Estimation of CTA potentiality in the search of Galactic Cosmic Rays accelerators

Gaia Verna - verna@cppm.in2p3.fr

Supervisor: Franca Cassol
Co-supervisor: Heide Costantini

CPPM Seminar November 23th

Outline

1. **Astroparticle physics ↔ Gamma-Ray astronomy**
   - the mistery of the CR origin
   - Galactic PeVatrons

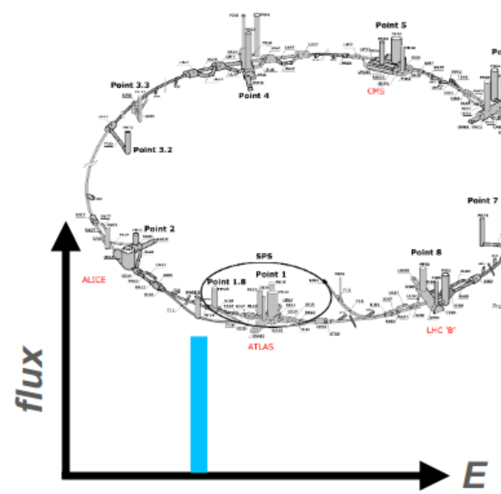
2. **Imaging Cherenkov telescopes:**
   - the Cherenkov Telescope Array (CTA):

