# Low frequency Radio Studies of Luminous Infrared Galaxies - Probes on Host Galaxy Properties

**Subhrata Dey[1]**

Arti Goyal[1], Katarzyna Małek[2]

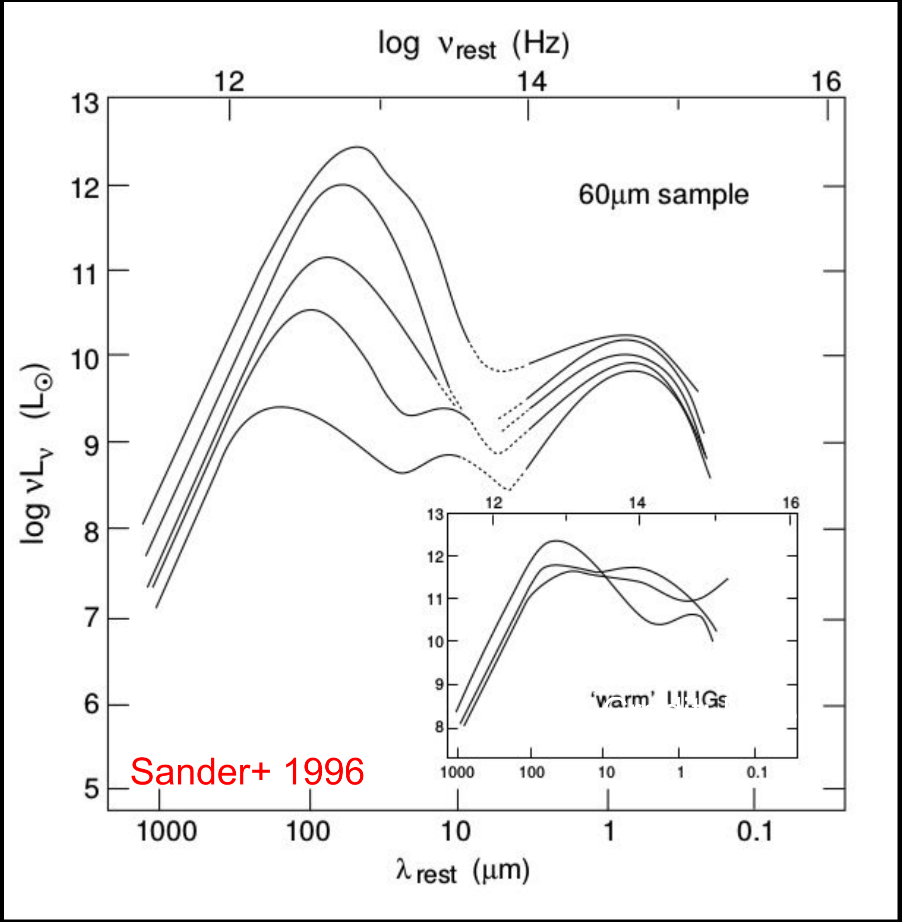
[1]Astronomical Observatory of Jagiellonian University, Krakow

[2]National Centre for Nuclear Research, Warsaw

# Definitions

- Infrared Galaxies [$\text{Log}(L_{IR}/L_{\odot}) \leq 11.0$]
- Luminous Infrared Galaxies( **LIRGs**): [$\text{Log}(L_{IR}/L_{\odot})) \geq 11.0$]
- Ultraluminous Infrared Galaxies (**ULIRGs**): [$\text{Log}(L_{IR}/L_{\odot}) \geq 12.0$]

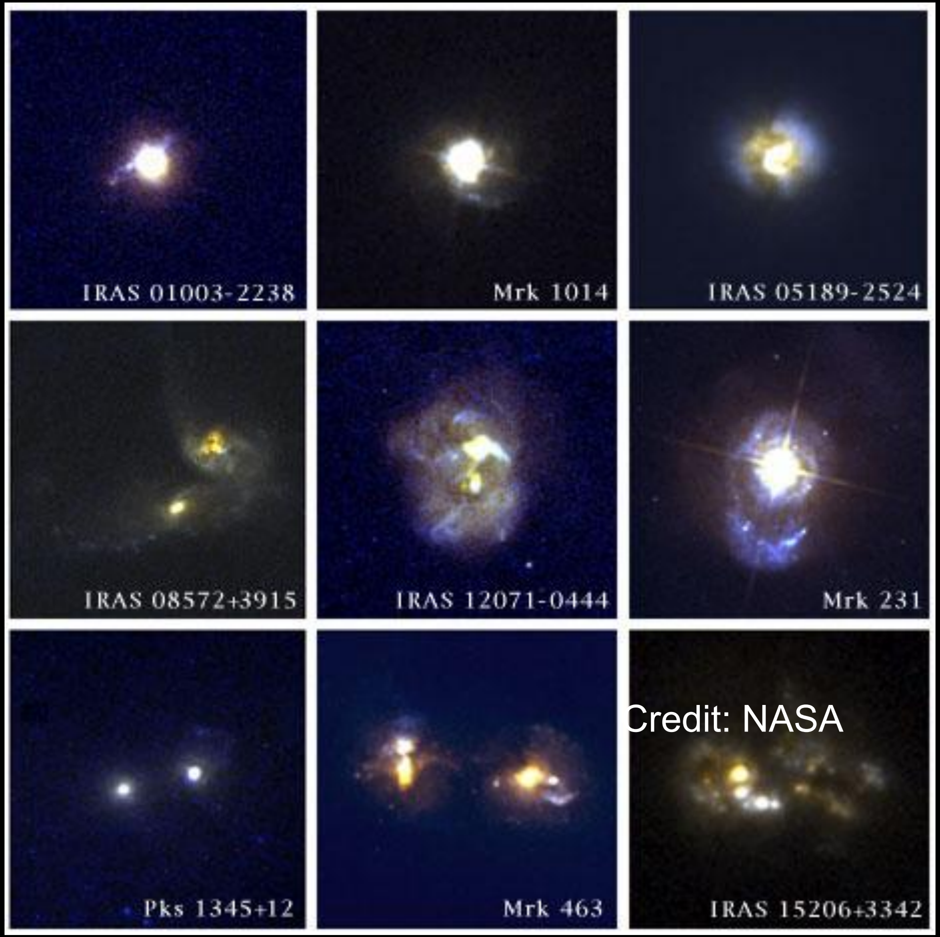
Analysis of first sample of ULIRGs - interacting galaxies



