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Panchromatic SED modelling of Infrared Bright Galaxies

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Thanks to: Arti Goyal, Katarzyna Małek, Krzysztof Chyży, Timothy J Galvin, Nicholas Seymour, Tanio Díaz Santos, Vassilis Charmandaris, Michał Ostrowski

LOFAR

Lofar Family Meeting, 12-16th June

Introduction

Luminous Infrared Galaxies(LIRGs): $L_{IR[8\text{-}1000\mu m]} = 10^{11}\text{-}10^{12} L_{\odot}$

Ultraluminous Infrared Galaxies (ULIRGs): $L_{IR[8\text{-}1000\mu m]} \geq 10^{12} L_{\odot}$

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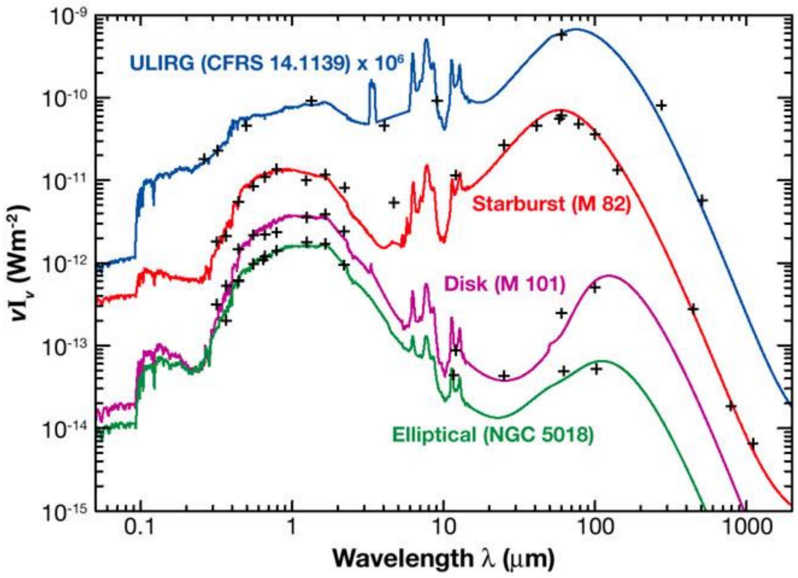
Galliano, F. 2004



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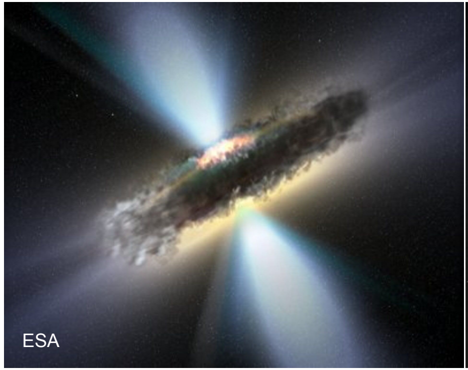
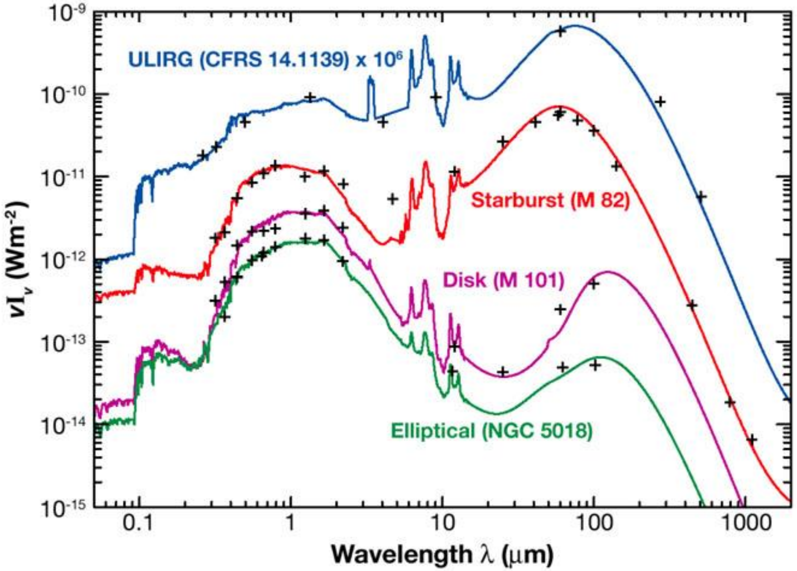
What is Powering them???



Active galactic nuclei and/or Massive bursts of star formation

Galliano, F. 2004



LIRGs: Sample Selection

- Selection criterion - $L_{IR} > 10^{10.75} L_{\odot}$ from list Condon et al. (1996) of IRAS bright galaxies with flux densities > 5.24 Jy at λ = 60 μm

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

Name	R.A. (h m s)	Dec. (° ′ ″)	z	$\log_{10}(L_{IR})$ ($L_{\odot}$)
(1)	(2)	(3)	(4)	(5)
ESO 500-G034	10 24 31.4	−23 33 10	0.0122	10.77
NGC 3508	11 02 59.7	−16 17 22	0.0128	10.65
ESO 440-IG058	12 06 51.9	−31 56 54	0.0232	11.18
ESO 507-G070	13 02 52.3	−23 55 18	0.0217	11.34
NGC 5135	13 25 44.0	−29 50 01	0.0136	11.12
IC 4280	13 32 53.4	−24 12 26	0.0162	10.85
NGC 6000	15 49 49.6	−29 23 13	0.0070	10.92
IR 16164-0746	16 19 11.8	−07 54 03	0.0271	11.29
ESO 453-G005	16 47 31.1	−29 21 22	0.0209	11.69
IR 18293-3413	18 32 41.1	−34 11 27	0.0181	11.62
ESO 593-IG008	19 14 31.1	−21 19 09	0.0485	11.77

1) source name, (2) R.A., (3) decl., (4) spectroscopic redshift from the NASA/IPAC Extragalactic Database (NED), (5) value of the absolute FIR luminosity from Table 1 of Condon+ 1996, except for NGC 3508, which is taken from Table 1 of Condon+ 1990.

