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

Lea Heckmann, David Paneque, Sargis Gasparyan, Matteo Cerruti, Narek Sahakyan, Axel Abert-Engels
on behalf of the MAGIC and *Fermi*-LAT collaborations and other MWL partners

MAGIC

Fermi Gamma-ray Space Telescope

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MAX-PLANCK-INSTITUT FÜR PHYSIK

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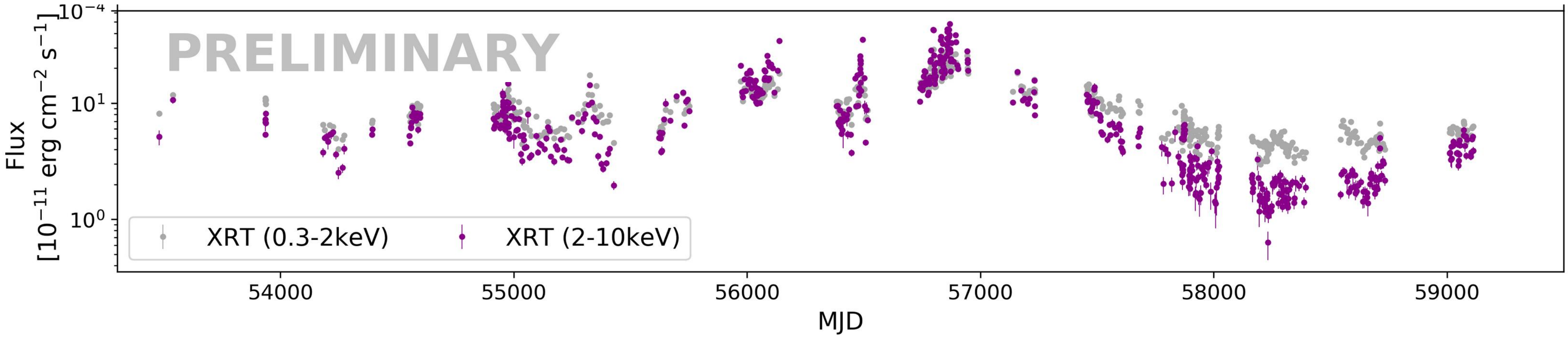

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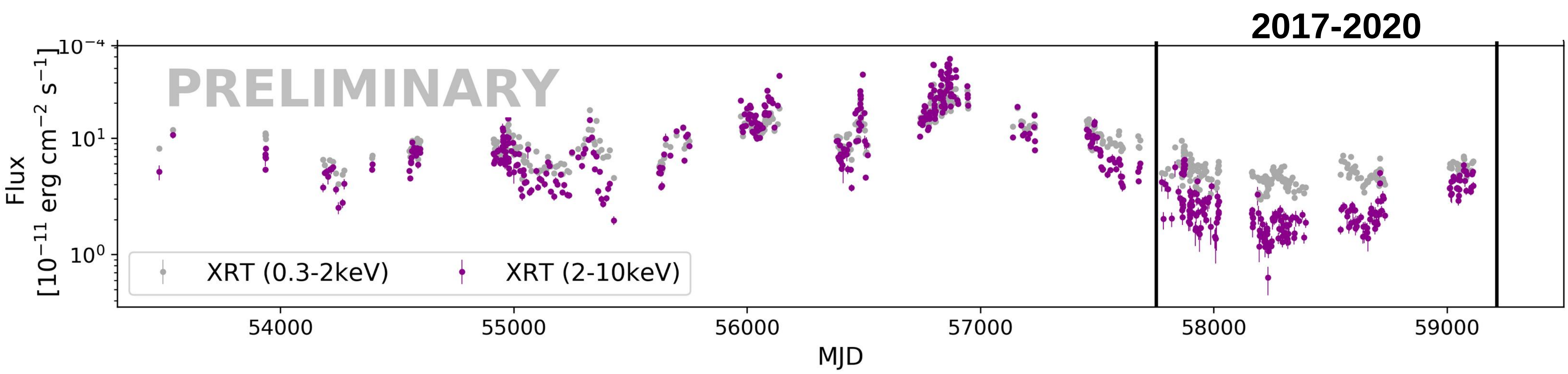

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- It can be studied in detail during both flaring and quiescent states
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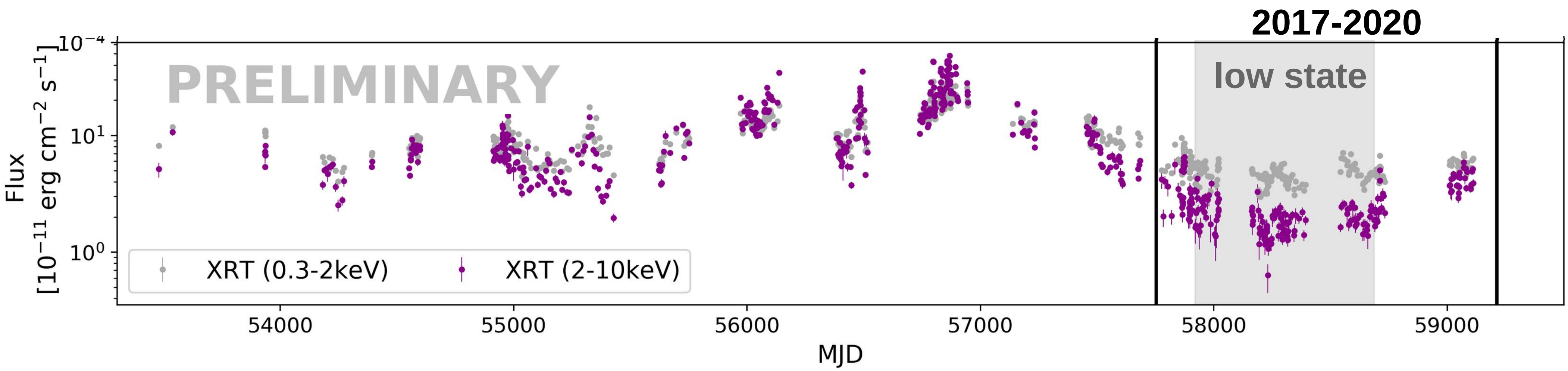
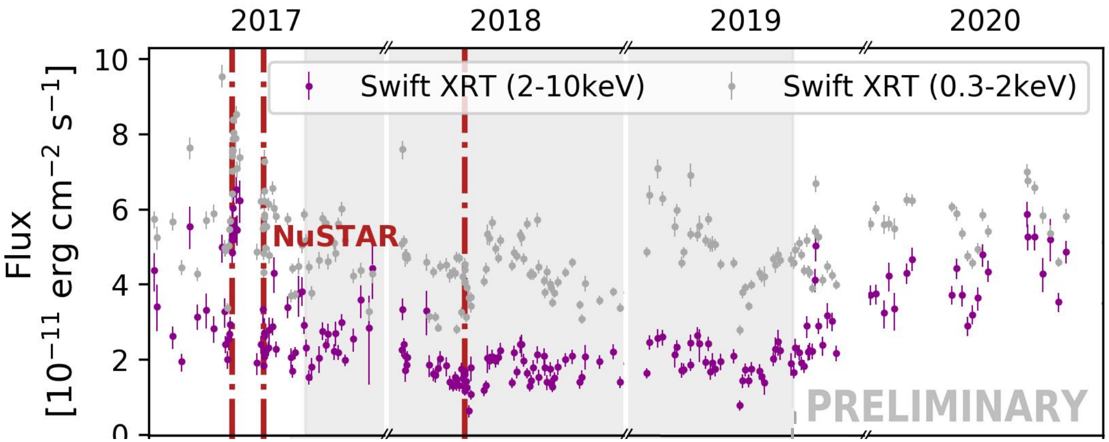
- **4 years of very low activity from 2017 to 2020**
- **2 years of historically low X-ray activity**
    - Is it a sort of **baseline**?



Mrk501 – low activity

- **2 years of historically low X-ray**



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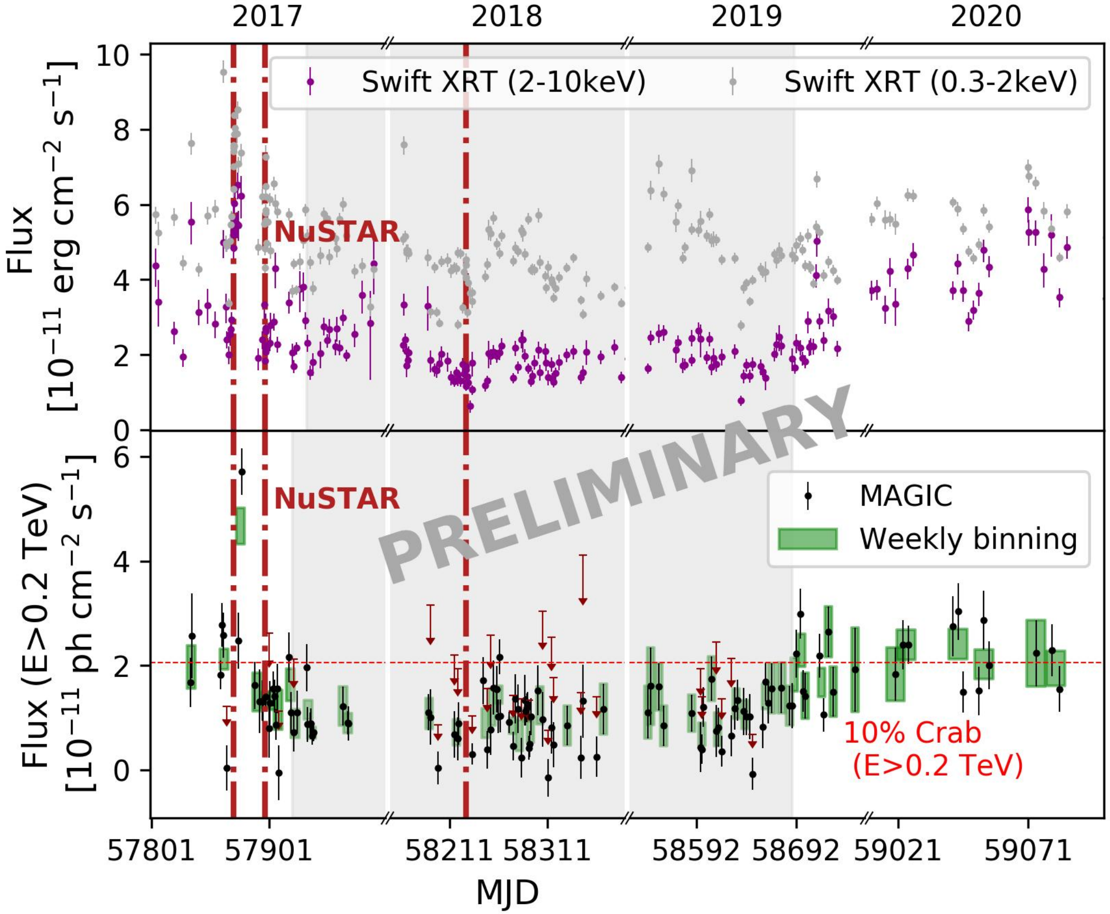
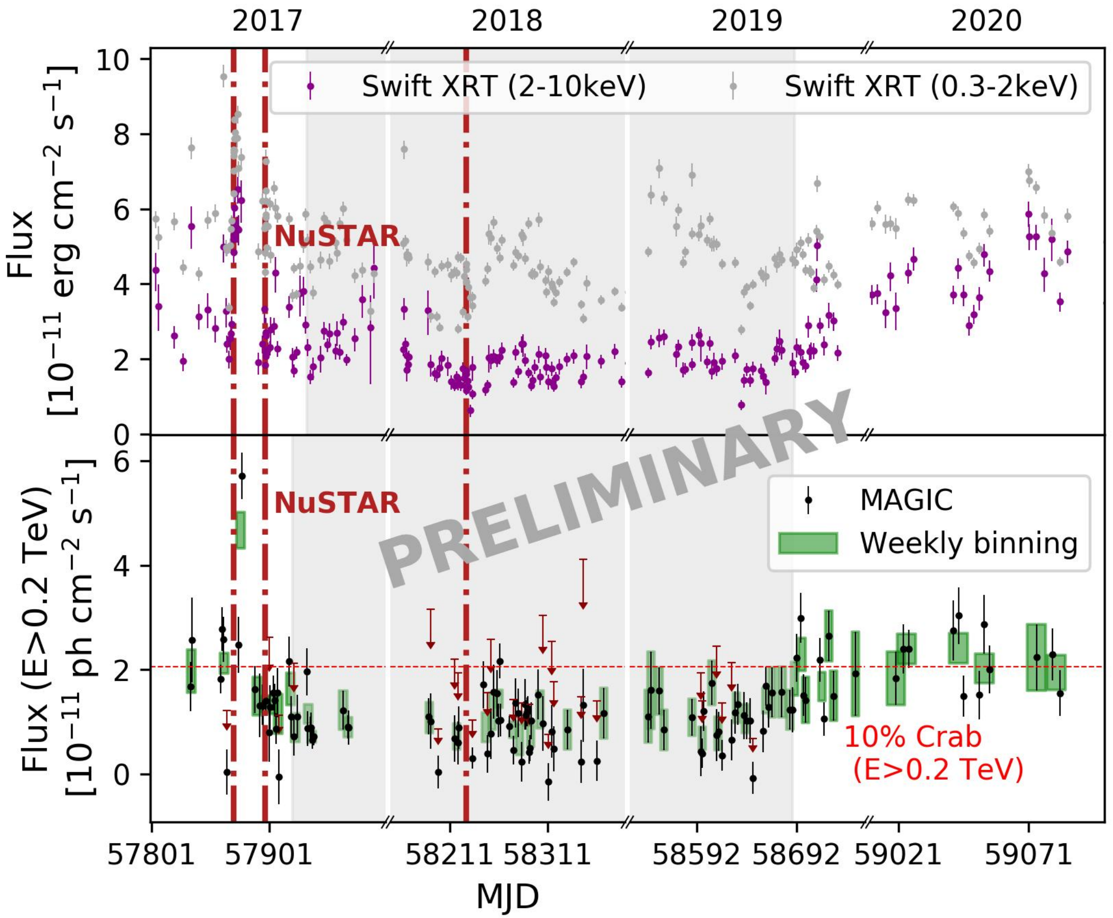


