MAX-PLANCK-INSTITUT FÜR PHYSIK

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

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

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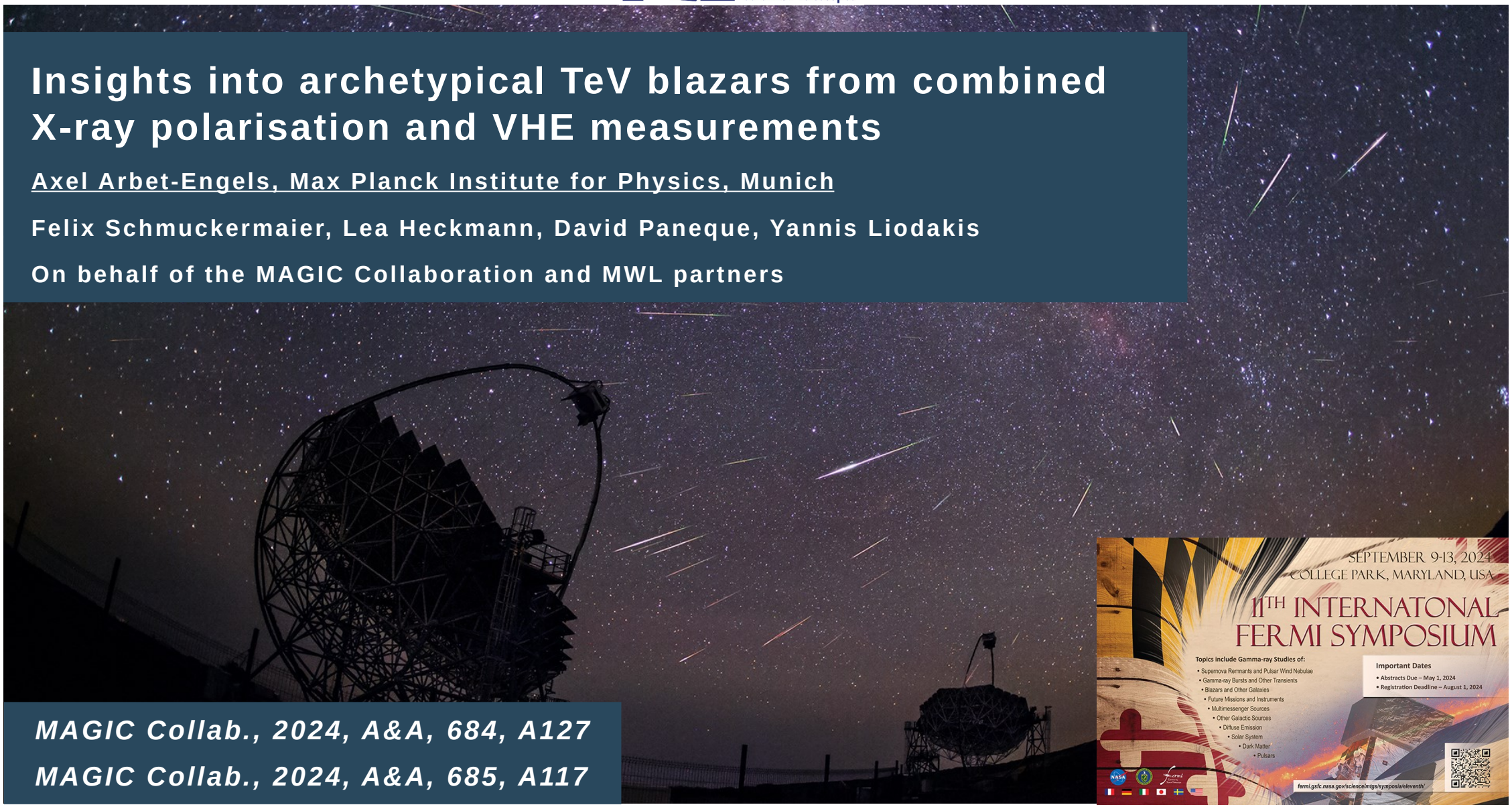
On behalf of the MAGIC Collaboration and MWL partners



MAGIC Collab., 2024, A&A, 684, A127

MAGIC Collab., 2024, A&A, 685, A117

Image credits: Daniel Lopez

A new view on blazar emission

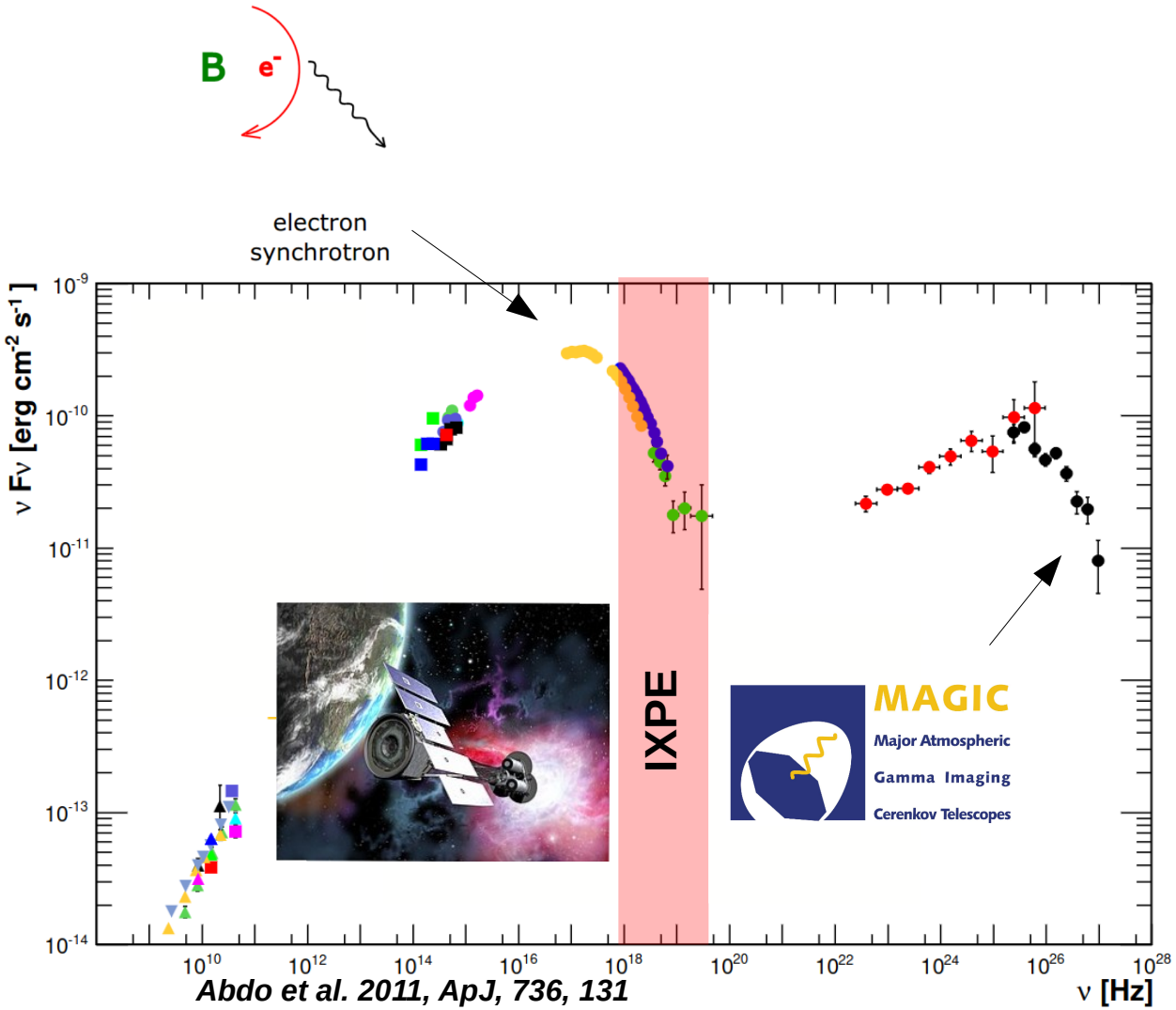
- ***IXPE :*** **first measurements of X-ray polarization (2-8 keV) in jets**

- **In HBLs, *IXPE* probes the 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 / VHE correlation suggests common emitting particles**

  (MAGIC Collab. A&A 655, A89 2021,
  Acciari et al, 2021, MNRAS, 504, 1427
  Abe et al., 2023 ApJS 266 37)



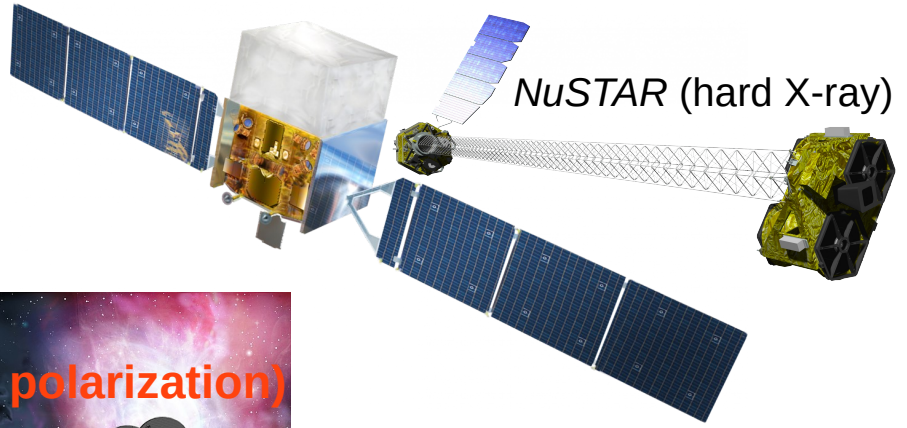
Extensive multi-wavelength campaigns on Mrk421 & Mrk501

- **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

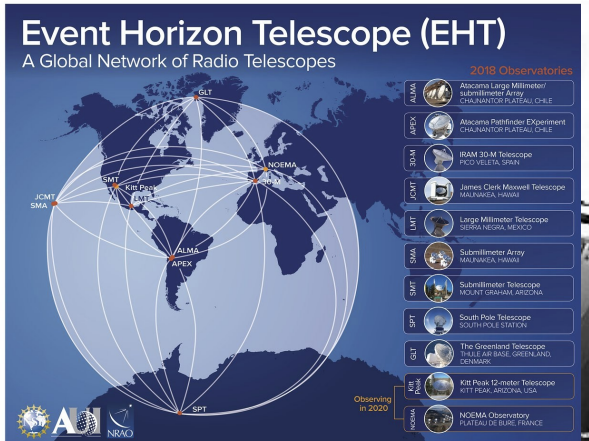
- **In 2022: Campaign with IXPE**

Fermi-LAT (MeV-GeV)



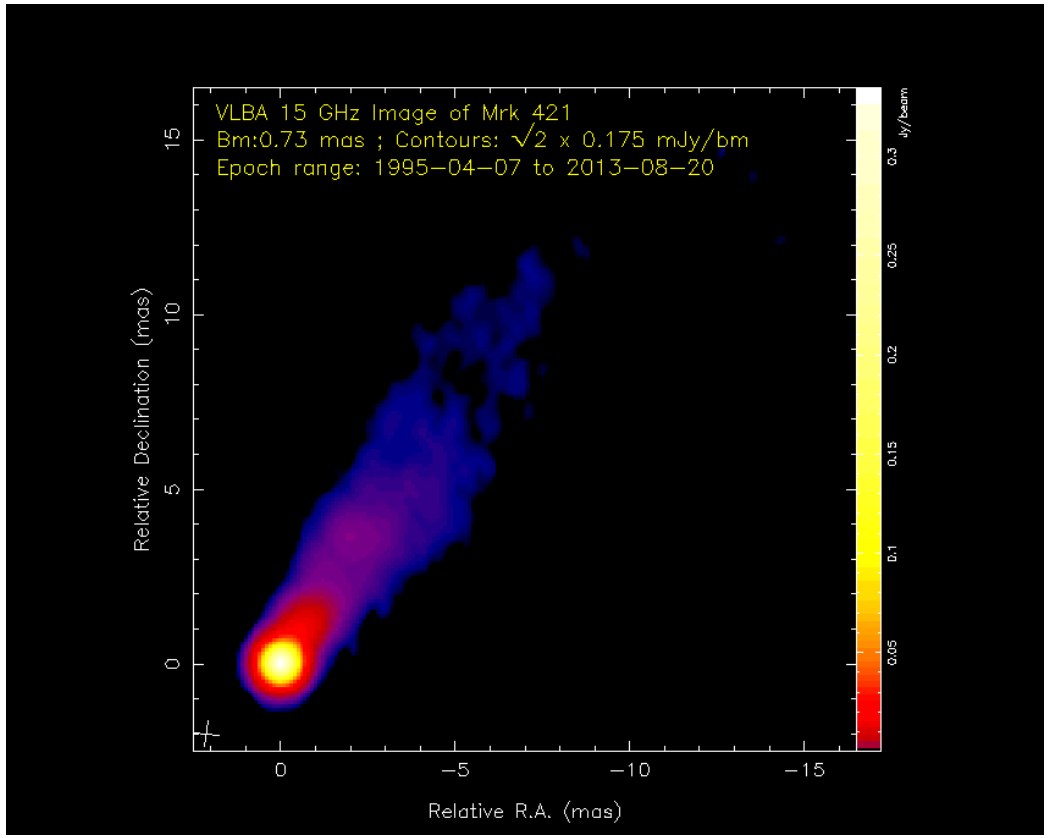
NuSTAR (hard X-ray)

Swift (UV/X-ray)



And many more...

