The radio nucleus of the nearby dwarf galaxy NGC 4395

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Outline

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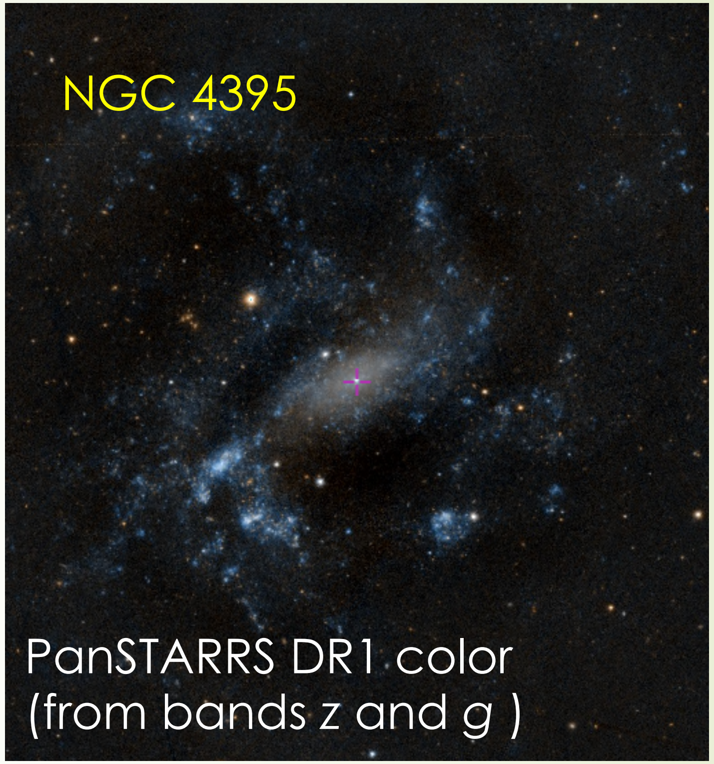
  - Status of searching for IMBH jets
  - AGN in the dwarf galaxy NGC 4395
- **Radio nucleus of NGC 4395**
  - Multi-resolution and multi-frequency radio observations
  - Two-component radio structure
  - Non-detection of the sub-pc-scale jet base tracing the IMBH
  - Nature of the components E and C
- **Summary and outlook**

