The challenge of understanding AGNs through extensive multiwavelength observations

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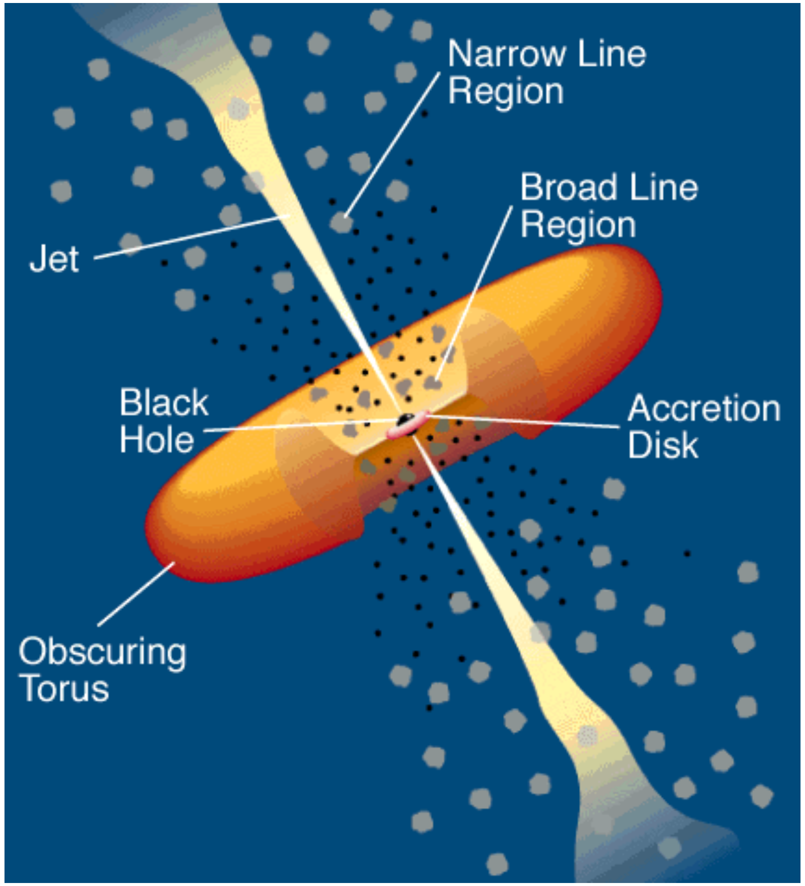
(Max Planck Institute for Physics)

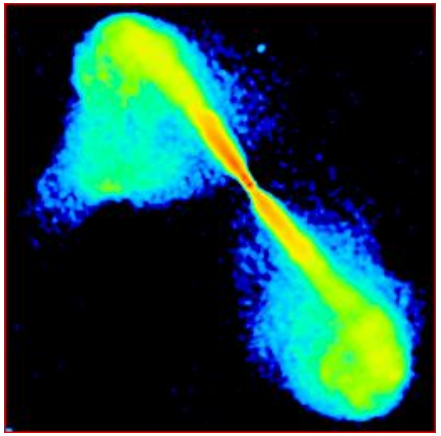
Ninth International Fermi Symposium (2021/04/14)

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 **<u>the largest structures in the Universe</u>**, 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 **<u>are direct probes of black hole physics</u>**.

Jets are **<u>extremely efficient accelerators of particles</u>** 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:

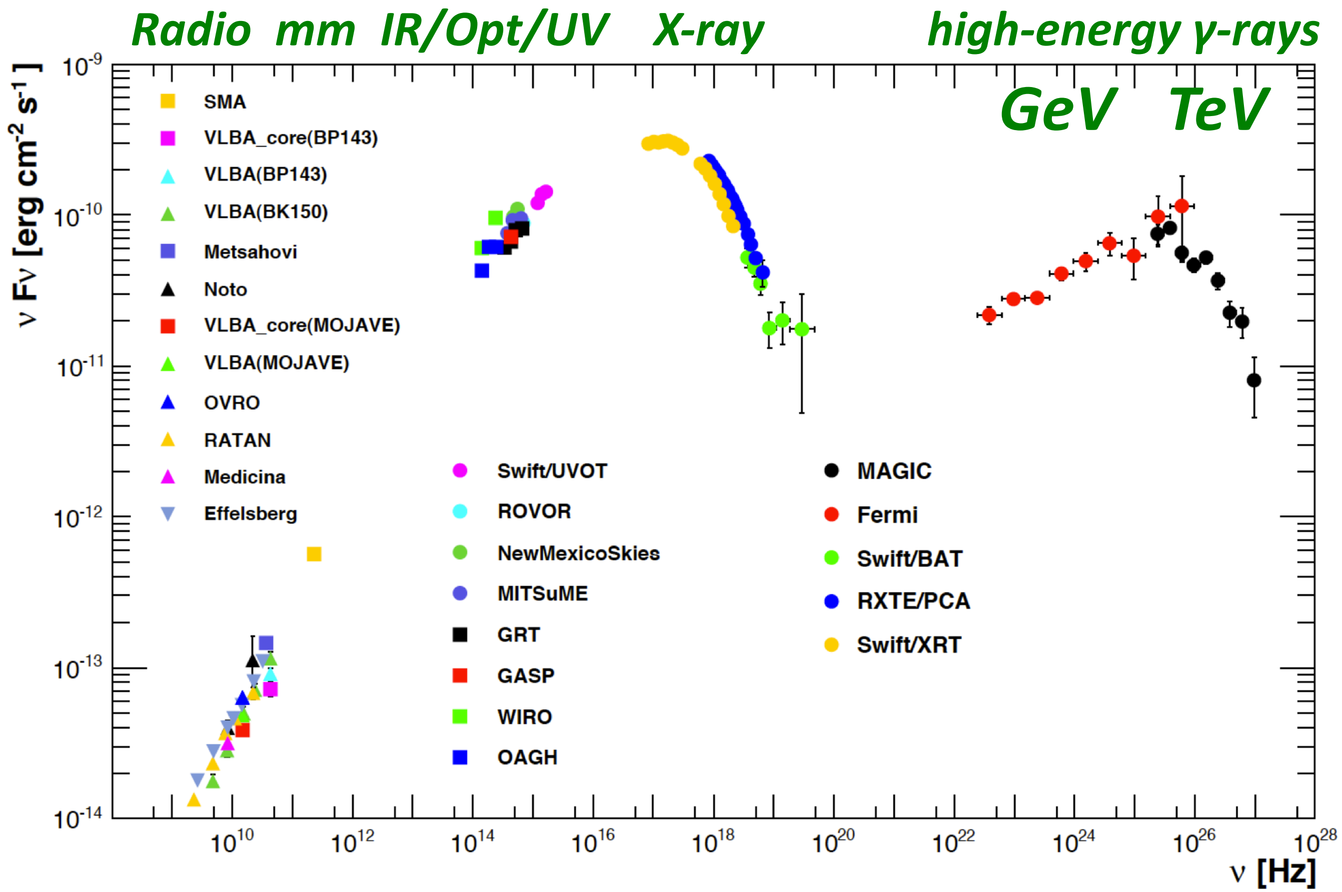
- Jet composition *(B and ultrarelativistic e-e+; something else?)*
- Jet magnetic field *(how strong? what is its structure?)*
- Jet launching *(rotating SMBHs vs accretion disks)*
- Jet evolution and energetics *(kinetic power, lifetimes, „feedback")*
- Particle acceleration *(shocks? turbulence? reconnection?)*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

Challenges when studying AGNs

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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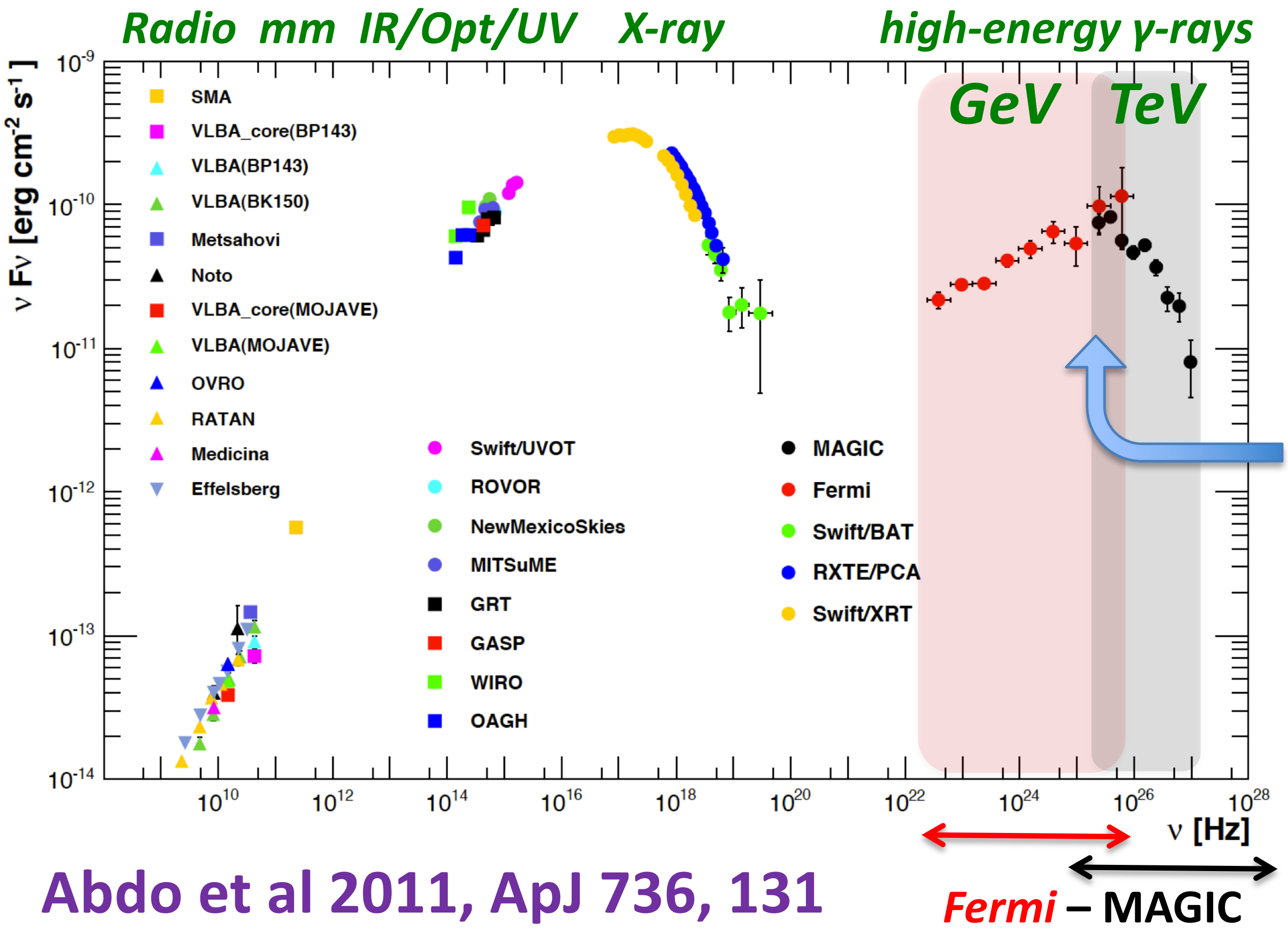


Spectral energy distribution (SED) of the Blazar Mrk 421

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

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

Abdo et al 2011, ApJ 736, 131

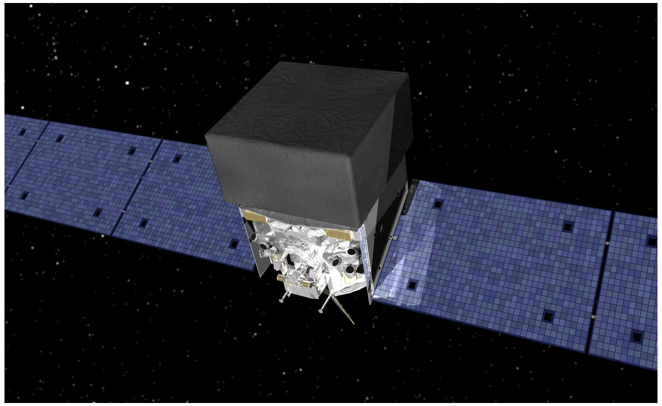
Instrumentation for gamma-ray astronomy

The last 10-15 years have seen large improvement in gamma-ray instrumentation

Pair production telescopes

e.g. EGRET, AGILE, *Fermi*

Direct detection of gamma



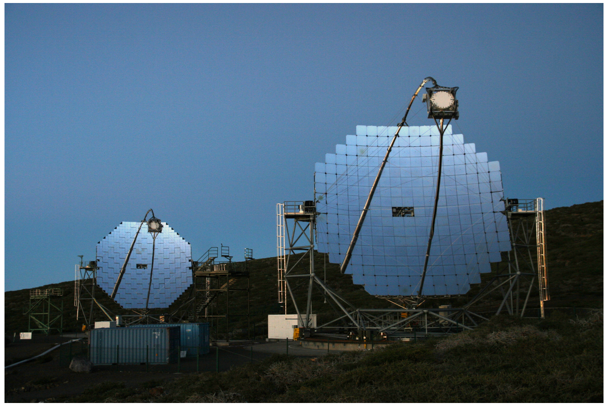
Space-based
Large duty cycle (~85%)
Large field of view (20-60 deg)
Excellent bkg rejection
Small effective areas (~m^2)
Energy range ~0.02 – 300 GeV

Good sensitivity

Imaging Atmospheric Cherenkov Telescopes (IACTs)

e.g.FACT, HESS, MAGIC, VERITAS

Indirect detection of gamma through Cherenkov Light



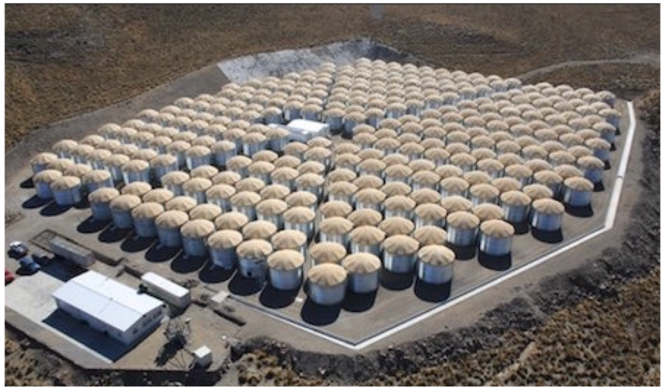
Ground-based
Low duty cycle (~10%)
Small FoV (2-4 deg)
Very Good bkg rejection
Large effective area (~10^5 m^2)
Energy ~50 GeV– 100 TeV

Excellent sensitivity

Extensive Air Shower (EAS) arrays

e.g. Milagro, HAWC, Tibet, ARGO

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 ~100 GeV– 100 TeV

Moderate sensitivity

Instrumentation for gamma-ray astronomy

The last 10-15 years have seen large improvement in gamma-ray instrumentation

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

Direct detection of gamma

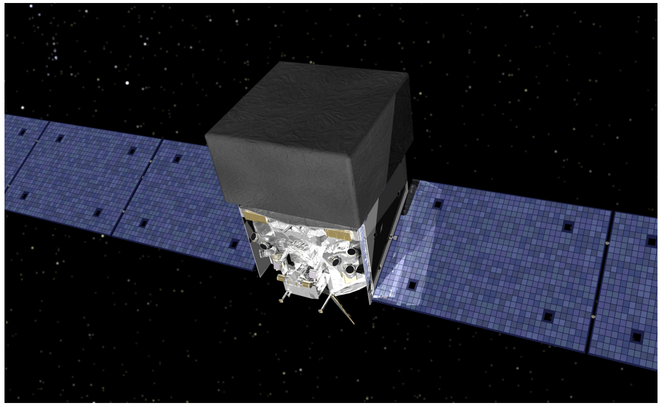
Imaging Atmospheric Cherenkov Telescopes (IACTs)
e.g.FACT, HESS, MAGIC, VERITAS

