# Multi-messenger characterization of Mrk501 during historically low X-ray and gamma-ray activity

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MAGIC

Fermi Gamma-ray Space Telescope

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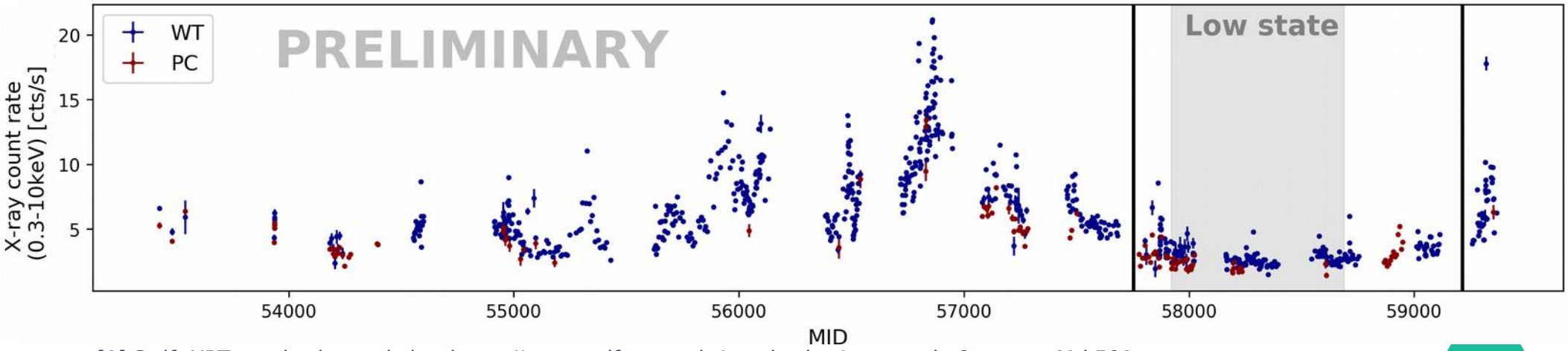
# Mrk501 – 2017 to 2020

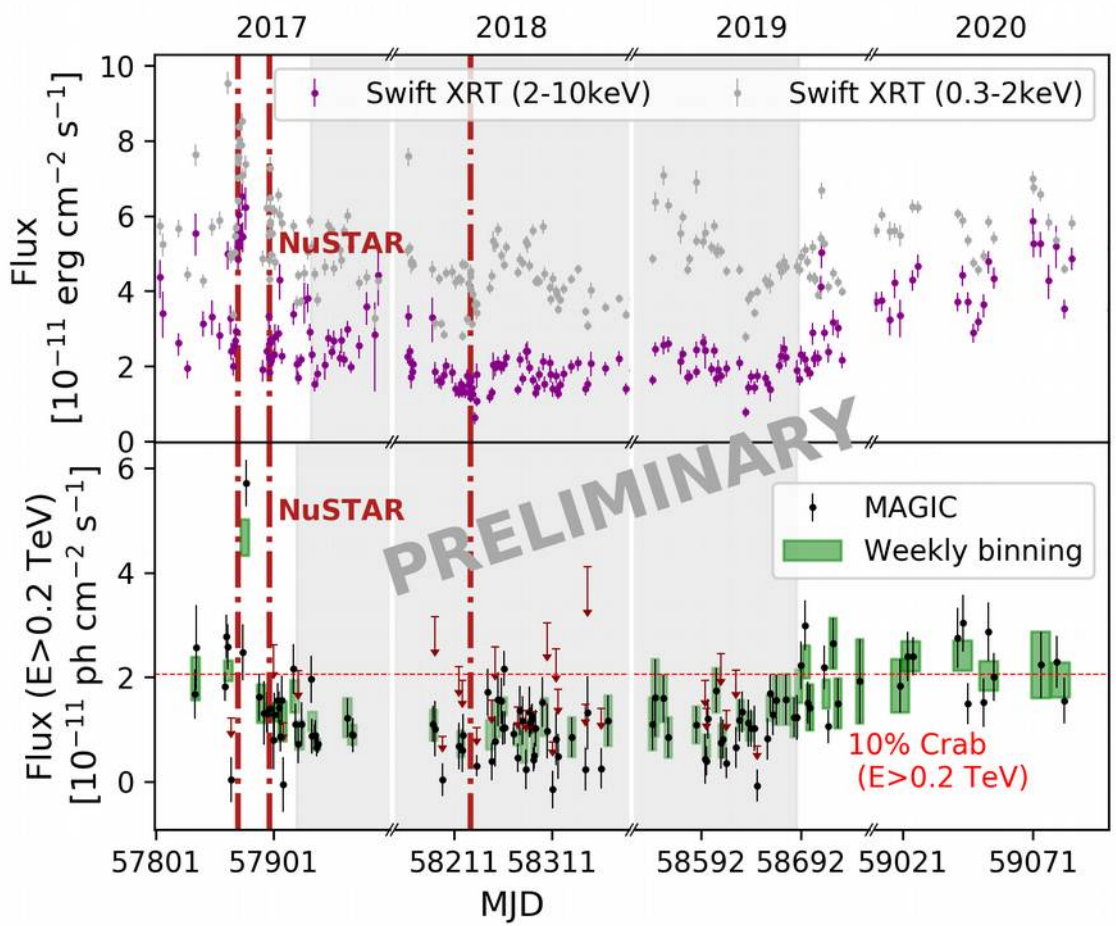
- **Mrk501** is one of our closest & brightest **blazars**
- It can be studied in detail in both during flaring and quiescent states
- Regular **MWL monitoring** is organized to disentangle its complex behavior
- **4 years of very low activity from 2017 to 2020**
- Recognized extremely low state, is it a sort of **baseline**?
  - **2 years of historically low X-ray and gamma-ray (>0.2 TeV) activity**




