Investigating AGN Variability with the Cherenkov Telescope Array

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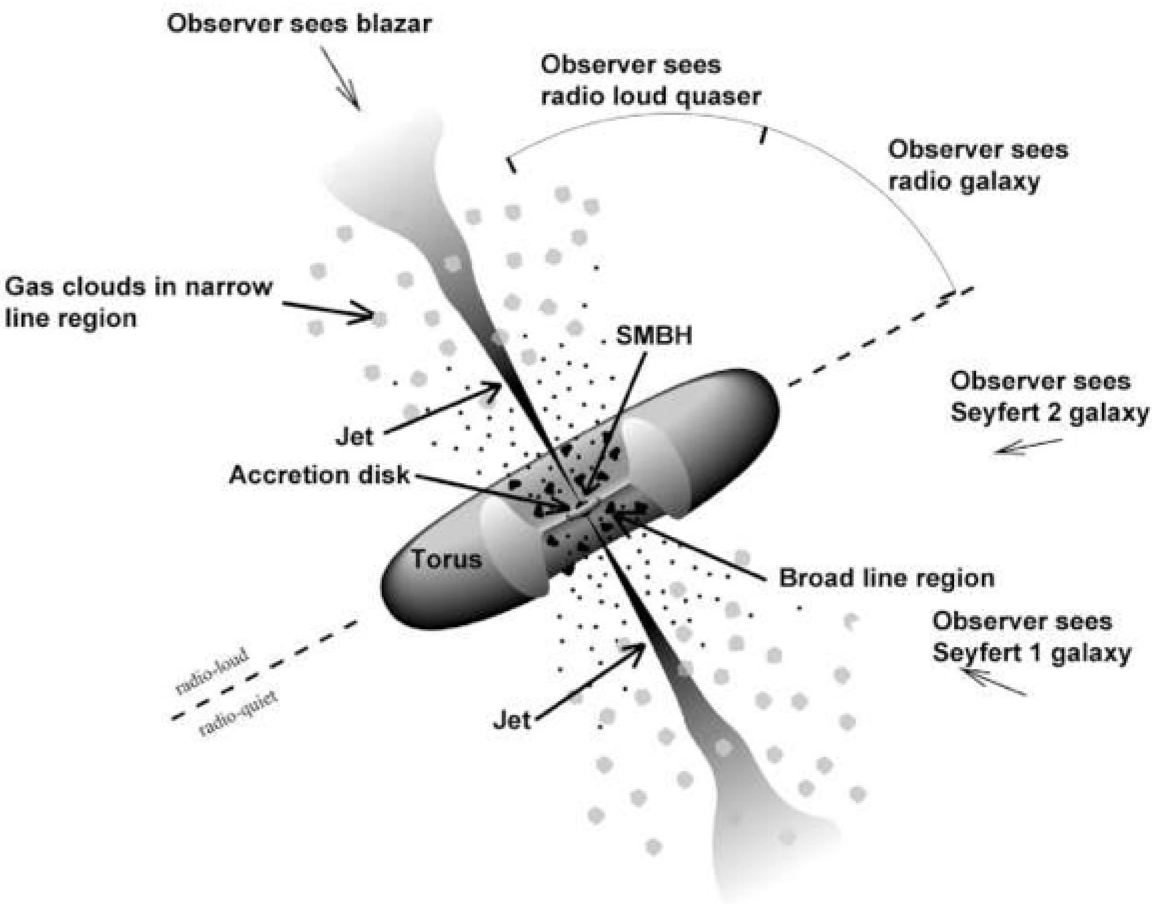
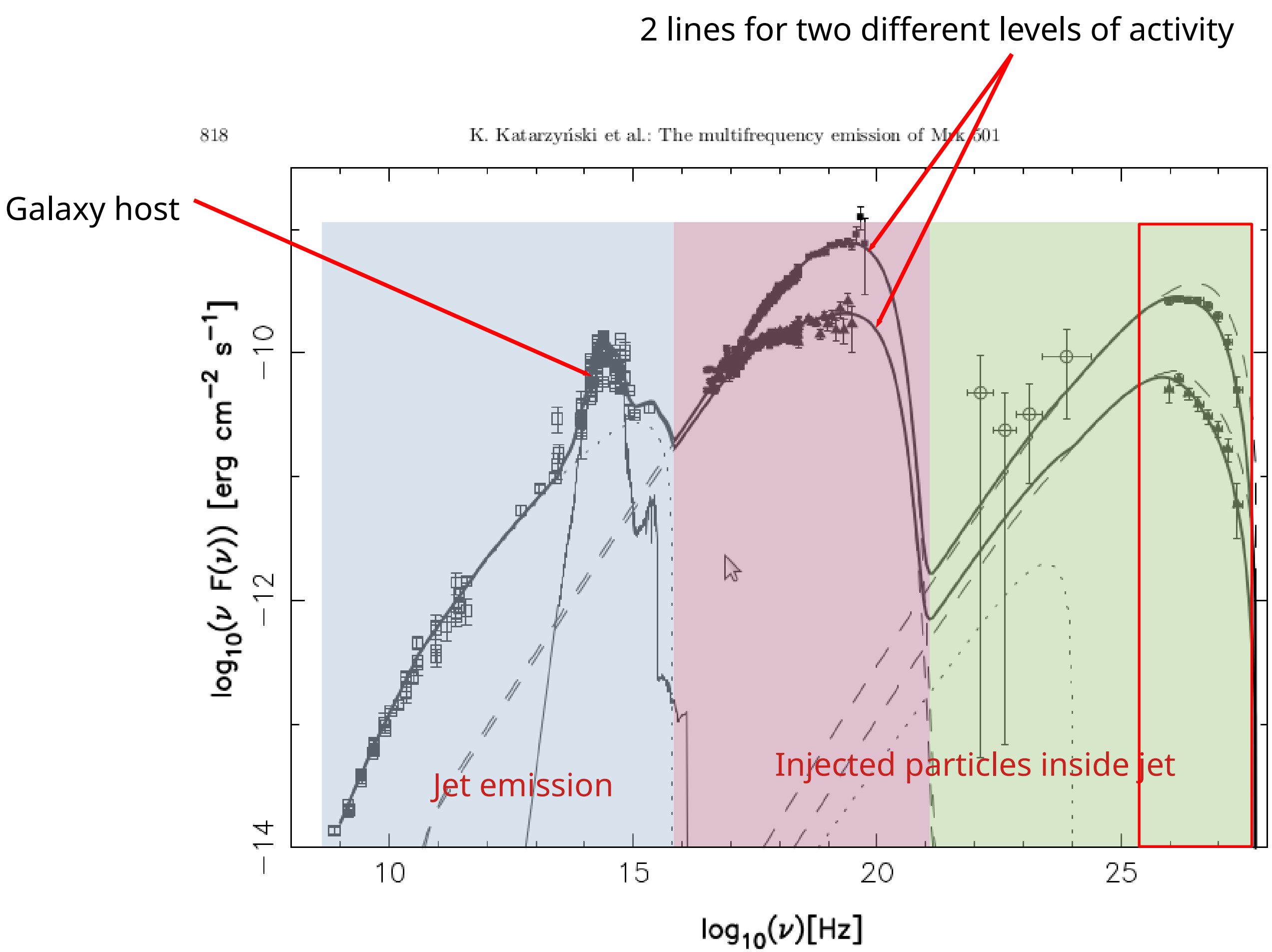
Introduction : Active Galactic Nucleus (AGN)



Credit : NASA, Fermi

- At the center of galaxy
- Super massive black hole (can present a jet)
- Emission from radio to gamma
- Focus on gamma emission (> 10 GeV) with Cherenkov telescopes
- Observe blazar

