Characterizing the emission of extreme HBLs with VERITAS

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy

Pedro Batista for the VERITAS Collaboration
DESY, Zeuthen, Germany
04.07.2022

pedro.batista@desy.de

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

xHigh Frequency Peaked BL Lac objects:

Spectral Energy Distribution (SED)

- The SED of HBLs is generally well described with a standard **one-zone Synchrotron Self Compton (SSC)** model
- However, the VHE data on some **extreme HBLs** objects challenges the standard SSC model predictions, showing
  - a TeV peak at energies > 1 TeV (~10^{26} Hz)
  - a hard intrinsic spectrum at sub-TeV energies with a spectral index < 2
- Leptonic scenarios generally require conditions beyond equipartition
- (Lepto-)hadronic scenarios reach the Eddington limit of the central black hole to properly describe the observed data

Source [1]	U_e/U_B [13]
1ES 0229+200 a	1.7×10^5
1ES 0229+200 b	2.0×10^4
1ES 0347-121 a	1.5×10^5
1ES 0347-121 b	3.4×10^4
1ES 0414+009 a	0.5
1ES 0414+009 b	9.3×10^2
RGB J0710+591	2.7×10^3
1ES 1101-232 a	2.4×10^3
1ES 1101-232 b	6.0×10^2
1ES 1218+304	4.5×10^3

Costamante, L. et al. 2018 (https://doi.org/10.1093/mnras/sty857)

xHigh Frequency Peaked BL Lac objects:

Spectral Energy Distribution (SED)

- The SED of HBLs is generally well described with a standard **one-zone Synchrotron Self Compton (SSC)** model
- However, the VHE data on some **extreme HBLs** objects challenges the standard SSC model predictions, showing
  - a TeV peak at energies > 1 TeV (~10^{26} Hz)
  - a hard intrinsic spectrum at sub-TeV energies with a spectral index < 2
- Leptonic scenarios generally require conditions beyond equipartition
- (Lepto-)hadronic scenarios reach the Eddington limit of the central black hole to properly describe the observed data

Source [1]	U_e/U_B [13]
1ES 0229+200 a	1.7×10^5
1ES 0229+200 b	2.0×10^4
1ES 0347-121 a	1.5×10^5
1ES 0347-121 b	3.4×10^4
1ES 0414+009 a	0.5
1ES 0414+009 b	9.3×10^2
RGB J0710+591	2.7×10^3
1ES 1101-232 a	2.4×10^3
1ES 1101-232 b	6.0×10^2
1ES 1218+304	4.5×10^3

Costamante, L. et al. 2018 (https://doi.org/10.1093/mnras/sty857)

xHigh Frequency Peaked BL Lac objects:

Spectral Energy Distribution (SED)

- The SED of HBLs is generally well described with a standard **one-zone Synchrotron Self Compton (SSC)** model
- However, the VHE data on some **extreme HBLs** objects challenges the standard SSC model predictions, showing
  - a TeV peak at energies > 1 TeV (~10^{26} Hz)
  - a hard intrinsic spectrum at sub-TeV energies with a spectral index < 2
- Leptonic scenarios generally require conditions beyond equipartition
- (Lepto-)hadronic scenarios reach the Eddington limit of the central black hole to properly describe the observed data

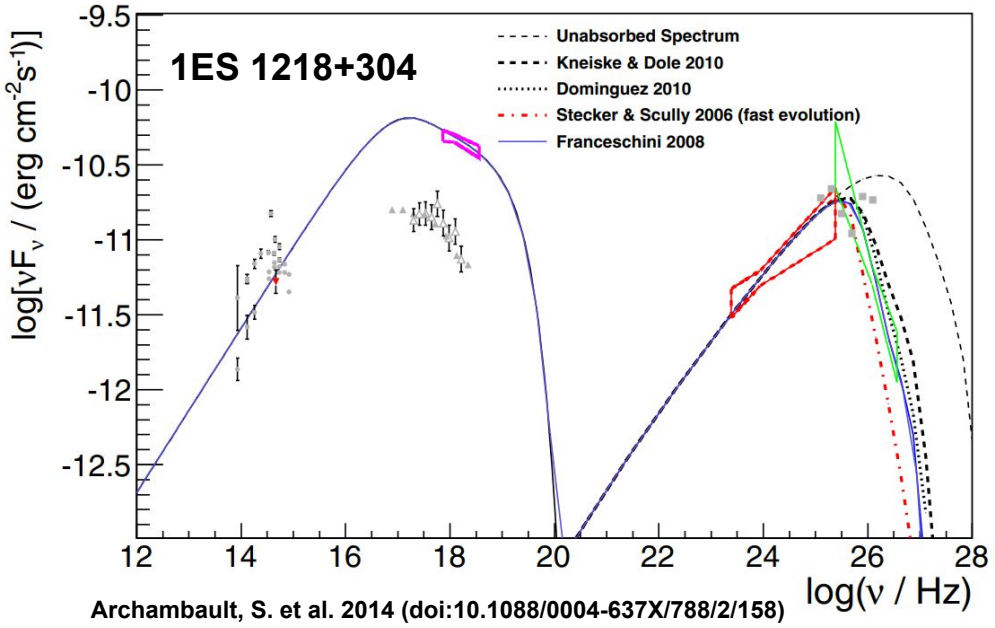
Source [1]	U_e/U_B [13]
1ES 0229+200 a	1.7×10^5
1ES 0229+200 b	2.0×10^4
1ES 0347-121 a	1.5×10^5
1ES 0347-121 b	3.4×10^4
1ES 0414+009 a	0.5
1ES 0414+009 b	9.3×10^2
RGB J0710+591	2.7×10^3
1ES 1101-232 a	2.4×10^3
1ES 1101-232 b	6.0×10^2
1ES 1218+304	4.5×10^3

Costamante, L. et al. 2018 (https://doi.org/10.1093/mnras/sty857)

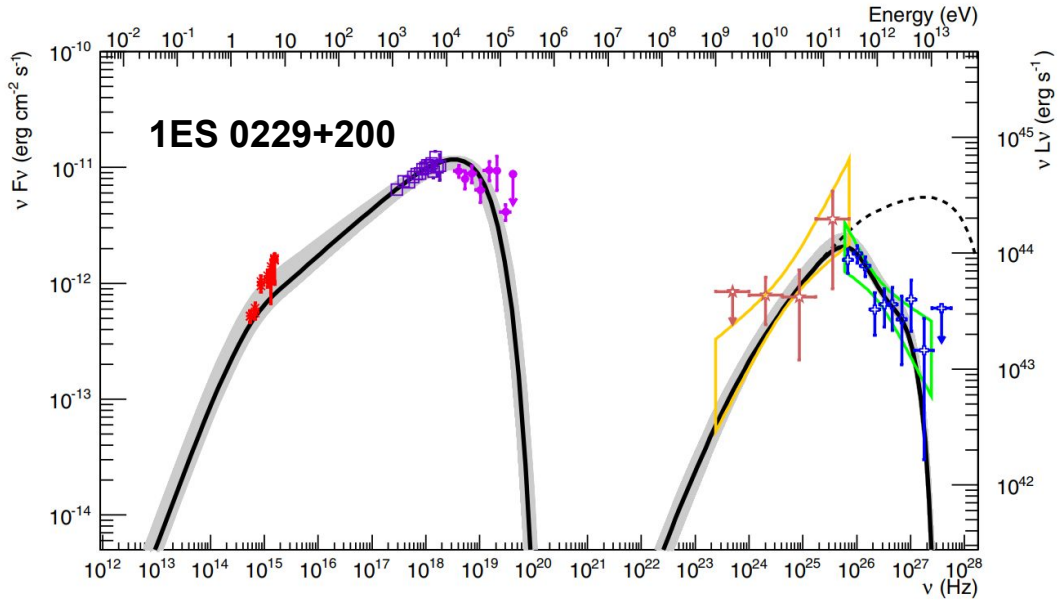
xHigh Frequency Peaked BL Lac objects:

Spectral Energy Distribution (SED)

- The SED of HBLs is generally well described with a standard **one-zone Synchrotron Self Compton (SSC)** model
- However, the VHE data on some **extreme HBLs** objects challenges the standard SSC model predictions, showing
  - a TeV peak at energies > 1 TeV (~10^{26} Hz)
  - a hard intrinsic spectrum at sub-TeV energies with a spectral index < 2
- Leptonic scenarios generally require conditions beyond equipartition
- (Lepto-)hadronic scenarios reach the Eddington limit of the central black hole to properly describe the observed data



Archambault, S. et al. 2014 (doi:10.1088/0004-637X/788/2/158)



Aliu, E. et al. 2014 (doi:10.1088/0004-637X/782/1/13)

VERITAS

The telescope

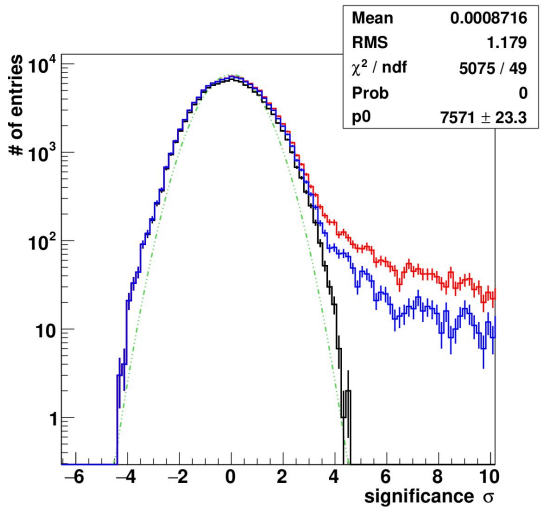
Located near Tucson, Arizona, currently operating with:

