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FACT First G-APD Cherenkov Telescope

5.5 years multi-wavelength variability of Mrk 421: evidence of leptonic emission from radio to TeV

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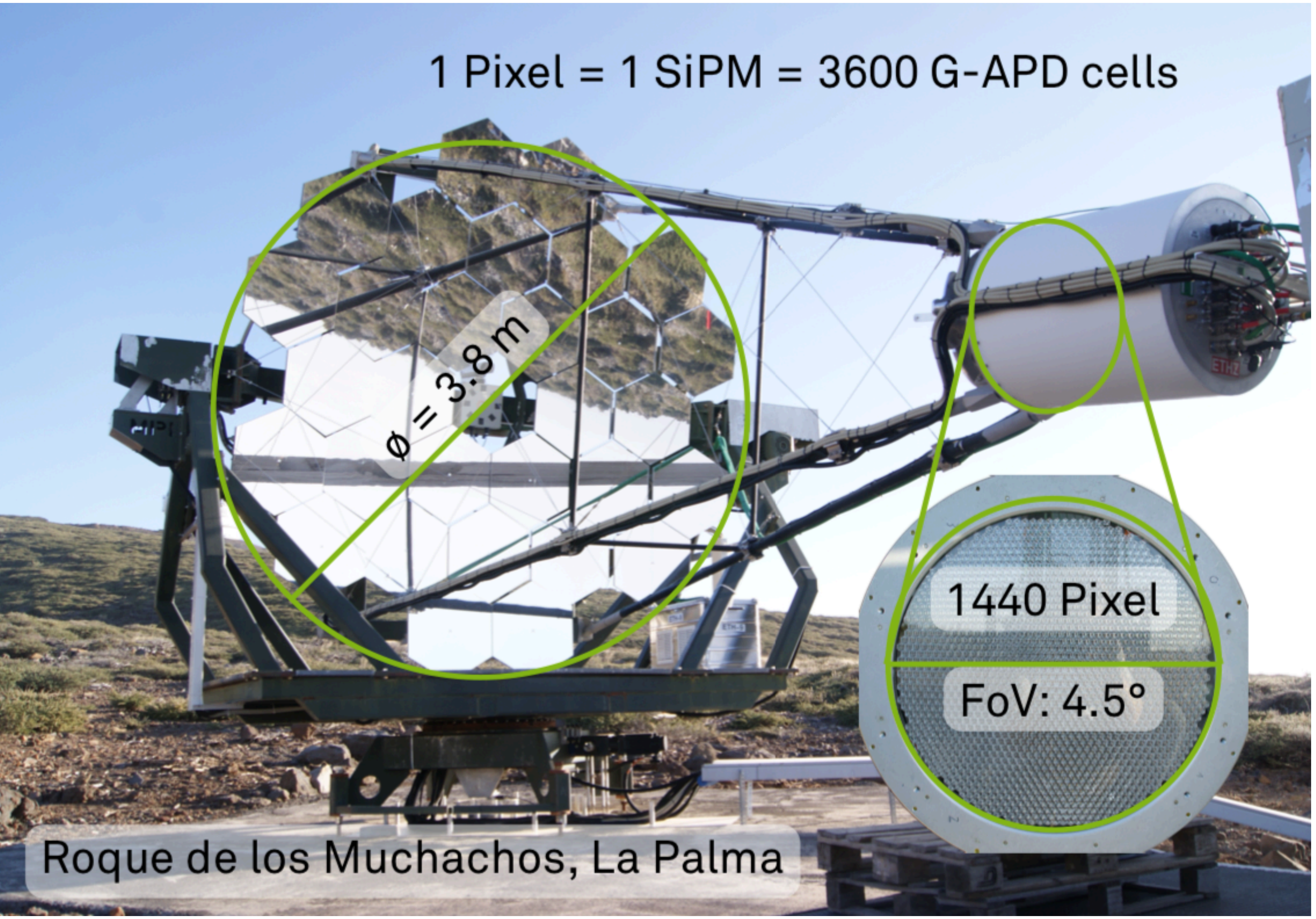
HEPRO VII, July 10, 2019

Credit: Miguel Claro

Outline

- The multi-wavelength observations of Mrk 421
- HBL blazar Mrk 421
- Light curves and flares
- Crosscorrelations of light curves
- Synthetic radio light curve
- Blazars observations strategies
- Summary and conclusions

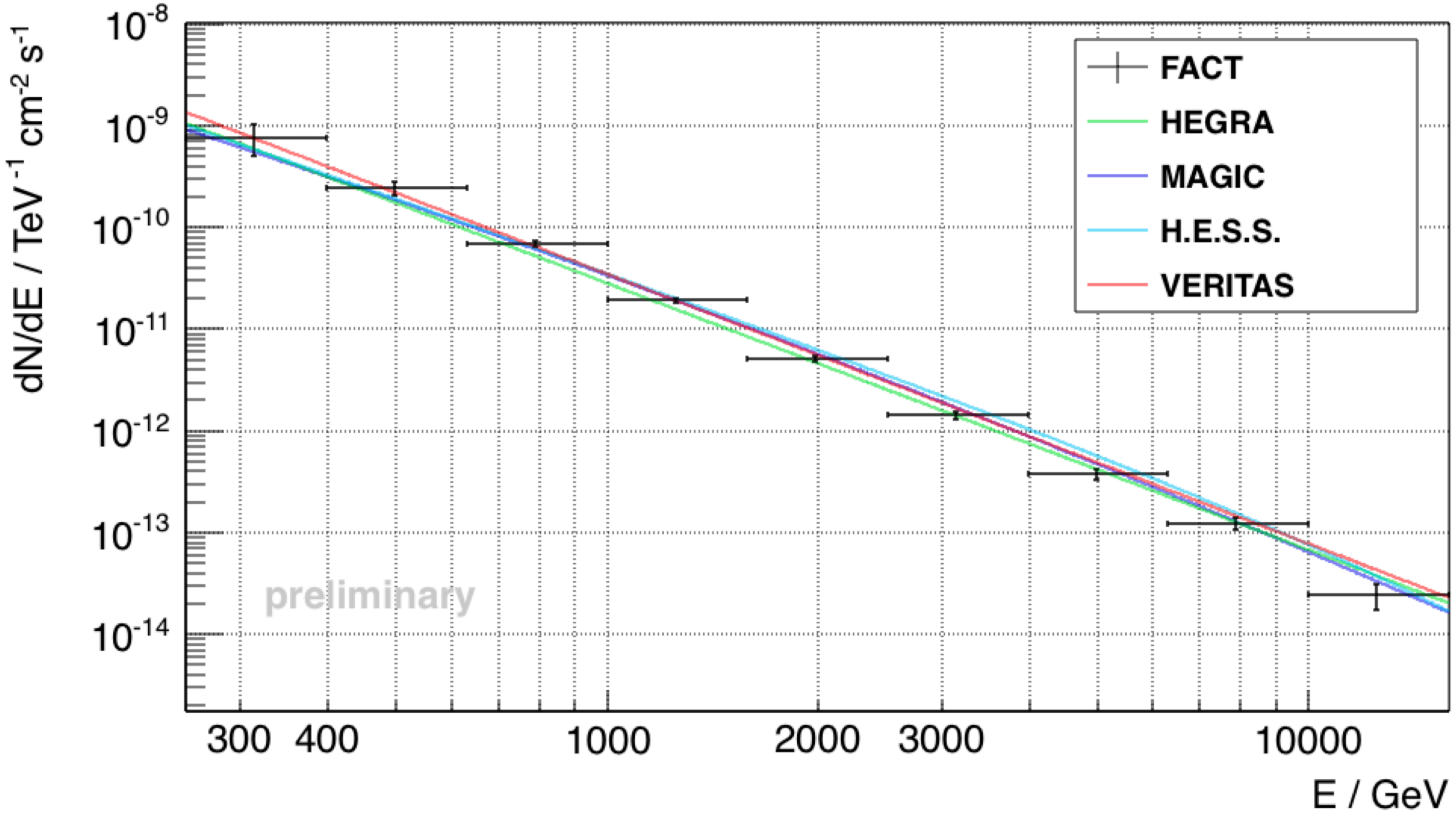
FACT: First G-APD Cherenkov Telescope



- Located at La Palma, Roque de Los Muchachos, 2200 m a.s.l.
- Operational since October 2011
- Mirror area: 9.5 m^2 (⌀3.8 m)
- Camera FOV 4.5°, comprised of 1440 pixels (0.11° / pixel)
- Silicon based photo sensors (G-APDs): observations with strong moon light possible
- Operated fully remotely, large duty cycle (>2500h of data in 12 months)
- Integrated sensitivity: 0.137 ± 0.004 Crab / 50h
- Unbiased monitoring strategy:
  - Blazars, quasars, AGNs: Mrk 421, Mrk 501, 1ES 2344+51.4, 1ES 1959+650, PKS 0736+01, IC 310
  - Crab
  - Multi-Messenger and MWL alerts: AMON20160218, HESE20160427, HESE20160731, V404 Cyg.
- Quick Look Analysis (QLA)

