Perplexing jet outflow and gamma-ray emission correlations - a challenge for the available relativistic jet models

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Outline of the project

Using millimeter very long baseline interferometry (VLBI) observations of the BL Lac object S5 0716+714 from August 2008 to September 2013, we investigate variations in the core flux density and orientation of the sub-parsec scale jet i.e. position angle. The γ-ray data obtained by the *Fermi*-LAT (Large Area Telescope) are used to investigate the high-energy flux variations over the same time period. **For the first time in any blazar, we report a significant correlation between γ−ray flux variations and position angle (PA) variations in the VLBI jet.** The cross-correlation analysis also indicates a positive correlation such that the mm-VLBI core flux density variations are delayed with respect to the γ-ray flux by 82±32 days. This suggests that the high-energy emission is coming from a region located ≥(3.8±1.9) parsecs upstream of the mm-VLBI core (closer to the central black hole). These results imply that the observed inner jet morphology has a strong connection with the observed γ-ray flares.

Determination of inner jet orientation

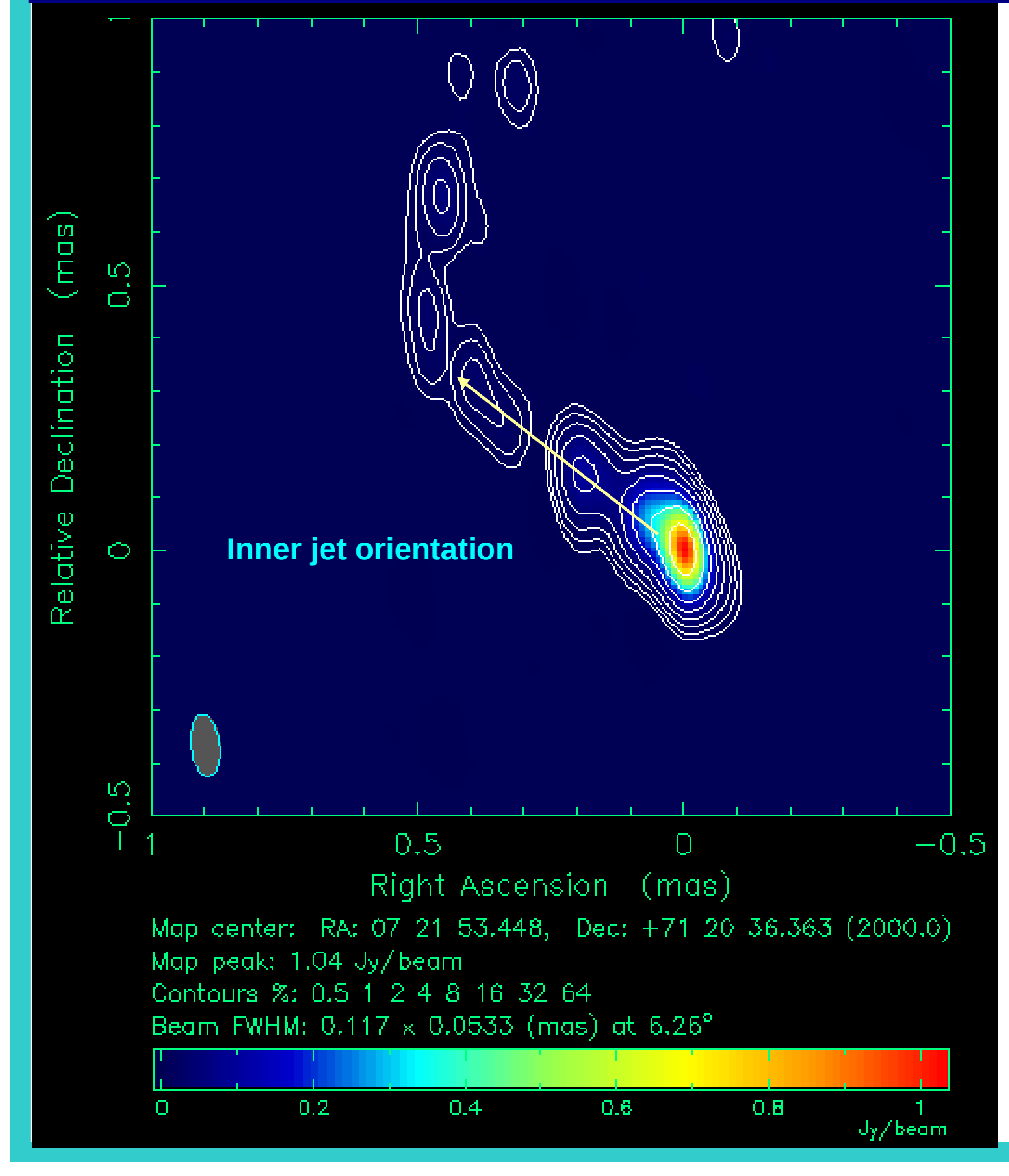

Fig. 1 : An example of 86 GHz VLBI images of the BL Lac object S5 0716+714 observed on February 18, 2013.

