Active Galactic Nuclei variability studies with the Cherenkov Telescope Array Observatory

I - AGN variablility studies with CTAO

- **A tool has been developed, based on Gammapy, to simulate and reconstruct AGN observations with CTAO : CtaAgnVar**
- **Goals :**
  - Simulations of gamma-like event from CTAO 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

I/O

→run simulations of gamma like event !

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

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

→ fitting models

→ see next slide !

→run simulations of gamma like event !

Results in an Astropy table with for each time step :
- best fit parameters
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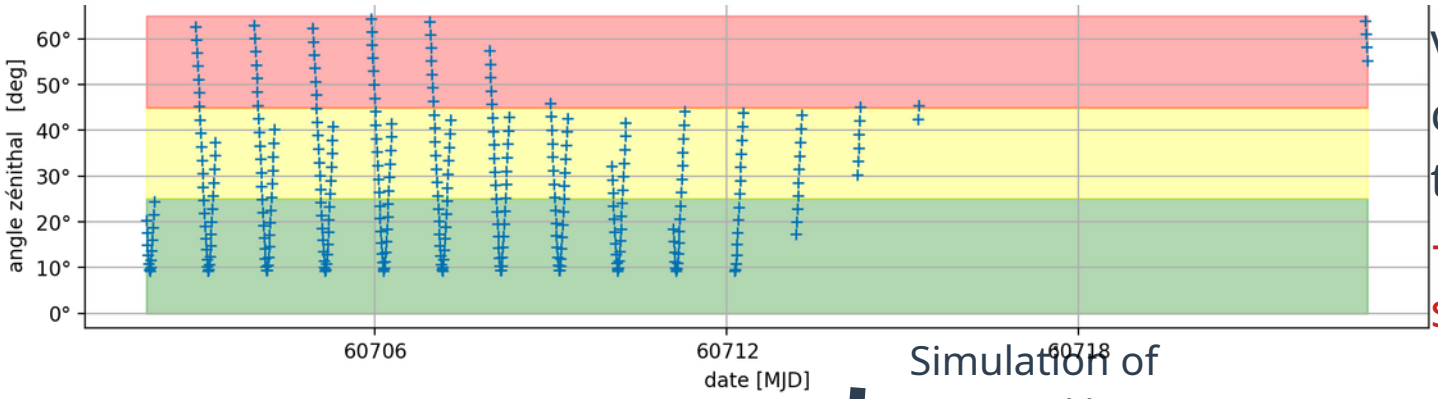
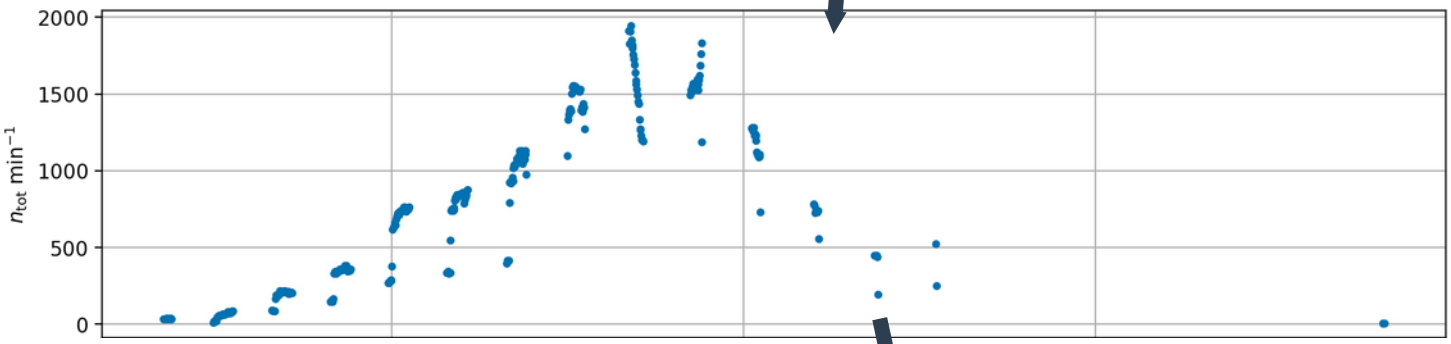
I – CtaAgnVar workflow



