WISE-NVSS SELECTED HEAVILY OBSCURED QUASARS WITH YOUNG RADIO JETS

CSS-GPS WORKSHOP

MAY 13, 2021

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TALK OUTLINE

1. **Background**
   A unique sample of heavily obscured quasars

2. **VLA Imaging**
   Results from a high-resolution VLA imaging survey

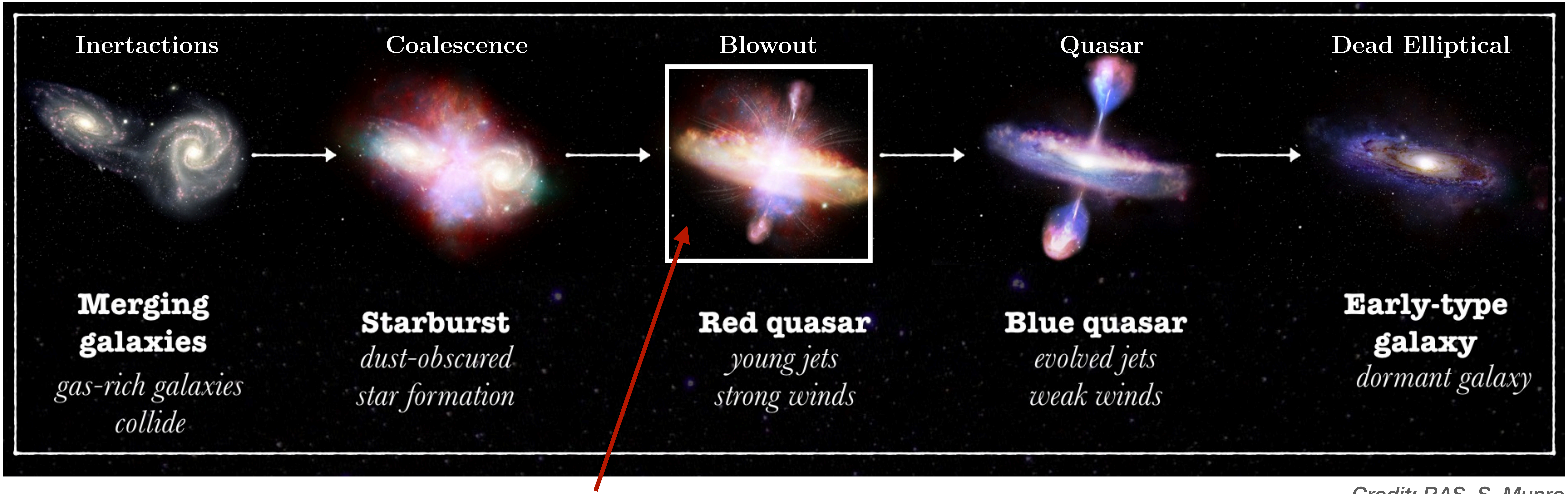
3. **Radio Spectra**
   What the radio spectra can tell us

4. **ALMA**
   A pilot study to probe the dust and molecular gas

5. **Ongoing & Future**
   Detailed multi-wavelength follow-ups

6. **Conclusion**

RAPID BLACK HOLE GROWTH TAKES PLACE IN A HEAVILY OBSCURED STATE

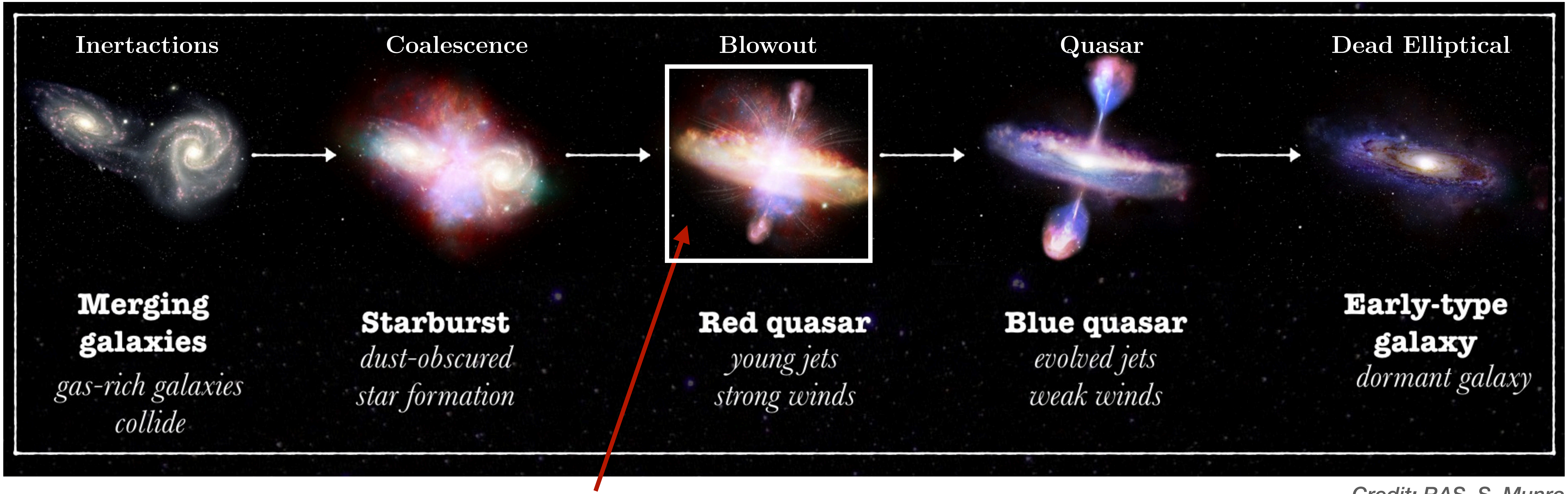


Credit: RAS, S. Munro

Merger triggered SMBH grows rapidly

Interacting with the host via jet, winds and expelling gas/dust

RAPID BLACK HOLE GROWTH TAKES PLACE IN A HEAVILY OBSCURED STATE



Credit: RAS, S. Munro

Red MIR-Optical colors, episode(s) of young, compact jet activity

SELECTION CRITERIA FOR OBSCURED QSO WITH COMPACT RADIO EMISSION

WISE

Cross-match

NVSS

SDSS/DSS

- Bright at 12/22 μm and very red WISE mid-IR colors
- Bright and unresolved (<45") radio source
- Optically faint or undetected

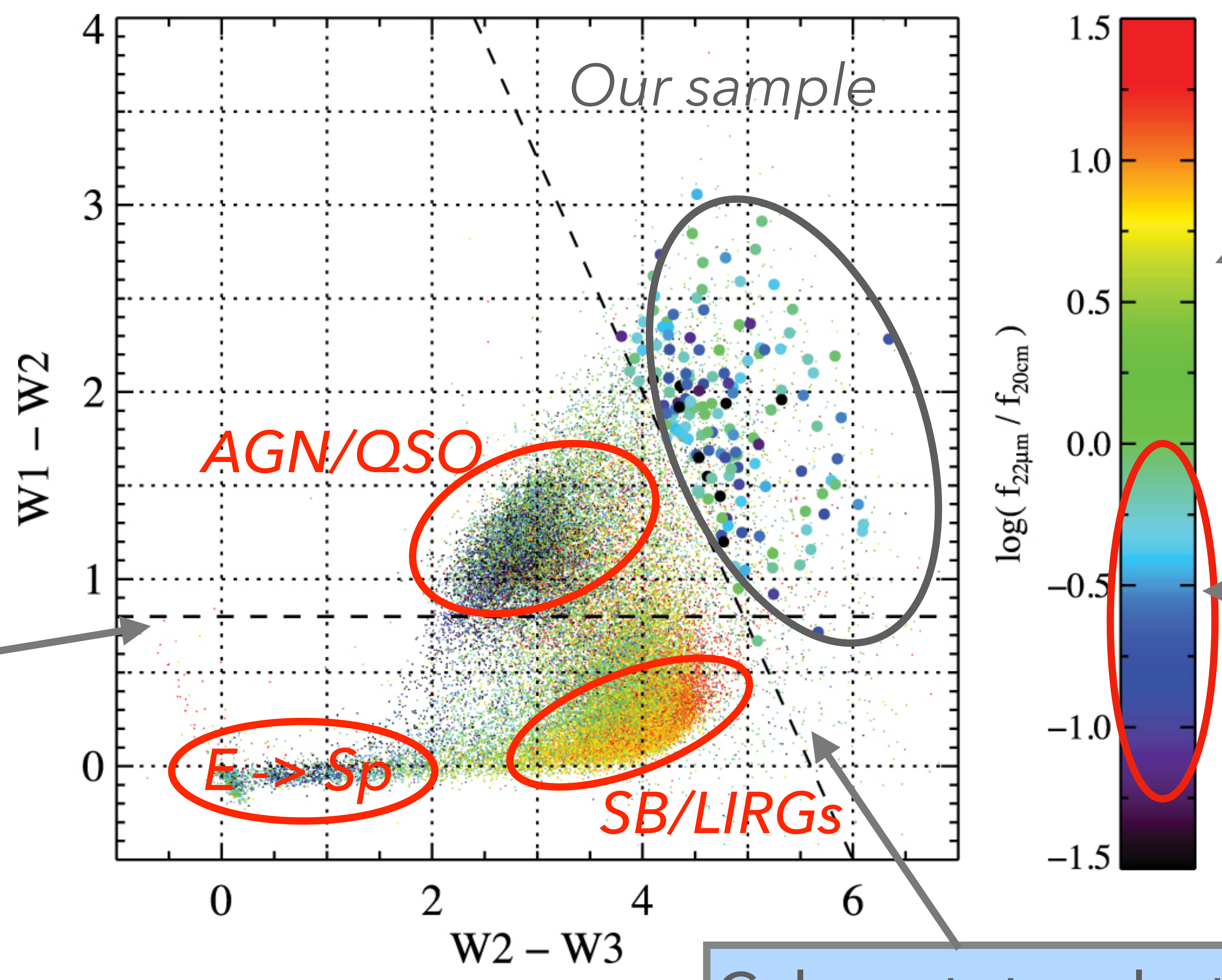
See Carol Lonsdale's Talk

THE SAMPLE OF HEAVILY OBSCURED RADIO QUASARS

156 sources

$L_{IR} \sim 10^{12.5-13.5} L_\odot$

$z \sim 0.47 - 2.8$



$q = Log \frac{f_{22\mu m}}{f_{21cm}}$

Radio intermediate or powerful

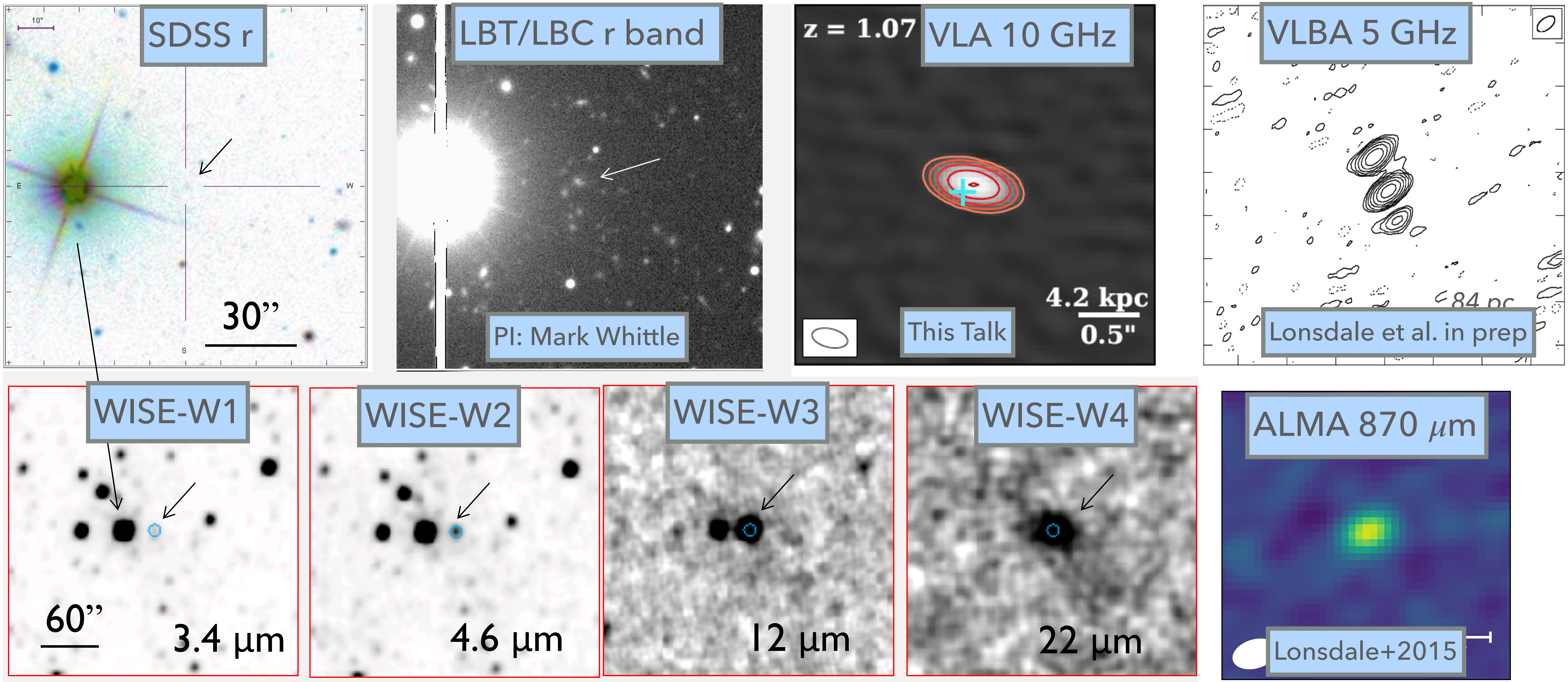
Stern et al. 2013 AGN selection

Color cuts to select reddest MIR colors

Lonsdale+2015

See Carol Lonsdale's Talk

A PANCHROMATIC VIEW OF AN OBSCURED RADIO QUASAR



*Different Source

A SAMPLE OF HEAVILY OBSCURED RADIO AGN

Created by Carol Lonsdale

SUB-ARCSECOND RESOLUTION VLA IMAGING

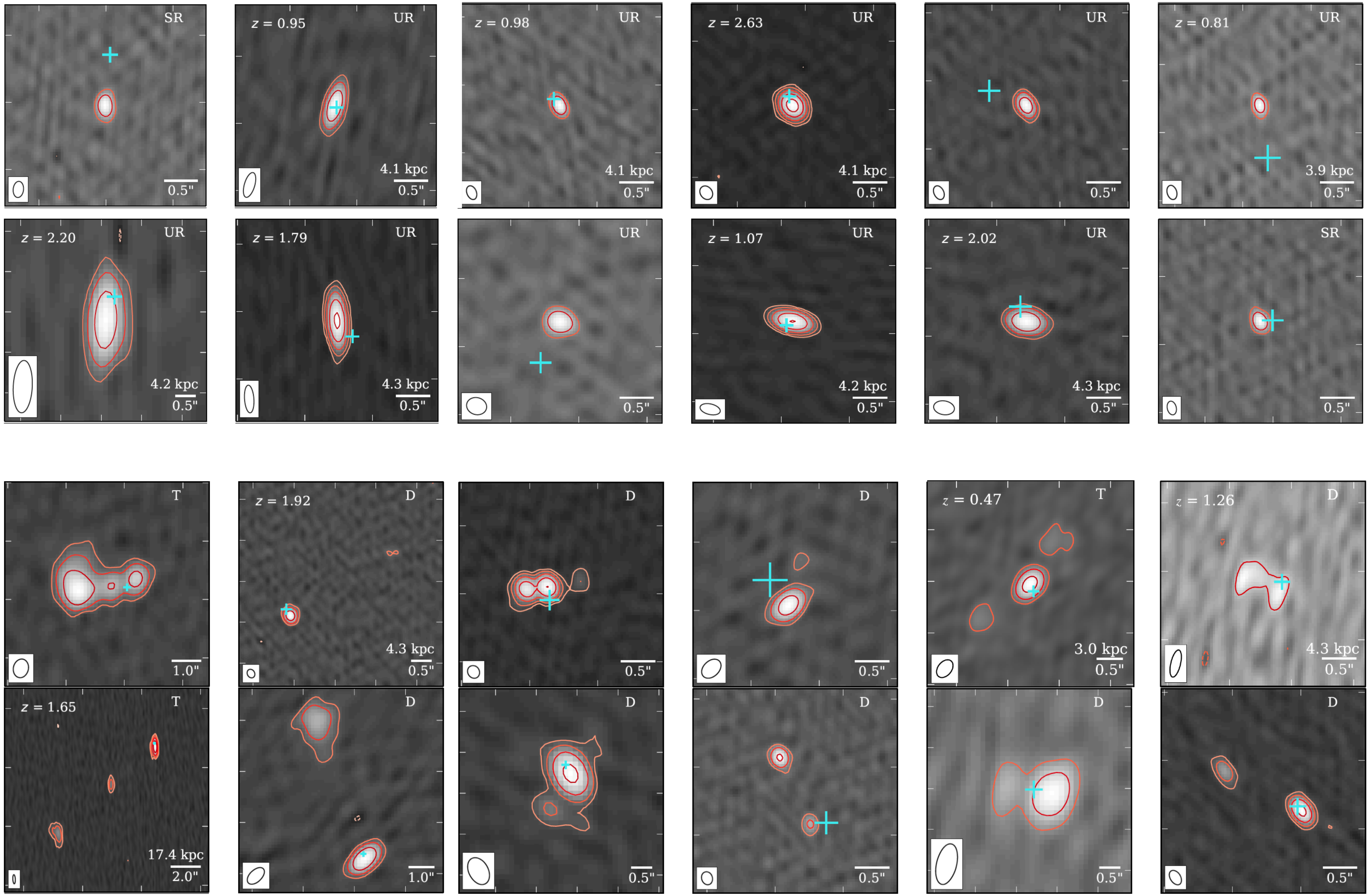
SUB-ARCSECOND VLA X-BAND (8-12 GHZ) IMAGING SURVEY

