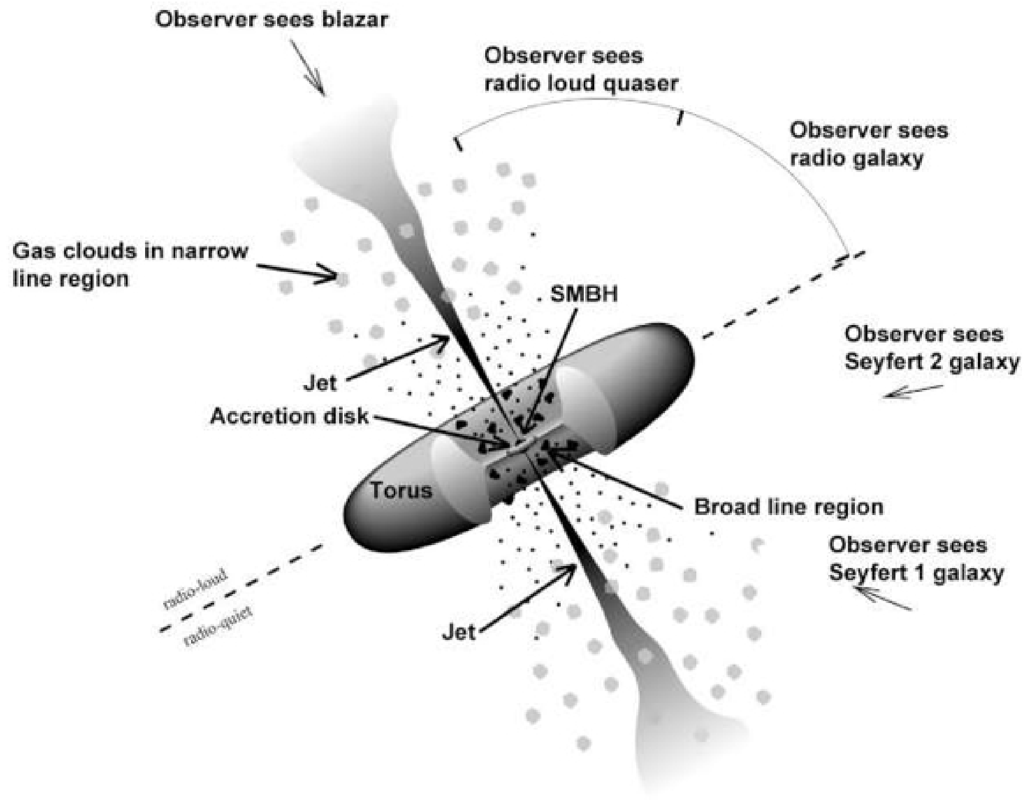
Active Galactic Nuclei variability studies with the Cherenkov Telescope Array Observatory

G. Grolleron, J. Becerra Gonzalez, J. Biteau, M. Cerruti, J. Finke, R. Grau, L. Gréaux, T. Hovatta, M. Joshi, J.-P. Lenain, E. Lindfors, W. Max-Moerbeck, D. Miceli, A. Moralejo, P. Morris, K. Nilsson, M. Petropoulou, E. Pueschel, A. Sarkar, S. Suutarinen, P. Romano, S. Vercellone, M. Zacharias
For the CTAO Consortium

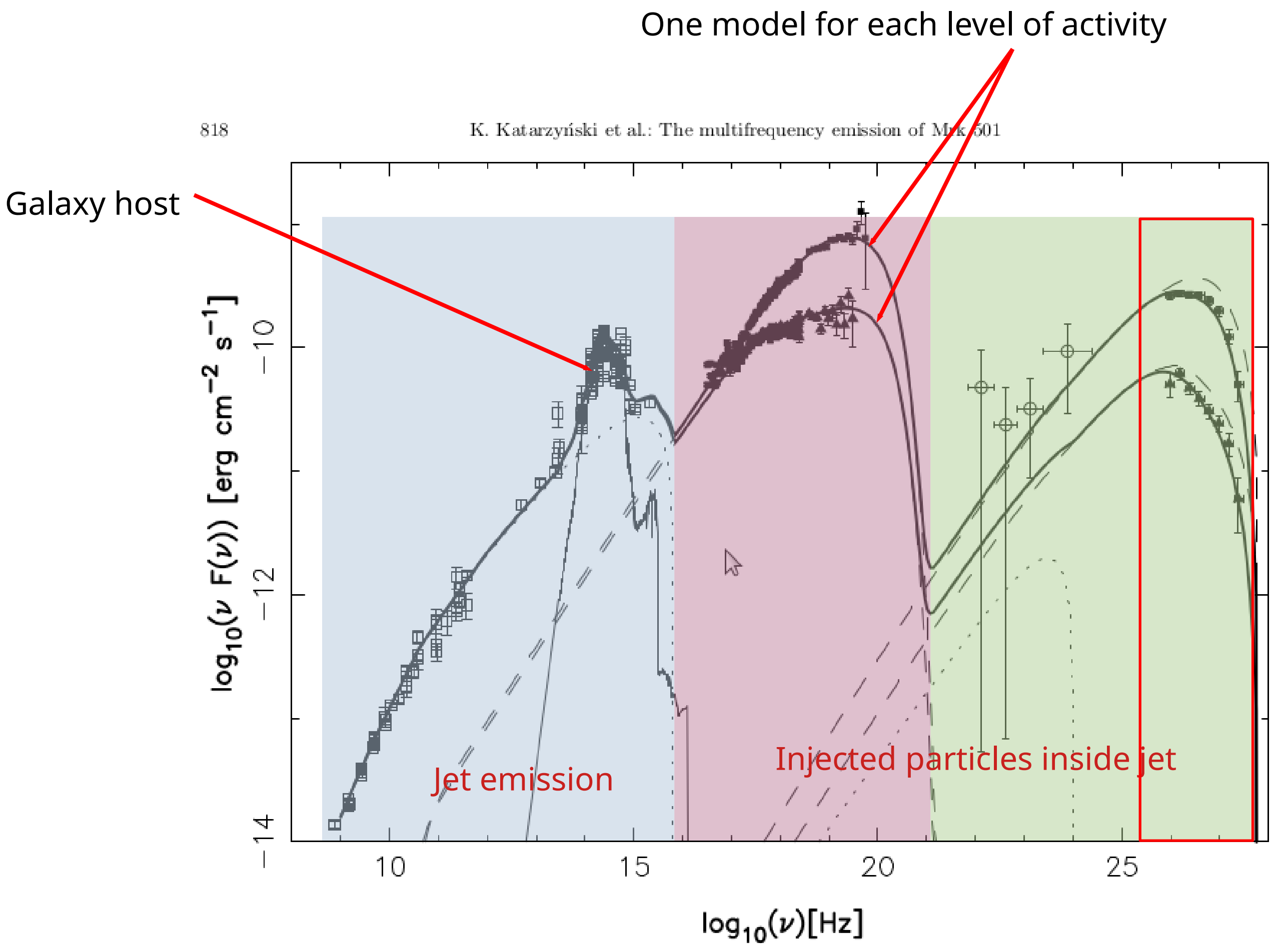
Introduction : Active Galactic Nucleus (AGN)



Credit : NASA, Fermi

- **Blazar = AGN with jet direction close to line of sight**
- **High energy gamma rays (and cosmic rays) factories**
- **Emission is varying on different time scale :**
  - Minutes for AGN flares
  - Years for long term behavior
- **Both scales gives information about :**
  - Acceleration processes
  - Population of accelerated particles
    - Hadrons or leptons ?
  - Accretion regime
  - Black hole surroundings and properties

Introduction : AGN – Spectral emission



Credit : Katarzynski et al. A&A, 2001

- **Left** : Synchrotron emission of injected particles
- **Right** : Inverse Compton (IC) of particles on photons or hadronic emission
- **Red box** : energy band of Cherenkov telescope observations

Introduction : AGN - Physical processes - Focus on VHE component

- **Hadronic processes :**
  - Synchrotron emission of accelerated protons + other processes (muon synchrotron emission, pion decay)

- **Inverse Compton emission : can be scatter of various radiation fields**
  - Synchrotron emission (SSC)
  - External IC :
    - Galaxy host
    - Accretion disk
    - Black hole dust torus
- **Extra Galactic Background (EBL) absorption :**
  - The VHE part of the emission is absorbed by the EBL through gamma-gamma interaction, the EBL is produced by all the galaxies in the Universe

I – AGN variablility study with CTA

- **A tool has been developed, based on Gammapy, to simulate and reconstruct AGN observations with CTA : CtaAgnVar**
- **Goals :**
  - Simulations of gamma-like event from CTA IRFs + spectral time dependent AGN modeling
  - Reconstruction of the source properties
    - Lightcurves, spectra, variability tests, ...
  - Can be used both for simulations and real data !

I – CtaAgnVar workflow

Inputs : models

Phenomenological models :
- → time dependent SED
- → one file per time step
- → dN/dE or nufnu

Semi-analytic models :
- → name of the analytic model (Gammapy one or wrapper)
- → time dependent parameters

Analytic models for static sources:
- → name of the analytic model (Gammapy one or wrapper)
- → parameters

Parameters file (.json):
- → sets general parameters
- → fitting models
- → see next slide !

