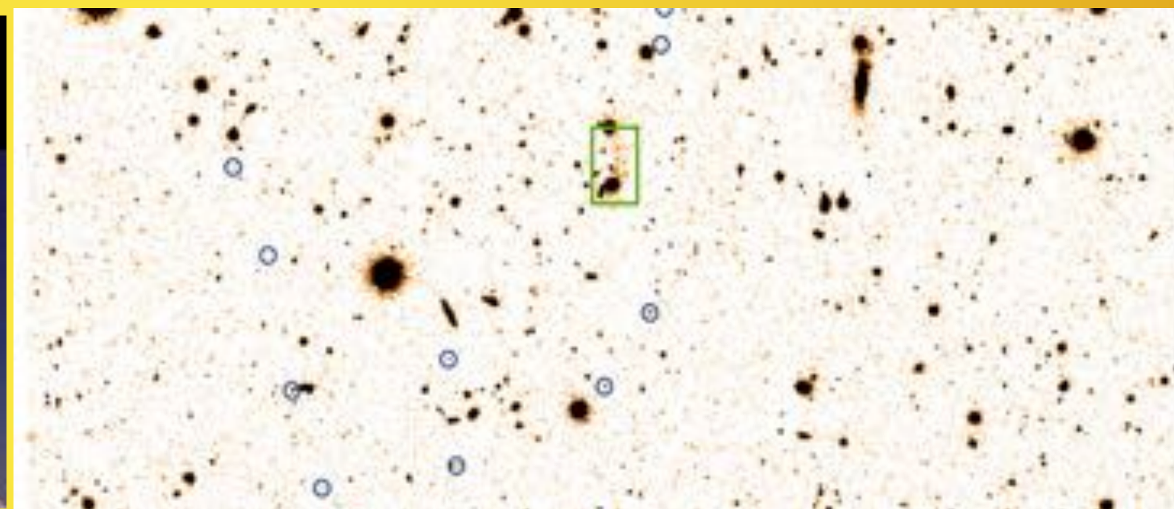
Infrared-Faint Radio Sources in Deep Extragalactic Fields



Veeresh Singh
(PRL, Ahmedabad)

Collaborators : C.H. Ishwara-Chandra, Yogesh Wadadekar, Sandeep Sirothia, Alexandre Beelen, Alain Omont, Jonathan Sievers

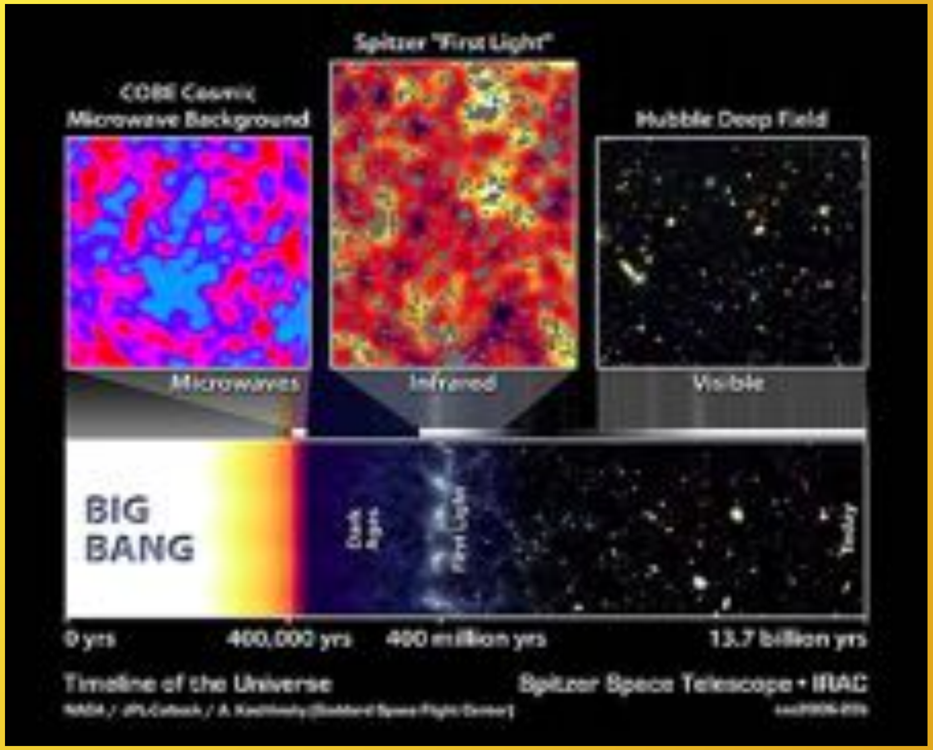
Outline

- Deep and large-area radio continuum surveys
- Science with deep surveys
- GMRT surveys
- Infrared-Faint Radio Sources (IFRSs)
- Search for IFRSs in deep fields
- Implication of the discovery of IFRSs
- Expectations from upcoming surveys

Why do we need deep field surveys?

Allow us to study the evolution of galaxies from the earliest cosmic epochs.
- To map a large volume (~1 Gpc^3) of the high-redshift universe.
- Combination of depth and area is required.

Importance of multiwavelength data



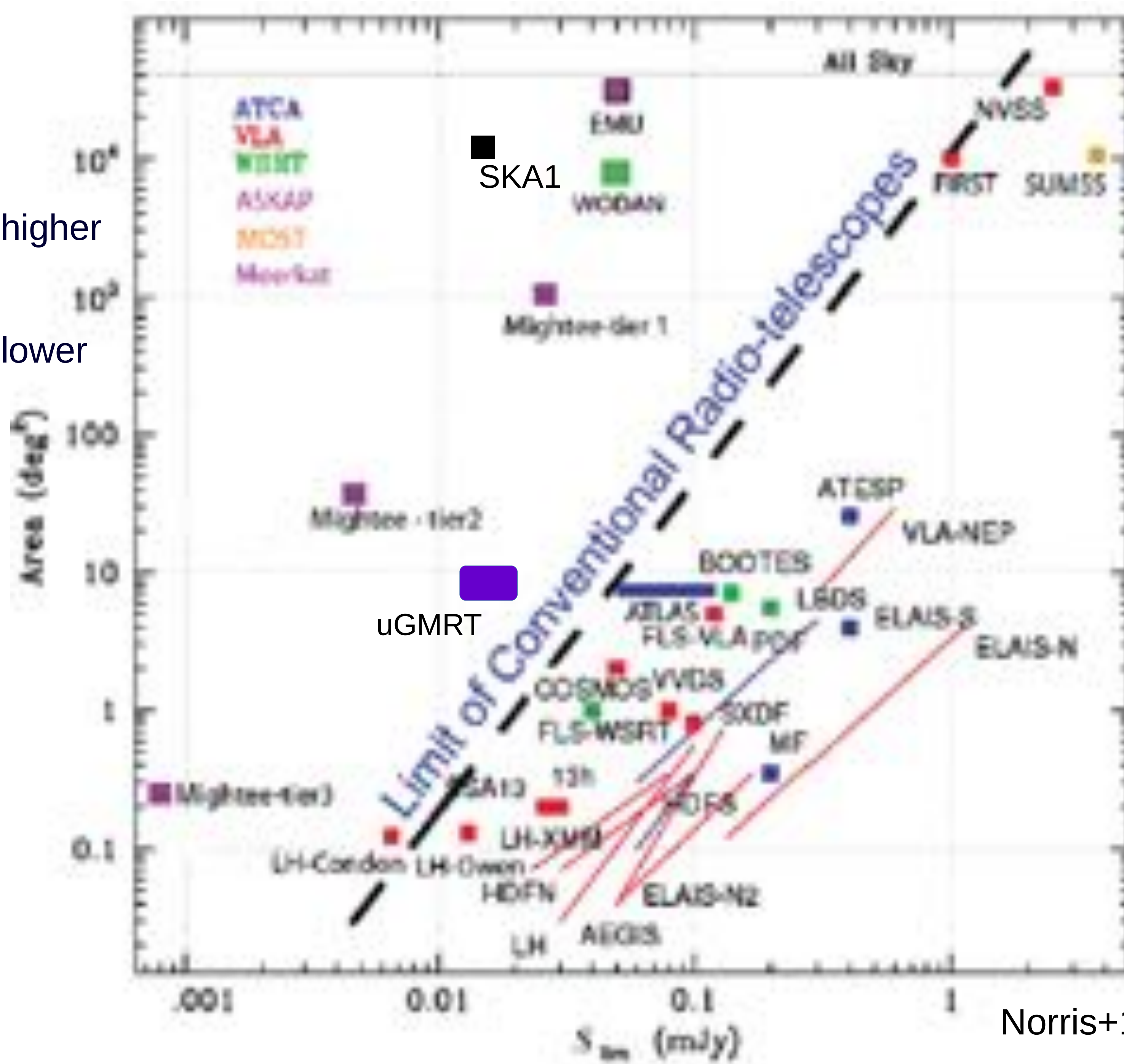
Deep and wide radio continuum surveys

Sensivity :
few order of magnitude higher

Area :
few order of magnitude lower

Deep fields and large area surveys are complementary.

We need both.



Norris+13

Science with deeper radio continuum surveys

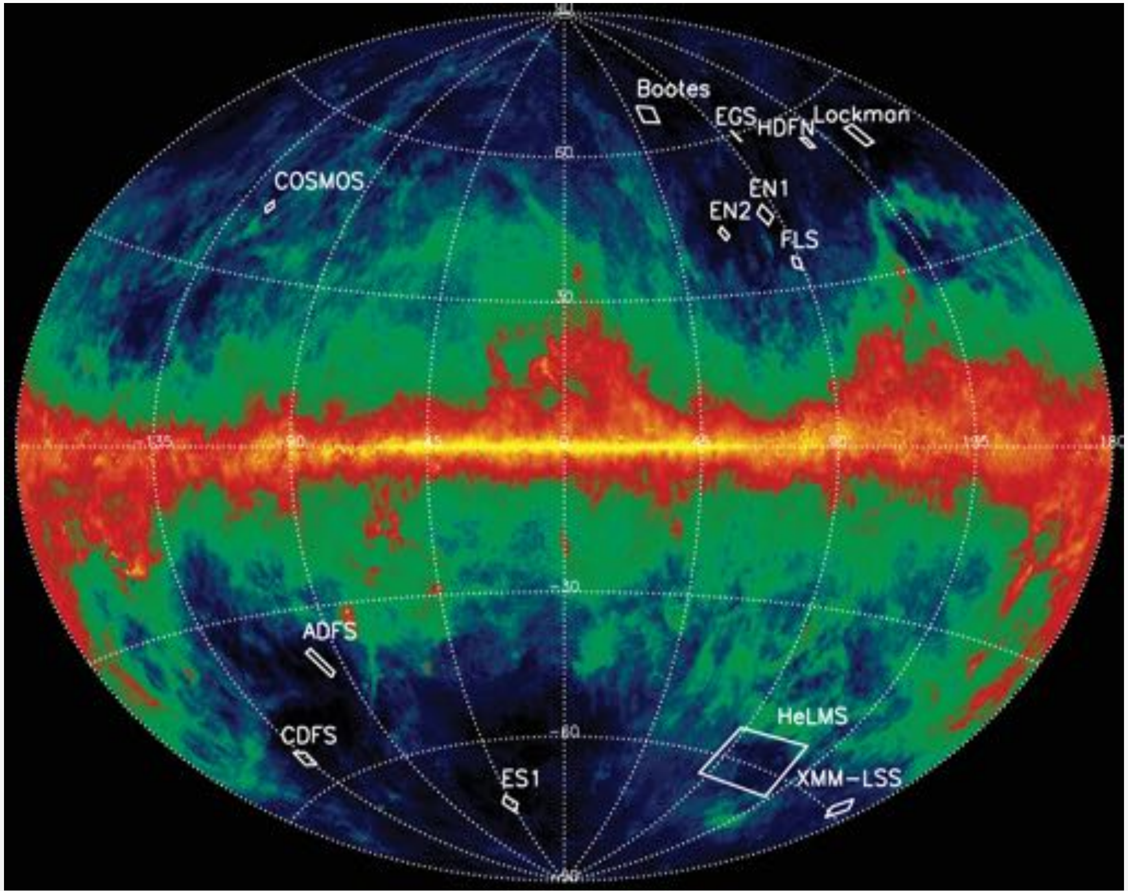
- Cosmic evolution of radio AGN activity at high-z
- Nature of μJy radio population (SFGs Vs. AGN)
- Unveils radio-loud and radio-quiet AGN at high-z
- With rms ~ 10 μJy/b at 1.4 GHz we can detect a radio-quiet AGN of $L_{1.4\ GHz}$ ~ 10^{23} W Hz^{-1} at z ~ 3.
- Powerful radio galaxies at higher redshifts
- AGN hosted in intensely star-forming galaxies (e.g. ULIRGs, SMGs) can be efficiently detected