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

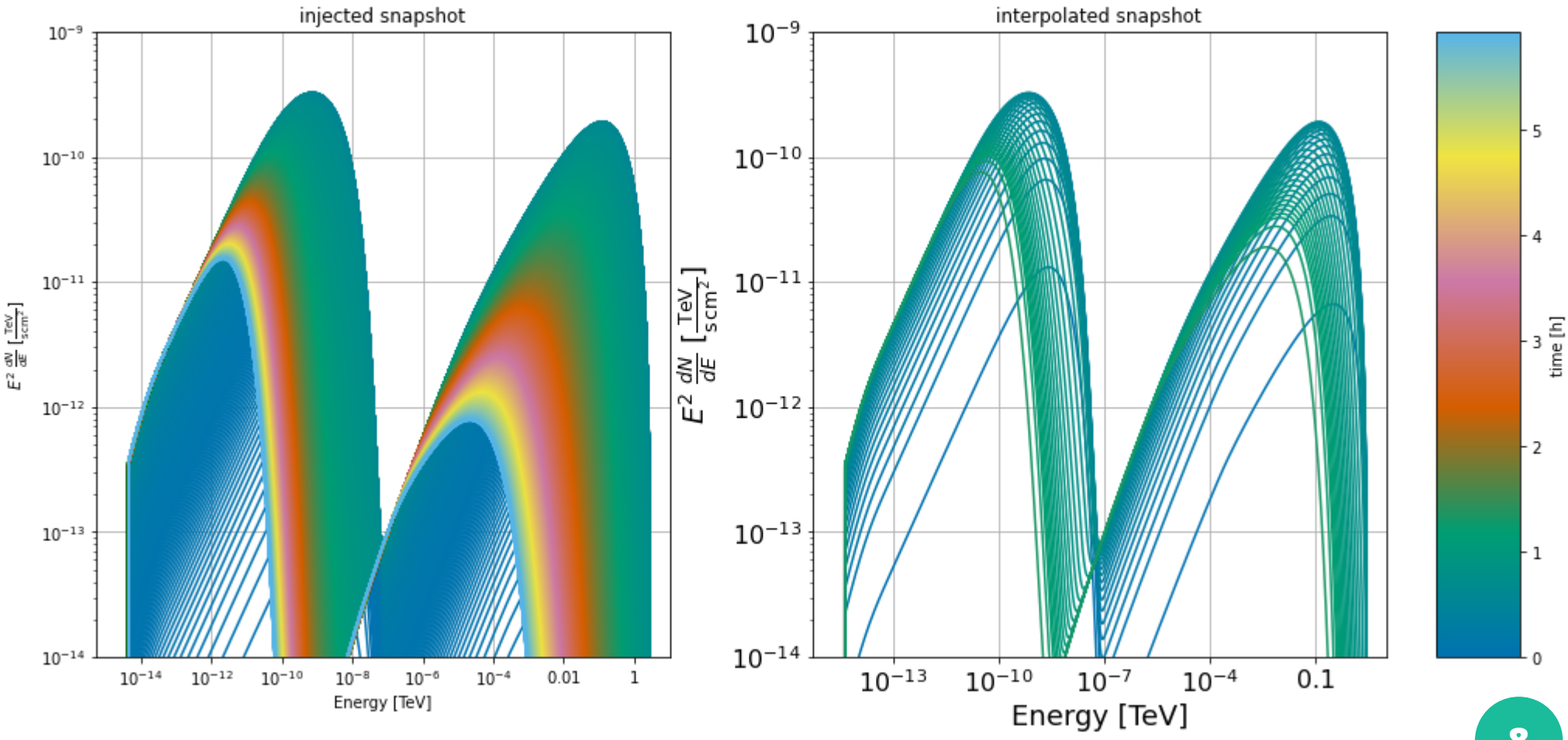
I – CtaAgnVar : Goodness of fit estimator

- 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

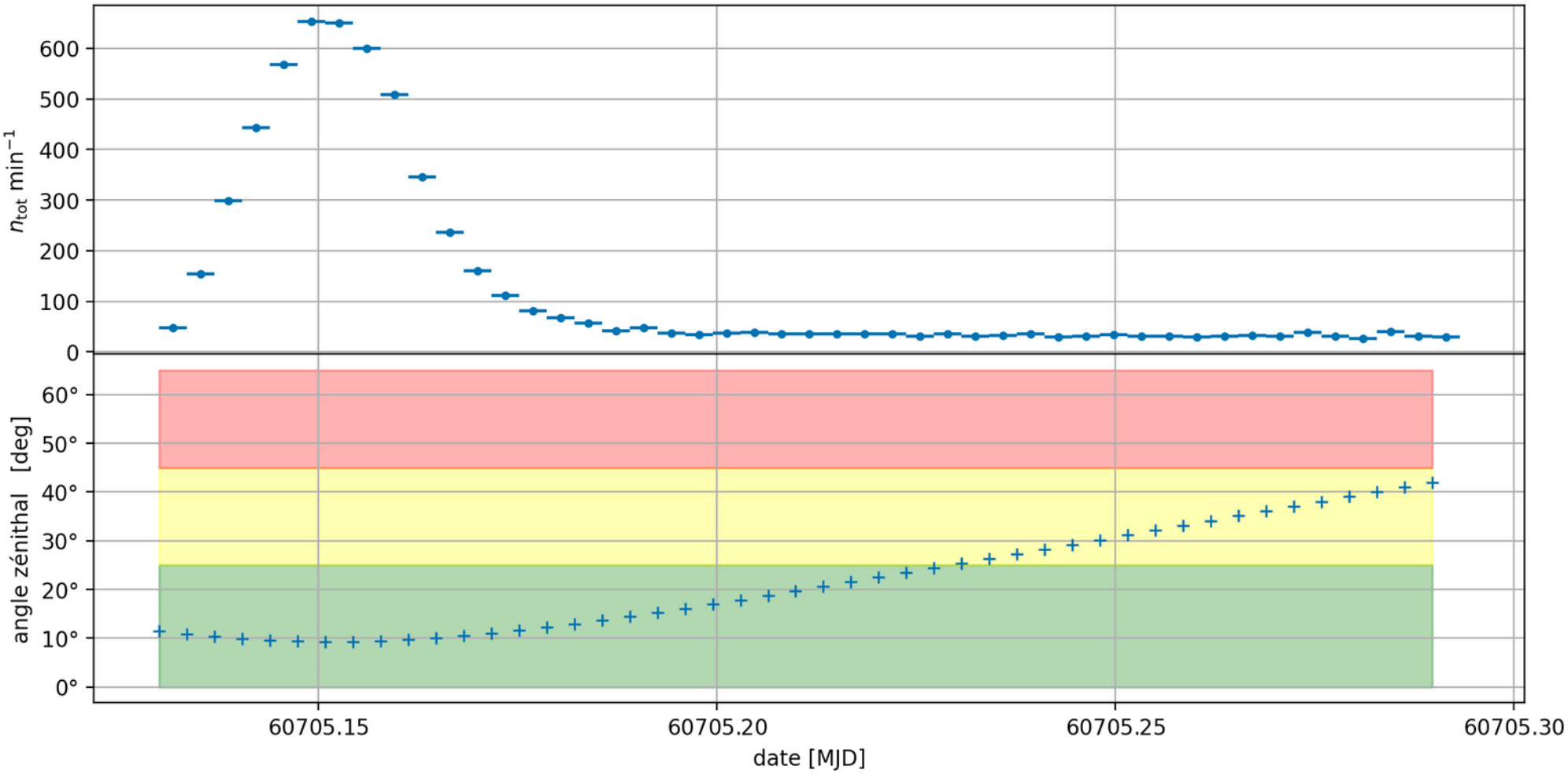
- Possibility to reconstruct LC in sub energy bands with a simple PL spectral reconstruction (free index or not)
  → make possible to compare LC at low energy vs high energy
  → actually the best reconstruction

