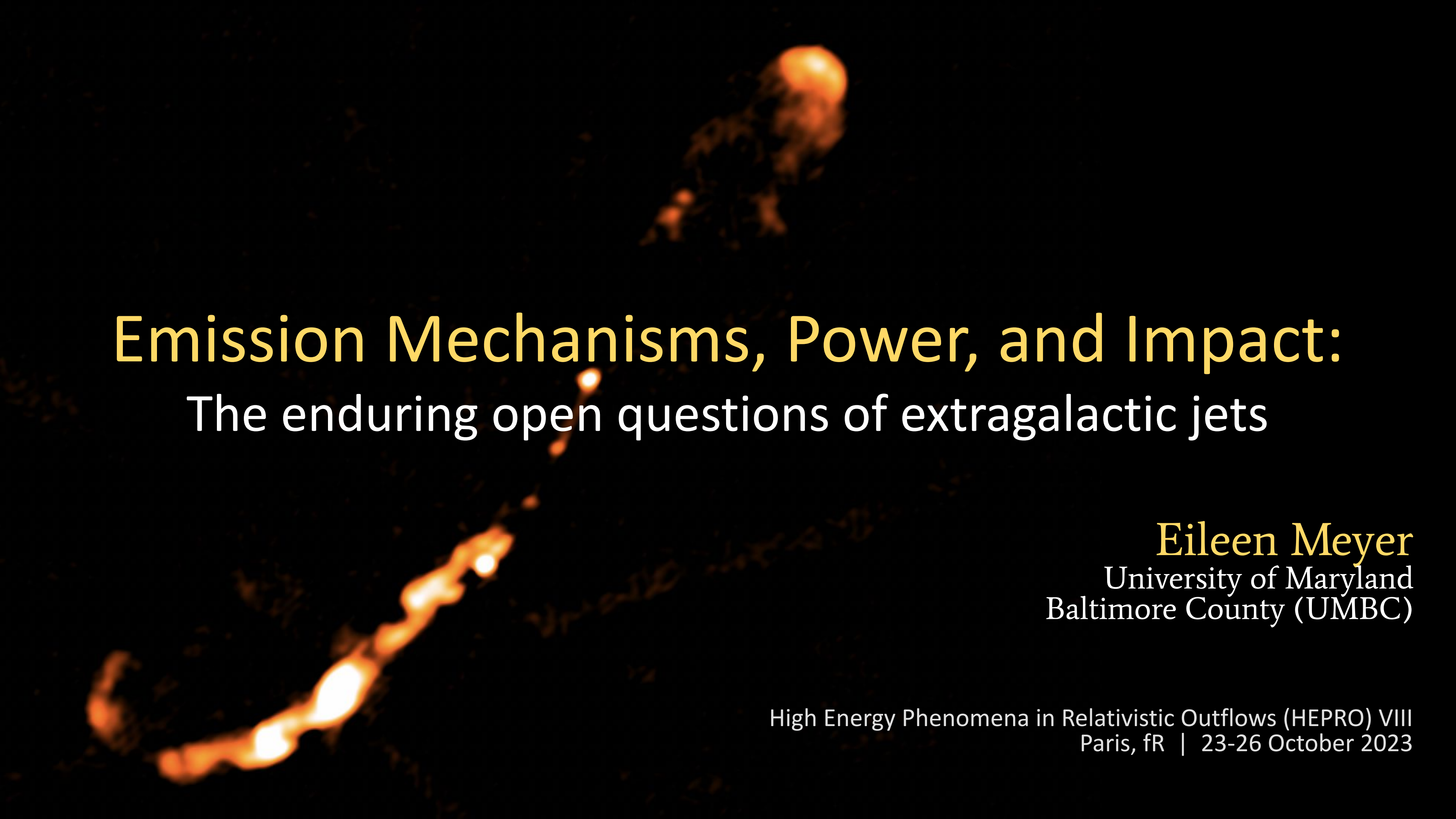
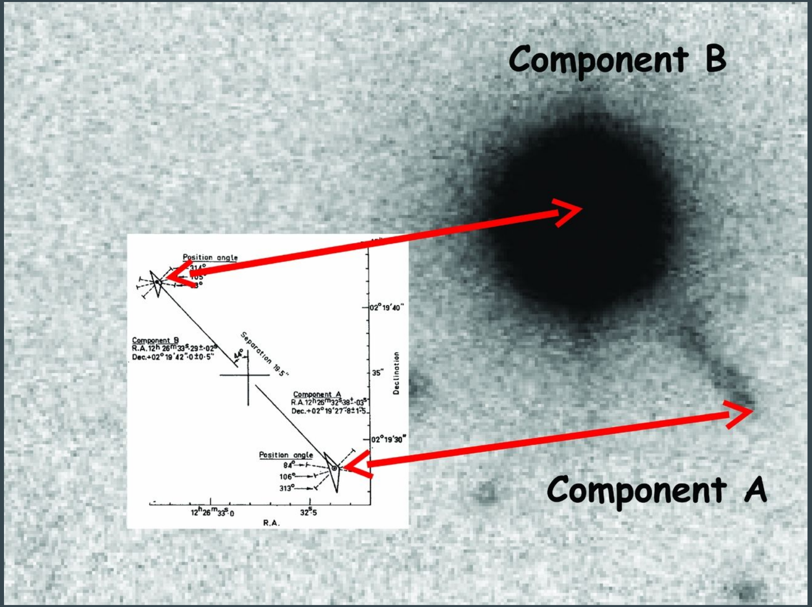


Emission Mechanisms, Power, and Impact:

The enduring open questions of extragalactic jets

Eileen Meyer
University of Maryland
Baltimore County (UMBC)

High Energy Phenomena in Relativistic Outflows (HEPRO) VIII
Paris, fR | 23-26 October 2023

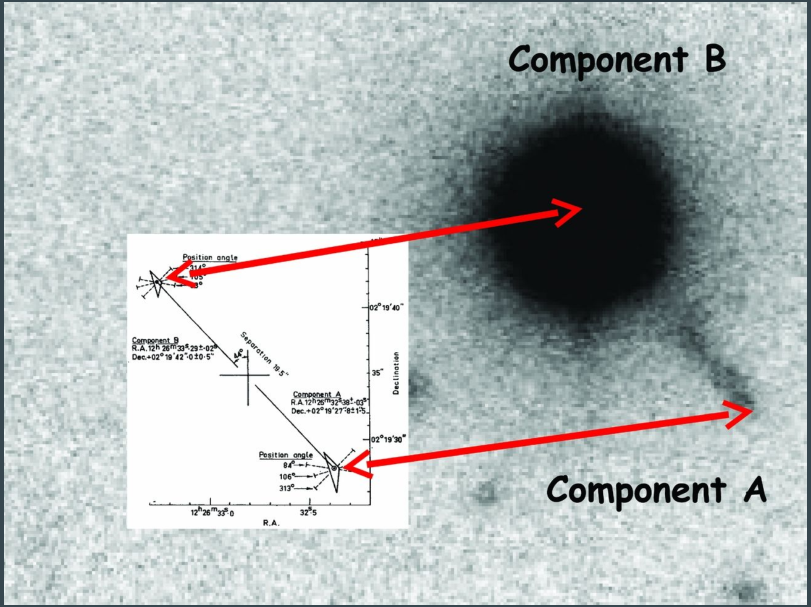


Hazard et al. 2018

Just over 60 years ago, 3C 273 became the first radio quasar & first identified extragalactic radio/optical jet

(Hazard, Mackey, & Shimmins 1963, Schmidt 1963)

Existence of radio-quiet quasars (as opposed to the 'original' radio-loud ones) realized shortly thereafter. (e.g. Sandage 1965)



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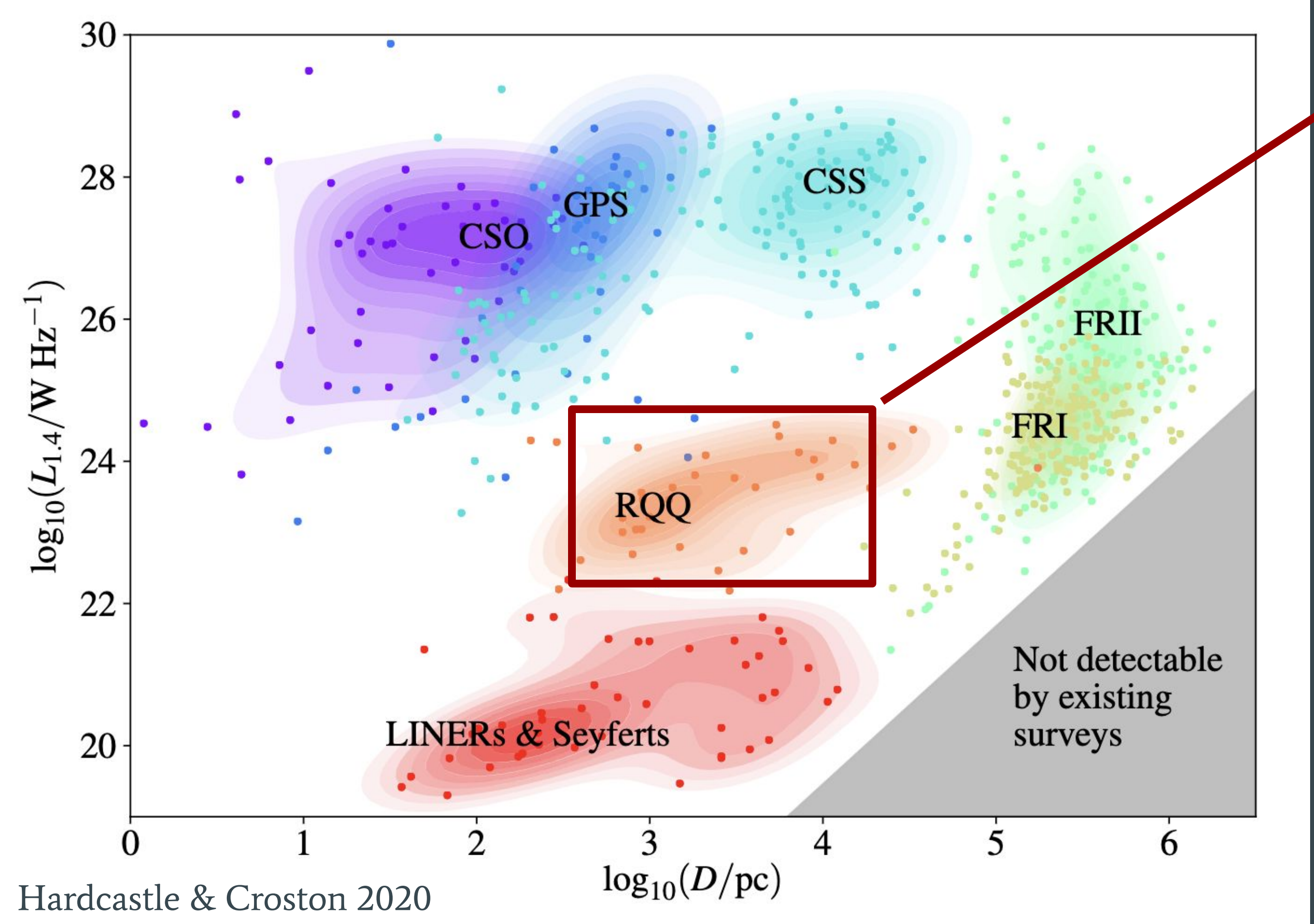
Where are we today?