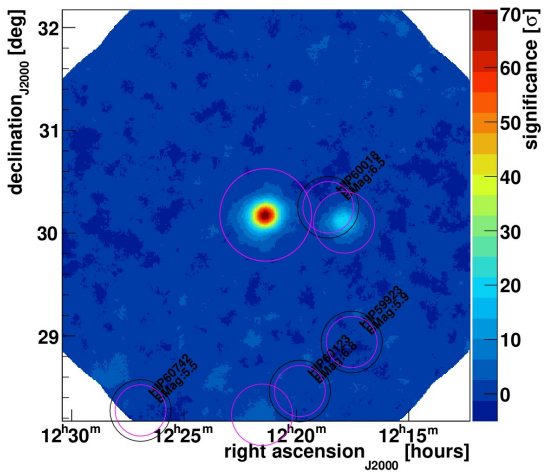
- **energy range**: 100 GeV to >30 TeV
- **energy resolution**: 15-25%
- **sensitivity**: 1% Crab in ~25h
- **angular resolution**: 0.1 deg at 1 TeV
- **source location accuracy**: error < 50 arcsec

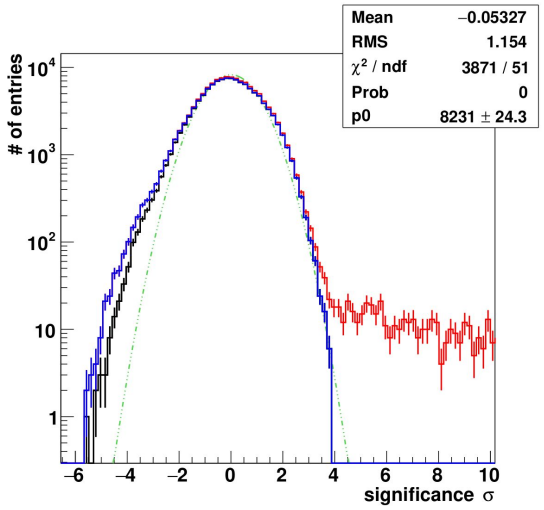
Characterizing the emission of extreme HBLs with VERITAS

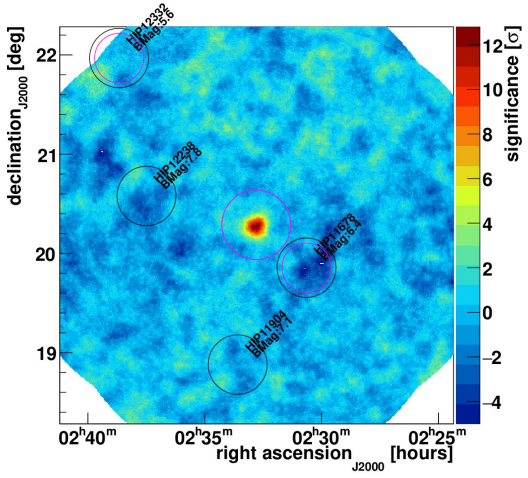
Sources:

	z [kpc]	VERITAS obs.	Exposure	σ
1ES 1218+304	0.182	2008-12-29 to 2021-02-09 [54829.49,59254.38] MJD	~175 h	70.6
1ES 0229+200	0.1396	2009-10-14 to 2021-01-12 [55118.32,59226.21] MJD	~ 185 h	11.6



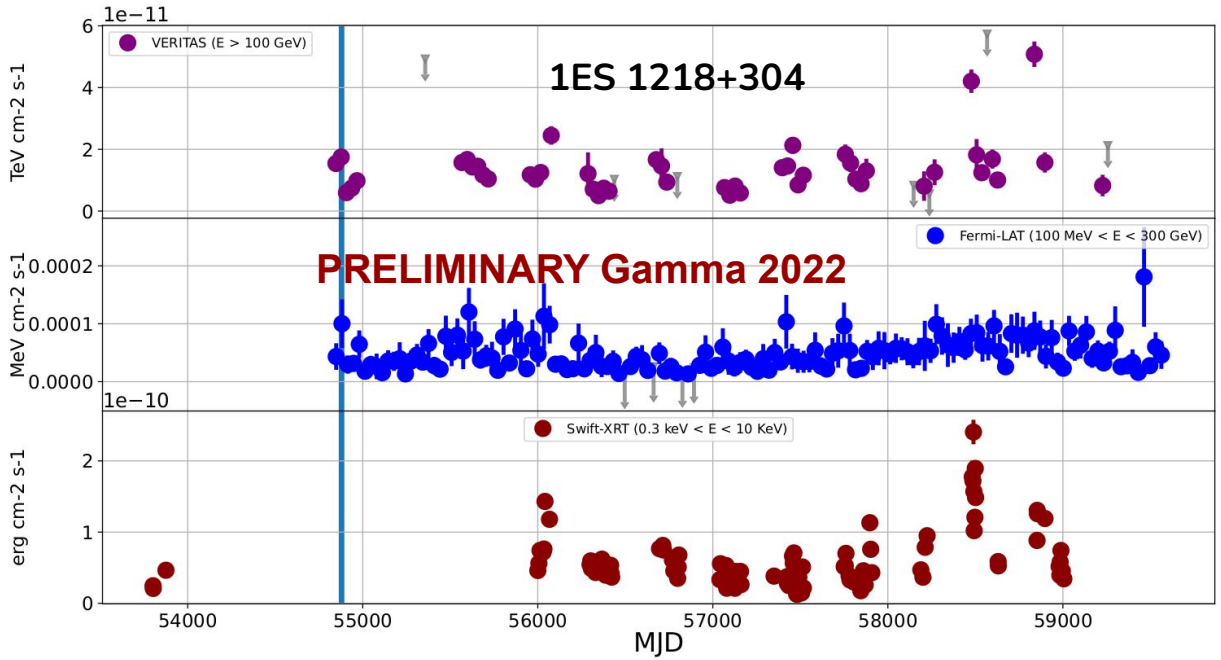






Characterizing the emission of extreme HBLs with VERITAS

1: Lightcurves

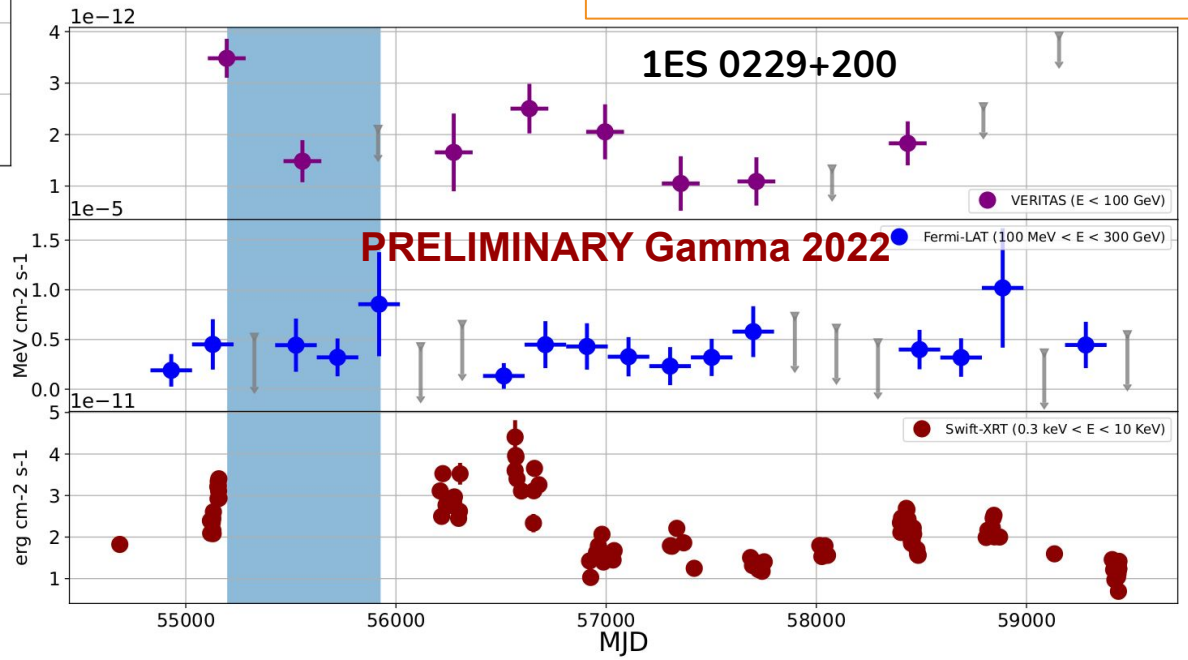


1ES 1218+304:

+ Monthly binned VHE data
+ Monthly binned HE data
+ Per observation binned X-ray data