Markarian 421 (Mrk421)



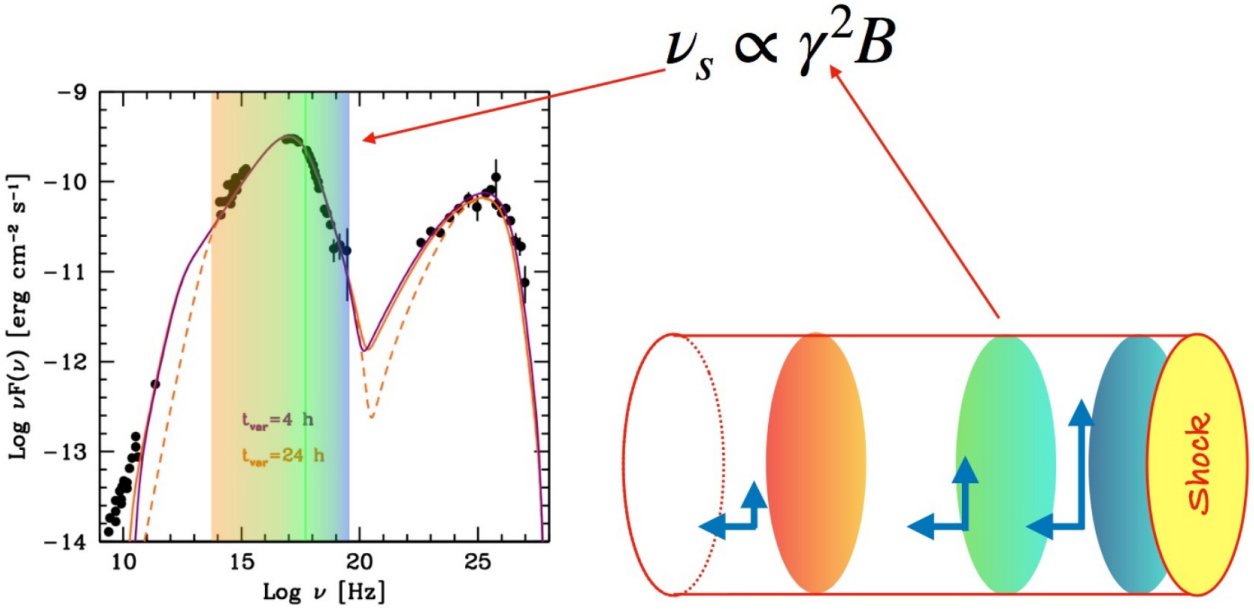
Credits: MOJAVE team

IXPE observations during 2022

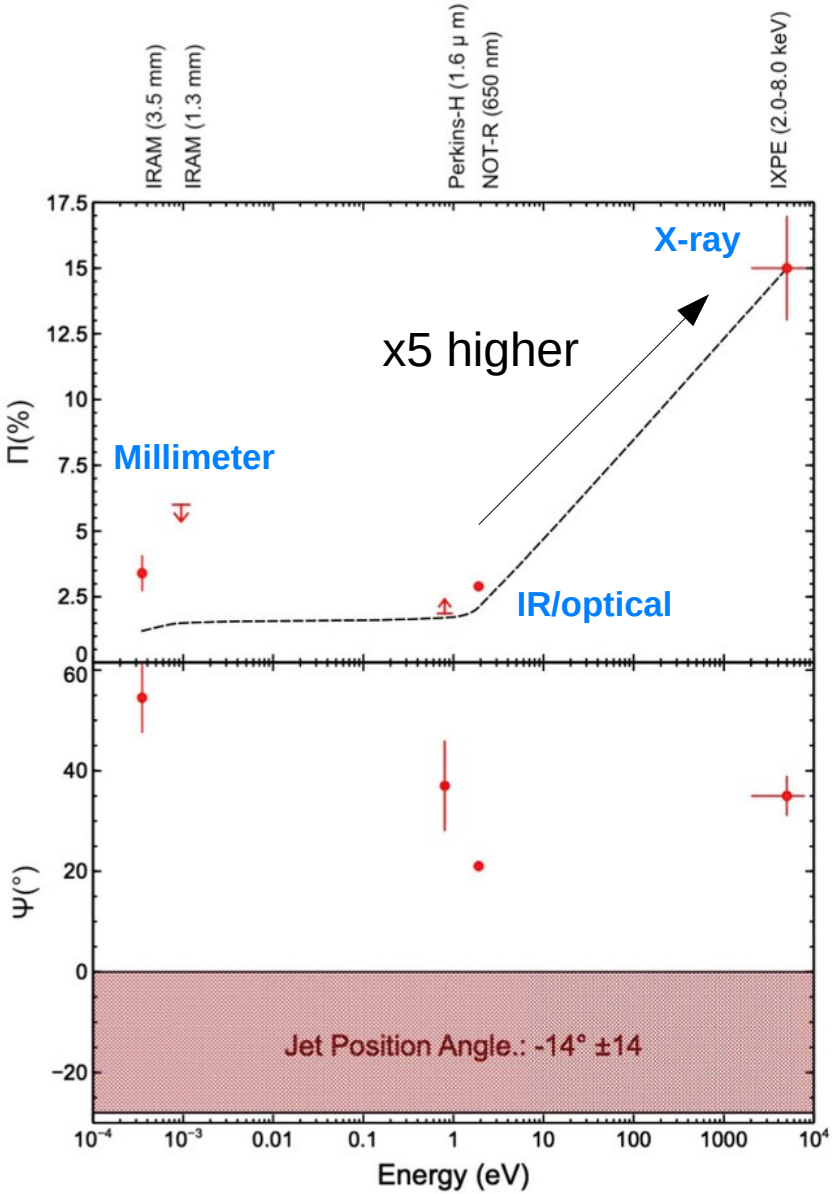
- **1st IXPE observation: 4th-6th May 2022**
  (Di Gesu et al. 2022)

  - *Polarization degree:* ~**15%**
  - *Polarization angle:* ~**35deg, aligned with optical/IR/millimeter**
  - **No significant variability in polarization properties**

  → **Shock acceleration in energy stratified jet**



Tavecchio, 2021



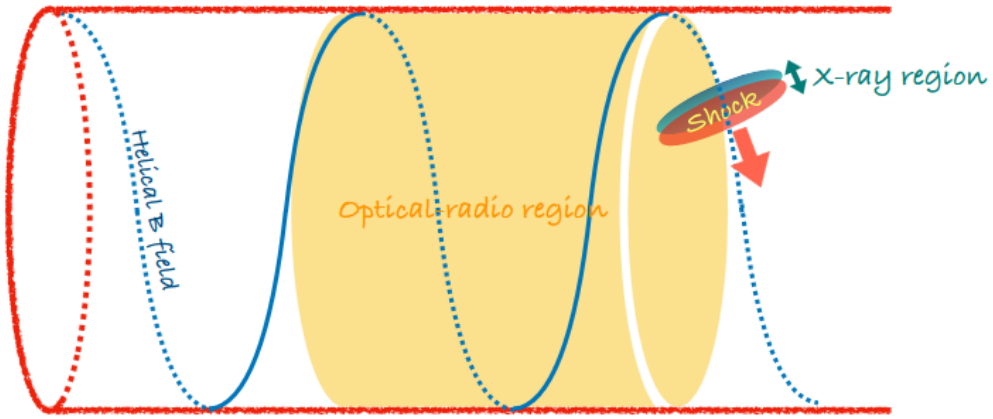
Di Gesu et al. 2022

IXPE observations during 2022

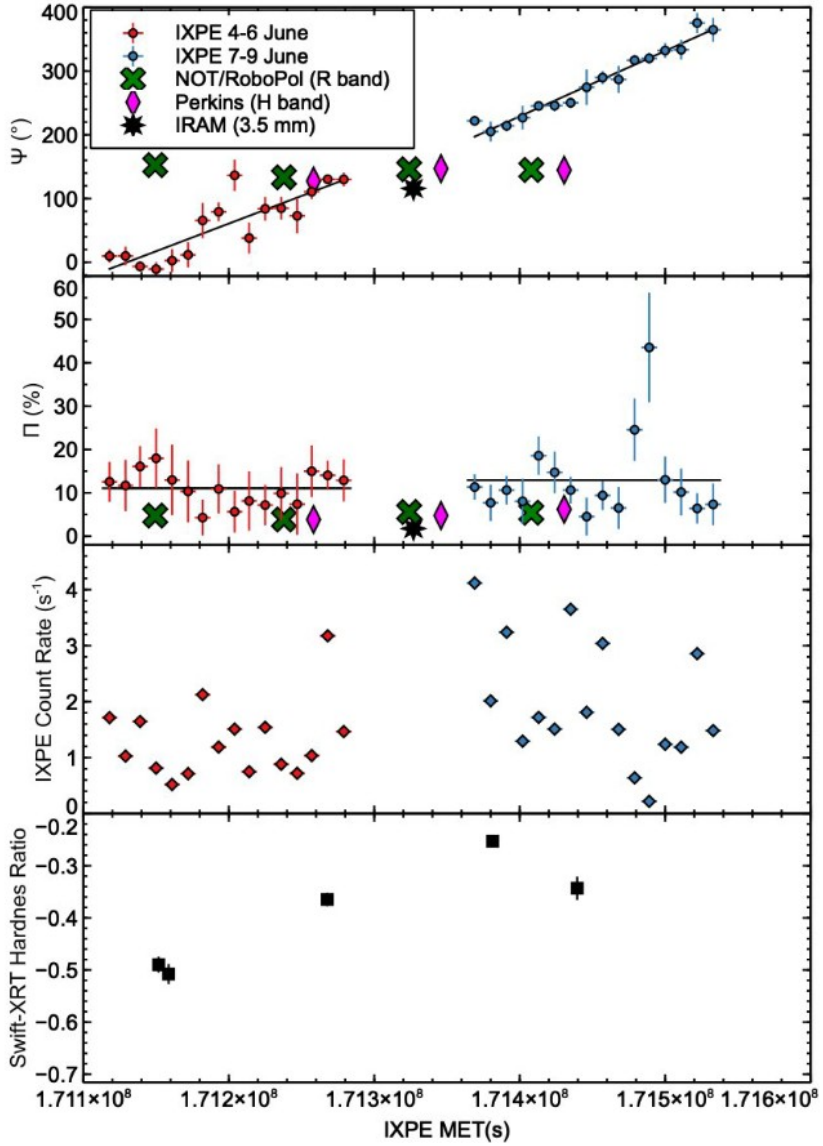
- **2nd and 3rd IXPE observation: 4th-6th June 2022 and 7th-9th June 2022**
  (Di Gesu et al., Nature, 2023)

