AGN jets in distant dusty galaxies:
An observational perspective

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Outline

- Radio galaxies : Jet-lobe systems in the plane of sky
- Radio Galaxies beyond the local Universe
- Radio surveys from GMRT and VLA
- Ultra steep spectrum (USS) radio sources as the tracer of HzRGs
- Optical, near-IR, mid-IR identification of USS sources
- Compact jet-lobe structure in dusty high-z galaxies

Motivation

High-z Radio Galaxies (HzRGs)

Unlike nearby radio galaxies

- Hosted in massive galaxies with very high star formation rates (few 100 - few 1000 $M_\odot$ yr^{-1})
  (Jarvis et al. 2001a; Willott et al. 2003)

- Likely to be progenitor of massive elliptical galaxies in local universe
  (Best et al. 1998; McLure et al. 2004)

- Often associated with over-densities i.e., proto-clusters and clusters
  (Venemans et al. 2007 Galametz et al. 2012)

HzRGs are important to understand the formation and evolution of galaxies at higher redshifts and in denser environments.

How to search high-z radio galaxies

Step 1: Wide and deep low-frequency continuum radio surveys

↓

Step 2: Probable HzRG candidates (e.g, USS, faint K-band counterparts)

↓

Step 3: Identify optical, IR counterparts

↓

Step 4: Redshifts from spectroscopic/photometric observations

(Jarvis et al. 2004, Bornancini et al. 2007, Ishwara-Chandra et al. 2010, Singh et. 2014)

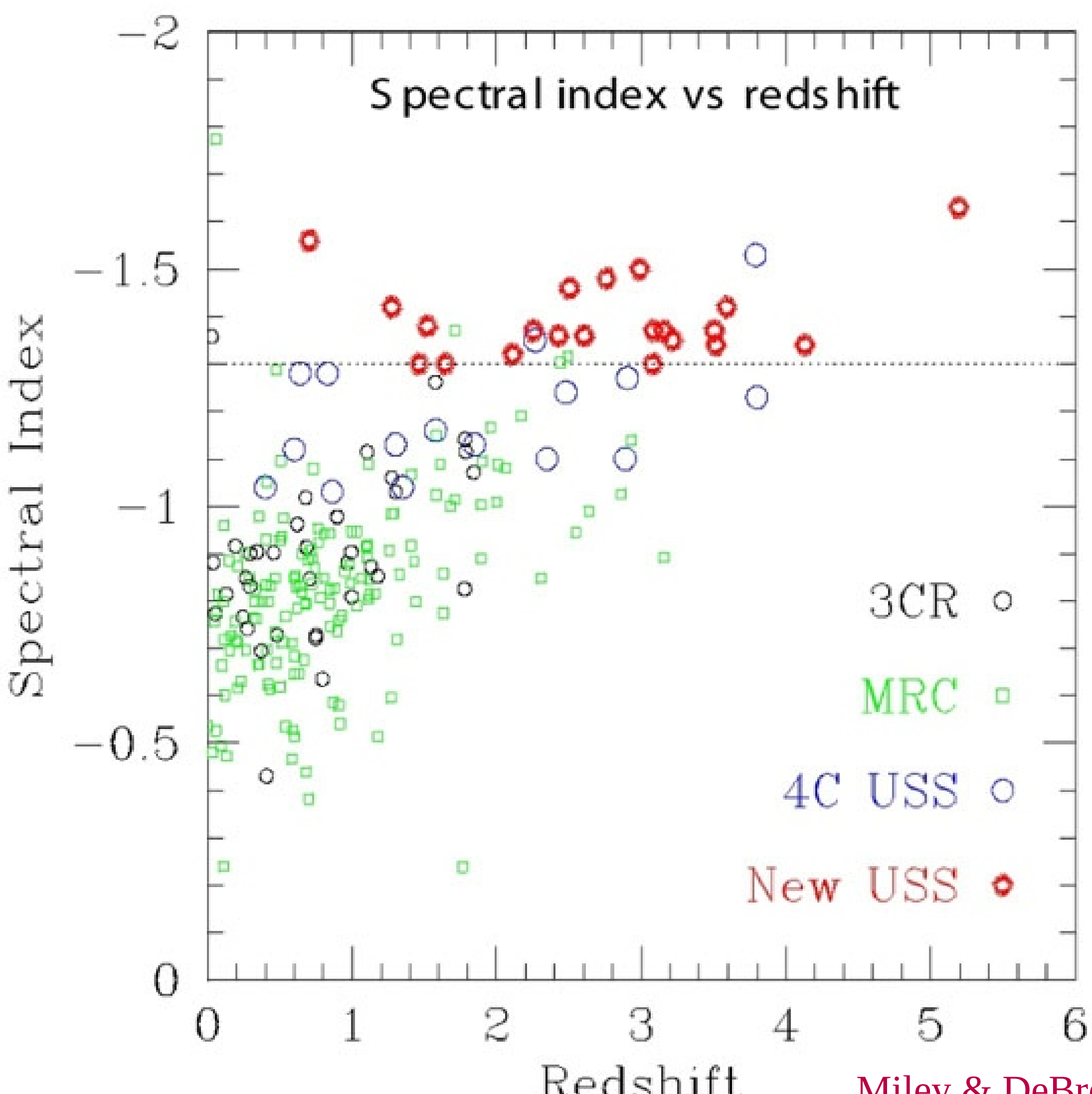
USS radio sources: HzRG candidates

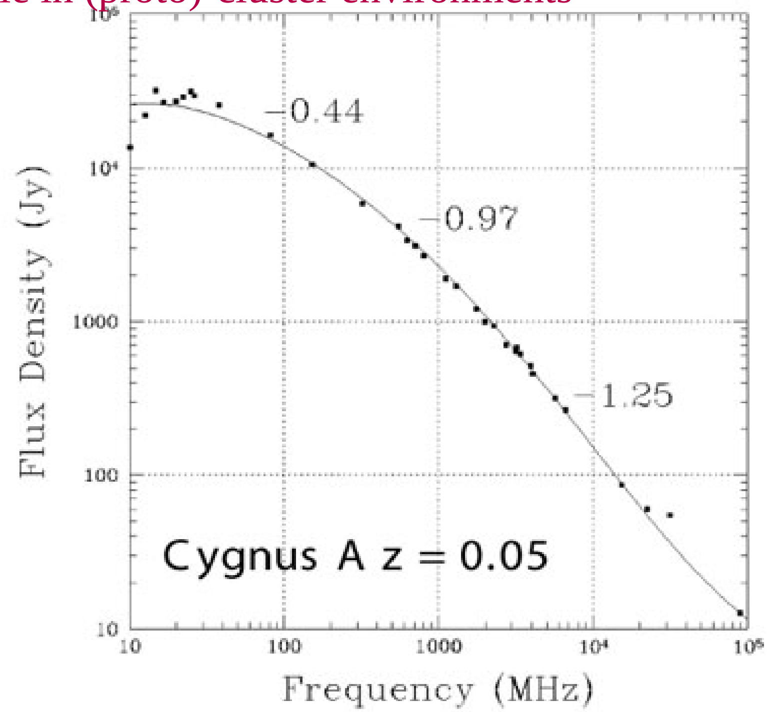
The conventional explanation

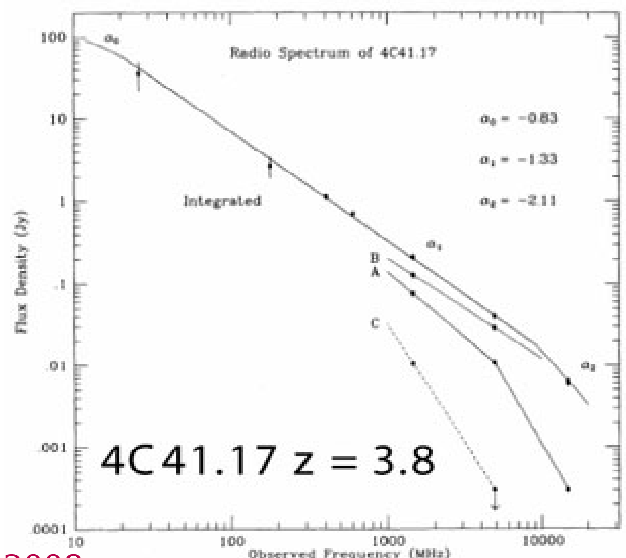
- a concave radio spectrum coupled with a radio K-correction

- radio jets expand in denser environments; a scenario more viable in (proto)-cluster environments

(Klamer et al. 2006; Bryant et al. 2009; Bornancini et al. 2010)







