

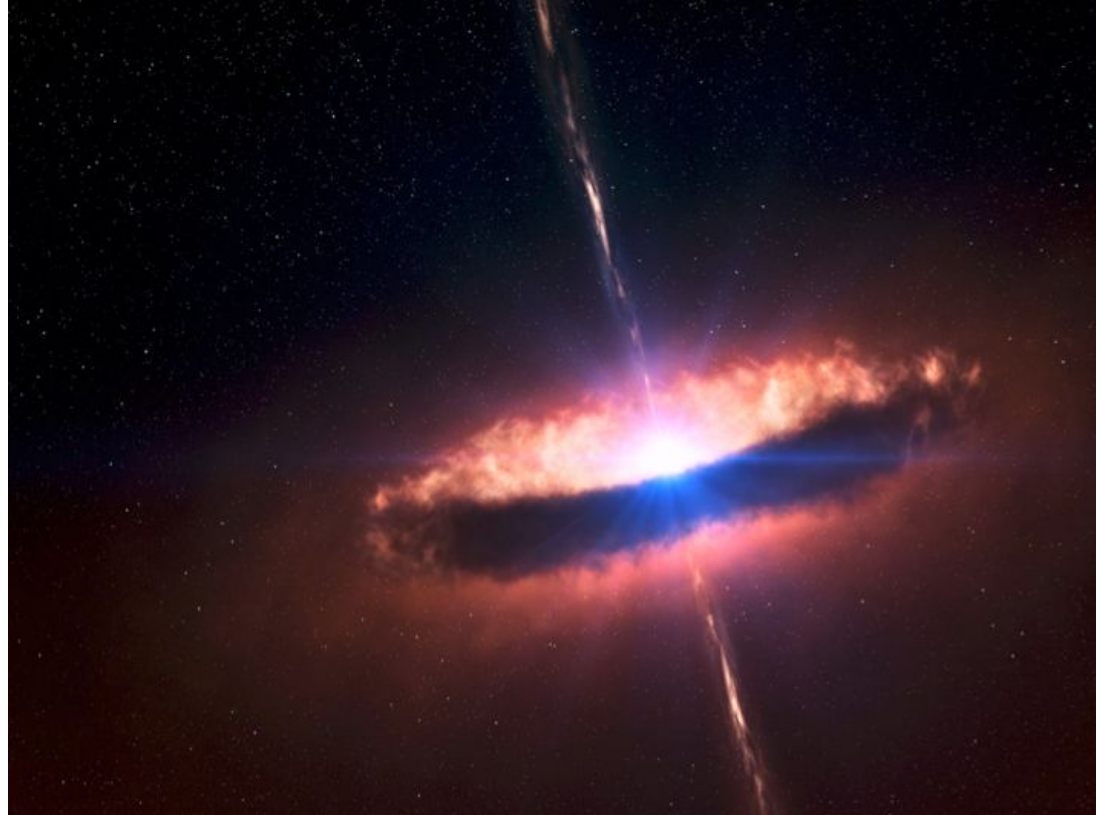
Insights into the high-energy emission of archetypical TeV blazars from the first X-ray polarization measurements

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



Blazars

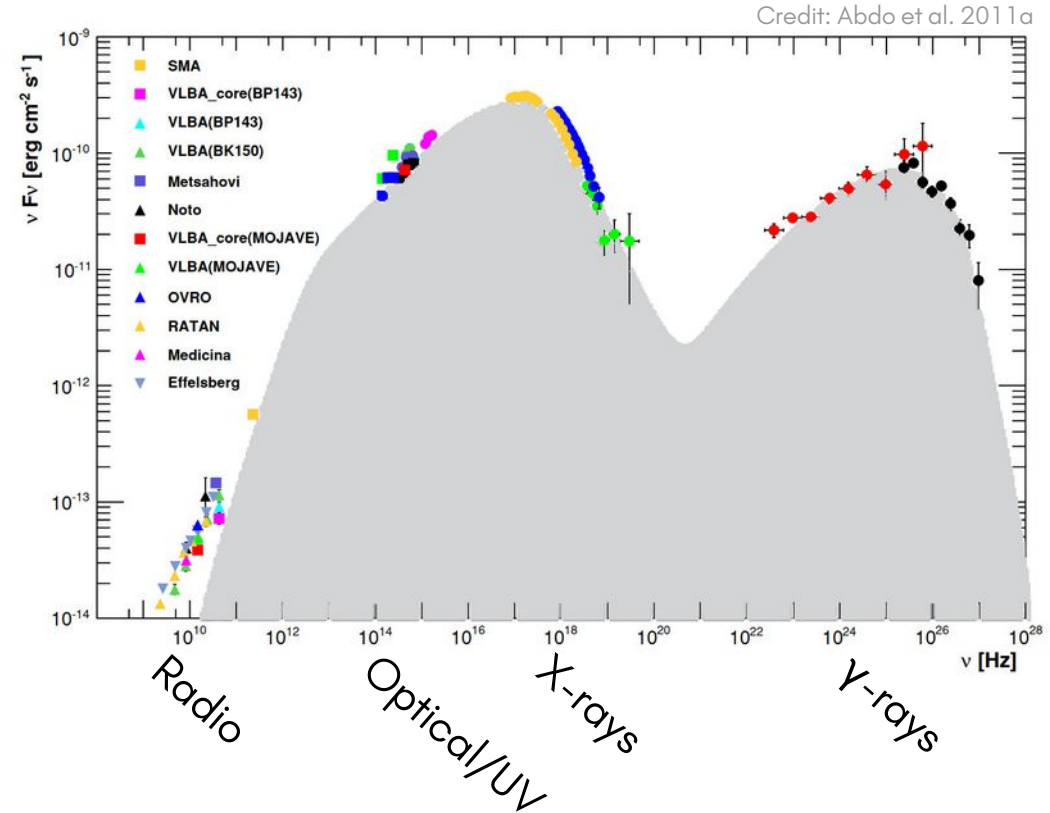
- Most luminous persistent sources in the universe
- Galaxies hosting supermassive black holes
- Jets aligned with our line of sight
- Potential emitters of neutrinos and cosmic rays
- High-energy physics laboratories