Data – Own radio observation

Observations

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

Antenna

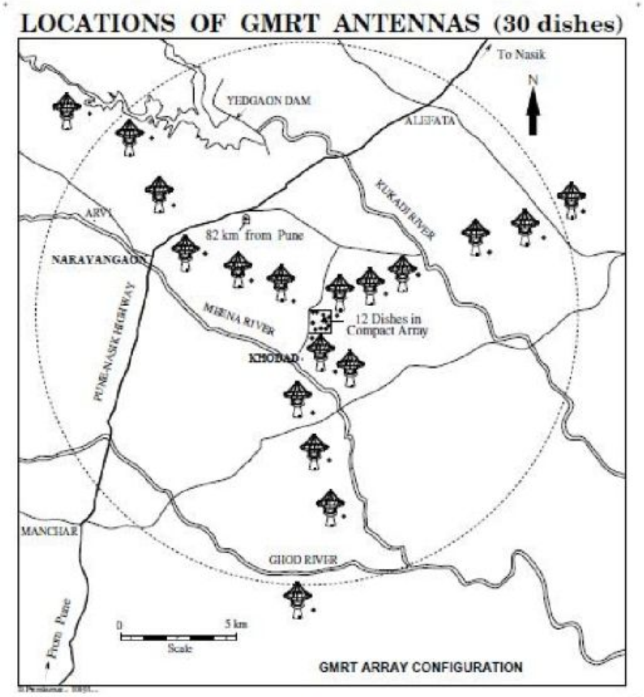


FIGURE – GMRT array configuration

Archival radio data

Very Large Aarray

- Telescope : Very Large Array (VLA)
- Frequencies : 1.4 GHz, 3GHz, 4.8 MHz, 8.4 GHz and 14.9 GHz

Antenna

The Galactic And Extra-Galactic All-Sky MWA Survey

- Telescope : Murchison Widefield Array
- Frequencies : 70–300 MHz

Antenna

We also have data from ATCA and SUMSS for some of our galaxies

Generation of broadband radio spectra - 80 MHz to 15.0 GHz

Radio SED modelling

- Synchrotron emission

$$S_\nu = A\left(\frac{\nu}{\nu_0}\right)^{\alpha}$$

- Synchrotron and Free-Free Emission

$$S_\nu = A\left(\frac{\nu}{\nu_0}\right)^{\alpha} + B\left(\frac{\nu}{\nu_0}\right)^{-0.1}$$

- Synchrotron and Free-Free Emission with Free-Free Absorption

$$S_\nu = (1 - e^{-\tau})\left[B + A\left(\frac{\nu}{\nu_{t,1}}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_{t,1}}\right)^{2}$$

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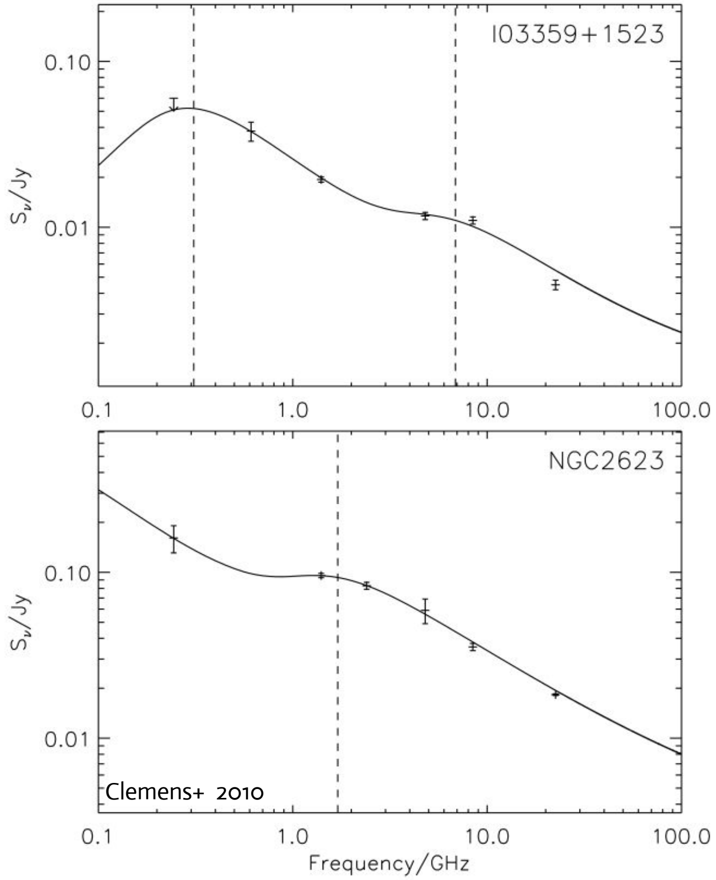

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$$S_\nu = (1 - e^{-\tau})\left[B + A\left(\frac{\nu}{\nu_{t,1}}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_{t,1}}\right)^{2}$$

Multiple Component Models

$$S_\nu = (1 - e^{-\tau_1})\left[B + A\left(\frac{\nu}{\nu_{t,1}}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_{t,1}}\right)^{2} + (1 - e^{-\tau_2})\left[D + C\left(\frac{\nu}{\nu_{t,2}}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_{t,2}}\right)^{2}$$

