Famous Black Hole Has Jet Pushing Cosmic Speed Limit

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Superluminal velocity and synchrotron cooling of X-ray knots

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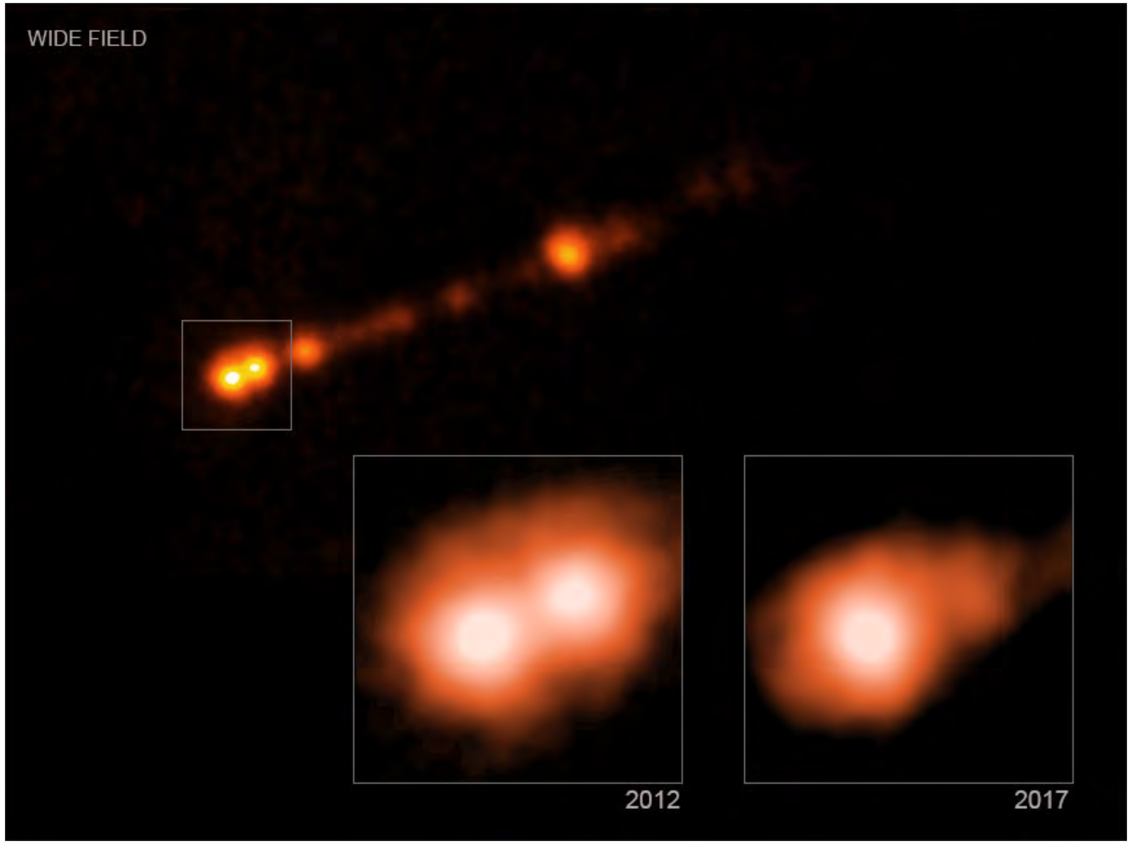
- Knot HST-1 and knot D of the M87 jet moving with *apparent superluminal velocities* of 6.3c and 2.4c.
- Actual jet velocities are 0.997c (HST-1) and 0.927c (D)
- Consistent with the previously measured motions of the optical, ultraviolet, and radio components.
- Knot HST-1 shows significant temporal variability consistent with synchrotron cooling
- **Strongest *direct* evidence to date that underlying flow is relativistic**
- **Relativistic flow can carry enormous energy**



