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Blazars from the new window of X-ray polarimetry: IXPE observations of Mrk 421

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The NASA/ASI Imaging X-ray Polarimetry Explorer (IXPE) was launched on December 9, 2021 thereby opening the new observational window of X-ray polarimetry. Blazars, which are active galactic nuclei (AGN) where the jet is oriented towards the observer, are prime candidates for X-ray polarization observations. For instance, a high degree of X-ray polarization is expected from High synchrotron Peak (HSP) blazars in the case of synchrotron radiation produced in an ordered magnetic field. Moreover, we expect different time variability patterns of the X-ray and optical polarization properties depending on which physical mechanism energizes the particles in the jets, e.g. shock acceleration, magnetic reconnection, and turbulence. We report on the first year IXPE observations of the archetypical HSP Mrk 421 and we discuss what X-ray polarimetry is teaching us about the inner physics of jets.

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1. X-ray polarimetry with the Imaging X-ray Polarimetry Explorer

The Imaging X-ray Polarimetry Explorer (IXPE) launch on December 9th, 2021 has opened the observational window of X-ray polarimetry. Indeed, IXPE [24] is the first space mission ever launched which is entirely dedicated to X-ray polarimetry. IXPE is a NASA mission, developed in partnership with the Italian Space Agency (ASI). It carries on board 3 Gas Pixel Detectors (GPD) that are sensitive to X-ray polarization in the 2.0-8.0 keV band and have imaging capability at an angular resolution of $\sim 30''$.
Polarimetry describes the astrophysical radiation by two observables: the polarization degree (Π), defined as the fraction of radiation intensity where the electric field vector oscillates in a preferential direction, and the polarization angle (Ψ) describing the electric vector position angle (EVPA). For practical purposes, it is often convenient to decompose the polarization properties of the radiation into three Stokes parameters I, Q, and U [20], where I is the total intensity, Q is the intensity polarized at angles of $\pm 90°$and U is the intensity polarized at angles of $\pm 45°$. In this framework, $\Pi = \sqrt{Q^2 + U^2}/I$ and $\Psi = \frac{1}{2} \arctan \frac{U}{Q}$.
In IXPE datasets, the polarization information is recorded in the form of photon-by-photon Stokes parameters. Thereby, one can derive the polarization of a point-like source (or of a region of interest, in the case of extended sources) by using the analytical procedure of [11], which prescribes the values and uncertainties of I, Q, U, Π,Ψ for a selected set of photons with know individual Stokes parameters. Alternatively, one can perform a spectropolarimetric fit as described in [21]. In this case, the I, Q, and U spectra of a specific source (or region of interest) are fitted simultaneously with X-ray spectral fitting programs (e.g., XSpec [1]). Models that describe the polarization properties as a function of energy are then used in the fit as multiplicative components. Both these methods are used in the following in the case of IXPE observation of the blazar Mrk 421.

2. The case of High Synchrotron Peak blazars

Blazars are a subclass of jetted Active Galactic Nuclei (AGN) where the jet is closely aligned to the observer's line of sight. Hence, because of the relativistic amplification, the jet emission dominates the spectral energy distribution (SED) of blazars by producing two broad humps. The first one is well understood as due to synchrotron emission, while the second one is due to Inverse Compton.
In the subclass of High synchrotron Peak (HSP) blazars, the peak of the synchrotron hump falls at X-ray energies. Thereby, in these objects, in the IXPE band, we probe freshly accelerated particles that radiate at energies close to the synchrotron peak. In the case of synchrotron, the polarization properties are a diagnostics of the level of order of the magnetic field, because polarization up e.g. 70% is expected when synchrotron radiation is produced in a uniform magnetic field. Moreover, according to current theoretical models, the time variability of the multiwavelength polarization is a potential diagnostic of the physical mechanism that accelerates particles in the jet. For instance, in the case of shock acceleration [22], which can occur also when the flow is unsteady [19], a high, substantially time-constant, X-ray polarization is expected because the shock compression is able to order the otherwise disordered magnetic field. Thereby, the X-ray polarization is larger than the

