

Illuminating the Active Universe · ESO Garching
14 September 2026

AGN observations in the gamma-ray band

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AGN at the highest energies · multi-instrument campaigns

In honour of Paolo Padovani — four decades of AGN

Outlook of this presentation

1. **Three challenges**
   why AGN are hard to observe — energy range, variability, and spatial scale

2. **AGN in the γ-ray sky**
   why blazars dominate the census — and what else is in there

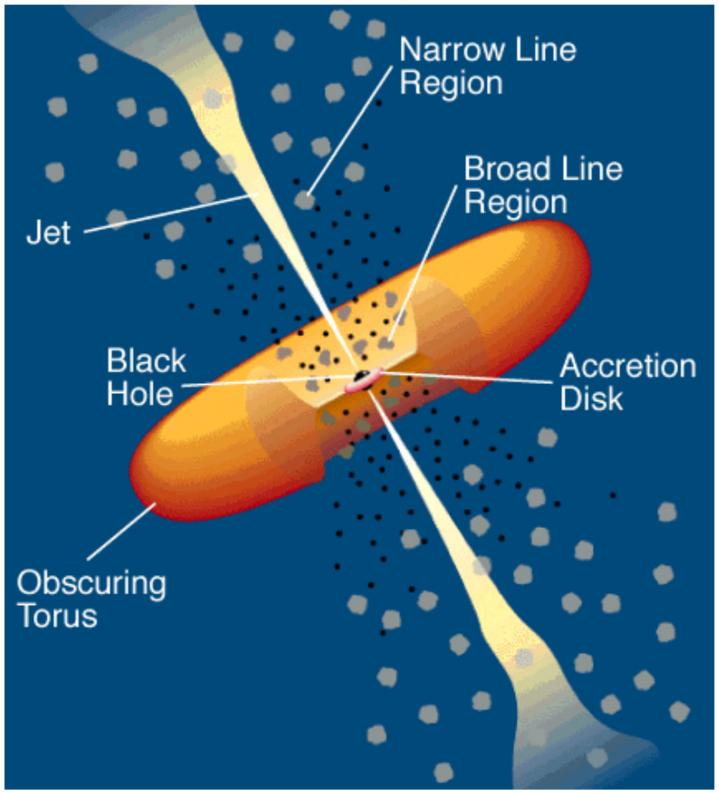
3. **Two blazars, two decades of observations**
   Mrk 421 and Mrk 501 as laboratories — what dense monitoring reveals

4. **Gamma rays meet neutrinos**
   TXS 0506+056, NGC 1068, NGC 4151 — jets and hidden coronae

5. **The future: what we we will do and what (still) will not be able to do**
   no longer will be limited by sensitivity — limited by temporal coverage

In my work: I have been constantly using Paolo's work

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



The picture

Urry & Padovani 1995, PASP 107, 803 **5021 citations (ADS, Sep13)**

The AGN cartoon every one of us shows.

I have never paid royalties.

The vocabulary

Padovani & Giommi 1995, ApJ 444, 567 **710 citations (ADS, Sep13)**

HBL / IBL/ LBL, which became HSP / ISP / LSP in 2010
Every blazar in the Fermi list wears that label today.

You cannot write a blazar abstract without it.

The map

Padovani et al. 2017, A&ARv 25, 2 **692 citations (ADS, Sep13)**

"jetted" vs "non-jetted". *Section IV lands on exactly this line.*

From a direction nobody expected.

Much of this vocabulary was built with Paolo Giommi, who spoke here a half hour ago.

A gamma-ray astronomer cannot give a AGN talk without speaking Paolo's language.



Act I

Three challenges

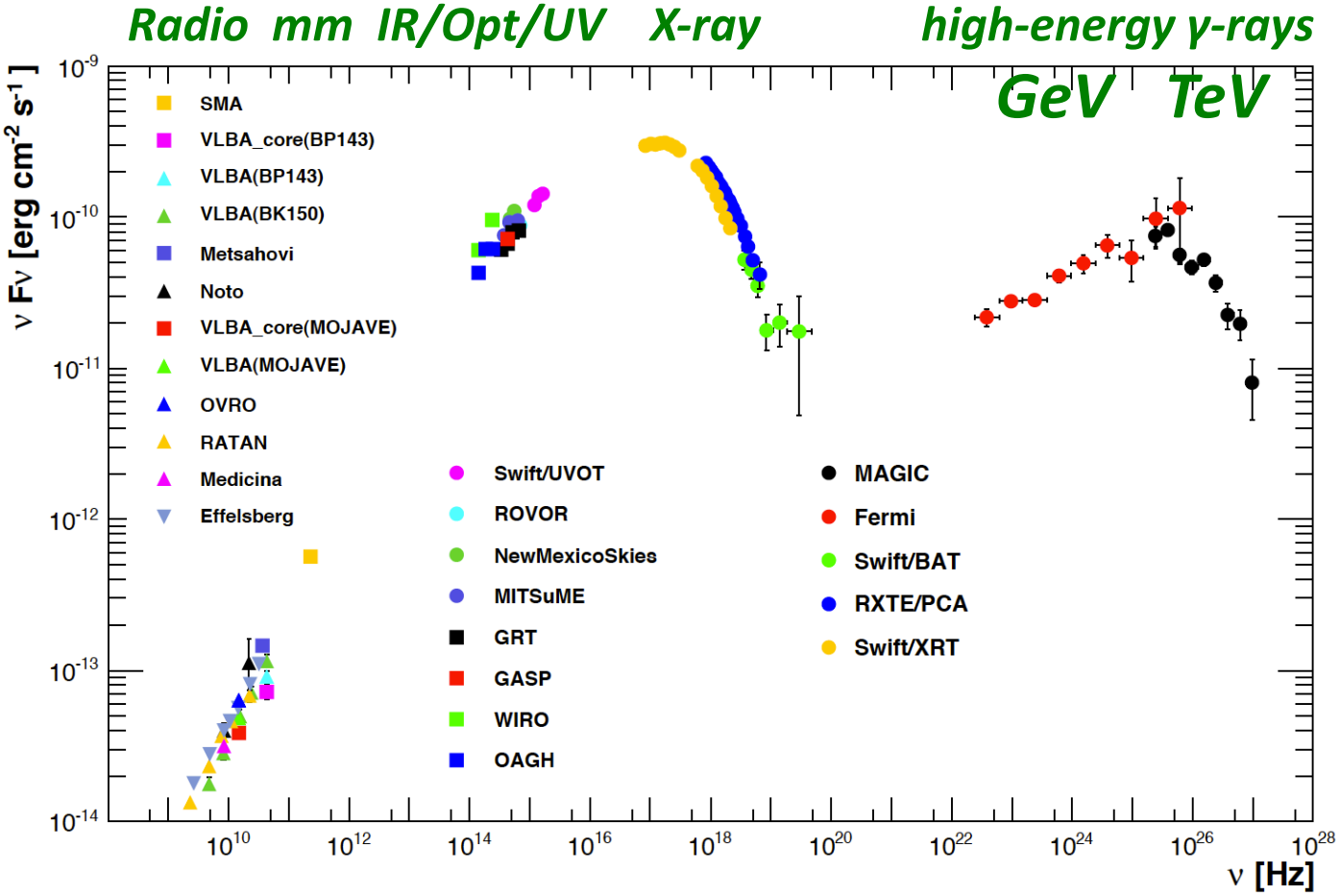
Despite the brightness of some AGNs/blazars, their observation and study needs to deal with several challenges

Challenges when studying AGNs (→blazars)

AGNs (→ blazars) emit radiation over a large energy range

Emission at different energies could be due to same particle population

→ *Need many instruments to fully characterize emission in these objects*



Spectral energy distribution (SED) of the Blazar Mrk 421

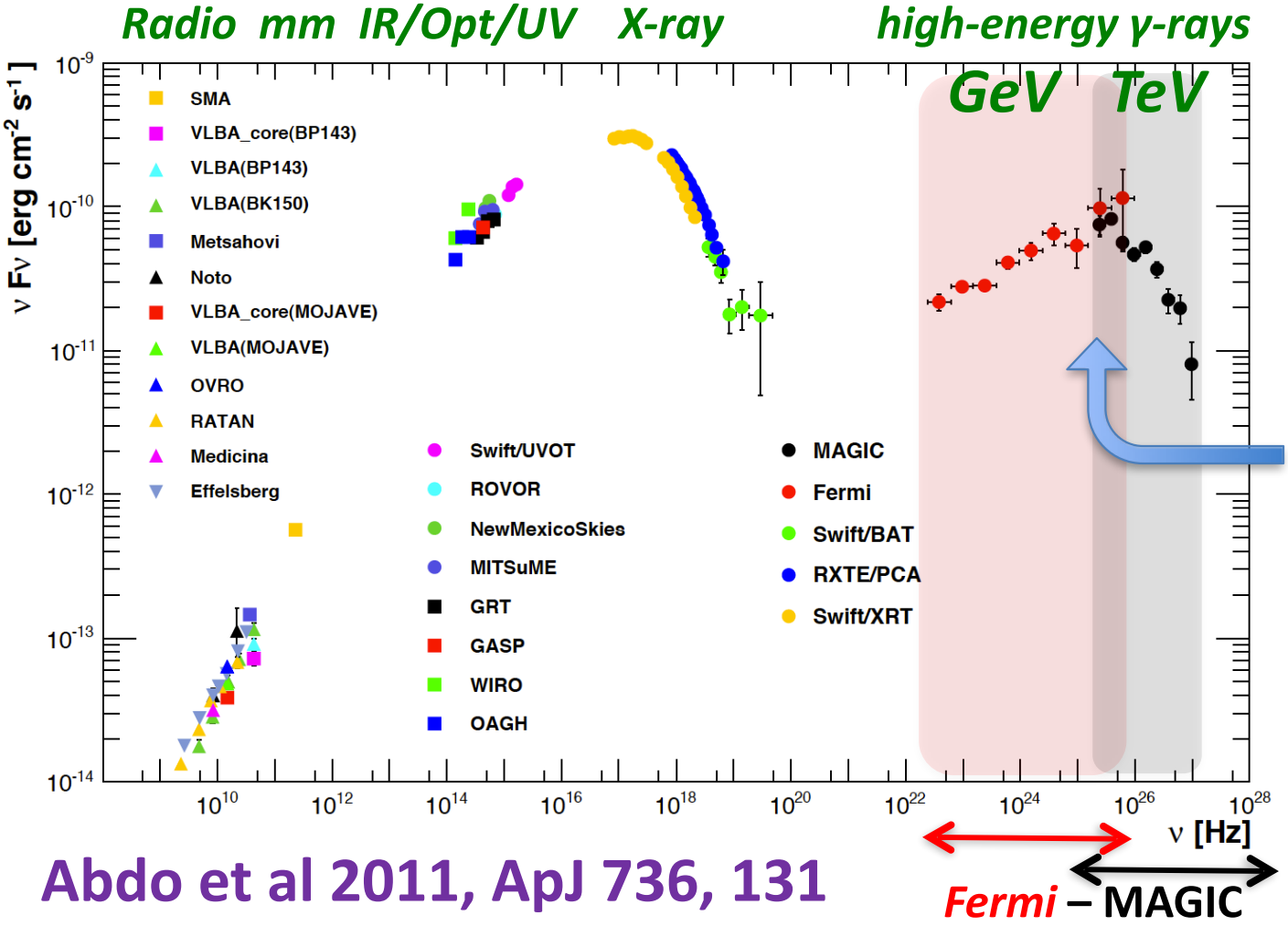
Abdo et al 2011, ApJ 736, 131

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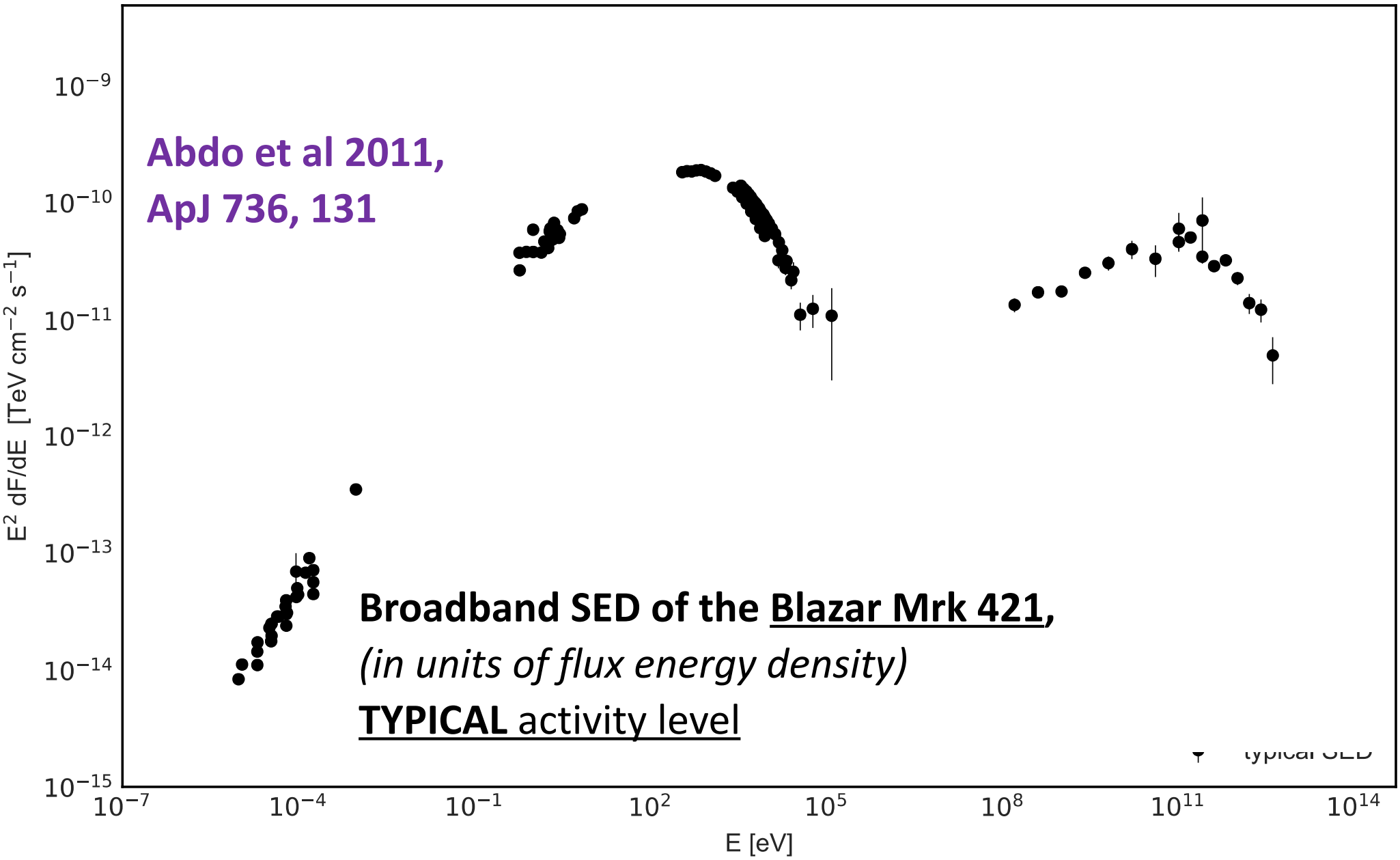
Abdo et al 2011, ApJ 736, 131

Spectral energy distribution (SED) of the Blazar Mrk 421

Gamma-ray bump of many sources could only be accurately measured with the advent of *Fermi*-LAT + modern IACTs like HESS/MAGIC/VERITAS

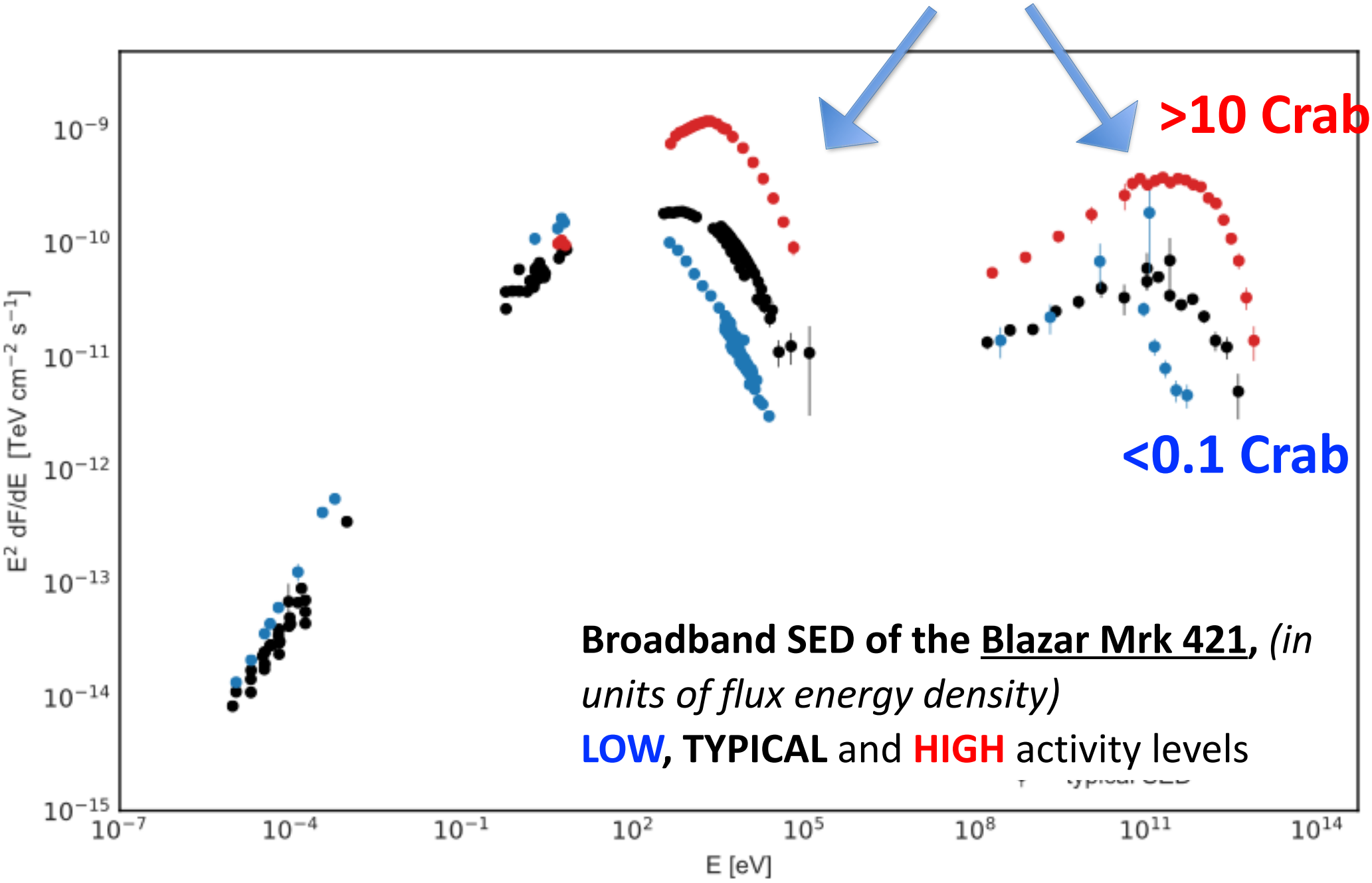
→ *Crucial for the theoretical modeling of the broadband emission*

Several AGN emit from radio to VHE



Sources show flux variations by orders of magnitude

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

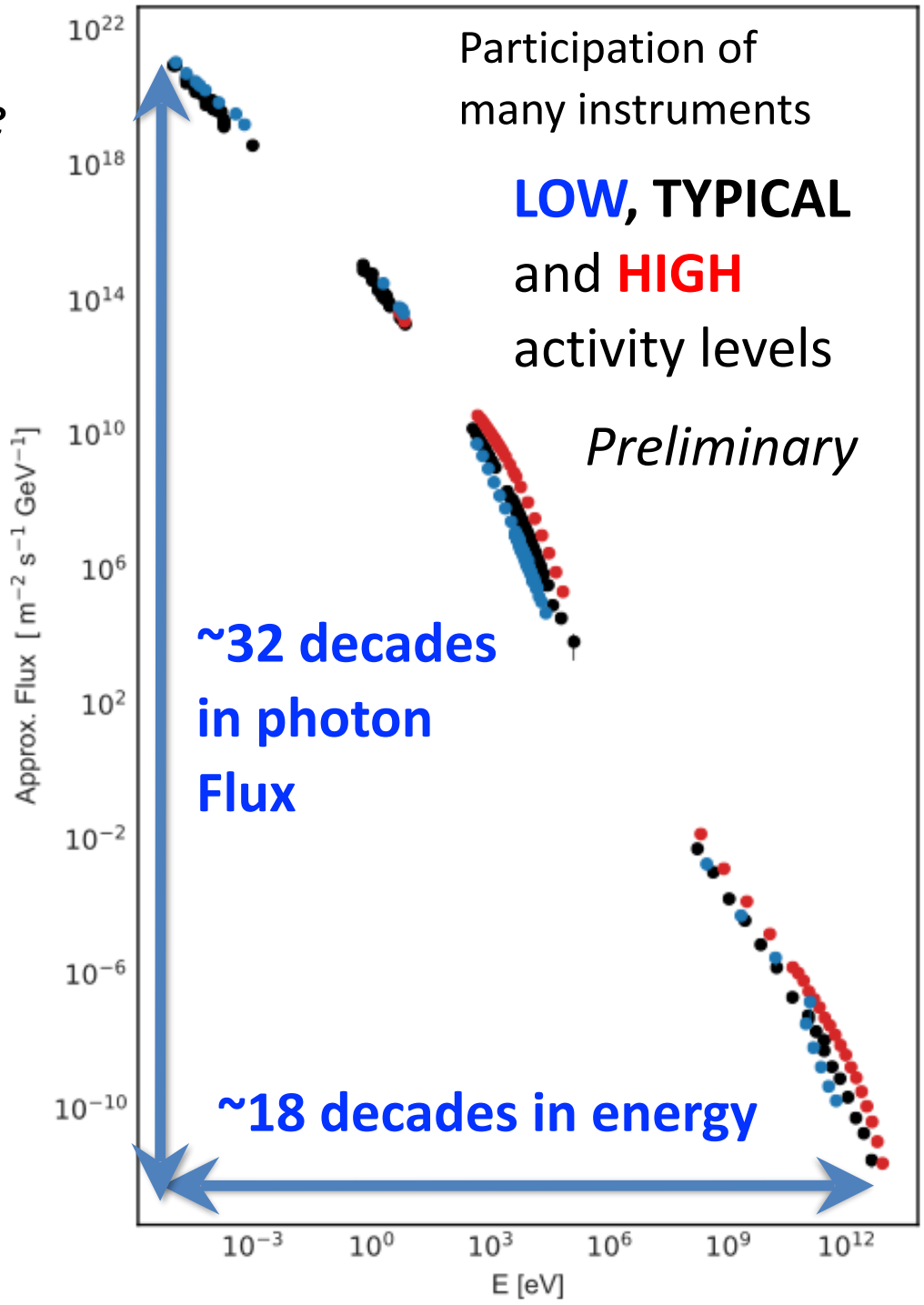


Broadband SED of the Blazar Mrk 421, *(in units of flux energy density)*

LOW, TYPICAL and **HIGH** activity levels

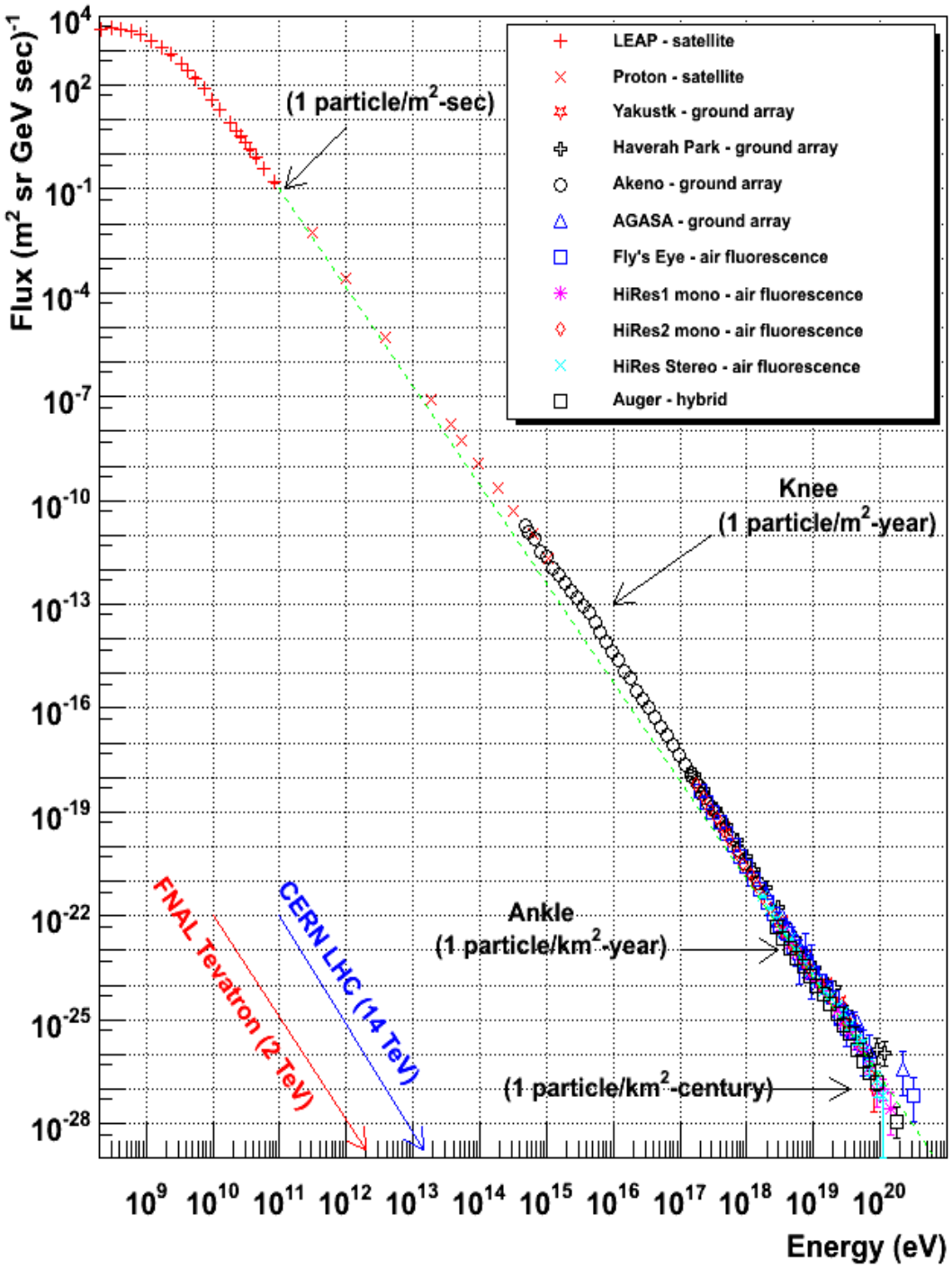
Broadband SED can be converted into a photon flux spectrum *(representation typically used to display the CR particle flux)*

Mrk421 photon flux spectrum

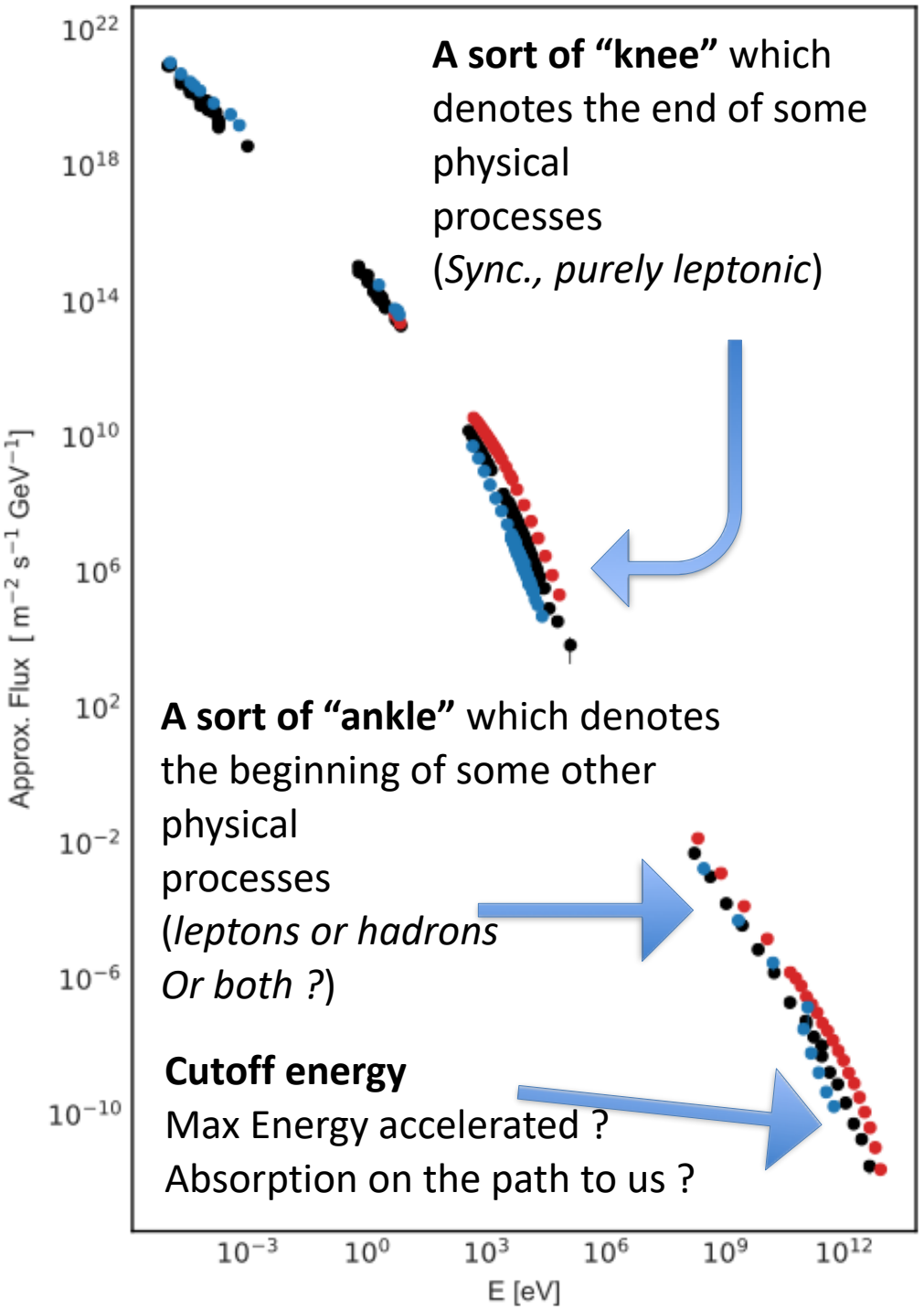


In this representation, the **Low**, **Typical** and **High** activities do not “look” that different ...

Cosmic Ray Spectra of Various Experiments



Mrk421 photon flux spectrum

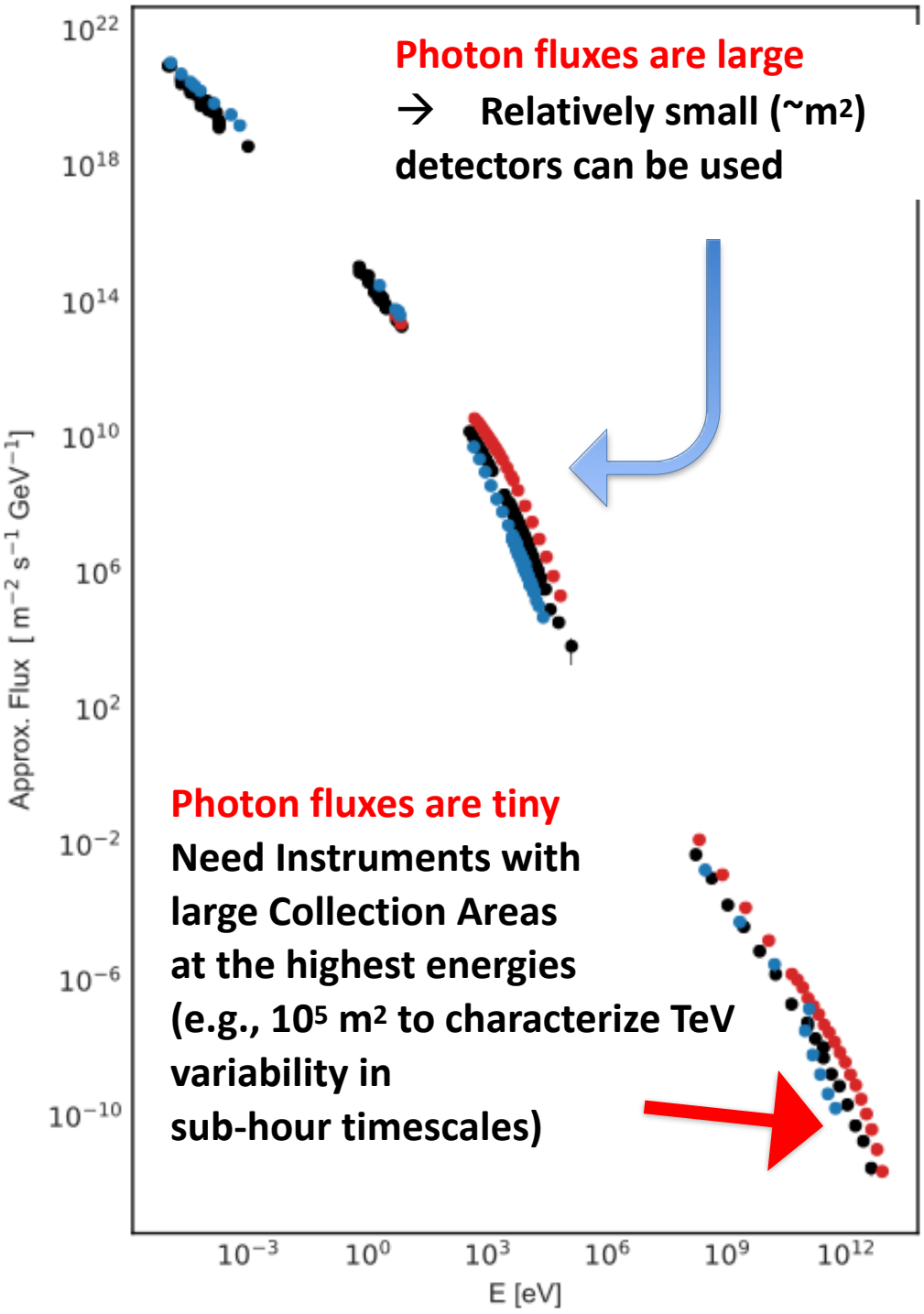


A sort of "knee" which denotes the end of some physical processes (*Sync., purely leptonic*)

A sort of "ankle" which denotes the beginning of some other physical processes (*leptons or hadrons Or both ?*)

Cutoff energy
Max Energy accelerated ?
Absorption on the path to us ?

