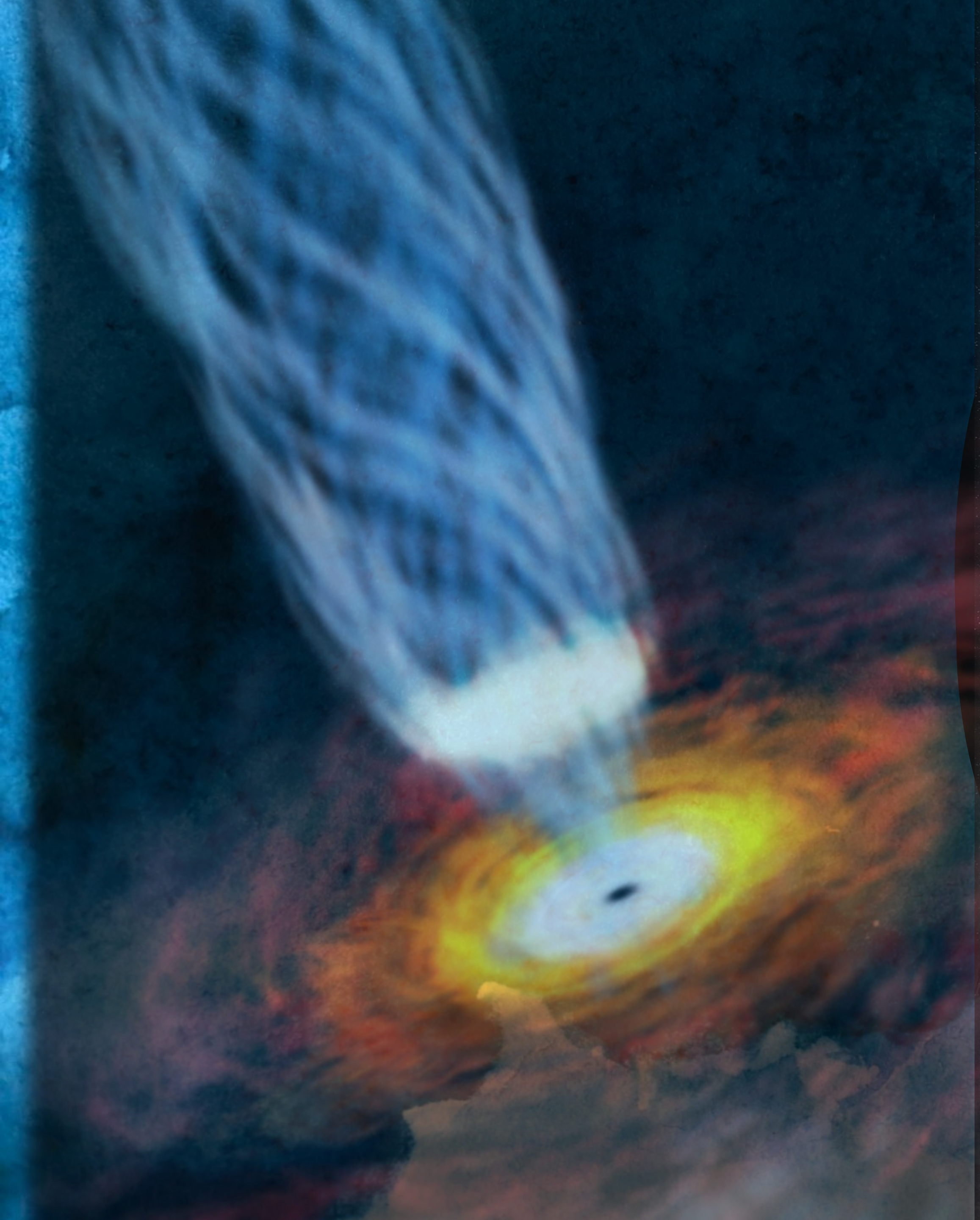


# Synergies between IXPE and MAGIC observations of blazars

Elisa Prandini

Padova University and INFN

# Blazars

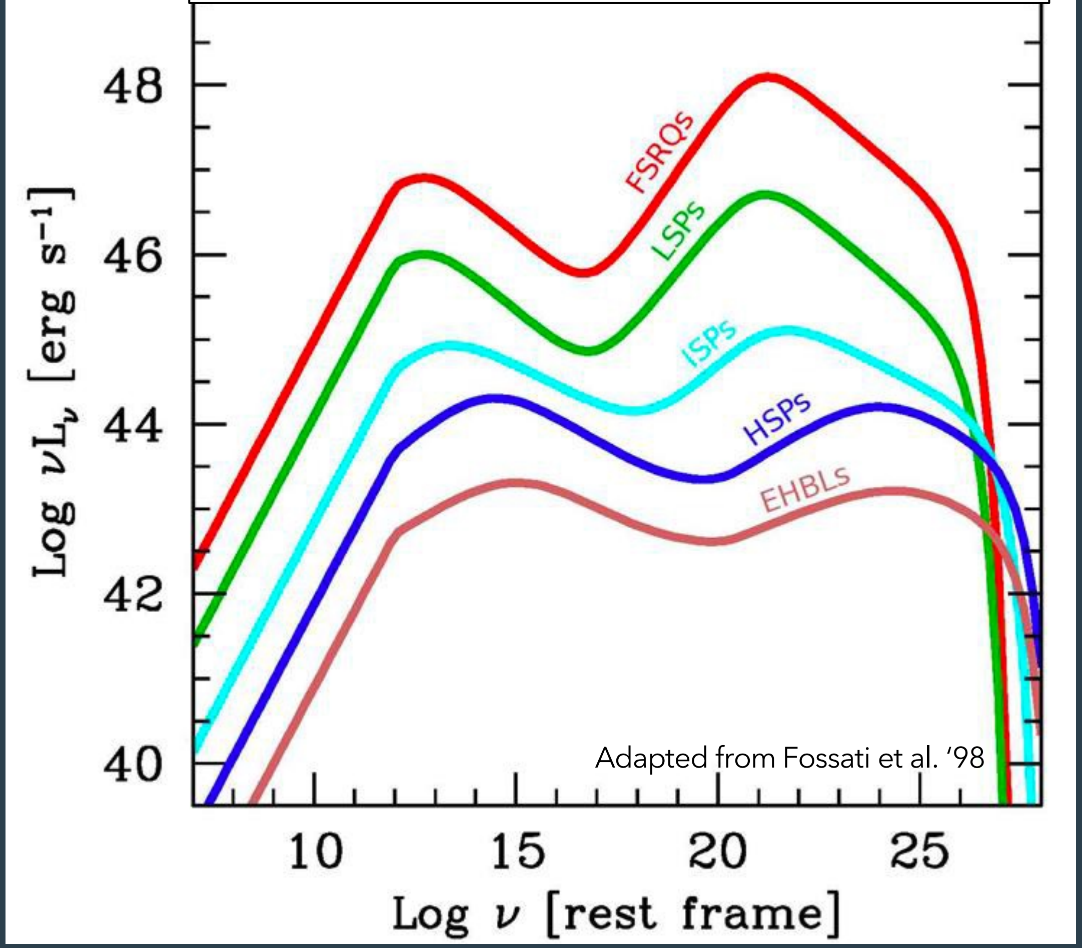
- Blazars: active galaxies with a relativistic jet pointing towards the observer

- Electromagnetic emission dominated by physical processes of accelerated particles in the jet (electrons+possibly hadrons)

- Classified according to the emission lines in the optical spectrum
  - FSRQ (strong lines, EW>5Å)
  - BL Lac objects

- BL Lacs further classified according to the synchrotron peak location of their SED

**Schematic view of blazars spectral energy distribution (SED)**

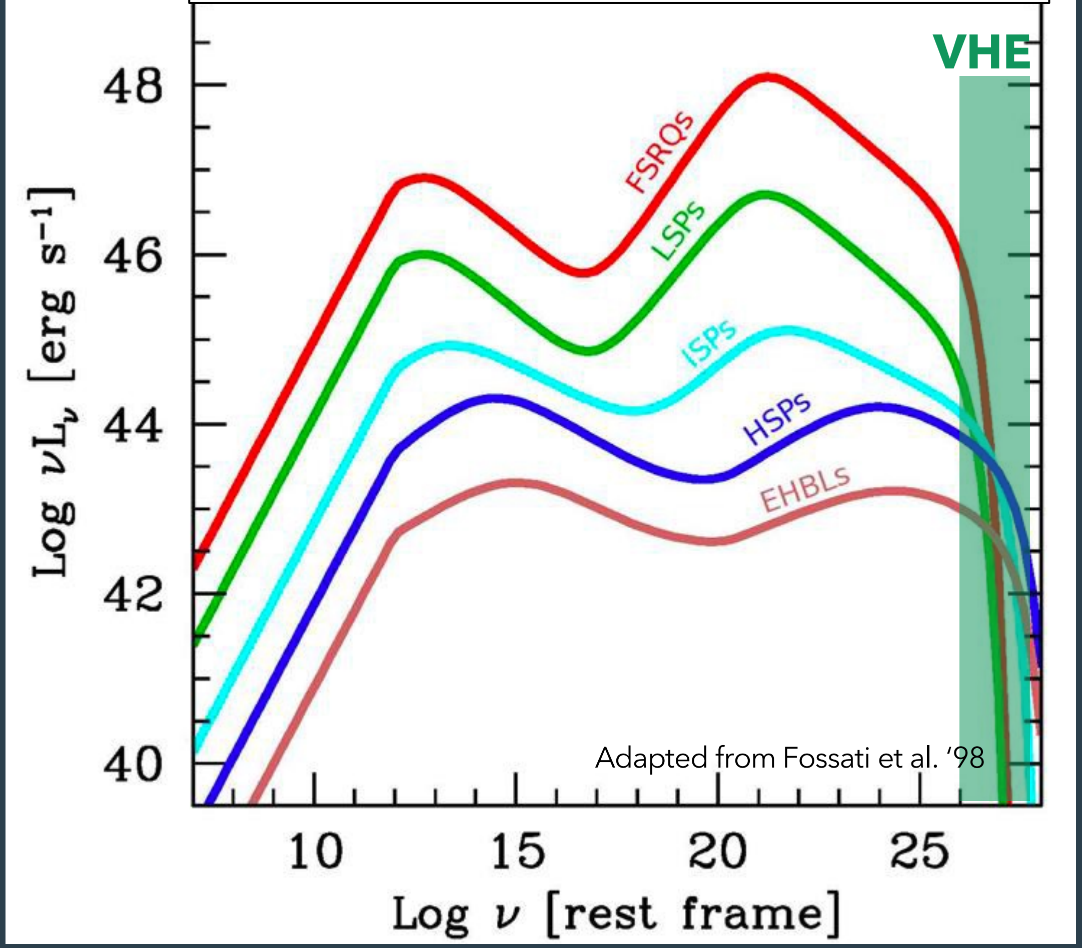


# Blazars at the highest energies

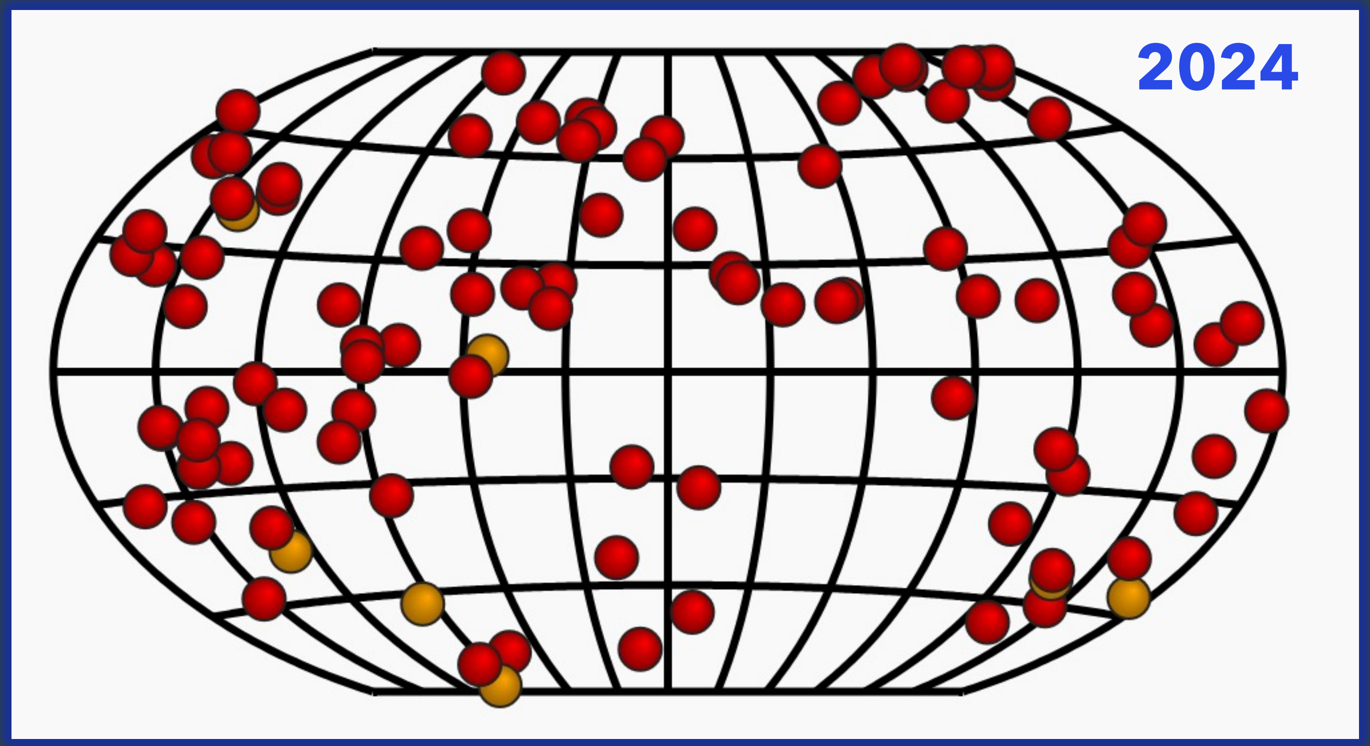
**VHE**: very high energy emission, defined as energy > 100 GeV (2.4 x 10^25 Hz)

- VHE observations of blazars cover the decreasing part of the second SED peak.
- Interestingly, the VHE flux is fainter for bright objects, such as FSRQs (threshold effect)

