UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

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cta cherenkov telescope array

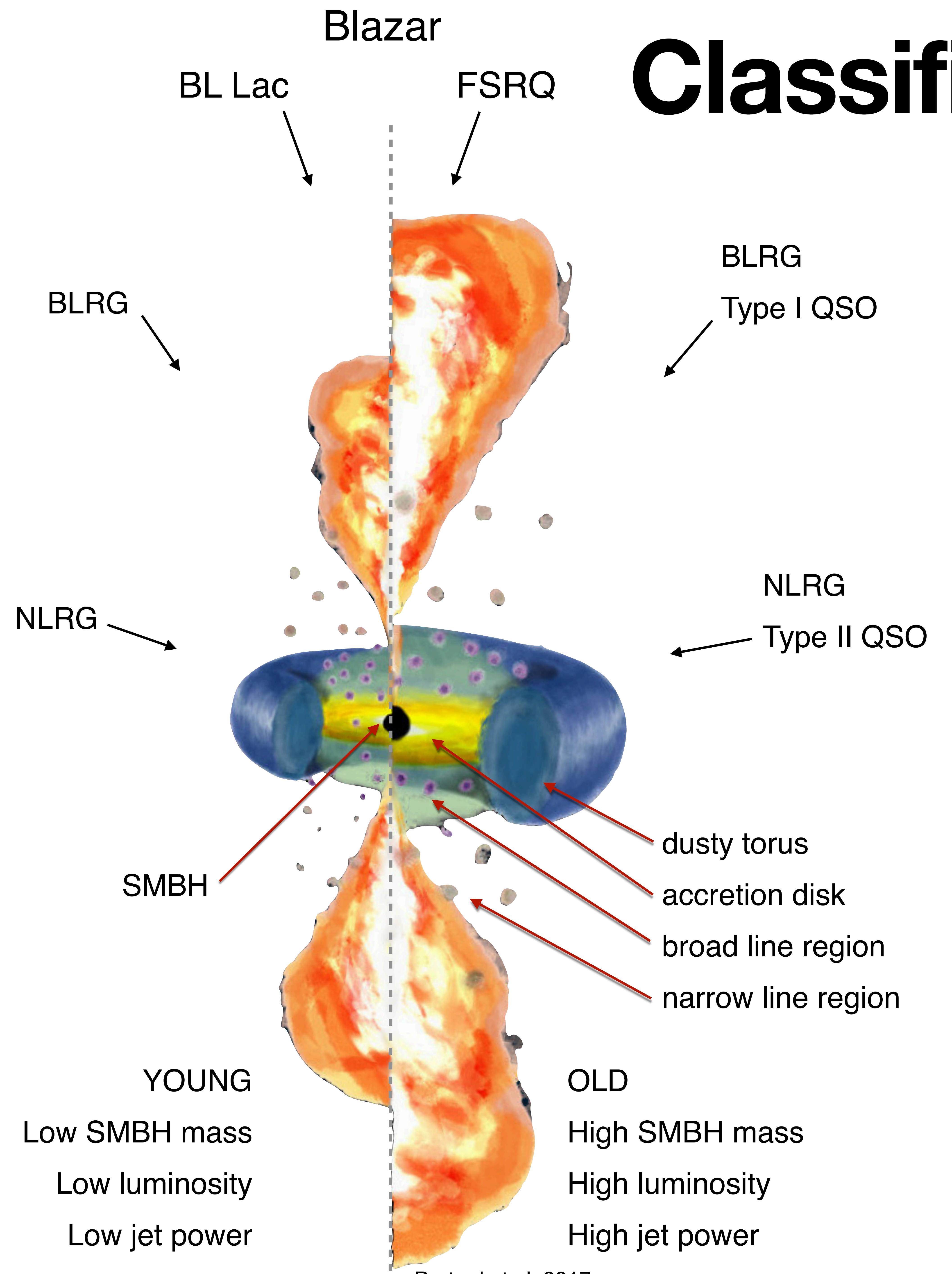
Variability of blazars: delays from long-term multi-wavelength observations

Vitalii Sliusar

University of Geneva, Department of Astronomy

CTA Swiss day 2022

Classification of AGNs



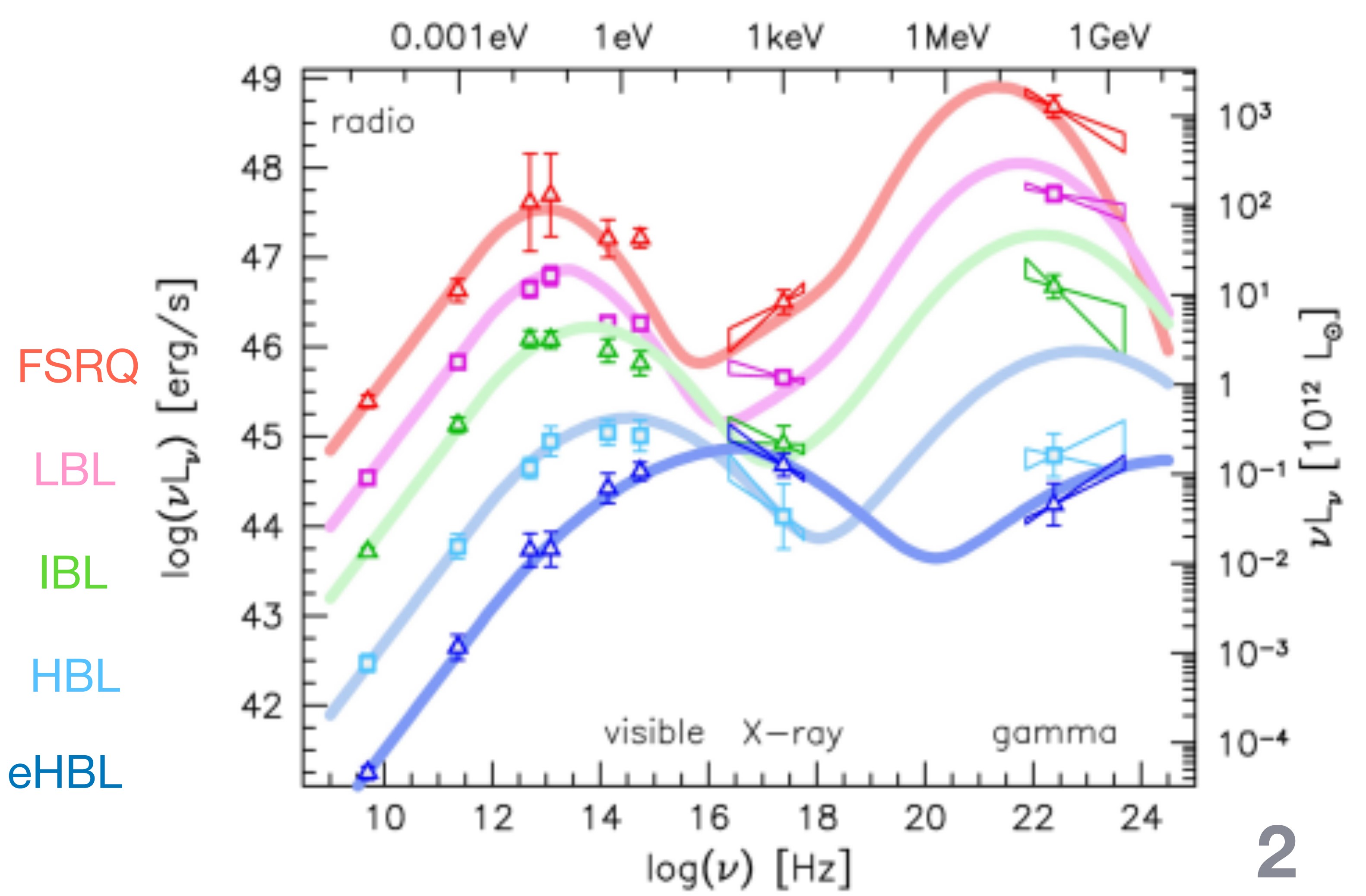
Bertoni et al. 2017.

Active Galactic Nuclei:

- Radio quiet:
  - *Seyfert 2 and Seyfert 1*
- Radio loud:
  - Radio galaxy:
    - *Narrow-line radio galaxy*
    - *Broad-line radio galaxy*
  - Blazars: BL Lac and FSRQ (<5% of AGNs)

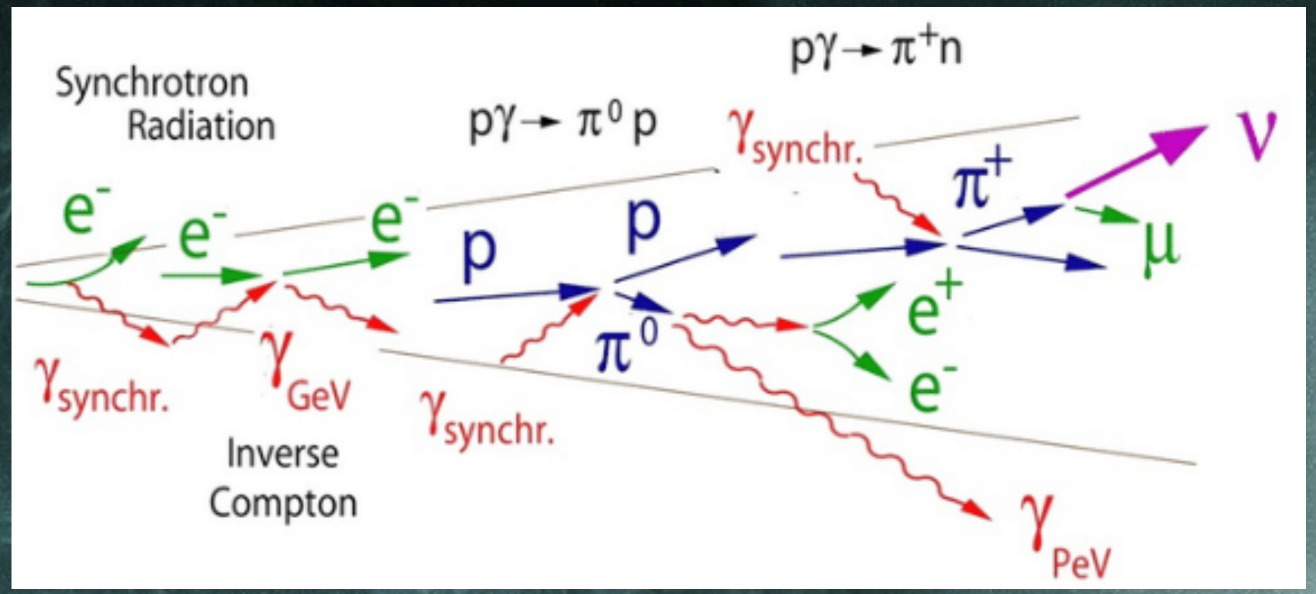
Blazars (Abdo et al. 2010, Fan et al. 2016):

- LBL: $\nu_p < 10^{14}$ (39%)
- IBL $10^{14} < \nu_p < 10^{15}$ (43%)
- HBL $\nu_p > 10^{15}$ (18%)



Fossati 1998, Blandford et al. 2019

Blazars: outlook



- **Acceleration of particles**
  - Diffusive shock acceleration
  - Relativistic reconnections
  - Stochastic acceleration
  - Magnetoluminescence

