# High-resolution Magnetic Field Structure in CTA 102 with 3mm GMVA observations

C. Casadio, A. P. Marscher, S. G. Jorstad, D. A. Blinov, N. R. MacDonald, T. P. Krichbaum, B. Boccardi,
E. Traianou, J. L. Gómez, I. Agudo, B-W. Sohn, M. Bremer, J. Hodgson, J. Kallunki, J-Y. Kim, A. J. Zensus

Max-Planck-Institut für Radioastronomie
MAX-PLANCK-GESELLSCHAFT

**Abstract:** We have investigated the behaviour and magnetic field structure of the quasar CTA 102 with 3 and 7 mm-VLBI polarimetric observations during a very active state of the source at all frequencies. The higher resolution (~50 µas) and lower opacity at 86 GHz, allow us to probe deeper into the innermost regions of the jet and to investigate physical conditions within the jet also during high-energy flares.

We perform the Faraday rotation analysis using 3 and 7 mm data and we compare the obtained rotation measure (RM) map with the polarization evolution in 7 mm VLBA images. We study the kinematics and variability at 7 mm and we infer the physical parameters associated to variability. From the analysis of γ-ray and X-ray data, we compute a minimum Doppler factor value required to explain the observed high energy emission.

*Results*. The Faraday rotation analysis shows a gradient in rotation measure with a maximum value of ~6×10$^4$ rad/m$^2$ and intrinsic electric vector position angles (EVPAs) oriented around the centroid of the core, suggesting the presence of large-scale helical magnetic field. Such a magnetic field structure is also visible in 7 mm images when a new superluminal component is crossing the core region. While 7 mm EVPAs display a different orientation when the component is exiting the core or crossing a stationary feature at ~0.1 mas. The interaction between the superluminal component and a recollimation shock at ~0.1 mas could have triggered the multi-wavelengths flares. The variability Doppler factor associated to such interaction is large enough to explain the high energy emission and it is in agreement with the Doppler factor obtained to explain the extraordinary optical flare by Raiteri et al. (2017).

The 3mm GMVA polarimetric data we present here have been obtained on 21 May 2016, 30 September 2016, and 31 March 2017. We also collected 43 GHz VLBA data from the VLBA-BU-BLAZAR program from June 2016 to April 2017, covering a time range similar to that covered by GMVA epochs.

