New constraints on the contribution of star formation and AGN activity in quasar radio emission from the LOFAR Two-metre Sky Survey

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Background

Open questions to the standard model

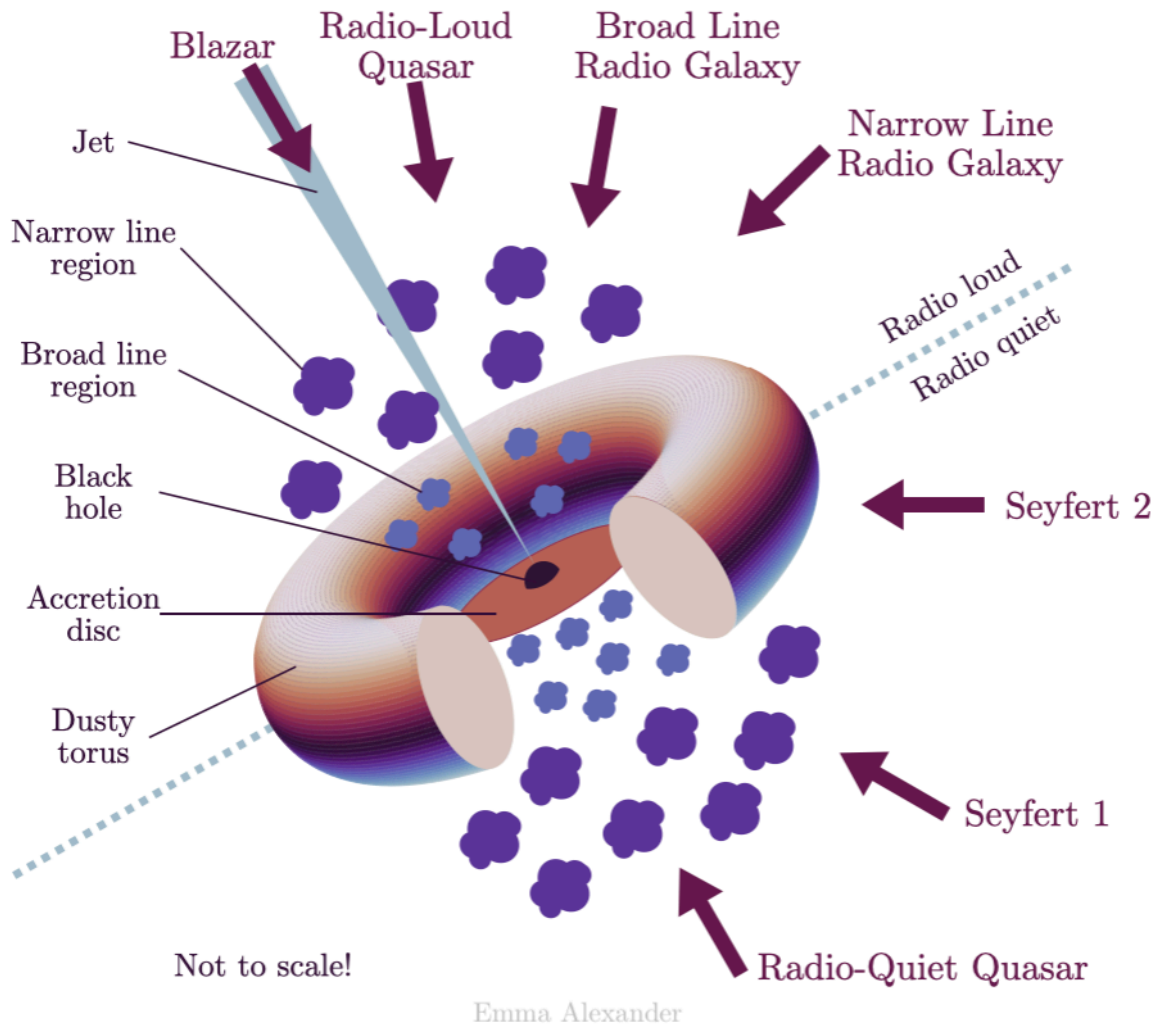
- Low spatial resolution due to observation limits

  ➡ ***Radio loud/quiet: dichotomy or continuous distribution?***

  ➡ ***How to distinguish between the host galaxy emission and weak AGN activities?***

  ➡ ***What powers the radio emission in radio-quiet quasars/red quasars?***

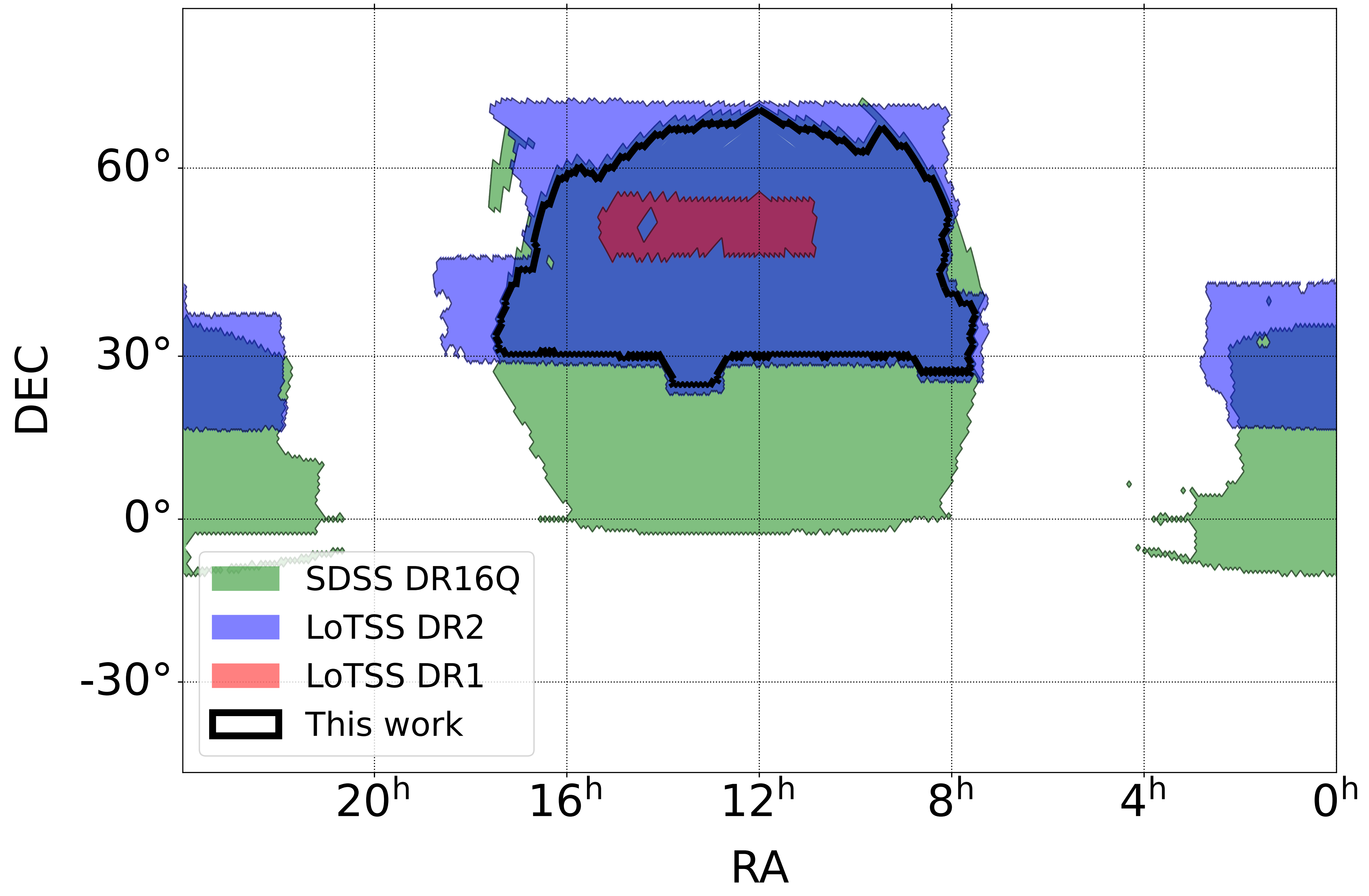
➡ ***What affects the powering efficiency of jets?***

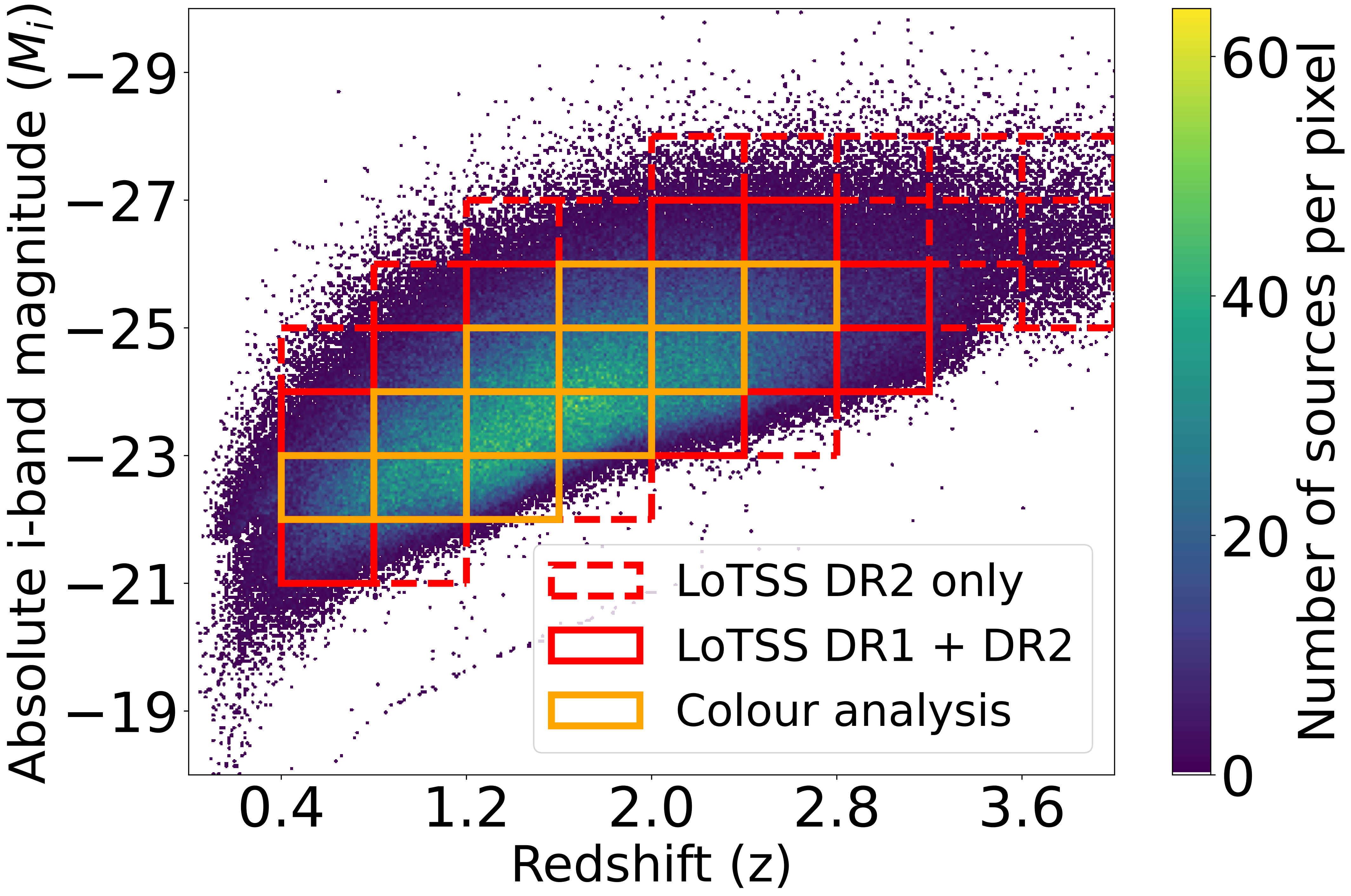


Data

From LoTSS DR1 to DR2

- Target selection: SDSS DR16 quasars in LoTSS DR2 field
- -> <u>361,119</u> quasars (=10x LoTSS DR1)
- Characterised by $i-$band magnitude and redshift