Extragalactic jets are incredibly diverse - huge range in power, physical scale



Hardcastle & Croston 2020

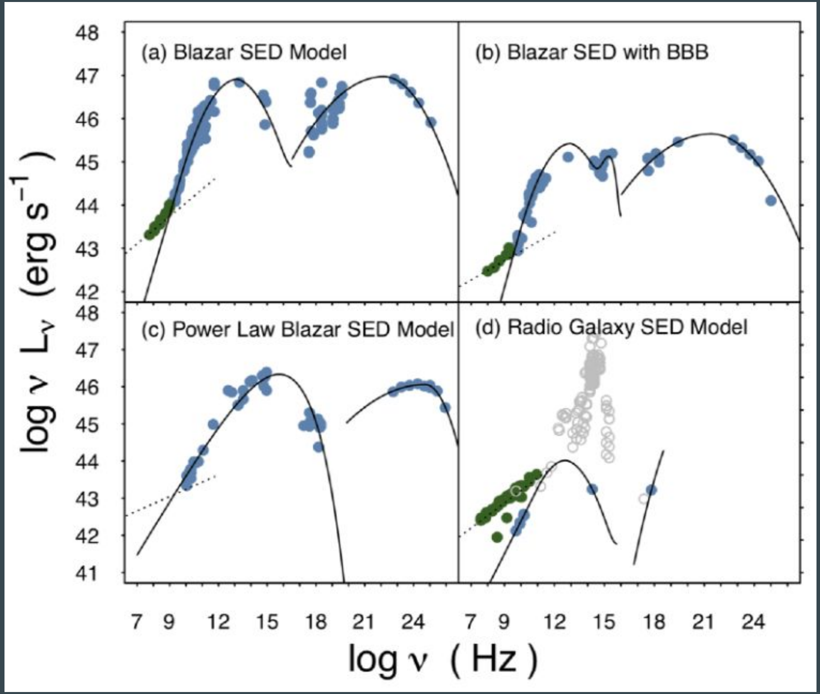
Down-scaled jets are also seen in radio-quiet AGN

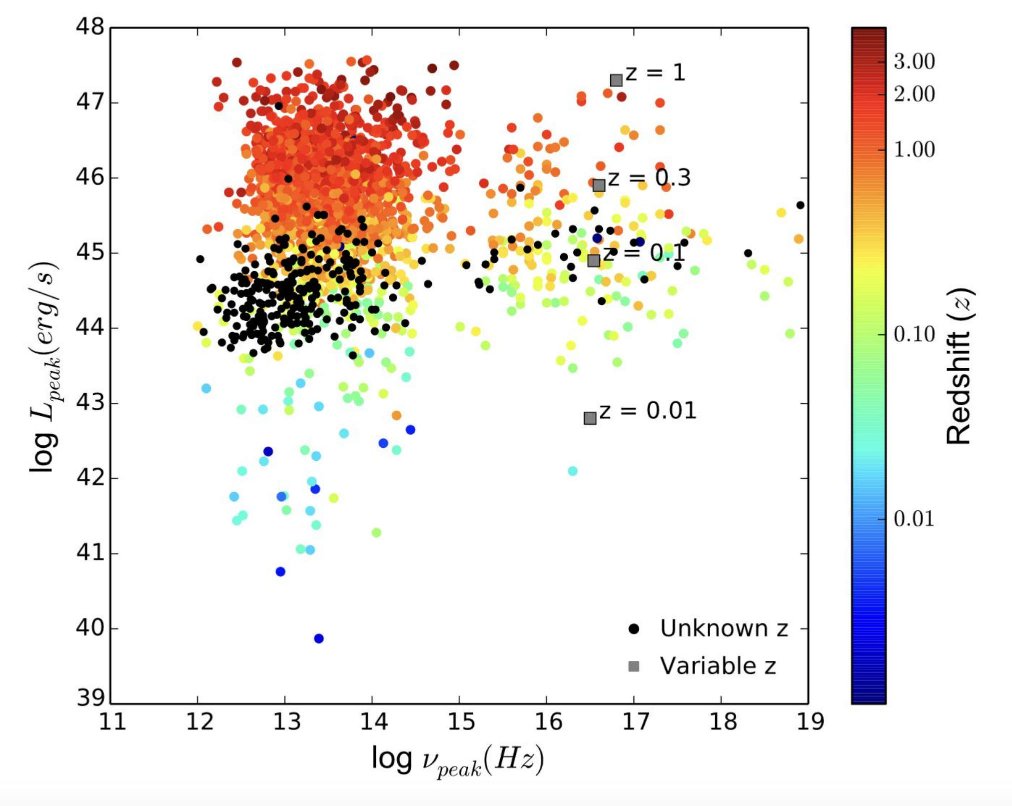
A continuum?

From moderately relativistic, mildly collimated radio-emitting outflows to full kpc-scale, highly collimated relativistic jets

Extragalactic jets are incredibly diverse - huge range in frequency of peak power output

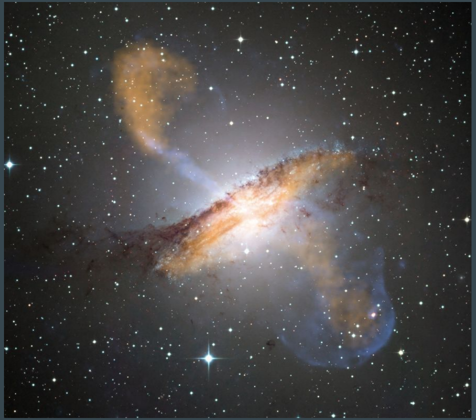
Synchrotron vF$_{\nu}$ peak varies from 10^{12}-10^{19} Hz
(Compton/VHE peak similarly wide-ranging)

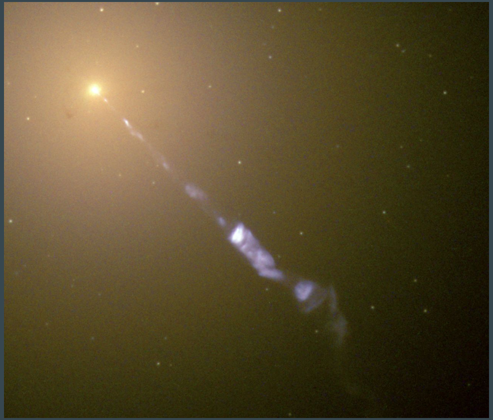


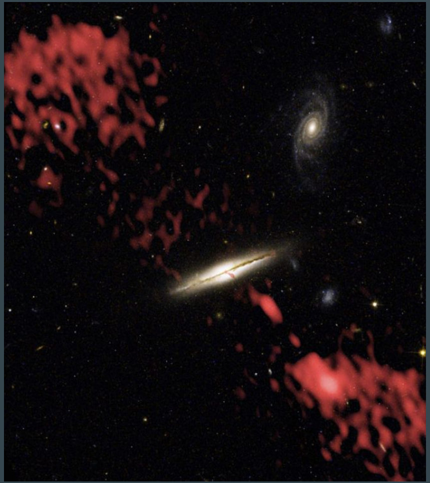


Keenan et al., 2021

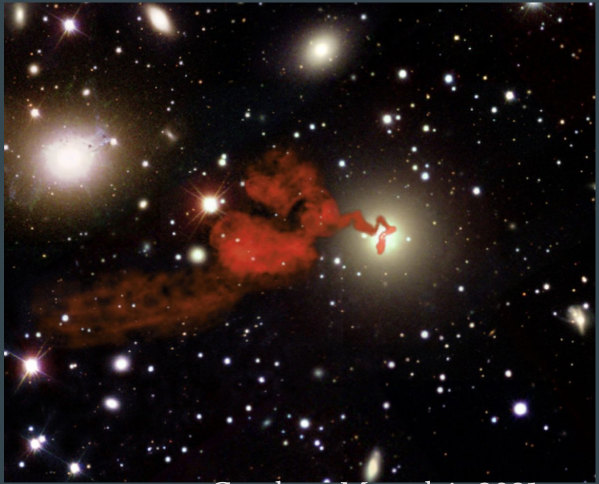
Extragalactic jets are incredibly diverse - different hosts