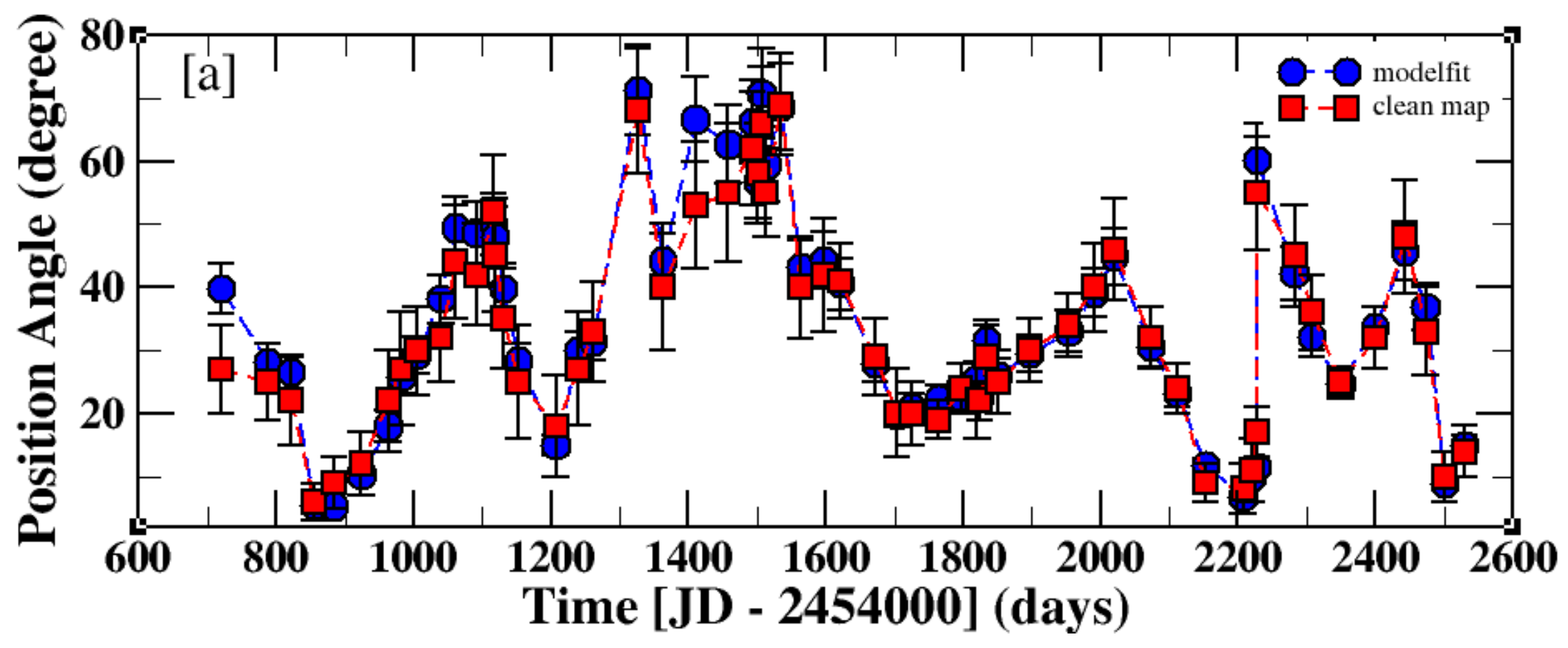

Fig. 2 : Position angle (PA) variations in the central region of the jet. The blue circles show the PA calculated using model-fitting, while those estimated directly from clean maps are in red (square symbols).

