# Probing the Sources of Reionization using Radio Observations

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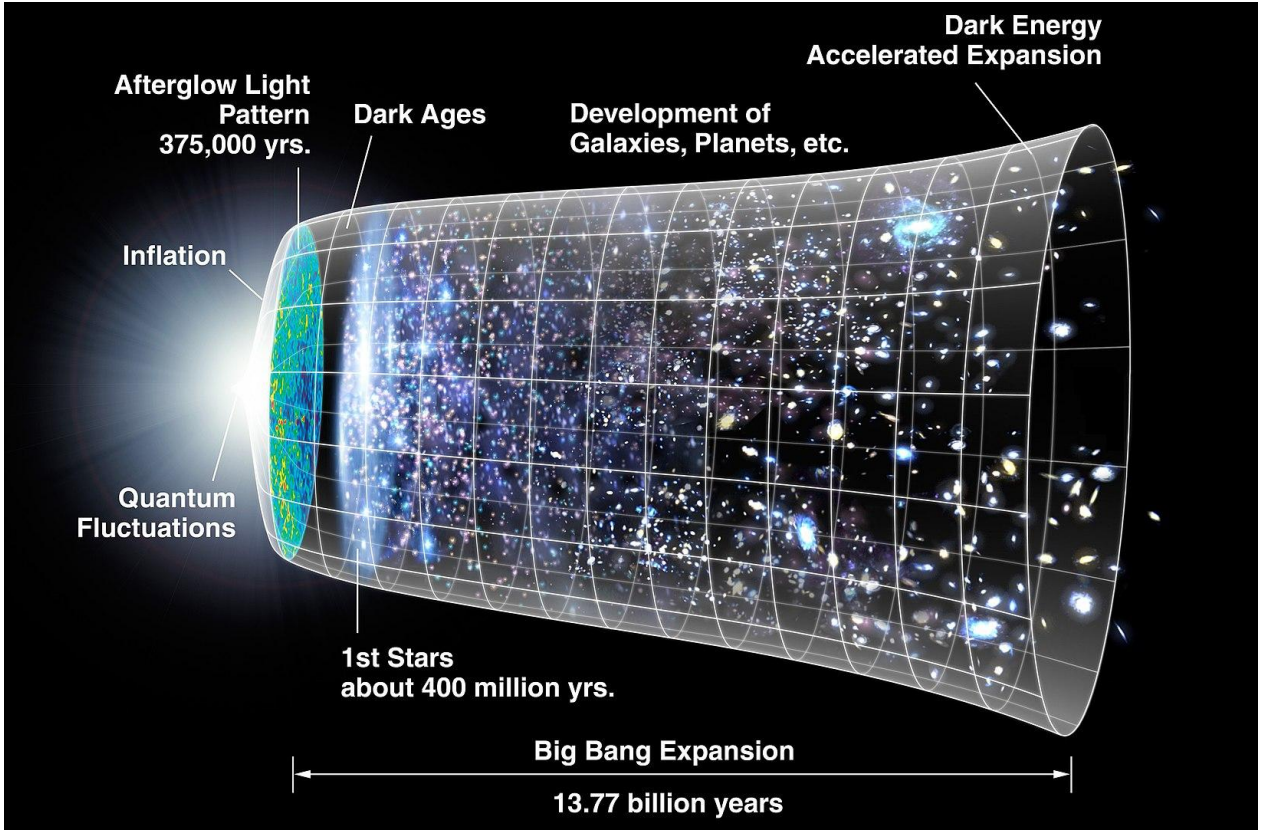
Based on Bait et al. 2024, arXiv:2310.18817

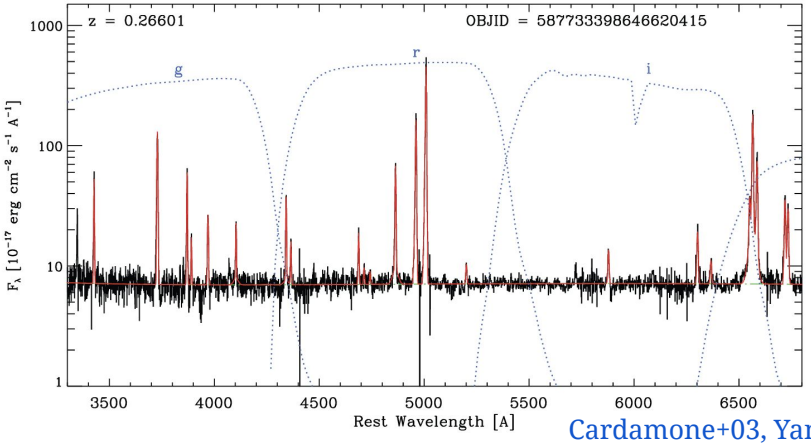
**SKACH Winter Meeting, 23rd January 2024**

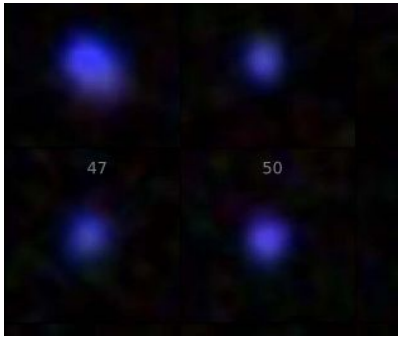
# Cosmic Reionisation

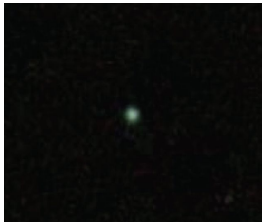



Credit: NASA

# Local analogues of high-z galaxies



Cardamone+03, Yang+17

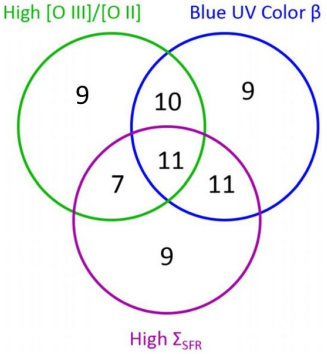
- Compact sizes, high SFR, young starbursts
- Low metallicity (12+log(O/H) < 8.0)
- High [OIII]/[OII] ratio
- **High LyC escape** ⇨ best candidates for cosmic reionisation (Izotov+16, Nature, Izotov+18, 21, 22, Schaerer+16, 18, 22)

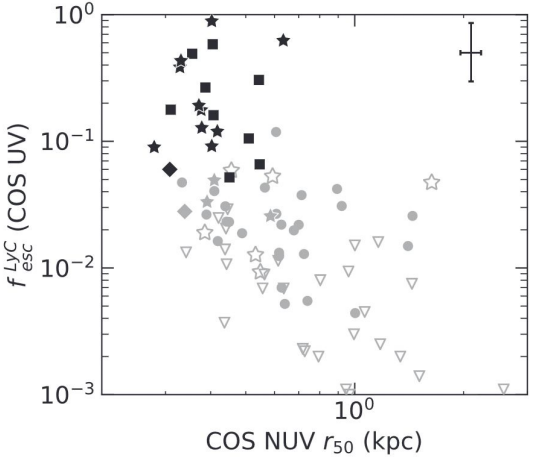
Recent JWST observations of $z > 6$ galaxies have similar properties to local analogues!

