Radio Continuum Observations of Sources of Cosmic Reionization

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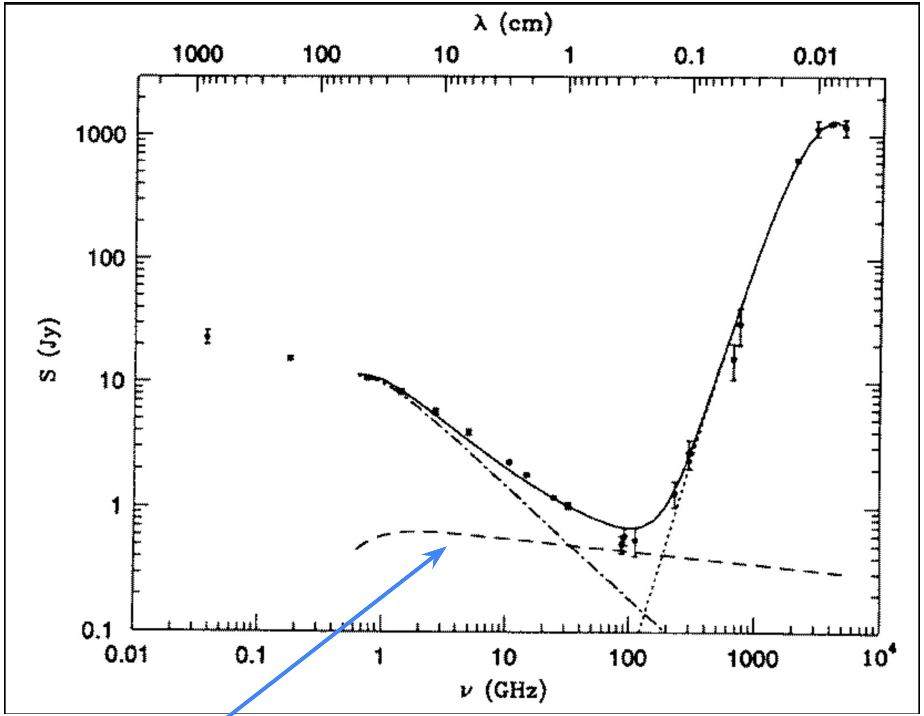
Radio Continuum (RC) Emission from Normal galaxies

- Thermal free-free emission from HII regions.
- Less dominant at $\boldsymbol{\nu}$ < 30 GHz
- Relatively flat spectral index of -0.1.
- Some dependance on electron temperature.
- Directly related to the **Lyman Continuum photon rate** in HII regions

