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

David Paneque,
Axel Arbet-Engels,
Lea Heckmann,
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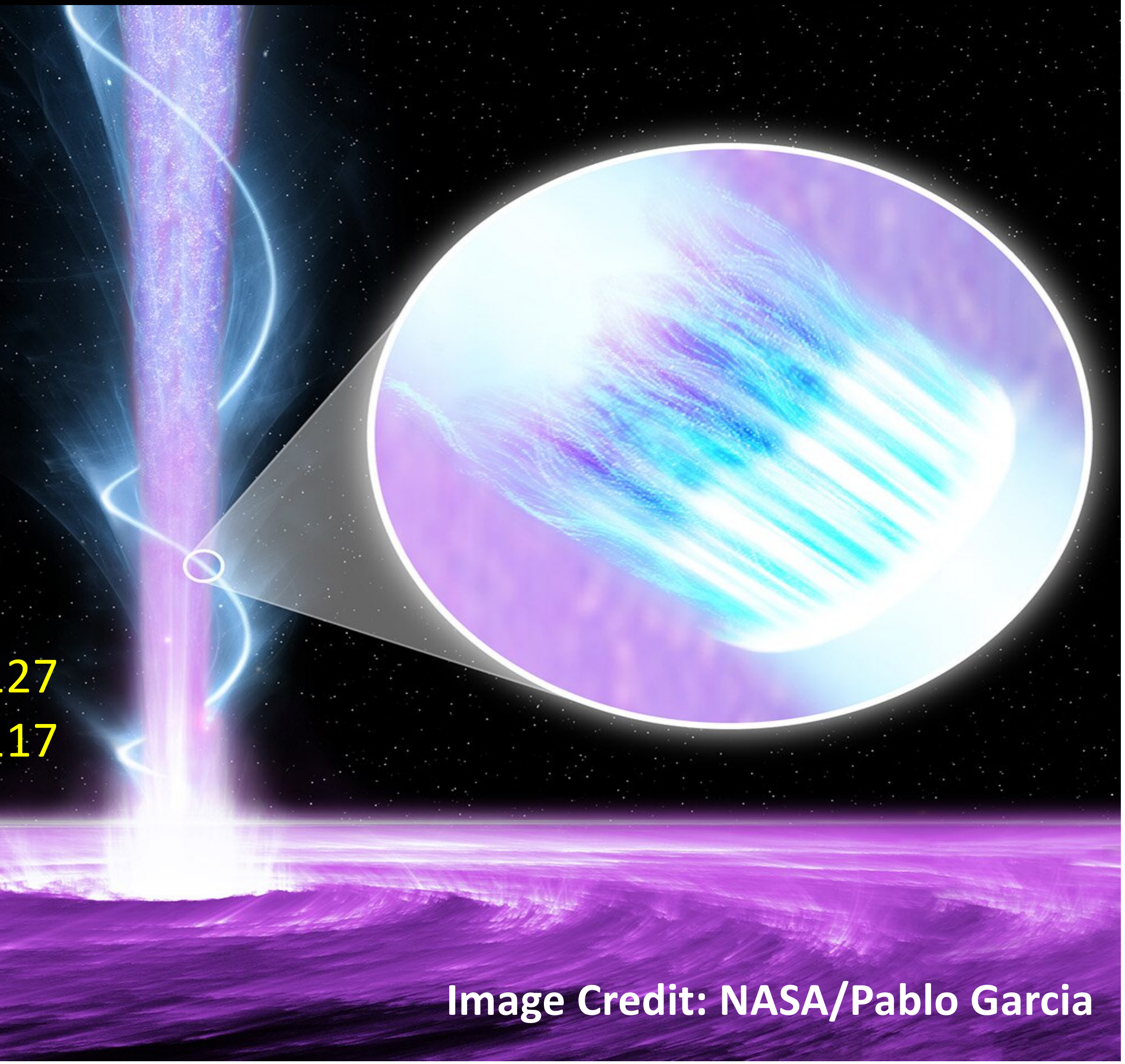
for the MAGIC collaboration
and MWL collaborators

MAGIC Collab., 2024, A&A, 684, A127
MAGIC Collab., 2024, A&A, 685, A117



RICAP 2024 (Frascati, 2024/09)

Image Credit: NASA/Pablo Garcia

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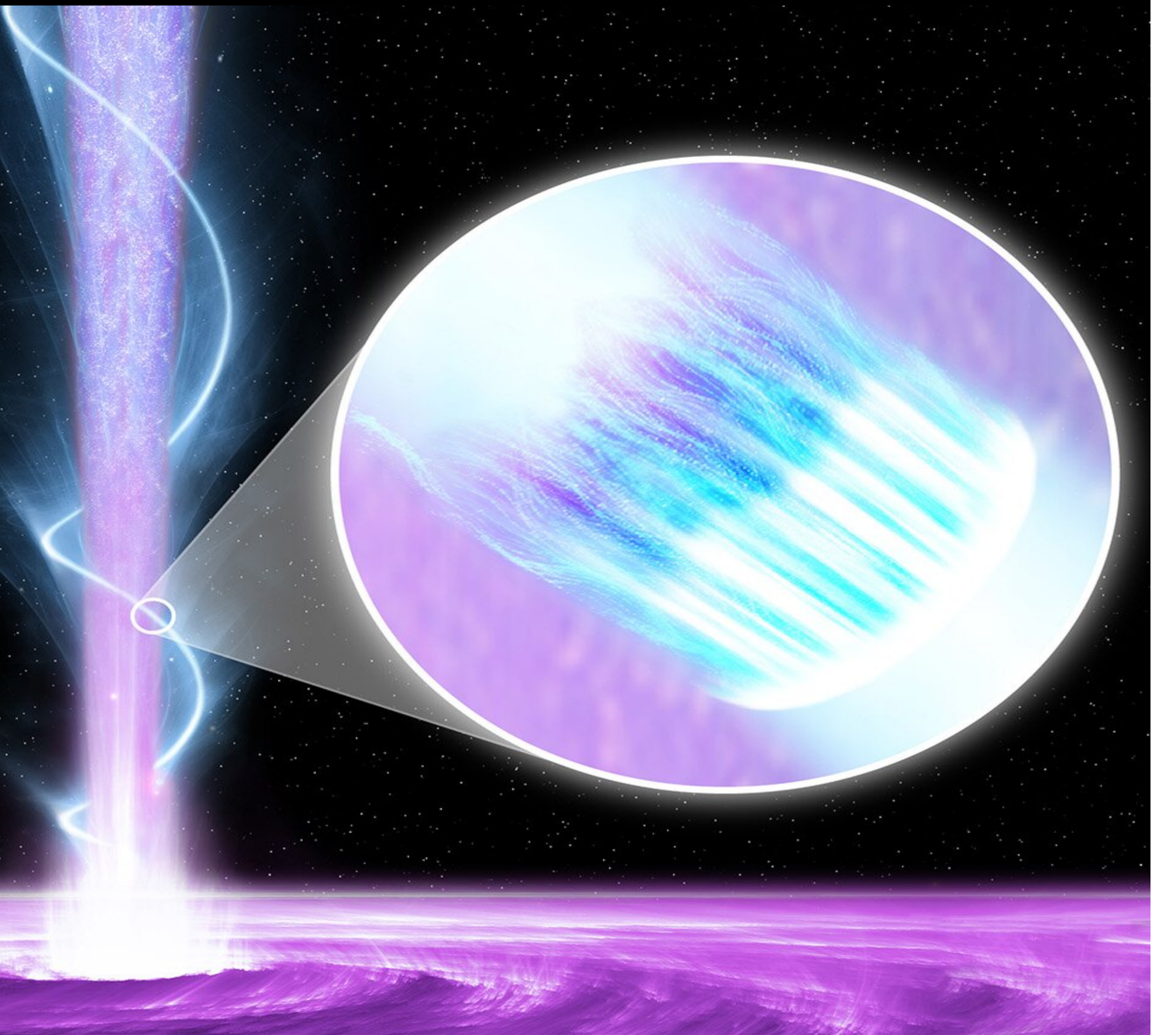


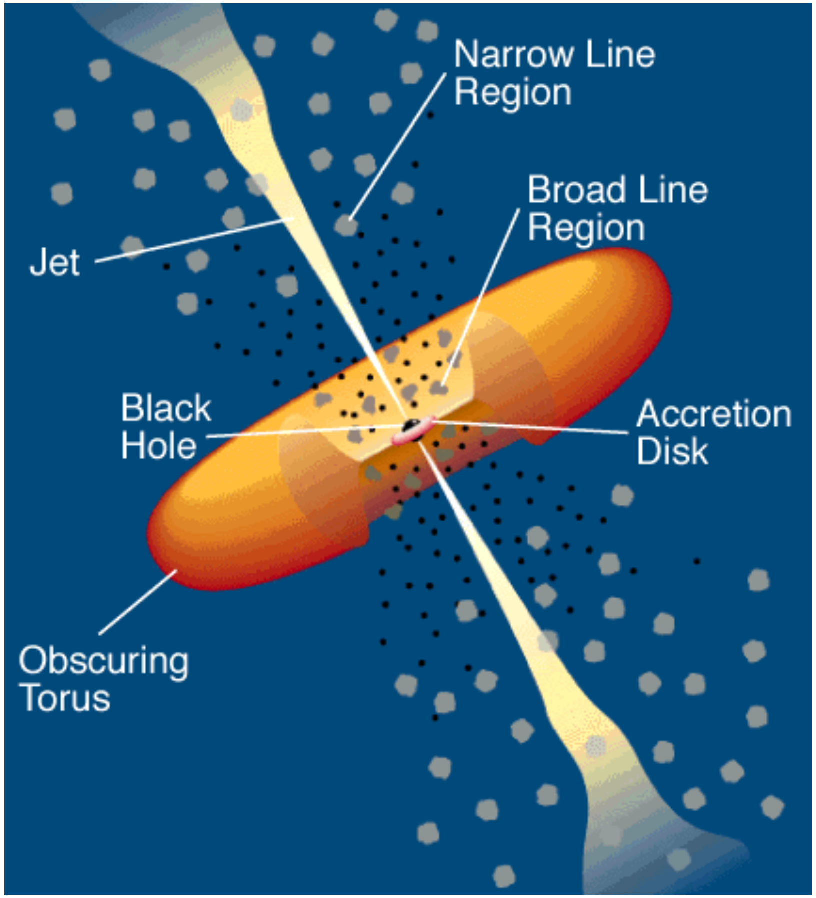
RICAP 2024 (Frascati, 2024/09)

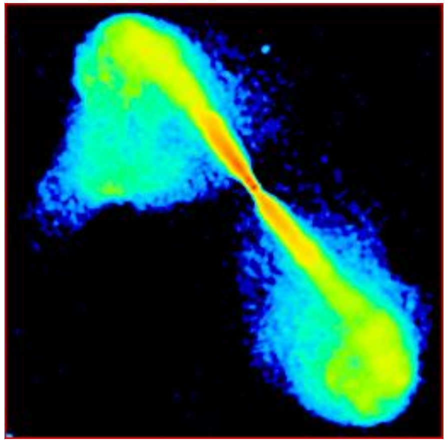
Image Credit: NASA/Pablo Garcia

AGNs are powerful particle accelerators

Pictorial description of an AGN

Image Credit: C.M.Urry & P. Padovani





AGN jets are collimated streams of plasma forming **the largest structures in the Universe**, reaching even Mpc scales.

Jets are produced by rapidly rotating supermassive (~ 10^6-10^9 $M_\odot$) black holes surrounded by magnetized accretion disks. Thus, jets **are direct probes of black hole physics**.

Jets are **extremely efficient accelerators of particles** to ultrarelativistic energies. Known to produce electrons with 10^{14} eV energies, and claimed to accelerate protons up to the highest observed energies $\geq 10^{20}$ eV

AGNs are powerful particle accelerators

AGNs (→ Jets) are extremely interesting cosmic sources

Although widely studied during the last half century at different frequencies (from low-frequency radio up to very high γ-ray photon energies) they are still superficially understood objects.