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

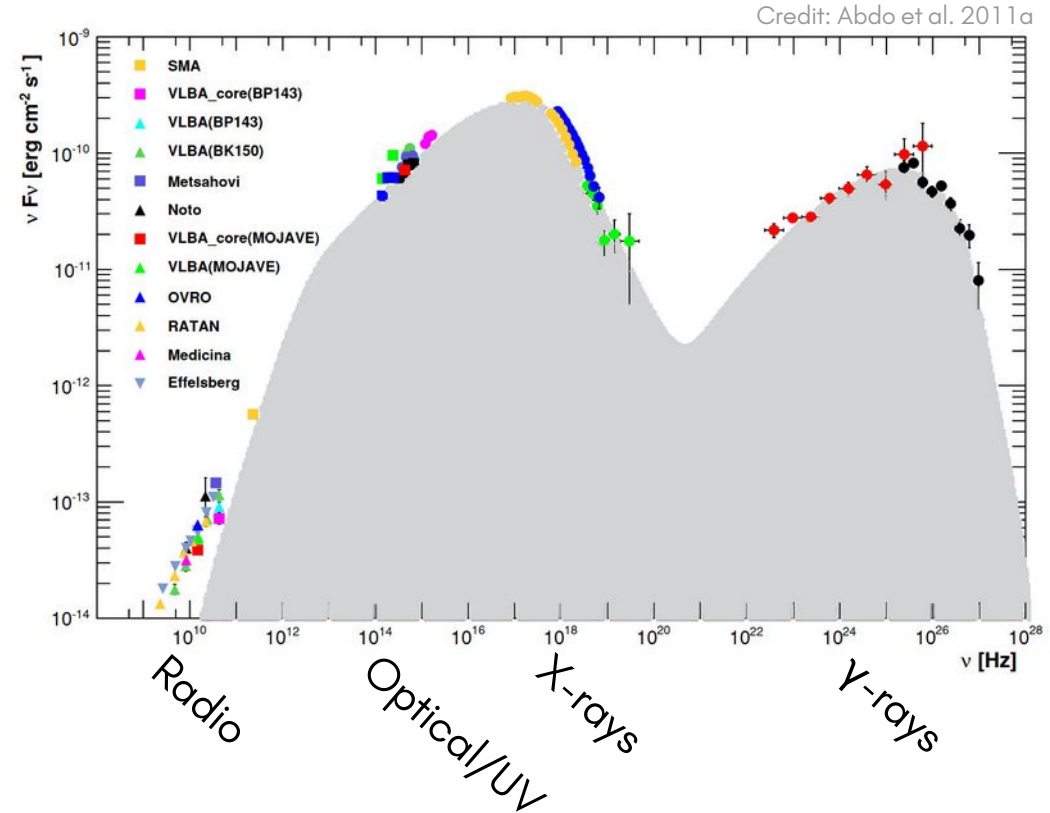
Blazars

- Their broadband emission
 - can cover from radio to gamma-rays
 - shows two distinctive bumps
 - varies with time and flux levels



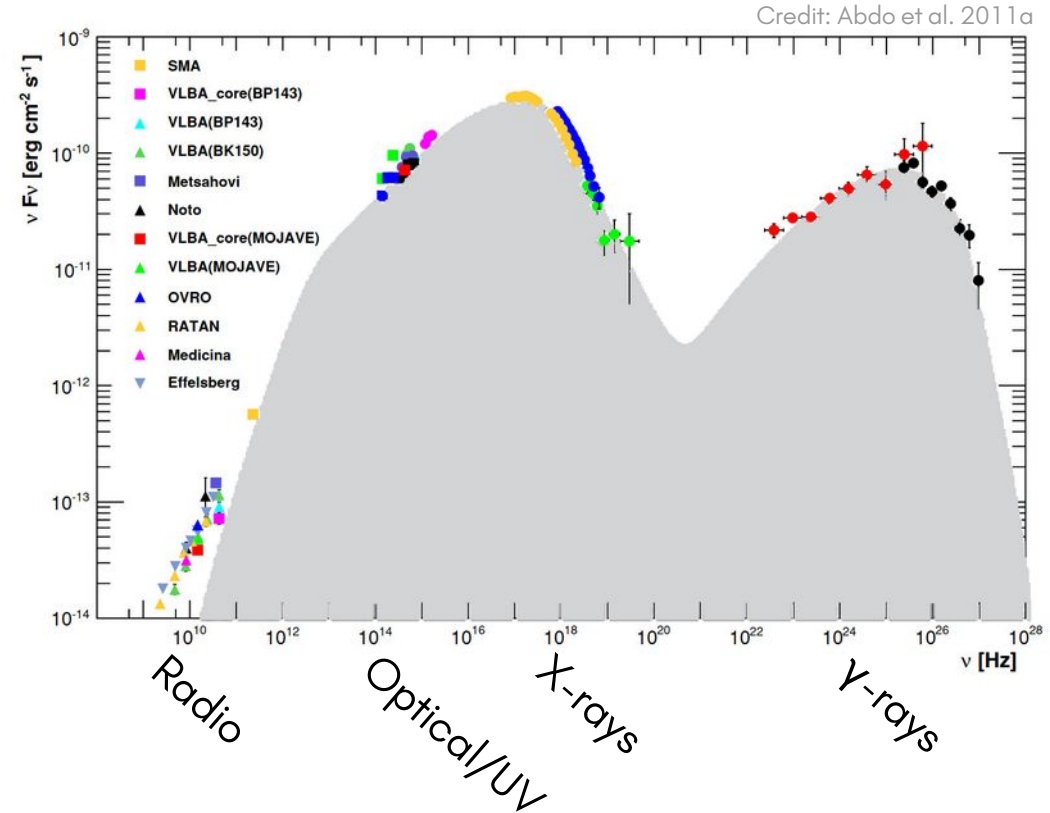
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- Open questions:



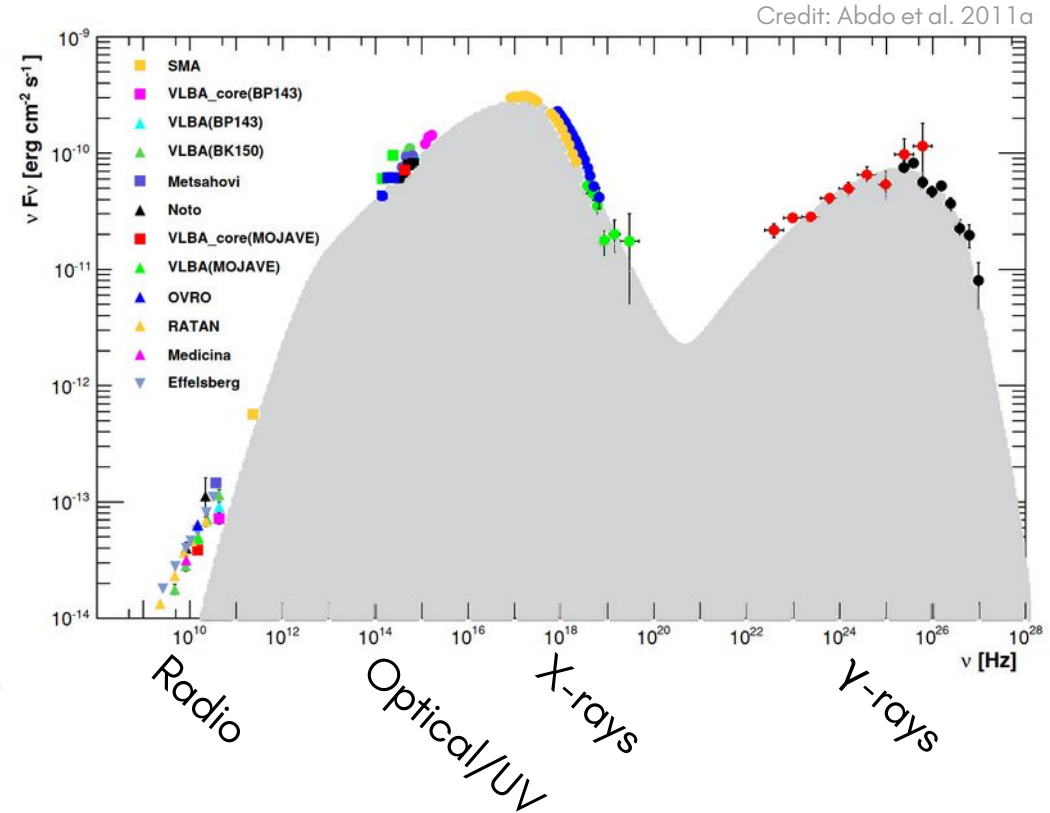
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 - What is radiating?
 - Electrons? Protons?