**Schematic view of blazars spectral energy distribution (SED)**



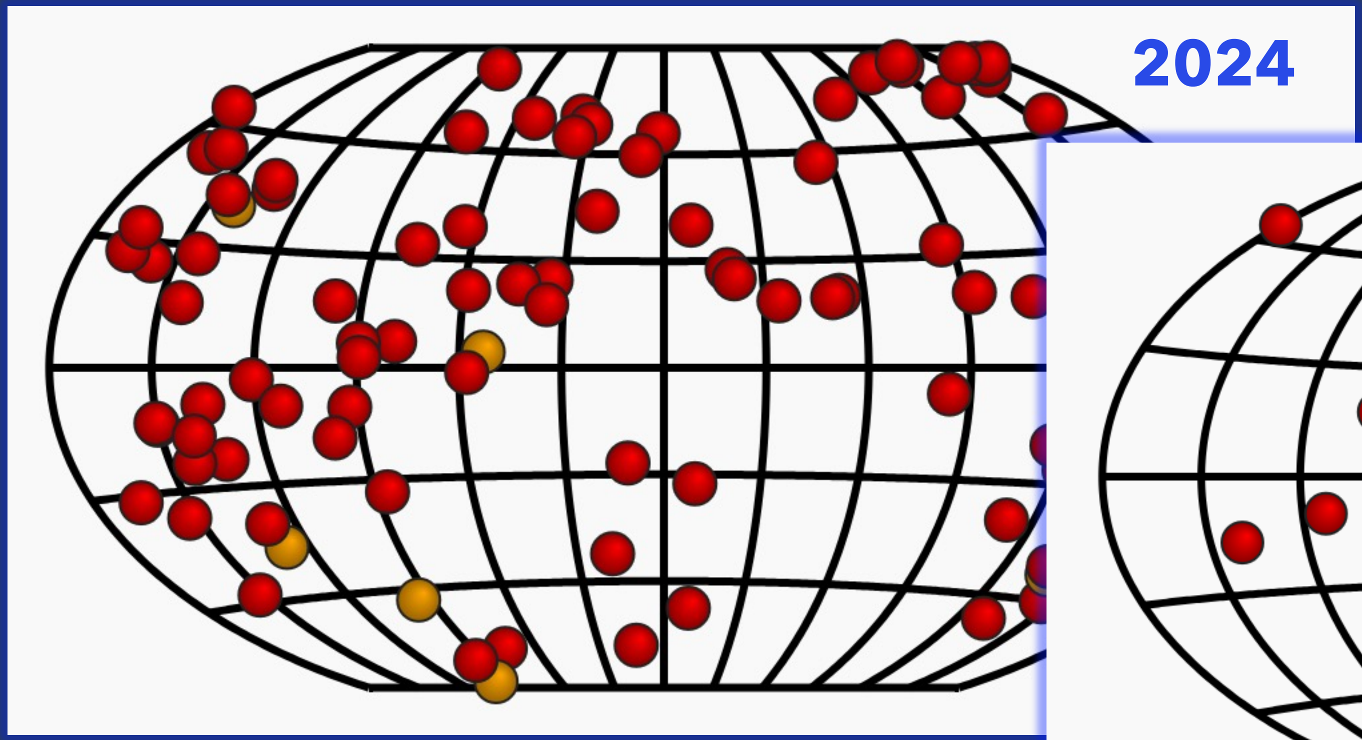
# TeVCAT: a catalogue for TeV-detected sources

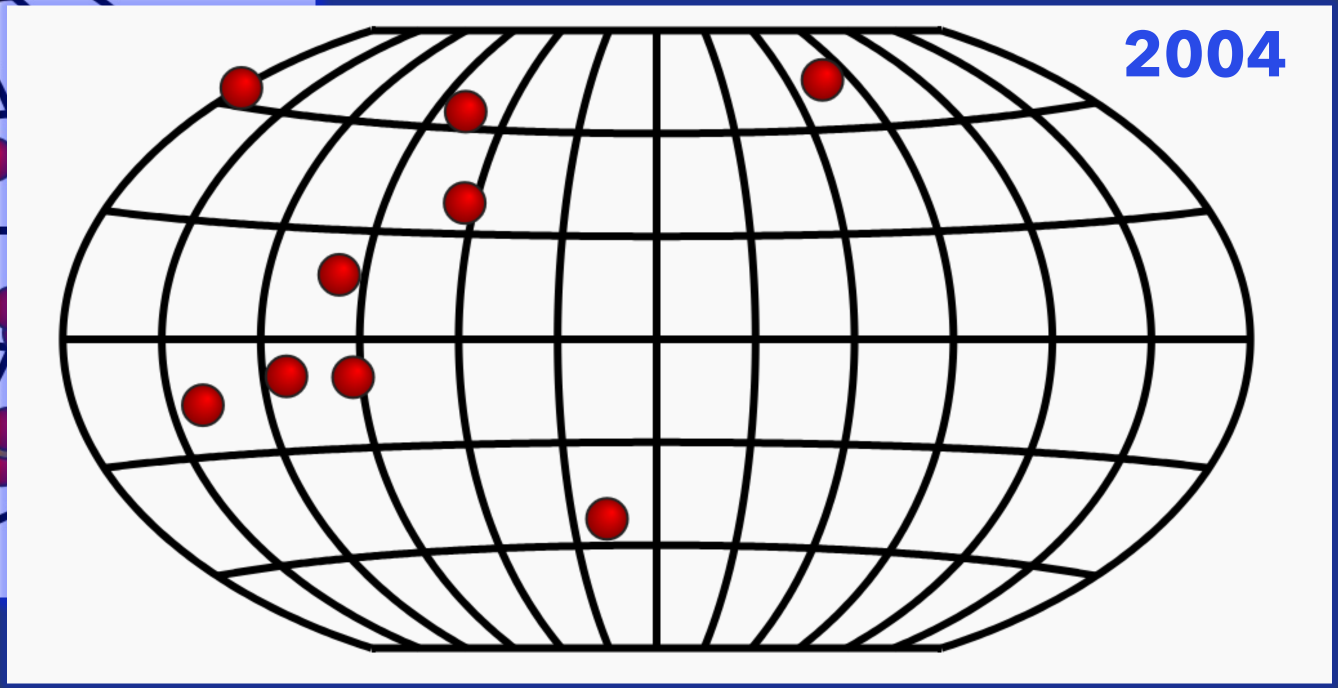



- 5 GRBs
- 2 starburst galaxies
- 4 radiogalaxies
- **87 blazars**
  - **10 FSRQ**
  - **77 BL Lac objects**

http://tevcat2.uchicago.edu/

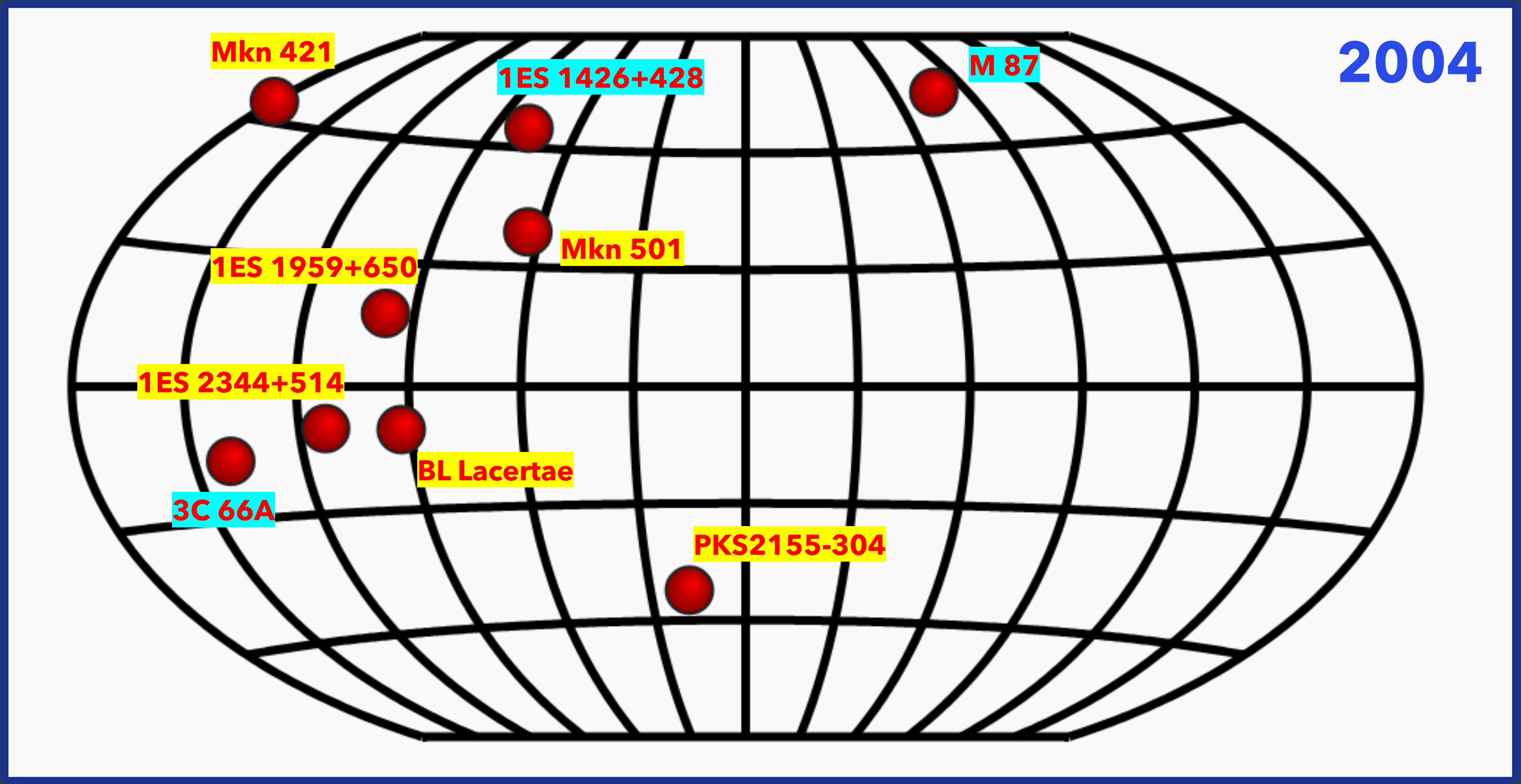
# TeVCAT: a catalogue for TeV-detected sources




http://tevcat2.uchicago.edu/

# TeVCAT: a catalogue for TeV-detected sources




First VHE gamma-ray blazars are also the first IXPE-detected blazars!

→ **Not a coincidence: strong connection between IXPE and MAGIC targets (and physics)**

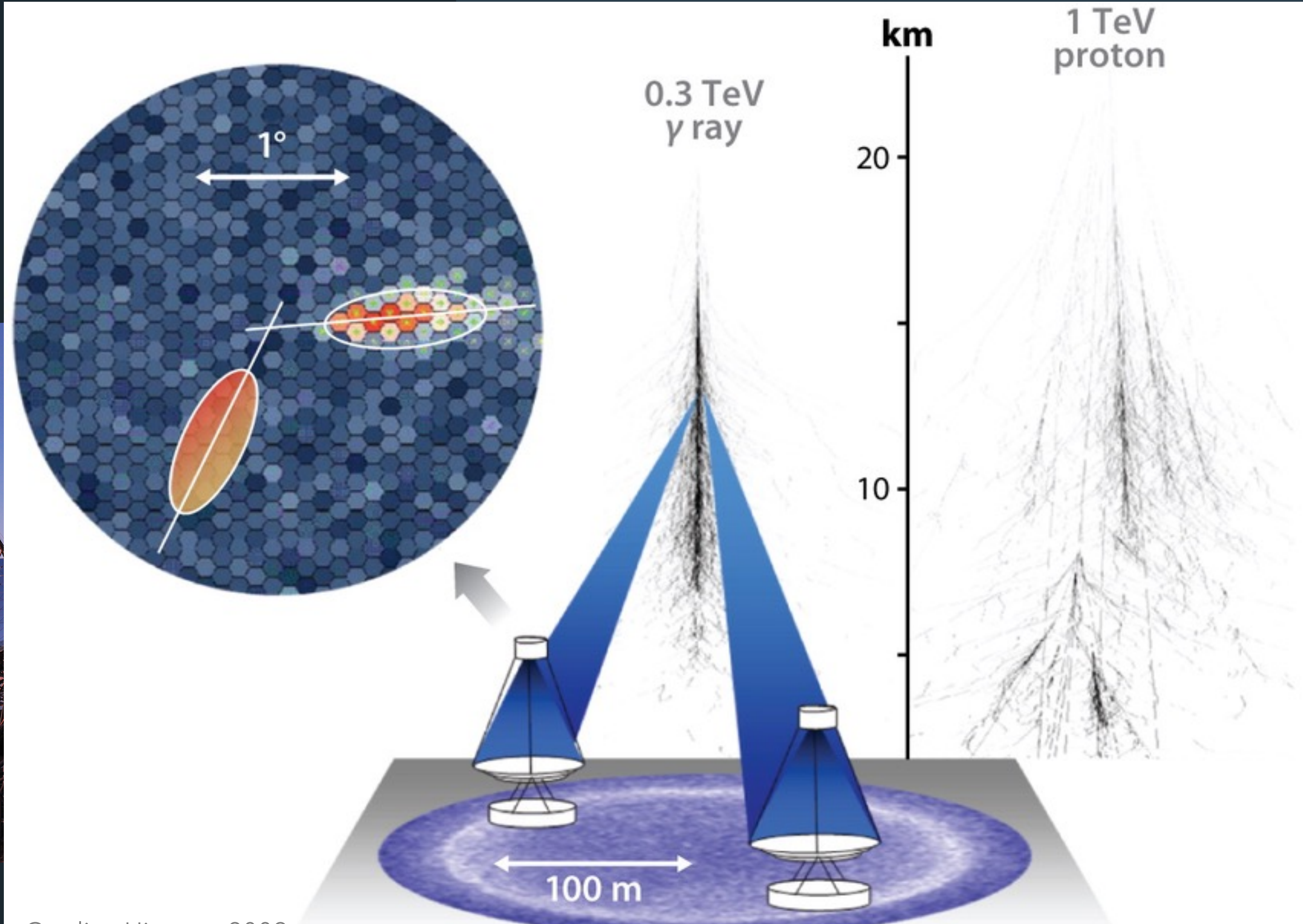
http://tevcat2.uchicago.edu/

# MAGIC Telescopes

- Two Imaging Atmospheric Cherenkov Telescopes
- La Palma, 2400 m asl
- Energy range: 60 GeV to several TeV (VHE: very high energy gamma rays)
- Limited Field of View (~3.5 degrees)

- **Observation strategy:**
  - Pointed observations
  - Regular monitoring of known VHE emitters
  - Search for new targets (also through ToO)

