Investigating AGN variability with the Cherenkov Telescope Array Observatory

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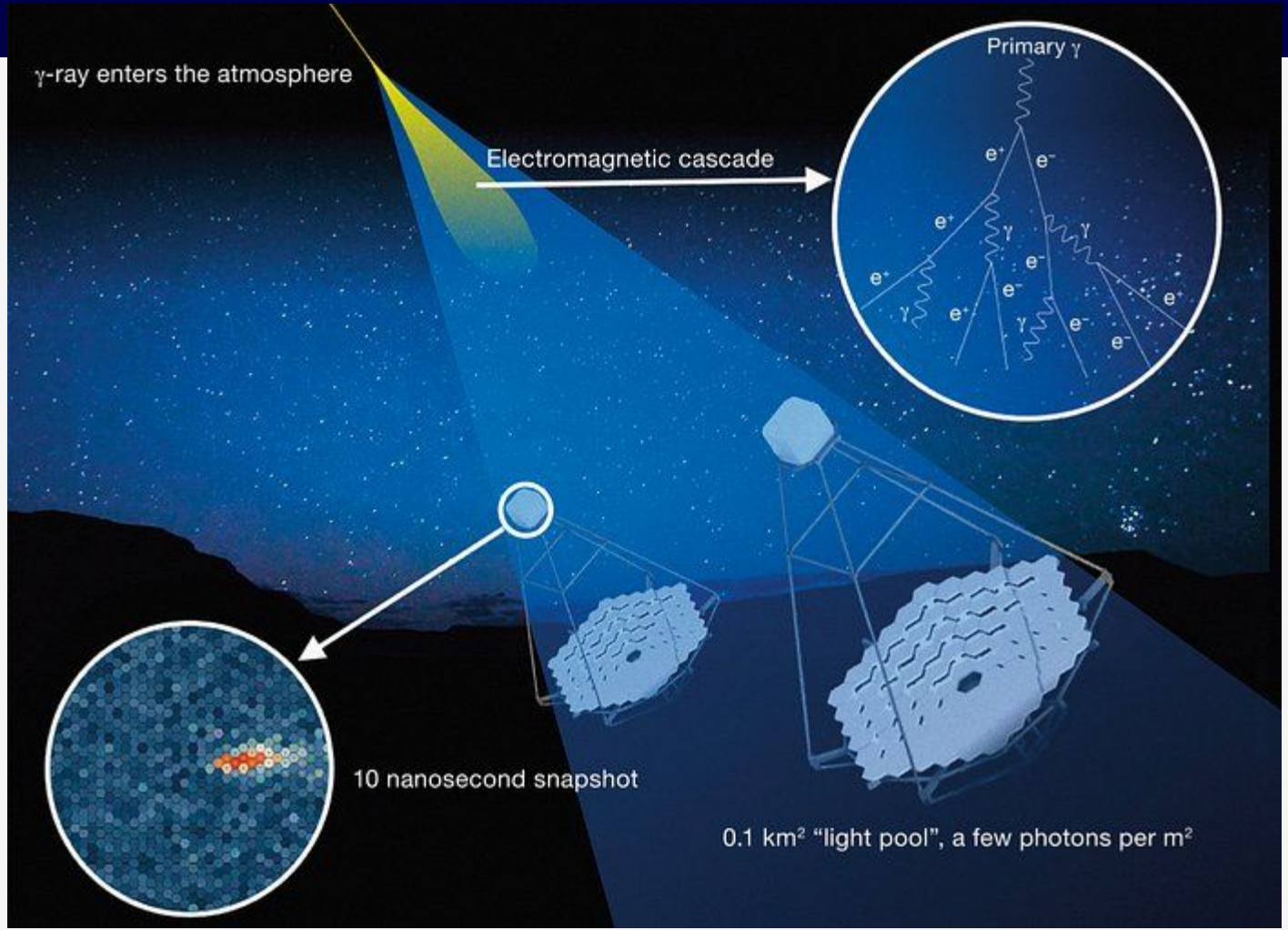
Preambule

I - The Cherenkov Telescope Array Observatory

II - The blazar model

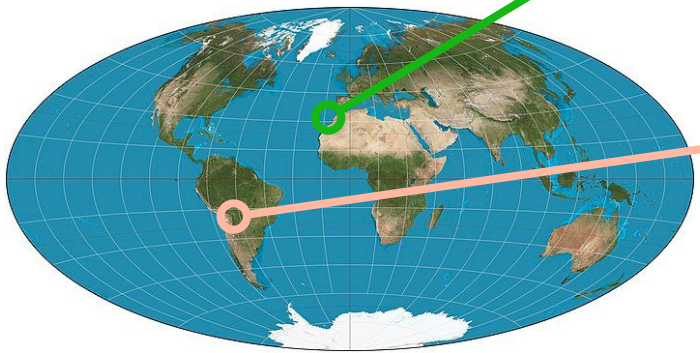
III - AGN variability studies with CTAO

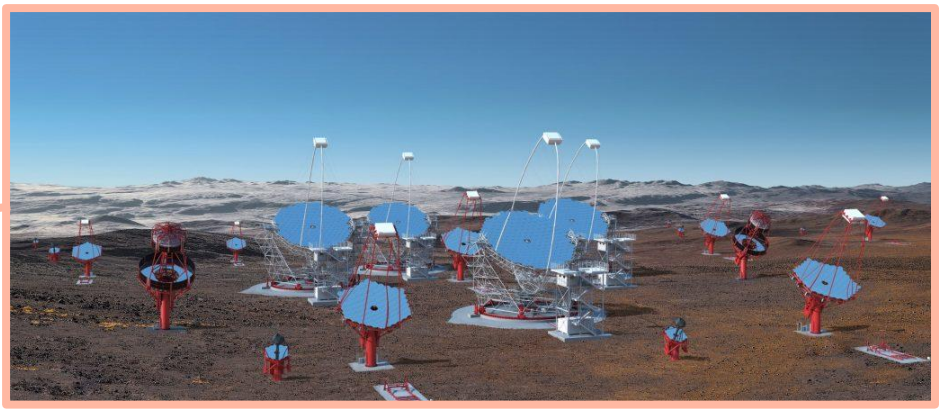
I - The Cherenkov Telescope Array Observatory


γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e⁺
e⁻
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m²

The future CTAO

- The **next generation** of Cherenkov telescopes
  - 2 sites
    - **North** (Spain)
    - **South** (Chile)





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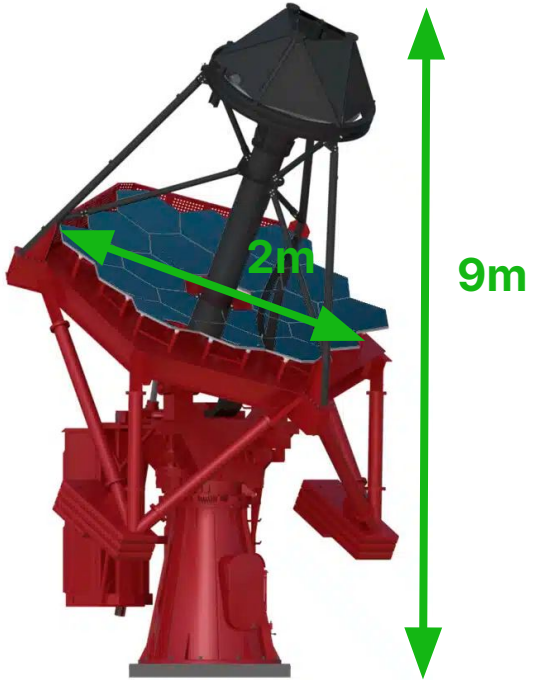
    - from 5 to 300 TeV



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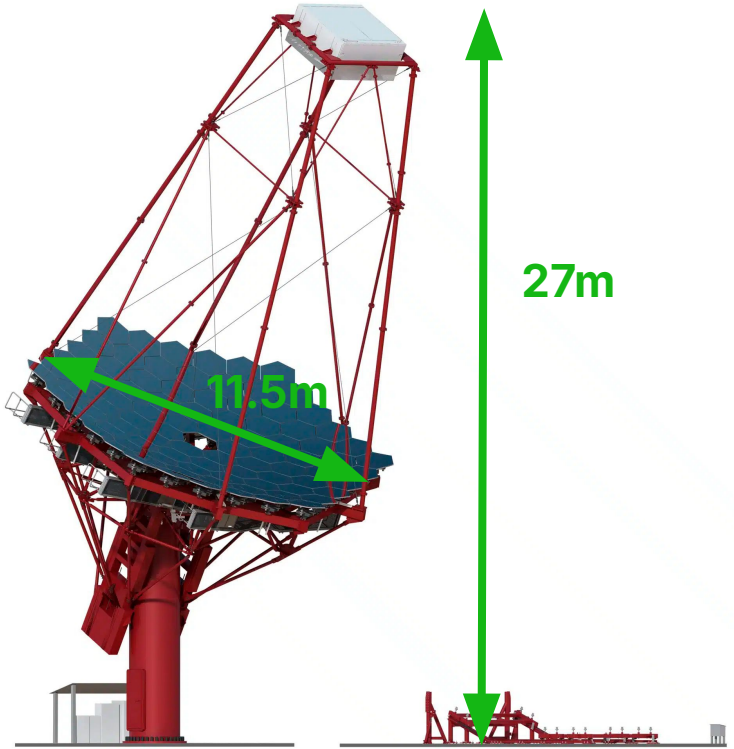

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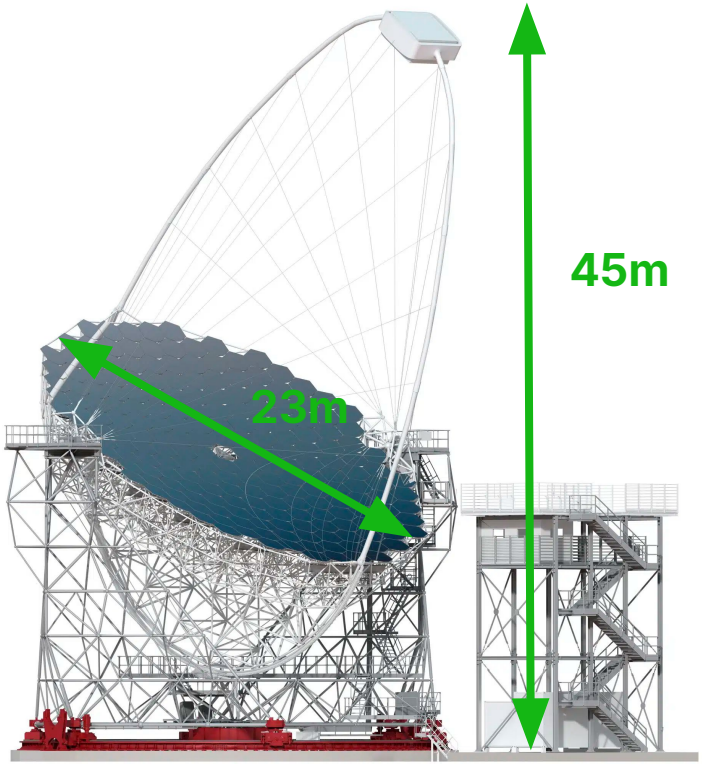

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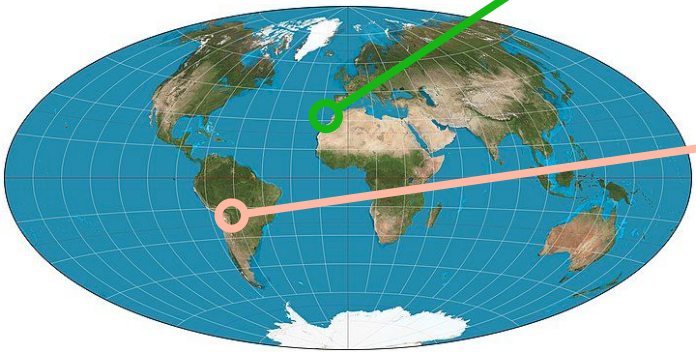

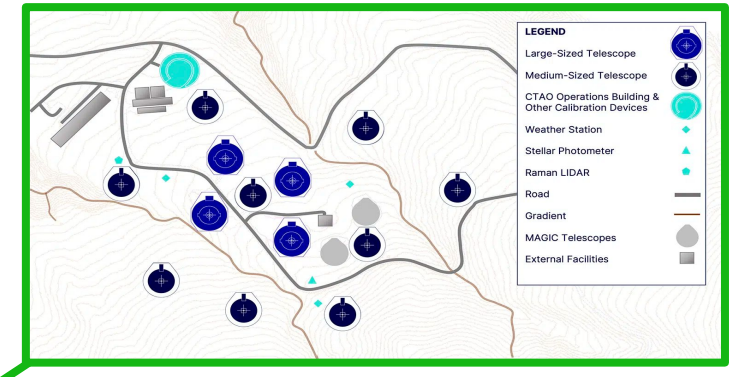

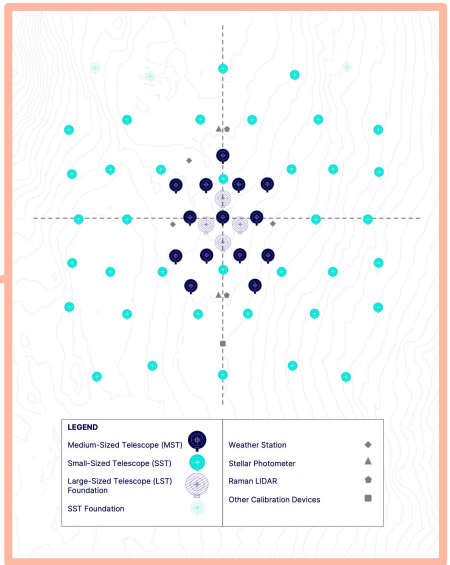

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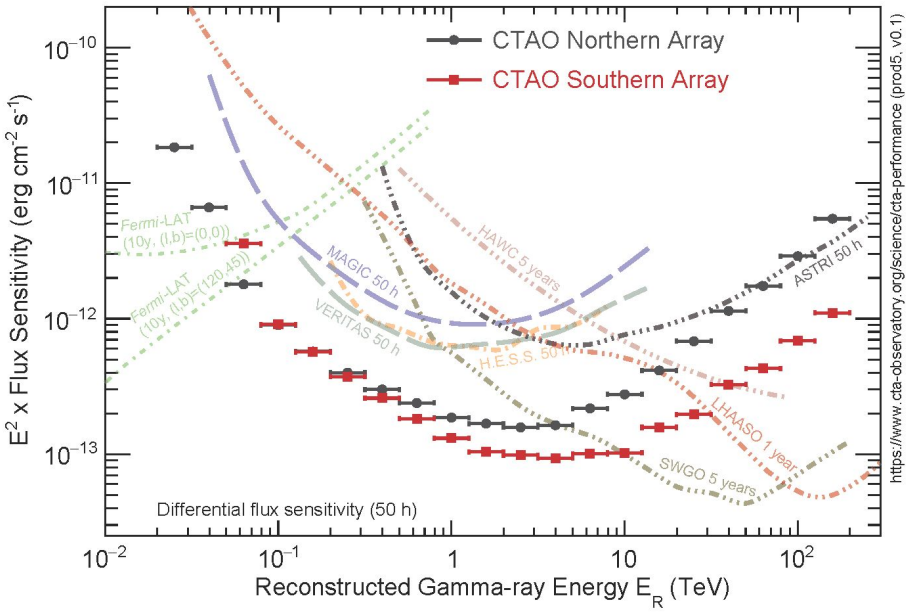

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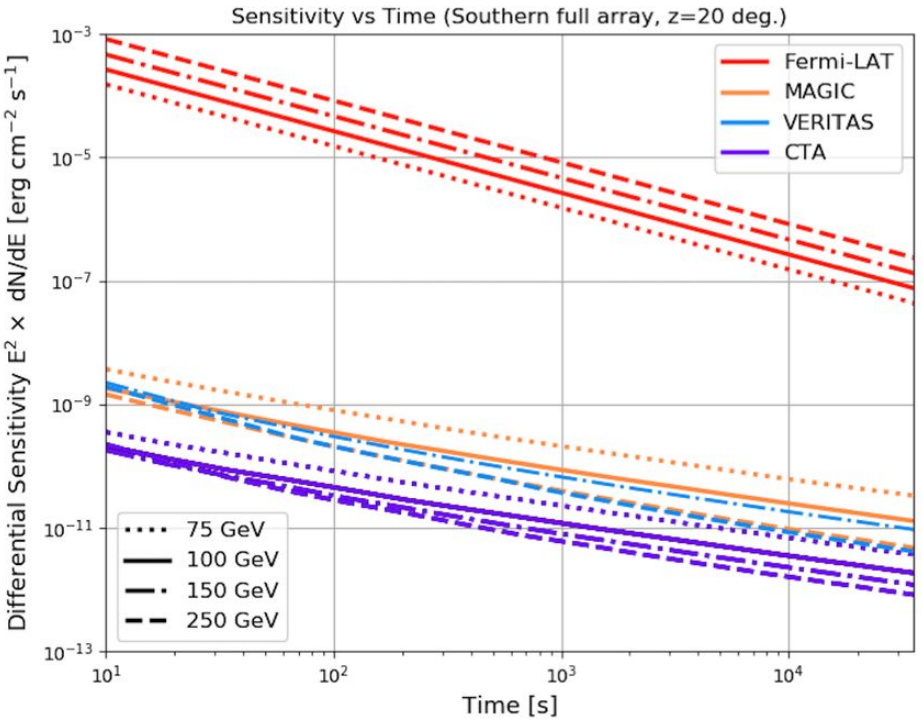
- Very interesting for **variability studies** !