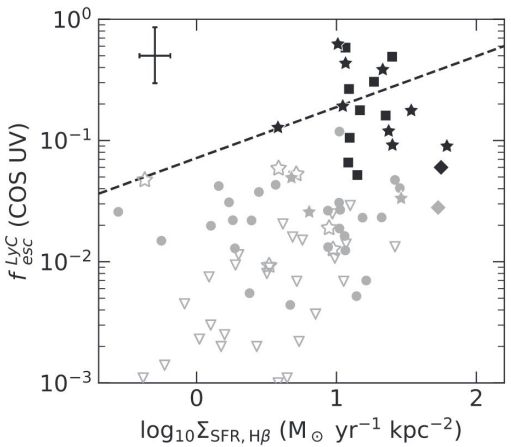
See Schaerer+22, Sun+22a,b, Brinchmann+22, Rhoads+22, Curti+22, Carnall+22, Tacchella+22, Matthee+22, Cameron+23

# Nature of LyC Emitters: Low-z LyC Survey (LzLCS)

- HST large program (136 orbits): PI Anne Jaskot
- **89** low-z ~ 0.25 - 0.35 galaxies with LyC measurements
- $f_{esc}$ correlates with O32, SFR density, sizes. (Flury +22)
- Correlates with UV absorbing line strengths (Saldana-Lopez+22)
- What leads to LyC leakage in galaxies?
- **The role of supernovae feedback is still not completely understood.**




Flury et al. 2022

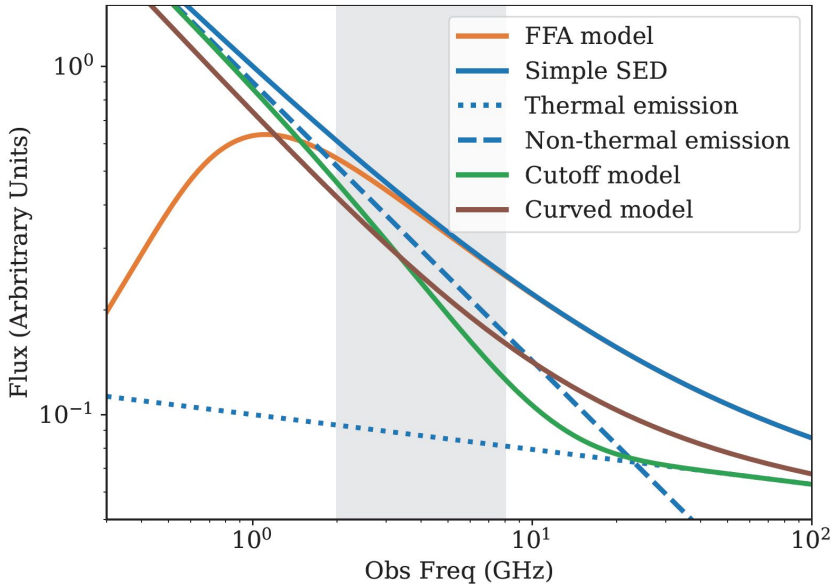
# Radio Spectrum at GHz

- Radio provides a complementary view
- **Non-thermal emission directly related to SNe rate – thus related to SNe feedback**
- **Radio is a dust-free tracer of SFR**

$$S_\nu = S_\nu^{\rm th} + S_\nu^{\rm nth} = A_1 \left(\frac{\nu}{\nu_\circ}\right)^{-0.1} + A_2 \left(\frac{\nu}{\nu_\circ}\right)^{\alpha_{\rm nth}}$$

**Thermal Component:**
optically thin regime
related to the LyC photon
production rate

**Non-thermal Component:**
Cosmic-rays, magnetic
fields,
SNe rate




Bait+23, submitted to A&A

# LzLCS VLA+GMRT Observations

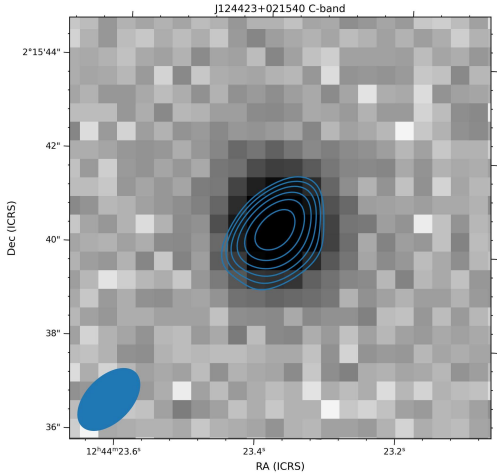
- **53 LzLCS sources observed** with the **VLA** at **C (6 GHz)** and **S (3 GHz)** bands + **19 L-band (21B-111, PI: Sanchayeeta Borthakur)** in the B-array.
- uGMRT low-freq observations of 6 sources (**ID: 43_061**) at 0.4, 0.65 and 1.2 GHz
- **VLA 23A-162** program **123 hours LzLCS+Izotov** remaining sources at C-, S- and L-bands.

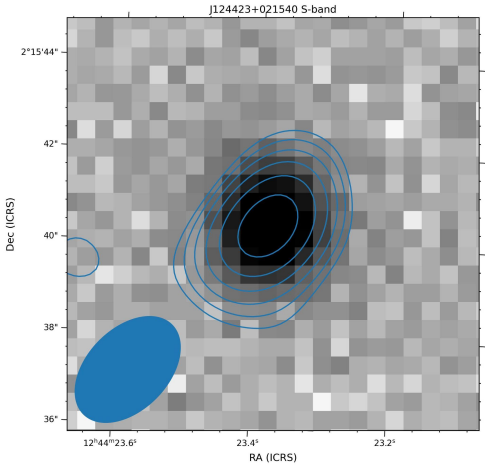
Giant Metrewave Radio Telescope (GMRT)