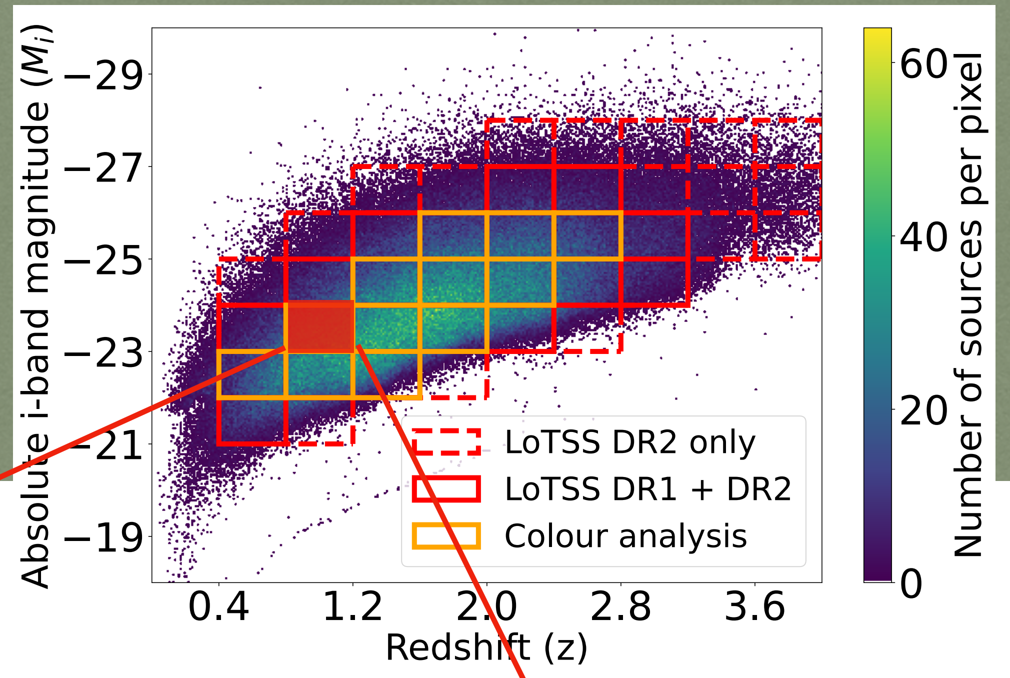




Modeling

Separating SF and AGN in radio flux density distribution

We start with binning samples into <u>different grids</u> => ensure similar accretion rate/redshift for the input



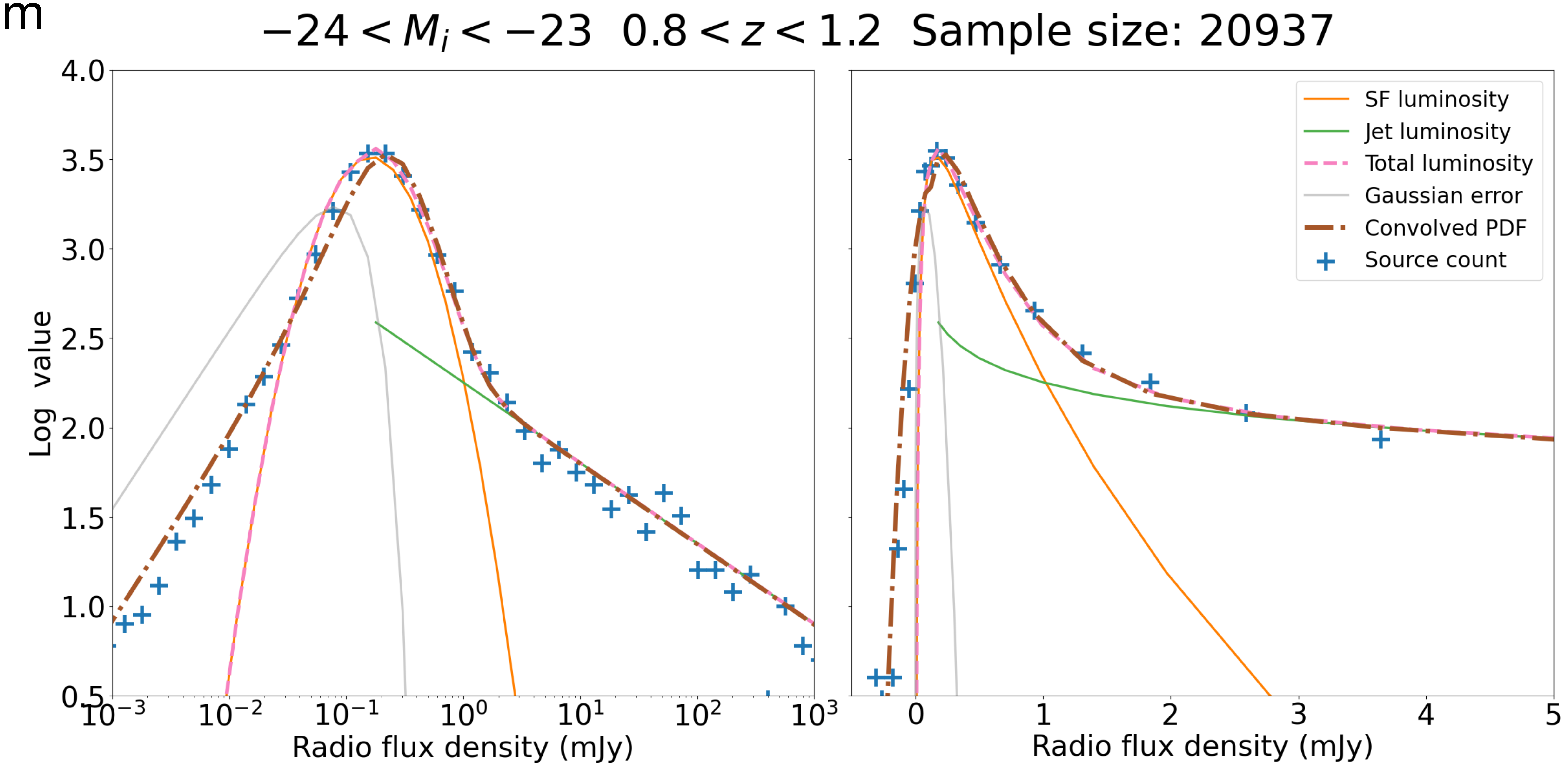
Requirement: 1,000 sources <u>minimum</u>

- AGN and SF contribute to the observed radio emission of <u>*every*</u> quasar

- Radio SF luminosities are drawn from Gaussian distribution on log space
  - Parameters: L_μ/Ψ **<u>(mean SF luminosity/SFR)</u>**, σ_ψ (scatter in SFR)

- AGN luminosities are drawn from single power-law distribution
  - Parameters: γ (power-law slope), ϕ/f **<u>(jet power normalisation)</u>**

- SF+AGN component = PDF of total flux density



Application 1: red quasars

- ~10% of quasars are significantly ‘redder’ in optical colour

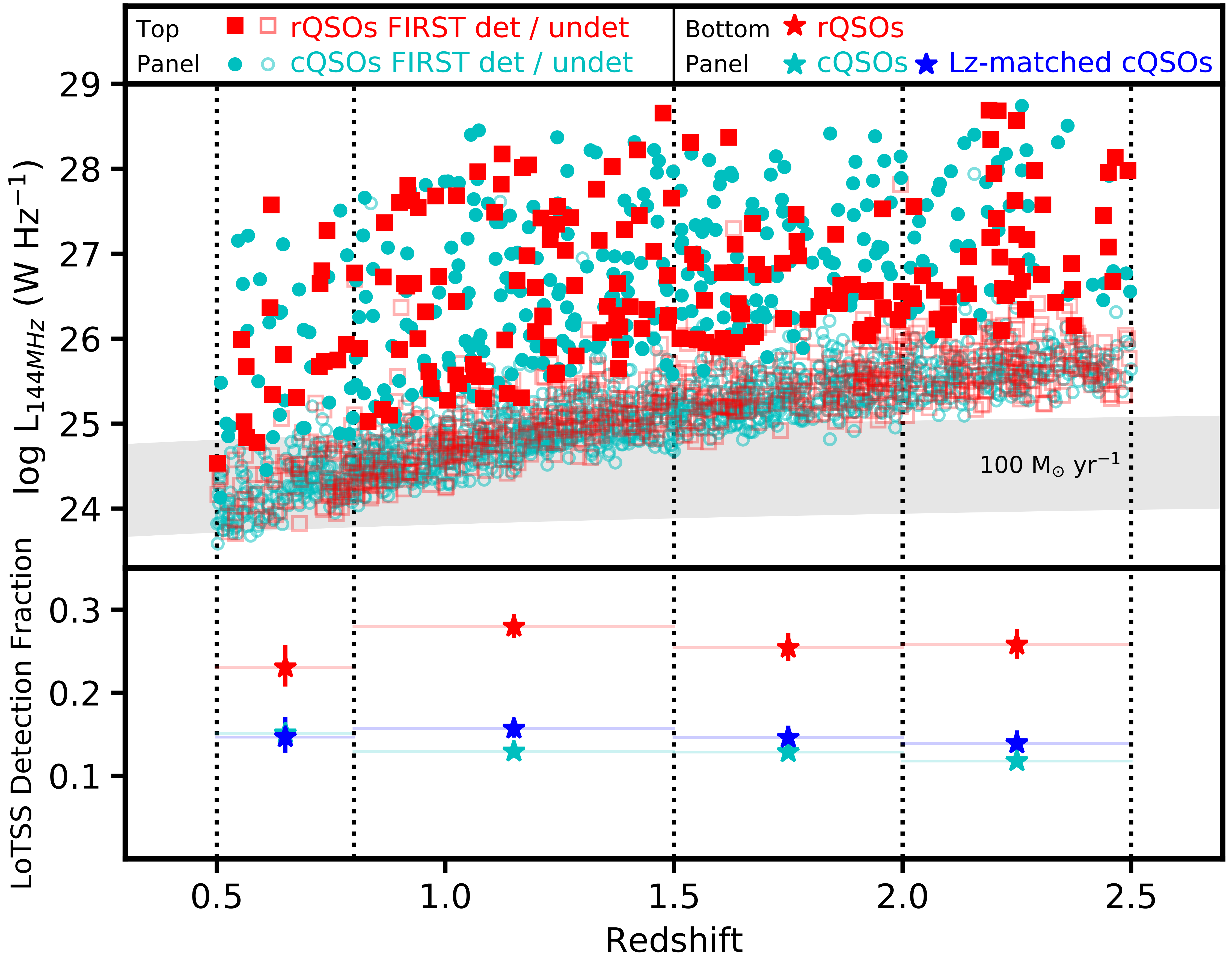
  ➡ **Red QSOs are dusty QSOs**

- Red QSOs tend to be more radio-loud (e.g. Rosario+20)

