CTAO
Cherenkov Telescope Array Observatory

Active Galactic Nuclei variability studies with the Cherenkov Telescope Array Observatory

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For the CTAO Consortium

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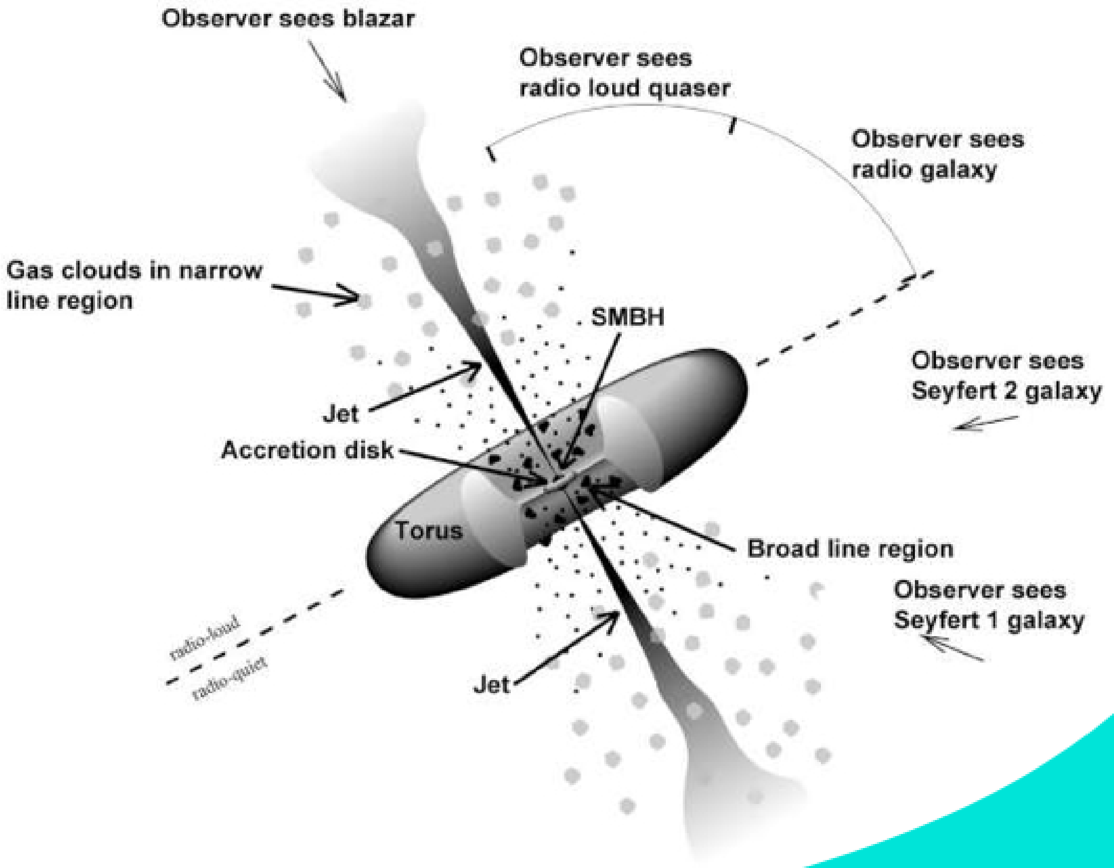
Introduction : Active Galactic Nucleus (AGN)

Introduction : AGN

AGN model

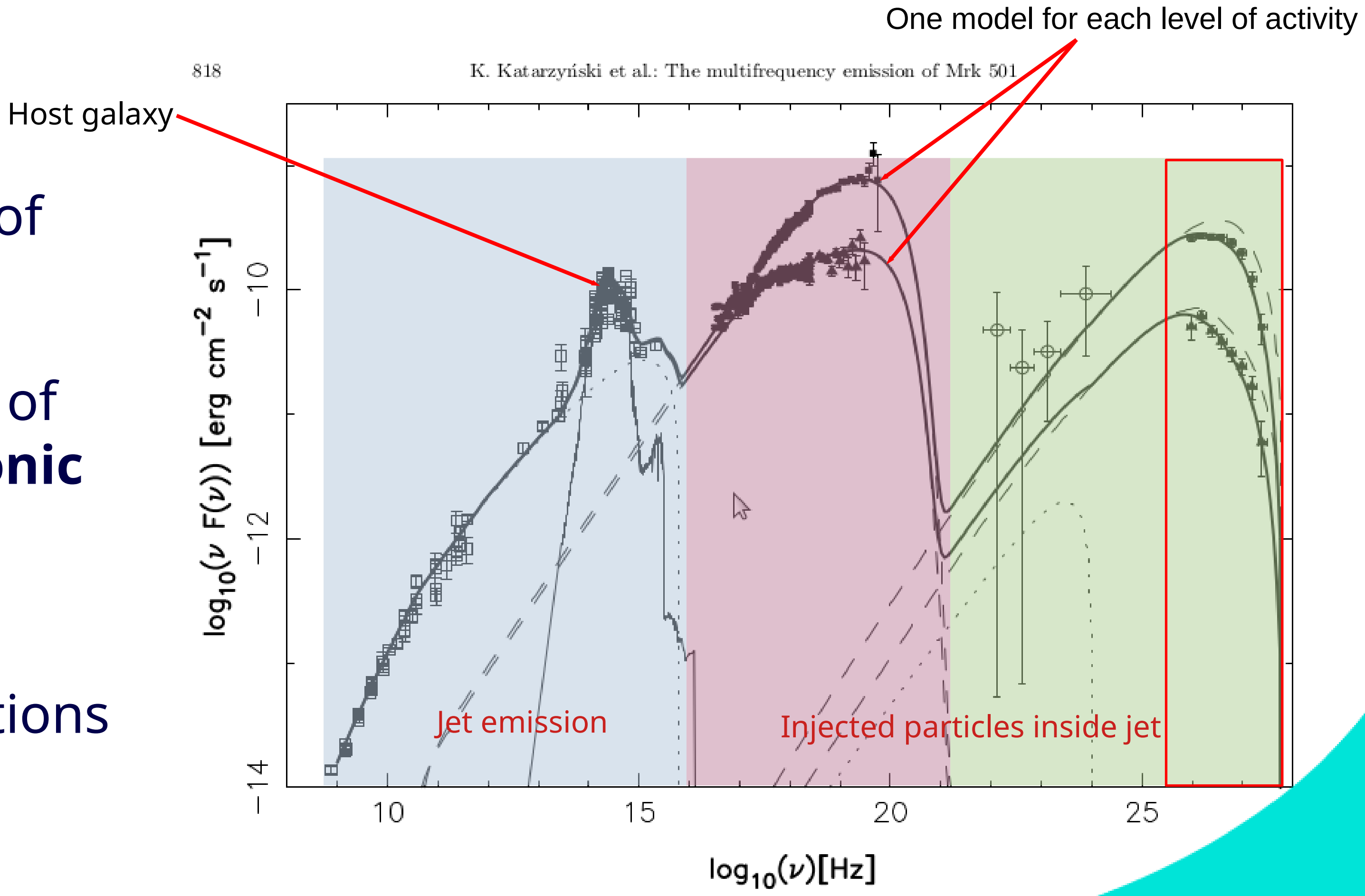
- Blazar = AGN with jet direction close to line of sight
- High-energy gamma ray (and possibly cosmic ray) factories
- Emission is varying on different time scale :
  - Minutes for **AGN flares**
  - Years for **long-term behavior**
- Both scales gives information about :
  - **Acceleration** processes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



Introduction : AGN

Spectral emission

- **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 the very-high-energy (VHE) component

Hadronic processes

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

Inverse Compton (IC) emission : scatters on various radiation fields may contribute

- 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 variability study with CTAO

I – AGN variability study with CTAO

The **CtaAgnVar** pipeline

A tool has been developed, **based on Gammapy**, to **simulate** and **analyse** AGN observations with CTA : CtaAgnVar

Goals :

- Simulations of gamma-like events using CTA IRFs + **time dependent AGN spectral modeling**
- Reconstruction of the source properties : Lightcurves, spectra, variability tests, …
- Can be used both for **simulations** and **real data** !

I – AGN variability study with CTAO

The CtaAgnVar workflow

models

<u>Phenomenological models :</u>
→ **time-dependent SED**
→ one file per time step
→ dN/dE or νf_ν

<u>Semi-analytic models :</u>
→ name of the analytic model (Gammapy one or wrapper)
→**time-dependent parameters**

<u>Analytic models for static sources :</u>
→ name of the analytic model (Gammapy one or wrapper)
→ parameters

<u>Parameters file (.json):</u>
→ sets general parameters
→ fitting models

Simulations :

<u>Realistic observations sequence:</u>
→ compute **source visibility**
→ **dynamic selection of CTA IRFS** for each time bin

<u>Injected models computation :</u>
→ set **one spectral model ber time bin** from interpolation in time of injection

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

→ run simulations of gamma-like events !

I/O

Fit :

<u>Fitting model :</u>
→ 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

Analysis :

<u>Stack simulations :</u>
→ multiple realizations of the same lightcurve simulation
→ can sum likelihood and minimize

<u>**Flux computation**</u> :
→ **Whole energy band** : best fit model (goodness of fit estimator developed)
→ **specific energy band** : power law fit (gives flux and index)

<u>Visualization :</u>
→ multiple plots (LC parameters, flux, significance)
→ **hardness ratio** computation and **hysteresis quantification**

<u>**Non-constant time bins**</u> :
→ 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 – AGN variability study with CTAO

CTAO

The CtaAgnVar workflow

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Parameters file (.json):
→ sets general parameters
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Simulations :

Realistic observations sequence:
→ compute **source visibility**
→ **dynamic selection of CTA IRFS**

→ run simulations of gamma-like events !

- This interface :
  - Standard **gammapy** dataset **format**

→ both deal with **simulated** and **real data** !

I/O

Fit :

Fitting model :
→ set the fitted model from parameter file
→ **compute the fit for each observation**
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→ fit results are saved

→ run fit !

