The Radio - FIR correlation in the faintest star-forming galaxies

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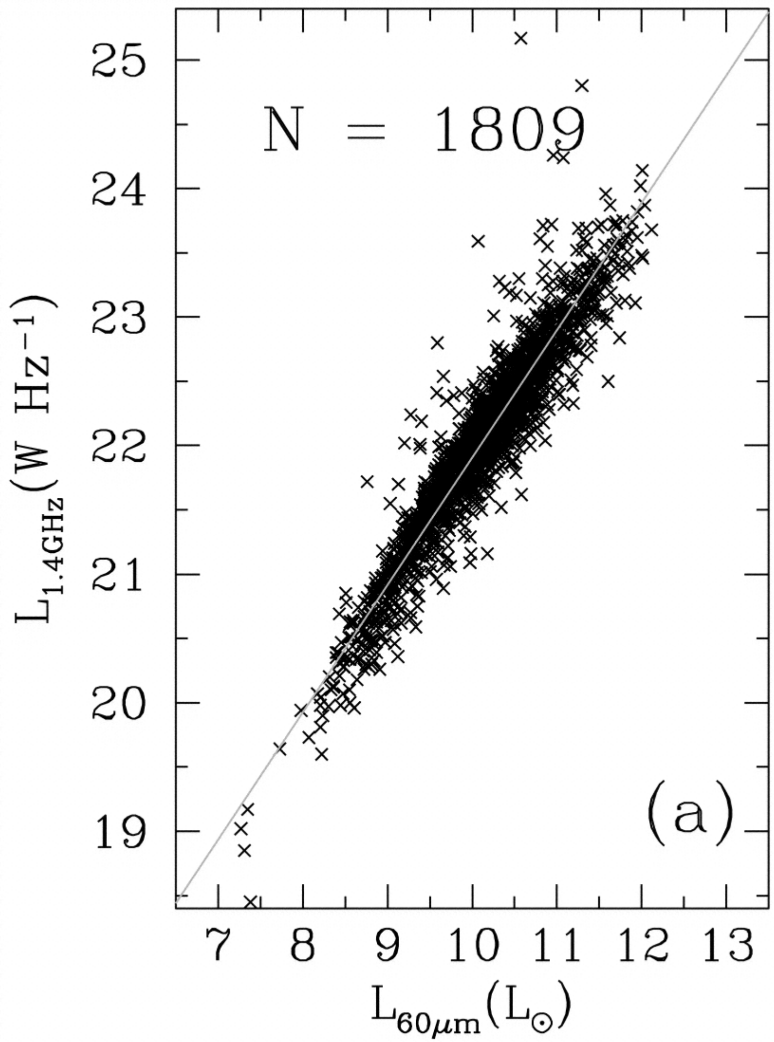
The Radio-FIR correlation

- 1.4 GHz Radio continuum is strongly correlated with Far InfraRed emission (FIR, TIR, S_{IR}) over many decades in L
- Star formation behind it all :
  FIR flux → energy of UV photons from young stars re-processed by dust
  Radio flux: **thermal part** → HII regions ionized by massive stars,
  non-thermal emission → Cosmic Ray electrons (CRe s) accelerated in SNRs of dying stars & interacting with the **magnetic field**
- Of late a consistent picture is emerging for explaining the correlation – where the energy in CRe s and magnetic field are 'equipartitioned' - magnetic field couples with the gas density through MHD turbulence – and the gas density in turn determines the star formation rate



Yun et al. (2001)

In Dwarf Galaxies

- The expectation for low luminosity galaxies

  → more CR electrons escape decreasing radio emission

  → decreasing dust / UV opacity causes lower FIR emission

  → 'conspiracy' maintains correlation (Bell, 2003; Lacki et al., 2010)