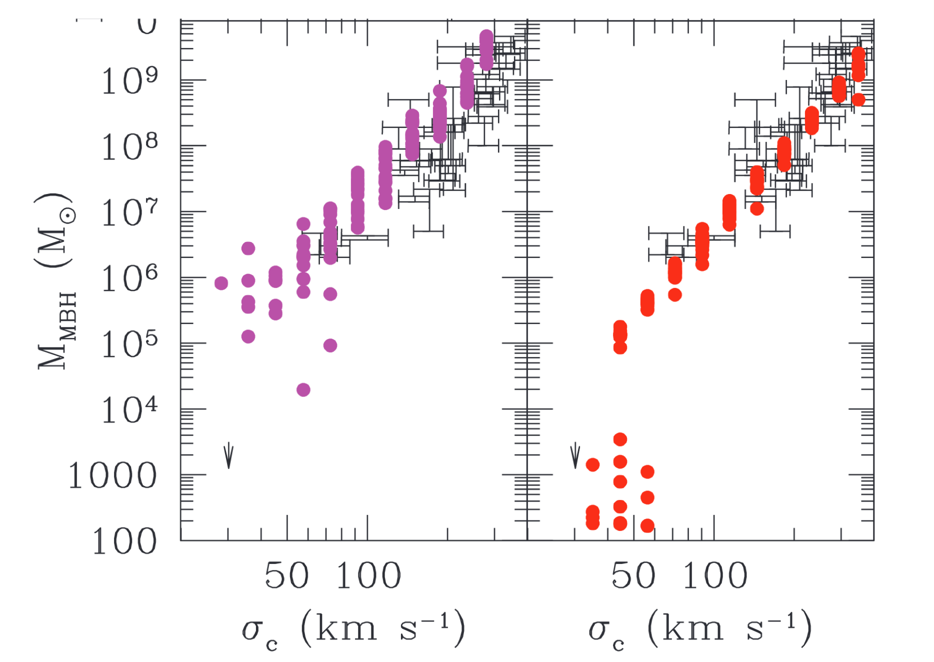


1.1 IMBHs

- **Mass**
  - $10^2 – 10^6$ solar mass (M_{sun})
- **Location**
  - low-mass ($M_* \lesssim 10^9$ M_{sun}) and low-luminosity stellar systems (stellar clusters, **dwarf galaxies**, hyper-luminous X-ray sources, tidal disruption events)
- **Status**
  - Found ~10 IMBHs with a mass of $\gtrsim 10^4$ M_{sun} in dwarf AGNs (e.g. Baldassare+ 2020)
  - Optical and X-ray observations selected several hundred accreting IMBH candidates (fraction < 1% in the sample of Reines+ 2013)
  - Radio counterparts for dwarf galaxies, ~0.3 % (Reines+ 2020)

Recent review papers: Greene+ 2020, Volonteri+ 2021, Reines 2022

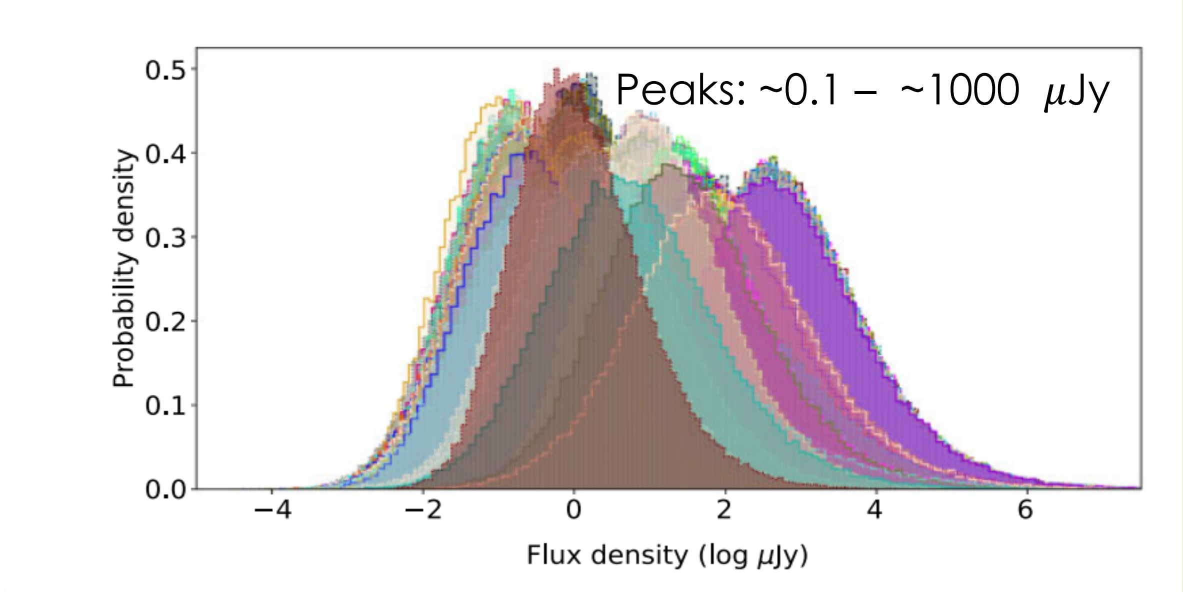
IMBHs
—Key to study BH seed formation mechanisms



Simulation results (Volonteri+ 2008)

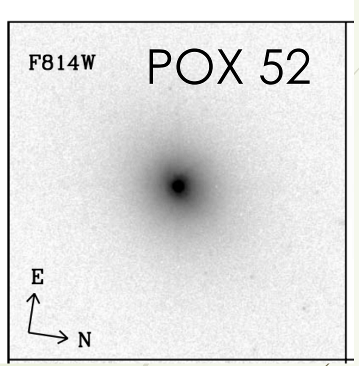
- **Left panel**
  - Direct collapse seeds, ~10^4 M_{sun}
  - **Large scatter for IMBHs**
- **Right** panel
  - Population III star seeds, ~10^2 M_{sun}
  - **Big drop for IMBHs**
- Black points with error bars: observational data