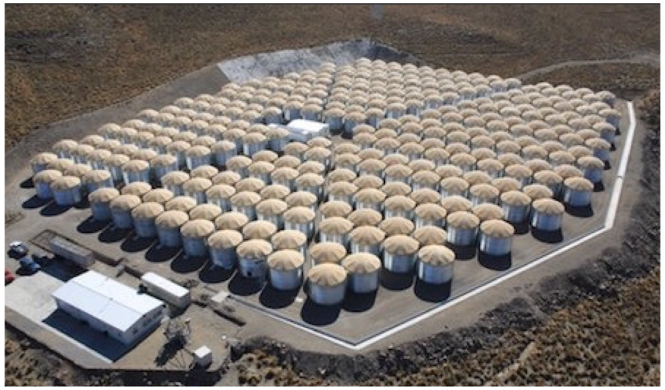
+ CTA-North

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

+ LHAASO

Already coming online …



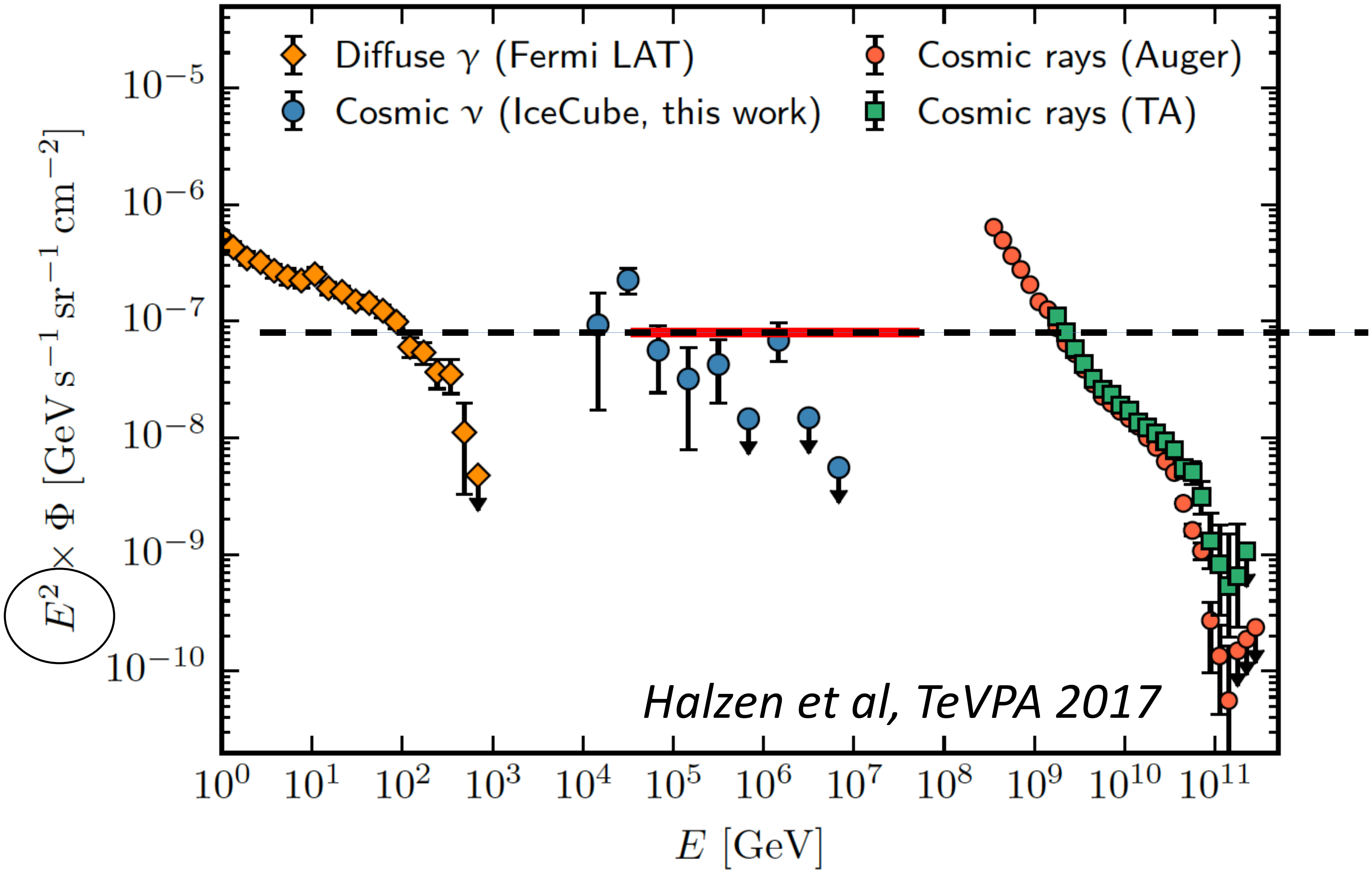


Space-based	**Ground-based**	**Ground-based**
Large duty cycle (~85%)	Low duty cycle (~10%)	Large duty cycle (~90%)
Large field of view (20-60 deg)	Small FoV (2-4 deg)	Big FoV (30-40 deg)

Complementary characteristics

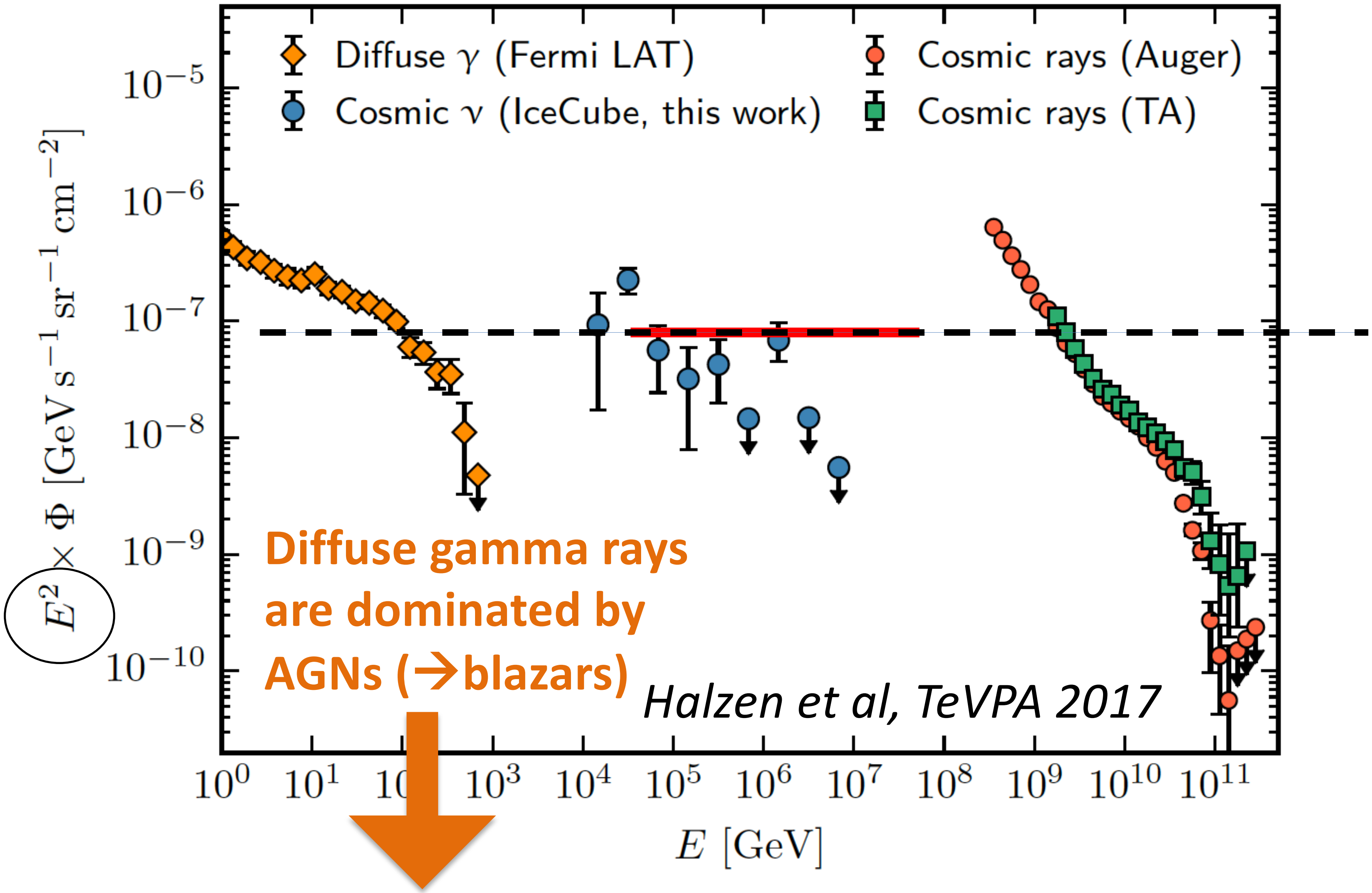
Energy range ~0.02 – 300 GeV	**Energy ~50 GeV– 100 TeV**	**Energy ~100 GeV– 100 TeV**
Good sensitivity	**Excellent sensitivity**	**Moderate sensitivity**

Energy in the Universe in gamma rays, neutrinos, and Cosmic Rays



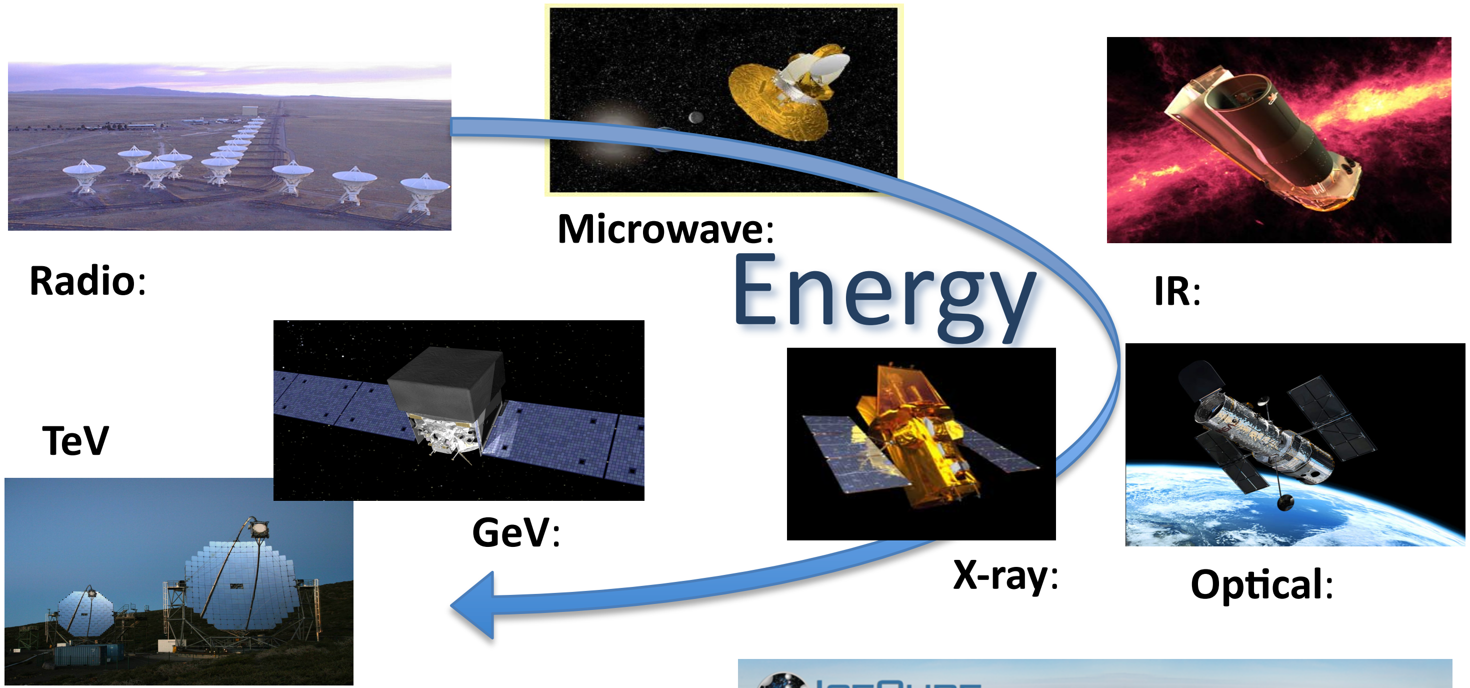
Energy in the Universe in

gamma rays, neutrinos, and Cosmic Rays



Sensible to consider that AGNs may produce UHECRs & HE-neutrinos

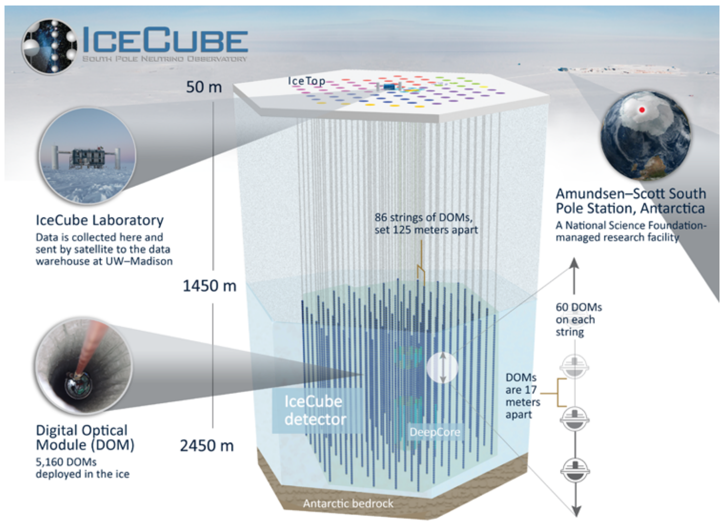
Multi-messenger astronomy helpful to break degeneracies



Electromagntic emission (from radio to VHE gamma rays)

TXS 0506+056
IceCube Collab. et al., Science 361, 146 (2018)

Trajectory deflections preclude usage for individual sources

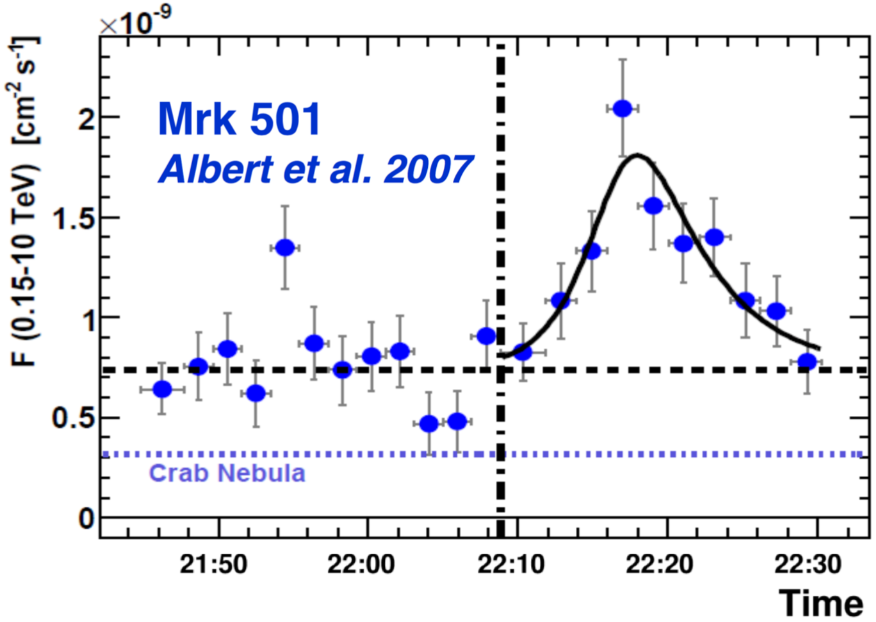


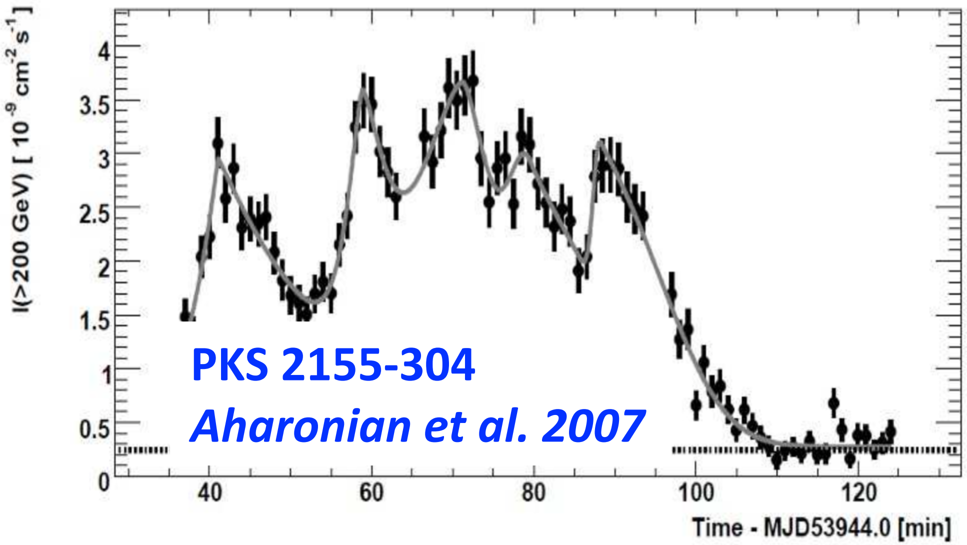
See also other possible neutrino-gamma relations in *Parallel-7* after 18:15 CET
(Wood, Garrappa, Jin, Oikonomou, and Negro)

High-Energy Cosmic Rays (e.g. Pierre Auger and Telescope Array)

High-Energy Neutrinos (e.g. IceCube)