- X-band (8-12 GHz) multi-configuration snapshot survey (A & B) with 0.2″ and 0.6″ resolution
- Goal: to characterize morphologies and radio spectra of our sample sources

Patil et al. 2020, ApJ, 896, 18

SUB-ARCSECOND VLA X-BAND (8–12 GHZ) IMAGING SURVEY

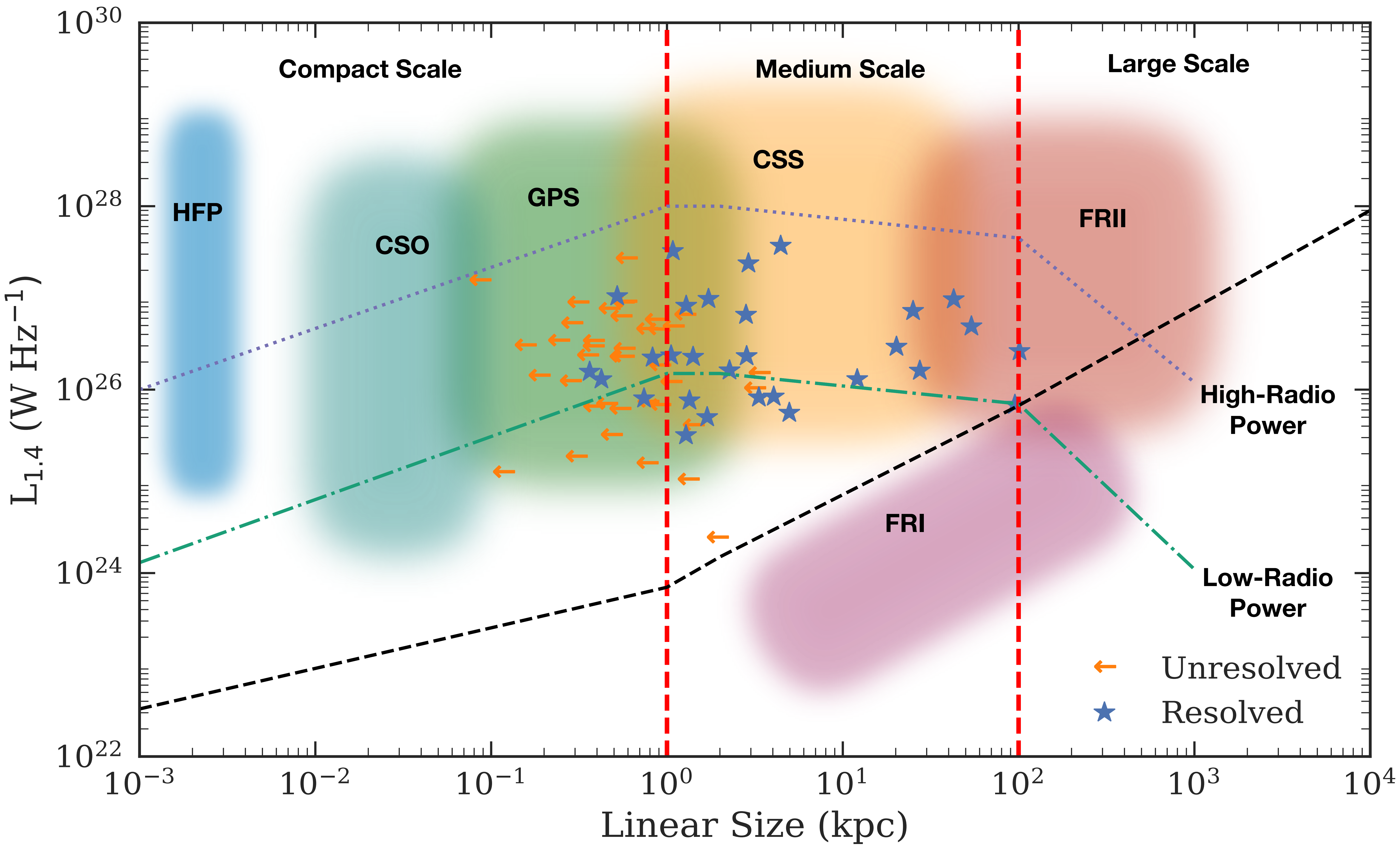
- 72% of sources are compact : median <0.2"; < 2 kpc at z~2
- 28% of sources are resolved: 0.5"-10"; 4-50 kpc
- A matched MIR blind radio survey (CENSORS) has larger sources: median 6"



Patil+2020

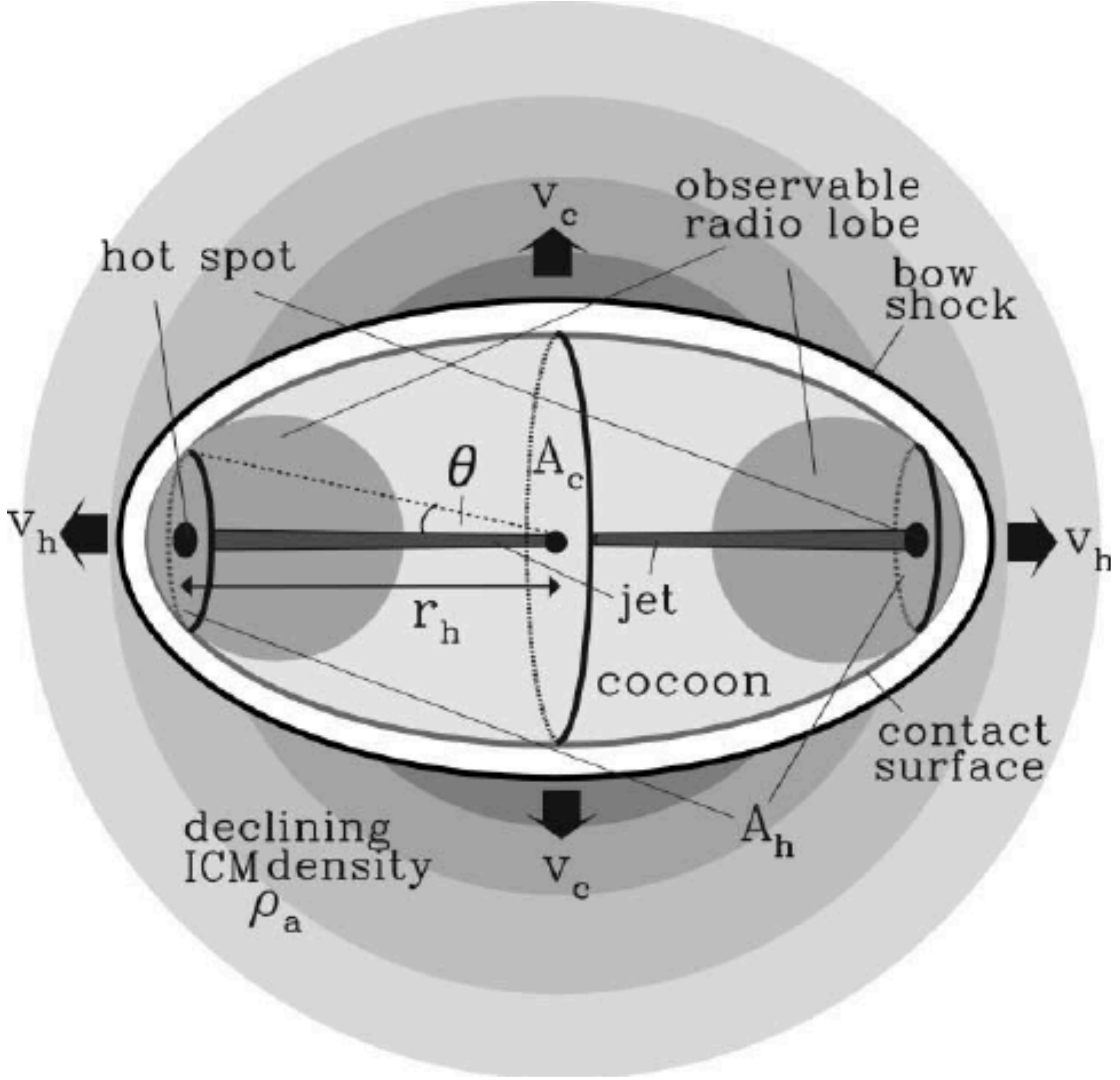
THE EVOLUTIONARY STAGE OF THESE SOURCES

Many sources are consistent with CSS, GPS sources



Linear Size vs Radio Power Diagram

APPLICATION OF ADIABATIC LOBE EXPANSION MODEL



Ito+2008

- Under the assumption of adiabatic expansion, the model can be approximated by analytical expressions of observables.

$$p_l = 7.76 \times 10^{-10} F_{43} t_{\rm Myr} R_l^{-3}$$

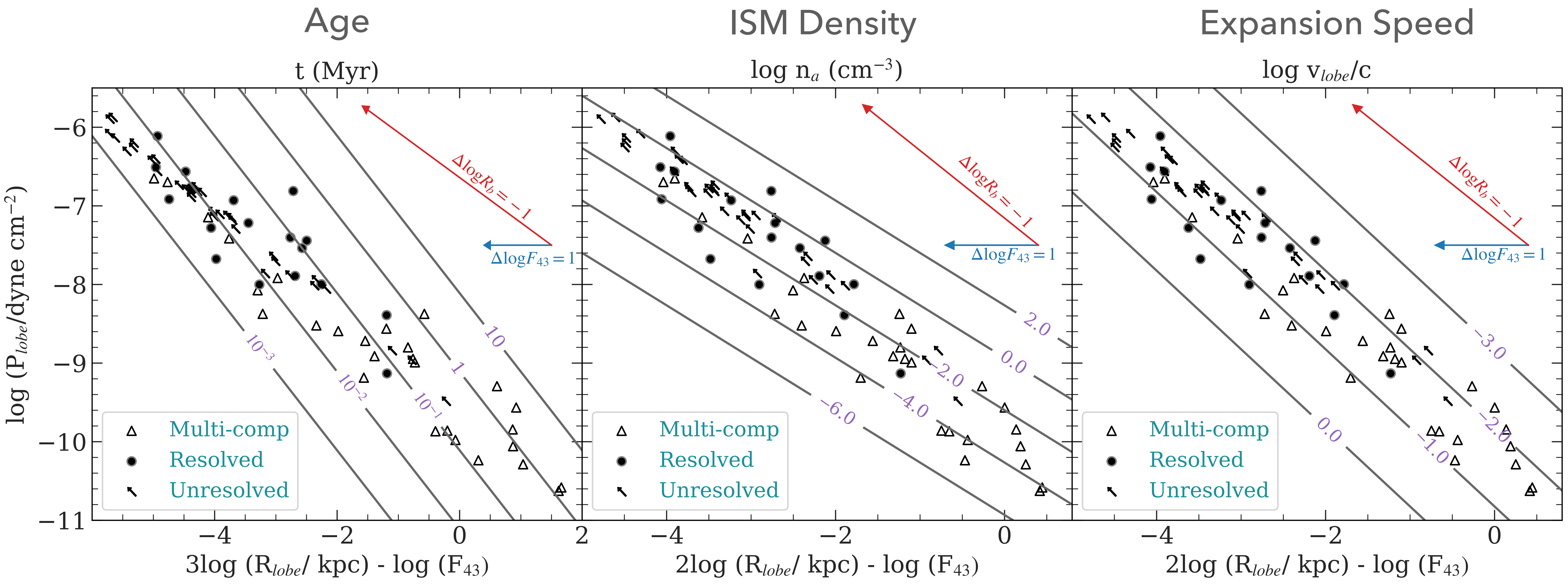
$$p_l = 1.17 \times 10^{-9} F_{43}^{2/3} n_a^{1/3} R_l^{-4/3}$$

$$p_l = 1.50 \times 10^{-12} F_{43} (V_l/c)^{-1} R_l^{-2}$$

Begelman 1996

t_{Myr} : Age
p_l : Lobe Pressure
n_a : Ambient density
F_{43} : Jet Power
V_l : Lobe Speed
R_l : Lobe Radius

APPLICATION OF ADIABATIC LOBE EXPANSION MODEL

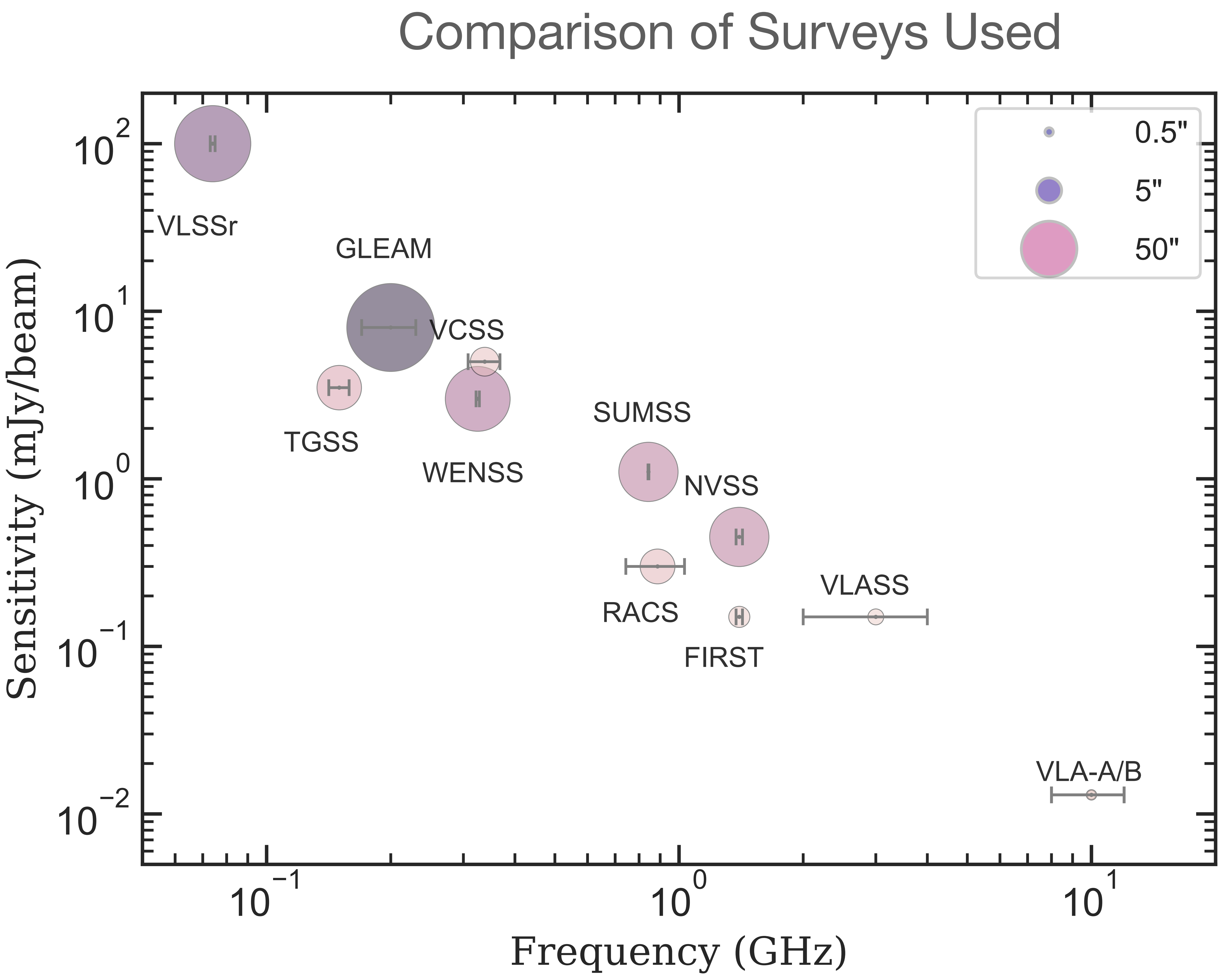


- The model suggests the more compact sources are indeed young ($10^3 - 10^4$ yrs) and expand into a relatively dense ISM at speeds 0.01c – 0.1c