# Detection technique



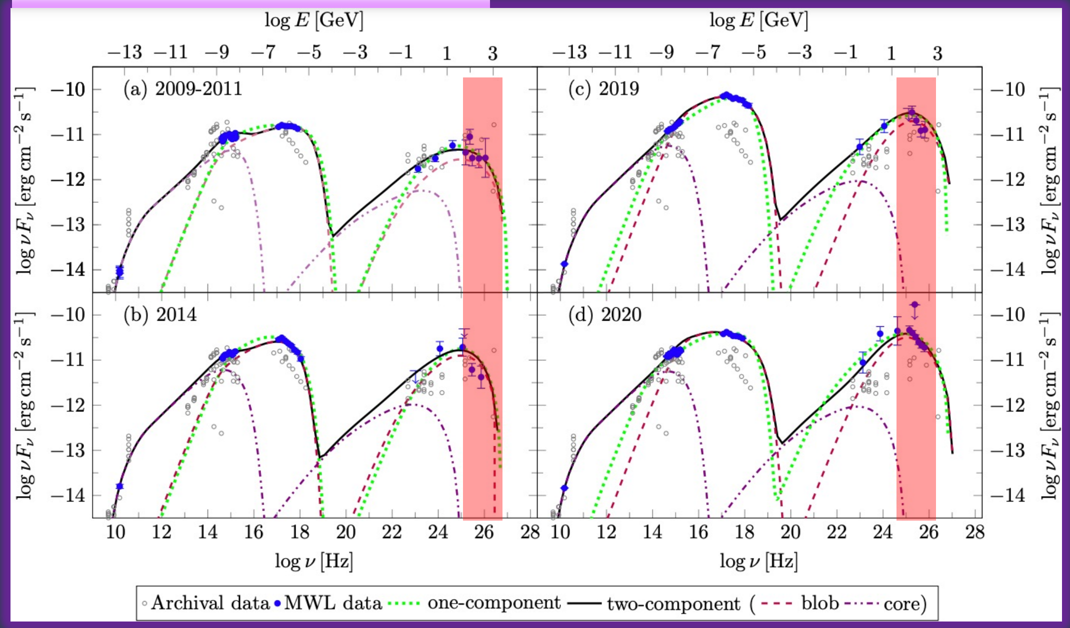

Credits: Hinton+ 2009

# MAGIC studies on blazars

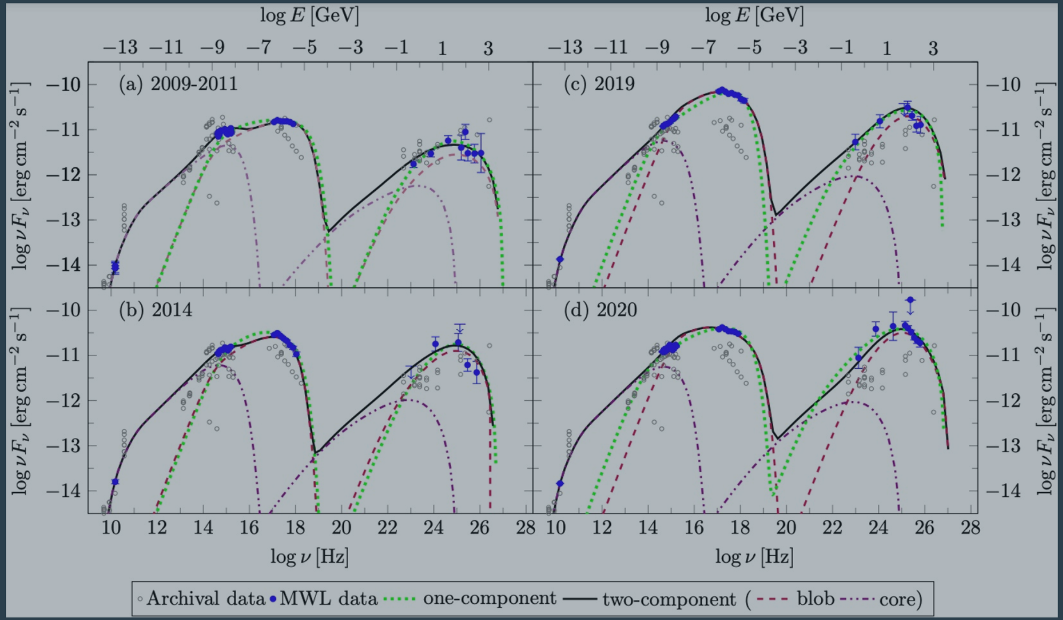
- **BL Lacs**
  - Characterize the emission over time at different timescales
  - Probe the jet properties and particle content: **multi-zone SSC**

BL Lac object: 1ES 0647+250

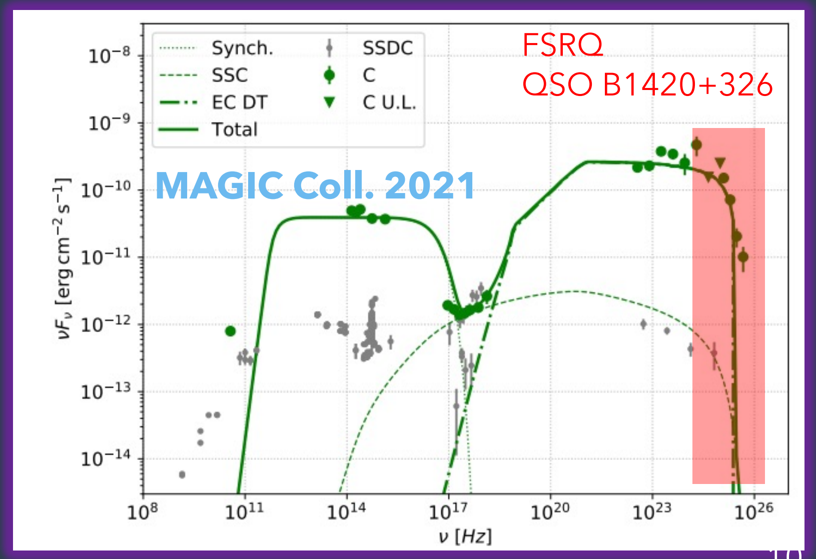
MAGIC Coll. 2022



# MAGIC studies on blazars



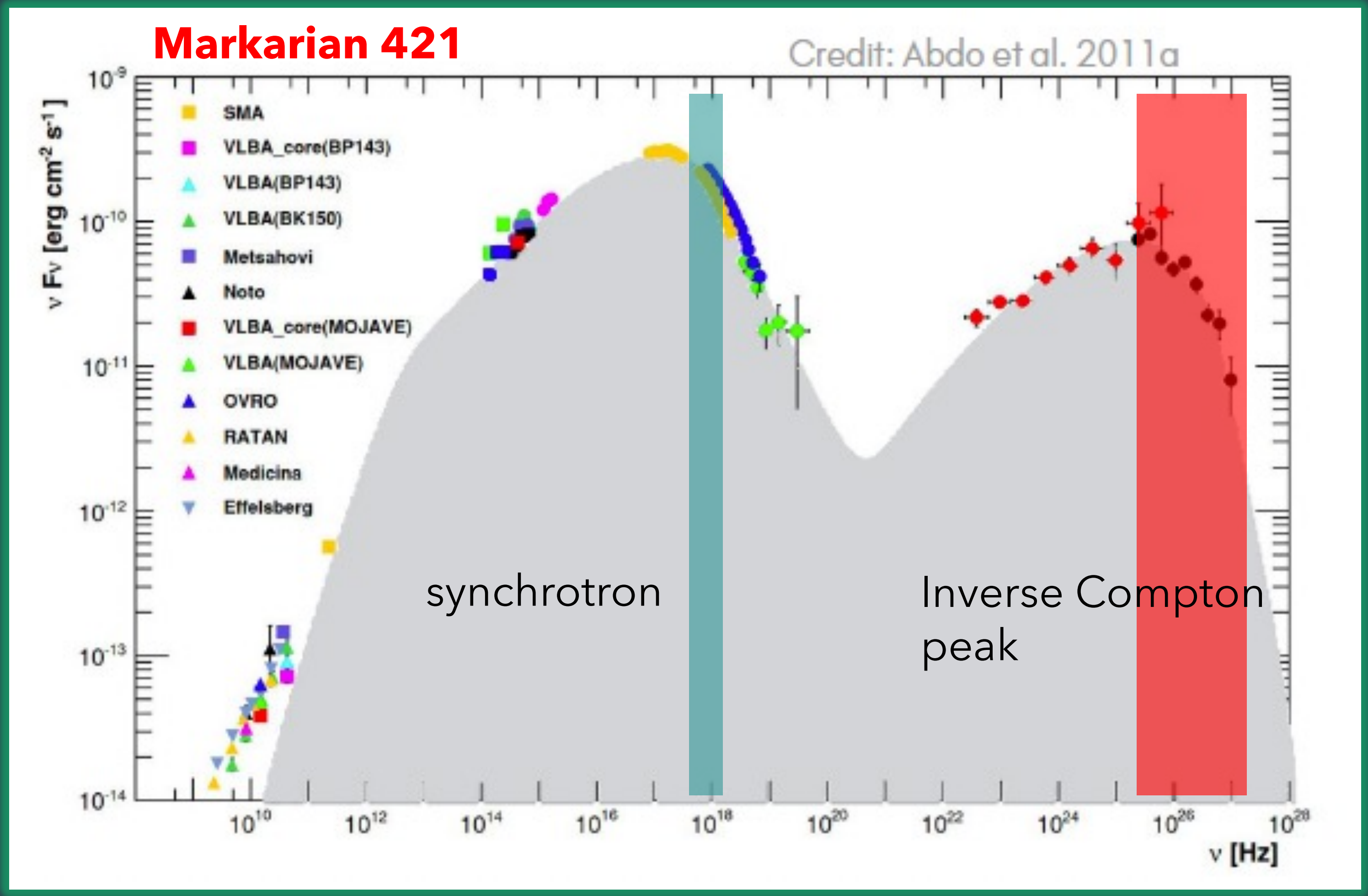

- **BL Lacs**
  - Characterize the emission over time at different timescales
  - Probe the jet properties and particle content: **multi-zone SSC**




- **FSRQs**
  - Characterize the emission mostly in flaring states
  - Constrain the size and location of the emitting region → probe **fast variability**
  - Probe the jet properties and particle content: External Compton

# Focus on Mkn 421

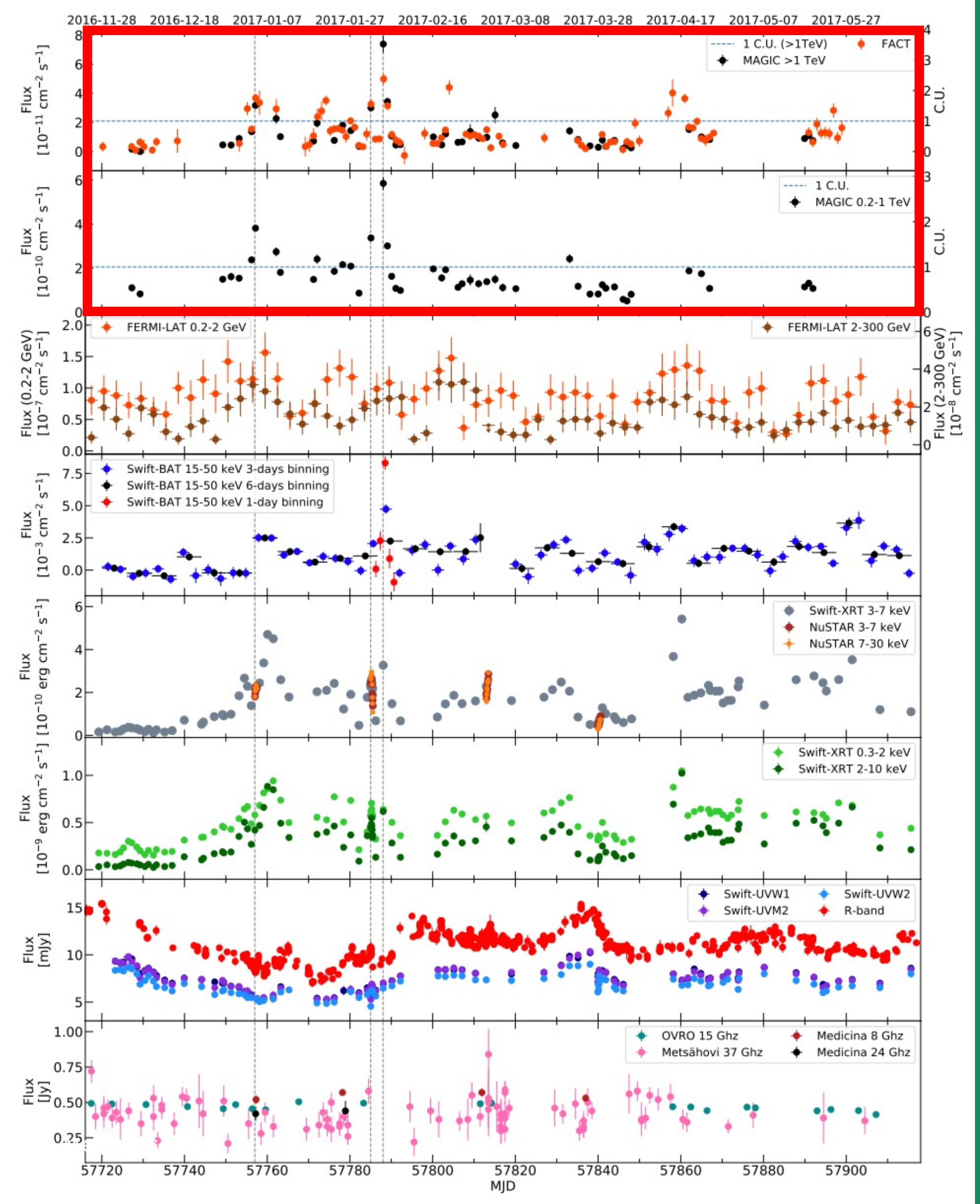
- Simplest model: SSC
- Both X-ray and VHE gamma rays: decreasing part of the peak



MAGIC Coll. 2021

# Focus on Mkn 421

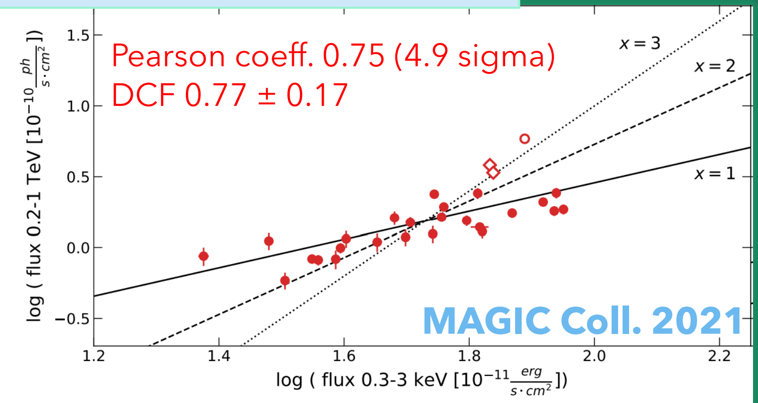
- Simplest model: SSC
- Both X-ray and VHE gamma rays: decreasing part of the peak
- Broadband variability: need for simultaneous observations!