Non-thermal Radio - TeV emission

Supermassive Black Hole 10^6-10^9 $M_\odot$

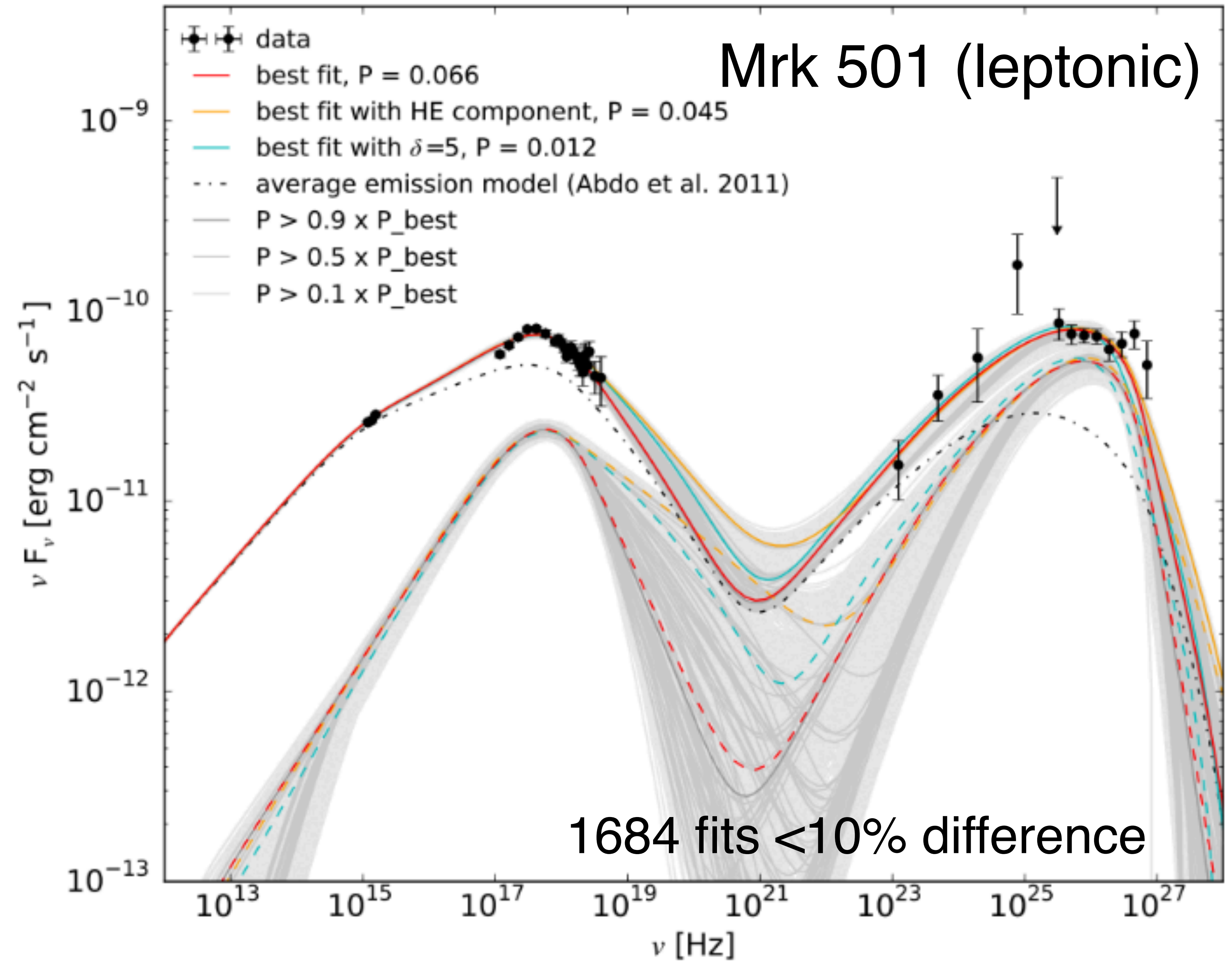
Extended plasma jet (~kpc - ~Mpc scales)

- **Radiative processes**
  - Leptonic: ultrarelativistic electrons, synchrotron and IC radiation
  - Handronic: proton-synchrotron, pion photoproduction:
  - Lepto-hadronic: mixture of leptonic and hadronic

Artistic view. Image credit: DESY, Science Communication Lab

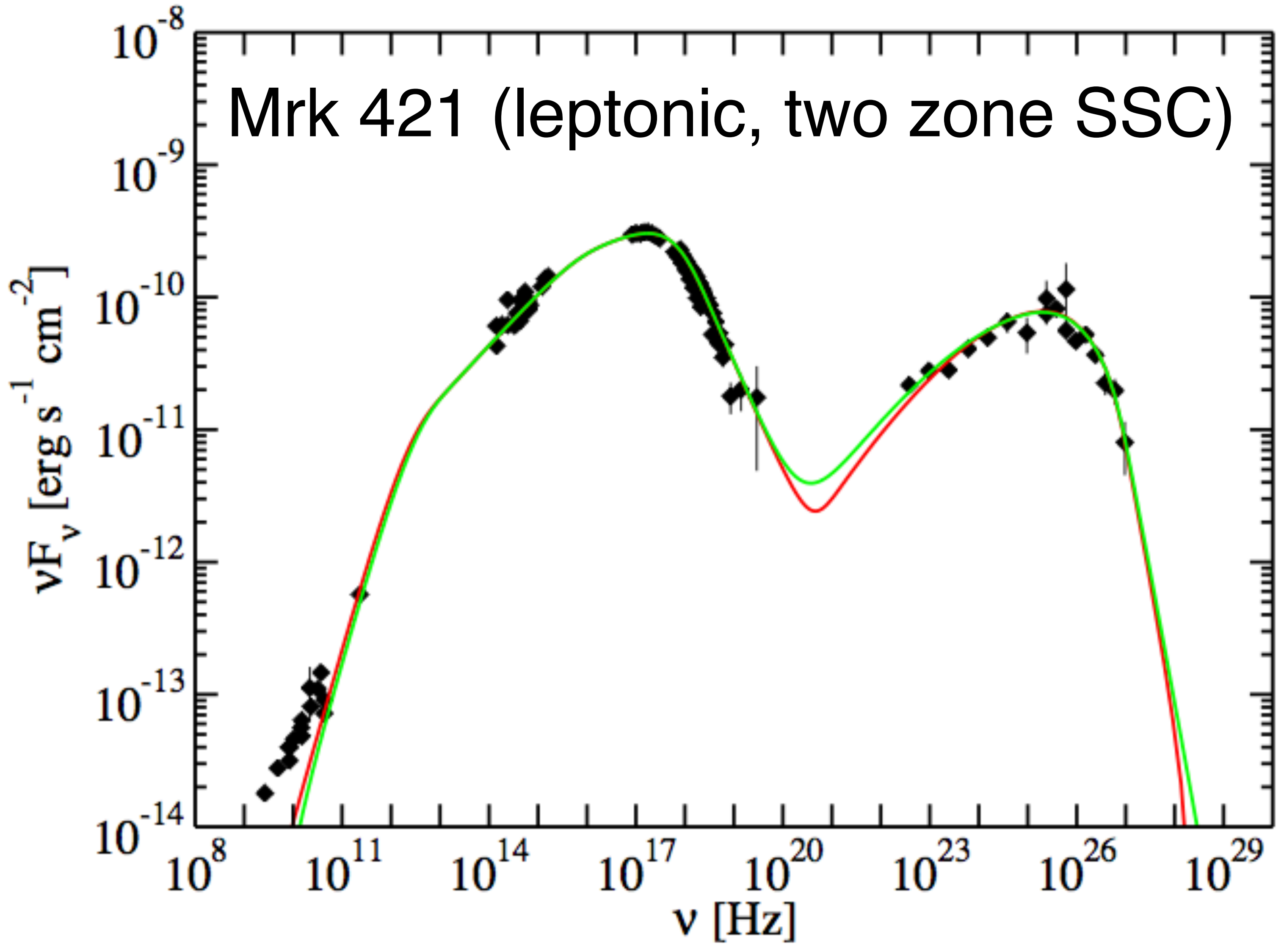
SED inter-model degeneracy

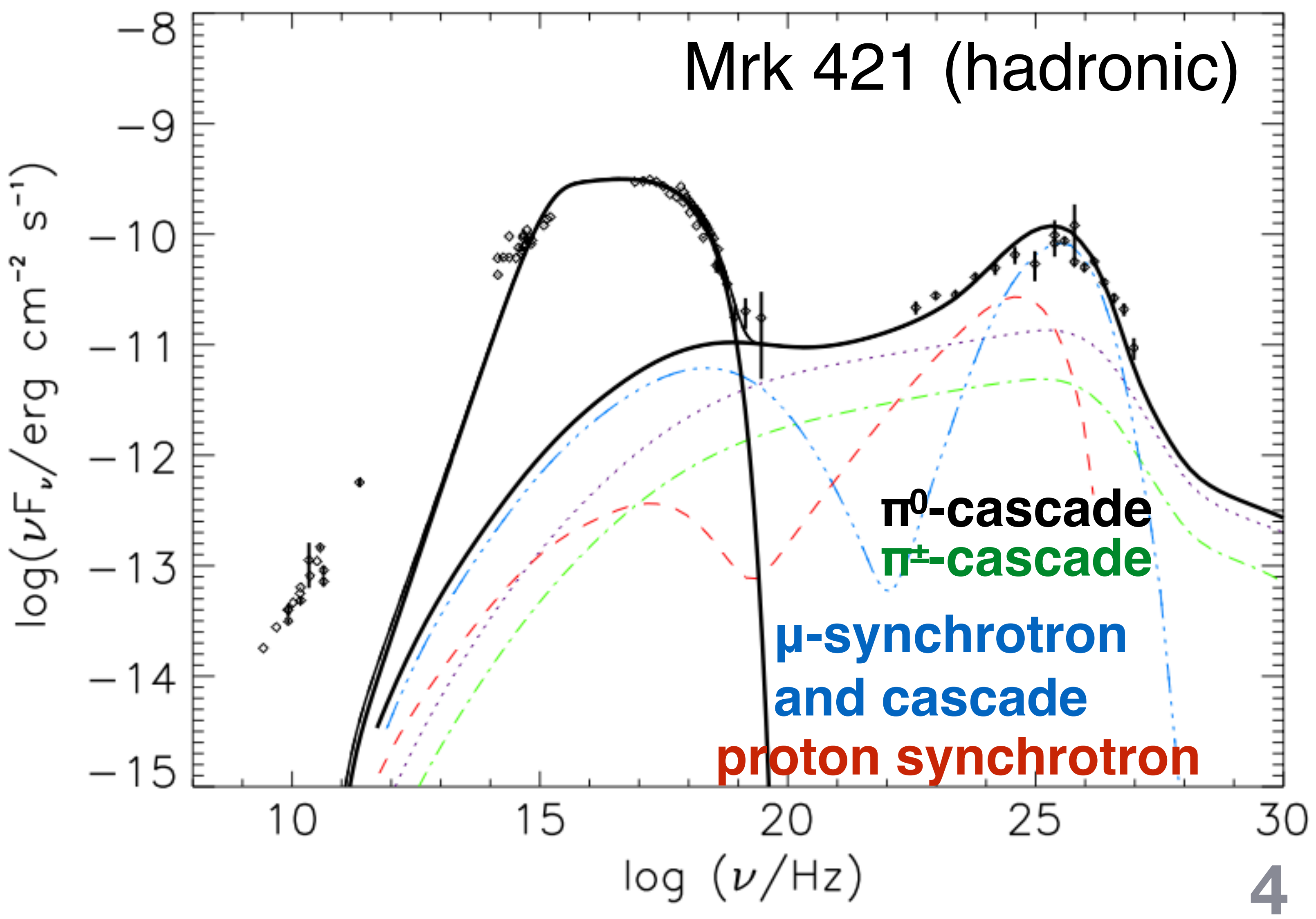
Ahnen et al. 2017, A&A 603, A31



- Mrk 421:
  - Leptonic scenario: electrons $E > 10^{13}$ eV
  - Hadronic scenario: protons $E > 10^{18}$ eV
- Mrk 501:
  - two zone SSC: quiescent region and a second variable emission region