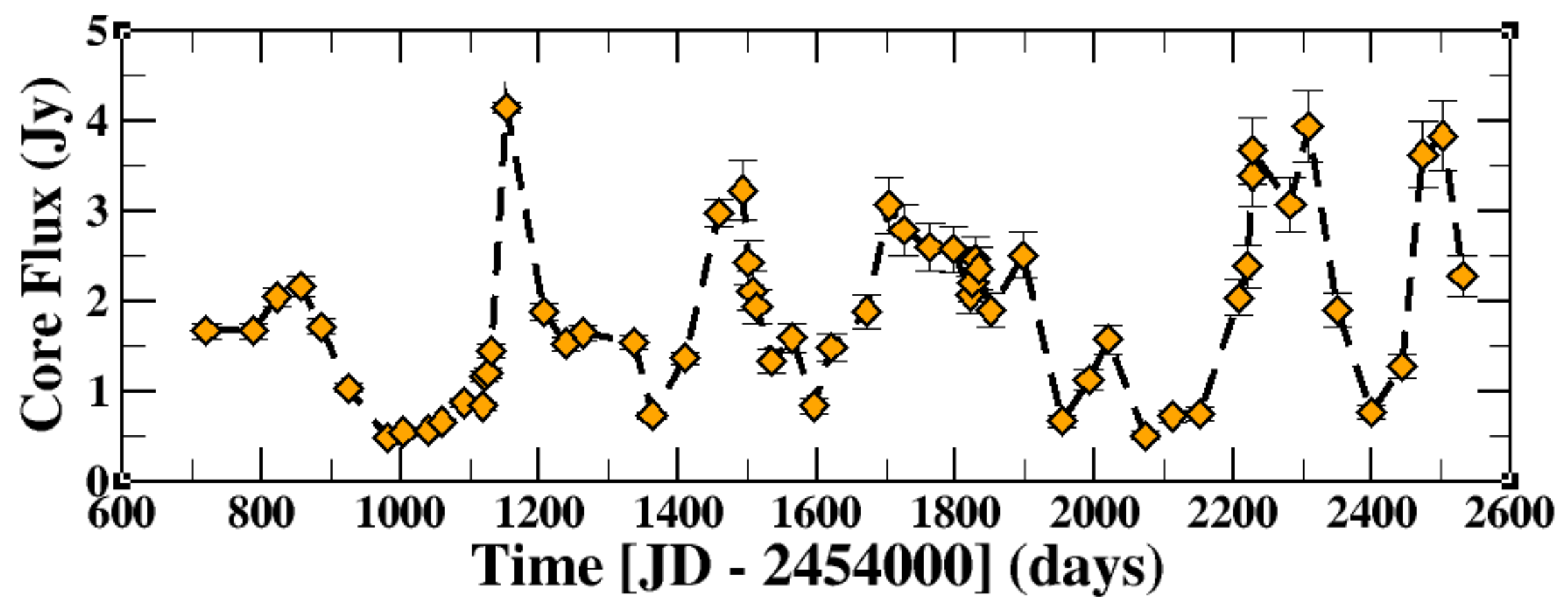

Fig. 3 : 7mm VLBI core flux density variations from August 2008 to September 2013.

The inner jet orientation variations are determined by taking a flux density-weighted average of all the clean delta components 3 times above the image noise level. We also used another method using the position angle of the innermost Gaussian modelfit component to estimate of the direction of the inner portion of the jet.

