

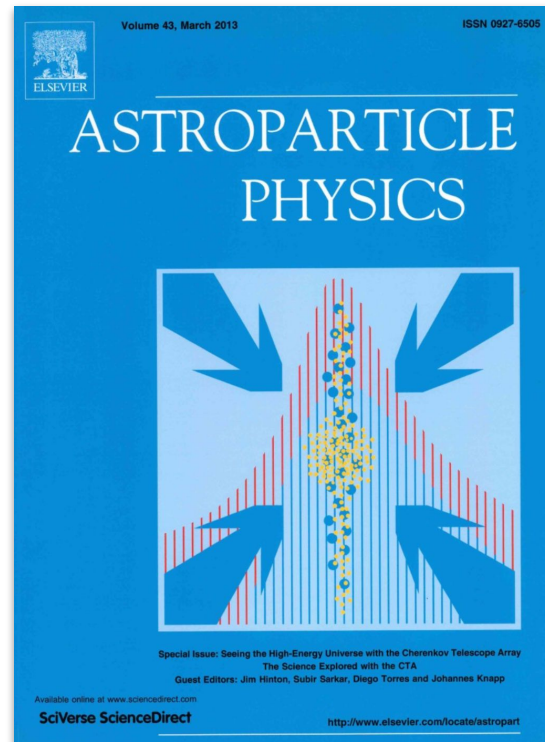
Active Galactic Nuclei population studies with the CTAO

Atreya Acharyya
on behalf of the CTAO AGN Population Task Force

IJCLab, 15th October 2026

Introduction

- The main objective of this task force is evaluating the population of AGN that will be realistically detectable with CTAO
- It is thought as work for a wider community: Let them know which sources are likely to be studied with CTAO over “reasonable” observing times (proposals)
- It strongly inherits from tasks performed in the (distant) past, to evaluate CTAO physics prospects over very different telescope layouts (added to APP special issue from 2013!)



Publication content

- The topics we cover include:
 - How many AGN will the CTAO be capable of detecting over reasonable observing times, and from which classes?
 - How many sources will be detectable during high activity episodes?
 - How far will these sources be?
 - How accurately will the CTAO reconstruct the luminosity function of BL Lac sources with the extragalactic survey?
- We rely on significant results from Fermi-LAT:
 - 4LAC-DR3 catalog, with revised redshift catalog
 - Light-curves from the Fermi-LAT Light Curve Repository
 - Blazar luminosity functions

Subtasks

- The content of the paper is mainly divided into 3 broad tasks:

Core simulations,
the CTAO AGN sky
from the extrapolation of
the Fermi-LAT average
spectra

The CTAO AGN sky
**Including variability
in core simulations**

The BL Lacs
luminosity function
reconstruction from the
CTAO extragalactic survey

**To be presented at a
future meeting**

Subtask 1: core simulations

⇒ AGN Detection Prospects from Fermi-LAT averaged spectra

- Simulation and analysis tools fully tested
 - gammapy v1.1
 - IRFs: alpha configuration
- Input catalogue updated (4LAC-DR3, revised z)
 - Review of redshifts for >500 bright AGN with hard spectra in 4LAC
 - ⇒ <https://doi.org/10.5281/zenodo.4721385>
- Data-driven based scheme for the Fermi-LAT spectrum extrapolation

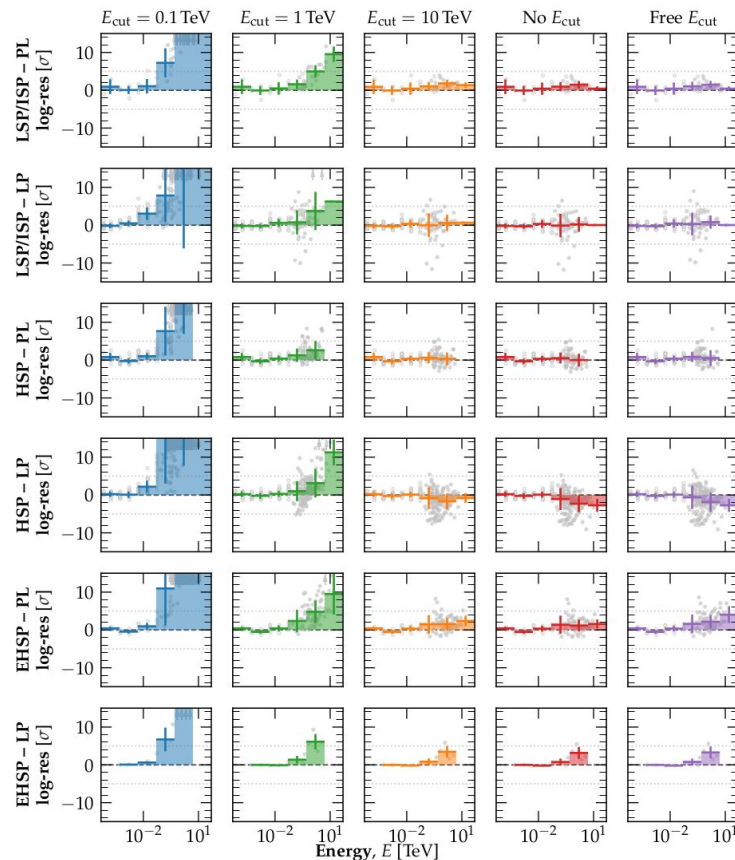
Subtask 1: extrapolation scheme

- Extrapolation scheme
 - Extend preferred Fermi-LAT spectrum to VHE (baseline model)
 - Add EBL absorption (Saldana-Lopez)
 - Add exp. cutoff at energy E_{cut}

$$E_{\text{cut}} \begin{cases} \cancel{0.1 \text{ TeV}} & \text{for } \cancel{\text{LSP \& ISP}} \\ \cancel{1 \text{ TeV}} & \text{for } \cancel{\text{HSP}} \\ 10 \text{ TeV} & \text{for EHSP} \end{cases} \Rightarrow \text{10 TeV for all source types}$$

⇒ Good match with current observations.