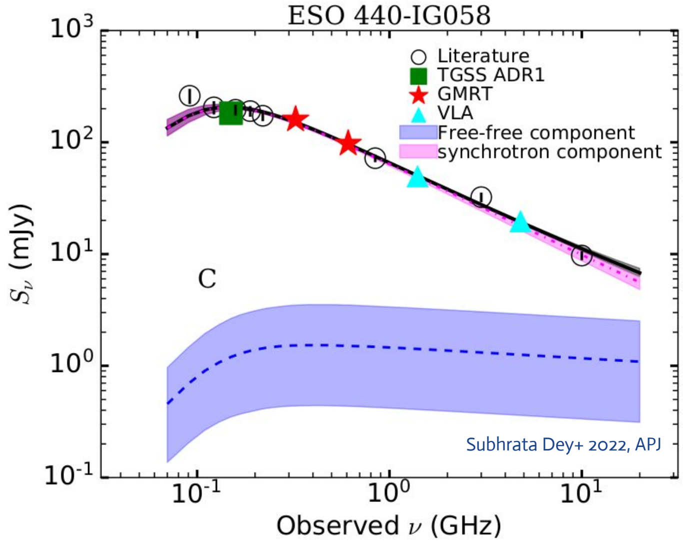
$$S_\nu = \left(\frac{\nu}{\nu_0}\right)^{-2.1}\left[B + A\left(\frac{\nu}{\nu_0}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_0}\right)^{2} + (1 - e^{-\tau_2})\left[D + C\left(\frac{\nu}{\nu_{t,2}}\right)^{0.1+\alpha}\right]\left(\frac{\nu}{\nu_{t,2}}\right)^{2}$$

Radio SED modelling

UltraNest, Nested sampling bayesian inference method was used to constrain each of described radio continuum models and to compare models.

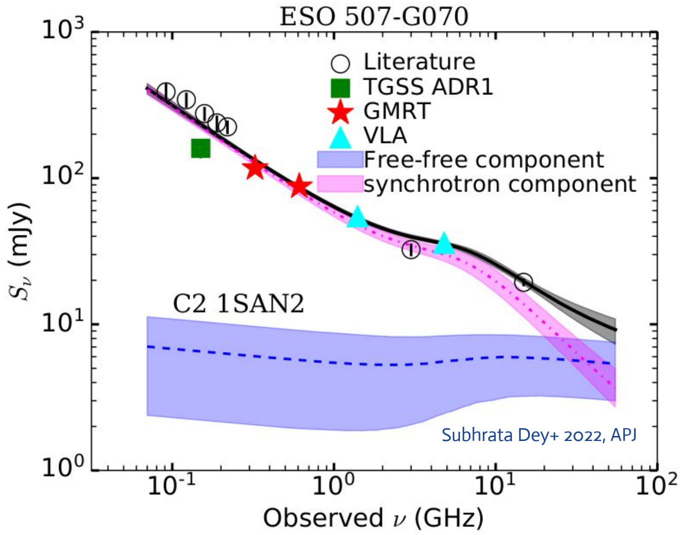
ESO 440-IG058

- Synchrotron free- free emission with absorption



ESO 507-G070

- Mix component model:
Synchrotron free-free emission with absorption and power law



Results

Non-thermal normalisation component

Name	Model	A (mJy)	B (mJy)	α	$\nu_{t,1}$ (GHz)	C (mJy)	D (mJy)	α_2	$\nu_{t,2}$ (GHz)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ESO 500-G034	C2 1SAN	$6.21^{+2.23}_{-1.83}$	$3.58^{+3.13}_{-2.48}$	$-1.18^{+0.11}_{-0.12}$	-	$154.37^{+11.53}_{-10.90}$	$3.80^{+3.20}_{-2.64}$	-	$0.52^{+0.07}_{-0.06}$
NGC 3508	PL	$62.20^{+2.55}_{-2.31}$	-	$-0.73^{+0.02}_{-0.02}$	-	-	-	-	-
ESO 440-IG058	C	$325.81^{+19.13}_{-16.75}$	$1.79^{+2.33}_{-1.28}$	$-0.82^{+0.03}_{-0.04}$	$0.14^{+0.02}_{-0.02}$	-	-	-	-
ESO 507-G070	C2 1SAN2	$39.95^{+4.46}_{-4.30}$	$5.10^{+3.25}_{-3.30}$	$-0.77^{+0.05}_{-0.06}$	-	$21.07^{+3.98}_{-4.20}$	$2.25^{+1.77}_{-1.53}$	$-1.50^{+0.38}_{-0.22}$	$7.49^{+1.85}_{-2.01}$
NGC 5135	C	$1294.29^{+80.51}_{-70.09}$	$7.34^{+8.88}_{-5.28}$	$-0.88^{+0.03}_{-0.05}$	$0.13^{+0.02}_{-0.02}$	-	-	-	-
IC 4280	C	$359.44^{+43.22}_{-30.17}$	$10.43^{+5.69}_{-5.93}$	$-0.89^{+0.09}_{-0.12}$	$0.13^{+0.03}_{-0.03}$	-	-	-	-
NGC 6000	SFG NC	$144.60^{+3.21}_{-3.26}$	$0.48^{+0.34}_{-0.32}$	$-0.66^{+0.01}_{-0.02}$	-	-	-	-	-
IR 16164-0746	SFG NC	$61.52^{+2.27}_{-2.33}$	$0.49^{+0.36}_{0.33}$	$-0.45^{+0.03}_{-0.03}$	-	-	-	-	-
ESO 453-G005	SFG NC	$22.34^{+1.06}_{-0.99}$	$0.52^{+0.32}_{-0.35}$	$-0.59^{+0.04}_{-0.04}$	-	-	-	-	-
IR 18293-3413	C2 1SAN2	$34.13^{+12.20}_{-9.91}$	$4.09^{+3.28}_{-2.75}$	$-1.33^{+0.12}_{-0.14}$	-	$373.64^{+42.37}_{-41.82}$	$4.19^{+3.08}_{-2.79}$	$-1.74^{+0.08}_{-0.05}$	$1.06^{+0.08}_{-0.09}$
ESO 593-IG008	C	$540.79^{+73.47}_{-47.65}$	$0.49^{+0.34}_{-0.34}$	$-0.87^{+0.03}_{-0.03}$	$0.10^{+0.02}_{-0.02}$	-	-	-	-

