U.S. NAVAL RESEARCH LABORATORY

VaDAR: Varstrometry for Dual AGN using Radio interferometry

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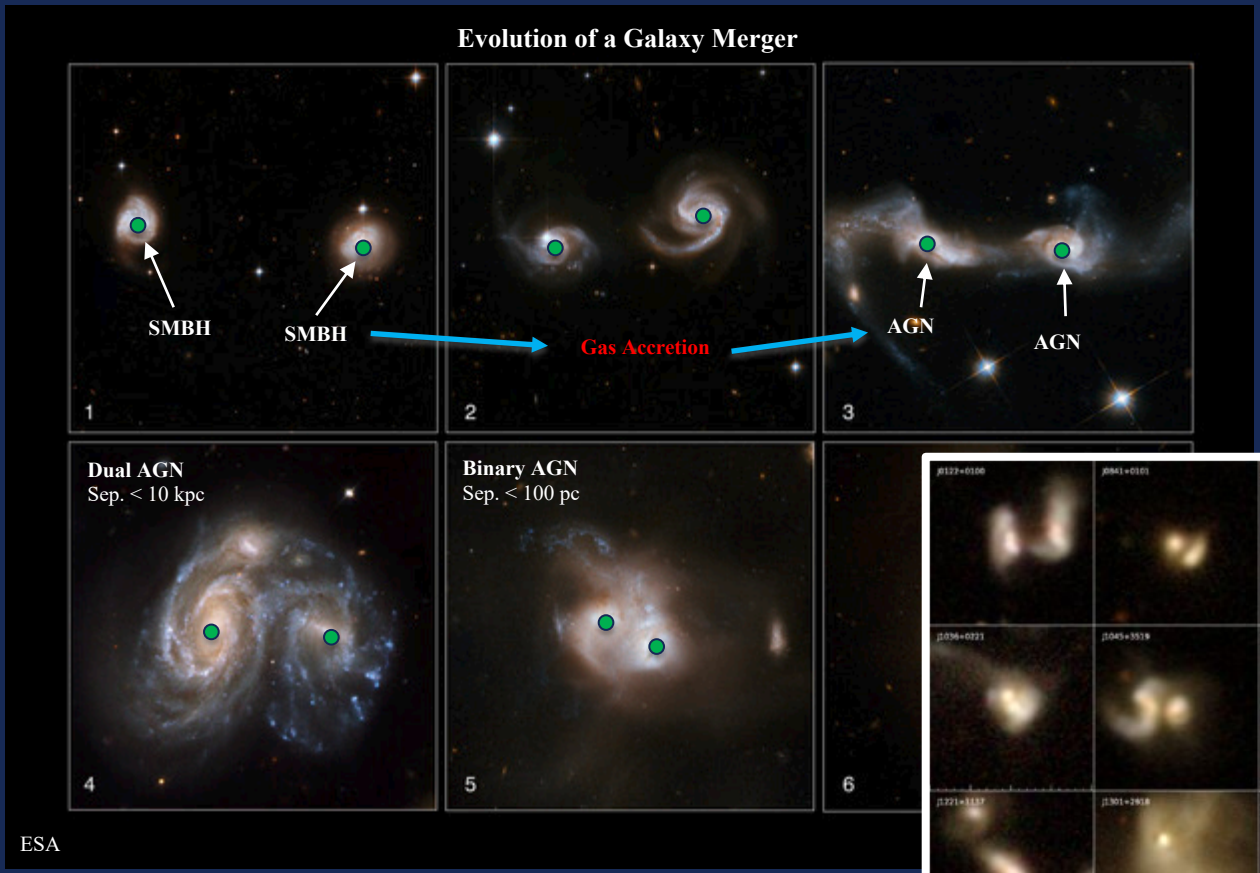
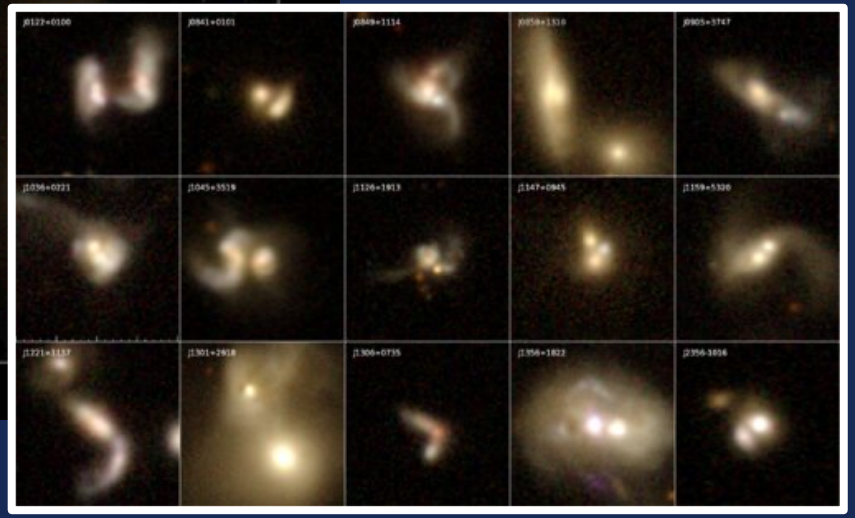
Collaborators: Tracy Clarke, Kristina Nyland, Nathan Secrest, Ryan Pfeifle, Henrique Schmitt, Shobita Satyapal, Barry Rothberg, Paula Fudolig

College of Science



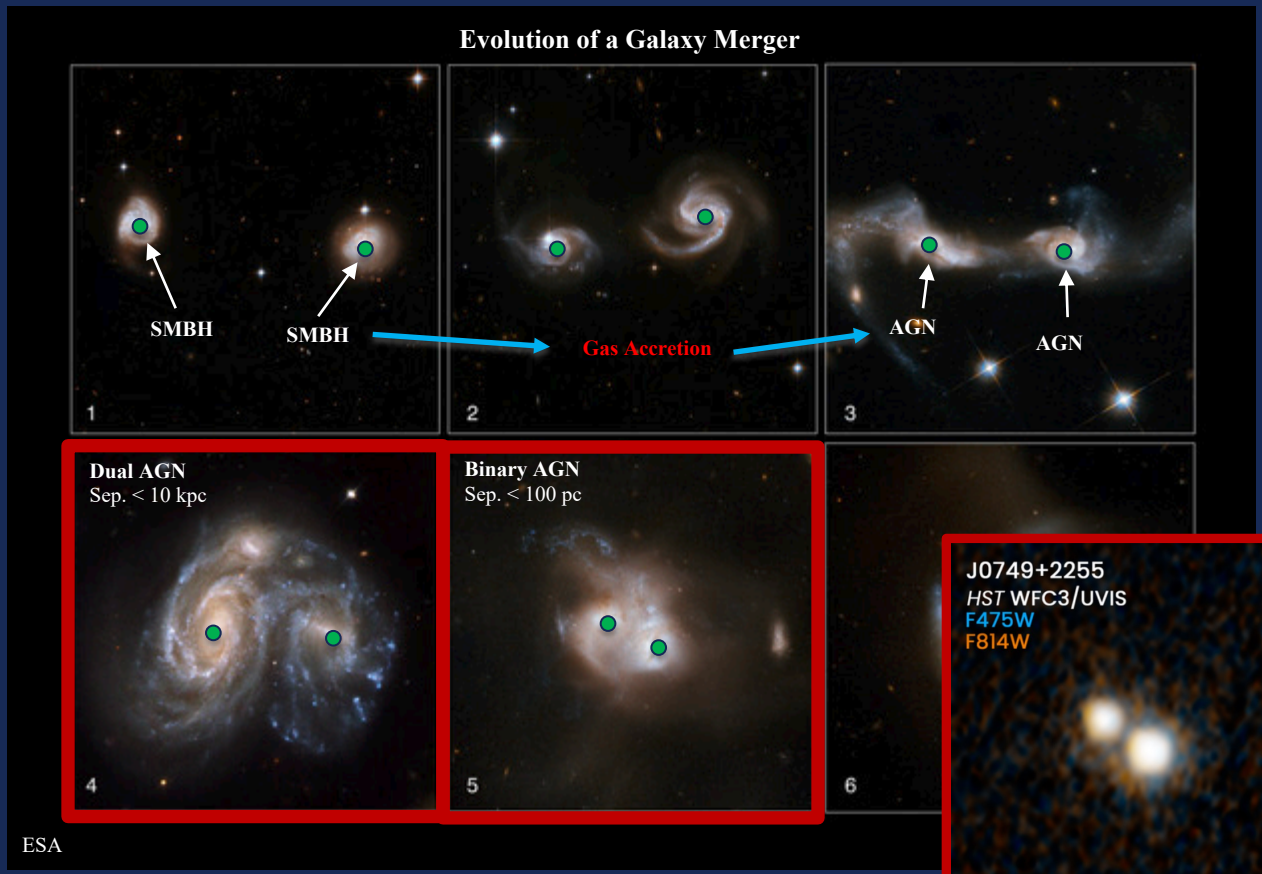
Galaxy mergers can result in pairs of gravitationally-bound supermassive black holes.

