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

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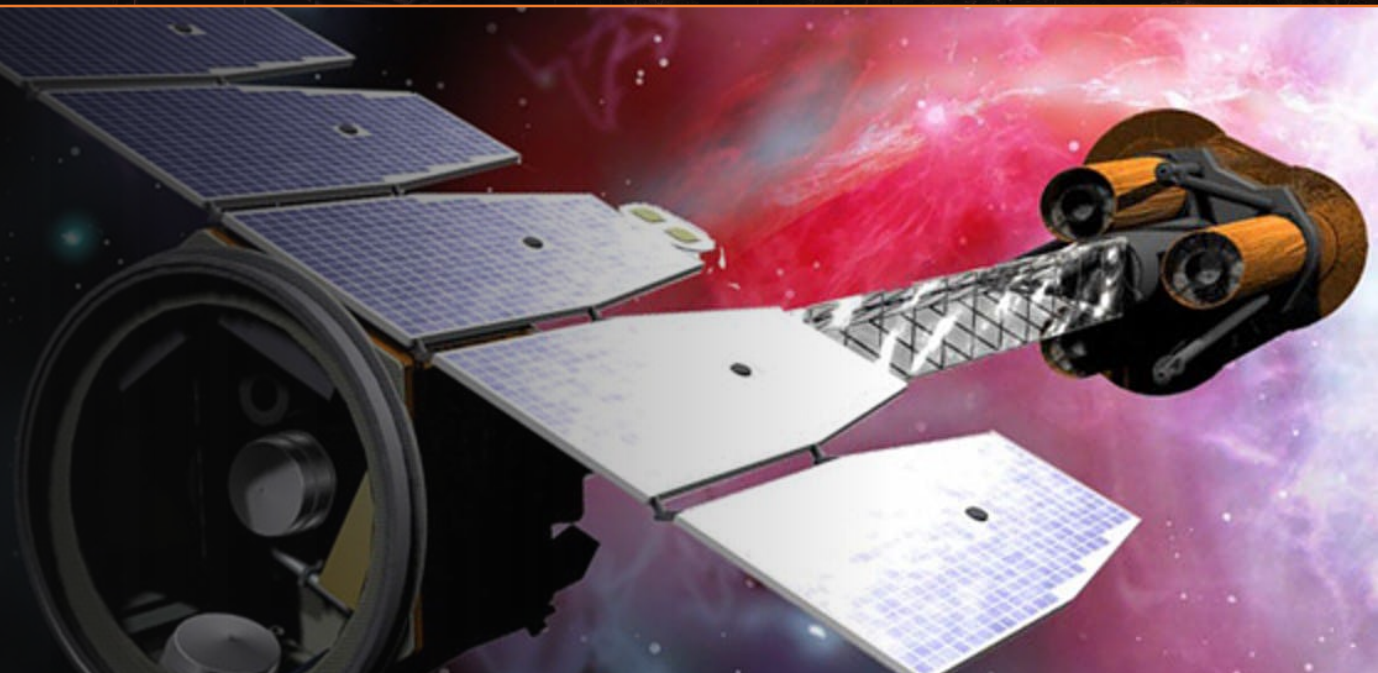
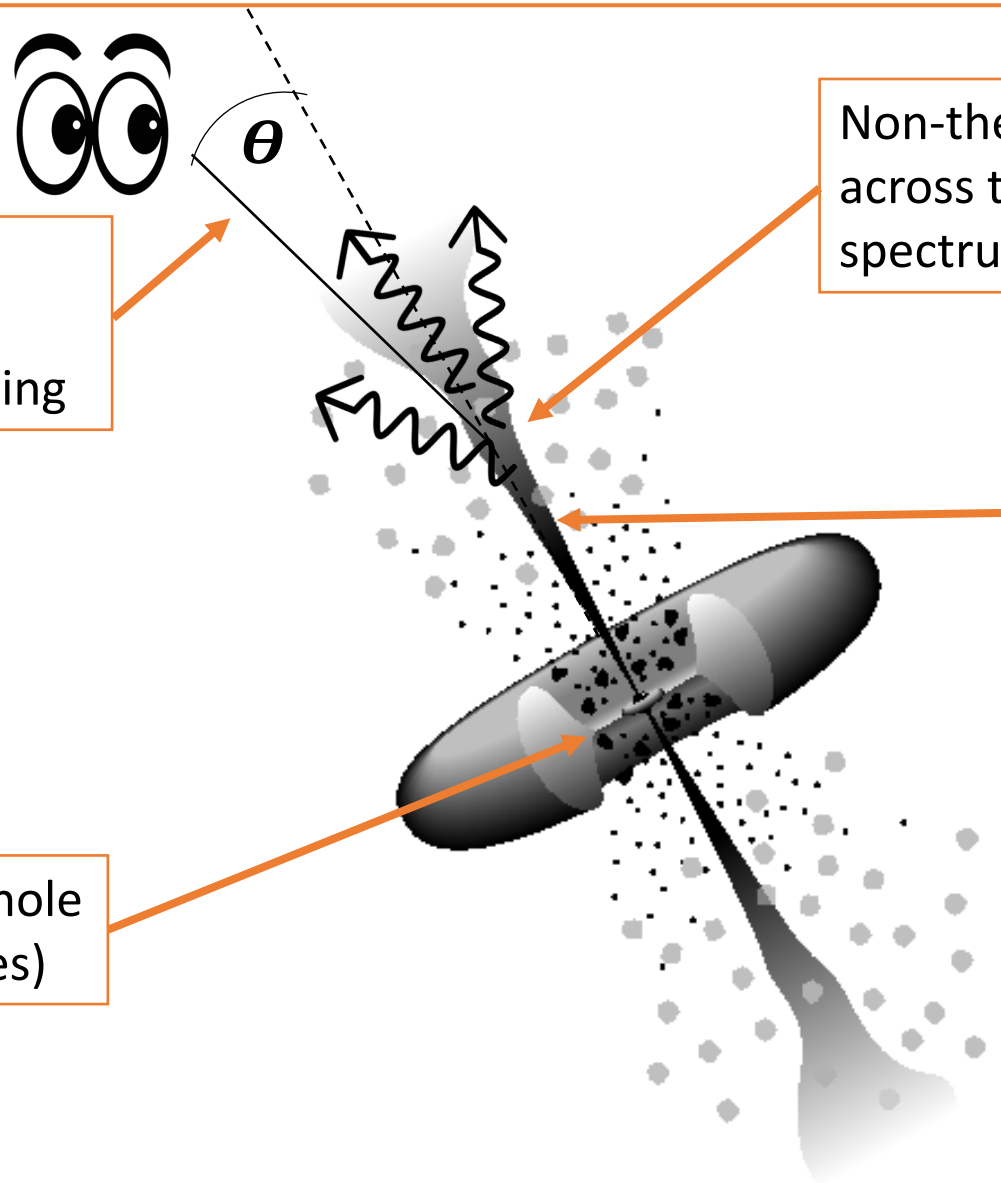
for the MAGIC collaboration and MWL partners

TeVPA 2023 - Naples



Introduction & background

Blazars



Observed at small viewing angle (< 10°)
→ Strong relativistic beaming

Non-thermal emission across the full EM spectrum: Radio to > TeV

Relativistic plasma jet
pc – Mpc scale

Super massive black hole
(10^6 – 10^9 solar masses)

Urry & Padovani 1995

Markarian 501 & 421 – archetypical blazars

Mrk 501 and Mrk 421 are **nearby** (z ≈ 0.034 / 0.031) and **very bright** BL Lac type objects:

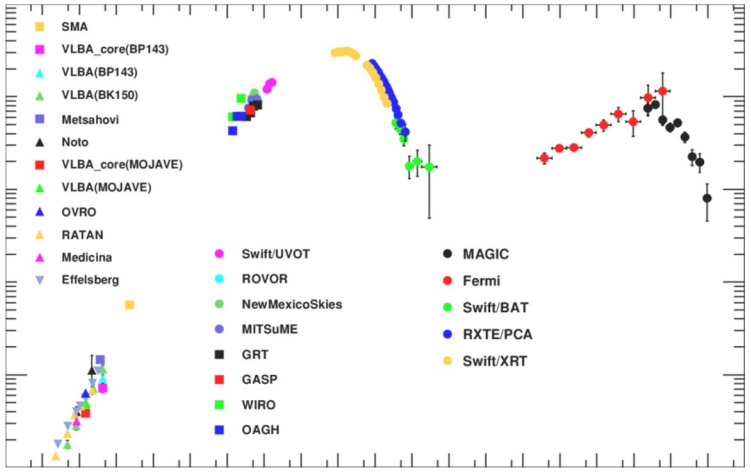
→ Ideal high-energy “laboratories” to study blazars

Both are high-synchroton peaked blazars ($\nu_S > 10^{15}$ Hz):

→ Low-energy SED component ranges from radio to x-ray

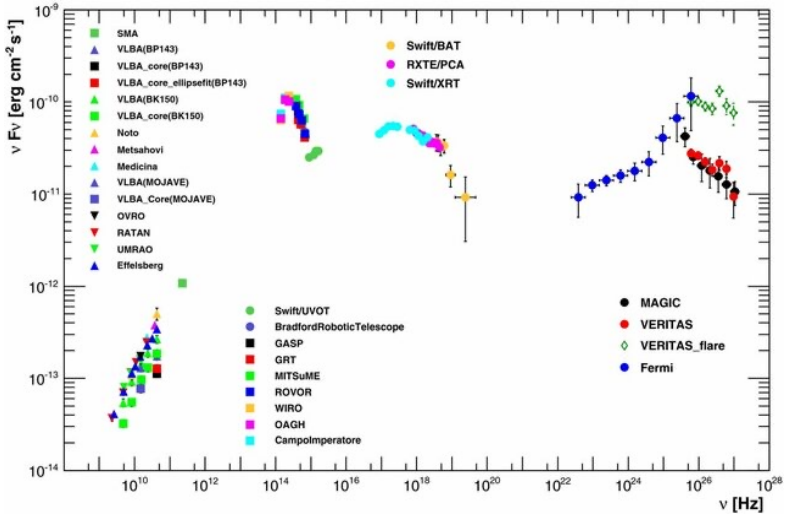
→ Originates from electron synchroton radiation

Mrk 421:



Abdo et al. 2011, ApJ, 736, 131

Mrk 501:



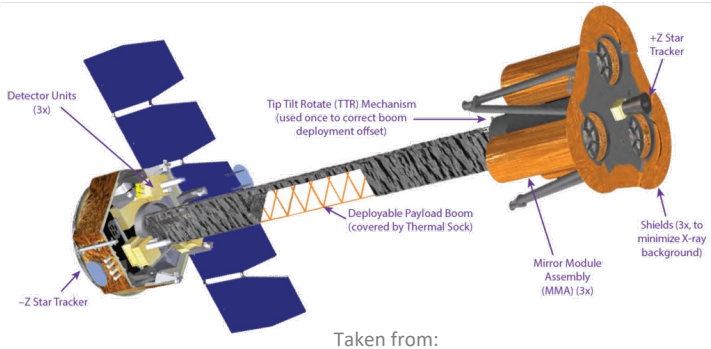
Abdo et al. 2011, ApJ 727, 129

Markarian 501 & 421 – archetypical blazars

IXPE provides the first polarization measurements in the X-ray band (2-8 keV)

→ Probes synchroton emission from the most energetic particles

→ Direct probe of acceleration mechanisms

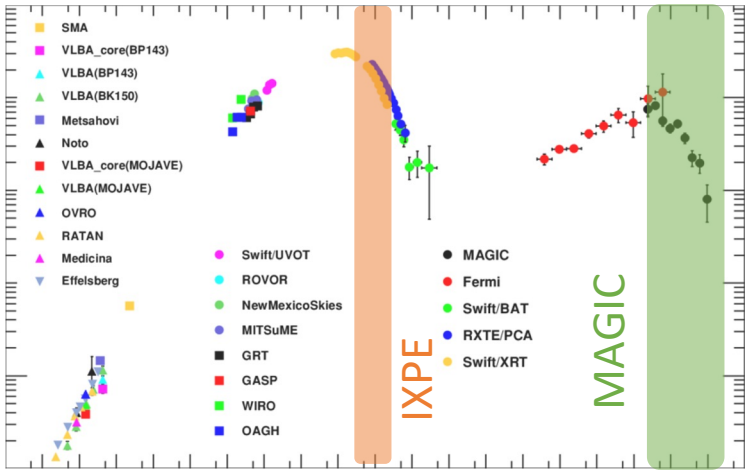


Taken from: https://wwwastro.msfc.nasa.gov/ixpe/for_scientists/presentations/20170601_huntsville.pdf

MAGIC covers the falling edge of the gamma-ray component

→ X-ray and gamma-ray pumps expected to be emitted by the same electron population due to correlated emission

Mrk 421:



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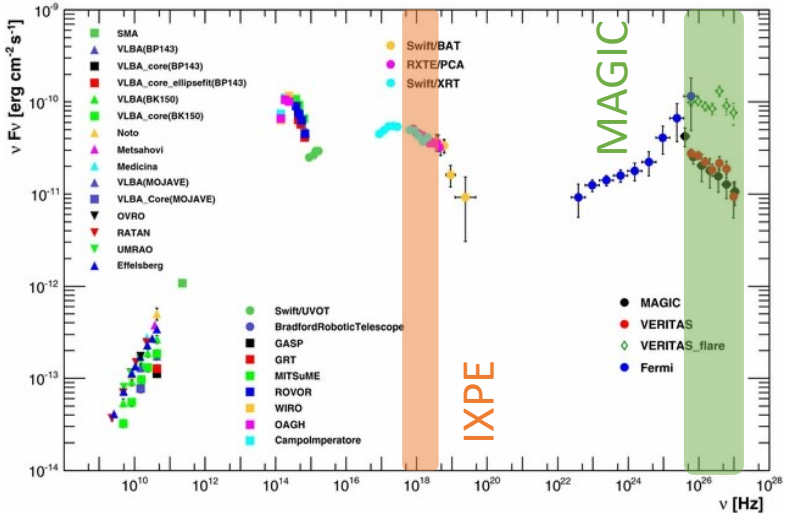
Mrk 501:



Abdo et al. 2011, ApJ 727, 129

Markarian 501

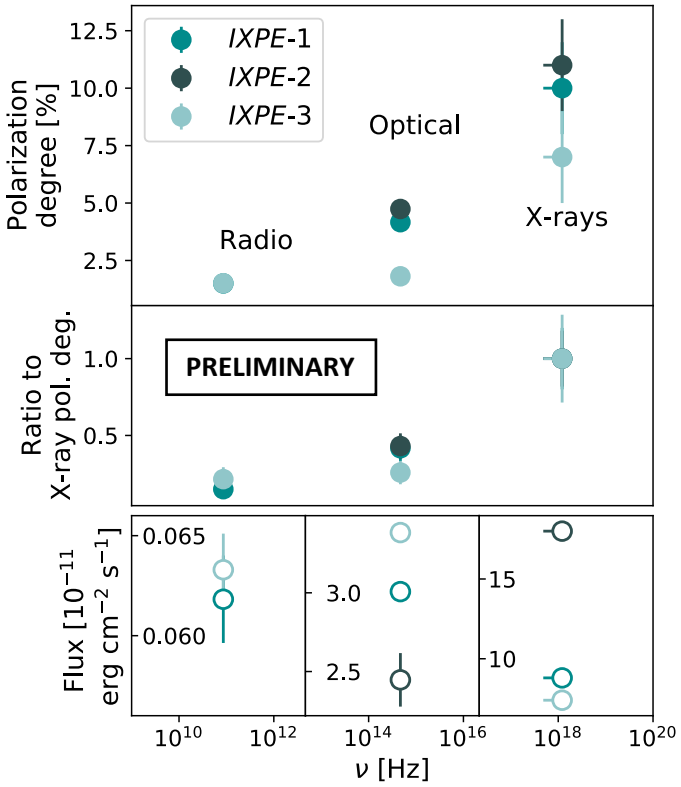
IXPE observations of Mrk 501 in 2022

IXPE 1 (8. – 10. Mar): Pol. degree of **10 ± 2%** at an EVPA of **134 ± 5°** aligned with optical/radio

