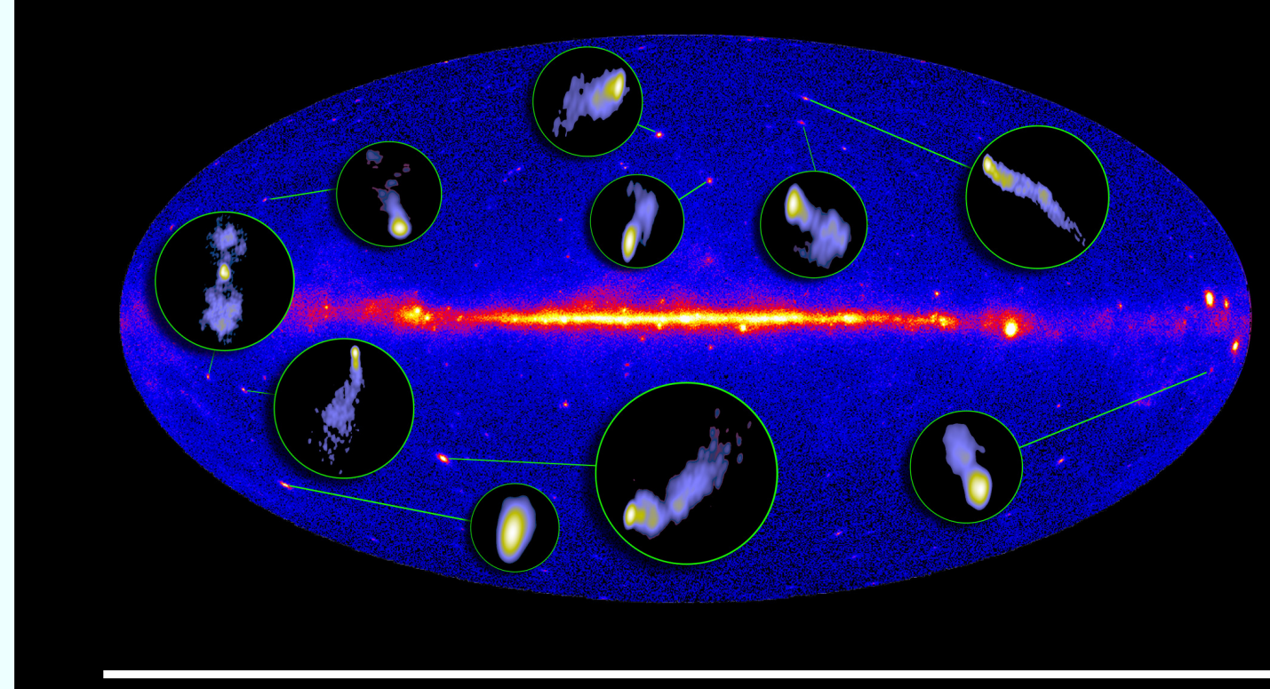

# Apparent parsec-scale jet opening angles and $\gamma$-ray brightness of active galactic nuclei

A.B. Pushkarev[1,2], M.L. Lister[3], Y.Y. Kovalev[4,5], T. Savolainen[5]

[1]*Crimean Astrophysical Observatory, Ukraine;* [2]*Pulkovo Observatory, Russia*

[3]*Purdue University, USA;* [4]*Astro Space Center, Russia;* [5]*Max-Planck-Institut für Radioastronomie, Germany*

