Search for the Galactic accelerators of Cosmic-Rays up to the knee with PeVatron Test Statistics (PTS)

Ekrem Oğuzhan Angüner
Gerrit Spengler

News about CTA PeVatrons Paper

CTA PeVatrons paper is ready to be submitted!

<u>Main results :</u>

- The PeVatron Test Statistics (PTS) method can offer a new approach to detect spectral signatures of PeVatrons.

- The PTS method can be used for mapping spectral parameter space of PeVatrons.
(PeVatron detection & rejection maps)

- The PTS method is tested on simulations of synthetic SNR PeVatron populations in the paper,
also in CTA GPS simulation study.
(Estimation of expected number of PeVatrons in CTA GPS)

- Deeper follow-up observation of PeVatron candidate sources with CTA is promising (order of 100 h).

- Moonlight observations of PeVatrons is promising (similar sensitivities with twice the observation time)

- Appendix : Derivation of lower limits
(Different statistical methods, gammapy API)

https://github.com/residualsilence/ecpli/tree/v0.18.2

E.O. Angüner, G. Spengler, H. Costantini, P. Cristofari, T. Armstrong and L. Giunti for the CTA Consortium, CTAC2022 (CTA PeVatrons Paper)

Sensitivity of the Cherenkov Telescope Array to spectral signatures of hadronic PeVatrons with application to Galactic Supernova Remnants

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Abstract

The local Cosmic Ray (CR) energy spectrum exhibits a spectral softening at energies around 3 PeV. Sources which are capable of accelerating hadrons to such energies are called hadronic PeVatrons. However, hadronic PeVatrons have not yet been firmly identified within the Galaxy. Several source classes, including Galactic Supernova Remnants (SNRs), have been proposed as PeVatron candidates. The potential to search for hadronic PeVatrons with the Cherenkov Telescope Array (CTA) is assessed. The focus is on the usage of very high energy γ-ray spectral signatures for the identification of PeVatrons. Assuming that SNRs can accelerate CRs up to knee energies, the number of Galactic SNRs which can be identified as PeVatrons with CTA is estimated within a model for the evolution of SNRs. Additionally, the potential of a follow-up observation strategy under moonlight conditions for PeVatron searches is investigated. Statistical methods for the identification of PeVatrons are introduced, and realistic Monte–Carlo simulations of the response of the CTA observatory to the emission spectra from hadronic PeVatrons are performed. Based on simulations of a simplified model for the evolution for SNRs, the detection of a γ-ray signal from in average 9 Galactic PeVatron SNRs is expected to result from the scan of the Galactic plane with CTA after 10 hours of exposure. CTA is also shown to have excellent potential to confirm these sources as PeVatrons in deep observations with $O(100)$ hours of exposure per source.

Keywords: Gamma rays: general, Cosmic rays, Galactic PeVatrons, (Stars:) supernovae: general, Methods: data analysis, Methods: statistical

1. Introduction

The term "PeVatron" is now widely used to designate astrophysical accelerators which energize particles (electrons, protons, and nuclei) up to the PeV (10^{15} eV) energy range. The interest in these objects is directly linked to the unsolved problem of the origin of cosmic rays (CRs) detected on Earth. More than a century of experiments have provided detailed measurements of the CR energy spectrum. For protons, accounting for $\sim 90\%$ of Galactic CRs, the spectrum follows a power–law in energy with an index of ~ -2.7 up to the "knee" at ~3 PeV energies (Blümer et al., 2009), where the index steepens to ~ -3.0. The ARGO–YBJ experiment has reported that the knee of the cosmic hydrogen and helium spectrum is measured below 1 PeV (ARGO-YBJ Collaboration et al., 2015). Magnetic effects can confine CRs with energies below the knee within the Galaxy (Ptuskin et al., 1993). The observation of Galactic CRs up to at least PeV energies motivates the search for their source, i.e. "Galactic PeVatrons". With PeVatrons becoming a recognised class of γ-ray sources, the importance of PeVatrons is well known across the wide range of multi–messengers, from radio to X/γ rays, and then even further to CRs and neutrinos (Filipović and Tothill, 2021). Several source classes, e.g. supernova (SN) Remnants (SNRs) (Bell, 1978), massive stars and stellar clusters (Aharonian et al., 2019), core–collapse SNe (Tatischeff, 2009; Bell et al., 2013; Zirakashvili and Ptuskin, 2016), pulsar winds (Amato, E. et al., 2003; Amato and Olmi, 2021; Guépin, Claire et al., 2020), star formation regions (SFRs) (Bykov et al., 2020), microquasars (Abeysekara et al., 2018) and superbubbles (Higdon and Lingenfelter, 2003; Binns et al., 2005), have been proposed as potential PeVatrons.

SNRs have long been the preferred candidates since several strong arguments support the SNR hypothesis (Blasi, 2013, 2019; Gabici el al., 2019). For example, the conversion of a reasonable fraction of the total explosion energy of SNRs into CRs can explain the measured CR energy density. Additionally, the detection of γ-ray emission from numerous SNRs confirms that SNRs accelerate particles efficiently and diffusive shock acceleration can somewhat account for the measured slope of the CR spectrum (Cristofari, 2021), although the exact spectral index of particles accelerated at SNR shocks, and injected in the ISM is still a matter of active debate (Malkov and Drury, 2001; Amato and Blasi, 2006; Recchia and Gabici, 2018; Celli et al.,

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Preprint submitted to Astroparticle Physics *November 25, 2022*

Motivation : PTS Paper

- The missing part was to test the PTS method on real observation data.

- In the PTS paper, we use public data from different gamma-ray observatories to look for Galactic PeVatrons by using the PTS method.

- In addition, The Southern Wide-field Gamma-ray Observatory (SWGO) sensitivity to spectral signatures of PeVatrons is investigated. (Off-collaboration paper, straw-man design)

- The paper is in a good shape, we plan to submit it after CTA PeVatrons paper is (hopefully) accepted.

PTS Paper (in preparation)

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Search for the Galactic accelerators of Cosmic-Rays up to the Knee with the Pevatron Test Statistic*

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ABSTRACT

The recently introduced Pevatron Test Statistic (PTS, see CTA Collaboration (2022)) is, for the first time, applied to data from γ-ray observatories to test for the origin of Cosmic Rays (CRs) at energies around and above the knee of the CR spectrum. Public data from γ-ray observatories are analyzed within hadronic emission models, and conservative assumptions with respect to possible systematic errors. It is outruled with a high statistical significance of more than 5σ that the two shell type Supernova remnants (SNRs) RX J1713.7-3946 and Vela Jr., as well as the γ-ray source HESS J1745-290, which is spatially coincident with the dynamical center of the Galaxy, are Pevatrons. These results were previously derived by other means but the analyses confirm the performance and reliability of the PTS. A new result is that an association between the γ-ray emission from the region which contains the SNR G106.3+2.7 and the Boomerang nebula is also outruled with a statistical significance of more than 5σ. No statistically significant conclusion with respect to an association to a Pevatron is drawn for the diffuse γ-ray emission around the Galactic Center (GC), and the two unidentified γ-ray sources LHAASO J2108+5157 and HESS J1702-420A. However, it is argued that data from the northern Cherenkov Telescope Array (CTA) and the Southern Wide-field Gamma-ray Observatory (SWGO) will respectively allow to decide whether these two sources are associated to a Pevatron or not. For SWGO, it is shown that the sensitivity with 5 years of data will be sufficient to probe large parts of the relevant parameter space of pointlike Pevatrons.

Keywords: Acceleration of particles — Astroparticle physics — Methods: statistical

1. INTRODUCTION

The flux of Cosmic Rays (CRs) which enter the atmosphere of the Earth is now being investigated for more than a century after its first detection (Hess 1912), for which the years 1936 Nobel prize was awarded. As, for example, reviewed in Amato & Blasi (2018); Amato (2014); Blasi (2013), the flux of CRs which are detected on Earth is dominated by protons, with helium being the second most abundant nuclei. The energy spectrum above $\sim$ 30 GeV up to the so called "knee" is very well approximated by a power-law with spectral index -2.7, although significant deviations from this simple model were meanwhile detected. The "knee" is a prominent feature in the CR energy spectrum where the spectral index steepens significantly. Although some recent evidence exists that the knee is even below 1 PeV for protons and helium (Bartoli et al. 2015), it is at least for heavy elements clear that the knee extends to energies well above 1 PeV (Hörandel 2003). As a characteristic energy of the knee, the value of 1 PeV is therefore used in the following. The origin of the knee is debated ever since its first discovery (Kulikov & Khristiansen 1958), with two models being particularly popular. As reviewed in Blümer et al. (2009), the first model is to identify the energy where the knee is observed in the CR spectrum with the maximal achievable energy of Galactic particle accelerators, and the second model proposes a connection between the knee and the maximal energy for which electrically charged particles are magnetically confined within the Galaxy. In addition to the origin of the knee, it remains to this date an

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What is a PeVatron ?

There is an ambiguity for the definition of "PeVatron" in the literature. In the PTS paper, we discuss it.

1 – Textbook definition : CR sources which can accelerate CR at least up to PeV energies.

- This means that PeV particles should exist at the acceleration site.
- They do not necessarily need to have particle spectral cutoff at or above 1 PeV. (i.e. a strong source with 500 – 600 TeV particle cutoff can be enough)
- They can be hadronic or leptonic accelerators.
- No clear physical motivation (1 PeV is an arbitrary number).

Definition based on max energy of individual particles

We focus on this definition

2 – Historical definition : CR sources which can contribute significantly to the knee seen at CR spectrum

- This means that PeV particles should exist at the acceleration site.
- Because the energy of the knee is well above 1 PeV, the maximum energy must be much larger than 1 PeV. (This requires particle cutoff energy above 1 PeV)
- They can be only hadronic accelerators.
- It must be possible to explain the steepening in the CR spectrum at knee. (i.e. propagation effects & intrinsic properties of PeVatrons)
- Physical motivation is the search for the origin of Galactic CRs.