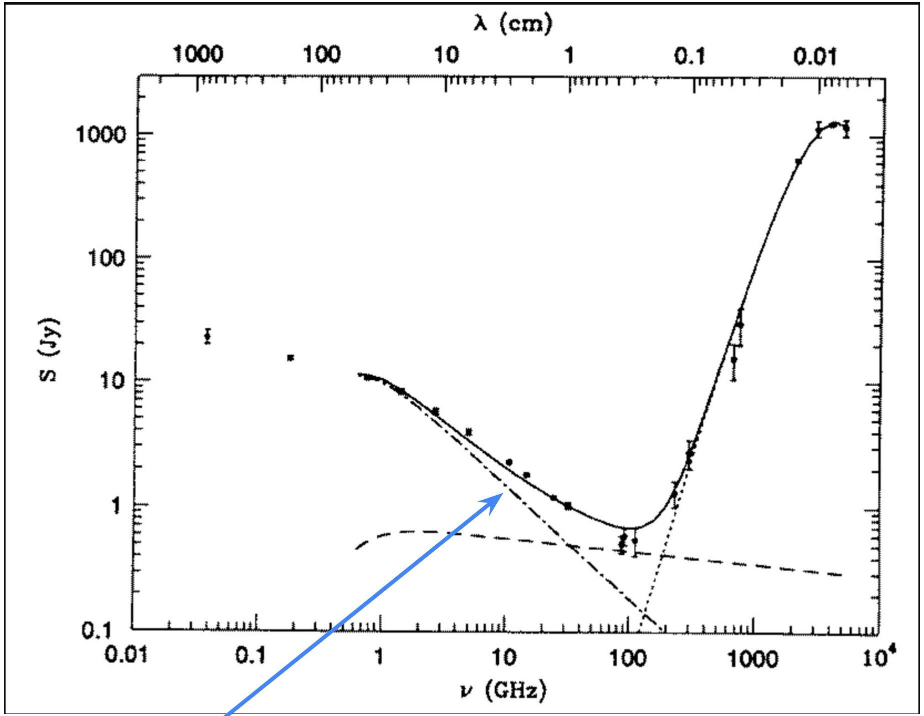


$S_{th} \propto A(T_e)\, \boldsymbol{\nu}^{-0.1}$

Condon et al. 1992

Radio Continuum (RC) Emission from Normal galaxies

- Non-thermal synchrotron emission
- Dominant at ***ν*** < 30 GHz
- Power-law spectrum: $\alpha \approx$ -0.8
- SNe explosions accelerate cosmic-ray electrons (CRe) under magnetic fields leading to synchrotron emission.
- Related to SNe rate, magnetic field strength, CRe energy spectrum

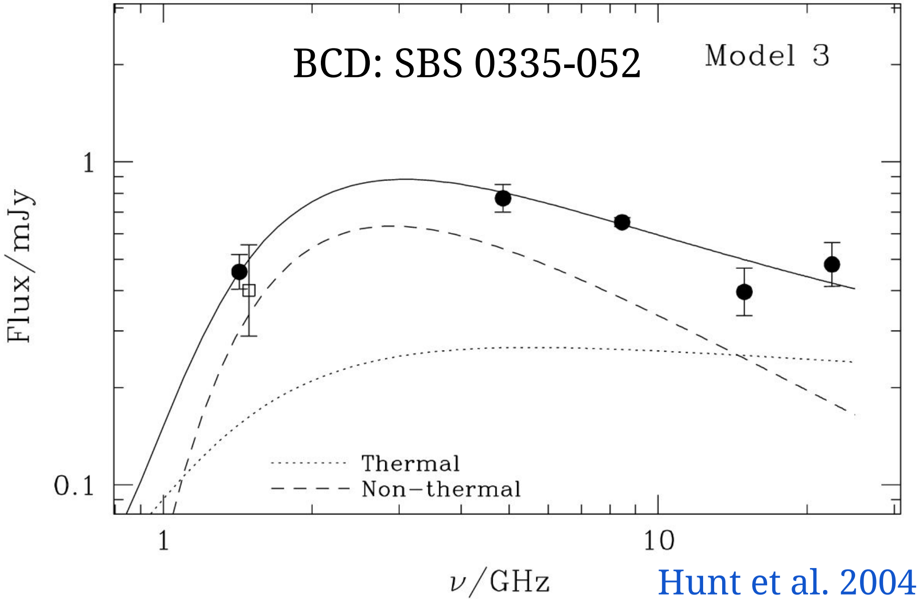


$$S_{\mathrm{th},0}\left(\frac{\nu}{\nu_0}\right)^{-0.1} + S_{\mathrm{nth},0}\left(\frac{\nu}{\nu_0}\right)^{+\alpha_{\mathrm{nth}}}$$