A SAMPLE OF HEAVILY OBSCURED AGN

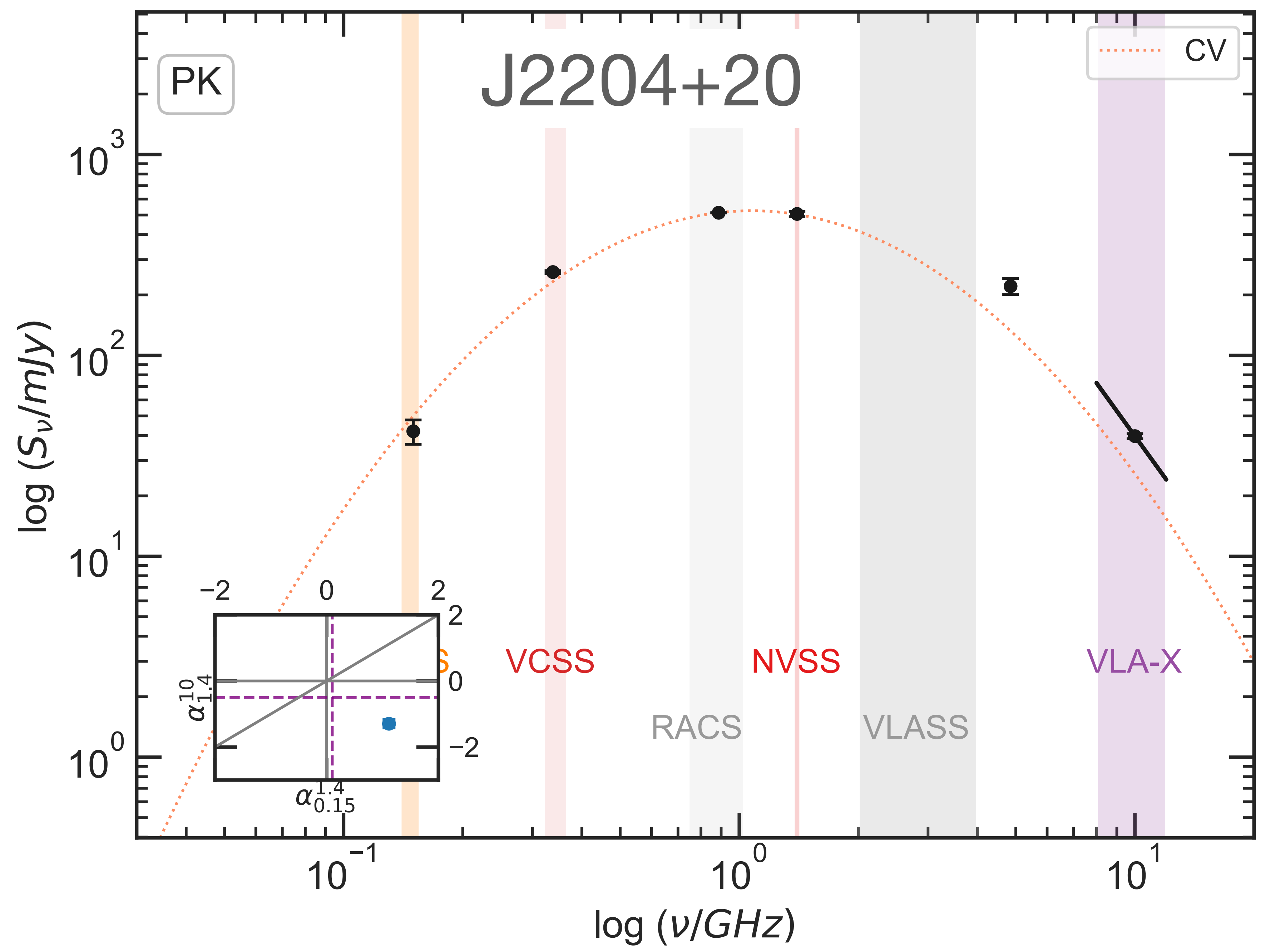
WHAT THE RADIO SPECTRA CAN TELL US?

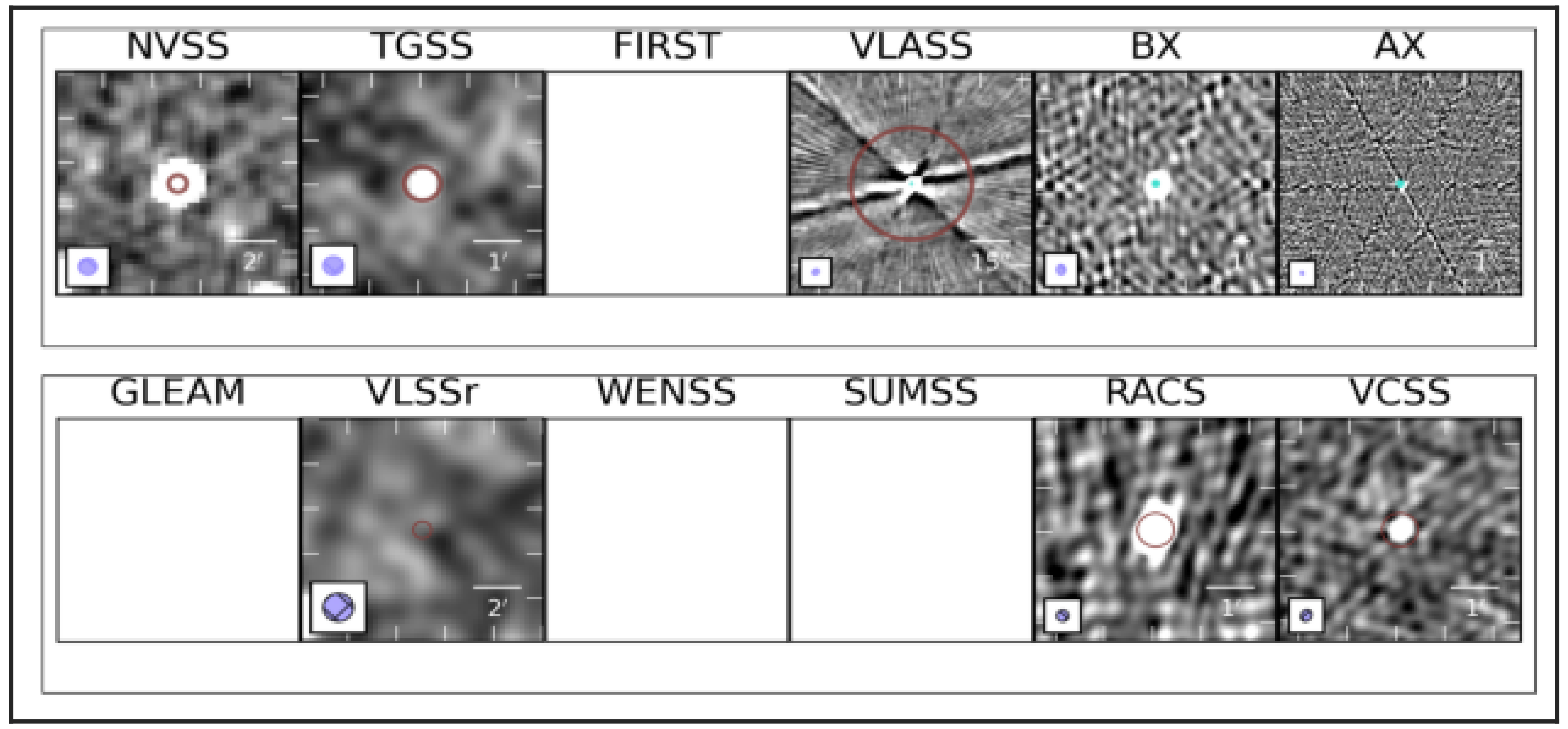
RADIO SPECTRA MODELING: FITTING AND QUALITY ANALYSIS



VCSS Data Courtesy: VLITE Team

An example





RADIO SPECTRA MODELING: FITTING AND QUALITY ANALYSIS

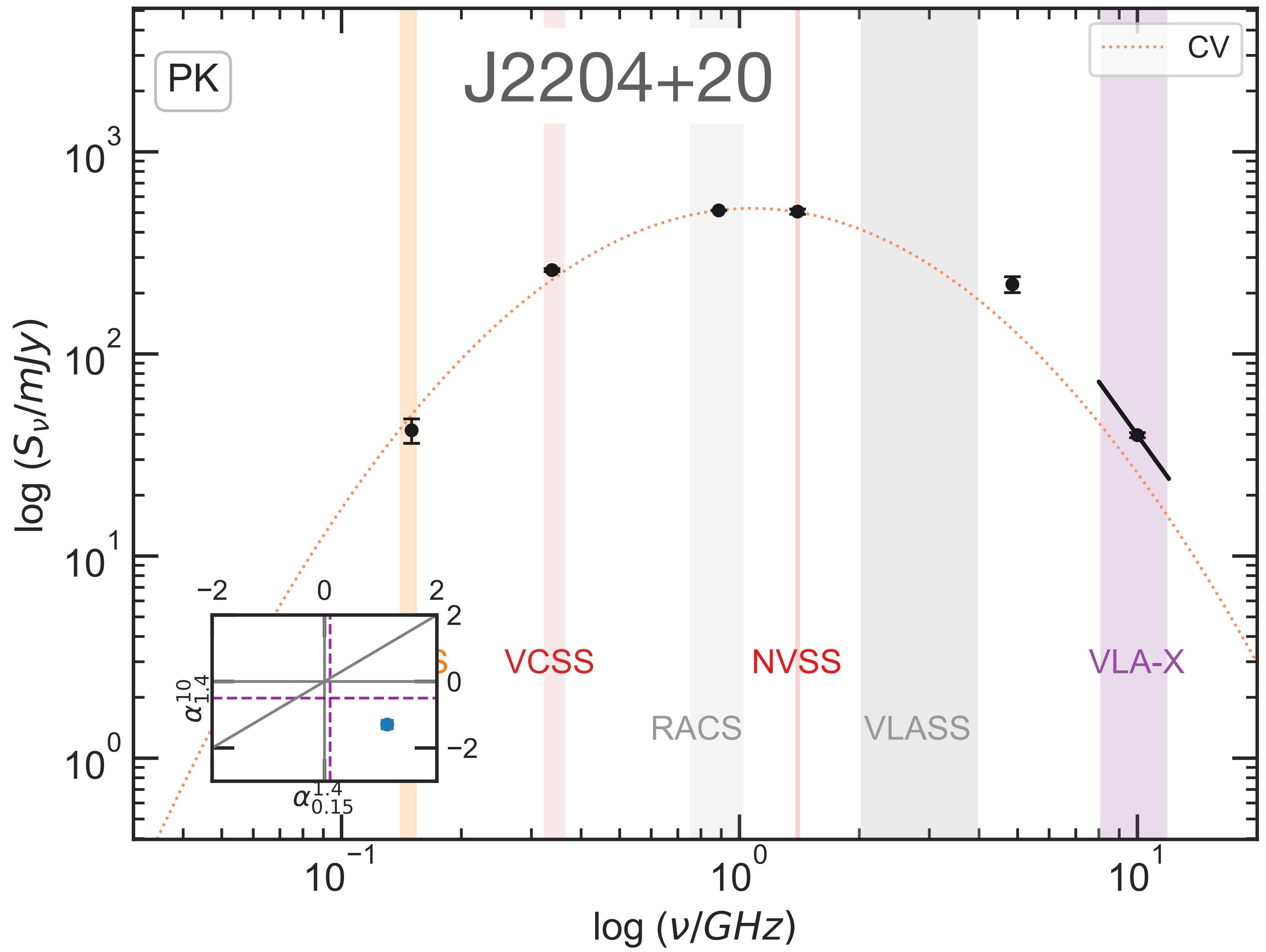
Two functions were fit

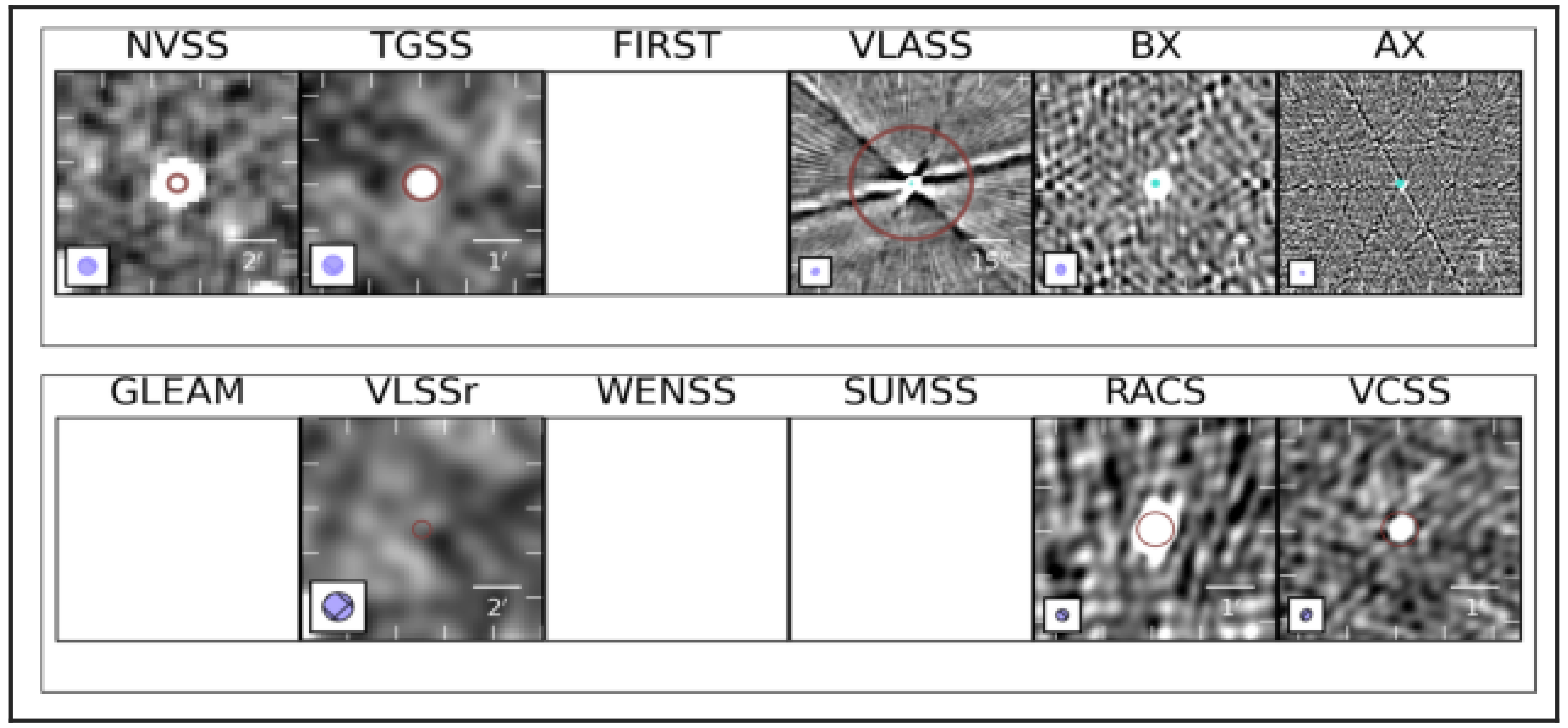
Power Law: $S_\nu \propto \nu^\alpha$

Parabola:

$S_\nu \propto \nu^\alpha e^{q(ln\nu)^2}$

Curvature Parameter



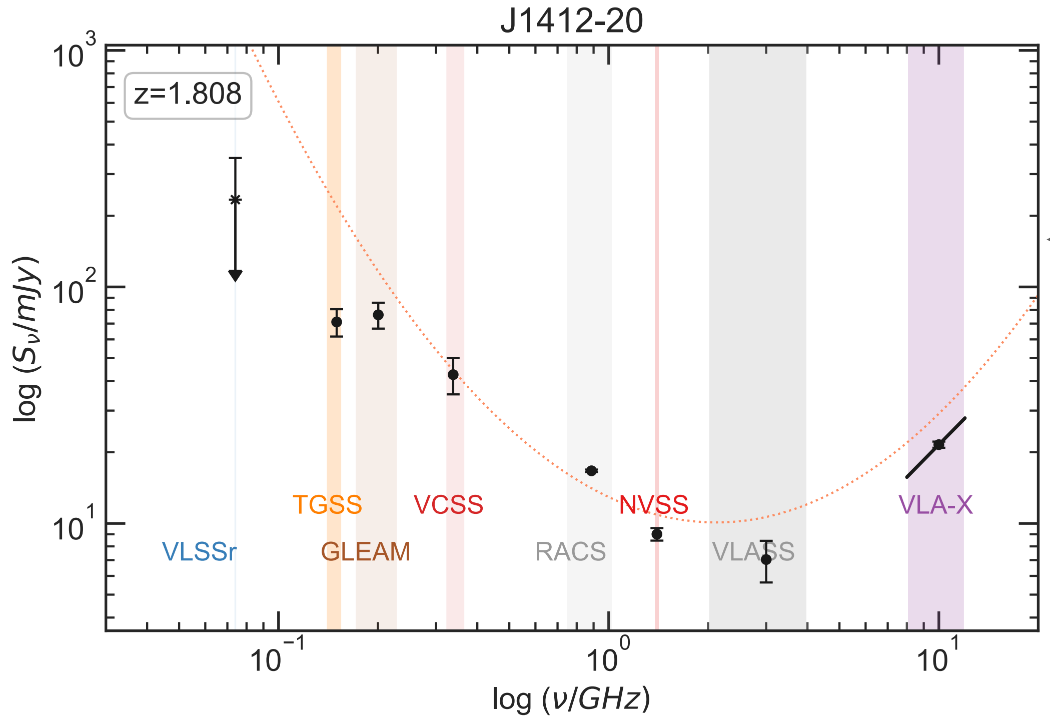


Visual inspection of spectra and continuum images to check for resolution effects

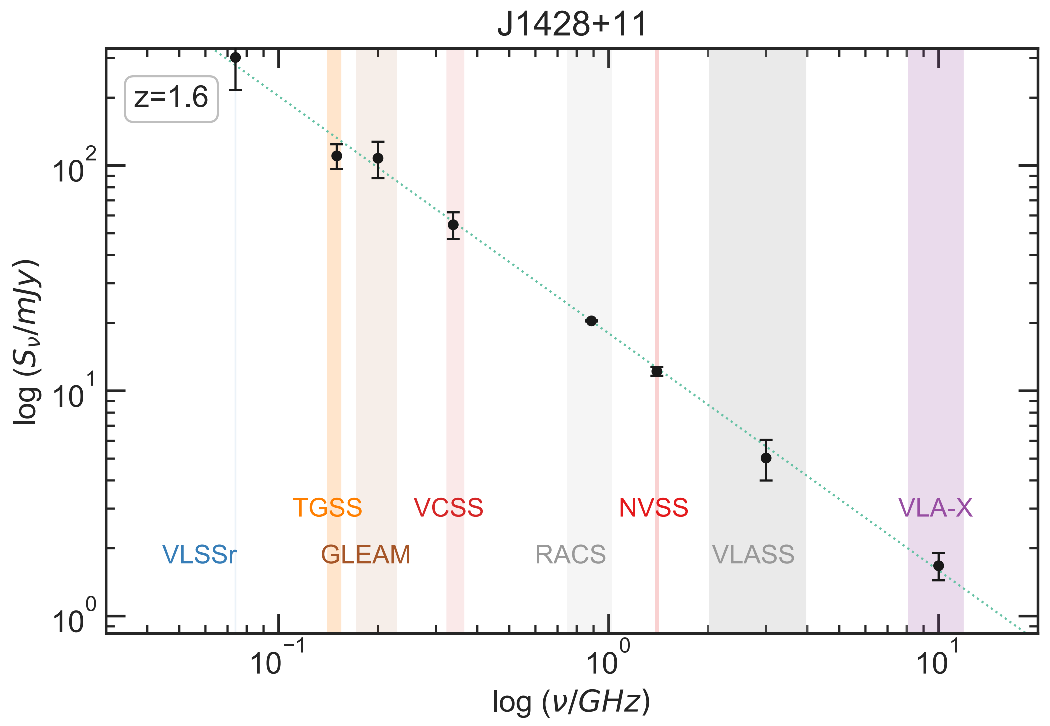
RADIO SPECTRAL CLASSIFICATION

Patil+ in prep

RADIO SPECTRAL CLASSIFICATION



3.2%



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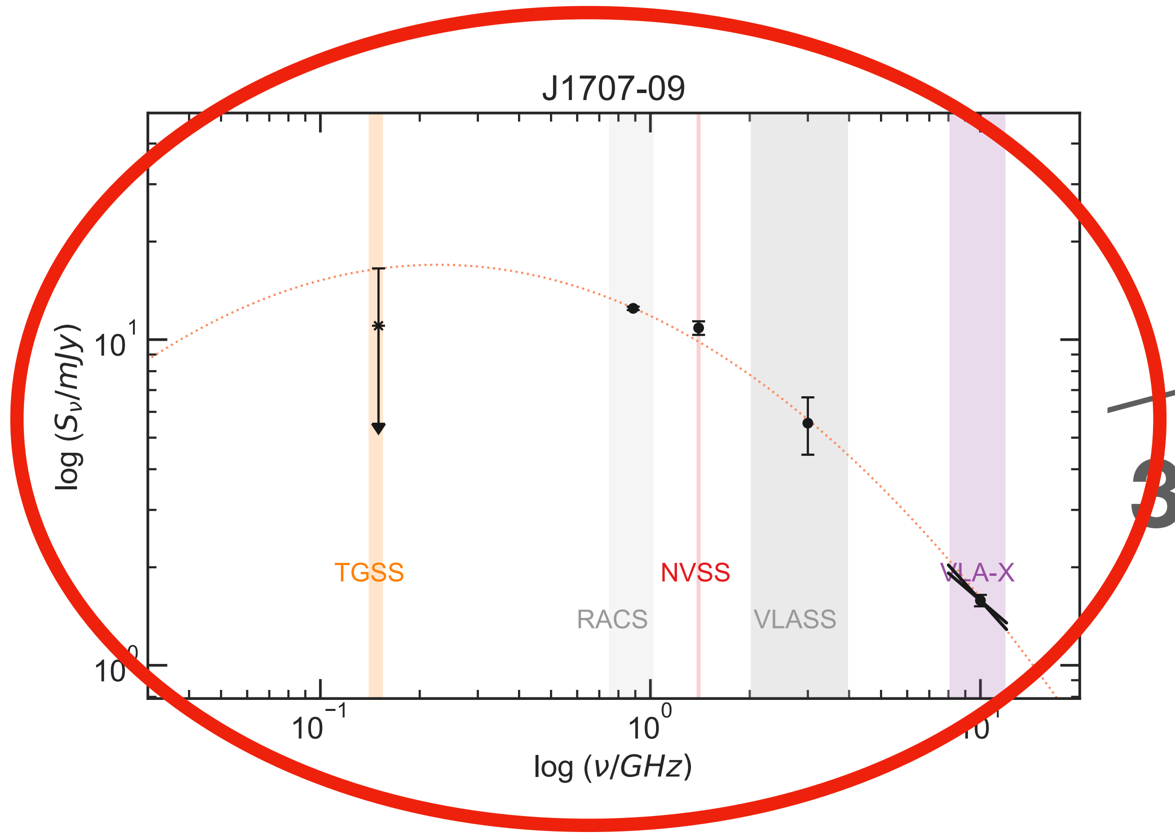
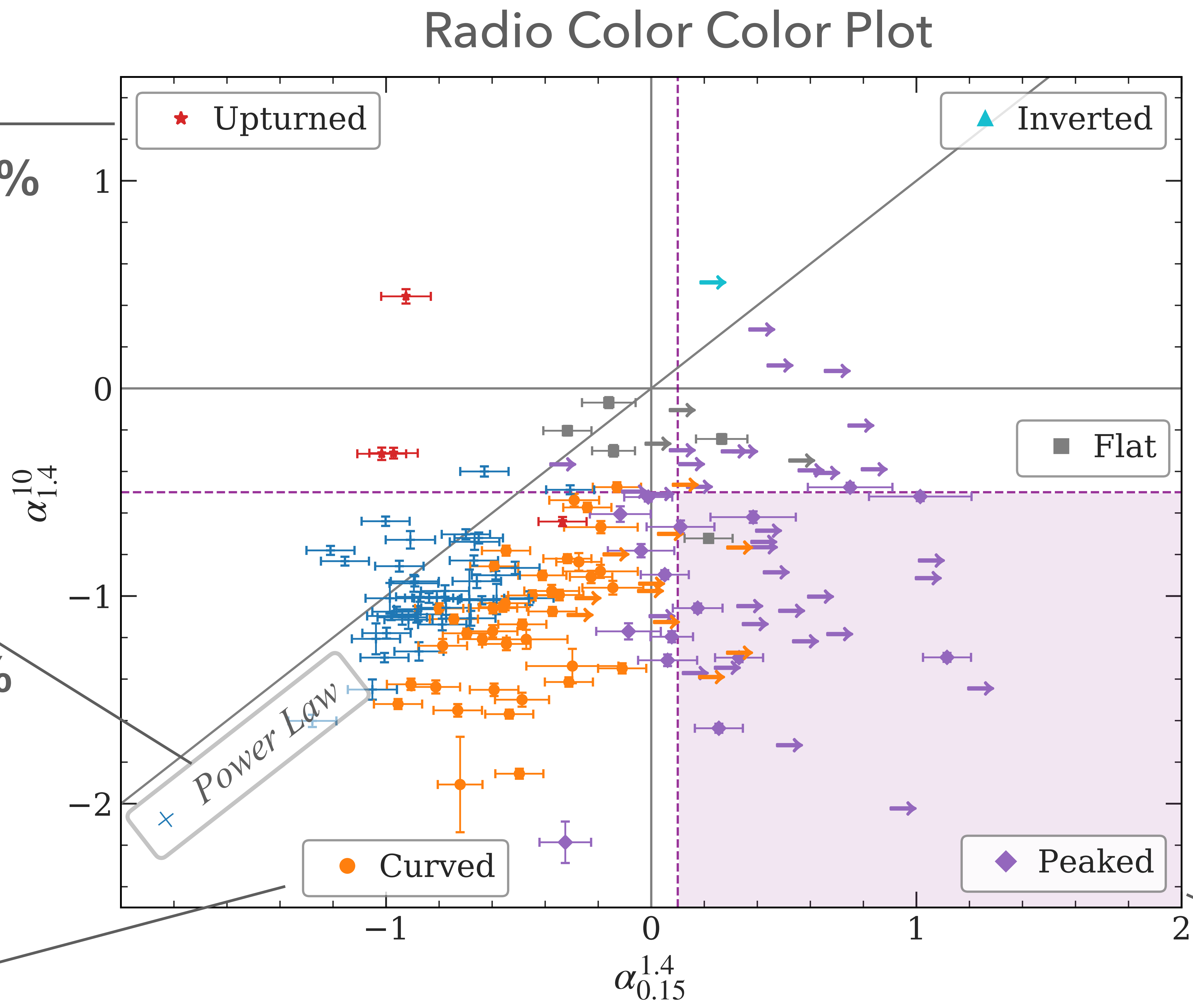
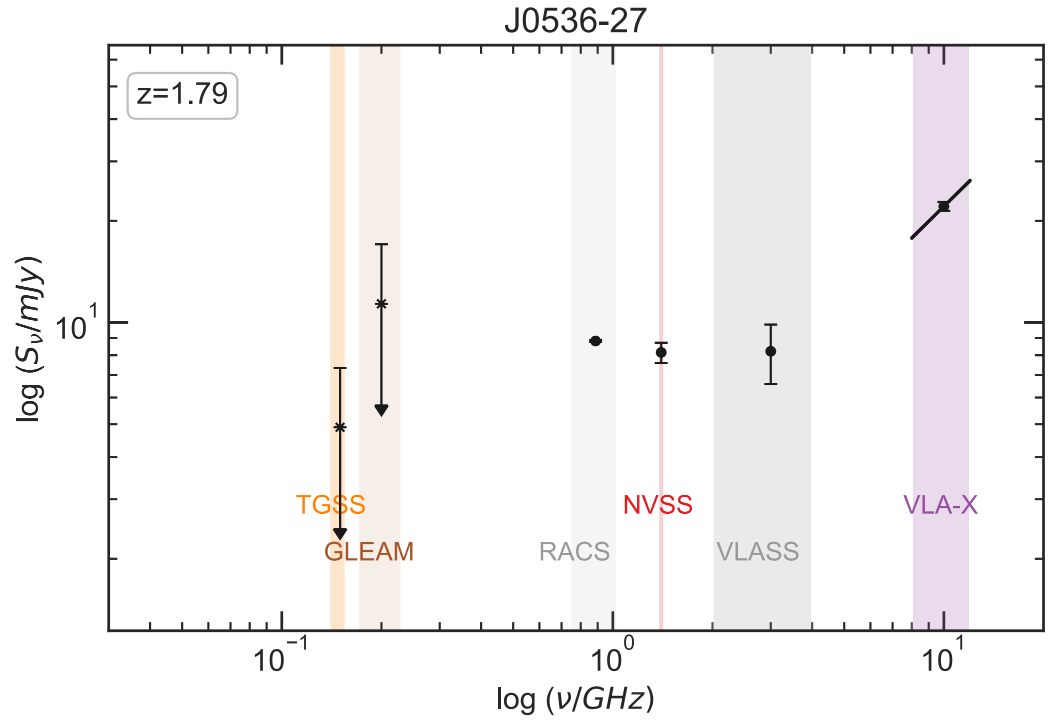


35 %

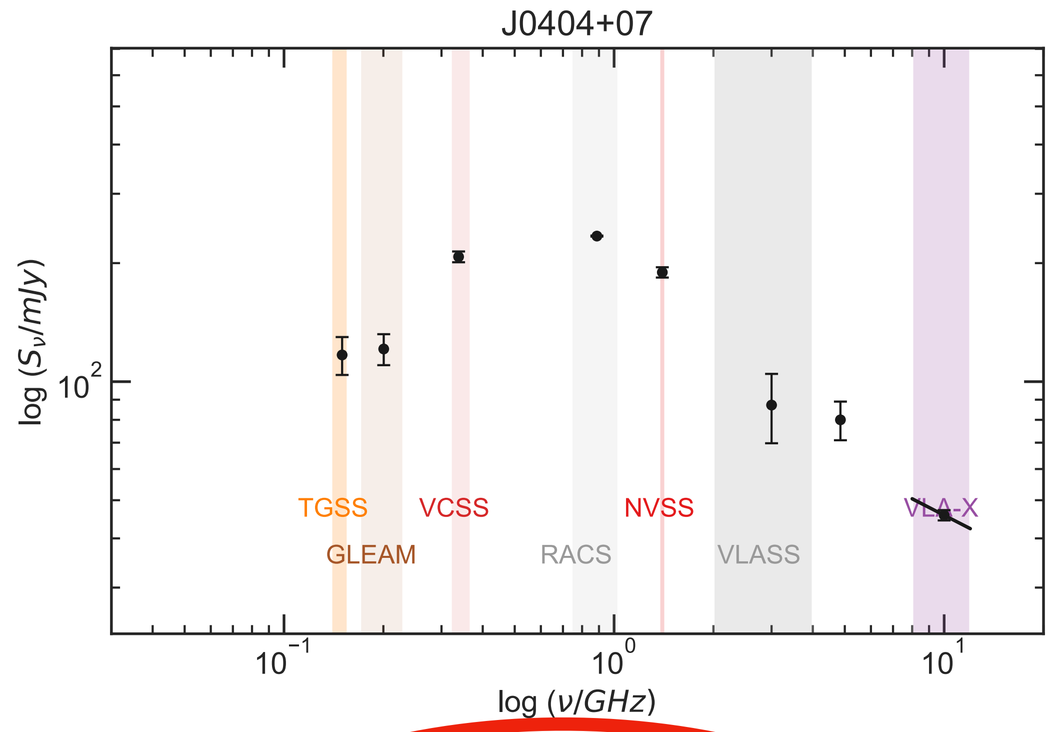


- Peaked –> Absorbed and compact radio emission –> Indicator of youth?

