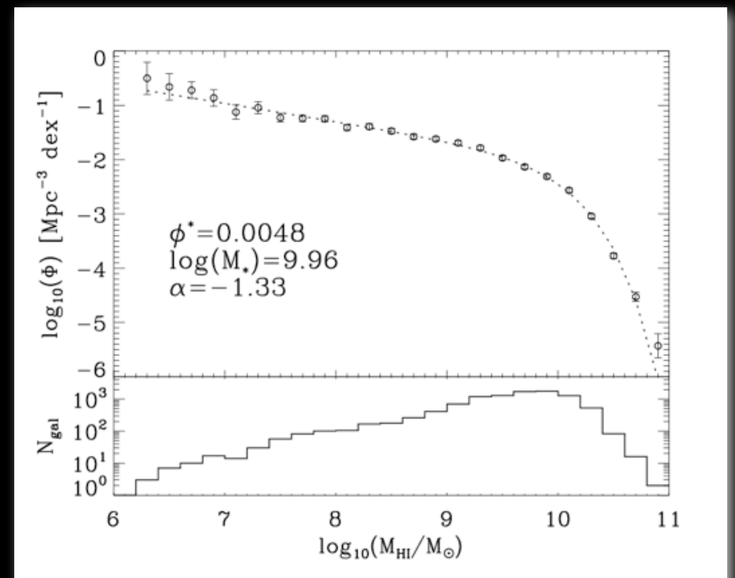


An incomplete list of highlights.....

- from HIPASS and Alfalfa (extragalactic) ...
  - statistics of gas rich galaxies
  - scaling relations (dependency of HI as function of size, concentration, colour, ...)
  - role of environment
  - HI mass function
  - no “dark galaxies”, stacking ...



Galex/Arecibo/SDSS survey
Catinella et al. 2010,2012



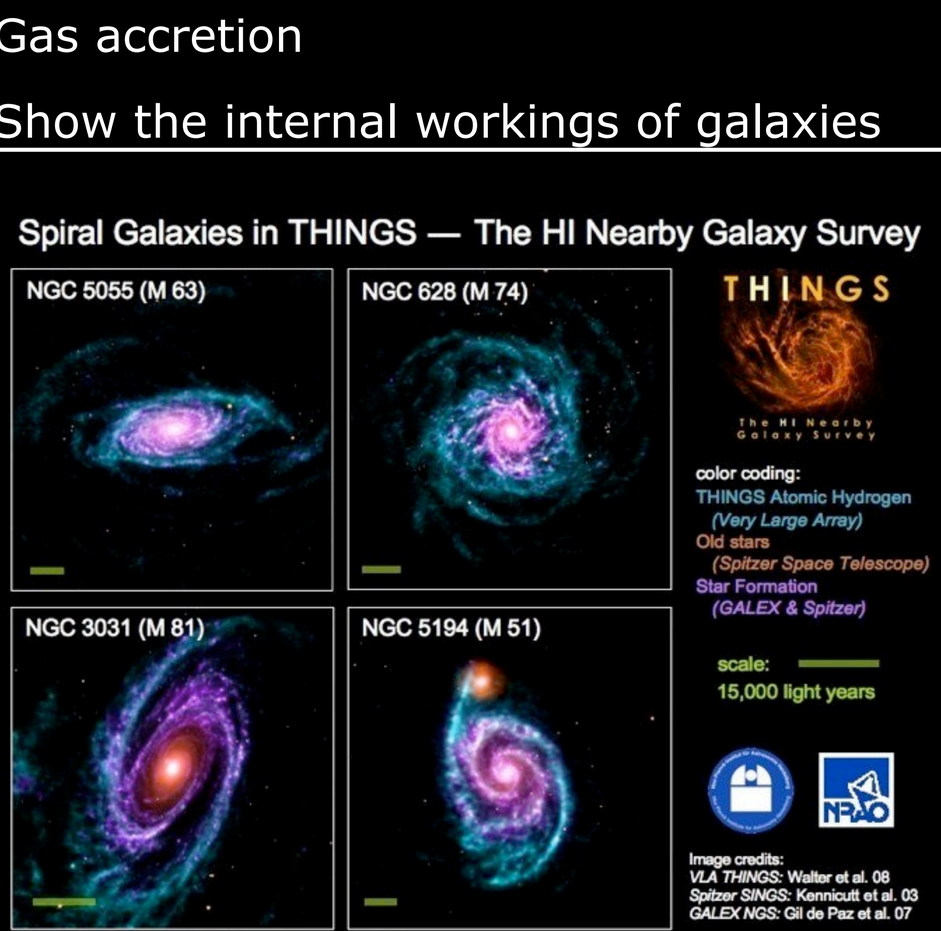
Statistics only known down to 10^6 $M_\odot$

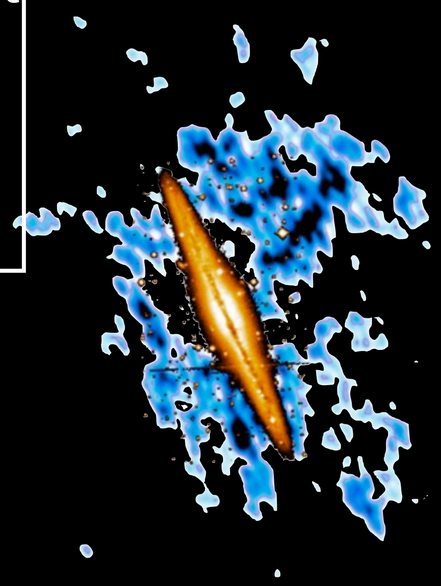
ALFALFA (Martin++ 2010)

...but the morphological/kinematical information is important!

Surveys of sample of galaxies: very time consuming even for relatively small samples (a few hundred objects)

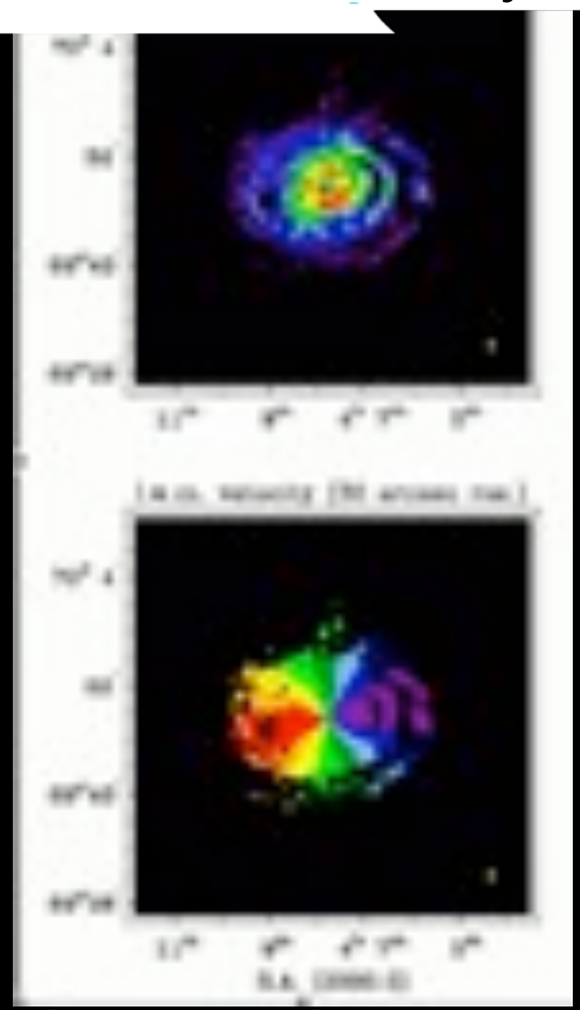
- Role of gas (HI) in galaxy evolution and role of environment
- Gas and starformation
- Gas accretion
- Show the internal workings of galaxies





Accreting HI around NGC891, Oosterloo et al.