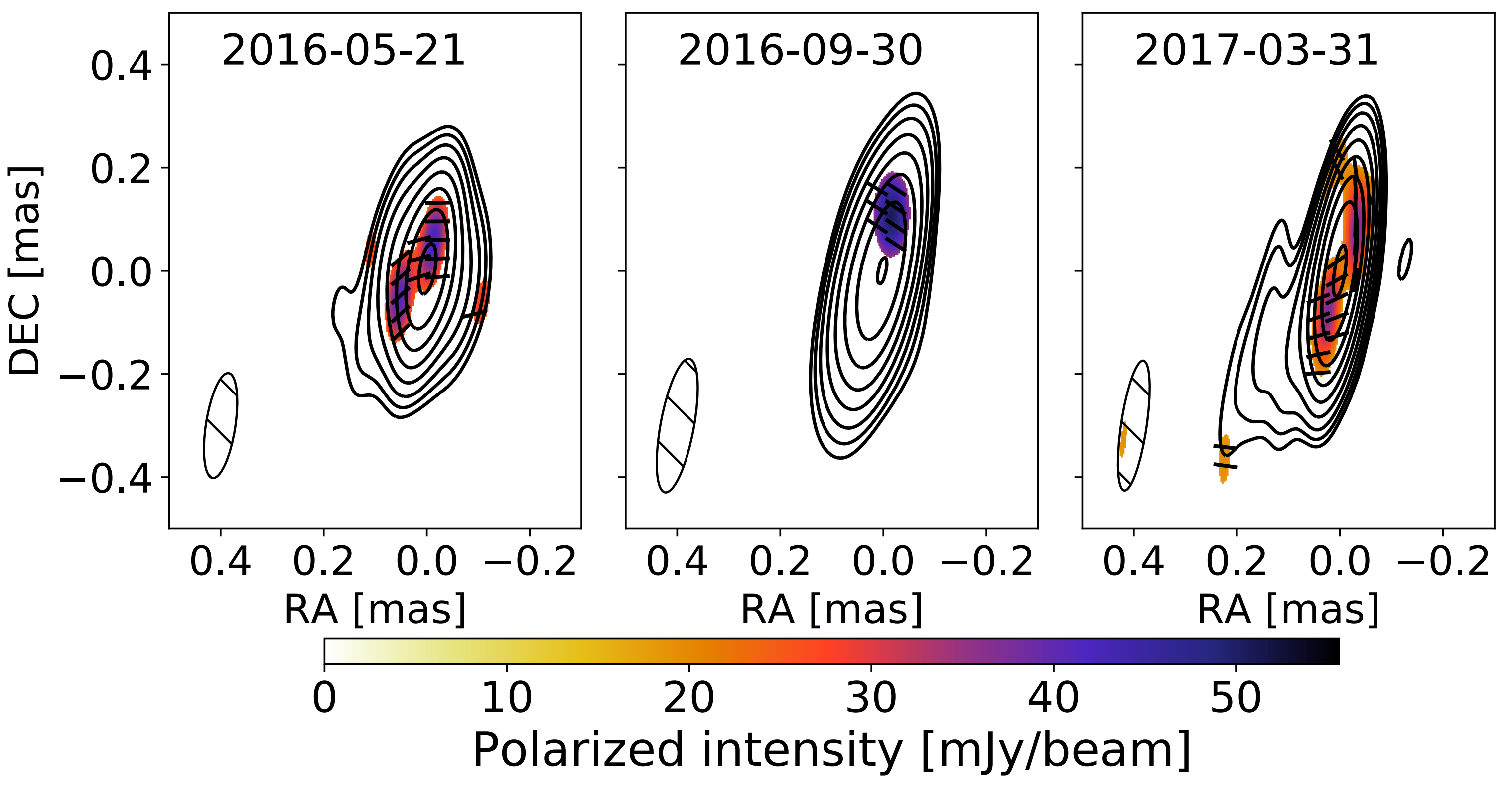

**Fig. 1.** 86 GHz GMVA polarimetric images of CTA 102. The restoring beams are 0.21x0.06, 0.26x0.06 and 0.25x0.05 mas, respectively. Total intensity peaks are 2.0, 1.77 and 3.79 Jy/beam and contours are drawn at 0.5, 0.85, 1.53, 3.02, 5.96, 11.74, 23.15, 45.65, 90 % of 3.79 Jy/beam. The maxima fractional polarization are between 8 and 14 % (1σ ~ 0.6-1.4%).

