# VLBI views on ULXs and accreting IMBHs

***Dr. Jun Yang***

*Senior Research Engineer & VLBI Support Scientist*

*Onsala Space Observatory, Chalmers University of Technology, Sweden*

The 16th EVN Symposium and Users meeting, Bonn, September 2-6, 2024.

# Onsala Space Observatory

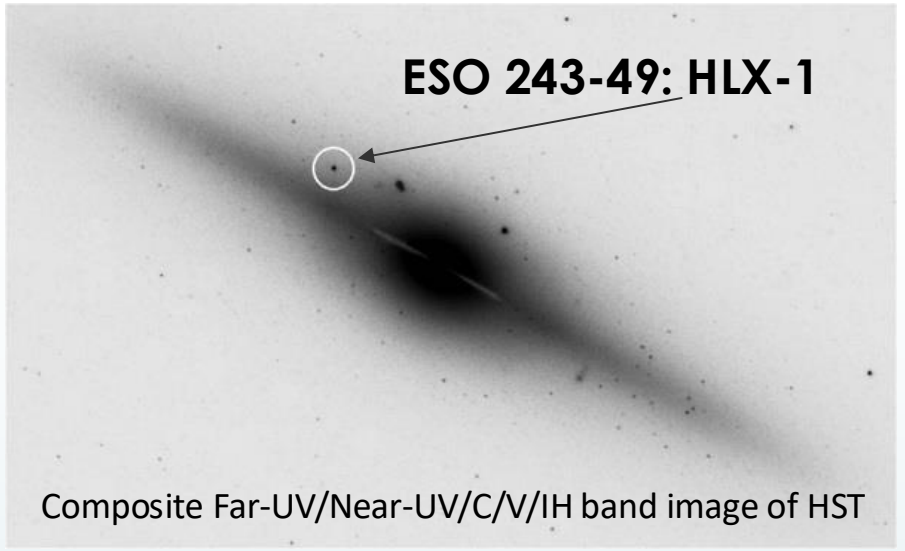
Swedish National Infrastructure for Radio Astronomy

Onsala60: 20 m (2.3-110 GHz)

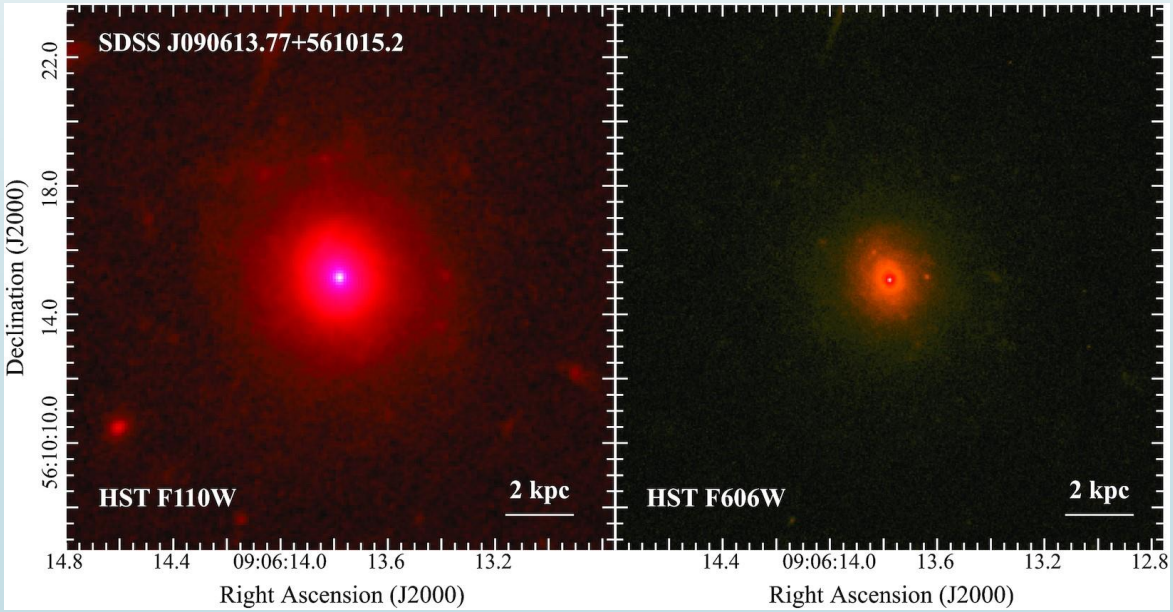
Onsala85: 25 m (1.4-7 GHz)

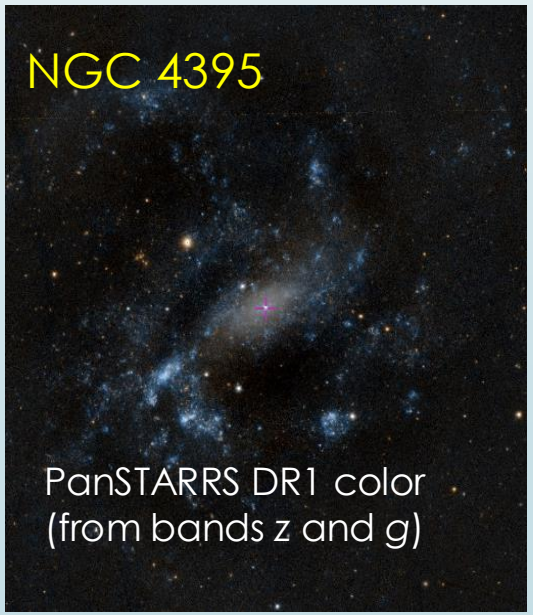
# Outline

- Introduction
  - Ultra-luminous X-ray sources (ULXs)
  - Intermediate-mass black holes (IMBHs)
- Jet and outflow activity from accreting IMBHs
- The innermost Jet in the Galactic hidden ULX Cyg X-3
- Summary



