CTAO
Cherenkov Telescope Array Observatory

AGN models within CTAO Science Data Challenge

Discussion session – ASTROVIBE workshop

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CTAO AGN variability Task Force

Caveat:

- Different variability time scales involved

    1) Long-term variability (month/year) (cf. e.g. Biteau @ CTAO meeting, Naples, 2022)

    2) "Fast" variability (minutes/hours/days)

- For CTAO Science Data Challenge, only a model for 1) was fully available and tested.

CTAO AGN Key Science Project (KSP)

Long-term variability

Fast variability

Programme	total N [h]	total S [h]	duration [yr]	observation mode
Long-term monitoring	1110	390	10 †	full array
AGN flares				
snapshots	1200	475	10 ∗	LSTs
snapshots	138	68	10 ∗	MSTs (assuming 10 sub-arrays)
verification ext. trig.	300	150	10 ∗	LSTs or MST sub-arrays
follow-up of triggers	725	475	10 ∗	full array
High-quality spectra				
redshift sample	195	135	3	full array
M 87 and Cen A	100	150	3	full array

Table 12.3 – Summary of required observing times for the northern site ("N") and the southern site ("S") for the different parts of the observation programme. The total duration of each programme is given in the fourth column, where a "∗" ("†") indicates a reduction of the yearly exposure time after 2 (5) years.

See also:
[CTA consortium (2019)]

Caveat: Following slides shamelessly borrowed from Biteau @ CTAO meeting, Naples, 2022

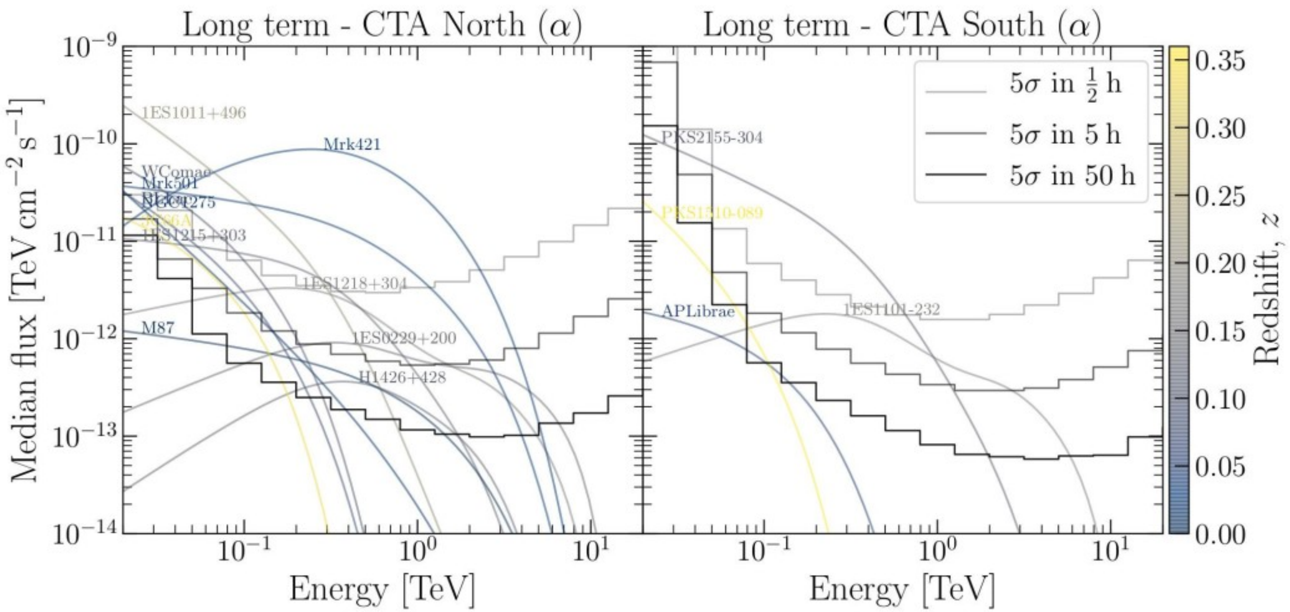
CTAO AGN Long-term monitoring program (LTM)

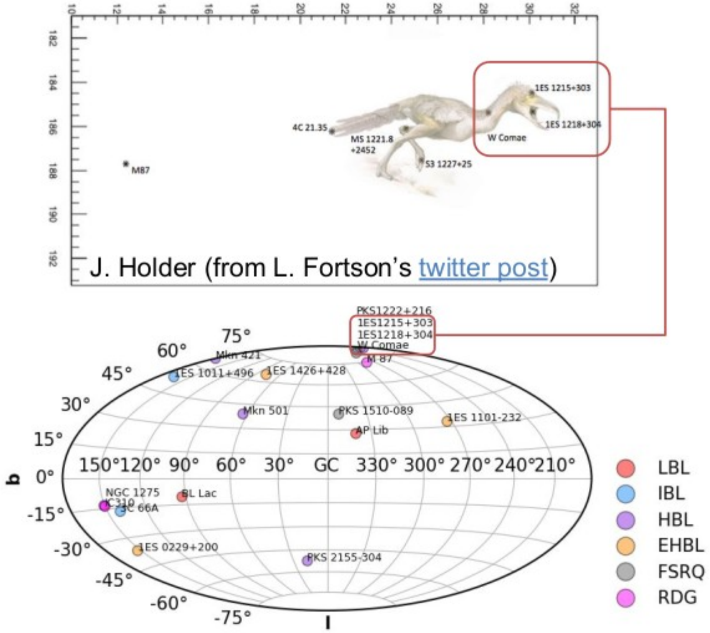
Unveil long-term variability (week-yr) of TeV AGN, self trigger on short-term flares (min-h)

10-yr lightcurves with weekly cadence to reconstruct:

- Flux distribution, hence duty cycle
- Power spectrum, including breaks: correlated with SMBH mass as in X-rays? McHardy+ '06