Definition based on particle spectrum

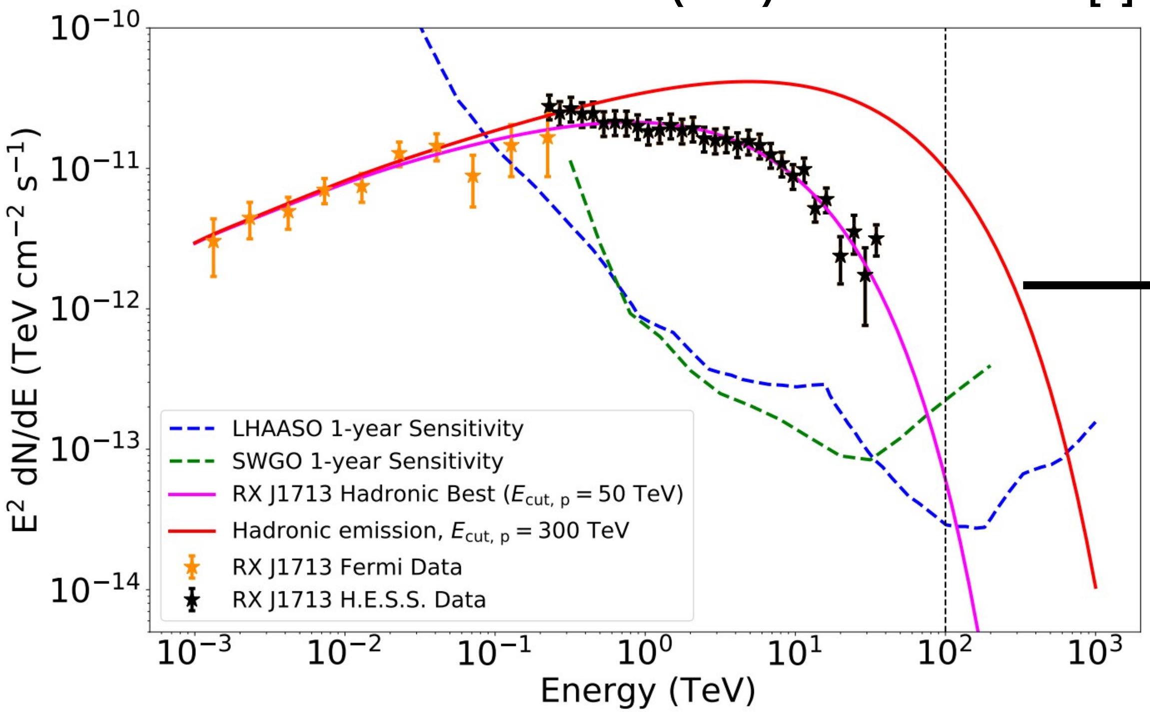
Search for spectral signatures of PeVatrons

Currently there are two traditional methods to search for PeVatron signatures, but both are not enough.

1 – The 95% C.L. lower limit on the proton energy cutoff (i.e. > 1 PeV)
(Not enough for robust identification, still a very good criterion for candidate selection)

2 – Significance of gamma-ray emission above 100 TeV (i.e. LHAASO sources)
(No information on spectral shape)

(SNR) RX J1713.7-3946 [1]

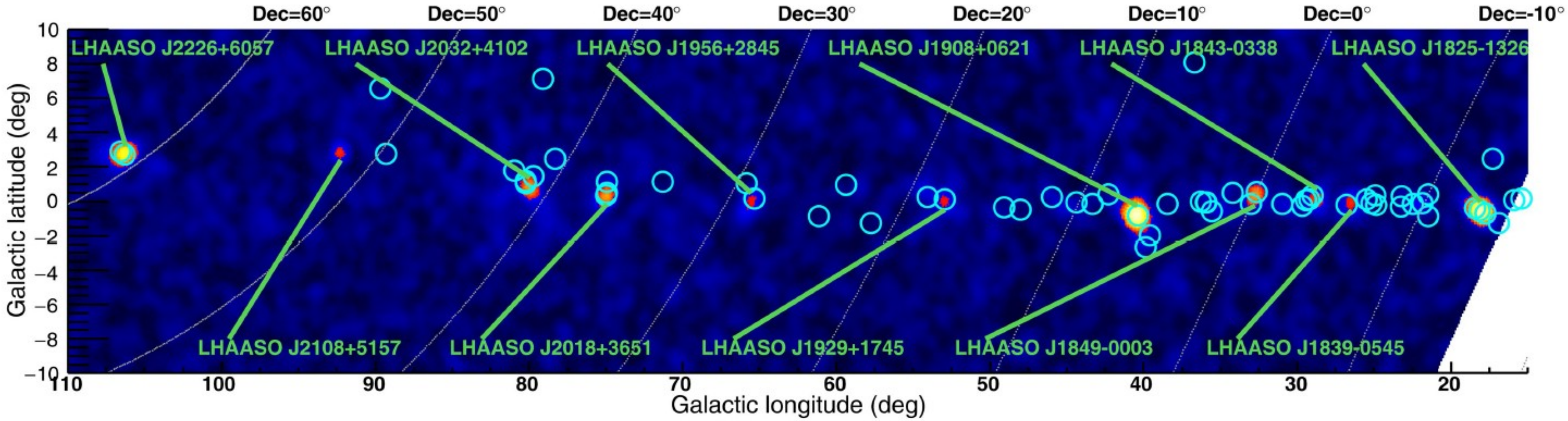


The 1-year straw-man design sensitivity of SWGO (green) is taken from https://github.com/harmscho/SGSOSensitivity.

A LHAASO-like experiment will see ~10 σ detection above 100 TeV, even this source is far from being a PeVatron (Historical definition)

Search for spectral signatures of PeVatrons

LHAASO E > 100 TeV Skymap [2]



- Not all sources giving significant E > 100 TeV emission *must* be PeVatrons (by historical definition). Indeed, E>100 TeV detection is needed for PeVatron detection, but not enough alone.

- One needs a method for quantifying the PeVatron nature of a source in an understandable way (i.e. significance), combining both lower limits on proton cutoff energy and E > 100 TeV detection.

- The PeVatron Test Statistics (PTS) can be used for PeVatron detection.

$$\mathrm{PTS} = -2 \ln \frac{\hat{L}(\lambda_{\mathrm{p}} = 1\,\mathrm{PeV}^{-1})}{\hat{L}(\lambda_{\mathrm{p}})}, \qquad S_{\mathrm{PTS}} = \mathrm{sign}(\Delta)\sqrt{\mathrm{PTS}}$$

Search for spectral signatures of PeVatrons

Likelihood of proton model with fixed Ep = 1 PeV

$$\mathrm{PTS} = -2\ln \frac{\hat{L}(\lambda_{\mathrm{p}} = 1\,\mathrm{PeV}^{-1})}{\hat{L}(\lambda_{\mathrm{p}})},$$

Likelihood of proton model with all parameters free

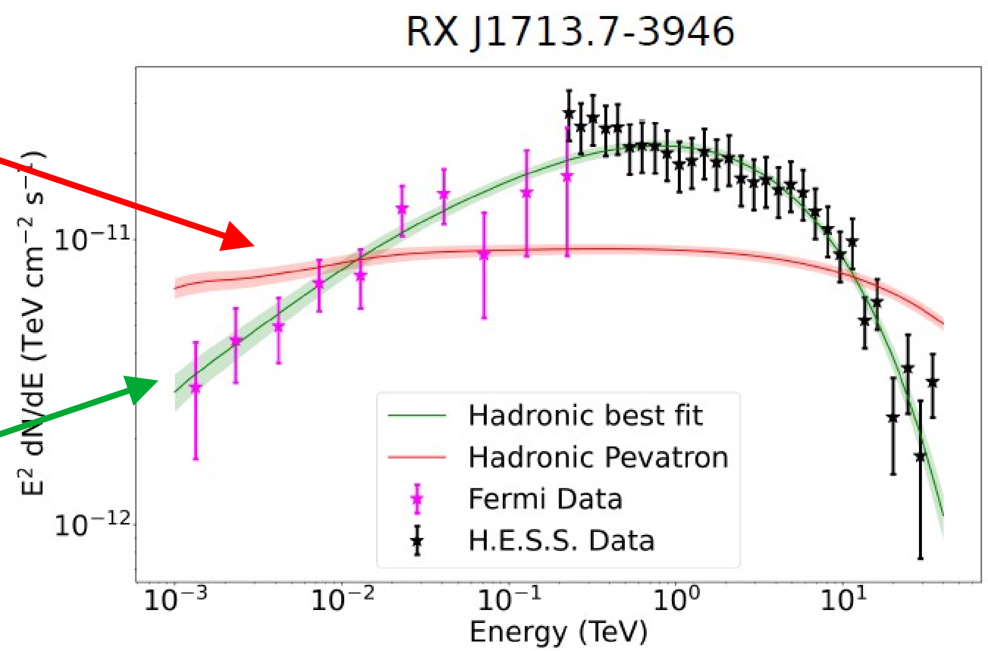
$$S_{\mathrm{PTS}} = \mathrm{sign}(\Delta)\,\sqrt{\mathrm{PTS}}$$