IXPE 2 (27. – 29. Mar): Pol. degree of **11 ± 2%** at an EVPA of **115 ± 4°** - ’’ - Liodakis et al. 2022

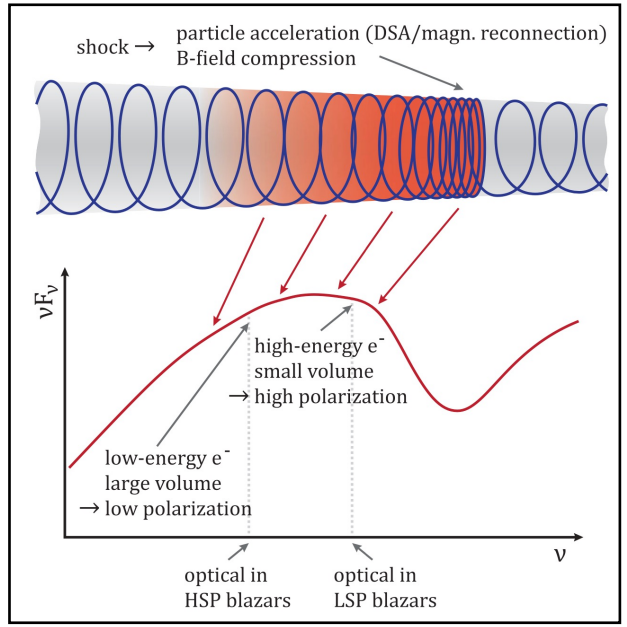
Liodakis et al. 2022

IXPE 3 (9. – 12. July): Pol. degree of **7 ± 2%** at an EVPA of **135 ± 8°** Lisalda et al., 2023 (in prep.)



→ Emission dominating high frequencies produced in regions with a higher degree of ordered magnetic field

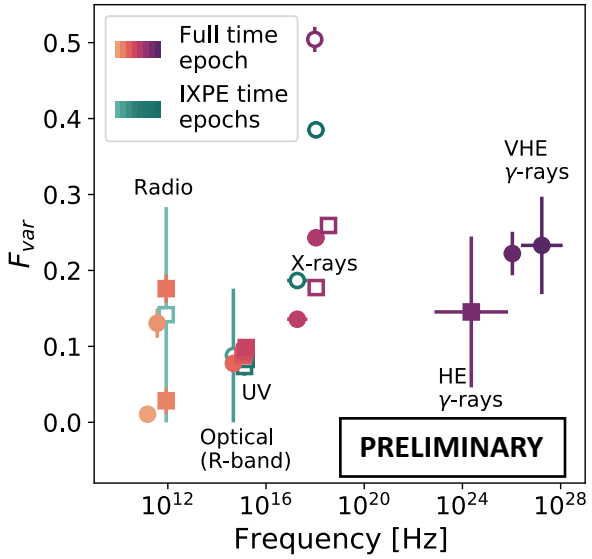
→ This may be explained by shock acceleration in energy-stratefied jet

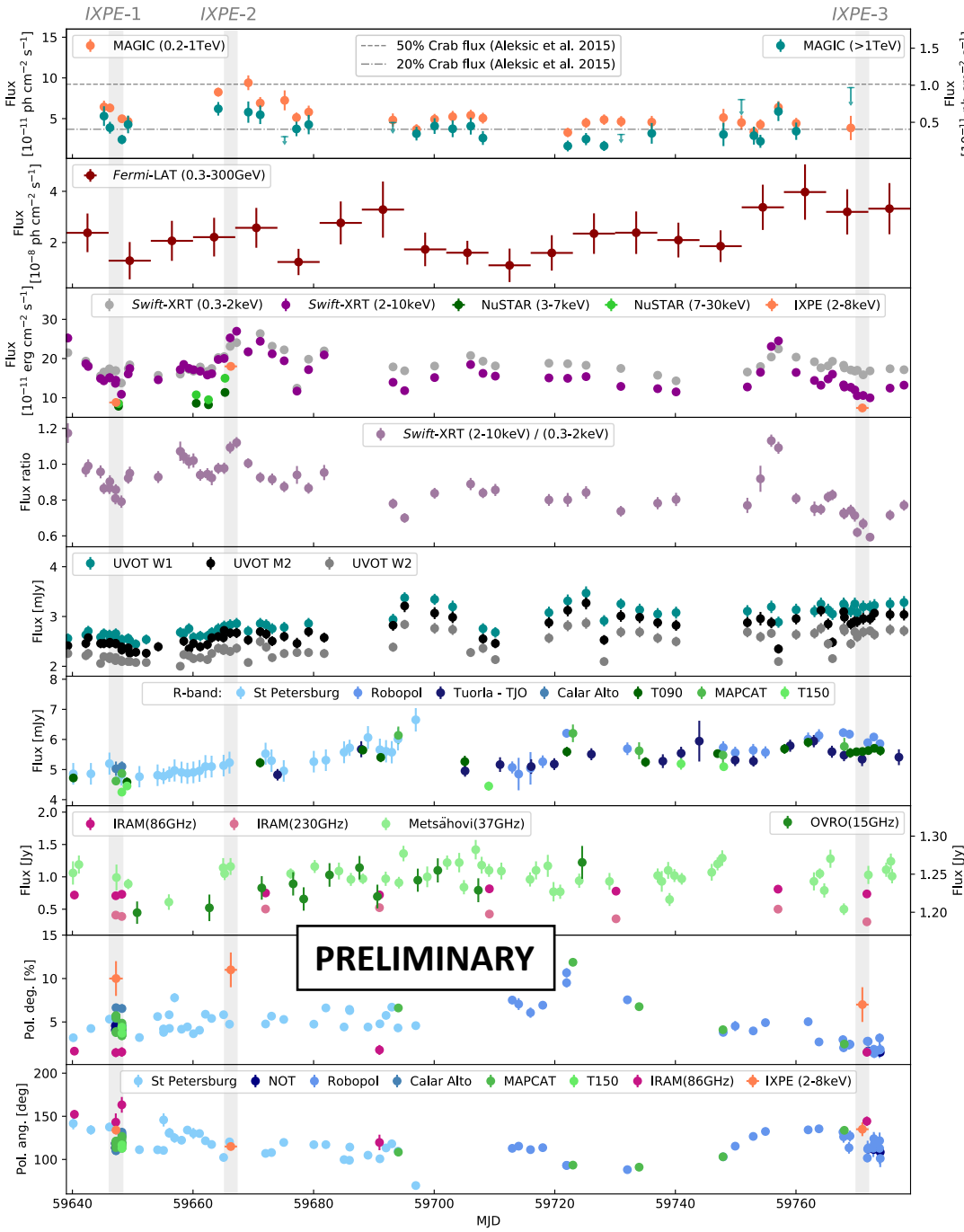


Angelakis et al. 2016

MWL light curves – Mrk 501

- We cover the period from March – July 2022
- We see typical behavior with moderate variability throughout the campaign





MAGIC (> 1 TeV)
MAGIC (0.2-1 TeV)

