Insights into archetypical TeV blazars from combined X-ray polarisation and VHE measurements

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On behalf of the MAGIC Collaboration and MWL partners
A new view on blazar emission

- **IXPE**: first measurements of X-ray polarization (2-8keV)

- In HBLs, **IXPE** probes high-energy tail of synchrotron component
  
  → **Emitted by the most energetic particles**
  → **Probe of acceleration mechanisms & B-field geometry**

- Important synergie with MAGIC
  
  → X-ray flux correlates with VHE
  
  Abe et al., 2023 ApJS 266 37 )
Extensive multi-wavelength campaigns on Mrk421 & Mrk501

- Nearby & bright TeV HBLs (z~0.03): easy to detect

- Yearly monitoring program running since ~2009
  - MAGIC observes every 2/3 days; “Unbiased”
  - Simultaneous radio-to-VHE coverage

- In 2022: Campaign with IXPE
Markarian 421 (Mrk421)

Credits: MOJAVE team
IXPE observations during 2022

- **1\textsuperscript{st} IXPE observation**: 4\textsuperscript{th} - 6\textsuperscript{th} May 2022
  (Di Gesu et al. 2022)
  - Polarization degree: \(\sim 15\%\)
  - Polarization angle: \(\sim 35\text{deg}\), aligned with optical/IR/millimeter
  - No significant variability
  → Shock acceleration in energy stratified jet
**IXPE observations during 2022**

- 2\textsuperscript{nd} and 3\textsuperscript{rd} IXPE observation: 4\textsuperscript{th} - 6\textsuperscript{th} June 2022 and 7\textsuperscript{th} - 9\textsuperscript{th} June 2022 (Di Gesu et al., Nature, 2023)
  
  - Polarization degree: constant, ~10%
  - Polarization angle: rotation, 80-90 deg/day
  
  → Emission zone follow helical path, detached from optical/radio zone

Di Gesu et al. 2023
Radio to VHE observations

- Campaign from April 2022 to June 2022 to follow-up IXPE observations
Radio to VHE observations

- Campaign from April 2022 to June 2022 to follow-up IXPE observations

- MAGIC observations with Swift-XRT, NuSTAR, XMM-Newton during IXPE epochs
Radio to VHE observations

- Campaign from April 2022 to June 2022 to follow-up IXPE observations

- MAGIC observations with Swift-XRT, NuSTAR, XMM-Newton during IXPE epochs

- Good NuSTAR coverage during IXPE polarization angle rotation

Preliminary

Fermi-LAT

Swift-XRT

NuSTAR

XMM-Newton

Swift-UVOT

Optical

Radio

Polarization degree (IXPE/optical/radio)

Polarization angle (IXPE/optical/radio)
VHE observations results

**IXPE 1 epoch:**
~ 25% Crab in 0.2-1TeV band

No significant VHE variability
(on daily and intranight timescales)

VHE spectrum best-fit
log-parabola: $\alpha \sim 2.6$, $\beta \sim 0.5$

**IXPE 2 epoch:**
~ 50% Crab in 0.2-1TeV band

No significant VHE variability
(intranight timescales)

VHE spectrum best-fit
log-parabola: $\alpha \sim 2.3$, $\beta \sim 0.5$
Radio to VHE observations

- IXPE 1 epoch

*Source in low state, SED shifted to lower energies*
Radio to VHE observations

- **IXPE 2 epoch:**
  *Source in average state*

- **IXPE 3 epoch:**
  *Source in enhanced state*

*No VHE data available...*

X-rays show harder and brighter flux

→ *X-ray variability during the polarization angle swing*
X-ray variability during polarization angle rotation

- Use NuSTAR to investigate variability patterns during polarization angle rotation
- Flux variability on ~1hr timescales in 3-7keV and 7-30keV during rotation
- ... log-parabola index also variable
X-ray variability during polarization angle rotation

IXPE 2

IXPE 3

Preliminary

→ Hysteresis loops clock-wise and counter clock-wise direction
X-ray variability during polarization angle rotation