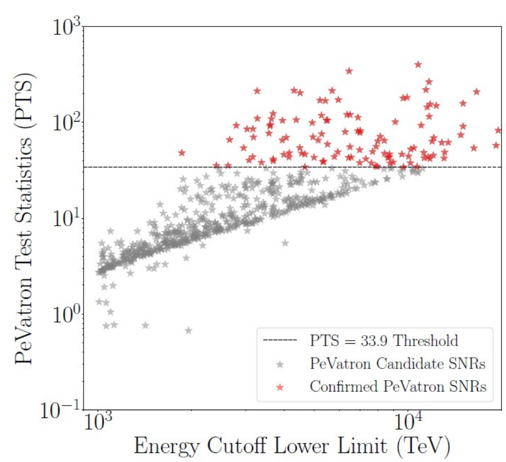
$$\Delta := 1\,\mathrm{PeV}^{-1} - \hat{\lambda}_{\mathrm{p}}$$

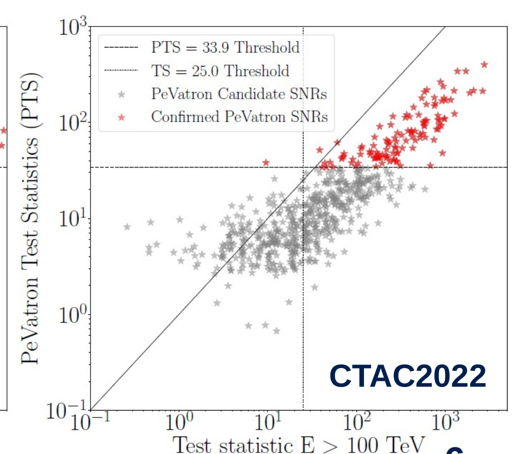
S_PTS > 5σ (5σ PeVatron Detection)

S_PTS < -5σ (5σ PeVatron Rejection)

|S_PTS| < 5σ (Data insufficient to decide)



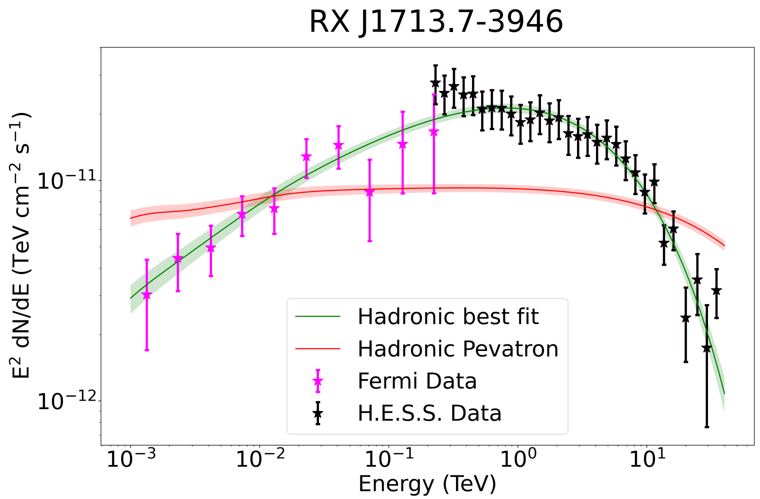


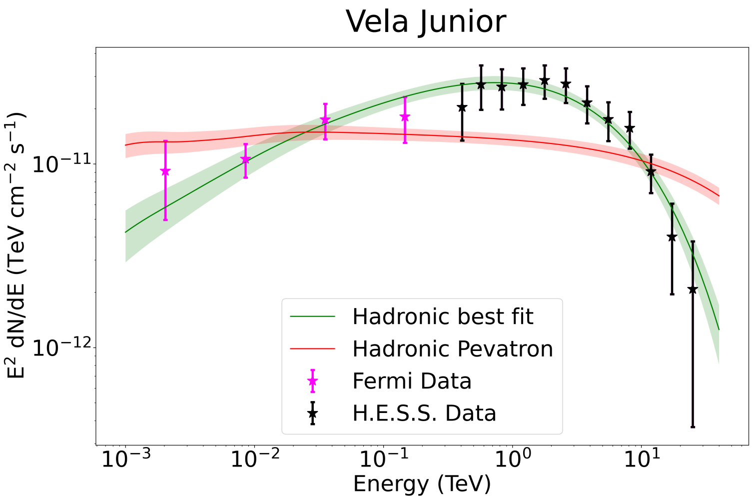


Validation of the PTS method and Rejecting PeVatron hypotheses: The Supernova Remnants RX J1713.7–3946 and Vela Junior [3]

- First, we have to show and validate that the PTS method works fine for well-known non-PeVatron cases.

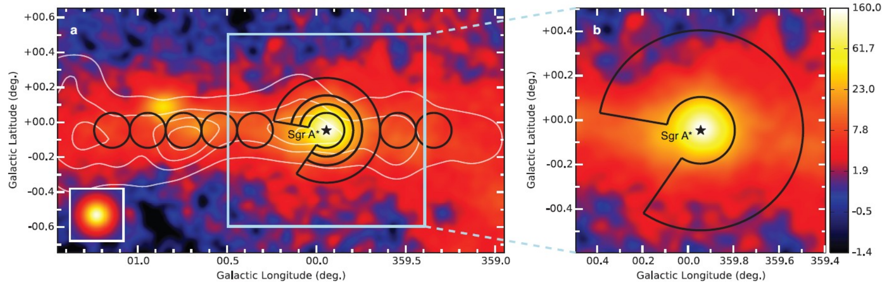
- Very conservative → Err_stat = max {Err_stat-, Err_stat+}, Error = max {Err_stat, Err_sys}, Err_sys = 20%

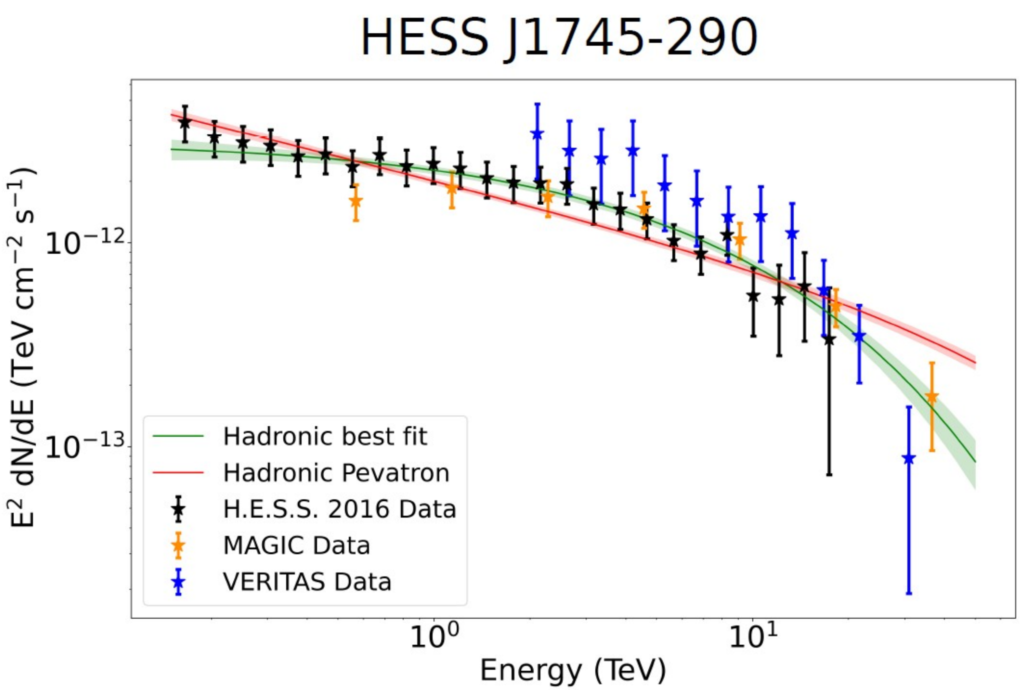


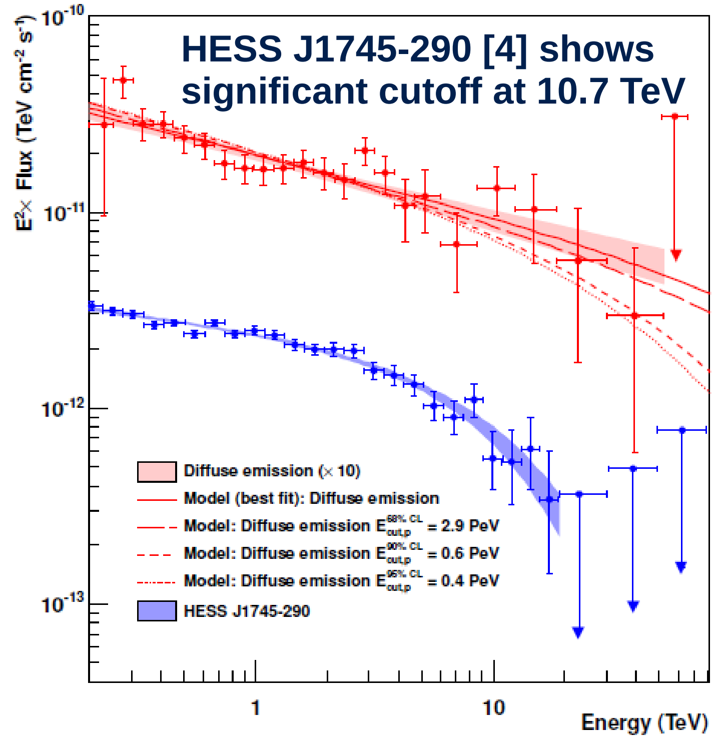


Source Name	Instrument Data	Energy Range (TeV)	ξ (%)	S_{PTS}	Γ_P	$E_{cut,P}$ (TeV)	$LL_{cut,P}$ (TeV)	p-value (%)
Vela Jr.	H	[0.4, 25.0]	20	-4.6	0.95 ± 0.63	21 ± 10	13	100
Vela Jr.	**H+F**	**[0.002, 25.0]**	**20**	**-7.2**	**1.71 ± 0.08**	**47 ± 11**	**33**	**97**
RX J1713	H	[0.2, 34.6]	0	-9.9	1.99 ± 0.04	105 ± 16	82	0
RX J1713	H	[0.2, 34.6]	10	-7.5	1.98 ± 0.07	92 ± 18	67	31
RX J1713	H	[0.2, 34.6]	20	-5.2	1.98 ± 0.11	81 ± 23	52	97
RX J1713	H+F	[0.0013, 34.6]	0	-28.9	1.76 ± 0.02	59 ± 4	52	0
RX J1713	H+F	[0.0013, 34.6]	10	-21.5	1.72 ± 0.03	53 ± 5	46	12
RX J1713	**H+F**	**[0.0013, 34.6]**	**20**	**-14.5**	**1.70 ± 0.04**	**49 ± 6**	**40**	**93**