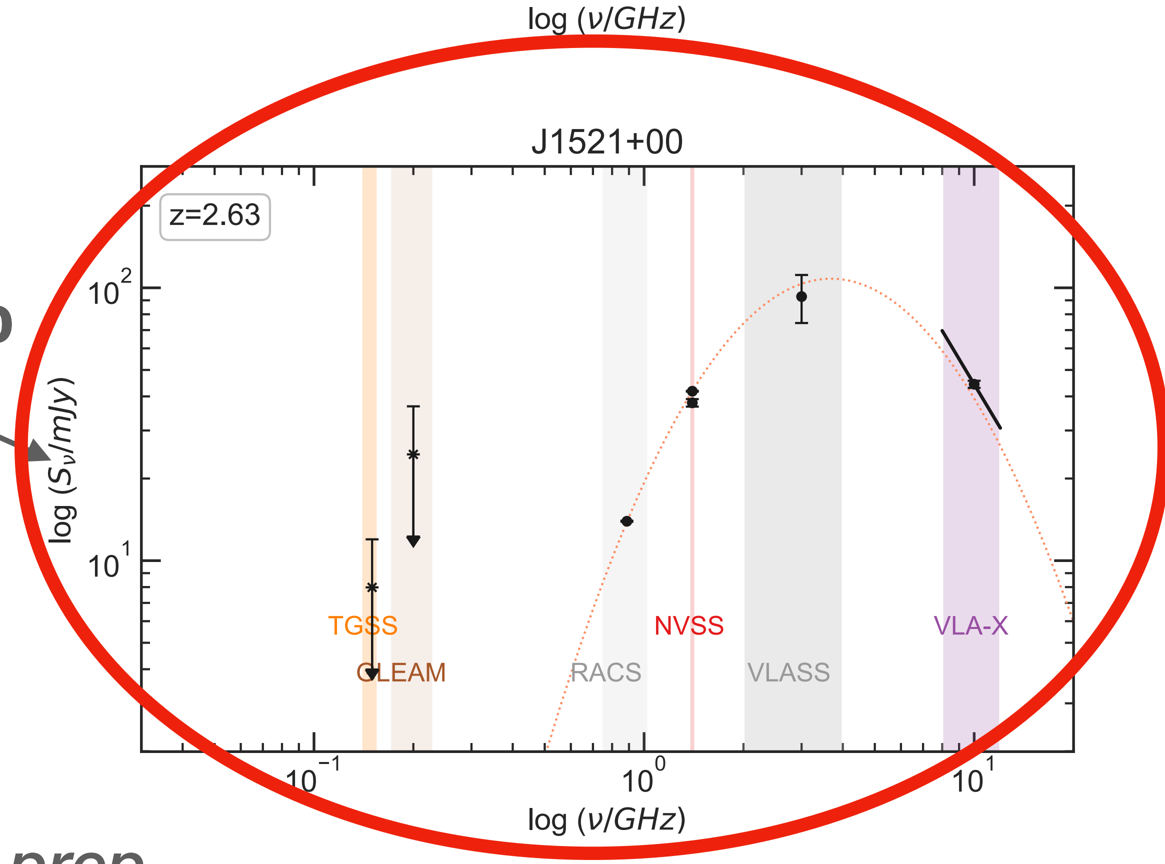
1.3%



4.5%



30%



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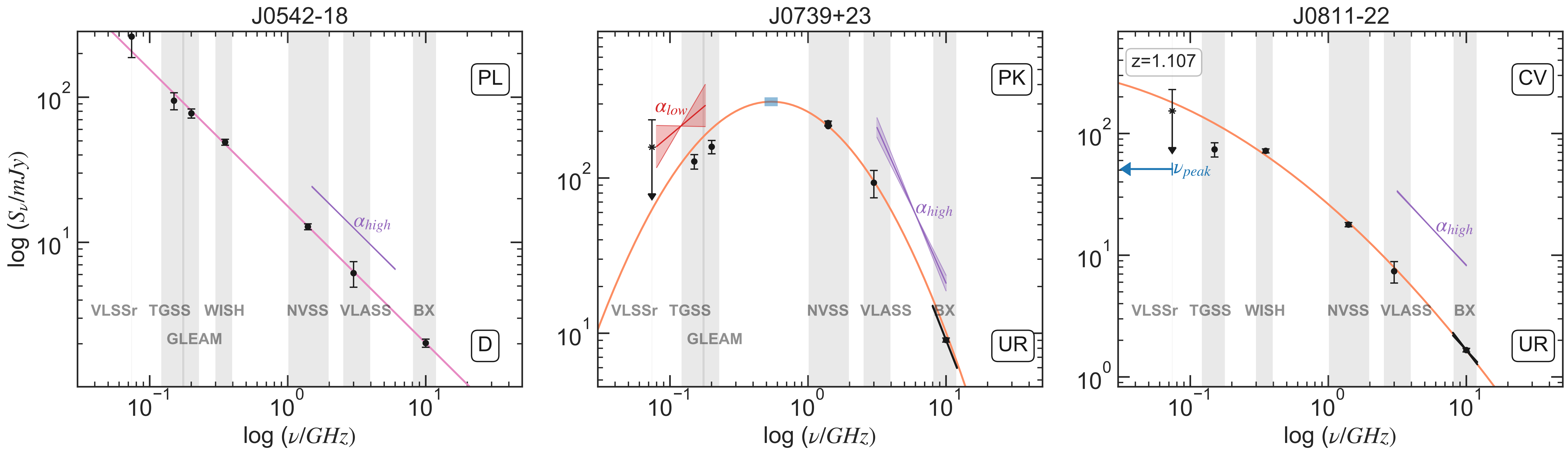
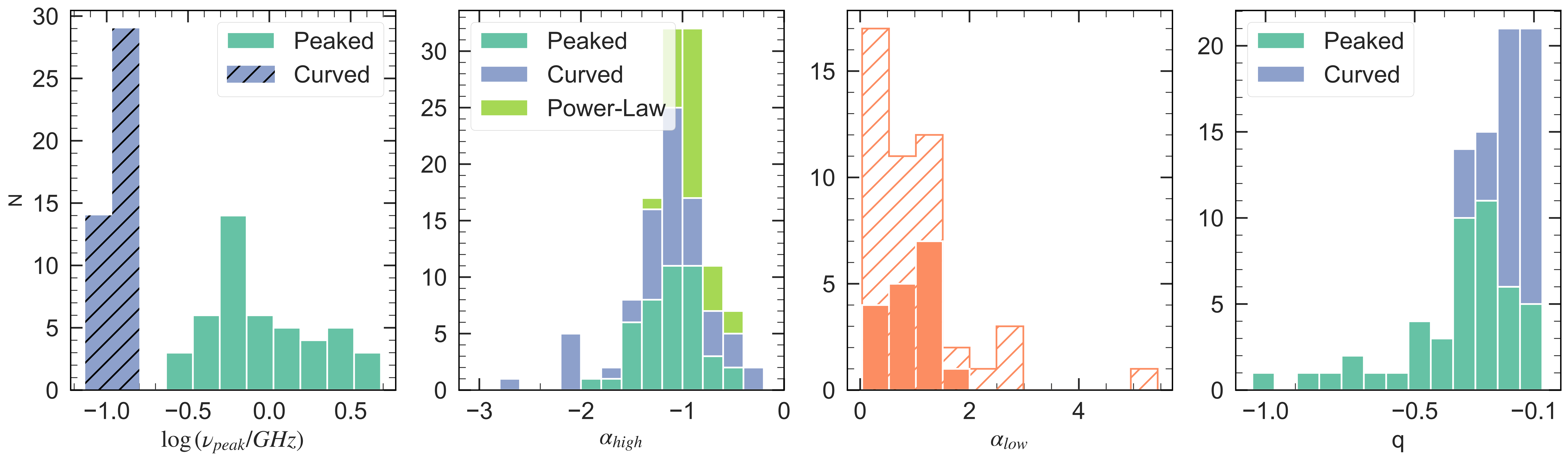
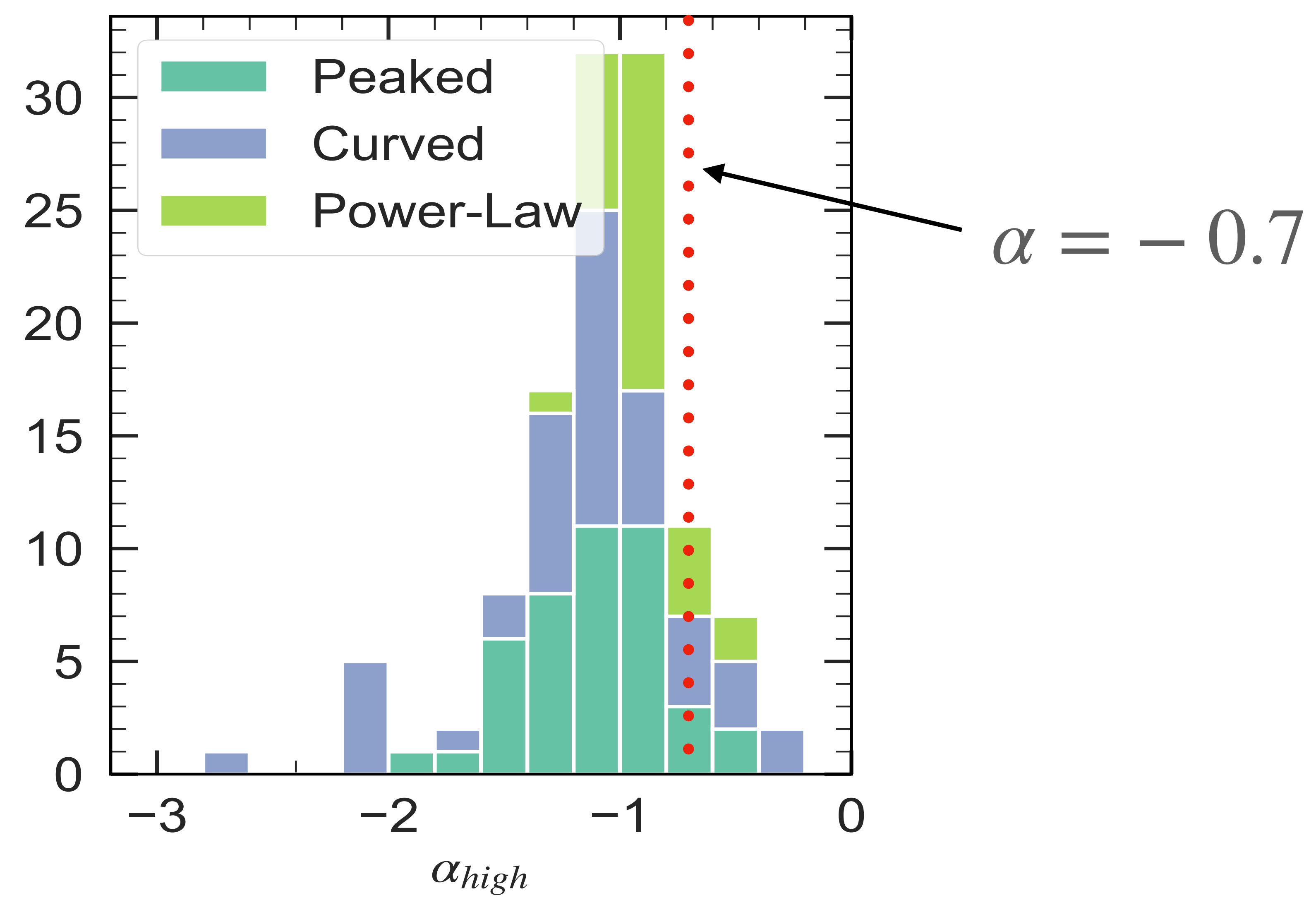
SPECTRAL SHAPE PARAMETERS AND DISTRIBUTIONS

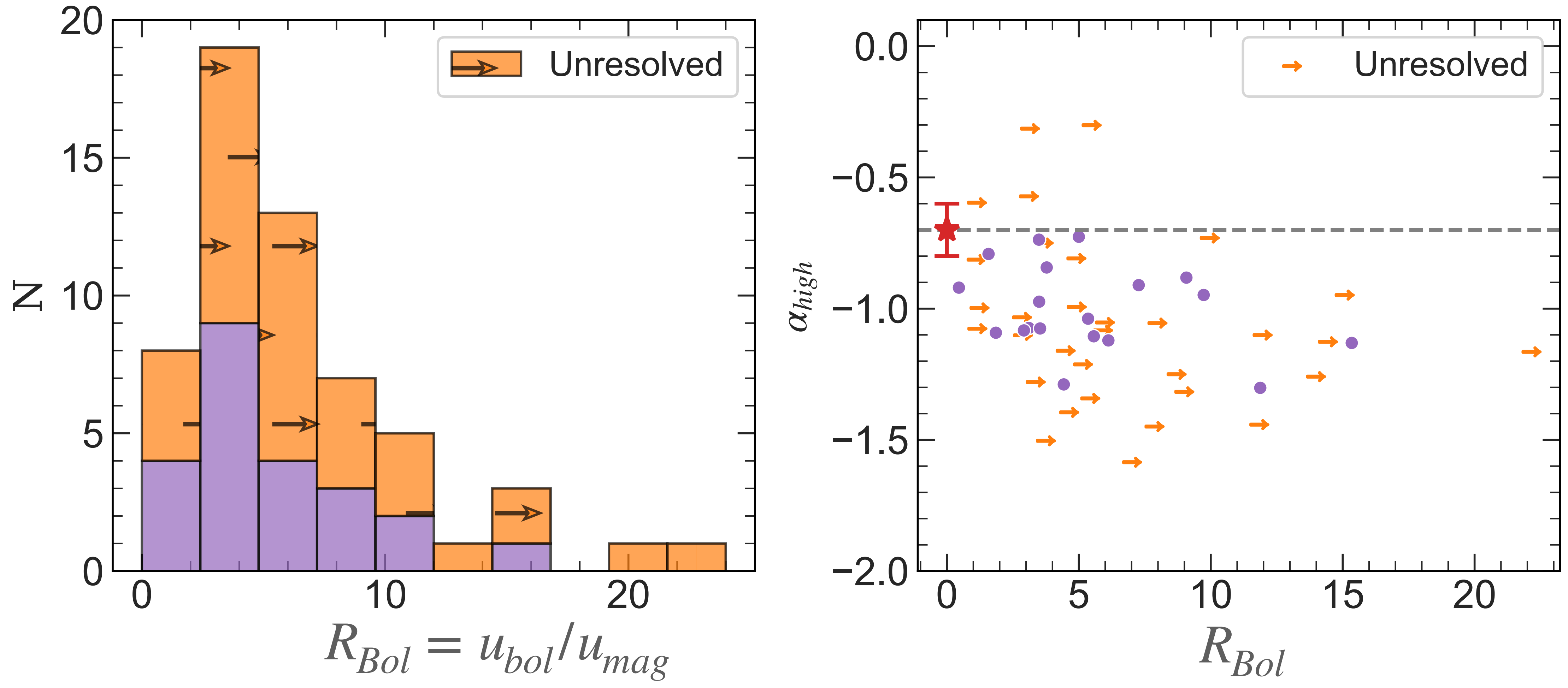




HIGH FREQUENCY SPECTRAL INDICES

- Median index = -1.0, steep compared to the canonical value of -0.7
- Possible causes:
  - Resolution effects - eliminated these (few).
  - Spectral aging - not likely
  - Inverse Compton scattering off CMB - no
  - Inverse Compton scattering of AGN radiation - likely due to luminous AGN
  - Dense ambient medium - possible as post-merger phase

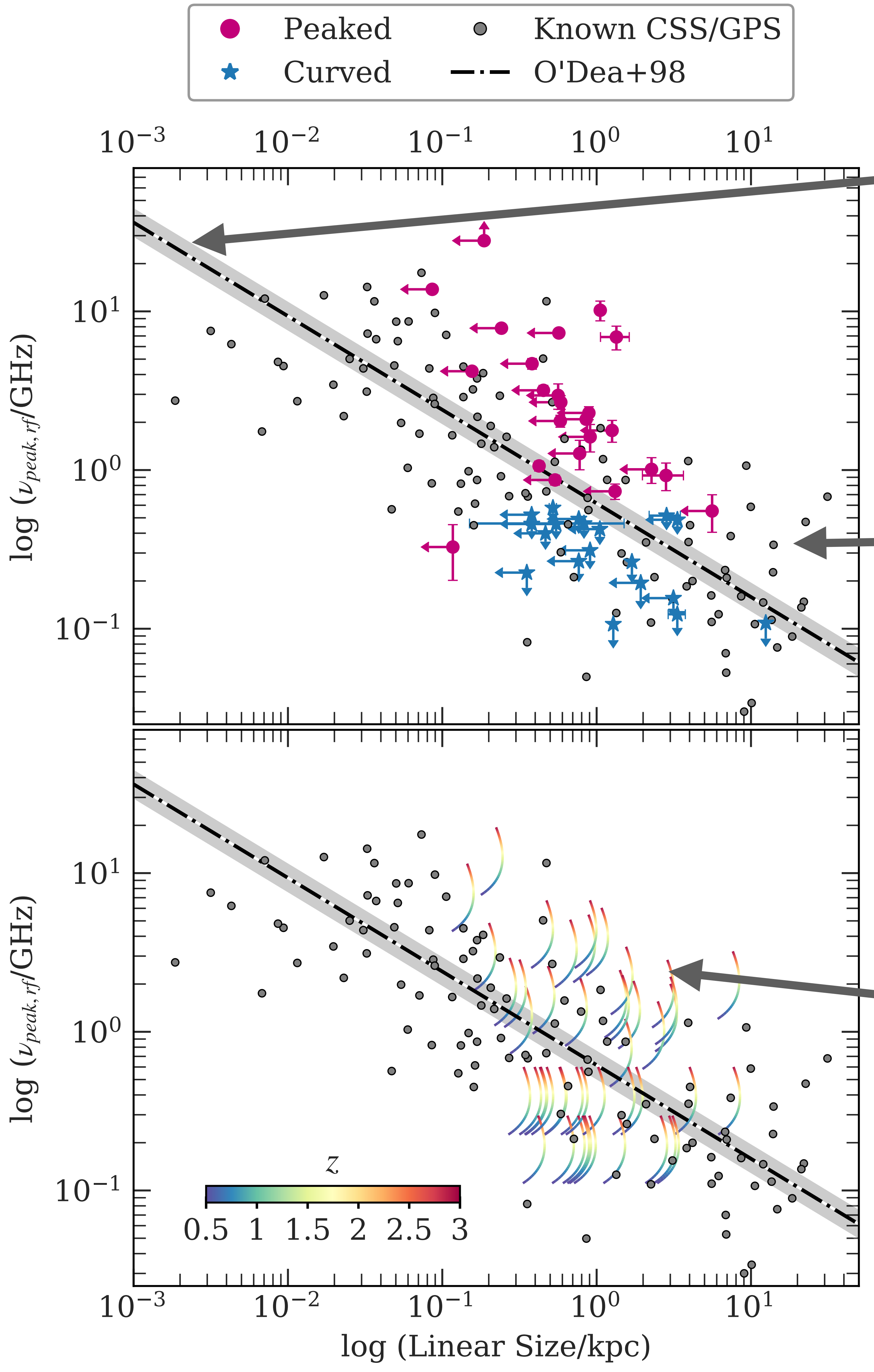




LINEAR SIZE VS TURNOVER RELATION

Most of the peaked sources lie close to the relation –> SSA is likely

A few significant outliers –> Possible causes: FFA or lower luminosity for which the relation is not well established.



