International Centre for Radio Astronomy Research

The GLEAMing of the first supermassive black holes: peaked-spectrum sources at high redshift

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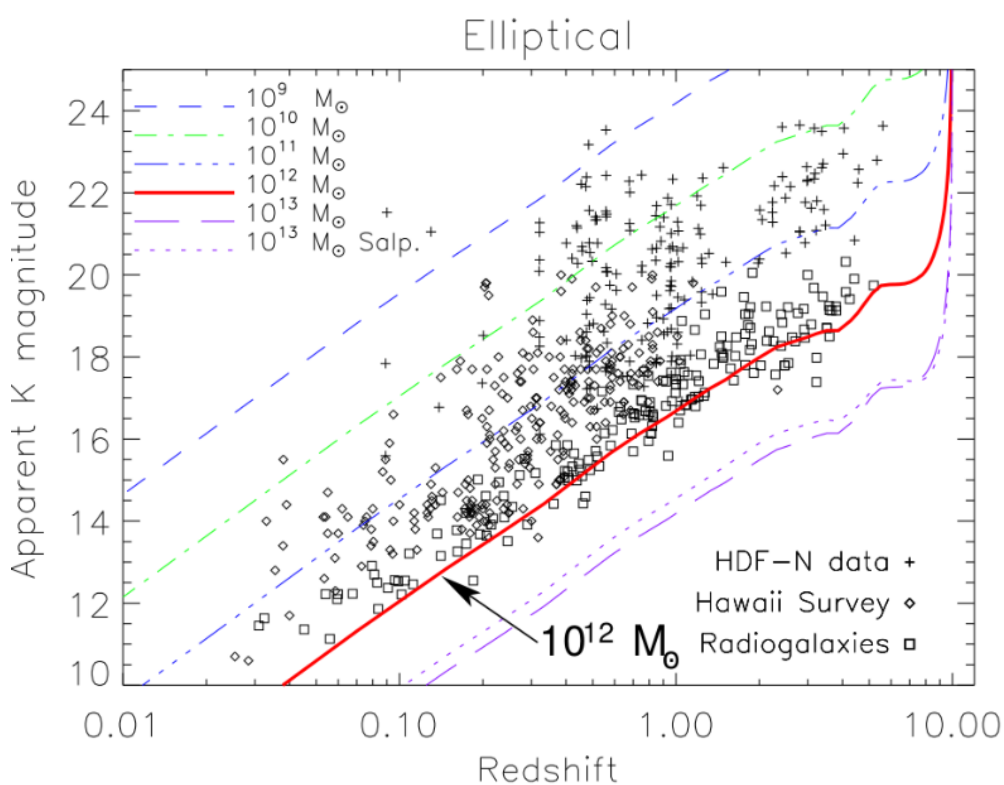
Curtin University | The University of Western Australia | Government of Western Australia, Department of the Premier and Cabinet, Office of Science

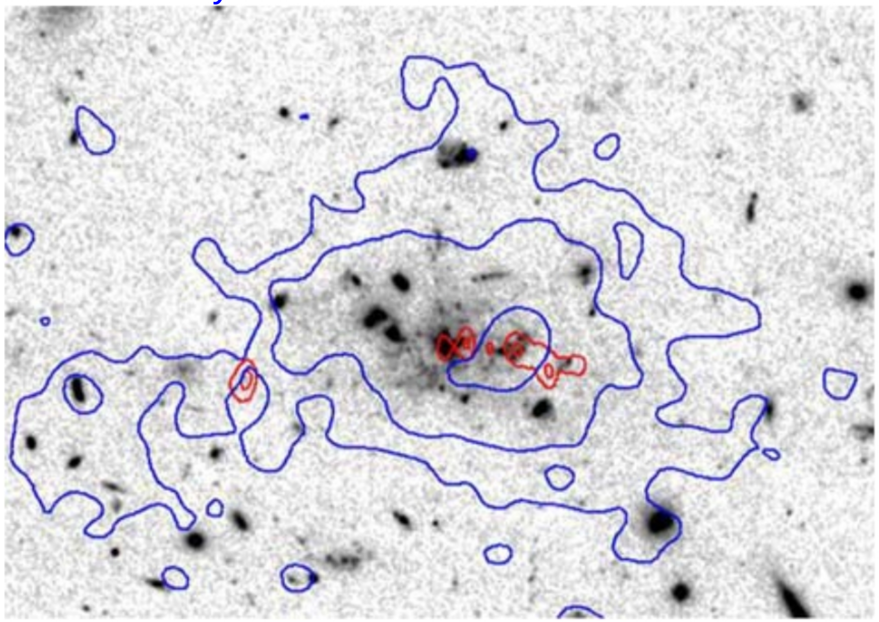
Why study HzRGs?

- Vital probes of massive galaxy formation and evolution (review by Miley & De Breuck 2008).
- Extreme SMBH and host galaxy growth – e.g. QSO J0313-1806 @ z = 7.64; $1.6 \times 10^9\ M_\odot$ BH, 670 Myr after the Big Bang (Wang et al. 2021).



Rocca-Volmerange et al. 2004

Greyscale: *Hubble* ACS
Red: VLA 8 GHz
Blue: VLT Lyα

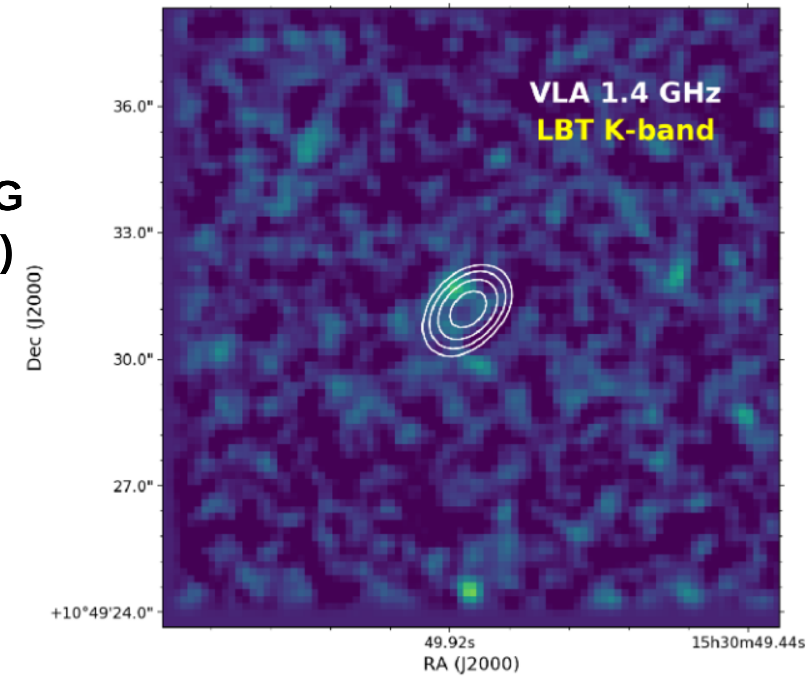


Miley et al. 2006
'Spiderweb Galaxy' @ *z* = 2.156

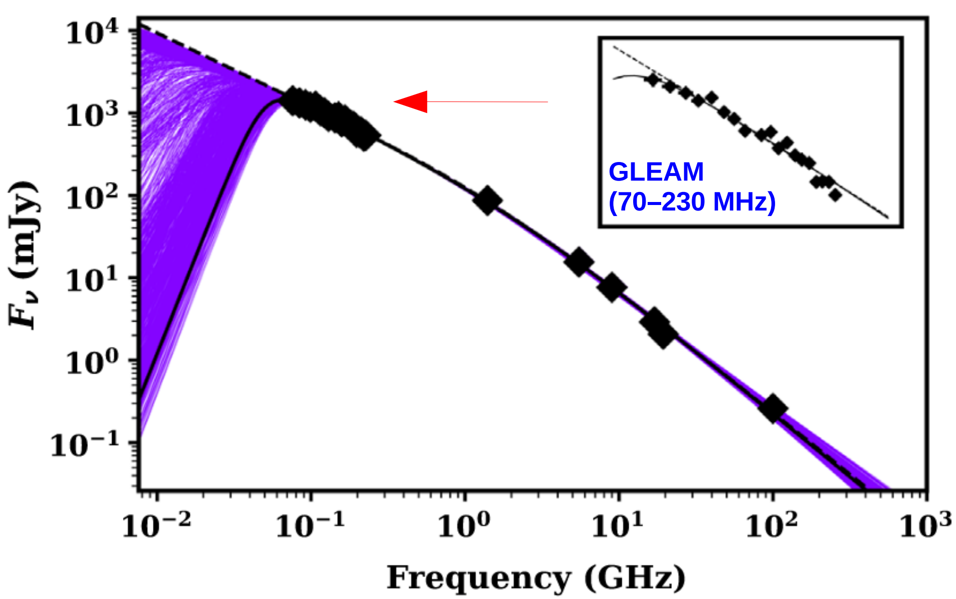
The importance of low-frequency radio observations

- HzRGs traditionally found via USS selection in the radio ($S_\nu \propto \nu^\alpha$ where $\alpha \leq -1.3$ (or -1.0); e.g. De Breuck et al. 2000).
- **Saxena et al. (2018)** discovered **TGSS J1530+1049, a HzRG at *z* = 5.72**. USS selected: **GMRT/TGSS (Intema et al. 2017)** + FIRST and NVSS. Optical spectroscopy.
- **Our HzRG project**: uses radio spectral steepness *and* curvature from **MWA/GLEAM (Wayth et al. 2015)**. Redshift from ALMA molecular lines.

