Long-term multi-band photometric monitoring of Mrk 501

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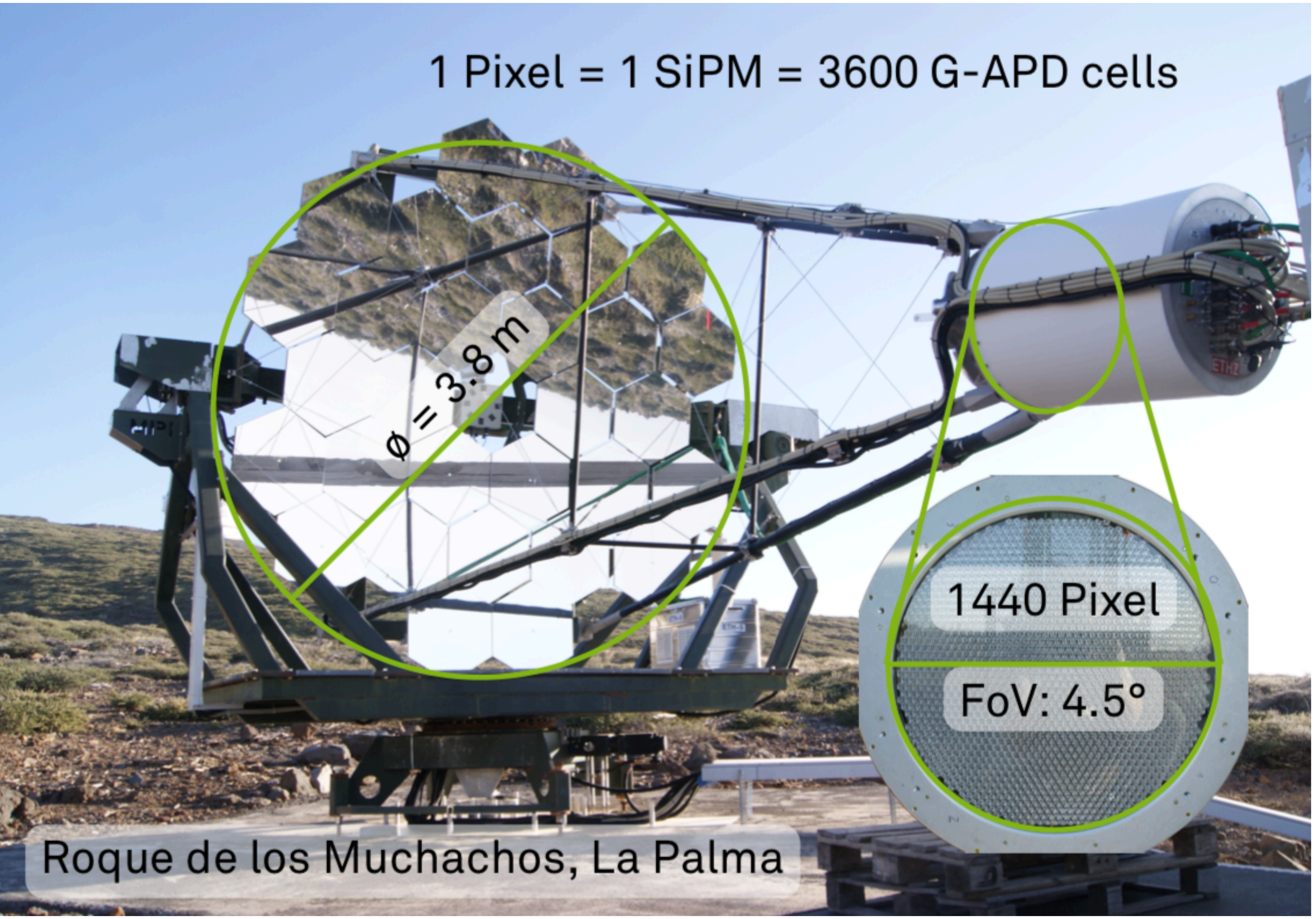
on behalf of FACT collaboration

Jets 2021, June 14-28, 2021

Image credit: DESY, Science Communication Lab

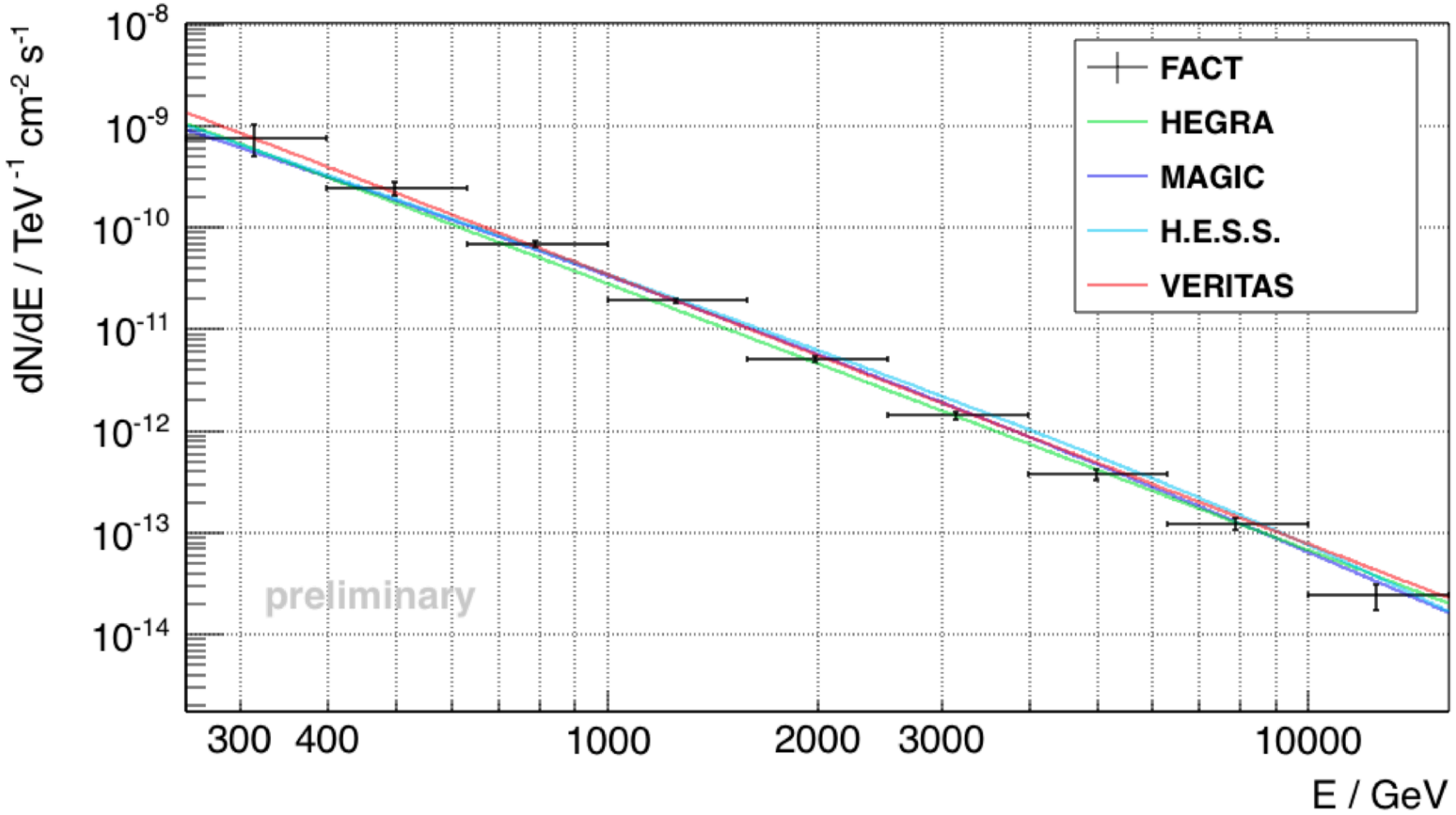
FACT: First G-APD Cherenkov Telescope



- Located at La Palma, Roque de Los Muchachos, 2200 m a.s.l.
- Operational since October 2011
- Mirror area: 9.5 m^2 (ø3.8 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 and automatically, large duty cycle (>2500h of data in 12 months)
- Integrated sensitivity: 0.137 ± 0.004 Crab / 50h
- Unbiased monitoring strategy:
  - Blazars, AGNs: Mrk 421, Mrk 501, 1ES 2344+51.4, 1ES 1959+650
  - Crab Nebula
  - Multi-Messenger and MWL alerts, e.g. AMON20160218, HESE20160427, HESE20160731, V404 Cyg.
- Quick Look Analysis (QLA)

