Probing the Sources of Reionization using Radio Observations

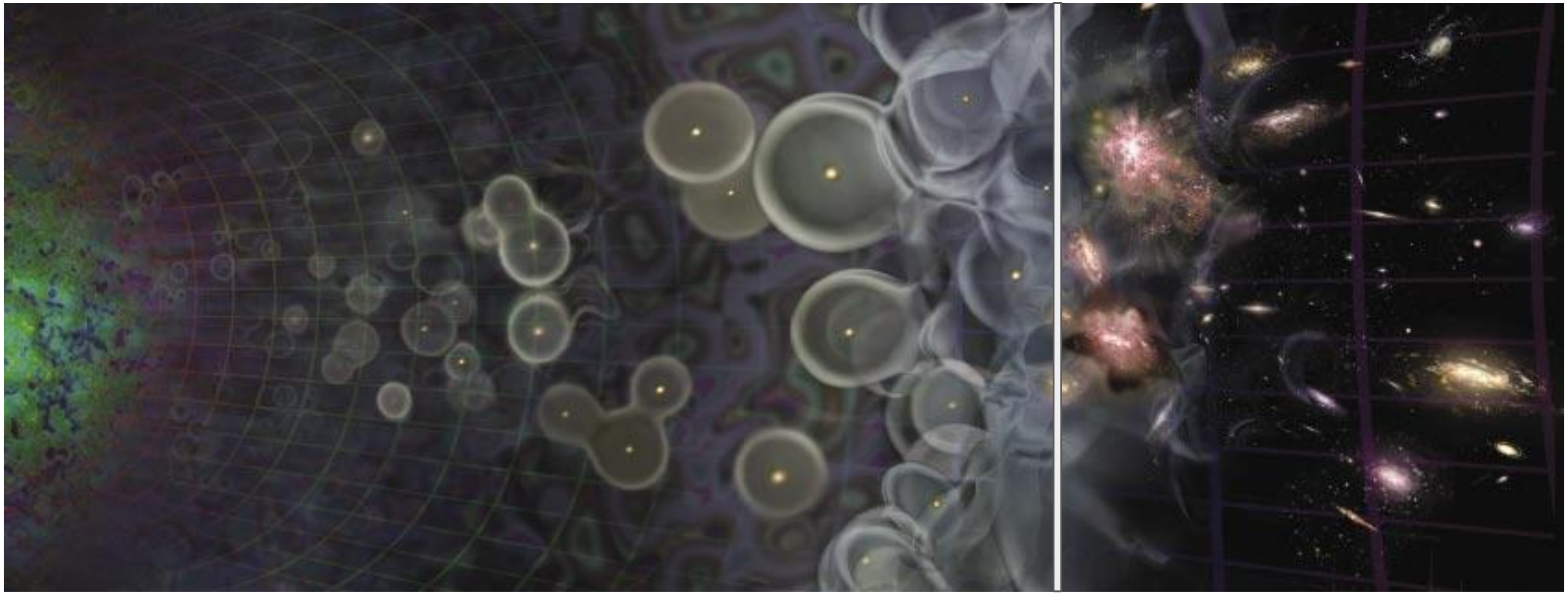
Omkar Bait
Observatoire de Genève

Daniel Schaerer, **Sanchayeeta Borthakur**, **Emmanuel Momjian**, **Yuri Izotov**, **Biny Sebastian**, Anne Jaskot, + LzLCS team

Based on Bait et al. 2023, arXiv:2310.18817

Cosmology in the Alps, Les Diablerets,March 2024

Cosmic Reionisation



First galaxies
(Reionization begins)

JWST revolution!

SKA soon in the future

$z \sim 6$
(EoR ends)

$z \sim 0$
(Present day)

Credit: Avi Loeb

What led to reionisation?

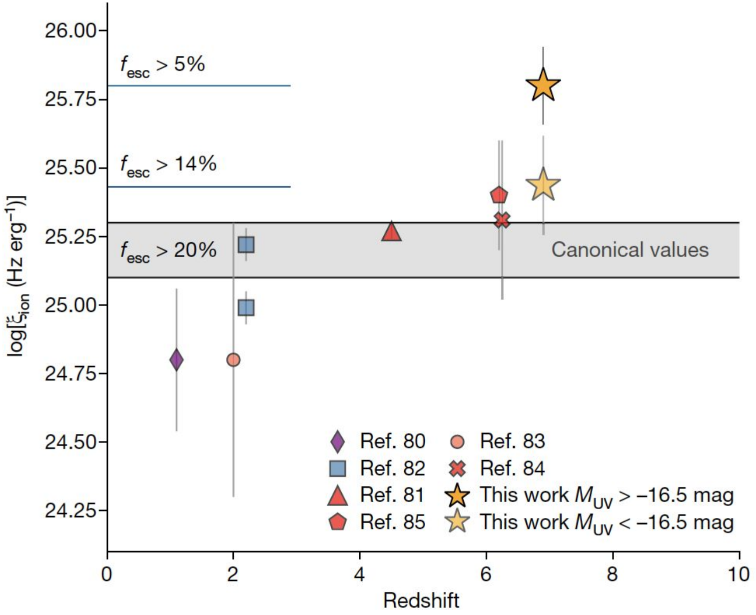
- Where do the ionizing photons to re-ionize the entire Universe come from?

Is it from star-formation in the first (dwarf) galaxies or from AGN?

- Dwarf galaxies!
- They produce large amounts of ionizing flux, enough to reionize the Universe.
- They are intensely star-forming.
- But do ionizing photons leak from the galaxies?

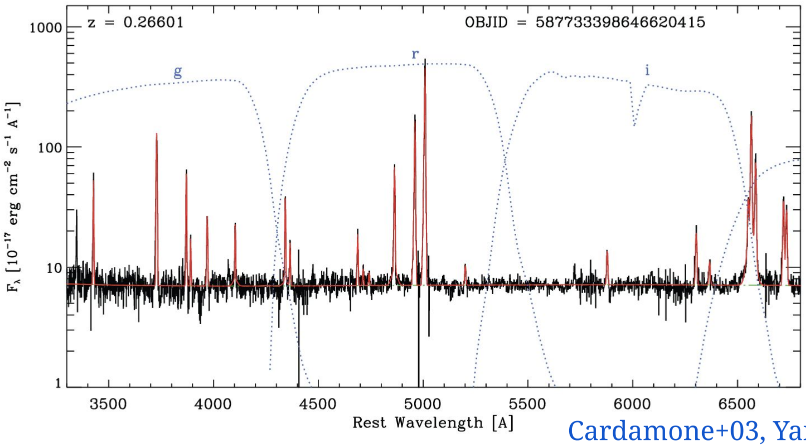
  This can't be answered easily by observing EoR galaxies, since the ionizing photons will be absorbed by the IGM.