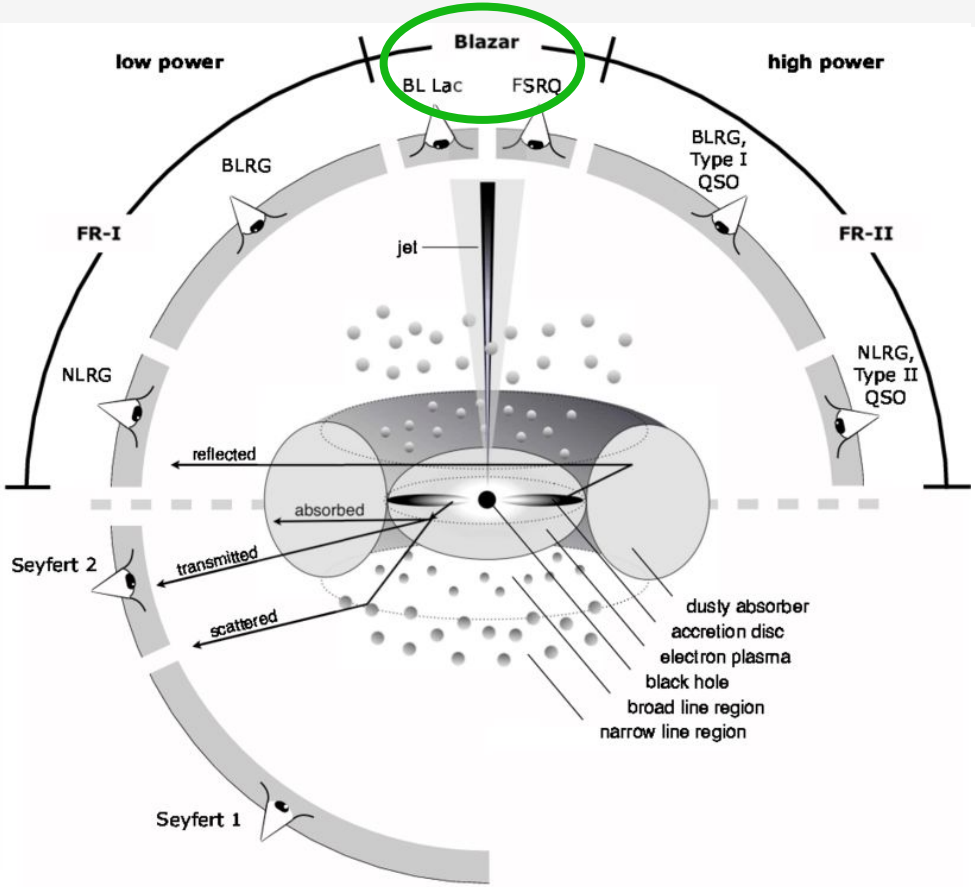
Fioretti et al. 2019

II - The blazar model

ESA/Hubble, L. Calçada (ESO)

Blazar model

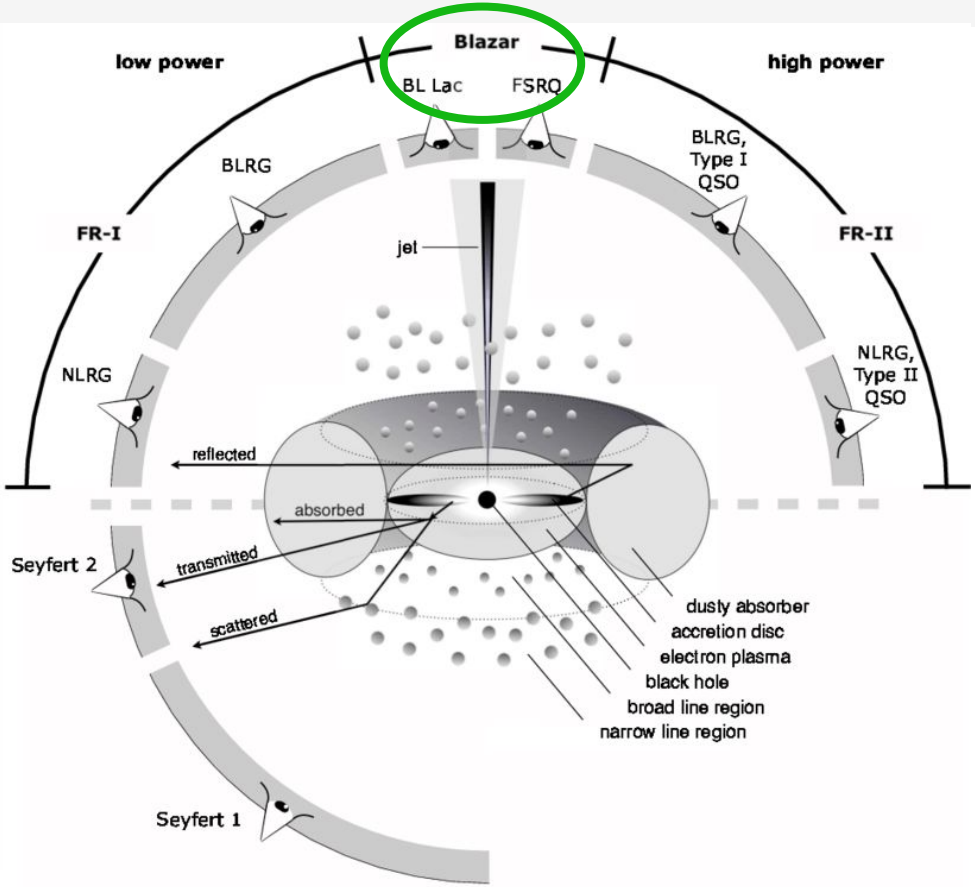
- AGN = compact object in the center of a galaxy
- Blazars = AGN with a **jet toward the observer**



Beckmann and Shrader (2012)

Blazar model

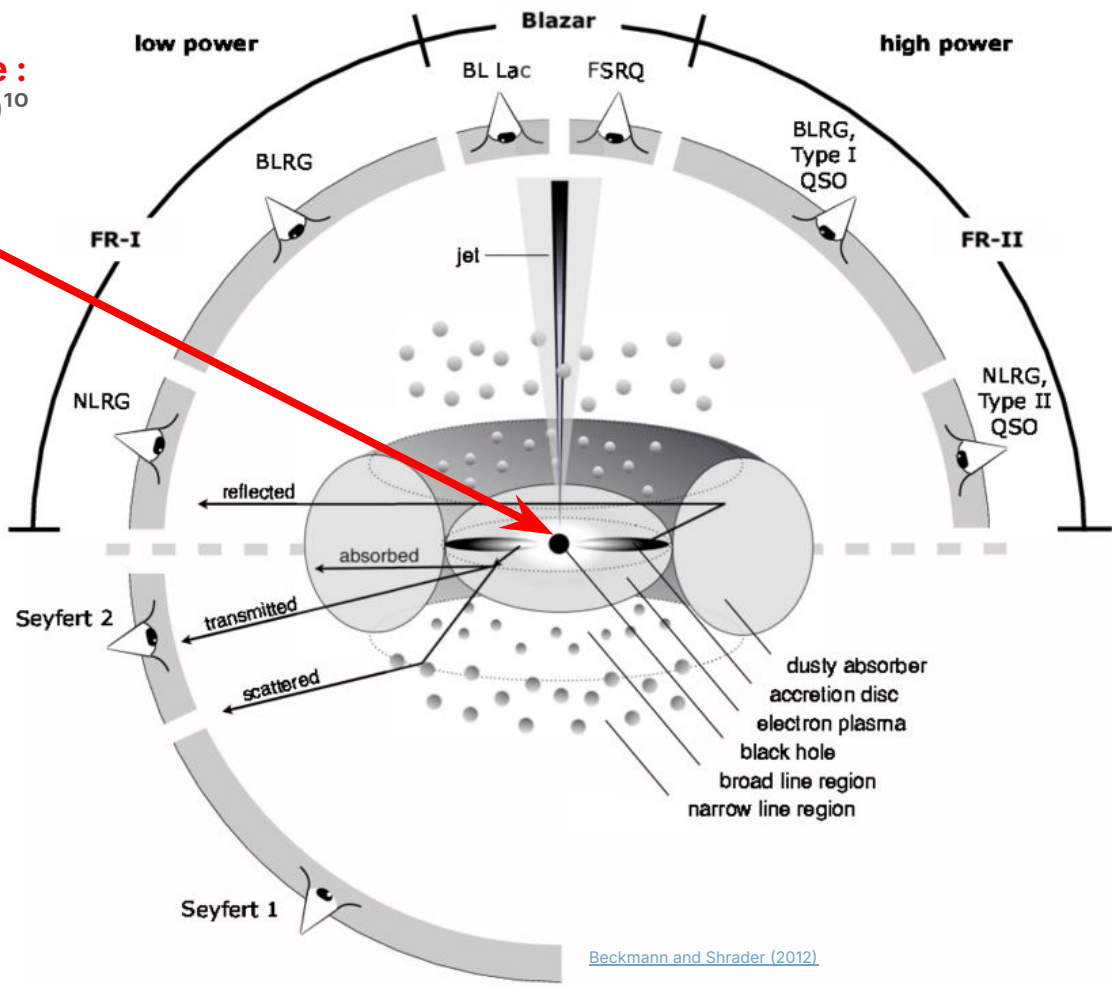
- AGN = compact object in the center of a galaxy
- Blazars = AGN with a **jet toward the observer**
- Emission over the whole electromagnetic spectrum, **from the radio to the very high energy gamma rays**



Beckmann and Shrader (2012)

Centrale black hole :

- from 10^5 to 10^{10} solar masses



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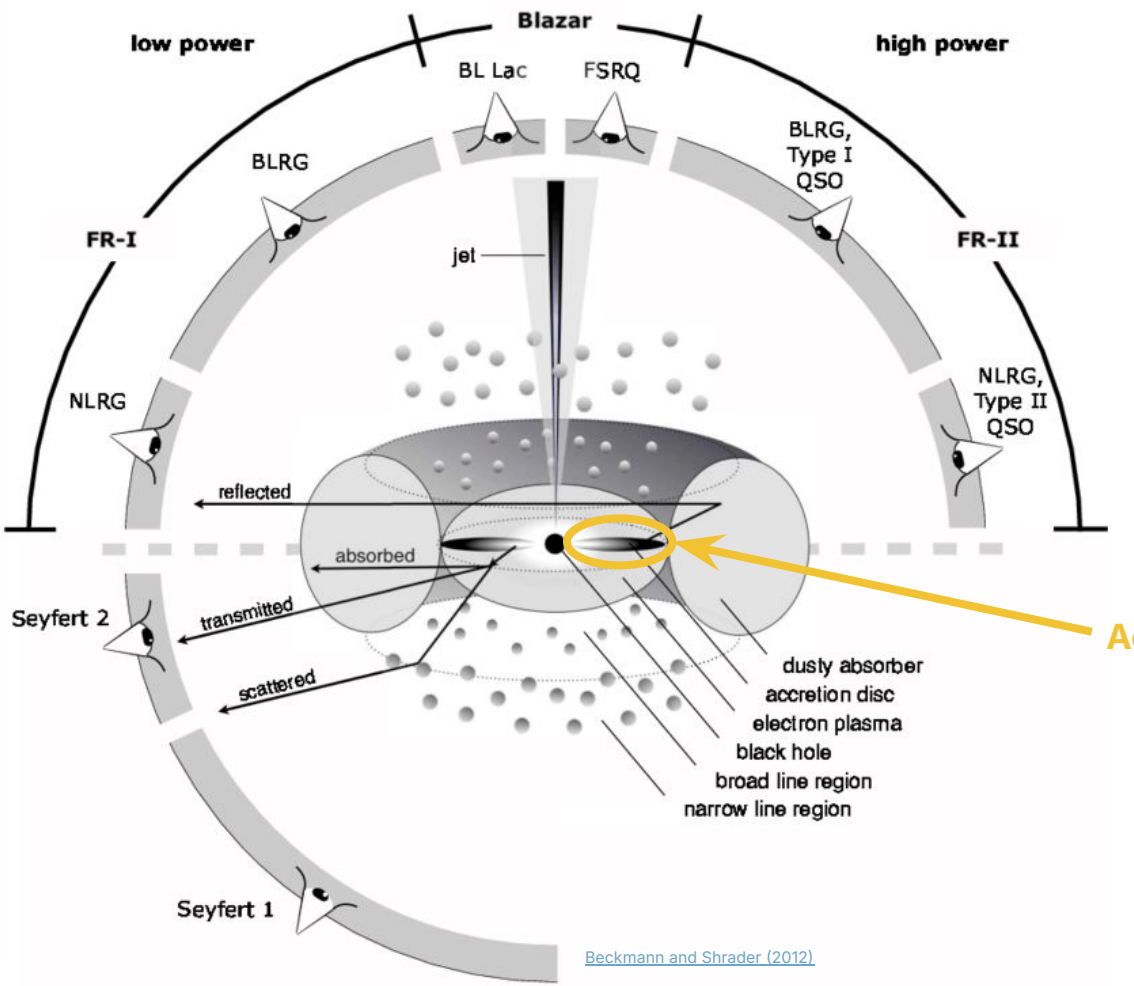
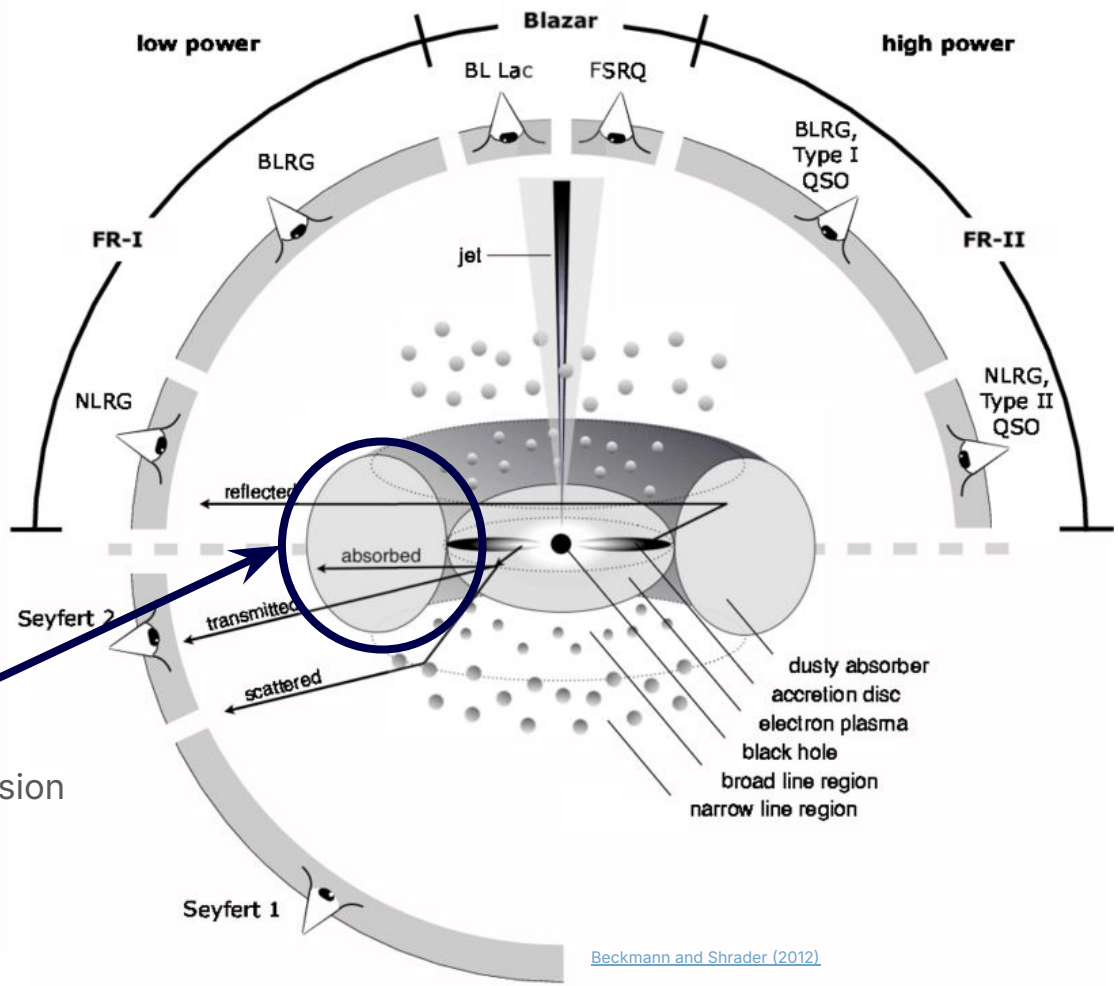


Beckmann and Shrader (2012)

Accretion disk :