Composite Far-UV/Near-UV/C/V/IH band image of HST

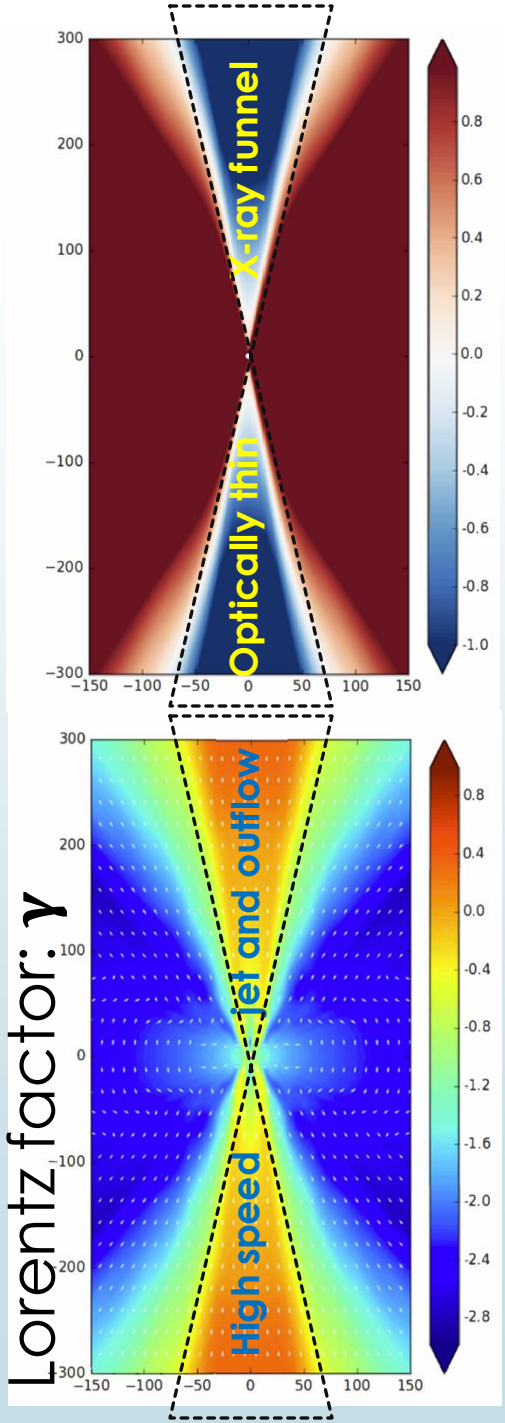


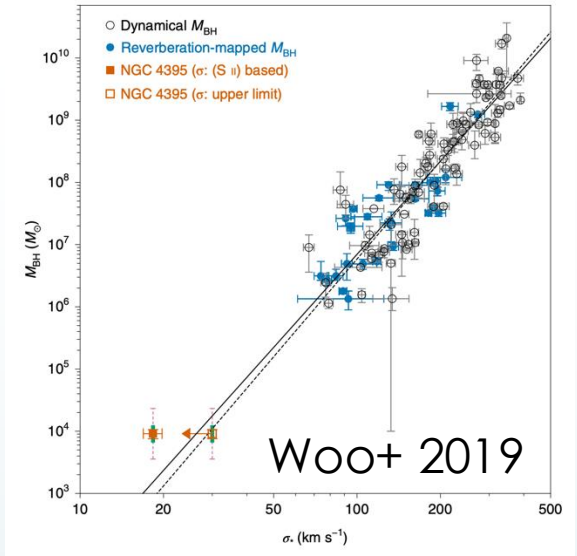



# 1. Introduction

- ULXs
  - General definition: $L_x > 10^{39}$ erg $s^{-1}$.
    - Eddington luminosity $L_{Edd} = 1.3 \times 10^{38}$ $(M/M_{sun})$ erg $s^{-1}$
    - Supercritical accretion for stellar-mass objects.
    - This is likely due to the geometric beaming of an X-ray funnel, e.g. simulation results in the right panels (Narayan+ 2017).
    - Extreme cases: Hyper Luminous X-ray sources (HLXs). They possibly result from IMBHs, e.g. ESO 243-49 HLX-1 (Farrell+2009).
  - Many ULXs are pulsars, e.g. NGC 5907 ULX (Gian Luca+ 2017).
  - Similar to SS433, some extragalactic ULXs show associated radio nebulae (e.g. Cseh+ 2012, Mezcua+2013).
  - VLBI detection of ULXs is limited to a few cases, e.g. Holmberg II X-1(Cseh+ 2015) and NGC 3310 (Argo+ 2018).

*See recent review paper: King, Lasota & Middleton 2023, New Astronomy Reviews.*






- **IMBHs**
  - Broadly definition
    - $M_{bh}$ is $10^2$ – $10^6$ solar mass ($M_{sun}$).
  - $M_{bh}$ uncertainty
    - **1σ ~0.3 dex** from optical broad emission lines (e.g. Reines+2013).
    - Another more accurate method is reverberation mapping, i.e. echo mapping.
      - IMBH in **NGC 4395**: **$M_{bh}$ = (8±4) x $10^3$ $M_{sun}$** (Gu+ 2024).
  - **Location**
    - Low-mass (**$M_* \lesssim 10^{9.5}$ $M_{sun}$**) and low-luminosity stellar systems (stellar clusters, **dwarf galaxies**, HLXs, **tidal disruption events**).
  - **Key questions**
    - **How do massive BHs grow together with galaxies on cosmic timescales?**
      - Massive BH seeds, binaries, mergers, low-frequency GW, …

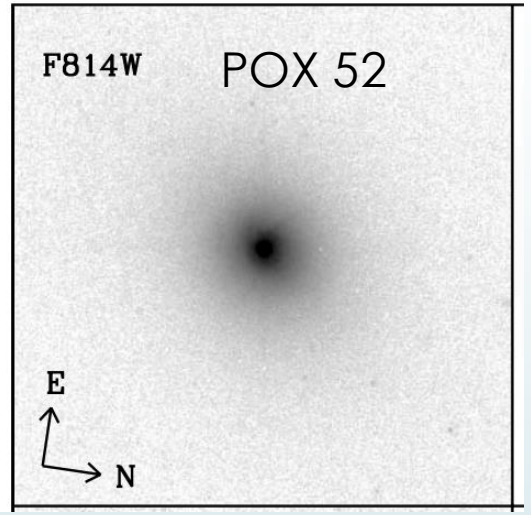
*See recent review papers: Greene+ 2020, Volonteri+ 2021, Reines 2022*

- **Search for accreting IMBHs**
  - Found ~10 (promising candidate) 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)
  - VLA surveys: radio counterparts for dwarf galaxies, ~0.3 % (Reines+ 2020).
- **VLBI observations of faint IMBH jets**
  - Free from low-surface brightness (<~$10^5$ K) emission of the star-forming activity.
  - Directly probe jet activity, i.e. dwarf AGN feedback, toward the very low-mass side of AGNs.
  - Study disc-jet coupling on mas scales during the mass gap.
  - Measure jet parameters to constrain models of sub-mJy IMBH jet populations
  - …

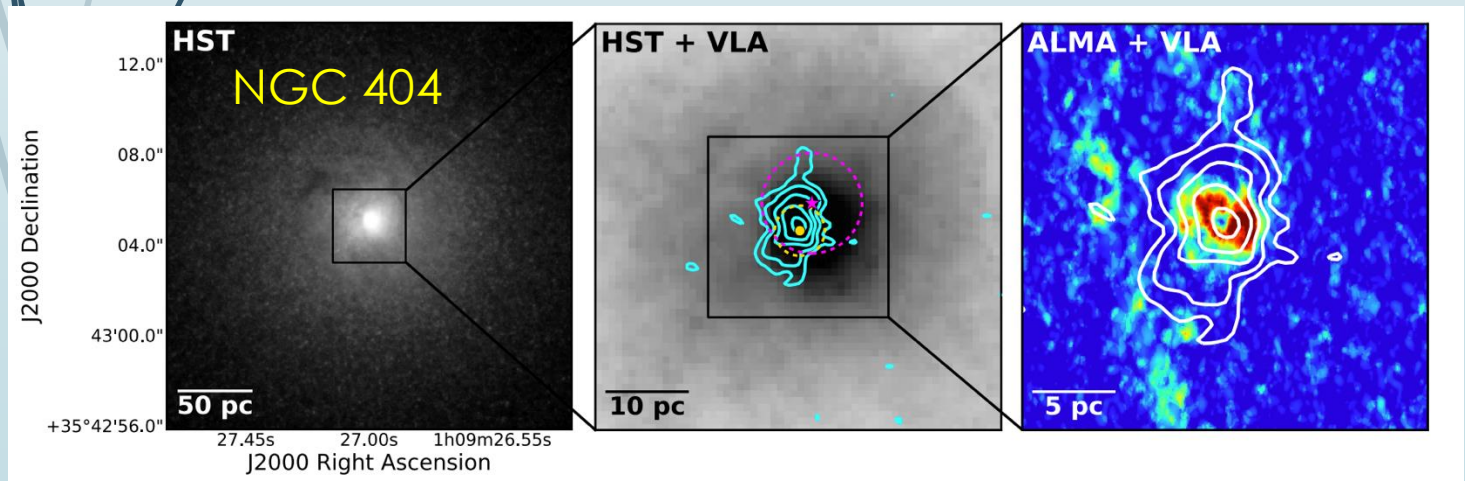
# 2. Jet and outflow activity from accreting IMBHs