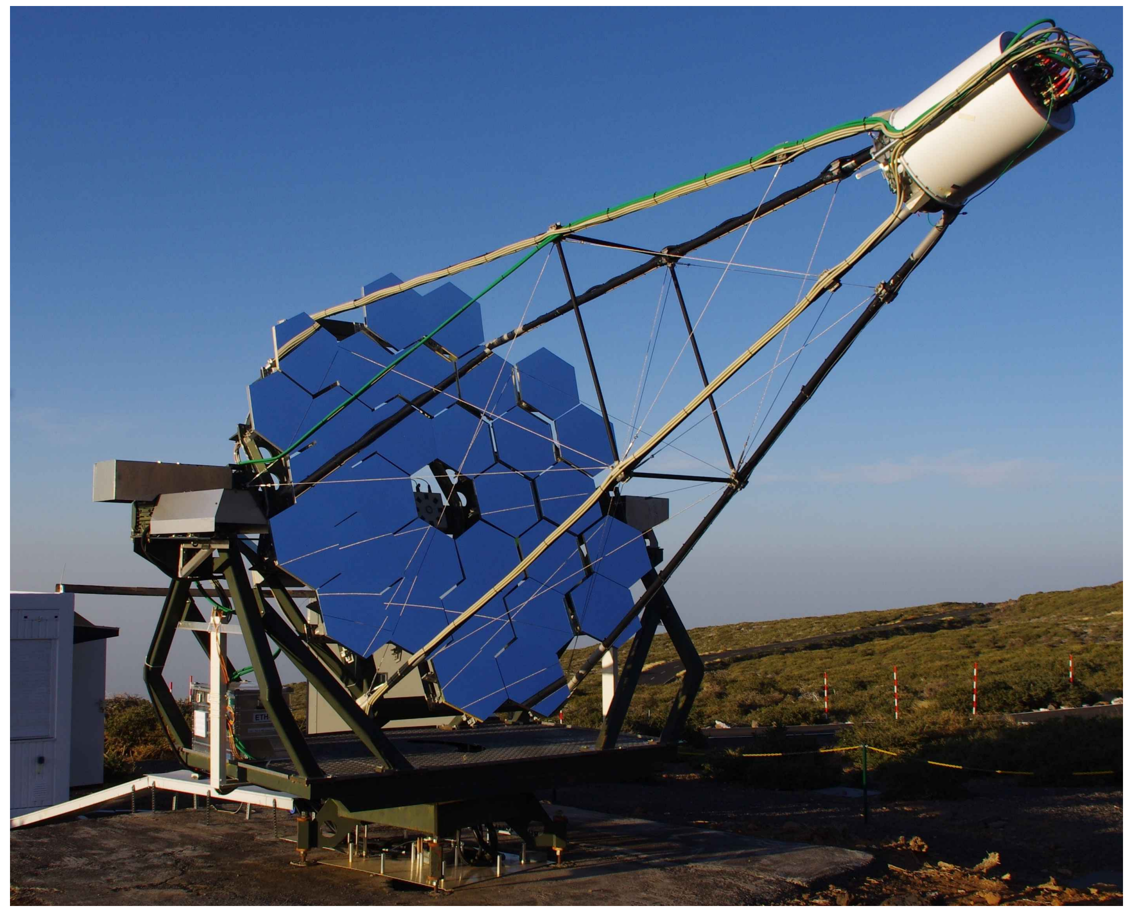
FACT: performance

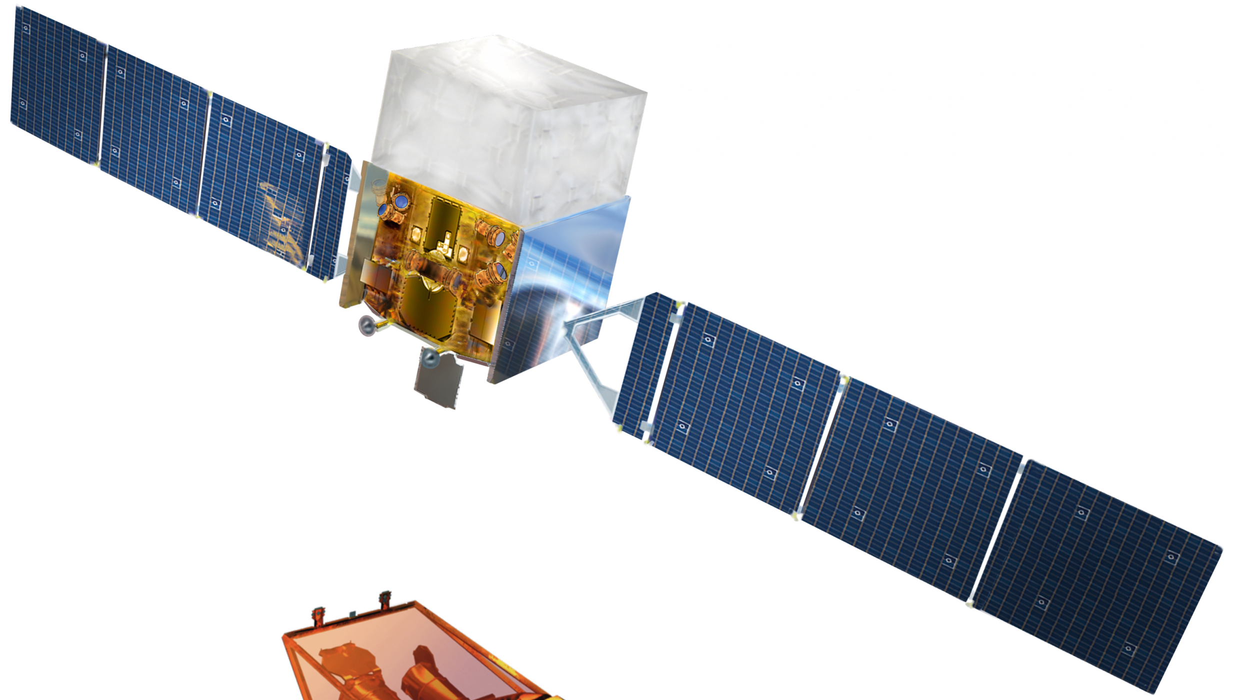
- Energy range: 300 GeV - 10 TeV
- Energy threshold: 540 GeV (Crab-Nebula-like spectrum) or ~580 GeV (PL spectral index 2.2, e.g. Mrk 421)
- Unfolded energy spectrum of the Crab Nebula:

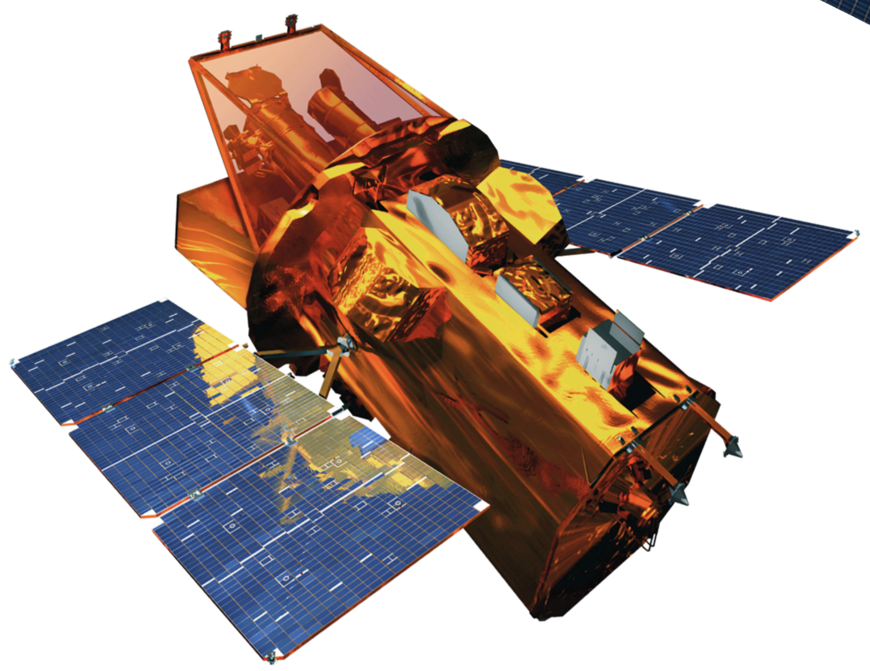


F. Temme et al., PoS, ICRC 2015

Multi-wavelength campaign

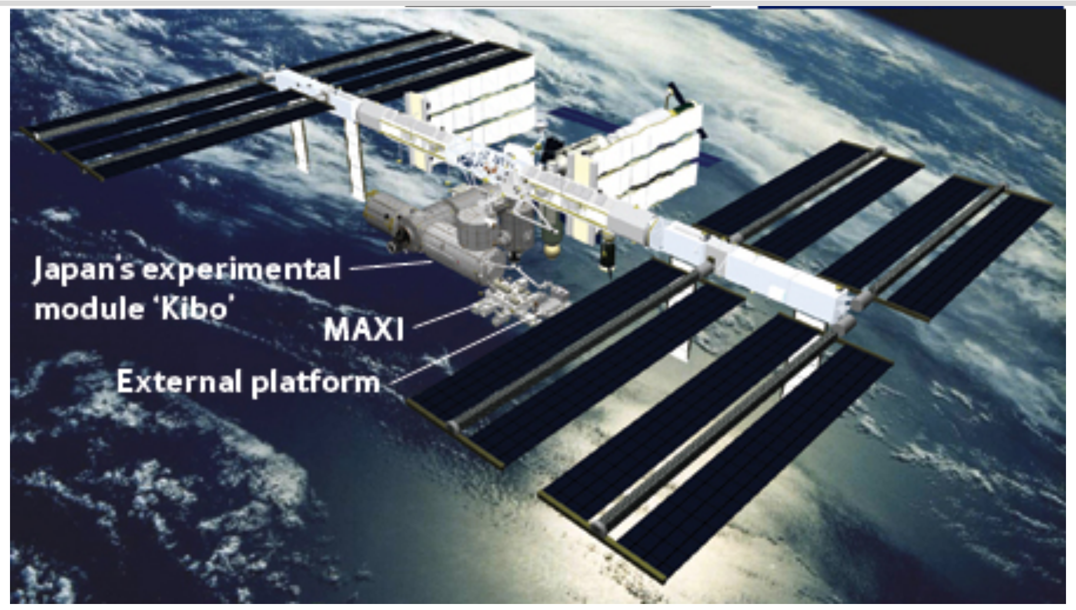


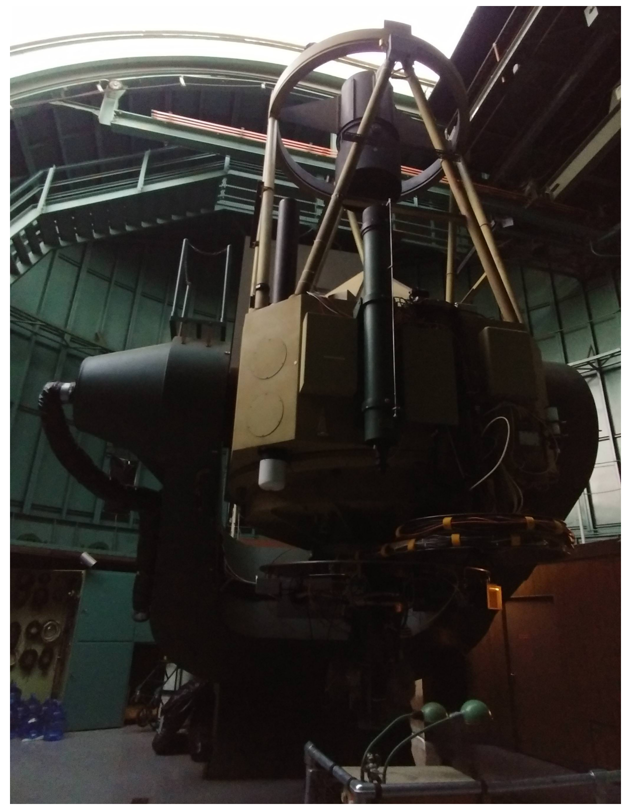




December 14, 2012 - April 18, 2018

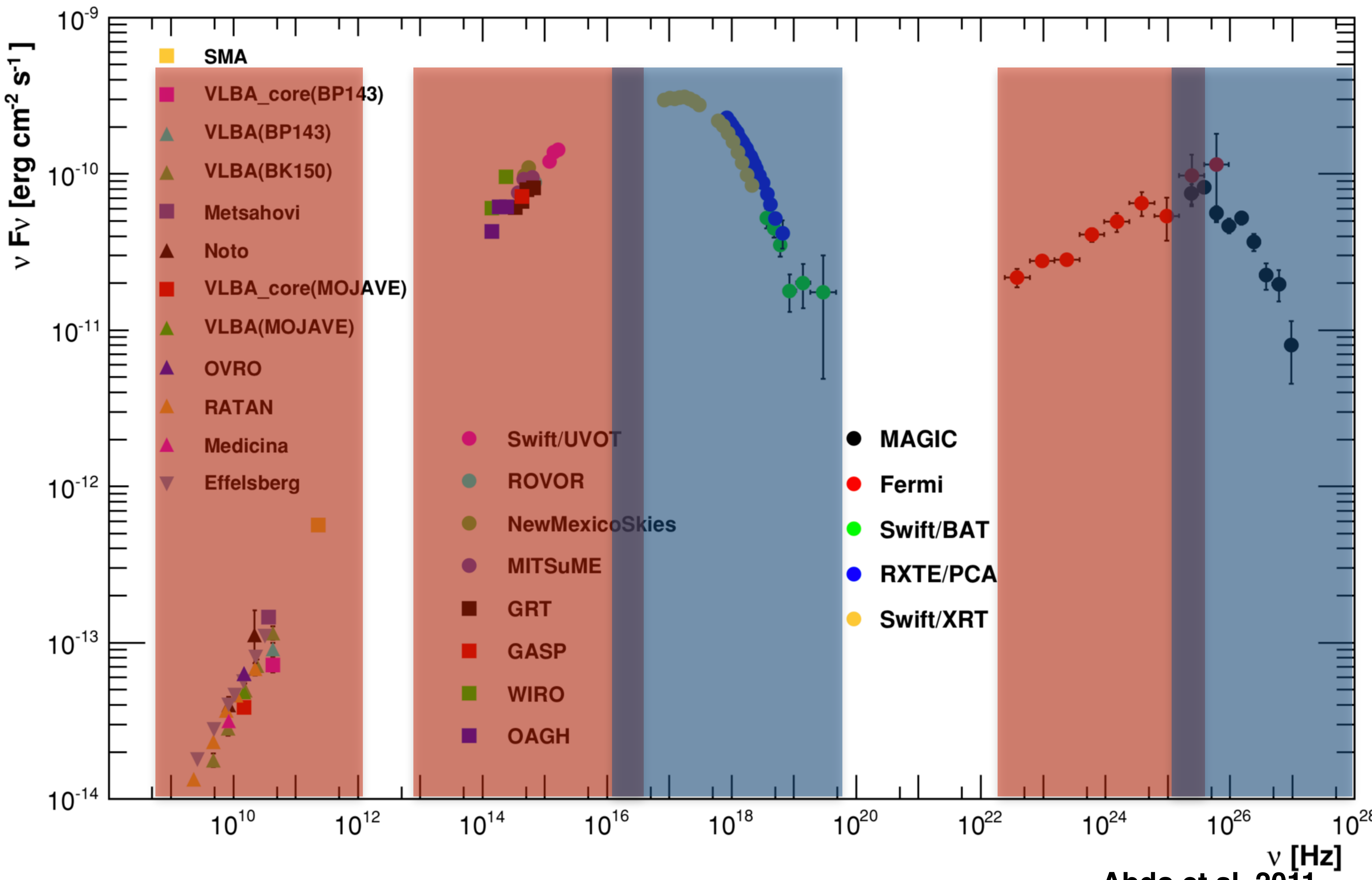
Instrument	*Band*	*Data*
FACT	> 580 GeV	584 nights / 2071 hours
Fermi-LAT	100 MeV - 300 GeV	1915 days
SWIFT/BAT	X-rays, 15-50 keV	1706 days (29344 orb.per.)
MAXI	2-20 keV	1181 days (18896 orb.per.)
Swift/XRT	0.3-2 keV, 2-10 keV	478 days / 652 hours
Swift/UVOT	UV (UVW1, UVM2, UVW2 filters)	752 measurements
Kuiper (1.54 m) & Bok (2.3 m) telescopes	V-band	379 measurements
OVRO (40 m)	Radio, 15GHz	329 measurements





Mrk 421

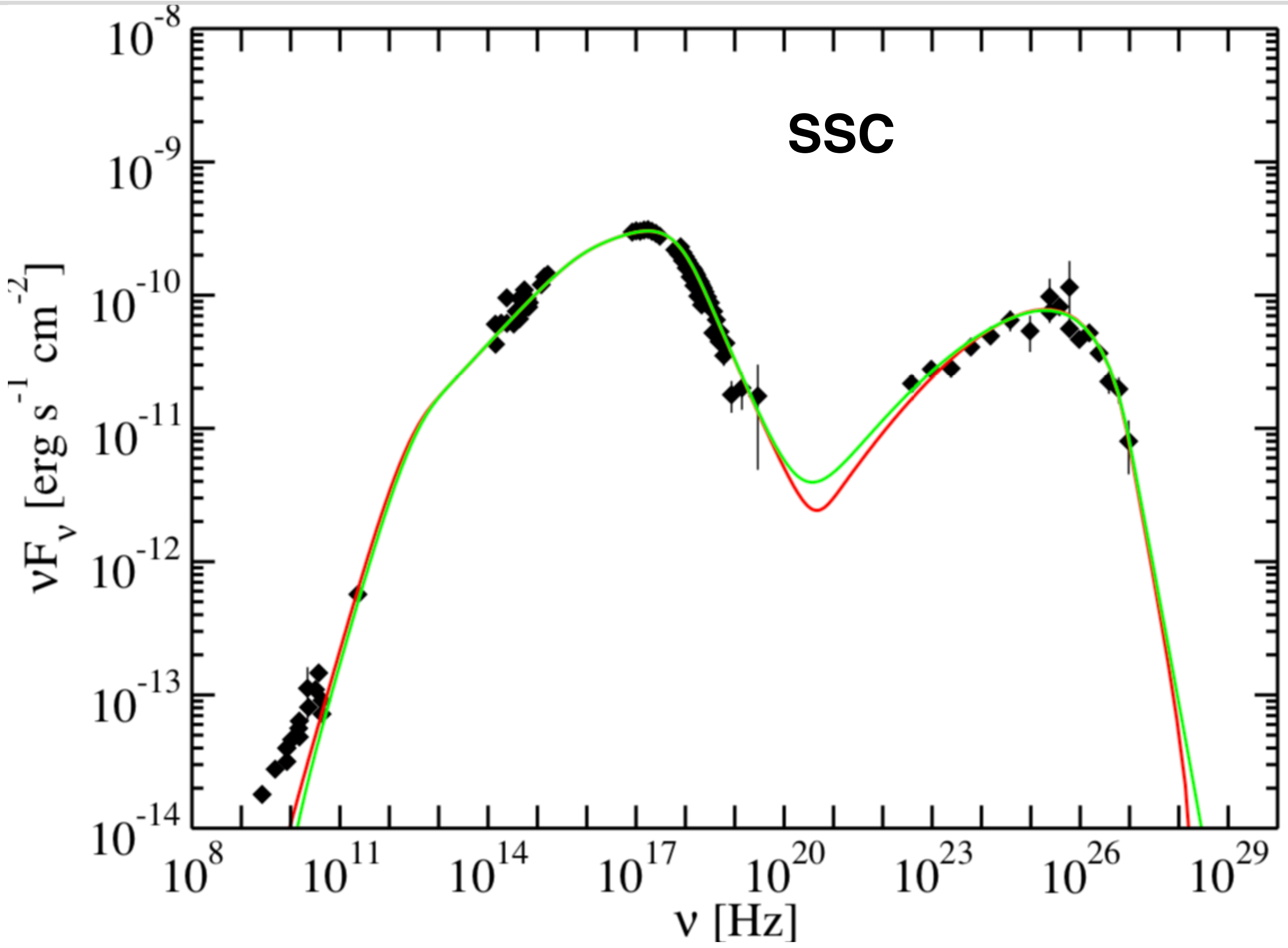
- Mrk 421 is HBL blazar, z=0.031
- Low energy hump:
  - synchrotron emission during relativistic electrons cooling
- High energy hump:
  - leptonic models:
    - one-zone SSC model (Celotti et al. 1998, Abdo et al. 2011)
    - multi-zone SSC model (Aleksić et al. 2015, Zhu et al. 2016)
  - hadronic models (Mastichiadis et al. 2013, Zech et al. 2017)
  - lepto-hadronic models:
    - synchrotron-proton model (Mücke & Protheroe 2001)
  - etc.



