EXPLORING THE HIGH ENERGY SPECTRAL CUT-OFF OF FSRQS USING CTAO

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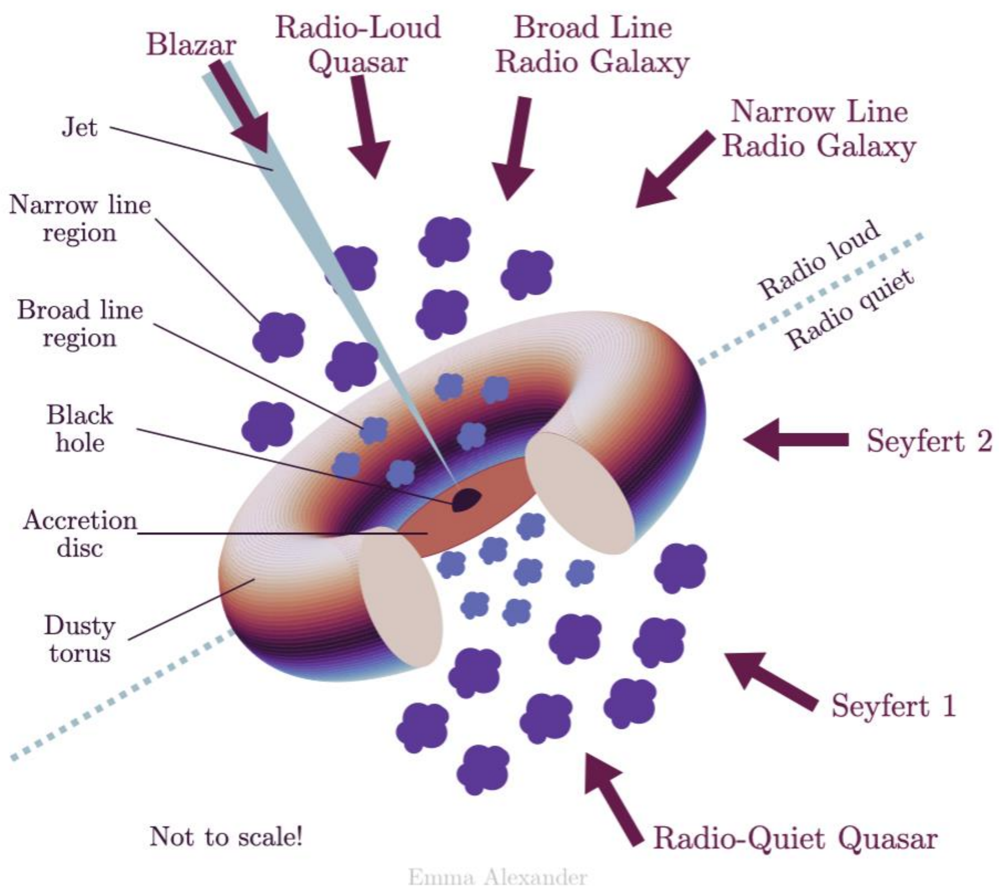
5/26/2025-2ND VHEGAM MEETING, BARI

FLAT SPECTRUM RADIO QUASAR

- Blazars are radio loud Active Galactic Nuclei (AGNs) with their relativistic jet orientated close to the line of sight;
- Two categories: flat-spectrum radio quasars (FSRQs) and BL LAQ objects;
- FSRQs have strong and broad optical emission lines, high bolometric luminosities, and are thought to have a much denser environment near the black hole.



GOALS OF THE PROJECT

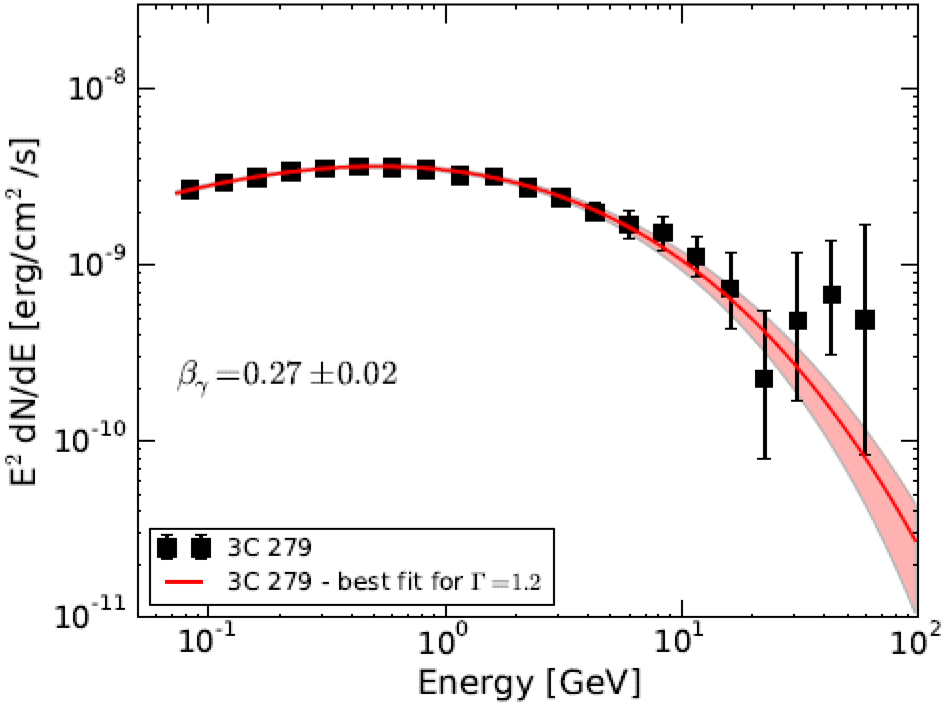
- Our goal is to assess CTAO's ability to define the spectral cut-off for various flaring FSRQs with different redshifts (ranging from 0.18 to 0.99);
- The gamma-ray energy spectrum can be described by:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_c}\right)^{\beta_\gamma}\right]$$

- The shape of the cut-off region in the gamma-ray spectrum may be connected with the cut-off region of primary particles;
- Assess CTAO's ability to distinguish between different spectral models connected with the distribution of the primary particles;
- See if we need both LSTs and MSTs to characterized these flares or we can use just the LSTs.

WHY CTAO

- Fermi has a bad sensitivity above 100GeV;
- We know that FSRQs can emit at energies higher than 100GeV during flares!
- CTAO is optimized for gamma-ray energies between 150 GeV to 300 TeV!



Romoli et al. 2016

STARTING POINTS OF THE PROJECT

- Find the spectral cut-off in the SED of real FSRQs in the Northern hemisphere during 4 flaring episodes:
  - PKS 0736+017;
  - PKS 1222+216;
  - Ton 599;
  - OP 313.
- Do the same with 3 Southern hemisphere sources:
  - PKS 1510-089;
  - 3C 279;
  - PKS 0346-27.

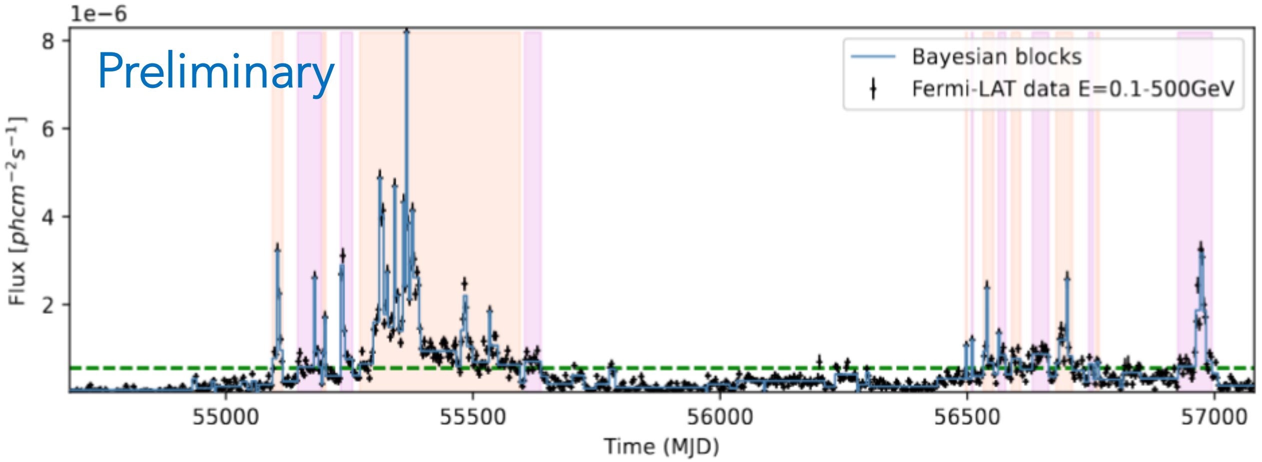
Source	Period	Energy range (GeV)	Redshift
PKS 0736+017	2014/01/01 - 2021/01/01	0.1-500	0.189
PKS 1222+216	2008/8/4 - 2015/3/1	0.1-500	0.434
Ton 599	2020/10/15 - 2025/1/1	0.1-500	0.725
OP 313	2022/1/1 - 2025/3/31	0.1-500	0.997
PKS 1510-089	2008/08/04- 2017/01/01	0.1-500	0.361
3C 279	2013/01/01 - 2020/01/01	0.1-500	0.539
PKS 0346-27	2017/01/01 - 2023/01/01	0.1-500	0.991