$S_{147.5}$ = 170 mJy; linear size = 3.5 kpc



Saxena et al. 2018



Drouart et al. 2020

Discovery of GLEAM J0856: a HzRG at z = 5.55

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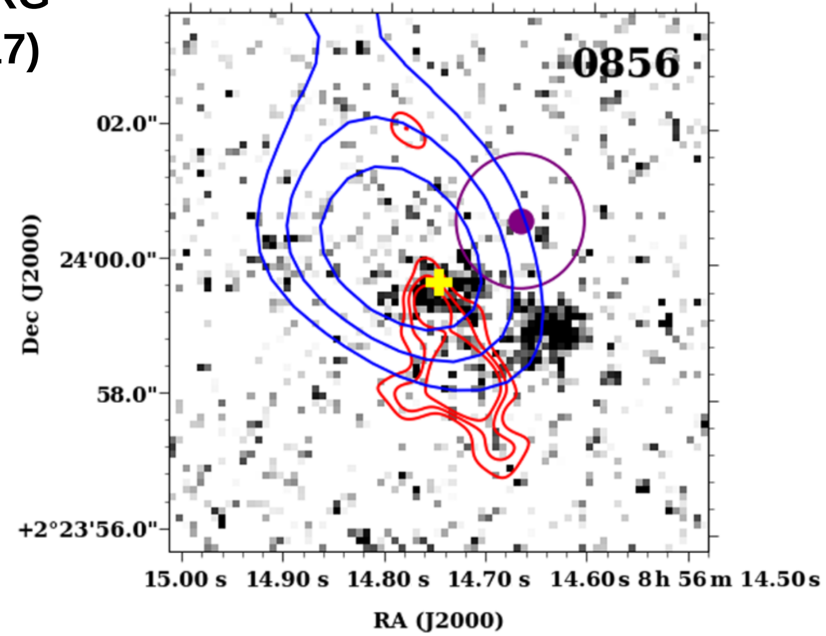
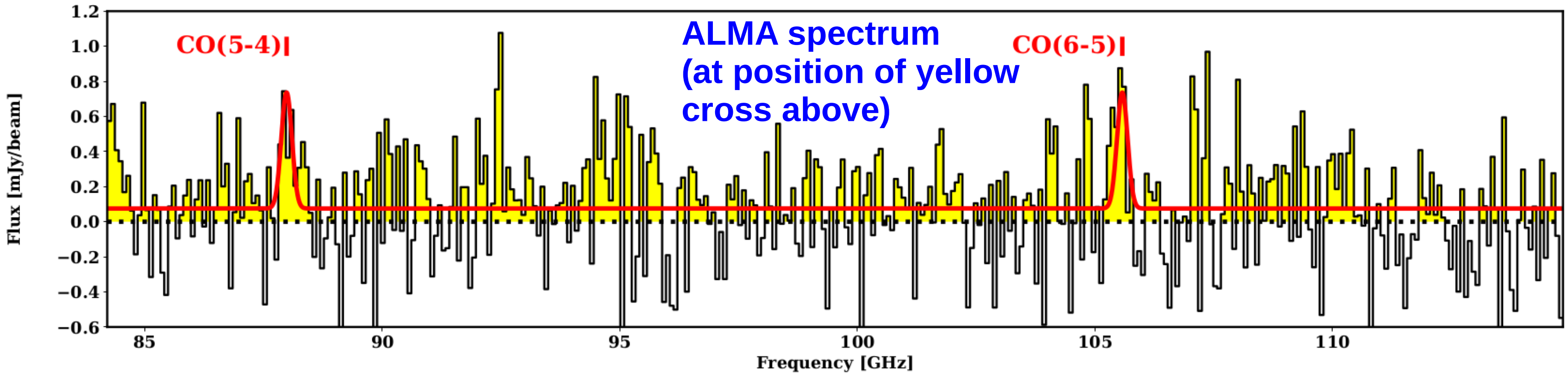
Greyscale: VLT HAWK-I K_s-band
Red: ALMA 100-GHz continuum
Blue: ALMA 100-GHz line emission
Purple: GLEAM position
S_{151} = 890 mJy; α / β -1.02 / -0.84
Linear size ≈ 7.3 kpc



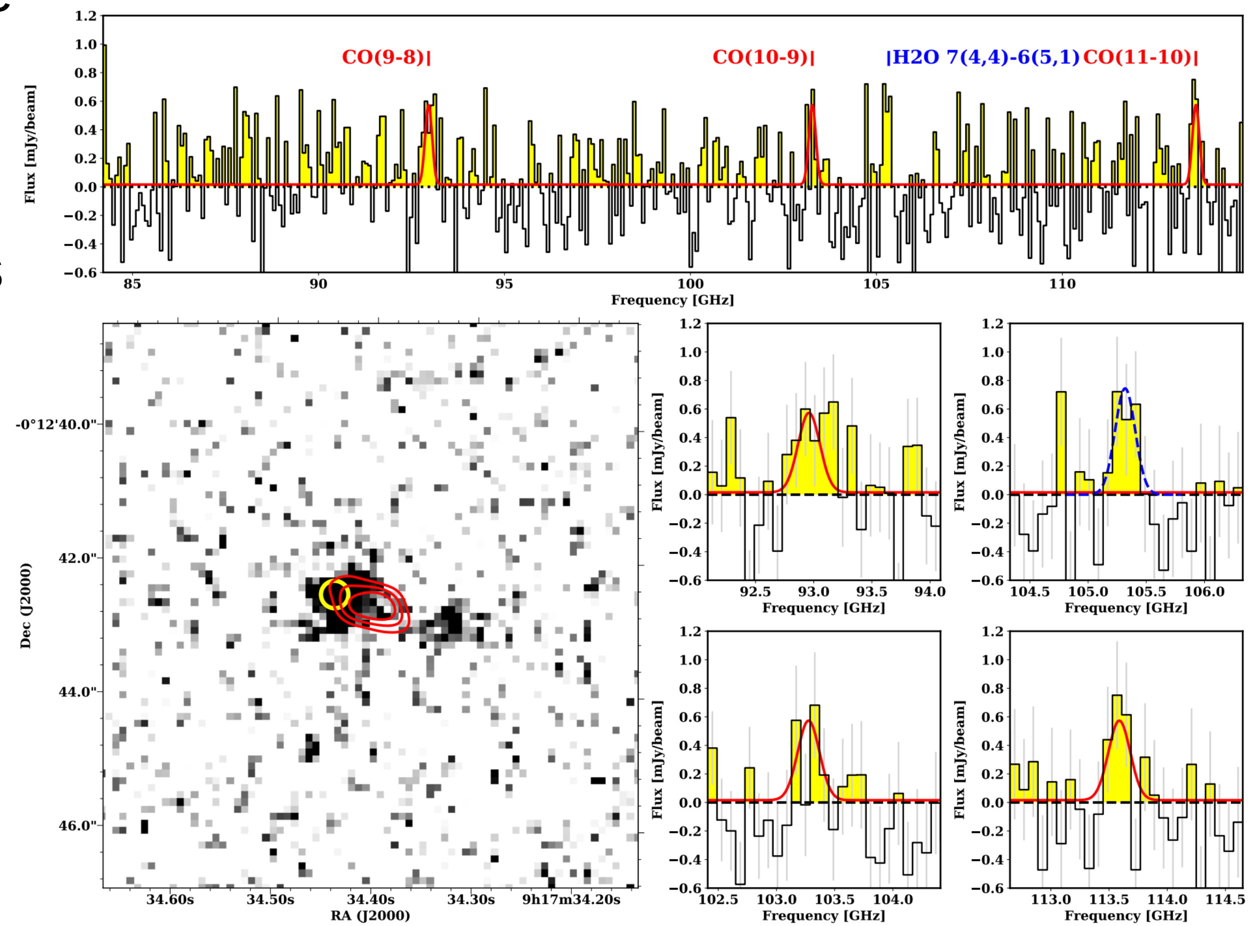
Paper on our pilot sample now published (Drouart et al. 2020, PASA, 37, e026)



GLEAM J0917 – ALMA and JVLA observations

- Pilot study suggested GLEAM J0917 could be at z = 10.15.
- ALMA DDT re-observation of CO lines (PI Drouart; 2 × 40 min).
- JVLA DDT *Q*-band: CO(4-3) and [CI(1-0)] if z = 10.15 (5 hr on source; PI Drouart.)
- **Both follow-up observing campaigns: no molecular lines detected.**

