universität innsbruck

MAX-PLANCK-INSTITUT FÜR PHYSIK

MAGIC

First broadband characterization of the TeV blazars Mrk 421 and Mrk 501 with simultaneous X-ray polarization measurements

Lea Heckmann, Axel Arbet-Engels,
Felix Schmuckermaier,
David Paneque, Ioannis Liodakis
for the MAGIC collaboration and MWL partners

Blazars

- Most luminous persistent objects in the γ-ray sky
- Potential emitters of ν and cosmic rays

Credit: http://www.astro.princeton.edu/~lilew/

Blazars

- Most luminous persistent objects in the γ-ray sky
- Potential emitters of ν and cosmic rays

- Open questions:

Credit: http://www.astro.princeton.edu/~lilew/

Blazars

- Most luminous persistent objects in the γ-ray sky
- Potential emitters of ν and cosmic rays

- Open questions:
  - What is radiating?
    - Electrons? Protons?

Credit: http://www.astro.princeton.edu/~lilew/

Blazars

- Most luminous persistent objects in the γ-ray sky
- Potential emitters of ν and cosmic rays

- Open questions:
  - What is radiating?
    - Electrons? Protons?
  - How are the particles accelerated?
    - Shocks? Magnetic reconnection?

Credit: http://www.astro.princeton.edu/~lilew/

Blazars

- Most luminous persistent objects in the γ-ray sky
- Potential emitters of ν and cosmic rays

- Open questions:
  - What is radiating?
    - Electrons? Protons?
  - How are the particles accelerated?
    - Shocks? Magnetic reconnection?
  - In which environment?
    - One-zone? Multiple-zones? ...?
    - Where in the jet? (radius, magnetic field, Doppler factor,...)

Credit: http://www.astro.princeton.edu/~lilew/

A new window

- Imaging X-ray Polarimetry Explorer (IXPE)

Credit: http://ixpe.iaps.inaf.it/

  - X-ray satellite launched Dec 2021
  - Energy range: from 2 keV to 8 keV

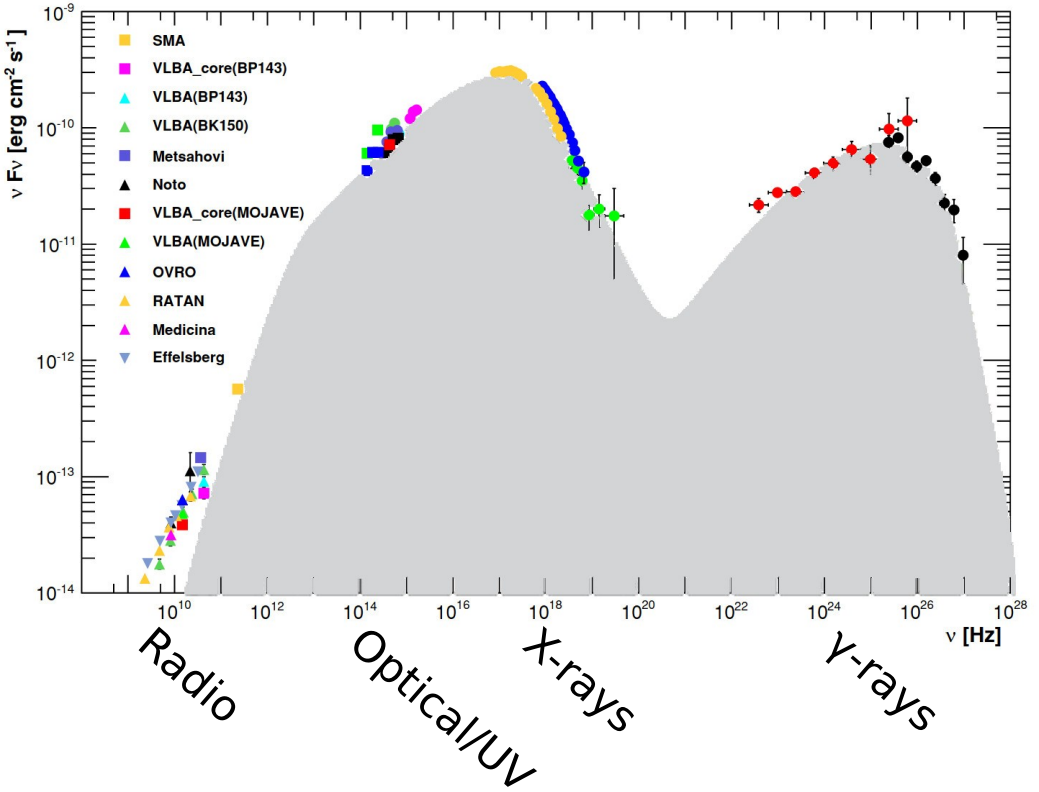
A new window

- Imaging X-ray Polarimetry Explorer (IXPE)