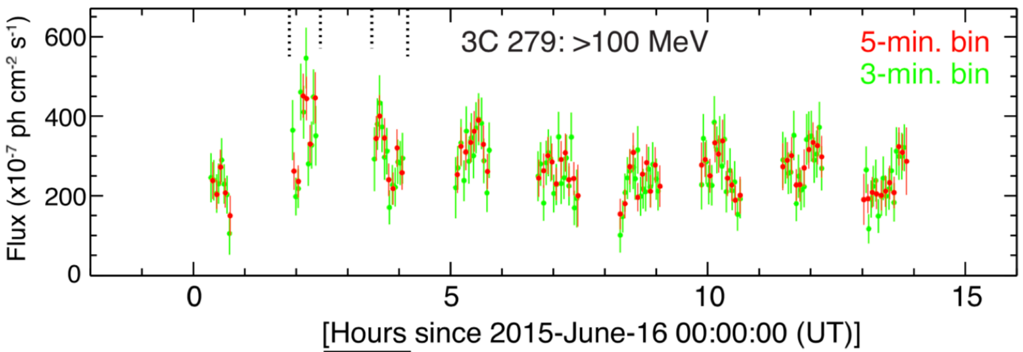
AGNs show SHORT variability timescales

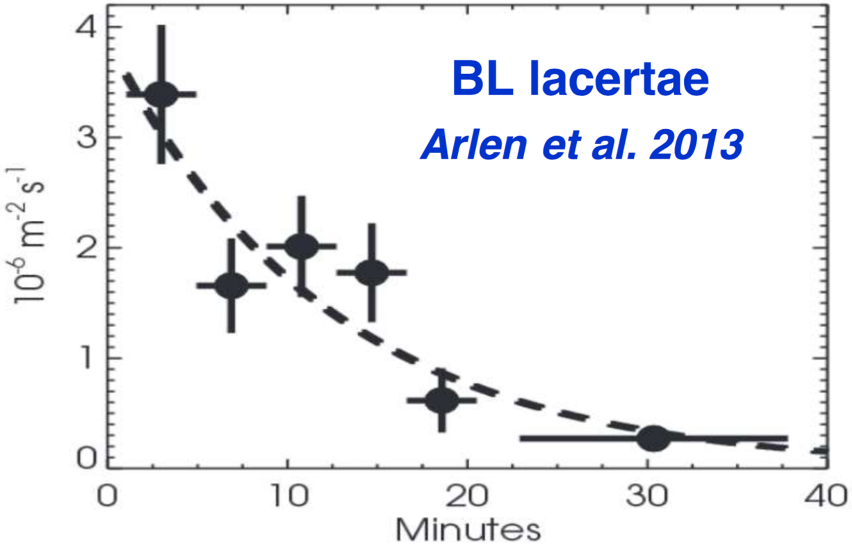




3C279

Ackermann et al 2016

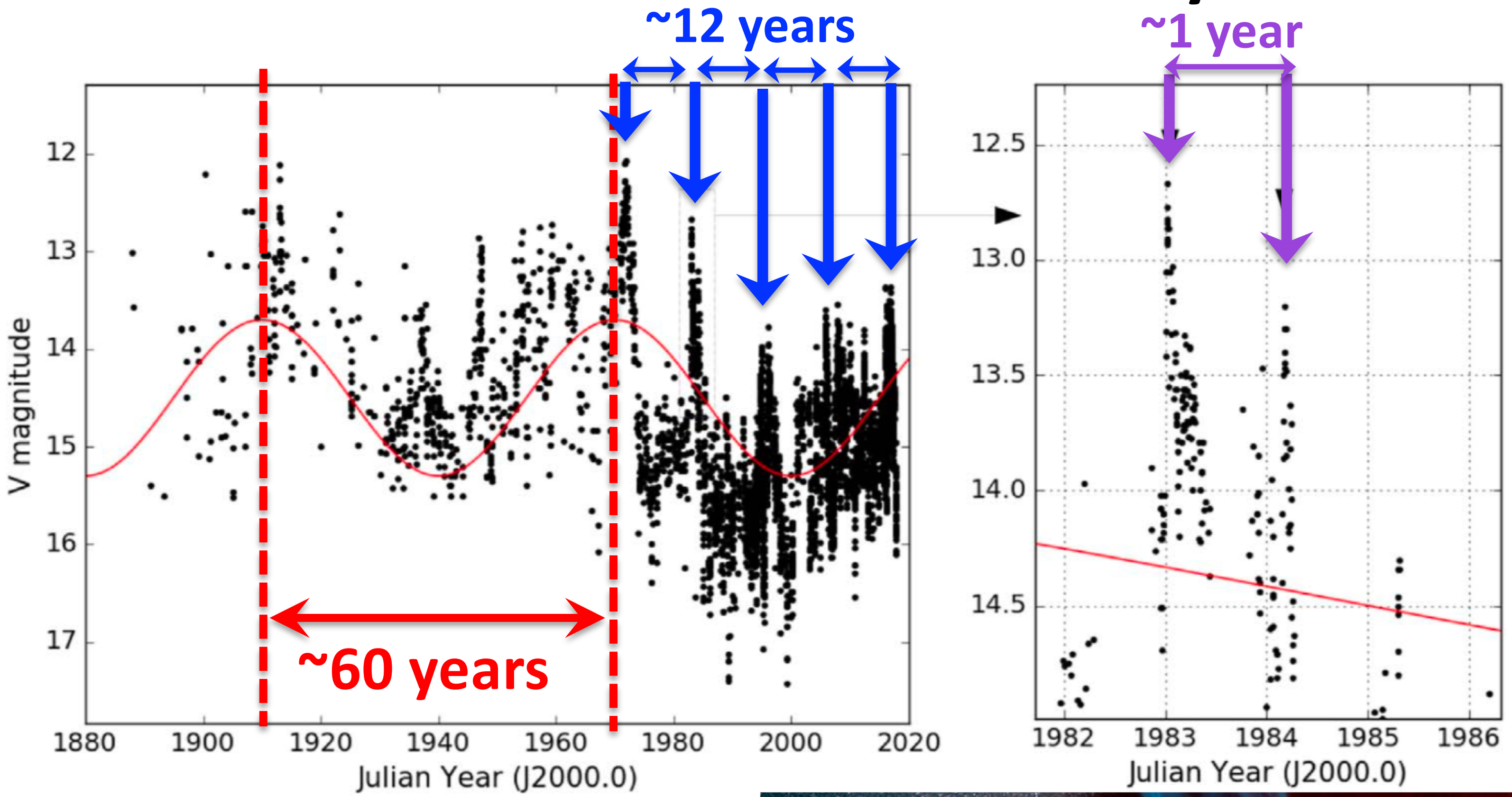




Sub-hour flux variations bring crucial information to study the accelerating & cooling, the size of region and their environments

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

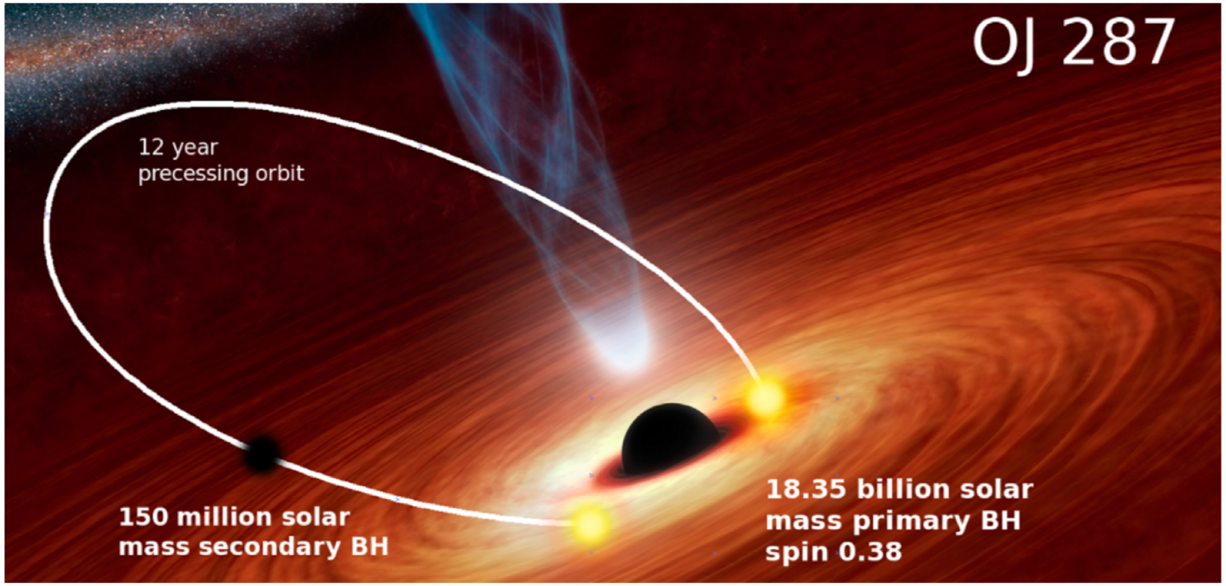
AGNs show LONG variability timescales



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



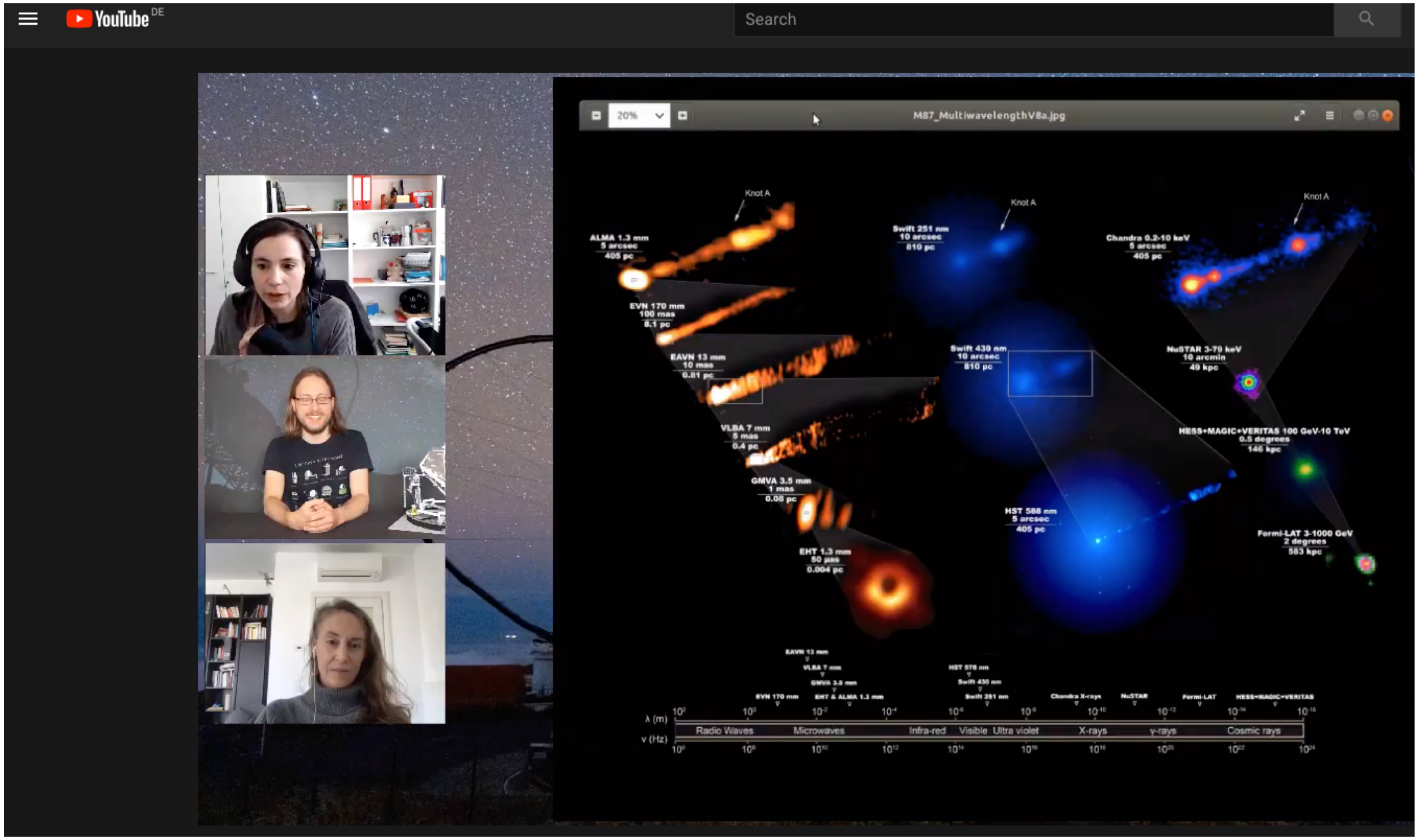
Apparent morphology of AGNs "differs with energy"

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*

e.g., see latest paper on M87 with EHT: Algaba et al 2021, ApJL 911 L11

+ beautiful video by EHT on youtube → **https://www.youtube.com/watch?v=q2u4eK-ph40**



And fun&nice youtube live event on April 14th at 11:00 CET

https://www.youtube.com/watch?v=7zo1XSa0MCc

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^{16}*)

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 *micro-parsecs* to *mega-parsecs* → *dynamic range> 10^{9}*)

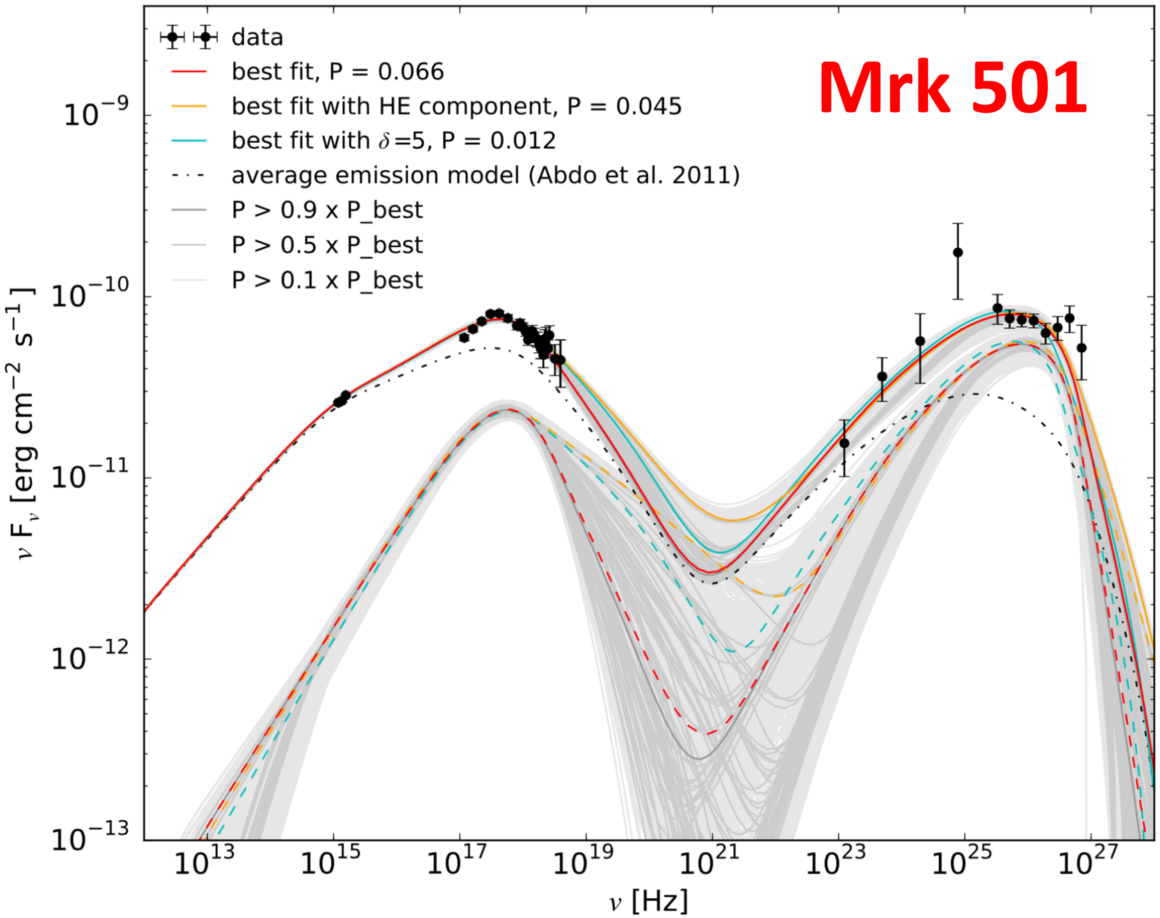
And variability and spatial extension are energy dependent, as well as our instrumental ability to characterize these properties

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

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

Large intra-model degeneracy for broadband SEDs

Broadband emission (*solid lines*) described with a "quiescent" region (*black dot-dashed line*) responsible for the average state reported in Abdo et al. 2011 (*ApJ 727, 129*), plus a **second emission region (*dashed lines*) modelled with grid-scan strategy using 10^8 realizations.**



Ahnen et al 2017
***A&A* 603 , A31**

The SED plot shows in different shades of grey all model curves (1684) with a data-model agreement better than 10% of that of the best model.