Drouart et al. 2020



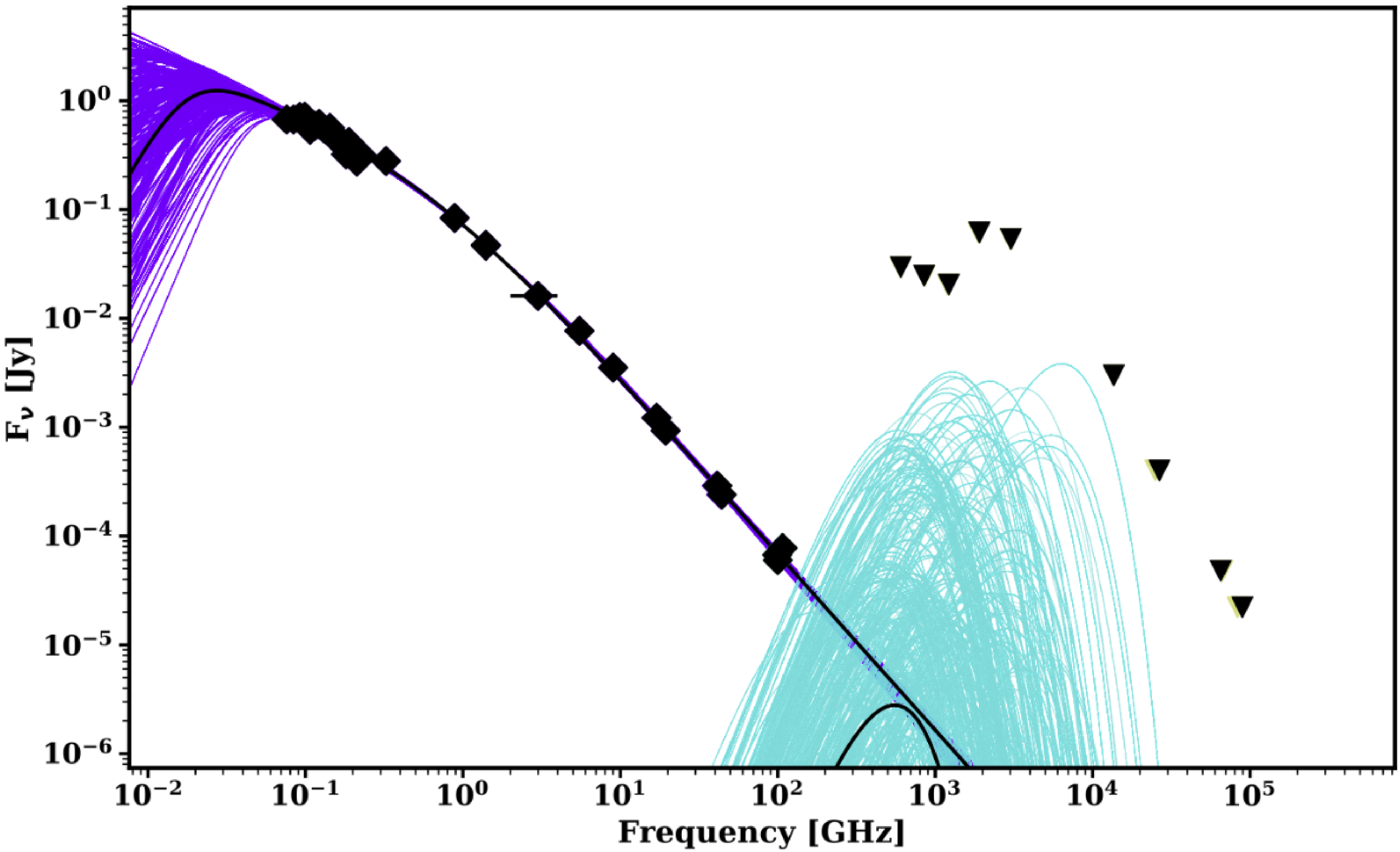
Greyscale: VLT HAWK-I K_s-band

Red: ALMA 100-GHz continuum

S_{151} = 465 mJy; α / β -0.94 / -0.87

Largest angular size ≈ 1 arcsec

GLEAM J0917 broadband radio–IR SED

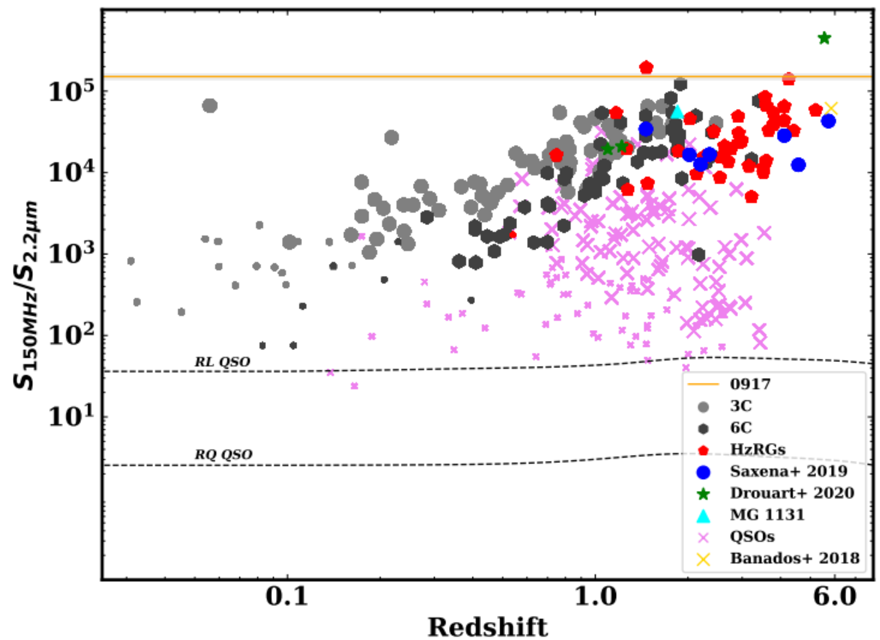


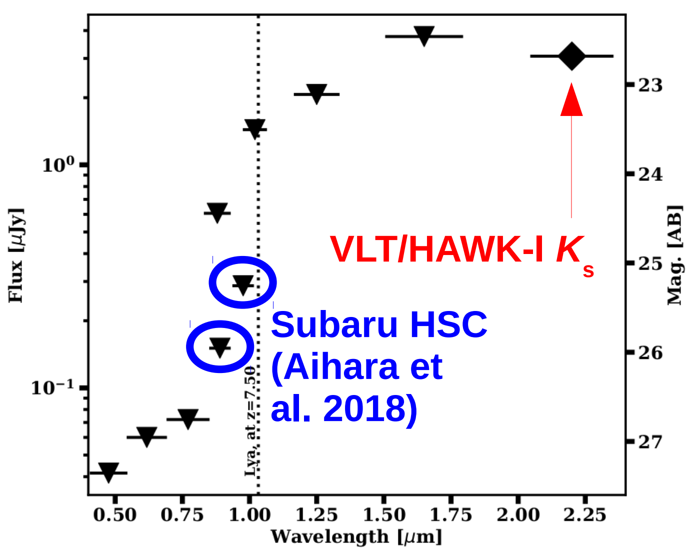
Drouart et al. 2021, submitted

GLEAM J0917 – an enigmatic source

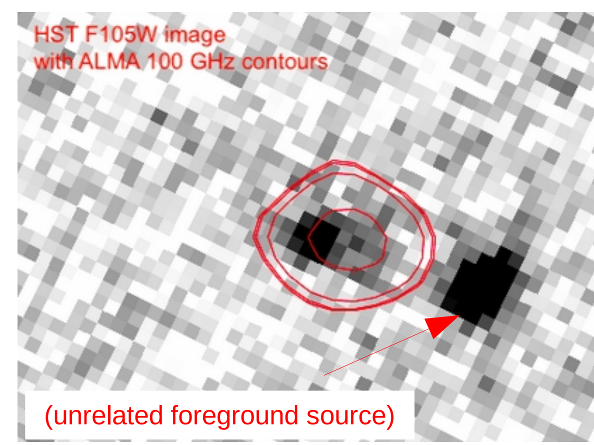
- **Multi-wavelength follow-up study: Drouart et al. 2021, PASA, submitted.**
- Very radio-loud object. Molecular gas-poor system; also lack of dust (< 10^7 $M_\odot$).
- A peculiar object if $z < 5$.
- **More likely solution: $z > 5$.**
- ***HST* imaging and grism observations taken**; Cycle 28 (PI Seymour).
- First *HST* imaging observation (F105W) also consistent with a very high-z source. *Stay tuned: grism observations currently being analysed.*

N. Wright – 3rd-yr project @ ICRAR/Curtin





Drouart et al. 2021, submitted



Seymour et al. in prep.

GLEAM J0917 – an enigmatic source

Polarimetric properties:

Not polarised at our observing frequencies below 10 GHz.

MWA interplanetary scintillation (IPS) observations (Morgan, Chhetri et al.):

Half of the flux density at 162 MHz is on a scale ≤ 0.5 arcsec (≤ 3.1 kpc for z ≥ 5).

Upcoming Long Baseline Array VLBI 2.3-GHz observations in July (PI Broderick):

Up to 200x improvement in angular resolution cf. our ALMA 100-GHz data.

