HAWC J2227+610: a potential PeVatron candidate for the CTA in the northern hemisphere

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Outline

Goal:

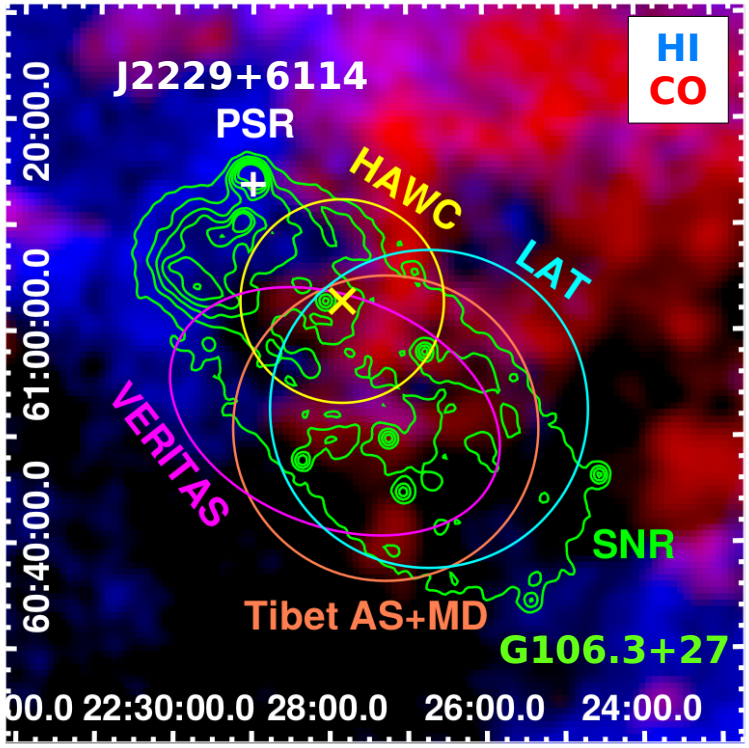
Testing the capability of CTA-North in constraining
the spatial and spectral properties of the VHE emission from
HAWC J2227+610

Plan:

1. HAWC J2227+610: general information and MW data
2. Simulations and analysis for CTA-North
   - morphological study
   - spectral study
3. Conclusions

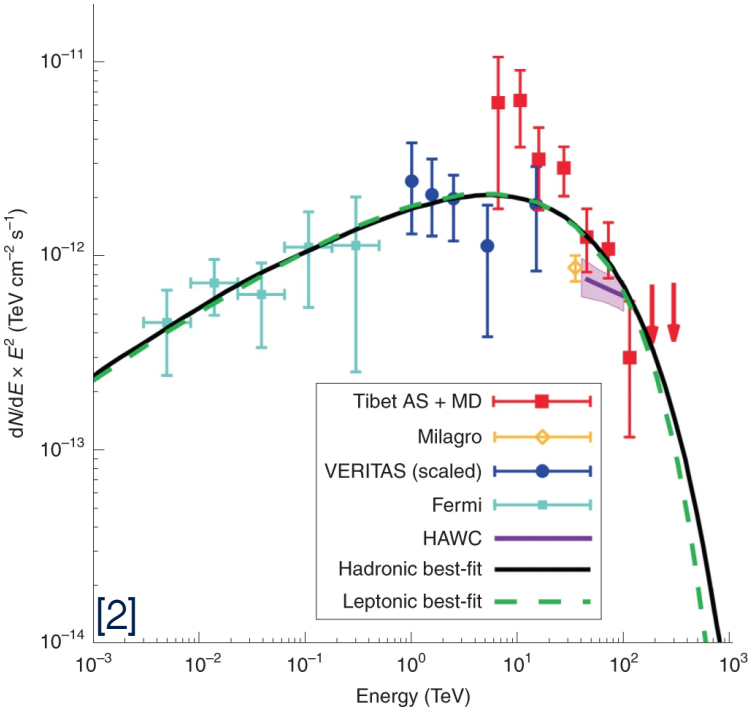
HAWC J2227+610: MW data

- Radio:
  - lines: HI and CO maps (FCRAO)
  - continuum (1.42 GHz) (DRAO)
- X-rays:
  - Suzaku, XMM-Newton, Chandra



[1]

- Gamma-rays:
  - Fermi-LAT [3, 500] GeV
  - VERITAS [0.9, 16] TeV
  - Milagro 35 TeV
  - HAWC [40, 110] TeV
  - Tibet AS+MD [6, 115] TeV
  - LHAASO [20, 501] TeV

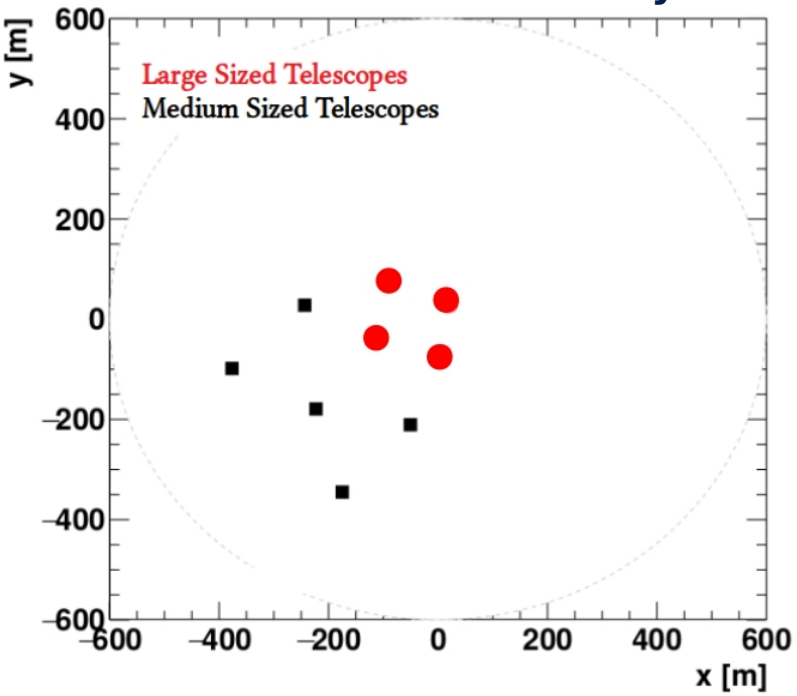


[2]

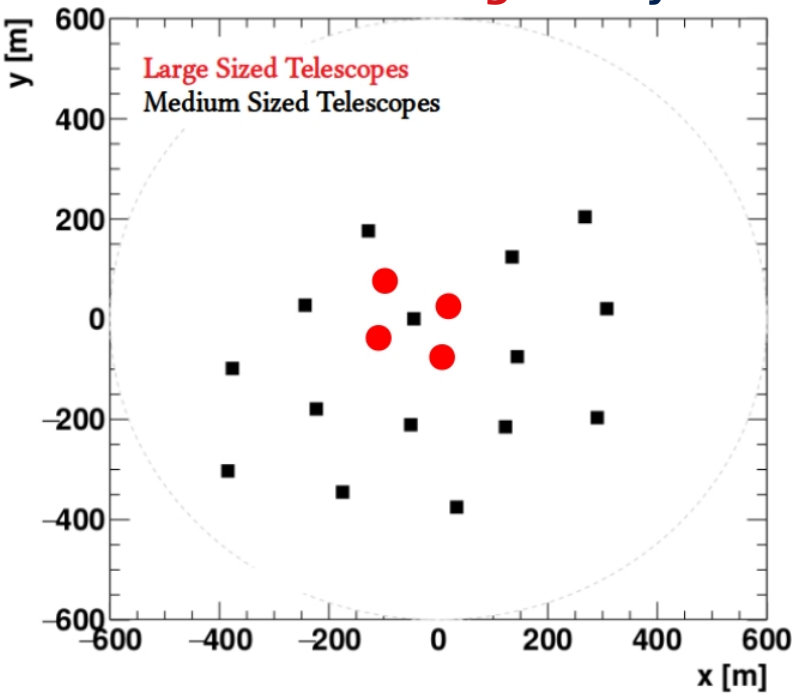
Simulations

- CTA-North array layouts considered in this work
  - **small** (4 LSTs, 5 MSTs)
  - **large** (4 LSTs, 15 MSTs)