Fermi-LAT

Swift-XRT
NuSTAR
IXPE

Swift-UVOT

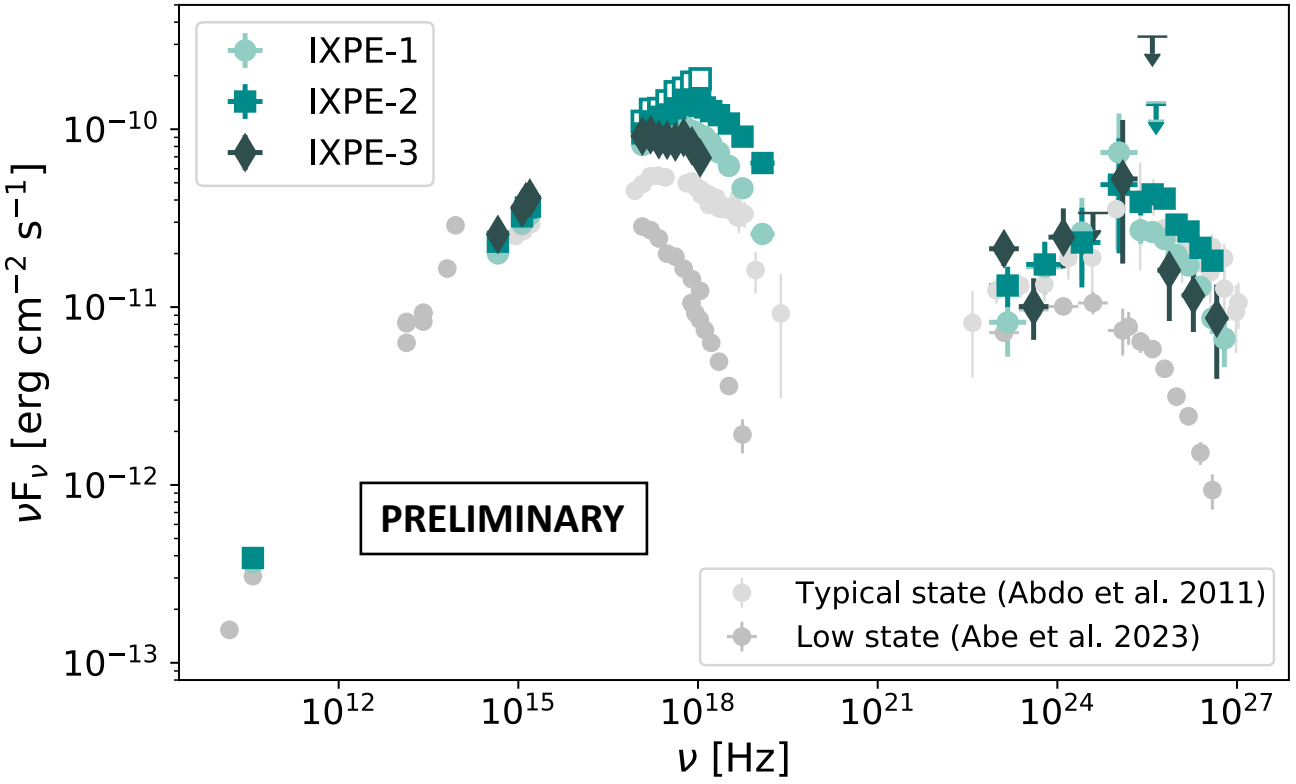
Optical

Radio

Pol. degree (radio, optical, X-ray)

Pol. angle (radio, optical, X-ray)

Boradband SEDs



→ Enhanced activity in the synchroton peak

→ Low compton dominance; Gamma-ray component close to average state

→ Unusally high synchroton peaked blazar ($\boldsymbol{\nu}_S > 10^{17}$ Hz) behavior revealed for IXPE 1 & IXPE 2

Two zone model

- Polarization behavior points towards an energy-stratified jet (→ multiple emission zones)
- Assume two emission zones:

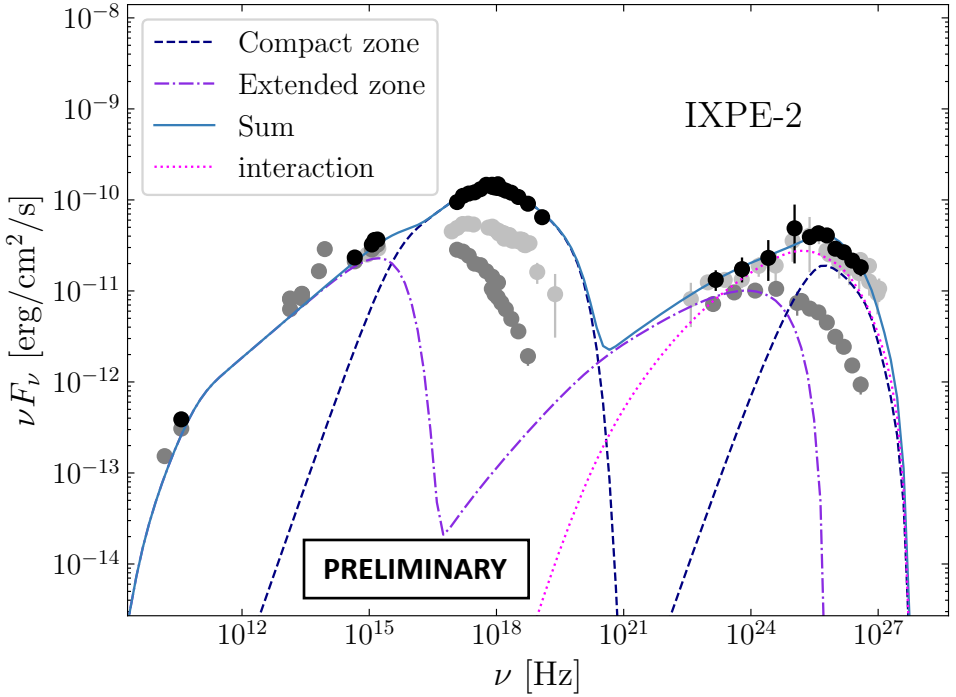
  → **Compact zone:** Nearby shock front; dominates X-ray and gamma-ray emission

  → **Extended zone:** Larger extent downstream the shock; dominates the optical/UV emission

- Spectral shape of the electron energy distribution in agreement with shock acceleration

- Compact model alone underpredicts the UV emission

→ Multiple emission zones are needed!



Summary – Mrk 501

We see increasing polarization degree with frequency:
→ Favors a shock in energy stratefied jet model
→ Makes magnetic reconnection in turbulent fields less suitable

We assume multiple emission zones in an energy stratefied jet:
→ Two zone model with an *extended* and a *compact* zone
→ Strong constraints on the electron distribution nearby the shock front;
Great description of data achieved

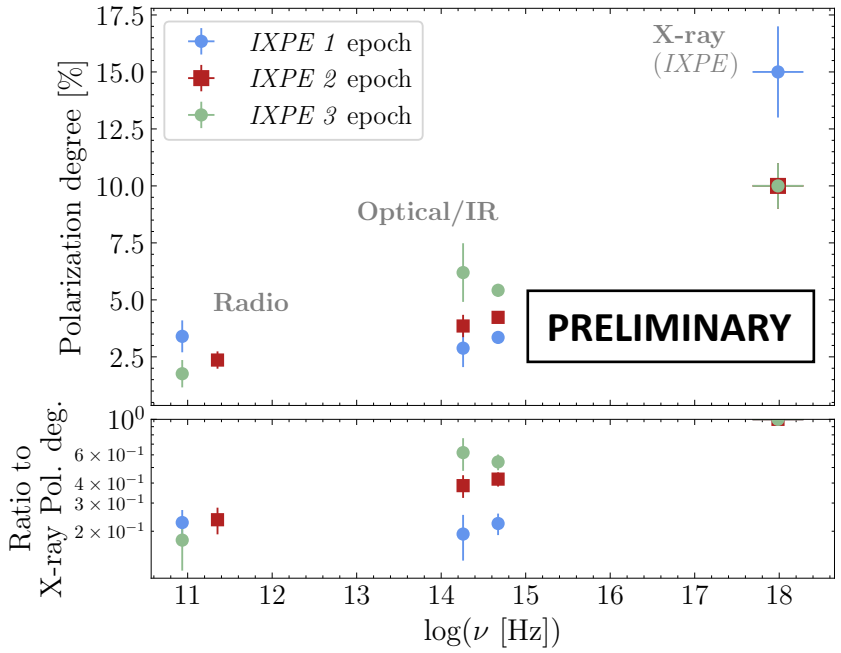
Markarian 421

IXPE observations of Mrk 421 in 2022

IXPE 1 (4. – 6. May): Pol. degree of **15 ± 2%** at an EVPA of **35 ± 4°** Di Gesu et al. 2022