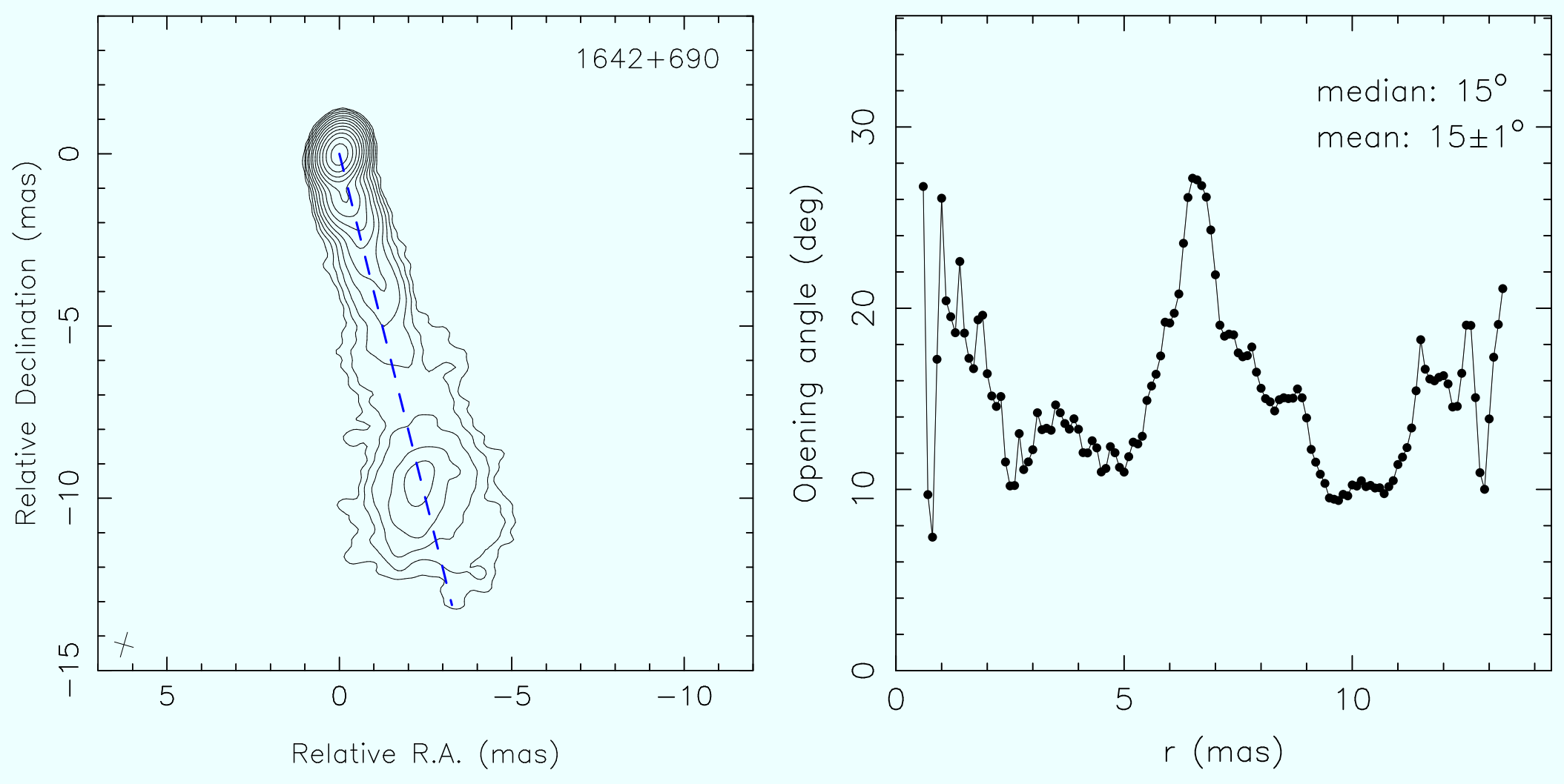

**Fig. 1.** *Left:* MOJAVE stacked-epoch image of 1642+690 at 15 GHz. The blue dashed line is the jet axis. *Right:* Apparent opening angle of the jet along its axis.