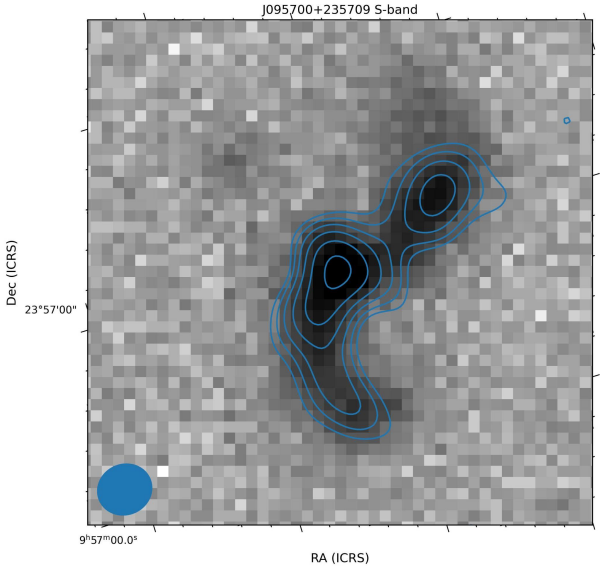
Very Large Telescope Array
Credit: NRAO

# VLA Observations of LzLCS

- **53 LzLCS sources observed** with the JVLA at **C- (6 GHz)** and **S- (3 GHz)** bands. RMS ~ 5 - 8 μJy/beam
- **24/53 detected in both C and S bands.**

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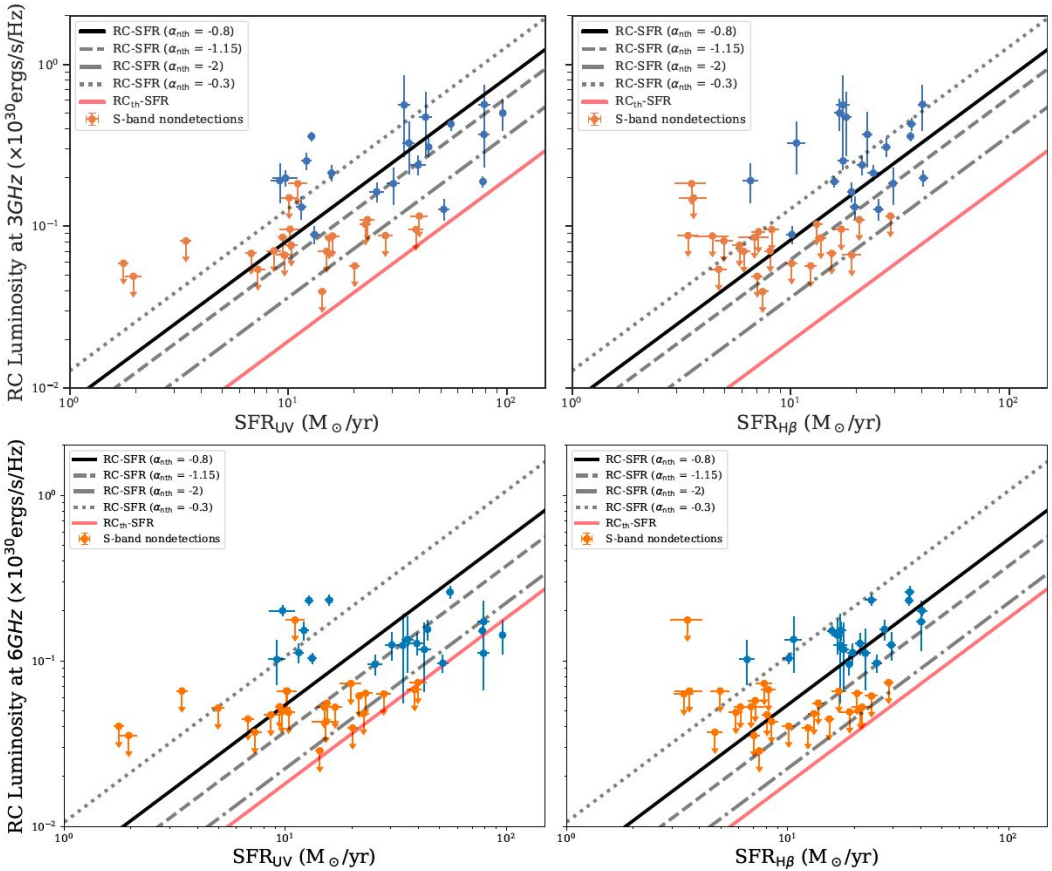
# RC-SFR relation of LzLCS sources




- Non-thermal emission is present in LzLCS sources.
- Thus directly supporting the presence of SNe.
- SFR from different tracers show a lot of scatter.

- Non-detection sample could be thermally dominated, but also FFA can suppress.
- Stacking can be useful.

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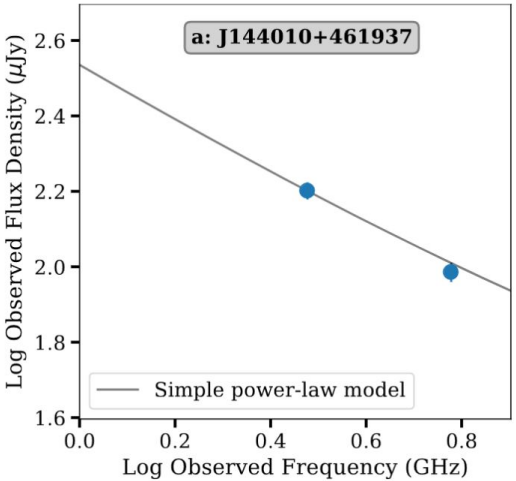
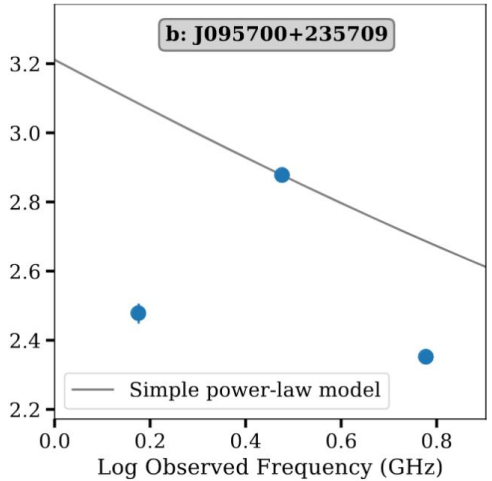
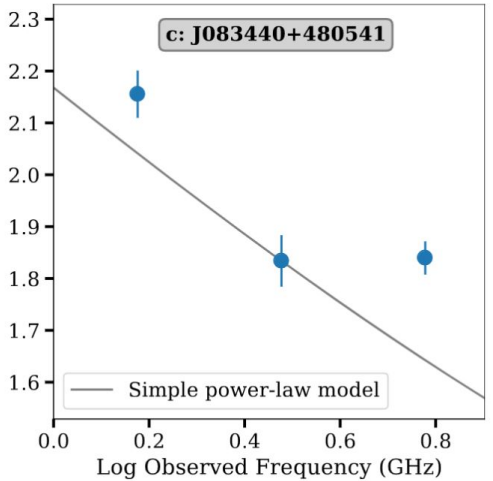
# A diversity in the radio-SEDs