Smooth Chandra/HRC observation of M87 jet

Jets, black holes, and the formation of structure – a question of scales

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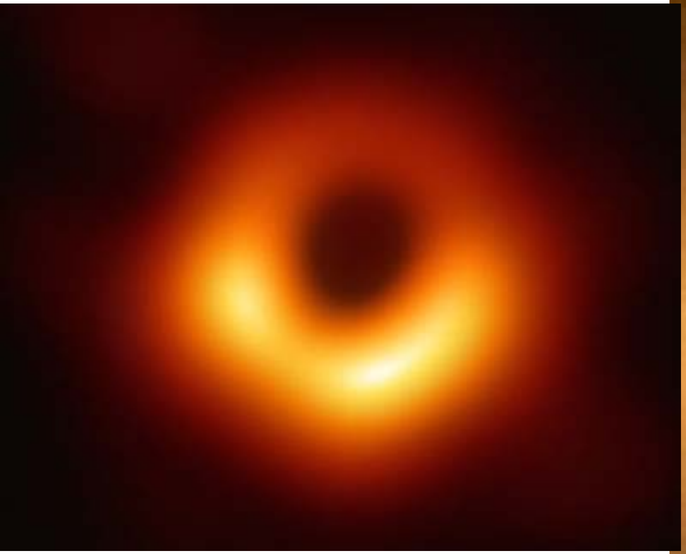
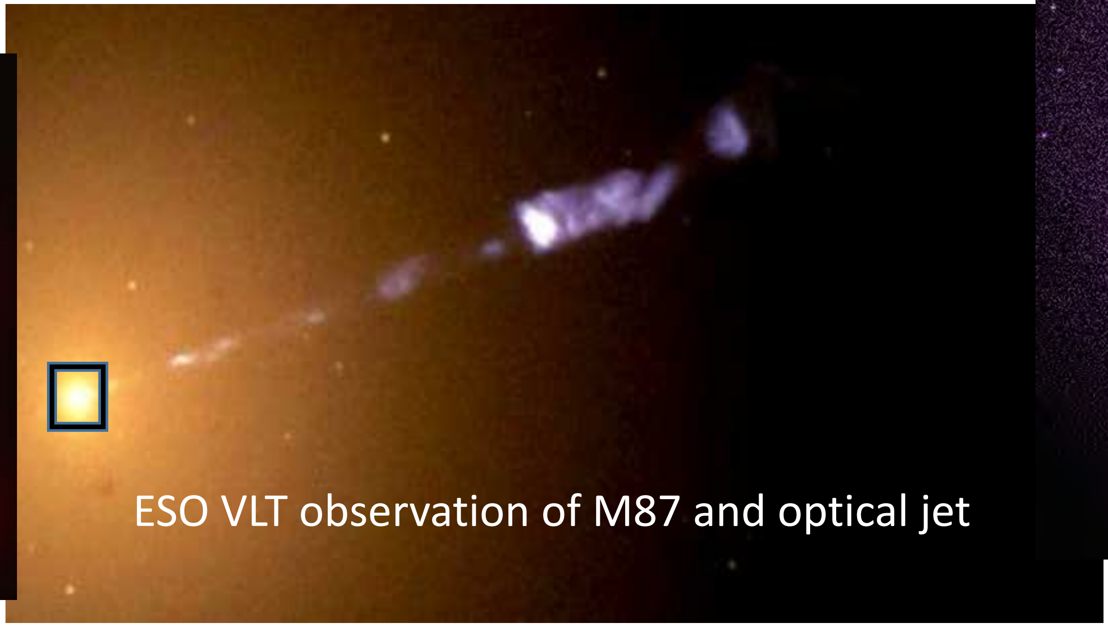
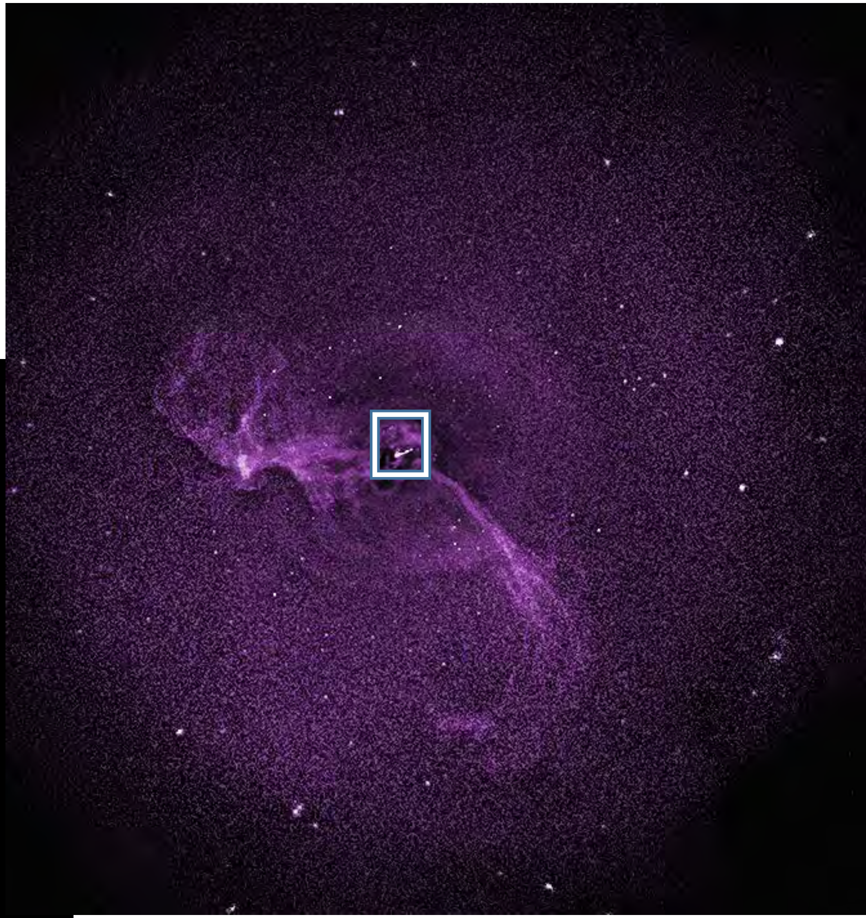
- M87 – central galaxy of Virgo cluster – SMBH at center
- Impact of BH extends 8 orders of magnitude in scales!
- Similar to something that is the size of a penny affecting an entire continent!
- Relativistic flow key to massive energy transport through small jet