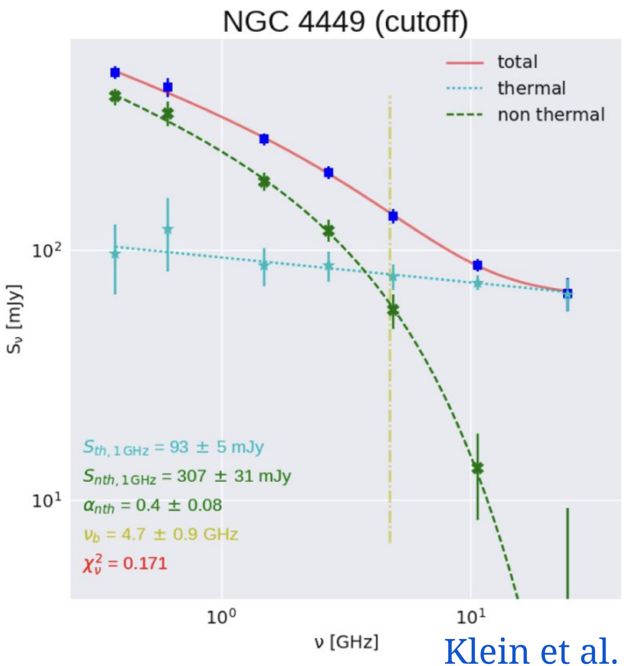
$$S_{\mathrm{nth}} \propto \boldsymbol{\nu}^{\alpha}$$

Condon et al. 1992

Radio-SED models



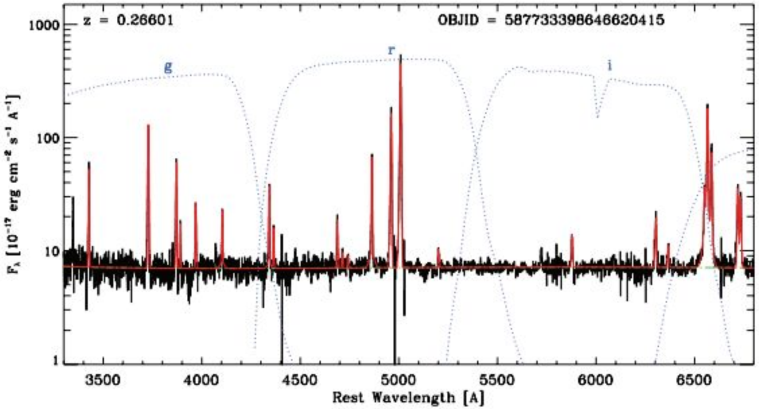
Hunt et al. 2004

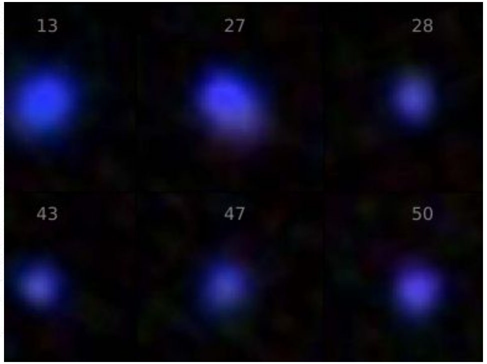


Klein et al. 2018

- Low-frequency turnover from free-free absorption, synchrotron self-absorption.
- Break/Cutoff in the spectrum.

Compact Emission Line Galaxies (CELGs)