[1] Swift-XRT monitoring website: https://www.swift.psu.edu/monitoring/source.php?source=Mrk501

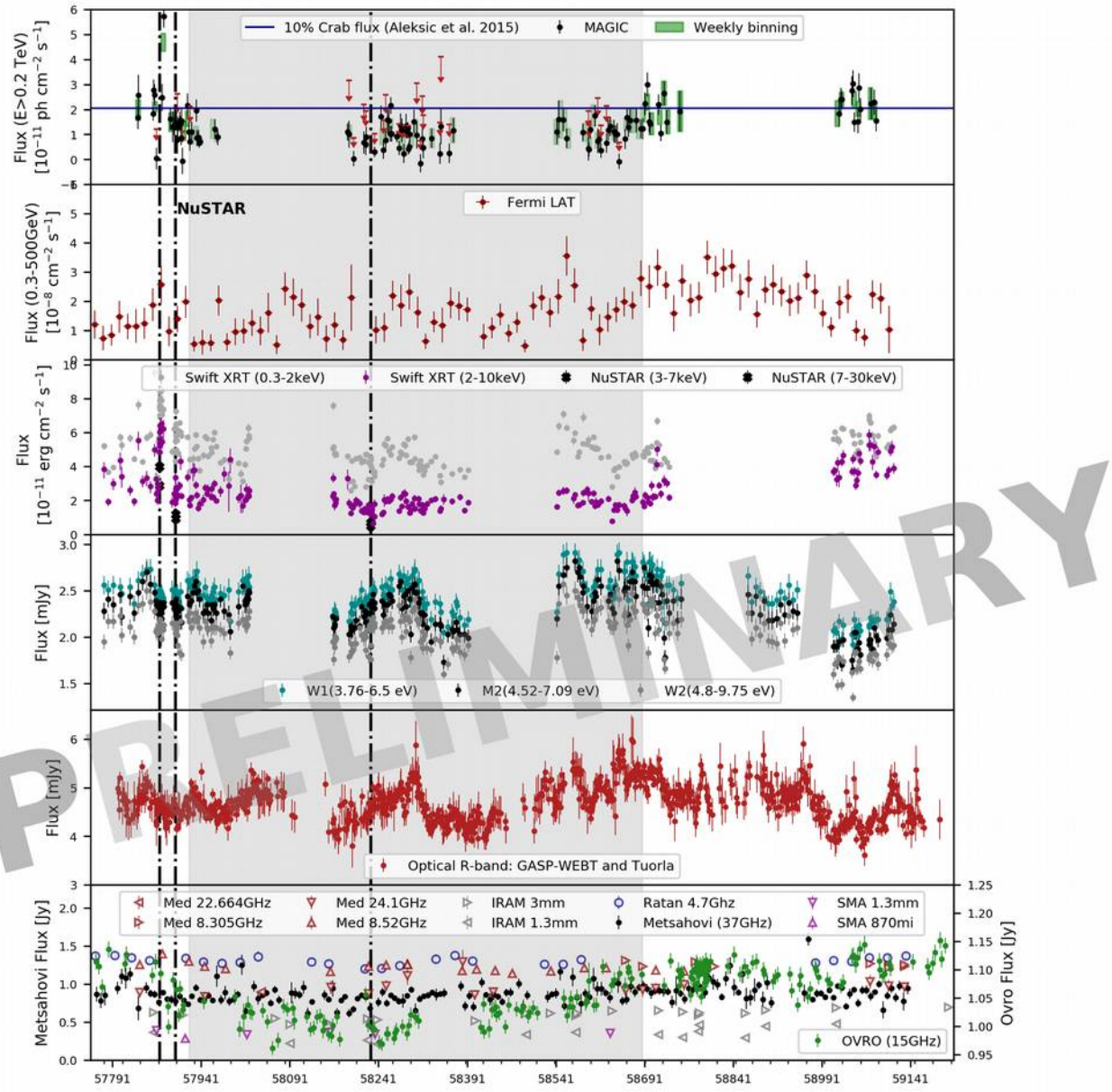
# Mrk501 – low activity

- Recognized extremely low state, is it a sort of **baseline**?
  - **2 years of historically low X-ray and gamma-ray (>0.2 TeV) activity**
  - Identified by a Bayesian block algorithm applied to the MAGIC lightcurve
  - From mid of 2017 to mid of 2019
  - **VHE flux constant** at ~5% that of the Crab
  - Simultaneous low activity in X-rays