EHT image of M87 SMBH



ESO VLT observation of M87 and optical jet



Chandra X-ray image of Virgo cluster and M87 jet

Overview – Jet Physics and X-ray Observations

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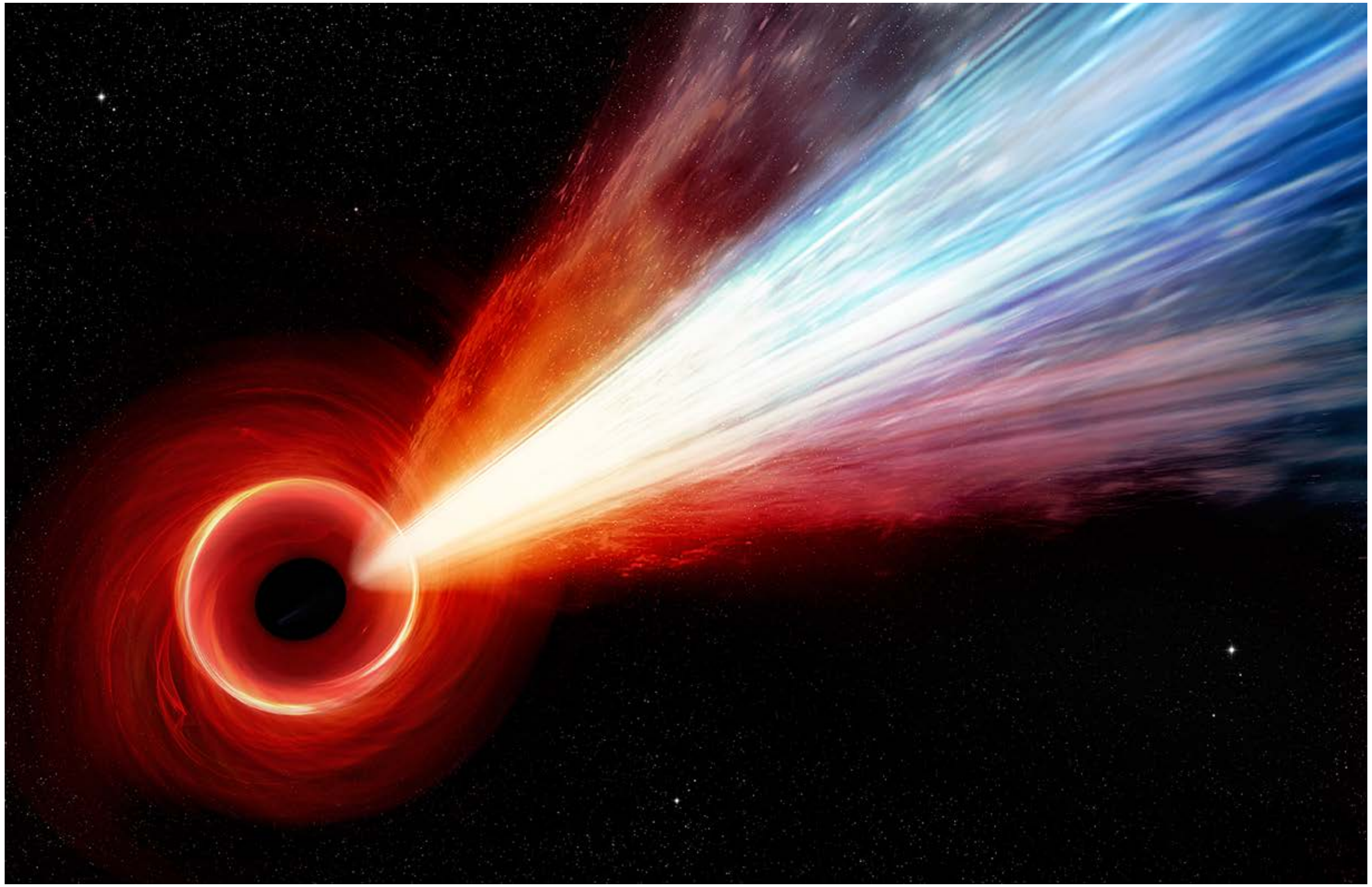
- Jets are collimated flows launched from central SMBH
- We typically measure morphology, synchrotron spectrum, impact on surrounding medium, etc., but not fundamental jet properties
- We try to infer fundamental jet properties from observables – ***definitely not a direct relation!***
- Understanding how jets work is ***central*** to our understanding of key astrophysical process including how SMBHs form and grow, how galaxies form and evolve, and why the local Universe looks the way it does today!