CHOOSE THE CORRECT FLARING PERIOD

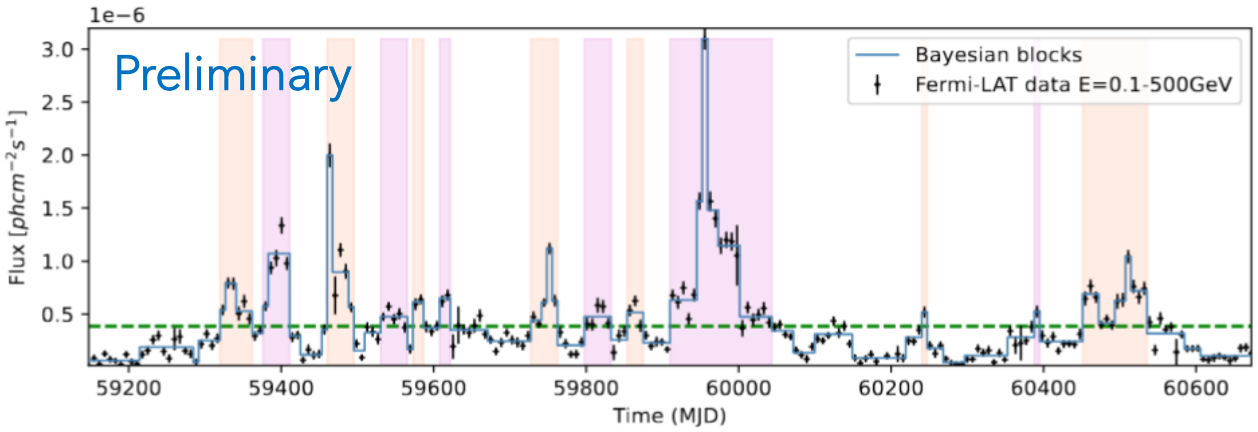
- We used the same stategy reported in DOI: https://doi.org/10.22323/1.444.0701
- Flaring periods are found using the following equation from Ishida et al. 2023:

$$F_\gamma^{\mathrm{th}} = F_\gamma^q + s\langle F_\gamma^{\mathrm{err}}\rangle$$

- And the HOP algorithm explained in Meyer et. 2019 to defined the rising time, peak time and decay time in every flare;
- Only the most intense flare of each FSRQs.



PKS 1222+216

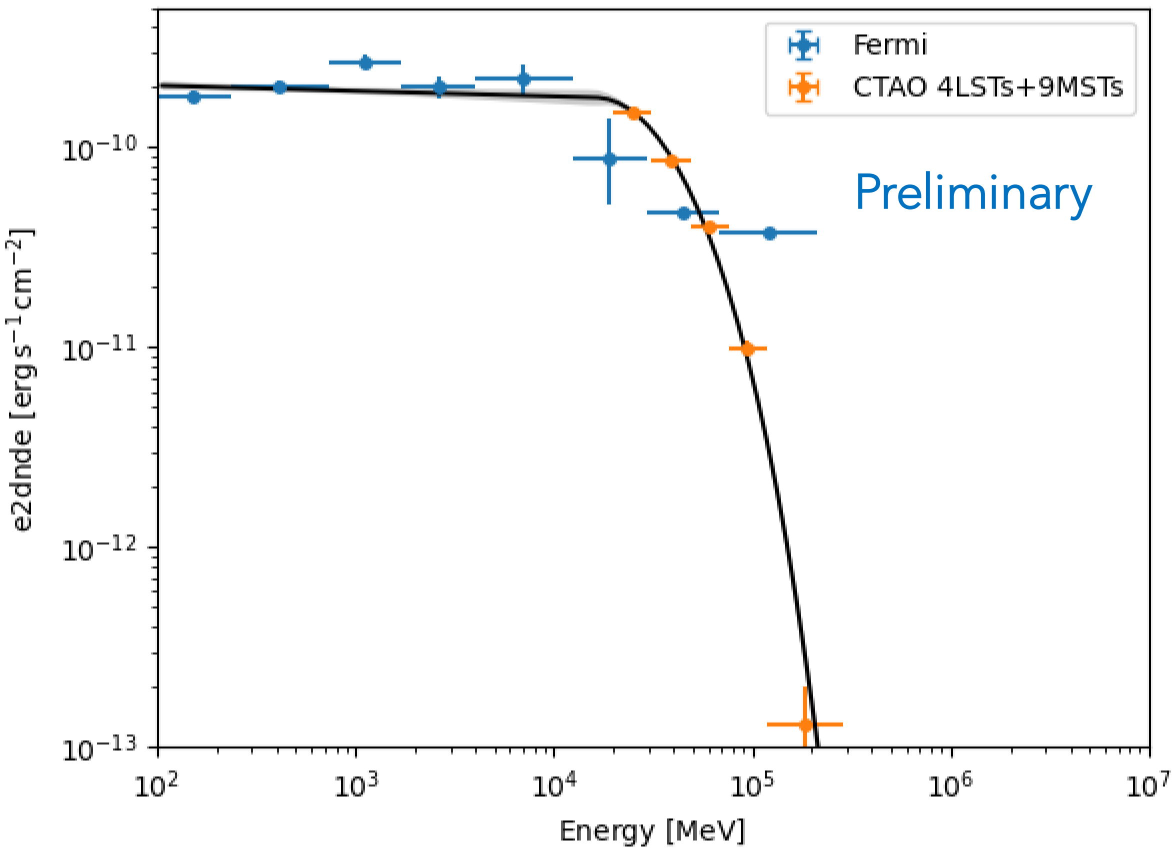


Ton 599

SIMULATION OF CTAO DATA AND JOINT FIT WITH FERMI-LAT DATA

- From Fermi-LAT data we simulated CTAO data using the IRFs we want and the power law with exponential cut-off model used to fit Fermi data:
  - o 4 LSTs for Nothern sources;
  - o 4 LSTs+9MSTs for Nothern sources;
  - o 14 MSTs for the Southern sources;
  - o 14 MSTs + 11 SCTs for the Southern sources in a scenario beyond the alpha configuration;
- We do a joint fit of Fermi-LAT + CTAO datasets.

