# Cherenkov Telescope Array potential in the search for Galactic PeVatrons

**Ekrem Oğuzhan Angüner**
**for the CTA Consortium**

# Outline

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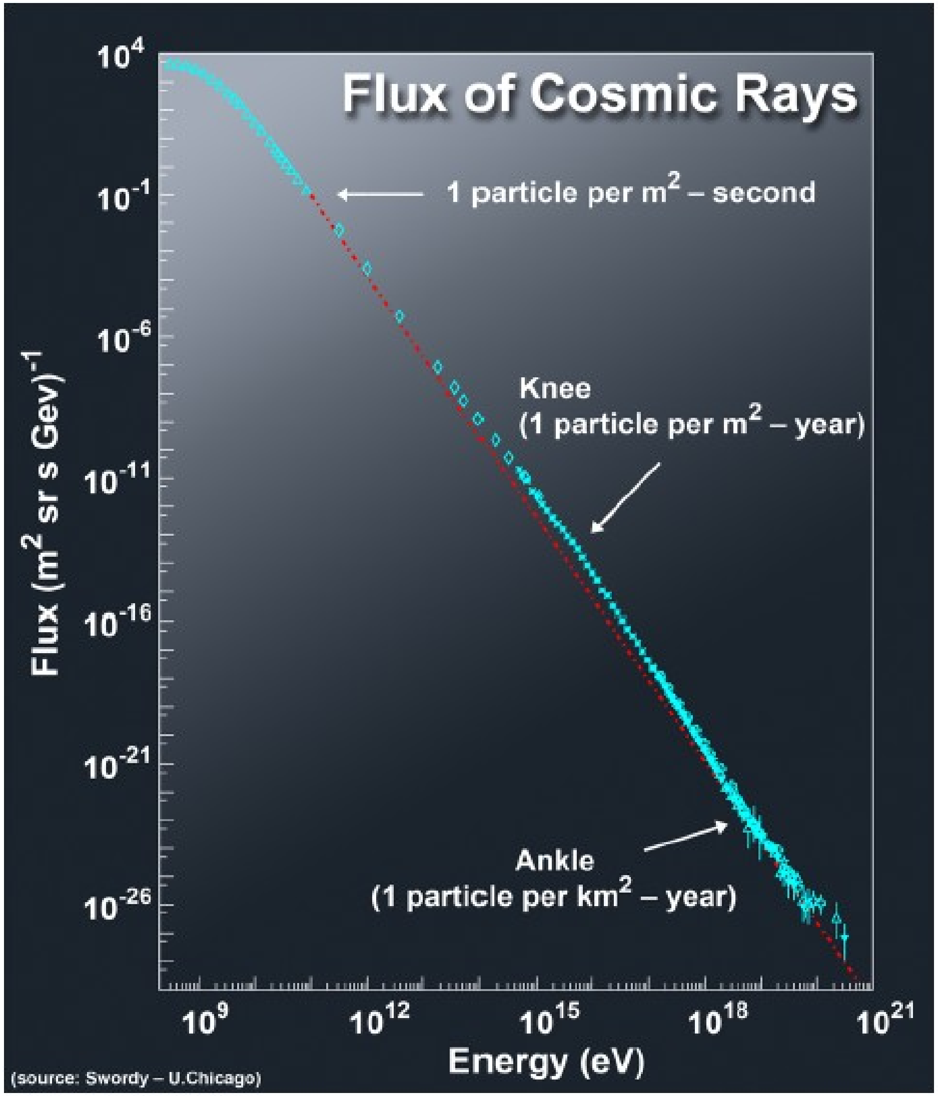
- Cherenkov Telescope Array
- Simulations and data analysis
- Results
- Large scale simulations
- Conclusions & Future studies