Standard Spectrum




Turnover + Steep spectrum




Broken spectrum

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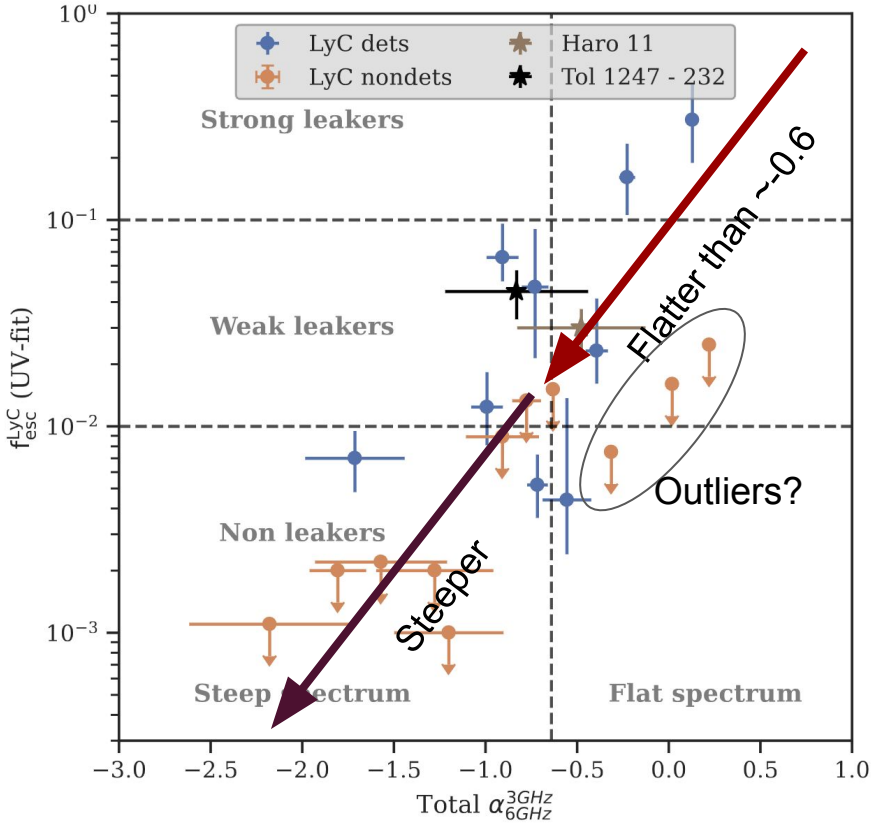
# $f_{esc}$ - spectral index relation



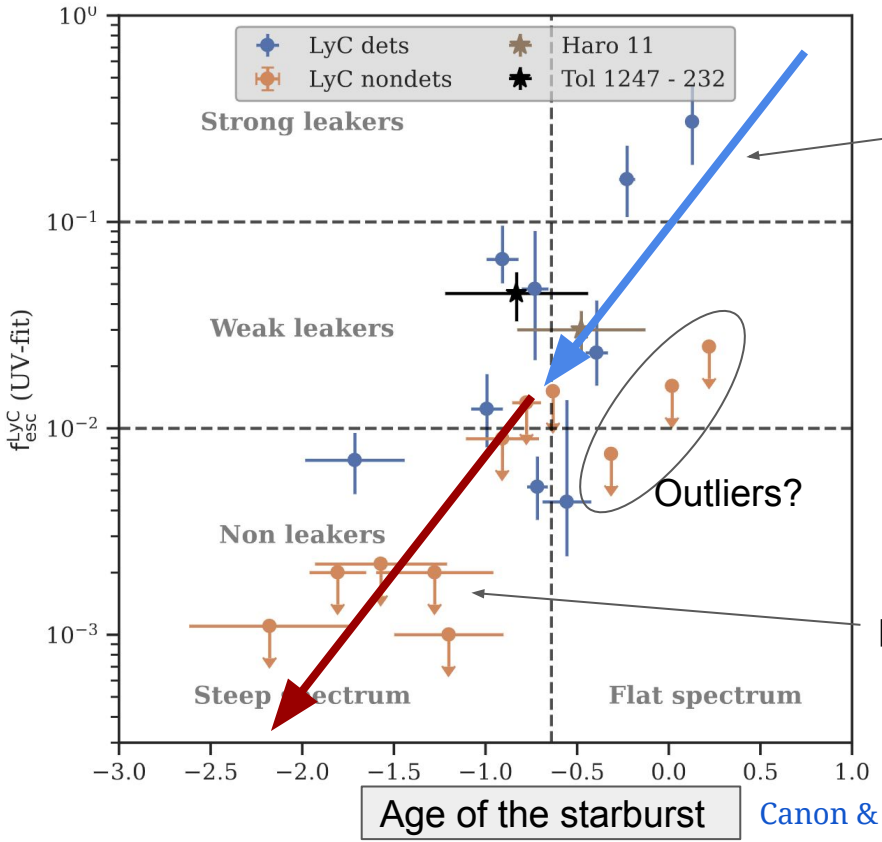

Why high $f_{esc}$ galaxies show a flat spectrum? Young ages/free-free absorption, flat cosmic-ray energy spectrum. Hunt & Hirashita 2006

Need more data for high $f_{esc}$ sources!

Non-leakers systematically show steep radio spectrum.

Bait+23, submitted to A&A

# $f_{esc}$ - spectral index relation – time dependence



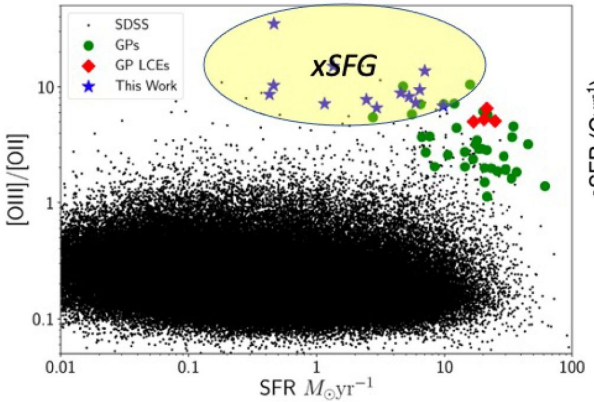

Young and compact starbursts (< 10 Myrs)