Results

Thermal normalisation component

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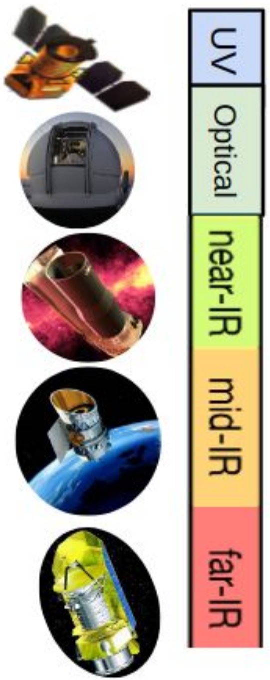
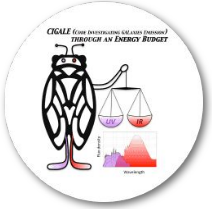
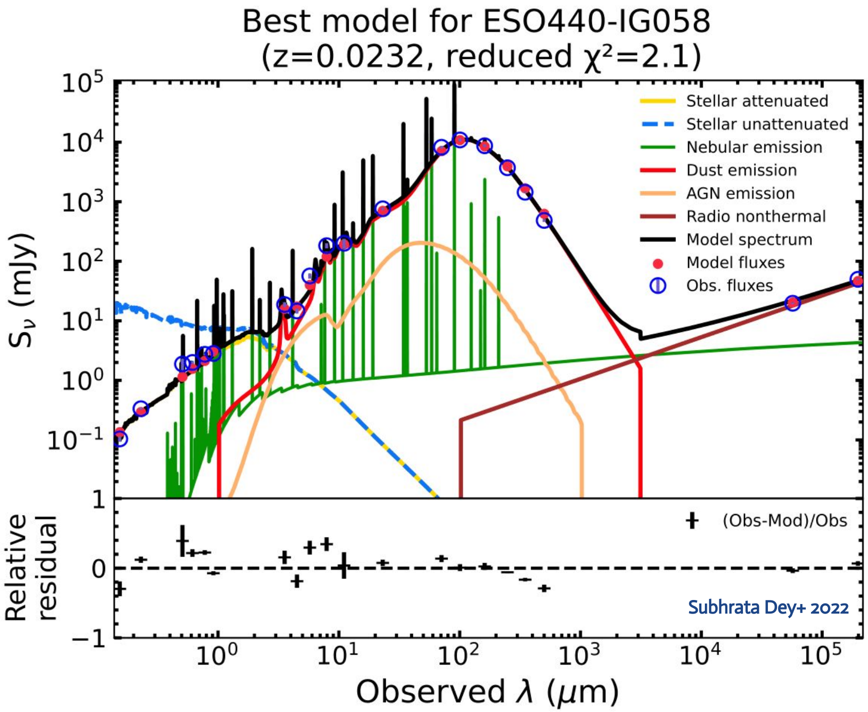
UV-radio SED modelling