3. **My PhD project**

4. **Conclusions and outlooks**

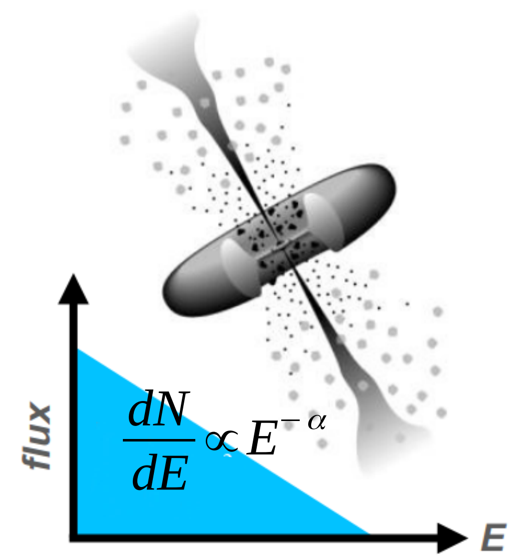
Particle accelerators

Particle Physics ↔ Astroparticle Physics



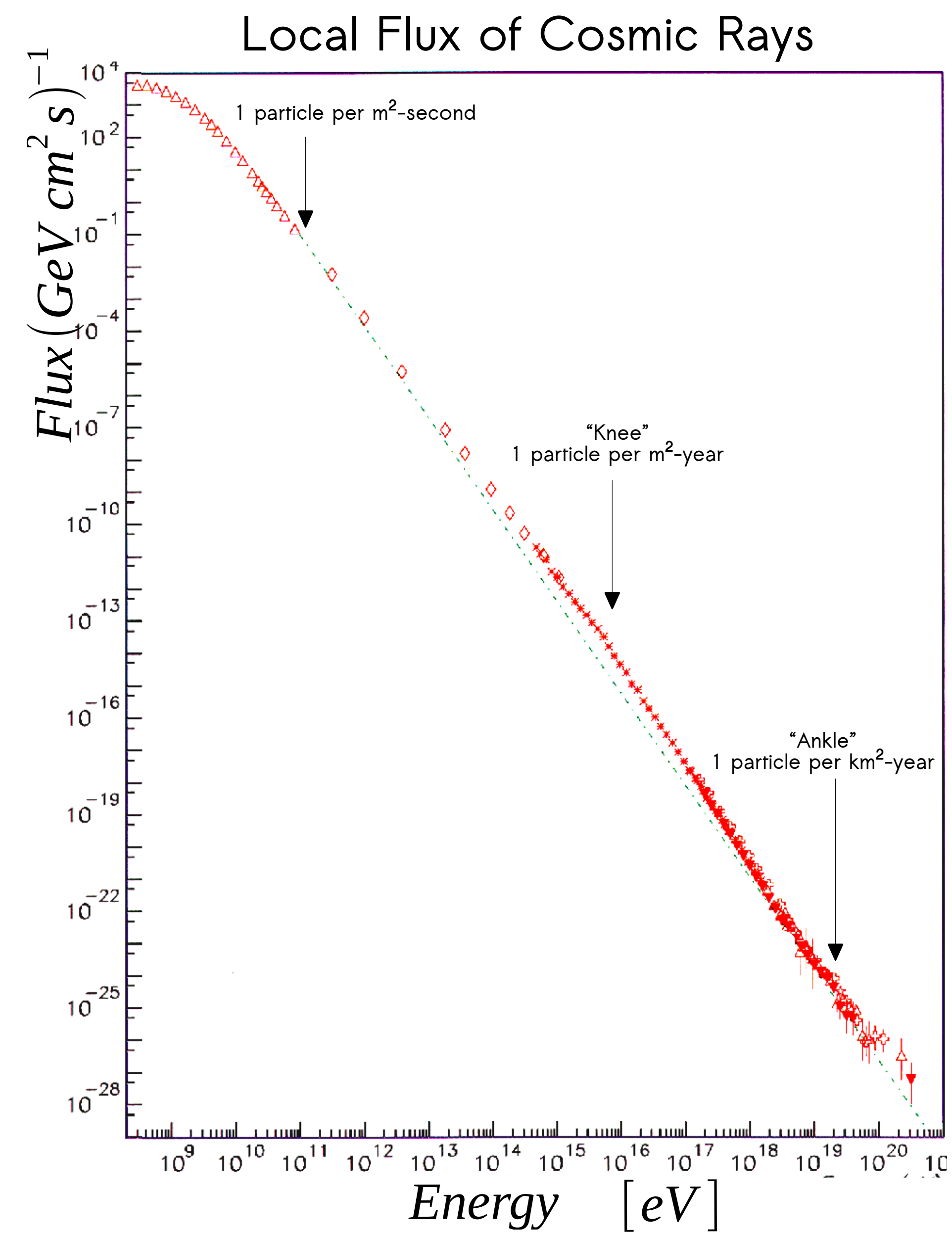
series of radio-frequency cavities

human accelerators



diffusive shock acceleration

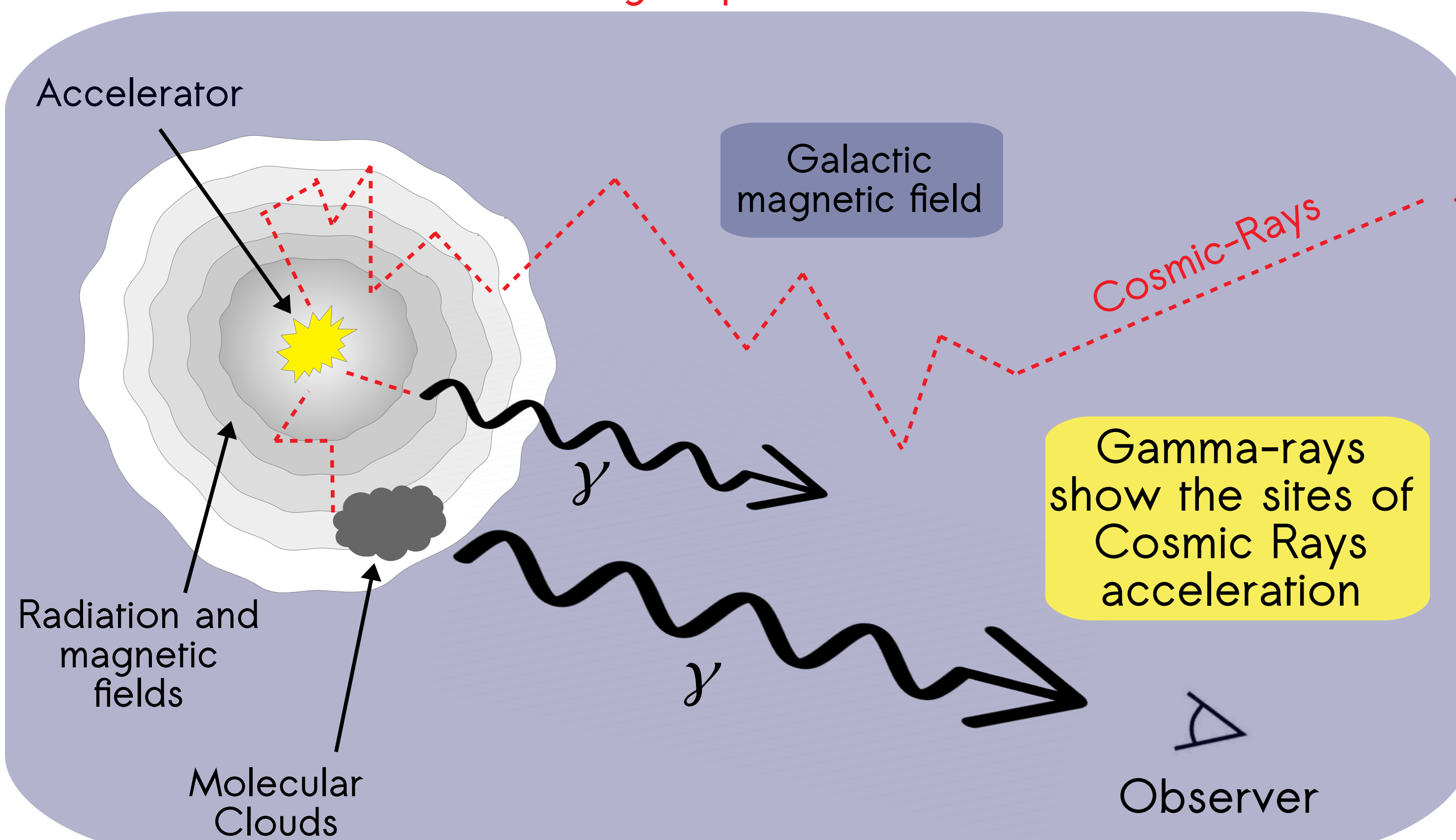
cosmic accelerators

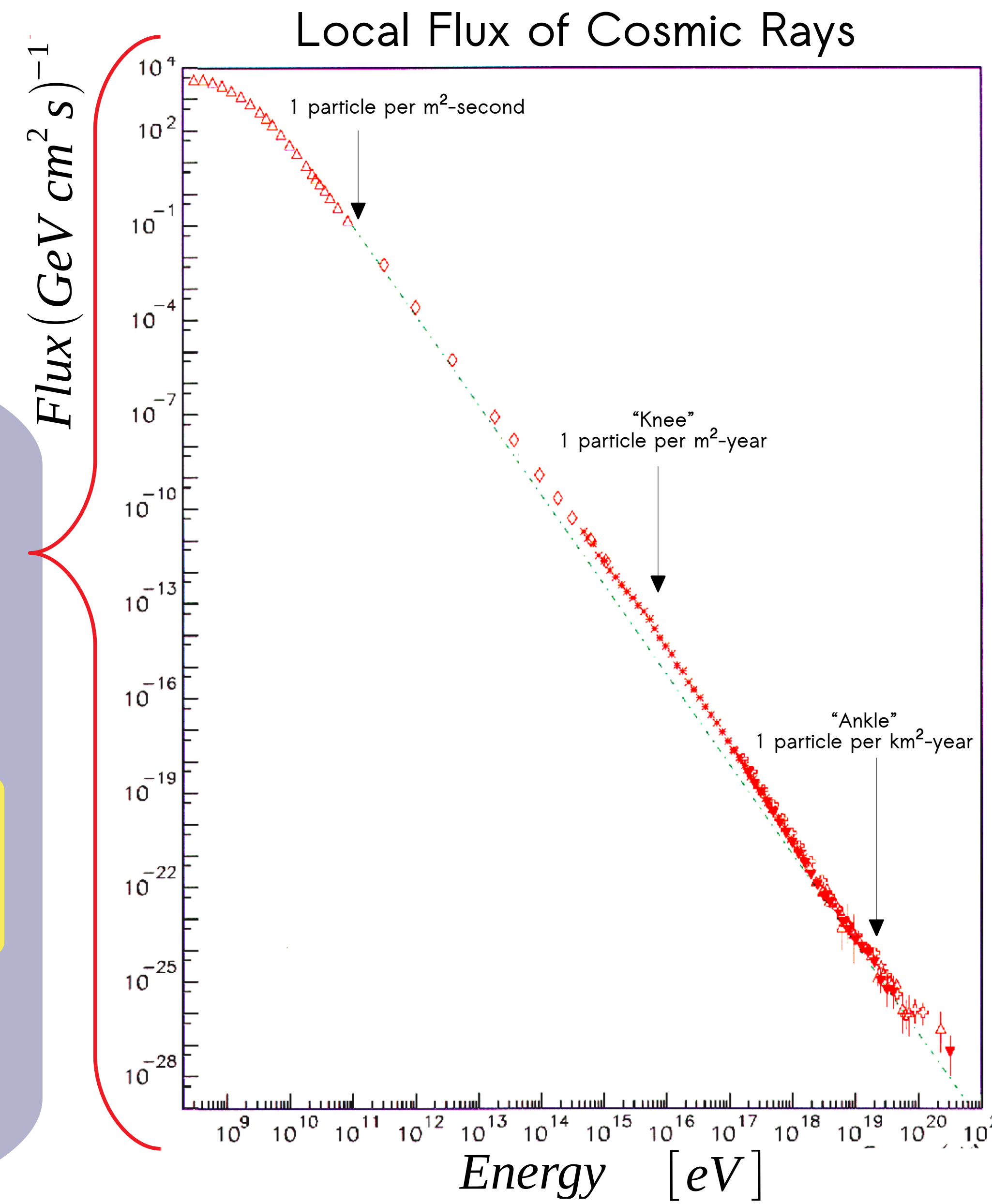


Gamma-Rays and Cosmic Rays

Astroparticle Physics ↔ Gamma-ray Astronomy

gamma radiation is related to the
non thermal emission
from populations of accelerated
charged particles