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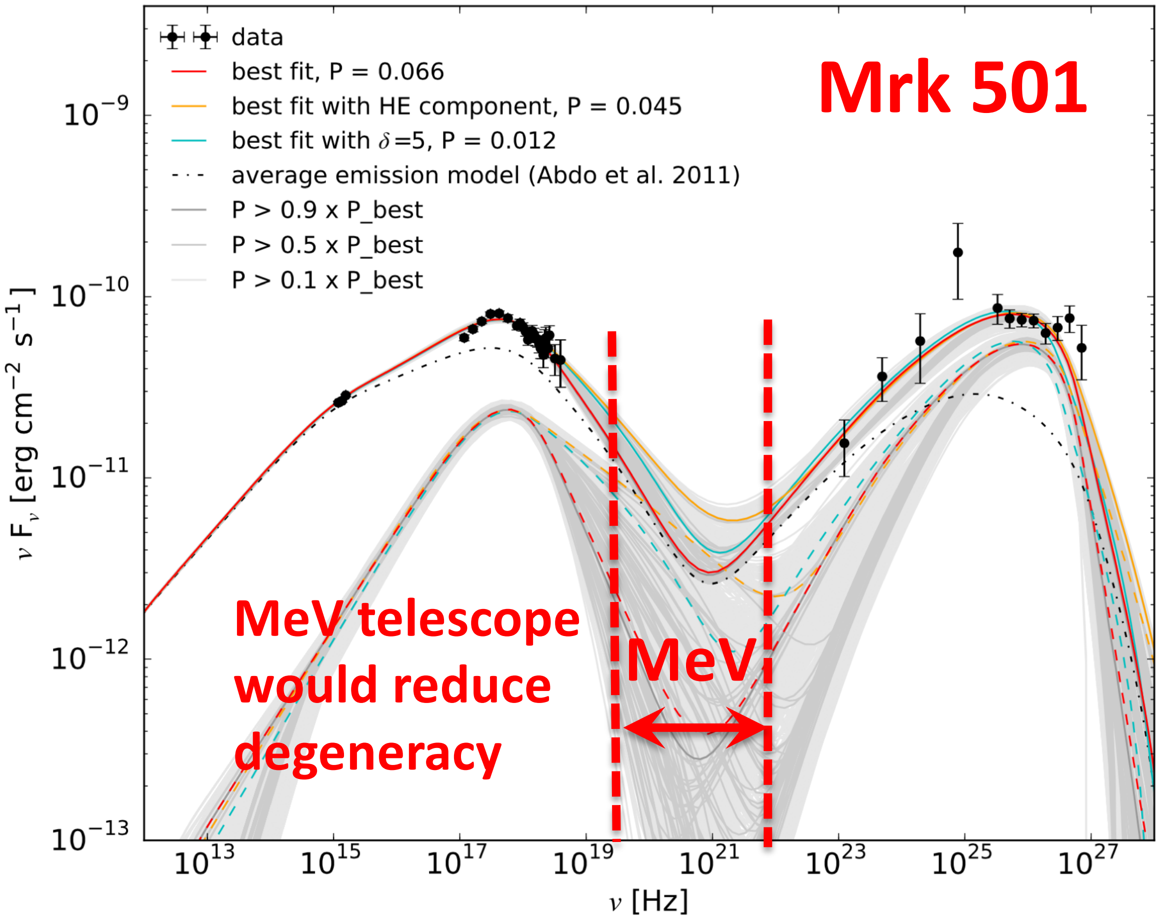

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Large inter-model degeneracy for broadband SEDs

Leptonic scenario
→ need electrons with $E>10^{13}$ eV

Hadronic scenario
→ need protons with $E>10^{18}$ eV

Abdo et al., ApJ 736 (2011) 131

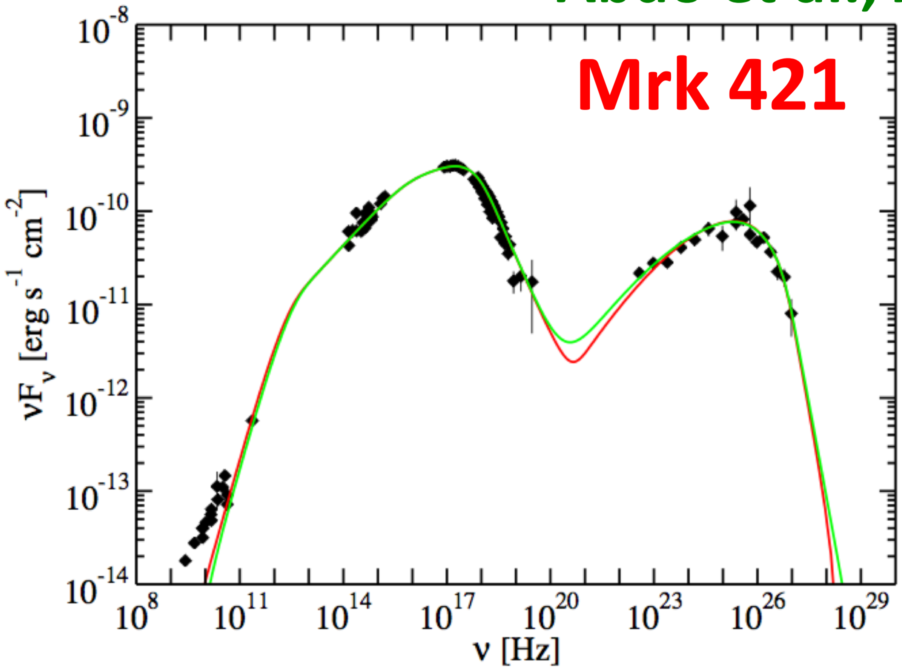

Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{\rm var} = 1$ day (red curve) and $t_{\rm var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

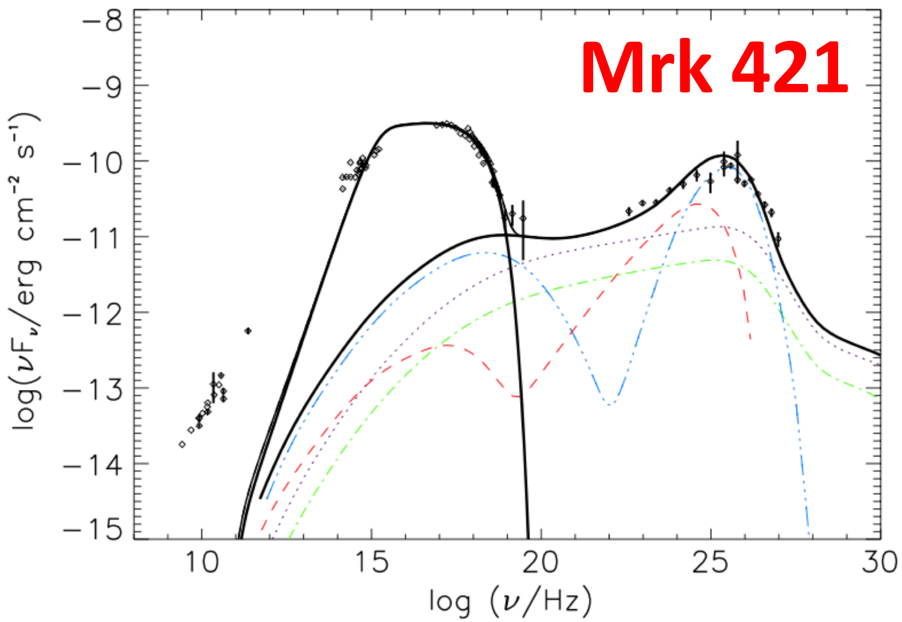

Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which also includes the synchrotron emission of the primary electrons at optical/X-ray frequencies). The resulting model parameters are reported in Table 3.

See later talk from Anita Reimer for details on theoretical models of multi-instrument data from AGNs

Large inter-model degeneracy for broadband SEDs

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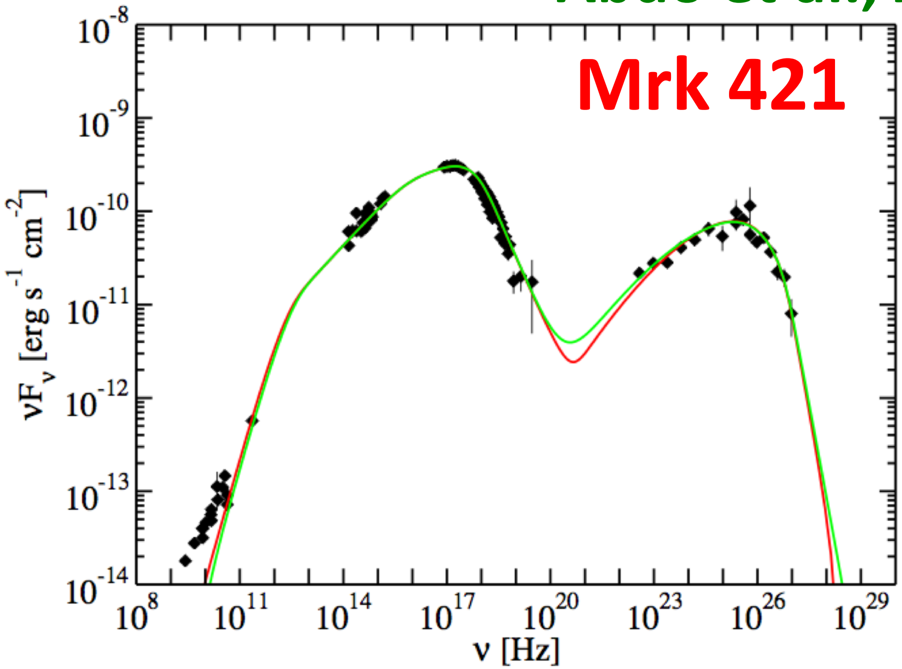
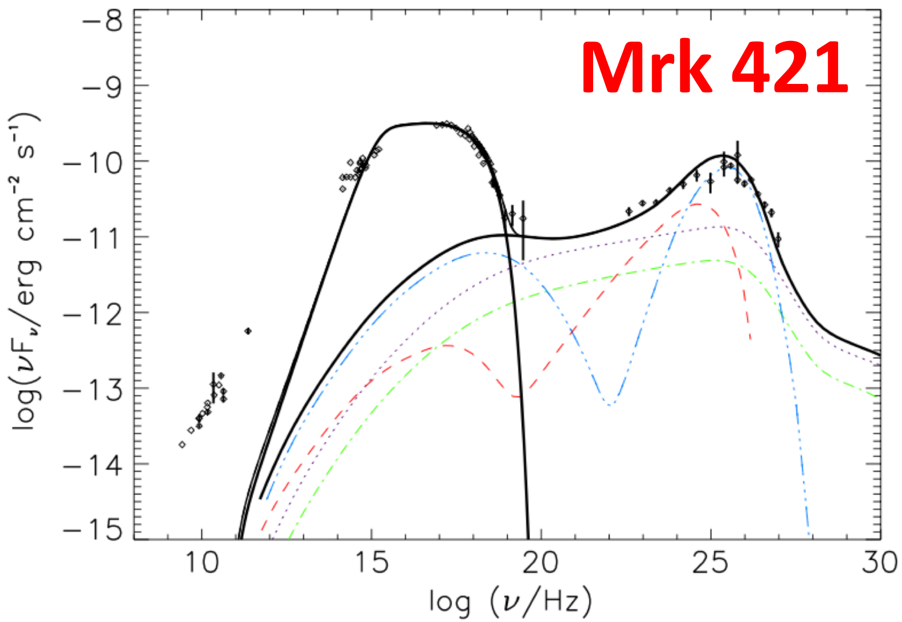


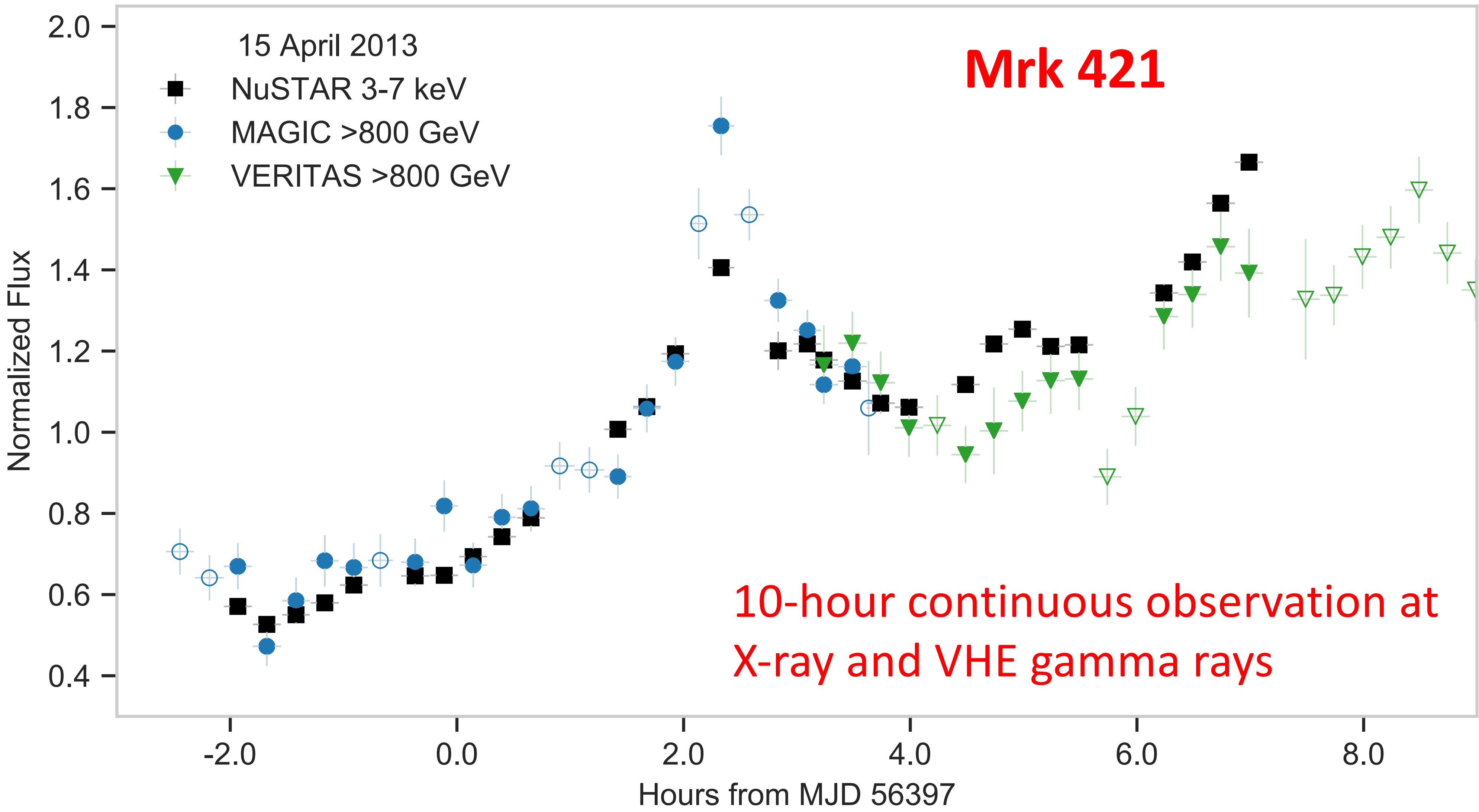


Multi-band variability is key to distinguish between models

But quantifying variability and correlations among enerby bands (*e.g. VHE vs X-rays*) is not a simple task either… even for extensive observations of bright sources like Mrk421.

