



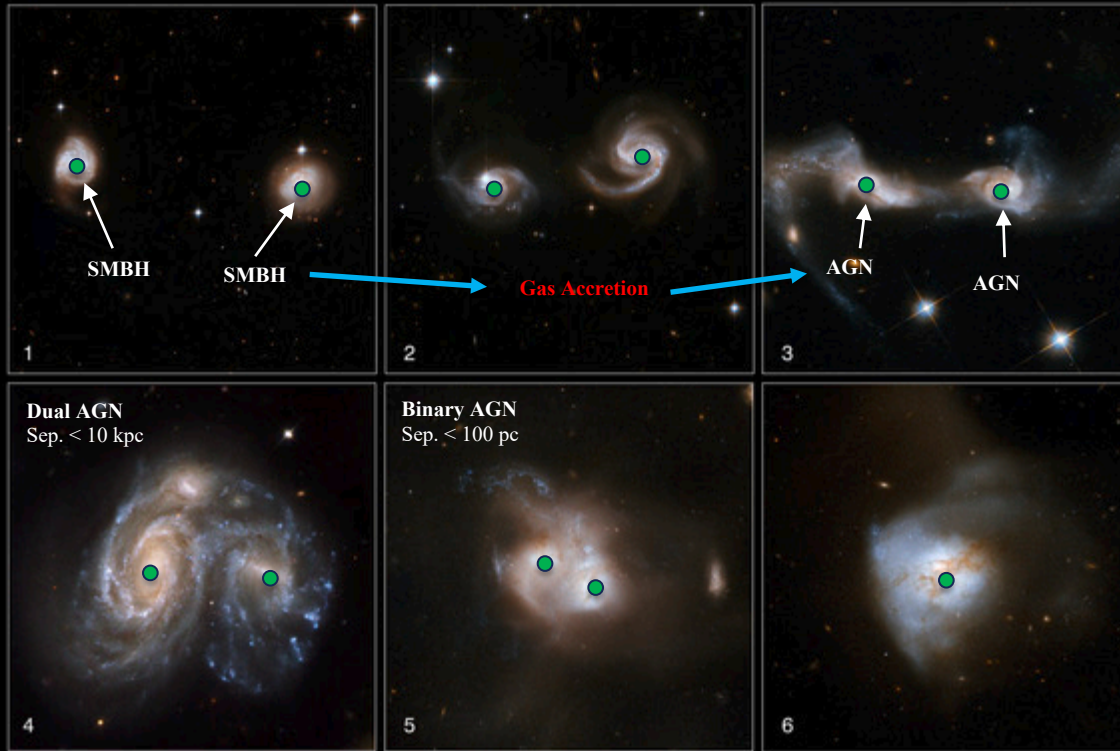
Varstrometry for Dual AGN using Radio interferometry: VaDAR with the VLBA

Emma Schwartzman

George Mason University, US Naval Research Lab

Collaborators: Tracy Clarke (USNRL), Nathan Secrest (USNO), Kristina Nyland (USNRL), Ryan Pfeifle (NASA GSFC), Paula Fudolig (GMU), Henrique Schmitt (USNLR), Barry Rothberg (USNO), Shobita Satyapal (GMU)

Evolution of a Galaxy Merger



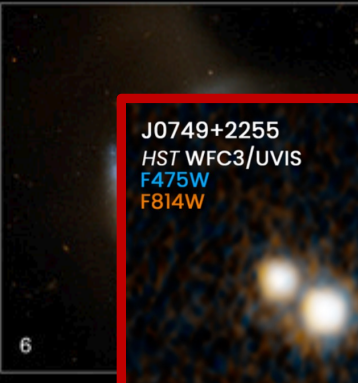
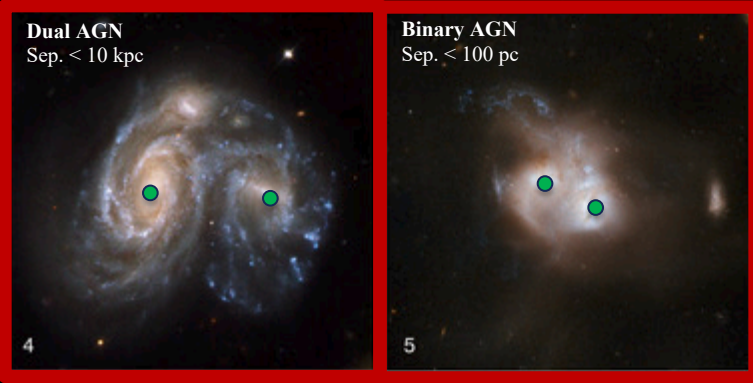
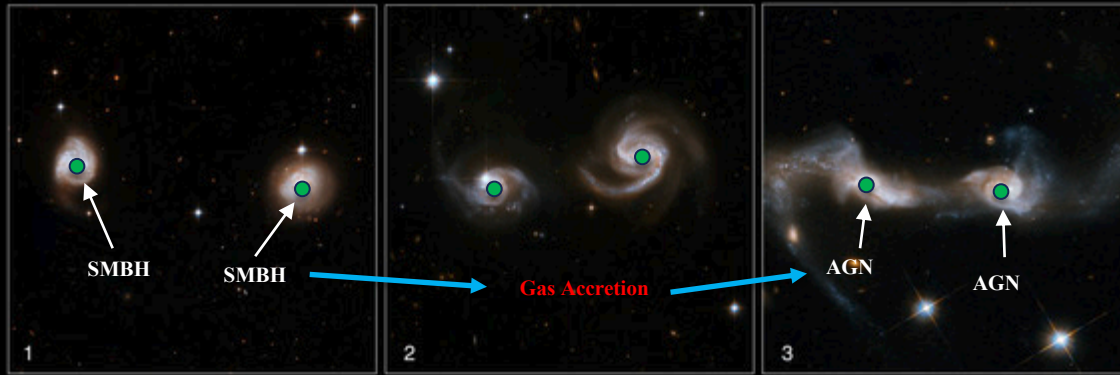
ESA

Multi-AGN Systems:

Dual & binary AGN

~100 confirmed systems

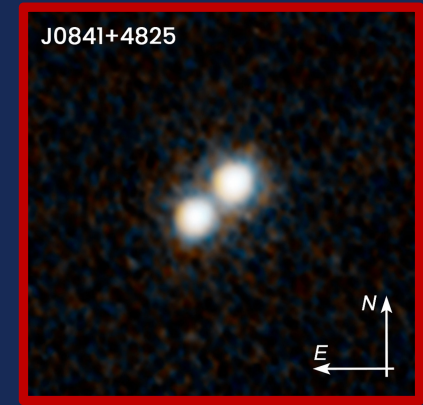
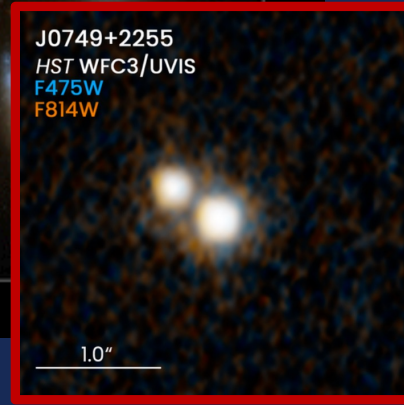
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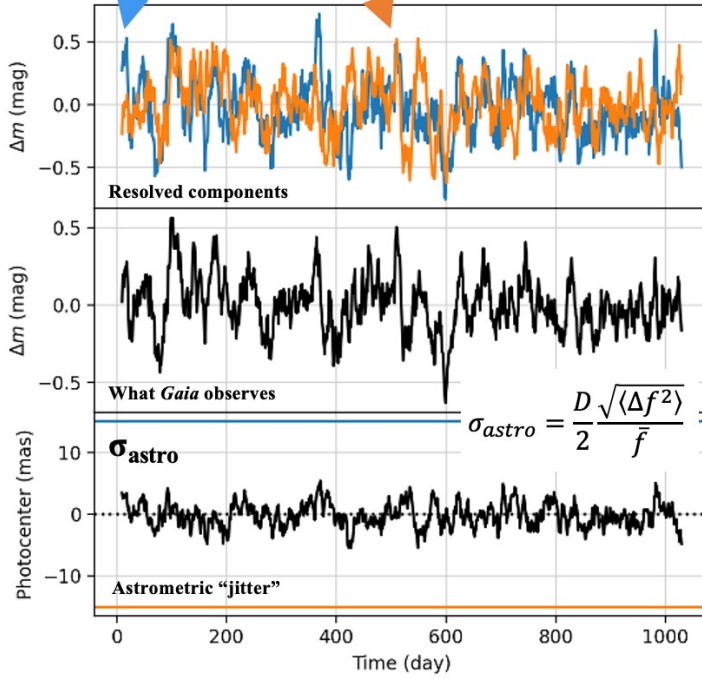
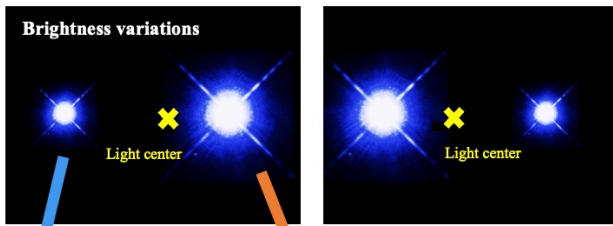
What systematic methods exist for the detection of multi-AGN?