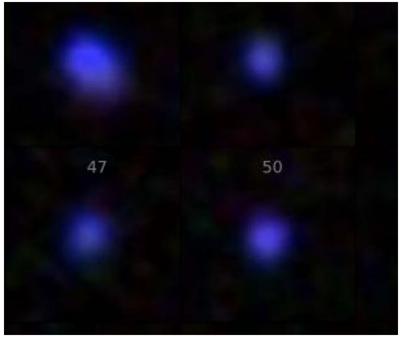
- **We have to rely on local analogues!**

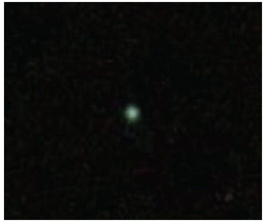


Atek et al. 2024

Local analogues of high-z galaxies







Cardamone+03, Yang+17

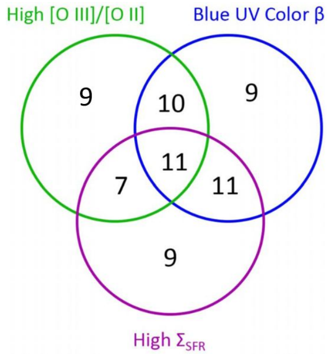
- Compact sizes, high SFR, young starbursts
- Low metallicity (12+log(O/H) < 8.0)
- High [OIII]/[OII] ratio
- **High LyC escape** ⇨ best candidates for cosmic reionisation (Izotov+16, Nature, Izotov+18, 21, 22, Schaerer+16, 18, 22)

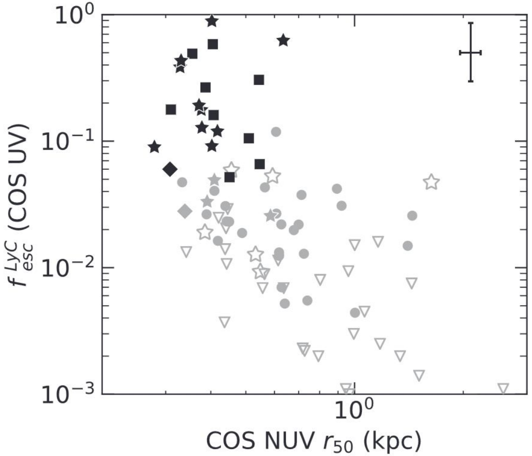
Recent JWST observations of $z > 6$ galaxies have similar properties to local analogues!

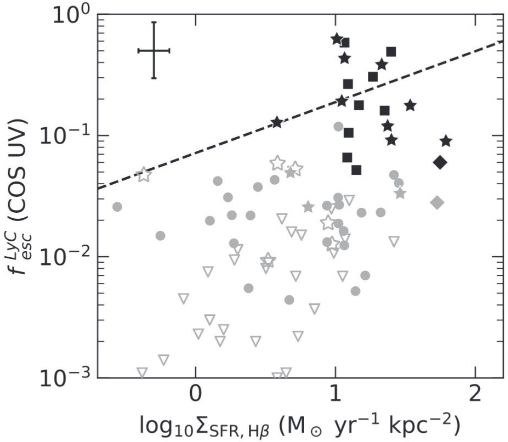
See Schaerer+22, Sun+22a,b, Brinchmann+22, Rhoads+22, Curti+22, Carnall+22, Tacchella+22, Matthee+22, Cameron+23

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

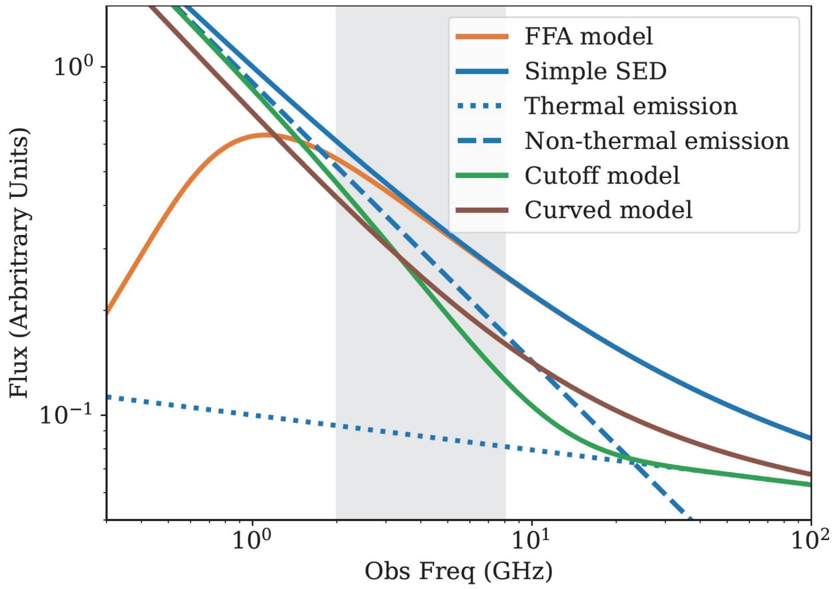
Radio Spectrum at GHz

- 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

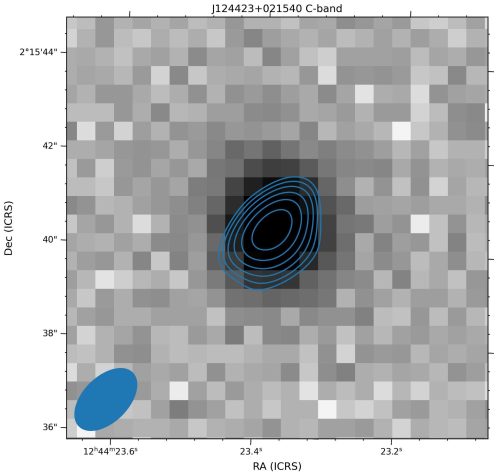
- **53 LzLCS sources observed** with the **VLA** at **C (6 GHz)** and **S (3 GHz)** bands + **19 L-band (21B-111, PI: Sanchayeeta Borthakur)** in the B-array.
- uGMRT low-freq observations of 6 sources (**ID: 43_061**) at 0.4, 0.65 and 1.2 GHz
- **VLA 23A-162** program **123 hours LzLCS+Izotov** remaining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

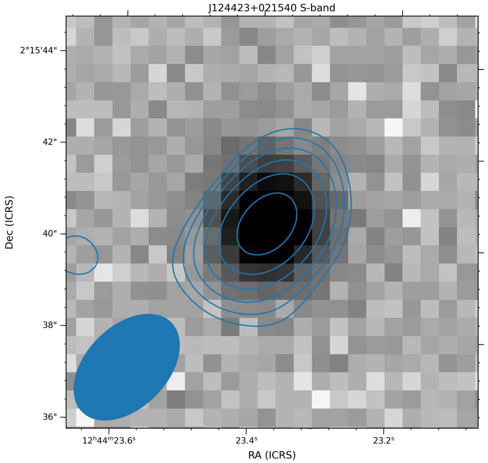
Giant Metrewave Radio Telescope (GMRT)