Relation from O'Dea 1998

Well-known luminous CSS/GPS/HFPs

Redshift tracks for sources with no z

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PEAKED SOURCES: EMITTING REGION SIZES

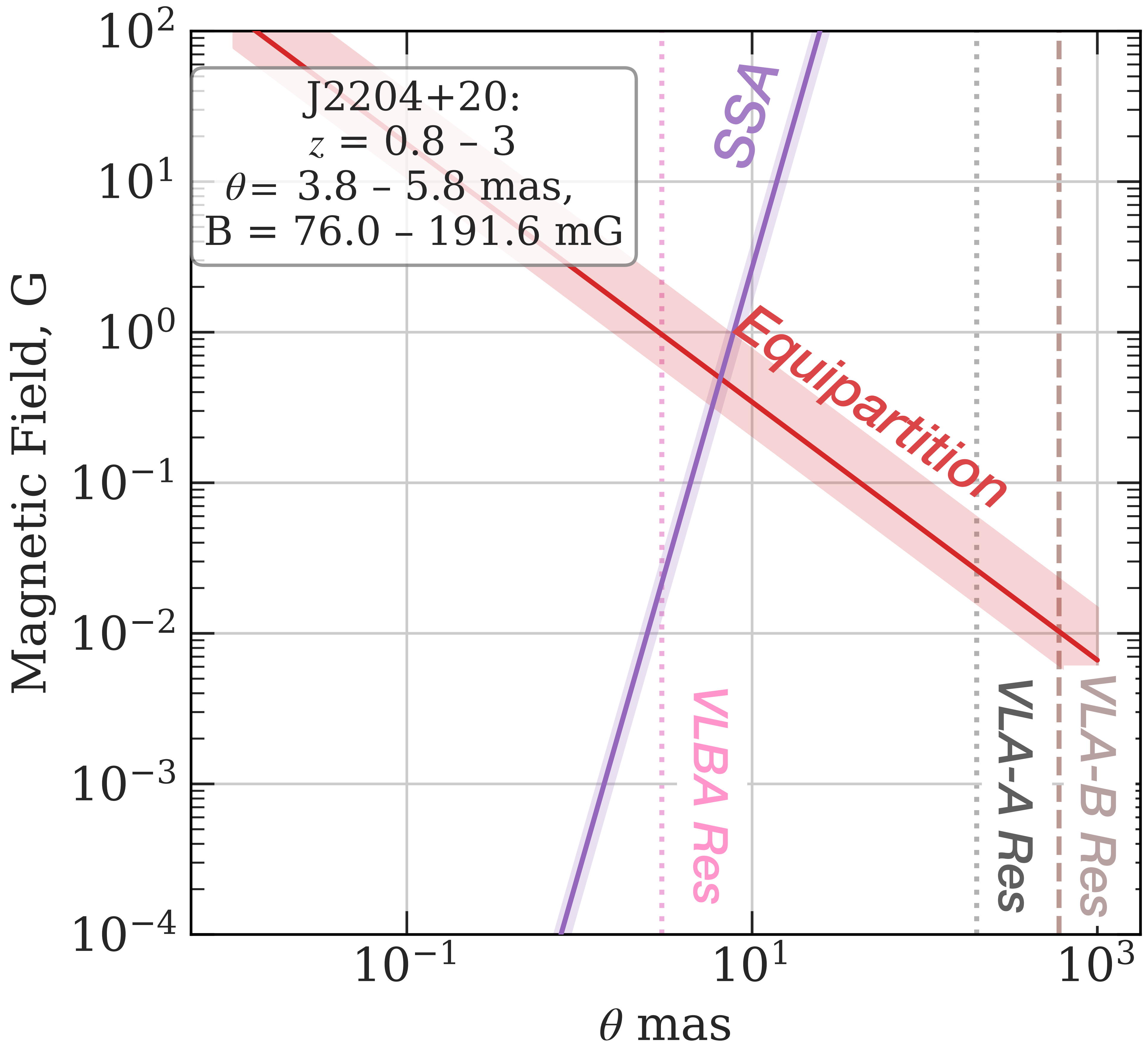
- If the turnover is due to SSA then,

$$B_{SSA} = 23\ \frac{\theta^4_{mas}}{S^2_{peak}}\frac{\nu^5_{peak}}{1+z}\quad \text{Gauss}$$

- Under the assumption of equipartition,

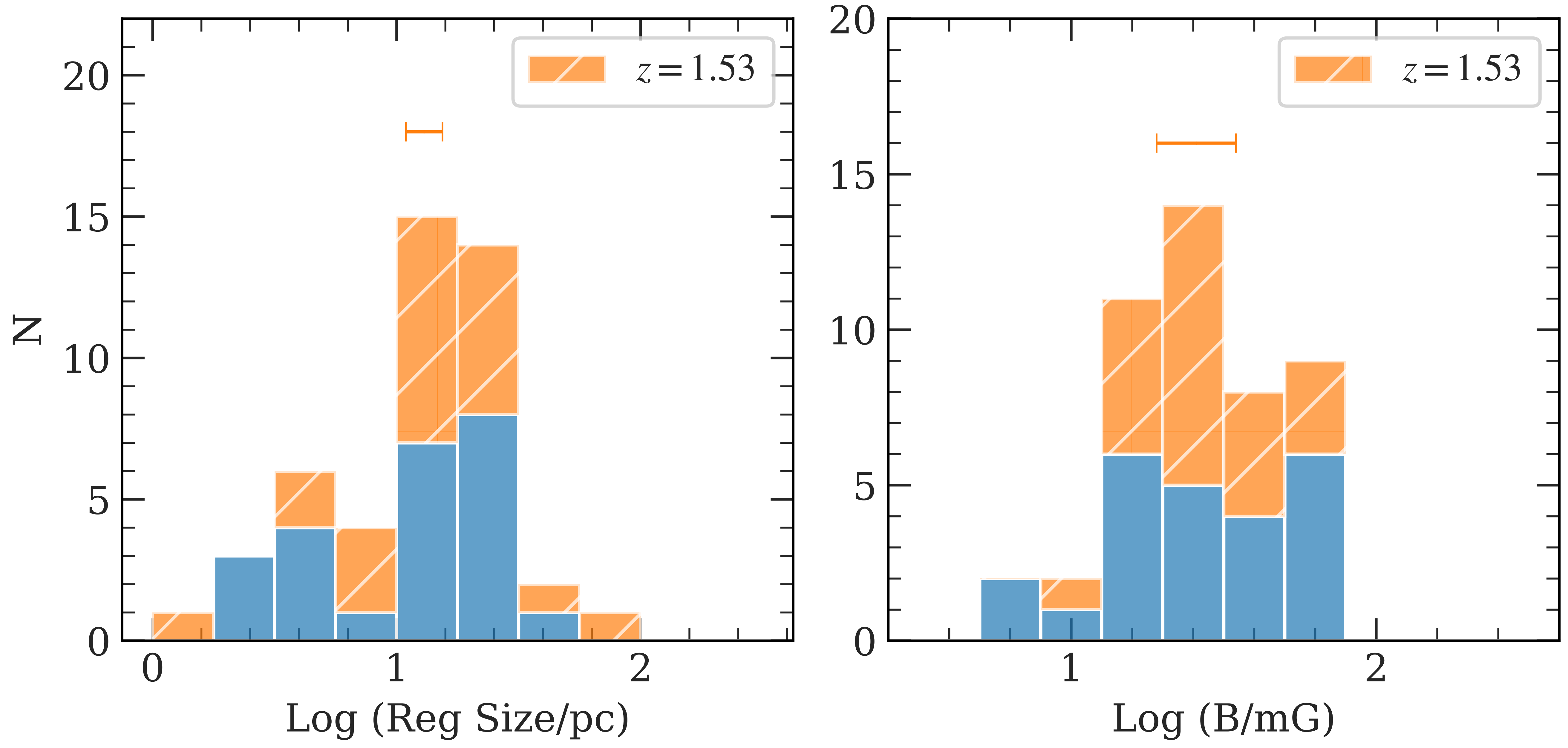
$$B_{EQ} \approx 0.0152\left[\frac{a}{f_{rl}}\frac{(1+z)^{4-\alpha}}{\theta^3_{mas}}\frac{S_{mJy}}{\nu^{\alpha}_{GHz}}\frac{X_{0.5}(\alpha)}{r_{Mpc}}\right]^{2/7}\quad \text{Gauss}$$

- Assume these are equal and solve for θ and B



PEAKED SOURCES: EMITTING REGION SIZES

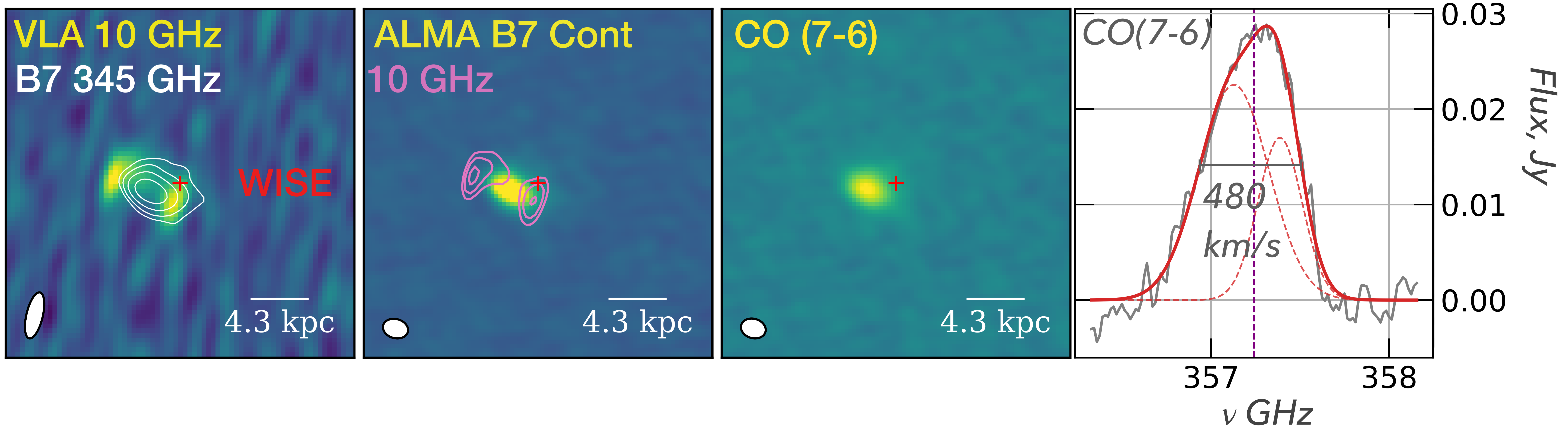
- Find θ and B from joint condition.
- Approximate region sizes ~ 1 - 100 pc
- High magnetic fields ~ 10 - 100 mG
- Physical condition in peaked sources are similar to CSS/GPS/HFP sources
- Peaked sources are likely to be young



ONGOING PROJECTS AND FUTURE WORK

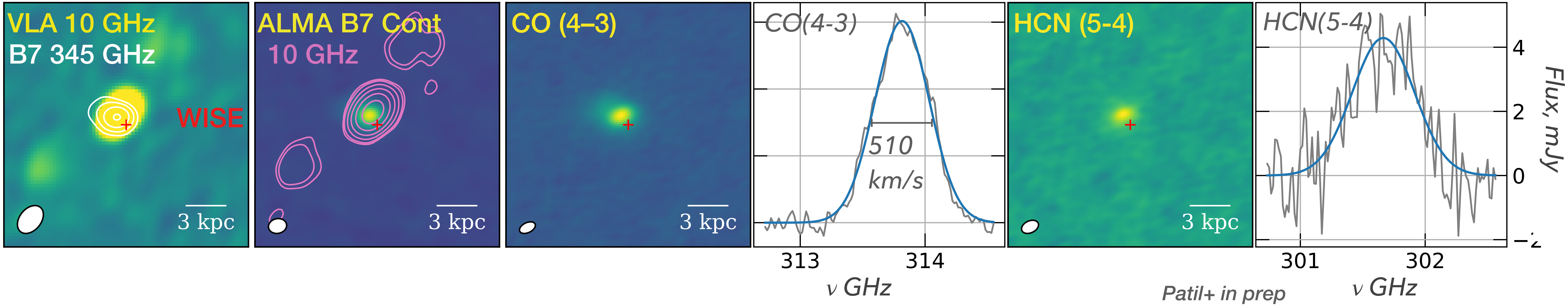
DIRECT DETECTION OF DENSE MOLECULAR GAS WITH ALMA

J0404-24, z = 1.258



*Preliminary Result

J0612-06, z = 0.47



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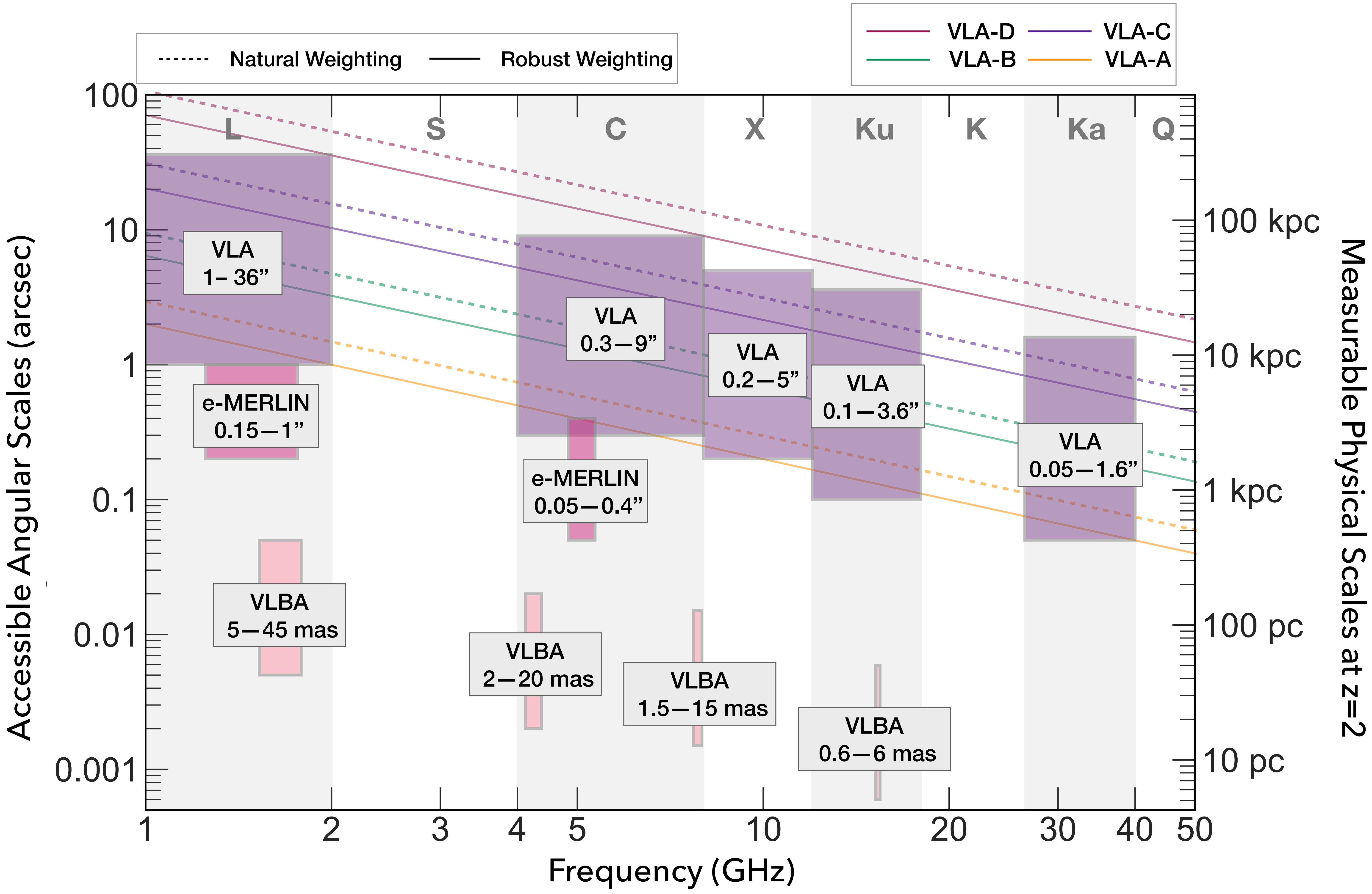
ONGOING PROJECTS AND FUTURE WORK