The Galactic Center Region : HESS J1745–290 Central Source

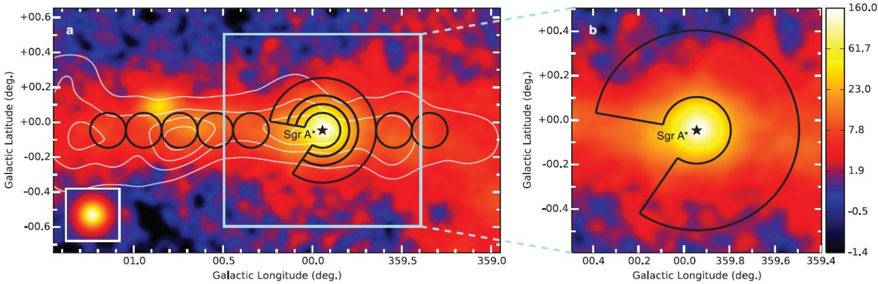


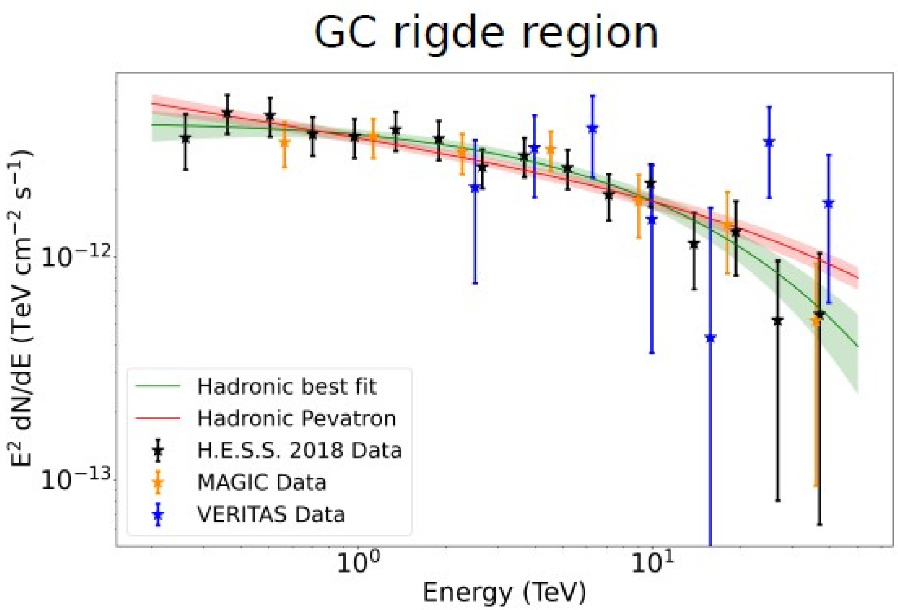


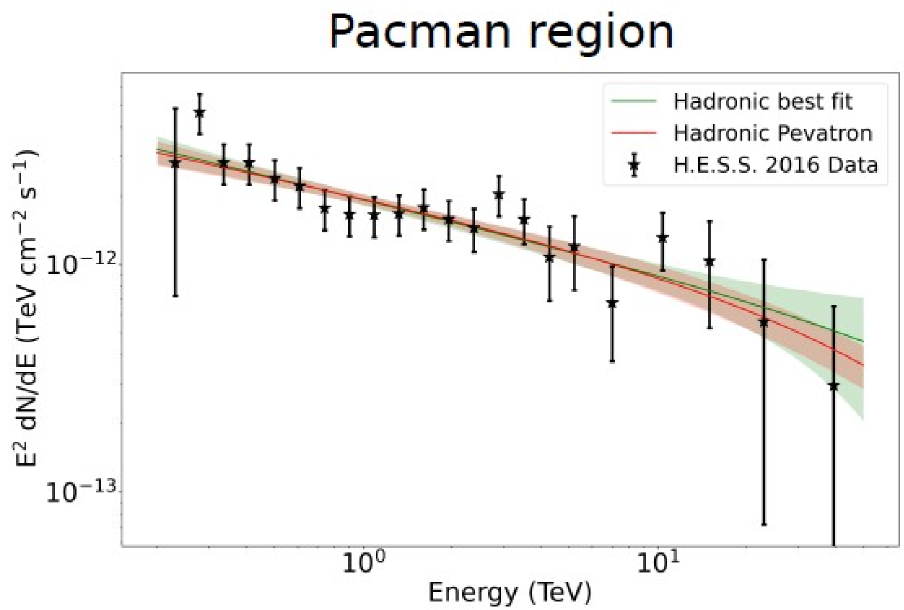


Source Name	Instrument Data	Energy Range (TeV)	ξ (%)	S_{PTS}	Γ_P	$E_{cut,p}$ (TeV)	$LL_{cut,p}$ (TeV)	p-value (%)
HESS J1745–290	H+M+V	[0.16, 36.5]	0	-9.0	2.12 ± 0.03	114 ± 18	89	0
HESS J1745–290	**H+M+V**	**[0.16, 36.5]**	**H+M: 20 V: 40**	**-5.8**	$\mathbf{2.06 \pm 0.09}$	$\mathbf{82 \pm 22}$	**54**	**87**

The Galactic Center Region : The Pacman & GC Ridge







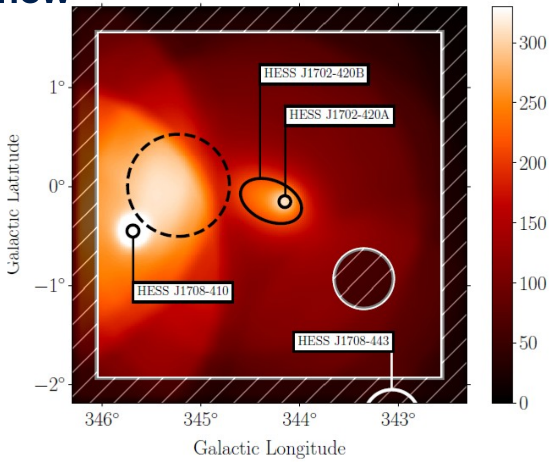
Source Name	Instrument Data	Energy Range (TeV)	ξ (%)	S_{PTS}	Γ_P	$E_{cut,p}$ (TeV)	$LL_{cut,p}$ (TeV)	p-value (%)
GC Pacman	H	[0.23, 39.6]	0	0.5	2.37 ± 0.09	Signif. $\ll 1\sigma$	185	68
GC Pacman	**H**	**[0.23, 39.6]**	**20**	**0.4**	**2.38 ± 0.09**	**Signif. $\ll 1\sigma$**	**172**	**82**
GC Ridge	H+M+V	[0.26, 39.8]	0	-2.4	2.08 ± 0.11	179 ± 93	83	96
GC Ridge	**H+M+V**	**[0.26, 39.8]**	**H+M: 20 V: 40**	**-2.3**	**2.03 ± 0.14**	**157 ± 87**	**69**	**100**

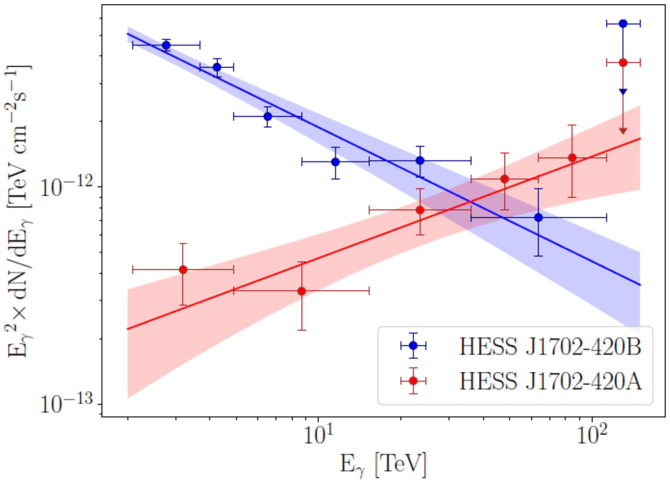
Two unidentified sources :
HESS J1702-420A and LHAASO J2108+5157

- HESS J1702A [5] source is a well-know PeVatron candidate and a good example of source confusion.

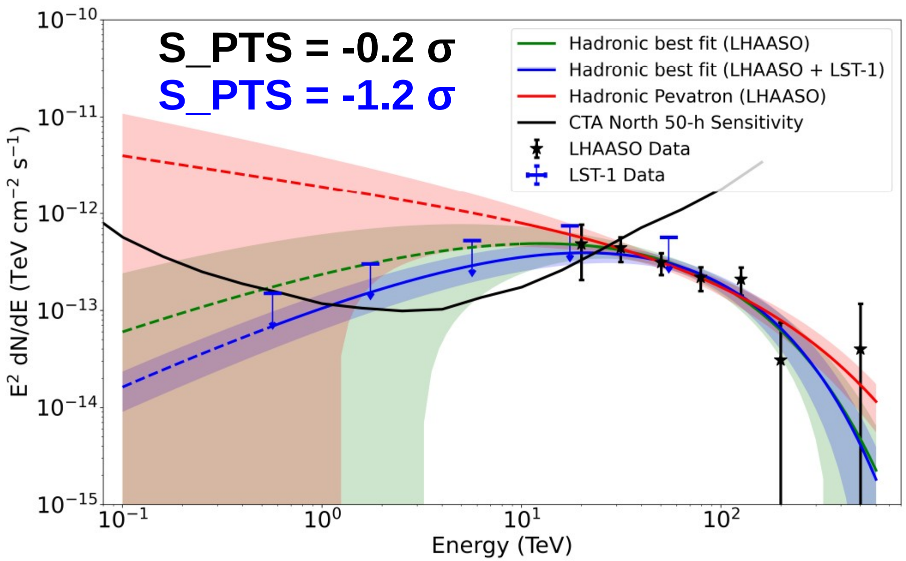
- The PTS method can be applied when sub-components are resolved, isolated cases (i.e. 3D likelihood).

