First study of Mrk 501 through the eyes of NuSTAR,VERITAS and the ***LIDAR-corrected*** eyesight of MAGIC

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and GASP-WEBT, F-GAMMA consortiums, and many campaign participants

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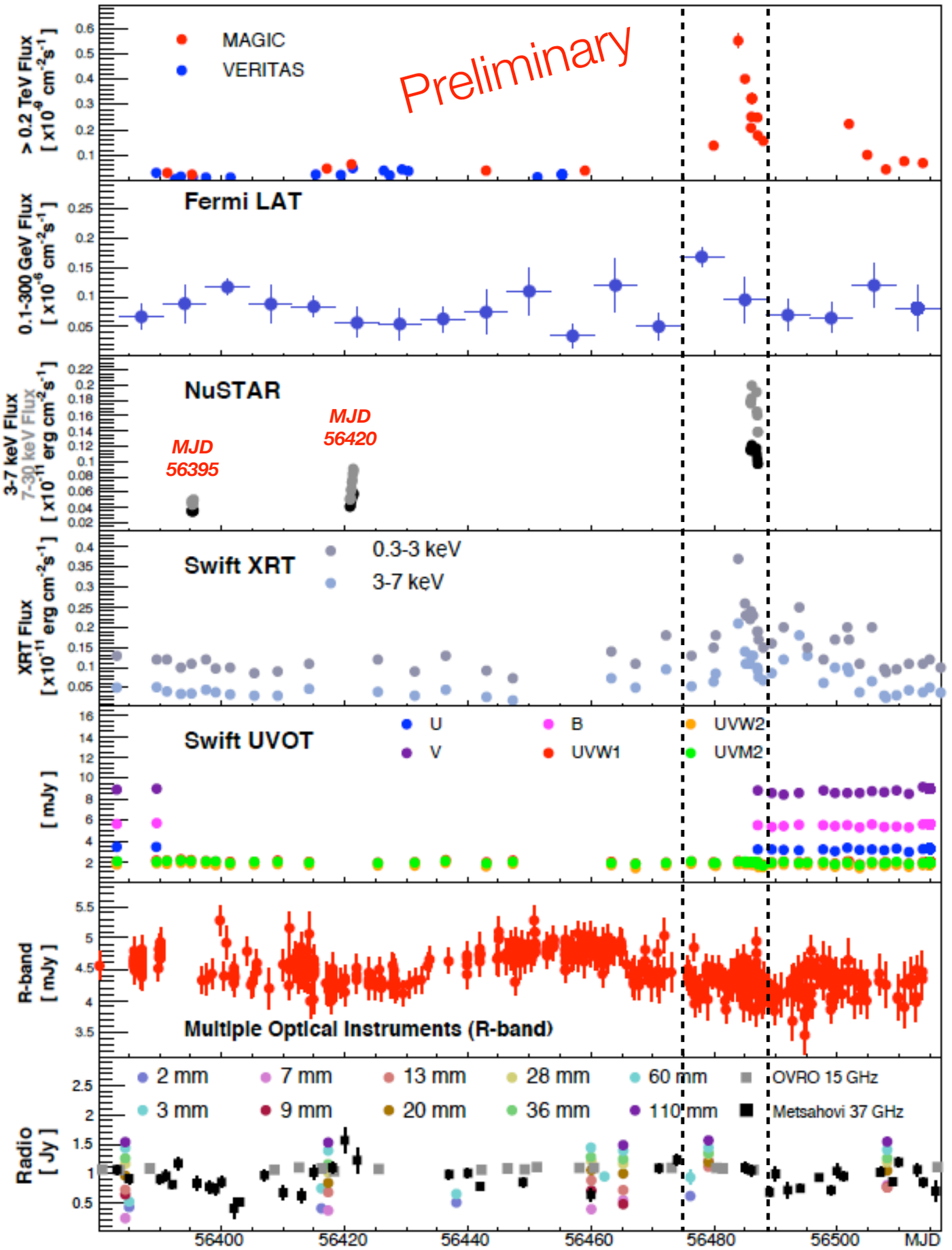
Introduction

- Mrk501: a nearby blazar (z=0.034), very bright in VHE (>100 GeV) gamma-rays
  - Known for frequent & fast activities (e.g., up to ~4.5 Crab Nebula Unit (>300 GeV) in 2009)
    - “Laboratory” for the AGN jet physics, to see changes in the physical states in jets
- Multi-wavelength campaign, to understand changing states without an ambiguity in “simultaneous or not”
  - In particular, this is the first time including NuSTAR, a hard X-ray satellite (3-79 keV)