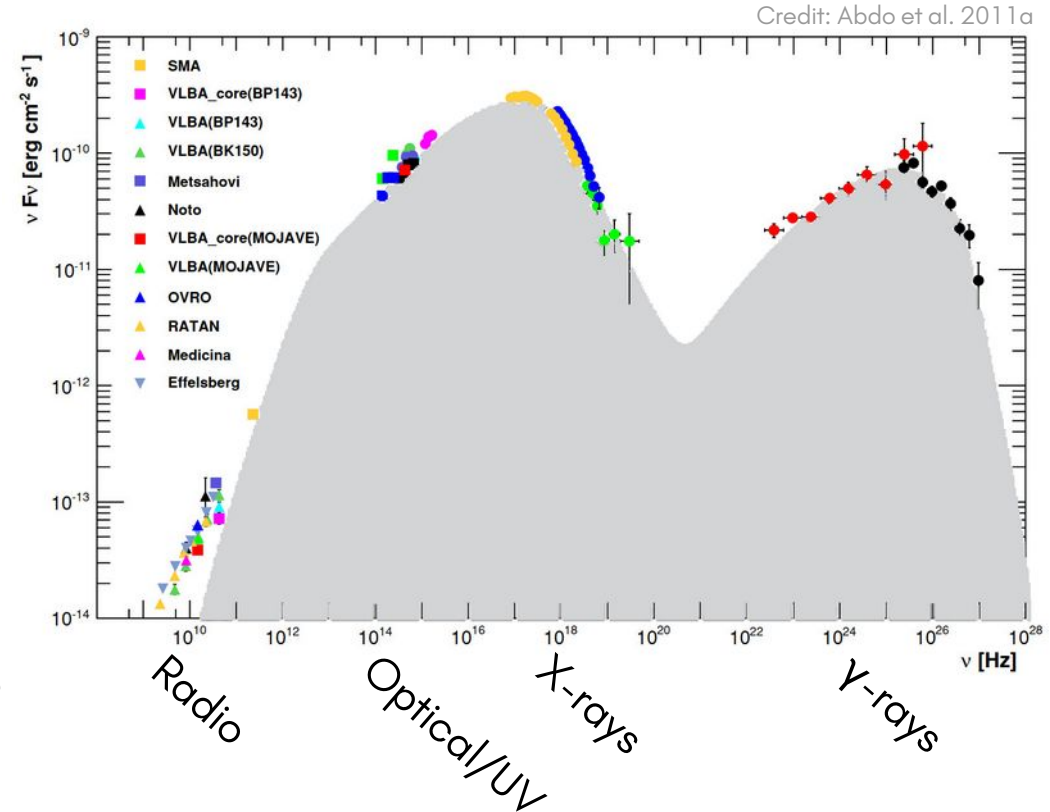
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 - What is the acceleration mechanism behind?
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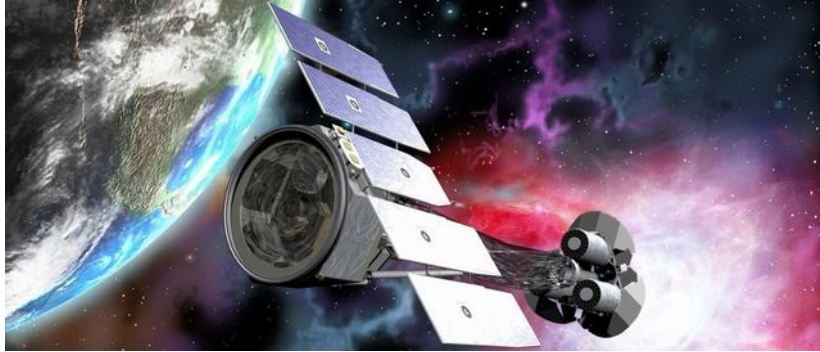
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 - What is radiating?
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 - What is the acceleration mechanism behind?
 - Shocks? Magnetic reconnection?
 - In which environment?
 - One-zone? Multiple-zones? Spine-sheath,...?
 - Where in the jet? (radius, magnetic field, Doppler factor,...)

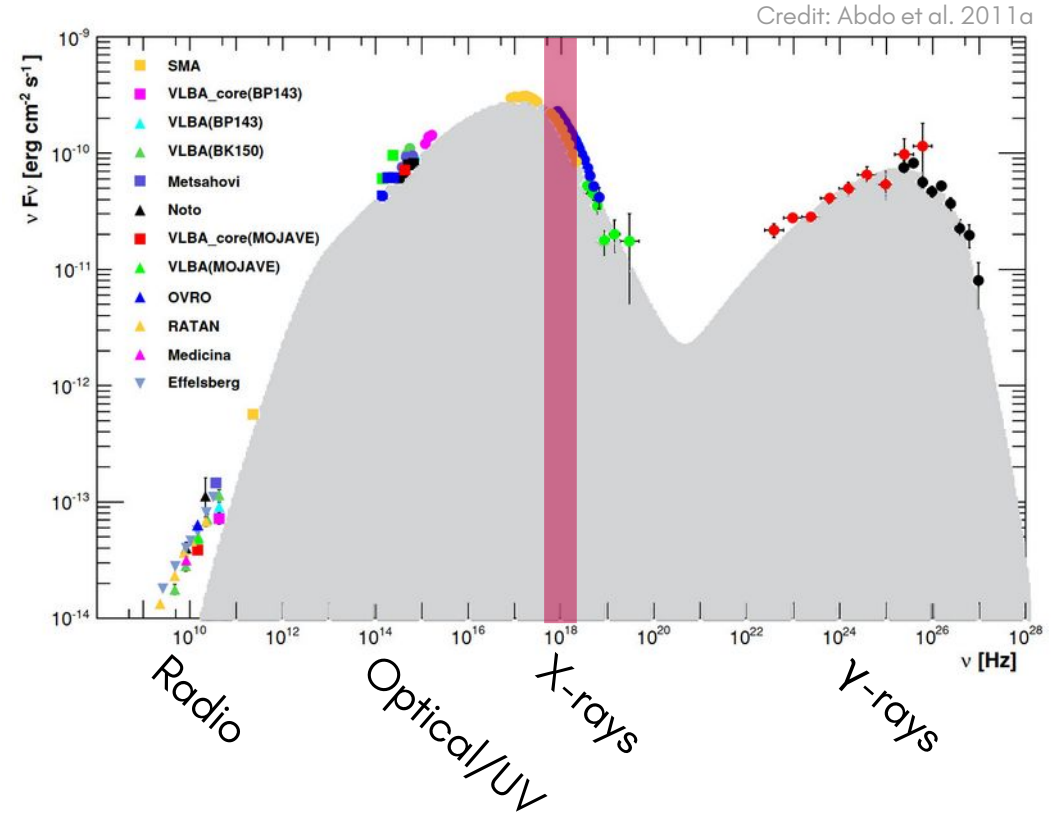


A new window

- Imaging X-ray Polarimetry Explorer (IXPE)