CTA-North small array



CTA-North large array



(Layouts considered for the *Prod3b* CTA Instruments Response Functions)

Simulations

- CTA-North array layouts
  - **small** (4 LSTs, 5 MSTs)
  - **large** (4 LSTs, 15 MSTs)
- Zenith 40°
- Obs: 50, 100, 200 hours

- `gammapy` v18.2
  - ROI 2°x 2°
  - spatial bin: 0.01°
  - [0.03, 160] TeV 10 bins per decade

  3D Fit Analysis

BACKGROUND

Mis-reconstructed CRs from CTA IRFs [3]

+

Diffuse gamma emission from CTA GPS [4]

HAWC J2227+610

Spectral emission

Hadronic model from **Tibet AS+MD** (`naima`)

Protons distribution	PLEC
Spectral index	1.8
Energy cutoff	499 TeV
W_p (E > 1 GeV)	$5 \cdot 10^{47}$ erg
Distance	800 pc
n_H	10 cm^{-3}

Spatial shape

Radio templates from FCRAO CO maps

- Template A
- Template B

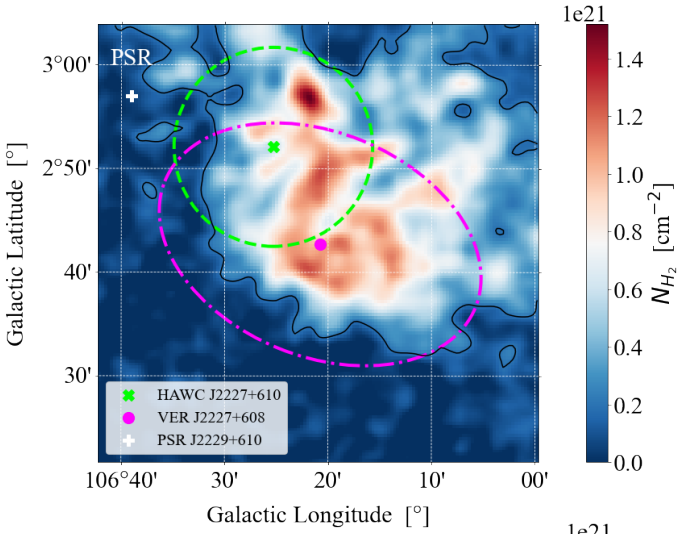
Radio Templates: CO line cube from FCRAO

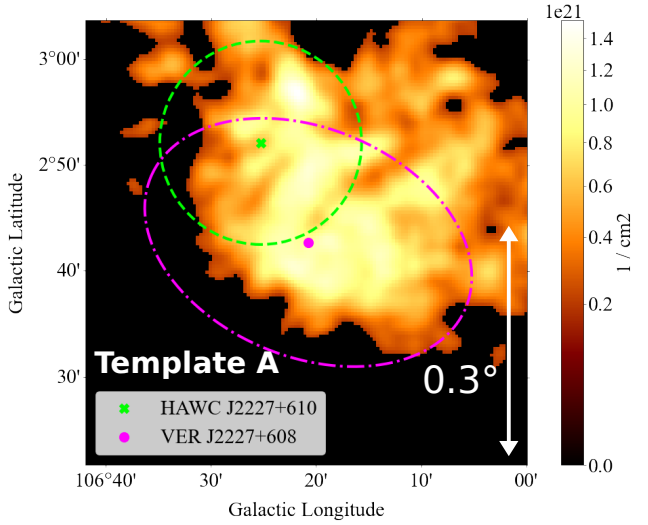
Column density maps

Morphological templates $(N_H > 2 \cdot 10^{20}\, cm^{-2})$

[-6.00,-4.00] km/s

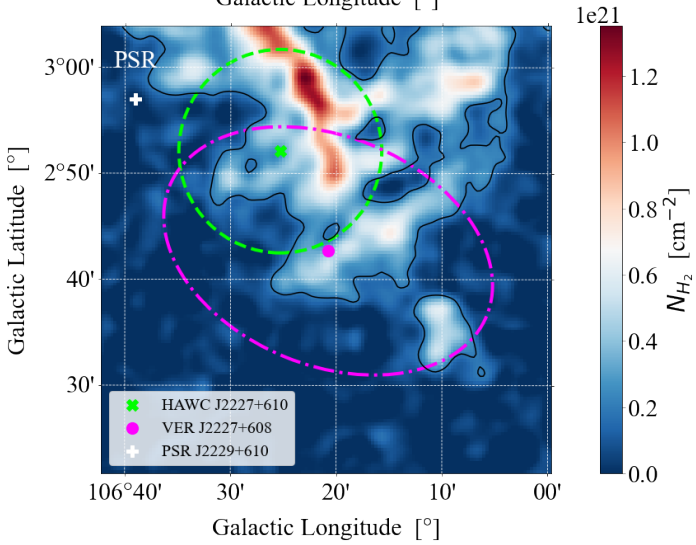
VERITAS [5]

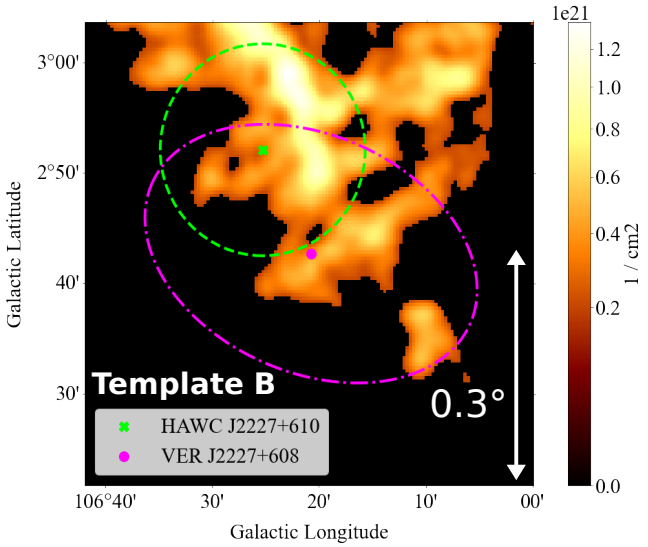




[-7.23,-5.59] km/s

Fermi-LAT [6]





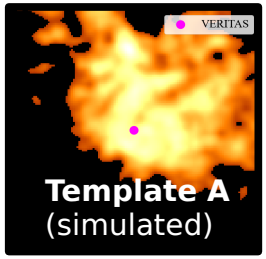
Analysis

	Morphological Study	Spectral Study
Simulations	Hadronic model; Template A / B	Hadronic model; Template A
Fit	Hadronic model; - Templates A / B - Point - Symm/Asymm Disk - Symm/Asymm Gaussian	- Hadronic (PLEC of p) - Leptonic (PLEC of e-) - PL - PLEC - LogParabola; Radio Template A

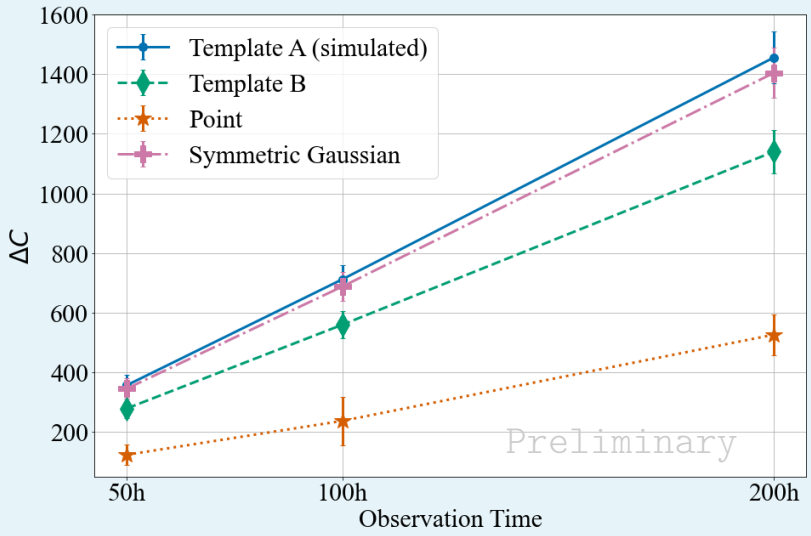
$$\Delta C = 2\left(\ln L - \ln L_0\right) \sim \chi^2$$