325 MHz GMRT radio surveys of deep fields

Y. Wadadekar, S. Sirothia, C.H. Ishwara-Chandra, V. Singh, A. Beelen, A. Omont

Deepest low frequency radio survey in the XMM-LSS field

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	



Herschel fields

Multi-λ data available

Multiwavelengths observations in XMM-LSS

VLA-VVDS
(VIMOS VLT Deep Survey)
SXDF
(Subaru XMM-N Deep Field)

Radio : GMRT, VLA

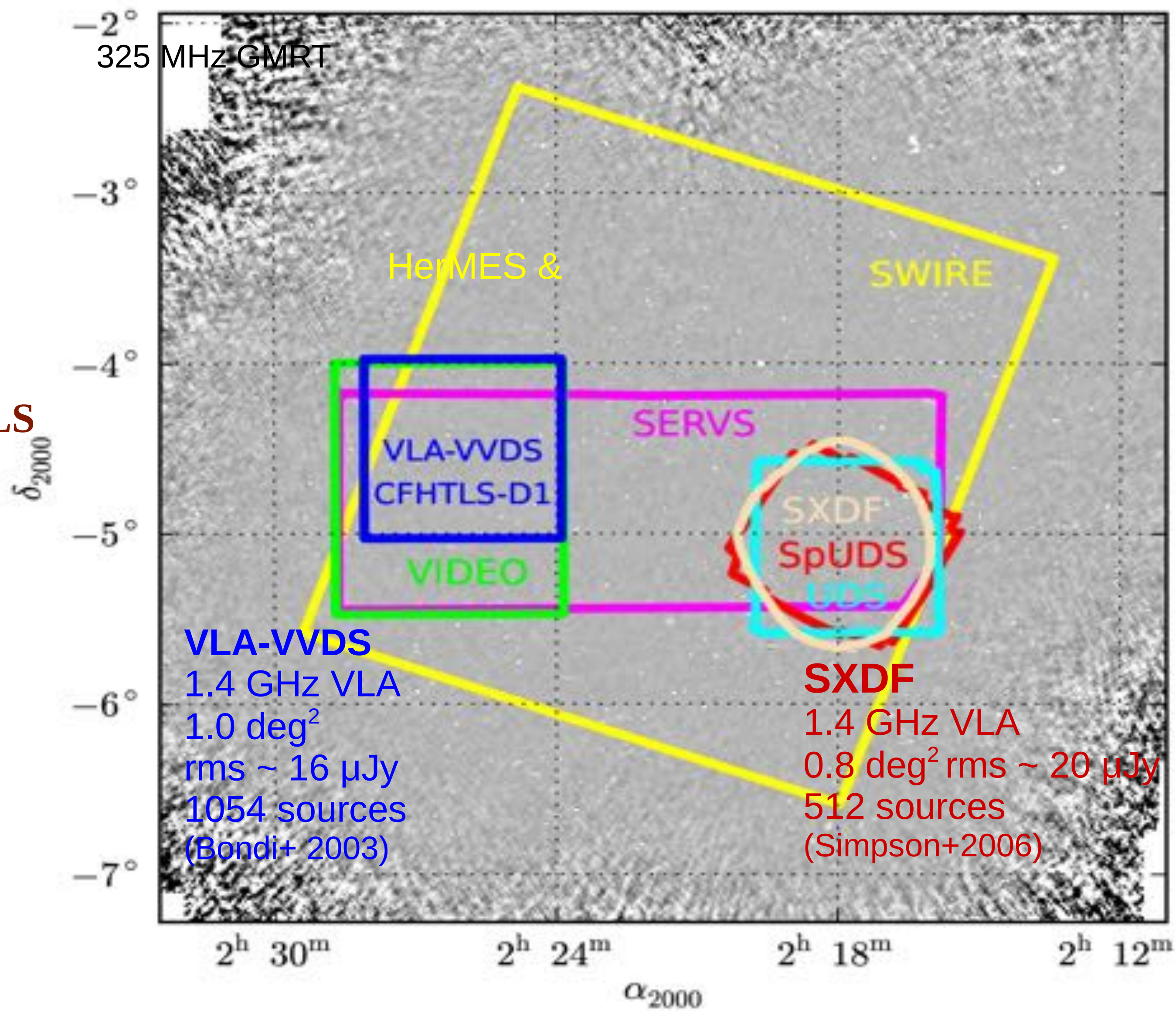
Optical : Subaru, VLT, CFHTLS
(m_R ~ 25, 27 mag)

Near -IR : VIDEO, UKIDSS
(m_K ~ 23, 24 mag)

Mid-IR : Spitzer surveys
rms @ 3.6 μm~ 1.3 – 2 microJy

Far-IR : Herschel surveys
rms@ 250 μm ~ 9 mJy

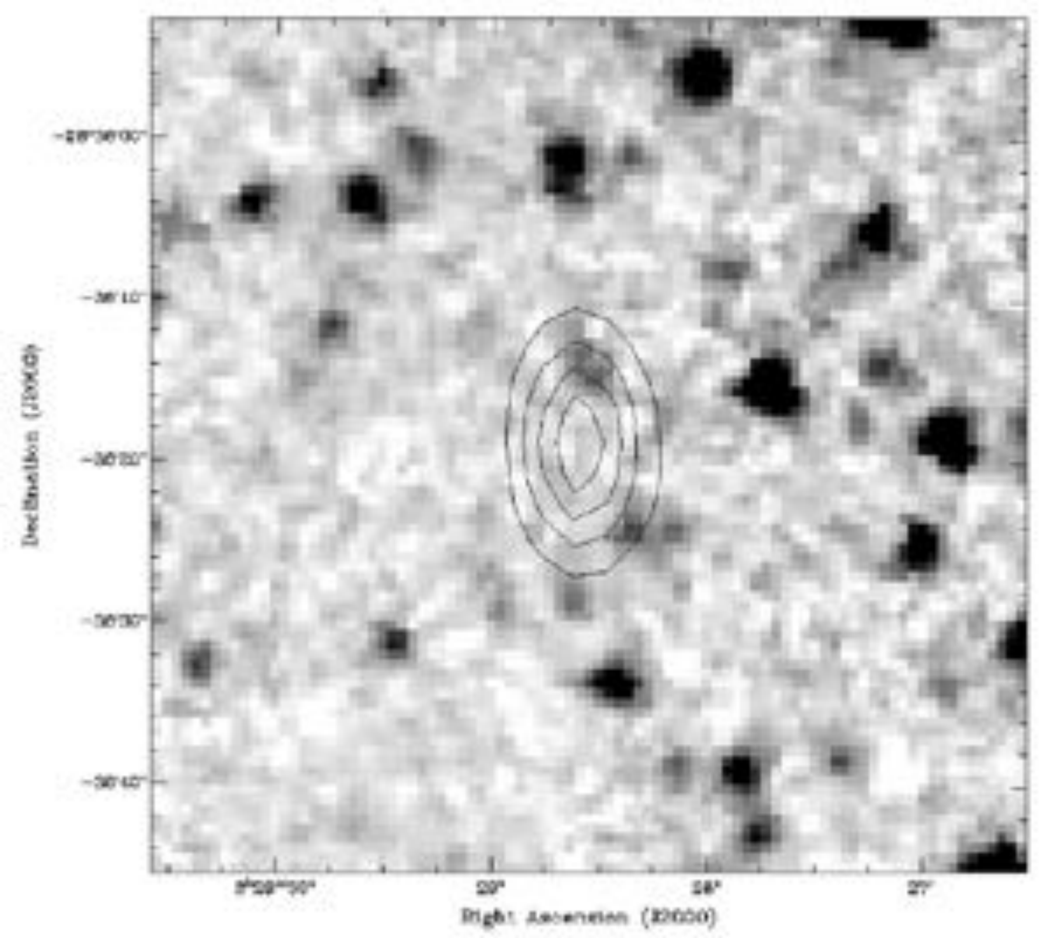
325 MHz GMRT
9 deg^2 rms ~ 150 μJy

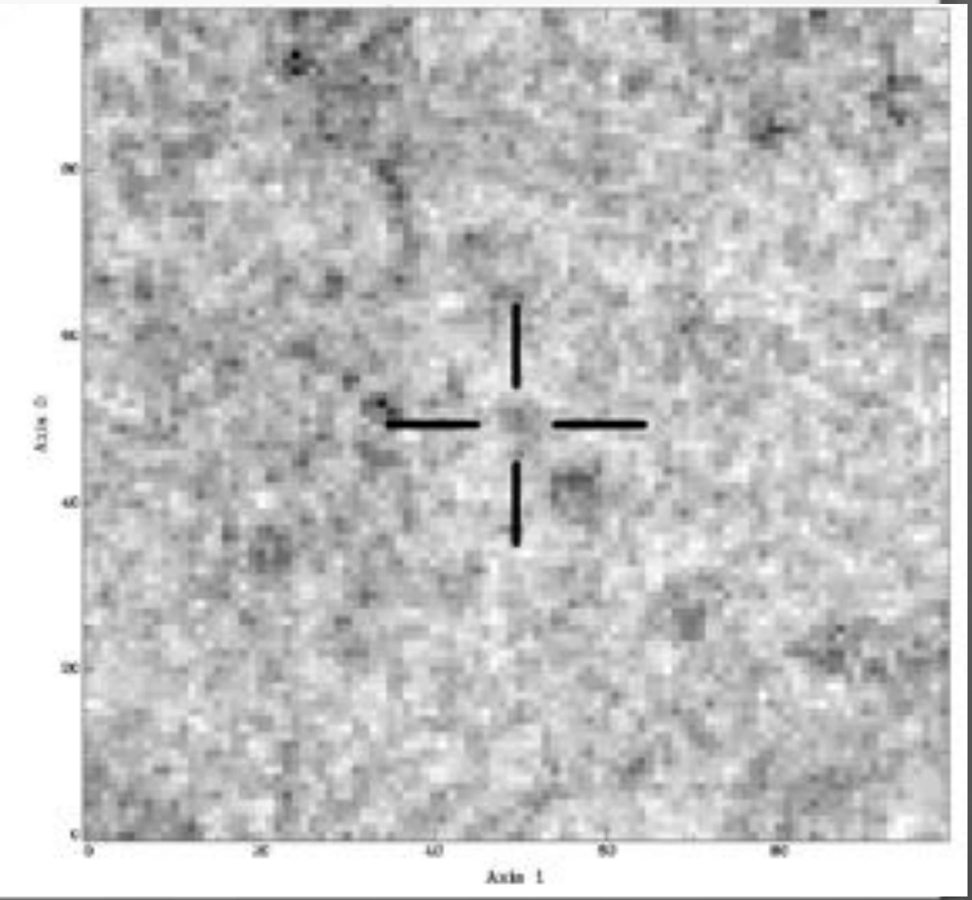


Singh et al.2014

Infrared-Faint Radio Sources (IFRS)

- First reported by Norris et al. 2006
- 22 radio sources in ATLAS with no IR counterpart
- No detection in 3.6 μm stacked image
  (median $S_{3.6\ \mu m}$ gives upper limit 0.2 μJy)





Nature of IFRSs?