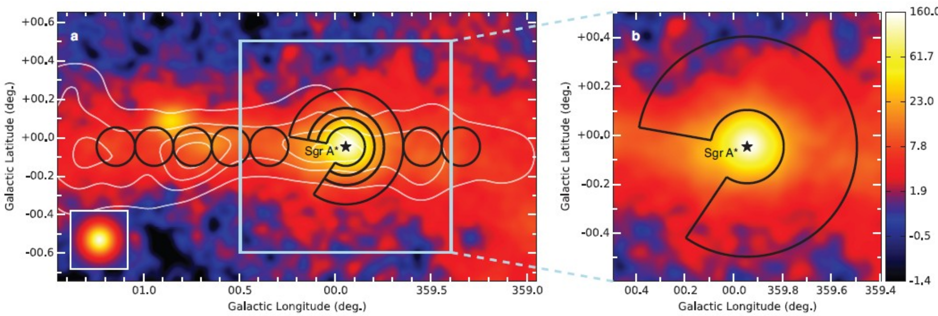
# Introduction : Cosmic Rays

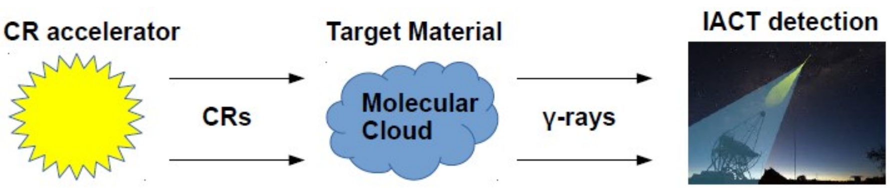


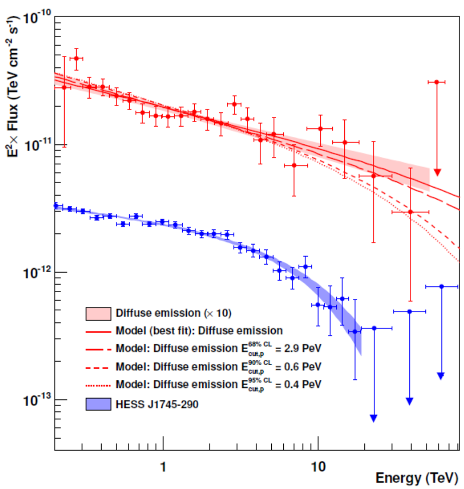

**The cosmic-ray spectrum measured from the Earth**

- The cosmic-ray (CR) spectrum shows two distinct features called "the knee" and "the ankle".
- The location of the knee for proton and He spectra is at 400–500 TeV [1].
- The knee feature can be the result of different 'knee' like features seen at increasing CR energies for increasing atomic number.
- In order to maintain the CR intensity at the observed level, the CR sources must provide $10^{41}$ erg/s [2].

