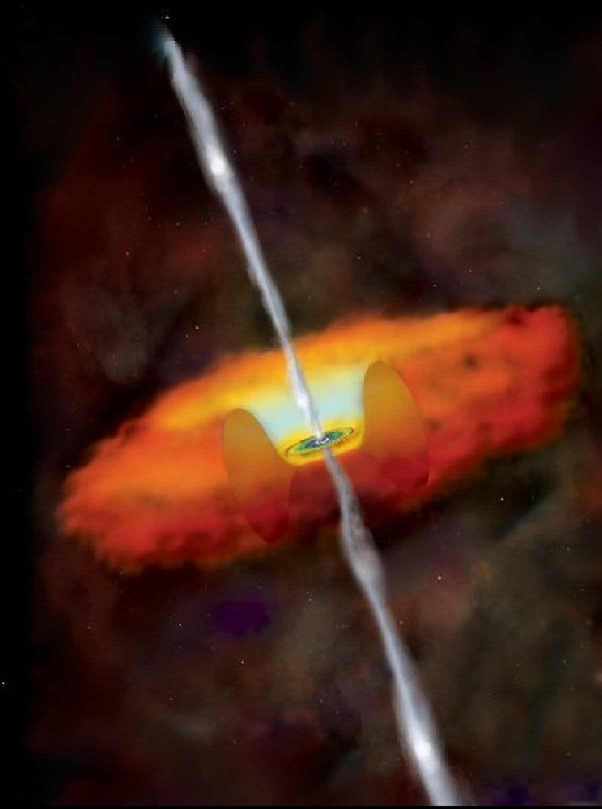
DEEP RADIO OBSERVATIONS IN THE LOCKMAN HOLE

Ibar et al. (2009) arXiv:0903.3600



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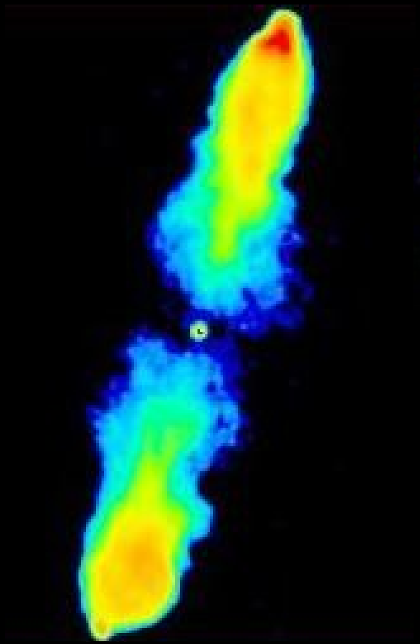
Introduction

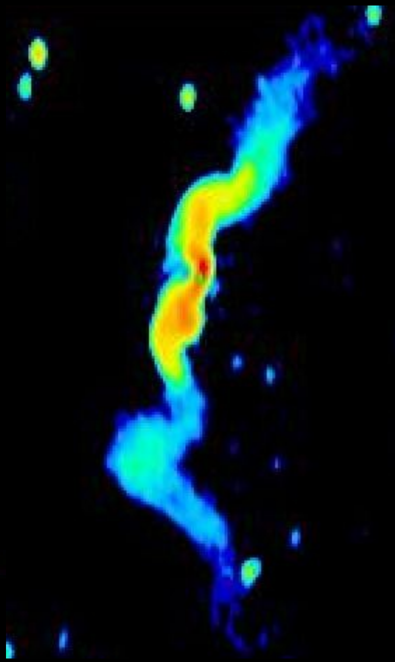
In early studies, radio observations were restricted to powerful (>1mJy) radio sources, typically associated with optically bright quasars and rare luminous galaxies.

(Condon 1984; Willott et al. 2002)

THE VLA TELESCOPE



3C223, FRII

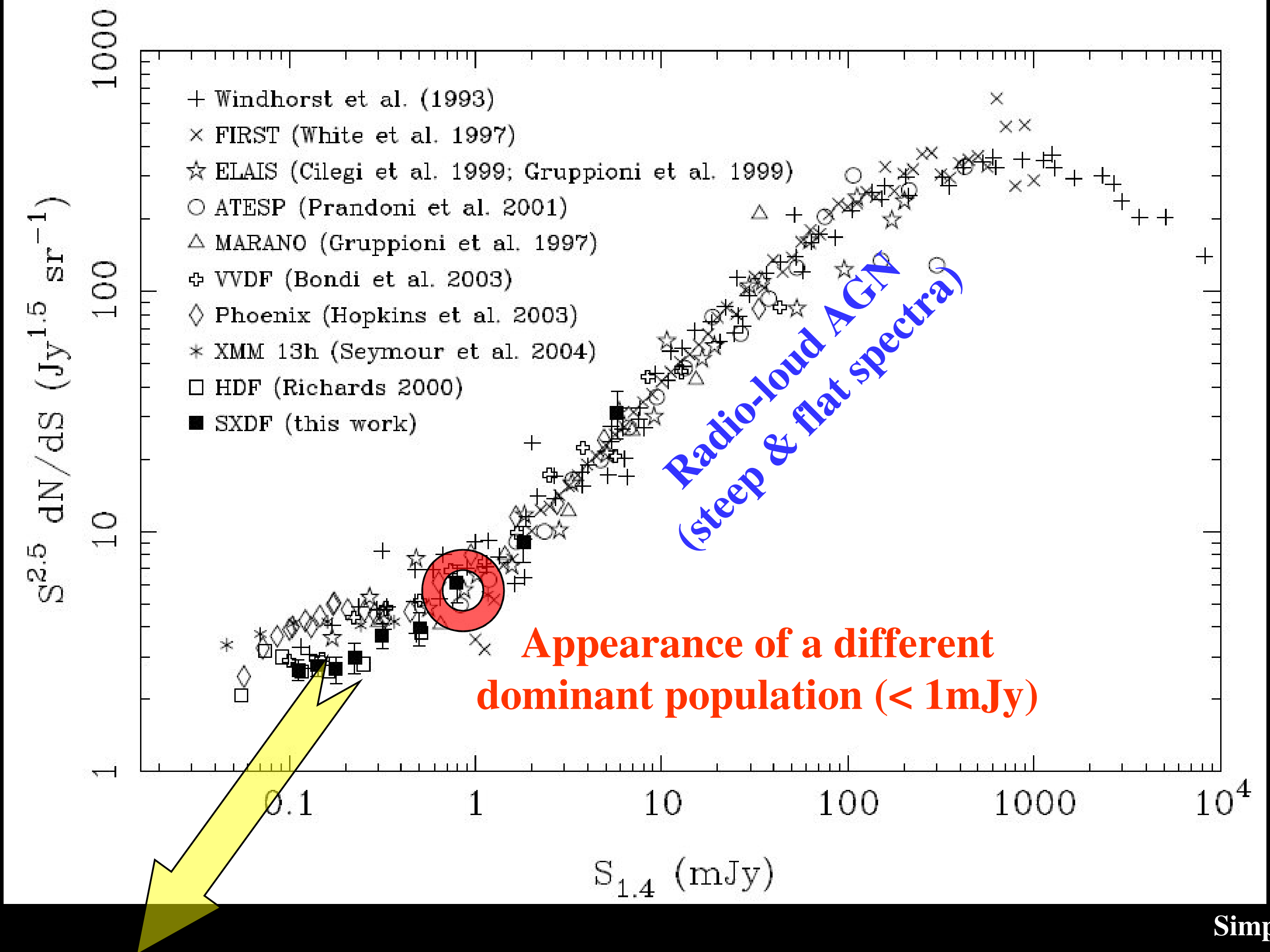


3C31, FR I

In the mid 1980s the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA) began to shed light on the mJy and sub-mJy radio regime.

(Windhorst et al. 1985; Mitchell & Condon 1985)

Introduction



Simpson et al. (2006)

This population is mainly composed by radio-quiet AGN and star-forming galaxies, although their relative fractions are unknown.

Approaches

How can we disentangle the nature of the sub-mJy radio population?