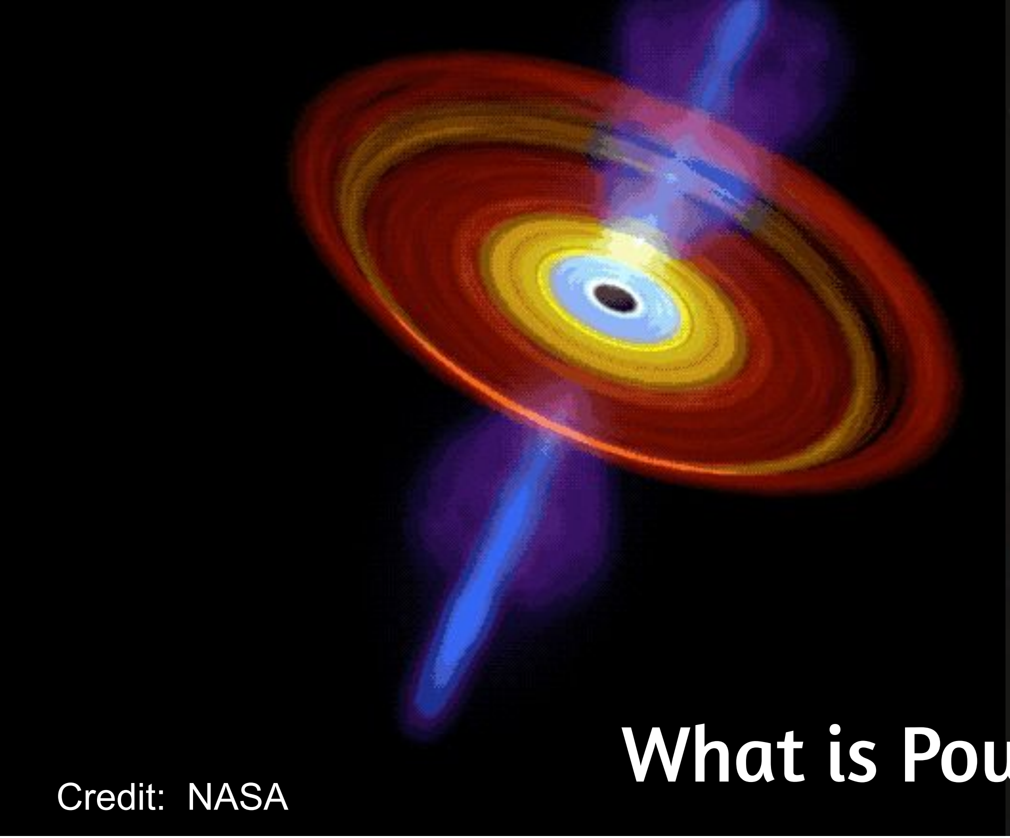
# Definitions

- ❖ Infrared Galaxies [$\text{Log}(L_{IR}/L_{\odot}) \leq 11.0$]
- ❖ Luminous Infrared Galaxies( **LIRGs**): [$\text{Log}(L_{IR}/L_{\odot})) \geq 11.0$]
- ❖ Ultraluminous Infrared Galaxies (**ULIRGs**): [$\text{Log}(L_{IR}/L_{\odot}) \geq 12.0$]

Analysis of first sample of ULIRGs - interacting galaxies




IR image of ULIRGs (8-1000 μm) (Jason Ware)



Credit: NASA

Credit: giphy

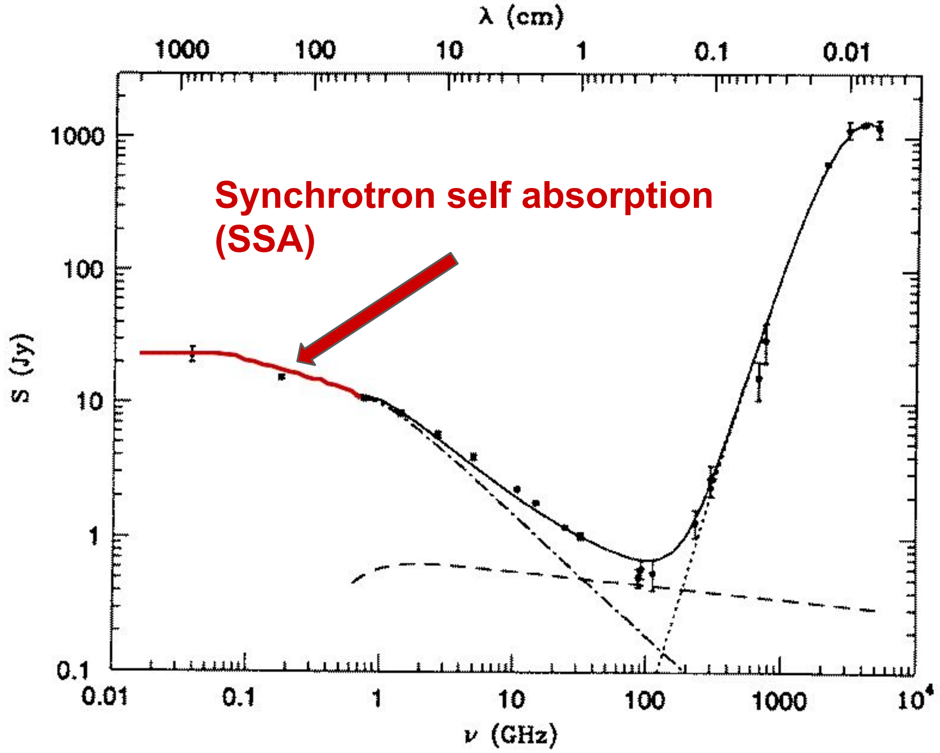
# What is Powering them ???

- ➔ Active galactic nuclei (Sanders+1999) and/or
- ➔ Massive bursts of star formation following collisions between gas rich galaxies
  ( Sander & Mirabel 1996; Lonsdale+ 2006)

# Why study the radio spectra ??

- Normal galaxies powerlaw, typical α = -0.75 ($S_v = v^{\alpha}$, Gioia et al. 1982)
  - Steeper
  - synchrotron

- **(U)LIRGS- Flatter spectra**
  - **-Synchrotron self absorption** (SSA) presence of an AGN
  - **-Thermal free-free absorption** cases of starburst dominated spectra (Clemens et al. 2010; Condon et al. 1992)



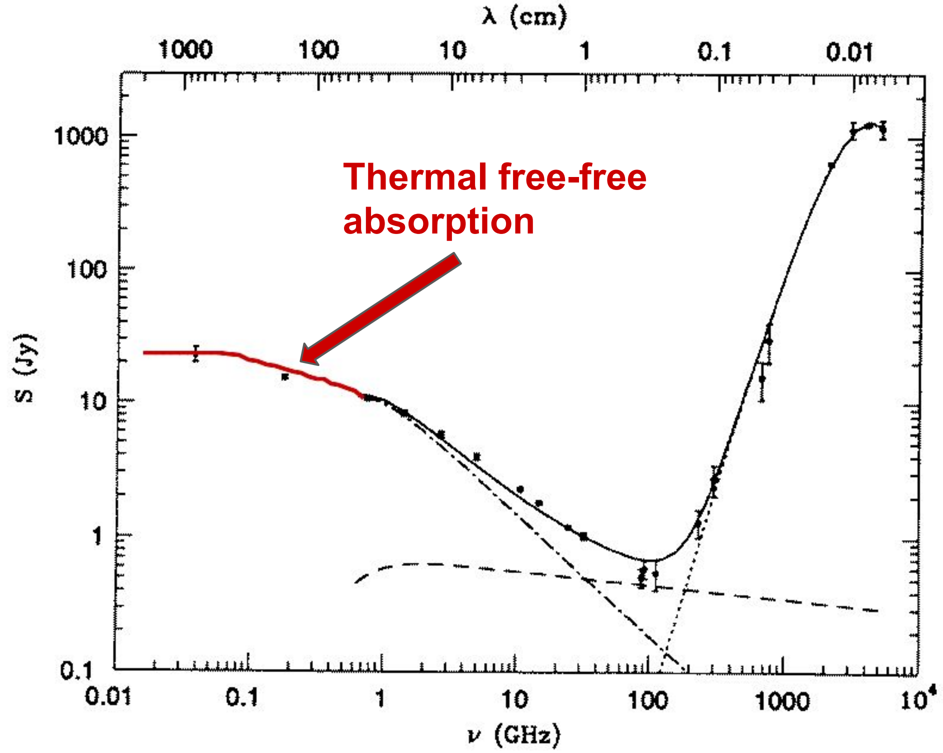

Condon, 1992

-High values of the far-infrared–radio flux ratio, q

# Why study the radio spectra ??

- Normal galaxies powerlaw, typical α = -0.75 ($S_{\nu} = \nu^{\alpha}$, Gioia et al. 1982)
  - Steeper
  - synchrotron

