VLBI studies of High-Excitation FRII radio galaxies

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The project

Extra-galactic jets are collimated outflows of relativistic plasma launched from the centre of active galaxies. High-frequency VLBI observations of nearby radio galaxies (RG) with jets oriented at large viewing angles allow us to probe the intrinsic jet properties in the immediate vicinity of the black hole, free from the strong Doppler boosting and projection effects. We aim at expanding the sample of sources which are suitable for jet formation studies by employing high-sensitivity observations of previously unexplored objects, characterised by different accretion modes. We especially focus on high-excitation FRII radio galaxies, in which the jet base is generally faint and less studied.

The jet base in High-Excitation and Low-Excitation Galaxies

We performed a preliminary study of a sample of nearby RG, which were classified as high-excitation galaxies (HEG) or low-excitation galaxies (LEG) based on their X-ray luminosity. We compared the mass-scaled expansion profiles of sources showing a parabolic jet base, observing that **jets in HEG appear wider than in LEG at the same distance from the black hole.** We interpreted this as possible evidence for the existence in HEG of a more extended disk-launched sheath surrounding the jet spine (Boccardi et al. 2021).

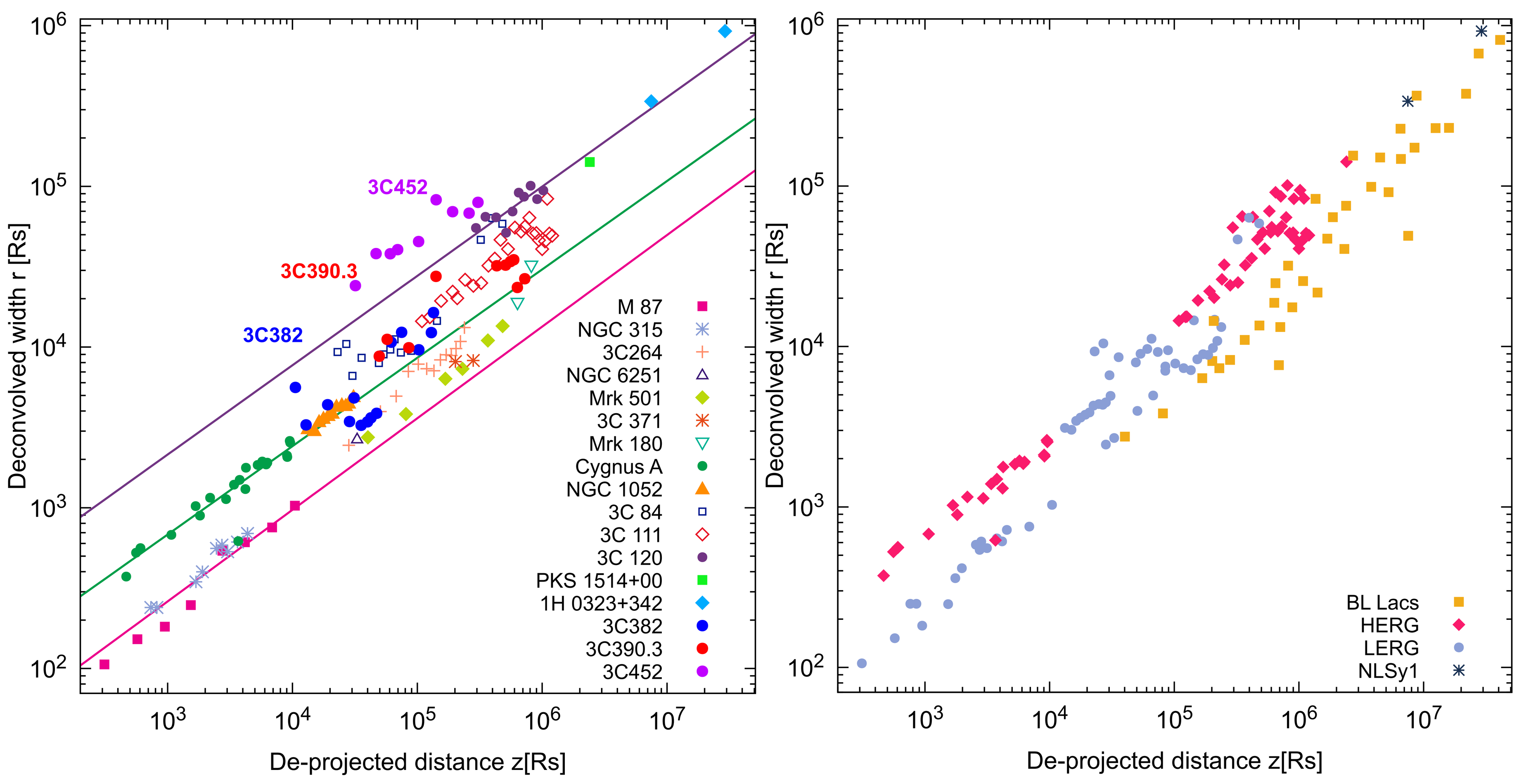
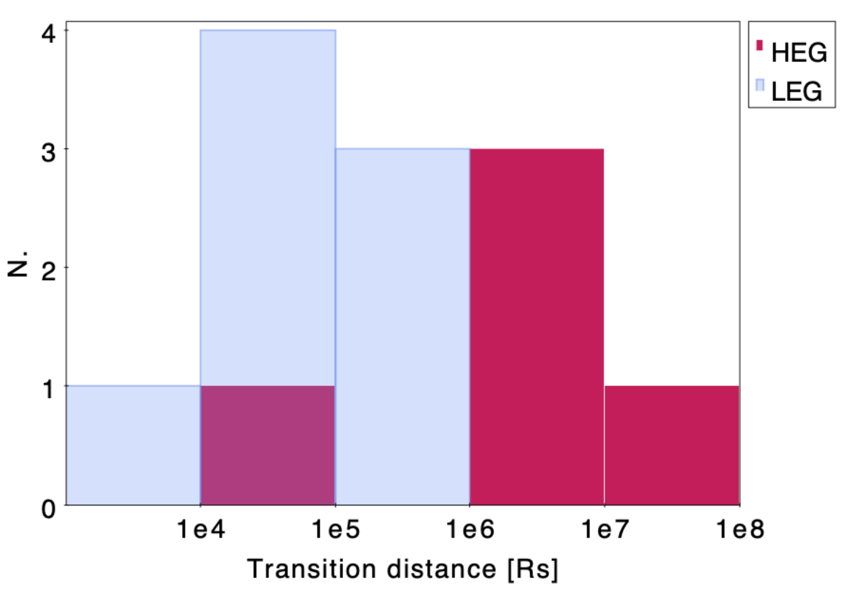