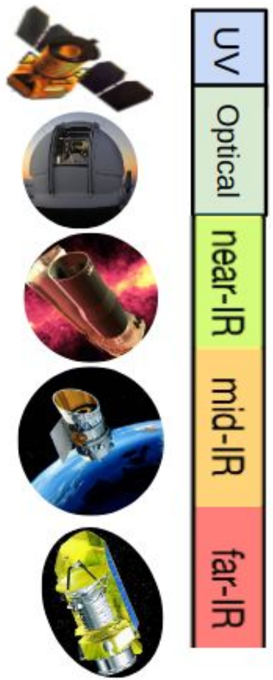


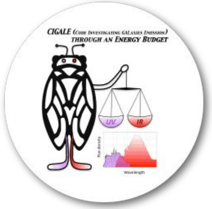


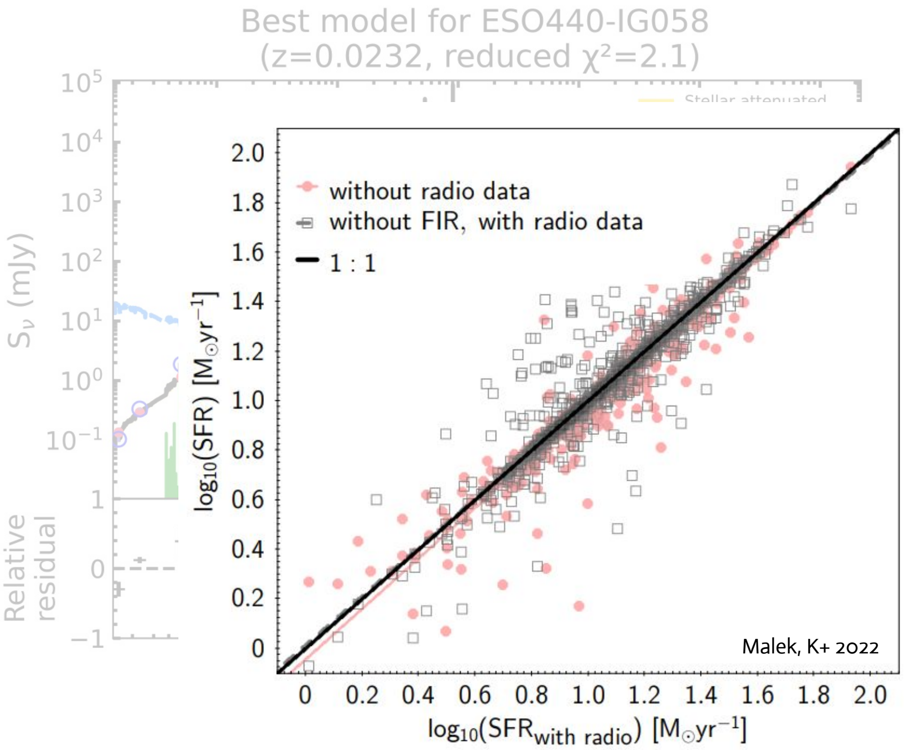


Inclusion of radio fluxes in our UV-IR SED modeling → the **L_{dust} and SFR** are estimated with **one-order magnitude better accuracies**

UV-radio SED modelling







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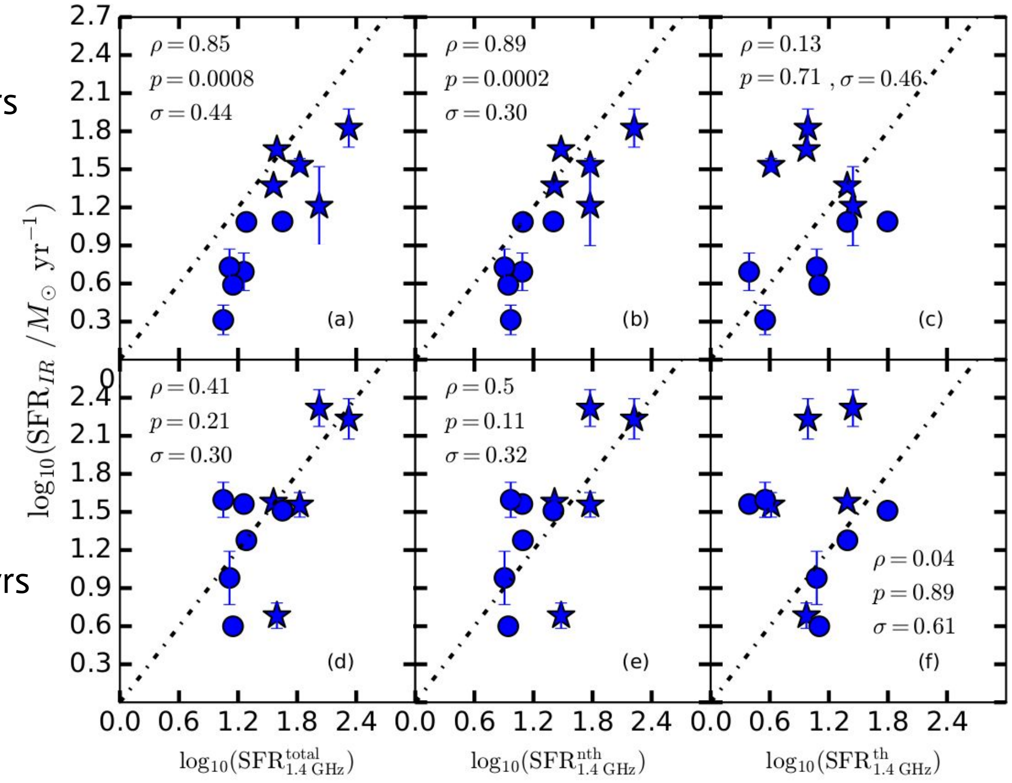
Comparison of SFR estimates from radio and UV-IR SED