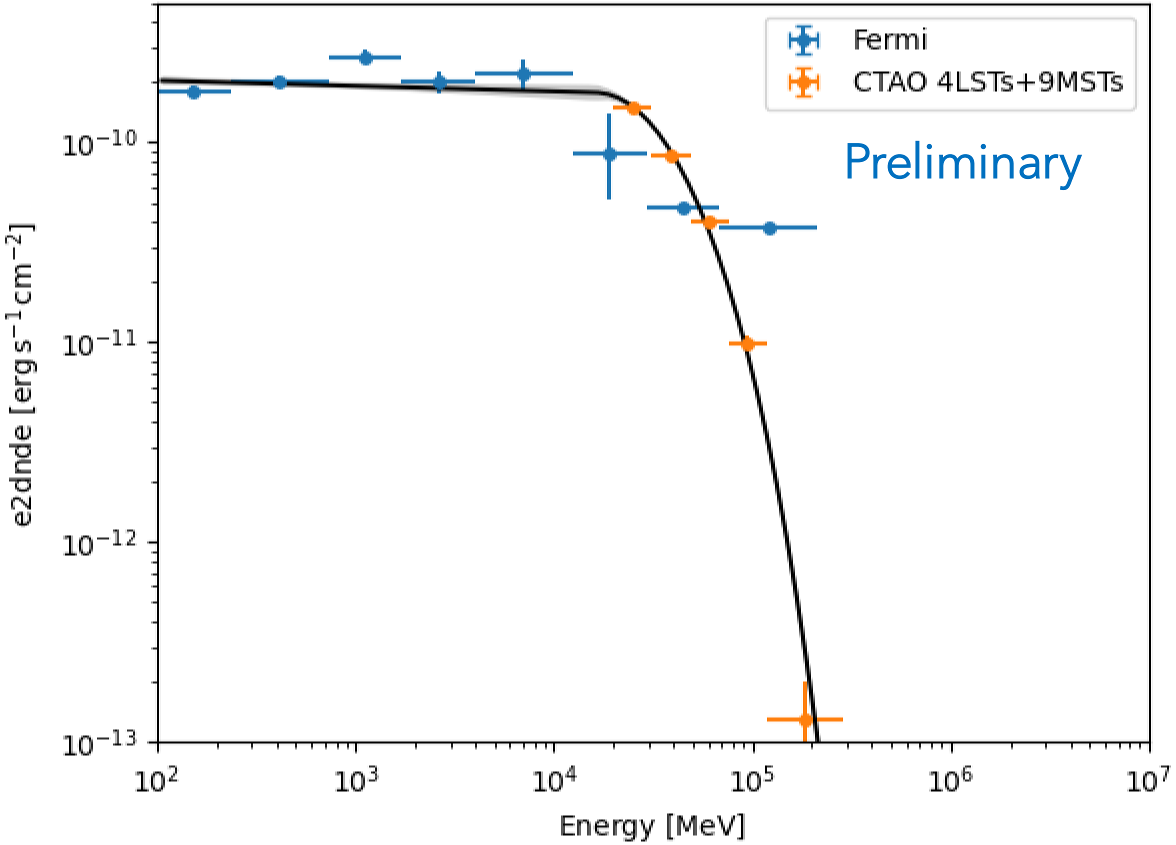
Ton 599 decay time SED



SIMULATION OF CTAO DATA AND JOINT FIT WITH FERMI-LAT DATA

- We did this procedure for 100 simulated CTAO datasets for each livetime:
  - o 30 minutes;
  - o 1 hour;
  - o 1.5 hours;
  - o 2 hours.
- For each configuration we chose;
- For each flaring period we chose;
- We calculated the average TS and energy cut-off error ratio for each livetime, configuration and flaring period.

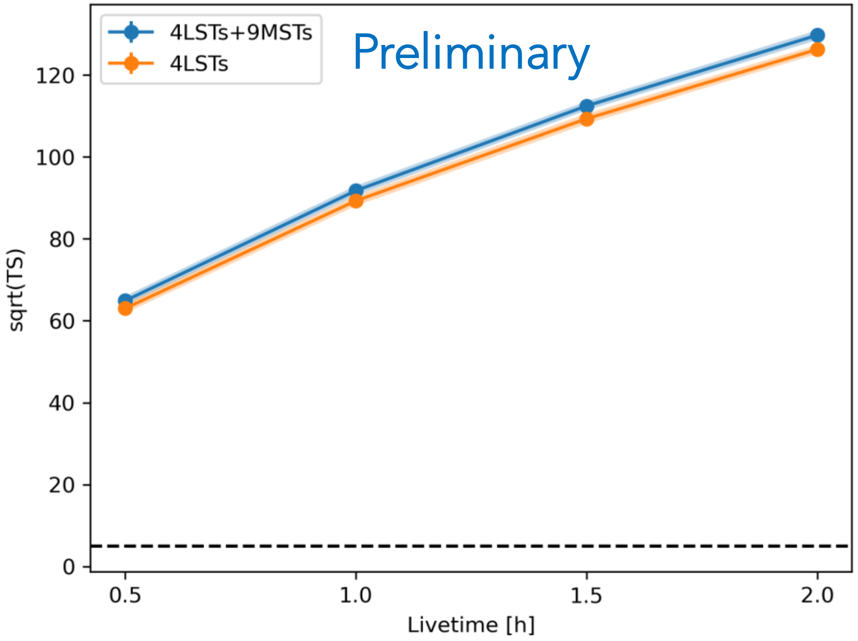
Ton 599 decay time SED

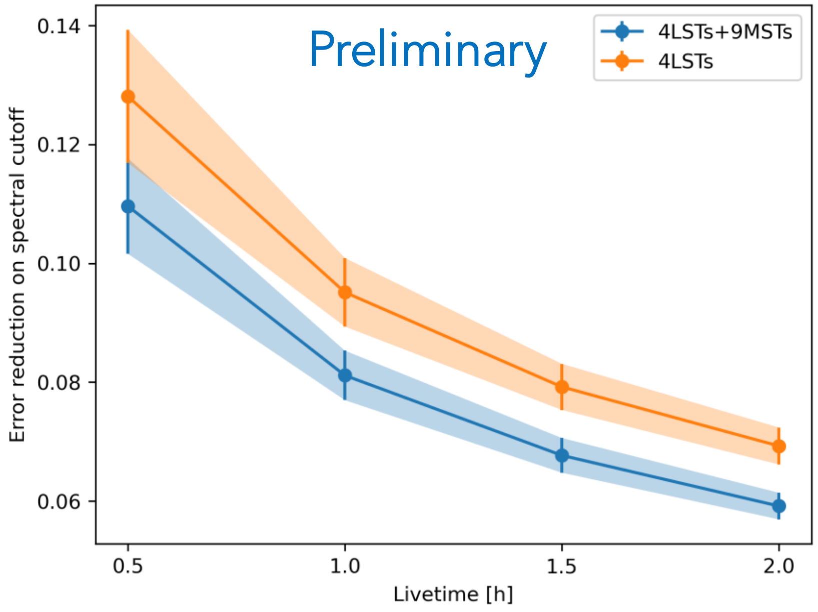


TS AND ENERGY CUT-OFF ERROR RATIOS COMPARISON

- Comparing all the average squared TS values we obtained during our simulations, after 2 hours of observations the squared TS of 4LSTs is:
  - 101.6% the squared TS of 4LSTs + 9MSTs for PKS 0736+017;
  - 98.3% the squared TS of 4LSTs + 9MSTs for our intermediate redshift FSRQs;
  - 99% for OP 313;
- After 30 minutes of observation the TS is always high enough to have a good detection of the flaring activity with both configurations, except for PKS 0736+017;
- Comparing all the average error ratio values we obtained during our simulations, after 2 hours of observations the error ratio obtained using 4LSTs + 9 MSTs is:
  - 9.6% larger than the value obtained with 4LSTs only our intermediate redshift FSRQs;
  - 14.7% for OP 313;
  - 2% smaller for PKS 0736+017.