optical/infrared/radio polarization because radiation at longer wavelengths is emitted in a region extending beyond the shock front with an increasingly disordered magnetic field. Conversely, for magnetic reconnection processes, a similar level of X-ray and optical polarization is predicted [4], with the polarization properties being smoothly modulated with time. Finally, if turbulence is prevalent in the jet, one can expect a rapid and erratic variability in both Π and Ψ that could lead to canceling the polarization in day-long observations.
Rotations of the optical polarization angle (Ψ_O) are another remarkable observational feature of blazars that is now routinely observed [2]. These episodes consist of a smooth, monotonic full rotation of Ψ_O that occurs over the course of a few to a few hundred days at a typical rotation rate of a few to a few tenths $^\circ$/day. It is been shown that a random walk of the polarization vector, induced for instance by turbulence in the jet, cannot reproduce the majority of the observed properties of the population of Ψ_O rotations [3, 8]. In cases where the rotation cannot be explained by a stochastic process, a helical structure of the magnetic field is often invoked as a deterministic cause of the observed rotations. However, a comprehensive understanding of the physical mechanism behind rotations had not been achieved yet.
All in all, HSP blazars are natural target candidates for an X-ray polarimeter. The combination of X-ray and optical/infrared/radio polarization measurements of blazars is a valuable tool to address key open questions about the jet's physics. In the first two years of operation, IXPE has successfully measured the X-ray polarization of the HSP blazars Mrk 501 [13], Mrk 421 [5, 6, 10], 1ES 1959+650 (Errando et al., in prep, Pacciani et al.,in prep.), and PG 1553+113 [18]. Here, we summarized the results of IXPE observation of the archetypical HSP blazar Mrk 421 (z=0.033).

3. May 2022: the first IXPE observation of Mrk 421

The IXPE satellite observed Mrk 421 for the first time on May 4th, 2022, for a net exposure time of ~97 ks. The source was caught at an average flux state, with IXPE measuring a flux of $\sim 8.7 \times 10^{-11}$ erg s^{-1} cm^{-2}in the 2.0-8.0 keV band. This observation provided a highly significant (i.e. $\sim 7\sigma$) detection of the 2.0-8.0 keV polarization. An analysis based on the [11] procedure and a joint spectropolarimetric fit of IXPE, XMM-EPIC, and NuStar quasi-simultaneous data returned consistent results for the polarization properties i.e. $\Pi_x = 15\pm2\%$ and $\psi_x = 35 \pm 4^\circ$. For the spectropolarimetric analysis, we used a model including the Galactic absorption (N_H =1.34$\times10^{20}$), a log-parabolic [17] synchrotron spectrum, and a polarization that is constant with energy (i.e. the POLCONST model in XSpec).
A series of 3, ~1 ks long Swift-XRT snapshots indicates that during the two-day long IXPE pointing the 2.0-8.0 keV flux of Mrk 421 rose by a factor of 2.2 with no change in spectral shape (i.e. the hardness ratio was constant). Conversely, we did not find any time variability of the polarization properties within the time frame of the IXPE pointing. To evaluate this, we used time bins in the range of 5-50 ks to split the IXPE dataset and create several time series of the Stokes parameters. For all the binning schemes, we find that the Stokes parameters are consistent with being time constant (i.e. the null hypothesis of obtaining a value of χ^2 at least as large as that of the constant model is always larger than 1%).
These pieces of information are most valuable when put into the multiwavelength polarization context. Fig. 1 summarizes the polarization properties of Mrk 421 in May 2022 in radio/millimeter