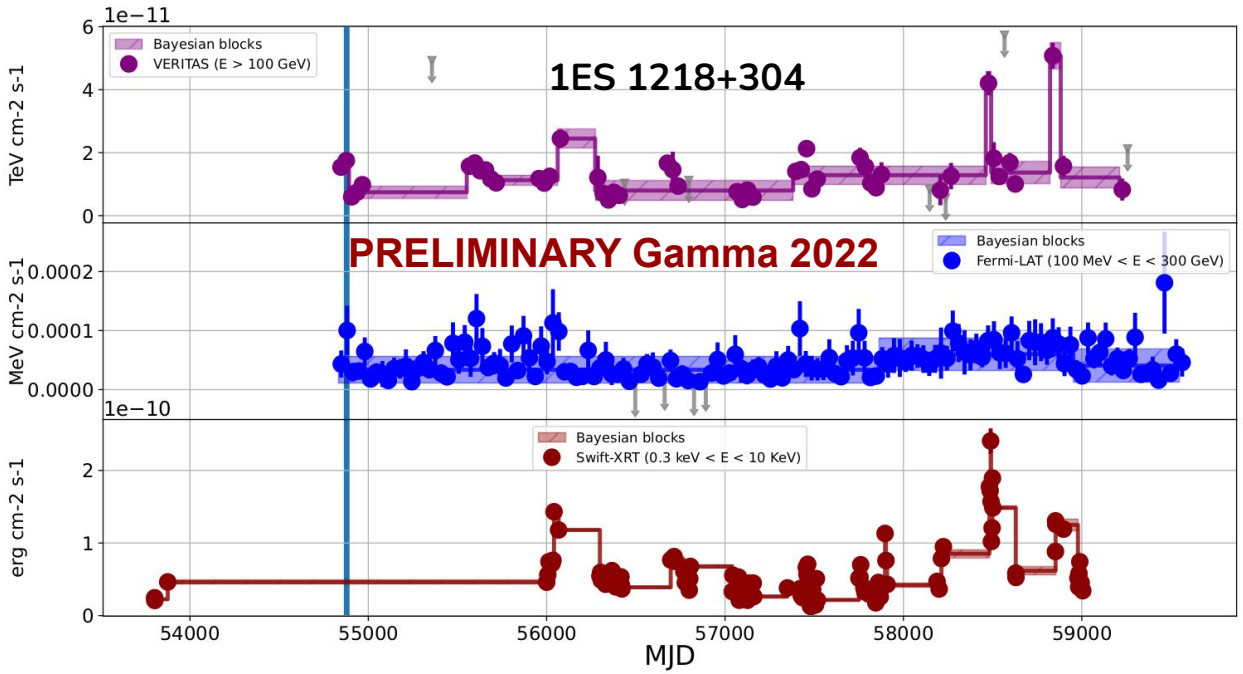
1ES 0229+200:

+ 6-monthly binned VHE data
+ 6-monthly binned HE data
+ Per observation binned X-ray data



Characterizing the emission of extreme HBLs with VERITAS

2: Flux state determination (Bayesian blocks analysis)

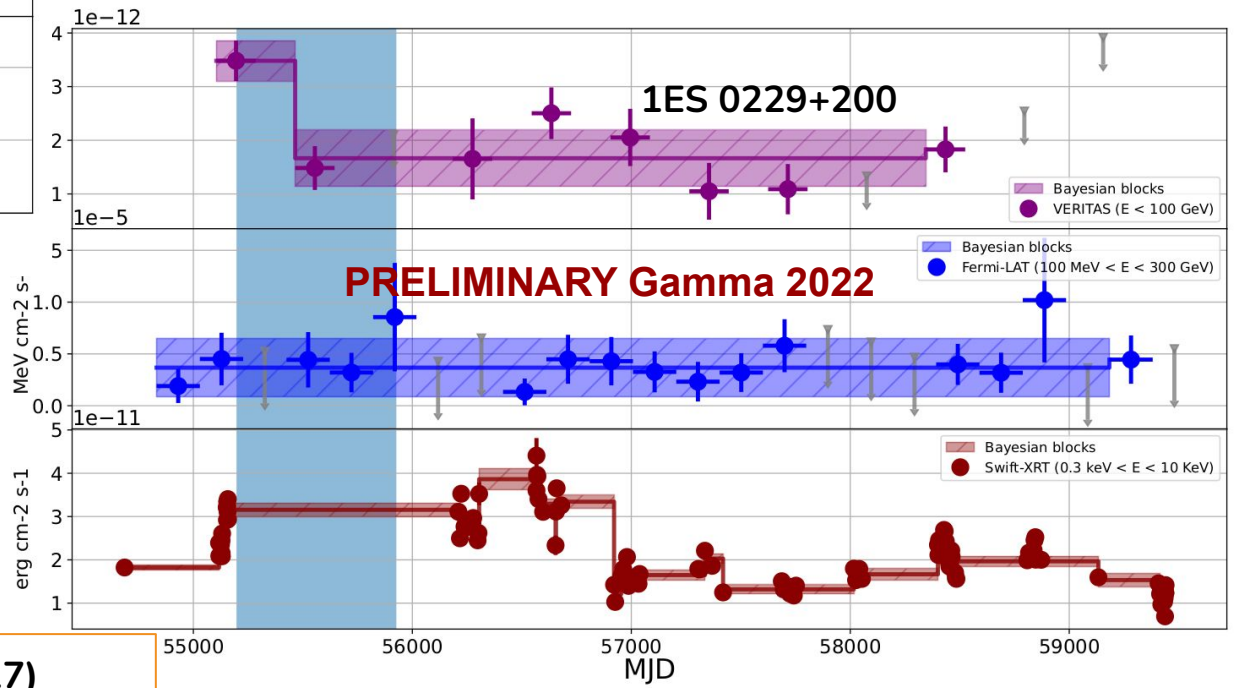


1ES 1218+304:

+ VHE shortest block resolved with selected timing binning: ~ 1 month
+ HE slight flux increase correlated with VHE flares

1ES 0229+200:

+ VHE shortest block resolved with selected timing binning: ~ 1 year
+ No observed variability in HE data