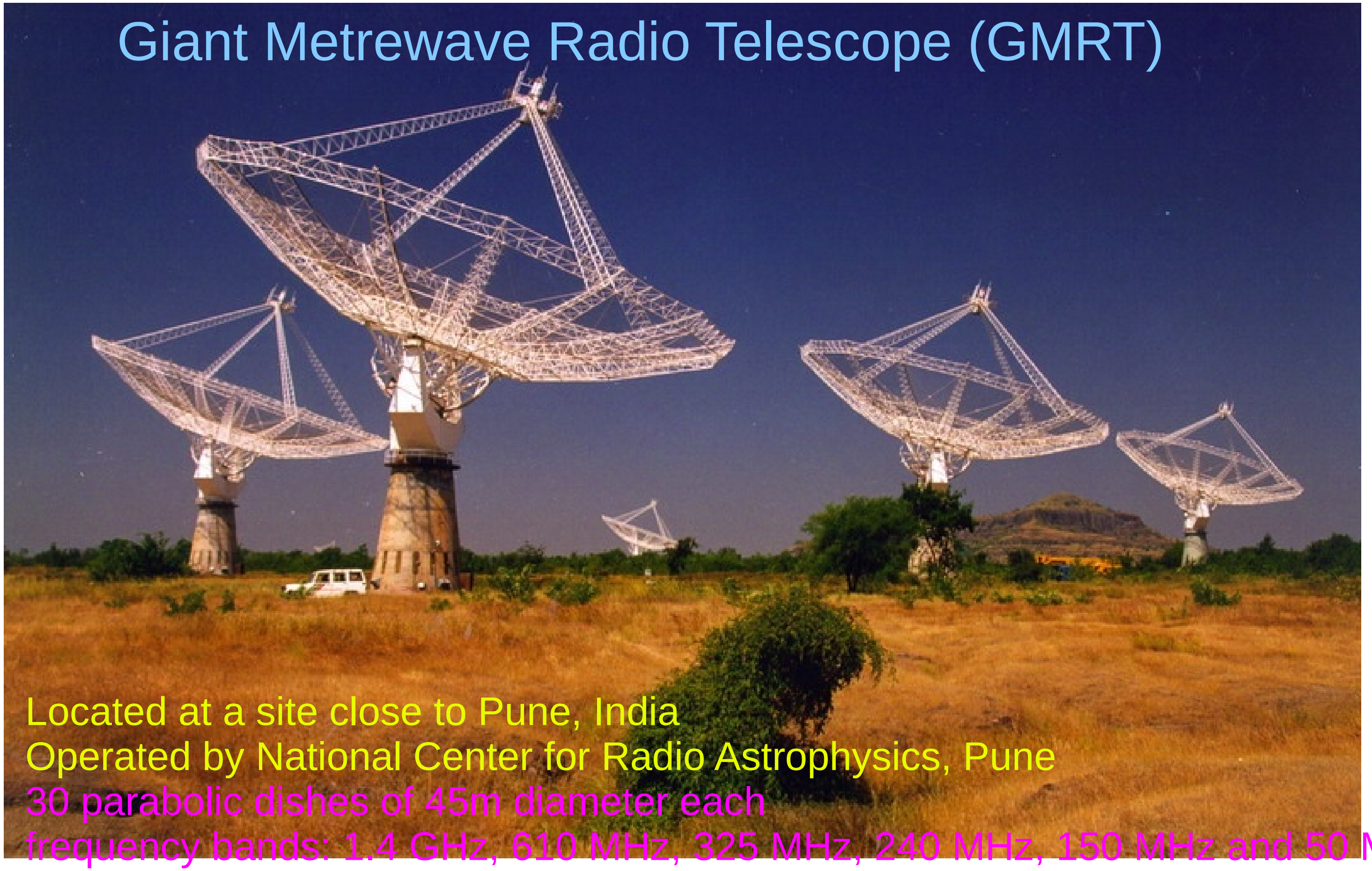
Miley & DeBreuck 2008

325 MHz GMRT radio observations of Herschel fields

advantage at low-frequency: large collecting area, large foV and adequate resolution (~ 9")

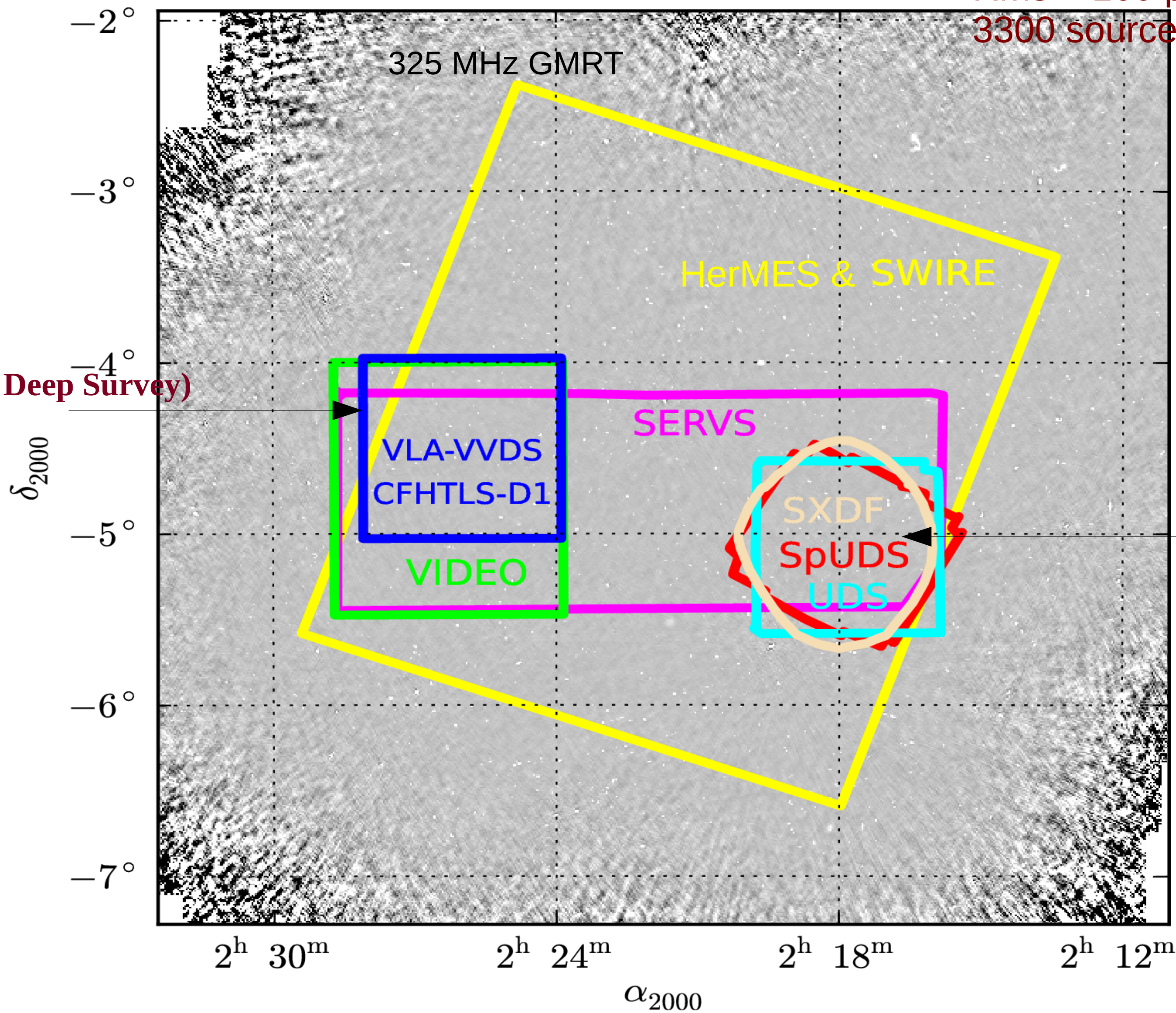
Field	Area	Total Time	Rms	No. of sources (≥ 5σ)
XMM-LSS	9 deg^2	40 h	160 μJy/b	3300
Lockman hole	18 deg^2	200 h	40 μJy/b	
ELAIS-N1	9 deg^2	100 h	40 μJy/b	

Deepest low frequency wide radio survey in XMM-LSS field (Wadadekar et al. In preparation)



Multiwavelengths observations in XMM-LSS

325 MHz GMRT
9 deg^{-2}
Rms ~ 160 μJy
3300 sources



VVDS (VIMOS VLT Deep Survey)