- **(U)LIRGS- Flatter spectra**
  - **Synchrotron self absorption** (SSA) presence of an AGN
  - **Thermal free-free absorption** cases of starburst dominated spectra (Clemens et al. 2010; Condon et al. 1992)

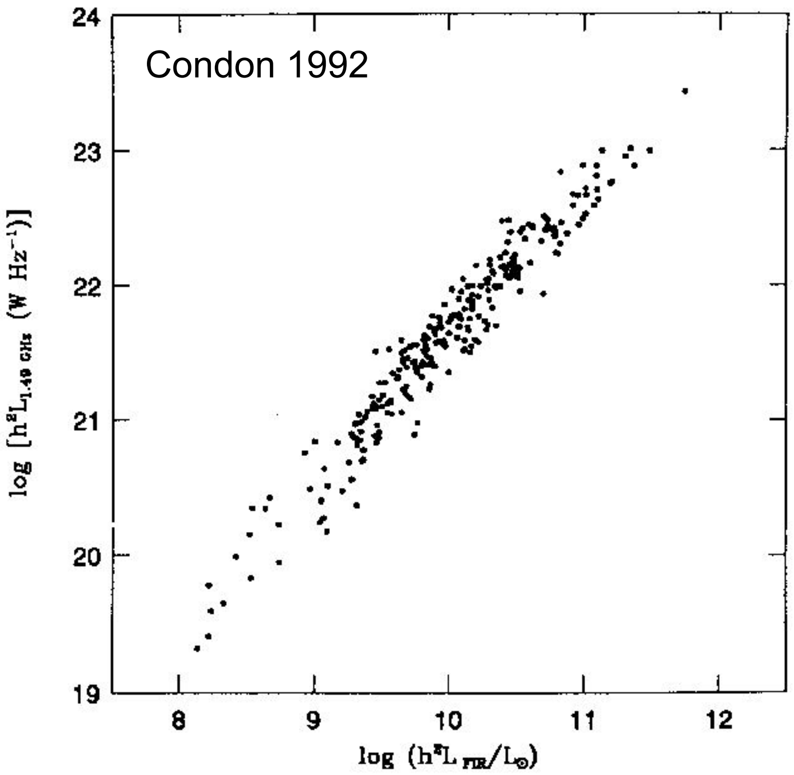



Condon, 1992

-High values of the far-infrared–radio flux ratio, q

# q- parameter

- Normal Galaxies show tight correlation between the amount of infrared power and the radio power
- Dust surrounding a hot massive star (mass > $8M_{\odot}$ ) gets heated.
- Dust Gas Re-radiate in IR
- Massive stars end up as Type II and Type Ib supernovae whose remnants (SNRs) accelerate the relativistic electrons which results in radio synchrotron emission.
- Measure of FIR to radio luminosities is called the “q” parameter.

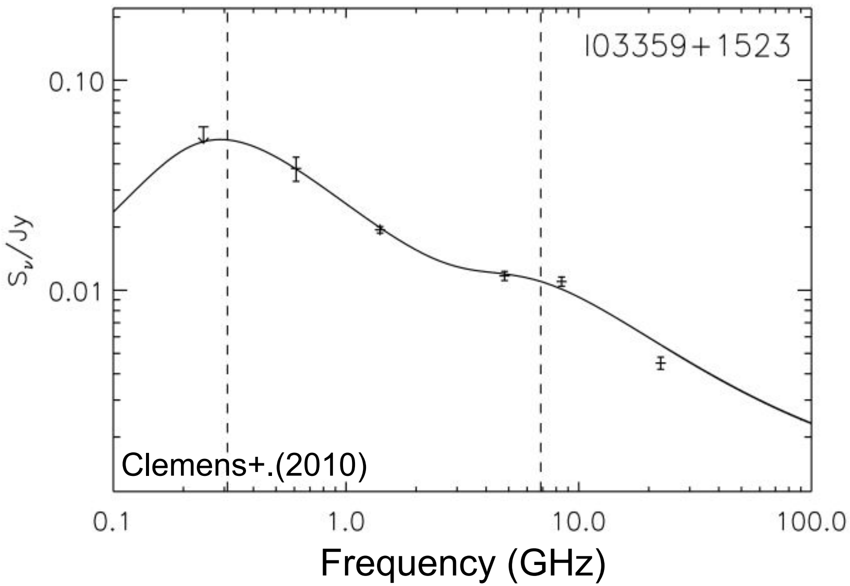


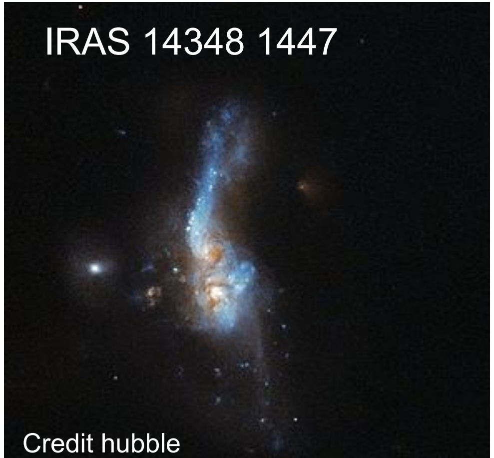
- The mean < q > for normal star forming galaxy is
  - $2.24 \pm 0.2[\log(L_{FIR} / L_{1.49GHz})]$

- (U)LIRGS = 1.9 to 3.11 (Condon et al. 1991; Clemens et al. 2008)
- Large scatter which can be due to excess of FIR or the deficiency of radio emission in these sources.
- The frequency of AGN powered ULIRGs increases sharply at $L_{IR} \geq 10^{12.3}$ (Veilleux et al. 1997)

- (U)LIRGs represent extreme cases of star formation activity and AGN nuclei.

- Clemens et al. (2010) low frequency radio spectra of 31 (U)LIRGs.
- Their low frequency spectra show a variety of shapes:
  -Turnover below 1.4 GHz
  -Steep
  -Two turnovers
- Population of electrons which resides in two different environments with diverse emission measures.
- Two emission components reside in the starburst region of merging nuclei of the two galaxies.
- (U)LIRGs are found to be interacting/merging galaxies (Cui et al. 2001; Chen et al. 2010)



# DATA and SAMPLE SELECTION

- 11 LIRGs assembled with selection criterion of $\log(L_{IR}) > 10.75 L_\odot$ from list Condon et al. (1996) of IRAS bright galaxies with flux densities greater than 5.24 Jy at $\lambda = 60\ \mu m$

- Counterparts exist in the TGSS DR4(TIFR Giant Metrewave Radio Telescope(GMRT) Sky survey)