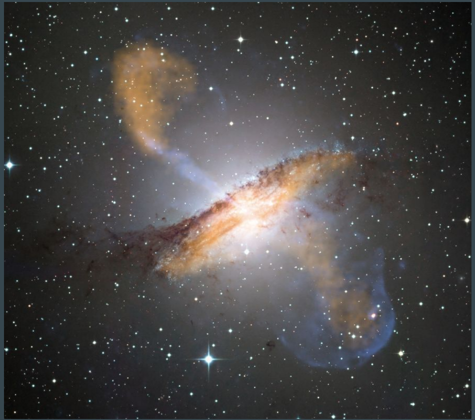


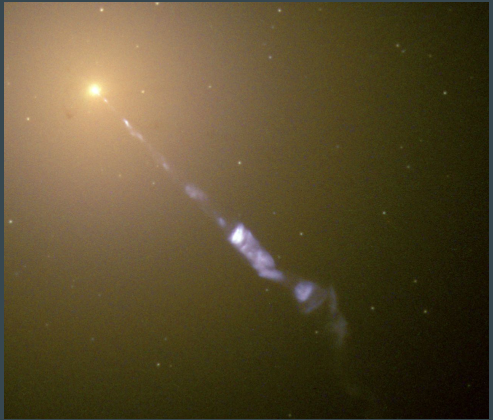
Keel et al., 2006

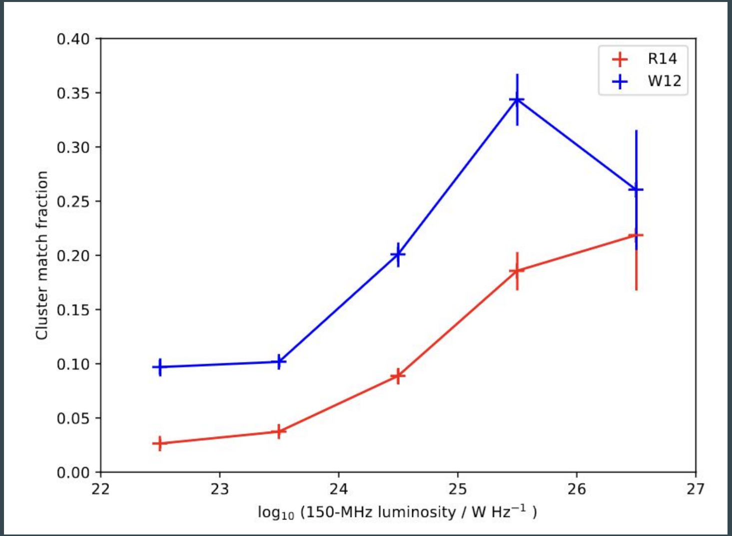


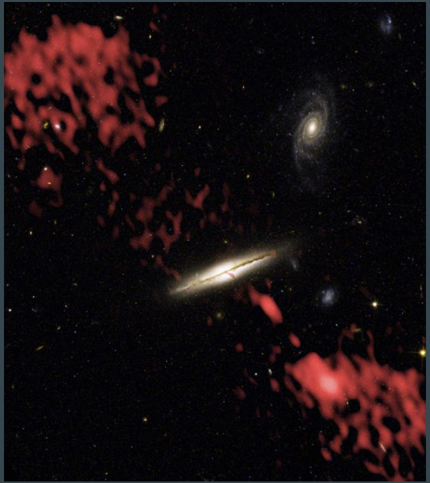
Gendron-Marsolais 2021

Extragalactic jets are incredibly diverse - different hosts, environments

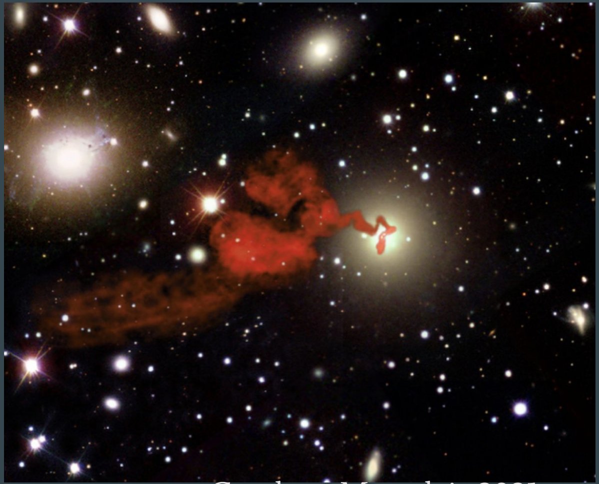








Keel et al., 2006



Gendron-Marsolais 2021

The fraction of AGN with a group/cluster association increases with 150 MHz radio luminosity – *yet more than 60 percent of even the most luminous radio galaxies in the LoTSS survey do not have a group/cluster association.*
(Croston et al., 2019)

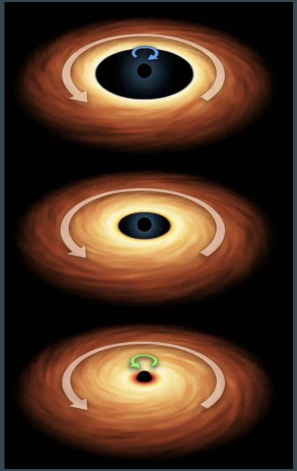
Still-open Questions

What physical 'ingredients' result in a jet, and what kind?

Black hole mass

Accretion rate & mode

Black hole spin



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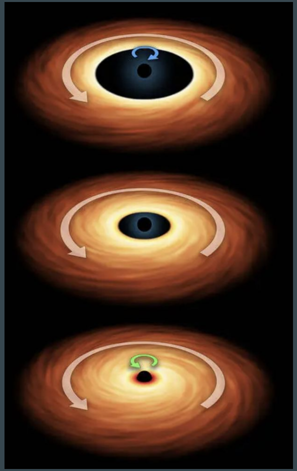
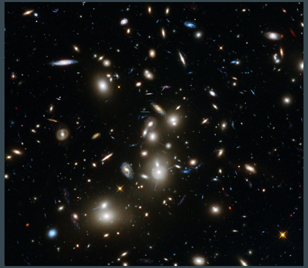
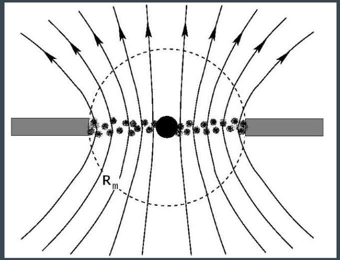


environment



Accretion history, disk magnetization



Still-open Questions

What physical 'ingredients' result in a jet, and what kind?

- *What are jets made of? What is their plasma composition?*
- *How are jets structured?*
- *How are particles accelerated in jets?*
  - *What is the emission mechanism at high energies?*

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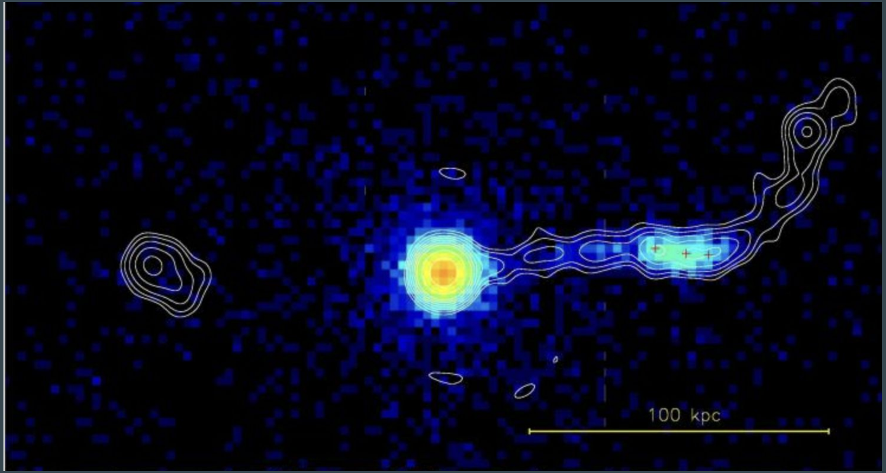
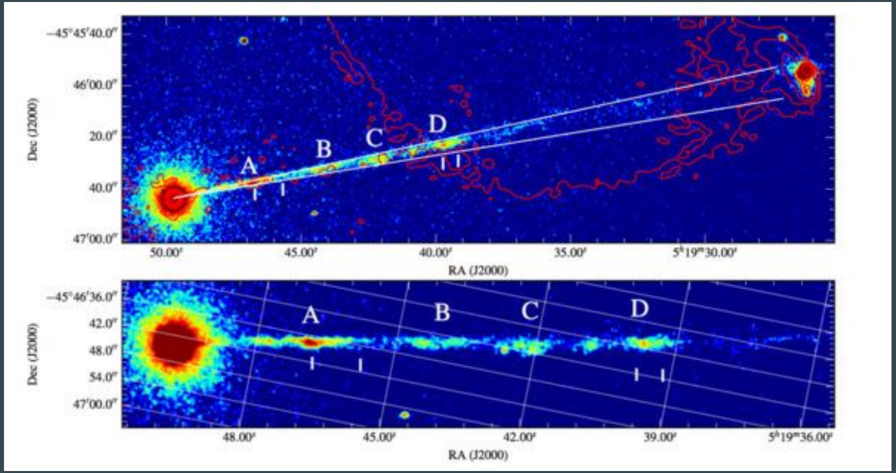
What is the origin of the X-ray emission from jets on kpc scales?

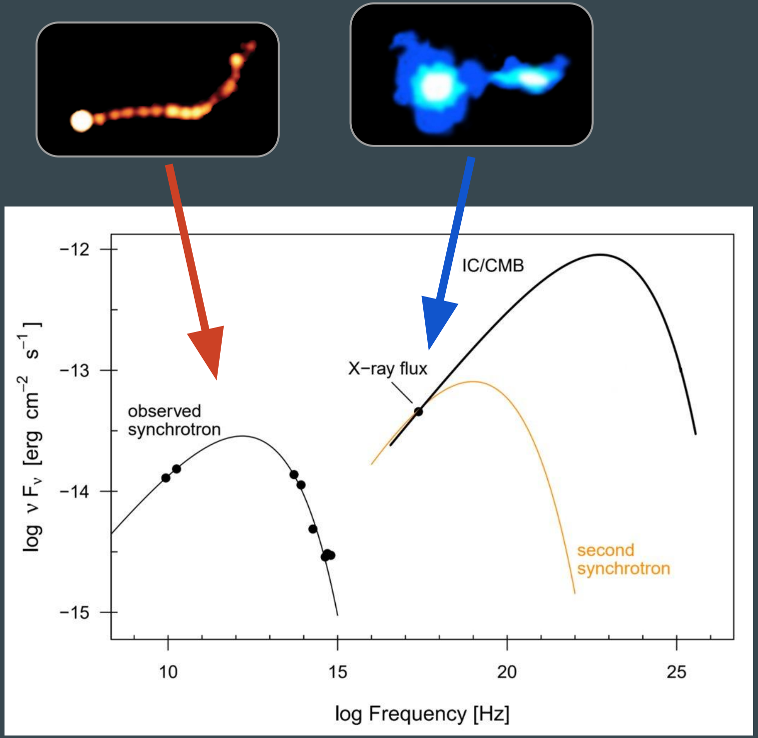


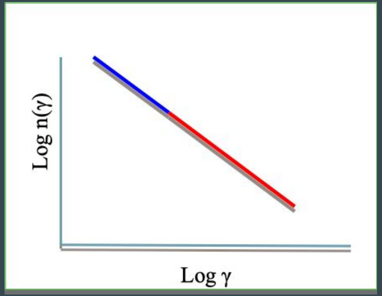


Jets: Possibilities include IC scattering of the CMB, “second” synchrotron emission. Synchrotron self-compton (SSC) disfavored as req. B field lower than equipartition by factor ~ 1000 (e.g. Schwartz et al., 2000)

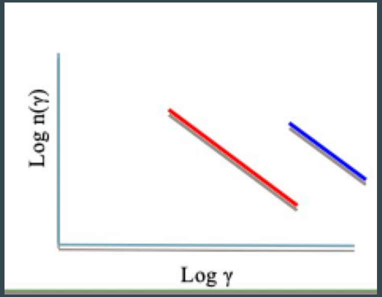
Hotspots: Early work (even prior to Chandra) settled on SSC as default model. Work by Hardcastle group later showed that it rarely works outside of brightest sources.

What is the origin of the X-ray emission from jets on kpc scales?