WHISP survey



Sauron and Atlas3D survey of early type galaxies

Oosterloo et al. 2010, Serra et al. 2012

....importance of multi-wavelength information!

R. Mo

In summary, as reference.....

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Where we are now

- Number sources detected in 1.4GHz surveys
  => NVSS: **1.7×10^6**
- Number sources at low freq
  => SUMSS ≈ 10^5, WENSS: **2×10^5**, VLSS ≲**10^5**
- Number HI detections (single dish profiles)
  => **5317 HIPASS**
  =>**30000 Alfalfa**

+ other much smaller samples but providing imaging (a few hundred objects)

We know about H I in 2 x10^4 galaxies,
~100 above z = 0.1!!!

Entering the new era!

Some surveys coming up soon....

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Low frequencies continuum surveys:

- TGSS - GMRT survey 150 MHz about 32,000 sq. deg of the sky north of declination of -30 degrees and reaching an rms noise of 7-9 mJy/beam at an angular resolution of about 20 arcsec. When complete, the survey is expected to detect more than **2 million sources** (Sirothia et al.)
- LOFAR continuum surveys (~20-150MHz)

  => LOFAR Calibration survey - MSSS - already started

1.4 GHz surveys

- continuum surveys **=> Aperif, ASKAP....**
- Line surveys **=> Apertif, ASKAP....**

Simultaneously observing line and continuum to optimise observing time!!

.....and other radio telescopes will be also interesting for deep fields

TIFR GMRT Sky Survey (TGSS)

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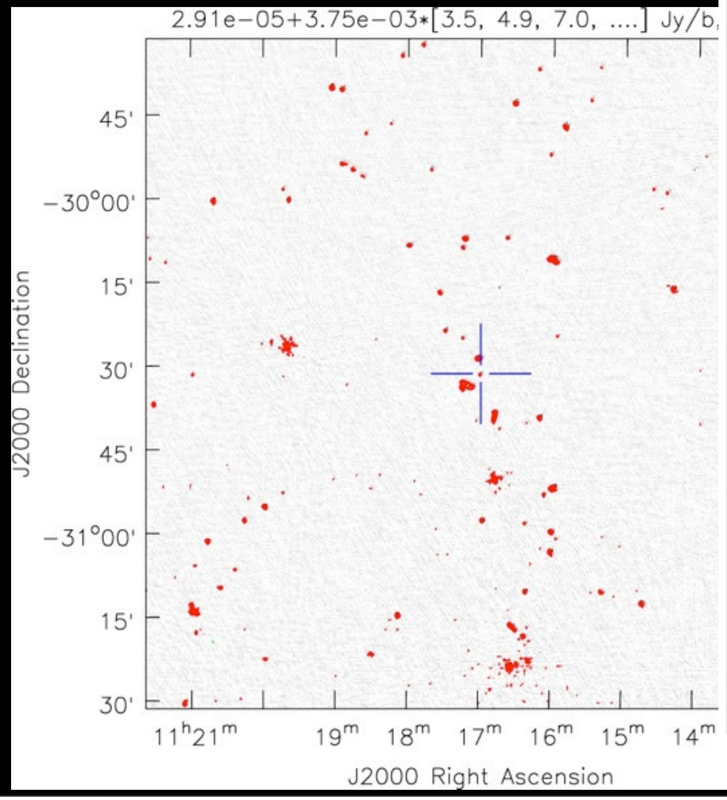
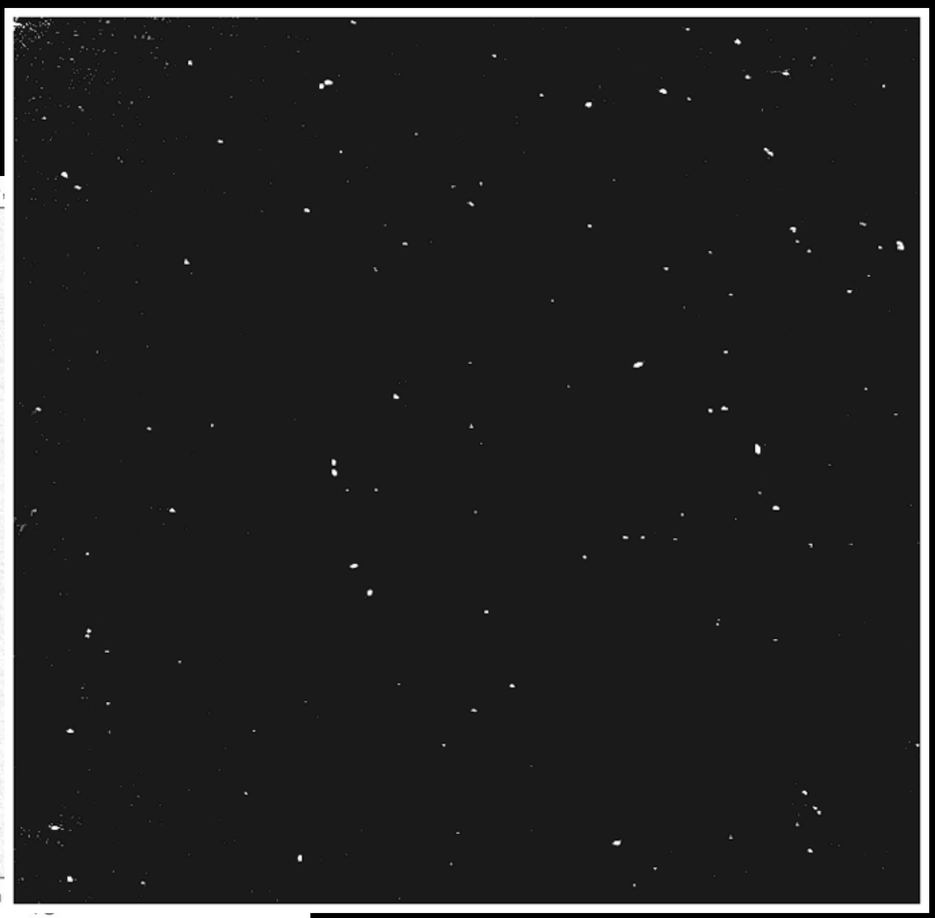
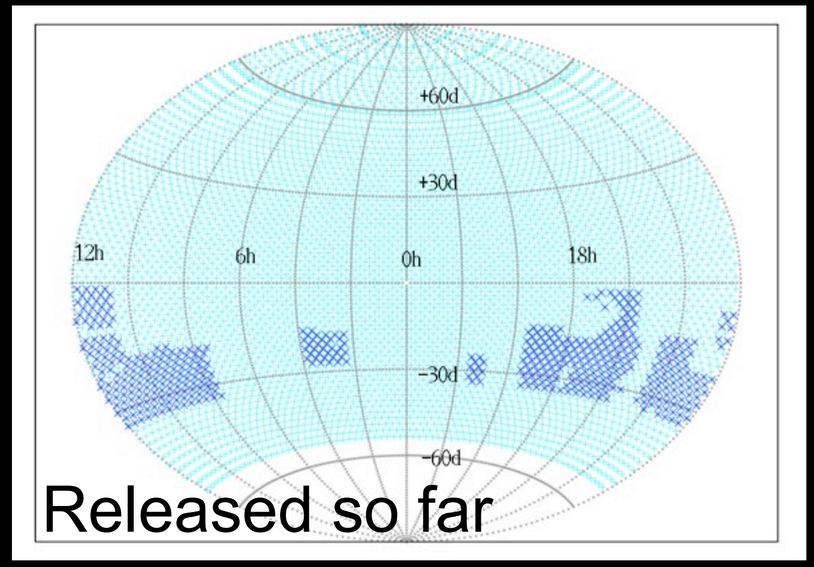
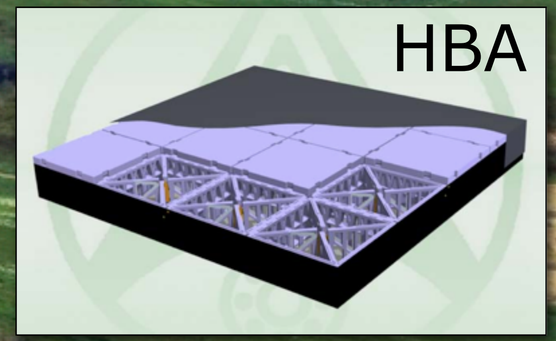