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

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Introduction : AGN - Physical processes - Focus on VHE component

- <u>Hadronic processes :</u> **Synchrotron emission of accelerated protons + other processes (muon synchrotron emission, pion decay)**
  - It leads to different emission spectrum
  - It is hard with current instruments to discriminate both models
  - But with CTA it should be possible

  → Simulate and analyze observations with CTA to quantify its capability to discriminate this model

- <u>Inverse Compton emission :</u> **can be done on various fields**
  - Synchrotron emission (SSC)
  - External IC :
    - Galaxy host
    - Accretion disk
    - Black hole dust torus

  → Again : simulate observations with such models and study how CTA should be able to reconstruct injected parameters

- <u>Extra Galactic Background (EBL) absorption :</u> **The VHE part of the emission is aborbed by the EBL light through gamma-gamma interaction, the EBL light is produced by all the galaxies in the Universe**

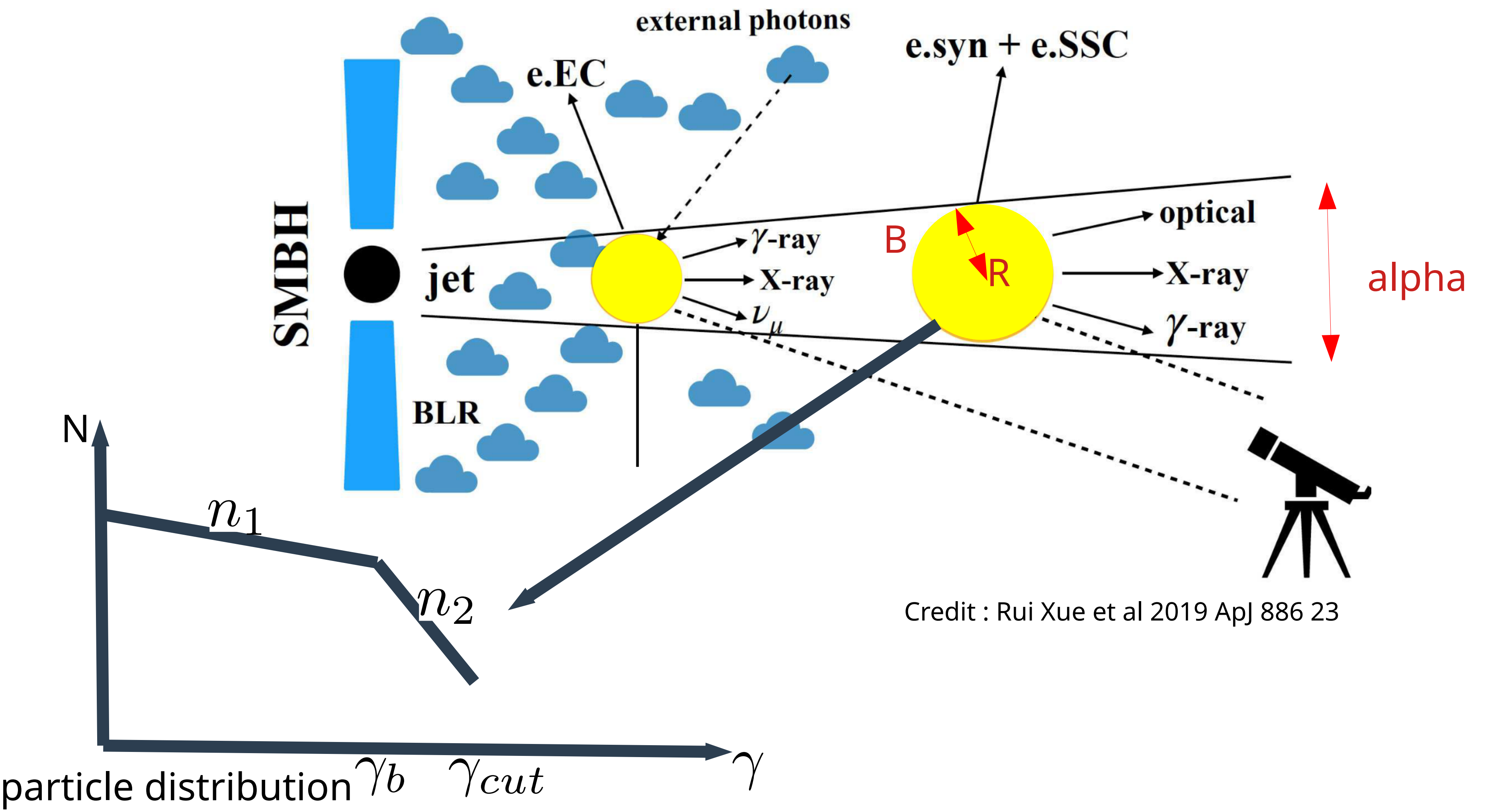
Introduction : AGN - Physical processes - Focus on VHE compo

- Hadronic processes : Synchrotron emissi ... on emission, pion decay)
  - It leads to different ...
  - It is har ...

- **The well known "Préfou in jet" problem :**
  - Préfou : lepto-hadronic model
  - Where are the préfou ?
    - Hidden In the dust torus ?
    - Close to the central black hole ?
    - ...

- ... (EBL) absorption : The VHE part of the emission is aborbed by the EBL light th... gamma interaction, the EBL light is produced by all the galaxies in the Universe