- **Deviations from the FIR/radio correlation** — **(e.g. Donley et al. 2005; Ibar et al. 2008)**
- **The radio spectral index** — **(e.g. Clemens et al. 2008)**
- **Morphology from sub-arcsecond observations** — **(e.g. Muxlow et al. 2005)**
- **Cross-match with X-ray surveys** — **(e.g. Simpson et al. 2006; Barger et al. 2007)**
- **Optical/NIR identification of the host galaxy:**
  - **Morphology** — **(e.g. Padovani et al. 2007)**
  - **Spectroscopy** — **(e.g. Barger et al. 2007)**
  - **Colour-colour diagrams** — **(e.g. Ciliegi et al. 2005)**

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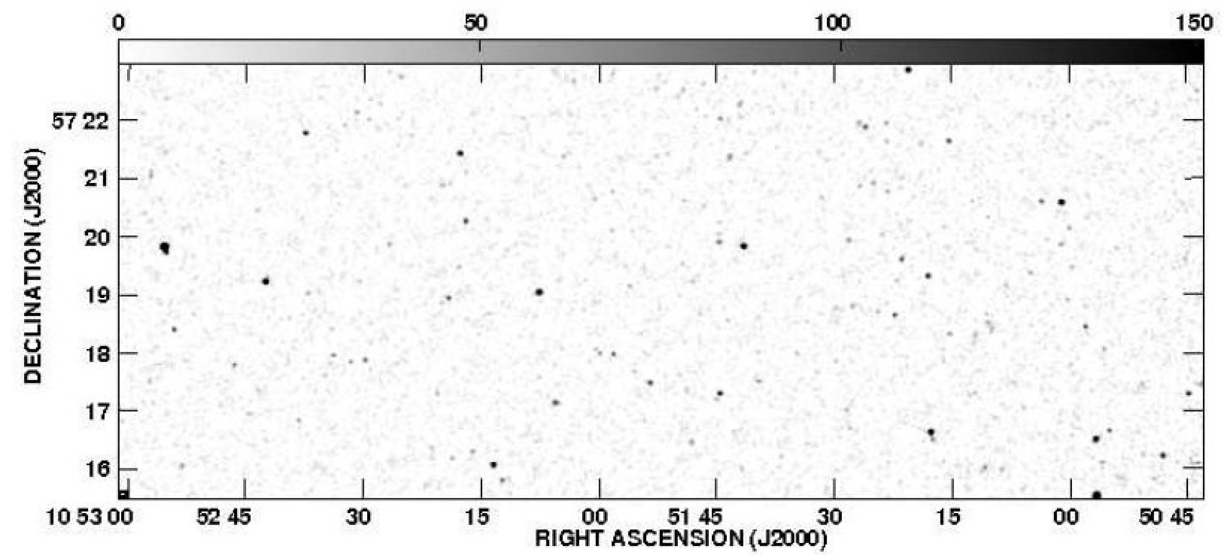
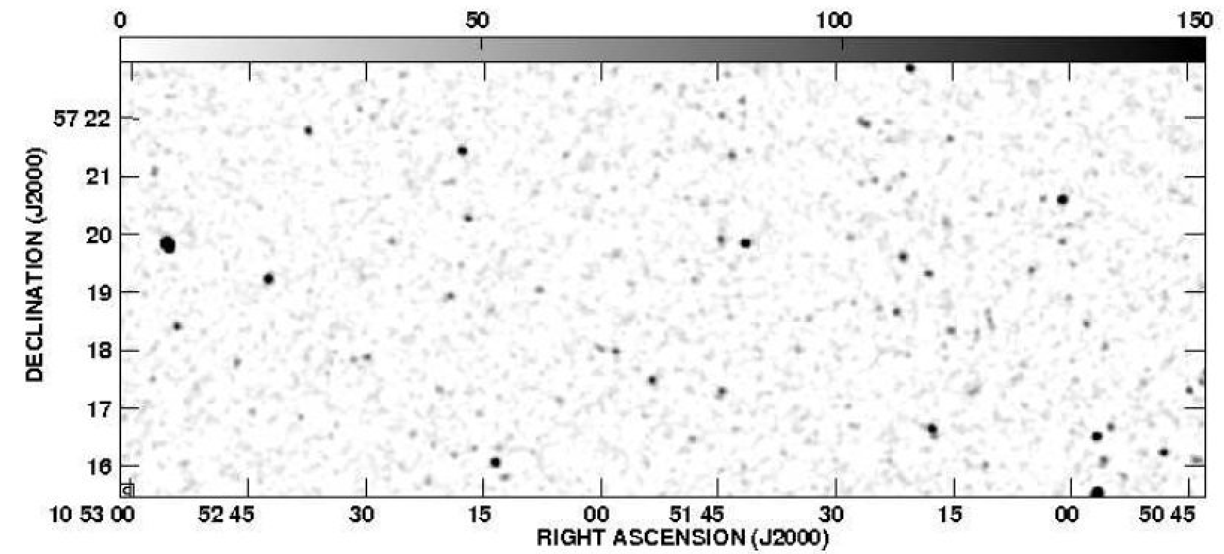
Radio observations in the Lockman Hole



VLA-1.4GHz

3 pointings (A+B configuration)
r.m.s. pointings ~ 7 - 11 µJy/beam
Area mosaic = 0.56 deg^2
FWHM = 4.3 x 4.2 arcsec^2
r.m.s. centre = 6.0 µJy/beam
Dyn. Range ~ 2,300:1
1,425 sources (> 5-σ)