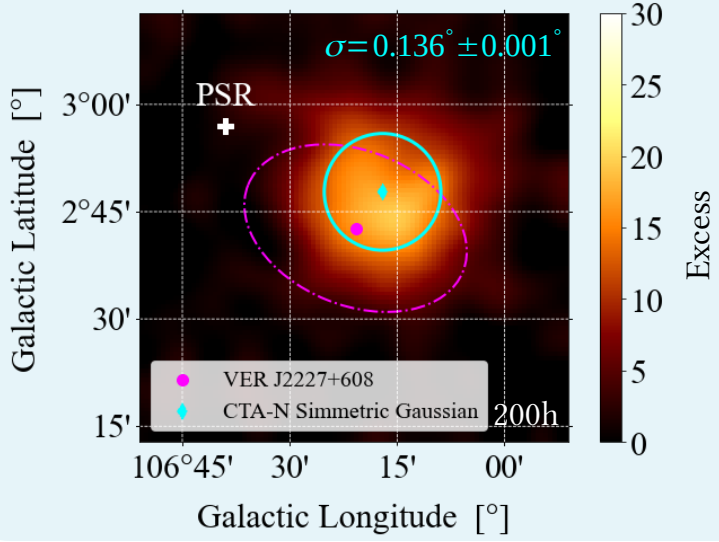
We consider average ΔC on 100 simulated observations considering as null hypothesis (H_0) the background model (which parameters are kept fixed in the fit)