Gamma-ray vs. core flux variations

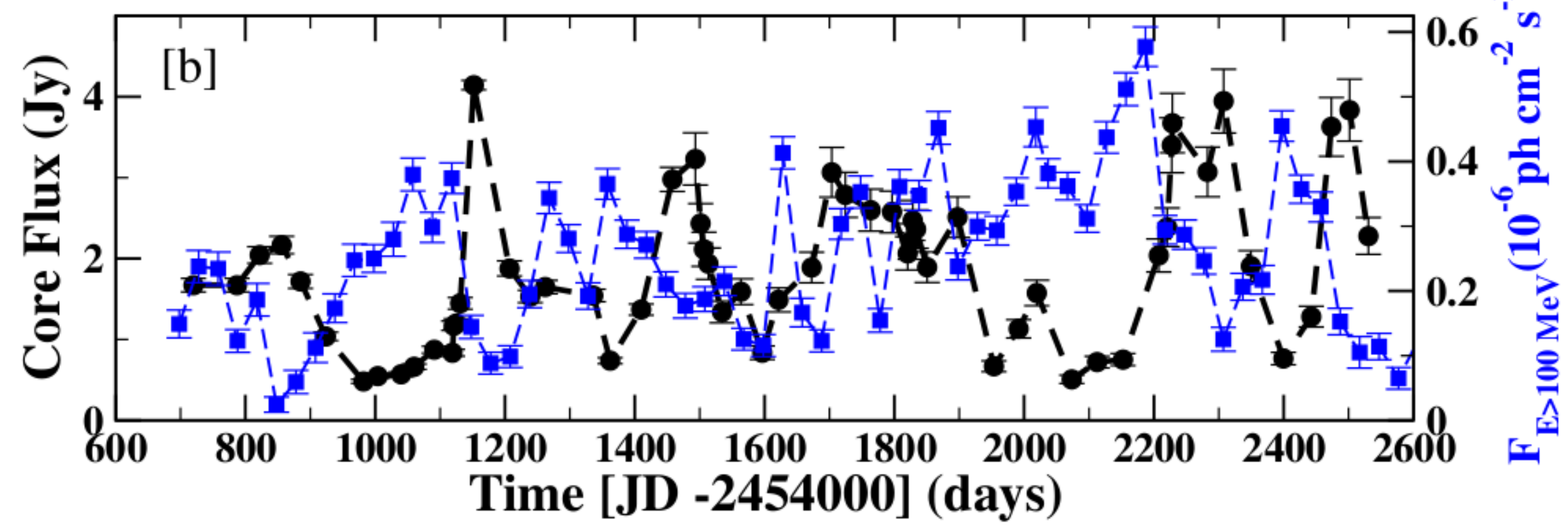

Fig. 4 : 7mm VLBI core flux density variations (black circles) superimposed with the monthly averaged gamma-ray flux variations (blue squares).

Cross-correlation analysis suggests a significant correlation between γ-ray and 7mm VLBI core flux variations with γ-ray flux variations leading the core flux variations by 82±32 days.

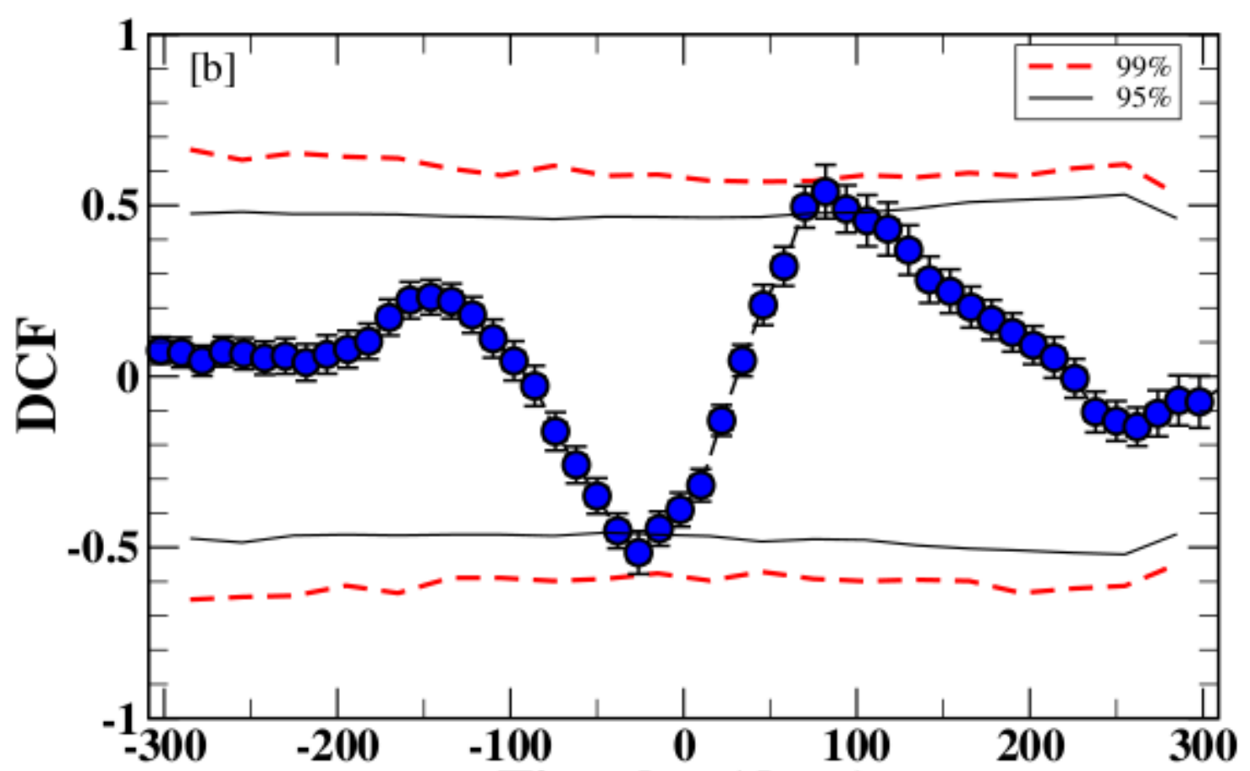

Fig. 5 : Cross-correlation analysis curve between the γ-ray and core flux density variations.