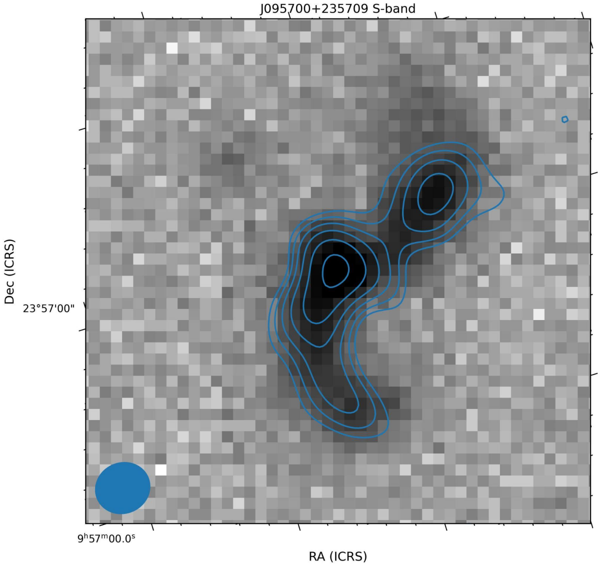
Very Large Array
Credit: NRAO

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.**

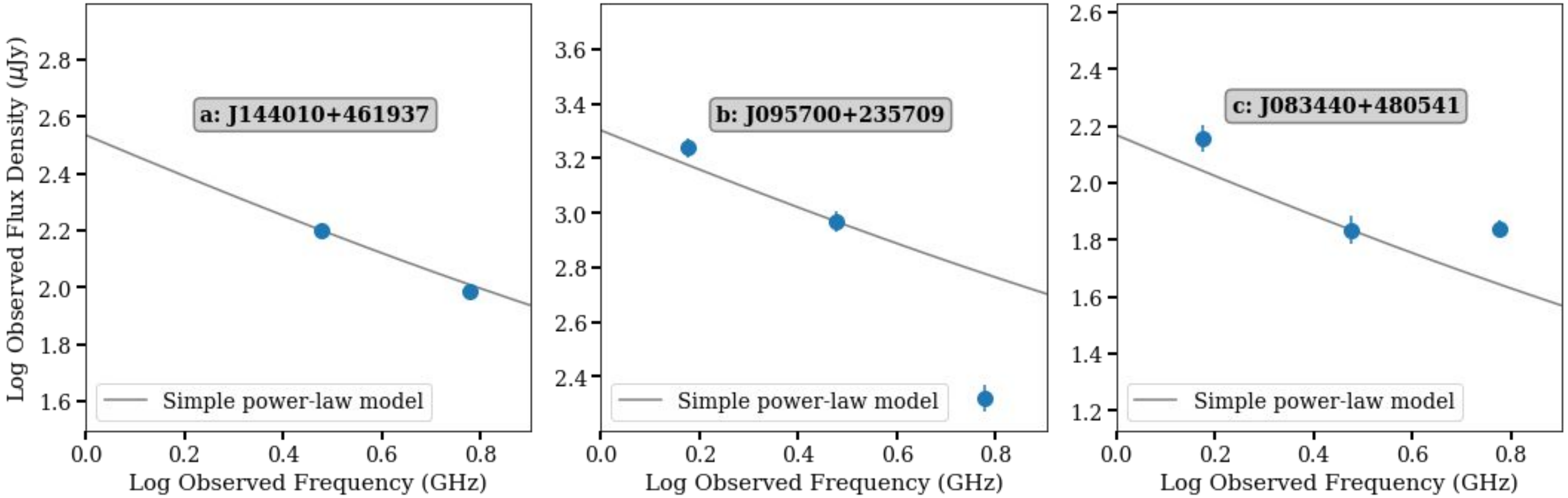






Bait+23, submitted to A&A

Diversity in the radio-SEDs



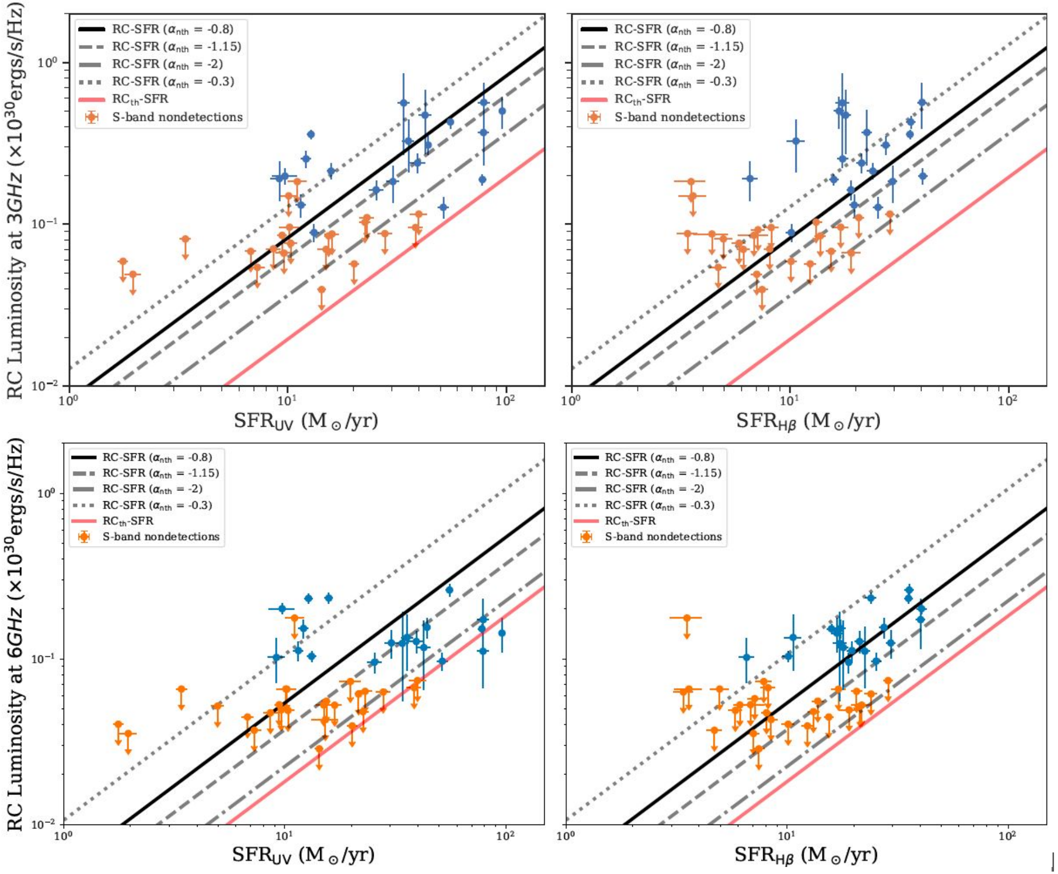
Standard Spectrum | Steep spectrum | Broken spectrum

Bait+24, under review in A&A

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.