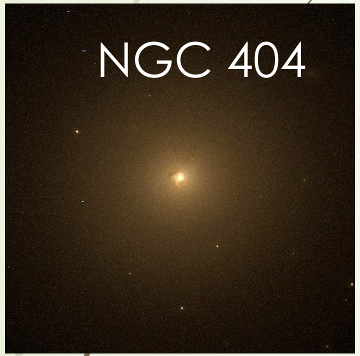
Possible 192 IMBH jet populations and the distributions of their flux density. One color per population (Liodakis 2022)



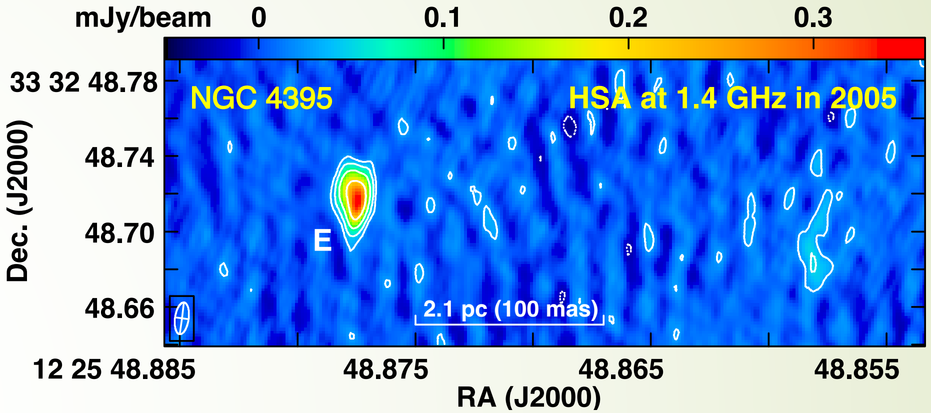
- ✓ VLBI observations
  - ✓ Free from star-forming activity
  - ✓ Directly confirm accreting IMBHs
  - ✓ Probe disc-jet coupling during the mass gap
  - ✓ Measure jet parameters to constrain the models of sub-mJy IMBH jet populations

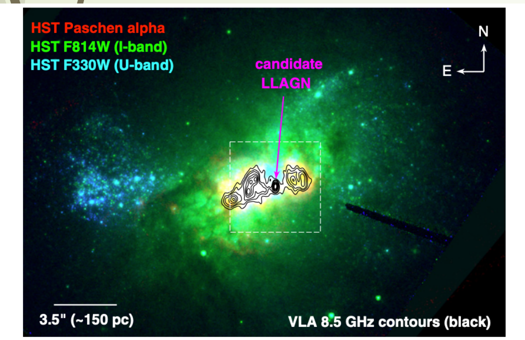
1.2 Status of searching for IMBH jets



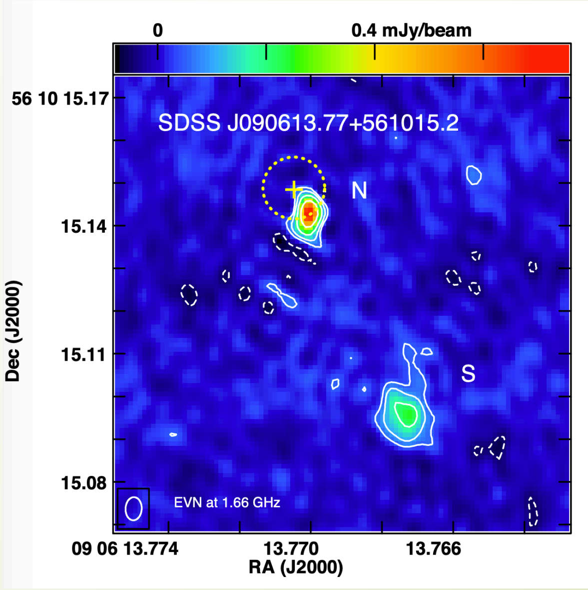


- An outflow-like feature (E) in NGC 4395 (Wrobel & Ho 2006)
- VLA non-detection in POX 52 (Thornton+ 2008)
- Dwarf starburst dwarf galaxy Henize 2–10 (Reines & Deller 2012)
  - Non-detection in the VLBA observations
- Nearby dwarf galaxy NGC 404 (Paragi+ 2014)
  - Non-detection in the deep EVN observations
- Jet in dwarf galaxy SDSS J0906+5610 (Yang+ 2020)





Radio non-detections ≠ non-existences.



