Multi-messenger characterization of Mrk 501 during historically low X-ray and γ-ray activity

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MAGIC

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Introduction

As highly energetic physics laboratories, blazars are prime candidates to reveal the mysteries of the most powerful parts of our Universe. **Mrk 501 is one of our closest and brightest blazars** which means it can be studied in detail in flaring and quiescent states. Therefore, regular multiwavelength (MWL) monitoring is organized to disentangle its complex behavior.

We present a data set of Mrk 501 reporting a **historically low activity** in very high energy (VHE) γ-rays and X-rays. Identified by a Bayesian block algorithm, the low-state **spans over two years**. It also occurs in the high energy (HE) γ-rays, although not at a historically low level. It might relate to the **baseline emission** of Mrk 501, and hence help us to reveal its underlying emission mechanisms.

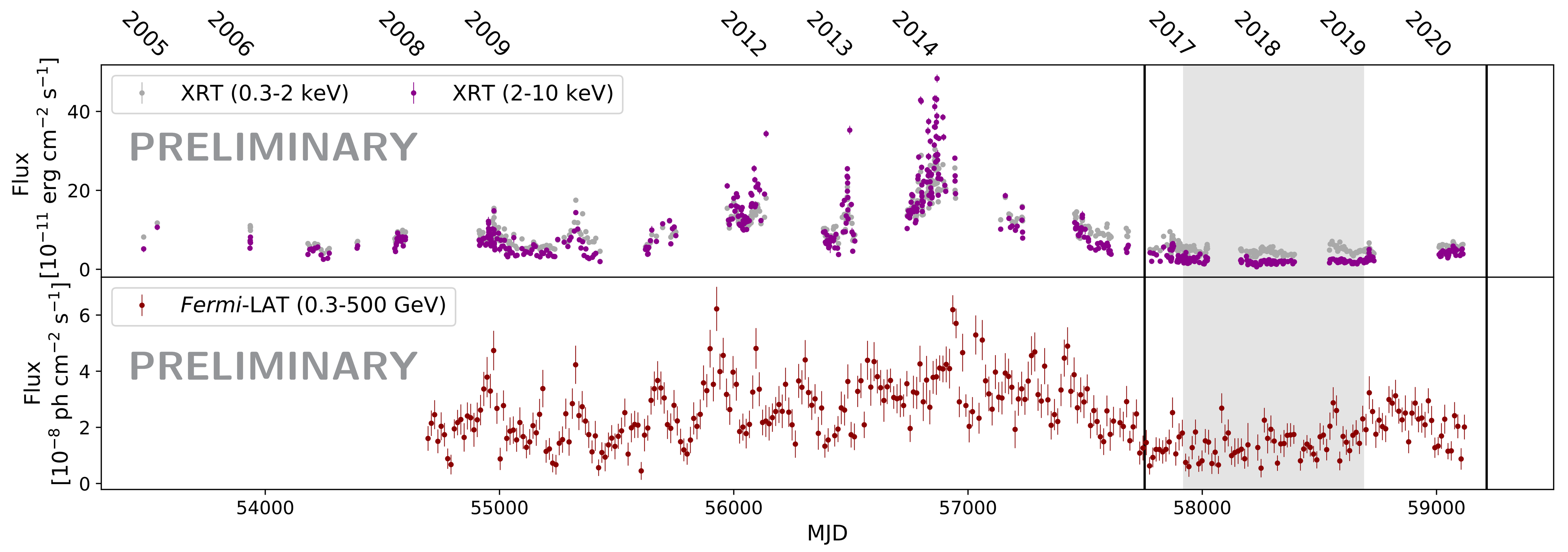

Fig. 1: Long-term Mrk 501 LC displaying data from Swift-XRT and Fermi-LAT. The vertical black lines mark the 4-year period featured in this work, and the grey area marks the identified low-state.

MWL Correlations

We investigate MWL correlations in our data sets using the discrete correlation function (DCF).

In our 4-year data set (2017 to 2020), we identify, for the first time during low activity states, a **significant ($>3\sigma$) correlation** between the **VHE γ-rays and X-rays** without a time lag.