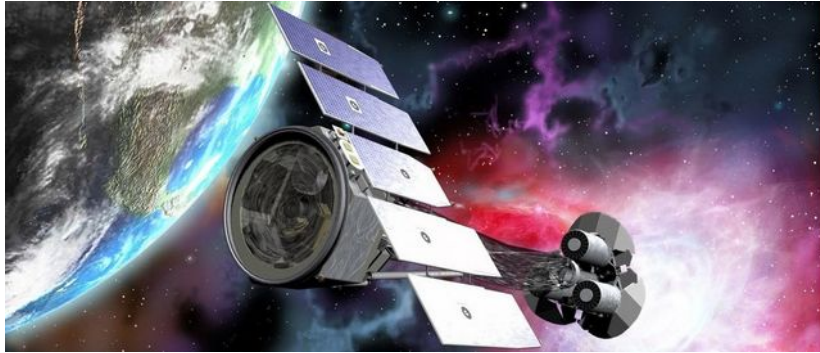


Credit: <http://ixpe.iaps.inaf.it/>



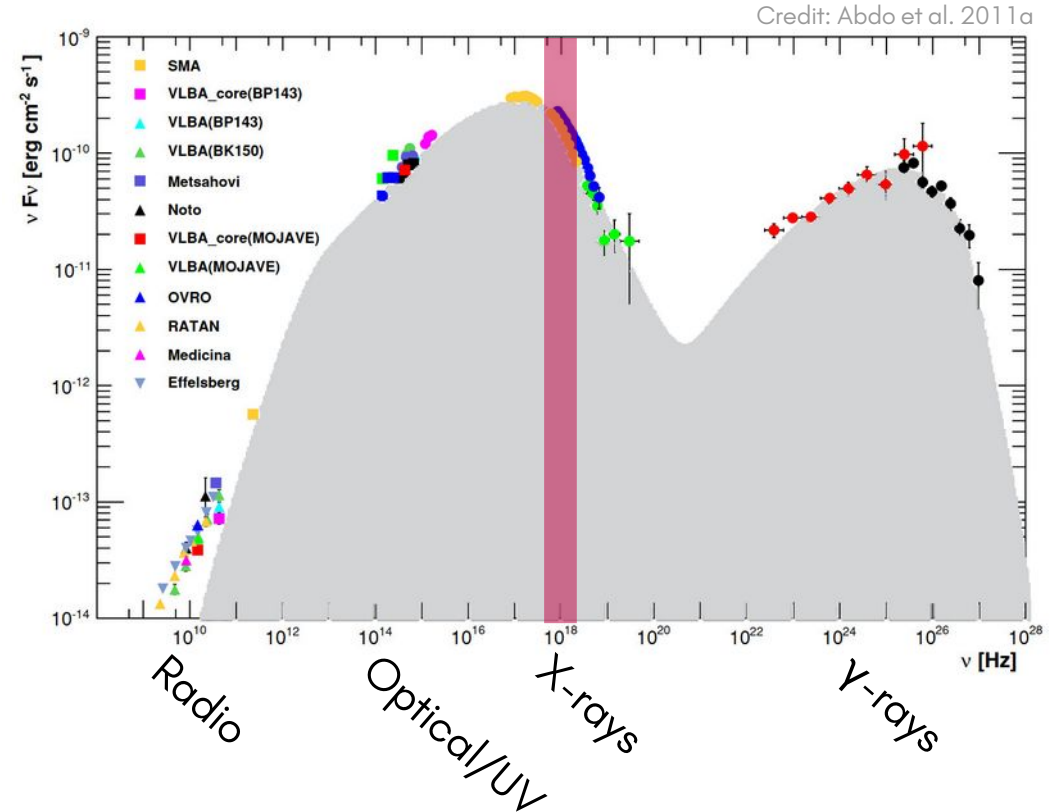
A new window

- 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
- Polarization measurements
 - probe the order of the magnetic fields in emission regions
 - acceleration mechanisms



A new window

Article

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

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Open access

 Check for updates

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nature

First X-ray polarization measurements of a blazar

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

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- Mrk 501 & Mrk 421
 - our closest and brightest TeV blazars
 - IXPE probes the falling edge of the synchrotron peak & therefore the most energetic particles
 - Direct probe of acceleration mechanisms

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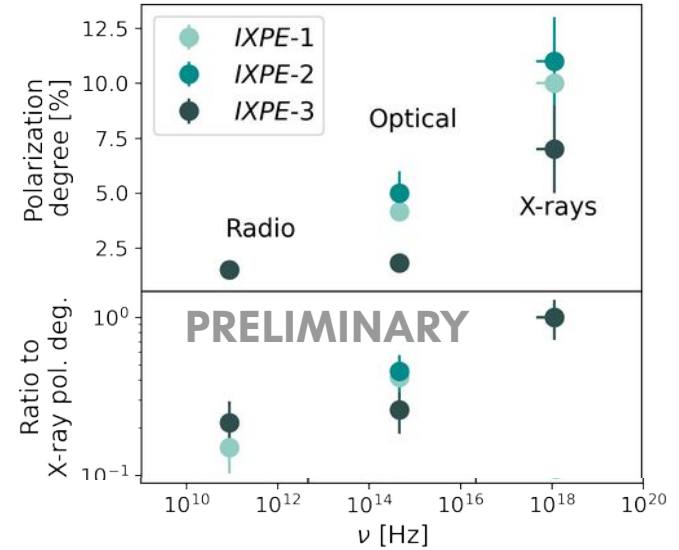
- Mrk 501 & Mrk 421
 - our closest and brightest TeV blazars
 - IXPE probes the falling edge of the synchrotron peak & therefore the most energetic particles
 - Direct probe of acceleration mechanisms
 - Same electrons are producing the VHE emission via Inverse Compton scattering
 - MAGIC follow-up in the VHE 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. 2023 (in prep.)

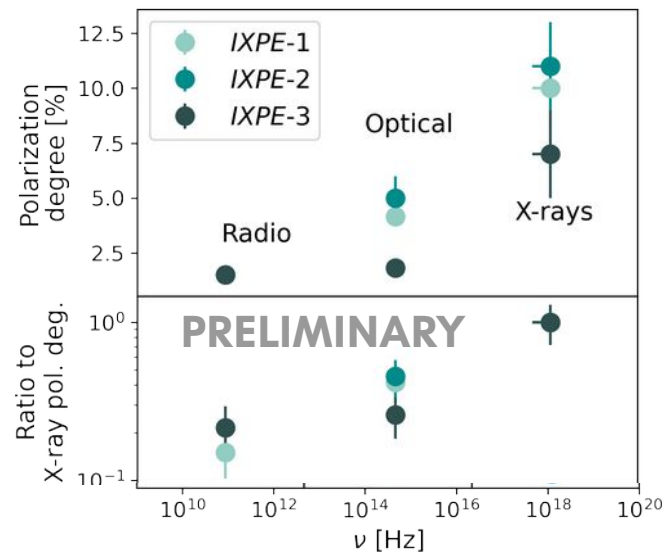
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 - X-ray ~factor 2 higher than optical
 - Drop in polarization for IXPE-3



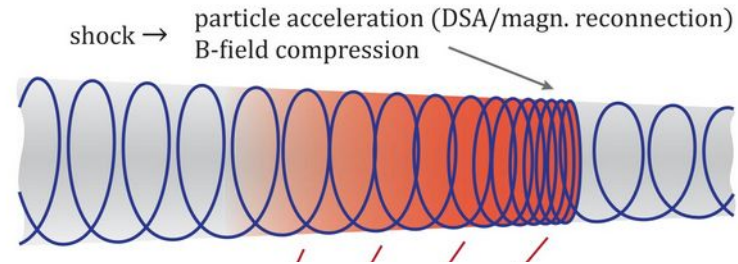
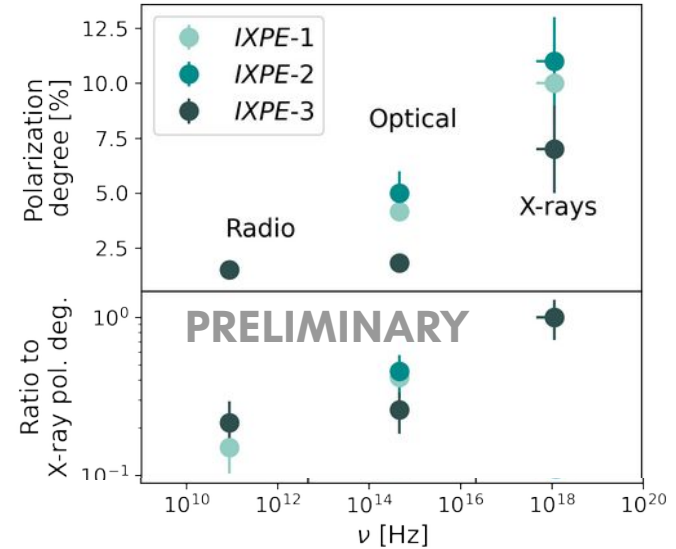
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 - In line with optical
 - Parallel to radio jet orientation