# Mrk501 MWL monitoring 2017-2020

- Gamma-ray:
  - MAGIC
  - *Fermi*-LAT
- X-ray:
  - *Swift*-XRT
  - **Three long *NuSTAR* observations**
- UV: *Swift*-UVOT
- Optical R-band:
  - GASP-WEBT
  - Tuorla
- Radio:
  - OVRO
  - Metsähovi
  - Ratan, Medina, SMA, IRAM



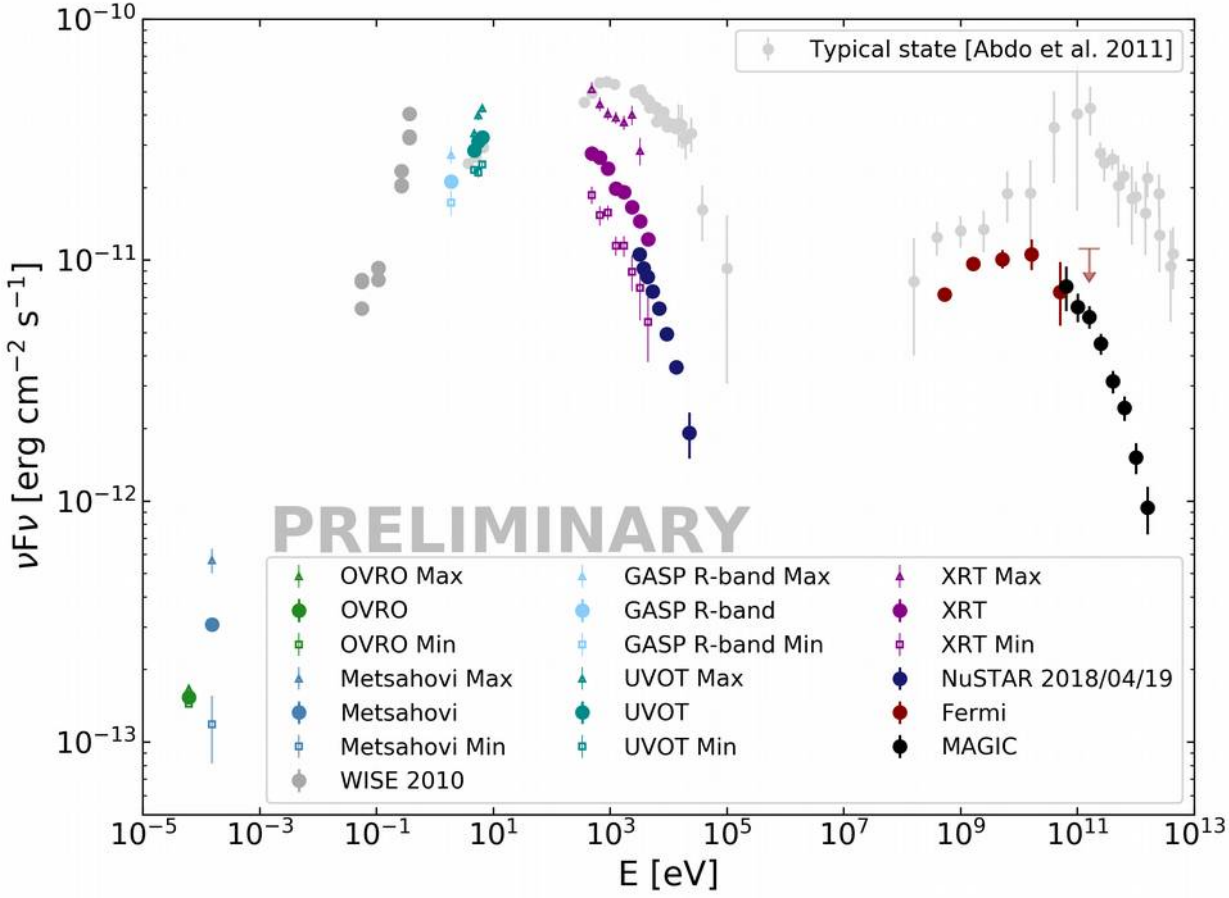
# Mrk 501 low state

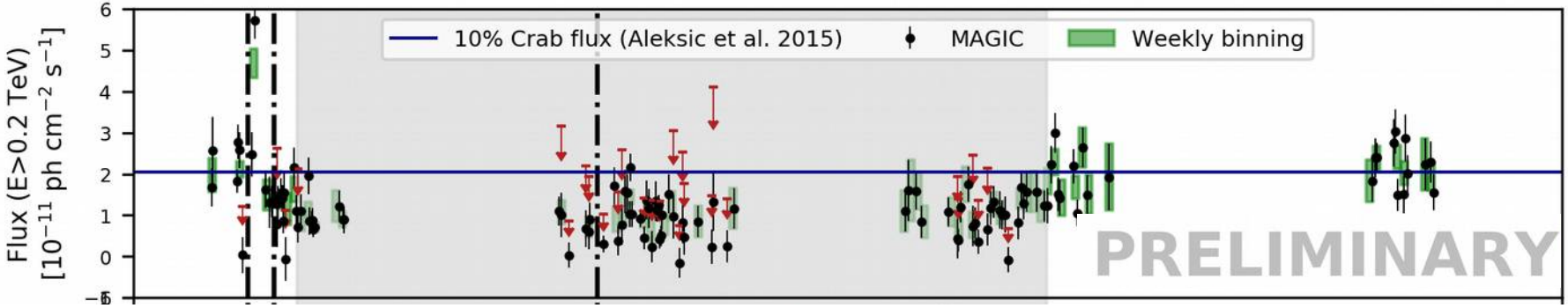
- Constant flux at VHE
- As usual little variability in lower energy bands