- Difficult to verify for low luminosity galaxies because

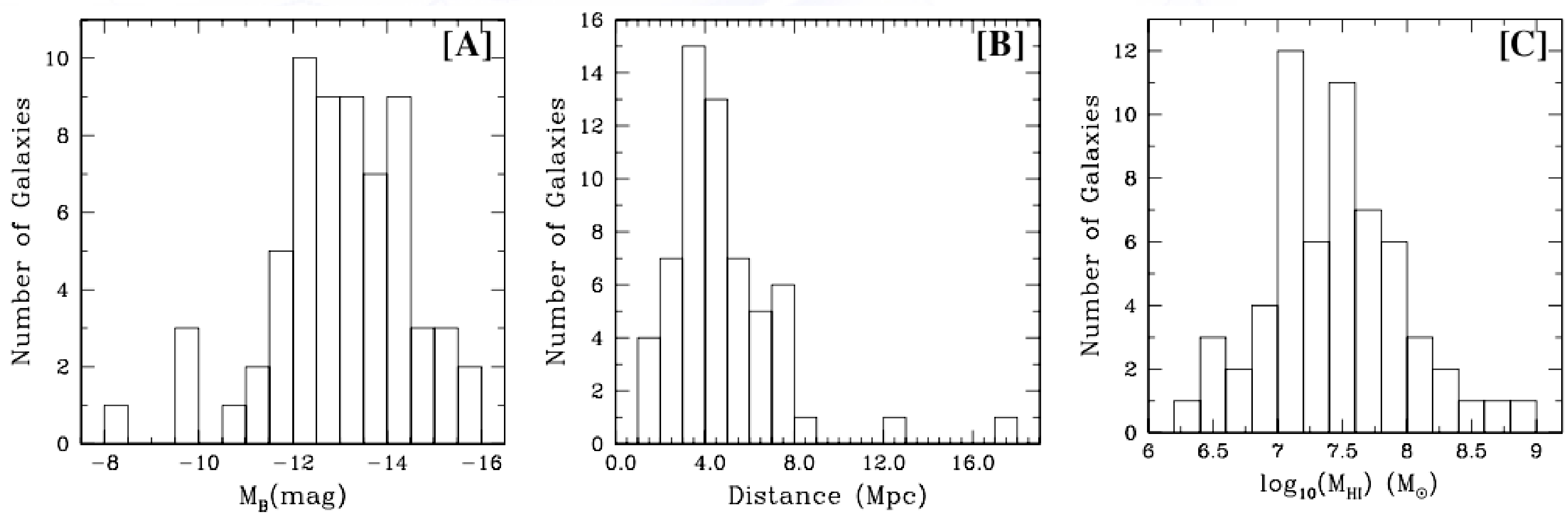
  → radio emission too faint

  → stacking images to get detectable emission

- Padovani (2011) predicts that star-forming dwarfs will contribute significantly to the number counts at faint levels in the proposed next generation deep sub - μJy surveys
- Measuring the radio continuum flux also allows one to estimate the total magnetic field strengths → crucial to test whether low mass galaxies seeded the IGM with magnetic fields in early epochs

Faint Irregular Galaxy GMRT Survey

- For 62 galaxies HI 21 cm emission observed, largest such sample
- Selection criteria: M_B > -14.5, HI Flux > 1 Jy km s^{-1}, D_{opt} > 1'
- Sample properties (Begum et al., 2008):