Many key questions regarding extragalactic jets remain open:

- Jet composition *(B and ultrarelativistic e-e+; something else?)*
- Jet magnetic field *(how strong? what is its structure?)*
- Jet launching *(rotating SMBHs vs accretion disks)*
- Jet evolution and energetics *(kinetic power, lifetimes, „feedback")*
- Particle acceleration *(shocks? turbulence? reconnection?)*
- What produces variability on various timescales (years down to minutes)

Large observational challenges when studying AGNs

1) AGN emission extends over a very wide energy range
(from *micro-eV* to *tens of Tera-eV* → *dynamic range> 10^{18}*)

2) AGN emission is variable on different timescales
(from *tens of years* down to *a few minutes* → *dynamic range> 10^{6}*)

3) AGN emission is spatially extended
(from to *mili-parsecs* to *mega-parsecs* → *dynamic range> 10^{9}*)

And variability and spatial extension are energy dependent, as well as our instrumental ability to characterize these properties

The complete (deep) characterization of the AGN broadband emission is a very complicated observational challenge, that requires enormous efforts from the community

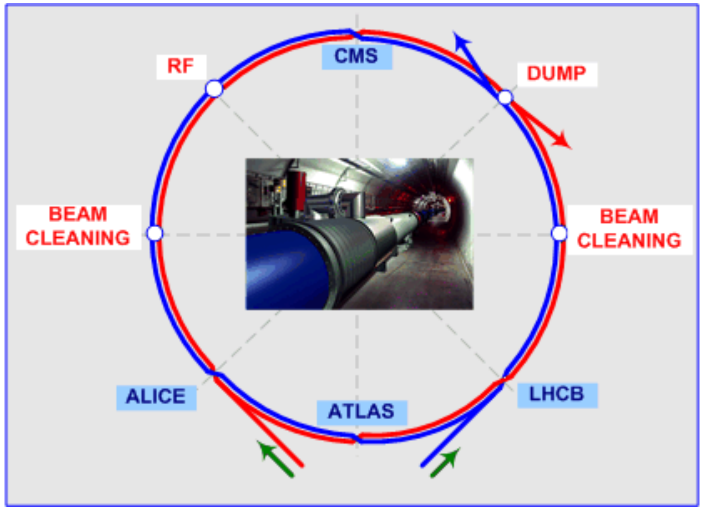
→ *Not surprising that AGNs are not well characterized after 50+ years of observations*

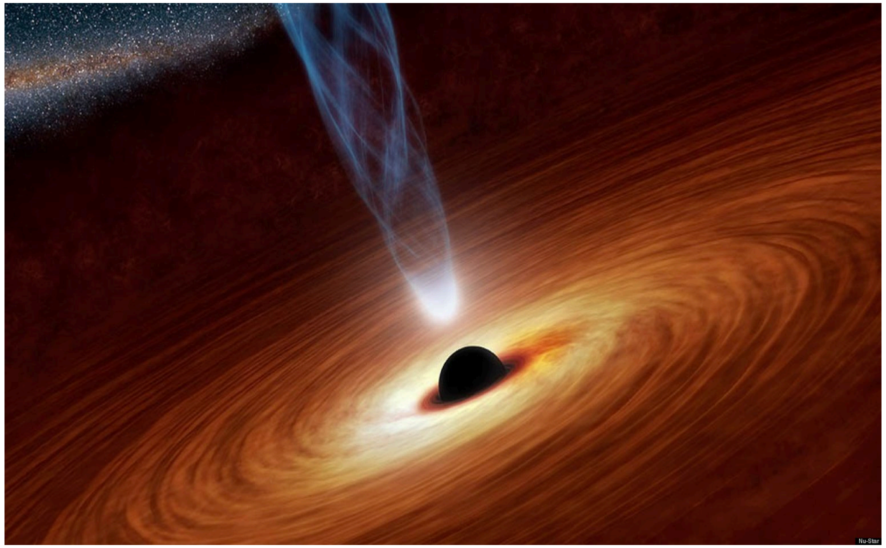
AGNs as our Extreme Particle Accelerators

LHC **vs** **bright AGN**

ATLAS/CMS
LHCb + Alice

MAGIC/VERITAS/HESS/Fermi,++
X-ray , Optical/radio, IceCube…





Physics studies with cosmic particle accelerators

Disadvantage: Cannot play with knobs in controlled environment

Advantage: Study extreme processes and environments

Much cheaper (*no need to build the accelerator…)*

The project requires "observing" over many years in order to integrate over sufficient data/effects → **long-term multi-instrument observations.**

Extensive multi-instrument observing campaigns on bright AGNs *(e.g., Mrk421 & Mrk501)*

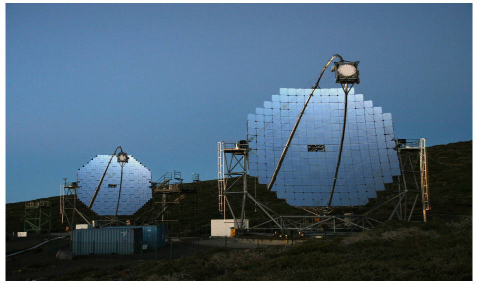
Easy to detect across all energy bands with many instruments in short times

→ “Relatively Easy” to characterize the entire SED in every “shot”

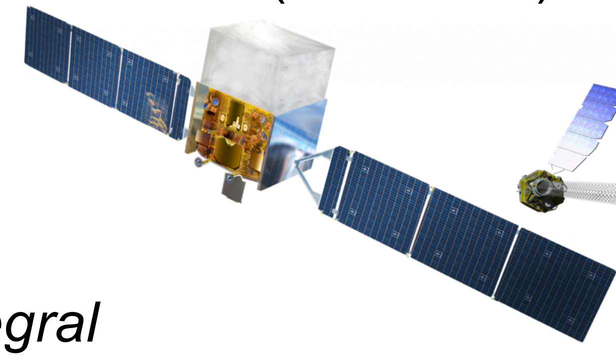
→ <u>Evolution of the entire SED</u>

→ **See things that cannot be seen for other AGNs (less bright)**

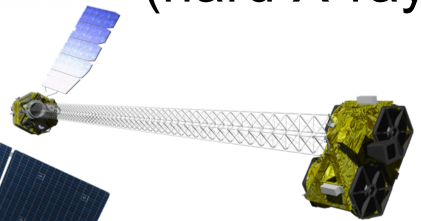
MAGIC (*TeV*)



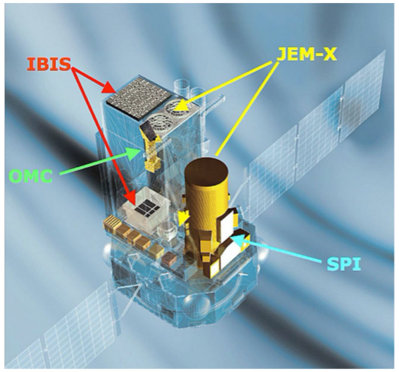
Fermi-LAT (MeV-GeV)



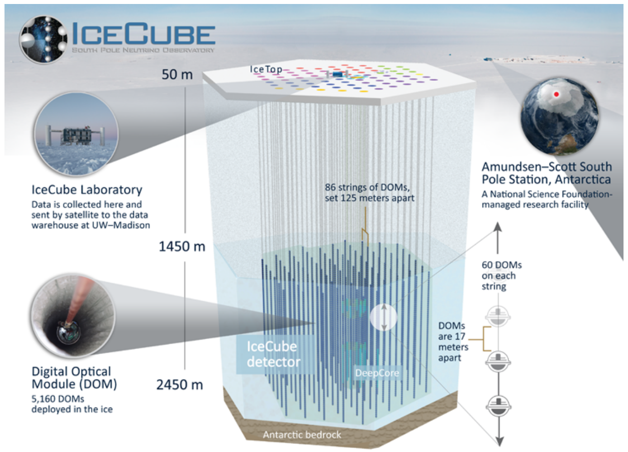
NuSTAR (hard X-ray)

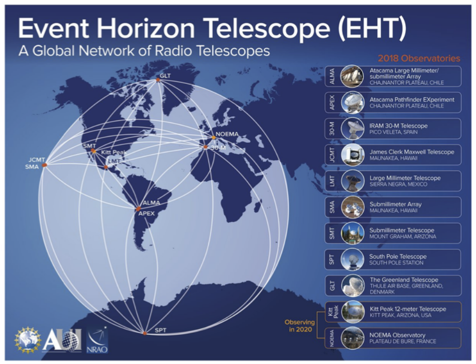


Integral (X-ray + MeV)



Swift and XMM (UV/X-ray)





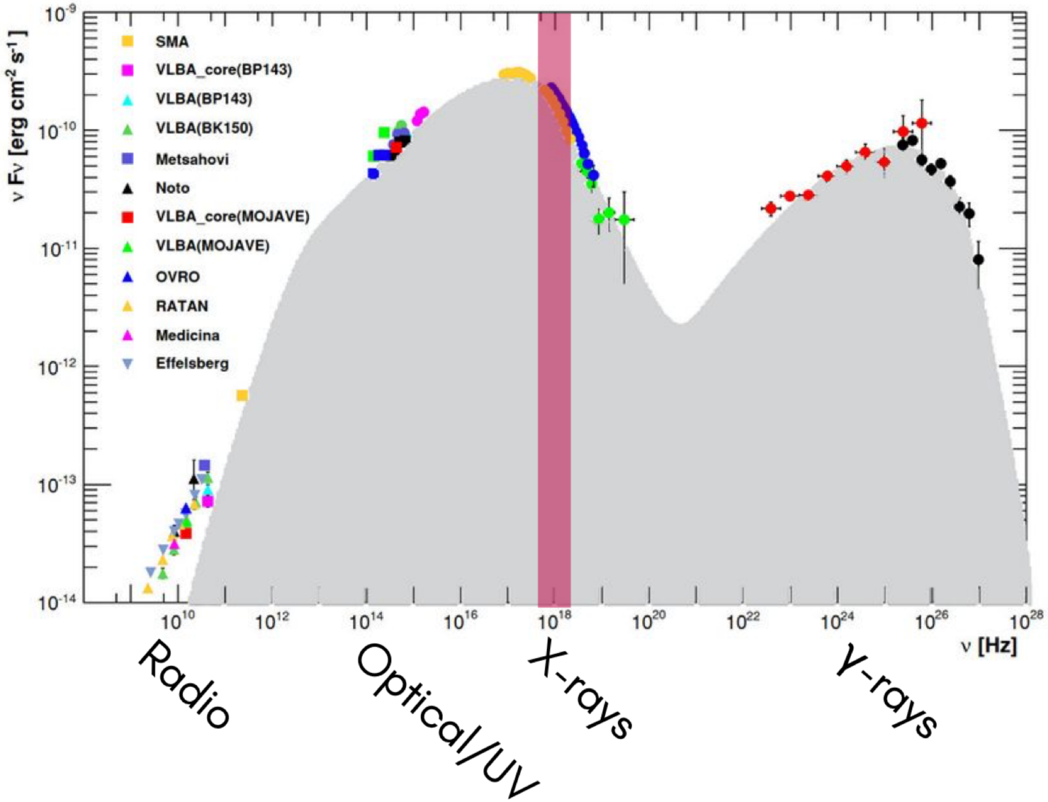
And many more...

A new window to study AGNs recently opened

→ X-ray polarization with the 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

<u>Crucial to correlate IXPE X-ray measurements with other wavelengths</u>

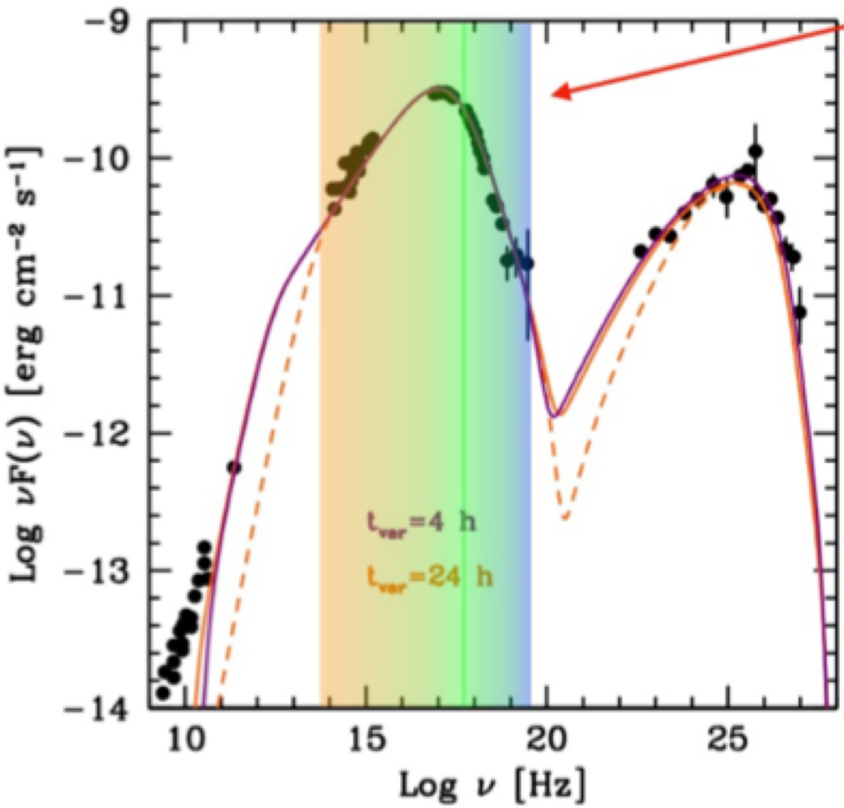
→ Imaging capabilities of IXPE (as well as most X-ray emissions) is ~20 arcseconds, which is not sufficient to resolve the structure of the objects. Variability and correlations needed to study the various locations of the multi-band emission

First observations of Mrk421 with IXPE occurred in May and June 2022

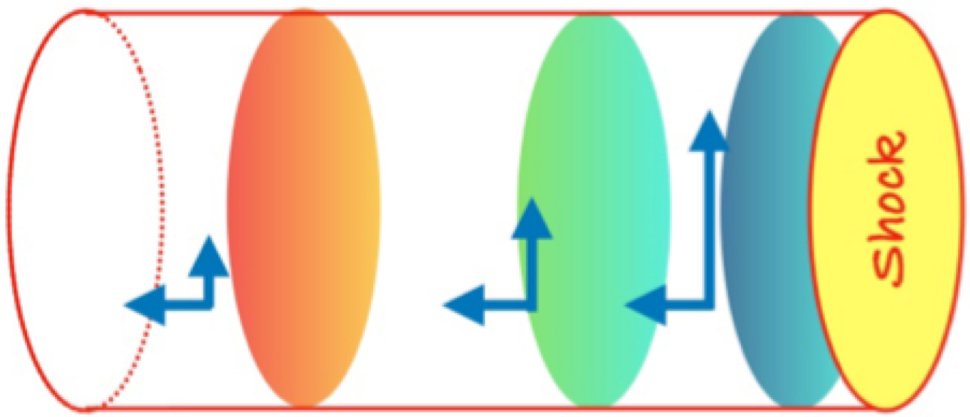
The IXPE team showed that the X-ray polarization degree of Mrk421 is about 2-5 times bigger than optical & about 5 times bigger than radio, which means that X-rays come from a region with higher order B field