1.4 GHz VLA
1.0 deg^{-2}
rms ~ 16 μJy
1054 sources
(Bondi et al. 2003)

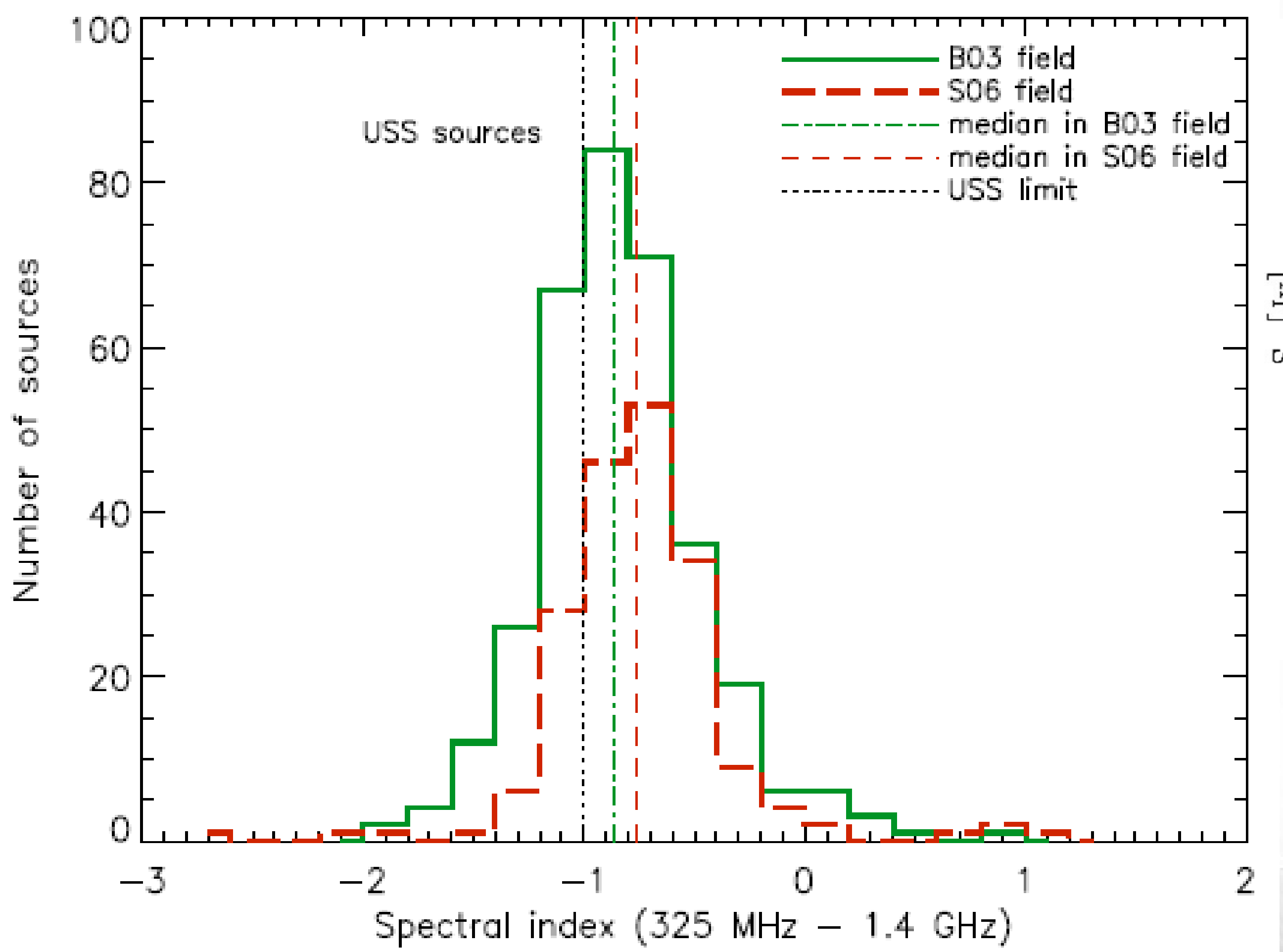
SXDF
(Subaru XMM-N Deep Field)

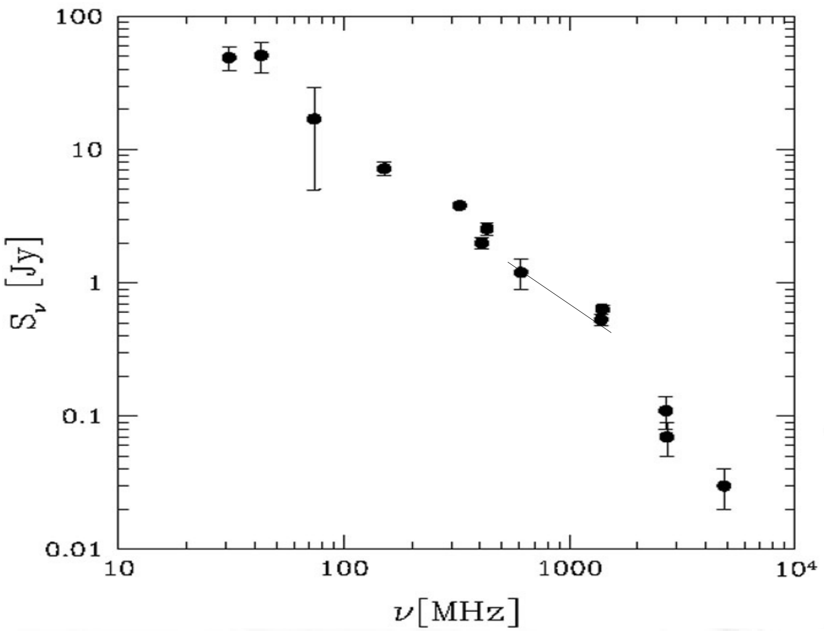
1.4 GHz VLA
0.8 deg^{-2}
rms ~ 20 μJy
512 sources
(Simpson et al. 2006)

Cross-matching of 325 MHz and 1.4 GHz radio sources

Radio spectrum a power law : $S_\nu \propto \nu^\alpha$

No. of sources	VVDS	SXDF
1.4 GHz	1054	512
325 MHz	343	200
Cross-matched	338	191
USS (α ≤ -1.0)	116	44





USS sample :

325 MHz – 1.4 GHz spectral index (α) ≤ -1.0

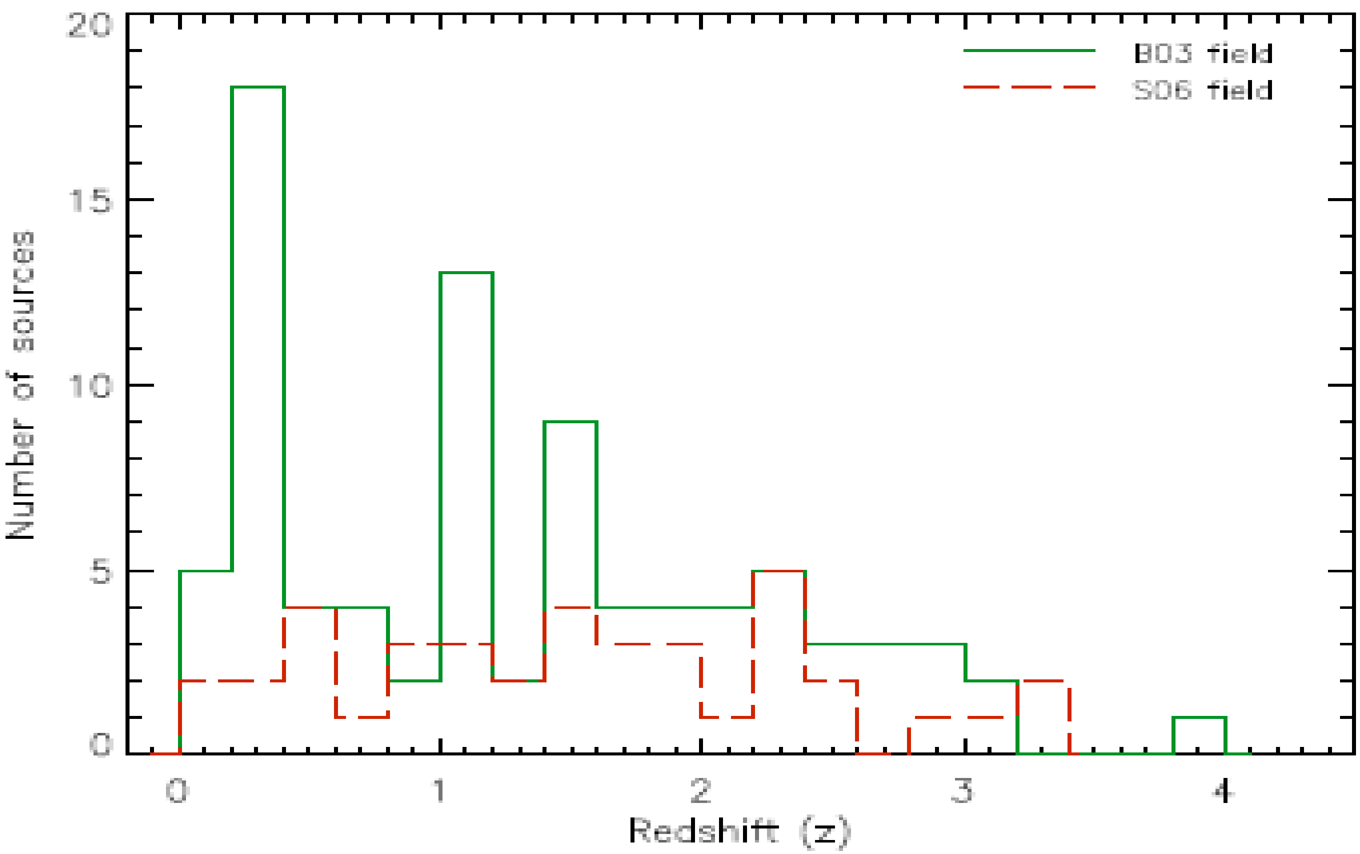
Total 160 USS sources

Singh et al. 2014 A&A

Redshifts of USS radio sources

Photo-z of 1.4 GHz radio population
VVDS field : Optical CFHTLS + near-IR VIDEO data
VIMOS VLT Deep Survey (VVDS) spectroscopic survey
McAlpine (2013).

SXDF : 11 band photo-z (u, B, V, R, i, z, J, H, K plus IRAC bands 1 and 2)
Visible Multi-Object Spectrograph (VIMOS)
Simpson et al. (2012).