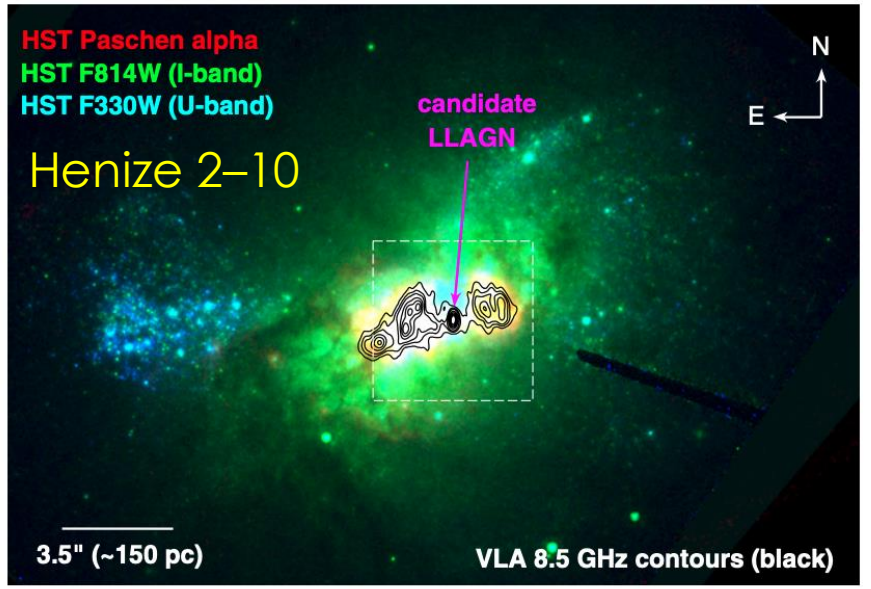
## 2.1 Early efforts on detecting IMBH jets

- VLA non-detection in POX 52 (Thornton+ 2008)
- Dwarf starburst dwarf galaxy Henize 2–10 (Reines & Deller 2012)
  - Non-detection on mas scales in the VLBA observations
- Nearby dwarf galaxy NGC 404
  - VLA detection of radio nucleus (Nyland+ 2017)
  - Non-detection in the deep EVN observations (Paragi+2014)



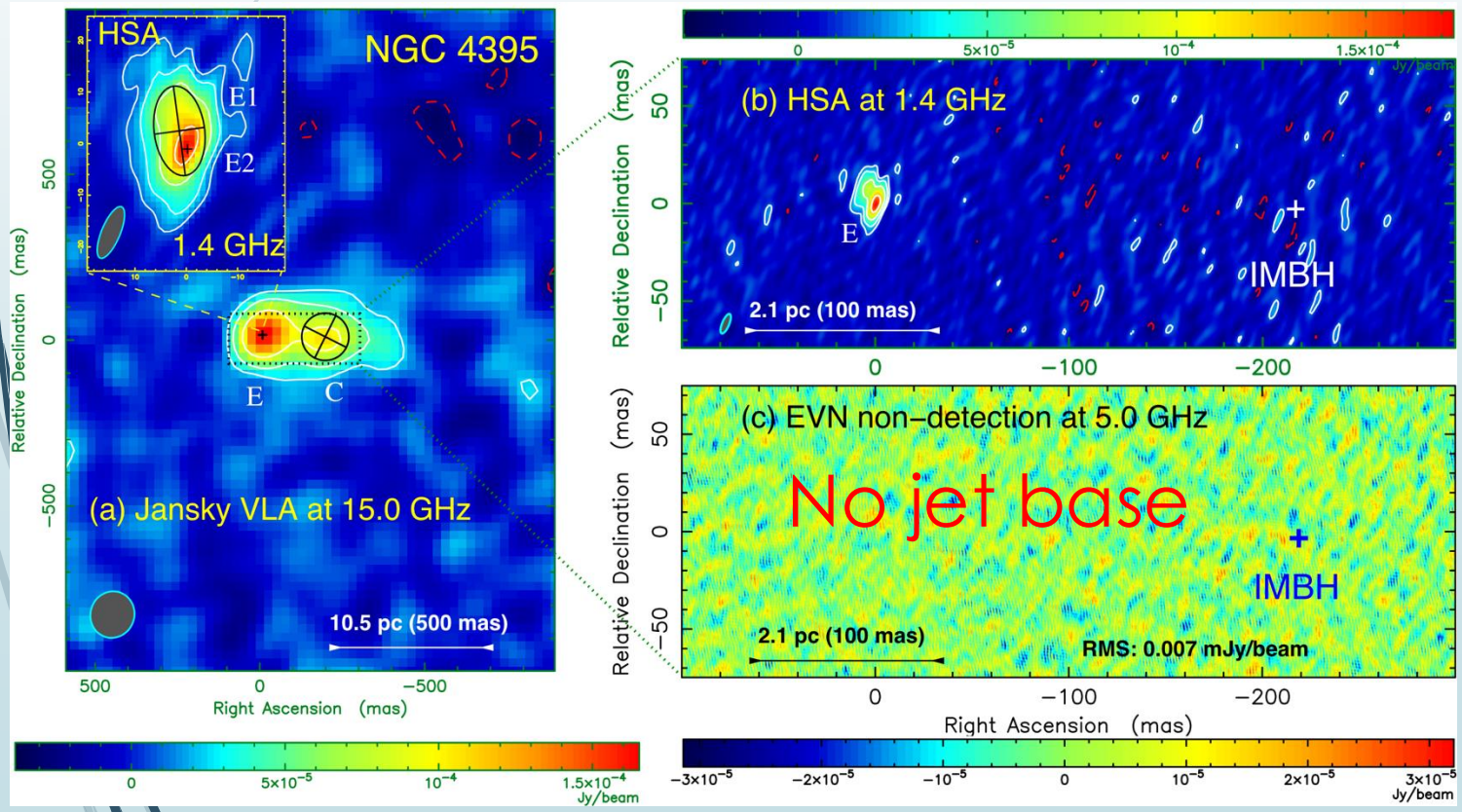

**Radio non-detections ≠ no IMBHs.**

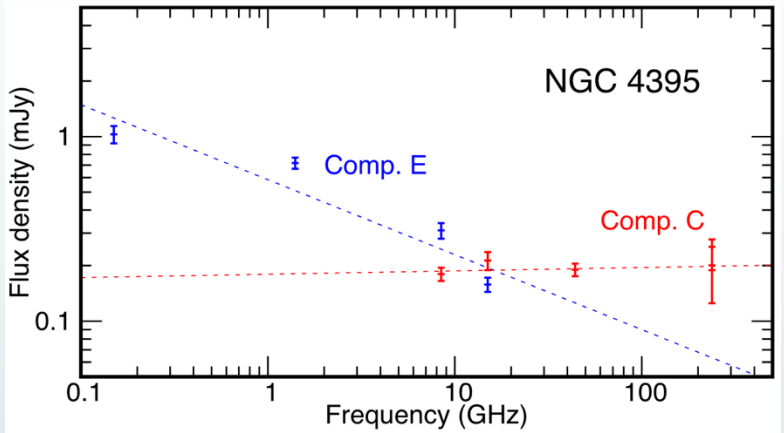


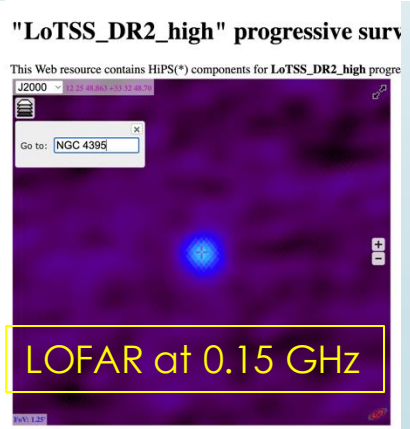



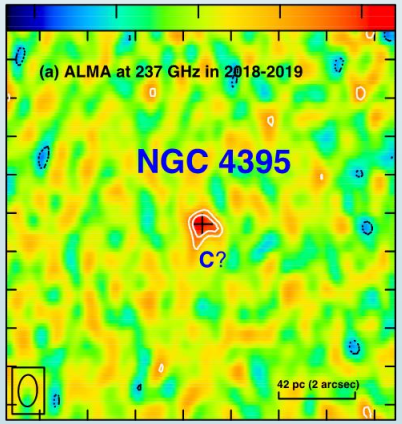
# 2.2 Revealing a pc-scale flat-spectrum radio nucleus