Abdo et al 2011, ApJ 736, 131

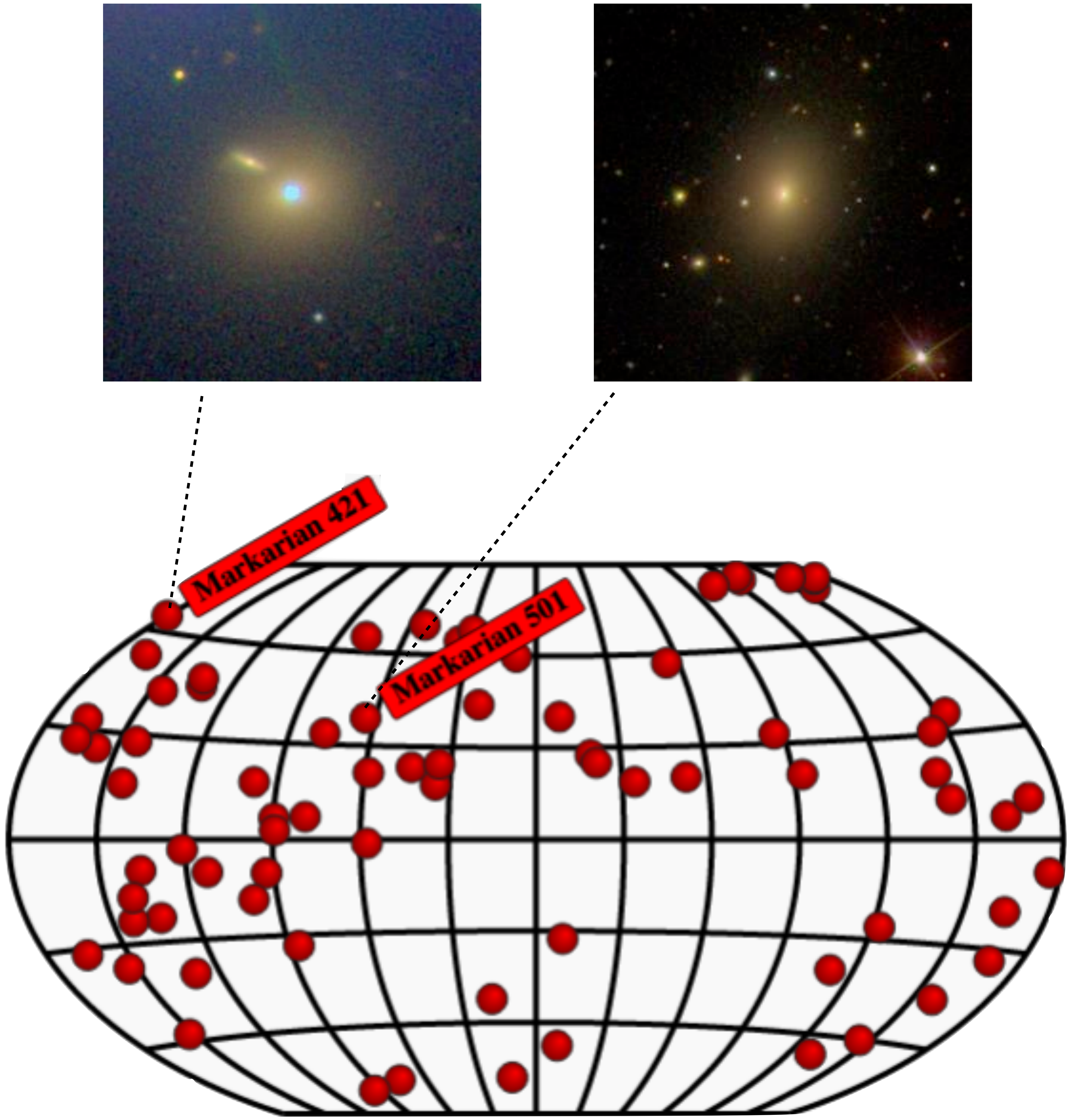




Multi-band variability is a key to distinguish between the models

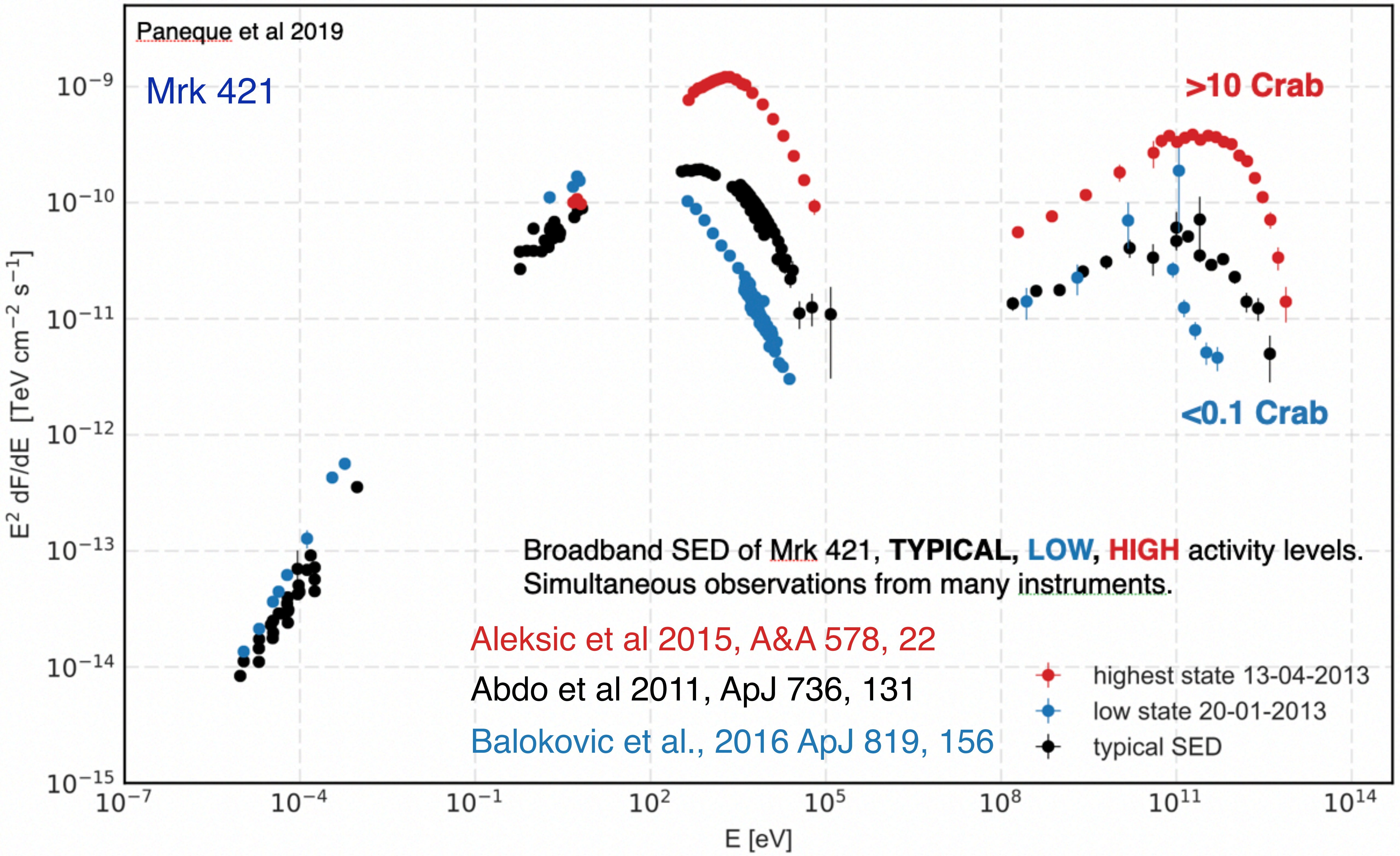
Mrk 421 and Mrk 501: blazar laboratories?

- Bright blazars
  - Easy to detect with IACTs, Fermi, in X-rays, optical and radio
    - Regular observations in TeV (MAGIC, FACT, Veritas, HAWC), optical and radio
  - Relatively easy to characterize the entire SED during single "observation"
    - Evolution of SED over time during individual flares
- No strong BLR effects
  - Less additional uncertainties than for FSRQs
- Nearby blazars (z ~ 0.03, ~140 Mpc)
  - Weak effect from EBL (unknown systematics for any blazar)
  - Imaging with VLBI (MOJAVE, VLBA) down to scales of 0.01 pc (100 - 1000 R_s)

