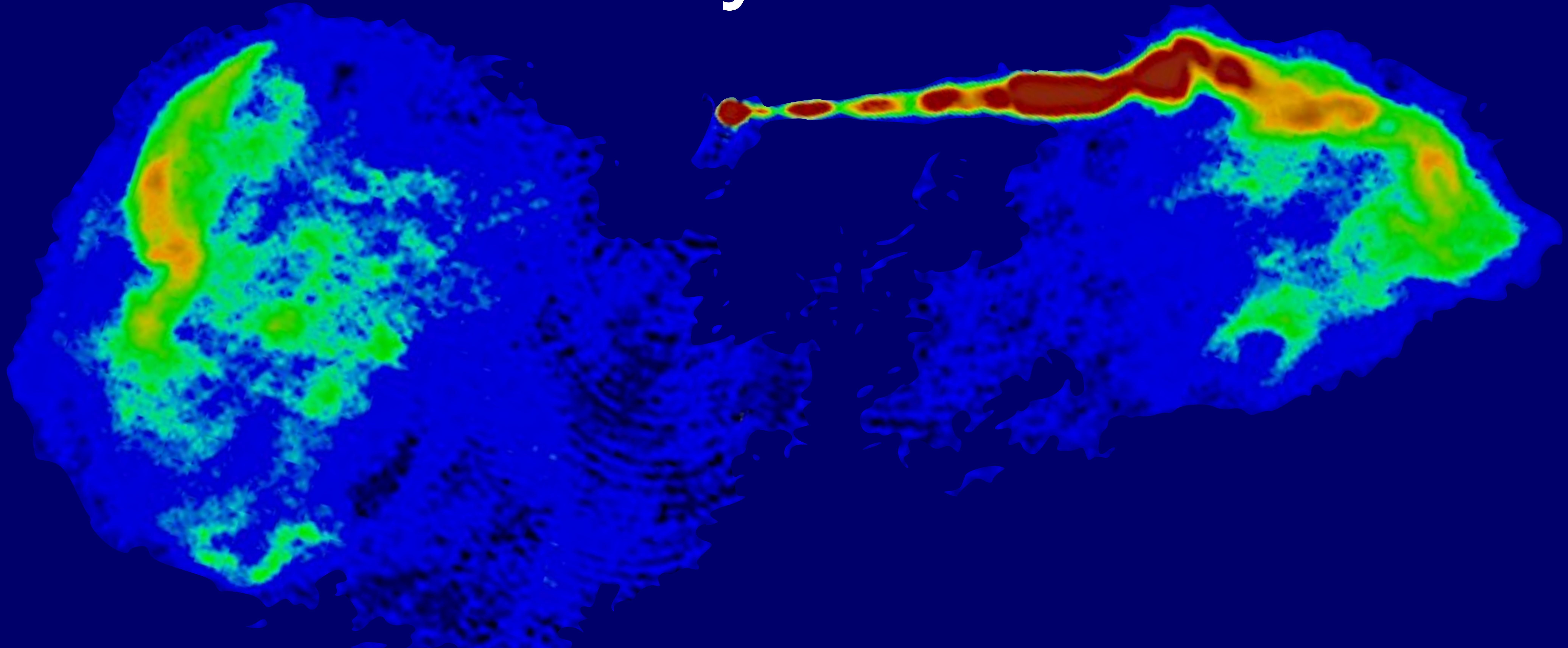
Detection of Superluminal Motion in the X-ray Jet of M87