- Ref.) A. Furniss, K. Noda, et al.,submitted to ApJ

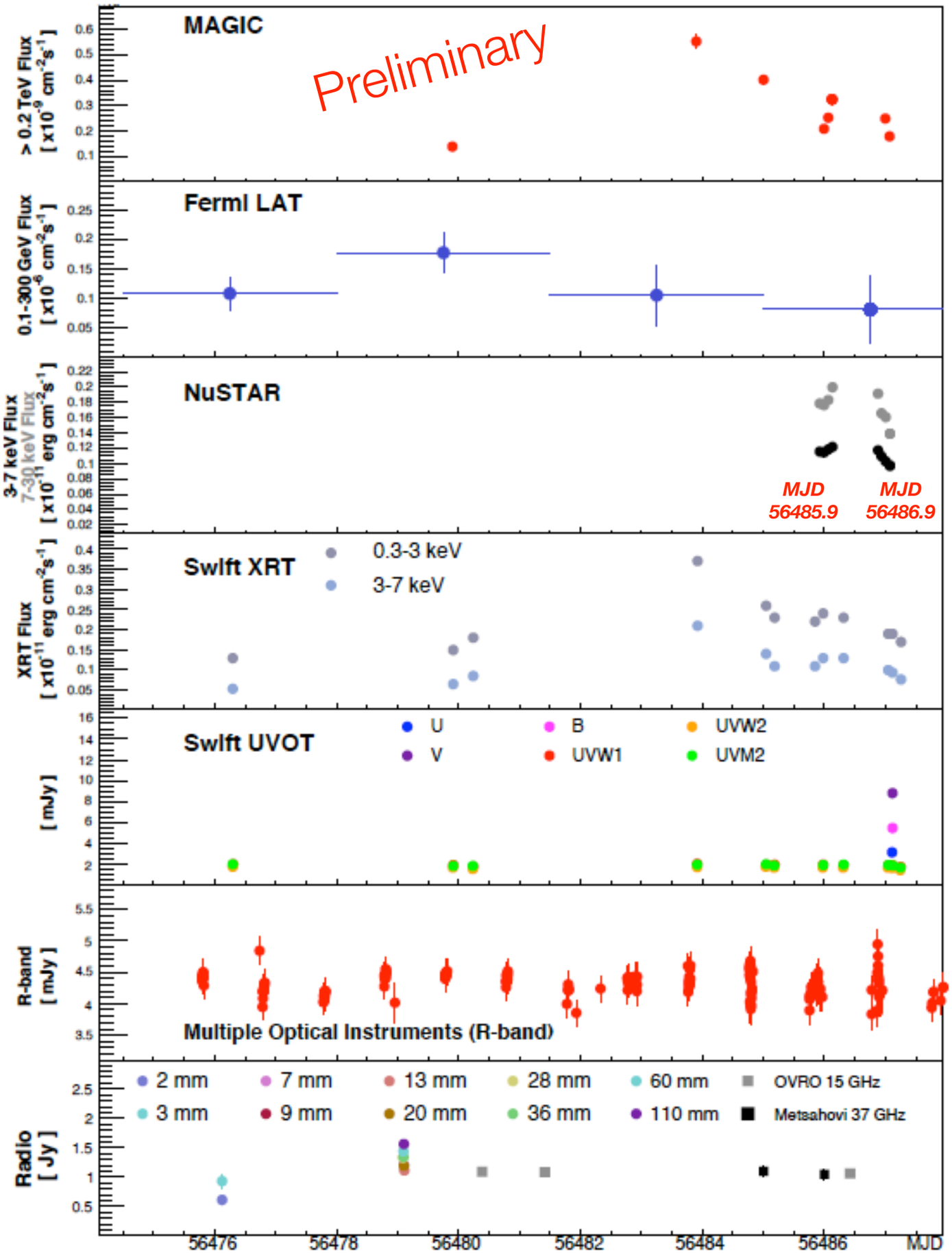
Dataset

- 4 months in 2013
  - E.g., by MAGIC, 9 Apr (MJD 56391) - 10 Aug (MJD 56514)
  - **2 campaigns** with *NuSTAR* in low states (~0.3 Crab in VHE)
- ToO triggered in MJD 56484, by a high rate observed by *Swift/XRT*
  - 5 consecutive nights with MAGIC (& *Swift/XRT*). Flux up to ~2.5 Crab
  - **2 additional campaigns** with *NuSTAR*, in MJD 56485.9 and 56486.9