15 targets: all known TeV-AGN classes over a wide redshift range



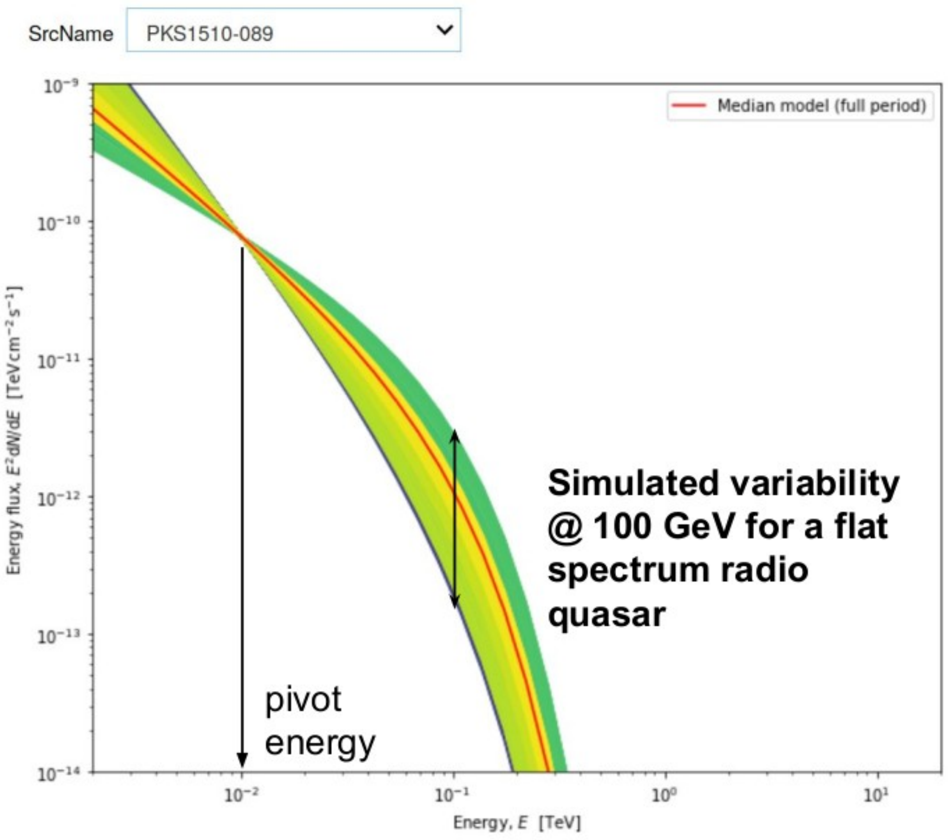


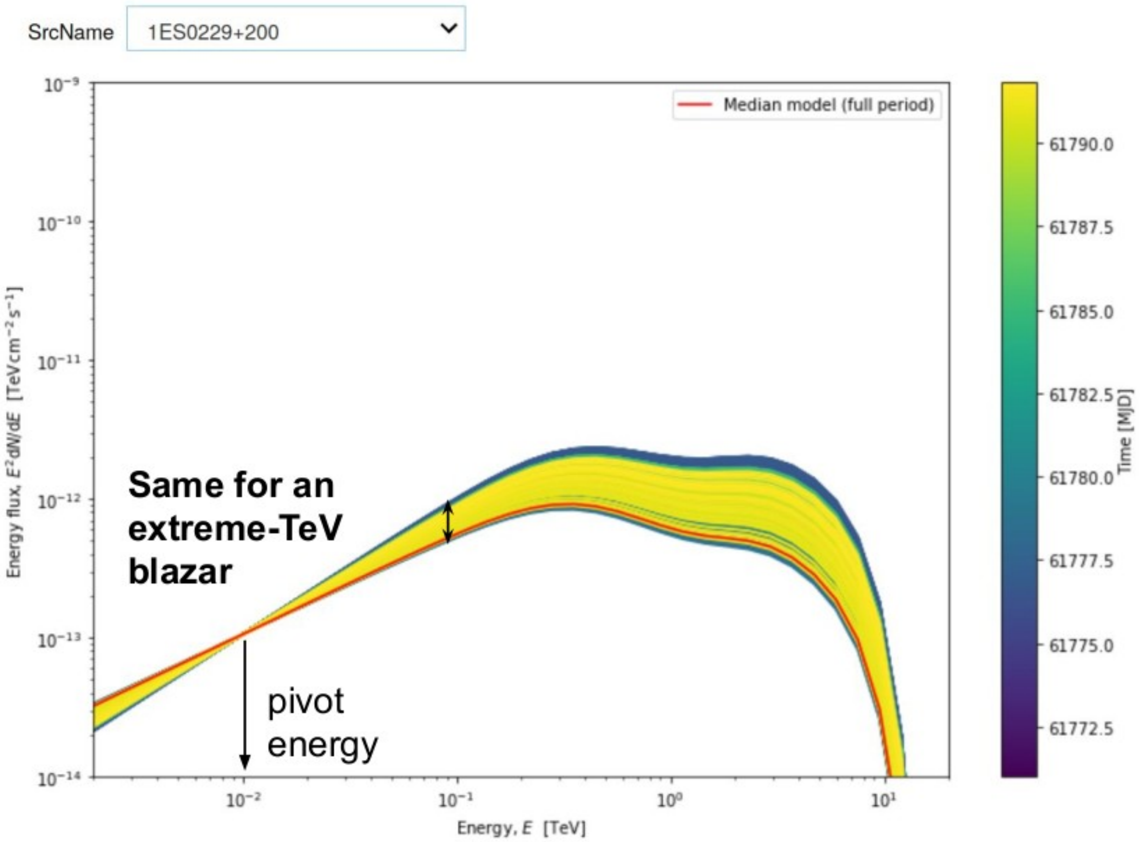
Credits: Jonathan Biteau

CTA AGN LTM: Simulated models

$$\phi_z(E,t) = \phi_0(t)\left(\frac{E}{E_0}\right)^{-\Gamma(t)-\beta\ln\frac{E}{E_0}} \mathrm{e}^{-\frac{E}{E_{\mathrm{cut}}}} \mathrm{e}^{-\tau_{\gamma\gamma}(E,z)} = \phi_z^{\mathrm{med}}(E)\left(\mathcal{LN}_t(\mu,\sigma)\right)^{1+b_\Gamma \ln\frac{E}{E_0}}$$

Spectral Model **Temporal Model**





Credits: Jonathan Biteau

CTA AGN LTM, also in CTAO SDC AGN models

Spectral model $\phi_z(E,t) = \phi_0(t)\left(\frac{E}{E_0}\right)^{-\Gamma(t)-\beta\ln\frac{E}{E_0}} e^{-\frac{E}{E_{\rm cut}}} e^{-\tau_{\gamma\gamma}(E,z)}$

Variable flux norm $\phi_0(t)$

Log-normal colored noise (Emmanoulopoulos +13 by W. Max-Moerbeck)

Fourier spectrum at cut-off energy $P_{E_{\rm cut}}(\nu)$:
broken power-law at ν_{12} going from pink to red noise

Variable index $\Gamma(t) = \Gamma_0 - b_\Gamma \ln\frac{\phi_0(t)}{\phi_{\rm ref}}$: harder when brighter

with $b_\Gamma^{-1} = \ln\frac{E_0}{E_{\rm pivot}}$ and $E_{\rm pivot} = 10$ GeV, based on PKS 2155-304

Rewritten model $\phi_z(E,t) = \phi_z^{\rm med}(E)\left(\mathcal{LN}_t(\mu,\sigma)\right)^{1+b_\Gamma\ln\frac{E}{E_0}}$

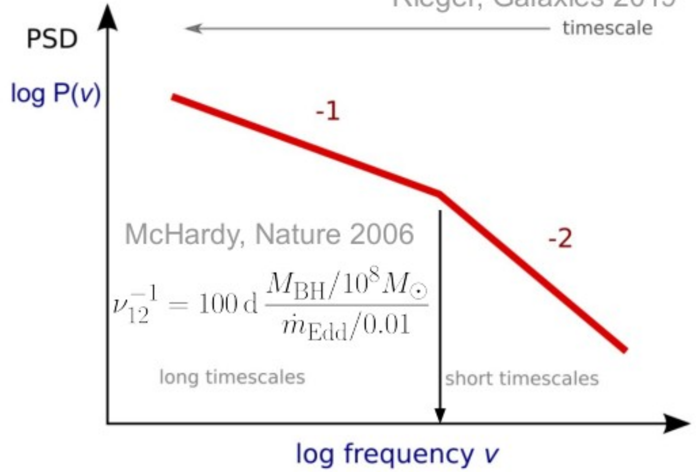
where $\mu = 0 \Rightarrow {\rm Med}\left(\phi_z(E,t)\right) = \phi_z^{\rm med}(E)$

and $e^{\sigma^2}-1 = \frac{V\left(\phi_z(E_{\rm cut},t)\right)}{\langle\phi_z(E_{\rm cut},t)\rangle^2} = \int_{\nu_{\rm min}}^{\nu_{\rm max}} P_{E_{\rm cut}}(\nu){\rm d}\nu$

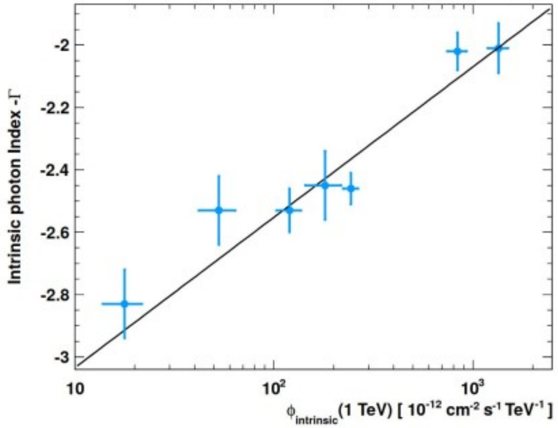
$F_{var}(E_{cut})$ = 1 ⇒ AGN-type dependent variability