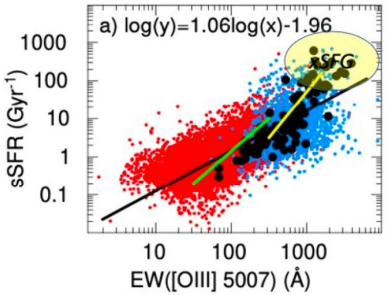
post-starbursts (≳10 Myrs)

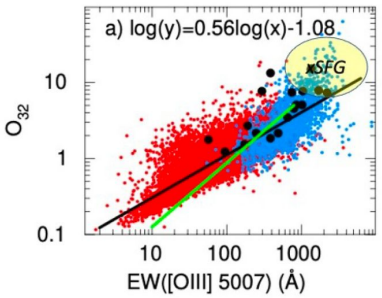
Canon & Skillman 2004, Hirashita & Hunt 2006

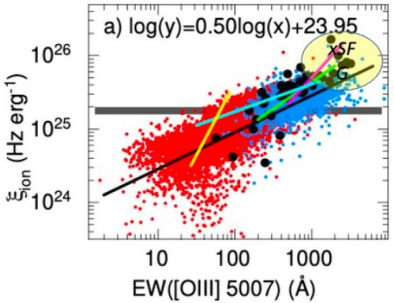
Bait+23, submitted to A&A

# Local extreme-SFGs (xSFGs)



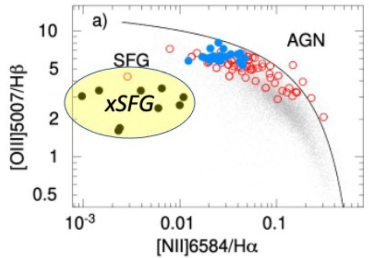



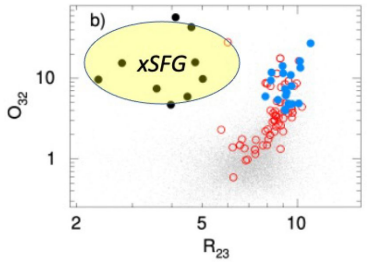



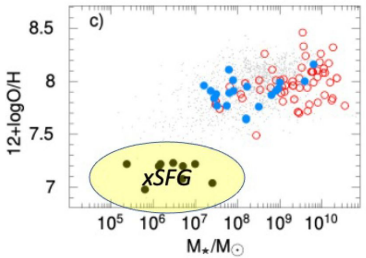



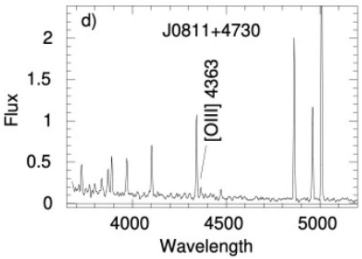

Izotov+21

- z~0.02-0.076
- Down to 12+log(O/H) = 6.98
- Extreme than Green peas, blueberries
- Ongoing HST-COS programs to measure LyC
- Follow up with JWST-MIRI, XMM-Newton at X-ray etc…



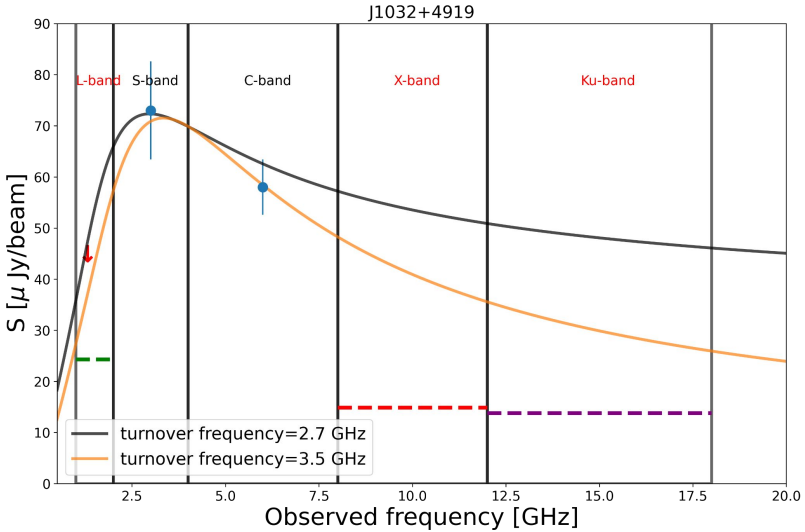



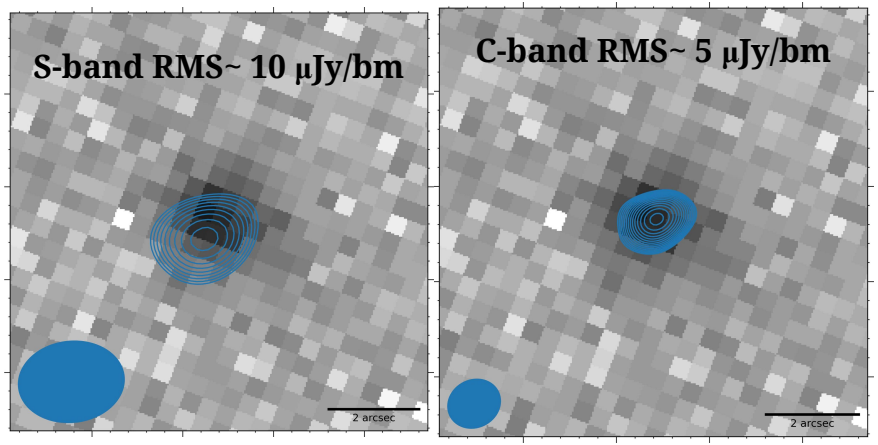



# Radio follow up of xSFGs

- **Ongoing VLA L-, S-, C-, X-, and Ku- band** observations
- uGMRT **325+610 MHz** follow up
- Study the **radio-SED** from (0.3-18 GHz)
- Thermal fraction, SNe rate + ISM properties