  → **SED with good MWL coverage**

  - Average spectra during the 2-year period of extremely low activity (“baseline”)
  - Min. & Max. variations displayed for the optical/UV and X-ray data (not significant for gamma-ray data)

  → Averaged SED very well suited to **investigate the nature** of this **extremely low-state emission (baseline)**

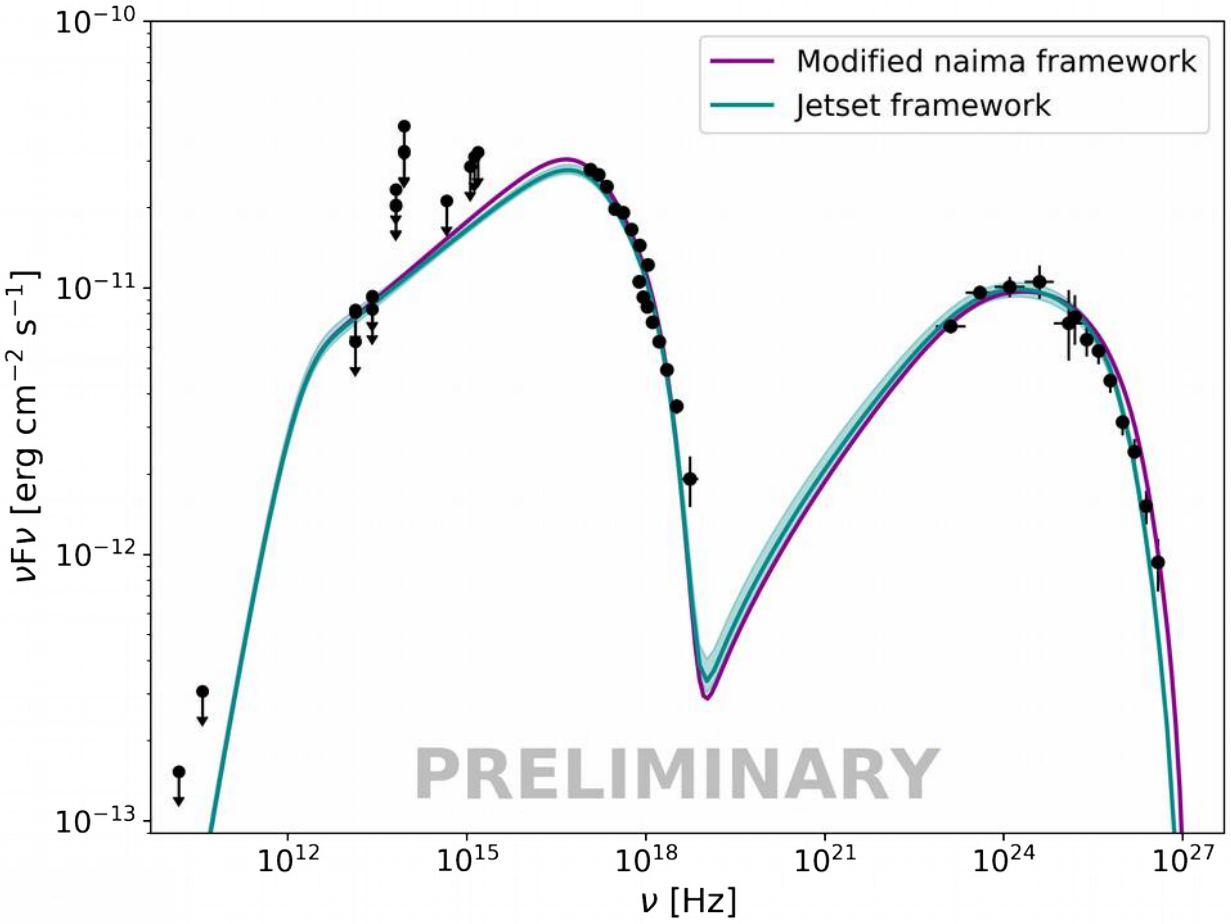


# Mrk 501 low state – leptonic scenario

- **Standard one-zone SSC model**
- Two independent frameworks
  - Modified naima framework using a MCMC sampler by S. Gasparyan
  - Public jetset framework using a minuit minimization result as a prior for a MCMC sampler

→ Both frameworks **describe the low state SED well** with **standard model parameters**




Low state with B=0.03

| | $W_e$ [erg/s] | $\alpha_1$ | $\gamma_{br}$ | $\gamma_{max}$ |
|---|---|---|---|---|
| Modified Naima | 6.84e43 | 2.62 | 2.43e5 | 1.14e6 |
| Jetset | 7.69e43 | 2.64 | 2.6e5* | 1.16e6 |

*Fixed to the Synchrotron cooling break

Broken power law used with $\alpha_2 = \alpha_1 + 1$, $\gamma_{min}$=1000 Γ, R=1e17 cm, $\delta$=10, z=0.034, Franceschini EBL