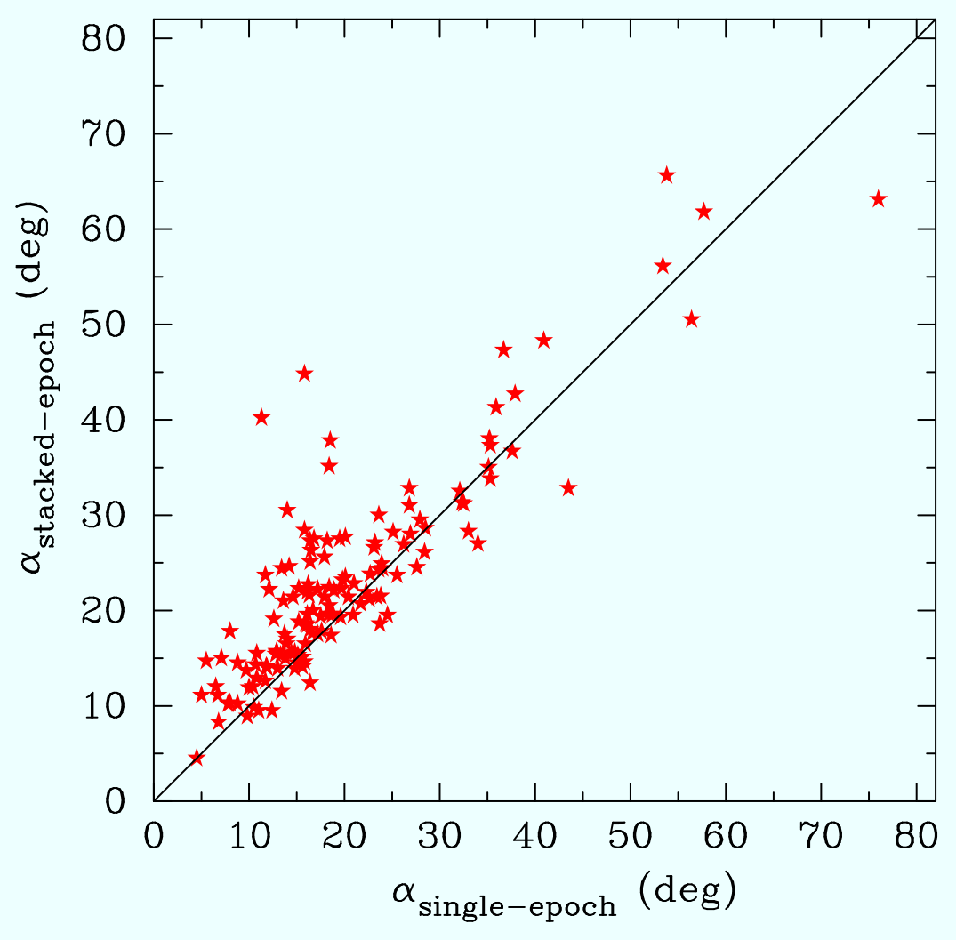

**Fig. 2.** Apparent opening angles from single-epoch and stacked-epoch images.

## Apparent opening angles

We used the 15 GHz naturally weighted MOJAVE VLBA stacked-epoch images. The opening angle of the jet was calculated as the median value of $\alpha = 2\arctan[0.5(d^2 - b_\varphi^2)^{1/2}/r]$, where $d$ is the full width at half maximum (FWHM) of a Gaussian fitted to the transverse jet brightness profile, $r$ is the distance to the core along the jet axis, $b_\varphi$ is the beam size along the position angle $\varphi$ of the jet-cut, and the quantity $(d^2 - b_\varphi^2)^{1/2}$ is the deconvolved FWHM transverse size of the jet. The direction of the jet axis was determined using the median position angles of all jet components over all the epochs from model fitting. In **Fig. 1** the 15 GHz total intensity map of 1642+690 is shown as an example together with opening angle of the jet as a function of angular distance to the core. The procedure of stacking all available epochs for a given source makes an assessment of the apparent opening angle more accurate as been sensitive to possible changes of directions along which different jet features might move over time resulting in a wider apparent opening angle that seen in a single-epoch image. In general, the single-epoch opening angles are in good agreement with those from the stacked-epoch images (**Fig. 2**).

The distributions of the measured opening angle for 162 LAT-detected and 53 non-LAT-detected sources are shown in **Fig. 3**. A Kolmogorov-Smirnov (K-S) test indicates a probability of only $p = 0.011$ for these two samples being drawn from the same parent population. In **Fig. 4** we show MOJAVE VLBI images of two LAT-detected quasars with the largest apparent opening angles.