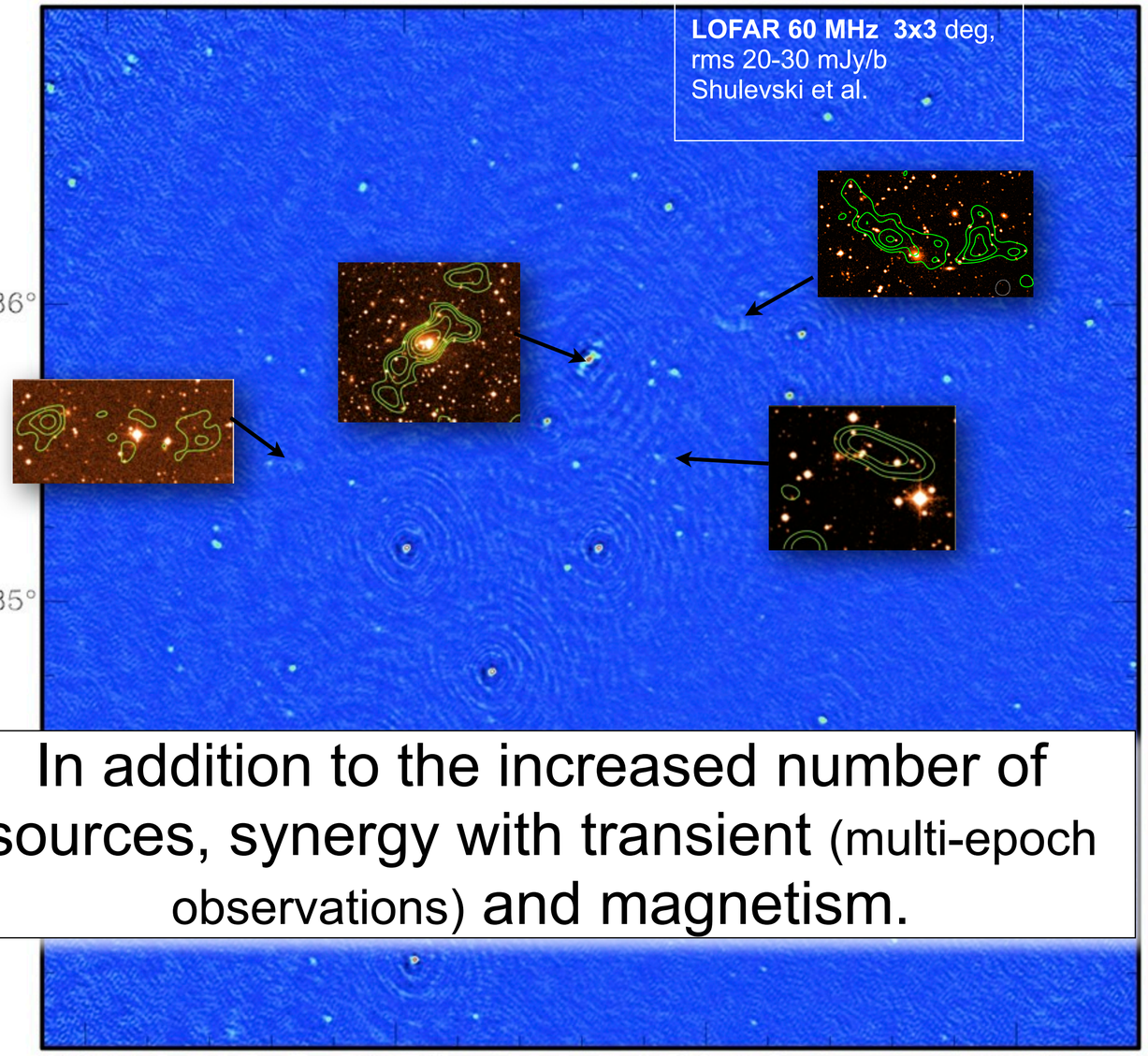


LOFAR Core (Aug 2011)



R. Mor

Surveys with LOFAR



In addition to the increased number of sources, synergy with transient (multi-epoch observations) and magnetism.

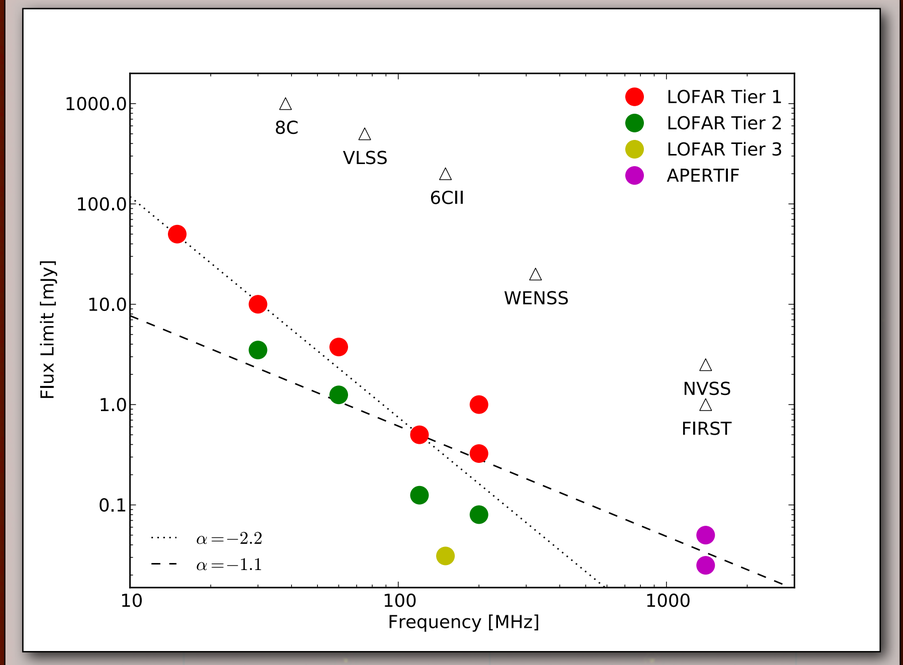
Rottgering et al.