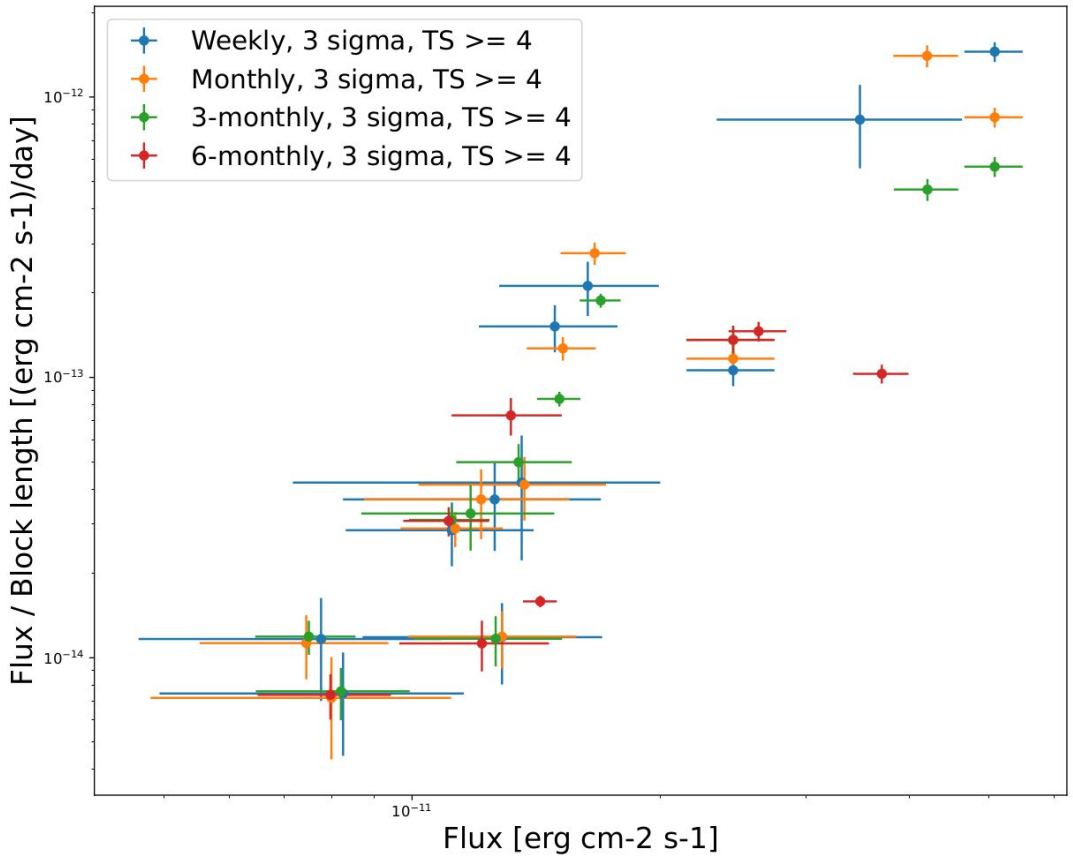


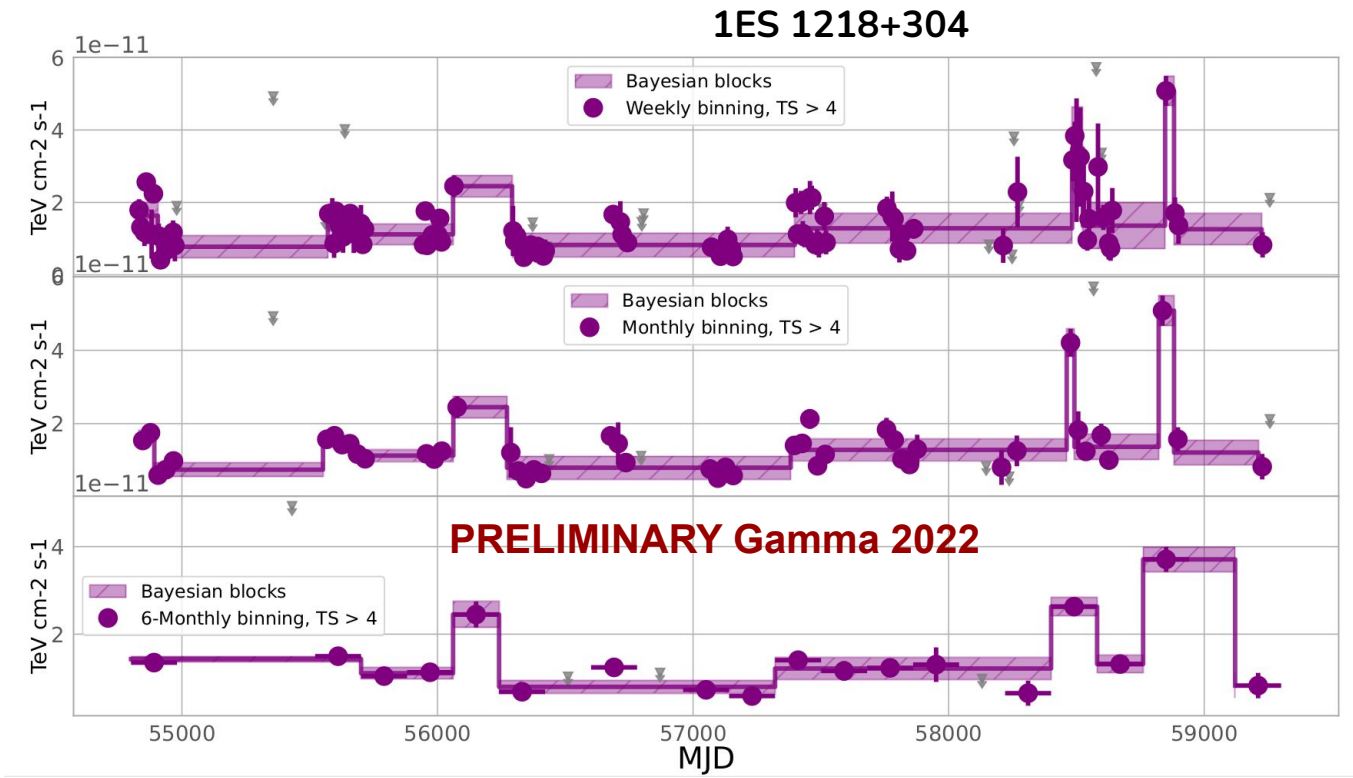
Change point significance: 3 sigma (fpr ~ 0.0027)

Characterizing the emission of extreme HBLs with VERITAS

Time binning

- Maximize time resolution without compromising statistical significance
- TS threshold < 4 for upper limits

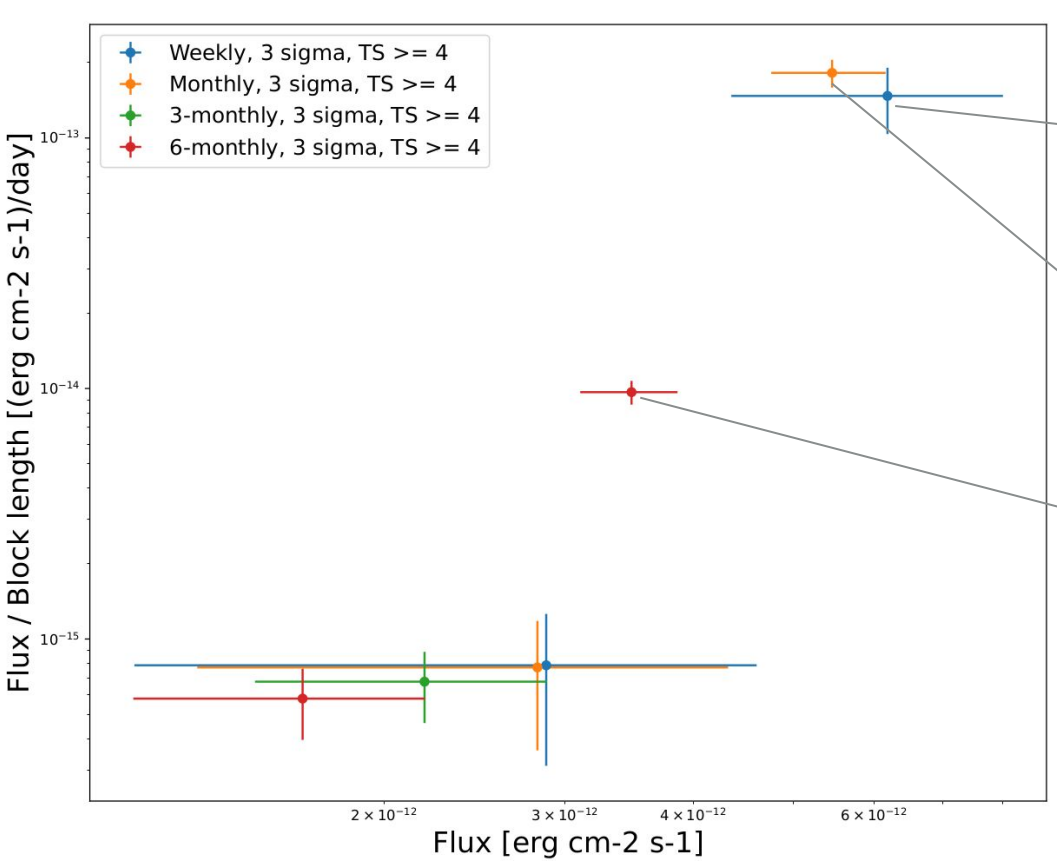


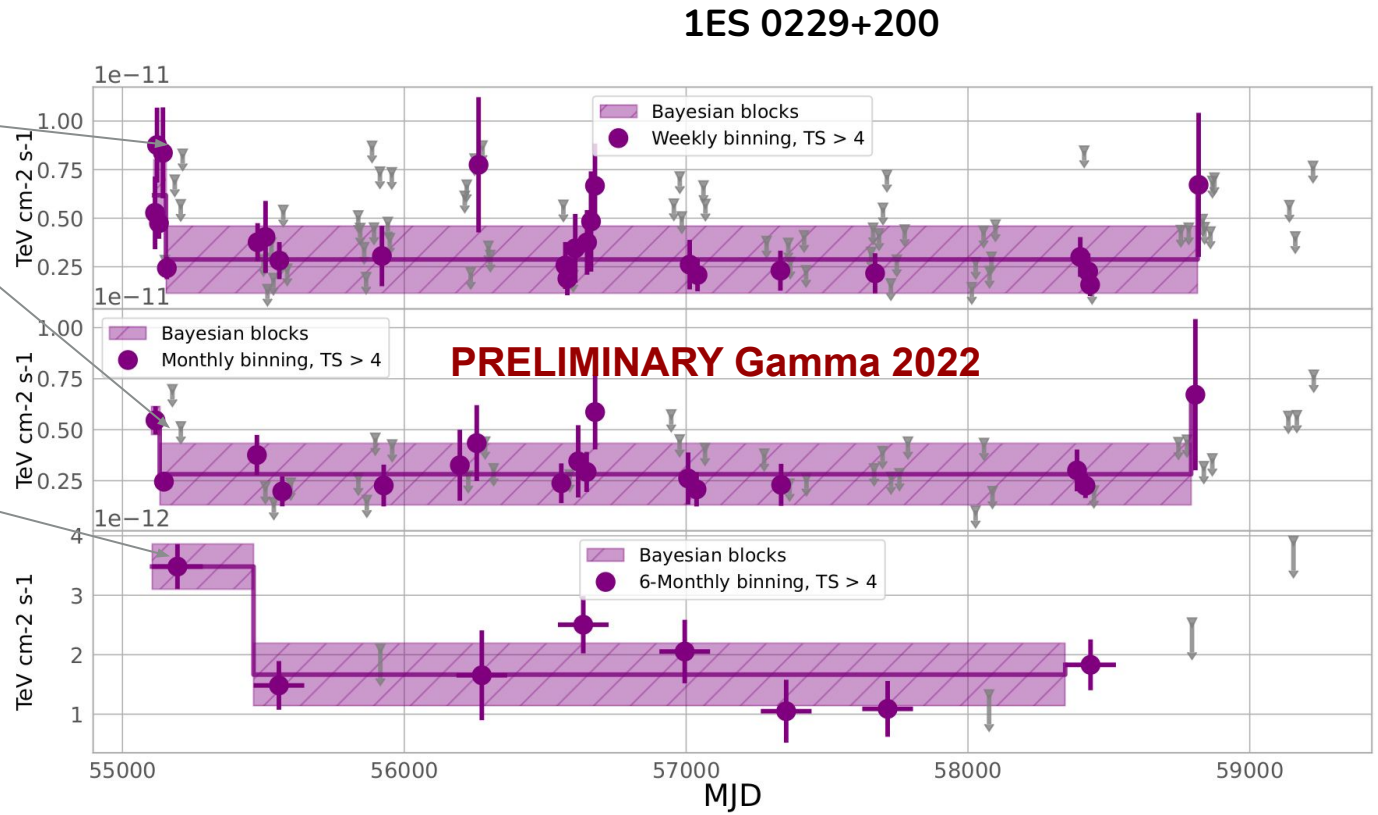


Characterizing the emission of extreme HBLs with VERITAS

Time binning

- Maximize time resolution without compromising statistical significance
- TS threshold < 4 for upper limits