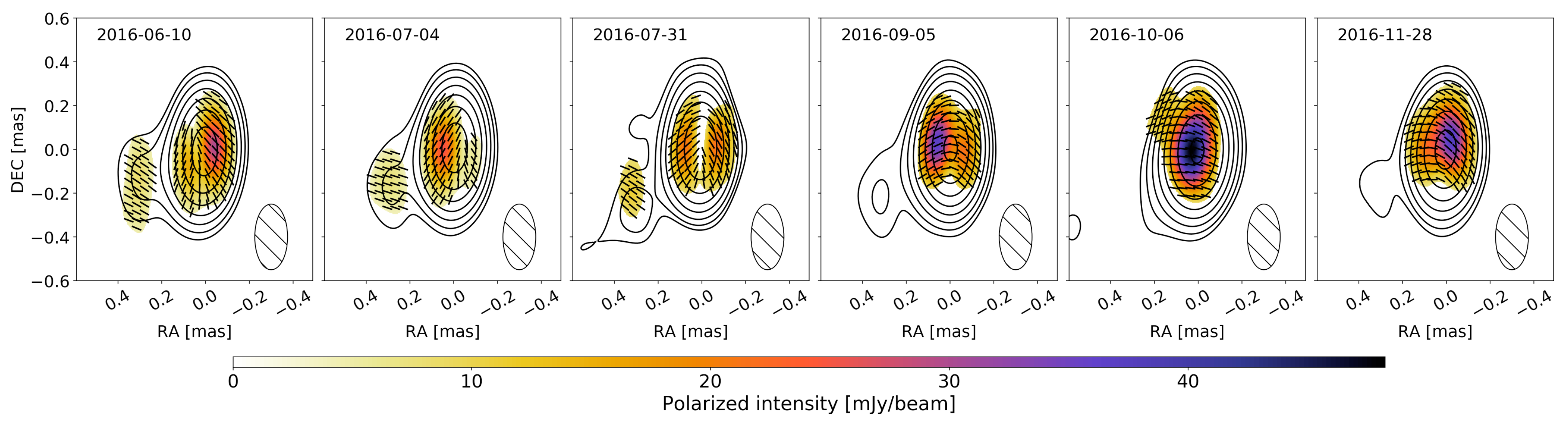

**Fig. 2.** 43 GHz VLBA polarimetric images of CTA 102. The common restoring beam is 0.15×0.3 mas. Total intensity peaks are 2.35, 2.39, 3.09, 3.59, 3.56, 2.07 Jy/beam and contours are drawn at 0.8, 1.53, 3.02, 5.96, 11.74, 23.15, 45.65, 90 % of 3.59 Jy/beam. Black sticks represent polarization vectors. In 2016-07-30 and 2016-09-05 the new superluminal component, K1, is crossing the core region. In 2016-10-06, K1 is exiting the core and EVPAs are mainly at 90°.

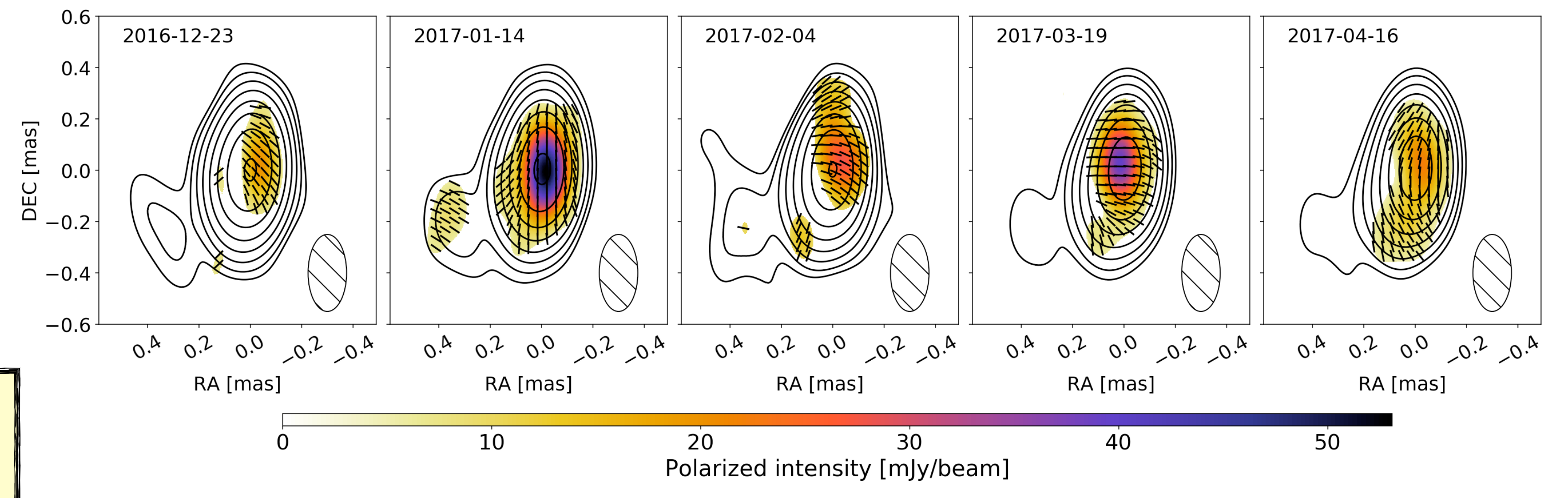

**Fig. 3.** Same as in Fig. 2. Total intensity peaks are 2.5, 2.6, 2.4, 1.8, 1.9 Jy/beam and contours are drawn at 0.8, 1.53, 3.02, 5.96, 11.74, 23.15, 45.65, 90 % of 2.6 Jy/beam. In 2017-01-14, K1 is crossing the recollimation shock at ~0.1 mas and EVPAs are mainly at 0°.

In order to recover more polarized emission and lower the rms of the map, we also performed the stacking (average) of the images in both total and linearly polarized intensity. The two stacked images at 43 and 86 GHz (Figure 3) were used to obtained the RM map of CTA 102 between these two frequencies. The computed RM values are the ones that minimize the nπ ambiguity in EVPAs.