Fig. 1. Left: Jet collimation profiles in sources showing a parabolic expansion. Results for three additional sources, namely 3C 382 (blue), 3C 390.3 (red), and 3C 452 (purple), which were not present in the analysis by Boccardi et al. (2021), are included here (Madika et al. in prep.). Right: profiles of all the sources in the original sample, divided per classes.



The jet collimation region was also found to be more extended in HEG than in LEG. With the exception of Cygnus A, HEG are observed to collimate on scales larger than $\sim 10^6$ R_s from the black hole, while jets in LEG are all transitioning below this limit. We suggest that disk-winds in HEG contribute to the achievement of a higher collimation degree in their jets.

Fig. 2. Distribution of the transition distance from a parabolic to a conical jet shape in LEG and HEG (Boccardi et al. 2021).

The twin-jet system in 3C 452

The radio galaxy 3C 452 is a rare example of FRII-HEG showing a two-sided jet on VLBI scales. It displays a unique combination of symmetric double morphology, large black hole mass ($M_{BH} = 3.5 \times 10^8\ M_\odot$, Marchesini et al. 2004), and vicinity ($z = 0.081$), which makes it an ideal target for studying jet formation in a powerful source. We have performed multi-frequency VLBI observations, obtaining a first view of the twin-jet on sub-parsec scales. As the jet is oriented close to the plane of the sky, we expect to be able to probe the properties of the thick torus obscuring the central engine. This may play an important role in the jet collimation process. **Our X-ray spectral analysis indicates that this is indeed a highly absorbed source, and the VLBI spectral study hints at the presence of free-free absorption at the jet base.**