Green-Peas: Cardamone et al. 2009

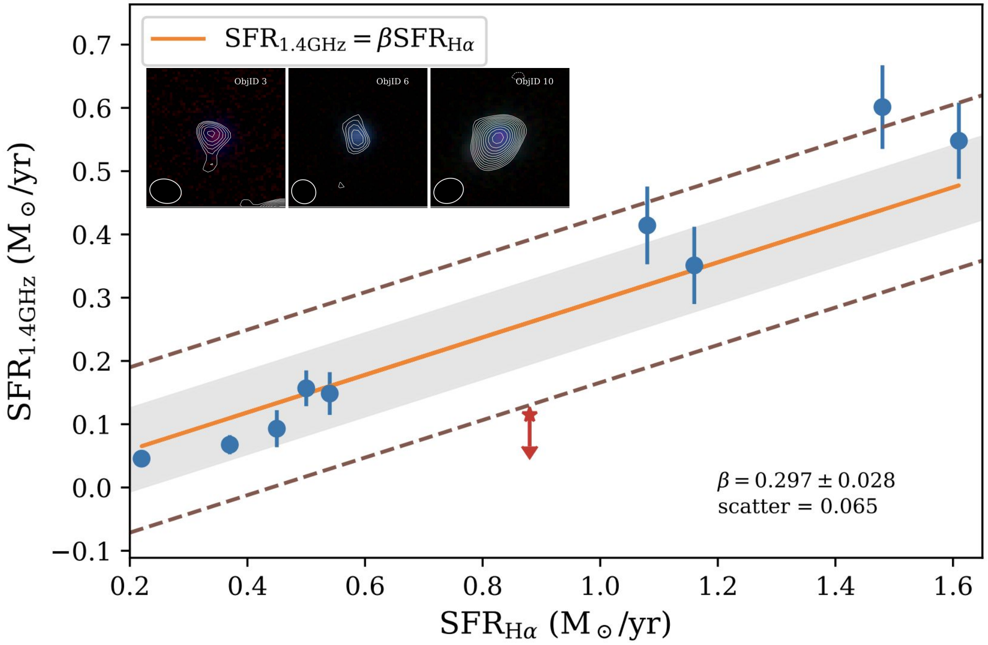
Blueberries: Yang et al. 2017

- CELGs show high excitation, low stellar mass and metallicity.
- CELGs are excellent analogues of high-z star-forming galaxies. (e.g., Schaerer+22, Rhoads+22)
- Usually show high LyC escape fraction, thus contributing to reionization. (Izotov+16)
- Low-z Lyman Continuum Survey (**LzLCS**) of 66 galaxies with z=0.2-0.4 having HST/COS observations to measure the **LyC escape fraction**. (Flurry+22)

RC at 1.4 Ghz for CELGs

- Green-peas (GPs) were detected in radio with stacking (Chakraborti et al. 2012)
- Direct detections (9/10) for Blueberries (BBs; Sebastian & Bait 2019).
- GPs and BBs show a deviation from the standard radio-SFR relation.
- Lack of non-thermal emission
- High equipartition magnetic fields.
- Similar to RC studies of BCDs, local starbursting dwarfs.
- Single frequency studies are limited.
- No systematic multi-frequency study of the radio-SED yet.

Sebastian & Bait 2019



Why a RC study of LzLCS?

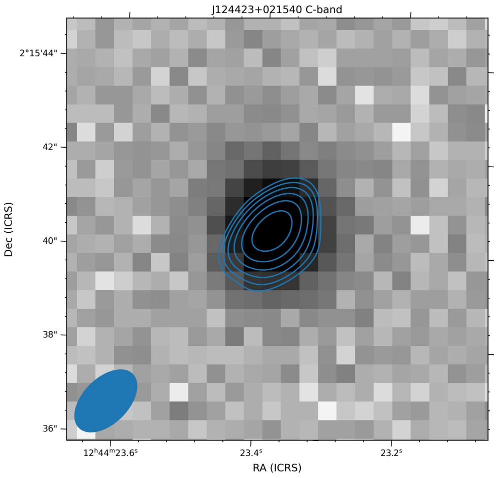
- **Non-thermal emission** is probably the only way to estimate the **SNe rate** in galaxies.
- The presence or absence of SNe will informs us about the **feedback mechanisms**.
- What is fraction of **thermal/non-thermal** radio continuum emission in LyC emitters ?
- What is the shape of the radio SED at low-frequencies for LyC emitters ? Presence of turnover, breaks/curvature? Modelling the full UV-radio SED.
- **Does the radio-SED properties depend on the leakage of ionizing photons, i.e. on f_{esc} ?**
- Does the RC emission of LzLCS sources follow the standard radio **(1.4 GHz)-SFR relation** of normal star-forming galaxies? Can we derive a **new** relation radio-SFR relation with the help of the SED?
- RC study at high-z is complicated due to inverse Compton CMB losses.
- Important guidance for studies of high-z galaxies with future radio facilities e.g., the **MeerKAT, SKA, and ngVLA**.