Revised, wrt. current IACT archives (SteVECat, Gréaux et al., 2023)

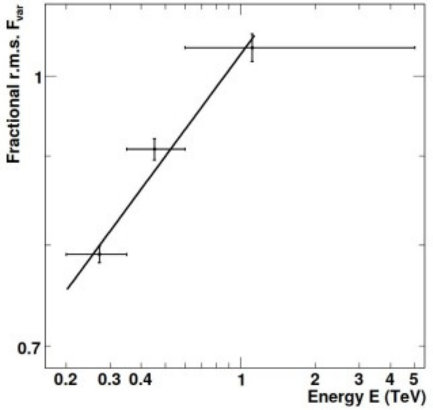
Rieger, Galaxies 2019



JB's thesis, chap. 4, Fig. 5



H.E.S.S., A&A 2010



Credits: Jonathan Biteau

Light curve reconstruction

GammaPy simu and reco

Using ctaagnvar pipeline
by G. Grolleron & J.P. Lenain

IRFs account for:

- ❑ Zenith angle
- ❑ NSB level

PWL fit in three *E*-ranges:

- ❑ 30-300 GeV
- ❑ 0.3-3 TeV
- ❑ 3-30 TeV

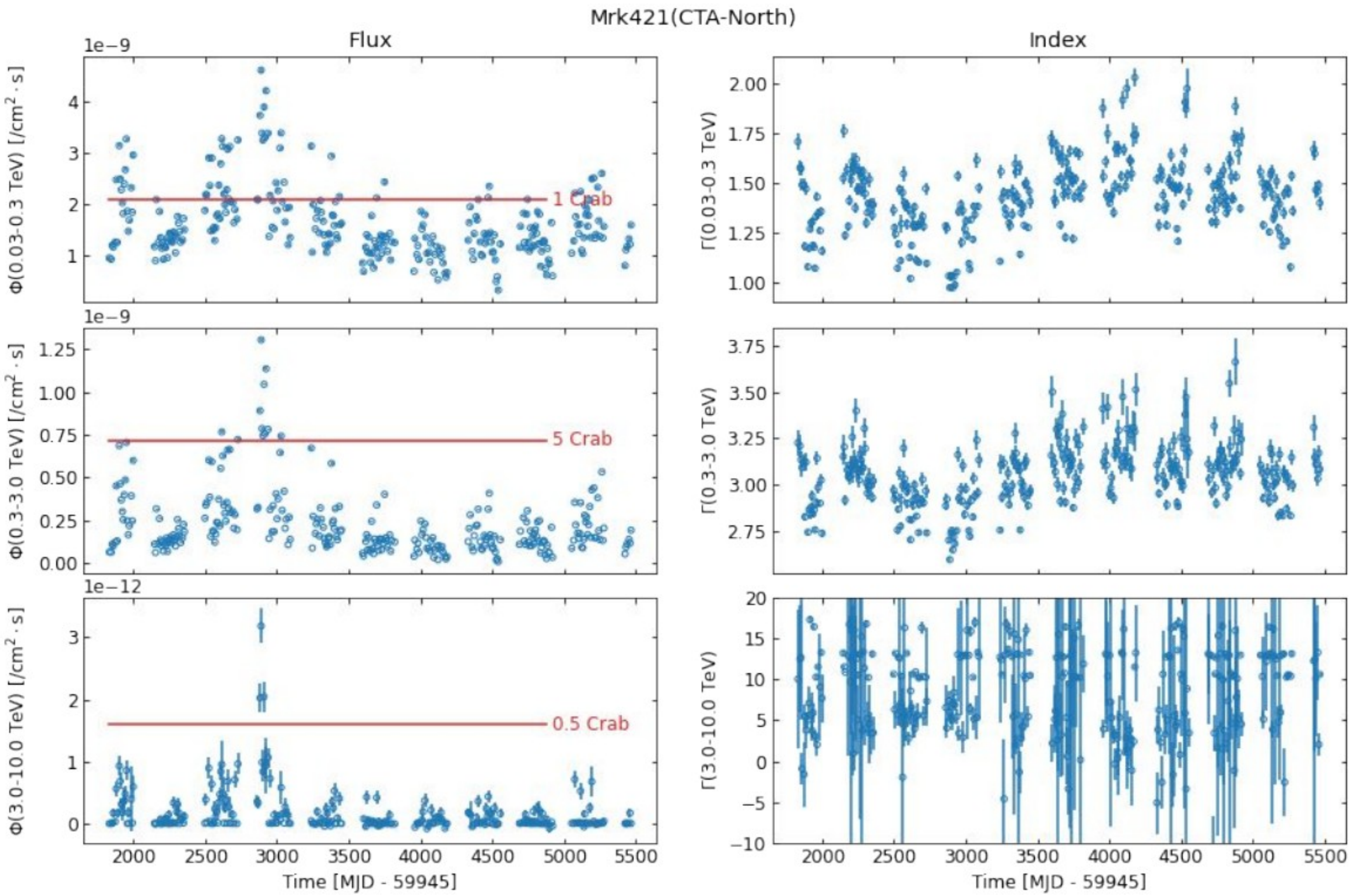
E-ranges also suggested for online reconstruction

cf. MWL operational requirements

Example: Mrk 421

This realization:

- ❑ LTM: 14h09' per year
- ❑ 11 runs (30') > 5 Crab in 10 years



Credits: Jonathan Biteau

cf. discussion session with G. Grolleron

Power spectral density and duty cycle

Fourier reconstruction

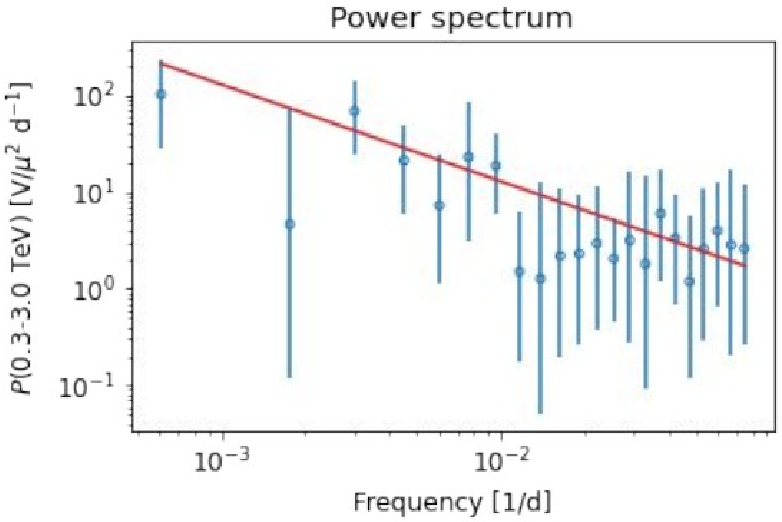
For now, simulation of pink noise (index =1) for all sources in the sample

Results on this realization of Mrk 421 monitoring:

- ❑ Index = **1.1 (1.2) ± 0.1 for 15 yrs (10 yrs)** S. Suutarinen
  + ongoing cross-checks with independent methods W. Max-Moerbeck, K. Nilsson

Next steps:

- ❑ 100 realizations → coverage (uncertainties)
- ❑ Breaks at 3, 30, 300 days → resolution on $\frac{M_{BH}/10^8 M_\odot}{\dot{m}_E/1}$