Chandra/HRC search for proper motions of the X-ray knots in the M87 jet

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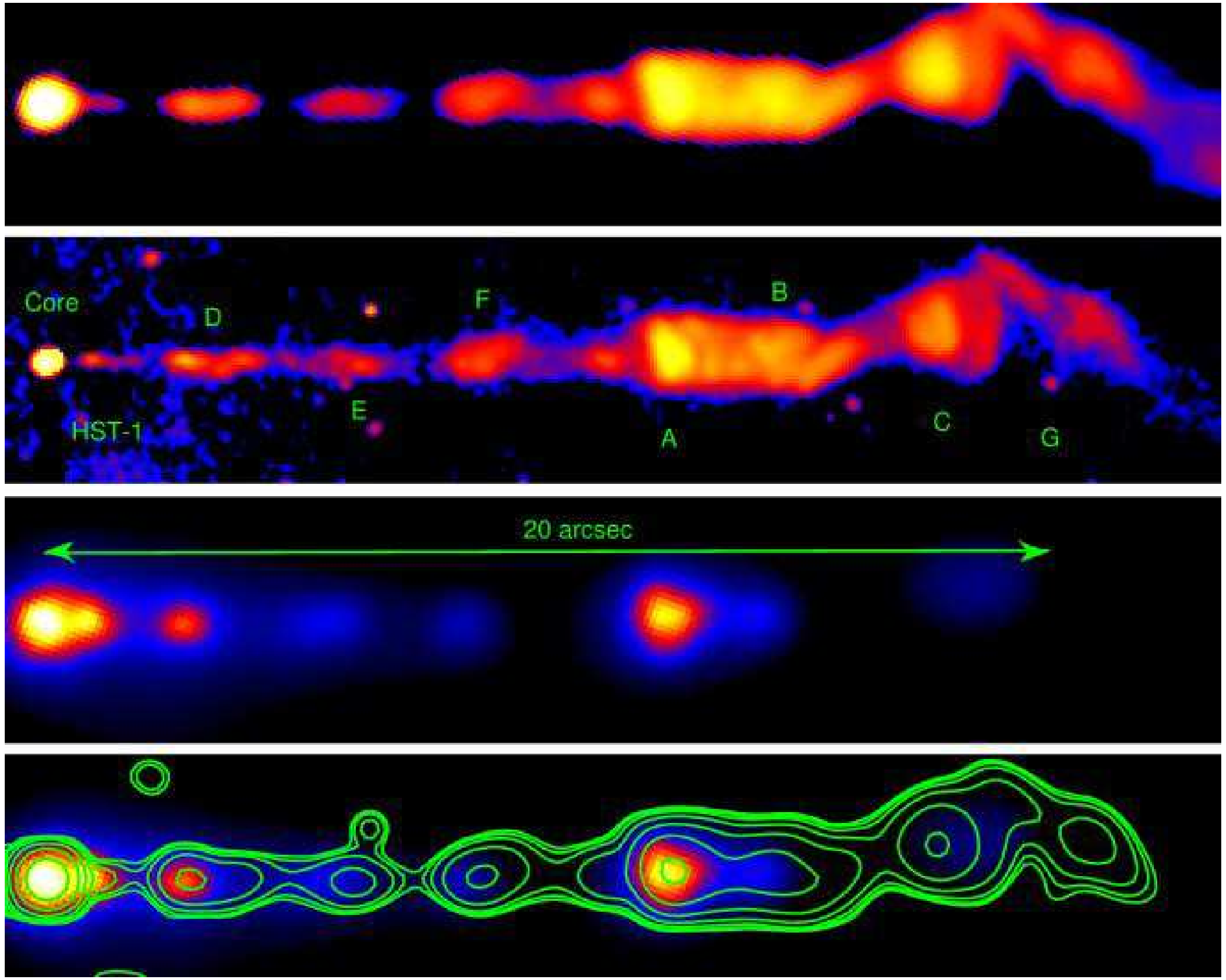
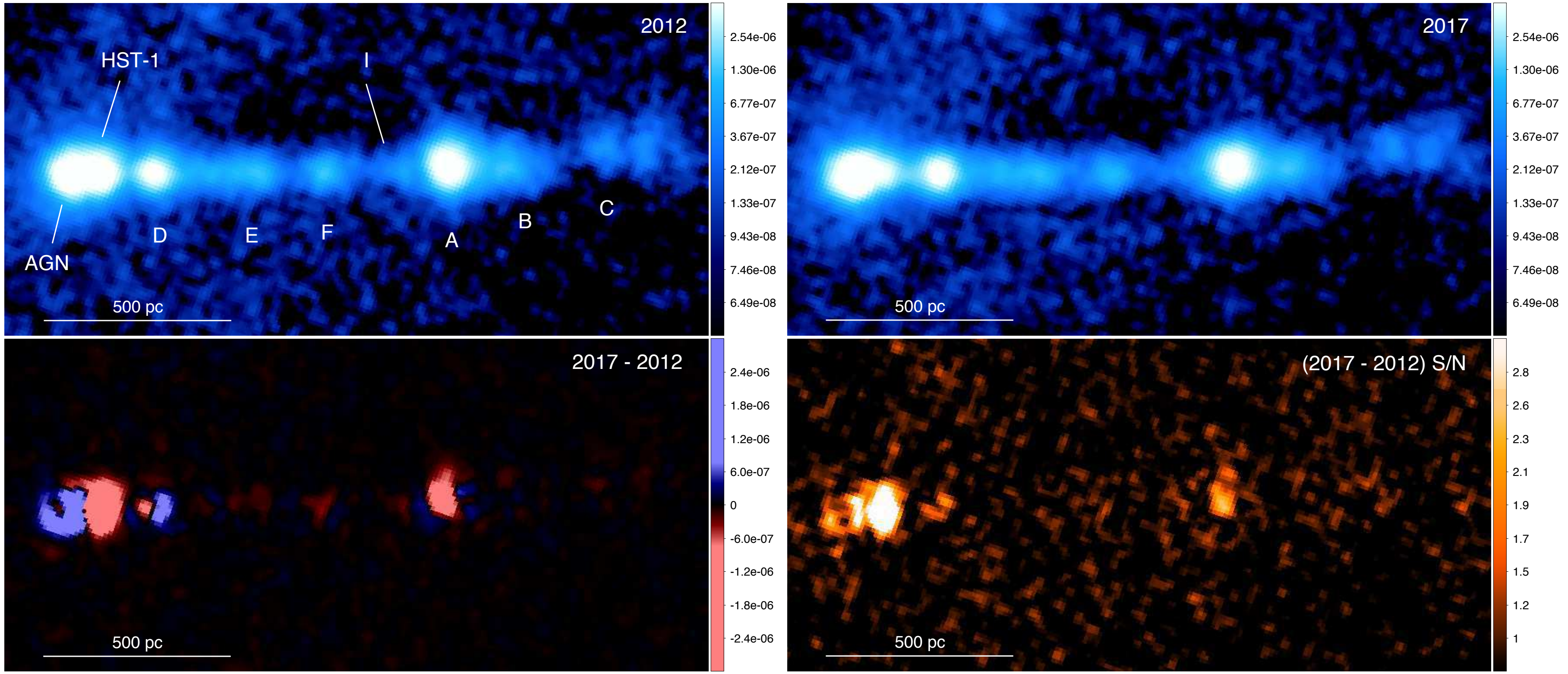
- M87 is the brightest and second closest (after Centaurus A) AGN jet
  - Proximity means that we have a resolution and sensitivity unmatched with any other target
- Two Chandra High Resolution Camera (HRC) observations of M87 jet taken 5 years apart
- The HRC has highest imaging resolution (<0.5”) on Chandra – ***this measurement is at the edge of Chandra’s capabilities.***
- Two primary science goals:
  - **Are the X-ray knots moving with the same velocity as the optical and radio knots?**
  - **What does this tell us about the underlying physics of jets?**