  ➡ **Rules out the assumption of different torus orientations**

- <u>What contributes to the radio excess?</u>

➡ **Correlate SF and jet component separately to quasar optical colours**



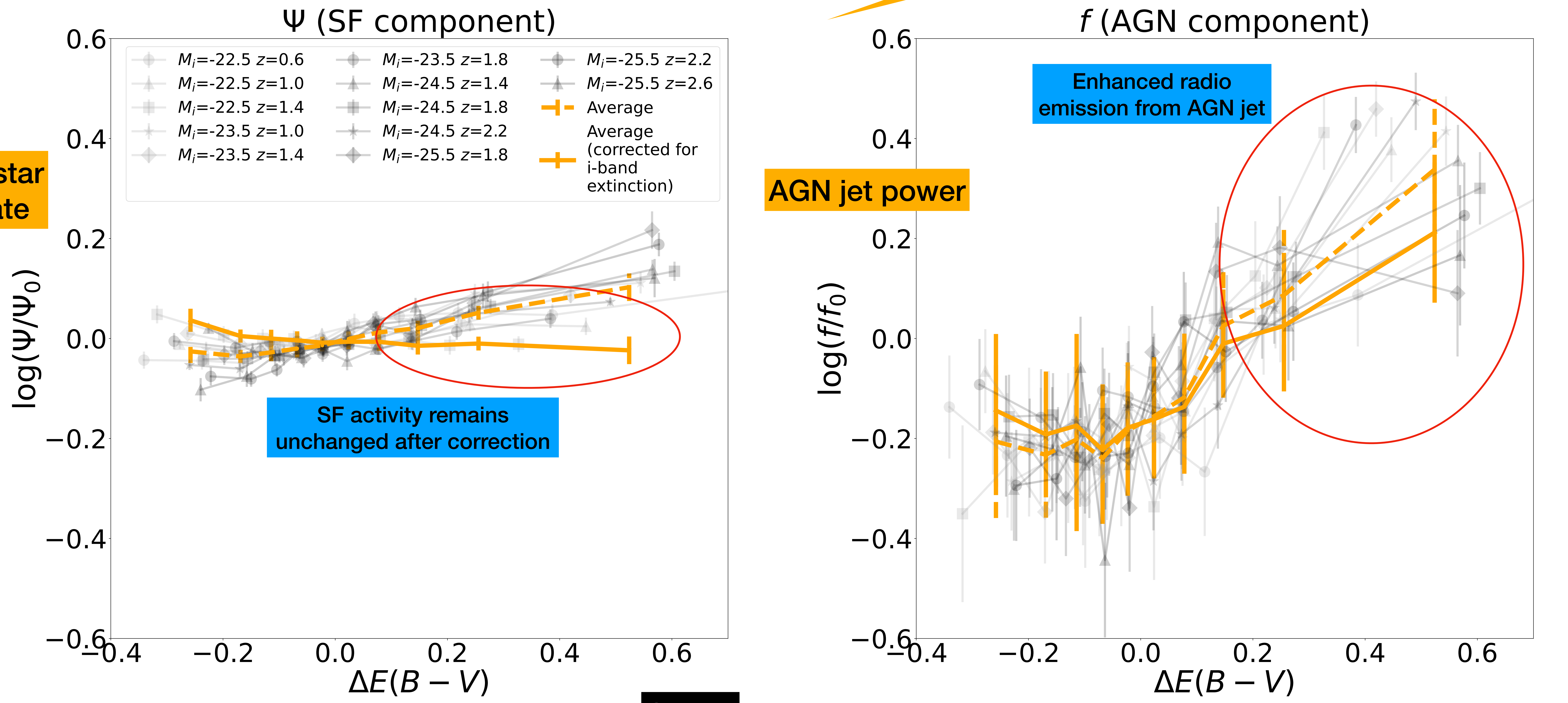
__Above__: red quasars (rQSOs) showing a higher detection fraction in LoTSS compared to blue (‘control’) quasars (cQSOs) (credit: Rosario+20)

Application 1: red quasars

Radio enhancement in red QSOs only takes place in AGN activity

Host galaxy star formation rate

AGN jet power



Colour

Blue end —— *Red end*

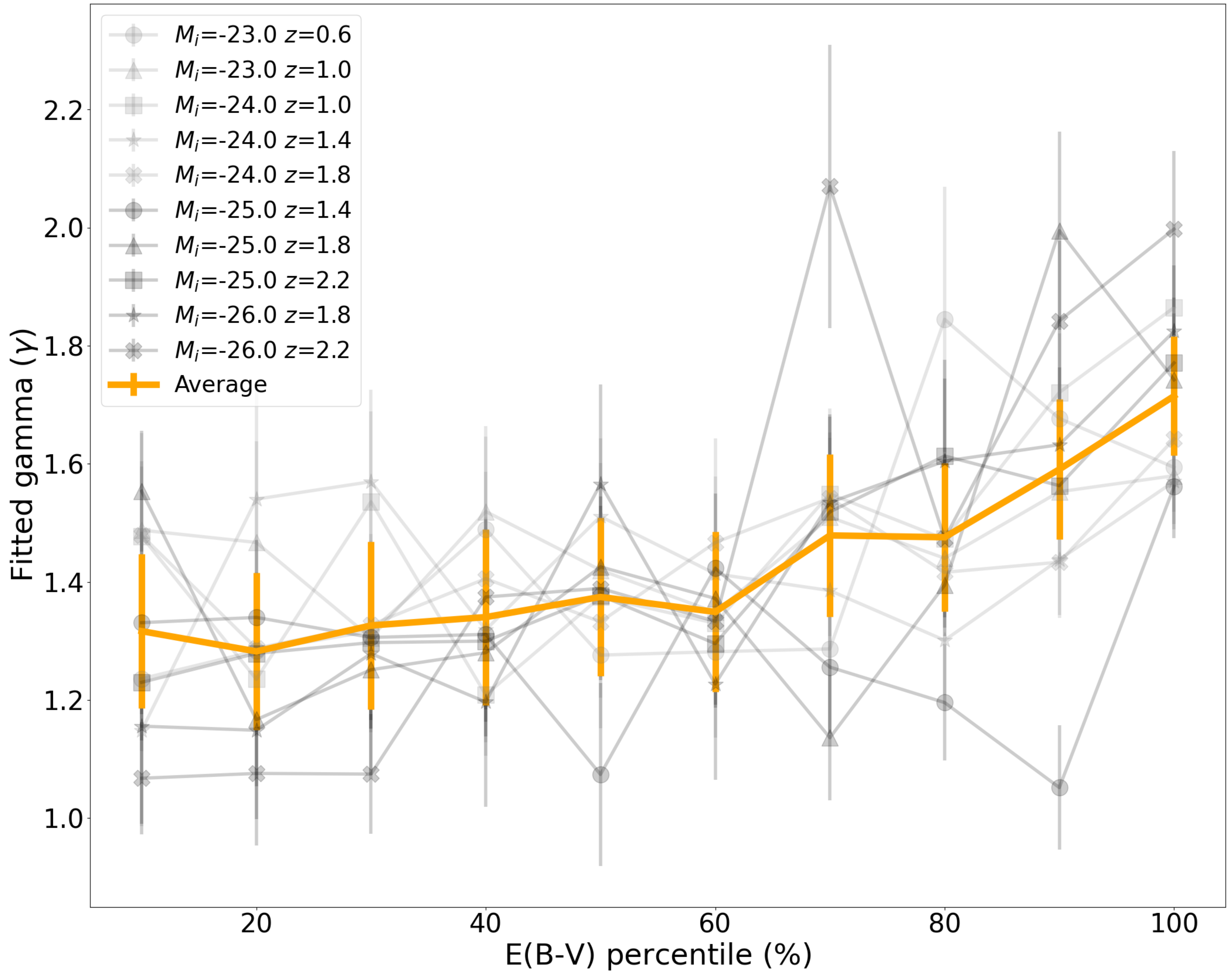
Application 1: red quasars

- SF component remains unchanged; AGN component increase with redness

  ➡ **Radio enhancement in red QSOs happens in the AGN activity**

- Signs of increasing power-law slope in redder colours

  ➡ **Radio enhancement happens more likely in radio-faint/intermediate sources**



Application 1: red quasars

Different evolutionary phase!

- Where does the red colour come from?

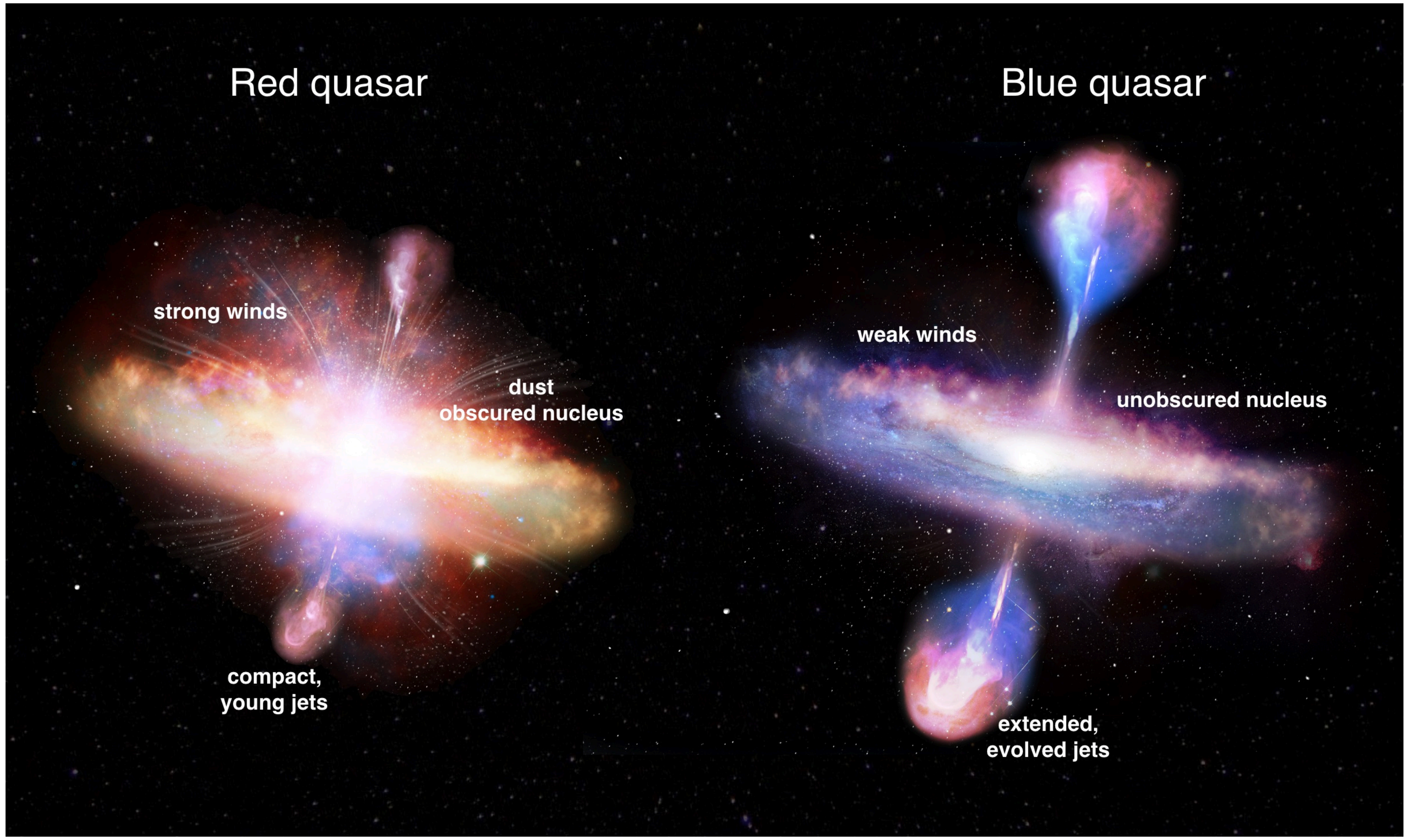
  ➡ **Merger-induced starburst takes place in quasar host: red QSOs**

  ➡ **AGN jet drives away the obscuring dust: blue QSOs**

- Why does the radio excess mostly comes from AGN component?