Di Gesu et al, ApJL 2022, 938. + Di Gesu et al., Nature, 2023

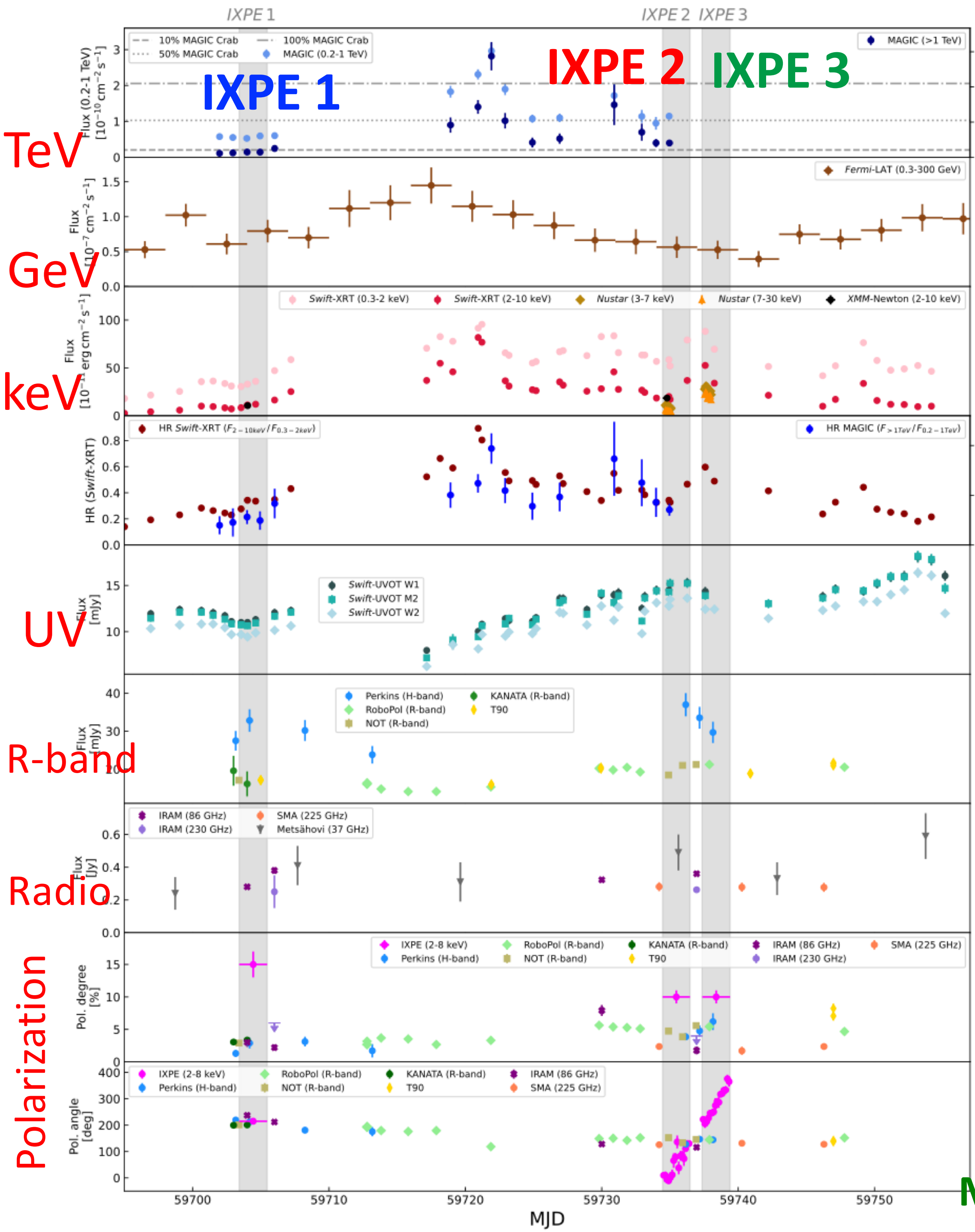
$$\nu_s \propto \gamma^2 B$$



→ Stratified jet



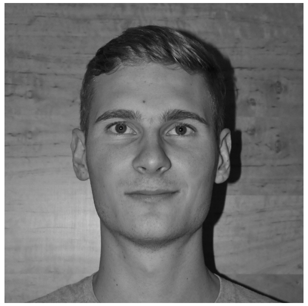
Tavecchio, 2021



First Multi-instrument observing campaign with IXPE of the bright AGN Mrk421

May-June 2022

Axel Arbet-Engels

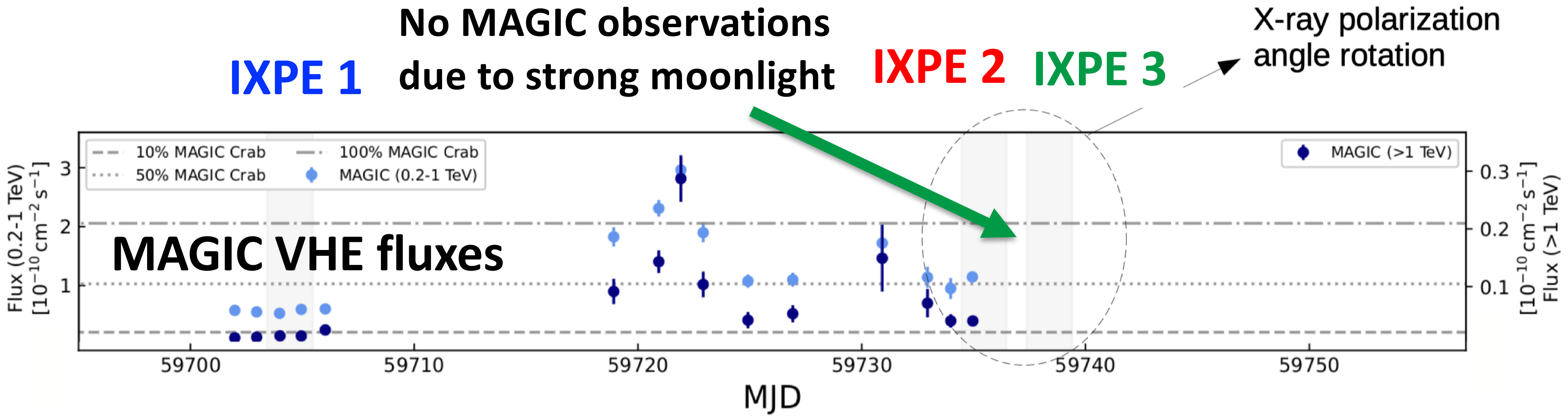


Felix Schmuckermaier

Good coverage of all energy bands

Polarization fraction in **X-rays** is larger than in **radio** and **optical**, although the alignment (EVPA) is approximately the same for IXPE-1 obs., **but rotation observed in IXPE-2 & IXPE-3**

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

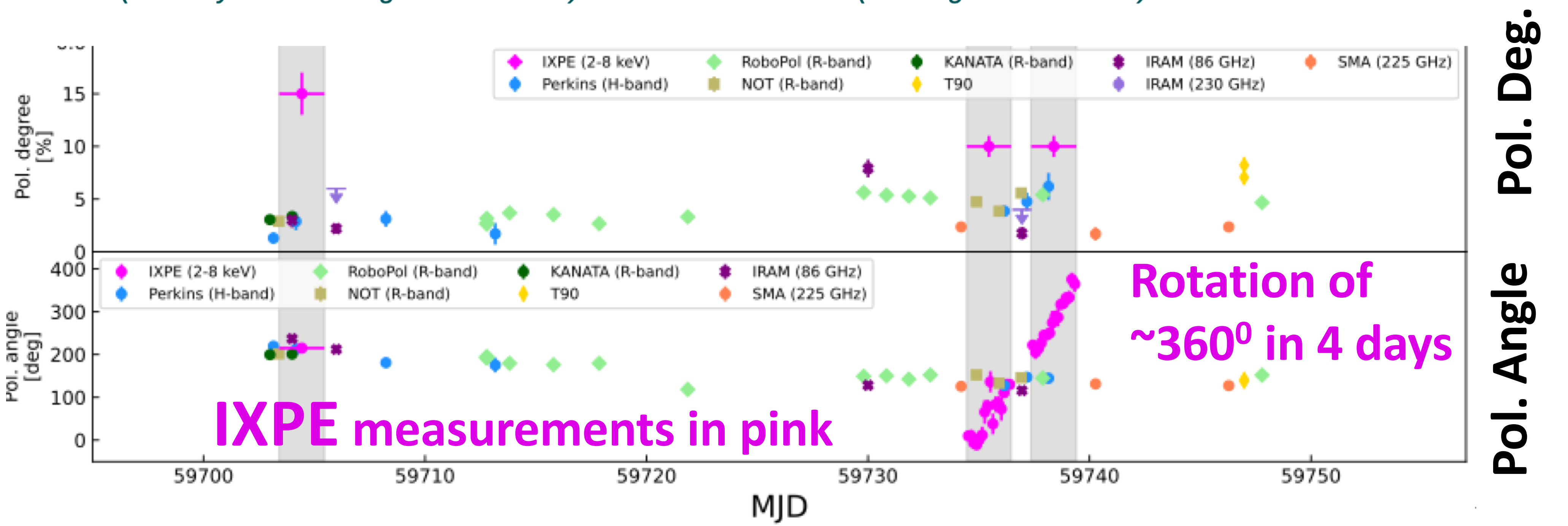


IXPE 1 epoch:
~ 25% Crab in 0.2-1TeV band

No significant VHE variability
(on daily and intranight timescales)

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

No significant VHE variability
(intranight timescales)



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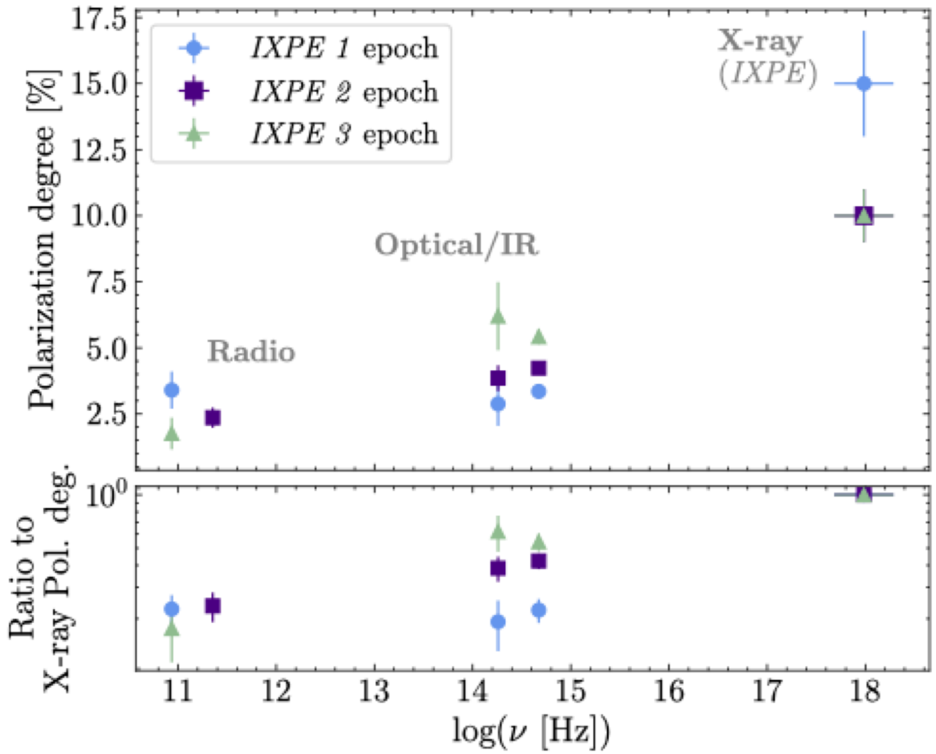
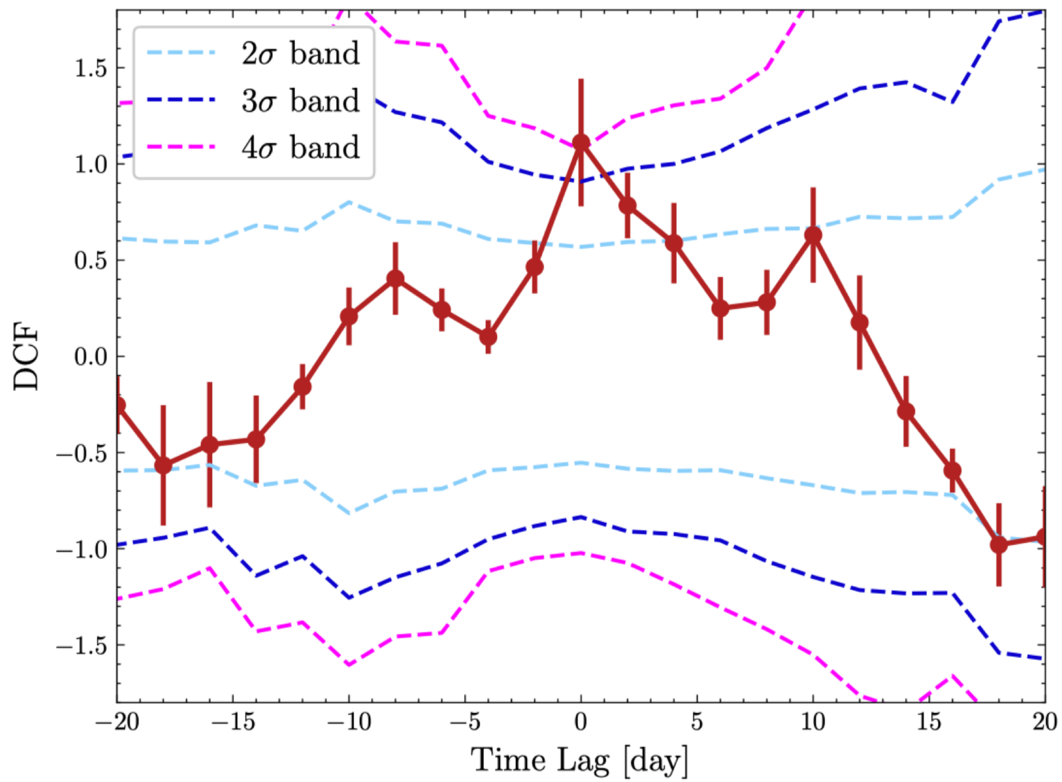