Broadband view M87 jet



- M87 is the second closest (d = 17 Mpc) AGN jet – 1”~86 pc
- $3 \times 10^{9}\ M_{\odot}$ SMBH at center
- Image on right is radio (top), optical (2^{nd}), Chandra/ACIS (3^{rd}), and radio contours on Chandra image (4^{th}) (Marshall+2002)
- Strong correspondence between the three bands

Multi-epoch Chandra/HRC observations of M87 jet (Snios+2019)



- 2012 (left) and 2017 (right) *Chandra*/HRC observations of M87 jet
- Bottom left – difference of the two images – red corresponds to brighter in 2012, blue to brighter in 2017
- Bottom right – S/N map

Proper motions, superluminal motions, and variability

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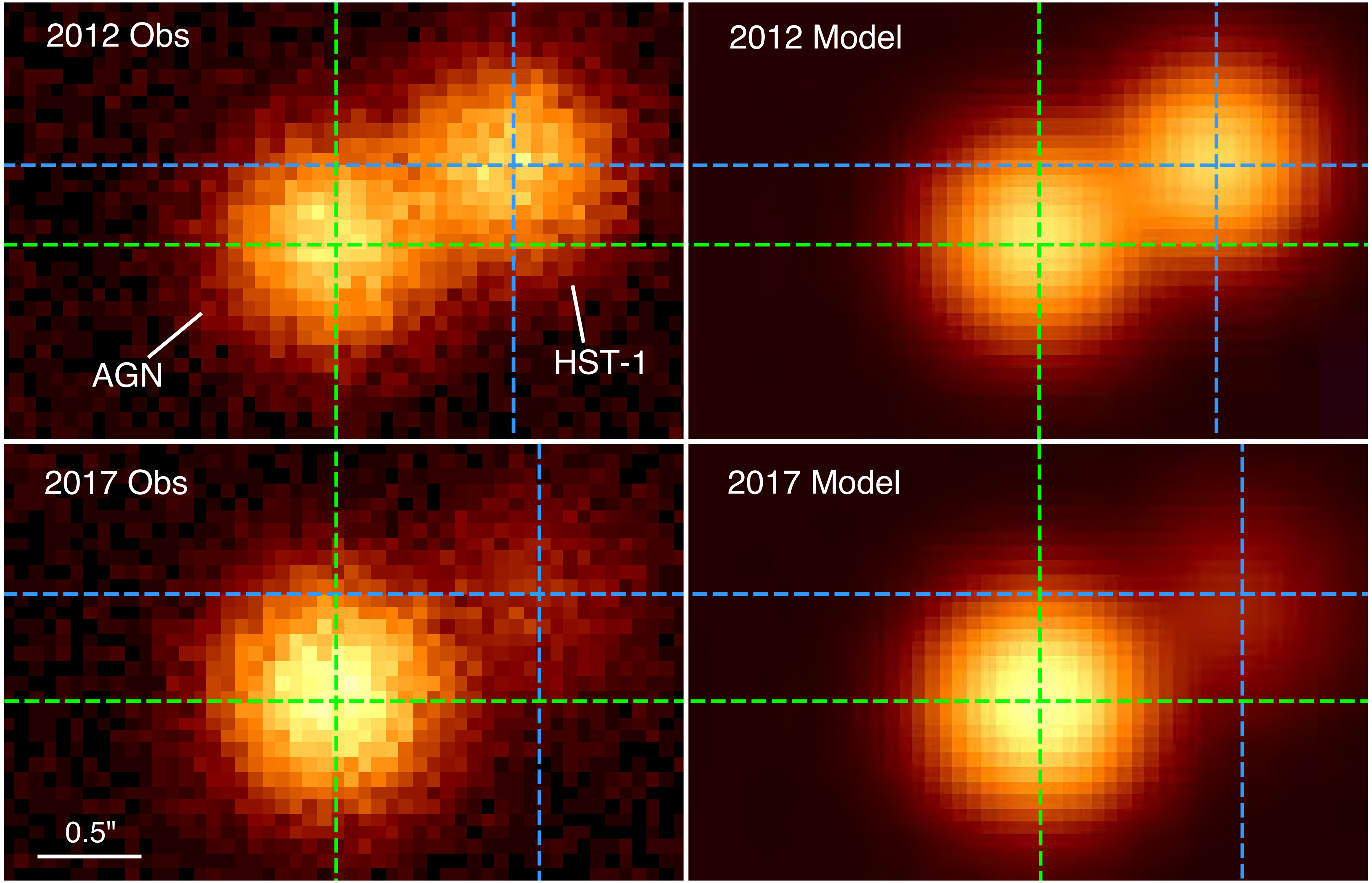