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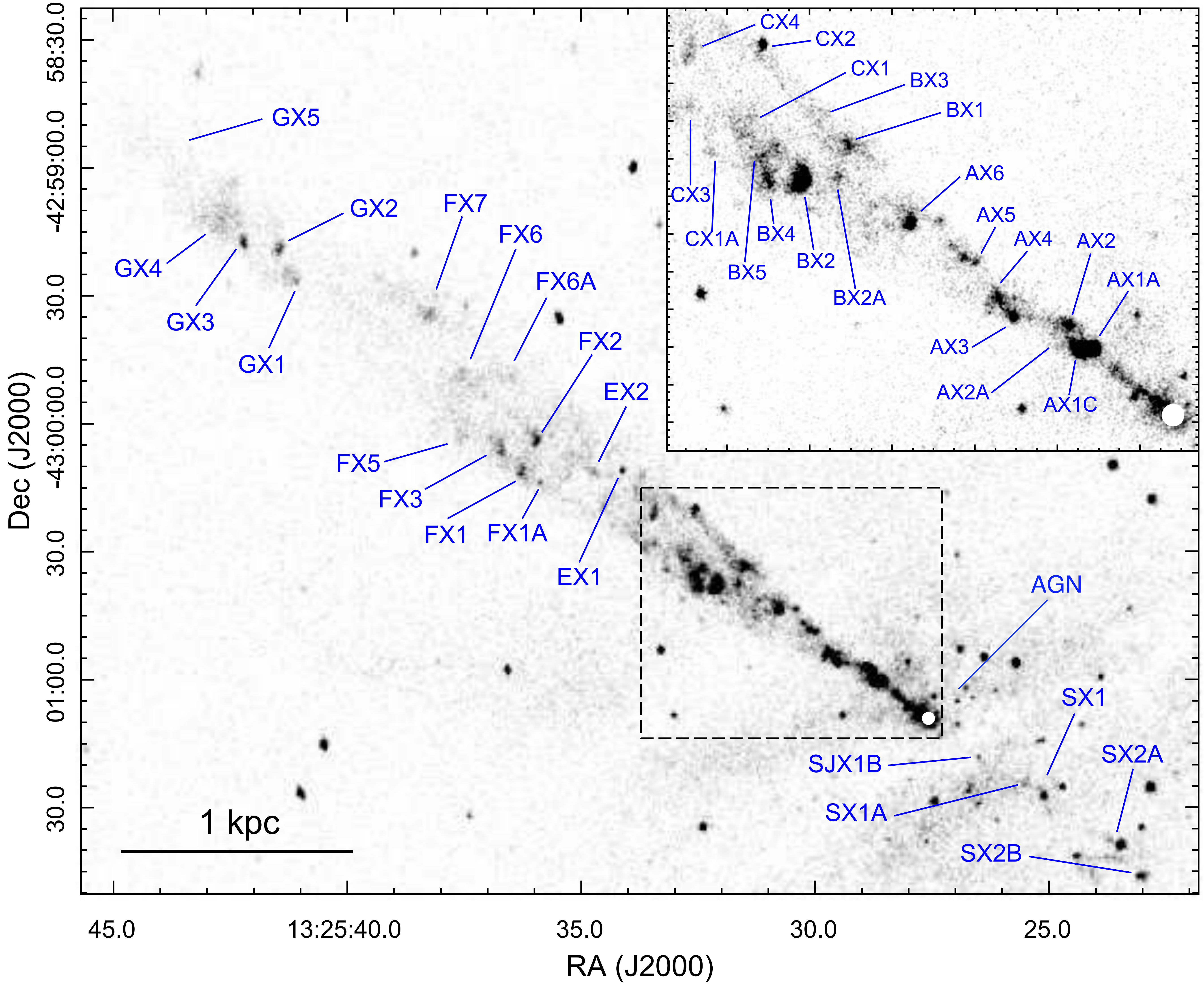
VLA/K.Reid

Radio Galaxy Jets

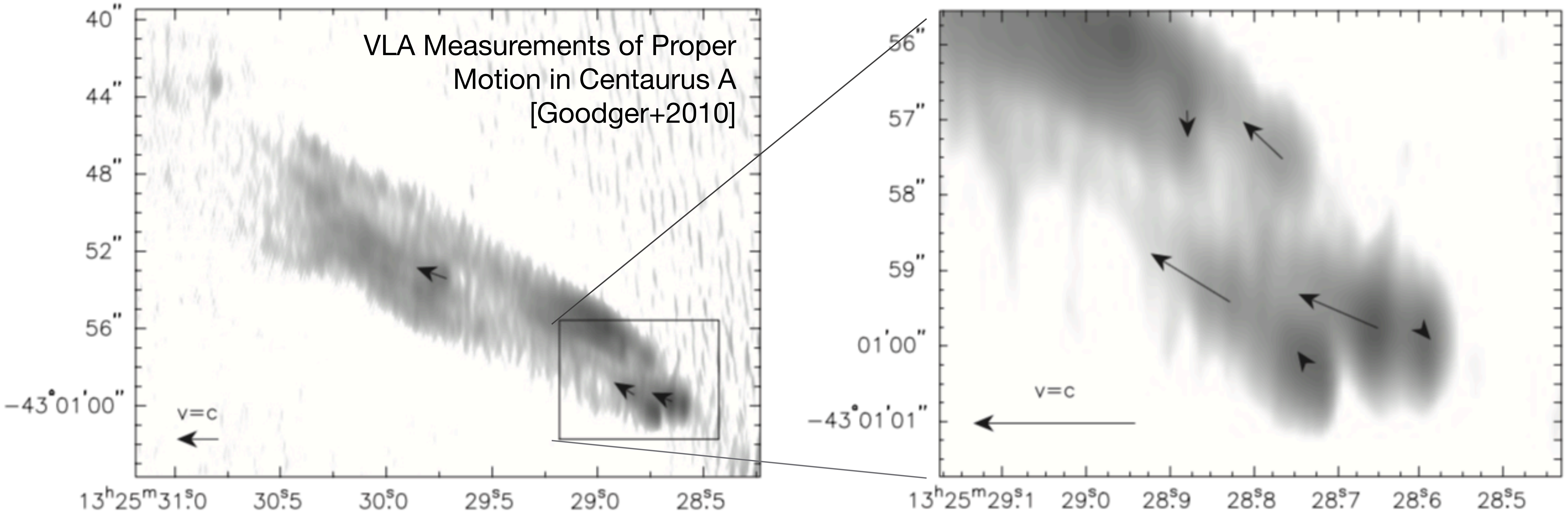
- Numerous radio galaxies known to have kiloparsec-scale jets
- Knotted structure in nearby jets observed in multi-wavelength observations
- Explore knot origins by investigating proper motion and variations in brightness of knots