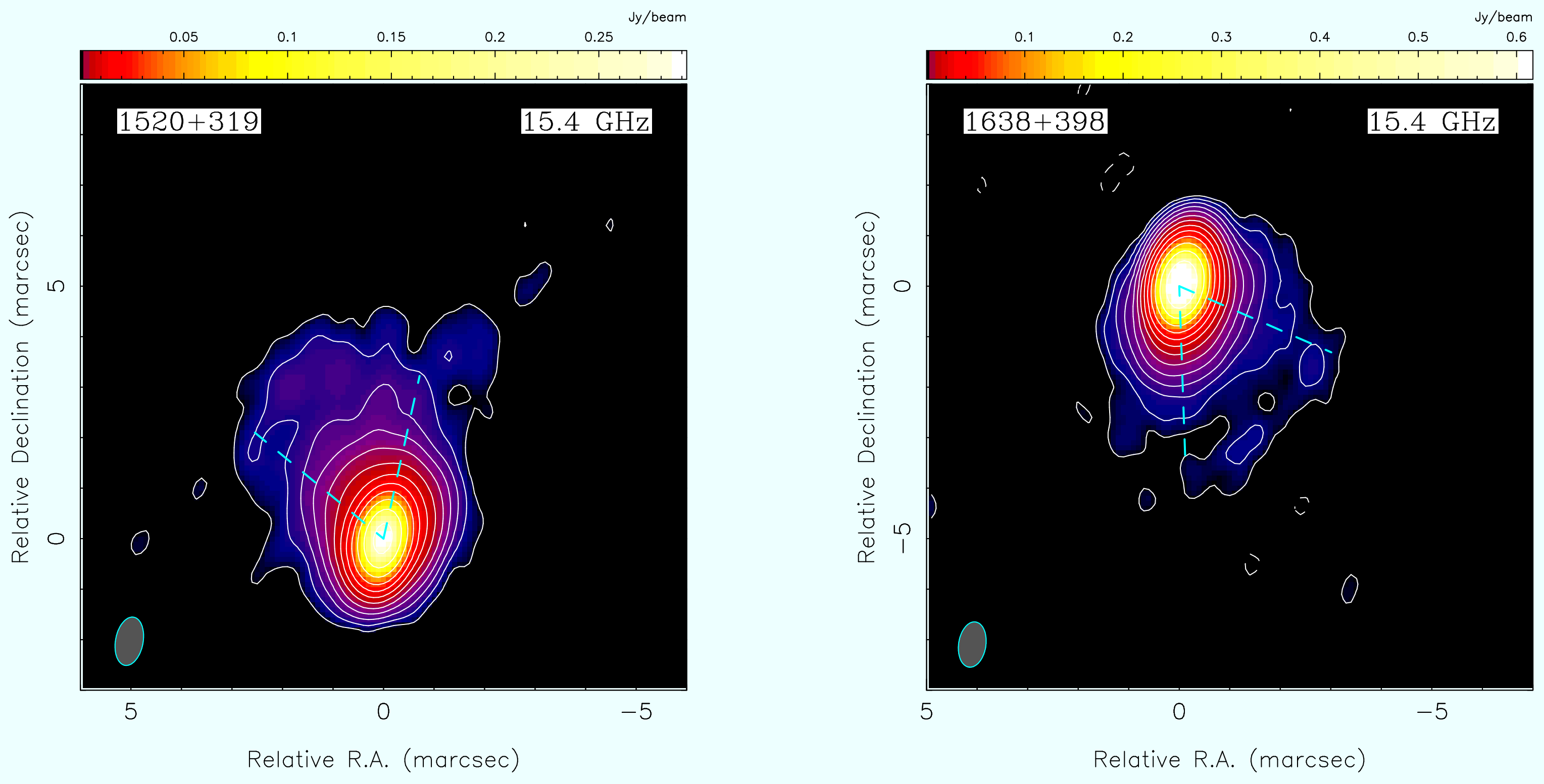

**Fig. 4.** MOJAVE images of LAT-detected quasars 1520+319 and 1638+398 that show the largest apparent opening angles.

## Viewing angles

The viewing angles $\theta$ can be derived from the relation $\theta = \mathrm{asin}\,(\alpha_{\text{int}}/\alpha_{\text{app}})$. Intrinsic opening angle is inversely proportional to Lorentz factor, $\alpha_{\text{int}} = \rho/\Gamma$, as predicted by hydrodynamical (Blandford & Königl 1979) and megnetic acceleration models (Komissarov et al. 2007) of relativistic jets, and confirmed by observations (**Fig. 5**; see also Pushkarev et al. 2009; Jorstad et al. 2005).