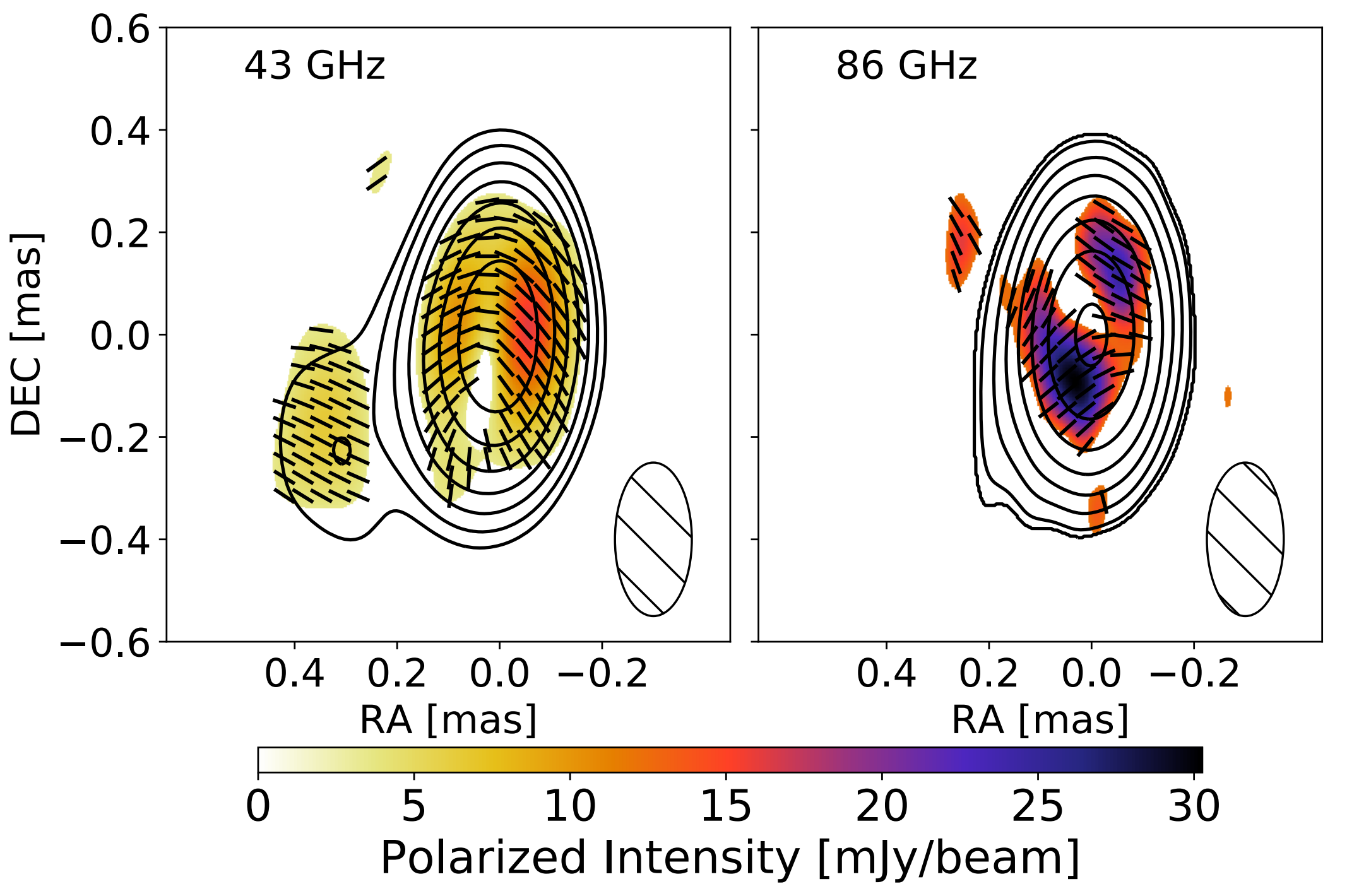

**Fig. 3.** 43 GHz VLBA (left) and 86 GMVA (right) stacked images. Black sticks represent EVPAs. The common restoring beam of 0.3x0.15 mas is displayed in the bottom right corner.