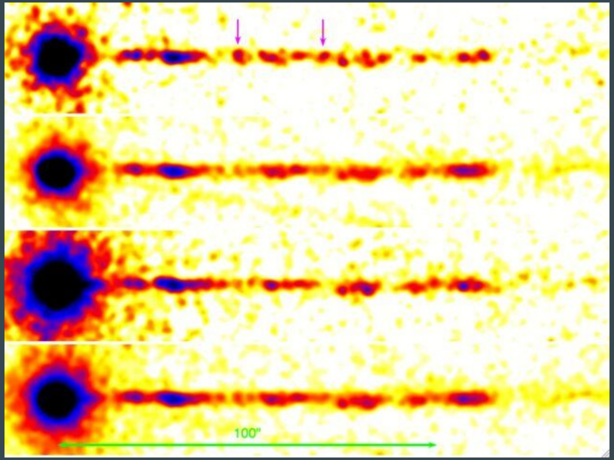


<u>IC/CMB</u> requires extending EED to low γ (blue line) → near and *super-Eddington power requirements*



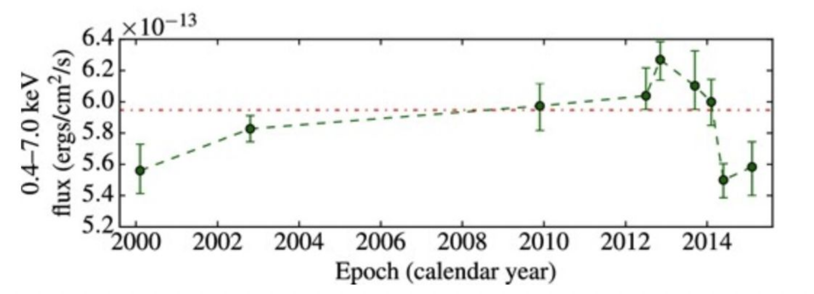
<u>Second synchrotron</u> **require**s second EED, orders of magnitude lower power requirements but now *in-situ particle acceleration up to TeV energies*

X-ray Jets are Variable



Several knots in Pictor A were seen to vary (fade) over a few years timeframe (Marshall et al., 2010)

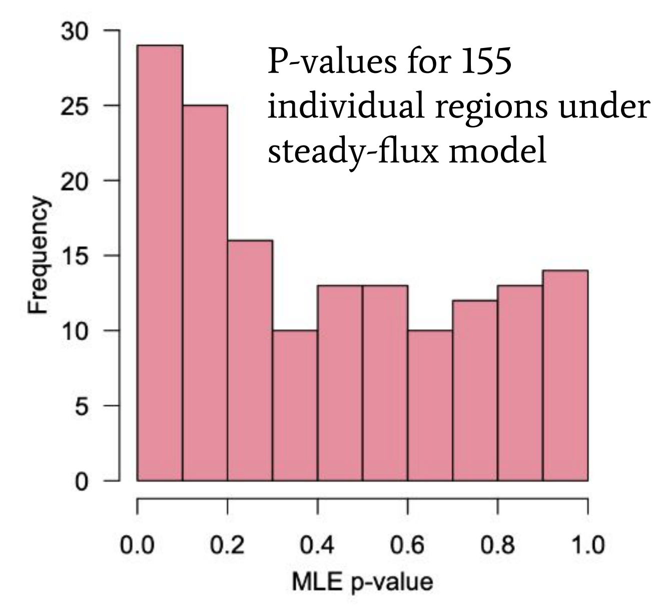
Variability is completely incompatible with an IC/CMB origin for the X-ray emission. Short timescales (years or less) imply extraordinarily small emitting volumes even under a synchrotron scenario.



Very short-timescale variability of the hotspot later reported by Hardcastle et al., 2016

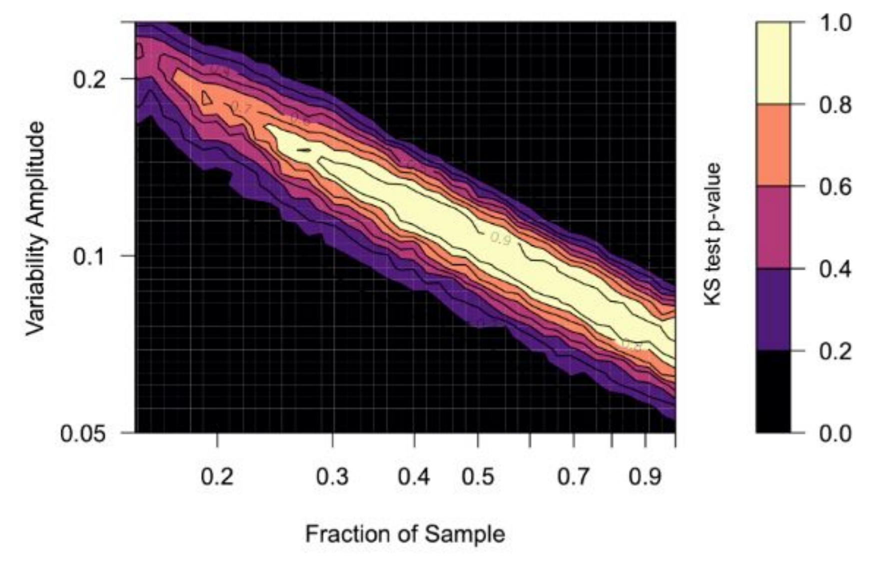
X-ray Jets are Variable

Recent population study of 53 X-ray jets shows low-level variability is common in jets, particularly at low redshift (Meyer et al., 2023)

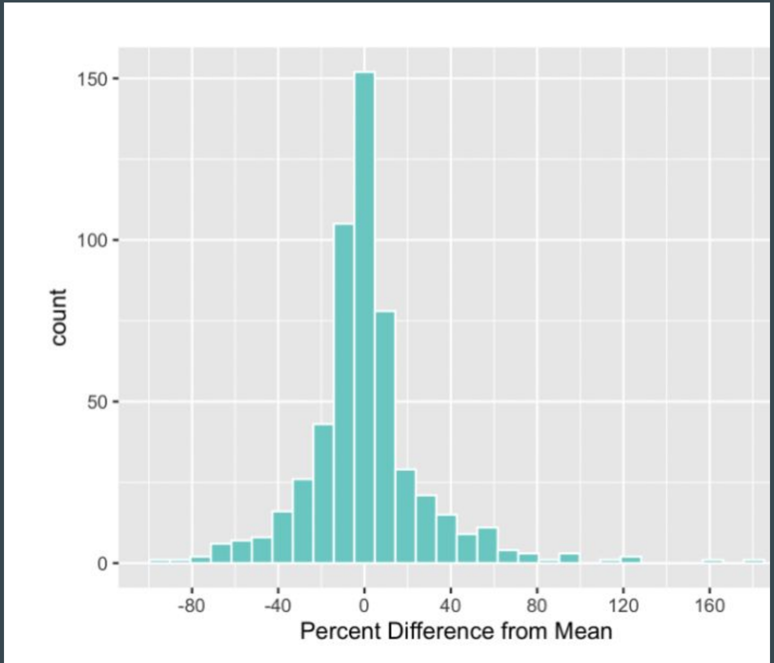


P-values for 155 individual regions under steady-flux model

Global p-value of 0.00019 under a KS test against the expected Uniform (0,1) distribution.



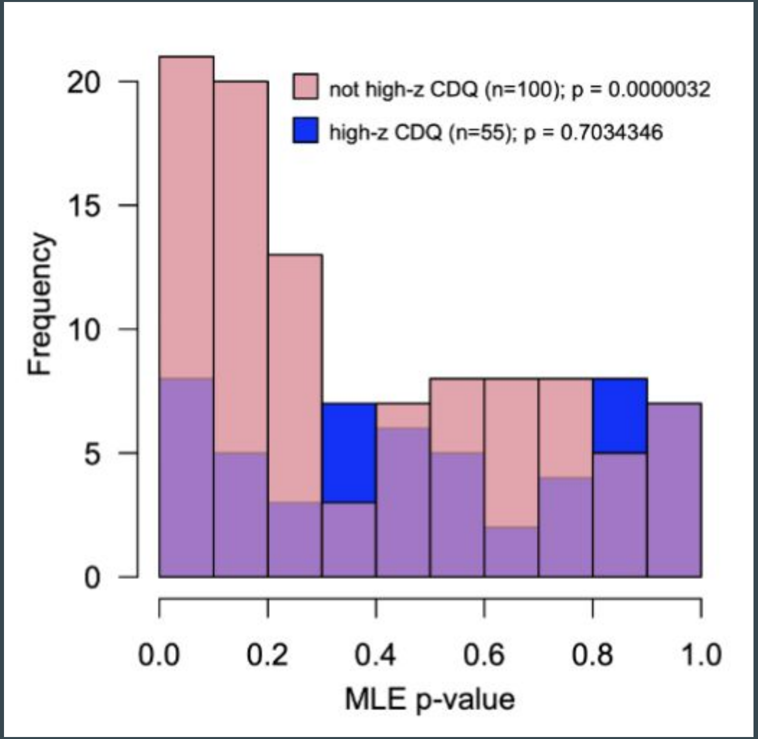
Simulations suggest 30-100% of the sample is variable.



Data suggest tens-of-percent variability is most typical.

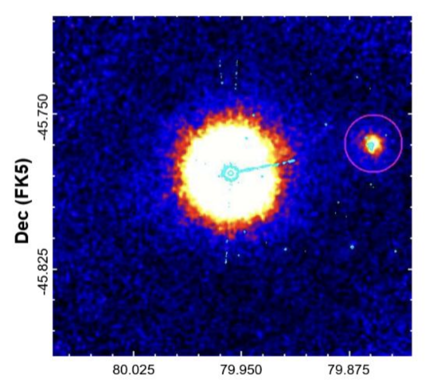
High-redshift jets do not show signs of variability.

This may be due to the increasing dominance of X-ray production via IC/CMB which is proportional to $(1+z)^4$

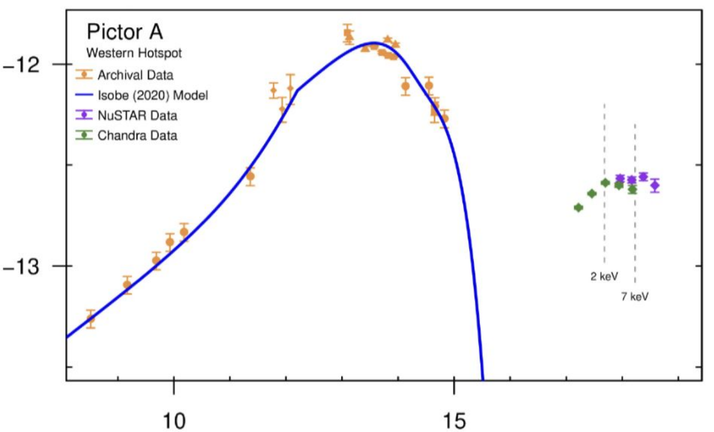


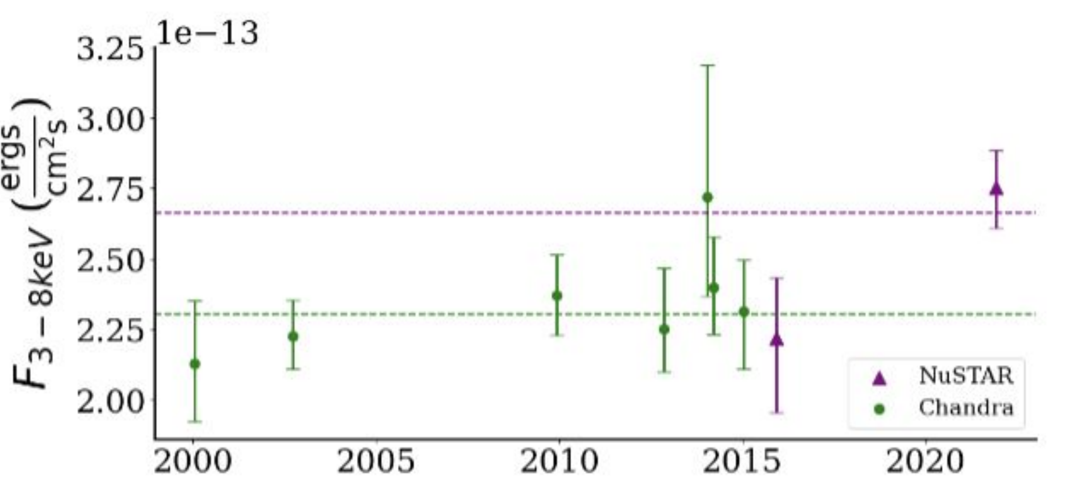
Meyer et al., 2023

X-ray Jets are Variable



Pictor A variability (total flux, 2-8 keV) confirmed at 6.7σ in joint Chandra + NuSTAR study (Shaik et al., subm.)