Mrk501 – low activity

- **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 Nebula
  - Simultaneous low activity in X-rays



Mrk501 variability & correlations

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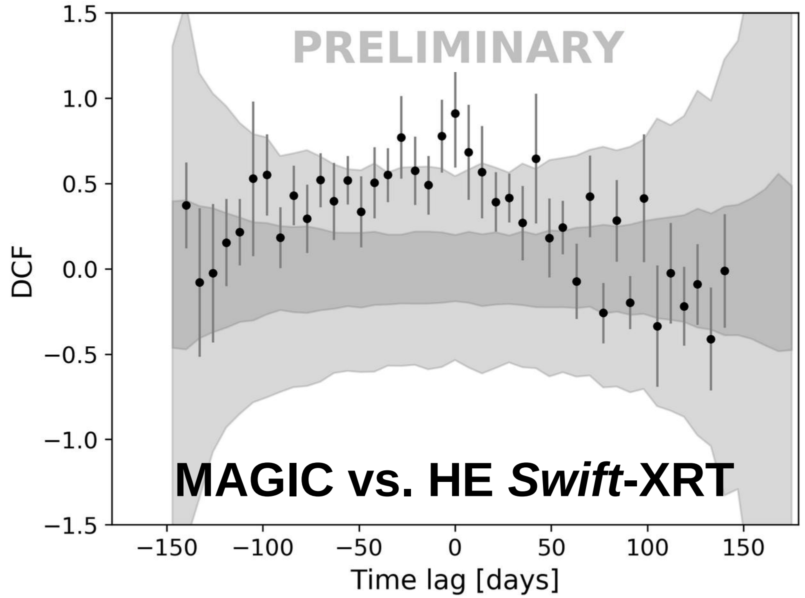

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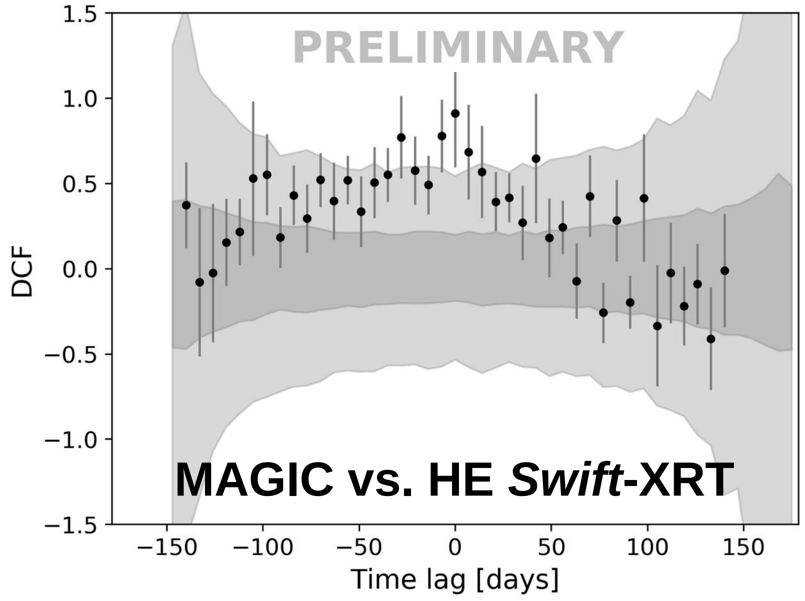

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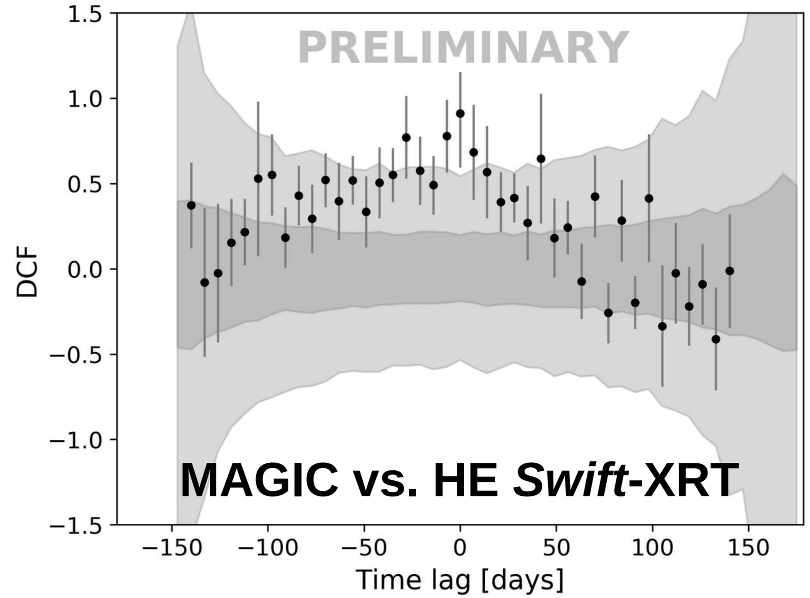

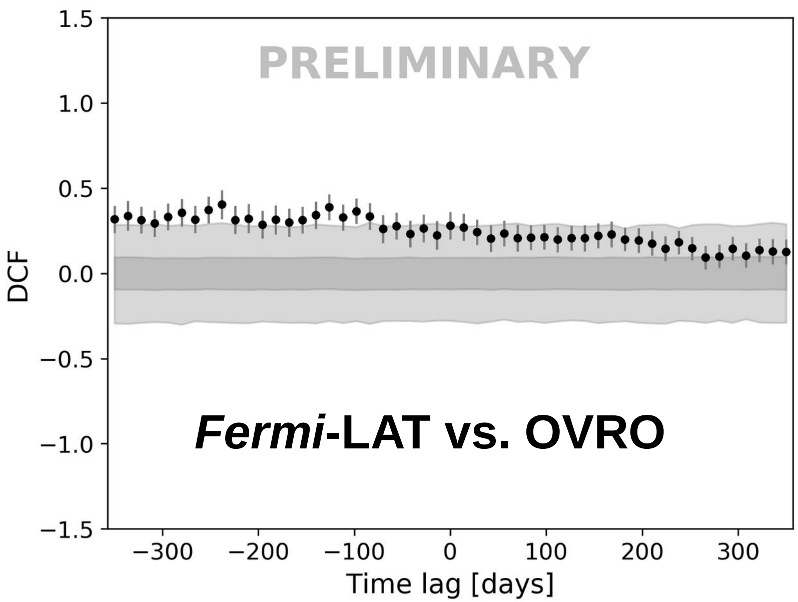

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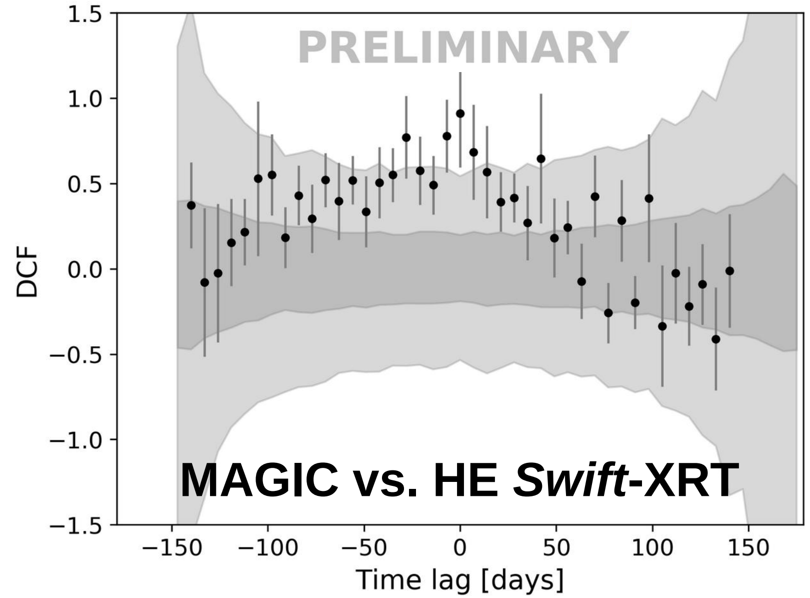

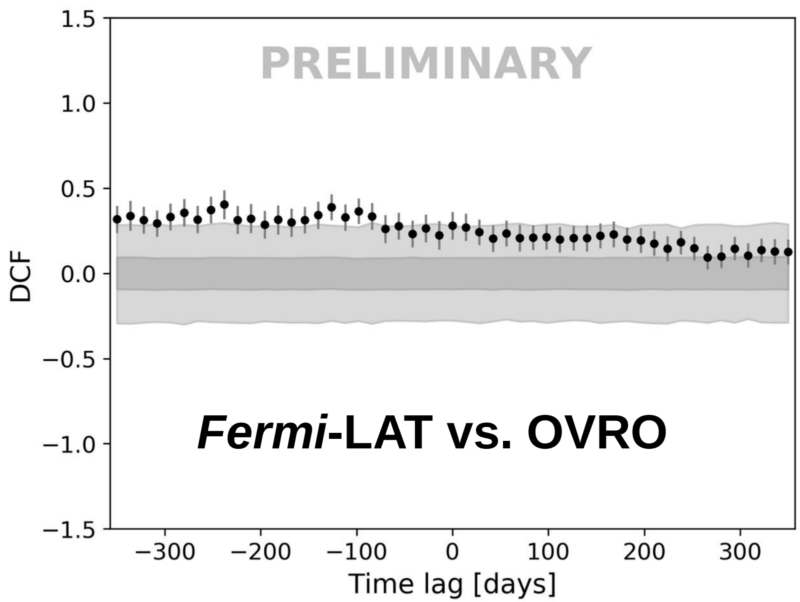

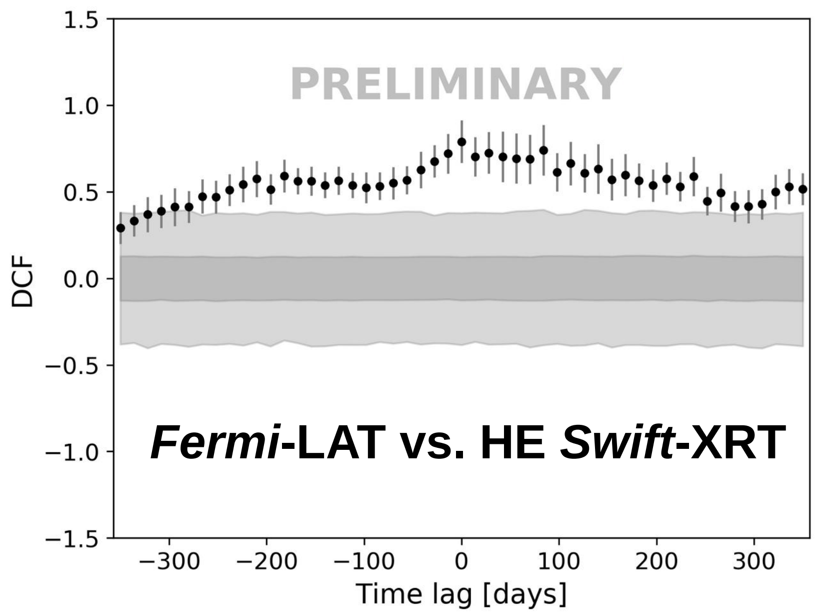

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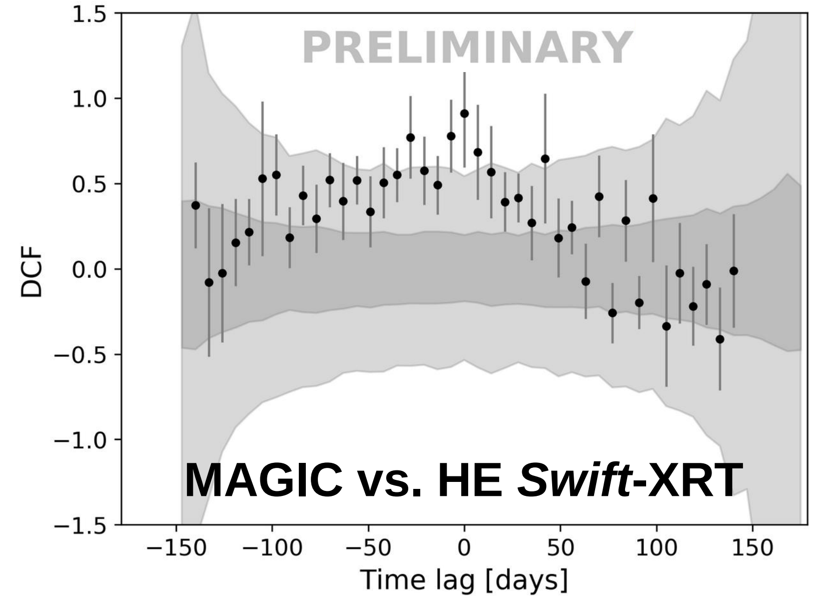