- ***HST* imaging and grism observations taken**; Cycle 28 (PI Seymour).
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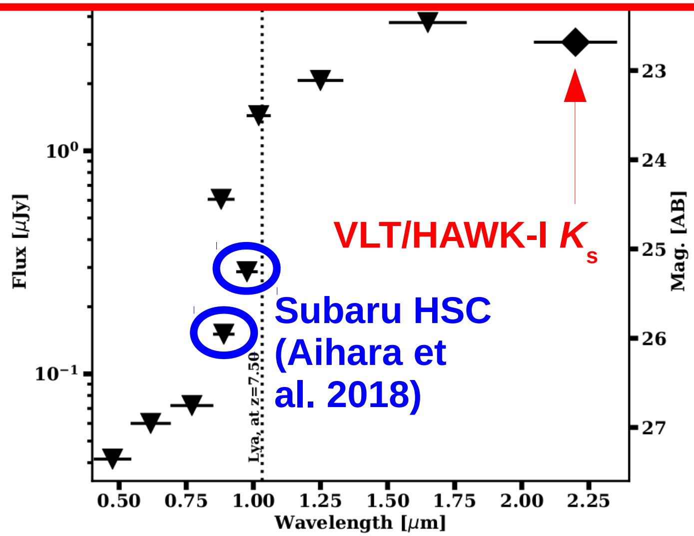
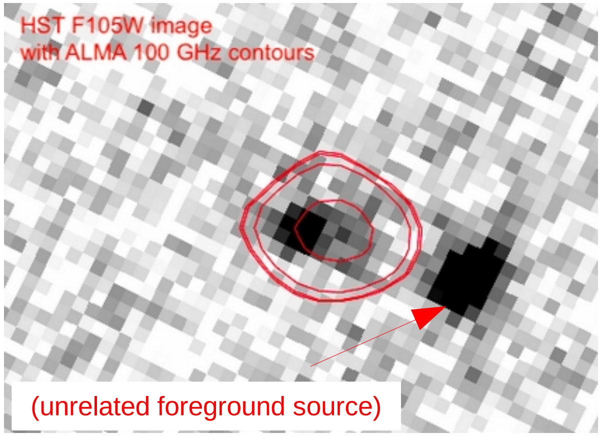


Drouart et al. 2021, submitted



Seymour et al. in prep.

LOFAR low-band observations

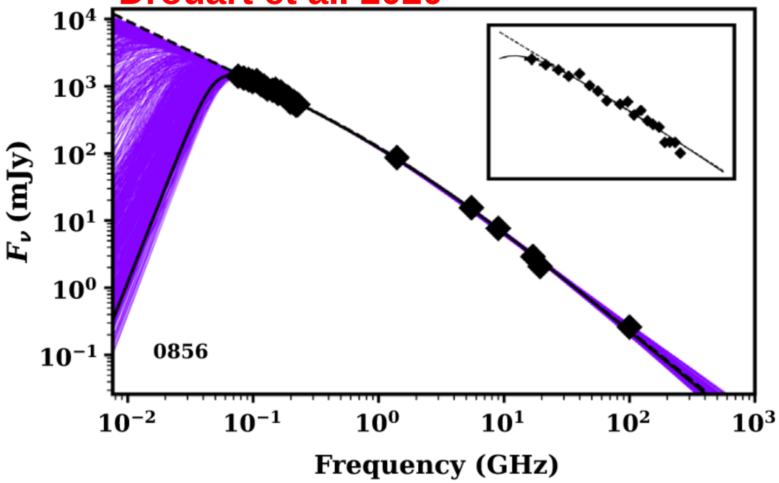
- **Constraining the low-frequency spectra of GLEAM J0856 and J0917.**
- **LOFAR project LC14_016 (PI Broderick).**

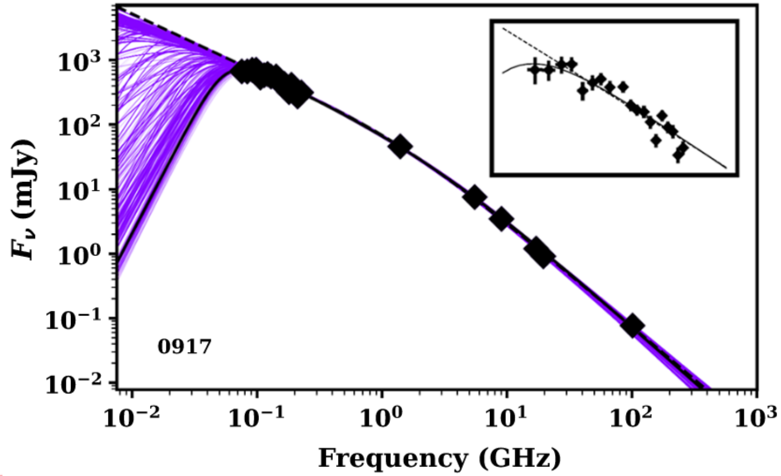
- 7 × 3-hr observations from 2020 June – September.
- Frequency range 34–66 MHz (i.e. lower than GLEAM).

- Using LBA direction-dependent pipeline (de Gasperin et al.) on CSIRO HPC cluster Pearcey.

In collaboration with George Heald (CASS) and Francesco de Gasperin (Hamburg). Thanks also to Nadia Biava (Bologna).

Drouart et al. 2020

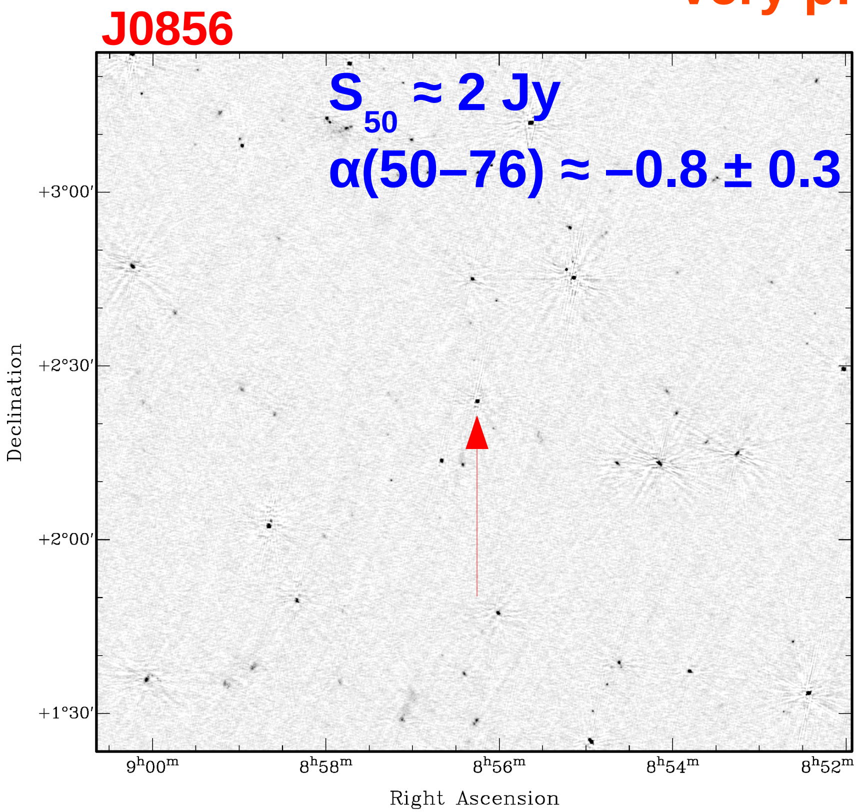


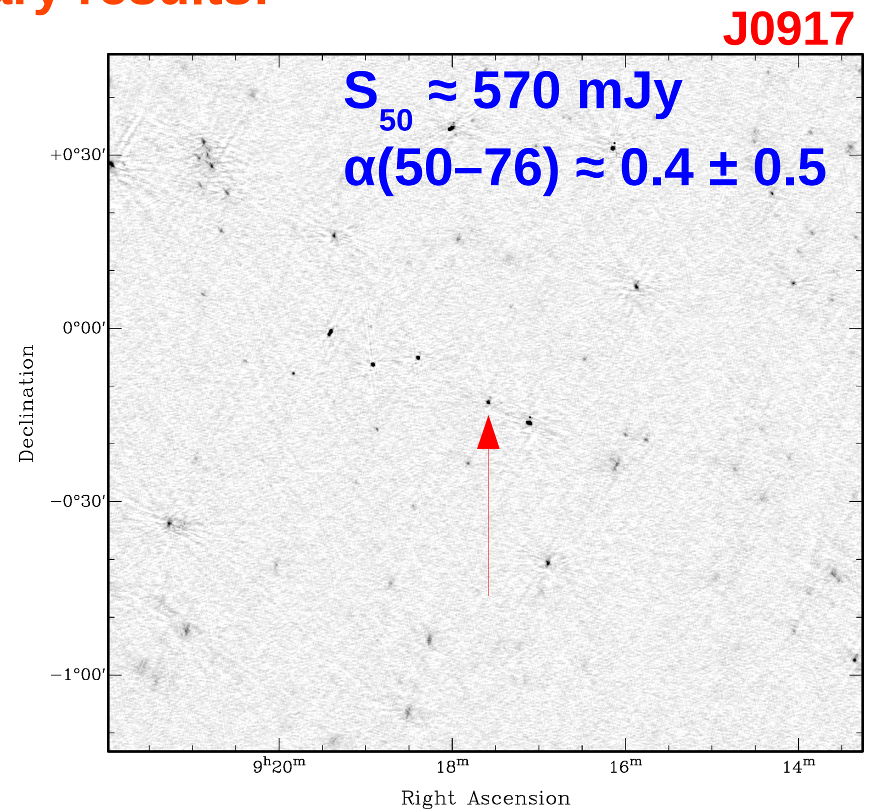


LOFAR low-band initial images

Broderick et al. in prep.