# Introduction : PeVatrons



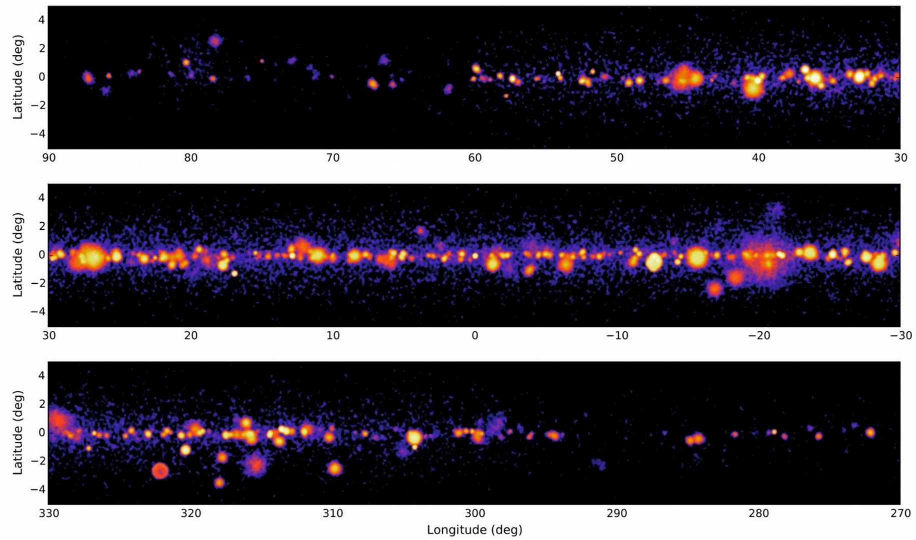




- PeVatrons → CR factories able to accelerate particles up to PeV ($10^{15}$ eV) energies.
  - 1 PeV protons → ~100 TeV gamma-rays assuming $E_{proton}$ / $E_{\gamma\text{-ray}}$ = 10 [3].
- The first detection of a Galactic PeVatron at the Galactic Center region [4].
  - The 95% C.L. lower limit on the proton cutoff energy is 0.4 PeV.
- PeVatron candidates:
  - Supernova remnants (SNRs), runaway CRs
  - Super massive black holes
  - Stellar clusters / star-forming regions [5]
- PeVatron sources are expected to have
  - Hard power-law spectra (~$E^{-2}$)
  - Spectra extending up to 50 TeV and beyond

# Cherenkov Telescope Array (CTA)

- The CTA is the next generation gamma-ray observatory consisting of ~100 telescopes.
  - Two sites → Northern and Southern hemisphere
  - The Southern array → measurements up to 300 TeV
- One of the key science projects of the CTA Consortium is the search for cosmic PeVatrons [6].
  - Dedicated 50 h of deep observations of the best five PeVatron candidates.
- Galactic Plane Survey (GPS)
  - Survey sensitivity → 2 – 4 mCrab
  - Energy threshold → 0.125 TeV
  - Average exposure → 10 – 15 h [7]
- The determination of efficient criteria to identify PeVatron candidates during the survey is essential.



**Simulated CTA GPS [7]**

# CTA Simulations & Data analysis

- A study based on simulations to determine efficient PeVatron selection criteria.

  - Simulate (50 h) CTA observations of the PeVatron candidate HESS J1641–463 [8].

  - Simulate (10 h) point sources → Power-law (PL) and Exponential Cutoff Power-Law (ECPL).

  - Cosmic-ray Background

  PeVatron Phase Space:
  - $\Phi_0$ (1 TeV) = (4, 8, 16, 24, 32, 40, 48) mCrab
  - $\Gamma$ = – 1.7, – 2.0, – 2.3
  - $E_{c,\gamma}$ = 50 TeV, 100 TeV, 200 TeV

$$\Phi(E) = \Phi_0 . \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$\Phi(E) = \Phi_0 . \left(\frac{E}{E_0}\right)^{-\gamma} . \exp - \left(\frac{E}{E_c}\right)$$

  - Energy Range → [0.1, 160.0] TeV

- Analysis of the simulates sources:

  - The reflected background estimation method [9].

  - Fit data to PL and ECPL models. Test statistics to determine the best spectral model.

  - Derive the 95% confidence level (C.L.) lower limits on the cutoff energy.

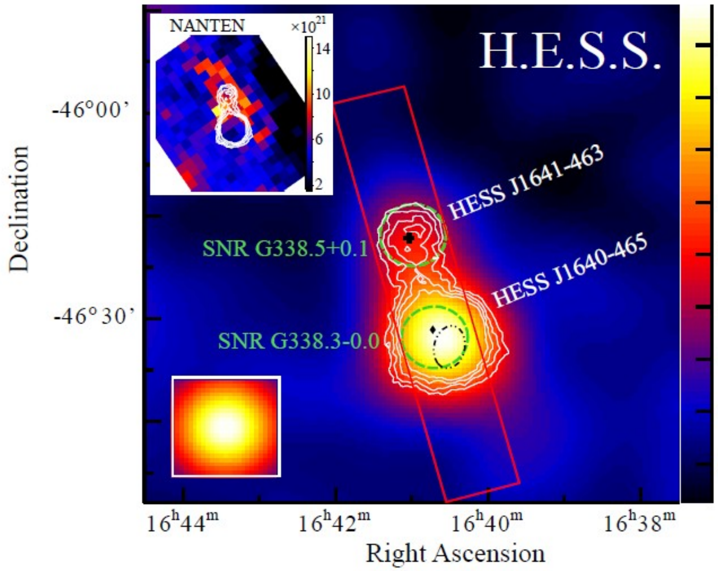
- 1st approach → 1000 Simulations, fit to ECPL model, take 5 percentile as 95% C.L. lower limits.