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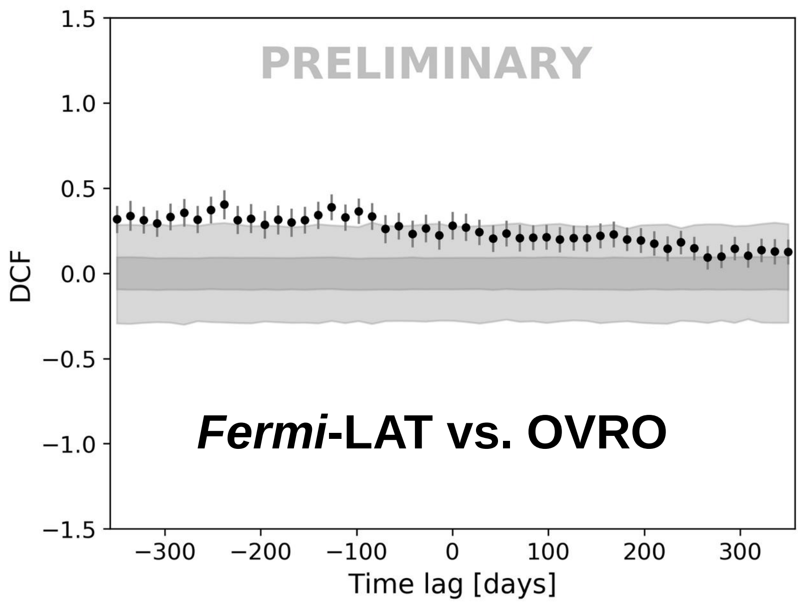
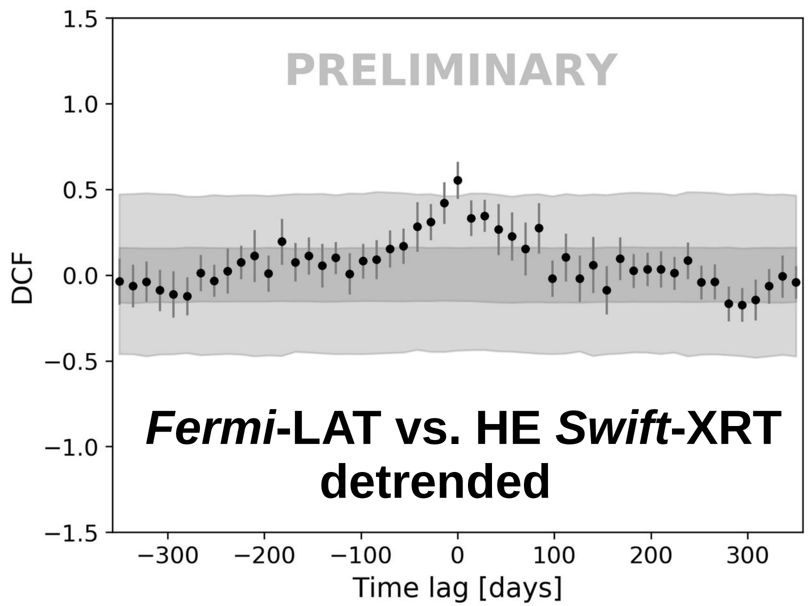
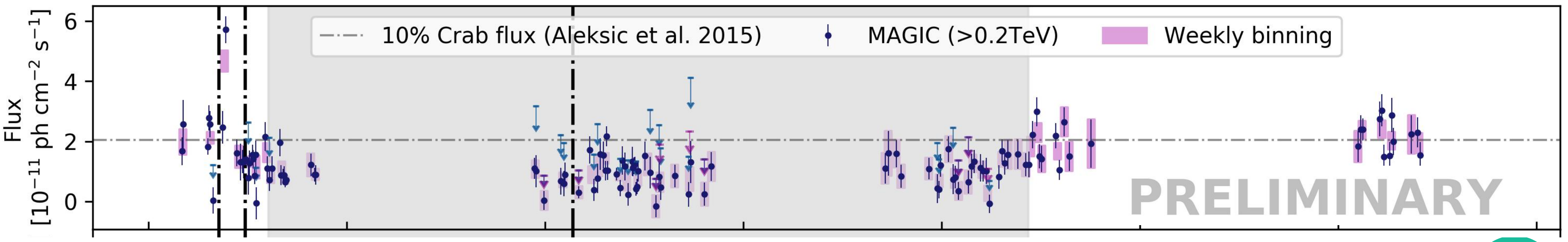




Mrk501 low state

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



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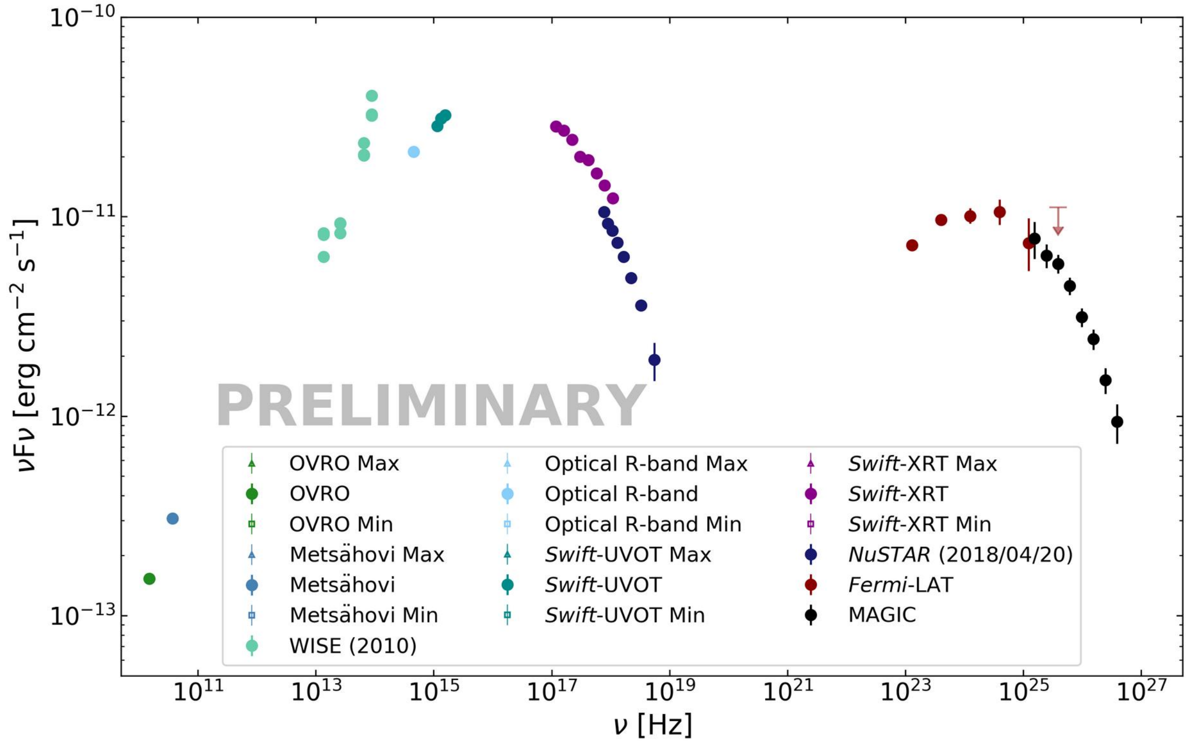
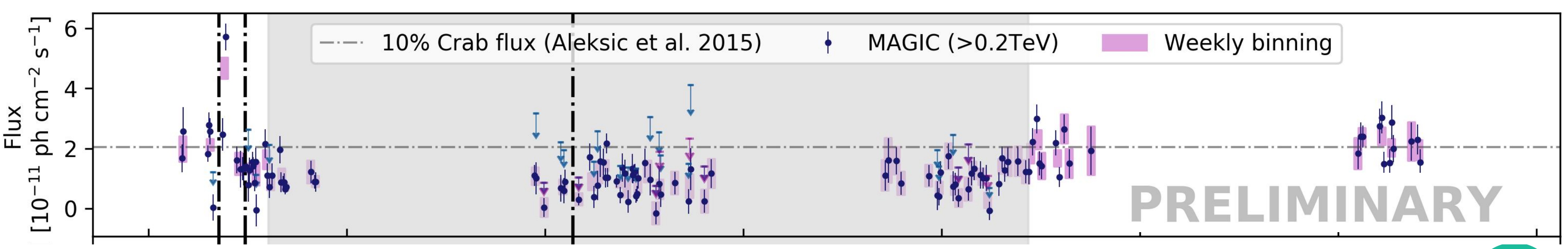
  - Average spectra during the 2-year period of extremely low activity (“baseline”)





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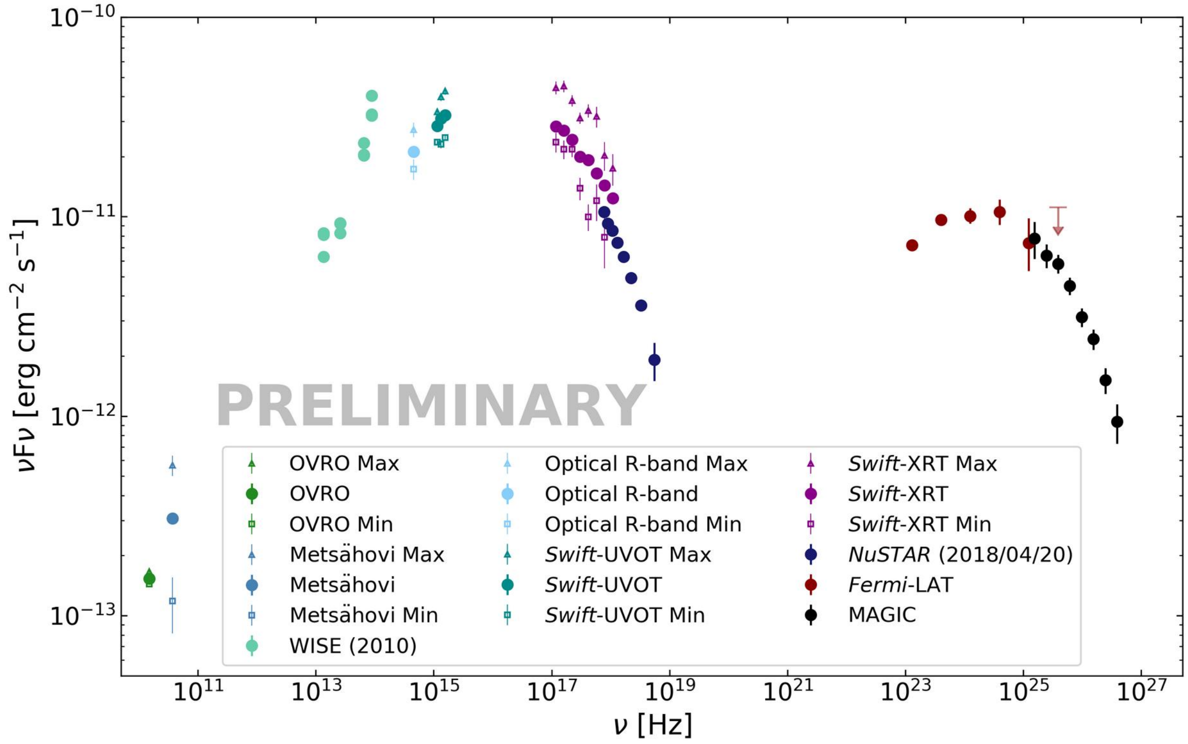