# SAMPLE OF LIRGS

Table 1: Basic information on our sample of LIRGs

| Name<br><br>(1) | RA (J2000)<br><br>(2) | Dec.(J2000)<br><br>(3) | $S_{150}$<br>(mJy)<br>(4) | $\sigma_{S_{150}}$<br>(mJy/b)<br>(5) | $S_{1400}$<br>(mJy)<br>(6) | $\alpha_{150}^{1400}$<br><br>(7) | z<br><br>(8) | size<br>($''$)<br>(9 ) | $log(L_{IR})$<br>($L_{\odot}$)<br>(10) | $q_{1400}$<br><br>(11) |
|---|---|---|---|---|---|---|---|---|---|---|
| ESO 500-G011 | 10 24 31.4 | -23 33 18 | 119.94 | 4.23 | 57.4 | −0.32 | 0.0122 | 13.4 | 10.77 | 2.4 |
| NGC 3508 | 11 02 59.7 | -16 17 22 | 368.8 | 5.63 | 69.3 | −0.74 | 0.0128 | 34.9 | 10.79 | 2.2 |
| ESO 440-IG058 | 12 06 51.9 | -31 56 54 | 173.54 | 6.26 | 51.7 | −0.54 | 0.0232 | 18.5 | 11.18 | 2.3 |
| ESO 507-G070 | 13 02 52.3 | -23 55 18 | 245.93 | 6.31 | 75.4 | −0.52 | 0.0217 | 25.7 | 11.34 | 2.3 |
| NGC 5135 | 13 25 44.0 | -29 50 01 | 758.01 | 7.70 | 199.8 | −0.59 | 0.0136 | 55.1 | 11.12 | 2.1 |
| IC 4280 | 13 32 54.3 | -24 12 26 | 166.7 | 4.34 | 58.7 | −0.46 | 0.0162 | 22.7 | 10.85 | 2.2 |
| NGC 6000 | 15 49 49.6 | -29 23 13 | 656.1 | 3.69 | 167.8 | −0.61 | 0.0070 | 84.3 | 10.92 | 2.5 |
| IR 16164-0746 | 16 19 11.8 | -07 54 03 | 178.08 | 7.54 | 66.8 | −0.43 | 0.0271 | U | 11.29 | 2.3 |
| ESO 453-G005 | 16 47 31.1 | -29 21 22 | 86.9 | 3.83 | 26.7 | −0.52 | 0.0209 | 5.8 | 11.04 | 2.7 |
| IR 18293-3413 | 18 32 41.1 | -34 11 27 | 447.05 | 13.40 | 226.1 | −0.30 | 0.0181 | 30.4 | 11.62 | 2.3 |
| ESO 593-IG008 | 19 14 31.1 | -21 19 09 | 374.7 | 4.59 | 60.7 | −0.81 | 0.0485 | 15.7 | 11.77 | 2.2 |

Columns : (1) source name; (2) right ascension; (3) declination; (4)150 MHz flux density from TGSS DR4; (5) rms error in 150 MHz flux density near the target position; (6) 1400 MHz flux density from NVSS survey; (7) Spectral index, α, between 150 MHz and 1400 MHz; (8) redshift; (9) resolved angular size of the sources as given in TGSS source catalogue DR4; U - unresolved in TGSS maps ; (10) infra-red luminosity; (11) q= $\log(L_{FIR} / L_{150MHz})$

# Observations

- Telescope : GMRT
- Date : June 2013
- Frequencies : 325 MHz and 610 MHz
- Analysis : AIPS

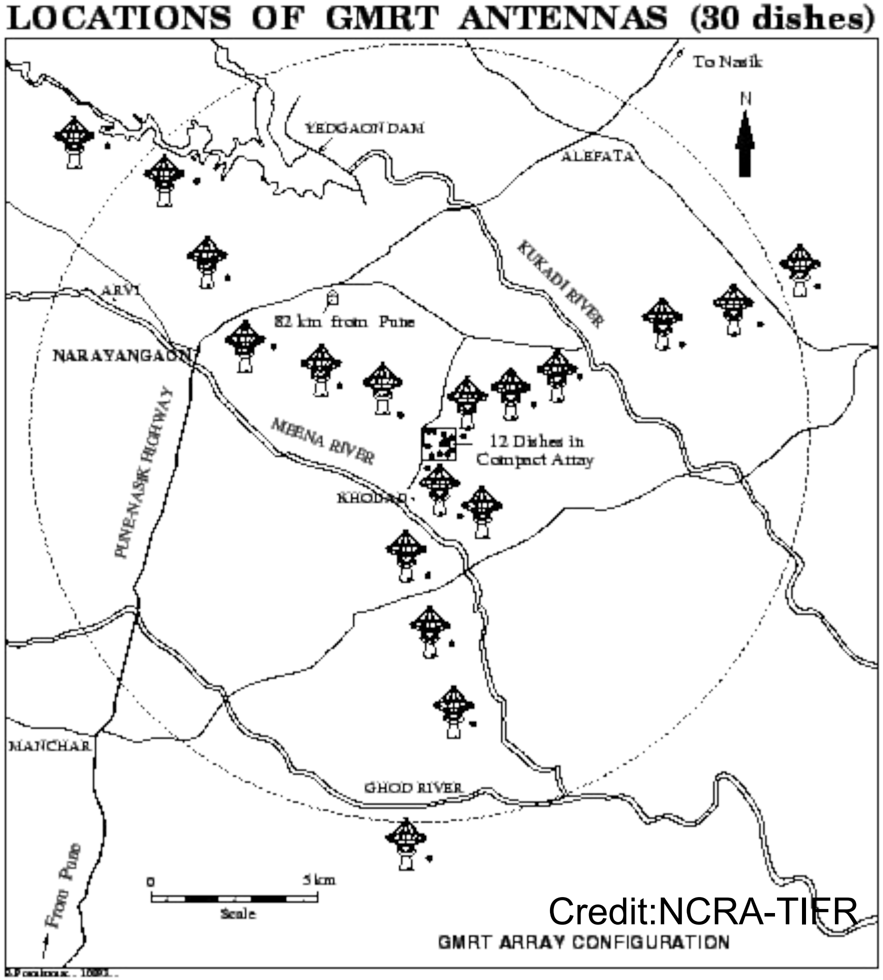
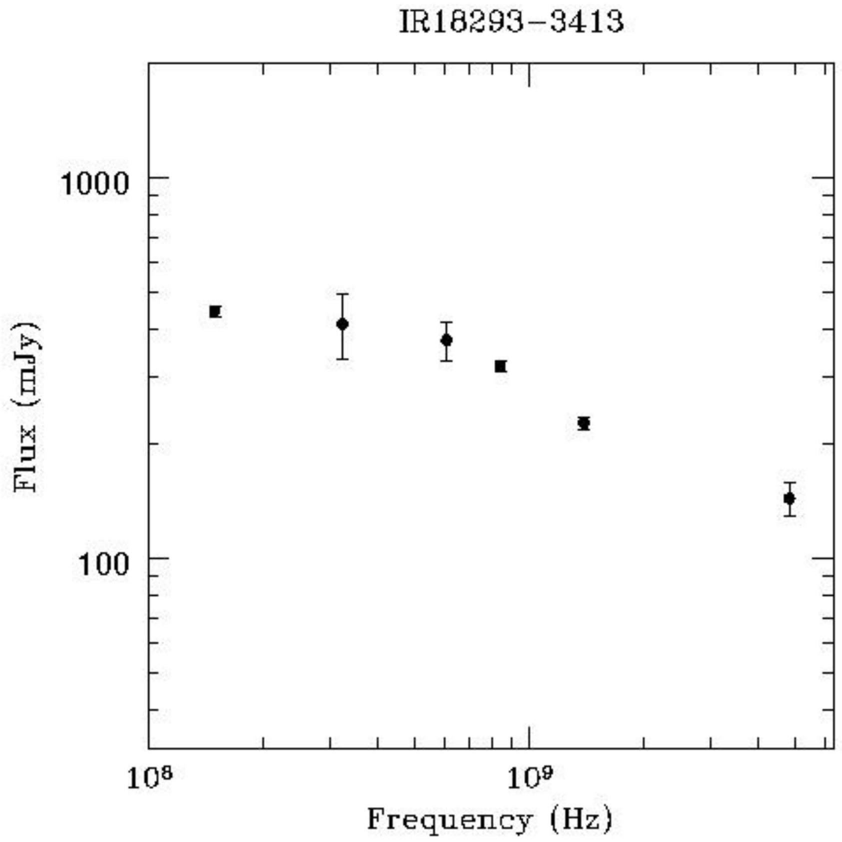
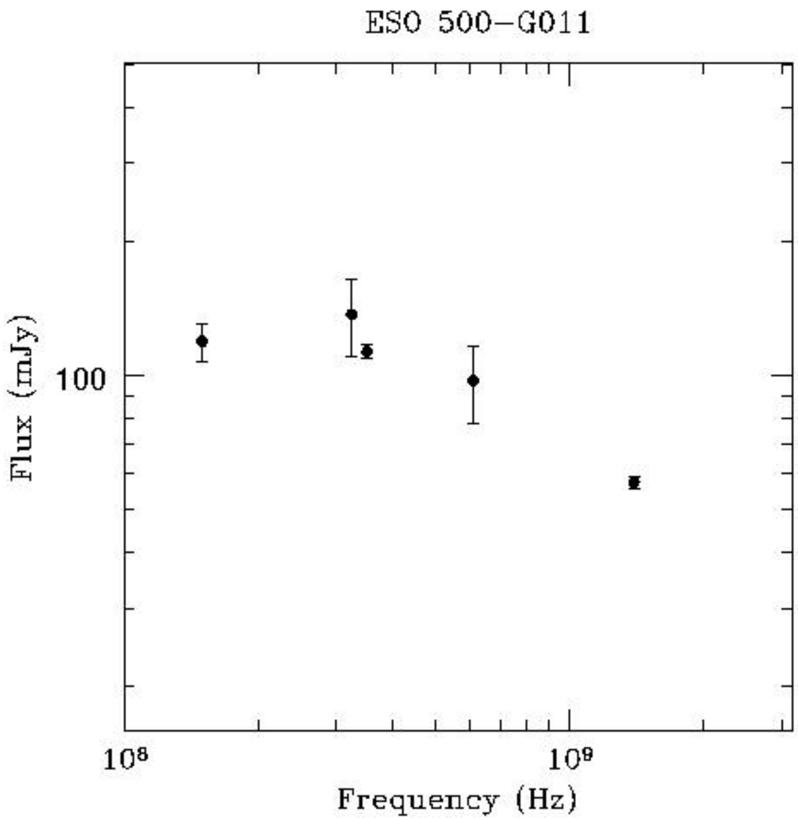