We simulated the viewing angle distributions for $\gamma$-ray bright and $\gamma$-ray weak AGN (**Fig. 6**) by fitting the corresponding apparent opening angle distributions and assuming flat distributions of $\rho$ within a range of $[0.1, 0.5]$ and Lorentz factor $\Gamma_{\text{LAT\_Y}} = [7, 25]$ and $\Gamma_{\text{LAT\_N}} = [3, 15]$. Probability density functions as well as empirical density functions for apparent opening angle distributions and final viewing angle distributions were fitted by the Generalized Lambda Distribution. As seen from **Fig. 6**, $\gamma$-ray bright AGN tend to have smaller angles to the line of sight comparing to those of $\gamma$-ray weak AGN, with median vaulues 3° and 6°, respectively. A probability of observing a jet at $\theta < \alpha_{\text{int}}/2 \simeq 0.5^\circ$ is 0.71%, implying that statistically we expect to have 1 such object in a sample of 162 sources.

## References

Blandford, R. D. & Königl, A. 1979, ApJ, 232, 34
Hovatta, T., Valtaoja, E., Tornikoski, M., Lähteenmäki, A. 2009, A&A, 498, 723
Jorstad, S. G., Marscher, A. P., Lister, M. L., et al. 2005, AJ, 130, 1418
Komissarov, S. S., Barkov, M. V., Vlahakis, N., & Königl, A. 2007, MNRAS, 380, 51
Lister, M. L., Cohen, M. H., Homan, D. C., et al. 2009, AJ, 138, 1874
Pushkarev, A. B., Kovalev, Y. Y., Lister, M. L., Savolainen, T., 2009, A&A, 507, 33

## Abstract

- We have investigated the differences in apparent opening angles between the parsec-scale jets of the AGN detected by the Fermi Large Area Telescope during its first 24 months of operations and those of non-LAT-detected AGN. We used 15.4 GHz VLBA observations of 215 sources from the 2 cm VLBA MOJAVE program. The apparent opening angles were determined by analyzing transverse jet profiles from the data in the image plane by using stacking images constructed from all available MOJAVE epochs for a given source.
- We confirm our earlier result based (Pushkarev et al., 2009) on the first three months of scientific operations of the LAT. The apparent opening angles of gamma-ray bright AGN are preferentially larger than those of gamma-ray weak sources, suggesting smaller viewing angles.
- Intrinsic opening angles for BL Lacs are wider those in quasars.