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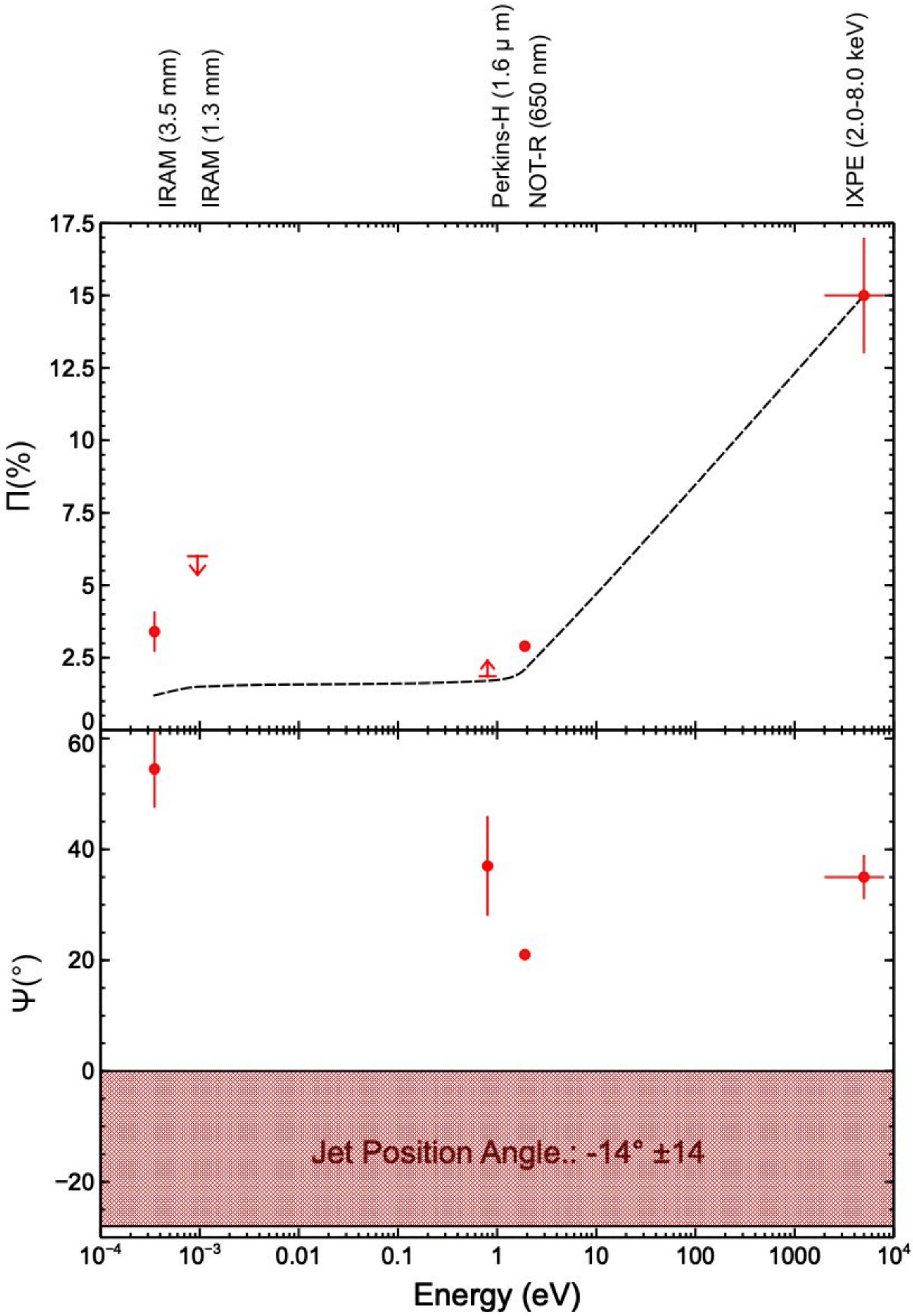

Figure 1: Multi-wavelength polarization degree (top panel) and angle (low panel) of Mrk 421 as a function of energy. The red circles represent detections, while the arrows indicate upper or lower limits. The instruments that provided each measurement are labeled on top. The dashed line represents theoretical estimations assuming the formalism of **?**] for a turbulent jet. In the second panel, the horizontal shaded area indicates the time-averaged jet position angle and its uncertainty, measured with the Very Long Baseline Array at 43 GHz [23].