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

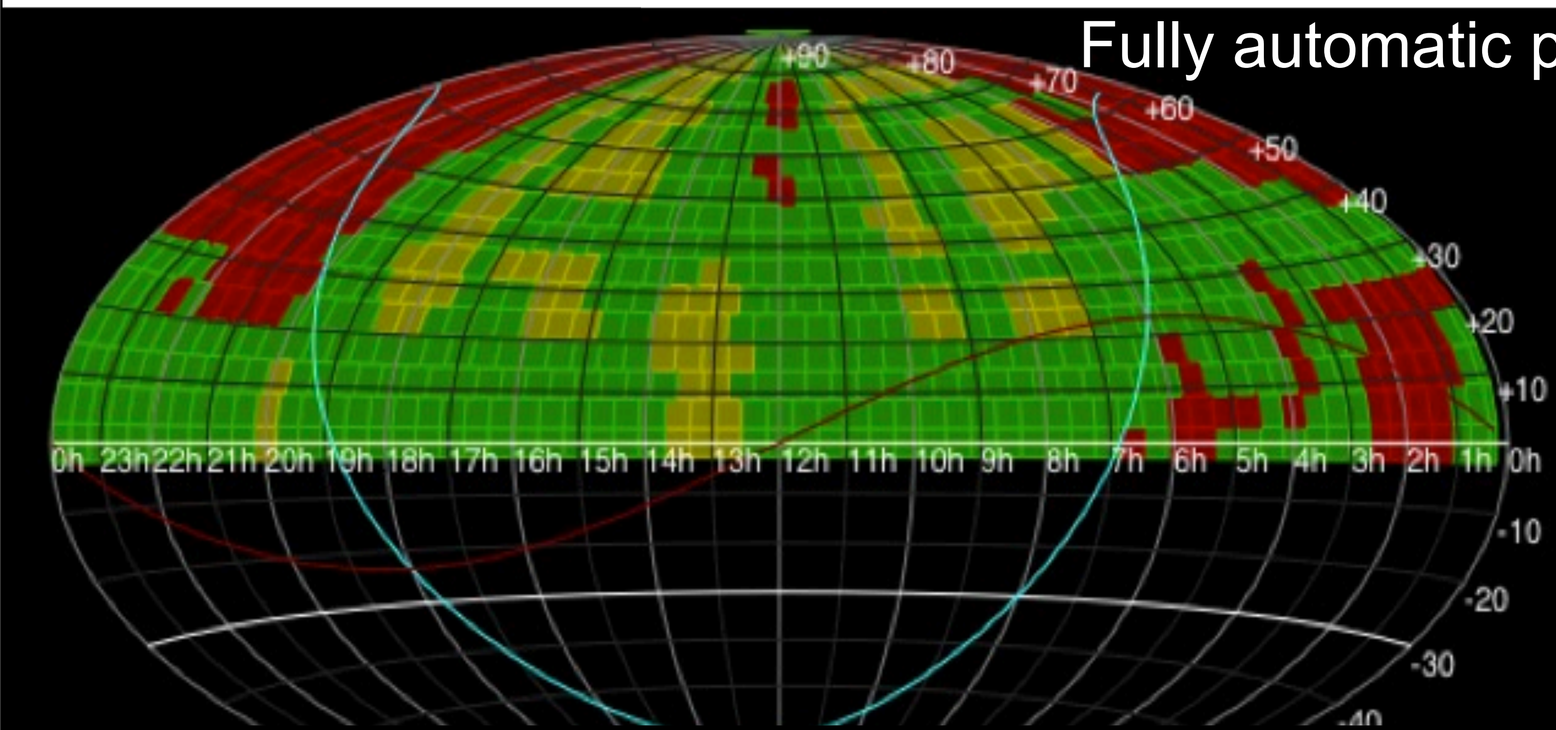
f[1] MHz	Area deg^2	rms mJy	BW MHz	Sources[2] /beam	Integration time[3] hrs	Number pointings	Days[4]	Total[2] sources
15	20626	10	4	17811	100.0	100	29	1.4e+06
30	20626	2	16	19106	22.3	218	56	3.5e+06
60	20626	0.75	16	30124	20.6	203	48	5.1e+06
120	20626	0.1	16	30016	3.8	1021	44	2.8e+07
200	20626	0.200	16	2472	1.0	3021	34	7.0e+06
200	1088	0.065	16	9373	9.3	150	17	1.4e+06

HBA (140 MHz) 7 hrsBW = 31 MHz
3°x3° (inner part of FOV)
res=24´´ × 21´´
Rms=0.8 mJy/beam ~10^3 sources

Orru`, Falcke et al.

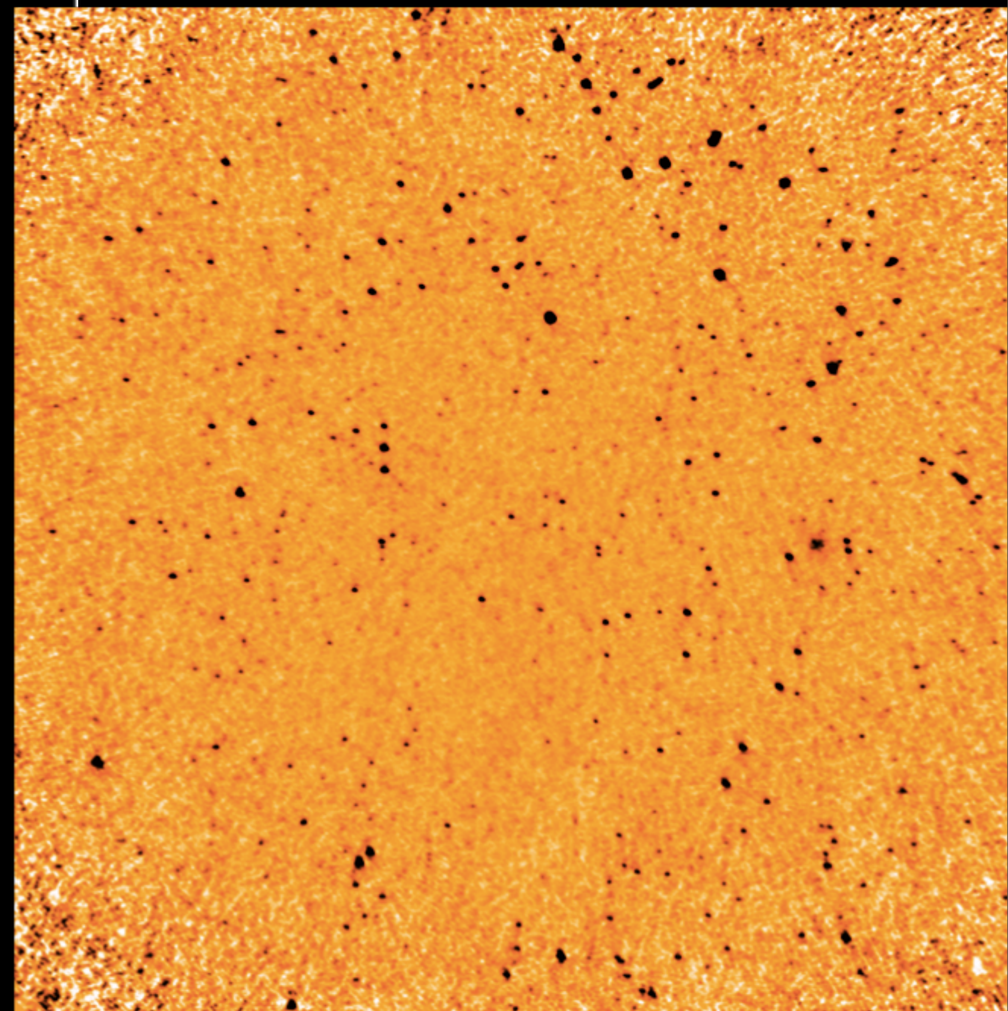


LOFAR Multifrequency Snapshot Sky Survey (MSSS)



Fully automatic pipeline to produce global sky model

Survey	MSSS-LBA	MSSS-HBA
Field of view per field (FWHM)	5.77° @ 60 MHz	2.42° @ 150 MHz
Sensitivity	15 mJy	5 mJy
Resolution	<100”	<120”
Bandwidth per field	16 MHz	16 MHz
Number of simultaneous fields	3	3
Time per field	9 x 11 min	2 x 7 min
Required number of fields	660	3616
Required on-source observing time (hr)	363	281



G. Heald & LOFAR MSSS Team

MSSS: LOFAR's First Survey

- **See http://www.astron.nl/~heald/msss/msssmap_lba_obs.html** *(courtesy G. Heald)*

- Multifrequency: 16, 2-MHz bands 30-180 MHz
  Throws open a HUGE new frequency window
- Snapshot: Multi-epoch short observation mode
  Groundbreaking search for transient sources
- Sky: Quickly cover entire northern sky
  LOFAR's first all-sky catalog, from the most sensitive survey at extreme low frequencies
- Survey: First large LOFAR imaging program
  Paves the way for still deeper surveys...