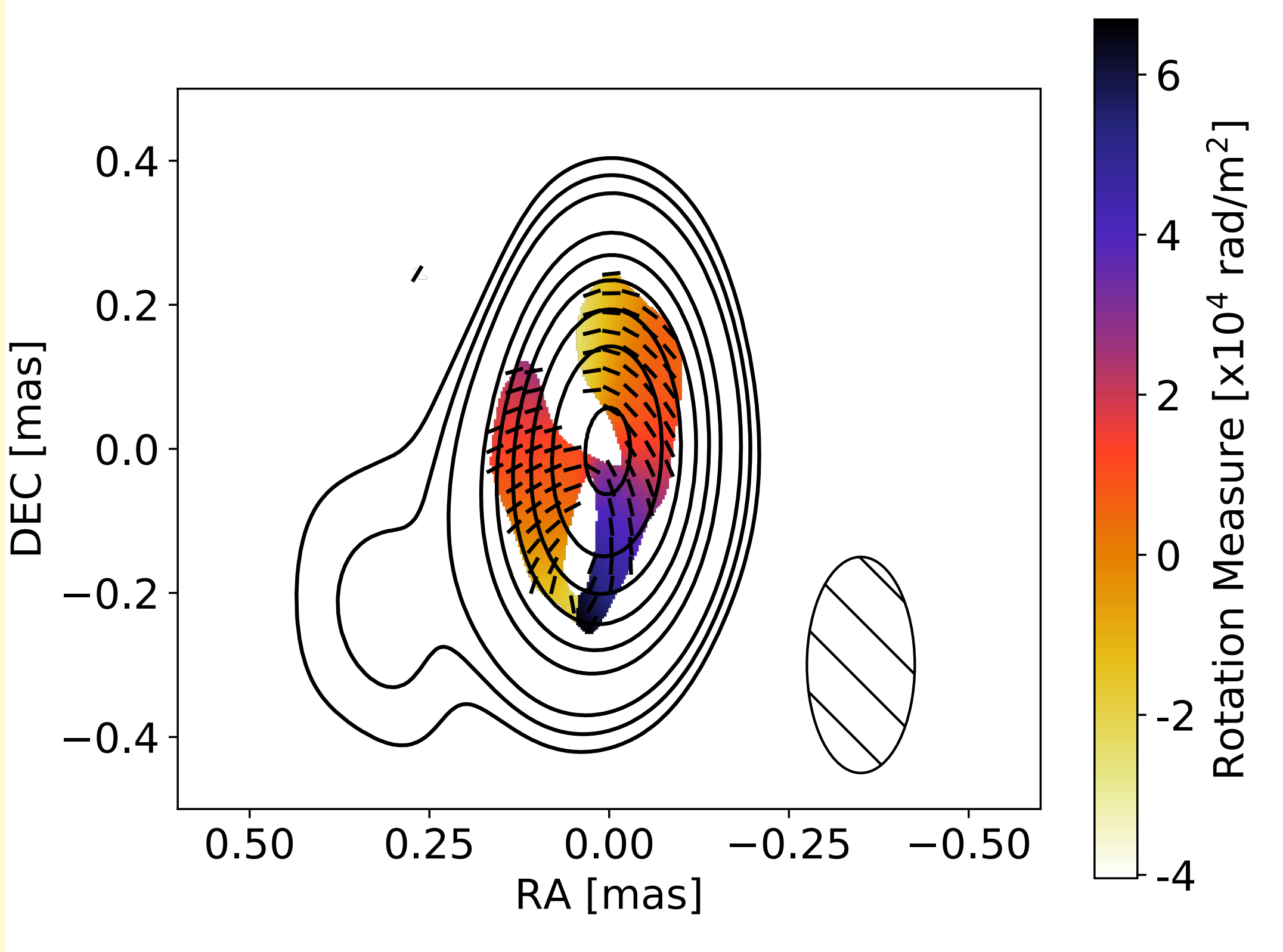

**Fig. 4.** RM map combining 86 GHz GMVA and 43 GHz VLBA stacked images. Beam size: 0.3X0.15 mas.

**The Faraday rotation analysis reveals:**

- a RM gradient around the core with a maximum value of ~6×10$^4$ rad/m$^2$
- intrinsic EVPAs rotating around the centroid of the core

Relativistic magneto-hydrodynamic simulations including large-scale helical magnetic fields in a Faraday rotating sheath surrounding the jet predict transverse gradient in RM (Broderick & McKinney 2010).

The observed EVPA orientation around the core center has been produced by simulations in which the jet is observed at very small viewing angles (Porth et al. 2011).