Very preliminary results!



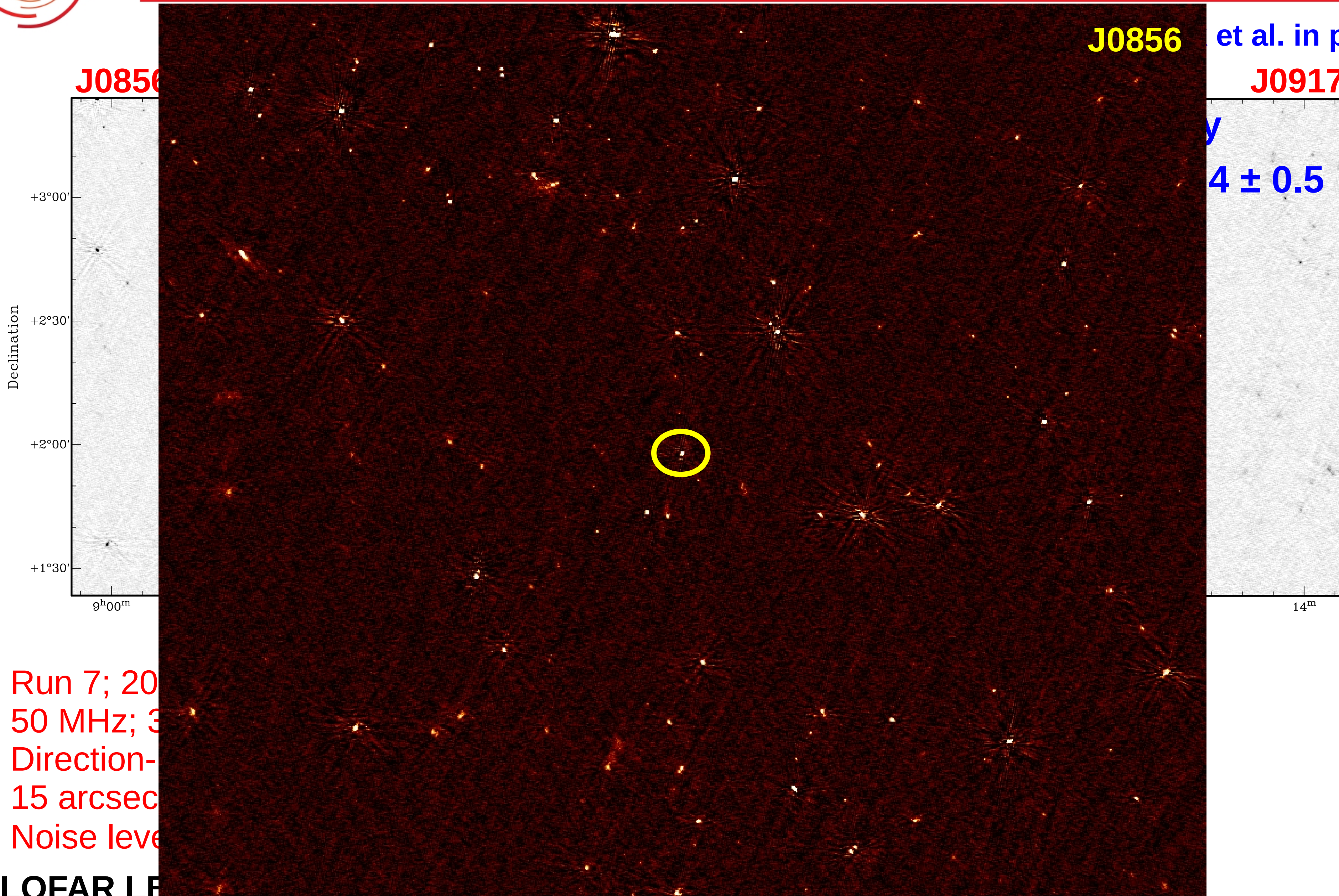


Run 7; 2020 September 13
50 MHz; 32 MHz bandwidth
Direction-independent cal. + one round direction-dependent cal.
15 arcsec resolution
Noise level ~5 mJy beam^{-1}

- **LOFAR LBA equatorial imaging – both sources clearly detected!**

LOFAR low-band initial images

et al. in prep.



Run 7; 20

50 MHz; 3

Direction-

15 arcsec

Noise leve

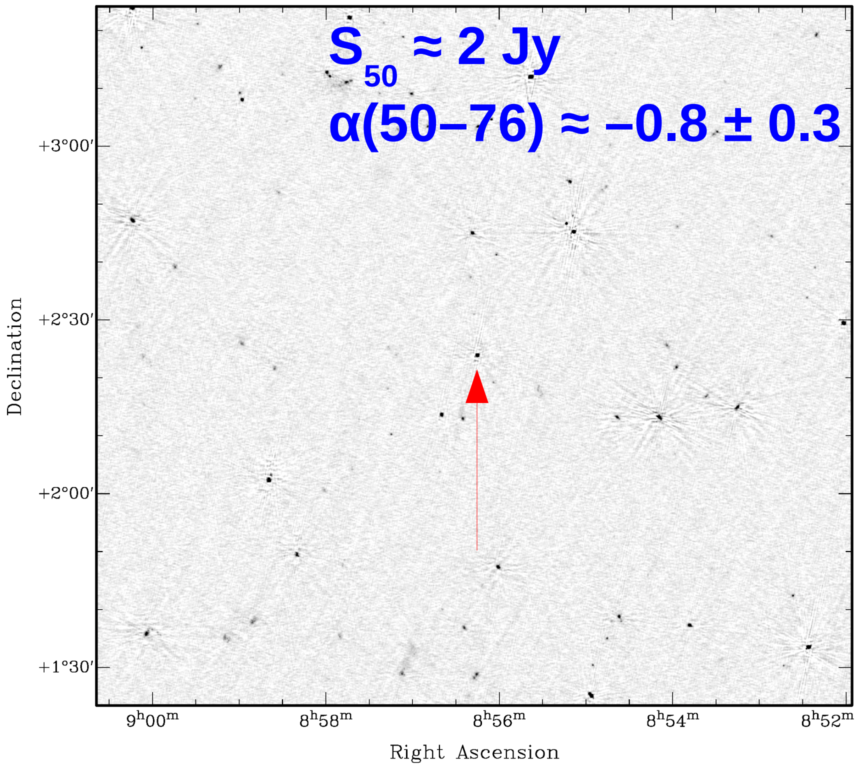
- **LOFAR LE**

LOFAR low-band initial images

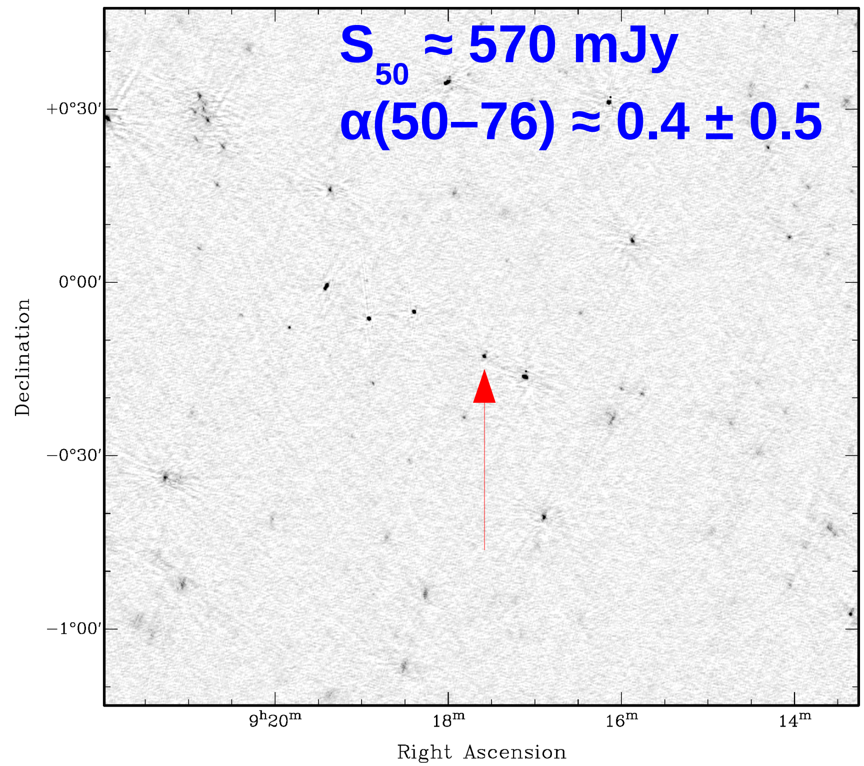
Broderick et al. in prep.

Very preliminary results!