  ➡ **Weak jet breaks down in dense ISM/circumnuclear environment**

  ➡ **Or wind shocks? (Petley+24)**



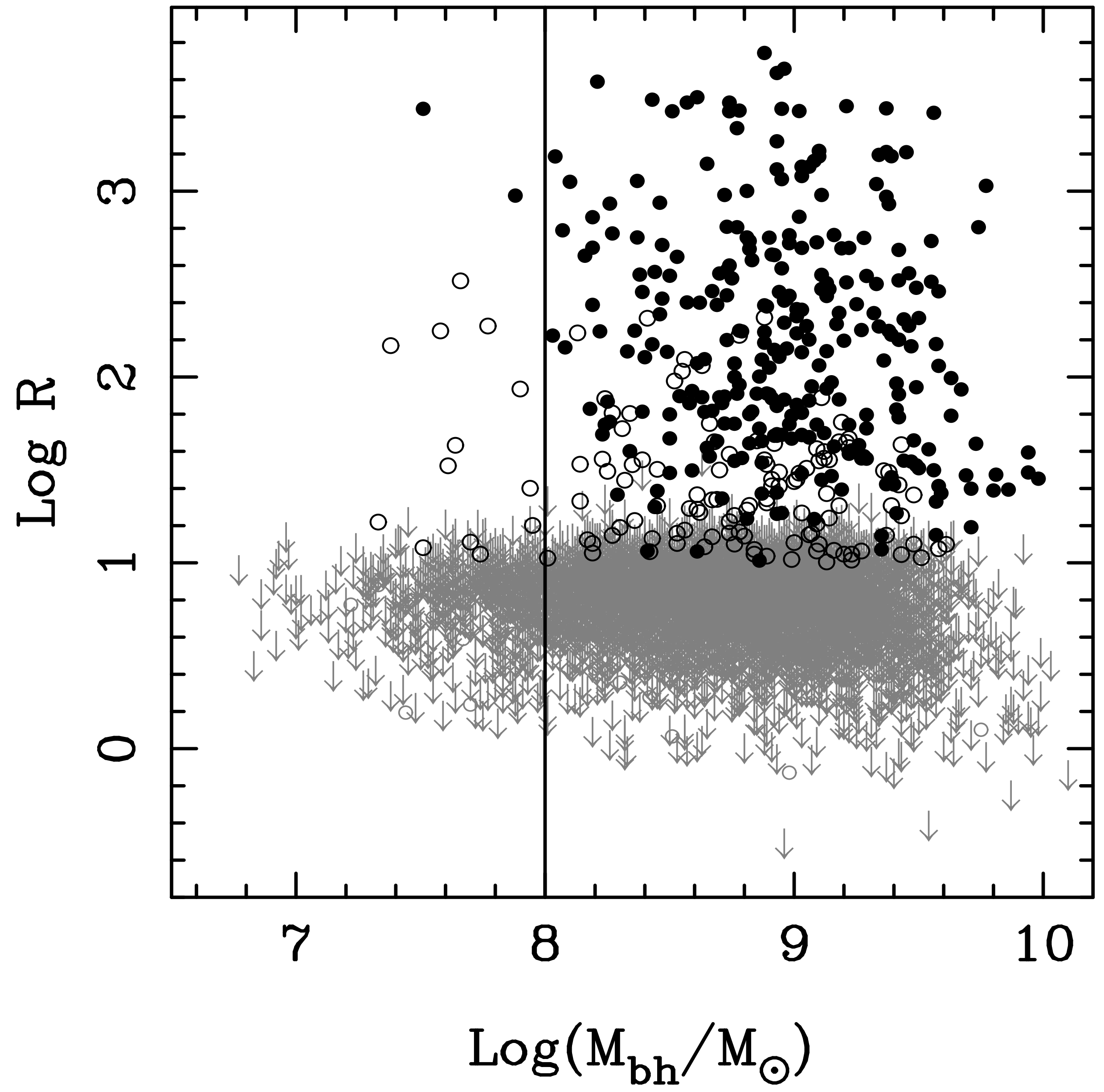
Above: *artist's impression of red and blue quasars outlining the evolutionary path and the key structures within each object (credit: S.Munro)*

Application 2: BH masses

- Does $M_{\rm BH}$ affect the radio loudness of quasars?
  - RL quasars host more massive BHs than RQ quasars (e.g. McLure&Jarvis+04)
  - No correlation between radio loudness and BH mass (e.g. Gurkan+19, Arnaudova+24)

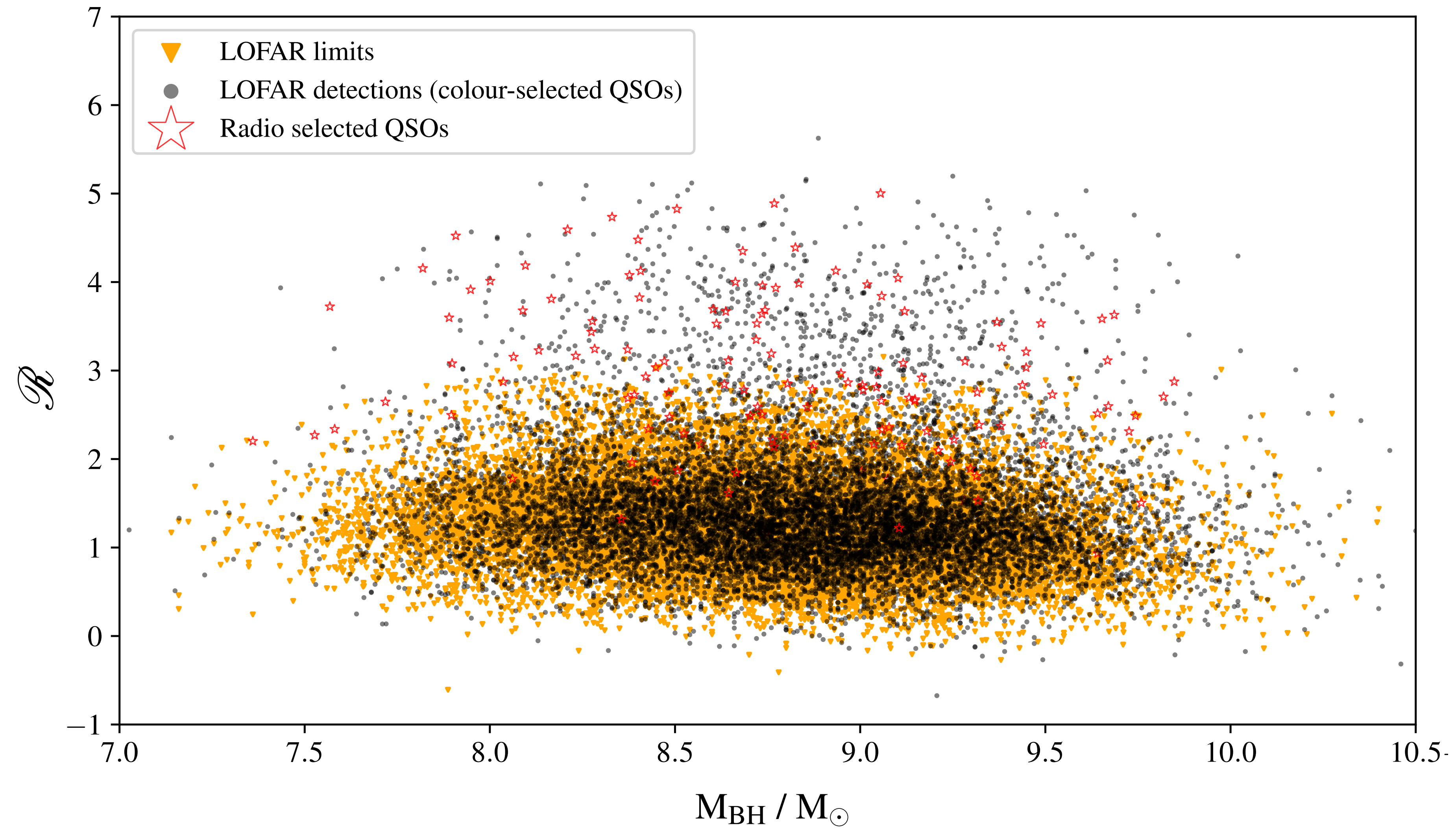
- <u>Need quantitative tool to constrain the influence on radio emission</u>

➡ **Correlate SF and jet component to $M_{\rm BH}$**



Above: *radio loudness - BH mass distribution from McLure&Jarvis+04;*

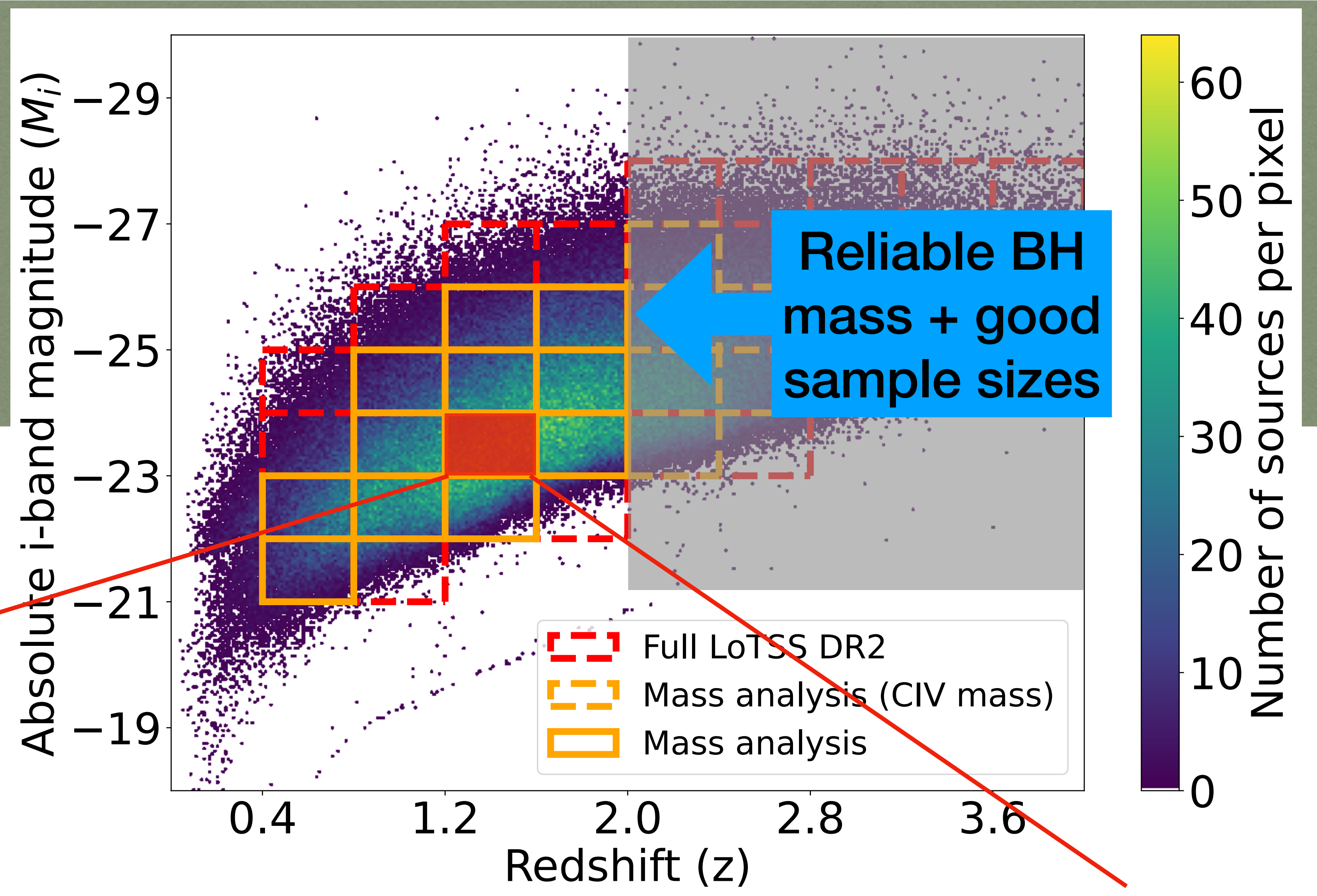
Below: *radio loudness - BH mass distribution from Gurkan+19*