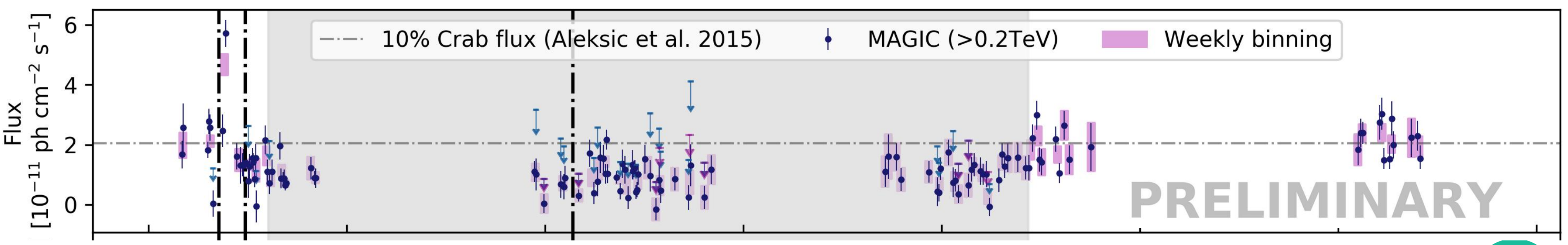

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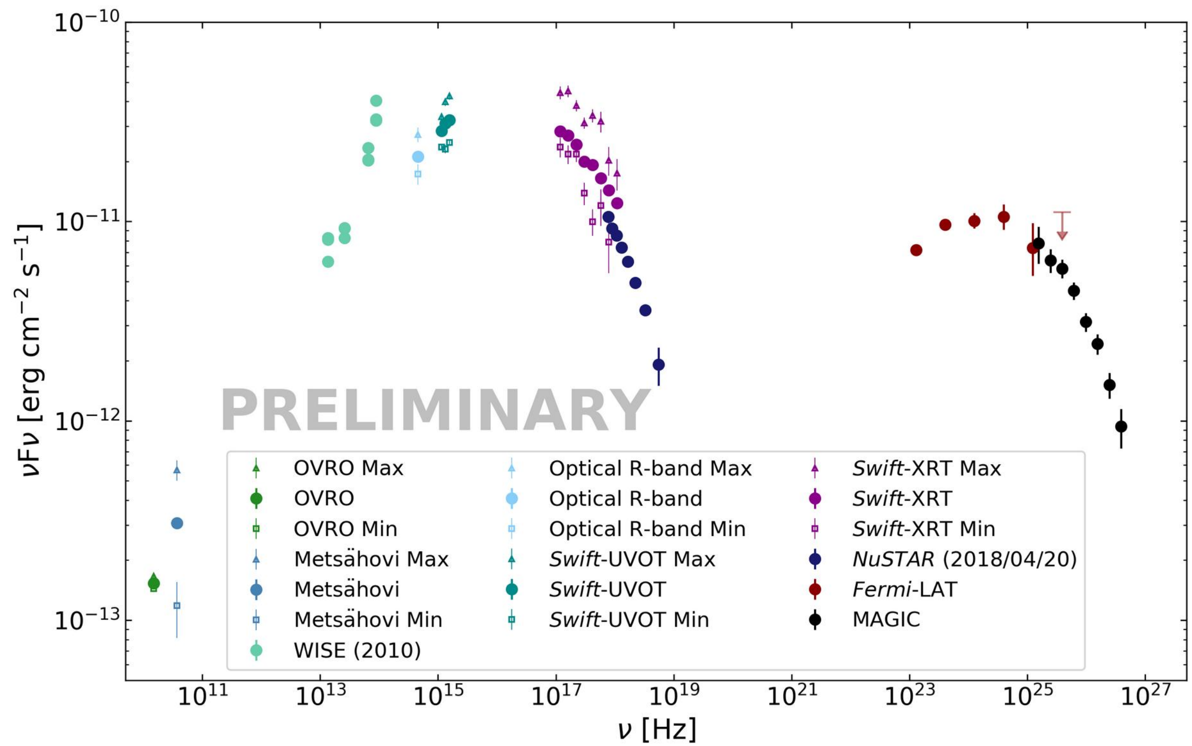

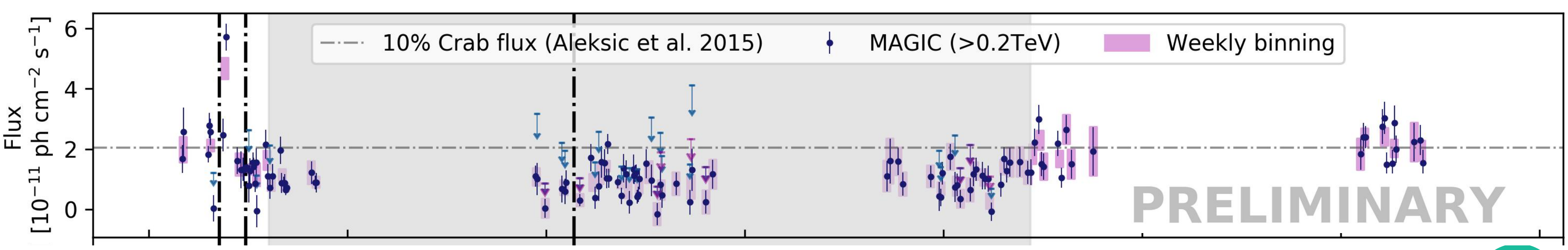

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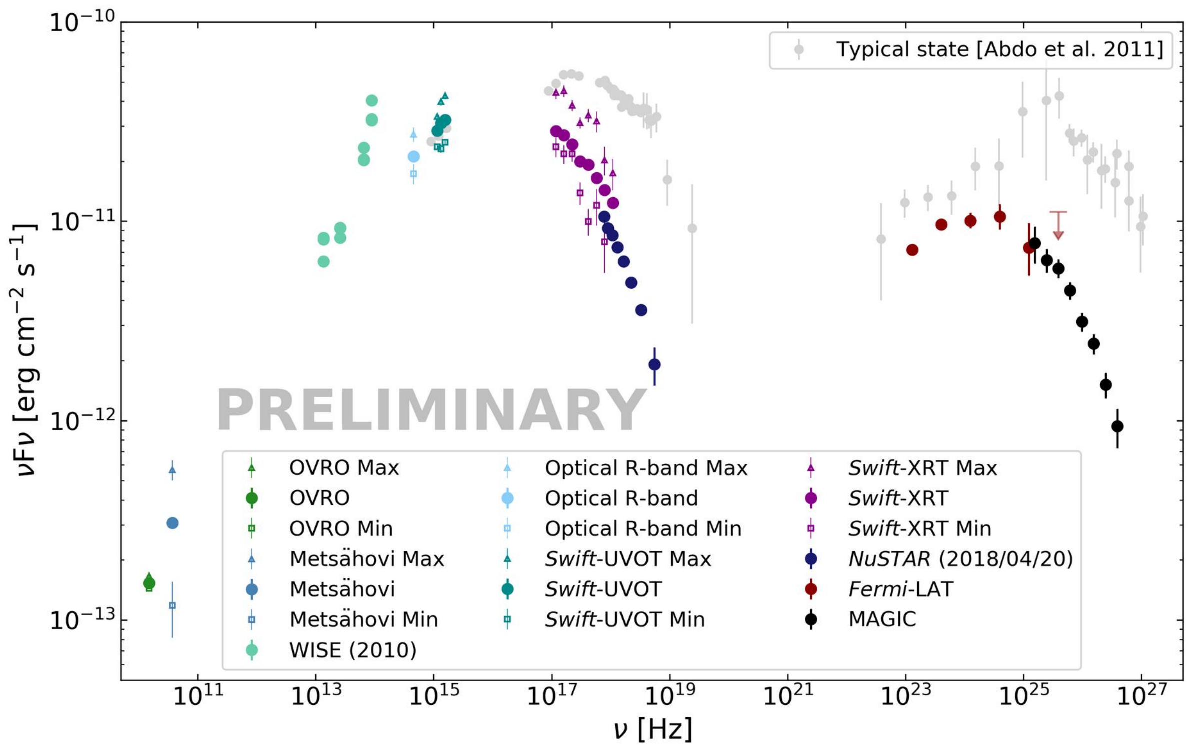
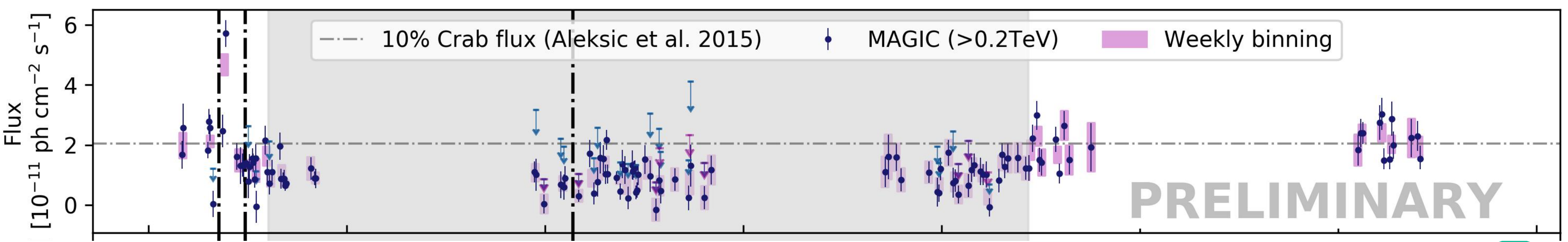
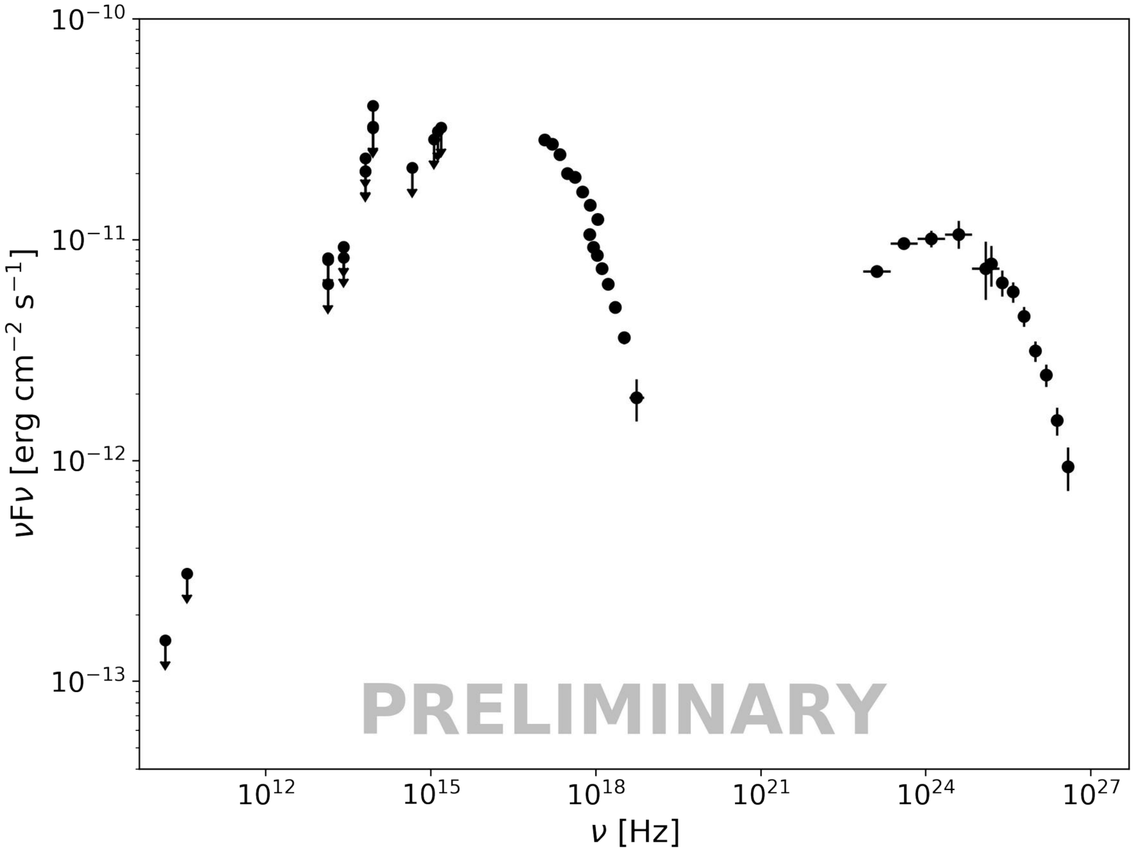