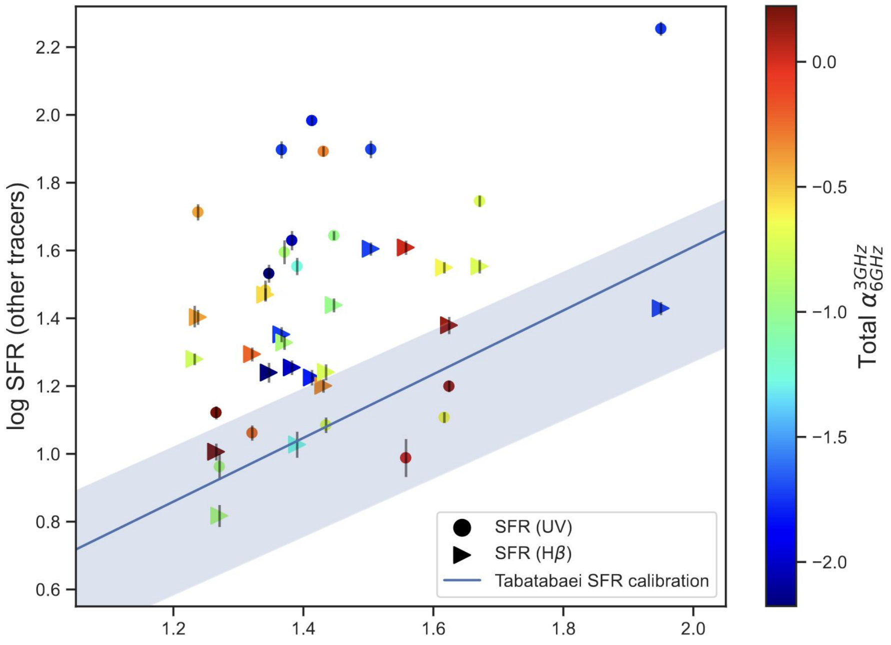
- Non-detection sample could be thermally dominated, but also FFA can suppress.
- Stacking can be useful.



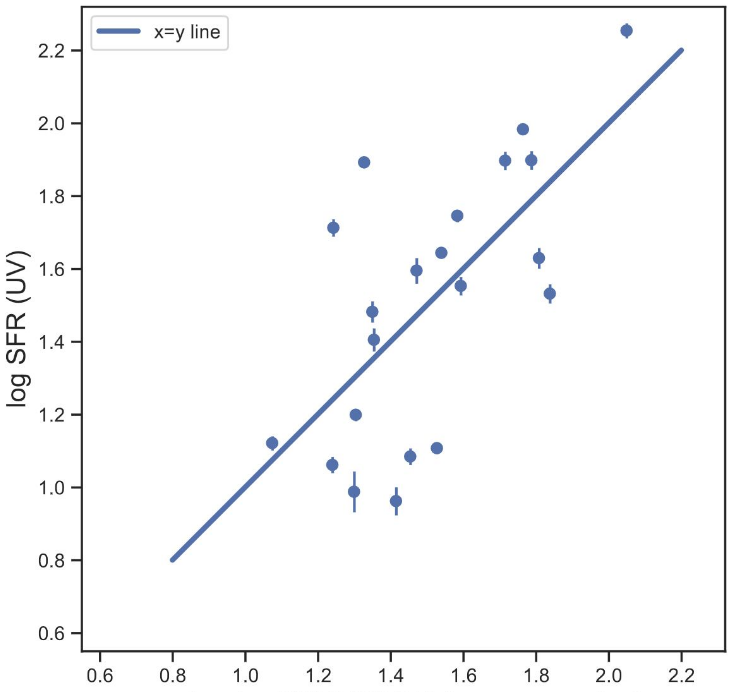
Bait+24, under review in A&A

Comparison of SFR (radio) with other tracers

Bait+24, under review in A&A



log SFR (Radio)

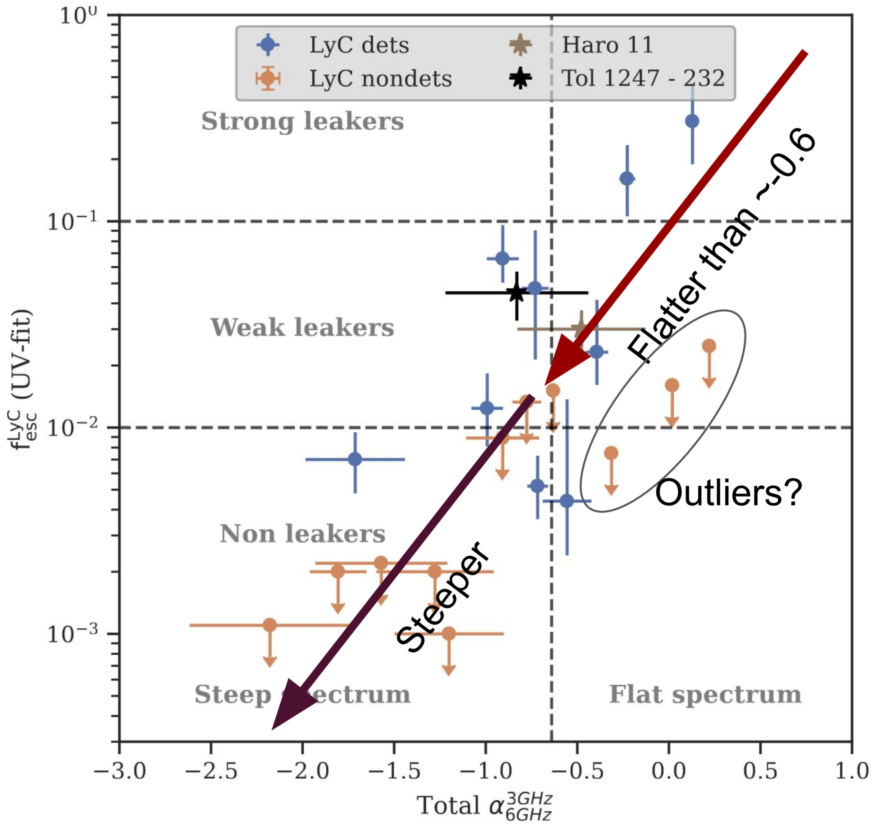


a + b x log SFR (Radio) + c (spectral index)

SFR Radio shows a lot of scatter with other tracers.

Adding spectral index can reduce the scatter.

f_{esc} - spectral index relation



Why do high f_{esc} galaxies show a flat spectrum?