  - *Polarization degree:* **constant**, **~10%**
  - *Polarization angle:* **rotation, 80-90 deg/day**

  → **Emission zone follows helical path, detached from optical/radio zone**



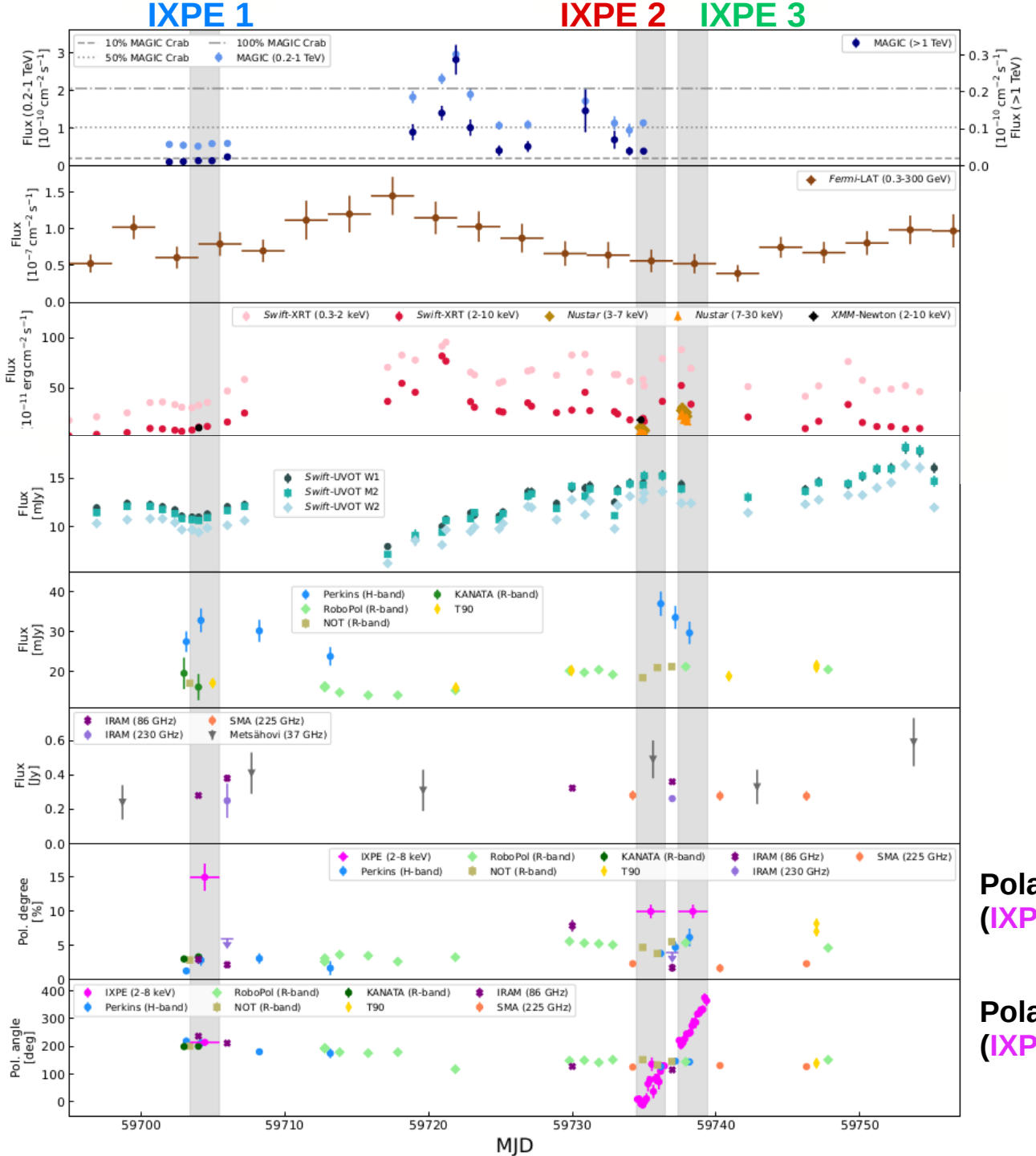
Di Gesu et al. 2023



Di Gesu et al. 2023

Radio to VHE observations

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



MAGIC >1TeV

MAGIC 0.2-1TeV

***Fermi*-LAT**

***Swift*-XRT**
NuSTAR
***XMM*-Newton**

***Swift*-UVOT**

Optical

Radio

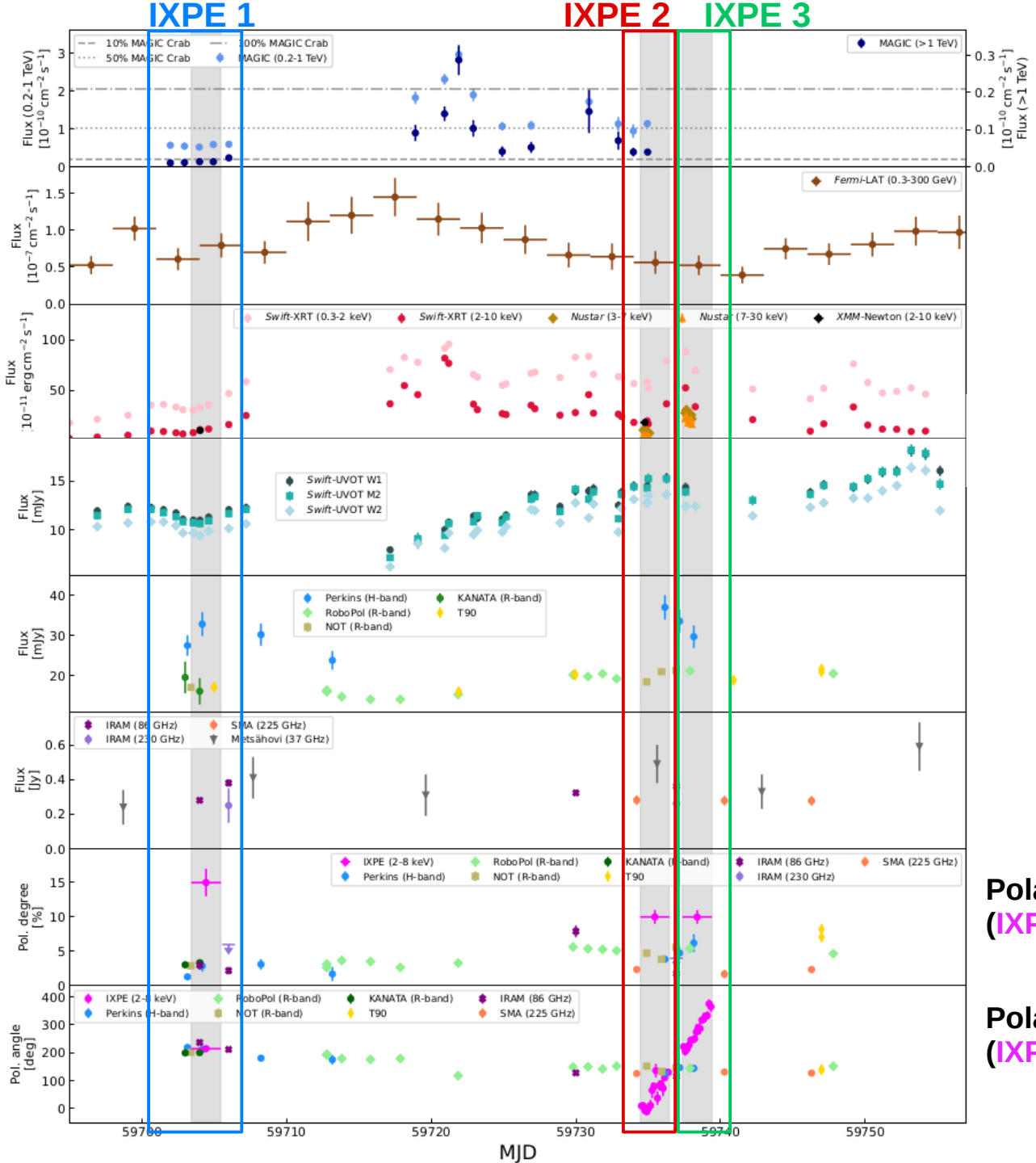
Polarization degree (IXPE/optical/radio)

Polarization angle (IXPE/optical/radio)

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



MAGIC >1TeV

MAGIC 0.2-1TeV

Fermi-LAT

Swift-XRT
NuSTAR
XMM-Newton

Swift-UVOT

Optical

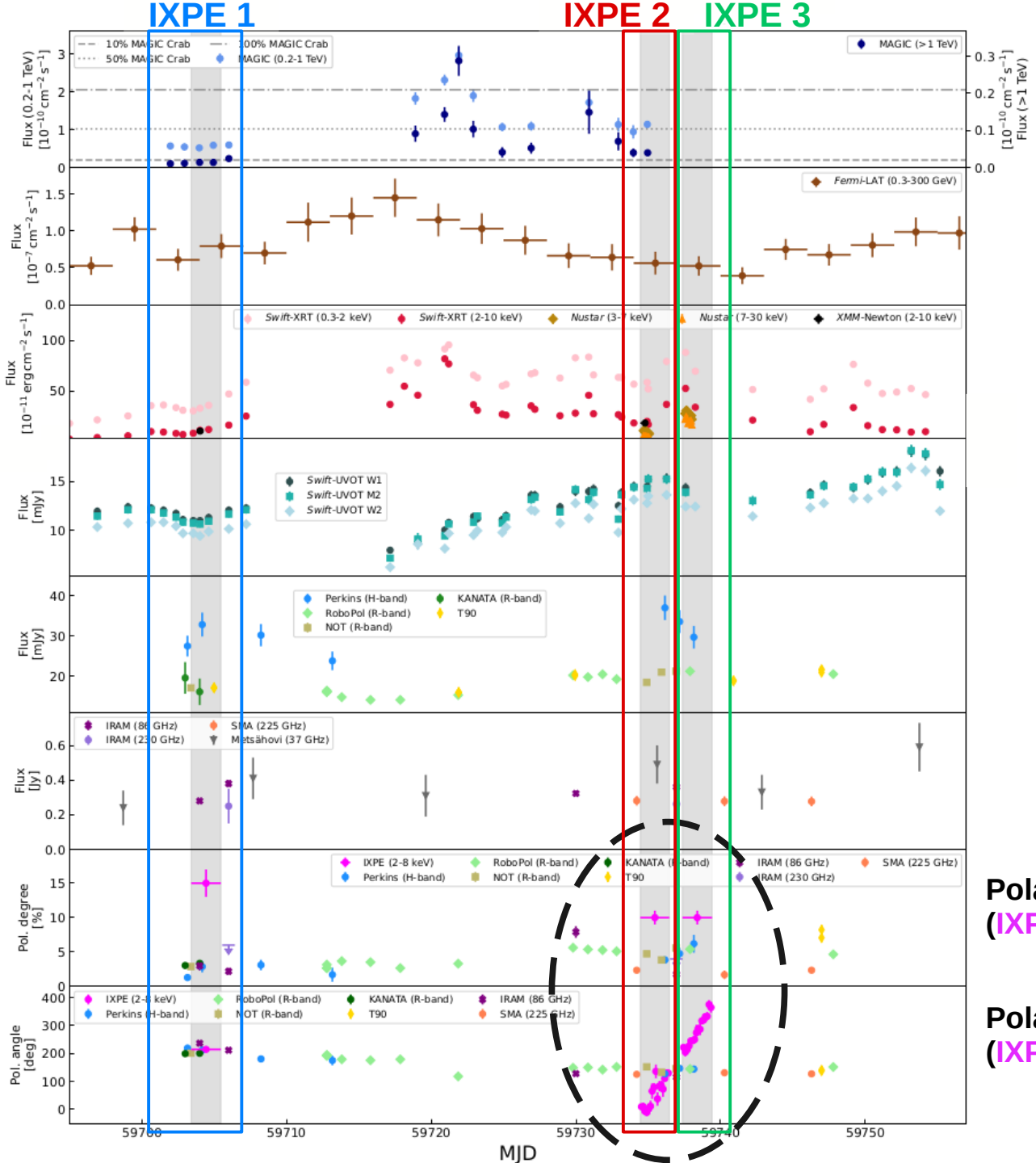
Radio

Polarization degree (IXPE/optical/radio)