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

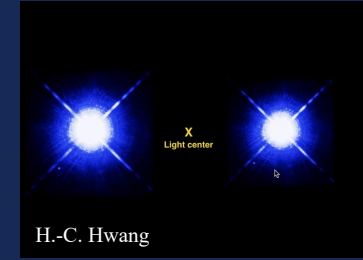
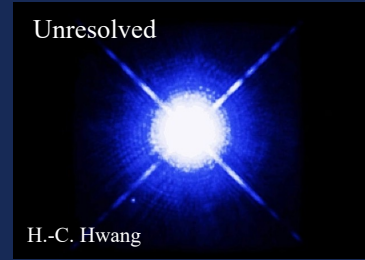


Hwang et al. ApJ. 2020.

ESA



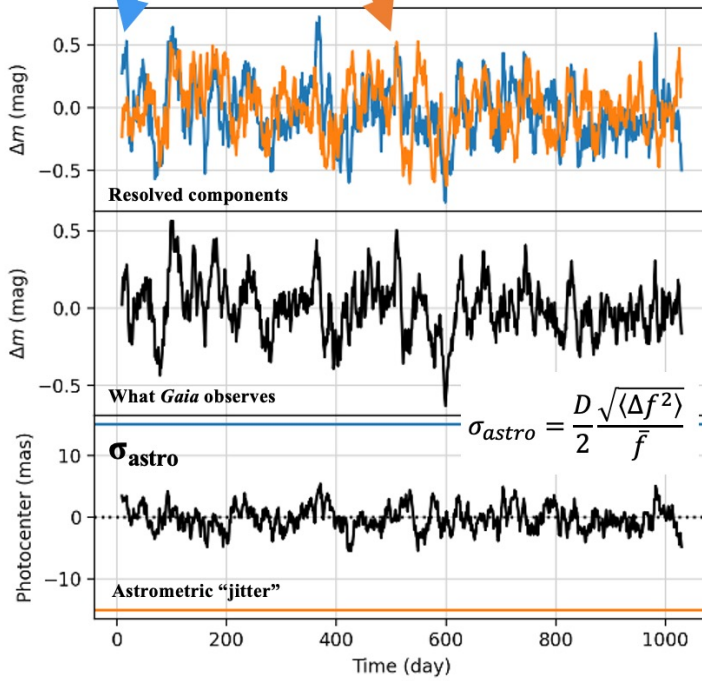
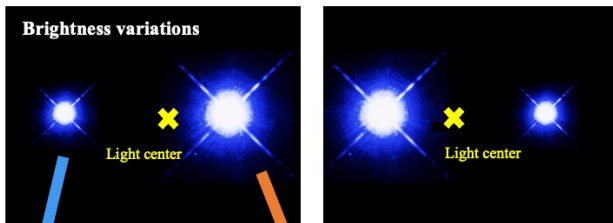
N. Secrest – private communication



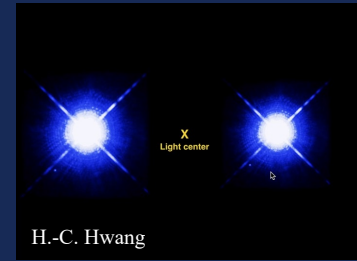
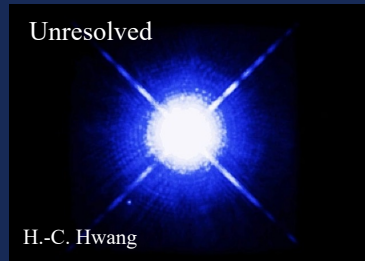
Gaia's large quasars catalog contains a subset identified as **astrometrically-variable**

Variability + astrometry = **varstrometry!**

Hwang et al. 2019



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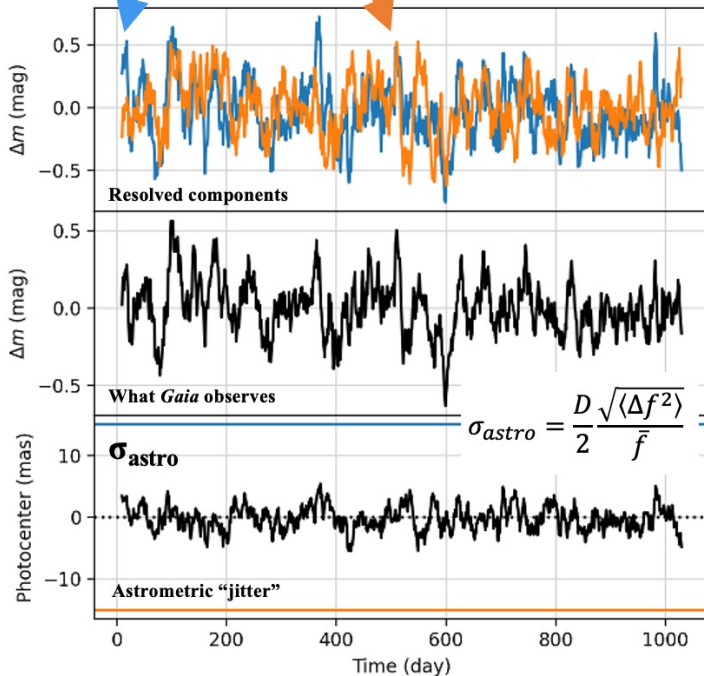
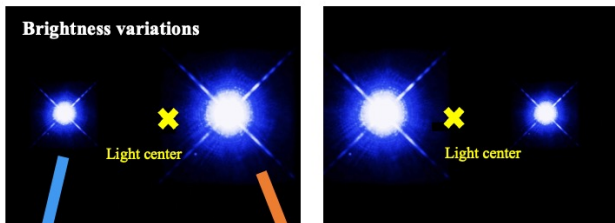


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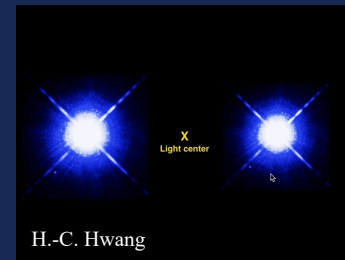
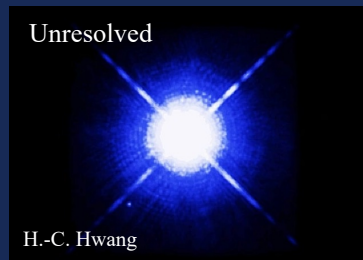
Astrometric excess noise: amount of statistical dispersion required such that *Gaia*'s astrometric solution for the source leaves no unexplained variance