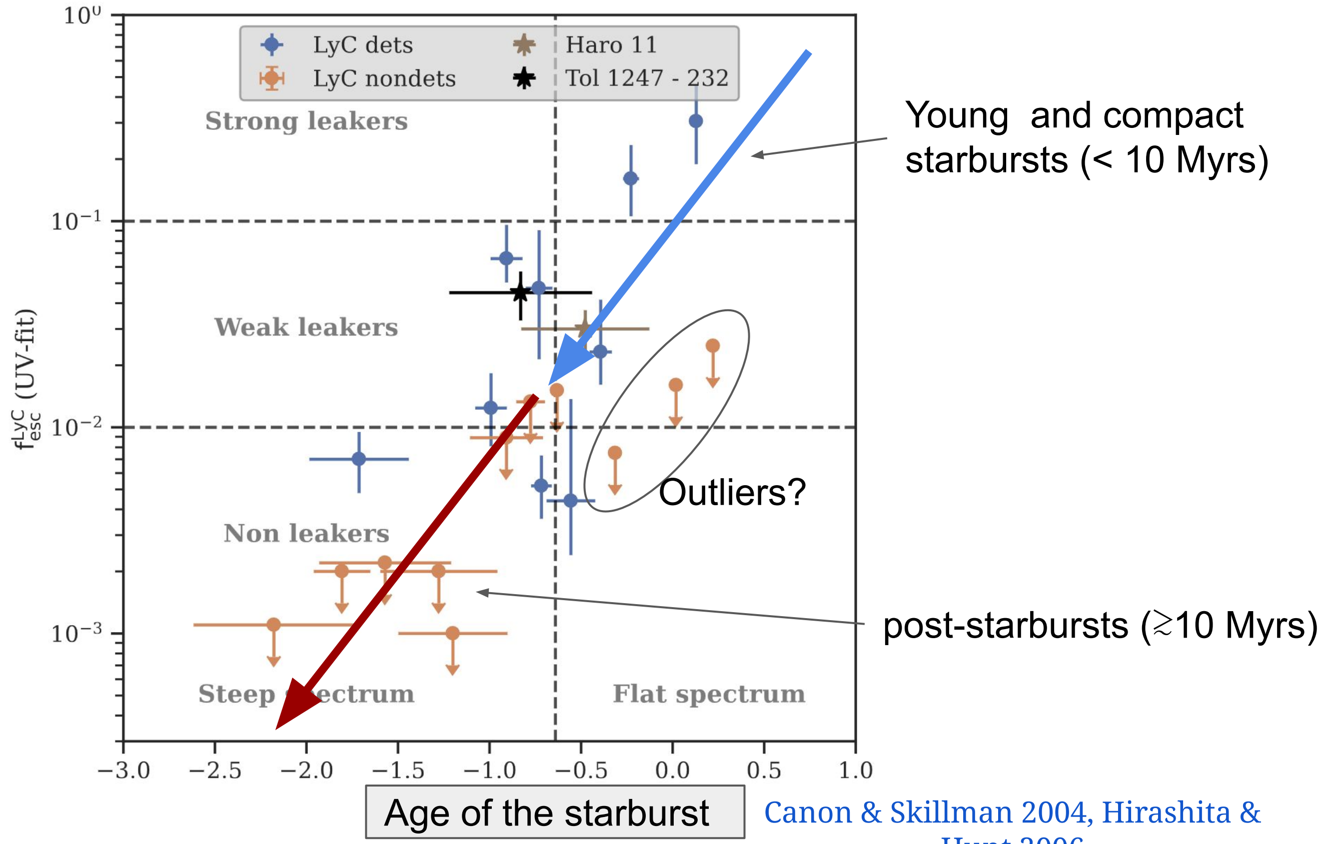
Young ages/free-free absorption, flat cosmic-ray energy spectrum. Hunt & Hirashita 2006

Need more data for high f_{esc} sources!

Non-leakers systematically show steep radio spectrum.

Bait+24, under review in A&A

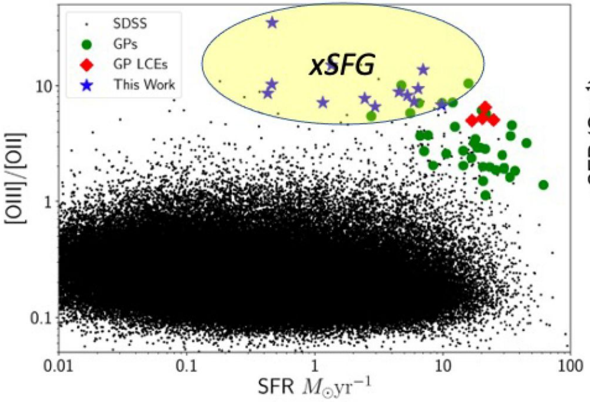
f_{esc} - spectral index relation – time dependence

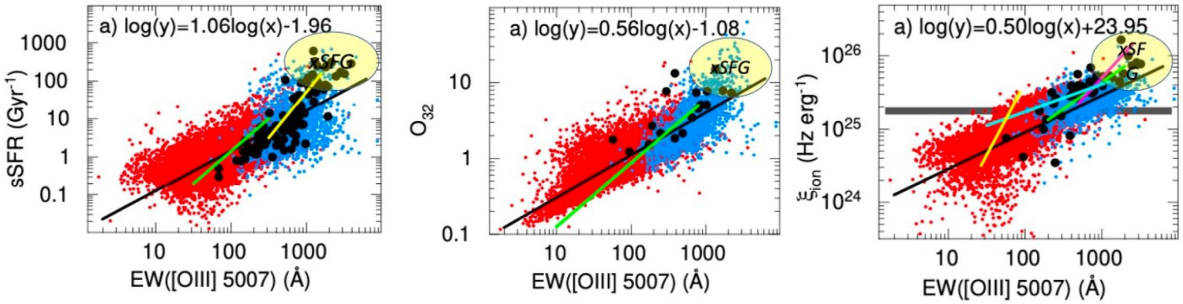


Canon & Skillman 2004, Hirashita & Hunt 2006

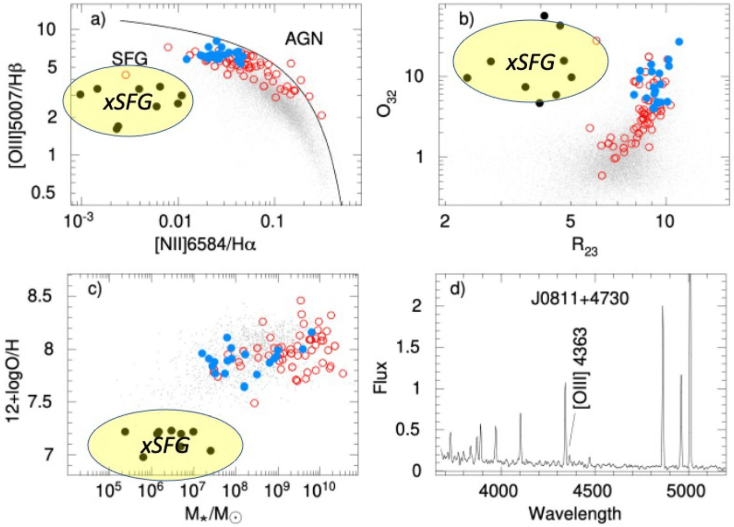
Bait+24, under review in A&A

Local extreme-SFGs (xSFGs)