IXPE 2 (4. – 6. June): Pol. degree of **10 ± 1%** and EVPA rotation of **81 ± 9 °/day** Di Gesu et al. 2023

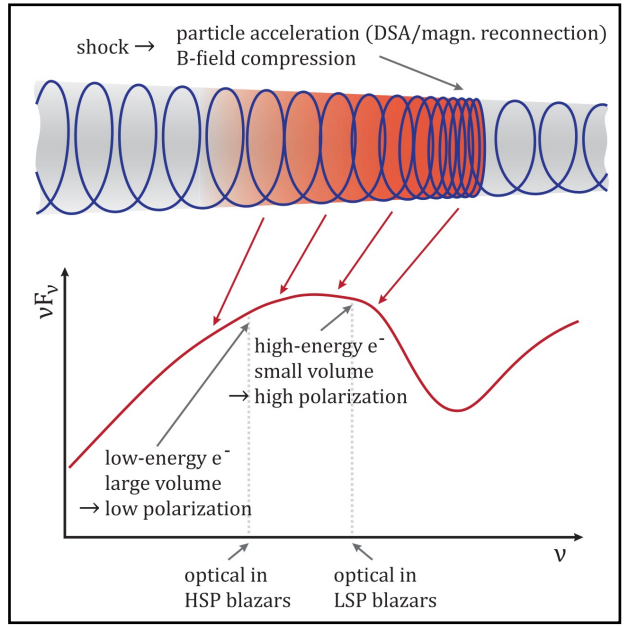
IXPE 3 (7. – 9. June): Pol. degree of **10 ± 1%** and EVPA rotation of **88 ± 8 °/day** Di Gesu et al. 2023



Similar to Mrk 501:

→ Emission dominating high frequencies produced in regions with a higher degree of ordered magnetic field

→ This may be explained by shock acceleration in energy-stratefied jet



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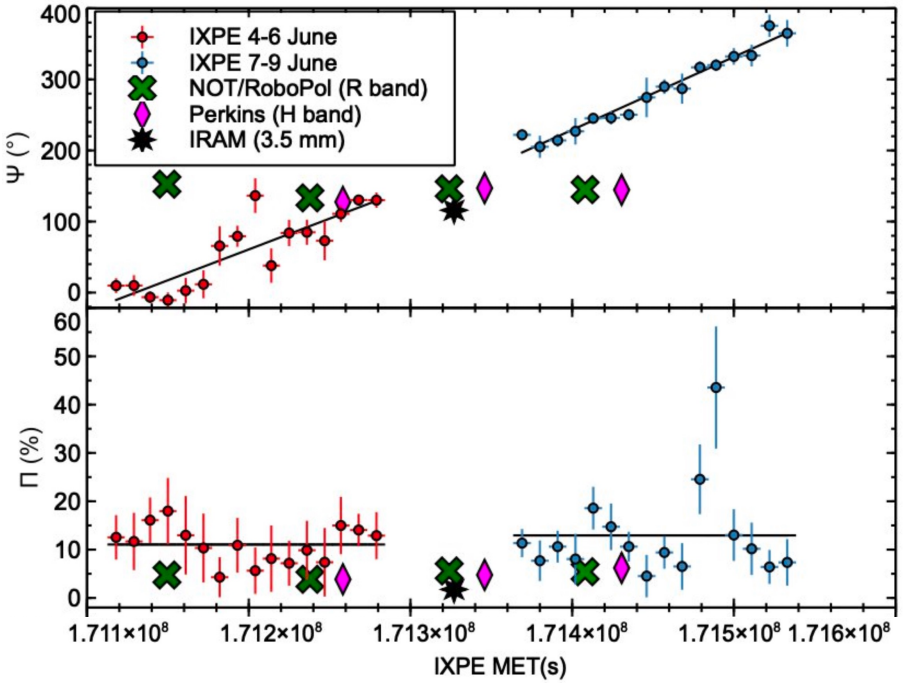
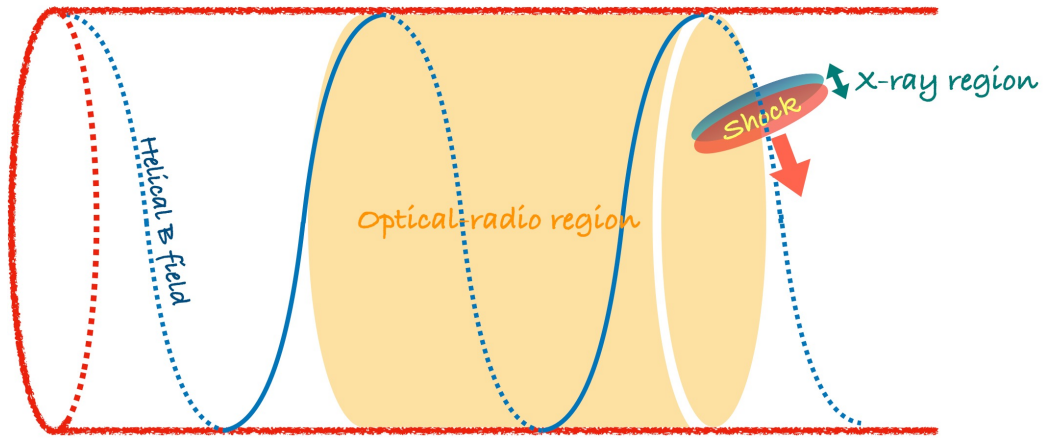