Credit: http://ixpe.iaps.inaf.it/

- X-ray satellite launched Dec 2021
- Energy range: from 2 keV to 8 keV

Credit: Abdo et al. 2011a



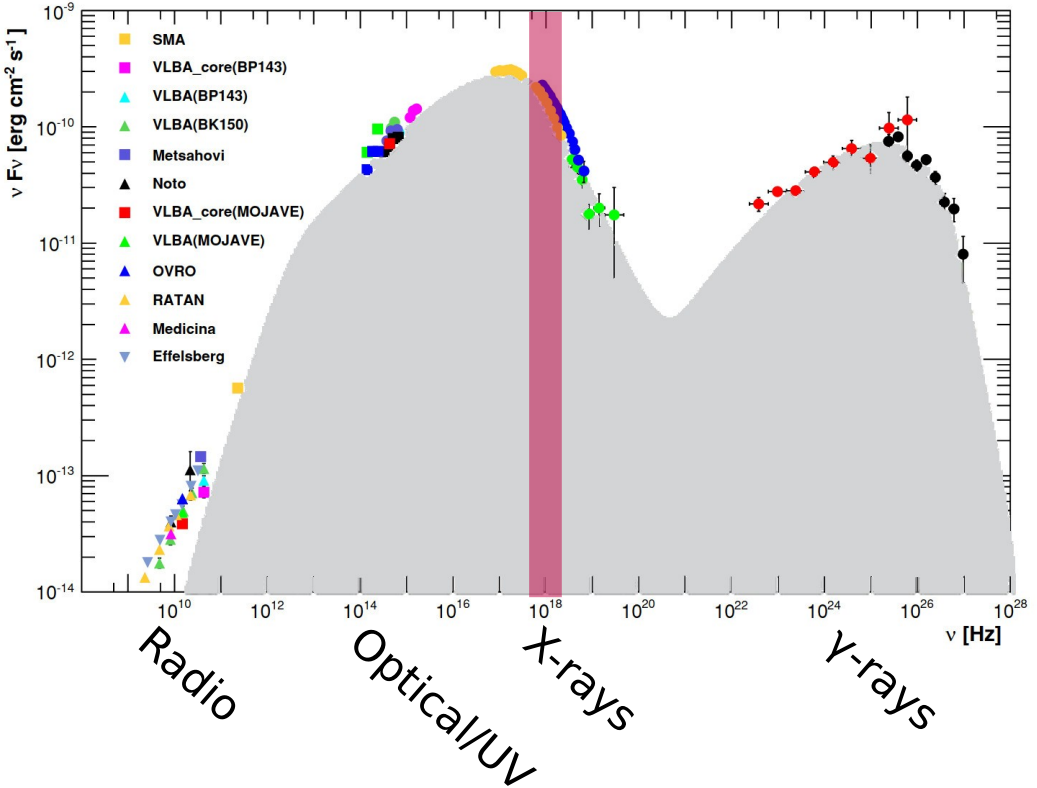
A new window

- Imaging X-ray Polarimetry Explorer (IXPE)

Credit: http://ixpe.iaps.inaf.it/

- X-ray satellite launched Dec 2021
- Energy range: from 2 keV to 8 keV

Credit: Abdo et al. 2011a

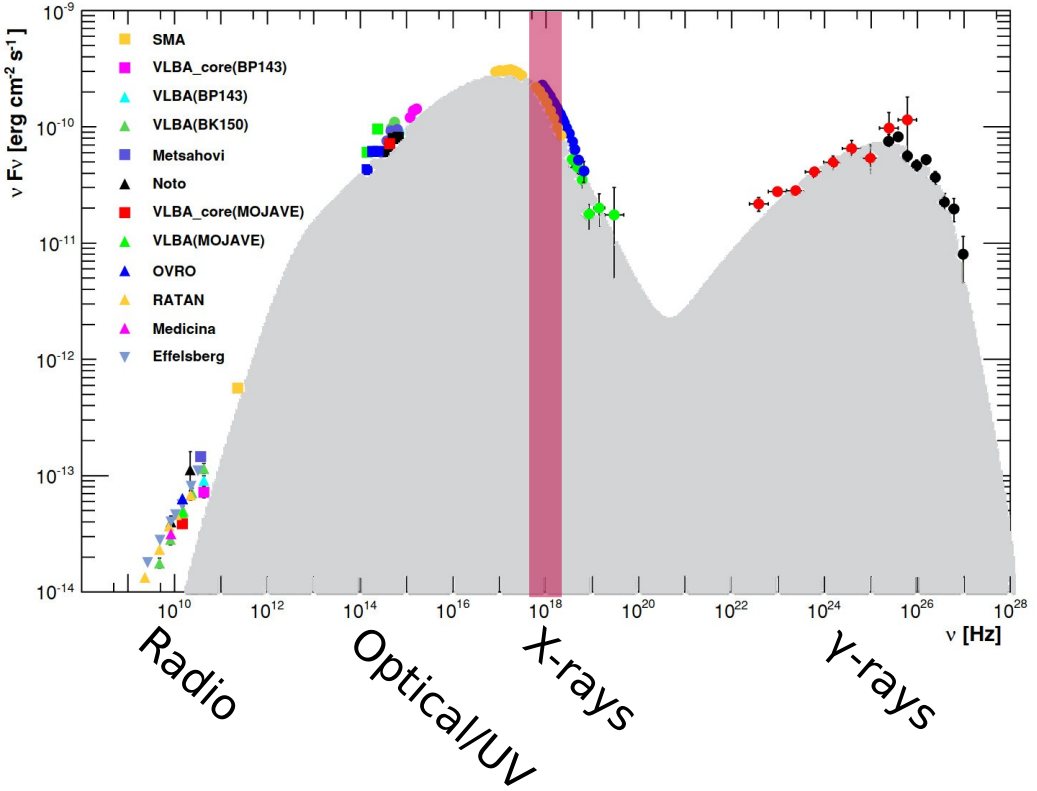


A new window

- Imaging X-ray Polarimetry Explorer (IXPE)

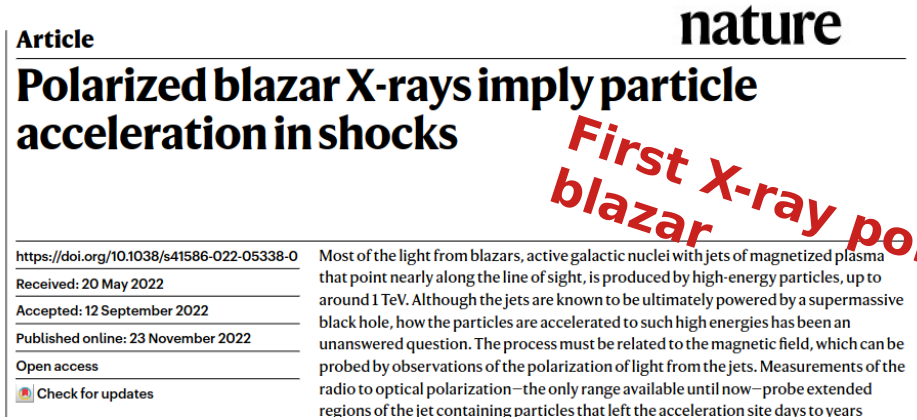
Credit: http://ixpe.iaps.inaf.it/

Credit: Abdo et al. 2011a



- X-ray satellite launched Dec 2021
- Energy range: from 2 keV to 8 keV
- Polarization measurements
  → probe the order of the magnetic fields in emission regions
  → acceleration mechanisms

