A deep continuum survey with the GMRT at 325 MHz

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Outline

The survey

The radio FIR correlation

A high z giant radio relic

Collaborators

This work was done as a part of an Indo-French project titled **Distant, obscured galaxies with GMRT and Herschel**

- Veeresh Singh, UKZN, South Africa
- Aritra Basu, MPifR, Germany
- Alexandre Beelen, IAS, France
- Prathamesh Tamhane, IISER, Pune
- C.H. Ishwara-Chandra, NCRA-TIFR, Pune
- Sandeep Sirothia, NCRA-TIFR and SKA-SA

Scientific Motivation for a 325 MHz survey

- radio counterparts of Herschel HerMES survey sources (and stacked blank sky!) - radio-FIR correlation, identify optical counterparts (and hence redshifts!), study obscured AGN and star-forming galaxies out to cosmological distances.

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- radio counterparts of Herschel HerMES survey sources (and stacked blank sky!) - radio-FIR correlation, identify optical counterparts (and hence redshifts!), study obscured AGN and star-forming galaxies out to cosmological distances.
- identify and study the zoo of objects with steep radio spectra e.g. high z radio galaxies.
- most other studies currently being pursued at higher radio frequencies can also be done with these data. e.g. studies of the impact of radio mode feedback on galaxy evolution.

Projects already completed

- identification and study of a sample of high redshift radio galaxies (Singh et al. 2014; Veeresh will give a talk about this.)
- the radio-FIR correlation in blue-cloud normal galaxies with $0 < z < 1.2$ (Basu et al. 2015)
- A giant, relic, high redshift radio galaxy (Tamhane et al. 2015, MNRAS submitted)

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GMRT data of XMMLSS field

- 40 hours of continuum imaging at 325 MHz with 16 overlapping pointings in snapshot mode (Proposal 20_006 - PI (Wadadekar))
- reaches nearly uniform rms of $\sim 150\mu$Jy over a $\sim$ 12 deg^2 area. Deepest multi-pointing survey with GMRT in P-band.
- data processing done by Sandeep Sirothia.
- **2 more fields still to be analysed (18 sq. deg in Lockman Hole and 9 sq. deg in ELAIS N1)**

The observational status of the radio FIR correlation

The correlation has been studied extensively at low redshifts. But detecting high redshift galaxies in FIR (except ULIRGs) remained a challenge until the advent of the Herschel telescope.

In the last 3 years half a dozen studies have focused on measuring this correlation upto $z \sim 2$. (e.g. Ivison et al. 2010, Bourne et al. 2011, Magnelli et al. 2014)

The situation is actually getting more confusing, in some sense, because the high redshift data have strong selection biases. But this should improve in the future as new data come in.

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What we need to study the high-z RFC

- a spectroscopic survey identifying galaxies in the redshift range of interest - the PRIMUS survey supplies these for our study.
- deep FIR and radio data for these galaxies.

The FIR data from Herschel

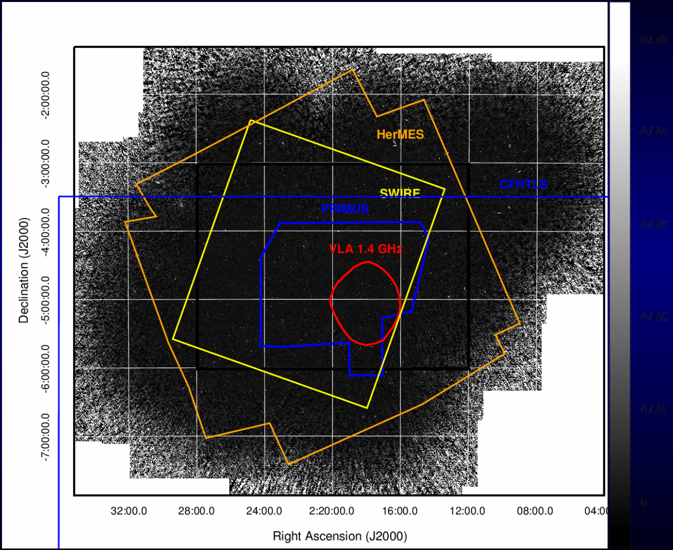
are from the Herschel Multi-tiered Extragalactic Survey: HerMES (Oliver et al. 2012)