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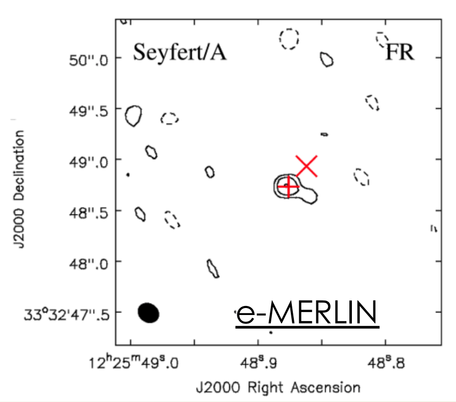
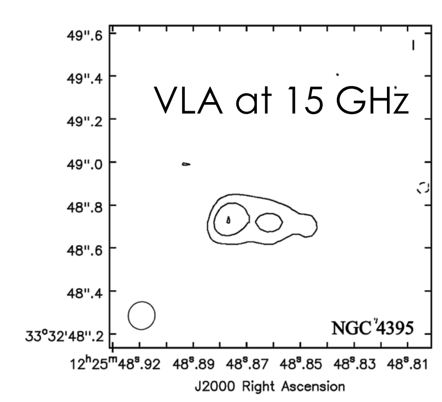
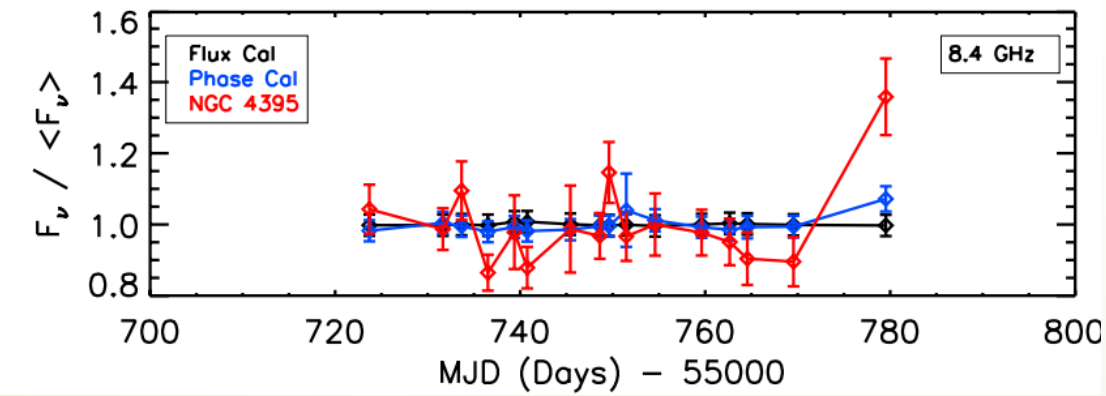
1.3 AGN in NGC 4395