Ton 599 decay time SED results





OUR OTHER SPECTRAL MODELS

- BKL is gammapy BrokenPowerLawSpectralModel:

$$\phi(E) = \phi_0 \cdot \begin{cases} \left(\frac{E}{E_{break}}\right)^{-\Gamma 1} & \text{if } E < E_{break} \\ \left(\frac{E}{E_{break}}\right)^{-\Gamma 2} & \text{otherwise} \end{cases}$$

- LP is gammapy LogParabolaSpectralModel:

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

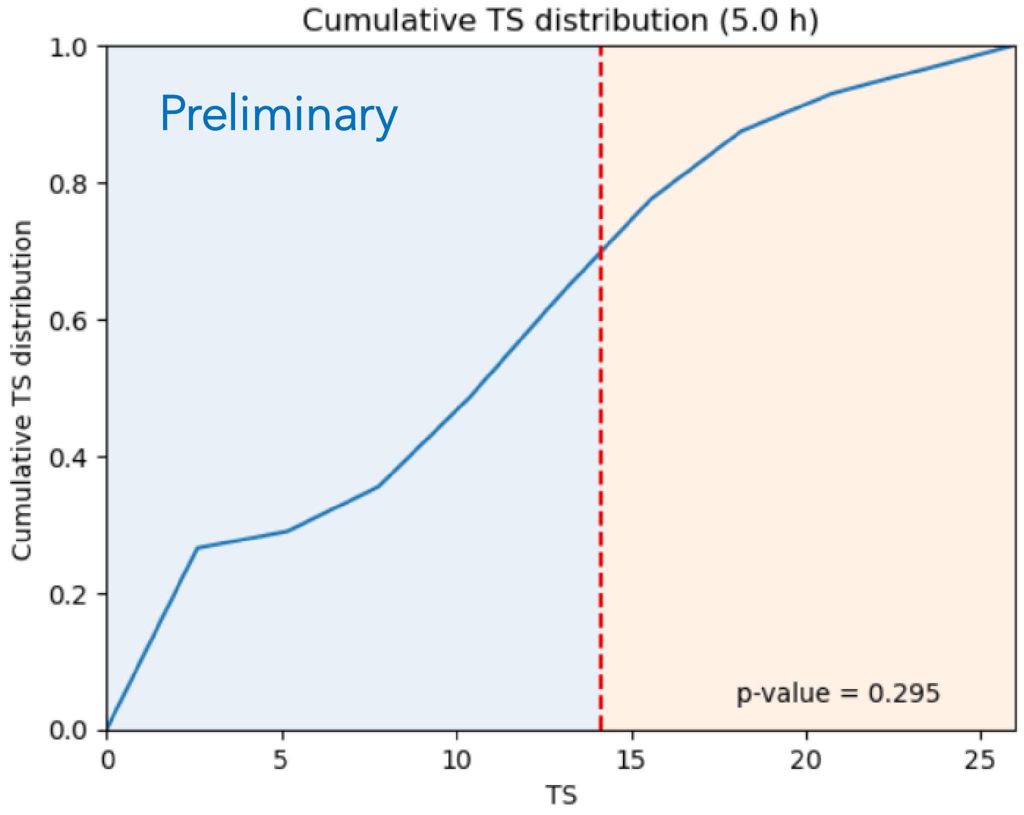
- PL + LP is the one presented in Van der Berg 2019:

$$\nu F_\nu = C_2 \nu \sqrt{\frac{\nu}{\nu_0}} \begin{cases} (\nu/\nu_b)^{-a/2} & \text{if } \nu \leq \nu_b \\ (\nu/\nu_b)^{-[a+b\ln(\nu/\nu_b)/2]/2} & \text{if } \nu > \nu_b \end{cases}$$

HOW WE DISTINGUISH BETWEEN DIFFERENT MODELS USING CTAO

- We follow the approach presented in Meyer et al. 2014;
- The test statistic is defined as: $TS = -2\ln\frac{\mathcal{L}_{ECPL}(D)}{\mathcal{L}_{max}(D)}$
- We compute the TS distribution for 1000 CTAO datasets simulated using the ECPL model;
- We then simulate 1000 datasets using one of the other models and obtain the average TS for different livetimes: 1, 2, 3, 4, and 5 hours.

Ton 599 rise time SED results



NEXT STEPS

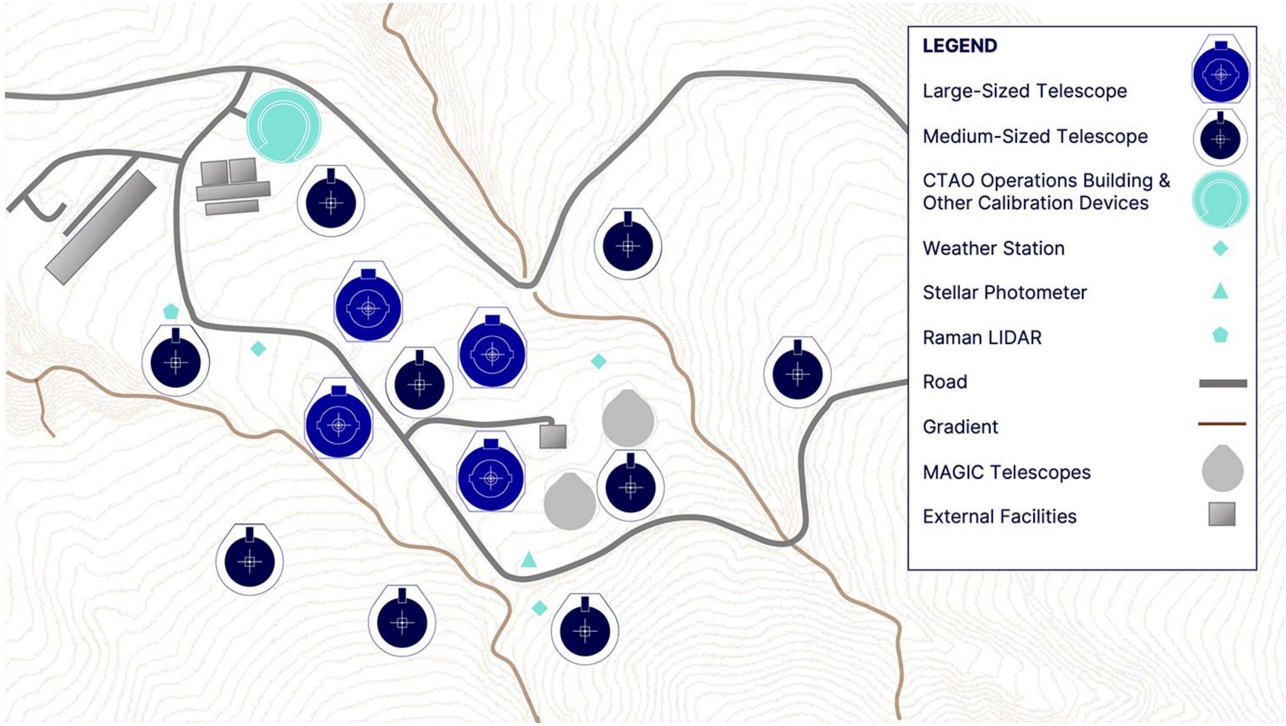
- Continue simulate 1000 datasets for each observation time, each CTAO configuration and each source and each model;
- Decide if we want to do this for the single little flares inside big windows flare;
- Put together all the results;
- Find a threshold on the redshift that tell us when the contribution of MSTs is important to investigate the spectral parameters of FSRQs flaring periods.