- HerMES is the largest GTO program with Herschel.
- observes 13 well studied fields to six depth levels in a wedding cake type coverage.
- achieves 5σ limits of 25.8,21.2,30.8 mJy in the SPIRE 250,350,500 μm bands in the XMM-LSS field over 18.9 deg^2.

The FIR data from Spitzer

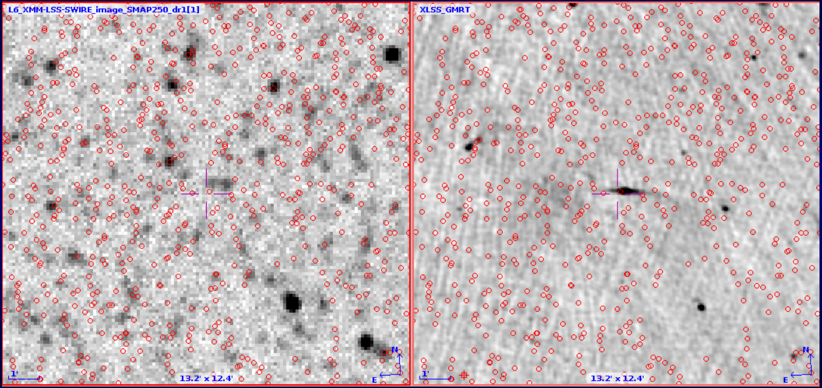
are from the decade old SWIRE survey (Lonsdale et al. 2003) which covers 9 deg^2 in the XMMLSS field with 4 IRAC bands (3.6,4.5,5.8,8.0 μm) and 3 MIPS bands (24,70,160 μm)
In our work, we only use the MIPS observations.

The coverage map



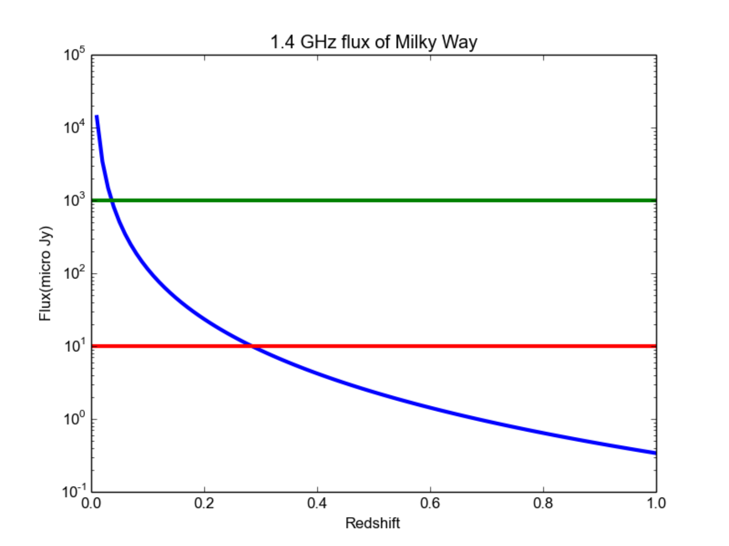
Basu et al. (2015)

Why do we need to stack?