I/O

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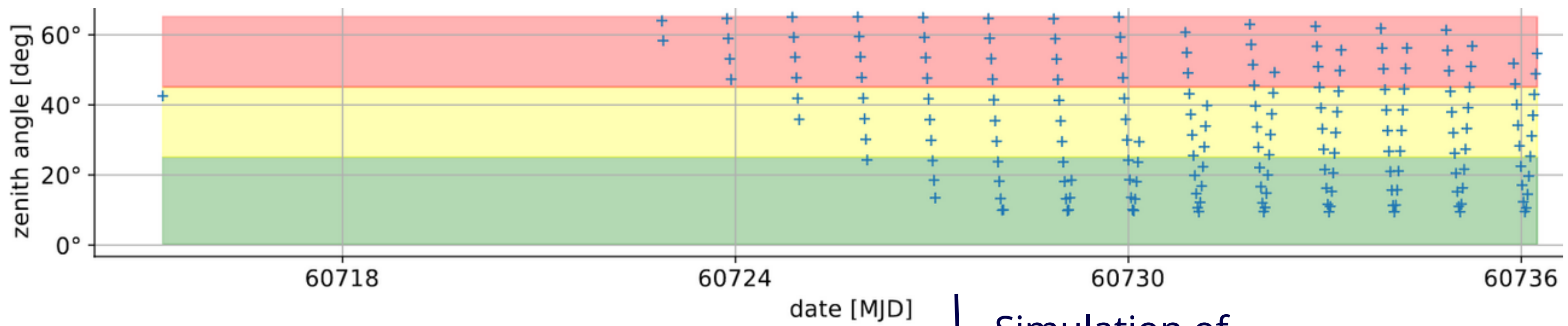
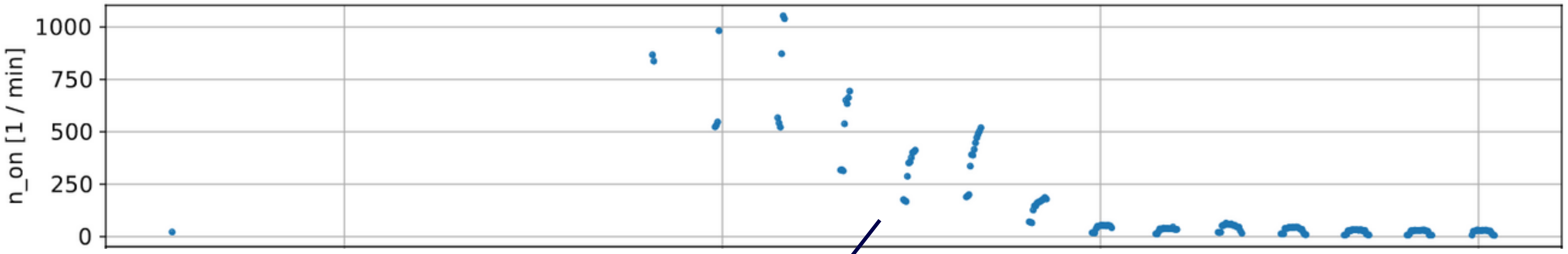
I – AGN variability study with CTAO

The CtaAgnVar workflow



Visibility computation + **tracking**
→ **Dynamical IRF selection**

Simulation of **gamma-like events**



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

I – AGN variability study with CTAO

CtaAgnVar : Goodness of fit estimator

- **Fit an analytical model** on data (power law (PL), PL with exp. cutoff, EBL absorbed, etc...)
- From the **simplest** to the **most complex**
- 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

Question to answer : To what extent is it possible to **reconstruct flare properties with CTAO** and are they in agreement with the injected properties ?

II – AGN flares simulations – Mrk 421

Description of the Mrk 421 flare model

- Mrk 421 simulations based on model from **Finke et al. ApJ 2008**, built from 2001 flare
- **SSC** model
- 20h flare → **a single 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