First large-scale test of production system
Populate the global sky model

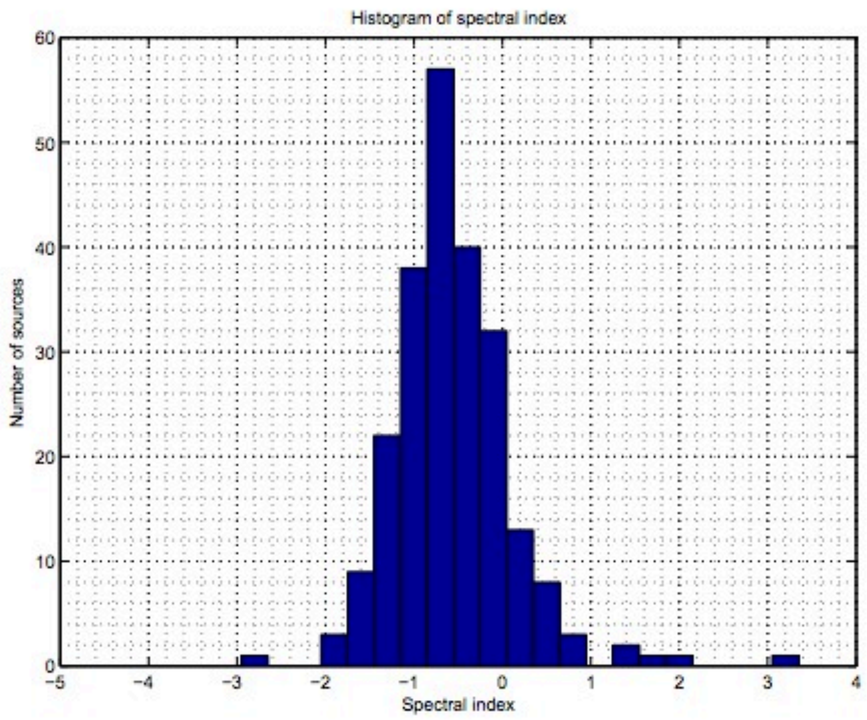
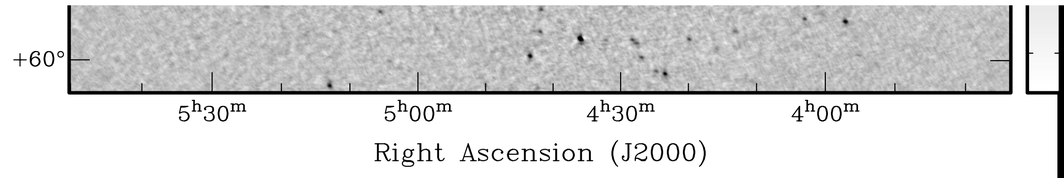


Figure 3: Histogram of spectral indices of 231 sources appearing in all 8 bands. The median spectral index is -0.66.



10x10 degrees, ~100 mJy/beam, beamsize ~ 60 arcsec

LOFAR Raw Data Volumes

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- 2688 dipoles (LBA), 200 MHz sampling, 2 polarizations, 12 bit digi

  ⇒ 13 Tbits/s ~ 1.6 TB/s ~ 138 PB/day

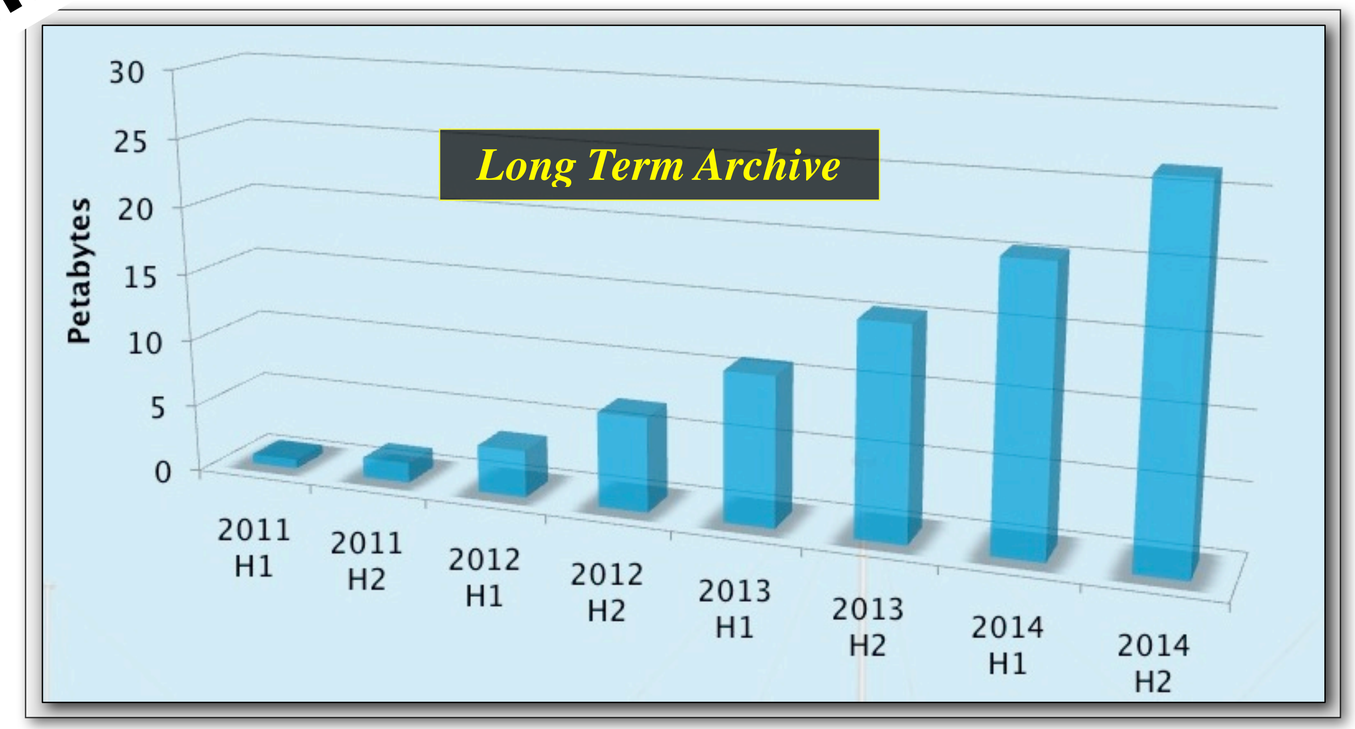
- 48 stations, 48 MHz total bandwidth, 8 independent b … p to 244)
- 1128 baselines, 242 sub-bands, 256 channels … ations, 1 sec correlator dump-time

  ⇒ ~ 10 TB/hr ~ 240 TB/day …/yr

Storage limits gi… 1 week process… window

LOF… a pathfinder …ata-intensive …stronomy!

See presentation from Michael Wise for details!