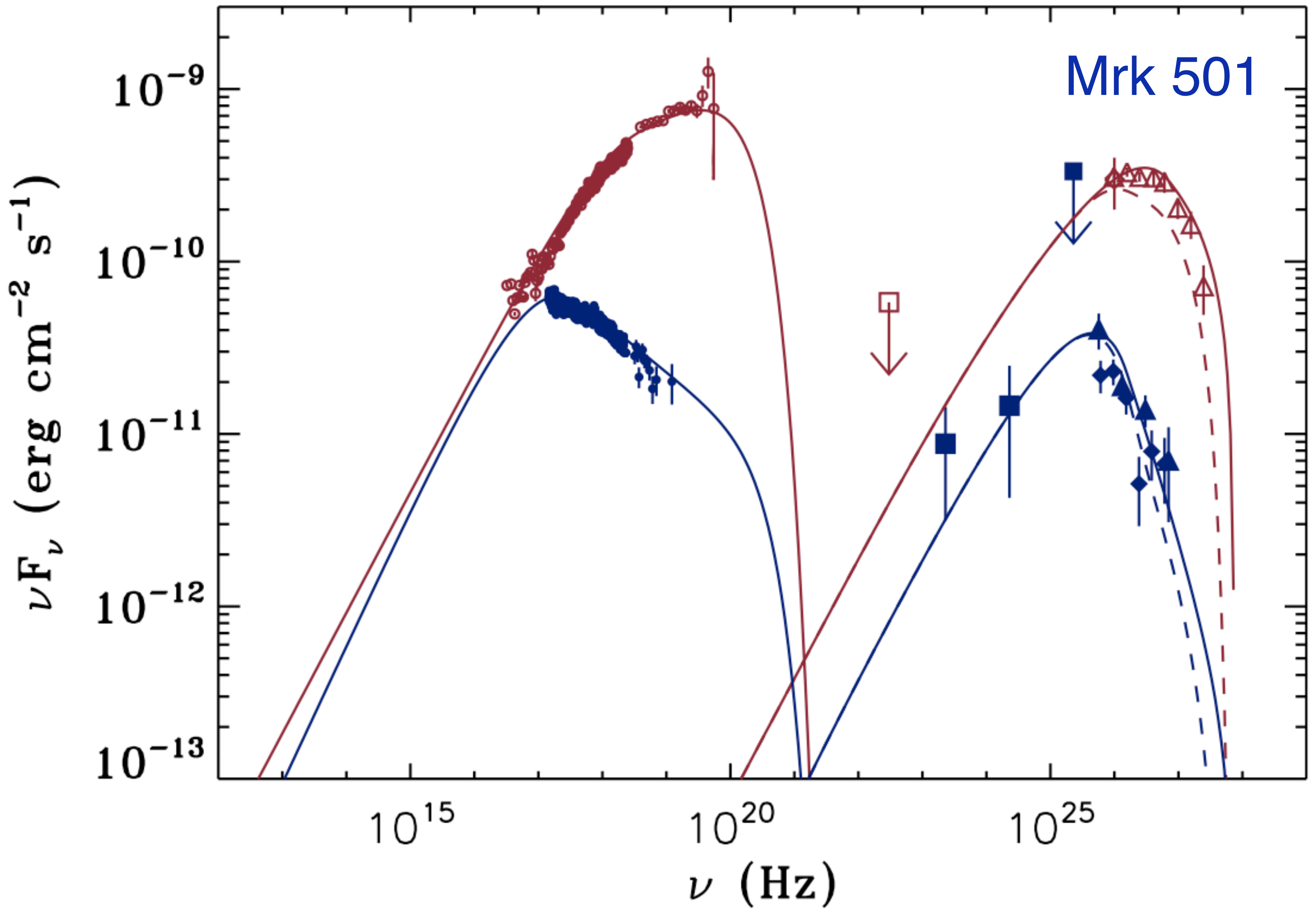


Spectral variability

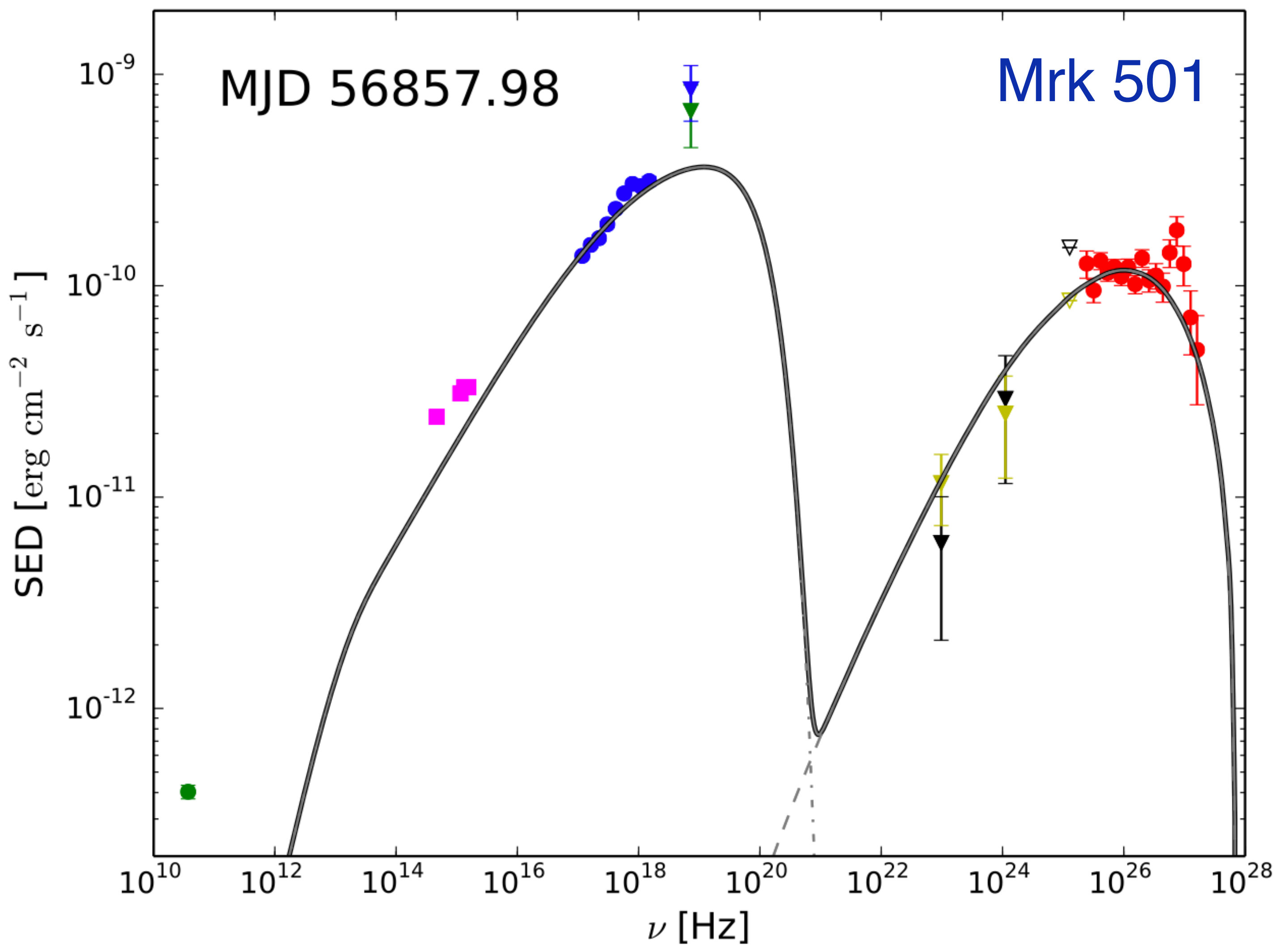
- Mrk 421:
  - Synchrotron peak shifts from typical HBL to IBL
  - One-zone SSC reasonably describes SED of Mrk 421
  - Flaring activity can also be described by two-zone SSC: one zone producing quiescent emission and another smaller zone producing intraday variability
  - Highest variability in X-rays and TeVs, lowest in radio and GeVs
  - Sub-hour variability on the top of flux variations occurring on multi-hour timescales (Acciari et al, 2020)



- Mrk 501:
  - Synchrotron peak shifts from HBL to eHBL
  - One-zone SSC reasonably describes SED of Mrk 501, but introduction of a second small region may be necessary to describe a feature at 3 TeV
  - Highest in X-rays and VHE, substantial variability in optical though not correlated with X-rays and VHE
  - Since about 2016 (MJD 57500) the source is in low state
  - Shortest variability of minutes-scale (Albert et al., 2007)



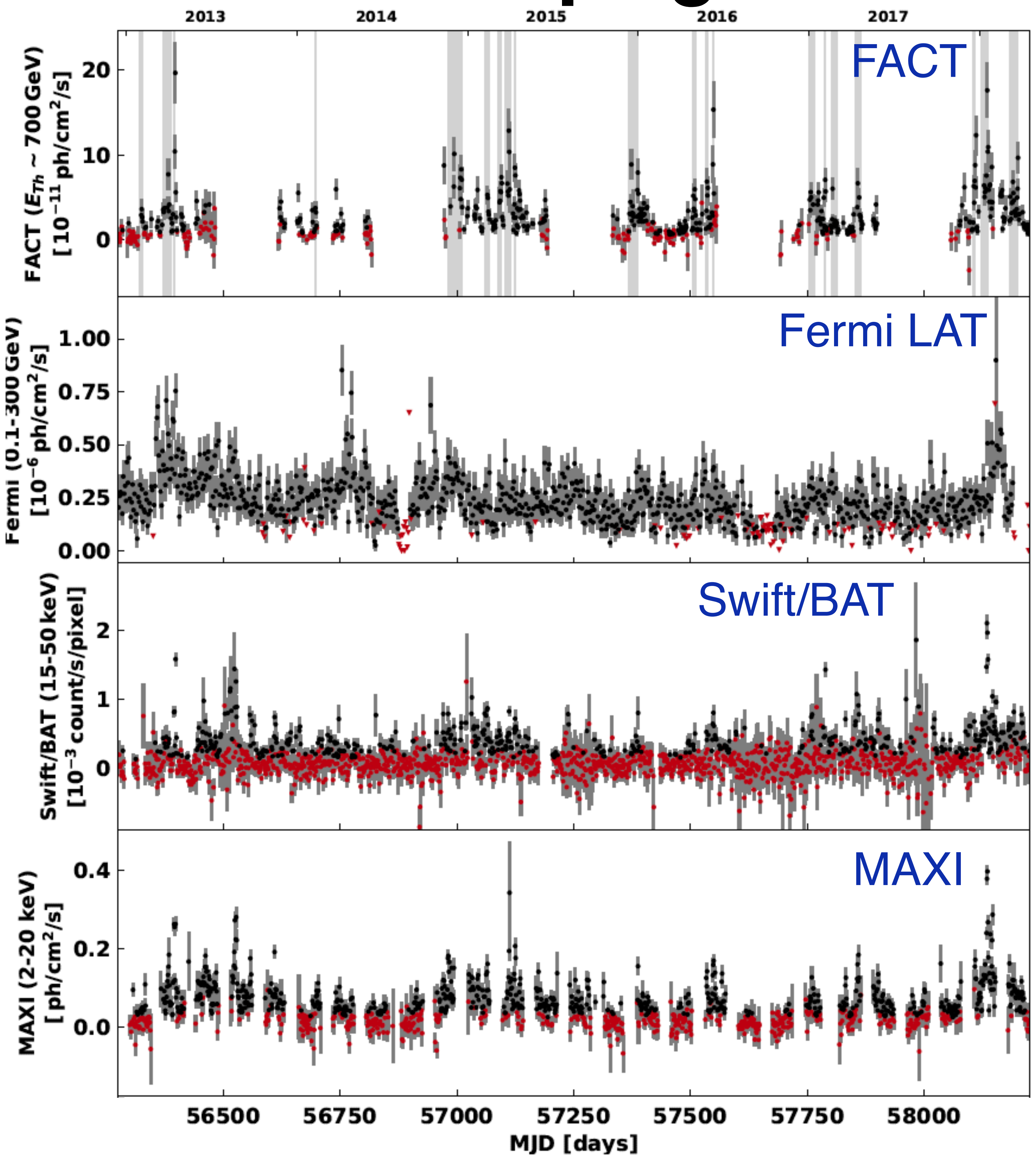
1997 outburst, Acciari et al. (2011)