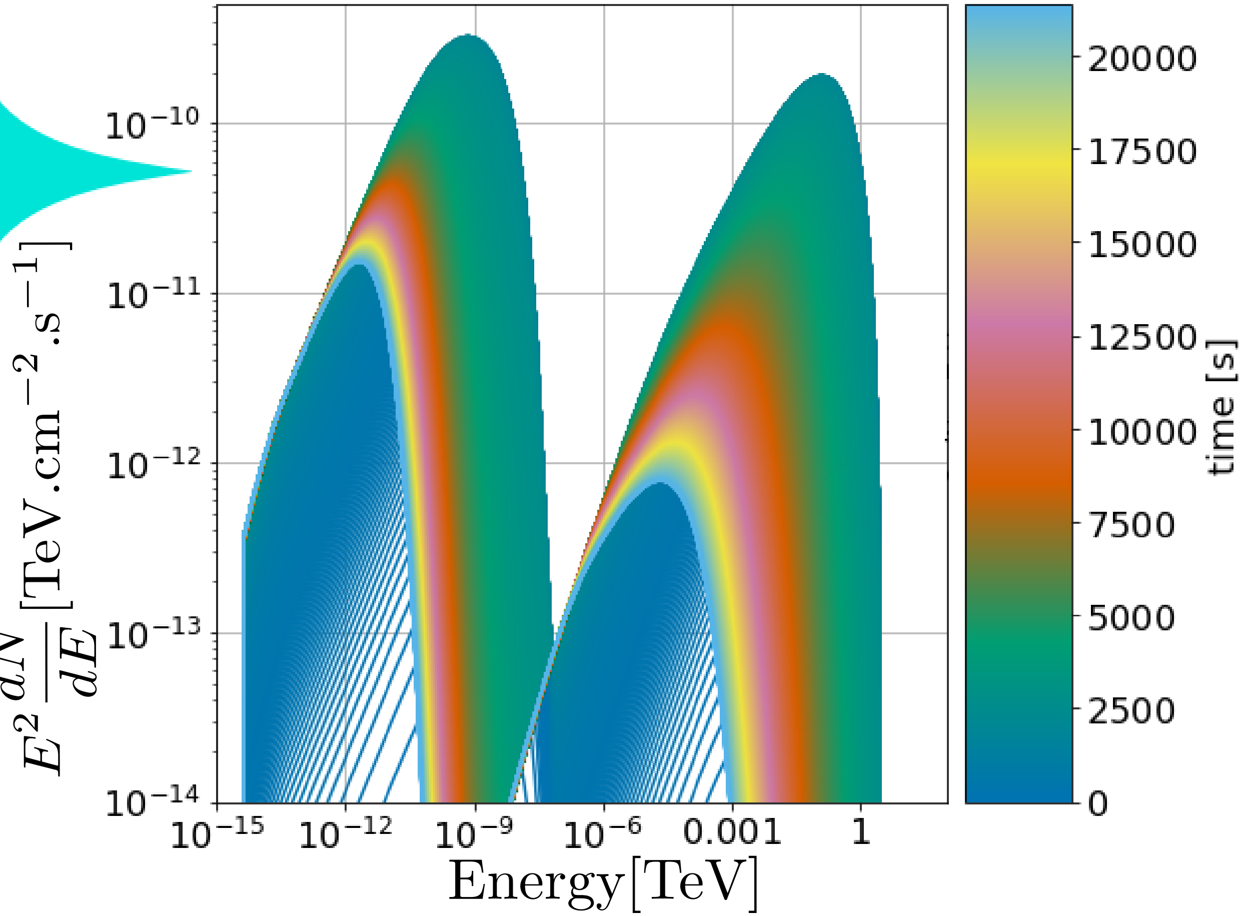
  → **hardness ratio** computation

II – AGN flares simulations – Mrk 421

Injection

Injected SEDs

The color shows the time evolution



II – AGN flares simulations – Mrk 421

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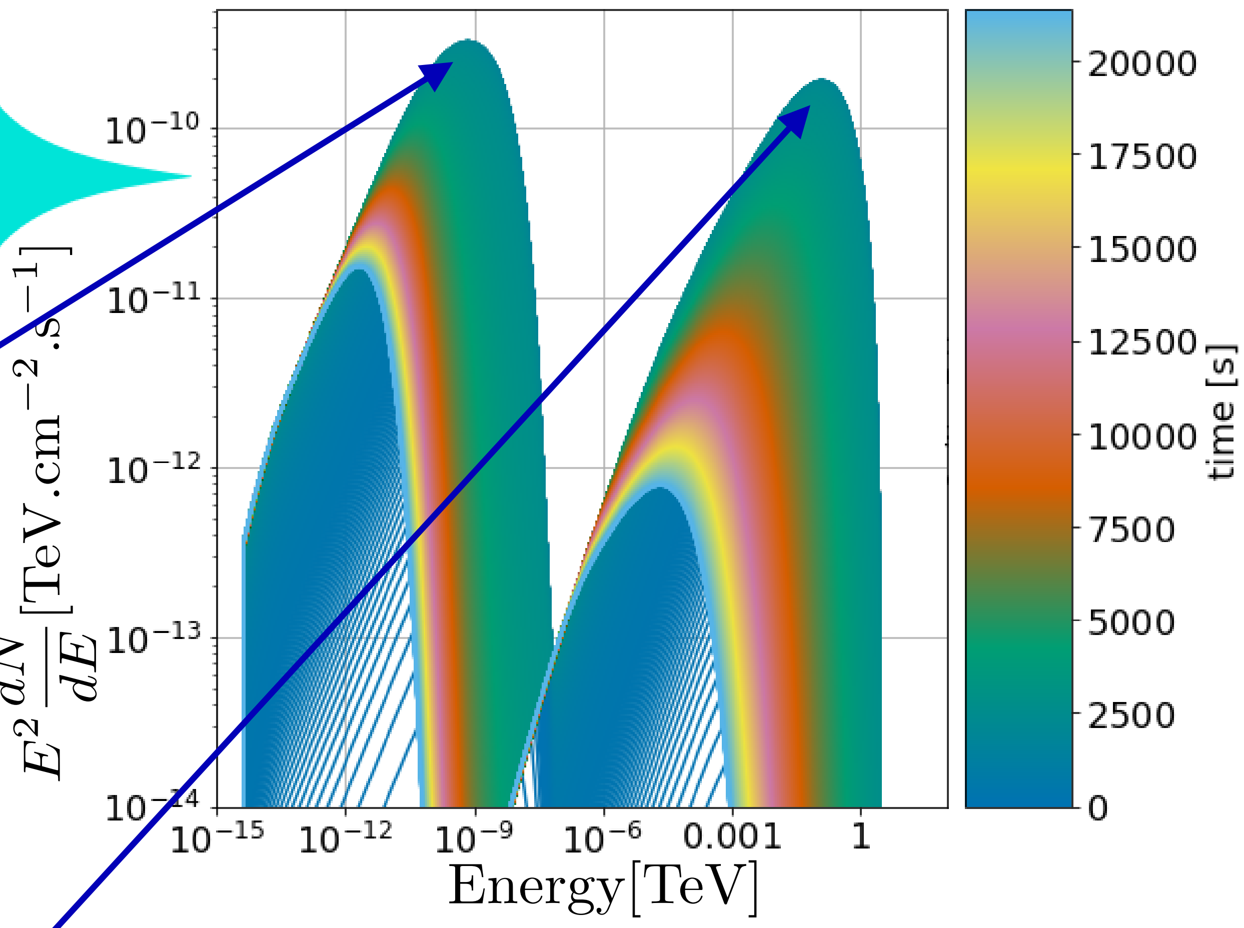
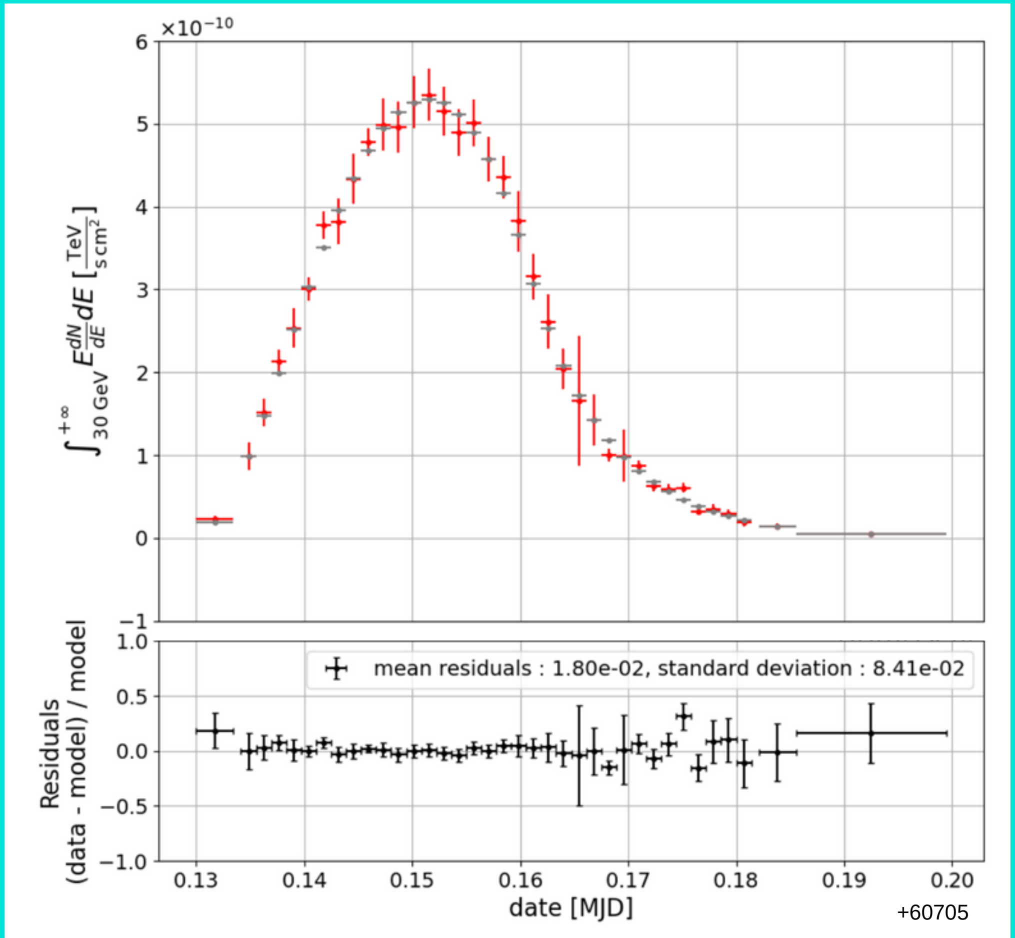


II – AGN flares simulations – Mrk 421



Reconstructed flux between 30 GeV - 30 TeV

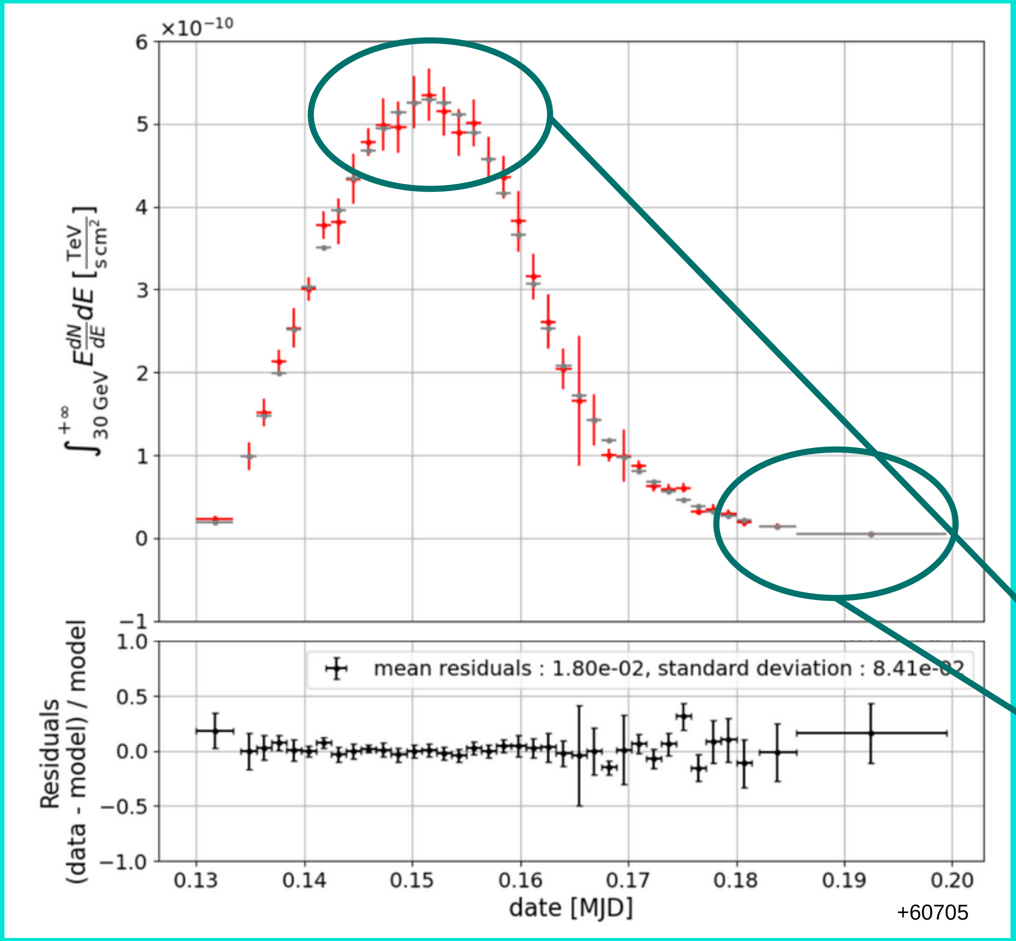
Reconstructed lightcurve

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 – AGN flares simulations – Mrk 421



Reconstructed flux between 30 GeV - 30 TeV

Reconstructed lightcurve

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

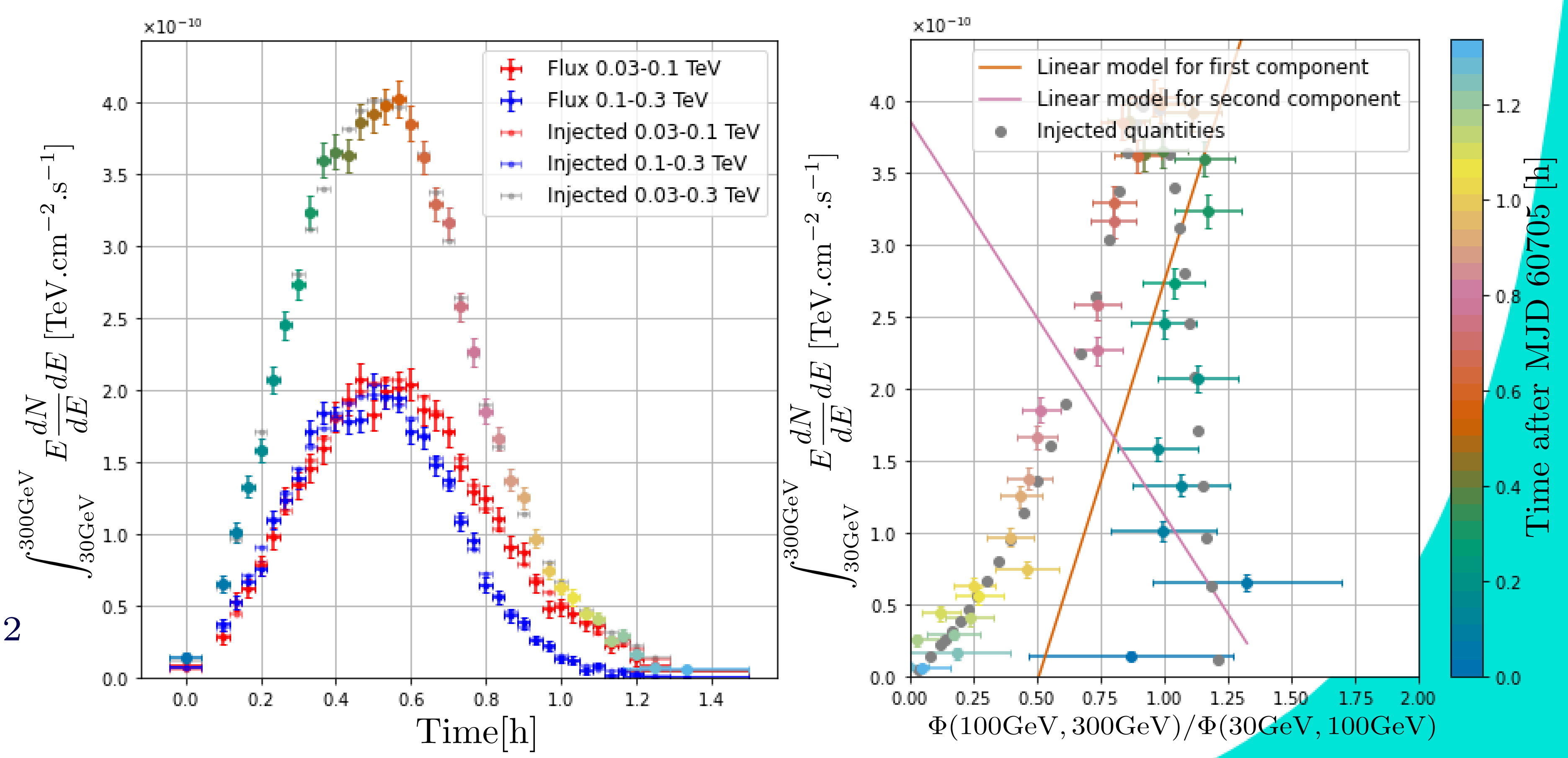
Non-constant time bins :