Dataset

- Zoom-up around ToO
- Quick look: Correlations between VHE (*MAGIC*) and X (*NuSTAR & XRT*)
- However, MAGIC data of this period (and later) were affected by a sand dust coming from Saharan desert (called *'Calima'*)
  - <u>Need a correction, or should be discarded...</u>



MAGIC telescopes

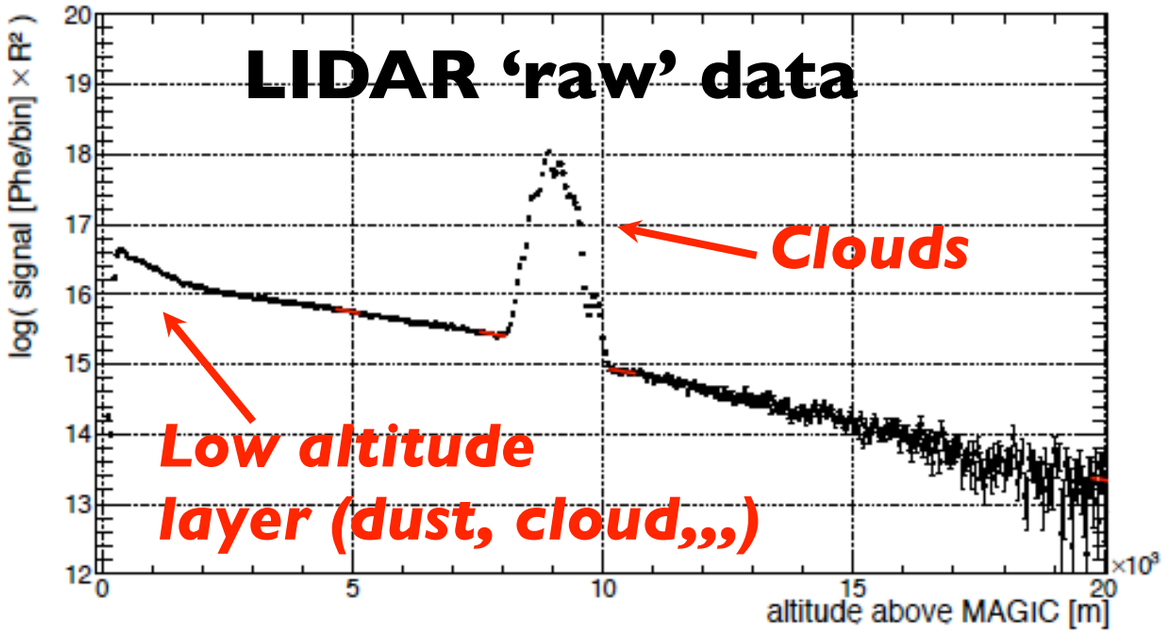
- La Palma, Canaries, Spain, 2200 m a.s.l.
- 2 Imaging Atmospheric Cherenkov Telescopes, with a diameter of 17 m
- Sensitivity (50h, 5σ, Li&Ma w/ 5 bgd. regions): 0.67 ±0.04% Crab (>290 GeV)
- Energy threshold : ~50 GeV
- Energy resolution : ~16%
- Ref.) Aleksic et al., Astropart. Phys. 02, 005 (2015)