Future large 20cm-band surveys

Combining continuum and line

One survey fits all!

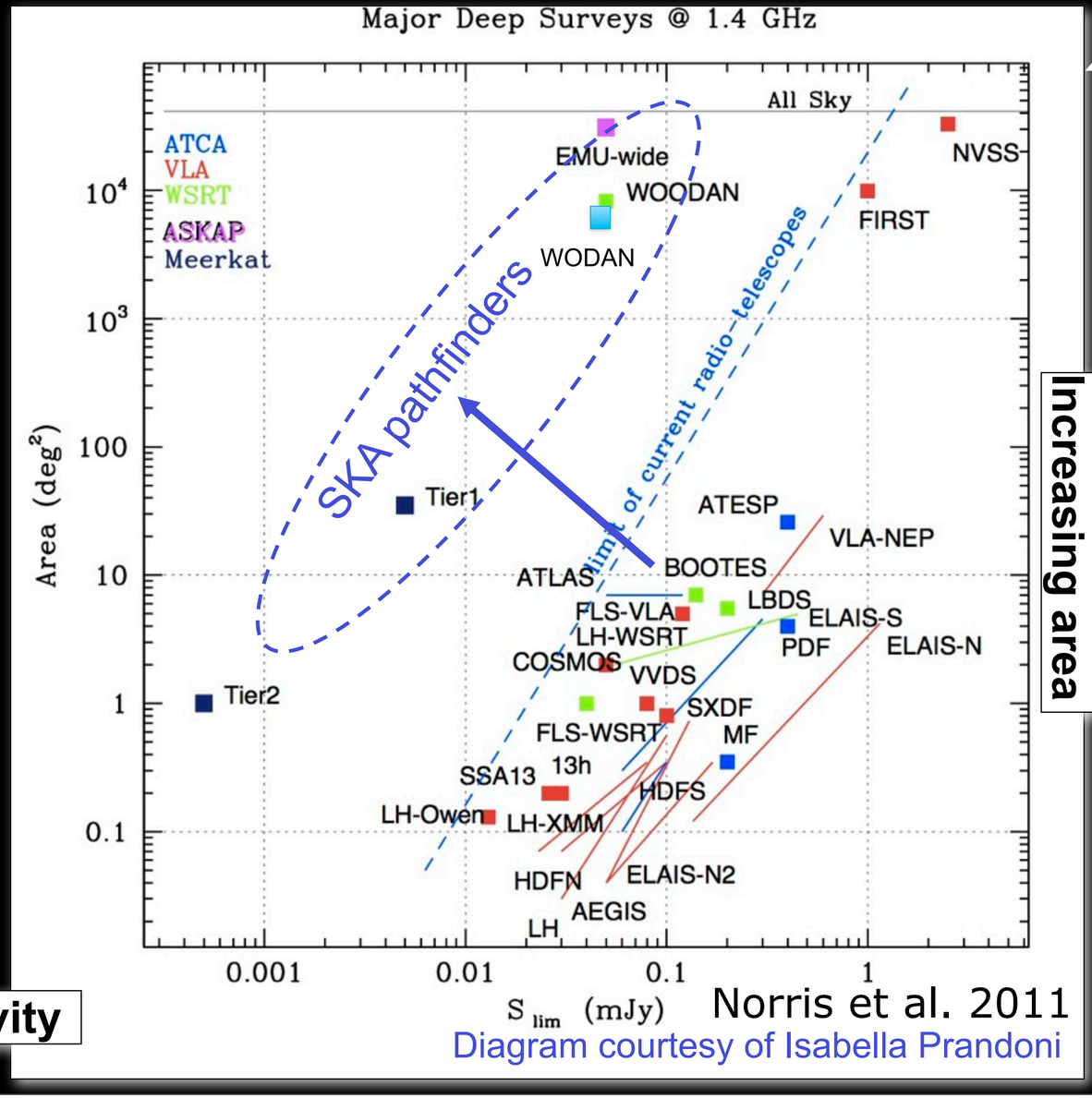
Major 20cm continuum surveys for SKA pathfinders

Continuum all-sky surveys for the SKA pathfinders/precursors
=> ASKAP (EMU)/Apertif (WODAN)

Estimate of the number of sources detected e.g. based on the extrapolation of source counts (Norris et al. 2011)

=> of the order of 100 million sources will be detected! (for rms~10 μJy over the **ENTIRE sky.**...)

Increasing sensitivity



Norris et al. 2011
Diagram courtesy of Isabella Prandoni

New possibilities for radio transients

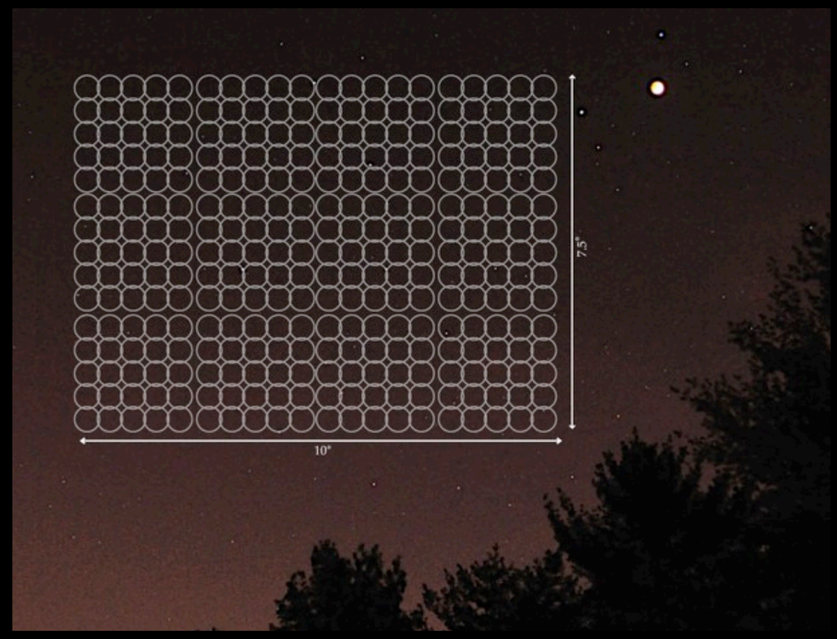
- The transient radio sky is poorly explored, particularly for short transients

$$A\Omega\left(\frac{T}{\Delta t}\right)$$

- Need large field of view to find them AND dedi… …rdware for fast transients
- Aperture array gives a lot of flexibili… …novative observing modes:
  - many station beams
  - incoherent addition
  - tied arrays
  - single sta…
  - fly'… …ode…
- …so be done in piggyback mode

See presentation from Joeri van Leeuwen for details!