- Time bins larger at the LC tails where the signal is lower
- Bin sizes : from 2 to 20 min

II - AGN flare simulations – Mrk 421

Hardness ratio

- Flux is reconstructed with a **PL fit**
- Hysteresis is predicted in injected model
- Detection based on **principal component analysis (PCA)** (Cf. Backup)
  - $p_{\text{value}} = 6.2 \times 10^{-2}$
  - 1.5σ significance



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

II - AGN flare simulations – Mrk 421

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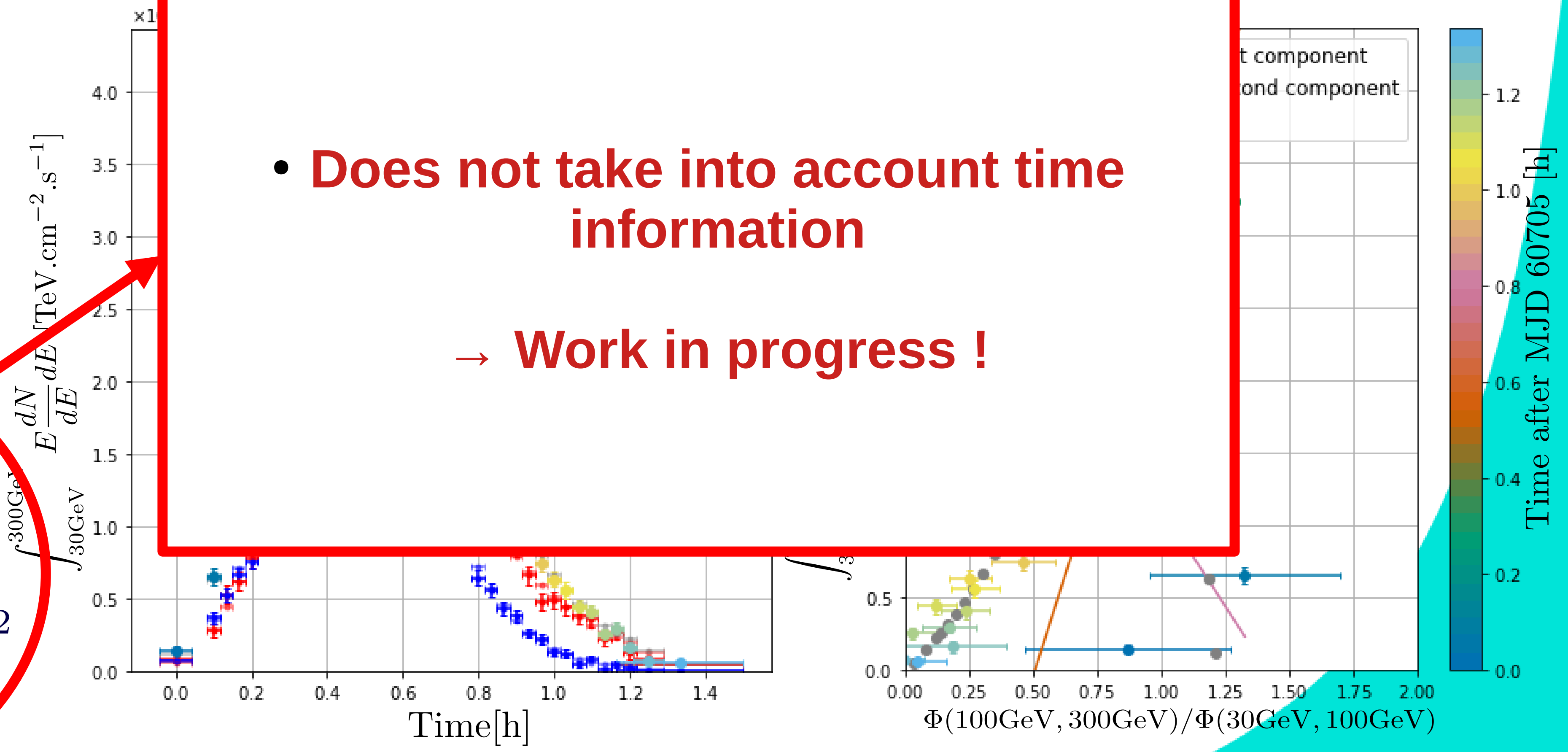


- **Does not take into account time information**

→ **Work in progress !**

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

II - AGN flare simulations – Mrk 421

Flares studies perspectives

- Simulations of different flare models have been done :
  - Magnetic reconnexion : Christie et al. (2019)
  - Lepto-hadronic model : Petropoulou et al. (2024)

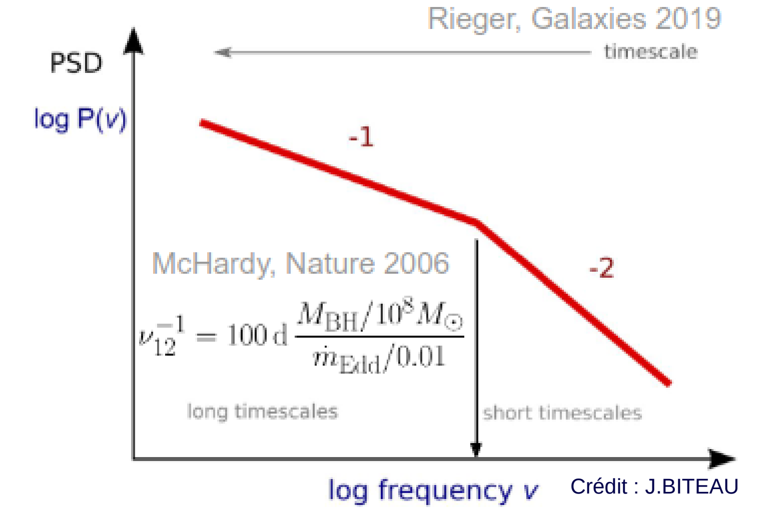
- Multiple time scales
  - From hours to weeks
- Comparison between models

III - AGN long-term monitoring program

III – AGN long-term monitoring - BL Lac

Description of the long-term AGN behavior

- BL Lac is one of the 16 AGN (Cf. Backup) 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 :

$$\Phi(E,t) = \Phi_0(t)\left(\frac{E}{E_0}\right)^{\Gamma(t)-\beta\ln(E/E_0)} \times \exp\left(\frac{-E}{E_{\mathrm{cut}}}\right) \times e^{-\tau_{\gamma\gamma}(E,z))}$$

Reconstruction of the **break position** gives information about **central black hole accretion regime**