Morphological study results: simulation with Template A

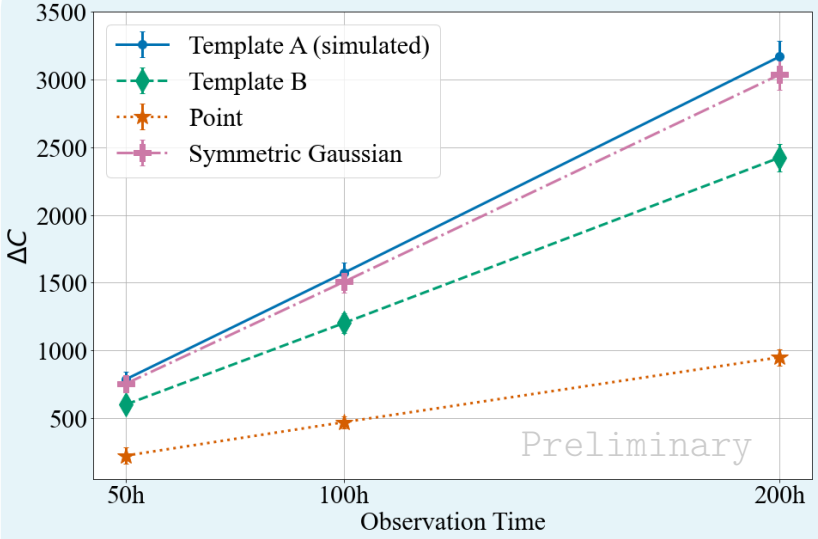


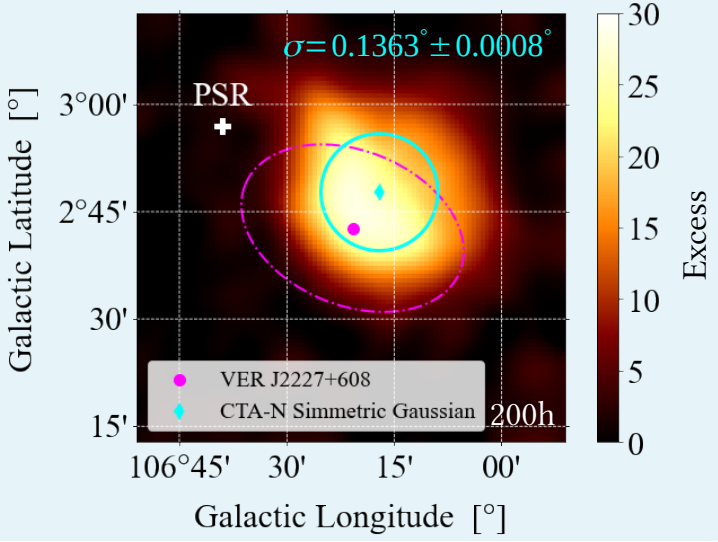
CTA-North small array



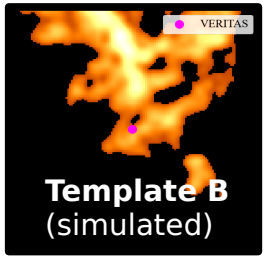


CTA-North large array

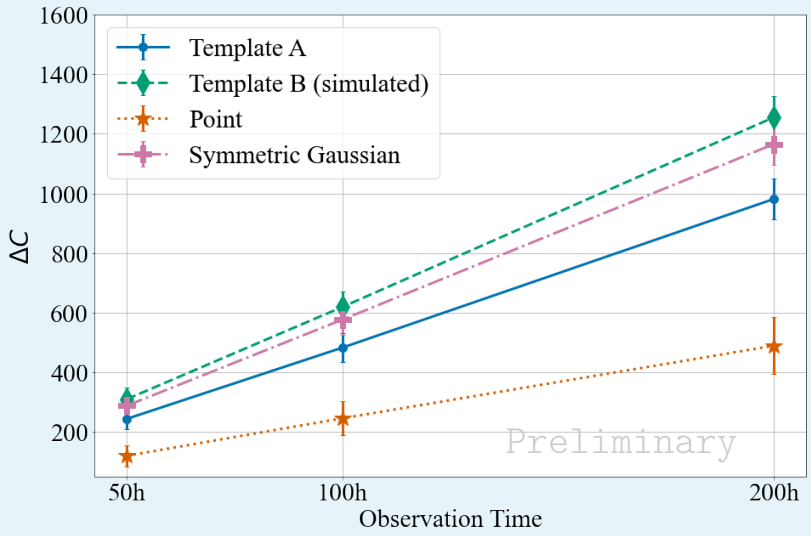


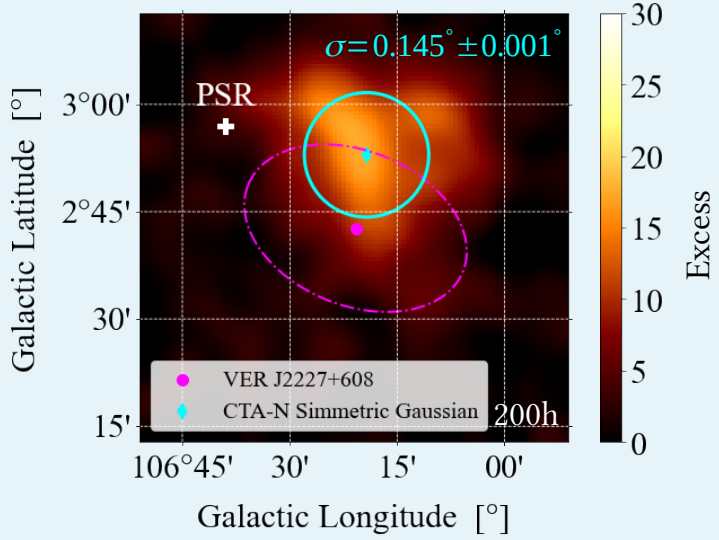


Morphological study results: simulation with Template B

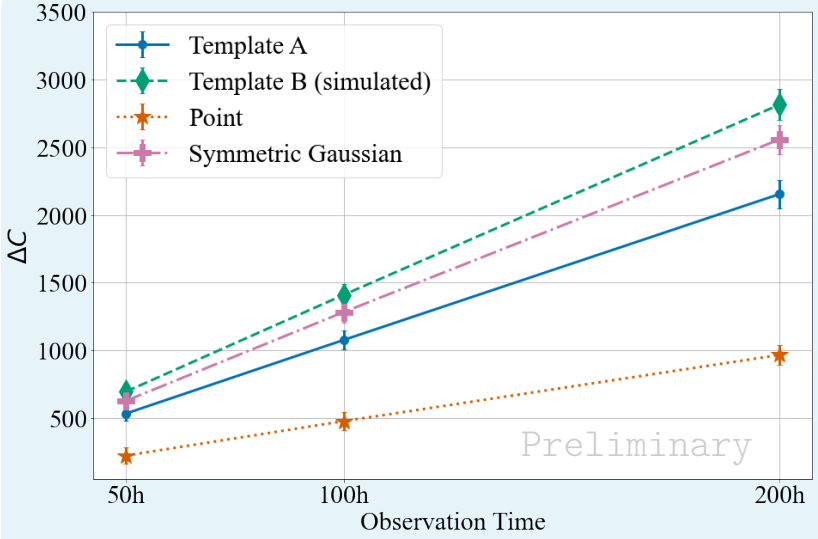


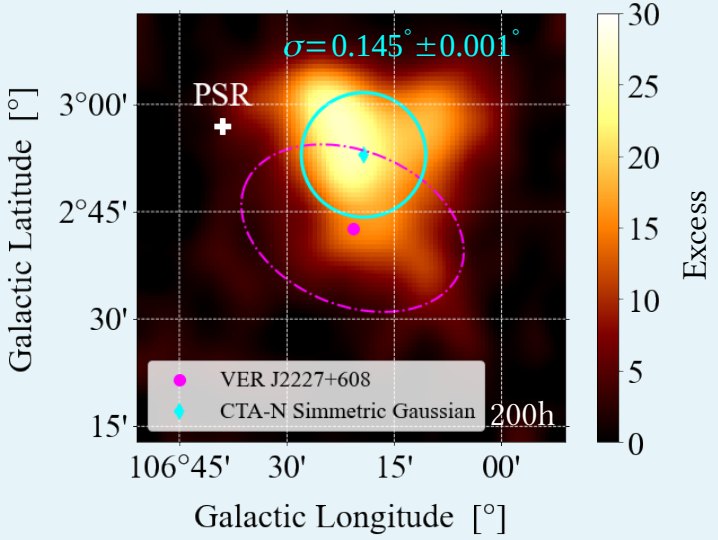
CTA-North small array





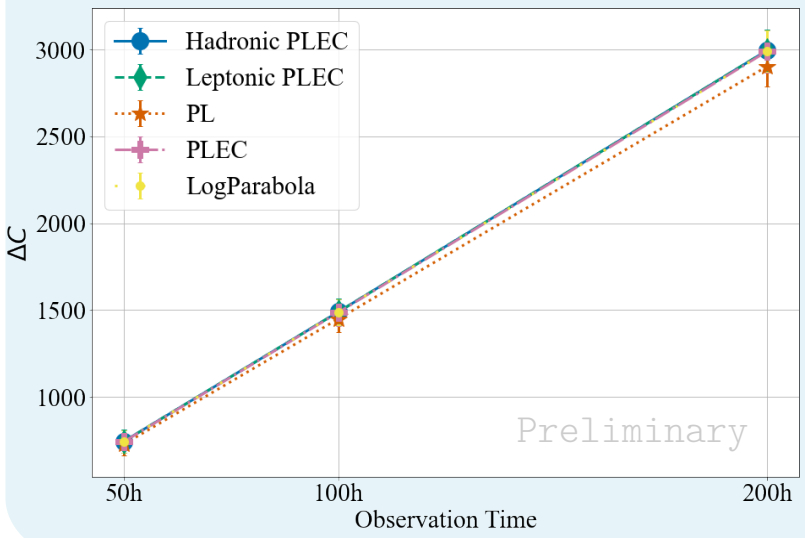
CTA-North large array



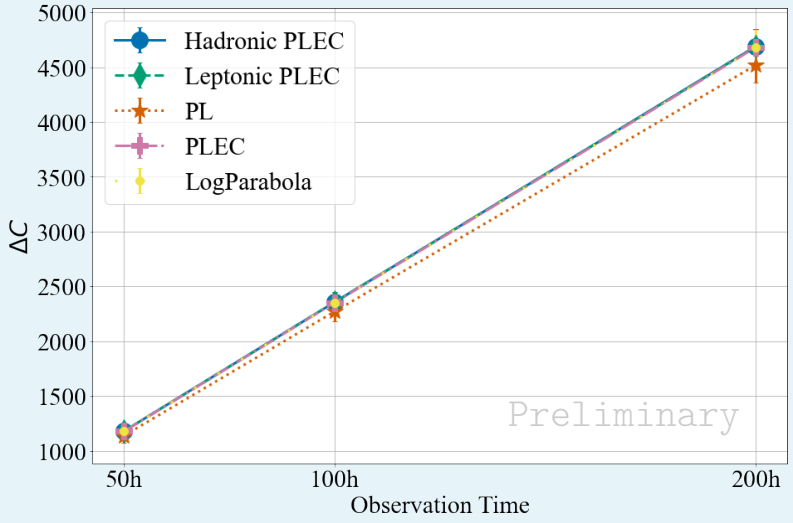


Spectral study results: model comparison

CTA-North small array



CTA-North large array

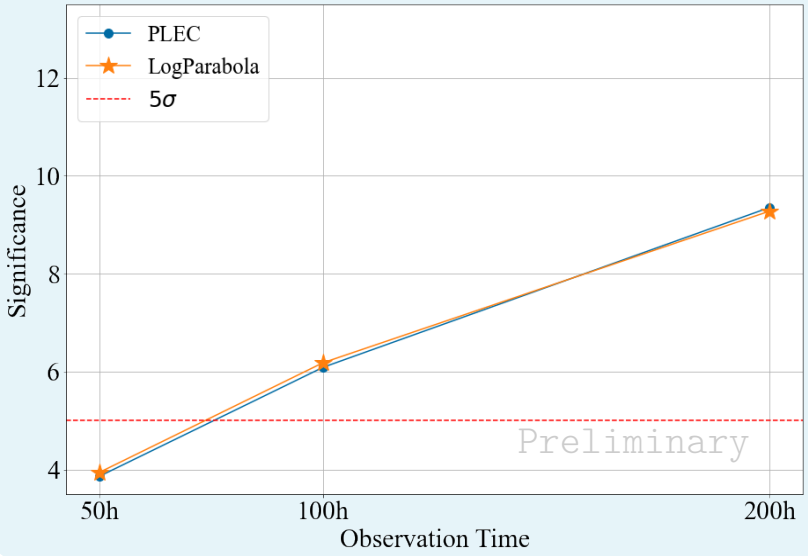


The average test statistic obtained with the different alternative hypothesis is equivalent for all the alternative models, except for the PL model, which achieves slightly lower average ΔC above 50 hours of observation.

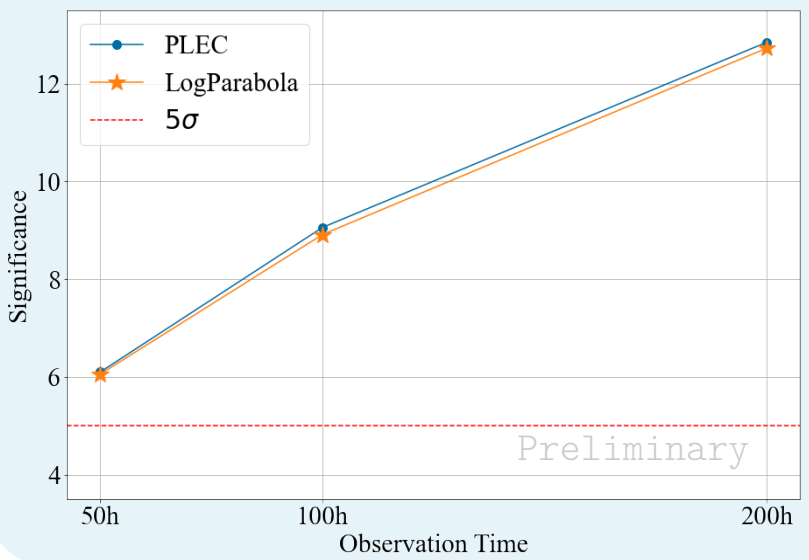
Spectral study results: cutoff detection

Average significance on 100 observations of PLEC and LogParabola models considering as null hypothesis the PL model:

CTA-North small array



CTA-North large array



The alternative hypothesis proves to be preferable, at more than $5\,\sigma$ confidence level, for almost all configurations and observation times.