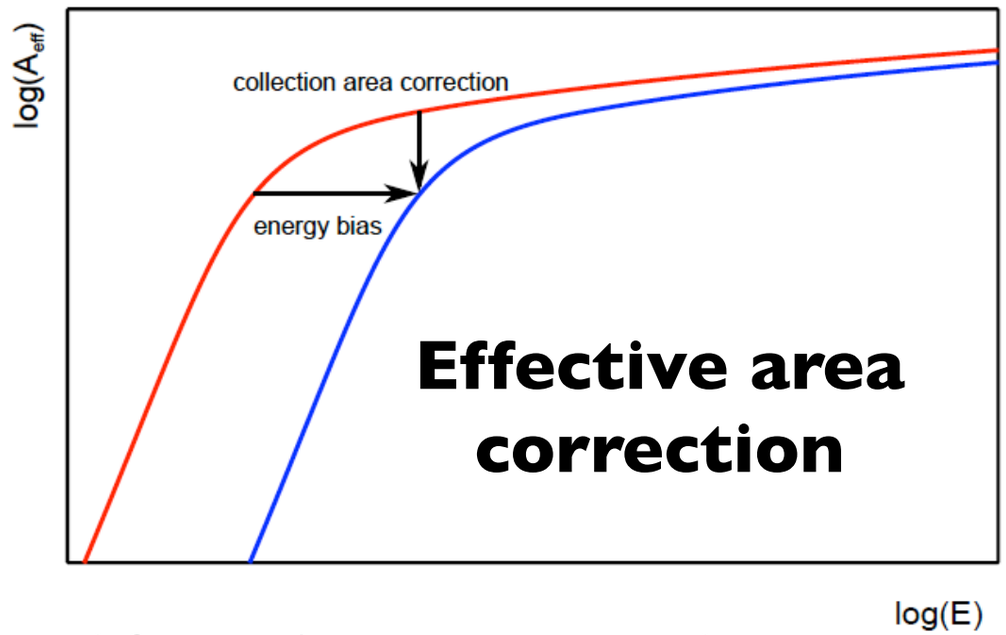
from the CTA press release :-)

LIDAR correction

LIDAR, next to MAGIC

- To correct data taken under adverse atmospheric conditions, and to recover data, which would be discarded otherwise.
- Strategy presented in ICRC 2013 (Fruck et al., #1054)





- Transmission τ(h) vs. altitude h, estimated from the LIDAR raw data
- 1st-order correction estimates E: $E_{true} = E_{est} / \tau$ (gnd)
- Effective area and energy corrected event-wise

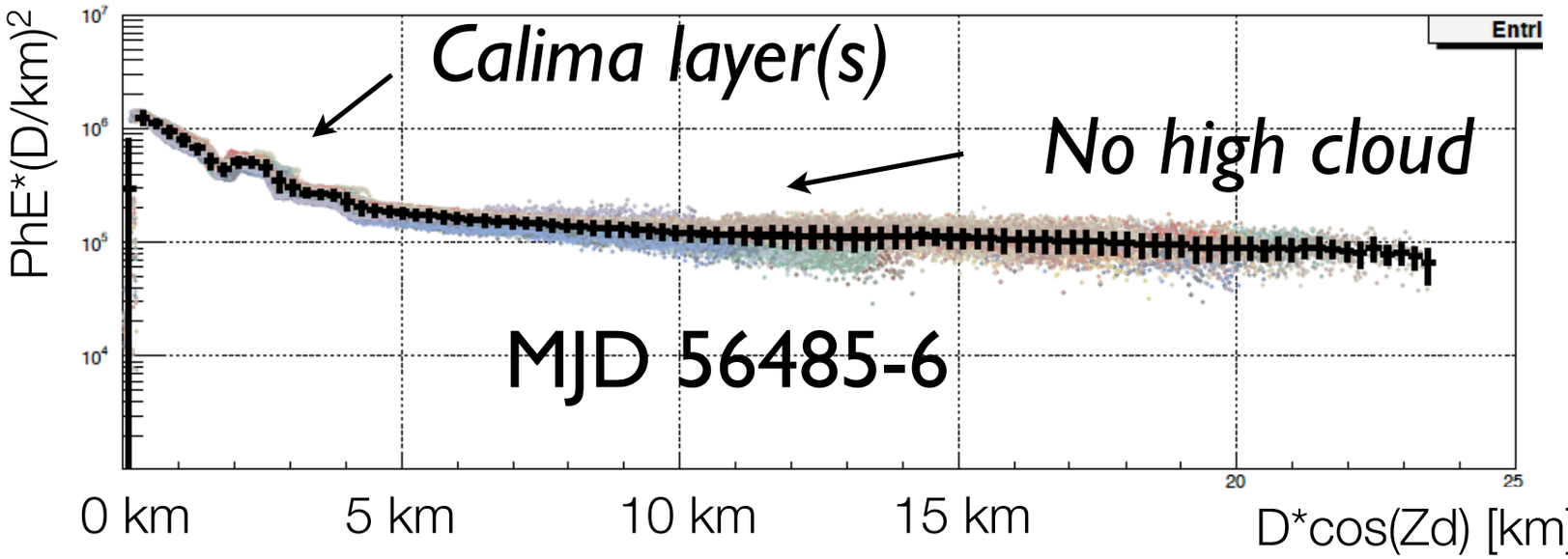
- Checked with Crab Nebula spectra taken under a few different conditions (Fruck et al., Proc. of AtmoHEAD 2014, 02003 (2015))