It’s not just the X-rays - Multiple-spectral-component (MSC) jets

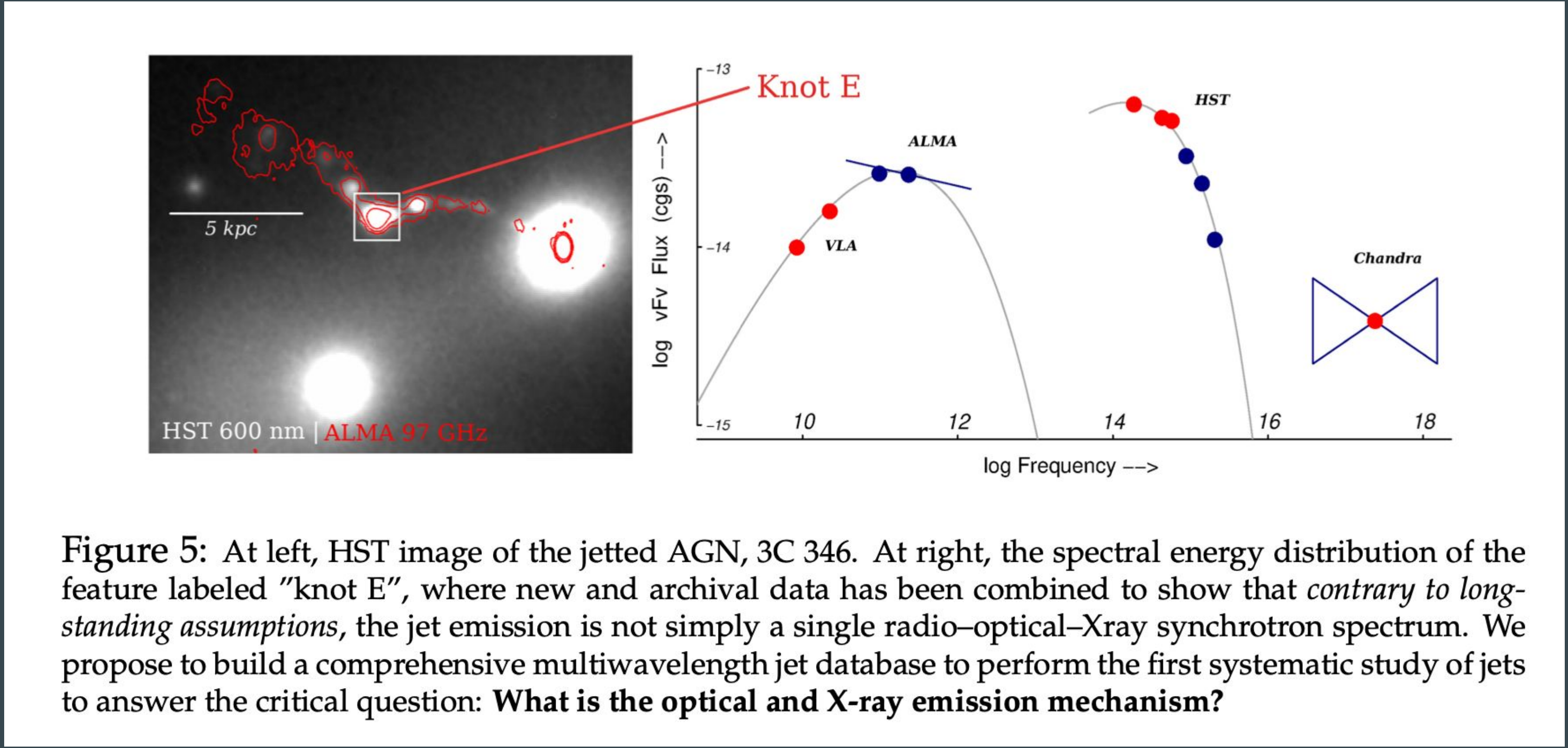


Figure 5: At left, HST image of the jetted AGN, 3C 346. At right, the spectral energy distribution of the feature labeled ”knot E”, where new and archival data has been combined to show that *contrary to long-standing assumptions*, the jet emission is not simply a single radio–optical–Xray synchrotron spectrum. We propose to build a comprehensive multiwavelength jet database to perform the first systematic study of jets to answer the critical question: **What is the optical and X-ray emission mechanism?**

It’s not just the X-rays - Multiple-spectral-component (MSC) jets

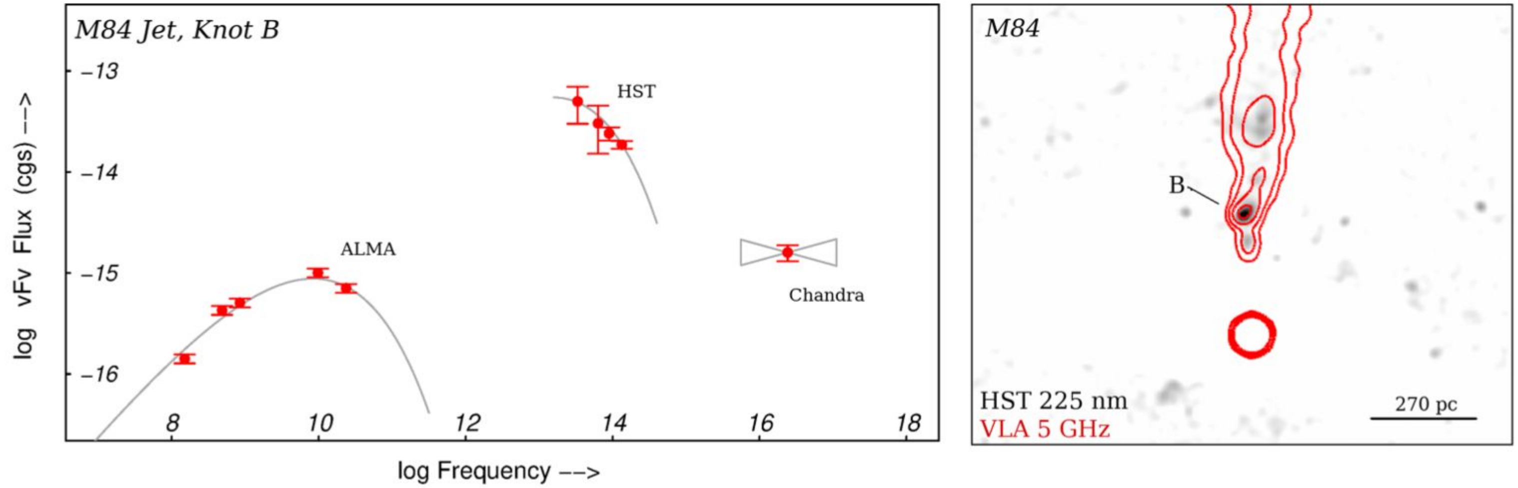
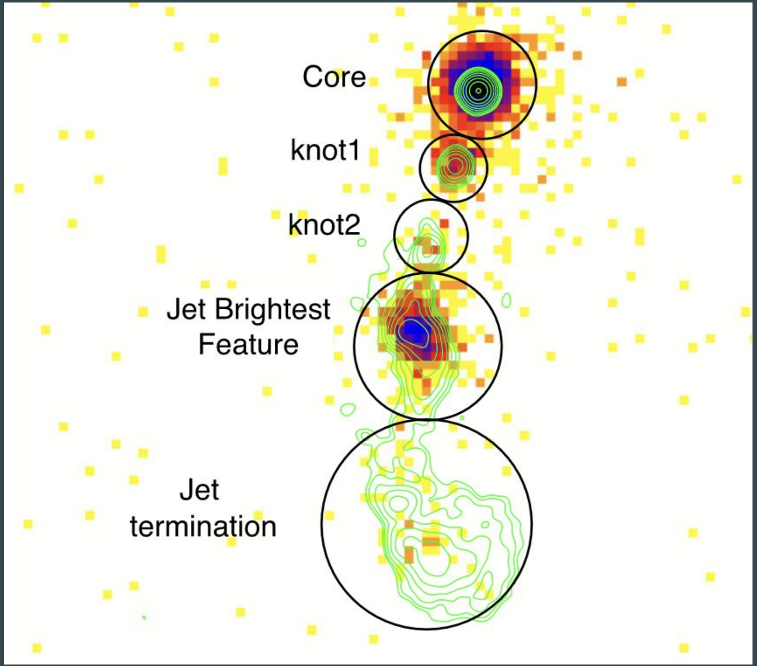
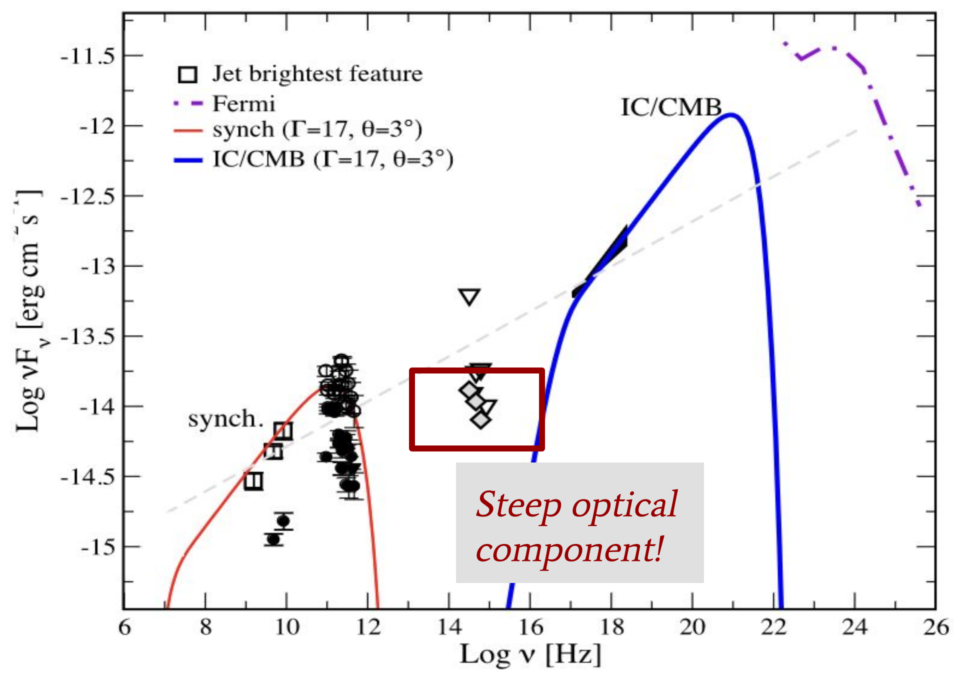


Figure 4: *M84 is a nearby LLAGN in the Virgo cluster (d=18.5 Mpc); the optical jet was recently discovered serendipitously in the HST archives [39]. At left, the full SED of knot B is shown, where it is clear there are (at least) 3 distinct spectral components. The 225 nm HST UV image of the jet is shown at right (galaxy light subtracted) with 5 GHz VLA contours overlaid. All four knots show a turnover in the radio synchrotron spectrum at* $\sim 10^{10}$ *Hz.*

Meyer et al., 2018

RGB J1512+020A





Steep optical component!