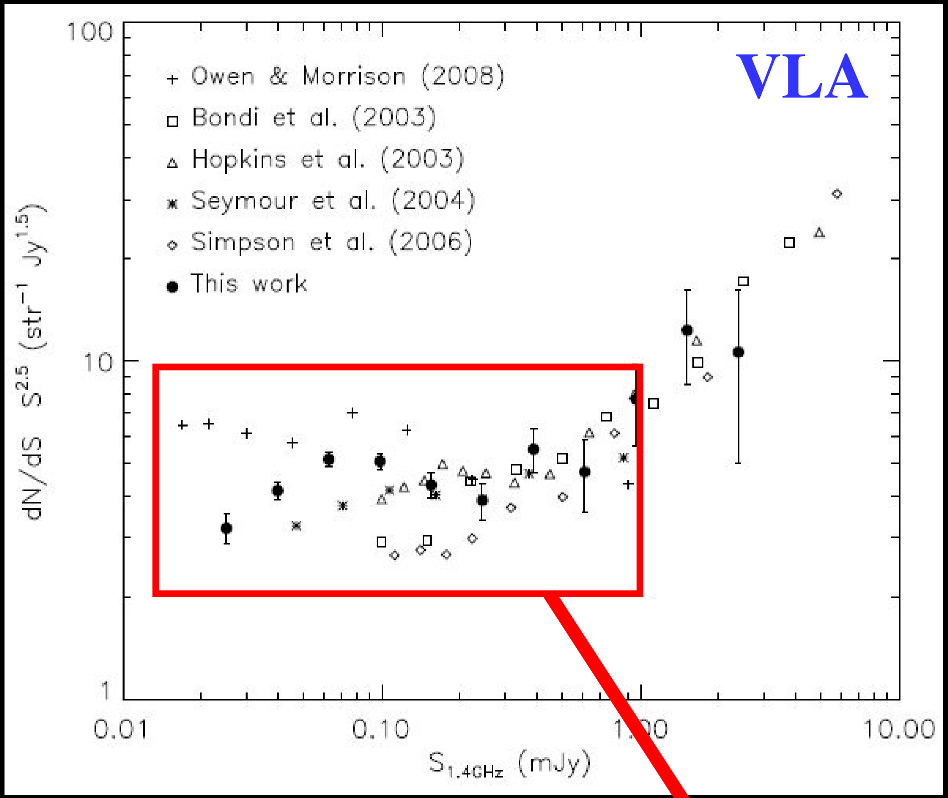


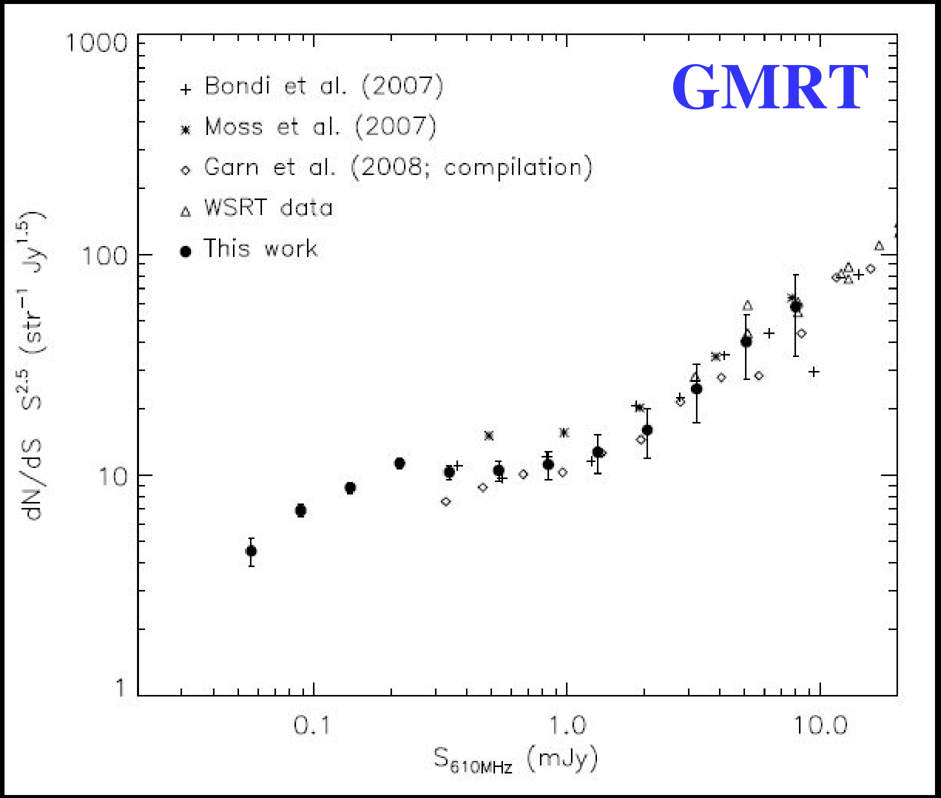
GMRT-610MHz

3 pointings
r.m.s. pointings ~ 24 -34 µJy/beam
Area mosaic = 0.98 deg^2
FWHM = 7.1 x 6.5 arcsec^2
r.m.s. centre = 14.7 µJy/beam
Dyn. Range ~ 2,200:1
1,587 sources (> 5-σ)

Results

THE NUMBER COUNTS





Effective Area:
~99% at 200 μJy
~86% at 100 μJy
Resolution Bias:
~4% at 200 μJy
~6% at 100 μJy

Scatter:
- Cosmic structure
- Source extractions
- Human errors
- Spurious sources

Effective Area:
~85% at 200 μJy
~40% at 100 μJy
Resolution Bias:
~2% at 200 μJy
~3% at 100 μJy

Results

THE RADIO SPECTRAL INDEX

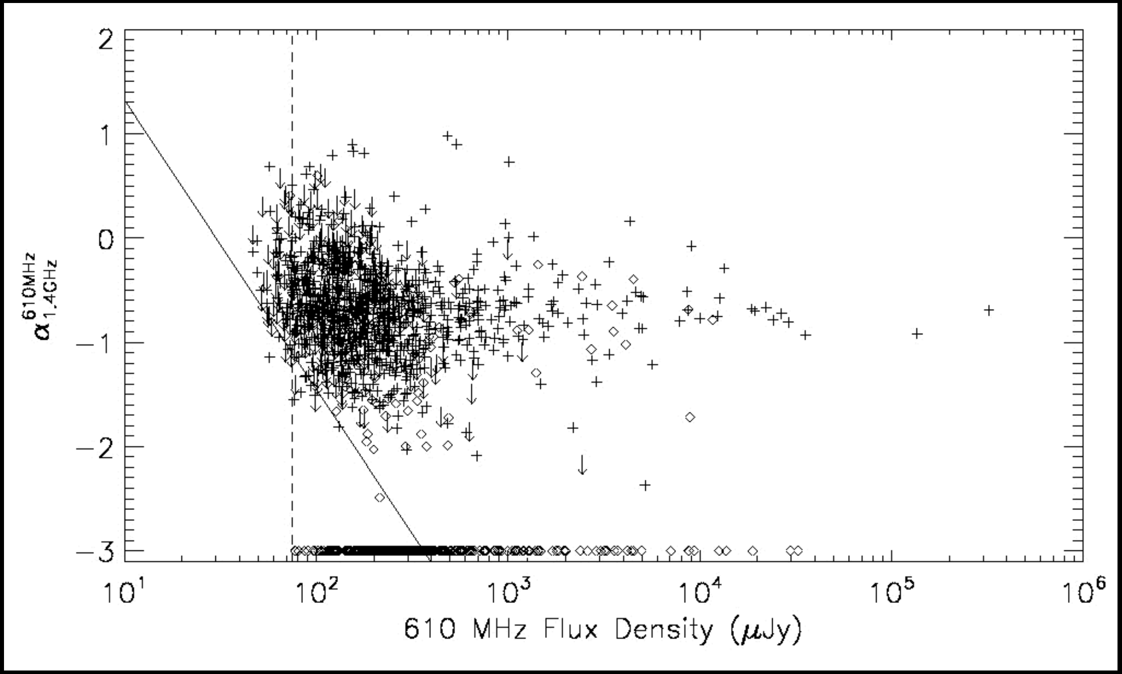
We find a wide non Gaussian distribution of spectral indexes ($\Delta\ \alpha \sim 0.4$ at all flux levels) and error dominated at $S_{1.4GHz} < 100\ \mu$Jy flux densities.

$$S_\nu \sim \nu^\alpha$$

-Lobe-dominated AGN and Star-forming galaxies

[$\alpha \sim -0.7$ spectrum]

Optically thin synchrotron emission



Deviations:

-Core-dominated radio-quiet AGN

[flat spectrum]

Compact synchrotron emission + Thermal bremsstralhung

(Blundell & Kuncic 2007)

-GHz-peaked sources (GPS)

[flat spectrum]

From scales < 1kpc,
"a young FR source"

(Snellen et al. 2000)

-Ultra steep spectrum sources (USS)

[steep spectrum]

Old optically thin synch. emission,
or at high redshift

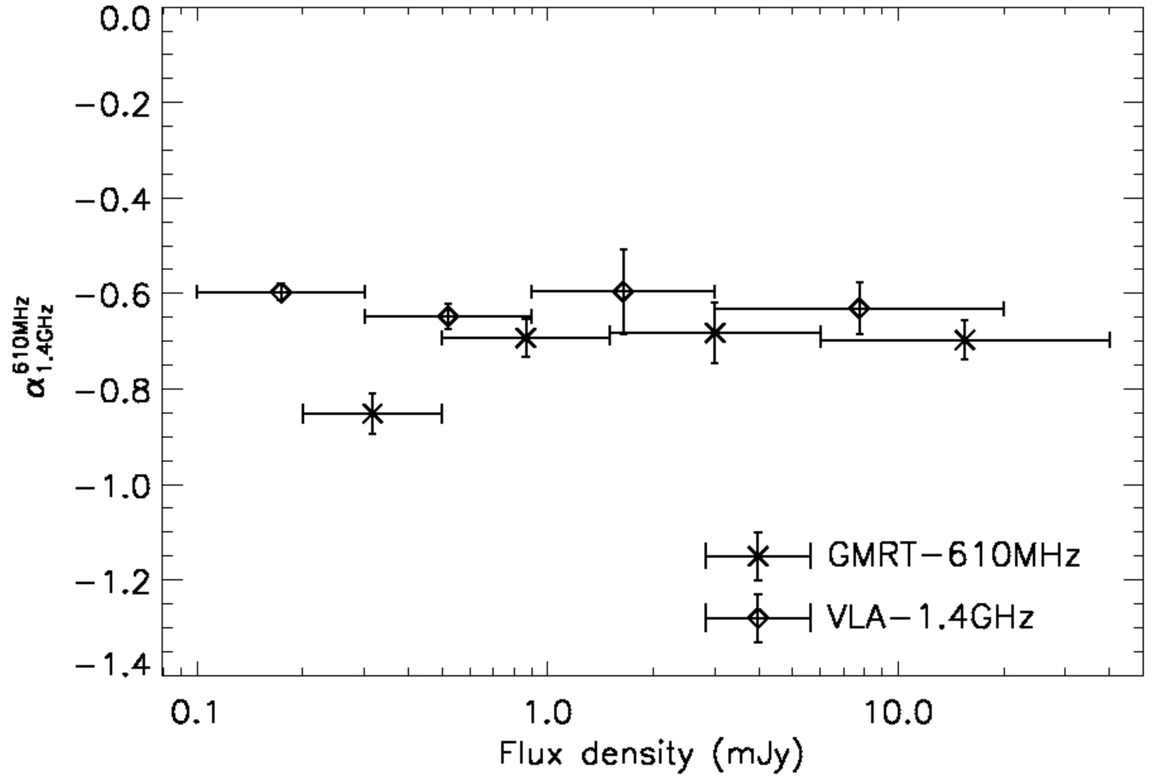
(Jarvis et al. 2001)