Simulations :

Realistic observations sequence:
- → compute runs if source is visible
- → dynamic selection of CTA IRFS for each time bin

Injected models computation :
- → set one spectral model by time bin from interpolation in time of injected

Observation setup:
- → from parameters file
- → set pointing, offset, ON/OFF regions, etc
- → initialize dataset collection with Gammapy

→run simulations of gamma like event !

I/O

Fit :

Fitting model :
- → set the fitted model from parameter file
- → compute the fit for each observation
- → computation of likelihood profile
- → fit results are saved

→ run fit !

I/O

Outputs :

Analysis :

Stack simulations :
- → multiple realization of the same LC simulation
- → can sum likelihood and minimize

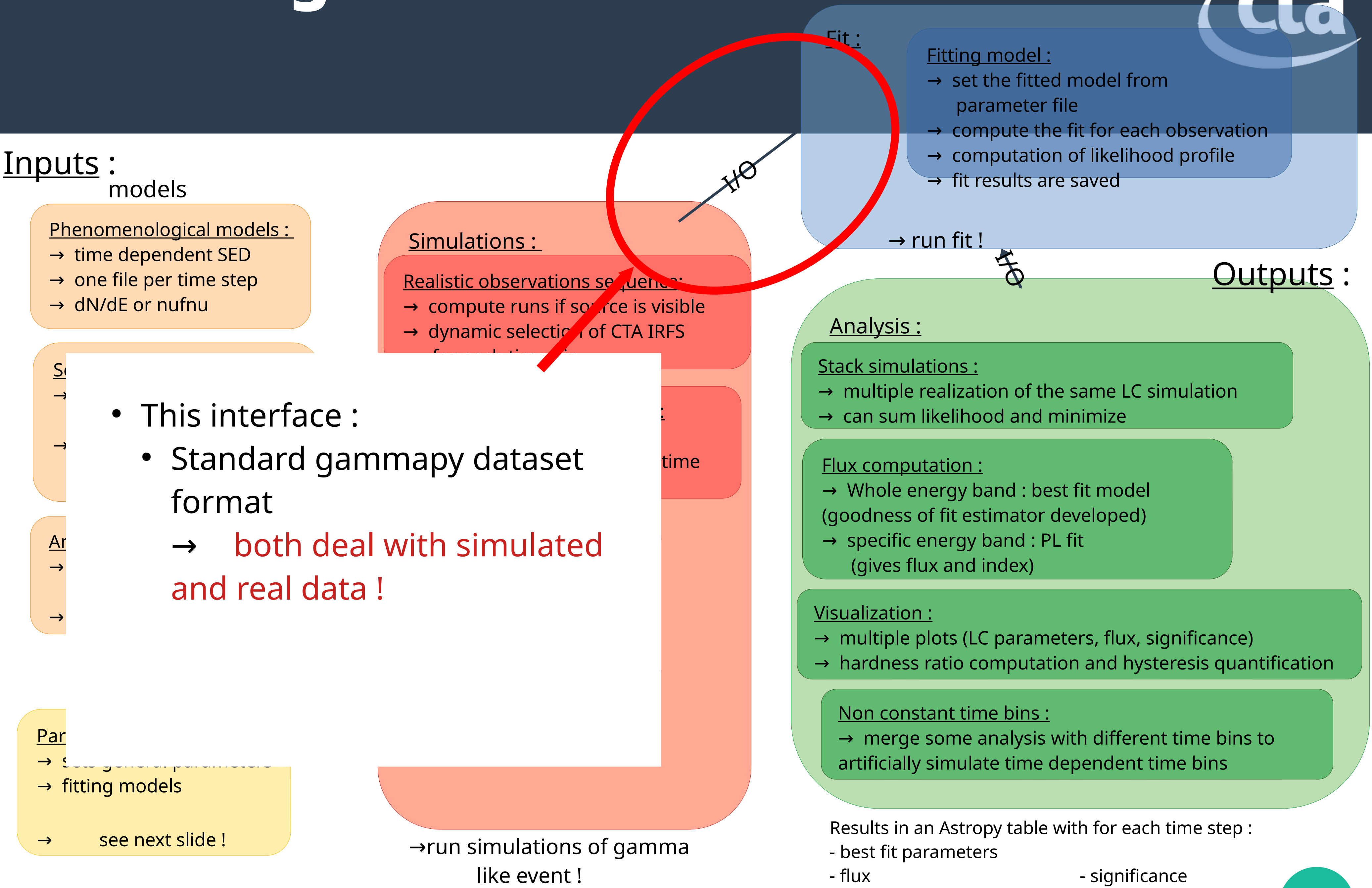
Flux computation :
- → Whole energy band : best fit model (goodness of fit estimator developed)
- → specific energy band : PL fit (gives flux and index)

Visualization :
- → multiple plots (LC parameters, flux, significance)
- → hardness ratio computation and hysteresis quantification

Non constant time bins :
- → merge some analysis with different time bins to artificially simulate time dependent time bins

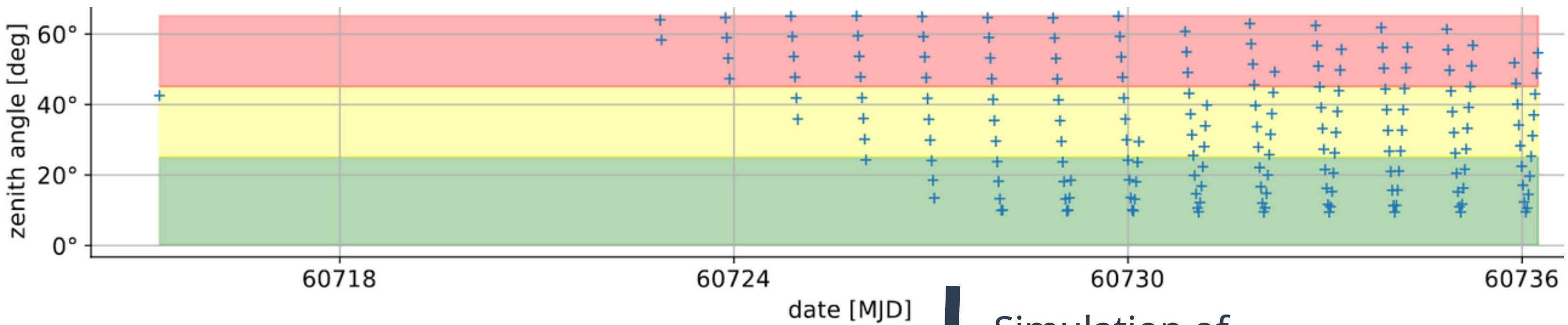
Results in an Astropy table with for each time step :
- best fit parameters
- flux
- significance

I – CtaAgnVar workflow



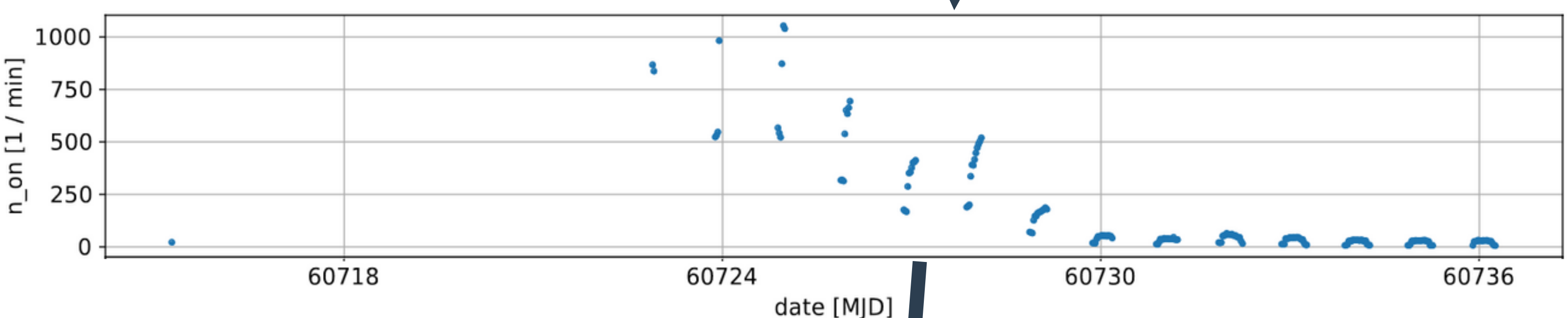
- This interface :
  - Standard gammapy dataset format
    → both deal with simulated and real data !