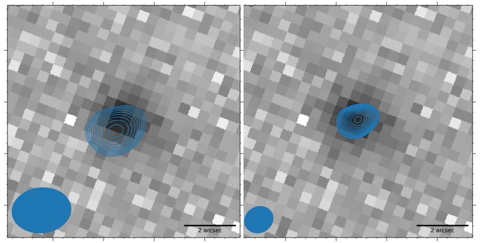
Izotov+21



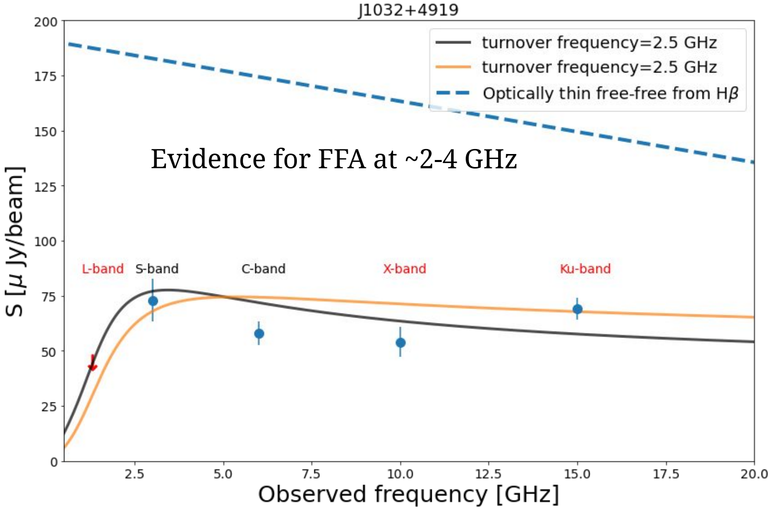
- z~0.02-0.076
- Down to 12+log(O/H) = 6.98
- Extreme than Green peas, blueberries
- Ongoing HST-COS programs to measure LyC
- Follow up with JWST-MIRI, XMM-Newton at X-ray etc…

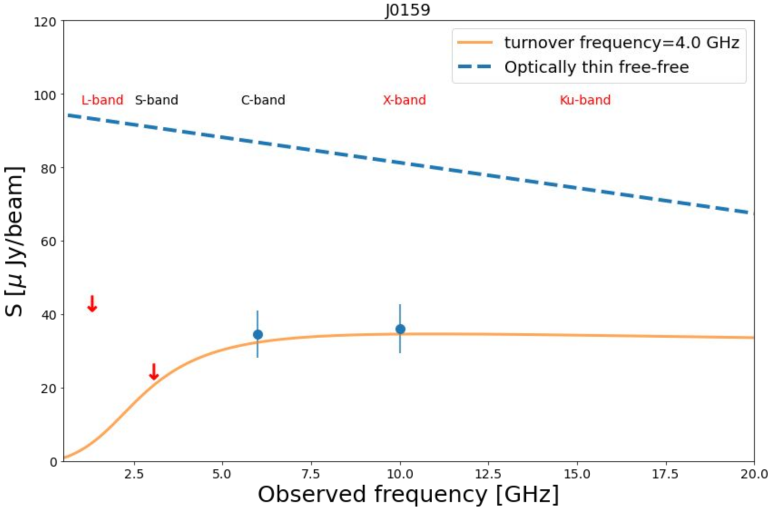
Radio follow up of xSFGs

- **Ongoing VLA L-, S-, C-, X- (10 GHz), and Ku- (15 GHz) band** observations.
- uGMRT **325+610 MHz** follow up
- Study the **radio-SED** from (0.3-18 GHz)
- Thermal fraction, SNe rate + ISM properties

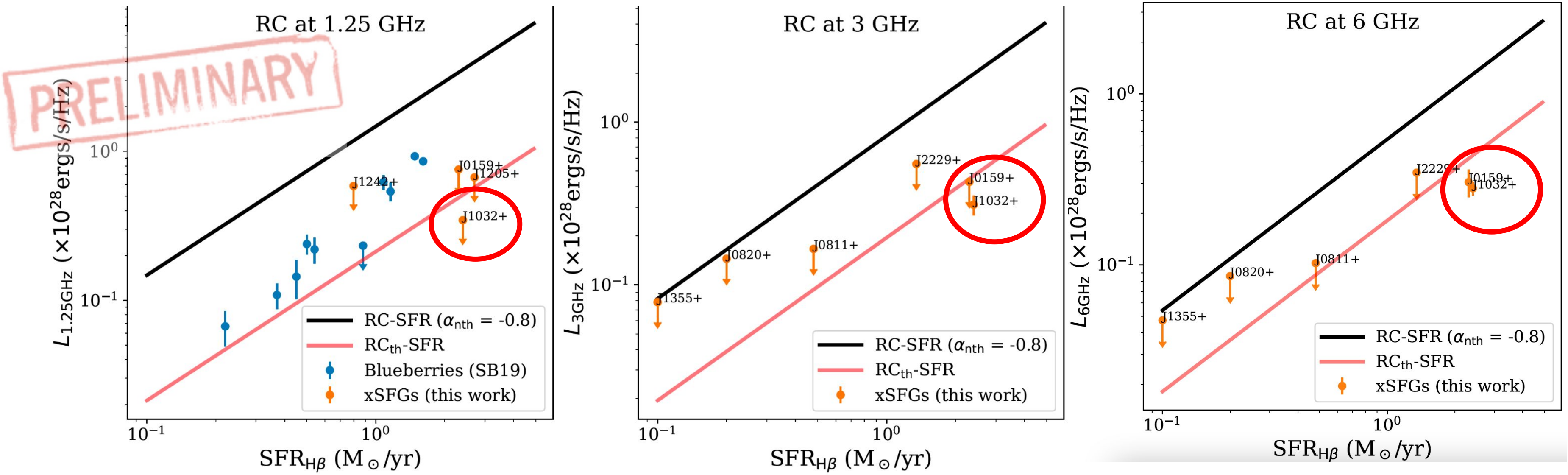


Bait+24, in prep





Optically thick HII regions in radio?



Bait+24, in prep

- The observed radio thermal flux is a factor of ~2 lower than that expected from Hbeta line!!
- Optically thick HII regions at 10-15 GHz? Need radio data at ~20-30 GHz to verify.
- This results have important implications on the nature of high-z galaxies and predictions for deep radio surveys using the SKA.