Mrk421 photon flux spectrum



@ keV energies

~10^6 photons [m-2 s-1]

~10^2 photons [cm-2 s-1]

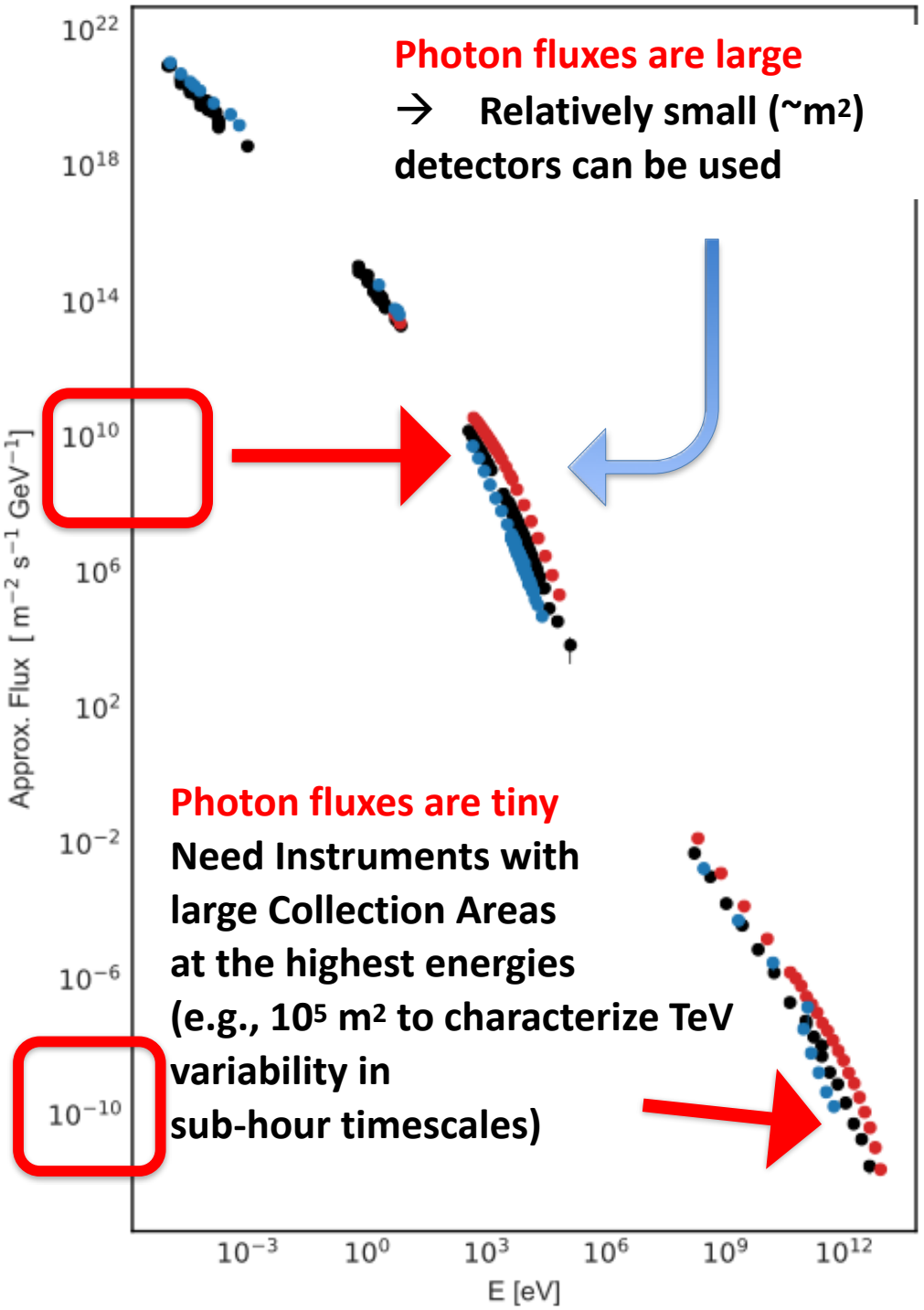
@ TeV energies

~10^{-6} photons [m^{-2} s^{-1}]

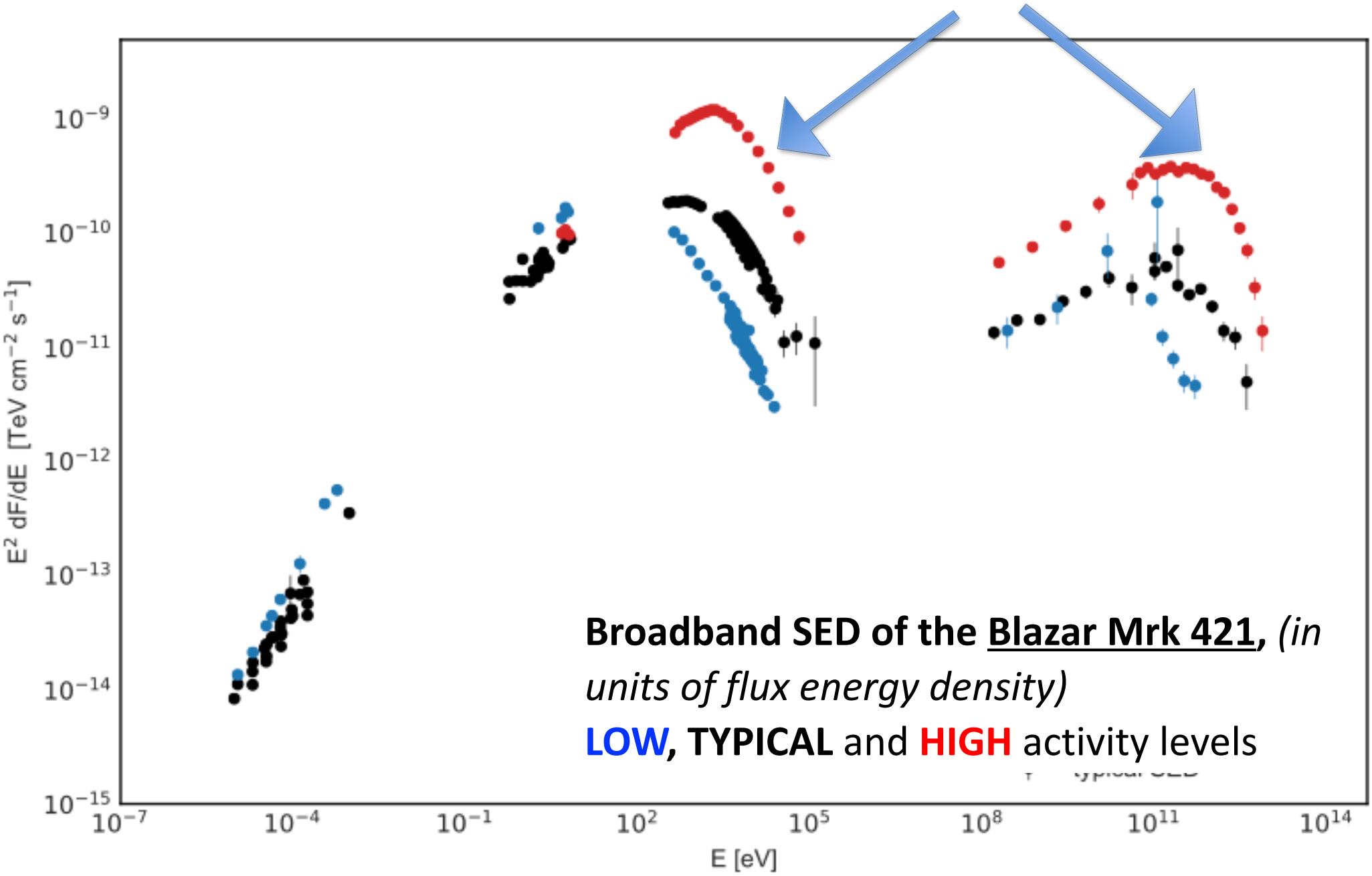
~1 photon [km^{-2} s^{-1}]

~10^3 photons [km^{-2} hr^{-1}]

Mrk421 photon flux spectrum



Energy flux emitted at **keV** and **TeV** is similar, **BUT** the actual number of photons at keV and TeV differ by 12 orders of magnitude



Broadband SED of the Blazar Mrk 421, *(in units of flux energy density)*

LOW, TYPICAL and **HIGH** activity levels

Techniques to detect gamma rays (and do gamma ray astronomy)

Indirect detection of the gamma rays

→Usage of the Earth atmosphere as part of our detector

→ **Turn a problem into an advantage**

→ Enables detection of very low photon fluxes, because now we are not "that limited" by the size of our detector

→ Only works for very high energies (>10 GeV) that produce atmospheric showers that we can detect

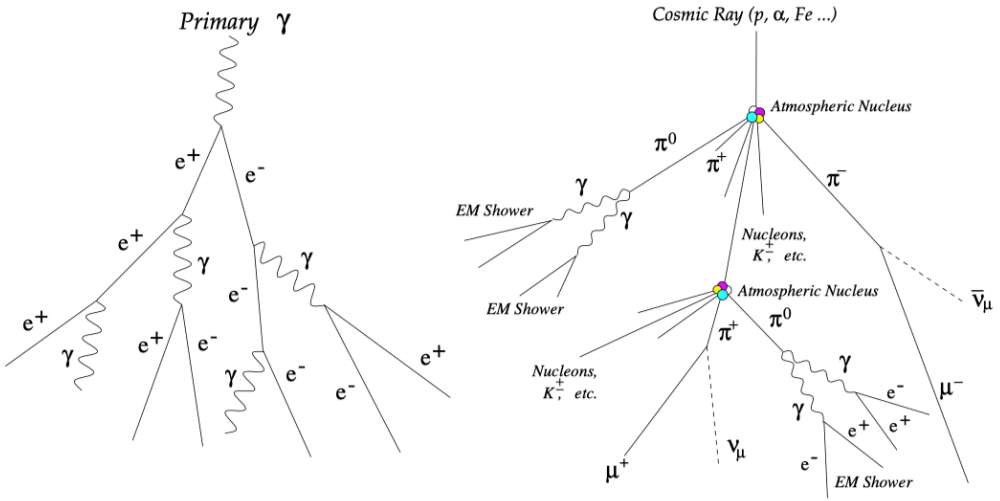


Figure 2.1: *Principal development of an EAS; a) induced by a $\gamma-ray$ and b) induced by a charged cosmic ray.*

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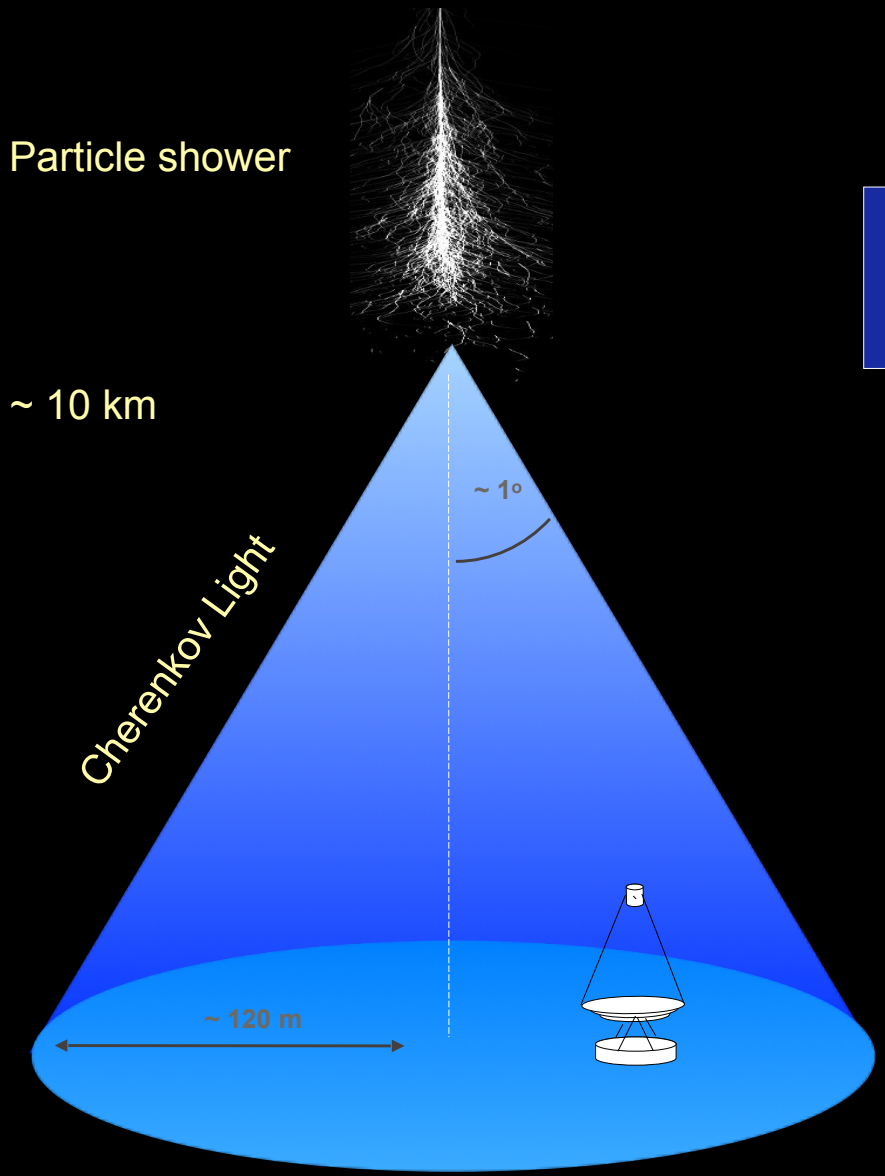
→ Only works for very high energies (>10 GeV) that produce atmospheric showers that we can detect

→ Two strategies to measure the atmospheric showers

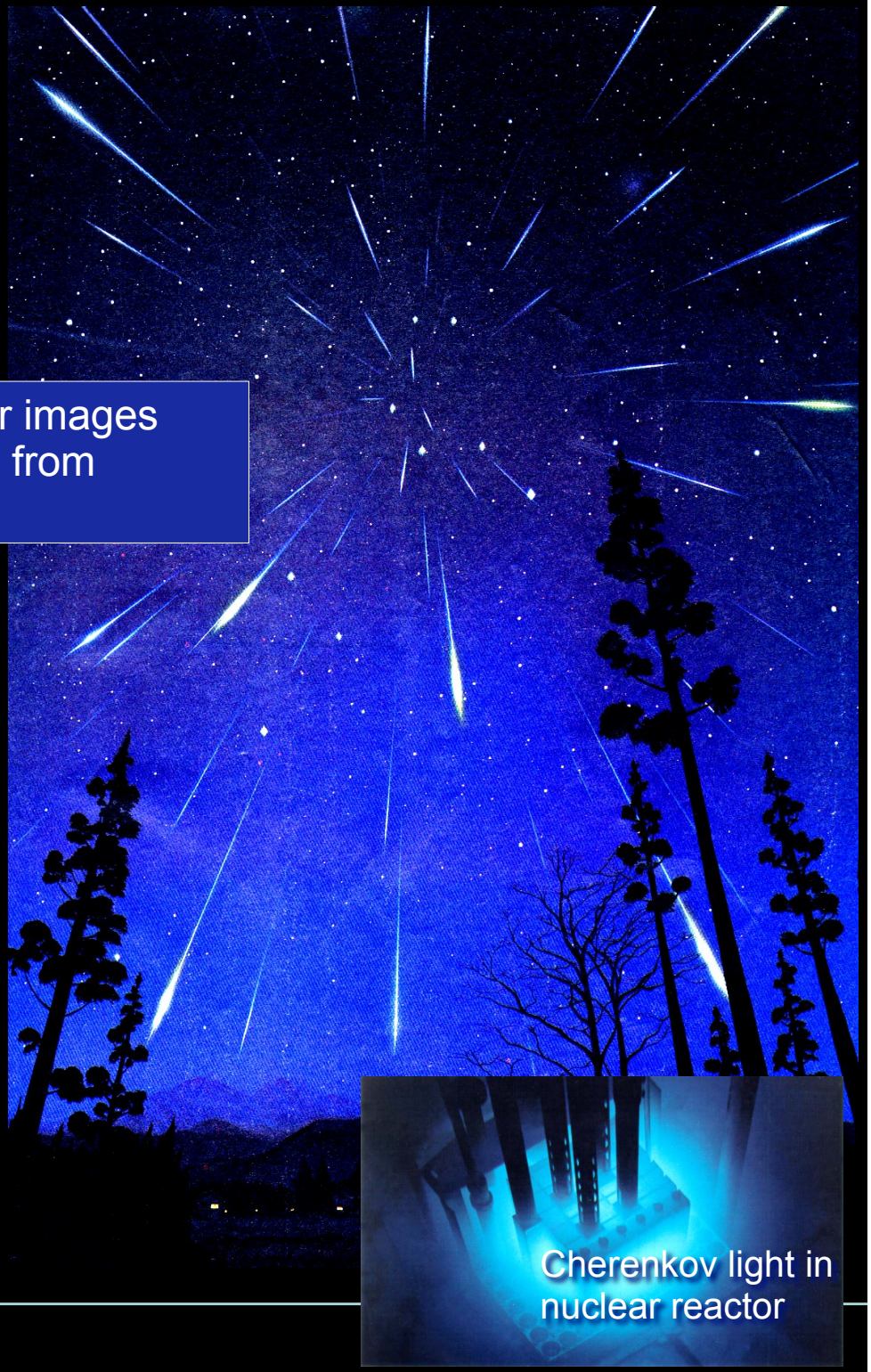
→ Detection of the Cherenkov Light (produced by e-/e+)
Imaging Atmospheric Cherenkov Telescopes

→ Detection of secondary particles at ground
Air Shower Arrays

Imaging Technique Principle



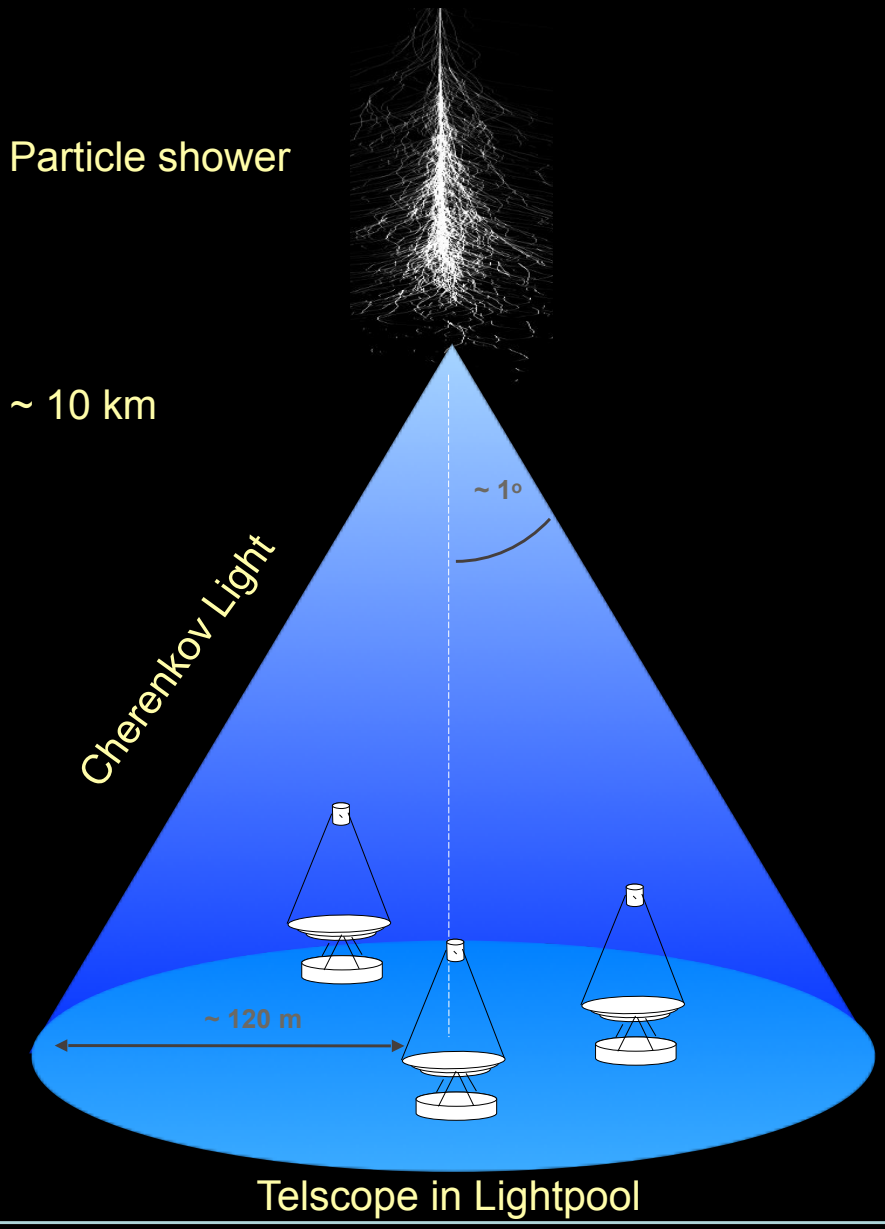
Shower images viewed from below

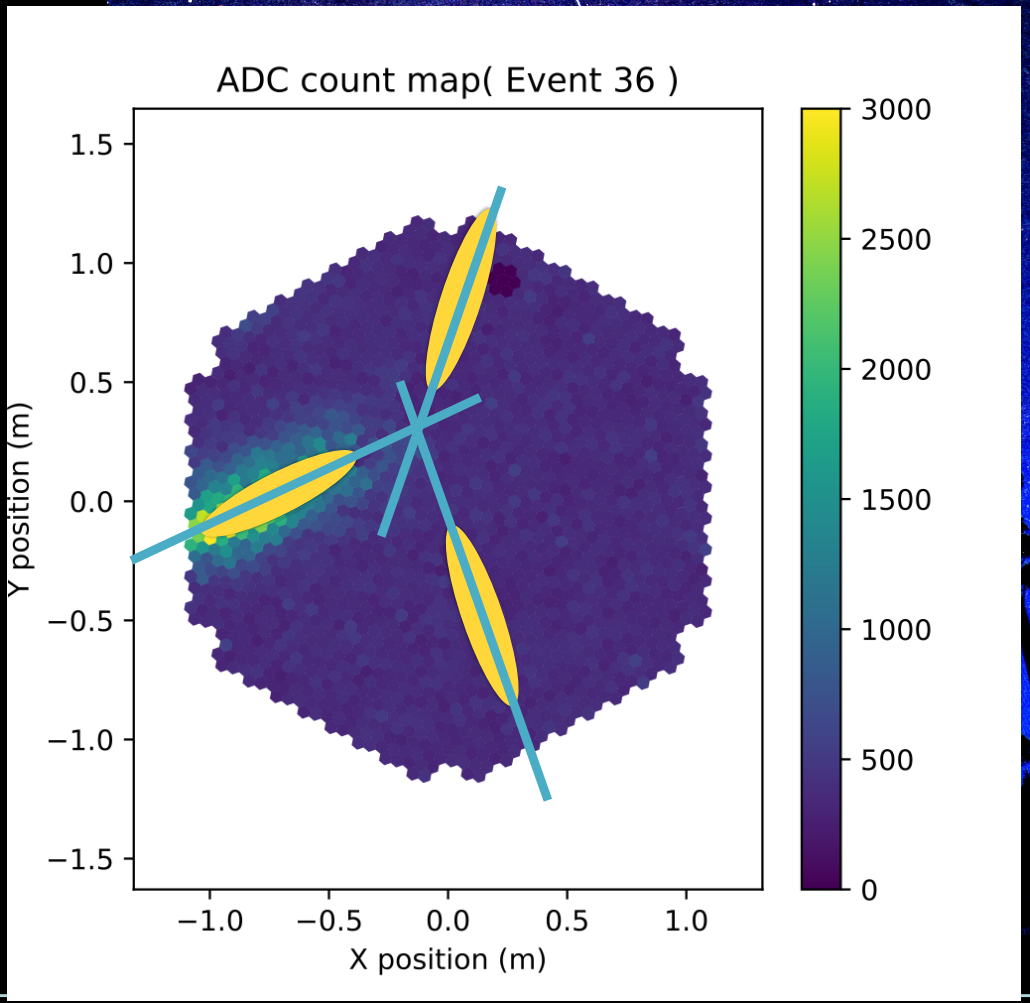


Imaging Technique Principle

Triangulation between several telescopes improves …

- angular resolution
- sensitivity (background reduction)
- energy resolution





The three big IACTs that are in scientific operation

VERITAS (4 telescopes, 12m diameter mirror)

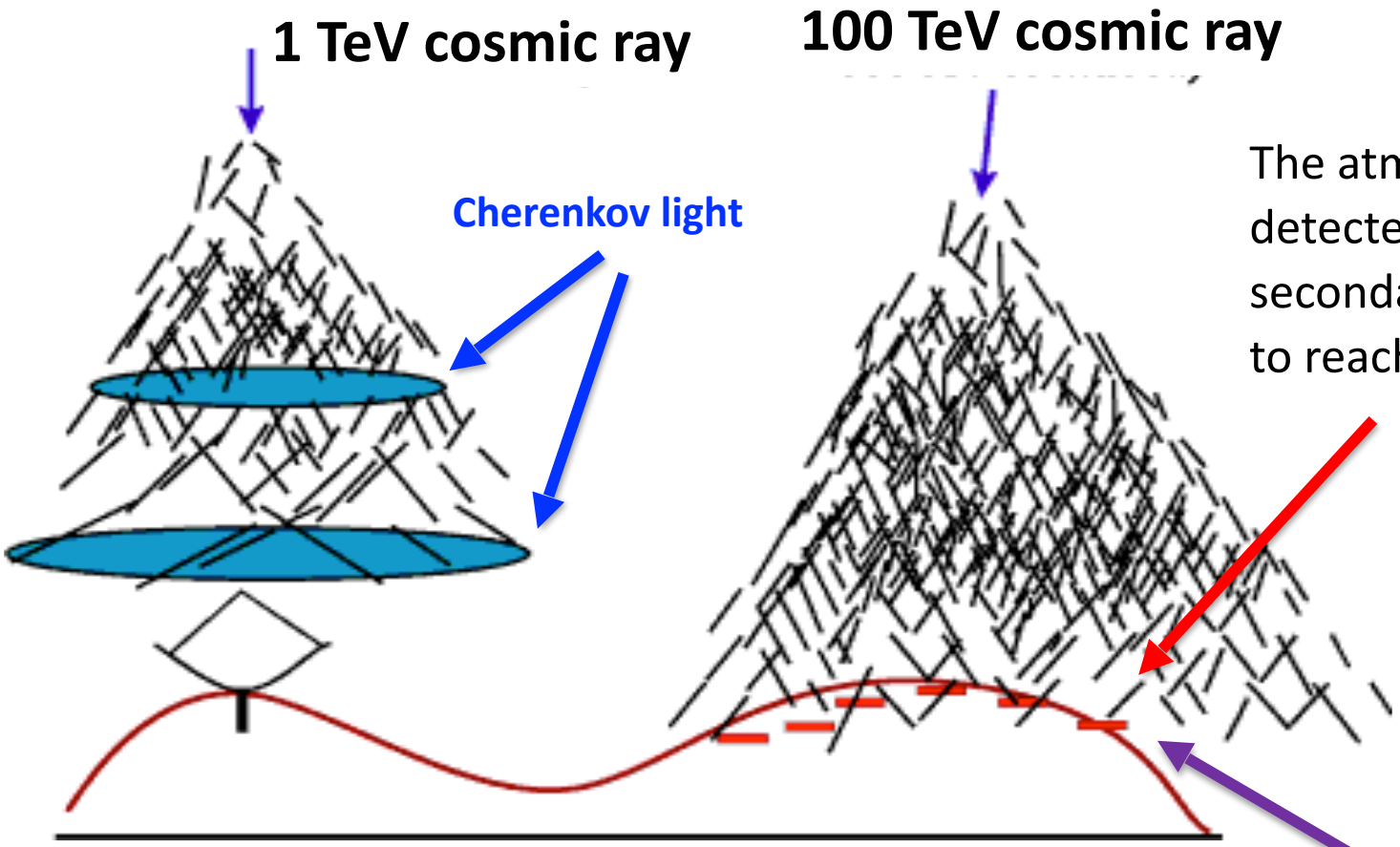


H.E.S.S.

(4 telescopes, 12m diameter + 1 telescope, 28m eq. diameter)

MAGIC (2 telescopes, 17m diameter mirror)

Indirect detection of gamma rays with Air Shower Arrays

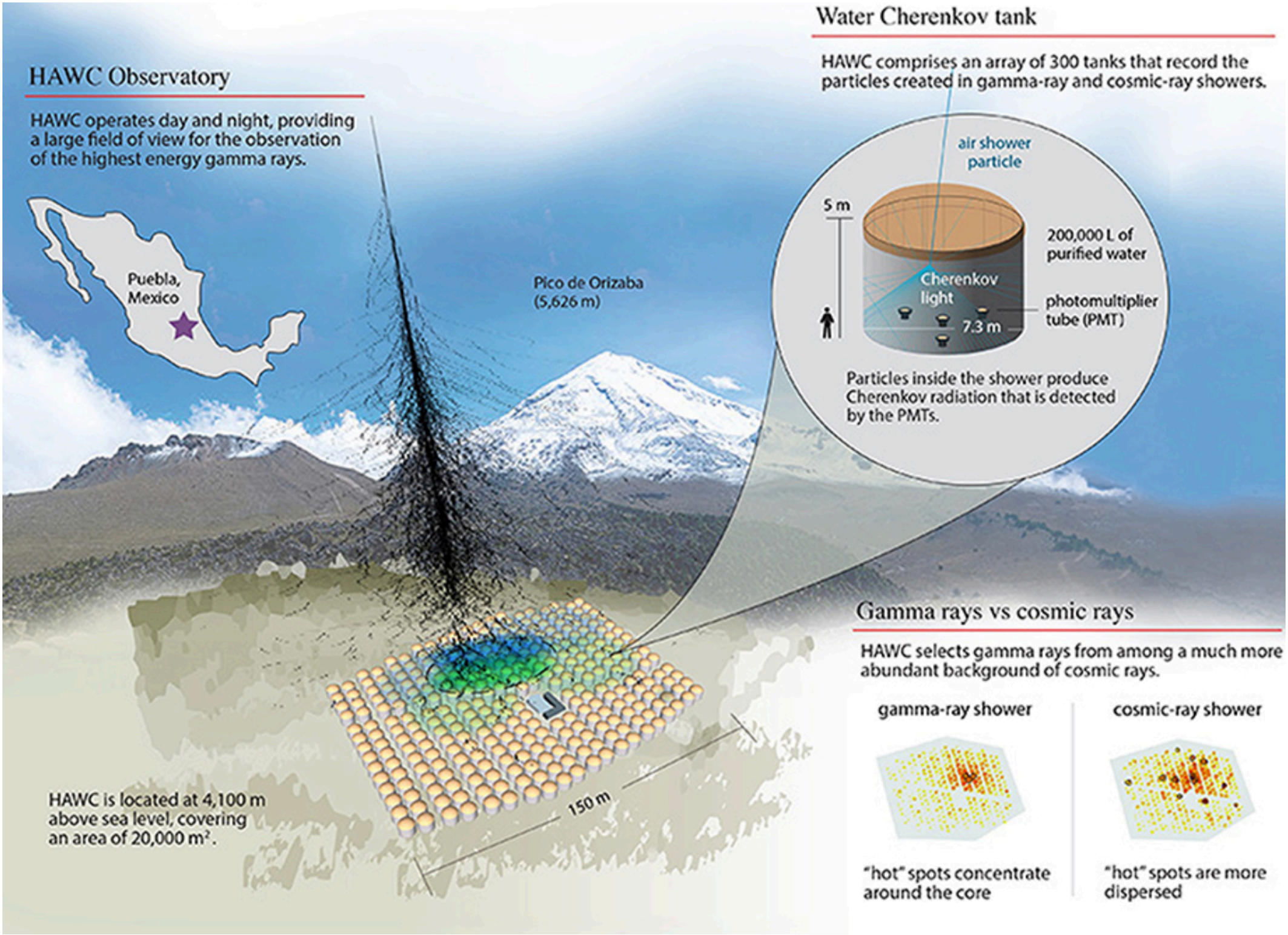


The atmospheric shower is detected through the secondary particles, that need to reach the detectors

The observation of an extensive air shower particle cascade using by collecting Cherenkov radiation (left) and observing the shower particles at ground level (right). From the Milagro collaboration (copyright © 2002, University of California).

→ Detectors need to be placed very high (4+ km a.s.l.)

→ Only efficient at very high energies (>10 TeV)

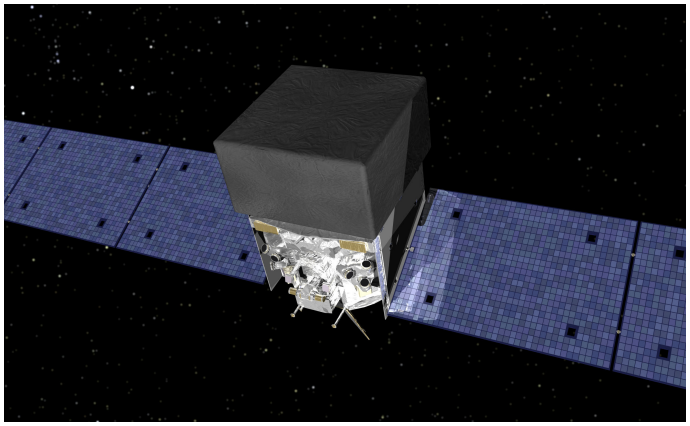

HAWC Observatory
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.
Puebla, Mexico
Pico de Orizaba (5,626 m)
HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².
150 m
Water Cherenkov tank
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.
air shower particle
5 m
200,000 L of purified water
Cherenkov light
photomultiplier tube (PMT)
7.3 m
Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.
Gamma rays vs cosmic rays
HAWC selects gamma rays from among a much more abundant background of cosmic rays.
gamma-ray shower
cosmic-ray shower
"hot" spots concentrate around the core
"hot" spots are more dispersed

Instrumentation for gamma-ray astronomy

Three ways of detecting high-energy gamma rays

Pair production telescopes
e.g. EGRET, AGILE, *Fermi*

Direct detection of gamma

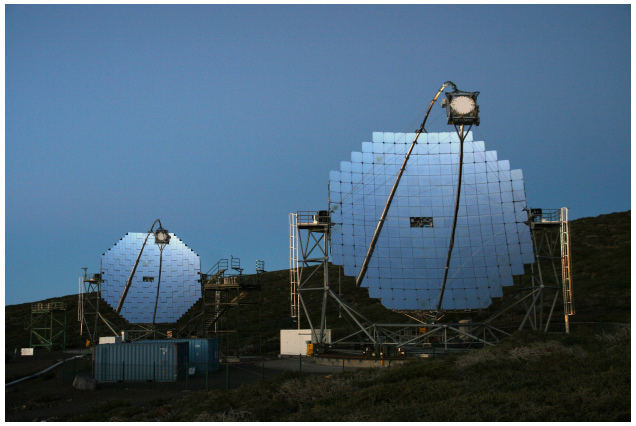


Space-based
Large duty cycle (~85%)
Large field of view (20-60 deg)
Excellent bkg rejection
Small effective areas (~m^2)
Energy range ~0.02 – 300 GeV

Good sensitivity

Imaging Atmospheric Cherenkov Telescopes (IACTs)
e.g., HESS, MAGIC, VERITAS

Indirect detection of gamma through Cherenkov Light

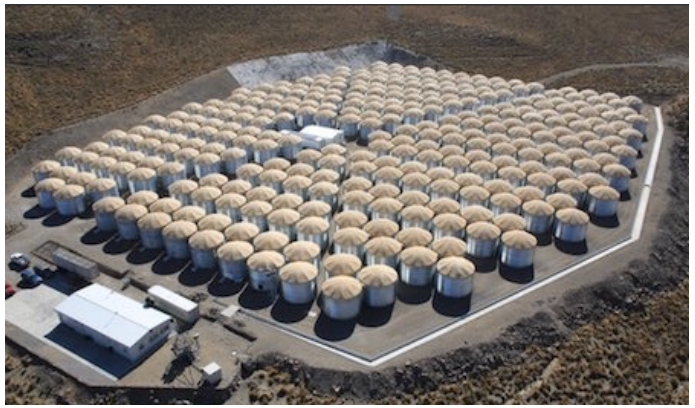


Ground-based
Low duty cycle (~10%)
Small FoV (2-4 deg)
Very Good bkg rejection
Large effective area (~10^5 m^2)
Energy ~50 GeV– 100 TeV

Excellent sensitivity

Extensive Air Shower (EAS) arrays
e.g. Milagro, HAWC, Tibet, ARGO
LHAASO

Indirect detection of gamma through secondaries



Ground-based
Large duty cycle (~90%)
Big FoV (30-40 deg)
Moderate bkg rejection
Good effective area (~10^2 m^2)
Energy ~1 TeV– 10 PeV