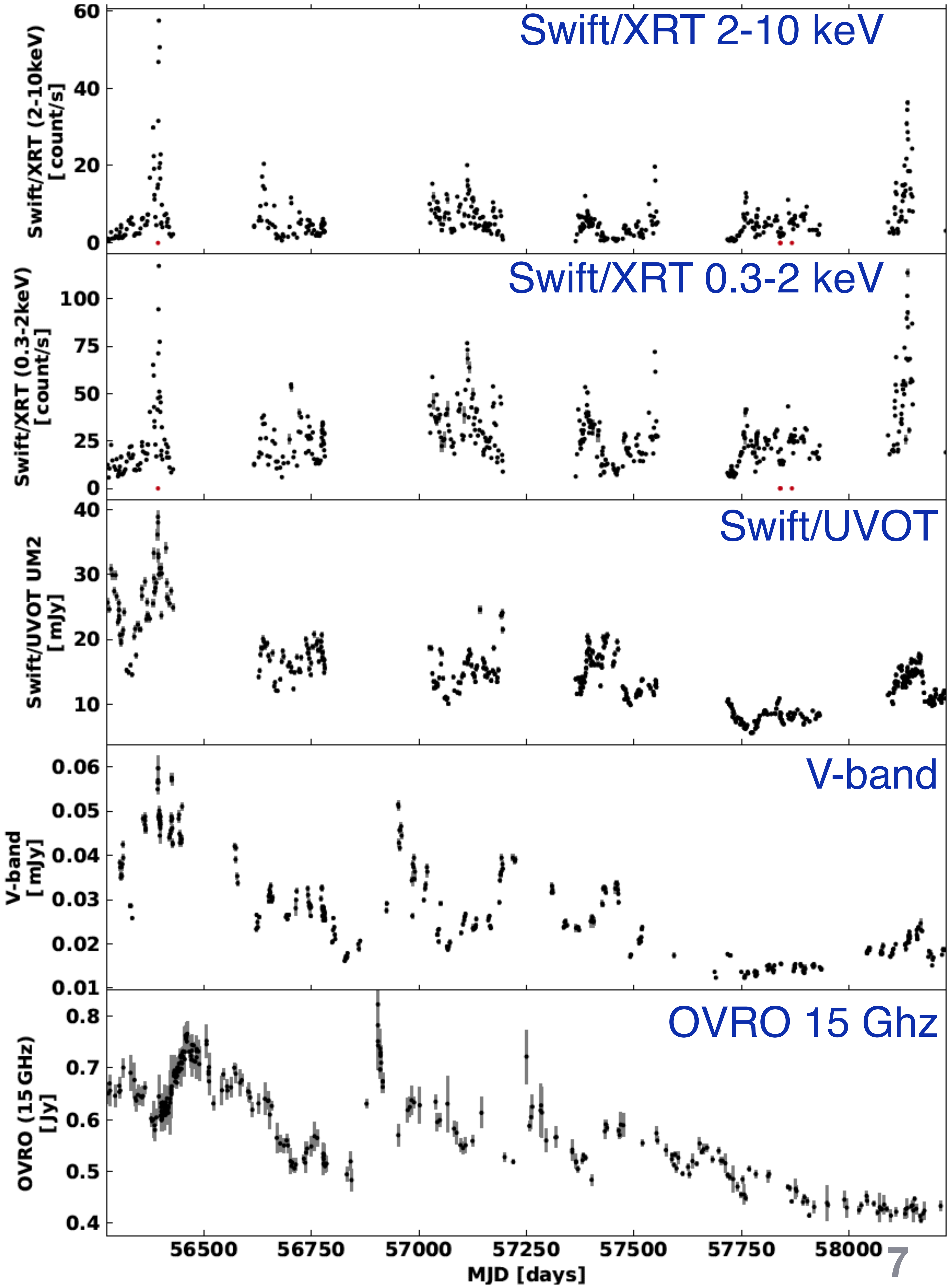


MW 2014, Acciari et al. (2020)

Mrk 421 long-term MWL campaign

Fact Collaboration+VS+MB+RW, A&A 647, 2021



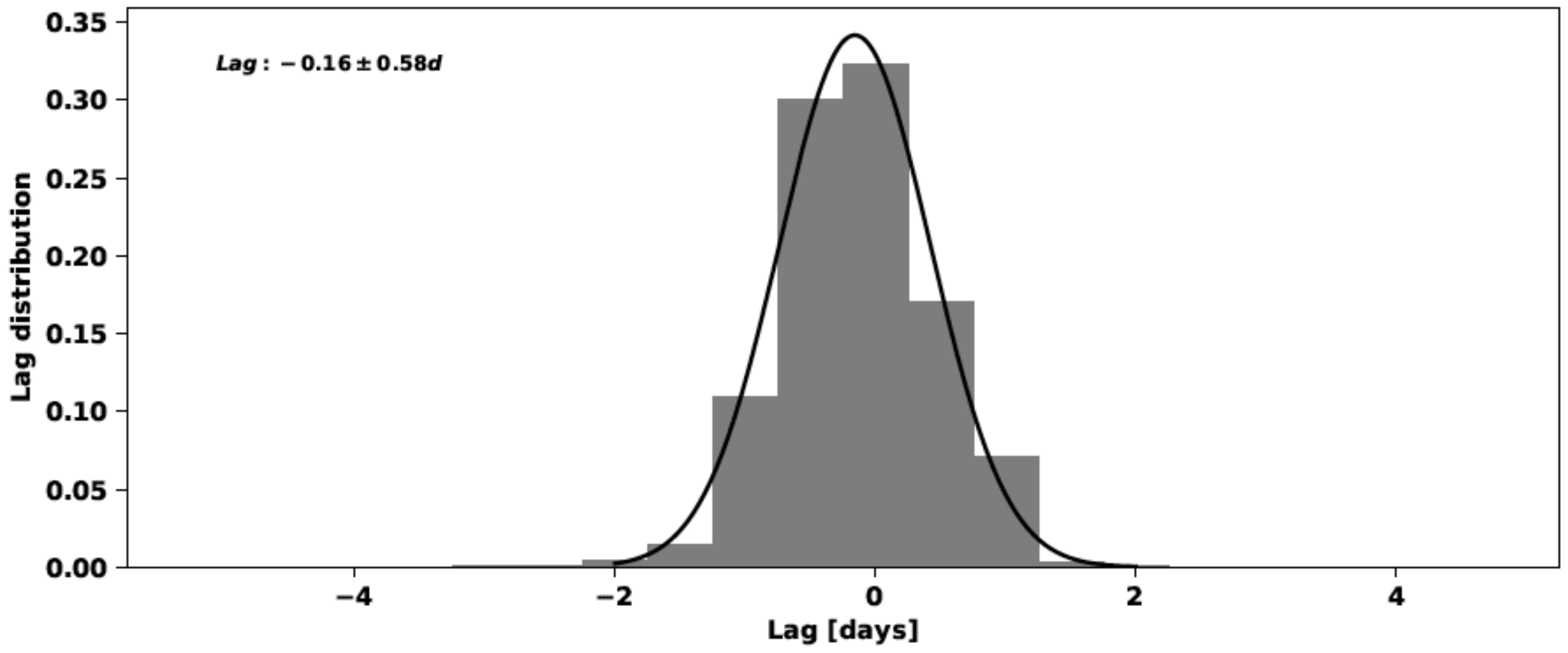


- Mrk 421 observations from December 2012 to April 2018
  - 2071 hours/584 days of unbiased VHE data from FACT
  - 9 instruments in total: from radio to VHE

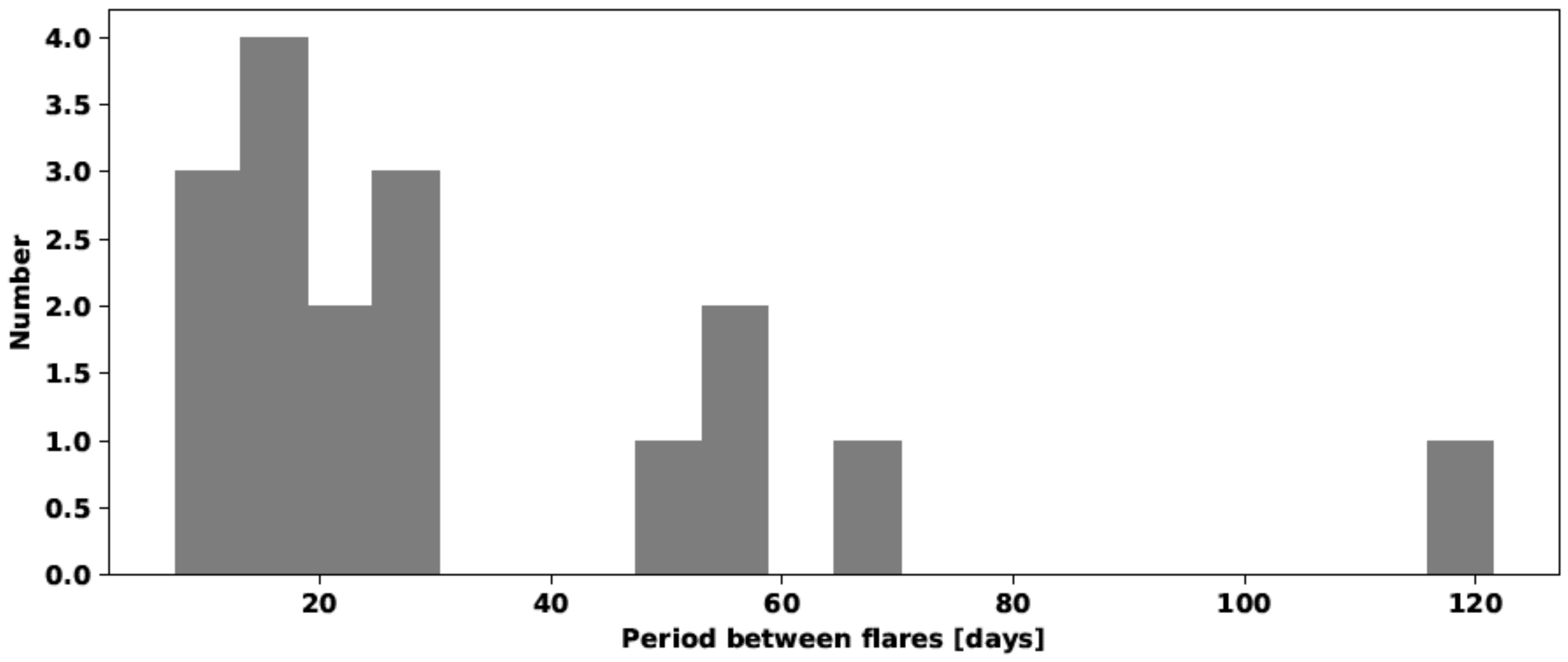
Mrk 421 long-term MWL campaign

Fact Collaboration+VS+MB+RW, A&A 647, 2021

- Mrk 421 MW campaign results:
  - F_{var} has a typical two peak structure:
    - lowest variability in radio and GeV
    - highest variability in X-rays and TeVs
  - X-rays are strongly correlated with TeVs with sub-day lag (<0.6 days)
  - Radio, optical and GeV are not correlated with X-rays or TeV
  - Radio, optical are widely correlated with GeV with later leading by 30-100 days.
  - Observed variability is compatible with one-zone SSC scenario
  - 22 individual TeV flares were identified:
    - distribution of time separation between those is peaking between 7.5 and 30 days
    - such time separation compatible with expected duration due to Lense–Thirring accretion disc precession