Mrk501 low state – leptonic scenario

- **Standard one-zone SSC model**
- Two independent frameworks



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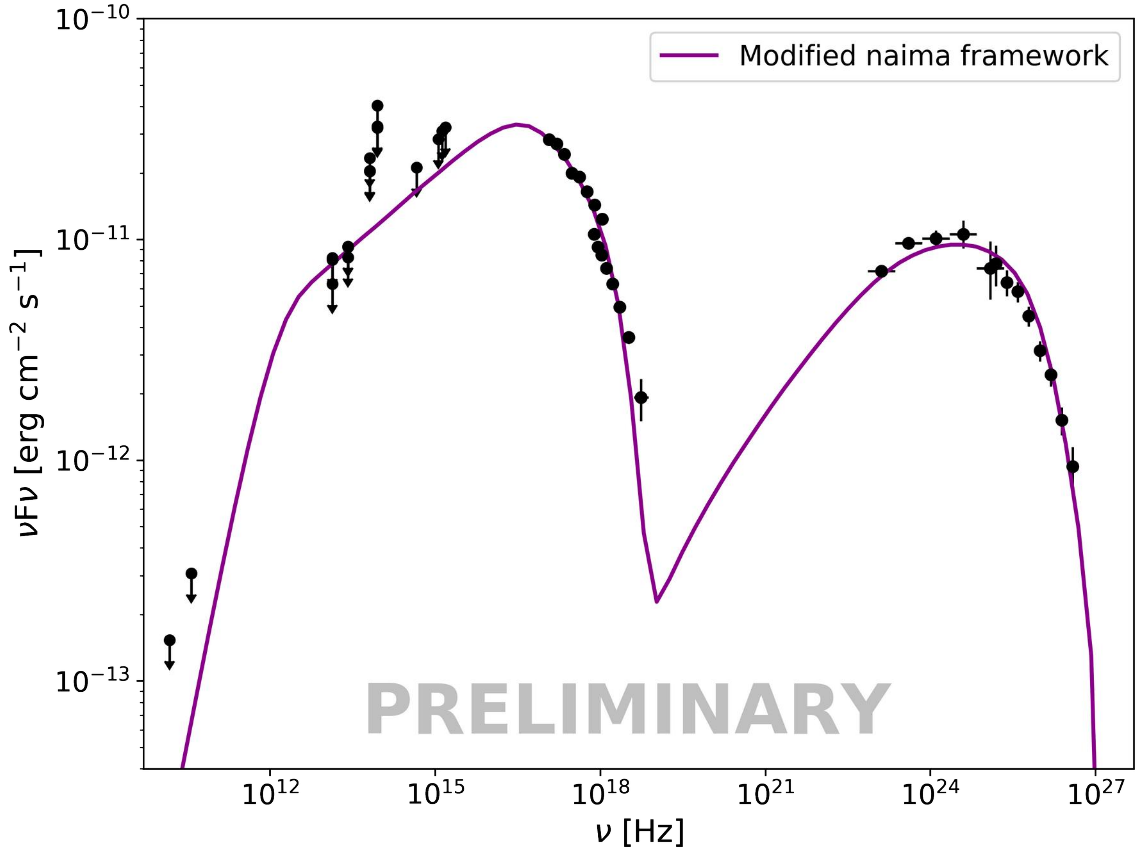

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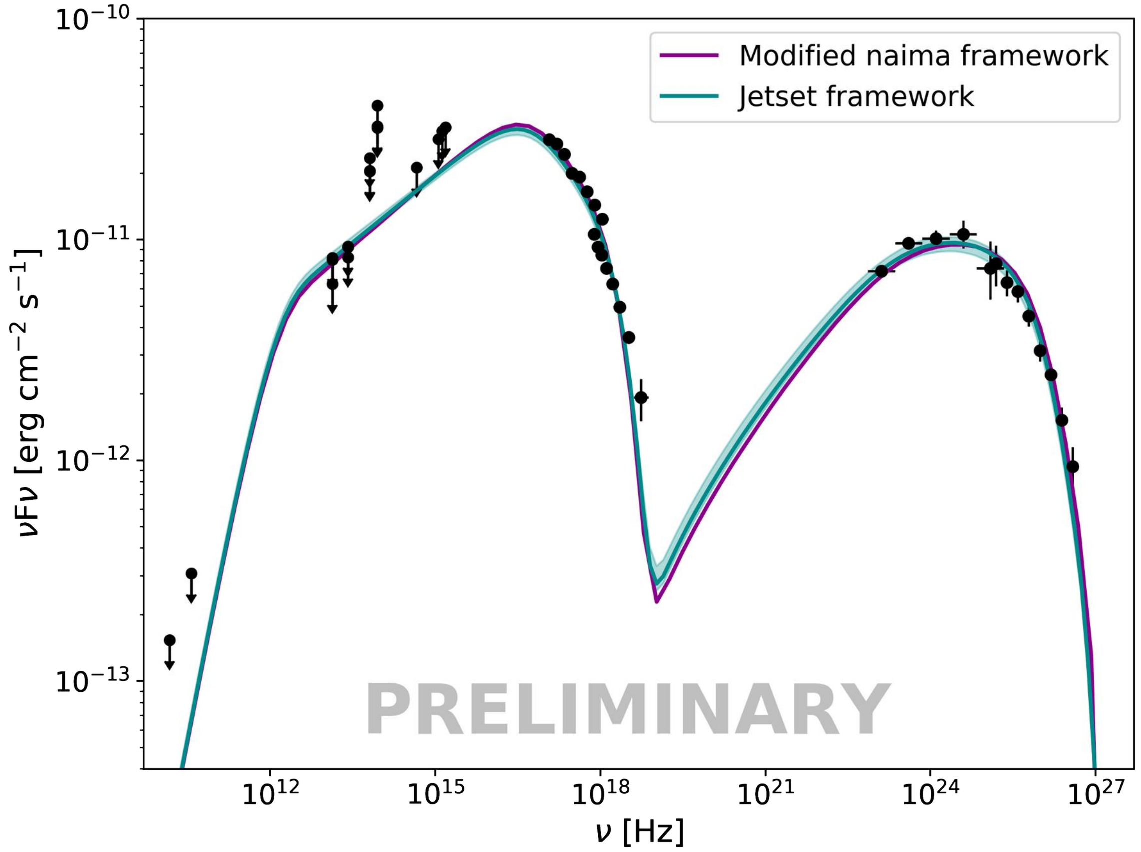

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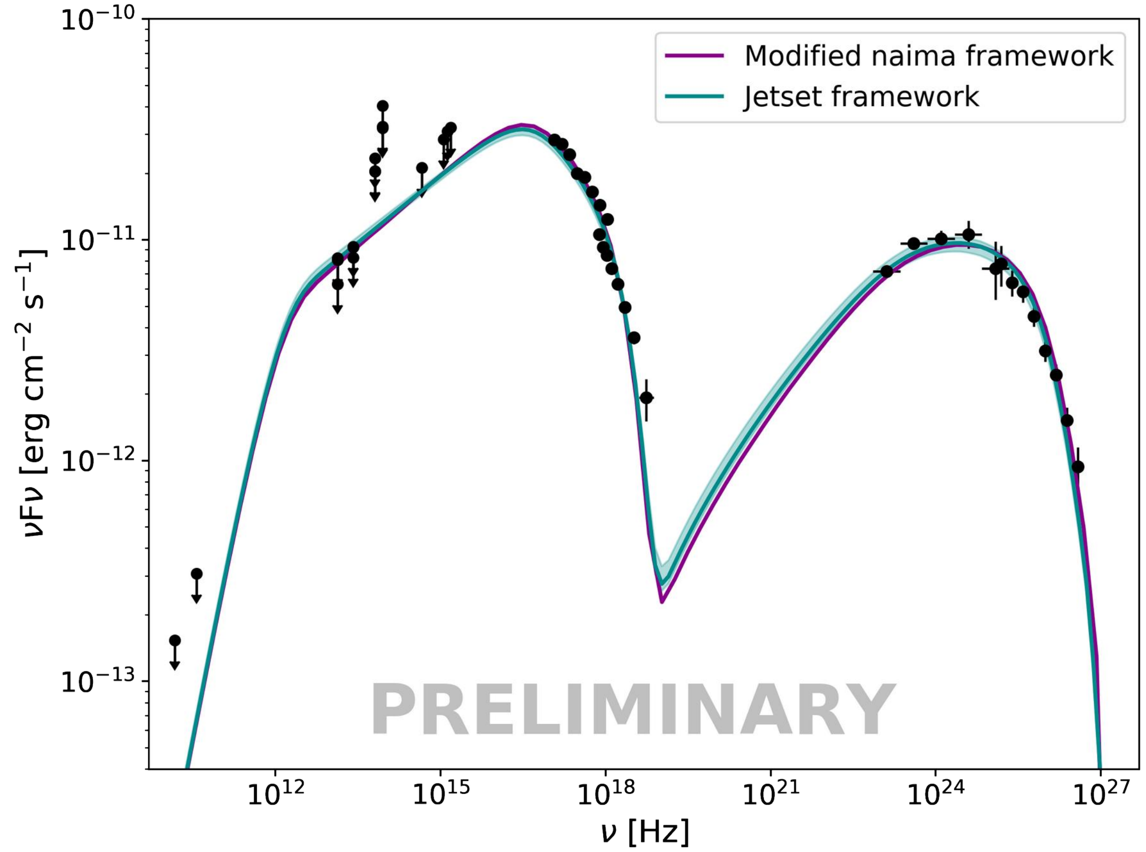
→ Both frameworks **describe the low state SED well** with **standard model parameters**
(see e.g. Abdo et al. 2011)



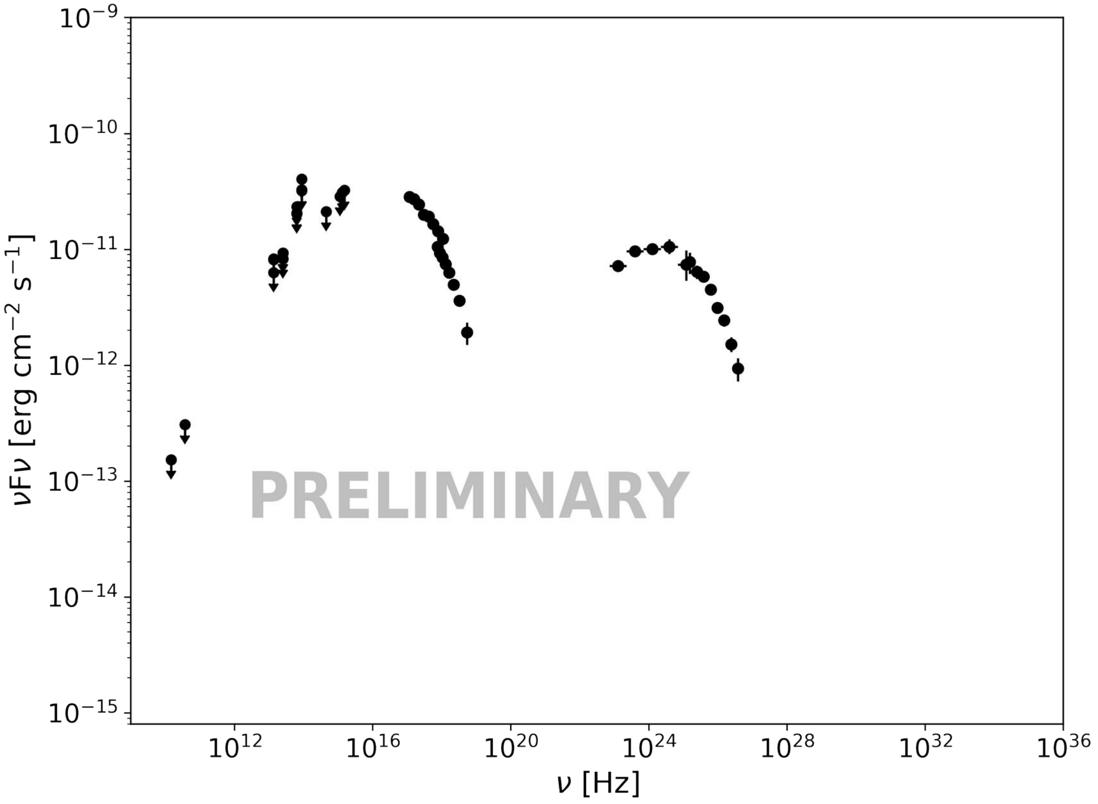
	L_e [erg/s]	α_1	γ'_{br}	γ'_{max}
Modified Naima	7.7×10^{43}	2.57	2.0×10^5*	1.2×10^6
Jetset	8.4×10^{43}	2.59	2.0×10^5*	1.2×10^6

U'_e [erg/cm^3]	U'_B [erg/cm^3]	U'_e/U'_B	L_{jet} [erg/s]
5.2×10^{-4}	2.5×10^{-5}	21	8.8×10^{43}
5.7×10^{-4}	2.5×10^{-5}	23	9.6×10^{43}

*Fixed to the cooling break
Broken power law used with $\alpha_2 = \alpha_1 + 1$, $\gamma_{min} = 1000$, $R = 1.1 \times 10^{17}$ cm, $\delta = 11$, $z = 0.034$, Franceschini EBL

Mrk501 low state – hadronic scenario

- Frameworks using the LeHa (Cerruti et al. 2015) and SORPANO (Gasparyan et al. 2022) codes