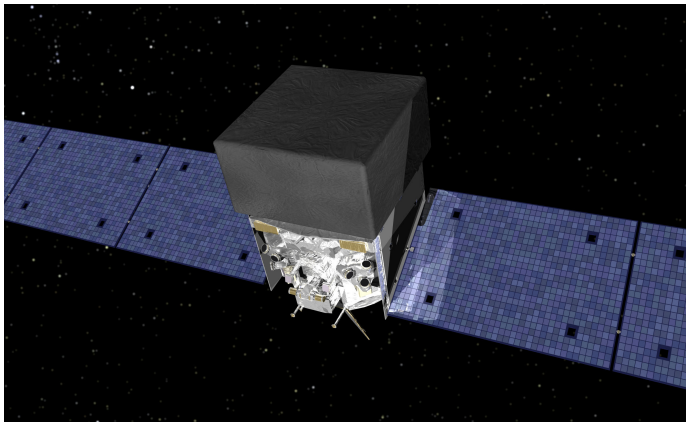
Moderate sensitivity

Instrumentation for gamma-ray astronomy

The last 20 years have seen large improvement in gamma-ray instrumentation

Pair production telescopes
e.g. EGRET, AGILE, *Fermi*

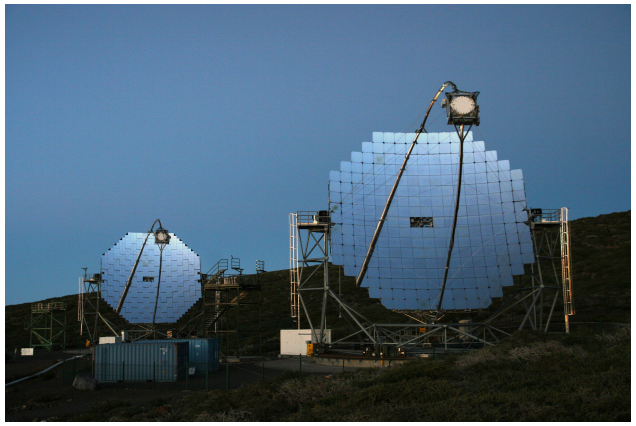
Direct detection of gamma



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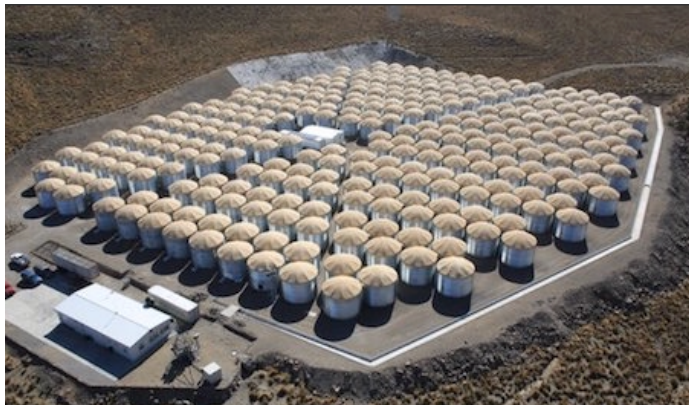
Indirect detection of gamma through Cherenkov Light



Ground-based
Low duty cycle (~10%)
Small FoV (2-4 deg)

Extensive Air Shower (EAS) arrays
e.g. Milagro, HAWC, Tibet, ARGO
LHAASO

Indirect detection of gamma through secondaries



Ground-based
Large duty cycle (~90%)
Big FoV (30-40 deg)

Complementary characteristics

Energy range ~0.02 – 300 GeV

Good sensitivity

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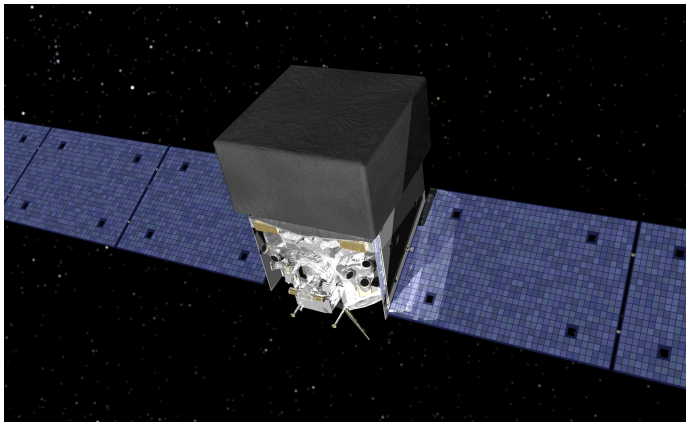
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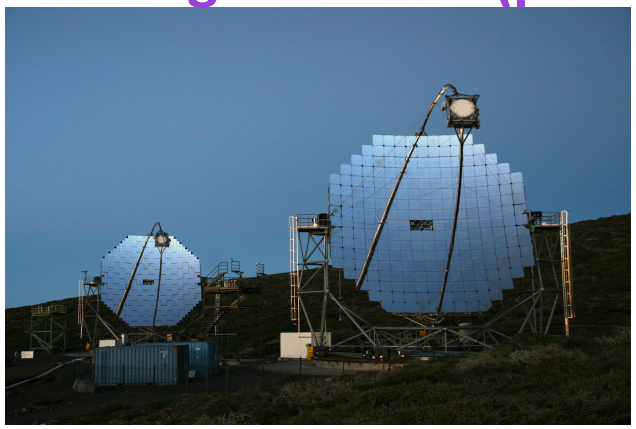
Extensive Air Shower (EAS) arrays
e.g. Milagro, HAWC, Tibet, ARGO
LHAASO

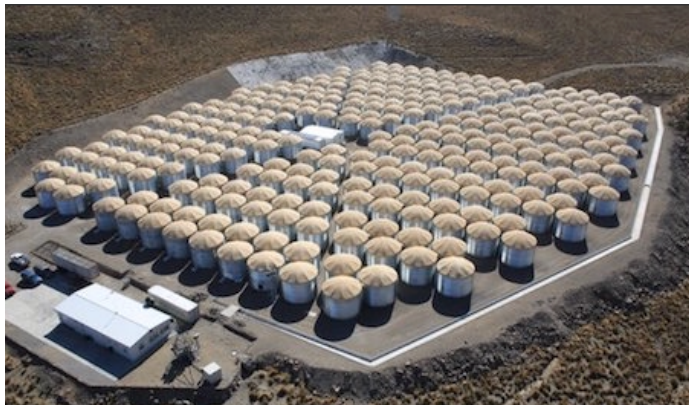
Direct detection of gamma

+ CTA-North +ASTRI

New generation (partially) already online …





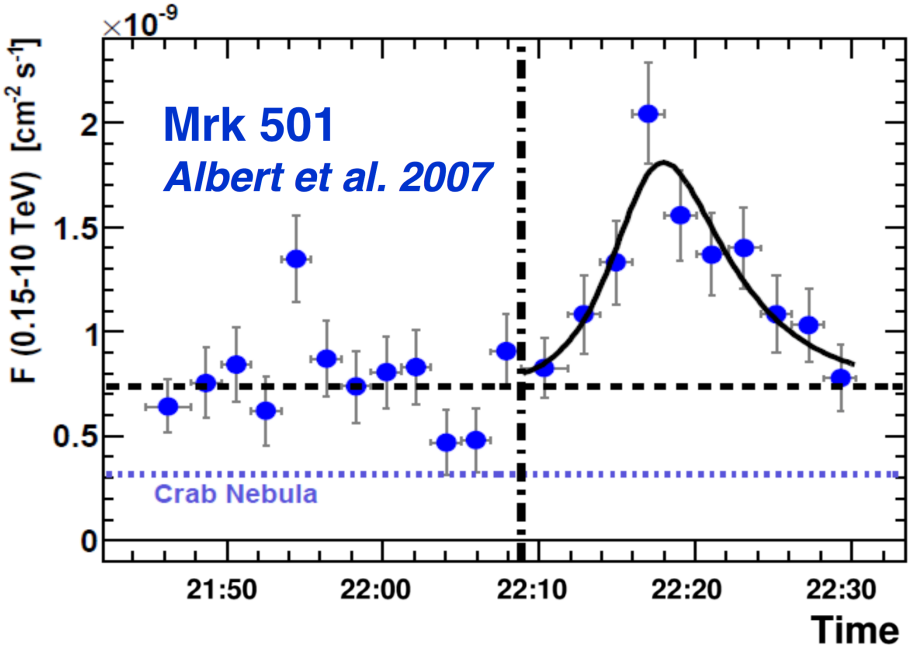


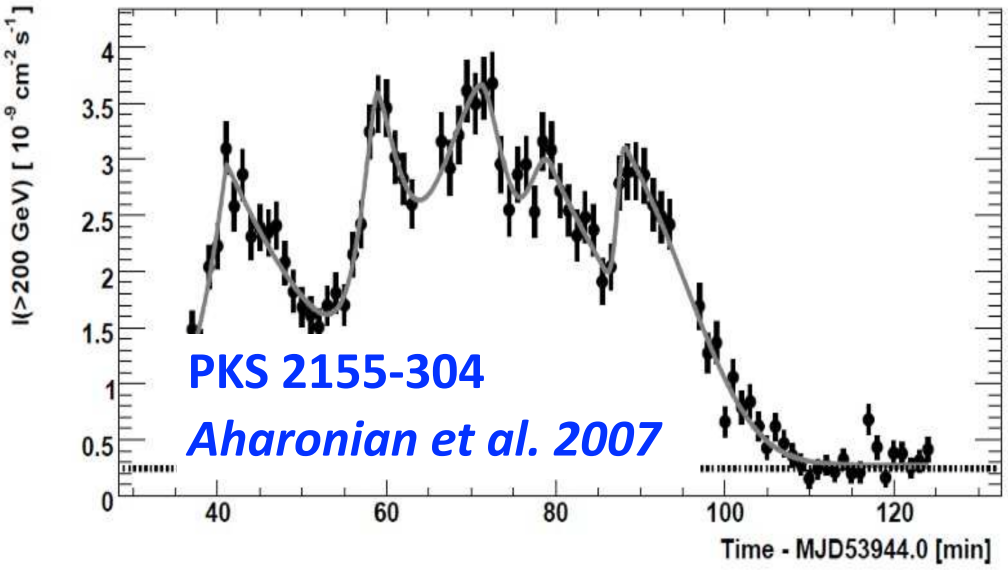
Space-based	**Ground-based**	**Ground-based**
Large duty cycle (~85%)	Low duty cycle (~10%)	Large duty cycle (~90%)
Large field of view (20-60 deg)	Small FoV (2-4 deg)	Big FoV (30-40 deg)

Complementary characteristics

Energy range ~0.02 – 300 GeV	**Energy ~50 GeV– 100 TeV**	**Energy ~1 TeV– 10 PeV**
Good sensitivity	**Excellent sensitivity**	**Moderate sensitivity**

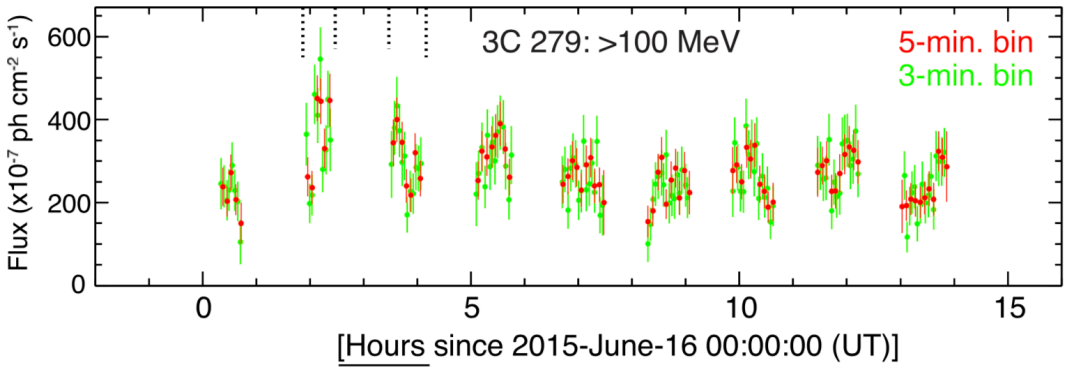
Blazars show SHORT variability timescales

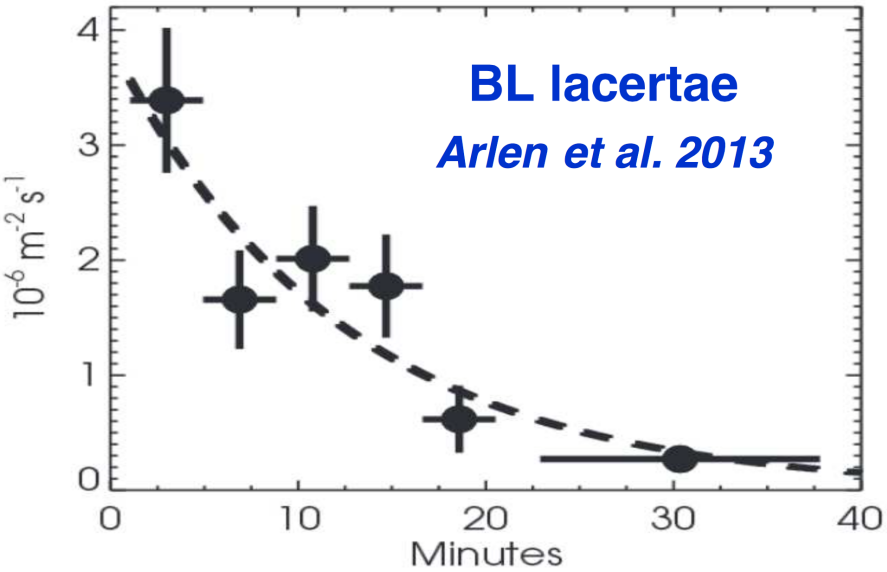




3C279

Ackermann et al 2016

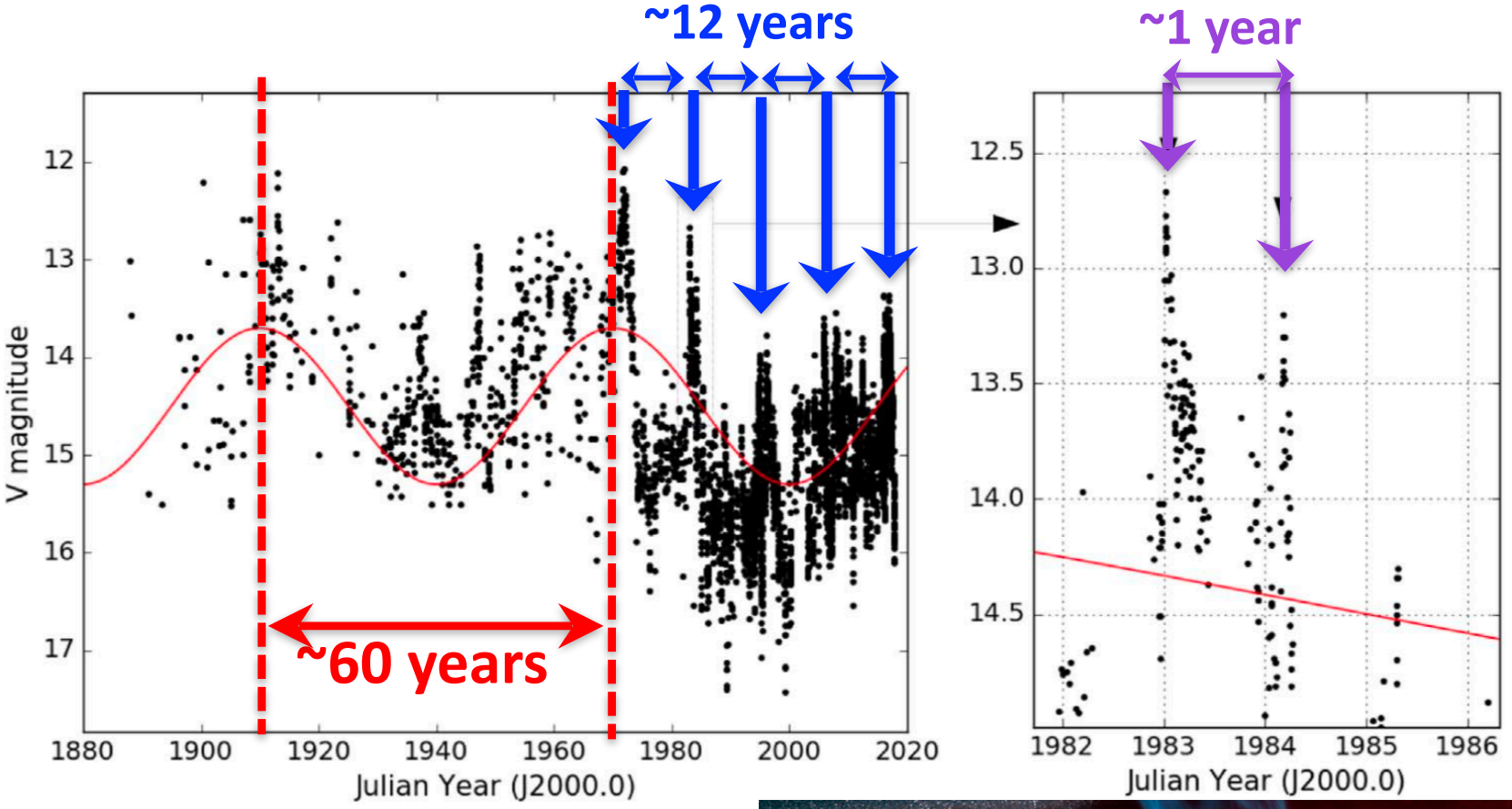




Sub-hour flux variations bring crucial information to study the accelerating & cooling, the size of region and their environments

(e.g. high doppler factors needed for short variability + TeV transparency)

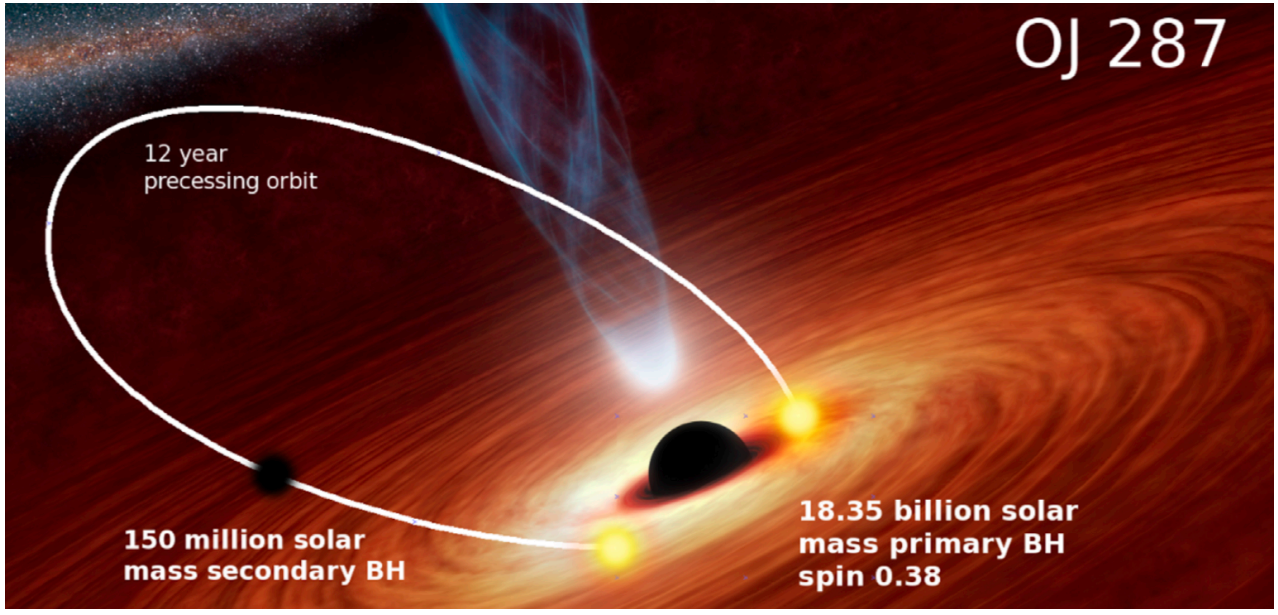
Blazars show LONG variability timescales



Century-long optical light curve of blazar OJ 287

Dei et al., ApJ 866 (2018) 11

Multi-year flux variations bring crucial information to understand the sources and their environment



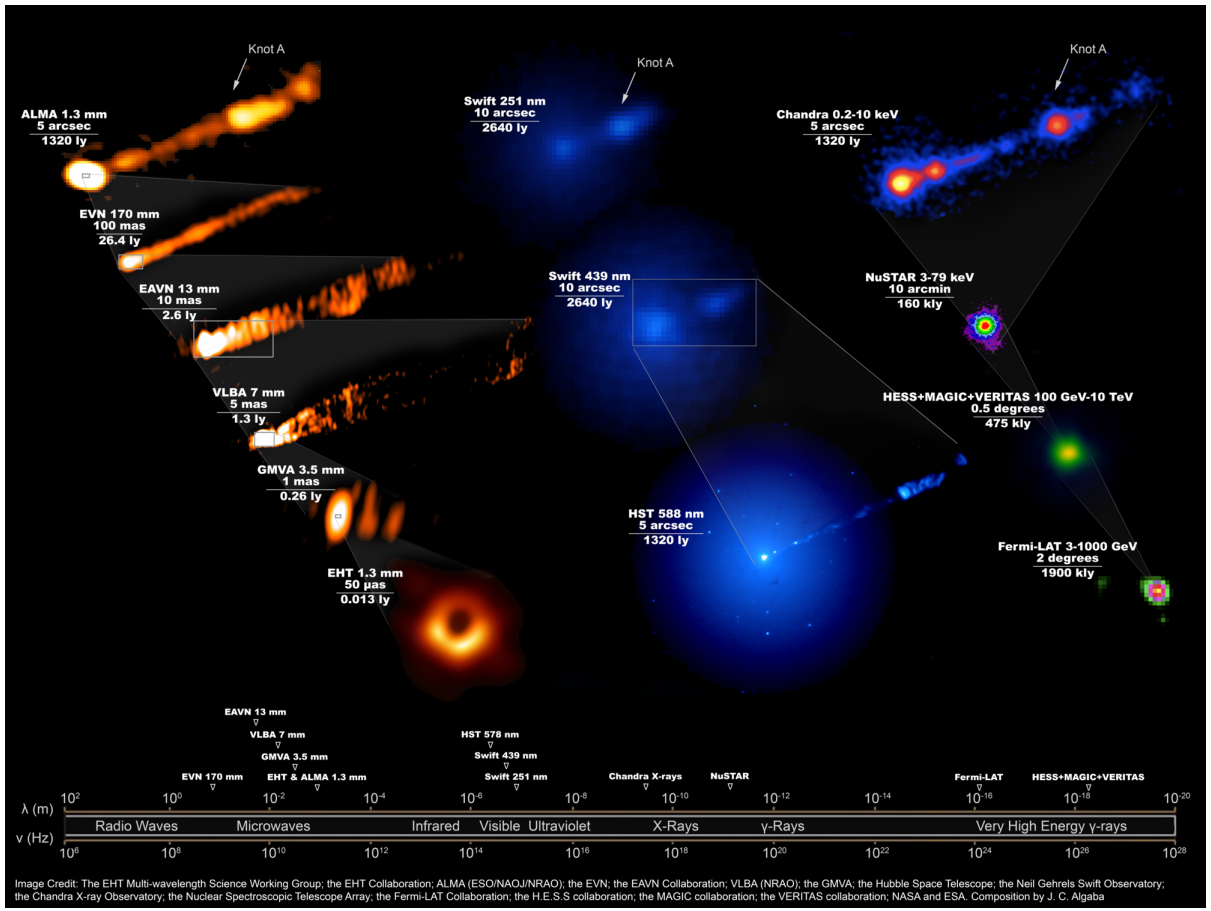
Later this afternoon — Omar Kurtanidze:
"Multi-band optical variability of OJ 287, 2015–2025"

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*



M87 from radio to VHE γ-rays — EHT, Fermi-LAT, H.E.S.S., MAGIC, VERITAS, NuSTAR, Chandra, Hubble and more

Algaba et al. 2021, ApJL 911, L11

- Spatial dynamic range: mini-parsec to mega-parsec, more than 10^9
- At γ-rays we measure a point. Where that point sits, we have to infer through variability and correlations

Three challenges, three enormous dynamic ranges

1	**Energy range** micro-eV → tens of TeV	**> 10^{18}**	You need every instrument, from radio dishes to Cherenkov telescopes.
2	**Variability** tens of years → a few minutes	**> 10^{6}**	And they must all observe at the same time.
3	**Spatial extent** mini-parsecs → mega-parsecs	**> 10^{9}**	While the angular resolution available changes by nine orders of magnitude too.

And variability and spatial extension are themselves energy-dependent, as is our instrumental ability to characterise them.

—> Not surprising that AGNs are not well characterized after 50+ years of observations

The complete (deep) characterization of the AGN broadband emission requires enormous efforts from the community

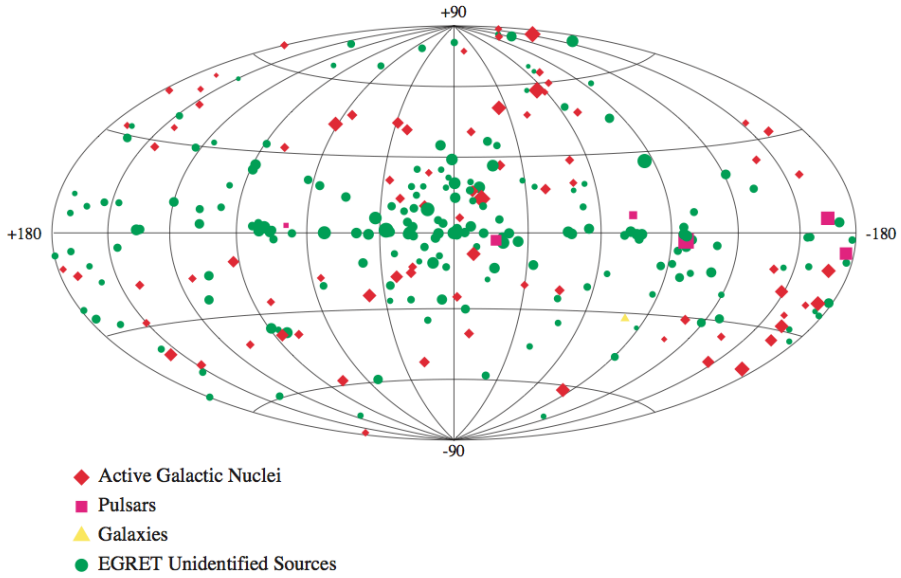


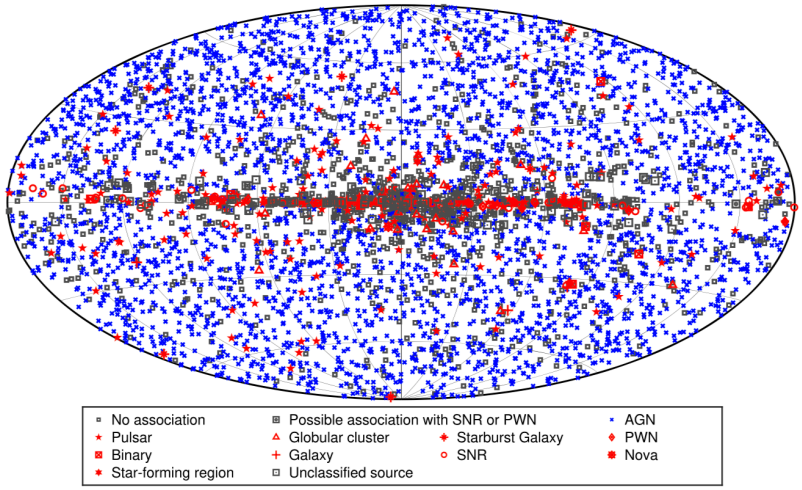
Act II

AGN in the γ-ray sky

Dramatic improvement in the gamma-ray sky during the last two decades
How many AGN are in the gamma-ray catalogues ?

The γ-ray sky, then and now





EGRET, 1999 — 271 sources, 66 blazars **Fermi-LAT 4FGL, 2020 — 5064 sources, 3207 AGN**

Twenty-one years, a factor ~20 in sources — and a factor ~50 in blazars.

- In both the GeV and the TeV bands the number of sources grows faster than Sqrt(T) owing to the improvement is in the instruments and the analysis, not only in the exposure.
- The 4FGL map is the most recent published all-sky source map: DR2–DR4 and the 16-year list are incremental releases, and 5FGL awaits a new interstellar-emission model.

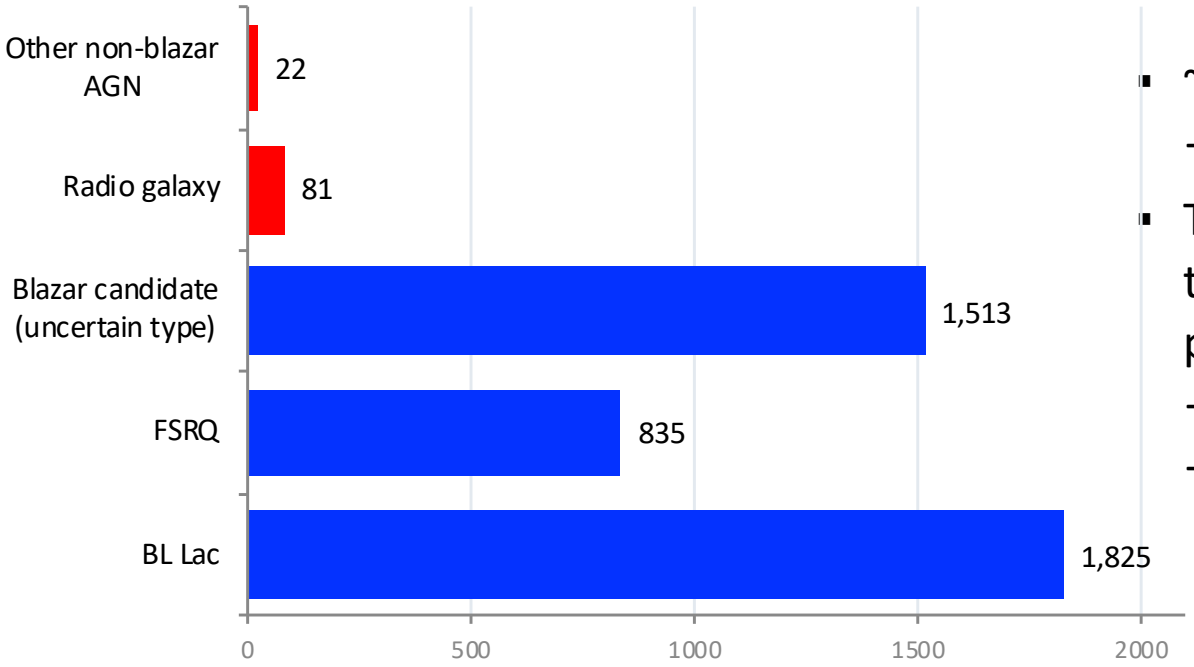
Hartman et al. 1999, ApJS 123, 79 · Abdollahi et al. 2020 (4FGL) · Ballet et al. 2026 (FL16Y)

We are still discovering. The census on the next slide is not a final answer

The current census: 7220 γ-ray sources, most of them are AGN

Fermi-LAT 16-year Source List (FL16Y) — Ballet, Bruel, Burnett & Lott 2026, arXiv:2602.22148

7220	**2115**	**~4280**	**~84%**
γ-ray sources	unassociated (29%)	AGN	of associated sources



- ~4170 blazars against ~100 non-blazar AGN —> about forty to one.
- The 1513 “blazar candidates of uncertain type” are a spectroscopy bottleneck, not a physics statement:
  —> 36% of all blazars here are unclassified,
  —> *and 69% of the 227 new ones.*

Roughly 84% of everything Fermi-LAT can identify is an active galaxy.
The γ-ray sky is an AGN sky; and mostly blazar sky

Why the γ-ray sky is almost all blazars ?

Blazars are rare objects

~1% of galaxies host an AGN

~10% of AGN have a jet

~1% of jetted AGN point at us

→ ***of order one blazar in 10^5 galaxies***

Why the γ-ray sky is almost all blazars ?

Blazars are rare objects

~1% of galaxies host an AGN

~10% of AGN have a jet

~1% of jetted AGN point at us

→ ***of order one blazar in 10^5 galaxies***

…and yet they dominate the catalogue

Relativistic beaming

Photon energy × **δ**

Energy flux × **δ^4**

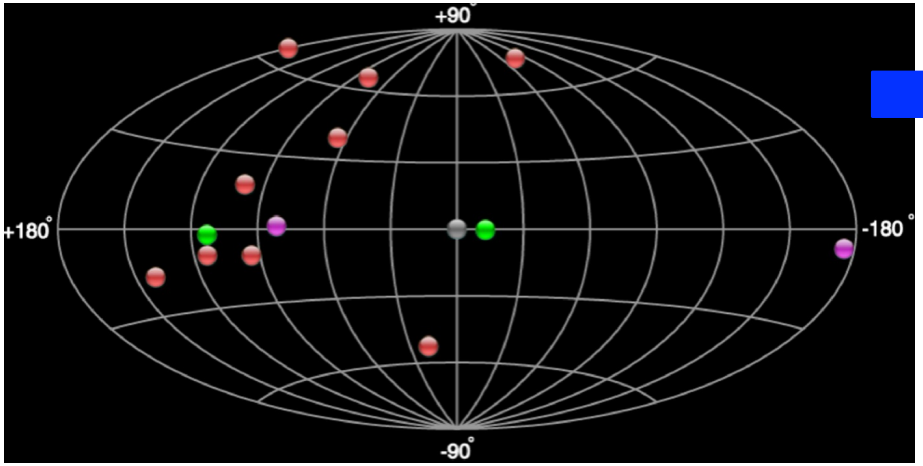
With δ ≈ 10, that is a factor ~10^4 in observed flux.

A rare object ten thousand times brighter beats a common object that is not.

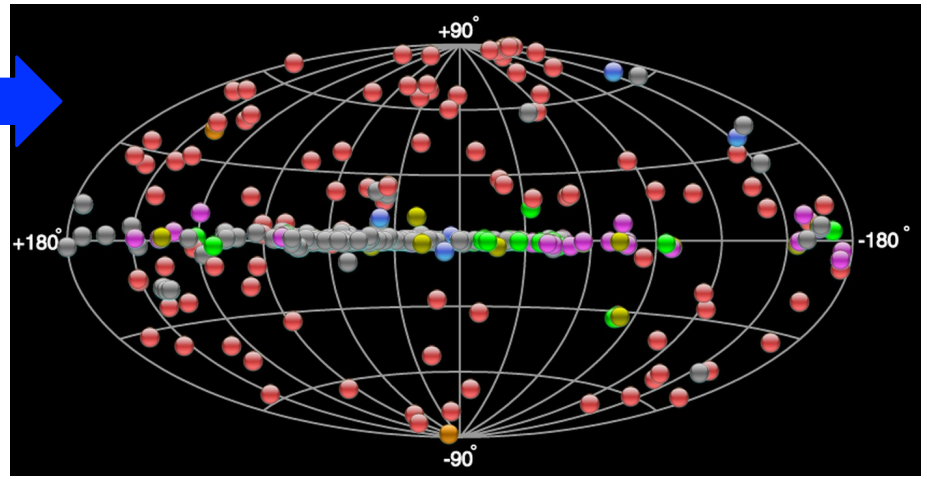
Heckman & Best 2014, ARA&A 52, 589 · Padovani et al. 2017 · beaming: Urry & Padovani 1995

The γ-ray AGN sky is a beaming-selected sky — a selection effect of precisely the kind Paolo Padovani and Paolo Giommi spent 2+ decades cataloguing.

One energy decade up: the VHE sky, then and now



Before 2004 — 14 sources, 9 AGN



TeVCat today — 337 sources, ~100 AGN

Twenty-two years, a factor ~24 in sources — but only a factor ~11 in AGN.

In the GeV sky the blazars grew fastest; here the Galactic plane did.

~100	AGN in TeVCat	**12**	FSRQs	**7**	radio galaxies

- Beaming-selected and peak-frequency-selected: two layers of selection.

Sky maps and counts: TeVCat (tevcat.org), Wakely & Horan — September 2026

Not only blazars: the ones we see without a boost

81 radio galaxies in the Fermi-LAT 16-year list

7 confirmed at VHE: NGC 1275 · 3C 264 · M 87 · Cen A · IC 310 · PKS 0625−35 · PKS 0548−322

PKS 0548−322 was an HBL in TeVCat until Sept 2025 — reclassified FR I on wide-angle-tailed morphology in RACS and VLASS, low core dominance, and host-galaxy absorption. The boundary is still moving.

M 87

TeV variability on timescales of days, from a source whose black hole we have imaged directly. The emitting region must be comparable to the horizon scale.

NGC 1275

The central galaxy of the Perseus cluster. Detected by MAGIC in 2010; strong episodic VHE activity since, including major flaring in 2022–2023.