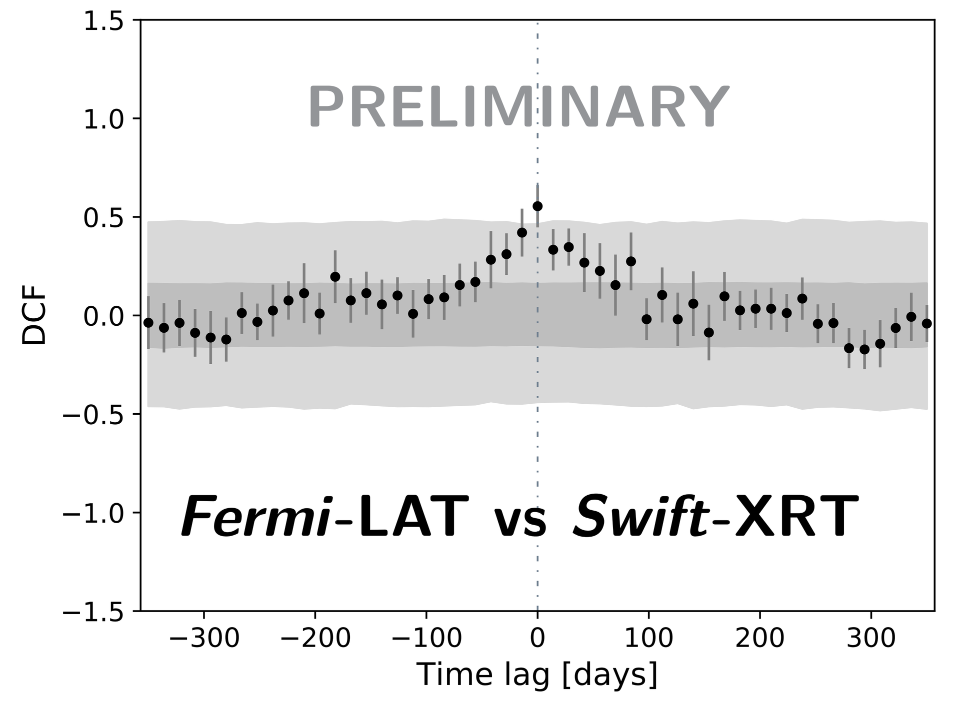

Fig. 2: DCF for Fermi-LAT (0.3-500 GeV) and Swift-XRT (2-10 keV) with 1σ and 3σ confidence levels.

Using the complete long-term 12 year data set (2008 to 2020), we find, also for the first time, a significant correlation between the **HE γ-rays and X-rays** without time lag.
This correlation holds for both short (weeks) and long (months to years) time scales.

These correlations support a leptonic, Synchrotron Self Compton (SSC), origin for the variable part of the blazar emission.

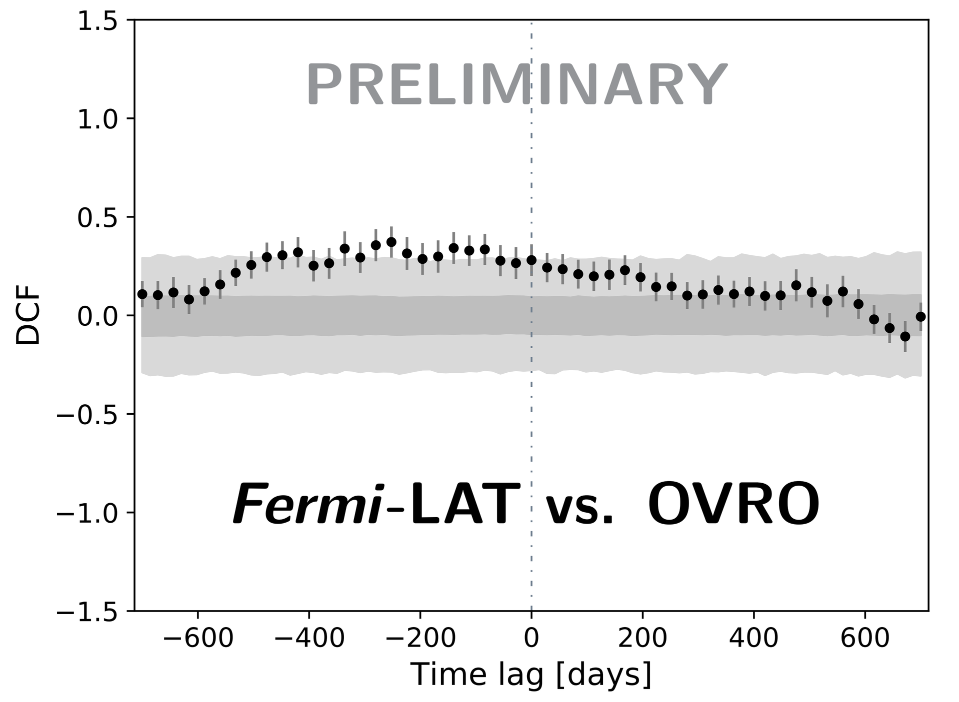

Fig. 3: DCF for LAT (0.3-500 GeV) and OVRO (15GHz) with 1σ and 3σ confidence levels.

For both time intervals, we find a significant correlation between **HE γ-rays and radio** with the **radio lagging the γ-rays by at least 100 days**. This places the γ-ray emitting region upstream of the radio bright regions.