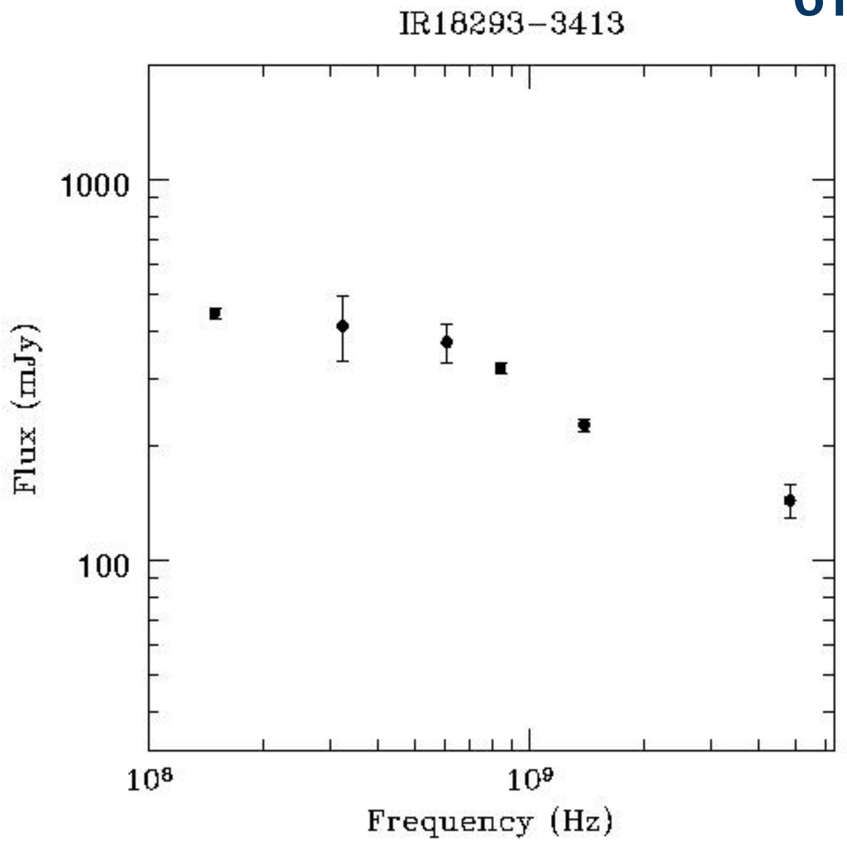

Figure: GMRT array configuration

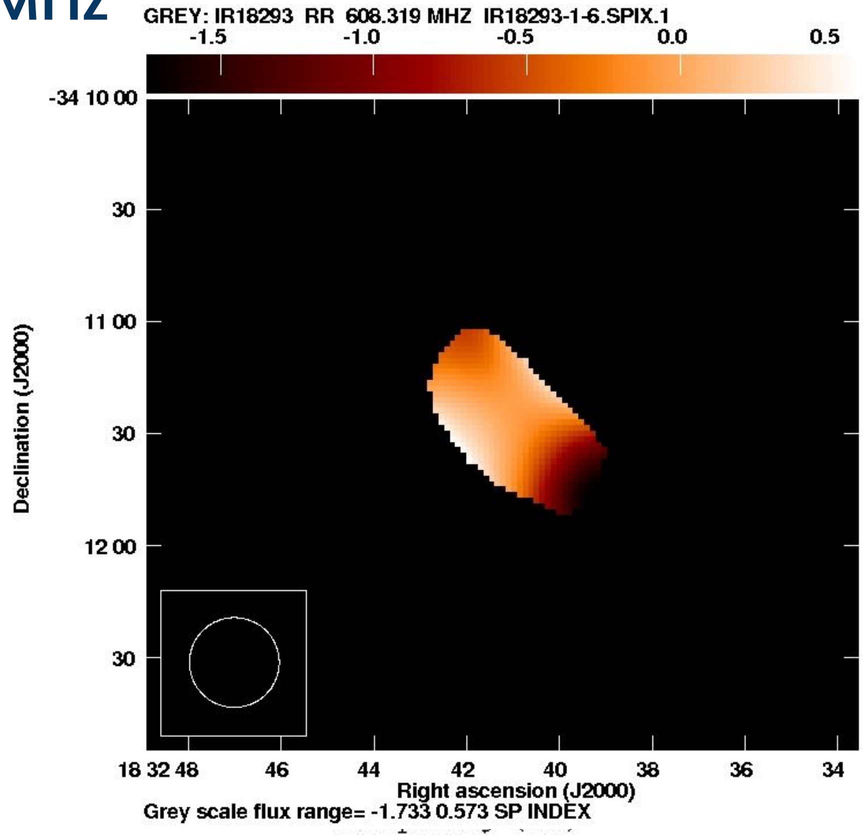
# Integrated radio spectra