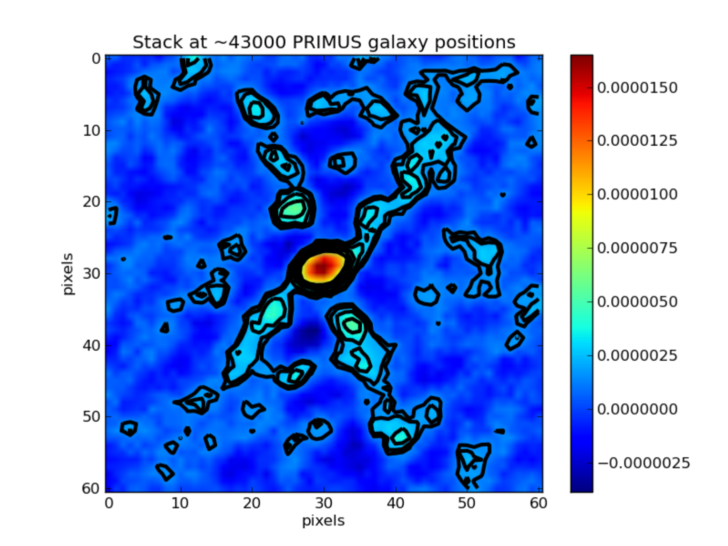


PRIMUS - 44000 robust redshifts over 2.88 deg^2 $\Rightarrow>$ 15000 sources deg^{-2}

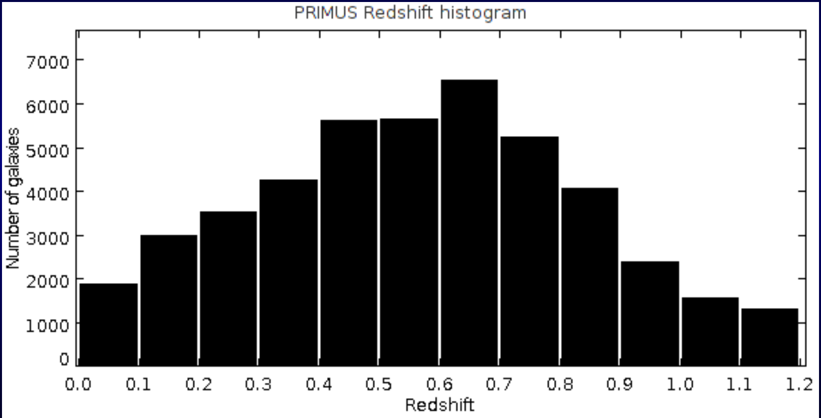
More reasons to stack



The radio stack of all galaxies



We bin in redshift (binwidth 0.1) and stack

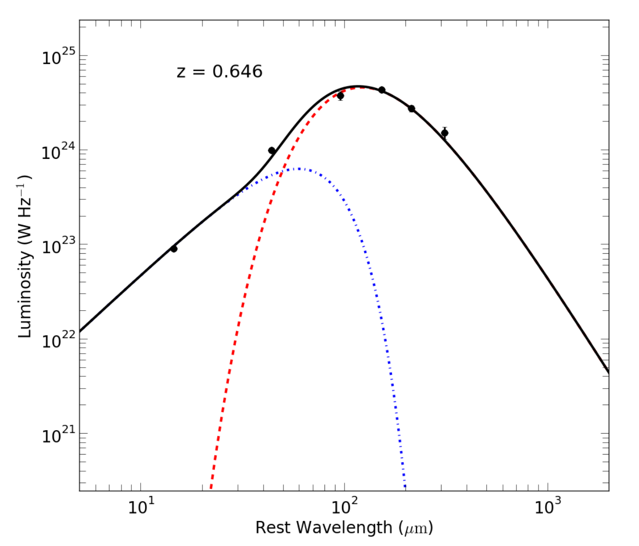


FIR spectrum - Greybody + power law, following Casey (2012)

$$S(\lambda) = A_{\rm GB}\frac{(1-e^{-\tau_\lambda})\lambda^{-3}}{(e^{hc/\lambda kT}-1)} + A_{\rm PL}\left(\frac{\lambda}{\lambda_{\rm c}}\right)^{\alpha} e^{-(\lambda/\lambda_{\rm c})^2} \quad (1)$$