II – AGN flares simulations – Mrk 421 – Finke et al. 2008

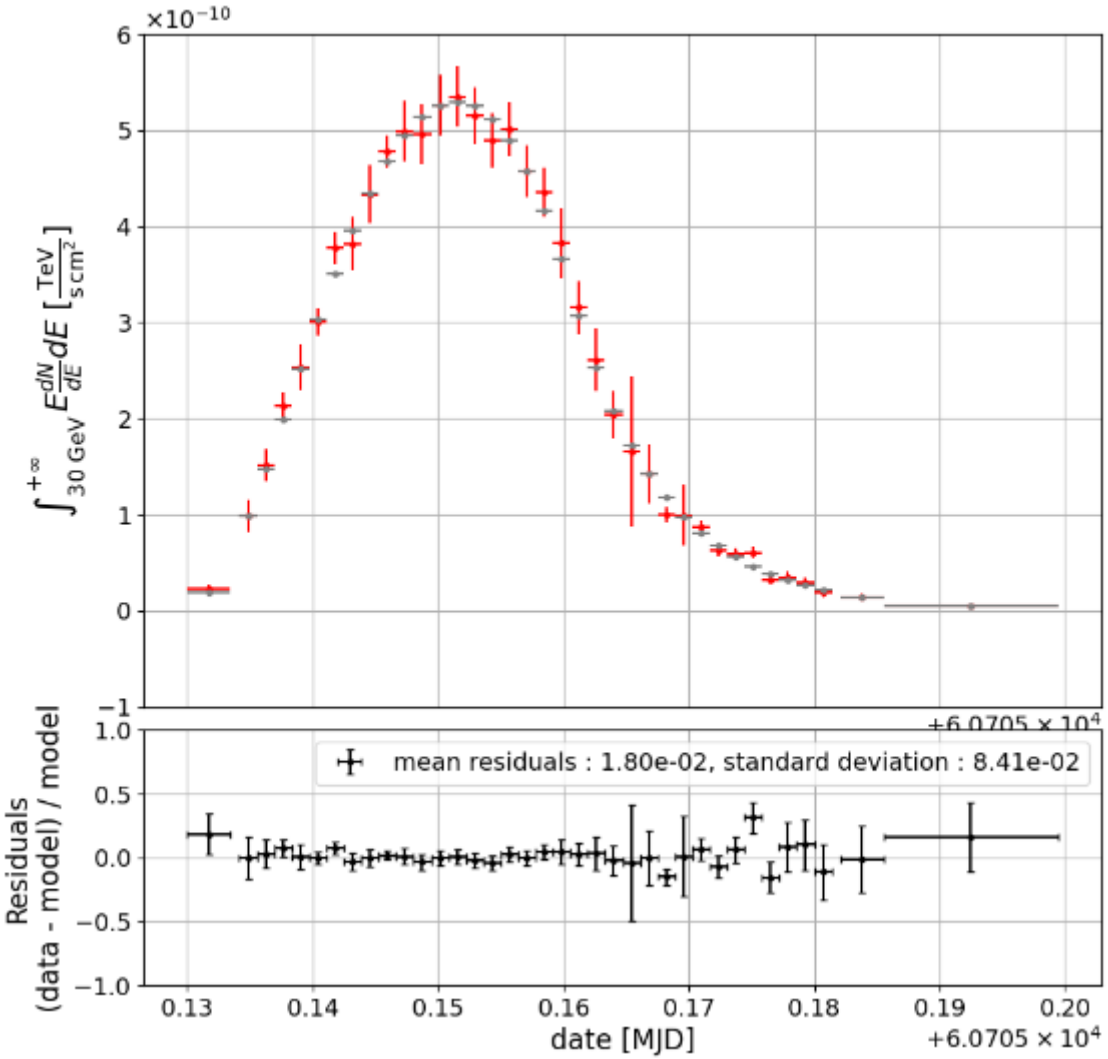
- Leptonic SSC, single zone



II – AGN flares simulations – Mrk 421 – Finke et al. 2008



II – Mrk 421 flare simulations - Light curve reconstruction