- LST-1 data, even upper limits, can be used to put constraints on the hadronic models.

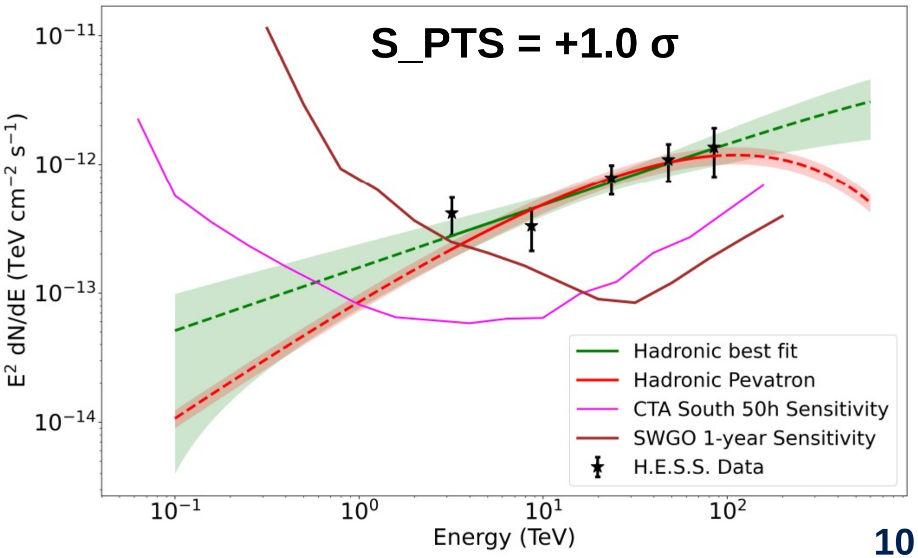




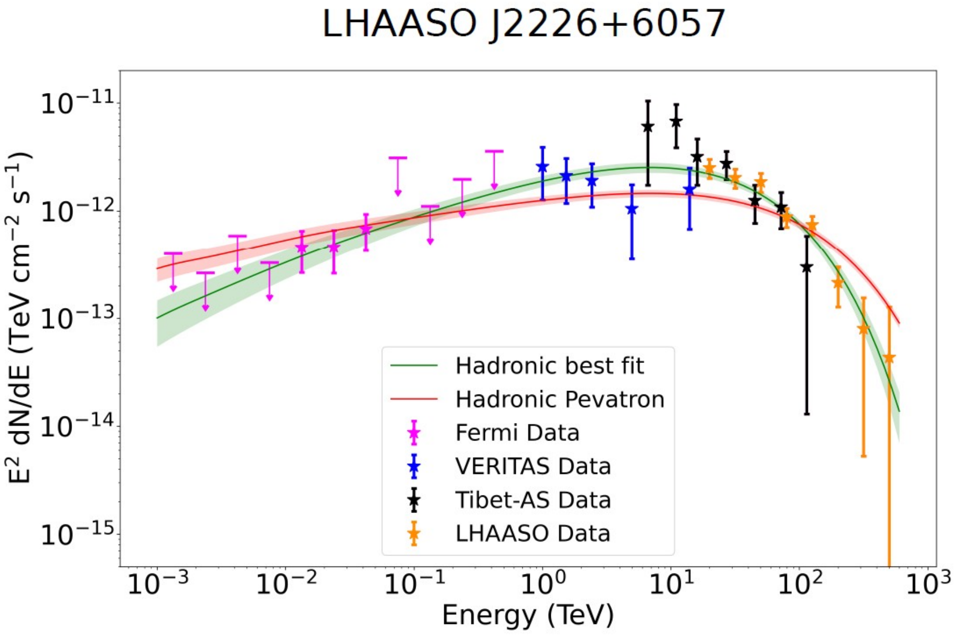
LHAASO J2108+5157 **[6,7]**



HESS J1702-420A



LHAASO J2226+6057 :
SNR G106.3+27 and The Boomerang PWN



- LHAASO J2226+6057 [2] is a well-know PeVatron candidate.

- None of the data alone could confirm or reject the PeVatron hypothesis

- By combining all data from Fermi, VERITAS, Tibet-AS and LHAASO experiments, one can significantly exclude the PeVatron hypothesis.

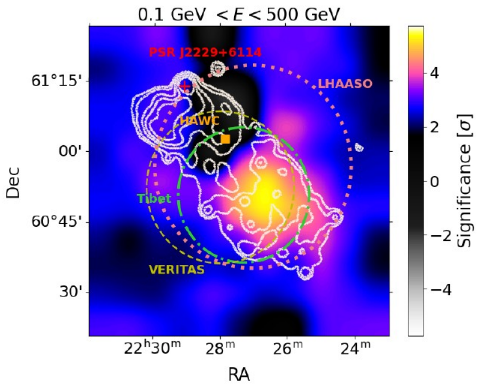
- This is due to our (historical) PeVatron definition and assuming that the source has single component.

- But...

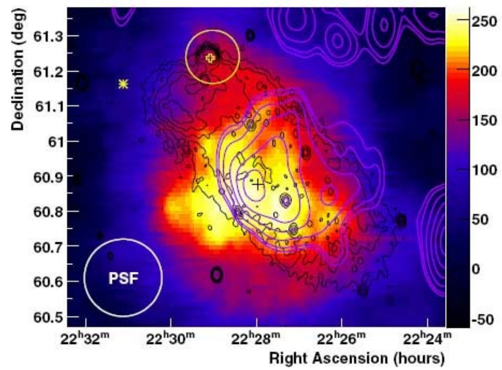
Instrument Data	Energy Range (TeV)	ξ (%)	S_{PTS}	Γ_p	$E_{cut,p}$ (TeV)	$LL_{cut,p}$ (TeV)	p-value (%)
F	[0.005, 0.301]	20	0.1	1.88 ± 0.18	Signif. $\ll 1\sigma$	0.2	78
V	[1.0, 13.9]	20	0.3	2.37 ± 0.34	Signif. $\ll 1\sigma$	6	70
T	[6.6, 114.0]	20	-0.5	2.36 ± 1.02	Signif. $\ll 1\sigma$	46	83
L	[20.0, 501.0]	0	-2.0	1.38 ± 0.76	241 ± 131	124	28
L	[20.0, 501.0]	20	-1.6	1.46 ± 0.93	256 ± 174	121	69
F_P+V+T+L	**[0.013, 501.0]**	**20**	**-5.2**	**1.62 ± 0.08**	**327 ± 60**	**241**	**71**

LHAASO J2226+6057 :
SNR G106.3+27 and The Boomerang PWN

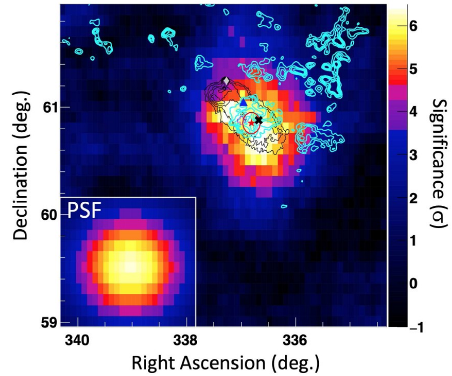
Fermi [8]



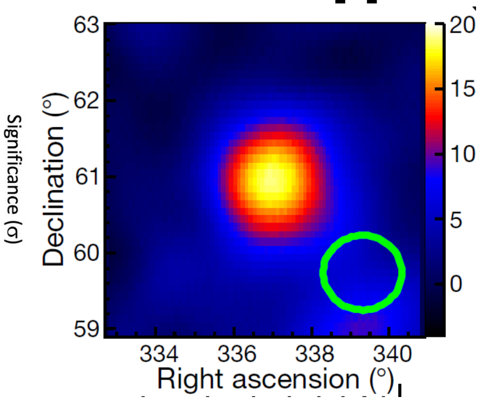
VERITAS [9]

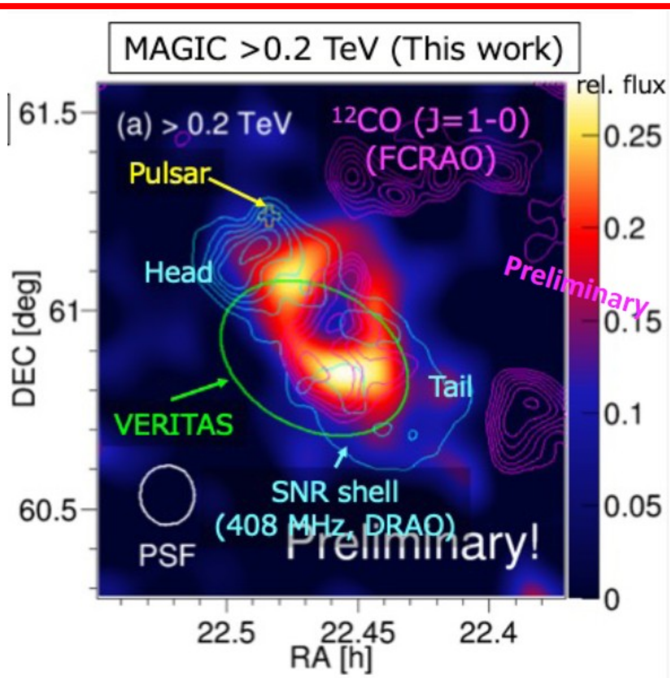


Tibet-AS [10]