Migliori et al., 2022

Still-open Questions

What physical 'ingredients' result in a jet, and what kind?

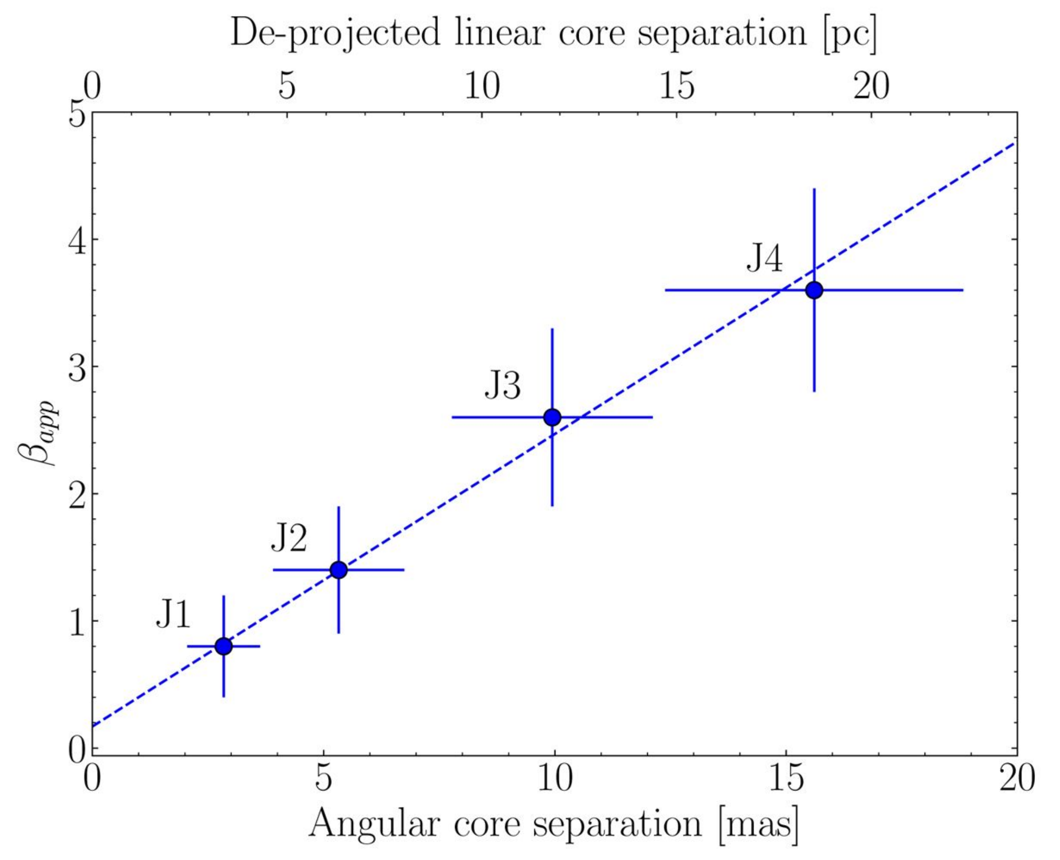
What are jets made of? What is their plasma composition?

How are jets structured?

How are particles accelerated in jets?

What is the emission mechanism at high energies?

Jet Structure - Velocity Profiles from pc to kpc scales

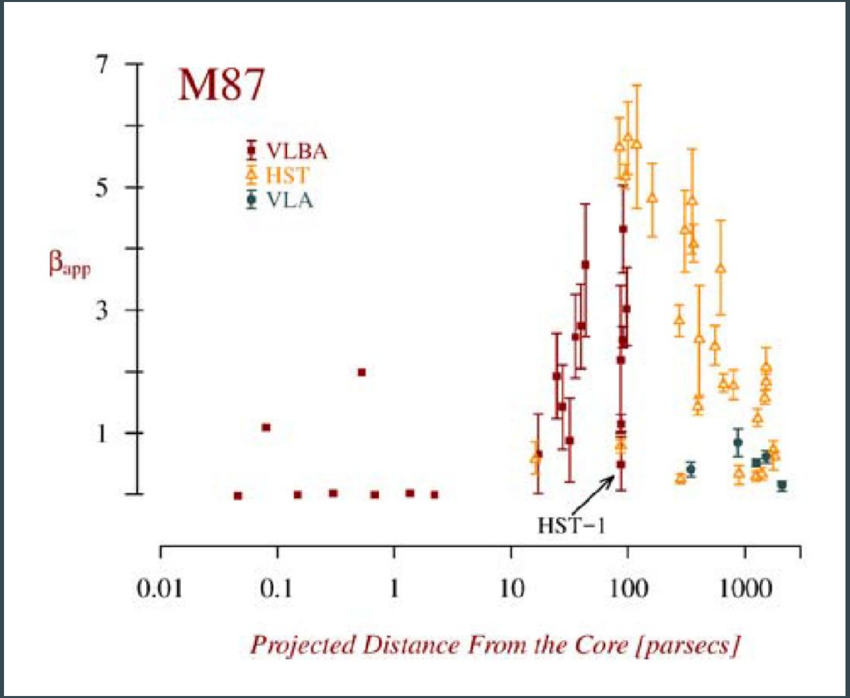


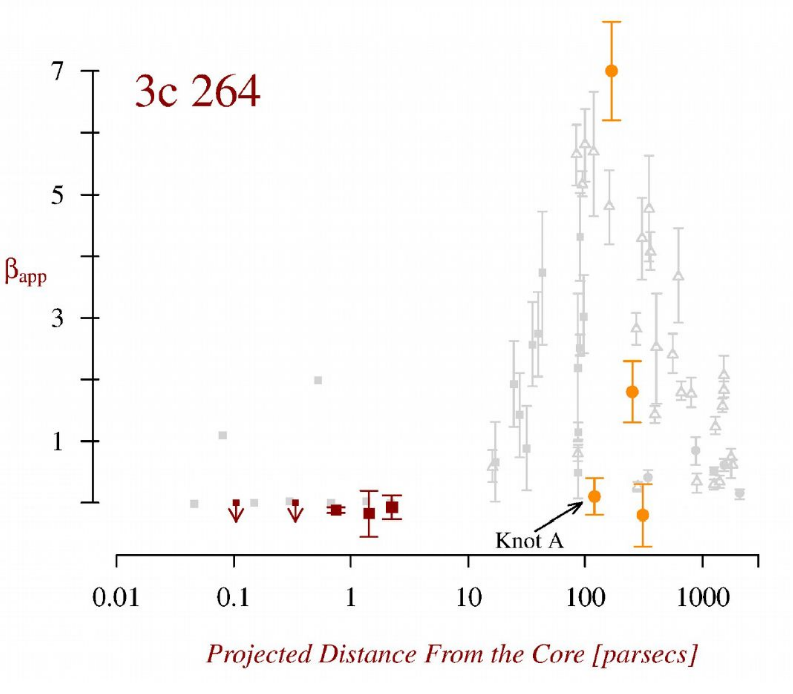
Large VLBI proper motions surveys show that apparent speeds increase with distance from the core.
(e.g. Lister et al., 2019)

In many sources, no sign of deceleration on VLBI scales.

Beautifully illustrated in here in PKS 2153-69
Angioni et al., 2020

Jet Structure - Velocity Profiles from pc to kpc scales

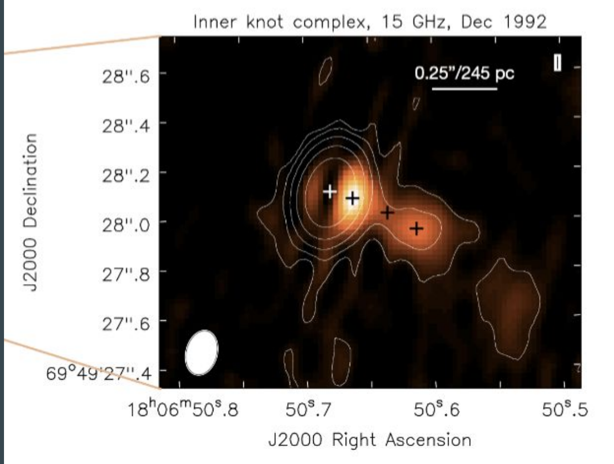


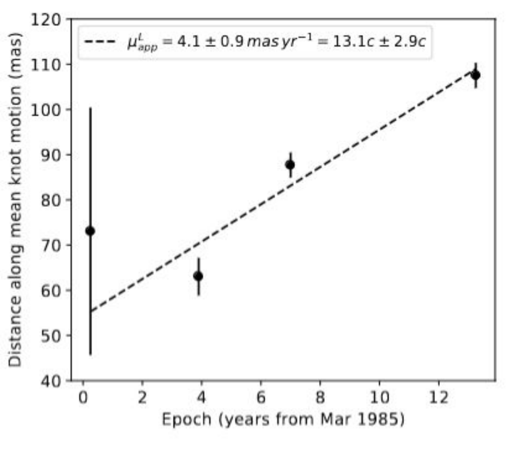


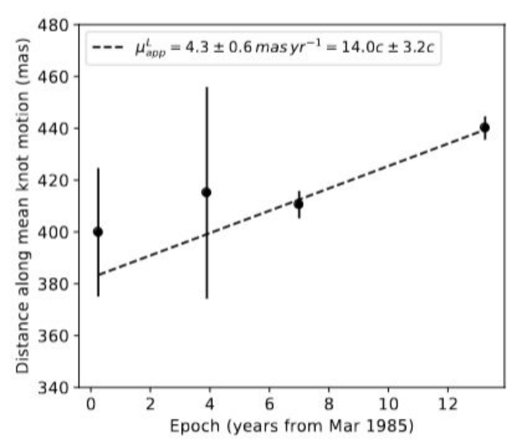
We are starting to have the time baselines with VLA and HST to get kpc-scale measurements

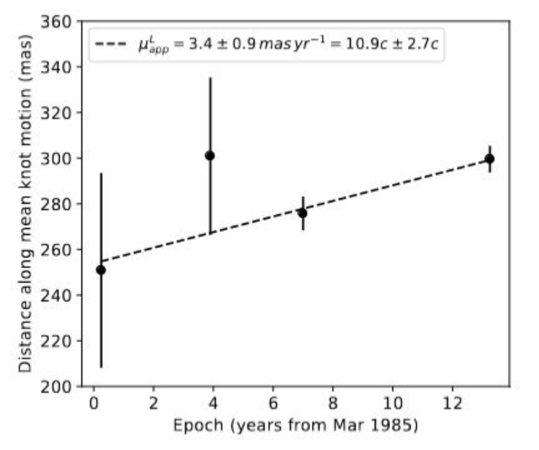
E.g. Meyer et al., 2013, Meyer et al., 2015