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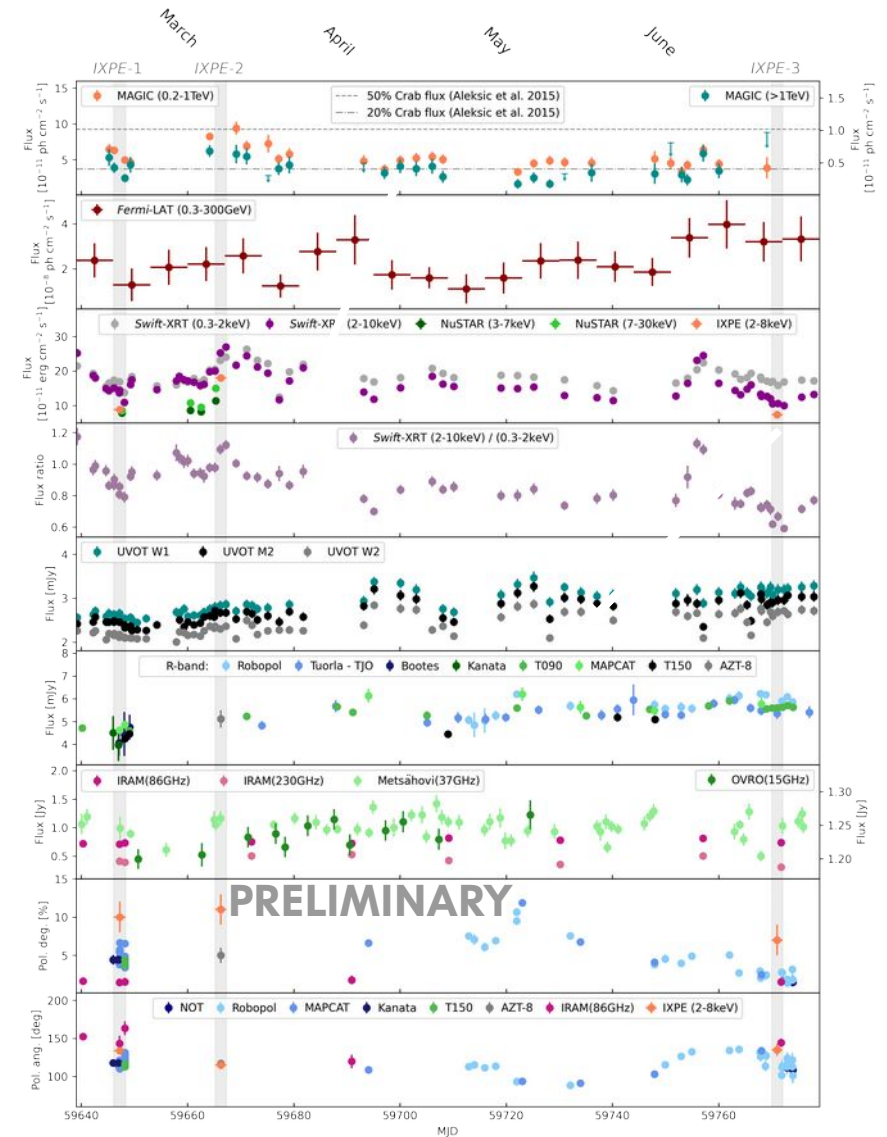
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- Shock acceleration in an energy stratified jet



Credit: Angelakis et al. 2016

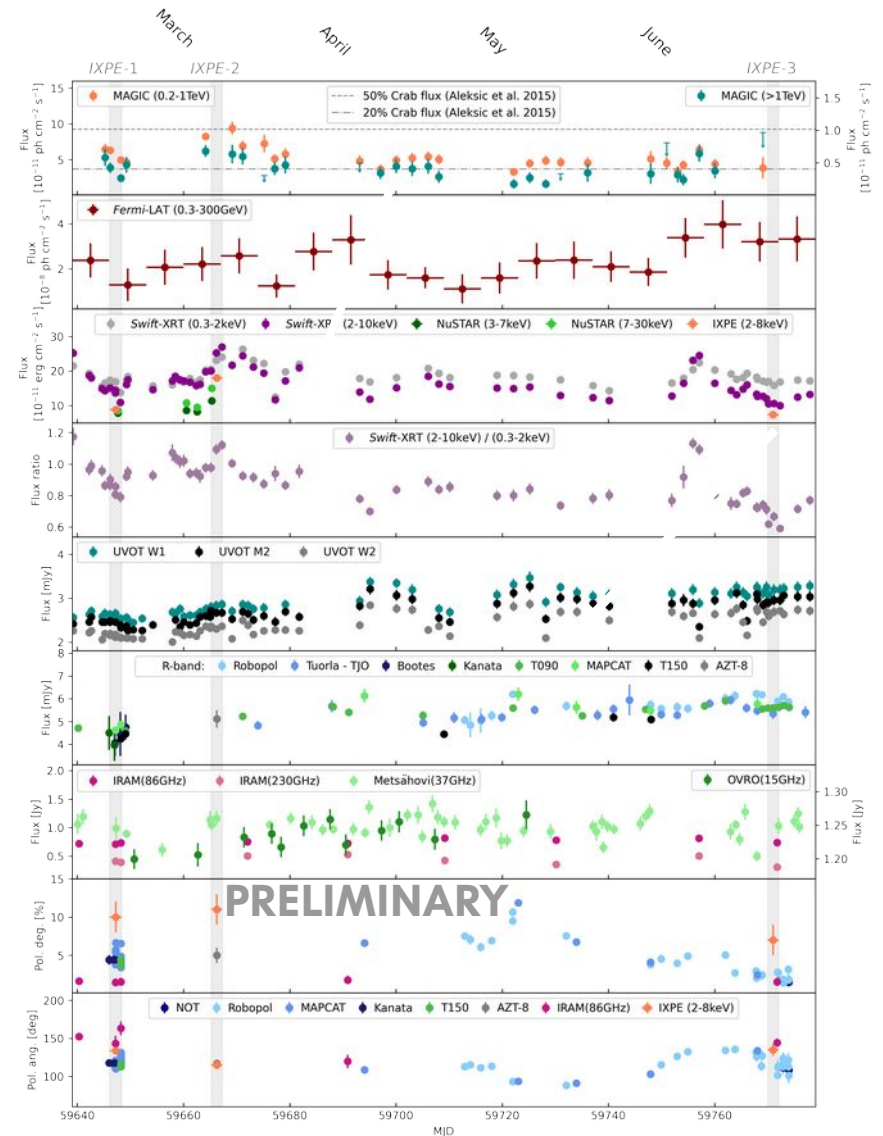
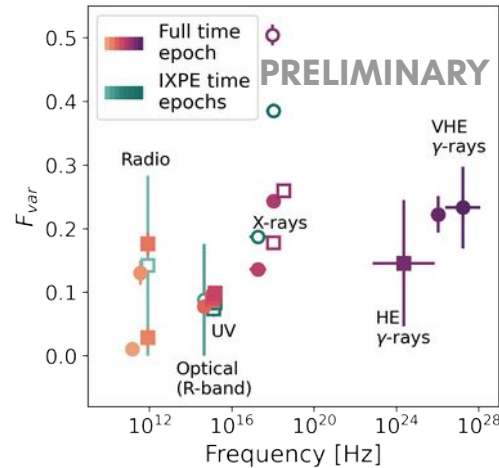
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- Full Multiwavelength (MWL) campaign from March to July 2022
- For the first time VHE (>0.2 TeV) simultaneous to X-ray polarization