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Hwang et al. 2019



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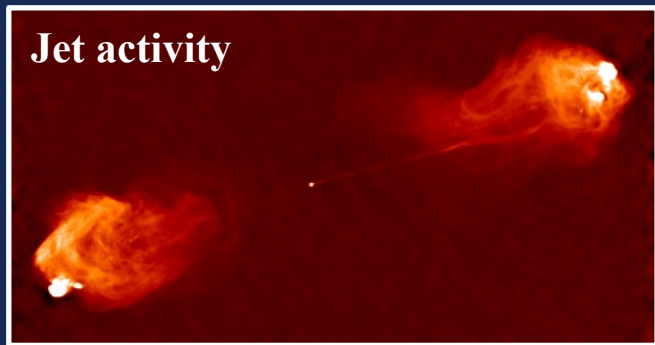
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AGN pair is unresolvable with *Gaia*, but with individual variability, the photocenter appears to vary

Variability + astrometry = **varstrometry!**

Hwang et al. 2019

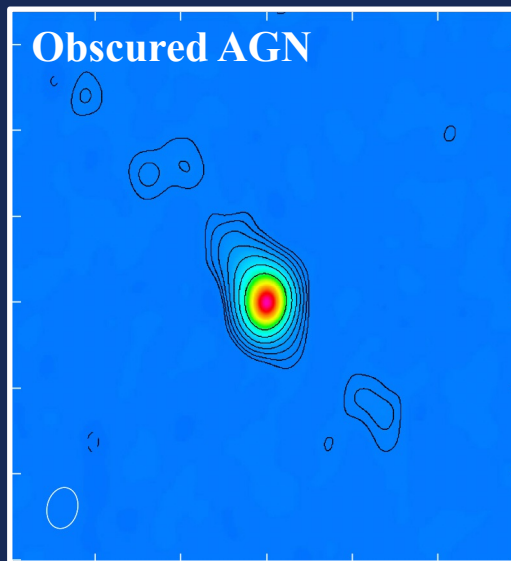
Drivers of Astrometric Variability



Jet activity

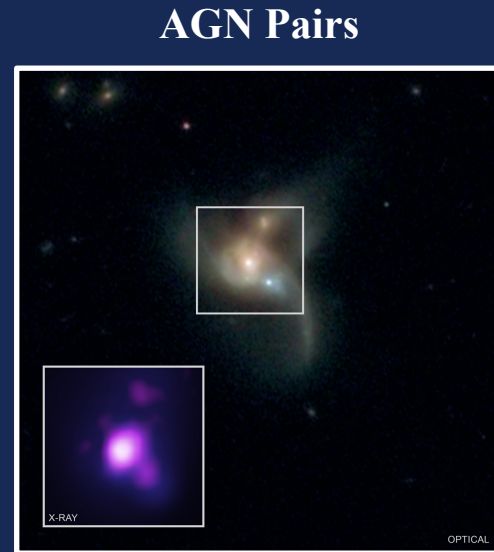
NRAO/AU

Peterson et al. 1999



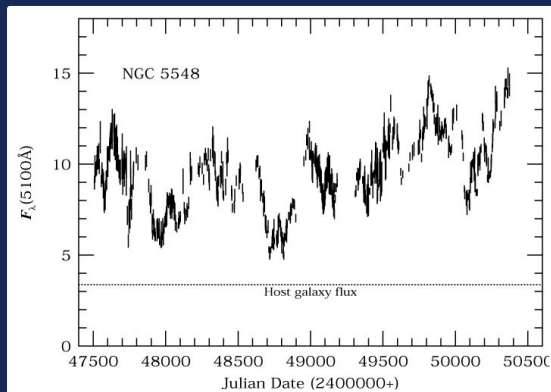
Obscured AGN

Hernandez-Garcia et al. ApJ. 2019.



AGN Pairs

Pfeifle et al. ApJ. 2019.

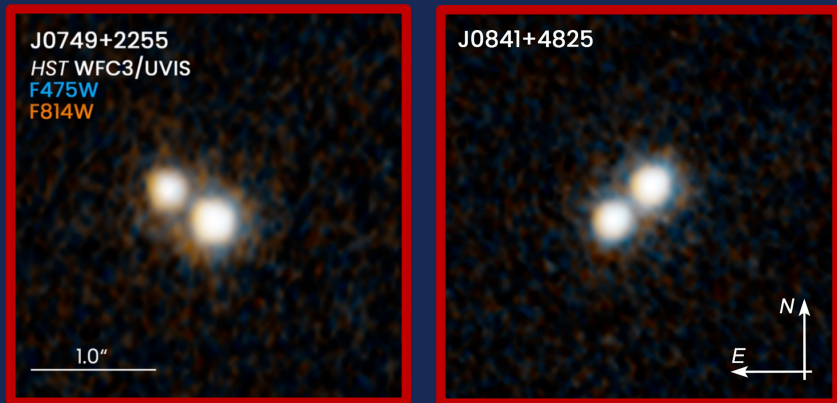


Also, gravitationally-lensed quasars, star+quasar superposition, host galaxy features...

Single AGN Variability

Schwartzman – VaDAR VLBA - IAP

VODKA: Varstrometry for Off-nucleus and Dual Sub-kpc AGN

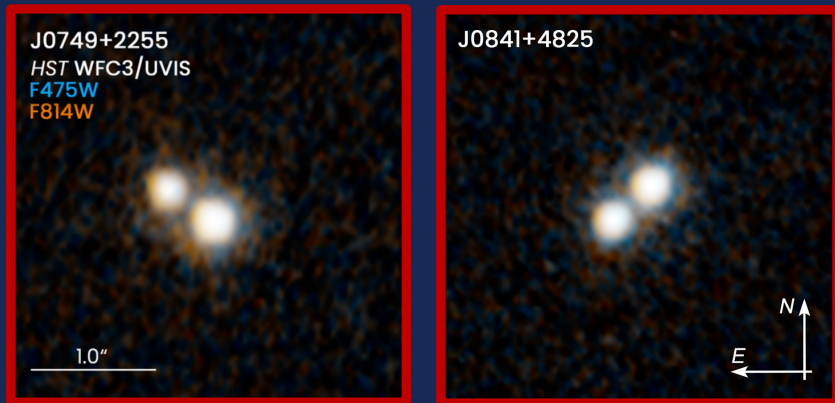


Hwang et al. ApJ. 2020.

Applied varstrometry to *HST* and Gemini observations

~40% identified as multi-AGN *or* gravitationally-lensed quasars

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Hwang et al. ApJ. 2020.

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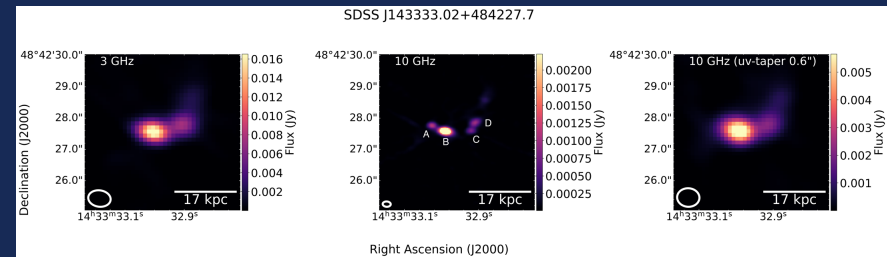
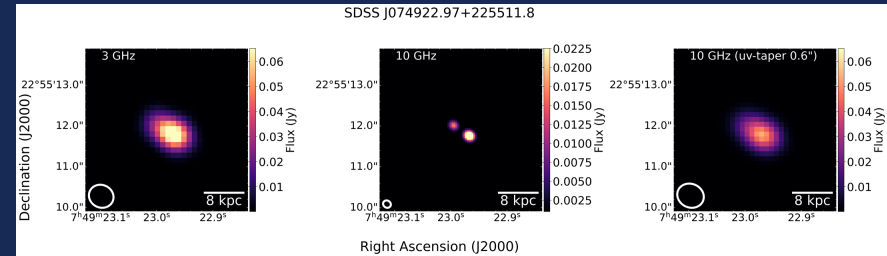
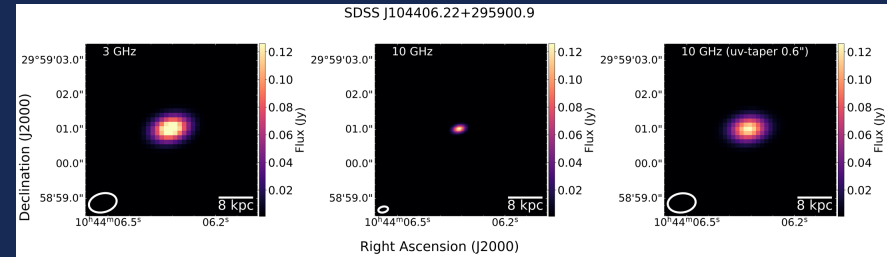
VaDAR: Varstrometry for Dual AGN using Radio interferometry