I – CtaAgnVar workflow



Visibility computation + tracking
→ Dynamical IRF selection

Simulation of gamma like events



- fit a spectral model for each time bins
  → goodness of fit estimator
- reconstruction of the flux lightcurve
  → adaptable time bin → based on significance detection

I – CtaAgnVar : Goodness of fit estimator

- Fit an analytical model on data (PL, PL with exp. cutoff, EBL absorbed, etc…)

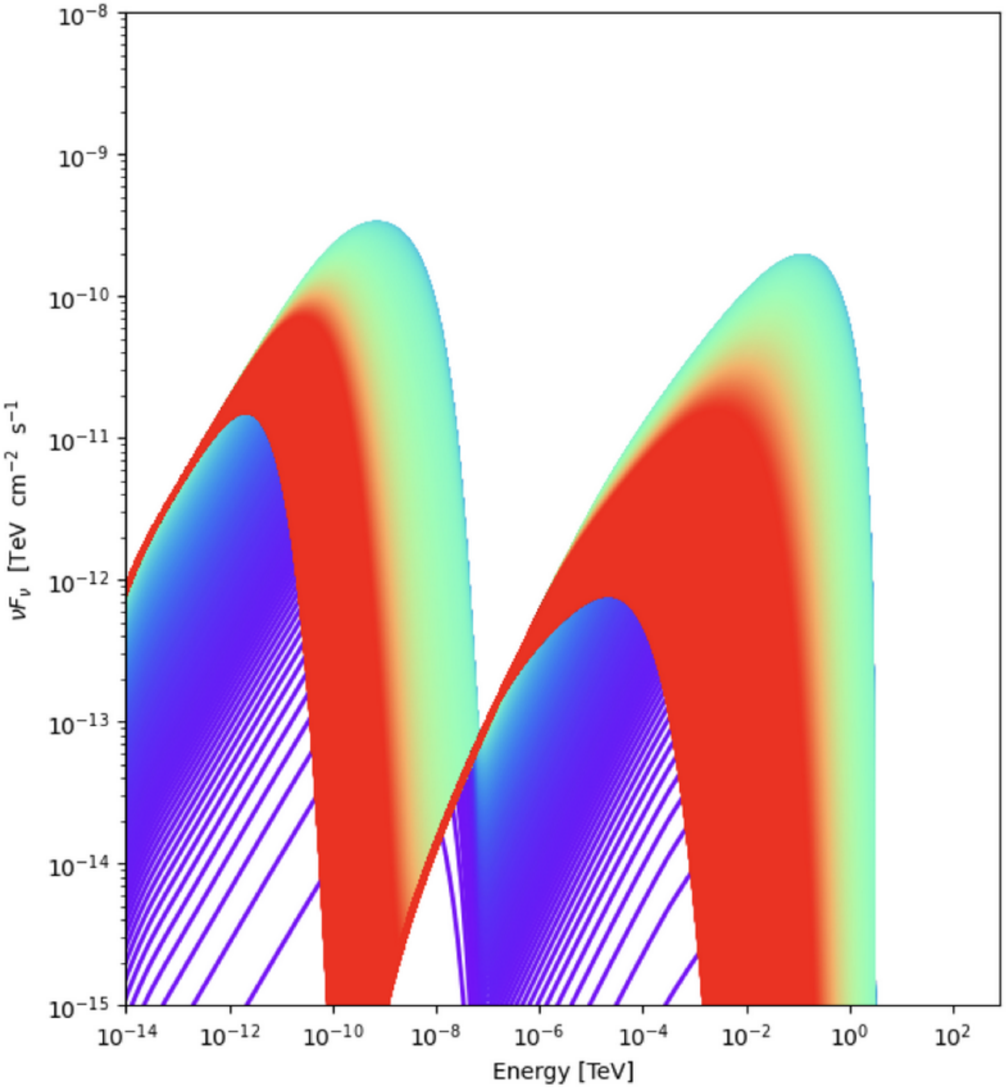
- Use a Test Statistic (TS) to infer the best spectral model for each time bins

- Details about definition in backup slides

II – AGN flares simulations – Mrk 421

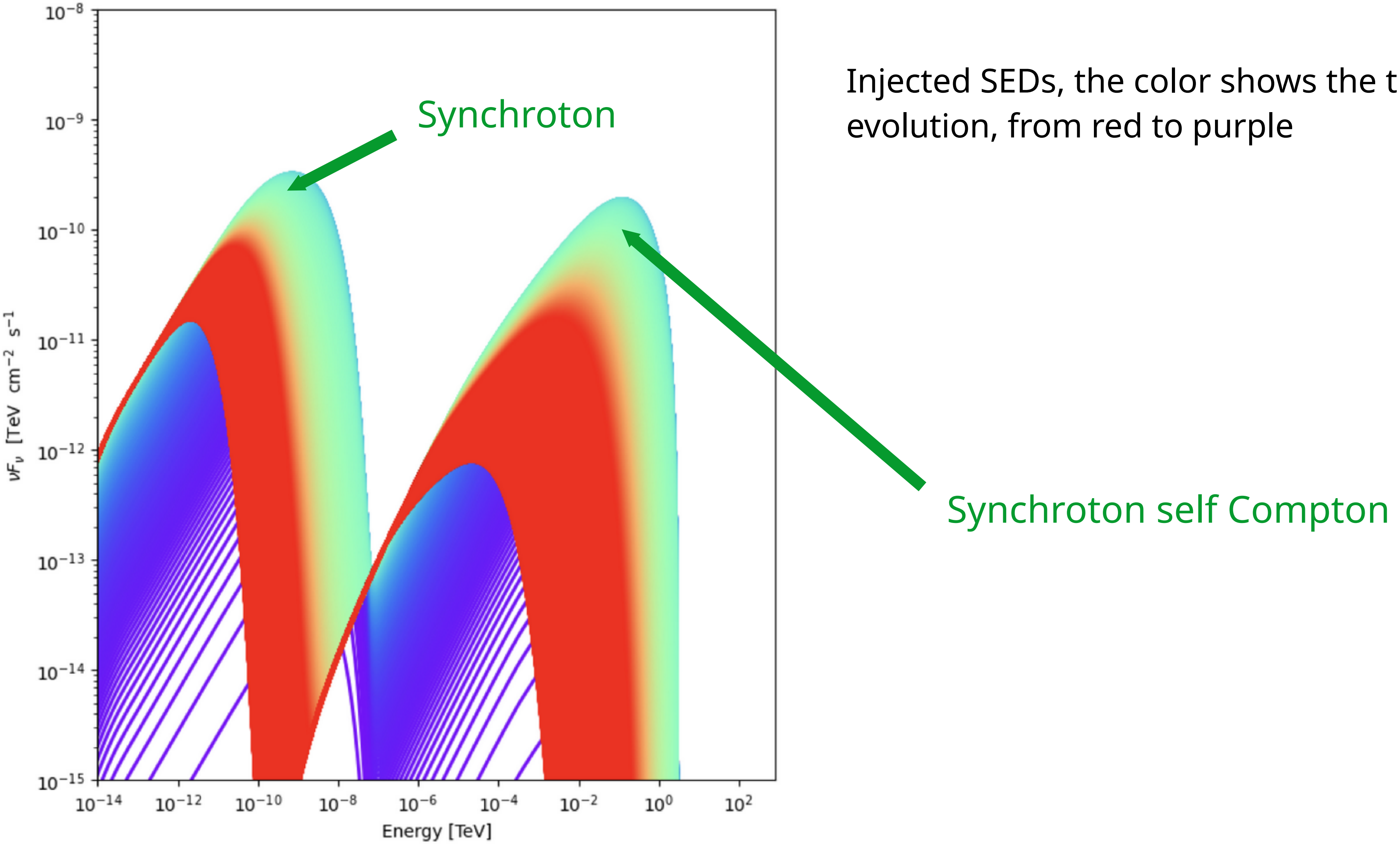
- **To illustrate the possibility :**
  - Mrk 421 simulations based on model from Finke et al. ApJ 2008, built from 2001 flare
  - SSC model
  - 20h flare → one night
- **Workflow :**
  - Perform the simulation of the flare observed
  - Fit a power law EBL absorbed model (+curvature or cutoff if statistically preferred)
  - Reconstruct spectrum + lightcurve in some energy bands
    - → hardness ratio computation
- **Question to answer : To what extent is it possible to reconstruct flare properties with CTA and are they in agreement with the injected properties ?**