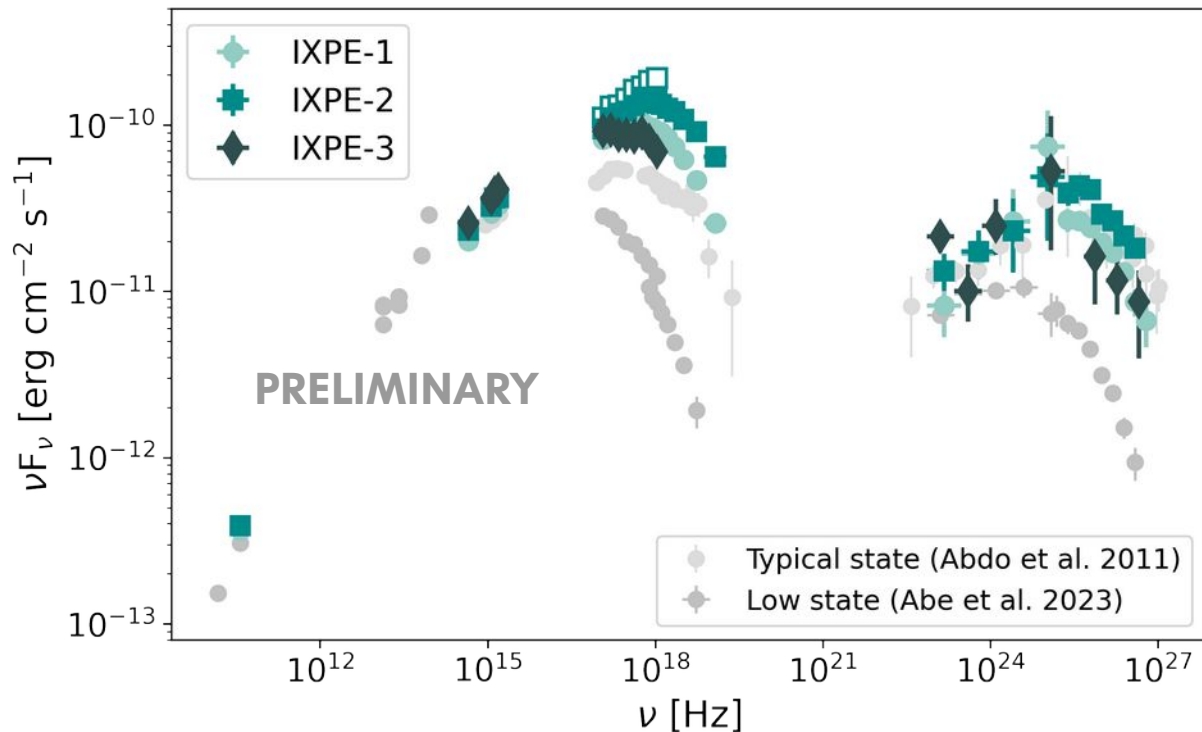
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- Full Multiwavelength (MWL) campaign from March to July 2022
- For the first time VHE (>0.2 TeV) simultaneous to X-ray polarization
- Shows typical behaviors:
 - VHE flux ~average level
 - Low variability
 - Evidence for X-ray to VHE correlation
 - Harder when brighter in X-rays