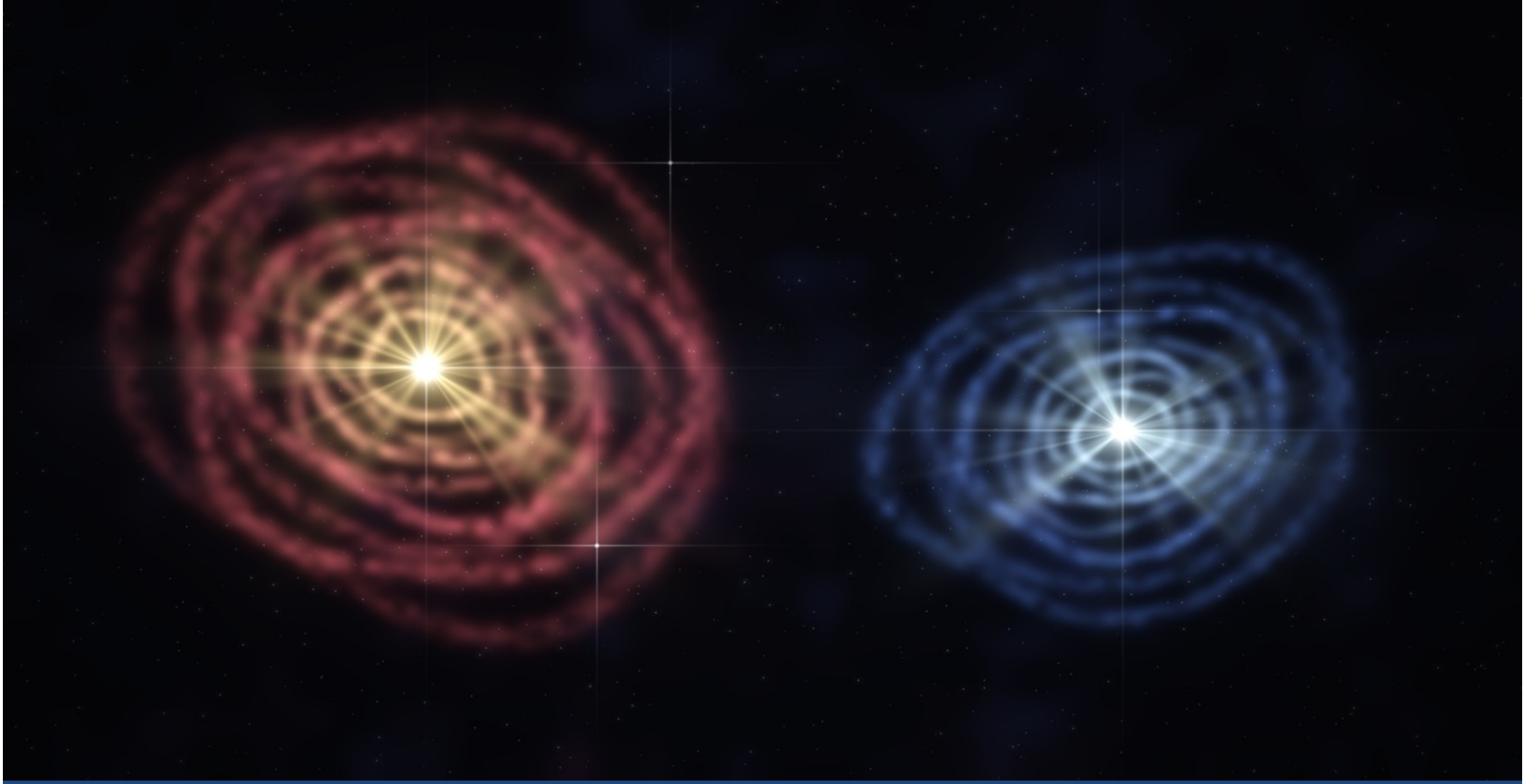
IC 310

Variability comparable to the light-crossing time of its own black hole, very hard to explain with a standard jet.

These are jets seen at a large angle, with little or no Doppler boost. We should barely see them at TeV, and yet we do. One learns more per object.

M 87: Aharonian+06, Acciari+09, Algaba+21 · NGC 1275: Aleksić+12, MACE+24 · IC 310: Aleksić+14

Faint, rare, and worth far more per photon.
The un-boosted AGN are where the jet gives up its geometry.



Act III

Two blazars, eighteen years

Mrk 421 and Mrk 501 : *targets for dedicated multi-instrument campaigns since 2009*

The goal is to use them as high-energy physics laboratories to study blazars

Extensive MW Campaigns on Mrk421 and Mrk501

A multi-instrument and multi-year project

Since 2009, we have substantially **improved TEMPORAL and ENERGY coverage** of the sources in order to obtain SEDs as simultaneous as possible, as well as to be able to perform multi-frequency variability/correlation studies over a long baseline and correlate with high resolution radio images and polarizations (to learn about the jet structure)

- **More than 25 instruments participate, covering frequencies from radio to VHE**

Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP-WEBT, KVA, Liverpool, Kanata…
UV: Swift-UVOT
X-ray: (RXTE), Swift-XRT, NuSTAR, IXPE
Gamma-ray: *Fermi*-LAT
VHE: MAGIC, VERITAS, FACT

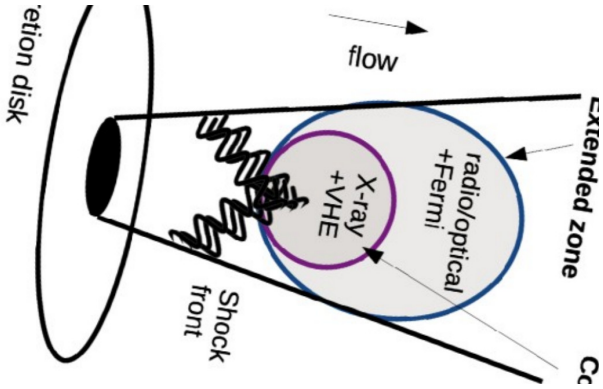
Monitored regardless of activity (*increase coverage during flares*)
→ observed every few days for about half year (*every year* !)

Why Mrk 421 and Mrk 501 ? the “fruit flies” of blazar physics ?

Bright — We reconstruct the entire SED in a single night — so we can watch the SED evolve, not just measure it once.

Nearby — z ≈ 0.03, ~140 Mpc. Almost no EBL absorption, and the VLBA resolves scales below 0.1 pc.

Simple — No strong broad-line region — one fewer unknown component than in any FSRQ.



Most other sources are harder to study (fainter, farther, more structured), hence a worse laboratory.

Nobody studies fruit flies only because fruit flies are fascinating.
Fruit flies get studied because one can watch every generation.

An honest caveat: these are two HSPs. Generalising from them is exactly the sort of selection effect that Paolo and Paolo spent twenty years warning us about.

Measured SED can be described with distinct theoretical scenarios

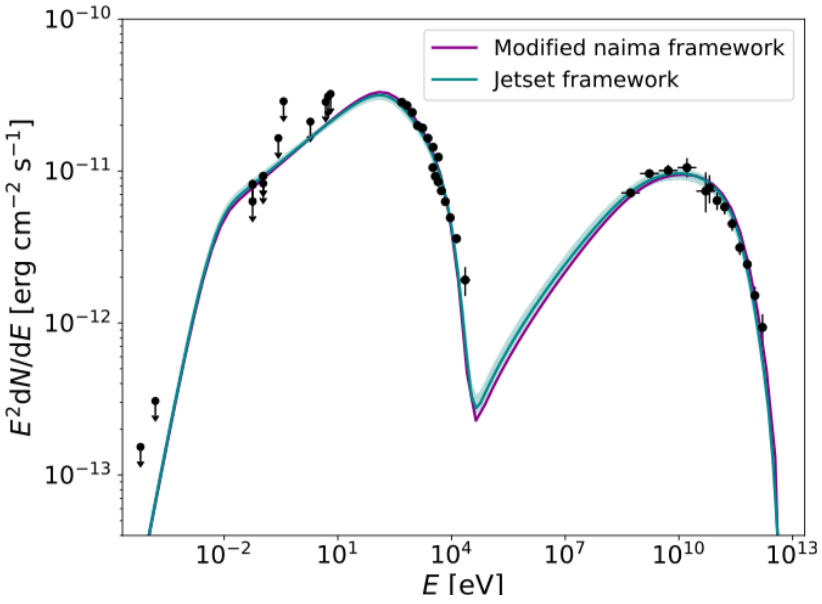
Abe et al., ApJS 266 (2023) 37

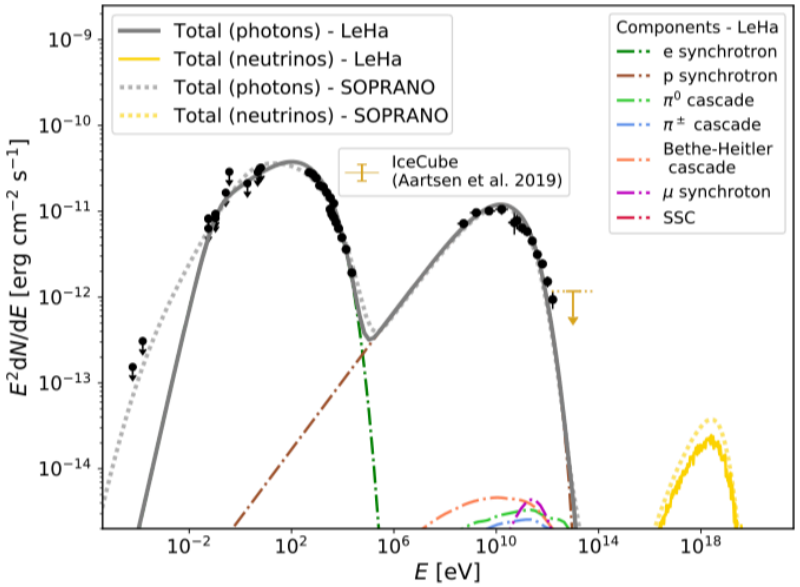
Mrk 501 showed a historically low activity in X-rays and VHE γ -rays from mid-2017 to mid-2019 with a stable VHE flux (>0.2 TeV) of 5% Crab Nebula flux

1) **Purely leptonic model**
(e-/e+, up to ~10^{12} eV)

2) Purely hadronic model
(protons up to ~10^{19} eV)

3) Lepto-hadronic model
(e-/e+, up to ~10^{12} eV, and protons up to ~10^{16} eV)





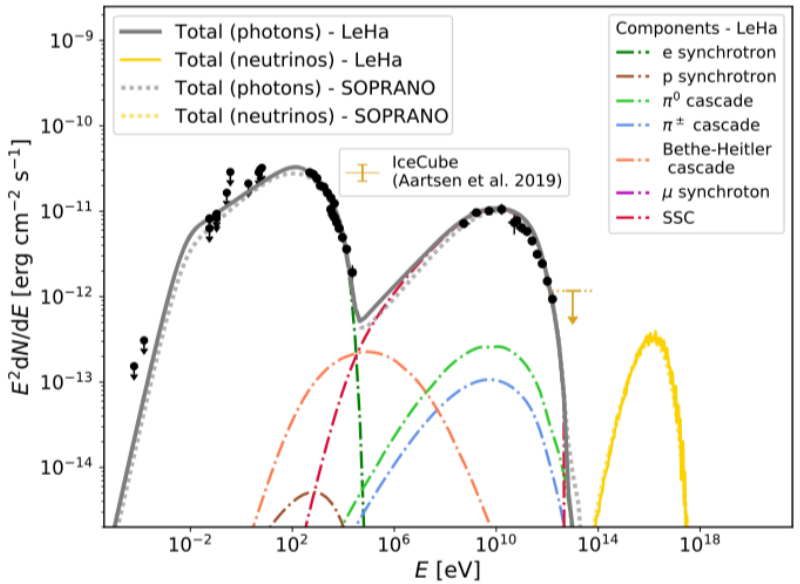


Table 5

Parameter Values from the Leptonic One-zone SSC Models used to Describe the Low-state SED of Mrk 501 Derived with Data from 2017 June 17 to 2019 July 23 (MJD 57,921 to MJD 58,687), as Described in Section 4.2.1 and Shown in Figure 10

	L_e (erg s^{-1})	α_1	γ'_{br}	γ'_{max}	U'_e (erg cm^{-3})	U'_B (erg cm^{-3})	U'_e/U'_B	L_{jet} (erg s^{-1})
Modified Naima	7.7×10^{43}	2.6	2.0×10^5[a]	1.2×10^6	5.2×10^{-4}	2.5×10^{-5}	21	8.8×10^{43}
Jetset	8.4×10^{43}	2.6	2.0×10^5[a]	1.2×10^6	5.7×10^{-4}	2.5×10^{-5}	23	9.6×10^{43}

Note. In the two model realizations, the radius of the emission region R' is fixed to 1.14×10^{17} cm, the Doppler factor δ to 11, and the magnetic field B' to 0.025 G. For the radiating electron distribution, a broken power law is used with the spectral indices fulfilling $\alpha_2 = \alpha_1 + 1$. The minimum energy of the electrons γ'_{min} is set to 1000. The table reports, for the broken power law describing the shape of the electron distribution, the first spectral index α_1, the break energy $\gamma_{br}{}'$ and the maximum energy γ'_{max} as well as the electron luminosity L_e, the energy densities held by the electron population U'_e and the magnetic field U'_B, their ratio, and the total jet luminosity L_{jet}. For the EBL γ-ray absorption at a redshift $z = 0.034$, the model from Franceschini et al. (2008) is used.

[a] Fixed to the cooling break.

Abe et al., ApJS 266 (2023) 37

Model parameter values related to the leptonic (up) and hadronic (right) models for the SED of the baseline emission of Mrk501.

The three distinct scenarios possible

Multi-band variability & correlations needed to break model degeneracies

Degeneracy is broken by the time axis, exactly where Andrea Tramacere goes tomorrow at 15:10.

Table 6

Parameter Values Obtained by the LeHa Code for the Hadronic and Lepto-hadronic One-zone Models Used to Describe the Low-state SED of Mrk 501 Derived with Data from 2017 June 17 to 2019 July 23 (MJD 57,921 to MJD 58,687), as Described in Section 4.2.2 and Shown in Figure 11 (hadronic), and in Section 4.2.3 and Figure 12 (lepto-hadronic)

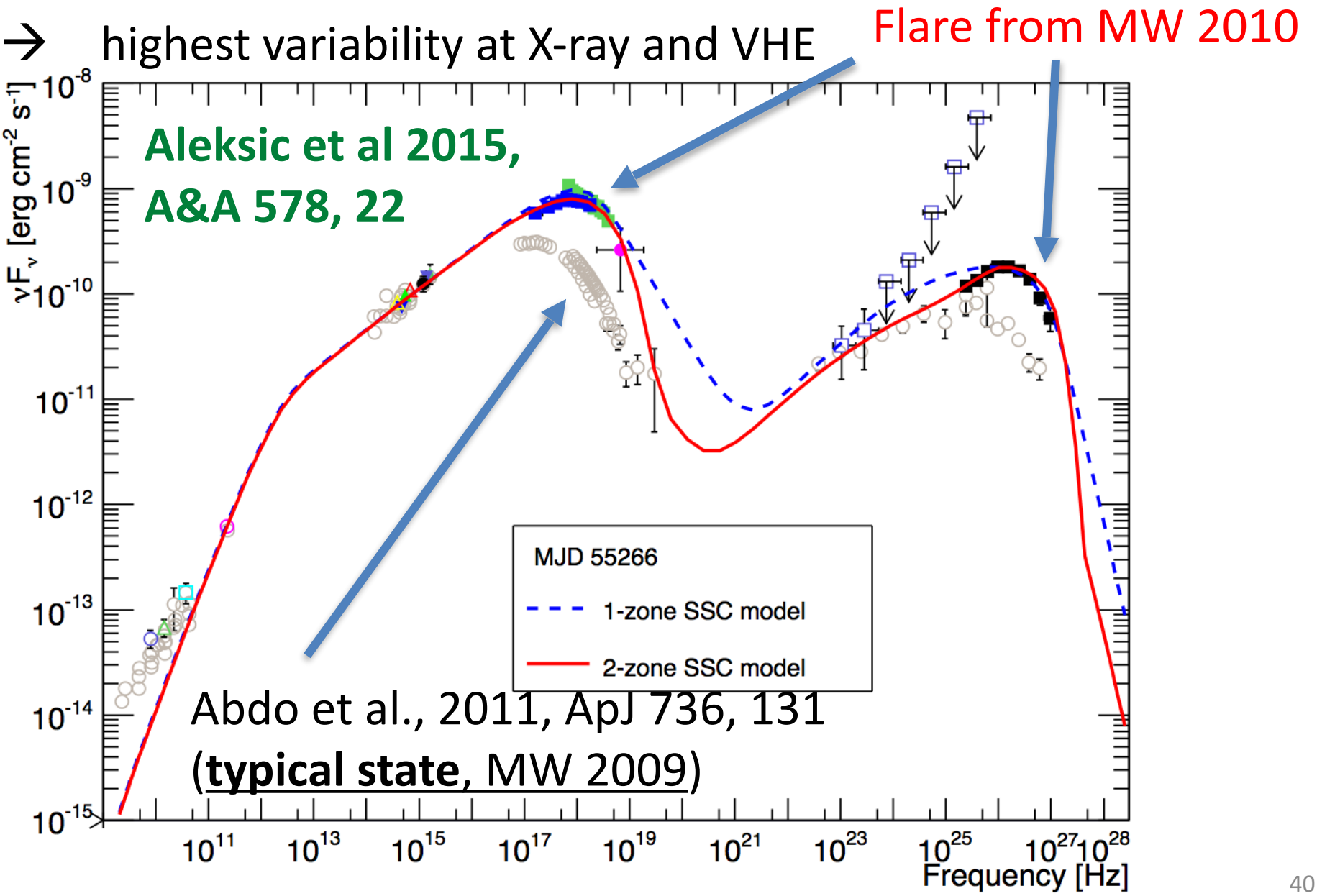
	Hadronic	Lepto-hadronic
B' [G]	3	0.025
R' [cm]	1.14×10^{17}	1.14×10^{17}
N'_{total} [1/cm^3]	3	2.3×10^4
n'_e/n'_p	2.2	0.01
$\alpha_{e,1}$	2.5	2.6
$\alpha_{e,2}$	…	3.6
$\gamma'_{min,e}$	400	1×10^3
$\gamma'_{br,e}$	…	2.0×10^5
$\gamma'_{max,e}$	3.5×10^4	1.2×10^6
α_p	2.2	2.0
$\gamma'_{min,\ p}$	1	1
$\gamma'_{max,\ p}$	1.1×10^{10}	2×10^7
U'_e [erg cm^{-3}]	2.2×10^{-7}	5.3×10^{-4}
U'_B [erg cm^{-3}]	0.36	2.5×10^{-5}
U'_p [erg cm^{-3}]	0.05	5.6
U'_e/U'_B	6.1×10^{-7}	21.2
U'_p/U'_B	0.14	2.3×10^5
L_{jet} [erg s^{-1}]	3.1×10^{46}	1.7×10^{48}

Mrk421 has shown X-ray and VHE spectral variability during flares

X-ray and VHE spectra becomes harder when flaring

→ SED bumps shift to high energies

→ highest variability at X-ray and VHE



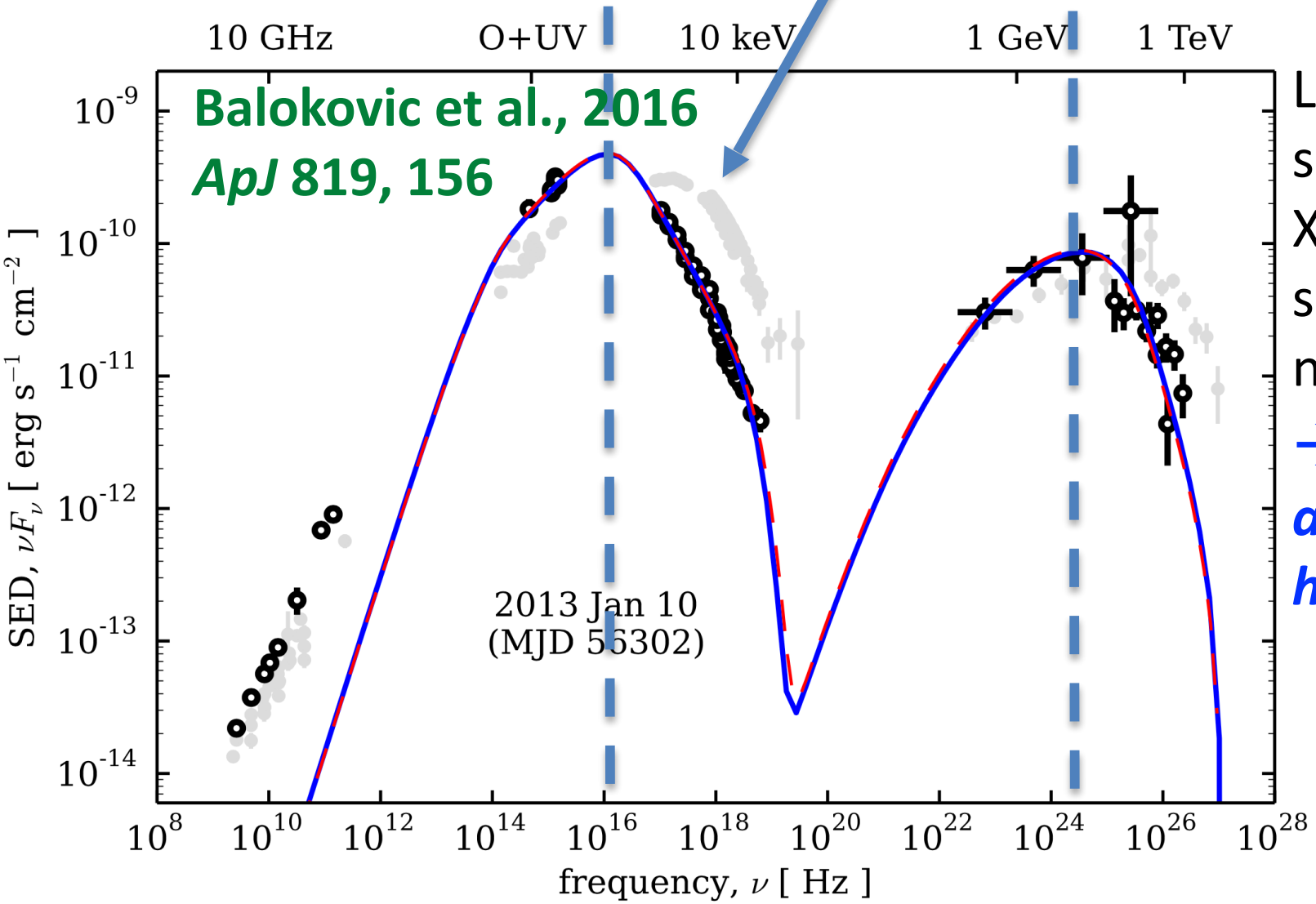
Mrk421 suffers a personality crisis (in 2013)

Peak position at ~10^{16} Hz (~40 eV)

Factor 10 lower than typical

→ ***"HBL moving towards IBL"***

-Abdo et al., 2011, ApJ 736, 131 (**typical state**)



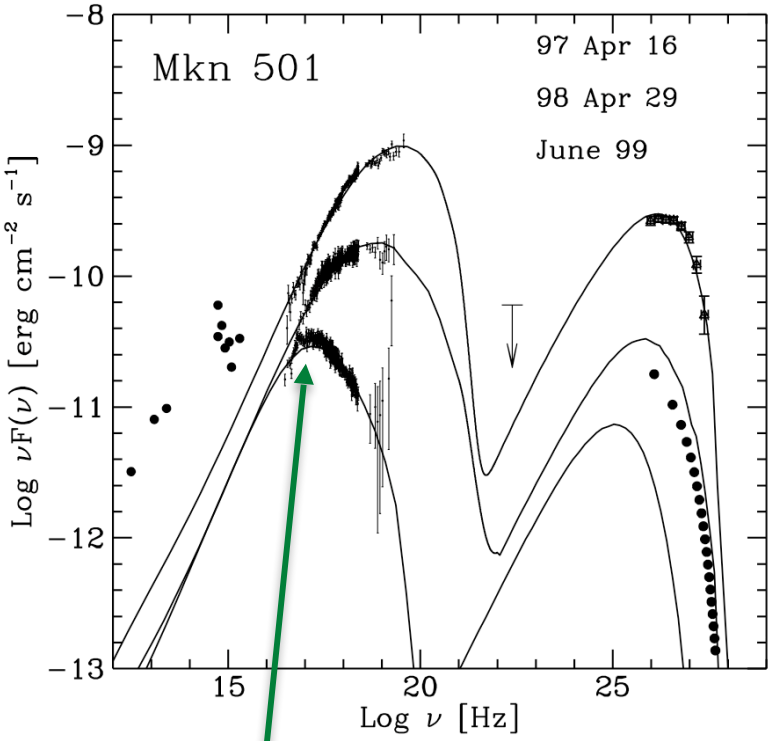
Low activity softened the X-ray and VHE spectra, but did not bring cutoffs

→ ***Electrons accelerated to highest energies***

Mrk501 has shown X-ray and VHE spectral variability during flares

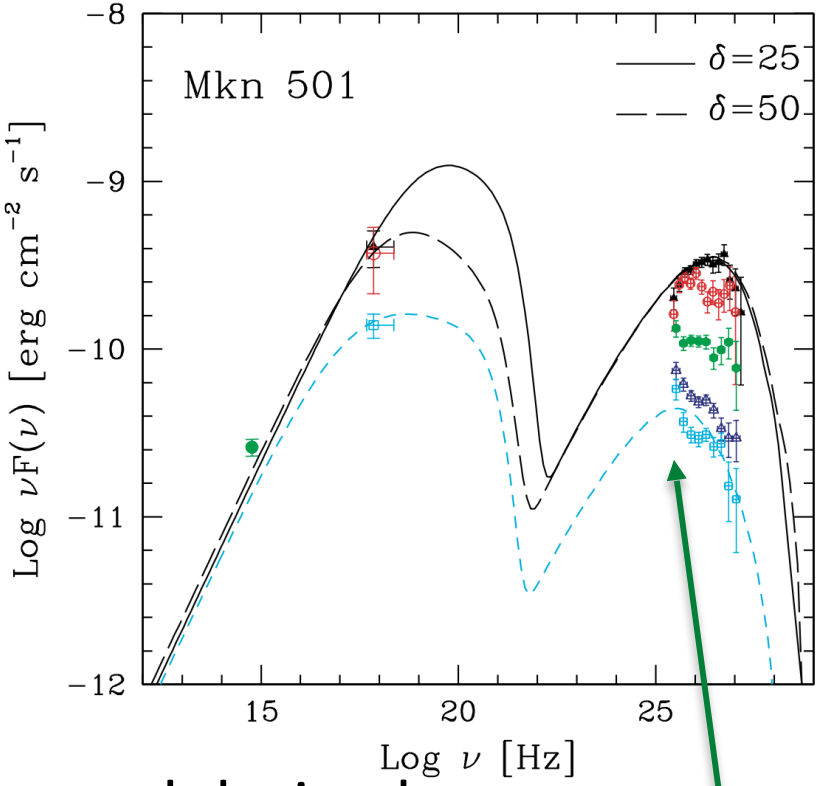
(Historical) flare in 1997

Tavecchio et al., 2001, ApJ 554,725



(fast variability) flare in 2005

Albert et al., 2007, ApJ 669,862



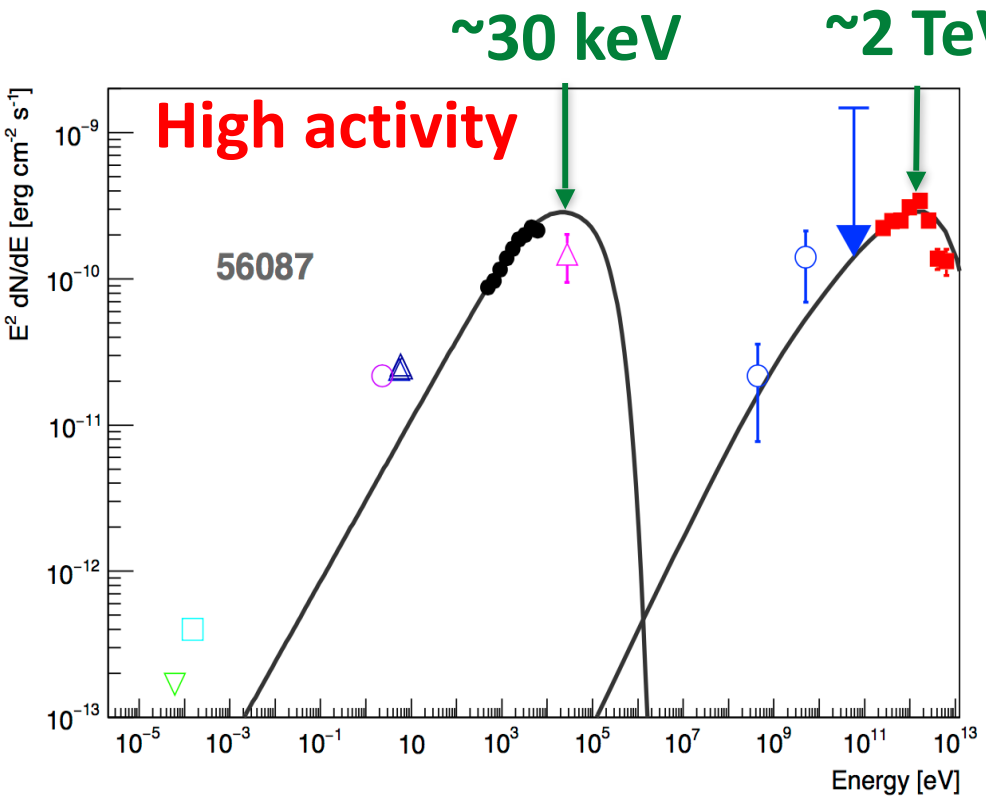
Hard spectra in Mrk501 not observed during low states,

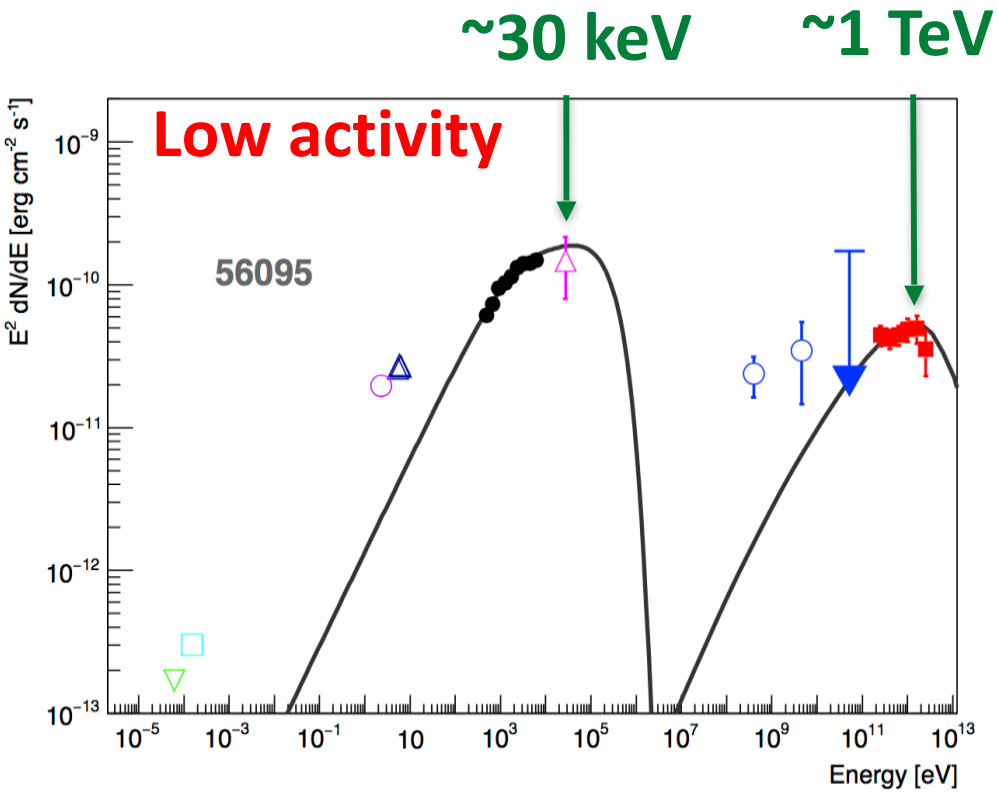
< 1 keV

< 0.1 TeV

Mrk501 suffers a personality crisis (in 2012)

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during MW 2012)





Radio:
OVRO
Metsahovi

X-ray:
Swift/XRT
Swift/BAT

Gamma ray:
Fermi-LAT
MAGIC

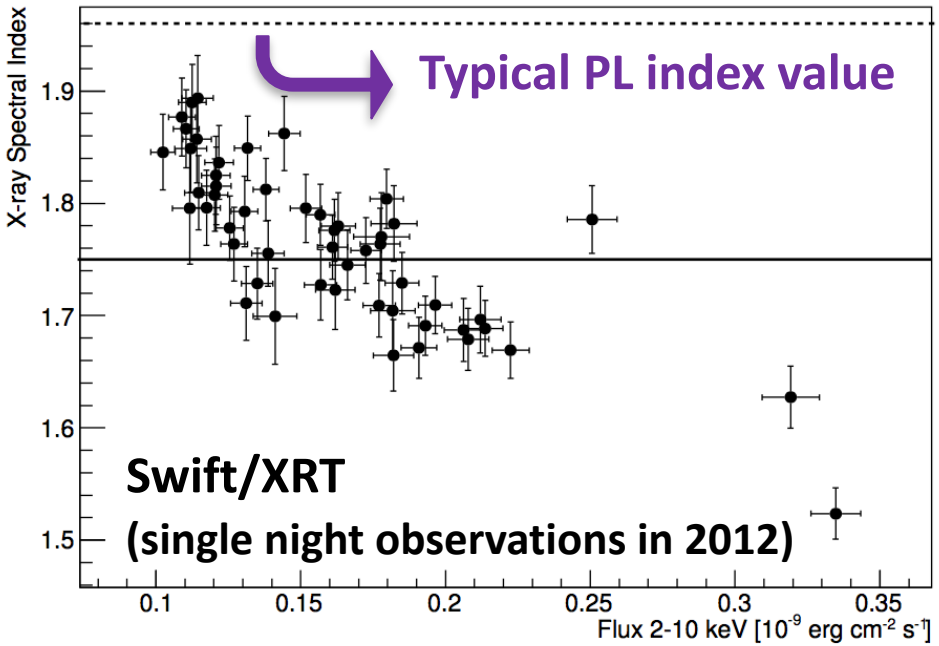
Optical/UV:
R-band (WEBT+)
Swift/UVOT

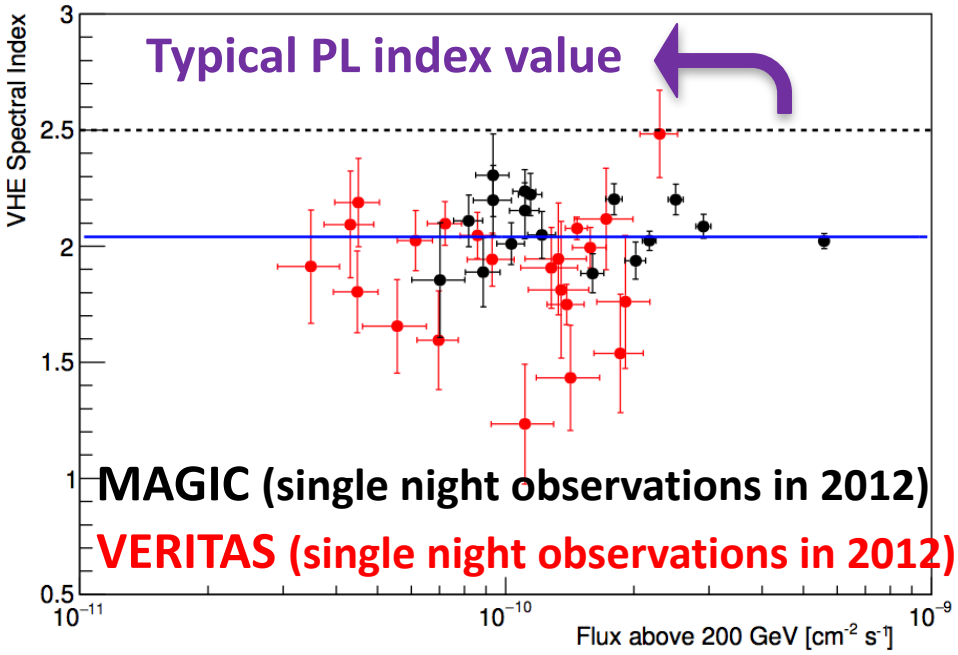
Ahnen et al., 2018
A&A 620 , 181

Mrk501 suffers a personality crisis (in 2012)

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during MW 2012)

Ahnen et al., 2018 A&A 620 , 181





→ **Mrk 501 behaved as Extreme HBL**

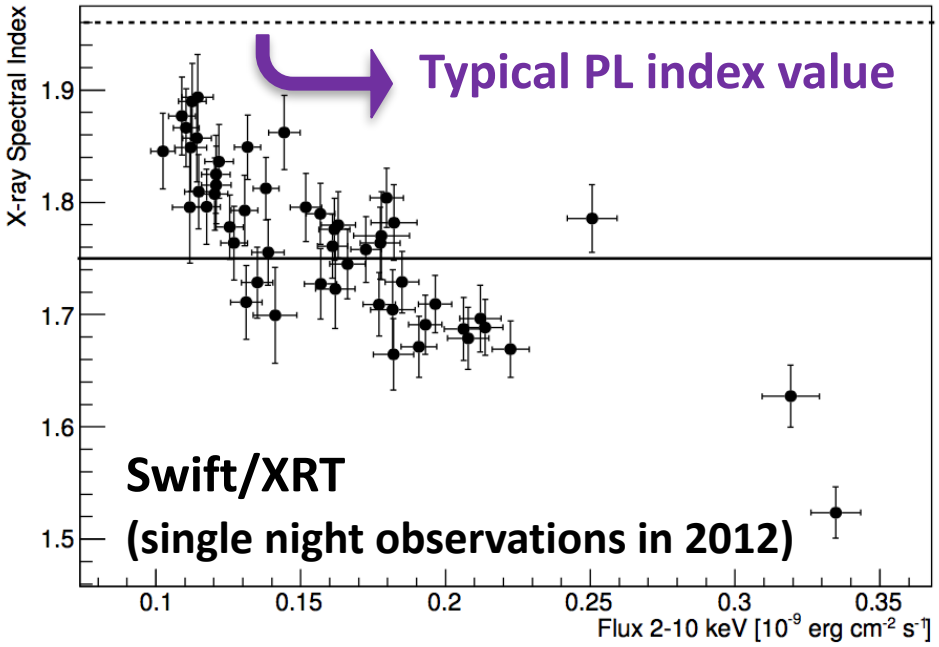
Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)

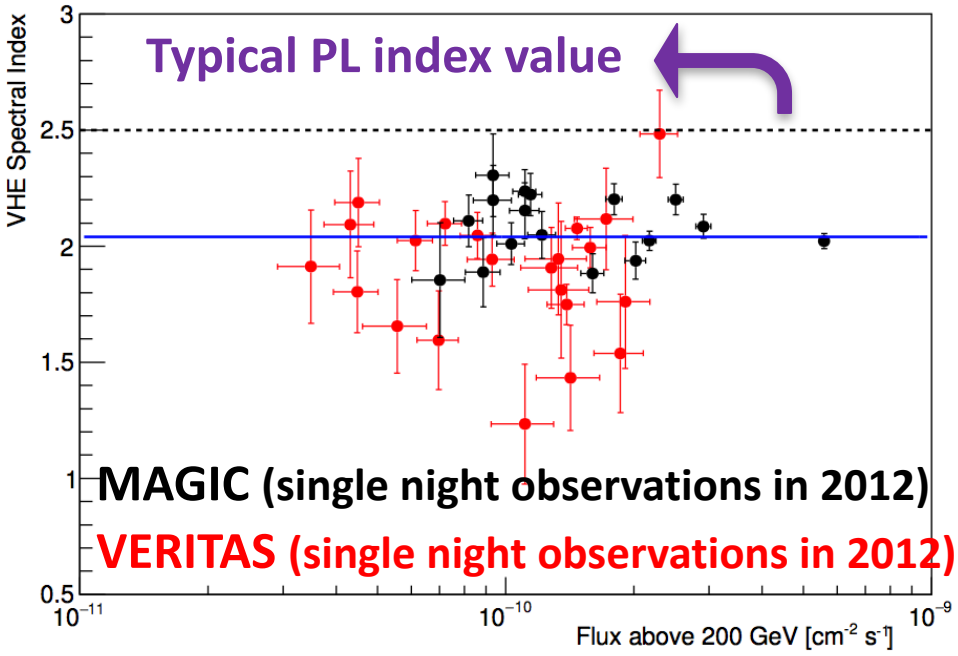
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

Mrk501 suffers a personality crisis (in 2012)

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during MW 2012)

Ahnen et al., 2018 A&A 620 , 181





Mrk501_F^{TeV} > ~10 x 1ES0229_F^{TeV}

Similar quality spectra need observations 100 time longer than those needed for Mrk501

Precision on 1ES 0229 needs CTA !!