A new window for understanding blazars



Article

nature

Polarized blazar X-rays imply particle acceleration in shocks

https://doi.org/10.1038/s41586-022-05338-0
Received: 20 May 2022
Accepted: 12 September 2022
Published online: 23 November 2022
Open access
Check for updates

Most of the light from blazars, active galactic nuclei with jets of magnetized plasma that point nearly along the line of sight, is produced by high-energy particles, up to around 1 TeV. Although the jets are known to be ultimately powered by a supermassive black hole, how the particles are accelerated to such high energies has been an unanswered question. The process must be related to the magnetic field, which can be probed by observations of the polarization of light from the jets. Measurements of the radio to optical polarization—the only range available until now—probe extended regions of the jet containing particles that left the acceleration site days to years

First X-ray polarization measurements of a blazar

- Mrk 501

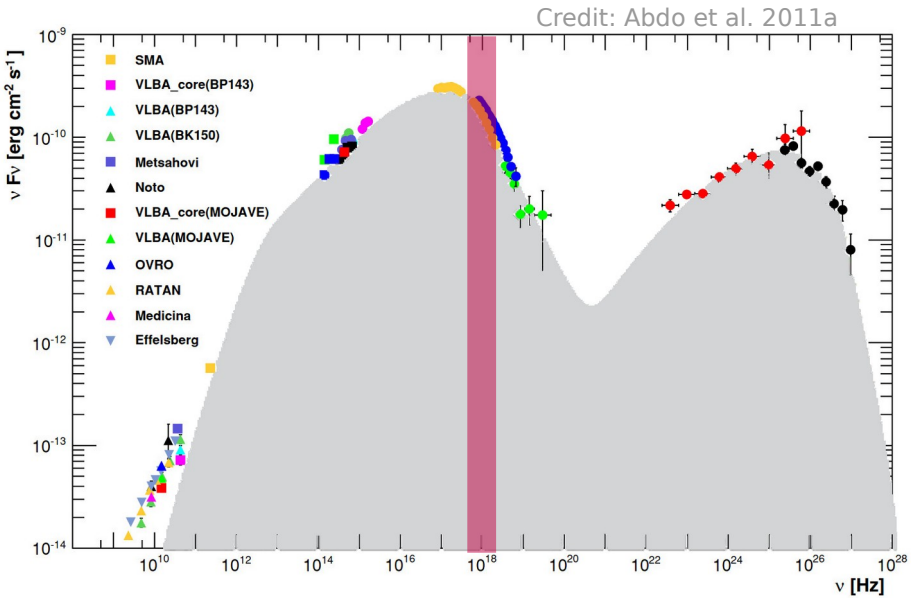
A new window for understanding blazars

- Mrk 501 & Mrk 421
  - our closest and brightest TeV blazars

A new window for understanding blazars

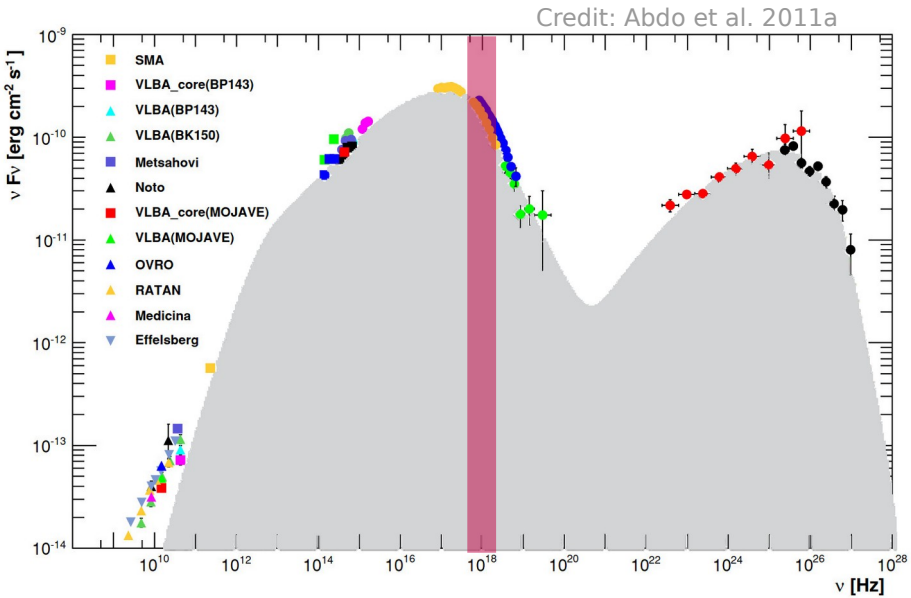
- Mrk 501 & Mrk 421
  - our closest and brightest TeV blazars

A new window for understanding blazars



- Mrk 501 & Mrk 421
  - our closest and brightest TeV blazars
  - IXPE probes the falling edge of the synchrotron peak emitted by the most energetic particles within the jet

A new window for understanding blazars



- Mrk 501 & Mrk 421
  - our closest and brightest TeV blazars
  - IXPE probes the falling edge of the synchrotron peak emitted by the most energetic particles within the jet
  - These electrons are also producing the VHE emission via Inverse Compton scattering
    → **MAGIC follow-up in the VHE band together with IXPE**

Mrk 501

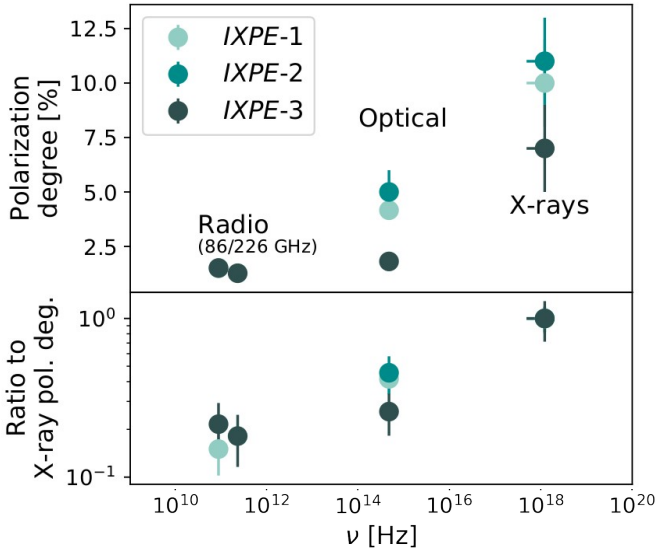
- IXPE pointings in 2022:
  - IXPE-1 & IXPE-2 in March 2022 Liodakis et al. 2022
  - IXPE-3 in July 2022 Lisalda et al. 2024 (submitted)