E: Non-thermal radio emission with a steep spectrum.
C: Near the optical centroid (+). Non-detection in the VLBI maps



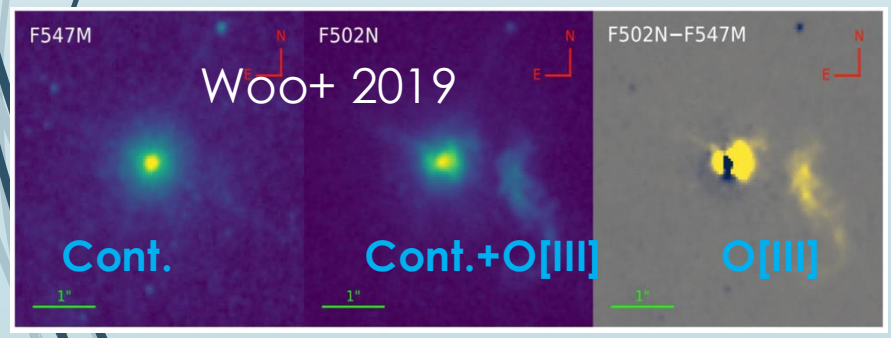



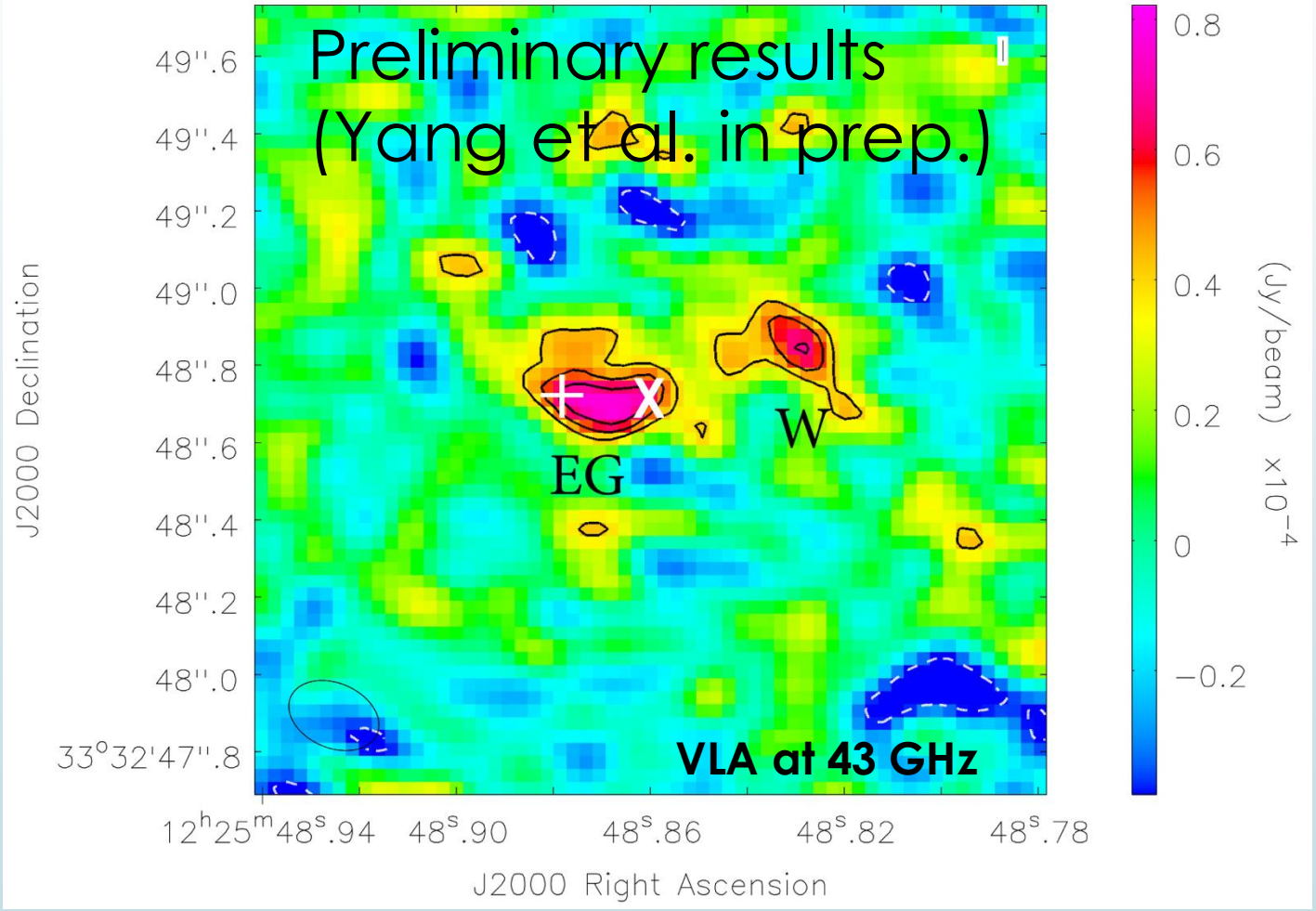




Reference: Yang et al. 2022

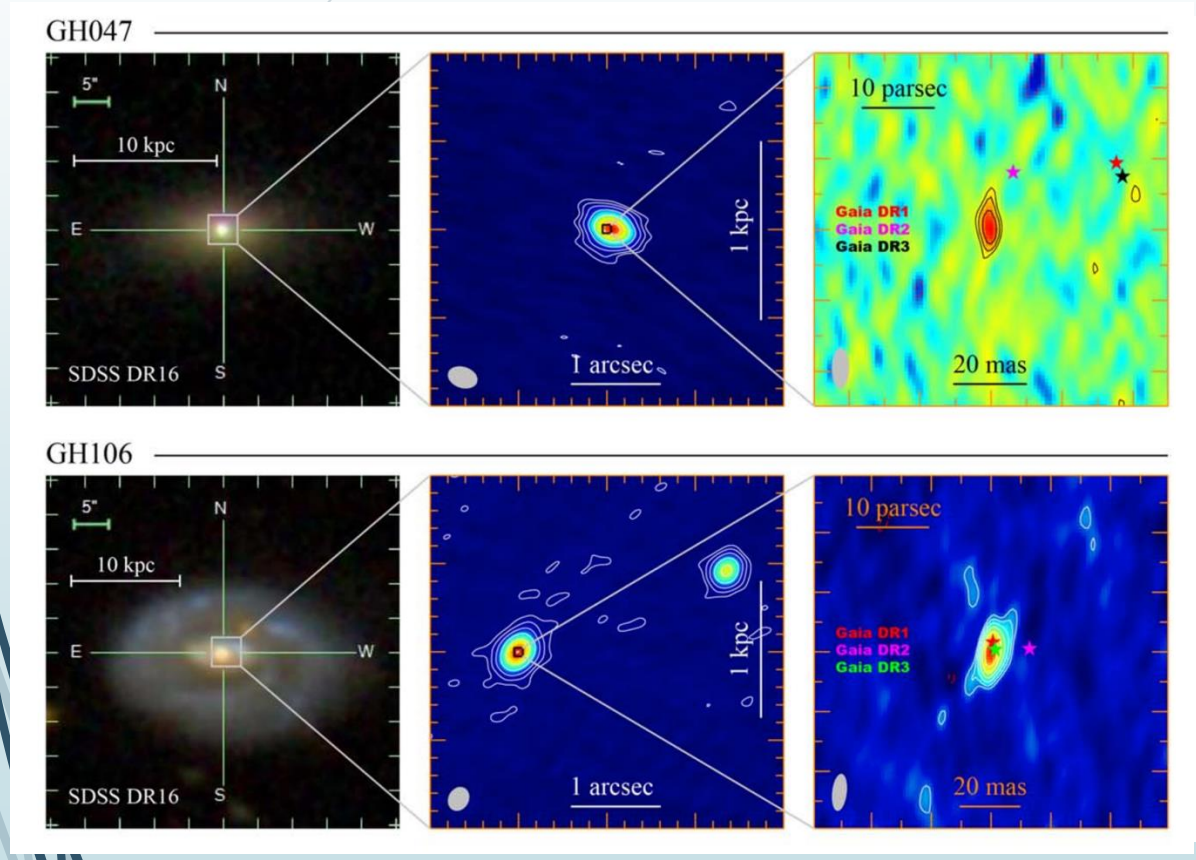
# NGC 4395: detection of a polar outflow