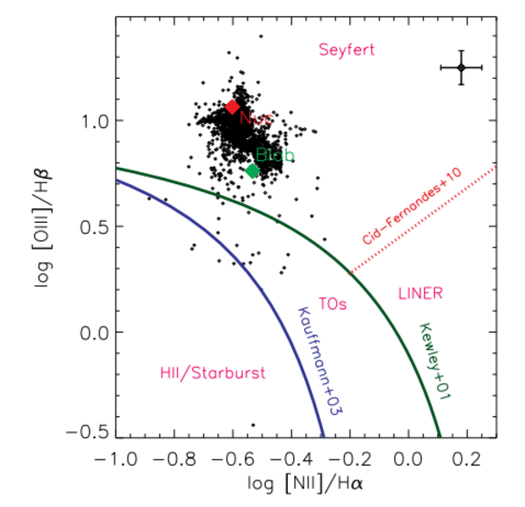
- Distance: 4.3 Mpc (scale 1 mas = 0.021 pc)
- Very low-luminosity: $L_{bol} = 10^{40.3}$–$10^{41.7}$ erg s^{-1} (Brum+ 2019)
- e-MERLIN observations: ~ 1 mJy at 1.5 GHz (Baldi+ 2021)
- Two-component structure at 15 GHz (Saikia+ 2018)
- IMBH mass: ~10^4 – ~10^5 M_{sun}
  - Recent reverberation measurement: $M_{bh} = 10^{4.0 \pm 0.4}$ M_{sun}

    (including the systematic uncertainty, Woo+ 2019)
- No significant variability at 8.4 GHz on timescales from days to weeks (King+ 2013).
- No hint for starbursts in the entire nuclear region (Brum+ 2019)





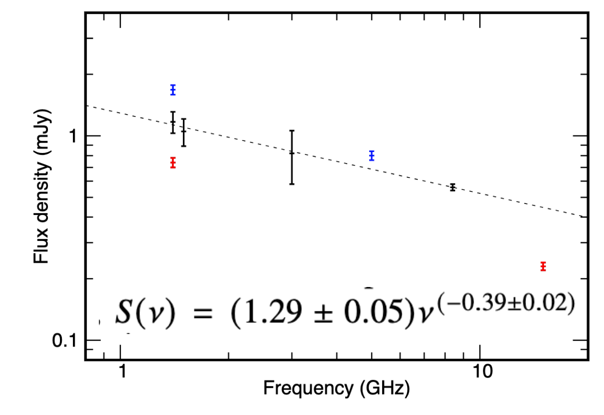




2. Radio nucleus of NGC 4395

2.1 Multi-resolution and multi-frequency radio observations

Array	Date	Frequency	PI	Project Code
HSA	**2008 May 4**	**1.4 GHz**	**Wrobel**	**BW089**
EVN	**2022 Jan 18**	**5.0 GHz**	**Yang**	**EY039**
Jansky VLA	2016 Dec 15	12–18 GHz	Saikia	16B-189
ALMA	2018–2019	237 GHz	Seth	2017.1.00572.S