Total | Non-thermal | Thermal

10 Myrs

100 Myrs



Subhrata Dey+ 2022

★ Merging Galaxies

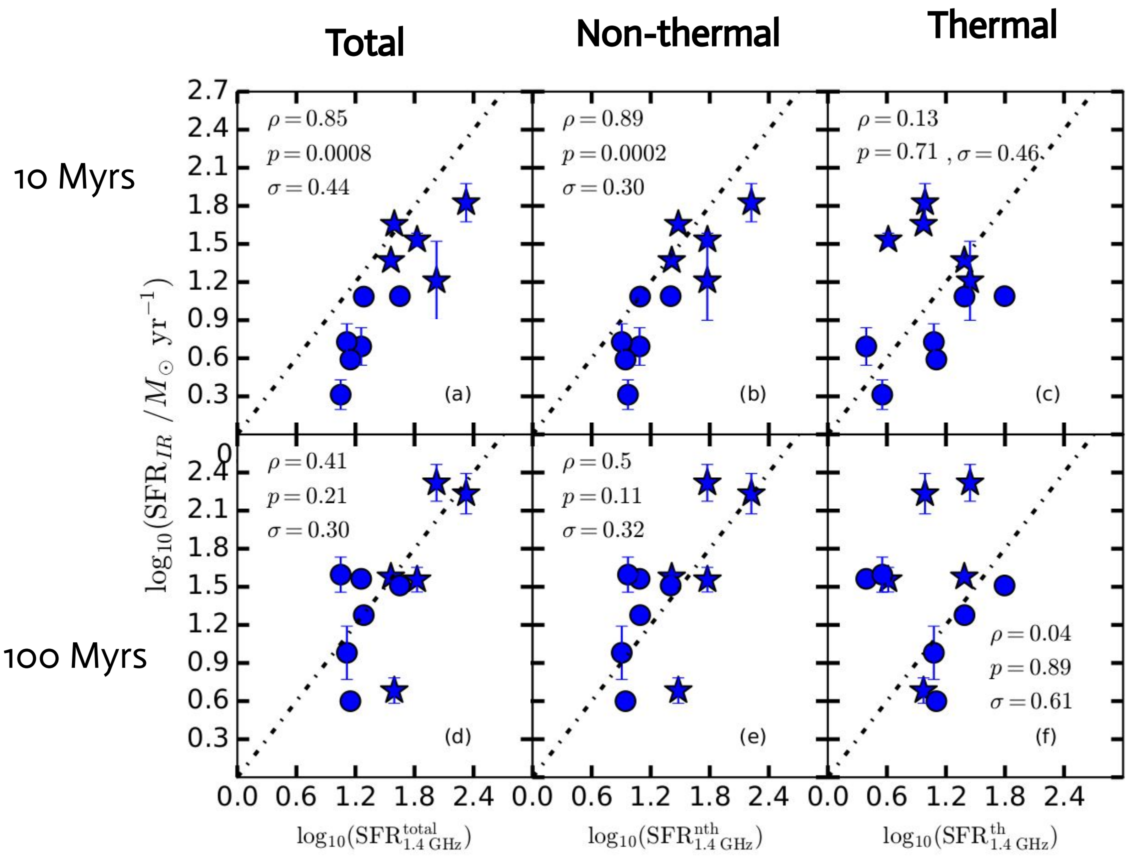
● Non-merging galaxies

Comparison of SFR estimates from radio and UV-IR SED

Much better correspondence of **SFR_{radio}** (total and non-thermal) with **SFR_{IR}** estimated 10 Myr ago.

Considering magnetic field ~50μG → synchrotron lifetime ≈ 3.3×10^5 yr

Synchrotron emission -> Effective indicator of recent SFR in galaxies.



★ Merging Galaxies

● Non-merging galaxies

Subhrata Dey+ 2022

ULIRGs: Sample Selection

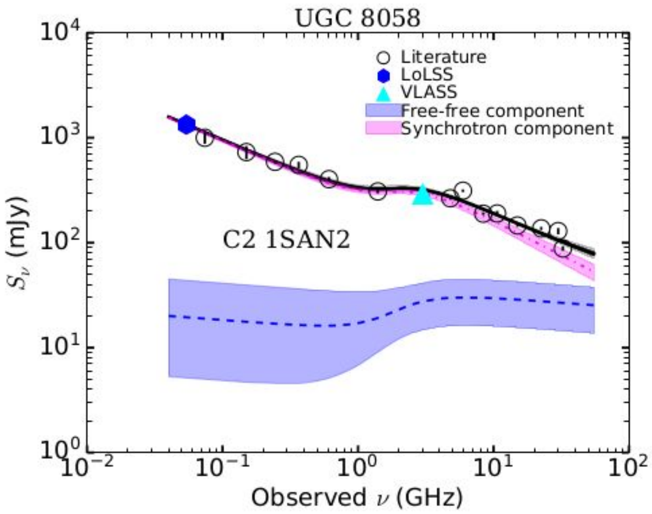
Source Name	R.A.(J2000)	decl.(J2000)	z	$\log_{10}(L_{IR})$	Ref.
	(h m s)	(° ′ ″)		($L_\odot$)	
(1)	(2)	(3)	(4)	(5)	(6)
IRAS F00183-7111	00 20 34.69	-70 55 26.7	0.3300	12.93^a	(f)
IRAS F03538-6432	03 54 25.21	-64 23 44.7	0.3007	12.62^b	(f)
IRAS 08572+3915	09 00 25.39	+39 03 54.40	0.0582	12.09^c	(g)
UGC 05101	09 35 51.60	+61 21 11.5	0.0393	11.90^c	(g)
IRAS 10565+2448	10 59 18.12	+24 32 34.46	0.0431	11.98^c	(g)
IRAS 12112+0305	12 13 46.00	+02 48 38.0	0.0733	12.28^d	(h)
UGC 08058	12 56 14.23	+56 52 25.2	0.0421	12.49^c	(g)
IRAS 13305-1739	13 33 16.54	-17 55 10.7	0.1483	12.21^d	(h)
UGC 8696	13 44 42.11	+55 53 12.7	0.0373	12.09^c	(g)
IRAS F14348-1447	14 37 38.40	-15 00 20.0	0.0823	12.30^c	(g)
IRAS 14394+5332	14 41 04.38	+53 20 08.7	0.1050	12.04^d	(h)
IRAS 17179+5444	17 18 54.40	+54 41 48.5	0.1476	12.20^e	(h)
IRASF 23529-2119	23 55 33.00	-21 03 08.7	0.4285	12.52^b	(f)
IRAS 23389+0300	23 41 30.31	+03 17 26.4	0.1450	12.09^e	(h)

1) source name, (2) R.A., (3) decl., (4) spectroscopic redshift from the NASA/IPAC Extragalactic Database (NED), (5) value of the absolute FIR luminosity (a)Spoon+ 2009, (b)braun+ 2011, (c)Clemens+ 2010, (d)Kim & Sanders 1998, (e)Veilleux+ 1999 (6) reference for the source selection: (f) Galvin+ 2016, (g) Clemens+ 2010, (h) Nandi+ 2021

Radio SED modelling

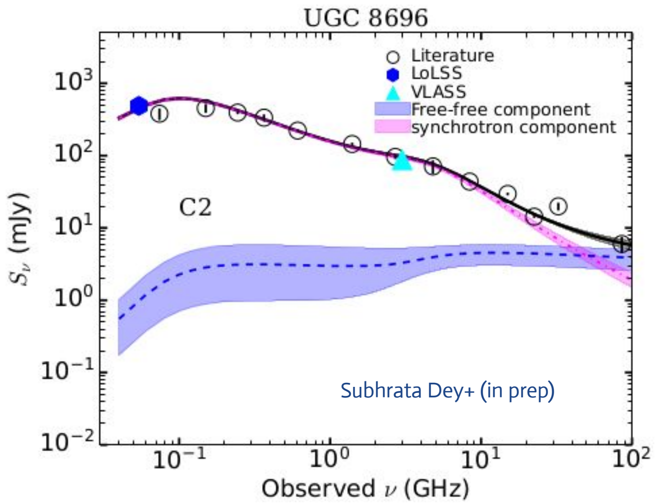
UGC 8058

- Mix component model:
  Synchrotron free-free emission with absorption and power law