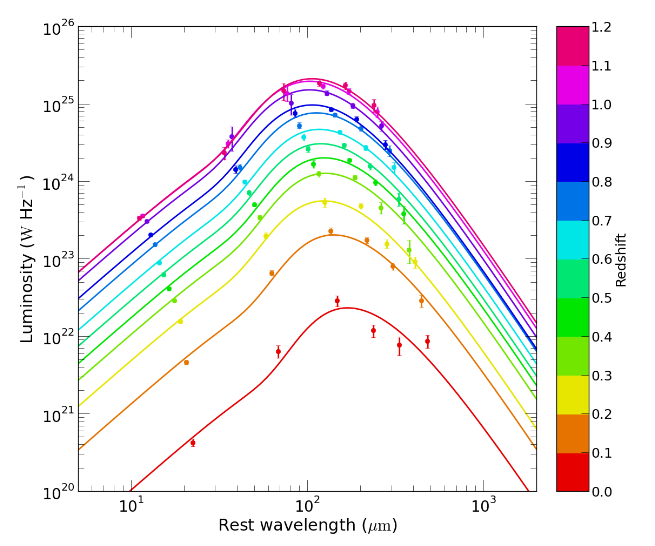
Here, $A_{\rm GB}$ and $A_{\rm PL}$ are the greybody and mid-IR power-law amplitude normalization respectively, $\lambda_{\rm c}$ is the mid-IR turnover wavelength, α is the mid-IR power-law index, $\tau_\lambda = (\lambda_0/\lambda)^\beta$ is the optical depth and is unity at λ_0 (assumed to be 200 μm), β is the dust emissivity index, T is the greybody temperature and h, c, k are the Planck constant, speed of light and Boltzmann constant, respectively. Characteristic dust temperature ($T_{\rm dust}$) is given by Wein's displacement law, $T_{\rm dust} = b/\lambda_{\rm peak}(\mu{\rm m})$, where, $b = 2.898 \times 10^3 \mu{\rm m}\ {\rm K}$ and $\lambda_{\rm peak}$ is the peak wavelength of the fitted SED.

Fit done separately in each bin



Basu et al. (2015)

The K-correction in FIR



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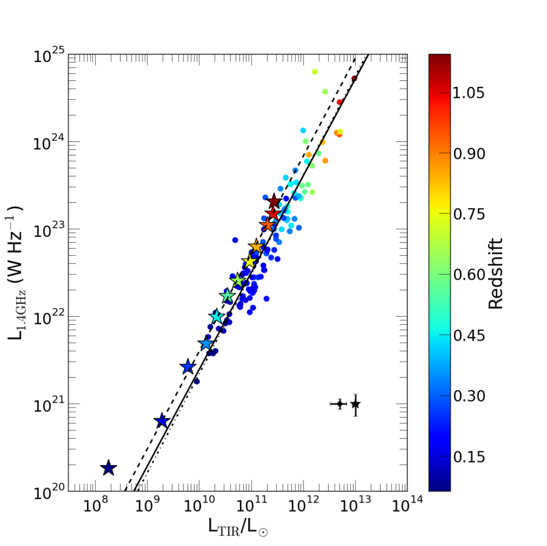
1) the slope in log-log space, b, given by, $L_{\rm radio} \propto L_{\rm FIR}^{b}$ and 2) the parameter 'q' defined as $q = \log_{10}(L_{\rm FIR}/L_{\rm radio})$. Here, $L_{\rm radio}$ and $L_{\rm FIR}$ are the luminosities at a radio and FIR band, respectively.