- The flux from the core and some of the knots show significant variability between the two epochs
- The core and HST-1 were modeled with 2D Gaussians

Results

Knot HST-1 moving 24.1 mas yr^{-1} -> 6.3c!
Knot D moving at 9.4 mas yr^{-1} or 2.4c!
HST-1 variability consistent with synchrotron cooling

Superluminal velocity of X-ray knots

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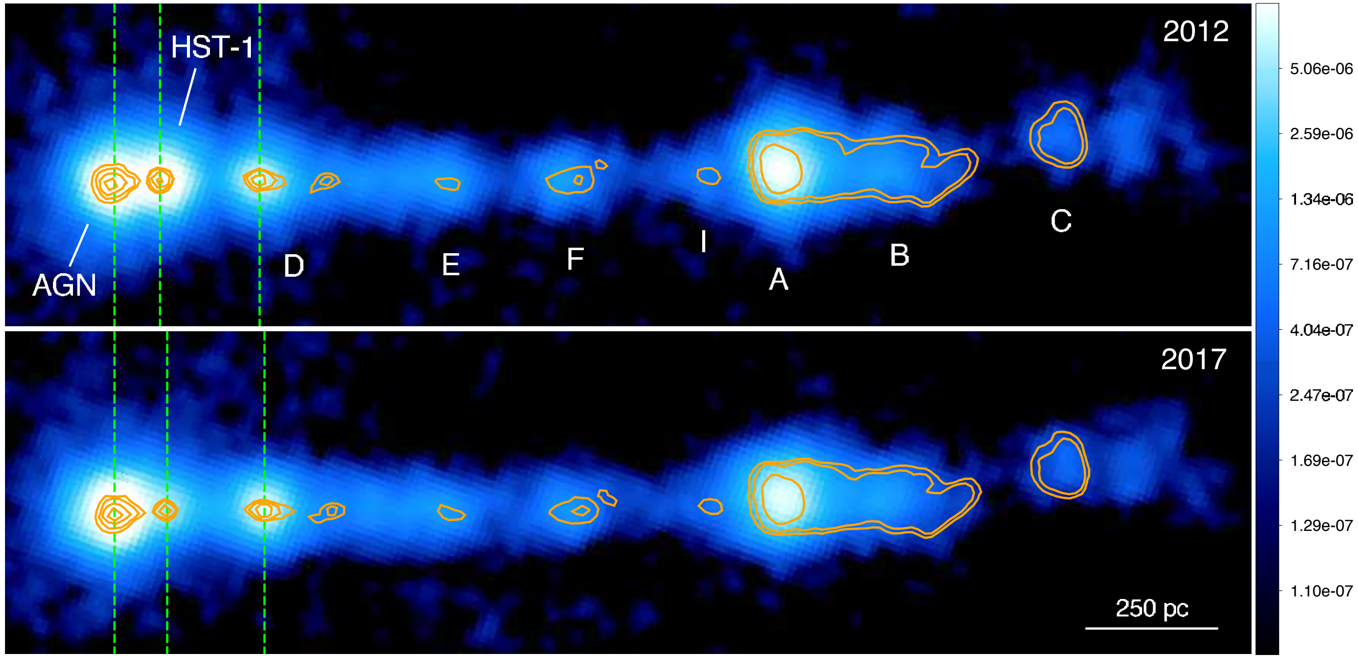