Polarization angle (IXPE/optical/radio)

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
- **NuSTAR coverage during IXPE polarization angle rotation**



MAGIC >1TeV

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***Fermi*-LAT**

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***XMM*-Newton**

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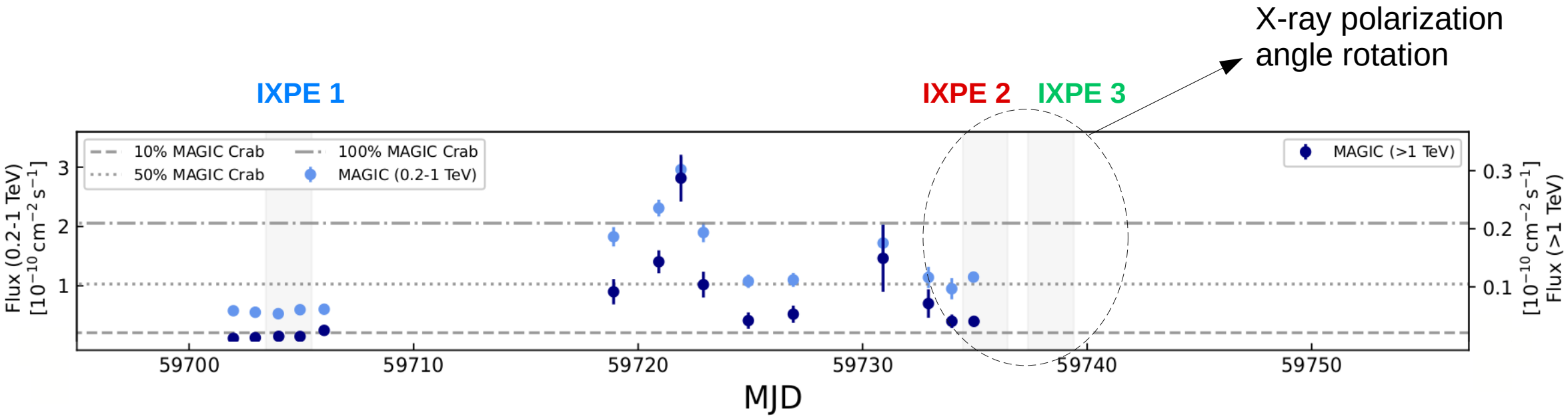
Optical

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: **α ~ 2.6, β ~ 0.5**

$$\frac{\mathrm{d}N}{\mathrm{d}E} = f_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log_{10}(E/E_0)}$$

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

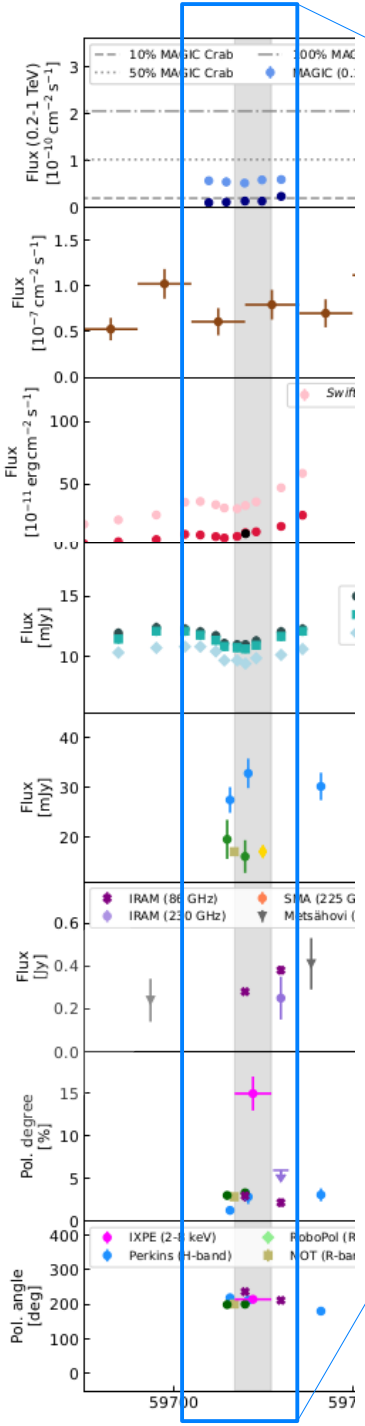
No significant VHE variability (intranight timescales)

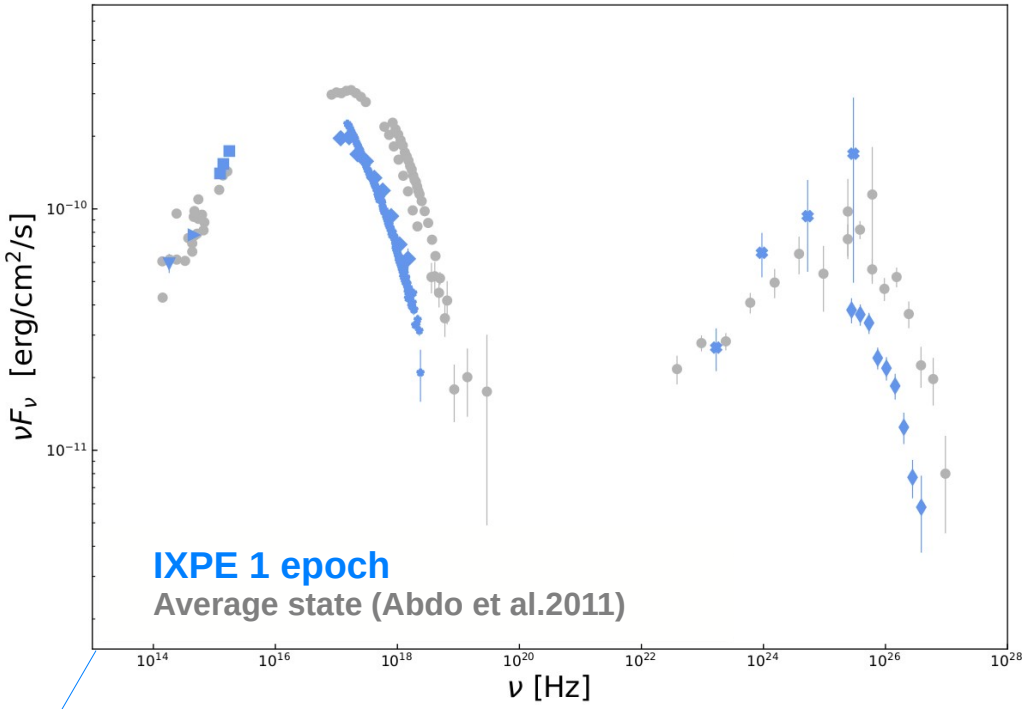
VHE spectrum best-fit log-parabola: **α ~ 2.3, β ~ 0.5**

Radio to VHE observations

- **IXPE 1 epoch**

  Source in **low state,** *SED shifted to lower energies*





Radio to VHE observations

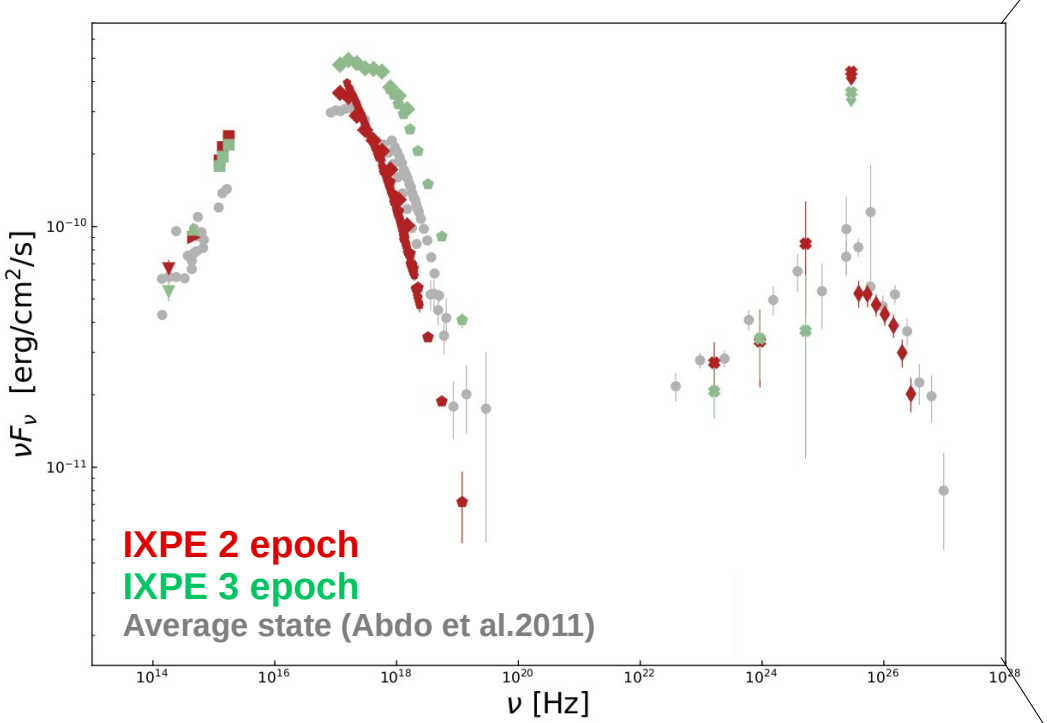
- **IXPE 2 epoch**:
  Source in **average state**

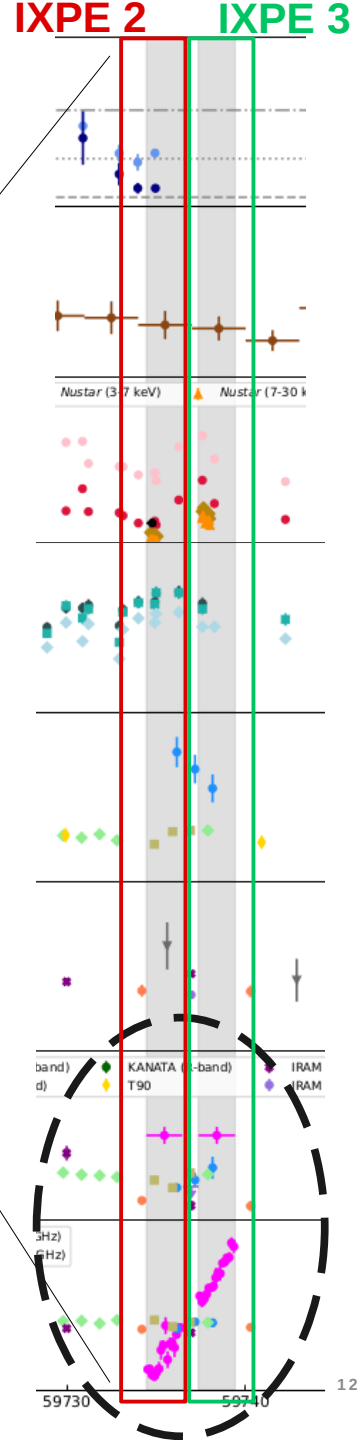
- **IXPE 3 epoch:**
  Source in **enhanced state**

  No VHE data available...