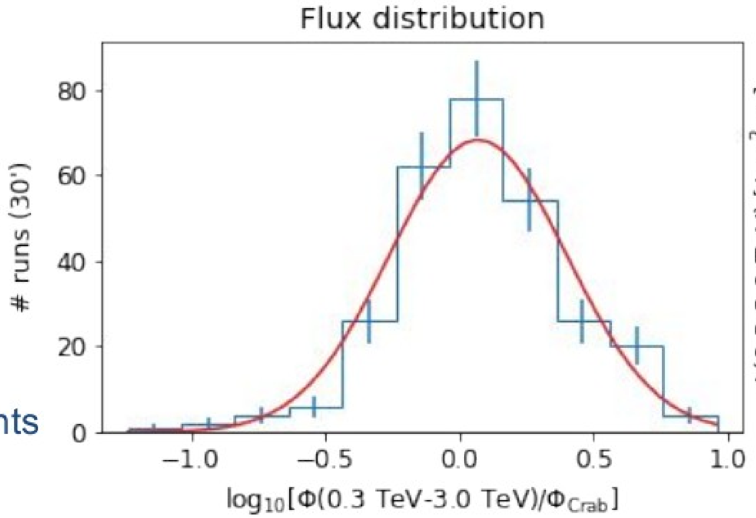
Flux distribution and duty cycles

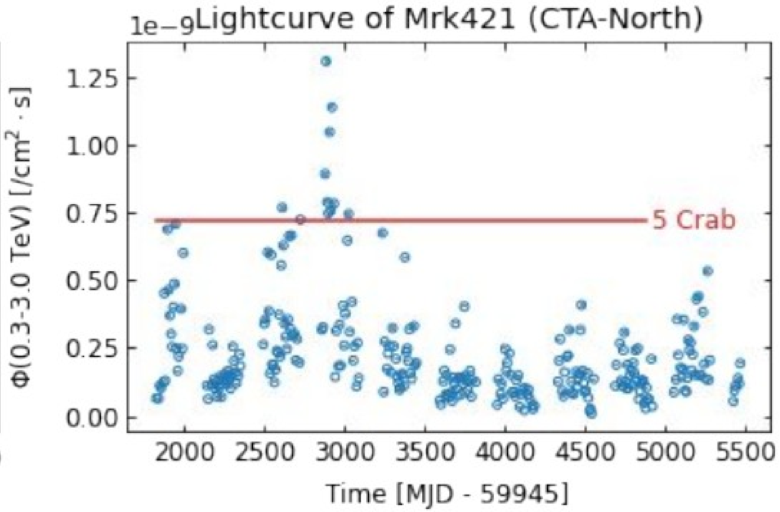
Definition of flux thresholds for **high states**

A. $\Phi_{>0.1\mathrm{TeV}}$ > 10% Crab Units

B. $\Phi_{>0.1\mathrm{TeV}}$ > **X** ×⟨$\Phi_{>0.1\mathrm{TeV}}$⟩with **X**=(1,4,10) for (EHSP, HSP, LSP)

Criteria A and B ensure:
high-σ detection & ToO on exceptional events



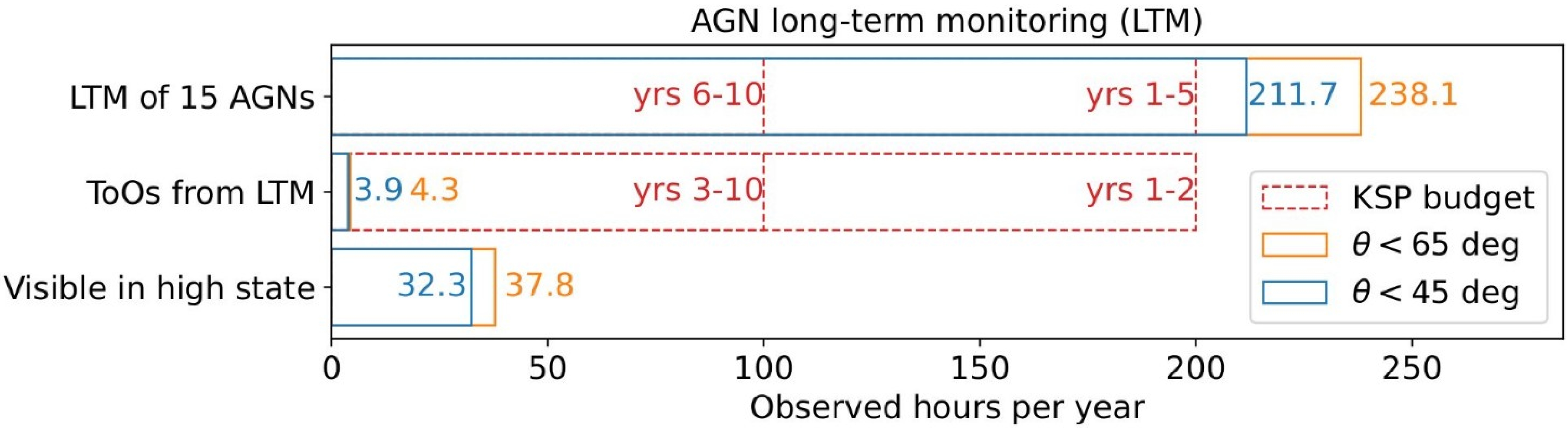


Credits: Jonathan Biteau

Time budget

Long-term monitoring: 210-240h per year for 15 fields depending on max zenith angle, θ

- Bad-weather accounted for, but assumes perfect weather forecast with systematic re-schedule
- Assumes highest priority for AGN-LTM, when some external ToOs will supersede these observations
- All in all → **within the budget of yrs 1-5**.