Varstrometry applied to radio interferometry (VLA, VLBA)

- higher resolutions + sensitivities, no obscuration

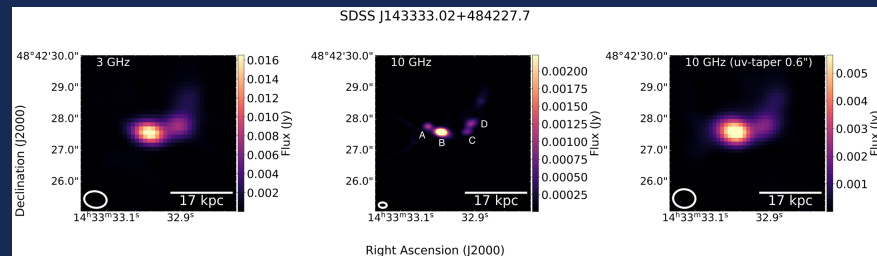
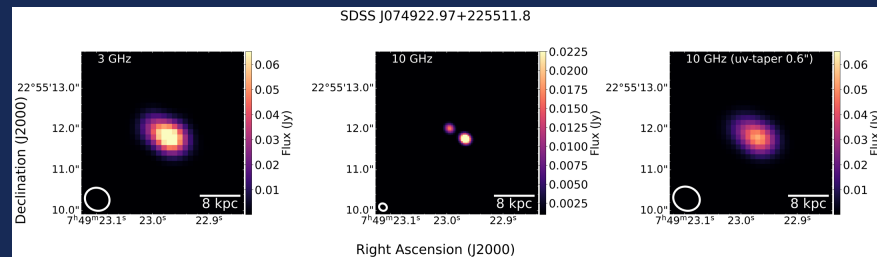
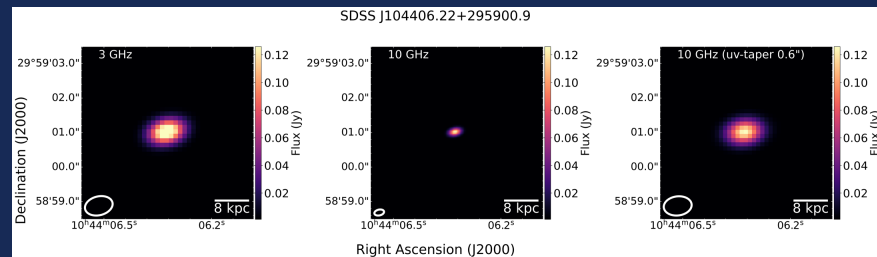
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- Very Large Array (VLA) → sub-arcsecond resolution
- SDSS DR16Q + *Gaia* EDR3, AENS > 5 σ , VLASS (3 GHz) radio detection



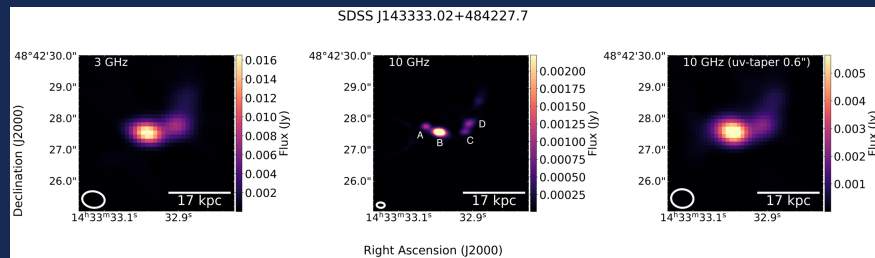
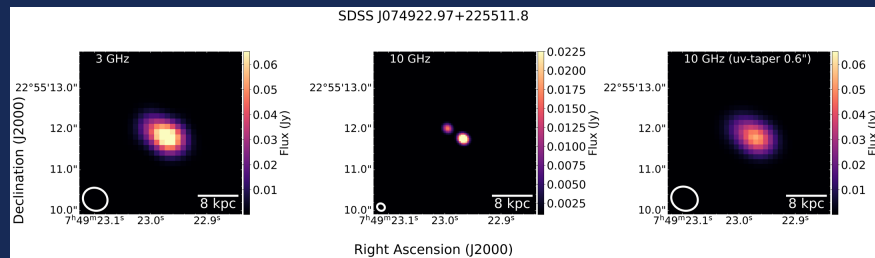
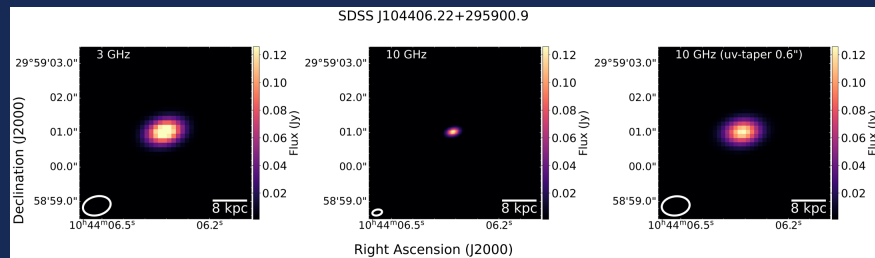
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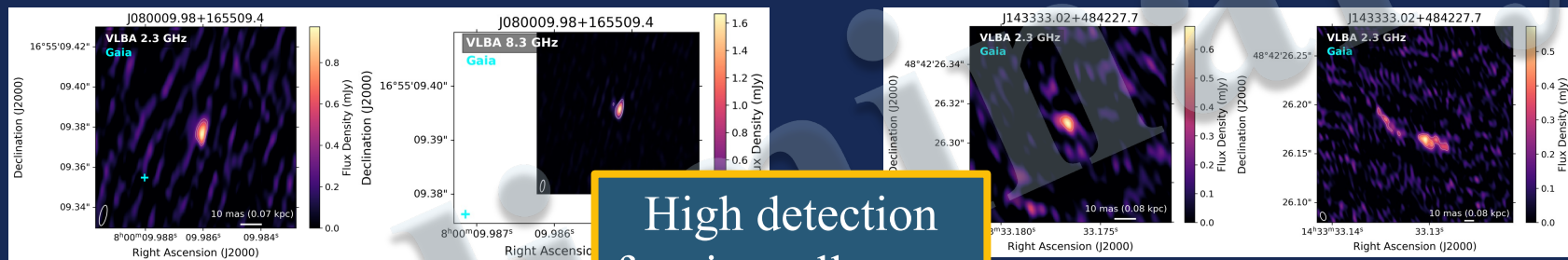
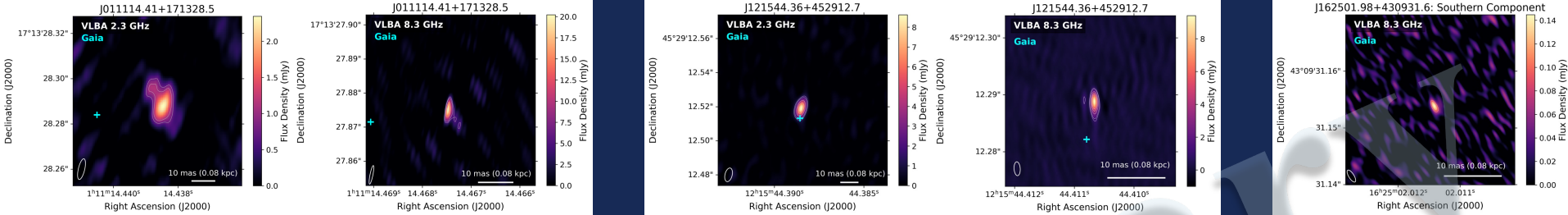
- Very Large Array (VLA) \rightarrow sub-arcsecond resolution
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- 44% identified as multi-AGN *or* gravitationally-lensed quasars