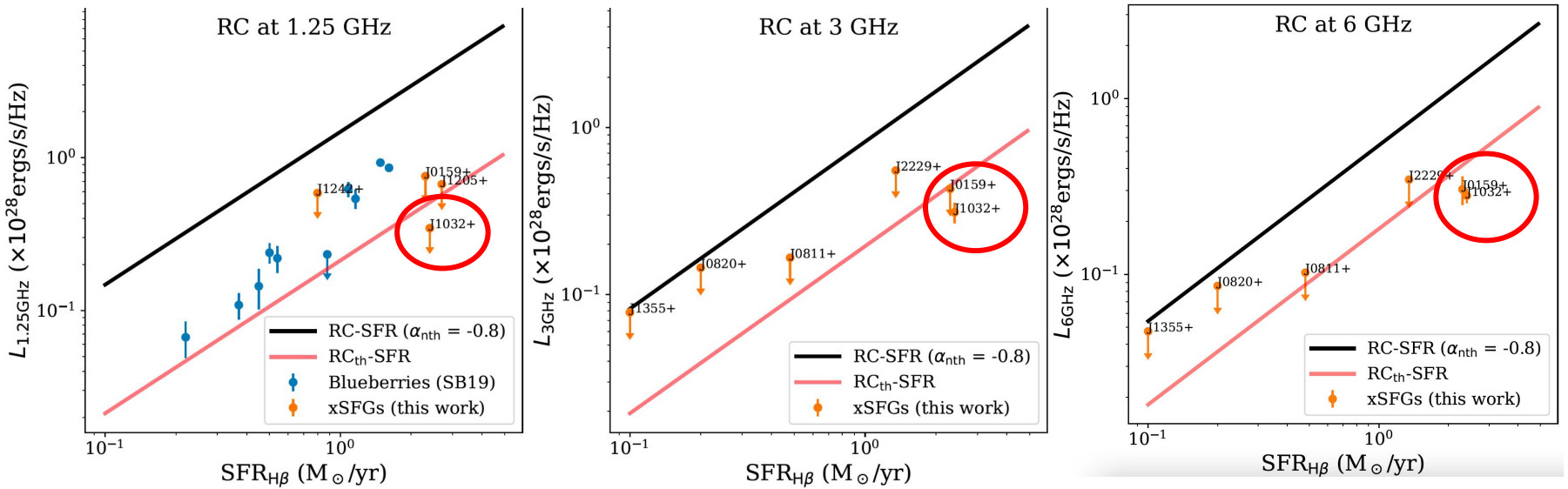

Flat spectral index ~ -0.23

Evidence for FFA at ~2.5 GHz

Bait+24, in prep

PRELIMINARY

# Extreme Radio Continuum Suppression




- The observed radio thermal flux is a factor of ~2 lower than the expected value !!
- Presence of low-luminosity AGN? intermediate mass black holes?
- Our JWST- MIRI and X-ray observations could shed some more light.
- This results have important implications on the nature of high-*z* galaxies and predictions for deep radio surveys using the SKA.

Bait+24, in prep

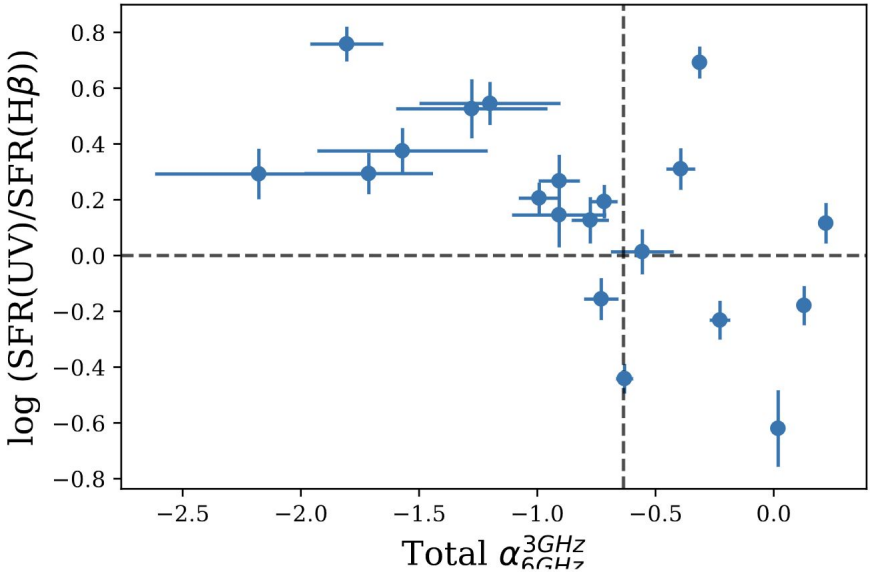
# Summary and Status

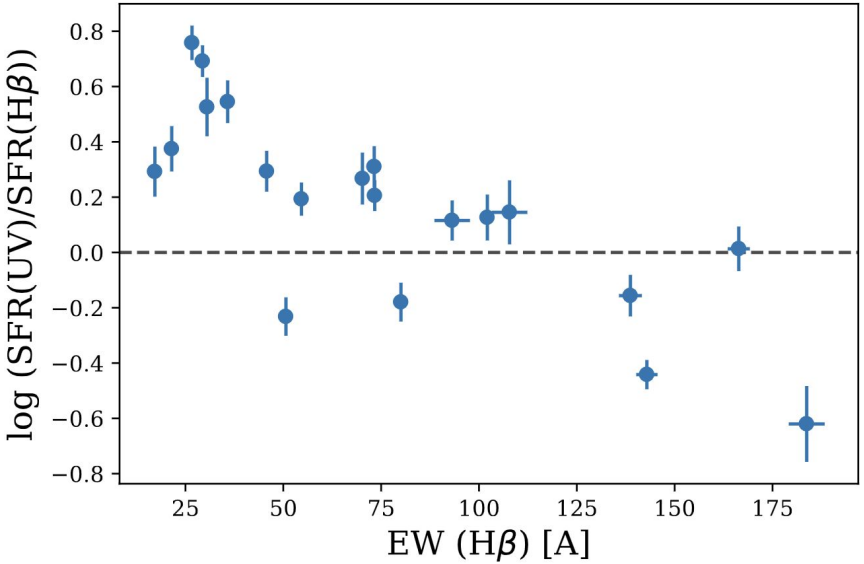
- Large diversity in their radio-SEDs at GHz frequencies: steep spectrum, turnover and breaks in the spectrum.
- RC-SFR relation has a large scatter → needs a reliable SFR tracer for such galaxies.
- **LyC escape is correlated to the radio spectral index at ~GHz frequencies.**
- Our study highlights the role of cosmic-rays and magnetic fields in LyC leakage.
- Rest of the LzLCS sources observed with the VLA in cycle 23.
- **Extreme star-forming galaxies pose new puzzles in our understanding of EoR galaxies.**
- New high frequency observations (at 10-18 GHz) and JWST-MIRI data upcoming.
- Important implications for deep radio surveys in the SKA era.