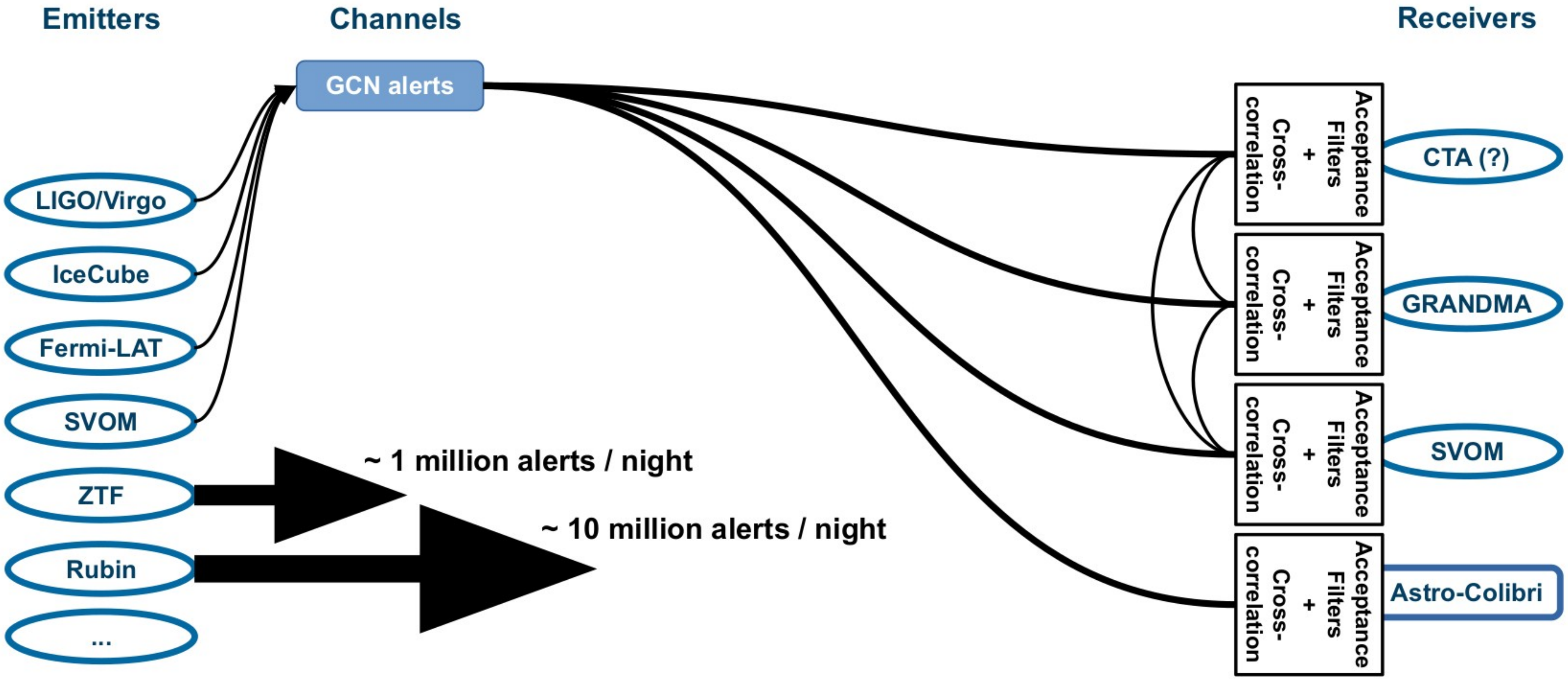


ToOs on high-states: 10% of high states in 15 fields caught by this program

- Snapshot program: How much of the remaining visible high-state time? *To be determined*
- External triggers: How many? From which facilities / platform? *See next slide*

Credits: Jonathan Biteau

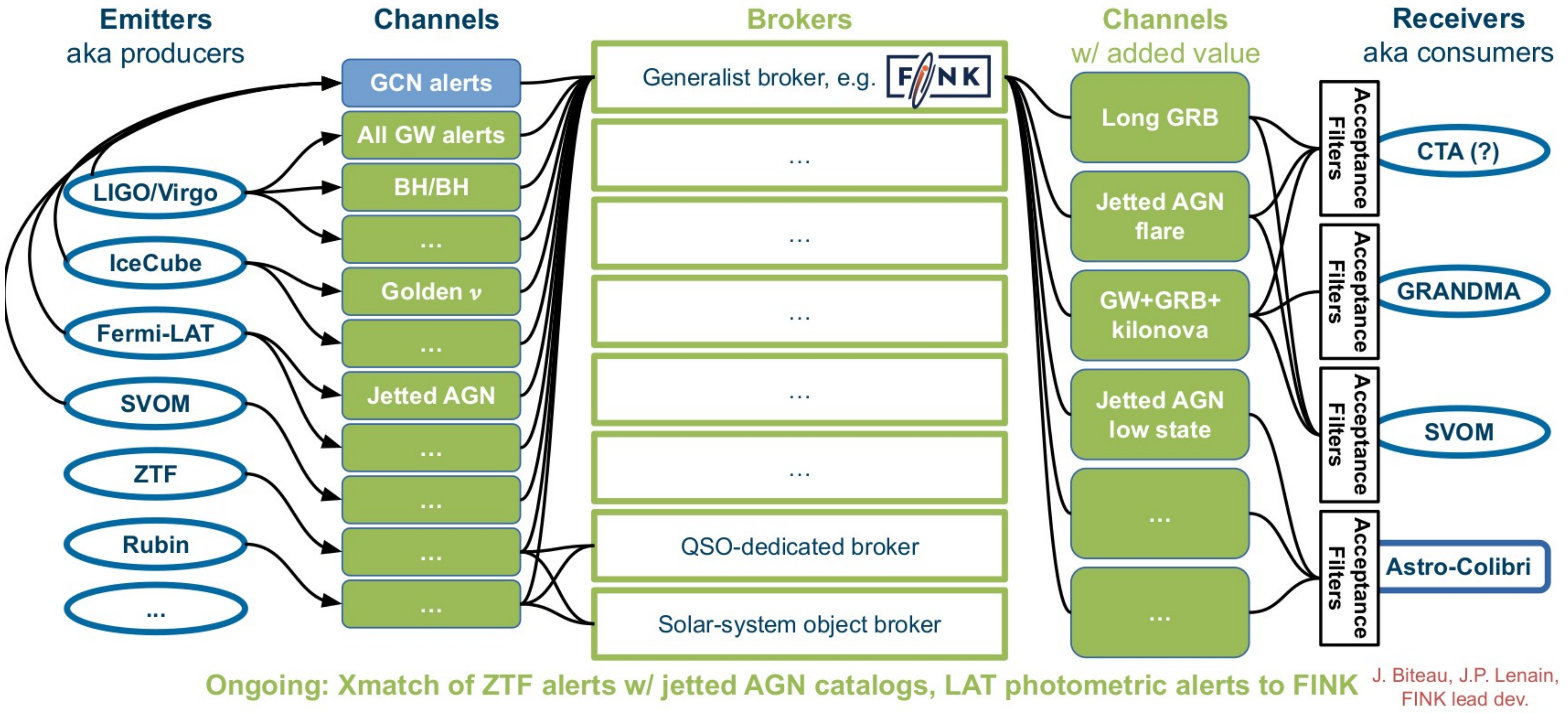
External ToOs: the current scheme



The current scheme hardly scales in the era of time-domain astronomy!

Credits: Jonathan Biteau

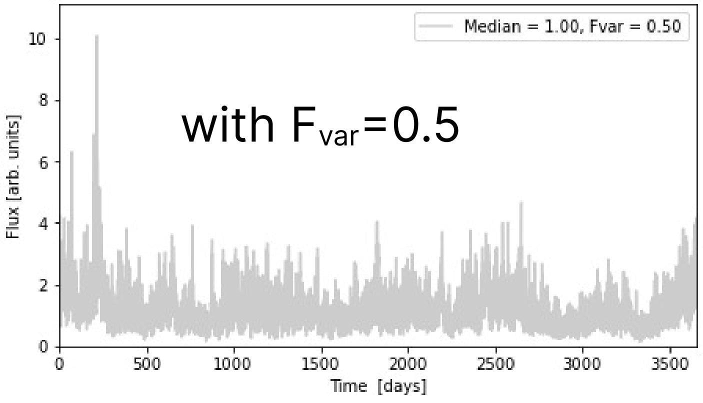
External ToOs: the broker scheme

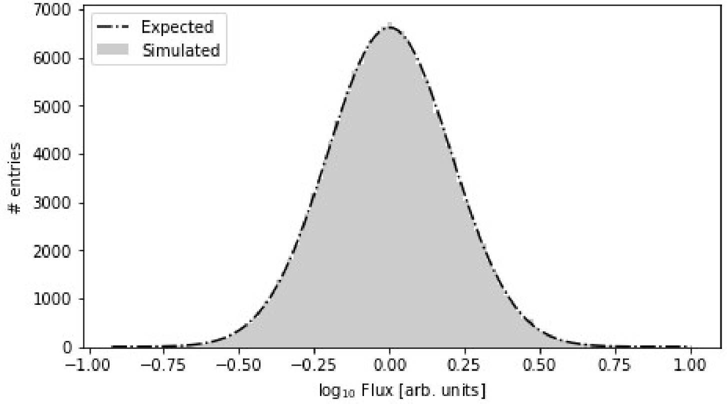


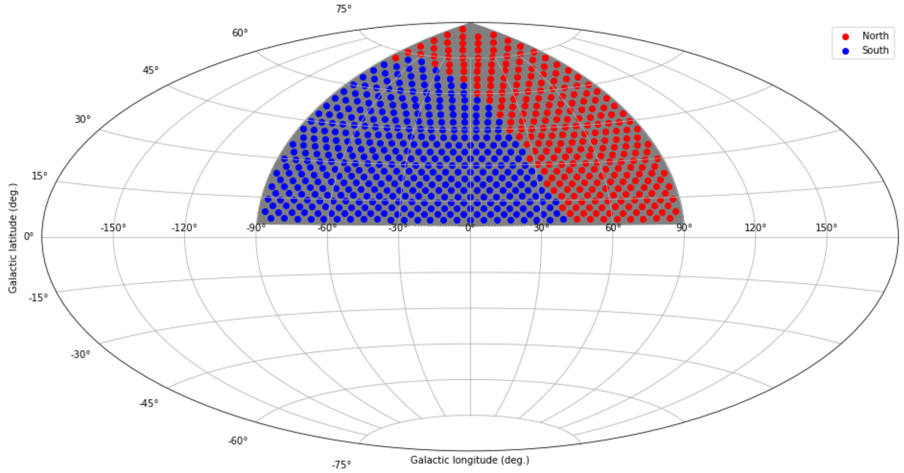
Since Nov. 2022, FLaapLUC alerts also fed into FINK