Normalized light curves for single night (2013 April 15)

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

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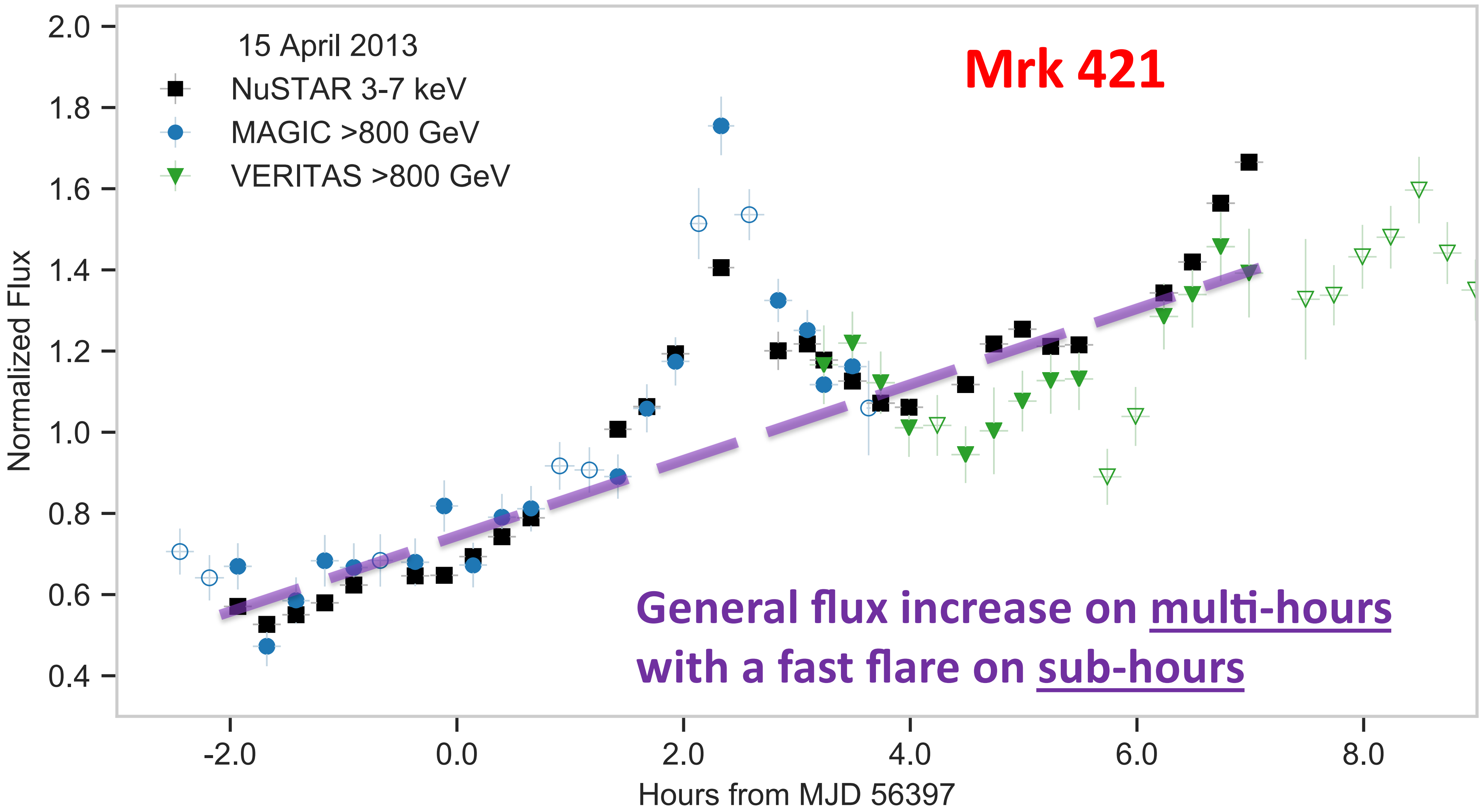
Acciari et al. ApJS 2020, 248, 29



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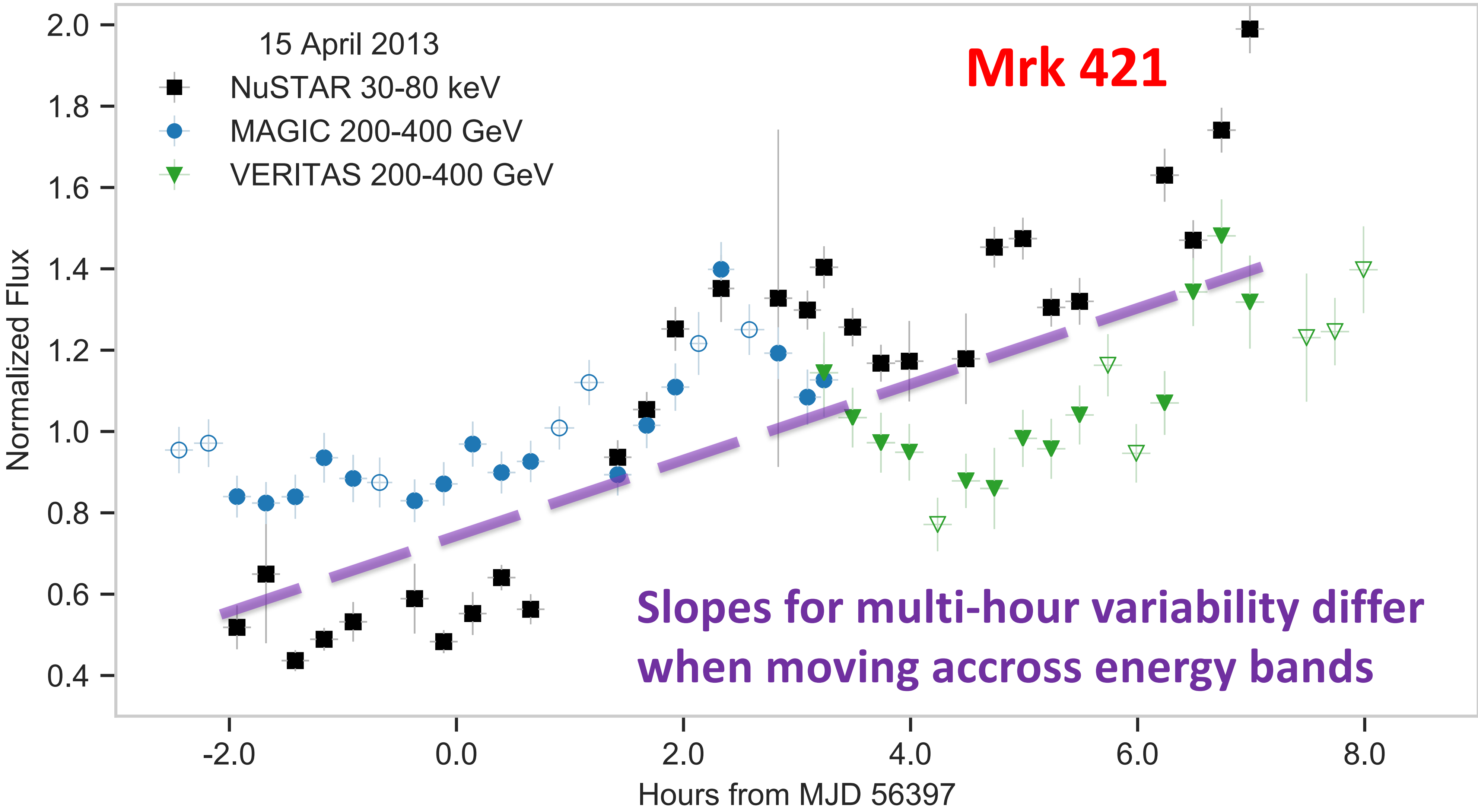

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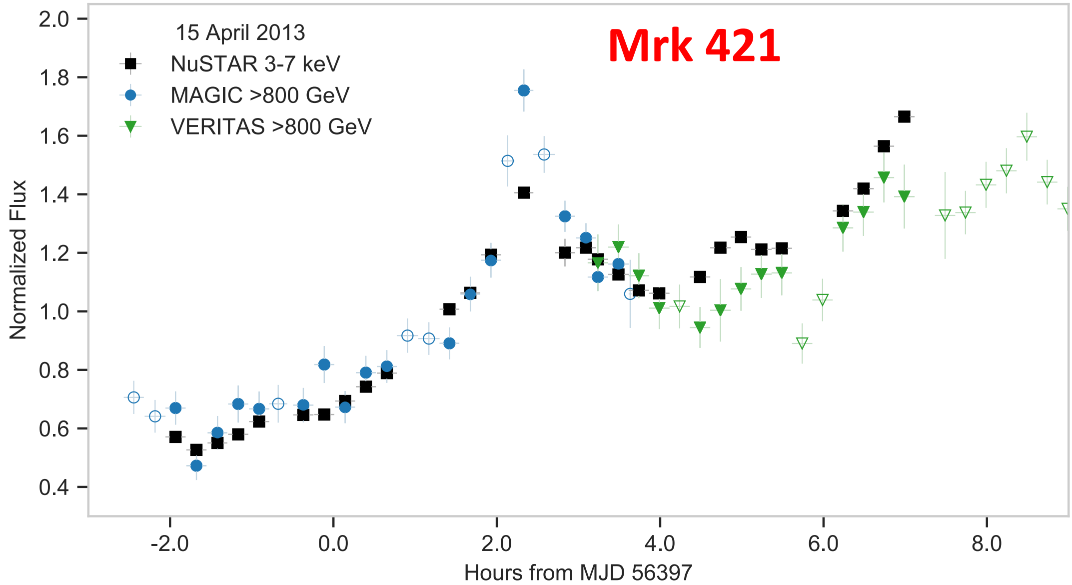
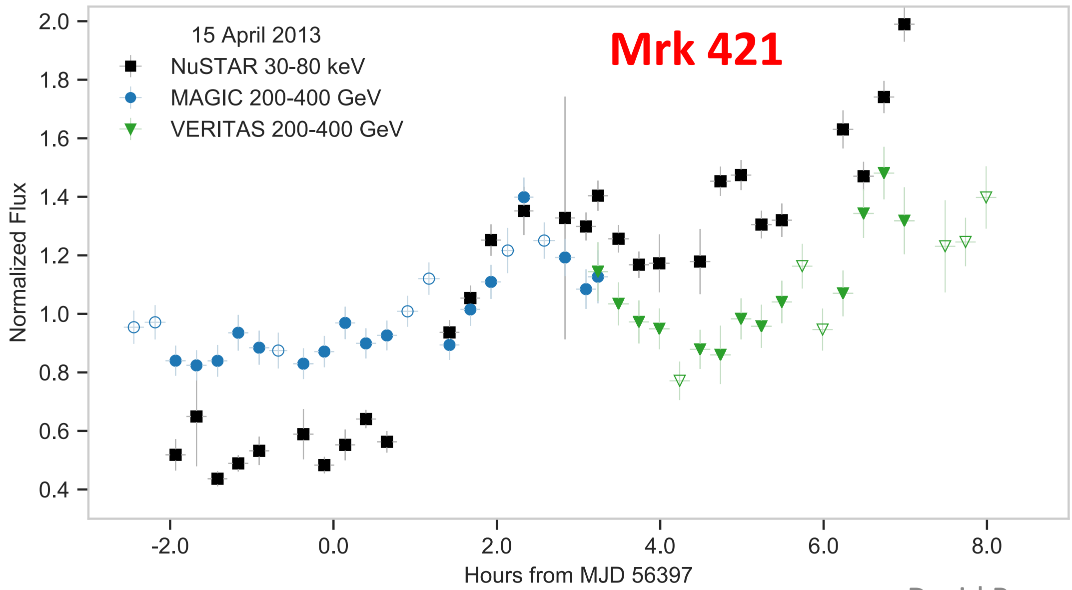


MAGIC + VERITAS >0.8 TeV
NuSTAR 3-7 keV

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

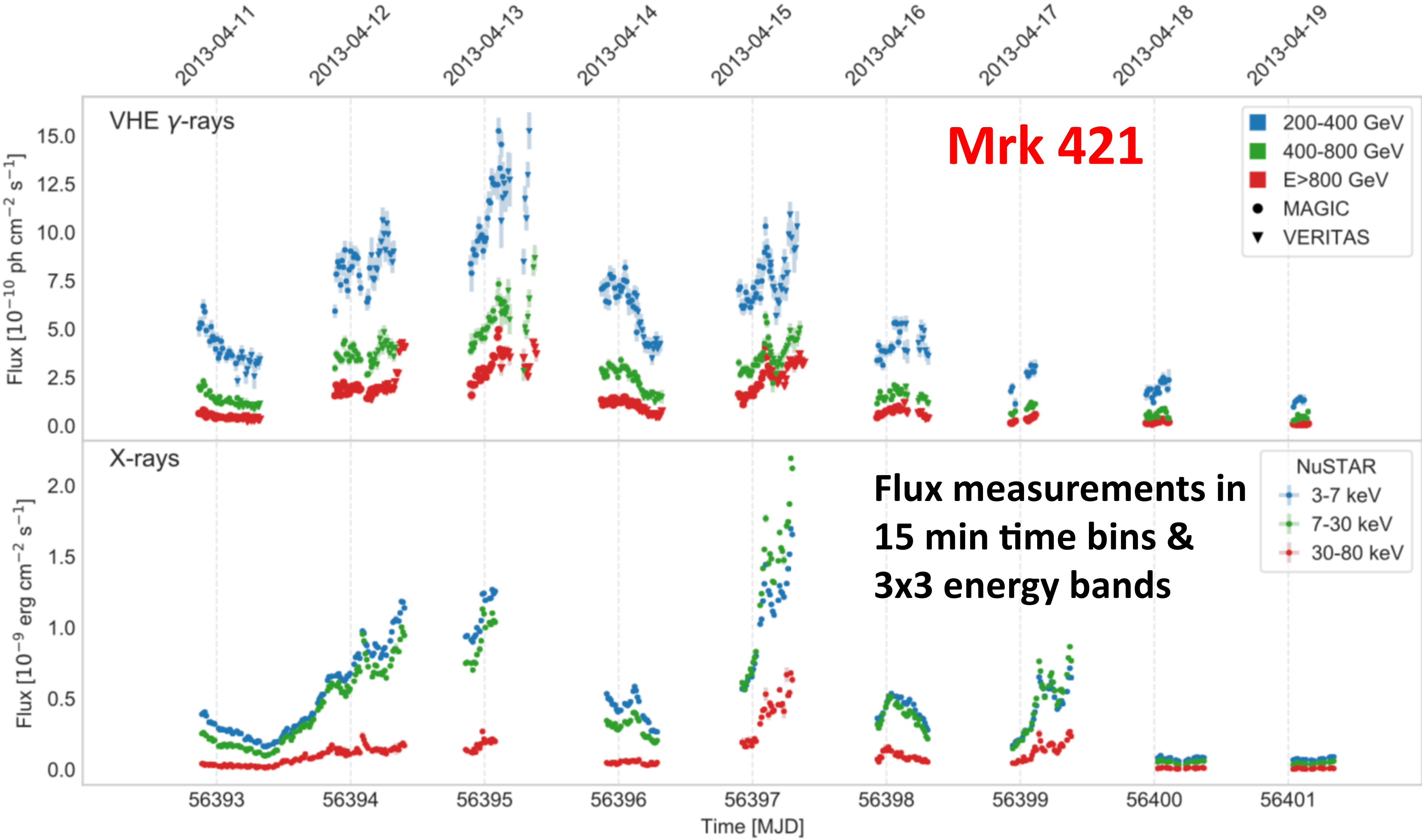


MAGIC + VERITAS 0.2-0.4 TeV
NuSTAR 30-80 keV

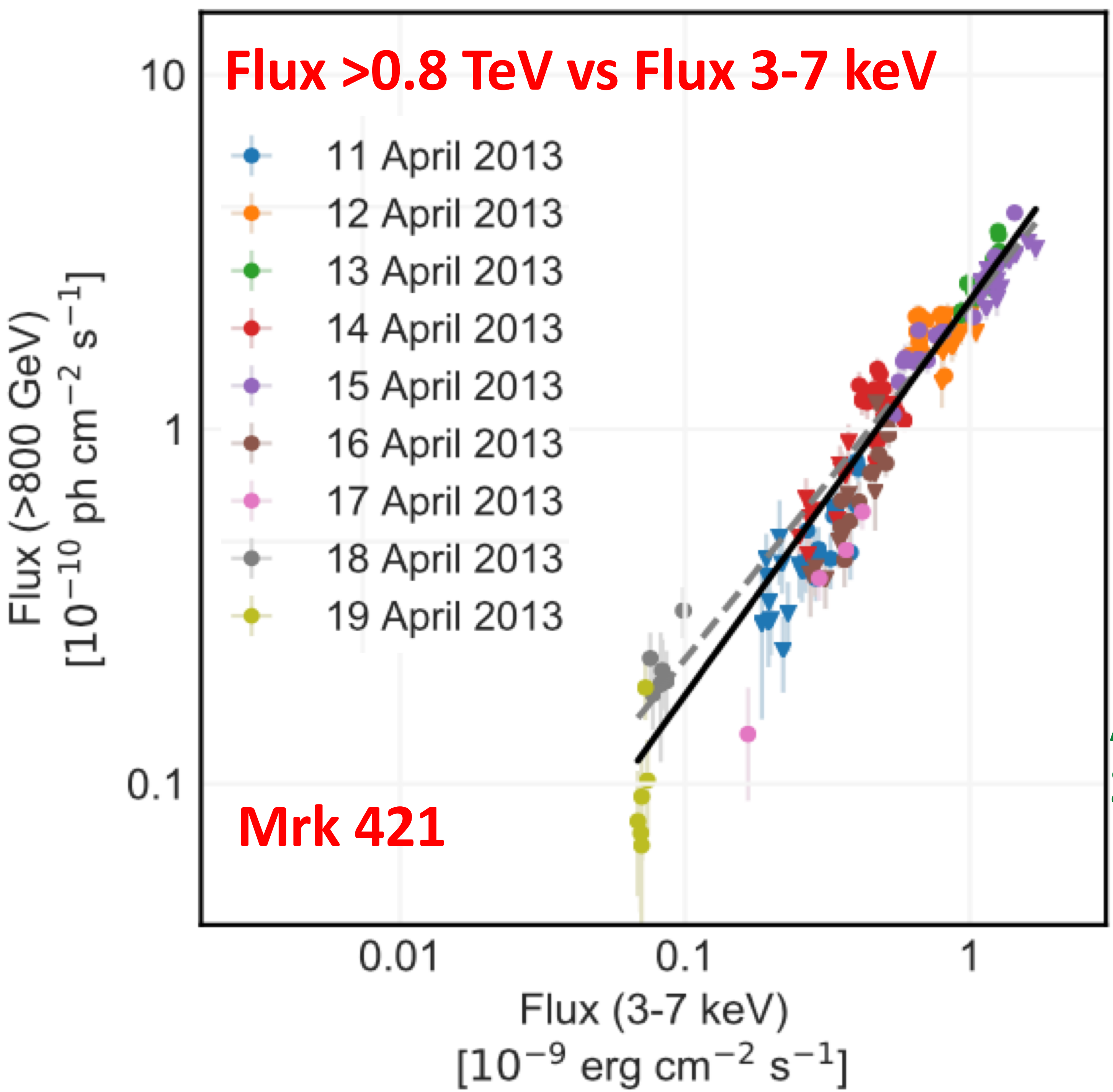
Full VHE and X-ray LCs for Mrk421 activity 2013 April