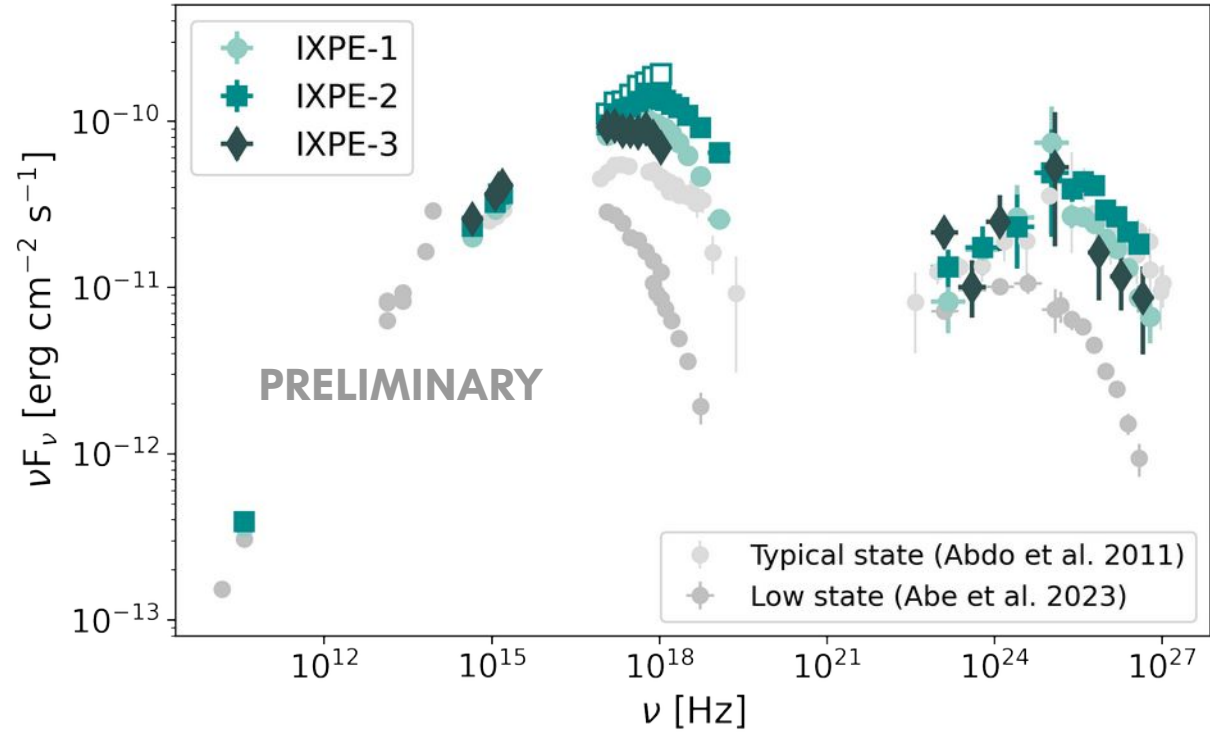
Mrk 501

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



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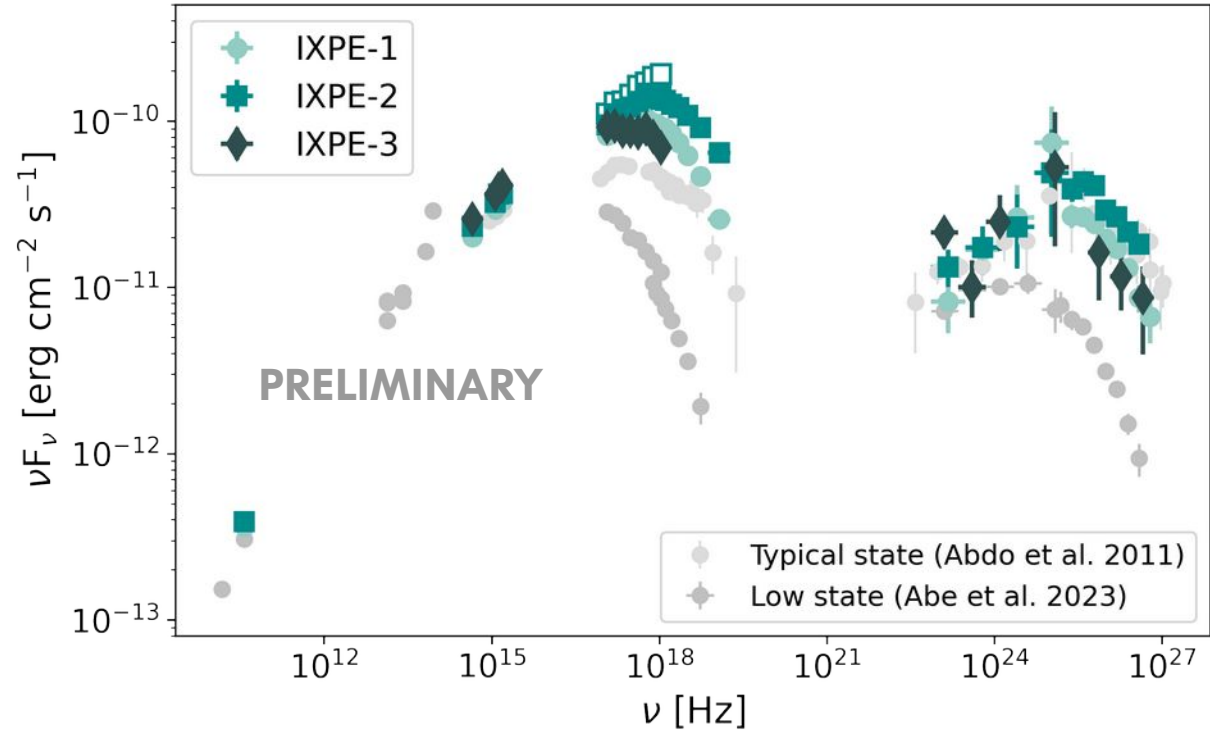
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 - Low Compton Dominance (CD)



States	ν_s [Hz]	ν_{IC} [Hz]	CD
$IXPE-1_{\text{pheno}}$	$5.4 \pm 0.2 \times 10^{17}$	$2.1 \pm 0.4 \times 10^{25}$	0.30
$IXPE-2_{\text{pheno}}$	$7.9 \pm 0.6 \times 10^{17}$	$2.5 \pm 1.1 \times 10^{25}$	0.30
$IXPE-3_{\text{pheno}}$	$9.0 \pm 7.8 \times 10^{16}$	$2.4 \pm 10.3 \times 10^{24}$	0.18
Typical _{pheno}	$2.9 \pm 0.2 \times 10^{17}$	$4.8 \pm 1.3 \times 10^{25}$	0.49
Low _{pheno}	$1.1 \pm 0.4 \times 10^{16}$	$1.5 \pm 1.0 \times 10^{24}$	0.24

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 - Shift to lower energies for IXPE-3
 - Low Compton Dominance (CD)
- Theoretical description – two zones
 - Compact region:
 - Dominating in the X-ray/VHE
 - Extended region:
 - Dominating at lower energies
 - Stretches further along the jet



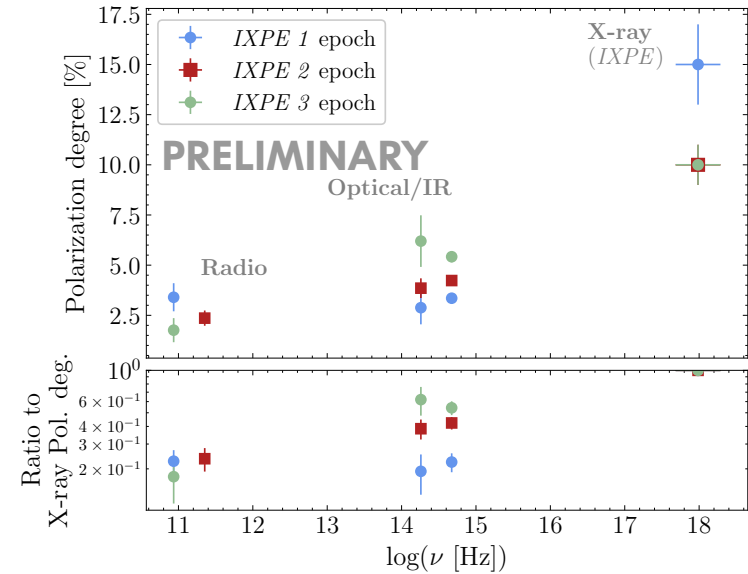
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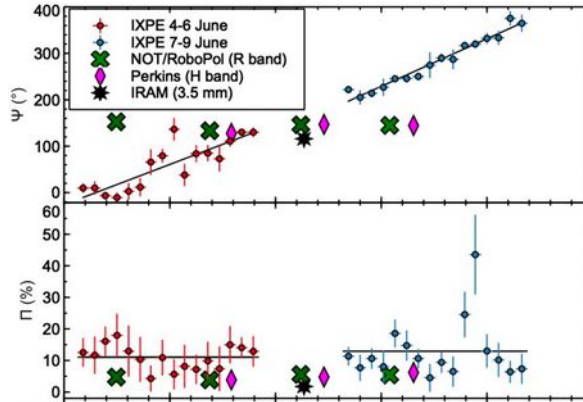
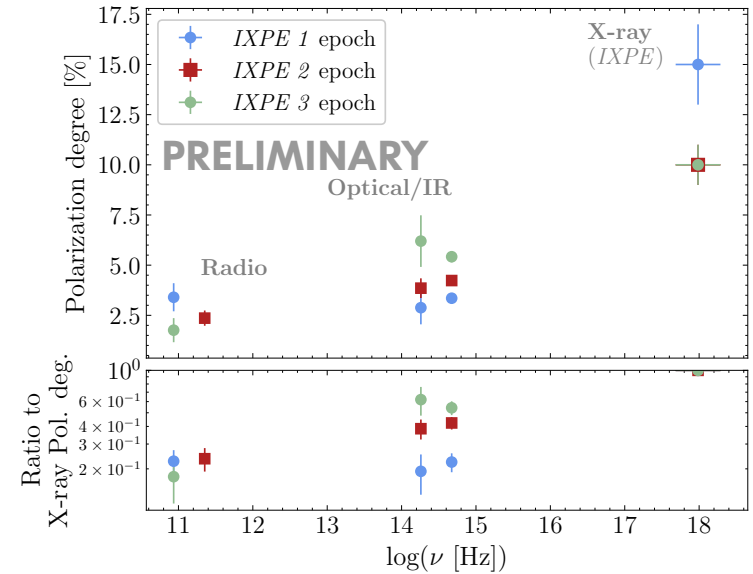
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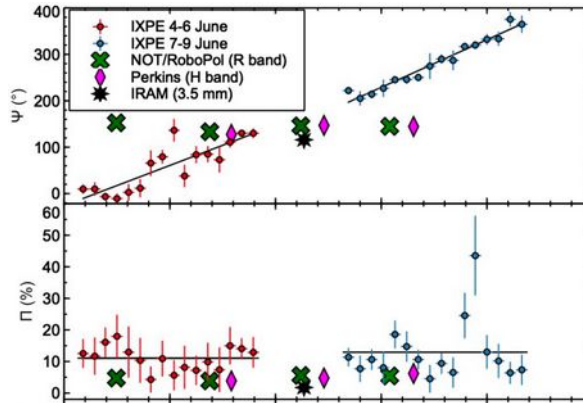
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29 - 08 - 2023