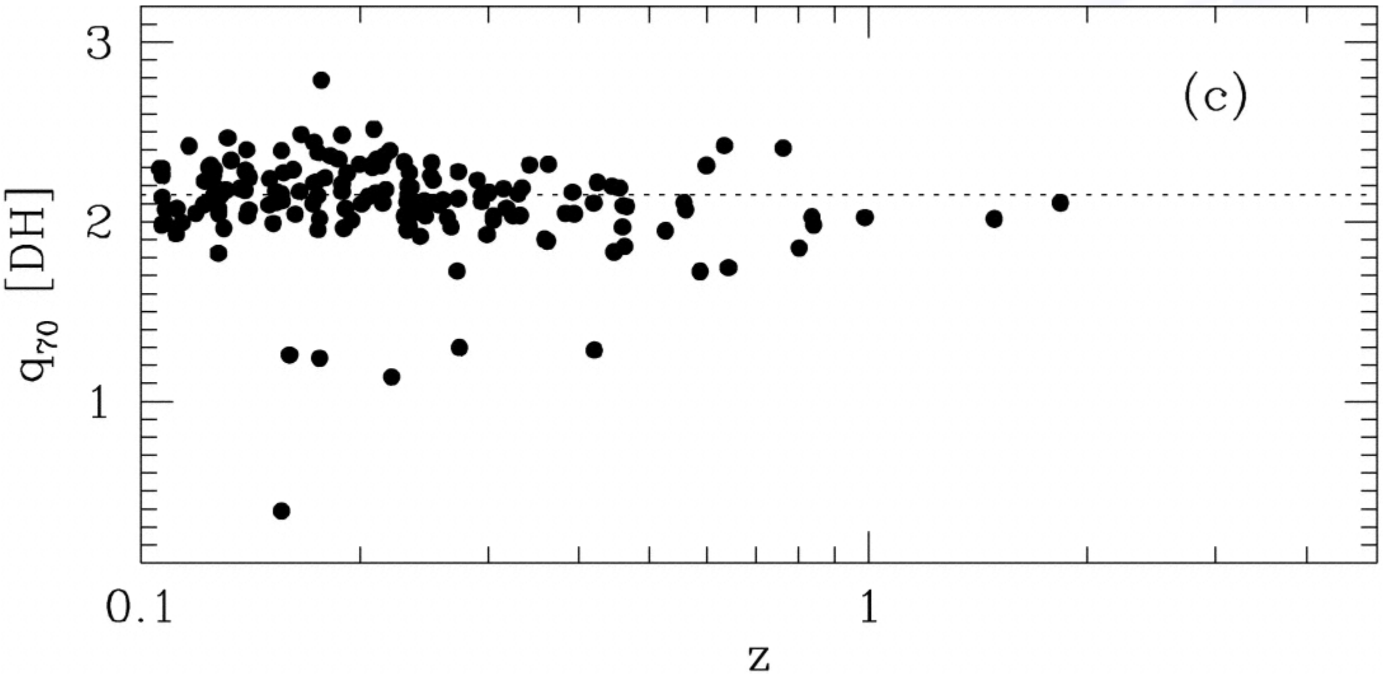


$\langle M_B \rangle \sim -13$ $\quad$ $\langle D \rangle \sim 4$ Mpc $\quad$ $\langle M_{HI} \rangle \sim 3 \times 10^7 M_\odot$

- Fraction of gas in baryonic mass, <fgas> ~ 0.7
- Metallicity ~ 0.1 solar or lower

The quantity to be measured

- We use Appleton et al. (2004)'s method to check correlation



$$q_{\rm IR} = \log\left(S_{\rm IR}/S_{20\ \rm cm}\right)$$

- $$L_{1.4\rm GHz} = a L_{\rm IR}^{b}$$

$$q = -\left(\frac{1}{b}\right)\log_{10} a + \left(\frac{1-b}{b}\right)\log_{10} L_{1.4\rm GHz}$$

q is constant only when b = 1 → b value to be checked also ...

Samples

Sample/galaxy	Number of galaxies
NVSS }	57
MIPS 70 μm }	26
FUV	46
Common	24
UGC 5456	1

- Stacking of: NRAO VLA Sky Survey (radio 1.4 GHz) and *Spitzer* MIPS 70 μm → *GALEX* FUV data for estimating star formation rate
- 13 of the MIPS subsample galaxies have detectable emission in 70 μm band → only 1 NVSS subsample galaxy has detectable radio continuum emission

Samples

Sample/galaxy	Number of galaxies	M_B	D_{Ho} (arcmin)	M_{HI} ($10^7 M_\odot$)	D (Mpc)
NVSS	57	−13.1	1.7	2.8	4.8
MIPS 70 μm	26	−13.1	2.0	2.6	3.4
FUV	46	−13.1	1.7	2.6	4.5
Common	24	−13.1	2.0	2.2	3.4
UGC 5456	1	−15.1	1.9	5.9	5.6