- IFRSs were unexpected
- SED of a SFG or an AGN at (z) < 2, was expected to give rise 3.6 μm flux higher than the SWIRE detection limit
- Nature of IFRSs has been hard to determine
- Nearly all the information on them has been obtained at radio wavelengths
- Spectroscopy is difficult because the hosts are optically faint
- Well below the SWIRE detection threshold (Norris et al. 2006)

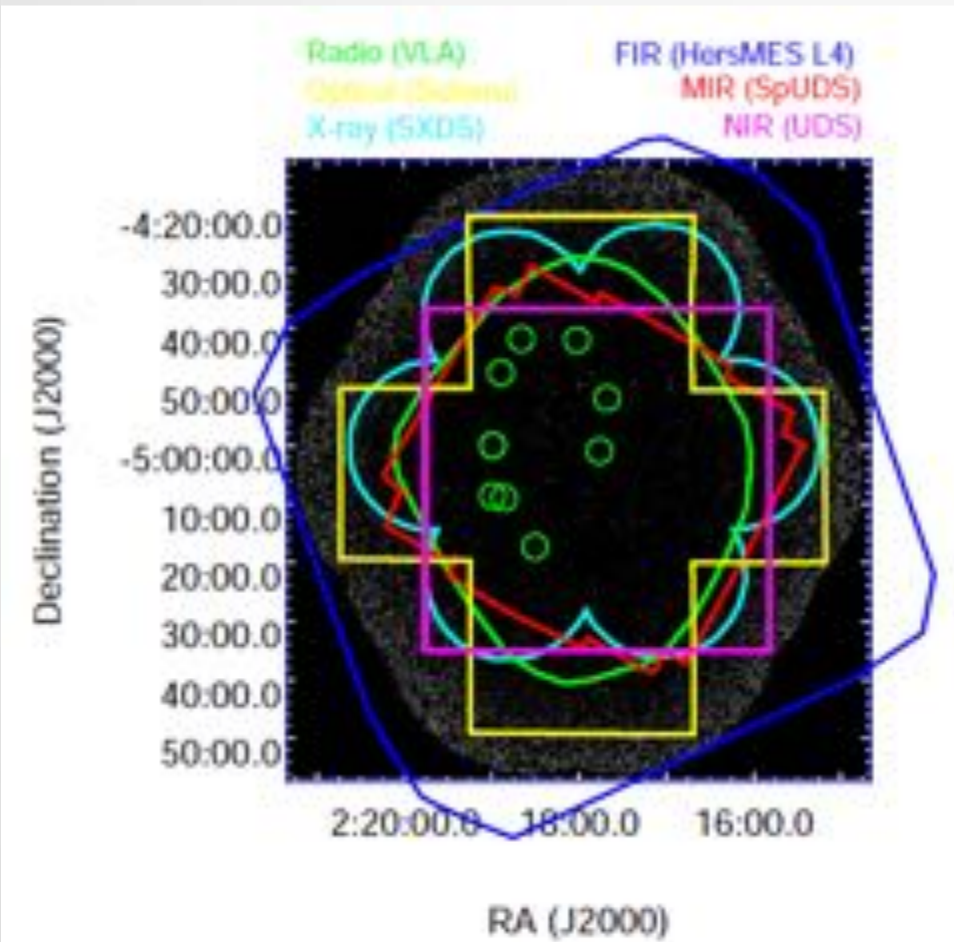
Infrared-faint radio sources (IFRSs)

- In last one decade IFRSs searches in deep fields have resulted 100 sources (Herzog+2016)
- Challenges : Faint or no optical, IR counterparts
- Majority of IFRSs lack redshift estimates
- For example, Zinn+2011 compiled a catalogue of 55 IFRSs (in CDFS, ELAIS-S1, xFLS, and COSMOS fields), although without redshift estimates.
- Herzog et al. (2014) carried out Very Large Telescope (VLT) observations and measured spectroscopic redhsifts of only three IFRSs at z = 1.84, 2.13, and 2.76.

IFRSs in the SXDF and VLA-VVDS

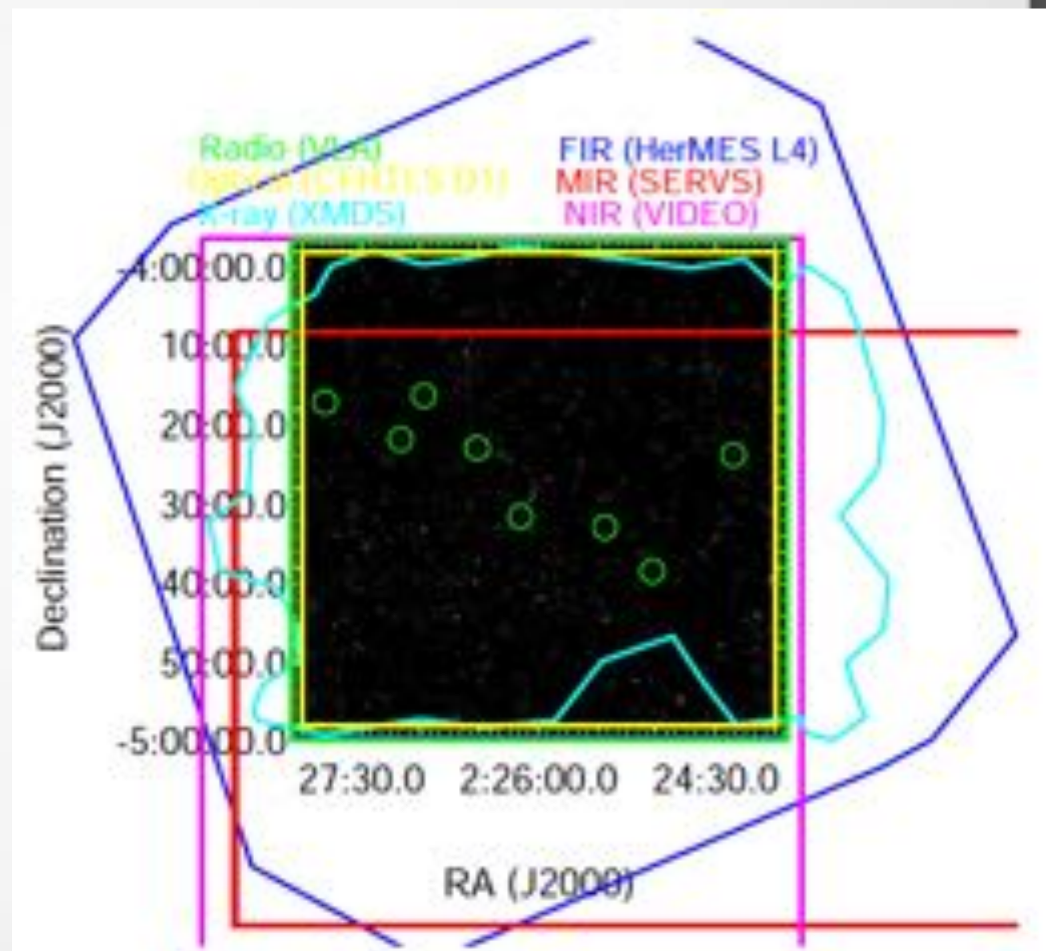
Deep Multiwavelength data are available in both fields.

512 radio sources (5σ ~ 100 μJy) in 0.8 deg^2



Subaru X-ray Deep Field (SXDF)

1054 radio sources (5σ ~ 80 μJy) in 1.0 deg^2



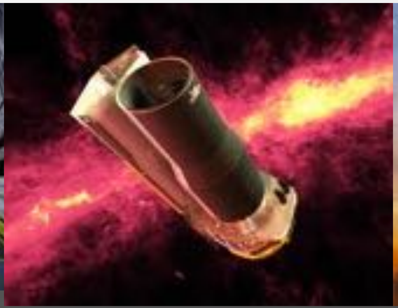
VLA - VIMOS VLT Deep Survey (VLA-VVDS)

Singh et al. 2016

Multiwavelength data

Band	Telescope	Depth (5σ)
Radio		
1.4 GHz, 610 MHz, 325 MHz	VLA, GMRT	100, 275, 750 µJy
Optical		
B, V, R, I', z'	Subaru, VLT, CFHTLS - D1	27.7, 25.9, 26.1 (R-band)
Near - IR		
J, H, K	UDS, VEDIO	24.2, 23.8 (K-band)
Mid-IR		
3.6, 4.5, 5.8, 8.0, 24 µm	Spitzer	1.3, 2.0 µJy at [3.6]
FIR		
100, 160, 250, 350, 500 µm	Herschel	11.2 mJy [250]
X-ray		
0.5 – 10 keV	XMM-N	$1.0 – 0.6 \times 10^{-16}$ erg cm^{-2} s^{-1}



Identification and Selection criteria for IFRSs

Identification method:

- Search 3.6 μm counterparts of radio sources by cross-matching catalogues
- Select the sources that meet following selection criteria
- Radio sources with no detected 3.6 μm sources will have only flux ratio limits

Selection Criteria

(i) $S_{1.4\ GHz} / S_{3.6\ \mu m} > 500$ (extreme radio to IR flux ratio)

& $S_{3.6\ \mu m} < 30\ \mu Jy$ (eliminate low-redshift radio-loud AGNs)

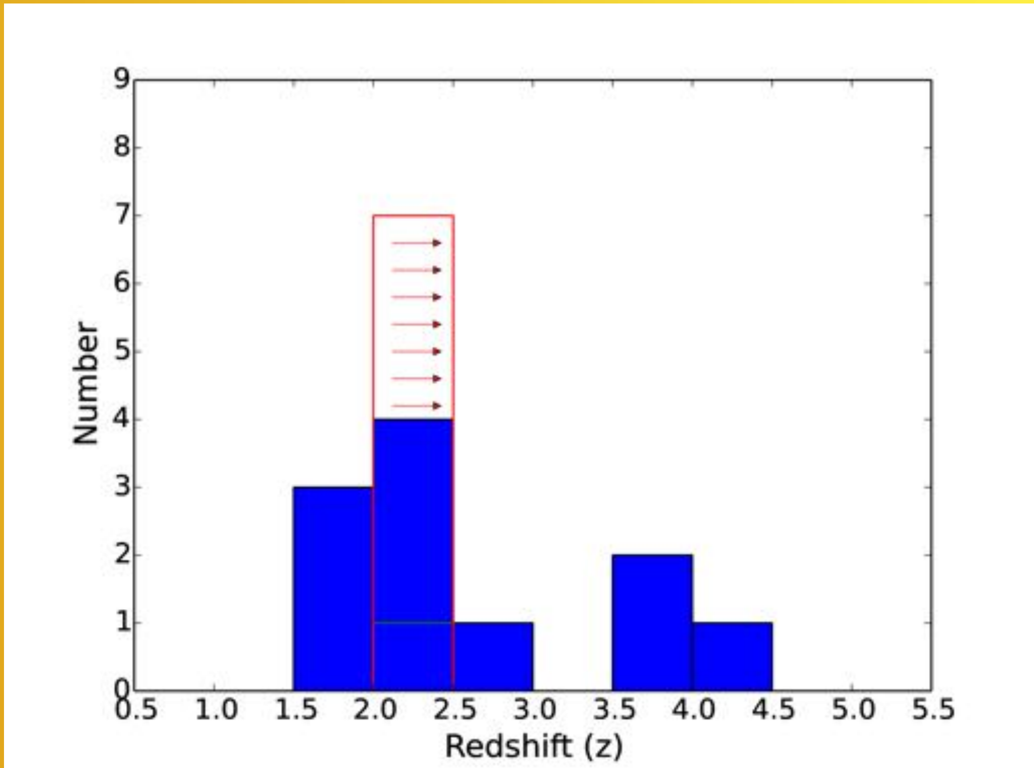
(ii) Candidate : Radio sources with undetected IR counterpart