Application 2: BH masses

Key assumptions

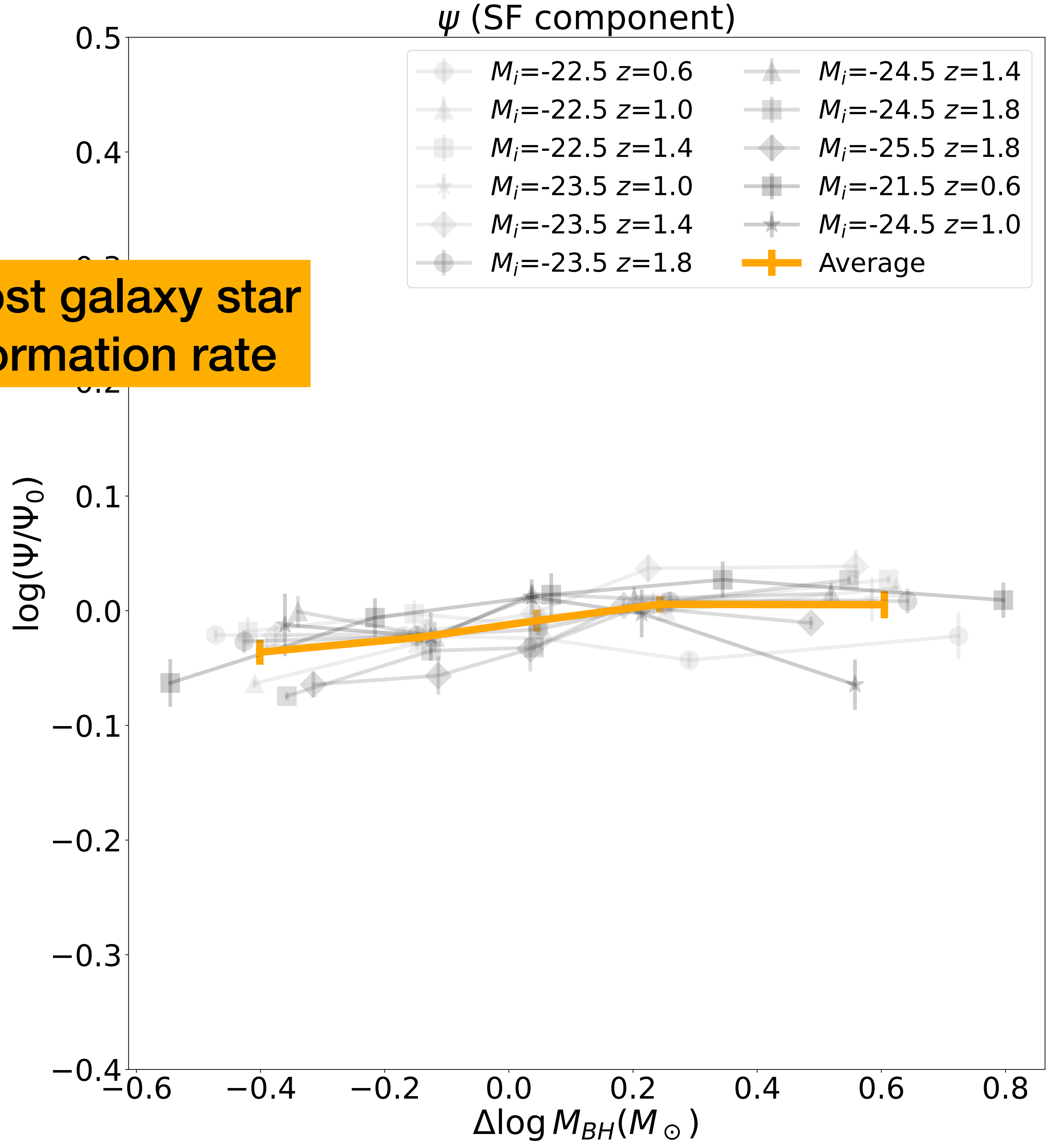
Within each grid we bin the quasars into 5 BH mass percentiles (0%-20%, 20%-40%, 40%-60%, 60%-80%, 80%-100%)



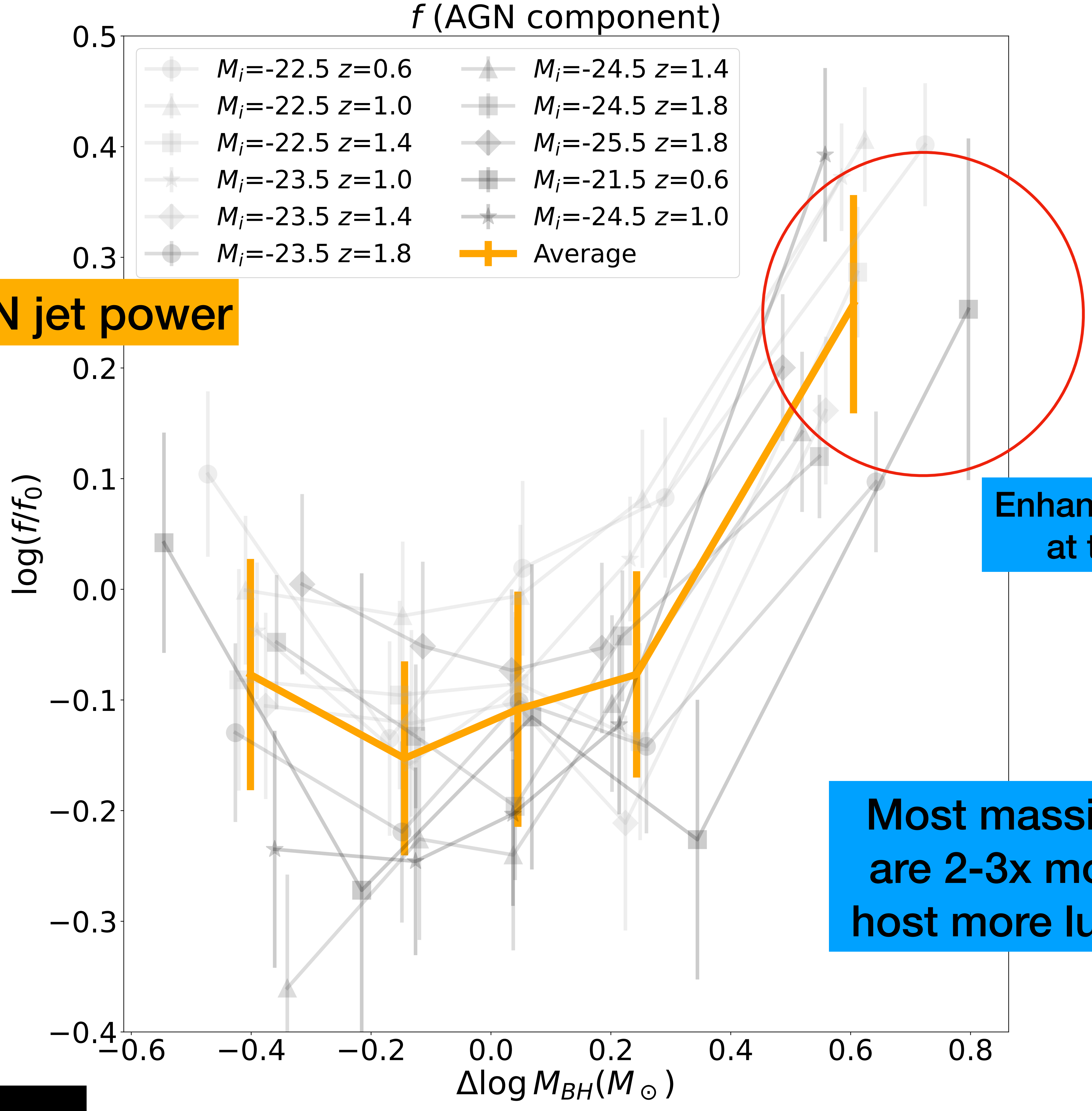
Application 2: BH masses

Within each grid we bin the quasars into 5 BH mass percentiles (0%-20%, 20%-40%, 40%-60%, 60%-80%, 80%-100%)

Host galaxy star formation rate



AGN jet power



Enhanced jet normalisation at top 20% BH mass

Most massive quasars are 2-3x more likely to host more luminous jets

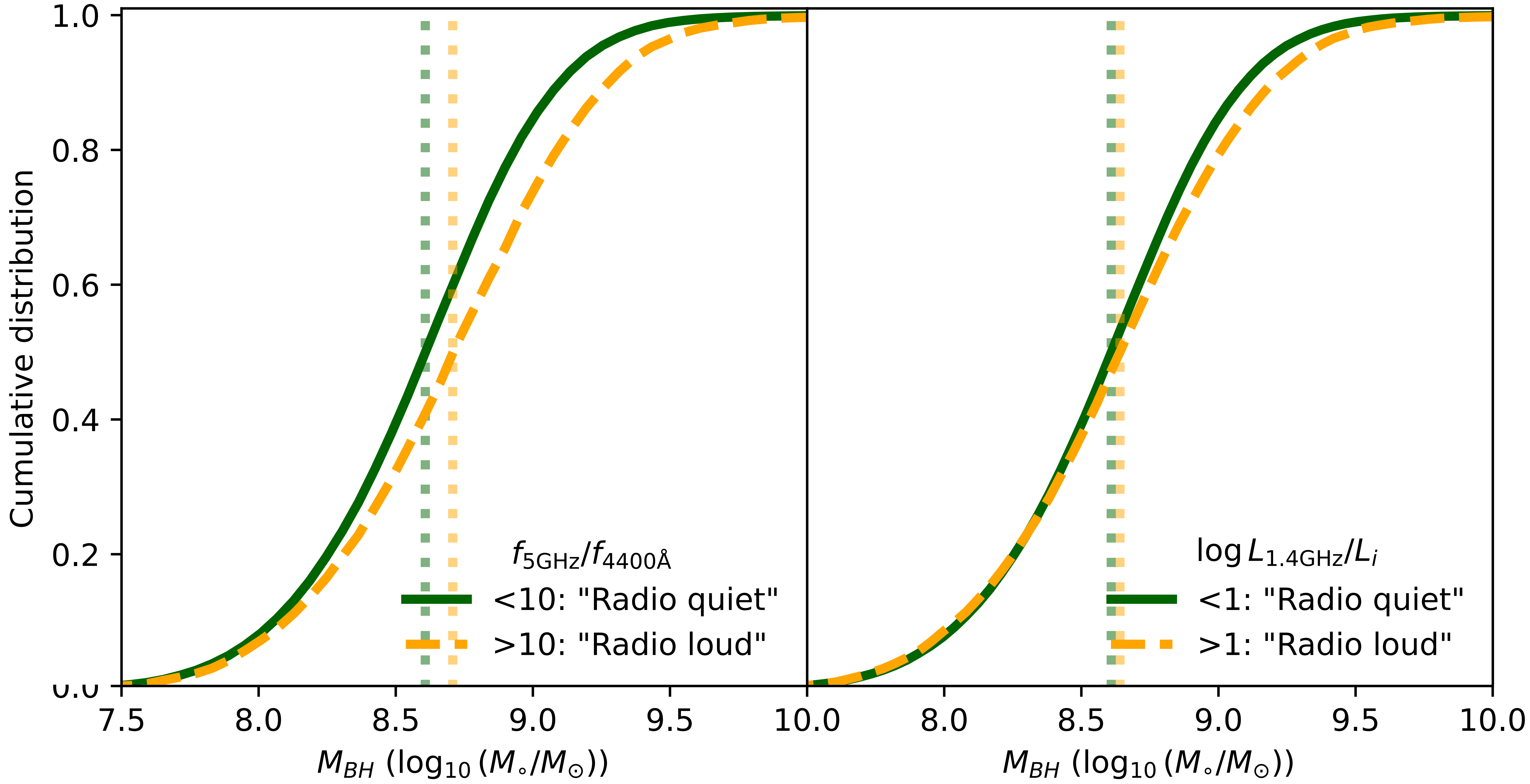
BH mass

Less massive —— ***More massive***

Application 2: BH masses

Motivation for a new definition of quasar radio loudness

McLure&Jarvis+04
'Flux definition'