This also resembles the situation in BL Lacertae, as recently found by Gómez et al. (2016)

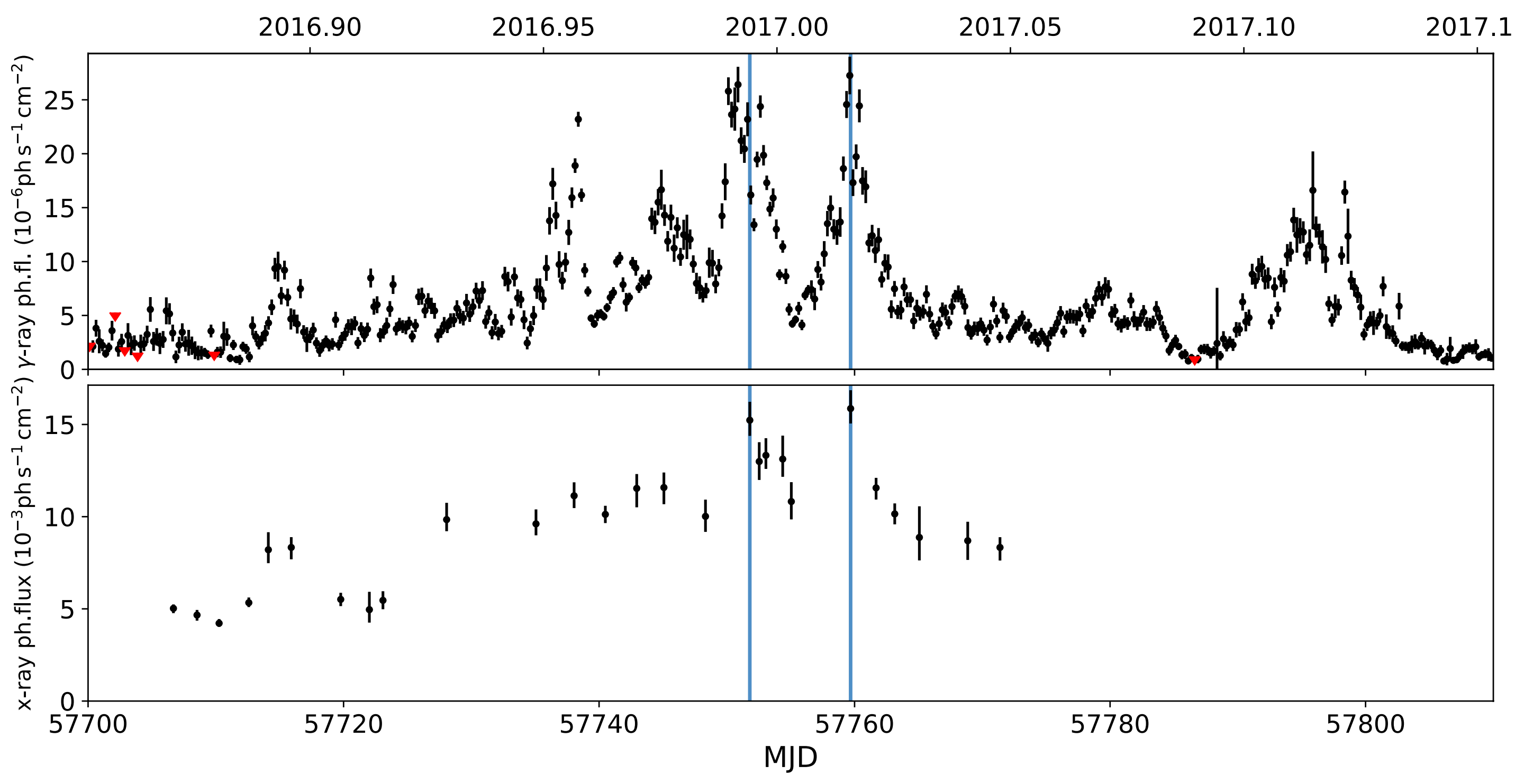

**Fig. 5.** Photon flux curves during the flaring period in γ-rays (top) and x-rays (bottom). The red triangles represent upper limits of the photon flux.