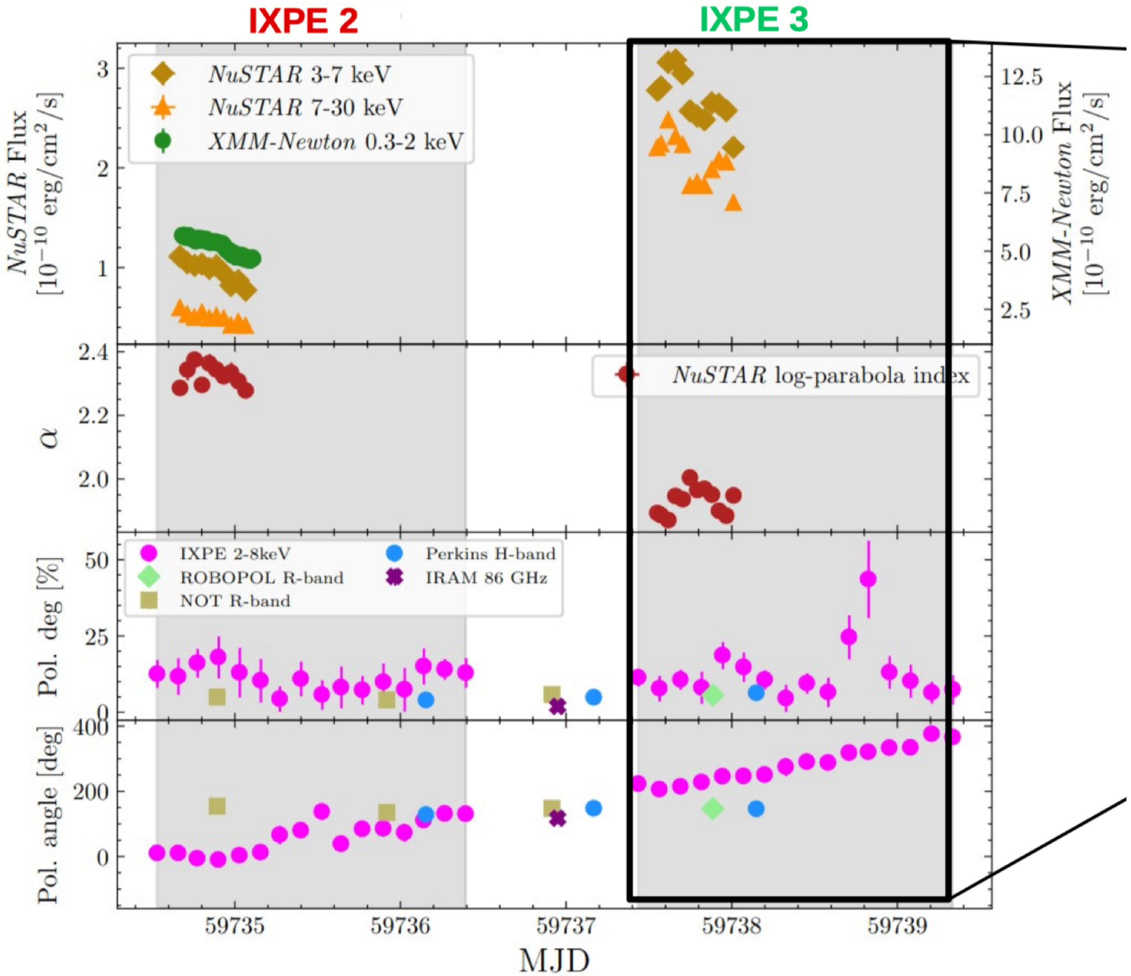
MAGIC Coll., 2024, A&A, 684, A127

MAGIC (0.2-1 TeV) vs Swift (2-10 keV)



MWL Data show TeV-keV correlation, and hence TeV emission also comes from highly-ordered B field region

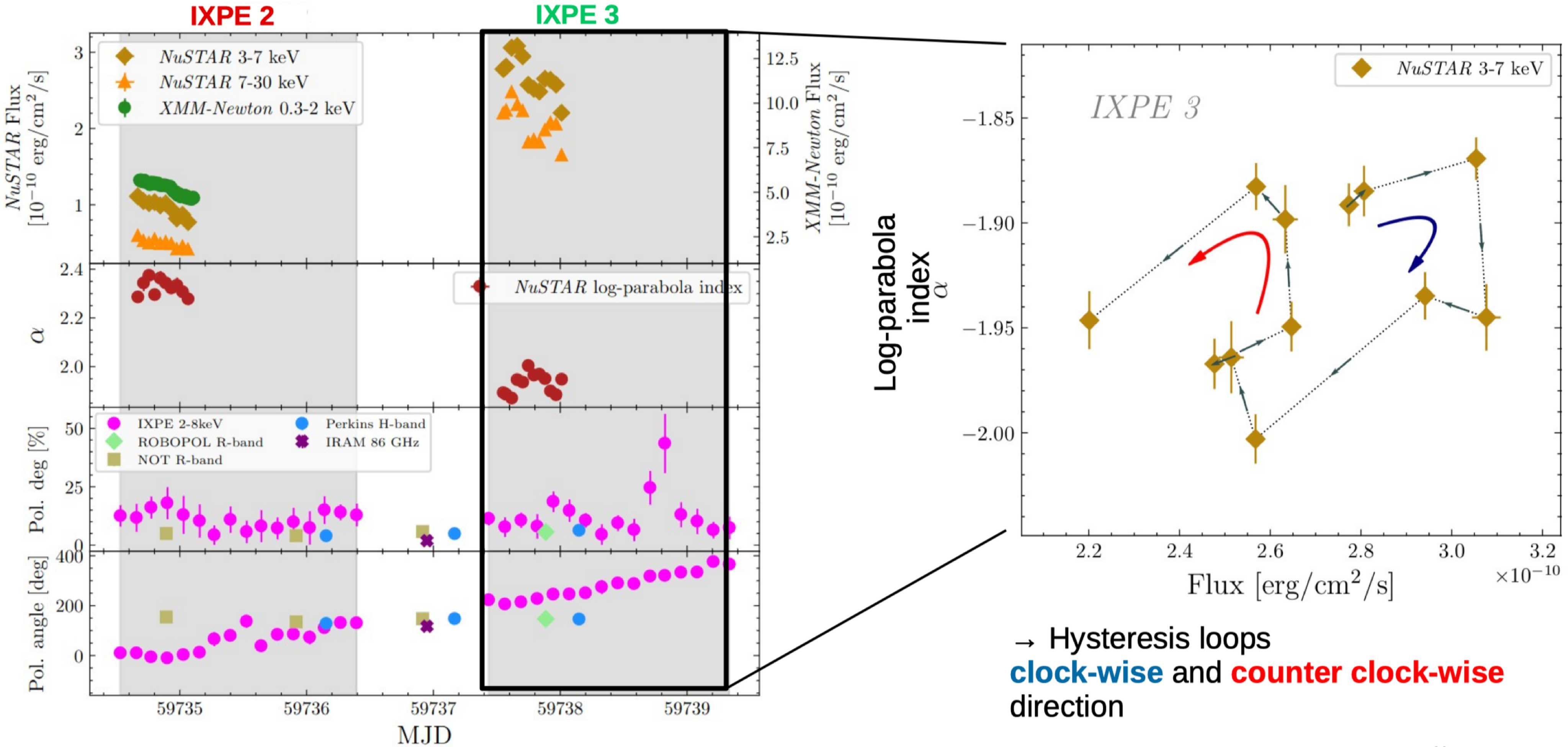
MAGIC Coll., 2024, A&A, 684, A127



Enchanced X-ray flux *(XMM and NuSTAR)* during IXPE-2 & specially for IXPE-3

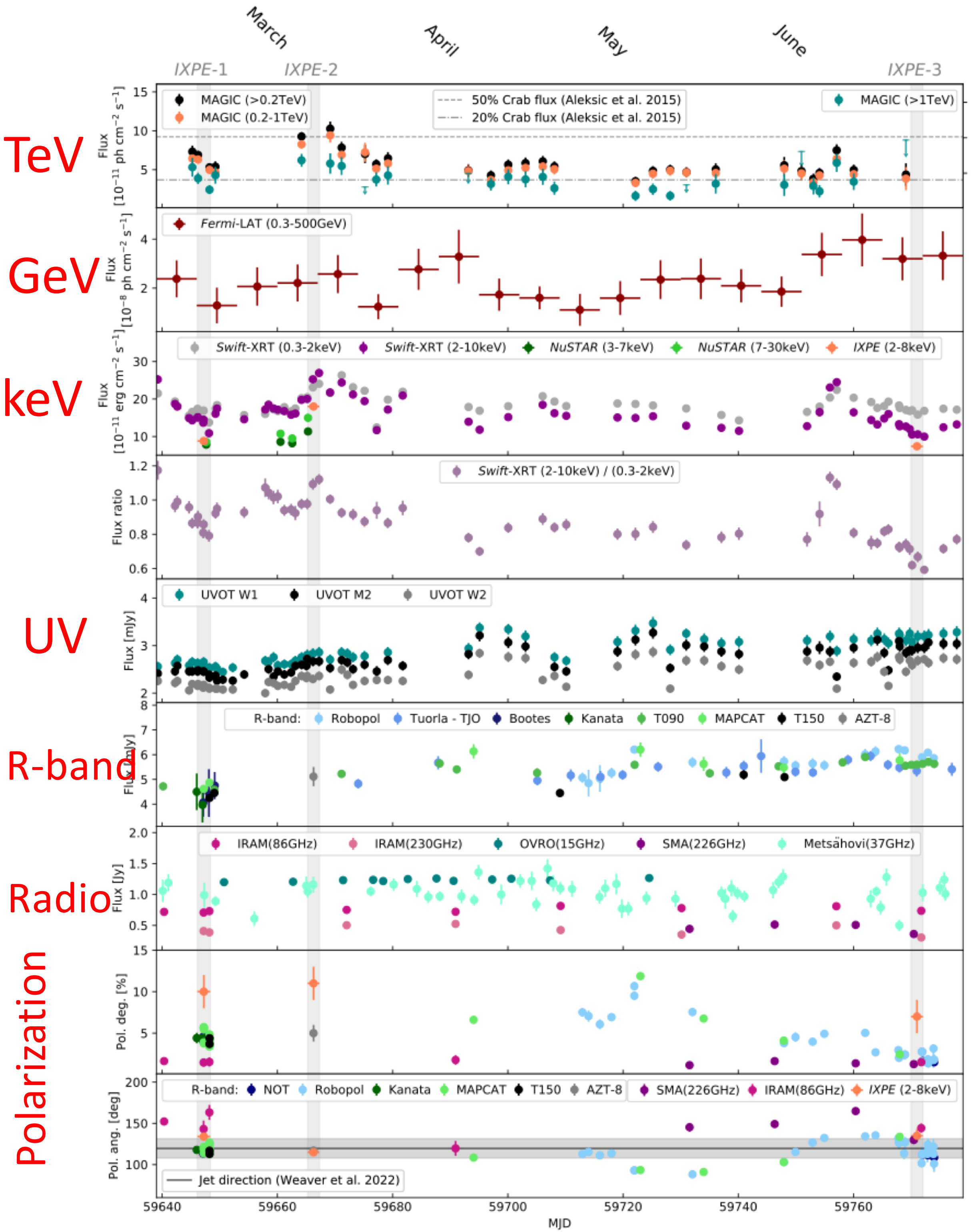
- TeV-keV correlation → TeV produced in region with **X-ray EVPA rotation**

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



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

- TeV-keV correlation → TeV produced in region with **X-ray EVPA rotation**
- NuSTAR during IXPE EVPA rotation shows **first spectral hysteresis with clock-wise (LE lags behind HE) & counter clock-wise (HE lags behind LE)**
  → **decrease in particle acceleration efficiency during rotation**