Jet Structure - Velocity Profiles from pc to kpc scales









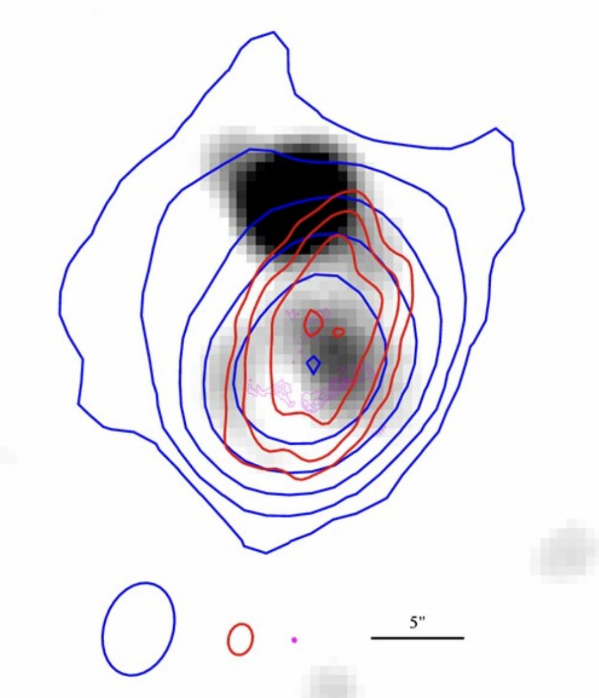
VLA study of 3C 371 shows mean proper motions ~ 10-14c at 100-400 pc scales
implying the jet bulk Lorentz factor $\Gamma \geq 10$ and viewing angle $\theta \leq 11^\circ$.

FR I jets are still accelerating through the first few hundred pc

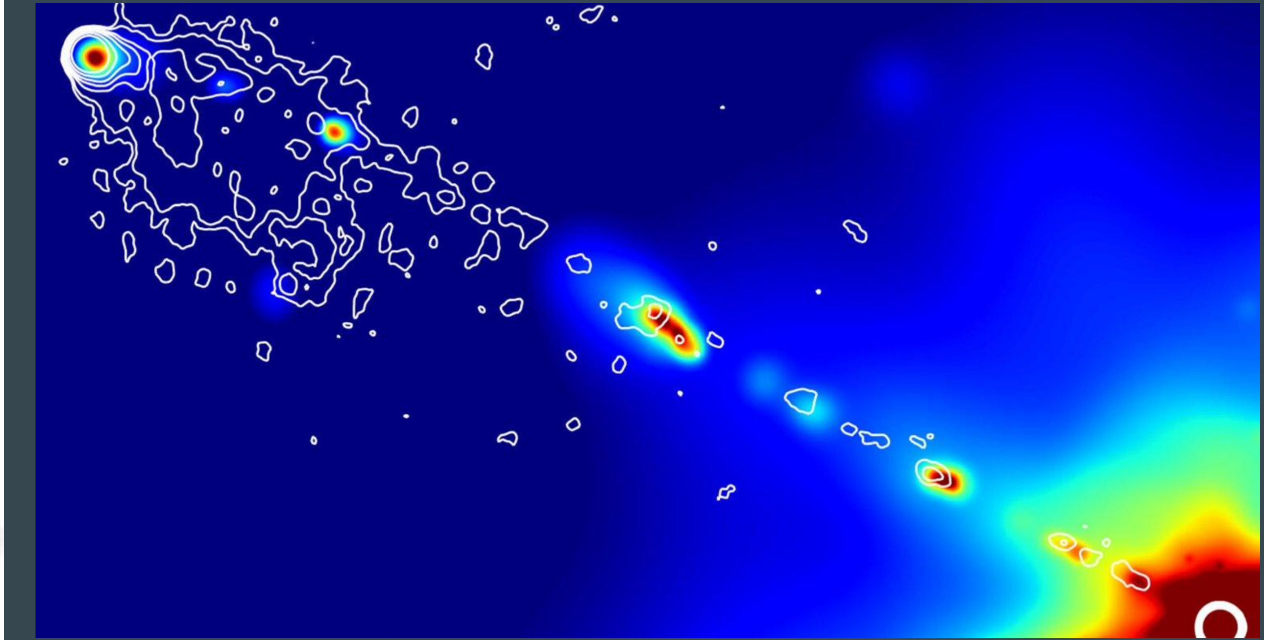
Agniva Roychowdhury PhD Thesis (CAgNVAS project)

Roychowdhury et al., in prep

Jet Structure - Offsets



Hotspot of 4C 74.26 - Chandra image with radio contours overlaid.
(Erlund et al, 2007)

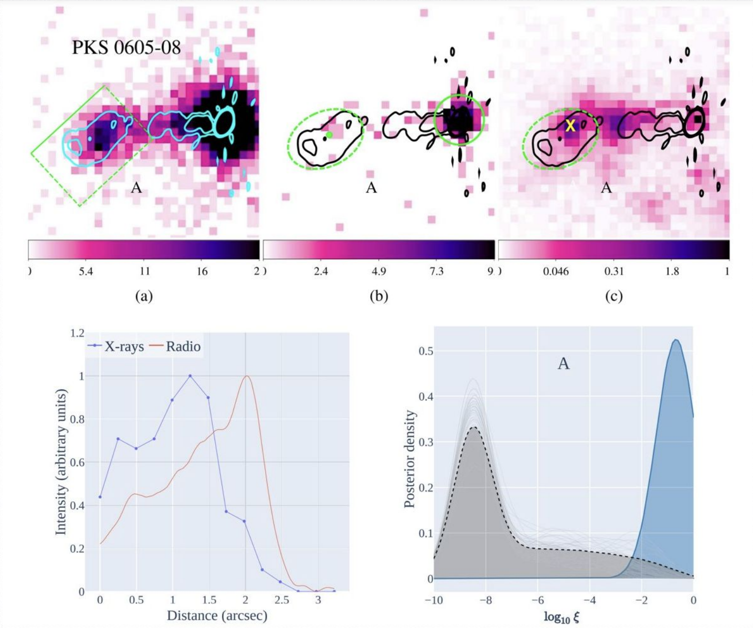


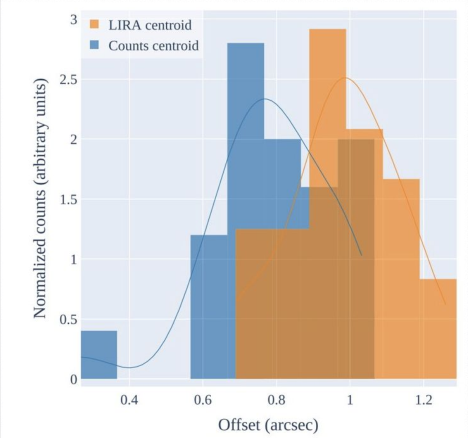
3C 111 - jet clearly shows X-ray first offsets
(Clautice *et al.* 2016)

Jet Structure - Offsets

Karthik Reddy PhD Thesis (Reddy et al., 2021, 2023)

Example offset





Reddy *et al.* (2021), ApJS, 253 (2), 37

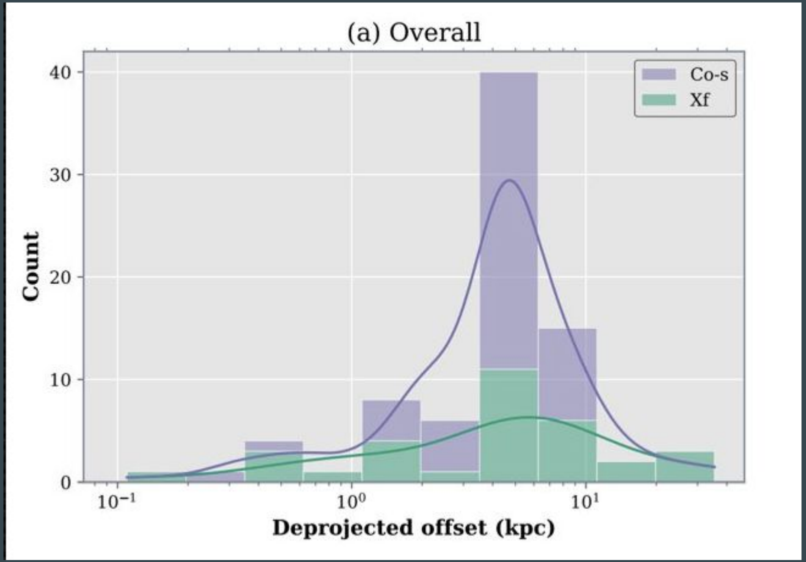
Sample:

Total Chandra detected X-ray jets: 199

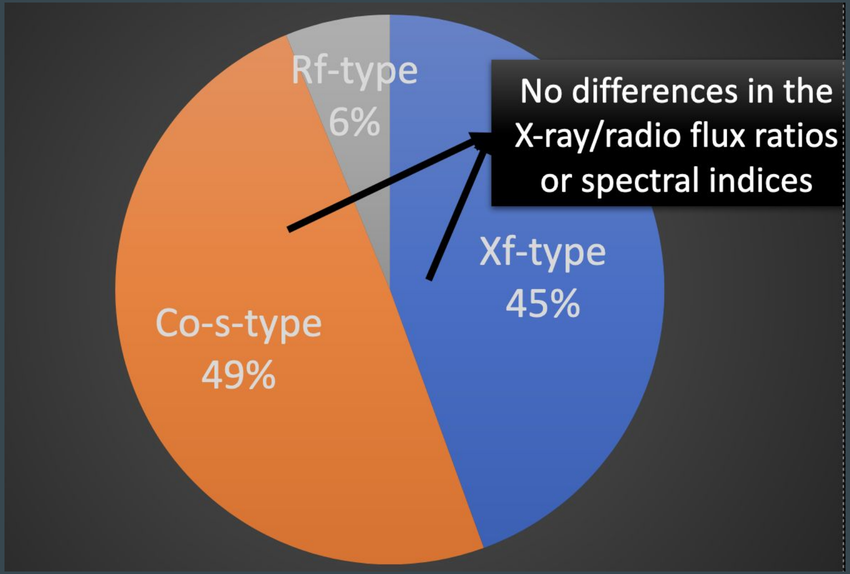
Total analyzed jets: 107 (including FR-I and hotspot-only jets)

Total FR-II jet knots: 114

Jet Structure - Offsets



About half the sample shows "X-ray first" offsets (Xf), while majority of apparent co-spatial sources would allow for similar offsets within localization errors.