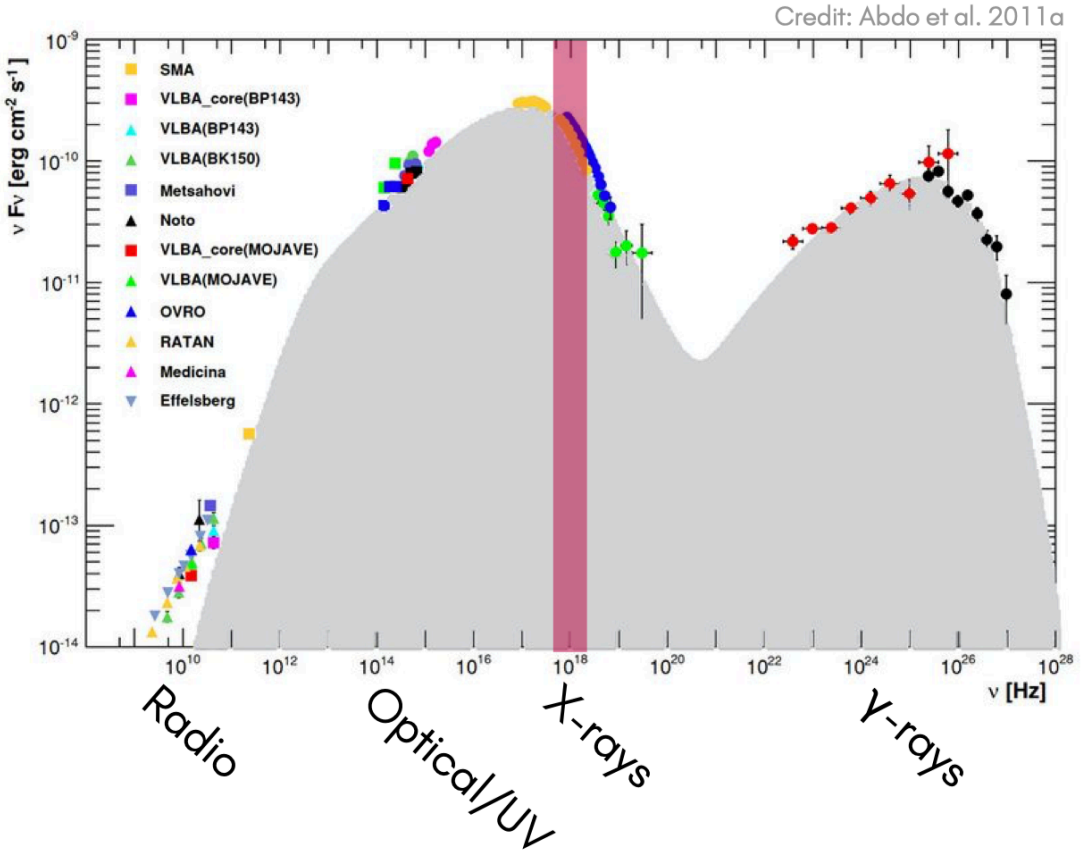
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

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/



- 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 and Mrk501 with IXPE occurred in 2022

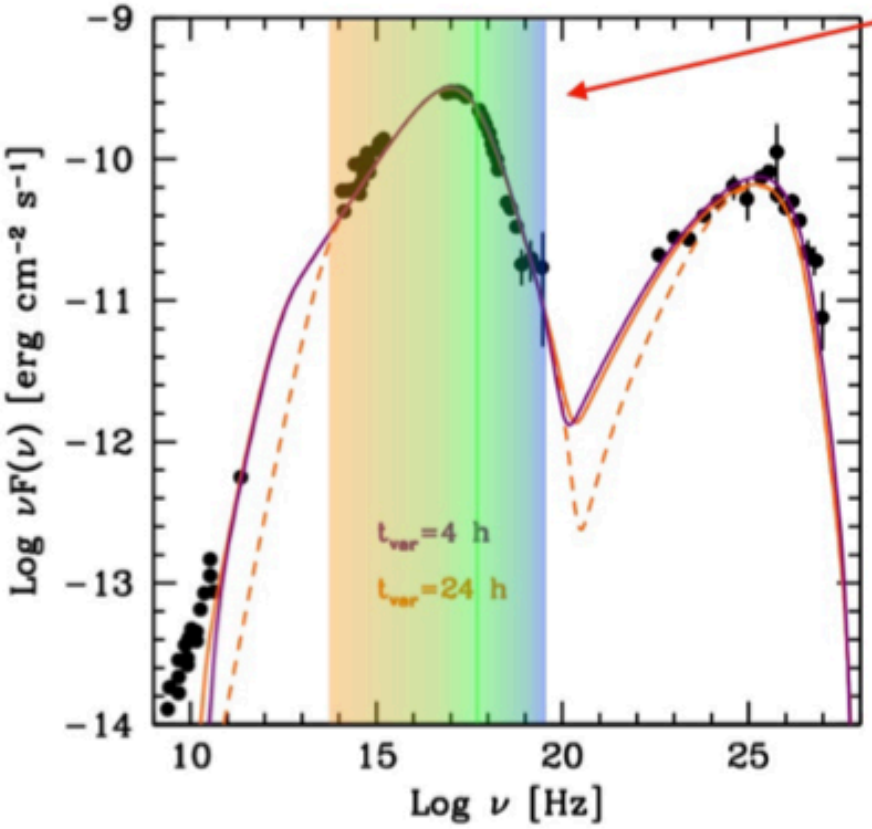
IXPE showed that the X-ray polarization degree of Mrk421 and Mrk501 many times bigger than optical & radio, and MAGIC showed that X-ray was correlated to VHE gamma rays:

→X-rays & VHE gammas come from a region with higher order B field

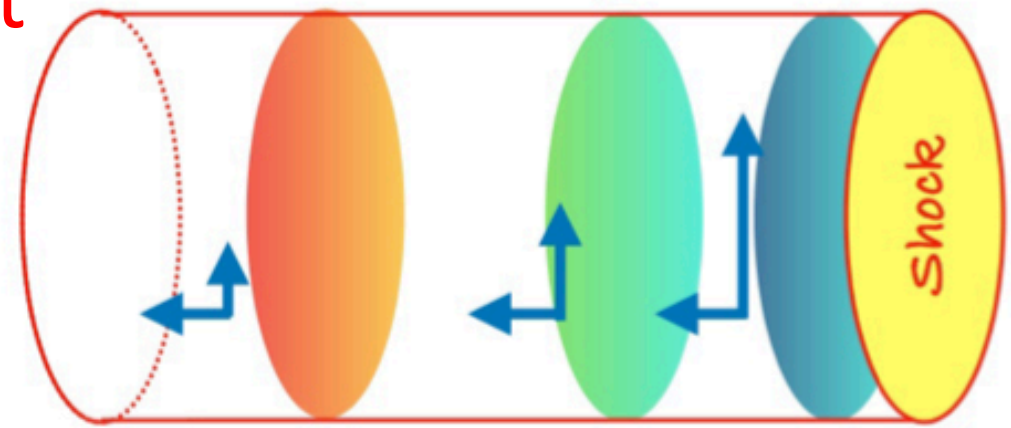
Liodakis et al. 2022, Nature 611, 677 · Di Gesu et al. 2022, ApJL 938, L7 · see S. Bianchi, Tue 10:00

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

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

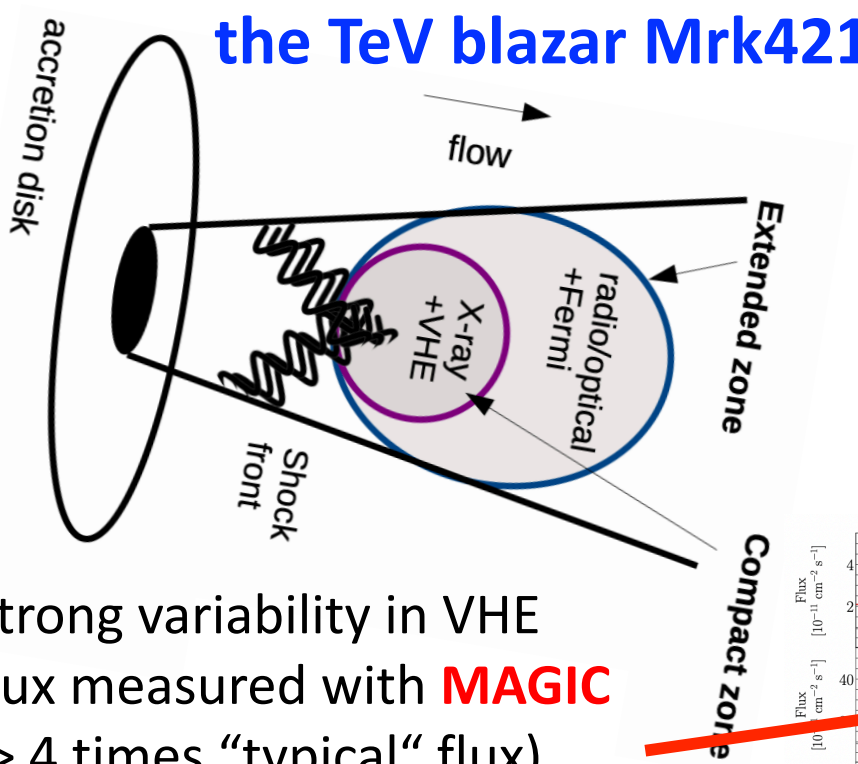


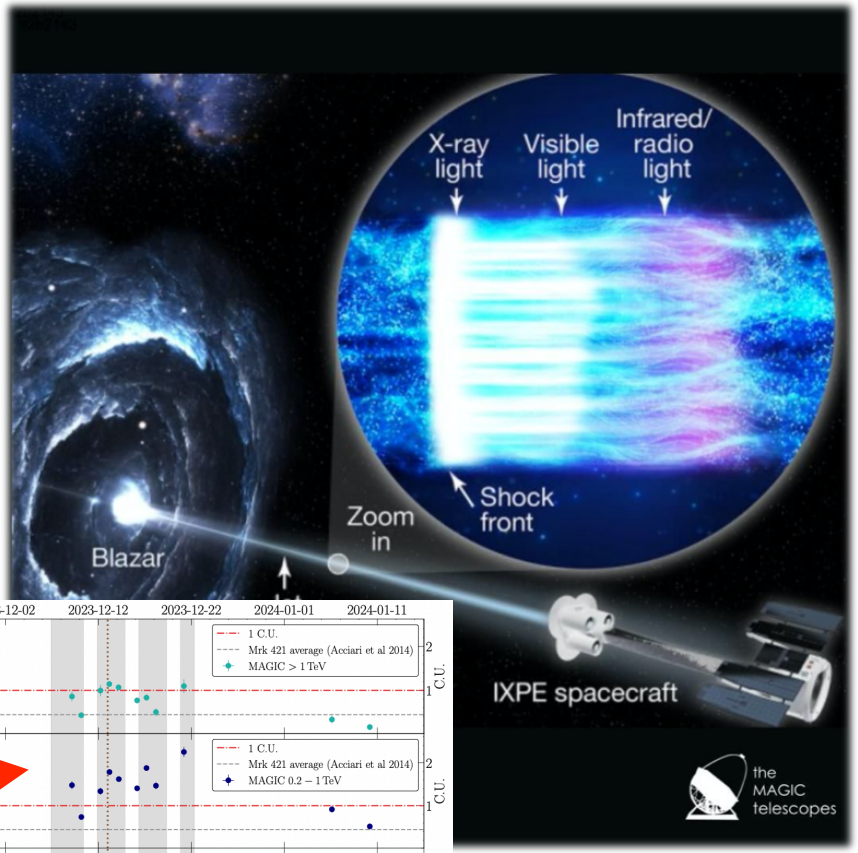
→ Stratified jet



Tavecchio, 2021

Flare in December 2023 for the TeV blazar Mrk421





Strong variability in VHE flux measured with **MAGIC** (> 4 times “typical“ flux)

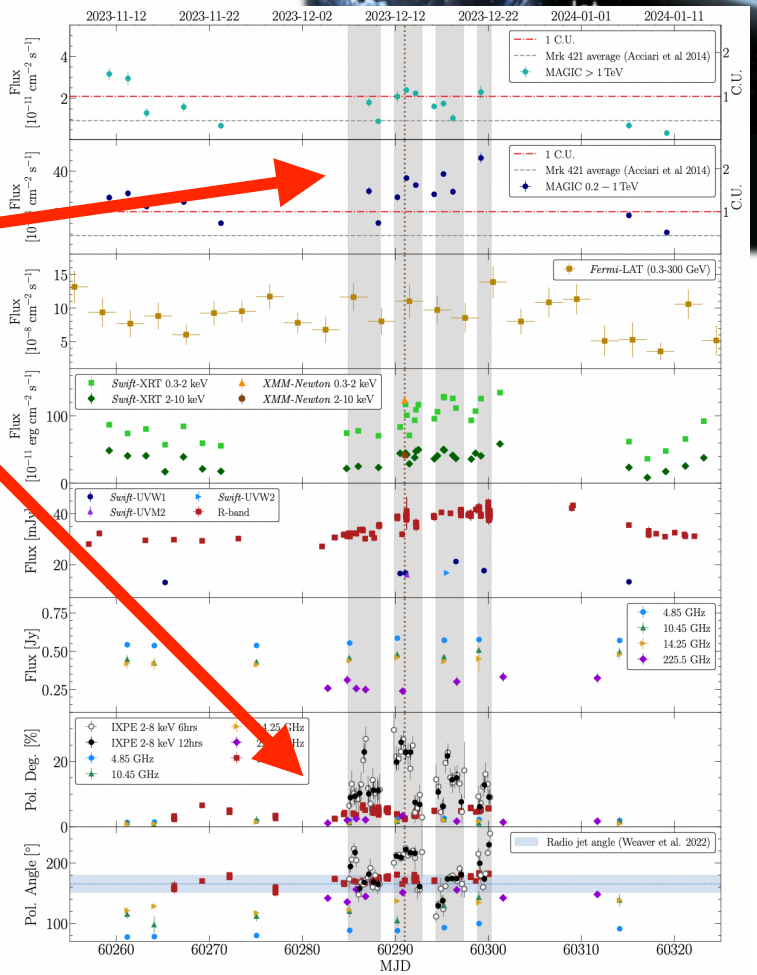
Strong variability in polarization degree+angle @ X-ray with **IXPE**

First VHE flaring event with simultaneous X-ray polarization

→ Shock acceleration (with magnetic field stronger closer to the shock + turbulence)

2025A&A...695A.217M

A. Arbet-Engels, L. Heckmann, D. Paneque



GeV

keV

UV R-band

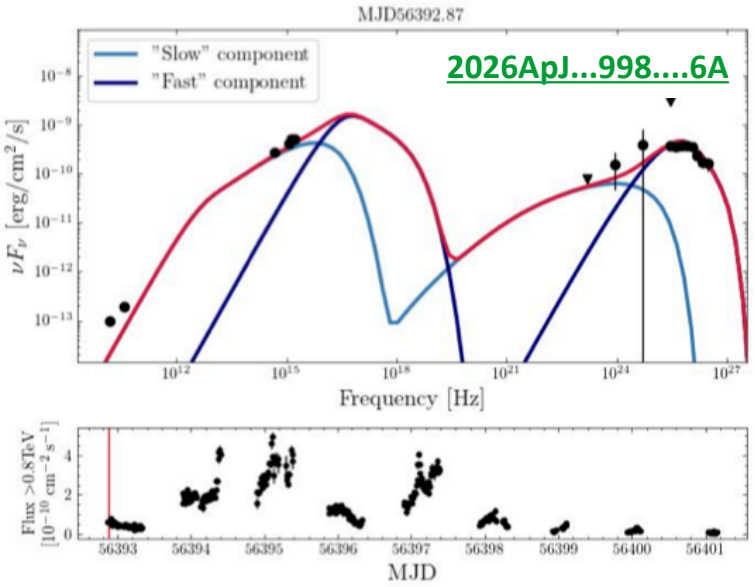
Radio

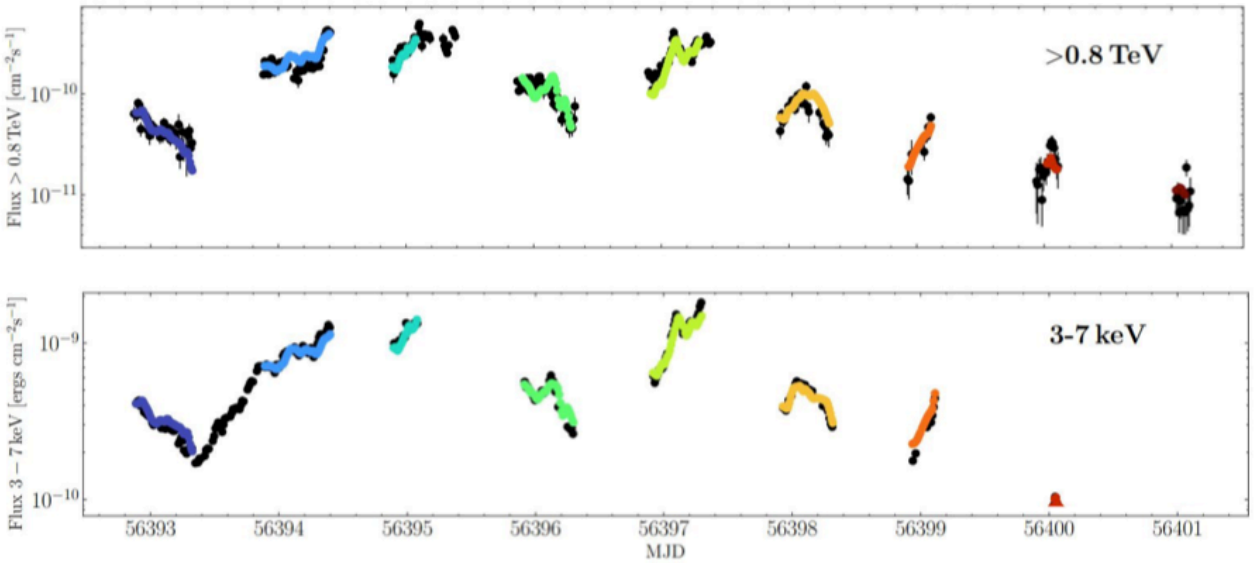
Polarization

Time-dependent modelling of 240 broadband SEDs in 15 min bins

Flare of Mrk421 in April 2013: One of the brightest, up to **~15 Crab units**, 9 consecutive days (Apr 11-19), 43 h of simultaneous MAGIC / VERITAS + NuSTAR coverage

2026ApJ...998....6A **A. Arbet-Engels, D. Paneque, M. Polkas, M. Petropoulou**





- Mrk 421 flare of April 2013: **X-ray & MAGIC** spectra **resolved down to 15-min scale**
- Modelled with **time-dependent leptonic scenario**; Particle cooling self-consistently included
- **MAGIC DL3 files publicly released** (>40hrs) + multi-wavelength data

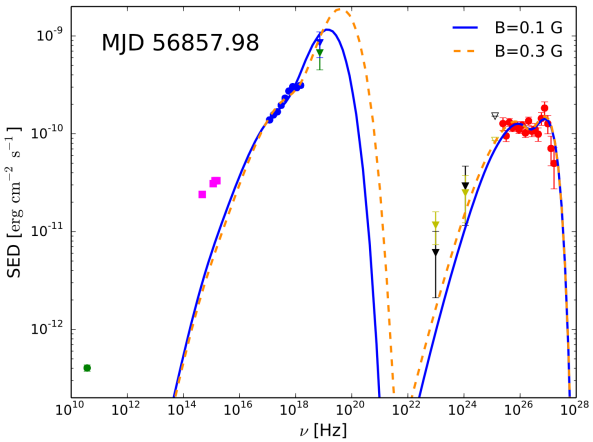
Zenodo repos:
1) https://zenodo.org/records/17064461 (MAGIC DL3)
2) https://zenodo.org/records/17054582 (Broadband SEDs)

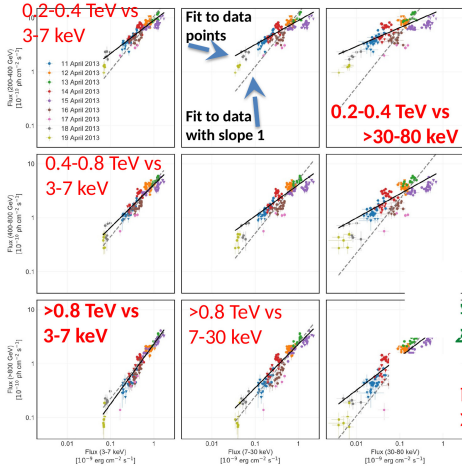
Spectral hysteresis in X-rays and, for the first time, at VHE. Features in the MWL data collected can be reproduced by a time-dependent leptonic model.
—> Sub-hour variability reproduced with changes in the injected electron slope and luminosity

Eighteen years, two sources, many lessons

- Mrk 501 became an extreme HBL in 2012 — while quiescent
- A narrow ~3 TeV spectral feature in Mrk 501, July 2014 (>3σ)
- Nine different X-ray/TeV correlation patterns in one flare
- X-ray polarisation angle rotating at ~80° per day
- Mrk 421 drifted towards IBL in 2013
- An unexplained ~20 keV excess in Mrk 421, February 2016
- Sub-hour spectral hysteresis, favouring shocks
- Flares that need shocks and turbulence together

Not one of these was predicted.





These are probably not anomalies:

This is what a blazar looks like when you finally watch it closely enough.



Act IV

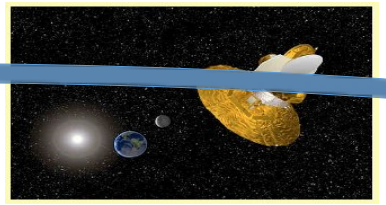
Gamma rays meet neutrinos

Two kinds of AGN accelerator — and both of them benefitted very much from Paolo's work

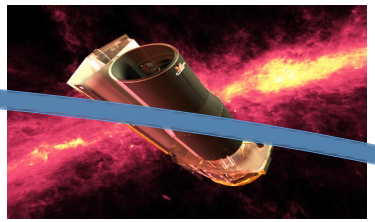
Detection and energy of gamma rays, crucial link between time domain astronomy and multi messenger astrophysics

Radio:





Microwave:



IR:

Electromagntic emission (from radio to VHE gamma rays)



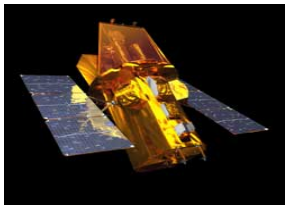
TeV



GeV

PeV





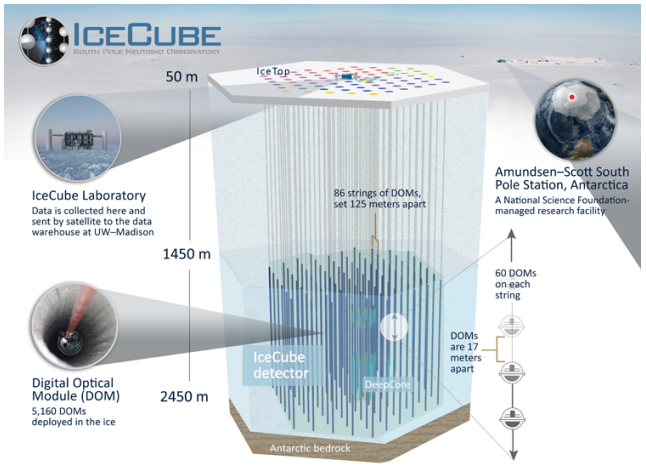
X-ray:



Optical:



Trajectory deflections preclude usage for individual sources





Gravitational Waves (e.g. Advanced Ligo)

High-Energy Cosmic Rays (e.g. Pierre Auger & TA)

High-Energy Neutrinos (e.g. IceCube, KM3Net)

TXS 0506+056: the source that had to be re-classified to work

22 Sept 2017	IceCube-170922A — a ~290 TeV neutrino, with a good direction.
Within hours	Fermi-LAT: the blazar TXS 0506+056 is in the middle of a six-month γ-ray flare.
Within days	MAGIC detects it at VHE. The coincidence reaches ~3σ. (Science 361, eaat1378, 2018)
Then the twist	Padovani et al. dissect the region (MNRAS 480, 192) — and conclude it is not a BL Lac at all (MNRASL 484, L104).

A masquerading BL Lac

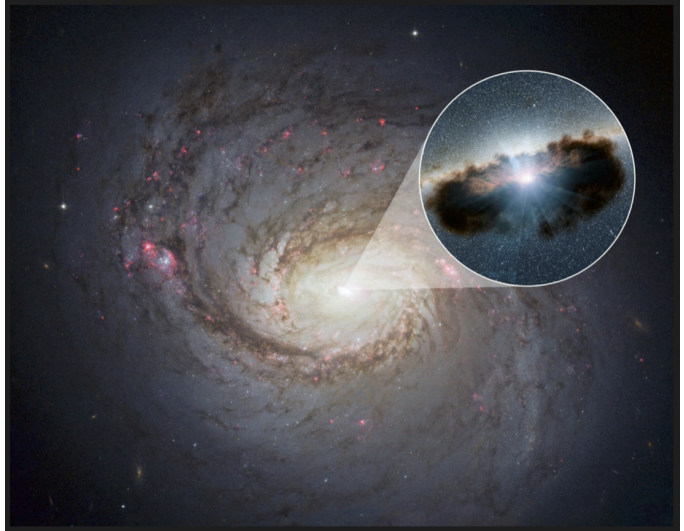
An FSRQ whose broad lines are swamped by the beamed continuum. The hidden broad-line region supplies exactly the target photons a hadronic interaction needs.

The first plausible neutrino source in the sky is a blazar whose classification had to be redone

Nine years on, TXS 0506+056 is still the best blazar–neutrino association we have. Every IceCube alert now triggers IACT follow-up within hours; the great majority return upper limits — which is how the programme is supposed to work, and how it constrains models.

Narek Sahakyan & Xavier Rodriguez will do this properly on Wednesday
I am only giving you the γ-ray observer's quick taste

Composite Starburst/Seyfert 2 Galaxy NGC1068: the hottest spot in the IceCube data (2011-2020)



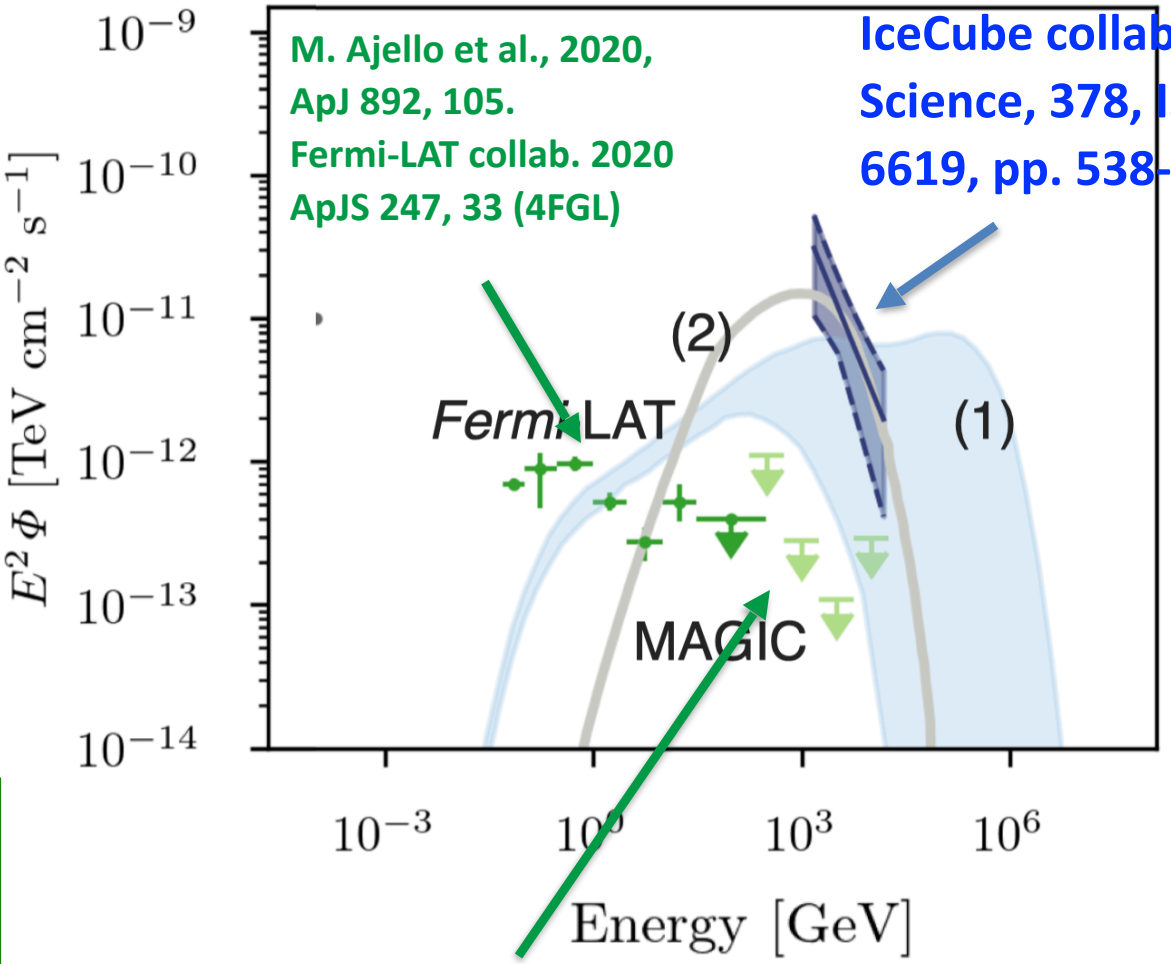
NGC 1068 as seen by Hubble Space Telescope (HST) with an artistic impression zoom-in on the central active galactic nucleus. Image credit: NASAESA/JPL-Caltech.

MAGIC upper limits on NGC1068 (95% C.L.) imply strong gamma ray absorption, and hence crucial for the interpretation of the IceCube neutrino excess

A crucial VHE γ-ray result is a non-detection. (Chiara Bellenghi has the neutrino side, Wednesday 09:40)

Global significance: 4.2σ

Astrophysical neutrino events = 79^{+22}_{-20}
Spectral index = 3.2 ± 0.2



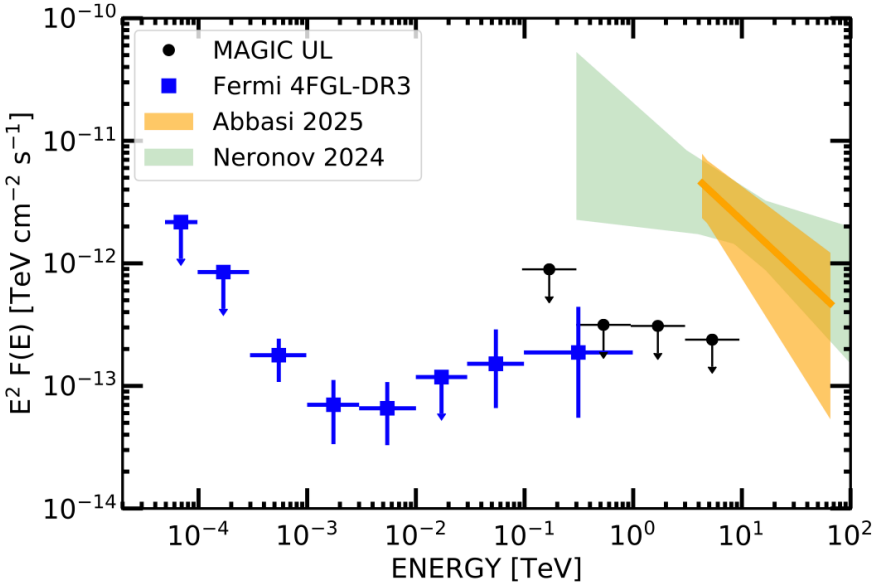
Theoretical models for neutrino flux prediction

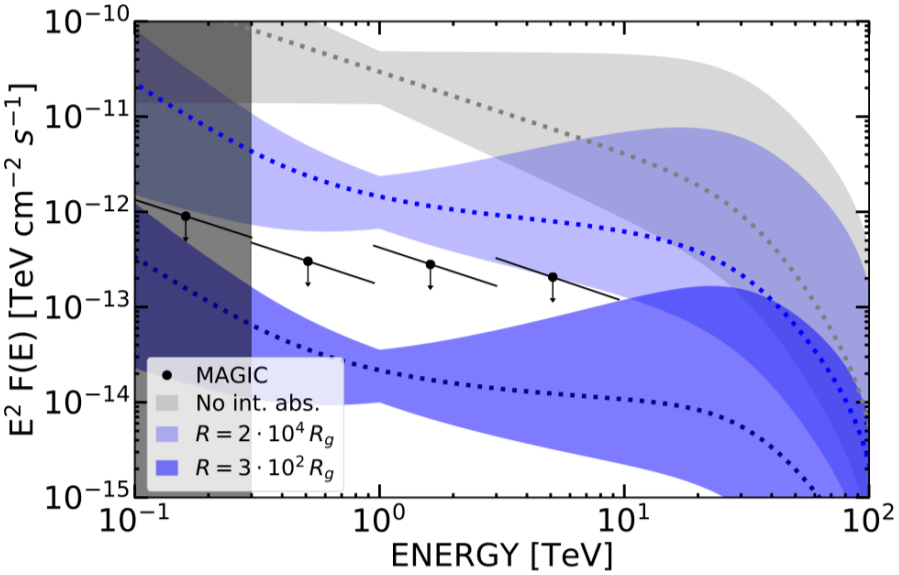
MAGIC collaboration, 2019, ApJ 883, 135

(1) Y. Inoue et al., ApJL'20
(2) K. Murase et al., PRL'20

NGC 4151: constraining a gamma-ray obscured neutrino source

2025A&A...702A..38A A. Lamastra, S. Mangano, S. Menon, E. Peretti





- Seyfert 1/1.5 at 15.8 Mpc, only 0.18° from the 4th most significant IceCube northern hotspot: **2026ApJ..1000L..26A**
- ~3σ neutrino excess (Neronov+ 2024, Abbasi+ 2025)
- 29 h good-quality MAGIC data, Zd ≲ 35°, wobble 0.4°, analysis threshold ≈100 GeV

MAGIC upper limits lie more than an order of magnitude below the IceCube flux in the band where the two instruments overlap (4–60 TeV).