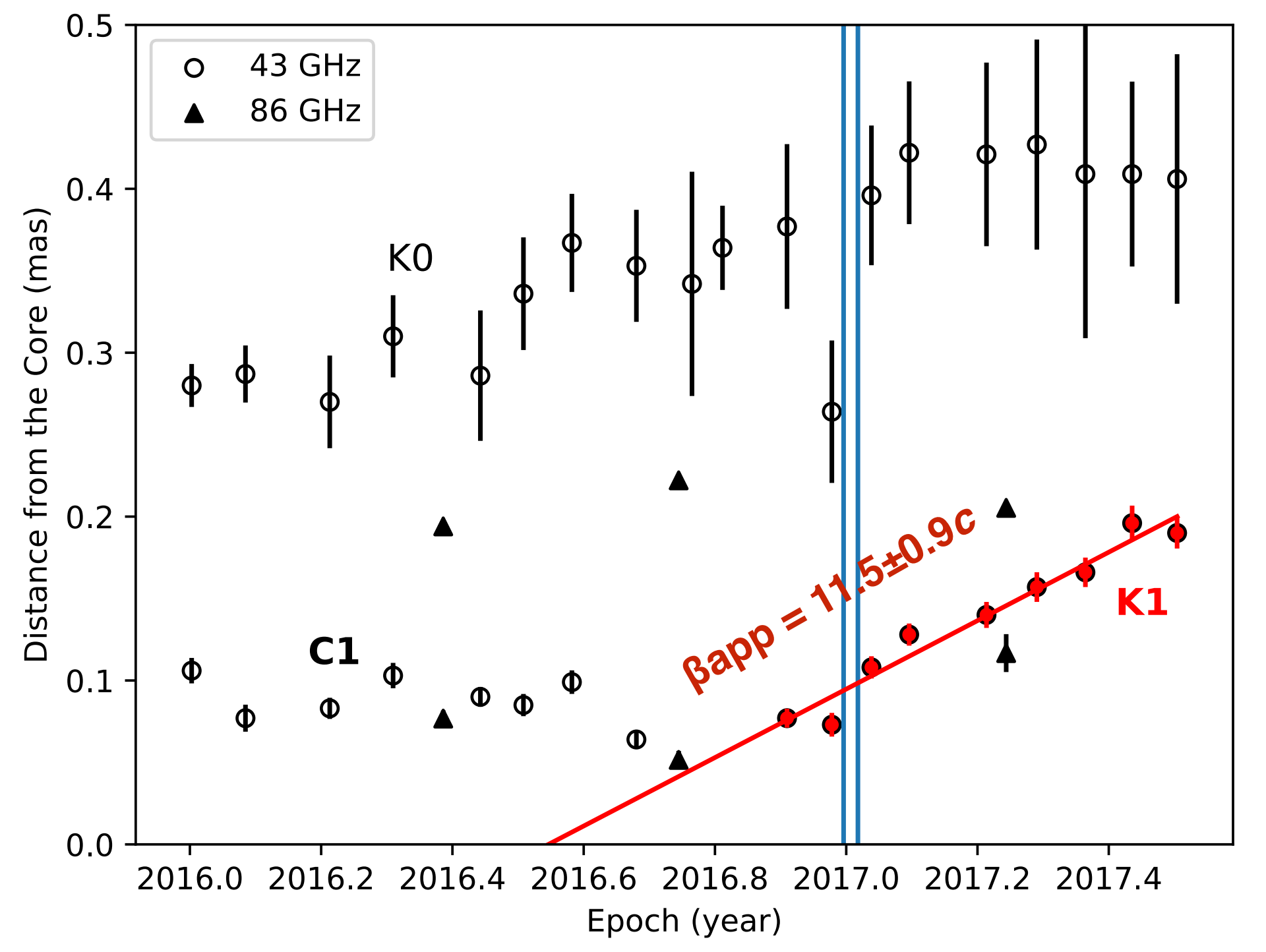

**Fig. 6.** Distance from the core vs. time of the 43 and 86 GHz model-fit components. The red line is the linear fit of K1 positions and blue vertical lines mark the time of the two high energy events considered (see Fig. 5).