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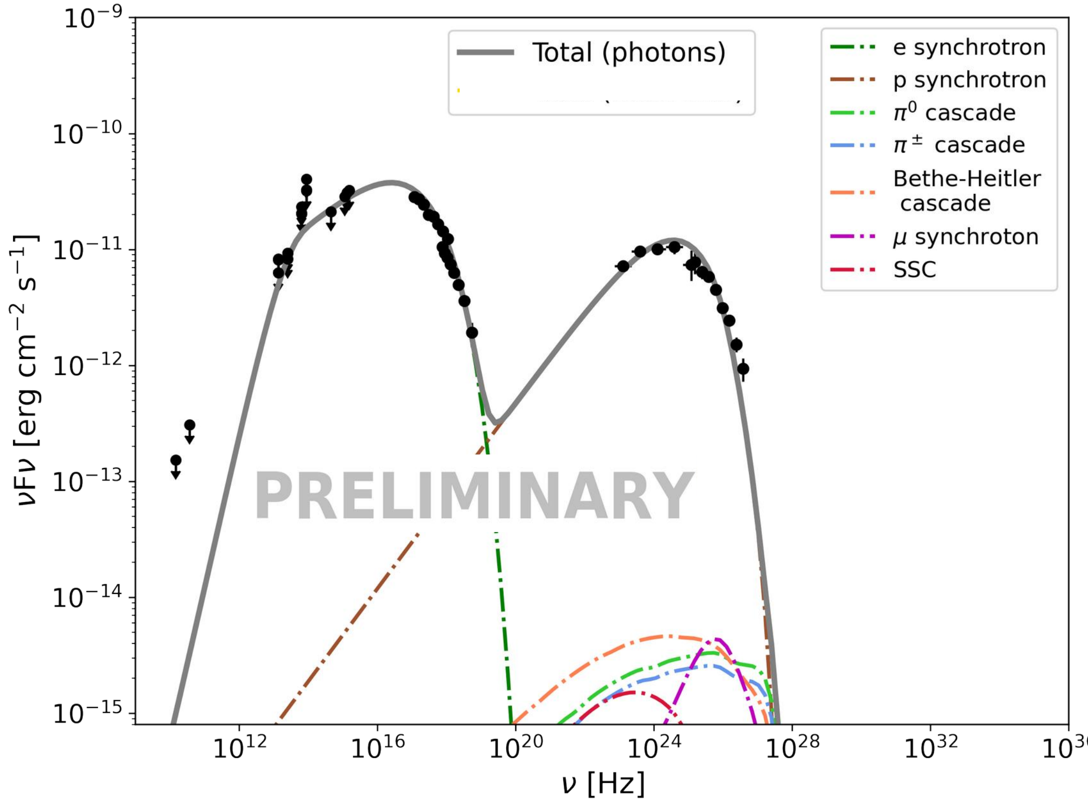

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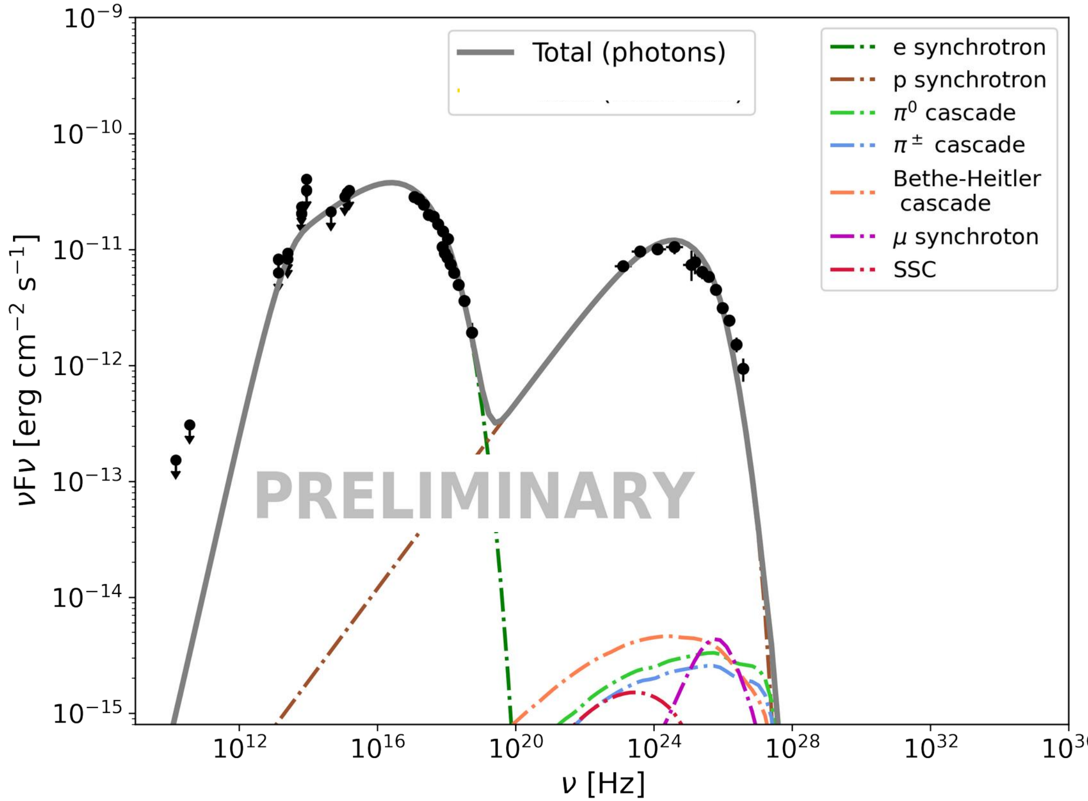
  → **Describes the low-state SED reasonably well**

  - with standard model parameters and low variability

B [G]	3
R [cm]	1.1×10^{17}
N'_{total} [1/cm^3]	3
$n'_{\mathrm{e}}/n'_{\mathrm{p}}$	2.2
$\alpha_{\mathrm{e},1}$	2.5
$\alpha_{\mathrm{e},2}$	-
$\gamma'_{\mathrm{min,e}}$	400
$\gamma'_{\mathrm{br,e}}$	-
$\gamma'_{\mathrm{max,e}}$	3.5×10^4
α_{p}	2.2
$\gamma'_{\mathrm{min,\,p}}$	1
$\gamma'_{\mathrm{max,\,p}}$	1.1×10^{10}

U_{e} [erg/cm^3]	2.2×10^{-7}
U_{B} [erg/cm^3]	0.36
U_{p} [erg/cm^3]	0.05
U_{e} / U_{B}	6.1×10^{-7}
U_{p} / U_{B}	0.14
L_{jet} [erg/s]	3.1×10^{46}



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  → **Describes the low-state SED reasonably well**

  - with standard model parameters and low variability
  - **in agreement with the IceCube ULs**

B [G]	3
R [cm]	1.1×10^{17}
$N'_{\rm total}$ [1/cm^3]	3
n'_e/n'_p	2.2
$\alpha_{e,1}$	2.5
$\alpha_{e,2}$	-
$\gamma'_{\rm min,e}$	400
$\gamma'_{\rm br,e}$	-
$\gamma'_{\rm max,e}$	3.5×10^4
α_p	2.2
$\gamma'_{\rm min,\,p}$	1
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U_e [erg/cm^3]	2.2×10^{-7}
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U_e / U_B	6.1×10^{-7}
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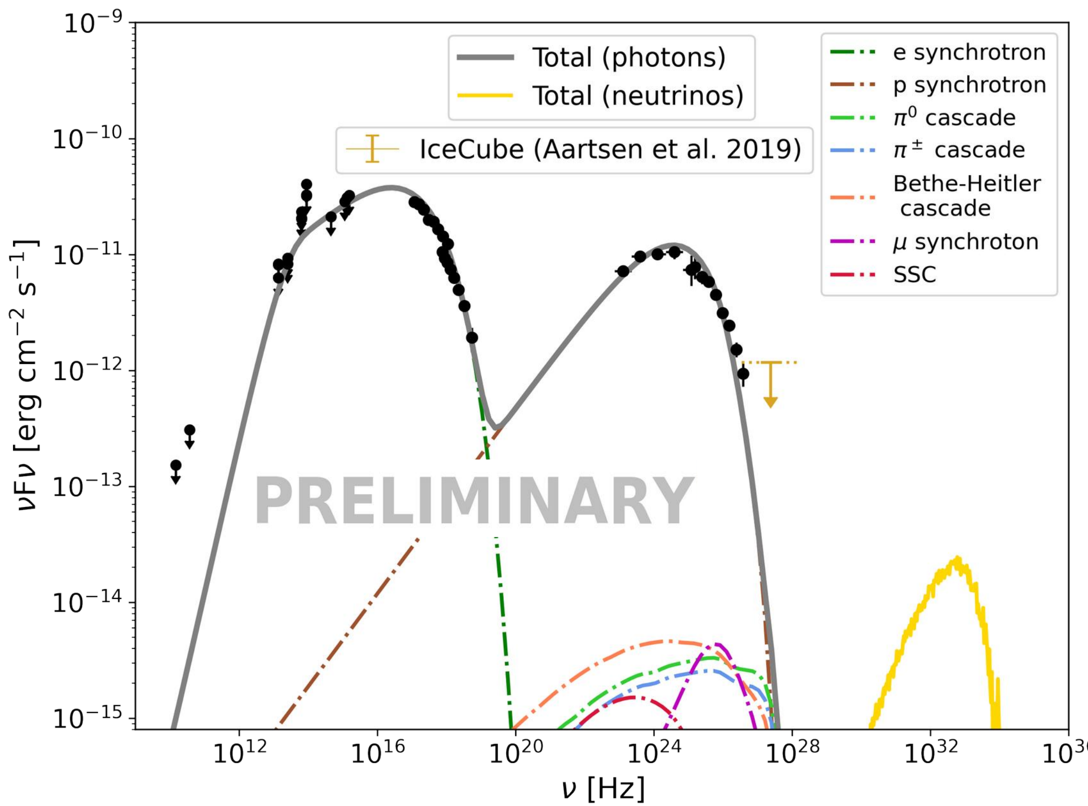
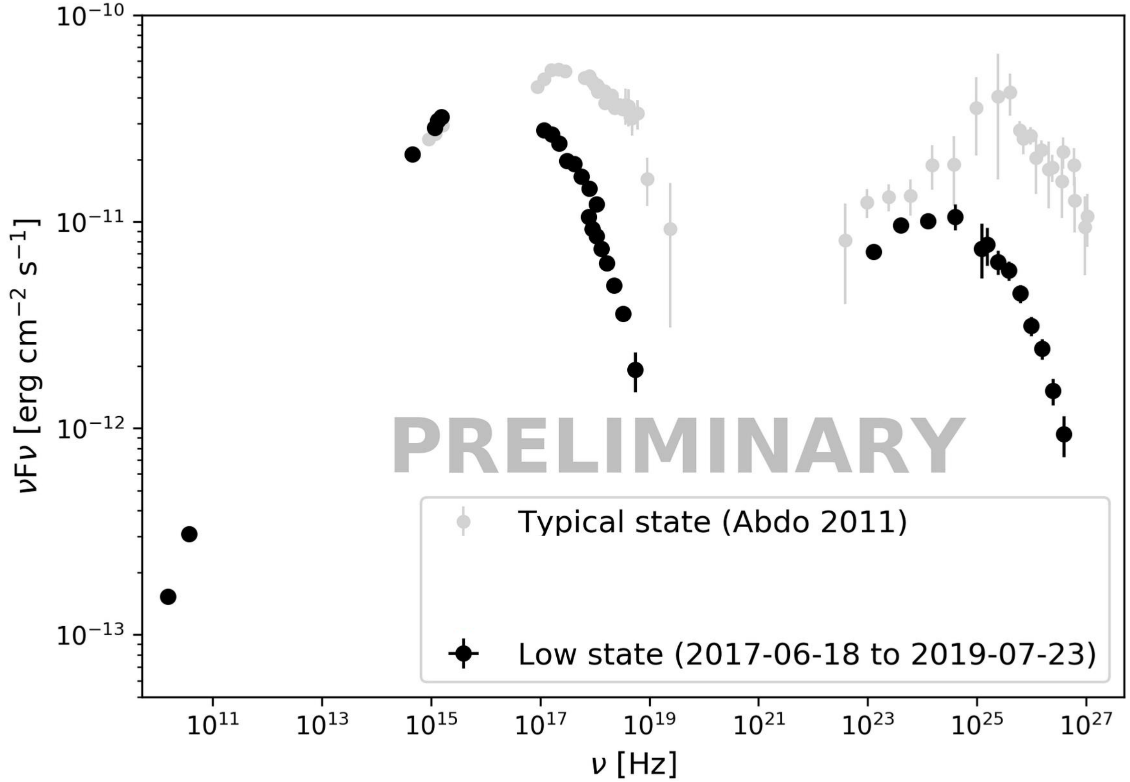
Neutrino rates per year:
Expected by the model: **1e-5**
IceCube best fit number: **10.3/10**