J0856



J0917



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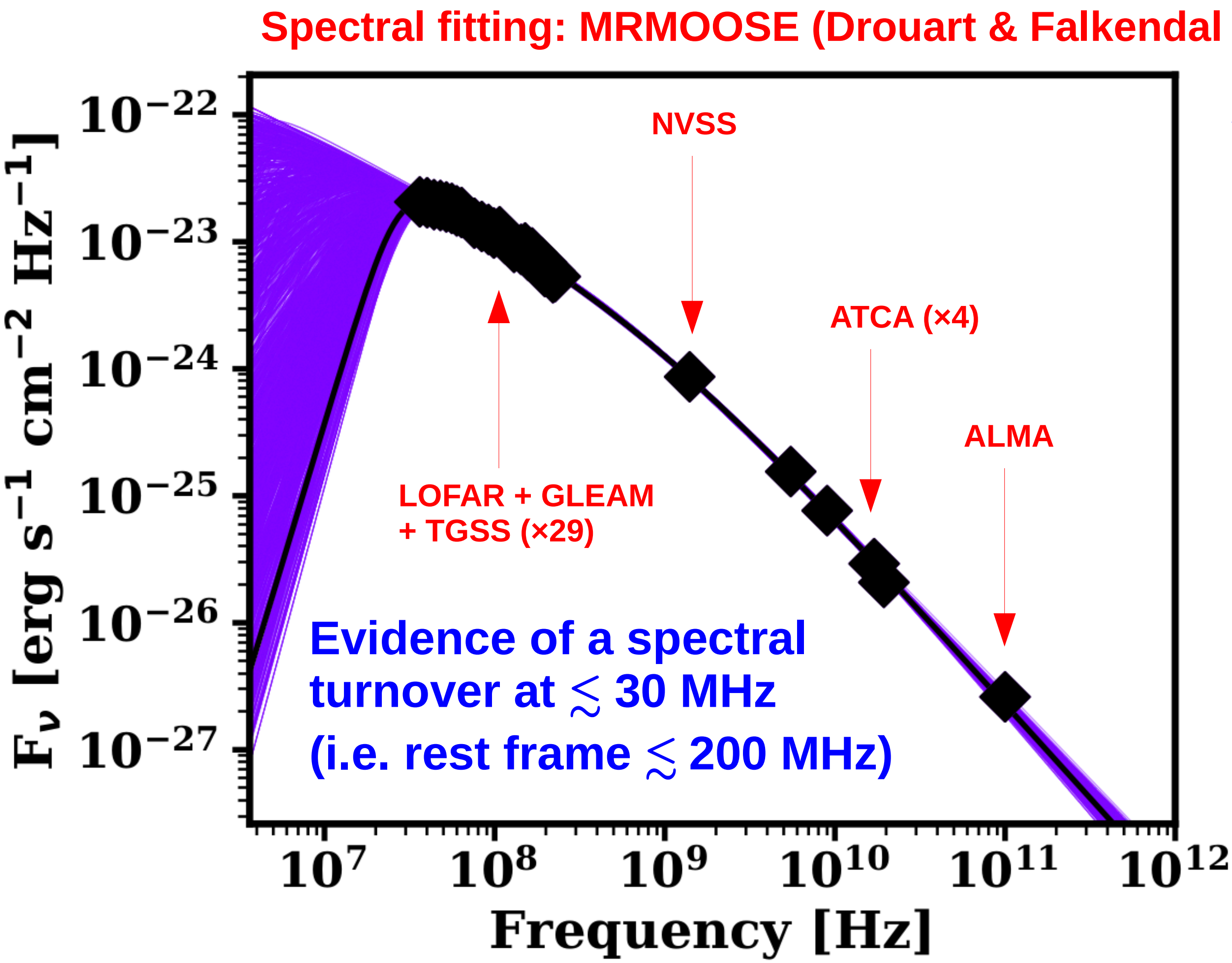
GLEAM J0856 radio spectrum



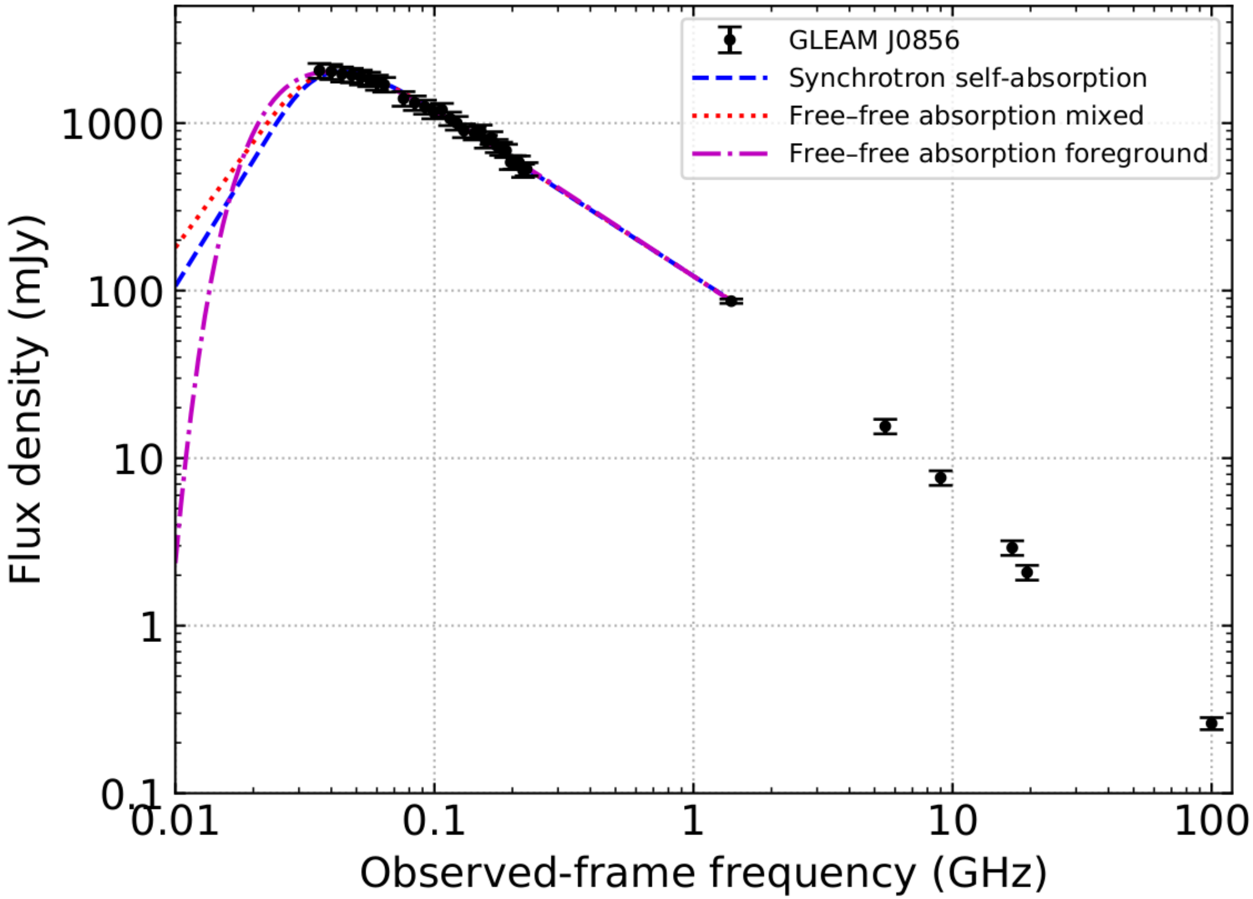
An interesting test case for low-frequency flux scale accuracy (LOFAR+GLEAM+VLSSr)?

GLEAM, VLSSr: Baars et al. 1977
LOFAR: Scaife & Heald 2012

Corrections (~0.85×) applied to LOFAR measurements to line up low-frequency flux scales to first order.

- Image 8 × 4-MHz channels across the LOFAR bandwidth (36, 40, …, 64 MHz).
- Full direction-dependent calibration still to be applied.
- Other runs to be processed as well.
- Noise level per 4-MHz channel: ~10–20 mJy beam^{-1} for one run!

GLEAM J0856 radio spectrum



Using standard model formulae with an upper frequency cutoff of 1.4 GHz for the fitting (higher-frequency spectral steepening).

Cannot distinguish between SSA and FFA with current data.

Equatorial LOFAR imaging for ν < 30 MHz? Potential LOFAR 12–31 MHz northern sky survey; test observations have started (van Weeren et al.).

- Turnover frequency ~ 30–40 MHz (rest frame ~ 200–260 MHz).
- Peak flux density ~ 1.7–2 Jy, α_{thin} (≤ 1.4 GHz) ~ -1.
- B_{equip} ~ 0.9 mG (Duffy & Blundell 2012 framework; curved radio spectra).

Expanding our pilot study

- GLEAM Year 1 catalogue (GLEAM Exgal; Hurley-Walker et al. 2017), and GLEAM Year 1 + 2 where available (GLEAM SGP; Franzen et al. 2021). **72-231 MHz.**
- ESO VISTA VIKING NIR survey (Edge et al. 2013). **2.15 μm (K_s-band).**
- Sample defined over **~1200 deg²** (~20 × GAMA-09 pilot study).