JVLA Observations

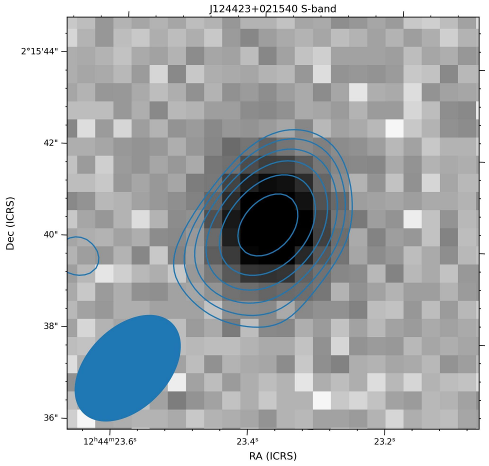
- **53 LzLCS sources observed** with the JVLA at **C (6 GHz)** and **S (3 GHz)** bands **(PI: Sanchayeeta Borthakur)**.
- We imaged all the JVLA **online calibrated data** using CASA **tclean**.

Band	Bandwidth (GHz)	Sources	Integration Time (mins)	Resolution (arcsec)	RMS (μJy)	Detections
C (6 GHz)	4	53	30	1.6	4.6	25
S (3 GHz)	2	53	30	3.2	8.1	25
L (1.5 GHz)	1	17	90	6.9	8.1	4