The cutoff fitted with PLEC model is around 50 TeV.

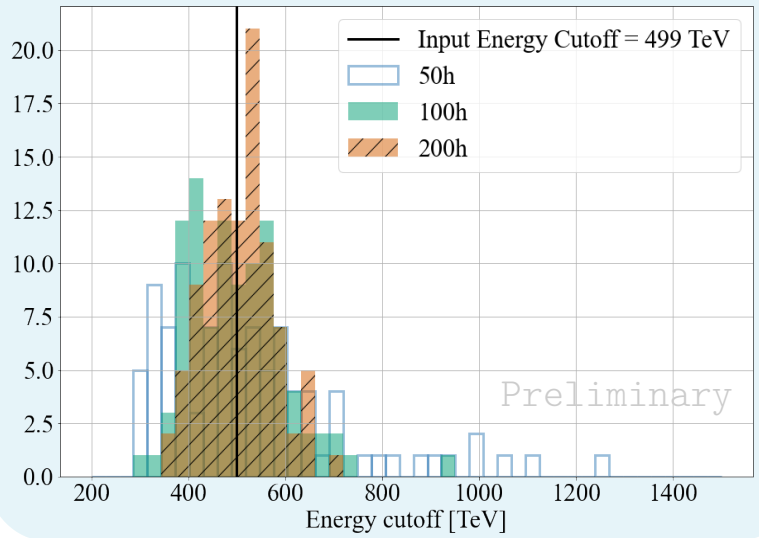
Spectral parameters of the hadronic model

The fit with the hadronic model permits to recover the simulated spectral parameters with a **relative dispersion** (*) (standard deviation over mean) that is decreasing with the observation time and the array size

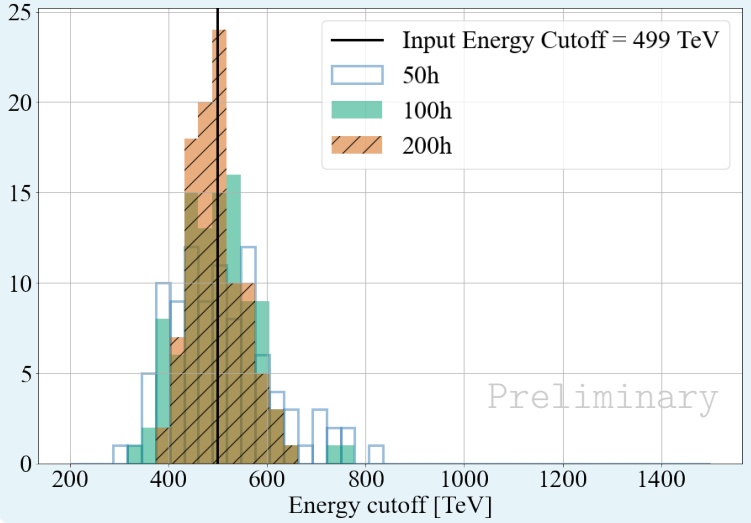
Percentage of relative dispersion for the cutoff parameter

	energy cutoff	
	small	*large*
50 h	36.0%	20.7%
100 h	20.1%	15.2%
200 h	14.2%	10.6%

CTA-North small array



CTA-North large array

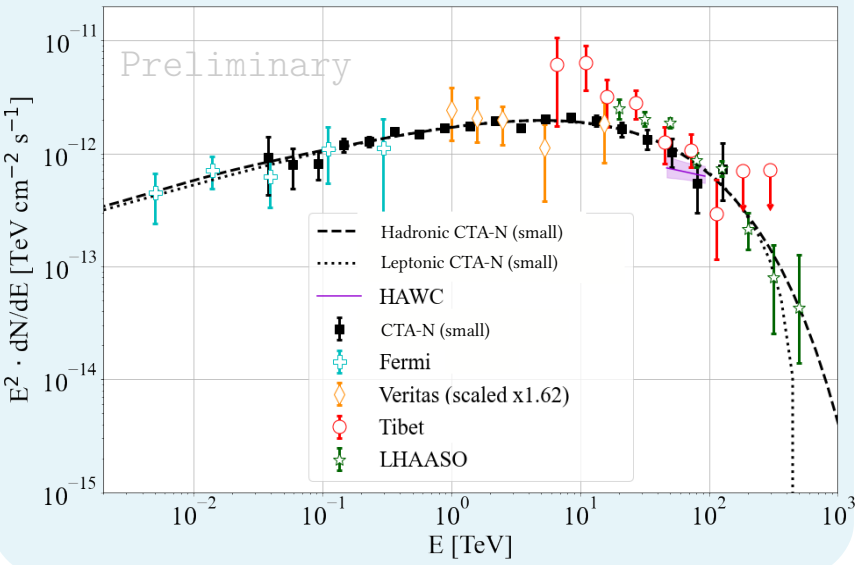


(*) standard deviation over mean

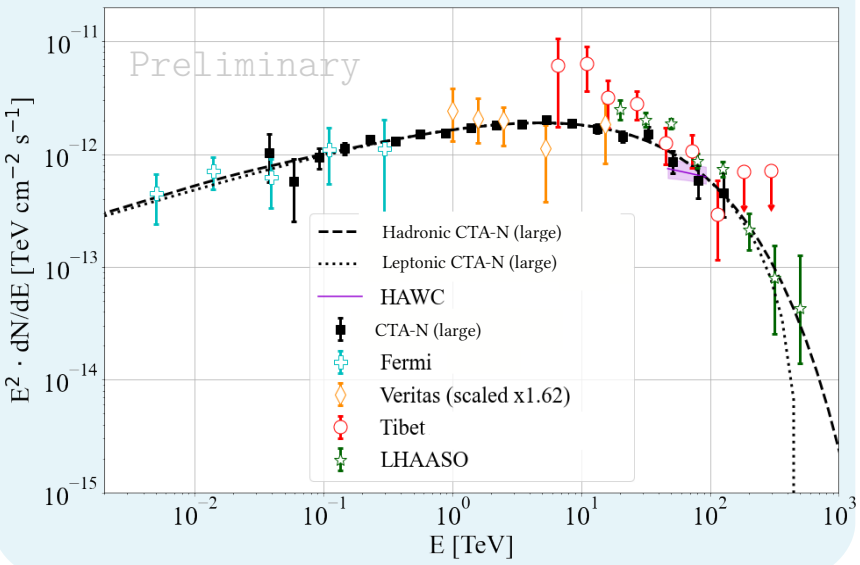
Flux points

Flux points of HAWC J2227+610 as seen by CTA-North in the **small** and **large** configurations after 50 hours of observation and the best hadronic and leptonic model fitted by the CTA-North:

CTA-North small array



CTA-North large array



Conclusions

- HAWC J2227+610 spectral and spatial emission has been studied considering the:
  - hadronic model proposed by Tibet AS+MD
  - spatial templates associated to nearby molecular clouds
- 3D analysis with `gammapy` has been performed considering CTA-North **small** (9 tel) and **large** (19 tel) arrays and several observation times.