Mrk 501

- IXPE pointings in 2022:
  - IXPE-1 & IXPE-2 in March 2022 Liodakis et al. 2022
  - IXPE-3 in July 2022 Lisalda et al. 2024 (submitted)

- Polarization degree:
  - X-ray ~factor 2 higher than in optical
  - Drop in polarization for IXPE-3

MAGIC Collaboration et al. 2024, A&A, 685, A117



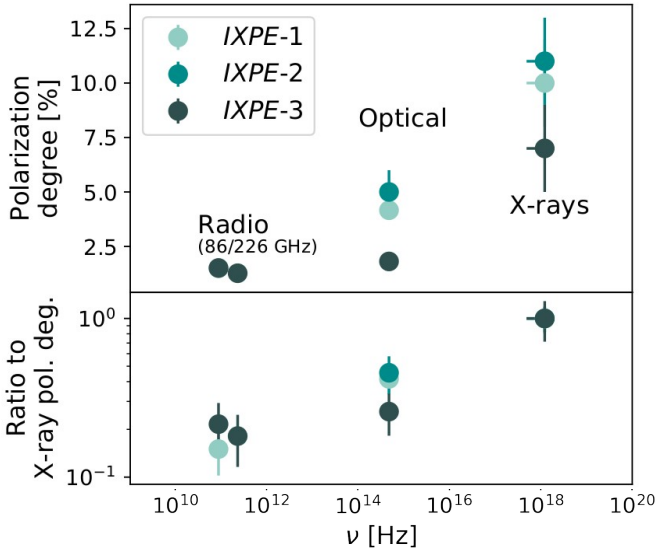
Mrk 501

- IXPE pointings in 2022:
  - IXPE-1 & IXPE-2 in March 2022 Liodakis et al. 2022
  - IXPE-3 in July 2022 Lisalda et al. 2024 (submitted)

- Polarization degree:
  - X-ray ~factor 2 higher than in optical
  - Drop in polarization for IXPE-3

- X-ray Polarization angle:
  - In line with optical
  - Parallel to radio jet orientation

MAGIC Collaboration et al. 2024, A&A, 685, A117



Mrk 501

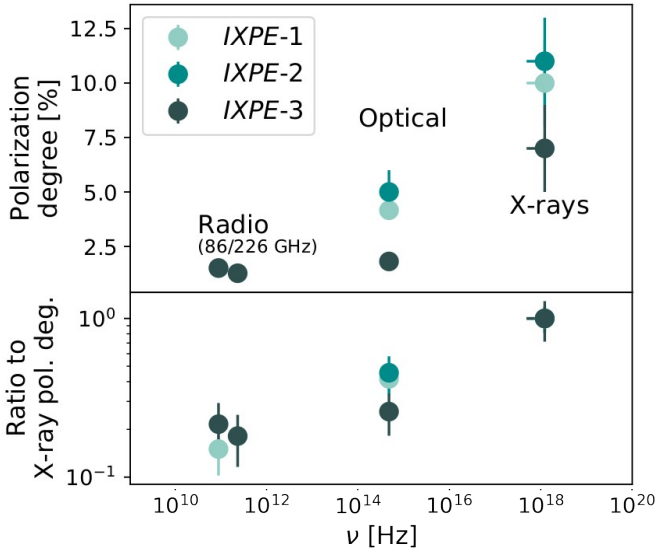
- IXPE pointings in 2022:
  - IXPE-1 & IXPE-2 in March 2022 Liodakis et al. 2022
  - IXPE-3 in July 2022 Lisalda et al. 2024 (submitted)

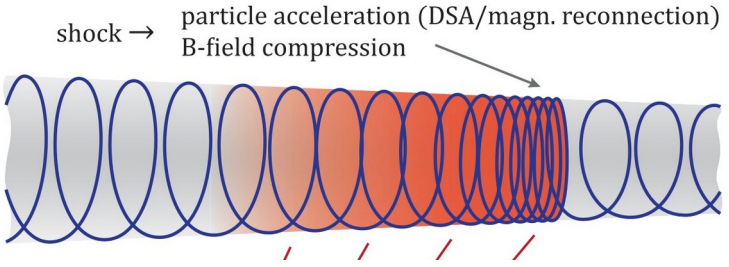
- Polarization degree:
  - X-ray ~factor 2 higher than in optical
  - Drop in polarization for IXPE-3

- X-ray Polarization angle:
  - In line with optical
  - Parallel to radio jet orientation

  → Shock acceleration in an energy stratified jet

MAGIC Collaboration et al. 2024, A&A, 685, A117





Credit: Angelakis et al. 2016

Mrk 501

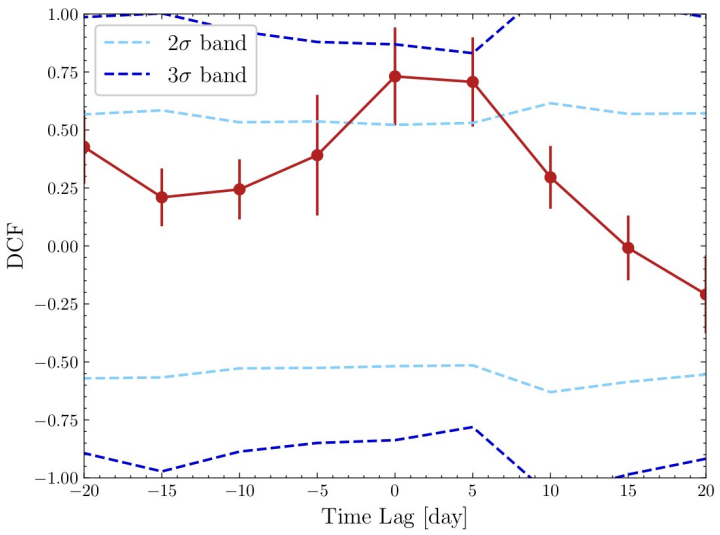
- Full Multiwavelength (MWL) campaign from March to July 2022
  - **For the first time VHE (>0.2 TeV) simultaneous to X-ray polarization**