Results

THE RADIO SPECTRAL INDEX

There is no compelling evidence for an evolution in radio spectral index down to ~100 μJy at 1.4GHz.

Bootstrapped median, α , between -0.6 and -0.7



We conclude the principal mechanism responsible of the radio emission in the sub-mJy radio population is given by optically thin synchrotron radiation: star-forming galaxies or lobe-dominated radio-quiet AGN.

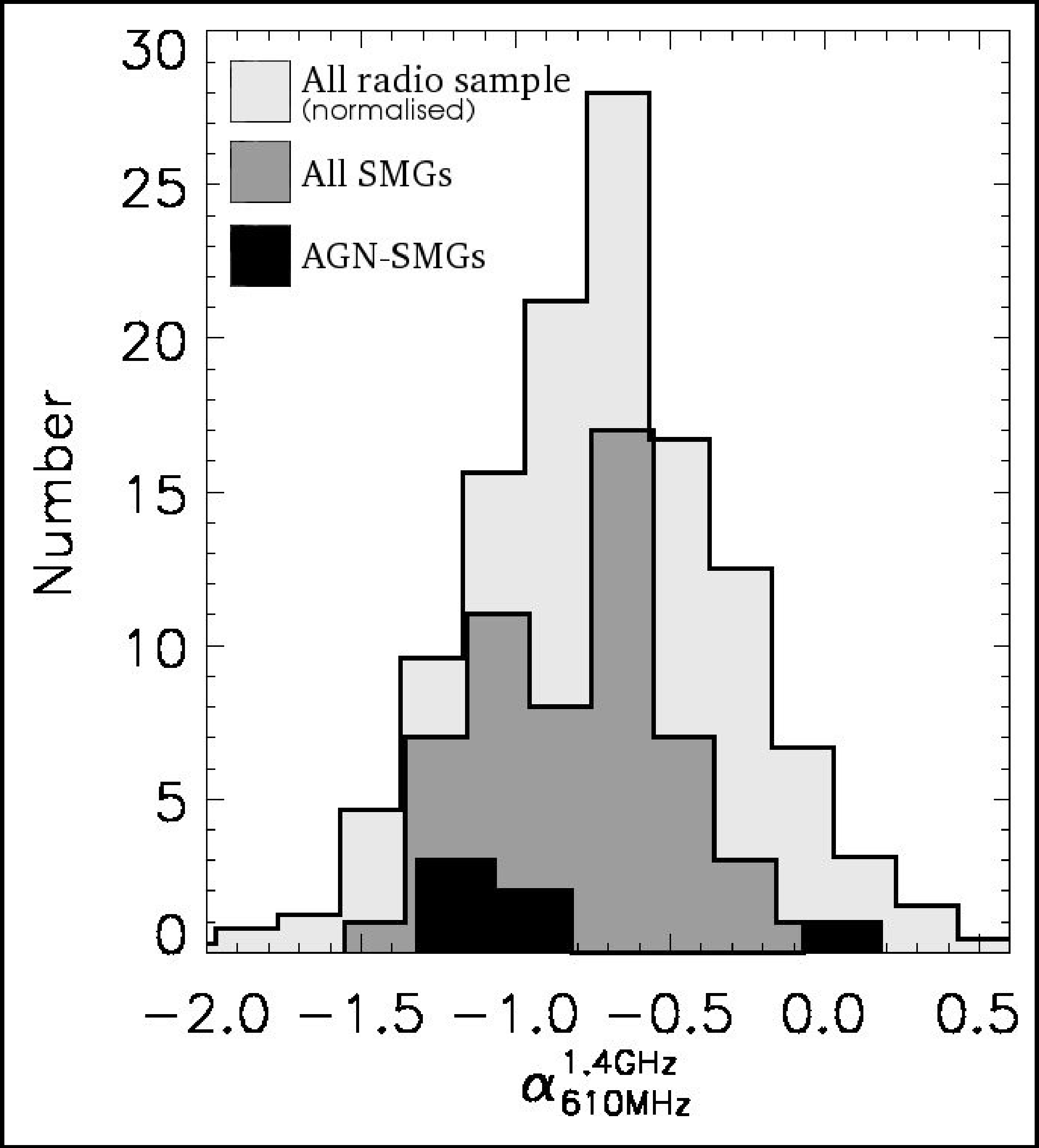
Preliminary results

THE RADIO SPECTRAL INDEX OF SMGs

The LOCKMAN HOLE has been observed with **AzTEC**, **SCUBA**, **MAMBO** and **Bolocam** cameras.

Slight evidence for steeper radio spectral indexes in SMGs.

α might be used as an indicator for AGN activity in high-z massive star-forming galaxies.



Approaches

How can we disentangle the nature of the sub-mJy radio population?

- **Deviations from the FIR/radio correlation** (e.g. Donley et al. 2005; Ibar et al. 2008)
- **The radio spectral index** (e.g. Clemens et al. 2008)
- **Morphology from sub-arcsecond observations** (e.g. Muxlow et al. 2005)
- **Cross-match with X-ray surveys** (e.g. Simpson et al. 2006; Barger et al. 2007)
- **Optical/NIR identification of the host galaxy:**
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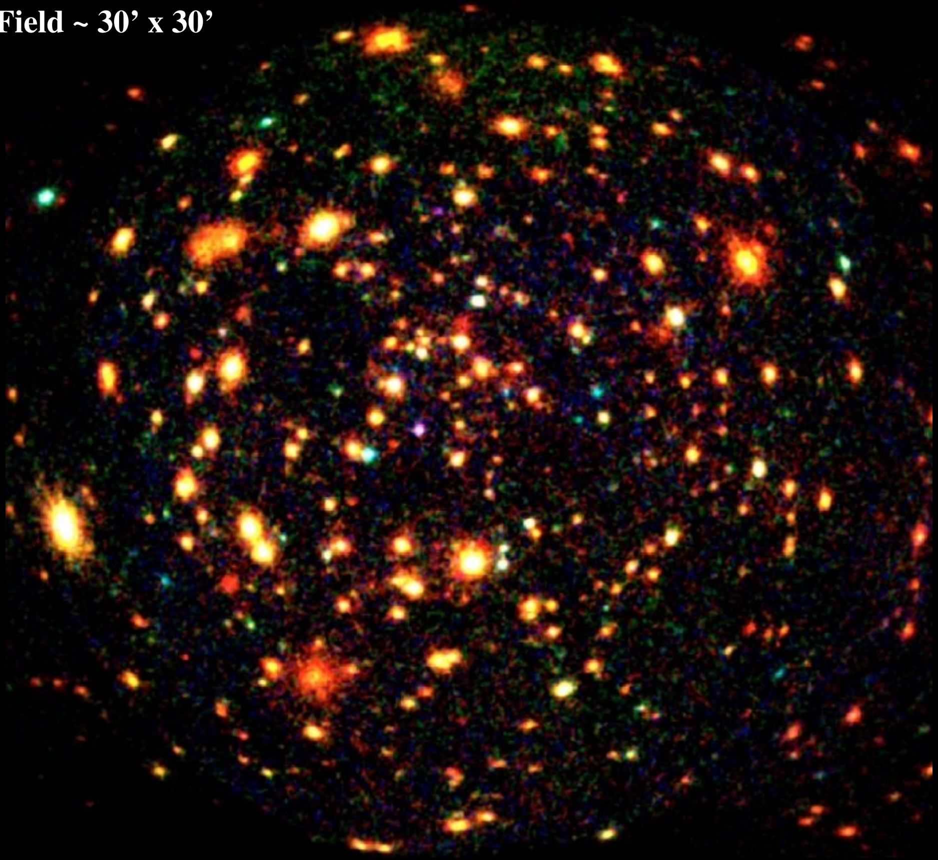
  - **Colour-colour diagrams** (e.g. Ciliegi et al. 2005)