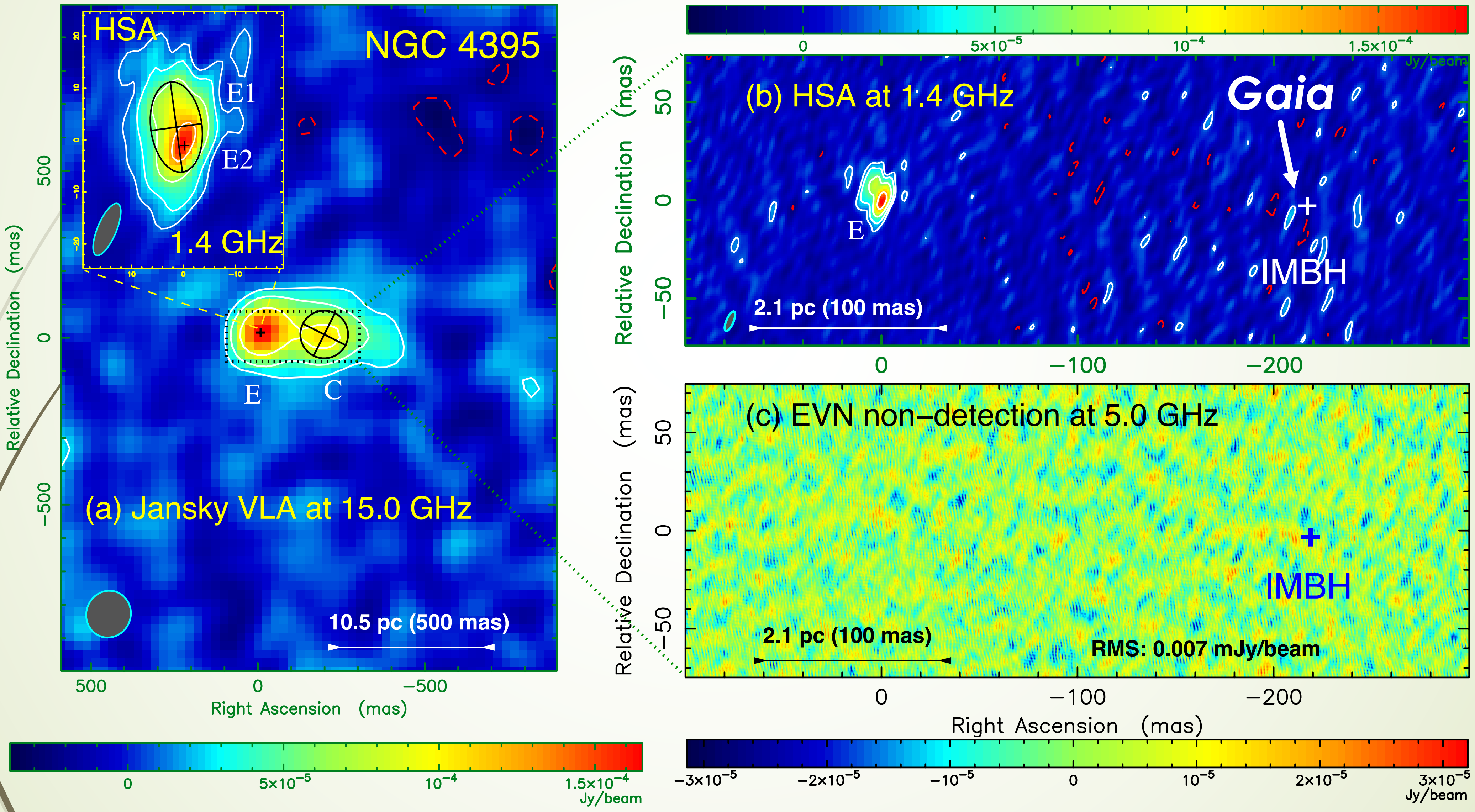


Non-simultaneous spectrum.

Table 1. Summary of the flux density measurements of NGC 4395 in literature.

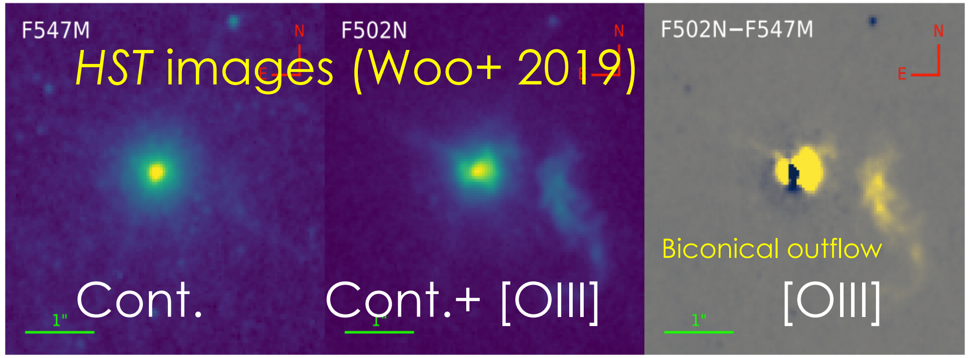
Freq. (GHz)	$S_{\rm int}$ (mJy)	$S_{\rm pk}$ (mJy beam^{-1})	FWHM (arcsec)	Array	Date	Structure	Reference
1.4	1.17±0.14	1.20±0.14	5.4×5.4	VLA	1994 Jun 09	Unresolved	FIRST (Becker et al. 1995)
1.4	1.68±0.09	1.54±0.04	1.7×1.1	VLA	1999 Aug 29	Unresolved	Ho & Ulvestad (2001)
1.4	0.74±0.04	0.36±0.01	0.017×0.0072	HSA	2005 May 1	Elongated outflow	Natural weighting (Wrobel & Ho 2006)
1.5	1.05±0.16	0.71±0.10	0.27×0.24	*e*-MERLIN	2017.3–2019.3	Slightly extended	Low resolution (Baldi et al. 2021)
3.0	0.82±0.24	0.82±0.14	2.9×2.4	Jansky VLA	2020 Sep 12	Unresolved	VLASS 2.1 (Lacy et al. 2020)
5.0	0.80±0.06	0.68±0.06	1.7×1.1	VLA	1999 Oct 31	Unresolved	Ho & Ulvestad (2001)
8.4	0.56±0.02	0.56±0.02	0.29×0.26	Jansky VLA	2011.5–2011.7	Unresolved	16-epoch average (King et al. 2013)
15.0	0.23±0.01	0.17±0.01	0.13×0.12	Jansky VLA	2016 Dec 15	Two components	Saikia et al. (2018)