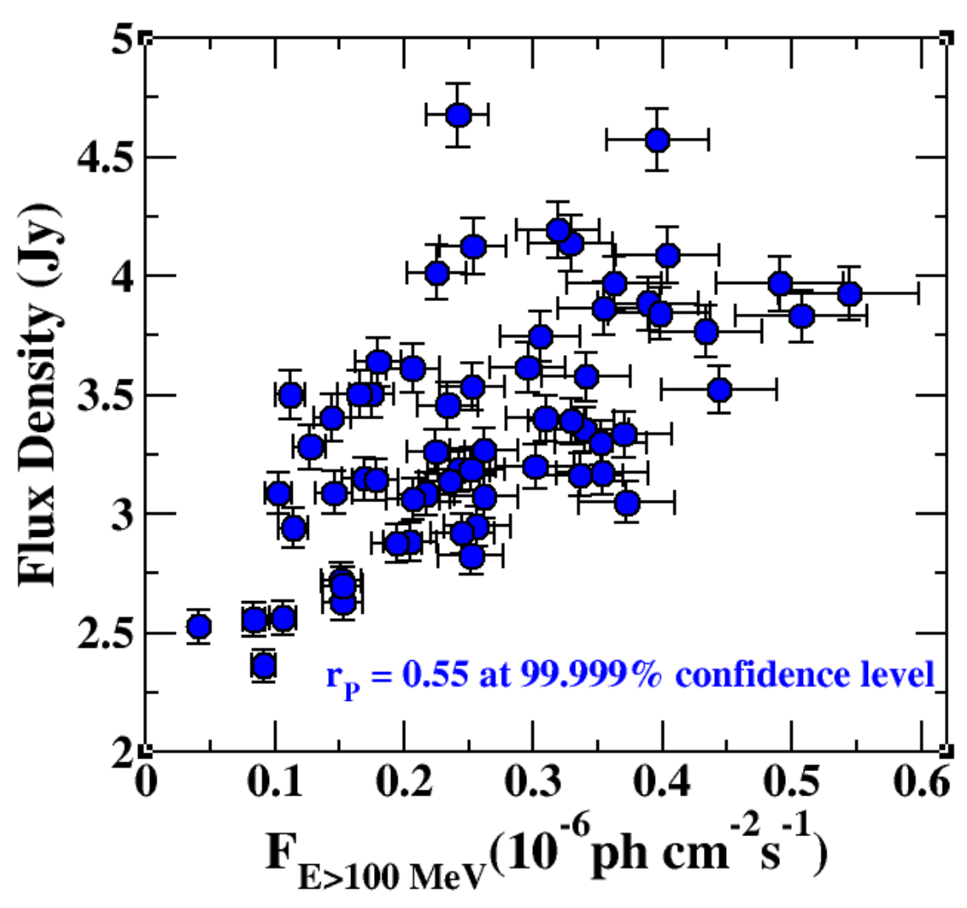

Fig. 6 : Flux-flux plot of the shifted core (by 80 days) vs. γ-ray data.