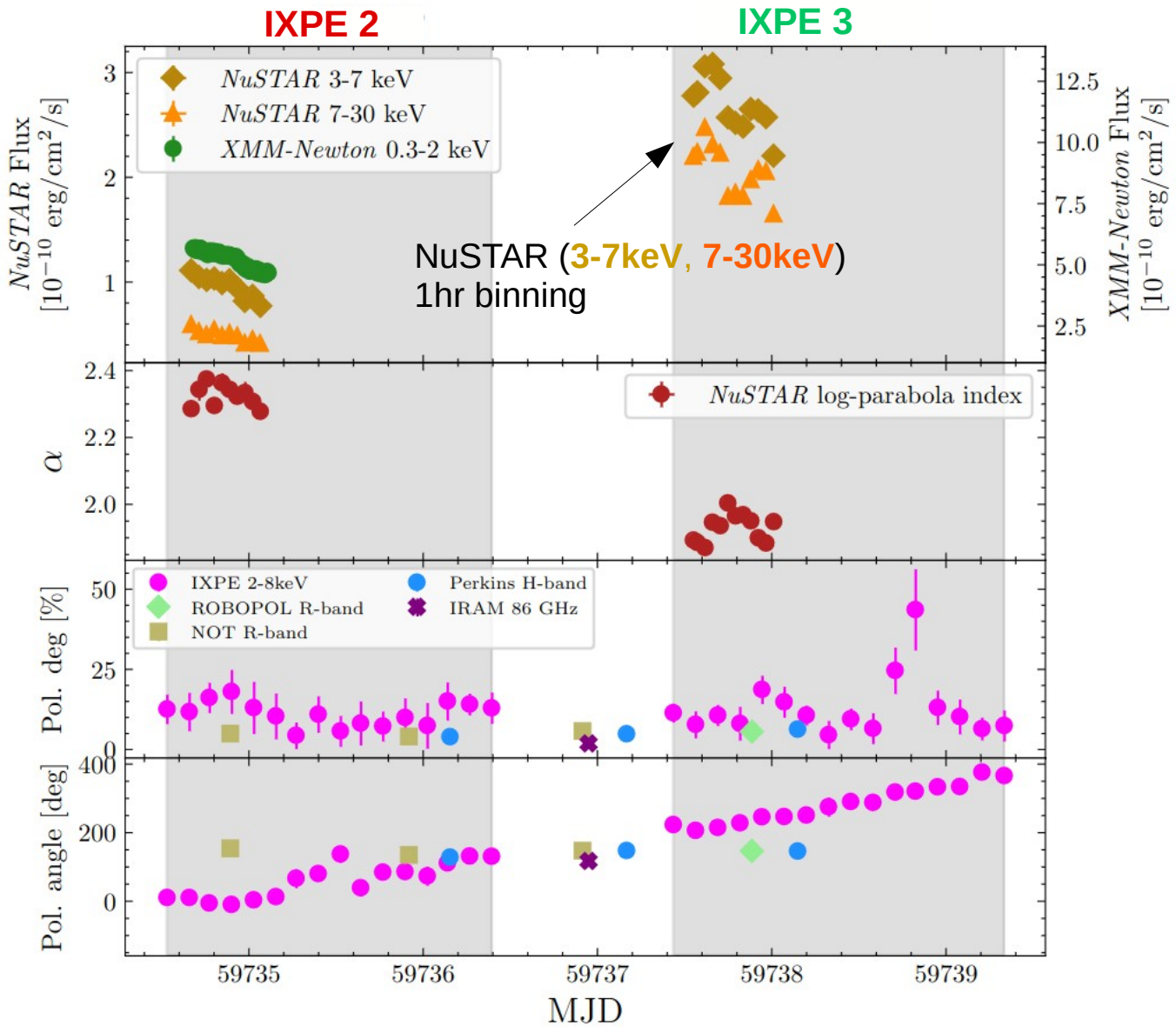
  X-rays show harder-when-brighter behavior

  → X-ray variability during the polarization angle swing



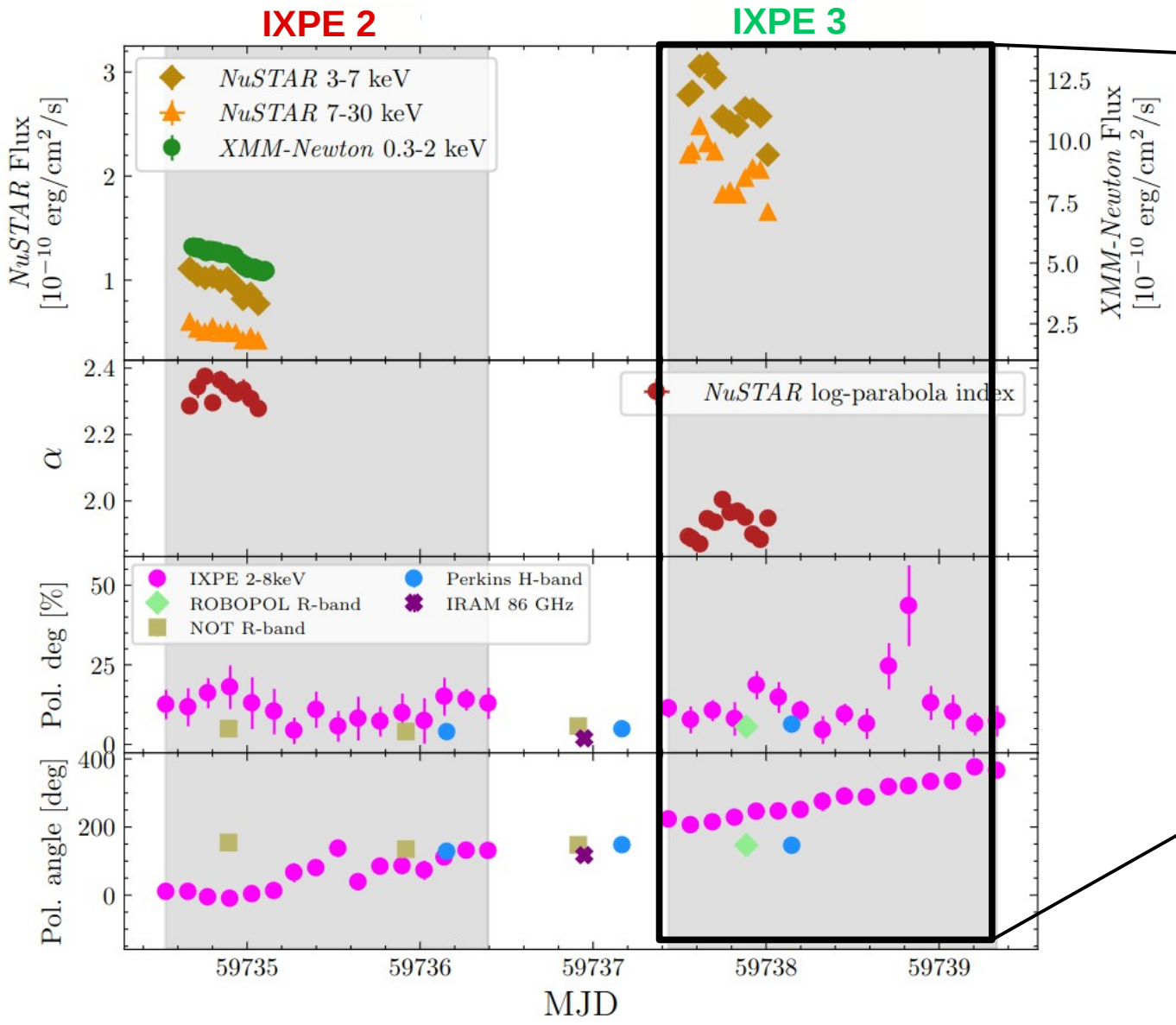


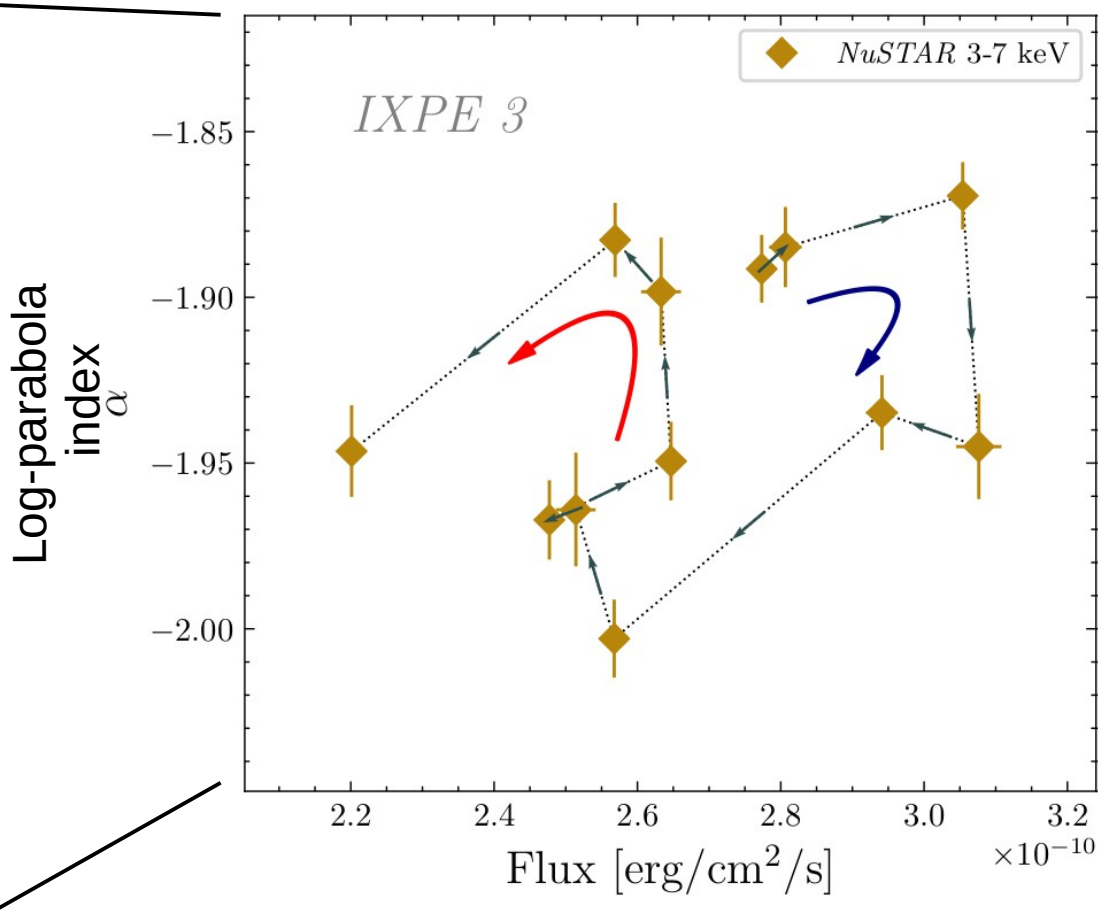
X-ray variability during polarization angle rotation



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

X-ray variability during polarization angle rotation





→ Hysteresis loops
clock-wise and **counter clock-wise** direction

X-ray variability during polarization angle rotation

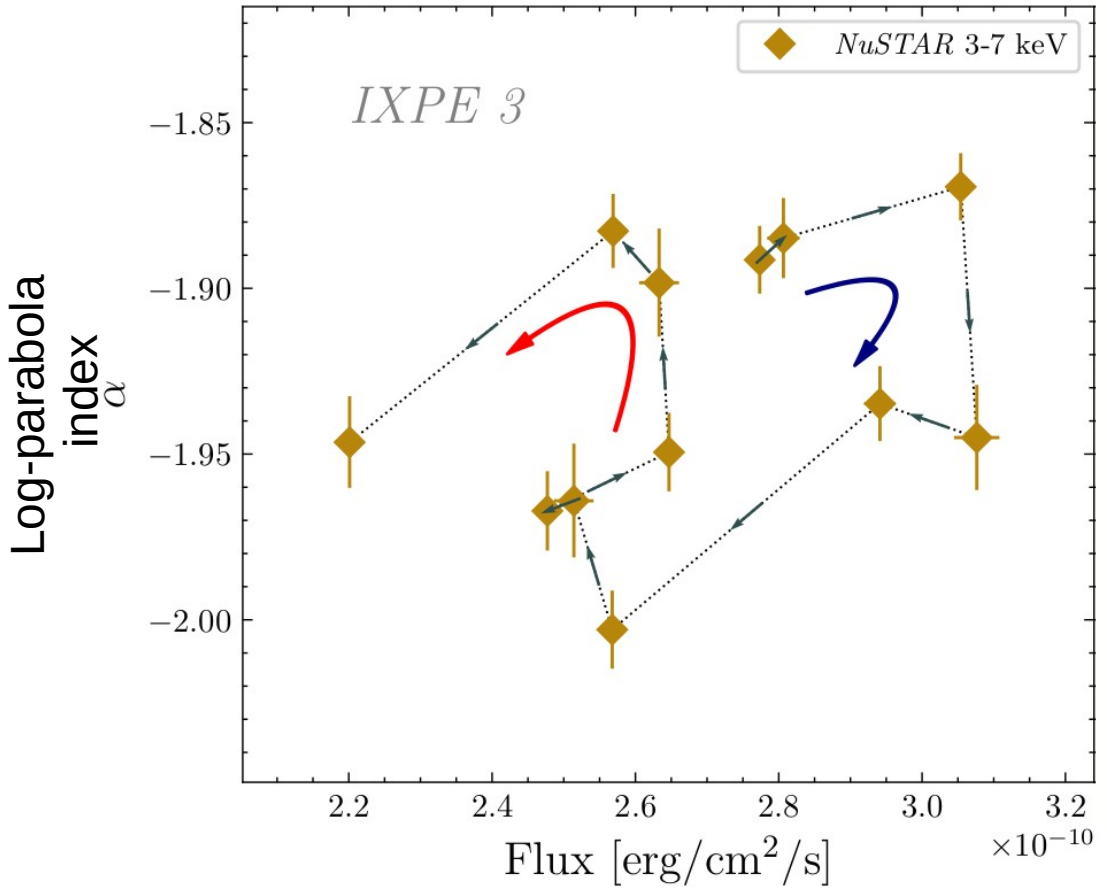
- **Clock-wise loop** *: low-energy lags behind high-energy*
  Suggests variability driven by synchrotron cooling
  (Kirk, et al. 1998):