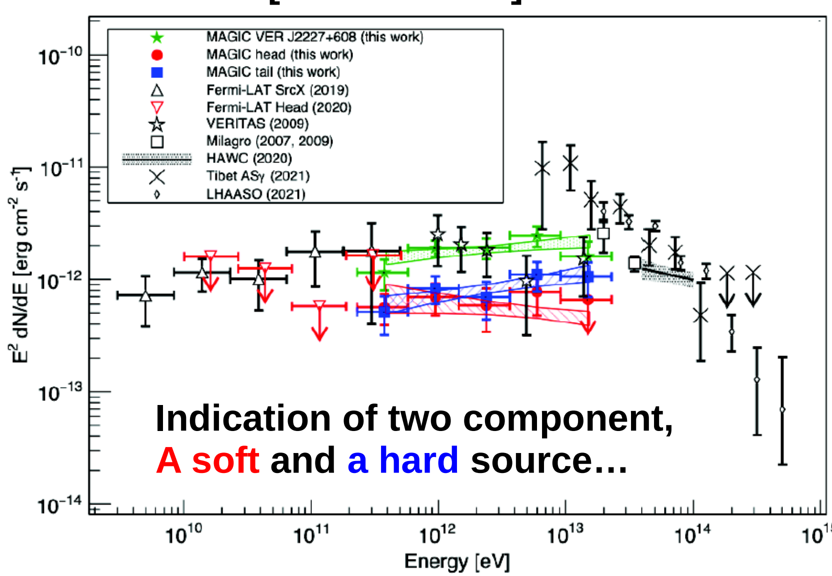


LHAASO [2]





MAGIC [Gamma 2022]



Indication of two component,
A soft and a hard source…

A word on gamma-gamma absorption

- Gamma-gamma absorption is basically due to creation of electron-positron pair in photon-photon interactions. Both distance to source and interstellar photon field comes into play.

- It's a very important effect especially above E > 200 TeV energies. One has to take these effects into account in the search for Galactic PeVatrons.

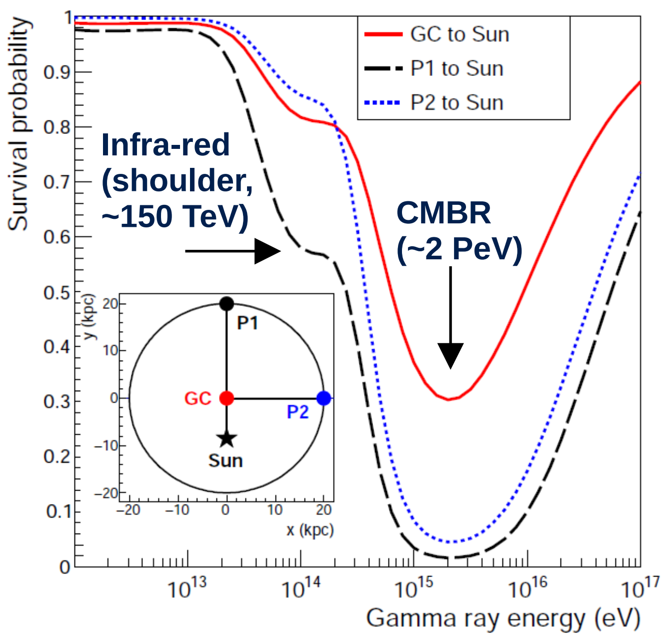


FIG. 13: Survival probability of gamma rays for three different trajectories in the Galactic plane, plotted as a function of the gamma ray energy. The inset shows the position of the sources.

Vernetto, S., & Lipari [11]

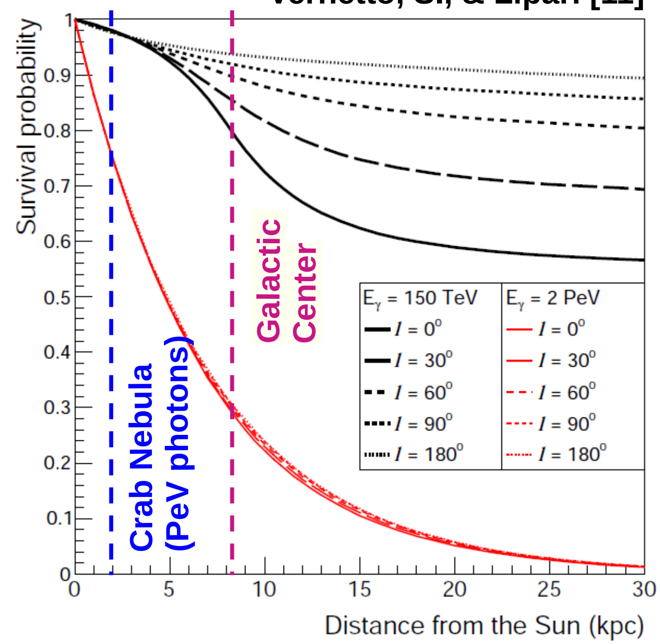


FIG. 14: Survival probabilities of gamma rays of energy 150 TeV and 2 PeV as a function of the source distance, for lines of sight with different Galactic longitudes and fixed latitude $b = 0°$.

The potential of PeVatron searches with spectral gamma-ray data for SWGO [12]

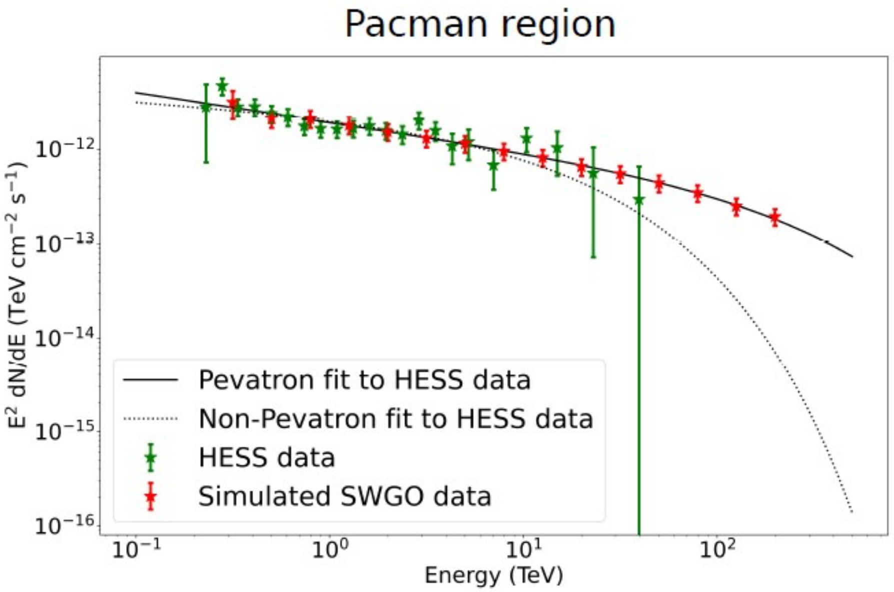
- SWGO simulations of selected source (S_{PTS} > 0) spectra assuming 5-year SWGO observations : GC Pacman region and HESS J1702-420.

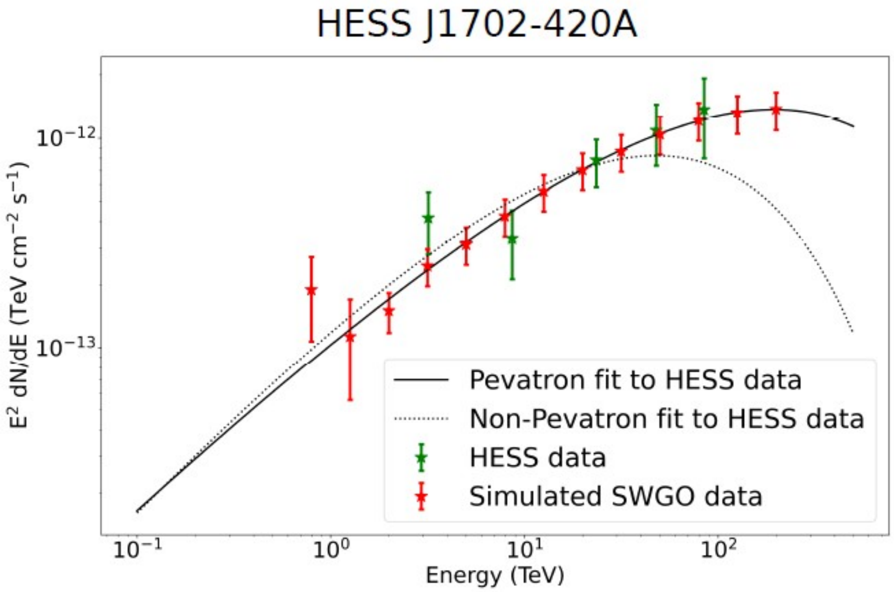
- Two different edge-case scenarios :

1-) These sources can accelerate protons up to knee (Ep_cut = 3 PeV) so they are PeVatrons.
2-) These sources are not PeVatrons Ep_cut = 172 TeV and 436 TeV for Pacman and J1702, respectively.