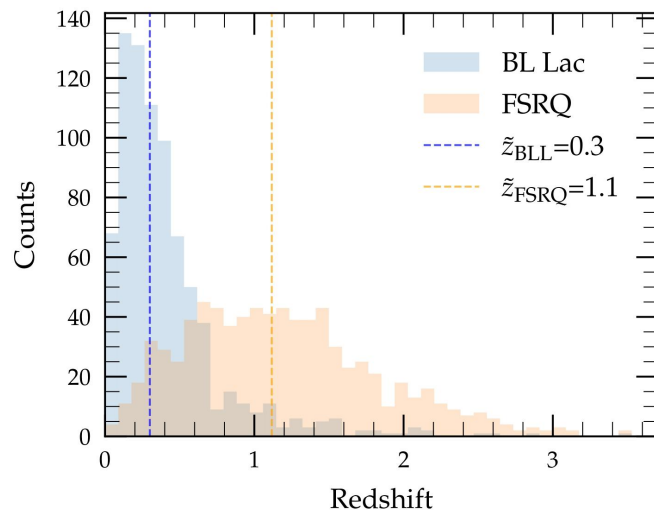
⇒ Added as annex to the paper



Subtask 1: core simulations

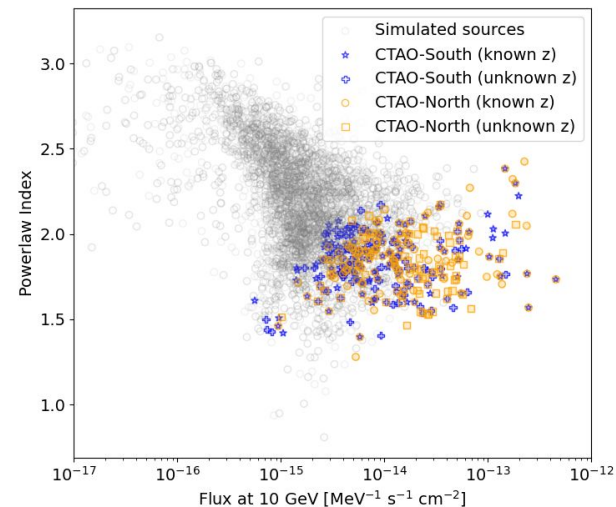
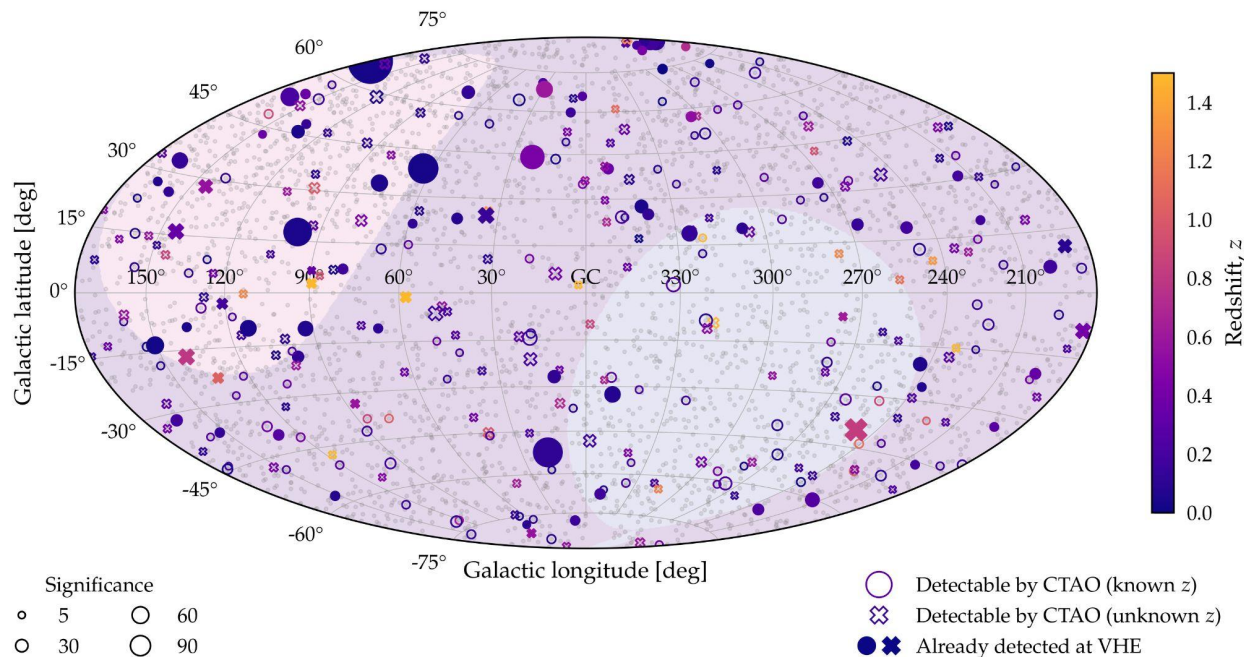
⇒ AGN Detection Prospects from Fermi-LAT averaged spectra

- Simulations based on 4LAC-DR3 catalog,
- Assume 5 and 20 h observing time
- We define the *static sample*:
 - 1788 AGN with known redshift
 - 2018 AGN with simulated redshift
- Treatment of unknown redshift:
 - Strategy 1: fixed redshift ($z=0.3$ or $z=1$ depending on SED class)
 - **Strategy 2: source class dependent redshift distribution instead of fixed values**
 - Strategy 3: redshift scan to identify $z_{\max}$ achieving 5 sigmas in i.e. 5h or 20h



Subtask 1: core simulations

⇒ AGN Detection Prospects from Fermi-LAT averaged spectra



CTAO-detectable sources span the full sky and a broad range of properties

Subtask 1: core simulations

⇒ AGN Detection Prospects from Fermi-LAT averaged spectra

	Static sample					
	Known z (1788 sources)		Unknown z (2018 sources)		Total (3806 sources)	
	5h	20h	5h	20h	5h	20h
Observing time	5h	20h	5h	20h	5h	20h
CTAO-North	47	120	30	88	77	208
CTAO-South	66	133	24	87	90	220
CTAO (N+S)	84	178	45	139	129	317

Blazar sub-class	Static sample, 20h of observation									
	Known z (1788 sources)					Unknown z (2018 sources)				
	LSP	ISP	HSP	EHSP	Unclassified	LSP	ISP	HSP	EHSP	Unclassified
CTAO-North	18	19	72	10	1	9	22	54	2	1
CTAO-South	19	22	78	12	2	9	14	57	3	4
CTAO (N+S)	28	27	102	18	3	16	29	85	4	5

AGN type	Static sample, 20h of observation					Unknown z (2018 sources)		
	Known z (1788 sources)							
	BLL	FSRQ	BCU	RDG	AGN	BLL	FSRQ	BCU
CTAO-North	97	8	5	9	1	78	0	10
CTAO-South	111	6	5	10	1	73	0	14
CTAO (N+S)	145	11	7	14	1	121	0	18

- CTAO detects ~130 sources in 5h
- >300 sources in 20h exposures

Healthy comparison
with observations with
current IACTs
⇒ Most VHE AGN
within TeVCat detected
by CTAO

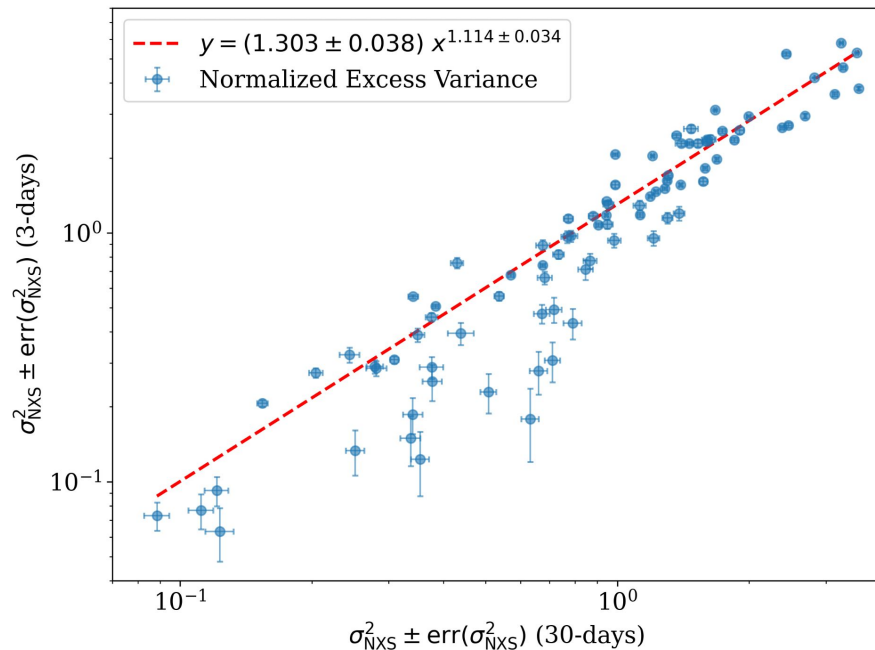
Subtask 2: including variability

- As a very large fraction of current VHE-detected extragalactic sources were discovered in flaring states, it makes sense to compare CTAO capabilities under a similar scenario
- Idea:
 - Use Fermi-LAT light curves to estimate daily-scale variability in the Fermi-LAT energy band
 - Apply a model to extrapolate the variable spectra to the CTAO energy band
 - Simulate and evaluate the CTAO detectability of sources in high states

Subtask 2: including variability

Methodology for evaluating the impact of variability:

- **Step 1:** Determination of the Normalized Excess Variance ($\sigma^2_{\text{NXS,LAT}} \pm \Delta\sigma^2_{\text{NXS,LAT}}$) for the available 3-days and monthly cadence light-curves in the Fermi-LAT Light Curve Repository (1429 valid LCs with strict quality cuts applied)
- **Step 2:** Determination of the power-law relation between $\sigma^2_{\text{NXS,LAT}}$ (3-days) and $\sigma^2_{\text{NXS,LAT}}$ (1 month) using 87 sources well constrained in both cadences, enabling the extrapolation of short-timescale variability from monthly scale variability