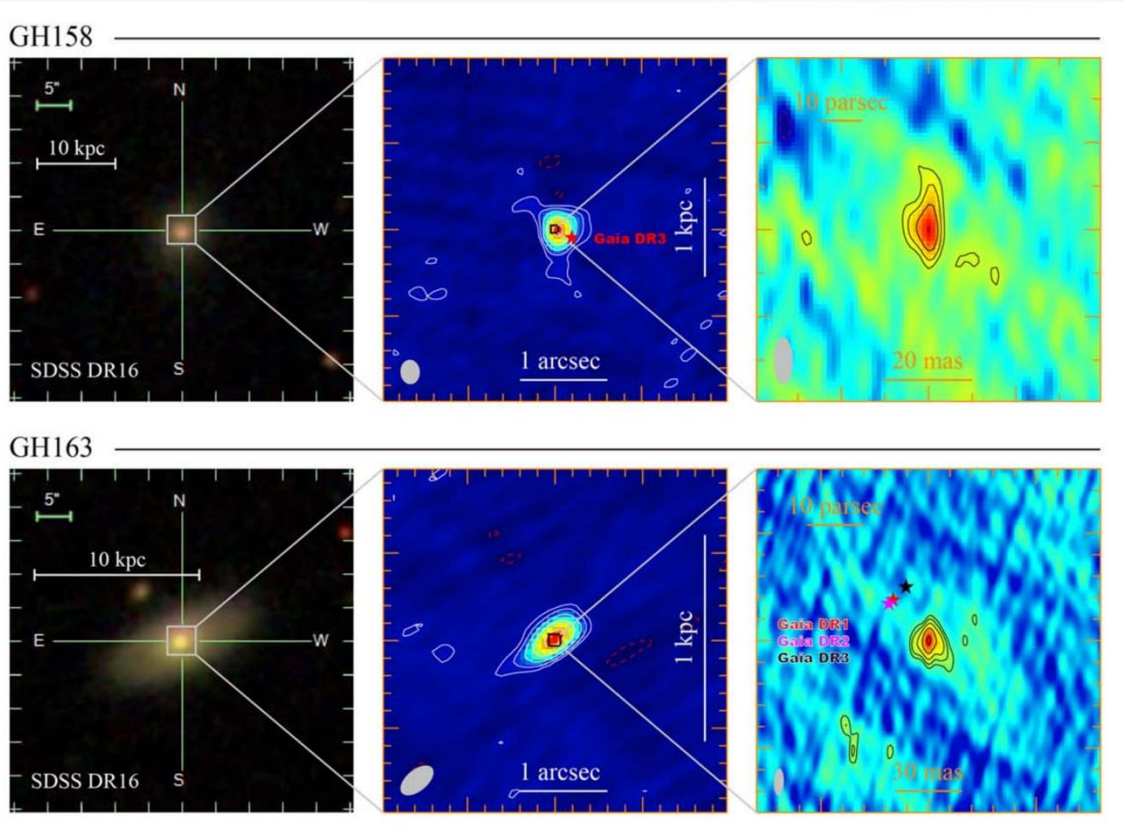
- Revealing a two-sided structure
  - Radio component E (HSA): +
  - Optical centroid (Gaia position): X
  - Peak brightness: 85 uJy/beam.
  - Map RMS: 13 uJy/beam.
  - Contours: (-3, 3, 4, 5) x RMS.
- Components EG and W are consistent with the O[III] outflow direction. revealed by HST observations (Woo+ 2019).
- Component E: a terminal shock resulting from a polar outflow.