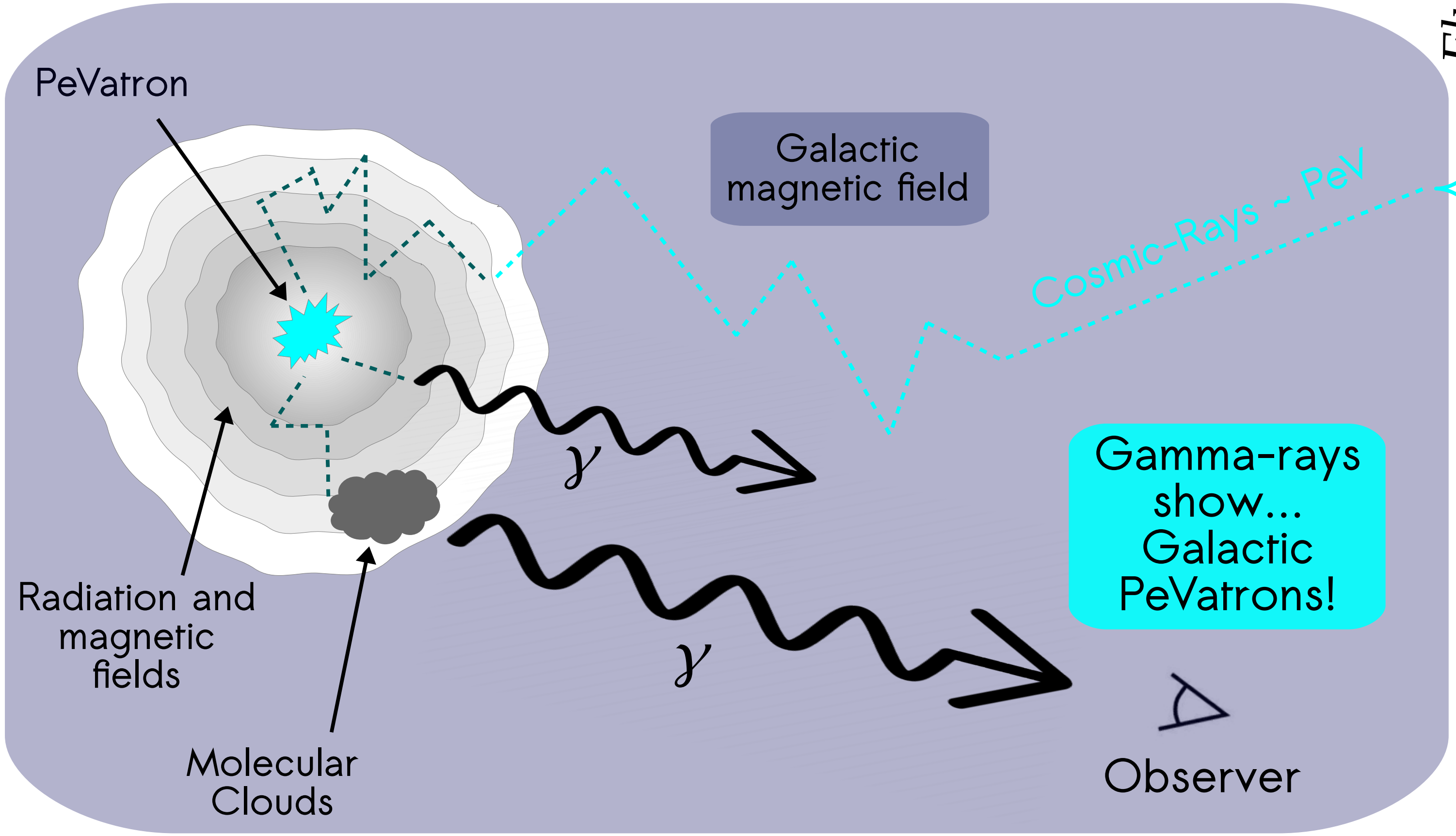


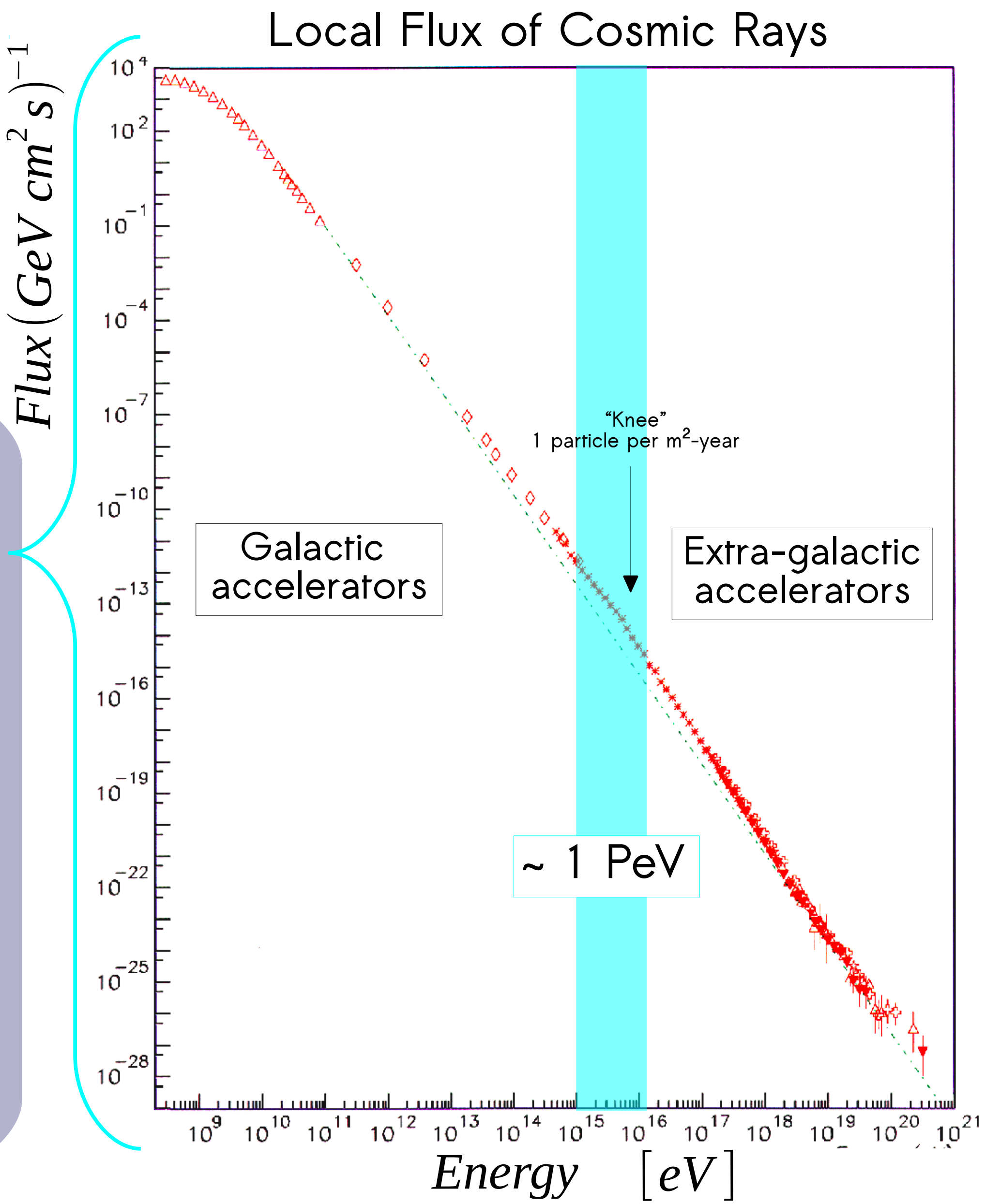


The hunt for Galactic PeVatrons

A **PeVatron** is a particle accelerator capable to accelerate charged particles at least at PeV energies

The study of PeVatrons' **multi TeV gamma-ray** spectrum would be crucial for understanding the different processes responsible for the formation of the "knee" in the CRs spectrum