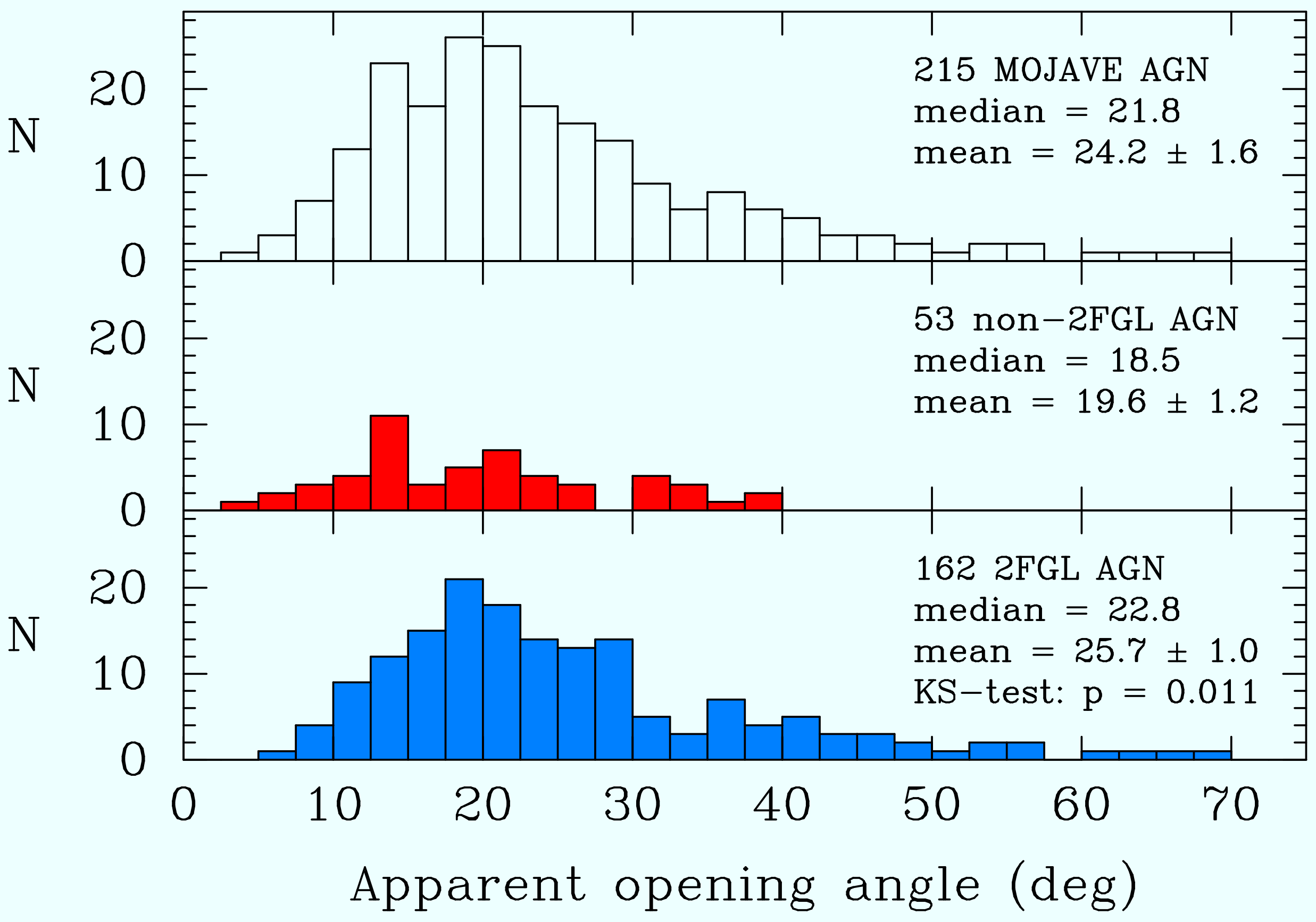

**Fig. 3.** Distributions of the **apparent opening angle** from jet-cut analysis for 215 MOJAVE AGN (*top panel*), comprising 53 non-LAT-detected (*middle panel*) and 162 LAT-detected (*bottom panel*) sources.

## Intrinsic opening angles

We have derived the values of the viewing angle $\theta$ and the bulk Lorentz factor $\Gamma$ for MOJAVE-1 AGN using jet speeds from the MOJAVE kinematic analysis (Lister et al. 2009) and variability Doppler factor from the Metsähovi AGN monitoring program (Hovatta et al. 2009). The overlap of the MOJAVE and Metsähovi programs comprises 56 sources.

The intrinsic opening angles $\alpha_{\text{int}} = \alpha_{\text{app}} \sin\theta$ were calculated for the 56 sources (**Fig. 5**). A K-S test indicates no significant difference ($p = 0.44$) between the samples of LAT-detected and non-LAT-detected sources, suggesting that the established systematic difference in apparent opening angles is most probably the result of projection effects, i.e., the $\gamma$-ray bright jets are aligned closer to our line of sight.

We also found that BL Lacs have on-average wider intrinsic opening angles ($2^\circ\!.7 \pm 0^\circ\!.2$) than those of quasars ($1^\circ\!.4 \pm 0^\circ\!.1$). The corresponding distributions are different at confidence level of $> 99.9\%$ according to the K-S test. This result is consitent with the higher speeds observed in more powerful outflows of quasars suggesting a better jet collimation.