## 2.3 More VLBA detections of steep-spectrum features from the sample of Greene & Ho (2004) — IMBH ejecta.

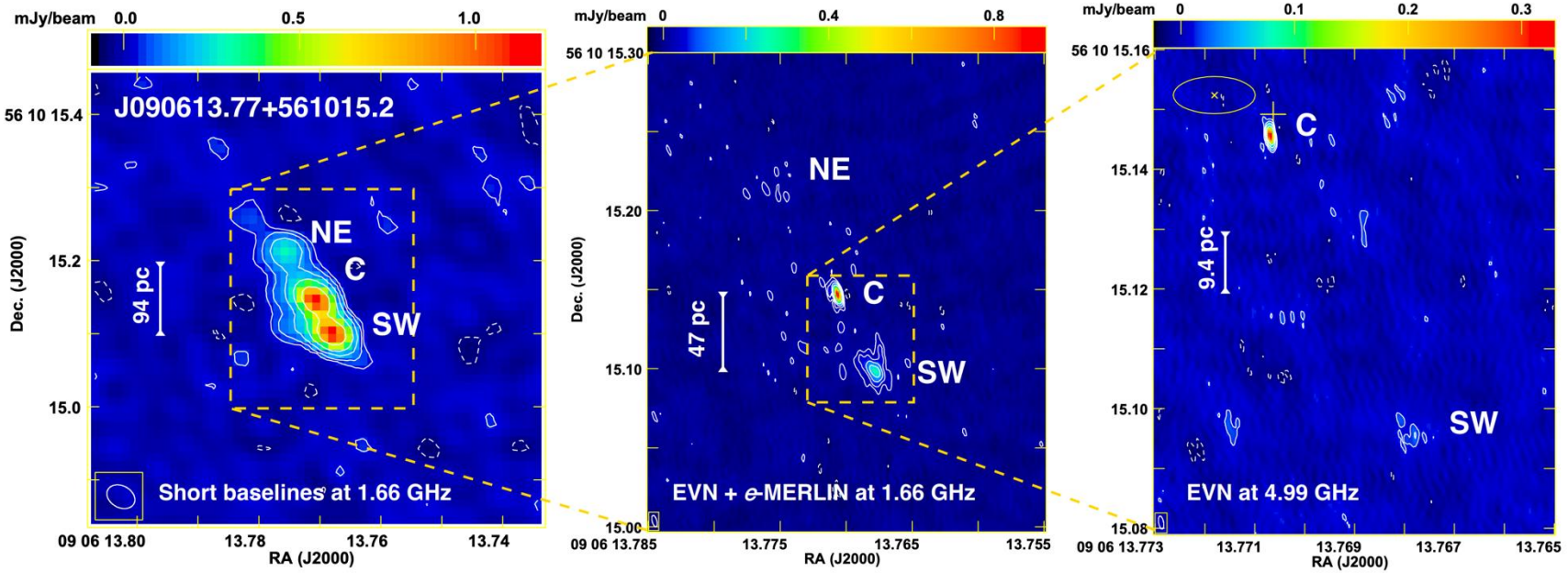


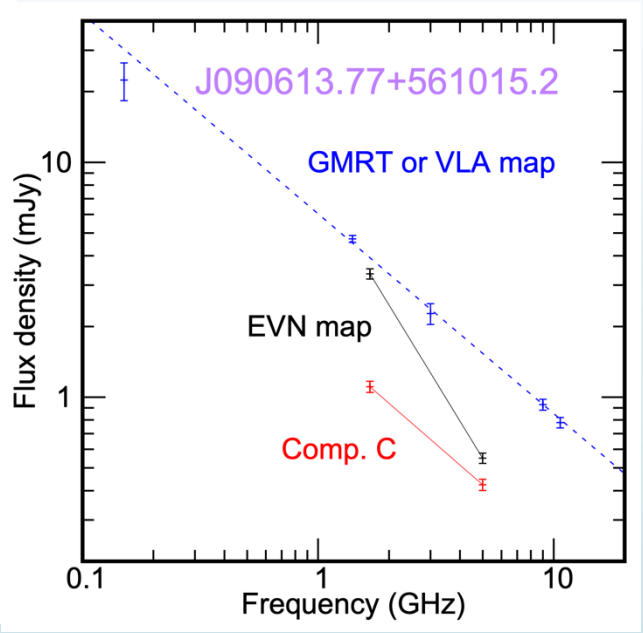




Xiaolong Yang et al, 2022, ApJ, 941, 43

# 2.4 Discovery of an episodic, powerful and large-scale Jet

- **SDSS J0906+5610**: A dwarf galaxy at z= 0.0465 (Source ID: 9, Reines et al. 2013).
- $M_{BH}= 3.6^{+5.9}_{-2.3} \times 10^5 M_{sun}$(including systematic uncertainty, Baldassare et al. 2016).

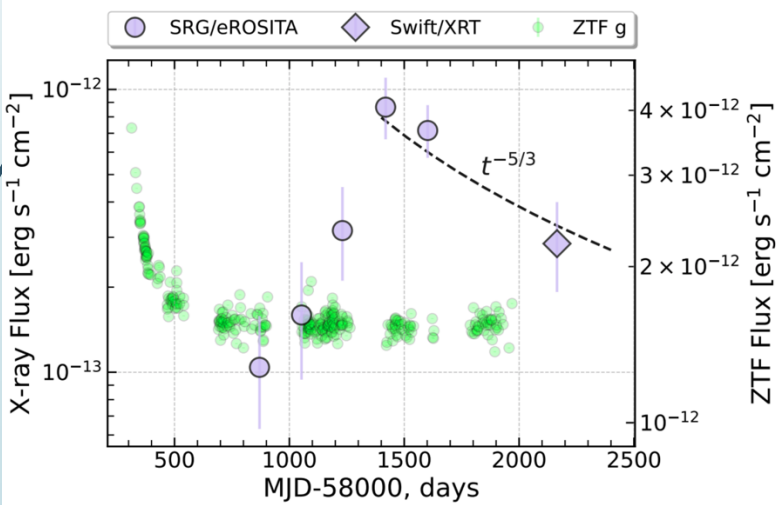


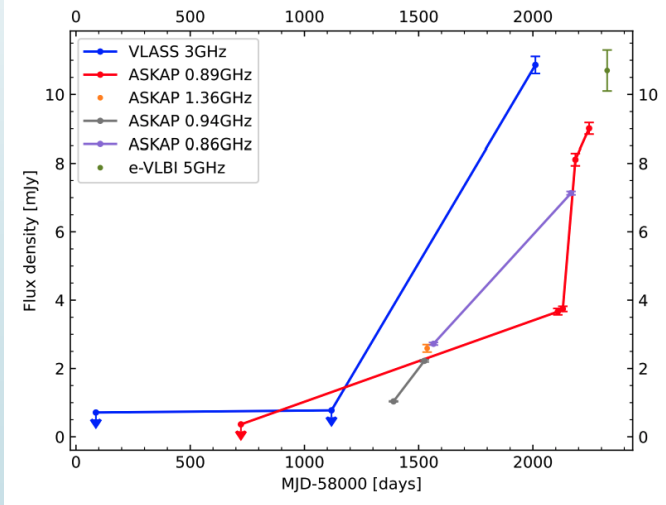



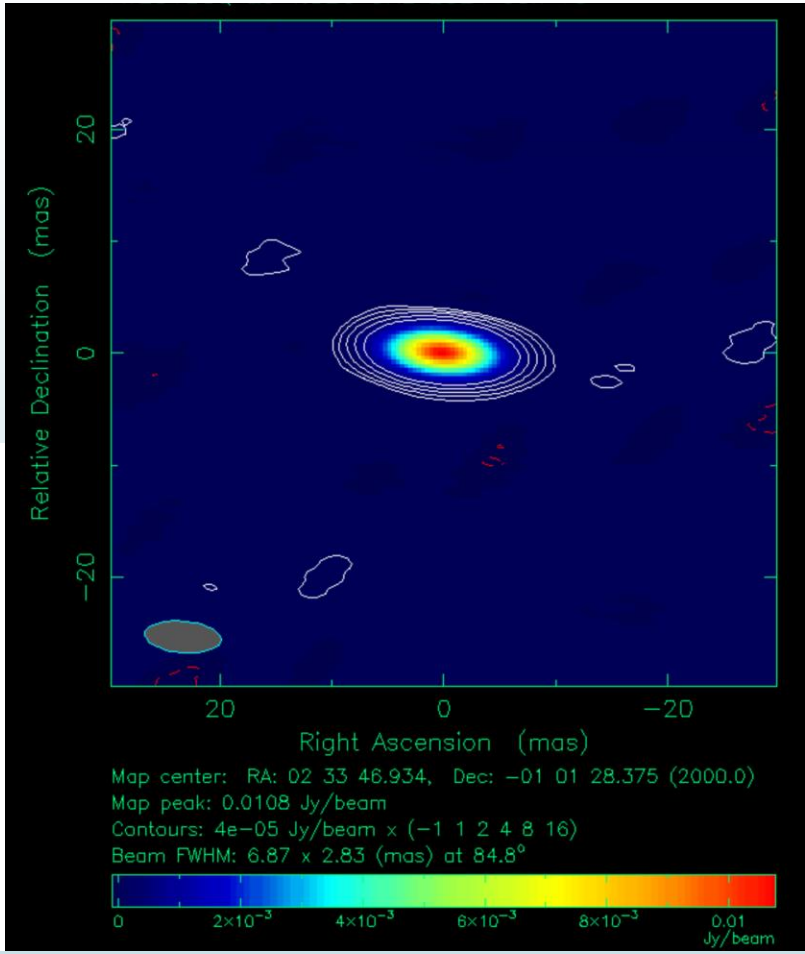

- **A clearly seen two-sided jet structure** with respect to the optical *Gaia* position (yellow plus).
- Component C shows an elongated structure and a steep spectrum. So, it is a relatively new ejecta instead of a jet base.

# 2.5 Locating a candidate IMBH via a TDE

- **AT2018cqh** was identified as a TDE by eROSITA X-ray observations in the dwarf galaxy SDSS J023346.93−010128.3 at $z$ = 0.048 (Bykov+2024).
- Candidate IMBH $\mathbf{M_{bh}}$: **~$10^{5.8}$ $\mathbf{M_{sun}}$**
- Detected a compact feature near the Gaia position with the EVN at 5 GHz on 2024 Jan 16.
- More follow-up observations are ongoing.