X-rays - TeV lag distribution

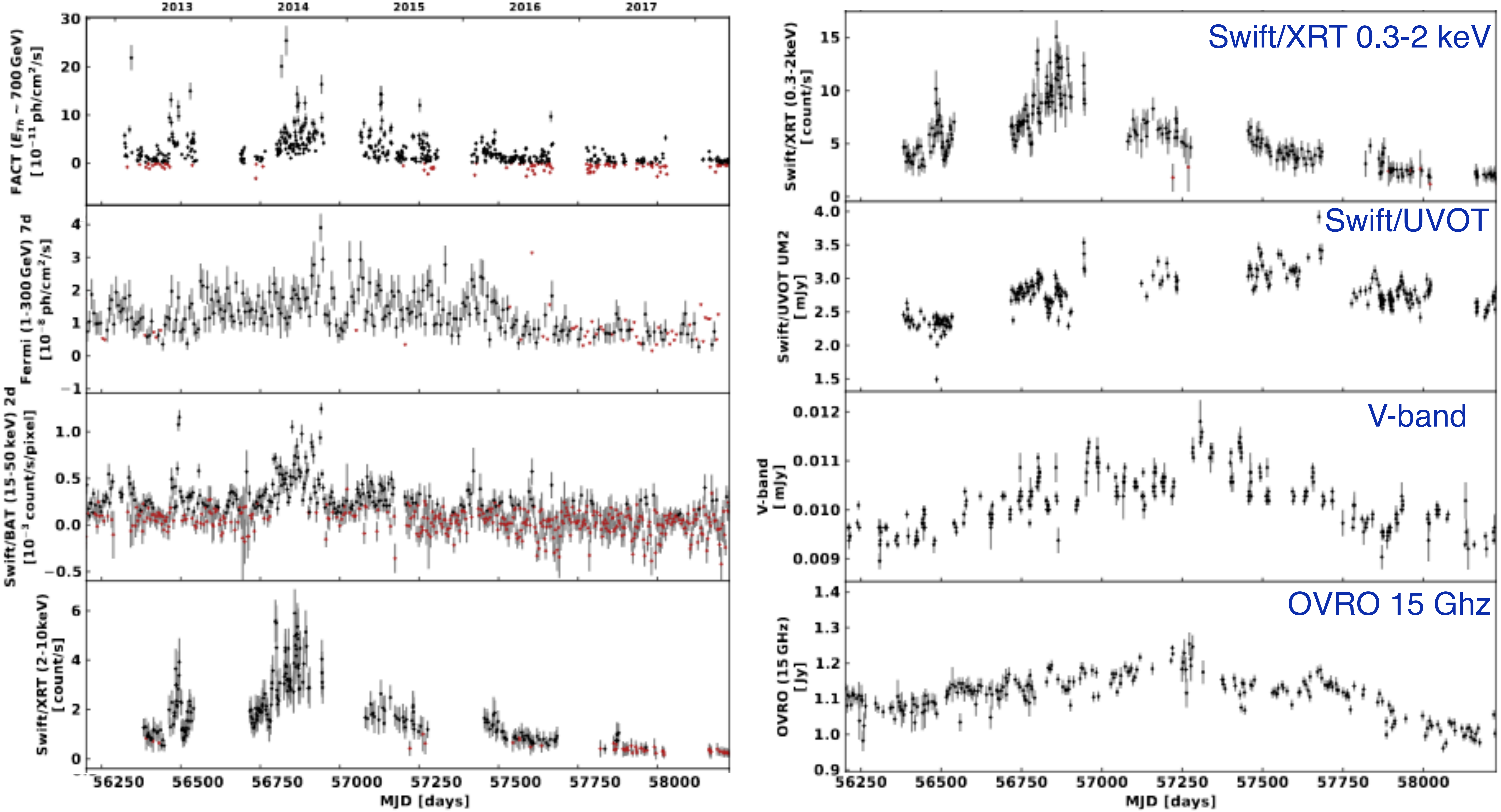


Inter-flare period for TeV flares

Mrk 501 long-term MWL campaign

Fact Collaboration+VS+MB+RW, A&A 655, 2021

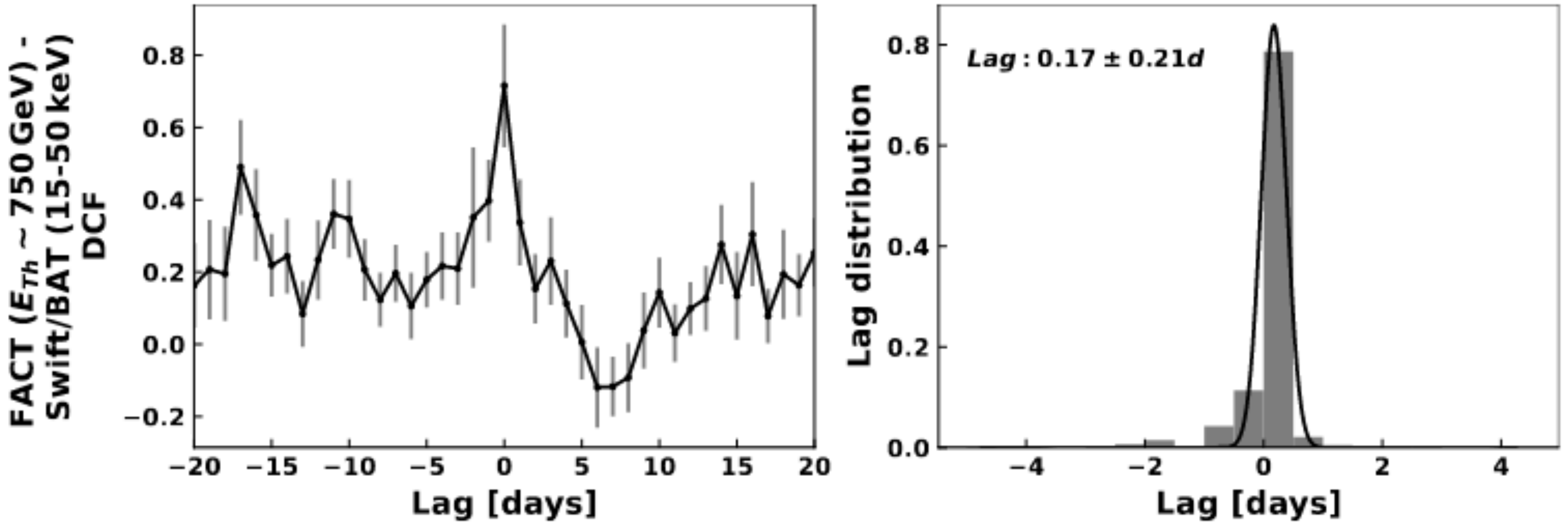
- Mrk 501 observations from December 2012 to April 2018
  - Data from radio to VHE (FACT, 630 nights / 1783 hours), 8 instruments in total, unbiased observations
  - Mrk 501 was found in all states: typical, high and low state (after MJD 57600)



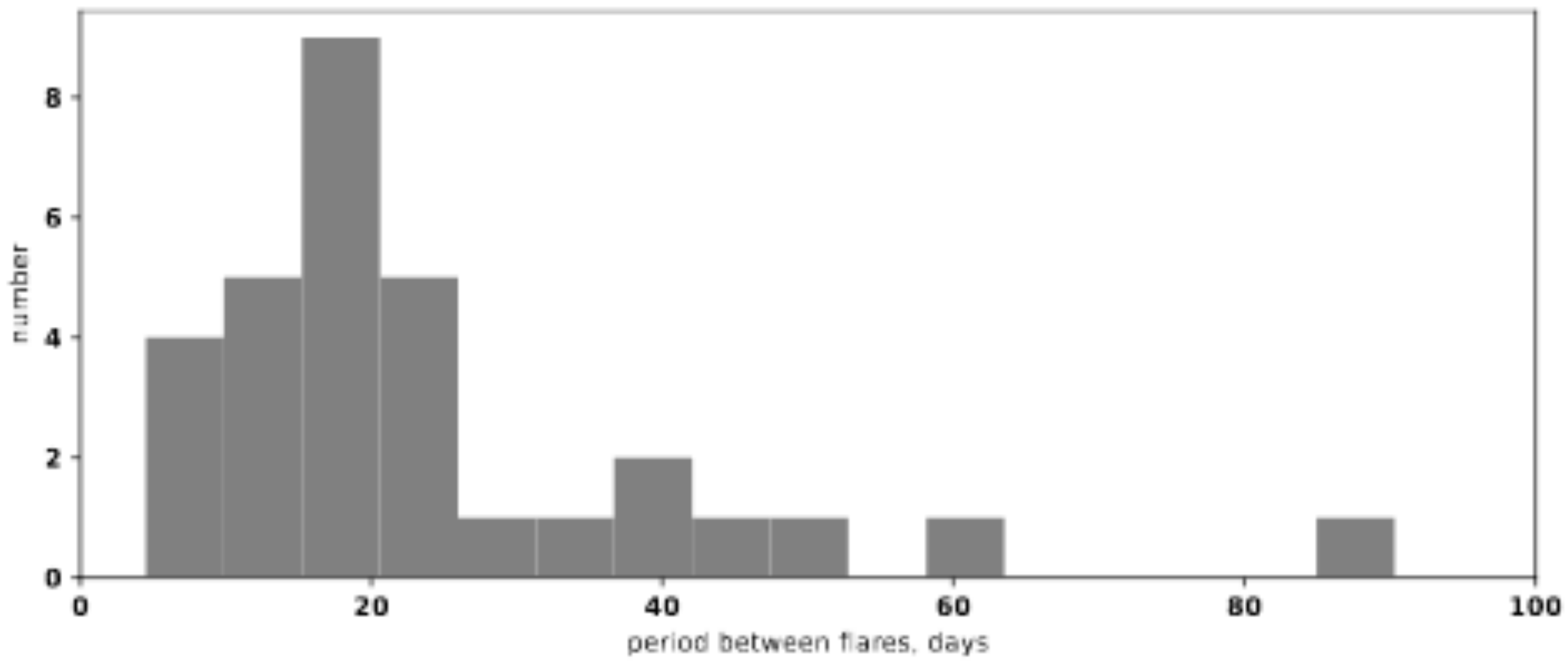
Mrk 501 long-term MWL campaign

Fact Collaboration+VS+MB+RW, A&A 655, 2021

- Mrk 501 MW campaign results:
  - F_{var} has a typical two peak structure:
    - lowest variability in radio and GeVs
    - highest variability in TeVs and X-rays
  - X-rays strongly correlated with TeVs with a 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 lagging by ~200 days.
  - Observed variability is compatible with one-zone SSC scenario
  - 37 individual TeV flares were identified:
    - distribution of time separation between them is peaking between ~15-20 days
    - such time separation compatible with expected duration due to Lense–Thirring accretion disc precession