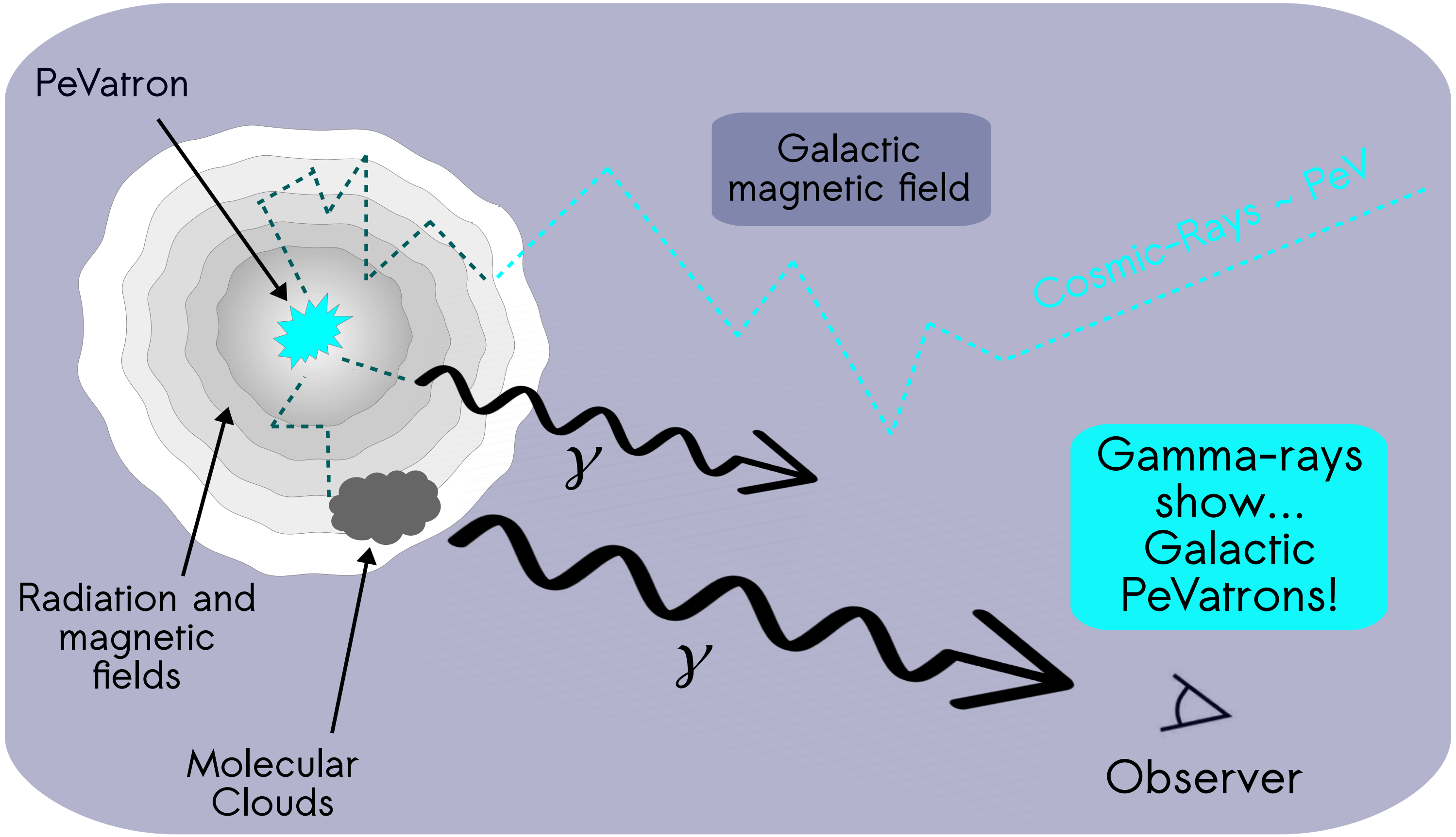




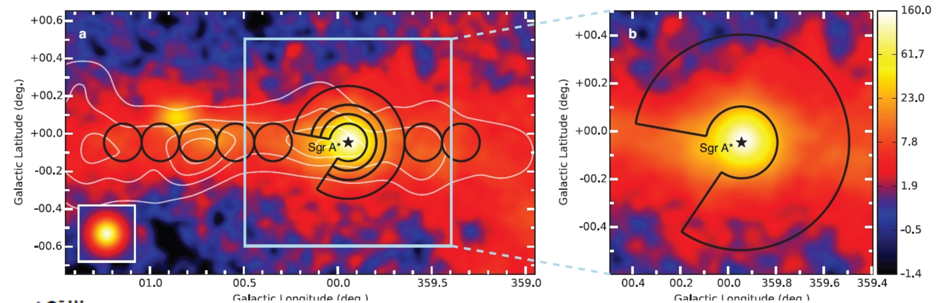
The hunt for Galactic PeVatrons

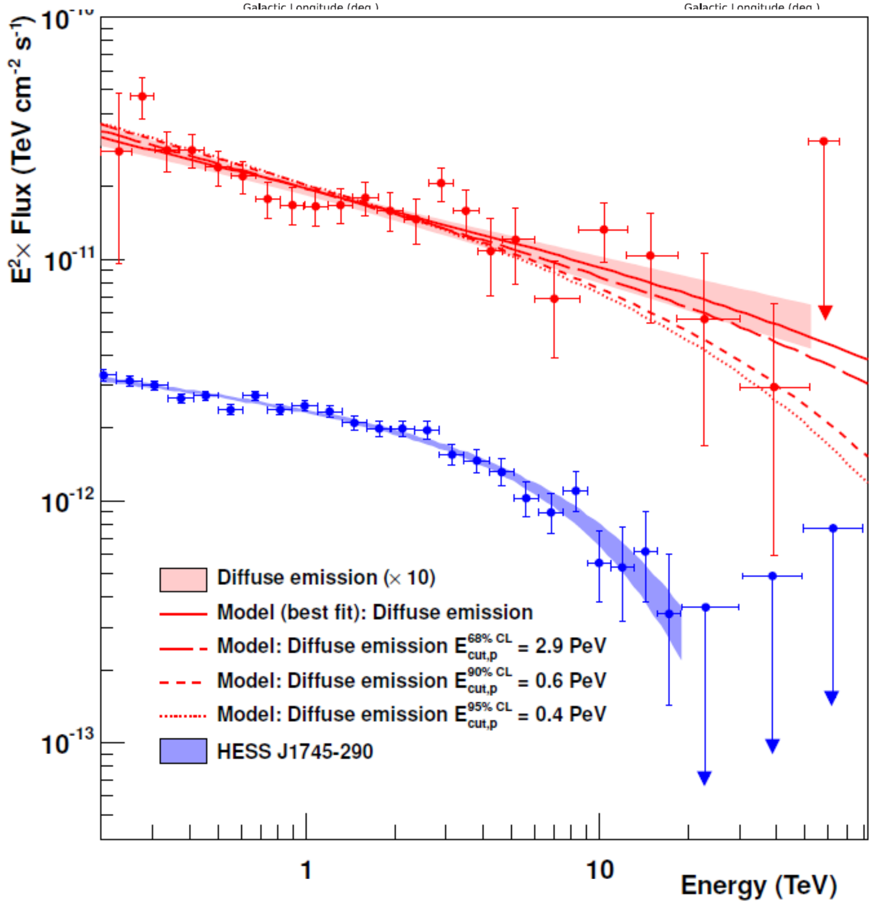
A **PeVatron** is a particle accelerator capable to accelerate charged particles at least at PeV energies

The study of PeVatrons' **multi TeV gamma-ray** spectrum would be crucial for understanding the different processes responsible for the formation of the "knee" in the CRs spectrum