Gamma-ray flux vs. jet orientation variations

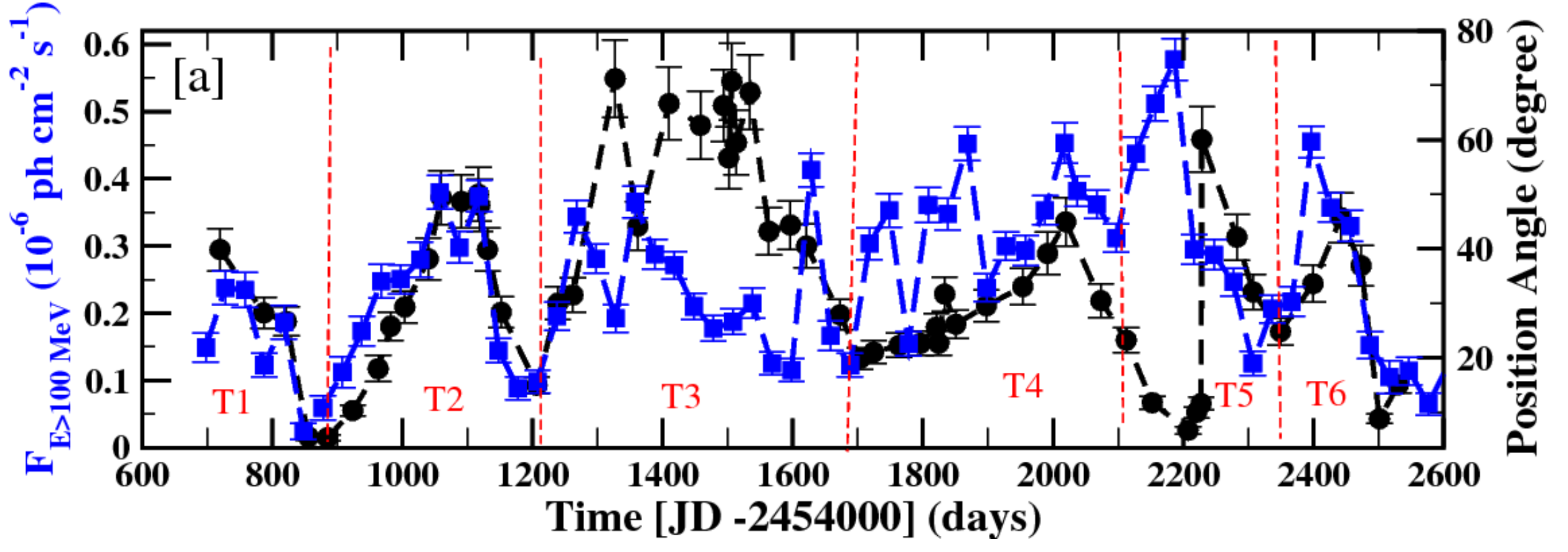

Fig. 7 : Inner jet orientation variations (black circles) superimposed with the monthly averaged γ-ray flux variations (blue squares).

We found a significant correlation between γ-ray flux and jet orientation variations.

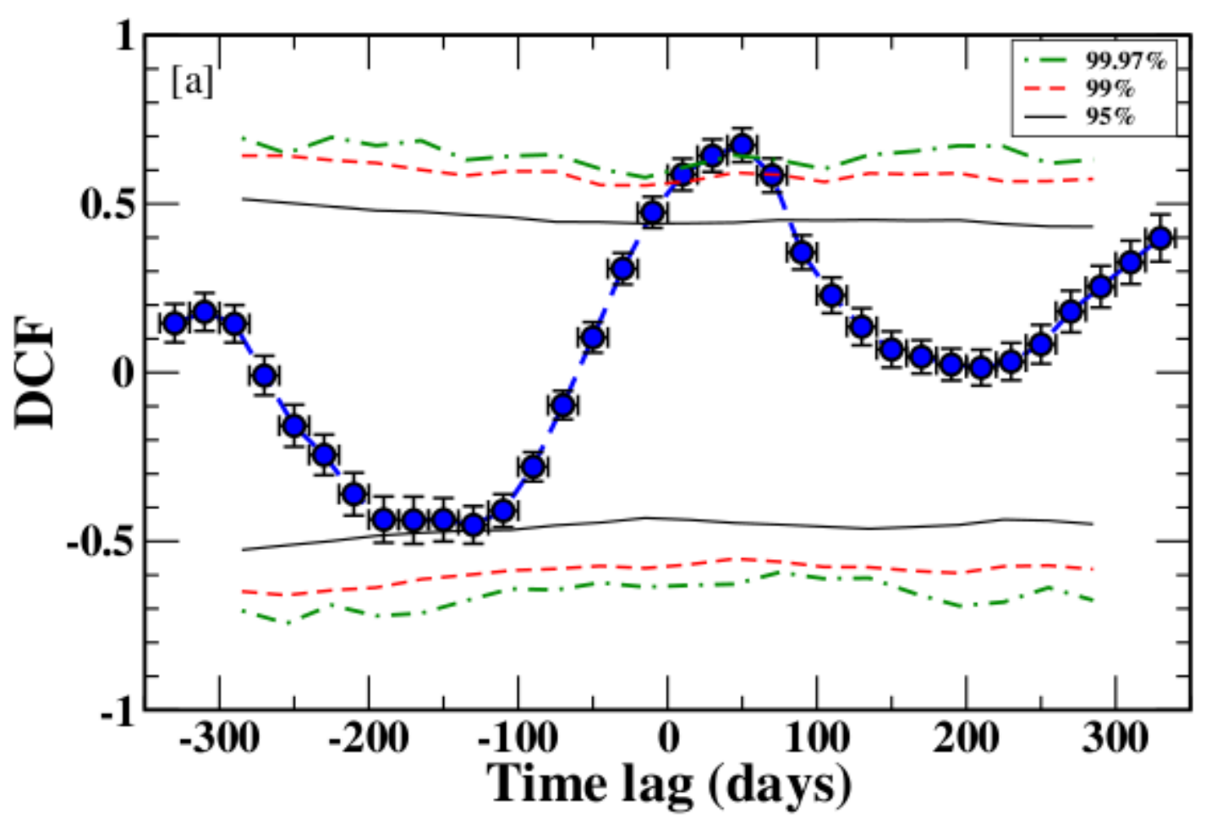

Fig. 8 : Cross-correlation analysis curve between γ-ray and jet orientation variations.