Subtask 2: including variability

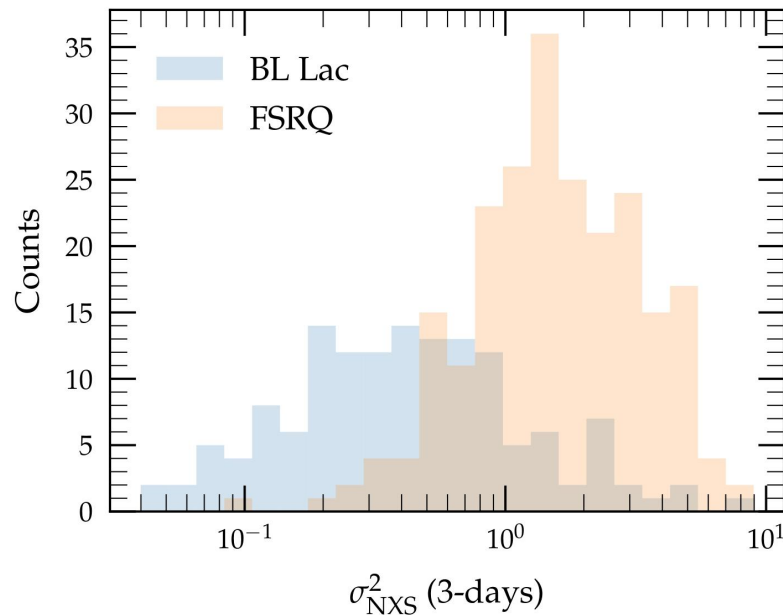
Methodology for evaluating the impact of variability:

- **Step 3:** Use of $\sigma_{\text{NXS,LAT}}^2$ (3-days) (measured when available or estimated from $\sigma_{\text{NXS,LAT}}^2$ (1 month) via the relation calibrated above) as a proxy for the daily variability in the Fermi-LAT band.
- **Step 4:** Selection of sources with enough variability on the 1-month scale

Reference variability sample: 407 sources with measured/estimated $\sigma_{\text{NXS,LAT}}^2$ (3-days), separated into BL Lacs and FSRQs.

Extension to full sample: assign $\sigma_{\text{NXS,LAT}}^2$ (3-days) to BL Lacs and FSRQs without measurements by drawing from class-specific distributions.

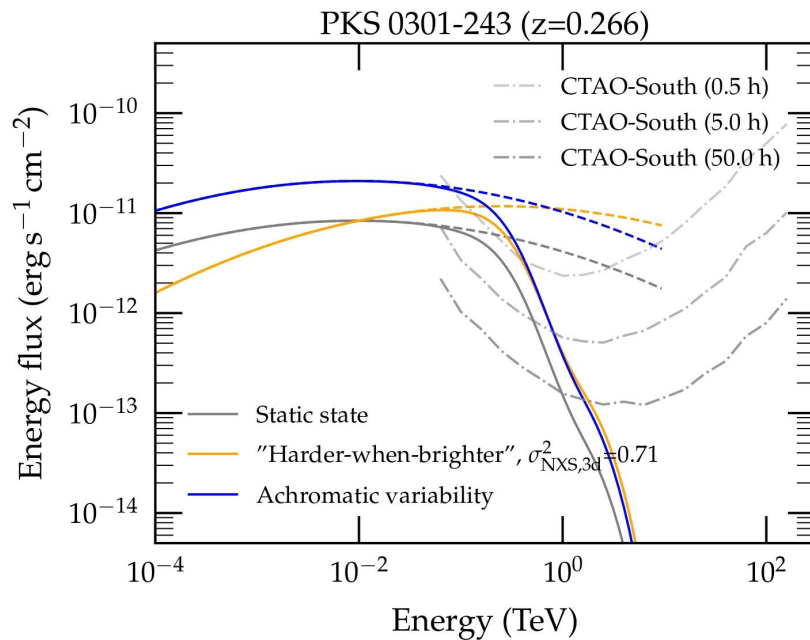
Final variability sample: 2278 sources used to simulate high-state detections.



Subtask 2: including variability

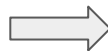
Variability properties extended to full blazar population (2278 sources)

- **Step 5:** Model daily-scale variability in the CTAO energy range:
 - Two scenarios: “achromatic variability” (constant spectral index and only flux normalisation varies) and “harder-when-brighter” (flux and index vary in correlated way)
- **Step 6:** Implement variability model in simulations
 - For each source, select top 10% brightest states
 - Simulate 2h and 5h observations to evaluate CTAO detectability in flares



Subtask 2: Impact of variability on CTAO detections

AGN type	Static sample, 20h of observation					Unknown z (2018 sources)		
	Known z (1788 sources)					BLL	FSRQ	BCU
CTAO-North	97	8	5	9	1	78	0	10
CTAO-South	111	6	5	10	1	73	0	14
CTAO (N+S)	145	11	7	14	1	121	0	18



Observing time	Variability sample (2278 sources)					
	Static state		Harder-when-brighter		Achromatic	
	5h	20h	2h	5h	2h	5h
CTAO-North	73 (40)	185 (66)	137 (60)	200 (81)	254 (97)	326 (115)
CTAO-South	81 (29)	192 (48)	155 (42)	210 (54)	232 (71)	306 (85)
CTAO (N+S)	118 (54)	280 (92)	210 (77)	297 (106)	353 (132)	458 (157)

Static sky (full population): >300 sources detectable in 20h

Including variability (bright states):

- ~300 in 5h (harder-when-brighter)
- ~450 in 5h (achromatic)

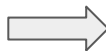
Variability strongly enhances detectability

AGN type	Known z (1595 sources)			Unknown z (683 sources)			Total (2278 sources)		
	BLL	FSRQ	Other	BLL	FSRQ	Other	BLL	FSRQ	Other
CTAO-North	92	34	1	67	2	0	159	36	1
CTAO-South	114	31	0	62	0	0	176	31	0
CTAO (N+S)	147	45	1	97	2	0	244	47	1

AGN type	Known z (1595 sources)			Unknown z (683 sources)			Total (2278 sources)		
	BLL	FSRQ	Other	BLL	FSRQ	Other	BLL	FSRQ	Other
CTAO-North	128	109	1	82	2	0	210	111	1
CTAO-South	135	84	0	82	0	0	217	84	0
CTAO (N+S)	184	141	1	123	2	0	307	143	1

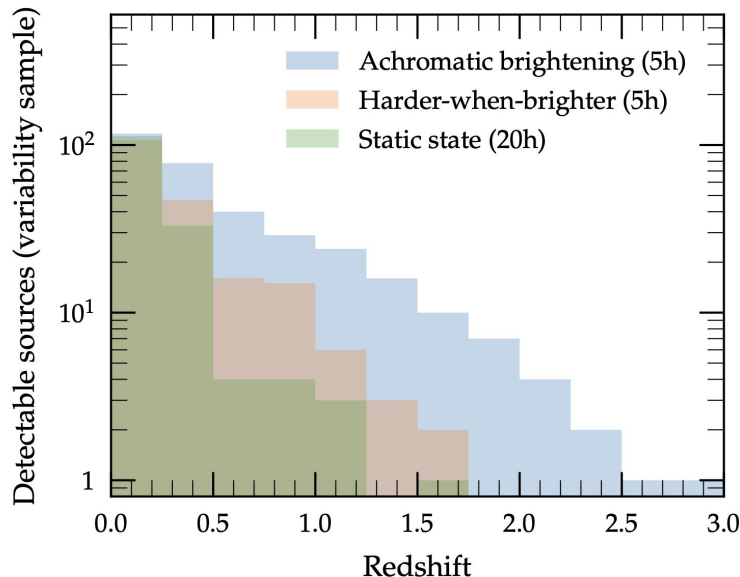
Subtask 2: Impact of variability on CTAO detections

AGN type	Static sample, 20h of observation								
	Known z (1788 sources)					Unknown z (2018 sources)			
	BLL	FSRQ	BCU	RDG	AGN	BLL	FSRQ	BCU	
CTAO-North	97	8	5	9	1	78	0	10	
CTAO-South	111	6	5	10	1	73	0	14	
CTAO (N+S)	145	11	7	14	1	121	0	18	



Observing time	Variability sample (2278 sources)					
	Static state		Harder-when-brighter		Achromatic	
	5h	20h	2h	5h	2h	5h
CTAO-North	73 (40)	185 (66)	137 (60)	200 (81)	254 (97)	326 (115)
CTAO-South	81 (29)	192 (48)	155 (42)	210 (54)	232 (71)	306 (85)
CTAO (N+S)	118 (54)	280 (92)	210 (77)	297 (106)	353 (132)	458 (157)

Variability extends detections to higher redshift



Additional results: CTAO detectable source catalogs

Catalog of sources detectable in average state:

Table C2. Content of the generated catalogs, listing all sources detected over 20 hours of observation during their average states. For clarity, only few entries are shown. Column description can be found in Table C1.