- pp and p-gamma interactions give comparable gamma ray and neutrino output
- Implied intrinsic L_gamma (>300 GeV) = 10^{42}–10^{43} erg s^{-1}, i.e. ≲5% of L_bol ≈ 1.9 × 10^{44} erg s^{-1}
- Substantial internal γγ absorption is required. $\tau_{\gamma\gamma} \propto R^{-1}$, so the more compact the source, the larger the opacity
- **Upper limit on the size of the neutrino production region (≈ 4 × 10^{-2} pc for MBH = 4.6 × 10^{7} $M_\odot$); compatible for R ≈ 3 × 10^{2} Rg**

Second Seyfert after NGC 1068 that may host a neutrino source optically thick to gamma rays
Same picture for Sy 1 and Sy 2. CTAO will extend the spectral reach.

NGC 4151 — a second candidate

MAGIC: ~29 h in March–June 2024. Upper limit above 200 GeV of 2.3×10^{-12} cm^{-2} s^{-1} (95% CL). Indication of another γ-ray obscured candidate neutrino source.

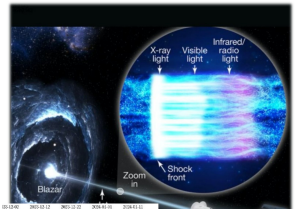
Two Seyferts now point the same way.
A class is forming.

Two populations, two mechanisms:

JETTED
TXS 0506+056 — neutrinos from the relativistic jet, and γ-rays that escape.

NON-JETTED
NGC 1068, NGC 4151 — neutrinos from a compact, γ-opaque region near the hole.

Paolo drew that line in 2017 to organise the radio and the optical.
It turns out it also organises the neutrinos.



The jetted route is a relativistic jet pointed at us. The non-jetted route is a hidden corona a few thousand gravitational radii out. Same messenger, two different machines: neutrinos, unlike γ-rays, do not care about absorption.

MAGIC Coll. 2025, arXiv:2507.16527 · Padovani 2017, A&ARv 25, 2 · Padovani et al. 2024, Nat. Astron.

A dichotomy built for radio and optical data turns out to divide a messenger that barely existed when it was drawn.

Chiara Bellenghi will report more in depth about it on Wednesday 09:40)

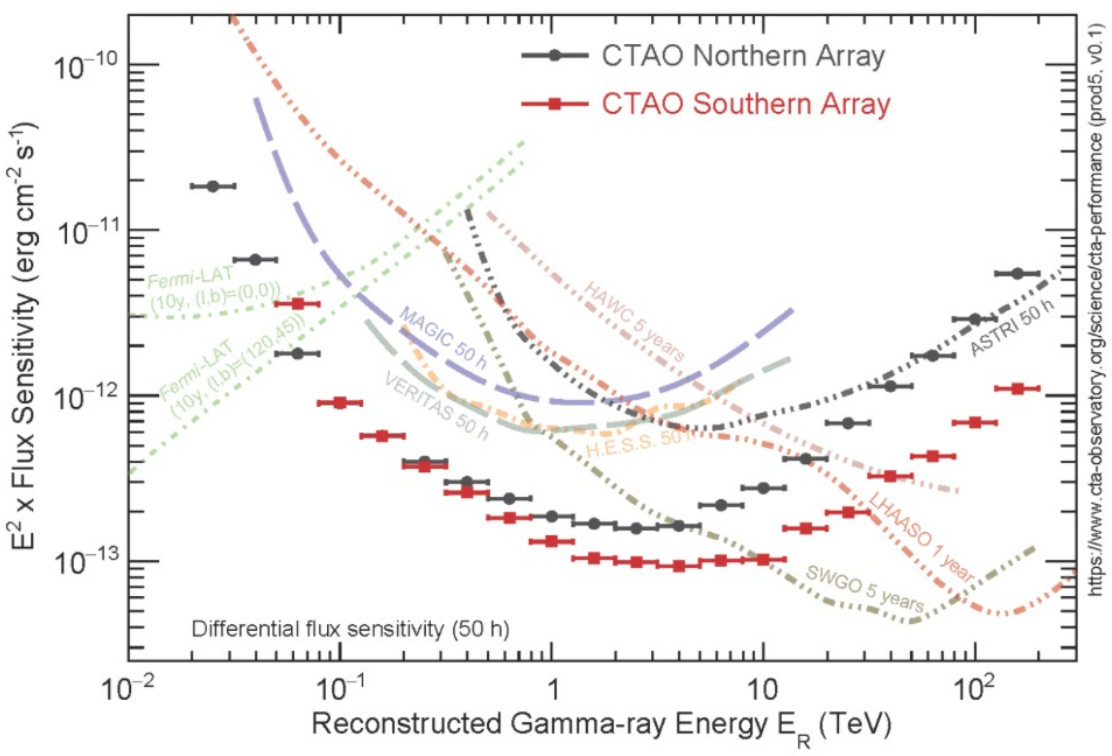


Act V

What comes next

CTAO arriving soon, will improve many things, but a gap opens up behind it

CTAO: large sensitivity & energy coverage, arriving soon



differential flux sensitivity, 50 h — CTAO North and South

Both arrays and both hemispheres: CTAO-South carries the sensitivity above ~10 TeV, CTAO-North below it.

×5 better sensitivity than the current generation, over a wider energy range

LST-1 is taking data. The LST sub-array on La Palma is inaugurated Oct. 14–16

CTAO-North complete around 2030.

For AGN specifically:

- An order of magnitude more VHE AGN: case studies become population studies, including the faint un-boosted ones.
- EBL and redshifts, exactly where Paolo Goldoni goes next, at 14:40.
- Extreme blazars: what Mrk 501 did in 2012 becomes routinely measurable.

CTAO Consortium 2019, arXiv:1709.07997 · AGN yield ≈ ×10: Sol et al. 2013

This is the depth problem, solved thanks to superb sensitivity and energy coverage

… but sensitivity is not the only thing that is missing

Every waveband in our campaigns is densely covered — except the sub-TeV γ-rays.

- From one site: at most ~6 hours on a source in a night. Then the Sun comes up.
- The physics we are chasing, how the emission evolves hour by hour, unfolds precisely in the gaps.
- Several times I have aligned Chandra, XMM-Newton, NuSTAR and IXPE on the same target on the same date. Getting several oversubscribed satellites to observe simultaneously is very complex
- And then lost the VHE band to one night of cloud over La Palma.

Those datasets cannot be recovered.

Satellite time is allocated once. No two flares are identical.

What one site gets out of every 24 hours:

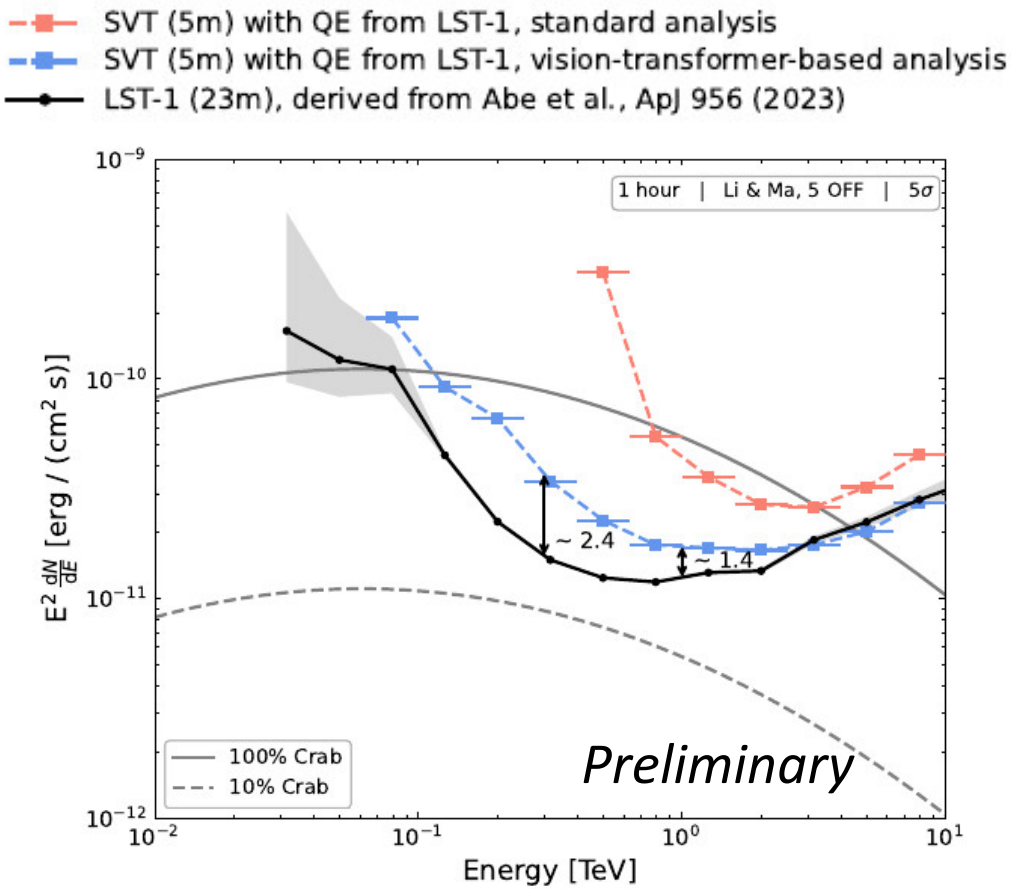
~6 h of usable darkness	**the other ~18 hours, from a single site, are simply lost**

AGN studies (and transient source studies, in general) need more TeV temporal coverage for better monitoring and catching flaring episodes

Only possible if cost per Cherenkov Telescope station/observatory is cheap

An idea: Small telescopes (cheap) with novel (efficient) analysis

For many decades we focussed on analyzing camera images (with perhaps time gradient): used O(10) parameters/event. We made a first case study (on simple simulations) that uses a video-vision-tansformer-based analysis on camera movies *(not images)*.



1-hour differential sensitivity — lower is better

Same telescope, different analysis

red → *blue*

A 5 m telescope with the standard analysis has no useful sensitivity below ~0.4 TeV. The transformer, on the same simulated events, reaches ~6× lower in energy and up to 10× deeper in flux.

5 m with transformers vs 23 m LST-1

blue → *black*

Within ~2.4× at 0.3 TeV and ~1.4× at 1 TeV — against 20× the mirror area.

Jobst, Heckmann, Heinrich & Paneque (submitted) — arXiv:2608.31148

Sensitivity set by the analysis, not by the size of the telescope

What such telescopes would bring to AGN science

Monitoring

- A source followed around the clock instead of until the Sun comes up: 6 h → 24 h.
- For Mrk 421 and Mrk 501 this is the missing axis — not deeper, continuous.
- Hourly broadband SED modelling in ordinary states, not only in the brightest week of a decade.

Flares

- A flare that starts at dawn over La Palma is currently lost. With longitude coverage it is caught from the first minute.
- The rise/fall, where the acceleration/ cooling physics is, gets measured instead of inferred.

And the same capability is not only for AGN: GRB afterglows decay from the moment of the trigger, and the Einstein Telescope will issue gravitational-wave alerts minutes before the merger — both useless to a telescope that cannot be pointing.

Sensitivity and availability are different features. We have spent forty years pushing for the first one. Perhaps in near future we need to push in different direction

Seven things to take away

- **Three challenges, three dynamic ranges** — energy > 10^{18}, time > 10^{6}, space > 10^{9} , and they are not independent.
- **The γ-ray sky is an AGN sky** — ~84% of what Fermi-LAT identifies is an active galaxy, and it is beaming-selected.
- **Degeneracy is broken by variability** — not by a better fit. One SED cannot tell an electron from a proton.
- **More time coverage, more complexity** — eighteen years on two blazars, and every new observable adds a dimension rather than removing one.
- **Polarimetry plus TeV is a picture** — ordered fields, energy-stratified shocks, and turbulence on top.
- **Neutrinos gave us two accelerators** — the jet and the hidden corona, jetted and non-jetted, as advertised in 2017.
- **CTAO will bring a large boost in sensitivity and energy coverage, but not temporal coverage**
  Great results expected for AGNs, but need to fix the temporal coverage problem.

Paolo — thank you

You gave this field its cartoon, its vocabulary, its selection effects — and contributed substantially to first neutrino sources (jetted and not-jetted)

And you are not leaving the field — only ESO. TU Munich gets you next, and so do the neutrinos.

Four decades of photons — now go and do it with neutrinos.

David Paneque · Max-Planck-Institut für Physik · ESO Garching, 14 September 2026

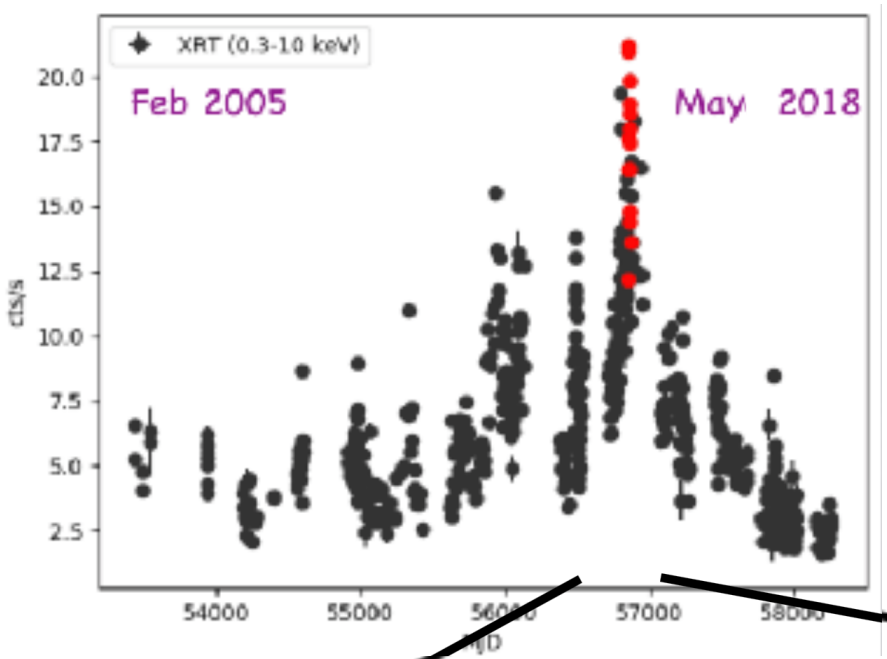
Backup

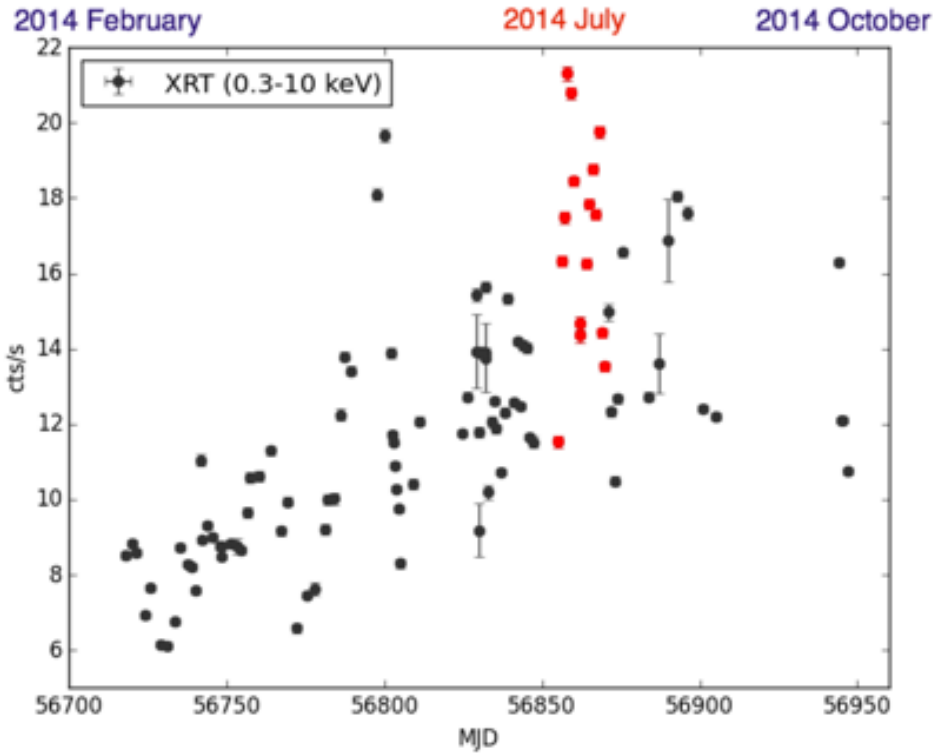
Large flaring activity of Mrk501 in July 2014

Swift-XRT

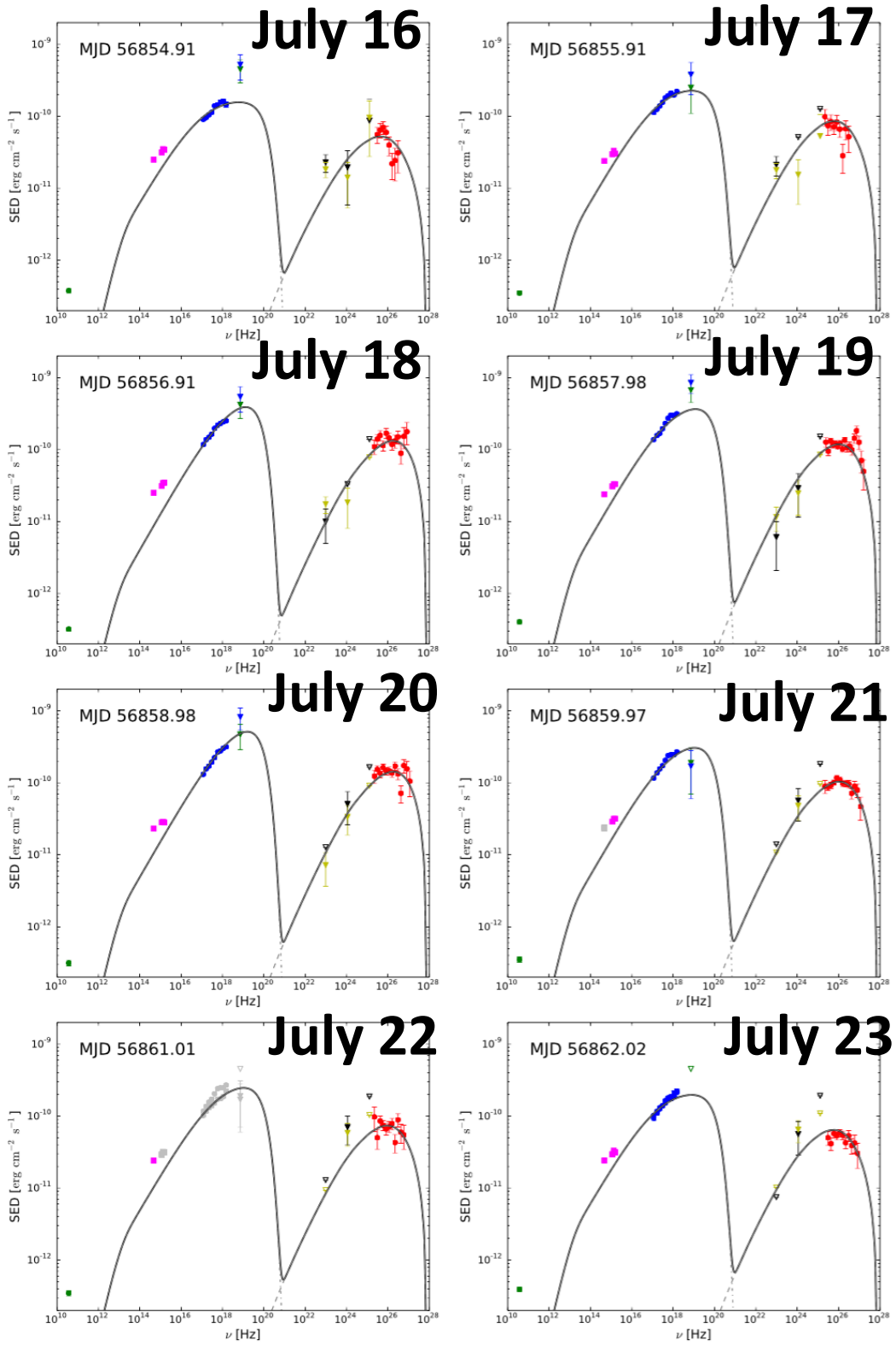
Historical light curve

in ~**15 years**





Largest X-ray activity occurred in July 2014

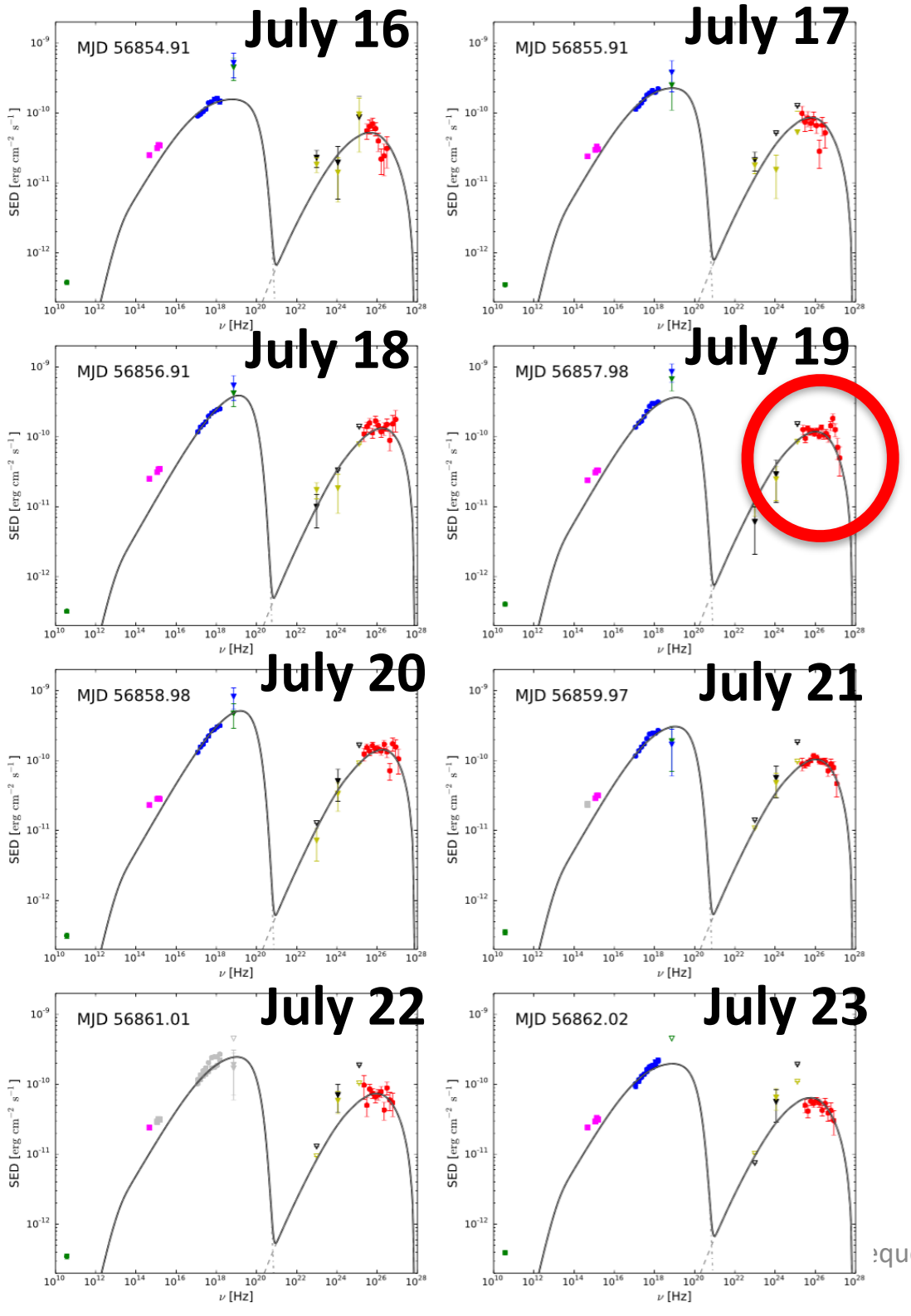


Large flaring activity of Mrk501 in July 2014

Acciari et al A&A 2020, 637, 86

Broadband SEDs can be constructed for single (observations) nights

→ One-zone SSC can describe the most prominent and variable components



Large flaring activity of Mrk501 in July 2014

Narrow feature at ~3 TeV found in the VHE spectrum of MJD 56857.98 (July 19th, 2014), when X-ray flux was highest

This feature is inconsistent at more than 3**σ** with the classical functions for VHE spectra (*power law, log-parabola, and log-parabola with exp. cutoff*)

statistical fluctuation (>3σ) or new component ?

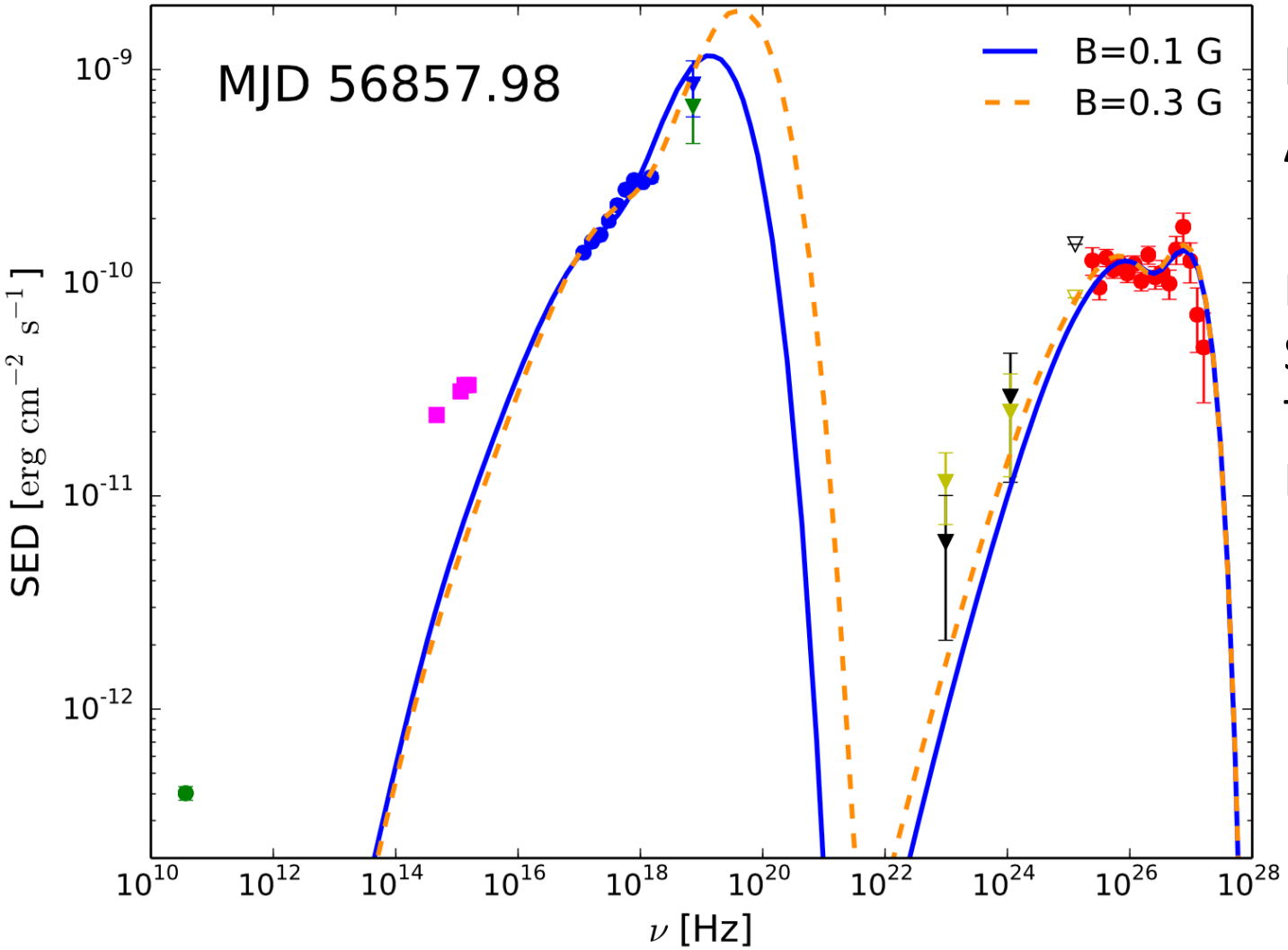
Pile-up in the electron energy distribution due to stochastic acceleration

Acciari et al A&A 2020, 637, 86

$\text{Time}_{\text{Acceleration}}(\gamma_{eq}) \sim \text{Time}_{\text{Cooling}}(\gamma_{eq}) << \text{Time}_{\text{Escape}}$

Usual **log-parabolic EED at $\gamma << \gamma_{eq}$, Relativistic Maxwellian EED at γ_{eq}**

Mrk501



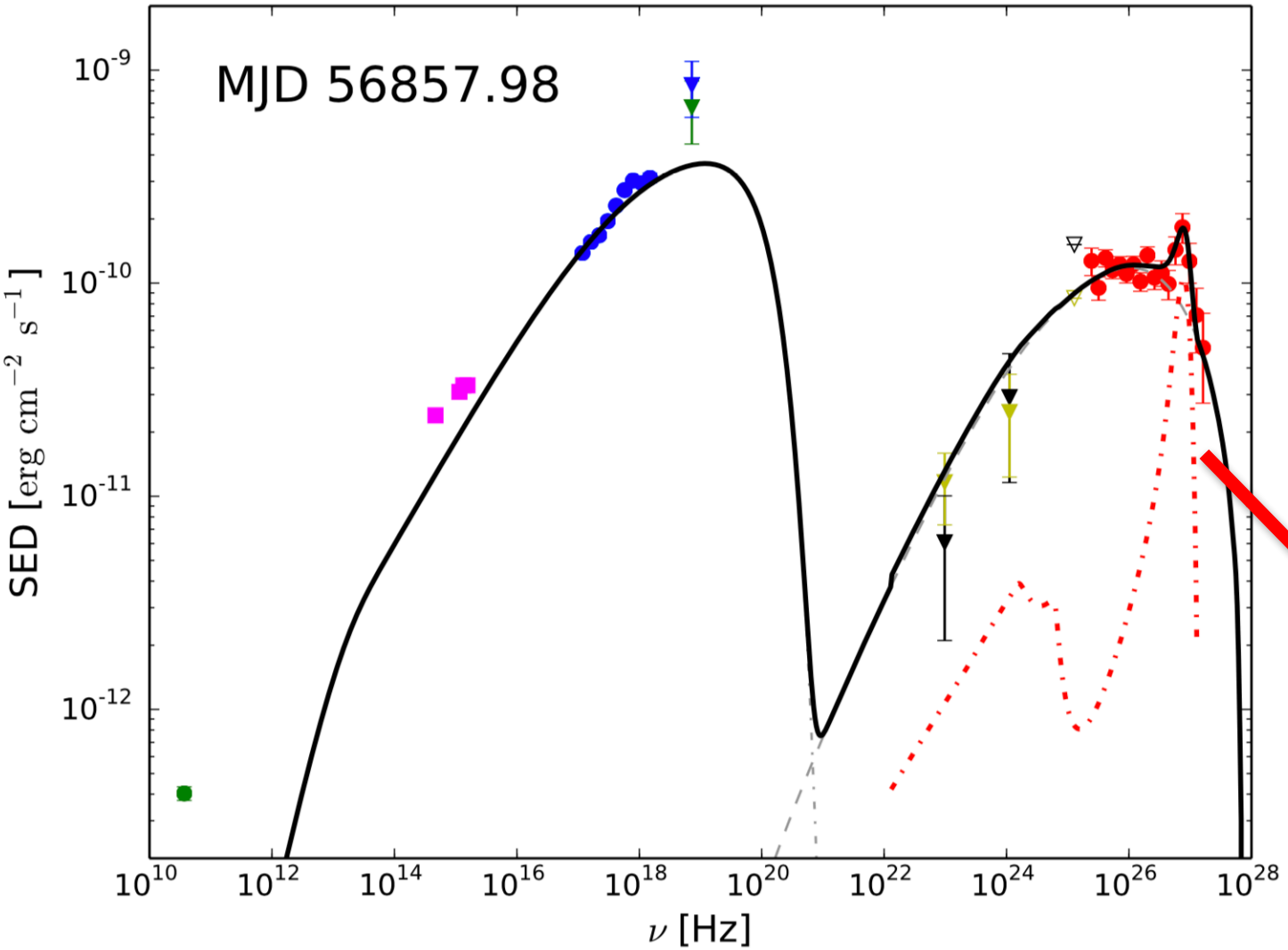
Model performed by Andrea Tramacere

Based on
Stawarz&Petrosian 2008
Tramacere et al 2011
Lefa et al 2011

Additional component produced via an Inverse Compton pair cascade induced by electrons accelerated in a magnetospheric vacuum gap close to the Black Hole

Acciari et al A&A 2020, 637, 86

Mrk501

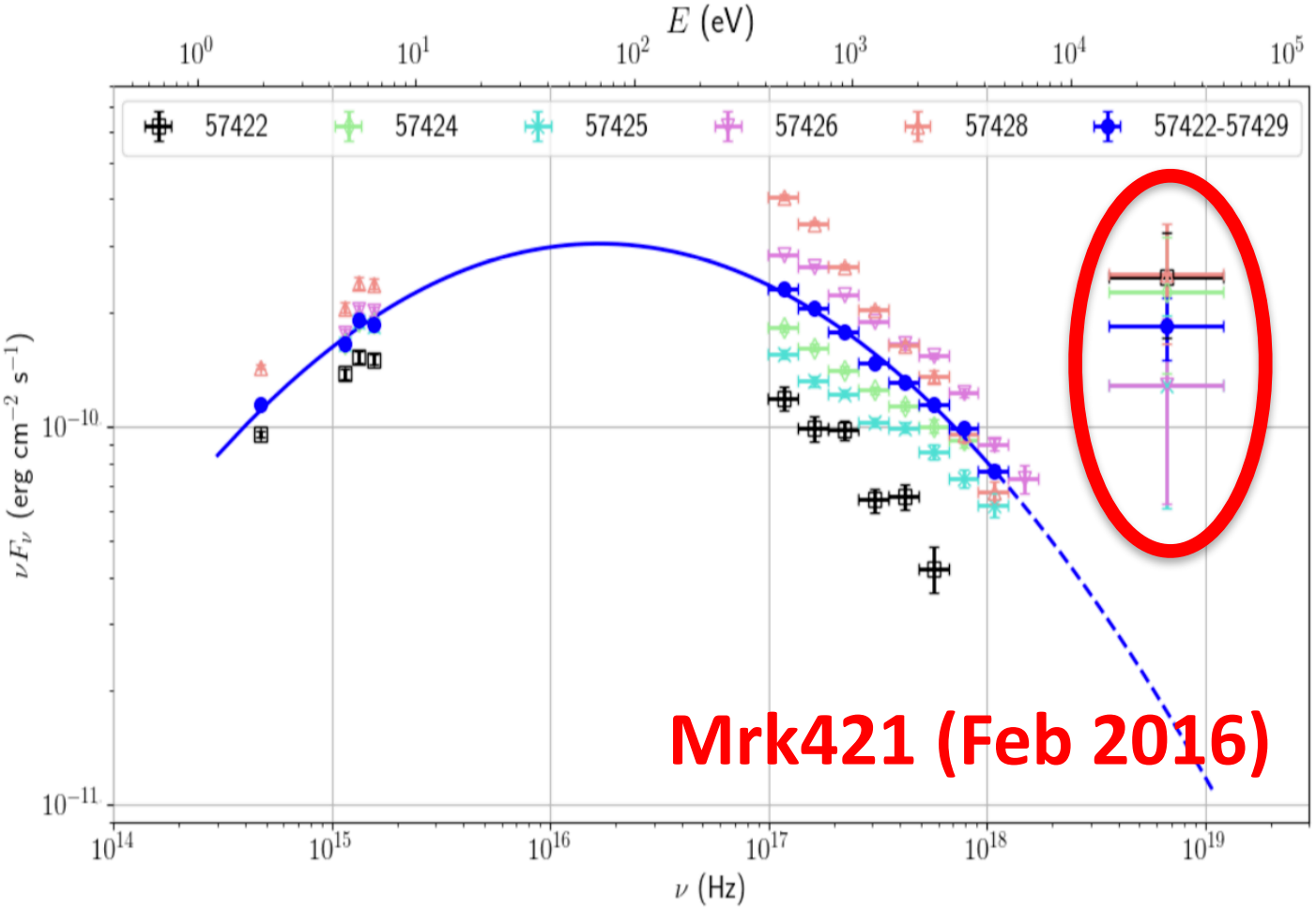


Model by Christoph Wendel (for details, see arXiv:2012.05215)