First Multi-instrument observing campaign with IXPE of the bright AGN Mrk501

March-July 2022

Axel Arbet-Engels

Lea Heckmann

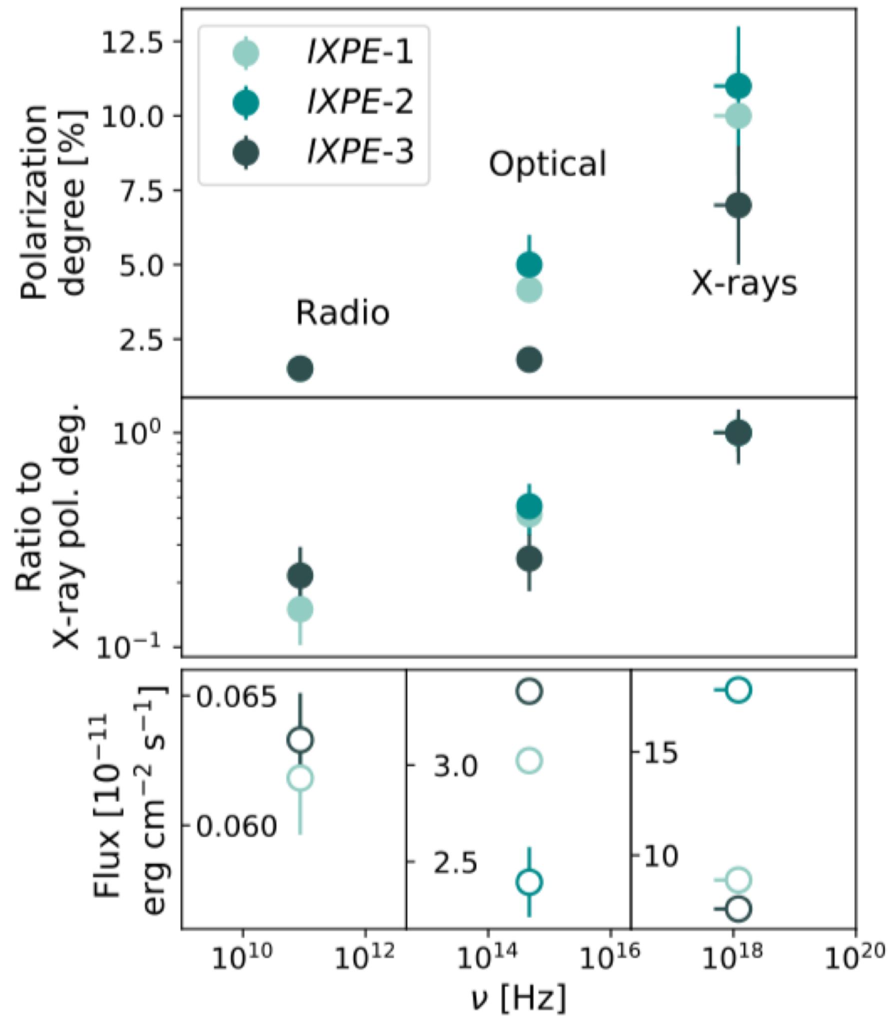
Good coverage of all energy bands

Polarization fraction in X-rays is larger than in radio and optical, although the alignment (EVPA) is approximately the same

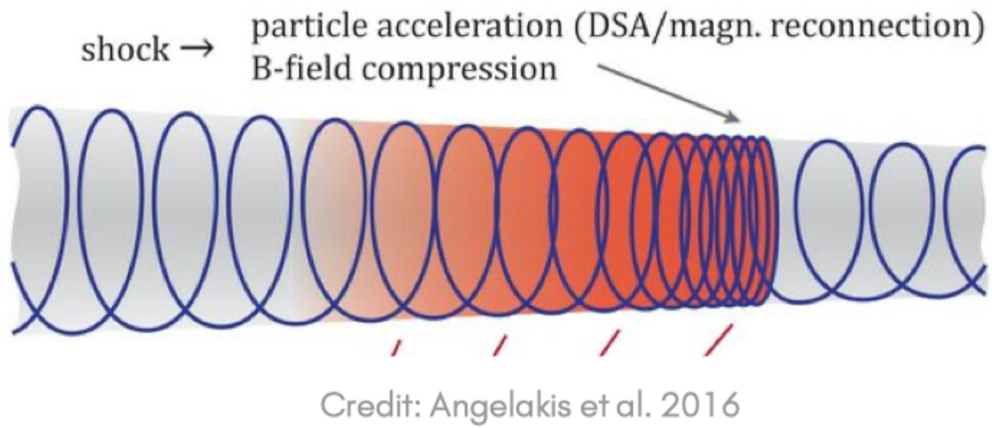
MAGIC coll. 2024, A&A, 685, A117

IXPE team showed that X-ray polarization fraction is about 2-4 times bigger than optical, and about 5 times bigger than radio, which means it comes from a region with higher ordered B field

Liodakis et al, 2022, Nature 611, 677 & Lisanda et al 2024 (submitted)



Shock acceleration in stratified jet



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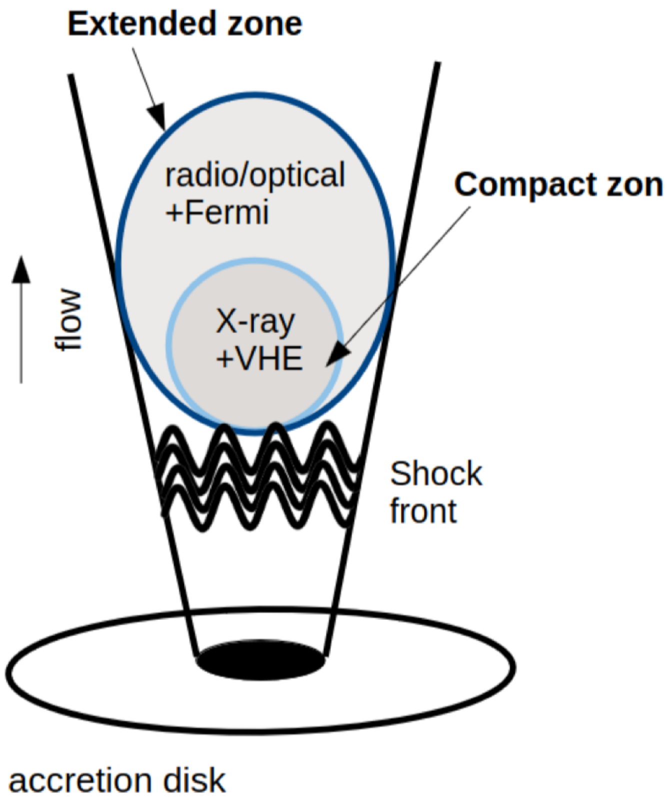
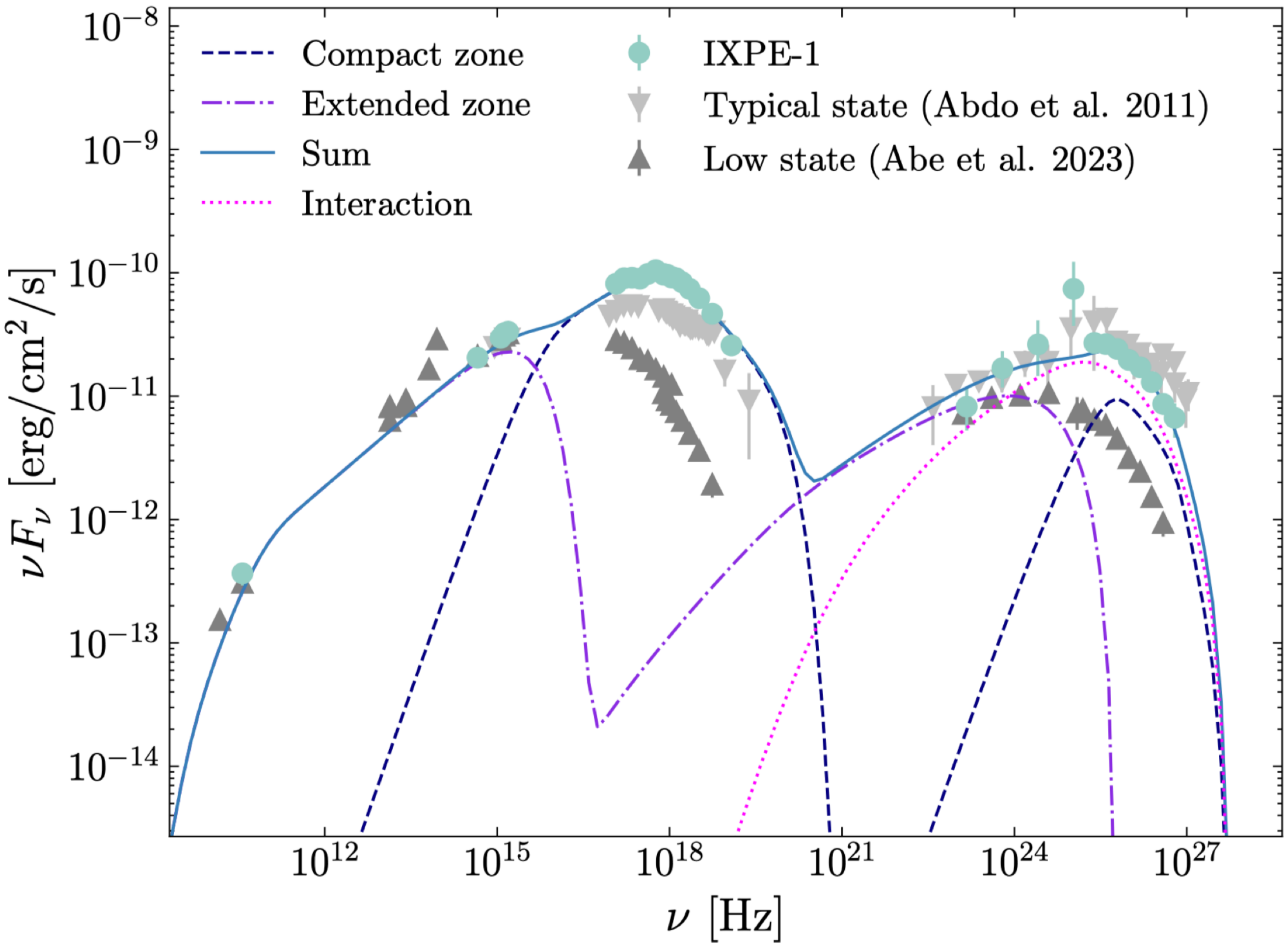
MAGIC coll. 2024, A&A, 685, A117

Broadband Spectral Energy Distribution (SED)

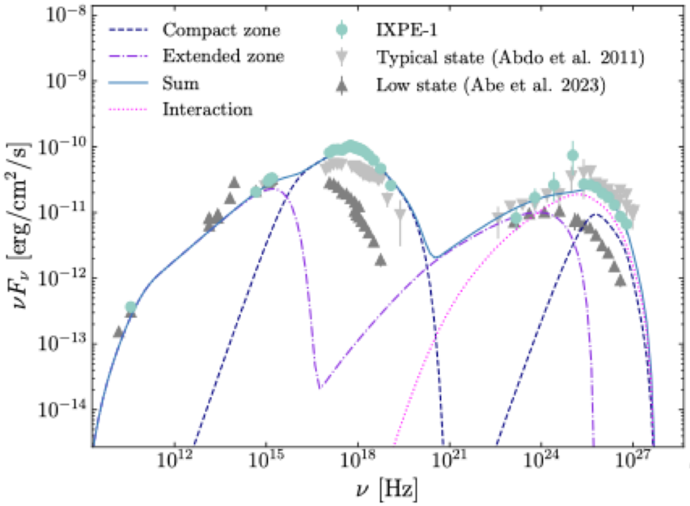
Description of the SED with a two-zone SSC theory model

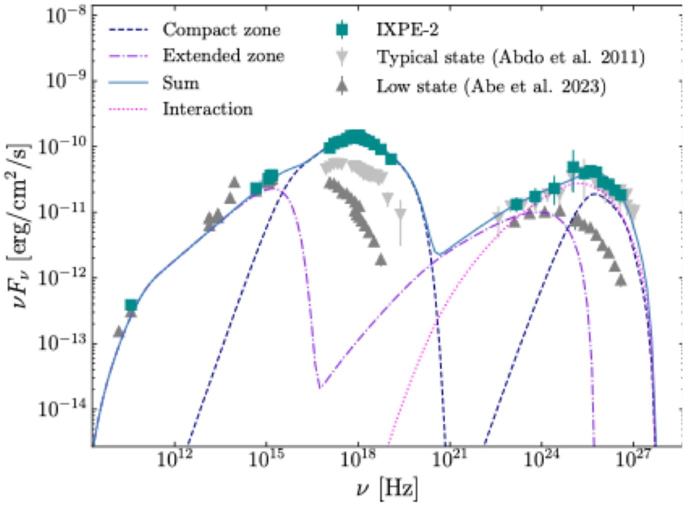
MAGIC coll. 2024, A&A, 685, A117

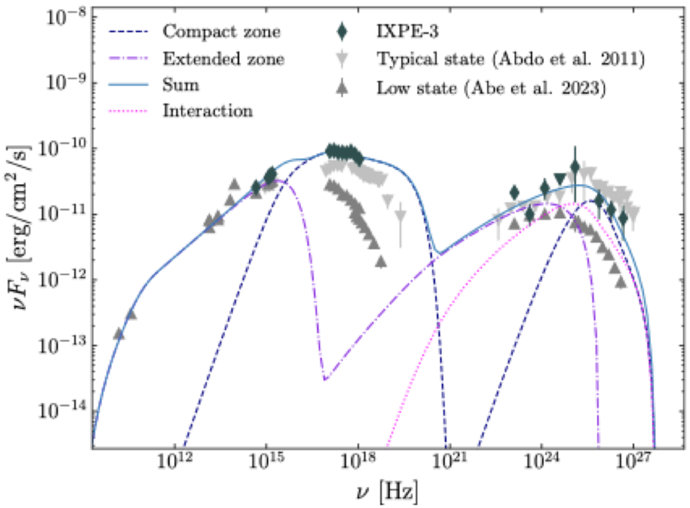




- Each component made of N turbulent plasma cells:
  - → Pdeg ~ 70% / N^0.5
  - → Relative size tuned to match observed optical/X-ray polarization







Measured SEDs during the 3 IXPE observations can be described with a two-zone SSC theoretical model

Table 3. Parameters of the two components of the leptonic model obtained for the three IXPE epochs.