- **Goal: build a sample of HzRGs within the Epoch of Reionisation ($z > 6.5$).**

http://www.mwatelescope.org/multimedia/images/

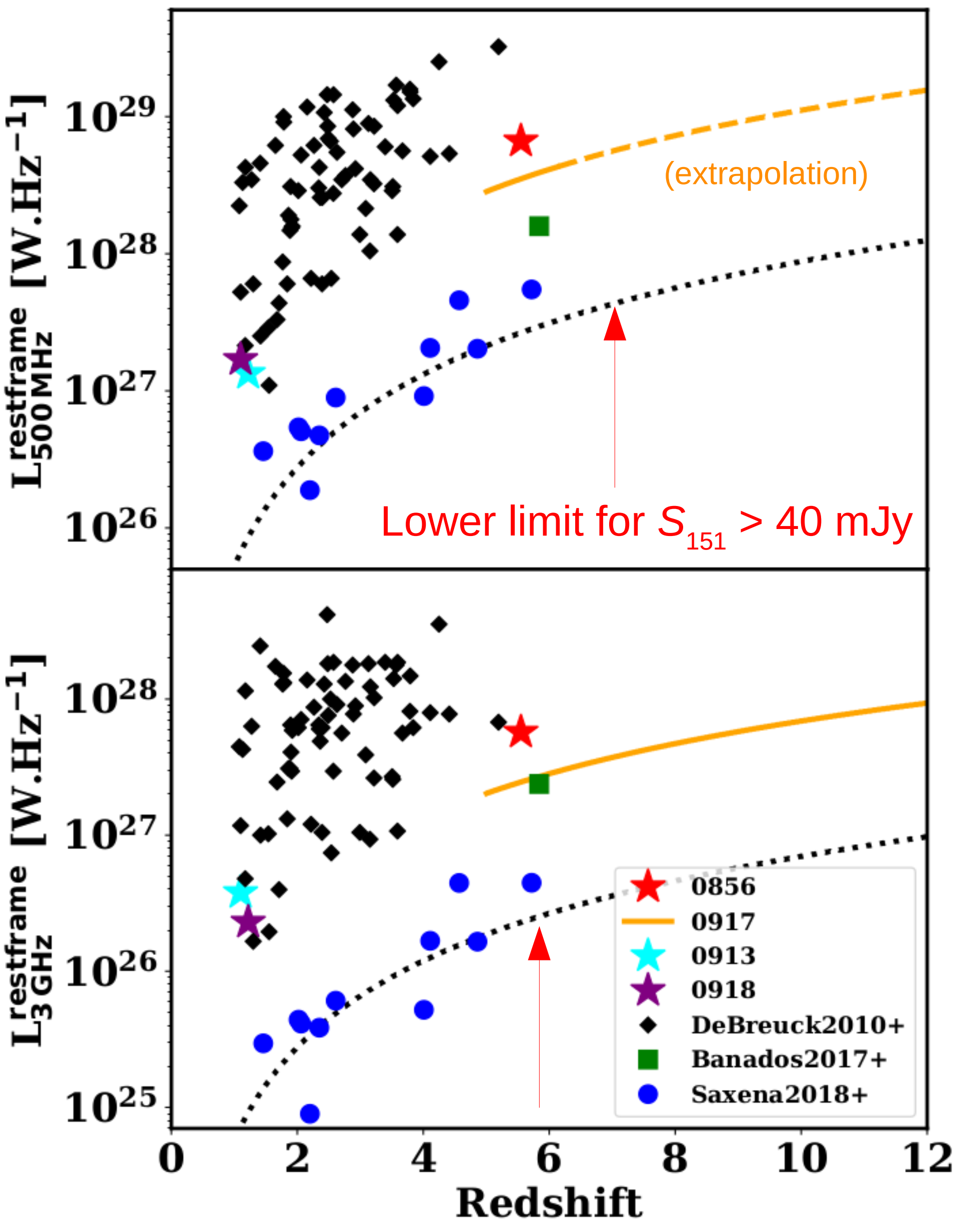
https://www.eso.org/public/images/eso0704b/

Sample selection criteria

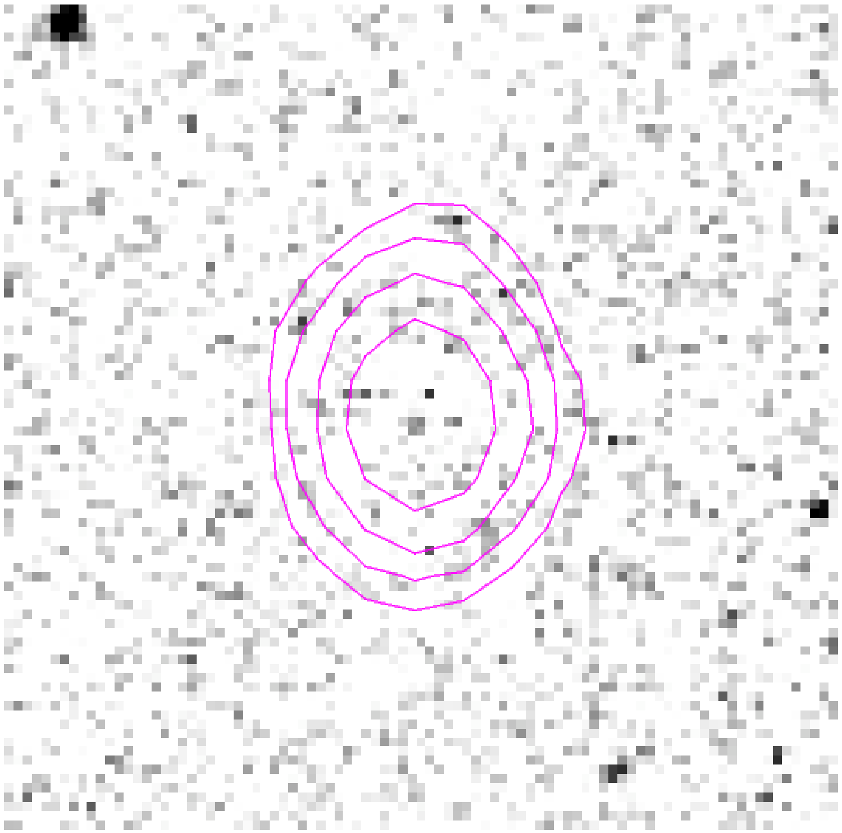
Adapted from Drouart et al. 2020

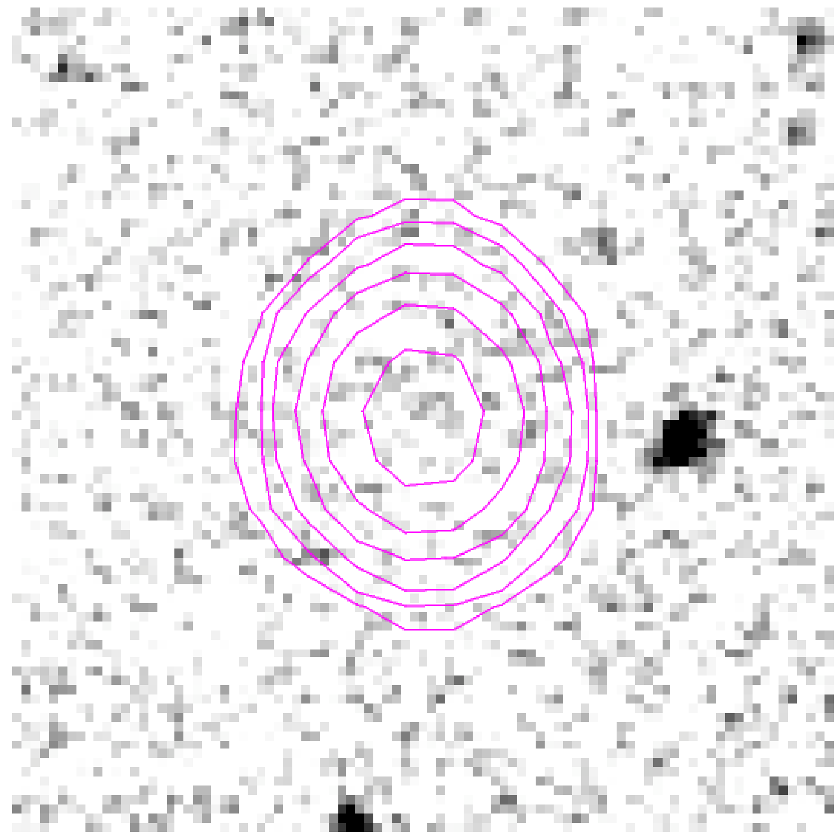
Key considerations:

- Radio flux densities
  ***S_{151}* > 40 mJy**
- Radio morphology
  LAS ≤ 5 arcsec
  (see e.g. Blundell & Rawlings 1999; Saxena et al. 2017)
- Radio spectrum
  Steepness: α ≤ -0.7
  Curvature: β ≤ -0.3α – 0.51
- Near-infrared magnitude
  ***K_s* > 21.2 (5σ; AB)**
  (see e.g. Ker et al. 2012)