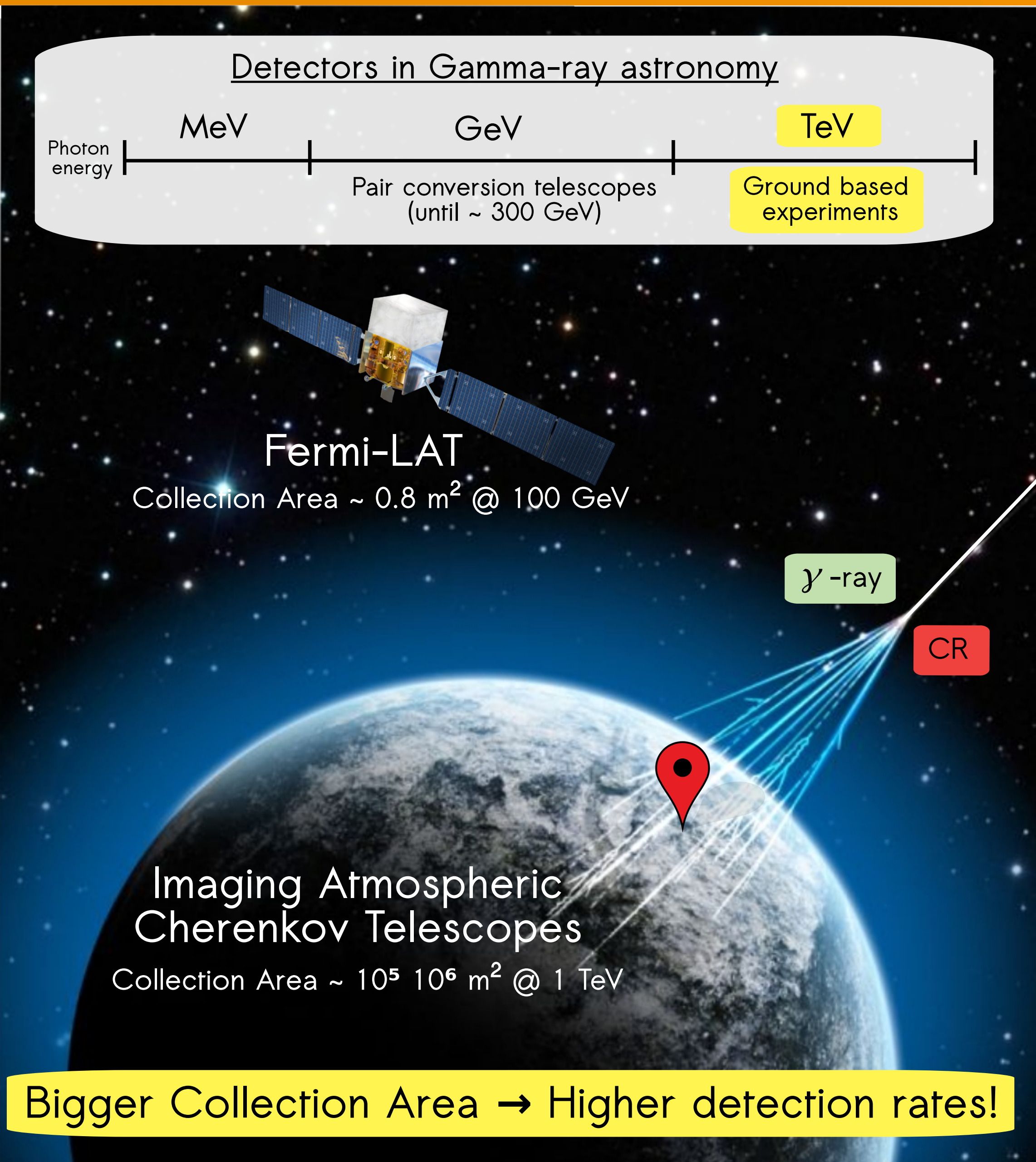
Gamma-ray Flux of the Galactic Center

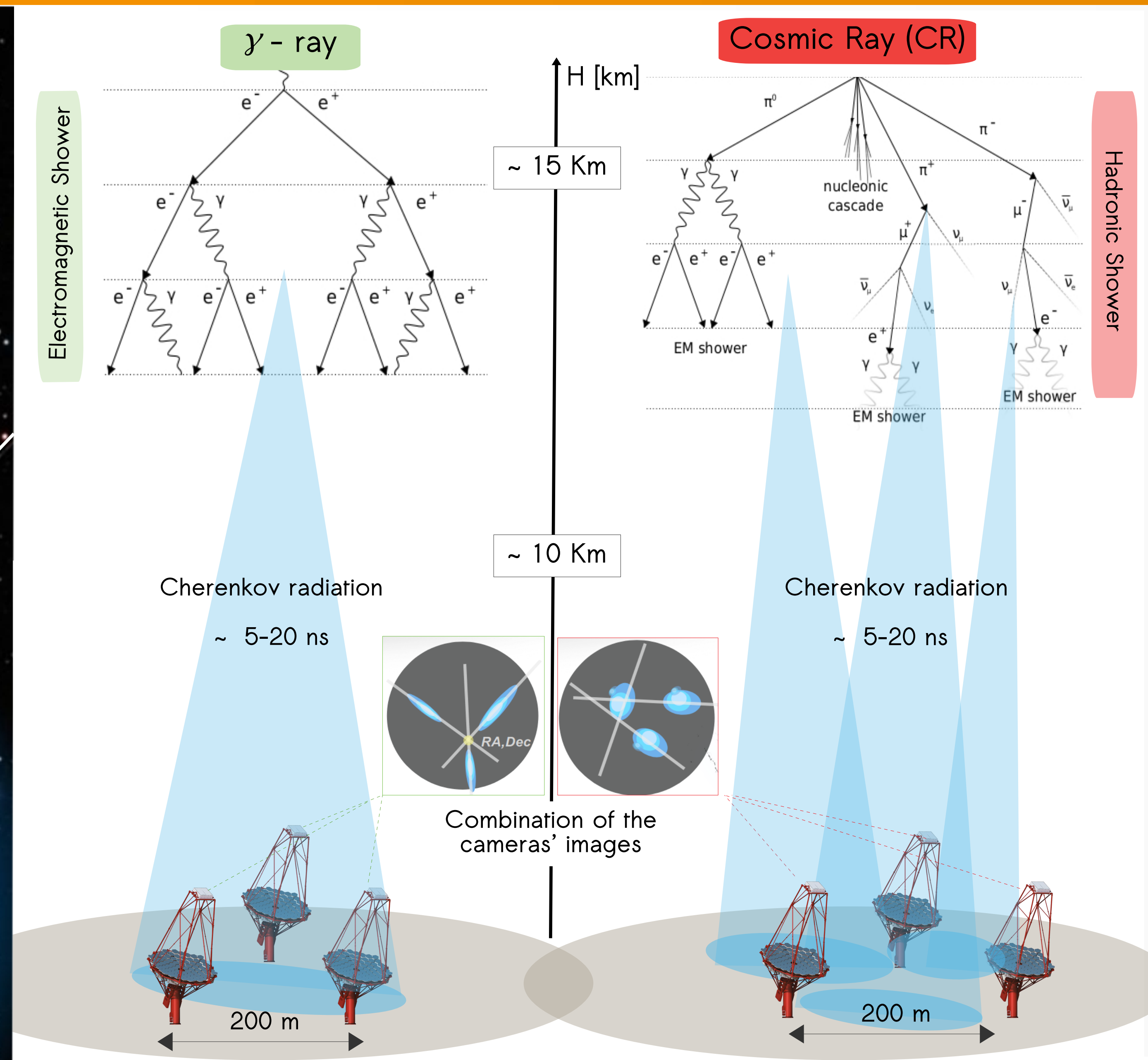




[1] HESS Collaboration. 2016, Nature, 531, 476, doi: 10.1038/nature17147

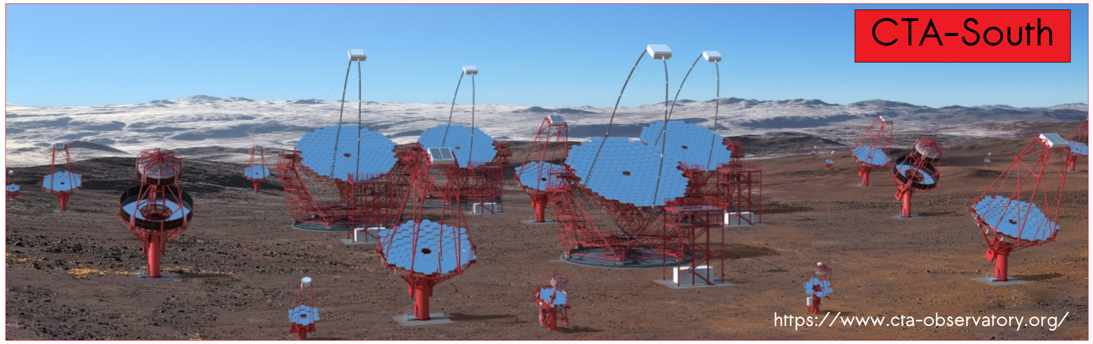
Gamma-ray astronomy and imaging Cherenkov telescopes

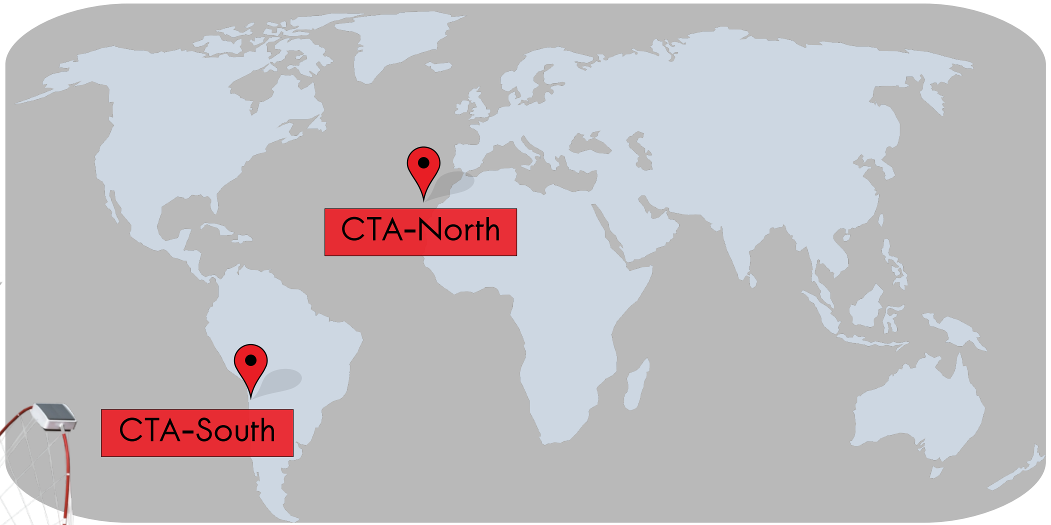


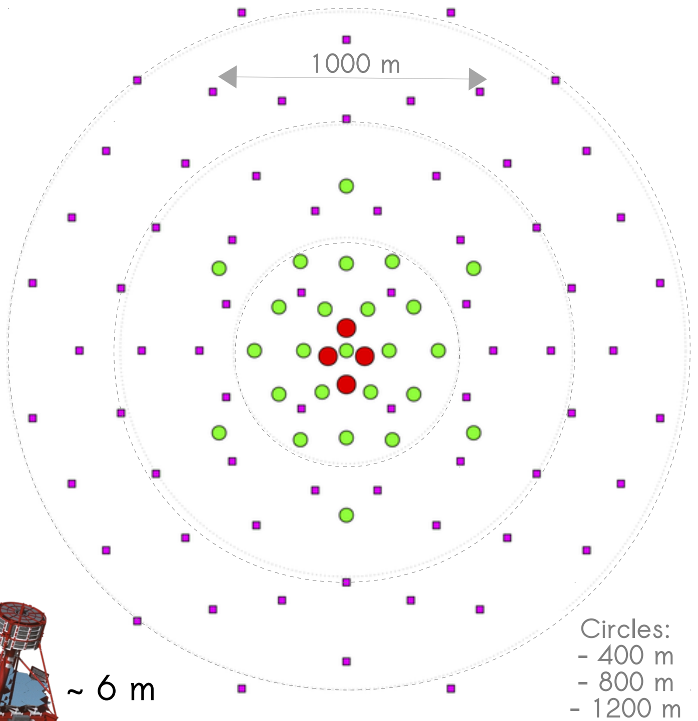


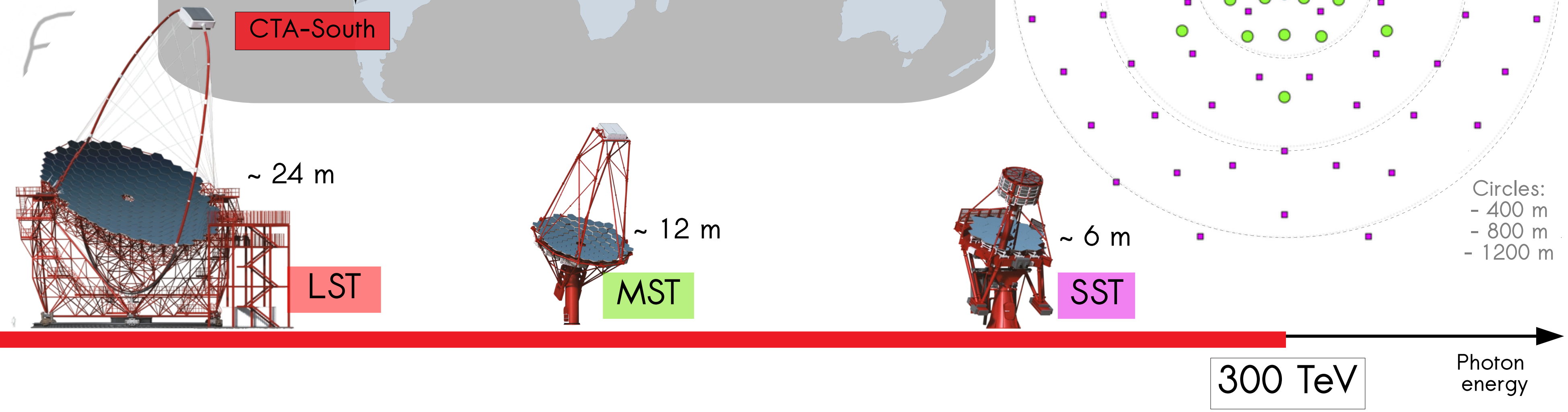
CTA: the Cherenkov Telescope Array

CTA will be the largest ground-based gamma-ray detection observatory in the world