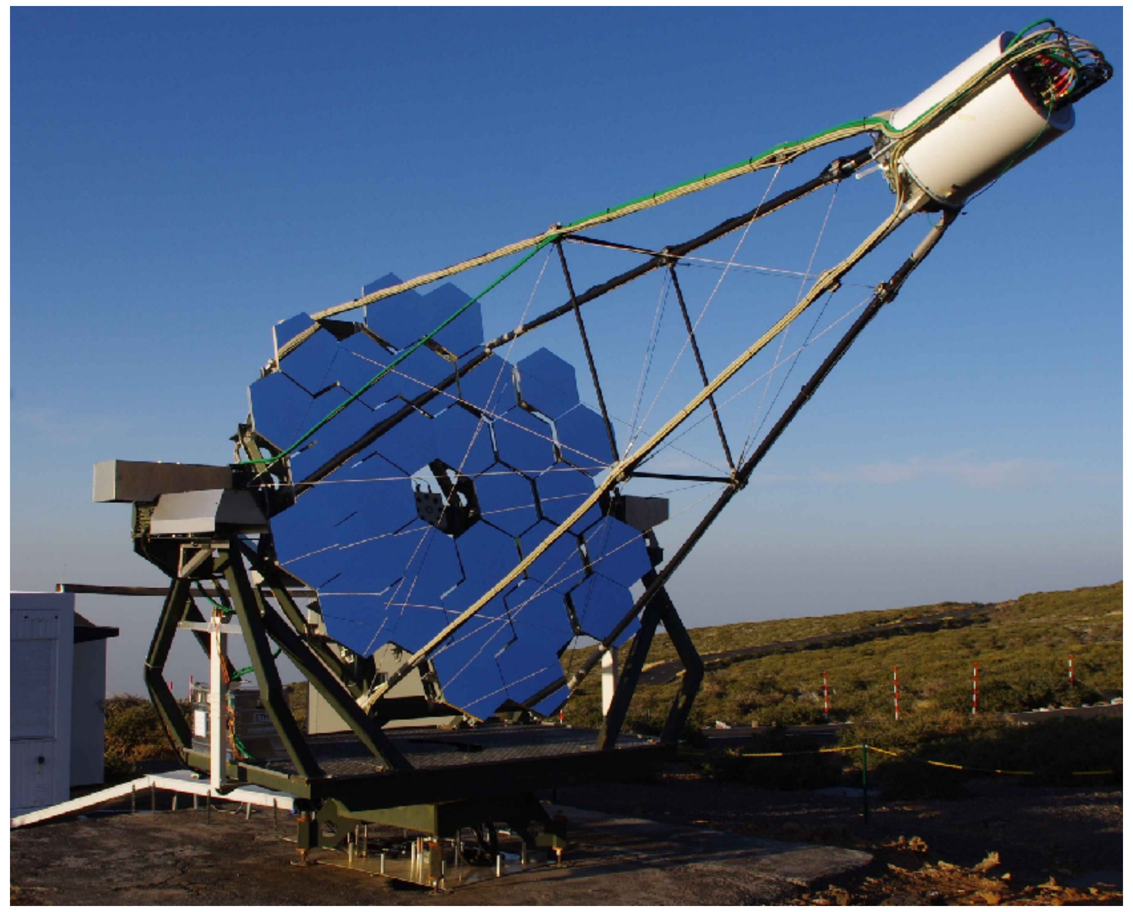
FACT: performance

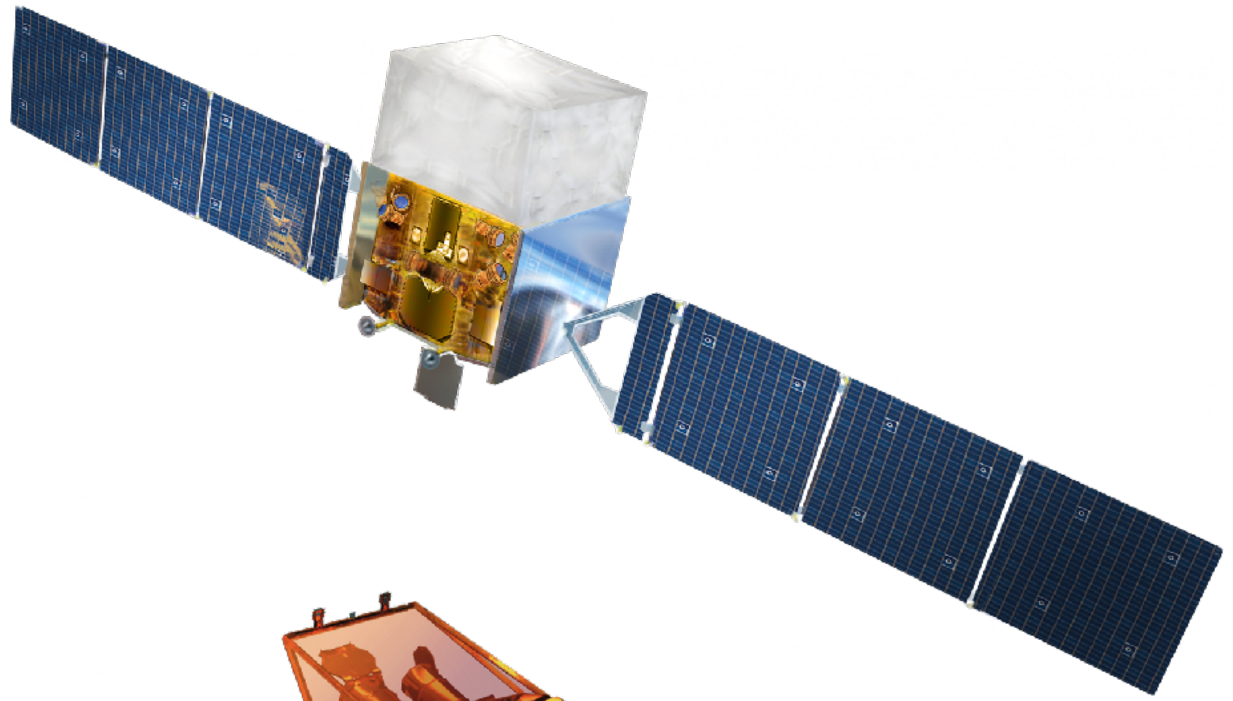
- Energy threshold: ~700 GeV (PL spectral index 2.2, e.g. Mrk 421, Arbet-Engels+2021)
- Unfolded energy spectrum of the Crab Nebula:

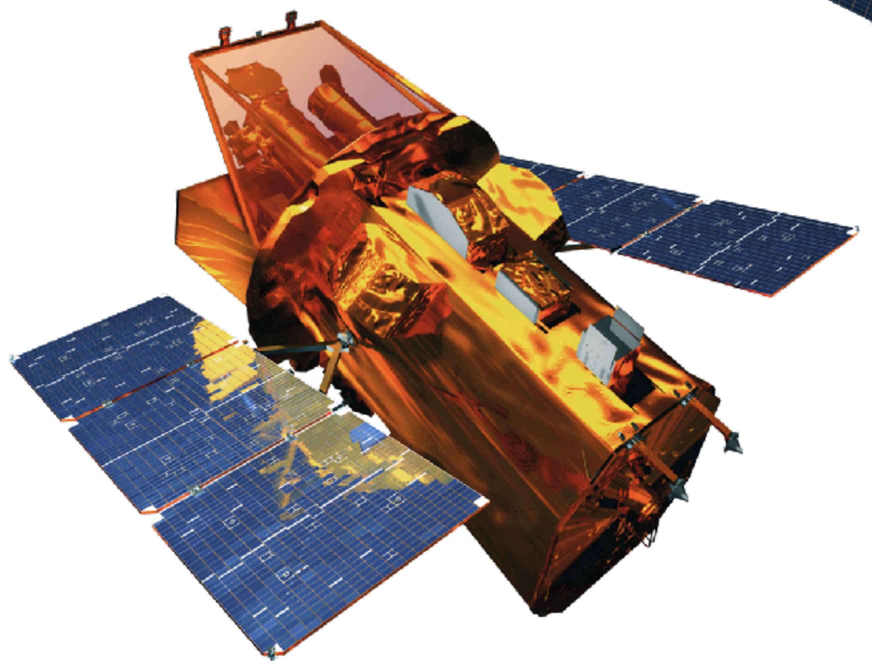


F. Temme et al., PoS, ICRC 2015

Multi-wavelength campaign

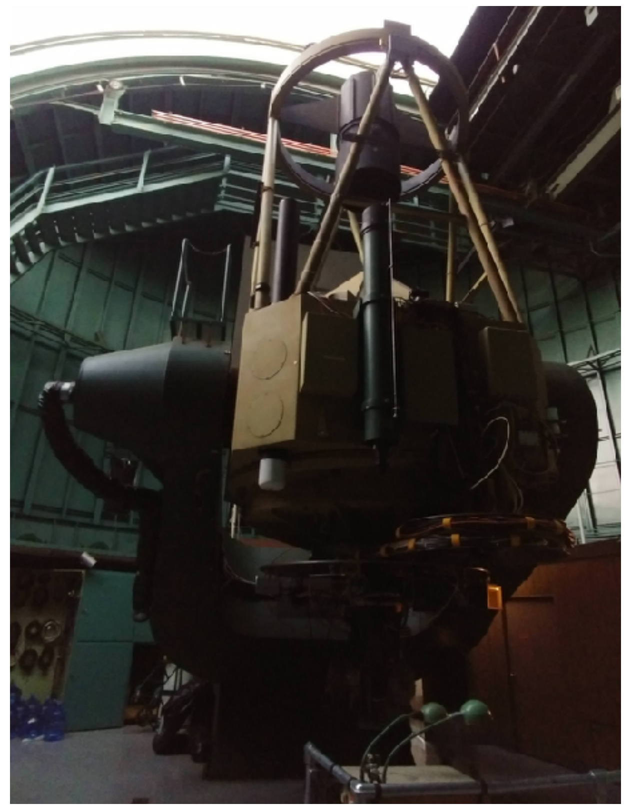


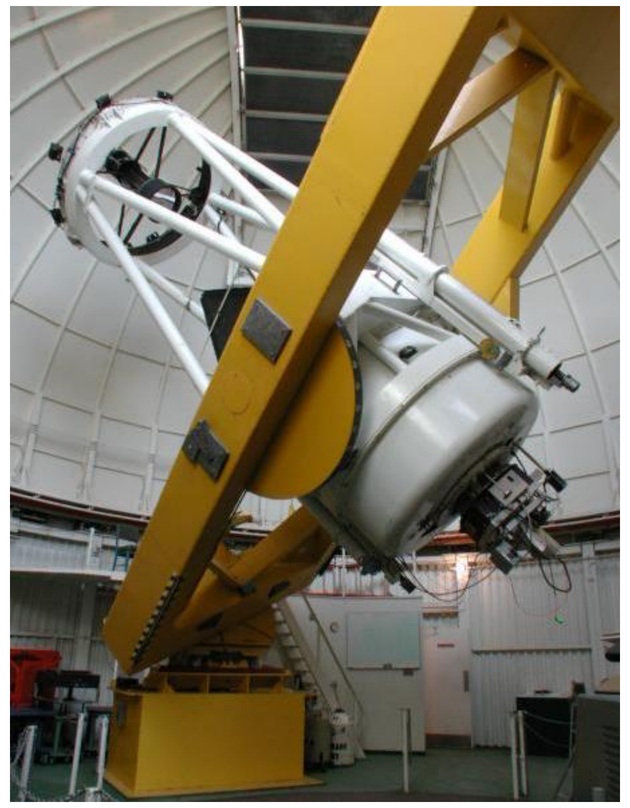




December 14, 2012 - April 18, 2018

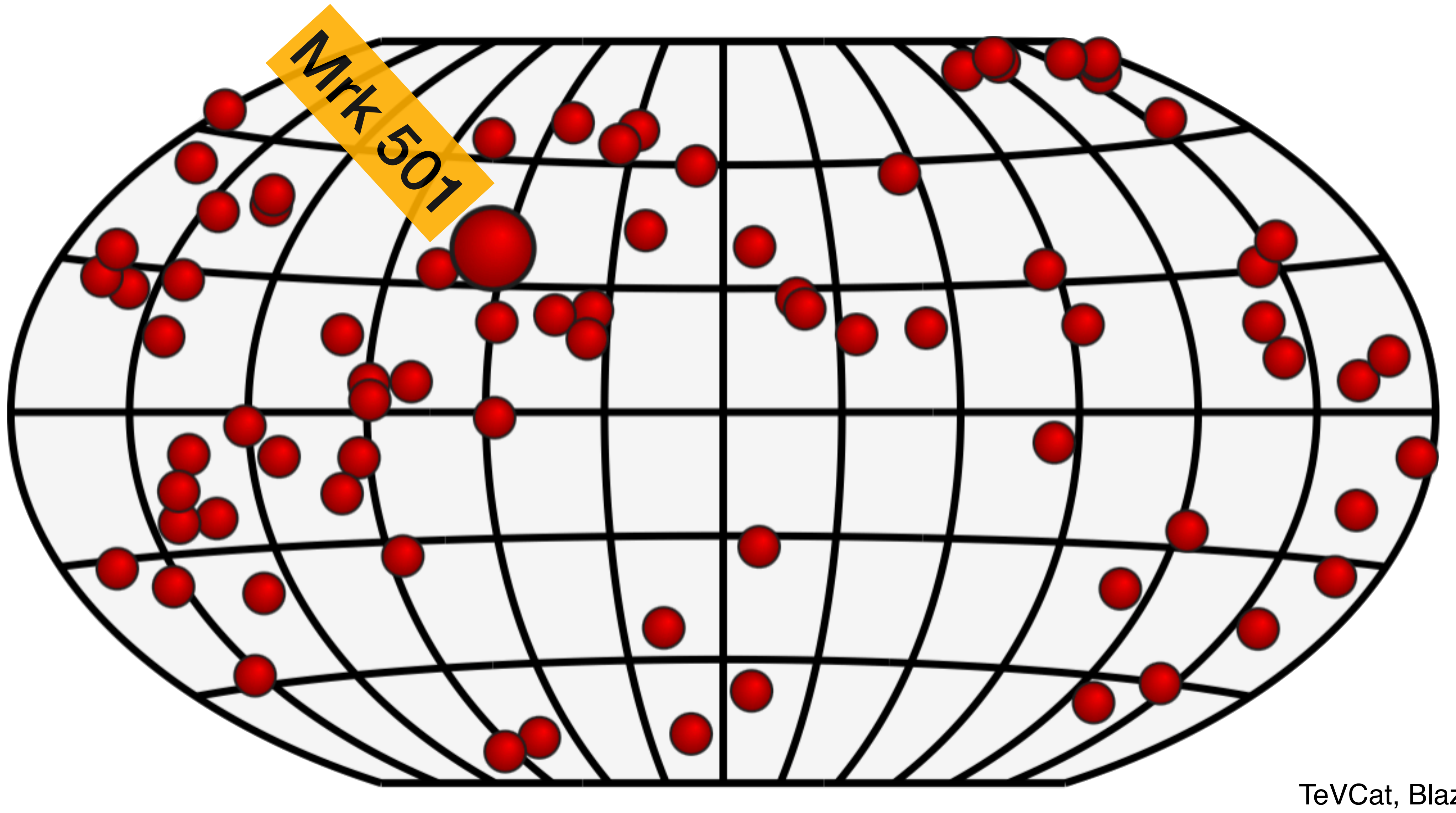
Instrument	*Band*	*Data*
FACT	> 580 GeV	584 nights / 2071 hours
Fermi-LAT	100 MeV - 300 GeV	1915 days
SWIFT/BAT	X-rays, 15-50 keV	1706 days (29344 orb.per.)
Swift/XRT	0.3-2 keV, 2-10 keV	478 days / 652 hours
Swift/UVOT	UV (UVW1, UVM2, UVW2 filters)	752 measurements
Kuiper (1.54 m) & Bok (2.3 m) telescopes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