Source_Name	Flux1000	SpectrumType	PL_Index	Pivot_Energy	LP_Index	LP_beta	CLASS	4LAC_z	nu_syn
J0001.6–4156	2.82×10^{-10}	PowerLaw	1.78	$4.05 \times 10^{+03}$	1.69	0.07	bcu	-	$7.33 \times 10^{+15}$
J0009.3+5030	2.49×10^{-09}	LogParabola	1.99	$1.38 \times 10^{+03}$	1.88	0.07	bll	-	$1.26 \times 10^{+15}$
J0013.9–1854	2.71×10^{-10}	PowerLaw	1.93	$3.04 \times 10^{+03}$	1.91	0.02	bll	0.095	$8.71 \times 10^{+16}$
J0015.6+5551	3.37×10^{-10}	PowerLaw	1.85	$6.88 \times 10^{+03}$	1.86	-0.01	bll	-	$5.69 \times 10^{+15}$
J0021.9–5140	6.06×10^{-10}	PowerLaw	2.01	$1.83 \times 10^{+03}$	1.98	0.04	bll	0.250	$6.61 \times 10^{+14}$
J0035.2+1514	1.12×10^{-09}	LogParabola	1.83	$2.30 \times 10^{+03}$	1.64	0.12	bll	1.090	$9.71 \times 10^{+14}$
J0035.9+5950	3.08×10^{-09}	LogParabola	1.77	$3.18 \times 10^{+03}$	1.67	0.05	bll	-	$1.12 \times 10^{+17}$
J0039.1–2219	2.39×10^{-10}	PowerLaw	1.80	$4.11 \times 10^{+03}$	1.77	0.02	bll	0.062	-
J0043.8+3425	2.61×10^{-09}	LogParabola	1.94	$1.36 \times 10^{+03}$	1.85	0.06	fsrq	0.966	$5.89 \times 10^{+13}$
J0045.3+2128	1.41×10^{-09}	LogParabola	1.81	$2.14 \times 10^{+03}$	1.67	0.08	bll	-	$7.94 \times 10^{+15}$
J0045.7+1217	8.70×10^{-10}	PowerLaw	1.99	$2.17 \times 10^{+03}$	1.96	0.03	bll	-	-
J0047.9+3947	7.09×10^{-10}	PowerLaw	1.98	$2.32 \times 10^{+03}$	1.96	0.01	bll	0.252	-
...	...	...	...	...	...	...	...	...	...

Table C2 – continued

nuFnu_syn	HE_EPeak	HE_nuFnuPeak	Frac_Variability	SED_class	Sim_z	Detected_in_5h	CTAO-N	CTAO-S
1.90×10^{-12}	$3.32 \times 10^{+04}$	4.82×10^{-07}	0.49	HSP	0.103	False	False	True
1.20×10^{-12}	$3.18 \times 10^{+03}$	2.65×10^{-06}	0.41	HSP	0.261	False	True	False
5.13×10^{-12}	$4.00 \times 10^{+04}$	3.17×10^{-07}	0.00	HSP	0.095	False	False	True
7.88×10^{-12}	-	-	0.14	HSP	0.218	False	True	False
2.09×10^{-12}	$2.48 \times 10^{+03}$	6.56×10^{-07}	0.26	ISP	0.281	False	False	True
3.51×10^{-12}	$1.04 \times 10^{+04}$	1.52×10^{-06}	0.29	ISP	0.175	False	True	True
1.49×10^{-11}	$9.88 \times 10^{+04}$	5.91×10^{-06}	0.49	HSP	0.598	True	True	False
-	$7.86 \times 10^{+05}$	4.93×10^{-07}	0.00	-	0.061	True	True	True
3.01×10^{-13}	$4.56 \times 10^{+03}$	2.82×10^{-06}	0.44	LSP	0.966	False	True	False
5.57×10^{-12}	$1.87 \times 10^{+04}$	2.00×10^{-06}	0.87	HSP	0.425	False	True	False
-	$4.08 \times 10^{+03}$	9.39×10^{-07}	0.30	-	0.254	False	True	True
-	$9.36 \times 10^{+03}$	7.49×10^{-07}	0.48	-	0.252	False	True	False
...	...	...	...	...	...	...	...	...

Additional results: CTAO detectable source catalogs

Catalog of sources detectable during bright states:

Table C3. Content of the generated catalogs, listing all sources detected over 5 h of observation during any of the two top-10% bright states assuming harder-when-brighter or achromatic variability scenarios. For clarity, only few entries are shown. Column description can be found in Table C1.

Source_Name	Flux1000	SpectrumType	PL_Index	Pivot_Energy	LP_Index	LP_beta	CLASS	4LAC_z	nu_syn	nuFnu_syn
J0001.4-0010	1.08×10^{-10}	PowerLaw	1.94	$4.31 \times 10^{+03}$	1.66	0.13	bl1	0.462	$3.61 \times 10^{+12}$	2.47×10^{-13}
J0006.3-0620	1.27×10^{-10}	PowerLaw	2.15	$2.24 \times 10^{+03}$	2.12	0.12	bl1	0.347	$8.32 \times 10^{+12}$	8.18×10^{-12}
J0006.4-5621	8.95×10^{-11}	PowerLaw	2.48	$9.95 \times 10^{+02}$	2.42	0.18	bl1	0.291	$2.08 \times 10^{+12}$	4.18×10^{-13}
J0008.4-2339	1.82×10^{-10}	LogParabola	1.72	$4.58 \times 10^{+03}$	1.46	0.20	bl1	0.147	-	-
J0013.9-1854	2.71×10^{-10}	PowerLaw	1.93	$3.04 \times 10^{+03}$	1.91	0.02	bl1	0.095	$8.71 \times 10^{+16}$	5.13×10^{-12}
J0014.1-5022	2.99×10^{-10}	PowerLaw	2.11	$2.21 \times 10^{+03}$	2.11	-0.00	bl1	0.010	$4.57 \times 10^{+17}$	2.59×10^{-12}
J0015.6+5551	3.37×10^{-10}	PowerLaw	1.85	$6.88 \times 10^{+03}$	1.86	-0.01	bl1	-	$5.69 \times 10^{+15}$	7.88×10^{-12}
J0018.4+2946	2.60×10^{-10}	PowerLaw	1.73	$5.29 \times 10^{+03}$	1.63	0.08	bl1	0.100	-	-
J0022.0+0006	1.10×10^{-10}	PowerLaw	1.59	$1.18 \times 10^{+04}$	1.63	-0.05	bl1	0.306	$1.35 \times 10^{+17}$	7.77×10^{-13}
J0023.9+1603	2.46×10^{-10}	PowerLaw	2.10	$2.17 \times 10^{+03}$	2.00	0.12	bl1	-	$5.75 \times 10^{+13}$	7.61×10^{-13}
J0024.7+0349	1.41×10^{-10}	PowerLaw	2.47	$1.15 \times 10^{+03}$	2.46	0.07	fsrq	0.545	-	-
J0028.5+2001	3.38×10^{-09}	LogParabola	2.22	$6.45 \times 10^{+02}$	2.09	0.11	fsrq	1.552	$2.57 \times 10^{+12}$	6.58×10^{-13}
...	...	...	...	...	...	...	...	...	...	...

Table C3 – continued

HE_EPeak	HE_nuFnuPeak	Frac_Variability	SED_class	Sim_z	In_nxs	Sim_nxs	CTAO-N	CTAO-S	H-W-B	Achromatic
$1.55 \times 10^{+04}$	1.49×10^{-07}	0.00	LSP	0.462	-	2.46	False	True	False	True
$1.36 \times 10^{+03}$	1.61×10^{-07}	0.49	LSP	0.347	-	2.36	False	True	False	True
$3.00 \times 10^{+02}$	2.09×10^{-07}	0.00	LSP	0.291	-	4.95	False	True	False	True
$1.76 \times 10^{+04}$	3.92×10^{-07}	0.00	-	0.147	-	4.95	True	False	False	True
$4.00 \times 10^{+04}$	3.17×10^{-07}	0.00	HSP	0.095	-	1.00	False	True	True	True
-	-	0.16	HSP	0.010	-	2.46	False	True	True	False
-	-	0.14	HSP	0.218	-	0.63	True	False	False	True
$5.07 \times 10^{+04}$	5.44×10^{-07}	0.06	-	0.116	-	0.29	True	False	True	True
-	-	0.00	HSP	0.306	-	1.00	False	True	True	False
$2.19 \times 10^{+03}$	2.90×10^{-07}	0.00	LSP	0.425	-	3.79	False	True	True	False
$4.64 \times 10^{+01}$	4.45×10^{-07}	1.99	-	0.545	-	4.24	True	False	False	True
$4.22 \times 10^{+02}$	4.88×10^{-06}	2.07	LSP	1.552	-	2.34	True	False	True	True
...	...	...	...	...	...	...	...	...	...	...