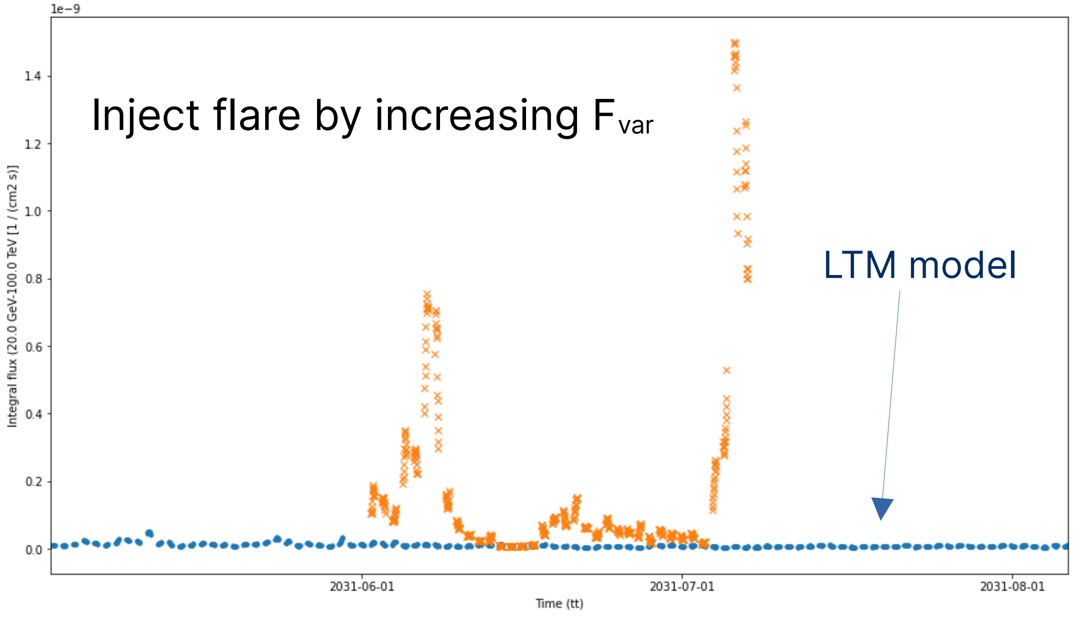
Credits: Jonathan Biteau

But, will you finally tell us about AGN models in CTAO SDC ?









EGAL survey, from synthetic population (BL Lac, FSRQ)

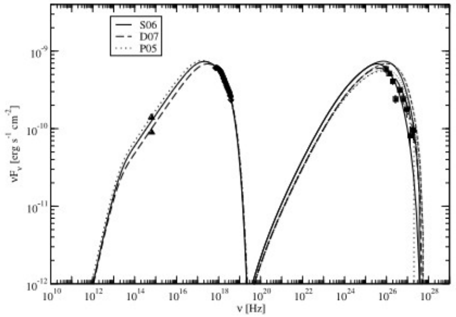
+ AGN LTM
+ AGNpop (4LAC)
+ AGN flares (extern from Fermi-LAT)
+ Cen A
+ starbursts
+ IGMF-induced pair halo...

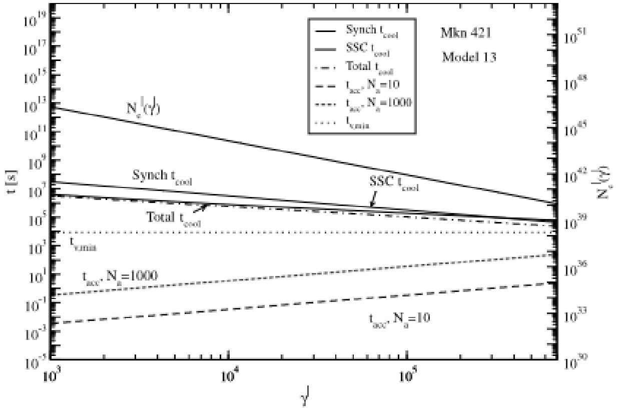
Fast variability

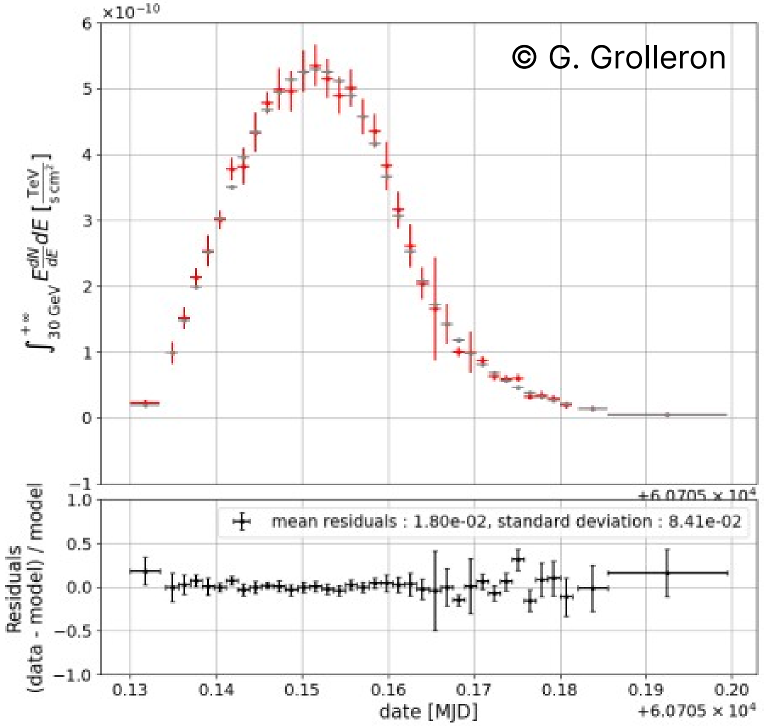
- Phenomenological models at hand
  - 1-zone/multi-zone
  - Pure leptonic or lepto-hadronic
  - Applied to already published data from current IACTs
    - Simulations for CTAO applied on same flares
- In the wake of TXS 0506+056, gave birth to the Blazar Hadronic Code Comparison Project (Cerruti et al., 2022)