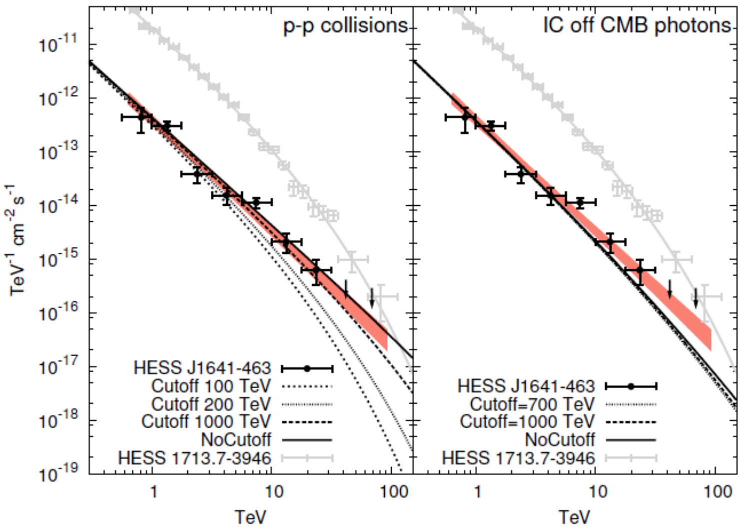
  2nd approach → Use profile likelihood method [10].

# PeVatron candidate source HESS J1641–463

- HESS J1641–463 [8] is a promising PeVatron candidate source.
  - Point-like H.E.S.S. source
  - Exhibits a hard spectrum
    Γ = – 2.07, Φ (> 1TeV) = ~18 mCrab
  - No clear sign of a cutoff
  - Extending up to few tens of TeV

- There are dense gas regions coincident with the source position.
  - Interstellar medium properties (NANTEN data)
  - $n_{gas} = 100\ cm^{-3}$
  - distance = 11 kpc



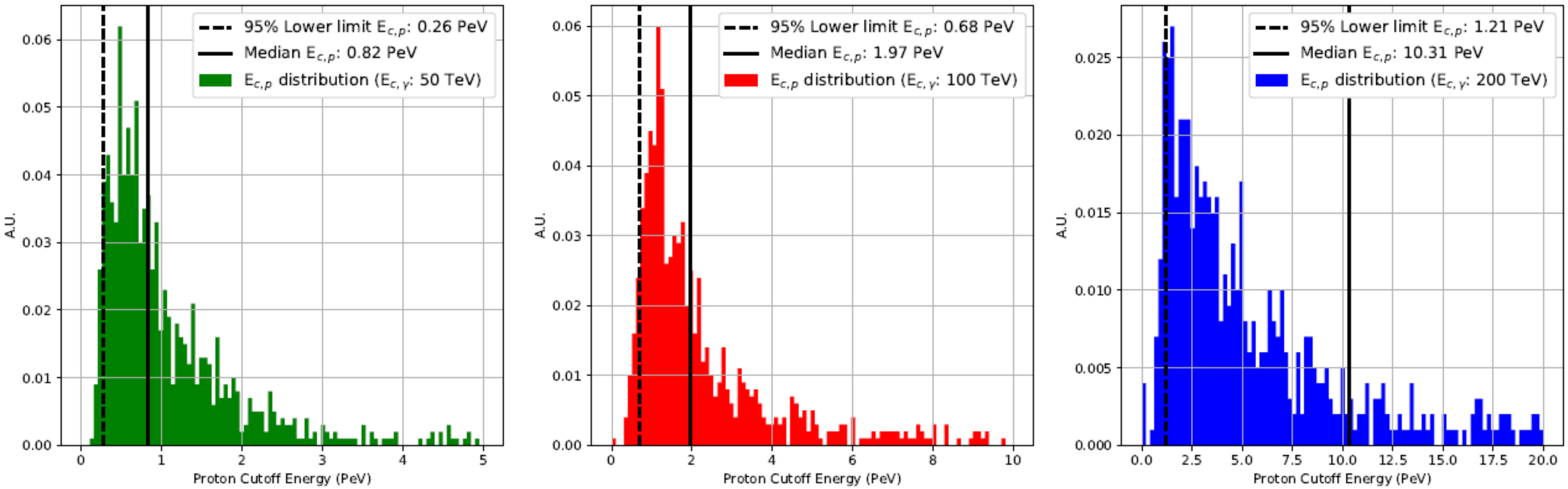



# PeVatron candidate source HESS J1641–463

- We simulated 50 h CTA observations of HESS J1641–463.