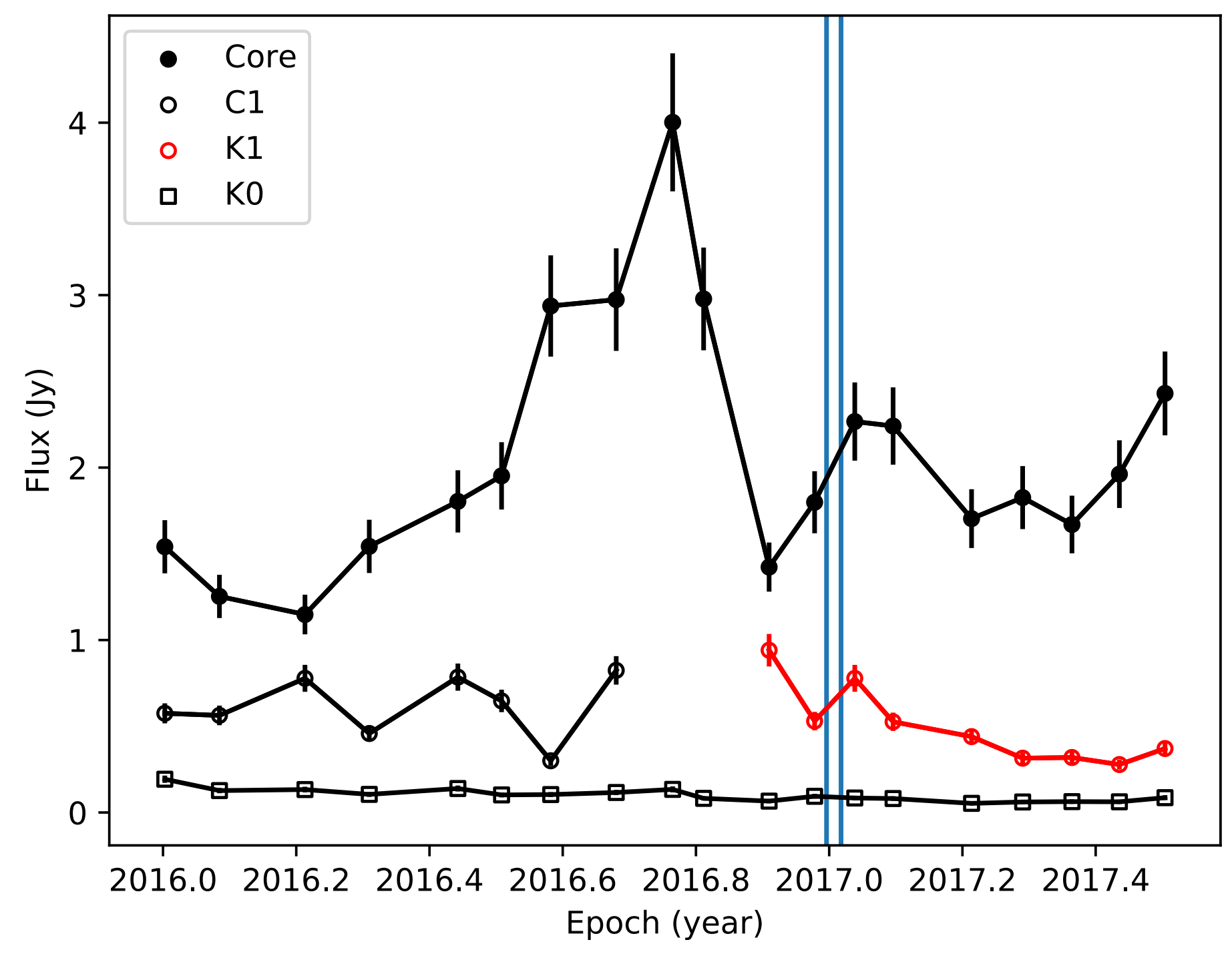

**Fig. 7.** Light curves of 43 GHz VLBA model-fit components. Blue vertical lines are the same as in Fig. 6. K1 increases its flux density while it crosses C1.

Using the method in Mattox et al. 1993, we determine a lower limit for the Doppler factor (δ ≥ 15) required to explain the two γ-ray and X-ray flares in late December 2016 - early January 2017. From the kinematics analysis at 43 GHz we found a new superluminal component (K1) ejected in 2016.55±0.07 (18 July 2016). During the high-energy events, K1 is crossing a stationary feature (C1) at ~ 0.1mas, previously associated with a recollimation shock (e.g. Fromm et al., 2013). The variability Doppler factor during the interaction is δvar = 34±4. Combining δvar with βapp we obtained the viewing angle (θvar= 0.9±0.2°) and the Lorentz factor (Γvar = 20.9±1.9) associated to the variation.

**References:** Broderick, A. E. & McKinney, J. C. 2010, ApJ, 725, 750; Fromm, C. M., Ros, E., Perucho, M., et al. 2013, A&A, 551, A32; Gómez, J. L., Lobanov, A. P., Bruni, G., et al. 2016, ApJ, 817, 96; Jorstad, S. G., Marscher, A. P., Lister, M. L., et al. 2005, AJ, 130, 1418; Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1993, ApJ, 410, 609; Porth, O., Fendt, C., Meliani, Z., & Vaidya, B. 2011, ApJ, 737, 42; Raiteri, C. M., Villata, M., Acosta-Pulido, J. A., et al. 2017, Nature, 552, 374

www.mpifr-bonn.mpg.de/research/vlbi