New HzRG candidates

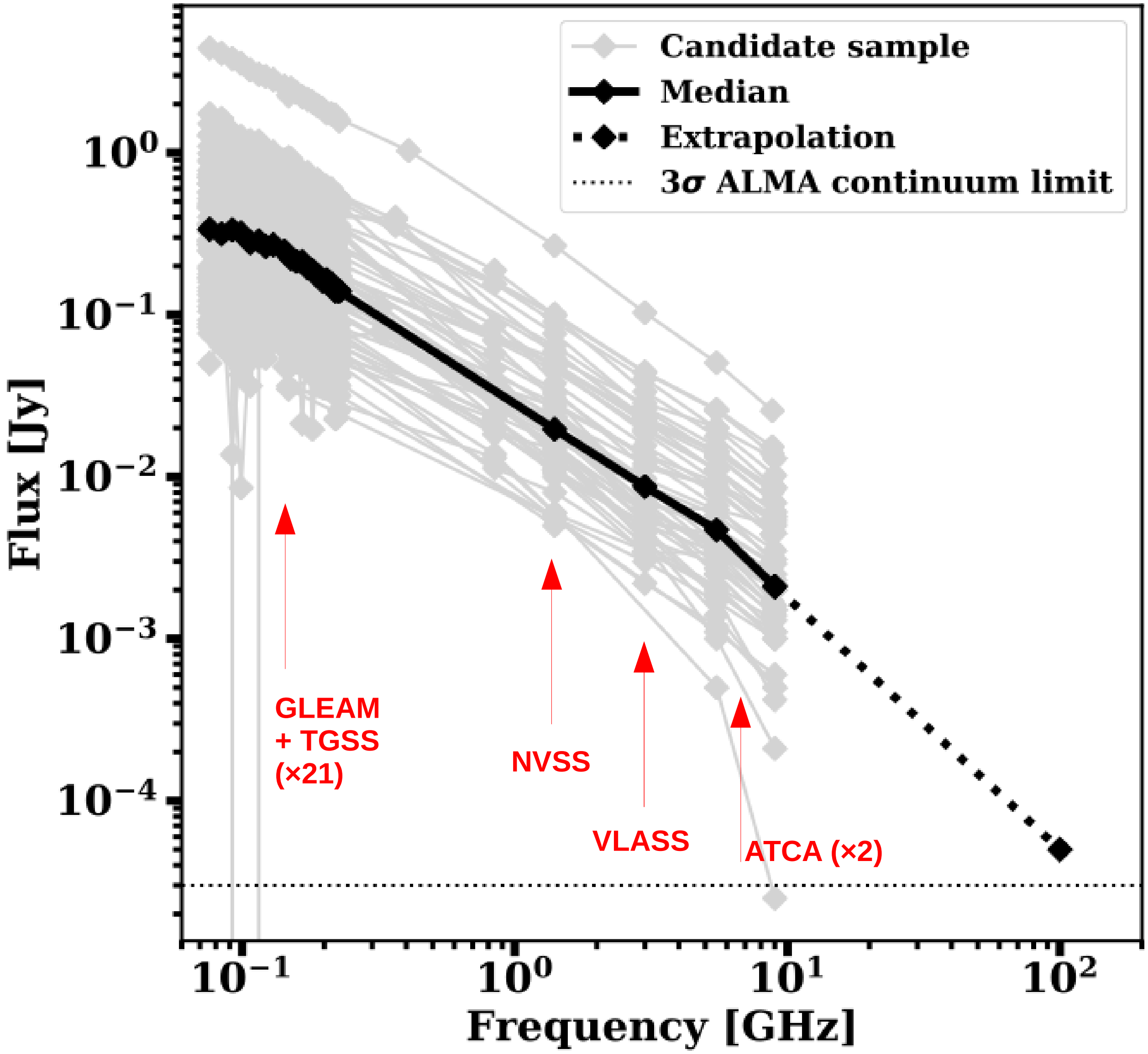




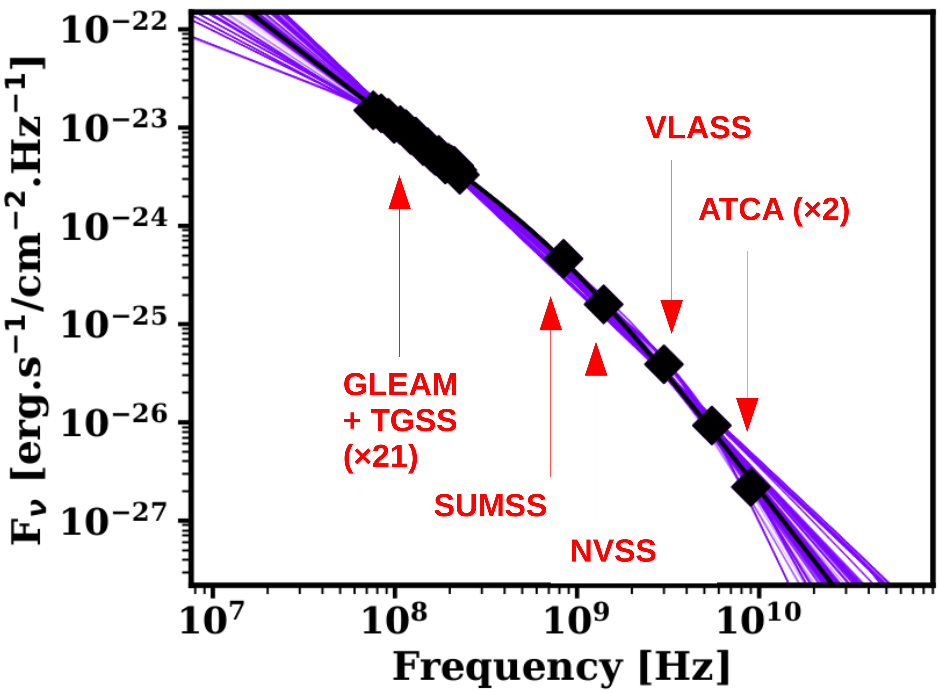
- VIKING K_s overlaid with 1.4-GHz FIRST contours (Becker et al. 1995).
- Also used 3-GHz VLASS (Lacy et al. 2020), 890-MHz RACS (McConnell et al. 2020) and 5.5/9-GHz ATCA data (our observing campaign in 2020 May + December).

- **New sample: 55 sources. ~70% with LAS ≤ 2 arcsec (≤ 13 kpc @ z ≥ 5).**
- **Sample definition paper: Broderick et al. in prep.**

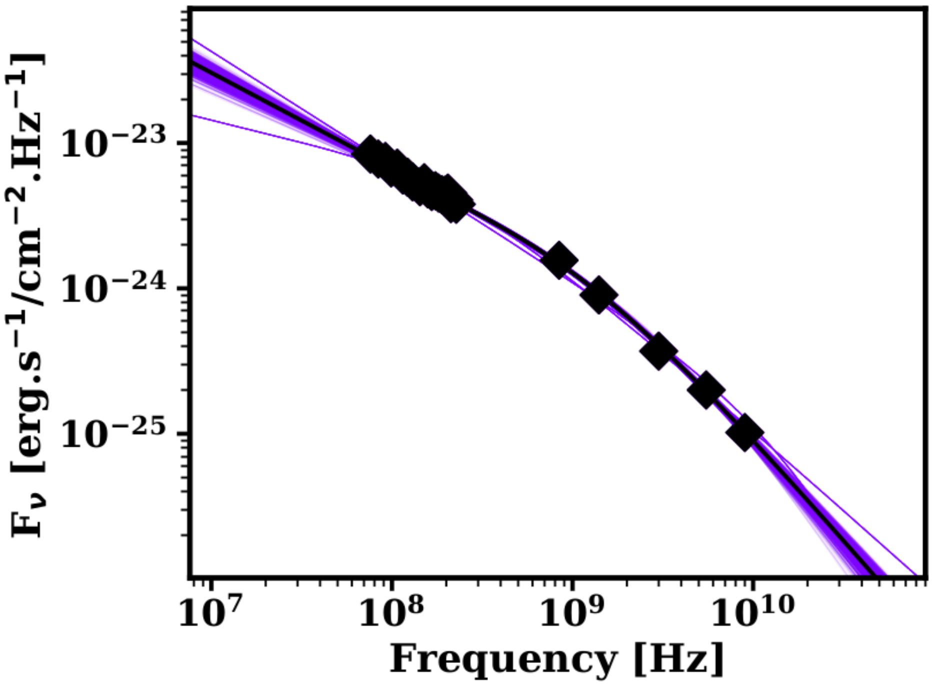
Broadband radio spectra



Broadband radio spectra



α_{low} = -1.42, α_{high} = -2.44, ν_{break} = 1.38 GHz



α_{low} = -0.66, α_{high} = -1.45, ν_{break} = 2.40 GHz

- SED fitting with MRMOOSE (Drouart & Falkendal 2018).
- Spectral modelling: energy loss mechanisms; information about ambient environments; further investigation of HzRG selection procedure (e.g. Morabito & Harwood 2018).
- Spectral breaks: determine jet ages/powers (e.g. Turner et al. 2018).

Broderick et al. in prep.

Next observing campaigns

VLT HAWK-I deep K_s-band imaging

ALMA imaging + spectroscopy.

Proposals submitted for recent ESO and ALMA deadlines

Conclusions and future work

- Discovery of GLEAM J0856 @ z = 5.55. Second-most distant radio galaxy currently known.

- Solving the mystery of the enigmatic source GLEAM J0917 – stay tuned!

- LOFAR LBA detections of GLEAM J0856/J0917 down to 36 MHz. Tentative detection of turnover at ~30–40 MHz for J0856. Ongoing work to constrain low-frequency spectra of both J0856/J0917.

- Defined new sample of 55 HzRG candidates. Building on success of Drouart et al. (2020, 2021) pilot study.

Find z > 6.5 powerful radio galaxies: exciting EoR science!