My PhD project

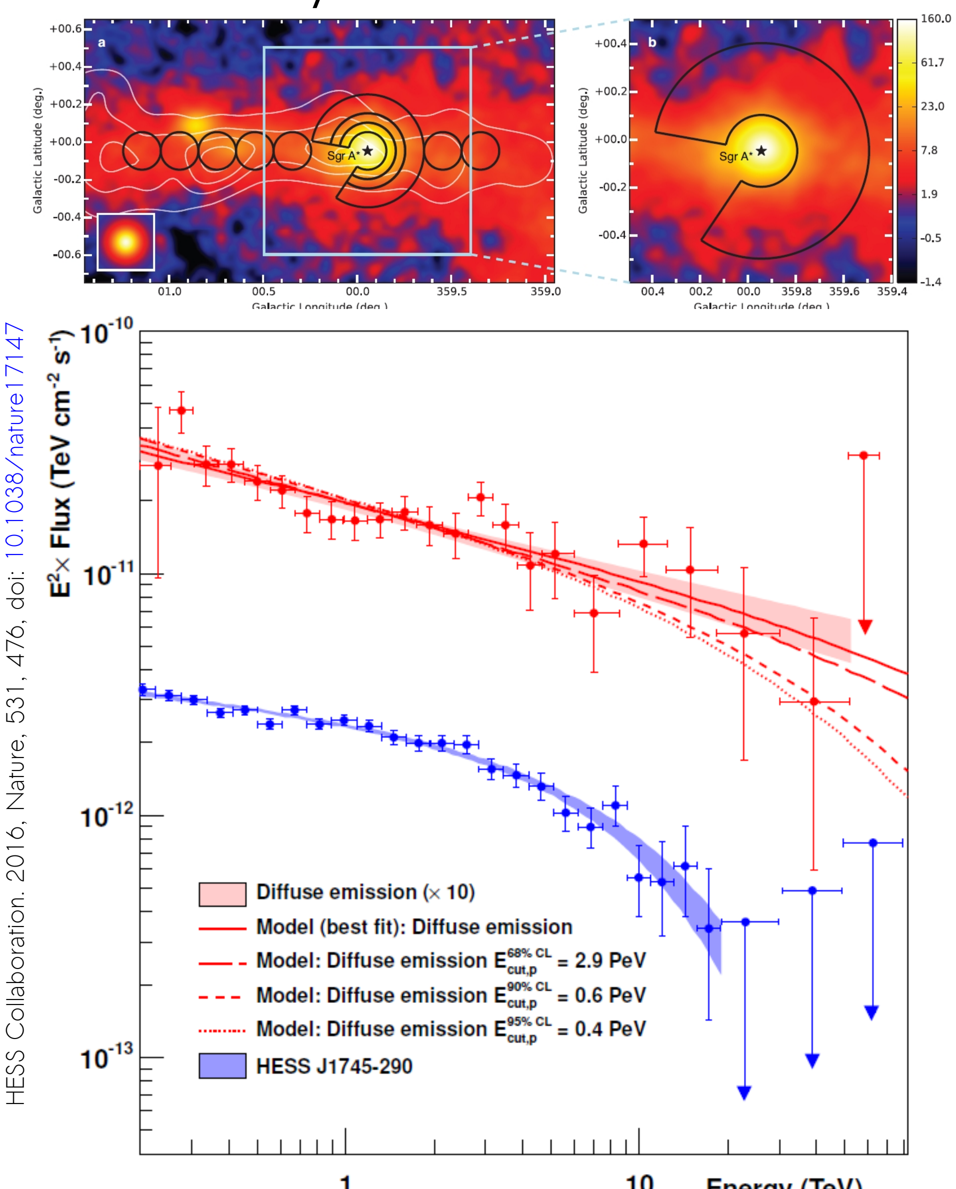
I. **Spectral analysis of simulated gamma ray sources:**
   - potentiality of CTA in the detection of a very high energies spectral cutoff

II. **Optimization of CTA-North's sensitivity at very high energies:**
   - dedicated reconstruction of the telescopes' truncated images
   - comparison of the performance for the baseline - threshold configurations

III. **Prospective for the future observation of existing PeVatron candidates with CTA-North:**
   - HAWC J1907
   - HAWC J2227

I. Potentiality of CTA in the detection of a very high energies spectral cutoff

Gamma-ray Flux of the Galactic Center



HESS Collaboration. 2016, Nature, 531, 476, doi: 10.1038/nature17147

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

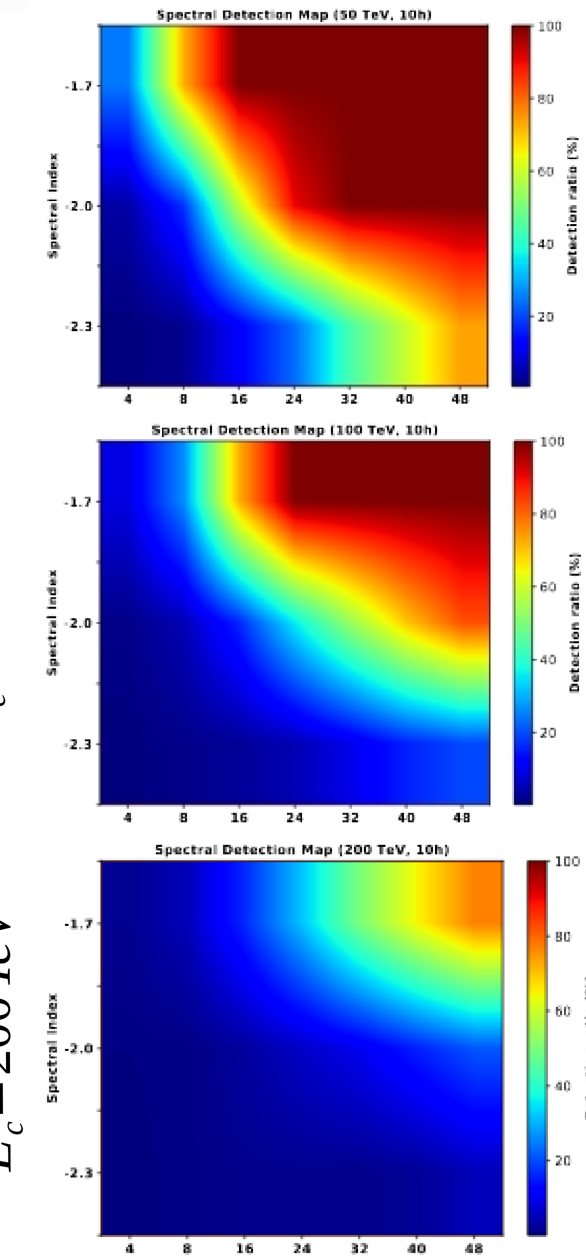
$$\Phi(E)=\Phi_0\left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\frac{E}{E_c}}$$