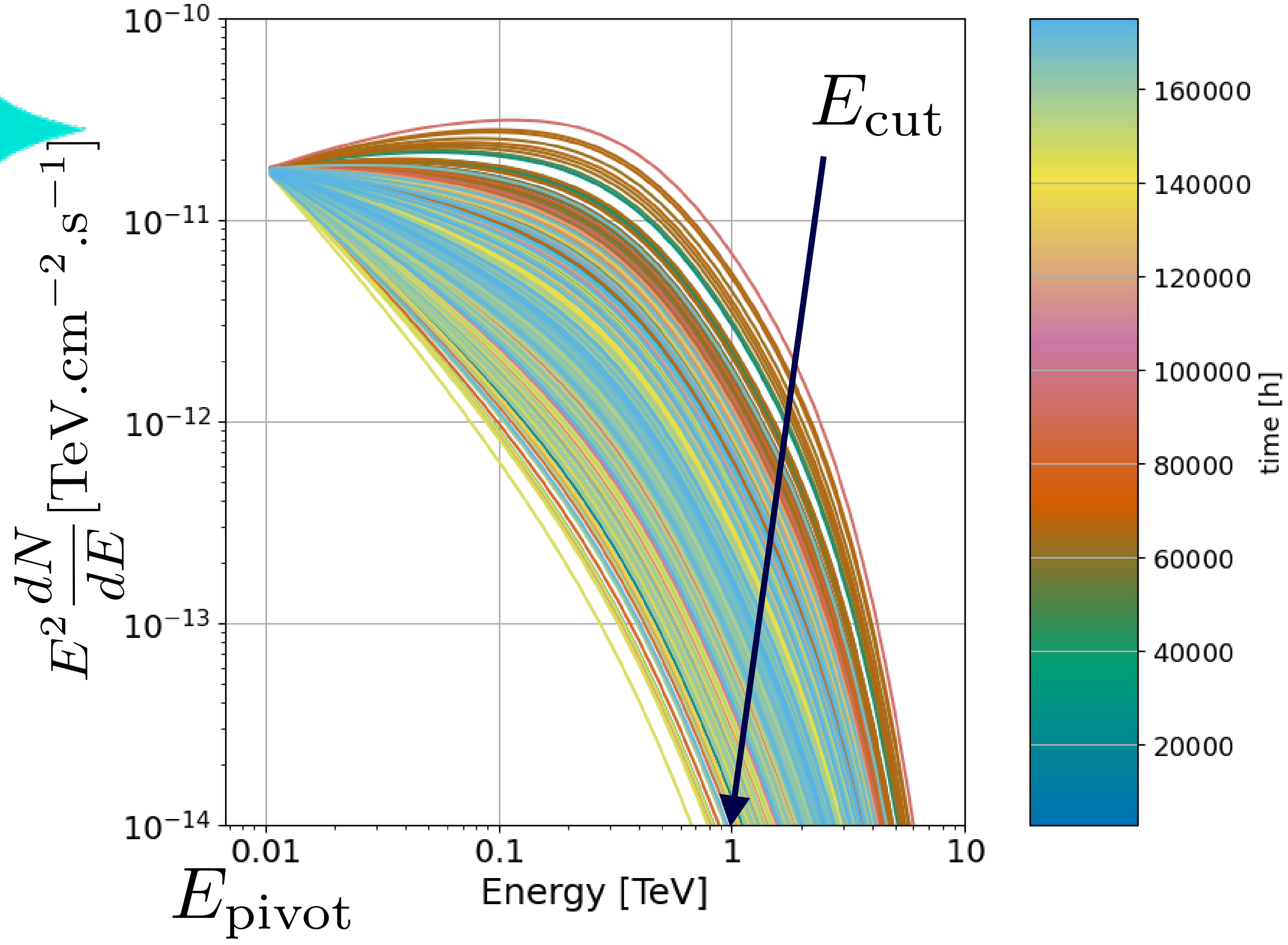
III – AGN long-term monitoring – BL Lac

Injection

Injected SEDs

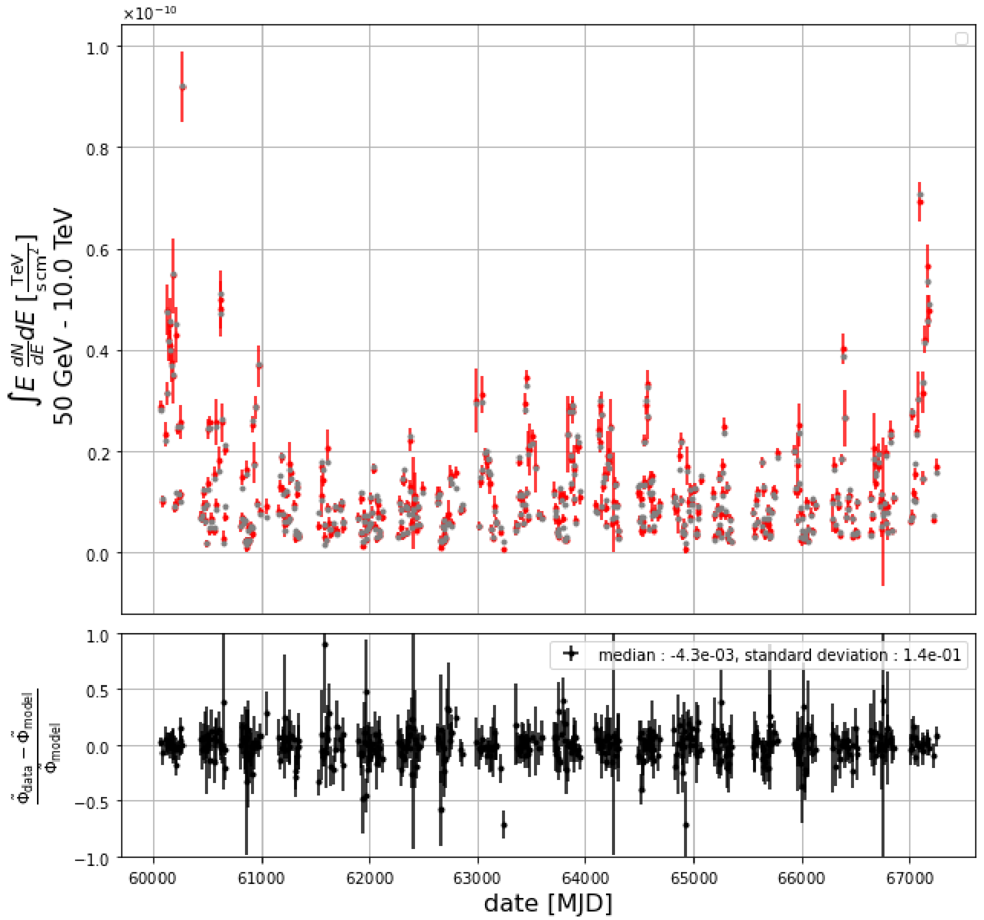
The color shows the time evolution

- Lightcurve spanning 20 years generated
  - **WITHOUT break in PSD**

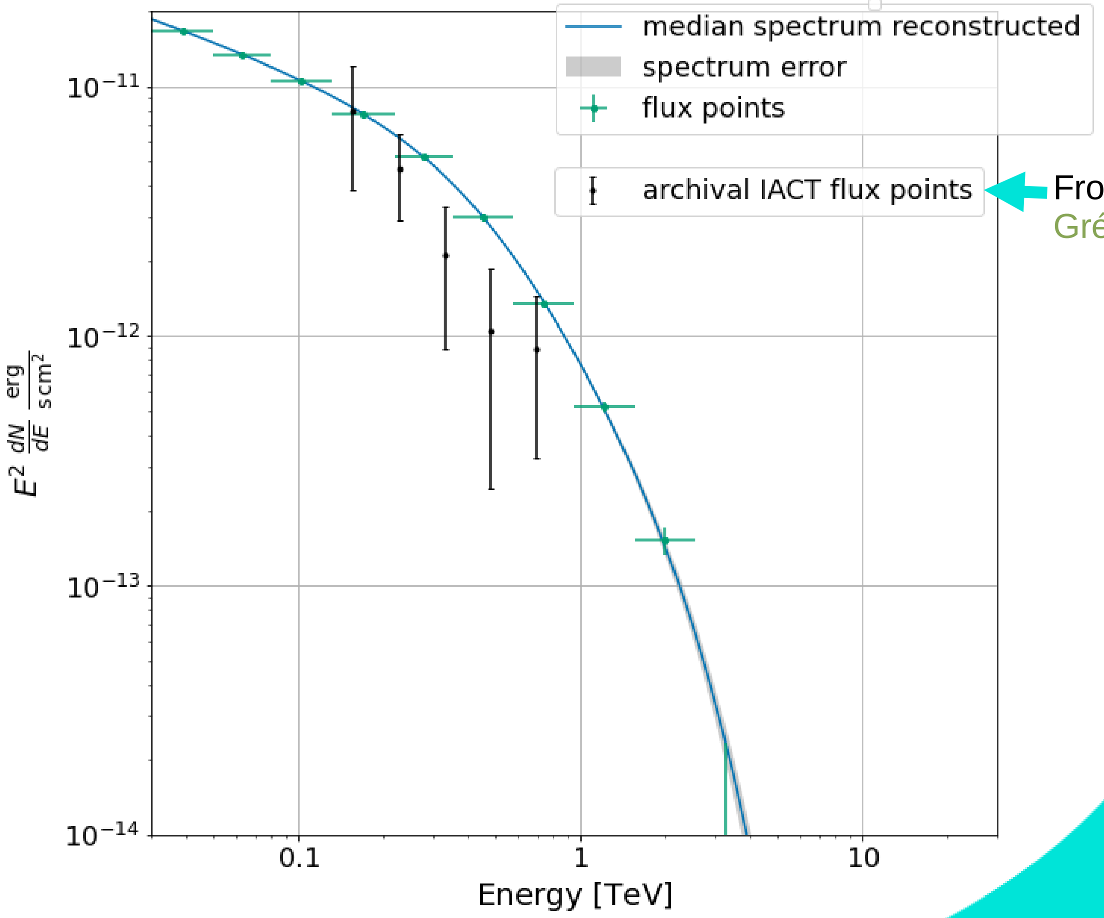


III - AGN long-term monitoring – BL Lac

Lightcurve reconstruction



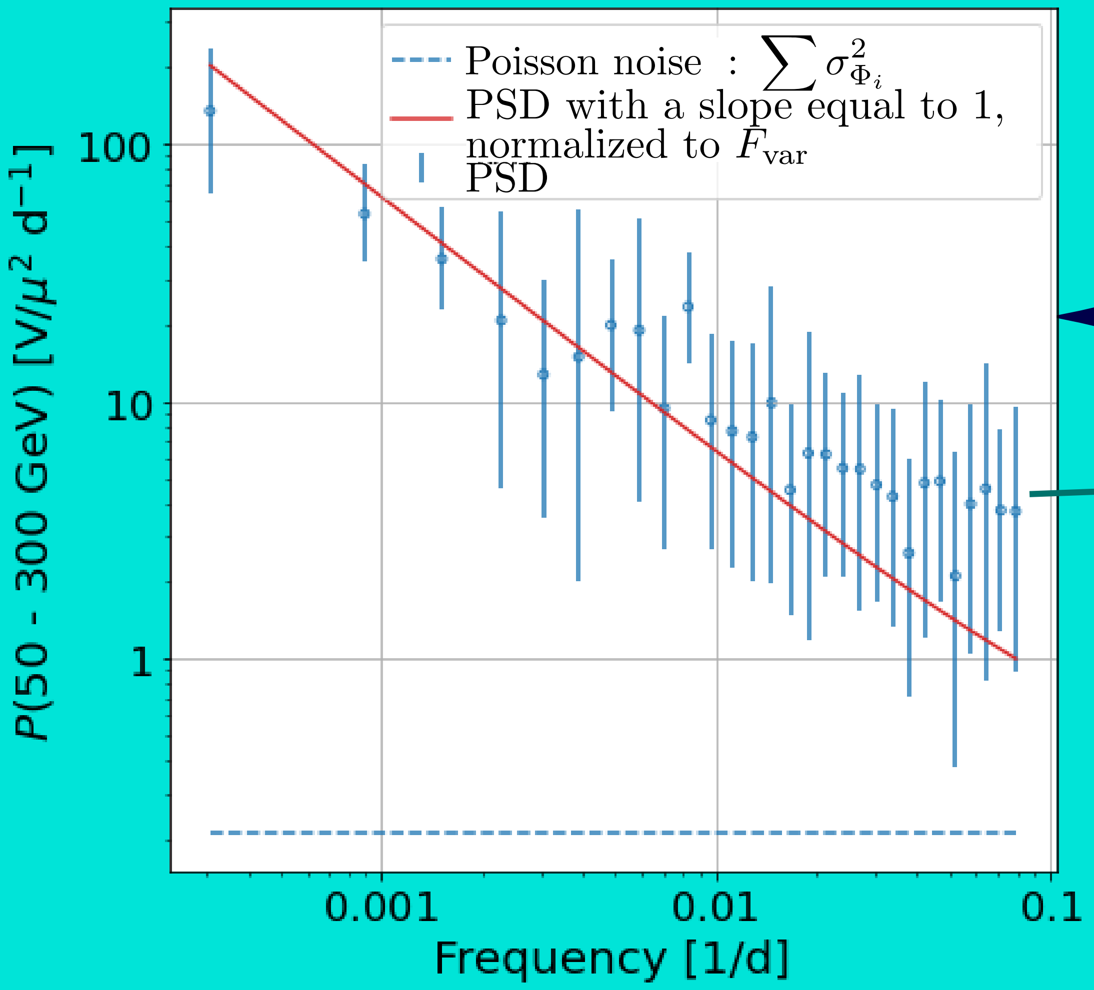
Flux lightcurve over 50 GeV reconstructed for **20 years** of data observed with a **weekly cadence**, grey points are injected values.