No differences in the X-ray/radio flux ratios or spectral indices

Reddy et al., 2021, 2023

See also the ATLAS-X catalog:
https://astro.umbc.edu/Atlas-X/

Summing Up the Large-Scale Jet Picture

- X-rays are presumably synchrotron in most cases, but:
- Why do jets produce multiple (2 or even 3?) populations of electrons with very different γ_{max}?
- Variability implies tiny, pc-scale emitting volumes: 1000x smaller than jet
- Is magnetic reconnection the in-situ particle acceleration mechanism?
- Data are consistent with near-ubiquitous X-ray-first offsets, on the order of kpc size
- Jets are still accelerating and/or reach top speeds on 100 pc scales
  - Implications for the 'one zone' blazar models?
  - Studies limited to a few sources → need larger samples

Needed:

- More theoretical work towards clear observational diagnostics
- High-resolution, Sensitive Optical/UV and X-ray Polarimetry (IXPE and Hubble successors). Highly valuable for constraints on emission mechanism
- High-resolution X-ray imaging (AXIS - proposed X-ray probe mission)

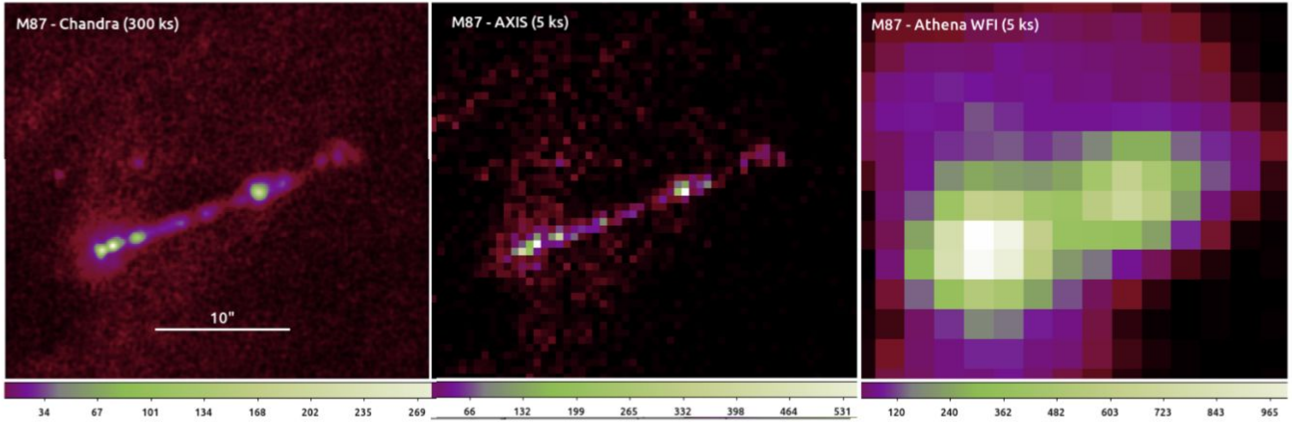
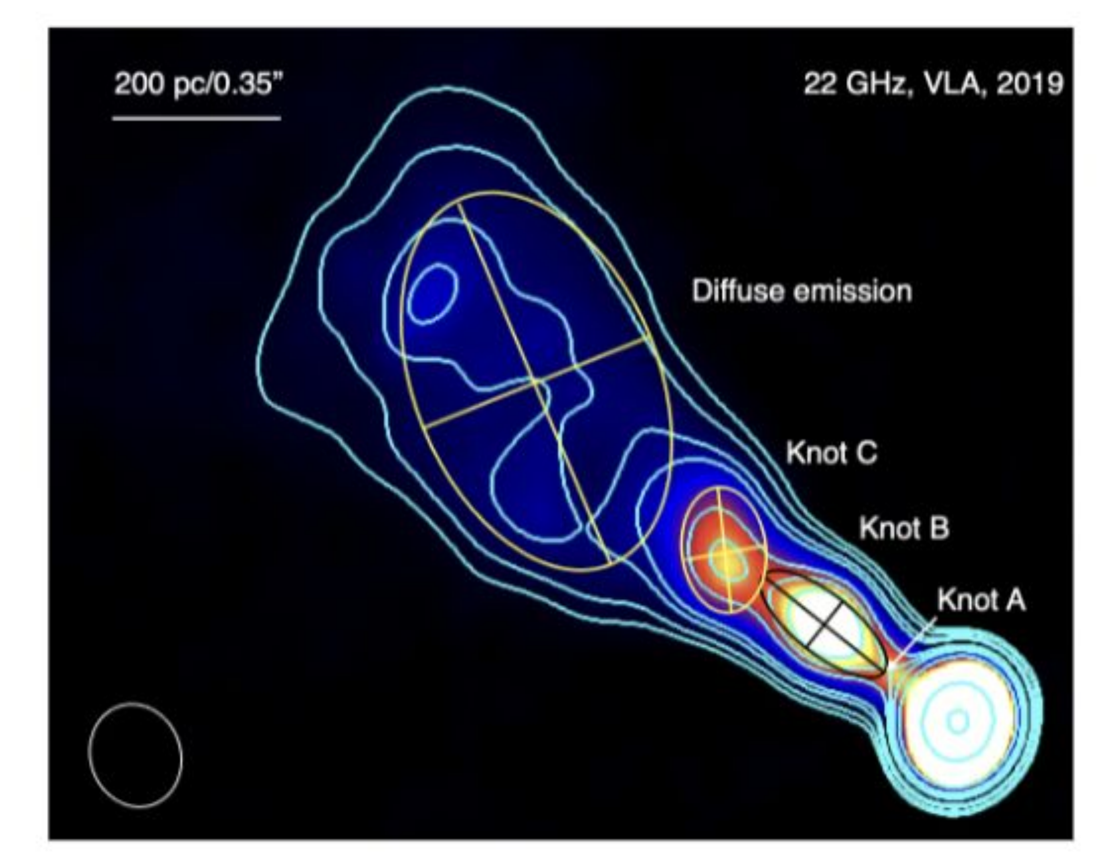
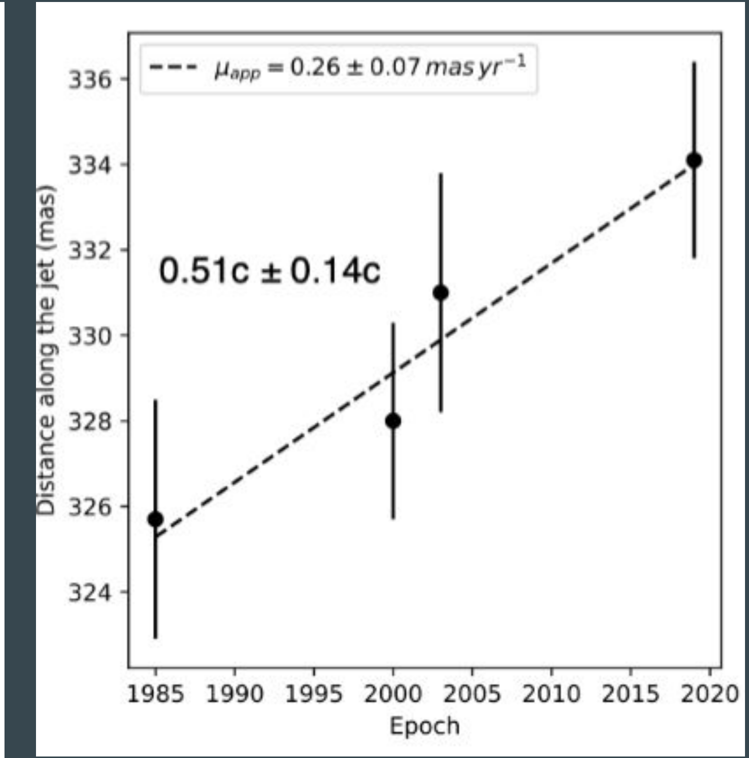


Figure 1. Comparison of M87 observations with different observatories. At left, the actual *Chandra* deep image (~300 ks) used to generate the deconvolved emission model with LIRA. Middle, a simulated AXIS exposures of 5 ks. At right, a 5 ks exposure with the *Athena* WFI. Despite the higher sensitivity of *Athena*, only AXIS provides the spatial resolution required for a detailed jet observations.

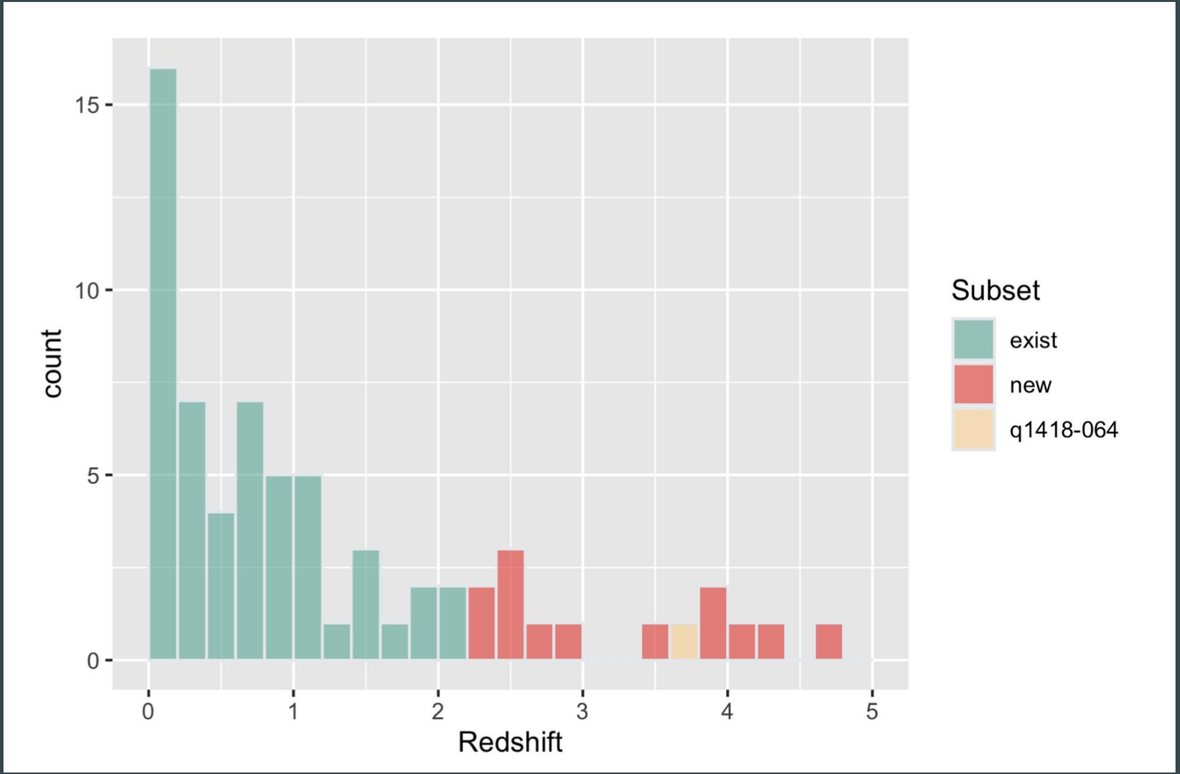
Backup Slides

Jet Structure - Velocity Profiles from pc to kpc scales





3C 78 Roychowdhury 2023, submitted



Current Chandra program will re-observe 12 high-redshift jets to improve our population test of variability.