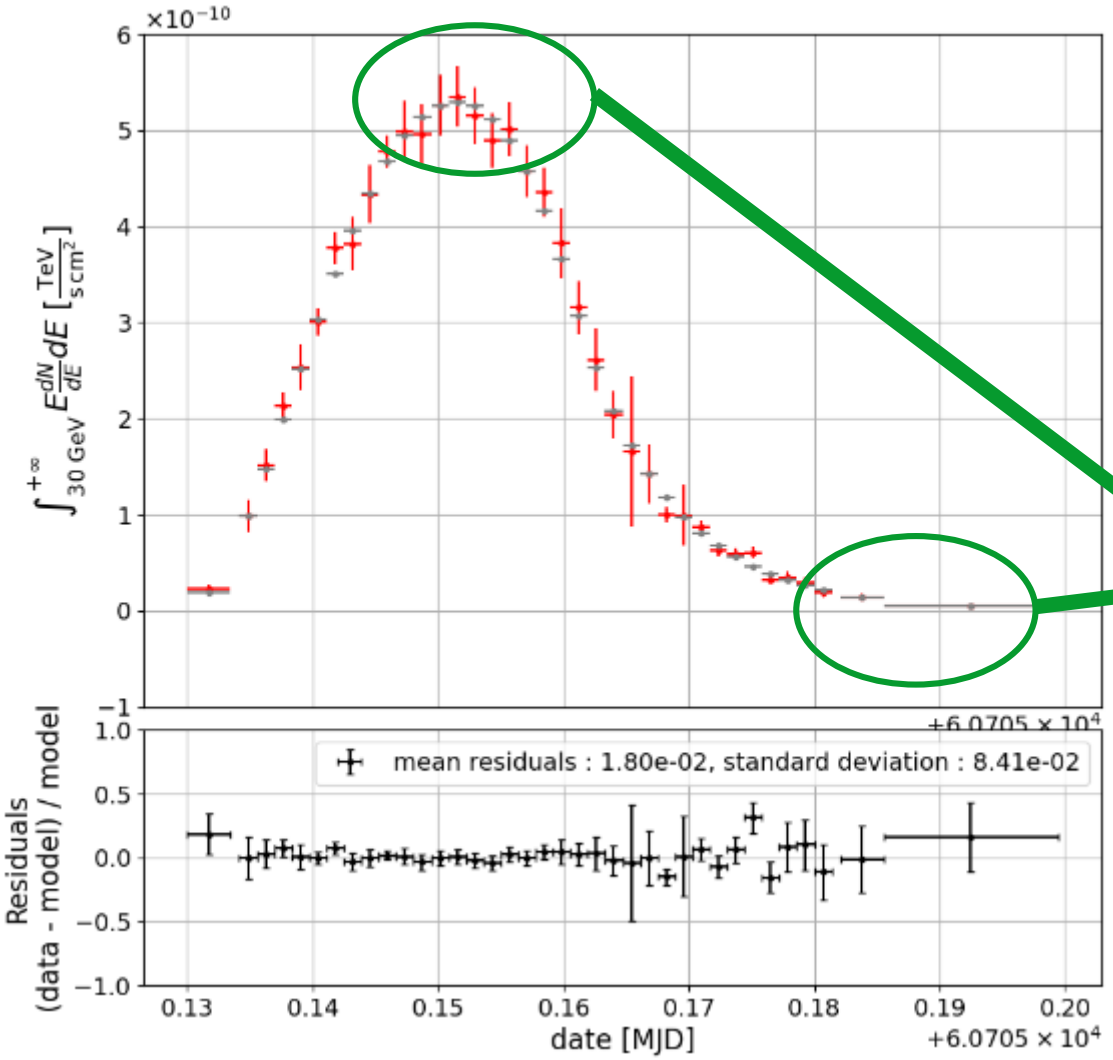
Reconstructed flux above 30 GeV

- **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

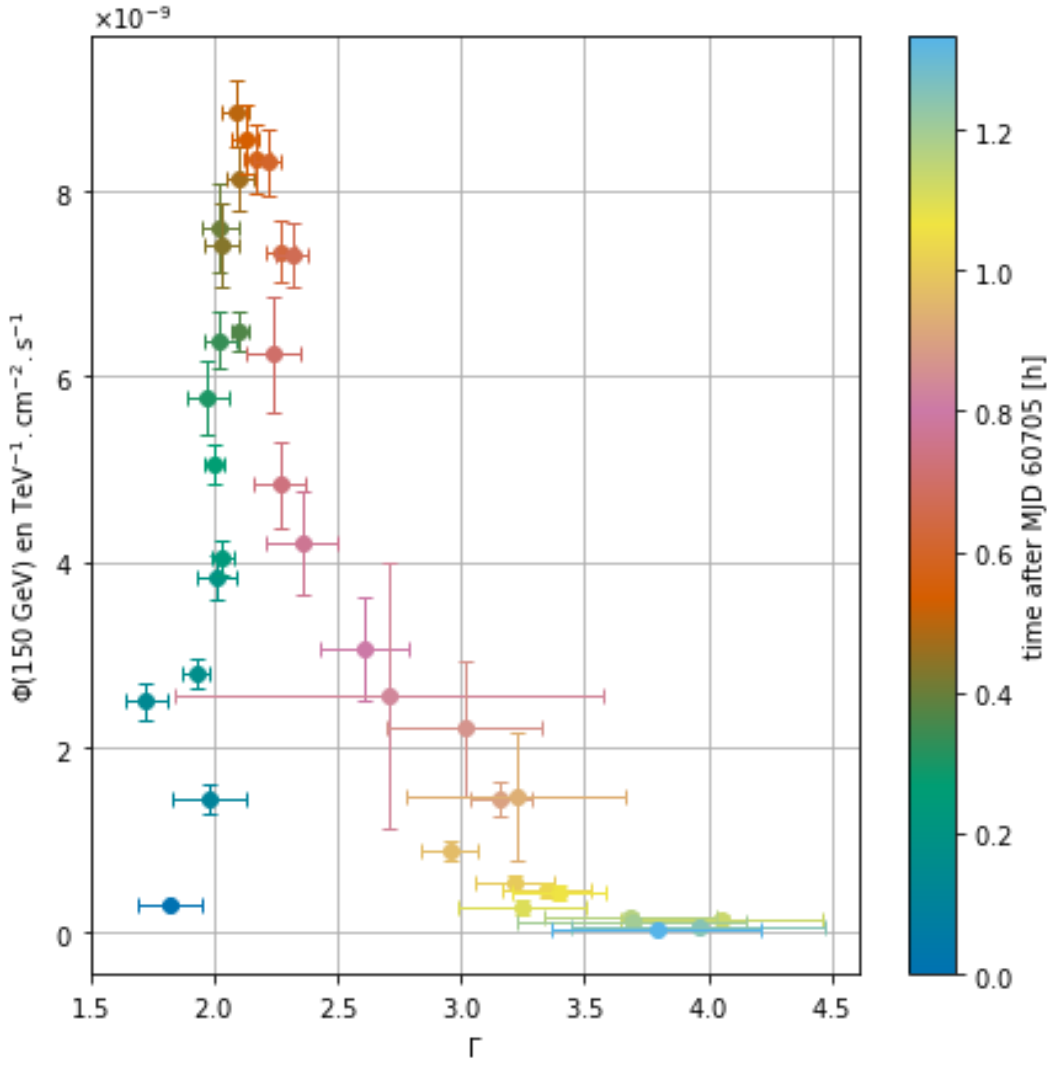
II – Mrk 421 flare simulations - Light curve reconstruction