X-ray Observations

The Lockman Hole has the lowest Galactic line-of-sight column density

$N_H = 5.7 \times 10^{19}\ cm^{-2}$

Red: 0.5-2.0 keV; Green: 2.0-4.5 keV; Blue: 4.5-10 keV
Field ~ 30’ x 30’



Brunner et al. (2008)

Brunner et al. (2008) published the deepest XMM-Newton observation for a total of 1.16 Ms (18 pointings). The maximum final effective exposure was 637 ks in the mosaic centre.

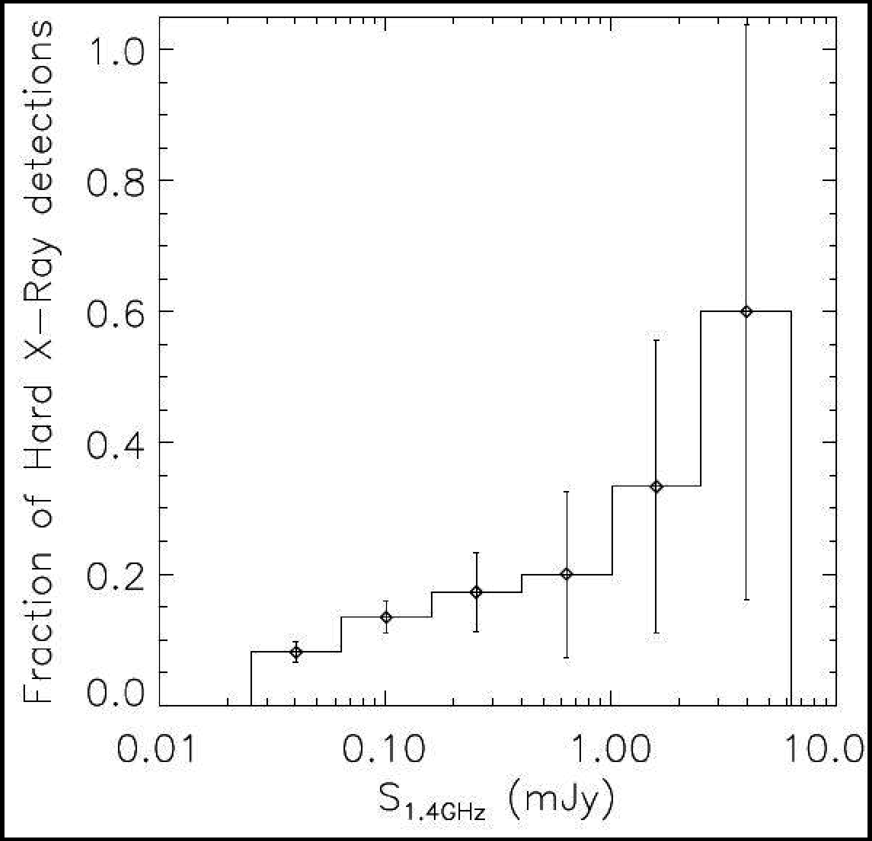
Area mosaic = 0.196 deg^2
Sources with a Likelihood > 10:
340 in the Soft X-ray band (0.5-2.0 keV)
266 in the Hard X-ray band (2.0-10.0 keV)

X-ray Observations

We find a decreasing trend for the number of radio sources detected in the hard X-ray catalogue.

This may suggest a dominant star-forming galaxy population in the sub-mJy radio regime.

There is, however, an spectroscopic/ photometric classification for the X-ray sources (Lehmann et al. 2001; Szokoly et al., *in preparation*).



X-ray Observations

At $S_{1.4GHz}$ < 300 µJy, there are 72 sources detected in the hard X-ray band, from which:

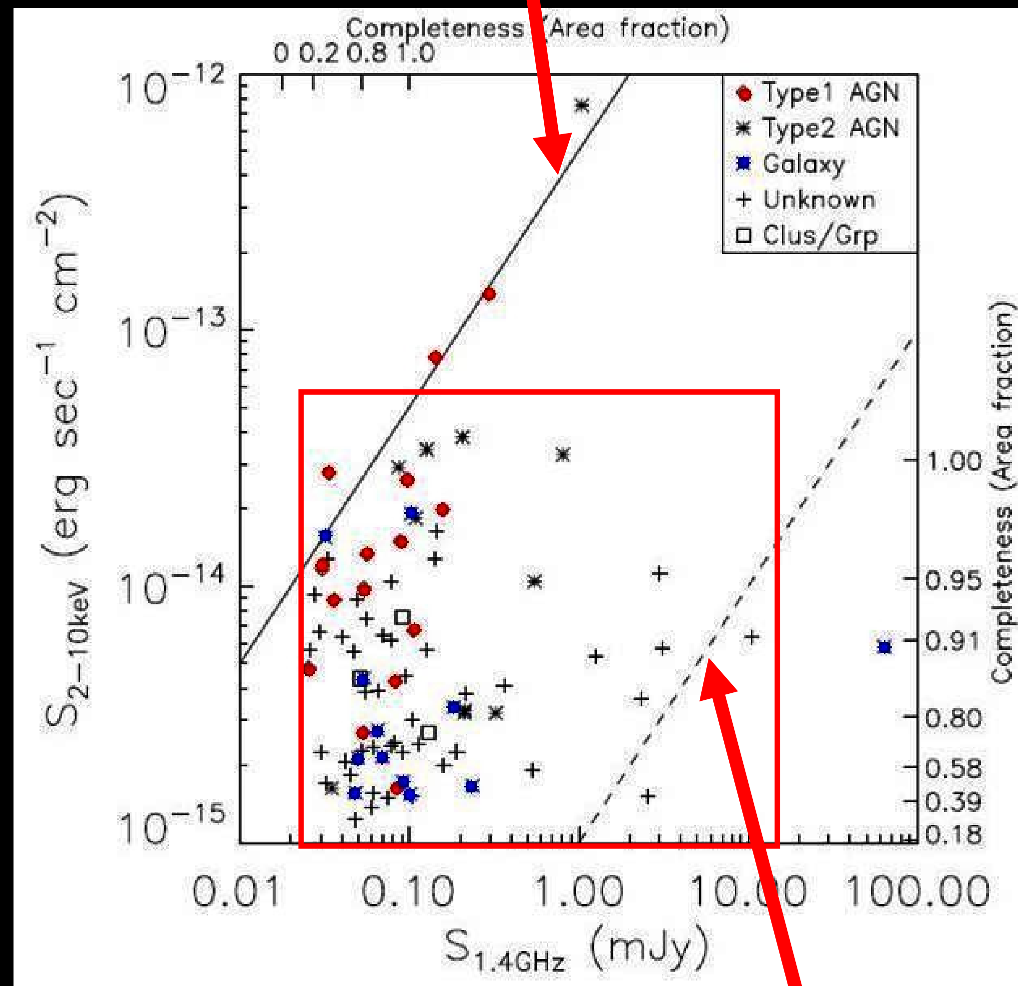
Class	Number
Type 1 AGN	16
Type 2 AGN	7
Galaxy	11
Clus/Grp	3
Unknown	35

Not all hard X-ray detections are AGN. Indeed, at fainter X-ray fluxes there is a large fraction of normal galaxies!.