Balokovic+12;
Arnaudova+24
'Luminosity definition'

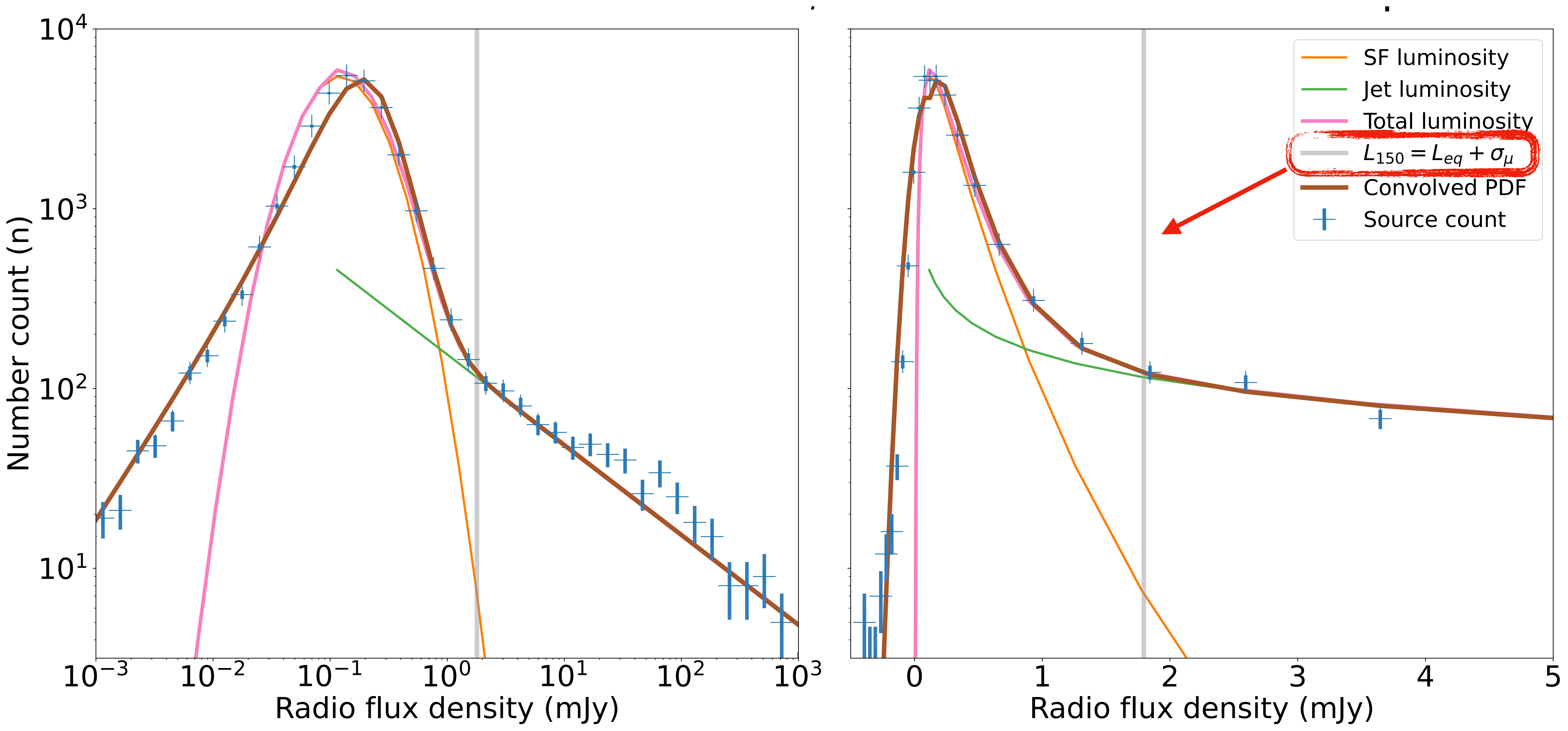
(Scaled from LOFAR 144MHz observation to 1.4 GHz assuming a spectral slope of -0.7)

- Different definitions of radio loudness give different results *on the same data*

➡ **Traditional definitions based on observation norms rather than physical picture**

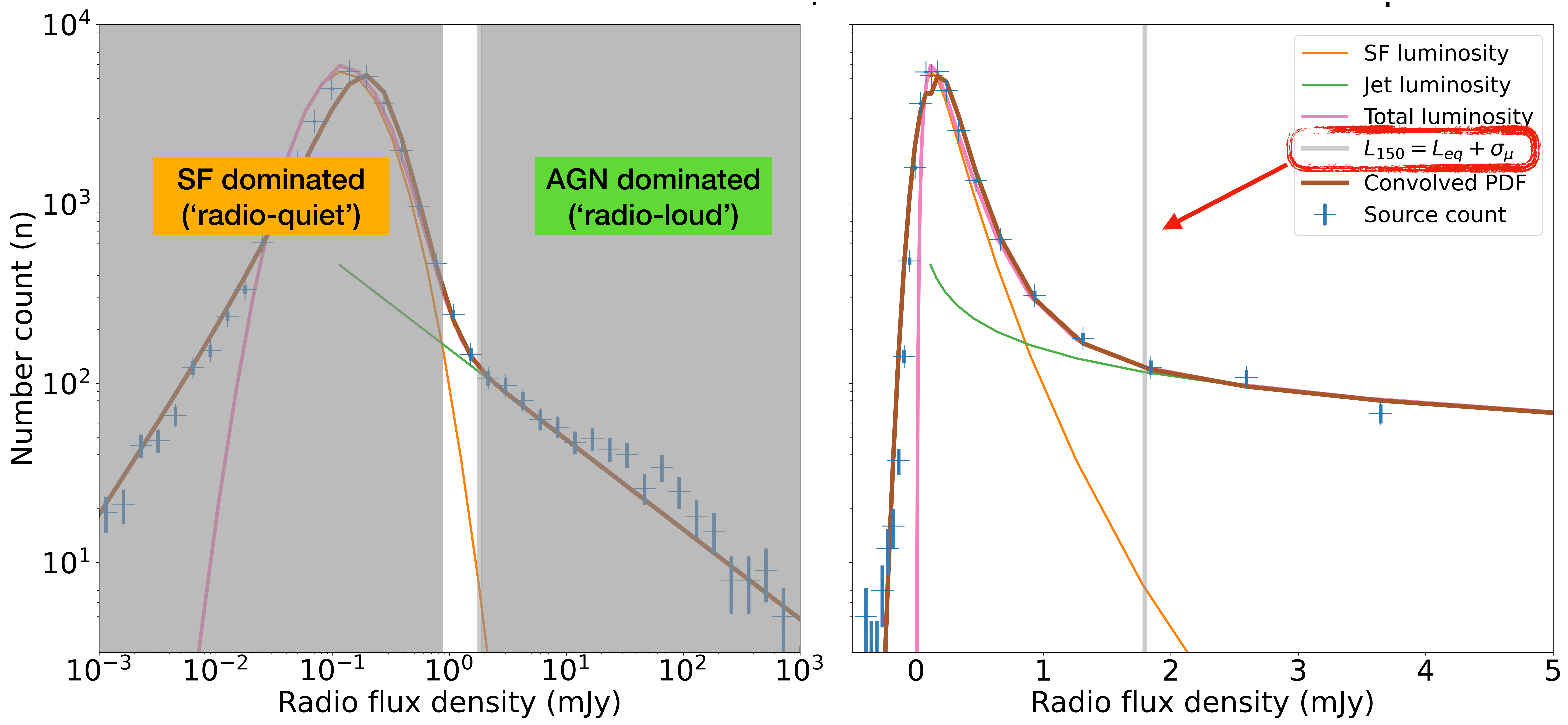
Application 2: BH masses

A physically motivated definition for quasar radio loudness



Application 2: BH masses

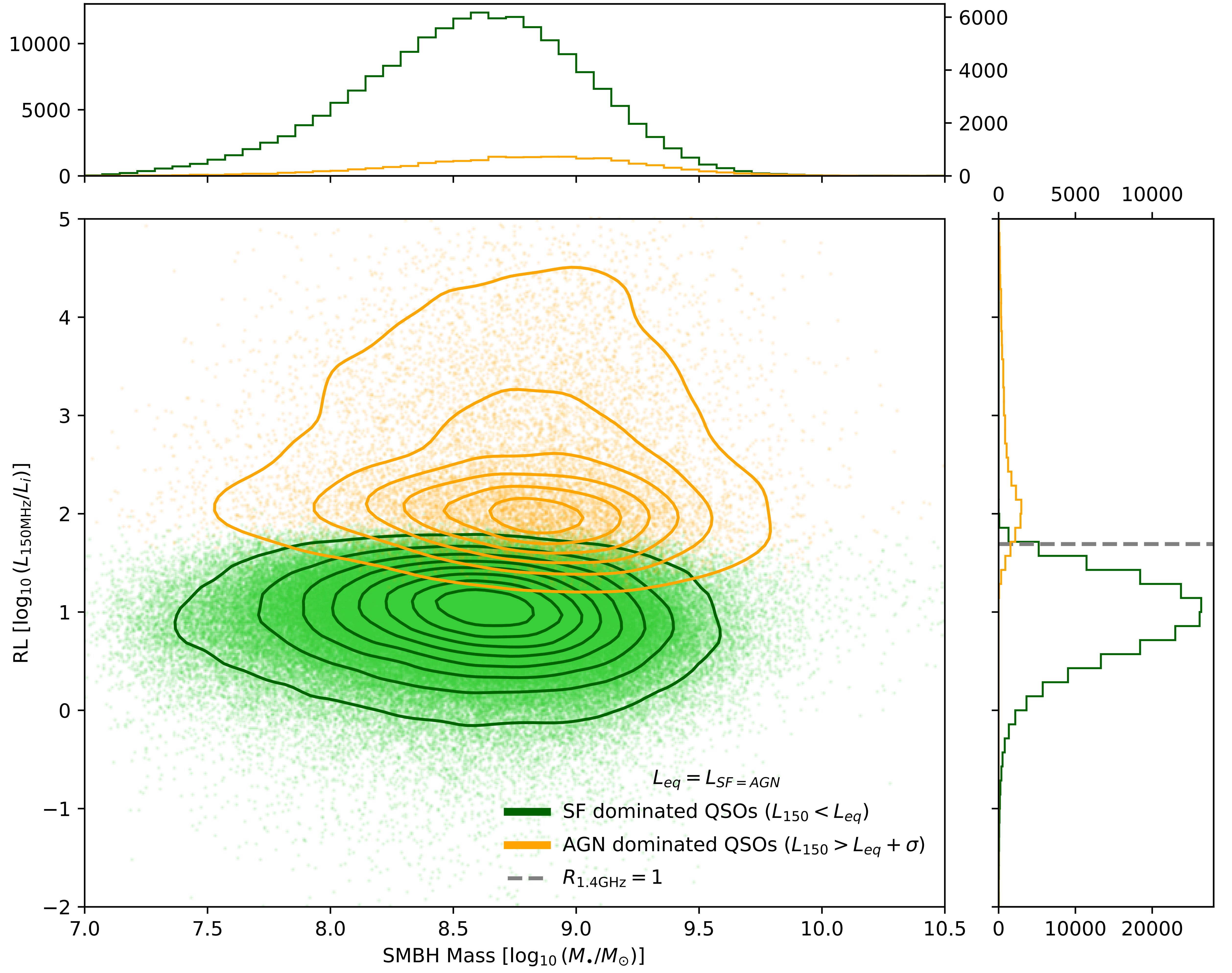
A physically motivated definition for quasar radio loudness