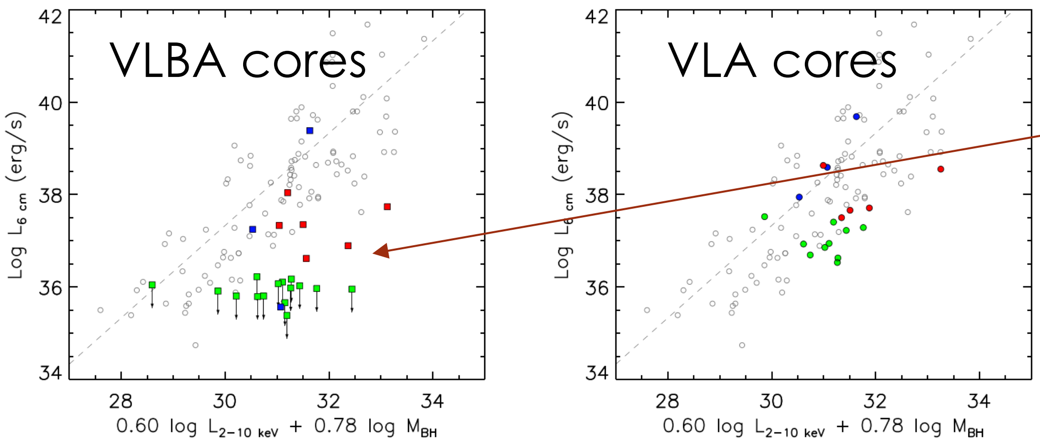
2.2 Two-component radio structure



2.3 Non-detection of the IMBH jet base

Method	RA (J2000)	σ_{ra} (mas)	Dec. (J2000)	σ_{dec} (mas)	Reference
HSA	$12^{\rm h}25^{\rm m}48^{\rm s}.8774$	6	$+33°32'48''.715$	6	Wrobel & Ho (2006)
Gaia DR3	$12^{\rm h}25^{\rm m}48^{\rm s}.85994$	1.4	$+33°32'48''.7110$	1.4	Gaia Collaboration et al. (2022)
Pan-STARRS1	$12^{\rm h}25^{\rm m}48^{\rm s}.86002$	13.4	$+33°32'48''.7063$	4.9	Chambers et al. (2016)