→ CTA is able to significantly **detect the extension** of the source and to attribute higher detection significance to the simulated molecular cloud template compared to the alternative one;

→ CTA is not able to disentangle the **hadronic** emission assumed in this work from a **leptonic** one;

→ CTA permits to correctly reproduce the simulated parent proton spectrum characterized by a **500 TeV cutoff.**

cherenkov
telescope
array

Thank you for your attention

References

[1] Ge et al. “REVEALING A PECULIAR SUPERNOVA REMNANT G106.3+2.7 AS A PETAELECTRONVOLT PROTON ACCELERATOR WITH X-RAY OBSERVATION”
(2021)
https://astro.paperswithcode.com/paper/revealing-a-peculiar-middle-aged-supernova

[2] Tibet AS-gamma collaboration “Potential PeVatron supernova remnant G106.3+2.7 seen in the highest energy gamma rays”
(2021)
https://www.nature.com/articles/s41550-020-01294-9

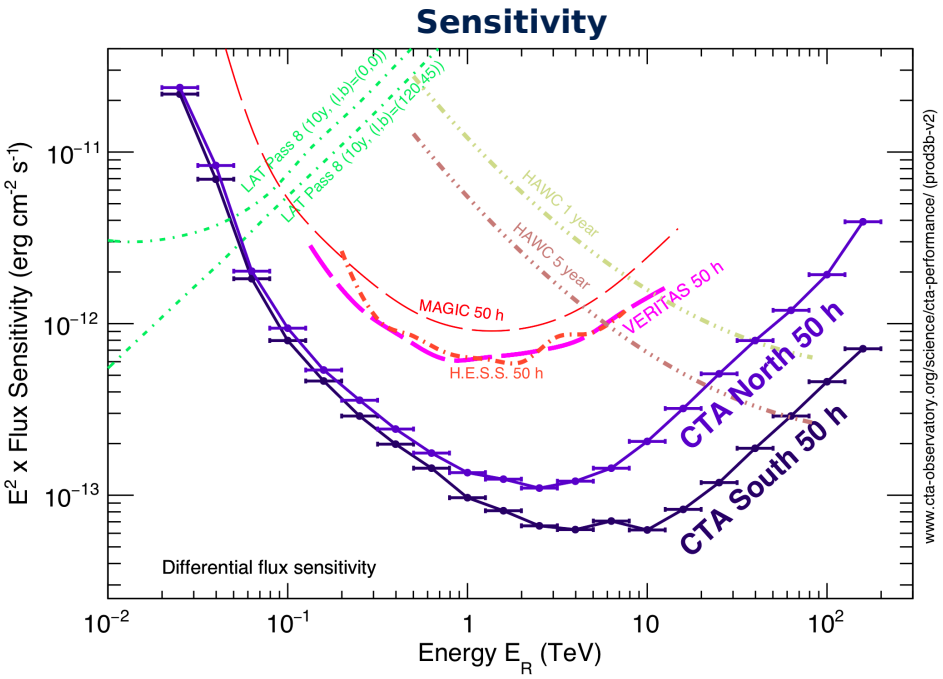
[3] Maier et al. “Performance of the Cherenkov Telescope Array”
(2019)
https://pos.sissa.it/358/733/pdf

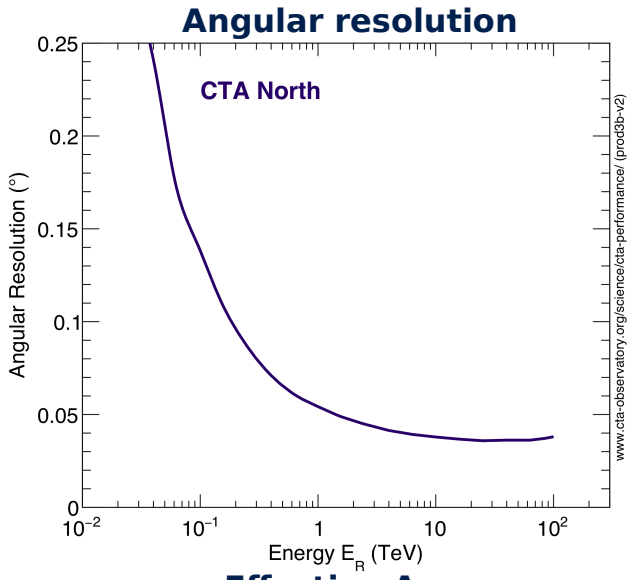
[4] Remy et al. “Survey of the Galactic Plane with the Cherenkov Telescope Array”
(2021)
Proceedings of this conference

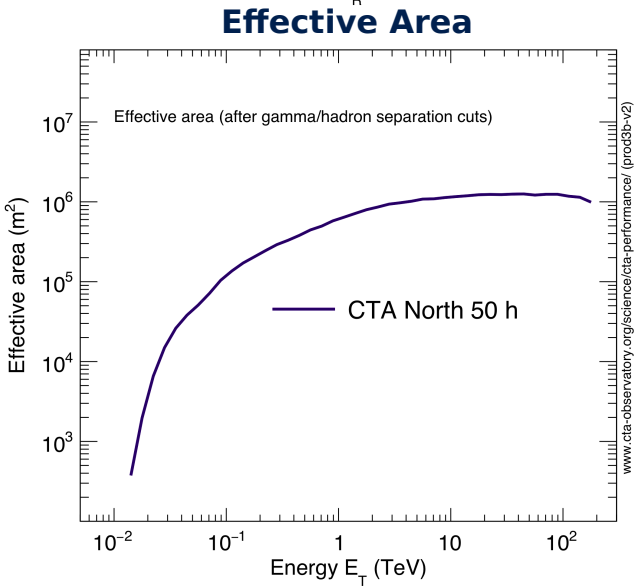
[5] Acciari et al. “DETECTION OF EXTENDED VHE GAMMA RAY EMISSION FROM G106.3+2.7 WITH VERITAS”
(2009)
https://ui.adsabs.harvard.edu/abs/2009ApJ...703L...6A/abstract

[6] Xin et al. “VER J2227+608: A HADRONIC PEVATRON PULSAR WIND NEBULA”
(2019)
https://iopscience.iop.org/article/10.3847/1538-4357/ab48ee