Conclusions

Baseline detectability (average state)

>300 AGN in 20 h

~130 sources in 5 h snapshots

Impact of variability

~300 (harder-when-brighter)

~450 (achromatic)

Redshift reach

$z \lesssim 1.5$ (average)

$z \lesssim 2-3$ (flares)

Source population

Dominated by HSPs

Also ISPs, LSPs, radio galaxies

FSRQs: ~10 → ~50–150 (flares)

Key impact

Robust VHE AGN population studies

Access to high- z gamma-ray universe

Acknowledgements

Editorial committee, led by T. Hassan

A. Acharyya

J. Biteau

A. Domínguez

P. Goldoni

E. M. de Gouveia Dal Pino

L. Gréaux

T. Hassan

J.-P. Lenain

L. Passos Reis

S. Pita

L. Stuari

A. Taylor



Currently undergoing SAPO review

The image features decorative blue wavy lines in the top and bottom corners, composed of many thin, overlapping lines that create a sense of motion and depth. The central text is in a bold, blue, sans-serif font.

Luminosity function

Subtask 3: BL Lac luminosity function reconstruction

- Blazar population studies provide insights into the spatial distribution and evolution of these objects over cosmic time
- The gamma-ray luminosity function (GLF) describes the number of sources per unit comoving volume per unit luminosity
- Current TeV samples are biased toward flaring sources
- This limits reliable population studies

Subtask 3: BL Lac luminosity function reconstruction

- **Step 1:** Define a GLF and generate a random population of blazars
 - Simulate EGal survey observations (CTAO sensitivity)
 - Ajello et al. 2015 parameters are assumed for the GLF

Smoothly broken power-law:

$$\Phi(L_\gamma, \Gamma) = \frac{A}{\ln(10) L_\gamma} \left[\left(\frac{L_\gamma}{L_*} \right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*} \right)^{\gamma_2} \right]^{-1} \times \exp \left(-\frac{(\Gamma - \mu(L_\gamma))^2}{2\sigma^2} \right)$$

LDDE evolution:

$$\Phi(L_\gamma, z, \Gamma) = \Phi(L_\gamma, \Gamma) \times e(z, L_\gamma)$$

The intrinsic shape of GLF is fixed and evolution is modeled by redshift- and luminosity-dependent multiplicative factor,

defined as:

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{-p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{-p_2(L_\gamma)} \right]^{-1}$$

$$z_c(L_\gamma) = z_c^* \left(\frac{L_\gamma}{10^{48}} \right)^\alpha,$$

$$p_1(L_\gamma) = p_1^* + \tau [\log_{10}(L_\gamma) - 46],$$

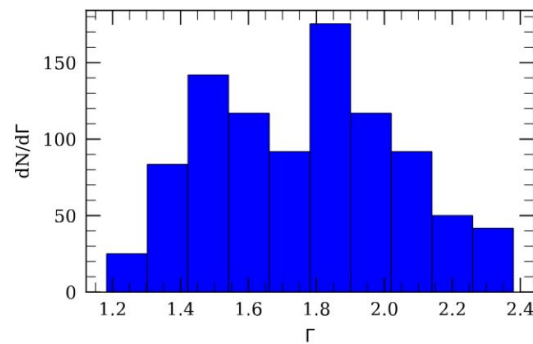
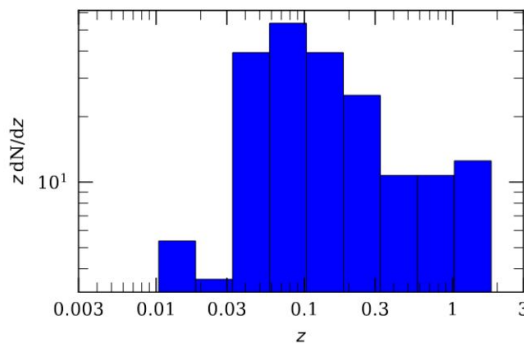
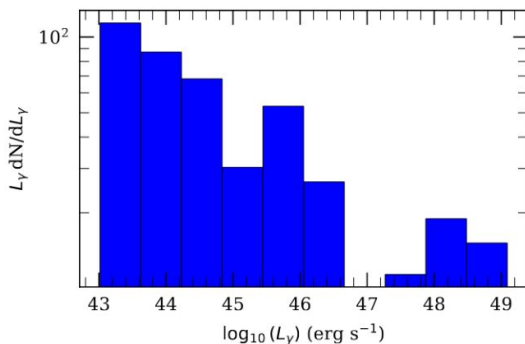
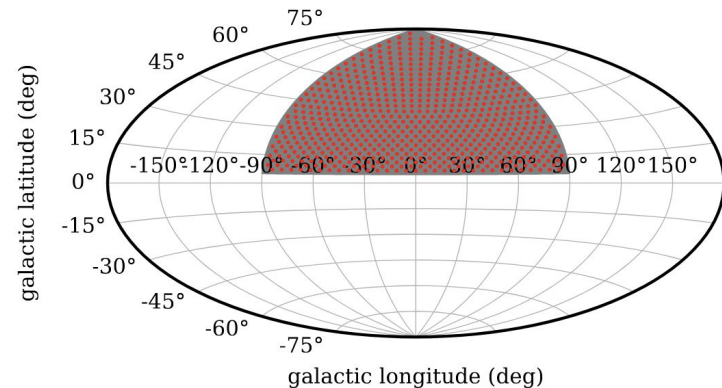
$$p_2(L_\gamma) = p_2^* + \delta [\log_{10}(L_\gamma) - 46].$$

$\log_{10}(A \text{ [Mpc}^{-3}\text{]})$	γ_1	γ_2	$\log_{10}(L_* \text{ [erg/s]})$	p_1^*	p_2^*	τ	z_c^*	α	δ
$-8.34^{+0.08}_{-0.09}$	$0.50^{+0.01}_{-0.01}$	$1.83^{+0.02}_{-0.02}$	$48.04^{+0.46}_{-0.44}$	$3.39^{+0.03}_{-0.03}$	$-4.96^{+0.05}_{-0.05}$	$3.16^{+0.03}_{-0.03}$	$1.25^{+0.03}_{-0.02}$	$0.072^{+0.002}_{-0.002}$	$0.64^{+0.01}_{-0.01}$

Subtask 3: BL Lac luminosity function reconstruction

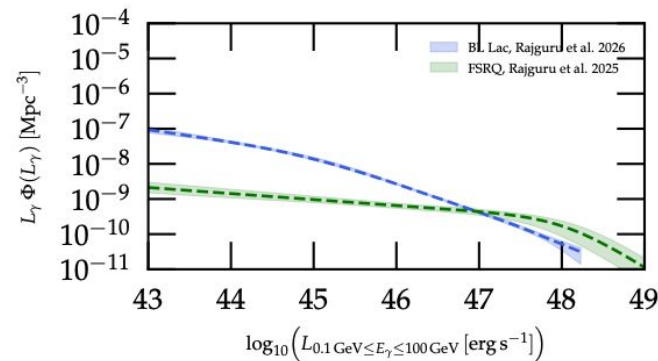
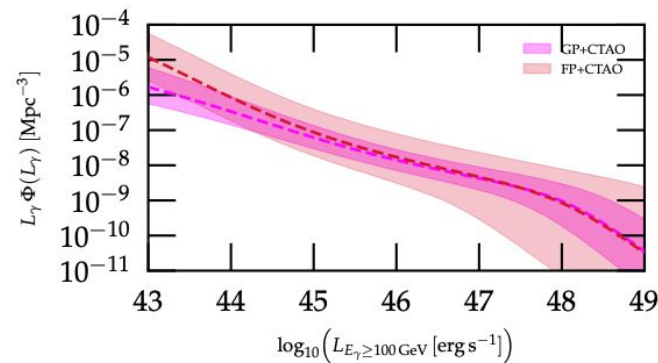
- **Step 2:** Perform a gammapy analysis (equivalent to the one from the rest of the paper) to study their detectability