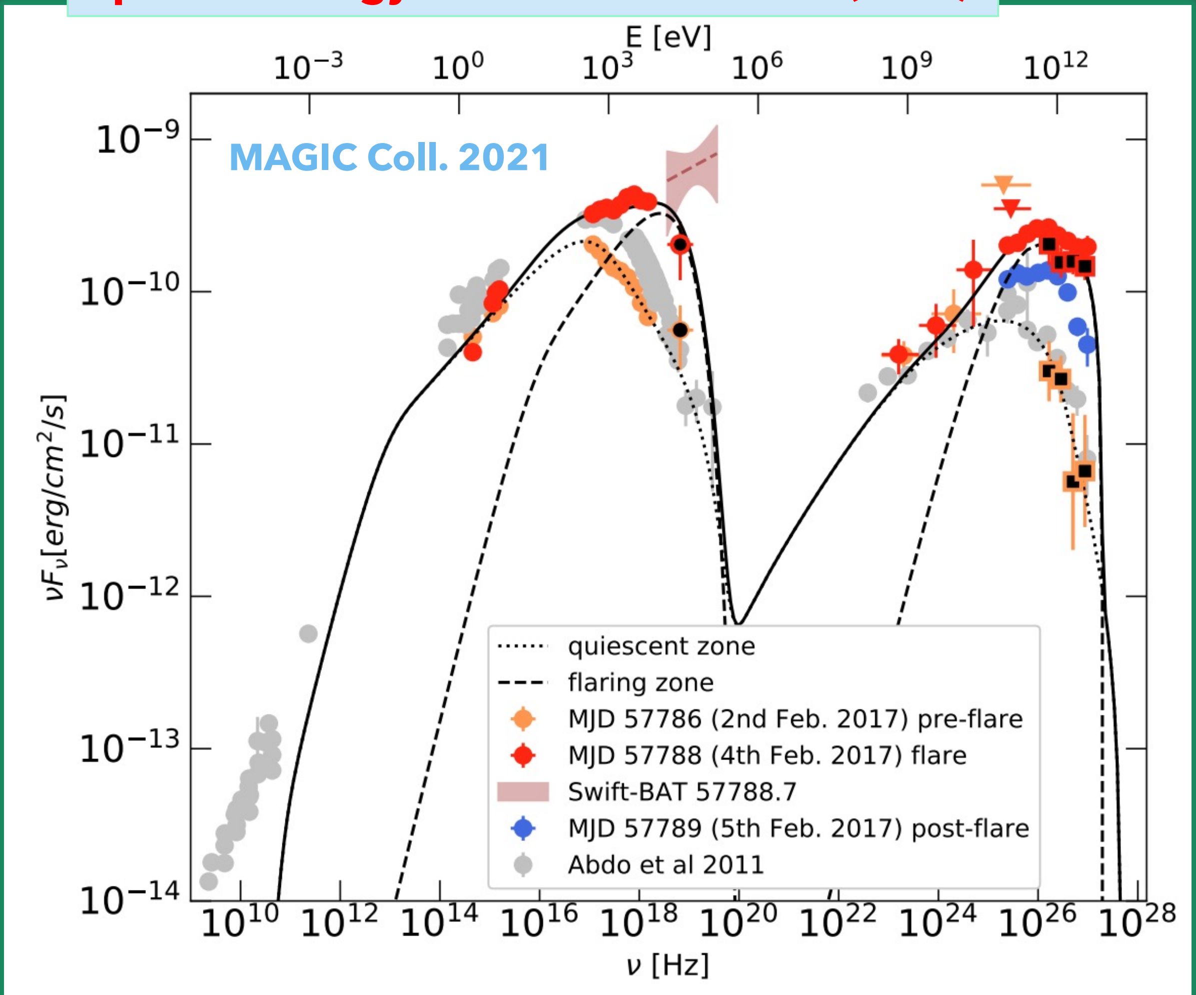
# Focus on Mkn 421

- Simplest model: SSC
- Both X-ray and VHE gamma rays: decreasing part of the peak
- Broadband variability: need for simultaneous observations!
- Strong correlation: X-ray and VHE gamma rays

**MAGIC-XRT correlation**

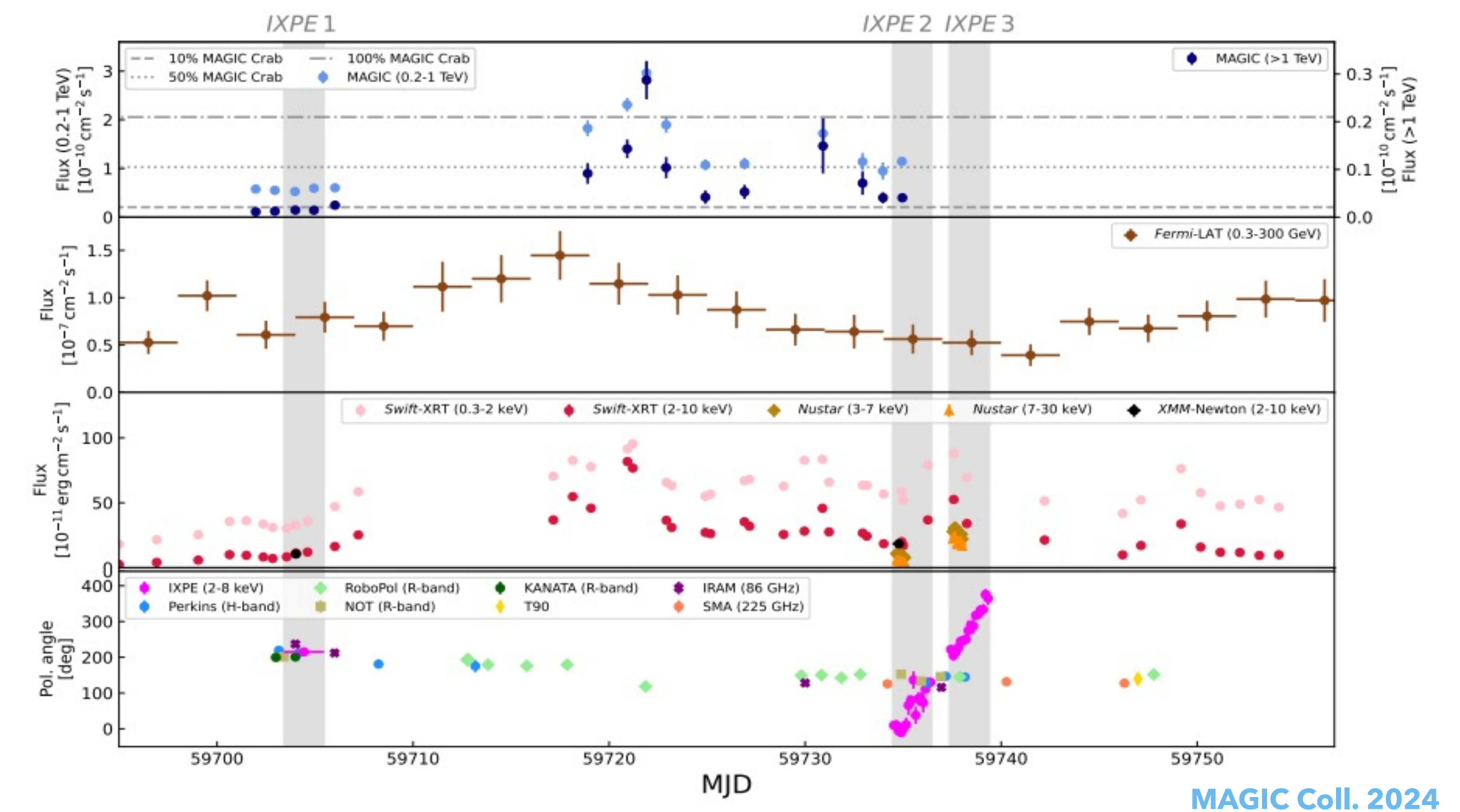



**Spectral energy distribution in 2017 (flare)**




→ Multi-zone emission model favored

# MAGIC-IXPE combined observations of Mkn 421

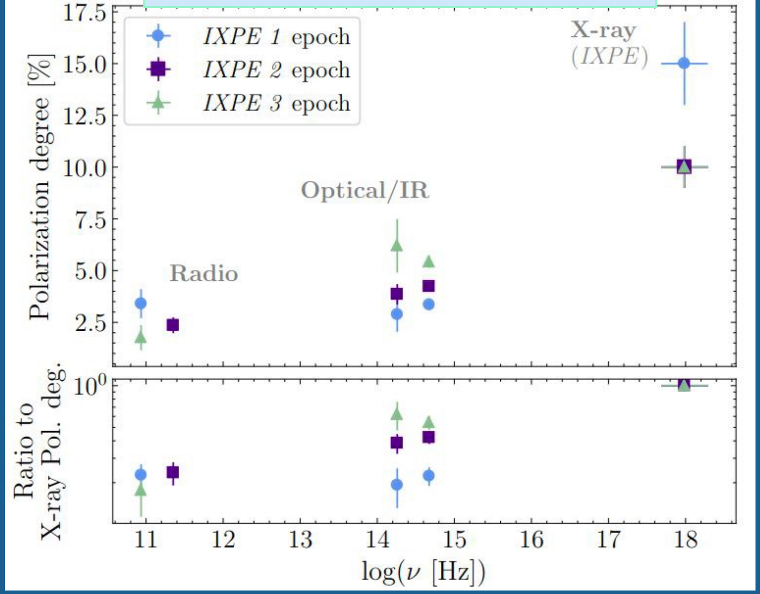



MAGIC Coll. 2024

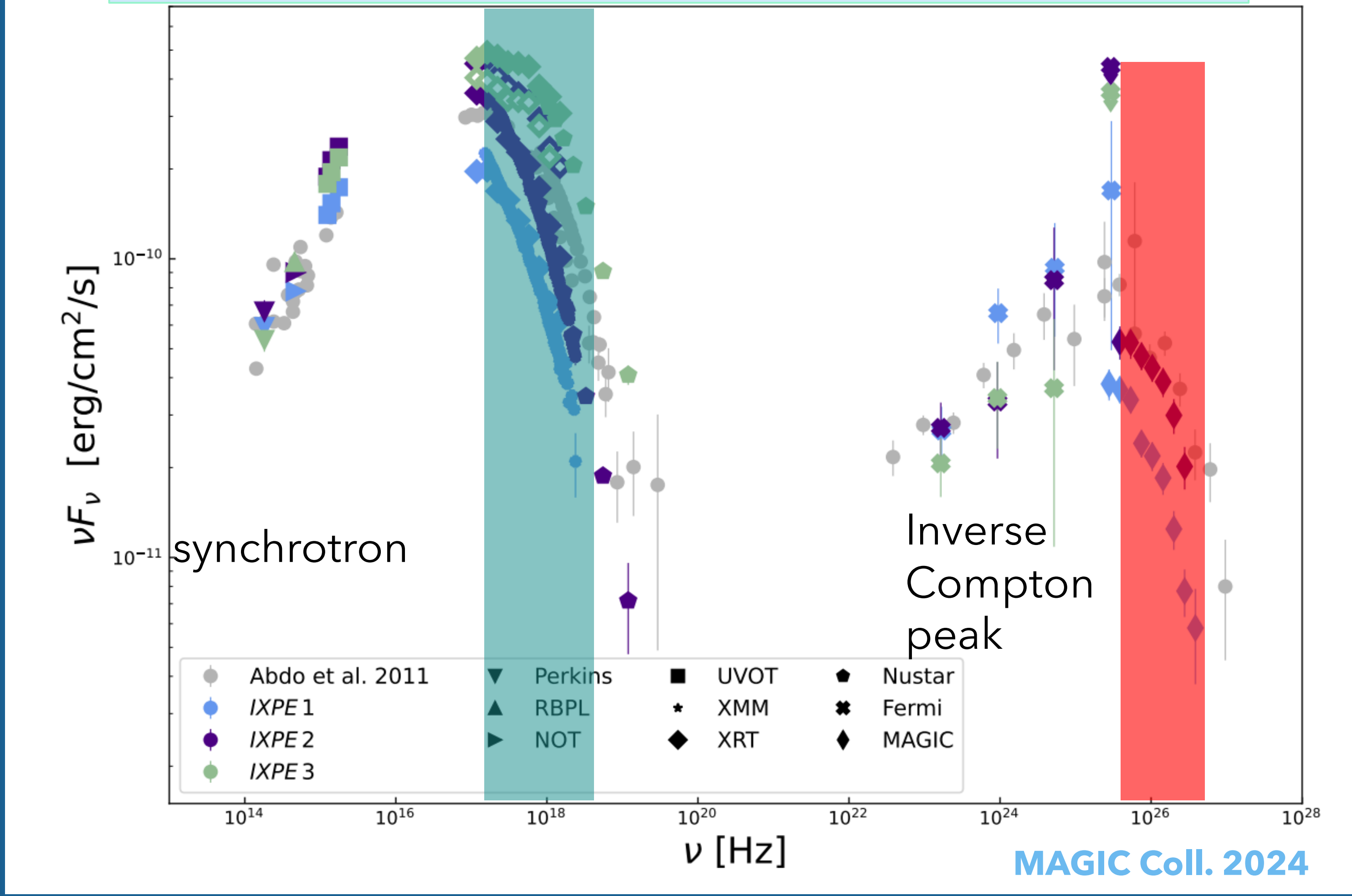
# MAGIC-IXPE combined observations of Mkn 421

- 3 coordinated observations in 2022
- X-ray polarization larger than optical

**Polarization degree**




**Spectral energy distribution during IXPE campaign (2022)**

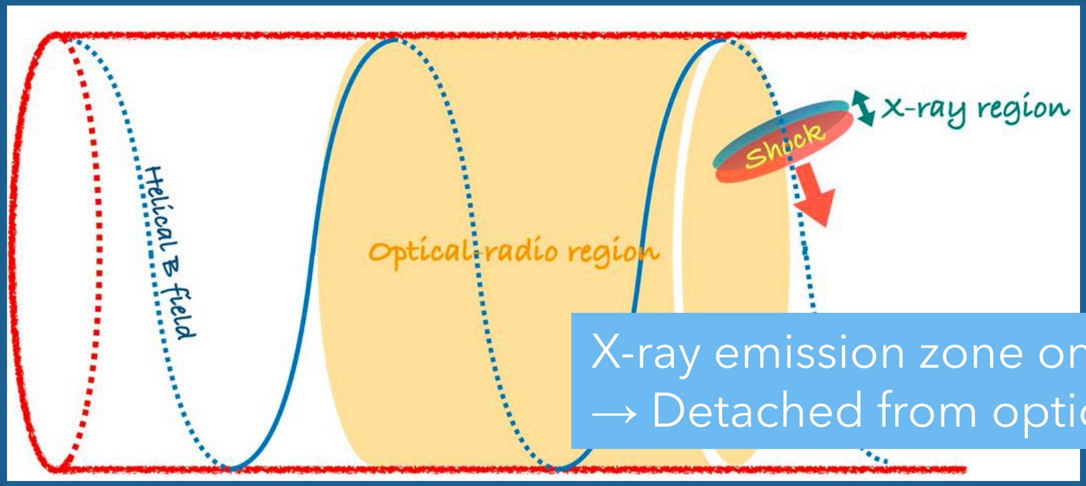



MAGIC Coll. 2024

# MAGIC-IXPE combined observations of Mkn 421

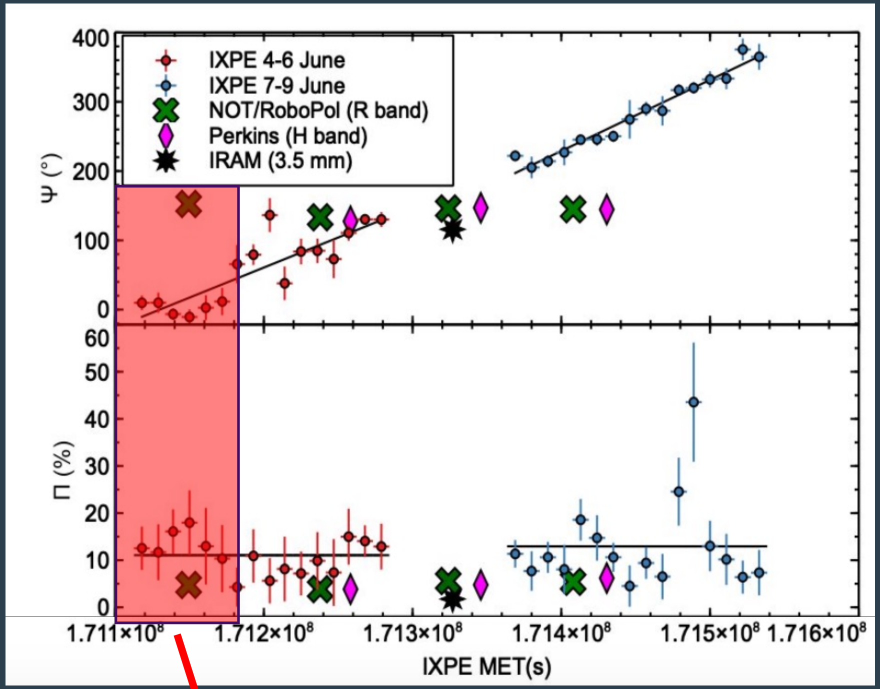
- 3 coordinated observations in 2022
- X-ray polarization larger than optical
- X-ray polarization angle: full rotation in June 2022