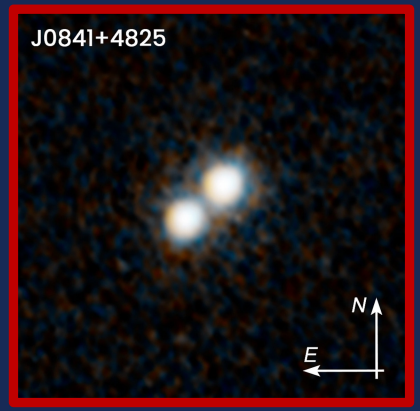


Pfeifle et al. 2019

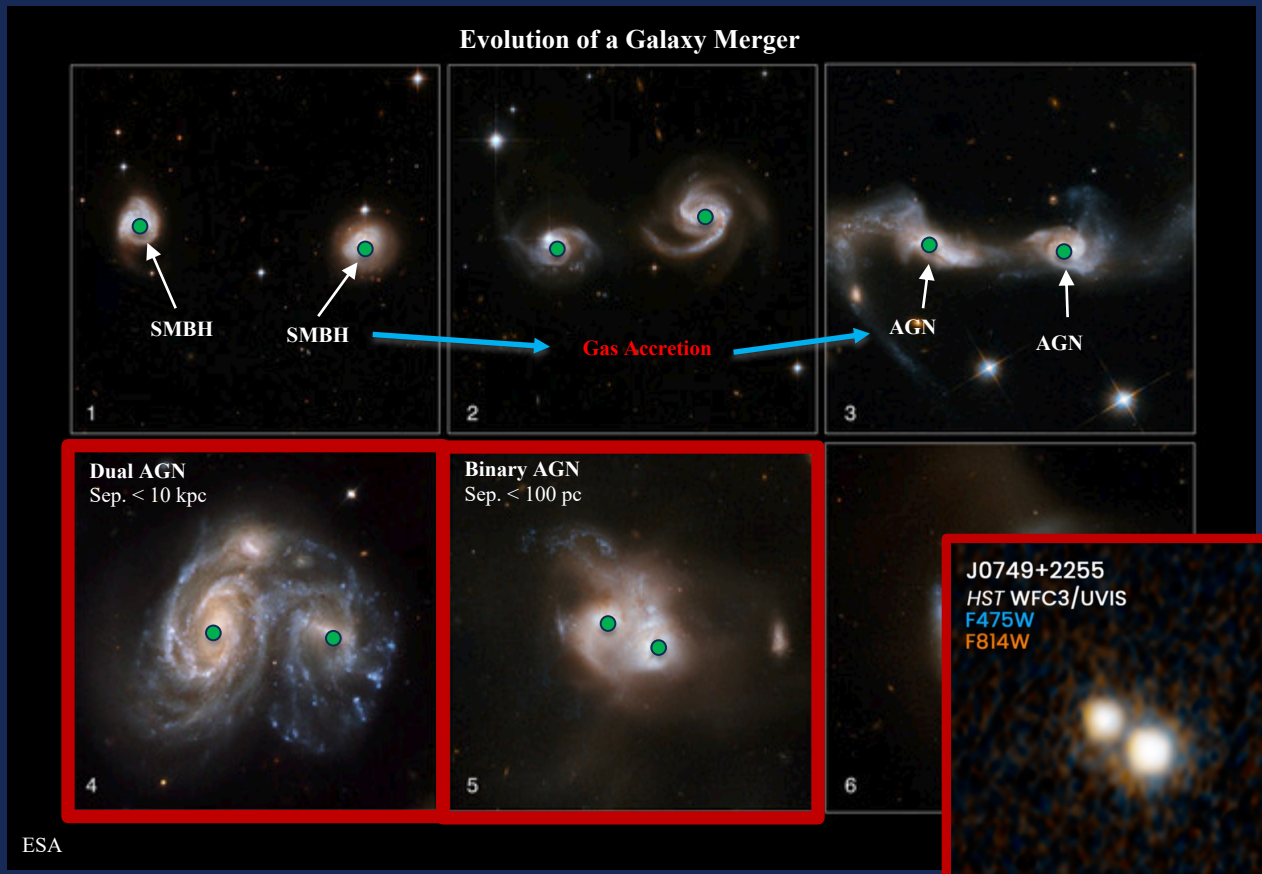
Multi-AGN Systems:

~100 confirmed duals
1 confirmed binary
(Rodriguez+07)





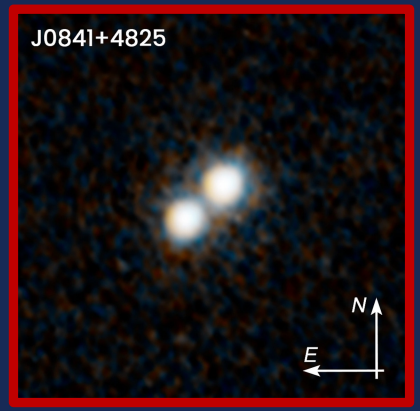
Hwang et al. ApJ. 2020.



Multi-AGN Systems:

What systematic methods exist for the detection of multi-AGN?

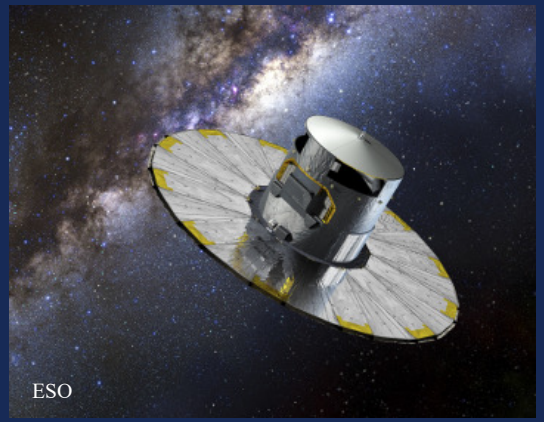
A new method pairs precise astrometric measurements with high-resolution radio observations.

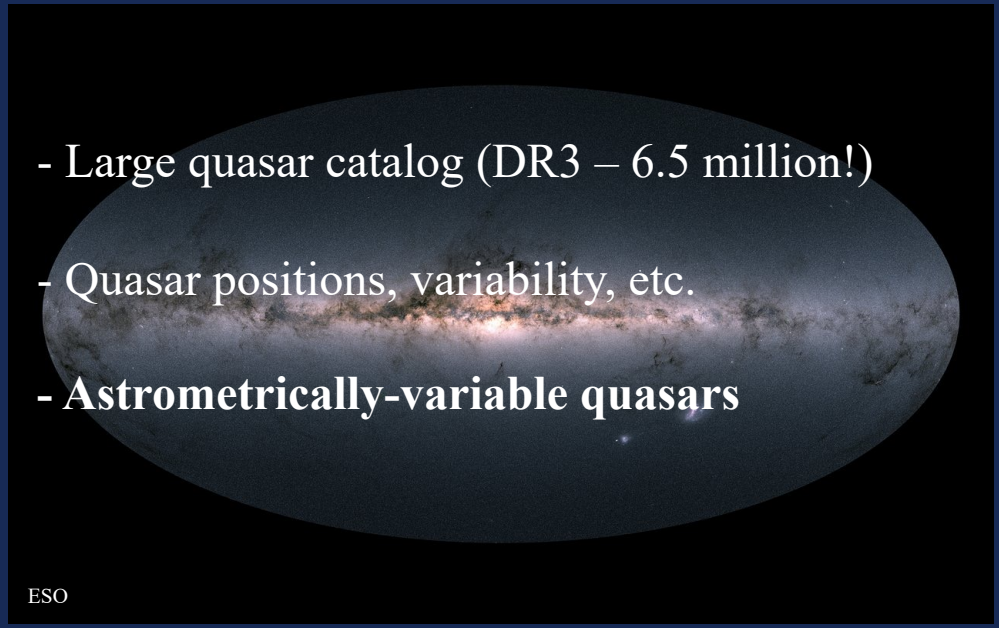


Hwang et al. ApJ. 2020.

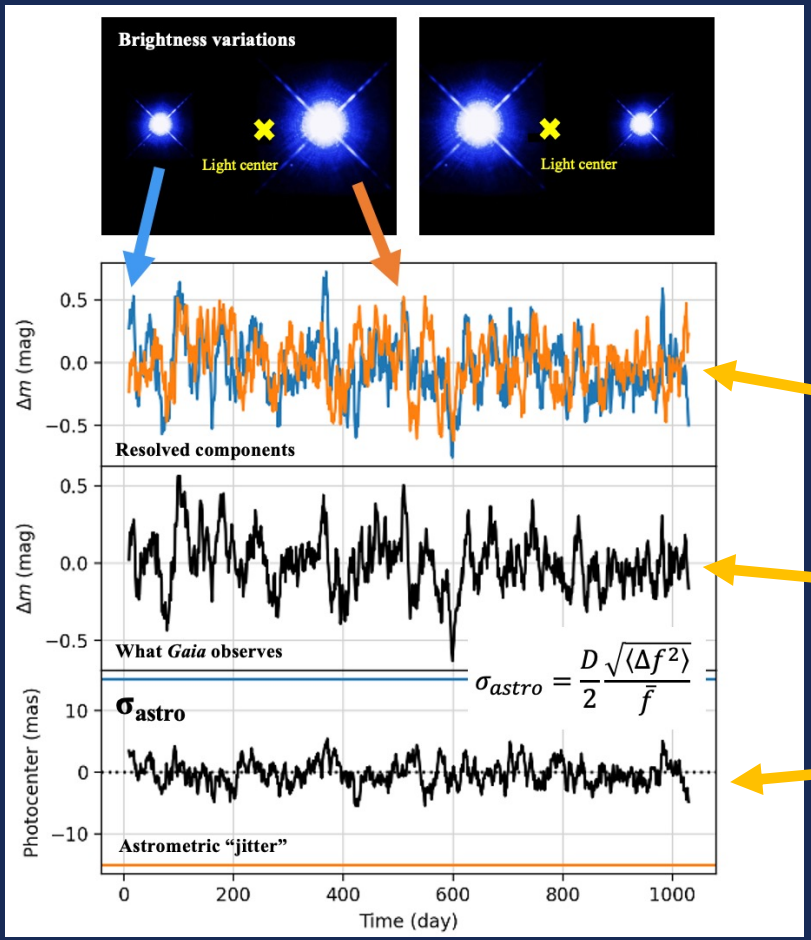
Gaia

Global astrometry space mission



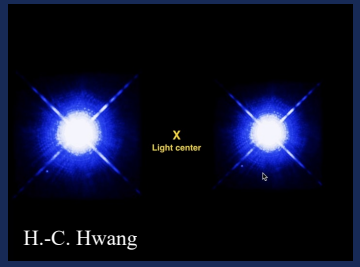


Sample of **astrometrically-variable quasars**:
entirely new method for identifying AGN pair systems