# Thank You

# Extra Slides

# Steep spectrum sources are post-starburst?

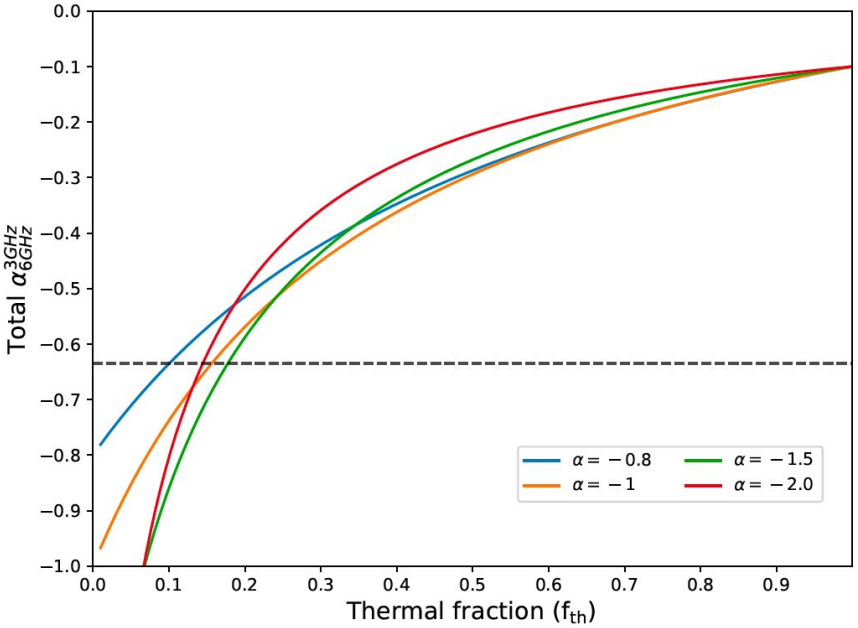


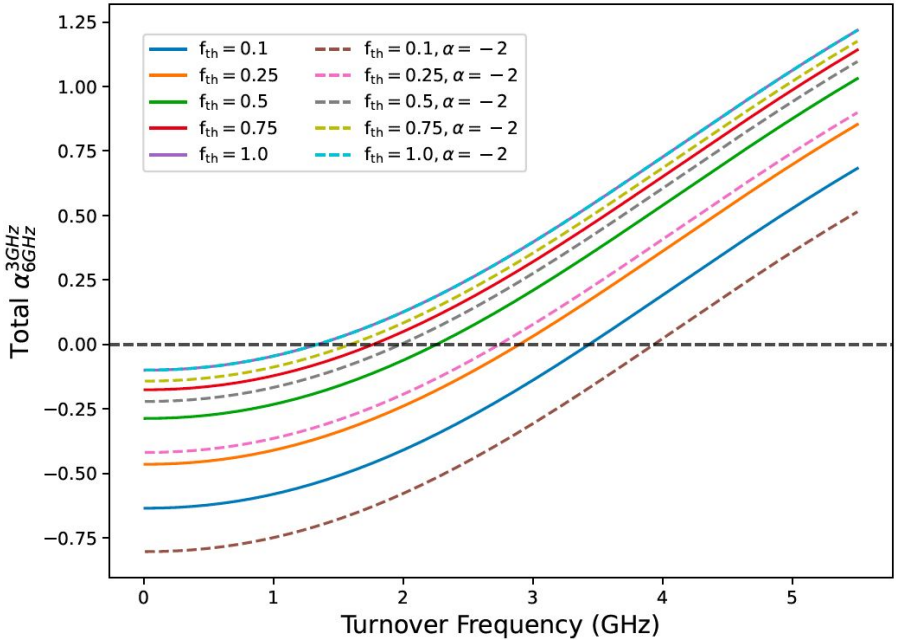

- Steep spectrum sources have higher UV-SFR (~100 Myrs tracer) vs. Hβ-SFR (~10 Myrs tracer).
- Thus is a sign of galaxies with a declining star-formation histories (or post-starbursts).

Bait+23, submitted to A&A

# How to flatten a radio spectrum



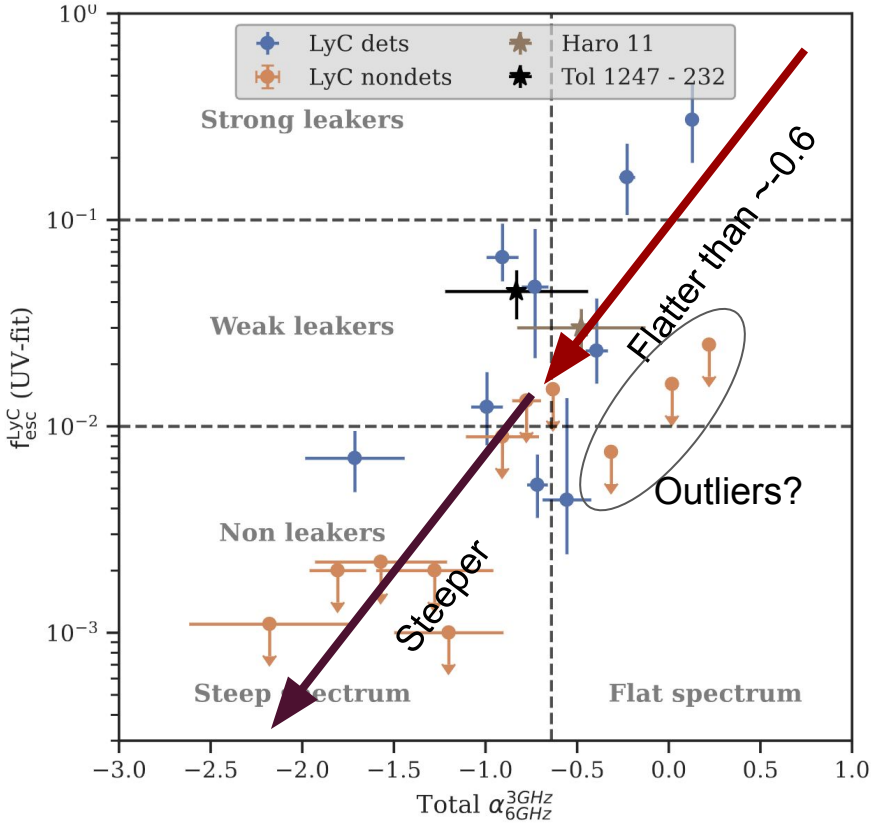

Thermal fraction (less SNe)