Di Gesu+ 2023




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

Di Gesu+ 2023




MAGIC observations

# Mkn 421: MAGIC-IXPE connections

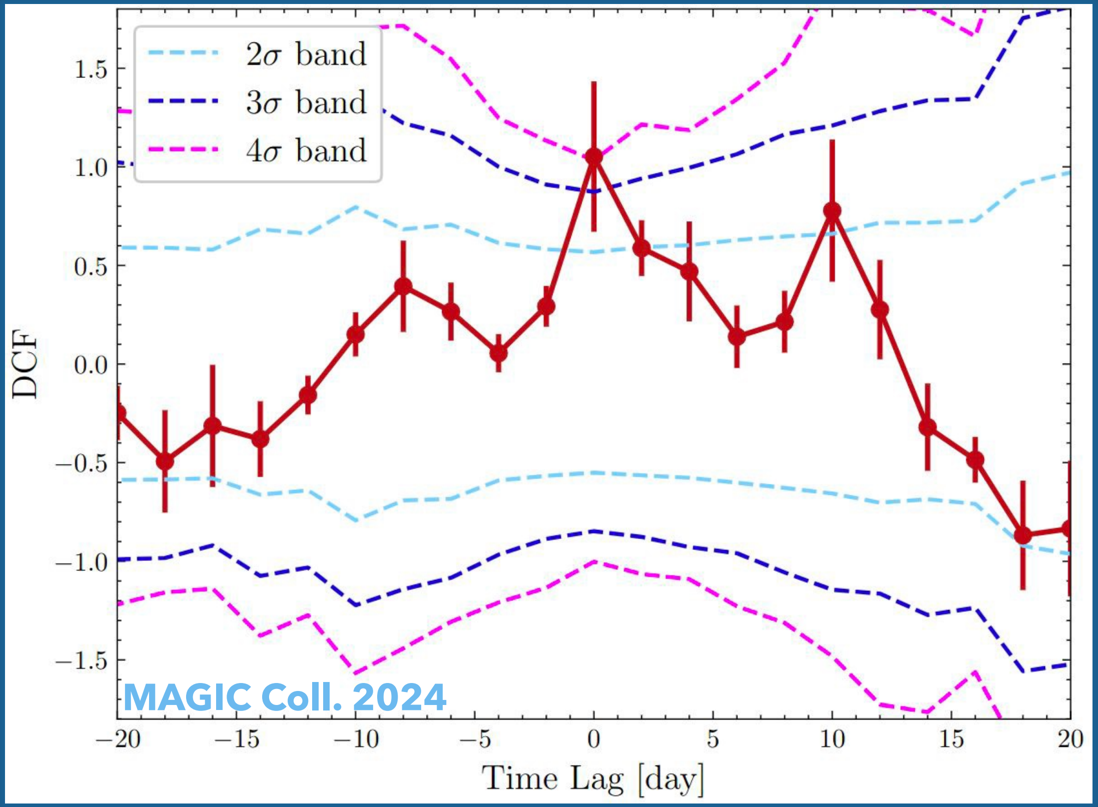
X-ray (Swift) –VHE: strong hint of correlation

→ Time interval: May-June 2022

→VHE co-spatial with X-ray

*Strong connection between X-ray and VHE, pointing to a common origin (typical for HSPs)*
*→ Simultaneous coverage is crucial to probe the physics of the emitting region*

Discrete correlation function
Mkn 421 (X-ray – VHE)



# Recent highlights: Mkn 501

Paper on MAGIC+IXPE simultanous observations in 2022 (MAGIC+ 2024)

- 3 IXPE pointings (Liodakis+ 2022, Lisalds+ 2024)

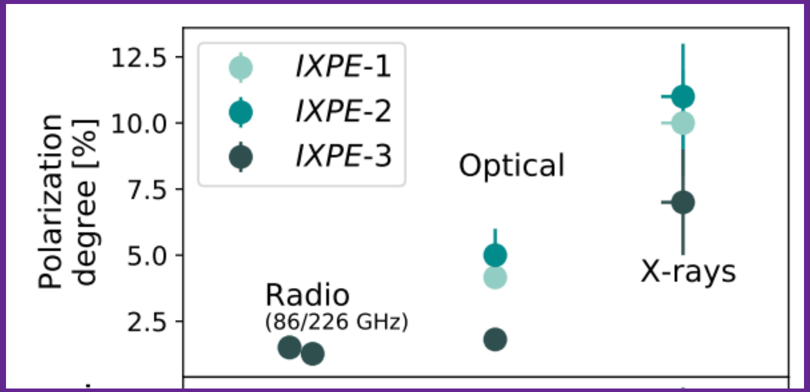
<u>Polarization degree</u>

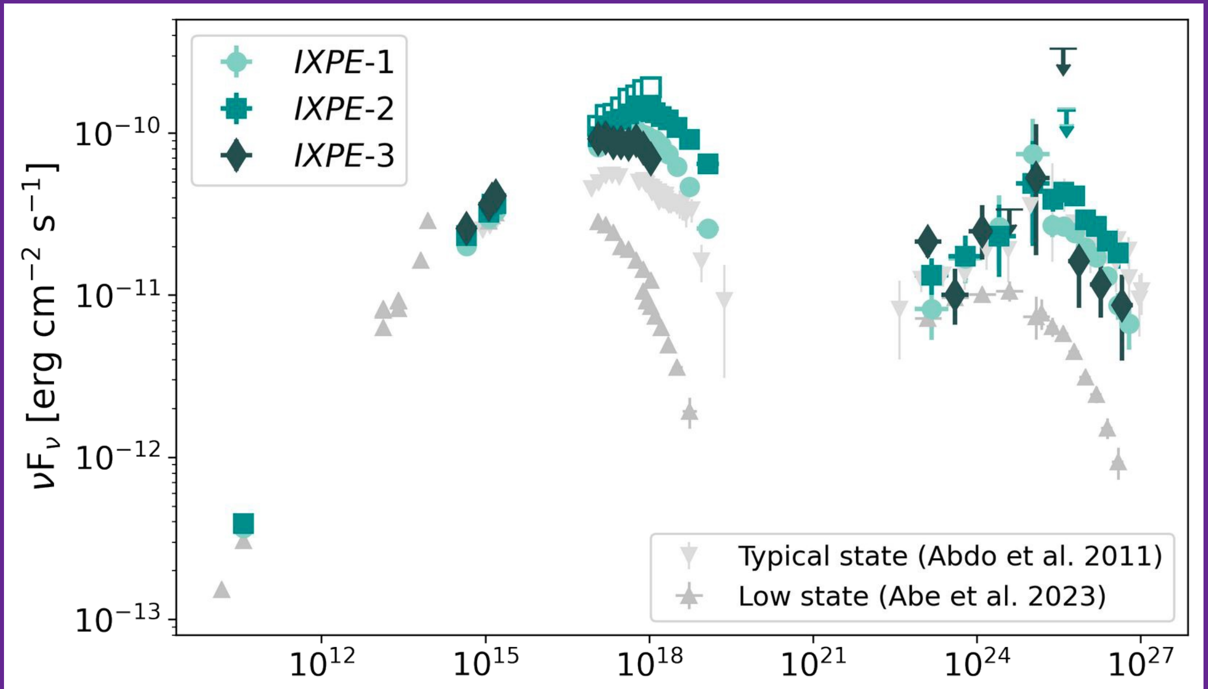
- X-ray ~factor 2 higher than in optical
- Drop in polarization for IXPE-3

<u>X-ray polarization angle</u>

- In line with optical
- Parallel to radio jet orientation

→ Shock acceleration in an energy stratified jet

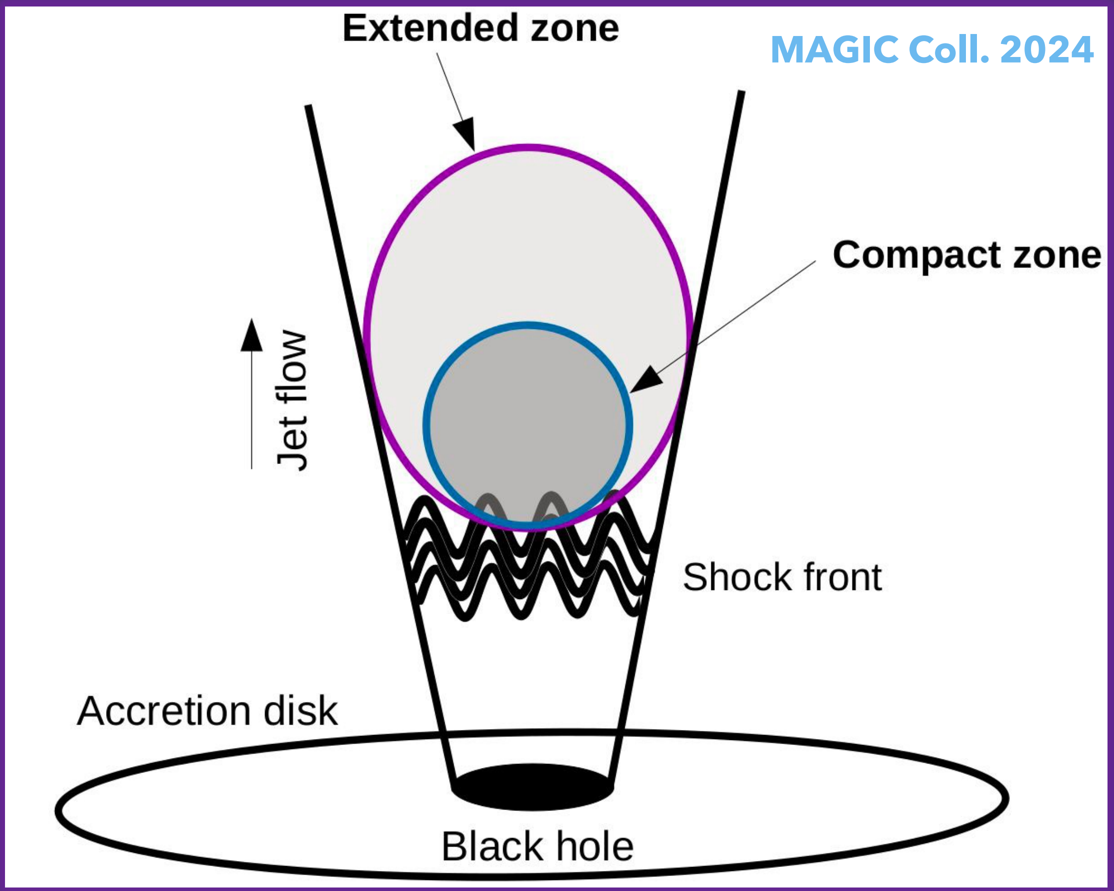


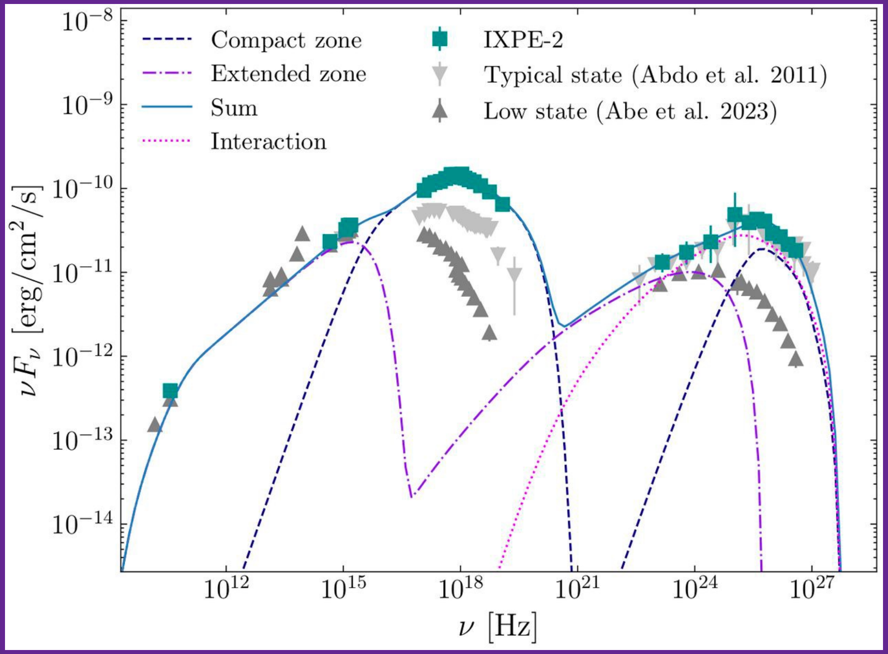

MAGIC Coll. 2024

# Recent highlights: Mkn 501

**Emission model**




- **Role of MAGIC**: constrain the second zone properties, the same responsible for X-ray emission.