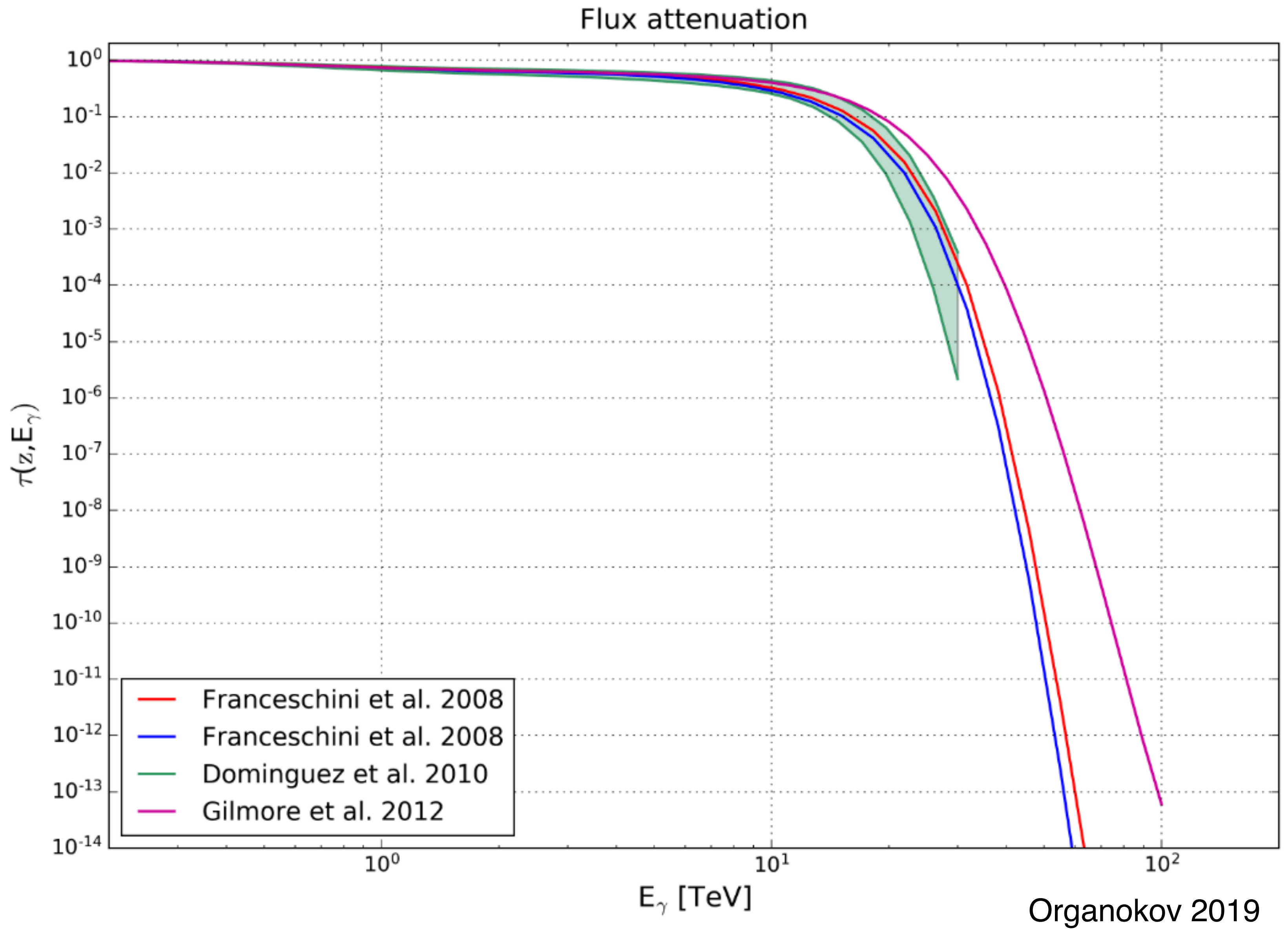


Why Mrk 501?

- Bright blazar
  - Easy to detect with IACTs, Fermi, in X-rays, optical and radio
    - Regular observations in TeV (MAGIC, FACT, VERITAS, HAWC, et al.), optical and radio
  - Relatively easy to characterize the entire SED during single "observation"
    - SED snapshots of individual flares
- No strong BLR effects
  - Less additional uncertainties than for FSRQs
- Nearby blazar (z ~ 0.03, ~140 Mpc)
  - Imaging with VLBI (MOJAVE, VLBA) down to scales of 0.01 pc (100 - 1000 R_s)
  - Minimal effect from EBL (which is not well known, and introduces systematics for VHE blazar science)