- **Thermal** emission
- **Optical** and **UV**



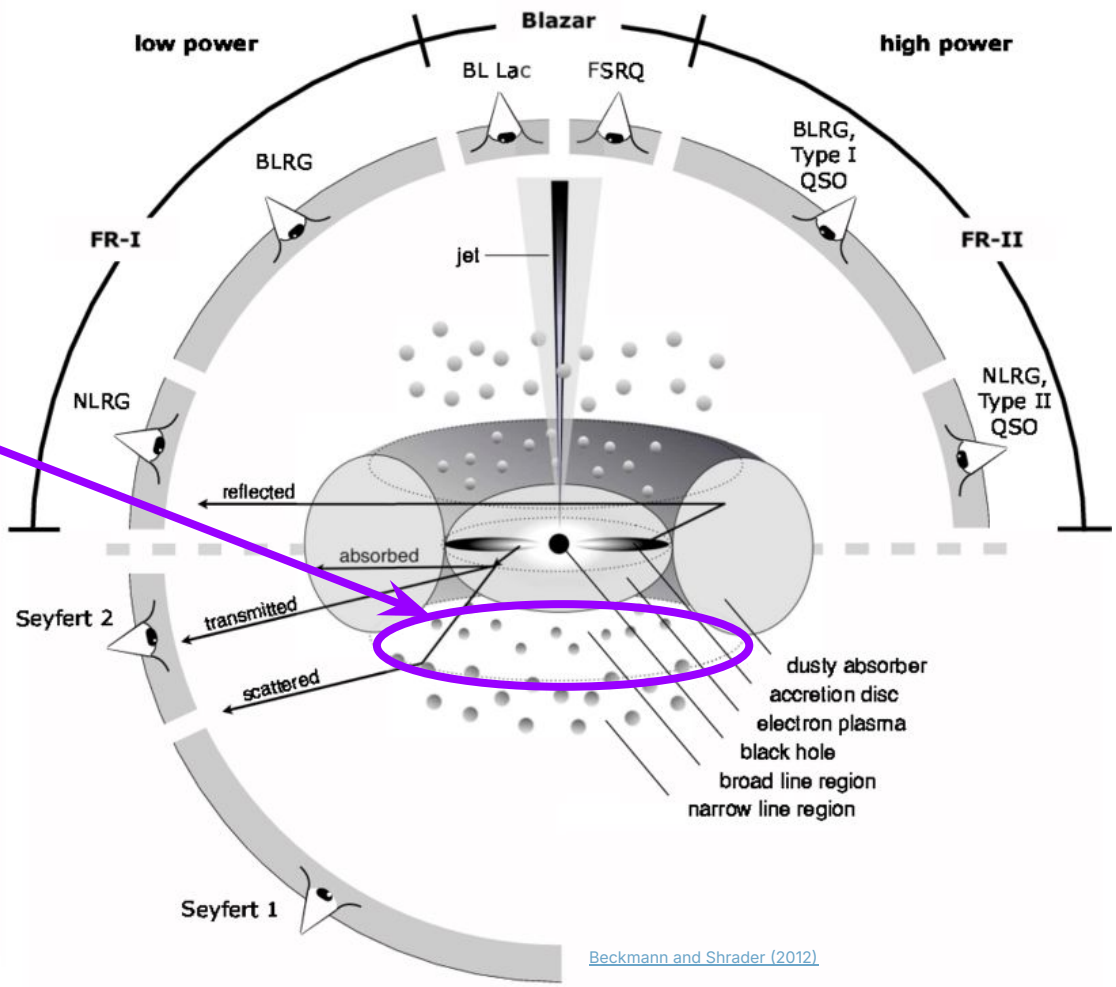
Beckmann and Shrader (2012)

Dust torus :

- **thermal** emission
- **IR**

Broad line region :

- ionized particles
- 10^4 km/s → broad emission lines
- **X rays and high energy** emission through inverse Compton (See later)



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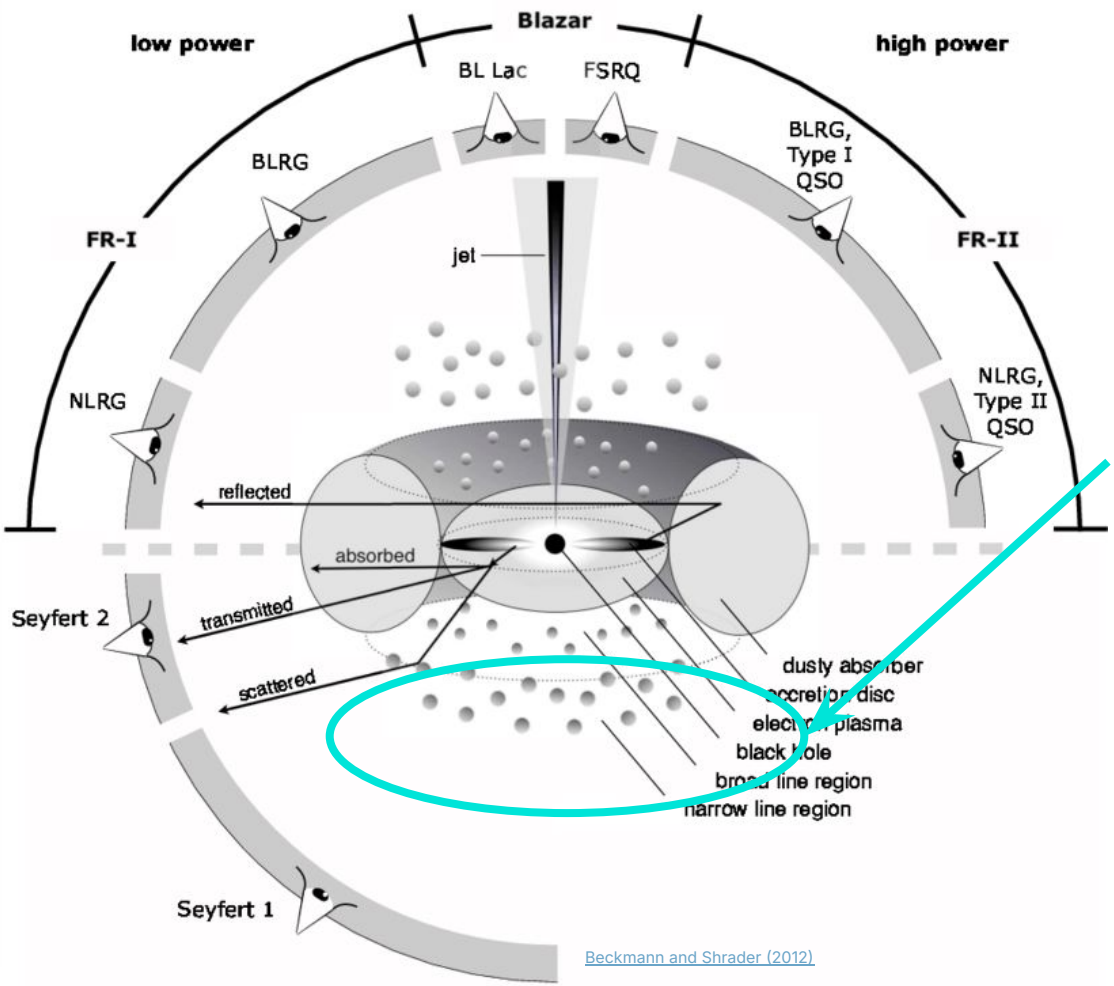
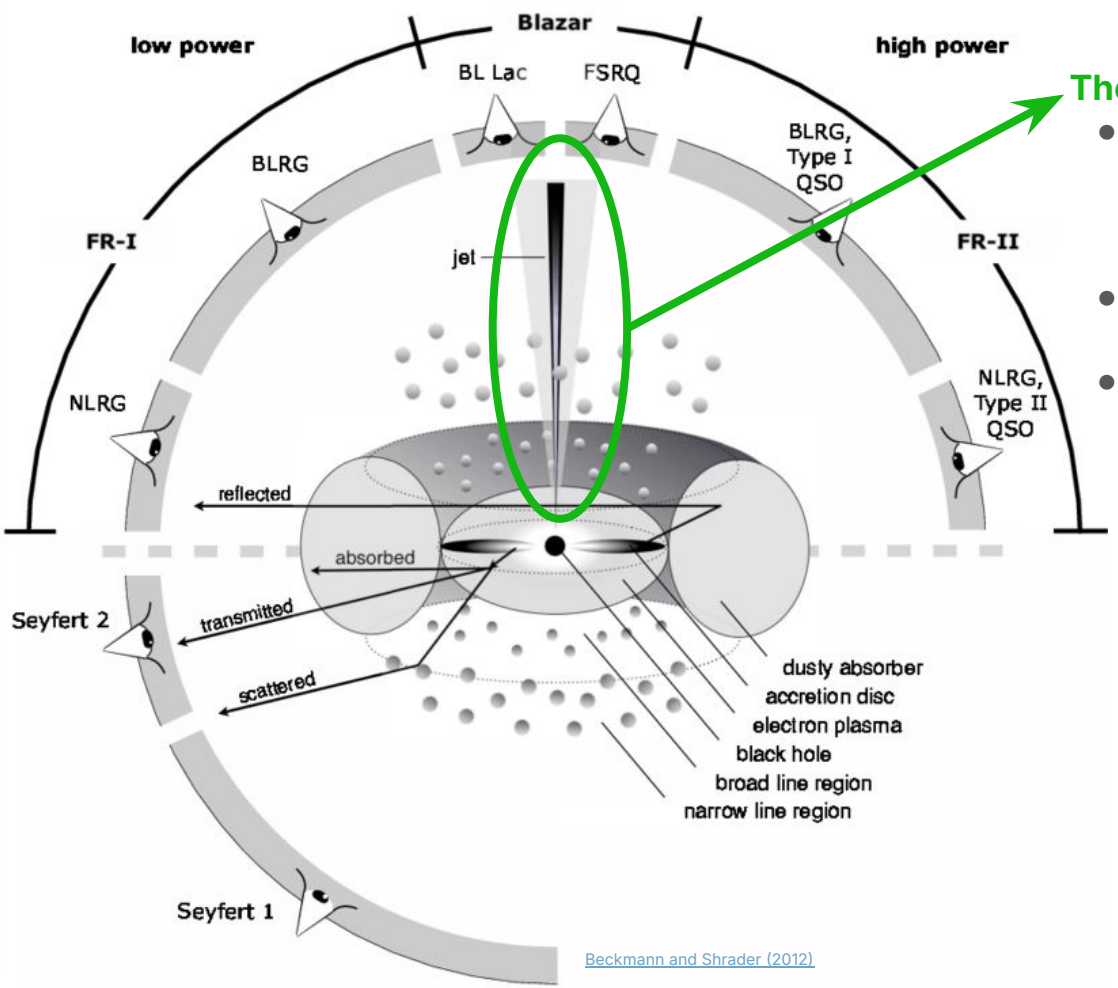


Beckmann and Shrader (2012)

Narrow line region :

- 10^3 km/s
  → thin emission lines



Beckmann and Shrader (2012)

The Jet :

- **Plasma** of **relativistic** particles
  - **Leptons** or **hadrons**
- **Non-thermal** emission
- from radio to high energy gamma rays (and possibly cosmic rays)

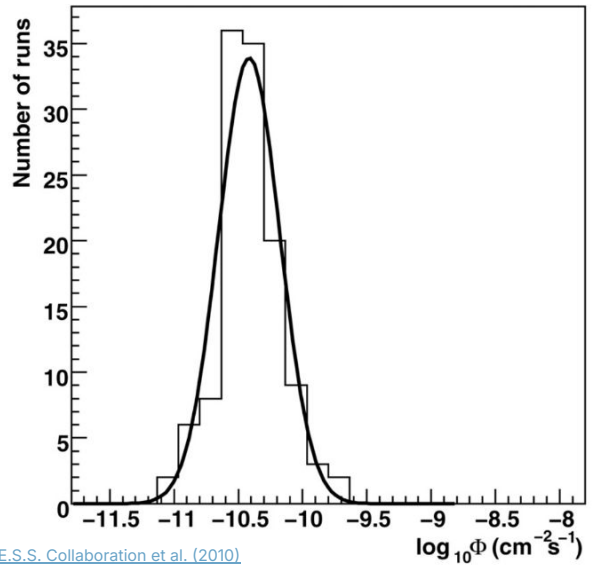
III - AGN variability studies with CTAO

AGN long-term monitoring program with CTAO

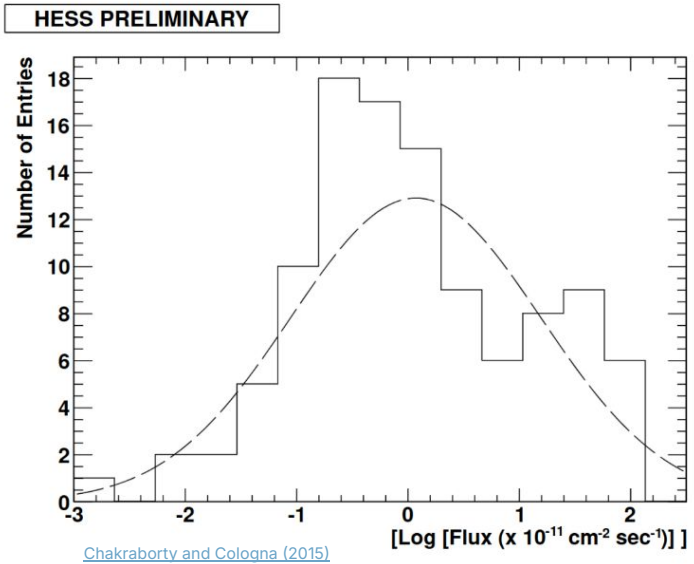
AGN long-term behavior

- Distribution **log-normal** of the **flux** (gaussian)

PKS 2155-304 (without flaring activities)



H.E.S.S. Collaboration et al. (2010)



Chakraborty and Cologna (2015)

Mrk 501

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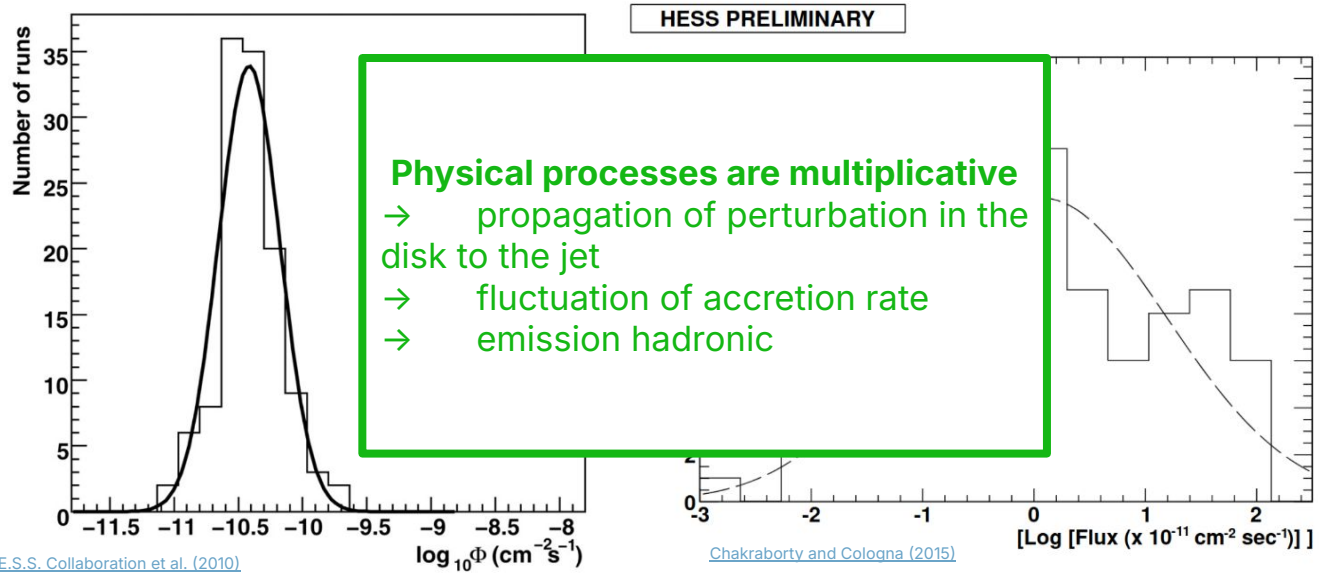

Physical processes are multiplicative
→ propagation of perturbation in the disk to the jet
→ fluctuation of accretion rate
→ emission hadronic

Mrk 501

H.E.S.S. Collaboration et al. (2010)

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AGN long-term behavior

- Distribution **log-normal** of the **flux** (Gaussian)
- **Power spectral density (PSD)** follow a power law (possibly broken)
  - slope = 1 (pink noise)
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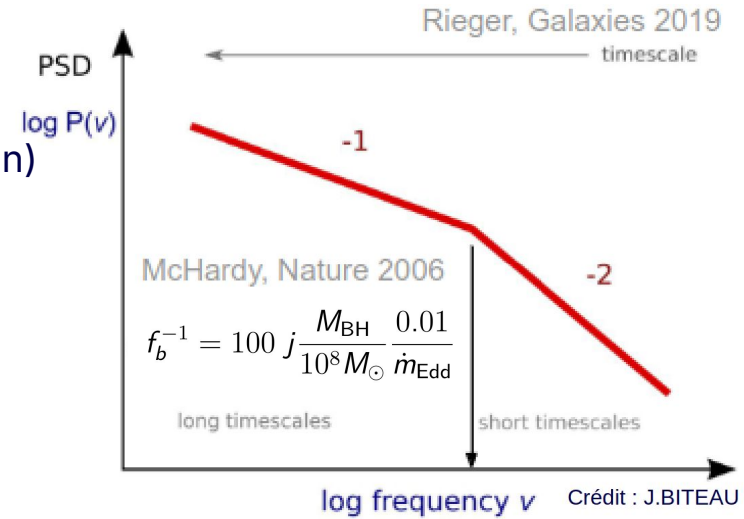

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$$\Phi(E,t) = \Phi_0(t)\left(\frac{E}{E_0}\right)^{-\Gamma(t)-\beta\ln(E/E_0)} \times \exp\left(\frac{-E}{E_{\text{cut}}}\right) \times e^{-\tau_{\gamma\gamma}(E,z))}$$