114 detectable sources were identified out of 25,049 within the field of view after integrating over the relevant parameter space



Subtask 3: BL Lac luminosity function reconstruction

- **Step 3:** MCMC reconstruction. GLF accurately reconstructed, depending on priors
 - We reconstruct the luminosity function using MCMC, accounting for CTAO's survey selection function
 - Gaussian priors + CTAO: The input luminosity function is recovered well
 - Flat priors + CTAO: The lower-luminosity population is well constrained, while uncertainties increase at high luminosity
 - CTAO can provide meaningful, survey-based constraints on the VHE AGN population





Backup slides

Variability properties are not driven by selection or flux-dependent bias

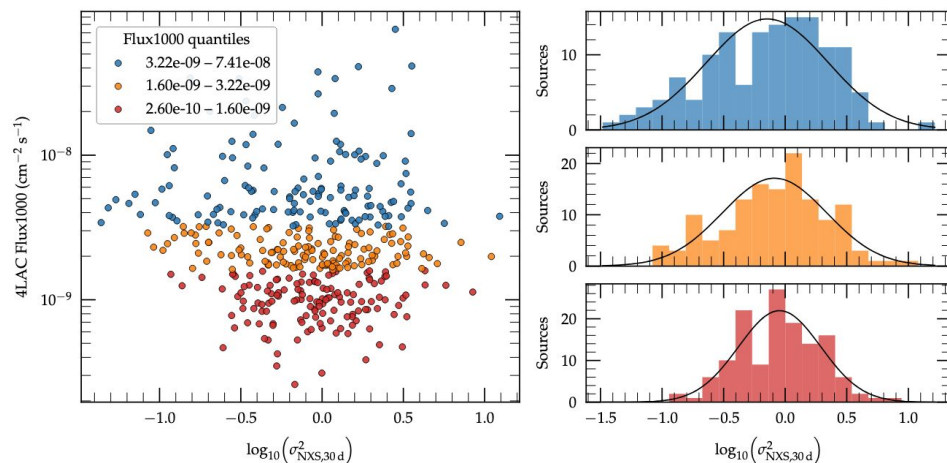
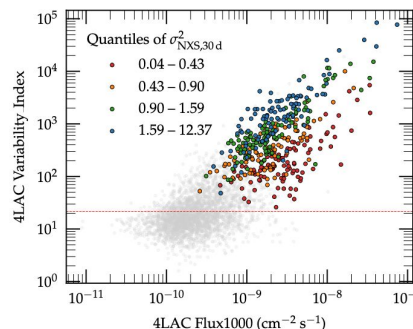
- LCR selection ($VI > 21.67$) does not bias variability → Threshold is weaker than excess-variance requirement

- Wide spread at fixed flux/ VI ($\geq 1-2$ dex in $\sigma^2_{\text{NXS},30\text{d}}$) → No intrinsic bias from selection

- $\sigma^2_{\text{NXS},30\text{d}}$ distribution stable vs flux (similar medians) → No strong flux dependence

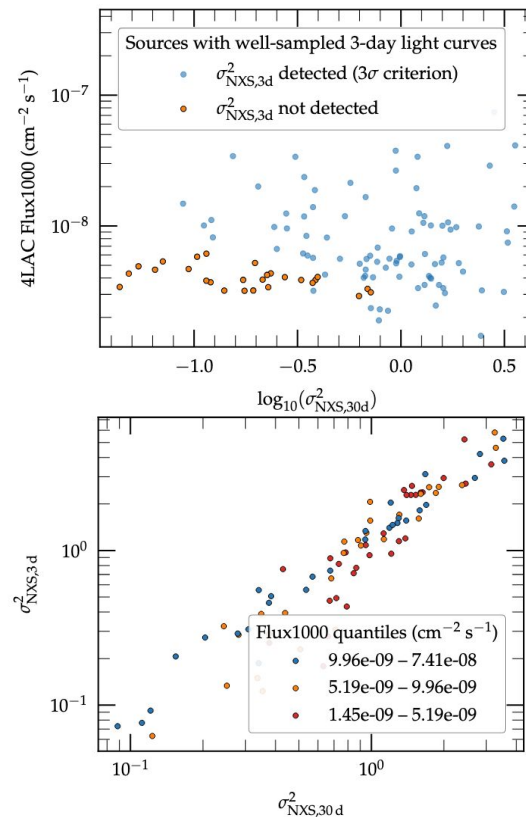
- Low-flux truncation = sensitivity effect → Low-variability sources become undetectable

- Central distribution unchanged → Variability regime is intrinsically stable



Scaling relation is robust and can be applied to fainter sources statistically

- No $\sigma^2_{\text{NXS},3\text{d}}$ detection only at low flux & low $\sigma^2_{\text{NXS},30\text{d}}$ → Absence driven by limited sensitivity, not intrinsic lack of variability
- No high-flux / high-variability source lacks short-timescale variability → No evidence for a separate population without fast variability
- $\sigma^2_{\text{NXS},3\text{d}} - \sigma^2_{\text{NXS},30\text{d}}$ relation is tight and consistent → Same trend across all flux bins
- No strong dependence on SED class → Relation stable in slope/normalization
- Calibration sample (87 sources) not biased in variability amplitude → Difference is mainly brightness, as expected



Simulation details

- CTAO performance simulated with Gammapy v1.1 using 1D ON/OFF method (fixed ON radius 0.11° , OFF/ON ratio = 5); significance via Li & Ma significance.
- Simulations use CTAO Prod5 IRFs (Alpha configuration: LSTs, MSTs, SSTs); energy threshold defined by peak background rate.
- Zenith-angle treatment (depends on source declination and site latitude): discrete IRFs (20° , 40° , 60°) assigned based on source culmination; $ZA \geq 65^\circ$ excluded.
- Method validated against ctools (v1.7.3), yielding consistent detection significances.

Extragalactic GeV sky details

- 4LAC-DR3: 3,814 sources (50 MeV–1 TeV, 12 yrs Fermi-LAT), ~98% AGNs, dominated by blazars.
- Blazar breakdown: 1,458 BL Lacs, 794 FSRQs, 1,493 BCUs; ~84 TeV blazars, typically detected during flares.
- Provides spectra, synchrotron peaks, SED classes, and long-term light curves → variability & evolution studies.
- Missing SEDs supplemented with 3HSP catalog + Yang et al. → LSP/ISP/HSP (+ EHSP).
- ~50% have redshift → limits high- z studies; also includes additional AGN classes beyond blazars.

Redshift revision details

- BL Lac redshifts are often uncertain (~50% unknown) due to featureless optical spectra
→ limitation for TeV population studies.
- To reduce bias (especially at $z \geq 0.3$), include spectroscopic lower limits from intervening gas clouds (absorption lines) alongside measured redshifts.
- Focus on CTAO-relevant sample: 544 bright, hard blazars selected via high-energy TS (30–300 GeV).
- Systematic review using ZBLLAC, SDSS, etc., to validate/revise redshifts.
- Final sample: 241 secure redshifts + 57 lower limits → ~54% constrained; improved high- z representation for simulations.

Static sky modeling details

- Static sky built from 4LAC-DR3 average spectra (12 yrs Fermi-LAT) → representative of typical (non-flaring) GeV emission.
- Spectra modeled as power-law or log-parabola, then extrapolated to VHE with EBL absorption and intrinsic emission assumptions.
- Add exponential cutoff at 10 TeV (rest frame) to account for intrinsic suppression (e.g. IC peak, Klein–Nishina effects).
- Extrapolations validated against STeVECat (49 sources, 61 spectra) → comparison with real VHE data.
- Low cutoffs (0.1–1 TeV) underestimate flux; 10 TeV / free / no cutoff perform best → EBL attenuation largely sufficient to explain VHE suppression.

Variability characterization details

- Variability quantified using normalized excess variance (σ_{NXS}^2 , quantifying the amplitude of intrinsic variability relative to measurement noise) from Fermi-LAT light curves (3-day & monthly), with strict quality cuts.
- Significant variability selection: $\sigma_{\text{NXS}}^2 > 3 \Delta \sigma_{\text{NXS}}^2 \rightarrow$ 407 sources (monthly), 87 with 3-day constraints. Selection is found not to be critically sensitive to exact value of variability index threshold used in LCR.
- Variability properties extended to full blazar population via class-dependent distributions.
- Final variability sample: ~2300 sources $\rightarrow$ used to model flaring states in CTAO simulations.