# Mrk 501 low state – hadronic scenario

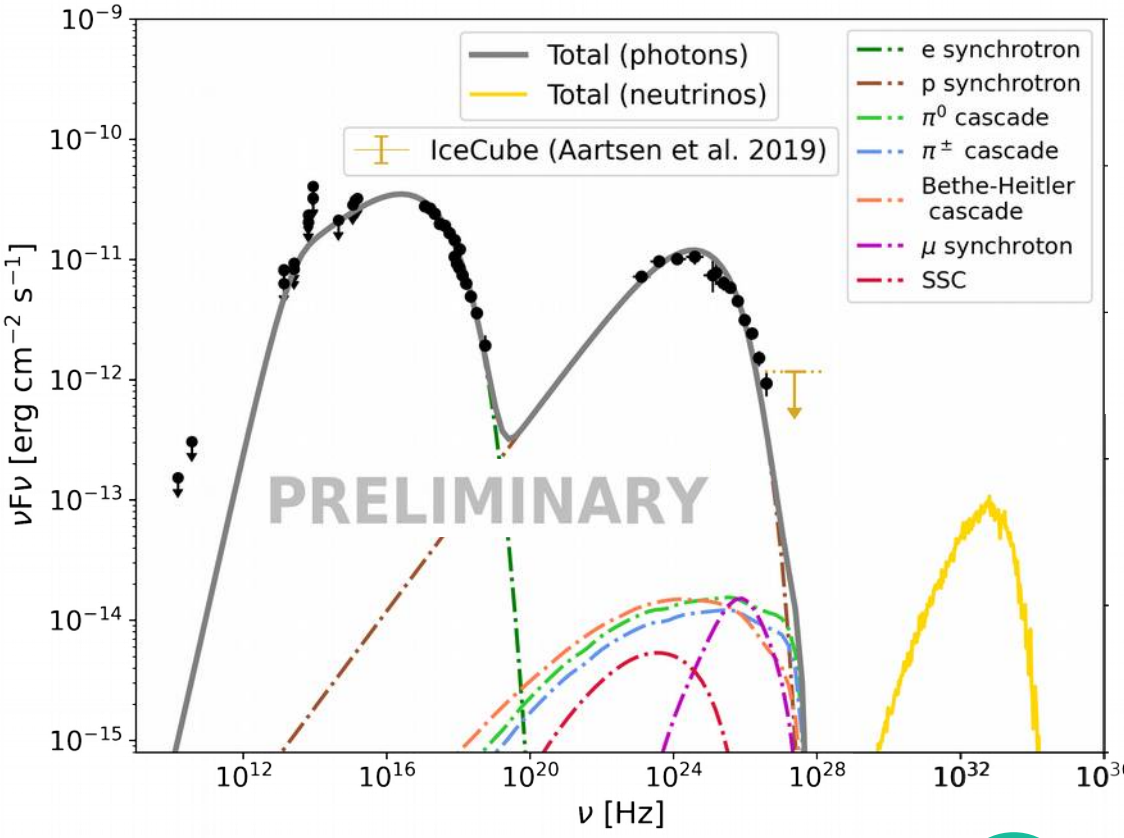
- Framework using the LeHa code (Cerruti et al. 2015)
  → **Describes the low-state SED reasonably well**
  - with standard model parameters and low variability
  - **in agreement with the IceCube ULs**

**Neutrino rates per year:**
Expected by the model: **1.1e-4**
IceCube best fit number: **10.3/10**

| parameter | value |
|---|---|
| B [G] | 2 |
| R [cm] | 1e17 |
| e density [$cm^{-3}$] | 12 |
| p density [$cm^{-3}$] | 0.24 |
| slope e spectrum | 2.5 |
| $\gamma_{min,e}$ | 500 |
| $\gamma_{max,e}$ | 4.5e4 |
| slope p spectrum | 2.2 |
| $\gamma_{min,p}$ | 1 |
| $\gamma_{max,p}$ | 1.4e10 |

Simple power law used, $\delta$=10, z=0.033, Franceschini EBL

| parameter | value |
|---|---|
| $U_e$ / $U_B$ | 4.55e-06 |
| $U_p$ / $U_B$ | 1.23 |
| Jet luminosity [erg/s] | 1.71e+46 |