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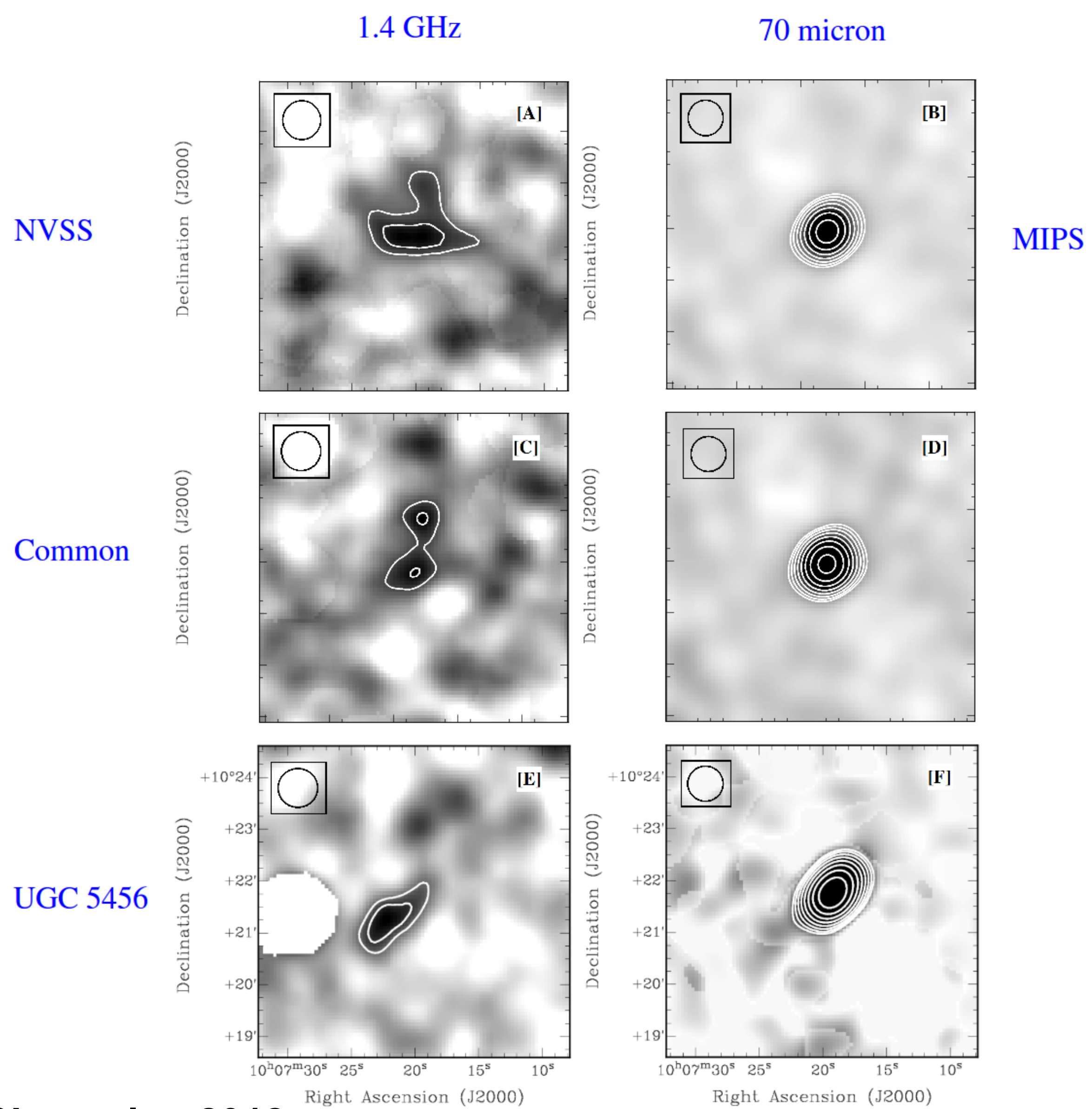
Method

- NVSS has effective continuum bandwidth of 45 MHz, resolution of 45 arcseconds, and noise level of 0.45 mJy per beam
- Spitzer MIPS 70 micron band has a bandwidth of 19 micron and resolution of 19 arcseconds
- The Spitzer PBCD s (all galaxies less than 2 arcmins in extent) were convolved to a FWHM of 41 arcseconds using kernel from Aniano et al. (2011)
- For both sets images were co-added after being weighed by the inverse of the variance of the background flux
- For NVSS, on co-adding images for 57 galaxies the background rms reduced to 66 μJy per beam
- For Spitzer 70 micron images, on co-adding 51 PBCDs the background noise reduced from 0.2 MJy per steradian to 0.03 MJy per steradian

Stacked images



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Results of stacking – FIR flux