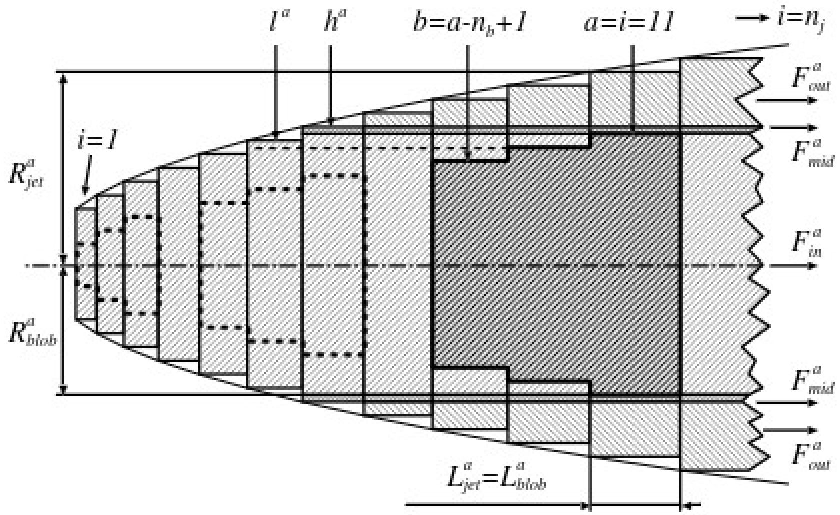
Fast variability

- 1-zone SSC model
- E.g. Katarzyński et al. (2003), Finke et al. (2008)





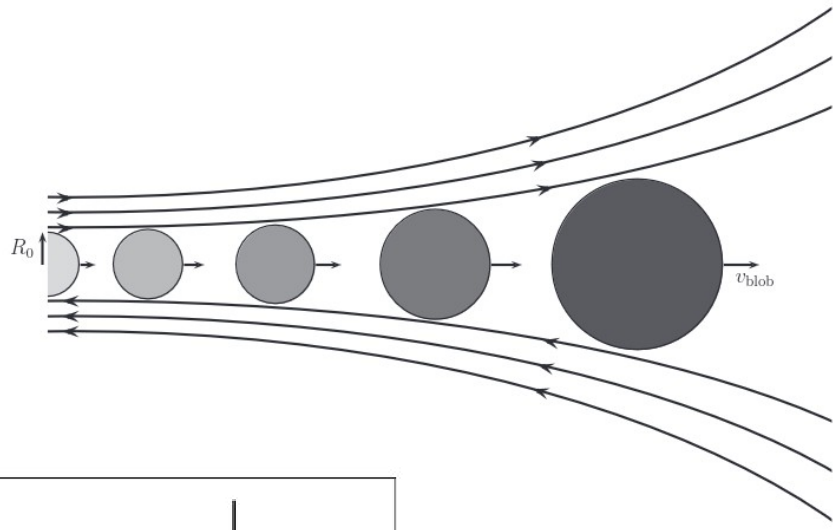


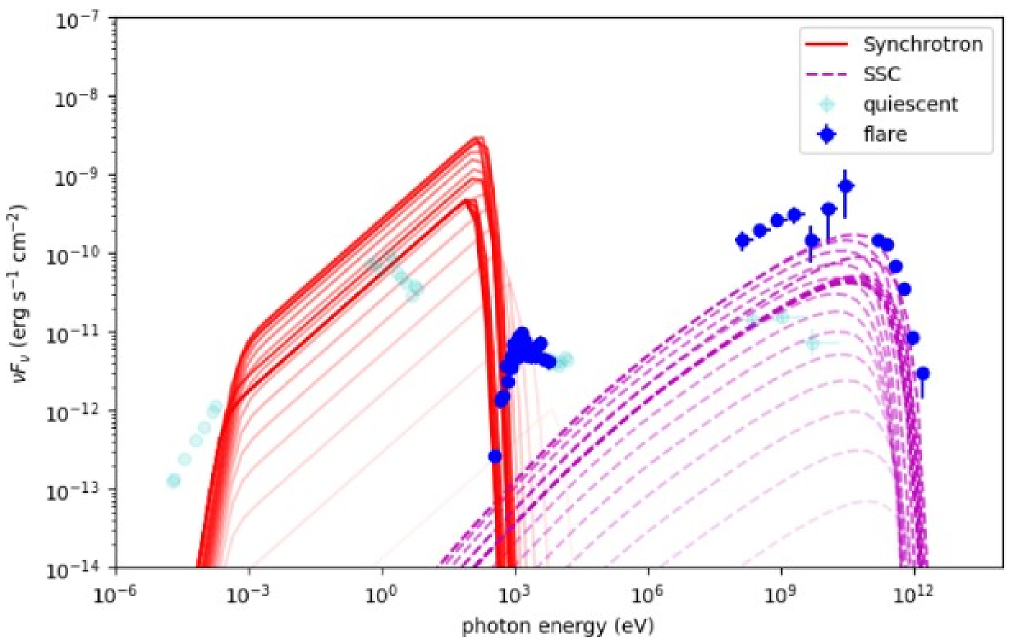


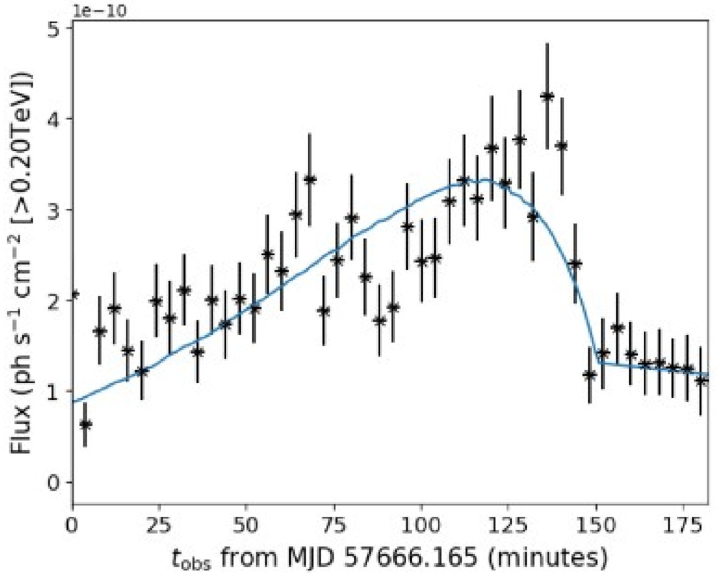
Mrk 421

Fast variability

- Particle acceleration from magnetic reconnection
- 1-zone SSC model
- E.g. Morris et al. (2019)