Introduction : AGN - Physical processes - Single zone blob in jet model

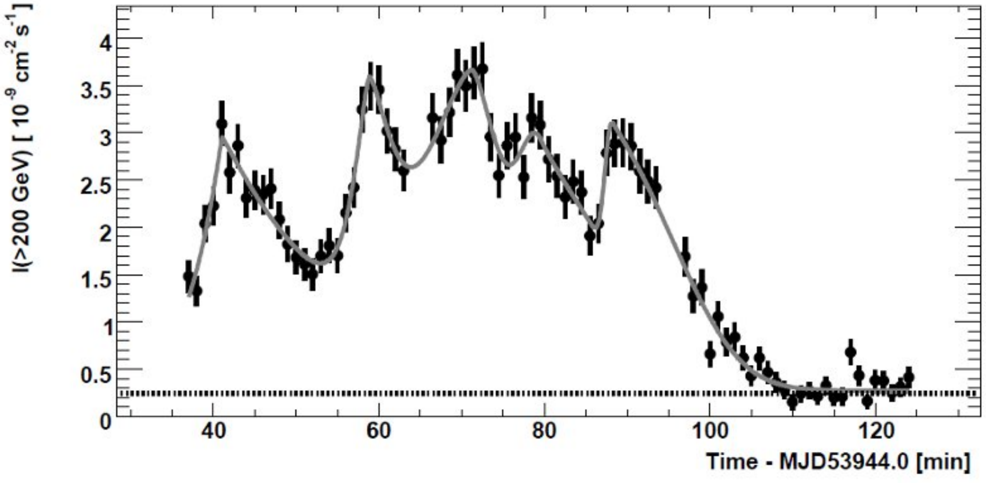


Credit : Rui Xue et al 2019 ApJ 886 23

Introduction : AGN - Physical processes

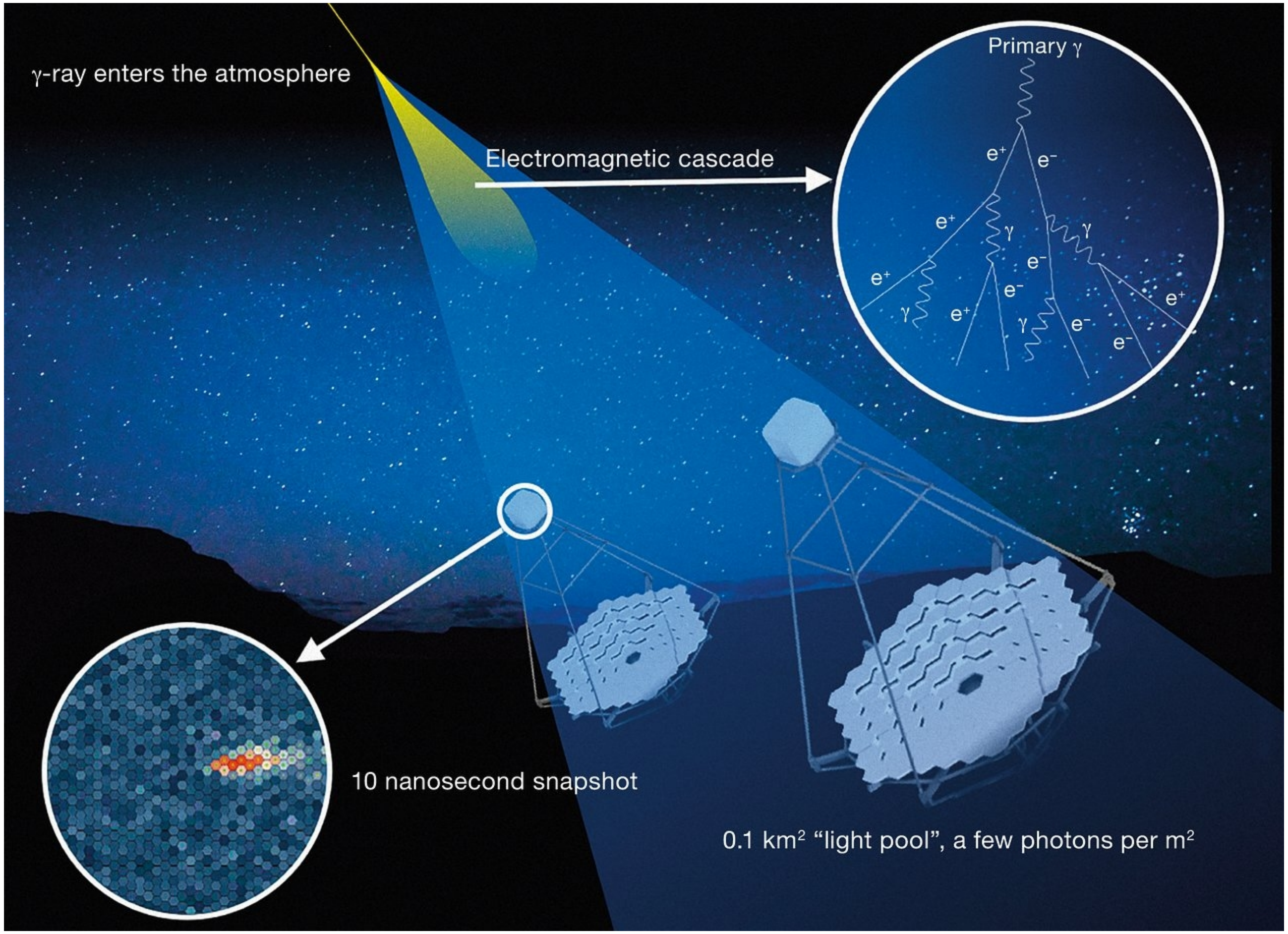
- **AGN can present variability in time on short and long time scale**

  → Simulate and analyze observations with CTA one short and long time scale to study the CTA performances.
  - which variability time scale can be reconstruct ?
  - what is the best cadence strategy to study AGN on long term time scale ?
  - May this time variability discriminate hadronic / leptonic models ?



Aharonian et al. 2007 (H.E.S.S. Collaboration)

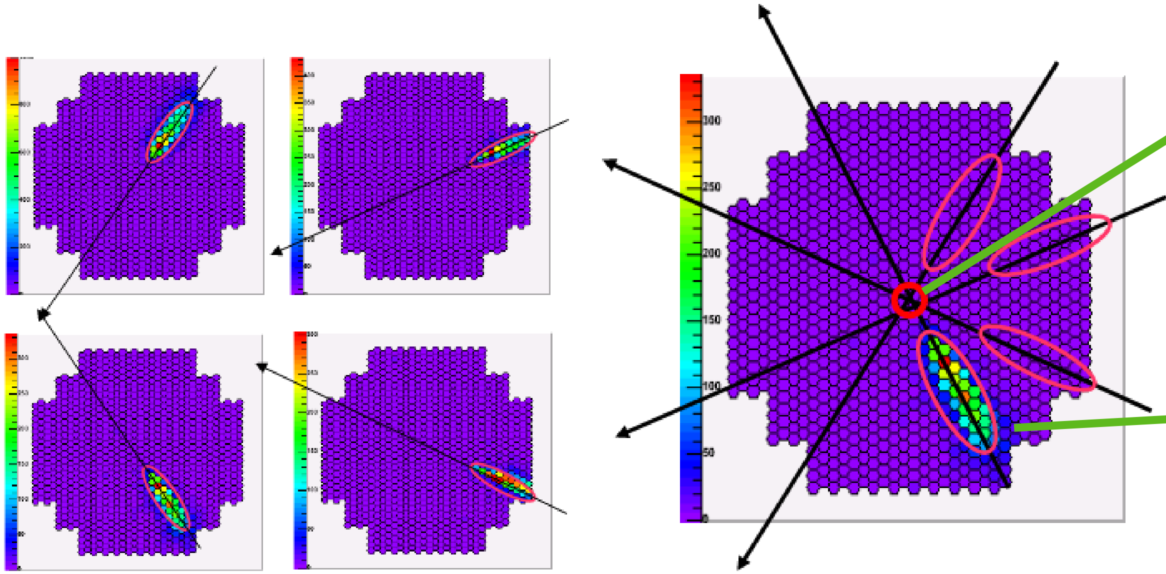
Introduction : Cherenkov radiation induced in atmosphere



Credit : CTAO/ESO

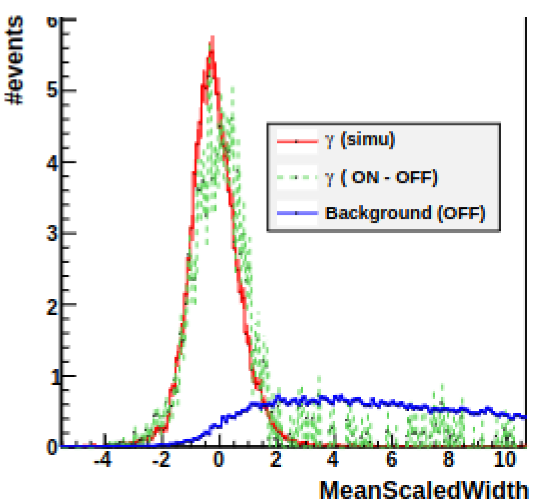
- Cherenkov light : a particle propagating in a medium can emit Cherenkov light if its speed is greater than the speed of light in this medium
- When a gamma ray coming from the universe goes into atmosphere, it creates a particles spray, some of that particles can be fast enough to emit Cherenkov light
- We can observe this light with ground base telescope and then reconstruct the energy and direction of the initial gamma ray
- Cosmic rays create Cherenkov light too : it's background for us
  → need to discriminate between gamma ray and cosmic ray reconstruction