X- (Swift/BAT) - TeV lag distribution and lag distributions

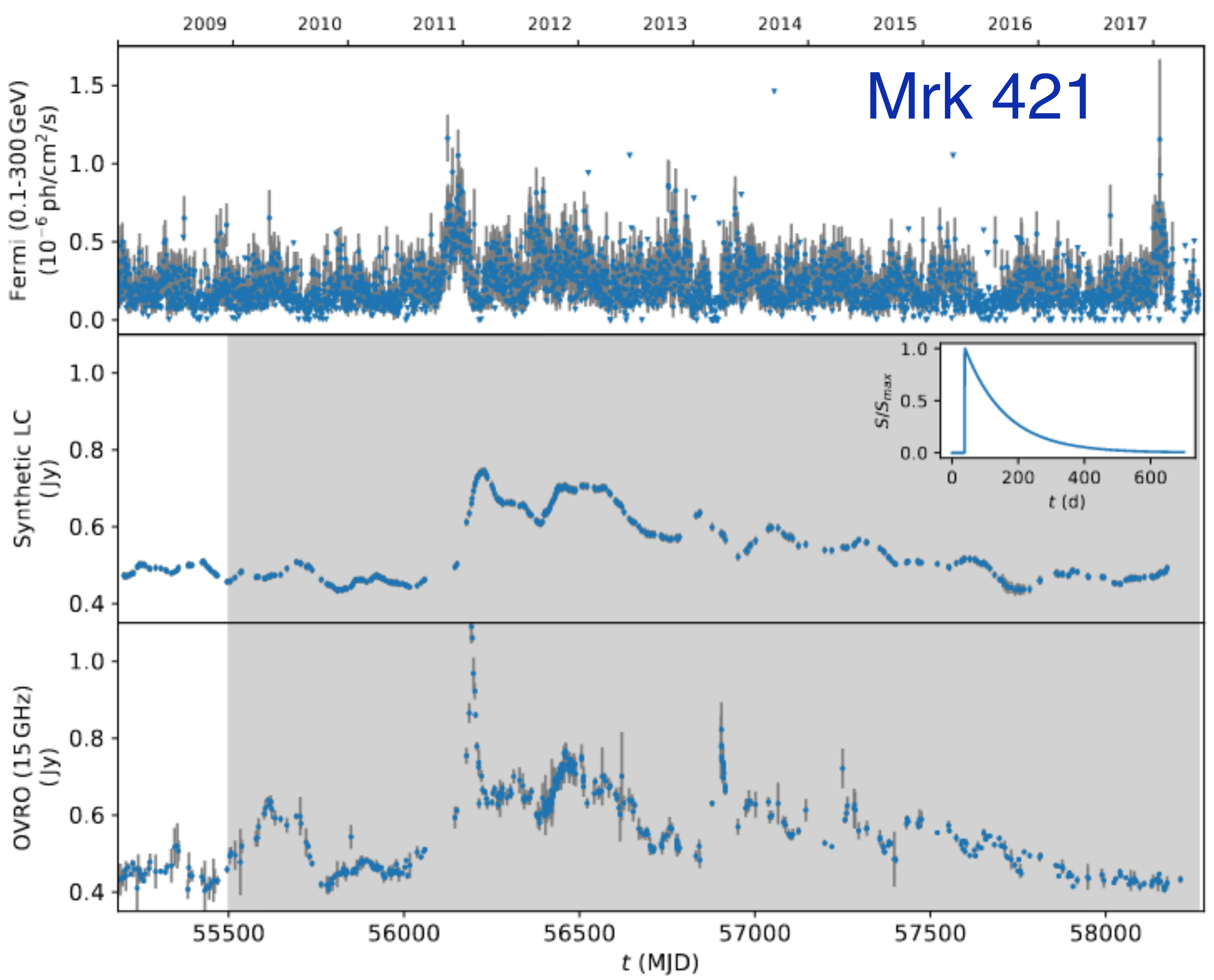


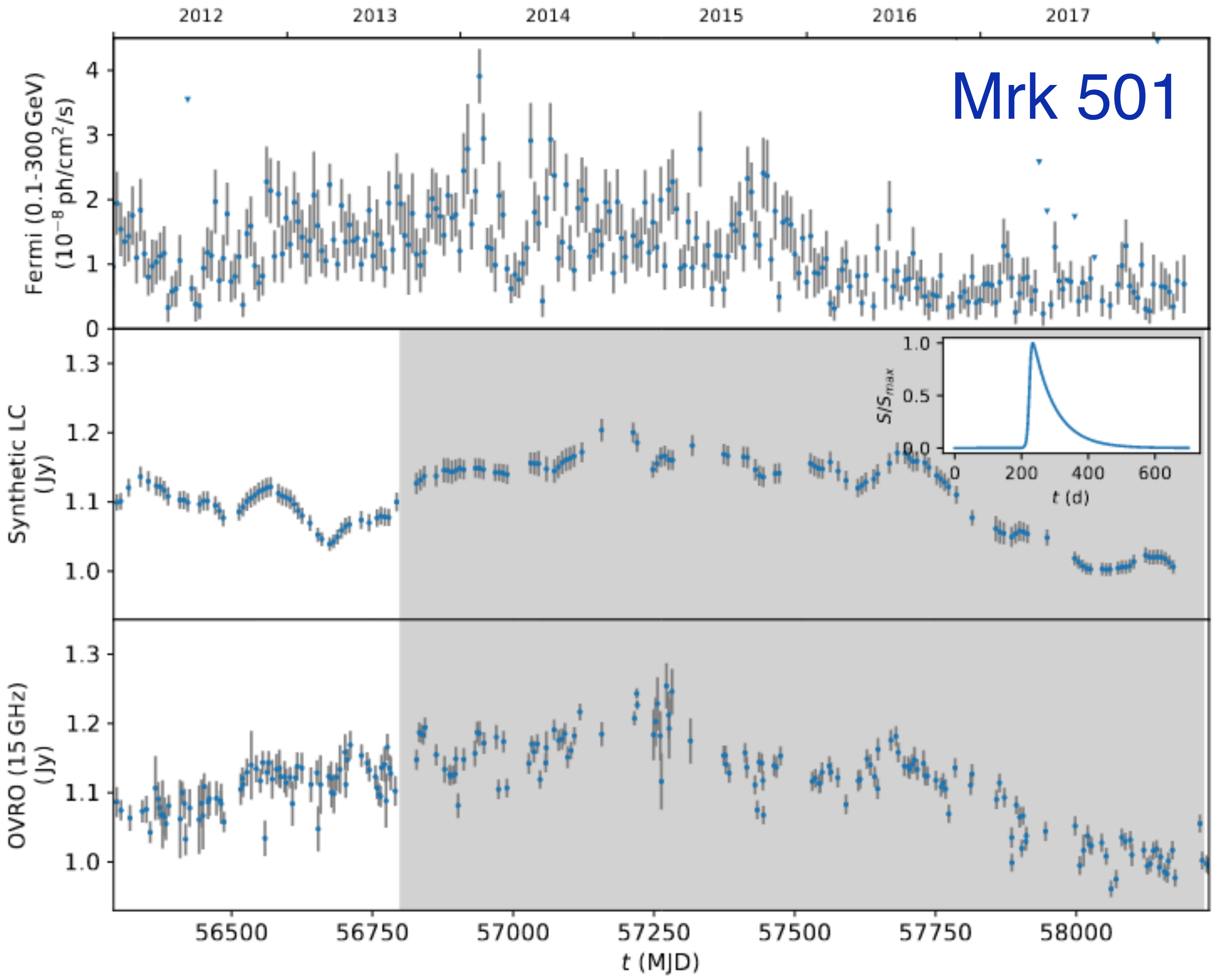
Inter-flare period for TeV flares

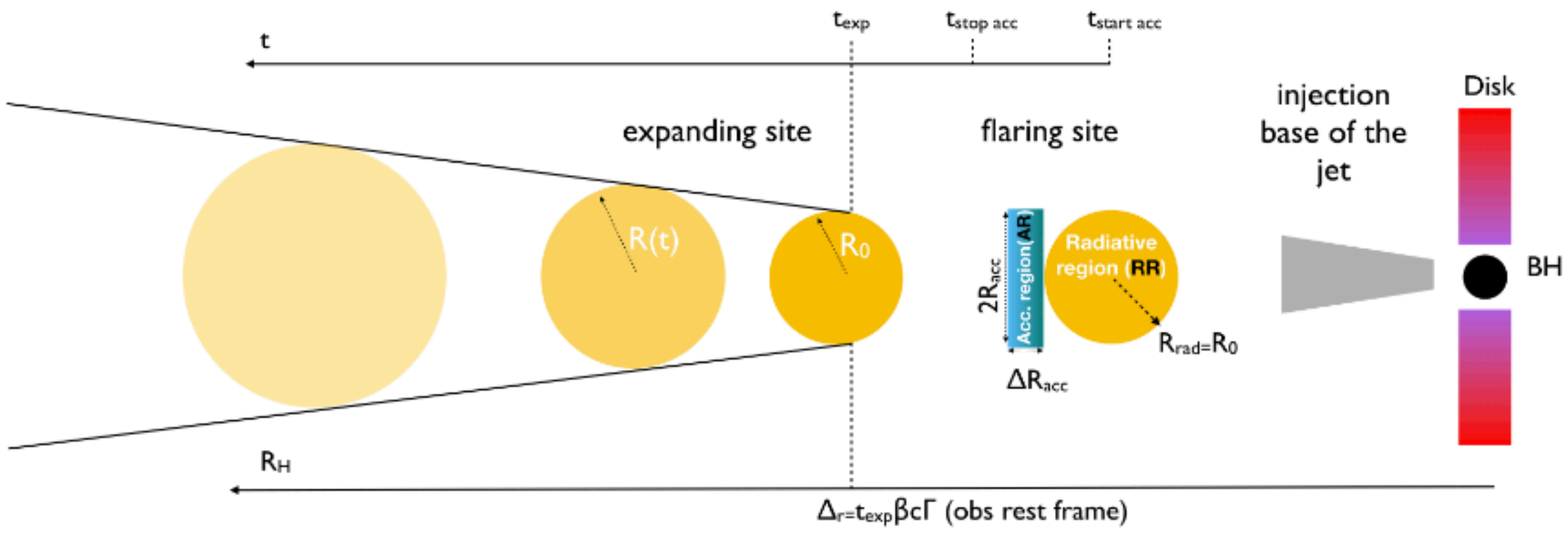
Radio–γ–ray connection

Tramacere+VS+RW+MB+et al. 2022

- Long-term MWL campaigns:
  - The radio emission can be reproduced accurately convolving the GeV variations by a delayed asymmetric response (a fast rise and a slower decay after a delay of ~43 days and ~217 days for Mrk 421 and Mrk 501 respectively)
  - Fast radio flare (MJD 56897) cannot be reproduced (different response?)
- Modelling:
  - Simplified conical jet model can be used (Türler et al. 1999, Esposito et. 2015)
  - Adiabatic blob expansion model proposed and implemented in JetSeT (Tramacere 2020):
    - self-consistent numerical and phenomenological framework to explain radio and γ-ray responses and delays
    - expansion rate constrained to < 0.3c yields conical jet profile at scale above ≈1-10 pc
    - gamma-rays-radio correlation and delay cast doubt on lepto-hadronic mechanism