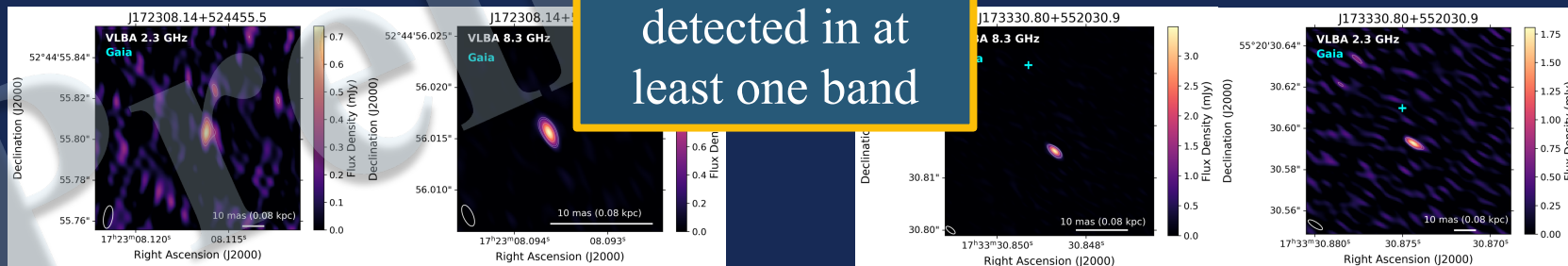
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- Very Long Baseline Array (VLBA) → sub-milliarcsecond resolution
- Seven of original 18 selected for follow-up
- 3 & 10 GHz (S- and X-bands)

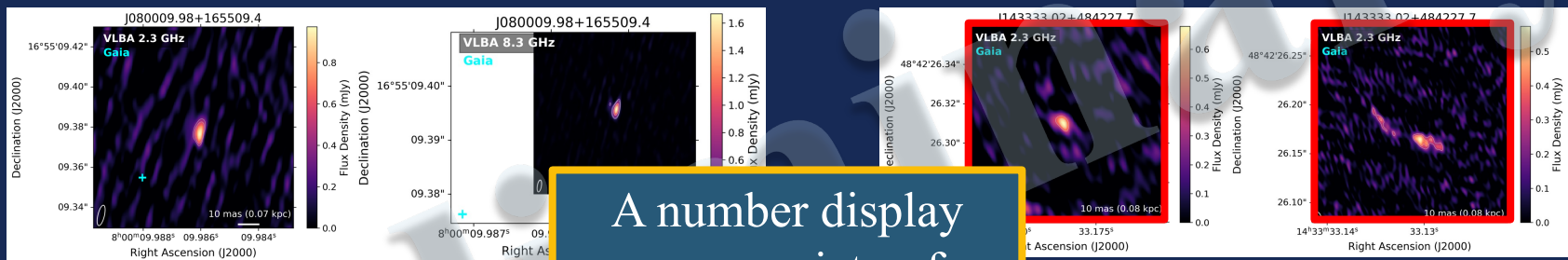
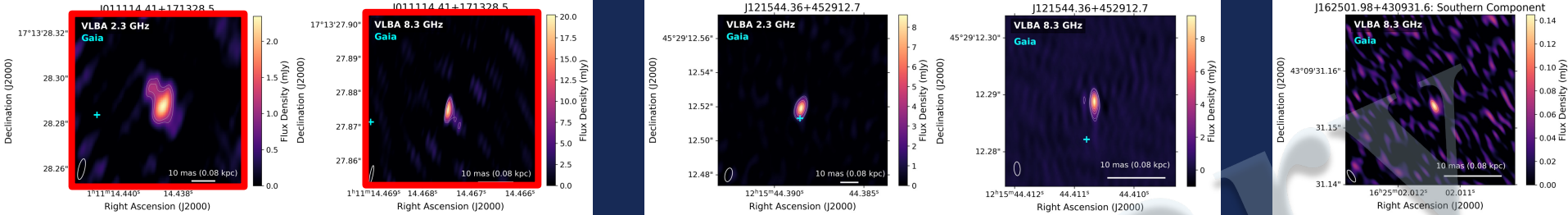




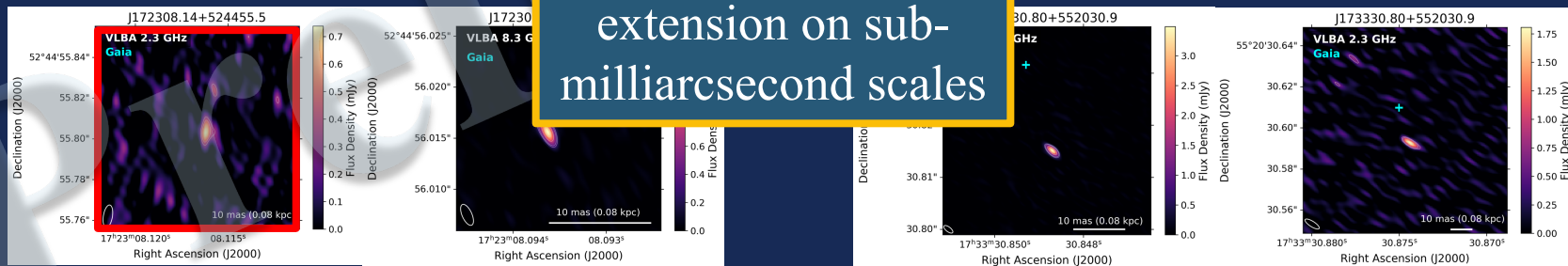
High detection fraction: all seven detected in at least one band