THANK YOU FOR YOUR ATTENTION

ADDITIONAL SLIDES

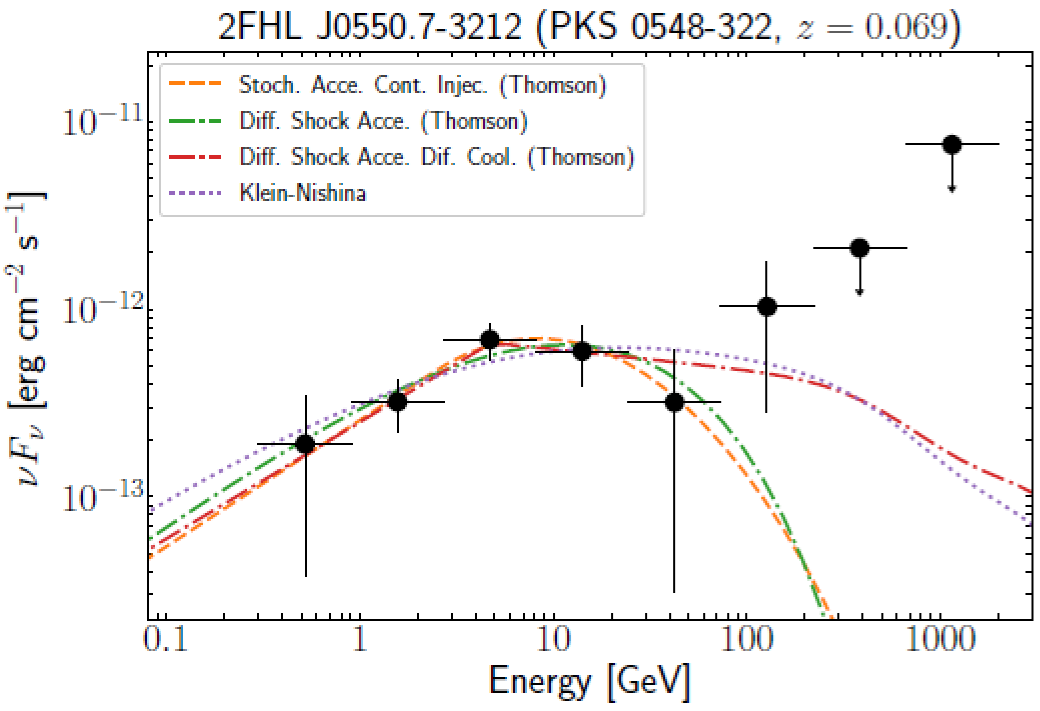
CTAO'S NORTHERN HEMISPHERE ARRAY

- Located at La Palma;
- 4 Large-Sized telescopes with a 23m diameter, 20 GeV-150 GeV;
- 9 Medium-Sized telescopes with a 12m diameter, 150 GeV – 5 TeV;
- Both are single reflectors.



POSSIBILITIES

- Starting from Fermi-LAT data we want to simulate differents datasets and see if observing with LSTs only is actually sufficient for determining where the cut-off is or if LST+MSTs result in significantly better results.
- We want to determine if one of these 4 theoretical models is a favored spectral model for our FSRQs:
    - First-order Fermi acceleration + TS (PL+EC);
    - Stochastic acceleration + TS (LP+PL);
    - First-Order Fermi Acceleration with Different Acceleration / Cooling Regimes and TS (BPL);
    - Klein-Nishina regime (KN);
    - LP and LP + EC both in TS.



Van der Berg et al. 2019

MODELS EXPLANATION

- PL+EC means radiative cooling or decreasing probability for HE particles to cross the shock front

$$n_e(\gamma_e) = n_{e;0}\gamma_e^{-p}\exp\left(-\frac{\gamma_e}{\gamma_c}\right)$$

- LP + PL means the electron distribution resulting from stochastic acceleration with continuous injection could be

$$n_e(\gamma_e) = n_{e;0}\begin{cases}(\gamma_e/\gamma_b)^{-a} & \text{if } \gamma_e \leq \gamma_b \\ (\gamma_e/\gamma_b)^{-[a+b\ln(\gamma_e/\gamma_b)]} & \text{if } \gamma_e > \gamma_b\end{cases}$$

- BPL means two different physical processes dominate in different energy ranges, such as radiative vs. adiabatic cooling, the electron distribution can be described by

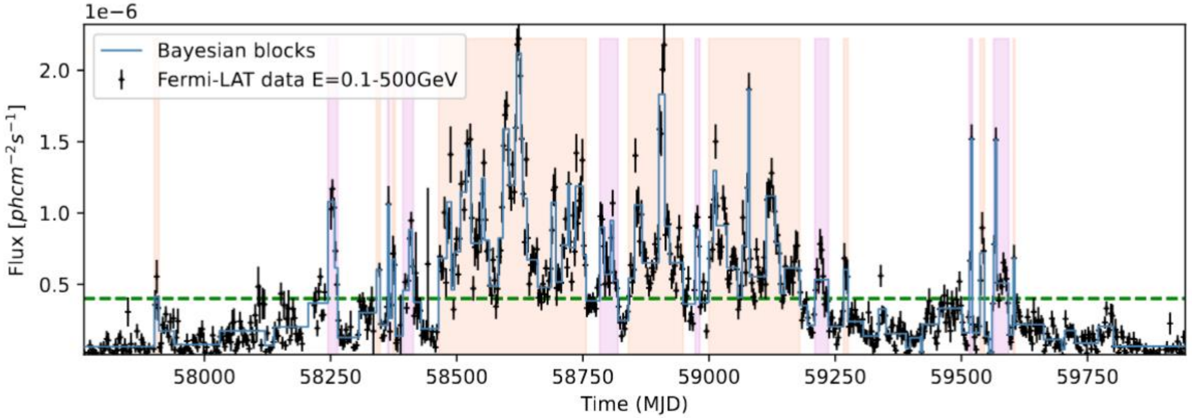
$$n_e(\gamma_e) = n_{e;0}\begin{cases}(\gamma_e/\gamma_b)^{-q} & \text{if } \gamma_e \leq \gamma_b \\ (\gamma_e/\gamma_b)^{-s} & \text{if } \gamma_e > \gamma_b\end{cases}$$

STARTING POINTS OF THE PROJECT

- Using gammapy we want to analyze Fermi-LAT data and simulate CTAO data for each flare using Prod5 IRFs for Northern hemisphere sources;
- For CTAO South sources, we want to use the Alpha confguration F4 IRFs and then add SCTs in a scenario beyond the Alpha configuration;
- We will use Bayesian Blocks to find the flaring activity and then gammapy to fit the data and simulate CTAO data;
- Find the flaring periods using the Bayesian blocks and the HOP algorithm.

WE ADD TWO MORE SOURCES

- We expect that the contributes of the MSTs on the TS of a source is smaller at increasing redshift;
- In order to have an idea at wich redshift this happens, we add 2 sources:
  - PKS 0346-27, South (z=0.991);
  - PKS 0736+017, North (z=0.18941).