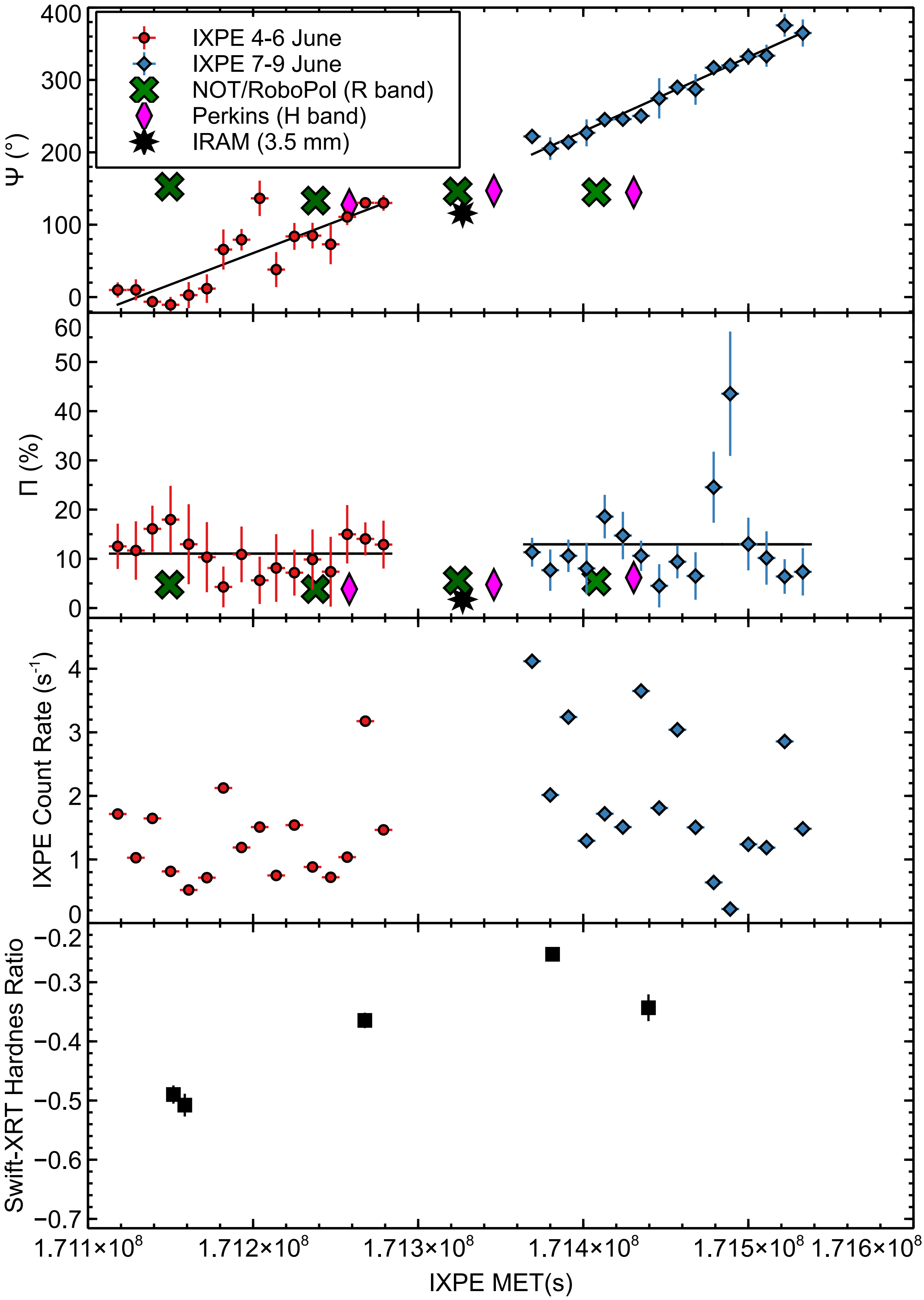

Figure 2: From top to bottom: time evolution of the X-ray polarization angle, degree, IXPE photon count rate in time bins of ~3 hours within the IXPE pointings of 4 June (red circles) and 7 June (blue diamonds) 2022, and hardness ratio in the X-ray band (black squares) measured with Swift-XRT. As a comparison, we display the polarization properties from simultaneous radio (IRAM: black stars), infrared (Perkins: magenta diamonds), and optical observations (NOT/RoboPol: green crosses).

(Π_R, Ψ_R from Institut de Radioastronomie Millimetrique, IRAM, telescope), infrared (Π_{IR}, Ψ_{IR} from Perkins telescope), optical (Π_O, Ψ_O from Nordic Optical Telescope), and X-ray. The key finding is that Π_X is larger than Π_R, Π_{IR}, Π_O by at least a factor of ~3. This and the lack of substantial time variability points to shock acceleration occurring in an energy-stratified jet. Turbulence may increase with the distance from the acceleration site, thereby disordering the magnetic field and determining $\Pi_{R,IR,O} < \Pi_X$. In Fig. 1, we also show as a comparison the multi-wavelength polarization expected if the magnetic field is turbulent (dashed line). Assuming the match with Π_X, this model underestimates Π_R, Π_{IR}, Π_O. Therefore, we conclude that the magnetic field should at least be partially ordered. Finally, one can see in Fig. 1 that there is a discrepancy between the multi-wavelength Ψ values and the time-averaged[1] jet position angle measured at 43 GHz with the Very Long Baseline Array ($-14° \pm 14°$, [23]). This mismatch can be explained if e.g. the radio emission region is detached from the X-ray emission region [7], or the jet bends between the sites of high- and low-frequency emission [14].