Monochromatic and bolometric versions

For the monochromatic case, we define $q_{70\mu\mathrm{m}} = \log_{10}(L_{70\mu\mathrm{m}}/L_{1.4\mathrm{GHz}})$ and for the bolometric case, we define:

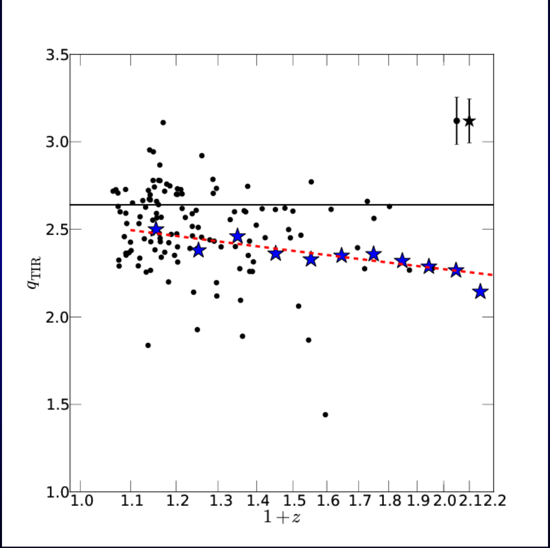
$$q_{\mathrm{TIR}} = \log_{10}\left[\frac{L_{\mathrm{TIR}}(\mathrm{W})}{3.75\times 10^{12}}\right] - \log_{10}[L_{1.4\mathrm{GHz}}(\mathrm{W\ Hz^{-1}})] \quad (2)$$

The correlation with bolometric FIR luminosity



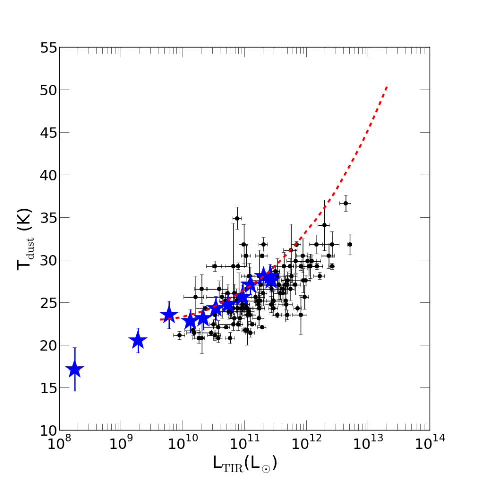
Basu et al. (2015)

The evolution of q_{TIR} with redshift



Basu et al. (2015)

Dust temperature as a function of FIR luminosity



Magnelli et al. 2014a, Basu et al. 2015

Future prospects

- optical spectroscopic samples with tens of thousands of galaxies are now routine - PRIMUS, VIPERS, DEEP2, VVDS, GAMA, zCOSMOS. Many more are in progress. But these are mostly flux-limited samples with Malmquist biases. We need more surveys like the stellar mass selected KROSS which will study ~ 1000 galaxies at $z = 1$.

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- Deep radio data are also routine now e.g. with JVLA, Smolcic et al. image 2 deg^2 to 2 μJy rms at 1.4 GHz in 384 hours, EMU on ASKAP will reach 10 μJy over 75% of the sky. SKA1-Mid surveys will do even better.

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- the situation in the FIR is not very hopeful because to get higher sensitivity while still beating confusion one needs a super-Spitzer, which is nowhere on the horizon.

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Summary

- radio–FIR correlation to hold true within the redshift range 0–1.2 for faint non-AGN star-forming galaxies about 2-3 orders of magnitude fainter than galaxies with direct detections.
- Accurate FIR k-correction via modeling with mid and FIR data is critical.
- The slope of the correlation, for bolometric FIR luminosity ($L_{\rm TIR}$), $b = 1.11 \pm 0.04$ is close to but steeper than 1.
- $q_{TIR} \propto (1+z)^{-0.16 \pm 0.03}$ probably caused by the non-linear slope of the correlation. Within these uncertainties there is no evolution of the RFC out to $z \sim 1$