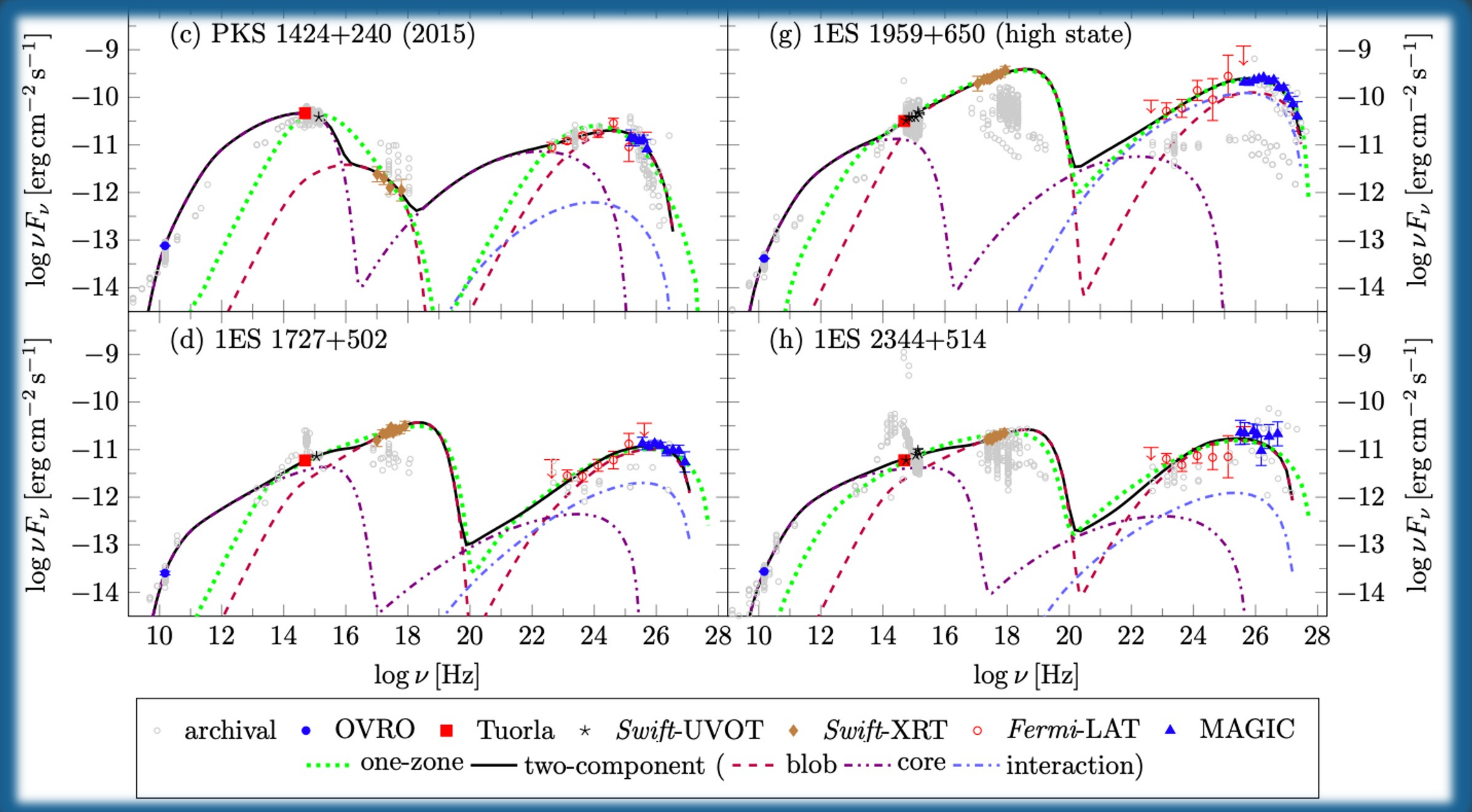


# MAGIC blazars and the two zone leptonic model

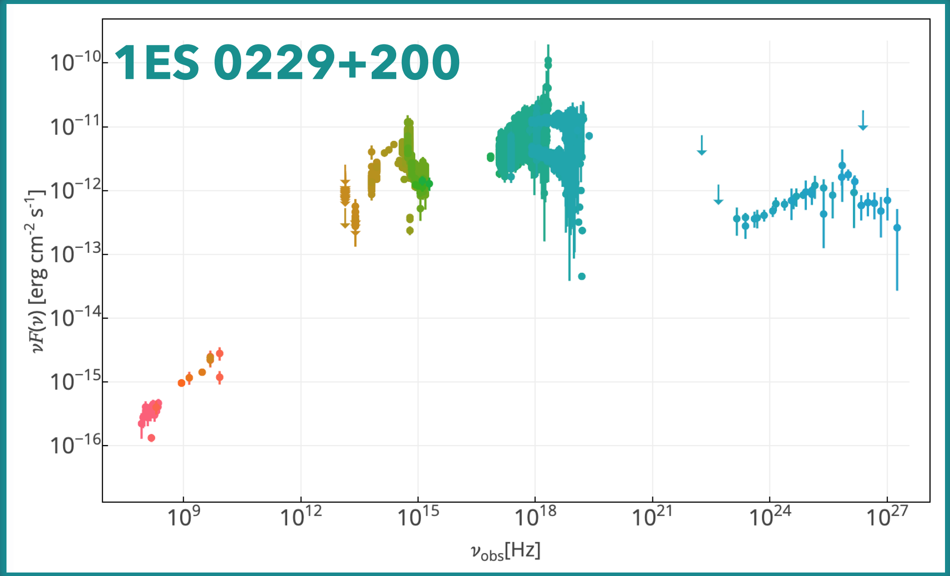
MAGIC Coll. 2020

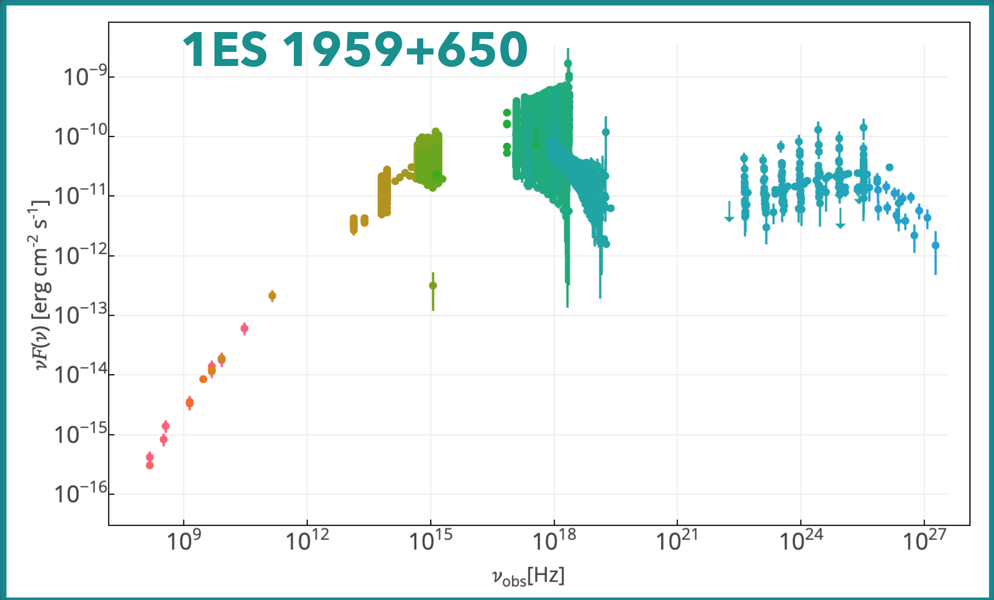
- **Two-zone leptonic model** (SSC + interaction component) proposed to interpret the data, including polarization

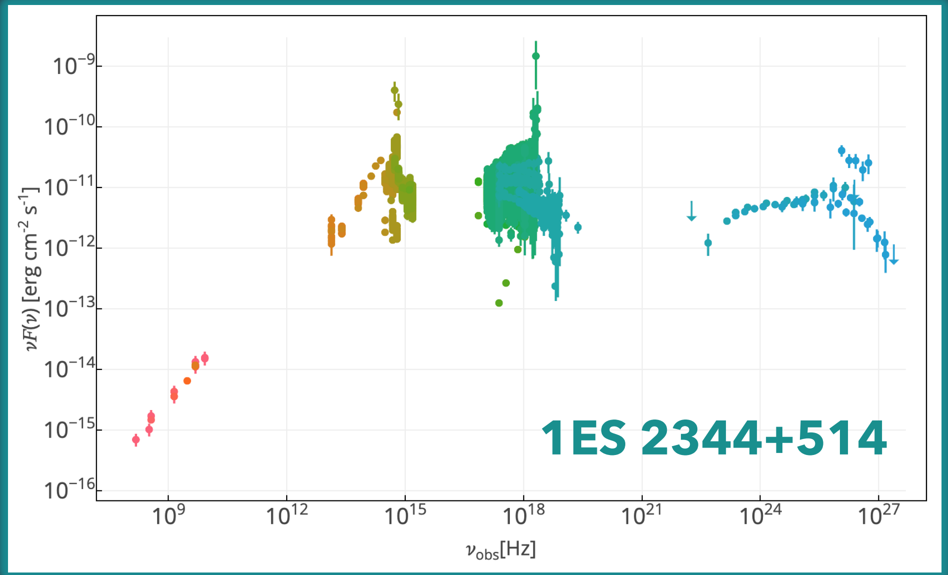
- TeV emission strongly connected with X-ray emission (same electron population)

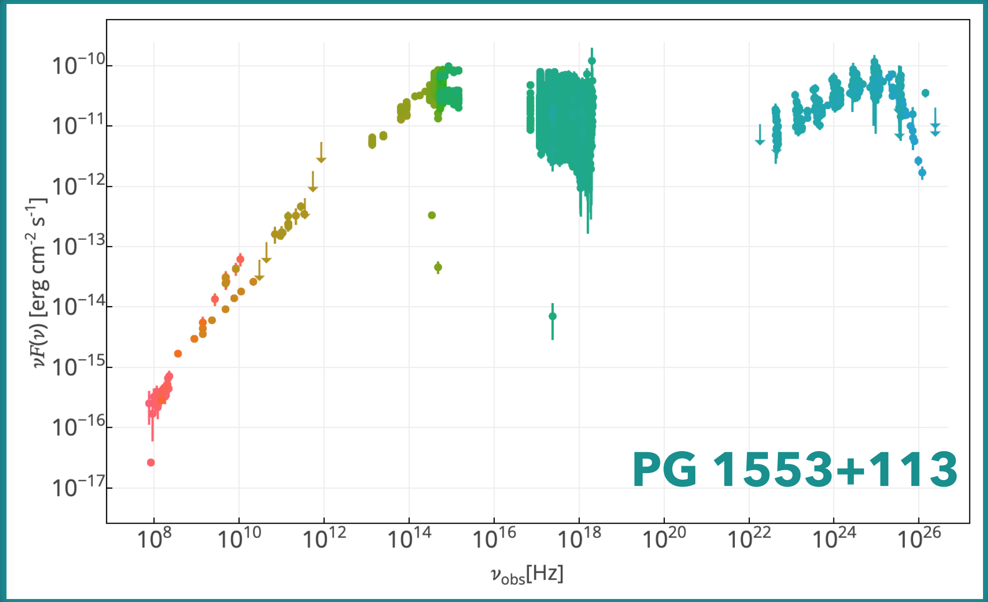


# MAGIC & IXPE studied blazars



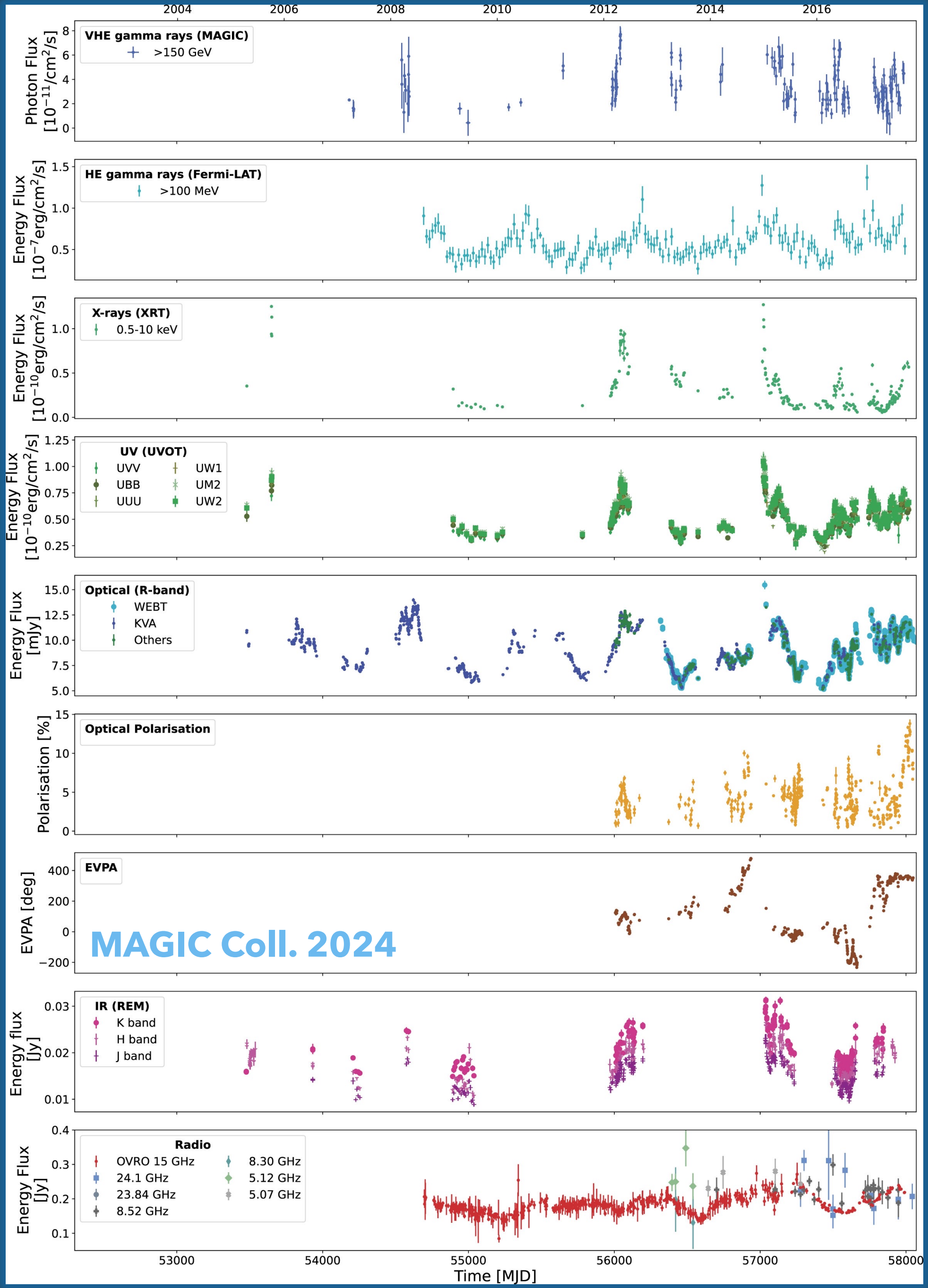




SEDs from mmdc Markarian Multiwavelength Data Center (https://mmdc.am/)

# Insights on PG 1553+113

**Goal**: characterize the variability patterns at VHE (and MWL)

- MWL Data from 2014 to 2017
- Non uniform coverage
- Quasi-periodic oscillations in gamma-rays (hints in optical and radio)
- No QPOs in X-ray and VHE
- Optical polarization and EVPA monitored since 2015
  - Optical polarization up to 15%
  - Clear rotations