N. Secrest – private communication

AGN pair, unresolvable with *Gaia,* light center appears to shift



If it was resolvable with *Gaia,* we might observe a lightcurve for both AGN

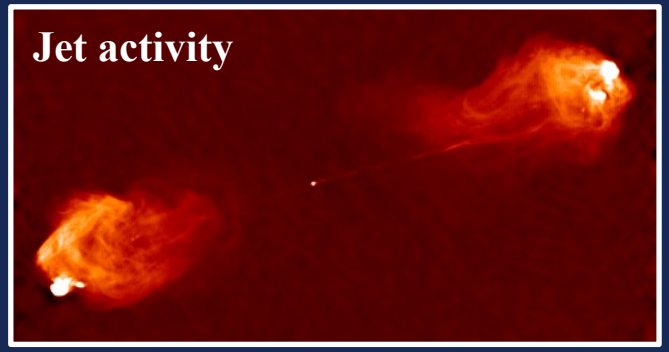
Instead, we see a joint-variability lightcurve, indistinguishable from a slightly variable single AGN

Shifting light center manifests in astrometric data – excess "jitter" in astrometry

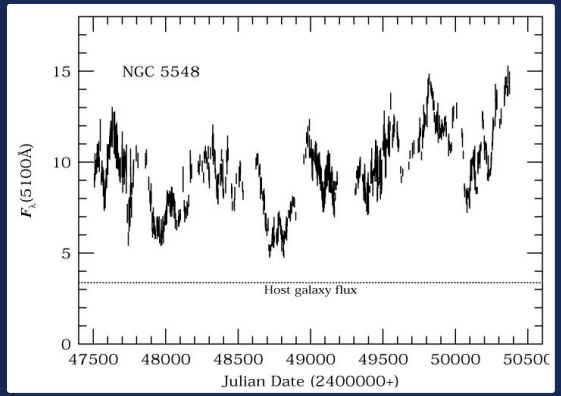
Variability + astrometry = **varstrometry!**

Hwang et al. 2019

Drivers of Astrometric Variability

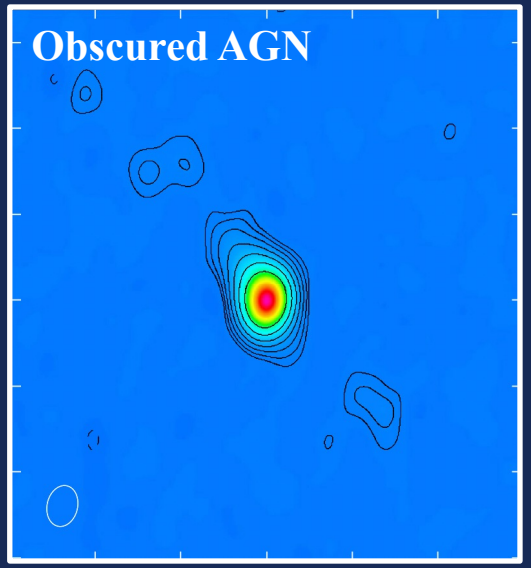


NRAO/AU



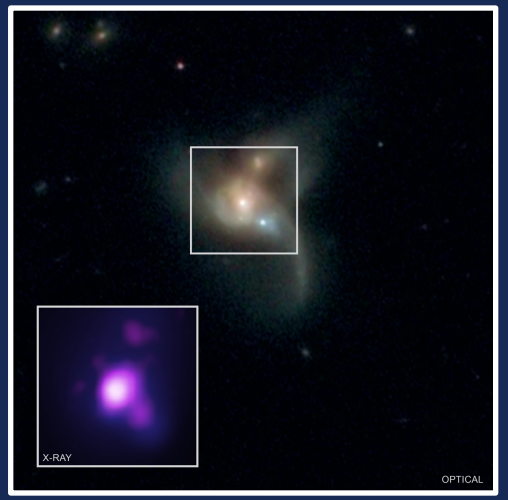
Peterson et al. 1999

Single AGN Variability



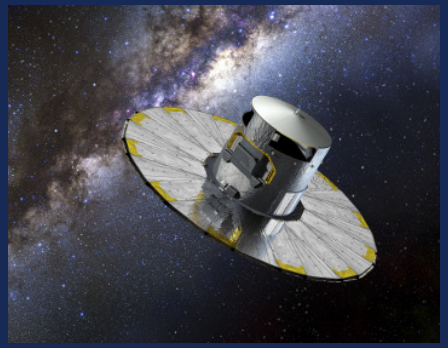
Hernandex-Garcia et al. ApJ. 2019.

AGN Pairs



Pfeifle et al. ApJ. 2019.

Radio Varstrometry



ESO/*Gaia*

+

NRAO/*VLA*

VaDAR: Varstrometry for Dual AGN using Radio interferometry

Combining high-resolution radio interferometry with high-precision astrometric variability measurements

Is the VaDAR method a possible systematic method for future searches for multi-AGN?

Can this method produce a population of multi-AGN in a new redshift/separation regime?

What are the properties of the sample selected by VaDAR?

VLA Observations

Sample:

18 quasars (SDSS DRQ16), cross-matched with *Gaia* EDR3 (within 1.5")

- *astrometric_excess_noise_sig* > 5
- z > 0.5
- *Gaia* G magnitude < 20

=148 QSO

- radio survey catalog fluxes
  - -VLASS, VLITE, etc.

=18 QSO

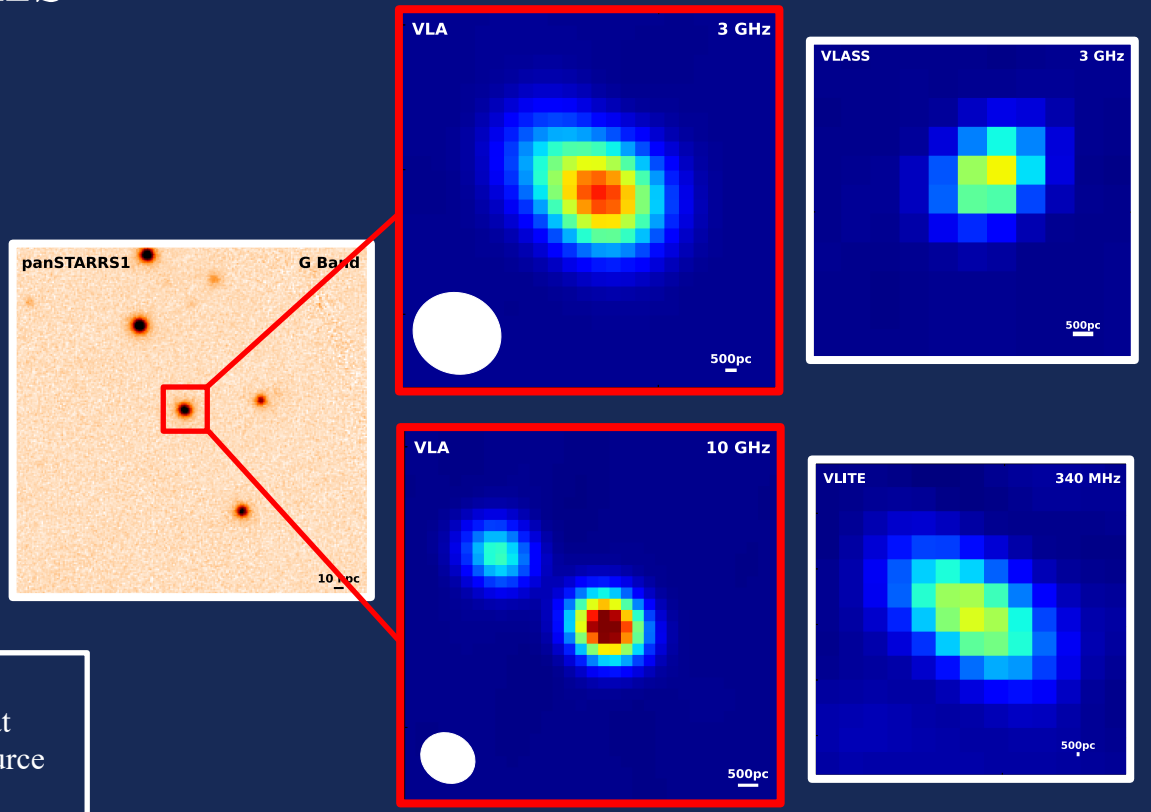
Observations:

VLA – A configuration

S-band (2-4 GHz, 0.65", LAS 18")

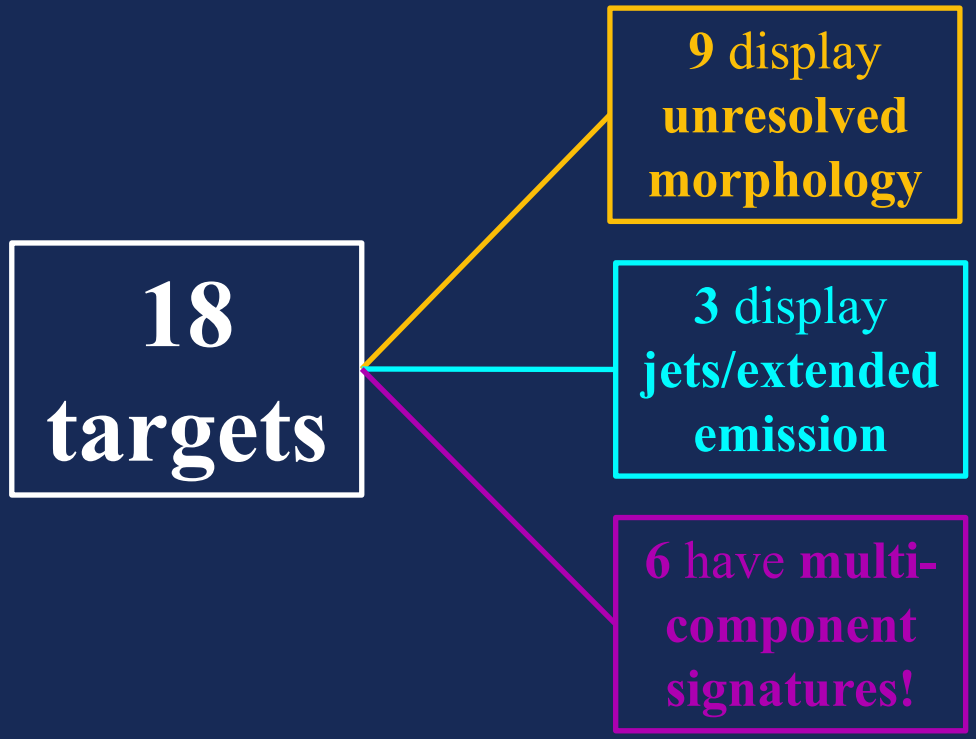
X-band (8-12 GHz, 0.2", LAS 5")