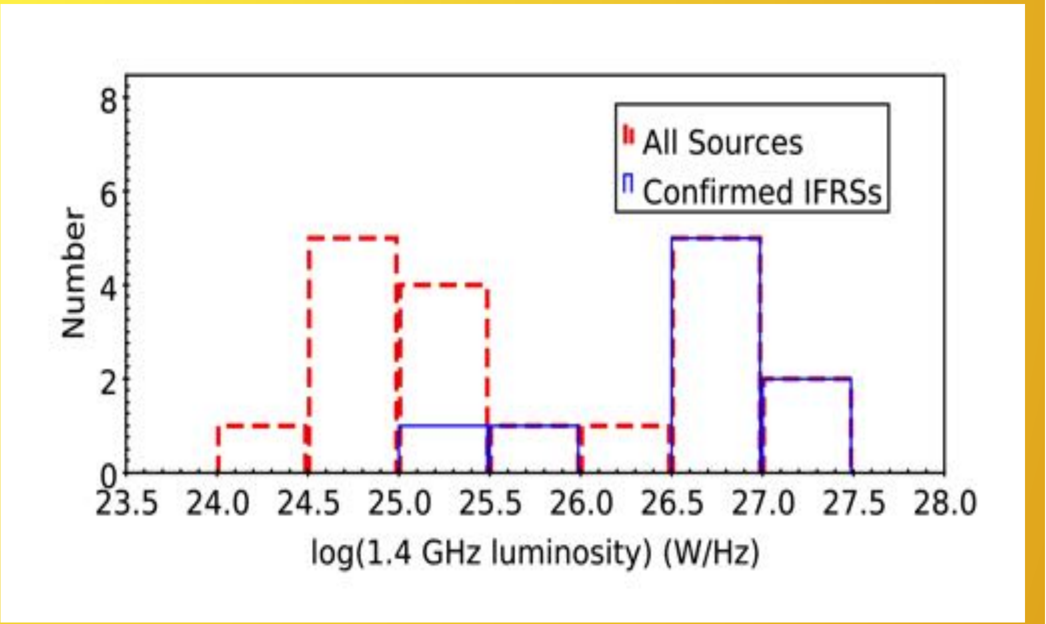
These are arbitrary limits but include almost all known IFRSs.

9 confirmed and 10 candidate IFRSs in 1.8 deg^2

Nature of IFRSs

- High-redshift radio sources (z ~ 1.68 – 4.3; and z > 2.0)
- Radio-loud AGN

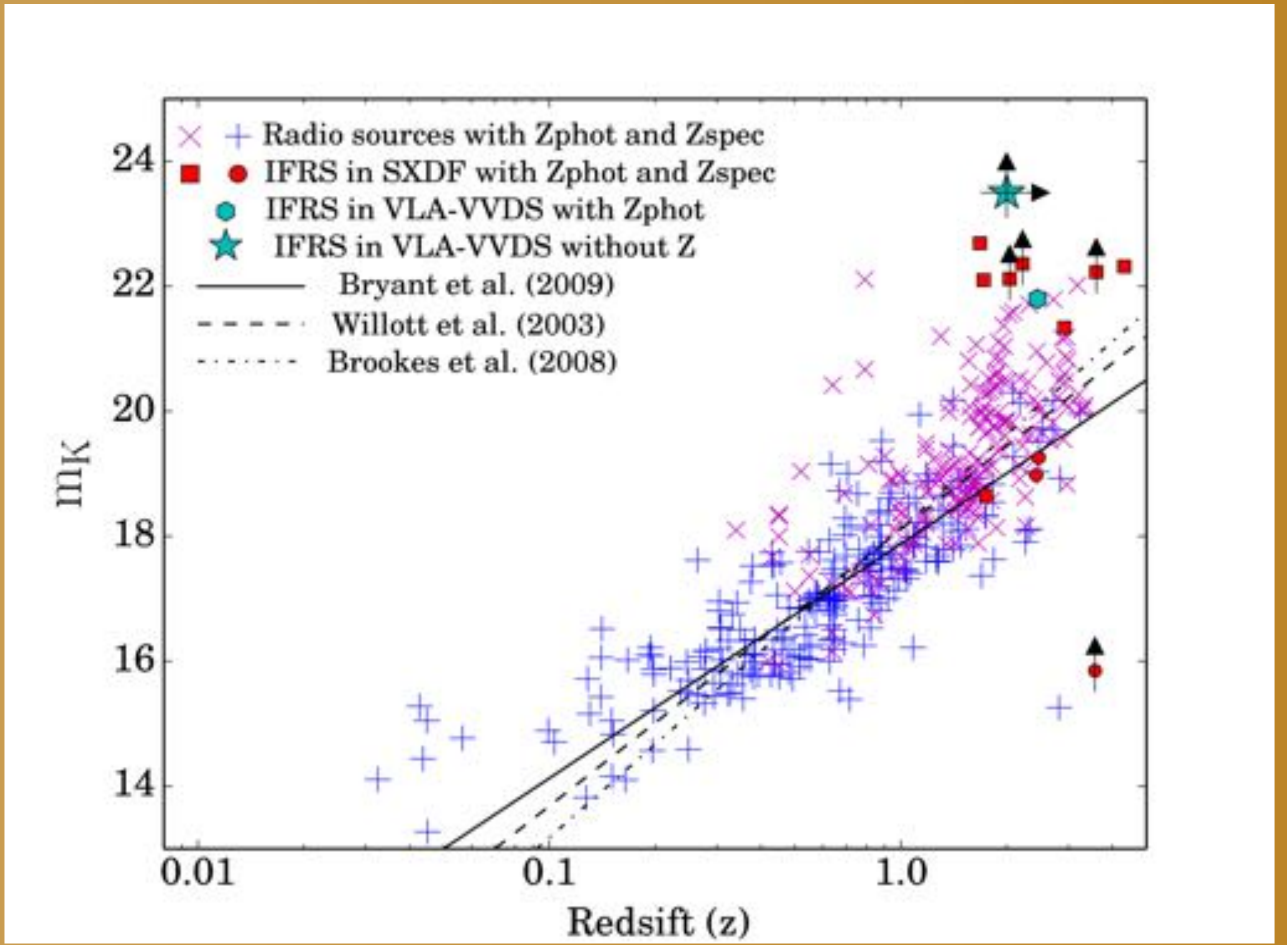




IFRSs without redshifts

- All IFRSs in the SXDF have redshifts estimates
- While all except one IFRSs in the VLA-VVDS field lack redshift estimates.

Crude estimates of z from K-z empirical relation



K-band limiting mag 23.8
=> IFRSs are at z > 2.0

IFRS without redshifts

Redshifting the SEDs of known radio sources

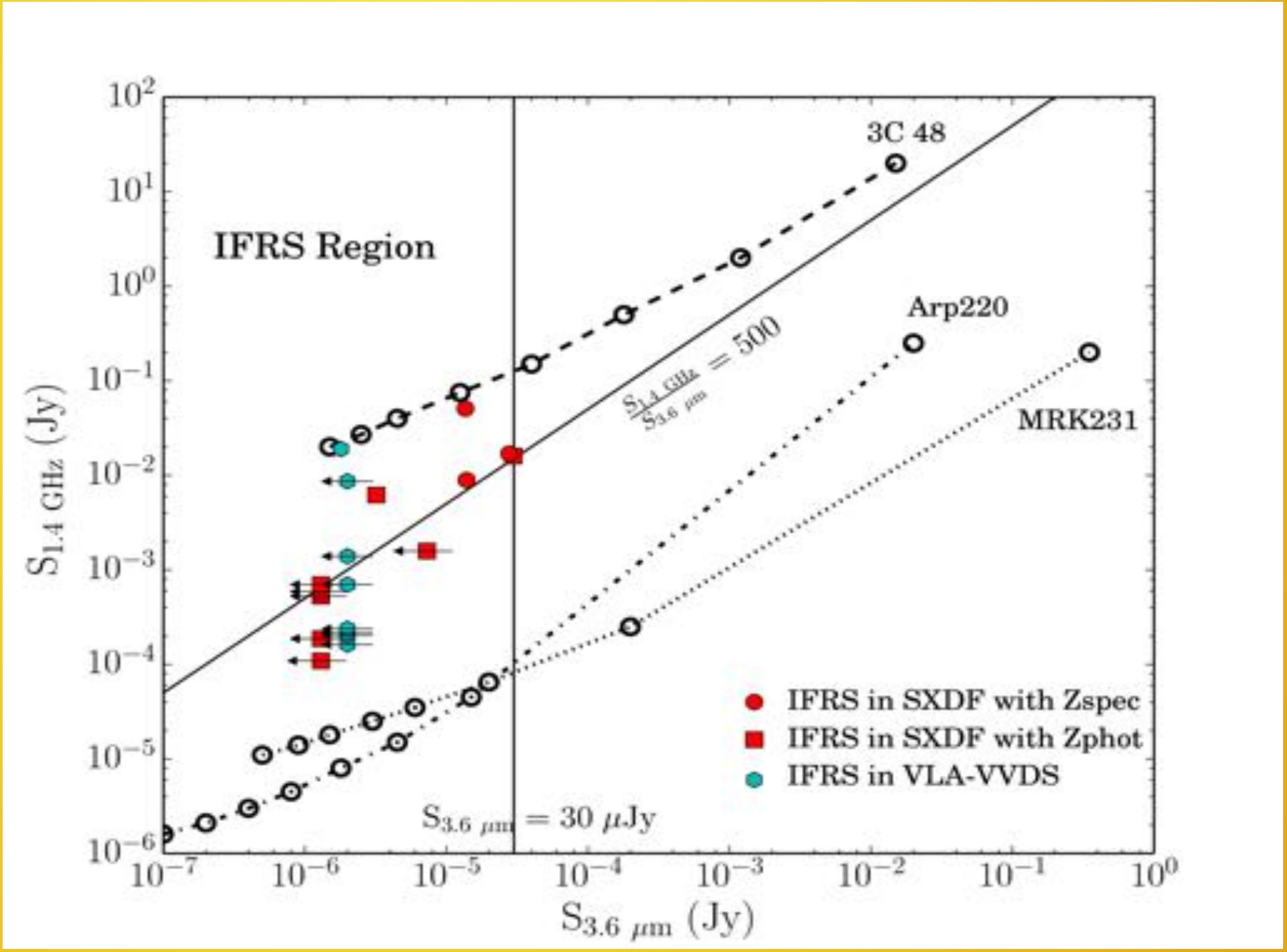
- Change in $S_{1.4\ GHz}$ and $S_{3.6\ \mu m}$ of known radio sources w.r.t. *z*
- $S_{1.4\ GHz}$ and $S_{3.6\ \mu m}$ of IFRSs can constrain redshift