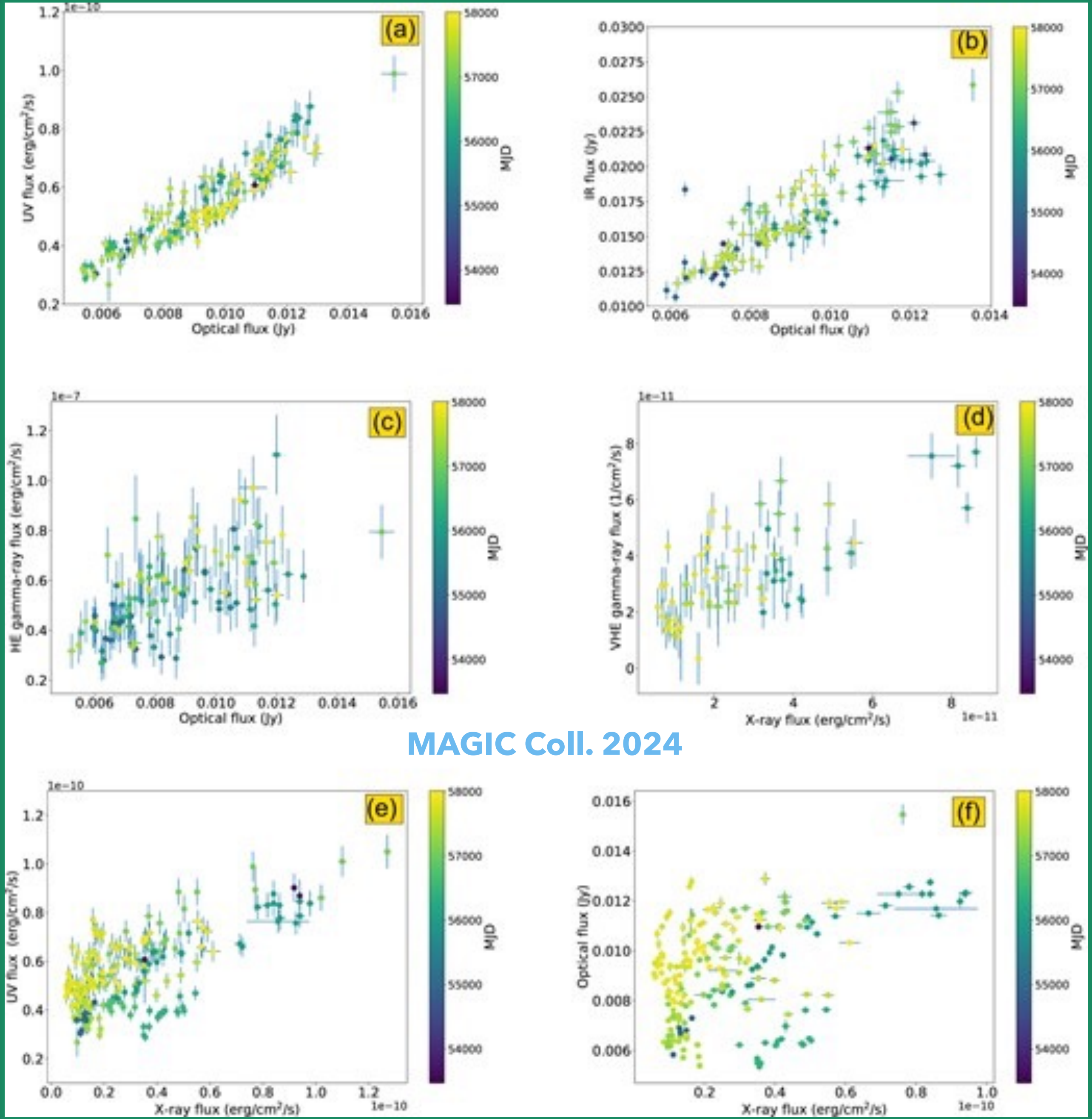


# Insights on PG 1553+113

Intra-band correlations: complex interplay

→ multi-zone model

| Band-1 | Band-2 | Spearman Coeff. | *p*-value | Panel |
|---|---|---|---|---|
| Optical | UV | 0.94 | 4e−88 | a |
| Optical | IR | 0.90 | 2e−50 | b |
| UV | HE $\gamma$-ray | 0.66 | 3e−10 | |
| Optical | HE $\gamma$-ray | 0.63 | 2e−14 | c |
| UV | VHE $\gamma$-ray | 0.62 | 9e−08 | |
| IR | HE $\gamma$-ray | 0.61 | 1e−05 | |
| X-ray | VHE $\gamma$-ray | 0.60 | 6e−08 | d |
| IR | UV | 0.60 | 4e−06 | |
| UV | X-ray | 0.55 | 6e−18 | e |
| Optical | X-ray | 0.37 | 4e−08 | f |
| HE $\gamma$-ray | VHE $\gamma$-ray | 0.39 | 0.006 | g |
| Optical | VHE $\gamma$-ray | 0.35 | 2e−05 | h |
| X-ray | HE $\gamma$-ray | 0.32 | 0.006 | i |
| IR | VHE $\gamma$-ray | 0.26 | 0.09 | |
| IR | X-ray | 0.29 | 0.02 | |




MAGIC Coll. 2024

# Insights on PG 1553+113

Intra-band correlations: complex interplay

→ **multi-zone model**

Confirmed by IXPE observations in 2023 revealing an orphan optical polarization swing → X-ray and optically emitting regions are separate or, at most, partially co-spatial.

| Band-1 | Band-2 | Sp[illegible] | [illegible] | [illegible] |
|---|---|---|---|---|
| Optical | UV | [illegible] | [illegible] | [illegible] |
| Optical | IR | 0.90 | 2e−50 | b |
| UV | HE $\gamma$-ray | 0.66 | 3e−10 | |
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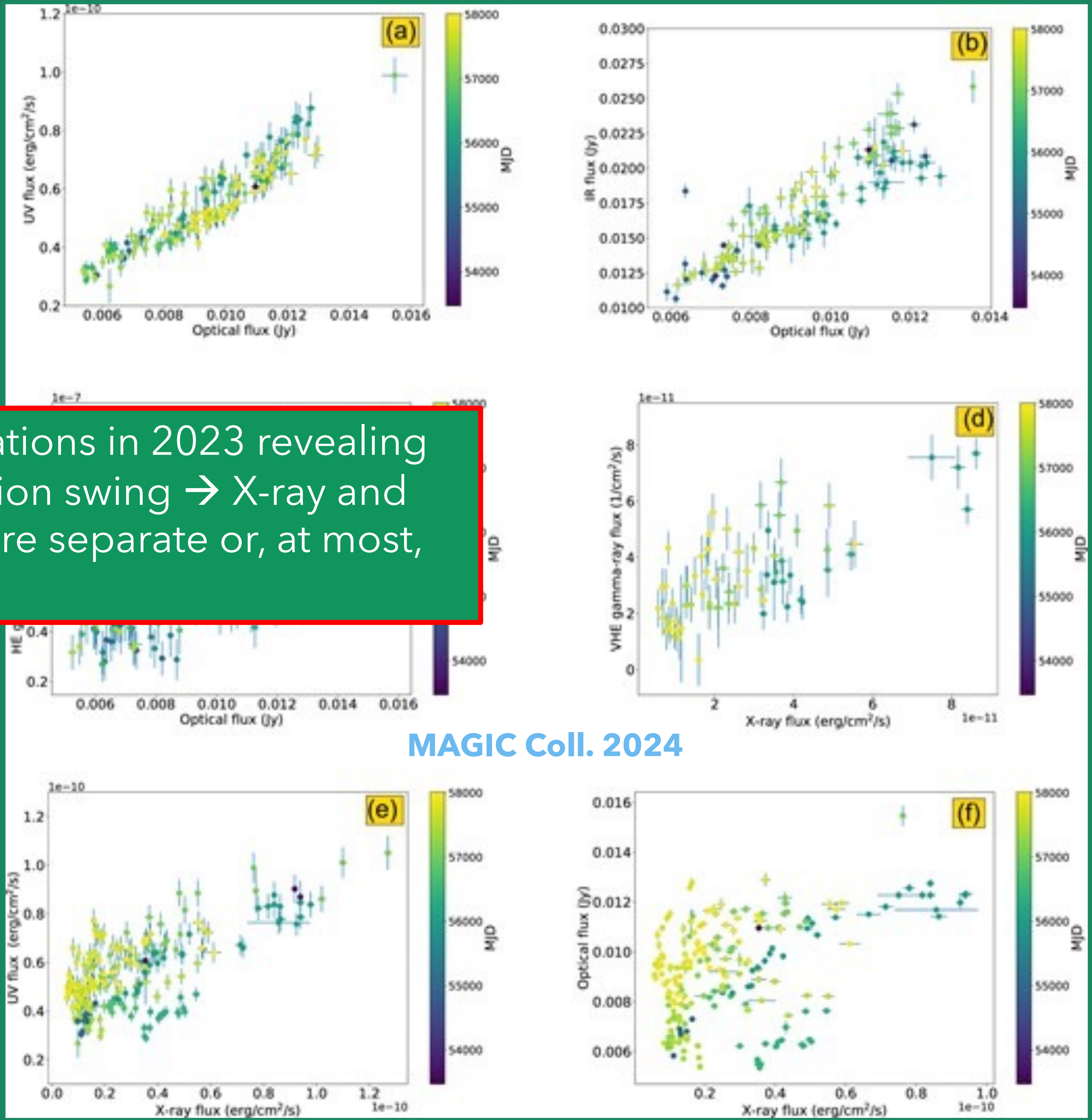



MAGIC Coll. 2024

# A look to the (near) future

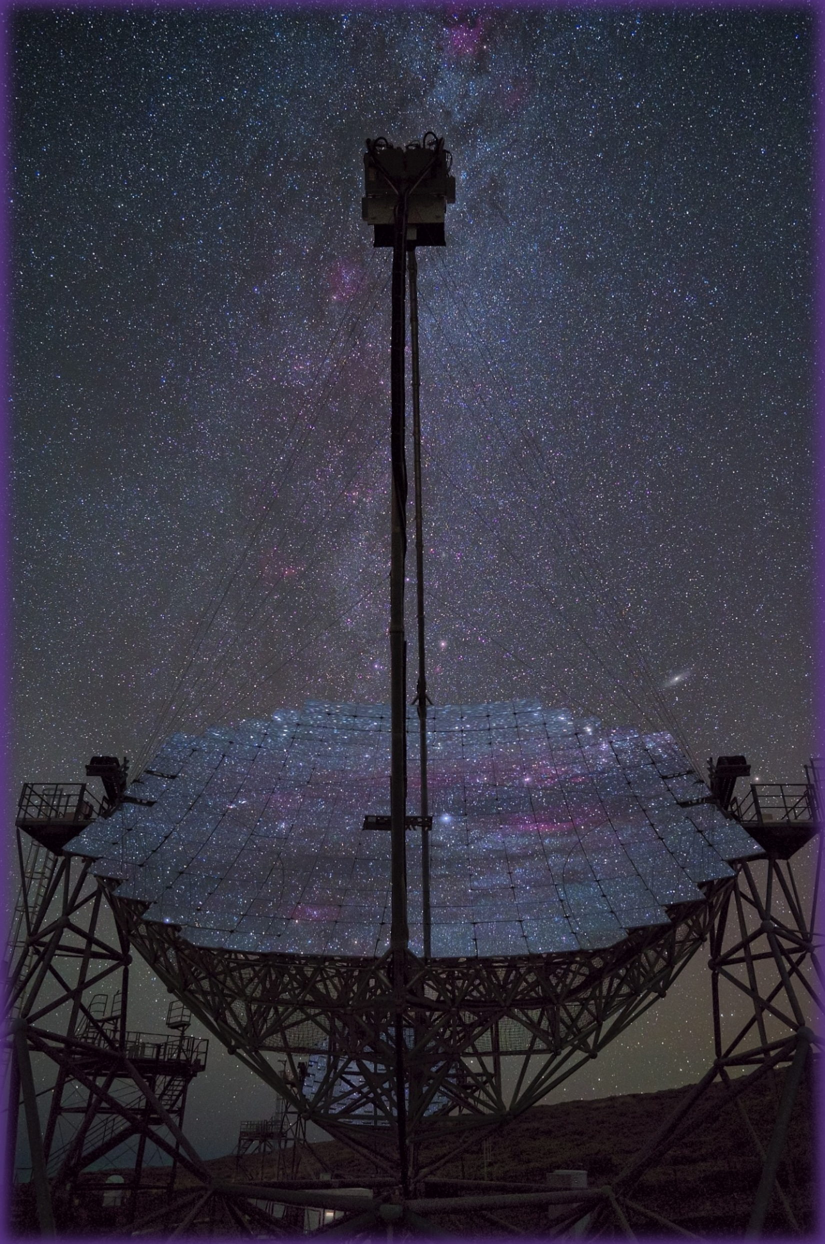

- MAGIC + IXPE observations
  - New promising targets to test emission models
  - Monitoring of well known sources
- CTAO first telescopes in operation soon (LST1 already taking data!)
- Combined and multi-epoch observations are crucial to probe the emission models

The MAGIC Collaboration is open to external PI – Call for proposals late Summer (if interested, contact us in time!)

https://magic.mpp.mpg.de/public/magicop/

# Conclusions

- **IXPE blazars** are sources of VHE gamma-rays
- In high-syncrotron peak blazars (HBLs), VHE photons are closely connected with X-ray emission and polarization: co-spatial.
- Role of VHE observations:
  - Spectrum reconstruction → modelling
  - Lightcurve:
    - Time variability study → constrain the size of the gamma-ray emitting region
    - Intra-band correlation studies
- Future observations: monitoring + new sources



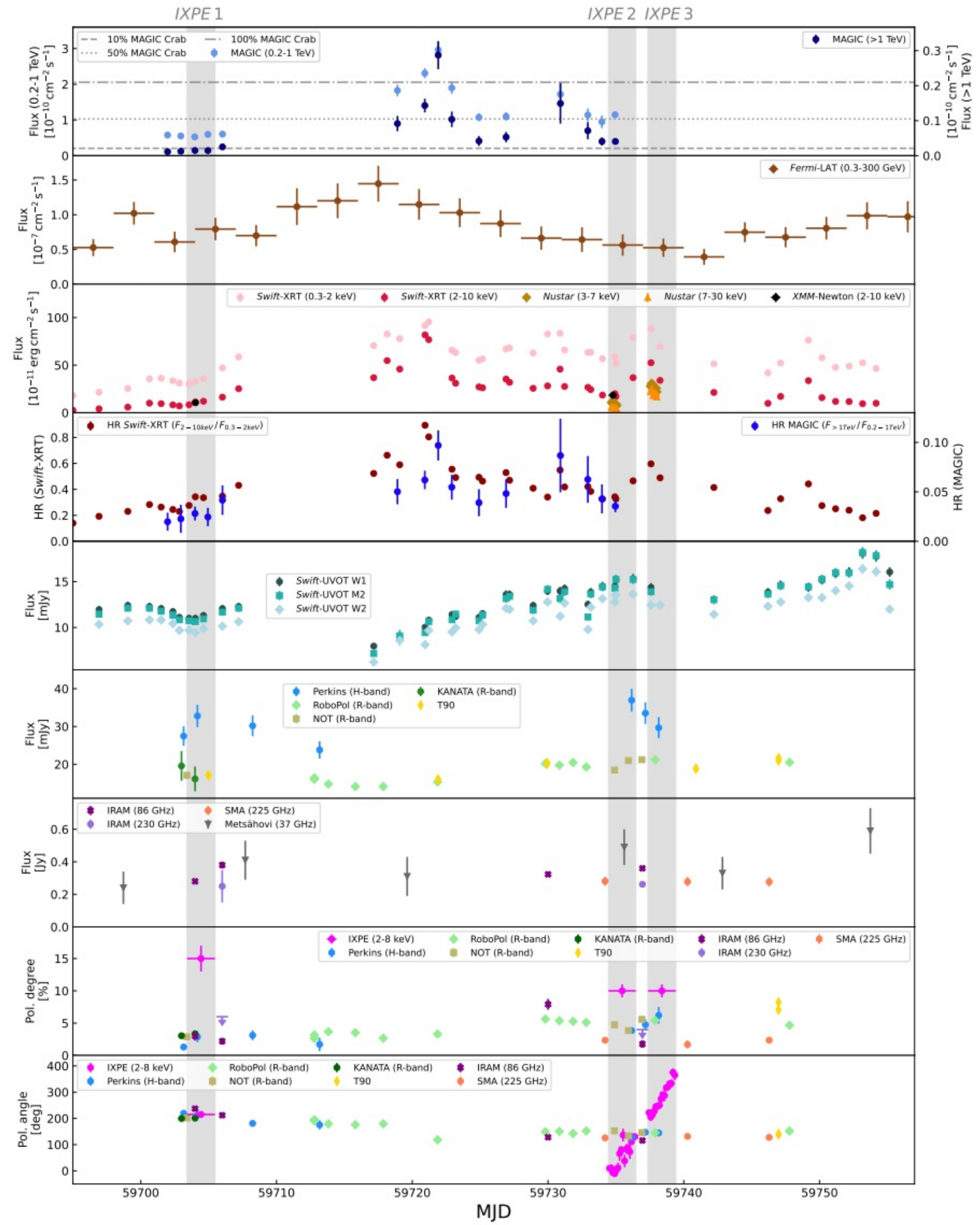
# Thank you!