Example of what we are planning with Apertif

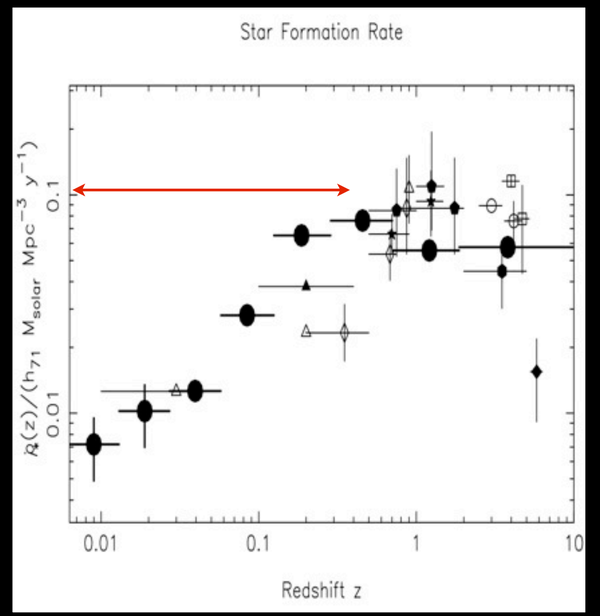


Exciting times ahead for HI work

- ASKAP & Apertif will survey HI over **ENTIRE sky**, uniform properties over entire sky
- Expected 10^6 galaxies, out to $z \geq 0.6$, most above $z = 0.1$, 15 arcsec resolution (**resolved**).
- in addition: H I absorption candidates out to z = 1
- + deeper surveys of smaller regions out to z = 1

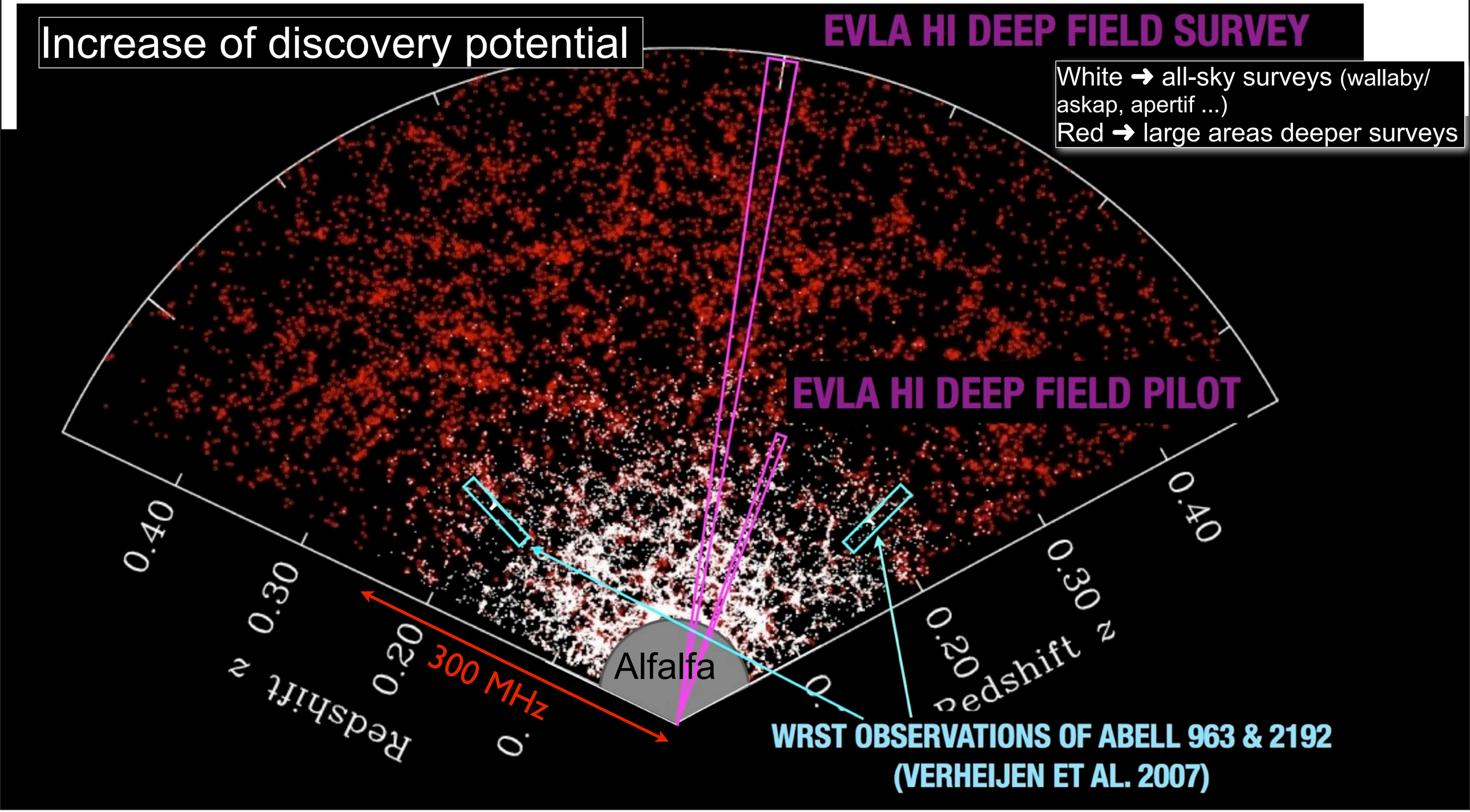
- *Large field of view* and *large bandwidth.*
  given collecting area, the spatial resolution of ASKAP & Apertif is near optimum for surveys of neutral hydrogen.
  Can be done together with continuum surveys

- Major new opportunity: can image the *entire* sky at high resolution, high sensitivity and out to large distances. **EVOLUTION**



Heavens et al.

Increase of discovery potential



In summary, as reference.....

Where we are now

- Number sources detected in 1.4GHz surveys
  => NVSS: **1.7×10^6**
- Number sources at low freq
  => SUMSS ≳ 10^5, WENSS: **2×10^5**, VLSS ≲**10^5**
- Number HI detections (single dish profiles)
  => **5317 HIPASS**
  => **30000 Alfalfa**
  + other much smaller samples but providing imaging (a few hundred objects)

We know about H I in 2 x10^4 galaxies, ~100 above z = 0.1!!!

Where we will be soon

- Low frequency surveys: 10^6 to 10^7 sources
- 1.4 GHz surveys: likely reaching 10^8 sources
- Number HI (emission) detections:
  10^6 galaxies, out to $z \geq 0.6$
  HI absorption out to redshift z~1

  ...and most of these HI detection will be spatially resolved! a major change in the science we can do!

They will obtain information about the line and continuum simultaneously. We can study gas content and non-thermal activity at the same time.

Getting ready for these changes: COSMOS Field, pilot EVLA survey

ASTRON

B array observations (5” resolution) z=0 (0.4 kpc) z=0.2 (22 kpc)
50 hours on source ➙ 2.5 Tb of data