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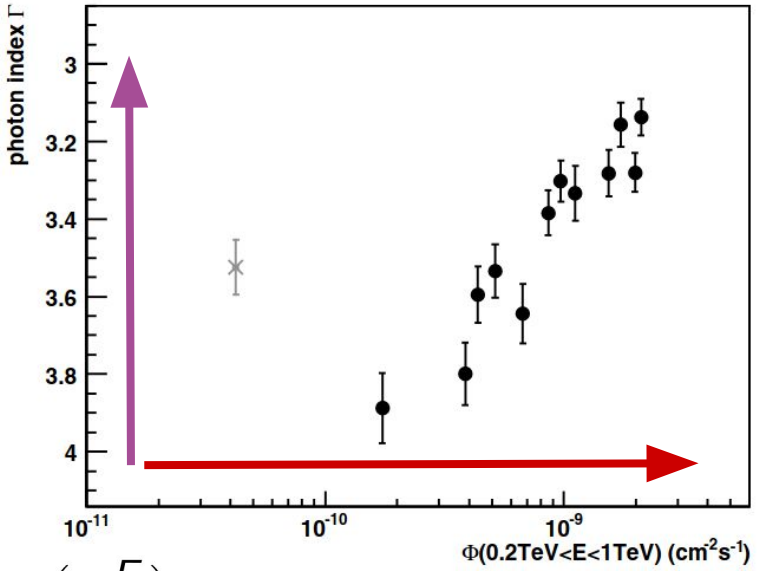
- With an **"harder when brighter behavior"**
  - based on PKS 2155-304 observations



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Based on long-term behavior (STeVECat, Gréaux et al. 2023)

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AGN long-term monitoring program of CTAO AGN key science project (KSP)

- Monitoring of 18 AGN during 20 years with observations of 30 min based on a weekly cadence

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)

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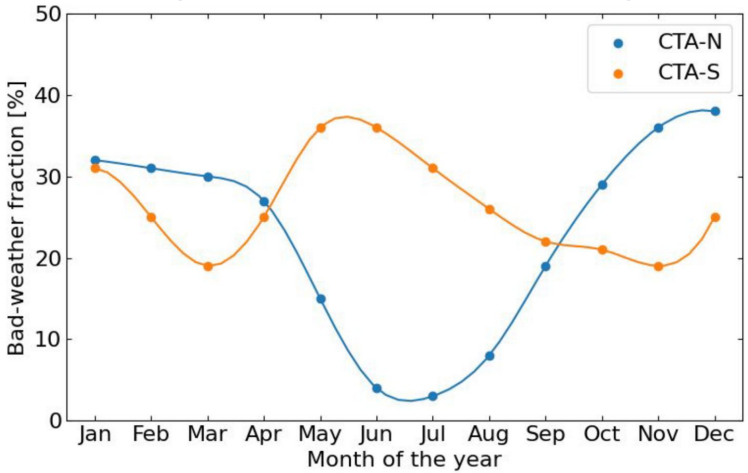
AGN long-term simulations: BL Lac

- Computation of the visibility
  - zenith angle **< 45°**
  - considering **the moon**
  - **bad weather fraction** (from meteo observations)



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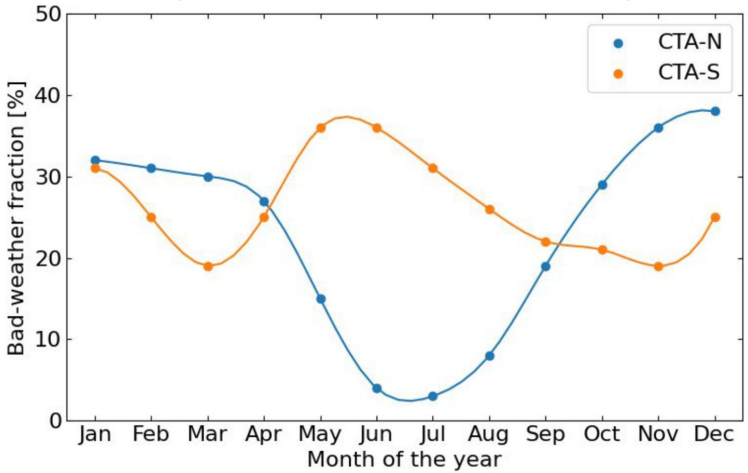

About 20 observations of 30 min with a weekly cadence per year are simulated

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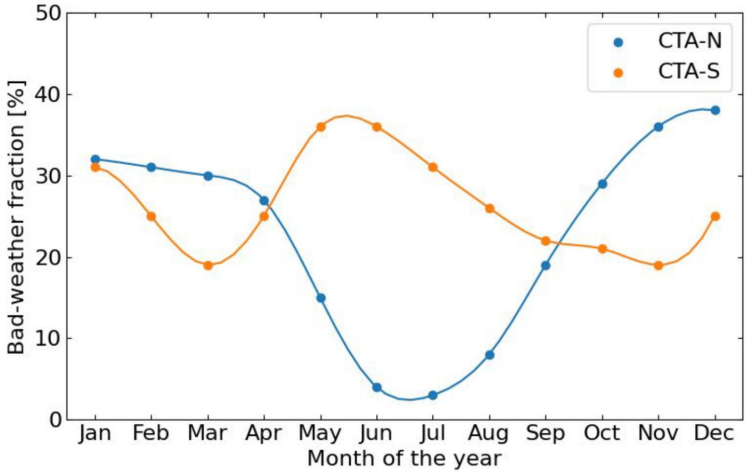
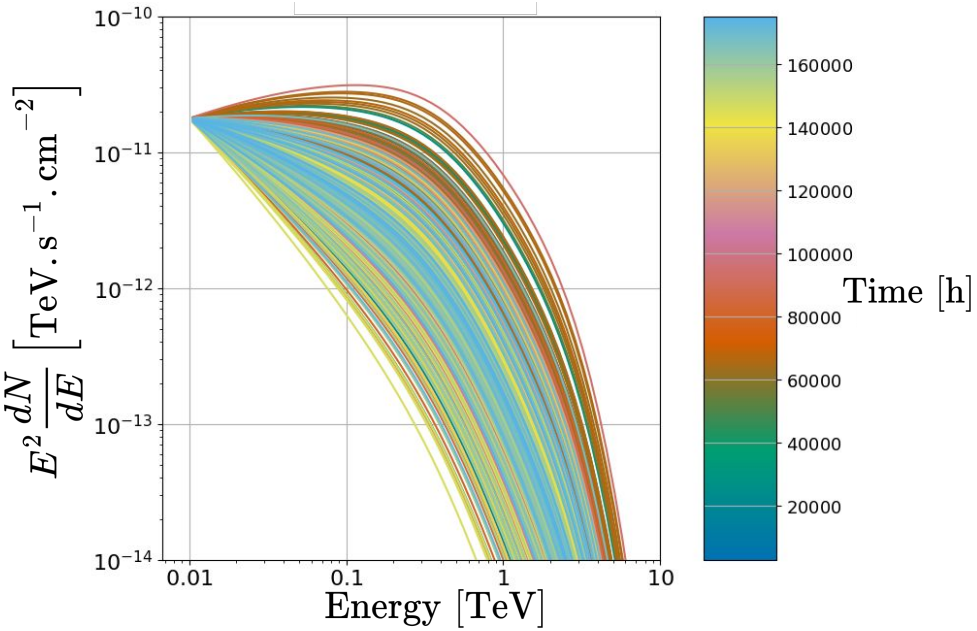
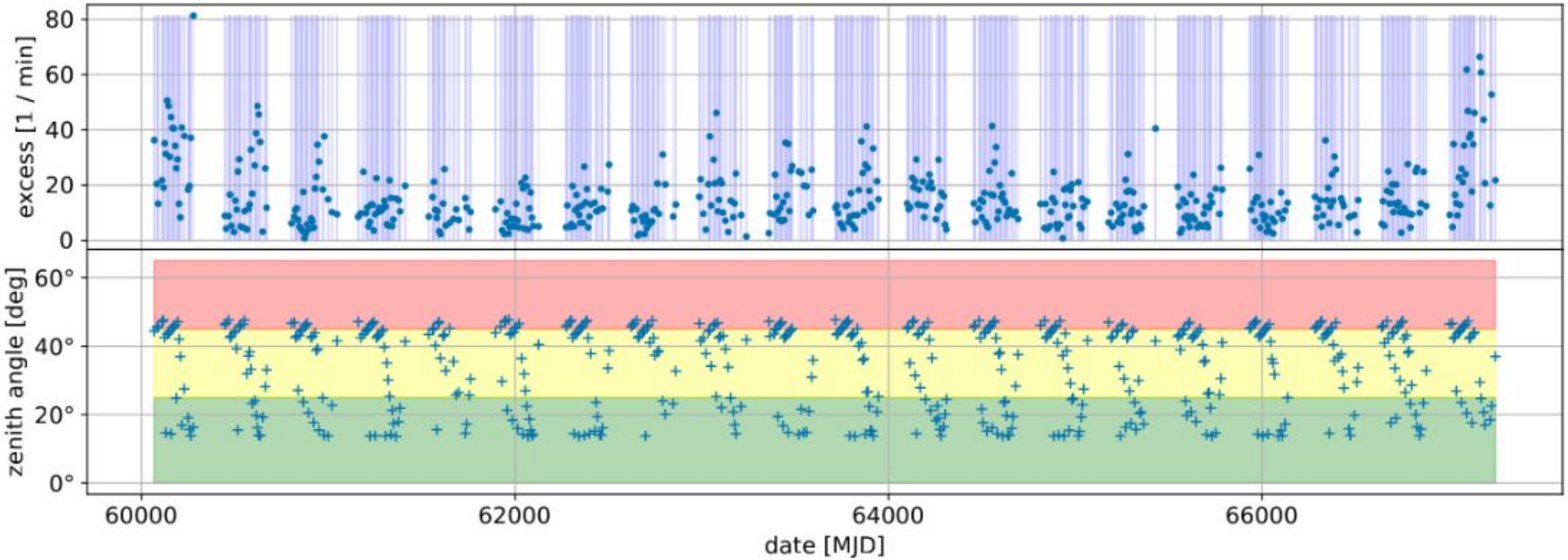


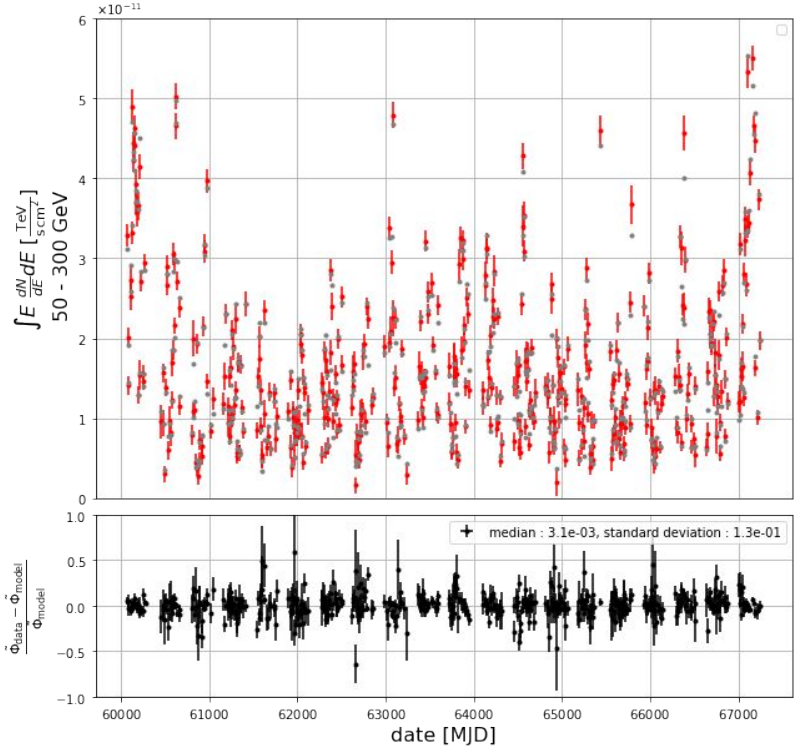




- The higher the zenith angle is, the lower CTAO is sensitive to low energy gamma rays
  - Take into account the position of the source in the sky

AGN long-term simulations: BL Lac reconstructed lightcurve

- **20 years lightcurve** between **50 and 300 GeV**
- Use of a statistical test to reject bad reconstructed points



AGN long-term simulations: BL Lac reconstructed PSD

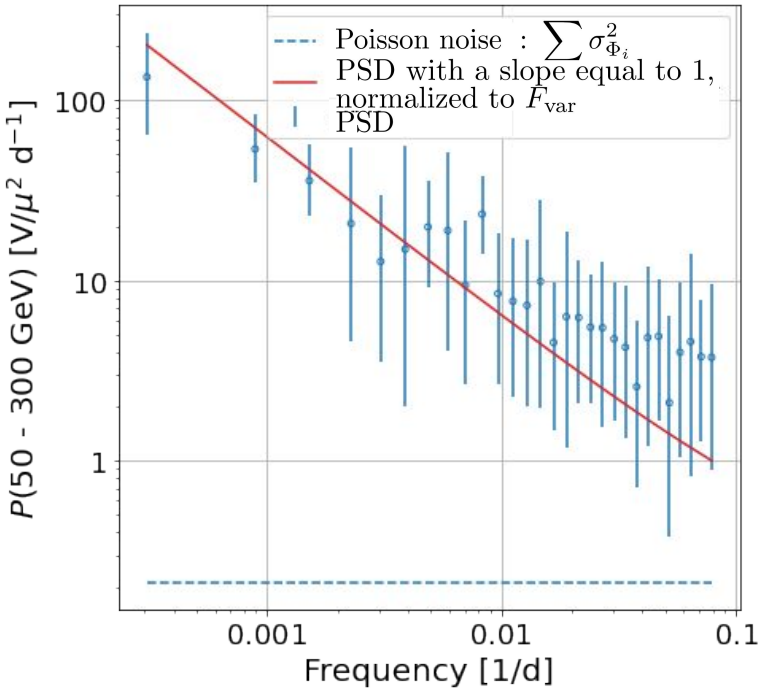
- Compute the **discrete Fourier transform** of the **lightcurve**

$$P(\nu) = A \times \left| \sum_{i=1}^{N} (\tilde{\Phi}_i - \mu) e^{2i\pi\nu t_i} \right|^2$$

AGN long-term simulations: BL Lac reconstructed PSD

- Compute the **discrete Fourier transform** of the **lightcurve**

- **Slope of 1** is **qualitatively** well reconstructed

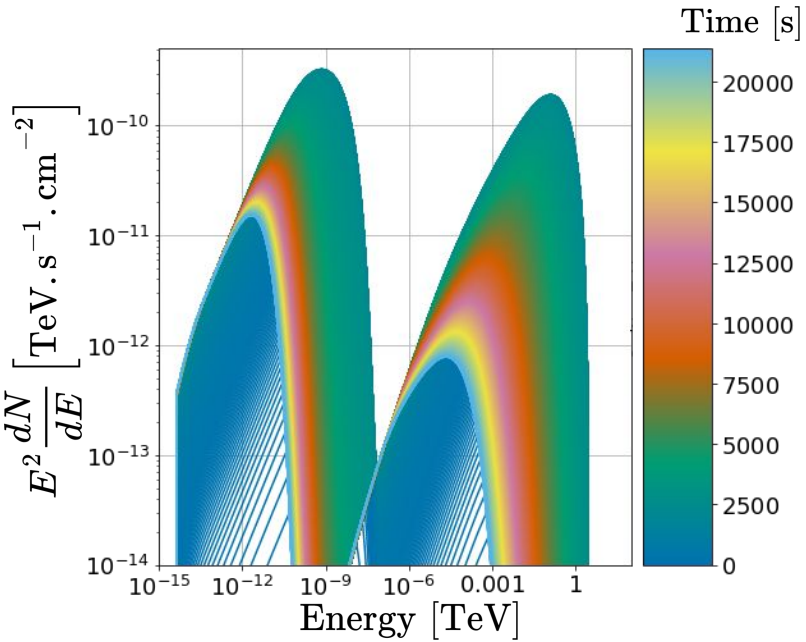


AGN variability studies with CTAO

AGN flares studies with CTAO

AGN flares: Mrk 421 SSC

- Synchrotron-self-Compton (SSC)
  - The gamma rays are produced by inverse Compton on the synchrotron emission of the particles in the jet
- Simulation based on a SSC model based on a 2001 flare of Mrk 421, Finke et al 2008
- Realistic simulations:
  - light pollution of the moon
  - evolution of the source position in the sky