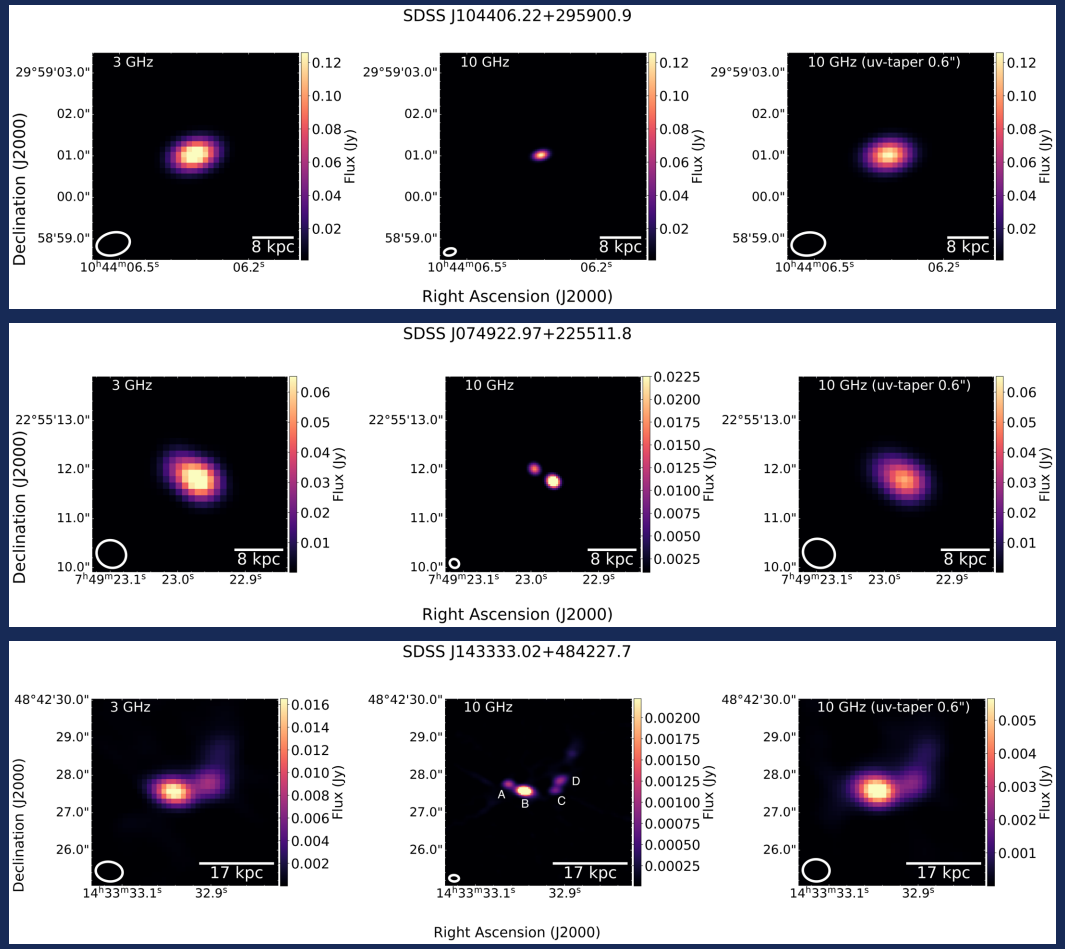
Astrometric excess noise: amount of statistical dispersion required such that *Gaia*'s astrometric solution for the source leaves no unexplained variance.



Schwartzman et al. in prep

Morphology Results:



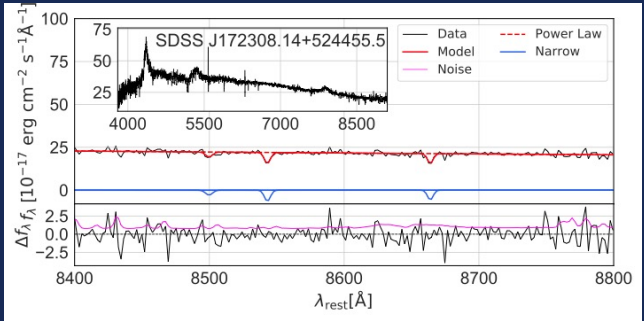


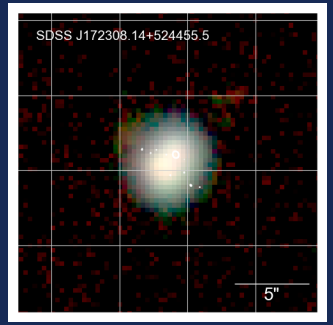
9 display **unresolved morphology**

6 have **multi-component signatures!**

3 display **jets/extended emission**

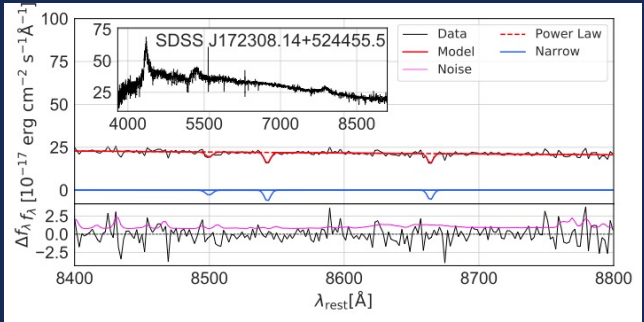
Schwartzman et al. 2023

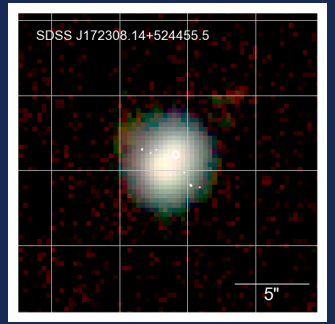




Contaminants:

4 Star+quasar superposition

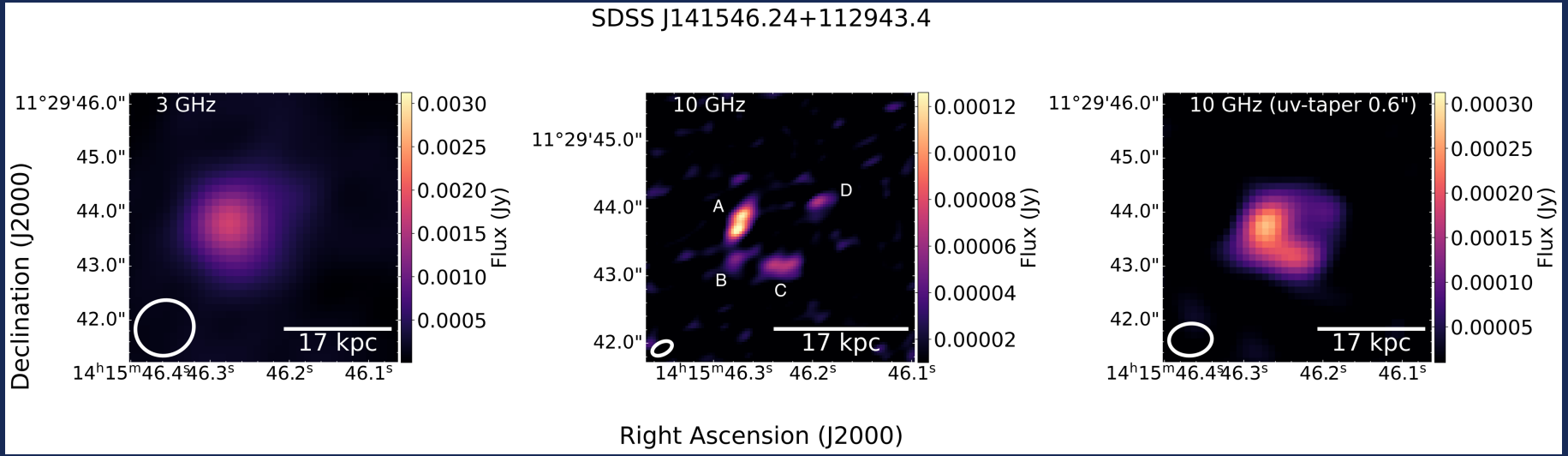




Contaminants:

4 Star+quasar superposition

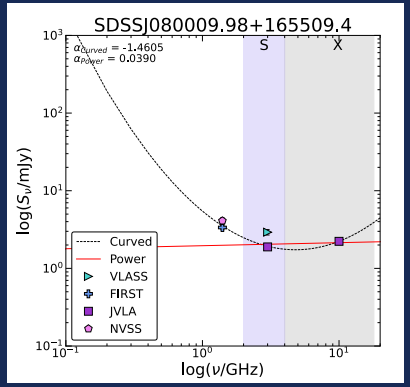
4 Gravitational lenses

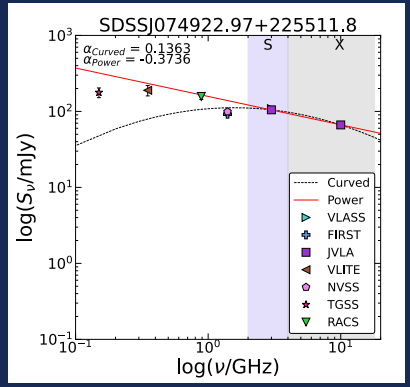


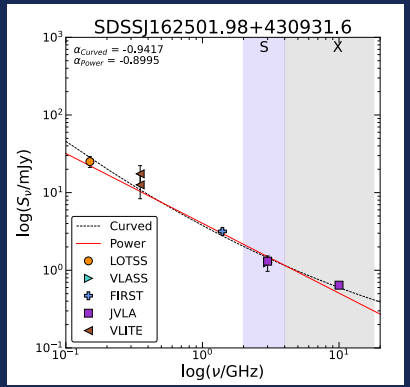
Schwartzman et al. 2023

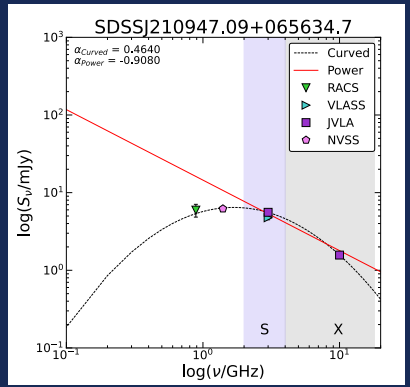
Radio Spectra

- Considerable existing survey data:
  - VLASS, RACS, LOTSS, NVSS, FIRST, TGSS, VLITE, etc.
- Spectra fitted with standard and curved power laws
  - Pallavi Patil's *radio_spectral_fitting* code (Patil+22)