Mrk 421

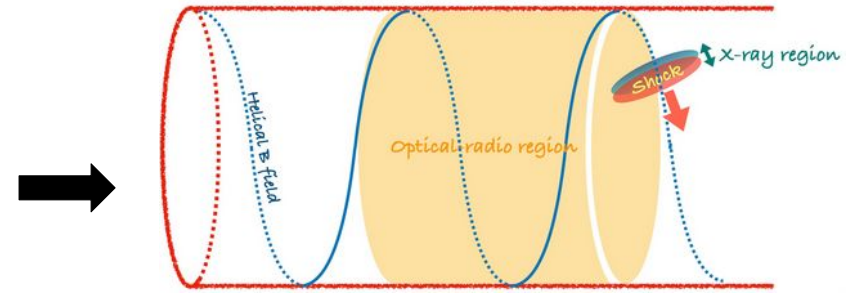
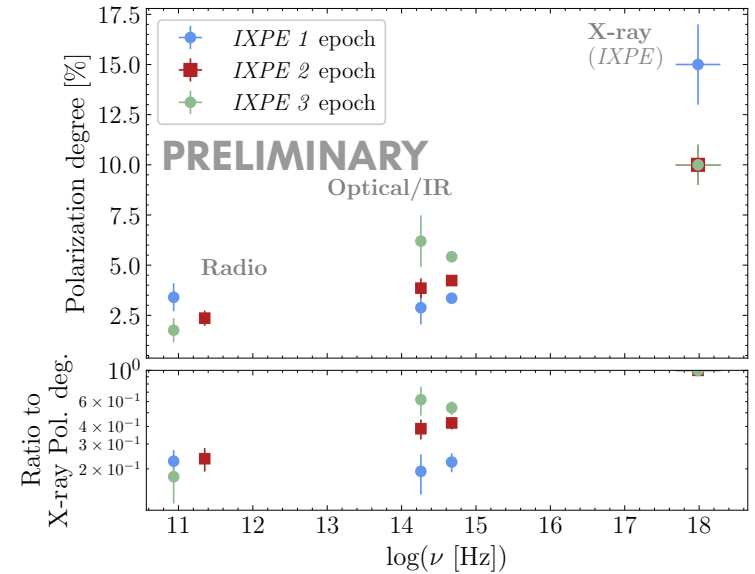
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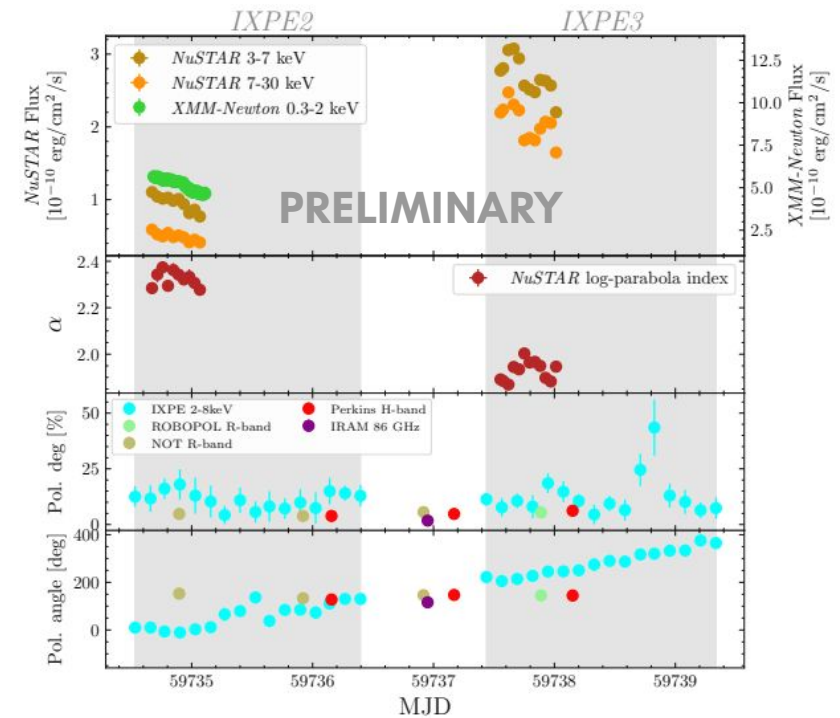
X-ray emission zone on helical path
→ Detached from optical/radio zone

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 - Low, average & enhanced states
 - Significant correlation between VHE and X-rays
 - VHE co-spatial to region where rotation is seen

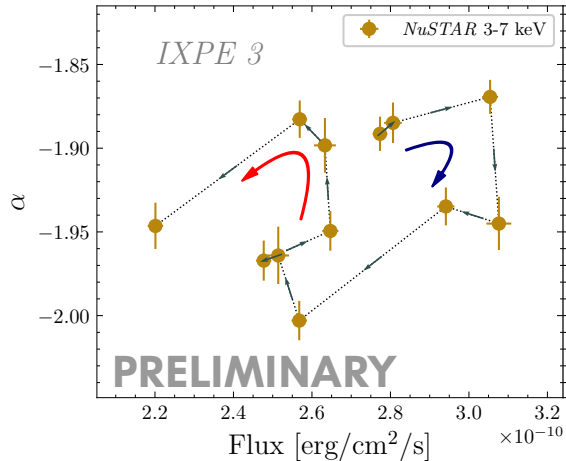
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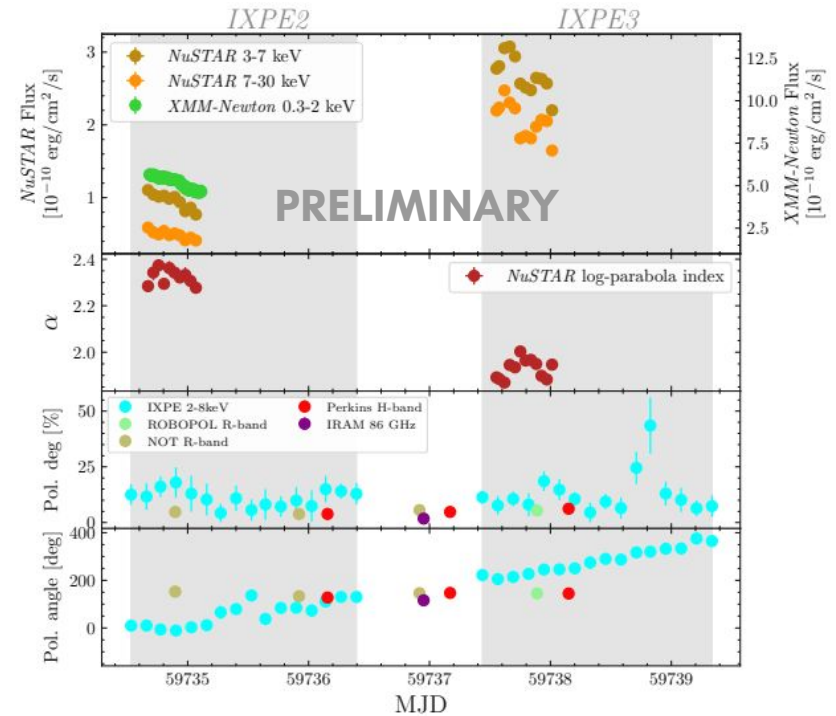


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- Evidence of spectral hysteresis:
 - First clock-wise (soft lag = LE lags behind HE):
 - Delay by synchrotron cooling
 - Then counter clock-wise (hard lag = HE behind LE):
 - Acceleration time scale \sim cooling time scale



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 mechanism**, 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
→ Constrains on geometry/magnetic field/electron distributions,...
 - VHE co-spatial to X-ray region → X-ray polarization also constrains at the highest energies

Thank you for your attention!