TeVCat, Blazars

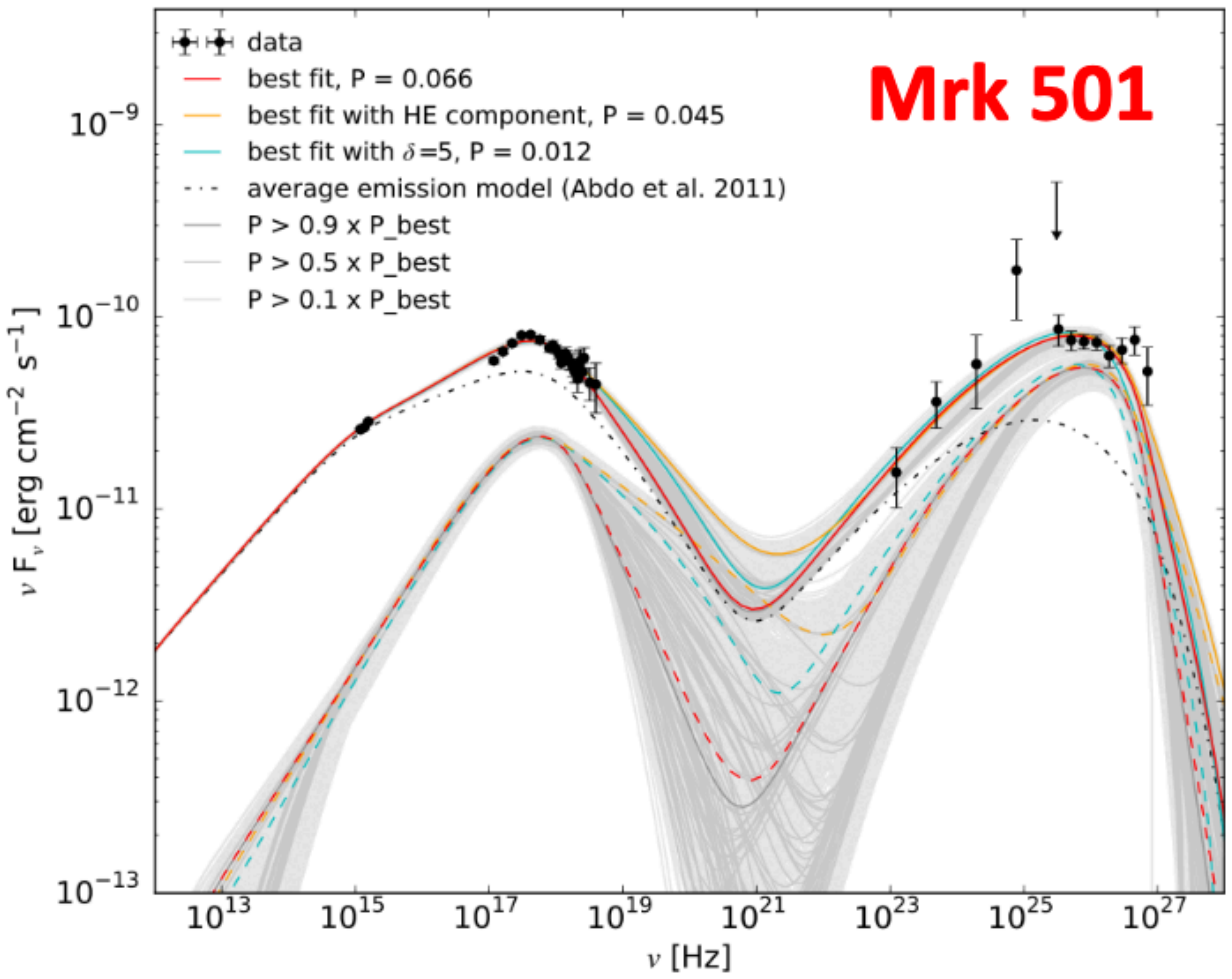


Organokov 2019

Mrk 501: overview

- Mrk 501 is a close HBL blazar
  - Bright and nearby blazar, z=0.034 (~140 Mpc)
  - $M_{BH} \sim 2\text{-}9 \times 10^8 M_\odot$
  - Imaged with VLBA up to <0.01-0.1 pc (<100-1000 rg)
  - Well defined jet structure extending for 10-20 mas (~10 pc)
- Low energy hump:
  - synchrotron emission during relativistic electrons cooling
- High energy hump:
  - leptonic models:
    - one-zone SSC model (Ahnen et al. 2017, Acciari et al. 2020)
    - multi-zone SSC model (Ahnen et al. 2017, Acciari et al. 2020)
  - hadronic models (Mastichiadis et al. 2013, Zech et al. 2017)
  - lepto-hadronic models:
    - synchrotron-proton model (Mücke & Protheroe 2001)
    - neutrino emission (Petropoulou 2015, Dermer Razzaque 2010)

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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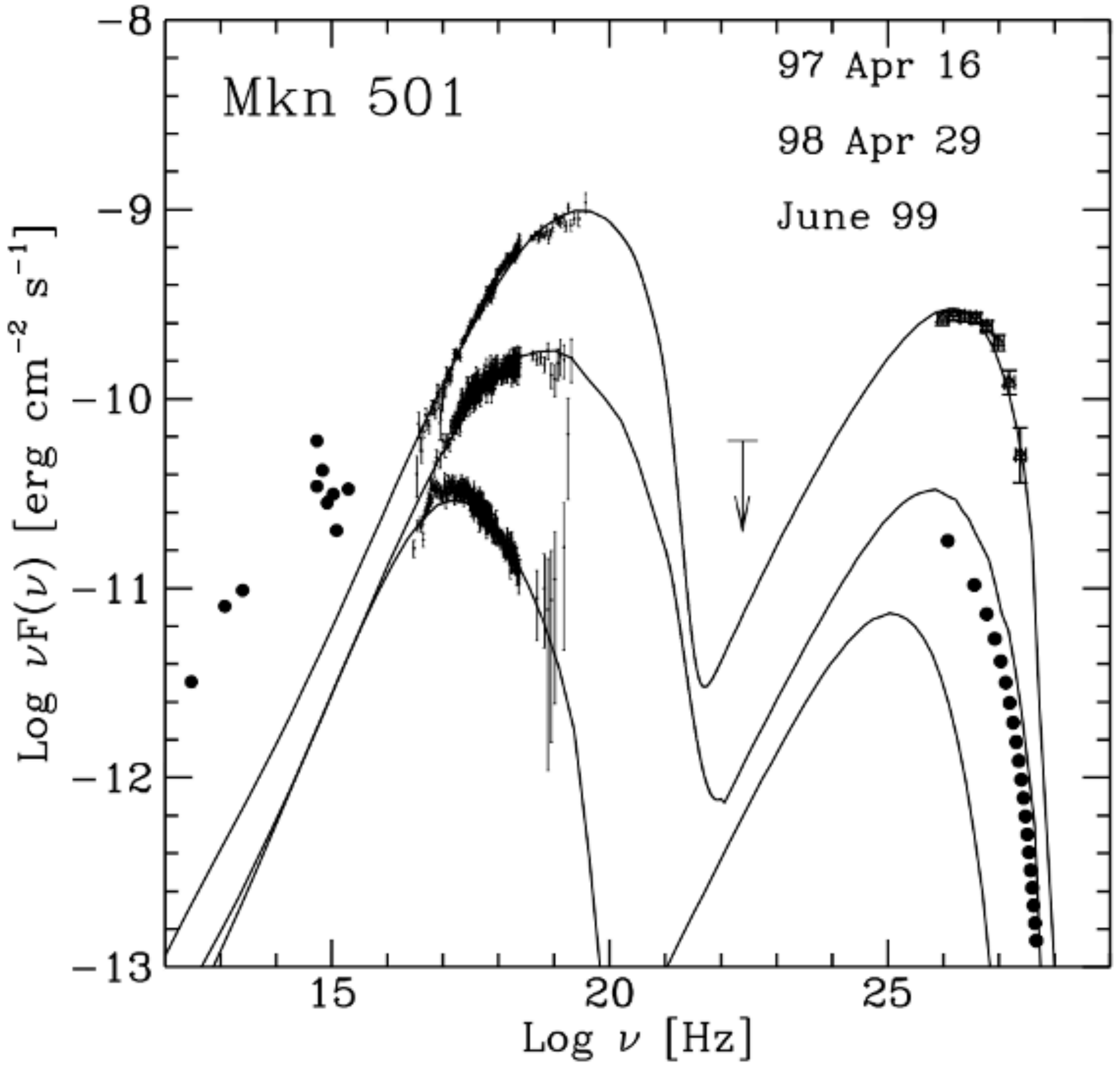
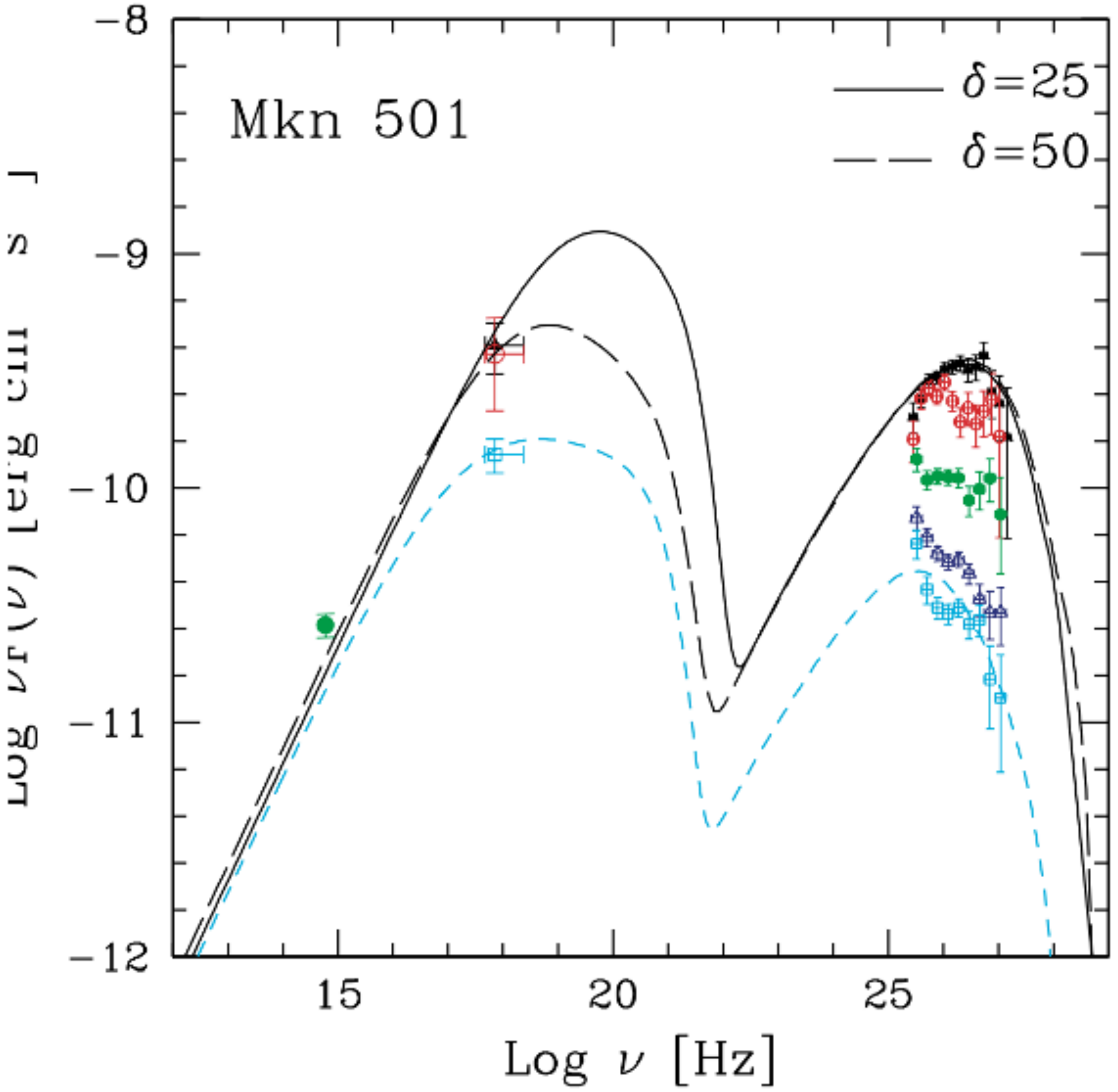
Spectral variability during flares