Di Gesu et al. 2023

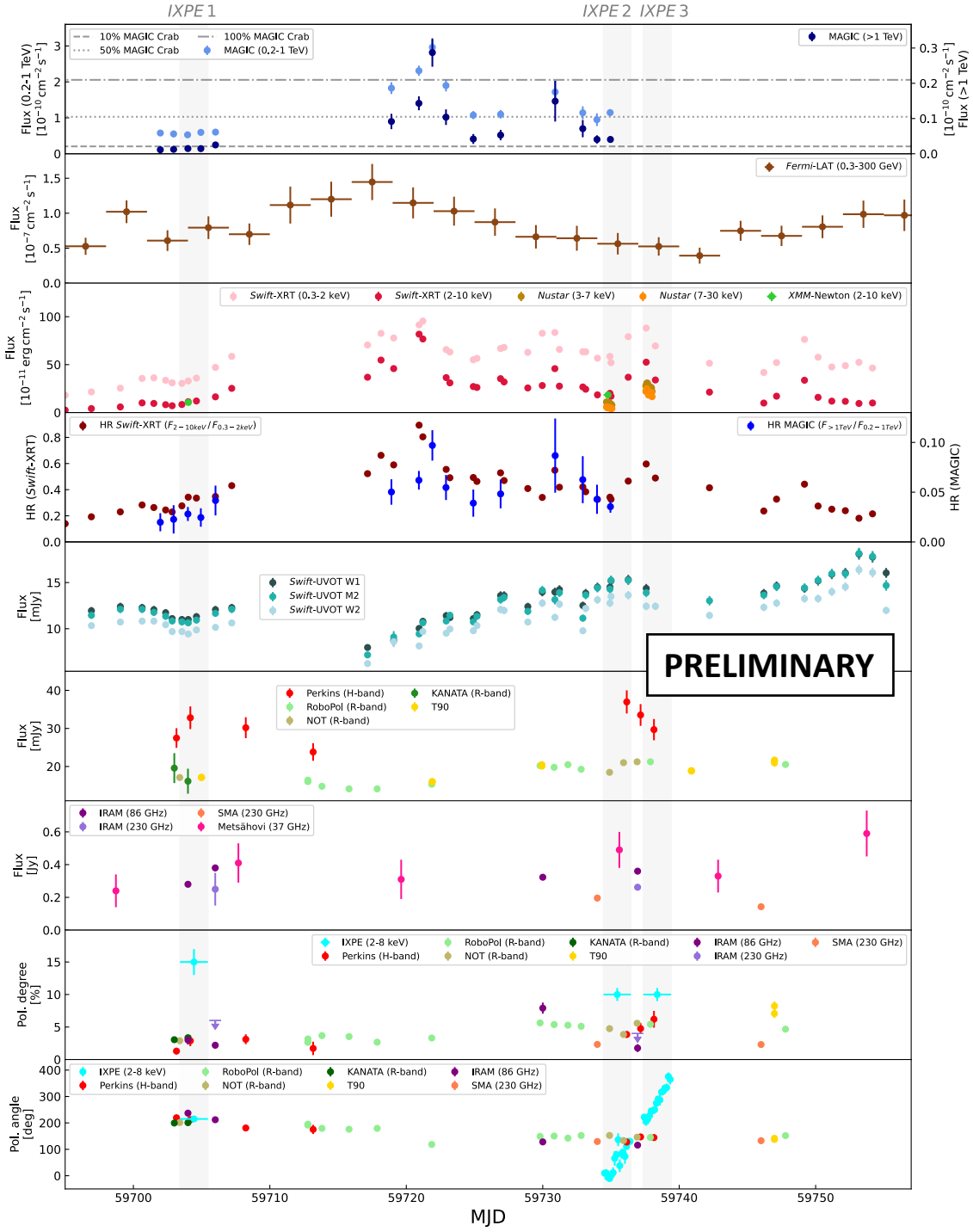


Di Gesu et al. 2023

→ Emission zone follows helical path
→ Detached from optical/radio emission zone

MWL light curves – Mrk421

- We cover the period from May – June 2022
- We complement the VHE + IXPE observations with detailed coverage in X-rays and polarization measurements in optical and radio



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Pol. degree (radio, optical, X-ray)

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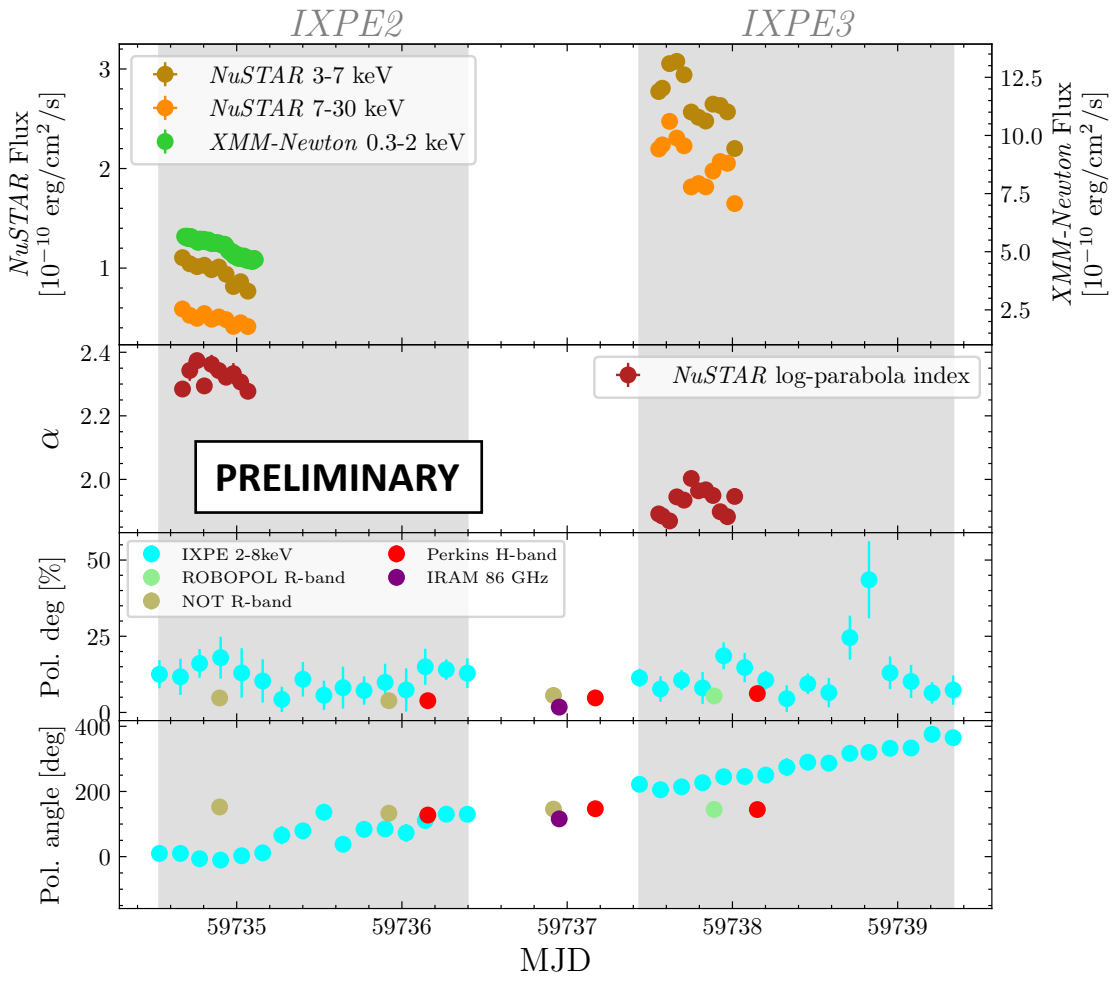
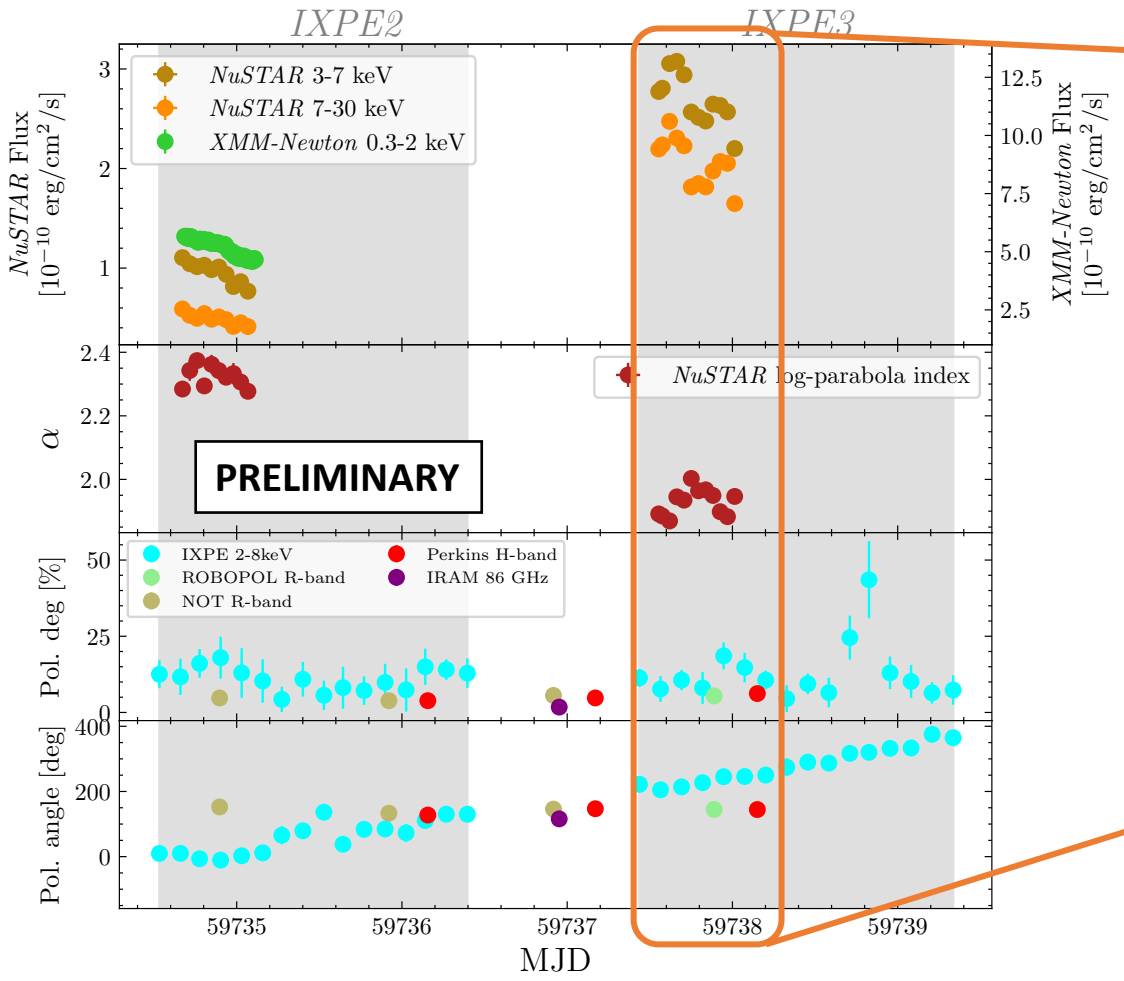
X-ray variability during IXPE 2 & 3