  $t_{acceleration} << t_{synch,cool}$

- **Counter clock-wise loop** *: high-energy lags behind low-energy*
  Suggests ~similar cooling and acceleration timescales
  (Kirk, et al. 1998):

  $t_{acceleration} \sim t_{synch,cool}$

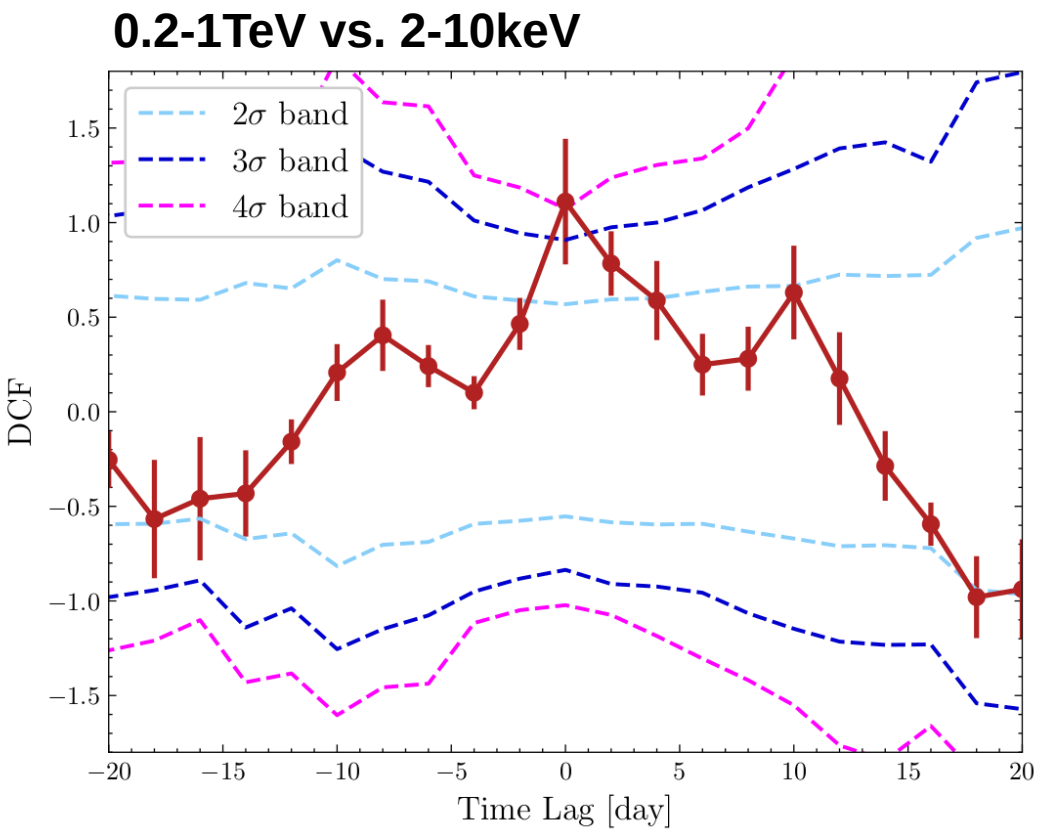
- *Contiguous clock-wise and counter clock-wise loops*
  imply **significant decrease in particle acceleration efficiency during rotation**



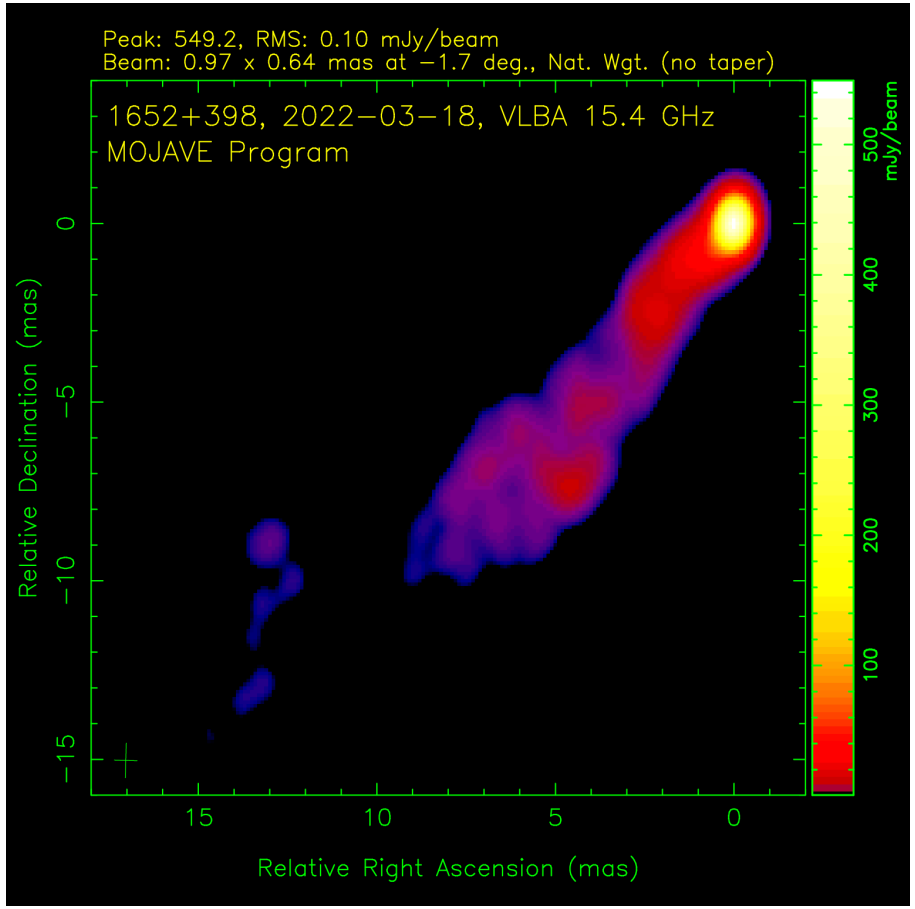
→ Hysteresis loops
clock-wise and **counter clock-wise** direction

VHE versus X-ray Correlation

- *VHE / X-ray correlation using* **April to June 2022 data**
- **~ 4σ significance**, *no time lag*
- **VHE emission likely co-spatial to X-ray, close to the shock front**



Markarian 501 (Mrk501)



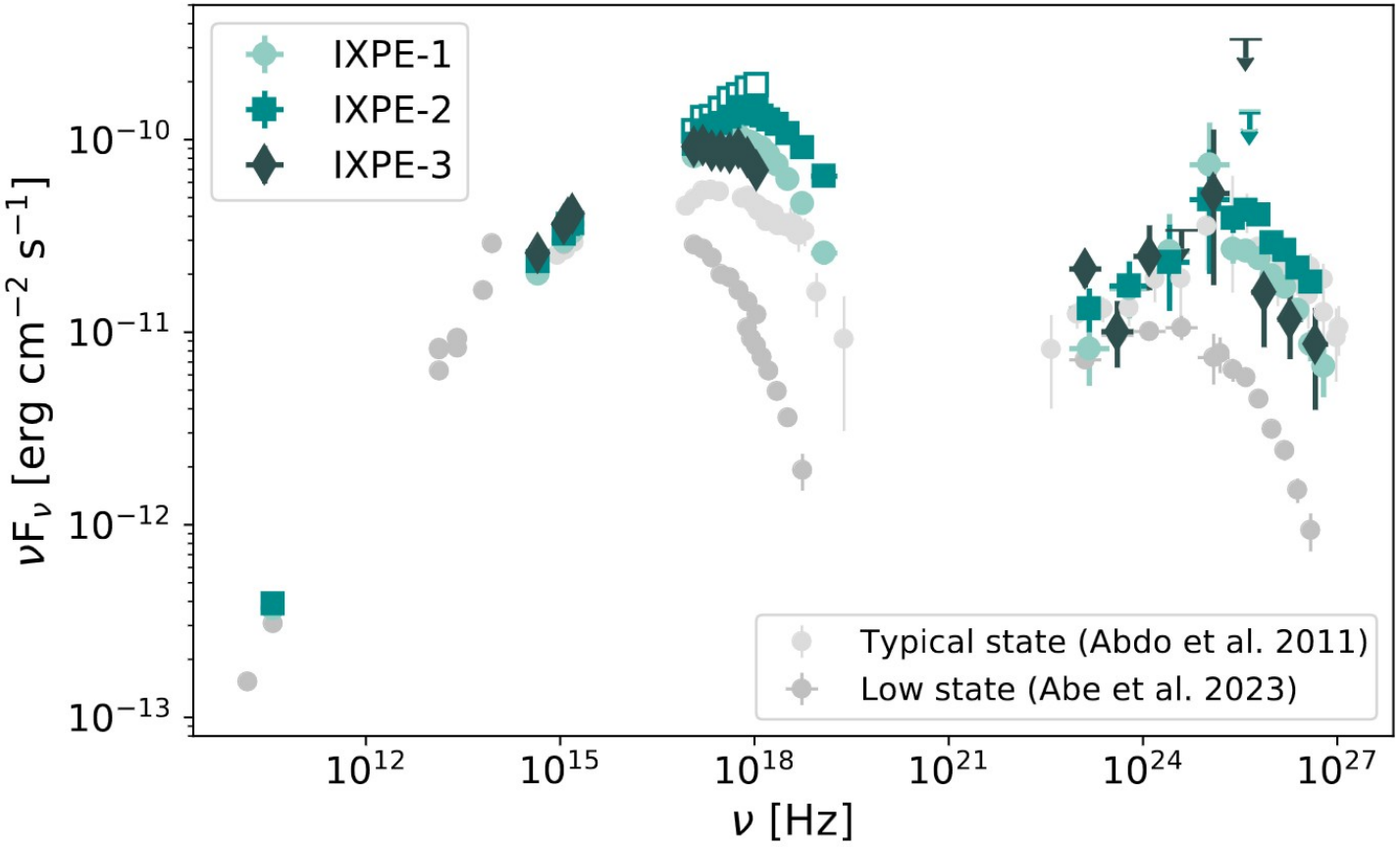
Credits: MOJAVE team

IXPE observations during 2022

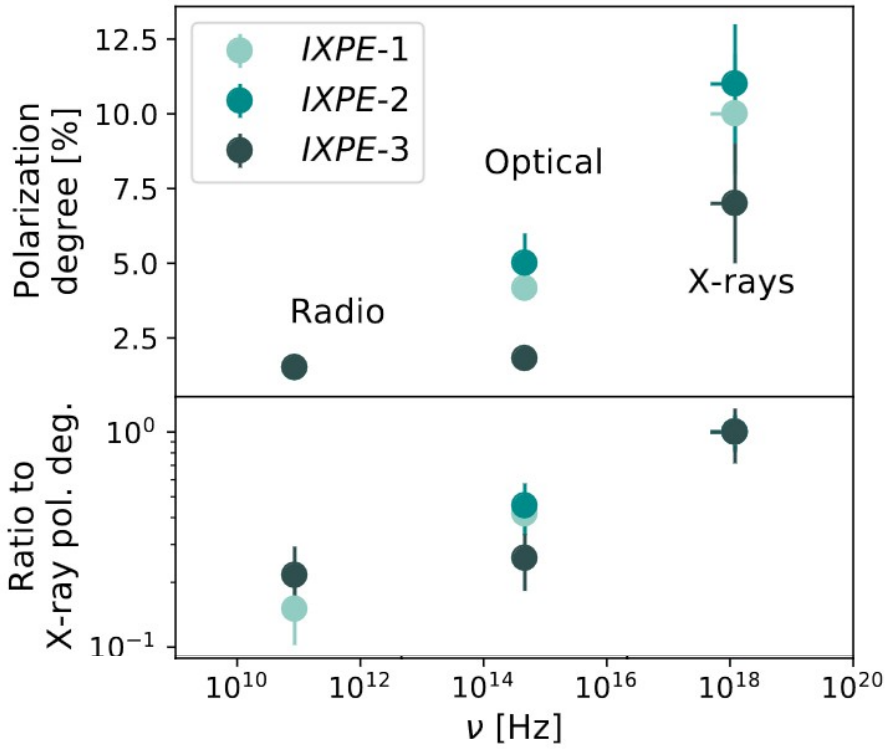
- **3 observations, from March to July 2022:**
  - **IXPE 1**: 8th -10th March 2022
  - **IXPE 2**: 27th -29th March 2022
  - **IXPE 3**: 9th -12th July 2022