Mrk 501

- Full Multiwavelength (MWL) campaign from March to July 2022
  - For the first time VHE (>0.2 TeV) simultaneous to X-ray polarization

- Shows typical MWL behaviors:
  - VHE flux ~average level & low variability
  - Evidence for X-ray to VHE correlation
  - Harder when brighter in X-rays

MAGIC Collaboration et al. 2024, A&A, 685, A117



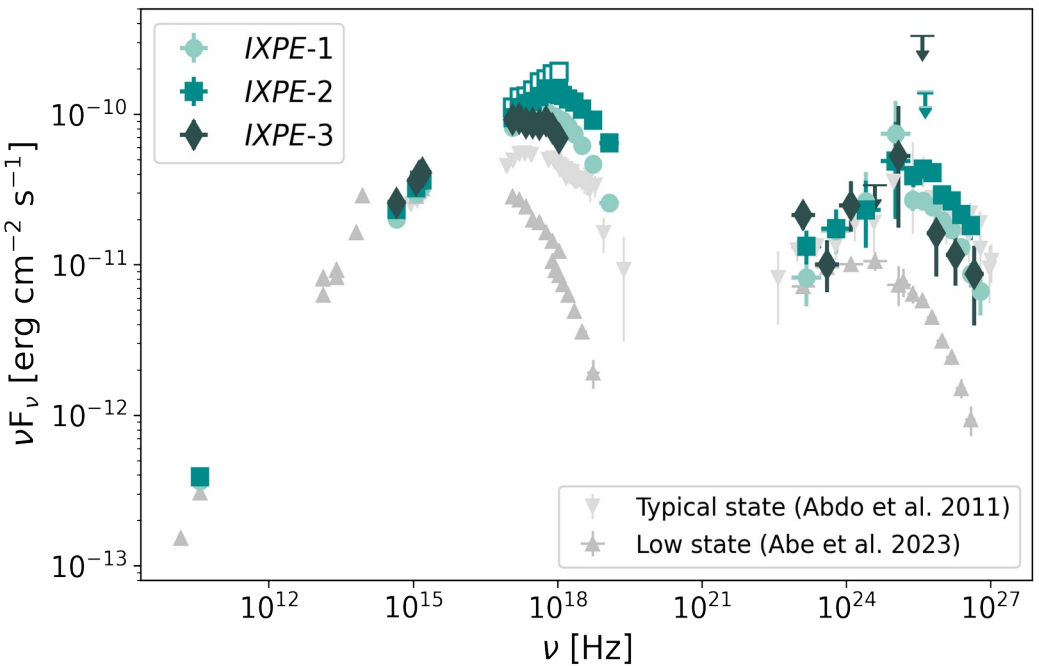
Mrk 501

- Full Multiwavelength (MWL) campaign from March to July 2022
  - For the first time VHE (>0.2 TeV) simultaneous to X-ray polarization

- Shows typical MWL behaviors:
  - VHE flux ~average level & low variability
  - Evidence for X-ray to VHE correlation
  - Harder when brighter in X-rays

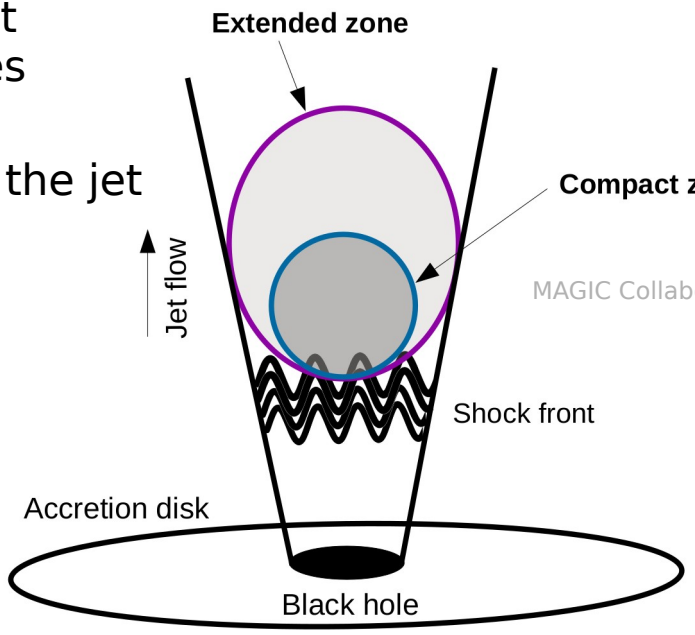
- However, spectra show more unusual features:
  - Extreme states for IXPE-1 & 2
    $\nu_{synch} > 2.4 \times 10^{17}$ Hz (~1keV)
  - Shift to lower energies for IXPE-3
  - Low Compton Dominance (CD)

MAGIC Collaboration et al. 2024, A&A, 685, A117



Mrk 501

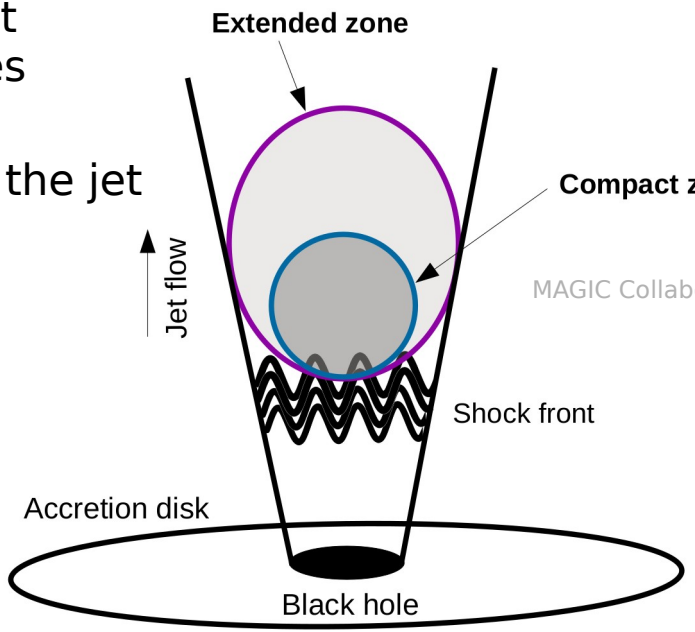
- Theoretical description – two zones
  - Compact region:
    - Dominating in the X-ray/VHE
  - Extended region:
    - Dominating at lower energies
    - Stretches further along the jet