Sample/ galaxy	SFR_{FUV} ($M_\odot$ yr^{-1})	$L_{70\,\mu m}$ (erg s^{-1})	$L_{70\,\mu m}^{high\,Z}$ (erg s^{-1})
NVSS	3.8×10^{-3}		
MIPS 70 μm	3.0×10^{-3}	1.3×10^{39}	1.2×10^{40}
Common	3.0×10^{-3}	1.4×10^{39}	1.2×10^{40}
UGC 5456	1.9×10^{-2}	2.4×10^{40}	6.0×10^{40}

- Calzetti et al. (2010) obtained a relation between surface densities of SFR and 70 micron luminosity for brighter and higher metallicity galaxies
- Faint dwarfs have lower emission compared to that predicted by this relation

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Results of stacking – radio flux

Sample/ galaxy	SFR_{FUV} ($M_\odot$ yr^{-1})	$L_{1.4\,GHz}$ ($W\,Hz^{-1}$)	$L_{1.4\,GHz}^{>L_*}$ ($W\,Hz^{-1}$)	$L_{1.4\,GHz}^{<L_*}$ ($W\,Hz^{-1}$)
NVSS	3.8×10^{-3}	2.5×10^{18}	6.9×10^{18}	1.2×10^{18}
MIPS 70 μm	3.0×10^{-3}			
Common	3.0×10^{-3}	1.2×10^{18}	5.4×10^{18}	9×10^{17}
UGC 5456	1.9×10^{-2}	1.1×10^{19}	3.4×10^{19}	8×10^{18}

- Bell (2003) gave functional forms of the relation between SFR and 1.4 GHz flux for galaxies with luminosities > L_* (better calibrated) and < L_* (more of an extrapolation)
- Faint dwarfs have luminosities lower than what is expected from the calibration based on brighter galaxies

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Results of stacking

Sample/galaxy	Number of galaxies	1.4-GHz flux (mJy)	70 μm flux (mJy)	q70	From Appleton et al. (2004)
NVSS	57	0.9±0.2		2.0±0.2	1.99±0.17
MIPS 70 μm	26		83±5		
Common	24	0.8±0.3	90±8	2.0±0.4	1.99±0.17
UGC 5456	1	3±1	560±30	2.3±0.3	2.15±0.16

- Ratio of the mean 1.4 GHz and 70 μm fluxes calculated following Appleton et al. (2004) → errorbars using bootstrap resampling
- 'Conspiracy' maintains correlation (Bell, 2003; Lacki et al., 2010) → both 1.4 GHz and 70 μm fluxes less than what is expected for brighter galaxies

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Estimating magnetic field strength

- SFR_{FUV} → $SFR_{H\alpha}$ (Roychowdhury et al. 2011) → luminosity → thermal radio emission from HII regions using Hα flux (Caplan & Deharveng 1986) → subtracted from total flux to get non-thermal flux → **Total equipartition magnetic field** (Beck & Krause 2005)

Sample/ galaxy	SFR_{FUV} ($M_\odot$ yr^{-1})	$L_{H\alpha}$ (erg s^{-1})	$L_{thermal}$ (W Hz^{-1})	Non-thermal percentage	B (μG)
NVSS	3.8×10^{-3}	5.7×10^{38}	$\sim8\times10^{17}$	∼70 per cent	∼1.6
MIPS 70 μm	3.0×10^{-3}	4.1×10^{38}			
Common	3.0×10^{-3}	4.1×10^{38}	$\sim7\times10^{17}$	∼40 per cent	∼1.4
UGC 5456	1.9×10^{-2}	4.5×10^{39}	$\sim6\times10^{18}$	∼50 per cent	∼1.8

- ~20% of those in spiral galaxies → but similar to what was predicted from trends between B and SFR in starburst dwarfs from Chyzy et al. (2011) → **not strong enough to effectively seed the Inter Galactic Medium** (model of Chyzy et al. 2011)