VVDS field
86/116 (74%) photo-z
11/86 Spec-z

$0.09 \leq z \leq 3.86$, median z ~ 1.18
53/86 ~ 61.5/% are at $z \geq 1.0$

SXDF
39/44 (~89%) photo-z
16/39 Spec-z

$0.03 \leq z \leq 3.34$, median z ~ 1.57
26/32 ~ 72 /% are at $z \geq 1.0$

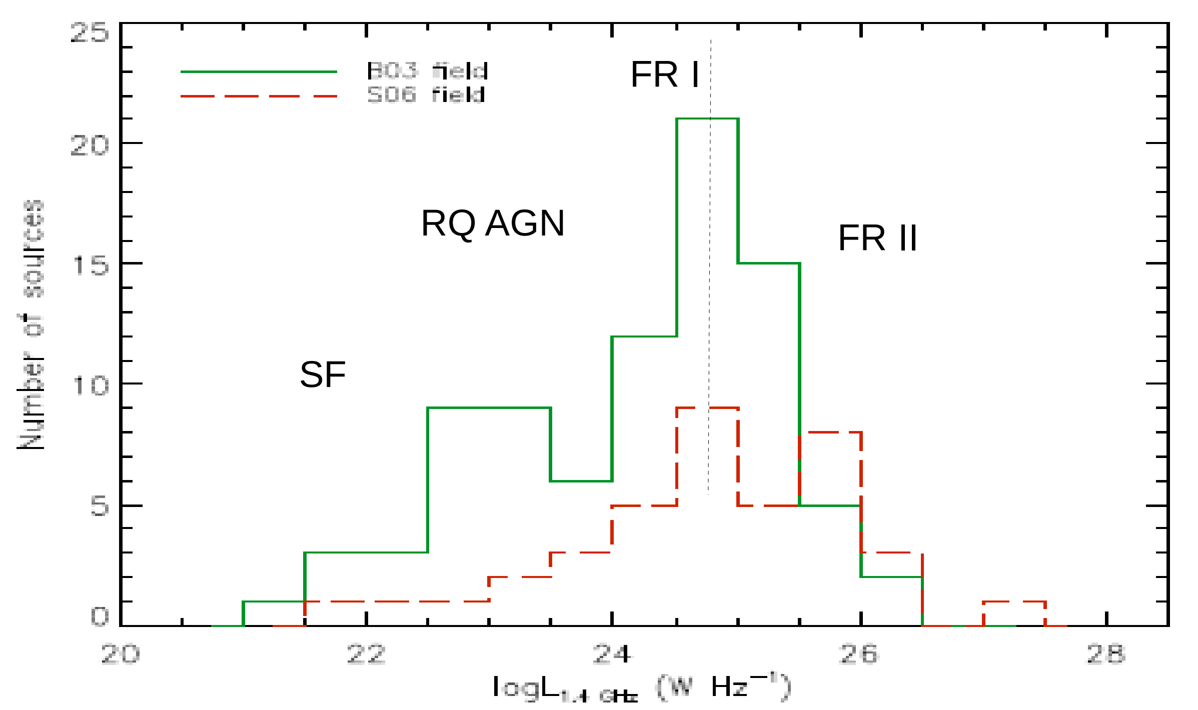
60% – 70% USS sources are at z > 1.0

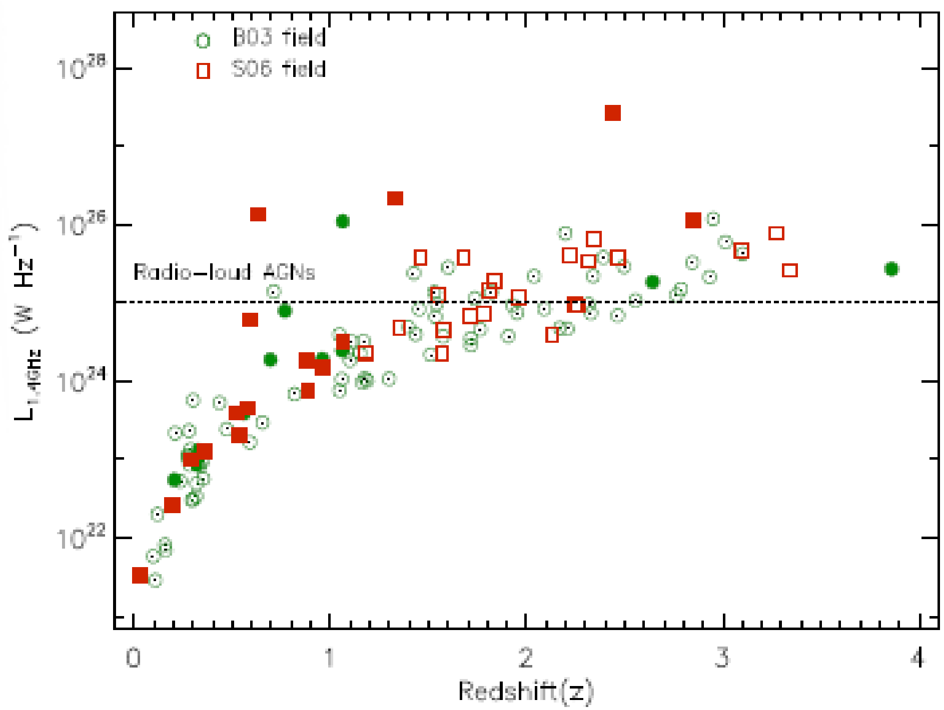
A fraction of sources without redshifts
Possible HzRG candidates

Peak at z ~0.3 : 6 known X-ray clusters at z ~ 0.26 – 0.35 (Pacaud et al. 2007; Adami et al. 2011)

Radio Luminosities

1.4 GHz





VVDS field :

$2.88 \times 10^{21} \leq L_{1.4GHz,} \leq 1.2 \times 10^{26}$ W Hz^{-1}

$L_{1.4GHz,\ median} \sim 3.16 \times 10^{25}$ W Hz^{-1}

SXDF :

$3.31 \times 10^{21} \leq L_{1.4GHz,} \leq 2.69 \times 10^{27}$ W Hz^{-1}

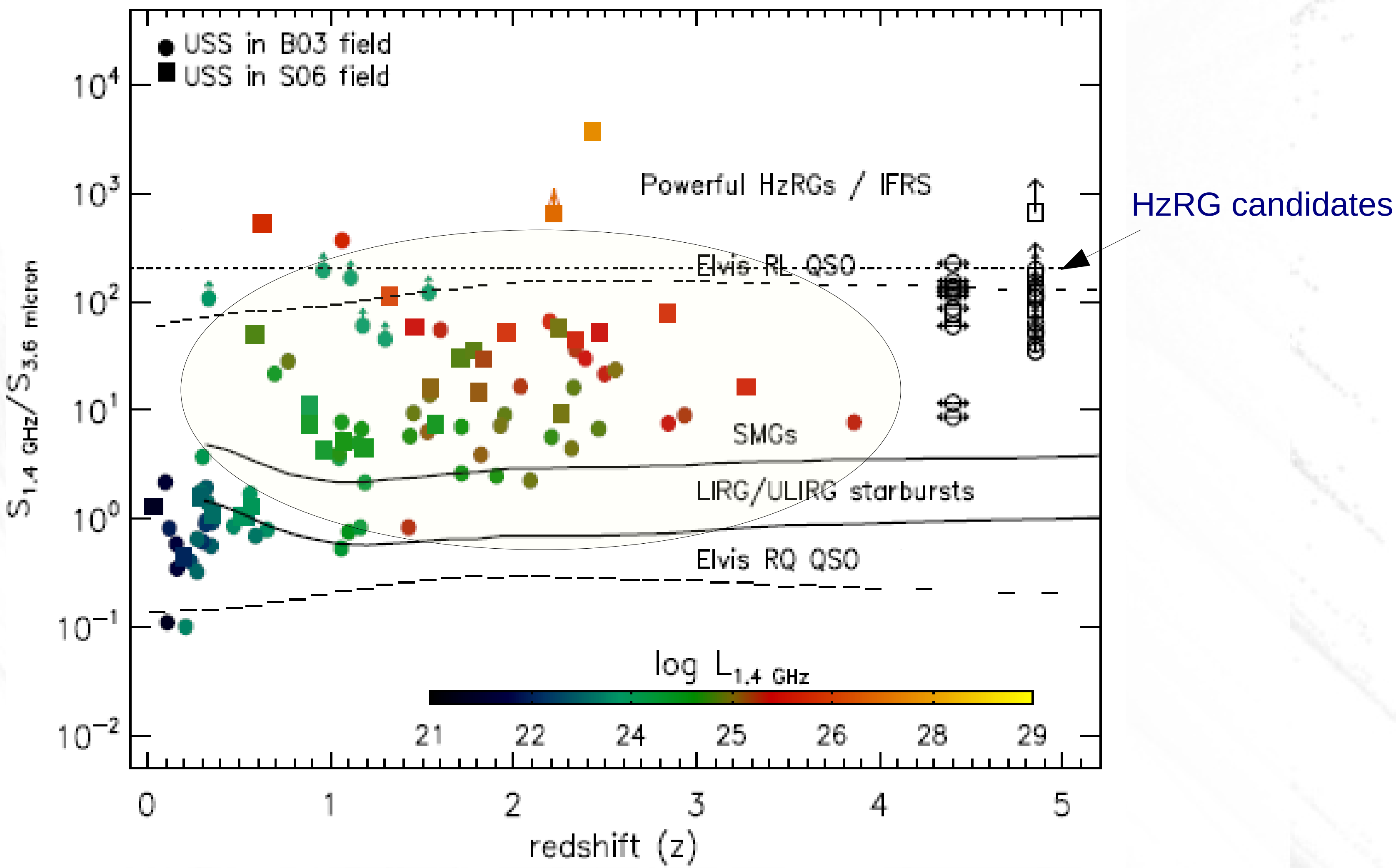
$L_{1.4GHz,\ median} \sim 7.24 \times 10^{24}$ W Hz^{-1}