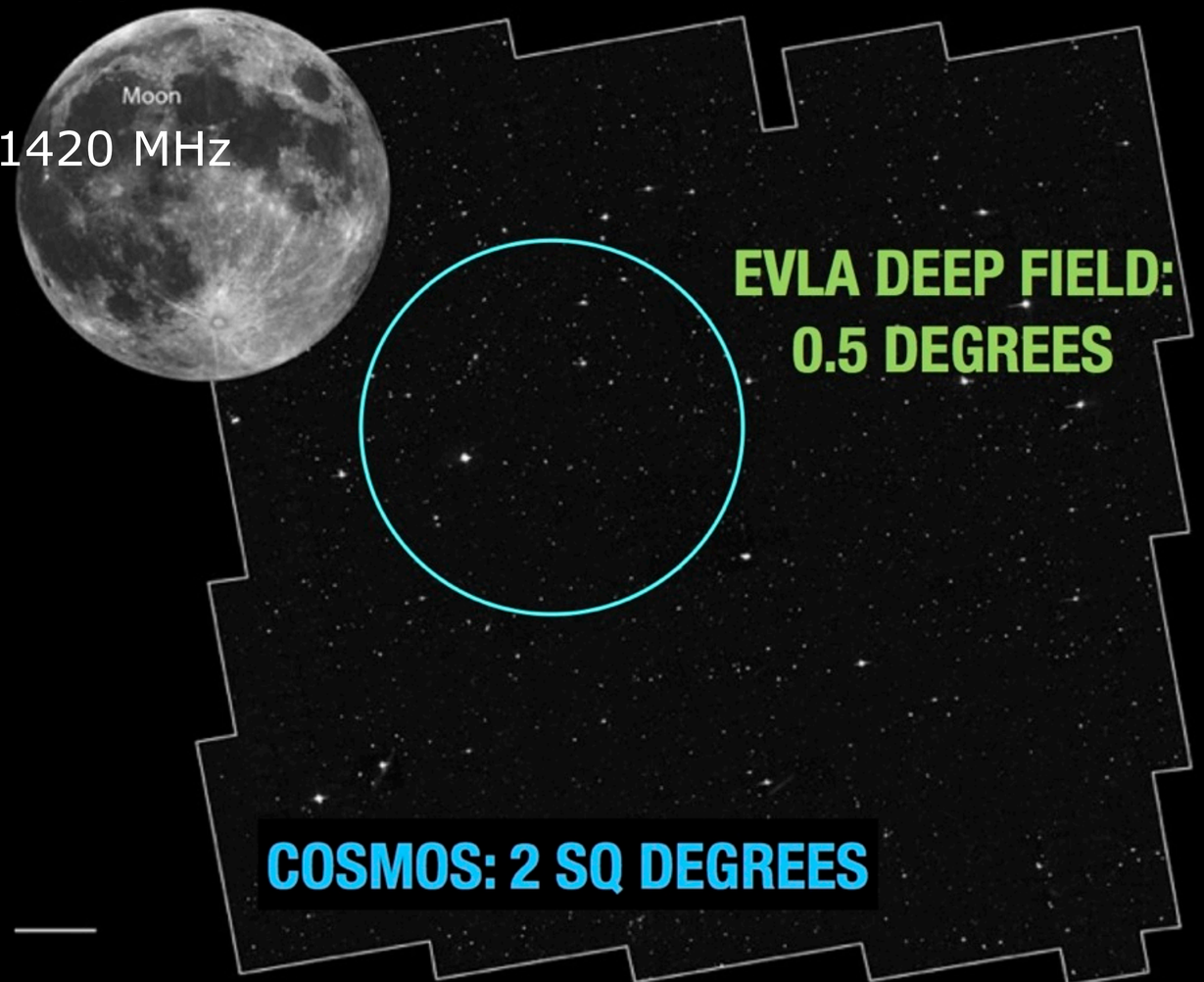
Correlator setup: 32 spectral windows covering 1190-1420 MHz

- ➡ 230 MHz => **Velocity coverage 58000 km/s (0<z<0.19)**
- ➡ 16384 channels
- ➡ 3.5 km/s velocity resolution

Noise line: 0.2 mJy/beam/ch
Column density: 6 x 10^{19} cm^{-2}

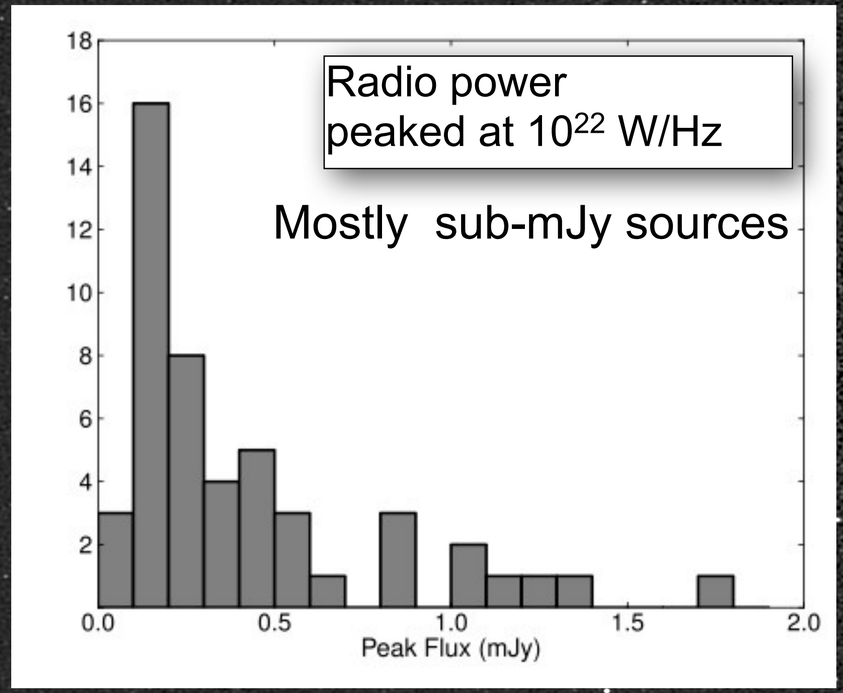
Noise continuum: μJy level!

van Gorkom, Fernandez et al.

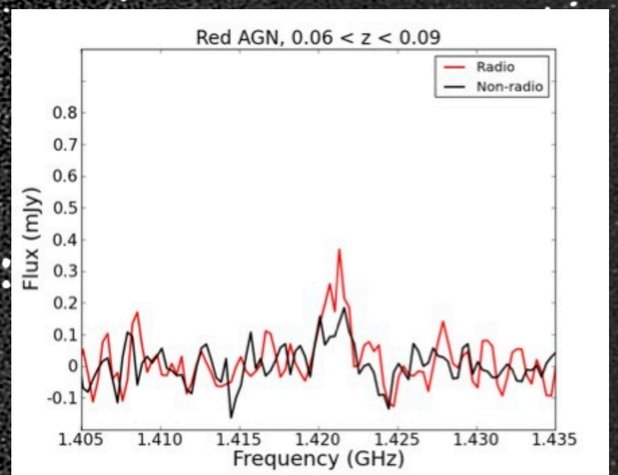


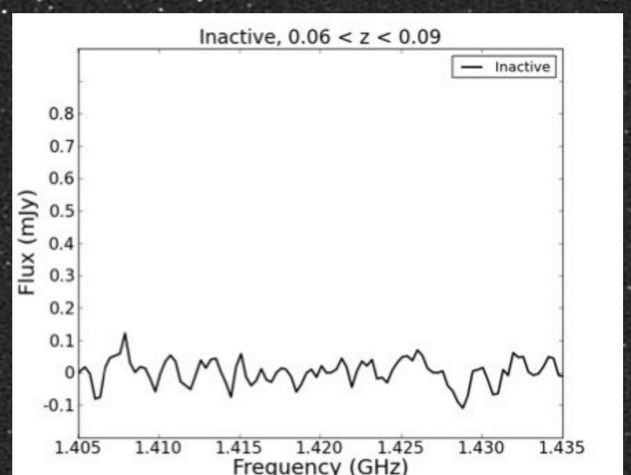
Getting ready for these changes: the Lockman Hole WSRT region

Originally continuum observations!
down to 10 microJy (more than 6000 radio sources)
Thanks to the broad band => **HI for free** up to redshift ~0.1 (not many single detection so stacking techniques used => SDSS spectra for stacking



STACKING RED GALAXIES (0.06<z<0.09):
HI easily detected in active (LINERS)
No HI in "inactive" objects





Gereb, Oosterloo, Morganti et al. 2012

Lockman Hole observed with the WSRT @1.4GHz - 6 deg^2 (Guglielmino et al. 2012)

Final remarks

- ✓ Great input from radio sourveys and deep field => now ready for the next major step forward
- ✓ Unprecedent possibilities for polarisation and transients....
- ✓ The possibility of performing simultaneously line and continuum observations has great potential (major step forward especially for line surveys...)
- ✓ Not only more sources but also different way to characterise objects => so more science!....
- ✓ Large fraction of the HI detections will be spatially resolved: more possibilities for studying the properties of the objects!
- ✓ Connecting much better with surveys at other wavelengths: crucial products will be provided by the radio.

Ray Norris is organising a new working group on radio surveys: if you are interested to be part, get in touch with him