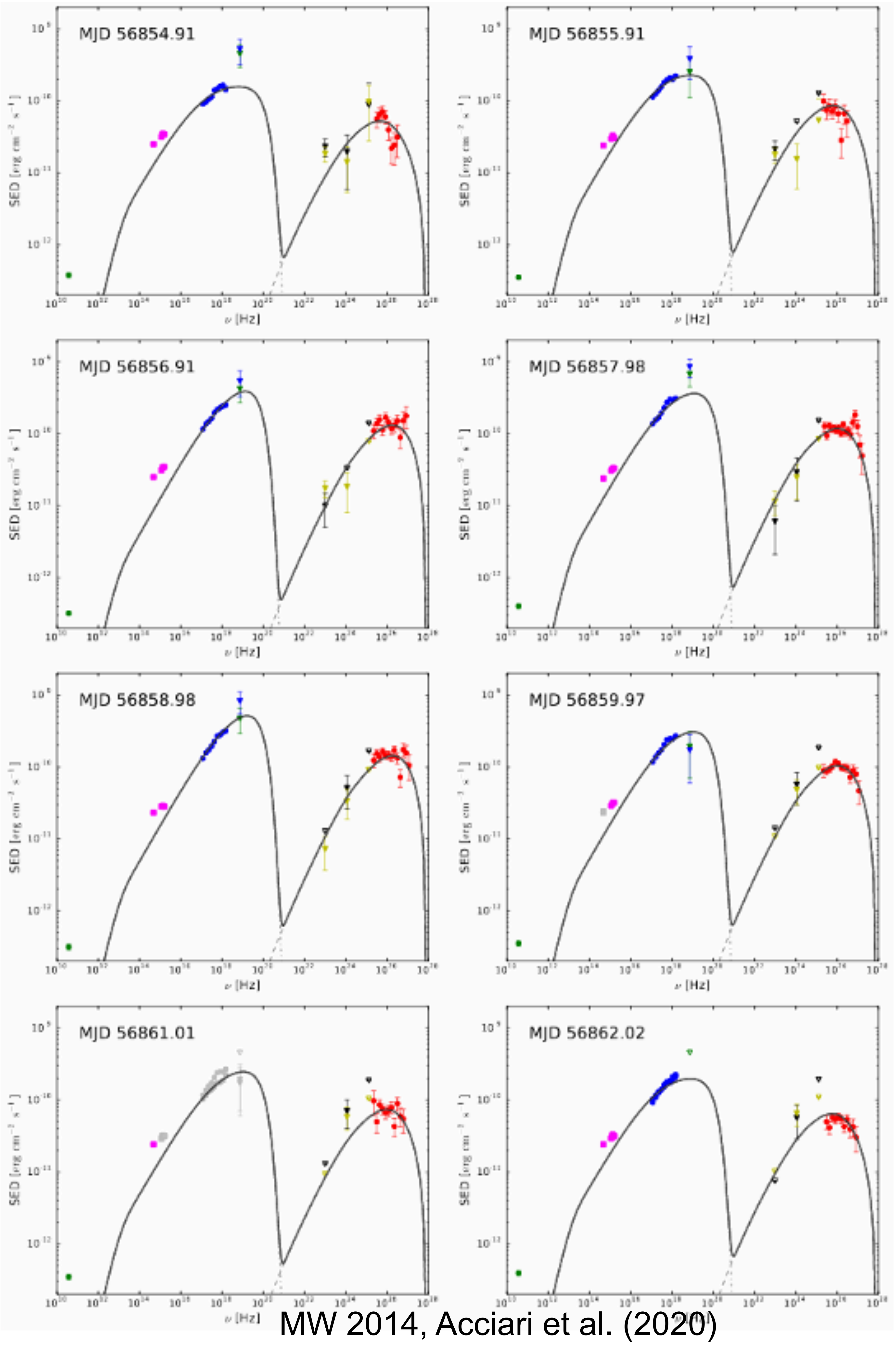
- Mrk 501 shows spectral variability in X-rays and VHE during flares
  - becoming EHBL during some flares
  - one-zone SSC generally does a good job, but introduction of a second small region may be necessary to describe a feature at 3 TeV:
    - may be an intermittent feature, since just occasionally present