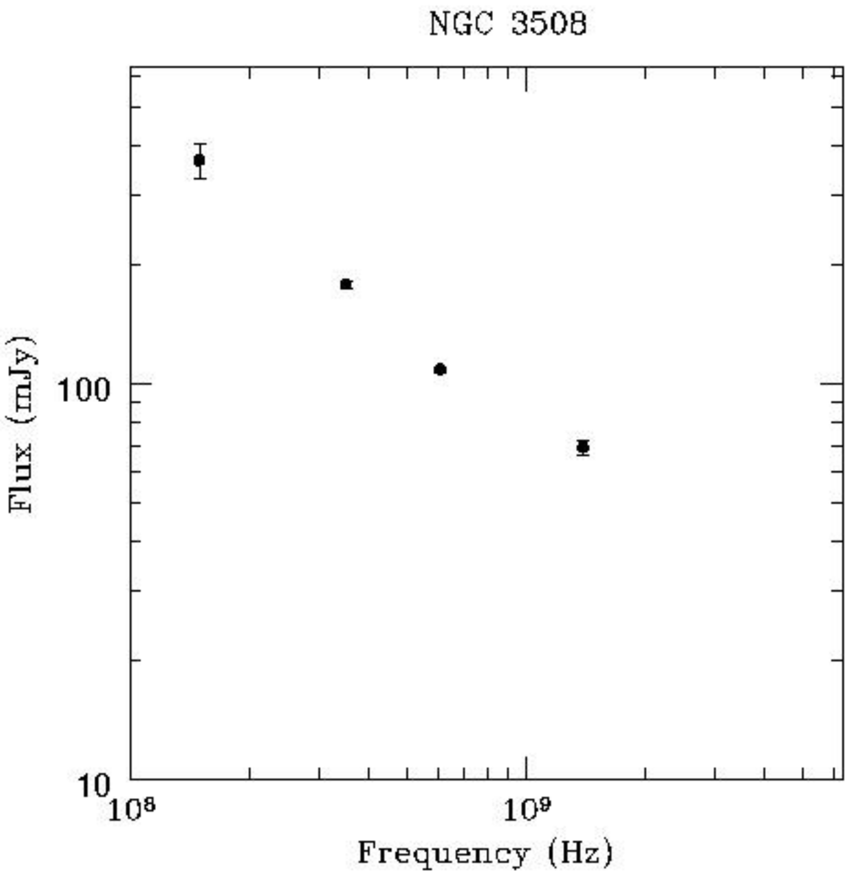


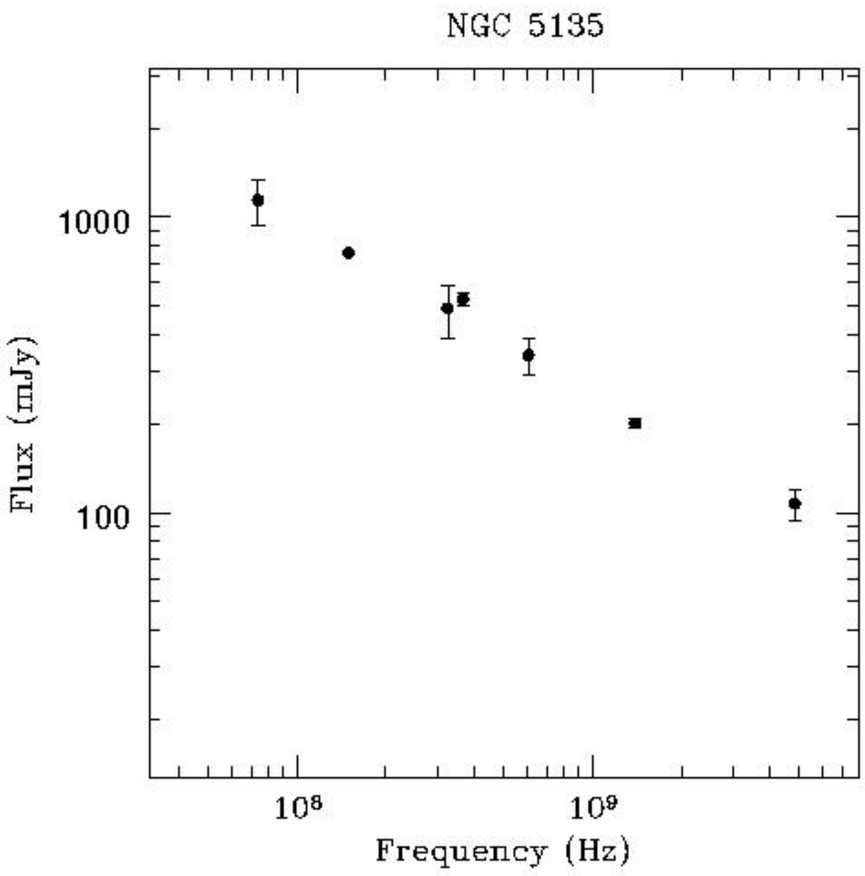



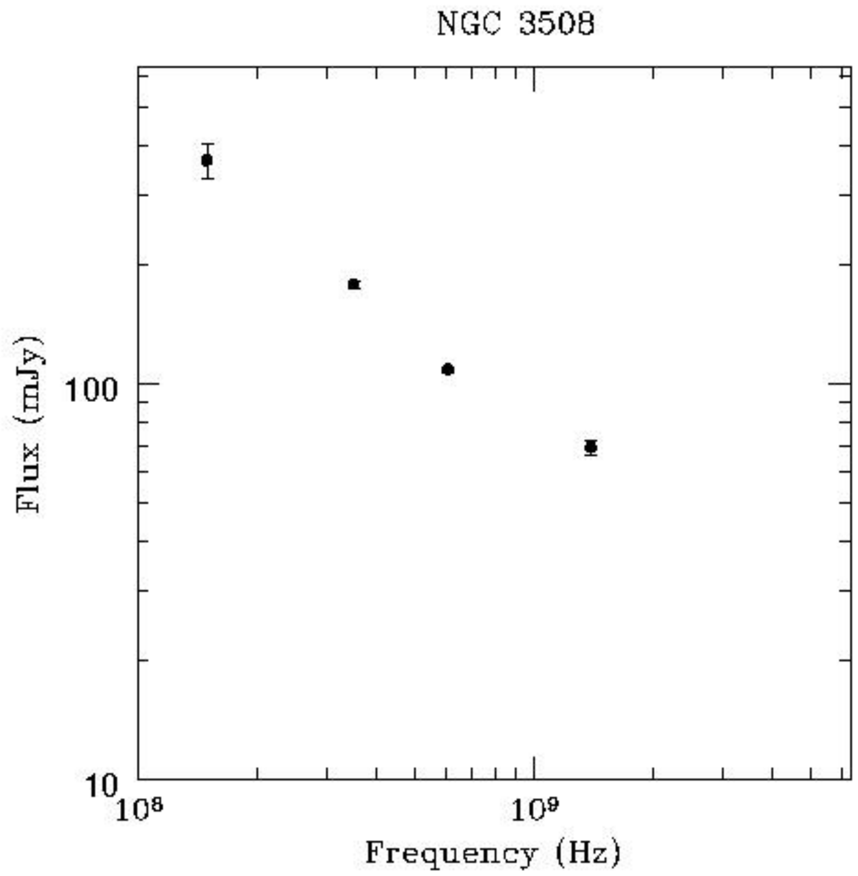
# Spectral index maps between 150 and 610 MHz