First view from kilo-parsec to sub-parsec scales

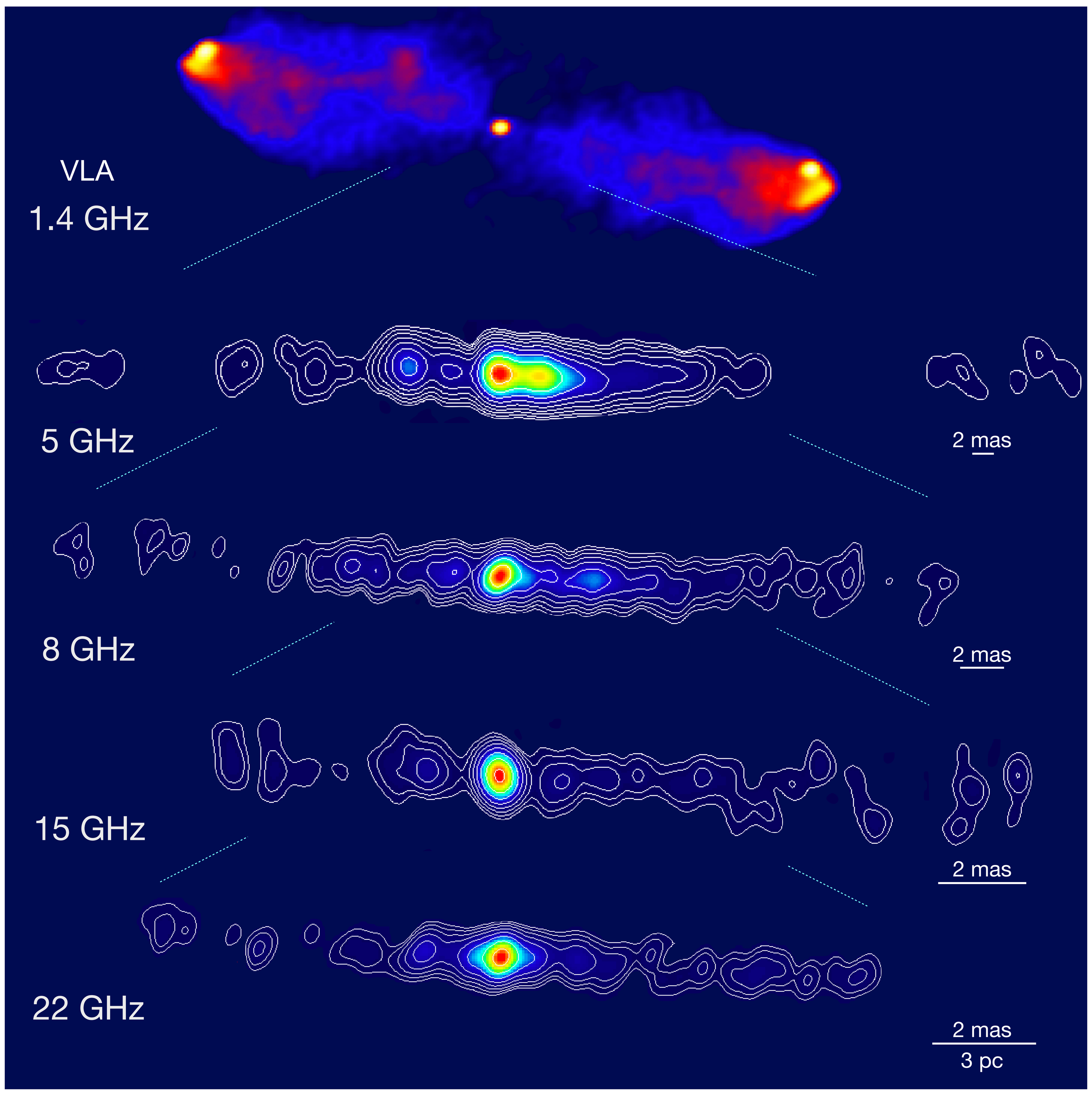


Fig. 3. Twin-jet structure of 3C 452 from kilo-parsec to sub-parsec scales. The top image was obtained from VLA data at 1.4 GHz. The following maps show the VLBI structure at 5 GHz, 8 GHz, 15 GHz, and 22 GHz. The observations were performed using the VLBA and the Effelsberg telescope. The maps have been aligned to the central brightest feature.