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- Spectra fitted with standard and curved power laws
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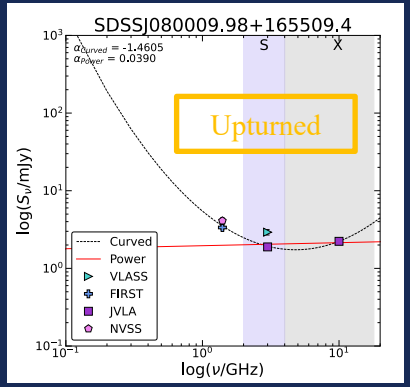
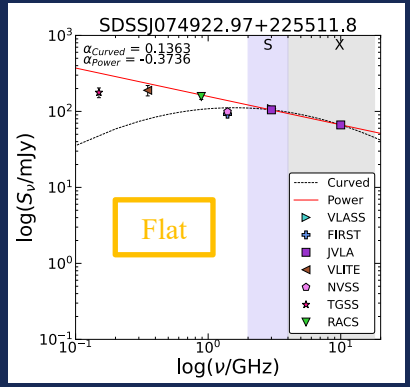
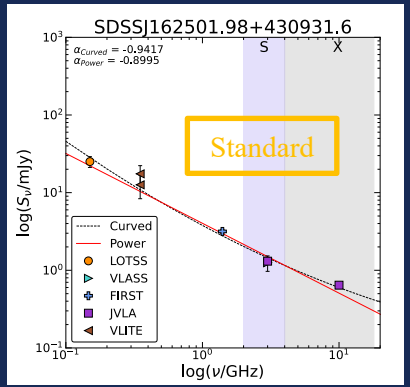
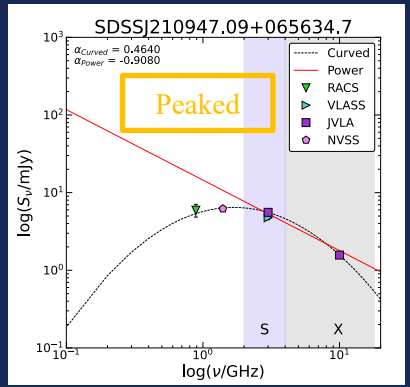
- Spectral shapes classified:

Standard Power Law: 4
Curved Power Law: 5
Peaked: 2
Flat: 3
Upturned: 4
Inverted: 0





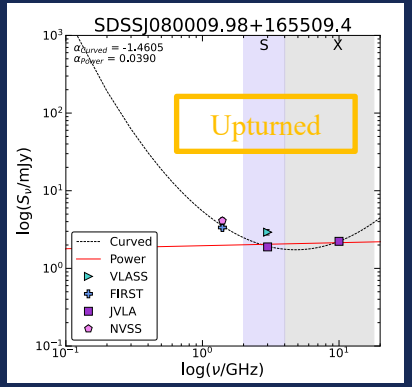


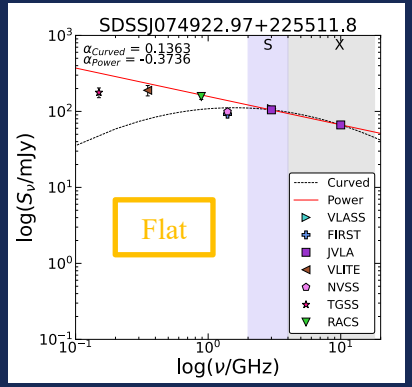


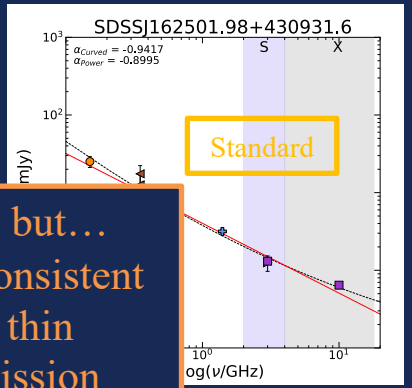
Radio Spectra

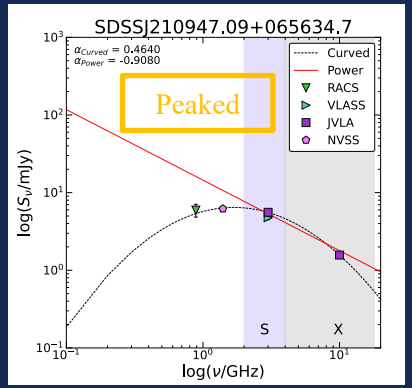
- Considerable existing survey data:
  - VLASS, RACS, LOTSS, NVSS, FIRST, TGSS, VLITE, etc.
- Spectra fitted with standard and curved power laws
  - Pallavi Patil's *radio_spectral_fitting* code (Patil+22)
- Spectral shapes classified:
  - Standard Power Law: 4
  - Curved Power Law: 5
  - Peaked: 2
  - Flat: 3
  - Upturned: 4
  - Inverted: 0

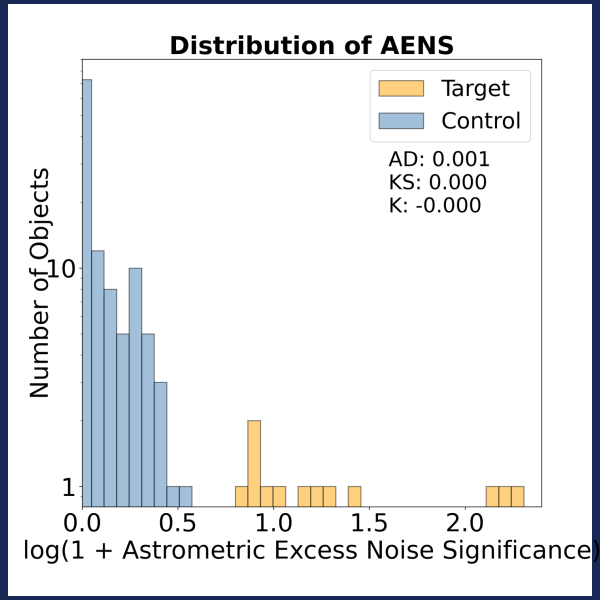
Diverse sample, but…
Spectral indices consistent with optically thin synchrotron emission

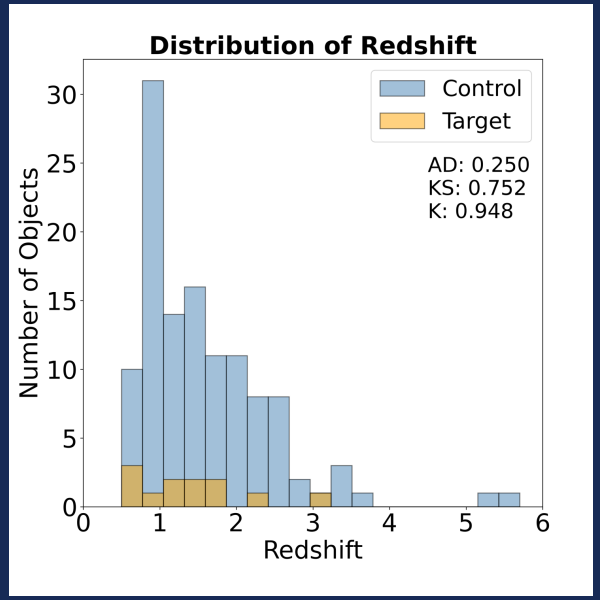


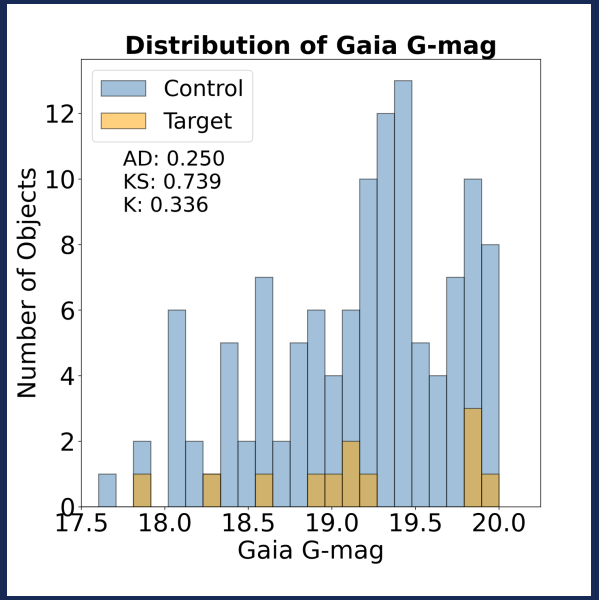












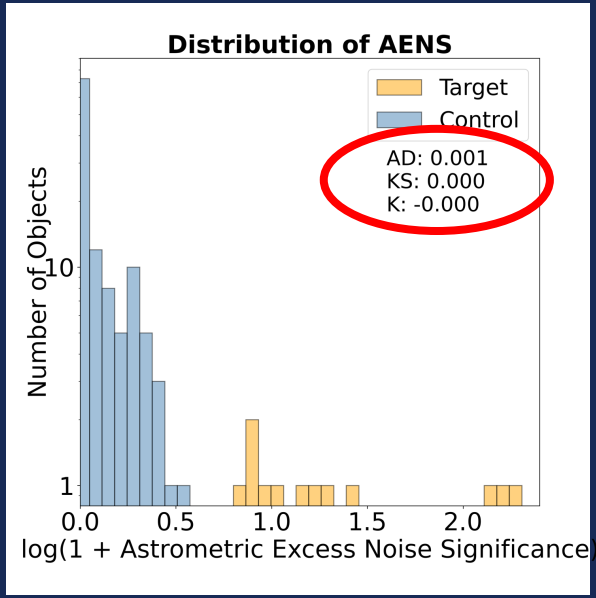
Schwartzman et al. 2023

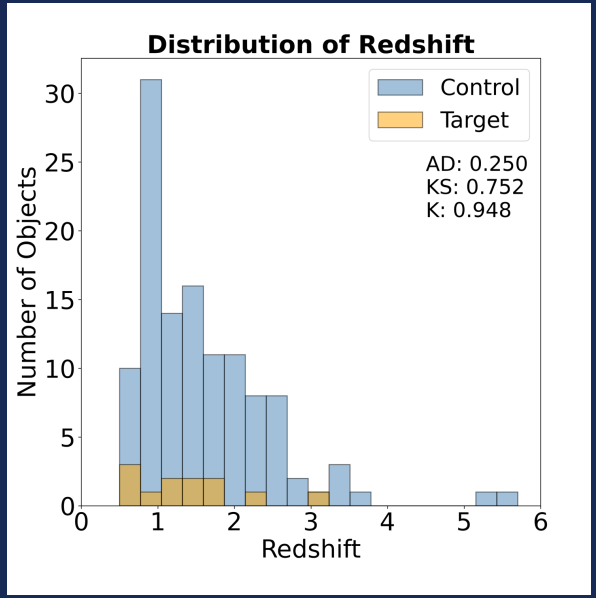
Targets: 12 objects with **AENS > 5**, G mag < 20, z > 0.5