Parameters	Compact zone			Extended zone		
	IXPE-1	IXPE-2	IXPE-3	IXPE-1	IXPE-2	IXPE-3
B' [10^{-2}G]	5.0	5.0	6.8	3.5	3.5	3.2
R' [10^{16}cm]	2.9	2.9	2.9	5.0	5.0	6.3
δ	11	11	11	11	11	11
U'_e [10^{-3} erg cm^{-3}]	0.8	1.2	0.8	2.8	2.8	2.0
n_1	2.37	2.25	2.20	2.2	2.2	2.2
n_2	4.00	3.67	3.20	(...)	(...)	(...)
γ'_{min}	5×10^4	4×10^4	3×10^4	2×10^2	2×10^2	2×10^2
γ'_{br}	6.0×10^5	6.0×10^5	1.6×10^5	(...)	(...)	(...)
γ'_{max}	5.5×10^6	5.5×10^6	4.8×10^6	5.7×10^4	5.7×10^4	7.2×10^4
U'_e/U'_B	8	12	4	57	57	50

Major change when going to IXPE-3 (from IXPE1/IXPE2) is in the magnetization and the emission region size

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

Conclusions

AGNs are intriguing & complicated "cosmic animals"

- This complexity can be hidden when the observations suffer from limited sensitivity, and limited **energy & time** coverage

→ Multi-band Variability & correlation studies *(from minutes to year timescales)* can be used to break degeneracies among theoretical scenarios

→ Extensive MWL campaigns on bright AGNs bring crucial information

→ Specially interesting when using novel instrumentation (*e.g., IXPE, EHT …*)

Conclusions

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→ Multi-band Variability & correlation studies *(from minutes to year timescales)* can be used to break degeneracies among theoretical scenarios

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IXPE opened a new window to better study AGNs, especially when combining the X-ray polarization results with the full MWL picture:

- VHE co-spatial to X-ray region

→ X-ray polarization provides constraints to the VHE emission

- X-ray polarization angle rotation in Mrk421 together with X-ray spectral hysteresis on hours → evolution of particle acceleration

- Energy stratified jet with different emission regions

→ Can be described with a two-zone scenario

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

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

+ more coming soon…

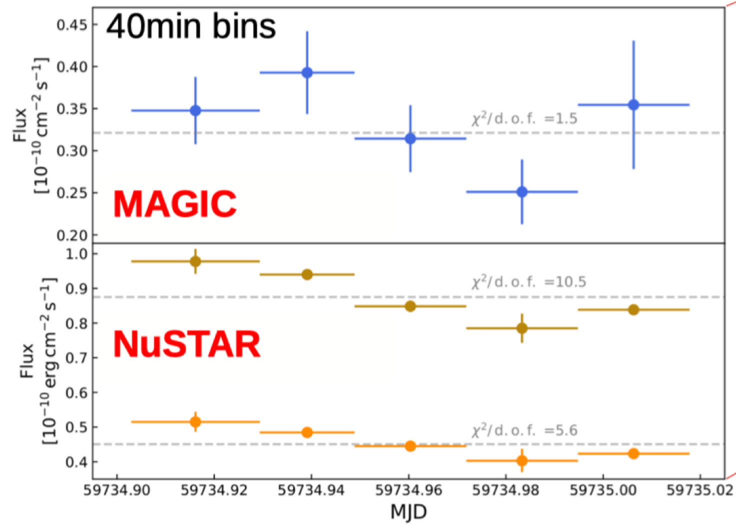
Backup

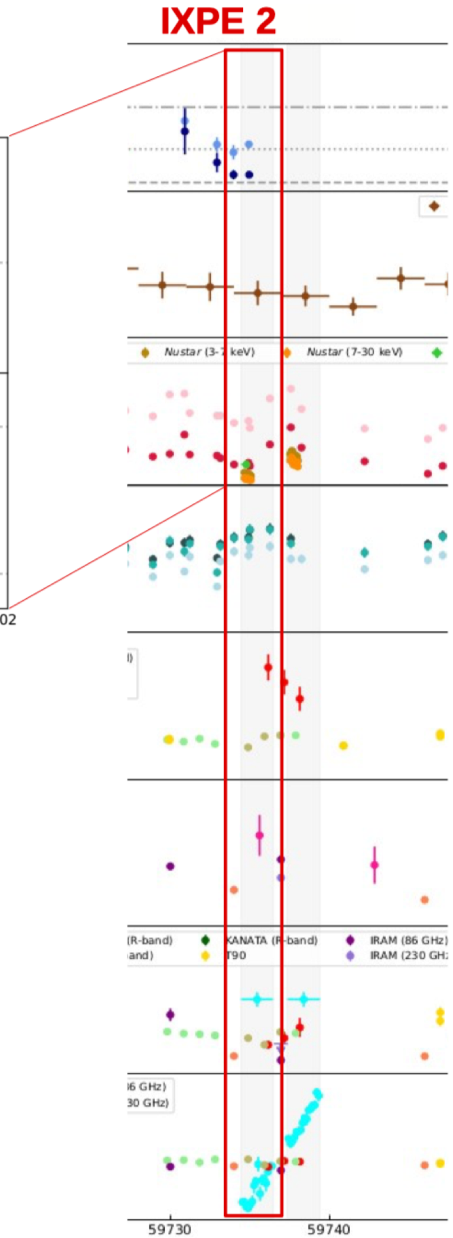
Mrk 421

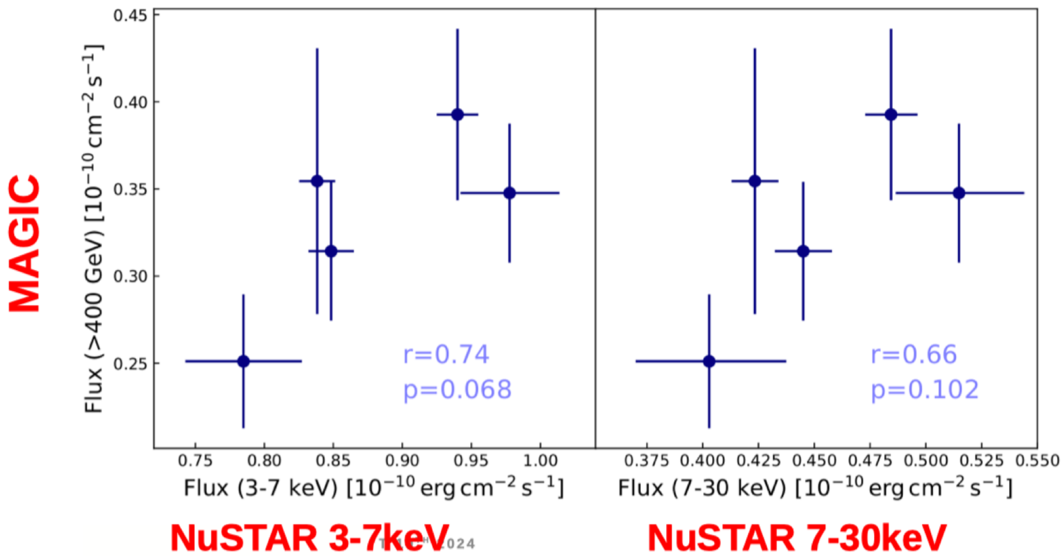
Axel Arbet-Engels et al., Fermi symposium 2024 (Maryland, September 2024)

VHE versus X-ray Correlation

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







Mrk 501

Lea Heckmann et al., Gamma-2024 conference (Milano, September 2024)

- 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

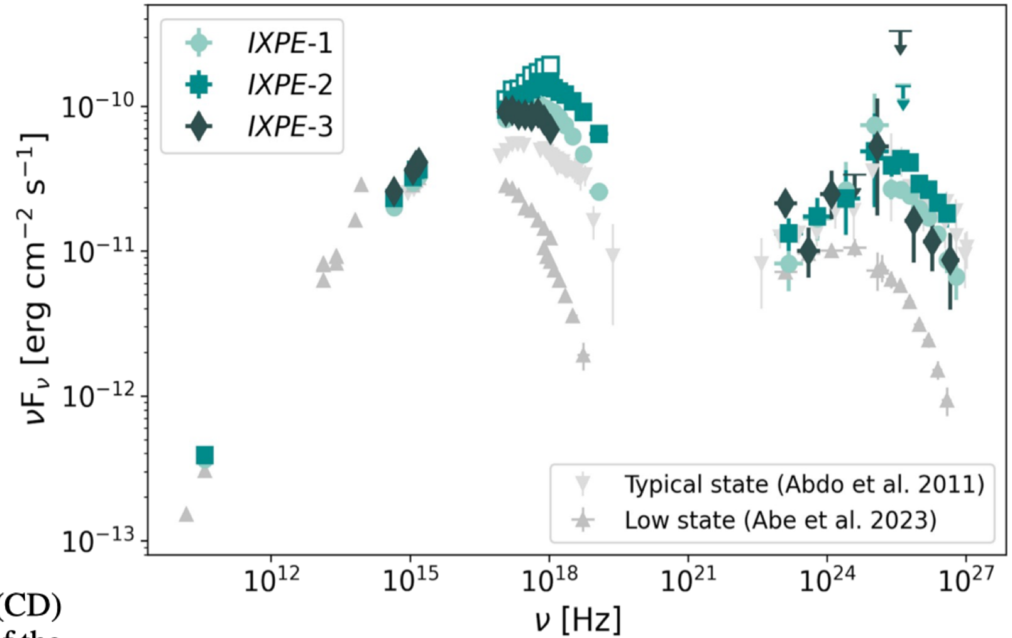


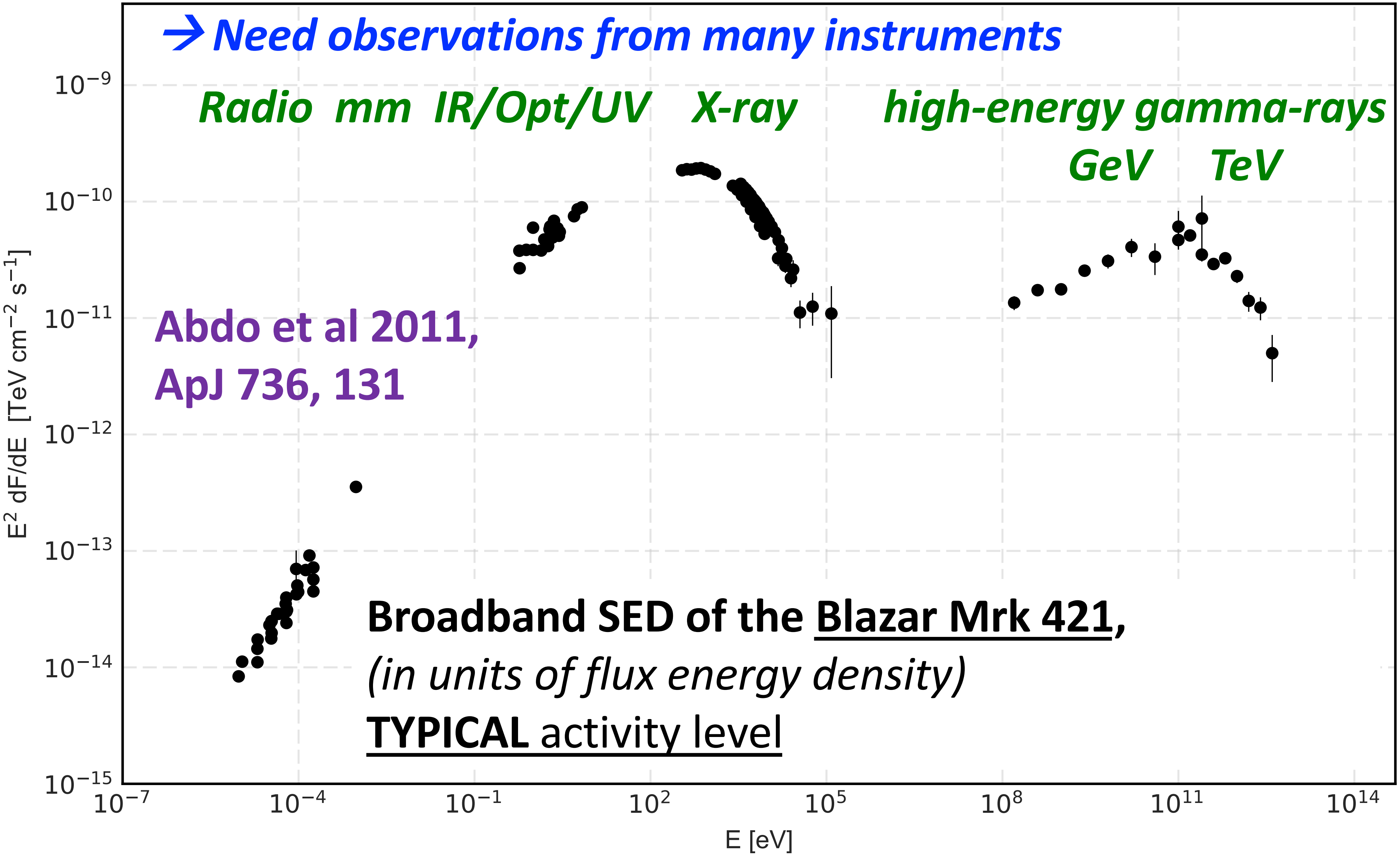
Table 2. Peak frequencies, ν_s and ν_{IC}, and Compton dominance (CD) for the different SEDs shown in Fig. 2 extracted from the maxima of the phenomenological description of Ghisellini et al. (2017).