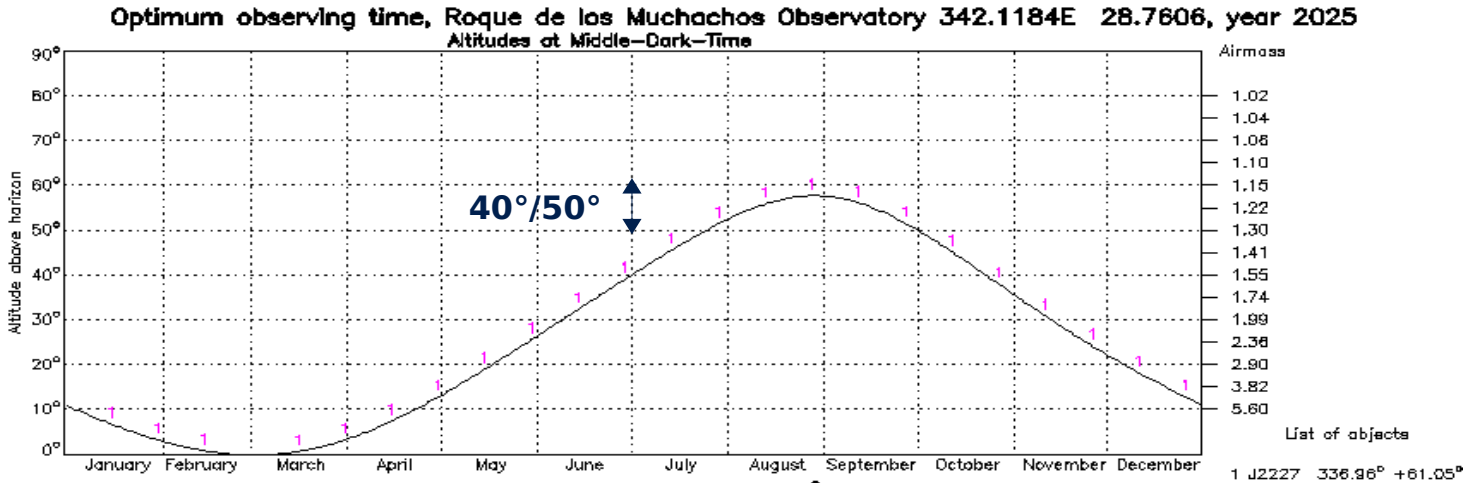
CTA-North: large



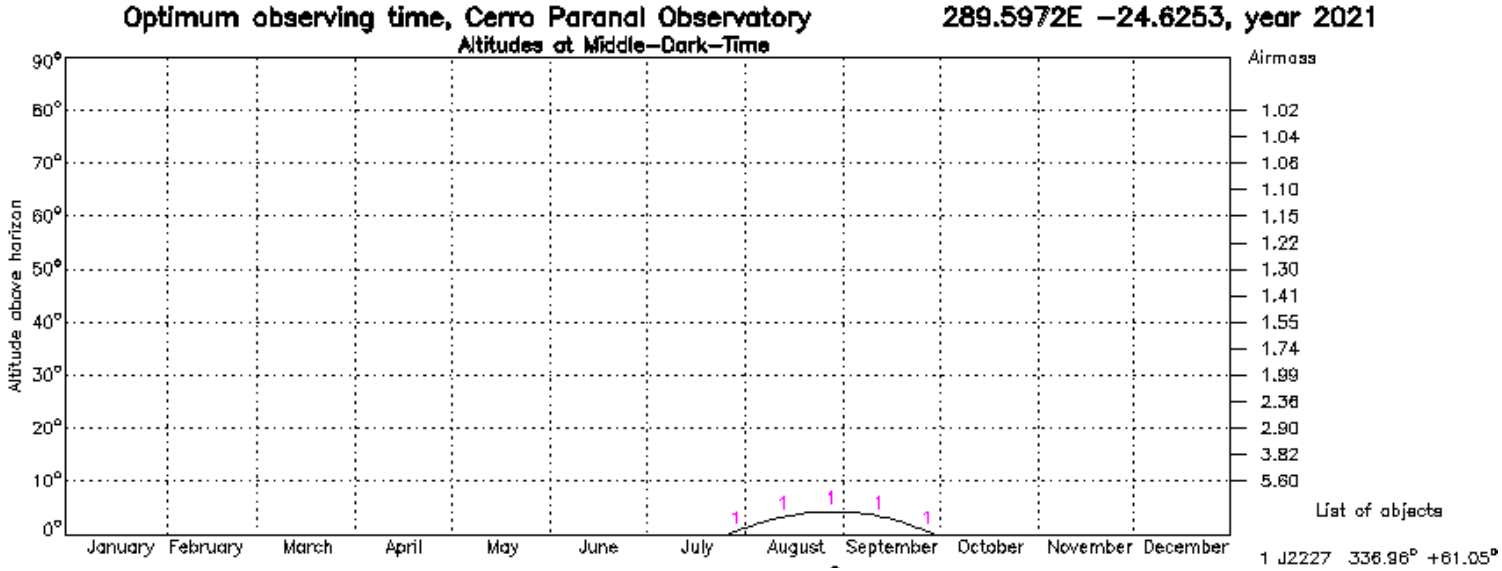




Visibility of HAWC J2227+610

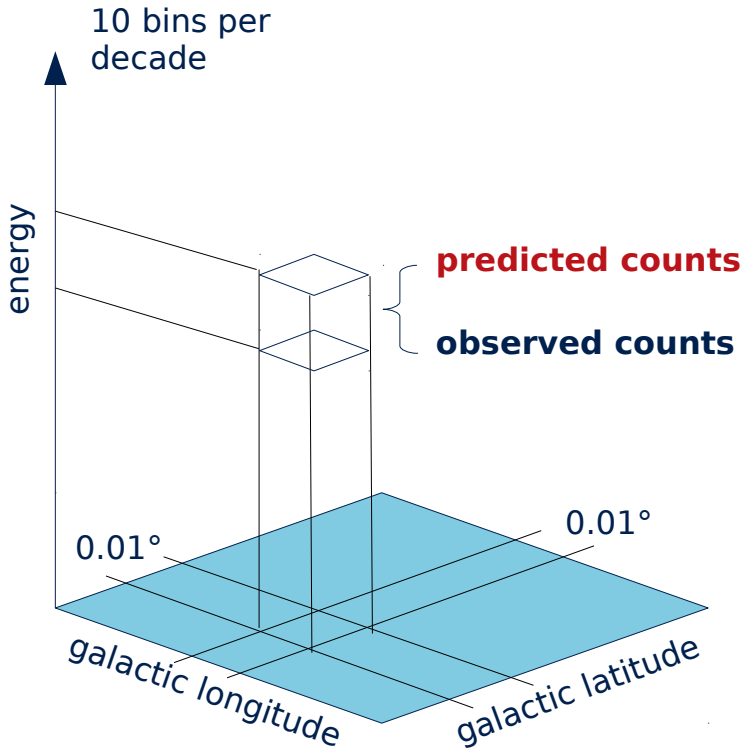


from CTA-North



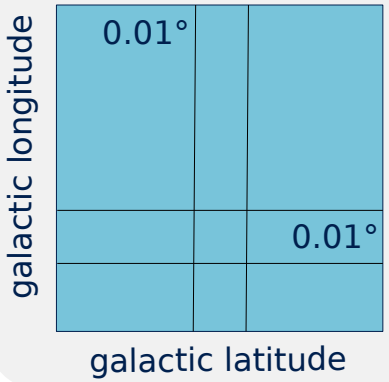
from CTA-South

Analysis: Test Statistic



Cstat
=
2[pred – obs + obs (log(obs) – log(pred))]

Morphological Study:

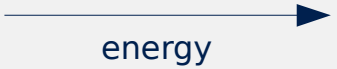


Rebinning
→ >5 counts per bin

- counts are integrated along the energy axis
- spatial matrix is unchanged

→ Cstat is evaluated

Specral Study:



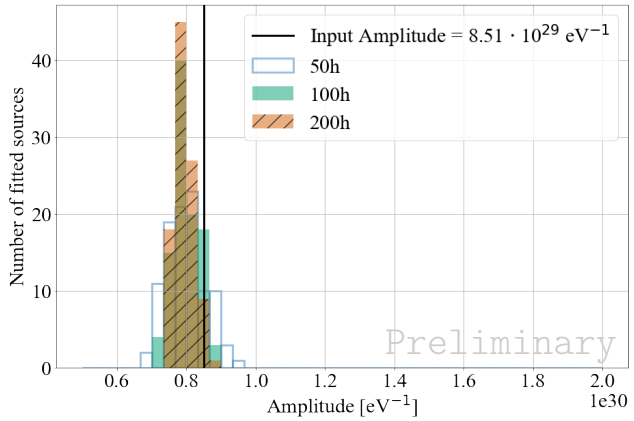
Rebinning
→ >5 counts per bin

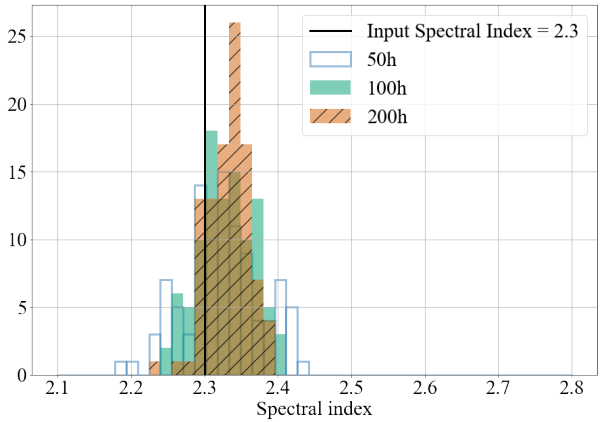
- a maximum number of 18 energy bins are considered
- counts are integrated along the spatial axes