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

Acciari et al. ApJS 2020, 248, 29



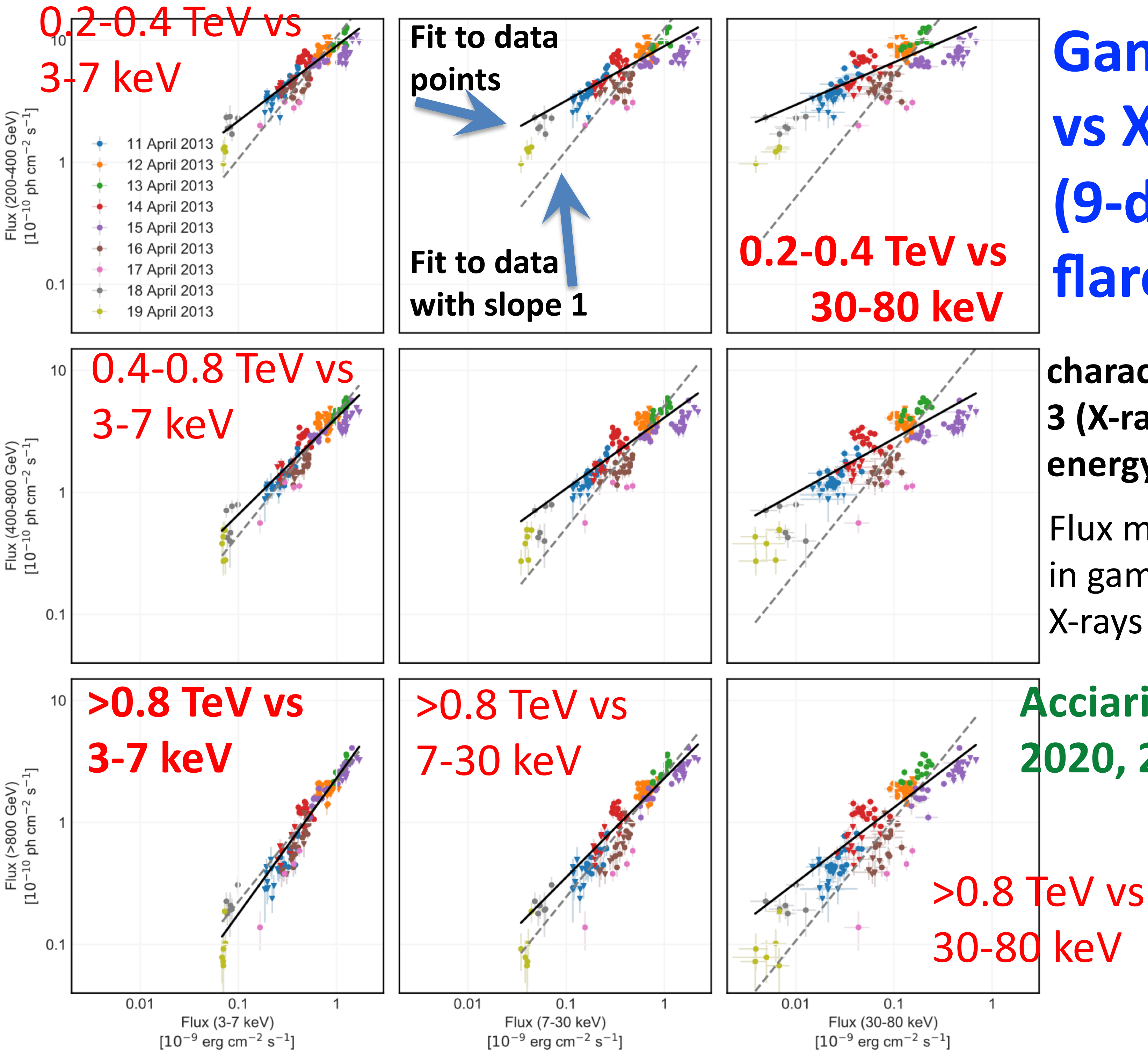
Flux measurements in 15 min time bins & 3x3 energy bands



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

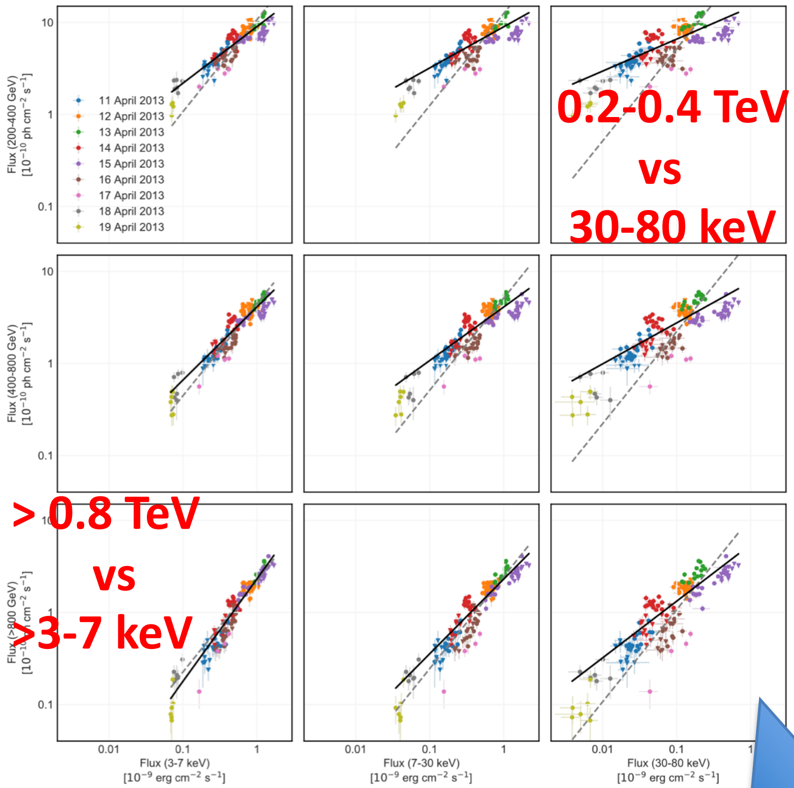


Gamma-ray vs X-ray flux (9-day “full” flare)

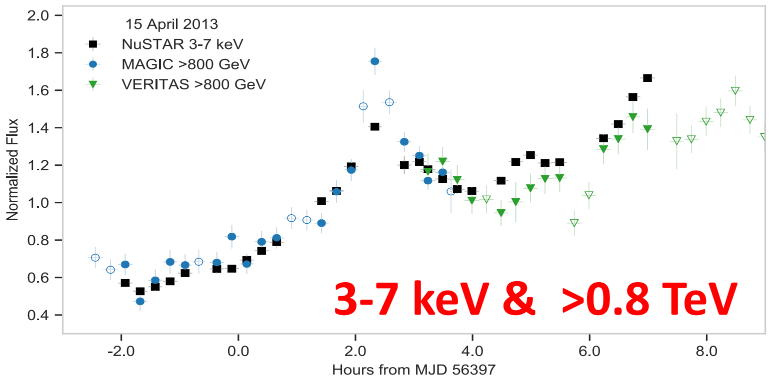
characterization in 3 (X-ray) x 3 (gamma) energy bands

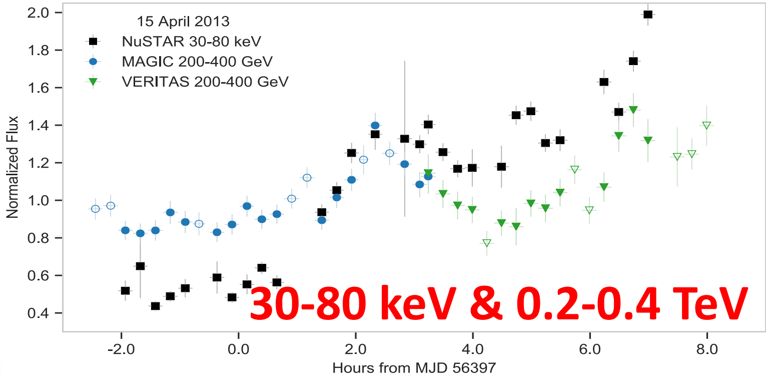
Flux measurements in gamma rays and X-rays @ 15min

Acciari et al. ApJS 2020, 248, 29



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





There is not such thing as a generic X-ray vs VHE correlation in a given AGN, it can have a strong energy dependence

The variability in a given energy band, and its relation with the other bands, can strongly depend on the probed timescale (sub-hours, hours, days, months)

Dynamics in AGN broadband emission is very complex

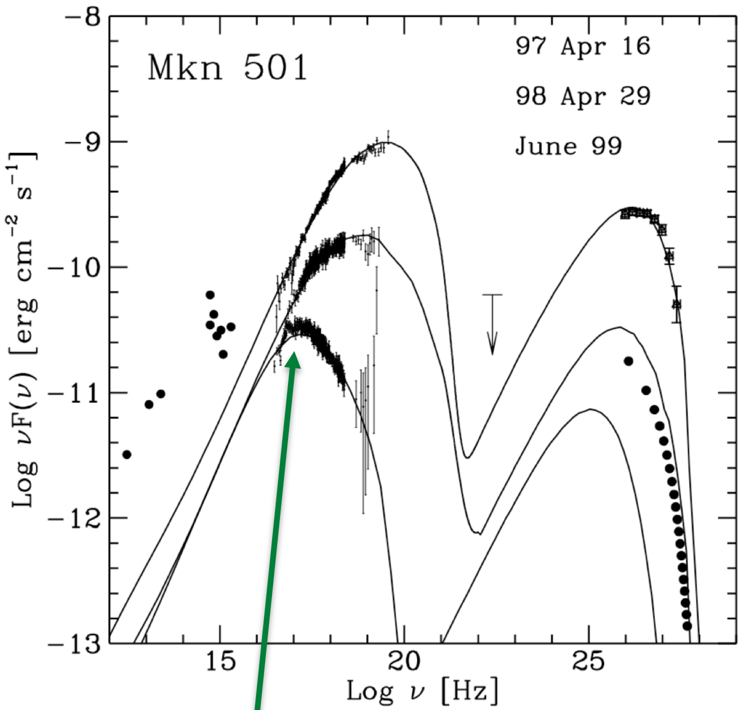
→ Important to cover many energy bands and timescales

Besides all the observational and theoretical (modeling) challenges mentioned before, we have the additional difficulty that, <u>occasionally</u>, AGNs show peculiar (rare) behaviours

<u>Typically:</u> Mrk501 shows X-ray & VHE spectral hardening during flares

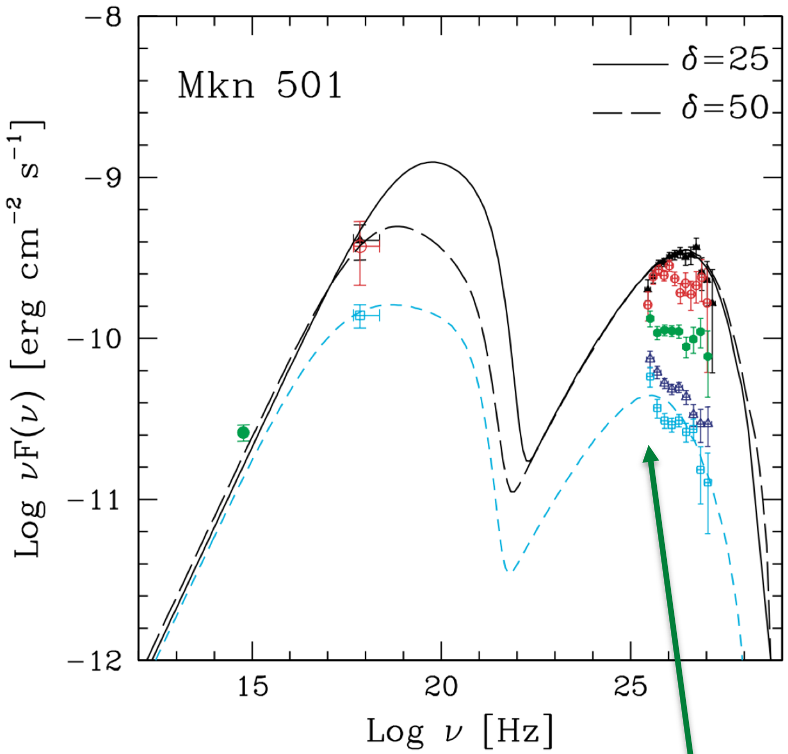
(Historical) flare in 1997

Tavecchio et al., 2001, ApJ 554,725



(fast variability) flare in 2005

Albert et al., 2007, ApJ 669,862



Hard spectra in Mrk501 <u>not observed</u> during low states,

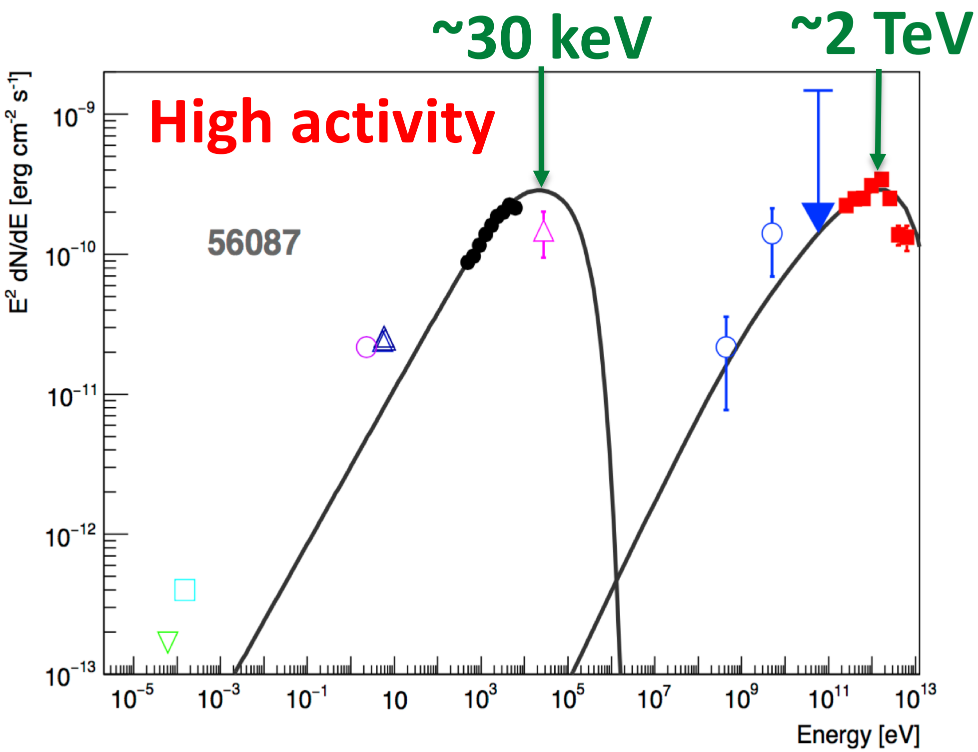
< 1 keV

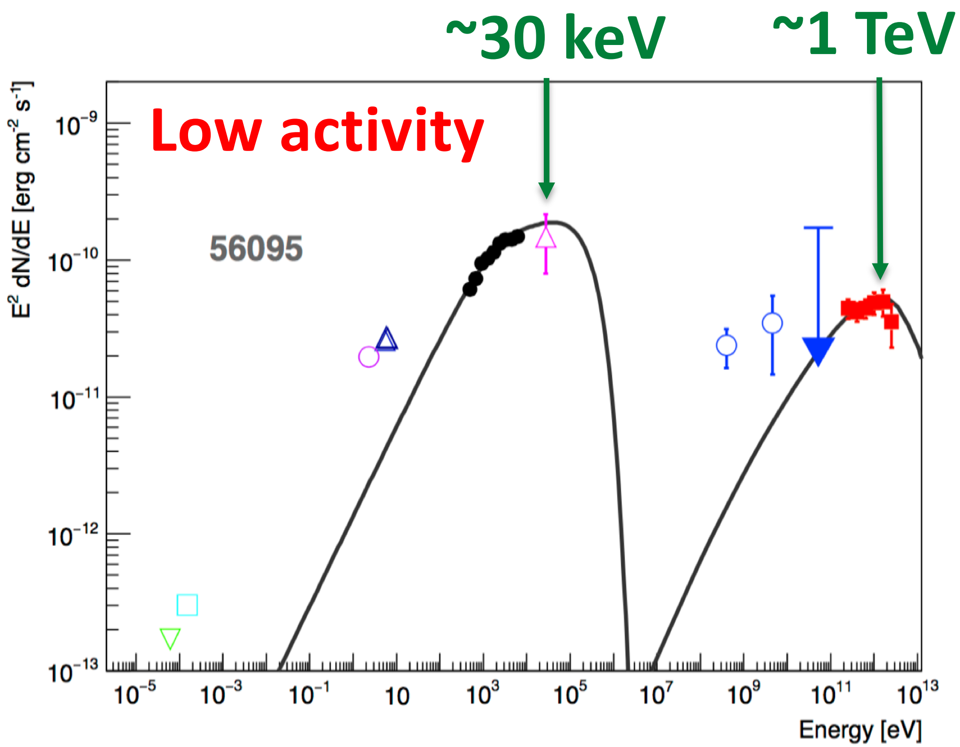
This is the typical behaviour of Mrk501, what we have seen in 20+ years of observations