States	ν_s [Hz]	ν_{IC} [Hz]	CD
IXPE-1$_{pheno}$	$5.4 \pm 0.2 \times 10^{17}$	$2.0 \pm 0.4 \times 10^{25}$	0.30 ± 0.07
IXPE-2$_{pheno}$	$7.9 \pm 0.6 \times 10^{17}$	$3.0 \pm 0.5 \times 10^{25}$	0.28 ± 0.06
IXPE-3$_{pheno}$	$1.0 \pm 0.1 \times 10^{17}$	$4.5 \pm 5.9 \times 10^{24}$	0.20 ± 0.27
Typical$_{pheno}$	$2.9 \pm 0.1 \times 10^{17}$	$4.6 \pm 0.8 \times 10^{25}$	0.49 ± 0.10
Low$_{pheno}$	$1.3 \pm 0.1 \times 10^{16}$	$1.8 \pm 0.4 \times 10^{24}$	0.26 ± 0.10

Observational challenge 1:

AGNs emit over a very wide energy range

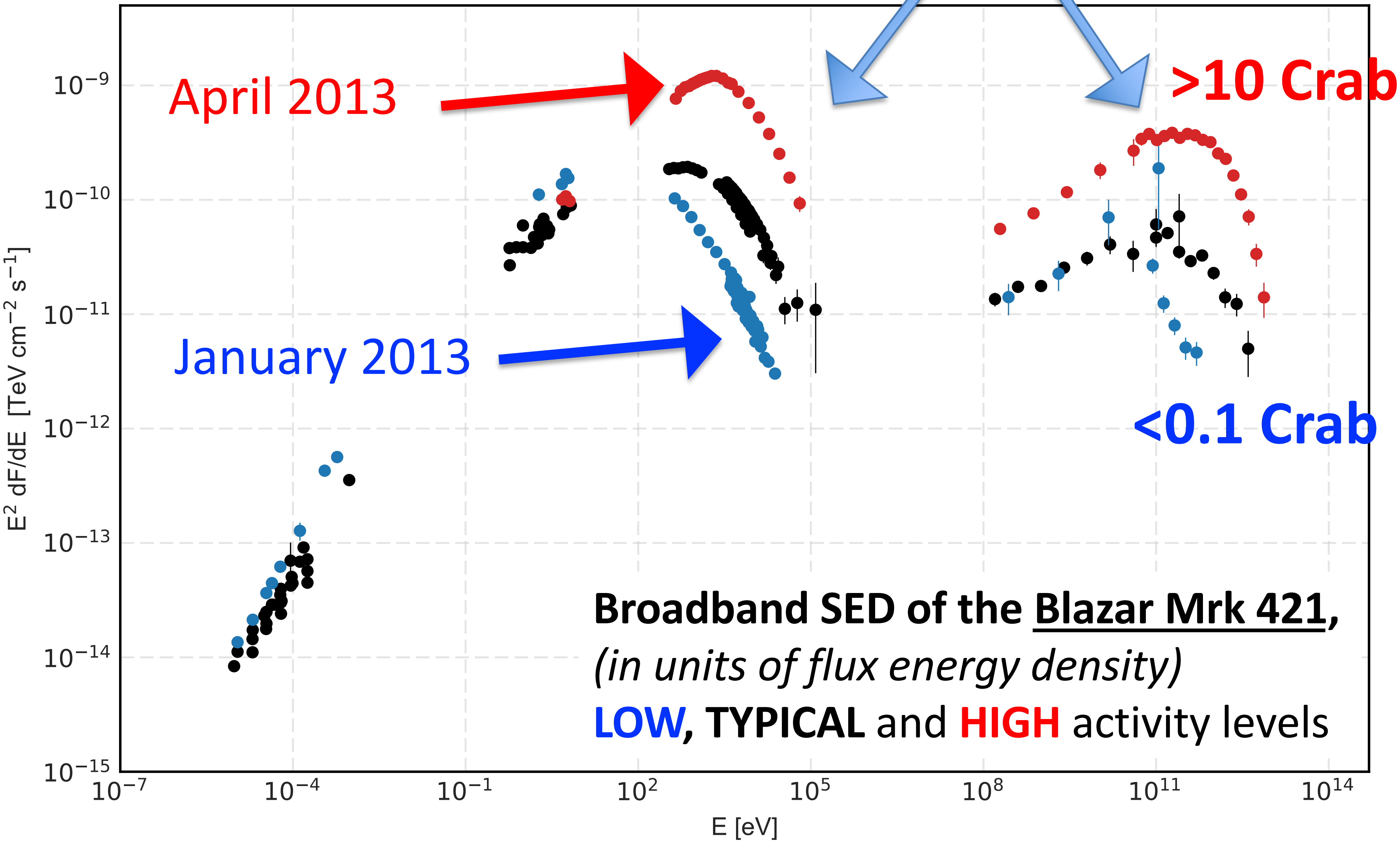
Emission at different energies could be produced by same particles



Observational challenge number 2:

AGNs show flux variations by orders of magnitude, on various timescales

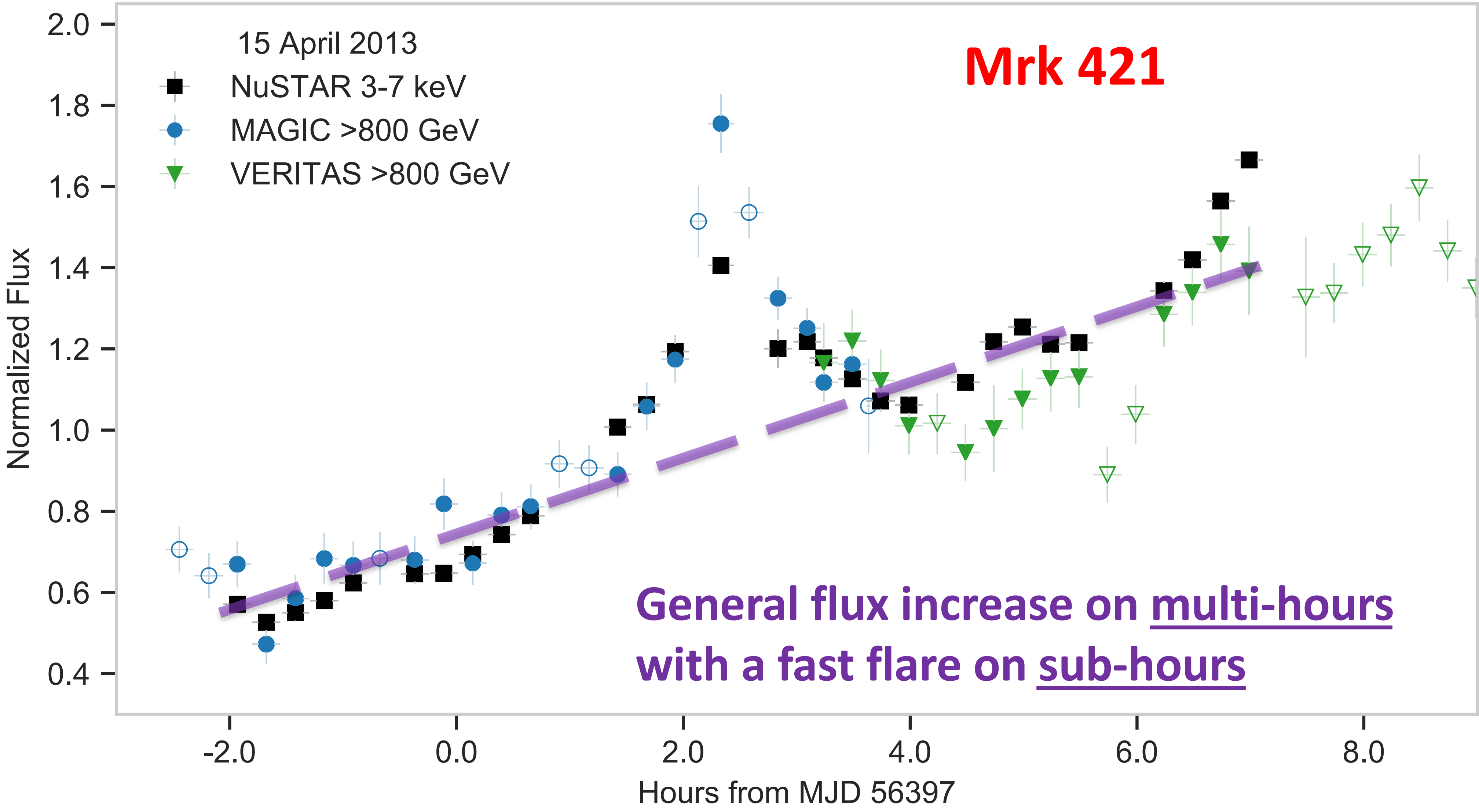
Change of energy flux by 2 orders of magnitude at X-rays and Gamma rays



Broadband SED of the Blazar Mrk 421,
(in units of flux energy density)
LOW, TYPICAL and **HIGH** activity levels