UGC 8696

- Mix component model:
  Synchrotron free-free emission with absorption



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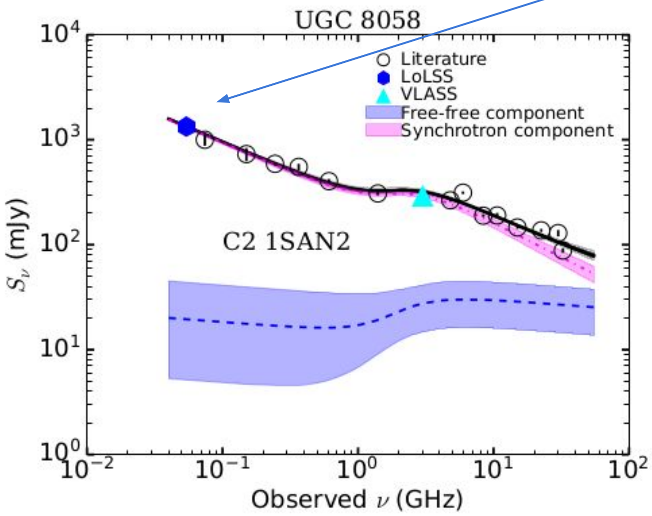
Lofar LBA Sky survey



UGC 8696

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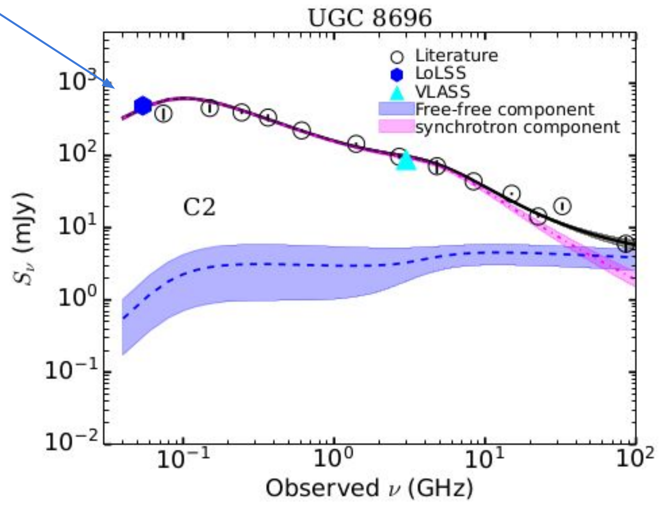

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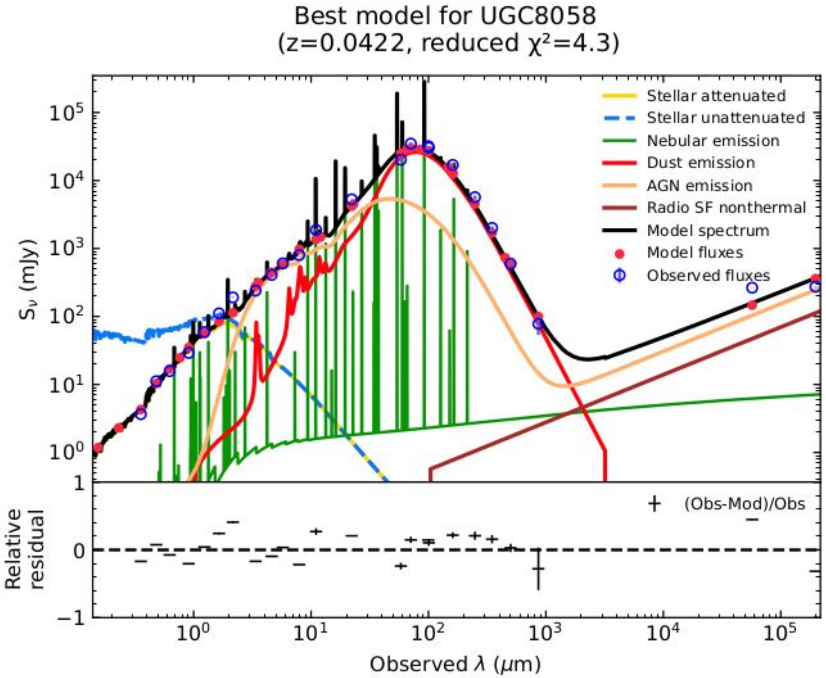
UV-radio SED modelling