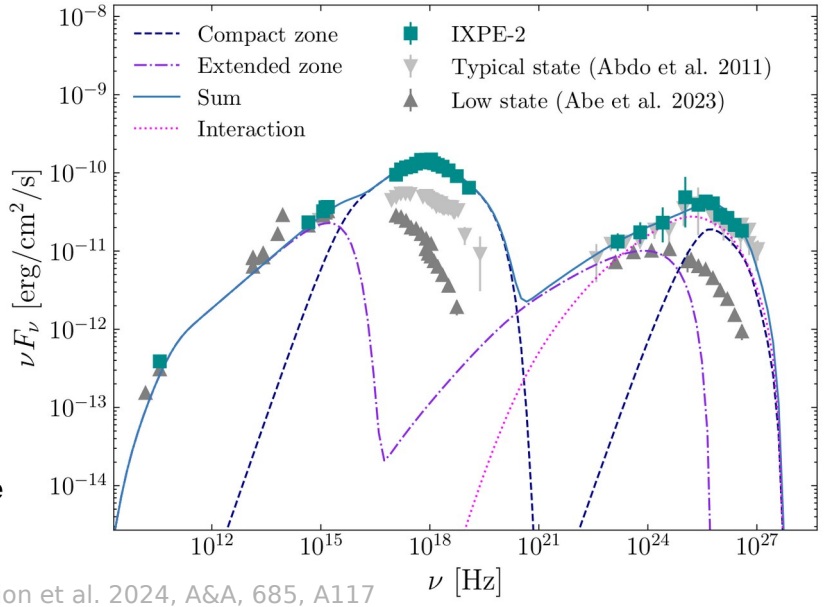


MAGIC Collaboration et al. 2024, A&A, 685, A117

Mrk 501

- Theoretical description – two zones
  - Compact region:
    - Dominating in the X-ray/VHE
  - Extended region:
    - Dominating at lower energies
    - Stretches further along the jet





MAGIC Collaboration et al. 2024, A&A, 685, A117

Mrk 421

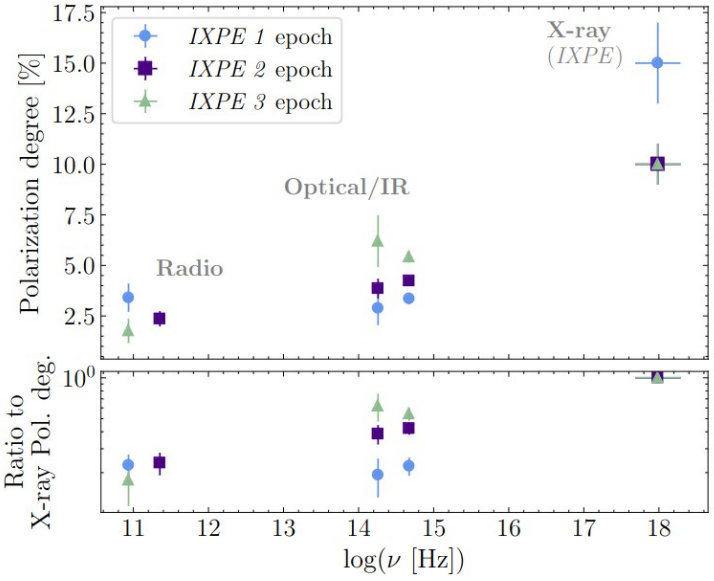
- IXPE pointings in 2022:
  - IXPE-1 in May 2022 Di Gesu et al. 2022
  - IXPE-2 & IXPE-3 in June 2022 Di Gesu et al. 2023

Mrk 421

- IXPE pointings in 2022:
  - IXPE-1 in May 2022 Di Gesu et al. 2022
  - IXPE-2 & IXPE-3 in June 2022 Di Gesu et al. 2023

- Polarization degree:
  - Even higher difference between X-ray and optical w.r.t. Mrk501 → Shock acceleration in an energy stratified jet

Abe et al. 2024, A&A, 684, A127



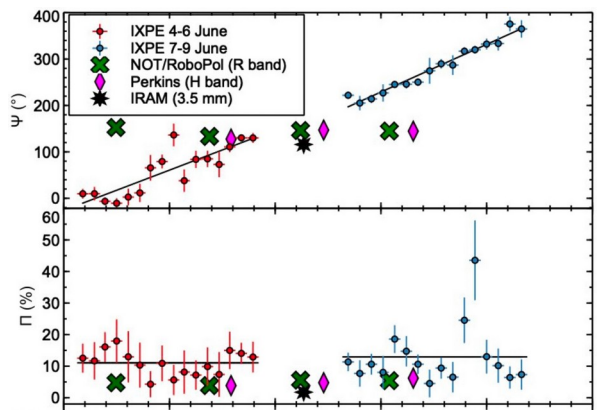
Credit: Di Gesu et al. 2023

Mrk 421

- IXPE pointings in 2022:
  - IXPE-1 in May 2022 Di Gesu et al. 2022
  - IXPE-2 & IXPE-3 in June 2022 Di Gesu et al. 2023

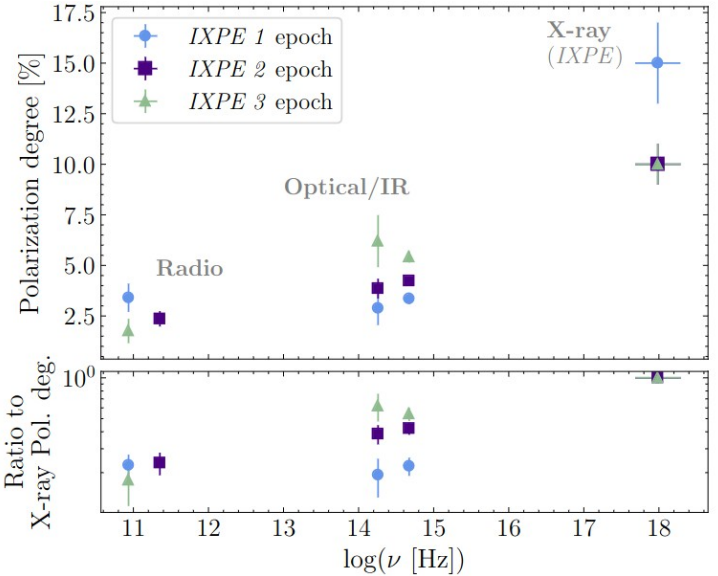
- Polarization degree:
  - Even higher difference between X-ray and optical w.r.t. Mrk501 → Shock acceleration in an energy stratified jet