- **Clock-wise loop**: low-energy lags behind high-energy
  Suggests variability driven by synchrotron cooling
  (Kirk, et al. 1998):
  \[
  t_{\text{acceleration}} \ll t_{\text{synch,cool}}
  \]

- **Counter clock-wise loop**: high-energy lags behind low-energy
  Suggests cooling and acceleration timescales \(\sim\) similar
  (Kirk, et al. 1998):
  \[
  t_{\text{acceleration}} \sim t_{\text{synch,cool}}
  \]

- **Contiguous clock-wise and counter clock-wise loops** imply significant decrease in particle acceleration efficiency during rotation

→ Hysteresis loops **clock-wise** and **counter clock-wise** direction
X-ray variability during polarization angle rotation

- Pol. angle rotation due to blob moving in a helical path?
  → Change of doppler factor $\delta$
  → Expect strong flux modulation, $F_{\text{obs}} \propto \delta^3 F_{\text{intrinsic}}$
  does that contradict observations?

- Assuming bulk Lorentz factor $\sim 20$ & jet viewing angle of $\sim 0.5$deg
  → Expected variability solely caused by $\delta$ evolution
  in agreement with NuSTAR variability

Sketch credits: Zhou et al. 2018
VHE versus X-ray Correlation

- VHE / X-ray correlation using April to June 2022 data
- \( \sim 4\sigma \) significance, no time lag
- VHE emission likely co-spatial to X-ray, close to the shock front
Markarian 501
(Mrk501)

Credits: MOJAVE team
IXPE observations during 2022

- 3 observations, from March to July 2022:
  - **IXPE 1**: 8\textsuperscript{th} - 10\textsuperscript{th} March 2022
  - **IXPE 2**: 27\textsuperscript{th} - 29\textsuperscript{th} March 2022
  - **IXPE 3**: 9\textsuperscript{th} - 12\textsuperscript{th} July 2022

- Moderate variability
  - VHE state close to “average”
  - X-ray state higher
  - Atypically low Compton-dominance
IXPE observations during 2022

Preliminary

\[ \begin{align*}
\nu F_\nu \text{ [erg cm}^{-2} \text{ s}^{-1}] & \quad \nu \text{ [Hz]} \\
10^{-10} & \quad 10^{10} \\
10^{-11} & \quad 10^{11} \\
10^{-12} & \quad 10^{12} \\
10^{-13} & \quad 10^{13} \\
10^{14} & \quad 10^{15} \\
10^{16} & \quad 10^{17} \\
10^{18} & \quad 10^{19} \\
10^{20} & \quad 10^{21} \\
10^{22} & \quad 10^{23} \\
10^{24} & \quad 10^{25} \\
10^{26} & \quad 10^{27}
\end{align*} \]

Preliminary

Typical state (Abdo et al. 2011)

Low state (Abe et al. 2023)
Preliminary modelling of Mrk501

\[ \text{accretion disk} \]

- Each component made of “N” turbulent plasma cells:
  \[ \langle P_{\text{deg}} \rangle \sim 70\% \times N^{-0.5} \]  
  (see e.g. Marscher et al. 2014)

- Relative size tuned to match observed optical/X-ray polarization
Conclusion

- For both Mrk421 & Mrk501, polarisation degree increases with energy
  → suggests shock acceleration, in energy stratified jet
  → X-ray emission close to the shock front

- $4\sigma$ positive X-ray/VHE correlation
  → VHE photons emitted close to shock front

- X-ray polarization angle rotation in Mrk421
  → Accompanied by X-ray spectral hysteresis on hour timescale
  → Indicate significant evolution of particle acceleration evolution

- SED well modelled in a two-zone scenario
Backup
**VHE versus X-ray Correlation**

*In IXPE 2 epoch, start of rotation, → ~ 2σ VHE/X-ray correlation using MAGIC/NuSTAR*
Modelling parameters

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<th>Parameters</th>
<th>“compact zone”</th>
<th>“extended zone”</th>
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<td>$B'$ [10^{-2},\text{G}]</td>
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<td>$\gamma'_\text{br}$</td>
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<td>$\gamma'_\text{max}$</td>
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