0.9–2.0 keV, Exposure-Corrected Image of Centaurus A [Snios+2019]



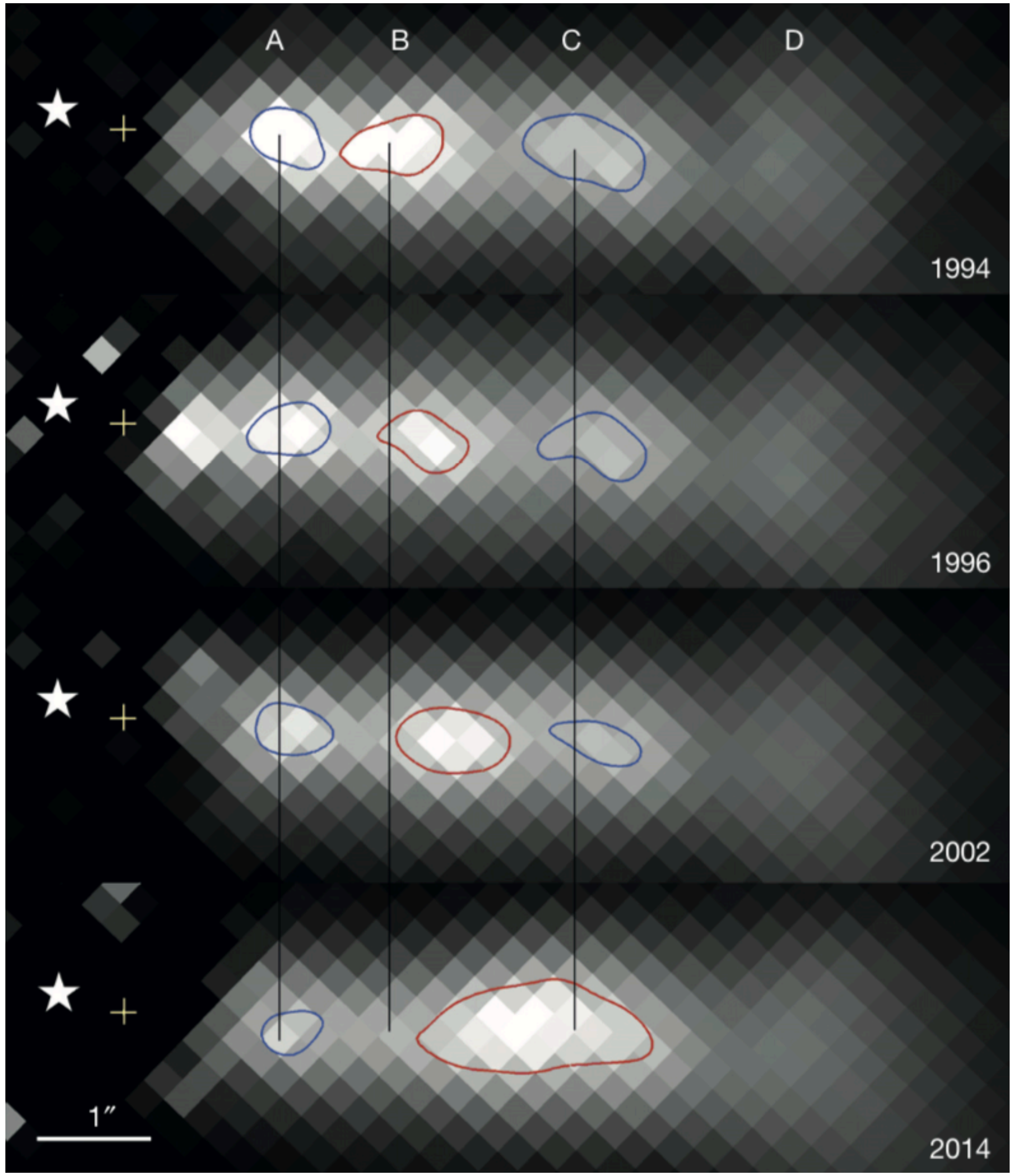
Proper Motion Studies

- Proper motion measurements limited to nearby, fast jets
- Majority of studies performed in radio, optical, and UV
- Previously no proper motions observed in X-ray jets