FR I < $P_{178\ MHz} \sim 10^{25}$ W Hz^{-1} < FR II

~ 40 % USS have radio luminosities typical of powerful FRII Radio galaxies

Unveiling the nature of USS radio sources using IR emission

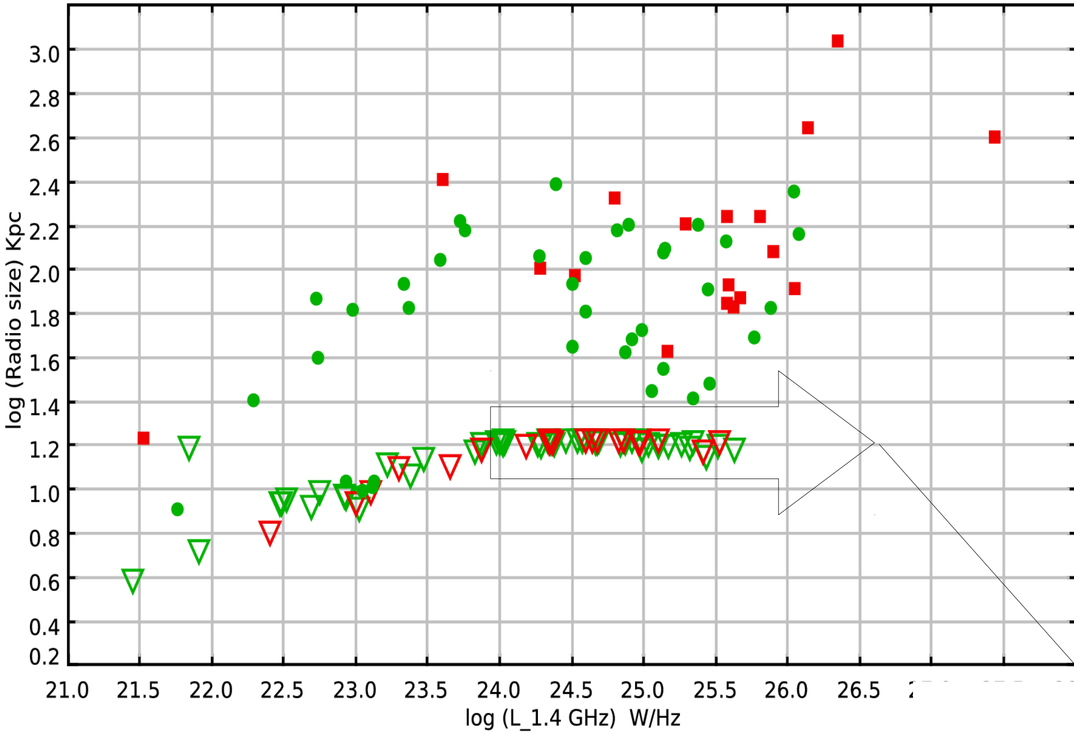
1.4 GHz radio to 3.6 micron flux ratio diagnostic



- A large fraction of USS sources falling in SMGs, LIRGs / ULIRGs regions
- Radio AGN hosted in SMG-like dusty obscured intensely Star forming galaxies at moderate redshifts

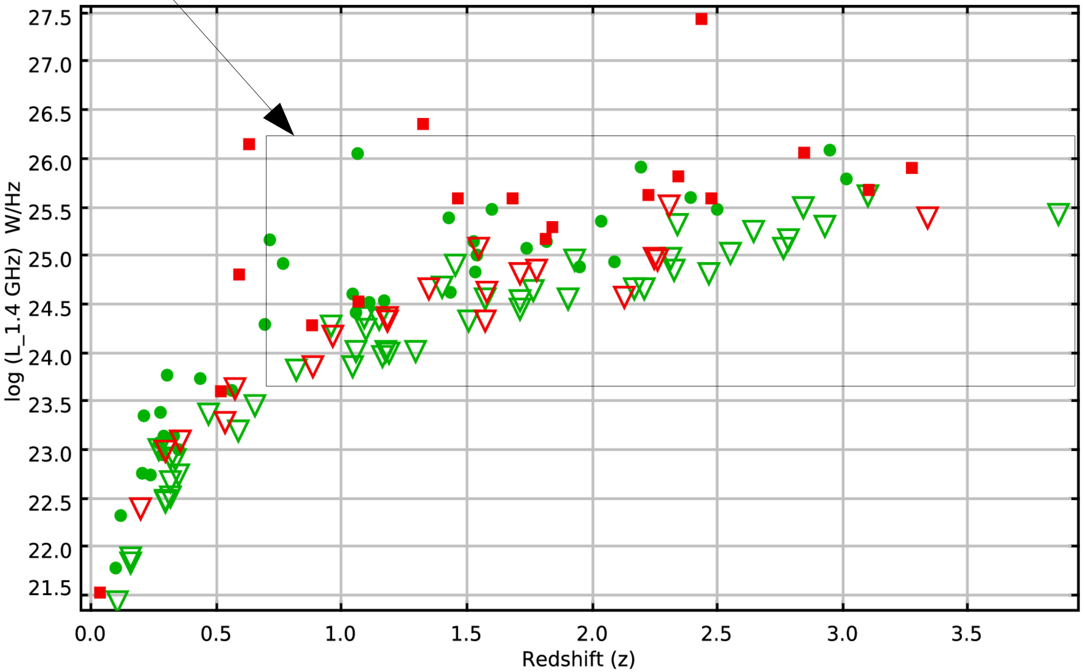
Singh et al. 2014 A&A

Total linear projected radio sizes of USS



- ~ 50% Unresolved sources in VLA and GMRT
- Radio sizes < 20 kpc
- CSS sources
- Candidates of young radio galaxies

High resolution (sub-arcsec to milliarcsec) e.g., **VLBA / VLBI observations are required to see small scale structures**.



VLBI observations of IRAS F00183−7111

An example of CSS in dusty galaxy

- Ultra Luminous InfraRed Galaxy
  $L_{bol} \sim 9 \times 10^{12} L_{sun}$ (z ~ 0.33)

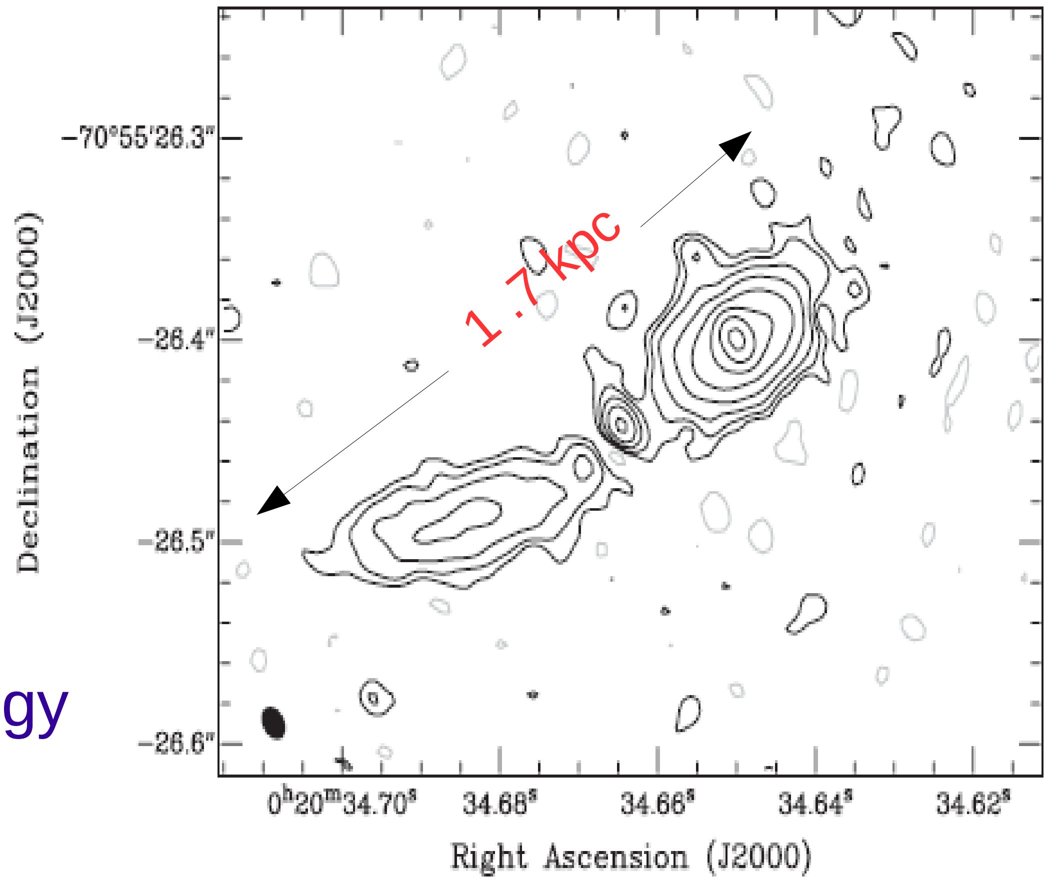
- Heavily dusty galaxy
  Large FIR excess
  $L_{FIR}/L_{B\text{-}band} \sim 360$