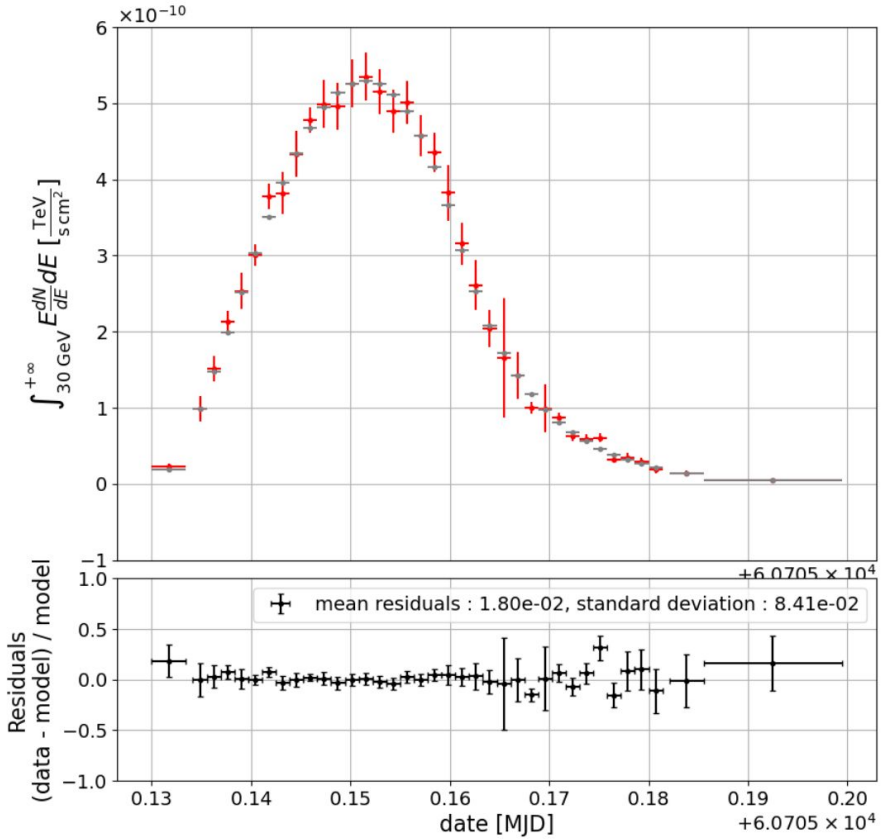


- Time resolution ≈ 10 s
- duration of the flare ≈ 5h

AGN flares: Mrk 421 SSC

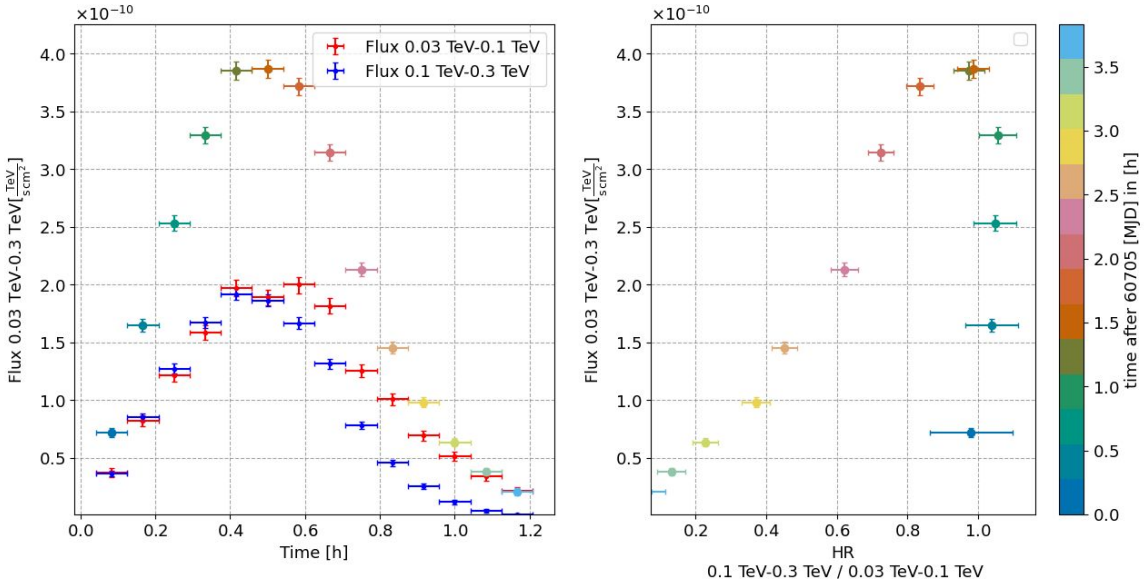
- Lightcurve is reconstructed:
  - model in gray and observations in red
  - with the **iterative spectral reconstruction** process
  - an **adaptable time bins**, based on detection significance

- With CTAO :
  - Excellent reconstruction of the lightcurve with a high resolution



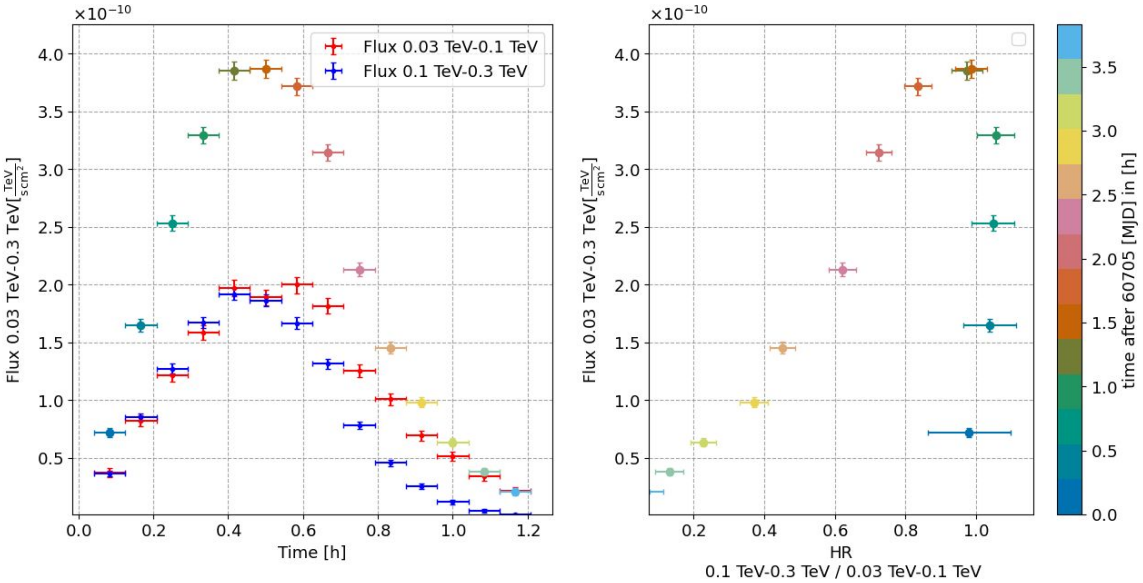
AGN flares: Mrk 421 SSC

- **Hardness ratio (HR) diagram**
  - computation of the flux in 2 energy bands
  - display the **sum versus the ratio**



AGN flares: Mrk 421 SSC

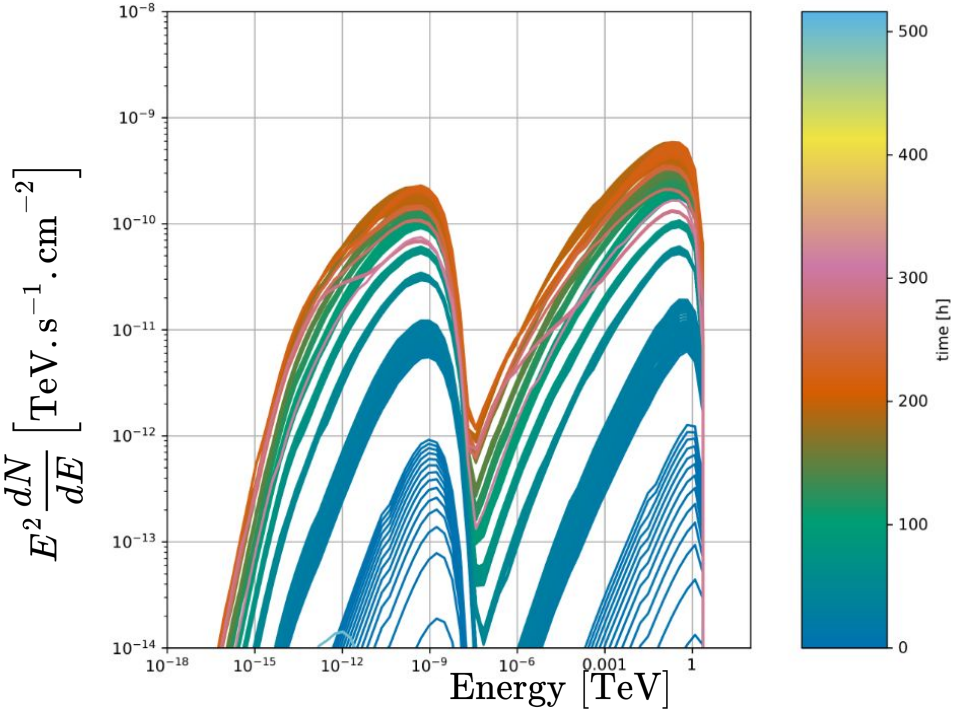
- **A statistical estimator has been developed to detect or not hysteresis in the HR diagram**
  - Can be used to search for LIV in this diagram



More than 3 sigma

AGN flares: Mrk 421 Magnetic reconnexion

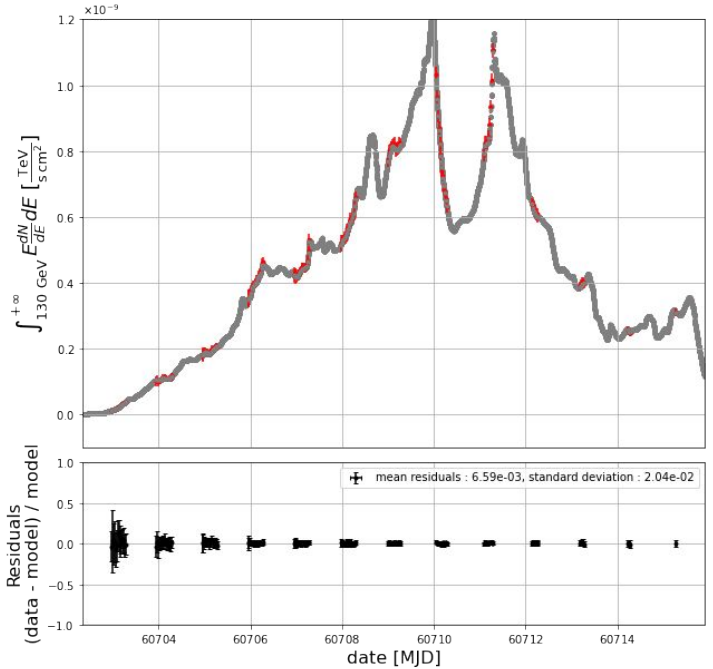
- Simulation based on a magnetic reconnexion model, adapted to a flare of Mrk 421, Christie et al. 2019
- Can see multiple flares



- Time resolution ≈ 10 s
- duration of the flare ≈ 5h

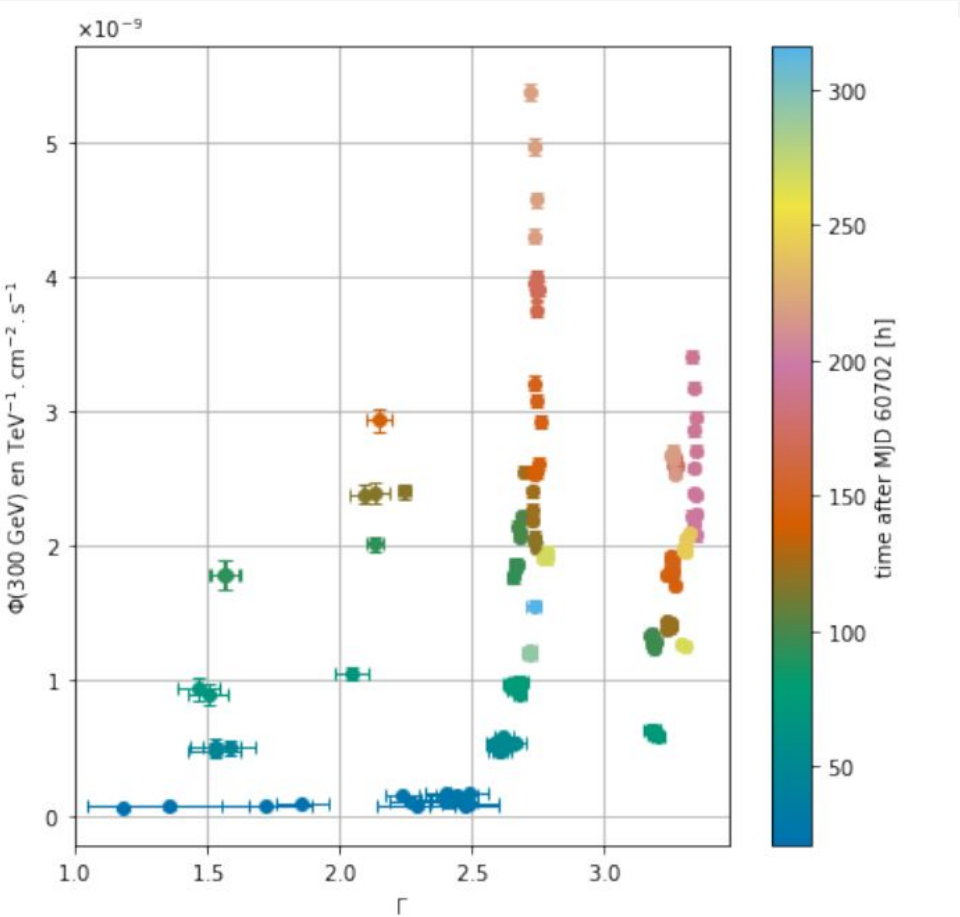
AGN flares: Mrk 421 Magnetic reconnexion

- model in gray and observations in red
- We can detect variability up to the minute time scale !
- The importance of the part of the flare that we are catching → intrinsic effects



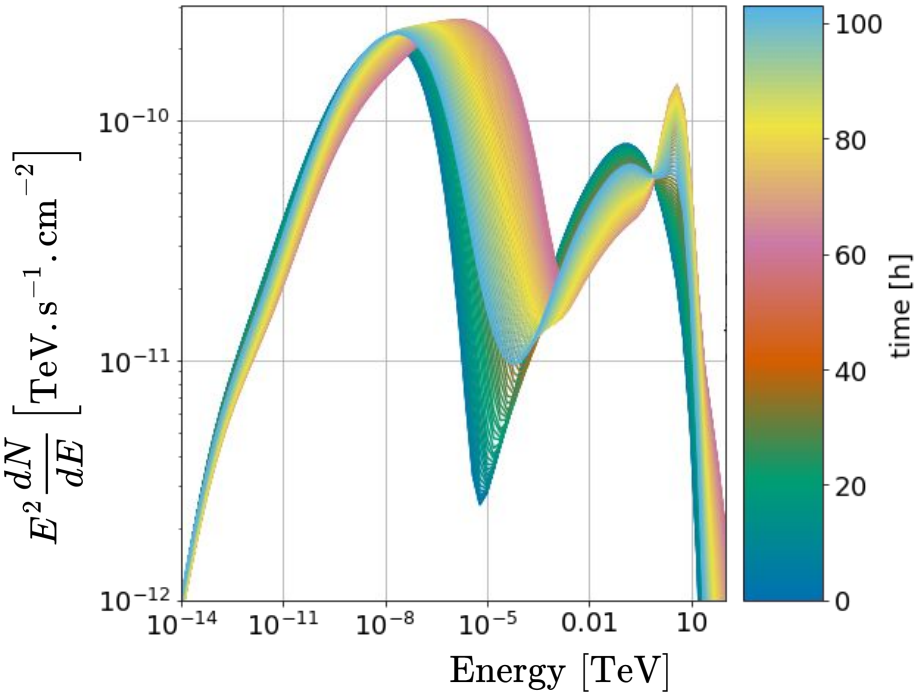
AGN flares: Mrk 421 Magnetic reconnexion

- Each sub-flare → no photon index variability
- If we do not catch these multiple sub flares → can wrongly think of a spectral variability



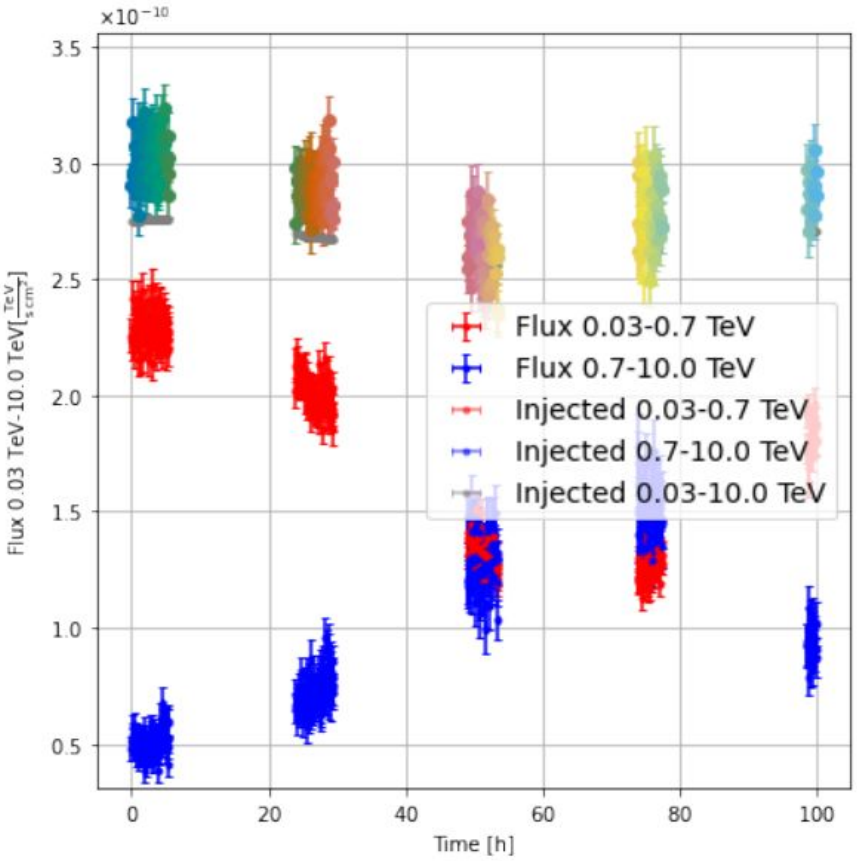
AGN flares: Hadronic

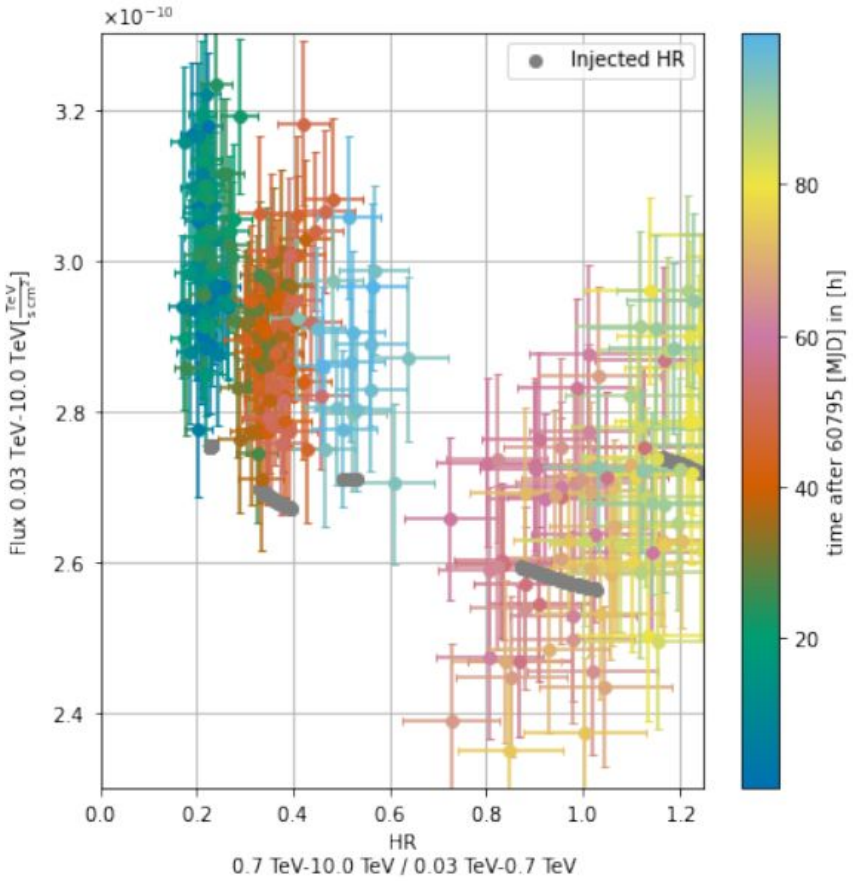
- Simulation based on a lepto-hadronic model, Petropoulou et al. 2019
- Can see that the emission > TeV comes after the one below