Based on these fractions, we estimate a fraction between 15 and 35 per cent of radio-quiet AGN contaminating the sub-mJy radio regime.

For radio-quiet AGN

(Brinkmann et al. 2000)



For star-forming galaxies

(Condon 1992; Ranalli et al 2003)

Conclusion

We conclude the principal mechanism responsible of the radio emission in the sub-mJy radio population is given by optically thin synchrotron radiation from star-forming galaxies: median, α , between -0.6 and -0.7

Based on a spectroscopic/photometric classification of radio sources detected in the X-ray wavebands, we estimate a fraction between 15 and 35 per cent of radio-quiet AGN in the the $30\ \mu Jy < S_{1.4GHz} < 300\ \mu Jy$ radio regime.

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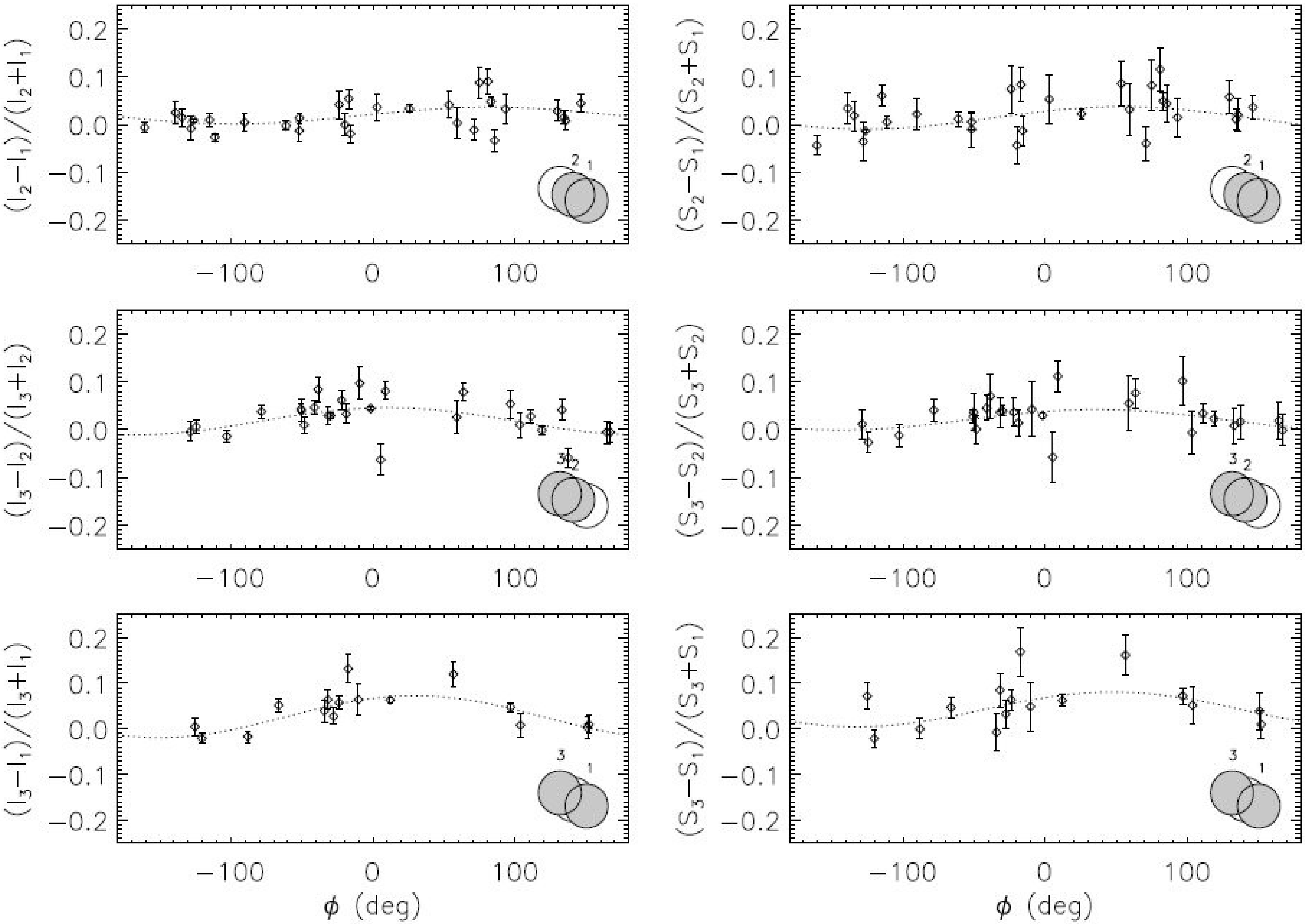
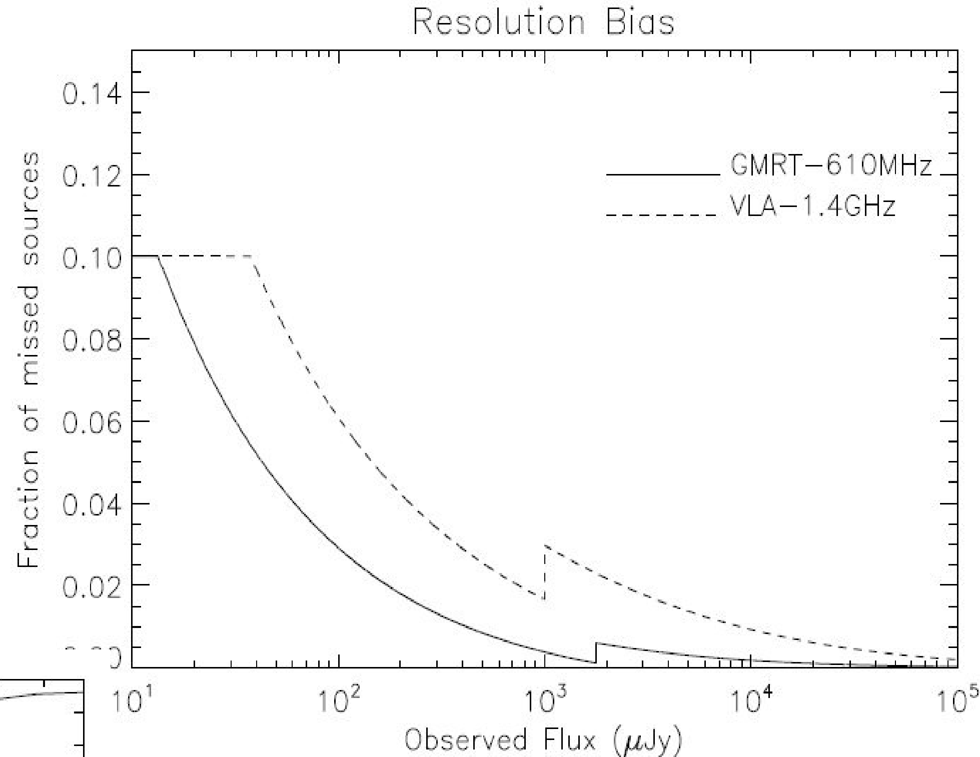
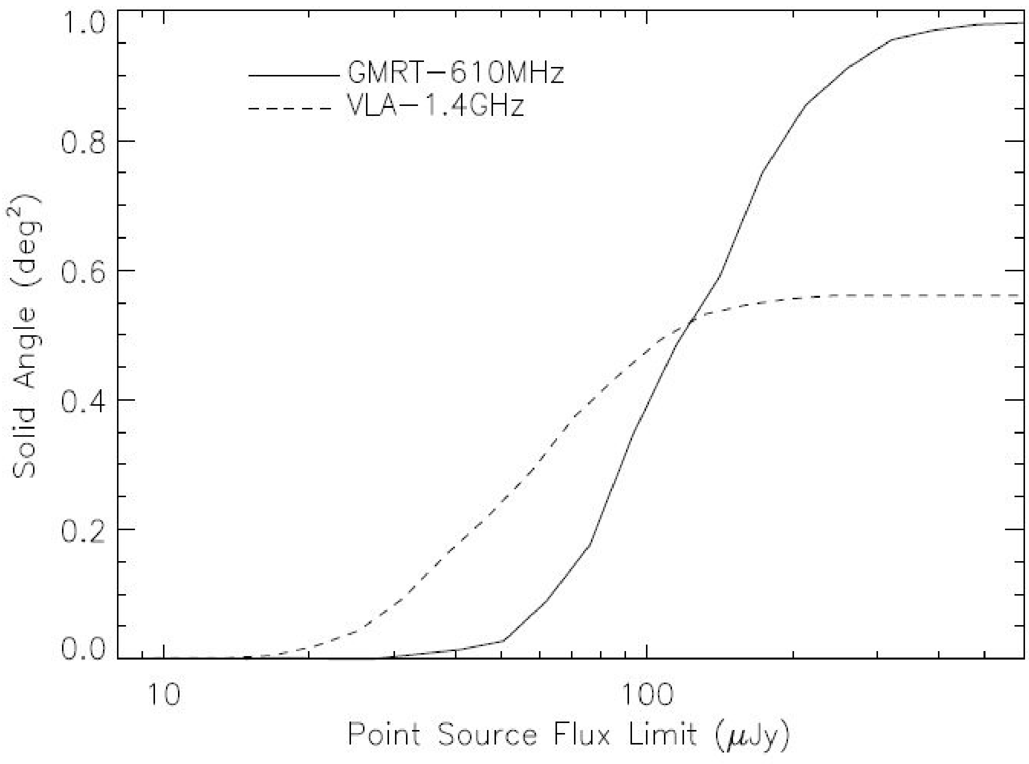
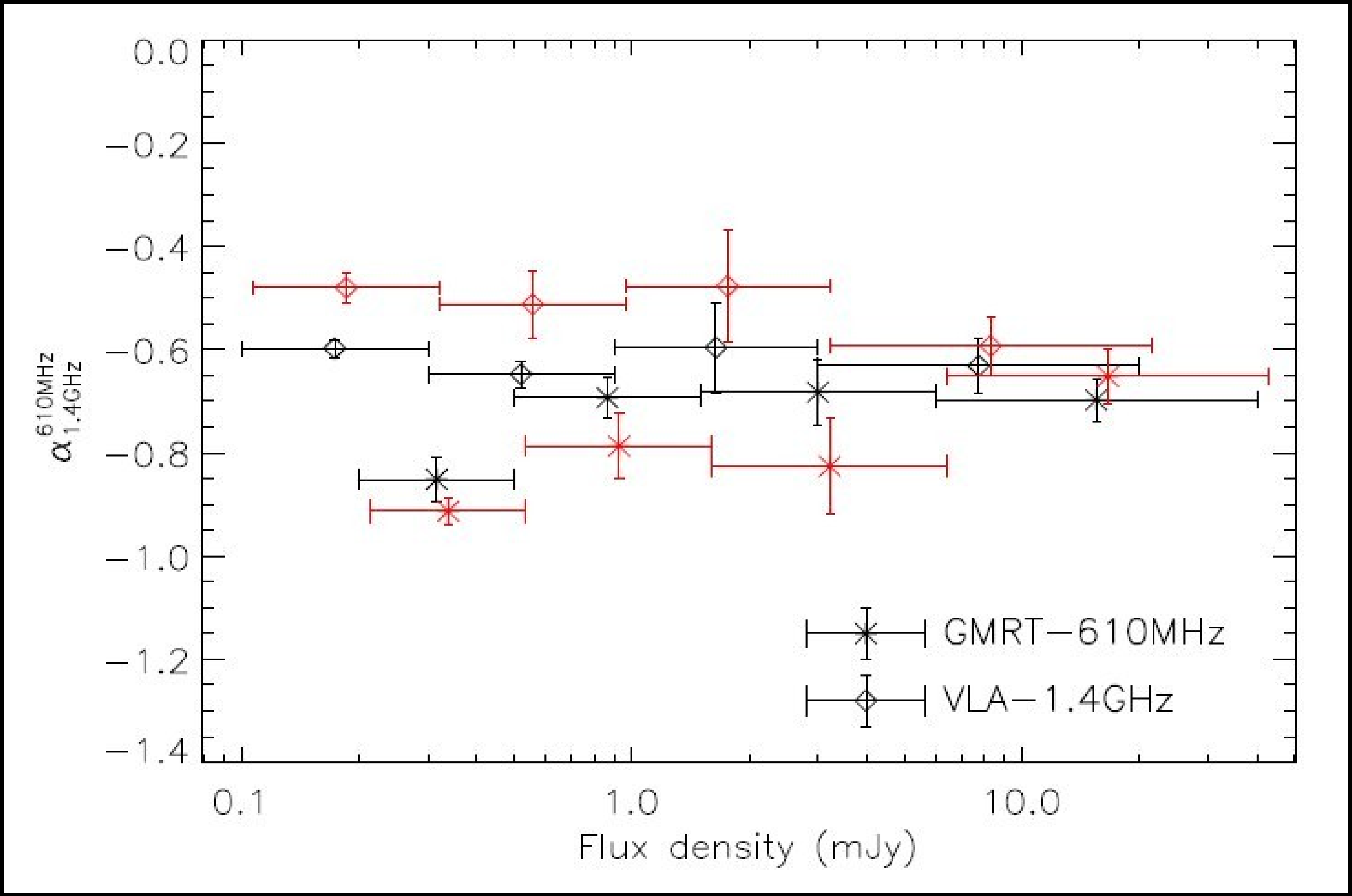
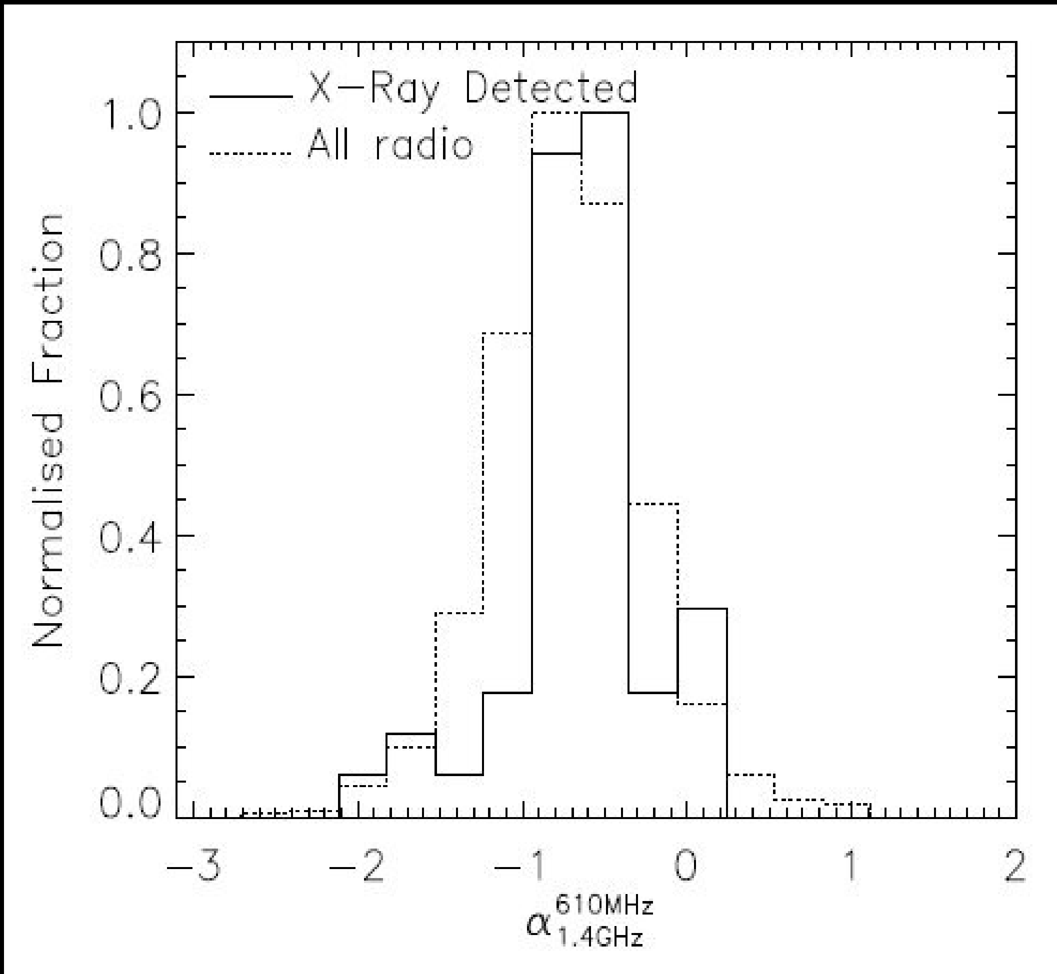