3C 48 : radio-loud AGN

Mrk 231 : LLAGN

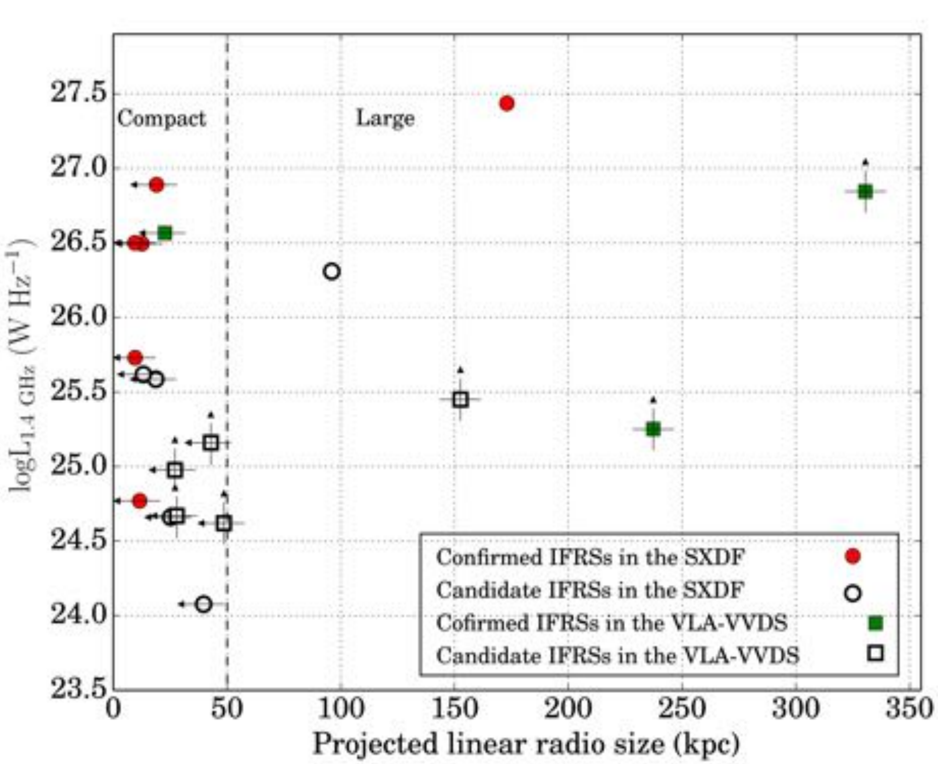
Arp 220 : Starburst galaxy

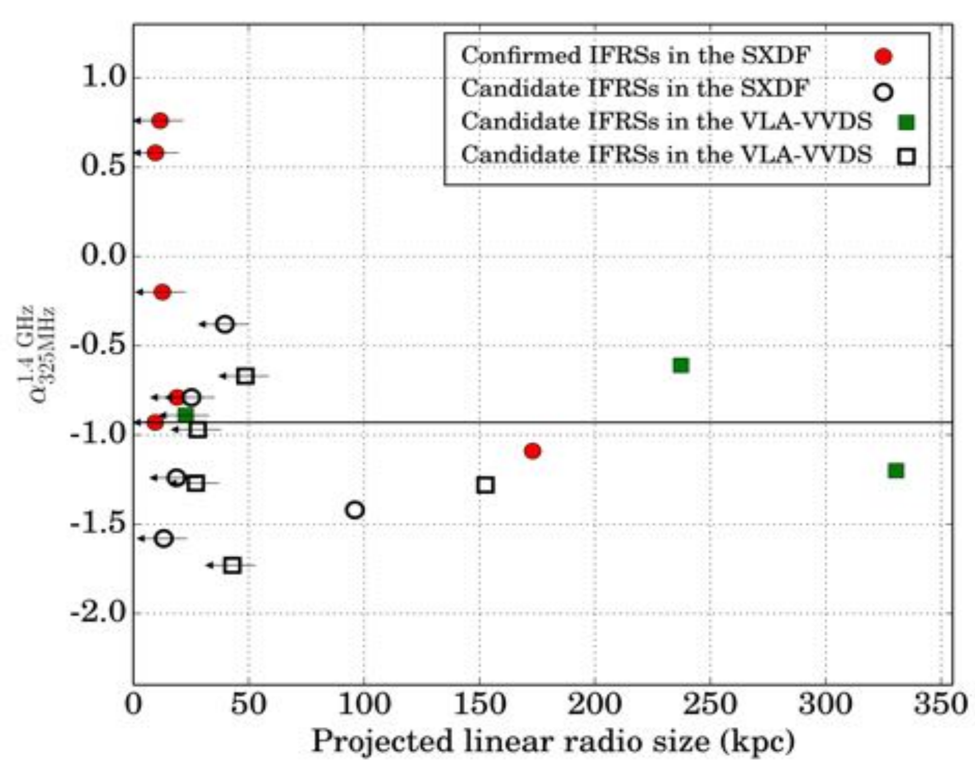
3C 48-like sources will become IFRS only at redshift of z > 3



Nature of IFRSs

- Inhomogeneous population
- Mostly compact but some extended sources
- Extended sources are relatively more powerful and show steep spectra (typical FR II radio galaxies)
- Compact IFRSs show flat/inverted spectra as well
- May constitute Compact Steep Spectrum (CSS) sources and Giga-hertz Peaked Spectrum (GPS) sources => young radio sources
- Candidate IFRSs mostly show steep spectrum => high-z sources





Multiwavelength counterparts

- The r-band magnitudes are widely distributed and ranges from 23.5 to 28.6 with the median of $\sim$ 26
- Only 03/19 show detection at 24 µm Spitzer/MIPS
- Only 01/19 detected at 250 µm Herschel/SPIRE
- Only one detected in X-ray (2 – 10 keV) band

IFRSs in dusty-obscured galaxies?

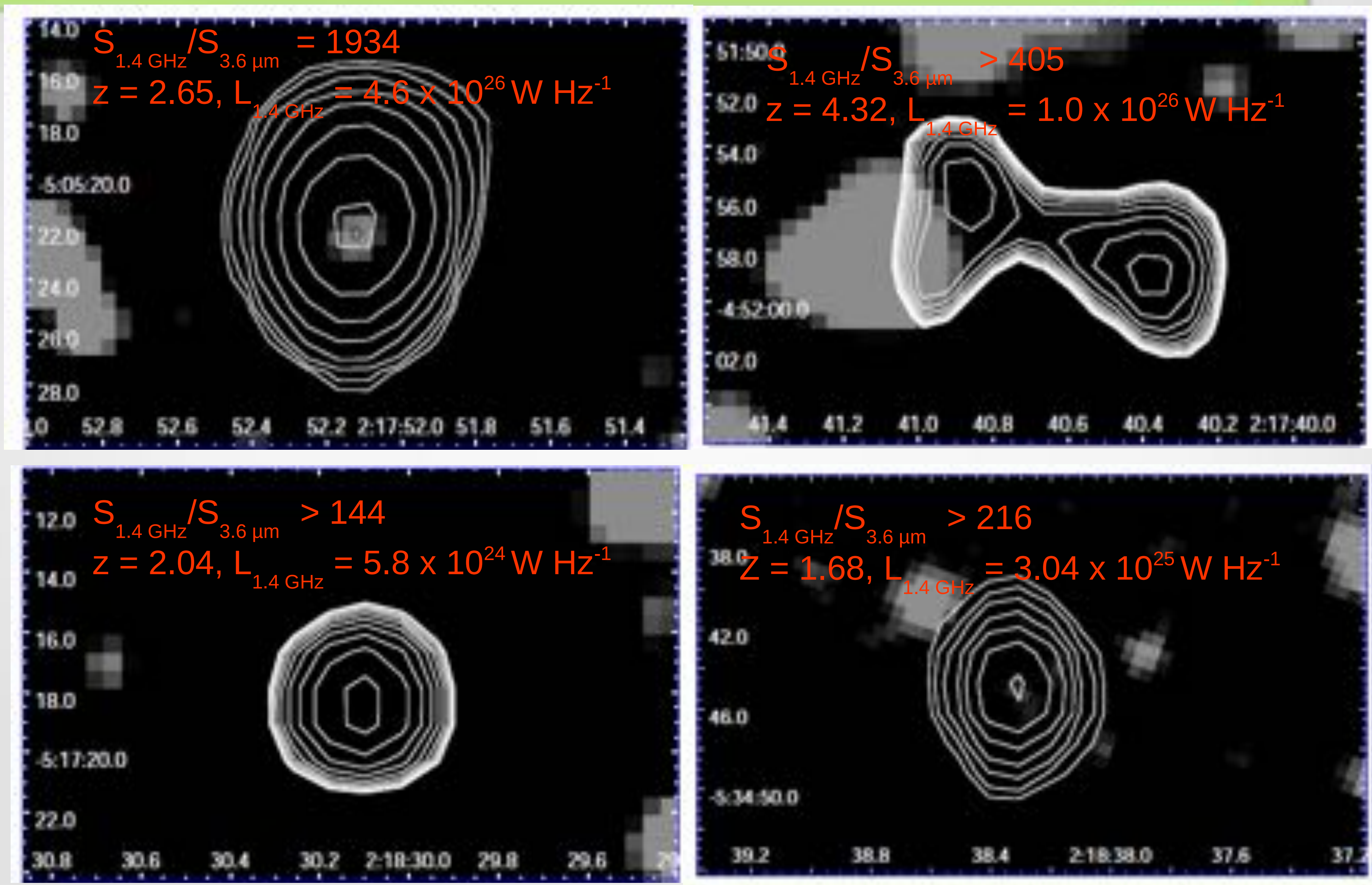
- Dusty-Obscured Galaxies (DOGs) are faint in optical but bright in MIR.
- Optical to MIR color ($m_{r\,-}$ [24]) of a fraction of IFRSs is similar to dusty-obscured Galaxies ($m_{r\,-}$ [24] > 7.5).
- Non-detection in X-ray may indicate AGN hosted in DOGs

Nature of IFRSs

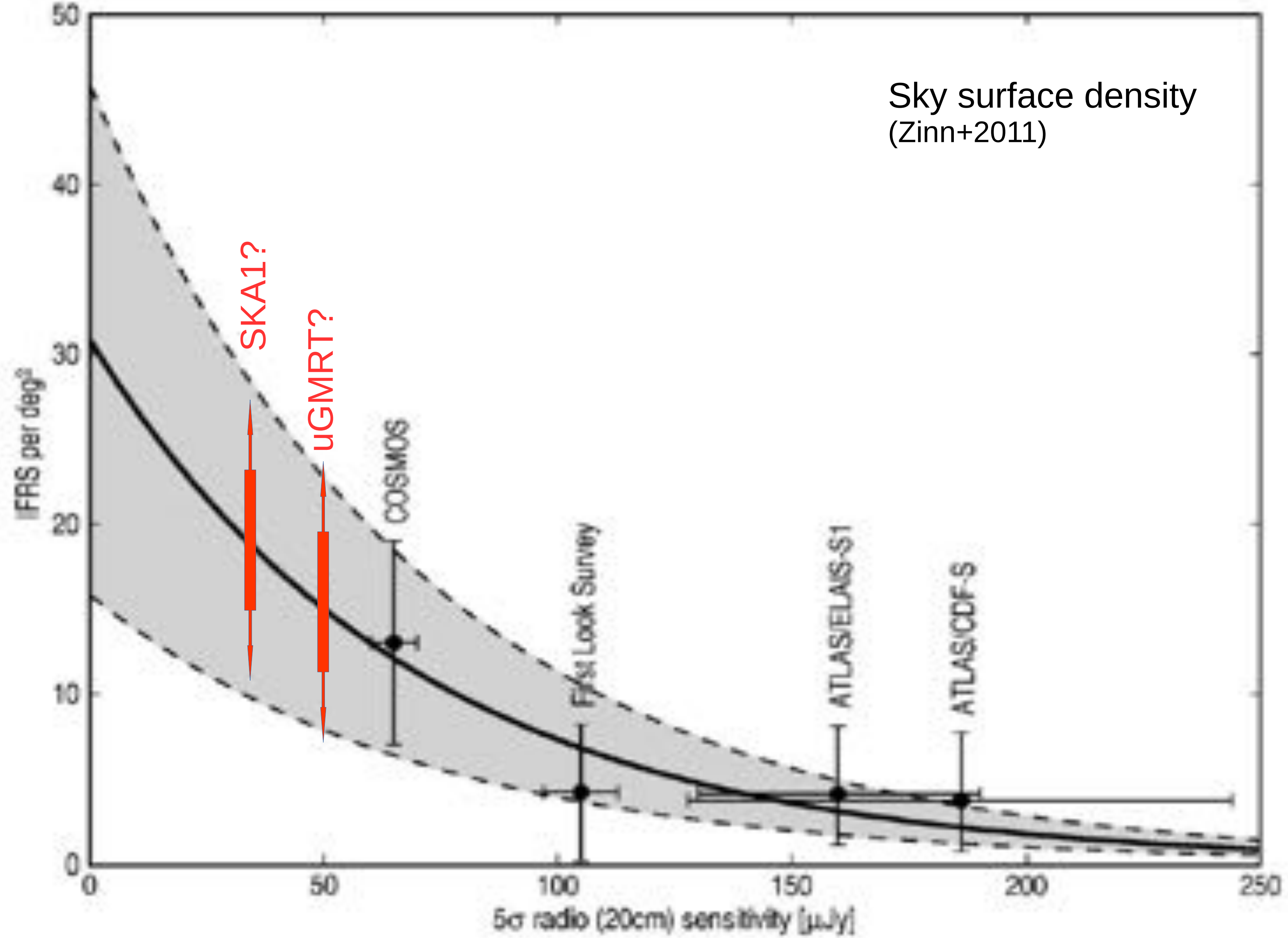
- Dwarf galaxies that host a radio-loud AGN
  (observationally unknown, and theoretically unlikely)
- Moderate-redshift radio-loud AGN with heavy dust extinction
- High-redshift radio-loud AGNs
- Radio lobes of unidentified radio galaxies
- Pulsars
- Unknown enigmatic objects