Reconstructed flux above 30 GeV

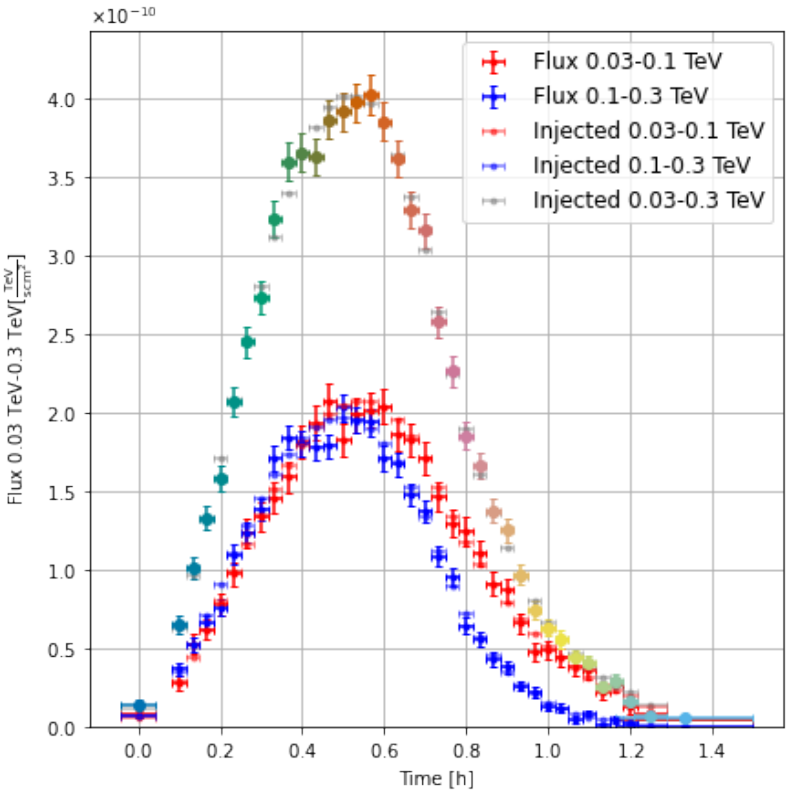
- **Flux is reconstructed with a PL fit EBL absorbed, which can be complicated by adding cutoff and curvature**
- **Non constant time bins :**
  - Time bins larger at the LC tails where the signal is lower
  - Bins size : from 2 to 20 min

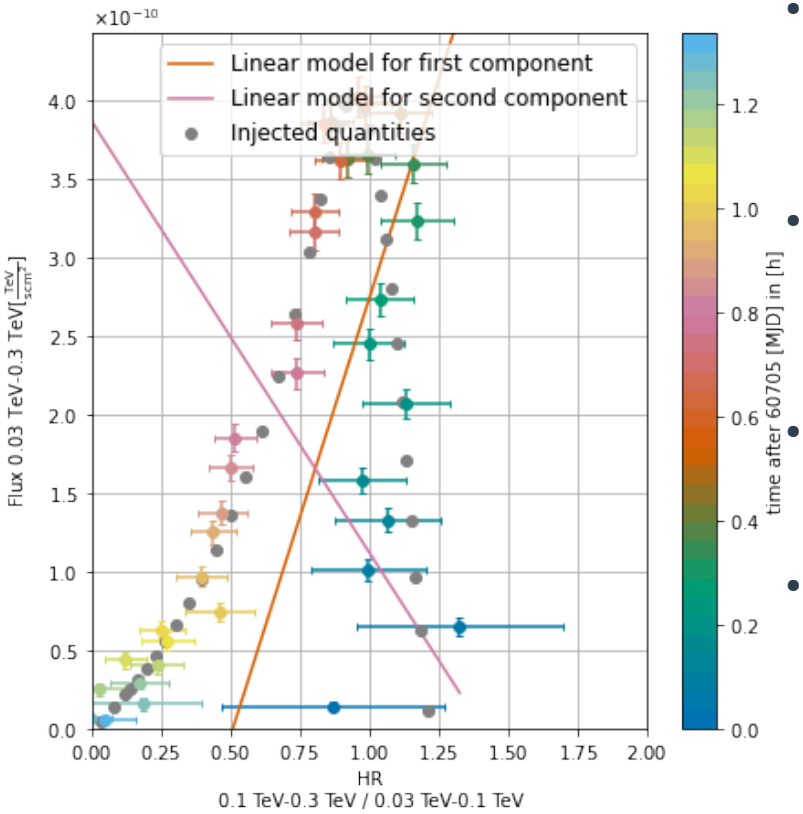
II – Mrk 421 flare simulations - Mrk 421 – Finke et al. 2008 - Flux / photon index correlations



- Fixed index during the rising phase
- Smoother when fainter during the decreasing phase