Based on Zdziarski 1988, Levinson&Rieger 2011, Ptitsyna&Neronov 2016 and Wendel et al 2017

Emission from narrow EED accelerated in Magnetospheric vacuum gap

A peculiar observation: Swift BAT excess

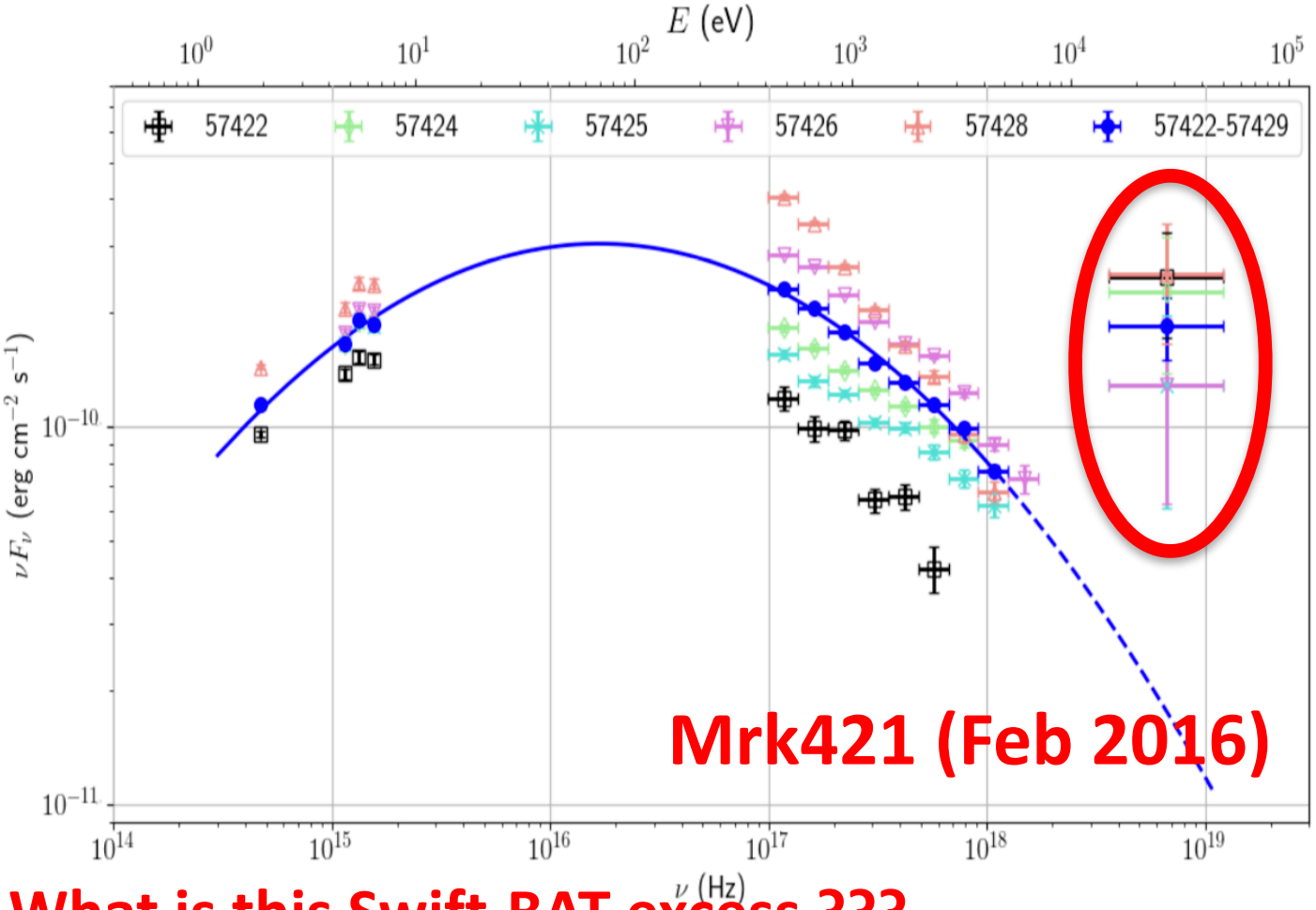


Acciari et al 2020, MNRAS in press (arXiv:2012.01348)

Single spectra (colors) during a 7-day time interval in 2016 Feb. 4—11

And also 7-day average spectra (blue)

A peculiar observation: Swift BAT excess



Acciari et al 2020, MNRAS in press (arXiv:2012.01348)

Single spectra (colors) during a 7-day time interval in 2016 Feb. 4—11

And also 7-day average spectra (blue)

What is this Swift-BAT excess ???

Onset of IC component (*as suggested Kataoka&Stawrz 2016 using NuSTAR hint*) ?

OR

Inverse-Compton produced by high-energy electrons from the spine region up-scattering the synchrotron photons from the layer (*as proposed by Chen 2017*) ?

OR

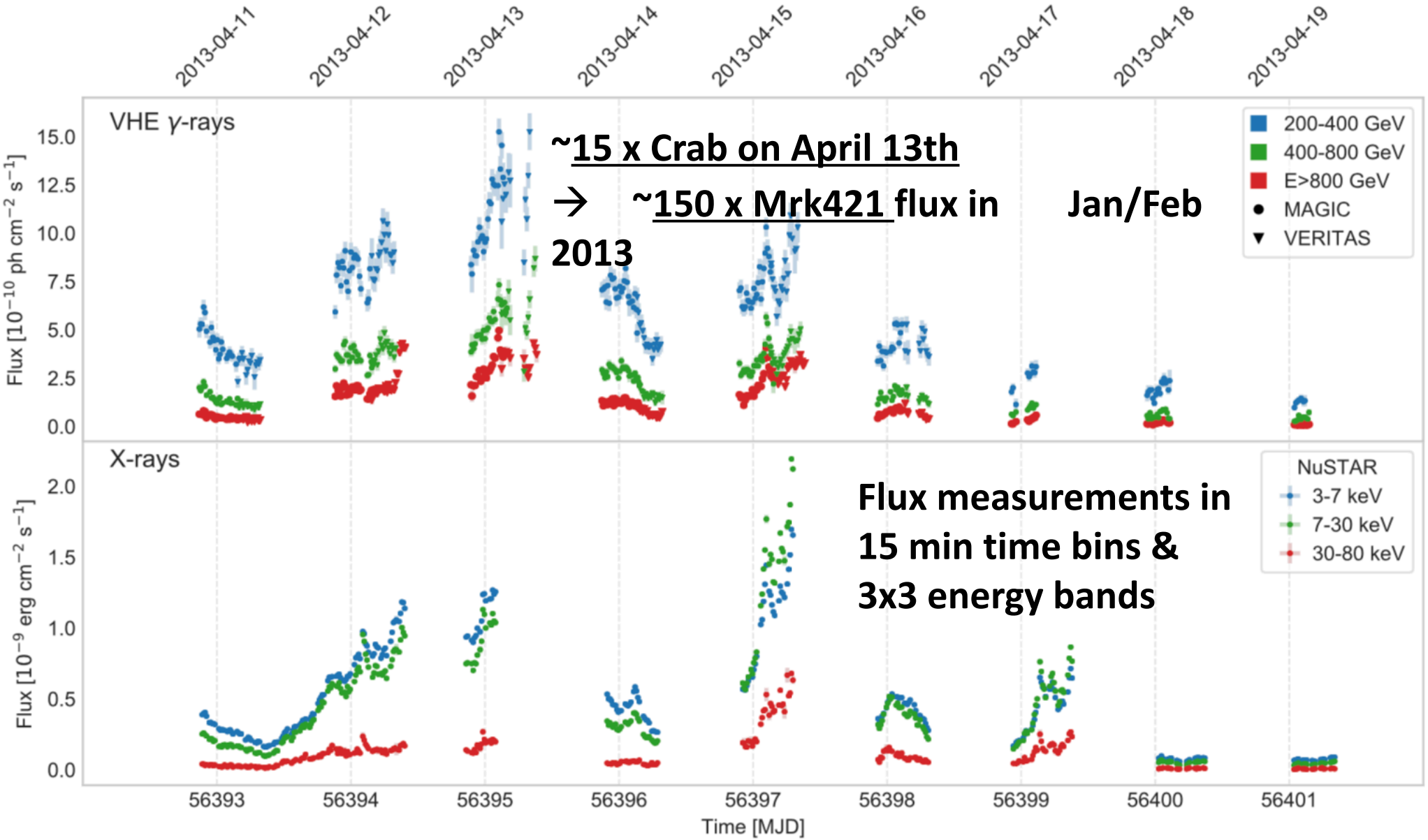
new narrow component, similar to Mrk501 in 2014 (*Acciari et al 2020*) ?

Mrk421 April 2013: Multi-band X-ray and VHE LCs

MAGIC+VERITAS observed for 70 hours and NuSTAR for 71 hours

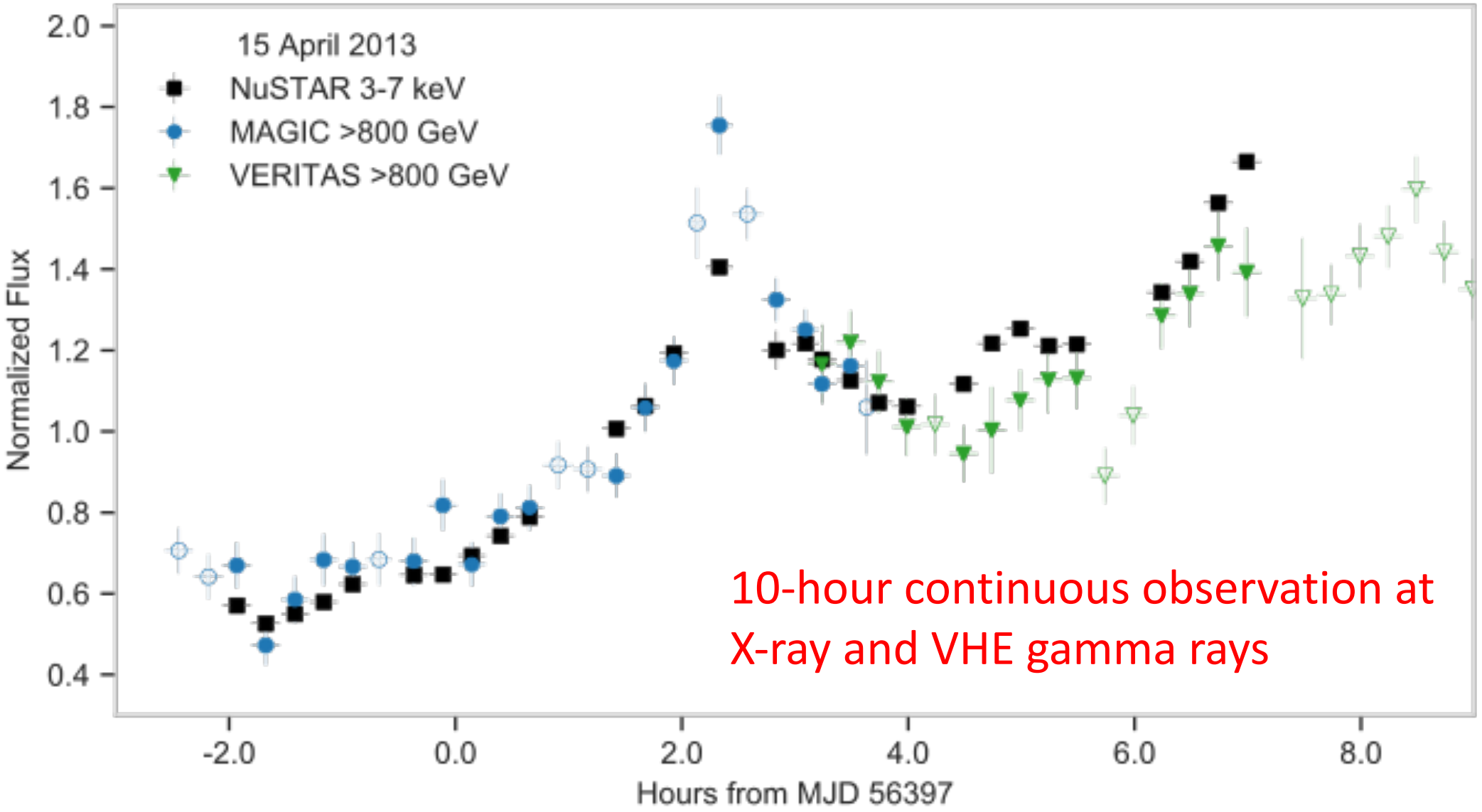
About 45 hours of strictly simultaneous VHE and hard X-ray data

Acciari et al. ApJS 2020, 248, 29



Normalized light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29

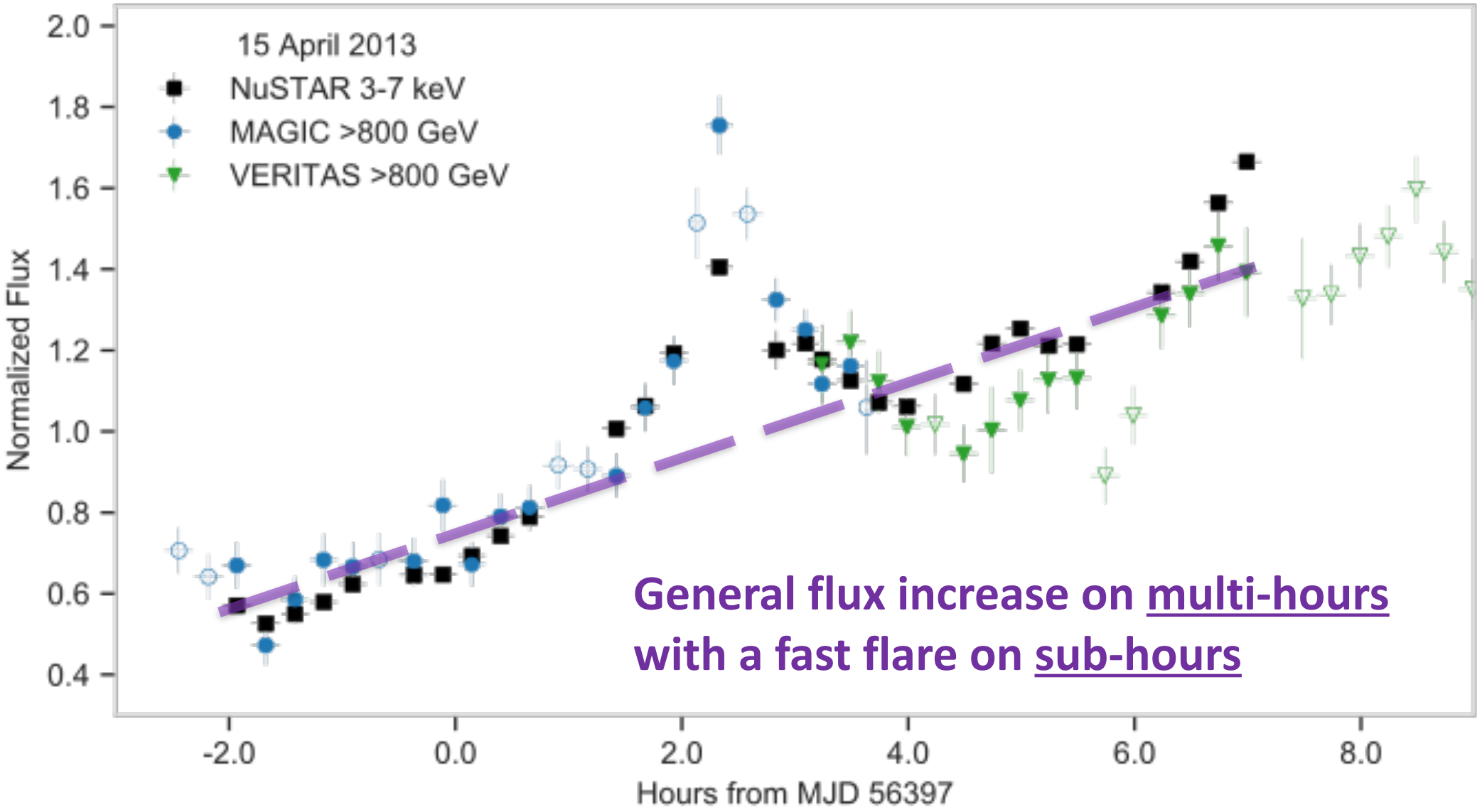


Normalized flux: flux normalized to night mean flux from simultaneous data

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

Normalized light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29

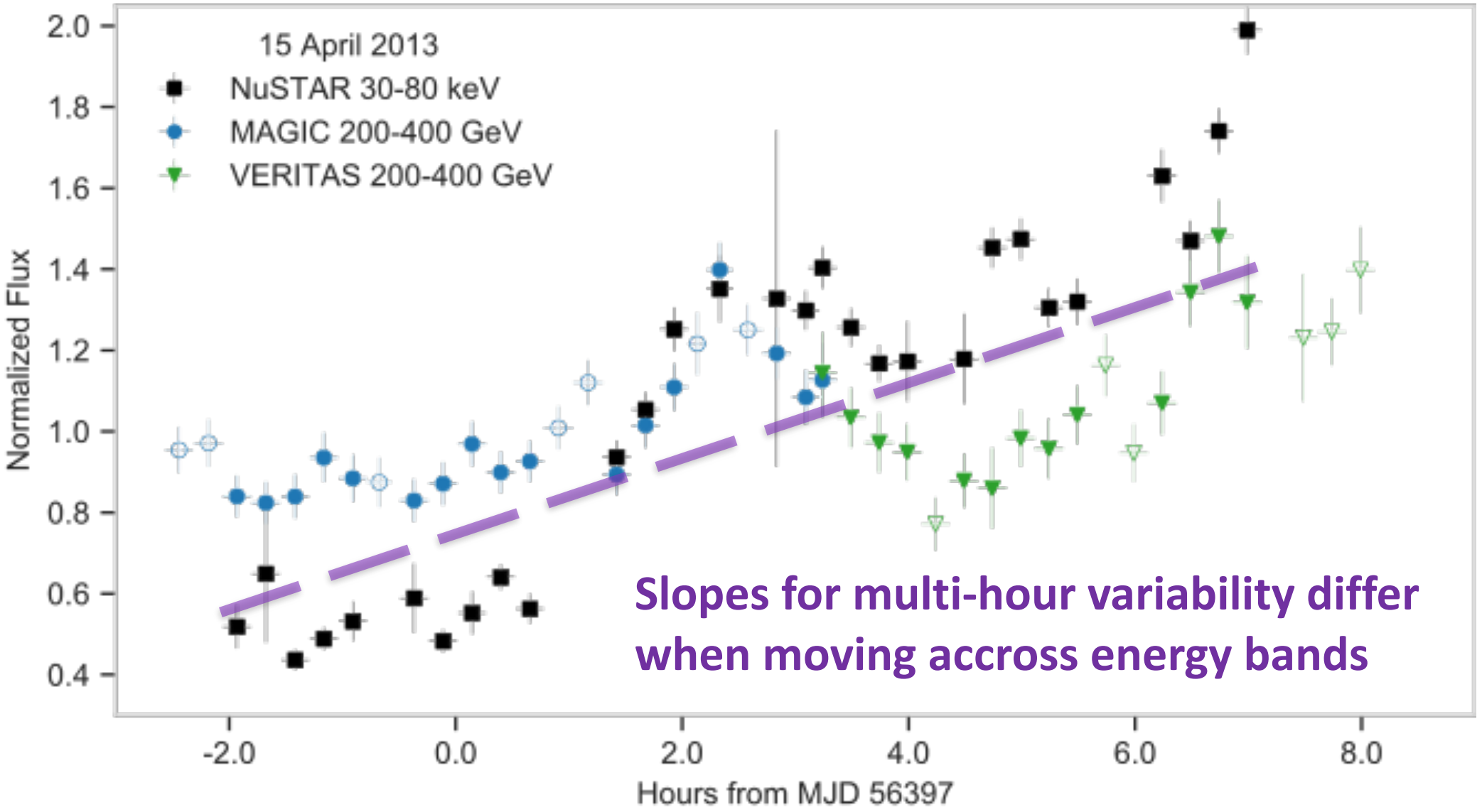


Normalized flux: flux normalized to night mean flux from simultaneous data

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Normalized light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29

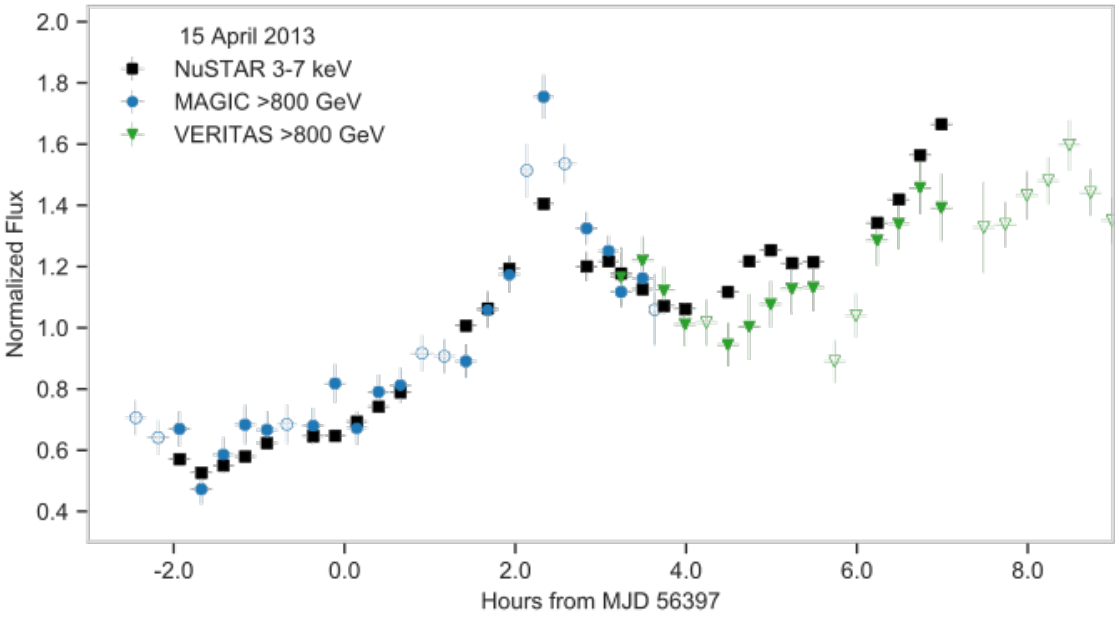


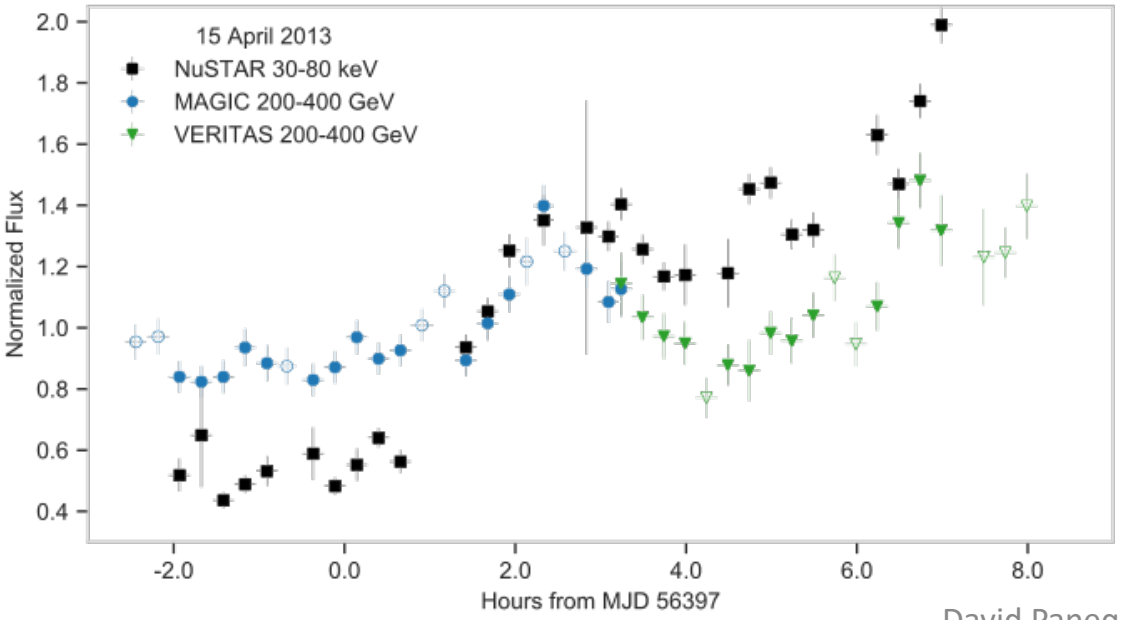
Normalized flux: flux normalized to night mean flux from simultaneous data

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

Normalized light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29





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

Function used to parameterize the main trends in the multi-hour X-ray& VHE Light curves

$$\mathrm{Flux}(t) = \mathrm{Slow}(t) + \mathrm{Fast}(t)$$

$$\mathrm{Slow}(t) = \mathrm{Offset}(1 + \mathrm{Slope} * t)$$

$$\mathrm{Fast}(t) = \frac{2}{2^{-\frac{t-t_0}{rise}} + 2^{\frac{t-t_0}{fall}}} \times (\mathrm{Flare\ Amplitude}) \times (\mathrm{Slow}(t_0))$$

Parameters:

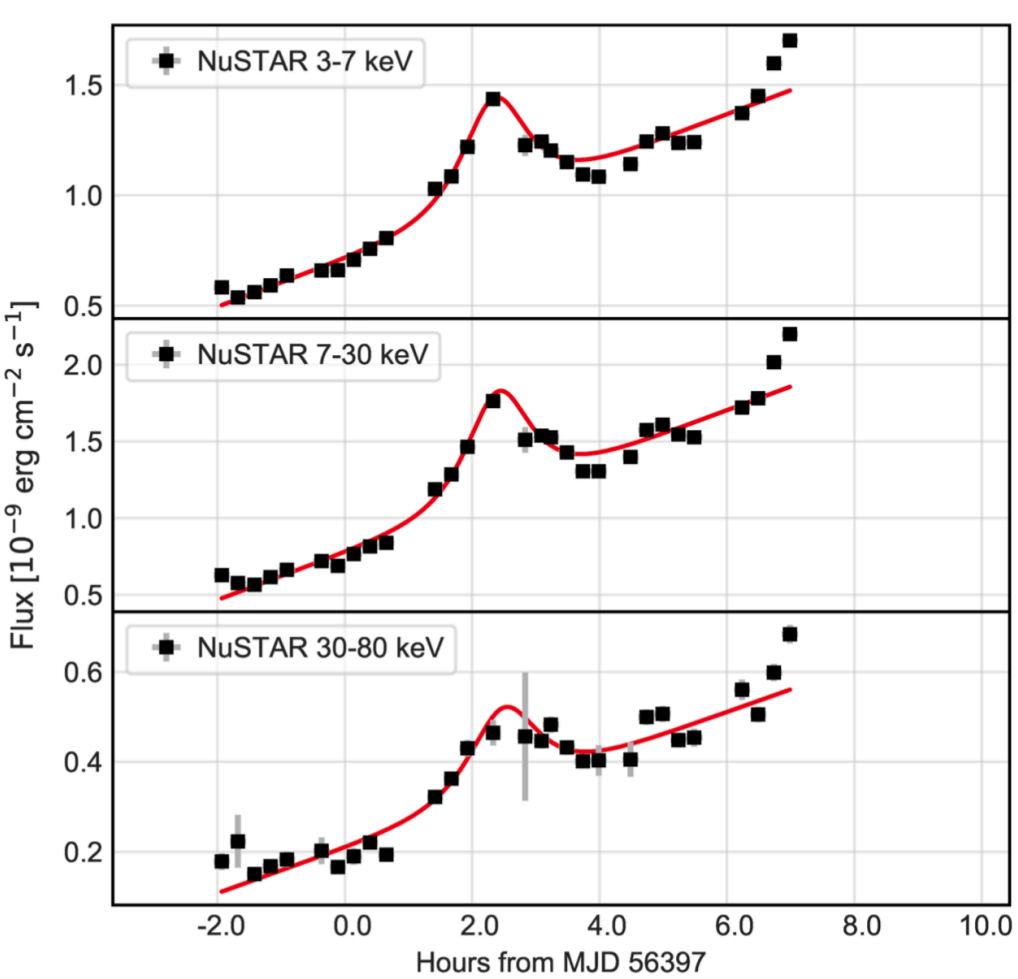
Simplification: rise=fall → timescale

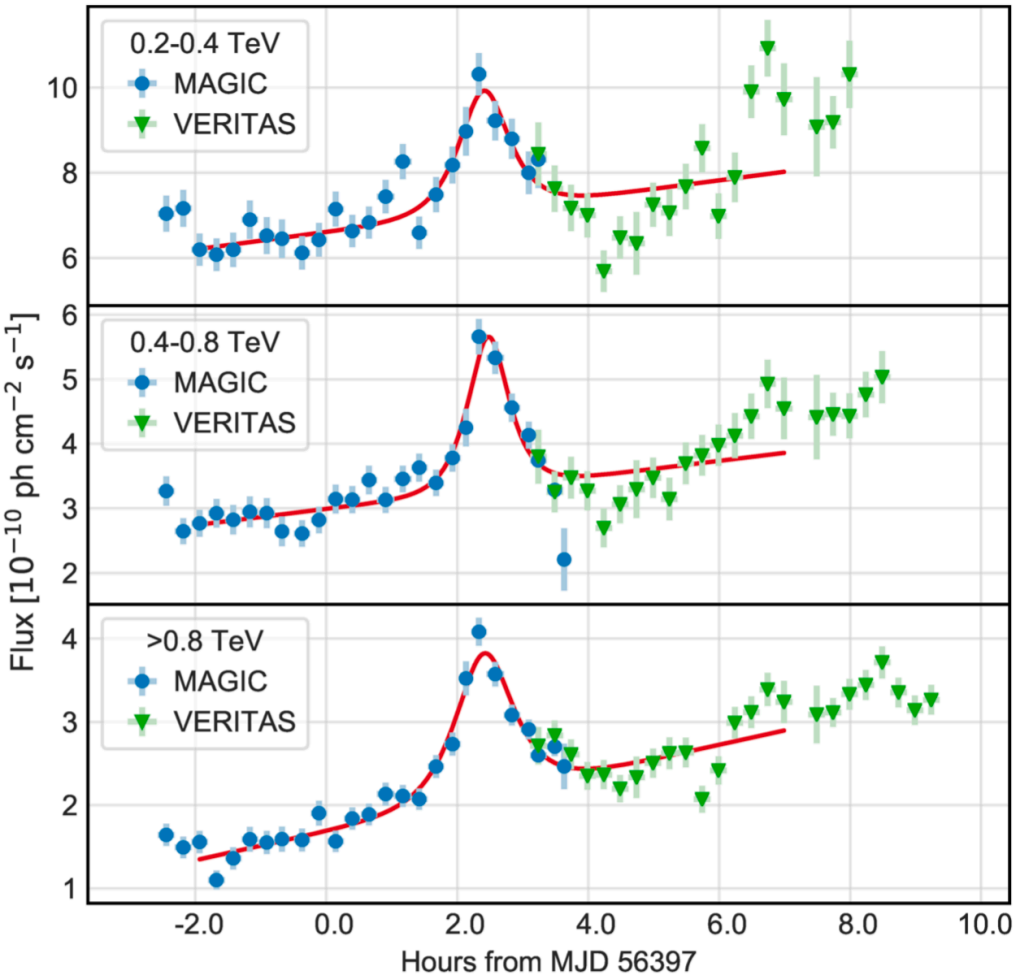
- offset = starting flux
- amplitude = max. strength of the flare relative to slow(t0) flux
- timescale = flux doubling time scale
- slope = (slow component) flux would increase by this factor in 1 day

This parameterization provides normalized slopes and amplitudes, which allows for a direct comparison of the values among different various X-ray and VHE bands

X-ray and VHE Light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29





The red curve shows a fit with a two-component function, applied to the time interval with simultaneous X-ray and VHE observations

→ Close relation between X-ray and gamma-rays →

Leptons !! → But *complex X-ray vs VHE variability and*

Acciari et al. ApJS 2020, 248, 29

Table 3. Parameters resulting from the fit with Eq. 3 to the X-ray and VHE multi-band light curves from 2013 April 15.