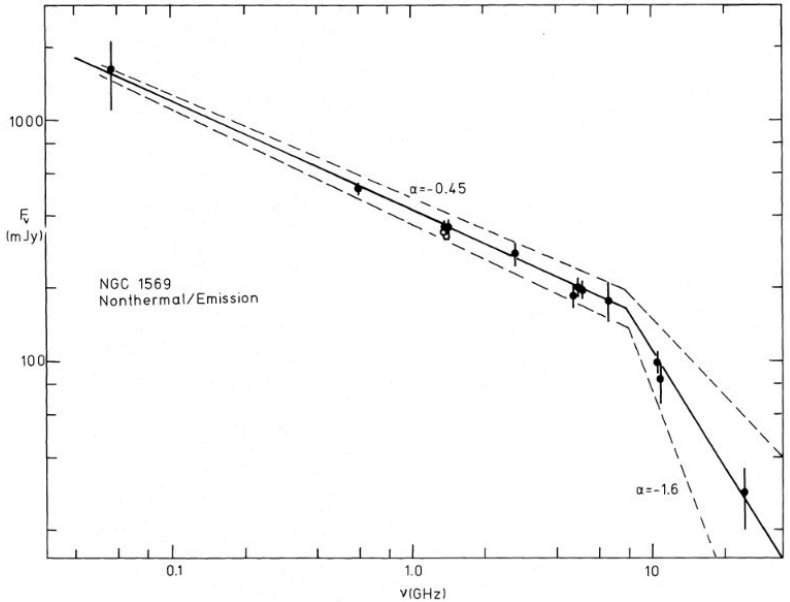

Free-Free Absorption (compact starbursts)

Bait+23, submitted to A&A

# How to steepen the radio spectrum




Bait+23, submitted to A&A

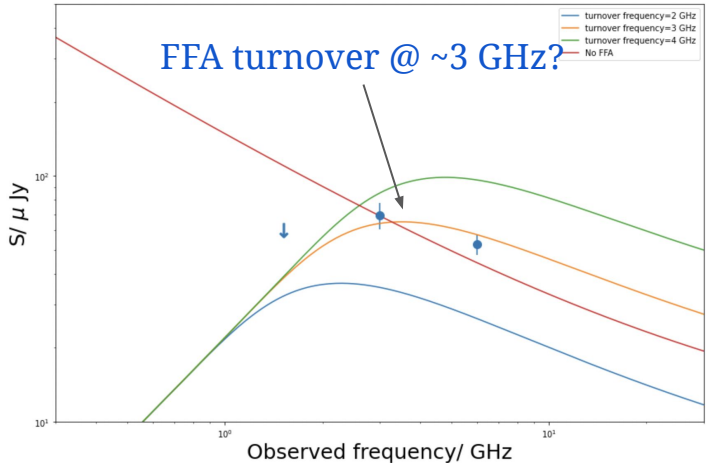



NGC 1569: cutoff model (single injection model), Israel & Bruyn 1988

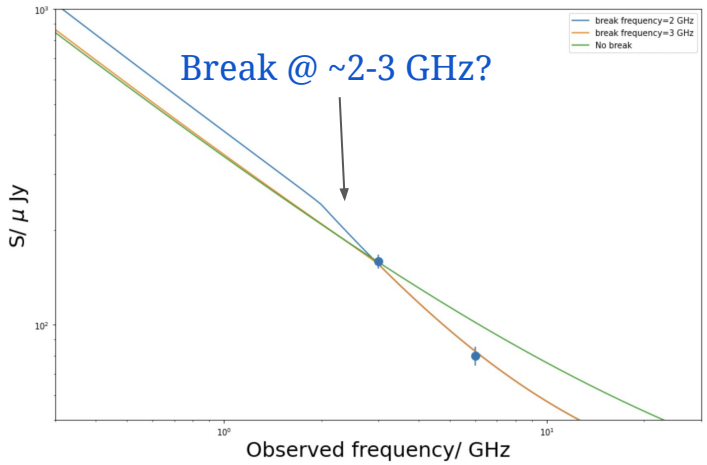
Other causes: CRe escape, IC losses

Observe at higher frequencies (10-30 GHz) to study the break

# A variety of radio-SEDs




Flat spectrum

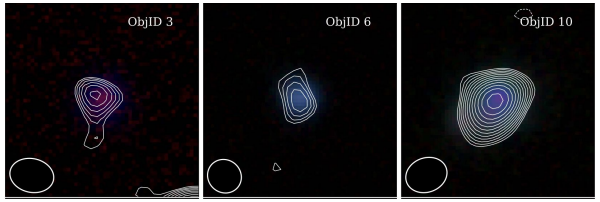



Steep spectrum

Bait+23, in prep

- **Flat spectrum sources** - high thermal fraction? Or free-free absorption at ~GHz? (e.g, Hunt+04, Clemens+10, Galvin+18)
- **Steep Spectrum sources** - Break in the spectrum? (e.g., Lisenfield+04, Klein+18)
- ½ of the sample shows steep spectrum, and 1/4th shows flat and the other 1/4th shows standard spectrum.

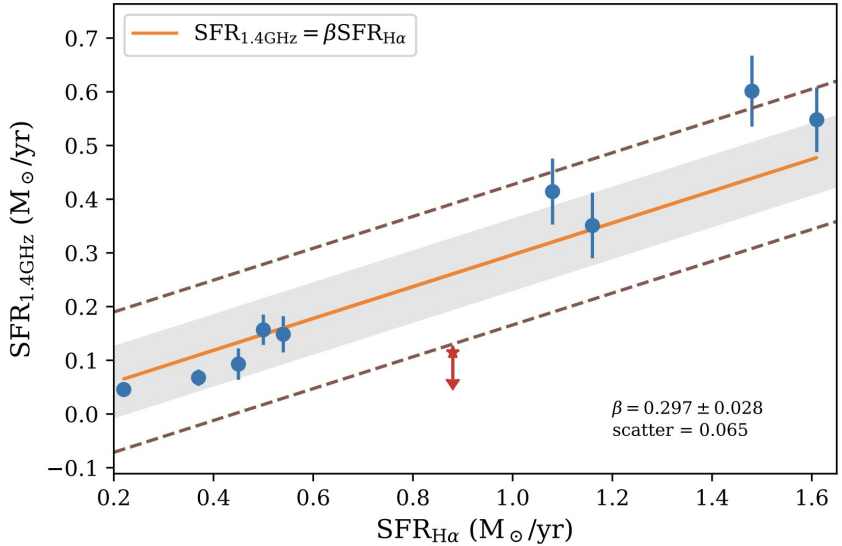
# Radio Study of local analogues




Local analogues do not follow the standard radio-SFR relation
(Sebastian & Bait 19, Chakraborty+13)

**RC@1.4 GHz is highly suppressed!**

Young ages or free-free absorption?




Sebastian & Bait 2019, ApJ, 882L, 19S

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- uGMRT low-freq observations of 6 sources (**ID: 43_061**) at 0.4, 0.65 and 1.2 GHz
- **VLA 23A-162** program **123 hours LzLCS+Izotov** remaining sources at C-, S- and L-bands.

| 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 |