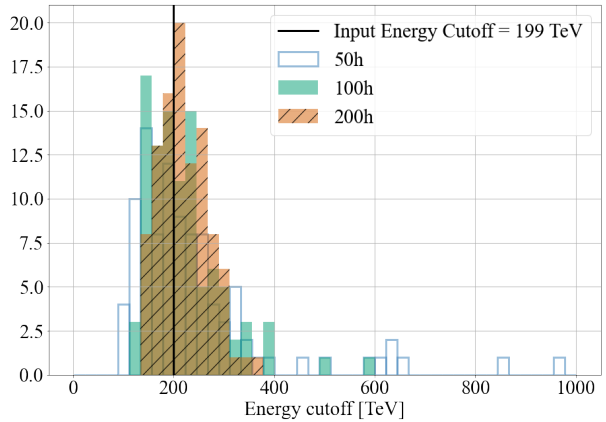
→ Cstat is evaluated

Spectral parameters of the leptonic model

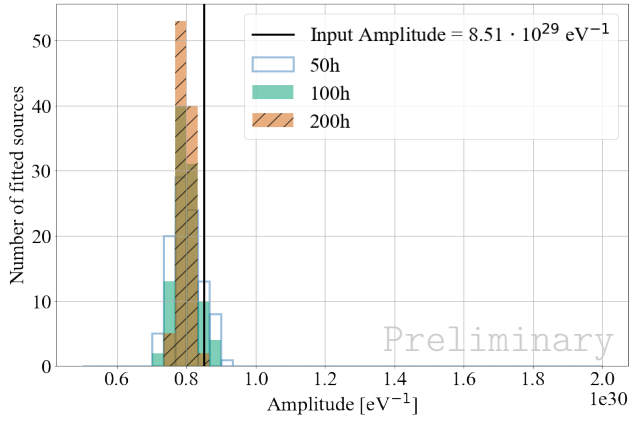
CTA-North small array

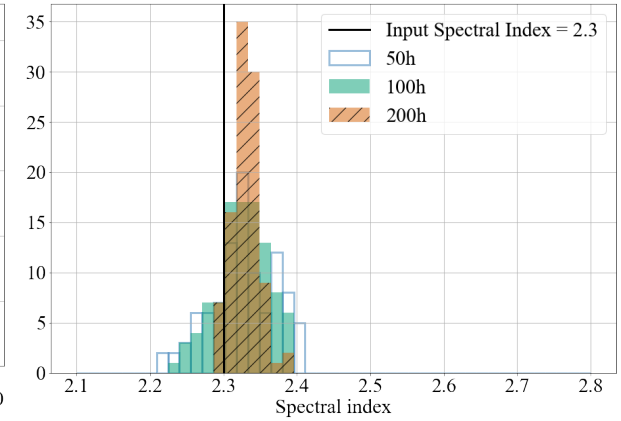


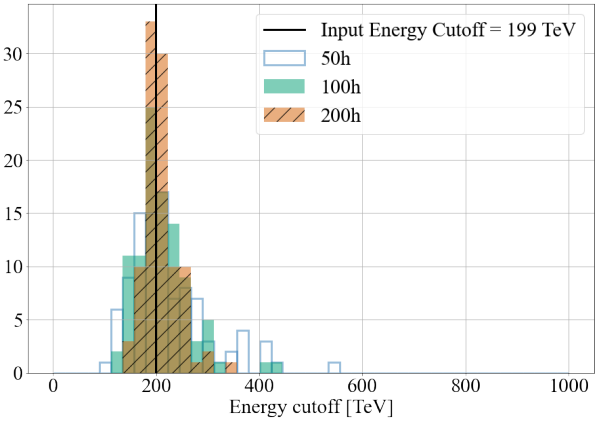




CTA-North large array

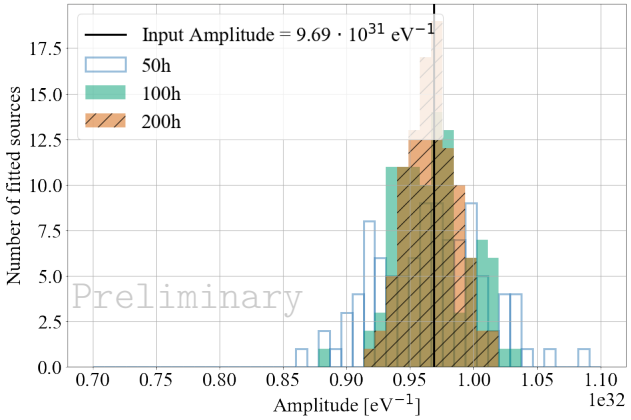


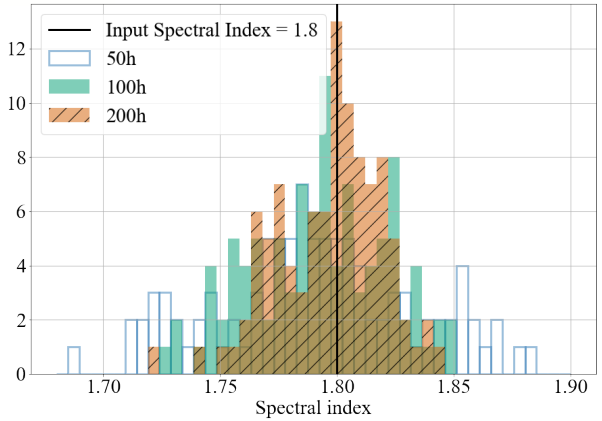


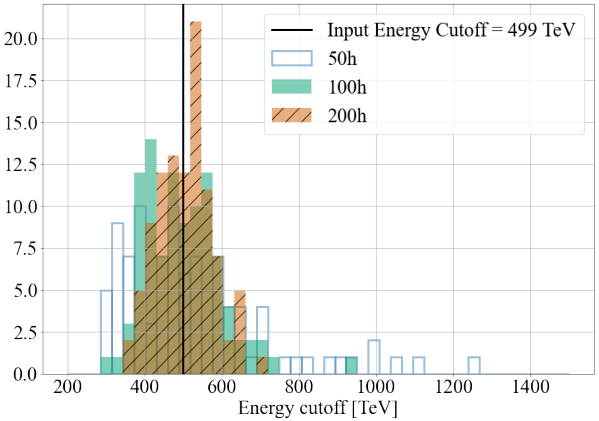


Spectral parameters of the hadronic model

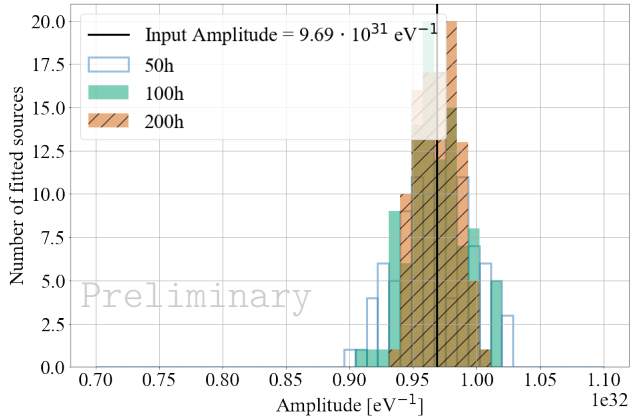
CTA-North small array

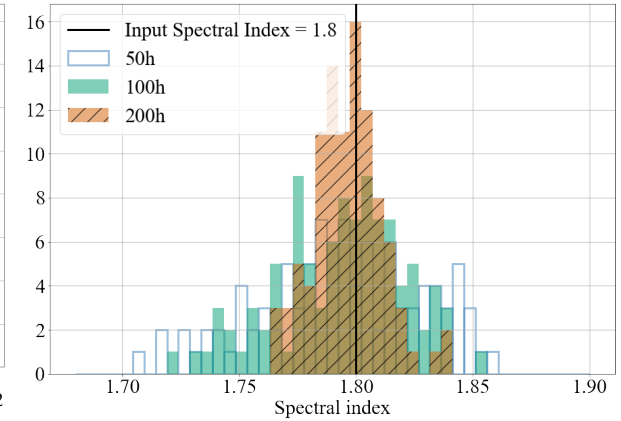


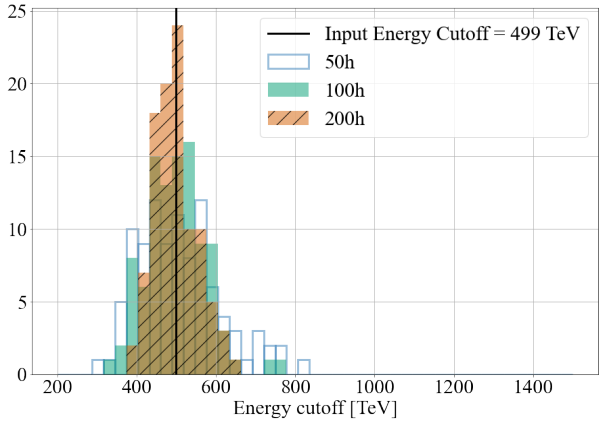




CTA-North large array







Percentage of relative dispersion
(i.e. standard deviation over mean)

	amplitude		spectral index		energy cutoff	
	small	*large*	*small*	*large*	*small*	*large*
50 h	4.4%	3.0%	2.4%	2.0%	36.0%	20.7%
100 h	2.9%	2.3%	1.6%	1.5%	20.1%	15.2%
200 h	2.0%	1.6%	1.3%	0.8%	14.2%	10.6%