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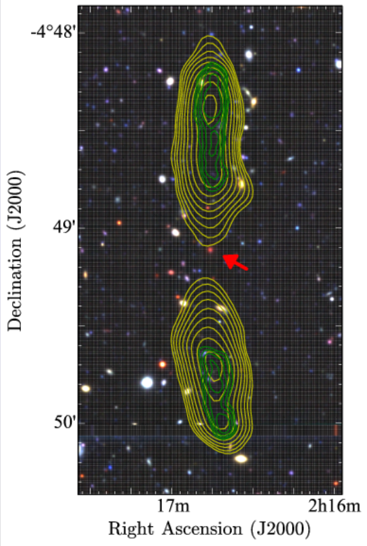
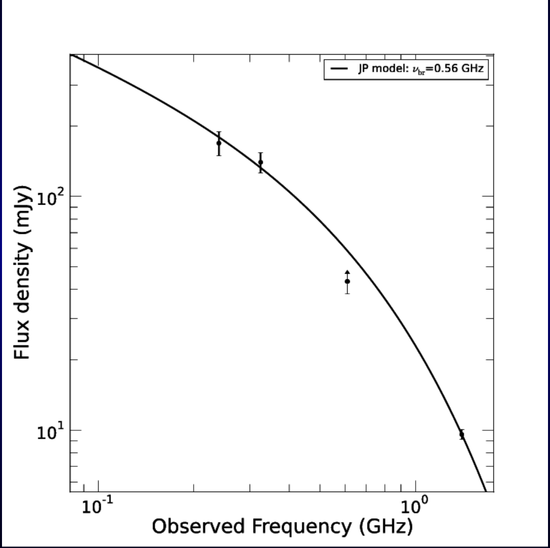
Giant radio galaxy at $z = 1.325$



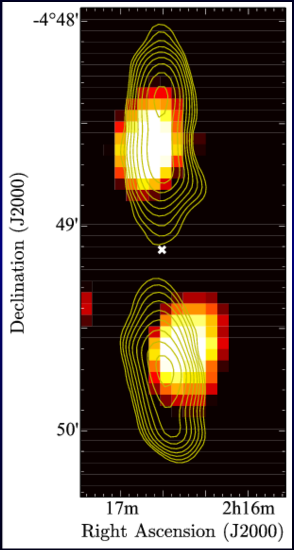
Tamhane et al. (2015)

Model fit to radio observations



Tamhane et al. (2015)

Diffuse X-ray emission from the lobes



Tamhane et al. (2015)

Summary

- The radio lobes are best detected at low radio frequencies observed using the GMRT at 0.325 GHz. The total angular extent at 0.325 GHz is $2'.4$, and corresponds to a projected linear size of $\sim$ 1.2 Mpc.
- The host galaxy is identified in deep optical (Subaru), near-IR (UKIDSS) and mid-IR (SpUDS). It is a red (R $-$ z$'$ = 2.0) galaxy that brightens in mid-IR bands.
- The relic nature of the radio galaxy is evident as the AGN core, jets and/or hot-spots remain undetected and the lobes exhibits a very steep radio spectral index, $\alpha_{0.325\ \mathrm{GHz}}^{1.4\ \mathrm{GHz}}$ $\sim$ 1.4 — 2.5. The 0.24—1.4 GHz radio spectrum of the lobe emission is convex and steepens sharply above 0.325 GHz due to radiative losses.

- The comparison of radio and X-ray spectral and morphological properties suggests that X-ray emission is likely due to inverse Comptonization of CMB photons by low energy electrons compared to electrons radiating at 0.325 — 1.4 GHz frequencies.
- Using the ICCMB X-ray emission, we estimate the lower limit for the total energy in relativistic electrons to be $\sim$ 4.0 $\times$ 10^{59} erg s^{-1} (for $\gamma_{\rm e} \sim 10^3$) $\Rightarrow$ significant feedback from GRG into the surrounding inter galactic medium.
- The magnetic field strength estimated using X-ray and radio emission and by energy equipartition yield consistent field strengths of $\sim$ 3.5 μG.