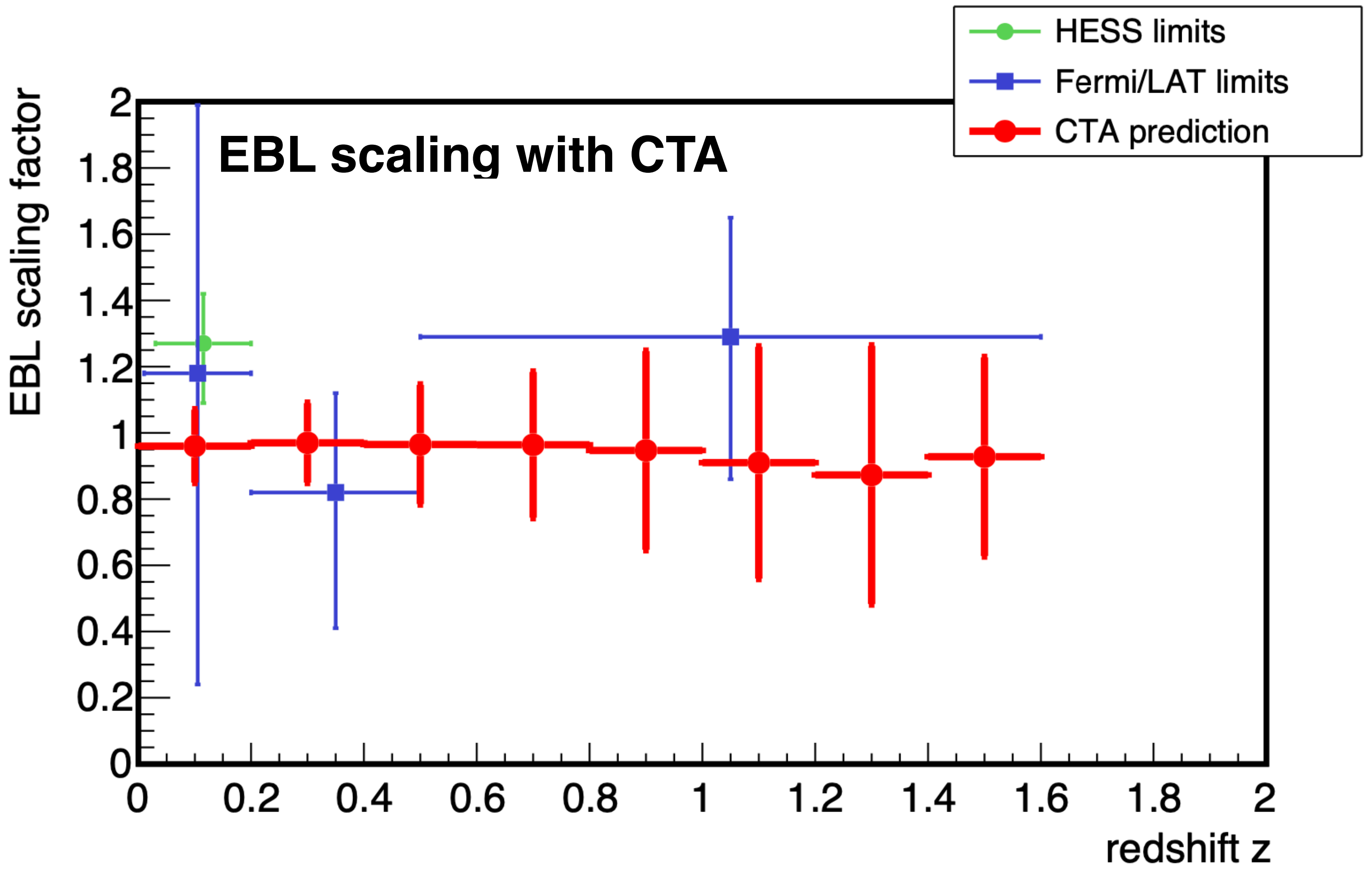


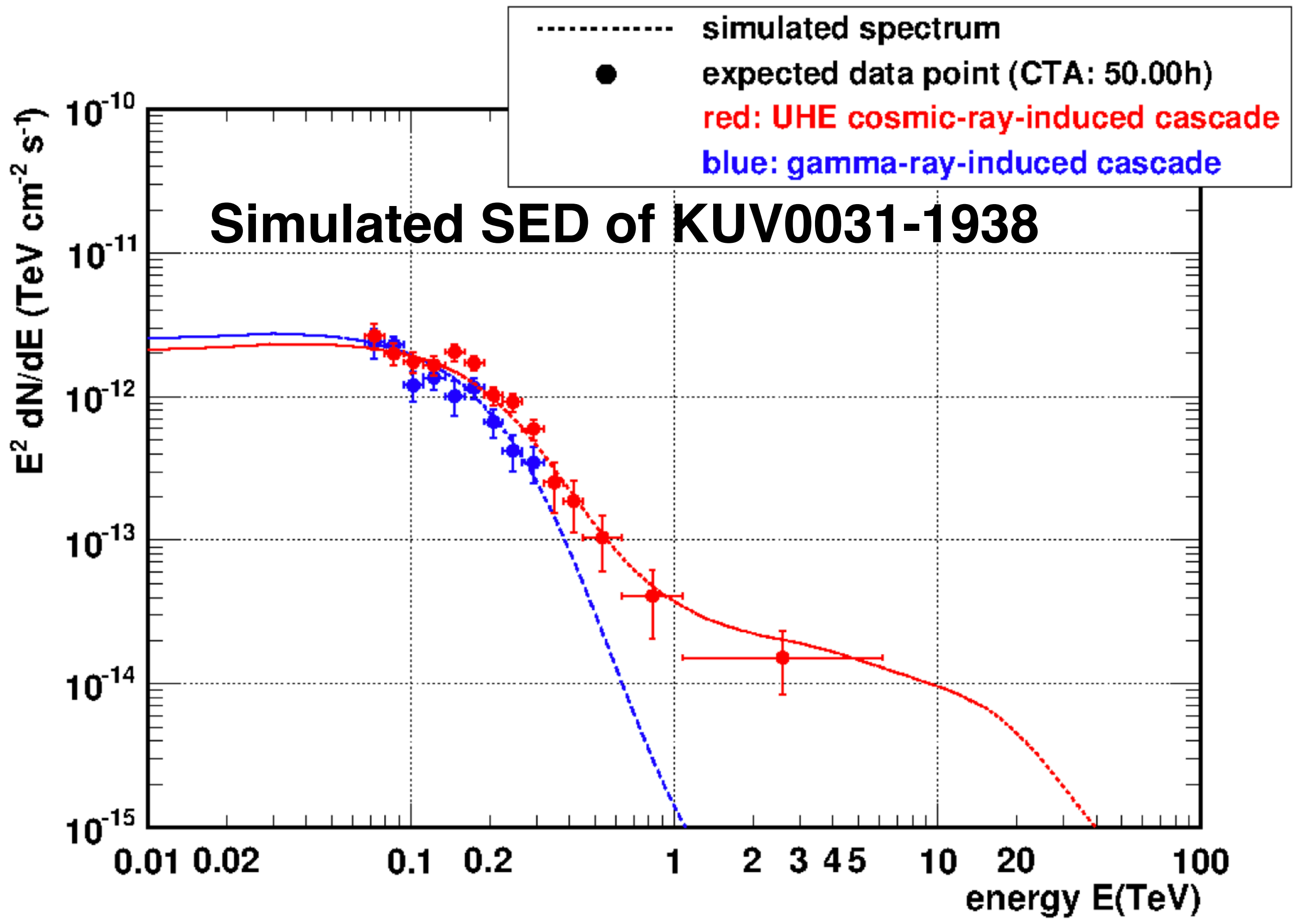


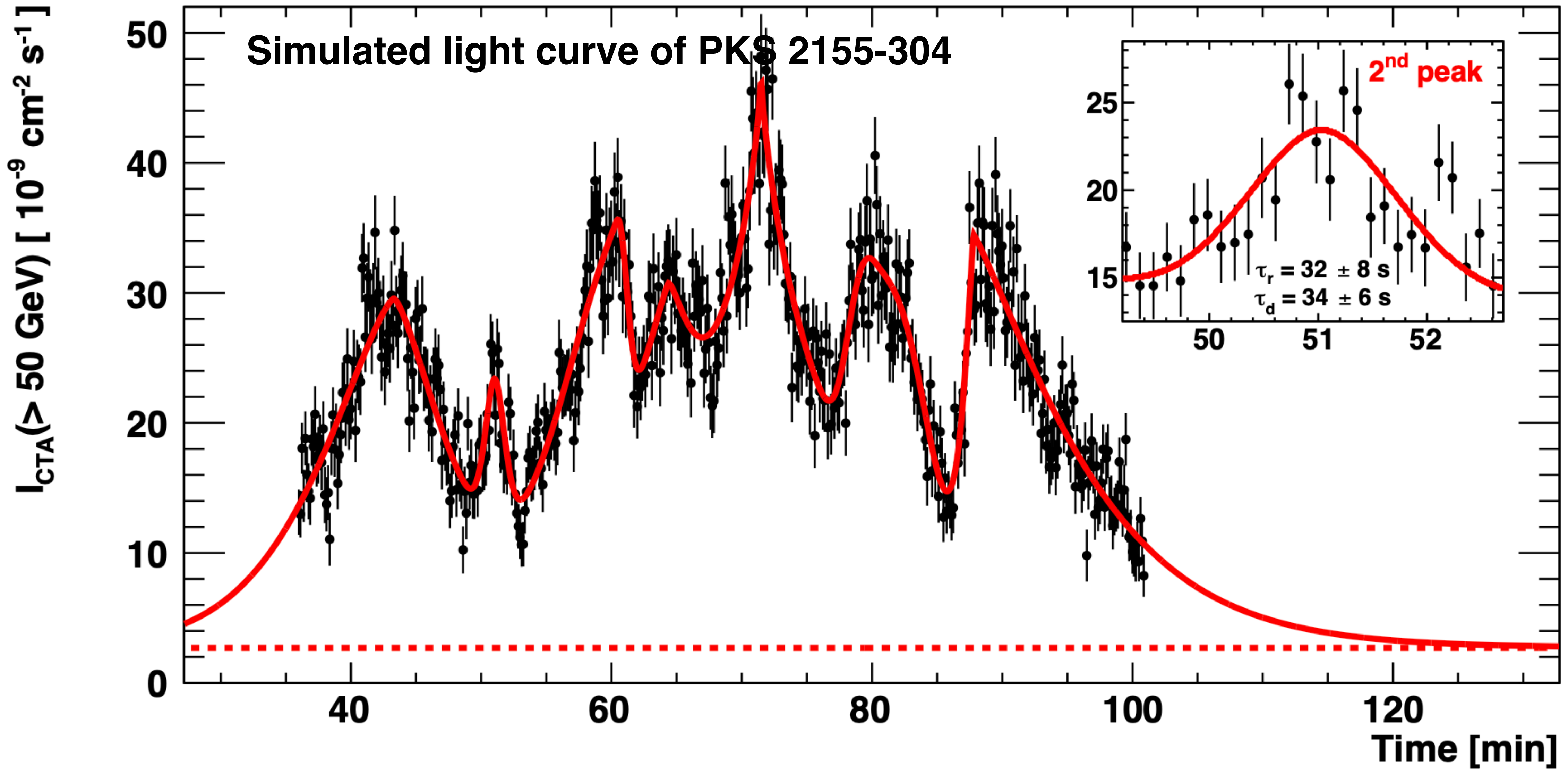
Blazars science with CTA

- CTA AGN observation strategy:
  - Sky surveys
  - MW campaigns using ToO and MoUs
  - Long-term monitoring
  - AGN flares follow-ups
  - High-quality spectra (LIV, EBL, IGMF studies)

- With CTA sensitivity and angular resolution it will be possible to:
  - Resolve the EBL density by observing blazars on different redshifts
  - Study rapid sub-minute timescales variability (also in low source state)
  - Construction of SEDs with better sampling in energy
  - SED evolution on ten-minutes scales for bright sources (Mrk 421, Mrk 501)
  - Intergalactic magnetic fields characterisation







CTA KSP, Science with CTA, Acharya et al. 2018

Conclusions

- Blazars are still poorly understood:
  - Simultaneous and dense MWL monitoring involving CTA is a key to disentangle and constrain models
- Long-term MWL campaigns:
  - Mrk 421:
    - X-rays and TeVs are tightly correlated with <0.6 days lag
    - 93% of the TeV flares are coincident with X-ray ones
    - Radio emission lags behind GeV by ~40 days and can be reproduced using adiabatic expansion
  - Mrk 501:
    - X-rays and TeVs are correlated with <0.38 days lag
    - "Only" ~50% of detected TeV flares are coincident with X-ray ones
    - Radio emission lags behind GeV by ~200 days and can be reproduced using adiabatic expansion
  - Common for Mrk 421 and Mrk 501:
    - The strongest variability is in the X-ray and TeV bands
    - Long term variability is compatible with SSC model. Lepto-hadronic and hadronic models are disfavoured by the X-rays and TeV cooling times and prediction from adiabatic blob expansion.

Thank you for your attention!

vitalii.sliusar@unige.ch