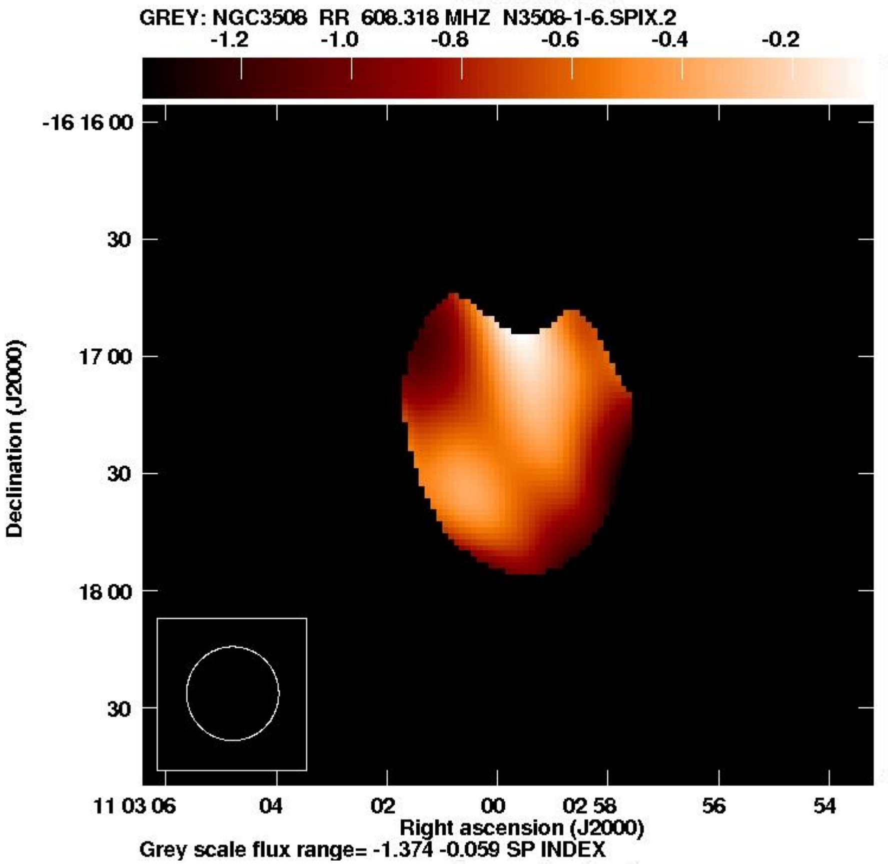


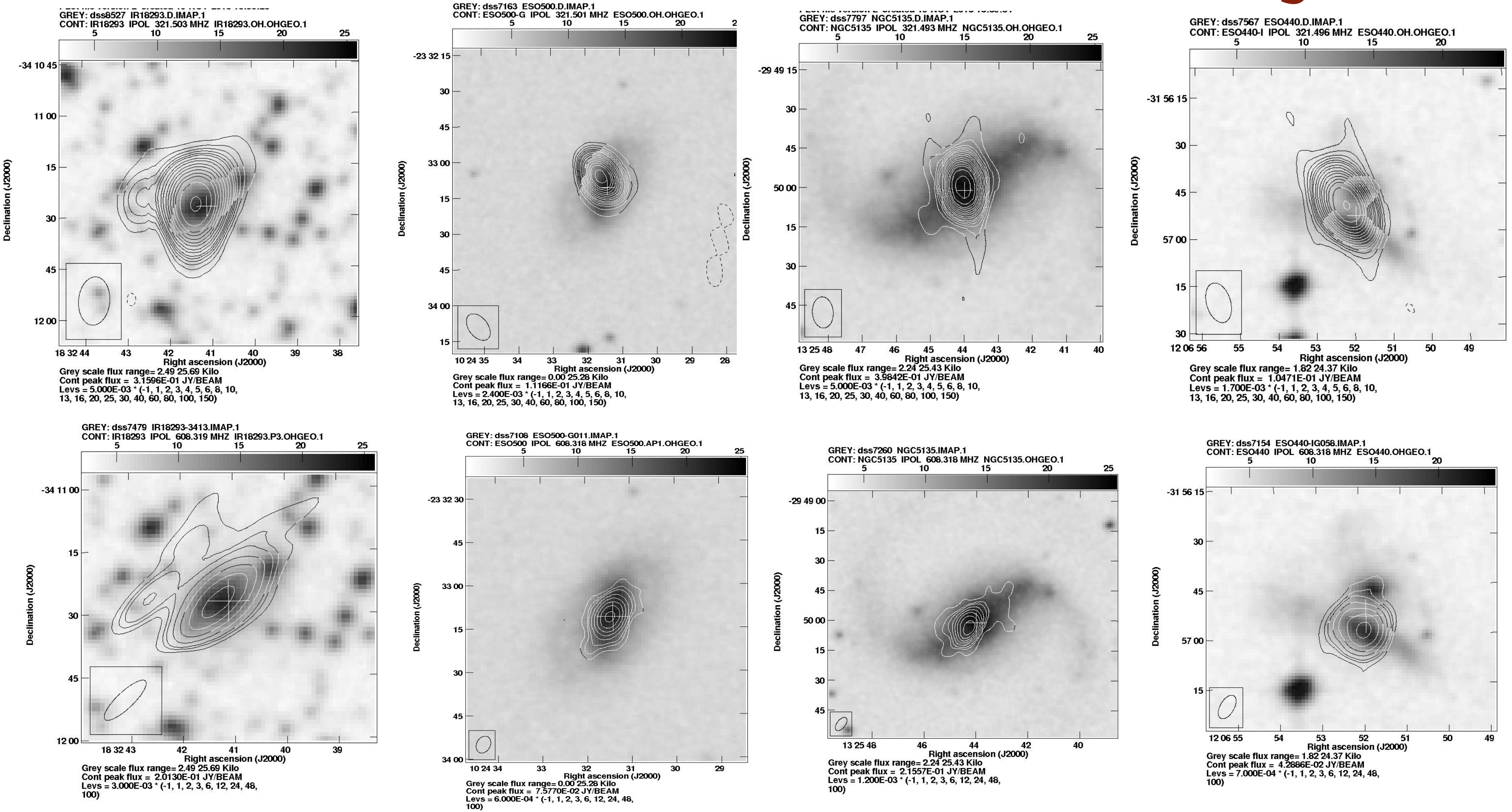

NGC 3508
Flux (mJy)
100
10
$10^8$
$10^9$
Frequency (Hz)


NGC 5135
Flux (mJy)
1000
100
$10^8$
$10^9$
Frequency (Hz)


NGC 3508
Flux (mJy)
100
10
10^8
10^9
Frequency (Hz)


GREY: NGC3508 RR 608.318 MHZ N3508-1-6.SPIX.2
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-16 16 00
30
17 00
30
18 00
30
Declination (J2000)
11 03 06
04
02
00
02 58
56
54
Right ascension (J2000)
Grey scale flux range= -1.374 -0.059 SP INDEX

# 325 MHz and 610 MHz contours on DSS images



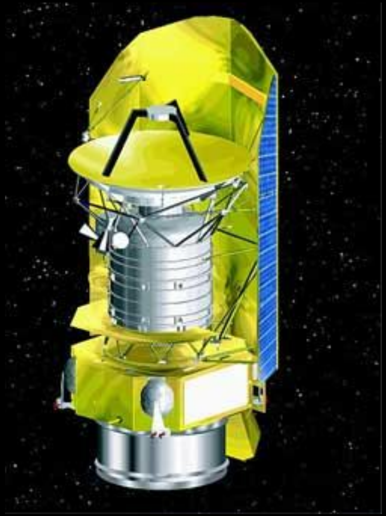
# Spectral Energy Distribution fitting from FIR to FUV (CIGALE)