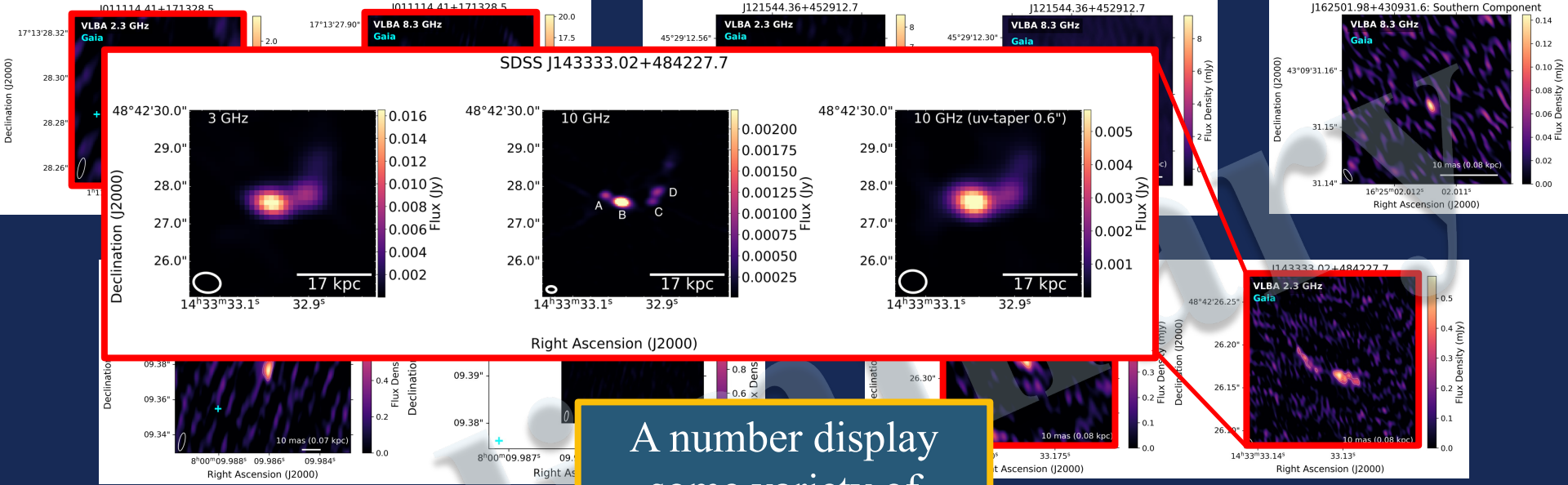


Schwartzman et al. in prep

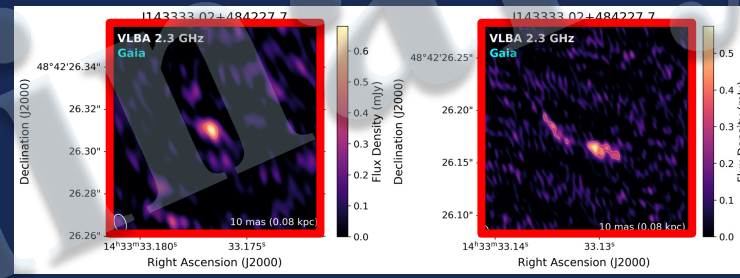
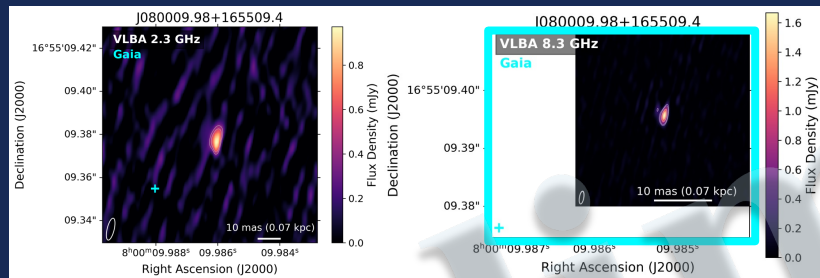
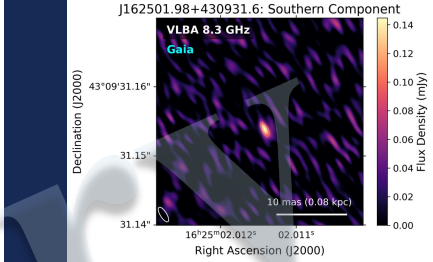
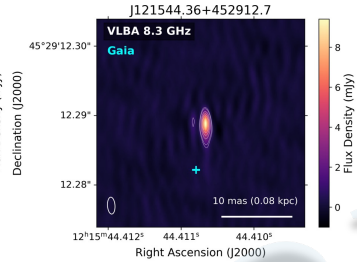
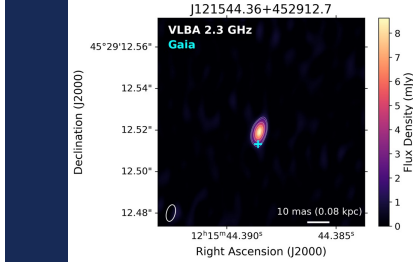
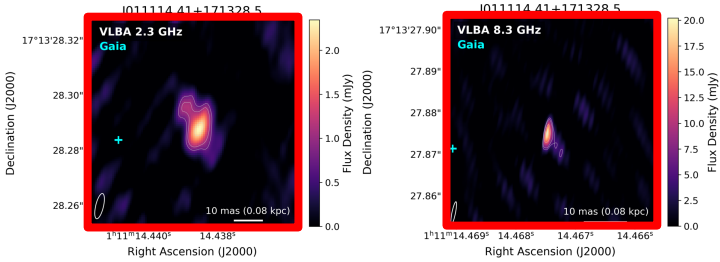


A number display
some variety of
extension on sub-
milliarcsecond scales

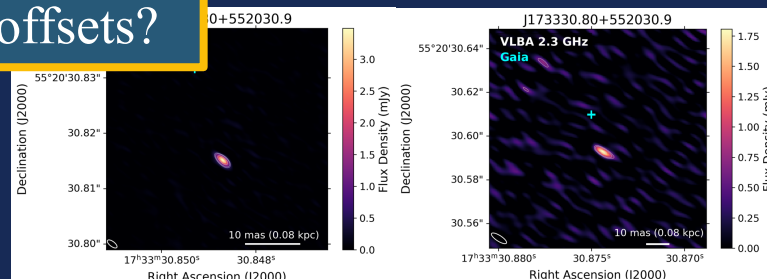
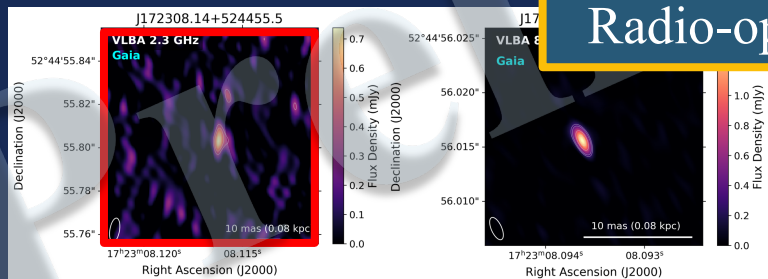




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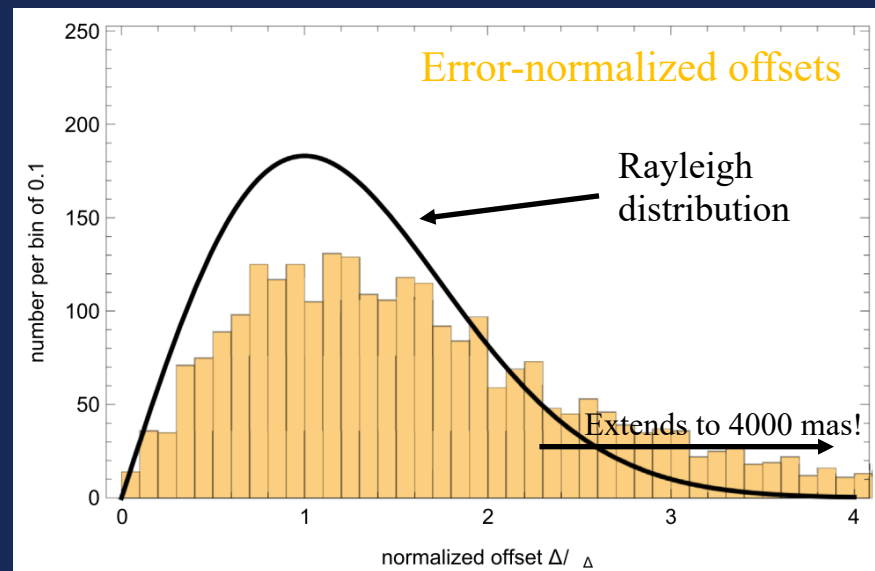
Radio-optical offsets?



Schwartzman et al. in prep

Radio-Optical Offsets

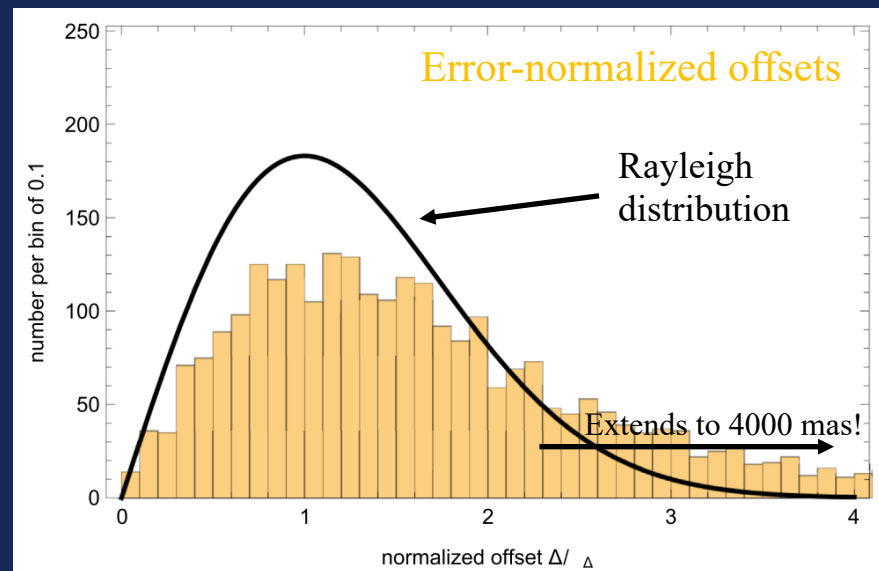
- International Celestial Reference Frame:
 - Radio \rightarrow VLBI, several thousand quasars
 - Optical \rightarrow *Gaia*, comparable precision