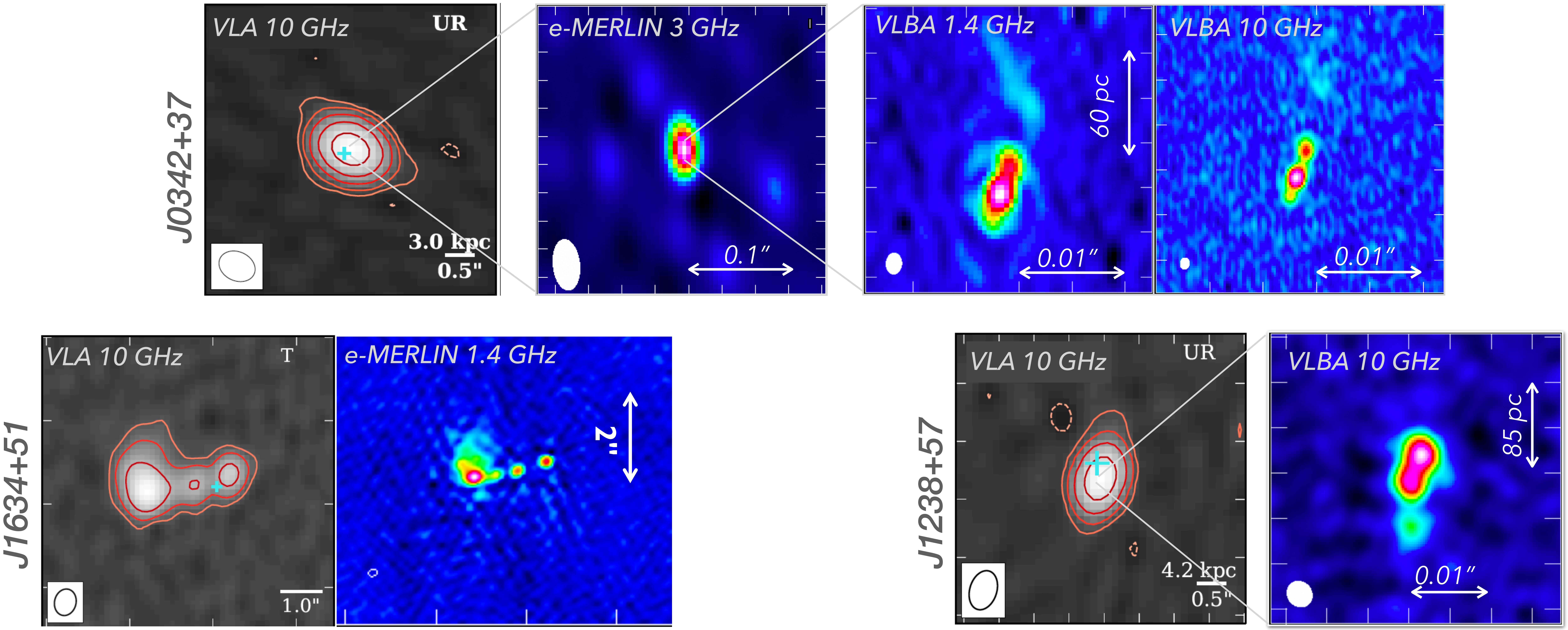
MULTI-RESOLUTION AND MULTI-BAND RADIO IMAGING

Aim: To obtain multi-frequency images at the similar resolution and build spectral maps

- 3 Radio telescopes
- 5 Observing proposals
- Two subsets: 12 most compact sources and 20 sources with >1-2″ emission



MILLIARCSECOND SCALE IMAGING WITH VLBA AND e-MERLIN



Well-resolved morphologies on 10-100 mas scales -> recently triggered jets

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CONCLUSIONS

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VLA Imaging

- Sample: WISE-NVSS, z~2 obscured quasars
- 72% are compact: <0.2, <1.7 kpc (near-nuclear)
- Intermediate power; high pressures; low space density
- Adiabatic lobe expansion model suggests young ages

Radio Spectra

- Steep higher frequency spectra: IC losses from MIR?
- 80% of unresolved are curved or peaked
- LS-ν_{peak} relation –> SSA
- SSA+Equipartition yields <100 pc & 10-100 mG
- Model yields v. young sources & dense ISM

ALMA

- ALMA pilot study of dense ISM/CO kinematics
- A strong continuum is detected and of thermal origin
- Broad CO lines are seen potentially indicating outflows

Ongoing and Future Work

- Multi-ν spectral mapping using VLA
- VLBI maps of very compact sources
- NuSTAR probes AGN and high columns