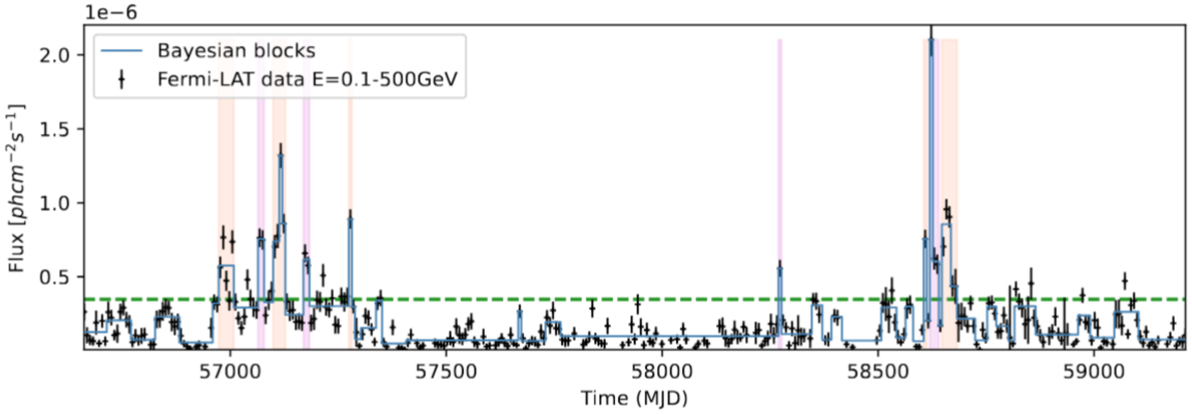


Figure 7. PKS 0736+017

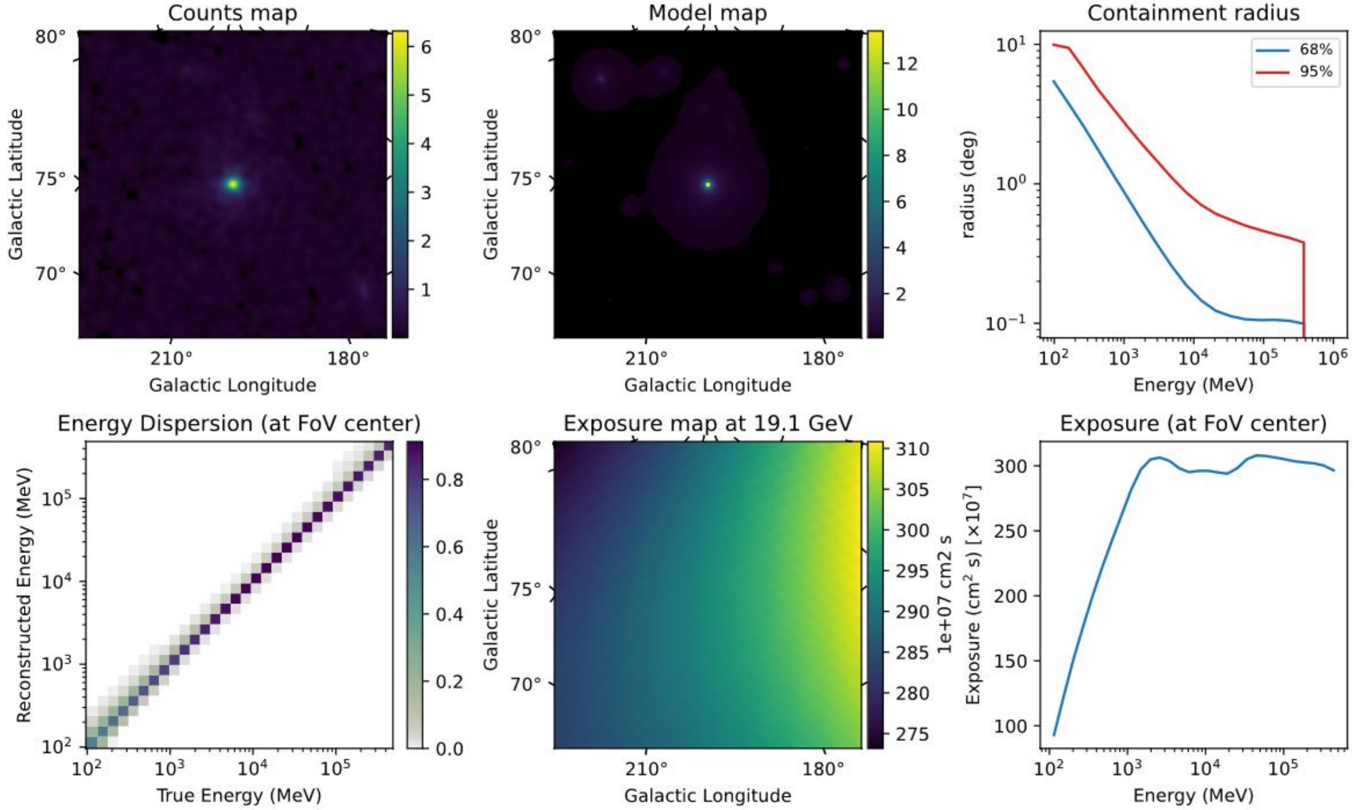
MAJOR FLARING PERIODS

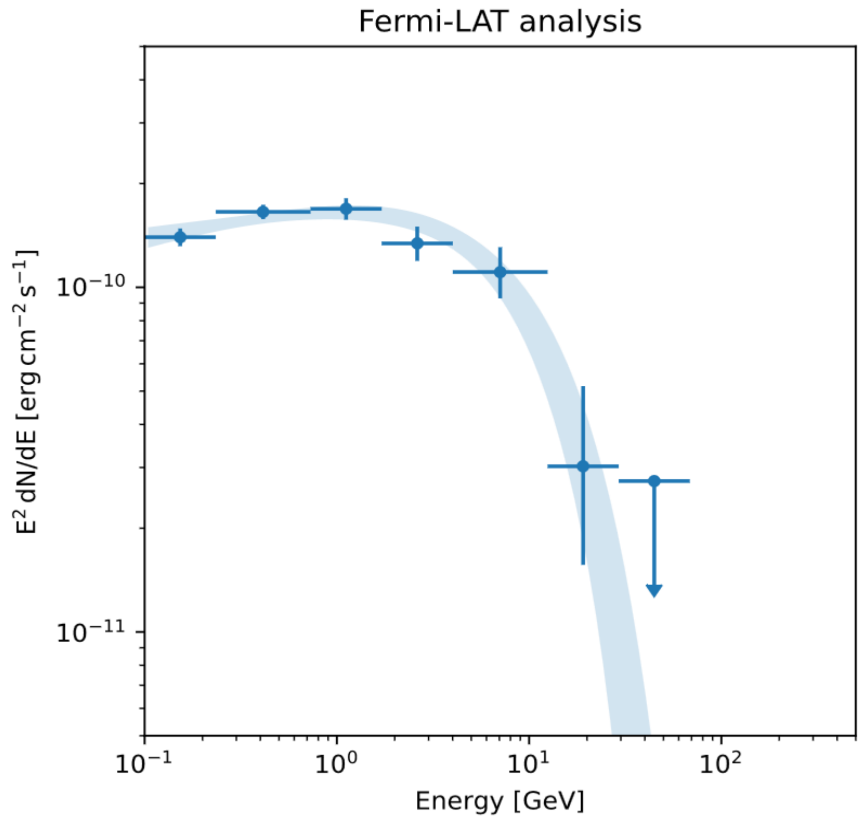
- We choose to analyze the SEDs of the rising and decaying times of the 4 major flaring periods of the blazars:

Table 2. times

Source	Peak flux ($\mathrm{ph\,cm^{-2}s^{-1}}$)	Start time	Peak time	End time
PKS 1222+216	8.19×10^{-6}	55271.2	55365.8	55595.5
PKS 1222+216	3.22×10^{-6}	55094.1	55104.6	55115.1
PKS 1222+216	3.16×10^{-6}	56925.8	56973.9	56994.9
PKS 1222+216	2.9×10^{-6}	55232.2	55235.2	55256.2
Ton 599	3.1×10^{-6}	59910	59955.7	60043.5
Ton 599	2.0×10^{-6}	59460.3	59463.8	59495.4
Ton 599	1.12×10^{-6}	59727.3	59751.9	59762.4
Ton 599	1.07×10^{-6}	59375.9	59397	59411.1

GAMMAPY RESULTS FOR FERMI-LAT DATA - PRELIMINARY





I seek the same stategy reported in DOI: https://doi.org/10.1051/0004-6361/202452349

OUR MODELS

- LP + PL + EC is a compound gammapy spectral model made by the LogParabolaSpectralModel and ExpCutoffPowerLawNormSpectralModel (This model parametrises a cutoff power law spectral correction with a norm parameter.)

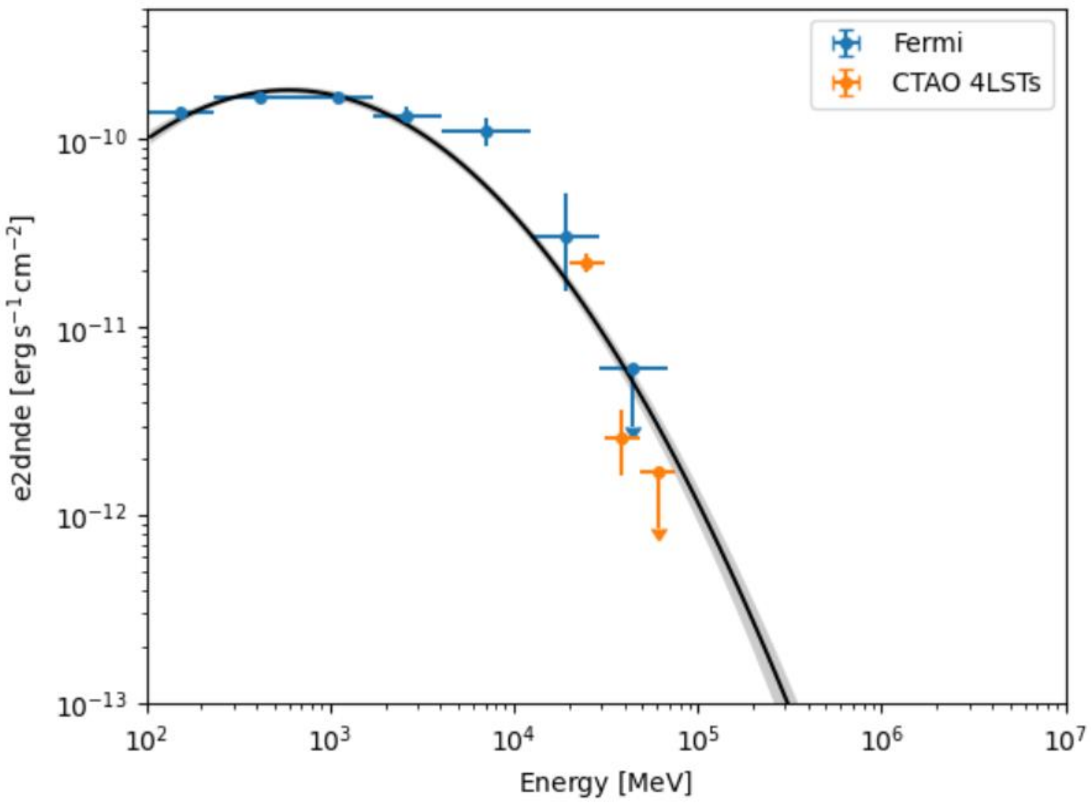
$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