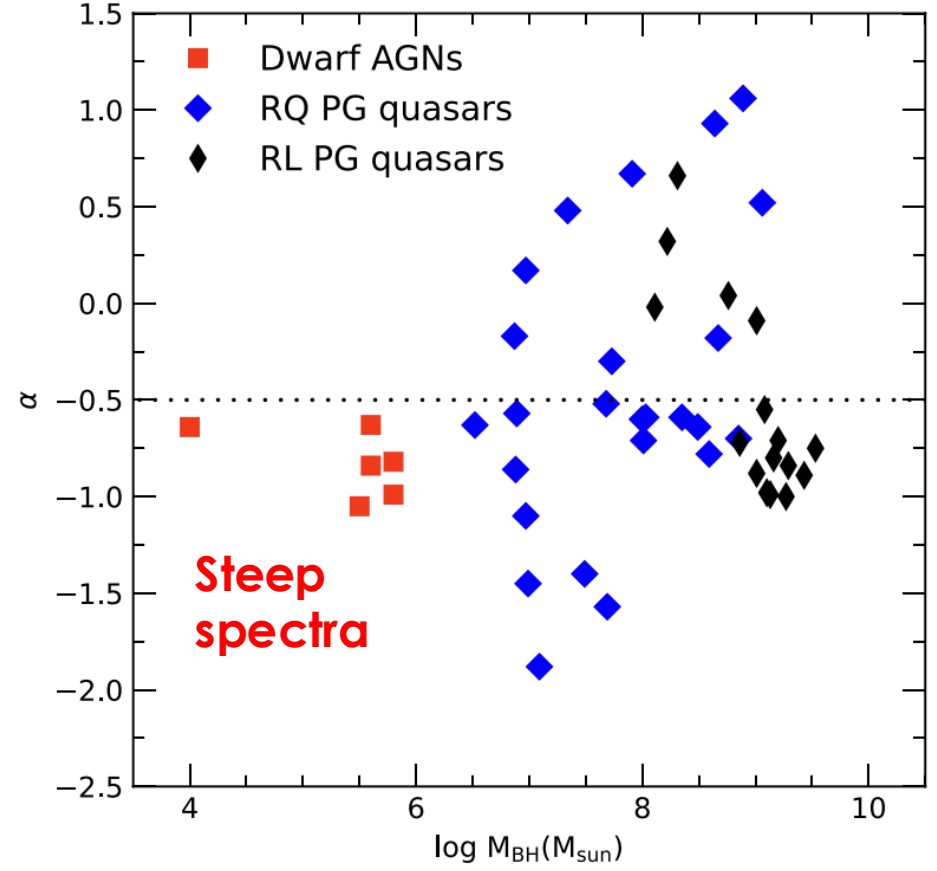



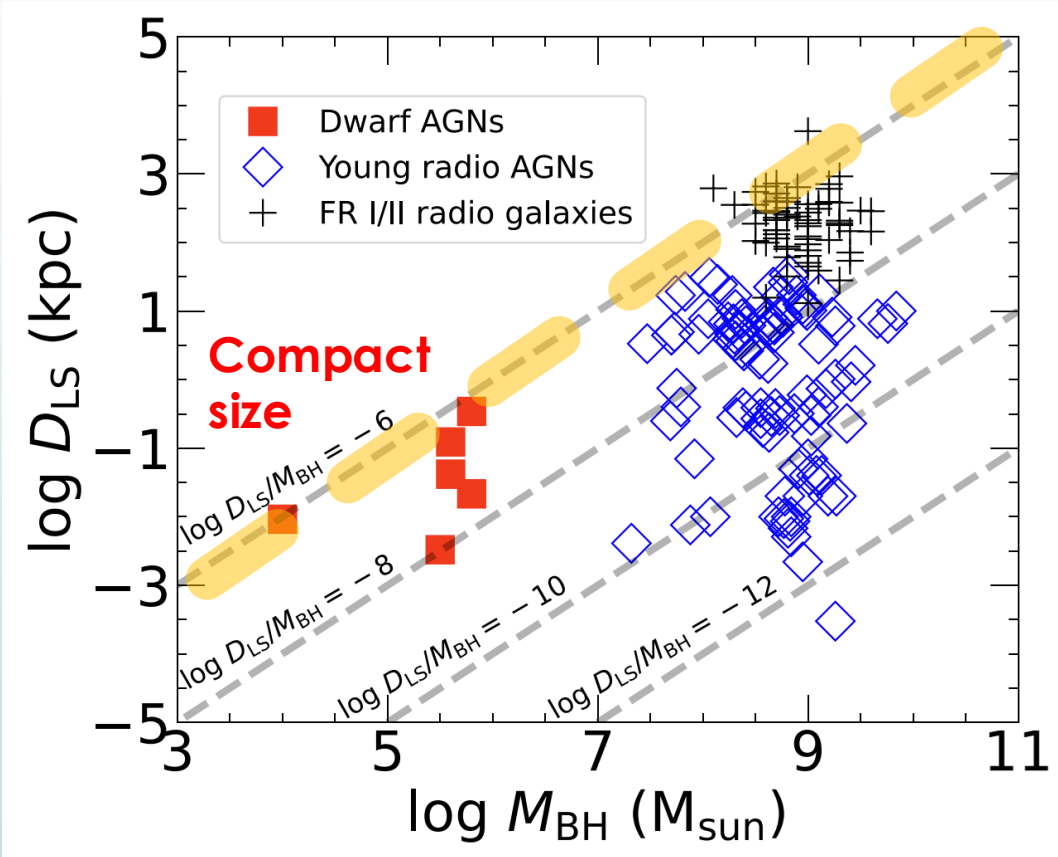



# 2.6 Jet activity vs BH mass

Left: Radio spectral index versus BH mass.
Right: maximum linear size of jets on cosmic timescales.

Six VLBI-detected dwarf AGNs
- NGC 4395
- SDSS J0906+5610
- Four GH sources(Yang et al. 2022)

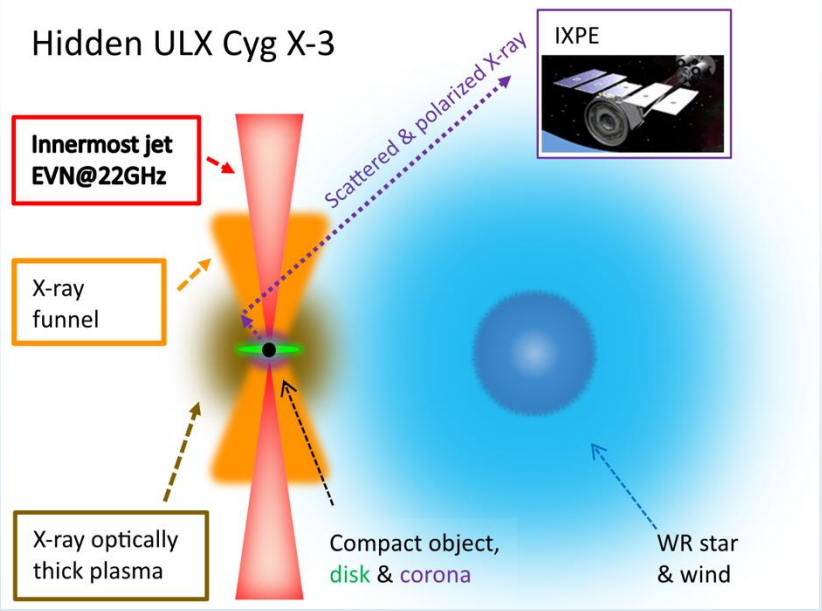


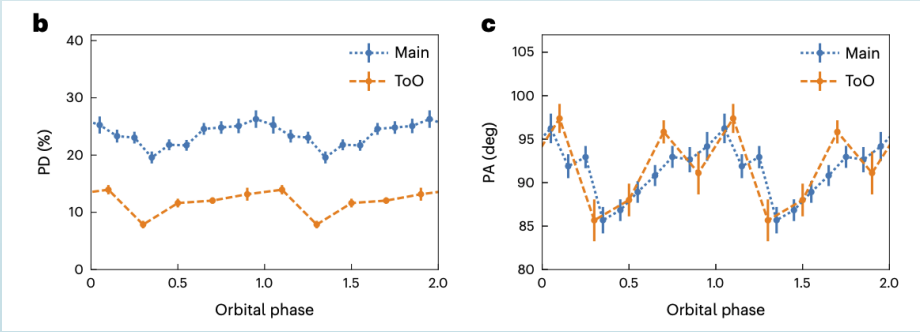

- Radio loud and quiet PG quasars selected by Laor et al. (2019).
- $D_{LS}$: projected linear size of a two-sided jet. Have some systematic errors (e.g. Tb et al.)..