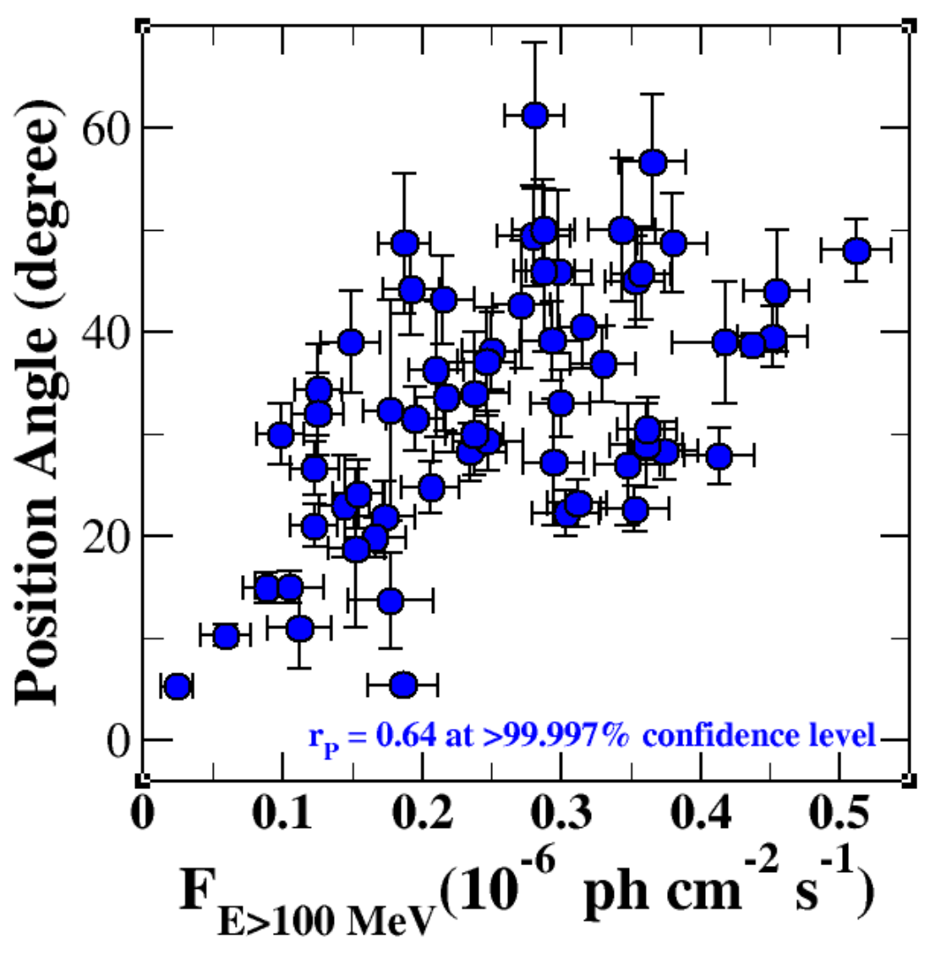

Fig. 9 : Jet orientation plotted vs. γ-ray flux.

Tentative models

The observed correlations can be interpreted as a moving shock propagating down a relativistic jet with non-axisymmetric pressure and/or density gradients/patterns or a shock moving in a bent jet. A moving shock will induce significantly increased emission at the locations where it intersects with regions of enhanced electron density and/or magnetic field. The measured correlations suggest that the γ-ray flares precede the mm-VLBI core flares, and the time lag depends on the physical conditions of the emission region. Longer time lags can be expected via opacity effects and/or if the two emission regions are separated (as shown in Fig. 10). Because Doppler boosting is a sensitive function of viewing angle, substantial changes in amplitude of jet emission can be seen by the observer. Correlated variations between the γ-ray emission and orientation of the jet flow is obvious if the two share the same boosting cone as shown in Fig. 10 (top). However if the two emission regions are pointed in different directions the correlation between γ-ray flux and PA would be weaker (Fig. 10 bottom).