  - assume intrinsic cutoffs of 50 TeV, 100 TeV and 200 TeV (keep Γ and Φ fixed)

- Modeling of hadronic emission → Proton spectrum cutoff energy distribution




Median : 0.82 PeV
Lower limit : 0.26 PeV

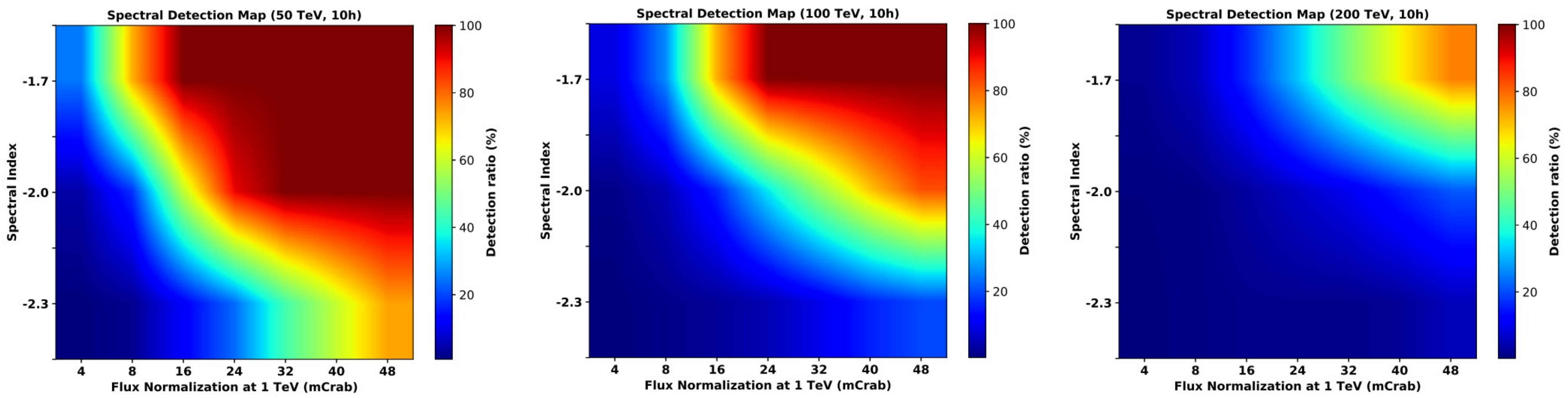
Median : 1.97 PeV
Lower limit : 0.68 PeV

Median : 10.31 PeV
Lower limit : 1.21 PeV

- HESS J1641– 463 (or similar hard spectrum sources) can contribute to the knee in the observed proton and helium spectra if they have cutoff in their spectra above 50 TeV.

# Spectral cutoff detection maps

- Spectral cutoff detection maps for intrinsic cutoff energies of 50 TeV (left), 100 TeV (middle) and 200 TeV (left)



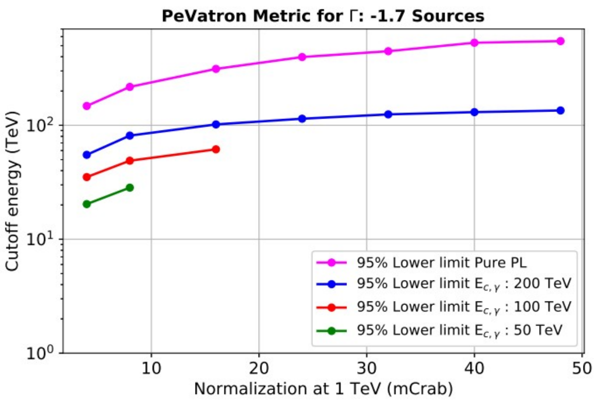

- The spectral cutoff detection probability increases with source brightness and/or as source spectrum gets harder due to the increased statistics at high energies.