From SteVECat, Gréaux et al. (2023)

Reconstructed **median spectrum** for BL Lac for the 20 years of data

III – AGN long-term monitoring – BL Lac



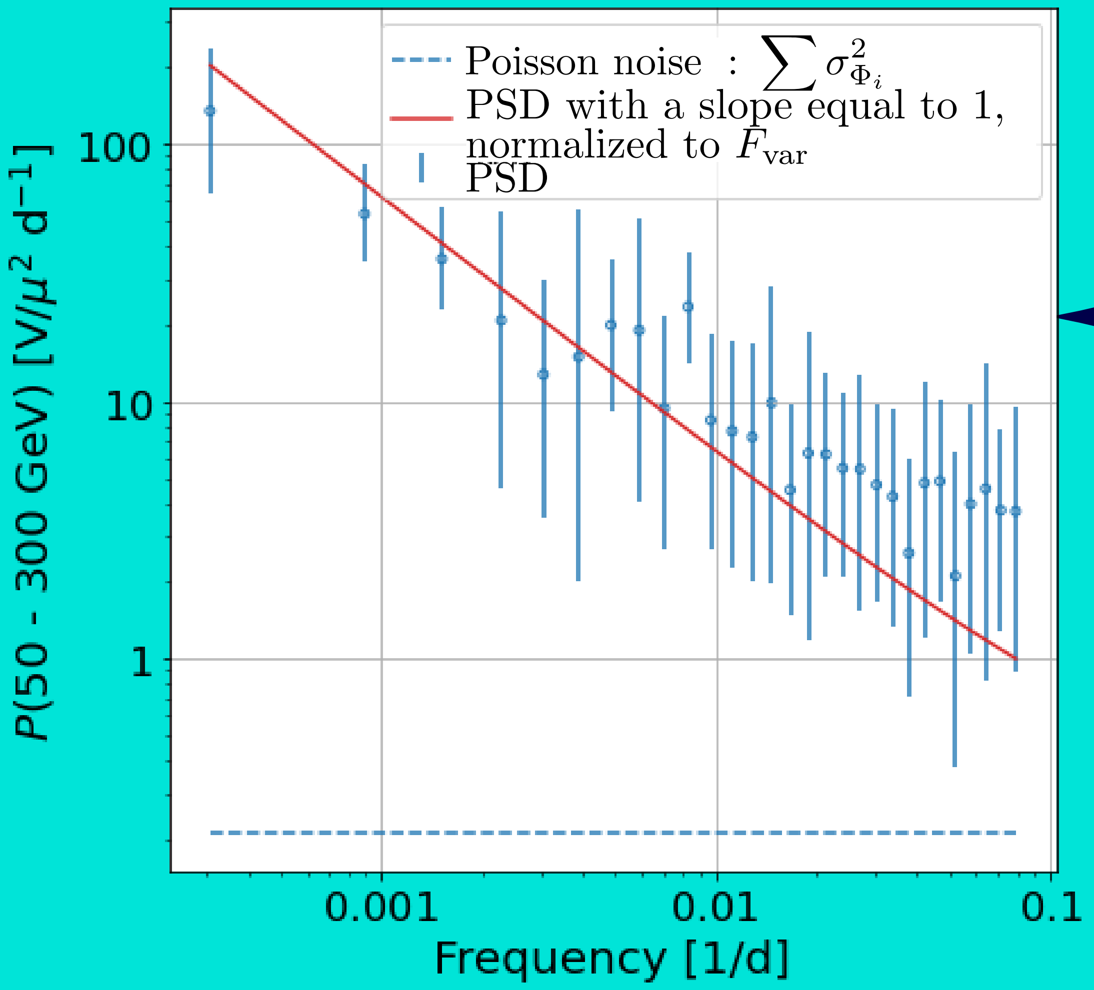
PSD observed for BL Lac

PSD reconstruction

Poisson plateau

Slope of 1 is qualitatively well reconstructed

III – AGN long-term monitoring – BL Lac



PSD observed for BL Lac

PSD reconstruction

- Simulations for the 16 sources are done
- **Adapting** the **cadence**
- Simulations **with break** are investigated
- To improve PSD reconstruction
  - → Reconstruction **within shorter energy bands with simple PL** is preferred
    - → based on comparison between injected and reconstructed flux (Cf. Backup)
    - → GOF estimator is much more efficient and constrained in this case

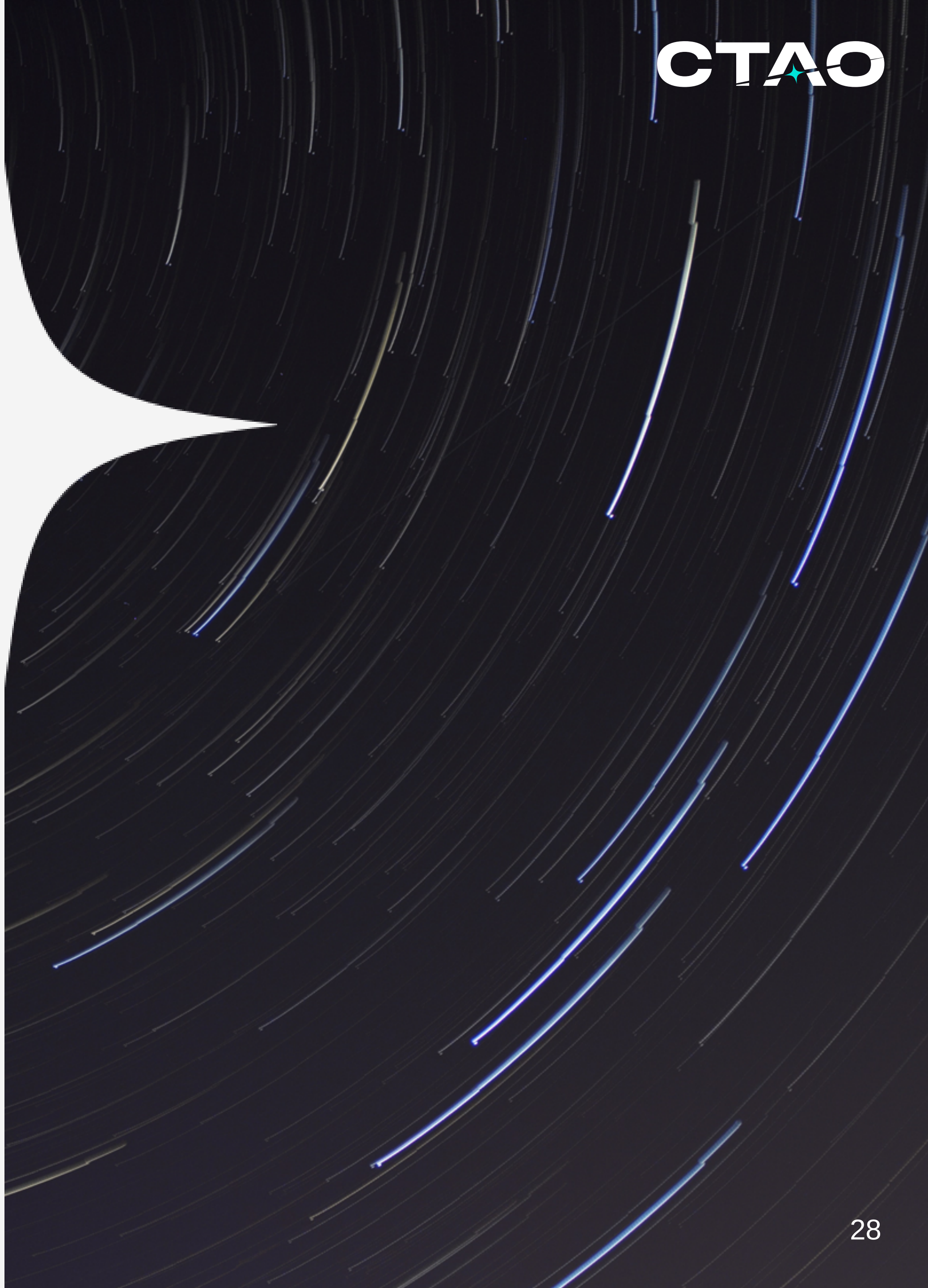
Conclusion

With CTAO

- Will be able to give a new view of 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**
- See also M. Zacharias poster about **multiwavelength studies**
- **CTAO Consorsium Publication in prep.**

CtaAgnVar

- Pipeline for **simulating and analyzing CTAO observations**
  - Massively used within CTAO EGAL working group
- Upcoming :
  - Simulations of Fermi-LAT based AGN modeling and **periodicity detection** done (publication in prep.)
  - **Analysis of LST and H.E.S.S. long-term monitoring data** has started