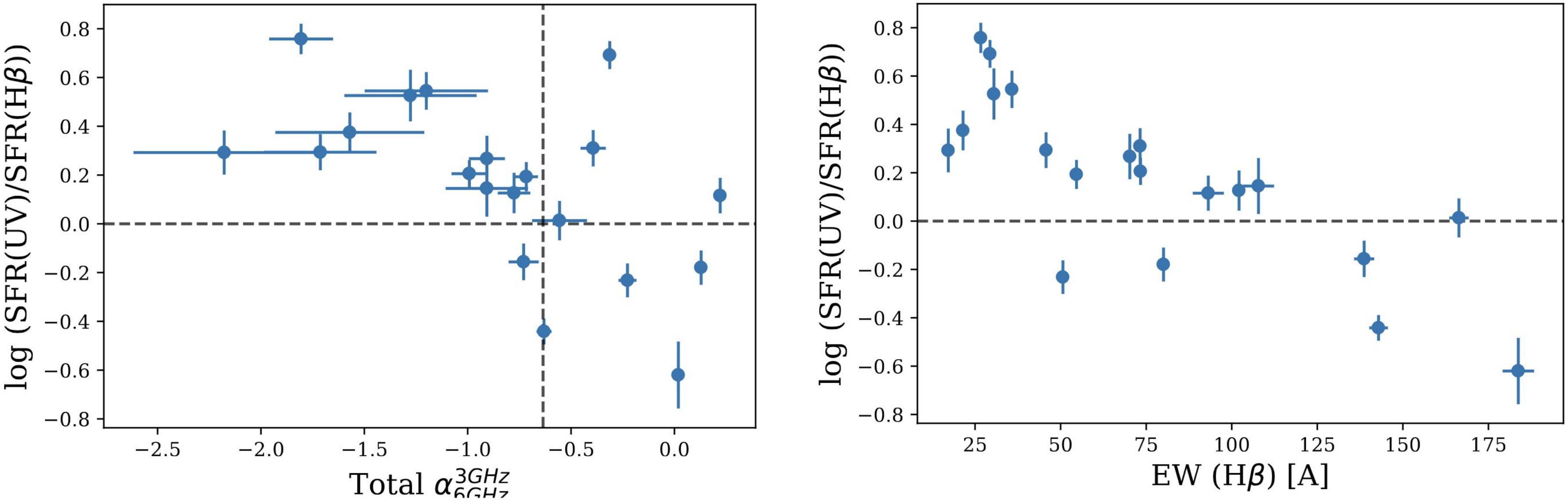
Summary and Status

- Large diversity in their radio-SEDs at GHz frequencies: steep spectrum, turnover and breaks in the spectrum.
- RC-SFR relation has a large scatter → extra information on spectral index helps to calibrate.
- **LyC escape is correlated to the radio spectral index at ~GHz frequencies.**
- This motivates to study the role of cosmic-rays and magnetic fields in LyC leakage.
- Strong leakers from LzLCS sources are observed with the VLA in cycle 23.
- **Extreme star-forming galaxies pose new puzzles in our understanding of EoR galaxies.**
- Need high frequency observations (at 20-30 GHz) and JWST-MIRI data upcoming.
- **Important implications for deep extragalactic radio surveys in the SKA era.**

Thank You

Extra Slides

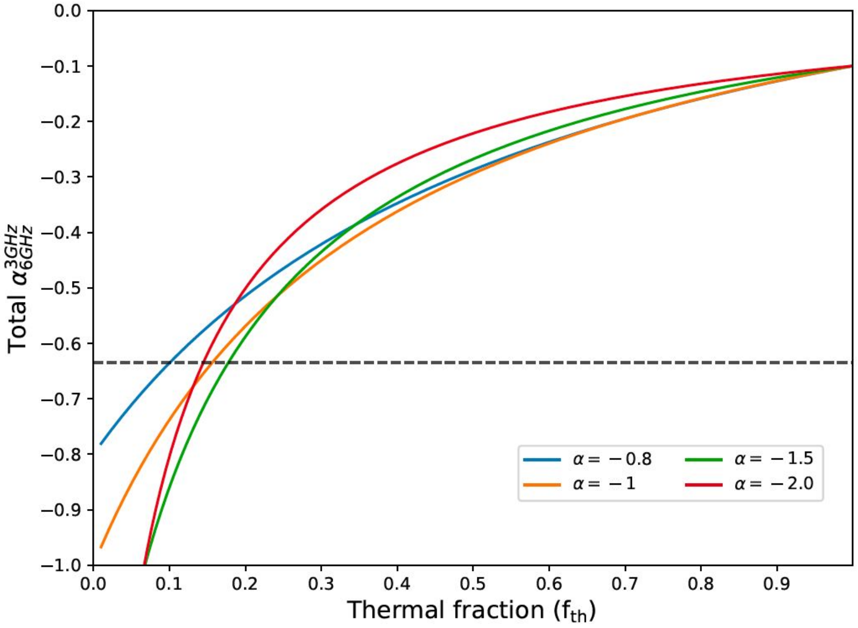
Steep spectrum sources are post-starburst?



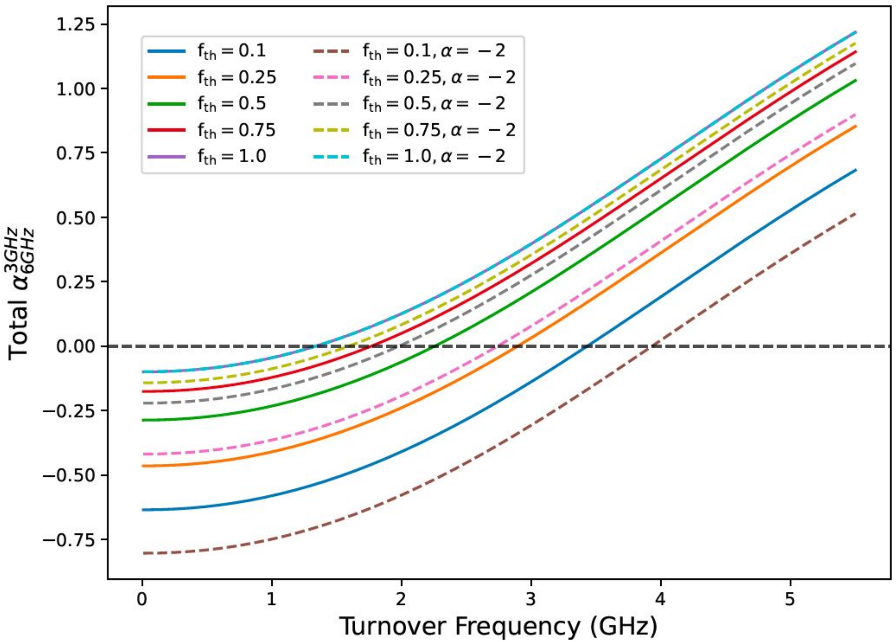
- Steep spectrum sources have higher UV-SFR (~100 Myrs tracer) vs. Hβ-SFR (~10 Myrs tracer).
- Thus is a sign of galaxies with a declining star-formation histories (or post-starbursts).

Bait+24, under review in A&A

How to flatten a radio spectrum



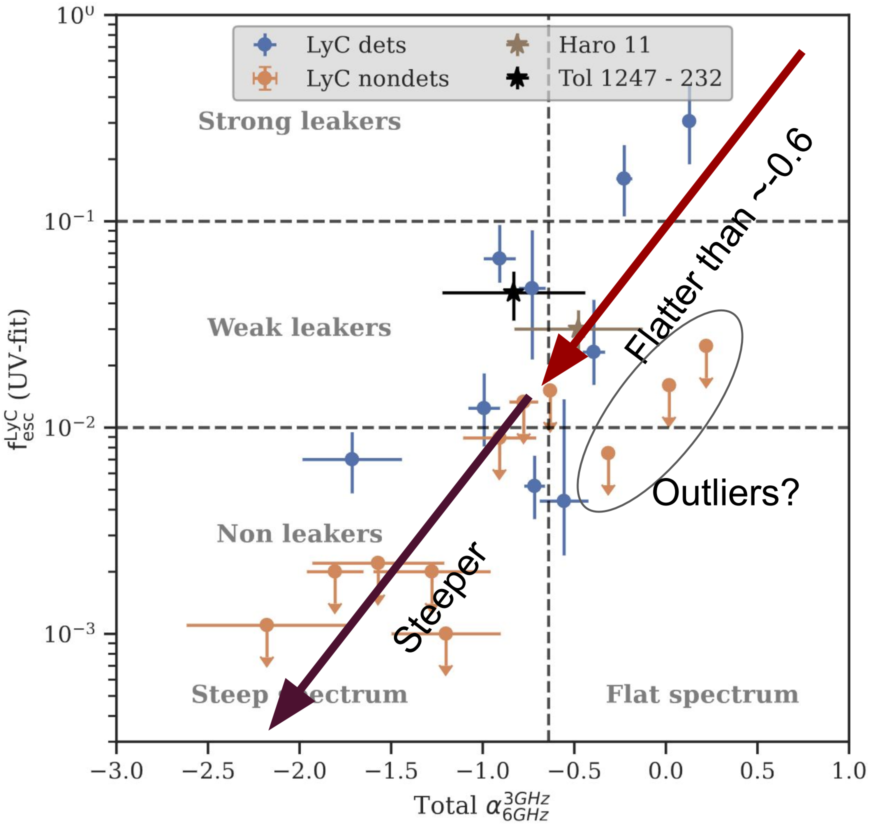
Thermal fraction (less SNe)