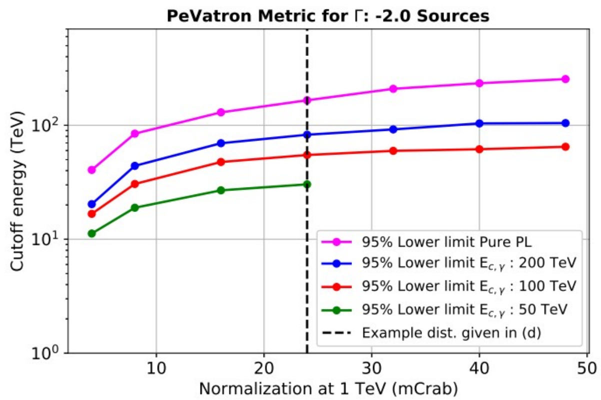
- The spectral cutoff of 50 TeV and 100 TeV for point sources can be detected with the foreseen CTA GPS performances.

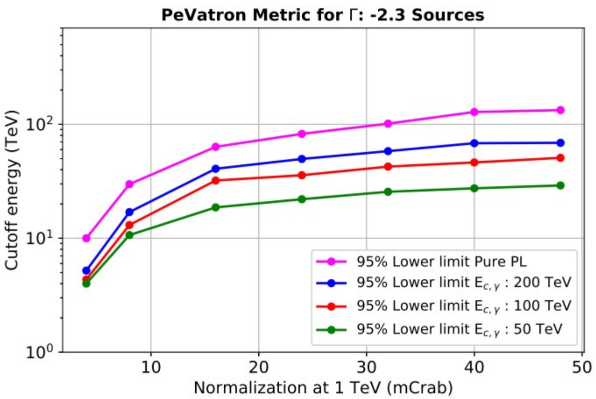
- The detection of intrinsic 200 TeV cutoff during the survey may be possible for very hard and bright sources.

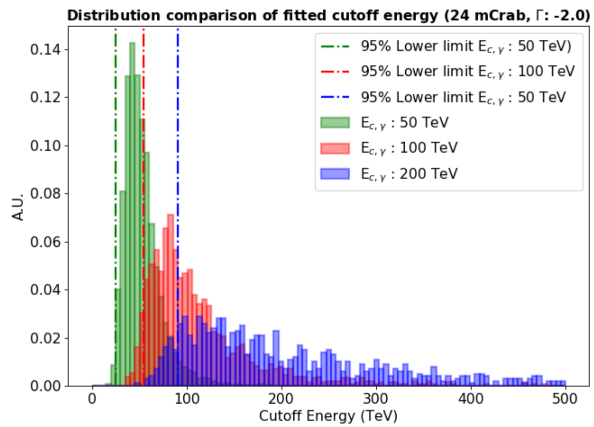
# PeVatron Metric

- PeVatron metric is a figure of merit for PeVatron candidate sources. The metric can provide relations between spectral parameters and derived 95% C.L. lower limits on the cutoff energy.




- The 95% C.L. lower limits on the cutoff energy increase
  - as the source gets brighter
  - as the source spectrum gets harder
  - as the intrinsic cutoff energy gets higher.

- This fact can be used for predicting the intrinsic cutoff energy of a source of interest.