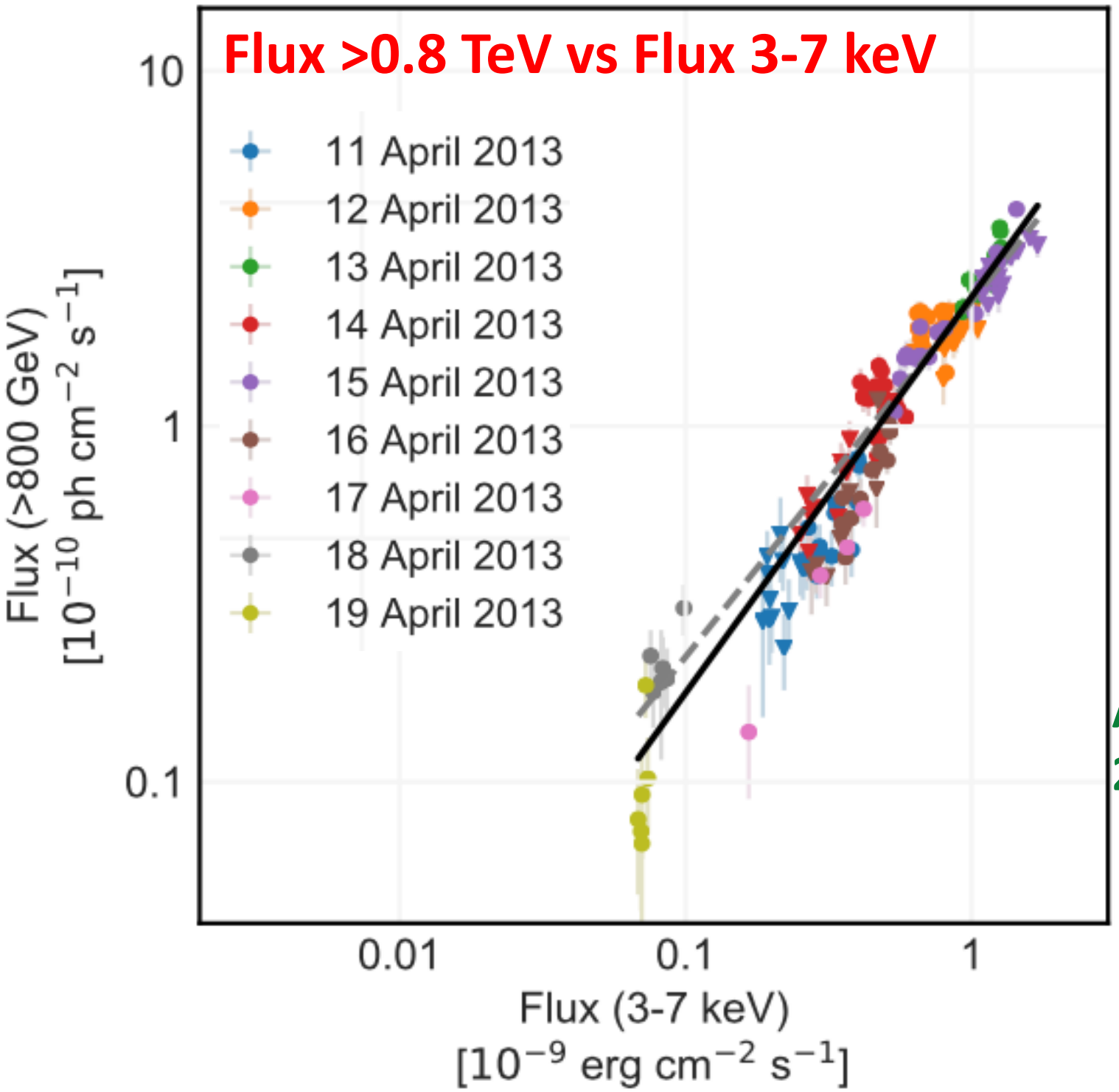
Band	$Offset^{a}$	$Slope$ [h^{-1}]	Flare Amplitude A	Flare flux-doubling time[b] [h]	Flare t_0 [h]	χ^2/d.o.f
15 April 2013						
3-7 keV	0.71 ± 0.01	0.153 ± 0.006	0.49 ± 0.07	0.30 ± 0.04	2.35 ± 0.06	836/24
7-30 keV	0.78 ± 0.02	0.199 ± 0.009	0.59 ± 0.11	0.30 ± 0.04	2.41 ± 0.06	889/24
30-80 keV	0.21 ± 0.01	0.241 ± 0.018	0.56 ± 0.18	0.32 ± 0.09	2.50 ± 0.10	111/24
0.2-0.4 TeV	6.60 ± 0.17	0.031 ± 0.008	0.40 ± 0.09	0.23 ± 0.07	2.41 ± 0.09	96.9/38
0.4-0.8 TeV	2.99 ± 0.07	0.042 ± 0.008	0.72 ± 0.09	0.19 ± 0.03	2.47 ± 0.04	68.1/42
>0.8 TeV	1.68 ± 0.05	0.103 ± 0.010	0.82 ± 0.08	0.27 ± 0.03	2.41 ± 0.04	90.0/45

[a] For VHE bands in 10^{-10} ph cm^{-2} s^{-1}, for X-ray bands in 10^{-9} erg cm^{-2} s^{-1}.

[b] Parameters t_{rise} and t_{fall} in Eq. 3 are set to be equal, and correspond to the Flare flux-doubling time in the Table.

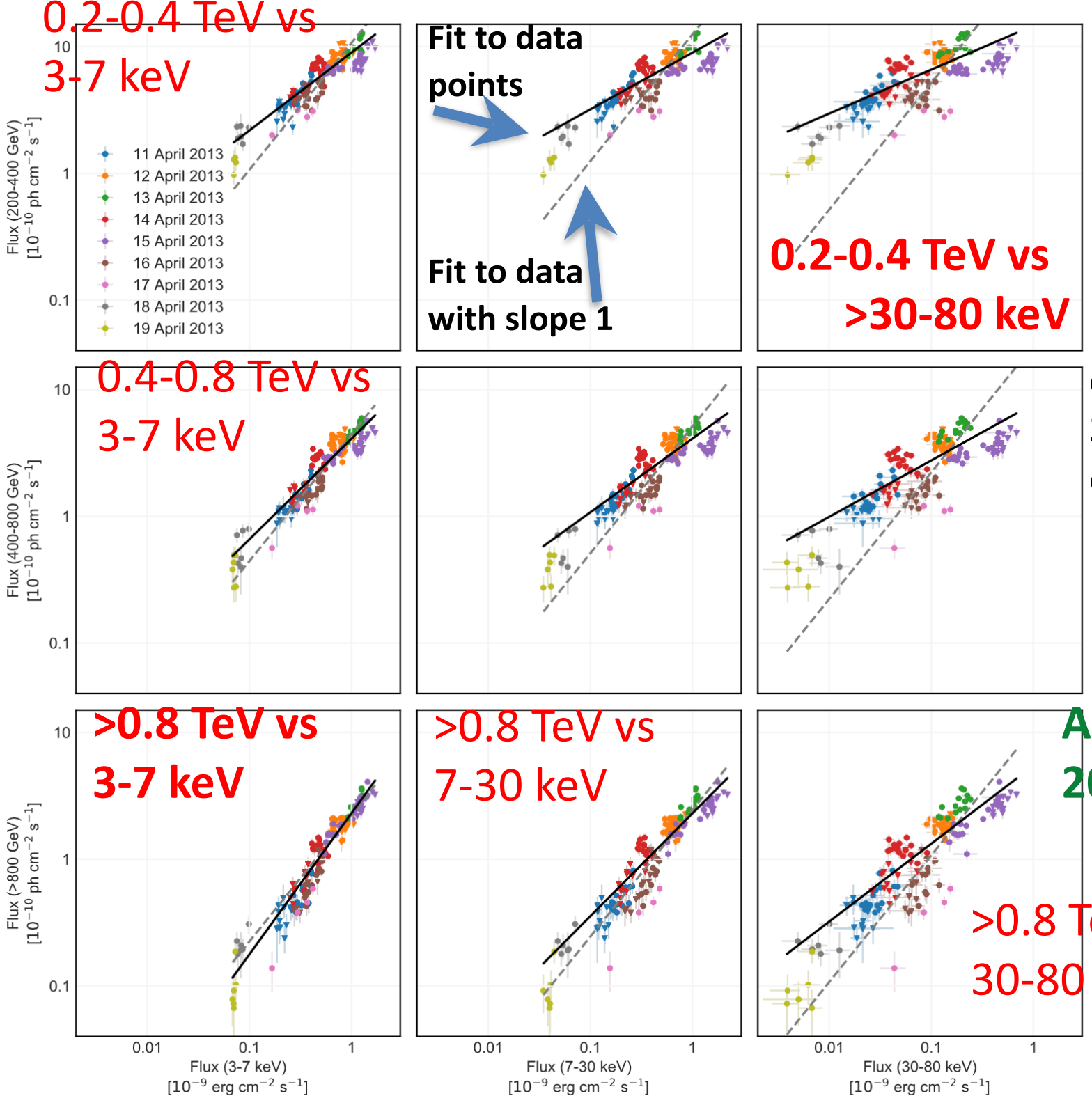
Large energy-dependence difference between the slow and the fast components

Gamma-ray vs X-ray flux (9-day "full" flare)



Flux measurements in gamma rays and X-rays @ 15min

Acciari et al. ApJS 2020, 248, 29

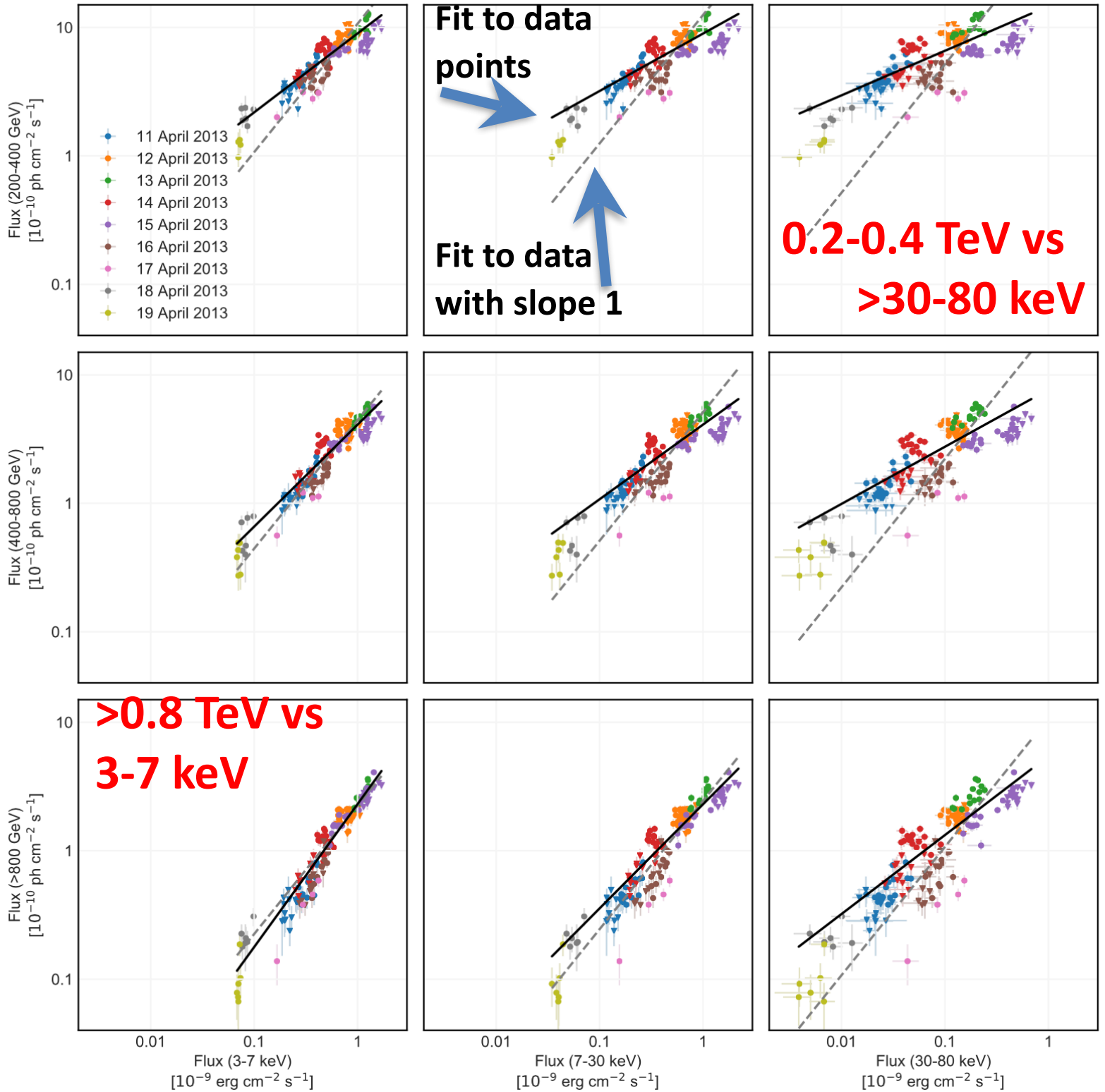


Gamma-ray vs X-ray flux (9-day "full" flare)

characterization in 3 (X-ray) x 3 (gamma) energy bands

Flux measurements in gamma rays and X-rays @ 15min

Acciari et al. ApJS 2020, 248, 29



Gamma-ray vs X-ray flux (9-day "full" flare)

characterization in 3 (X-ray) x 3 (gamma) energy bands

Flux measurements in gamma rays and X-rays @ 15min

Several flavours of X-ray vs VHE correlation when moving across bands

Quantification of the VHE vs X-ray correlations

Positive correlation exists (and very significant) for all the energy bands

Table 5. Correlation coefficients and slopes of the linear fit to the VHE vs X-ray flux (in log scale) derived with the 9-day flaring episode of Mrk421 in April 2013.

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VHE band	Xray band	Pearson coeff.	Nsigma in Pearson	DCF	Slope from linear fit	Chi2/d.o.f
200-400 GeV	3-7 keV	$0.920 + 0.011 - 0.013$	20.2	0.928 ± 0.117	0.61 ± 0.02	1183 / 162
	7-30 keV	$0.871 + 0.018 - 0.020$	17.0	0.879 ± 0.111	0.45 ± 0.03	1891 / 162
	30-80 keV	$0.790 + 0.028 - 0.032$	13.6	0.805 ± 0.108	0.35 ± 0.02	2277 / 162
400-800 GeV	3-7 keV	$0.946 + 0.007 - 0.009$	23.4	0.955 ± 0.114	0.79 ± 0.03	1038 / 170
	7-30 keV	$0.909 + 0.012 - 0.014$	19.8	0.918 ± 0.108	0.58 ± 0.03	1725 / 170
	30-80 keV	$0.838 + 0.021 - 0.024$	15.8	0.855 ± 0.105	0.45 ± 0.03	2160 / 170
>800 GeV	3-7 keV	$0.964 + 0.005 - 0.006$	26.0	0.971 ± 0.108	1.11 ± 0.03	704 / 170
	7-30 keV	$0.947 + 0.007 - 0.008$	23.5	0.955 ± 0.105	0.81 ± 0.03	1245 / 170
	30-80 keV	$0.892 + 0.015 - 0.017$	18.6	0.908 ± 0.103	0.61 ± 0.03	1736 / 170

Many different trends in the VHE vs X-ray correlation when moving across "nearby" energy bands

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Acciari et al. ApJS 2020, 248, 29

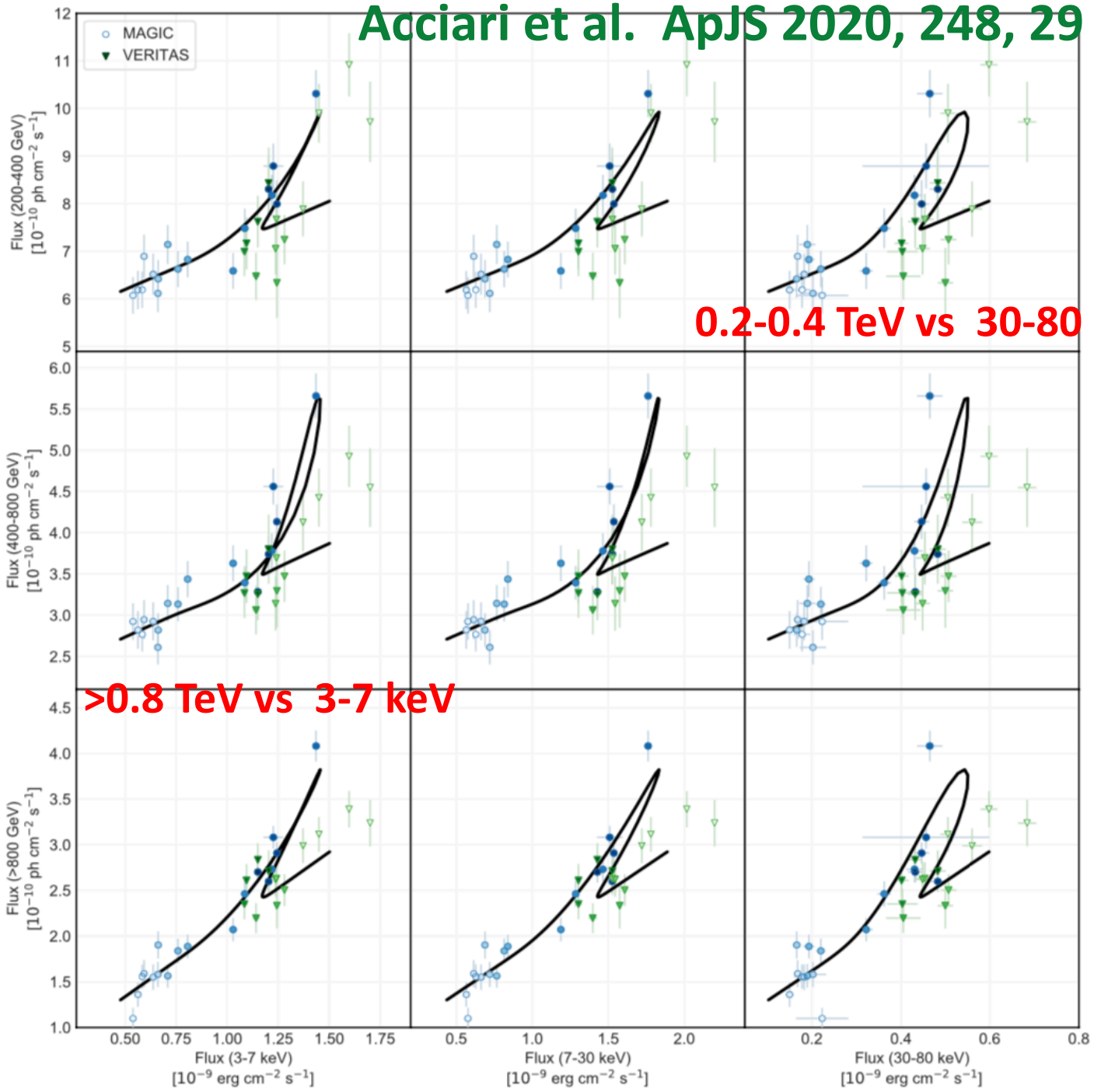
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Many different trends in the VHE vs X-ray correlation when moving across "nearby" energy bands

The combination > 0.8TeV and 3-7 keV shows the highest degree of correlation, highest slope, and less scattering

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Gamma-ray vs X-ray flux-flux plot (April 15th)



Curves depict the expectation from the envelopes from the fit function (slow+fast) to the light curve at the 3x3 energy bands

Figure 7. VHE flux vs. X-ray flux in three X-ray and three VHE energy bands for April 15. The black line is the track predicted by Slow+Fast component fit from Eq. 2. The lightness of symbols follows time: for MAGIC data lightness decreases with time, and for VERITAS data it increases in time, so that the central part of the night, where MAGIC and VERITAS observations overlap, is plot using darker symbols.

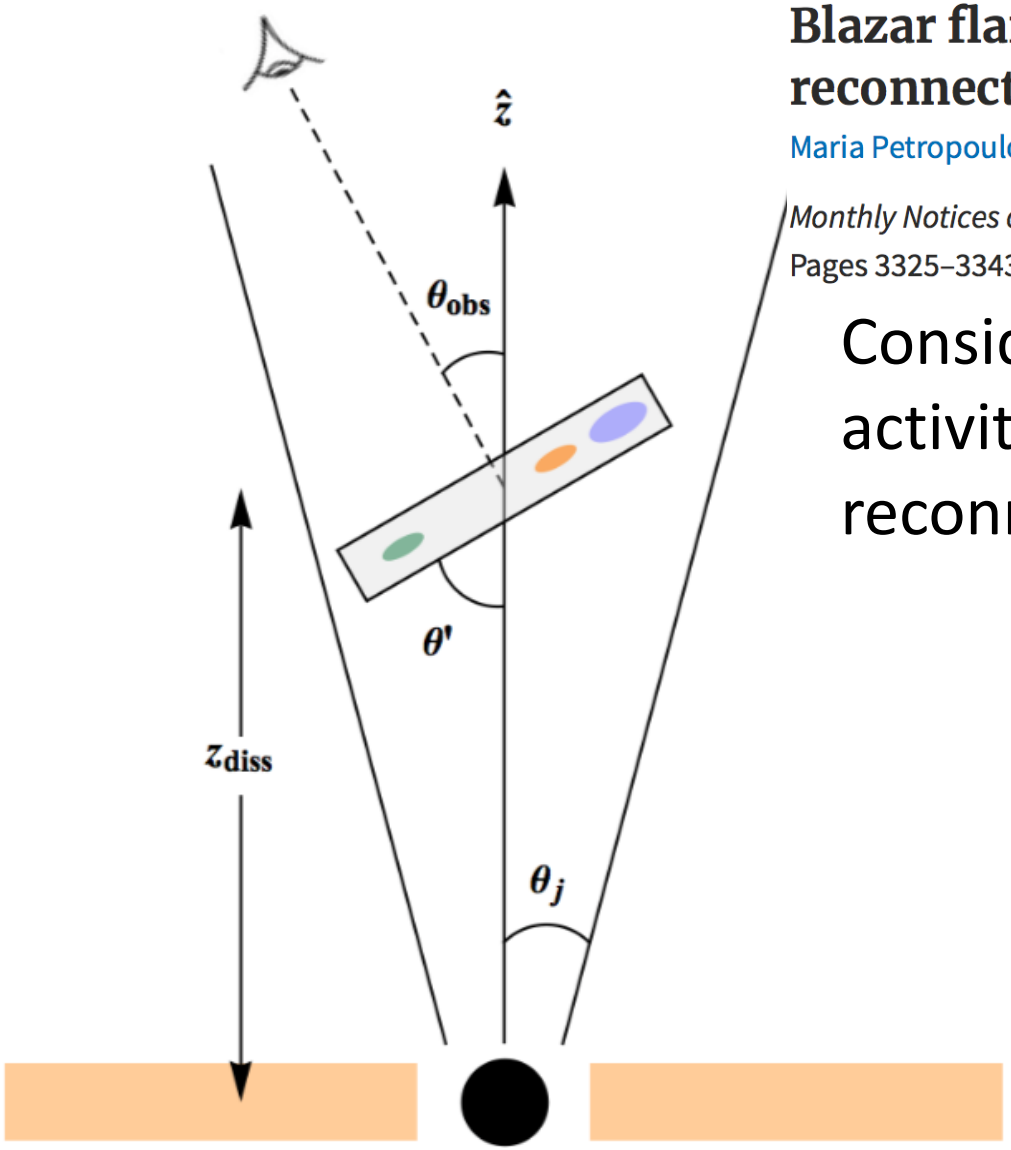


Figure 9. Sketch of a reconnection layer (of half-length L') forming in the jet at a distance z_{diss} (not in scale). The layer forms an angle θ' (as measured in the jet's rest frame) with respect to the jet axis. Plasmoids of different sizes and velocities move towards the sides of the layer while radiating. The jet has an opening angle θ_j and a bulk Lorentz factor Γ_j.

Blazar flares powered by plasmoids in relativistic reconnection

Maria Petropoulou ✉, Dimitrios Giannios, Lorenzo Sironi

Monthly Notices of the Royal Astronomical Society, Volume 462, Issue 3, 1 November 2016, Pages 3325–3343, https://doi.org/10.1093/mnras/stw1832

Considered that the large X-ray/VHE activity is produced in a magnetic reconnection layer

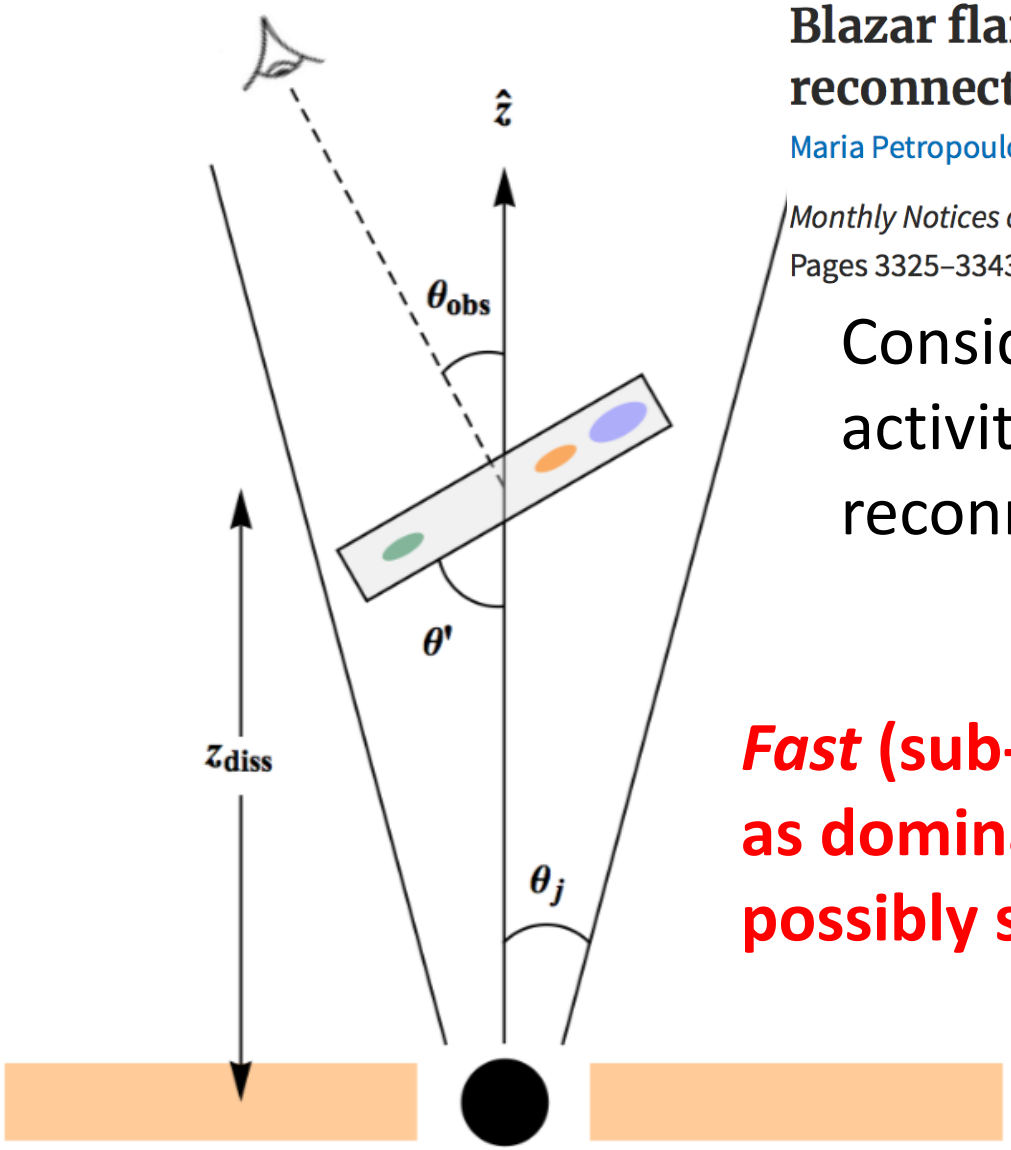


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Considered that the large X-ray/VHE activity is produced in a magnetic reconnection layer

Fast **(sub-hour) flares may be understood as dominated by a single plasmoid, possibly small and highly relativistic**

Slow **(multi-hour) but more luminous component of the light curve, may be understood as dominated by superposition of many plasmoids of different sizes and speeds**

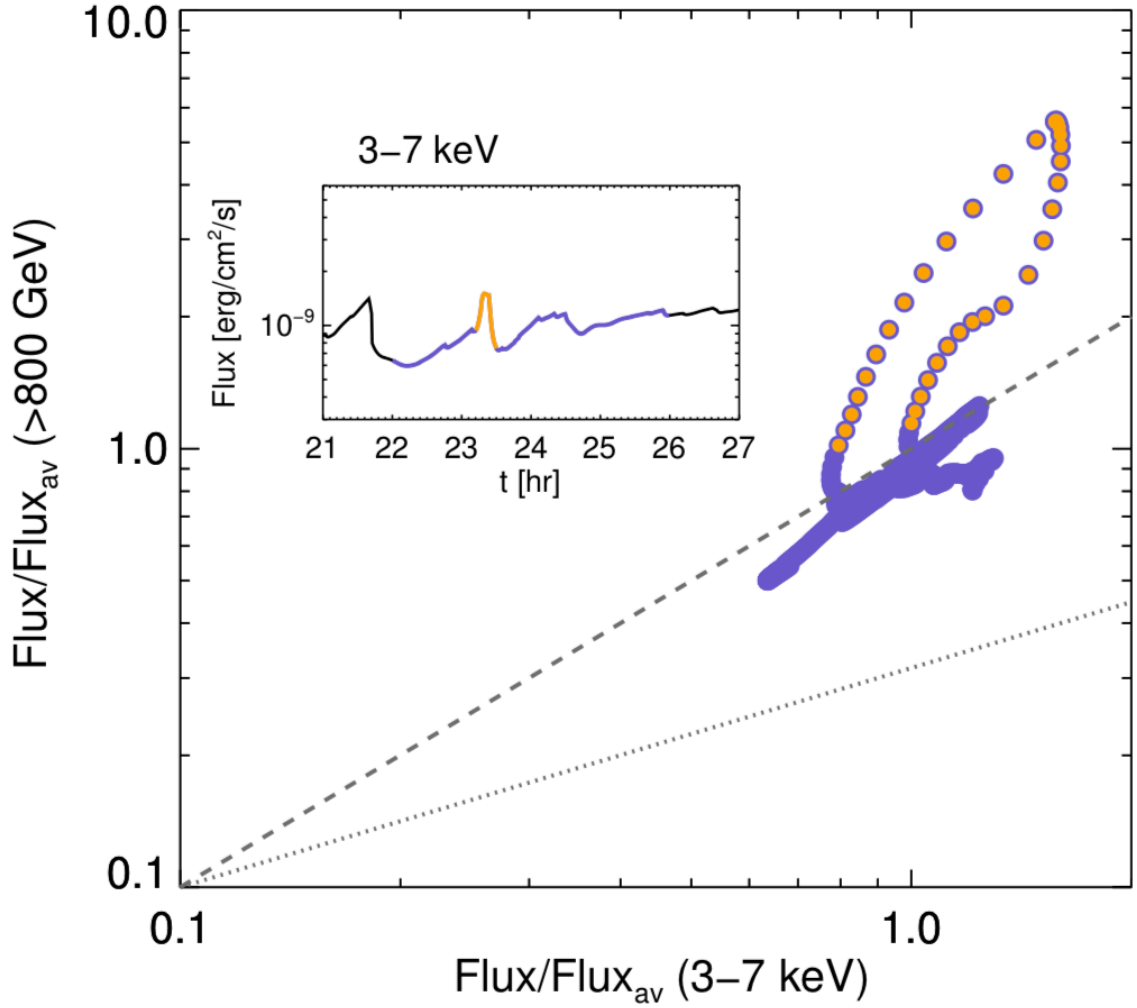
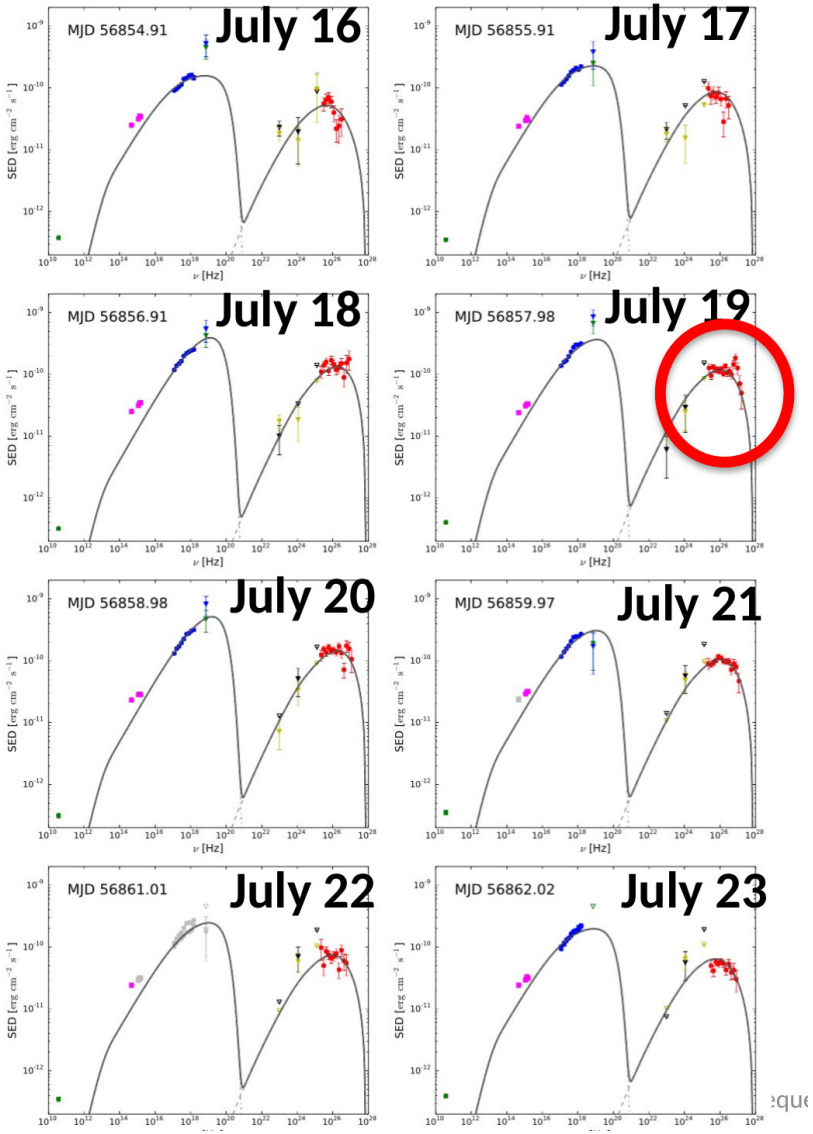


Figure 9. VHE flux (> 800 GeV) versus X-ray flux (3−7 keV) of a plasmoid-powered light curve, computed for a "vanilla" model of a BL Lac source (see model BL10 in Christie et al. 2019). The fluxes are extracted from a 4-hr time window of the total light curve (see purple line in the inset plot) and are normalized to their time-averaged values. The loop-like structure in the flux-flux plot is produced during a fast flare of duration ~ 0.3 hr (see orange points). Lines with slopes 1 (dashed) and 0.5 (dotted) are overplotted to guide the eye.

Flux-flux plot for a portion of a LC produced by plasmoids (**simulation**)

The loop is produced by a fast flare, dominated by a single plasmoid
Similar shape to that found in the data

Mrk 501, July 2014: a narrow feature at ~3 TeV

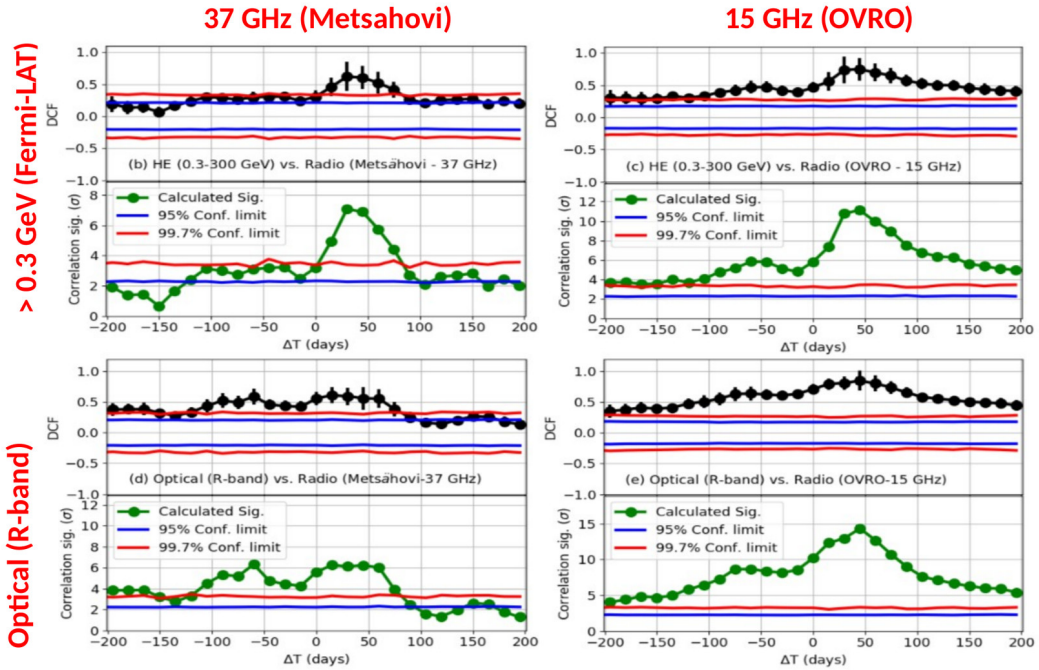


- Largest X-ray activity in ~16 years of Swift-XRT monitoring.
- Inconsistent at >3σ with power law, log-parabola, and log-parabola with exponential cutoff.
- Pile-up in the electron distribution from stochastic acceleration (Tramacere).
- Inverse-Compton pair cascade from a magnetospheric vacuum gap (Wendel et al. 2021, A&A 646, 115).
- TeV pion bumps from protons on >100 keV photons (Petropoulou, arXiv:2308.14184).
- Or — honestly — still a statistical fluctuation.

Acciari et al. 2020, A&A 637, A86

A >3σ feature on a single night. Either a new component, or a reminder that 3σ features happen.

Mrk 421: the radio–GeV lag, and where the emission sits



- Radio lags the GeV by ~45 days — confirmed with data not dominated by the 2012 flare, so it is intrinsic.
- A disturbance crossing the γ-ray photosphere first, then the radio photosphere ~0.2 pc further down the jet.
- The radio core sits ~2 pc from the black hole — so the optical and GeV emission is far out too, which is why VHE/X-ray usually does not correlate with optical/GeV.

Acciari et al. 2021, MNRAS 504, 1427, confirming Max-Moerbeck et al. 2014