Variability & Correlations in Blazars: Mrk421

Acciari et al. ApJS 2020, 248, 29

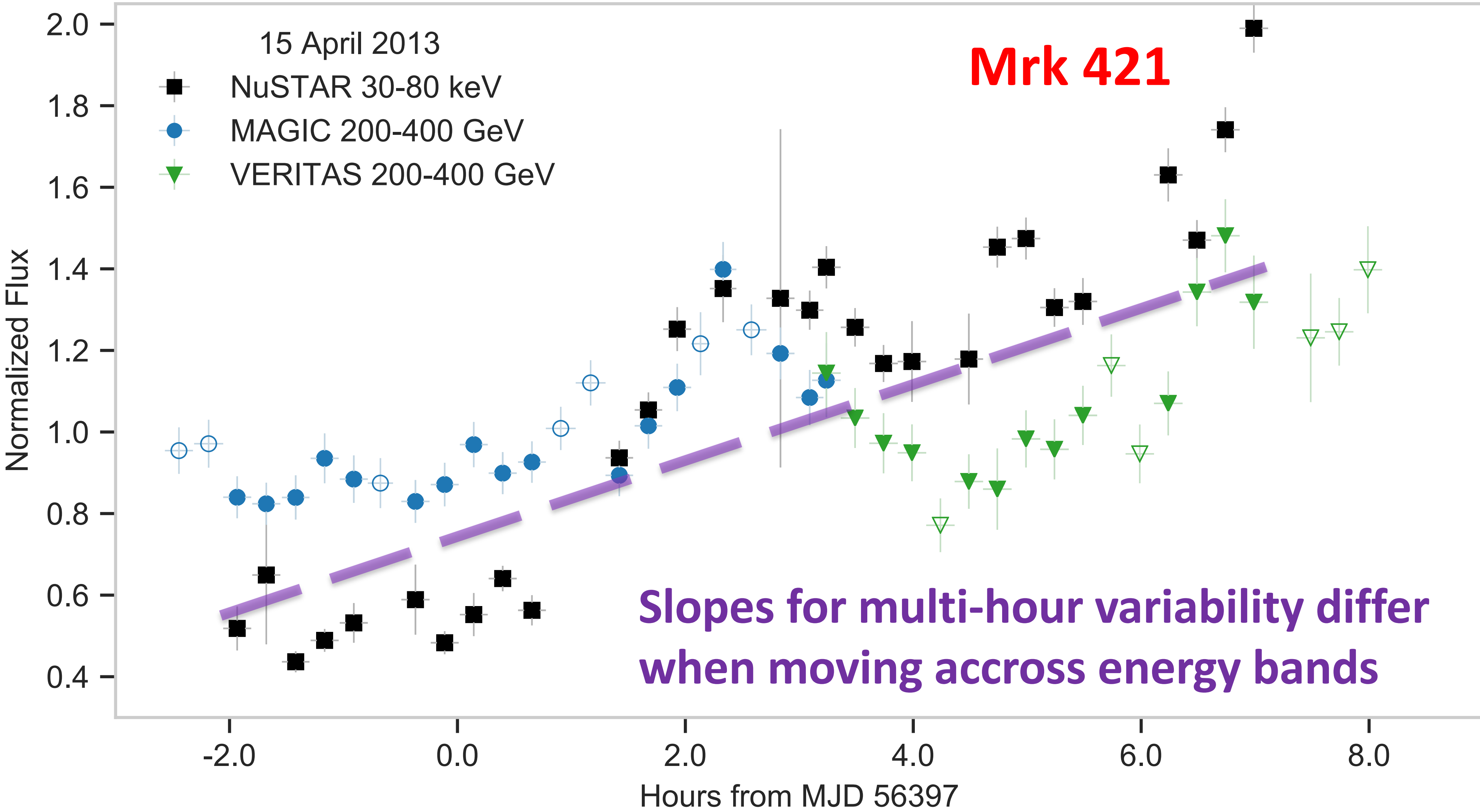


Normalized flux: flux normalized to night mean flux from simultaneous data

Full markers indicate time bins with strictly simultaneous VHE/X-ray data

Variability & Correlations in Blazars: Mrk421

Acciari et al. ApJS 2020, 248, 29



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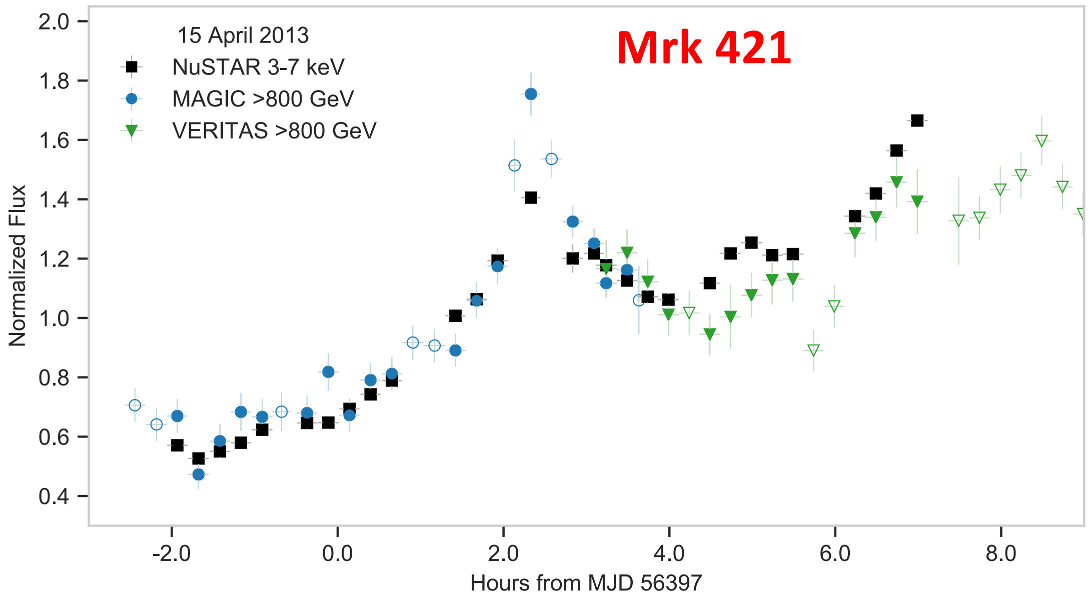
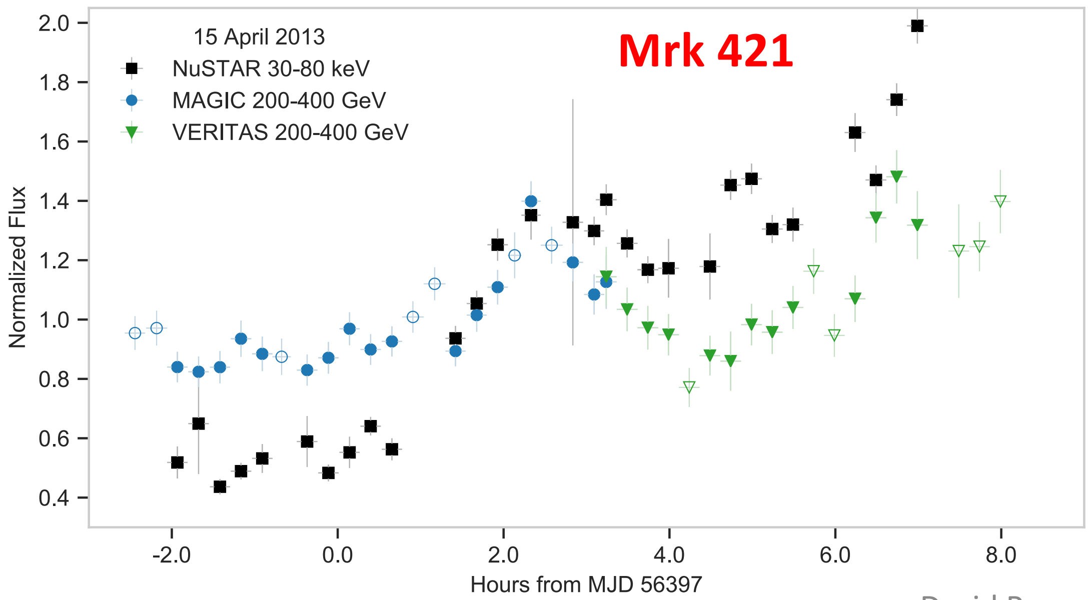


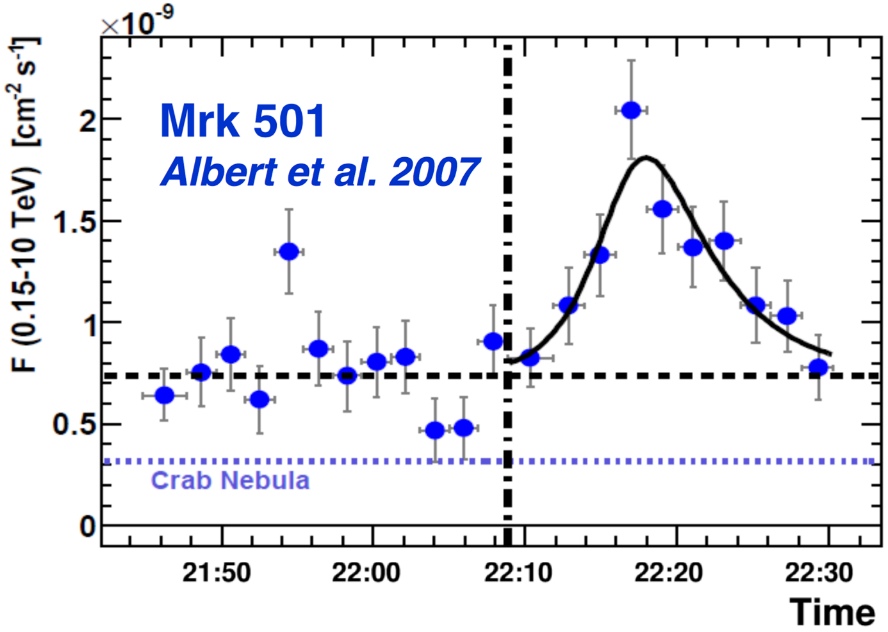


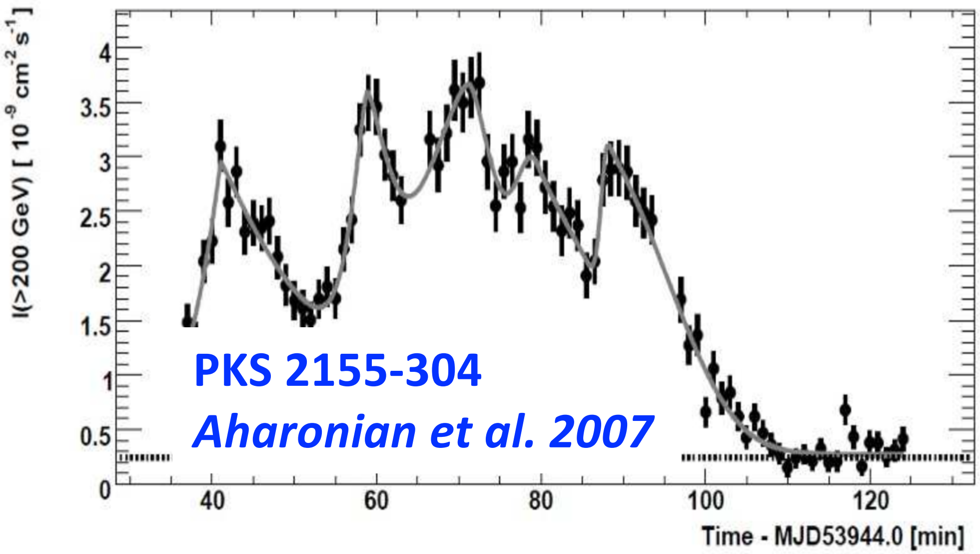
MAGIC + VERITAS >0.8 TeV
NuSTAR 3-7 keV

Large change in the overall shape and structure of LCs when moving across X-ray and VHE bands

MAGIC + VERITAS 0.2-0.4 TeV
NuSTAR 30-80 keV

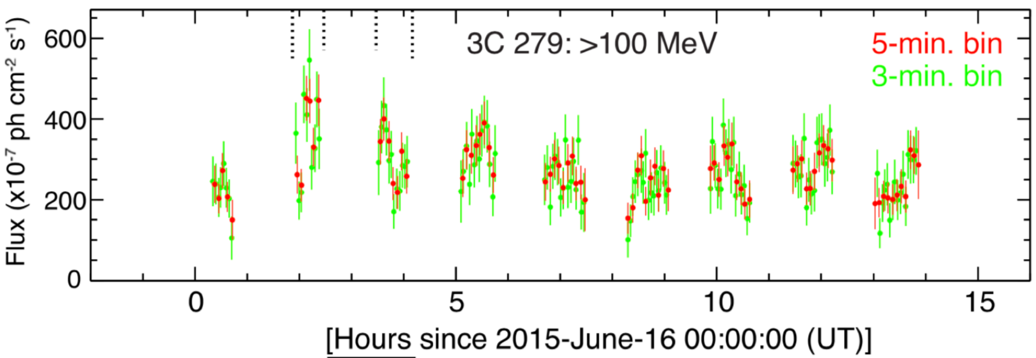
AGNs show SHORT variability timescales

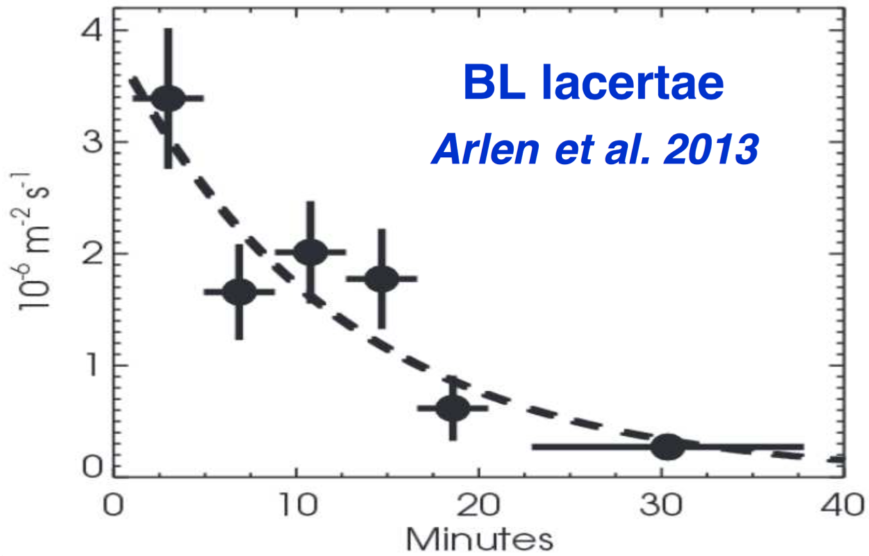




3C279

Ackermann et al 2016





Sub-hour (→minute) variability seen in many blazars by now

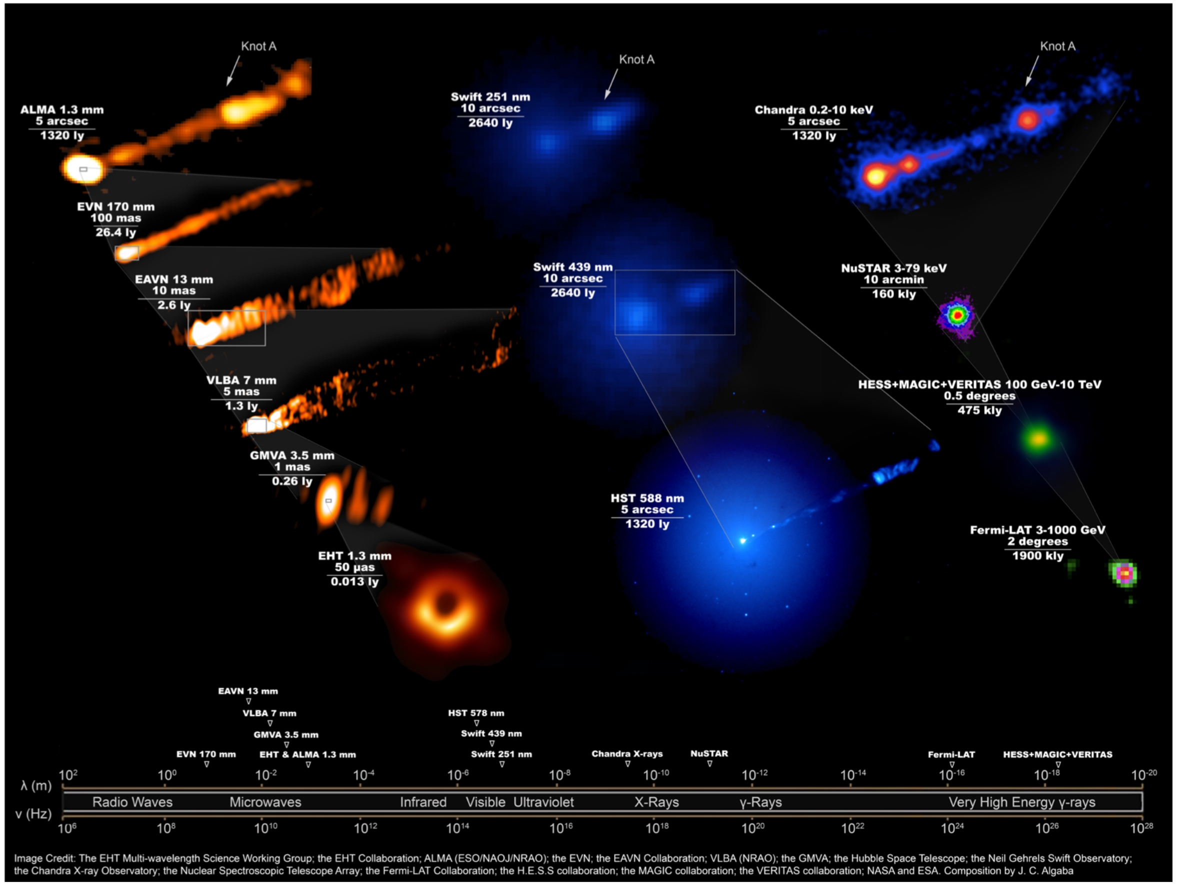
Fast flux variations are difficult to resolve, and even more difficult to observe them simultaneously with many instruments

Observational challenge number 3:

Apparent morphology of AGNs “differs with energy”

Shape of AGNs depend on the energy band used to characterize it. Moreover, the angular resolution of available instruments goes from **~10^{-4} arcsec at radio (10^{-5} arcsec with EHT) to ~0.1 deg at gamma rays**

→ *This complicates the comparison of the images at different energies*



EHT+Fermi+HESS+MAGIC +VERITAS+ NuSTAR + Chandra + Hubble + … Algaba et al 2021, ApJL 911, L11