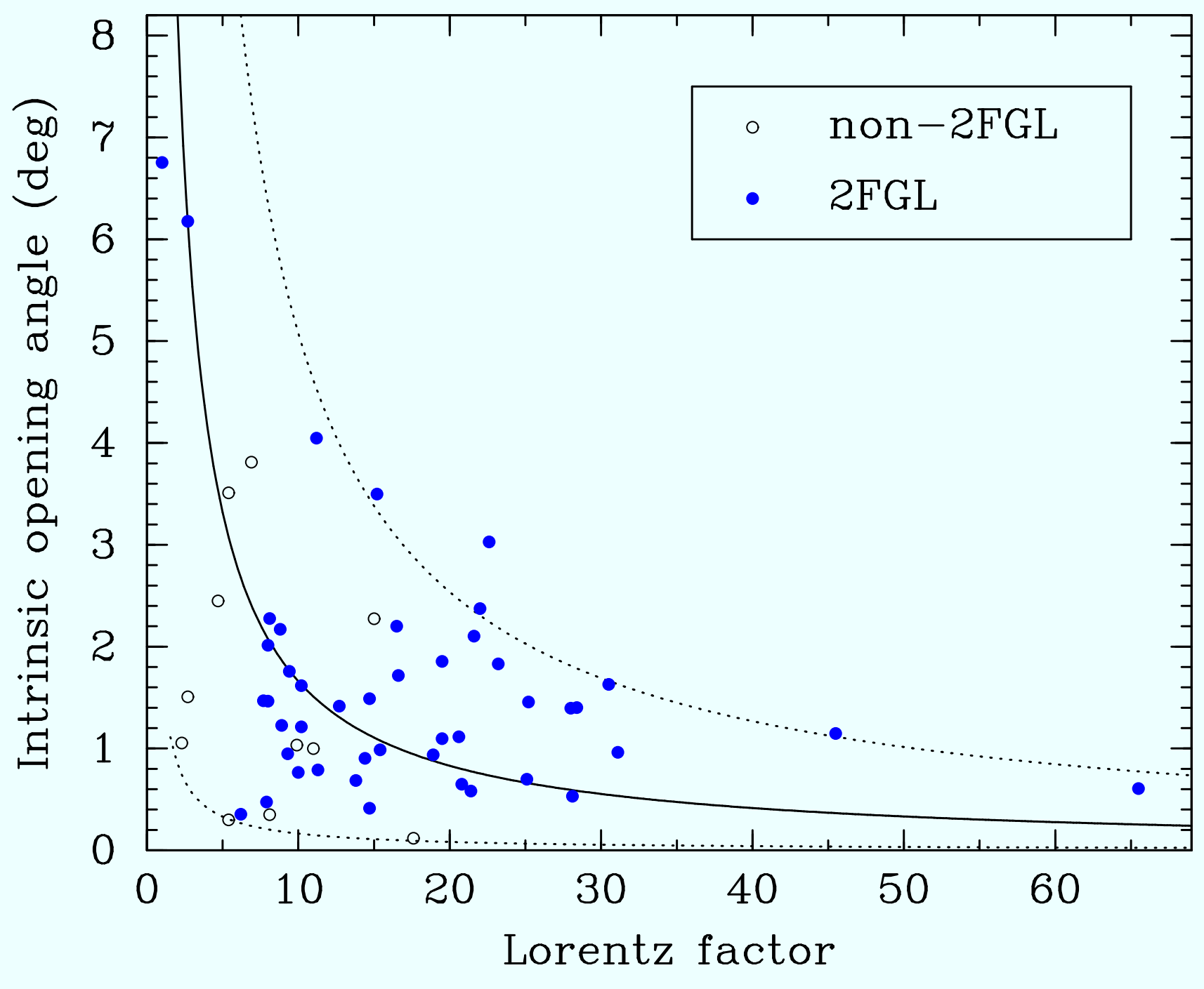

**Fig. 5.** Intrinsic opening angle vs. Lorentz factor for 56 jets. The solid line shows the median curve fit with the assumed relation $\alpha_{\text{int}} = \rho/\Gamma$, where $\rho$ is a constant (here $\rho = 0.29$ rad).