< 0.1 TeV

But… in year 2012, Mrk501 suffered a personality crisis

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during entire observing campaign in 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

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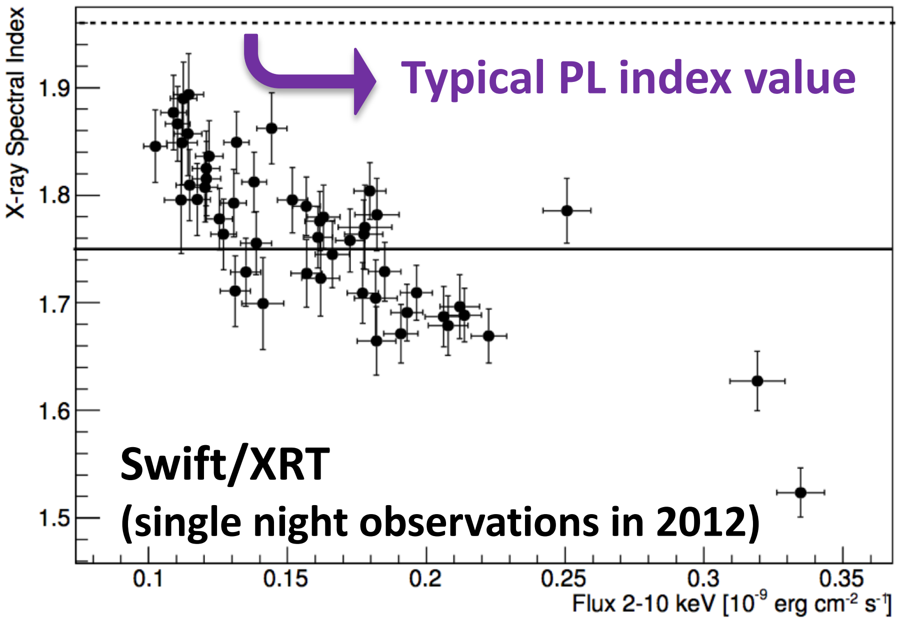
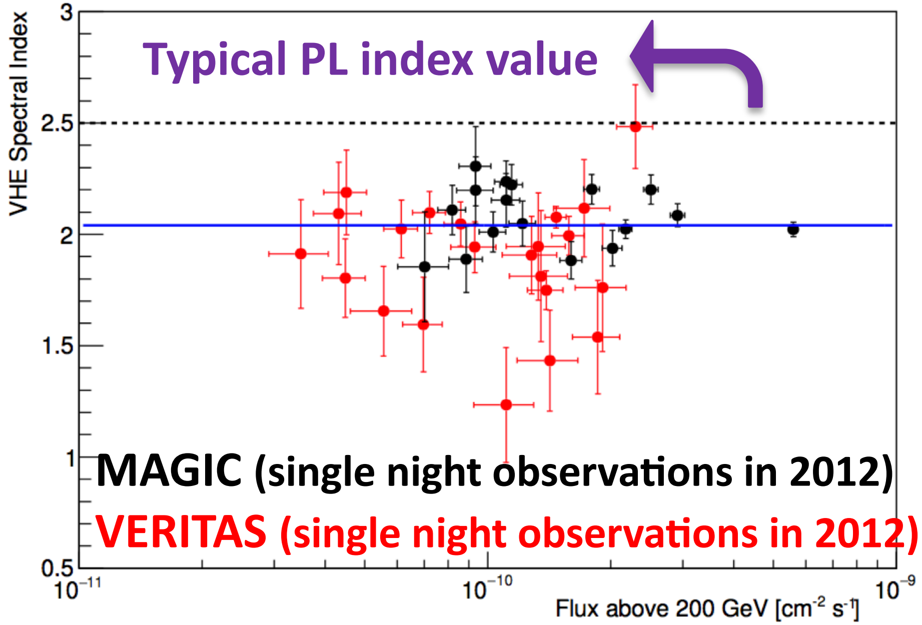




→ **Mrk 501 behaved as Extreme HBL!**

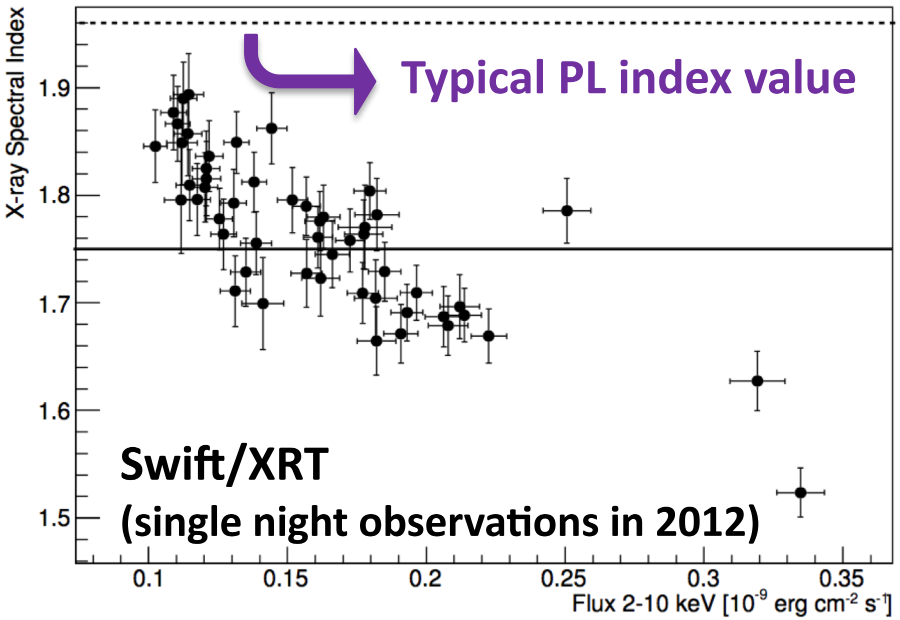
Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)

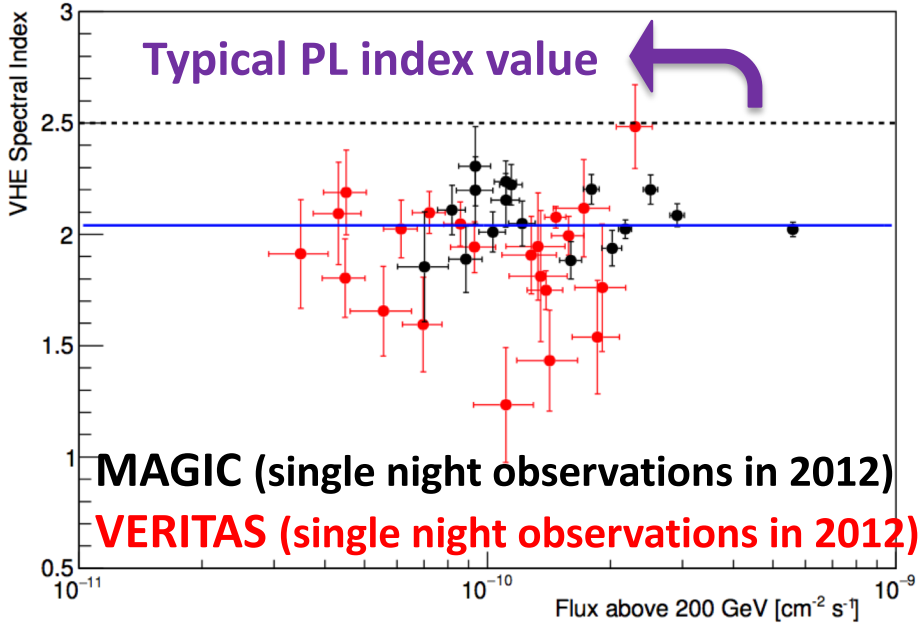
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

But… in year 2012, Mrk501 suffered a personality crisis

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

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



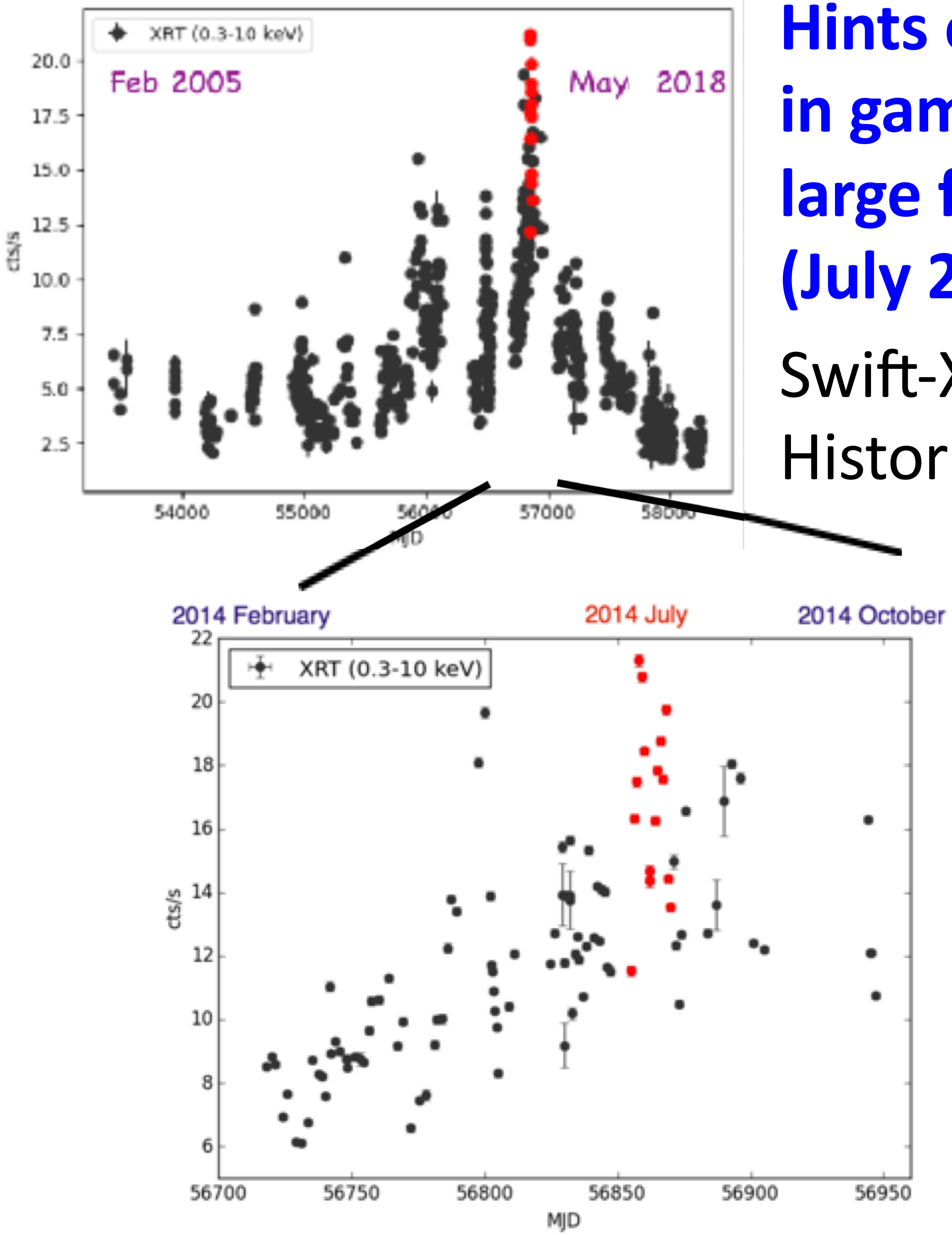


Mrk501_F^{TeV} > ~10 x 1ES0229_F^{TeV}

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

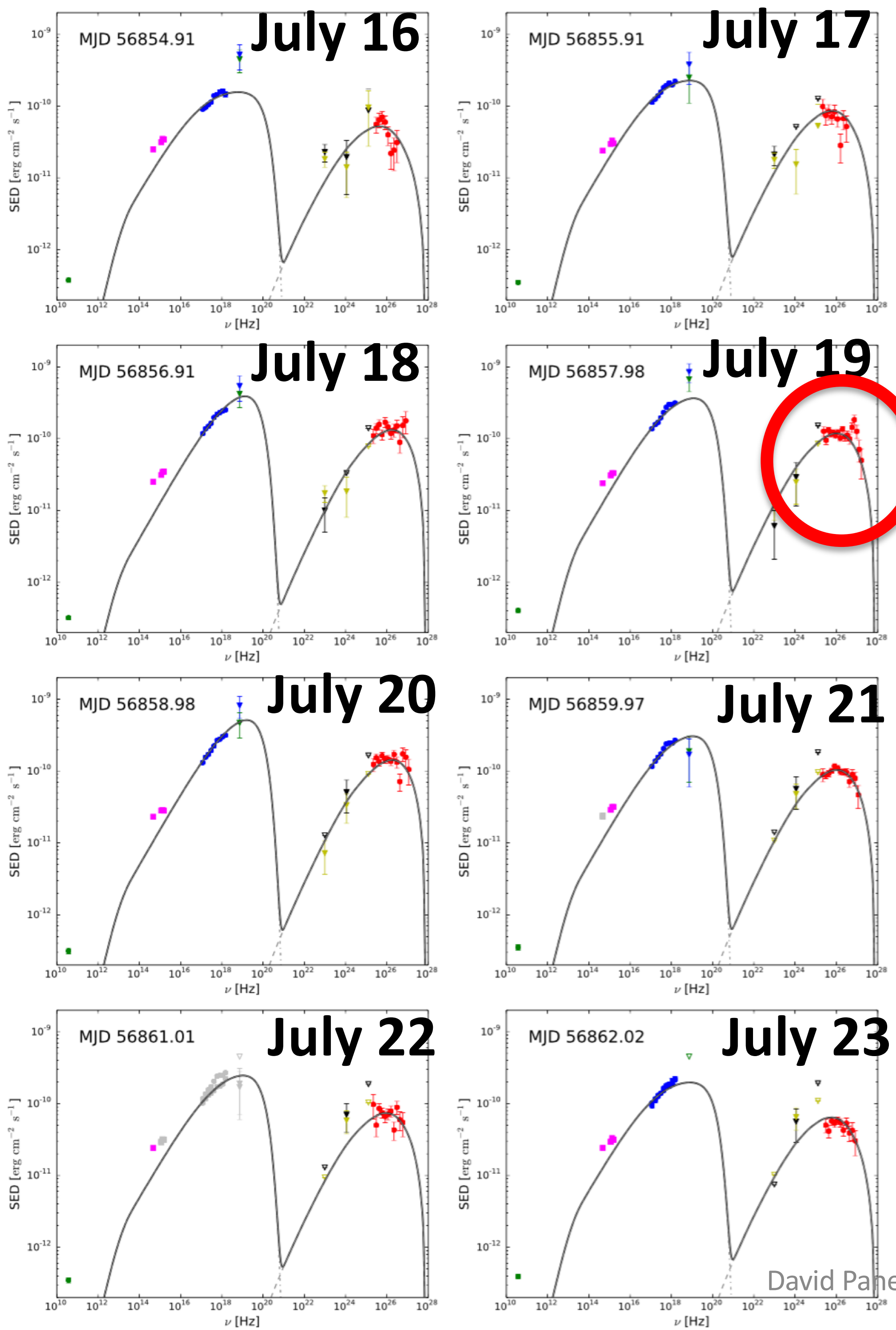


Hints of narrow spectral feature in gamma-ray spectrum during large flaring activity in Mrk501 (July 2014)

Swift-XRT

Historical light curve in ~**14 years**

Largest X-ray activity occurred in July 2014



Acciari et al
A&A 2020, 637, 86

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 ?