(I2−I1)/(I2+I1)
(S2−S1)/(S2+S1)
(I3−I2)/(I3+I2)
(S3−S2)/(S3+S2)
(I3−I1)/(I3+I1)
(S3−S1)/(S3+S1)
0.2
0.1
0.0
−0.1
−0.2
−100
0
100
ϕ (deg)
1
2
3

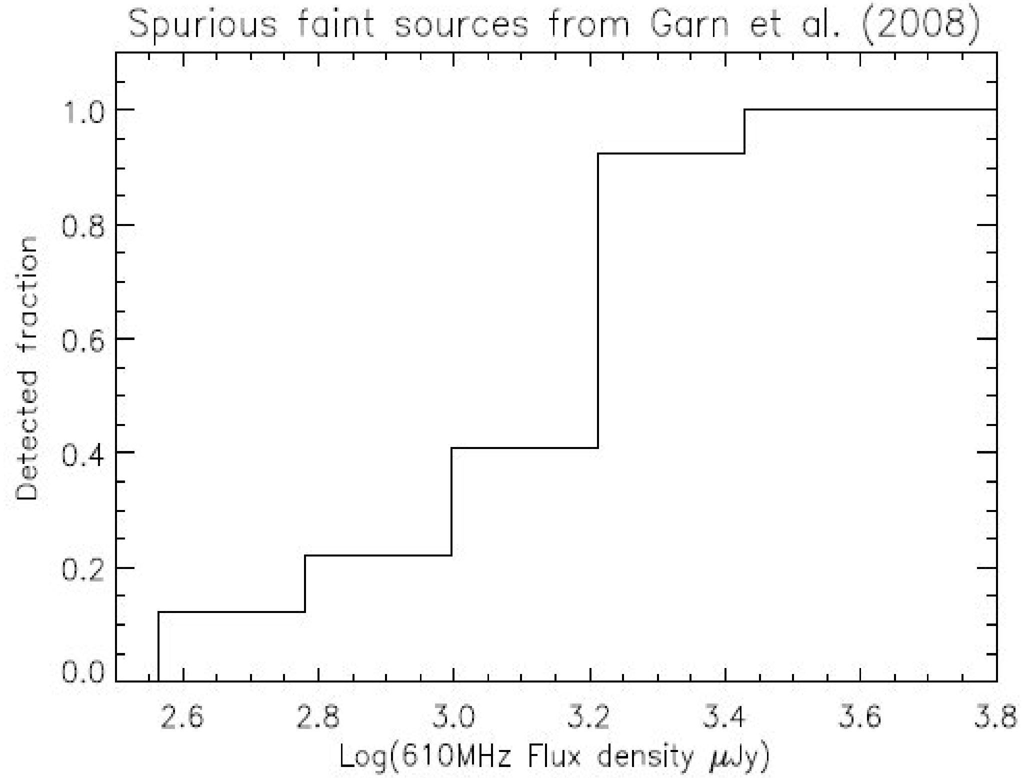

Resolution Bias
Fraction of missed sources
0.14
0.12
0.10
0.08
0.06
0.04
0.02
GMRT−610MHz
VLA−1.4GHz
10^1
10^2
10^3
10^4
10^5
Observed Flux (μJy)

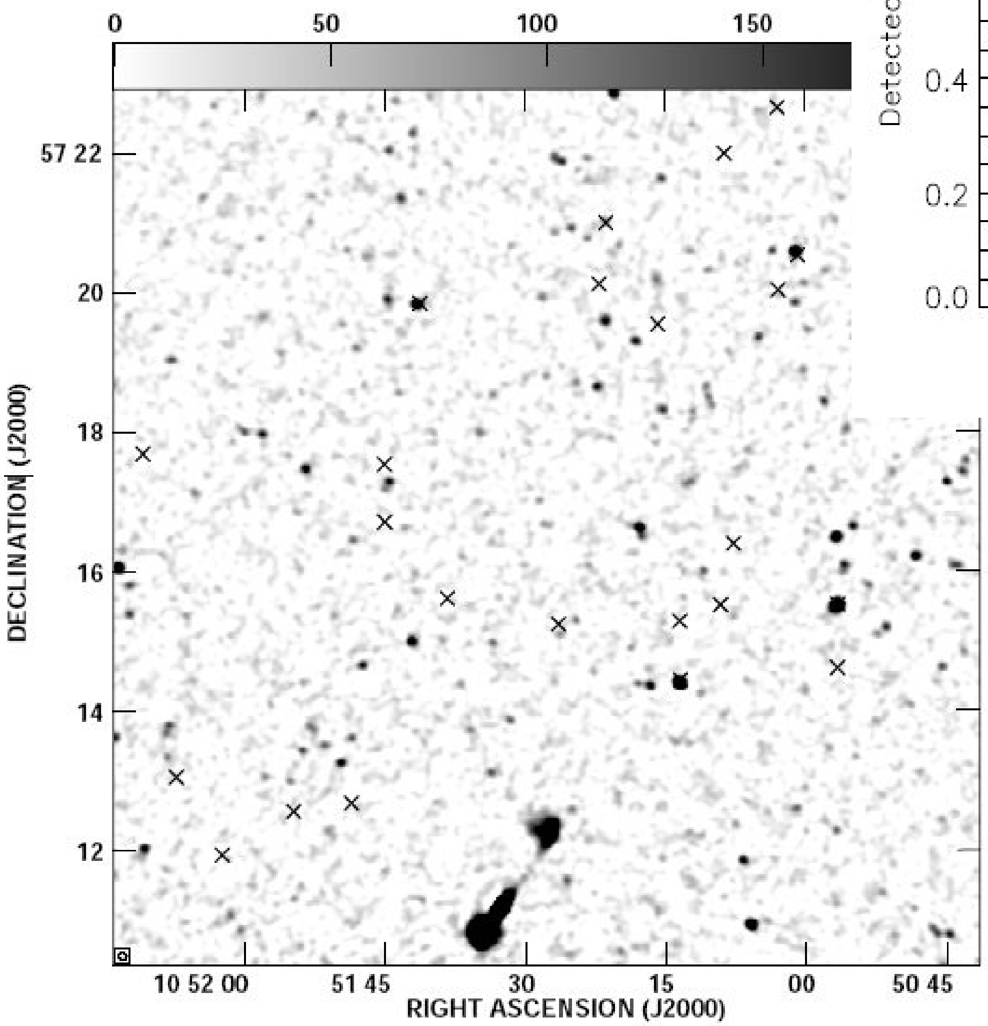

Solid Angle (deg^2)
1.0
0.8
0.6
0.4
0.2
0.0
GMRT−610MHz
VLA−1.4GHz
10
100
Point Source Flux Limit (μJy)


0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
$\alpha^{610MHz}_{1.4GHz}$
0.1
1.0
10.0
Flux density (mJy)
GMRT−610MHz
VLA−1.4GHz



Class	N	$\langle\langle \alpha^{610MHz}_{1.4GHz} \rangle\rangle$
Type 1 AGN	9	-0.79 ± 0.20
Type 2 AGN	8	-0.60 ± 0.12
Galaxy	6	-0.65 ± 0.26
Unknown	24	-0.58 ± 0.07
Cluster/Group	1	-1.87


Spurious faint sources from Garn et al. (2008)
Detected fraction
1.0
0.8
0.6
0.4
0.2
0.0
2.6
2.8
3.0
3.2
3.4
3.6
3.8
Log(610MHz Flux density μJy)


0
50
100
150
DECLINATION (J2000)
57 22
20
18
16
14
12
10 52 00
51 45
30
15
00
50 45
RIGHT ASCENSION (J2000)