# Large scale simulations

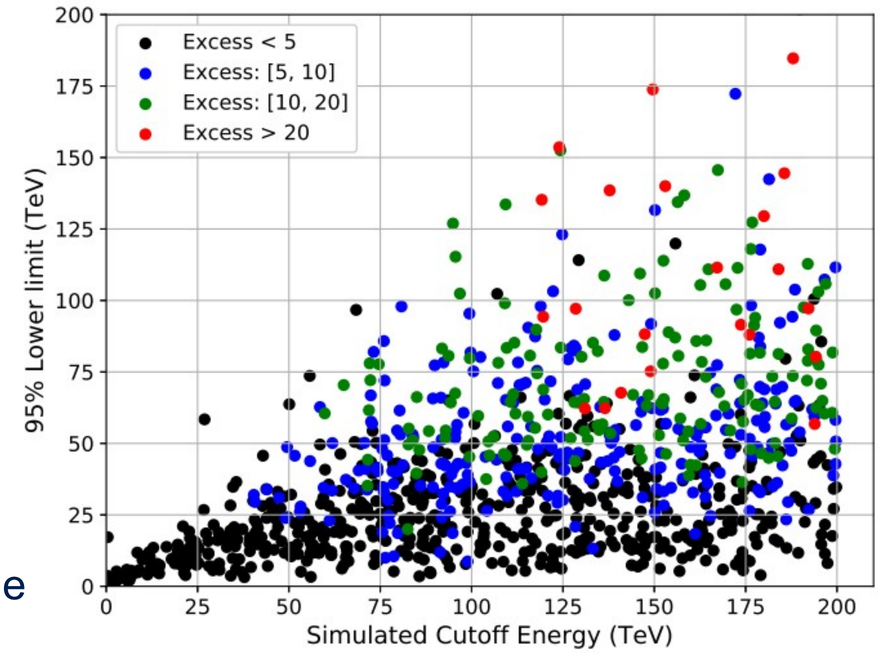
- Large scale simulations with 1000 sources to test the selection power of the metric.
- The sources are simulated by following ECPL models (random parameters,10 h).

  - Calculate the total number of excess events (above 50 TeV)
  - Calculate the 95% C.L. lower limits for each source.

- The 95% C.L. lower limits are derived by

  - Scramble $N_{On}$ and $N_{Off}$ events (Poisson)
  - Create 1000 fake spectra for each source.

- Strong correlation between the 95% C.L. lower limits and high energy excess.
- Both parameters are promising for the final selection criteria.
- No prediction on the intrinsic cutoff can be made
  - in the case of low excess
  - in the case of low 95% C.L. lower limits.




- Such sources are not promising candidates → can be ruled out.

# Large scale simulations

- PeVatron metric for the prediction of intrinsic cutoff.
  - The expected 95% C.L. lower limit → by interpolating between the metric lines.

Fitted index (Γ)

Fitted flux ($\Phi_0$ (1 TeV))