UGC 8058



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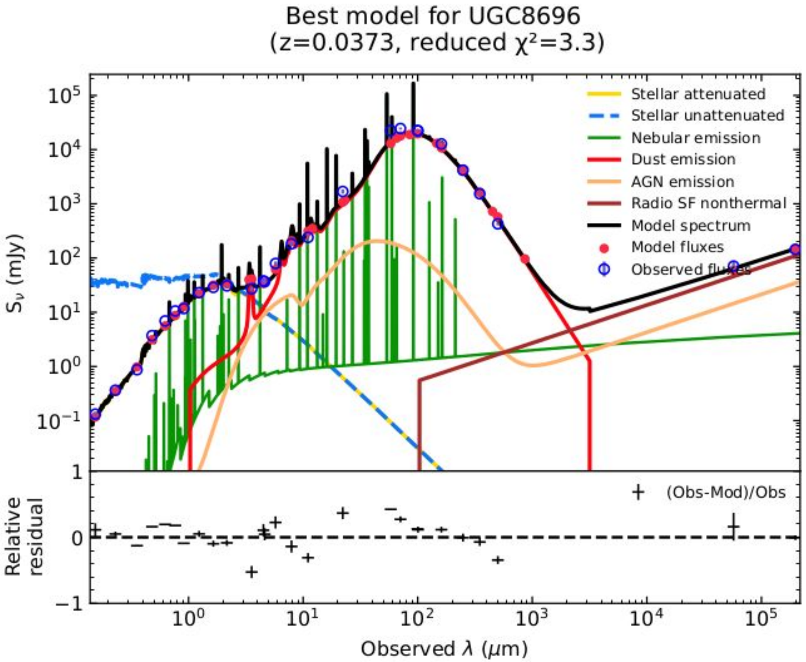
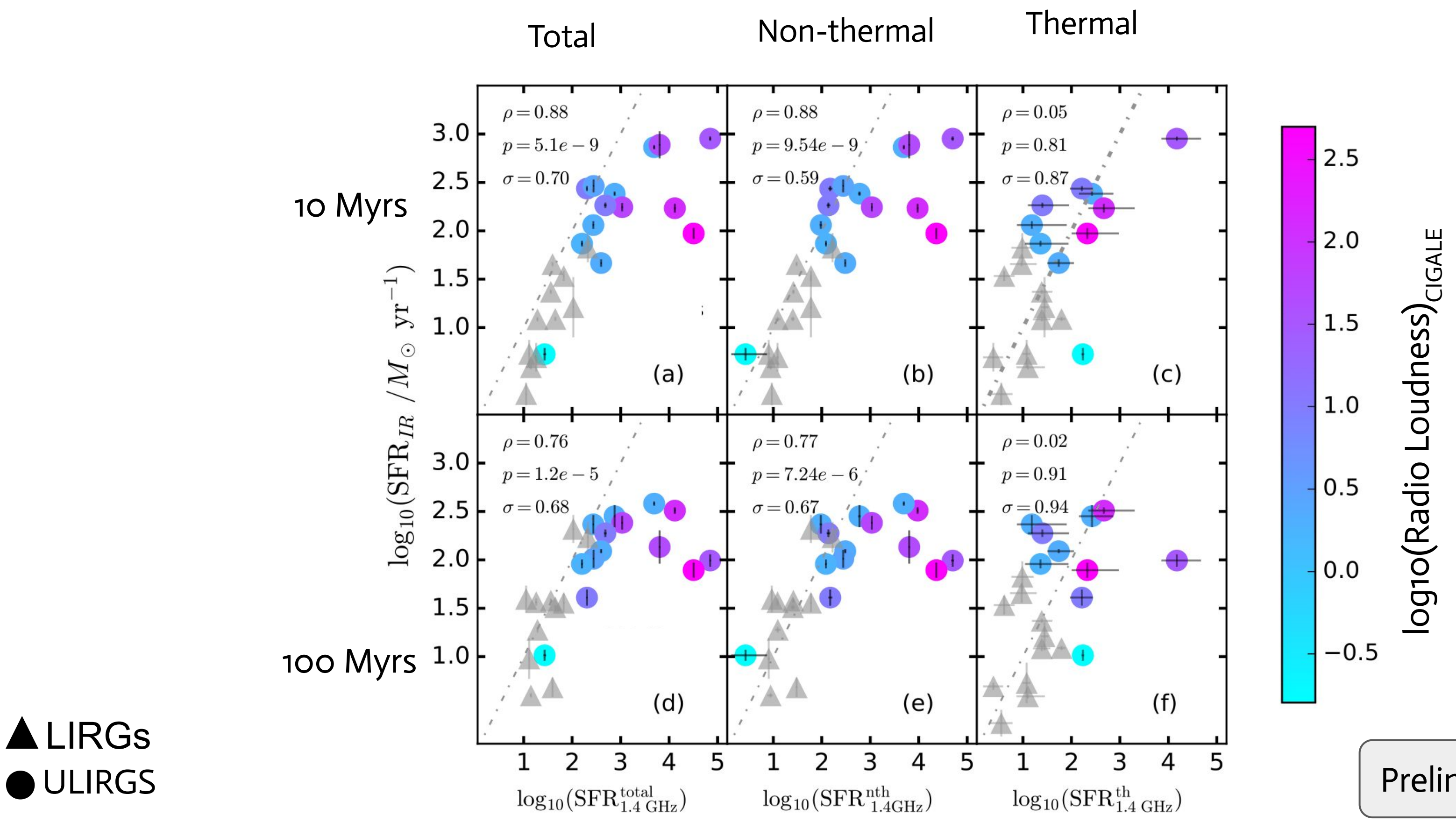


Subhrata Dey+ (in prep)

Comparison of SFR estimates from radio and UV-IR SED



Preliminary!

RESULTS

LIRGs

★ The radio-only SED → **complex features**, showing bends and turnovers.

★ The nonthermal spectral → varies between -0.45 and -1.75
Influence of star formation on the energetics of CRe.

★ **Inclusion of radio fluxes** in UV-IR SED modeling → the dust luminosities and SFR are estimated with **one-order magnitude better accuracies** than given in literature.

★ SFR_{radio}(total and non-thermal) estimated at 1.4 GHz show a close correspondence with SFR_{IR} (CIGALE) estimated **10 Myr ago** →
1.4 GHz SFR estimates is a good indicator of recent star formation.

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Preliminary !

ULIRGs

- ★ SFR_{radio}(total and non-thermal) estimated at 1.4 GHz show a close correspondence with SFR_{IR} (CIGALE) estimated both **10 Myr and 100 Myr ago**

Thank you :)

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