- Polarization angle:
  - Full rotation in June 2022 in X-rays



Credit: Di Gesu et al. 2023

Abe et al. 2024, A&A, 684, A127



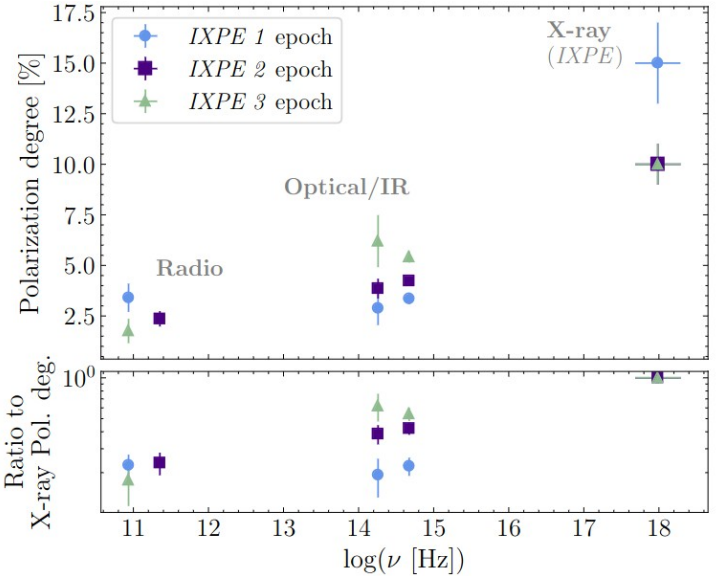
Mrk 421

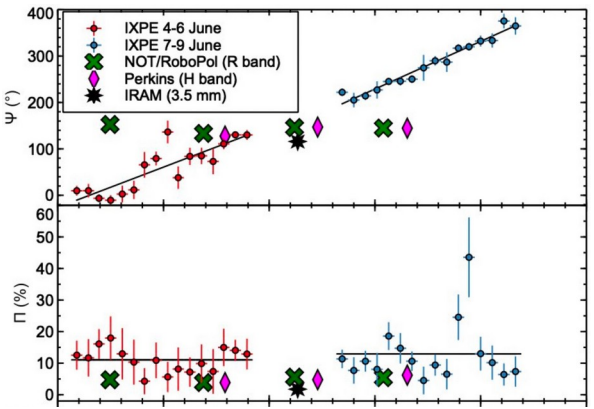
- IXPE pointings in 2022:
  - IXPE-1 in May 2022 Di Gesu et al. 2022
  - IXPE-2 & IXPE-3 in June 2022 Di Gesu et al. 2023

- Polarization degree:
  - Even higher difference between X-ray and optical w.r.t. Mrk501 → Shock acceleration in an energy stratified jet

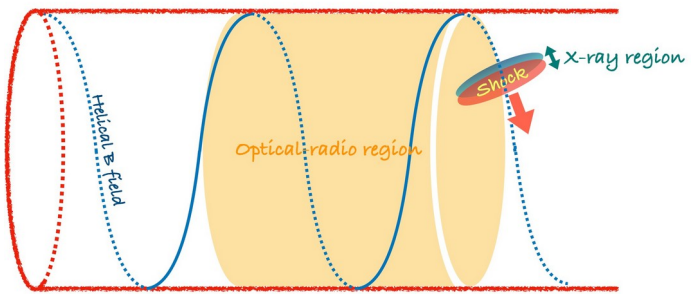
- Polarization angle:
  - Full rotation in June 2022 in X-rays

Abe et al. 2024, A&A, 684, A127





Credit: Di Gesu et al. 2023



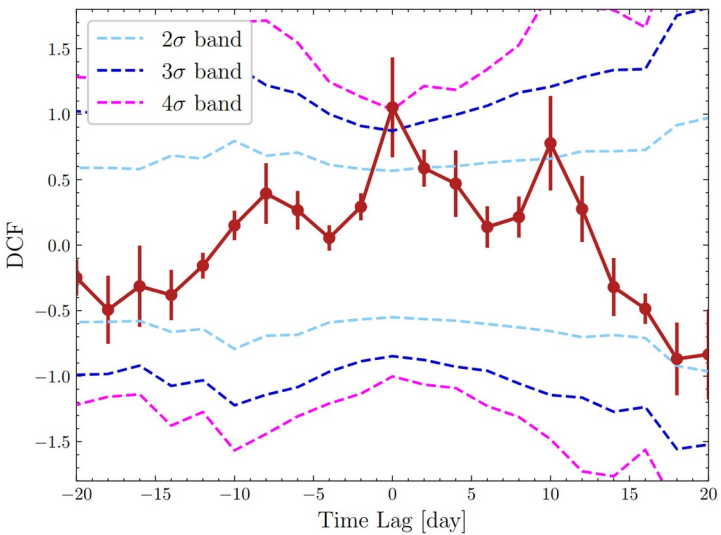
X-ray emission zone on helical path
→ Detached from optical/radio zone

Mrk 421

- Full MWL campaign from May to June 2022
  - **For the first time VHE (>0.2 TeV) with X-ray polarization**
  - Low, average & enhanced states during IXPE-1,-2,-3

Mrk 421

- Full MWL campaign from May to June 2022
  - For the first time VHE (>0.2 TeV) with X-ray polarization
  - Low, average & enhanced states during IXPE-1,-2,-3
  - Significant correlation between VHE and X-rays
    → **VHE co-spatial to region where rotation is seen**