- Median of the PTS distribution from 100 simulations each give :

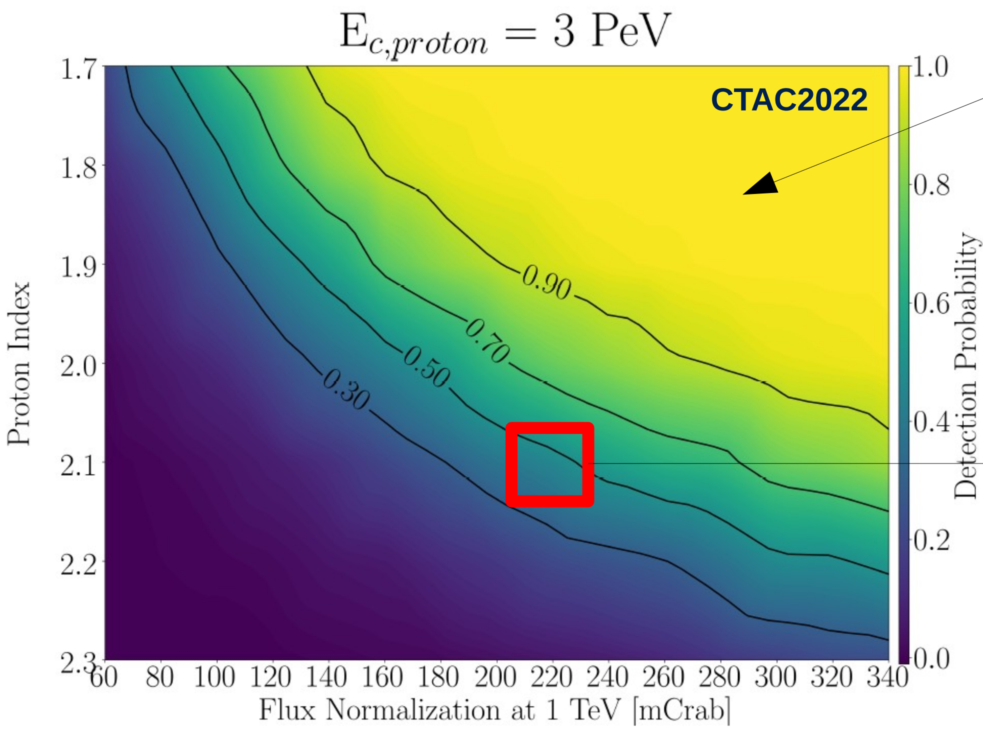
1-) S_PTS = 12 (Pacman) and S_PTS = 21 (HESS J1702)
2-) S_PTS = -23 (Pacman) and S_PTS = -11 (HESS J1702)



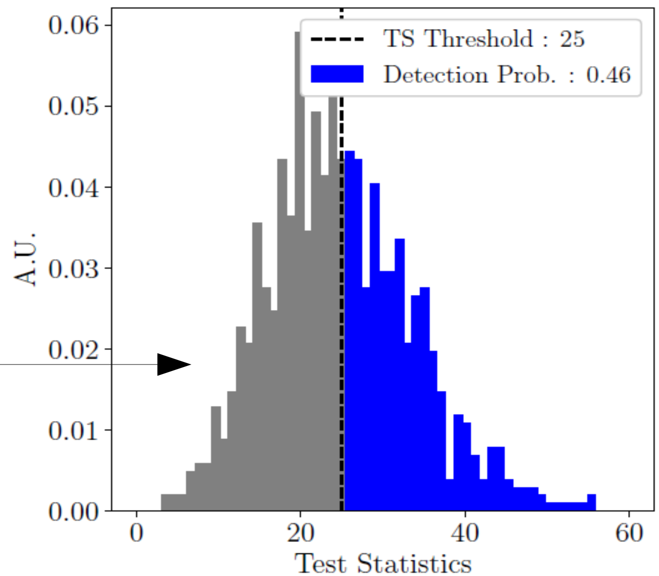


The 5-year straw-man design sensitivity of SWGO used in these simulations are taken from https://github.com/harmscho/SGSOSensitivity.

PeVatron Detection & Rejection Maps



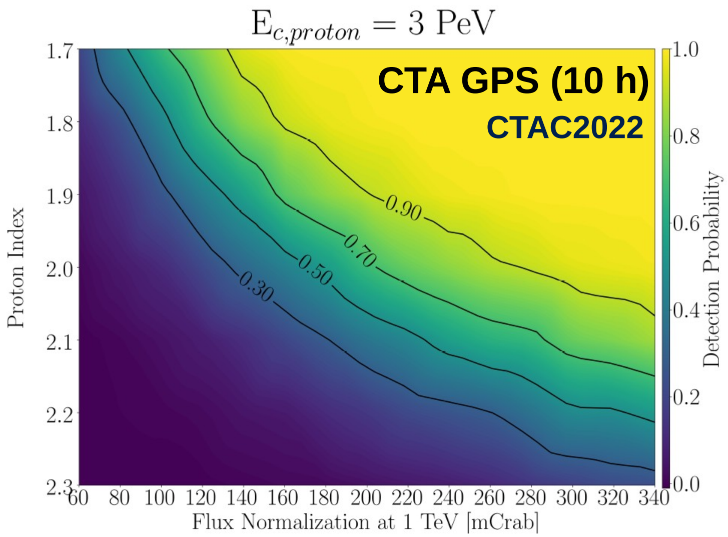
Yellow region : Phase space region in which a PeVatron with 3 PeV proton cutoff can be detected.

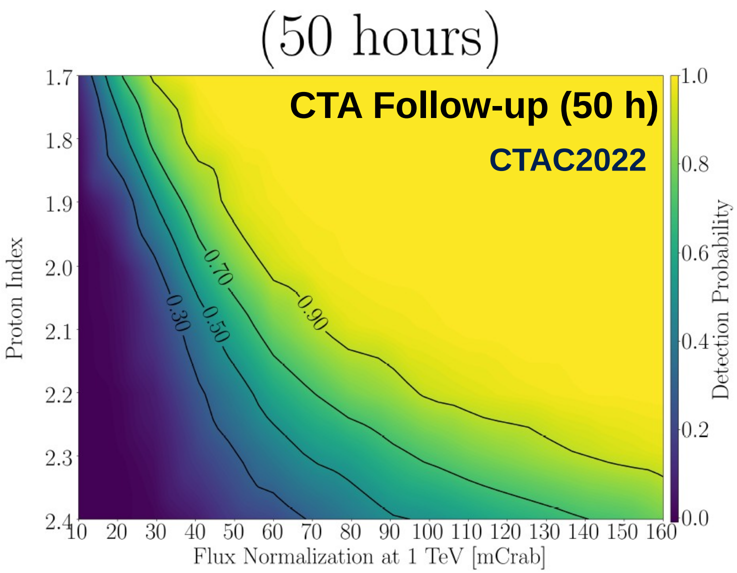


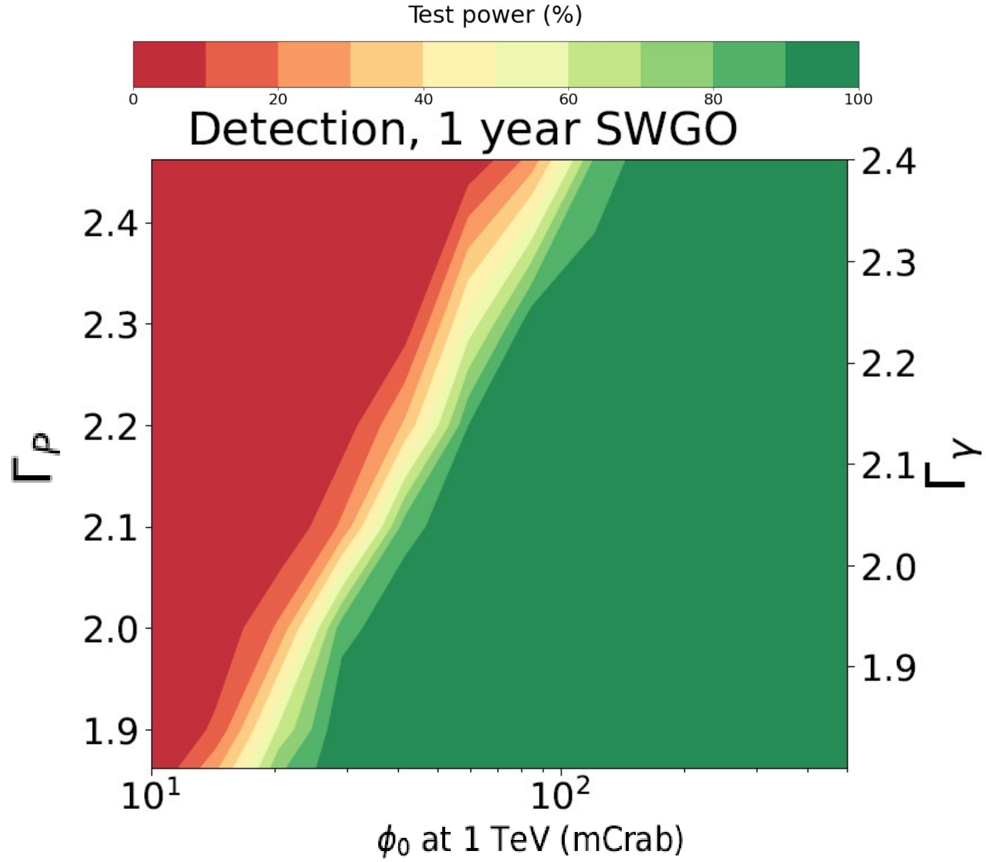
Distribution of 1000 PTS values in a single bin (True MC → Norm: 220 mCrab , Γ:2.1 , Ep = 3 PeV)

- **PeVatron detection (and rejection) maps can demonstrate the sensitivity of CTA (or any experiment, given the IRFs) to detect PeVatron sources in a given phase space.**
- **Similar maps can also be produced using gamma-ray models (spectral cutoff detection maps).**
- **These maps can be used for performance comparison of different array configuration.**

The potential of PeVatron searches with spectral gamma-ray data for SWGO







- 1-year SWGO detection map is comparable to 50 h CTA map. Systematics are not taken into account in this plots.