Introduction : gamma ray reconstruction and noise rejection

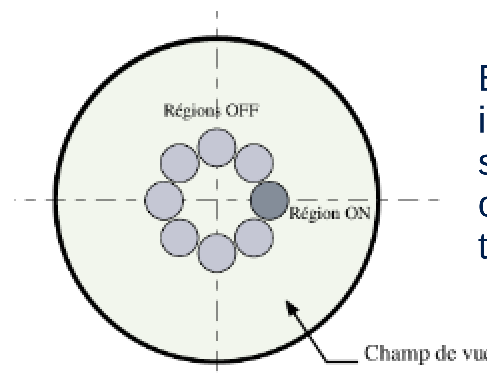


Stereoscopic reconstruction of the impact parameters

Energy of the primary particle computed from the charge in the camera



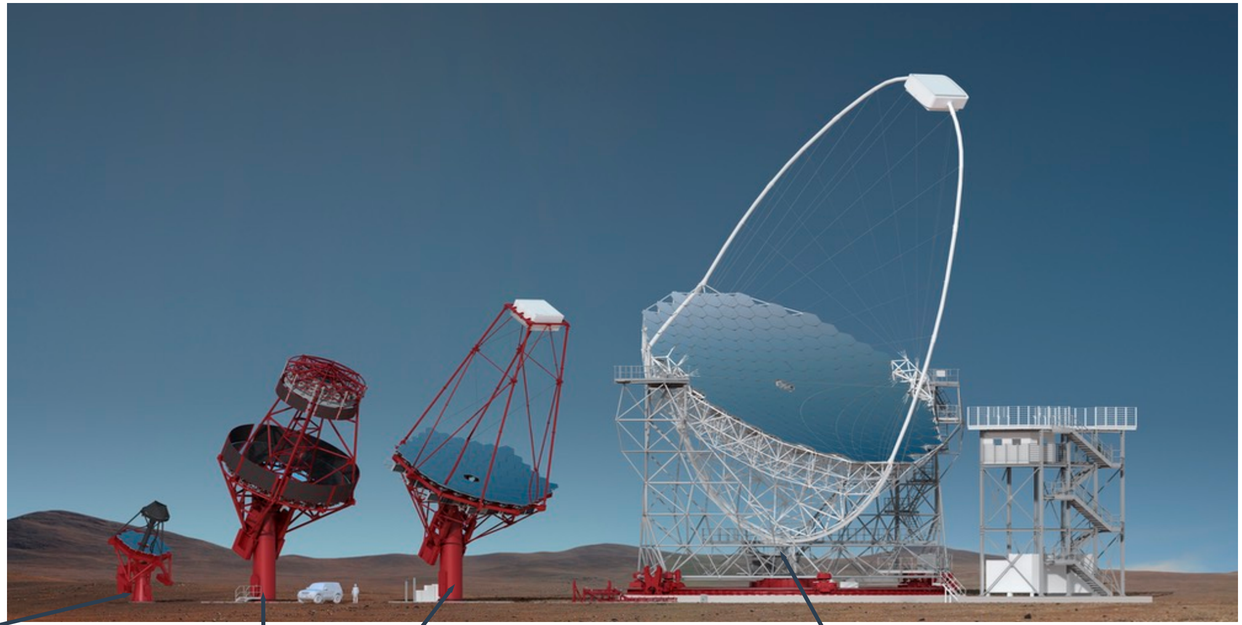
Discrimination gamma / hadrons
→reject most of the hadrons events and only keep the gamma-like events
- cut can be either strict or loose



Background measured in OFF region, and then subtract to the number of counts detected in the ON region.

Credit : M. de NAUROIS

Introduction : CTA - Telescopes



Credit : CTAO/ESO

SST : diameter ~ 4m
5 TeV – 300 TeV

SCT- MST : diameter ~ 10m
150 GeV – 5 TeV

LST : diameter ~ 20m
20 GeV – 150 GeV

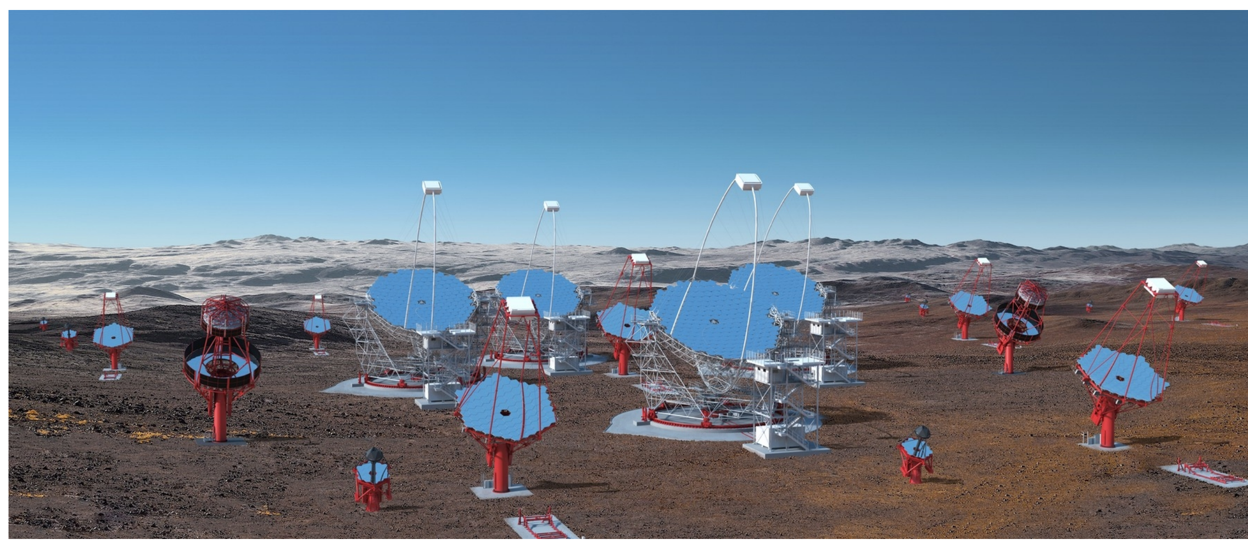
- Warning : SCT construction is still hypothetical
- LPNHE is involved in building MST camera (NectarCam)
- on my side : working on calibration (gain calibration)

Introduction : CTA - Sites

- 2 sites : one by hemisphere

- North : La Palma, Spain
  - 4 LST
  - 9 MST

- South : Atacama Desert, Chile
  - 4 LST
  - 14 MST (+SCT?)
  - 37 SST



Credit : CTAO/ESO

Introduction : Gammapy

- official Science Analysis Tool library for the CTA Observatory
- Simulation and analysis of data from H.E.S.S, MAGIC,VERITAS,Fermi and HAWC → wide range of energy
- Simulation : gamma like event (not Cherenkov cascade) !