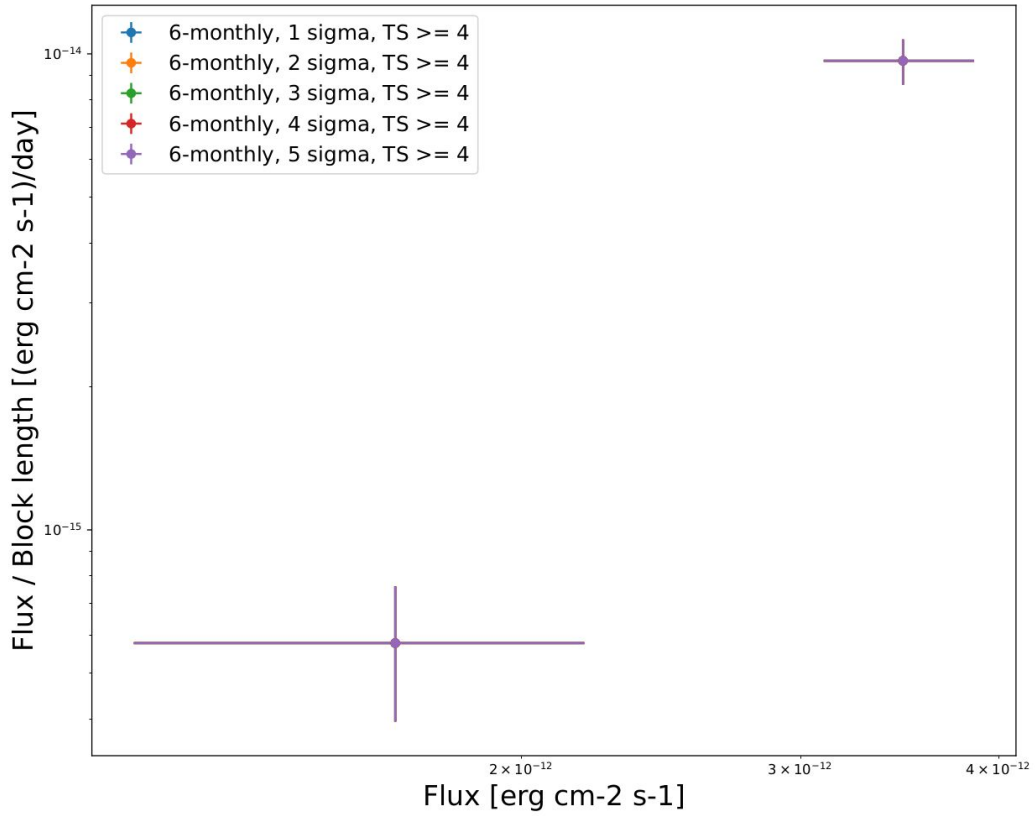


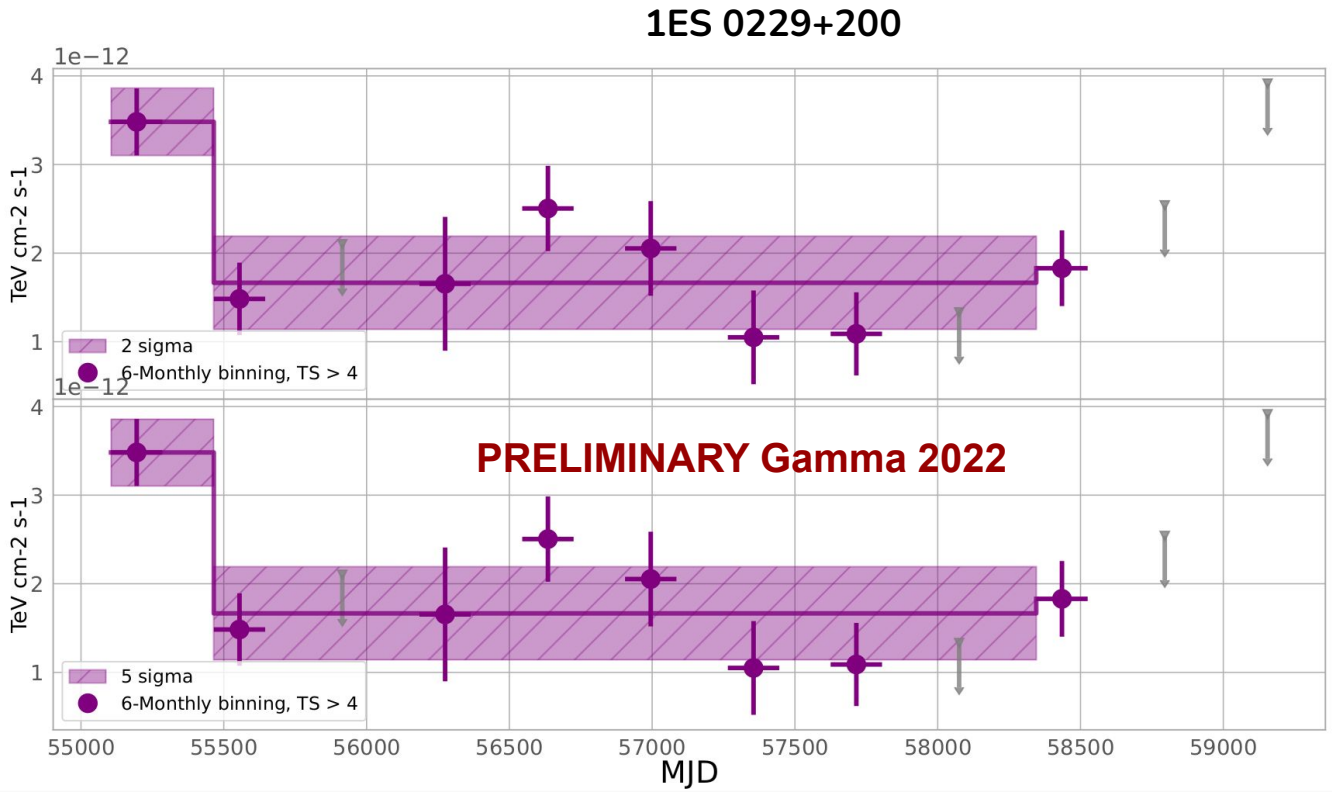


Characterizing the emission of extreme HBLs with VERITAS

5 sigma 1E S0229+200 variability

- Maximize time resolution without compromising statistical significance
- TS threshold < 4 for upper limits
- One 5 sigma change point for 1ES0229