II – Mrk 421 flare simulations - Injection



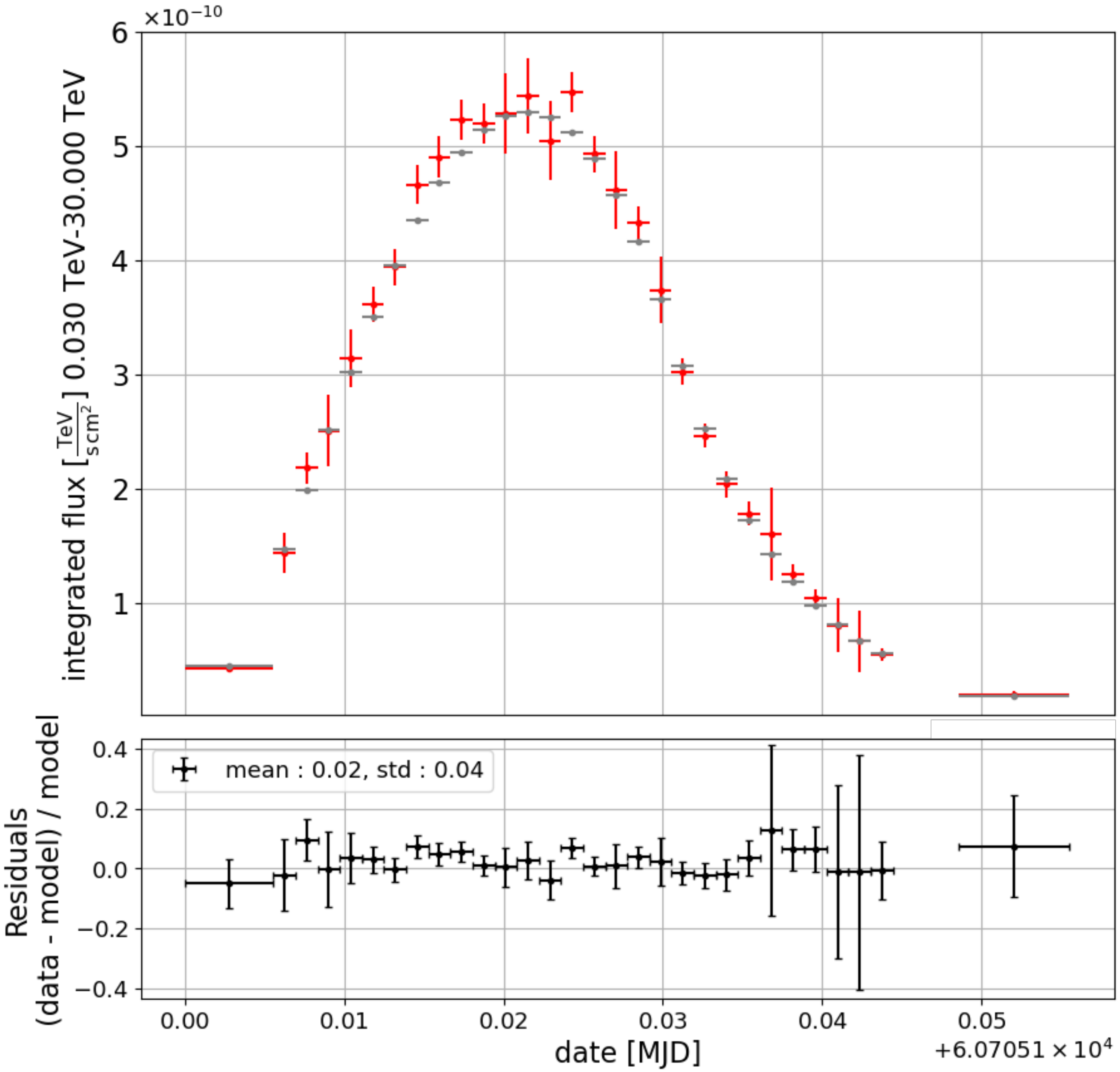
Injected SEDs, the color shows the time evolution, from red to purple

II – Mrk 421 flare simulations - Injection



Injected SEDs, the color shows the time evolution, from red to purple

II – Mrk 421 flare simulations - Light curve reconstruction



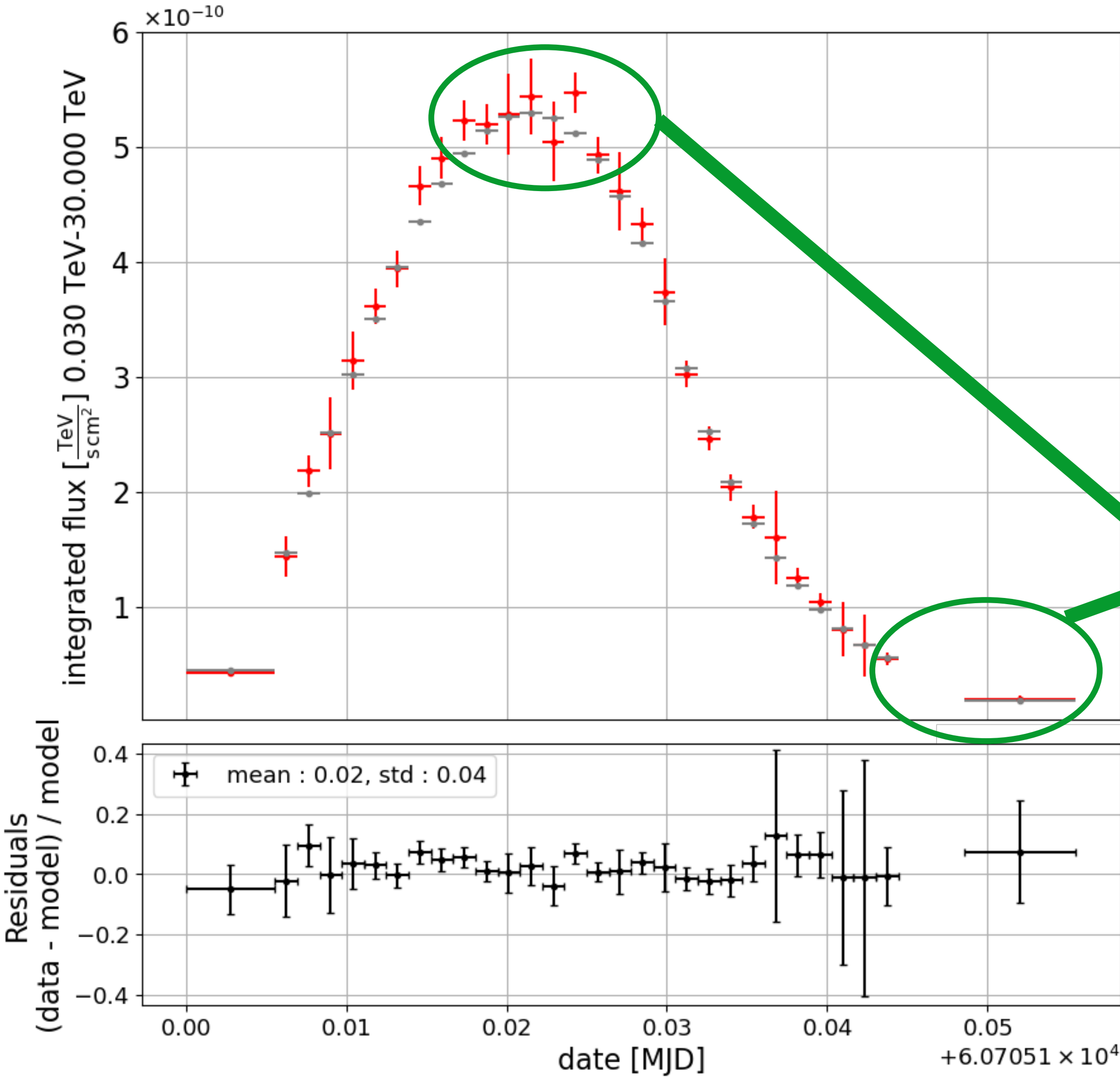
Reconstructed flux between 30 GeV - 30 TeV

- **Flux is reconstructed with a PL fit EBL absorbed, we can make this model more complex by adding cutoff and curvature**