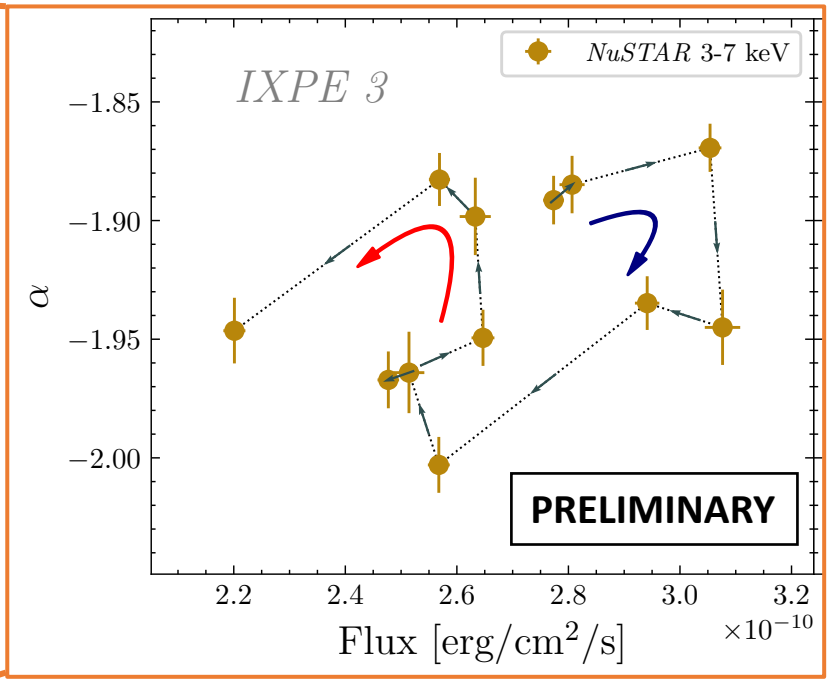


→ NuSTAR observations show significant variability of the flux and spectral shape during polarization angle rotation on ~1h timescale

X-ray variability during IXPE 2 & 3



NuSTAR 1h bins:



Evidence of spectral hysteresis:

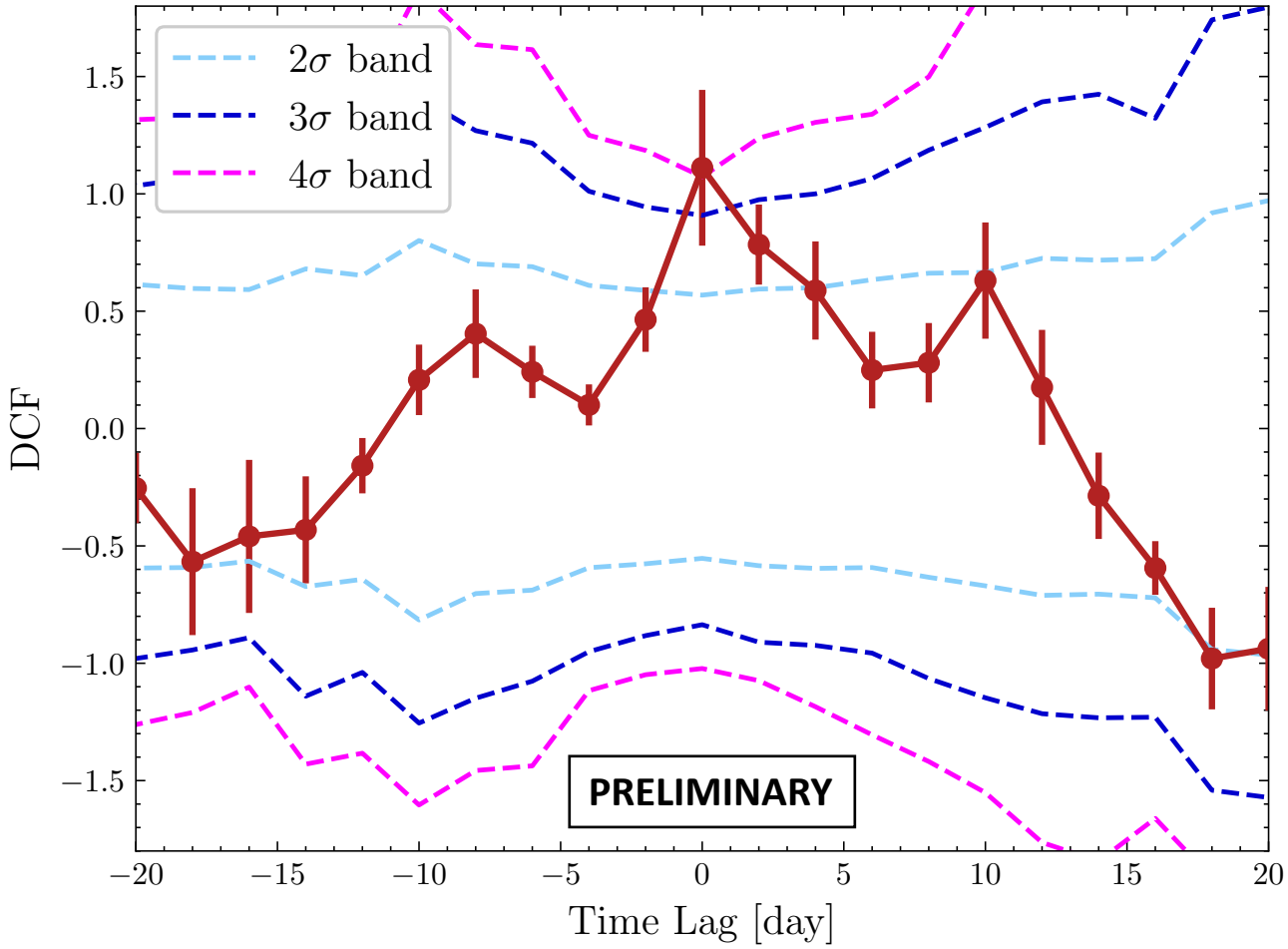
→ Suggests time delay between the emission of different energy bands