A gallery of IFRSs:

Unresolved point radio sources
Some shows double lobe structures



How many IFRSs we can expect in a survey?



IFRS sky surface density is much higher than that of powerful radio galaxies.

IFRS: Implications

- Increased AGN source counts
- Compton-thick AGN (required to explain X-ray background)
- a population of AGN-driven objects at very high redshifts ($z > 5$) places several constraints on the formation scenario of SMBHs
- The Millennium Simulation (Springel et al. 2005), to date the largest cosmological simulation probing ΛCDM cosmology, contains only one massive halo at $z = 6.2$, a candidate for quasar sufficiently bright to be observed by the SDSS

Summary

- Using deep radio continuum and auxiliary multiwavelength data we unveil the population of moderately radio-loud AGN at redshifts 1.7 – 4.3
- IFRS are most likely high-z radio loud AGN
- Deep radio continuum survey can find new/missing population of AGN
- Corresponding deep MW data are needed.

Thank you

SKA surveys will reveal more IFRSs

P. Kharb, D.V. Lal, V. Singh et al. 2016 (SKA science)

- We have submitted observing proposal to obtain deepest continuum radio surveys (10 μJy rms at 1.4 GHz) in ELAIS-N1.
  (V. Singh, Ishwara-Chandra, Y. Wadadekar, P. Kharb)

- Pathfinder surveys for Square Kilometre Array (SKA) surveys

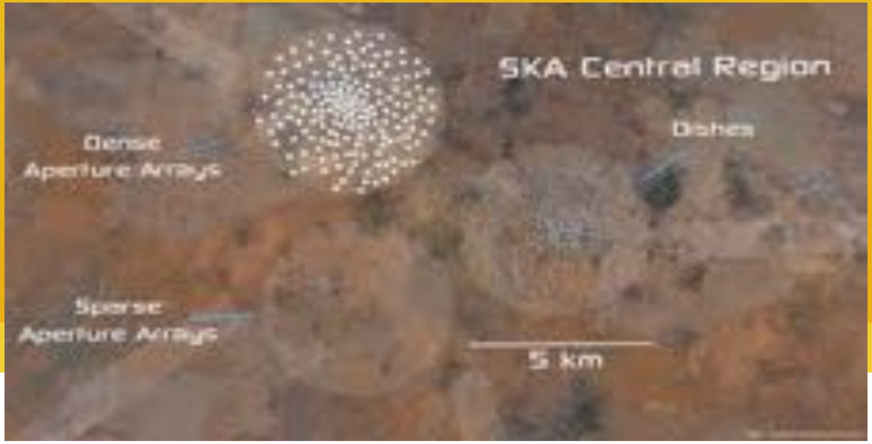
✓ Seemless frequency coverage from 120 MHz to 1500 MHz

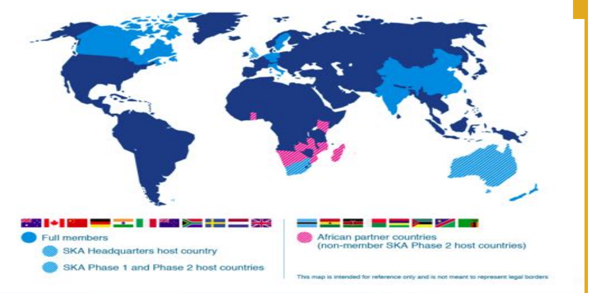
✓ Increased instantaneous bandwidth of 400 MHz

✓ Imaging sensitivity improvement factor ~ 2.5

✓ Improved dynamic range

✓ Next best will be SKA-I





Square Kilometre Array

World's largest, most sensitive radio telescope

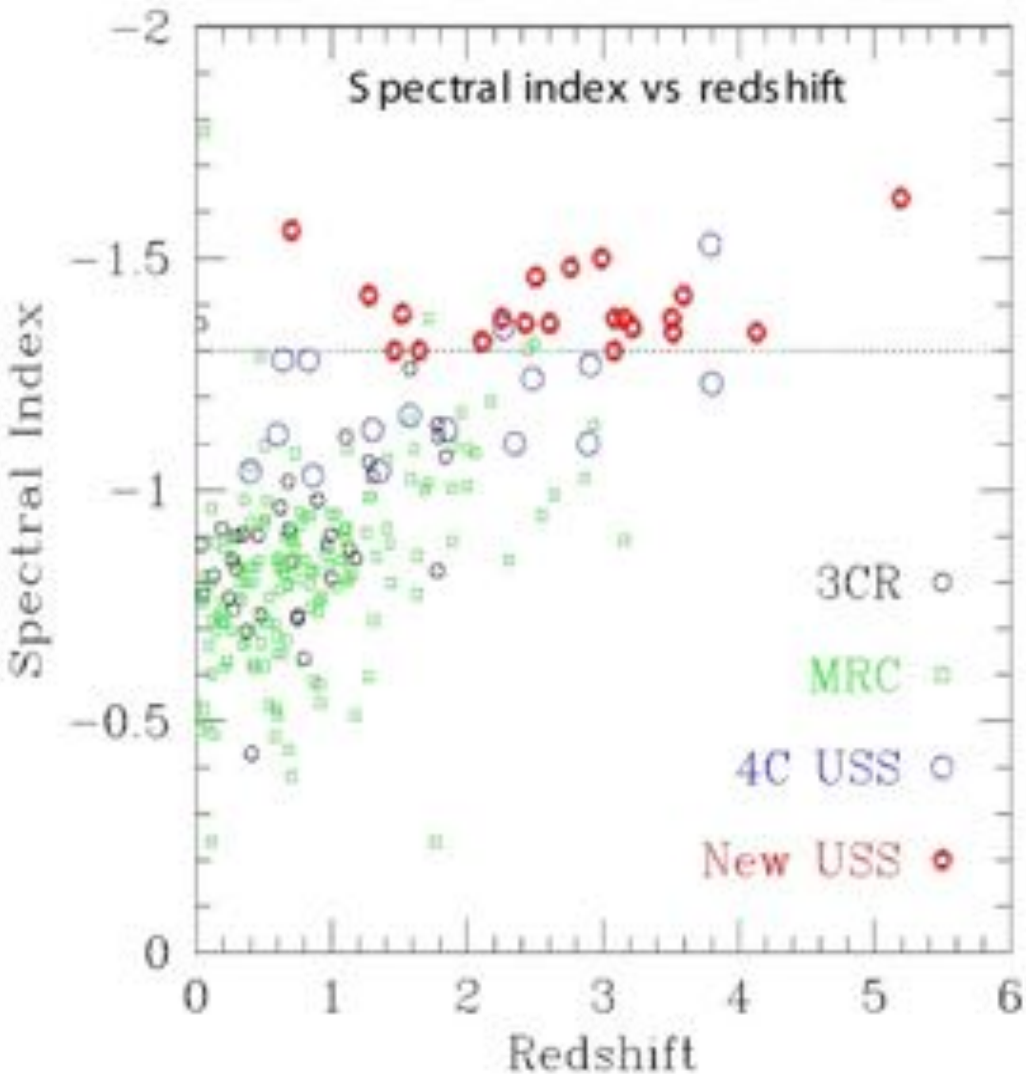
Thousands of linked dishes/antennas across Australia, NZ and Southern Africa

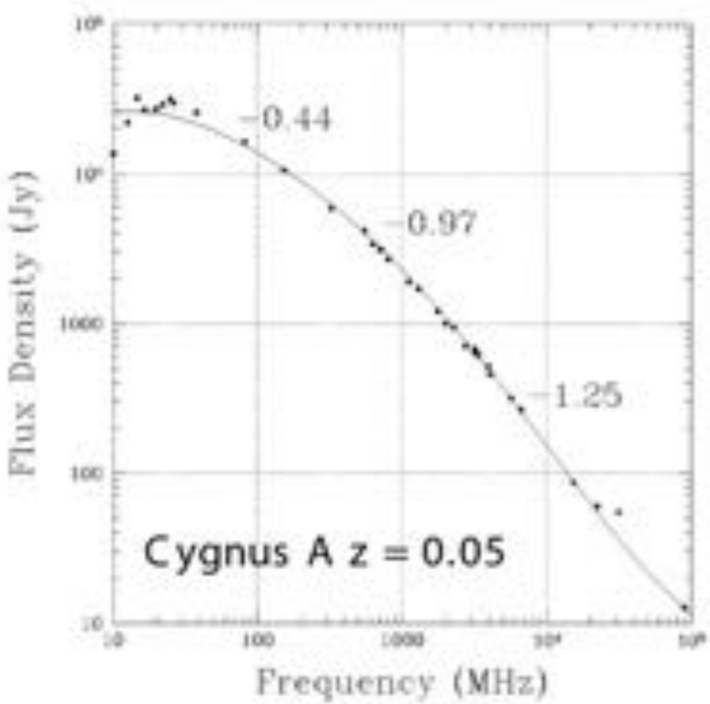
Combined collecting area of 1 km^2 (1 million m^2)

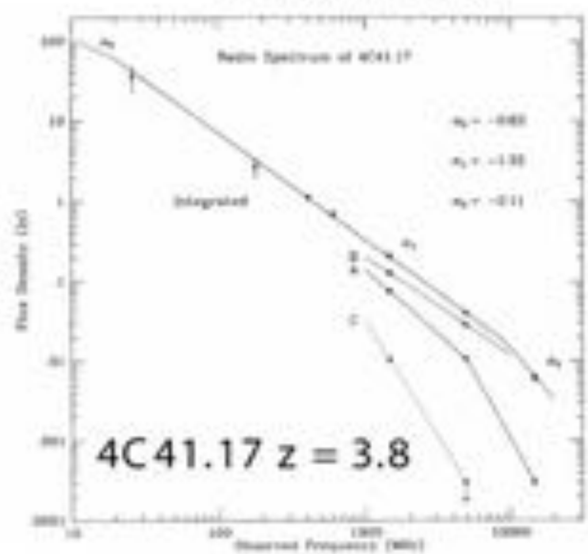
Funded by consortium of 10 countries, est. cost over £1b