- PL + LP is the one presented in van der Berg 2019

$$\nu F_\nu = C_2 \nu \sqrt{\frac{\nu}{\nu_0}} \begin{cases} (\nu/\nu_b)^{-a/2} & \text{if } \nu \leq \nu_b \\ (\nu/\nu_b)^{-[a+b\ln(\nu/\nu_b)/2]/2} & \text{if } \nu > \nu_b \end{cases}$$

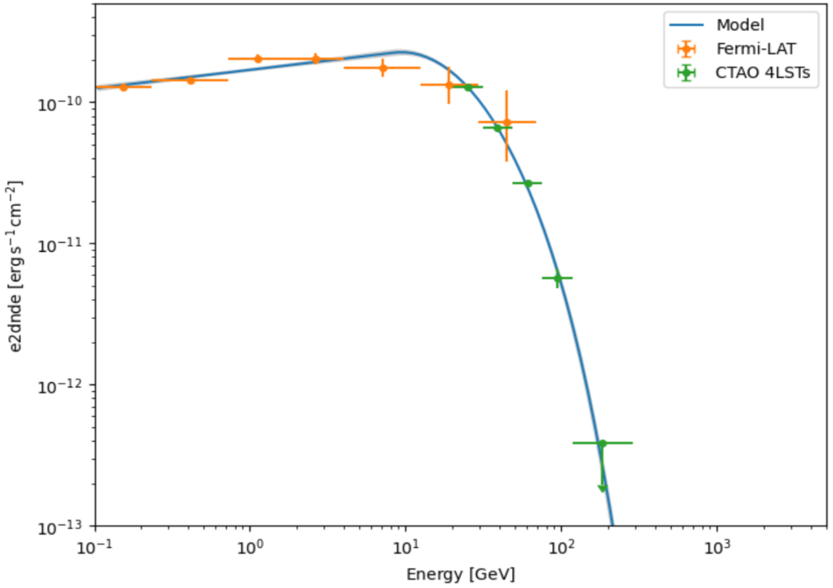
LAST TIME, WE STOPPED HERE: FITTING THE SIMULATED SED WITH DIFFERENT MODELS

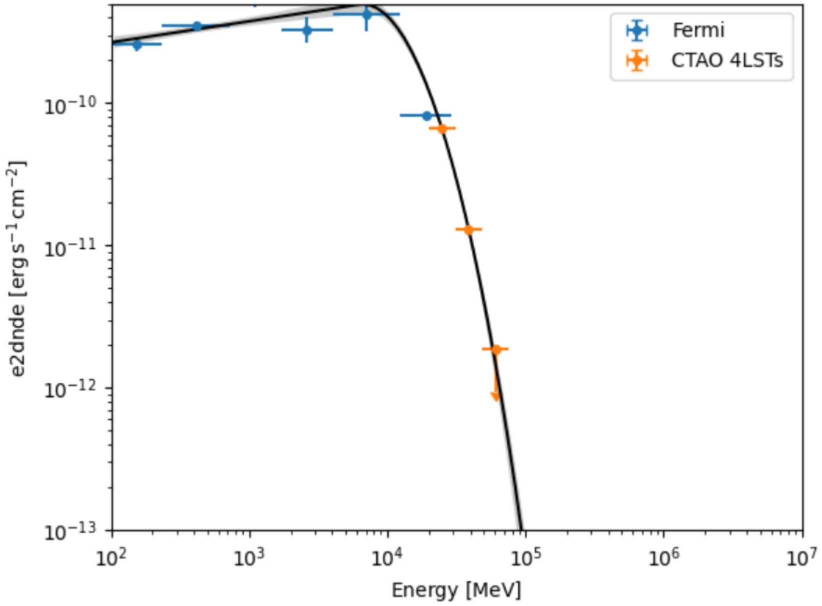
- We want to determine what model is favoured for our FSRQs and if CTAO can distinguish between different models;
- The models we are using are:
  - First-order Fermi acceleration + TS (PL+EC);
  - Stochastic acceleration + TS (LP+PL);
  - First-Order Fermi Acceleration with Different Acceleration / Cooling Regimes and TS (BPL);
  - LP and LP + EC both in TS.
- We can use the Akaike Information Criterium (AIC) or a maximum-likelihood ratio test and the Wilks theorem.



HOW WE DID IT AT THE BEGINNING

- We fitted the Fermi-LAT + CTAO datasets **jointly**;
- For each successful fit we plotted the SED with the model and calculated the AIC_mod;
- We calculated ΔAIC = AIC_mod – AIC_pl+ec
- We calculated the error ratio between the Fermi-LAT + CTAO energy cut-off error and the Fermi-LAT energy cut-off error to show the improvement in using the CTAO to asses the spectral parameters of a FSRQ;
- We compared the TS of using only LSTs and LSTs + MSTs.





HOW WE DO IT NOW

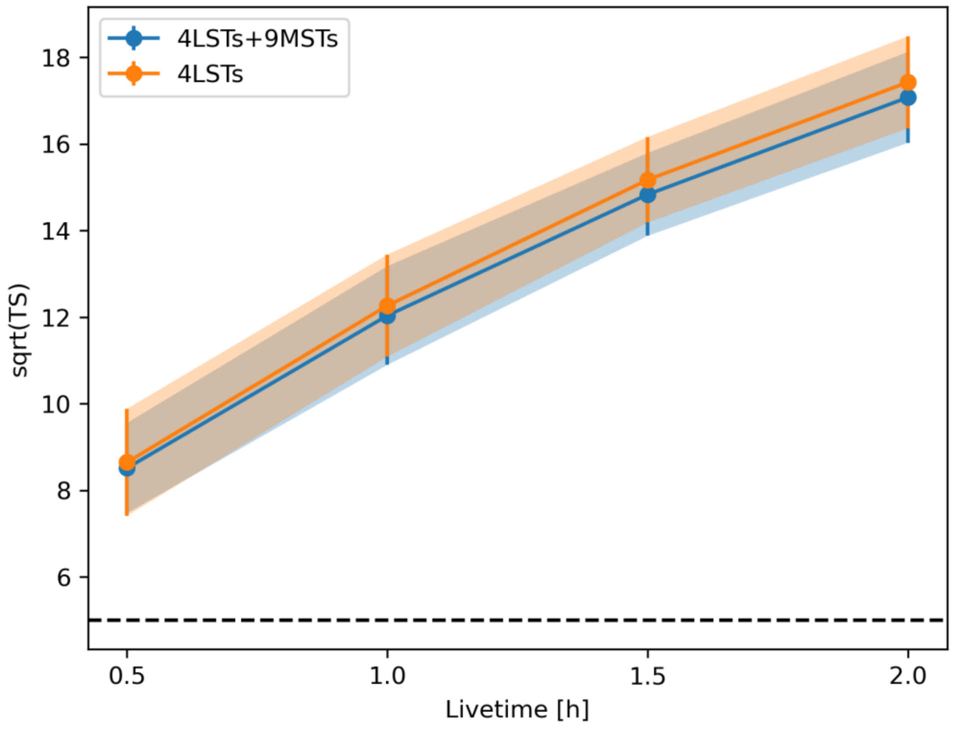
- From Model Selection and Multimodel Inference of Burnham and Anderson we know that:

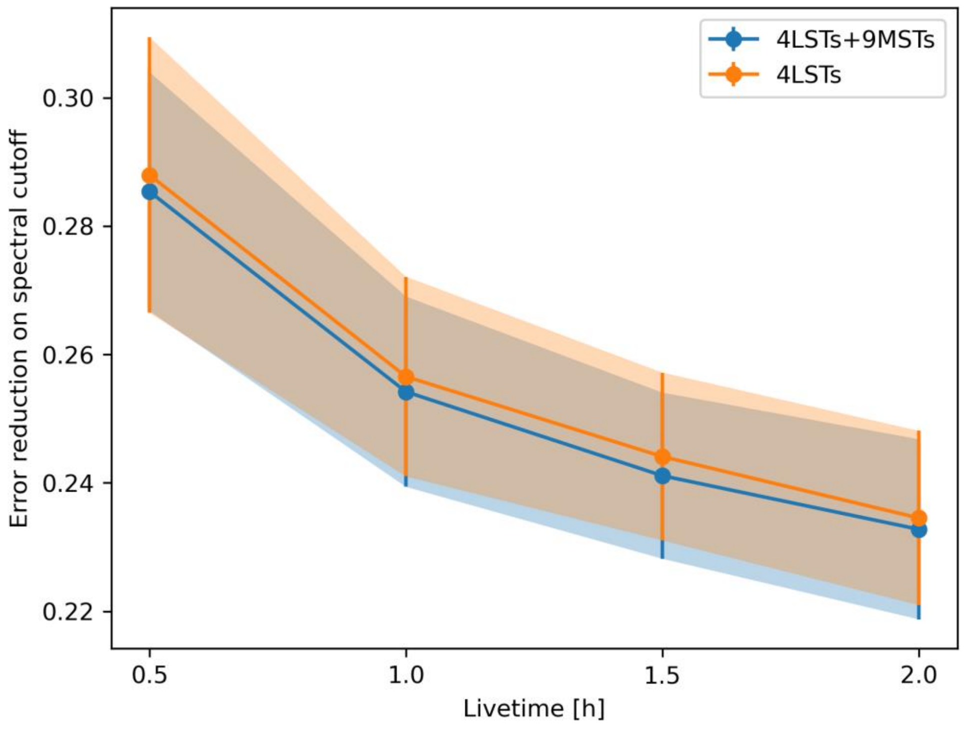
Δ_i	Level of Empirical Support of Model i
0-2	Substantial
4-7	Considerably less
> 10	Essentially none.

- We do the same fitting procedures but considering different observation times: 30 min, 1hour, 1.5 hour and 2 hours and we calculated ΔAIC to show when CTAO can distinguish between the 2 models;
- We do it simulating 100 datasets and calculating the mean of the ΔAIC, the energy cut-off error ratio and the TS.

HOW WE DO IT NOW: FIRST RESULTS

- Here I show the results of the rising part (59910- 59955.7) of one flare of Ton 599 seen by 4LST+9MSTs and 4LST:

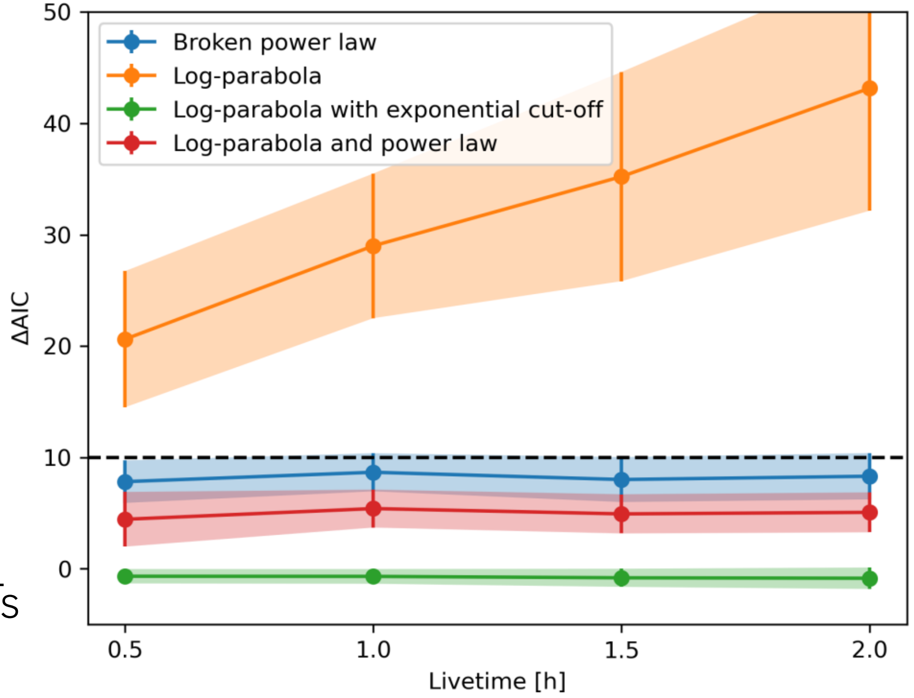




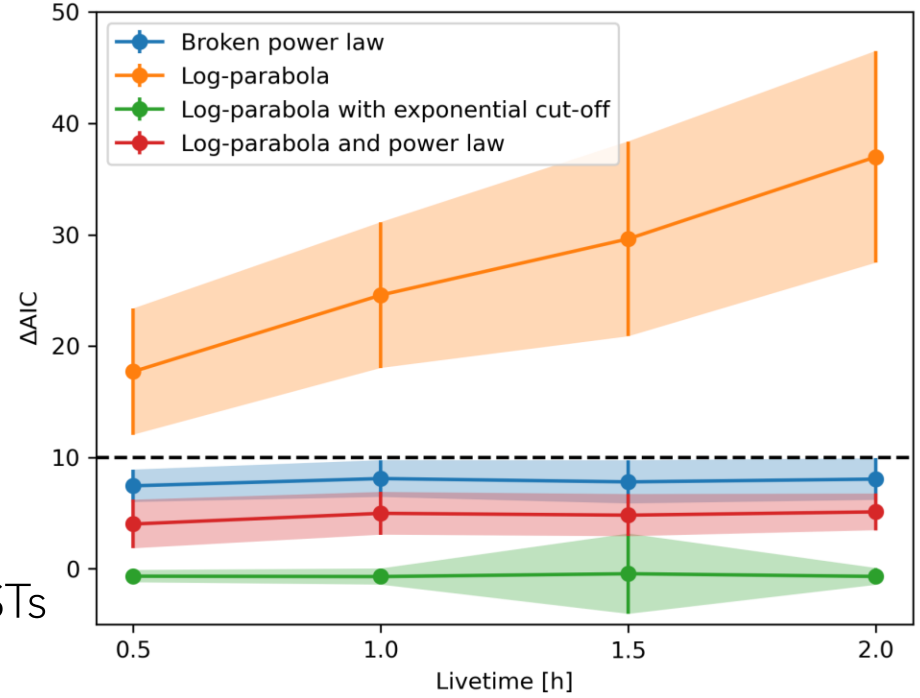
HOW WE DO IT NOW: FIRST RESULTS

- Here I show the results of the rising part (59910- 59955.7) of one flare of Ton 599 seen by 4LST+9MSTs and 4LST:

4LSTs+9MSTs



4LSTs



PAPER OUTLINE

- General introduction about FSRQs, Fermi-LAT and CTAO experiments;
- 1 paragraph about the Fermi-LAT analysis with tables that show our sample, the period of interest and the major flaring periods;
- 1 paragraph about gammapy analysis with Fermi-LAT data? This will be kinda new
- 1 paragraph about the SEDs simulation with gammapy with our strategy to simulate different spectral cut-off
- Introduction to the theoretical models to fit our SEDs
- Results
- Conclusions

If you agree with this outline, I start to write!

NEXT STEPS

- Do this analysis for every SED and for every CTAO configurations of our interest;
- Demonstrate the improvement of using CTAO to determine the spectral energy cut-off and the ability of the telescopes to discriminate between the different models;
- Do this with a good statistical approach;
- I would like to present this work at the **Extragalactic jets at all scales: a Cretan view** conference and at the 2nd VHEgam Meeting.