→ Clock-wise (LE lags behind HE) & counter clock-wise (HE behind LE) patterns observed

VHE vs X-ray correlation

→ Using the full campaign, there is significant correlation between VHE and X-ray emission (~4σ)

→ VHE emission is likely co-spatial to X-ray, close to the shock front



DCF for the full LC of VHE (0.2−1TeV) and Swift-XRT (2-10keV)

Summary – Mrk 421

We see increasing polarization degree with frequency:
→ Favors a shock in energy stratefied jet model
→ Makes magnetic reconnection in turbulent fields less suitable

We see increased activity in the X-rays during the EVPA rotation:
→ EVPA rotation in X-rays might be correlated to states of higher activity in BL Lacs
→ Hysteresis pattern points towards rapid change of acceleration efficiency

We see a correlation between X-ray + VHE gamma rays:
→ X-rays and VHE likely produced in the same region

Conclusion

→ First full MWL campaigns (from radio to TeV) simultaneous to IXPE observations performed

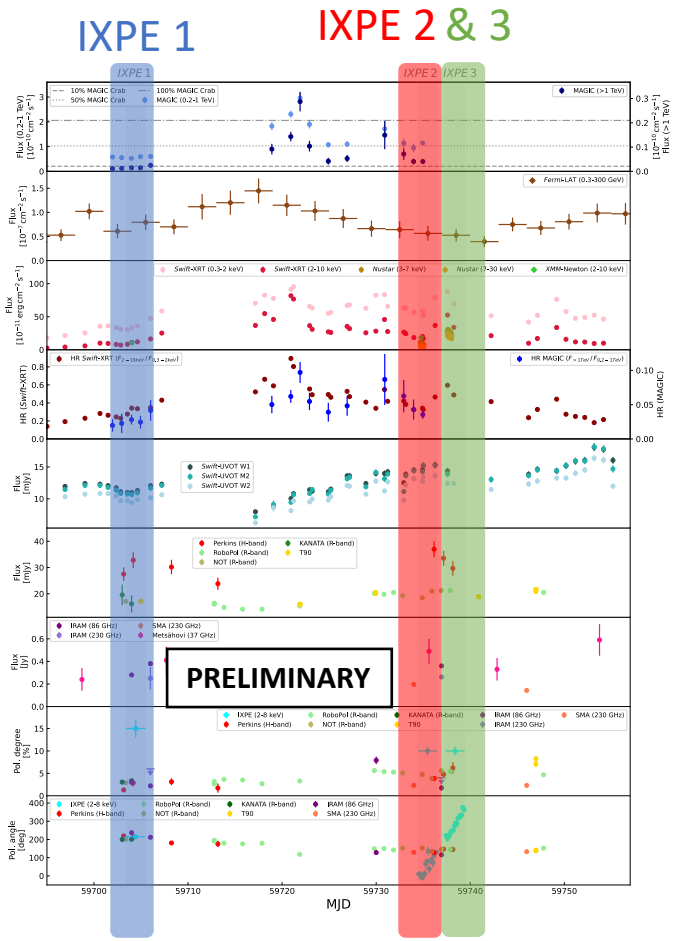
→ Additional IXPE observations, together with MWL coverage, planned in the near future. Many more results expected within the next years!

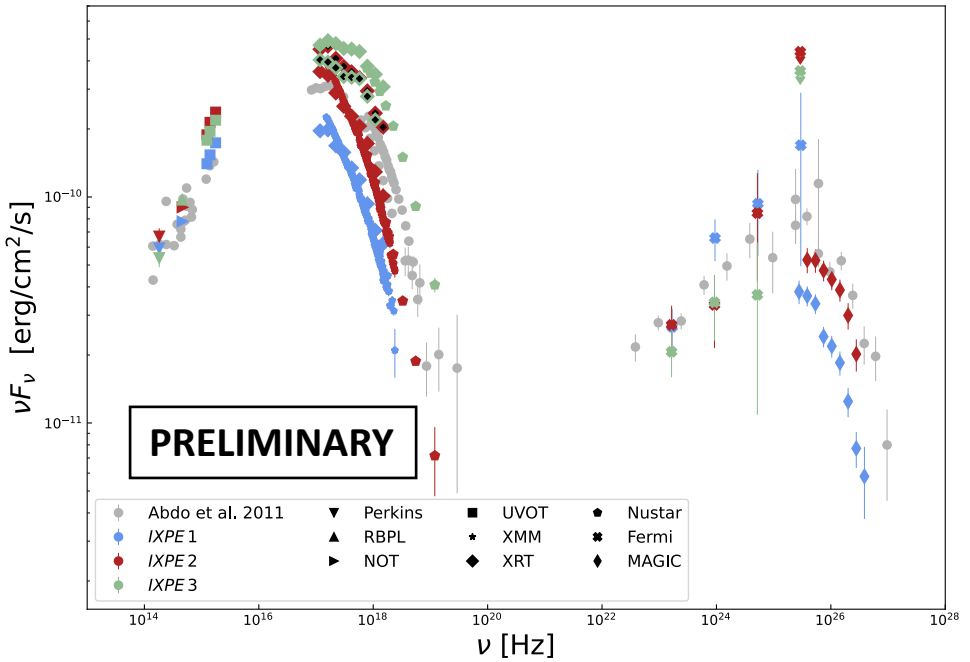
Thank you for your attention!

Interested in proposing observations with MAGIC ? Next MAGIC observing call (Cycle-19) will come very soon. It will be posted here: https://magic.mpp.mpg.de/public/magicop/ (Deadline for submitting proposals in the end of October or beginning of November)

Backup

Multi-wavelength emission – Mrk421





→ Low activity during IXPE 1; VHE (0.2-1TeV) around 25% Crab

→ Average activity at start of IXPE 2; VHE around 50% Crab

→ Source in enhanced state; high activity and variability in X-ray; No VHE data…

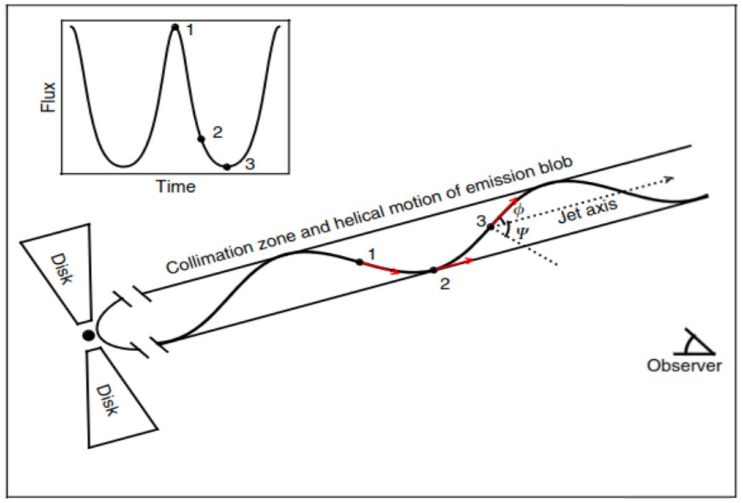
X-ray variability during IXPE 2 & 3 – Mrk421

Possible scenario of movement of blob in a helical path:

- Change of doppler factor depending on viewing angle
- Expect very strong modulation: $F_{obs} \propto \delta^3 F_{intr}$
- In contrast to observations?

→ Expected variability amplitude in agreement with NuSTAR data assuming typical values from blazar modelling

(i.e. jet viewing angle of 0.5deg and an emitting zone with Lorentz factor 20)



Sketch credits: Zhou et al. 2018