IFRSs without redshifts

- Steep radio spectral indicies suggest IFRSs to be high-z sources
- Ultra steep spectrum sources (α < -1.0) preferentially selects high-z sources (Singh et al. 2014)







Miley & DeBreuck 2008

Nature of IFRSs

An example of Compact Steep Spectrum radio source in dusty galaxy

VLBI observations of IRAS F00183−7111

- Ultra Luminous InfraRed Galaxy
  L_{bol} ~ 9 x 10^{12} L_{sun} (z ~ 0.33)

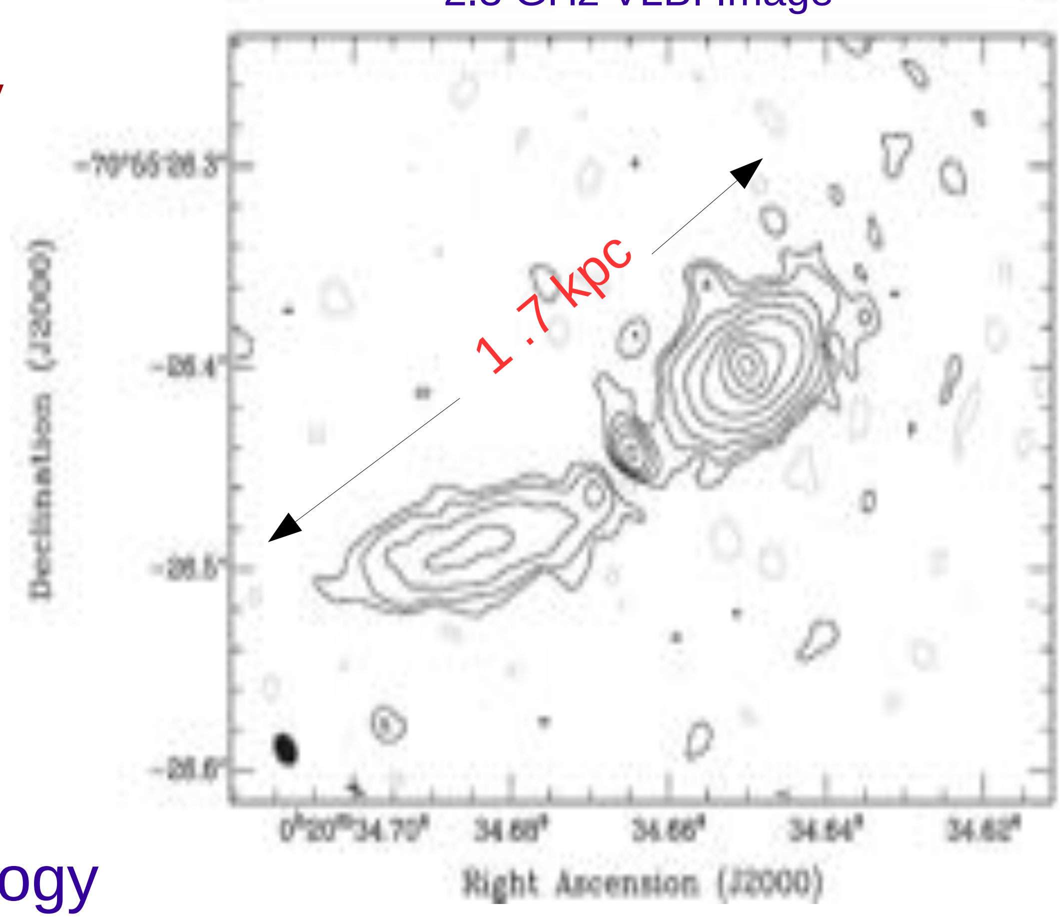
- Heavily dusty galaxy
  Large FIR excess
  $L_{FIR}/L_{B\text{-}band}$ ~ 360

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

- A compact double-lobe morphology

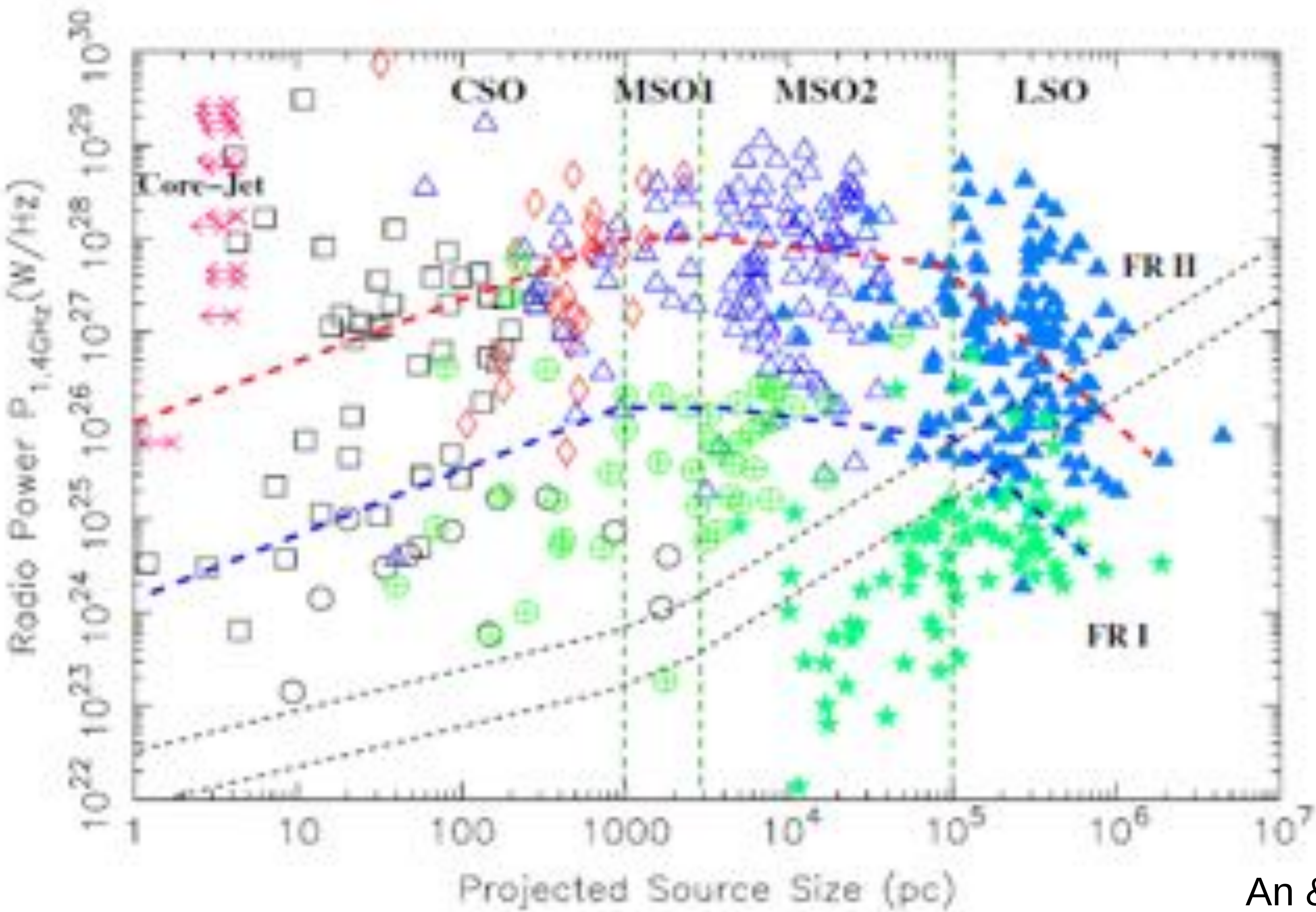
- Radio size : 1.7 Kpc

2.3 GHz VLBI Image

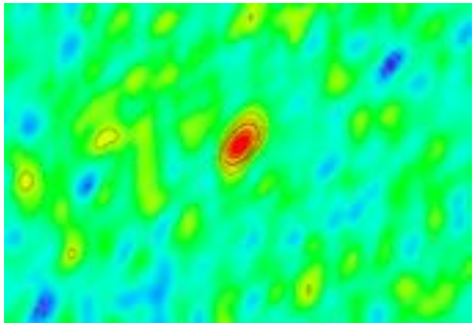


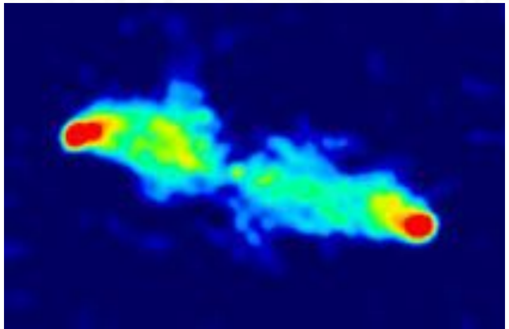
Norris et al. (2012)

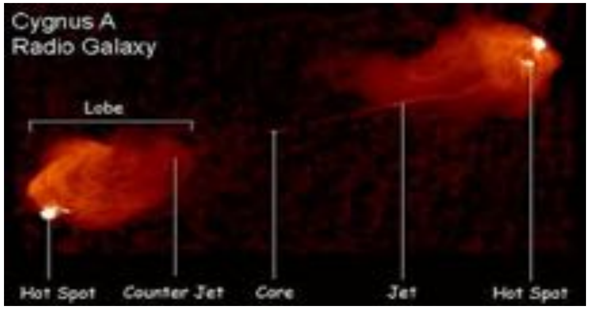
IFRSs can be young radio galaxies at high-z