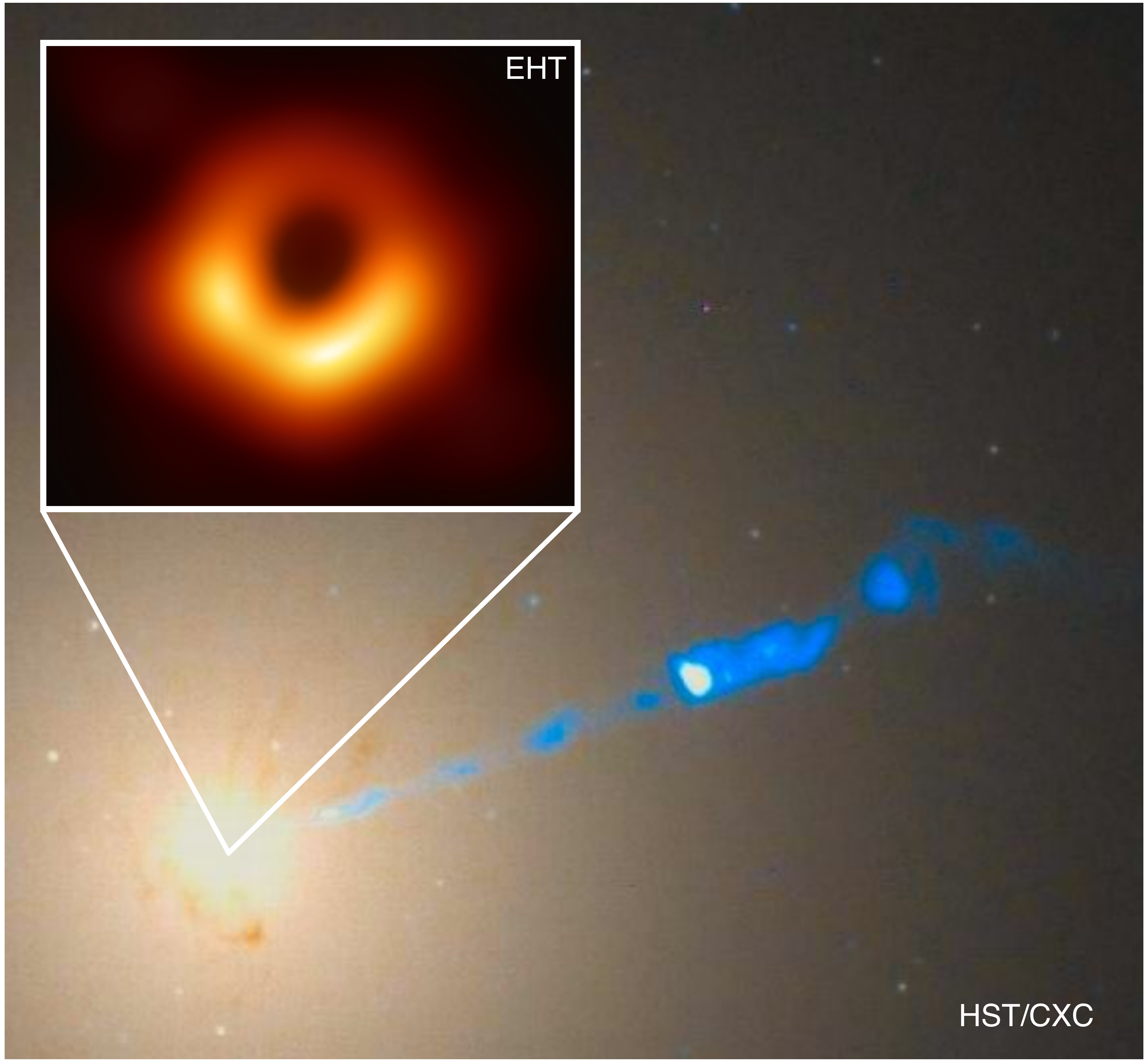
VLA Measurements of Proper Motion in Centaurus A [Goodger+2010]

HST Detection of Proper Motion in 3C 264 [Meyer+2015]