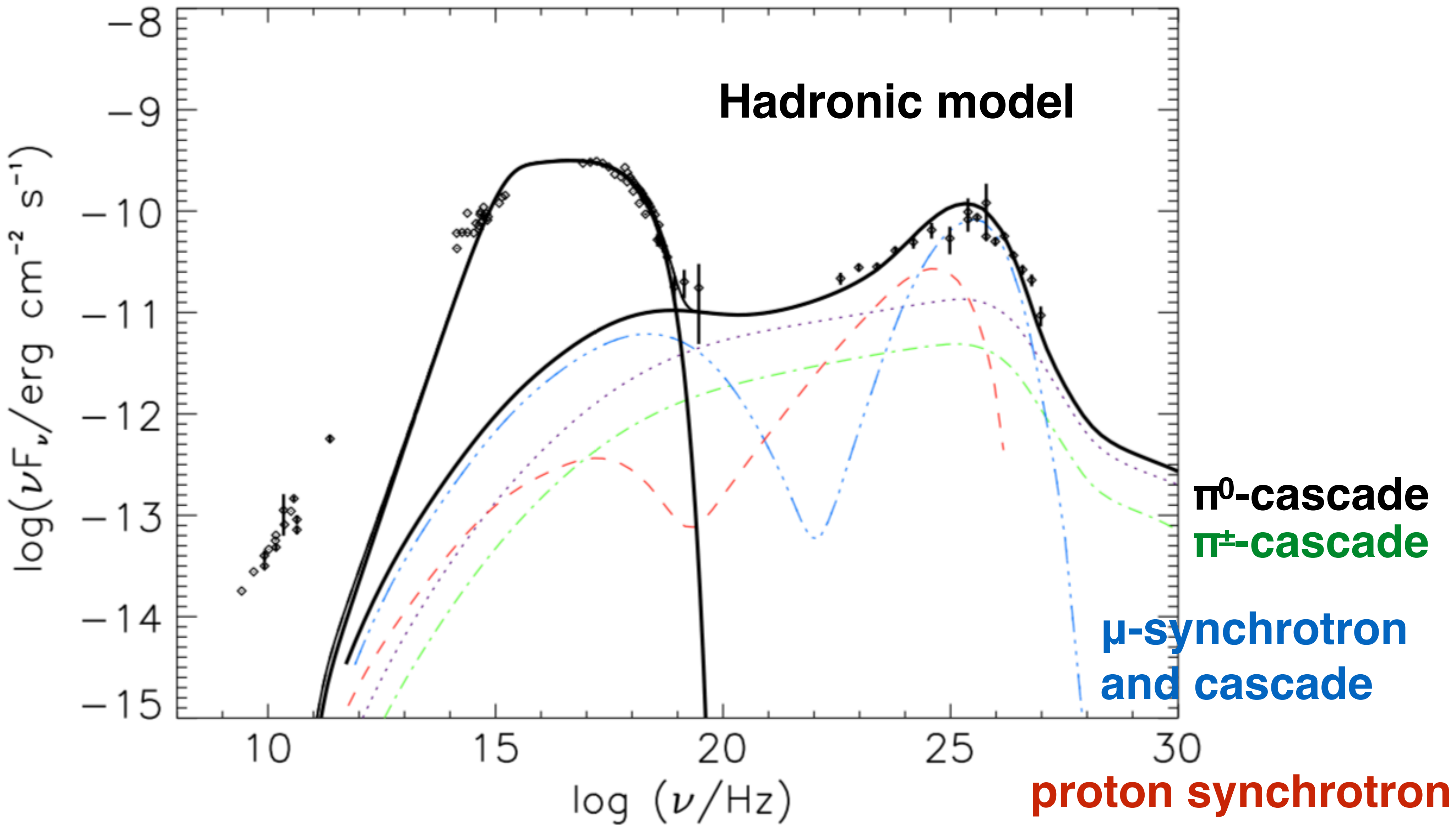
Abdo et al. 2011

Mrk 421: SED fittings

Abdo et al. 2011



Parameter	Symbol	Red Curve	Green Curve
Variability timescale (s)[a]	$t_{v,\min}$	8.64×10^4	3.6×10^3
Doppler factor	δ	21	50
Magnetic field (G)	B	3.8×10^{-2}	8.2×10^{-2}
Comoving blob radius (cm)	R	5.2×10^{16}	5.3×10^{15}
Low-energy electron spectral index	p_1	2.2	2.2
Medium-energy electron spectral index	p_2	2.7	2.7
High-energy electron spectral index	p_3	4.7	4.7
Minimum electron Lorentz factor	$\gamma_{\min}$	8.0×10^2	4×10^2
Break1 electron Lorentz factor	$\gamma_{\rm brk1}$	5.0×10^4	2.2×10^4
Break2 electron Lorentz factor	$\gamma_{\rm brk2}$	3.9×10^5	1.7×10^5
Maximum electron Lorentz factor	$\gamma_{\max}$	1.0×10^8	1.0×10^8
Jet power in magnetic field (erg s^{-1})[b]x	$P_{j,B}$	1.3×10^{43}	3.6×10^{42}
Jet power in electrons (erg s^{-1})	$P_{j,e}$	1.3×10^{44}	1.0×10^{44}
Jet power in photons (erg s^{-1})[b]	$P_{j,ph}$	6.3×10^{42}	1.1×10^{42}