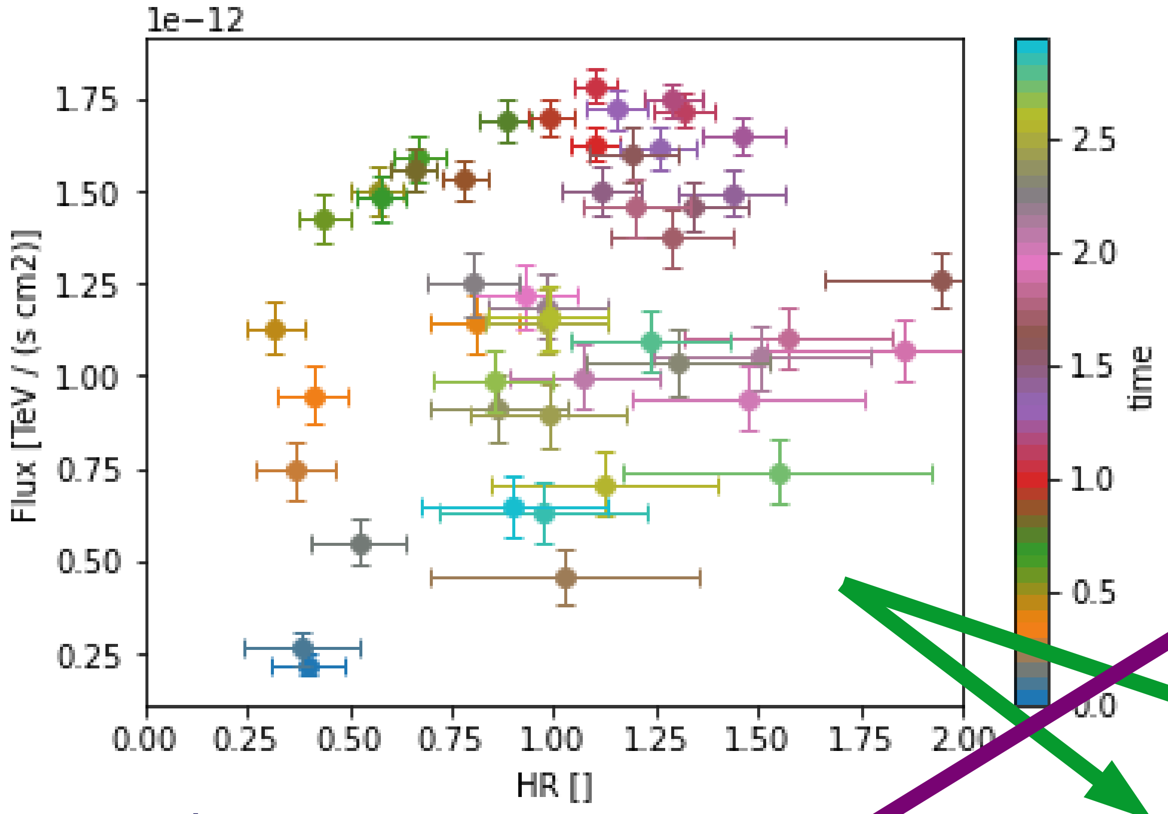


Thank you

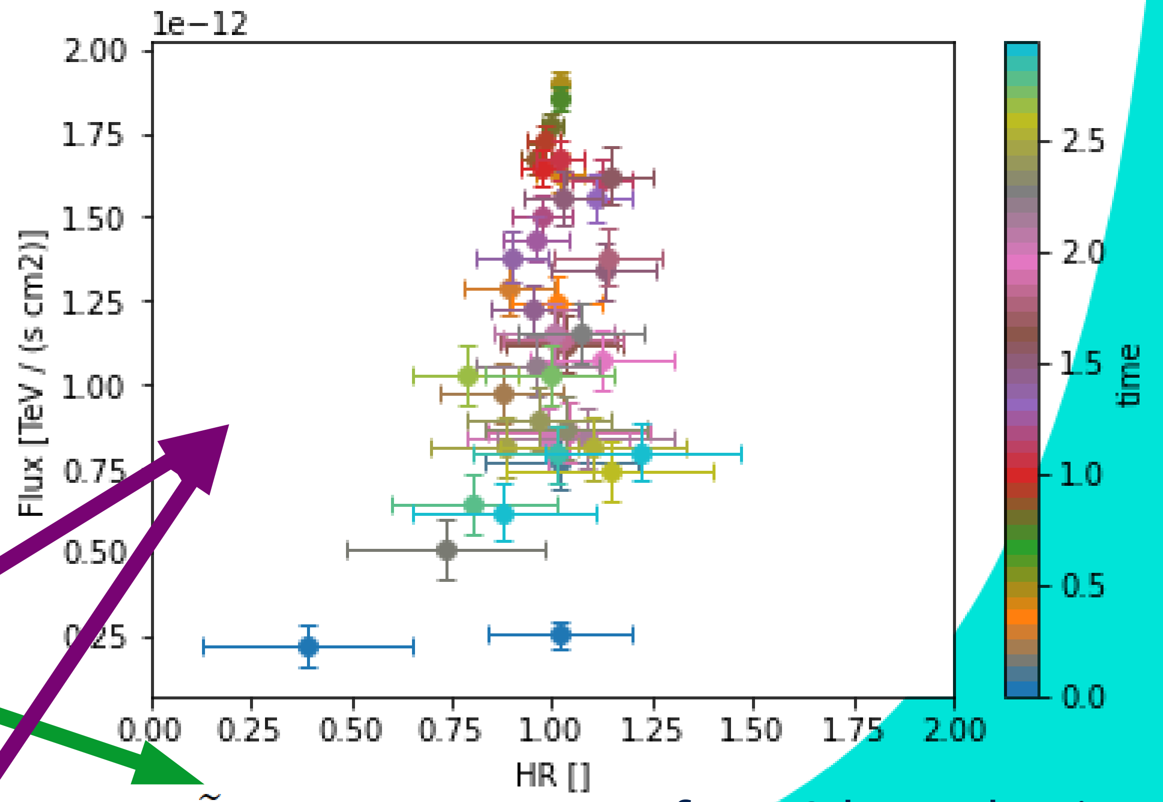
CTAO

BACKUP – Hysteresis detection in hardness ratio (HR) diagrams

Generation of H0 hypothesis from observed data



Observations



HR for H0 hypothesis = without hysteresis

$$\tilde{\Phi}_{H_0}(E_2, E_3) = \tilde{\Phi}(E_1, E_2) \times \langle \frac{\tilde{\Phi}(E_2, E_3)}{\tilde{\Phi}(E_1, E_2)} \rangle$$

BACKUP – Hysteresis detection in hardness ratio (HR) diagrams

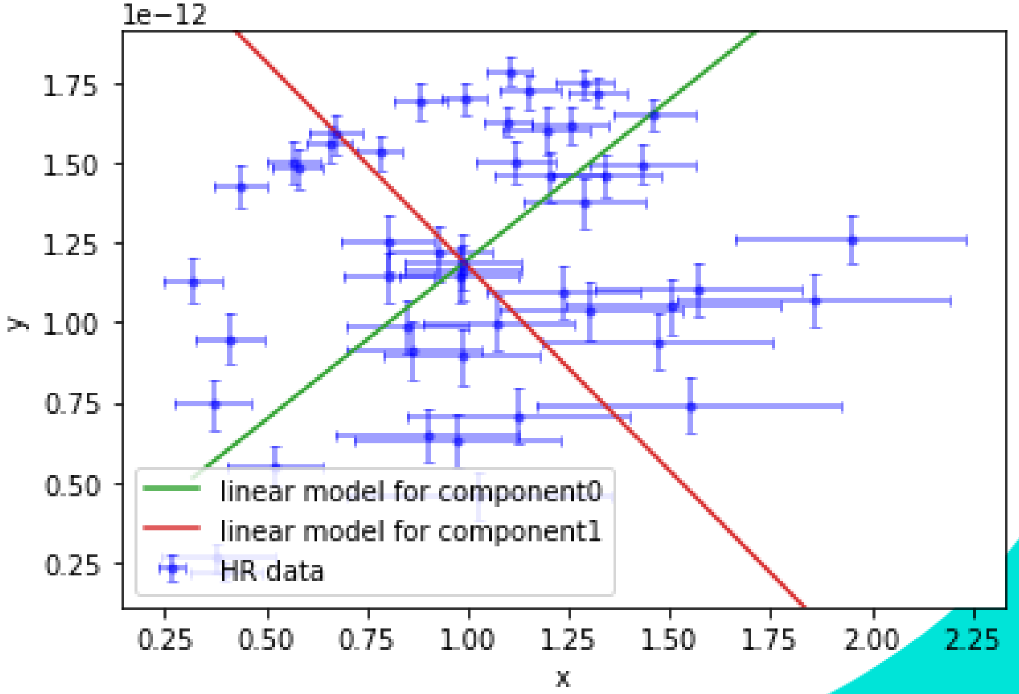
Scaling data before applying PCA

$$\tilde{X} = \frac{X - \langle X \rangle}{\sigma_X} \qquad \tilde{X}_0 = \frac{X_0 - \langle X_0 \rangle}{\sigma_X}$$

$$\tilde{Y} = \frac{Y - \langle Y \rangle}{\sigma_Y} \qquad \tilde{Y}_0 = \frac{Y_0 - \langle Y_0 \rangle}{\sigma_Y}$$

X and Y are the flux computed in the 2 different energy bands

Computation of explained variance ratio



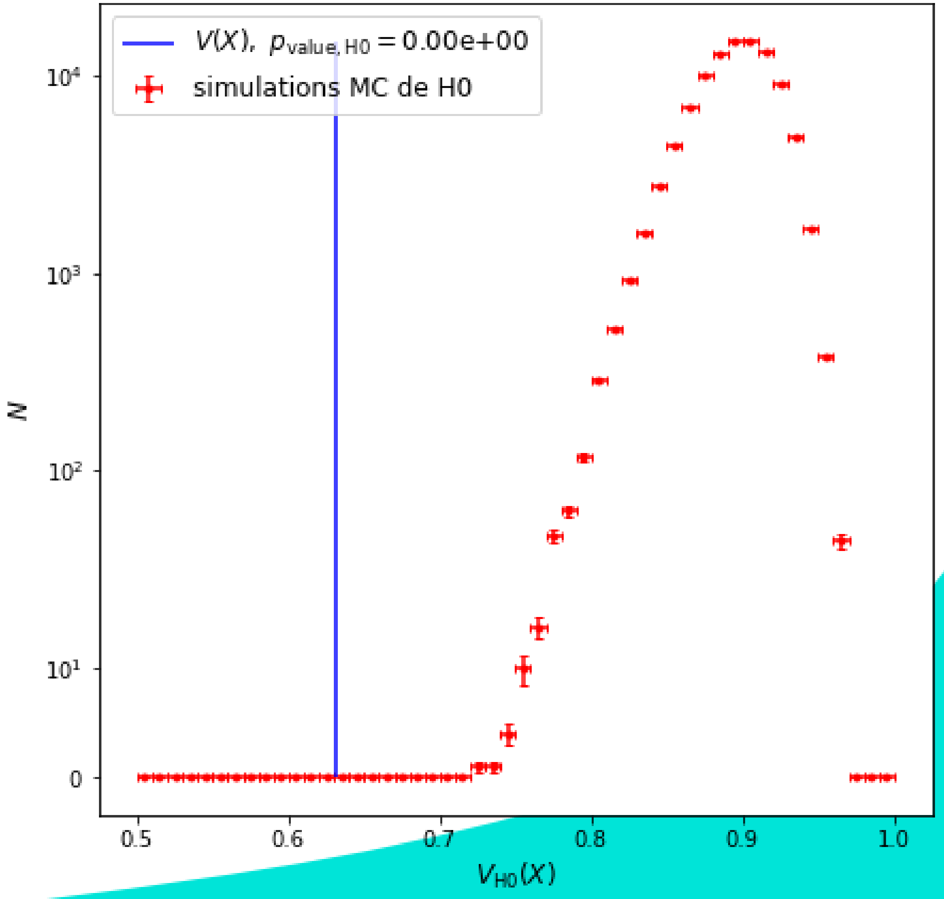
$$V(X) = \frac{\mathrm{Var}(X)}{\mathrm{Var}(X) + \mathrm{Var}(Y)}$$