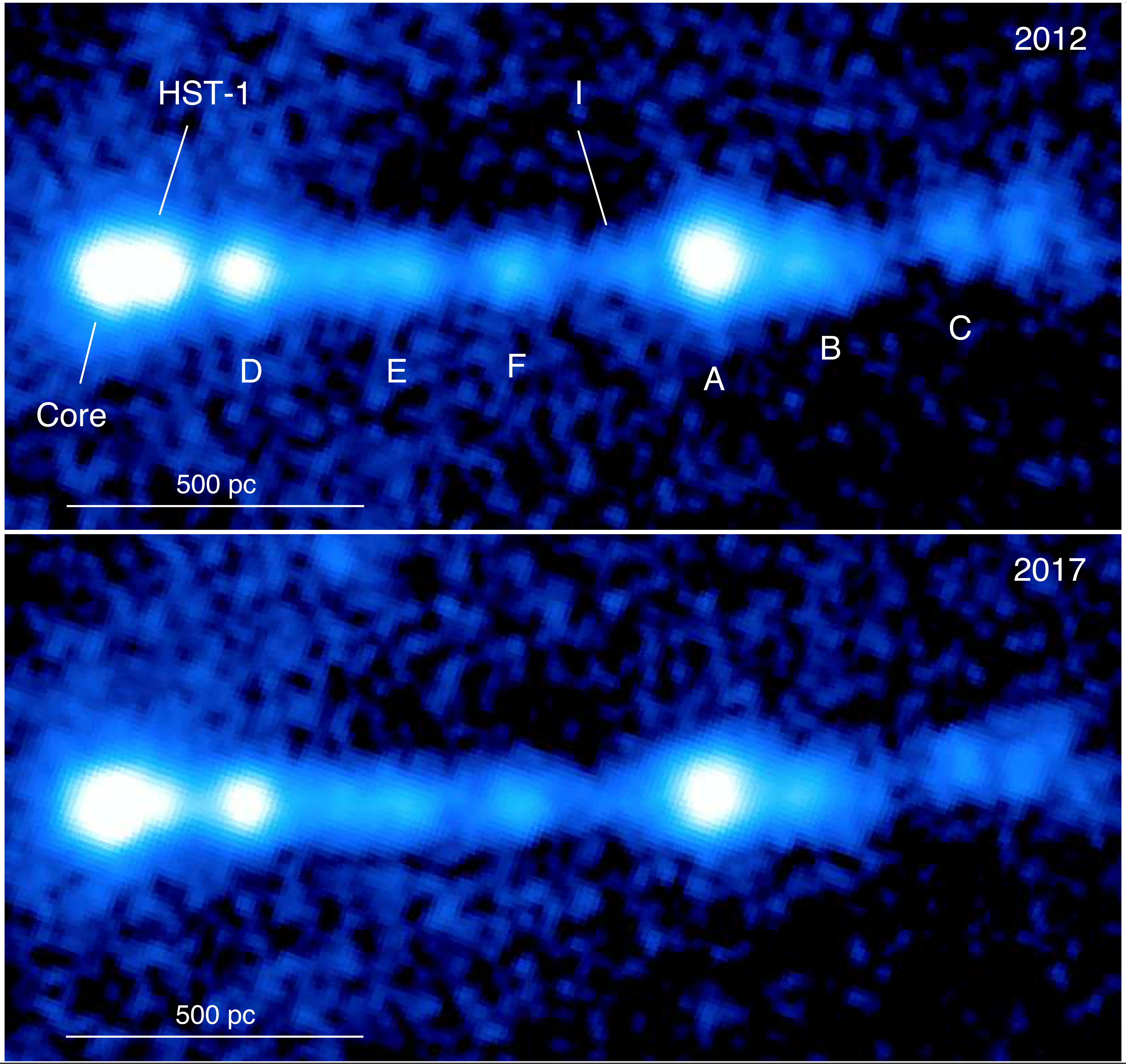
X-ray Knots in M87

- Bright, nearby FR I radio galaxy (16.4 Mpc; 81 pc arcsec^{-1})
- Prominent jet and knotted structure observed in radio, optical, UV, and X-rays
- Proper motion of its jet extensively studied in radio and optical/UV [Meyer+2013]
- Previously no proper motions observed in X-rays



Data Analysis

- Examined *Chandra* HRC observations of M87 taken over 5-year timespan (2012-2017)
  - HRC observations required for higher spatial resolution and to avoid pile-up
- Images co-aligned to high accuracy using cross-correlation fit on background point sources