SED evolution

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



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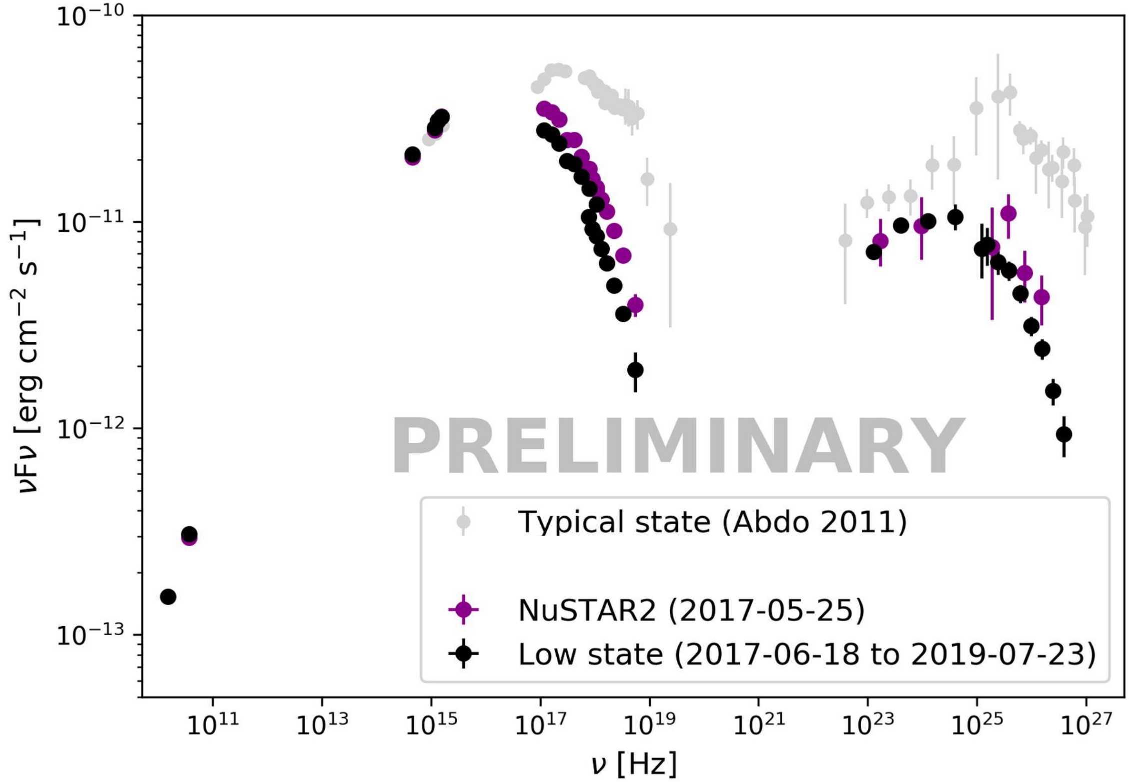
- **Additional NuSTAR observations** → Evaluation of the **SED evolution**
- 1 & 2 months before the low state



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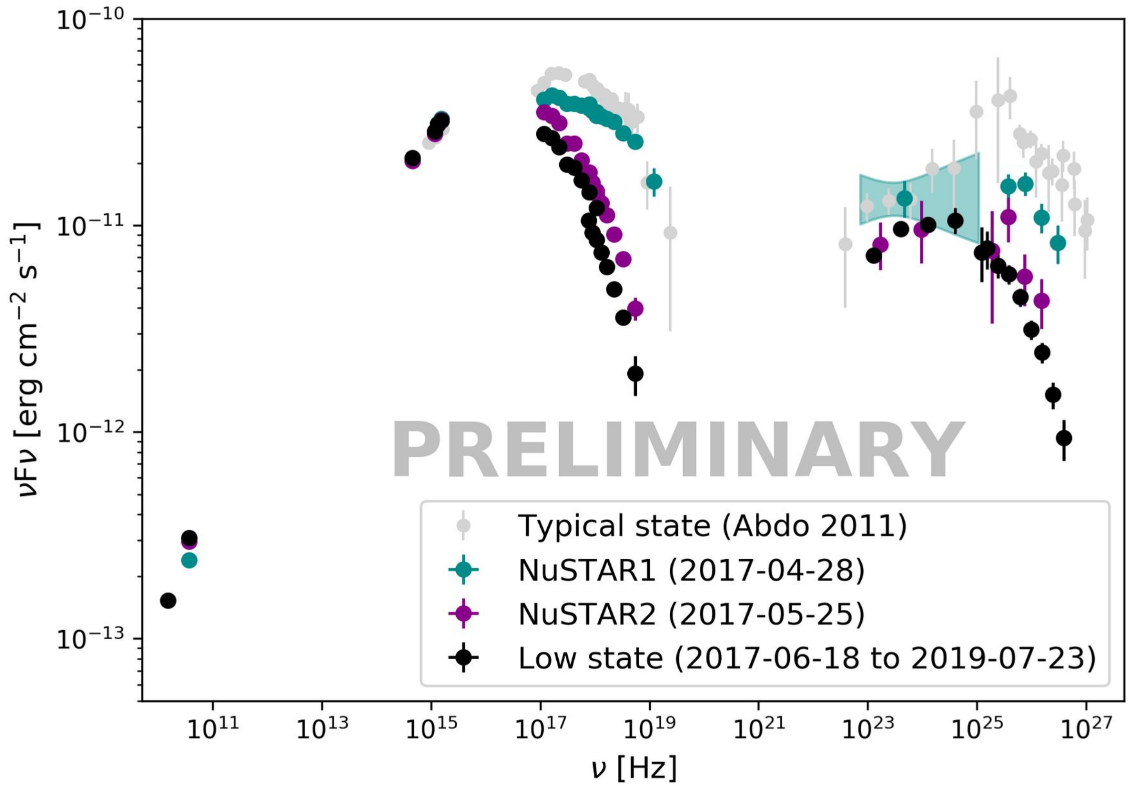

SED evolution

- **Additional NuSTAR observations**
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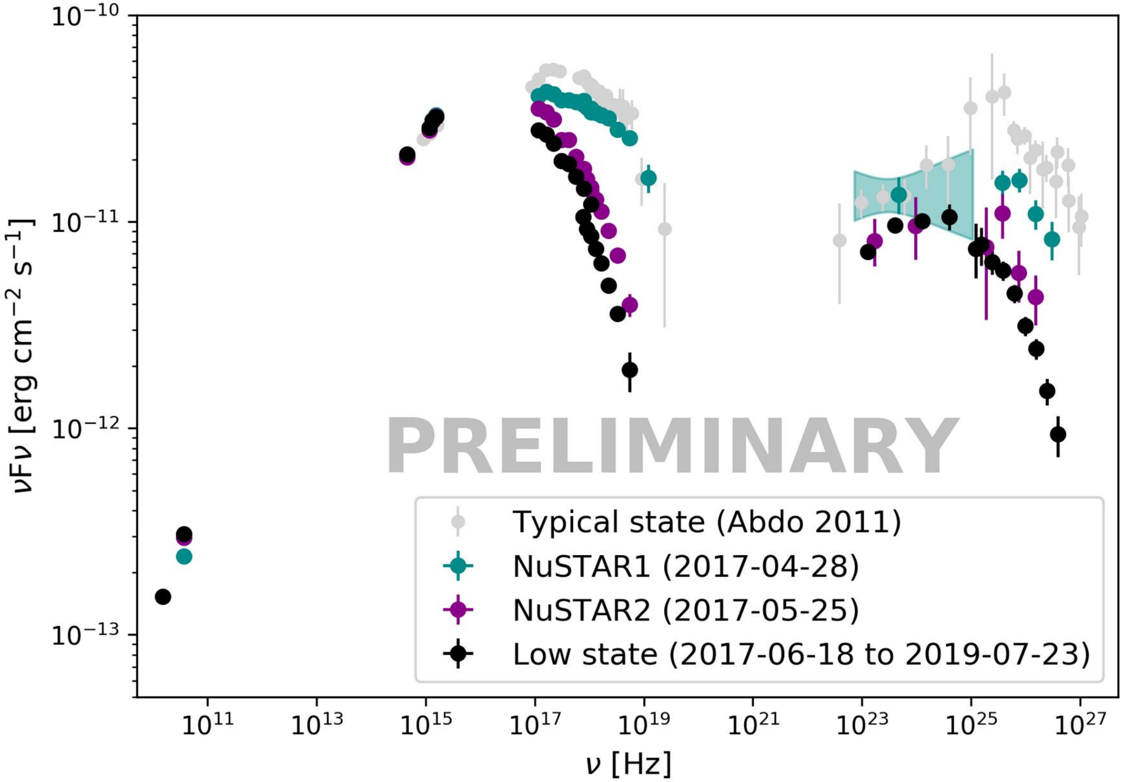
- 1 & 2 months before the low state

- One zone model:
  - Change driven by Change in B and therefore also γ_{br}
  - α adjusts, slightly softer during low state
  - γ_{max} lower during low state



a) Model for *NuSTAR*-1 with a magnetic field of B' =0.01 G

	L_e [erg/s]	α_1	γ'_{br}	γ'_{max}
Modified Naima	1.1×10^{44}	2.30	6.6×10^5*	7.2×10^6
Jetset	1.1×10^{44}	2.29	6.6×10^5*	7.3×10^6

b) Model for *NuSTAR*-2 with a magnetic field of B' =0.025 G

	L_e [erg/s]	α_1	γ'_{br}	γ'_{max}
Modified Naima	7.8×10^{43}	2.52	1.9×10^5*	1.5×10^6
Jetset	8.2×10^{43}	2.55	1.9×10^5*	1.6×10^6

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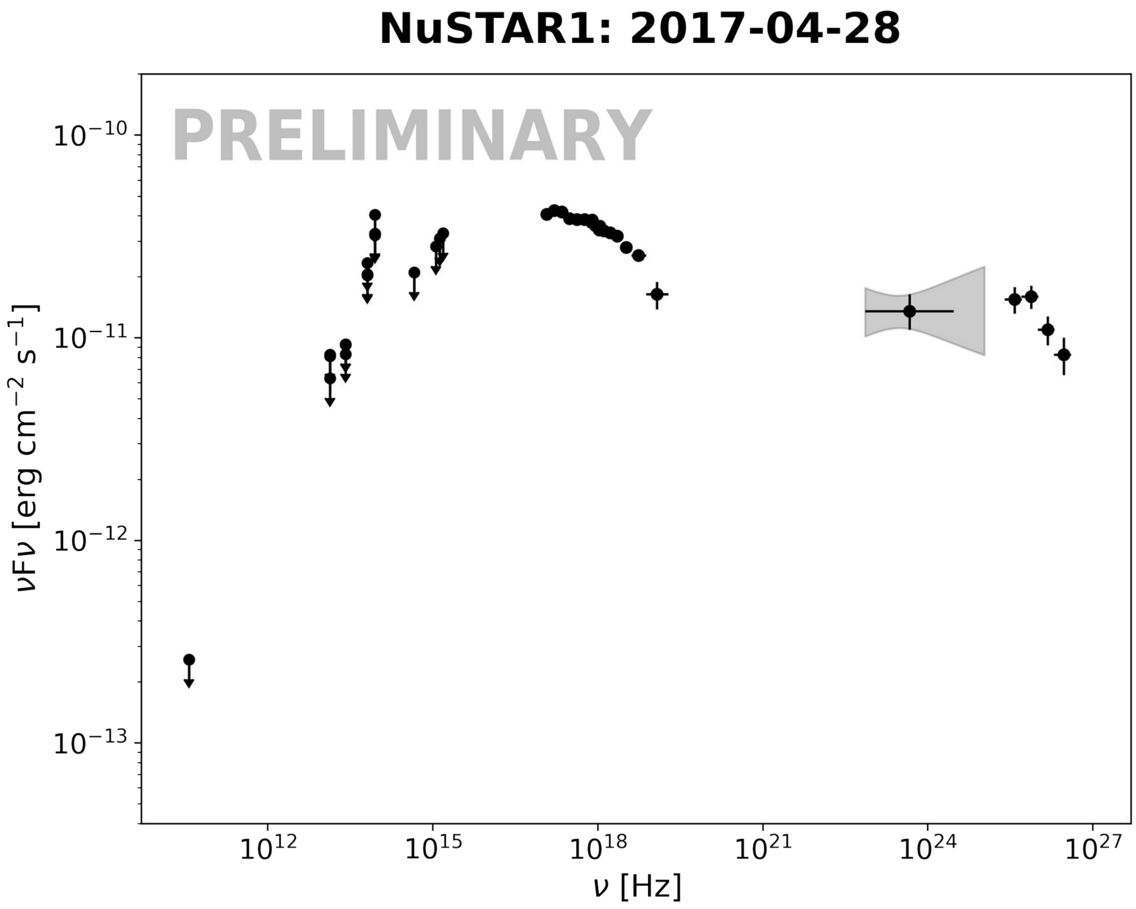
Broken power law used with $\alpha_2 = \alpha_1 + 1$, $\gamma_{min} = 1000$, $R = 1.1 \times 10^{17}$ cm, $\delta = 11$, $z = 0.034$, Franceschini EBL