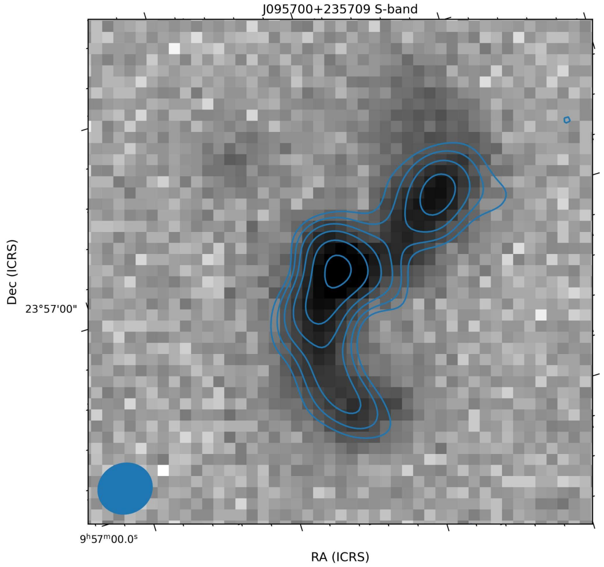
JVLA C, S and L band images



J124423+021540: C-band



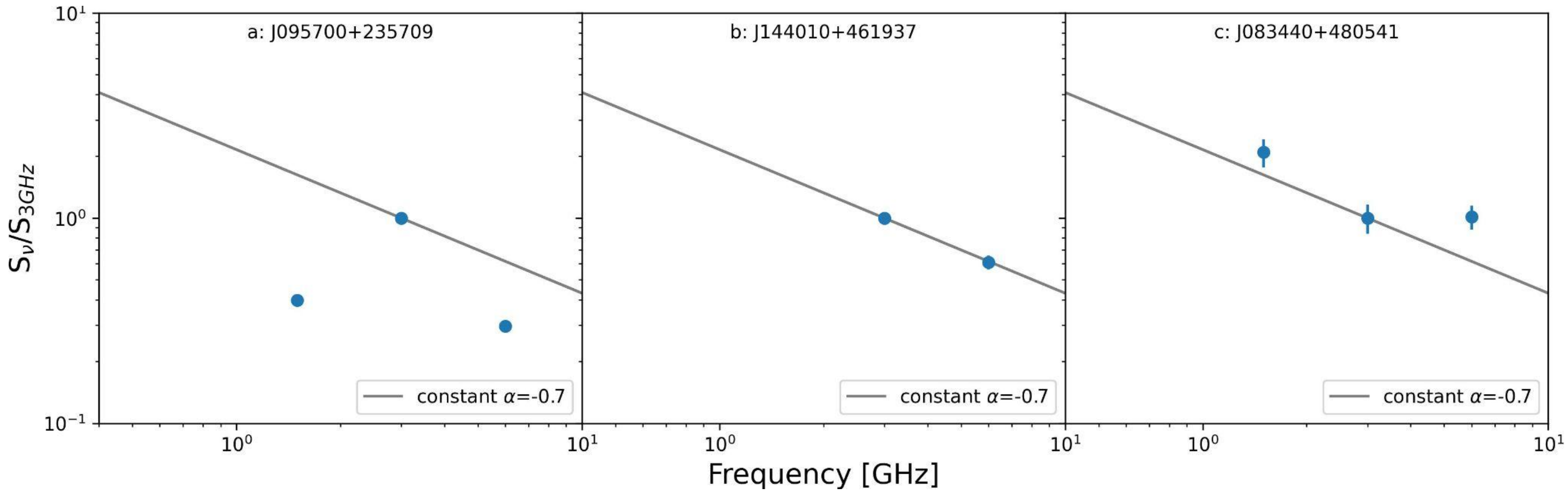
J124423+021540: S-band



J095700+235709: S-band

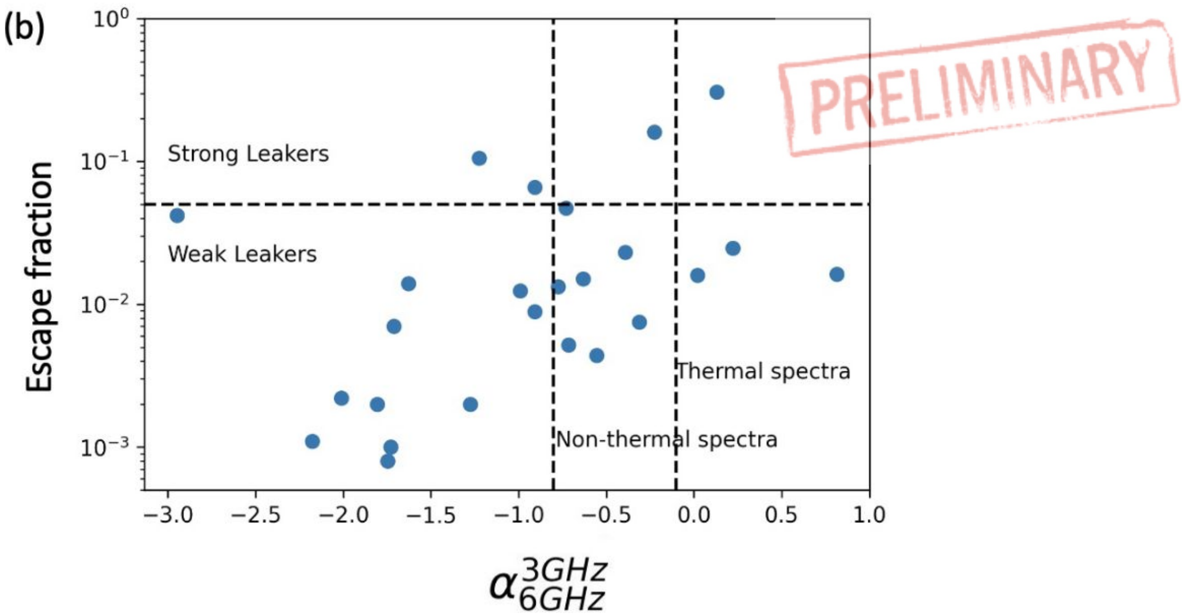
- Most sources are unresolved.
- One extended source: J095700+235709. Radio emission follows the optical counterpart.
- We can attempt a resolved SED model.