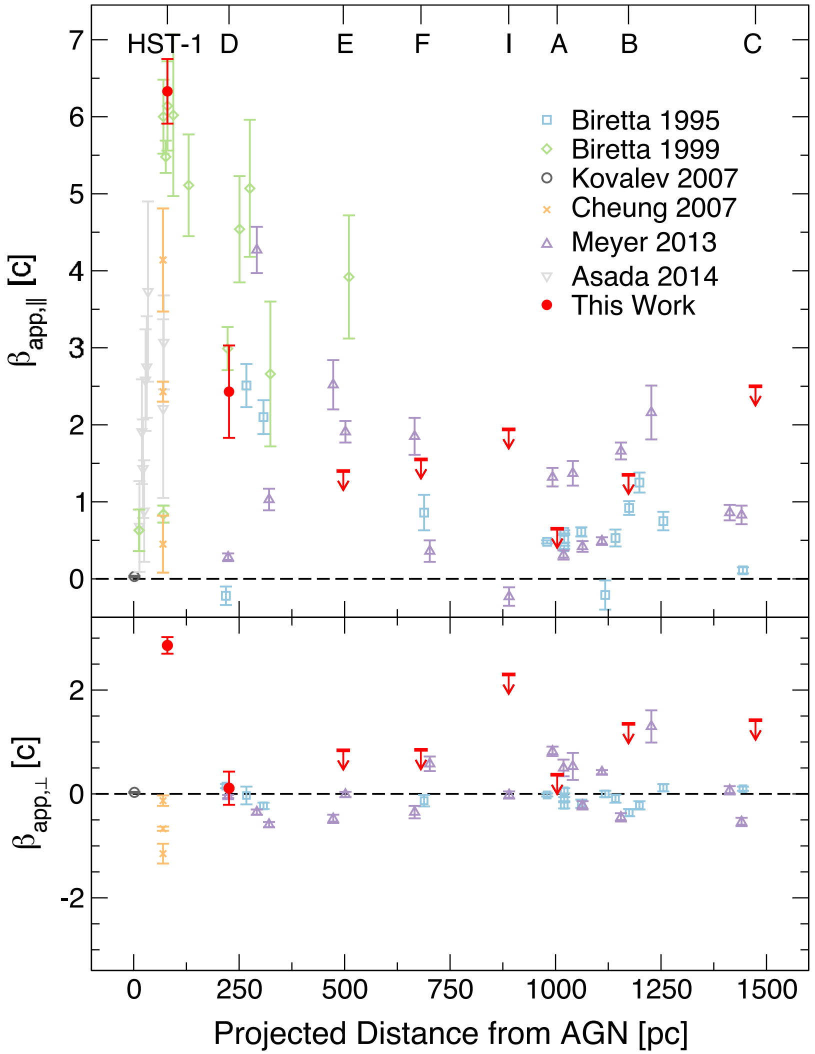

- Comparison of Chandra/HRC and HST (red contours – F275 filter) during the same years.
- **The shifts in position of the X-ray knots (HST-1 and D) and optical knots are consistent with each other**
- **-> X-ray and optical-emitting electrons are the same population**

Superluminal velocity of X-ray knots

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- We detect proper motions in knot HST-1 and knot D of 24.1 mas yr^{-1} and 9.2 mas yr^{-1}, respectively, corresponding to *apparent superluminal velocities* of 6.3c and 2.4c.
- Actual jet velocities are 0.997c (HST-1) and 0.927c (D)
- These velocities are consistent with the previously measured motions of the optical, ultraviolet, and radio components.
- Knot HST-1 shows significant temporal variability
  - Modeling of synchrotron losses consistent with spectral variability for equipartition magnetic field
- **Strongest direct evidence to date that underlying flow is relativistic**
- **Relativistic flow can carry enormous energy**