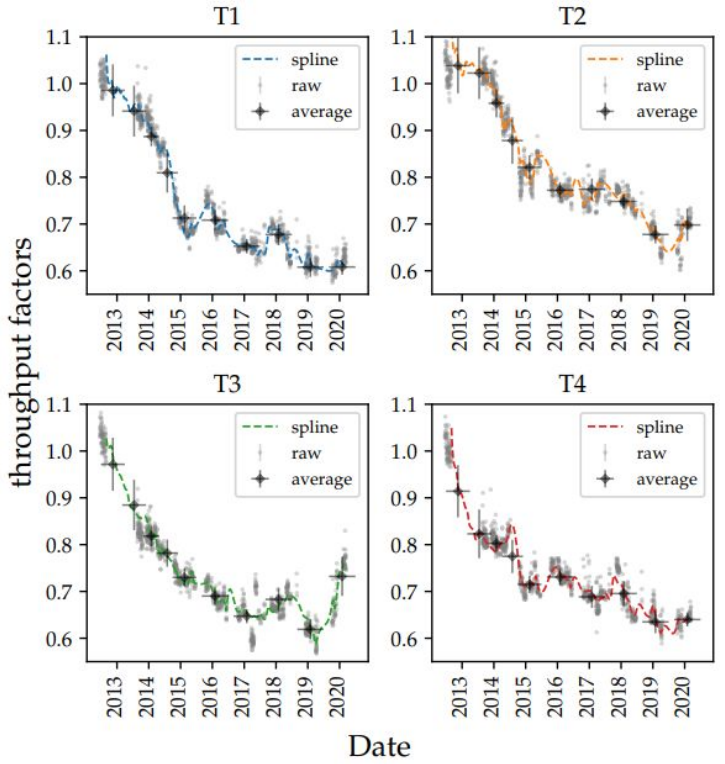


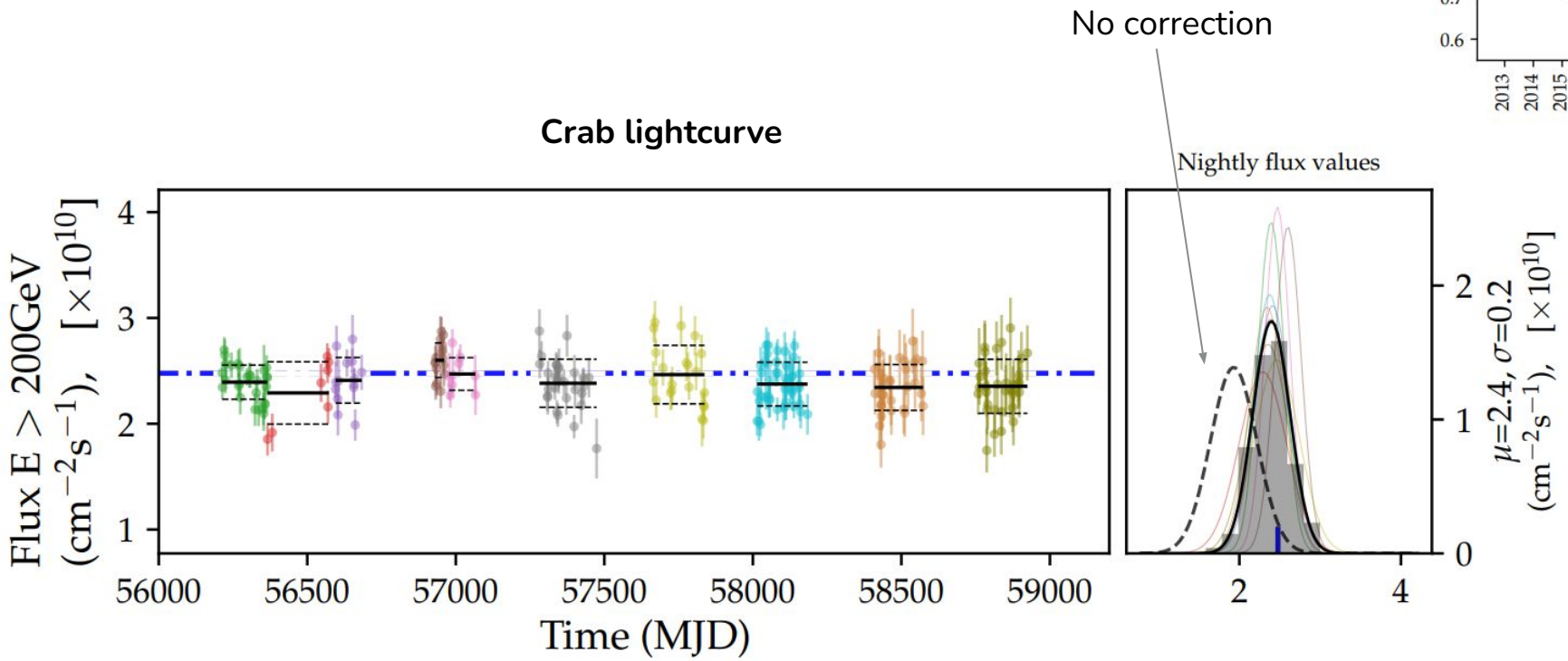


Characterizing the emission of extreme HBLs with VERITAS

The throughput corrections

- Detector “aging” is accounted for
- Equipment reflectivity and gains changes over the years, which is fully considered in IRF production
- “The throughput calibration of the VERITAS telescopes” (https://doi.org/10.1051/0004-6361/202142275)

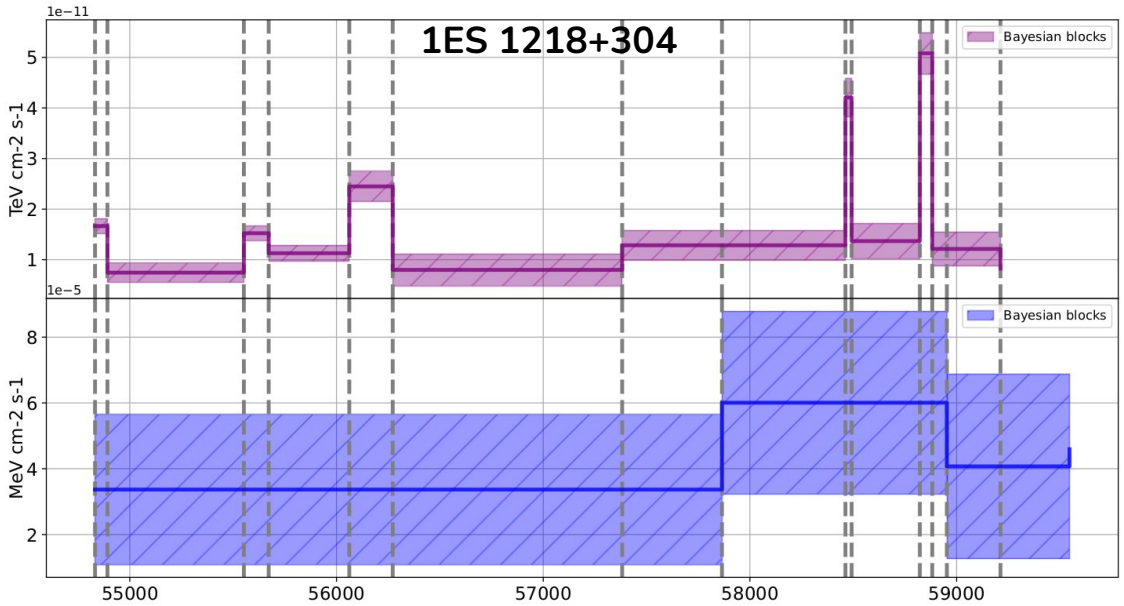




Characterizing the emission of extreme HBLs with VERITAS

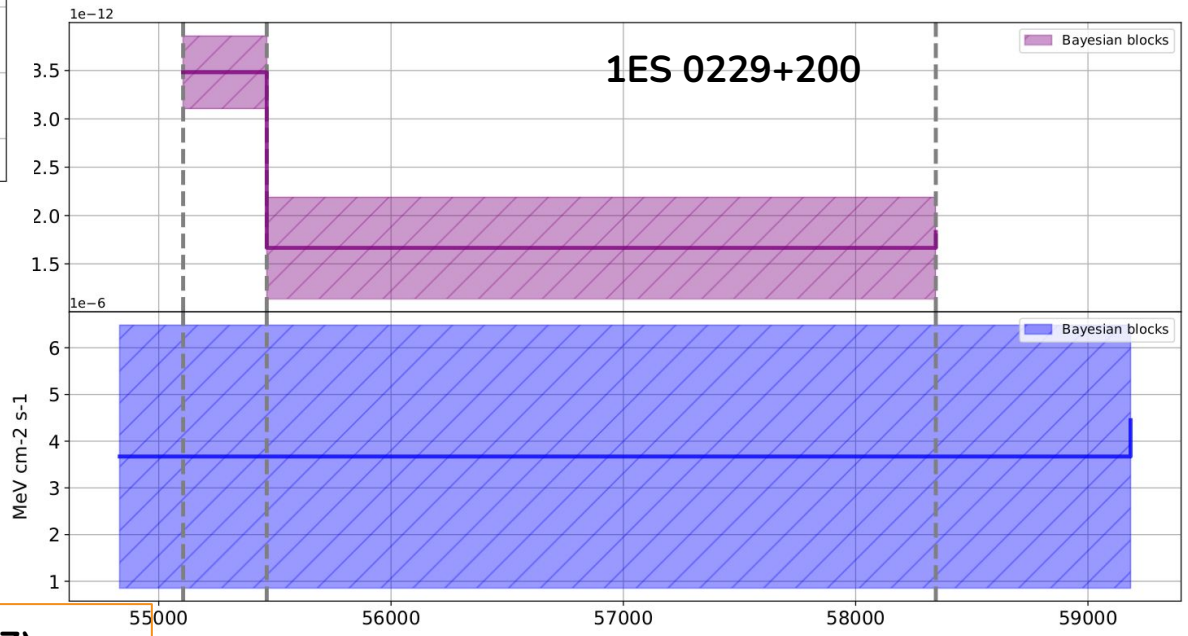
3: Time intervals determination

- Time intervals are determined by the smallest overlap between two blocks



1ES 0229+200:

+ VHE shortest block resolved with selected timing binning: ~ 1 year
+ No observed variability in HE data



1ES 1218+304:

+ VHE shortest block resolved with selected timing binning: ~ 1 month
+ HE slight flux increase correlated with VHE flares

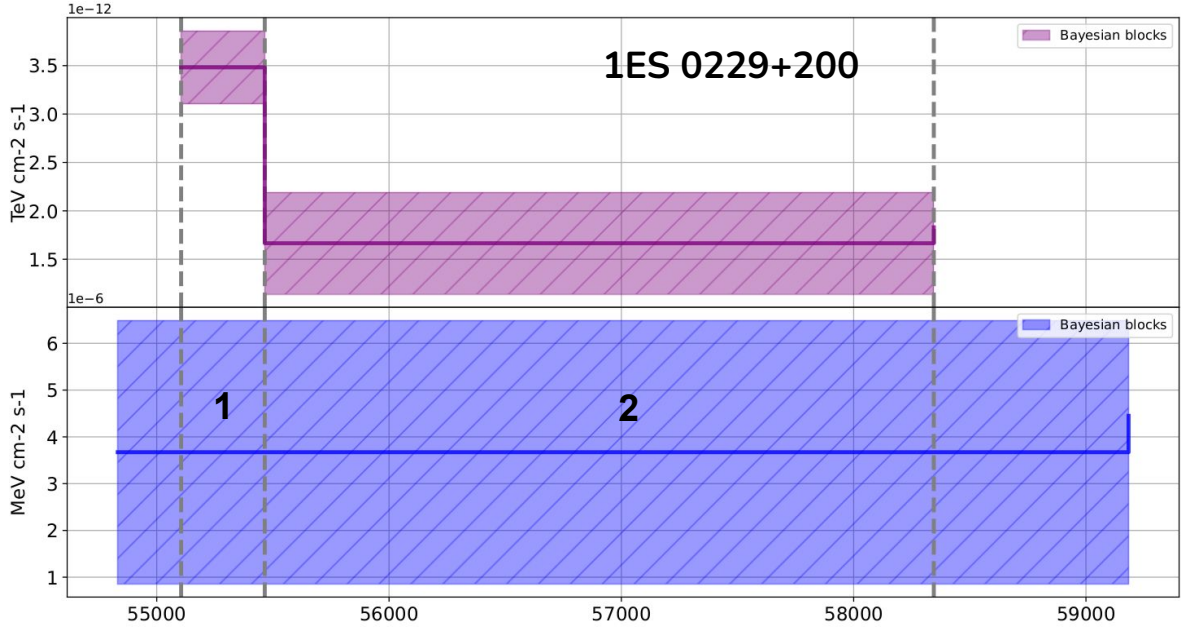
Change point significance: 3 sigma (fpr ~ 0.0027)