- duration of the flare ≈ 5 days

AGN flares: Hadronic





CONCLUSION

Conclusion

- AGN variability studies with CTAO:
  - **LTM program:**
    - Based on detection: not only the well known blazar (Mrk 421-501, PKS 2155) can be **deeply studied** (BL Lac e.g.)
    - Precise reconstruction of the **PSD slope** (**Break position** reconstruction ongoing)
  - **Flares:**
    - **spectral variability** can be investigated with **CTA**
    - Detection of **hysteresis in HR** diagrams with **statistical tool** (never been achieved before in gamma-rays)
      - **Discrimination** of **hadronic** and **leptonic models**
      - Use this estimator for LIV studies ?
    - Warning: intrinsic effect can become more visible and critical with CTAO

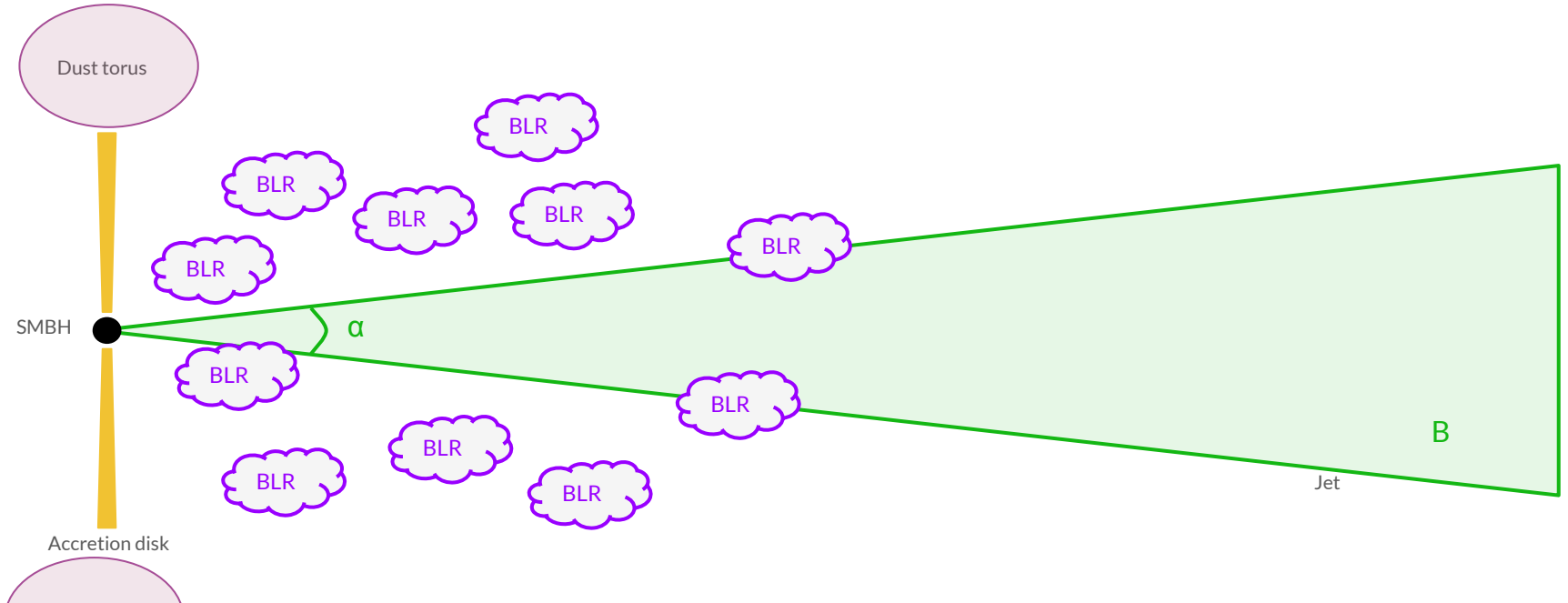
- All these simulations have been done with CtaAgnVar :
  - Python package based on Gammapy (the software for CTAO data analysis)
  - **Already used** by colleagues
    - LIV studies
  - Has been validated with **real data**
    - H.E.S.S., LST
  - Can be use for **any time dependant spectral studies**
    - With CTAO and **other experiments**

BACKUP slides

I - Active galactic nuclei and their high energy emission

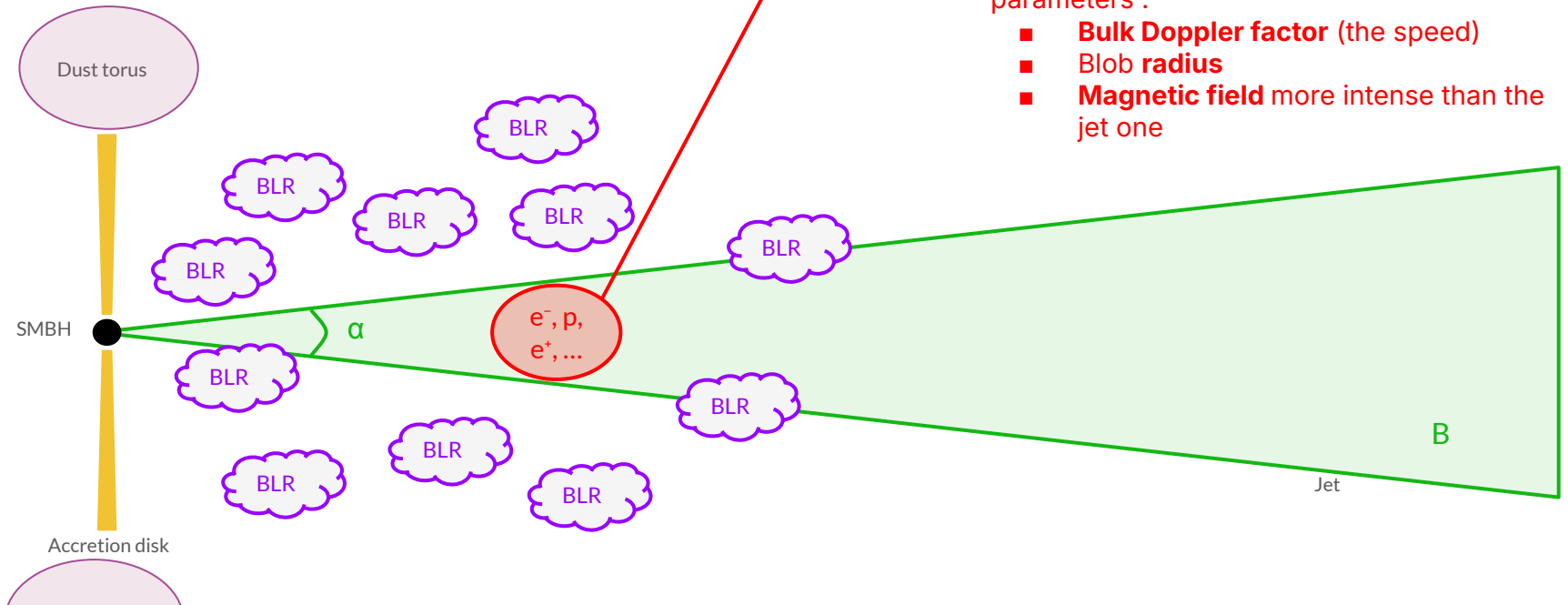
Blazar jet model

Blazar jet model



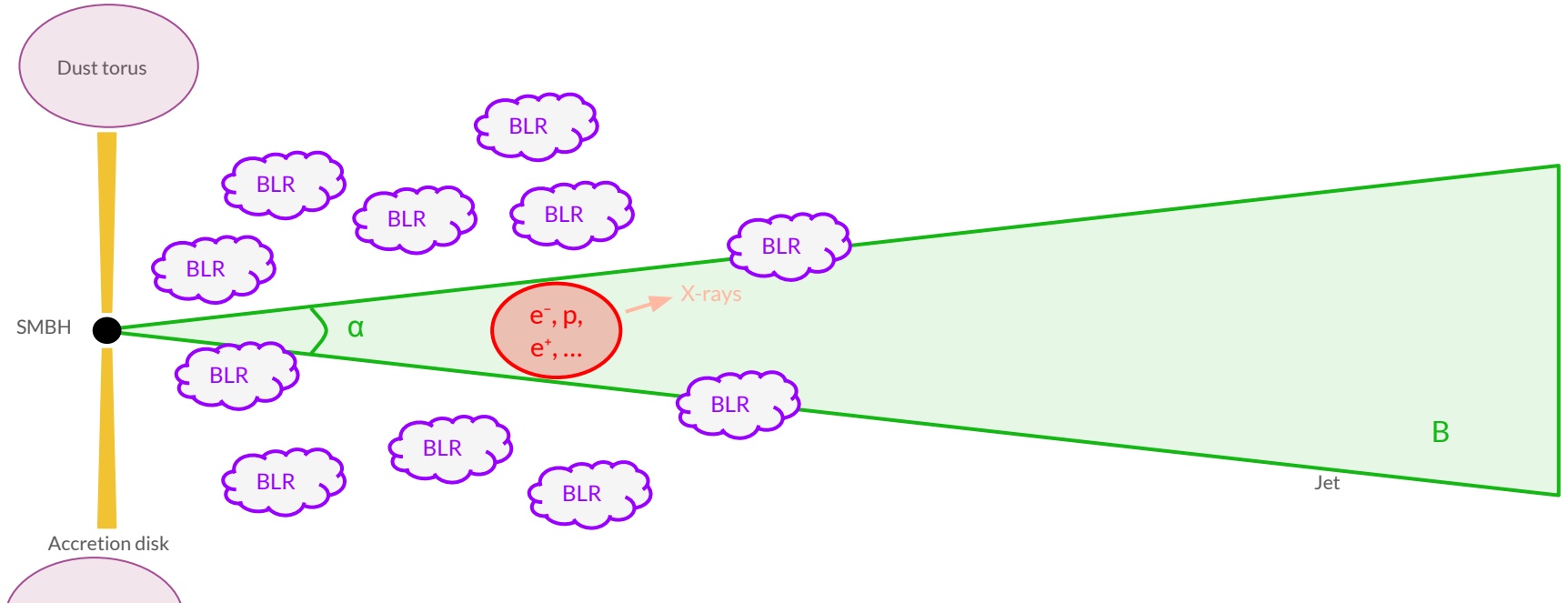
Blazar jet model

- **Blob** of accelerated particles :
  - **Injection of particles** or **stationary shock**
  - leptons only
  - or hadronic particles
  - Characterized by micro and macro physic parameters :
    - **Bulk Doppler factor** (the speed)
    - Blob **radius**
    - **Magnetic field** more intense than the jet one



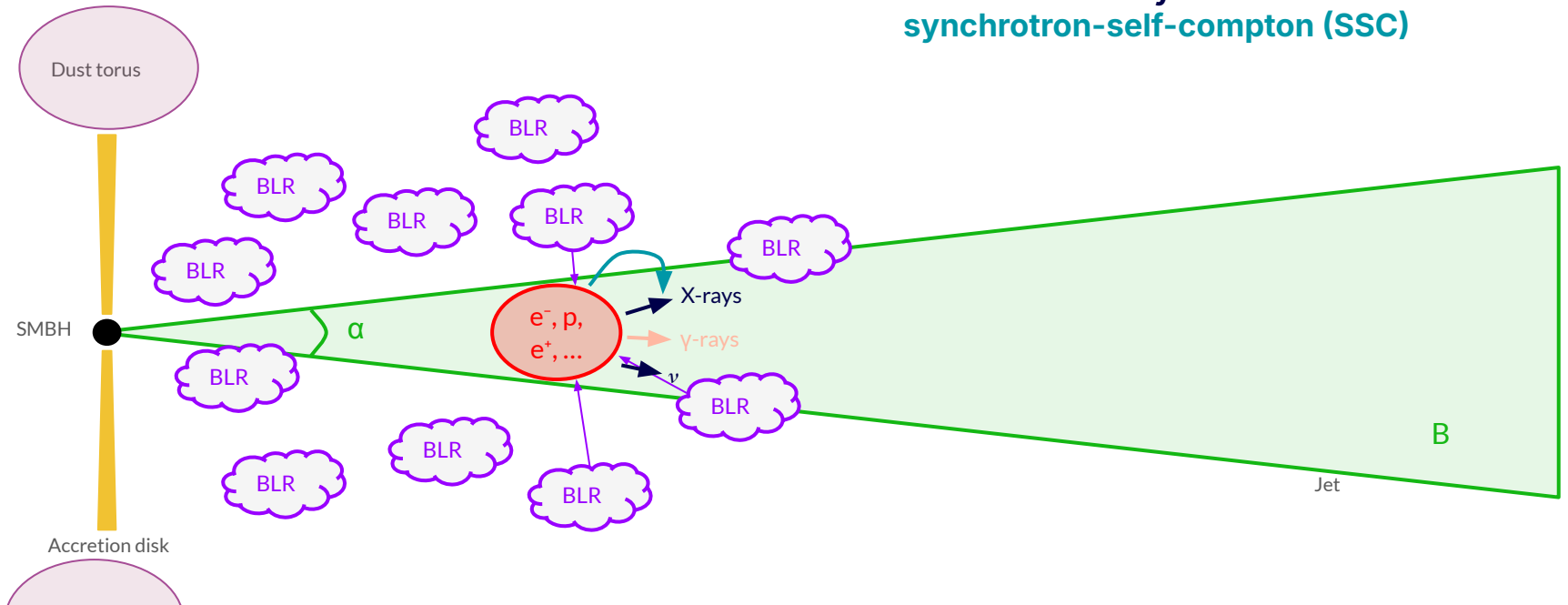
Blazar jet model

- **Blob** of accelerated particles :
- **X-rays** production through **leptonic synchrotron** emission



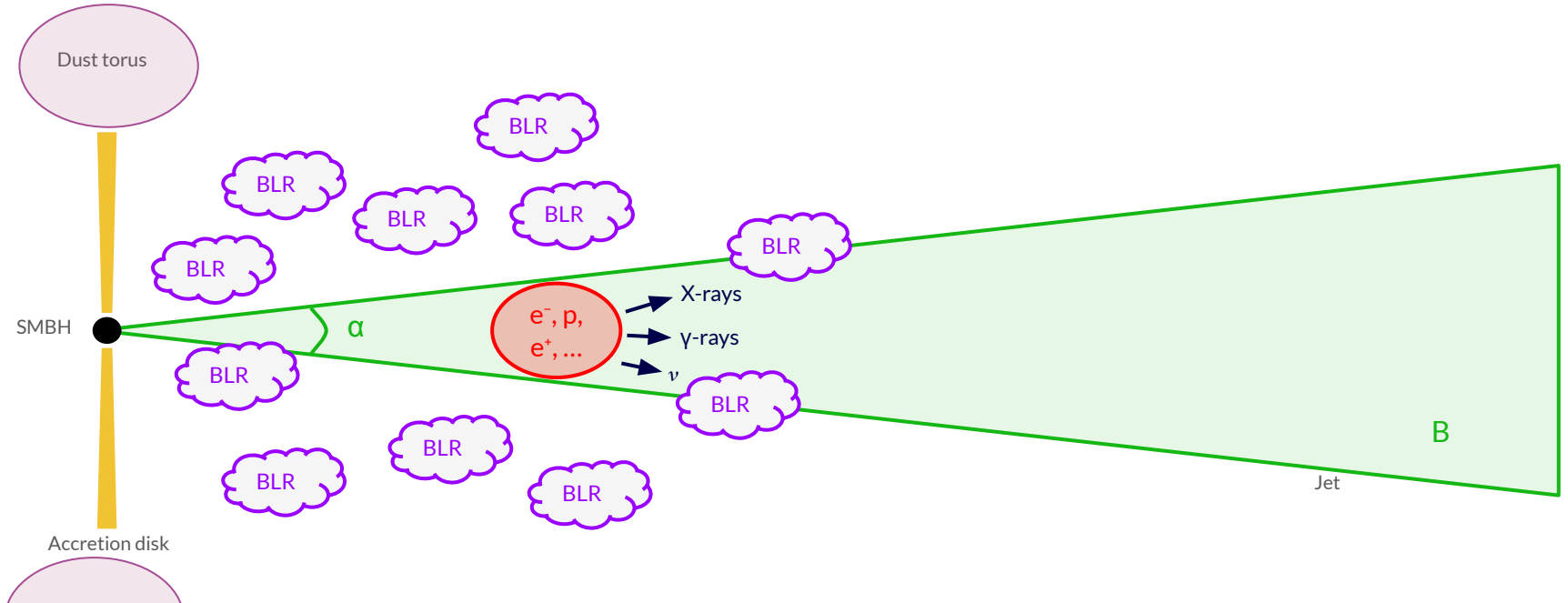
Blazar jet model

- **Blob** of accelerated particles :
- **X-rays** production through **lepton synchrotron** emission
- **γ-rays** creation with **IC** on **external photon fields** or on the **synchrotron** itself = **synchrotron-self-compton (SSC)**