# Backup slides

# TeVCAT non-blazar sources

| Name | RA | Dec | Type Tags | Distance | Catalog |
|---|---|---|---|---|---|
| GRB 221009A | 19 13 03 | +19 48 09 | XGal,GRB,I... | z=0.151 | Default Catalog |
| GRB 201216C | 01 05 28.88 | +16 30 58.0 | XGal,GRB,I... | z=1.1 | Newly Announced |
| GRB 190829A | 02 58 10.51 | -08 57 28.1 | XGal,GRB,I... | z=0.0785 | Default Catalog |
| GRB 180720B | 00 02 06.87 | -02 55 05.2 | XGal,GRB,I... | z=0.654 | Default Catalog |
| GRB 190114C | 03 38 01.17 | -26 56 46.73 | XGal,GRB | z=0.4245 | Default Catalog |
| 3C 264 | 11 45 05.0 | +19 36 23 | XGal,AGN,F... | z=0.021718 | Default Catalog |
| NGC 1275 | 03 19 48.1 | +41 30 42 | XGal,AGN,F... | z=0.017559 | Default Catalog |
| M 87 | 12 30 47.2 | +12 23 51 | XGal,AGN,F... | z=0.0044 | Default Catalog |
| Centaurus A | 13 25 30.3 | -43 00 15 | XGal,AGN,F... | z=0.00183 | Default Catalog |
| M 82 | 09 55 52.7 | +69 40 46 | XGal,*Brst | 3900.0 kpc | Default Catalog |
| NGC 253 | 00 47 32.54 | -25 17 25.4 | XGal,*Brst | 2500.0 kpc | Default Catalog |

# Mkn 421
# MAGIC + IXPE + MWL



# Mkn 421: hysteresis loops in NuSTAR data

- Two contiguous spectral hysteresis loops in opposite directions over a single exposure
- The first loop, in a **clockwise direction**, is likely the signature of synchrotron cooling causing a delay of the lowenergy X-ray photons with respect to the high-energy ones (soft lag).
- The subsequent **counter-clockwise loop** indicates a delay of the high-energy X-ray photons compared to the low-energy ones (hard lag), suggesting a system observed at energies for which acceleration timescale is comparable to the cooling timescale

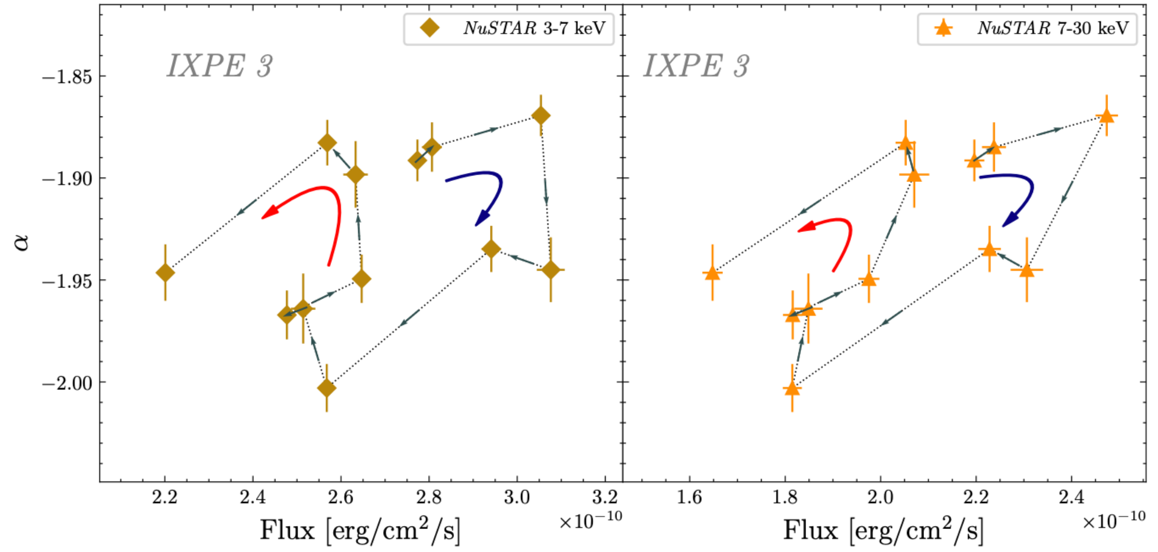
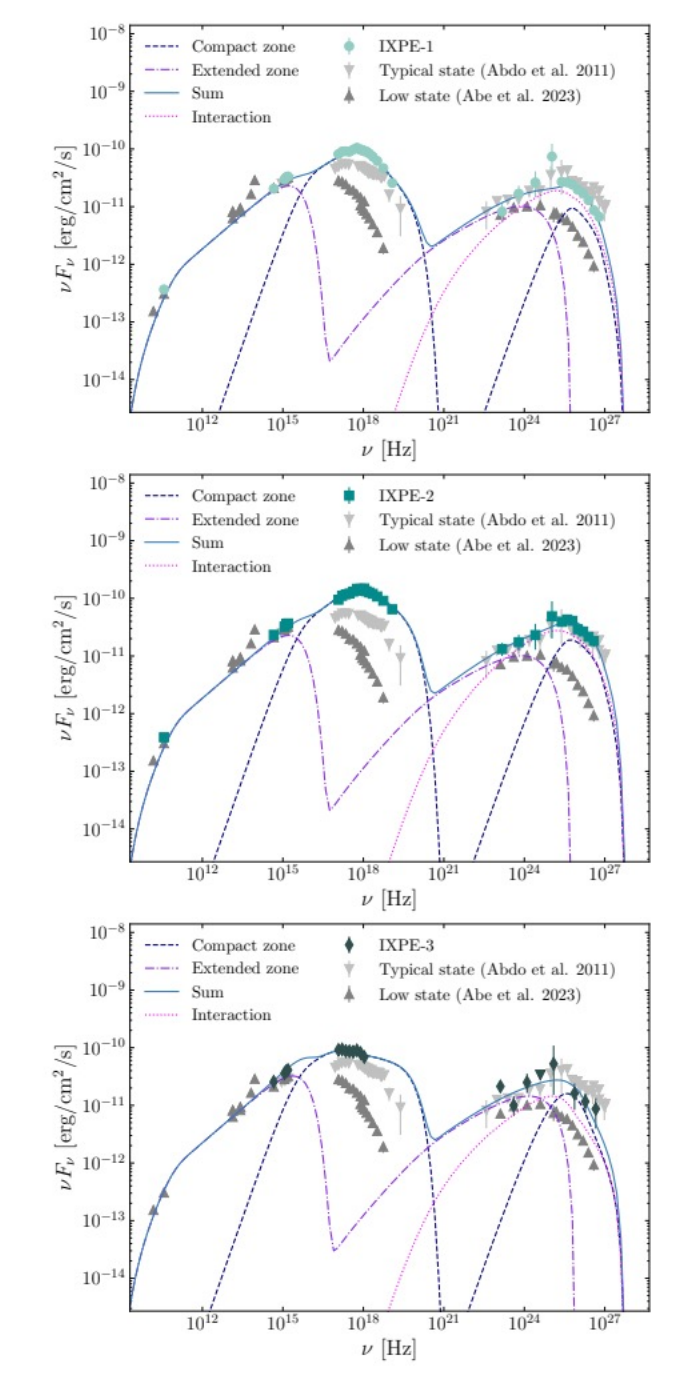
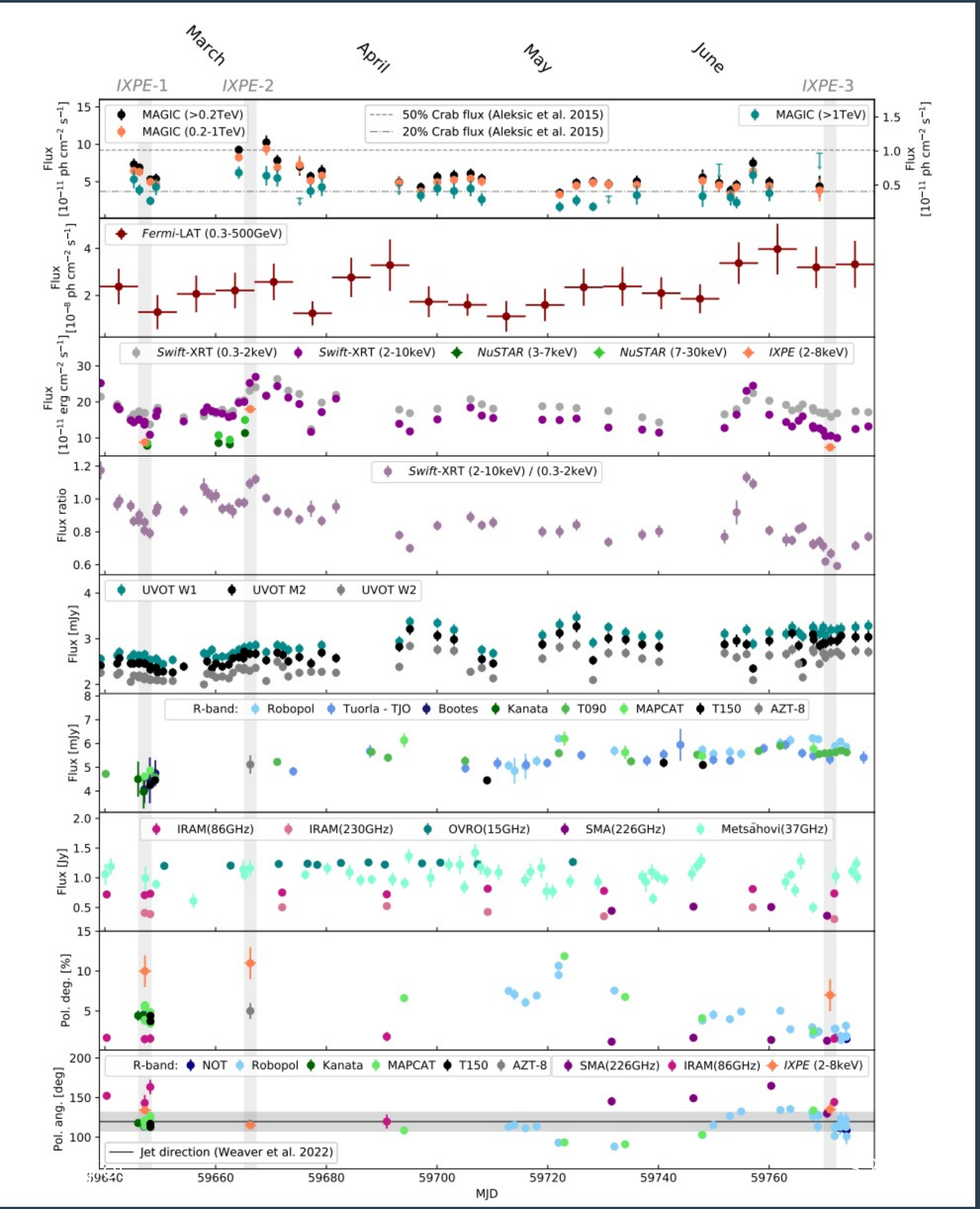



Fig. 8: Log-parabola photon index $\alpha$ versus 3-7 keV and 7-30 keV flux as measured by *NuSTAR* during the third *IXPE* observation (*IXPE 3* period). The data are 1 hour binned and $\alpha$ is obtained by fitting a log-parabola function that has a fixed curvature parameter $\beta = 0.45$. The grey arrows show the direction of time, and the blue and red arrows in the middle of the panels depict the clockwise and counter-clockwise directions observed in the data, respectively.

# Mkn 501



Compact zone
Extended zone
Sum
Interaction
IXPE-1
IXPE-2
IXPE-3
Typical state (Abdo et al. 2011)
Low state (Abe et al. 2023)
$\nu F_\nu$ [erg/cm$^2$/s]
$\nu$ [Hz]

March
April
May
June
IXPE-1
IXPE-2
IXPE-3
MAGIC (>0.2TeV)
MAGIC (0.2-1TeV)
50% Crab flux (Aleksic et al. 2015)
20% Crab flux (Aleksic et al. 2015)
MAGIC (>1TeV)
Flux [$10^{-11}$ ph cm$^{-2}$ s$^{-1}$]
Fermi-LAT (0.3-500GeV)
Flux [$10^{-8}$ ph cm$^{-2}$ s$^{-1}$]
Swift-XRT (0.3-2keV)
Swift-XRT (2-10keV)
NuSTAR (3-7keV)
NuSTAR (7-30keV)
IXPE (2-8keV)
Flux [$10^{-11}$ erg cm$^{-2}$ s$^{-1}$]
Swift-XRT (2-10keV) / (0.3-2keV)
Flux ratio
UVOT W1
UVOT M2
UVOT W2
Flux [mJy]
R-band: Robopol Tuorla - TJO Bootes Kanata T090 MAPCAT T150 AZT-8
IRAM(86GHz)
IRAM(230GHz)
OVRO(15GHz)
SMA(226GHz)
Metsähovi(37GHz)
Flux [Jy]
Pol. deg. [%]
R-band: NOT Robopol Kanata MAPCAT T150 AZT-8
SMA(226GHz)
IRAM(86GHz)
IXPE (2-8keV)
Jet direction (Weaver et al. 2022)
Pol. ang. [deg]
MJD


AGIC