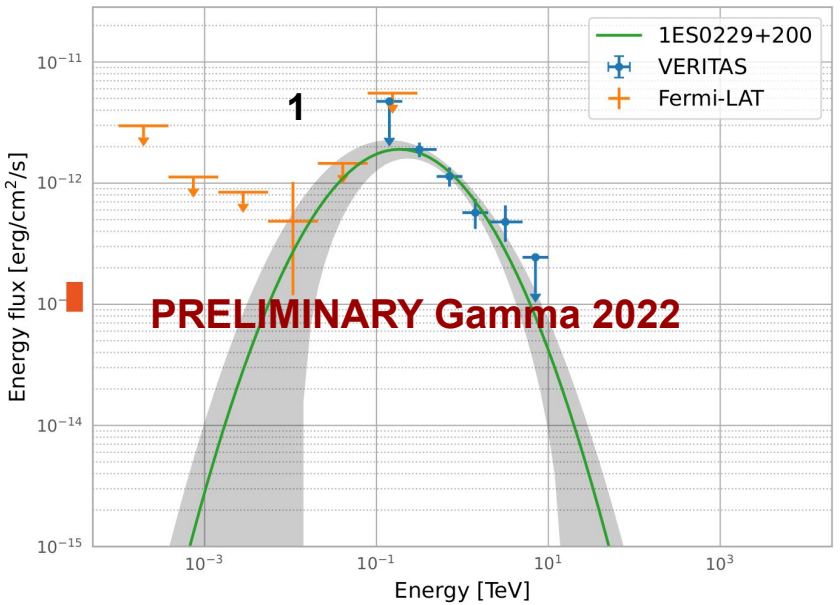
Characterizing the emission of extreme HBLs with VERITAS

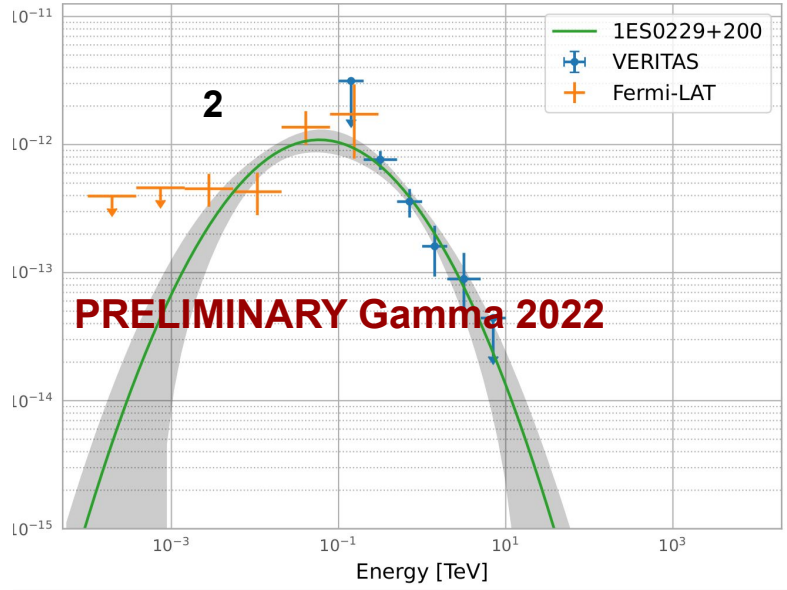
4: Spectral analysis (HE and VHE data)

- For the spectral analysis we use combined ***Fermi* + VERITAS event level data**, and assuming a spectral model shape , we determine the best fit parameters for each state (via forward folding)
- The individual flux points from Fermi and VERITAS are obtained with *fermipy* and *gammapy* respectively

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta log\left(\frac{E}{E_0}\right)}$$