# SED evolution

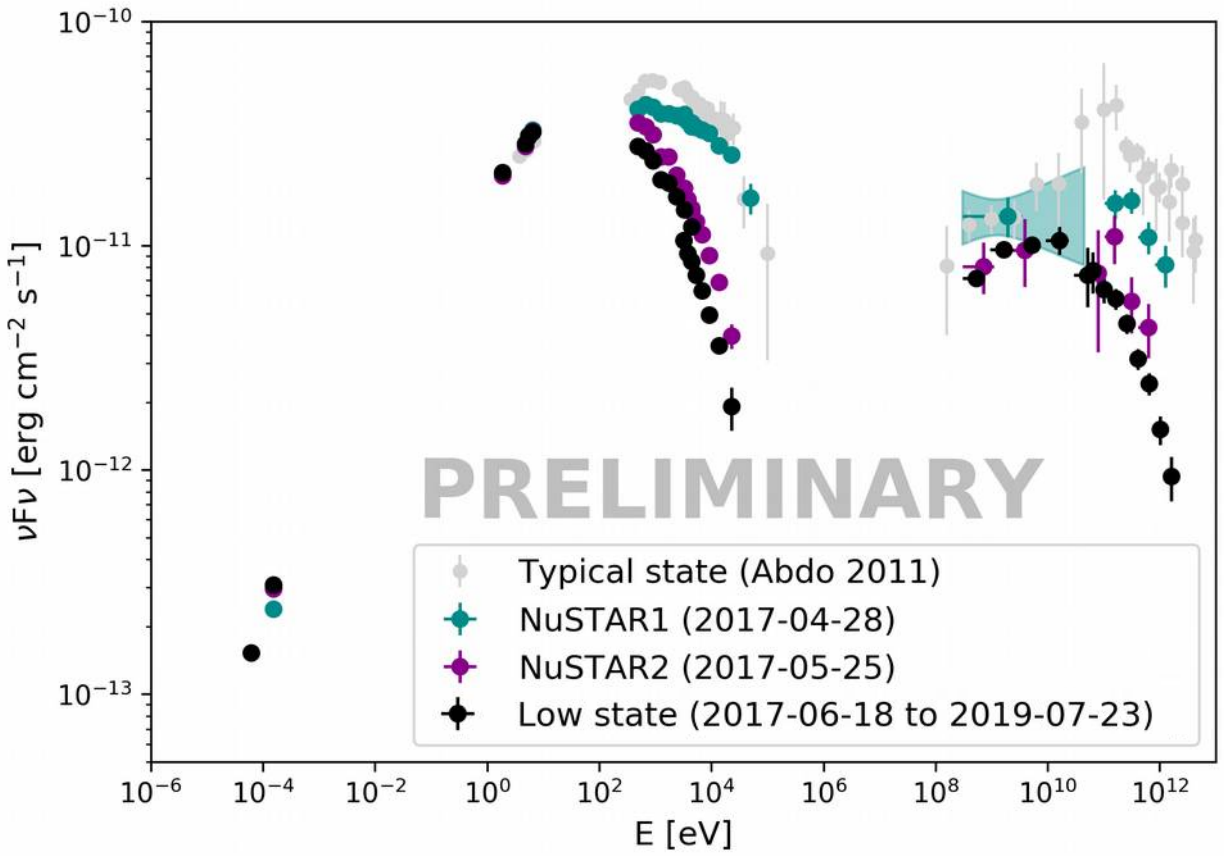
- **Additional NuSTAR observations** → Evaluation of the **SED evolution**

- **NuSTAR1**: 2017-04-28
  - **~2 months before the low state**
  - MAGIC & Fermi: data from ± 1 week
  - Simultaneous data in the lower energy wavebands

    + archival IR data

- **NuSTAR2**: 2017-05-25
  - **~1 month before the low state**
  - Fermi: data from ± 1 week
  - Simultaneous data for MAGIC & the lower energy wavebands