Low State Emission

The **2-year-long low-state** including a *NuSTAR* observation allows for building a detailed SED which we can use to investigate its nature.

We consider **leptonic SSC scenarios** using two frameworks (a modified *Naima* framework by S. Gasparyan and *JetSeT* by A. Tramacere), which can describe the data with standard parameters.

Moreover, we use **(lepto)-hadronic scenarios** applying the *LeHa* code by M. Cerruti which can reproduce the low-state SED. The **predicted neutrinos** per year $(10^{-3}/10^{-5})$ of these models agrees with the public IceCube data of Mrk 501.

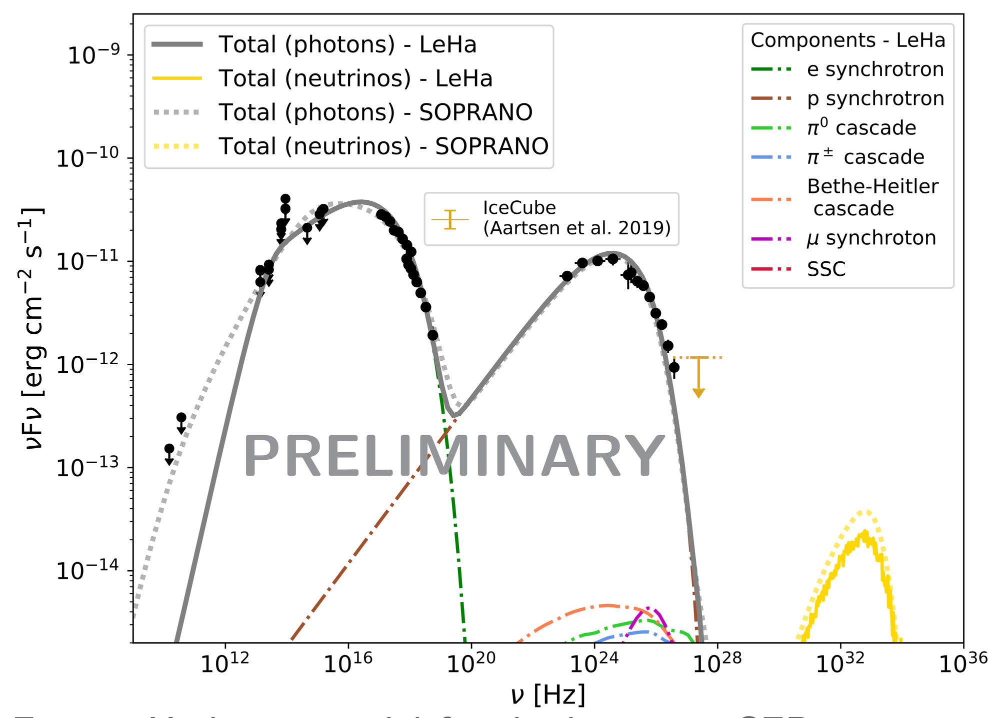

Fig. 4: Hadronic model for the low-state SED.

SED Evolution

Additionally, two *NuSTAR* observations were organized **1 and 2 months before the low-state**. These data allow one to investigate the **spectral evolution** towards the historically low activity.

In the **one-zone SSC** scenario, the change is explained by an **increase in the magnetic field** when approaching the low-state with minor modifications in the radiating electron distribution.

Since we want to probe the possibility of the low-state being the baseline emission of Mrk 501, we also consider a **two-zone scenario**. The **stable baseline emission** can be described by the low-state model while **another more active zone dominates in the X-rays and VHE**. If this zone then expands with time, we are able to reproduce the SED evolution. Moreover, the same scenario works for the typical state of Mrk 501 described in Abdo et al. 2011[1].