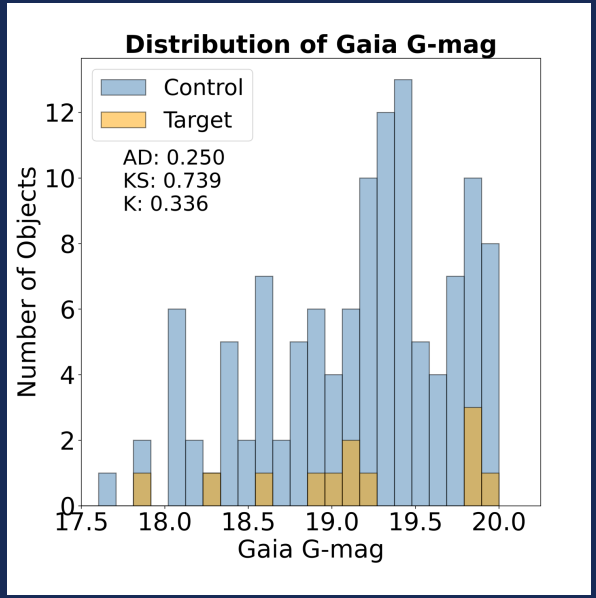
Controls: 120 objects with **AENS < 4**, G mag < 20, z > 0.5

i.e., no significant astrometric variability

Matched to targets based on sky coverage







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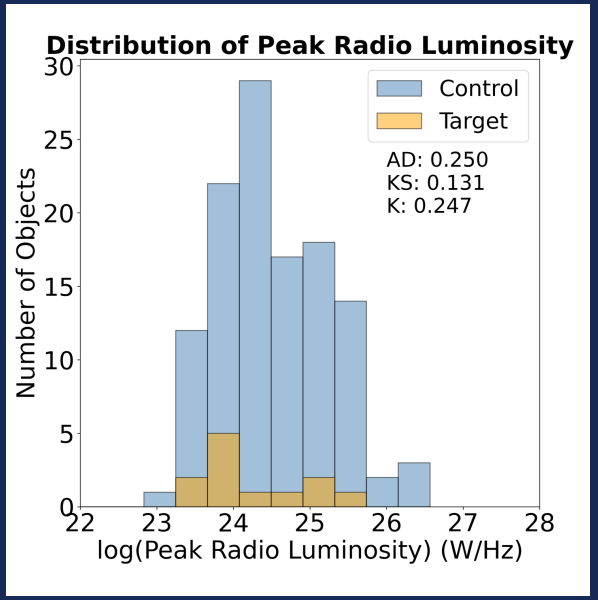
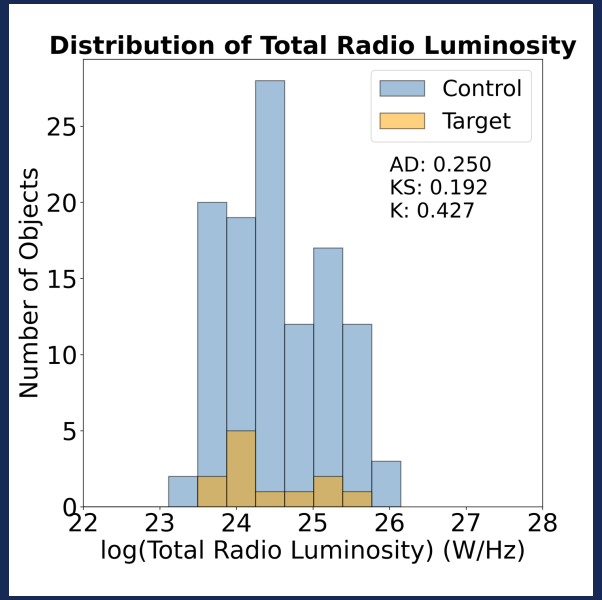
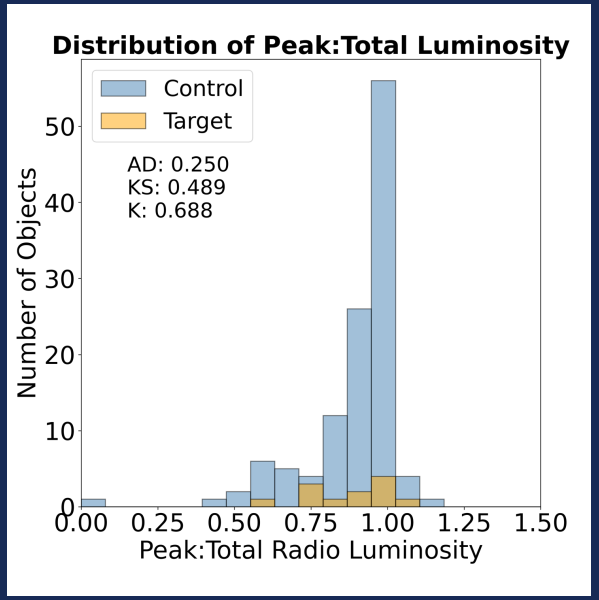
Matched to targets based on sky coverage

Samples are similar, save for AENS parameter







Schwartzman et al. 2023

Comparing important radio parameters…

Overall target sample is not significantly radio loud, in comparison to matched controls

Overall Sample Results:

18 targets

- **9** display **unresolved morphology**
- **3** display **jets/extended emission**
- **6** have **multi-component signatures!**

- **4** likely star+quasar superposition
- **4** identified as grav lenses
- Spectral indices consistent with optically thin synchrotron emission
- Overall target sample is not significantly radio loud, in comparison to matched controls

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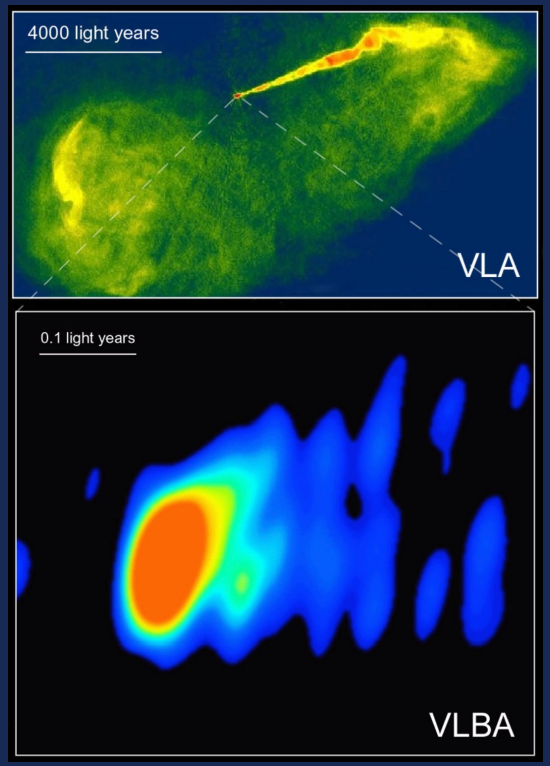
- **4** likely star+quasar superposition
- **4** identified as grav lenses
- Spectral indices consistent with optically thin synchrotron emission
- Overall target sample is not significantly radio loud, in comparison to matched controls
- **7** selected for VLBA follow-up

VLBA Follow-up



M87: NASA/NRAO

Sub-arcsecond scales

Sub-**milli**arcsecond scales

- Probe source structure on significantly smaller scales
  - small scale jets, binaries, etc.
- Contributes to overall sample classification

VLBA Observations

Sample:

18 quasars (SDSS DRQ16), cross-matched with *Gaia* EDR3 (within 1.5")

- *astrometric_excess_noise_sig* > 5
- z > 0.5
- *Gaia* G magnitude < 20

=148 QSO

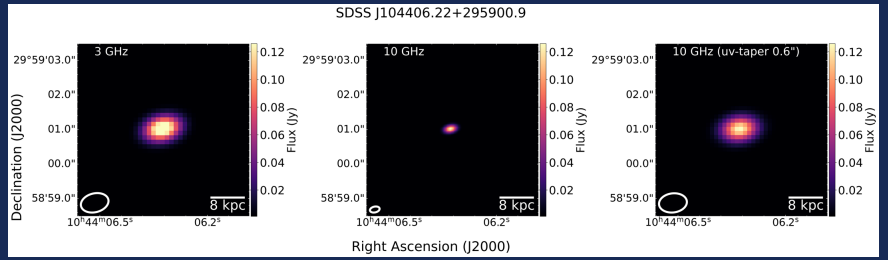
- radio survey catalog fluxes

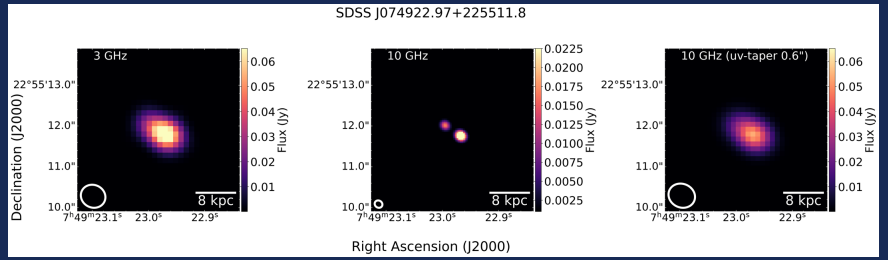
-VLASS, VLITE, etc.