VLBI Spectral analysis

We carried out a VLBI spectral study using simultaneous 5 GHz, 8 GHz, and 15 GHz observations. For each pair of images we performed a 2D cross-correlation analysis taking into account optically thin regions of the jet in order to properly align our images. The flux density S_ν is assumed to depend on the frequency as $S_\nu \propto \nu^a$.

The central feature shows a **highly inverted spectrum.** Between 5 and 8 GHz, the index exceeds the value expected in a synchrotron self-absorbed source ($\alpha > 2.5$), which may be **evidence for additional opacity.**

A strong asymmetry is observed between the jet and the counter-jet side in both maps. **The receding side shows a much flatter spectrum,** possibly **indicative of free-free absorption from the ionised inner-regions of the torus.**

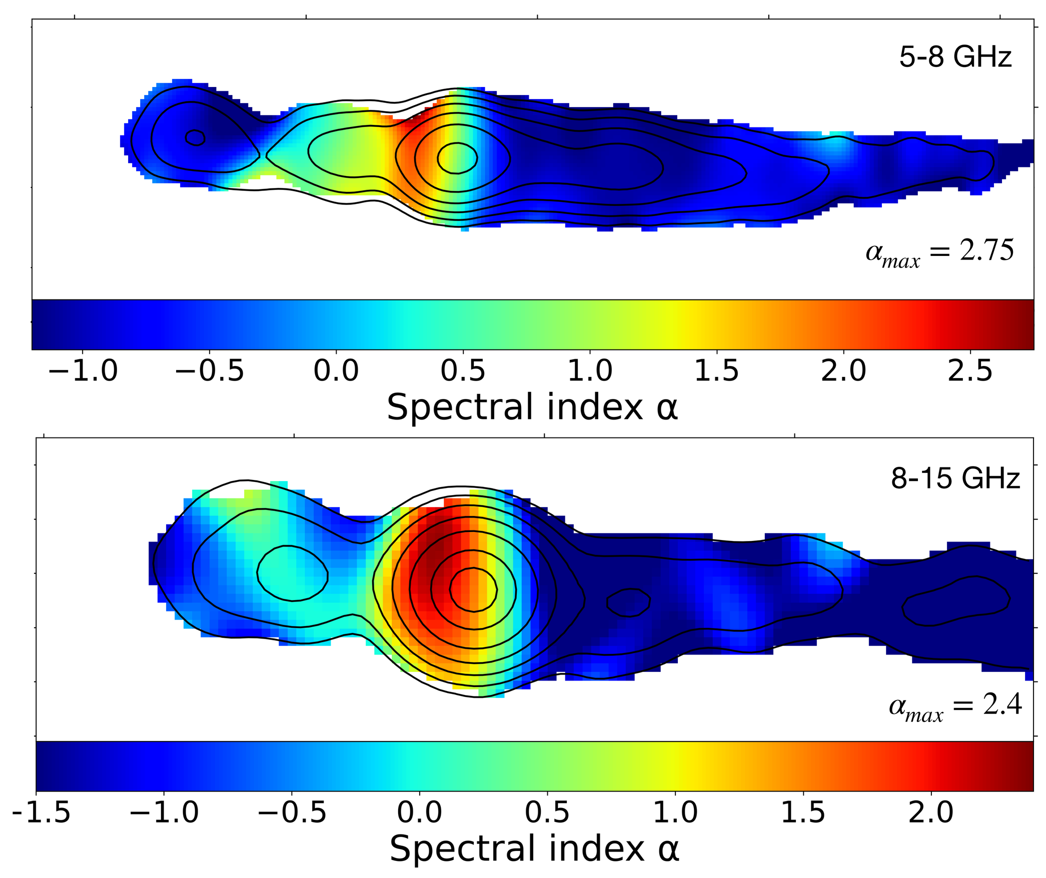


Fig. 4. Top: Spectral index map between 5 GHz and 8 GHz. The contours denote the 8 GHz continuum. Bottom: Spectral index map between 8 GHz and 15 GHz. The contours outline the 15 GHz continuum.