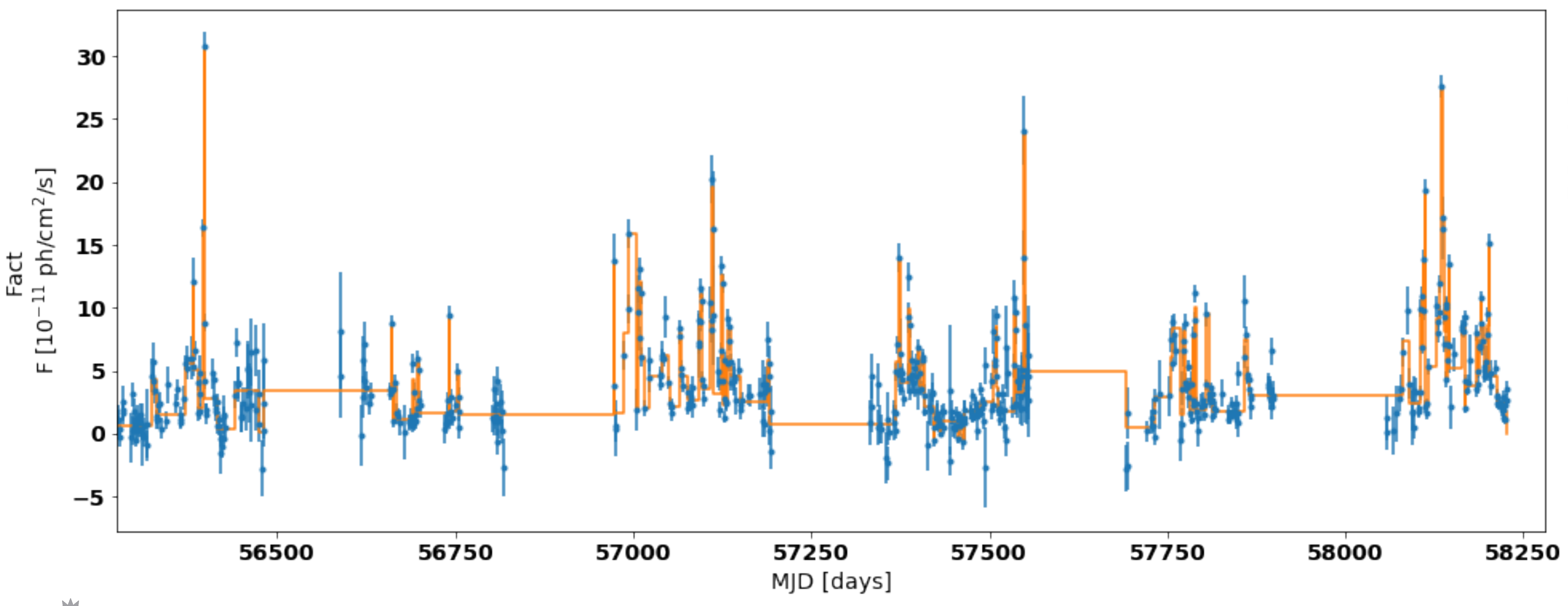


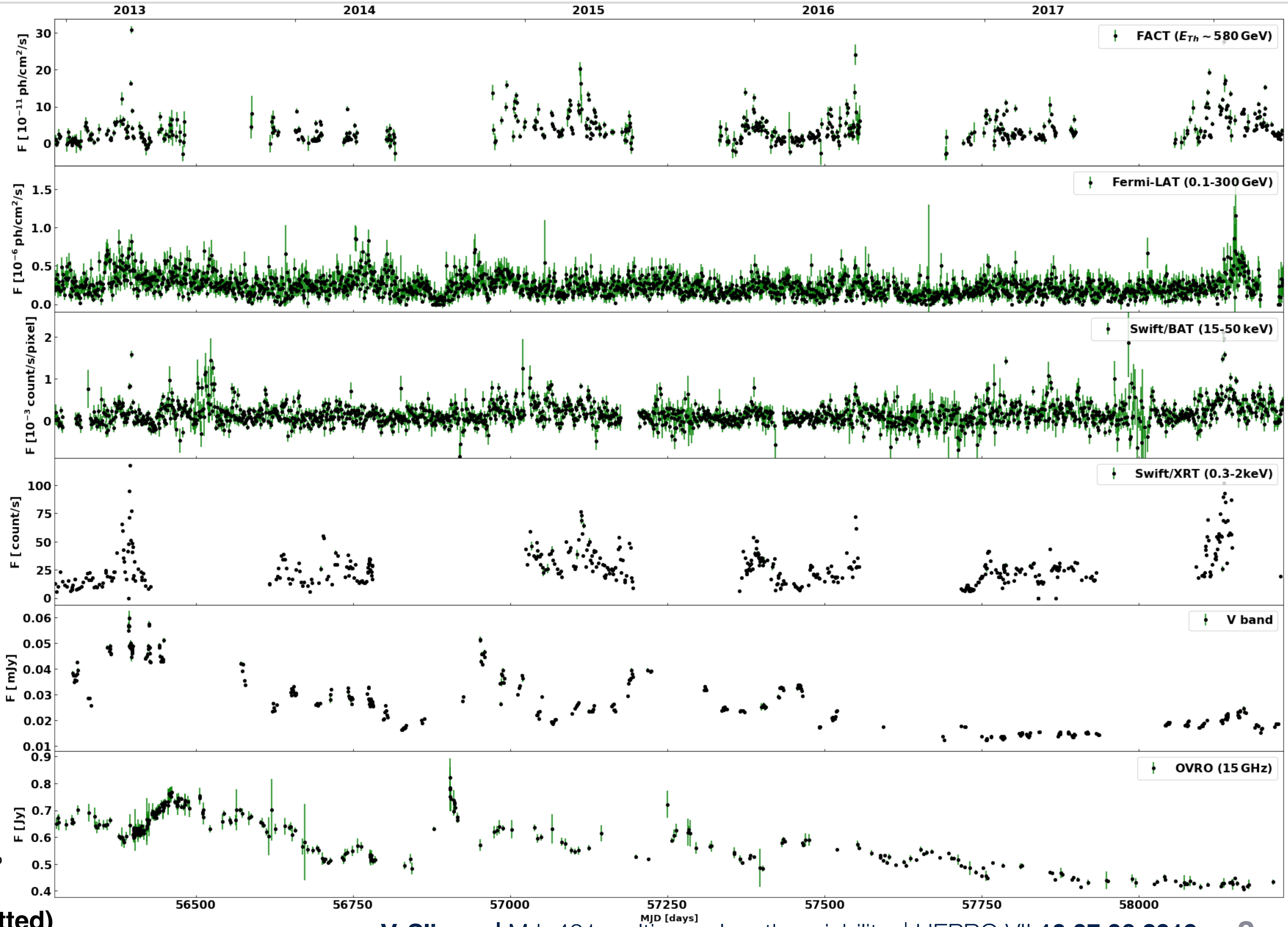
Parameter	Symbol	Value
Doppler factor	δ	12
Magnetic field (G)	B	50
Comoving blob radius (cm)	R	4×10^{14}
Power-law index of the injected electron distribution[a]	α_e	1.9
Power-law index of the injected proton distribution[a]	α_p	1.9
Minimum electron Lorentz factor	$\gamma_{e,\min}$	7×10^2
Maximum electron Lorentz factor	$\gamma_{e,\max}$	4×10^4
Minimum proton Lorentz factor[b]	$\gamma_{p,\min}$	1
Maximum proton Lorentz factor	$\gamma_{p,\max}$	2.3×10^9
Energy density in protons (erg cm^{-3})	u'_p	510
Ratio of number of electrons with respect to protons	e/p	90
Jet power (erg s^{-1})	$P_{\rm jet}$	4.5×10^{44}

5.5 years multi-wavelength light curves

FACT
First G-APD Cherenkov Telescope

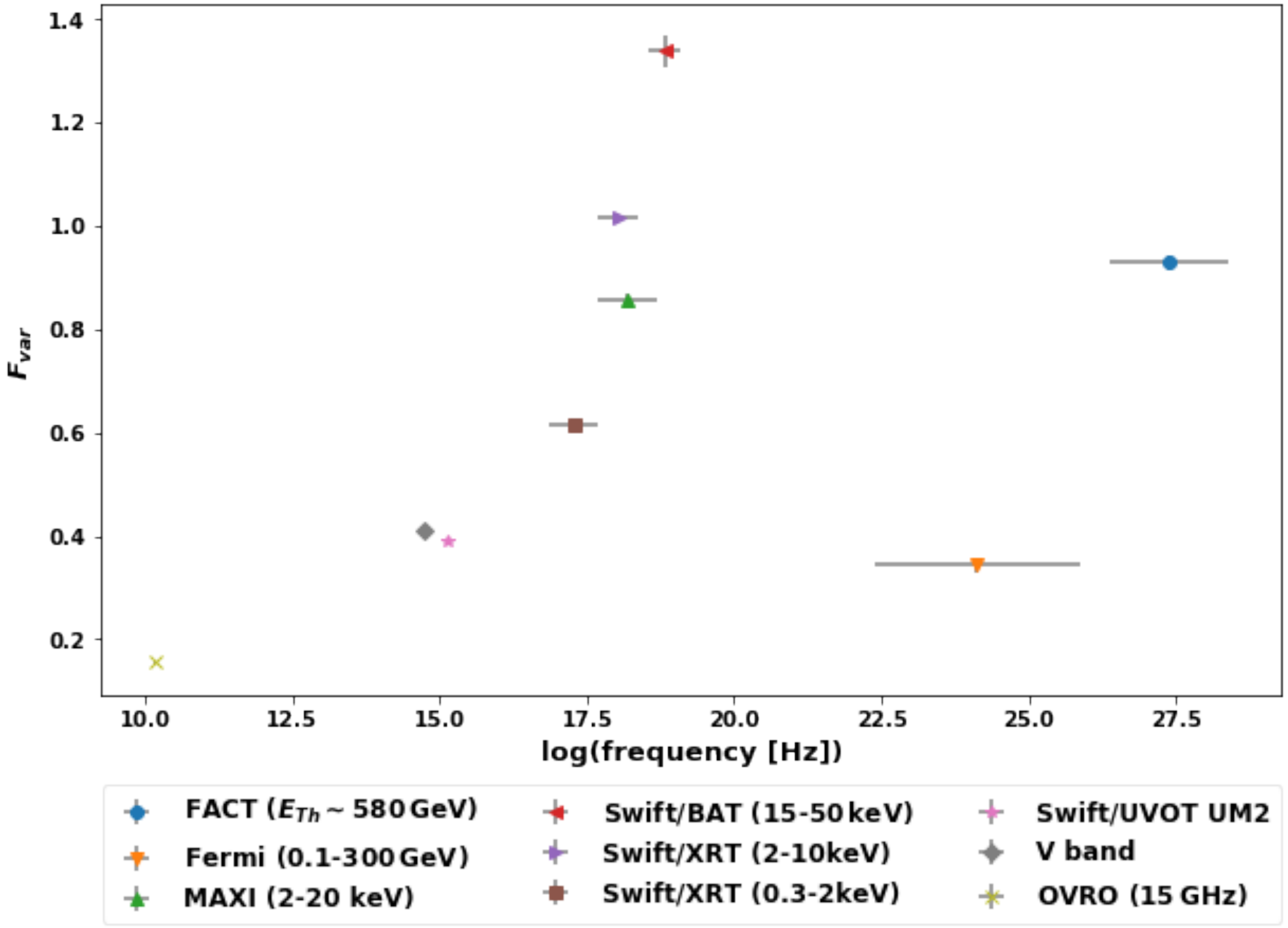
- Variability present in all bands
- Strong simultaneous X-ray and VHE flares
- 31 flares found:
  - 2 TeV only
  - 4 GeV only
  - 11 TeV & X-rays
  - 18 TeV & GeV & X-rays