MW 1997-99, Tavecchio et al. 2001



MW 2005, Albert et al. 2007

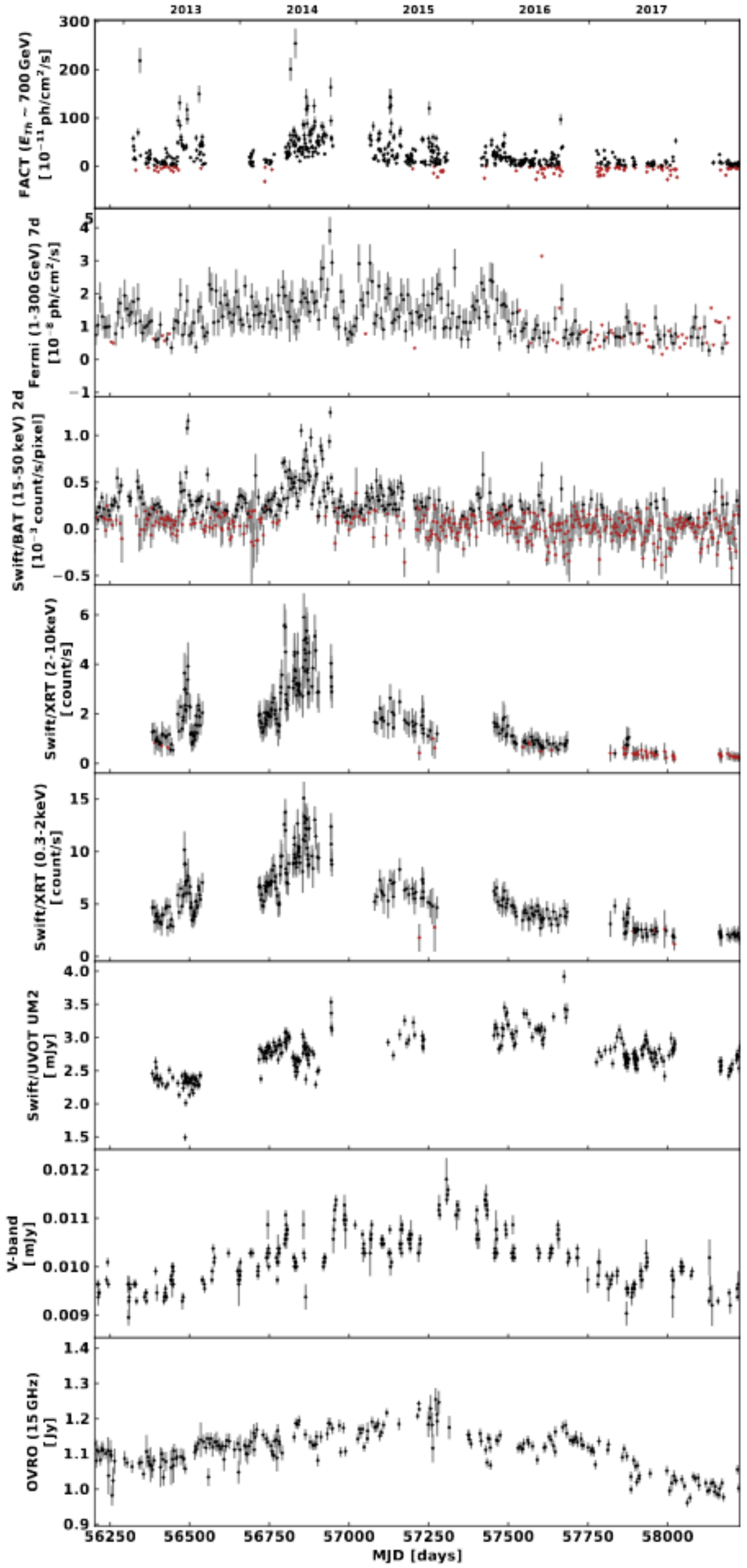


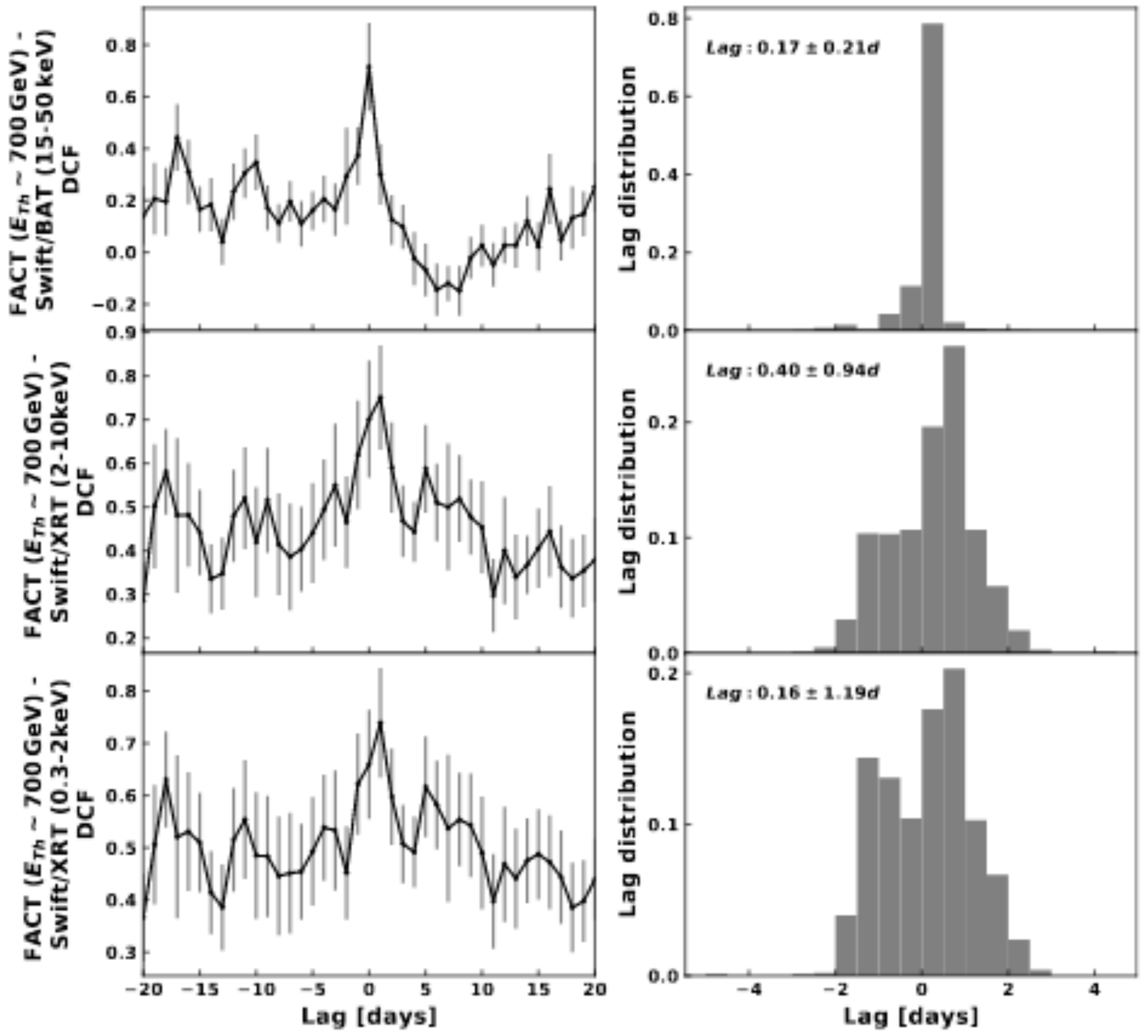
MW 2014, Acciari et al. (2020)

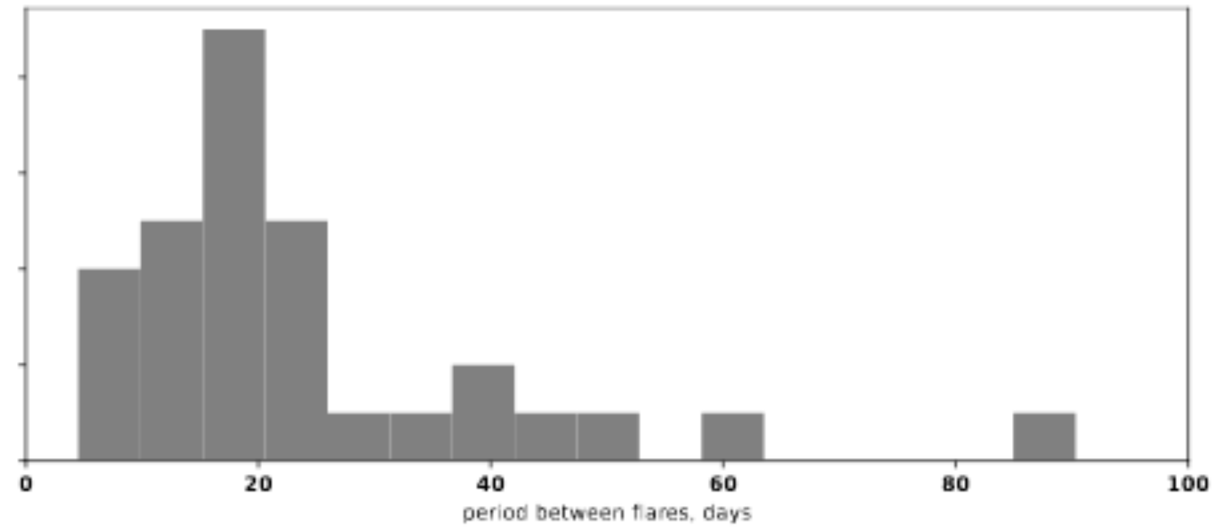
MWL campaigns: FACT Collaboration, in prep.

FACT
First G-APD Cherenkov Telescope

- Mrk 501 observations from December 2012 to April 2018
  - Mrk 501 was found in all states: typical, low, high
  - Data from radio to VHE (FACT), 8 instruments in total, unbiased observations
- Results:
  - F_{var} has a typical two peak structure, with lowest variability in radio and GeV
  - Highest variability in TeVs and X-rays
  - X-rays are strongly correlated with TeVs with sub-day lag (<0.4 days)
  - Radio, optical and GeV are not correlated with X-rays or TeV. Radio, optical are widely correlated with GeV with the latter leading by ~200 days.
  - Observed variability is compatible with one-zone SSC scenario
  - 37 individual days long flares. Distribution of time separation between those is peaking between ~17 - 20 days, being compatible with expected duration due to Lense–Thirring accretion disc precession.