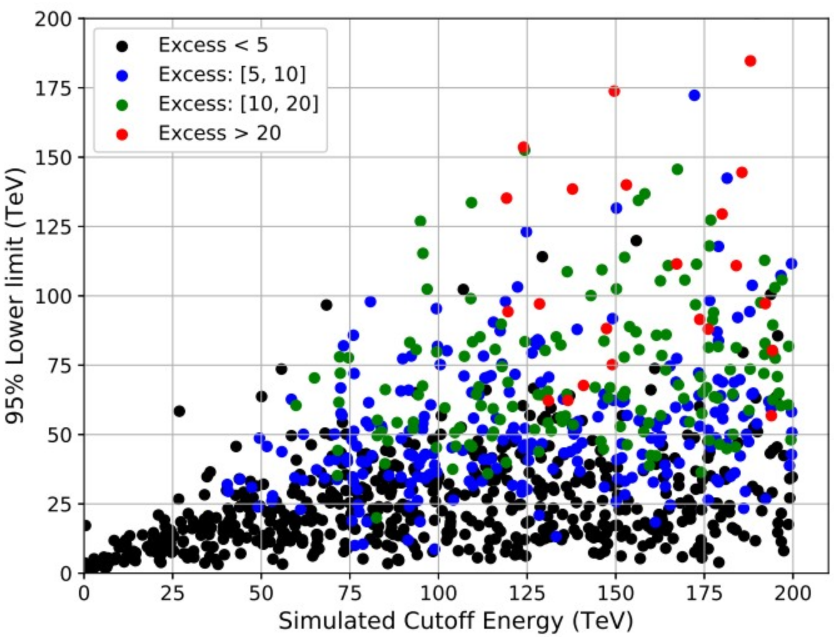
**Metric**

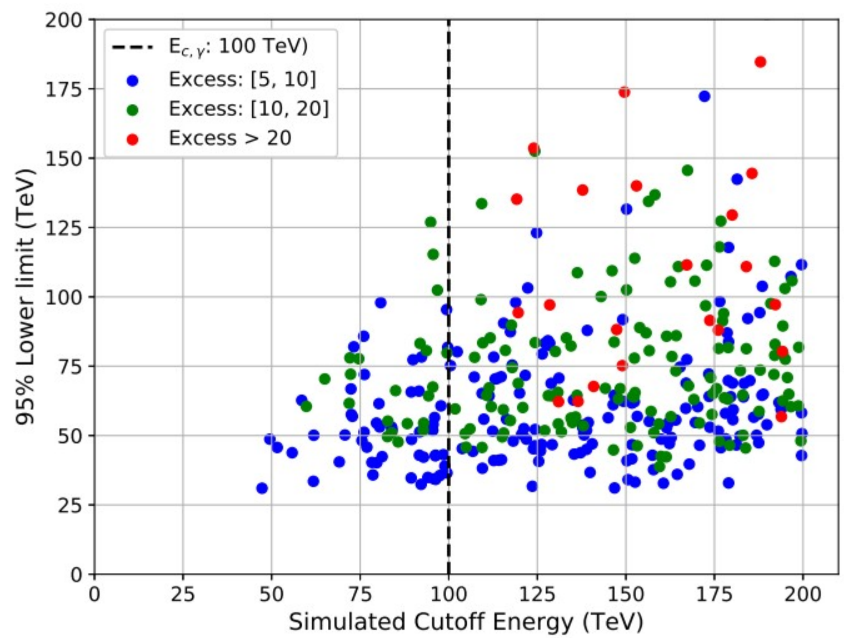
95% C.L. (Ec = 50 TeV)

95% C.L. (Ec = 100 TeV)

95% C.L. (Ec = 200 TeV)

Metric selection → 95% C.L. from data > expected 95% C.L. from the metric (case 100 TeV).
Excess selection → Rule out the sources with low excess at high energies.



# Conclusions & Future studies

- Our simulation studies suggest that intrinsic spectral cutoffs of 50 TeV and 100 TeV can be detected during the CTA GPS for a conservative observation time of 10 h.
  - 68% detection prob 50 TeV cutoff → $\Gamma$ = ~2.0, flux ~16mCrab
  - 68% detection prob 100 TeV cutoff→ $\Gamma$ = ~2.0, flux ~30mCrab

- We show that the 95% C.L. lower limit on the cutoff energy increases
  - with source brightness
  - as source spectrum gets harder
  - with increasing intrinsic cutoff.

- Preliminary investigation show that indications on the intrinsic cutoff energy can be estimated using the 95% C.L. lower limit and the excess events at high energies.

- Further studies are needed for the identification of the criterion to select the 5 most promising PeVatron candidates.

- On-going studies:
  - Investigation of extended sources
  - Hadronic modeling of PeVatron candidate sources
  - Investigation of systematic effects
  - Simulation of Galactic young SNR population studies [10]

# References

[1] B. Bartoli et al. [ARGO-YBJ and LHAASO Collaborations], Phys. Rev. D 92 (2015) no.9, 092005, doi:10.1103/PhysRevD.92.092005

[2] Gaisser T.K. (1990). Cosmic rays and particle physics, (Cambridge University Press)

[3] Kelner, S. R., Aharonian, F. A. & Bugayov, V. V. 2006, Phys. Rev. D, 74, 034018

[4] H.E.S.S. Collaboration, Abramowski, A., Aharonian, F., et al. 2016, Nature, 531, 476

[5] Aharonian, F., Yang, R., de Oña Wilhelmi, E., 2019, Nat.Astron., 3, no.6, 561-567

[6] Science with the Cherenkov Telescope Array, arXiv:1709.07997 [astro-ph.IM]

[7] Zanin, R. for the CTA Consortium, PoS(ICRC2017)740

[8] H. E. S. S. Collaboration, Abramowski, A., Aharonian, F., et al. 2014, A&A, 562

[9] Berge, D., Funk, S., & Hinton, J. 2007, A&A, 466, 1219

[10] Trichard, C. for the CTA Consortium, PoS(ICRC2017)846

[11] Cristofari, P., Mon.Not.Roy.Astron.Soc. 471 (2017) no.1, 201-209