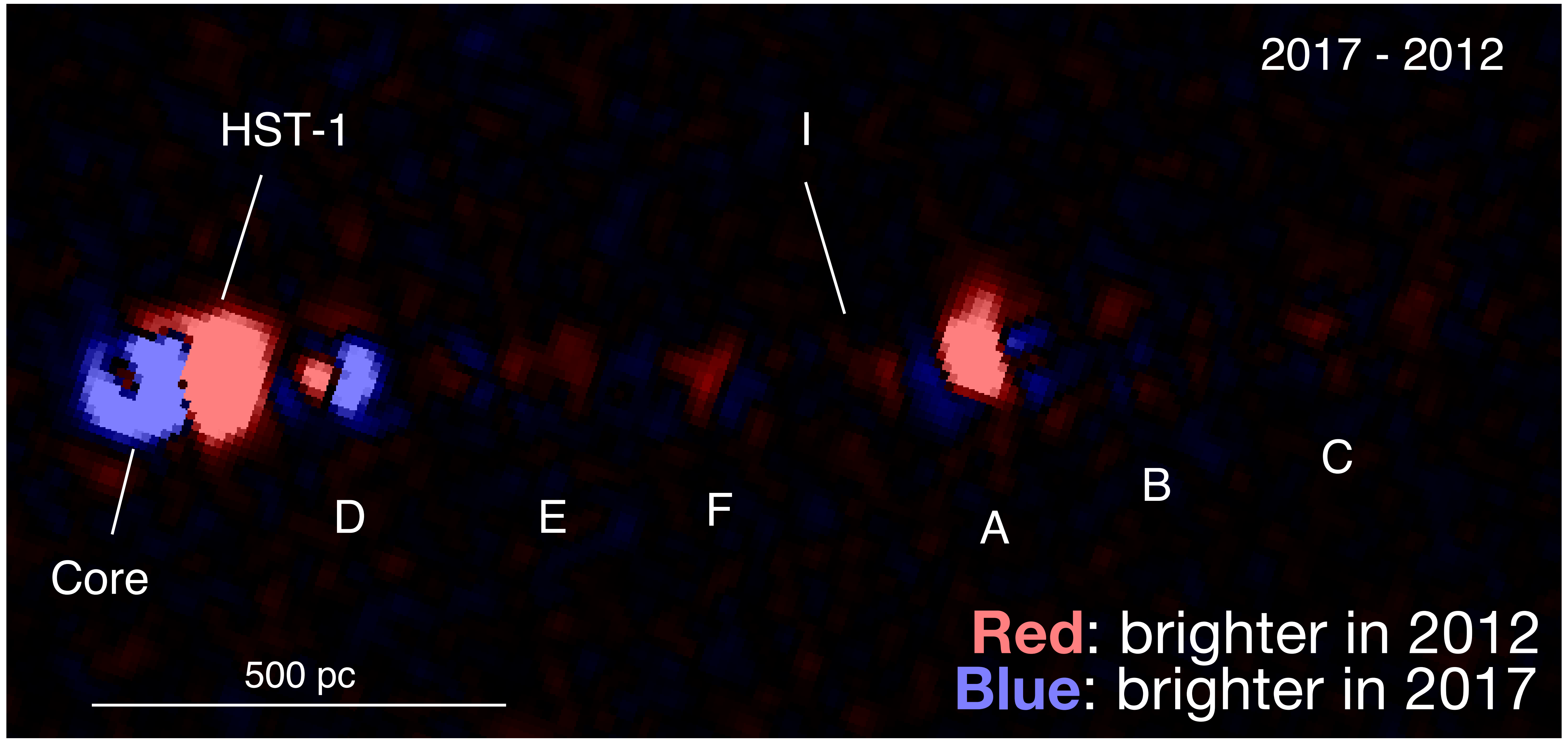
Proper Motion Measurements

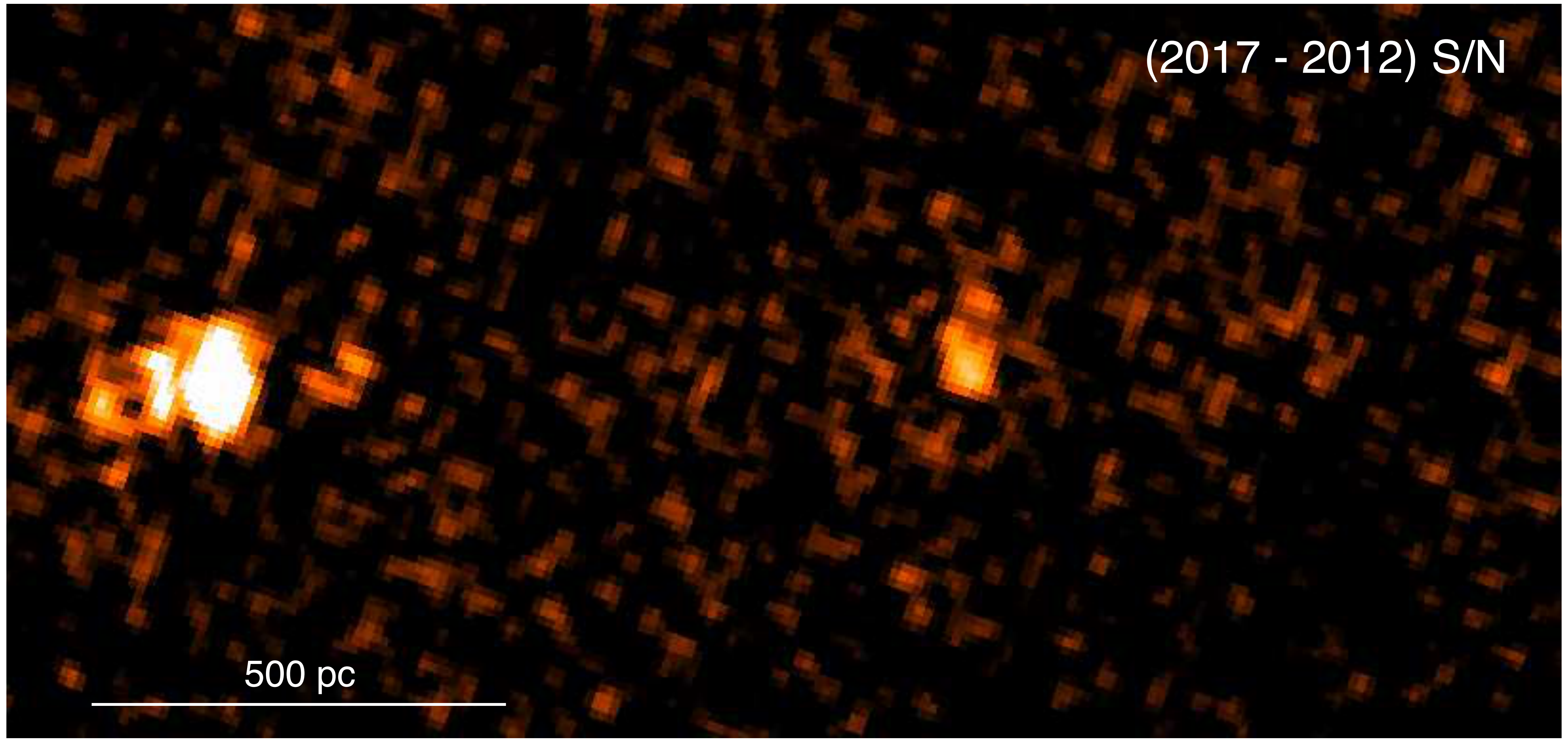
- Measured proper motion of each knot using cross-correlation fits
- Proper motion for Knot D:

$$\boldsymbol{v_{\parallel,D} = 9.2 \pm 2.3 \text{ mas yr}^{-1} = 2.4 \pm 0.6c}$$

$$\boldsymbol{v_{\perp,D} = 0.4 \pm 1.2 \text{ mas yr}^{-1} = 0.1 \pm 0.3c}$$

- Upper limits placed for outer knots (Knots E-C)
- Unable to fit HST-1 due to close proximity to AGN and significant brightness changes



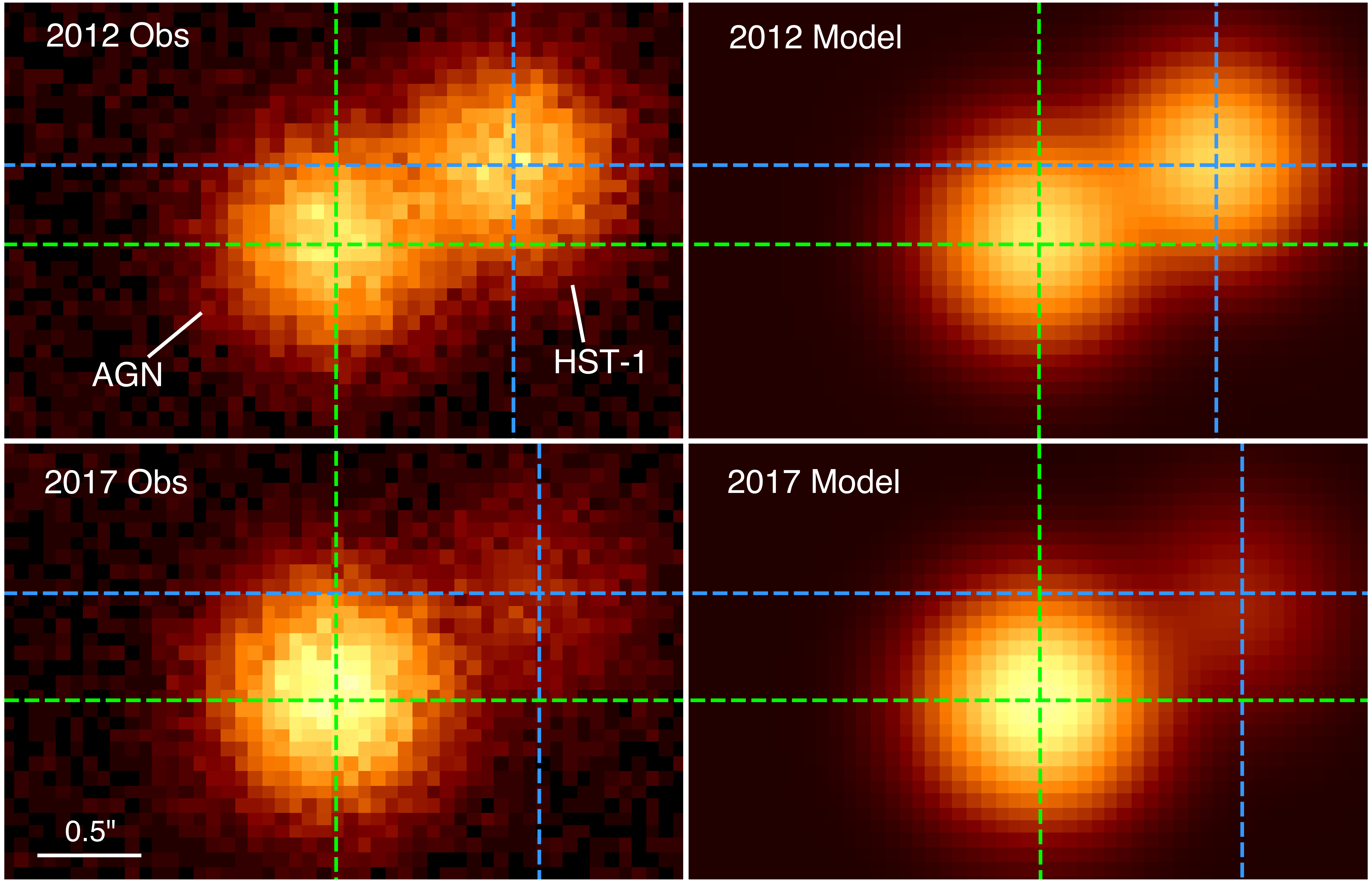


Proper Motion Measurements (II)