Blazar jet model

- This model is much simple
  - Stationary
  - Single emission zone
- can be more complex



Blazar jet model

- This model is much simple
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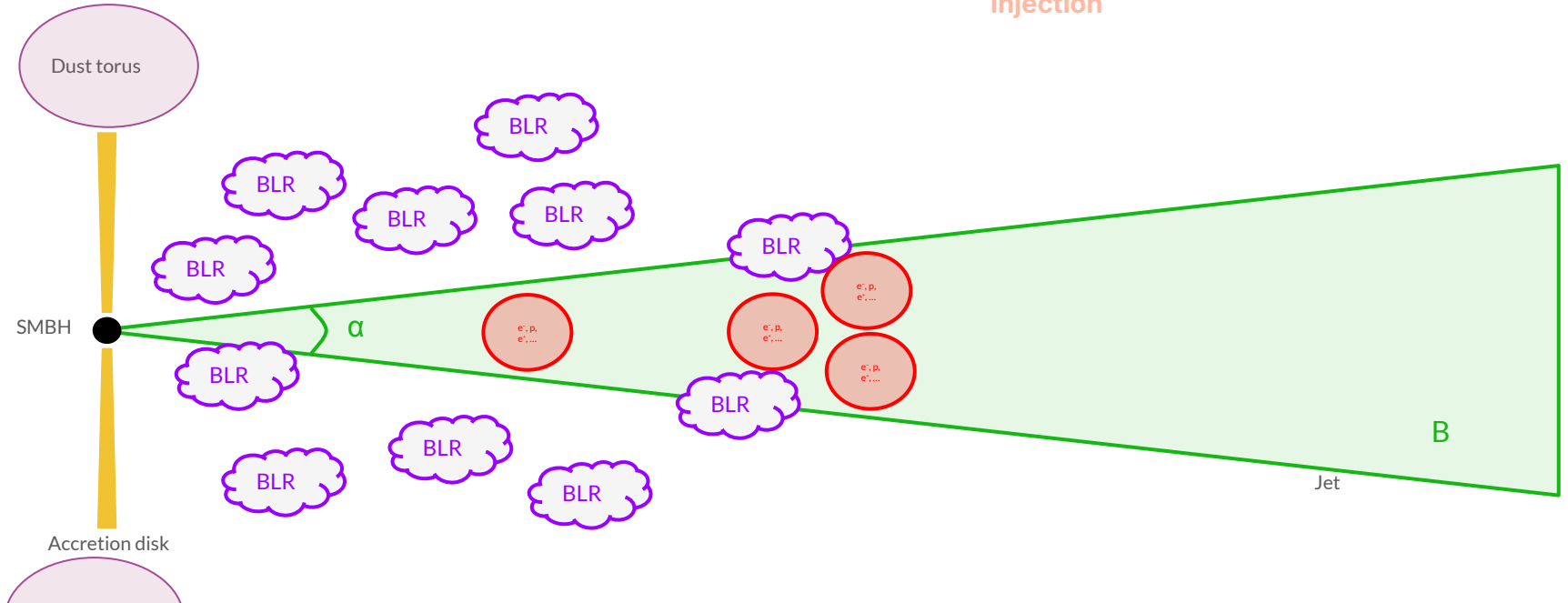
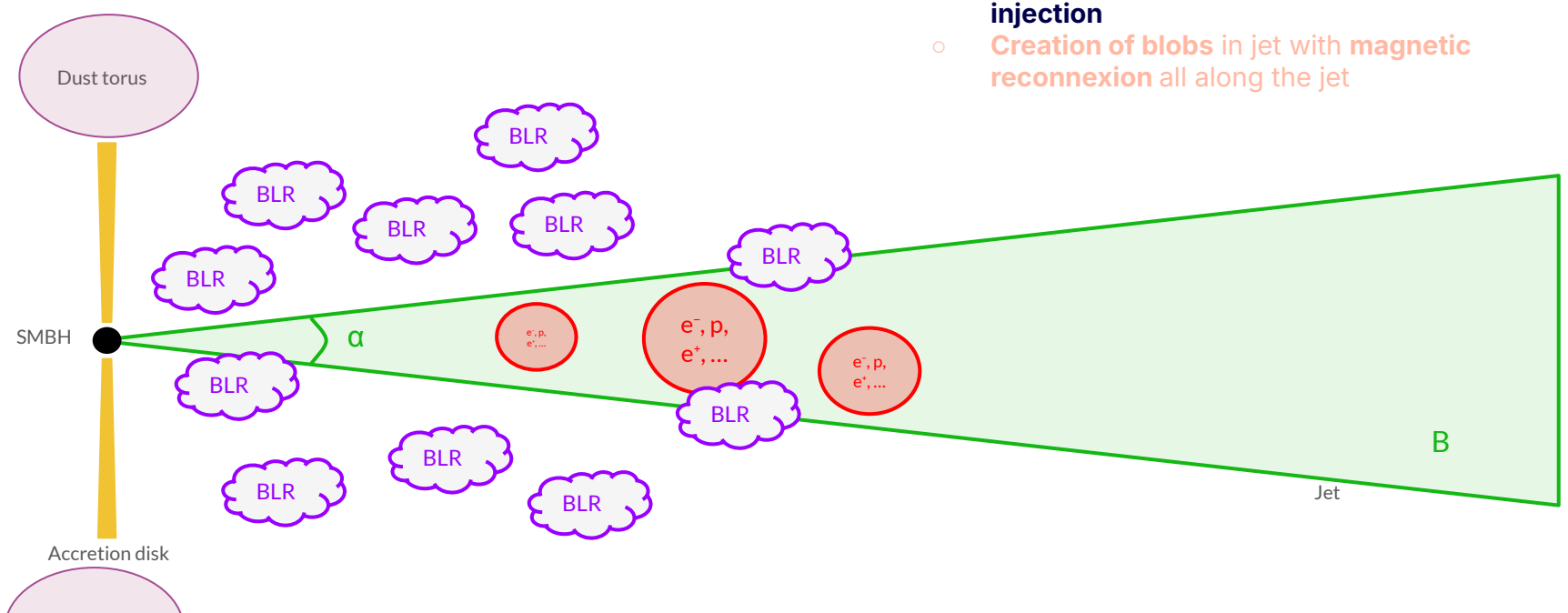
  - **Multiple zones** and **time dependent injection**

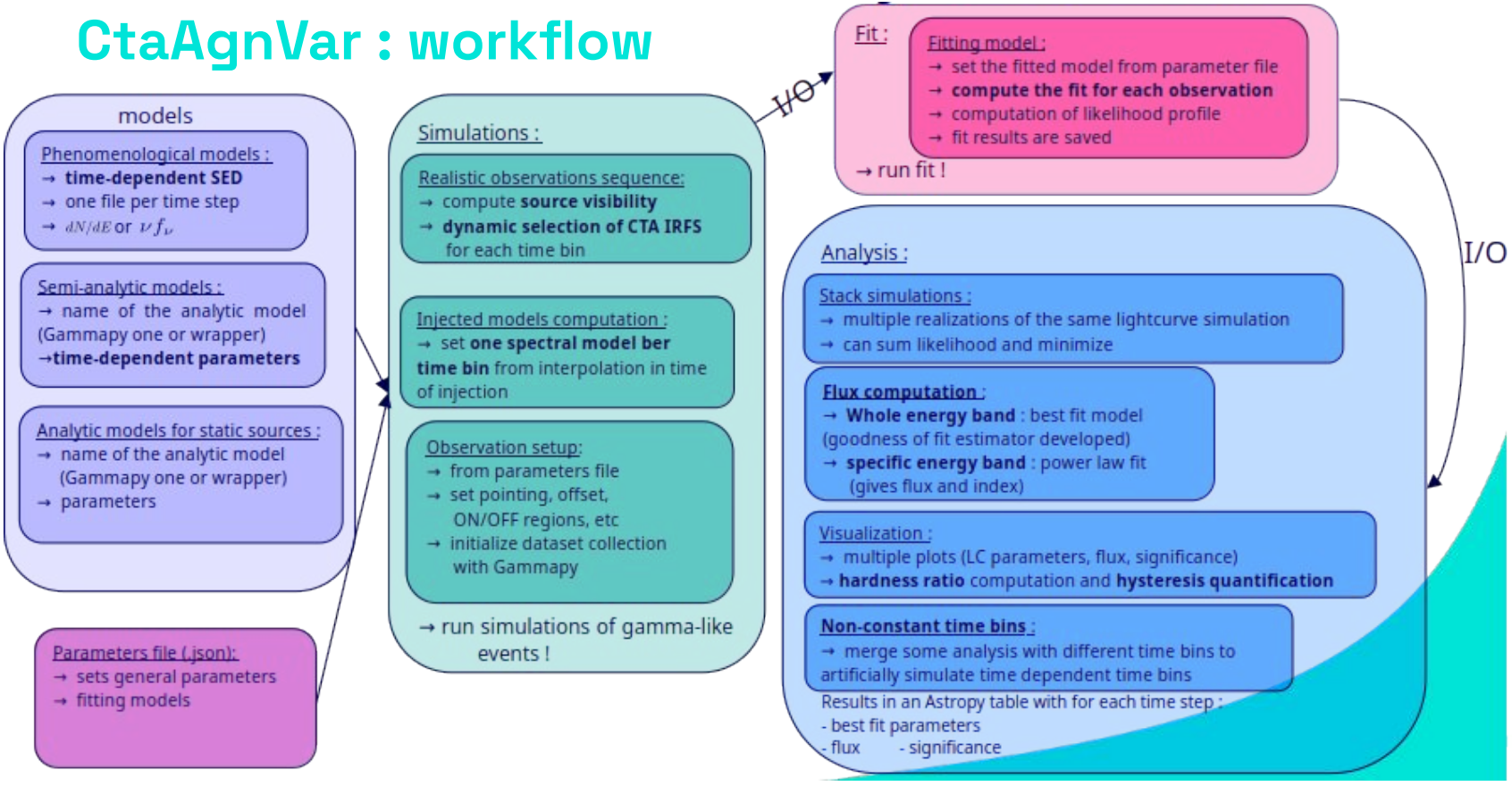


Blazar jet model

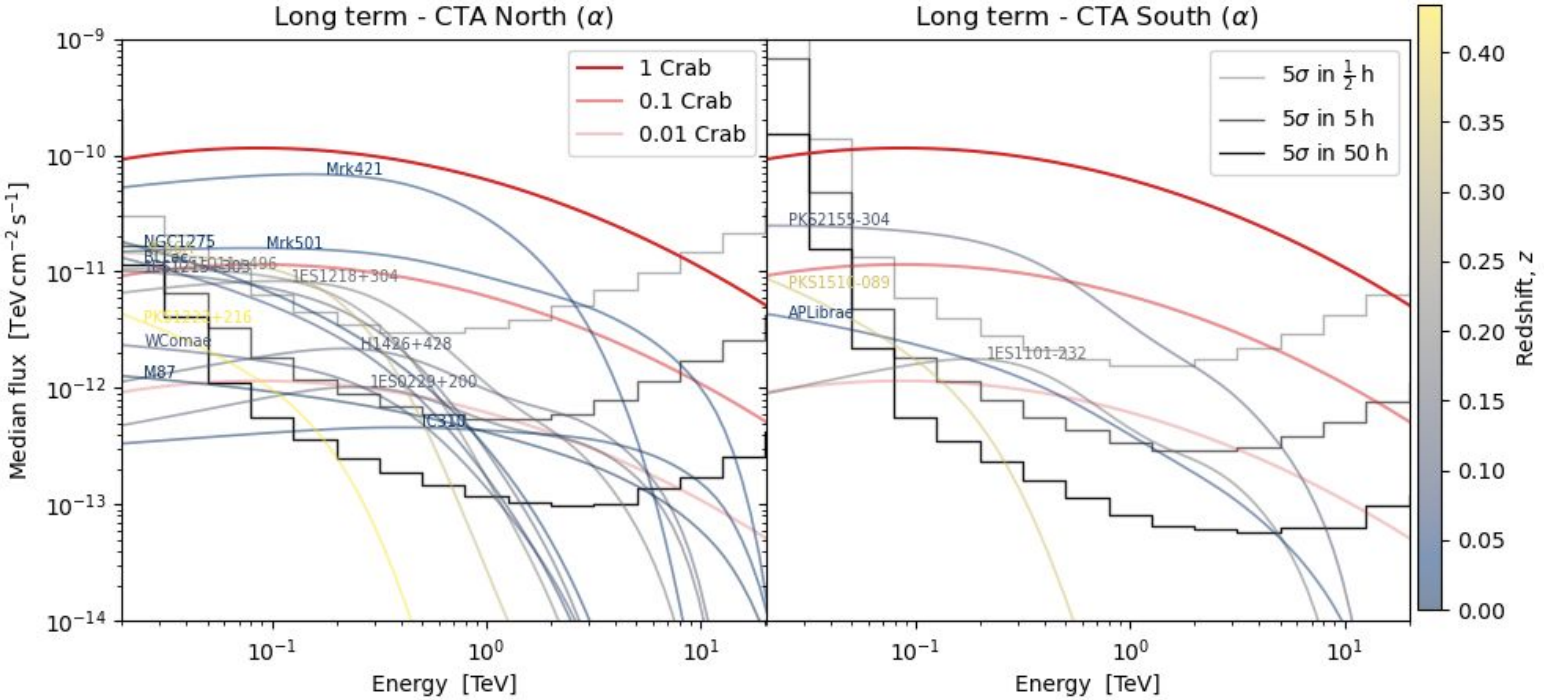
- This model is much simple
  - Stationary
  - Single emission zone
- can be more complex
  - **Multiple zones** and **time dependent injection**
  - **Creation of blobs** in jet with **magnetic reconnexion** all along the jet