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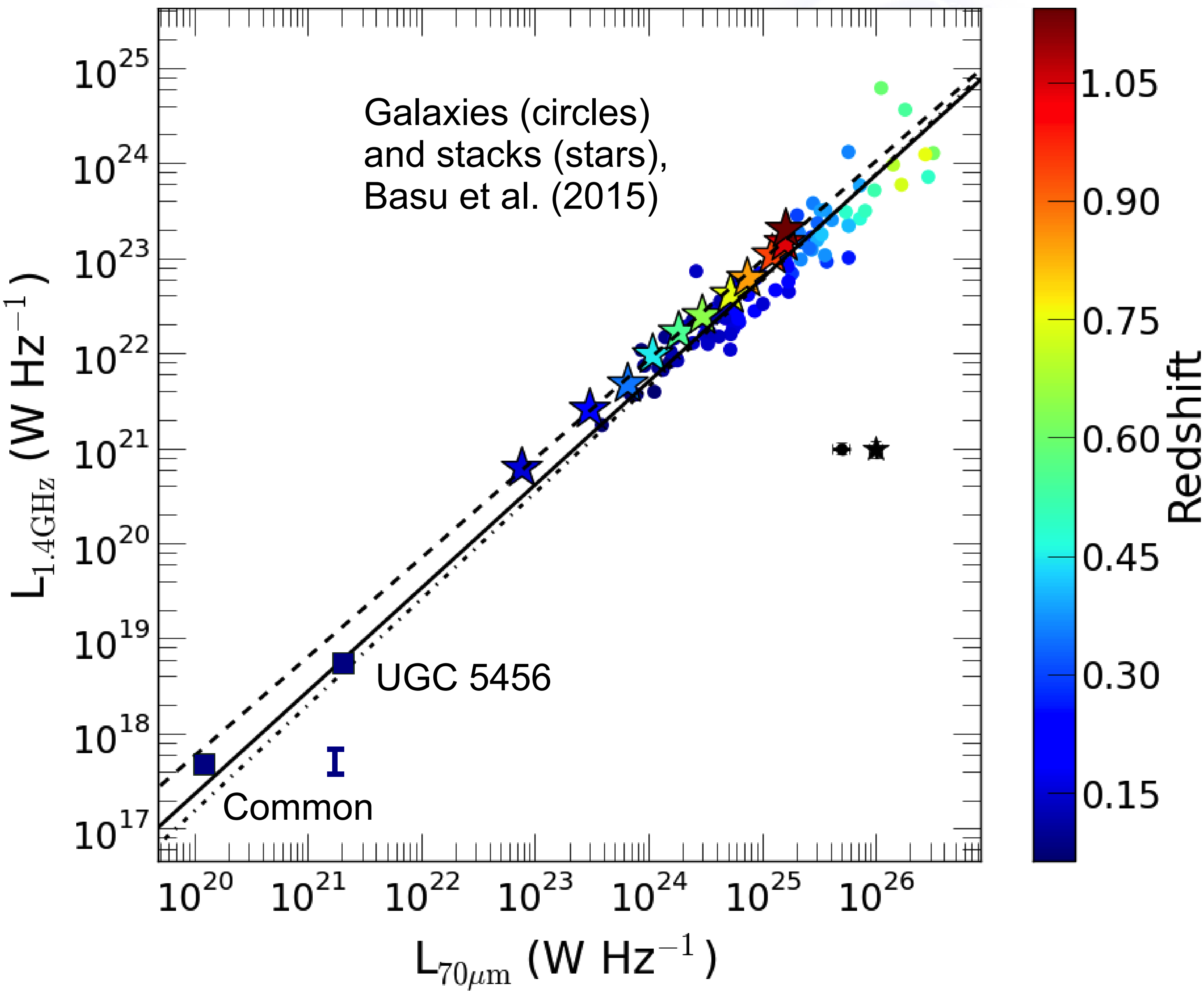
Slope of the Radio-FIR relation



Summary

- We used stacking to detect the radio continuum emission from extremely faint dwarf irregular galaxies
- Both the radio and 70 micron fluxes are lower than those predicted from correlations with SFR seen in L_* galaxies
- But the ratio of the two fluxes, the 'q' values is consistent with that measured for brighter galaxies
- The fluxes are also consistent with a super-linear slope of the non-thermal radio-FIR correlation → extending over 8 orders of magnitude
- The 'equipartition' total magnetic fields estimated are low, implying galaxies of this kind could not have seeded the IGM with magnetic field
- Giant Metrewave Radio Telescope (GMRT) and archival VLA observations of a sample of nearby dwarf irregulars with archival Hα, FUV and FIR observations, at 1.4 GHz and 325 MHz
- Spatially resolved study of the radio-FIR correlation & non-thermal spectral index planned with few hundred parsec spatial resolution