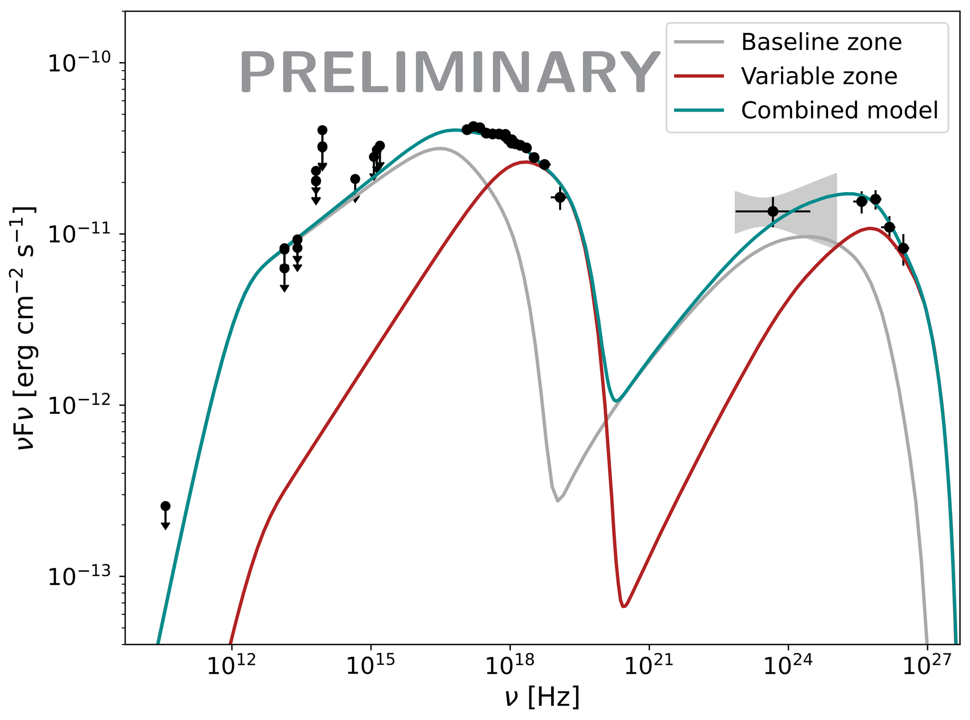

Fig. 6: Two-zone model for the NuSTAR-1 SED

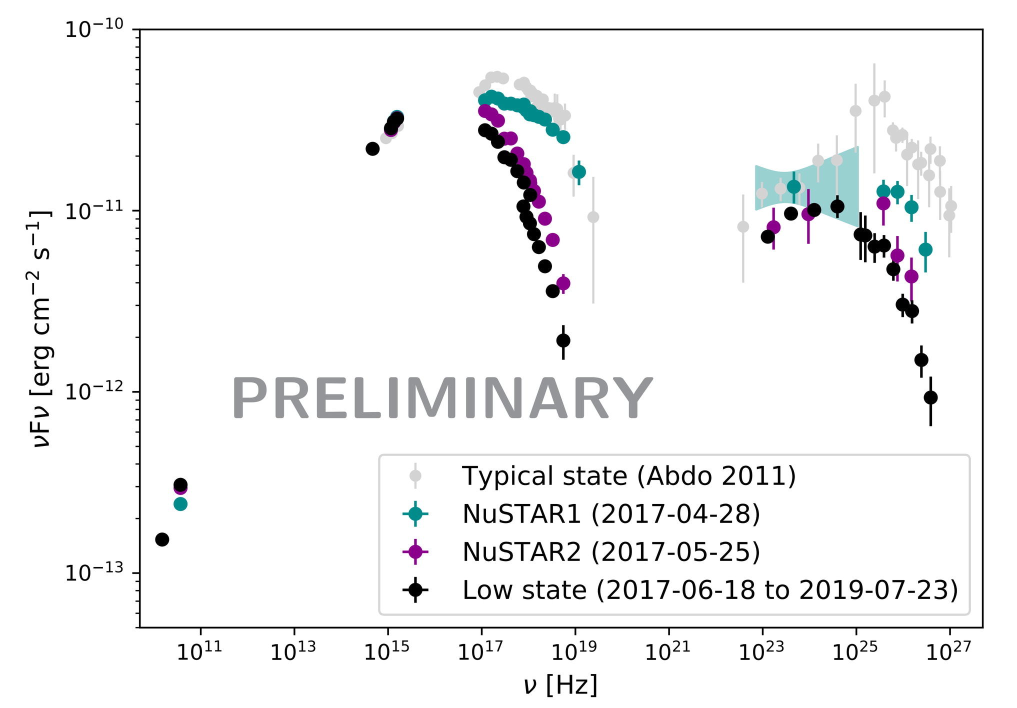

Fig. 5: SED evolution shortly before the low-state.

[1] Abdo, A. A. et al. 2011a, ApJ, 727, 129

Summary and Conclusions

From mid-2017 to mid-2019, Mrk 501 showed **historically low activity** in X-rays and VHE γ-rays. Variability and correlations suggest a **leptonic origin of the variable part of the blazar emission**. The multi-messenger data related to the 2-year **low-state can be modeled within standard one-zone leptonic scenarios, as well as within one-zone hadronic and lepto-hadronic scenarios**. These studies are used to evaluate the **potential existence of a steady baseline component in the blazar emission, which is often outshone by more variable regions**. This scenario holds for the SED evolution observed in our data set and the typical state of Mrk 501. X-ray/γ-ray polarization and MeV data would help to distinguish between the multiple theoretical scenarios. The details of this study can be found in a dedicated publication (submitted) (arXiv:2210.02547).