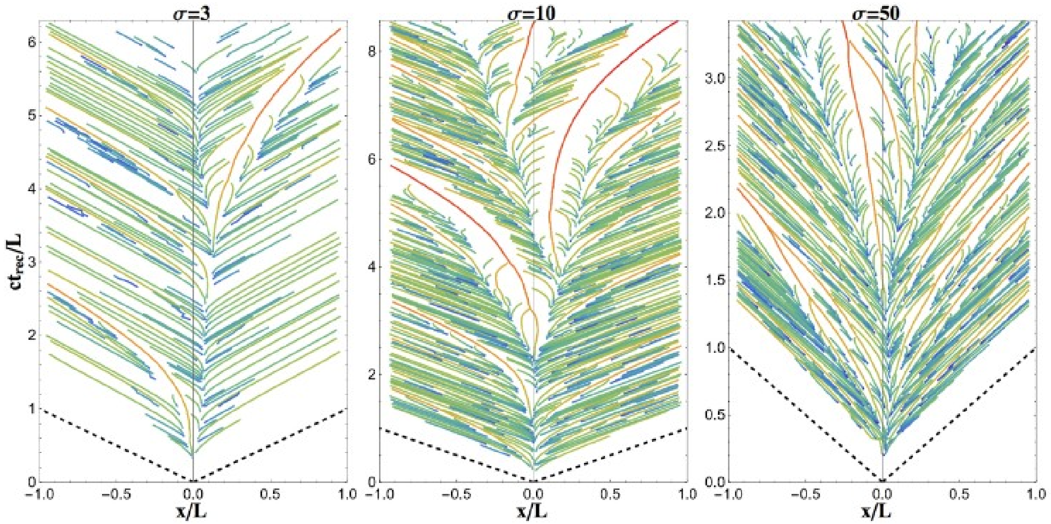




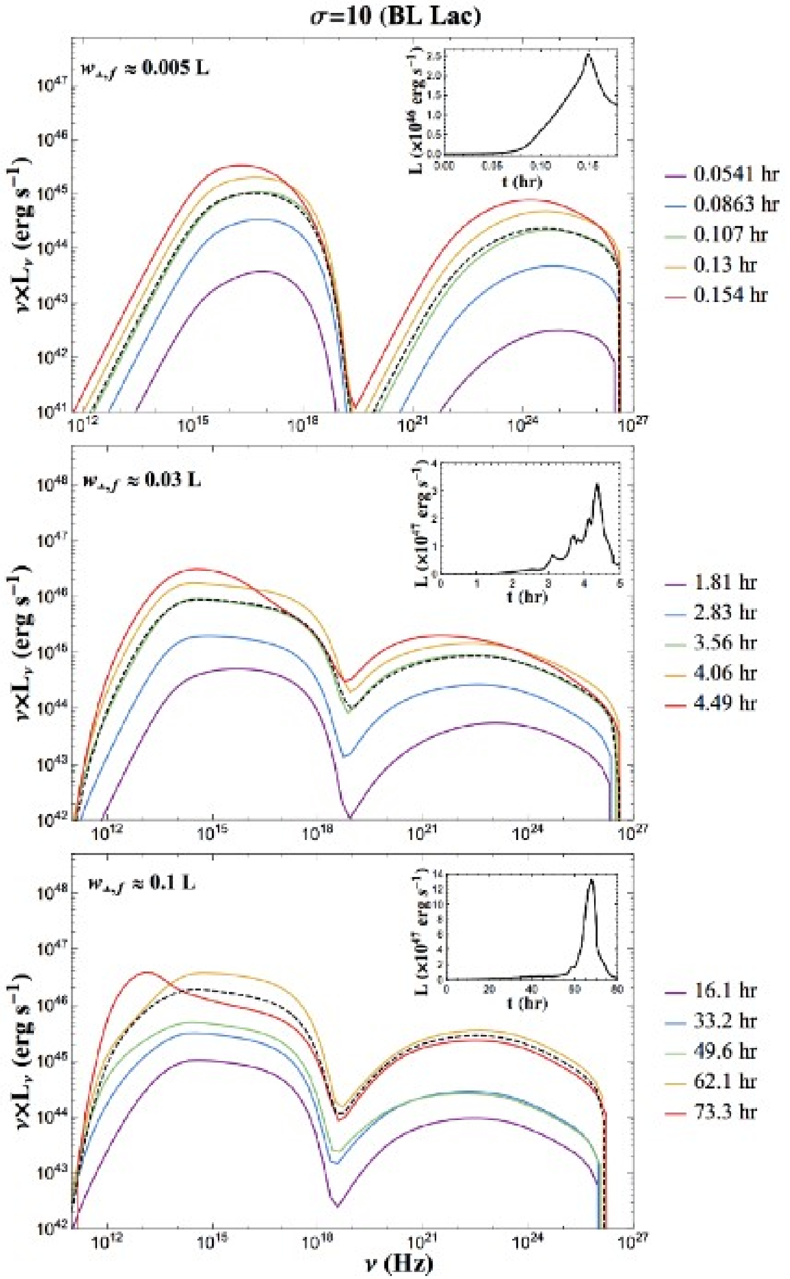
BL Lac
2016 flare

Fast variability

- Magnetic reconnection
- Multi-zone (chain of plasmoids)
- Leptonic (SSC, EIC)
- Christie et al. (2019)

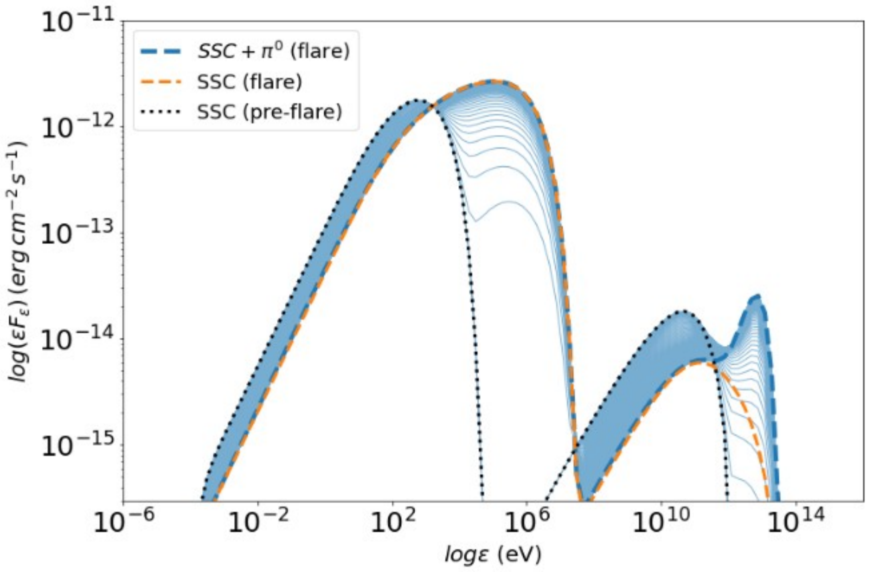


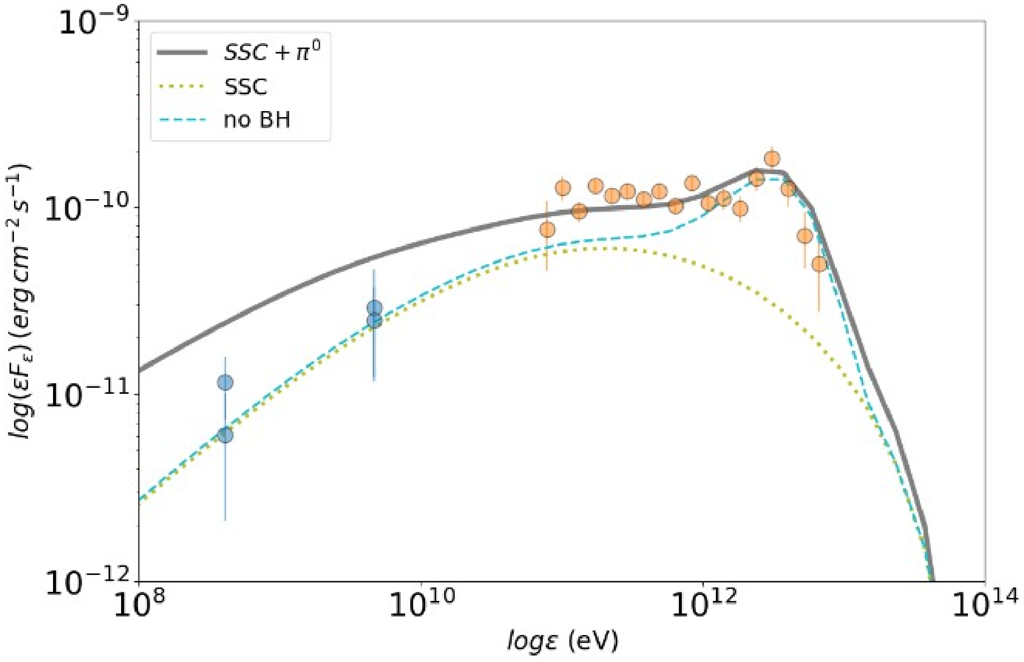
2D PIC



Fast variability

- Narrow spectral feature from Mrk 501 with MAGIC in 2014
- Lepto-hadronic: SSC+π^0:
  pγ (increasing during X-ray flare) → π^0 decay
- Petropoulou et al. (2024)





Thank you

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