# 3. The innermost jet in the hidden ULX Cyg X-3

- A high-mass X-ray binary system with a compact object accreting matter from a Wolf-Rayet star (van Kerkwijk et al. 1992).
- Short orbital period: 4.8 h (Parsignault et al. 1972).
  - Inclination angle: 30° (Antokhin, et al. 2022).
- Distance: 9.7±0.5 kpc from VLBI parallax (Reid & Miller-Jones 2023).
- Strong variability from radio to Gamma-ray wavelengths.
- Latest identification: an off-axis ULX by X-ray polarisation detection with IXPE (Veledina+ 2024a, 2024b).
  - High X-ray polarisation is due to Compton scatter along the outflow direction instead of the accretion disk.
  - Along the direction of the narrow X-ray funnel, X-ray luminosity would be boosted from the apparent $2\times10^{37}$ to a very high value of $>5\times10^{39}$ erg $s^{-1}$.
  - **X-ray funnel**: viewing angle ~30 deg and half opening angle <15 deg.

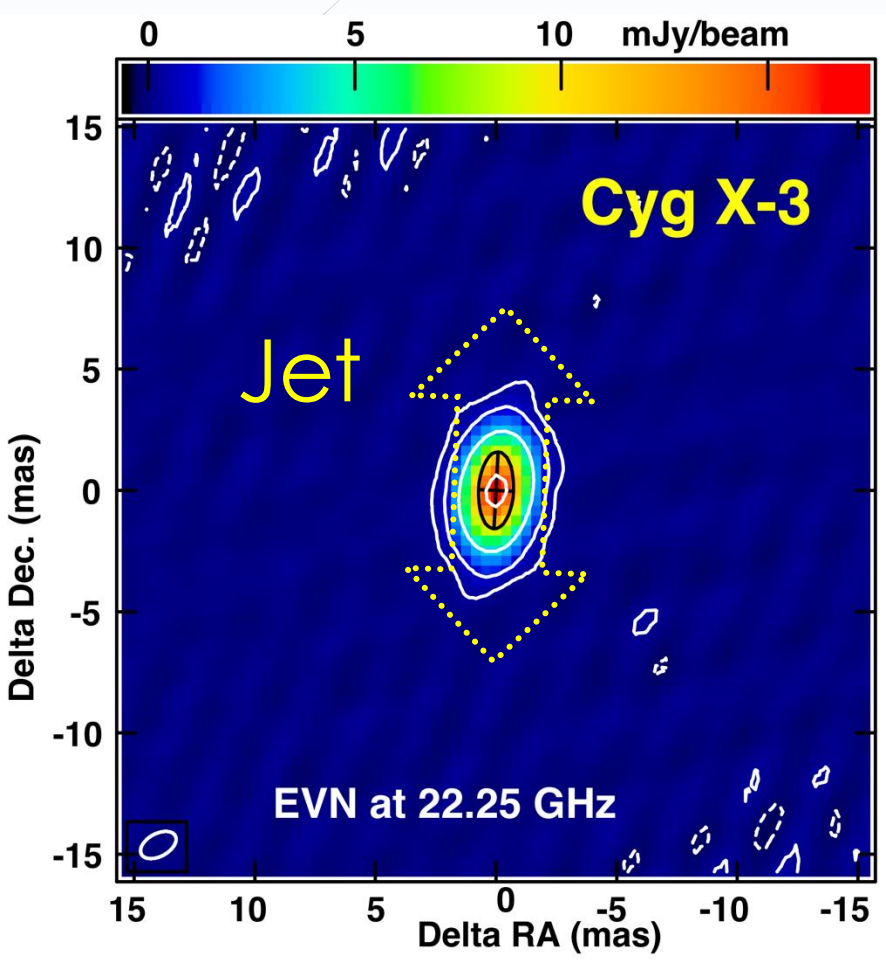



*IXPE*: the Imaging X-ray Polarimetry Explorer.

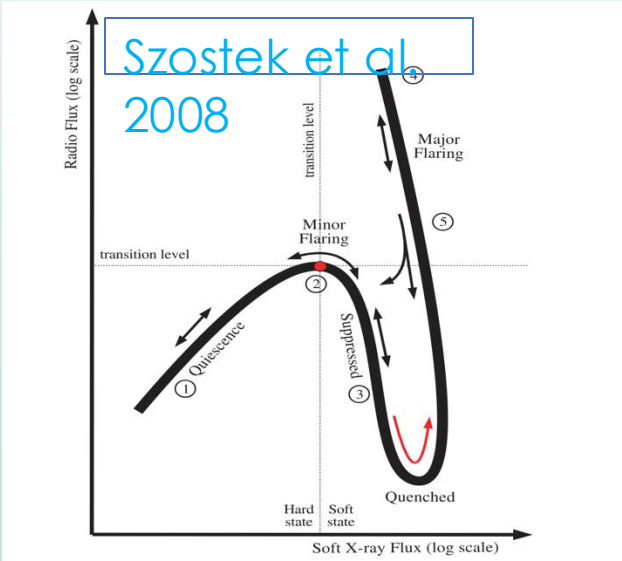


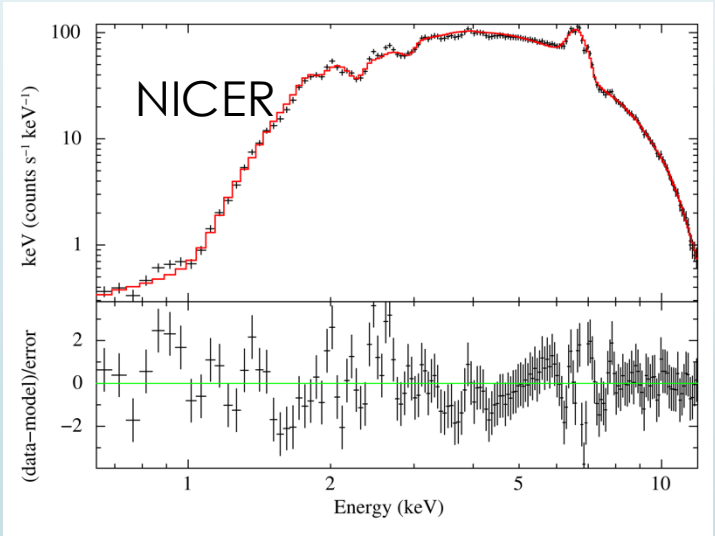

*IXPE* polarimetry (Veledina+ 2024)

# Detection of an elongated jet during X-ray quiescent state




- Total flux: ~80 mJy
- Jet length: 3.2 mas (projected size ~25 au).
- Jet PA: -3.1±0.4 deg. This is perpendicular to X-ray polarization PA (~90 deg) observed by IXPE from hard ultra-soft X-ray state (Veledina et al. 2024a, 2024b).



# Summary

- Found the smoking gun evidence for episodic, large-scale and powerful jet activity from IMBHs for the first time. VLBI-detected diffuse features in the GH sample might be also interpreted by optically thin ejecta from short-lived and compact IMBH jet activity.
- Detected a warm polar outflow in the pc-scale radio nucleus of NGC 4395. To date, this is not reported in any other AGNs.
- Located a candidate IMBH from the TDE AT2018cqh. This is also a promising method to uncover some unprecedented IMBHs (wandering IMBHs, binary systems, ...).
- Revealed the innermost jet in Cyg X-3 during the quiescent state and provided independent support for the ULX identification.