Variability modelling details

- Two variability scenarios tested to extrapolate GeV $\rightarrow$ VHE behaviour: achromatic and harder-when-brighter.
- **Achromatic:** spectral shape unchanged; variability only affects flux normalization.
- **Harder-when-brighter:** spectral index varies with flux $\rightarrow$ spectrum hardens in bright states (pivot at ~ 10 GeV).
- Bright states obtained by sampling variability realizations and selecting high-flux states.
- Variability amplitude set by σ_{NXS}^2 (3-day), applied to flux or spectral index depending on the scenario.

Luminosity function details

- **MCMC convergence and sampling robustness:** The reconstruction uses 20 walkers and 5000 steps with 50% burn-in, yielding ~250 effectively independent samples (based on autocorrelation times of 150–200 steps), ensuring reliable posterior estimates.
- **Why fix spectral parameters:** These parameters are held fixed to avoid degeneracies and over-expanding the parameter space, since CTAO statistics alone cannot meaningfully constrain spectral-index evolution.
- **Interpretation of flat vs Gaussian priors:** The allowed parameter ranges are motivated by the input LDDE model, but the Gaussian prior used in the MCMC is implemented as a Gaussian centered on the midpoint of those ranges, rather than directly sampling the published covariance from Ajello et al.
- **Origin of high-luminosity uncertainty:** The widening of the GLF uncertainty band at high luminosity is driven by low source counts (selection effects), not model failure—highlighting CTAO’s limited leverage on the bright-end slope.
- **Consistency check via “priors-only” case:** The pure Gaussian-prior (no CTAO likelihood) reconstruction reproduces the input GLF, validating that deviations in other cases arise from observational constraints rather than implementation bias.

Source statistics: Static sky

- Consistent numbers with Jean-Philippe and Santiago (obvious, same results!)

CTAO site selected	Static sky					
	Known z (1783 sources)		Unknown z (2015 sources)		Total	
	5h	20h	5h	20h	5h	20h
CTAO-North	50	121	29	82	79	203
CTAO-South	67	132	31	88	98	220
CTAO (N+S)	87	179	51	144	138	323

Source statistics: Variable sky

- Only comparing sources with available 3-day Fvar (LAT)

	Static sky					
	Known z (313 sources)		Unknown z (94 sources)		Total	
CTAO site selected	5h	20h	5h	20h	5h	20h
CTAO-North	25	37	17	31	42	68
CTAO-South	20	28	11	16	31	44
CTAO (N+S)	33	49	22	40	55	89

- “harder-when-brighter” variability
-> x1.6 more detectable sources

	"Harder-when-brighter" active state					
	Known z (313 sources)		Unknown z (94 sources)		Total	
CTAO site selected	5h	20h	5h	20h	5h	20h
CTAO-North	54	64	25	42	79	106
CTAO-South	39	51	22	34	61	85
CTAO (N+S)	69	85	37	59	106	144

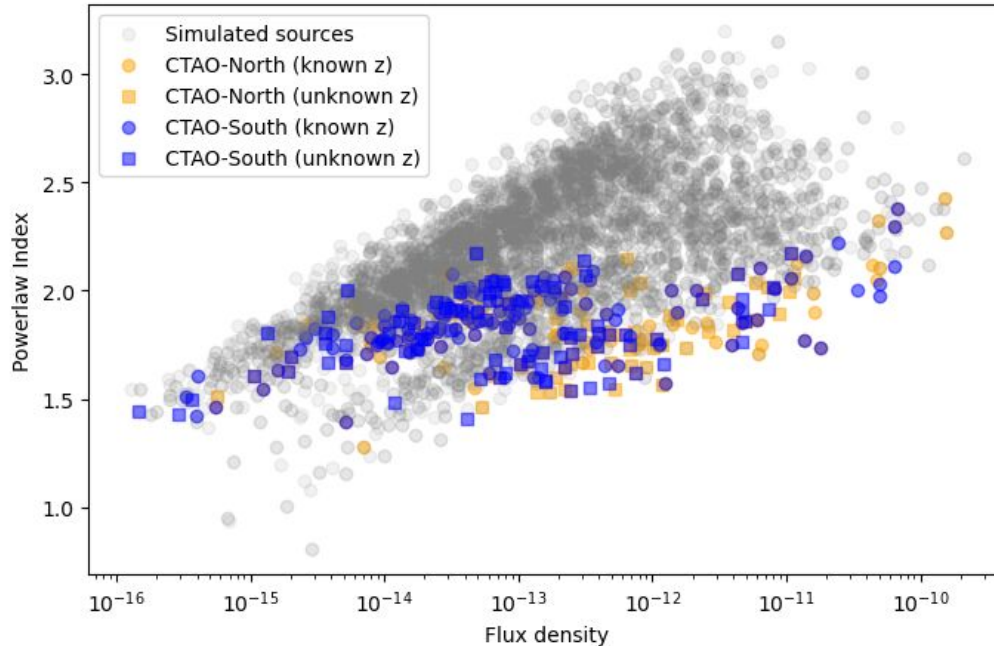
- Achromatic bright state
-> x2.3 more detectable sources

	Achromatic active state					
	Known z (313 sources)		Unknown z (94 sources)		Total	
CTAO site selected	5h	20h	5h	20h	5h	20h
CTAO-North	86	106	29	42	115	148
CTAO-South	66	83	22	40	88	123
CTAO (N+S)	116	139	41	67	157	206

**(note statistics dominated by
bright sources in GeVs)**

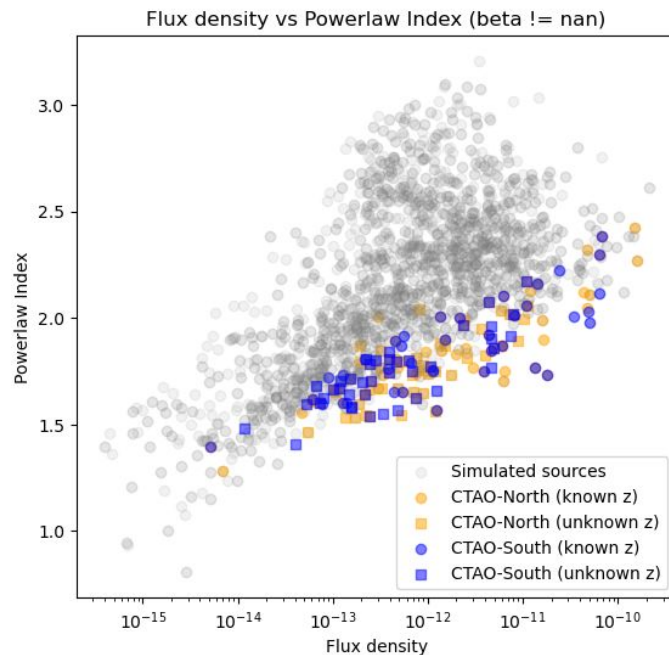
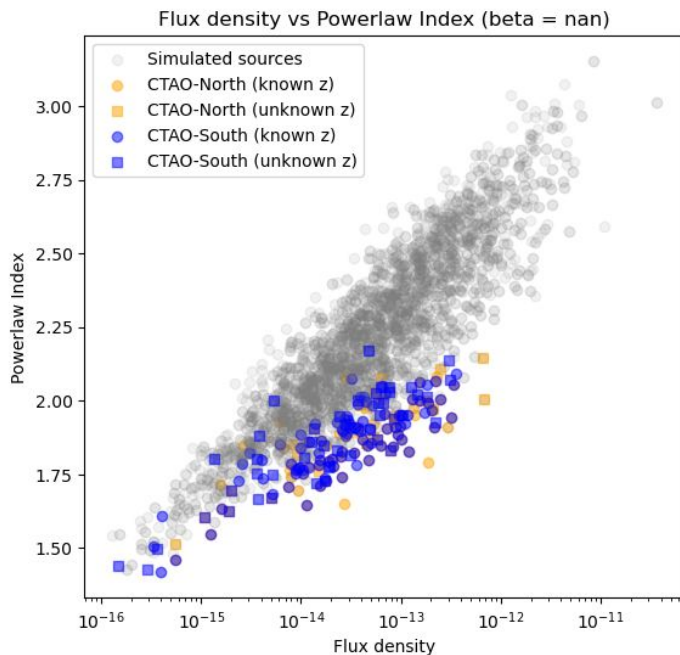
Flux-index figures