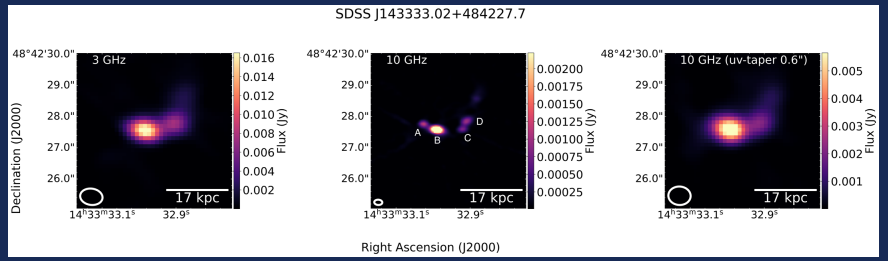
=18 QSO

VLBA follow up limited to targets with a VLA 3 GHz flux density **> 1 mJy**

= 7 QSO







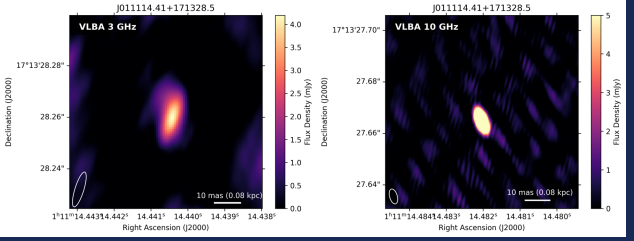
VLBA Observations

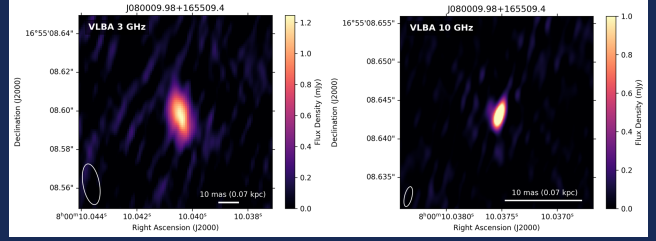
Source	Morphology	Spectral Shape
J0111	Multi-component	Flat
J0800	Unresolved	Upturned
J1215	Jet/Extended	Curved
J1433	Jet/Extended	Standard
J1625	Multi-component	Standard
J1723	Star+quasar	Upturned
J1733	Unresolved	Flat

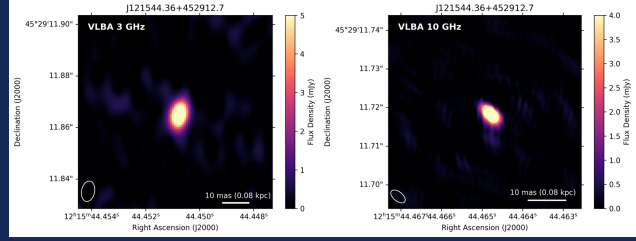
Preliminary calibration and imaging complete – work of **Paula Fudolig**, a first-year graduate student at GMU

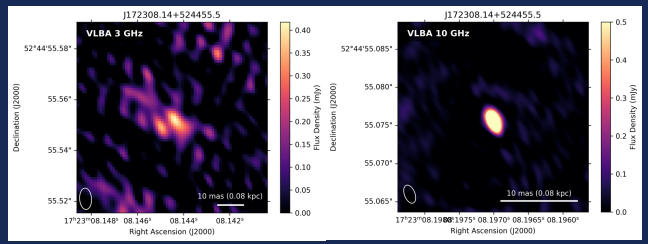
Final calibration is ongoing!

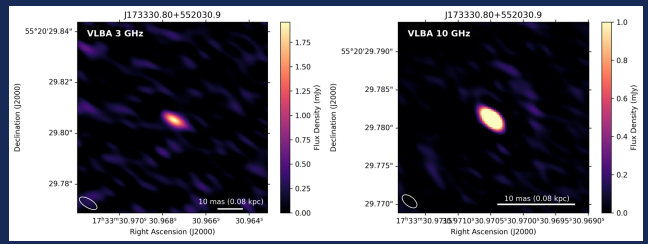
Observations:
S-band (2.2-2.4 GHz, 3.2 mas)
X-band (8.0-8.8 GHz, 0.85 mas)

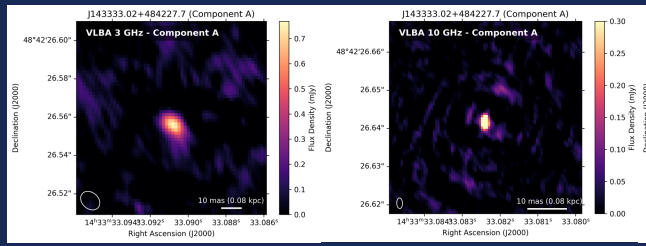


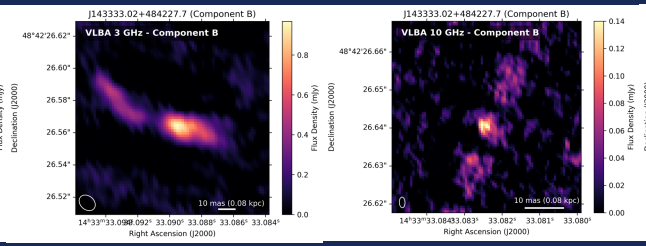


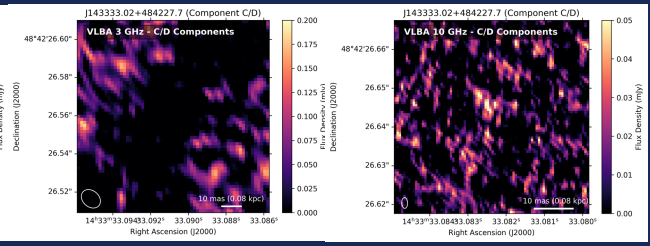


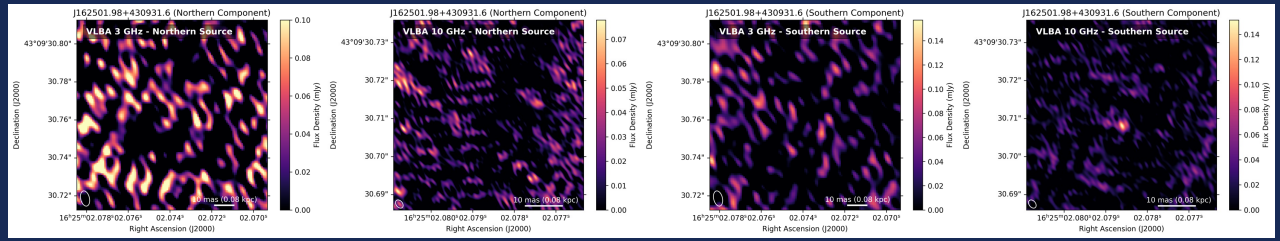












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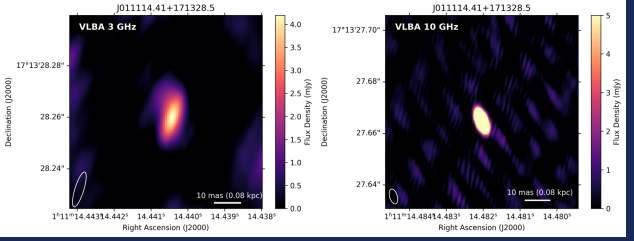
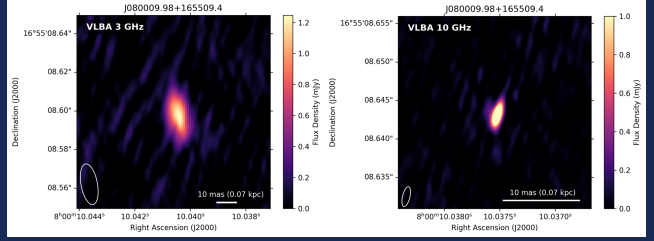
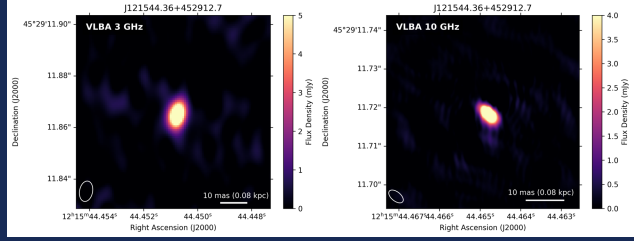
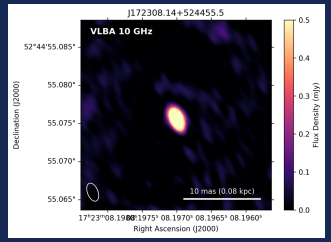
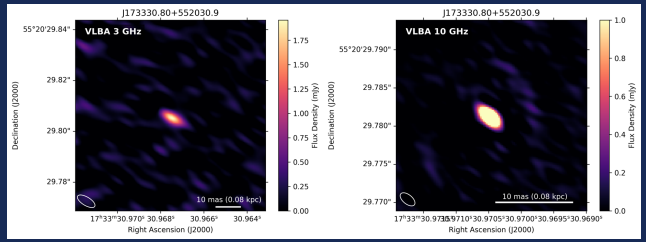
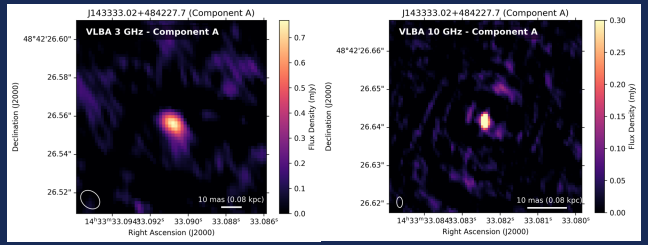