David Paneque

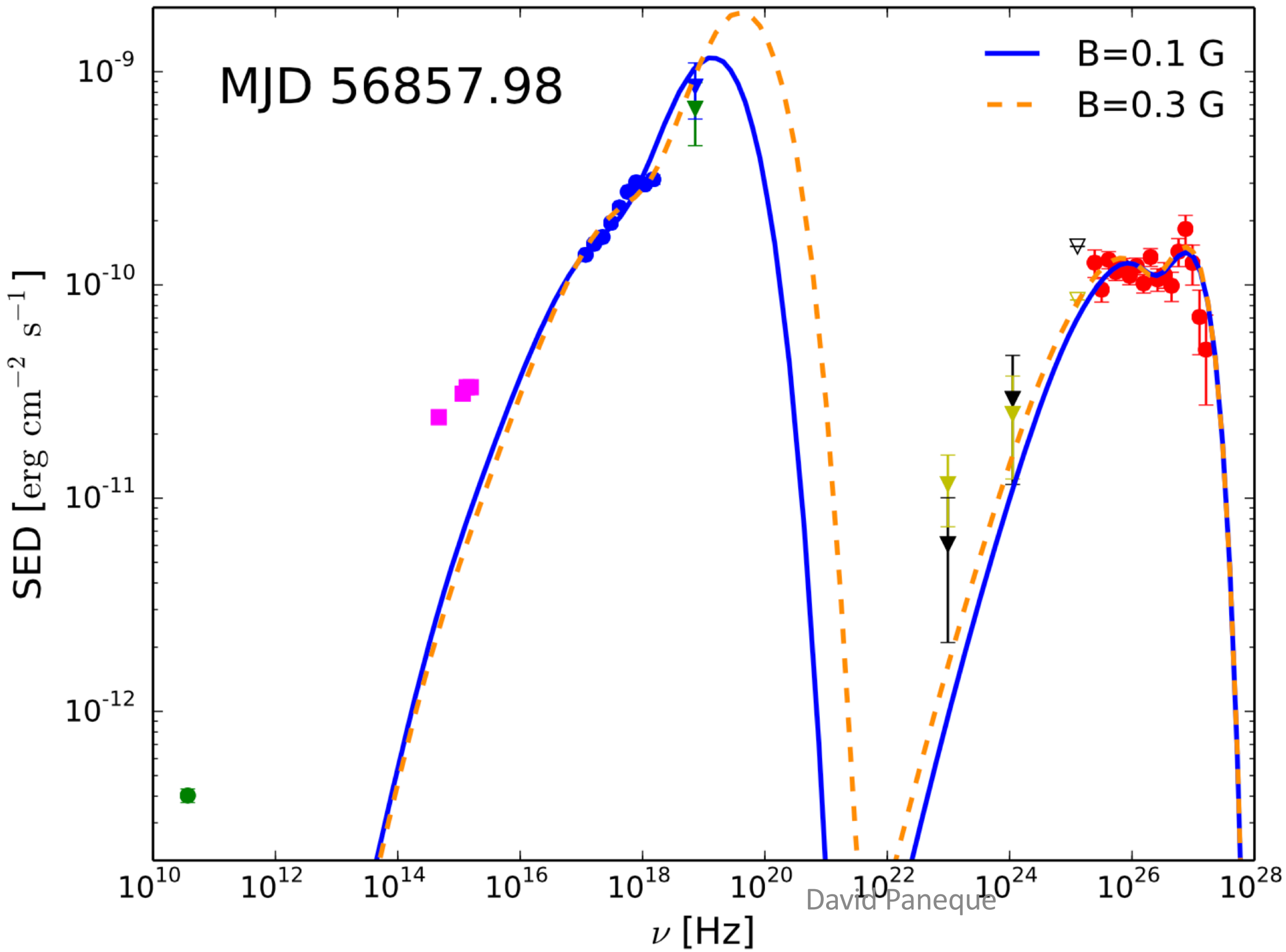
Pile-up in the electron energy distribution due to stochastic acceleration

Acciari et al A&A 2020, 637, 86

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

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

Mrk501



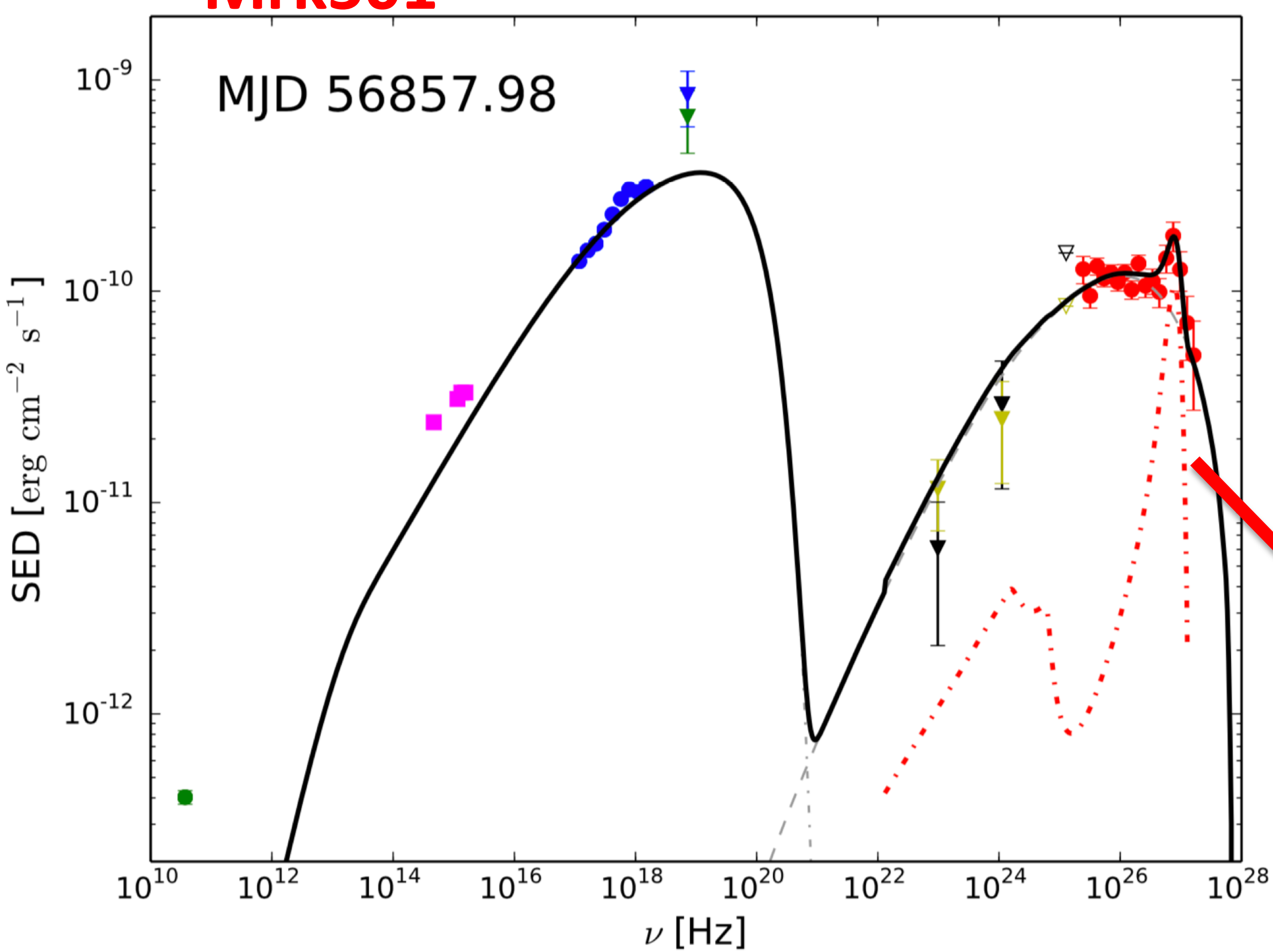
Model performed by Andrea Tramacere

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



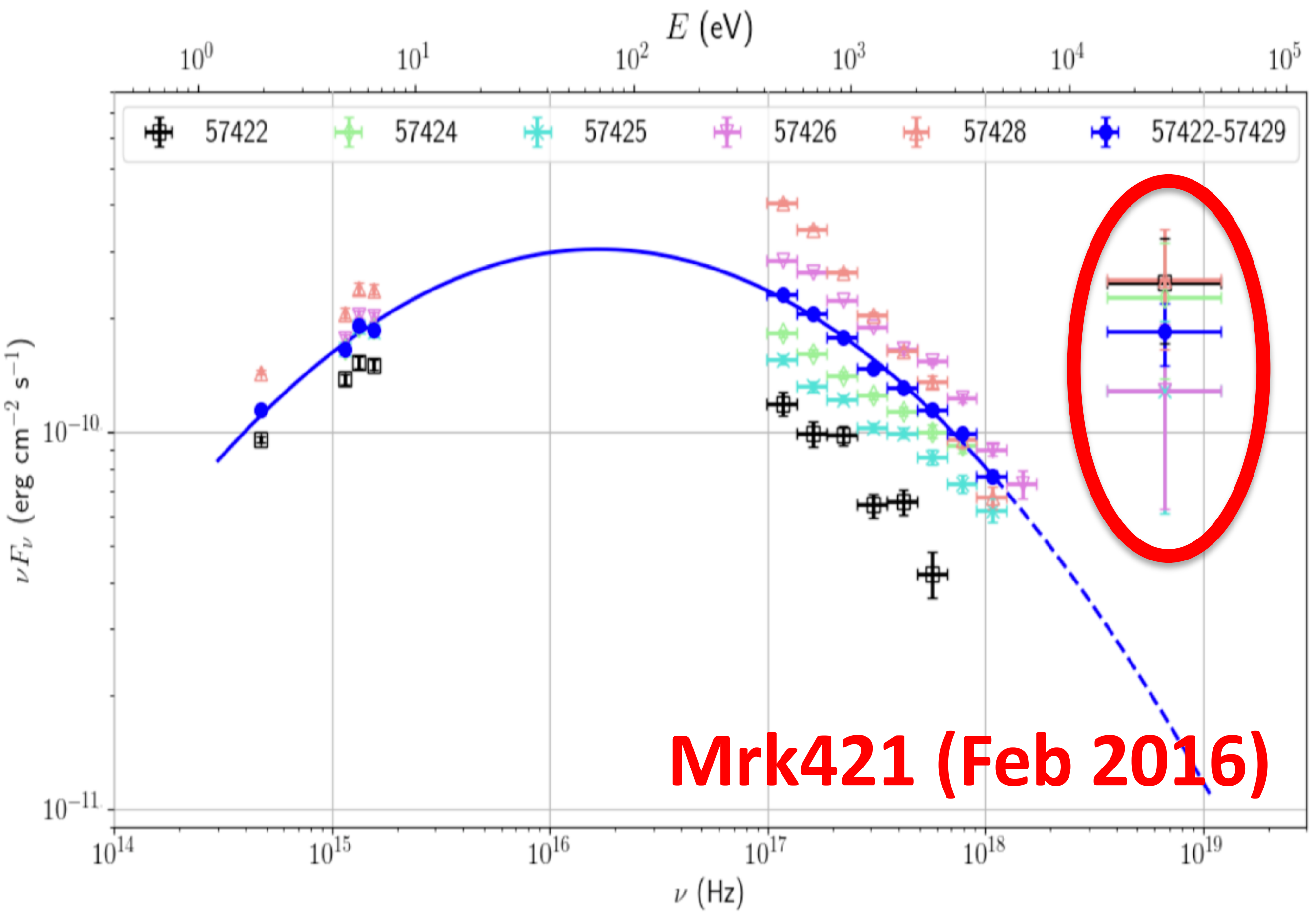
Model by Christoph Wendel

(for details, see Wendel et al A&A 2021, 646, 115)

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

Emission from narrow EED accelerated in Magnetospheric vacuum gap

Swift BAT excess in X-ray spectrum of Mrk421 in low state

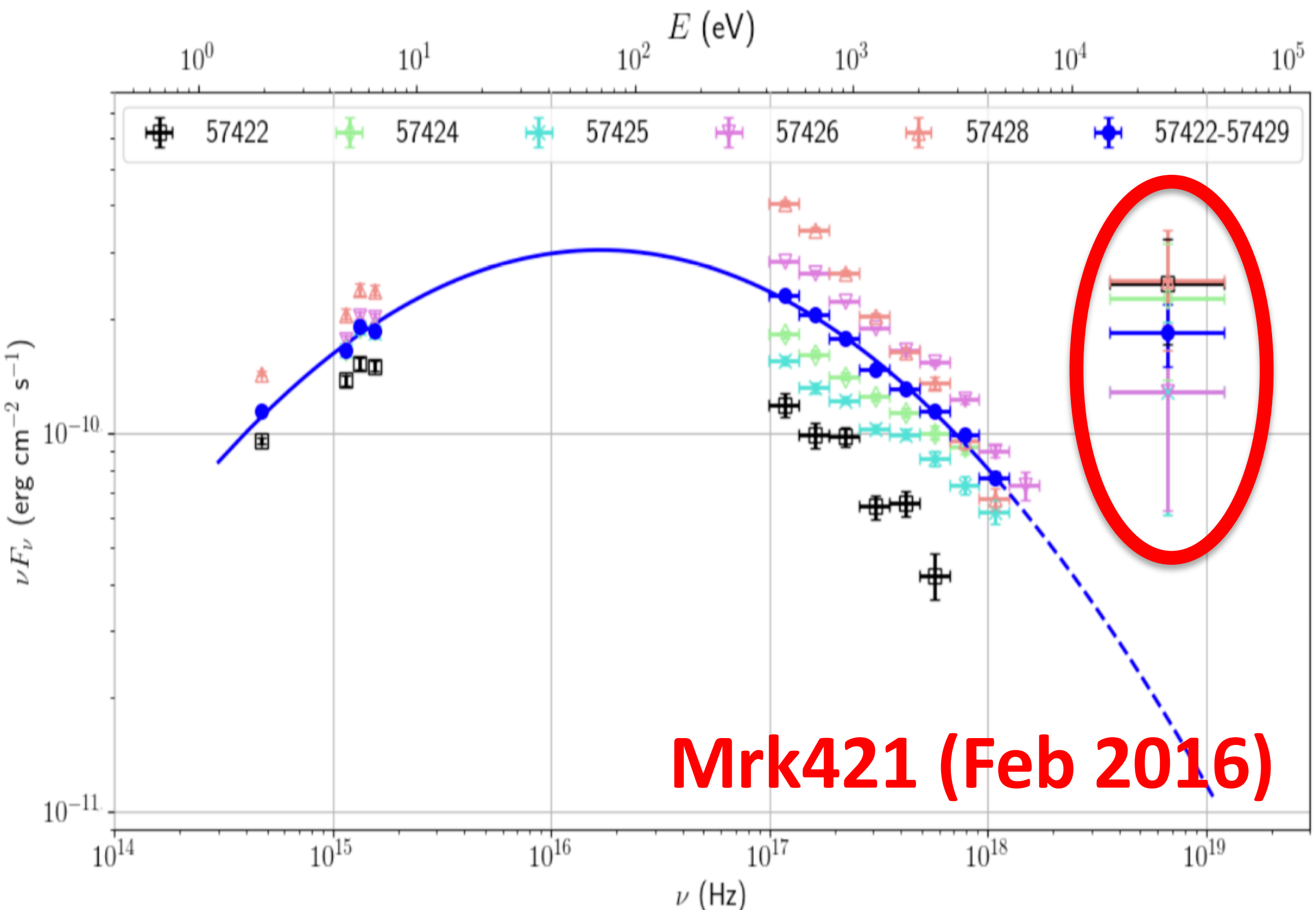


Acciari et al 2020, MNRAS in press (arXiv:2012.01348)

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

And also 7-day average spectra (blue)

Swift BAT excess in X-ray spectrum of Mrk421 in low state



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, as in Mrk501 in 2014 (*Acciari et al 2020, Wendel etal 2021)* ?

Conclusions and Outlook

AGNs are the most powerful (persistent) cosmic accelerators, studied for more than half century; but have very "complicated personalities"

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

Accurate AGN studies require wide broadband (radio to gamma-rays) AND temporal (years down to minutes) coverage

→ Characteriztion of gamma-ray band poor until last ~10-15 years

→ *major improvements coming online (e.g. CTA-North, LHAASO …)*

→ *and hopefully MeV telescopes in a few more years (see Parallel-6)*

→ Multi-band variability can break model degeneracies (*Boettcher talk, yesterday)*

→ Multi-messengers can break model degeneracies *(Reimer talk + Parallel-7)*

→ Polarization can break model degeneracies (*Zhang's talk, yesterday*)

→ Radio and optical polarization exist and already being used

→ This year will also get X-ray polarization data from IXPE (*October 2021*)

AGN studies are challenging; need big effort&coordination from a large number of people/instruments... ***but would it be fan if it was easy ?***