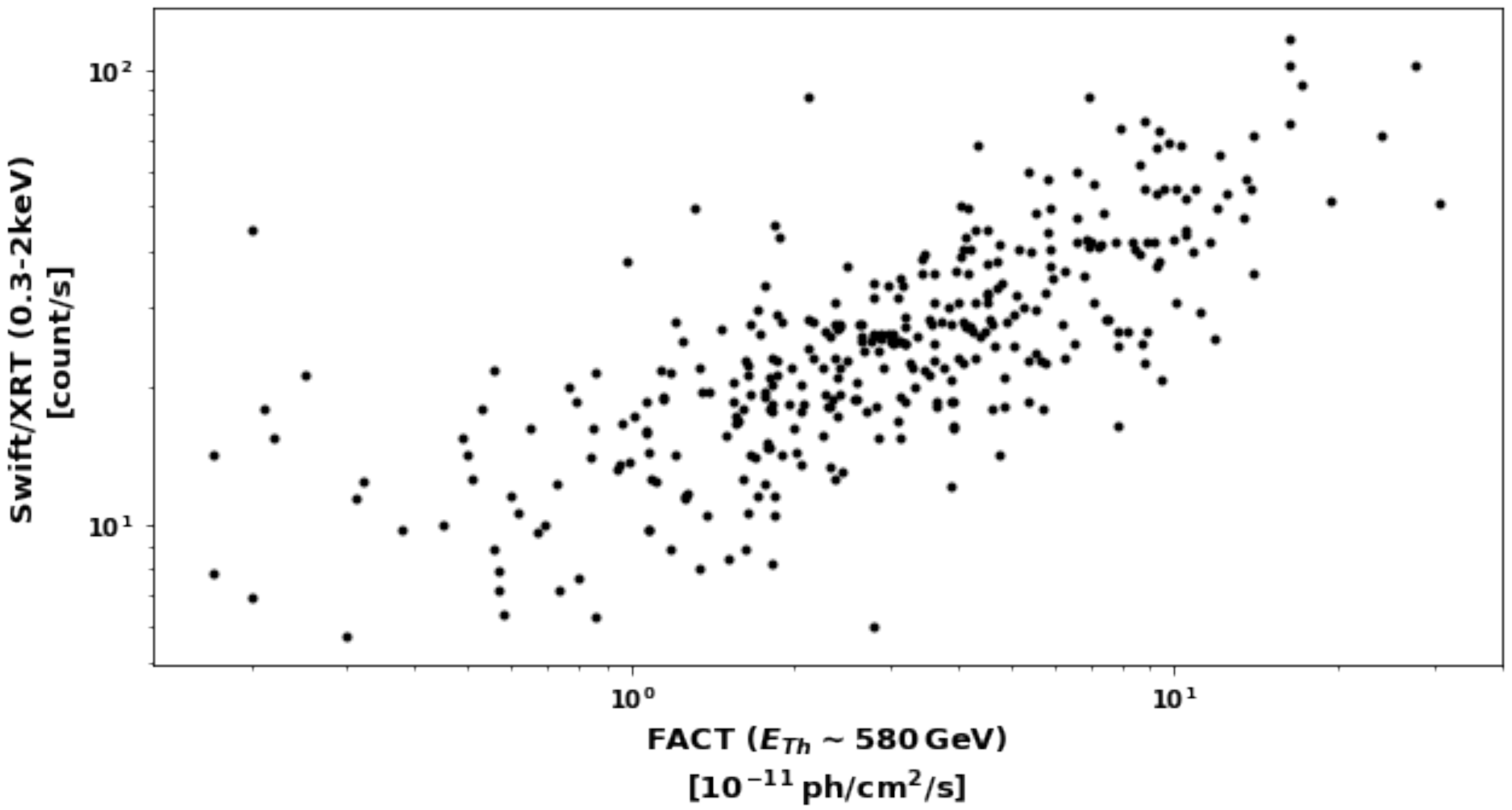




Arbet-Engels et al. (submitted)

Variability and Fvar



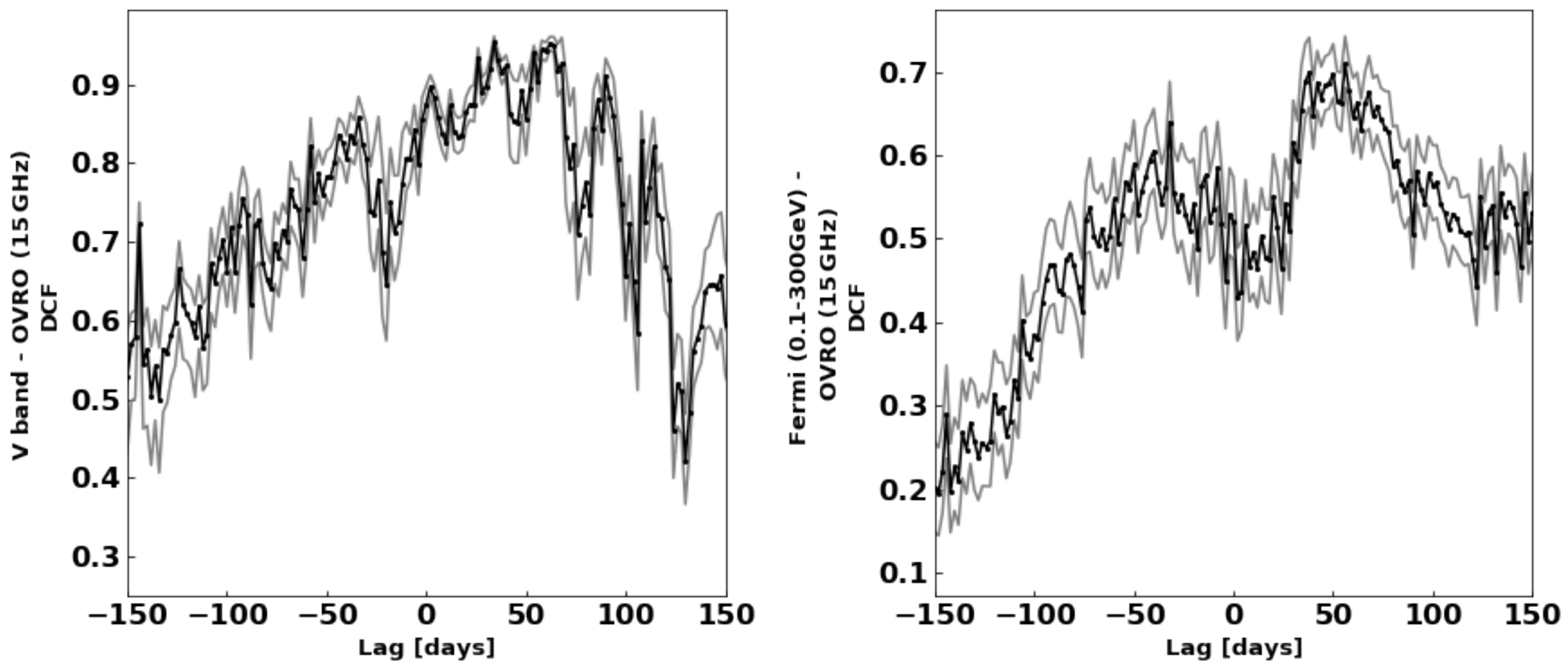


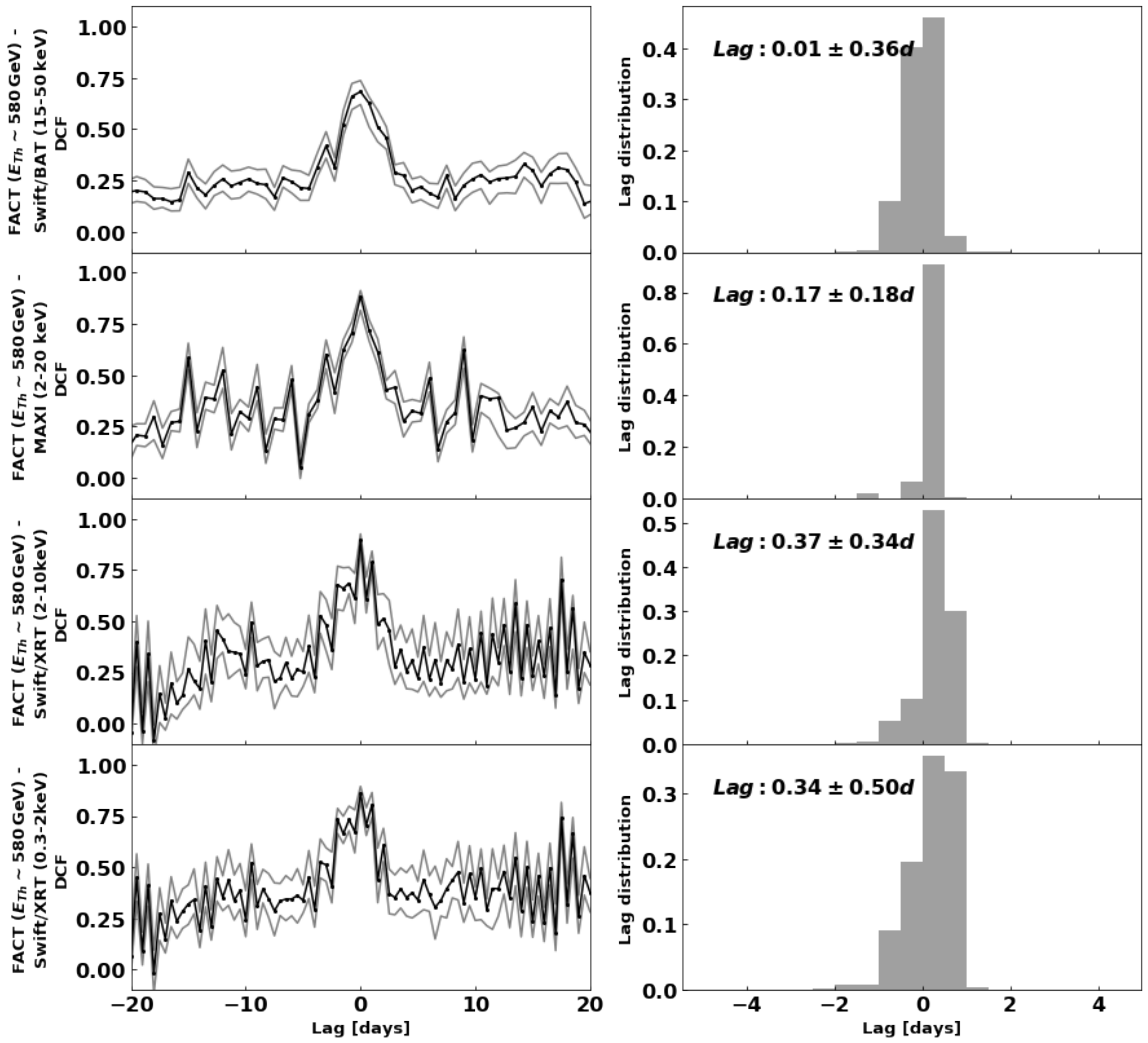
- Variability increased from radio to X-rays and from MeV to TeV
- Highest variability in hard X-rays
- TeV and X-ray are correlated, the slope is 0.43 ± 0.02 and can be related to variable electron cut-off energy