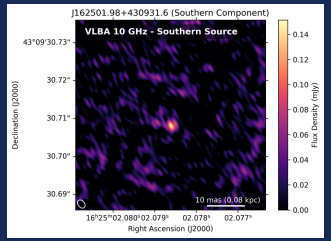




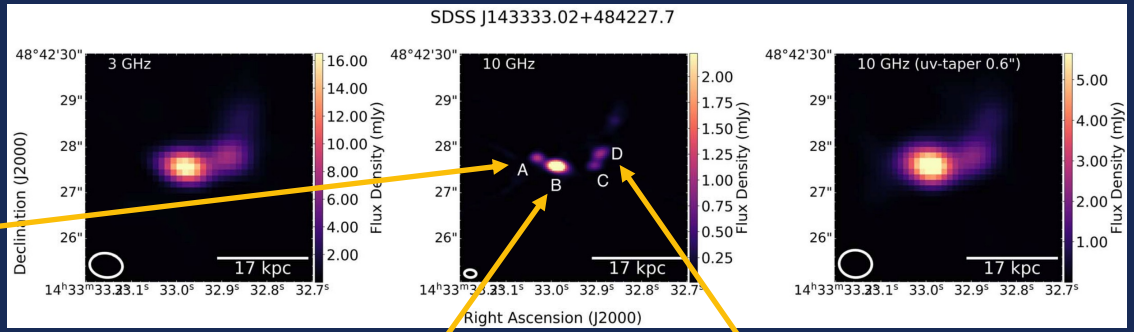


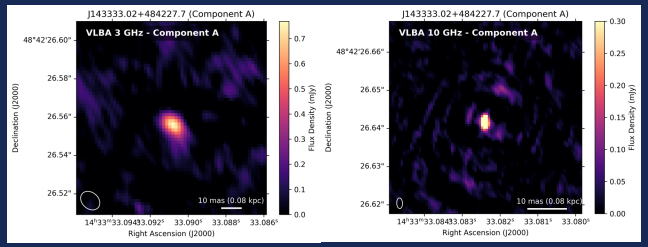


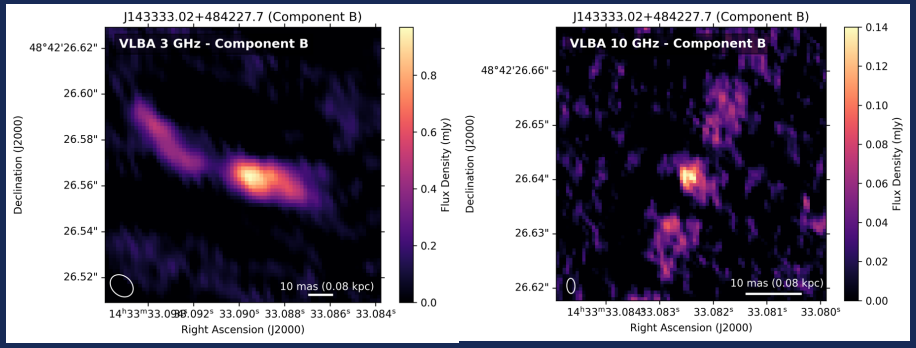
Mostly unresolved detections

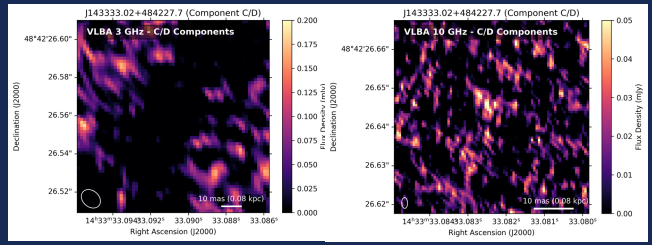


J1433:
- A: Unresolved detections

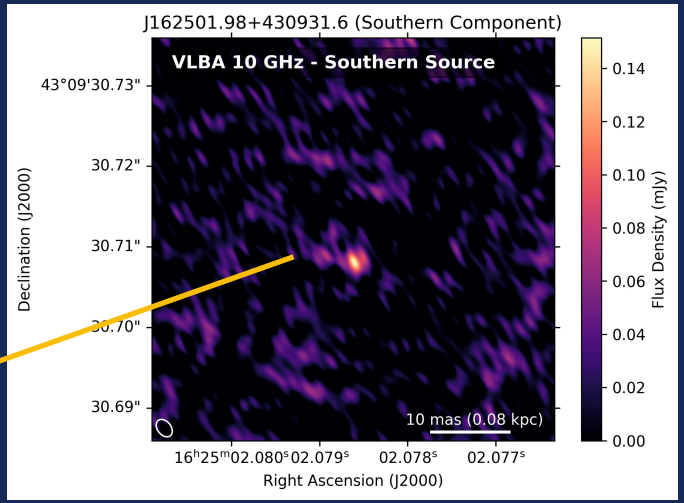


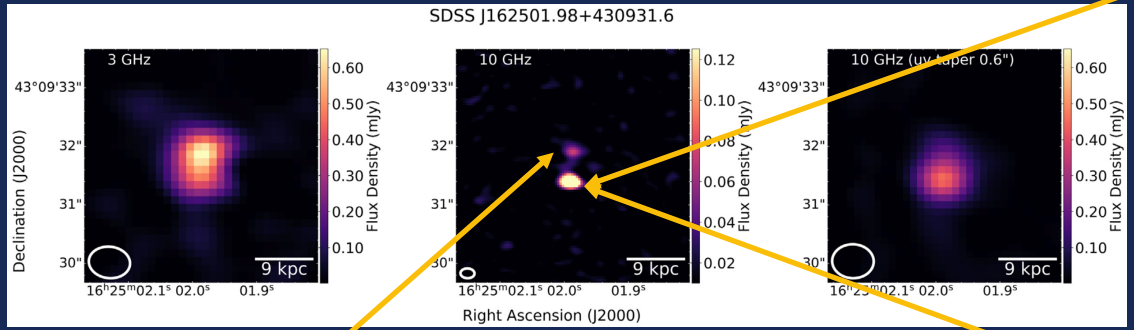


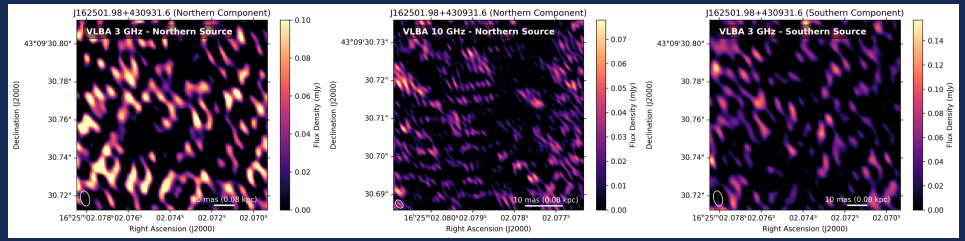




B: Extended emission
C/D: Non-detection



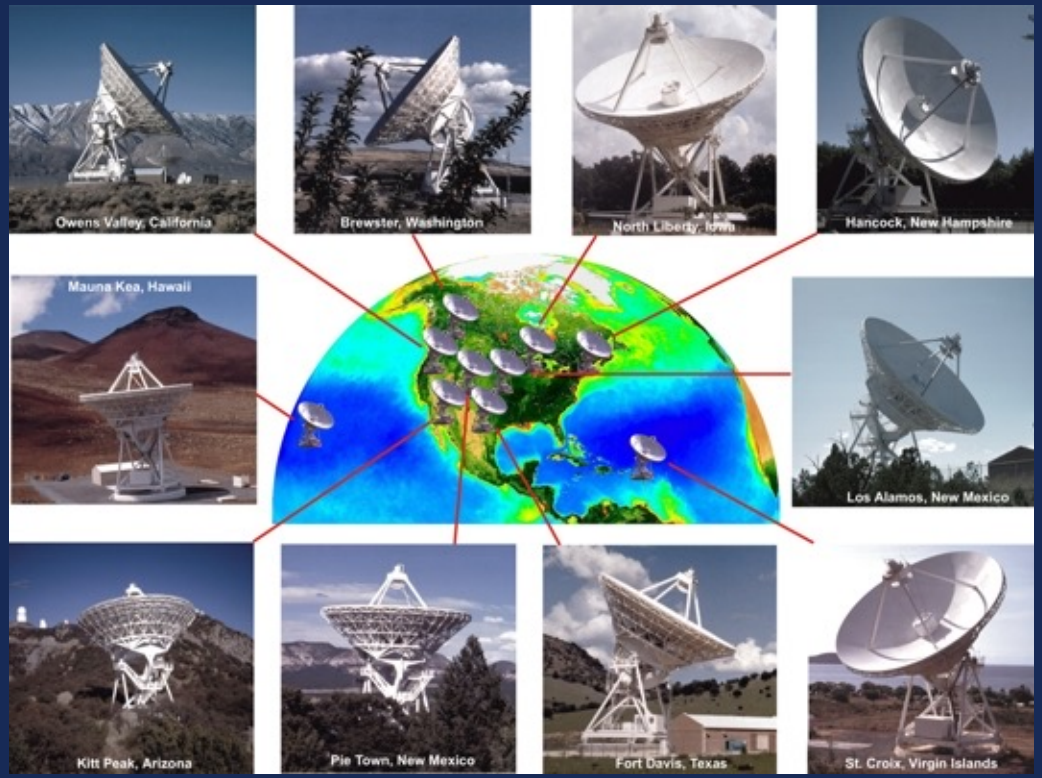




J1625:
Southern source –
detection at 10 GHz

VLBA Follow-up

- Calibration and imaging still in progress
- Interesting early results!
- Full sample published in later this year



Main Takeaways:

- VaDAR selects for a sample diverse in morphology and other radio properties
    - Diverse radio morphologies: 8 unresolved, 3 extended/jets, 6 multi-component
    - **44% either gravitational lenses or candidate dual AGN!**
    - 4 targets identified as gravitational lenses, 4 targets identified as star+quasar superposition
    - Spectral shape classification and spectral indices similarly diverse, though sample is majority optically thin synchrotron
- A study of the overall sample illustrated the likely lack of blazar overrepresentation
- VLBA calibration is ongoing, hoping for better smaller scale understanding