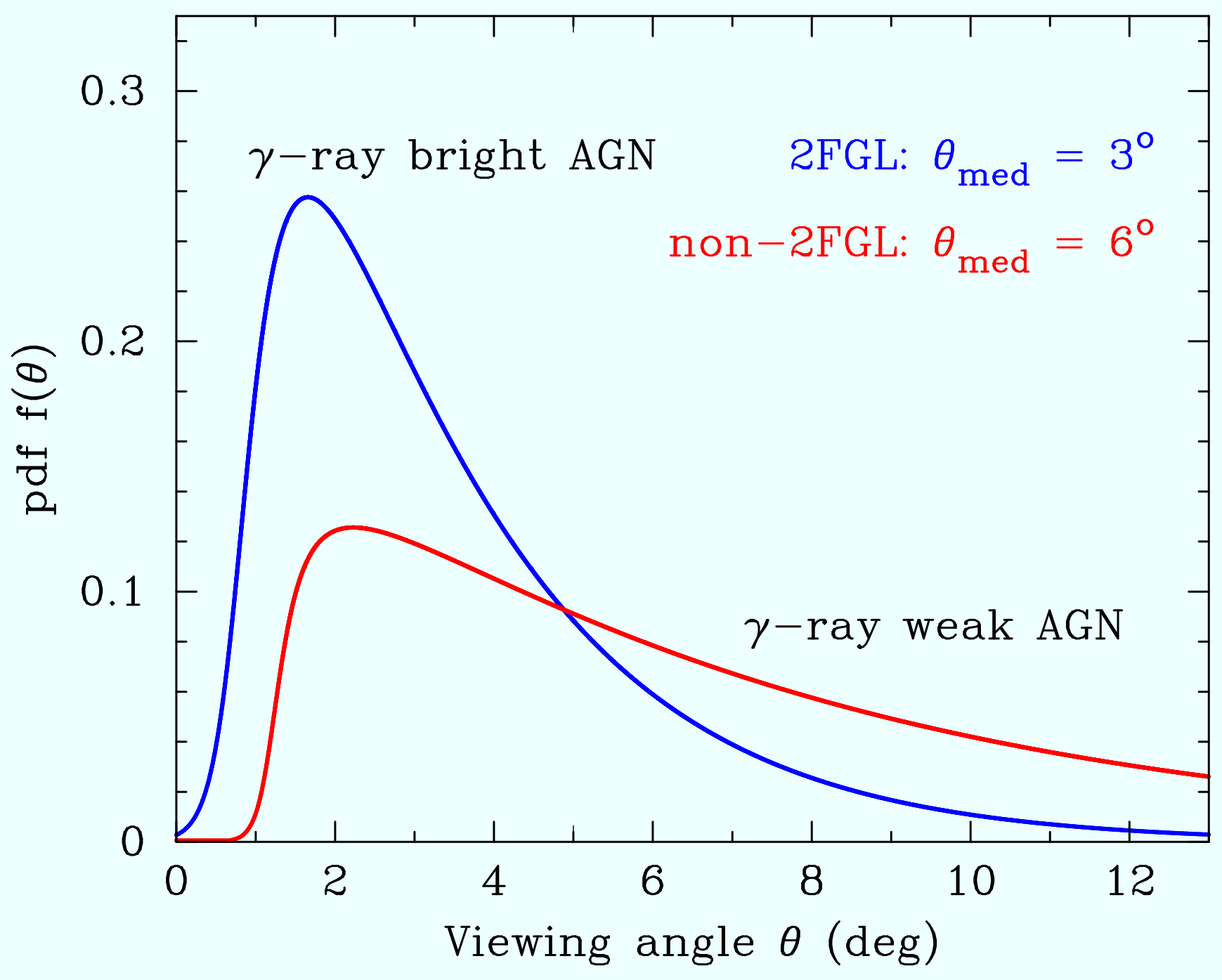

**Fig. 6.** Probability density function of viewing angle as derived from the apparent angle and Lorentz factor distributions of $\gamma$-ray bright (blue curve) and $\gamma$-ray weak (red curve) AGN.

## Acknowledgements

This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team. The MOJAVE project is supported under National Science Foundation grant AST-0807860 and NASA *Fermi* grant NNX08AV67G. The VLBA is a facility of the National Science Foundation operated by the National Radio Astronomy Observatory under cooperative agreement with Associated Universities, Inc.