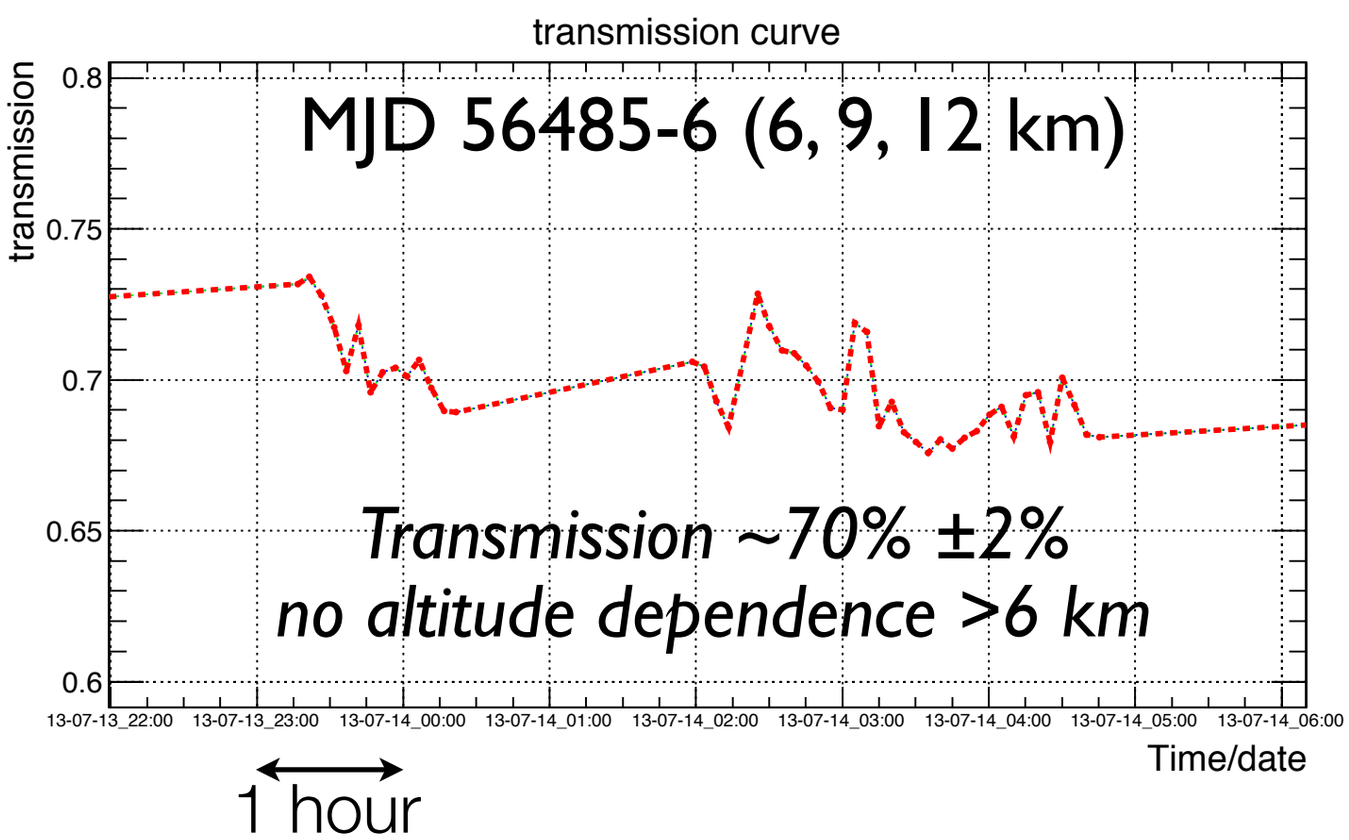
Specials in/after this work

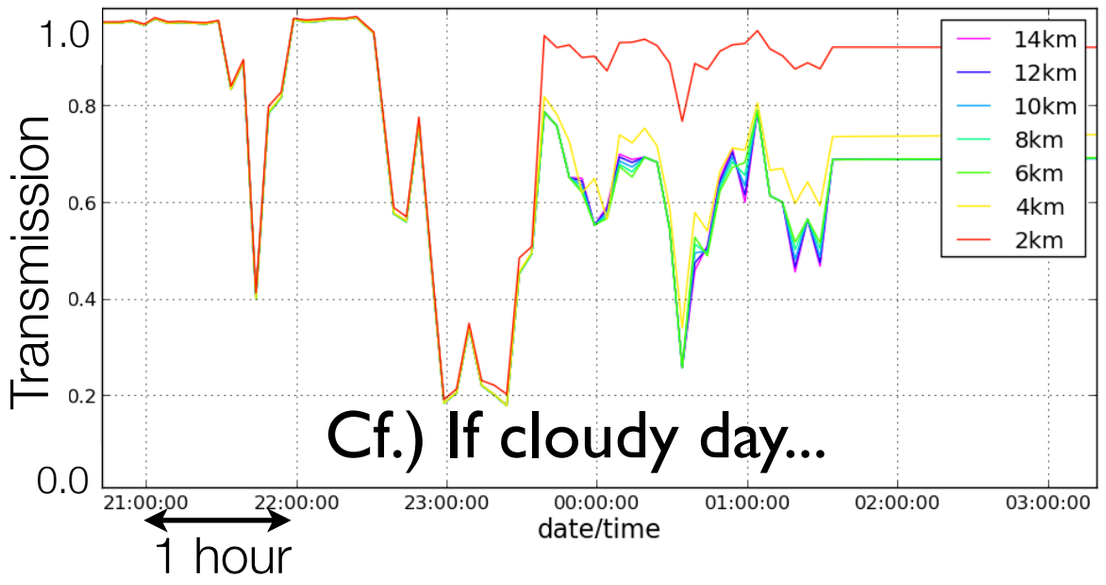
- ~17 hr affected out of ~22 hr observed...
  ==> **Corrected and recovered ~10 hr** of crucial data during flaring activity, to be 15.1 hr in total
    - Only for Calima = low-altitude dust attenuation (so the 1st-order correction should work well)
- **LIDAR used for first time in a physics paper with IACT observations** (Cf. Nolan et al., ApP **34** 304 (2010). A useful tech. study with PKS 2155-304 data, using a ceilometer measuring <7.5 km)
- New routines implemented & **debugged/checked in the MAGIC standard analysis** package (MARS)