BACKUP – Hysteresis detection in hardness ratio (HR) diagrams

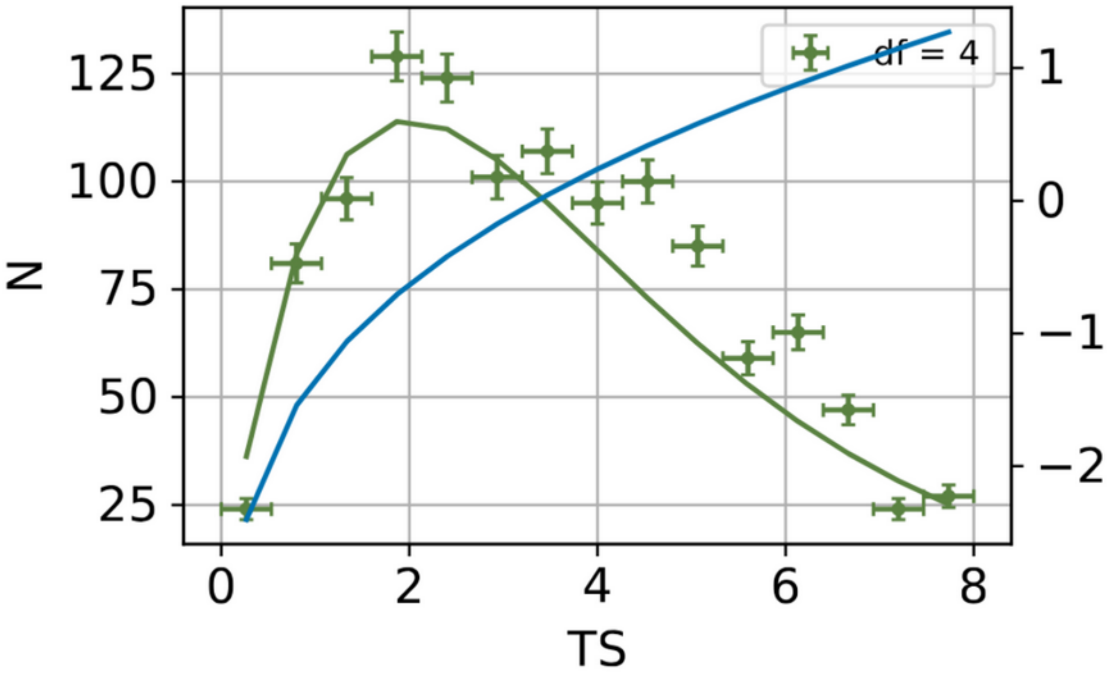
Construction of explained variance ratio distribution of H0 hypothesis with MC simulations within errors

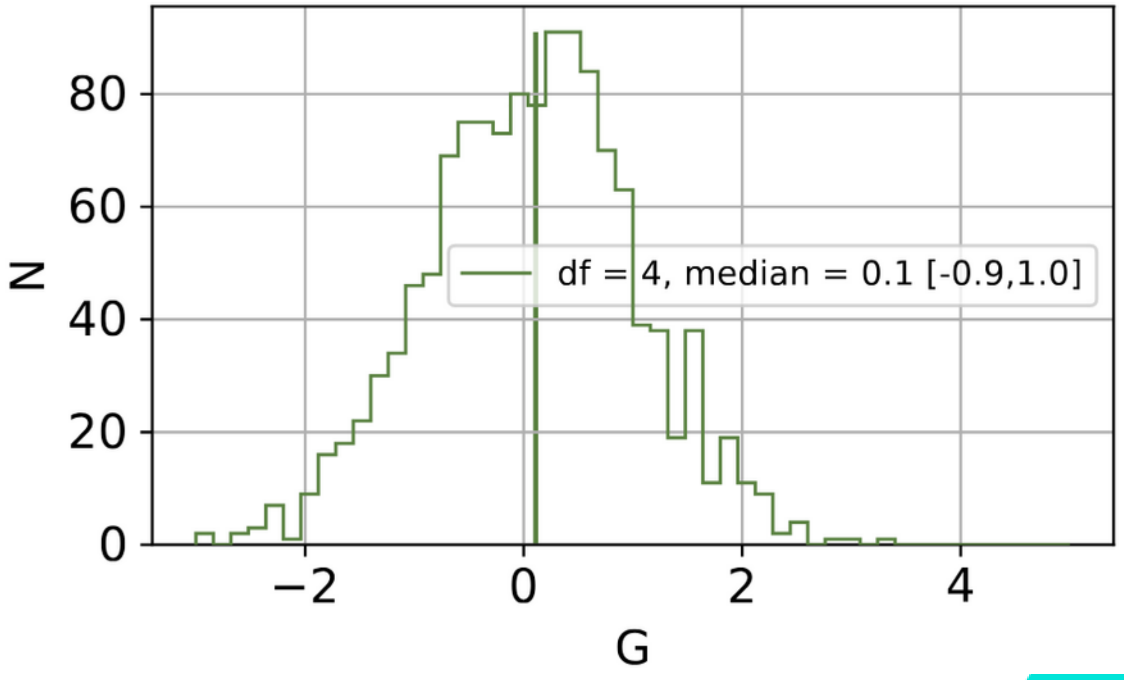
- In red : Distribution of V(X) computed from H0

- In blue : median value of V(X) computed from observed data



BACKUP – GOF estimator





$$\mathrm{TS}_{\mathrm{valide}} = -2\log\frac{L(N_{\mathrm{ON}}, N_{\mathrm{OFF}}, \alpha, \mu_{\mathrm{sig}}, \mu_{\mathrm{fond}})}{L(N_{\mathrm{ON}}, N_{\mathrm{OFF}}, \alpha, N_{\mathrm{ON}} - \alpha N_{\mathrm{OFF}}, \alpha N_{\mathrm{OFF}})}$$

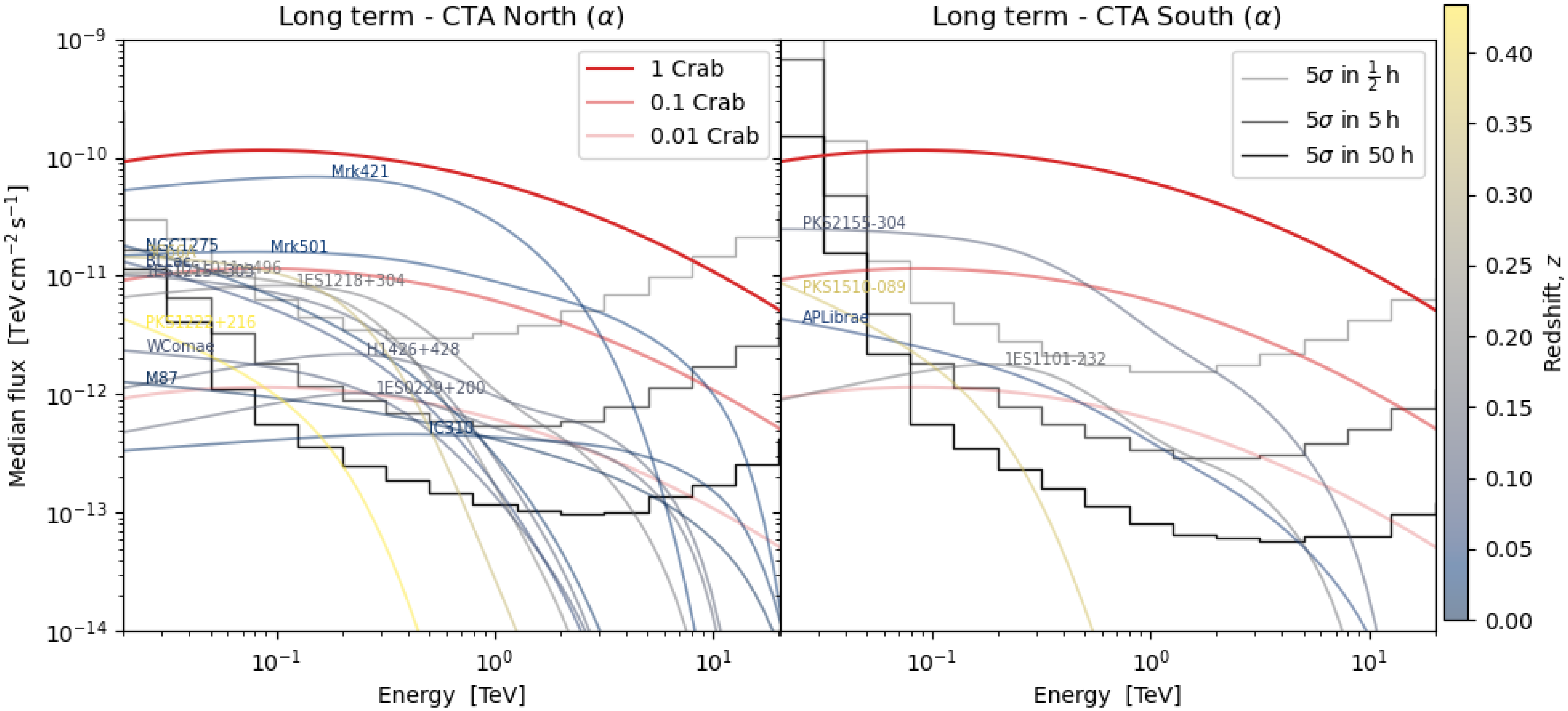
$$p_{\mathrm{value}}(\mathrm{TS}) = P(T > \mathrm{TS}|H) = S_{\chi^2_{\mathrm{m-n}}}(\mathrm{TS}) = \int_{\mathrm{TS}}^{\infty} \mathrm{PDF}_{\chi^2_{\mathrm{m-n}}}(k)\,dk$$

$$G(\mathrm{TS}) = S^{-1}_{\mathcal{N}(0,1)}(p_{\mathrm{value}}(\mathrm{TS}))$$

BACKUP – AGN long-term monitoring

Sources details

Type de source	Nom
UHBL	1ES0229+200(N), 1ES1101-232(S)
HBL	Mrk421(N), Mrk501(N), PKS2155-304(S), 1ES1215+303(N), 1ES1218+304(N), H1426+428(N)
IBL	3C66A(N), 1ES1011+496(N), WComae(N)
LBL	APLibrae(S), BLLac(N)
FSRQ	PKS1510-089(S), PKS1222+216(N)
radio galaxie	M87(N), NGC 1275(N), IC310(N)



BACKUP – AGN long-term monitoring

Comparison between injection et reconstruction