Grey points : injection

Red points : reconstructed flux

II – Mrk 421 flare simulations - Light curve reconstruction

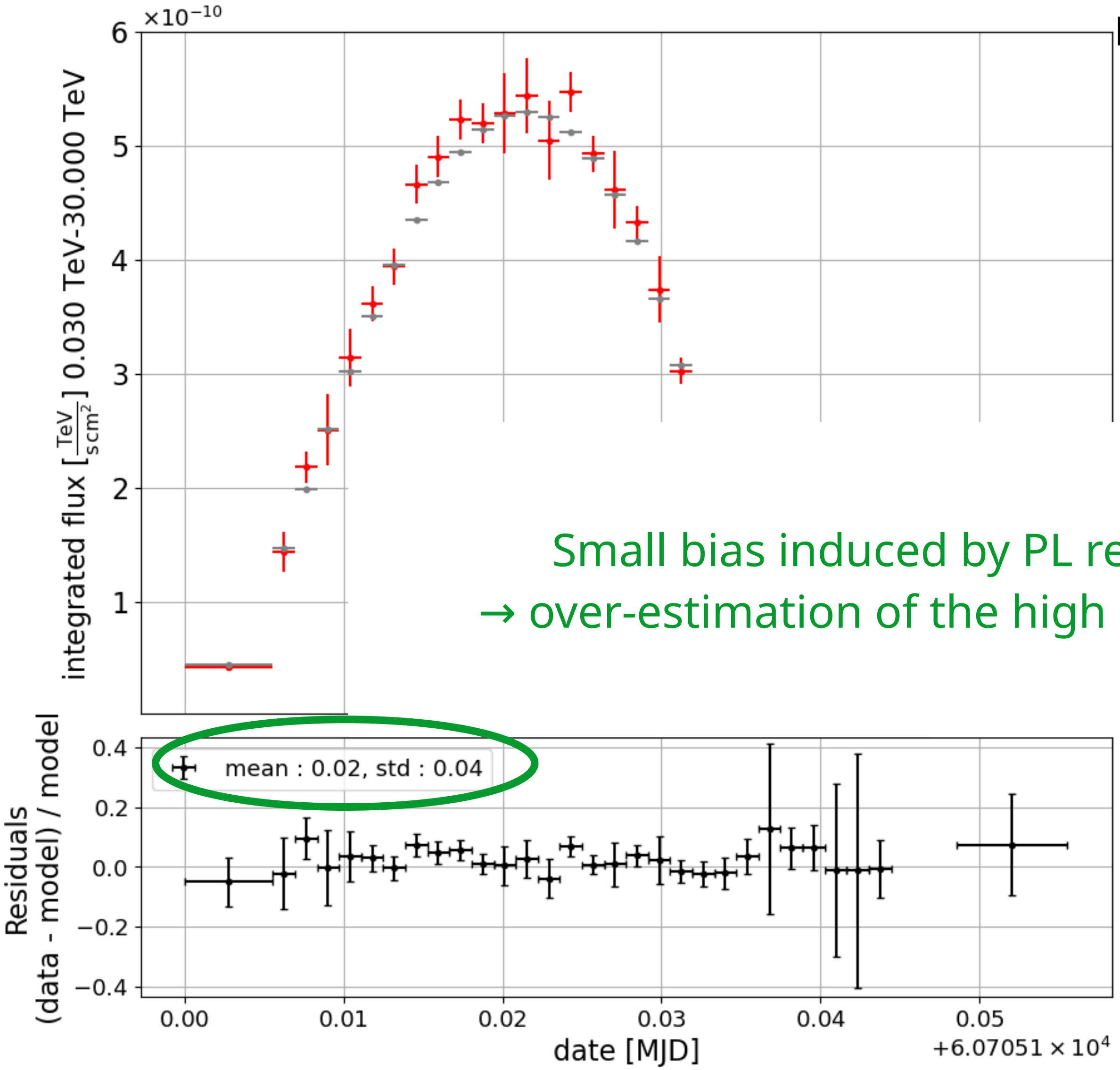


Reconstructed flux between 30 GeV - 30 TeV

- **Flux is reconstructed with a PL fit EBL absorbed, which can be complicated by adding cutoff and curvature**
- **Non constant time bins :**
  - Time bins larger at the LC tails where the signal is lower
  - Bins size : from 2 to 20 min

II – Mrk 421 flare simulations - Light curve reconstruction

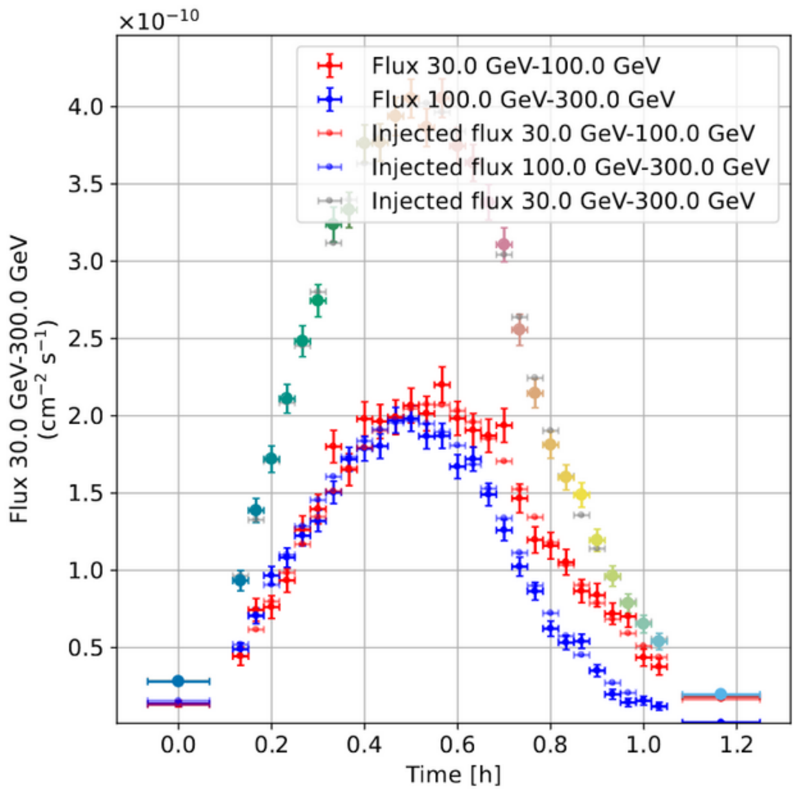
Reconstructed flux between 30 GeV - 30 TeV

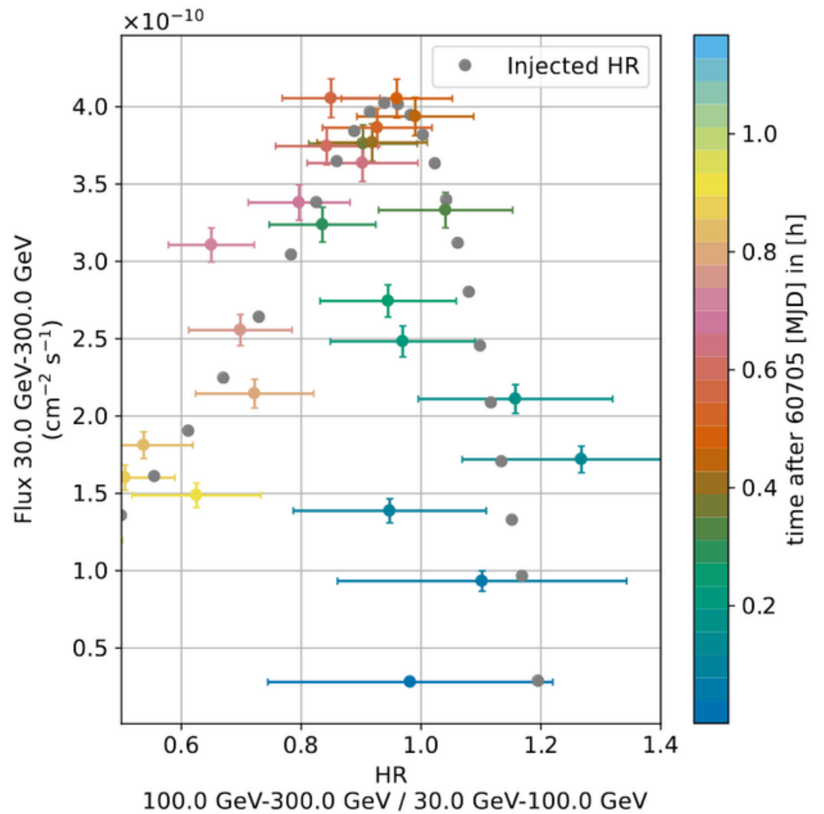


Small bias induced by PL reconstruction
→ over-estimation of the high energy spectrum

- **Flux is reconstructed with a PL fit EBL absorbed, which can be complicated by adding cutoff and**
- **time bins :**
  - arger at the LC tails where the signal is lower
  - Bins size : from 2 to 20 min

II – Mrk 421 flare simulations – Hardness ratio





- Flux is reconstructed with a PL fit
- Hysteresis is predicted in injected model
- Can see the hysteresis
- HR detection with principal component analysis

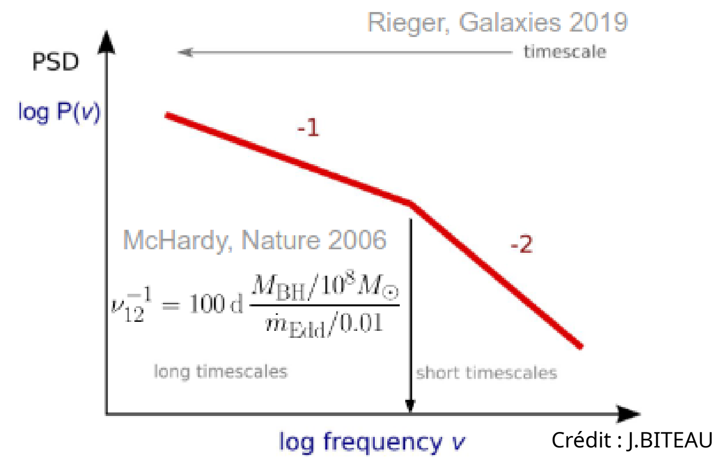
Left : flux LC in 3 bands (lowest, highest, sum is colored)
Right : HR diagram (injected).
The color evolution is linked to time evolution.