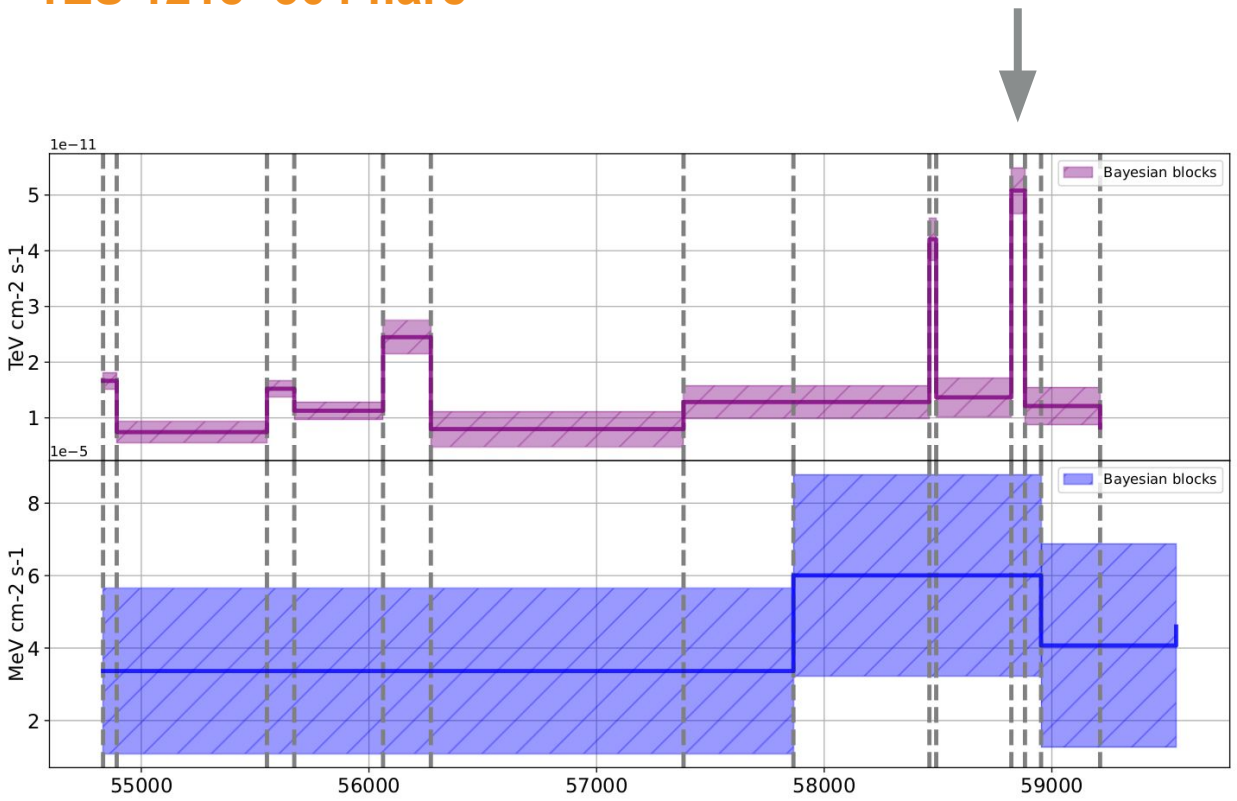




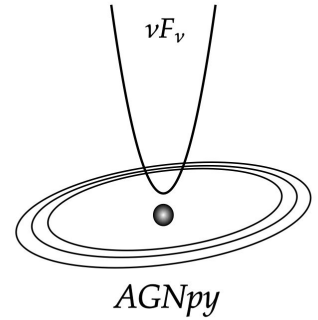


Characterizing the emission of extreme HBLs with VERITAS

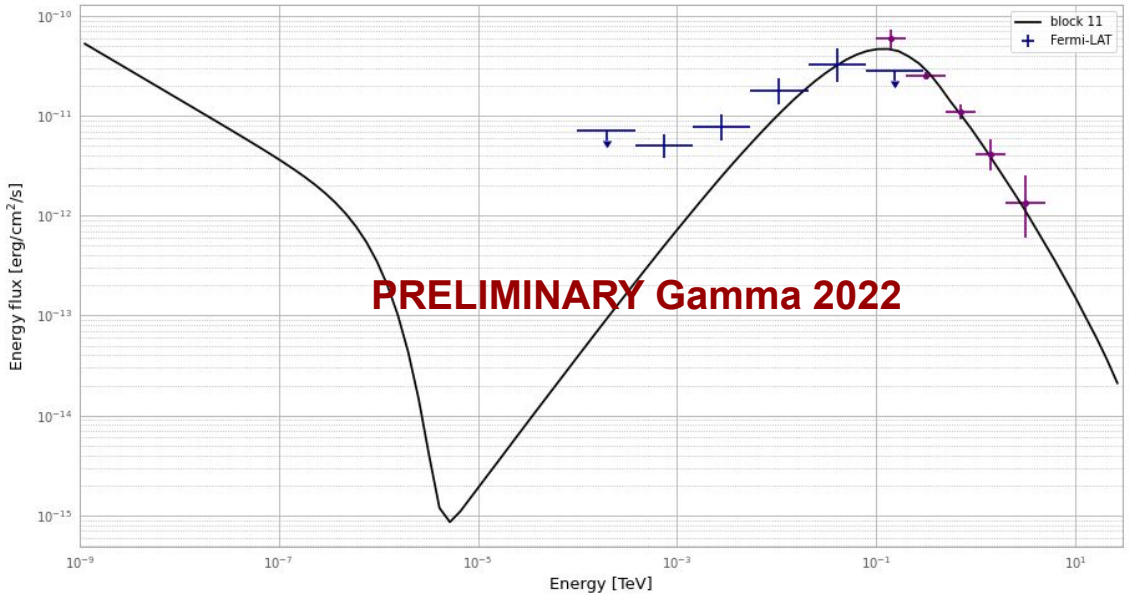
1ES 1218+304 flare



- Preliminary modeling using **a single zone SSC model (agnpy)** with a forward folding process, in a joint Fermi+VERITAS analysis
  - We clearly need the low energy data constraints on the emission model, but it is a successful proof of principle



https://agnpy.readthedocs.io/en/latest/index.html



Characterizing the emission of extreme HBLs with VERITAS

Summary

- Variability:
  - X-ray variability observed on the timescale of ~ day
  - HE observations for both sources present essentially no variability
  - 1ES 1218+304 shows variability on the timescale of ~ month on the VHE band
  - 1ES 0229+200 shows only one change point through 2 to 5 required sigma in the Bayesian blocks estimation, and the shortest flux state estimated is on the timescale of ~ year
- Spectral analysis:
  - We are working towards the refinement of the technique: we apply robust analysis methods, however it still requires further development
  - The fit on the event level data will allow us to have better control over the systematics over an expanded energy range (HE and VHE)
- Next steps:
  - Include low energy data in our analysis
  - Analyze our MWL data over all of our time periods and provide further physical interpretations about emission scenarios and its time evolution

Thank you!

Deutsches
Elektronen-Synchrotron

www.desy.de

Contact:

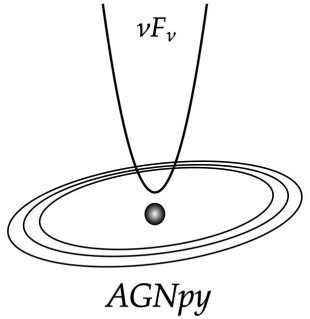
pedro.batista@desy.de

Backup

Characterizing the emission of extreme HBLs with VERITAS

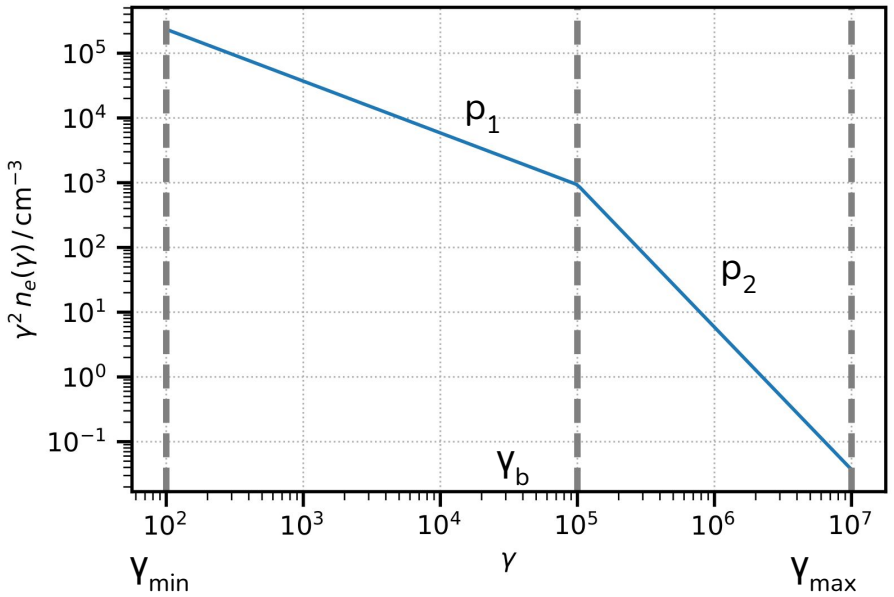
SSC Model

We use ***agnpy*** that provides a numerical computation of the photon spectra produced by leptonic radiative processes in jetted AGN



https://agnpy.readthedocs.io/en/latest/index.html

- Emission region of size **R**, moving relativistically, with a Doppler boosting factor of δ_D , with k_e electrons per centimeter cubic, distributed in energy from γ_{min} to γ_{max} in a broken power law, with slopes p_1 and p_2, with the slope change at γ_b, in a magnetic field **B**

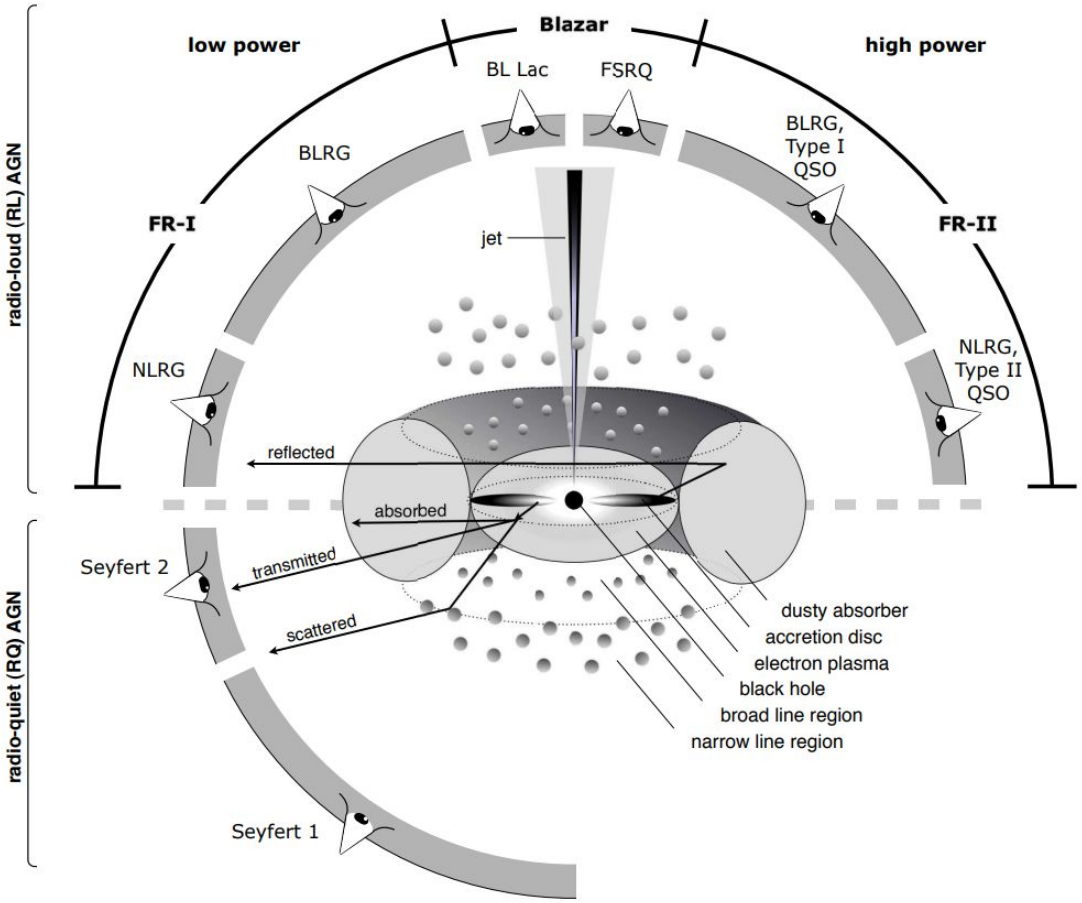


- The size of the emission region is constrained by the source variability (t_{var}), redshift (**z**) and Doppler boosting (δ_D)

$$R = \frac{c\delta_D t_{var}}{(1+z)}$$

High Frequency Peaked BL Lac objects:

- **BL Lacertae:**
  - Blazars with typically little or no emission lines, usually divided in, based on the location of their synchrotron peaks
    - Low-frequency-peak BL Lacs (LBLs or LSPs) - $\nu_{peak} < 10^{14}$ Hz
    - Intermediate-frequency-peak BL Lacs (IBLs or ISPs) - 10^{14} Hz $< \nu_{peak} < 10^{15}$ Hz
    - High-frequency-peak BL Lacs (**HBLs** or HSPs) - $\nu_{peak} > 10^{15}$ Hz



Beckmann & Shrader (https://doi.org/10.48550/arXiv.1302.1397)