- Point souce definitions are different between CTA and SWGO.

The potential of PeVatron searches with spectral gamma-ray data for SWGO

- Detection Maps (Ep = 3 PeV) :

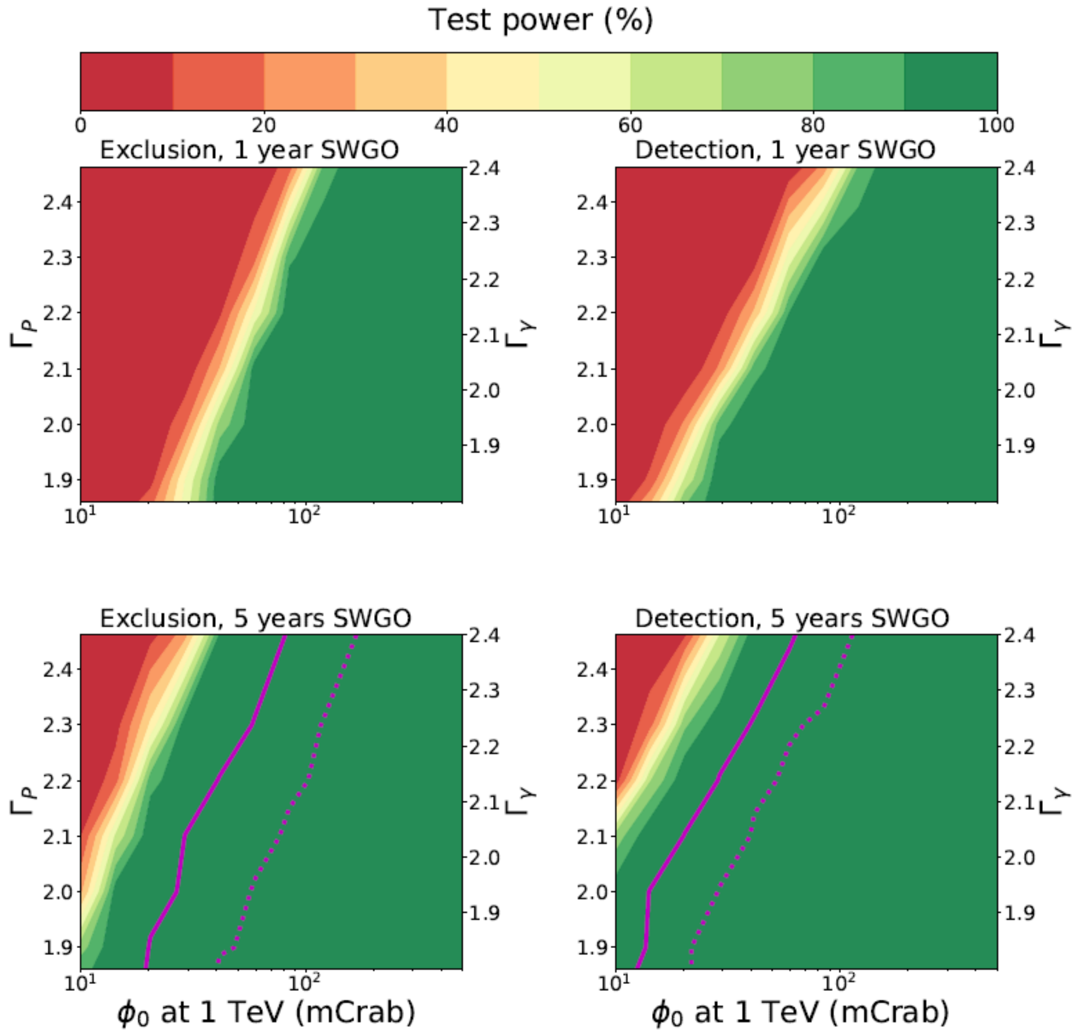
- Excellent detection power for 5-years

- Purple contours are 95% power for Ep = 2 PeV (solid) and Ep = 1.5 PeV (dashed)

- Exclusion Maps (Ep = 400 TeV) :

- Excellent exclusion power for 5-years

- Purple contours are 95% power for Ep = 600 TeV (solid) and Ep = 800 TeV (dashed)



The 5-year straw-man design sensitivity of SWGO used in these simulations are taken from https://github.com/harmscho/SGSOSensitivity.

Summary

- Application of the PeVatron Test Statistics method on observation data :

  - RX J1713 and Vela Jr. → (Verification of the PTS method, rejection of PeVatron hypothesis)
  - Galactic Center Region → HESS J1745-290, (Verification of the PTS method)

  - Galactic Center Region → The Pacman and GC Ridge regions
  (Further observations are needed)
  - LHAASO J2108+5157 and HESS J1702-420
  (Further observations are needed)

  - LHAASO J2226+6057 →
  (non-PeVatron conclusion based on PTS, single component) → (Ongoing)

- Combination of data from different instruments would be needed for PeVatron searches (i.e, CTA + SWGO).

- Systematics will be the most challenging task and can have significant effects.

- Gamma-gamma absorption should be taken into account for sources emitting above 200 TeV.

- Potential of SWGO (based on straw-man design sensitivity) is investigated using the PTS.
  SWGO has excellent PeVatron detection power for 5-year observations.

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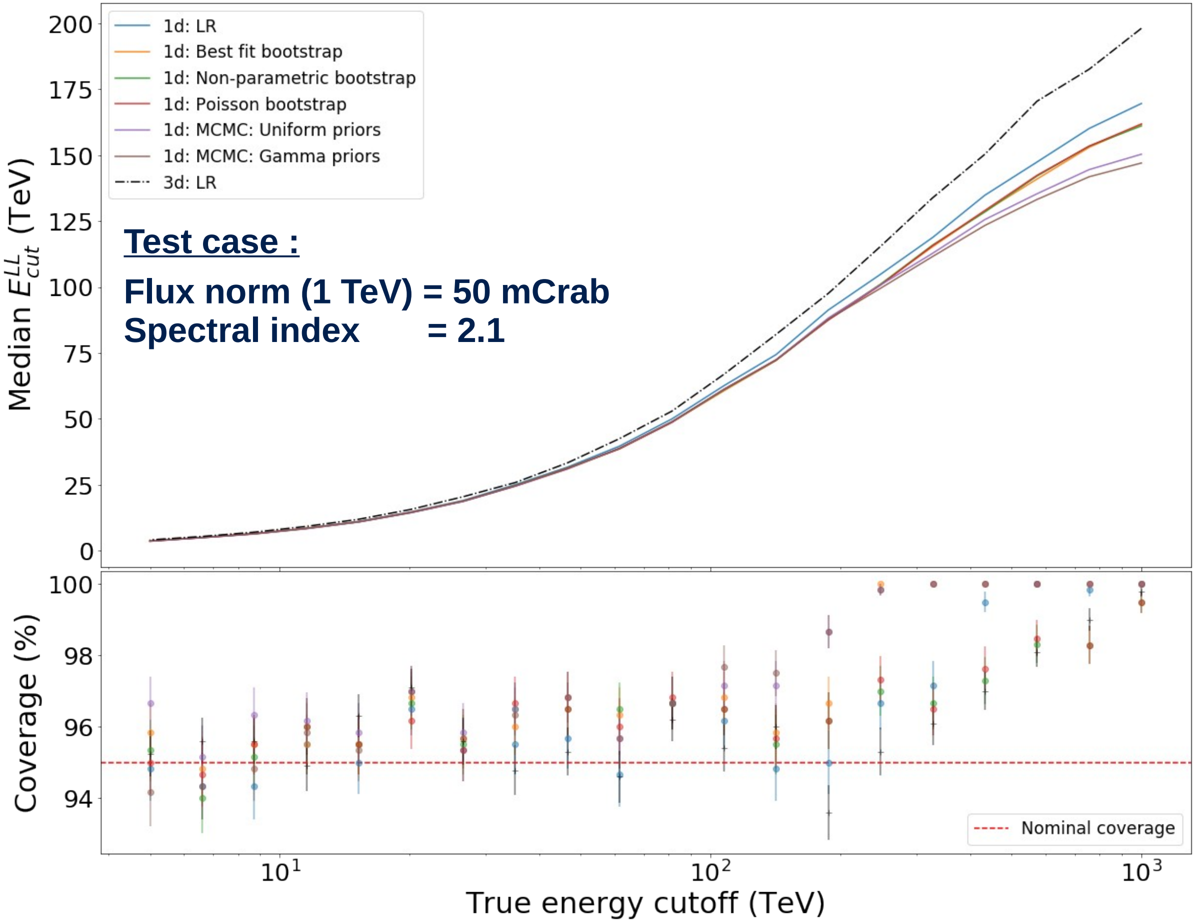
Backup 1 : Derivation of spectral cutoff lower limits

Comparison of 95% CL lower limits obtained from different methods



- Robust derivation of spectral cutoff lower limits is the key for PeVatron searches.
- CTA PeVatrons paper is designed to be 'the reference paper'.
- 3D likelihood provides the most sensitive method (if applicable).
- A public Gammapy API offering all methods is provided.
- The statistical methods provided can be used for any experiment data (HESS, HAWC, etc.)

https://github.com/residualsilence/ecpli → Gammapy 0.16

https://github.com/residualsilence/ecpli/tree/v0.18.2 → Gammapy 0.18.2

Backup 2 : Moonlight Follow-up Observations

- The aim is to investigate moonlight observations.
- We tested J1641 case (source confusion) using MCMC approach to derive 95% LL.
- Comparison plot show that we can reach the same level of 95% LL on this source (achieved by 50 h of nominal obs.) after 87 h of high NSB observations.
- This opens up the possibility that follow-up observations of selected PeVatron candidates can be performed by using moonlight observations.