Flux Index Energy cutoff

$E_c = 50\ TeV$

$E_c = 100\ TeV$

$E_c = 200\ TeV$



E. O. Angüner et al. CTA's potential in the search for Galactic PeVatrons arXiv:1911.06134v1

II. Optimization of CTA-North's sensitivity at very high energies

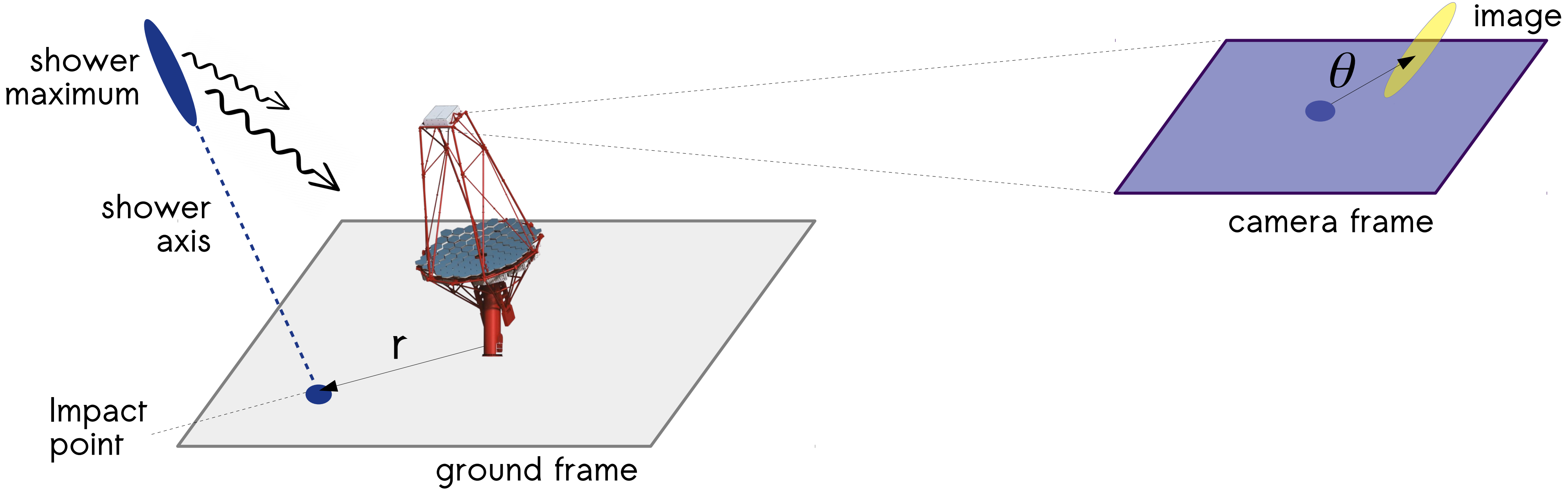
Motivation:
study the effect of **including truncated images** in the prototype reconstruction pipeline of CTA (*protopipe)* and to quantify the **possible benefit at high energies** (> 10 TeV)

II. Large distances, High Energies ↔ Truncated Images

Shower Events:
- with *impact point* distant from the telescope position
- "*energetic* enough" to trigger the telescope

→

...will produce **images** at the camera edge and only partially contained in it



→ θ (in the camera frame) depends on **r** (in the ground frame) and on the shower's **energy**

II. Reconstruction Pipeline

Shower Event

- True direction (RA, DEC)
- True energy
- primary particle (gamma, proton...)

Geometrical reconstruction

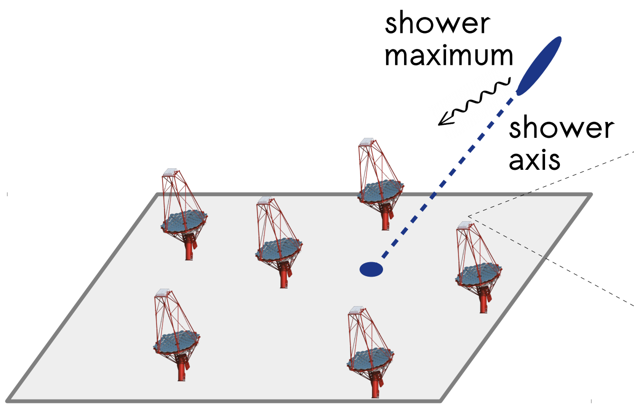
Random Forest: energy regressor

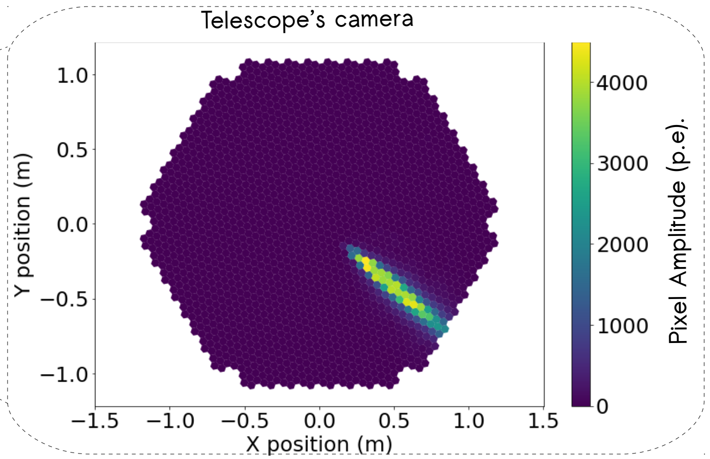
Random Forest: gamma/hadron classifier

...based on the extraction of the "Hillas parameters" from the Cherenkov images

Reconstructed Shower Event

- Reco direction (RA, DEC)
- Reco energy
- "gammaness" (i.e. probability of being a gamma shower)





Prototype of CTA's analysis pipeline: https://github.com/cta-observatory/protopipe

II. Standard Hillas and Fit image parameterization

STANDARD

Telescope's camera

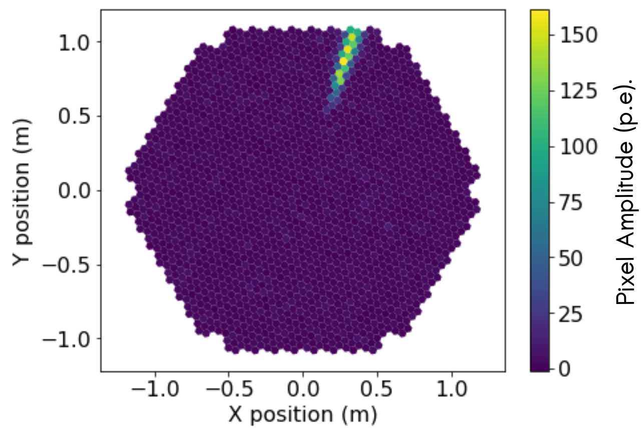
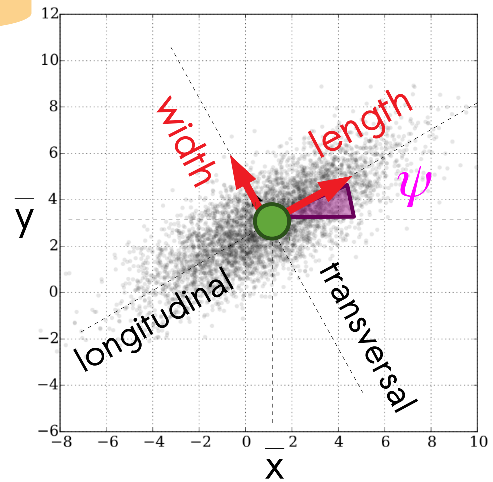


Image:
pixelized light distribution
In the camera



Hillas parameters:
Moments of a 2D distribution

0	order	size = tot #pe
I	order	centroid = $(\bar{x},\bar{y})$
II	order	length, width
III	order	long skewness
IV	order	long kurtosis
ψ		tilt angle from the x axis

2D GAUSSIAN FIT

2D Gaussian Model

$$G(A, \bar{x}, \bar{y}, length, width, \psi)$$

Observed signal in each pixel

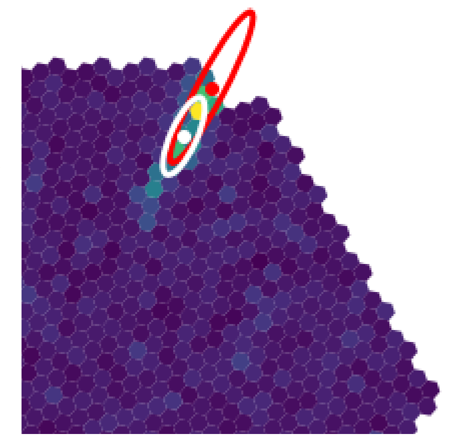
χ^2

Minimization (Minuit)

$$\hat{A}, \hat{\bar{x}}, \hat{\bar{y}}, \widehat{length}, \widehat{width}, \hat{\psi}$$