A **Python** package for gamma-ray astronomy

I – AGN variablility study with CTA

- **CTA : more sensitive by a factor 5 to 10 depending on energy**
- **To determine sciences cases :**

  → need to quantify the future capacities for AGN variability study

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

I – CtaAgnVar workflow

Inputs :

models

Phenomenological models :
→ time dependant 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

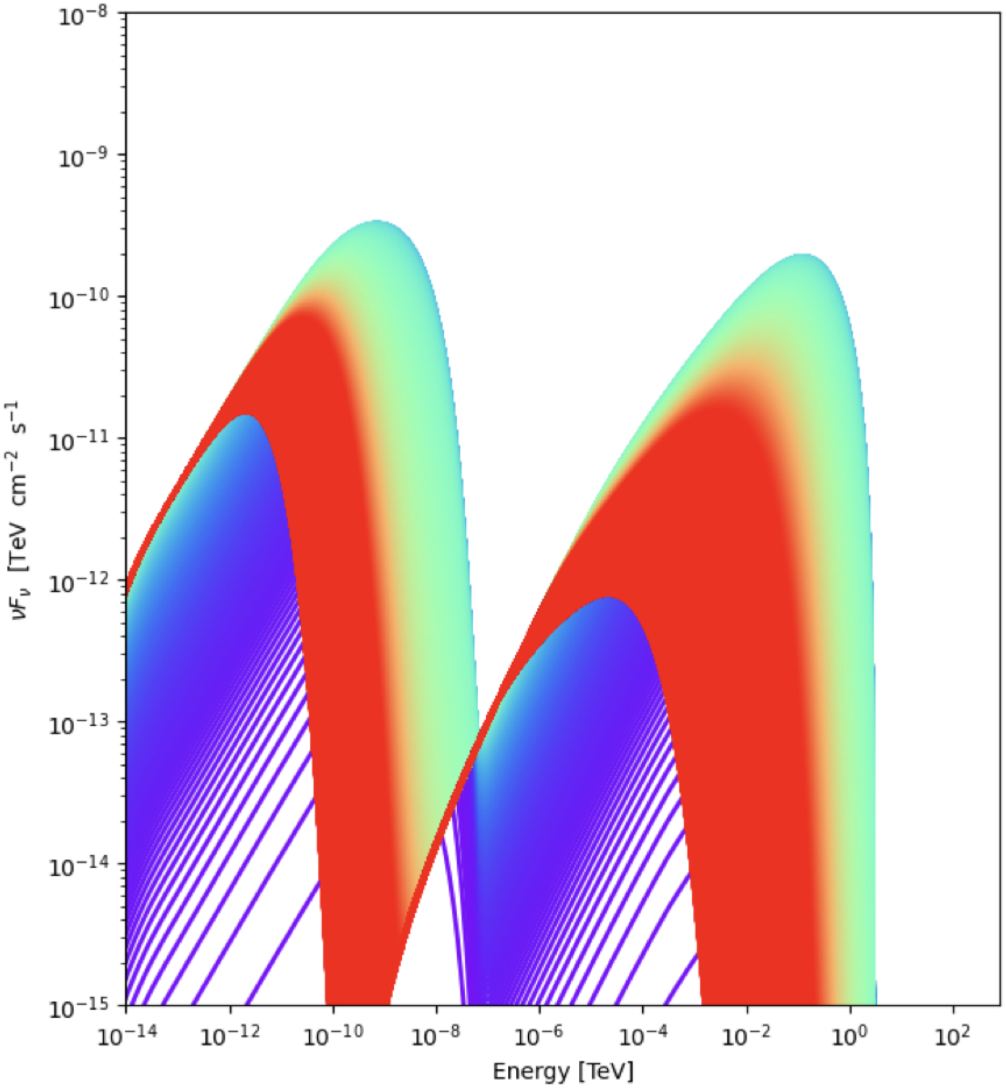
Non constant time bins :
→ merge some analysis with different time bins to artificially simulate time dependent time bins

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

II – AGN flares simulations – Mrk 421

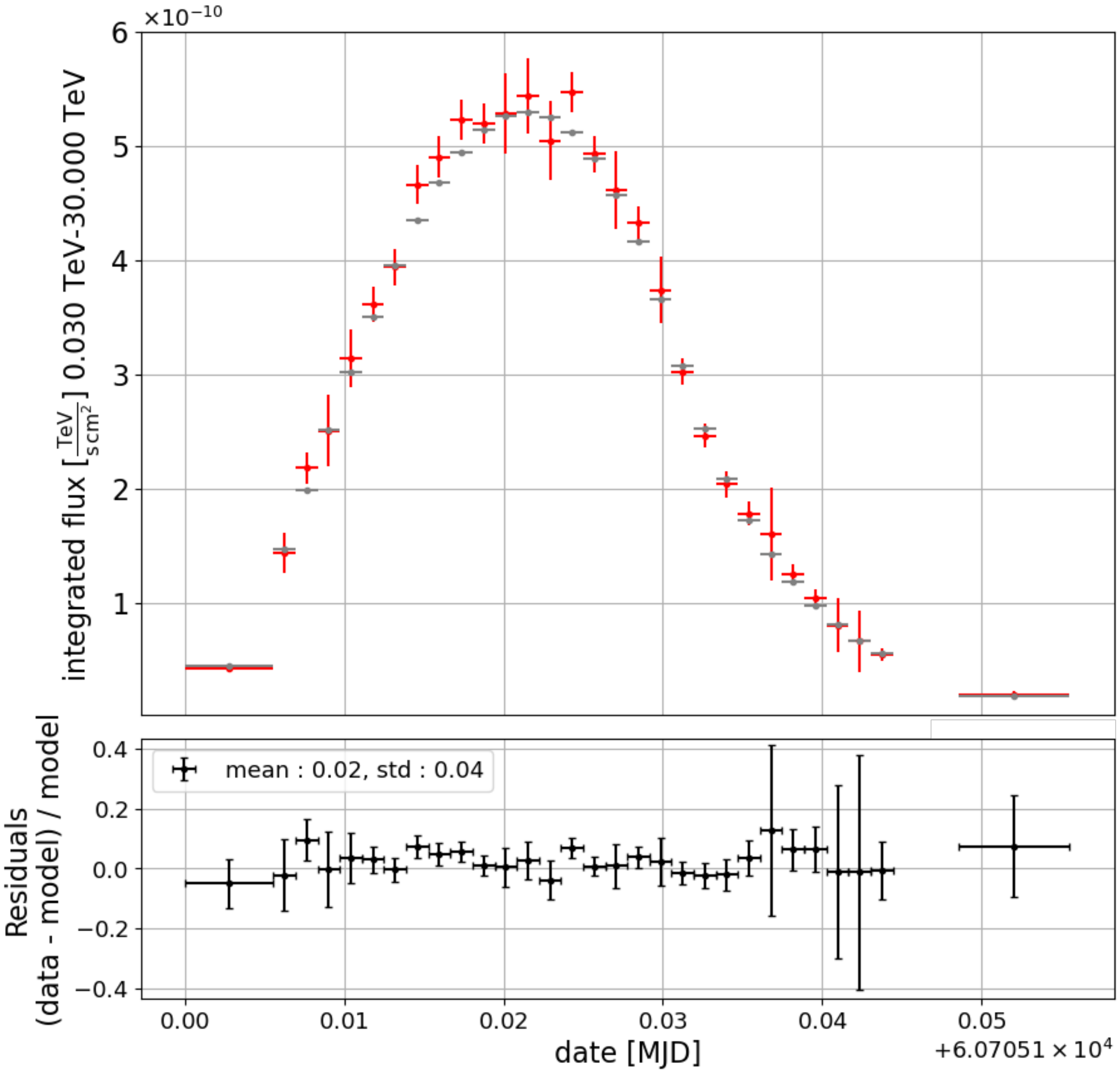
- **To illustrate the possibility :**
  - Mrk 421 simulations based on model from Finke et al. ApJ 2008, built from 2001 flare
  - SSC model
  - 20h flare → one night
- **Workflow :**
  - Perform the simulation of the gamma like event observed
  - Fit a power law EBL absorbed model (+curvature or cutoff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