    + archival IR data

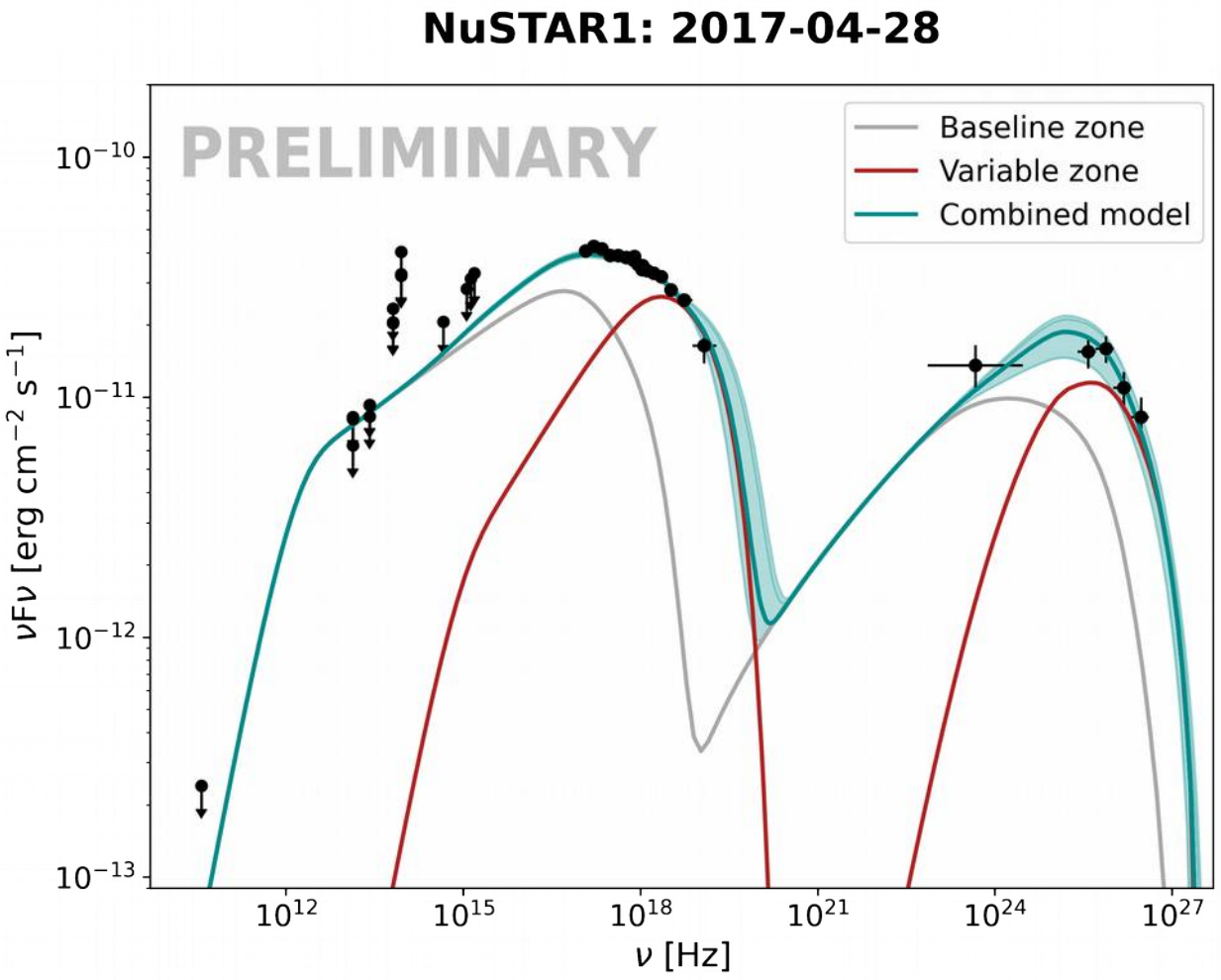


# Two-zone scenario

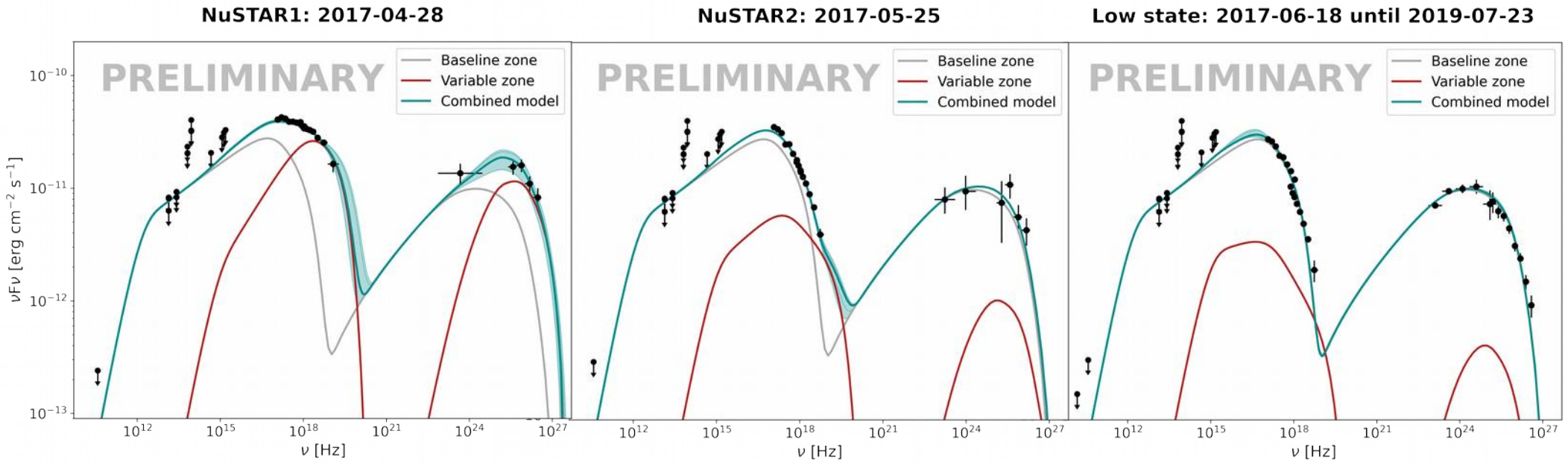
- Assumption:
  - **Stable & always present baseline emission**

    → use our low state model
  - Usually outshone by a **more dominant and variable region**