- Hard to compare powerlaw with logParabola fits



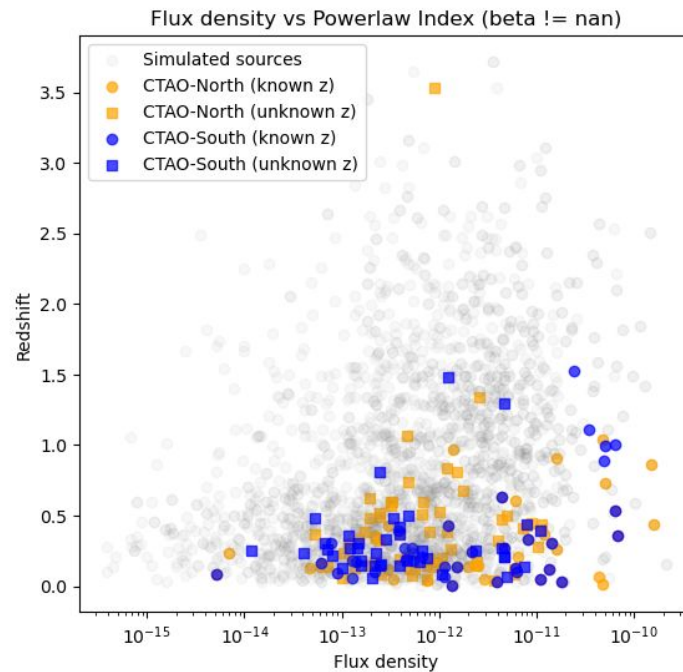
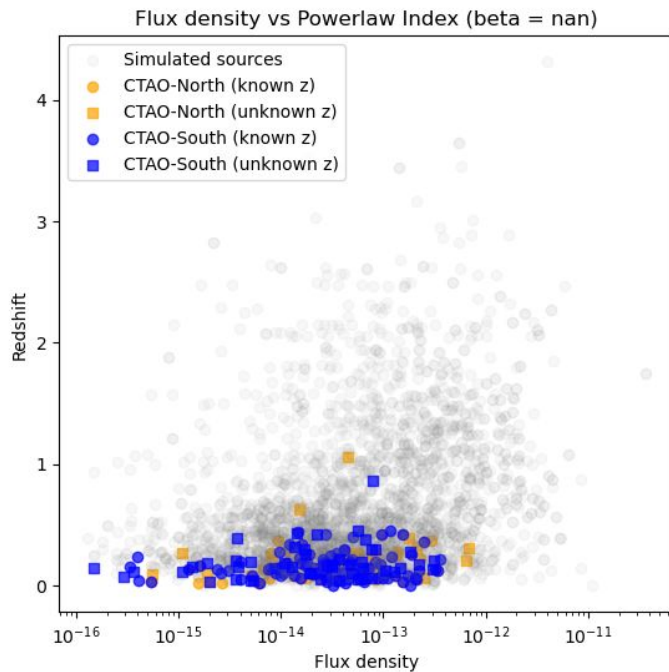
Flux-index figures

- Two very clear populations (for a common plot, we should not use flux density)



Flux-redshift figures

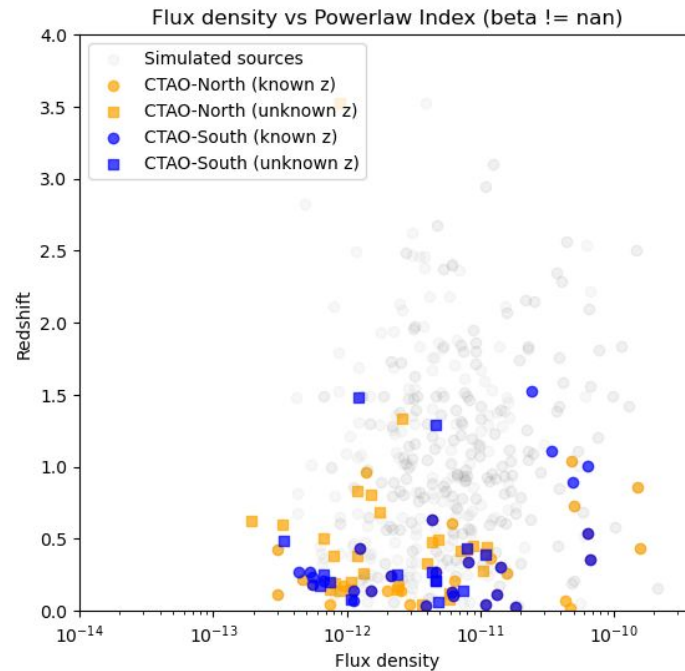
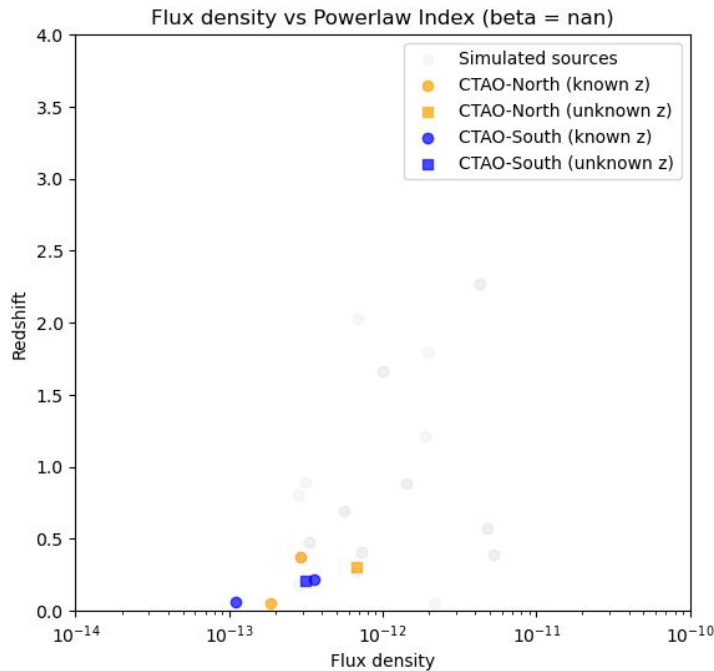
- Distant detections come from log-parabolas. They are brighter... But very obvious effect.



Flux-redshift figures

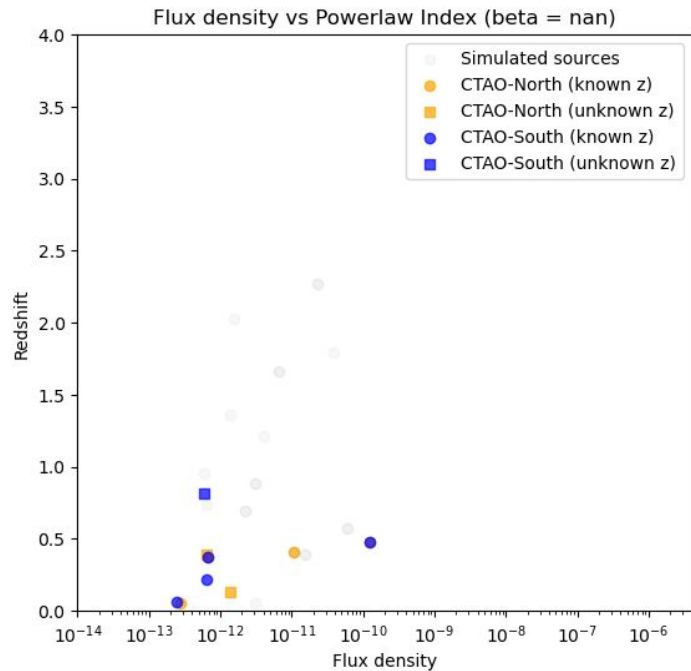
Only sources with 3-day Fvars (still in 20h)

- Sources with Fermi-LAT 3-day lightcurves are essentially all log-parabola fits



Flux-redshift figures

- **Achromatic** bright states



Only sources with 3-day Fvars (still in 20h)