4. June 2022: discovery of X-ray polarization angle rotation in Mrk 421.

Since the polarization of blazars is variable on e.g. ~months timescales, we opted for an observation strategy consisting of repeated visits of the same objects. Thereby, IXPE observed again Mrk 421 on 2022, June 4-6 (hereafter Obs. 2) and 7-9 (hereafter Obs. 3). The respective net exposure times of these two pointings were ~ 96 and ~ 86 ks. The source was caught again in average activity state, with IXPE measuring fluxes of ~1.6 and 3.0 $\times 10^{-10}$ erg s^{-1} cm^{-2}.

In these datasets, the polarization is undetected when considering the time-averaged data (i.e. $\Pi_X \leq 5$ and 4%, respectively). This suggests that some variability has occurred since May 2022. We explored the possibility that a variation of the polarization properties within the two observations is the cause of the canceling of the polarization in the time-averaged data. When split into shorter time intervals (e.g. in the range of 2−17 hours), both datasets display (Fig. 2) a smooth rotation of Ψ_X (i.e. Ψ_X varied > 360° over ~5 days) while Π_X appears to be constant. To gauge the reality of the rotation and to estimate the rotation rate $\dot{\Psi}_X$ we adopted a simple model of a rotation at a constant rate occurring at a constant polarization degree. Using a maximum-likelihood method, a fit of binned Stokes parameter time-series, and a fit in the Q-U plane, three independent analyses converge to the same result (i.e. $\dot{\Psi}_X = 80 \pm 9°/\text{day}$, $\Pi = 10\% \pm 1\%$ for Obs. 2 and $\dot{\Psi}_X = 91 \pm 8°/\text{day}$ and $\Pi_X = 10\% \pm 1\%$ for Obs. 3).

One can see from Fig. 2 that in addition, we found that no similar rotation was present in optical (NOT and Shinakas observatory), infrared (Perkins), and radio/mm (IRAM) data. The constant level of Π_X during the rotation, was like in May 2022, larger than Π_R, Π_{IR}, Π_O. Finally, the simultaneous Swift-XRT snapshots indicate that during the rotation, the X-ray spectrum was changing in a "harder when brighter" mode. These findings point again to a shock as the most likely particle acceleration mechanism in place in the jet of Mrk 421.

In this framework, to assess the cause of the observed rotation, we investigated the possibility that it could be produced through random walks of the polarization angle. By comparing the observations against simulated polarization time series, following [8, 9], we find that only about 2% of the

[1]See http://www.bu.edu/blazars/VLBA_GLAST/1101.html for the multi-epoch variability of the jet position angle.

simulated curves are consistent with the observations. This suggests that it is unlikely that the observed rotation is produced by a random variation of the polarization angle. Therefore, as a deterministic explanation, we propose that an off-axis emission feature, smaller than the jet cross-section (e.g., magnetosonic shock) propagates toward the observer and down a helical magnetic field [12, 15, 16, 25]. This would produce a $\Psi_X$rotation in the observer's frame and the rotation rate would be determined by the time required for the feature to execute an orbit around the jet axis, modulated by light-travel delay and possibly other relativistic effect.

5. Conclusions

The new observational window of X-ray polarimetry is now open, thanks to the launch of the IXPE satellite. The X-ray polarization diagnostic, when put into the multiwavelength context, is a valuable to address to key open questions about the physics of astrophyiscal jets. Thus far, all the IXPE observations of HSP blazars have consistently favored a scenario where shock acceleration occurs in an energy-stratified jet. Remarkably, in the IXPE observations of Mrk 421 of June 2002, we discover an X-ray polarization angle rotation that is consistent with being produced by a shocked emission feature propagating towards the observer down a helical magnetic field.
These findings point to the necessity of continuing with the monitoring of the X-ray and muti-wavelength polarization of HSP blazars e.g. to assess how the magnetic field conditions may vary on short (intraday) and long (months) timescales or in association with different state of activity (quiescient vs flaring) of the sources. This promises to enich our comprehension of the magnetic field geometry and particle acceleration processes that are in place in jets.

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