II – Mrk 421 flare simulations
Injection



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

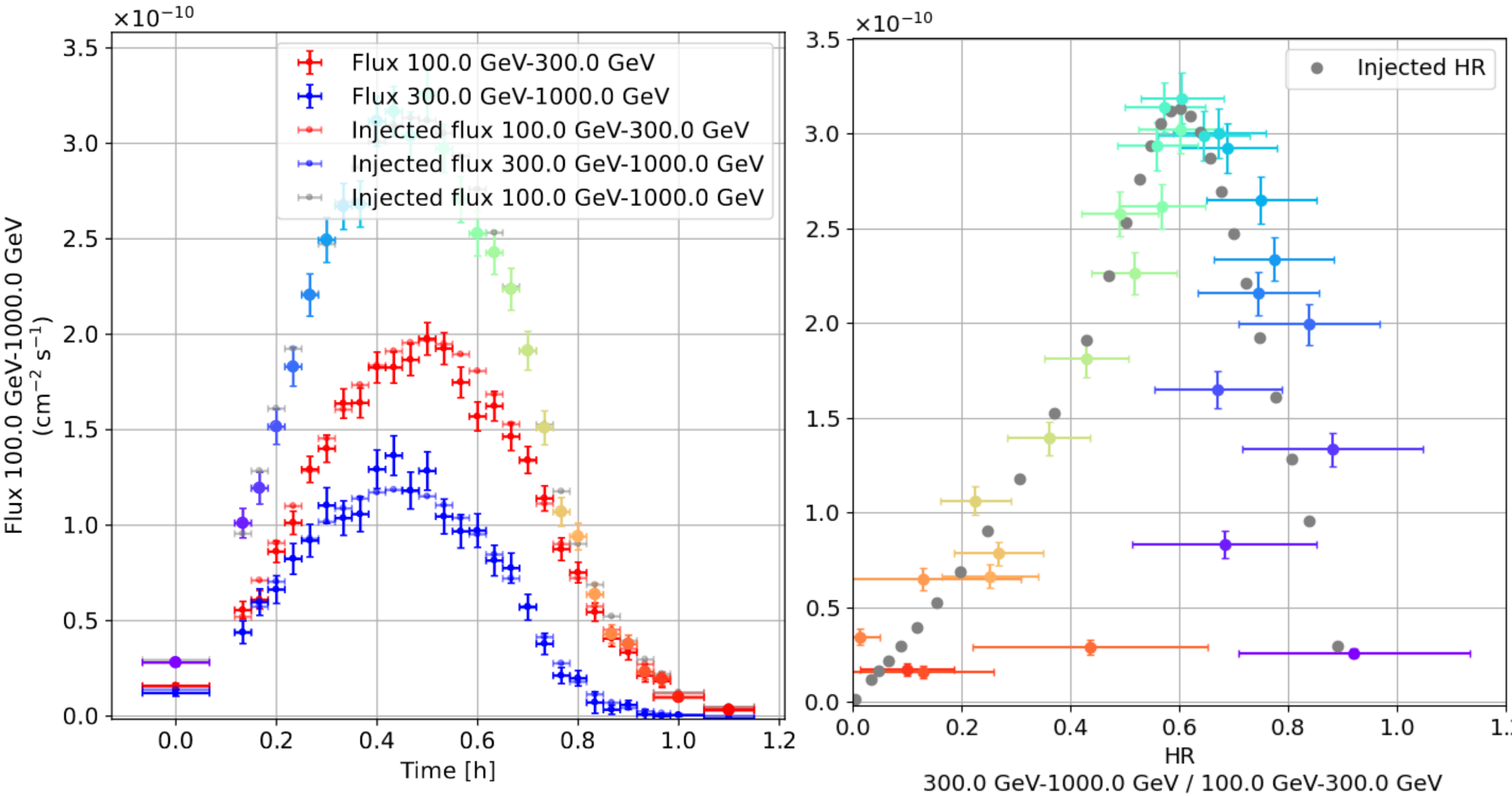
II – Mrk 421 flare simulations – Light curve reconstruction



Reconstructed flux between 30 GeV - 30 TeV

- **Flux is reconstructed with a PL fit EBL absorbed, this model 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 – Hardness ratio



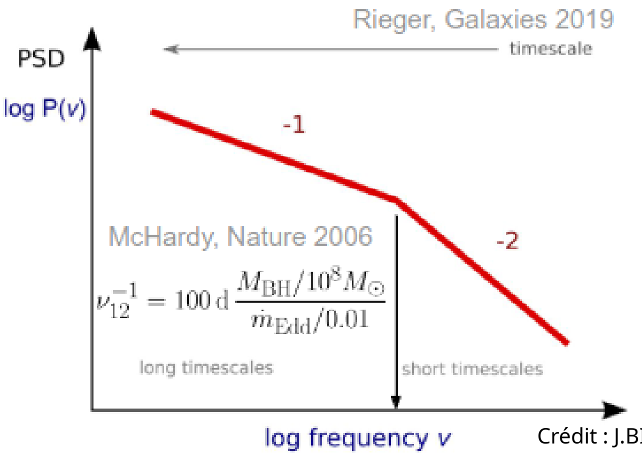
- **Flux is reconstructed with a PL fit**
- **Hysteresis is predicted in injected model**
- **Can see the hysteresis**

Cerruti et al., ICRC 2023

Left : flux LC in 3 bands, right : HR diagram. The dark blue points are the lowest energy band, red points are the highest one. Colored points are the sum of both energy bands, color evolution is linked to time evolution. Gray points are the theoretical values computed from injected model

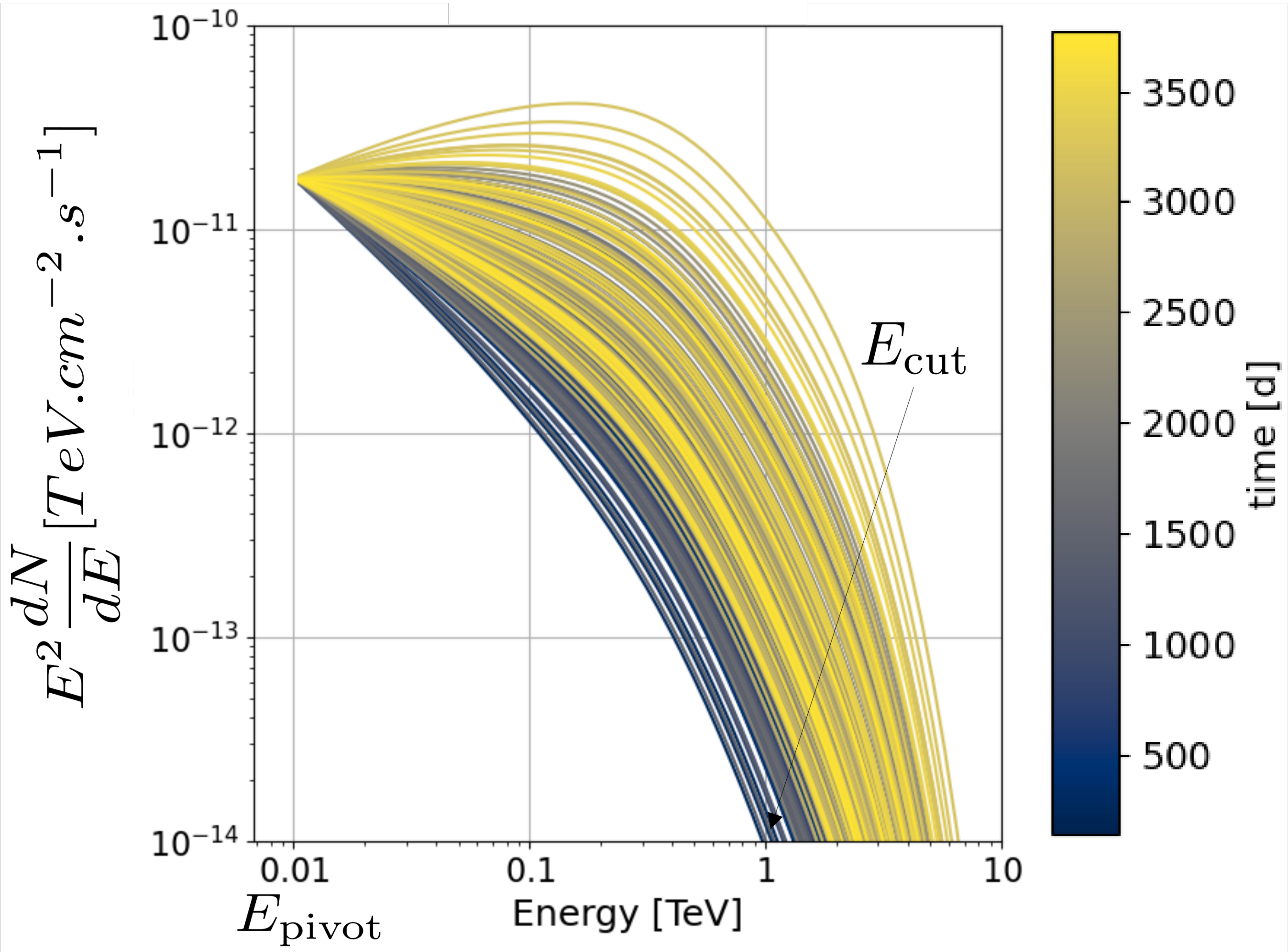
III – AGN long-term monitoring program - BL Lac