Typical Calima features

- Calima: typically lower than 5 km
- Stable transmission, more than by clouds



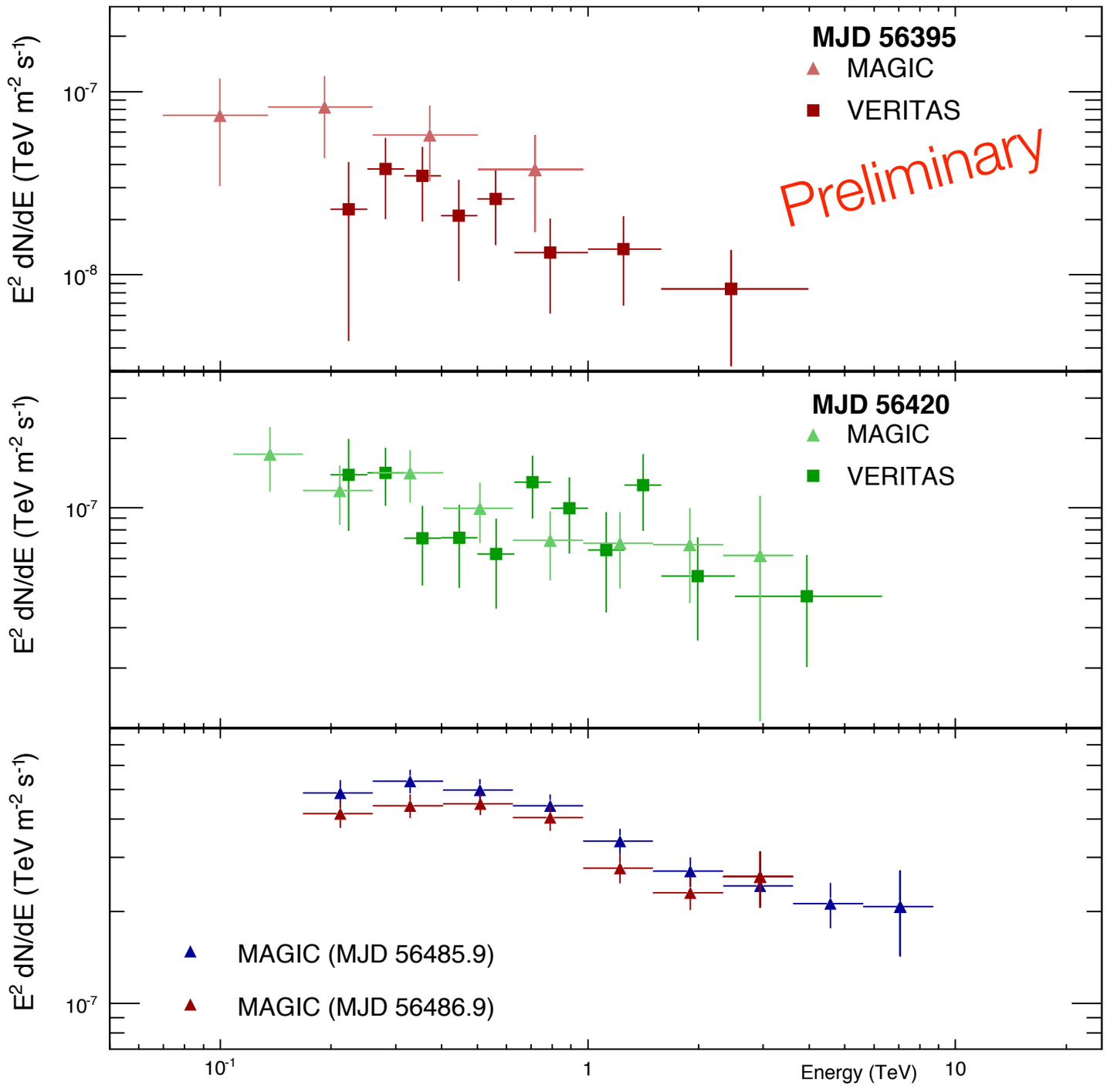




Systematic error increased accordingly (by τ(h) estimation)