    → Combination reproduces the observed blazar emission



# Two-zone scenario



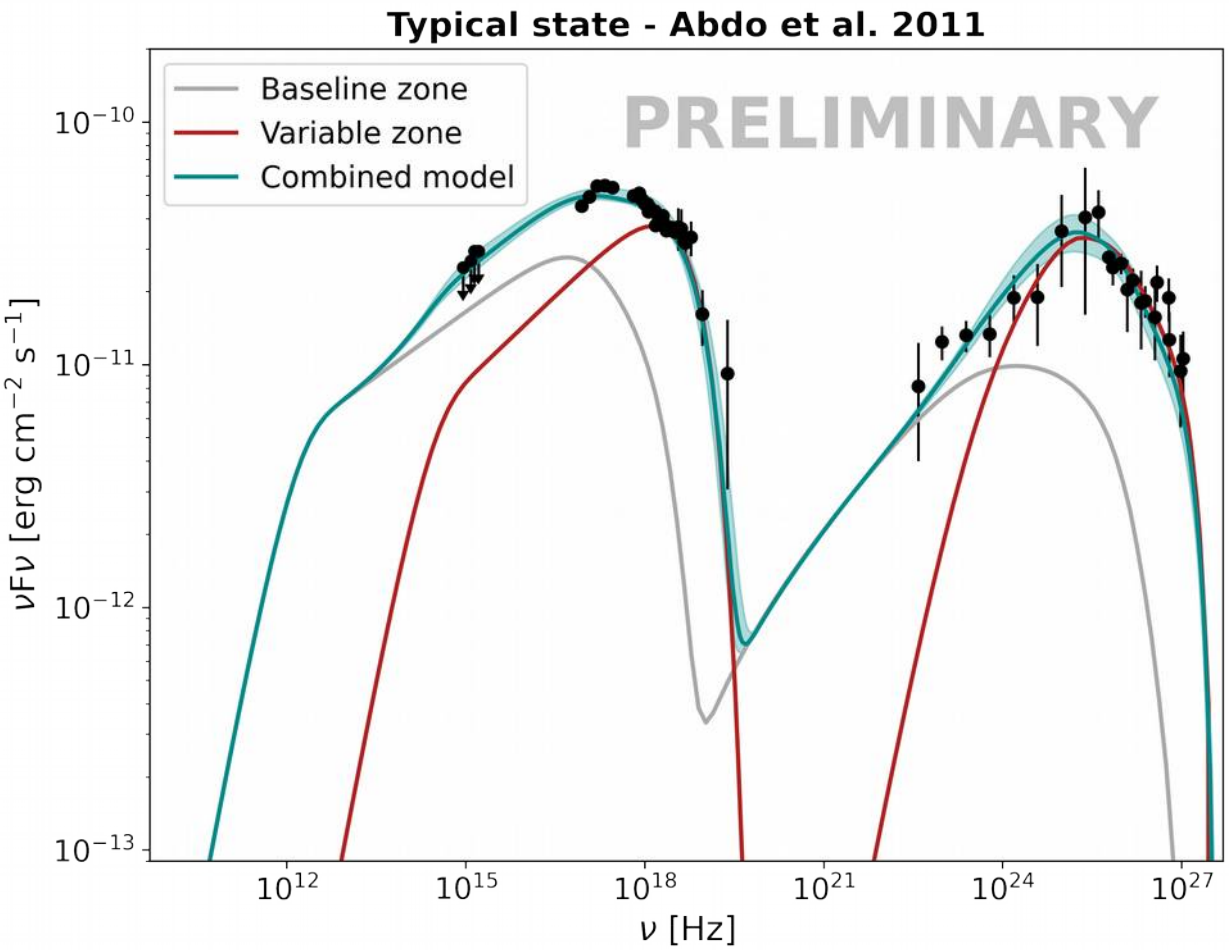

| | R [cm] | N [cm$^{-2}$] | B [G] | $\alpha_1$ | $\gamma_{min}$ | $\gamma_{br}$ | $\gamma_{max}$ |
|---|---|---|---|---|---|---|---|
| NuSTAR1[a] | 5e15 | 0.85 | 0.081 | 2.21 | 1.5e4 | 7.07e5* | 2.76e6 |
| NuSTAR2[a] | 1.2e16 | 0.06** | 0.081 | 2.55 | 1.5e4 | 2.97e5* | 2.71e6 |
| Low state[a] | 1.82e16*** | 0.02** | 0.081 | 2.83 | 1.5e4 | 1.95e5* | 2.19e6 |

*Fixed to the Synchrotron cooling break
**Fixed to expanding R assuming a spherical blob
***Fixed to same expanding velocity
[a] Broken power law used with $\alpha_2 = \alpha_1 + 1$, $\delta$=10, z=0.034, Franceschini EBL

# Two-zone scenario

- Application to previously published data

- **Typical state** from Abdo et al. 2011:
  - 4.5 months period in 2009
  - Exclusion of a flaring period in May 2009
- Our **two-zone model can explain the data** adding a more active region to our baseline emission
  - **Simple power law distribution** preferred for the electron distribution of the active region




| | R [cm] | N [cm$^{-2}$] | B [G] | $\alpha_1$ | $\gamma_{min}$ | $\gamma_{br}$ | $\gamma_{max}$ |
|---|---|---|---|---|---|---|---|
| Typical state[b] | 4.97e16 | 0.05 | 0.013 | 2.53 | 2.1e4 | - | 3.49e6 |

[b] Simple power law used, $\delta$=10, z=0.034, Franceschini EBL

# Summary & Outlook

- During the period from mid-2017 to mid-2019, Mrk501 showed **historically low activity in X-rays and VHE gamma rays**
- We demonstrated how this extremely low state (baseline emission ?) can be explained by both **standard leptonic and hadronic scenarios in agreement with additional multi-messenger data**
- These studies can be used to evaluate the **potential existence of a steady baseline component** in the blazar emission, which is often **outshone by the emission of more variable and active region.**
- More details will follow soon in a **dedicated publication** including
  - Variability and correlation studies
  - Detailed evaluation of our spectral studies and physical scenarios
- This is a first step towards disentangling the complex behavior of the most luminous persistent sources in our universe