Arbet-Engels et al. (submitted)

Crosscorrelations

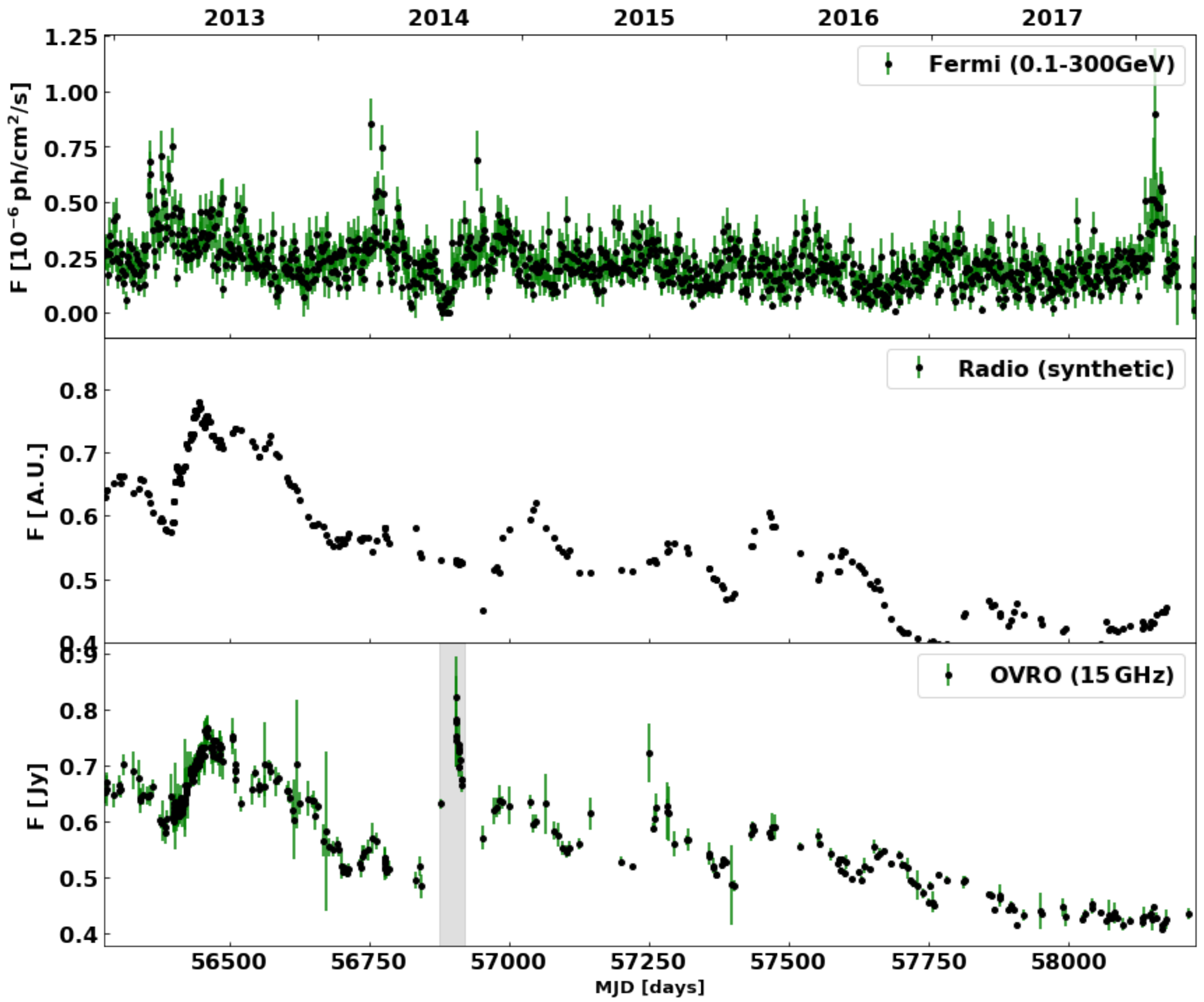
- TeV and X-ray are strongly correlated with 0.26±0.46 (1σ) days X-ray lagging behind
- Optical and radio light curves are broadly correlated. Optical variability is leading by 30-70 days
- GeV and radio light curves are broadly correlated. GeV variability leads by 40-70 days.
- GeV is not correlated with TeV and X-rays
- Observed variability compliant with SSC

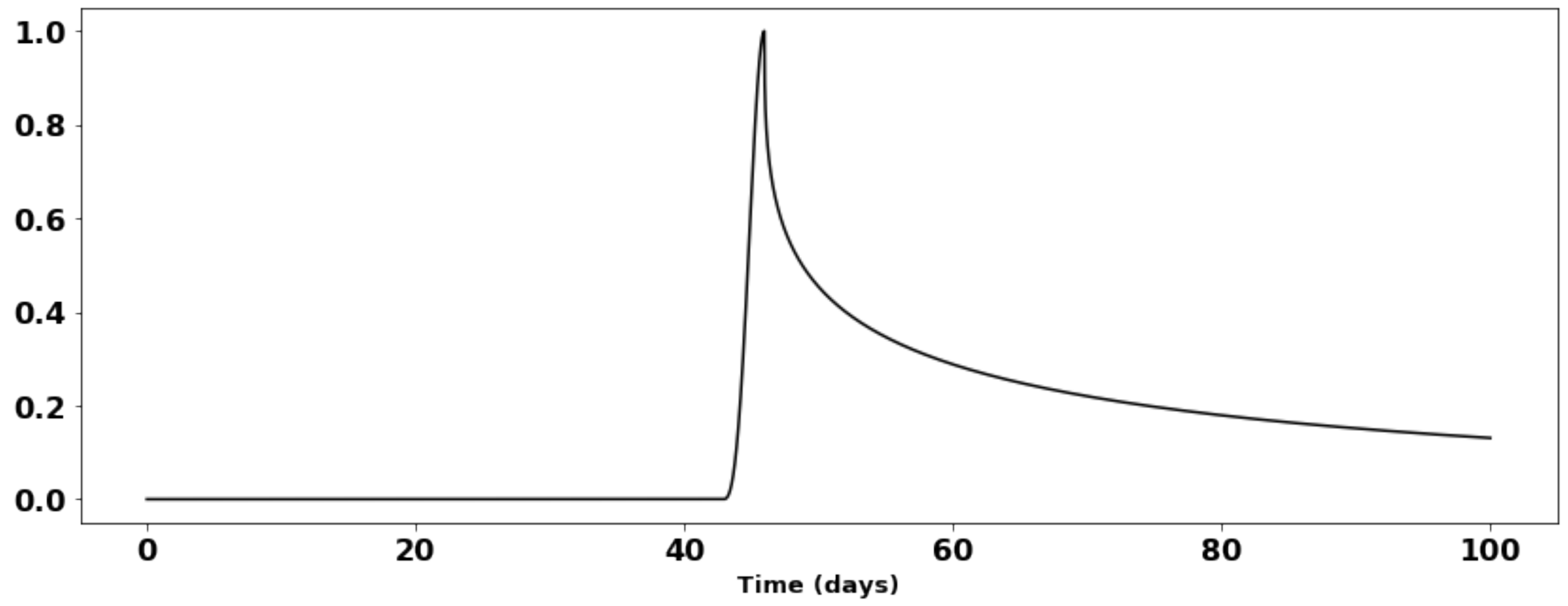




Arbet-Engels et al. (submitted)