II – AGN flares simulations – Mrk 421 – Finke et al. 2008





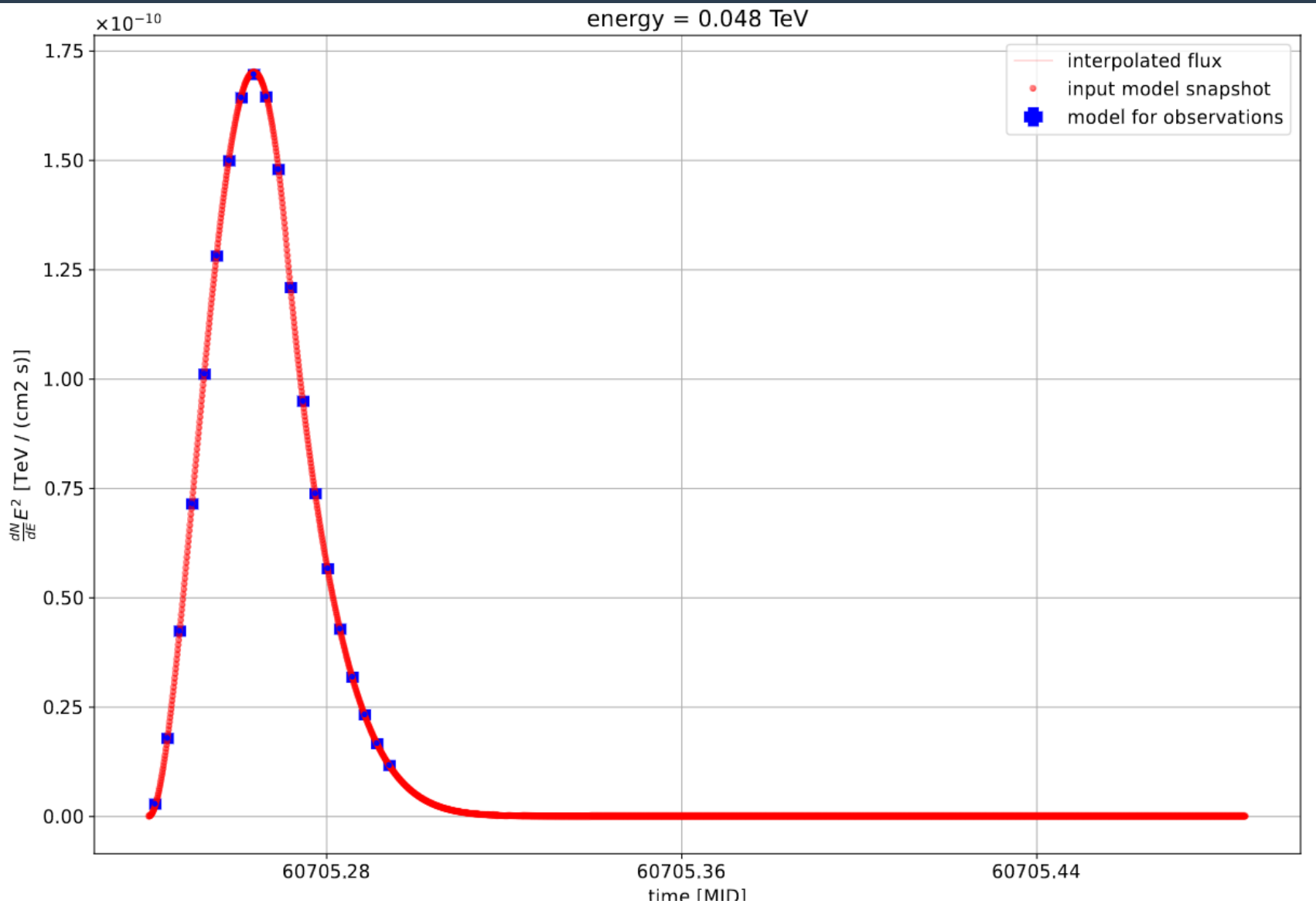
- Flux is reconstructed with a PL fit
- Hysteresis is predicted in injected model
- Can see the hysteresis
- HR detection with principal component analysis

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

Conclusion and perspectives

- **With CtaAgnVar :**
  - Perform simulations of CTAO observation of AGN flares
  - Reconstruct LC in specified energy bands
  - Reconstruct spectral variability
- **Work started with Alberto**

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

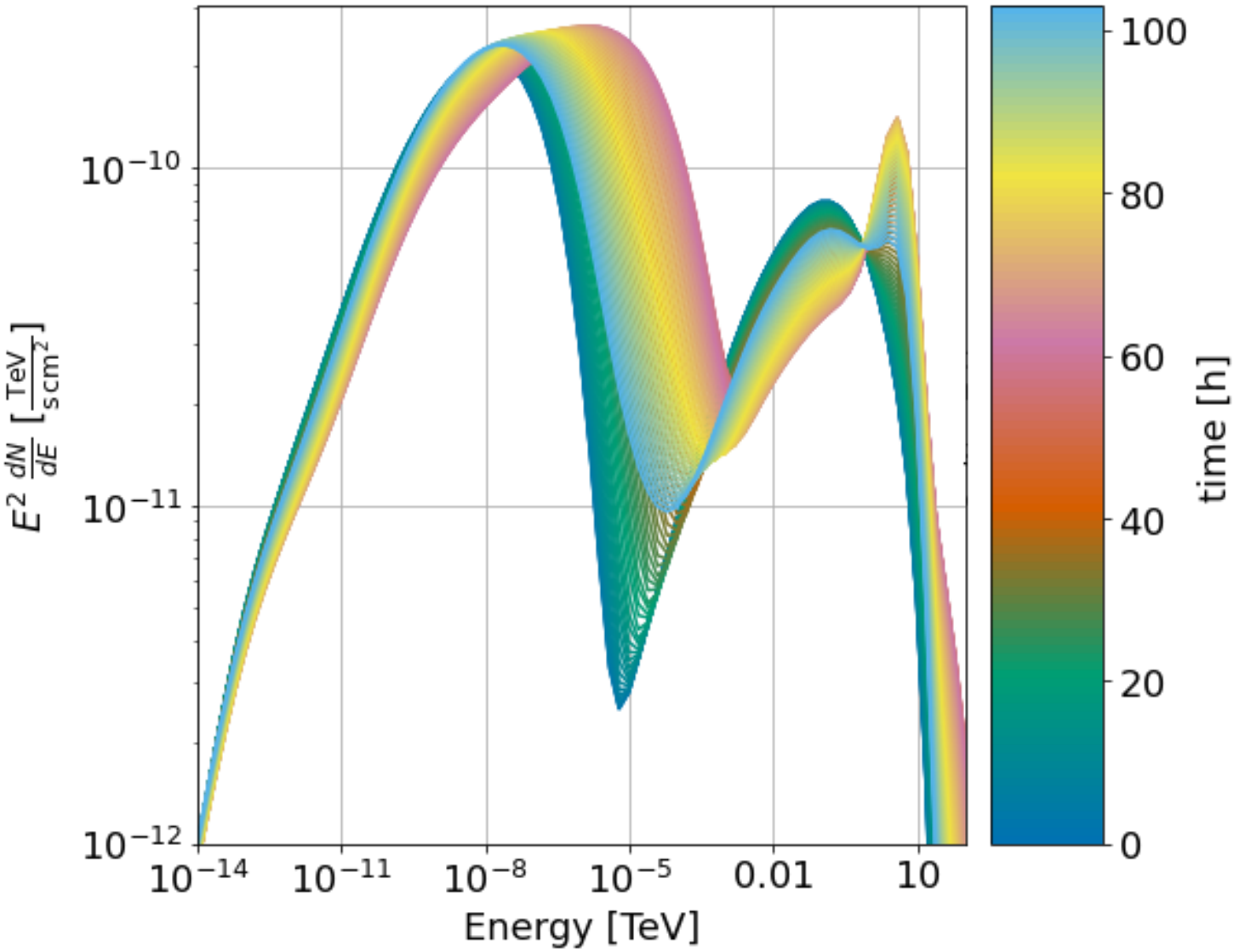
$$-2\log\frac{L(n_{\mathrm{on}}, n_{\mathrm{off}}, \alpha; \mu_{\mathrm{sig}}, \mu_{\mathrm{bkg}})}{L(n_{\mathrm{on}}, n_{\mathrm{off}}; n_{\mathrm{on}}, n_{\mathrm{off}})}$$