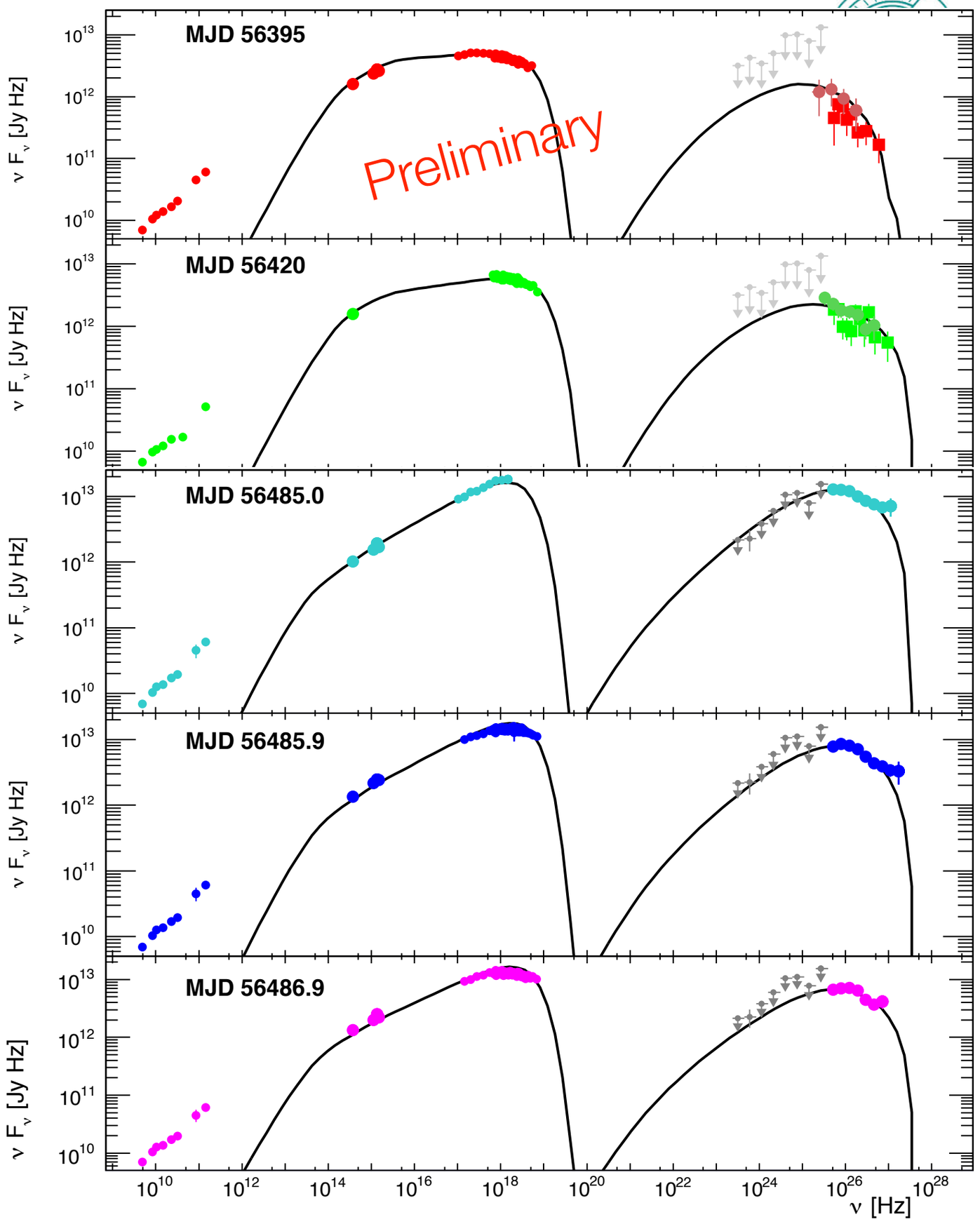
Spectral energy distributions

- VHE SEDs taken in the 4 campaigns
- MJD 56395, 56420: Not corrected, Zd 10-35 deg, E_{th} 70-100 GeV **Compatible between MAGIC & VERITAS**
- MJD 56485.9, 56486.9: **LIDAR-corrected**, Zd 12-60 deg, E_{th} multi-plied by x 1/ τ (gnd) **Reconstructed well => Detailed studies possible!**



MWL SED

- Added MJD 56485.0: Closest to the flare, without NuSTAR but with *Swift*/XRT
- Radio: as upper-limits. *Fermi*-LAT: integrated in 43, 28 days
- Modeled with an equilibrium version of a single-zone Synchrotron Self-Compton model (Böttcher et al. (2013))
  - <u>NuSTAR covers Synchrotron peaks in the flare nicely</u>
  - IC peaks well modeled with a relatively simple picture



Discussions

Parameter	MJD 56395	MJD 56420	MJD 56485.0	MJD 56485.9	MJD 56486.9
$\gamma_{min}\,[\times 10^4]$	1.5	2.1	2.0	2.0	2.0
$\gamma_{max}\,[\times 10^6]$	1.0	1.4	1.4	1.7	1.4
Injected particle index q	1.9	1.8	1.3	1.3	1.3
Escape time scale (fixed) η	100	100	100	100	100
Magnetic field $B\,[\mathrm{G}]$	0.06	0.05	0.03	0.03	0.03
Doppler factor (fixed) Γ	15	15	15	15	15
Emission region size $R\,[\times 10^{15}\mathrm{cm}]$	7.0	7.0	5.0	7.0	7.0