Application 2: BH masses

A coherent picture of BH mass influence on radio loudness

- No bimodality between RL and RQ quasars in BH mass

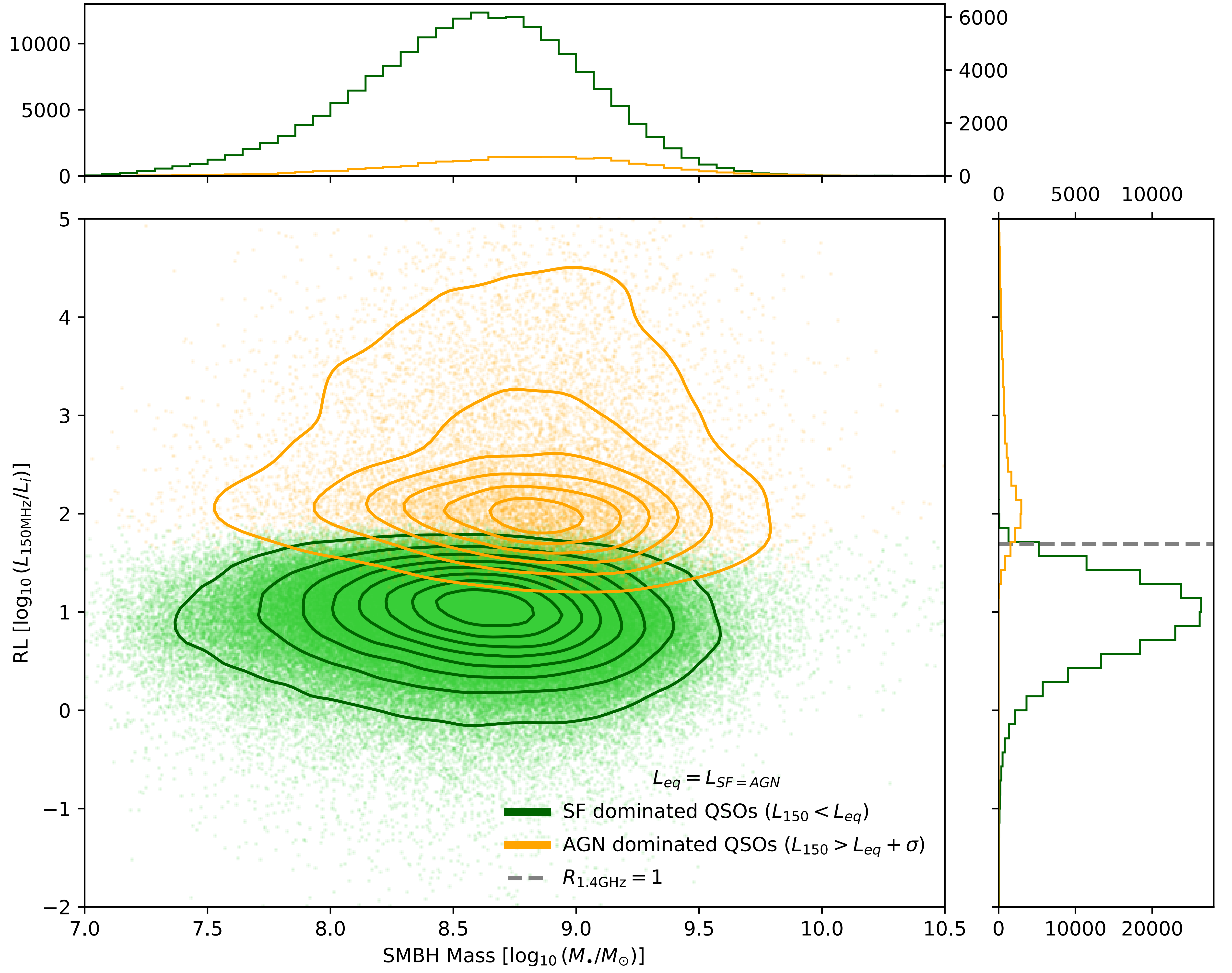


Application 2: BH masses

A coherent picture of BH mass influence on radio loudness

- No bimodality between RL and RQ quasars in BH mass

	SF dominated	Radio intermediate	AGN dominated	SUM
RQ	190023	9773	1244	*201040*
RL	1890	5278	10734	*17902*
SUM	*191913*	*15051*	*11978*	

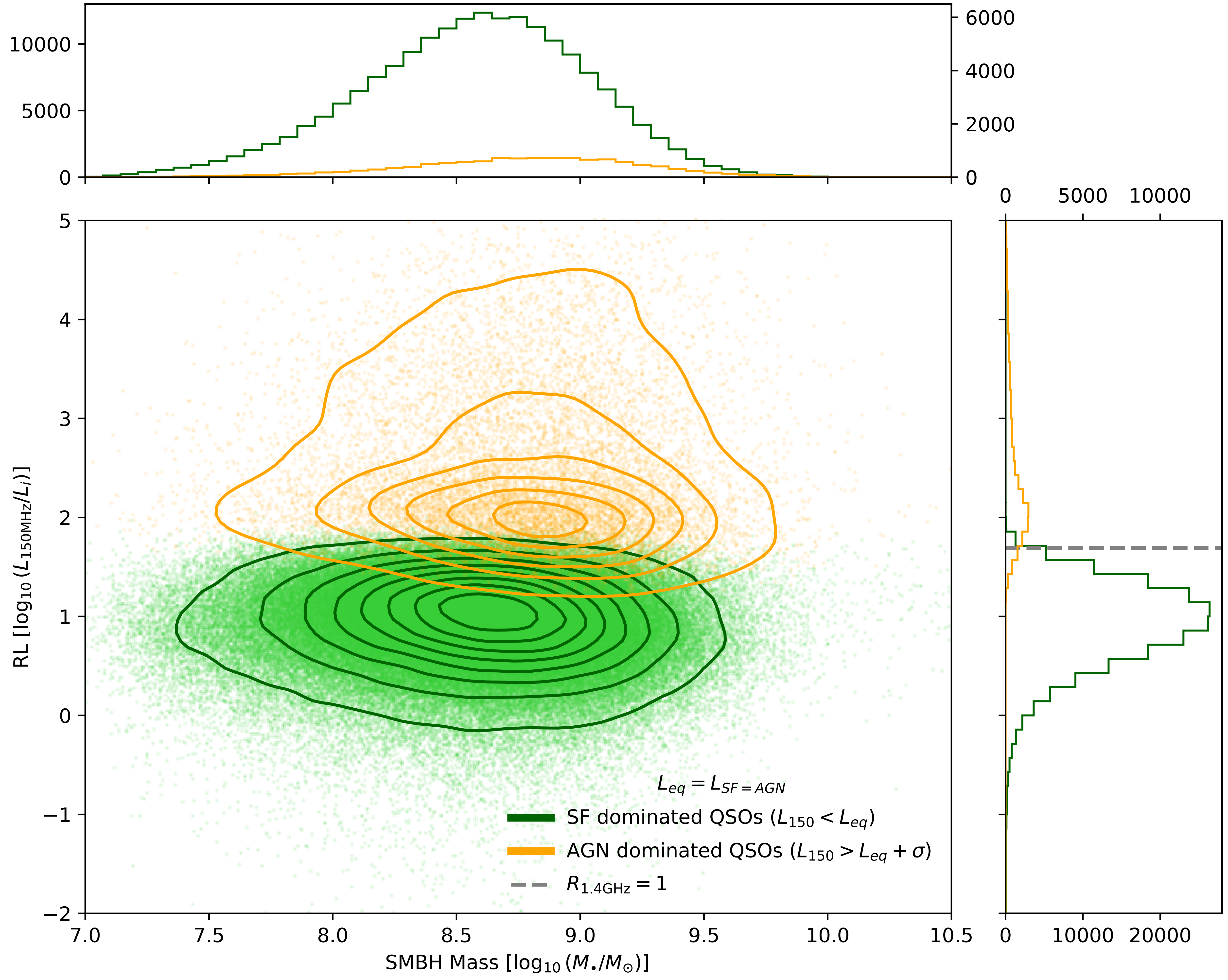


Application 2: BH masses

A coherent picture of BH mass influence on radio loudness

- No bimodality between RL and RQ quasars in BH mass
- $R = \log L_{1.4}/L_i > 1$ gives clean selection of RQ quasars ***(94.5% SF dominated)***, but included radio intermediate sources into the RL population that wipe out the trend ***(59.9% AGN dominated)***