- Powerful radio galaxy
  $L_{2.3GHz} = 6 \times 10^{25}$ W Hz^{-1}

- A compact double-lobe morphology

- Radio size : 1.7 Kpc

2.3 GHz VLBI Image



Norris et al. (2012)

CSS sources in distant dusty galaxies

A plausible scenario

- Radio jets have just turned on as recently as 10^4 years ago (O'Dea 1998)
- Jets are ploughing their way through the dense gas
- Jets will heat up and dispel the circumnuclear dense dusty material
- Eventually will become full fledged large radio galaxies
- Highly obscured radio-loud AGN, observed in the transition stage after the birth of the radio AGN, but before feedback effects dispel the interstellar medium and halt/mitigate the black hole accretion and starburst activity.

Thank you for your attention

Summary

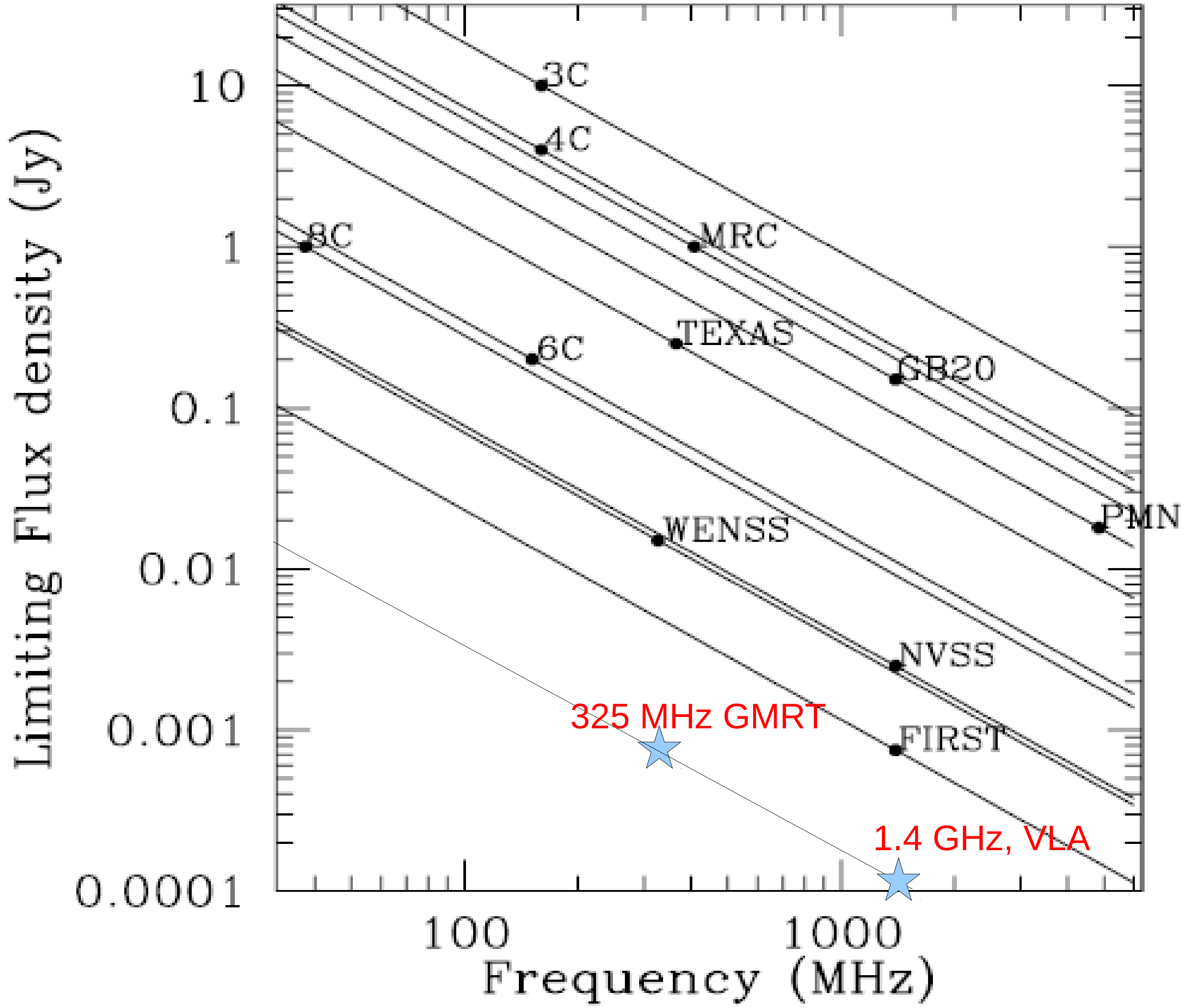
- We obtain a sufficiently large sample of 160 faint USS sources and investigate their nature using optical, near-IR and mid-IR counterparts from existing deep surveys.
- USS sources are systematically fainter with lower identification rate in optical, near-IR and mid-IR suggesting their high-z and/or obscured nature.
- The radio luminosity distribution infers that substantially high fraction (≥ 40 %) of sample sources have radio luminosities typical FRII radio galaxies.
- A large fraction (~ 50%) of USS have $S_{1.4GHz}$ / $S_{3.6\ micron}$ and redshifts similar to dusty SMGs/ULIRGs. These source are likely to be AGNs hosted in dusty obscured galaxies.
- USS sources without redshifts also do not have detection in deep K-bands and 3.6 micron Images. Flux ratio limits on radio to mid-IR infers these sources to be HzRGs or heavily obscured HzRGs at moderate redshifts (z ~ 2 - 3)
- USS criterion remains an efficient method to select high-z sources even at fainter flux densities.
- MeerKAT, SKA will explore further deeper in distant universe

Comparison with previous USS samples (HzRGs candidates)

HzRGs search limited to bright USS sample based on shallow or moderately deep radio surveys (e.g., De Breuck et al. 2002a, 2004; Broderick et al. 2007, Bryant et al. (2009); Bornancini et al. (2010)).

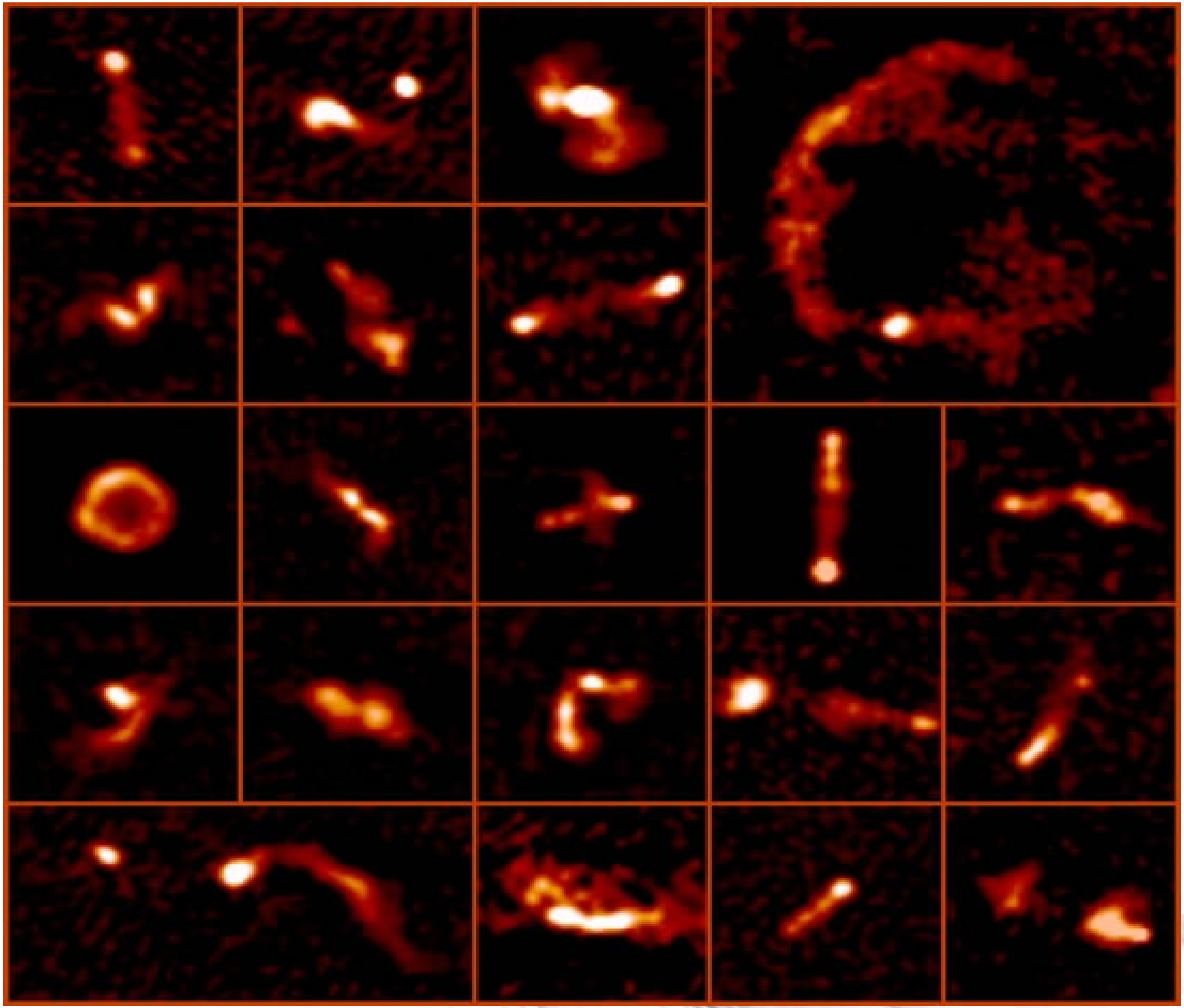
we are probing ~10 times deeper in submJy ($S_{1.4\ GHz}$ ≥ 0.1 mJy) regime