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Mrk 501 variability

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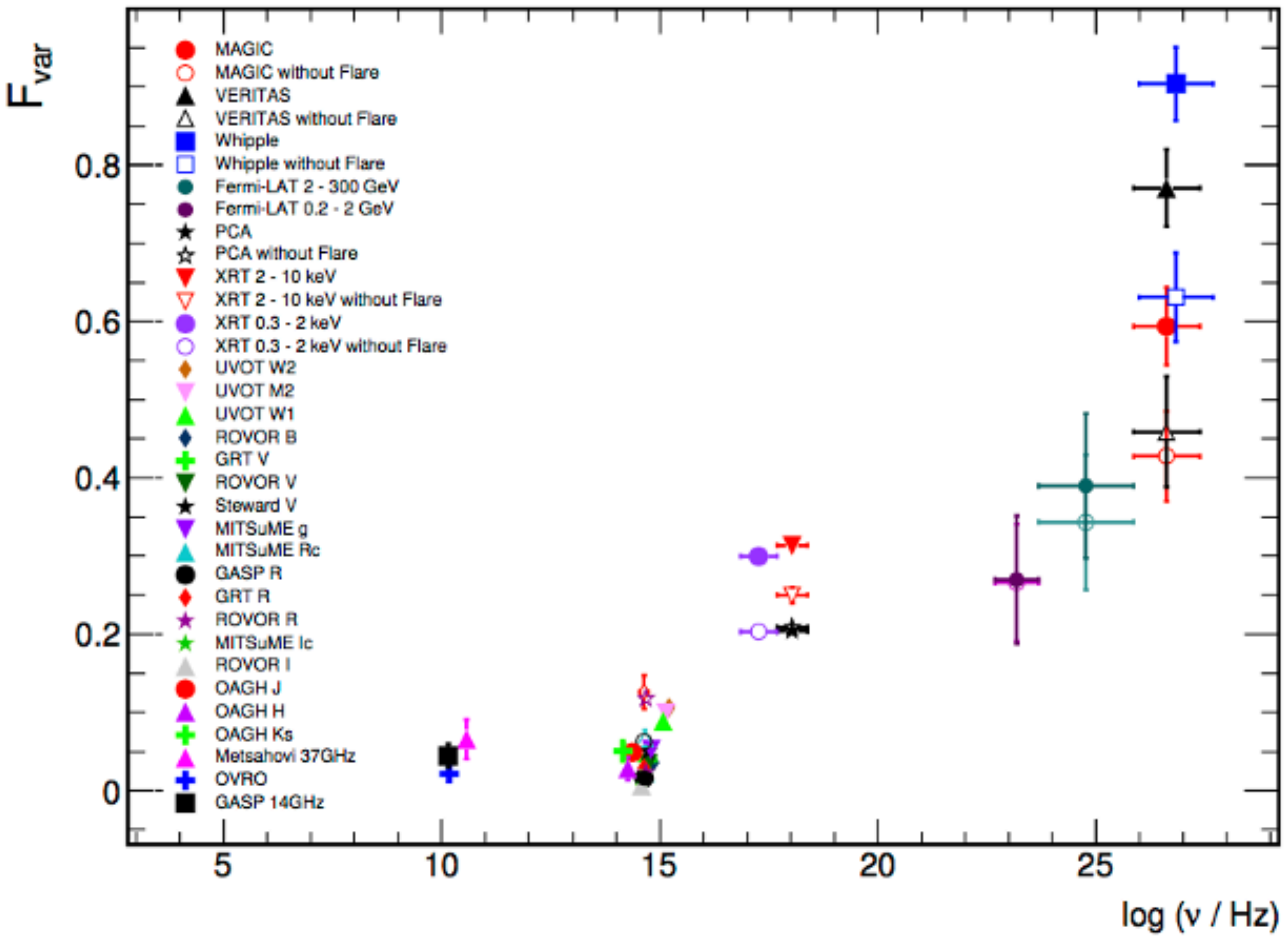
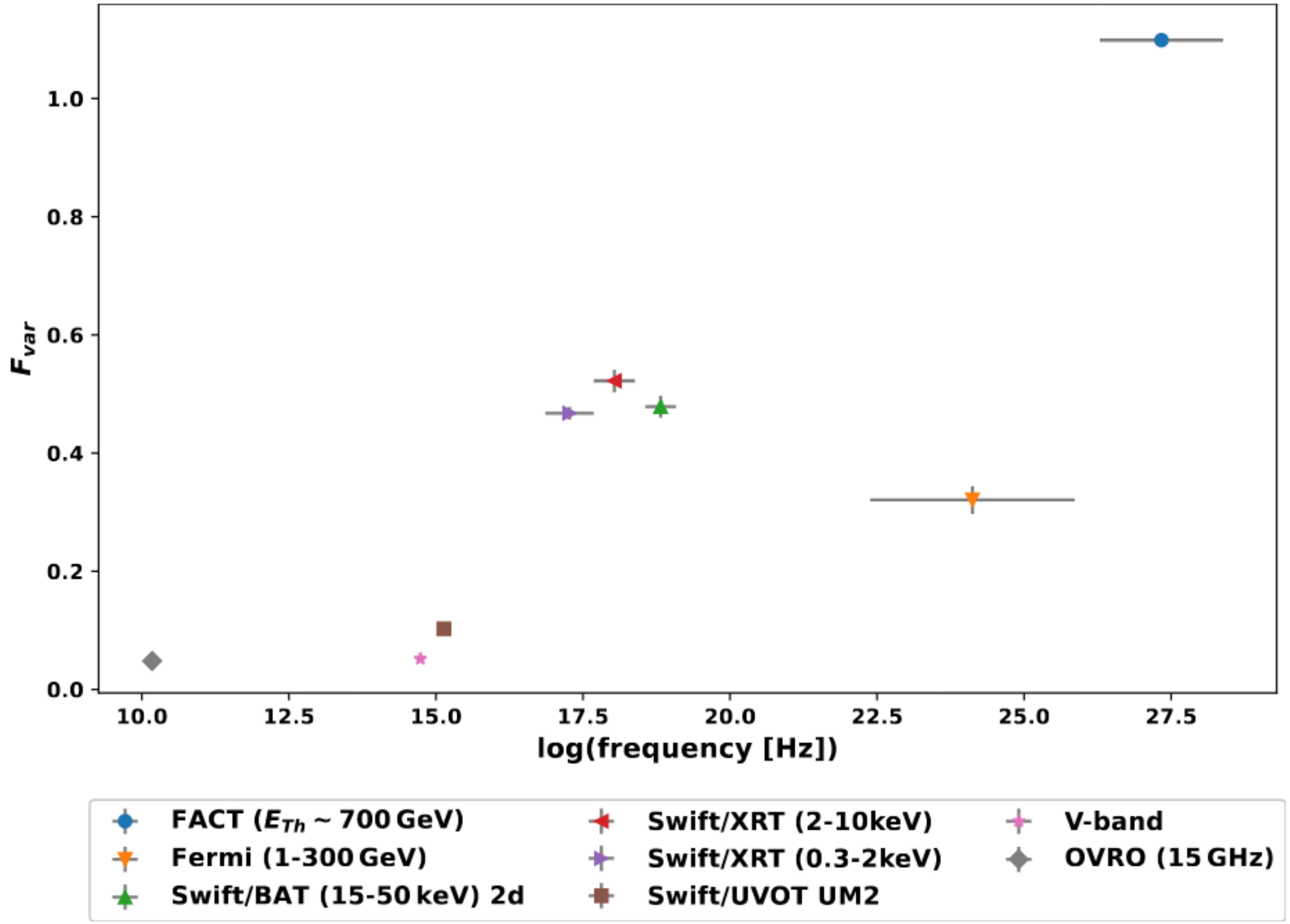
- Mrk 501 has different variability pattern during flares and on long-term periods

$$F_{\text{var}} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$



Ahnen et al. 2017



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Conclusions

- Mrk 501:
  - X-ray and TeV flares are well correlated (though only ~50% of the TeV flares were detected in the X-rays). The lag between the TeV and X-ray variations could be estimated as 0.31±0.38 days
  - The radio emission can be reproduced accurately by convolving the GeV light curve with a delayed response (a fast rise and a slow (127 days) decay after a delay of ≈217 days).
  - The strongest variability is in the X-ray and in the TeV bands.
  - Long term observations are compatible with one-zone SSC model.

- Next steps:
  - Multi-band variability and connection is fundamental to distinguish between emission models.
  - Temporal evolution to study short and long-term variability.

Thank you