Makarov et al. 2019

Radio-Optical Offsets

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 - Optical \rightarrow *Gaia*, comparable precision
- Significant radio-optical offsets
 - See histogram \rightarrow
 - Reduce overall accuracy
 - Interchangeability difficult



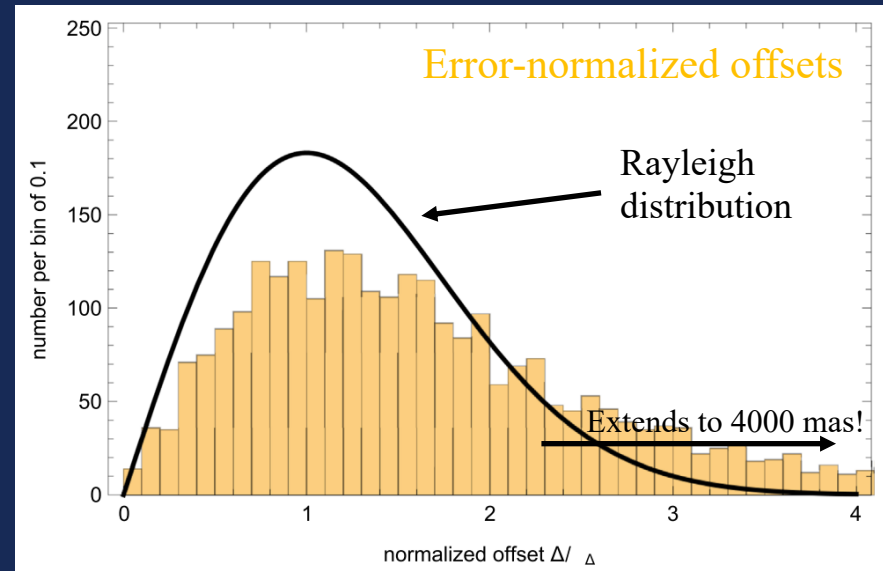
Makarov et al. 2019

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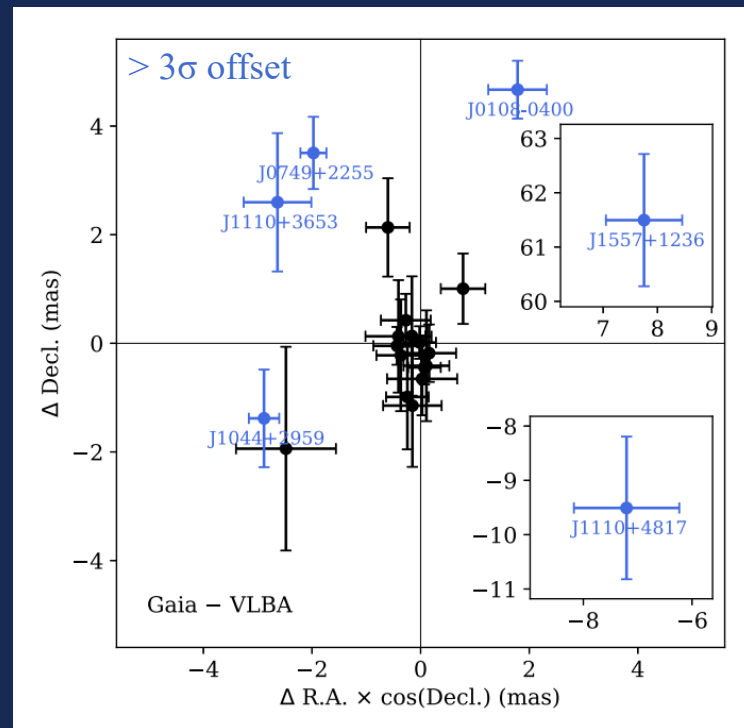
- Something to do with jets? (Kovalev+17, Petrov+19)
 - Offsets aligned with existing radio jets
 - Optical synchrotron component?
 - Host galaxy properties, dislodged (Makarov+17)/multi-AGN (Shen+19,21)



Makarov et al. 2019

Radio-Optical Offsets

~40% of VaDAR sample $> 3\sigma$ radio-optical offsets
~35% of VODKA sample $> 3\sigma$ radio-optical offsets



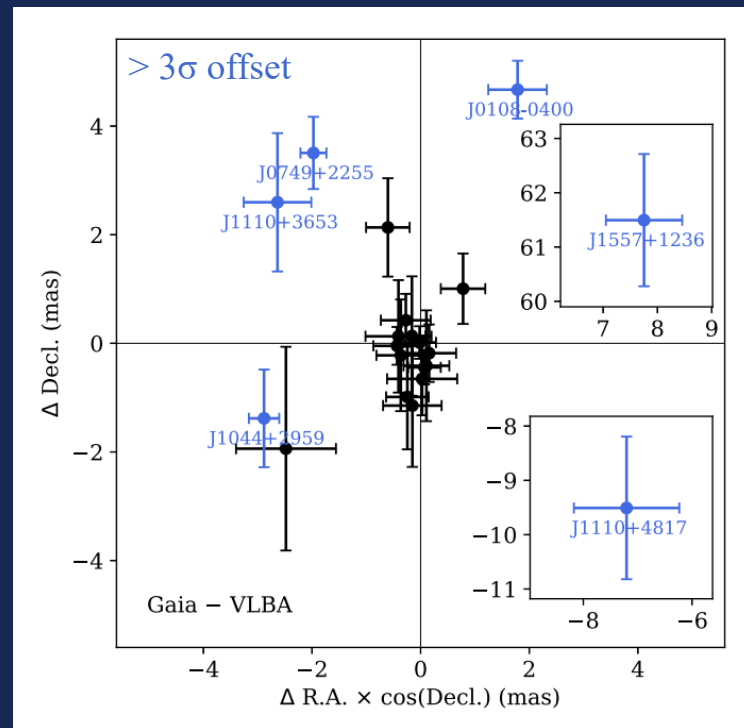
Chen et al. 2023

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- Culprits?

- *Gaia* systematics **X**
- Optical (mas-scale) jets **X**
- Intrinsic (regular) “jitter” **X**
- Optical signature that is too faint/small ?



Chen et al. 2023

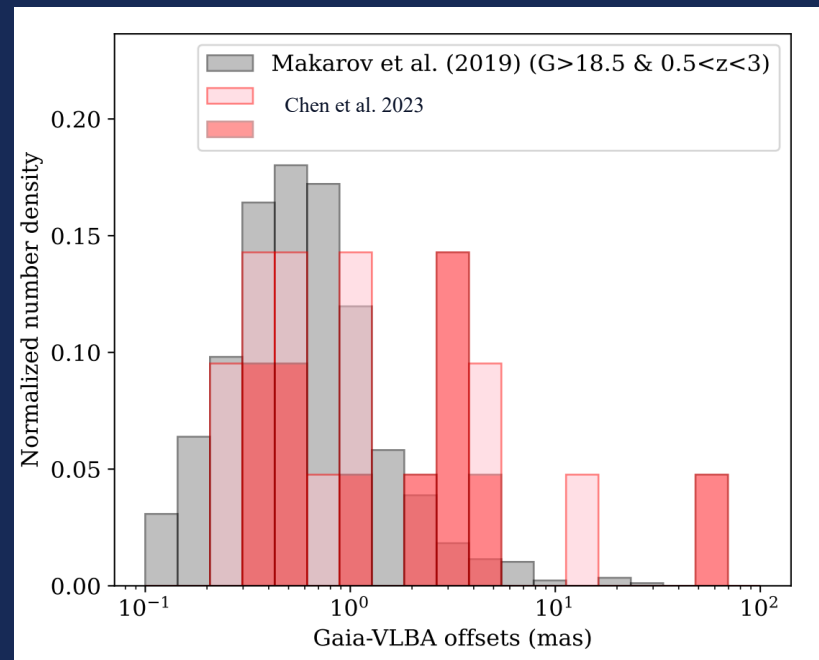
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- Varstrometry methods appear to select for a slightly higher fraction of quasars with $> 3\sigma$ radio-optical offset