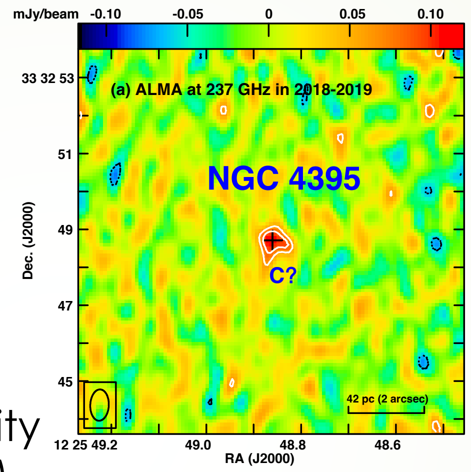


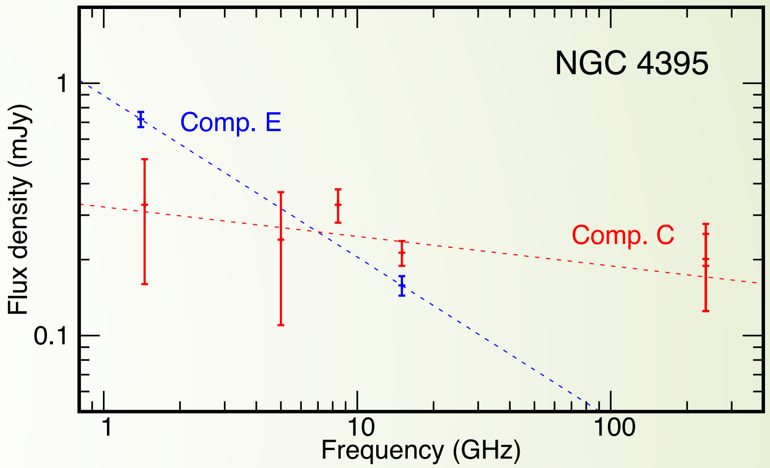
- Location of the IMBH
  - IMBH at the *Gaia* position
    - Absolute accuracy <10 mas
    - Compact optical nucleus (size <100 mas)
  - No IMBH at the HSA position
    - 218 mas offset with respect to the Gaia position
    - EVN non-detection at 5 GHz
- Upper limits for the IMBH jet base
  - 5σ = 0.035 mJy beam^{-1}
  - L_{5GHz} = 4.7 x 10^{33} erg s^{-1}
- Tentatively support weak or no disc-jet coupling on VLBI scales (Fischer+ 2021)

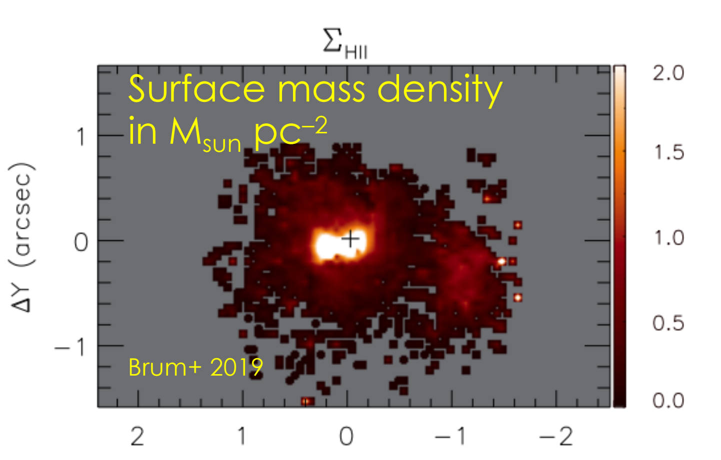
2.4 Nature the components E and C

Component E

- Features
  - Optically thin spectrum
  - Spectral index: -0.64 ± 0.5
  - HSA size: 16 x 9 mas
  - Low brightness temperature (~10^6 K)
  - No significant proper motion (<0.01 c)
- Probably formed by shocks
  - Dying ejecta or outflow from IMBH activity
  - Consistent with [OII] outflow (Woo+2019)
  - High density environment (Brum+ 2019)







- **Component C**
  - Detected at SNR~4.5 by the ALMA at 237 GHz
  - Likely has a flat spectrum
  - Very low luminosity $L_R = 8.6 \times 10^{34}$ erg s^{-1}
  - Diffuse morphology with a size of ~1.4 pc
  - Possible nature: Thermal free-free emission from a clumpy torus (e.g. Netzer 2015) or the biconical [OIII] outflow (Woo+2019, Baslom & Laor 2021).

3. Summary

- Presented a more complete view for the radio nucleus of NGC 4395.
- Provided a tight upper limit (~$10^{33.7}$ erg s^{-1}) for the radio luminosity of its potential sub-pc-scale jet base.
- Found a diffuse emission region (component C) surrounding the IMBH and possibly originating from free-free emission.

For more details, see the paper: Yang et al., MNRAS, stac1753

Outlook

- Jansky VLA observations between 10 and 45 GHz to study the component C.
- Future next-generation VLA observations at 4-12 GHz to further search for its jet base with a sensitivity of 0.1 μJy $beam^{-1}$.