Relatively faint and High-z sources in our sample



Radio galaxies with variety of morphologies

Factors : viewing angle, evolutionary stage (young, old), AGN parameters (AGN power, mass, spin of SMBH), Host galaxy, Environment (field, group, cluster)



Credit: VLSS

High-z radio galaxies with MeerKAT and SKA

* Ultra deep radio surveys (rms ~ few microJy at 1.4 GHz)

* Unveil the population of radio galaxies up redshift (z) ~ 5 - 6

* HzRGs Beacon for associated (proto)clusters at high-z

Nature of USS at faint (submJy) flux densities?

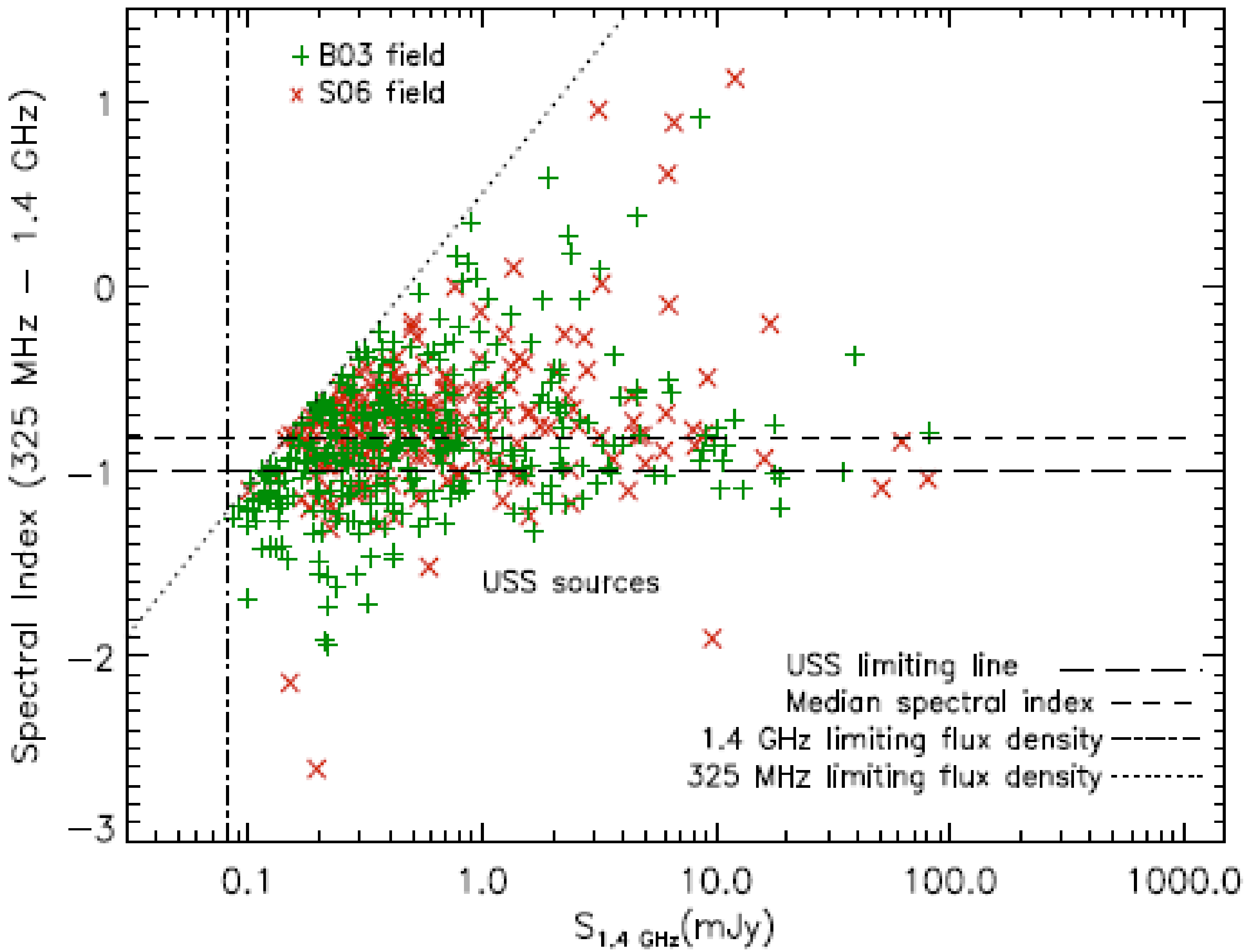
- Powerful radio galaxies at higher redshifts

or

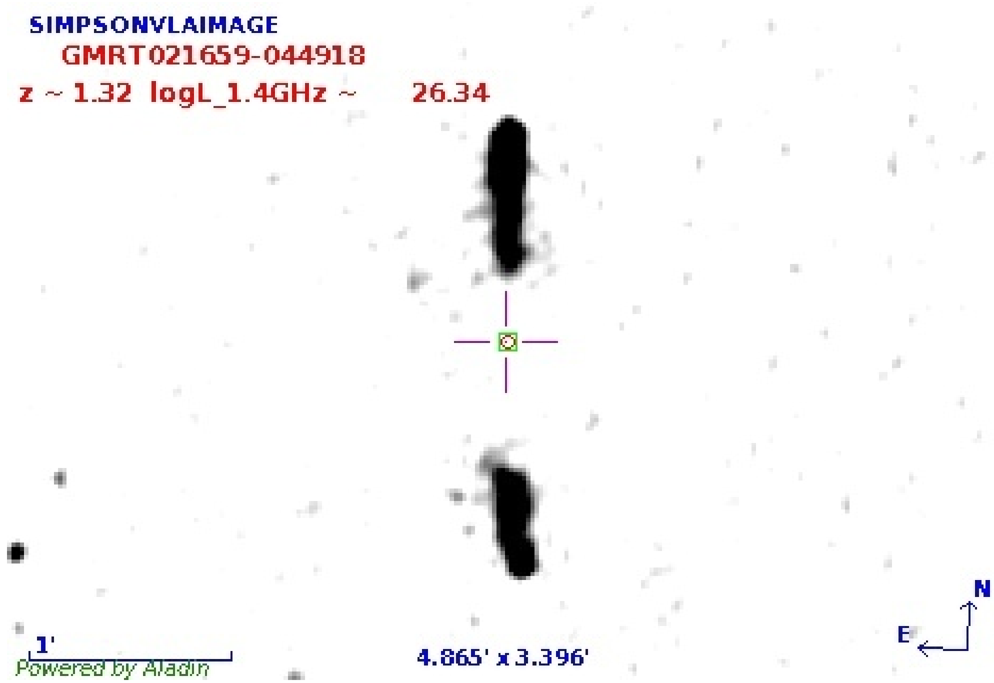
- Population of low-power AGNs at moderate redshifts