GeV - radio response





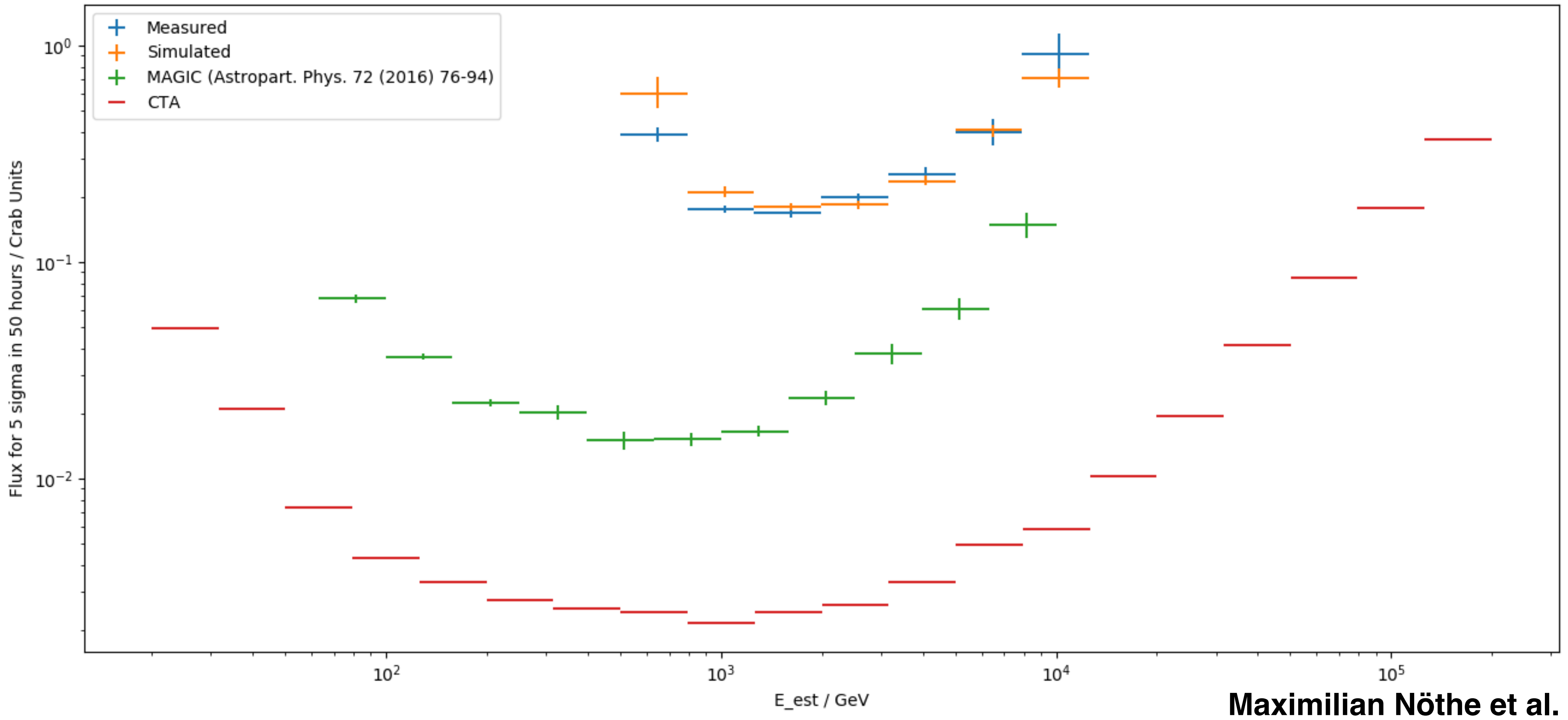
- Conical jet model used (Türler et al. 1999, Esposito et. 2015)
- 43 days delay of the response consistent with GeV - radio cross correlations
- Profile has fast rising time (~7 days) and the a slow decay over ~150 days
- GeV light curve convolution with response profile explains all but one fast radio flare (MJD 56897)

Arbet-Engels et al. (submitted)

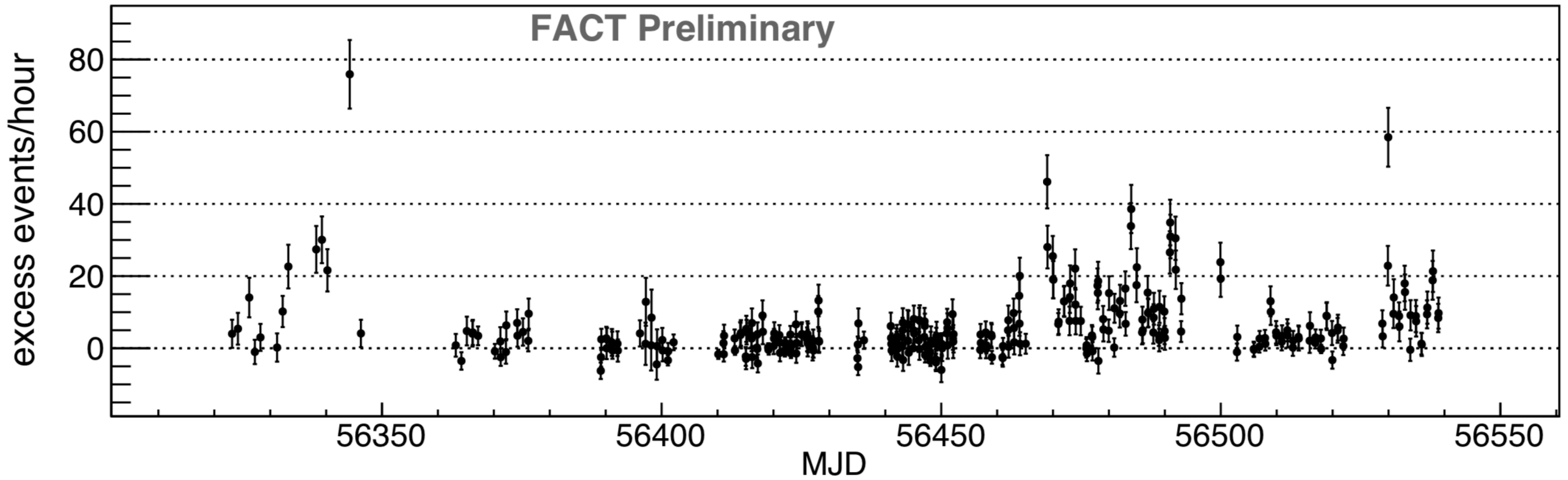
Blazars observations strategies

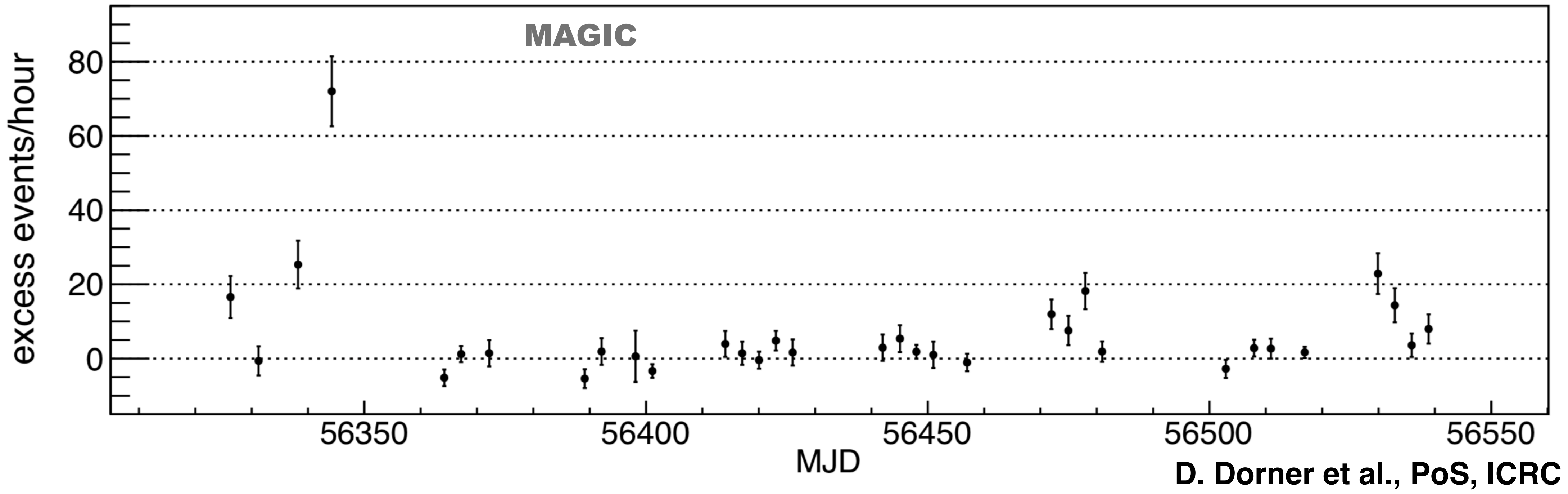
FACT
First G-APD Cherenkov Telescope

- Inline with CTA AGN KSPs:
  - long-term unbiased monitoring (30 min / 2 weeks ~ 12h / year)
  - high-quality spectra and time-resolved spectra
  - AGN flare monitoring from external triggers (Fermi, Swift, HAWC, …)
- Unbiased monitoring with great sensitivity:
  - short-term flares detection (TeV counterpart short-time scale X-ray flares (Paliya et al. 2015))
  - emission model constrains from cooling time and correlations
  - (quasi) periodicities
  - breaks in power spectra
  - size (location, geometry, nature) of emission region
- Triggered flare monitoring:
  - MWL observation
  - Spectrum-brightness dependence verification



Maximilian Nöthe et al. 2019 (in prep.)





D. Dorner et al., PoS, ICRC 2015. Mrk 501

Summary and conclusions

- One-zone SSC model requires magnetic fields of ≤0.1 G, while leptono-hadronic models ≥20 G.
- Within the shock in a jet model the estimated and observed cooling times are compatible with SSC (except radio), while being incompatible in X-rays and TeV for leptono-hadronic and hadronic models.
- The strongest variations of Mrk 421 occur in the X-ray and in the TeV bands.
- X-ray and TeV flares are very well correlated (93% of the TeV flares were detected in the X-rays). The lag between the TeV and X-ray variations could be estimated as 0.26±0.46 days, almost ten times more constraining than ever before.
- The radio emission can be reproduced accurately by convolving the GeV light curve by a delayed response (a fast rise and a slower decay after a delay of ≈43 days). This is a strong indication that synchrotron processes dominate the low energy emission component.

Thank you for your attention!

Credit: Ivan Jimenez, ESA