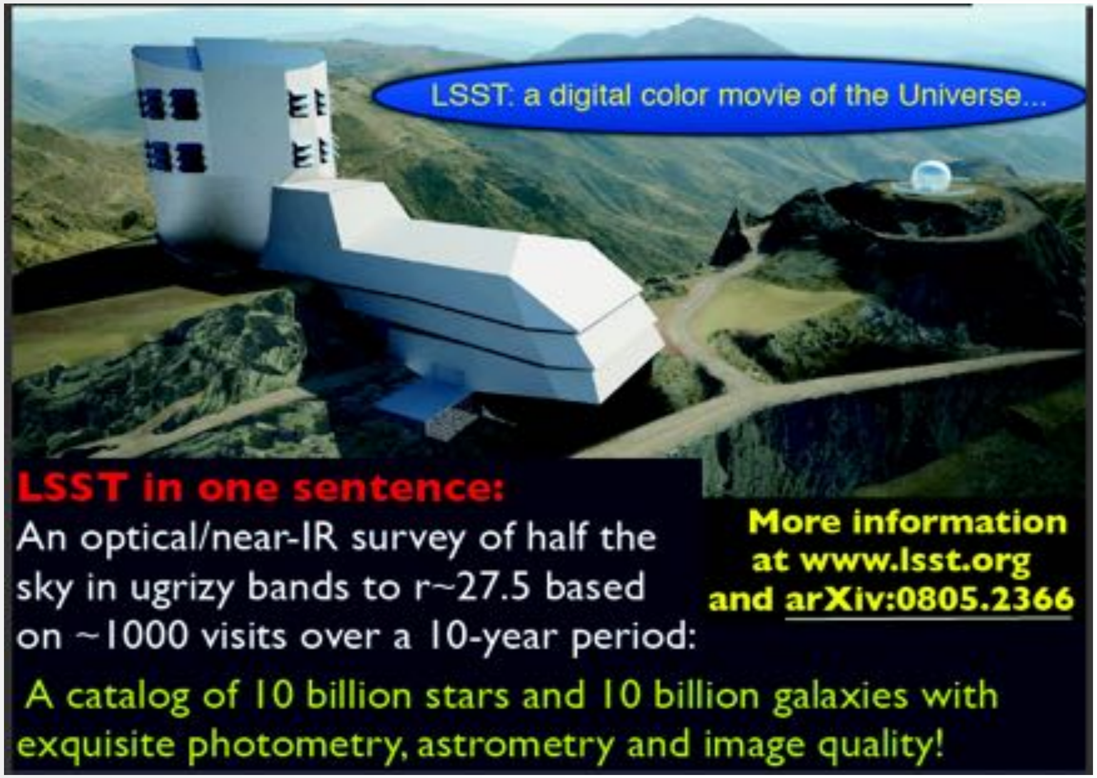
An & Baan 2012



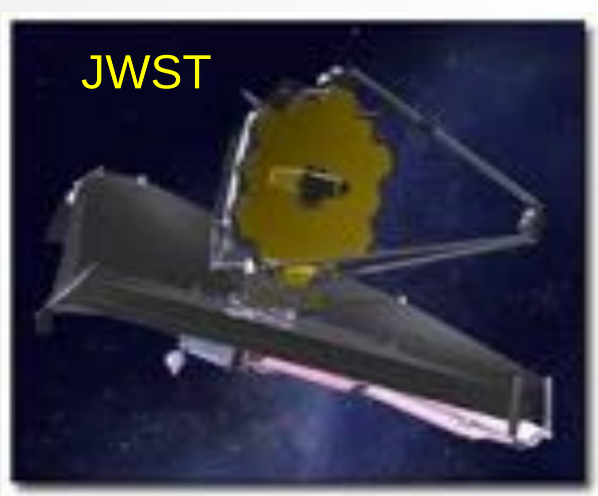


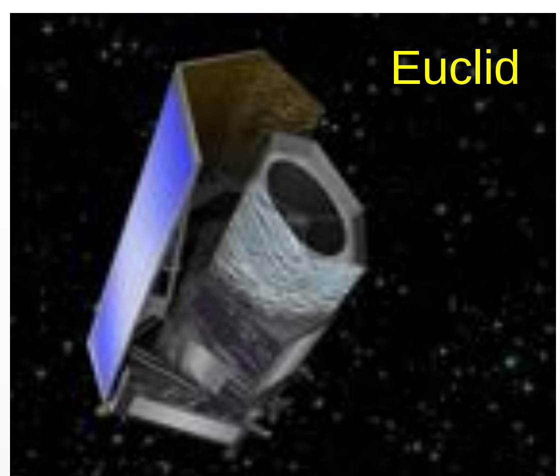


Synergies with other multiwavelegth upcoming telescopes (LSST, Euclid, JWST, eROSHITA)

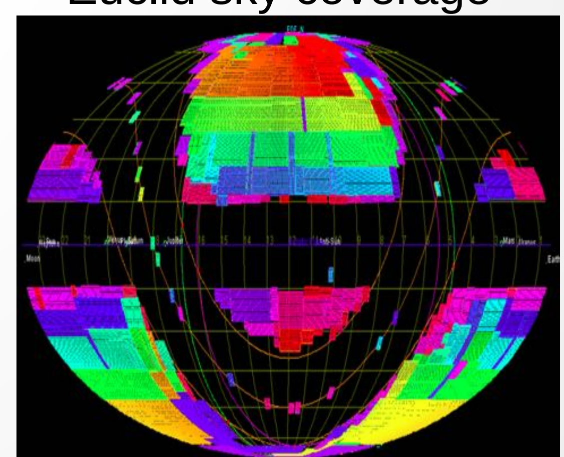


eROSHITA



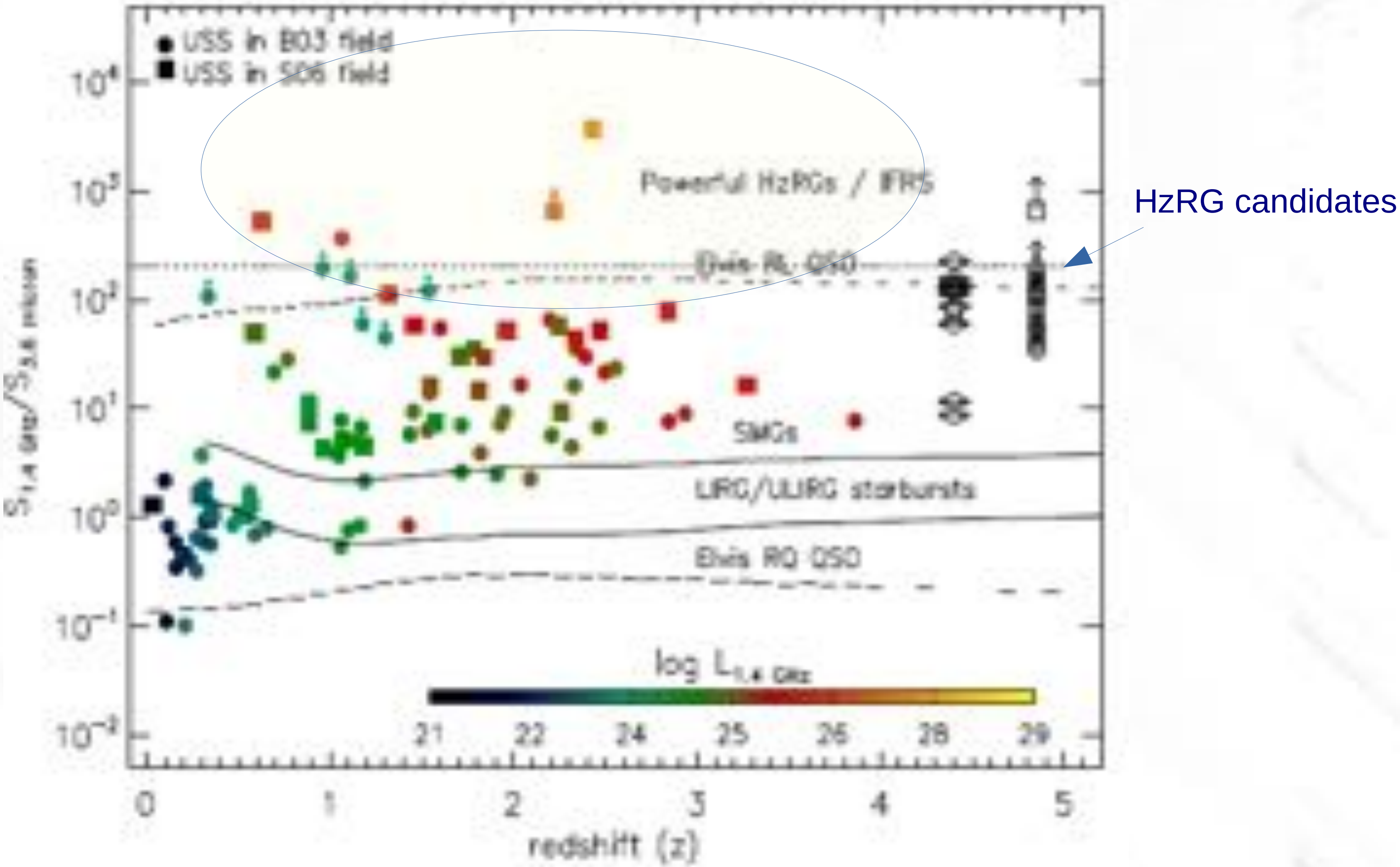


Euclid sky coverage



Unveiling obscured population of AGN using radio and IR

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

IFRS sample

RA (h m s)	DEC (d m s)	$S_{1.4\,GHz}$ (mJy)	radio size (arcsec)	$S_{3.6\,\mu m}$ (μJy)	$\frac{S_{1.4\,GHz}}{S_{3.6\,\mu m}}$	$S_{325\,MHz}$ (mJy)	$\alpha^{1.4\,GHz}_{325\,MHz}$	Redshift (z)	$L_{1.4\,GHz}$ (W Hz^{-1})
SXDF									
02 18 39.55	-04 41 49.4	50.82±0.07	15.4	13.63±0.254	3727.4	250±3.5	-1.09±0.01	2.43(s)	2.44×10^{27}
02 17 52.12	-05 05 22.4	6.19±0.05	≤ 4.6 (U)	3.20±0.254	1934.4	2.65±0.4	0.58±0.05	2.92	4.63×10^{26}
02 18 53.63	-04 47 35.6	16.95±0.07	≤ 4.6 (U)	27.84±0.254	608.8	22.8±0.8	-0.20±0.02	2.47(s)	8.45×10^{26}
02 18 51.38	-05 09 01.6	16.01±0.07	≤ 4.6 (U)	29.82±0.268	536.9	62.5±1.0	-0.93±0.01	1.75	3.41×10^{26}
02 18 03.41	-05 38 25.5	89.10±0.92	(U)	13.90±0.97	641			3.57(s)	1.09×10^{27}
02 18 38.24	-05 34 44.2	15.80±0.19	()	< 7.3	> 216			1.68	3.04×10^{25}
†02 17 40.69	-04 51 57.3	0.526±0.047	15.7	< 1.3	> 405	4.2±0.5	-1.42±0.01	4.32	1.01×10^{26}
†02 17 45.84	-05 00 56.4	0.589±0.013	≤ 4.6 (U)	< 1.3	> 453	5.4±0.4	-1.52±0.01	2.22	2.26×10^{25}
†02 18 01.23	-04 42 00.8	0.109±0.013	≤ 4.6 (U)	< 1.3	> 84	0.19±0.12	-0.38±0.01	1.72	2.22×10^{24}
†02 18 30.13	-05 17 17.4	0.187±0.013	≤ 4.6 (U)	< 1.3	> 144	0.59±0.13	-0.79±0.01	2.04	5.80×10^{24}
02 18 59.19	-05 08 37.8	0.698±0.014	≤ 4.6 (U)	< 1.3	> 537	0.23±0.12	0.76±0.02	3.60	8.66×10^{25}
VLA-VVDS									
†02 27 48.26	-04 19 05.3	0.162±0.017	≤ 6.0 (U)	< 2.0	> 81	0.67±0.15	-0.97±0.01		
†★02 25 02.13	-04 40 26.9	0.202±0.030	6.7 × 1.7 (53)	< 2.0	> 101	0.54±0.11	-0.67±0.01		
†02 26 58.10	-04 18 14.9	0.217±0.016	≤ 6.0 (U)	< 2.0	> 109	2.72±0.46	-1.73±0.01		
†02 27 09.90	-04 23 44.8	0.238±0.016	≤ 6.0 (U)	< 2.0	> 119	1.51±0.13	-1.27±0.01		
†02 26 31.12	-04 24 53.3	0.699±0.066	8.8	< 2.0	> 350	4.56±0.58	-1.28±0.01		
†02 25 26.14	-04 34 54.4	1.392±0.049	28.7	< 2.0	> 462	3.4±0.5	-0.61±0.01		
02 26 09.09	-04 33 34.7	8.643±0.020	≤ 6.0 (U)	< 2.0	> 4321	31.8±0.7	-0.89±0.01	2.45 (0.89 s)	
02 24 20.96	-04 25 44.6	18.967±0.025	39	1.8±0.3	> 10537	108.8±1.0	-1.20±0.01		

No measurements

Singh et al. (in preparation)

IFRSs : Present Vs previous studies

- Deeper 3.6 µm spitzer data, i.e, SpUDS (5σ ~ 1.3 µJy) and SERVS (5σ ~ 2.0 µJy) than previously used SWIRE (5σ ~ 7.3 µJy).
- Availability of deeper optical (m_r ~ 26 – 27.7), near-IR (m_K ~ 23 – 24) data allow us to obtain photometric redshift estimates
- Highest detection rate in the optical (17/19 IFRSs with optical counterparts)
- Highest fraction of IFRSs with redshift estimates
- IFRSs with confirmed redshifts at z > 3.0