- **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 – Lepto-hadronic :



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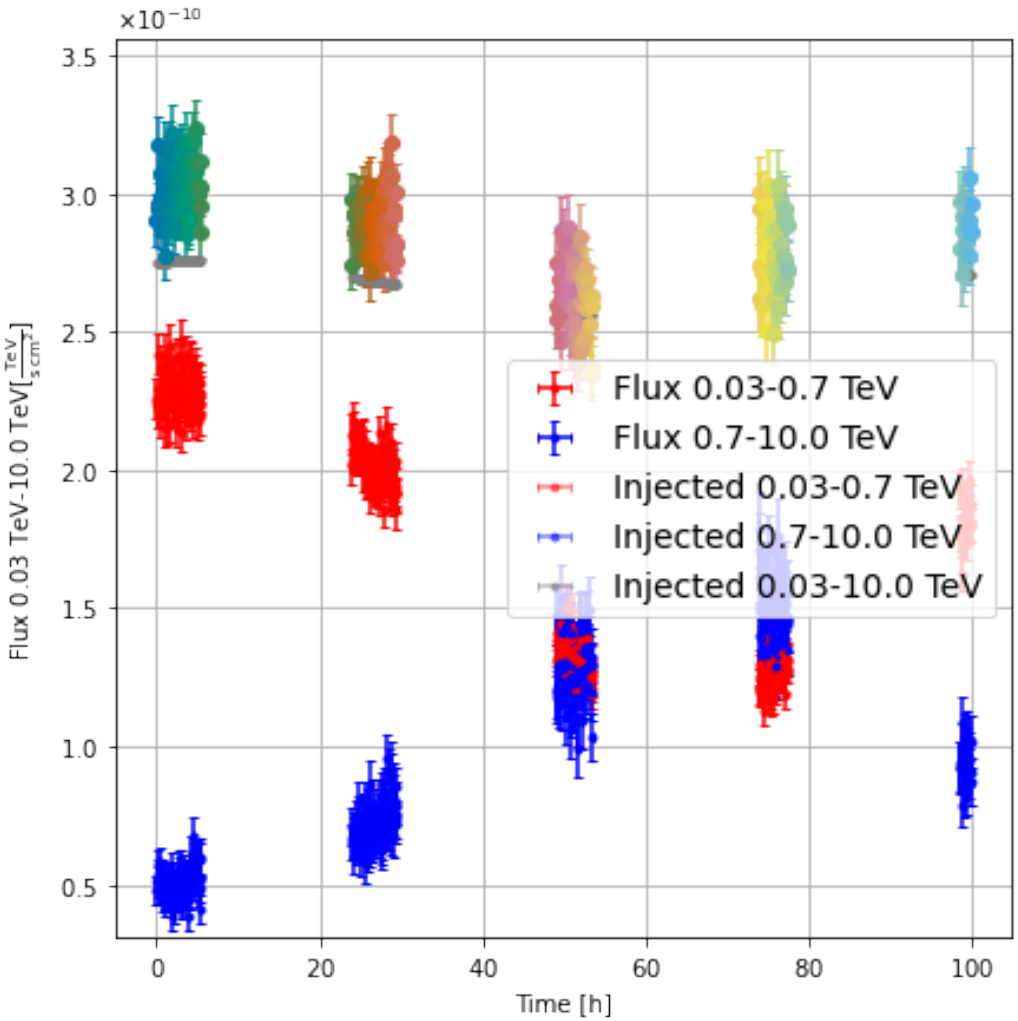