- AGN/HST-1 modeled as two, 2D Gaussians to quantify proper motion
- From model fits, shift in HST-1 was measured to be:

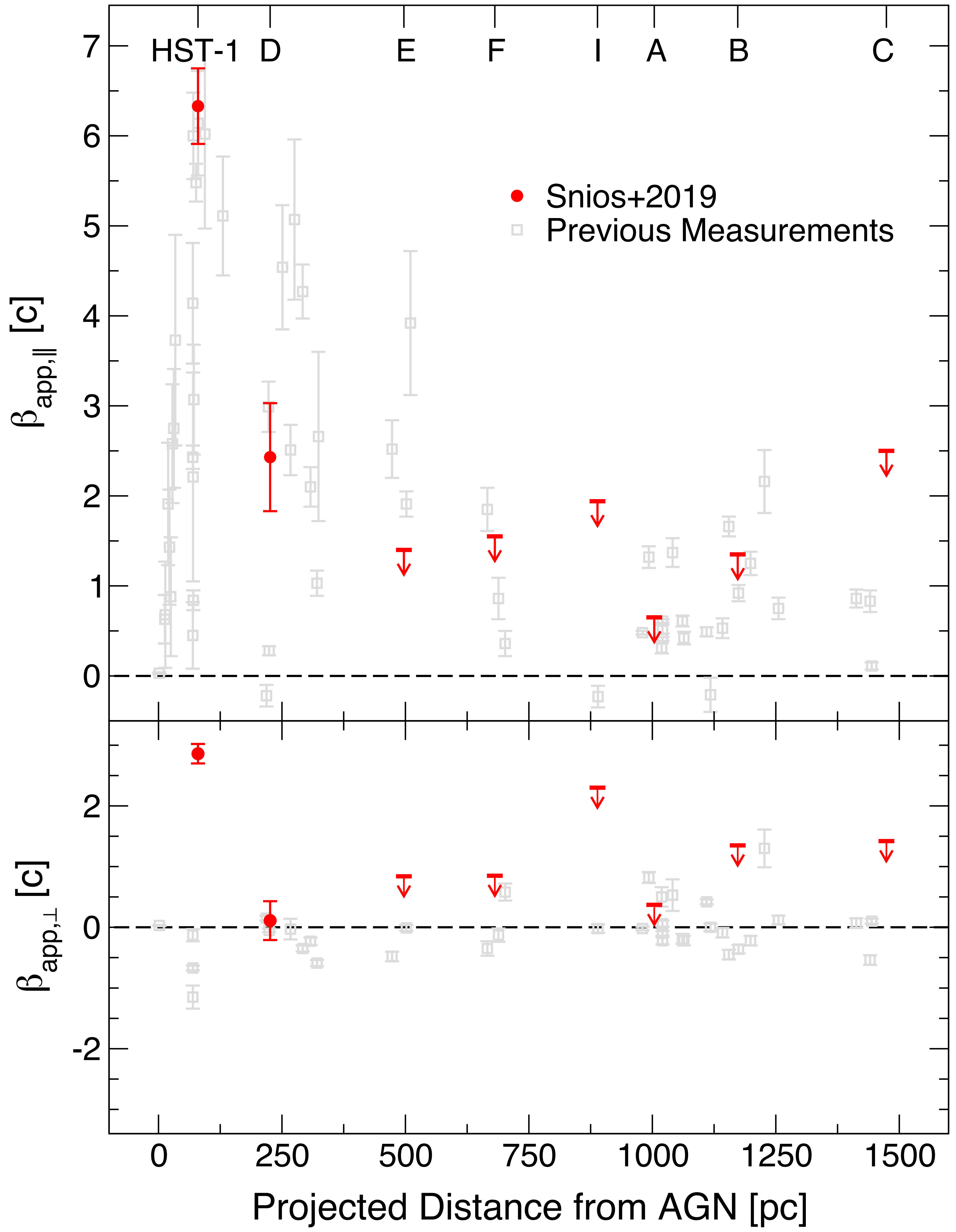
$$v_{\parallel,HST\text{-}1} = 24.1 \pm 1.6 \text{ mas yr}^{-1} = 6.3 \pm 0.4c$$

$$v_{\perp,HST\text{-}1} = 10.9 \pm 0.6 \text{ mas yr}^{-1} = 2.9 \pm 0.2c$$



Comparison of Proper Motions

- X-ray results compared with measurements from other wavelengths
- Results show excellent agreement for all knots
- Upper limits on outer knots close to other average proper motions
  - Follow-up observations as early as 2021 will provide a sufficiently long baseline to measure motion in majority of knots



Conclusions

- Difference maps for jet of M87 generated using *Chandra* HRC X-ray observations
- X-ray proper motion up to 24.1 mas yr^{-1} (6.3*c*) measured in the jet
- Results consistent to other wavelength measurements in both spatial positions and proper motion speeds
  - X-ray and UV/optical regions co-move in the jet
- Proper motion studies will increase as *Chandra* archive grows

For further details, see Snios et al., 2019, ApJ, 879, 8

Thank You