- **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**



Crédit : J.BITEAU

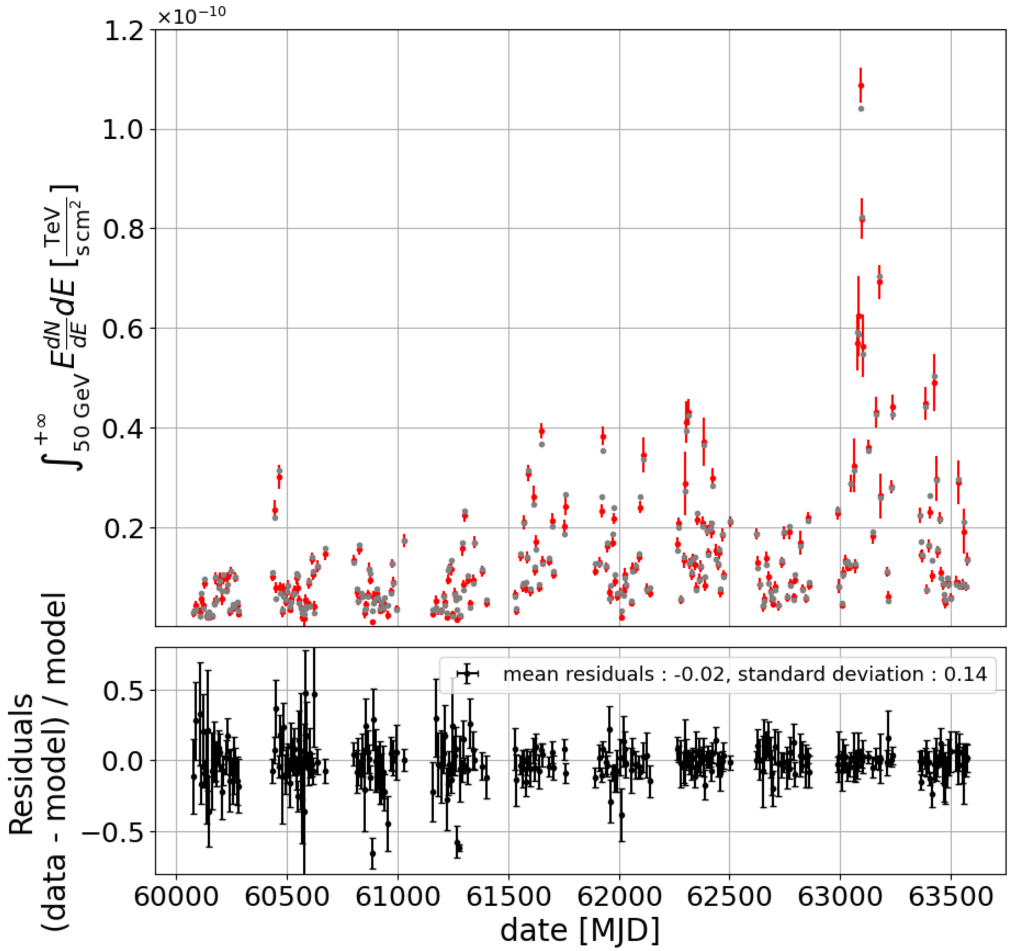
III – AGN long-term monitoring program - BL Lac injected model



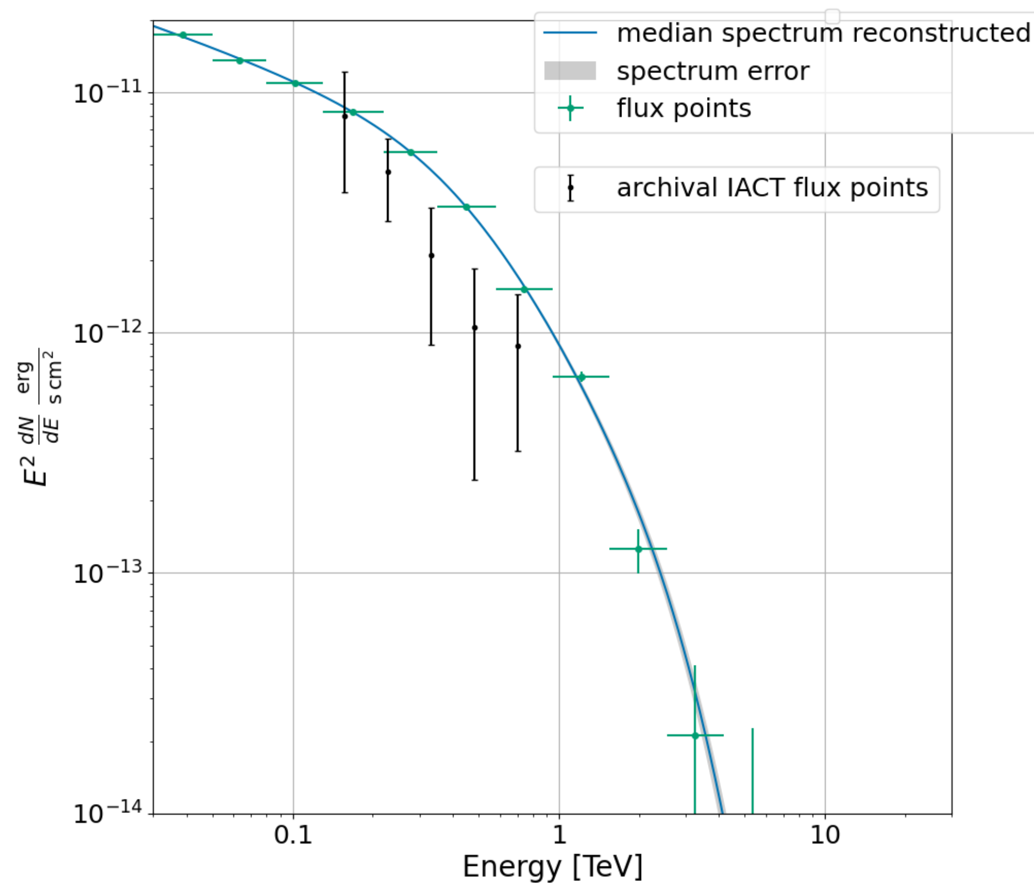
Injected SEDs, color evolution shows time evolution