or

- Mixed population



HzRGs


SIMPSONVLAIMAGE
GMRT021659-044918
z ~ 1.32 logL_1.4GHz ~ 26.34
1'
Powered by Aladin
4.865' x 3.396'
N
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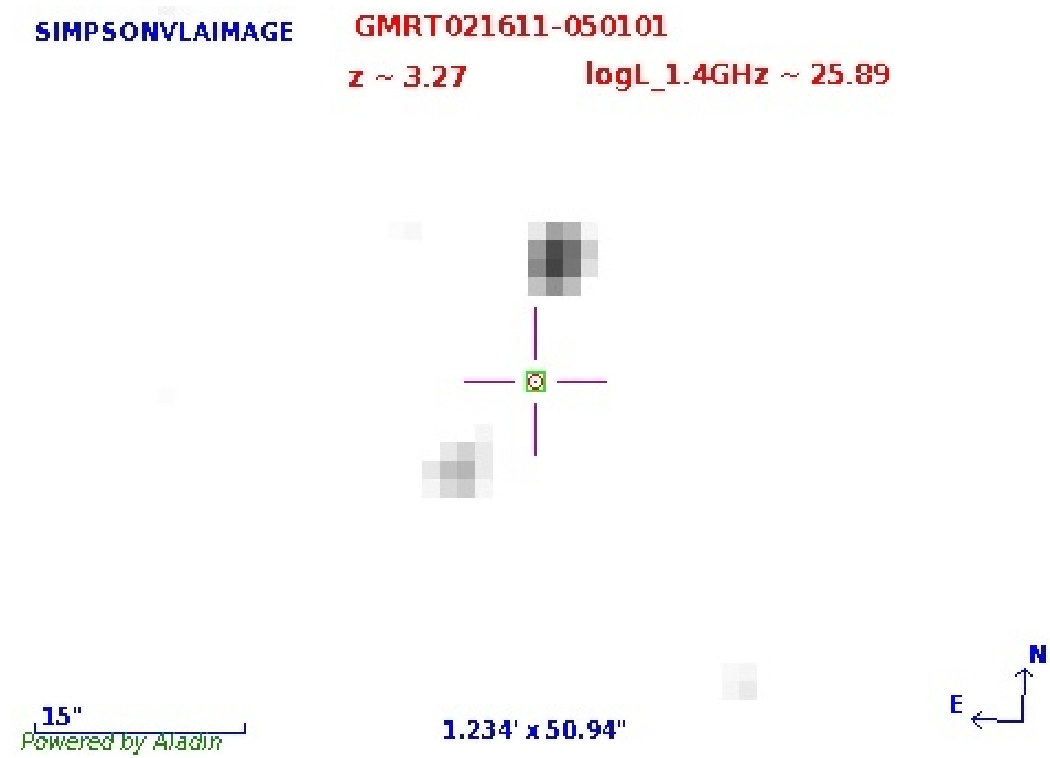
SIMPSONVLAIMAGE
GMRT021611-050101
z ~ 3.27 logL_1.4GHz ~ 25.89
15"
Powered by Aladin
1.234' x 50.94"
N
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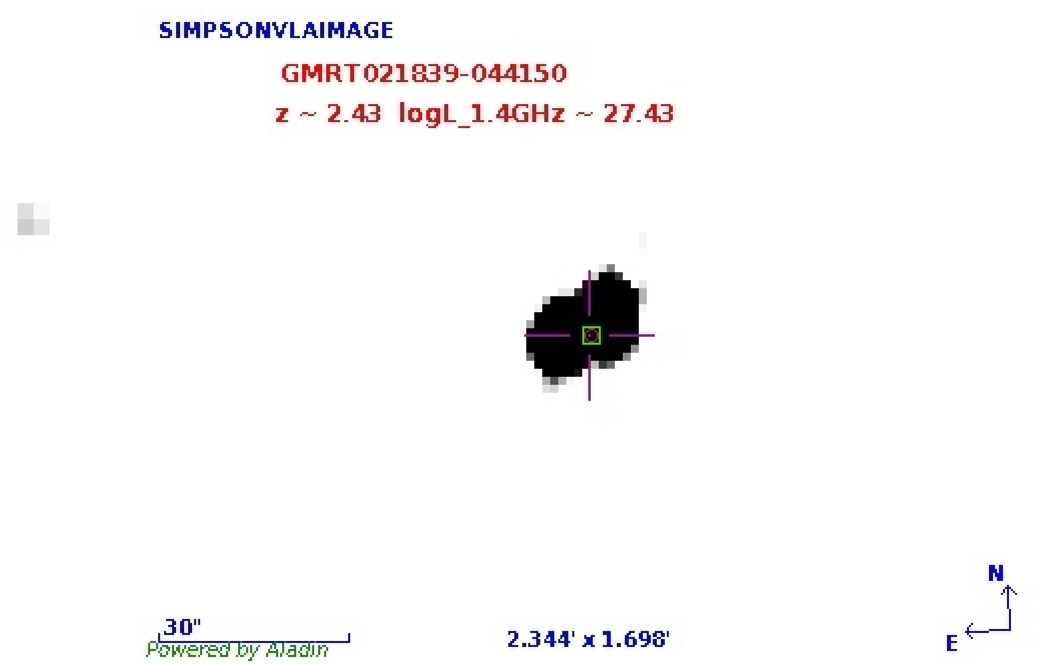
SIMPSONVLAIMAGE
GMRT021926-051535
z ~ 1.46 logL_1.4GHz ~ 25.58
15"
Powered by Aladin
1.703' x 50.94"


SIMPSONVLAIMAGE
GMRT021839-044150
z ~ 2.43 logL_1.4GHz ~ 27.43
30"
Powered by Aladin
2.344' x 1.698'
N
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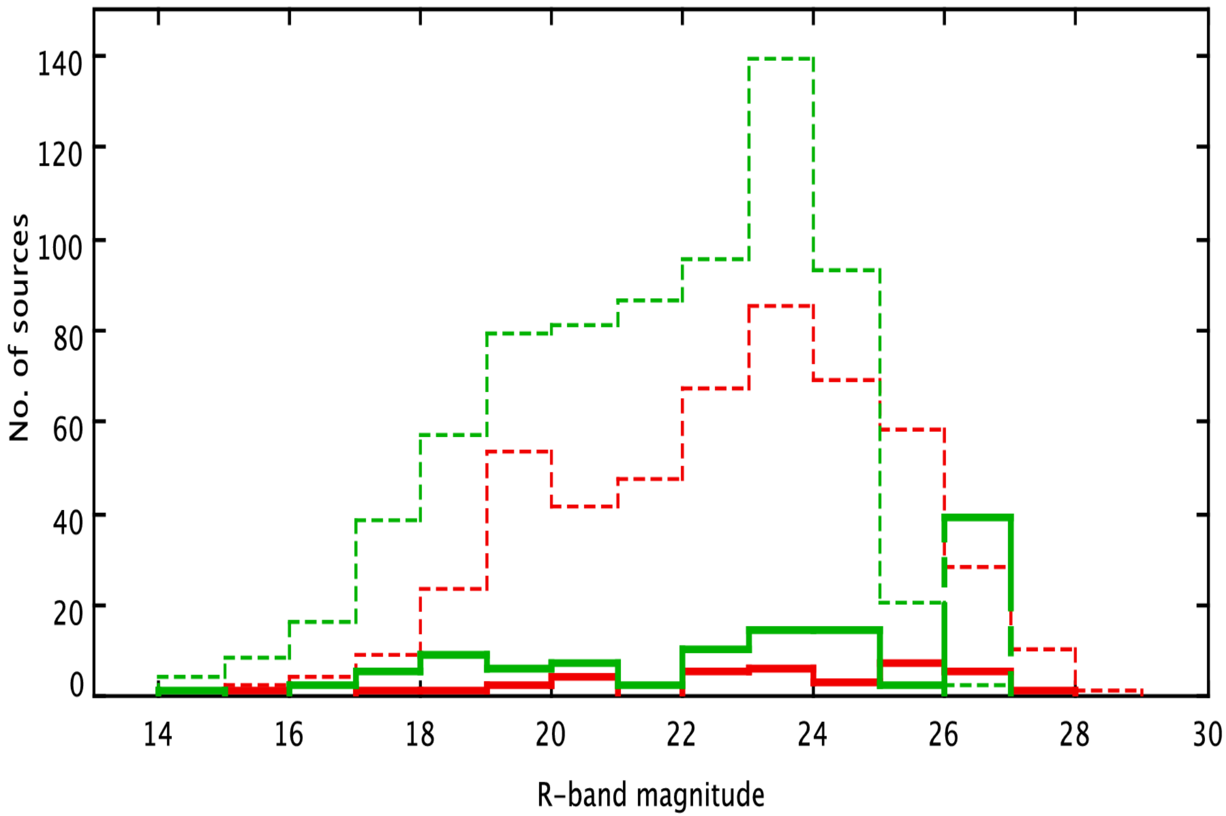
Optical, near-IR Identification rates

	VLA-VVDS	SXDF
	AB mags limits	AB ma[illegible] limits
B	26.5	28.4
V	26.2	27.8
R	25.9	27.7
I	25.0	27.7
Y	25.7	
Z	24.6	
J	24.5	23.7
H	24.0	23.5
K	23.5	23.7



VVDS : optical data limited to I_{AB} ~ 25.0 identify only 65 % USS sources

Optical near-IR identification rates of USS are lower than that for non-USS source

=> USS sources are systematically fainter

SXDF : Deeper optical data (I_{AB} ~ 27.7) identify nearly all USS sources

Young radio loud AGN residing in obscured environments

A significant fraction of our USS sources do have :

- $S_{1.4GHz}/S_{3.6micron}$ similar to SMGs/ULIRGs
- radio loud ($L_{1.4\ GHz}$ ~ 10^{25} – 10^{26} W Hz^{-1})
- unresolved at 1.4 GHz (resolution 6 arcsec)

(compact steep spectrum or GigaHertz peaked spectrum sources)

at z ~ 2, 6 arcsec resolution gives size limit < 50 kpc

A possible scenario :

a compact radio-loud AGN surrounded by vigorous starburst activity.

AGN jets of kpc-scale passing through the dense gas and starburst activity that confine them.

Planned high-resolution radio observations are expected to determine the morphology, physical extent, and brightness temperature of the radio emitting regions