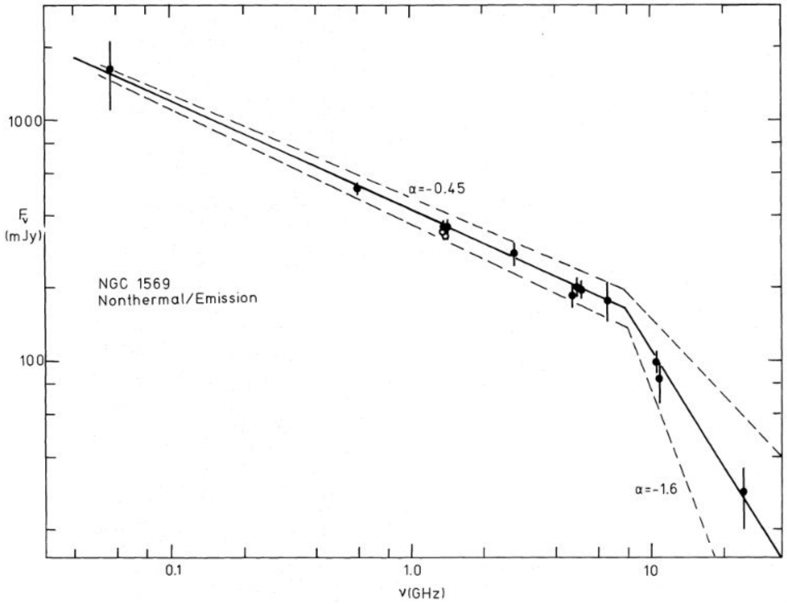
Free-Free Absorption (compact starbursts)

Bait+23, submitted to A&A

How to steepen the radio spectrum



Bait+23, submitted to A&A

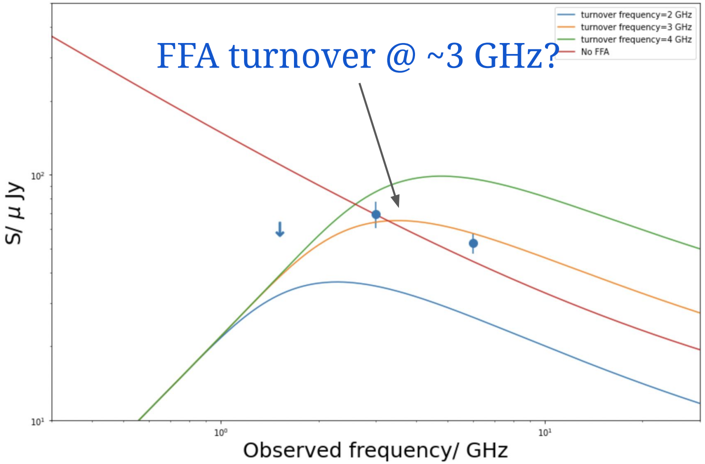


NGC 1569: cutoff model (single injection model), Israel & Bruyn 1988

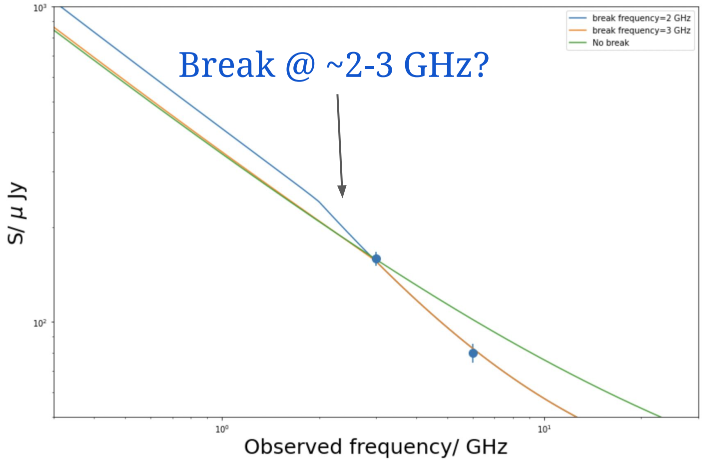
Other causes: CRe escape, IC losses

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

A variety of radio-SEDs



Flat spectrum

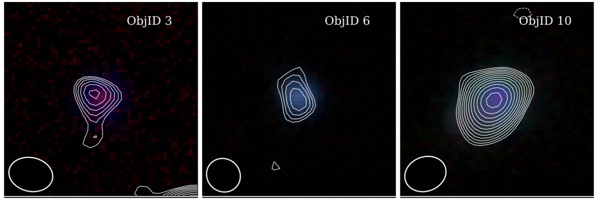


Steep spectrum

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.

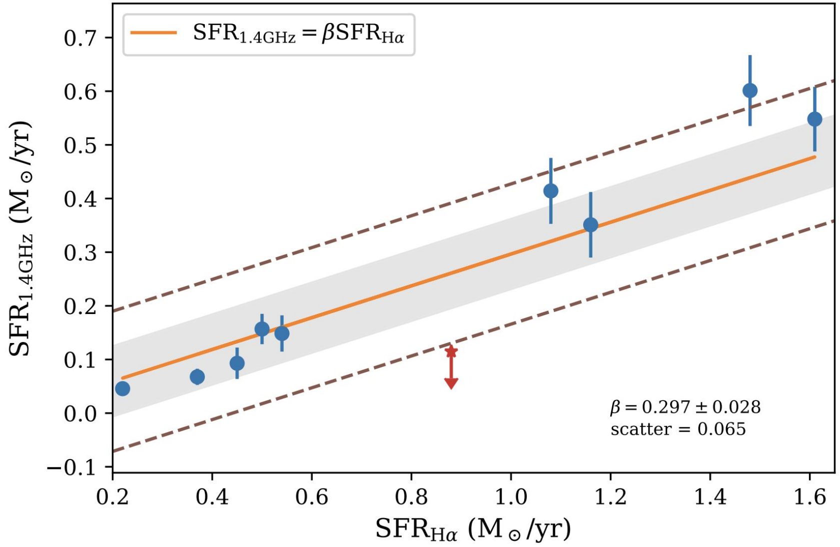
Radio Study of local analogues



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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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