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

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



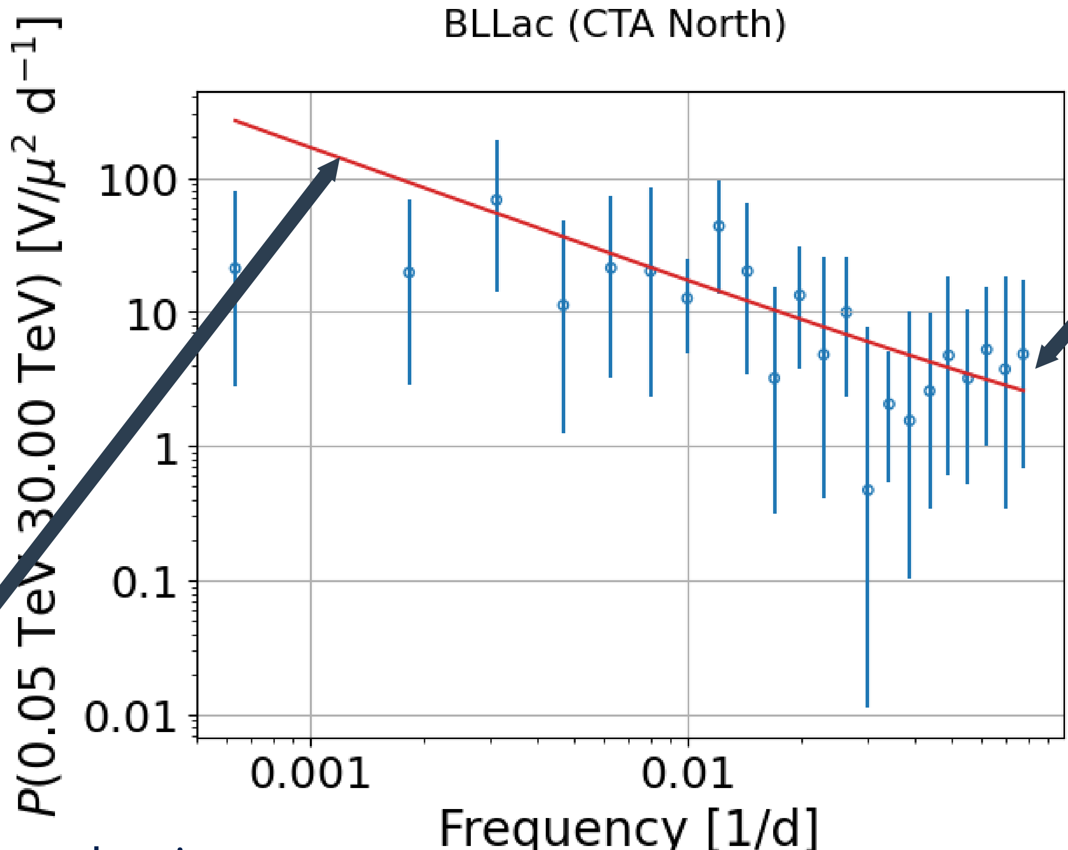
Flux lightcurve over 50 GeV reconstructed for 10 years of data observed with a weekly cadence, gray points are injected values.



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

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

PSD observed for



Poisson plateau

PSD slope = 1 : red noise

We can reconstruct injected PSD but :

- Need to do simulations with break between red and pink noise to quantify its reconstruction feasibility
- Adapt cadence (non constant) to improve the PSD reconstruction accuracy

Grolleron et al., ICRC 2023

Conclusion and perspectives

- **With CTA :**
  - Will be able to give a new look on AGN emission
  - Discrimination between models for AGN flares
  - Possibility to reconstruct with a high level of accuracy the long term PSD and the duty cycle of jetted AGN

Conclusion and perspectives

- **With CTA :**
  - Will be able to give a new look on AGN emission
  - Discrimination between models for AGN flares
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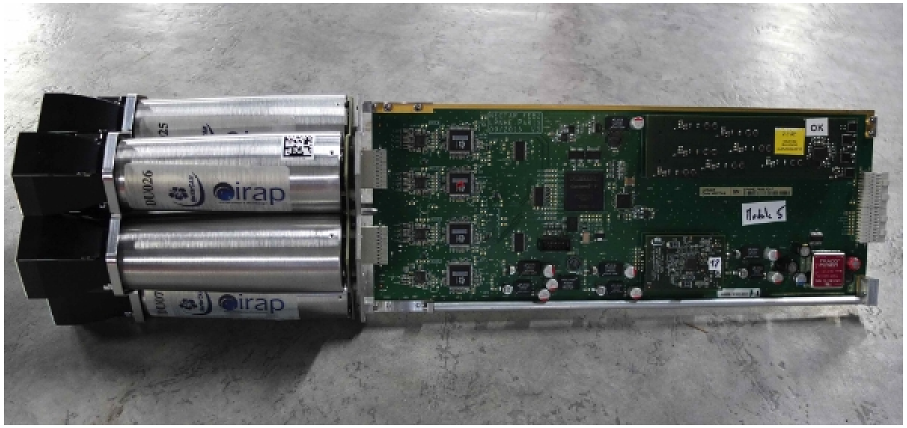
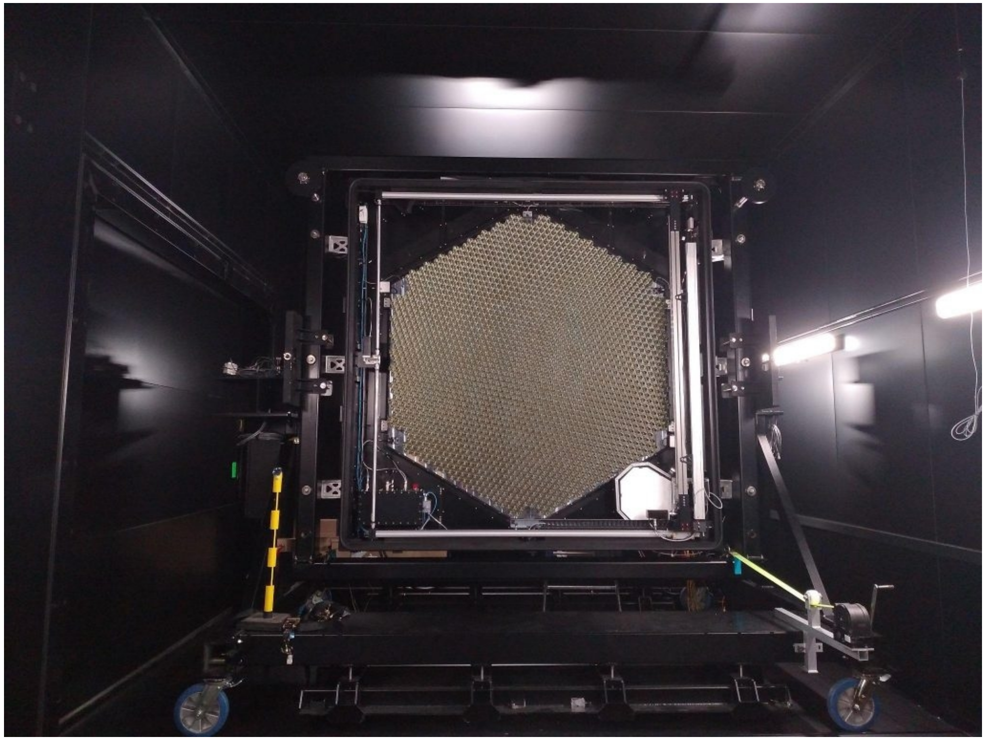
THANK
YOU

Backup : NectarCAM – The MST north camera

- **Camera for the northern MST**
  - 265 modules
  - 1855 pixels
  - 60 ns sampling capacity



1 module of 7 Photomultiplier, credit : NectarCAM collaboration (2016)



Credit : IJCLab – NectarCAM collaboration