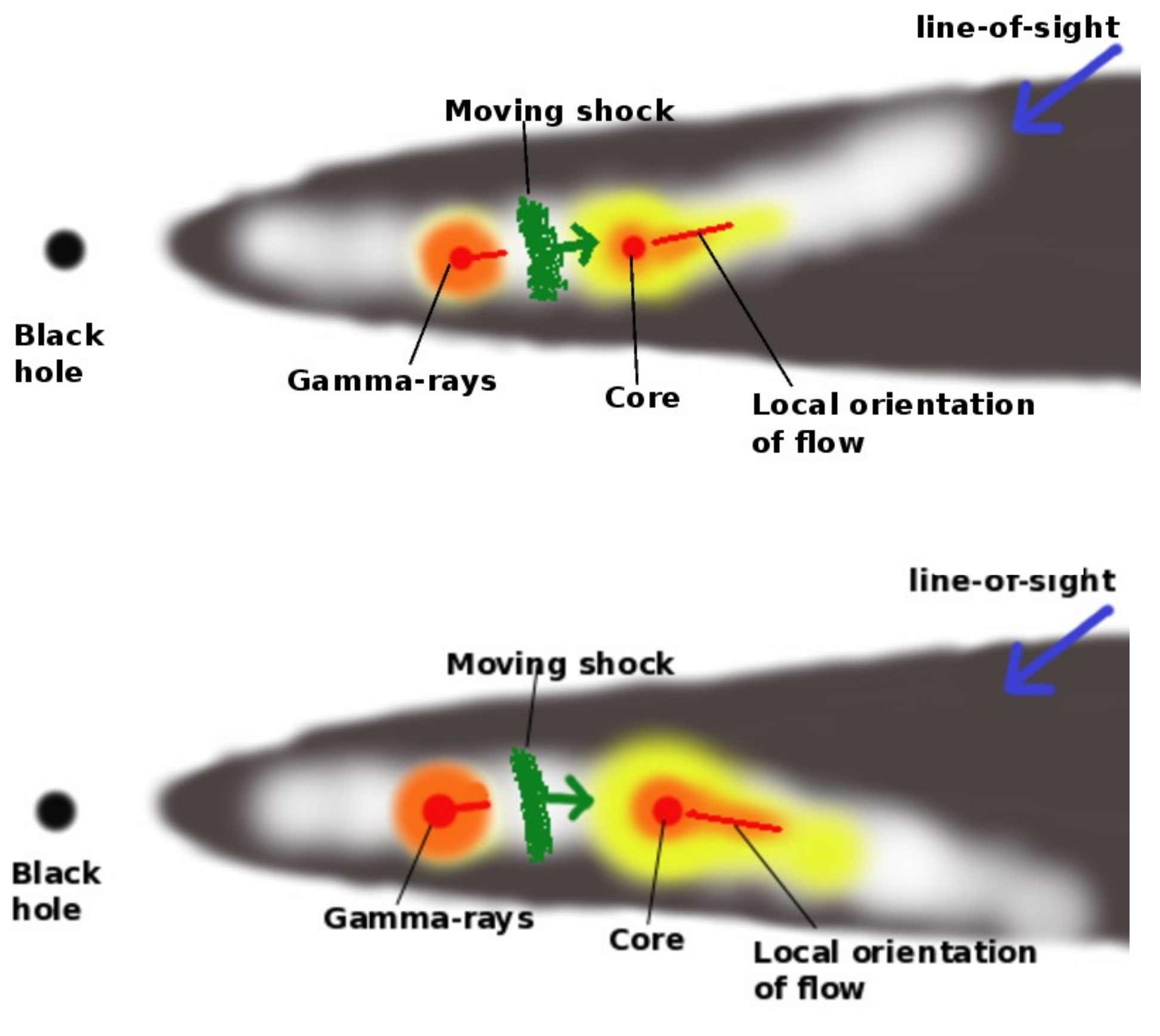

Fig. 10 : A sketch for the proposed scenario in S5 0716+714 (not to scale). The high density/pressure regions, shown in light gray color (superimposed on top of the underlying jet flow, which is in dark color), brighten relative to other regions of the jet by the passage of a moving shock. *Top* : case for a strong correlation, and *bottom* : a weak correlation.

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Summary and Conclusions

One of the most intriguing and challenging quests of current astrophysics is to understand the physical conditions and processes that give rise to the formation of relativistic jets in AGN, production of high-energy particles, and emission of γ-rays. Our analysis suggests a strong correlation between high-energy emission and inner jet morphology which puts the location of high-energy upstream of the 7mm VLBI core (closer to the central black hole).

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