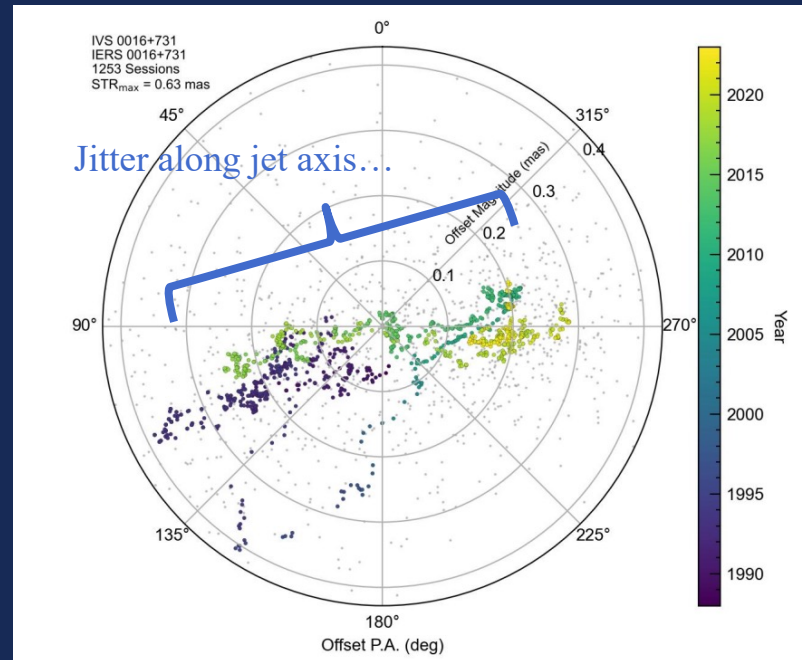


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Future Work

Varstrometry:

- *Gaia* future DRs (axis of variability, time series)
- *Gaia*+WISE (or *Gaia*-NIR) for host galaxies
- sort out the gravitational lenses
- further VLBI, move beyond pilot sample



Cigan et al. 2024

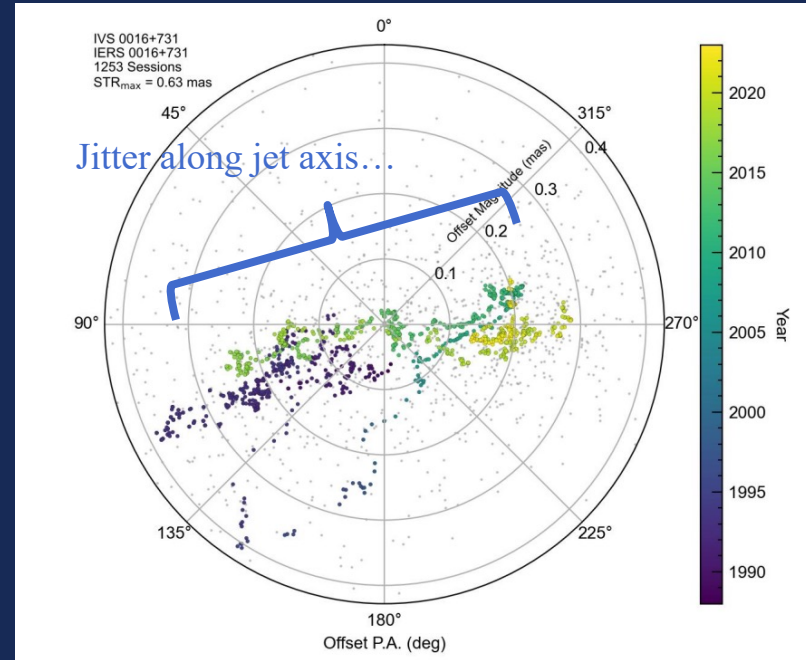
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New Missions:

- *Gaia*-NIR
- Next gen. optical/radio
- Theia is tricky
 - (I)MBH regime as progenitors
 - novel parameter space



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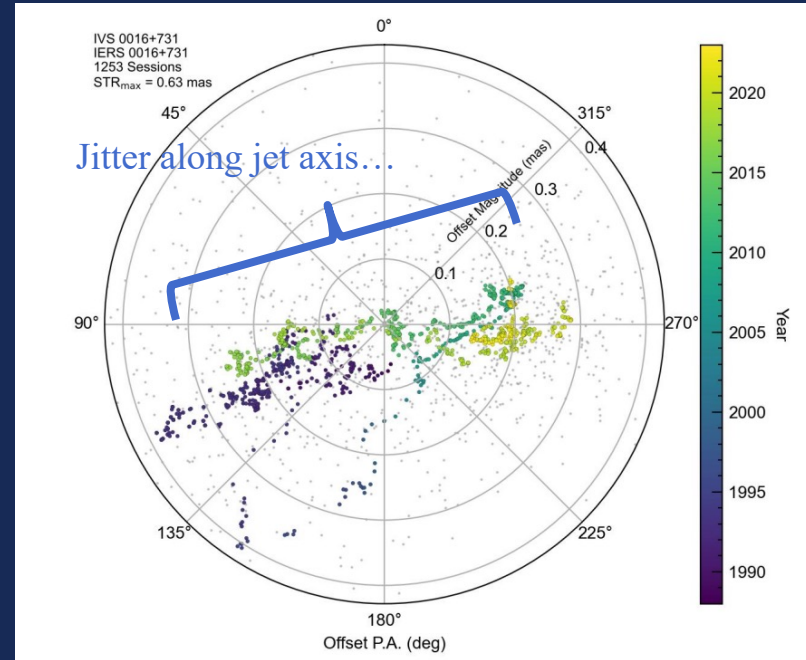
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- (sub)mas + faint optical jets
- refinements to ICRF
- opposite direction – work from multi-AGN inwards?



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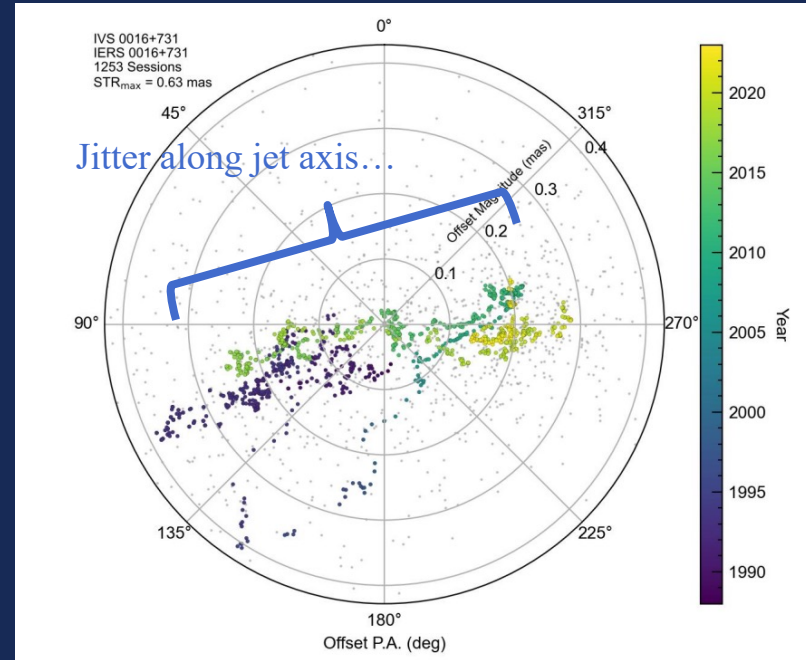
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Questions?