➡ **We provide model-confirmed clean selection for both RL and RQ quasars**



Application 2: BH masses

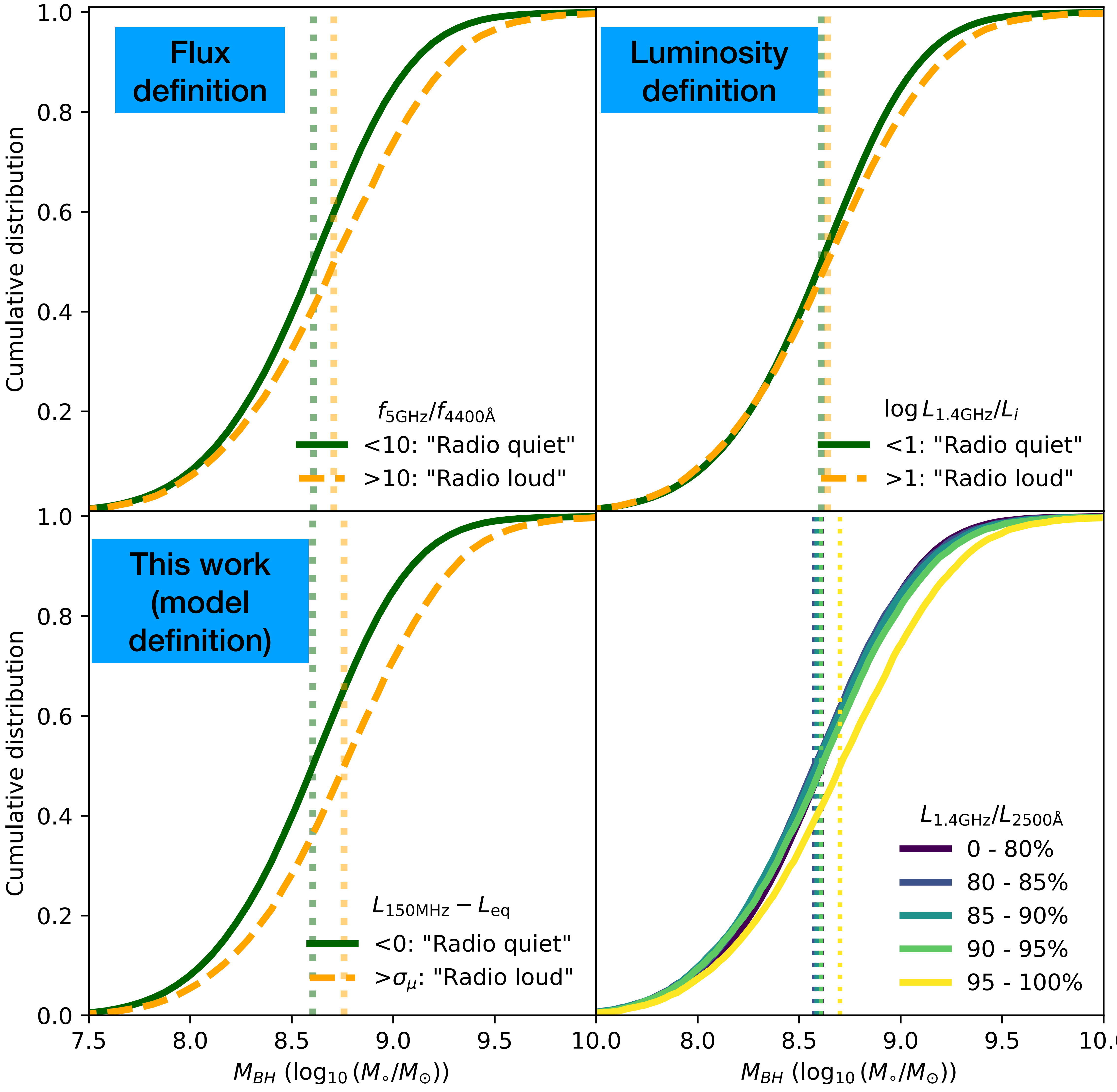
A coherent picture of BH mass influence on radio loudness

- RL quasars tend to be more massive on the high-mass end ($M_{\rm BH} > 10^{8.3} M_{\odot}$)
- Only 5% of the sources show enhanced radio loudness due to BH mass
- Only top 20% of BH mass support such enhancement

➡ **(Fancy) Massive central black holes are required to support powerful jets?**

➡ **(Fancy) Mixture of different accretion mode?**

➡ **(Not-so-fancy) biased BH mass measurements?**



Take-home messages

…and thanks for listening

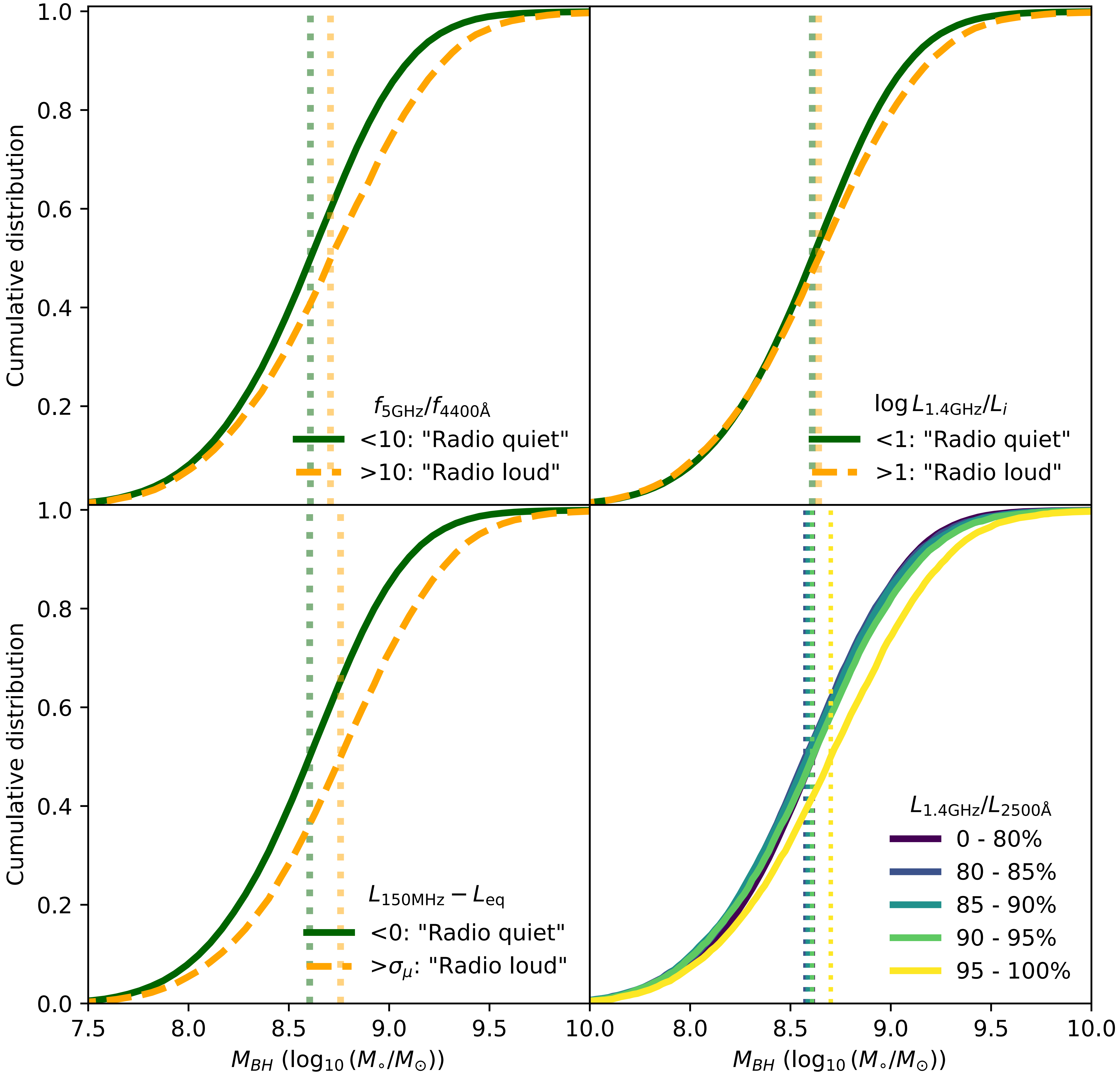
Reference:
Macfarlane et al. (2021; MNRAS, 506, 5888)
Rosario et al. (2020; MNRAS, 494, 3061)
McLure & Jarvis (2004; MNRAS, 353, L45)
Gurkan et al. (2019; A&A, 622, A11)
Yue et al. (2024; MNRAS, 529, 3939)
Petley et al. (2024; MNRAS, 529, 1995)

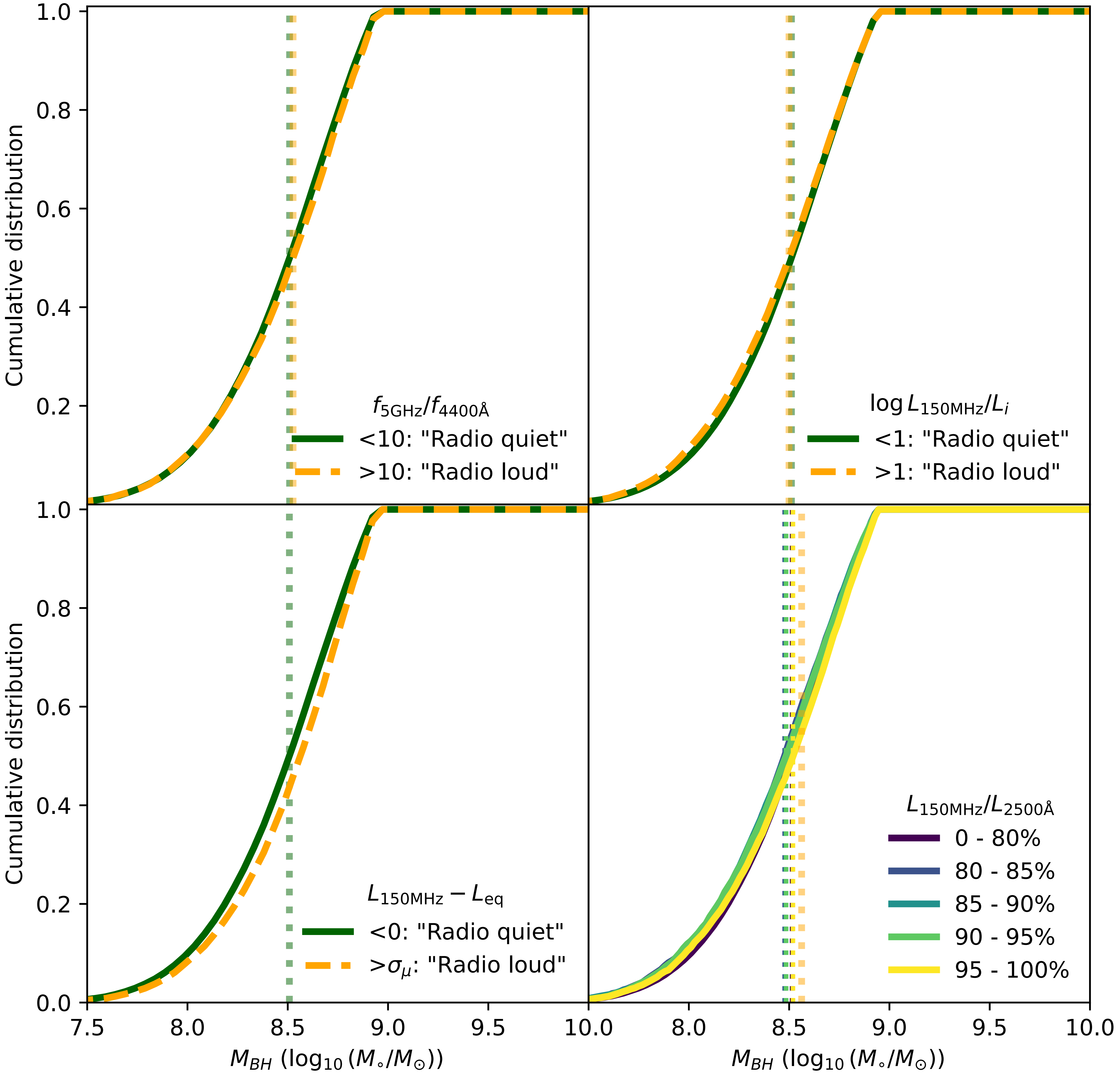
- We present a two-component model to disentangle *star-forming component* from host galaxies and *jet component* from AGNs in quasar radio emission
- Our model concludes the radio excess in red QSOs comes from AGN activity, not host galaxy SF
- Radio excess happens more likely in RQ/radio-intermediate sources, pointing to a weak jet/wind shock origin
- No significant connection between quasar radio emission and BH mass in both SF and AGN component for most of the sources
- However quasars with the most massive (top 20%) central BHs are able to support powerful jets that leads to excess in radio continuum that takes place in 5% of the sources

Full sample

The difference between RL/RQ disappears after removing top 20% of BH mass -> they are the <u>only</u> cause to radio enhancement

0-80% BH mass





BH mass cumulative distribution function in each of the $M_i - z$ grids to remove degeneracy