X-ray Spectral analysis

We present an X-ray spectral analysis using data from the XMM-Newton and NuSTAR satellite to test the presence of a torus obscuring the nucleus. The spectrum was extracted within a radius of 0.44 arcmin, in the 0.5-10 keV energy band (XMM-Newton) and 5-60 keV (NuSTAR).

model=scattered power law + intr. absorbed power law + reflected power law + iron emission line

- We obtain a relatively high X-ray luminosity $L_X = 8 \times 10^{43}$ erg/s.
- We model a prominent iron line, indicative of efficient accretion.
- The X-ray spectrum appears to be dominated by Compton reflection off cold matter.
- We estimate a high hydrogen intrinsic column density $N_H = (61.8 \pm 2.3) \times 10^{22}$ cm^{-2}

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Strongly absorbed source

(In agreement with Fioretti et al. 2013)

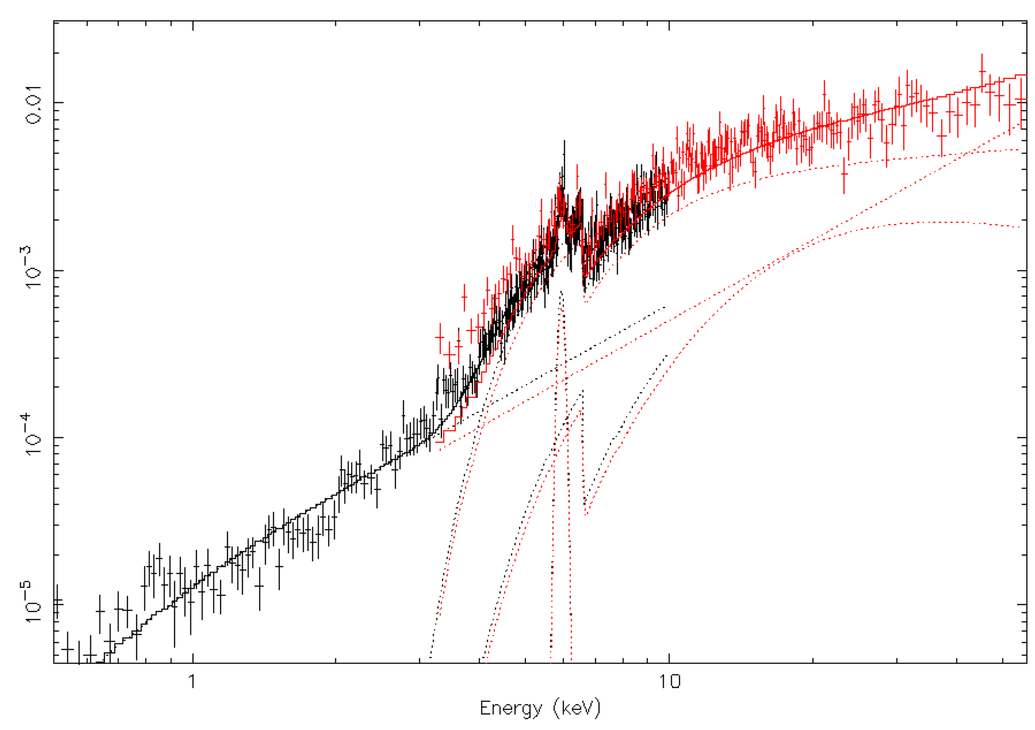

Fig. 5. X-ray spectrum of 3C 452 in the 0.5-60 keV energy band as observed by XMM-Newton (black) and NuSTAR (red). The best-fit models for the different X-ray components are also displayed.

References

- Boccardi et al. 2021, A&A, 647, A67
- Marchesini, D., Celotti, A., & Ferrarese, L. 2004, MN- RAS, 351, 733
- Fioretti, V., Angelini, L., Mushotzky, R. F., Koss, M., & Malaguti, G. 2013, A&A, 555, A44