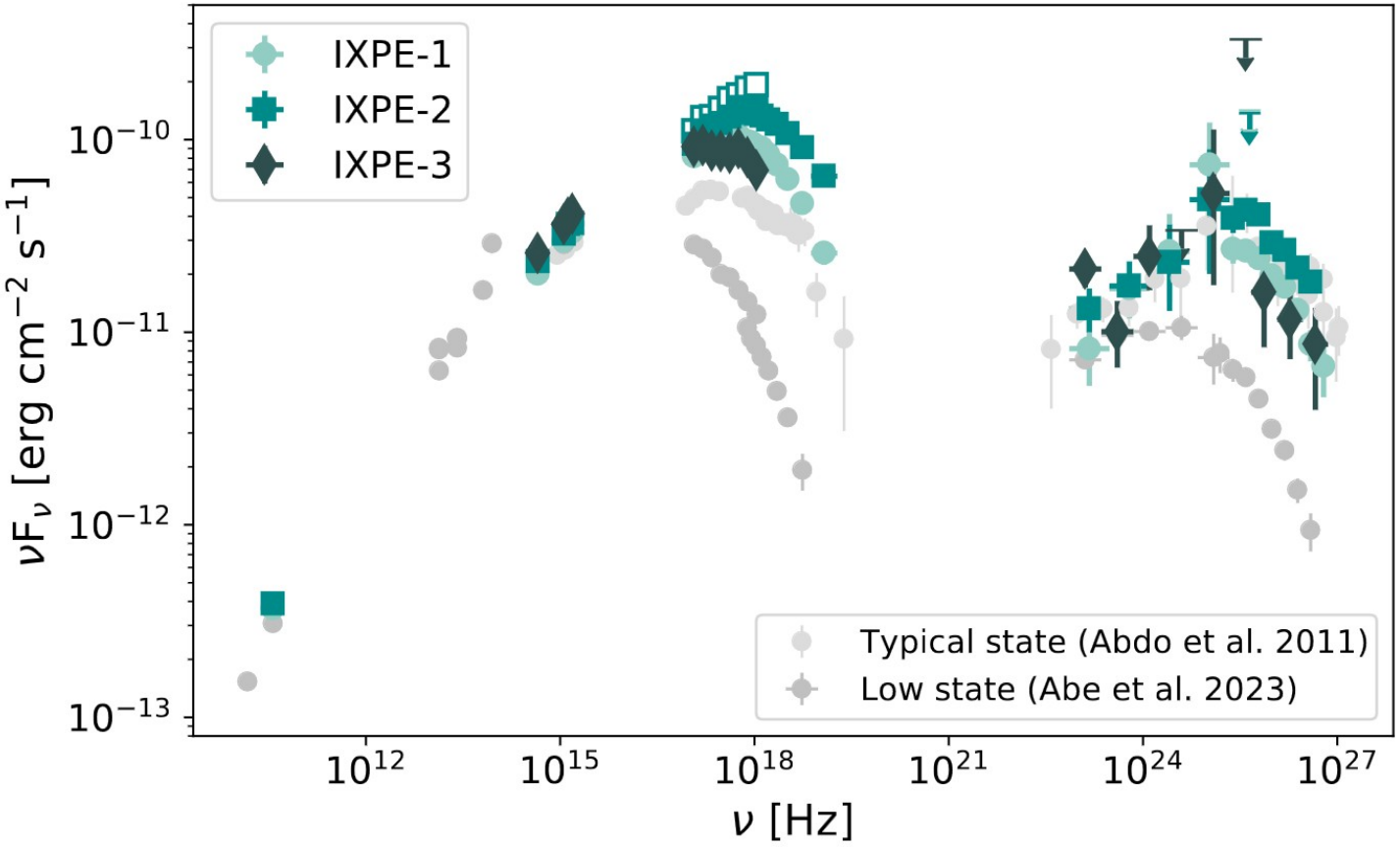
- Moderate variability
  - **VHE state close to "average"**
  - **High X-ray state**

→ **Atypically low Compton-dominance**

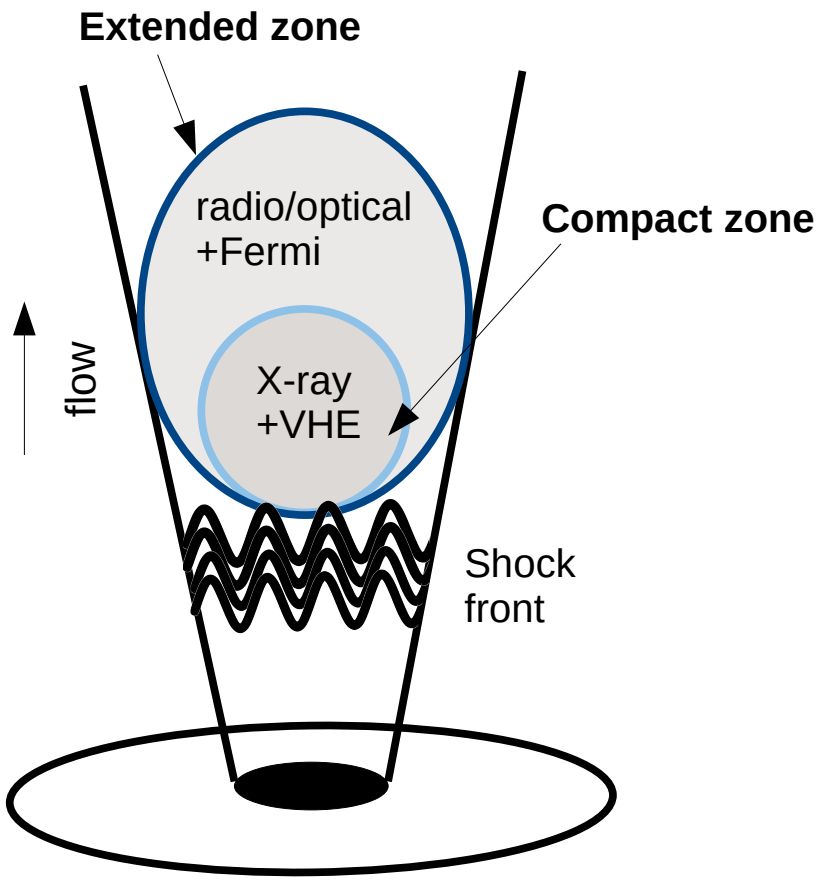


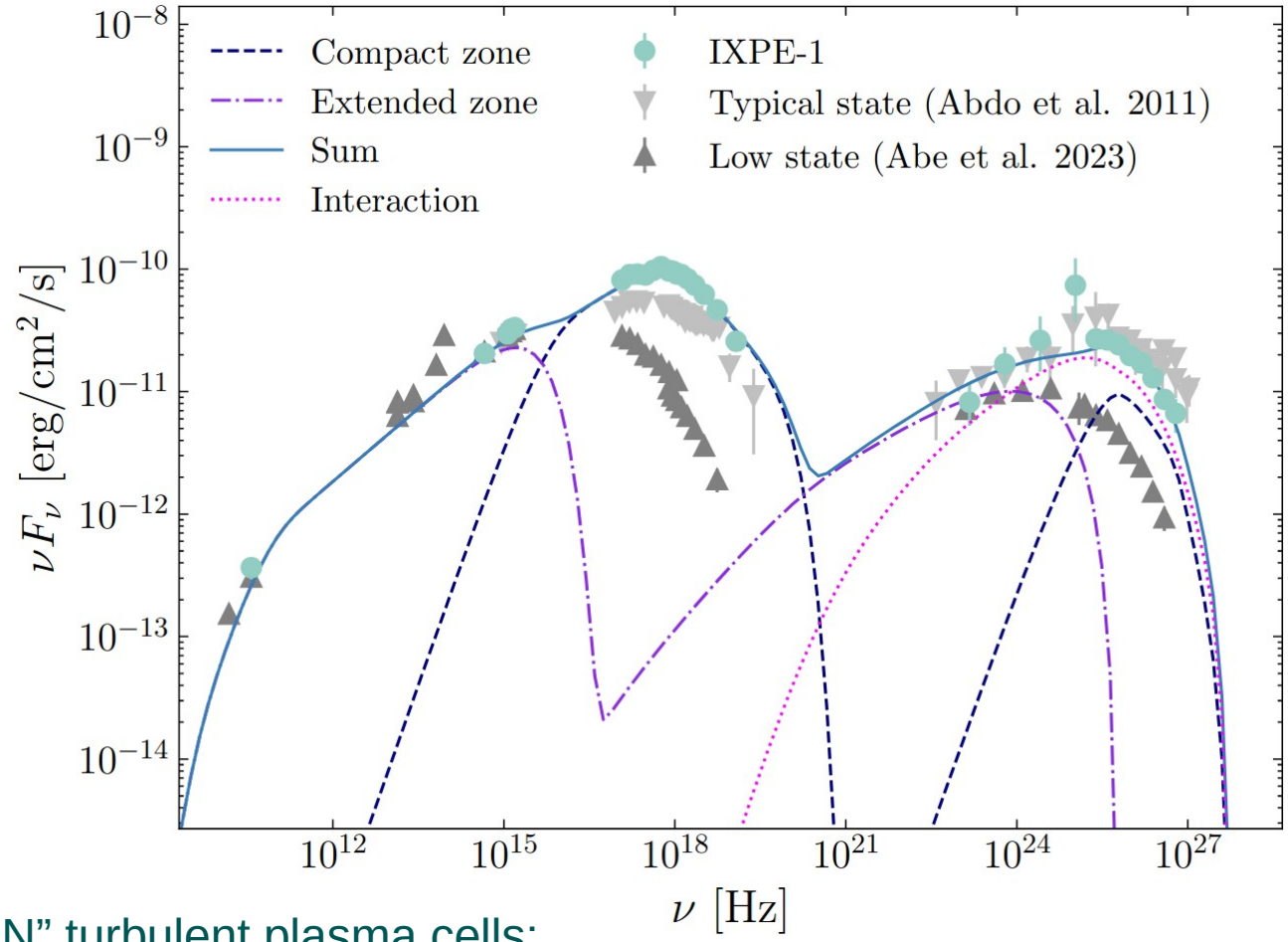
IXPE observations during 2022





Modelling of Mrk501 with polarization constraints





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

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

Conclusions

- *For both Mrk421 & Mrk501, polarization degree increases with energy*

  → *suggesting* **shock acceleration, in energy stratified jet**
  → **X-ray emission close to the shock front**