Cerruti et al., ICRC 2023

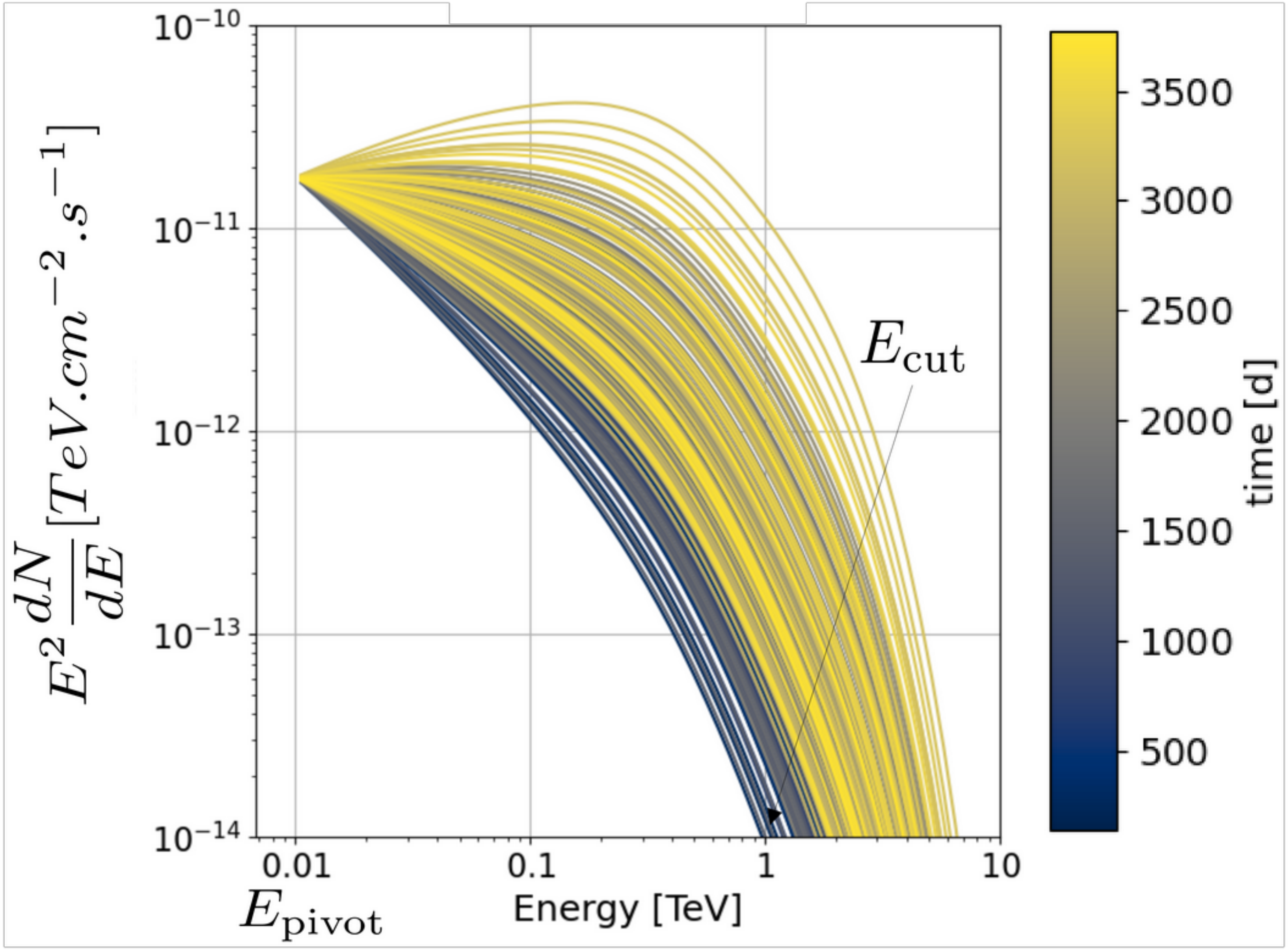
III – AGN long-term monitoring program - BL Lac

- **BL Lac is one of the promising AGN in CTA KSP**
  - One of the 16 AGN in the long term monitoring program in CTA AGN KSP
- **How to model long term behavior ?**
  - Power Spectrum Density (PSD) follows red noise + pink noise after break
  - Flux distribution is log normal

    → Generation of flux time series (from Emmanoulopoulos et al. 2013)
  - Spectral index follows a harder when brighter behavior (based on PKS 2155-304 observations)
  - Spectral model thus generated : $\phi_z(E,t) = \phi_0(t)\left(\frac{E}{E_0}\right)^{-\Gamma(t)-\beta\ln\frac{E}{E_0}} e^{-\frac{E}{E_{\mathrm{cut}}}} e^{-\tau_{\gamma\gamma}(E,z)}$
- **Reconstruction of the break position gives information about central black hole accretion regime**



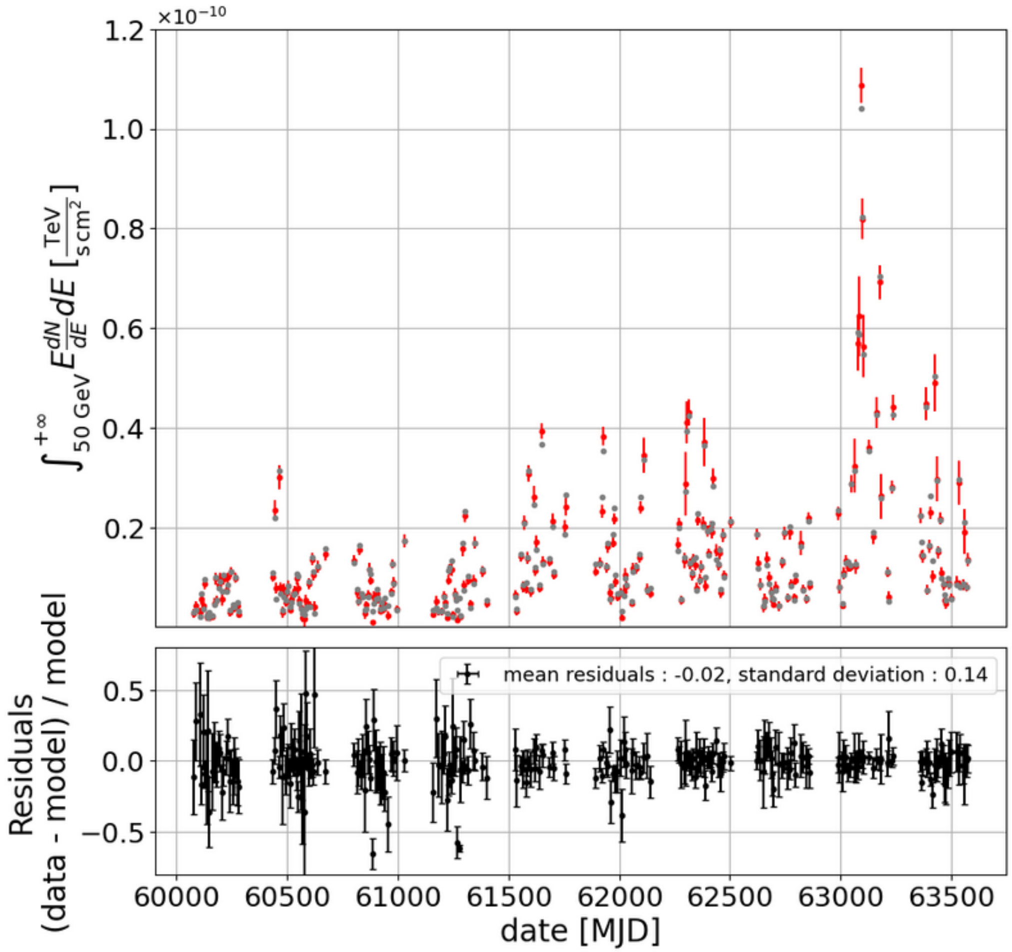
III – AGN long-term monitoring program - BL Lac injected model



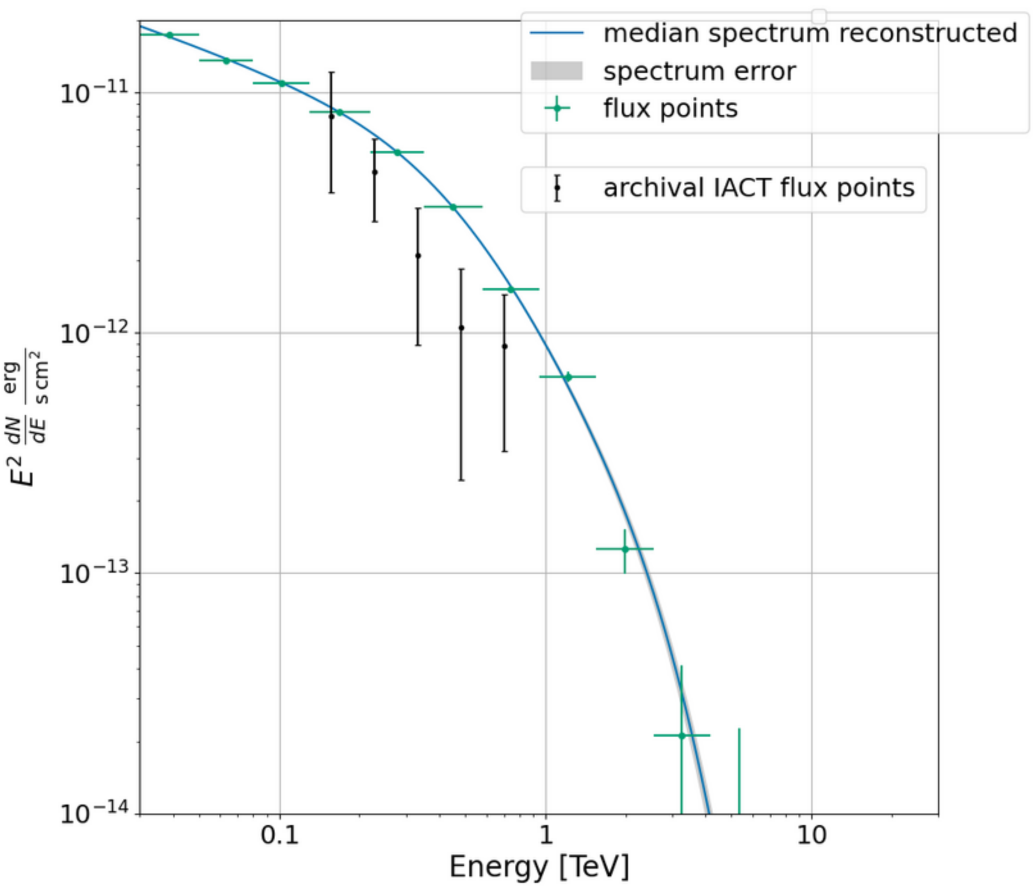
Injected SEDs, color evolution shows time evolution