Jet critical angle (fixed) $\theta\,[\mathrm{degrees}]$	3.8	3.8	3.8	3.8	3.8
Particle kinetic energy $L_e\,[\mathrm{erg/cm^2/s}]$	9×10^{42}	12×10^{42}	36×10^{42}	28×10^{42}	26×10^{42}
Equipartition parameter $\varepsilon = L_B/L_e$	1.8×10^{-2}	6.1×10^{-2}	5.3×10^{-4}	1.3×10^{-3}	1.4×10^{-3}

- Hardening in the particle injection
- Energy transfer from magnetic field to the particles
  - Magnetic reconnection? (e.g., Werner et al. (2014)) Slight decrease in R
- IC seems happening in the Klein-Nishina regime
  - VHE-X correlation favors a quadratic relation, which is a typical feature in the Thomson regime, but not contradictory (with reasonably steady B).

Summary

- Mrk 501: “Laboratory” to understand the AGN jet physics
- MW campaign in 2013, with NuSTAR for the first time
  - a better knowledge of Synchrotron peak, together with **strictly simultaneous** VHE observations of the IC peak
- MAGIC data affected by a sand layer from Saharan desert, are **corrected well with the LIDAR data.**
  - The first IACT physics publication with a LIDAR correction. ***A good news for CTA!***
- A simple SSC model works well, and discussions of the interpretation without any large ambiguity
  - showing the capability of the LIDAR correction