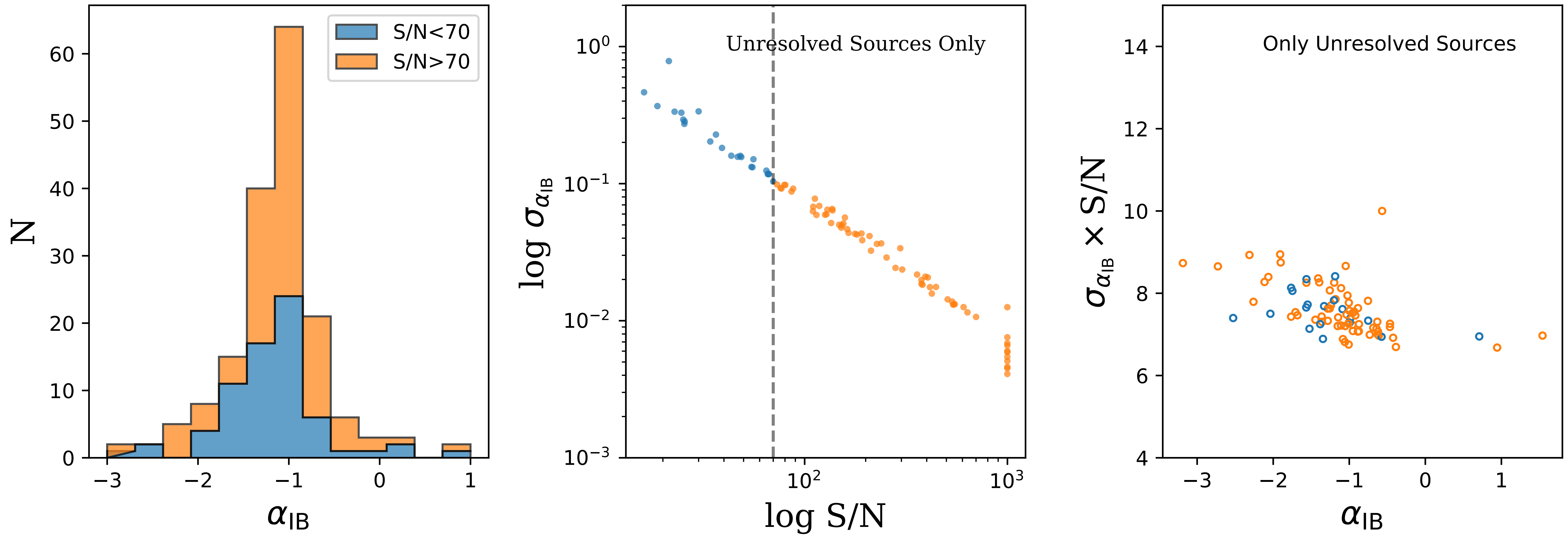
THANK YOU

ppatil@nrao.edu

ADDITIONAL SLIDES

X-BAND IN-BAND SPECTRAL INDICES

α_{IB} Reliability Analysis following Condon+2015

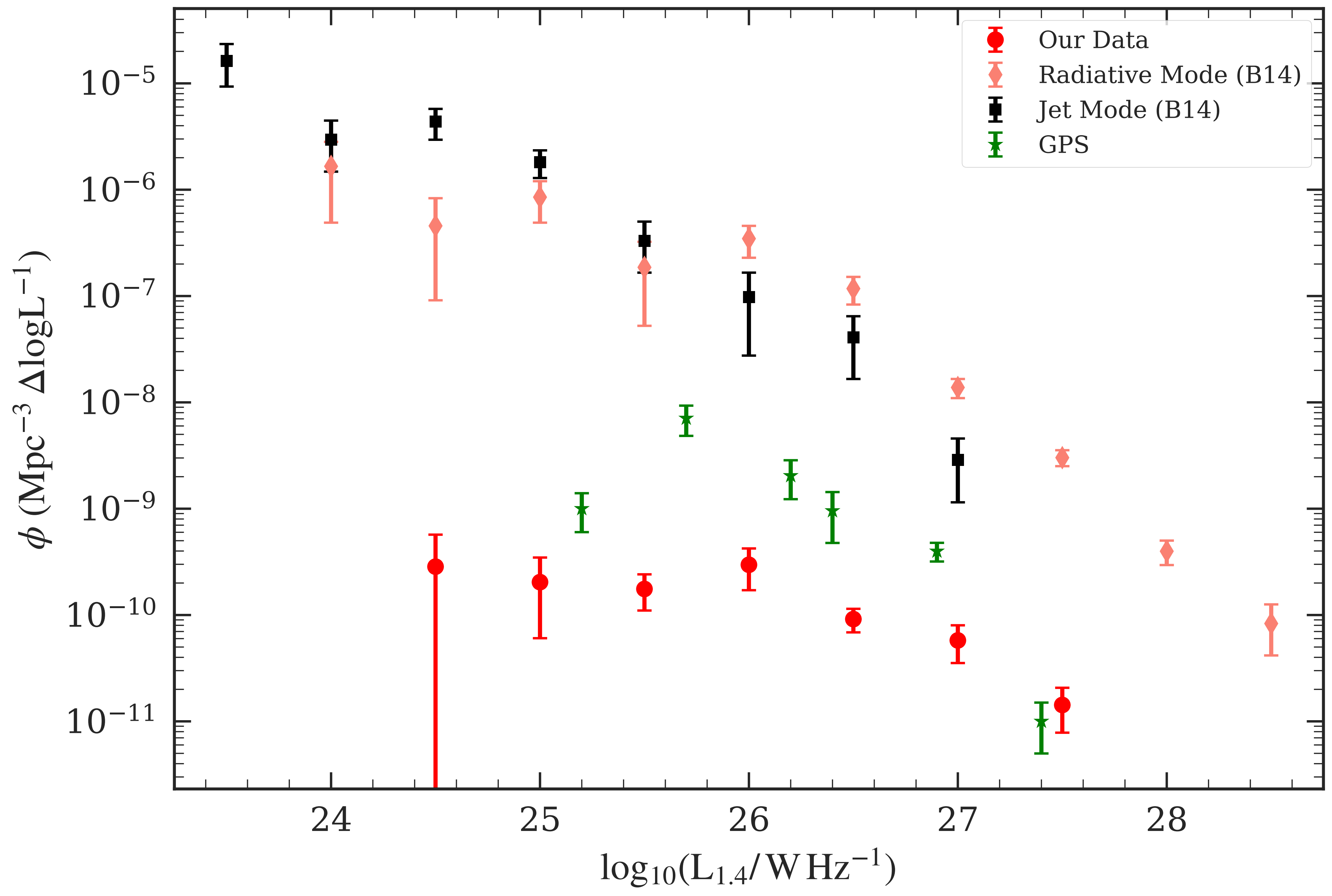


Errors on α_{IB} are below 0.1 for S/N $\gtrsim$ 70

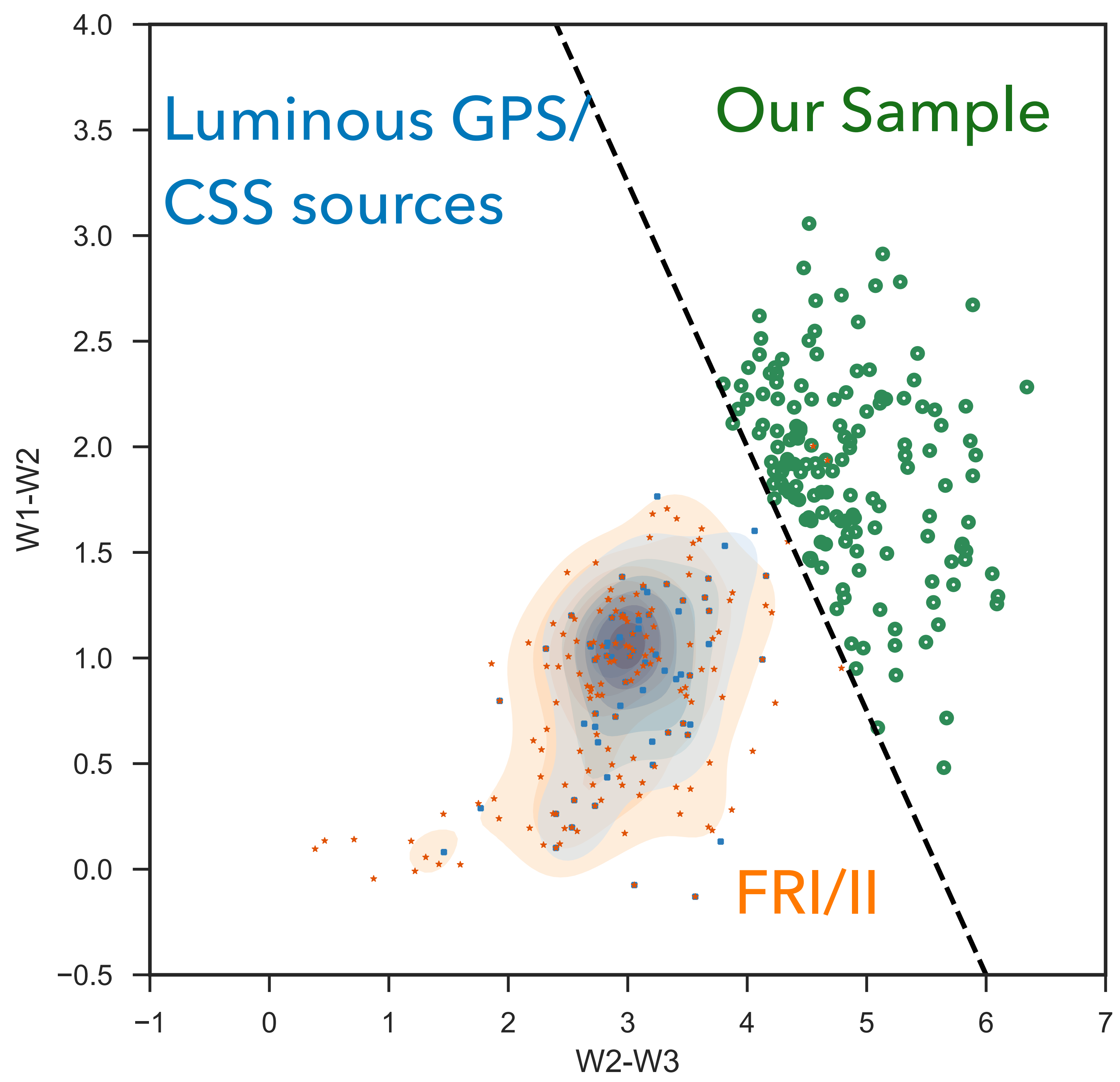
Median index is -1.0

RADIO LUMINOSITY FUNCTION

1.4 GHz Radio Luminosity Function

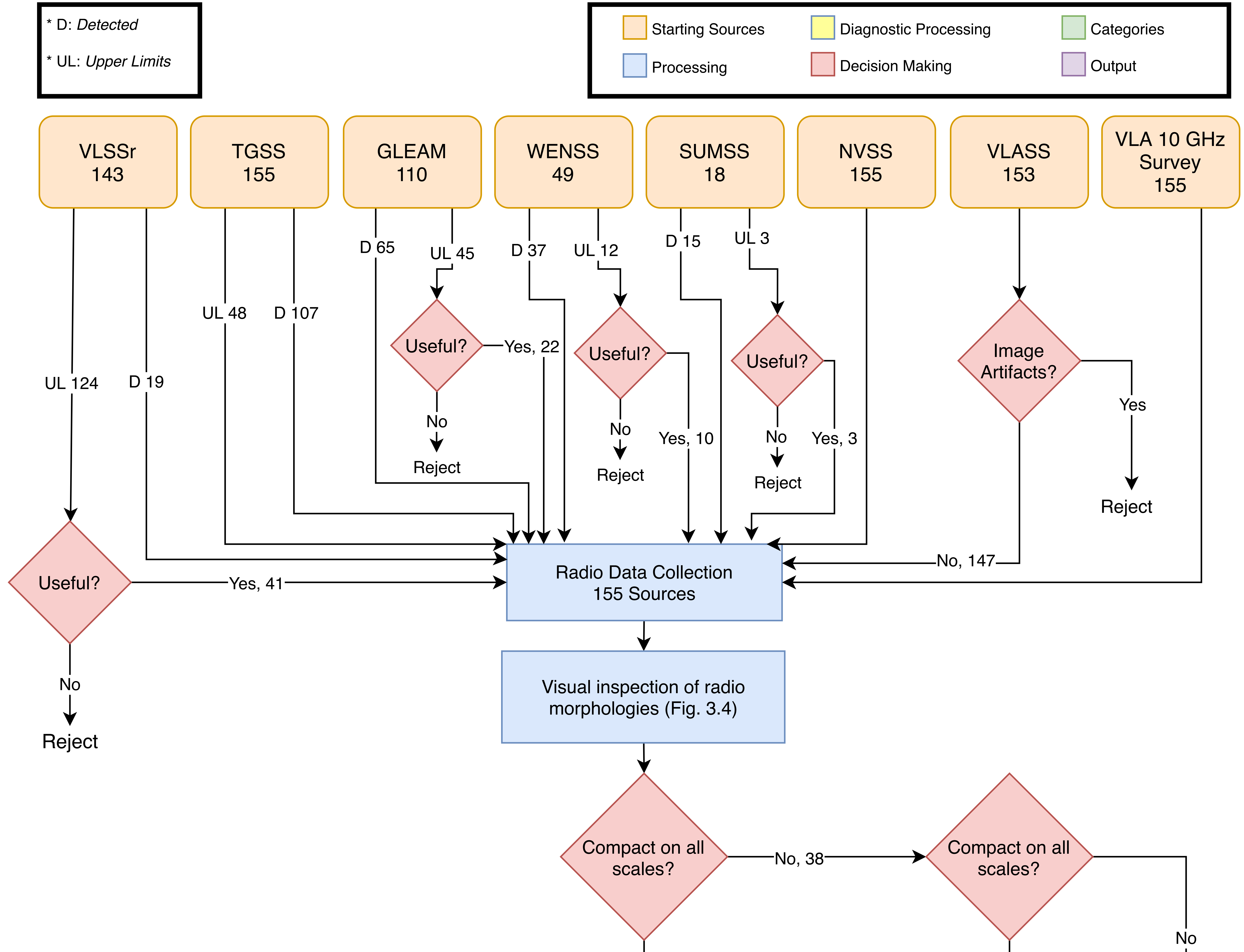


WISE Color-Color Plot



- Our MIR red sample is rare with ~10× lower space density than GPS, CSS sources and 1000× lower than radio AGN –> consistent with short lifetimes in obscured state.

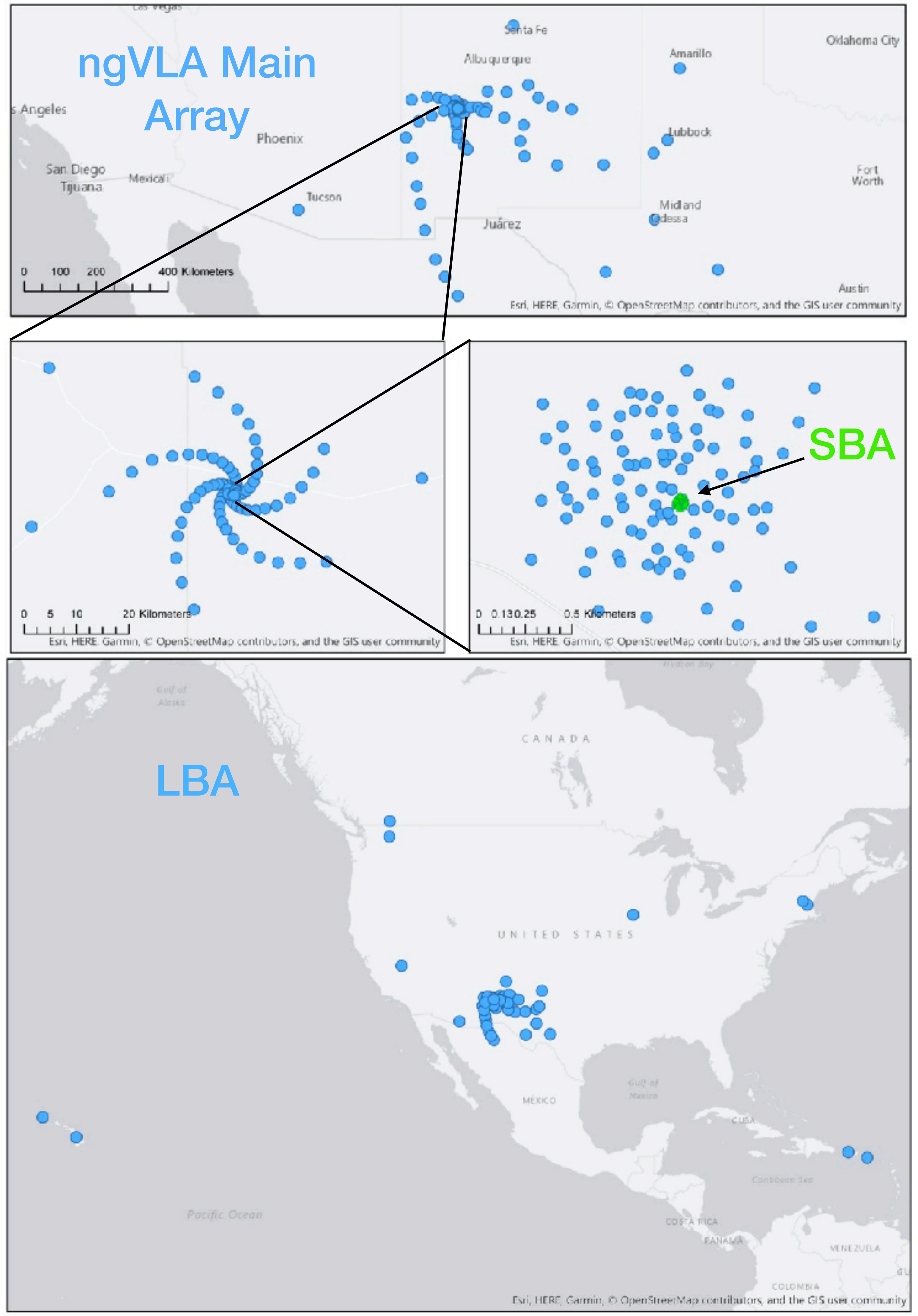
2. RADIO SPECTRAL ANALYSIS



RADIO SED FITTING: INTERACTIVE TOOL

FUTURE OUTLOOK: THE NEXT-GENERATION VERY LARGE ARRAY

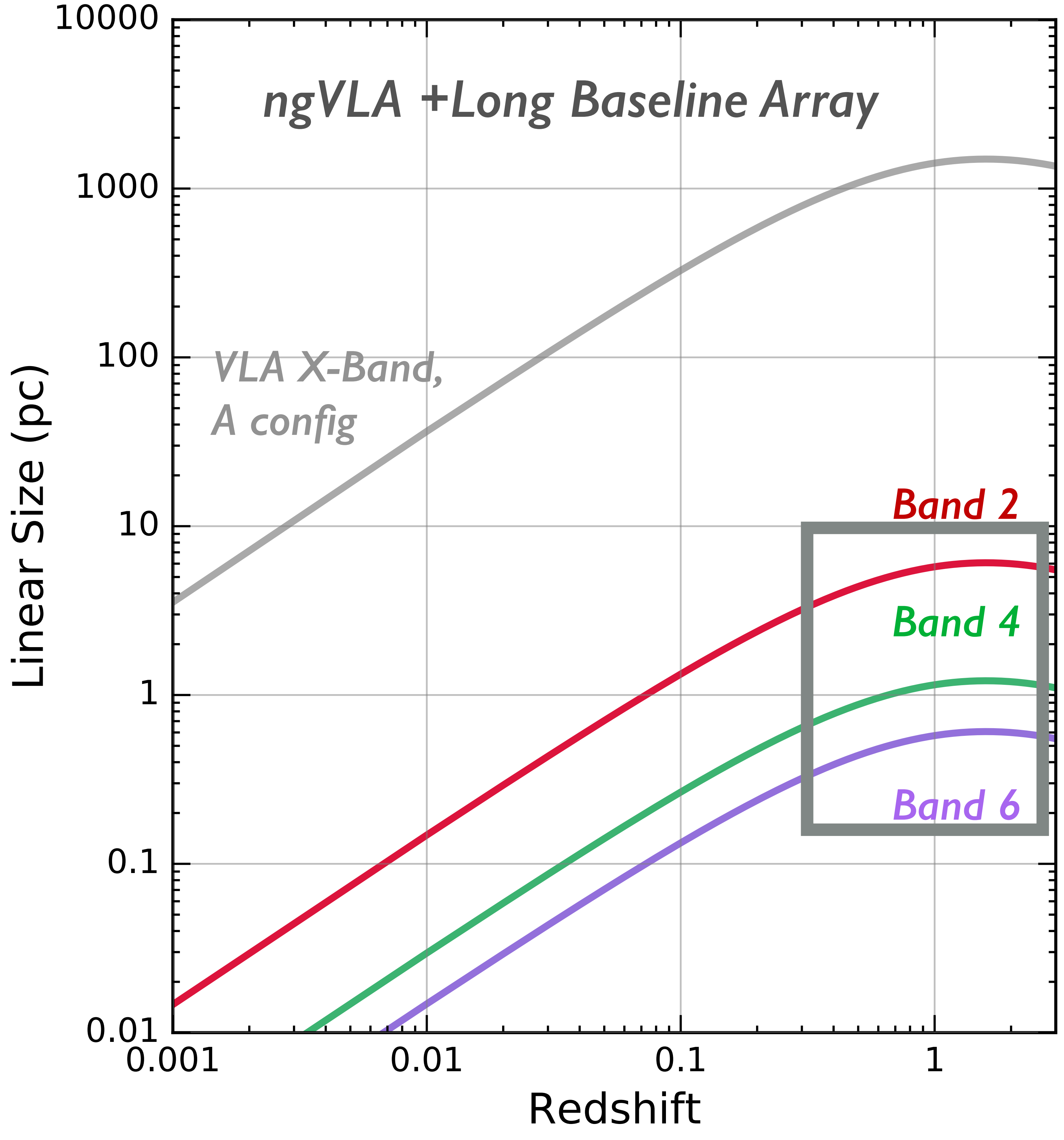
Reference Design



- Number of Antennas: ~ 214 (main) + 30 (LBA)
- Frequency Range: 1-116 GHz (detailed radio spectra)
- Resolution: 0.5-44 mas (main) + 0.06-5 mas (LBA)

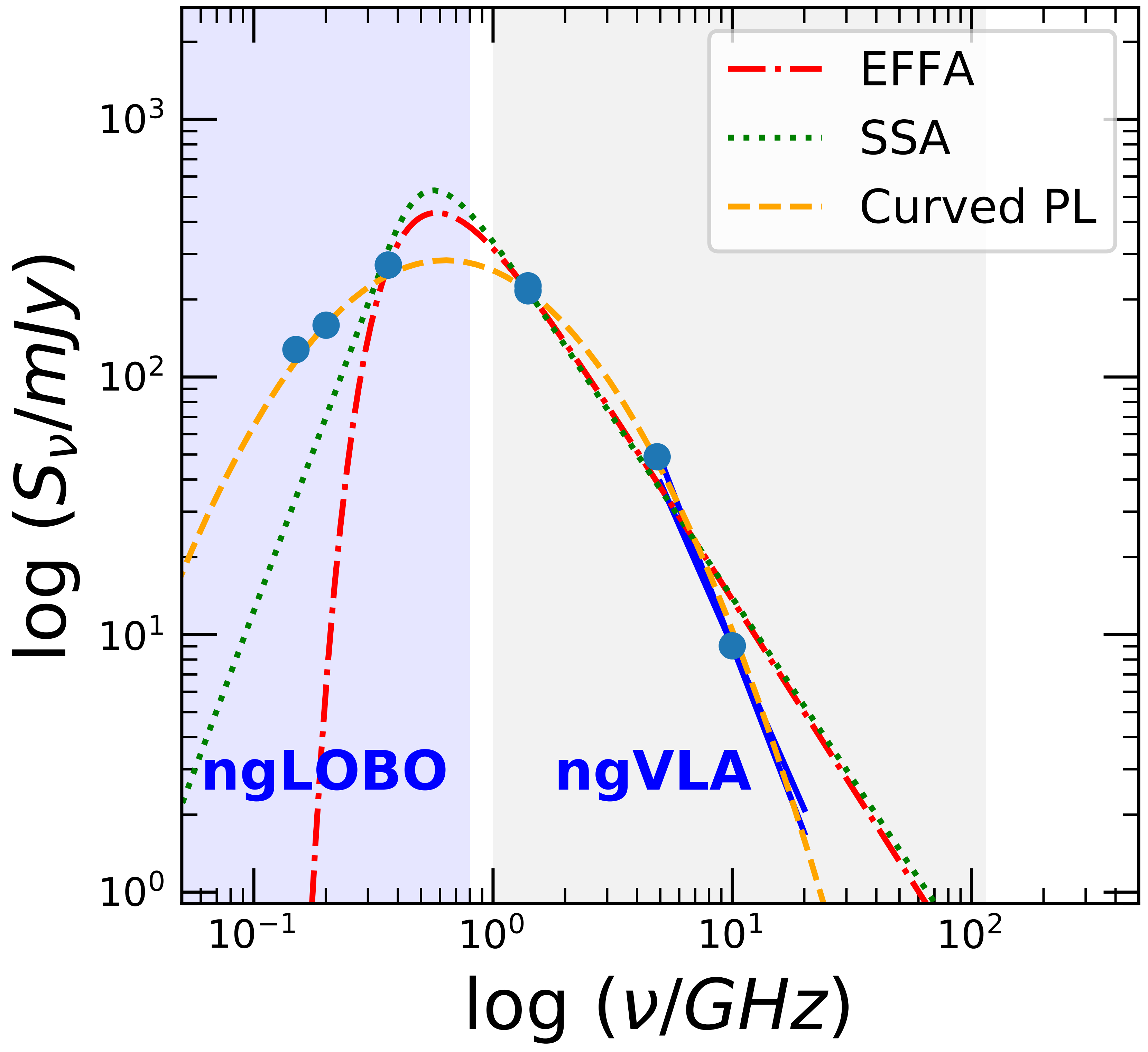
YOUNG RADIO AGN IN THE ngVLA ERA

- Map inner kpc scales with 10x better sensitivity
- Robustly characterize spectral turnover



Nyland, Patil+2018

Spatial and spectral mapping of pc-scale jets over z ~ 1-3



Patil et al. 2018, ASPC, 517, 595