- **Generation of a 10 years lightcurve**
- **WITHOUT break in PSD**

III – AGN long-term monitoring program - BL Lac lightcurve reconstructon

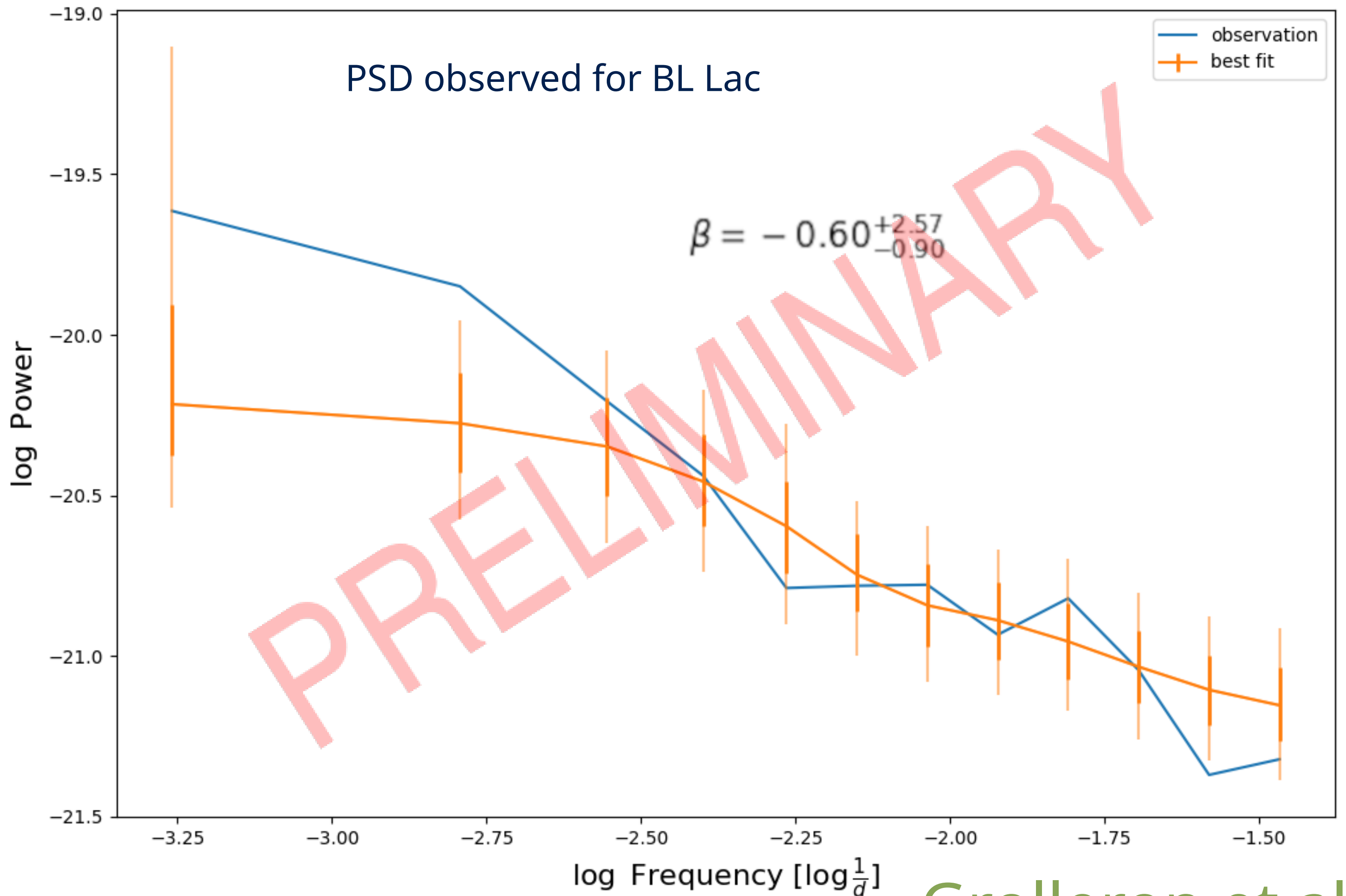


Flux lightcurve over 50 GeV reconstructed for 10 years of data observed with a weekly cadence, grey points are injected values.



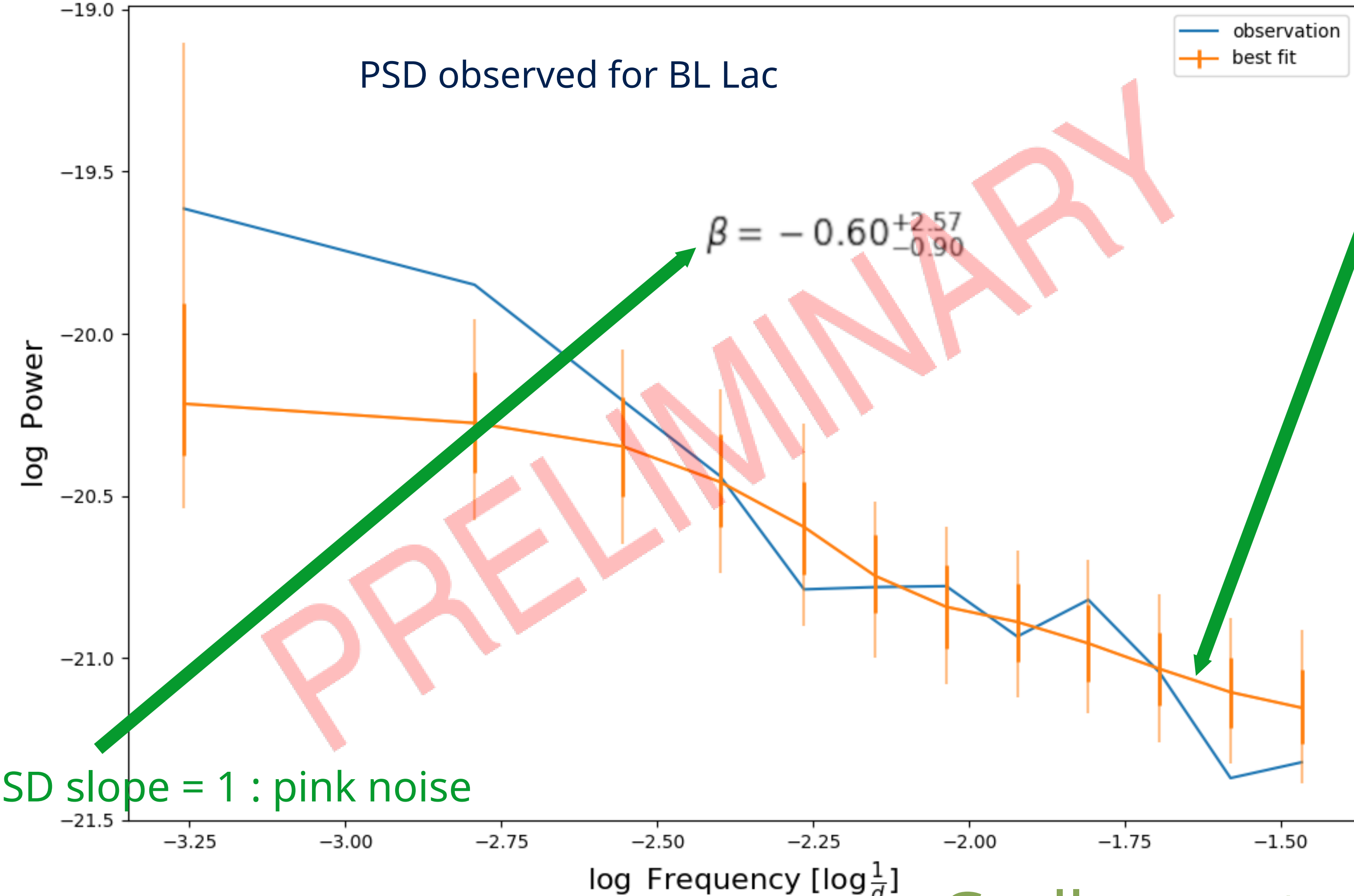
Reconstructed median spectrum for BL Lac for the 10 years of data