Two-zone scenario

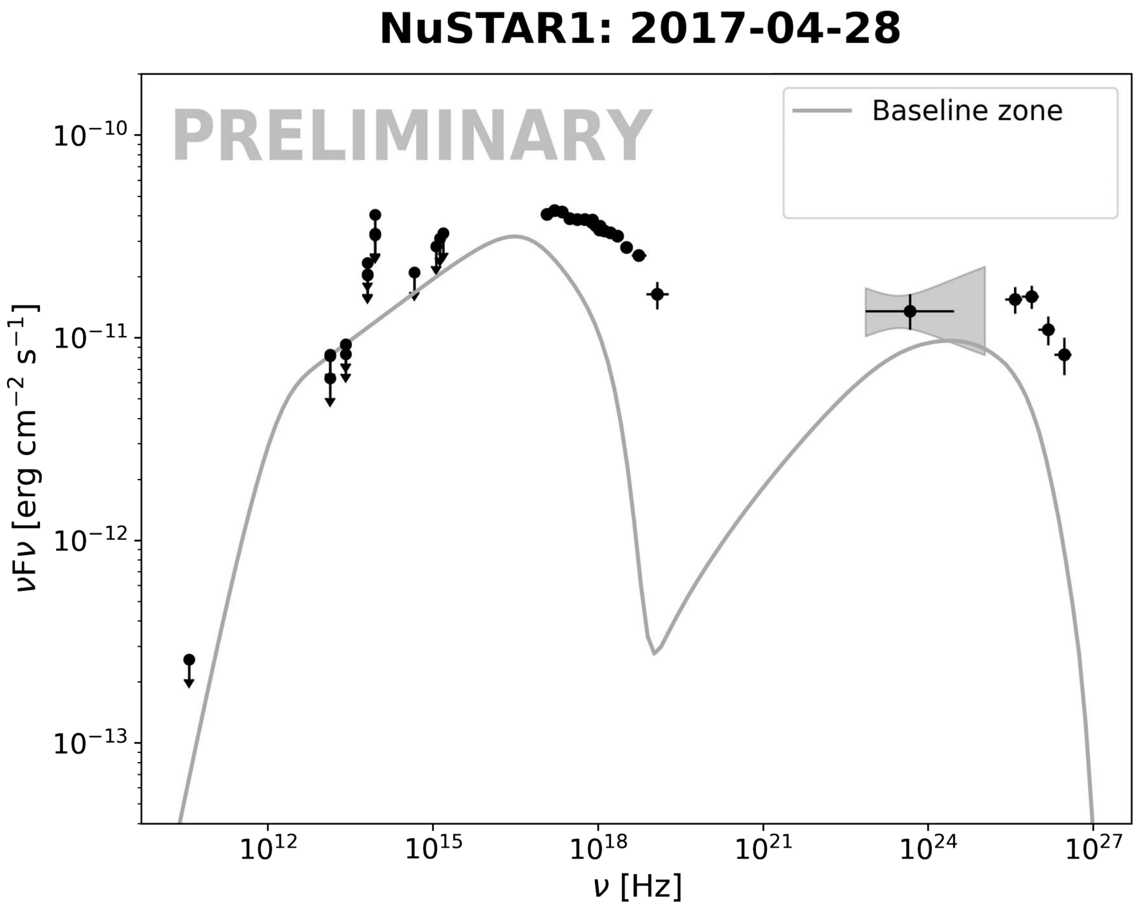
- Assumption:



Two-zone scenario

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

    → use our low state model



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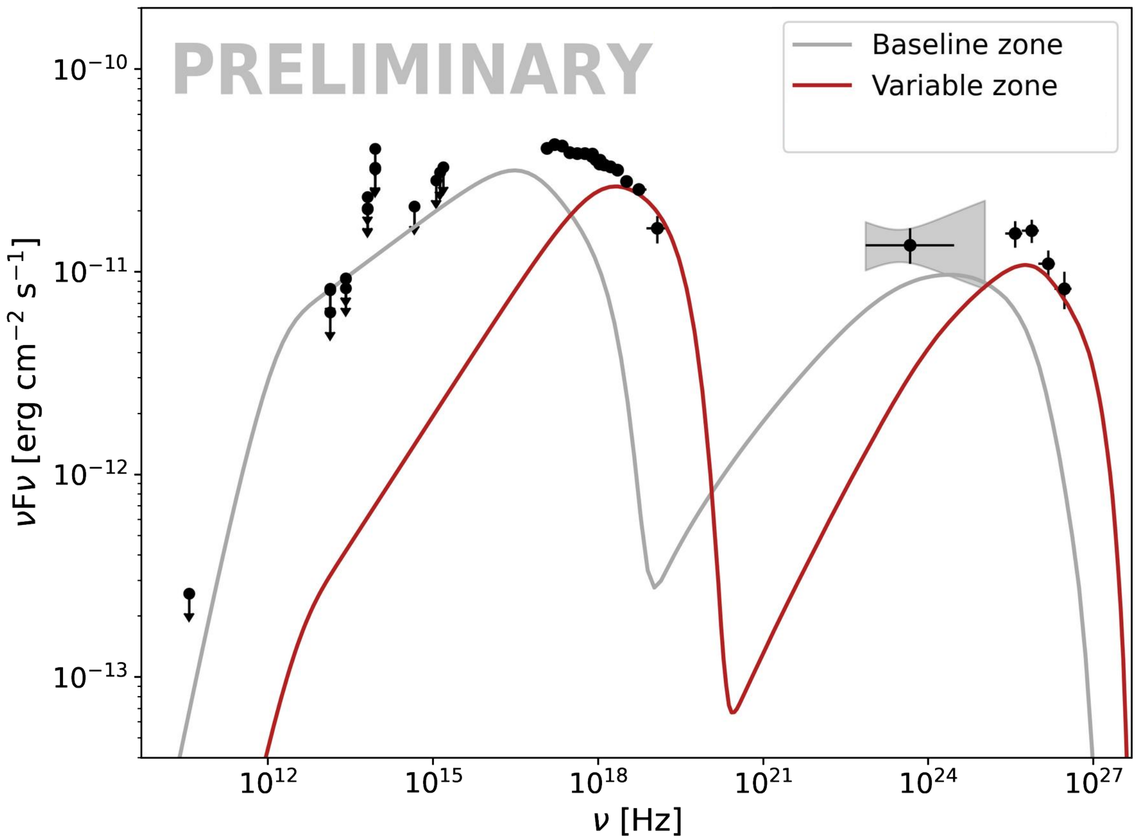
  - Usually outshone by a **more dominant and variable region**

NuSTAR1: 2017-04-28



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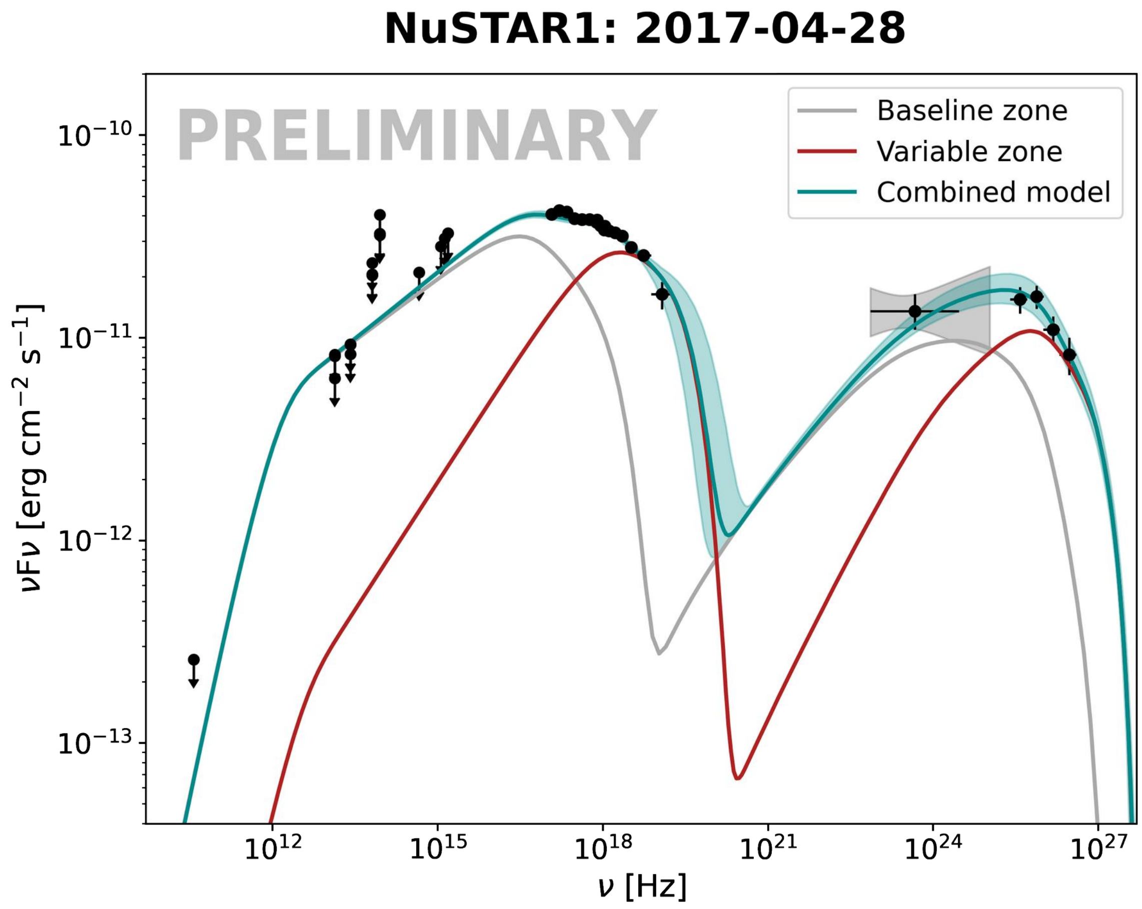

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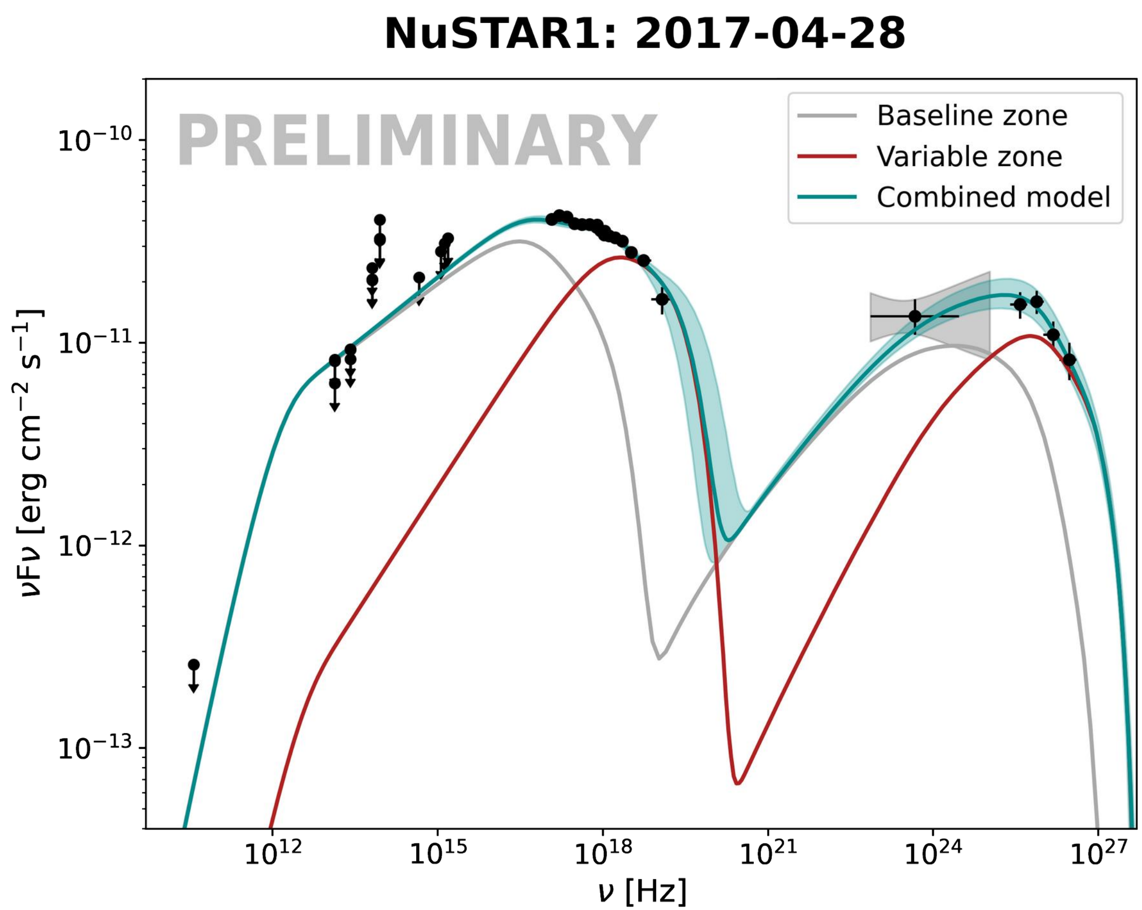
    → Combination reproduces the observed blazar emission
- Applied to the SED evolution (NuSTAR1 – low-state)
- Applied to the typical state of Mrk501 (Abdo et al. 2011)



Summary

- During the period from mid-2017 to mid-2019, Mrk501 showed **historically low activity in X-rays and VHE gamma rays**
- **Variability & correlations** hint towards a leptonic origin of the variable part of the blazar emission
  - For the first time, we find **correlation between X-rays and VHE** at more than 3σ significance **during low activity states**
  - **Radio lags behind the γ-rays by more than 100 days** → location γ-ray emission upstream of radio bright regions
  - Additionally, ***Fermi*-LAT and *Swift*-XRT show a correlation at more than 3σ level**
- 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**
- **For details wait for the upcoming publication**

Thank you for your attention!