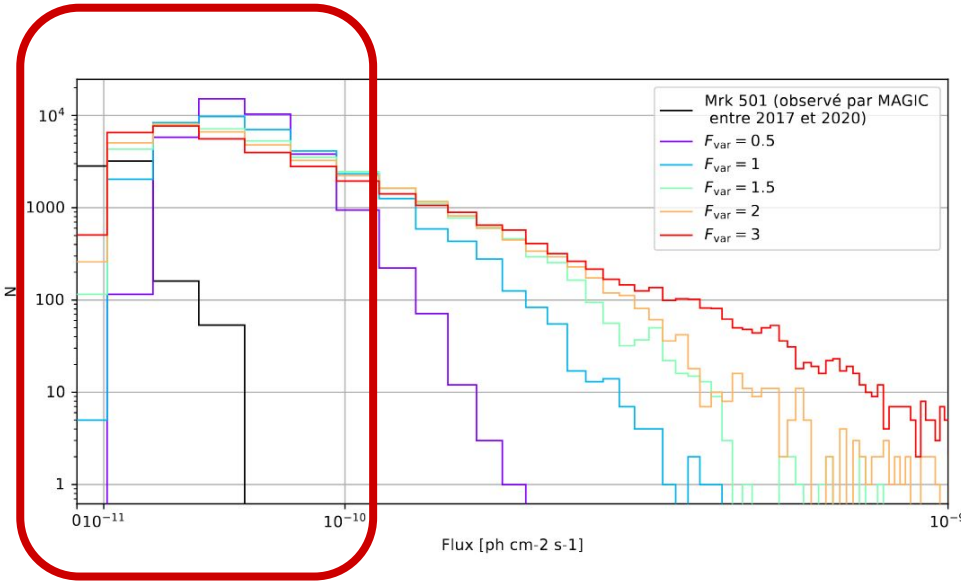
CtaAgnVar : workflow

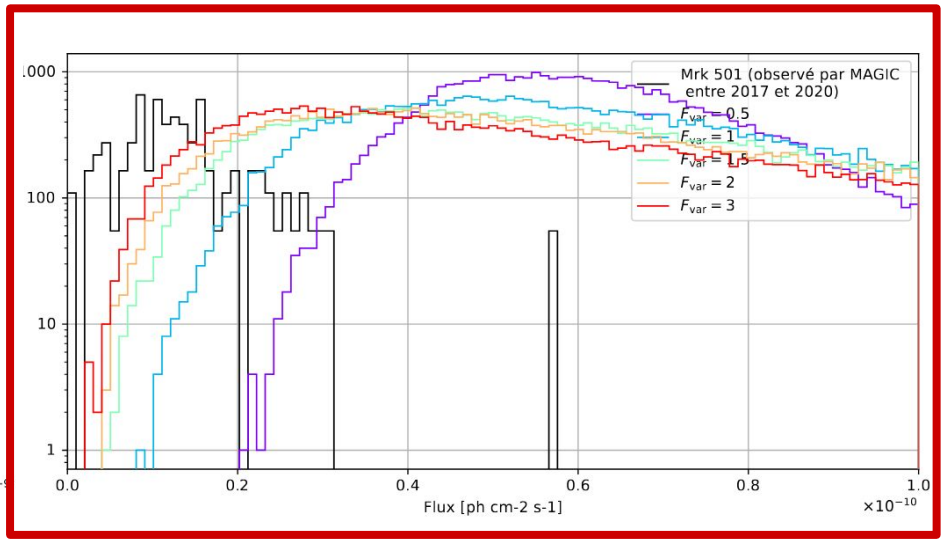


BACKUP : AGN LTM median spectrum

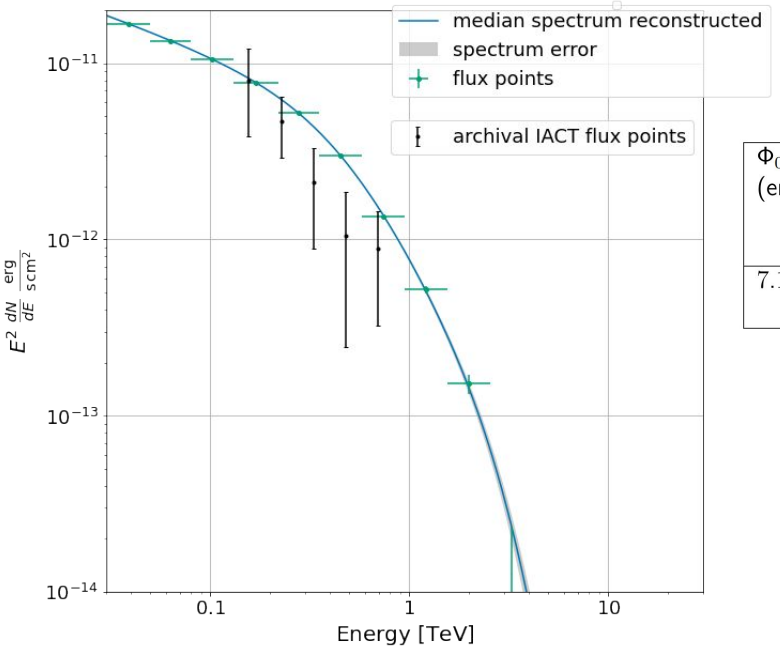


BACKUP : AGN LTM Fvar optimisation



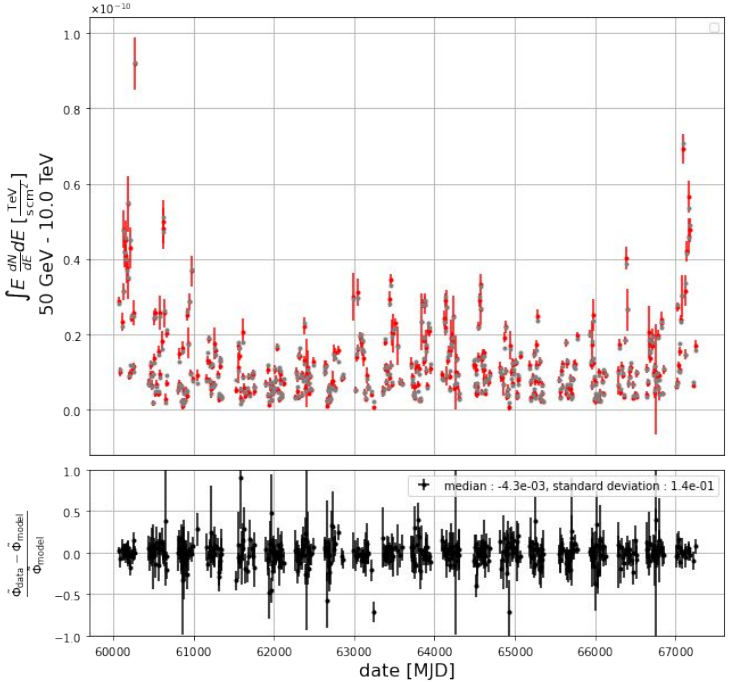


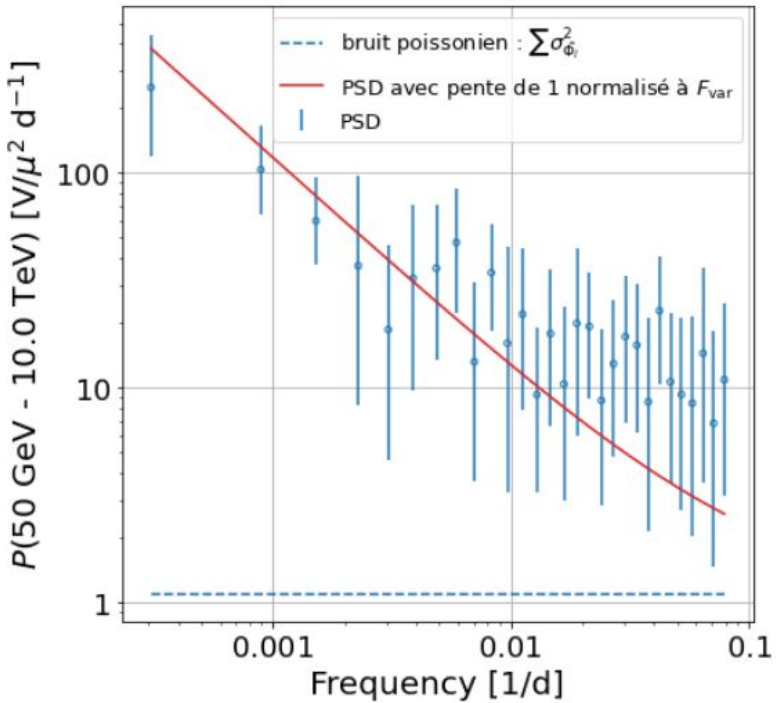
BACKUP : AGN LTM BL Lac reconstructed median spectrum



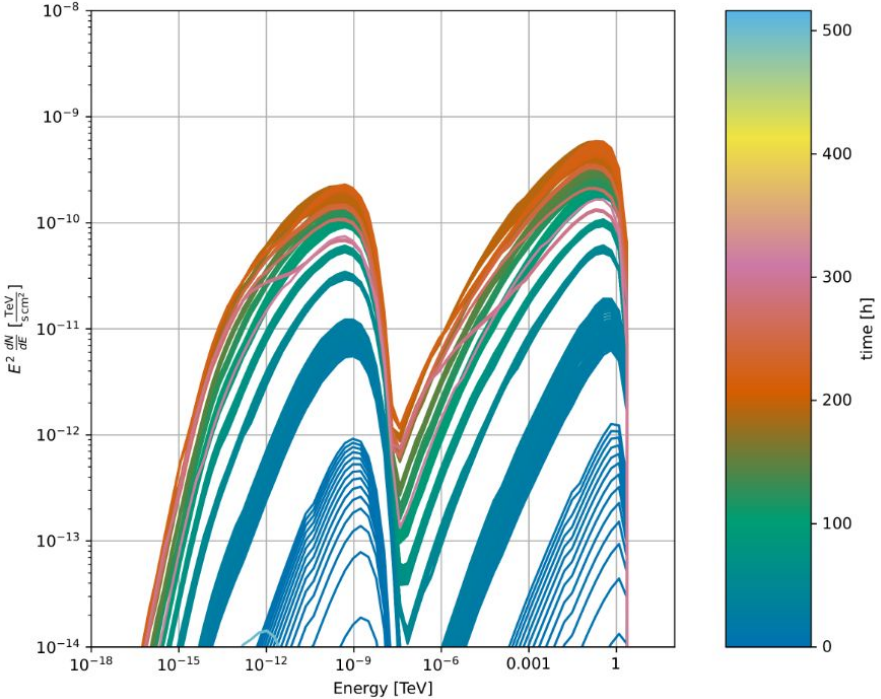
Φ_0 (en $TeV^{-1}.cm^{-2}.s^{-1}$)	Γ_0	E_0 (en TeV), fixé	E_{cut}^{-1} (en TeV^{-1})	β	z, fixé
$7.19 \pm 0.06 \times 10^{-10}$	2.40 ± 0.02	0.102	1.11 ± 0.11	$0.37 \pm 1.18 \times 10^{-2}$	0.069

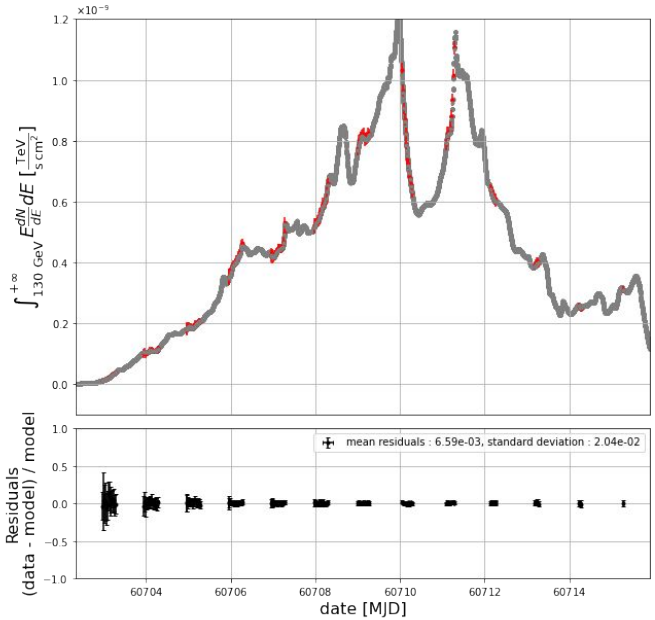
BACKUP : AGN LTM BL Lac full reconstructed LC





BACKUP : AGN flares - Christie et al. with magnetic reco.





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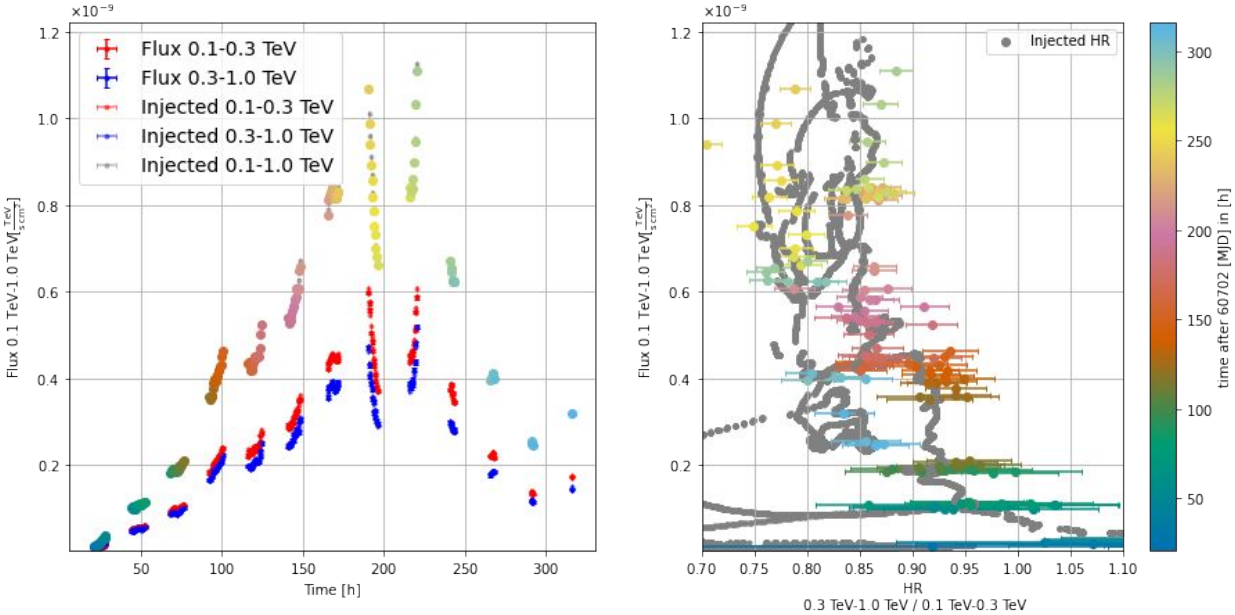
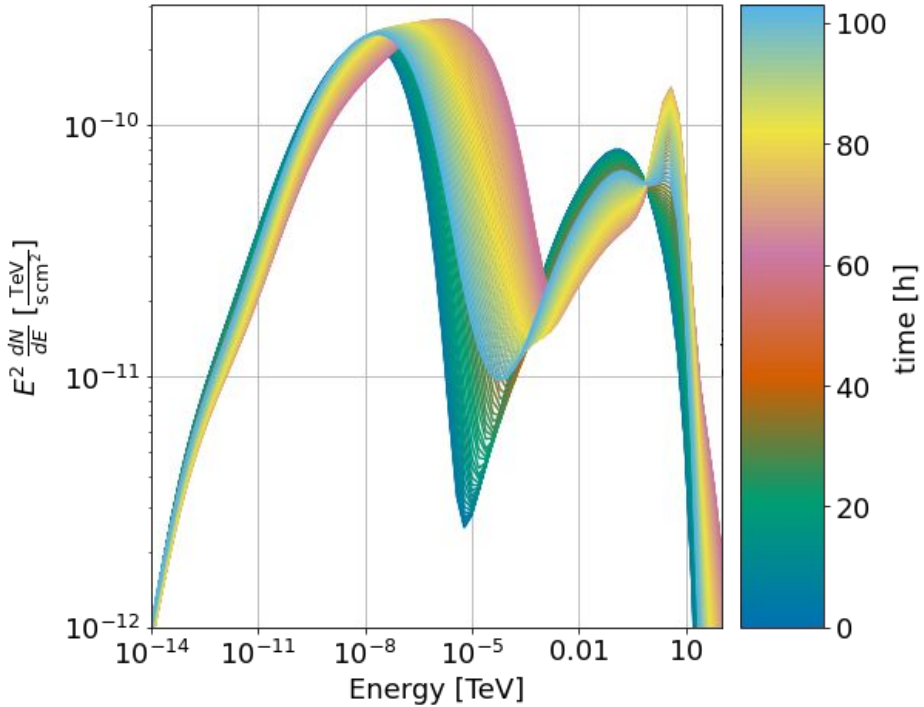


BACKUP : AGN flares - Petropoulou et al. Lepto-hadronic



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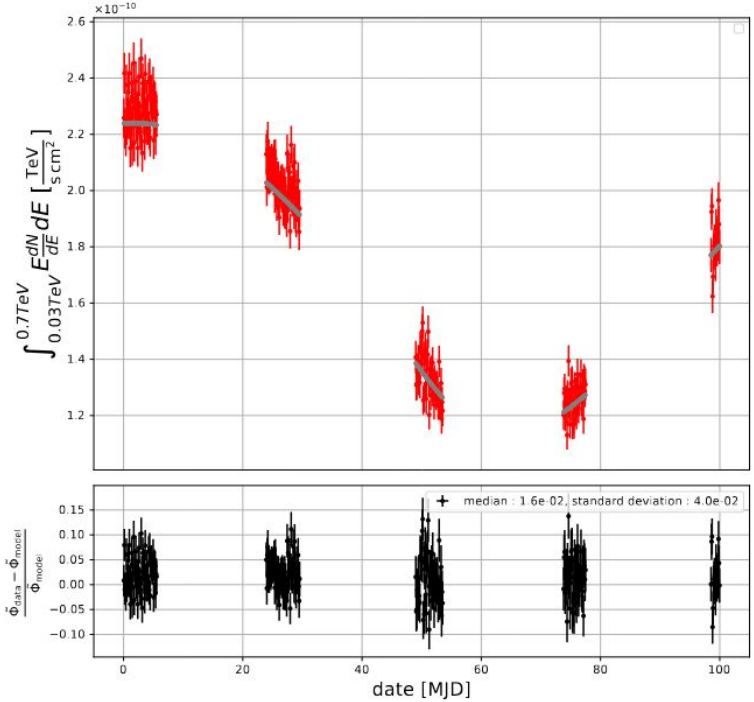

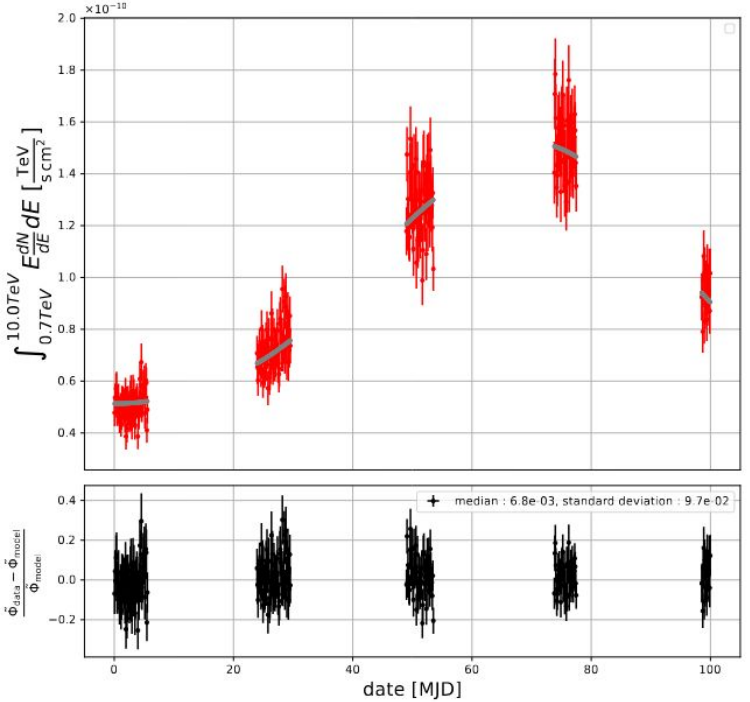

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