III – AGN long-term monitoring program - BL Lac PSD reconstruction



Grolleron et al., ICRC 2023

III – AGN long-term monitoring program - BL Lac PSD reconstruction

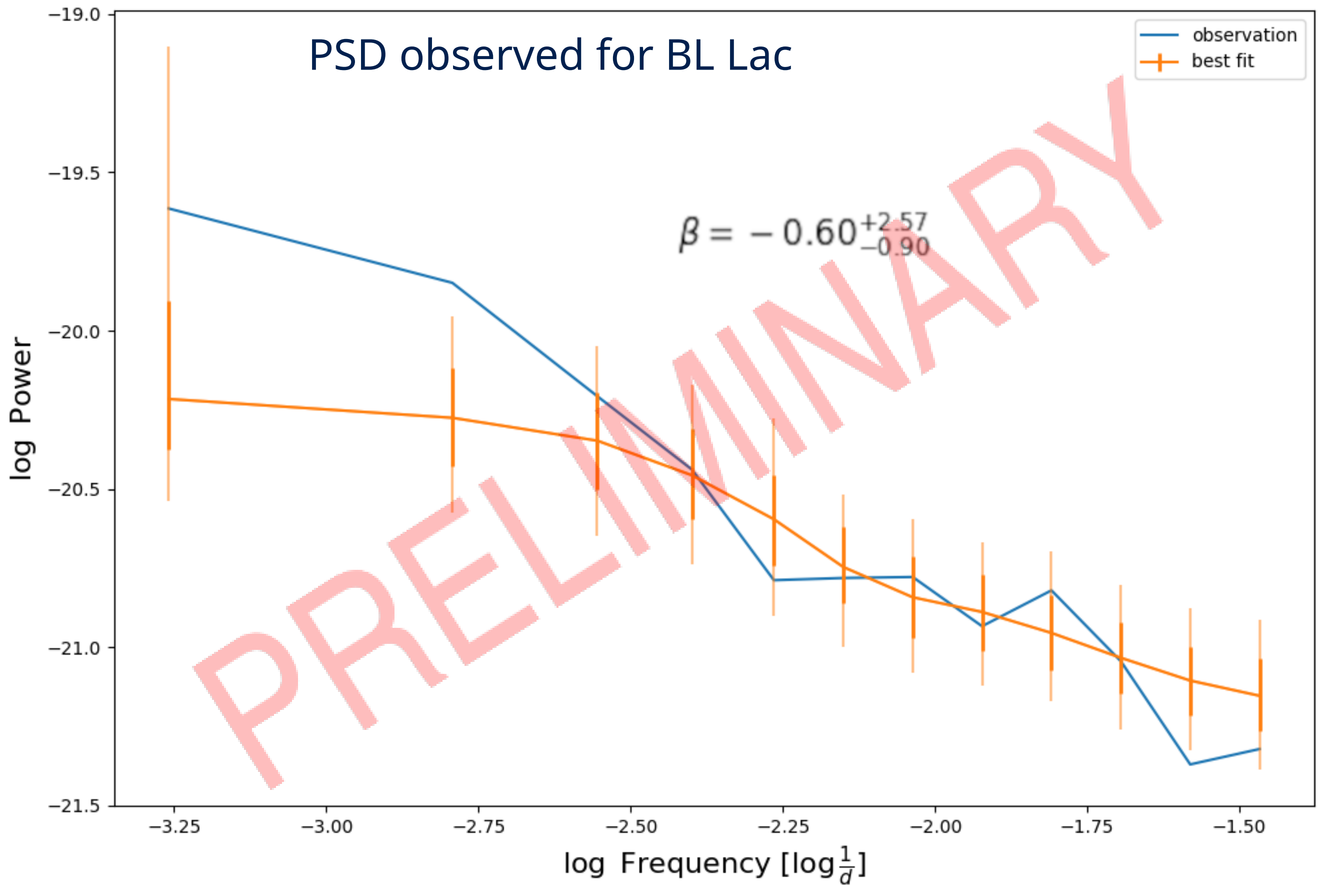


Poisson plateau

PSD slope = 1 : pink noise

Grolleron et al., ICRC 2023

III – AGN long-term monitoring program - BL Lac PSD reconstruction



We can reconstruct injected PSD but :

- Study the effect of the cadence on the PSD reconstruction to find good observing strategies.

Details about PSD fit :

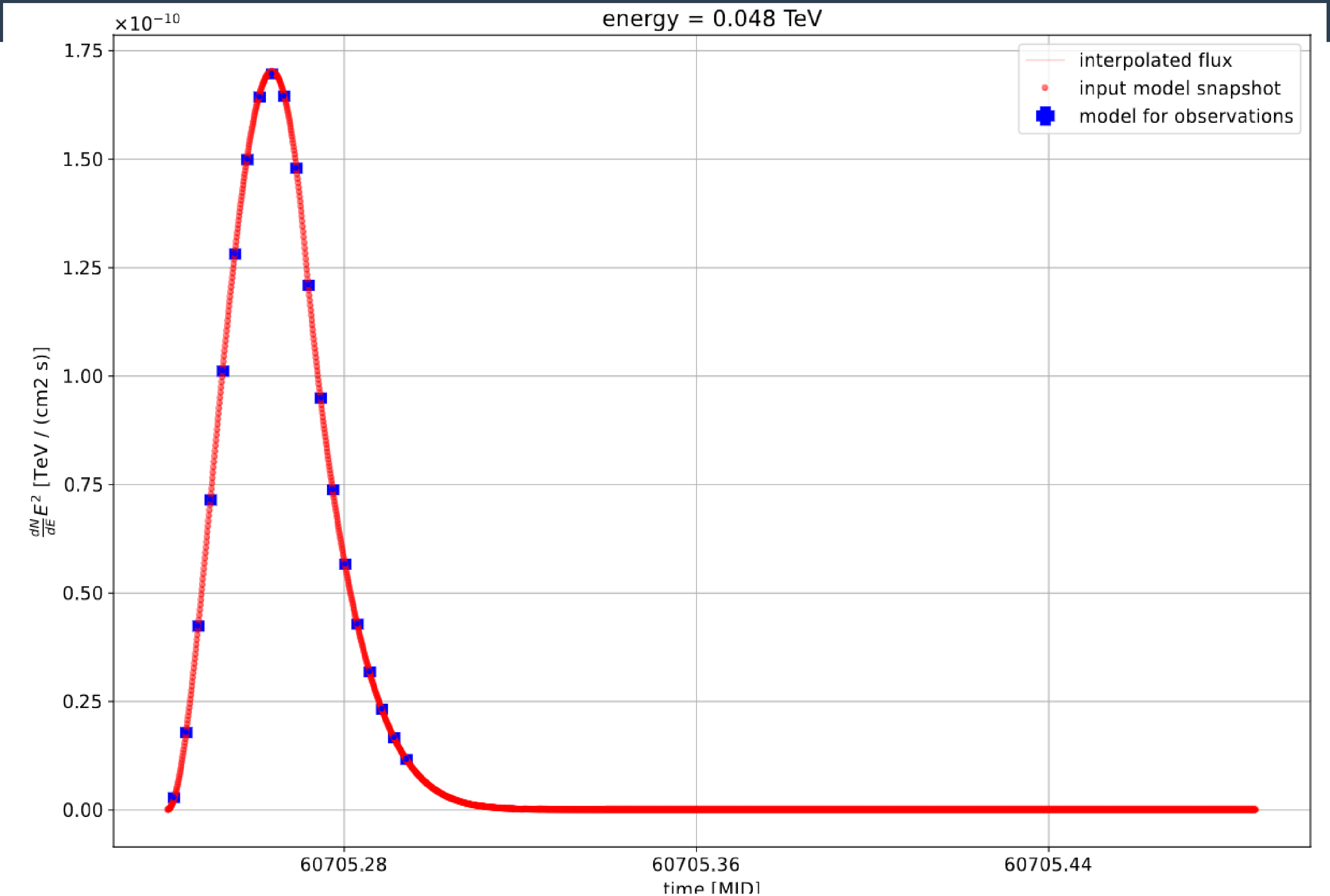
→ See poster presented by W. Max-Moerbeck

Grolleron et al., ICRC 2023

Conclusion and perspectives

- **With CTA :**
  - Will be able to give a new look on AGN emission
    - High accuracy for lightcurve reconstruction
  - Discrimination between models for AGN flares
    - Detection of spectral variability (with HR hysteresis)
  - Possibility to reconstruct with a high level of accuracy the long term PSD and the duty cycle of jetted AGN
- **CtaAgnVar :**
  - Pipeline for simulating and analyzing CTA observations
    - Massively used for AGN prospective within CTA EGAL working group
  - Upcoming :
    - Simulations of Fermi-LAT based AGN modeling and periodicity detection
    - Analysis of LST and H.E.S.S. long term monitoring data has started

Backup : differential flux for Mrk 421 flare



BACKUP – CtaAgnVar : Goodness of fit estimator

- **Fit an analytical model on data (PL, PL with exp. cutoff, EBL absorbed, etc...)**
- **TS : statistical test**

  → Likelihood to have data under expectation of best fit corrected by likelihood to have data under expectation of data

$$-2\log\frac{L(n_{\rm on},n_{\rm off},\alpha;\mu_{\rm sig},\mu_{\rm bkg})}{L(n_{\rm on},n_{\rm off};n_{\rm on},n_{\rm off})}$$

- **TS follows a Chi² with ndof (have been checked)**

  ndof : (number of energy bins (with excess > 10) – number of free parameters) * number of realizations
- **With this GOF estimator, we can assert validity of spectral reconstruction for each time bins**

BACKUP : Signifiance