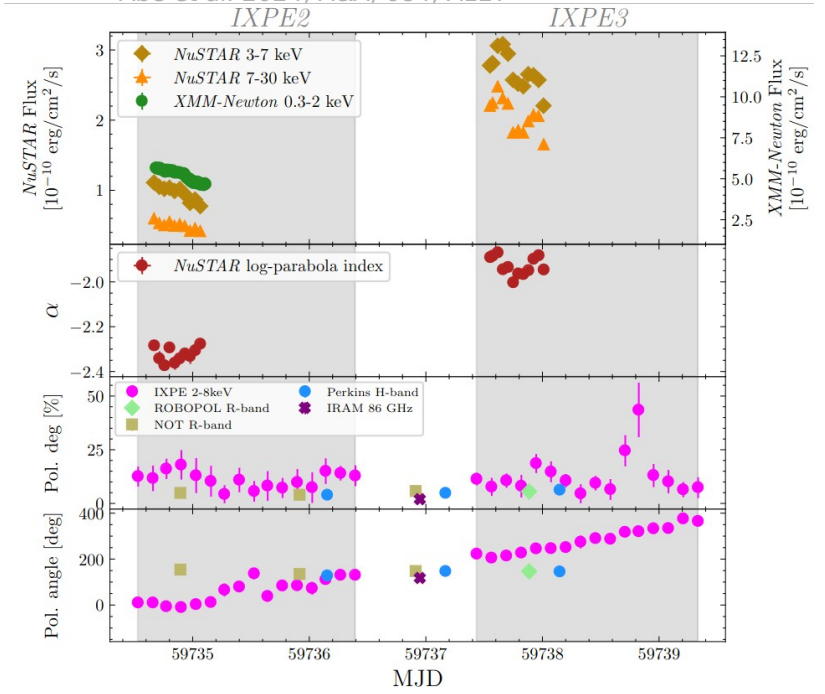


Abe et al. 2024, A&A, 684, A127

Mrk 421

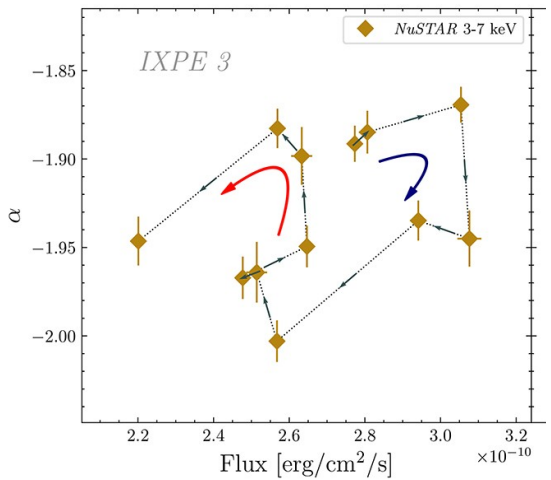
- Full MWL campaign from May to June 2022
  - For the first time VHE (>0.2 TeV) with X-ray polarization
  - Low, average & enhanced states during IXPE-1,-2,-3
  - Significant correlation between VHE and X-rays → VHE co-spatial to region where rotation is seen
  - Strong variability in hard X-rays observed by NuSTAR during polarization angle rotation:

Abe et al. 2024, A&A, 684, A127

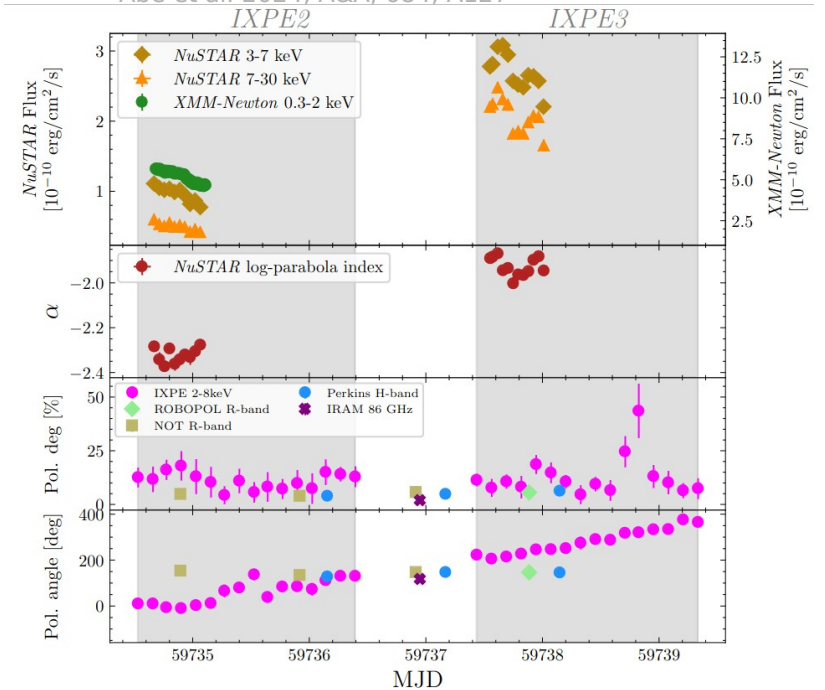


Mrk 421

- Full MWL campaign from May to June 2022
  - For the first time VHE (>0.2 TeV) with X-ray polarization
  - Low, average & enhanced states during IXPE-1,-2,-3
  - Significant correlation between VHE and X-rays → VHE co-spatial to region where rotation is seen
  - Strong variability in hard X-rays observed by NuSTAR during polarization angle rotation:



Abe et al. 2024, A&A, 684, A127



- **Evidence of spectral hysteresis:**
  - First clock-wise (soft lag = LE lags behind HE):
    - Delay by synchrotron cooling
  - Then counter clock-wise (hard lag = HE behind LE):
    - Acceleration time scale ~ cooling time scale

Summary

- **Blazars** are interesting objects to study due to their potential **multi-messenger nature** and because they are among the most extreme **particle accelerators** in our Universe

- **IXPE** opened a new window allowing us to better constrain their **acceleration and emission mechanisms**, especially when **combining the X-ray polarization results** with the **full MWL picture:**

  - Energy stratified jet with different emission regions
  - Connection between spectral/MWL flux level changes with polarization measurements → Constraints on geometry/magnetic field/ electron distributions,...
  - VHE co-spatial to X-ray region → X-ray polarization also provide constraints at the highest energies

Find our two papers here:

Mrk 501

Mrk 421

universität innsbruck

MAX-PLANCK-INSTITUT FÜR PHYSIK

MAGIC

Thank you for your attention!