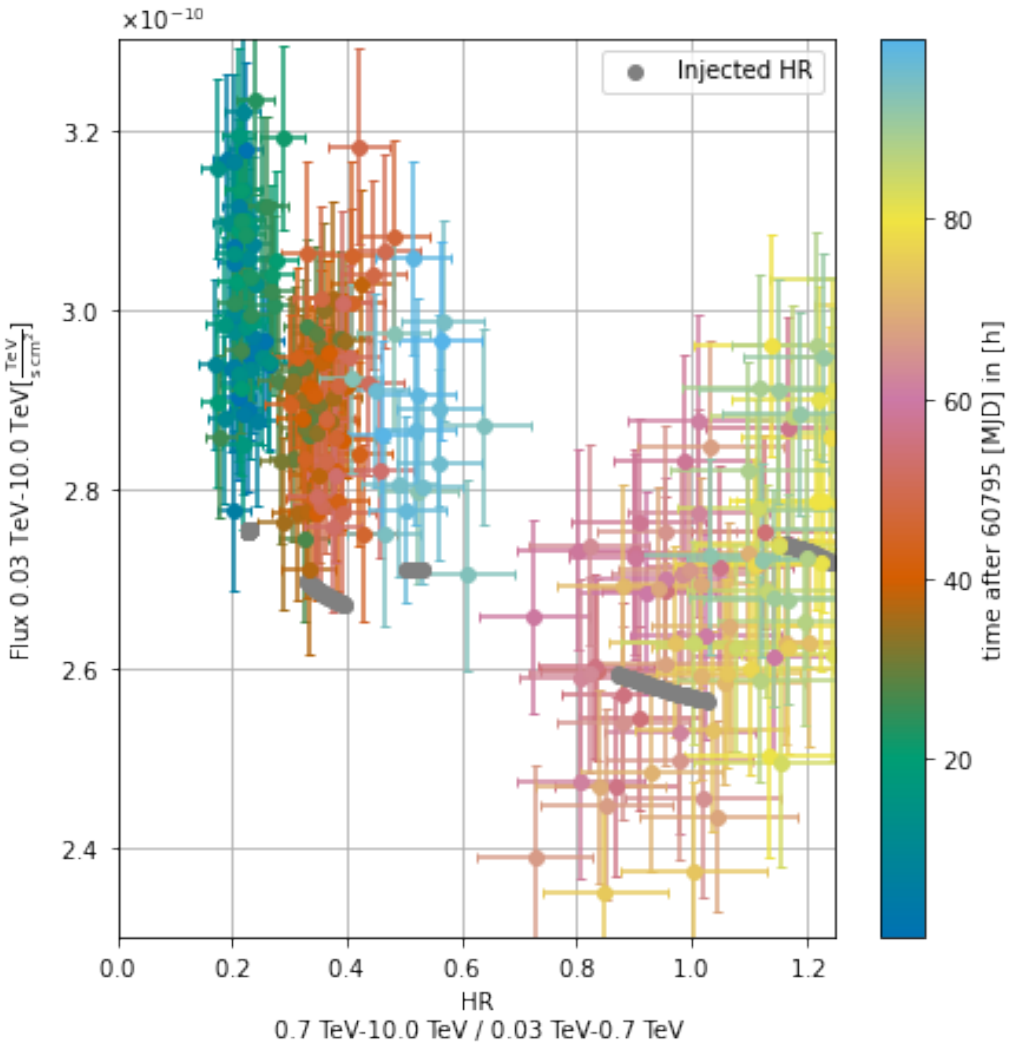
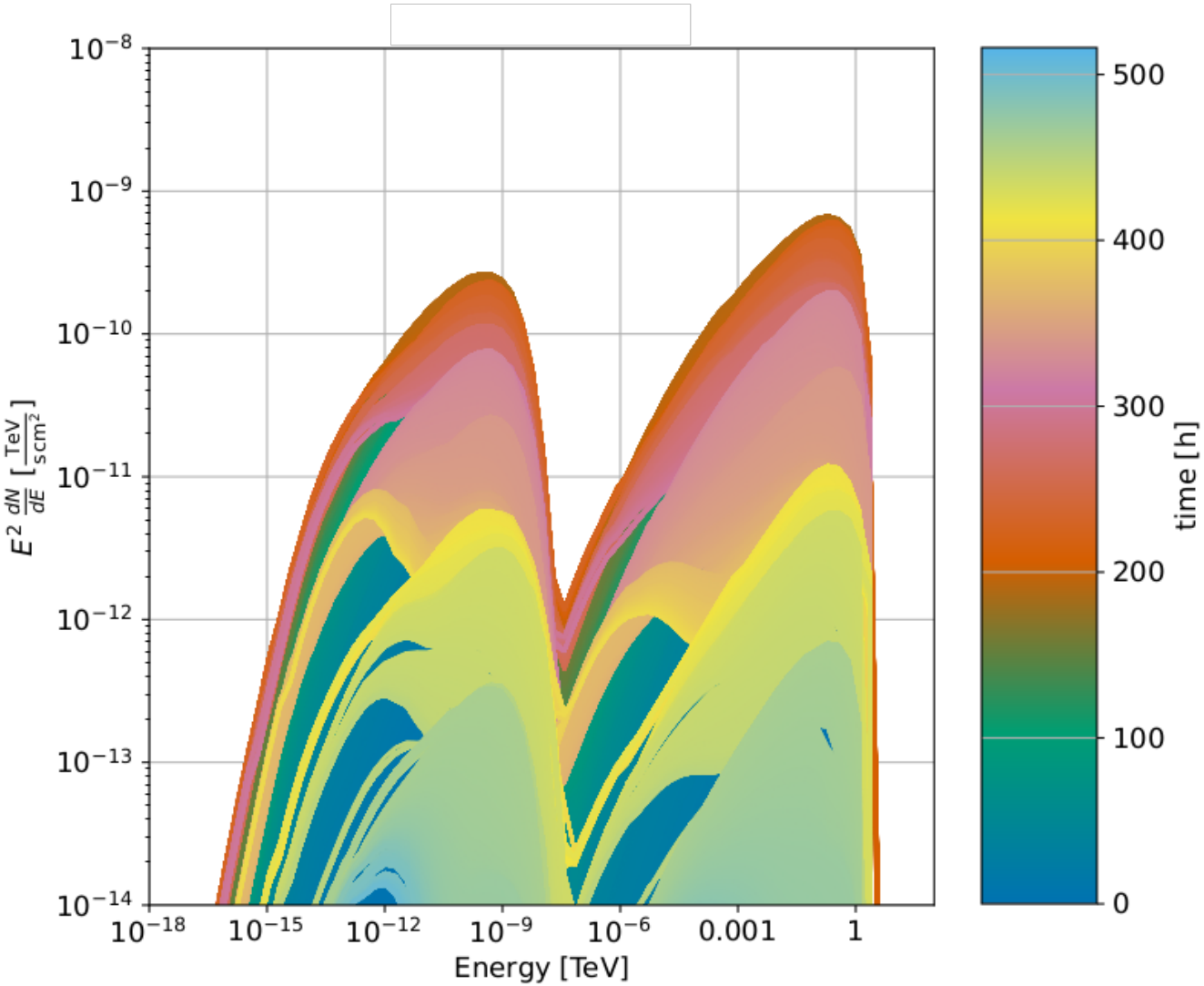




BACKUP – Multi zone with magnetic reconnexion :



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