UV, IR data from satellites, Galex, IRAS, Spitzer, Herschel etc

GALEX

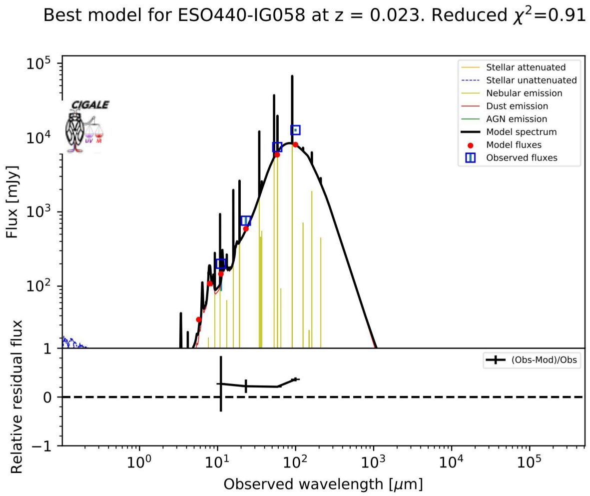
IRAS

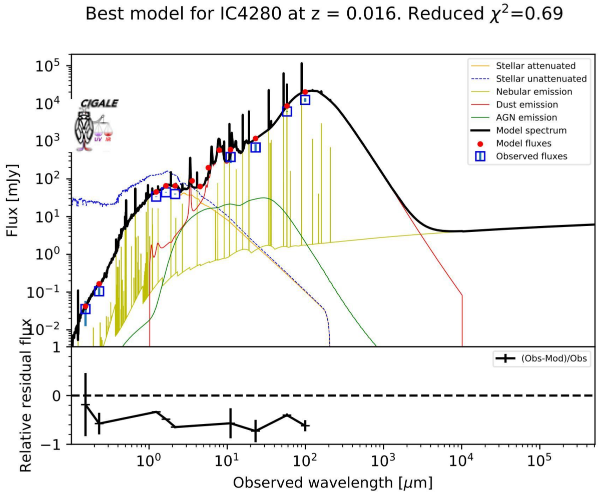
SPITZER

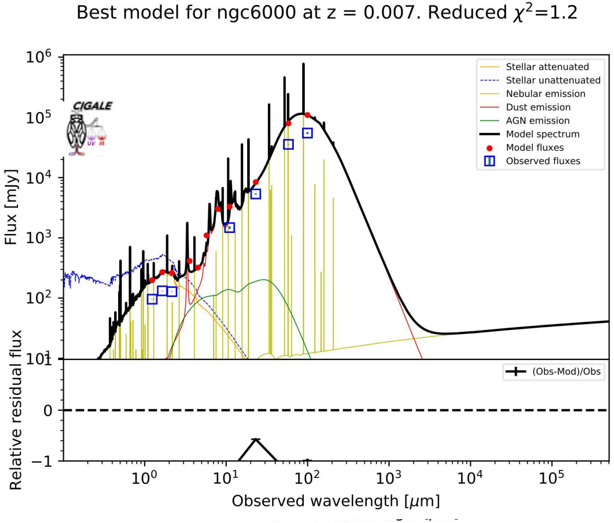


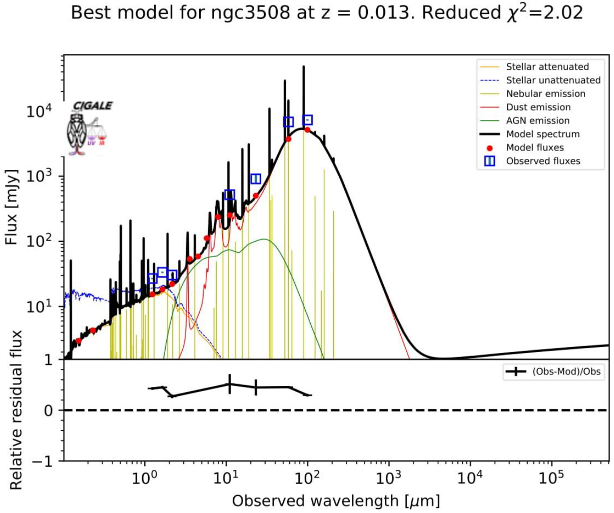
HERSCHEL

IMAGE CREDIT:  NASA


Best model for ESO440-IG058 at z = 0.023. Reduced χ²=0.91
Stellar attenuated
Stellar unattenuated
Nebular emission
Dust emission
AGN emission
Model spectrum
Model fluxes
Observed fluxes
(Obs-Mod)/Obs
CIGALE
Flux [mJy]
Relative residual flux
Observed wavelength [μm]


Best model for IC4280 at z = 0.016. Reduced χ²=0.69
Stellar attenuated
Stellar unattenuated
Nebular emission
Dust emission
AGN emission
Model spectrum
Model fluxes
Observed fluxes
(Obs-Mod)/Obs
CIGALE
Flux [mJy]
Relative residual flux
Observed wavelength [μm]


Best model for ngc6000 at z = 0.007. Reduced χ²=1.2
Stellar attenuated
Stellar unattenuated
Nebular emission
Dust emission
AGN emission
Model spectrum
Model fluxes
Observed fluxes
(Obs-Mod)/Obs
CIGALE
Flux [mJy]
Relative residual flux
Observed wavelength [μm]


Best model for ngc3508 at z = 0.013. Reduced χ²=2.02
Stellar attenuated
Stellar unattenuated
Nebular emission
Dust emission
AGN emission
Model spectrum
Model fluxes
Observed fluxes
(Obs-Mod)/Obs
CIGALE
Flux [mJy]
Relative residual flux
Observed wavelength [μm]

# PRELIMINARY RESULTS

- ★ The low frequency radio spectra show variety of shapes. The median spectral indices are :
  $\alpha_{150} = -0.34$, $\alpha_{325} = -0.59$, $\alpha_{610} = -0.64$.
  This flattening could be due to
  (a) 150 MHz is from TGSS snapshot and hence might miss some extended emission in a few galaxies
  (b) the galaxy spectrum is indeed turning over for these galaxies due to central AGN.
  This flattening is not seen above 325 MHz for which the median spectral index is close to that typical of optically thin synchrotron emission.

- ★ 4 out of 11 LIRGs (NGC 3508, NGC 5135, NGC 6000 and ESO 593) show a power law spectrum down to 150 MHz. 4 LIRGs show a flat radio spectrum ($\alpha > -0.5$) below 325 MHz.

- ★ This is consistent with the result obtained by Clemens et al.(2010) for whose sample of 20 LIRGs, 11 turned out to have flat spectra. This turn over could be due to AGN or free-free absorption.

- ★ The high resolution spectral index maps between 150 MHz and 610 MHz show a range, i.e., between 0 to -1.5 with the flatter spectrum occurring in the central parts of the disks for most of the galaxies.

- ★ From CIGALE fitting, best SFR obtained for our set of galaxies is 24.998± 13.281 $M_{\odot} yr^{-1}$

# Future Prospective

- This is a work in progress!

- SED fit using cigale code and obtain other parameter such as stellar mass, dust luminosity, AGN fraction of mid-infrared emission etc

- Detailed 3D modelling (Chyzy et al. 2018) of galaxy radio emission, and radiation transfer depending on the galaxy viewing angle and absorption processes


THANK YOU!!!