LzLCS Radio-SED (1.5-6 GHz): Initial Results



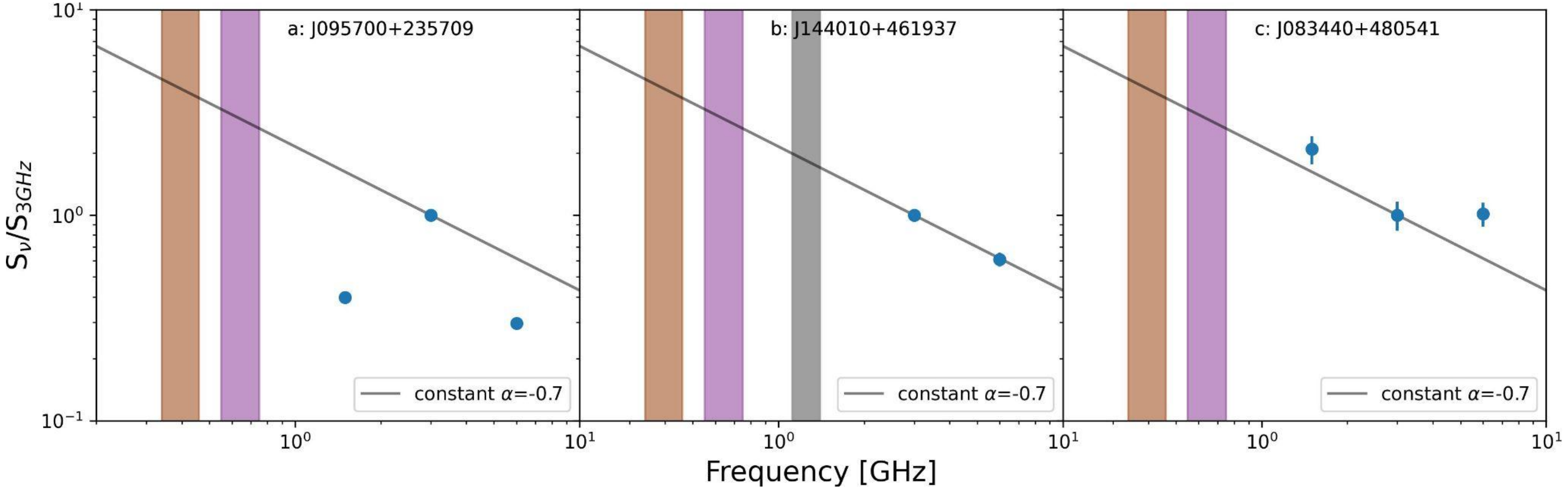
- Radio-SED relative to the flux density at 3 GHz for our L, S and C band data.
- The three panels from left to right shows example of a) **turnover**, b) **single power-law** and c) **curved/broken SED**.
- Modelling the SED will give important insights on the gas distribution in their ISM.

f_{esc} correlated to RC spectral index?



- Flattening of the spectra with increasing LyC f_{esc}? Higher thermal fraction with f_{esc}?
- Young ages, low SNe rate or strong outflows with increasing f_{esc}?

Future Work: uGMRT & JVLA



- uGMRT time for a Band-3 (0.4 GHz), Band-4 (0.65 GHz) & Band-5 (1.2 GHz) follow-up.
- Model the Radio-SED from 0.4-6 GHz and its dependence on f_{esc}.
- Robust estimation of the thermal/non-thermal fraction as a function of frequency.
- JVLA proposal to observe the remaining LzLCS sources.
- uGMRT time to observe a sample of extreme CELGs.

Summary

- RC emission of CELGs at 1.4 GHz shows a deviation from standard relation.
- Radio-SED study will provide important insights about **supernovae feedback, ionized gas distribution, magnetic fields** etc and their relation to f_{esc}.
- We **detected several** LzLCS sources in the JVLA bands.
- Upcoming observations at **low-frequency** the uGMRT.
- We can study the dependence of **radio-SED properties** with Lyman Continuum escape and other star-formation related properties.
- This study will provide important insights in **studying high-z galaxies** with future radio facilities e.g., the **SKA and ngVLA**.

Thank You