- *4σ 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*

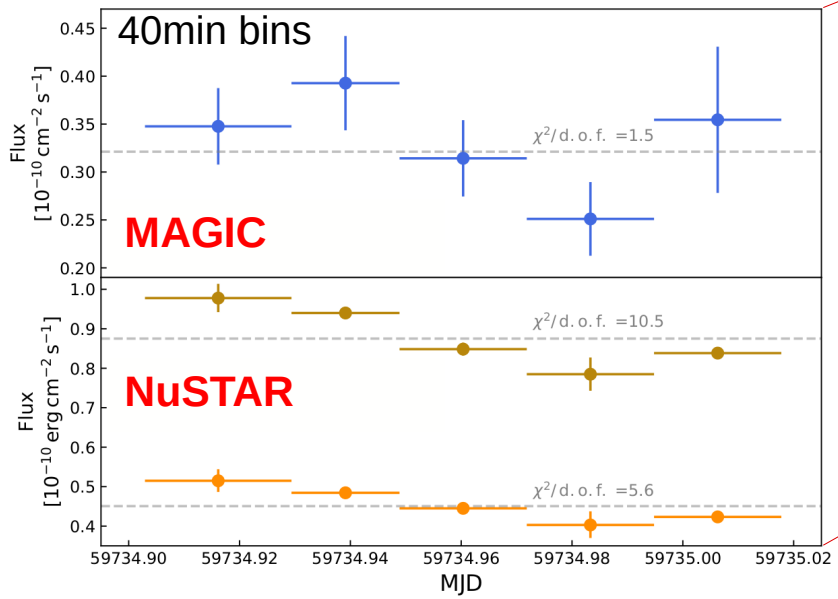
- **SED well modelled in a two-zone scenario**

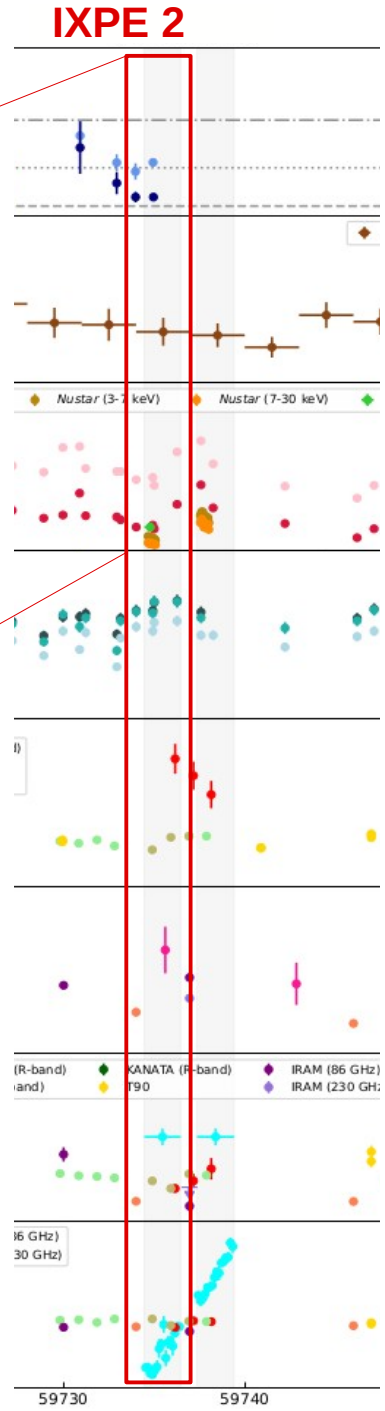
- **VHE Flare during the IXPE pointing in December 2023 → Stay tuned!**

Backup

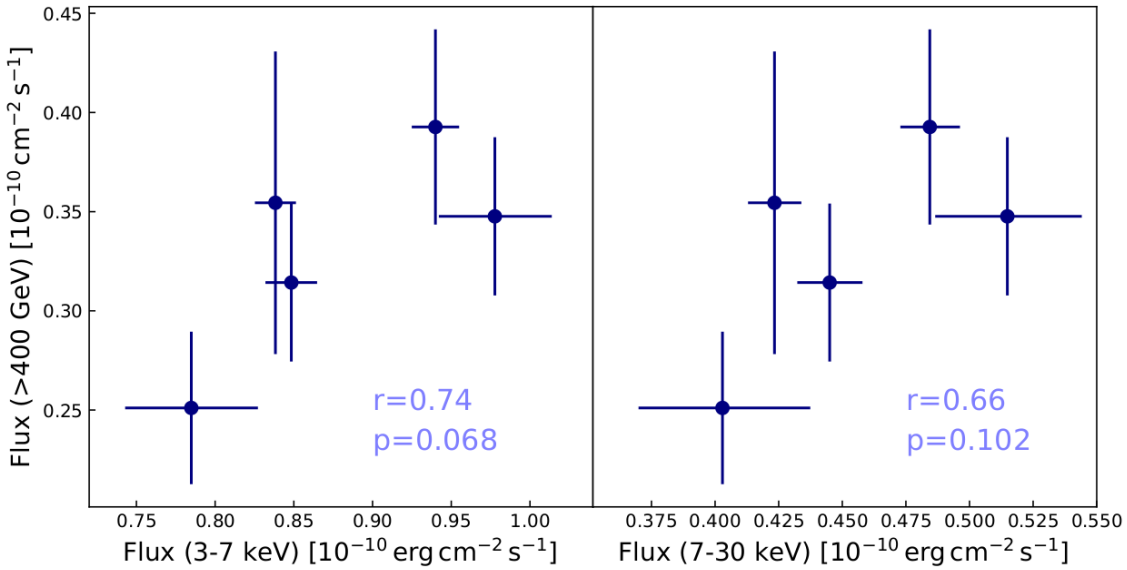
VHE versus X-ray Correlation

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





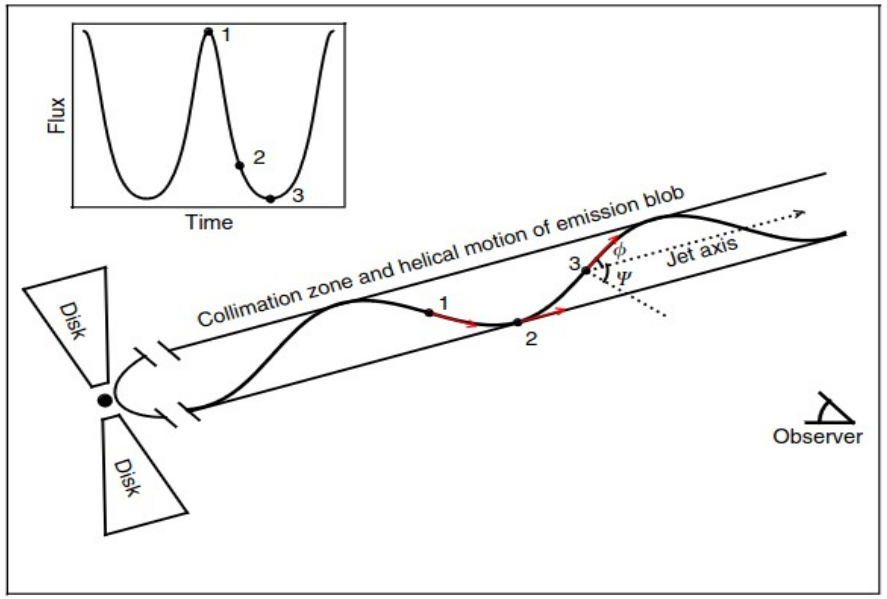
MAGIC



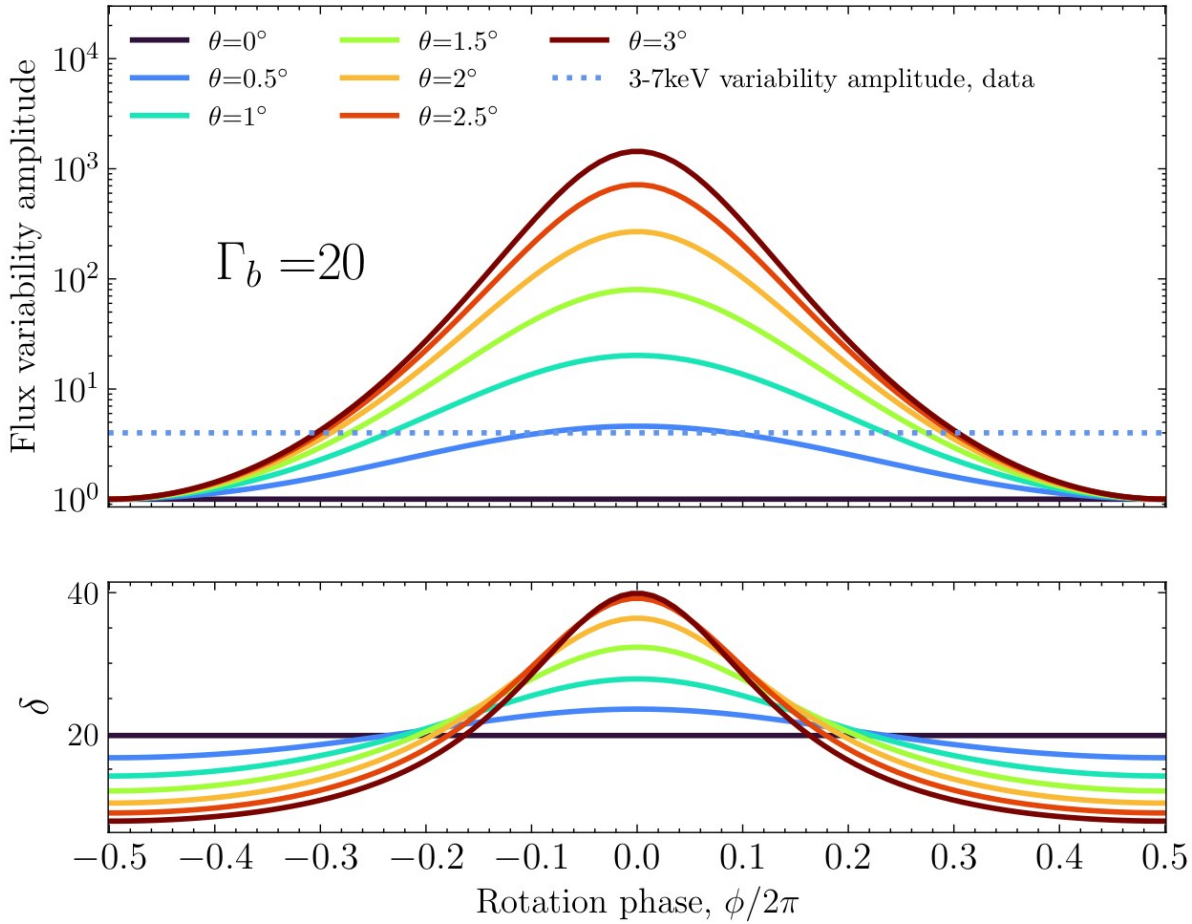
NuSTAR 3-7keV **NuSTAR 7-30keV**

X-ray variability during polarization angle rotation

- *Pol. angle rotation due to blob moving in a helical path?*
  → Change of doppler factor δ
  → Expect strong flux modulation, F_obs ∝δ ³ F_intrinsic
  does this contradicts observations?
- *Assuming* **bulk Lorentz factor ~ 20** *&*
  jet viewing angle of ~0.5deg
  → Expected variability solely caused by δ evolution in agreement with NuSTAR variability



Sketch credits: Zhou et al. 2018



Modelling parameters

Parameters	"compact zone"	"extended zone"
B' [10^{-2}G]	5.0	3.5
R' [10^{16}cm]	2.9	5.0
δ	11	11
U'_e [10^{-3} erg cm^{-3}]	0.8	2.8
n_1	2.37	2.2
n_2	4.00	–
γ'_{min}	5×10^4	2×10^2
γ'_{br}	6.0×10^5	–
γ'_{max}	5.5×10^6	5.7×10^4
U'_e/U'_B	8	57