+ covariance matrix

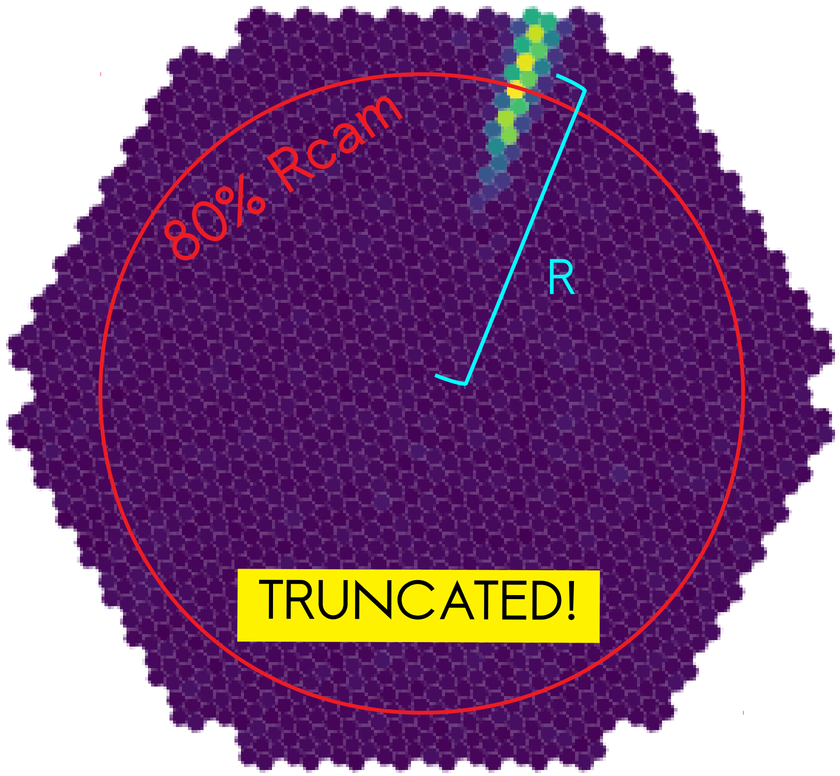
Standard Hillas
2D Fit



II. Prototype Pipeline

Shower Event → **Prototype Pipeline** — Reconstructed Shower Events

Images with **centroid** beyond the 80% of the camera radius, are NOT processed



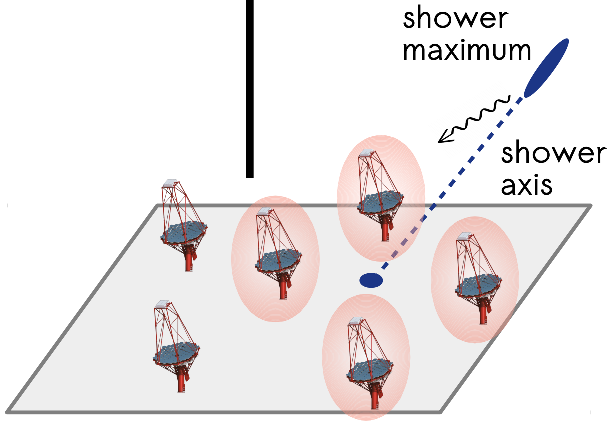
II. Prototype Pipeline

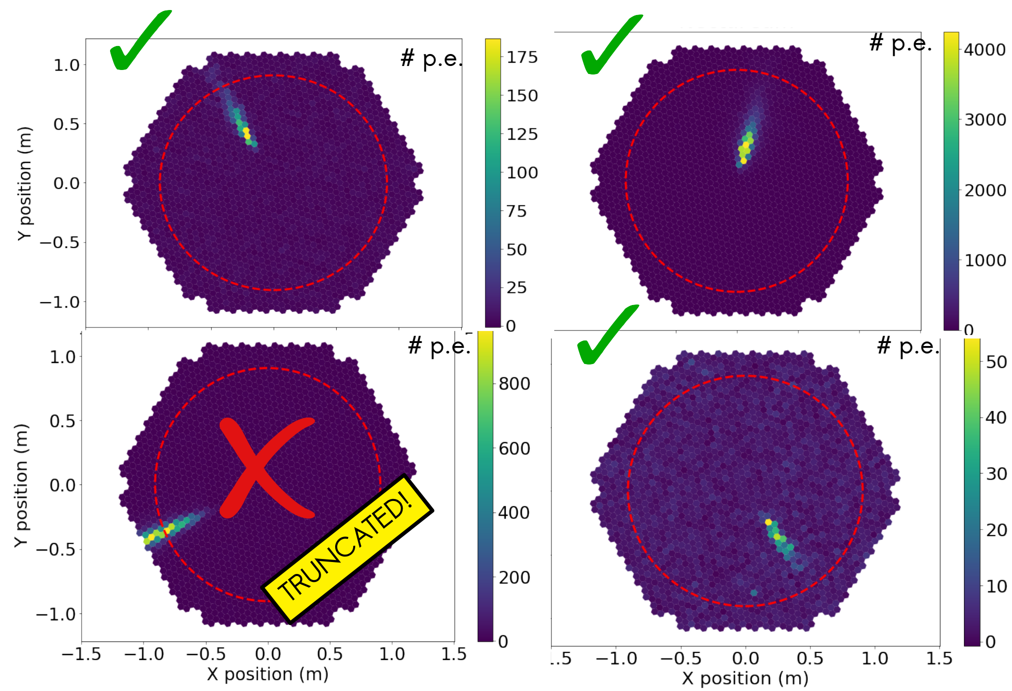
Shower Event →

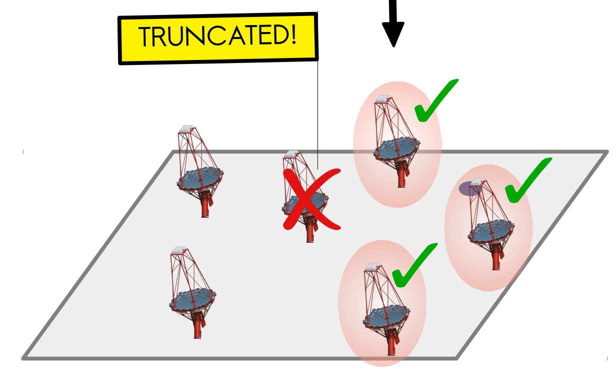
Prototype Pipeline

Images with **centroid** beyond the 80% of the camera radius, are NOT processed

→ Reconstructed Shower Events







Prototype of CTA's analysis pipeline: https://github.com/cta-observatory/protopipe

II. Two Alternative Pipelines

Shower Event →

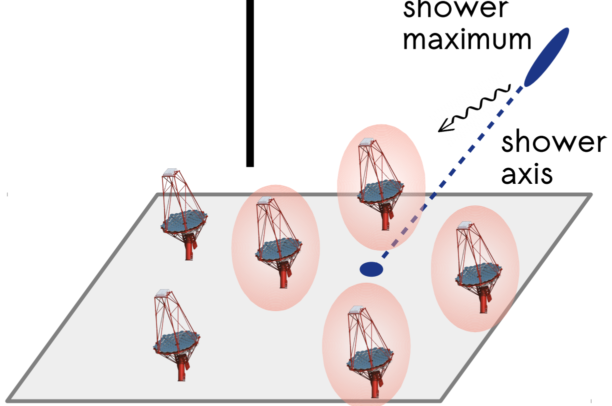
Alternative Pipelines

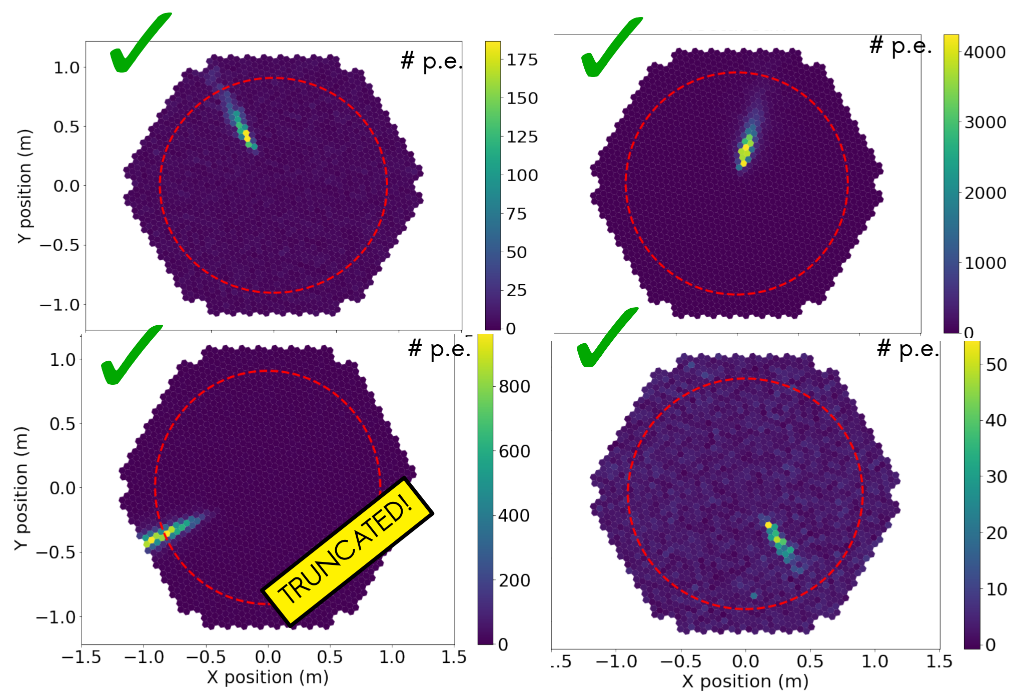
Images with **centroid** beyond the 80% of the camera radius, are **included** and parametrized with:

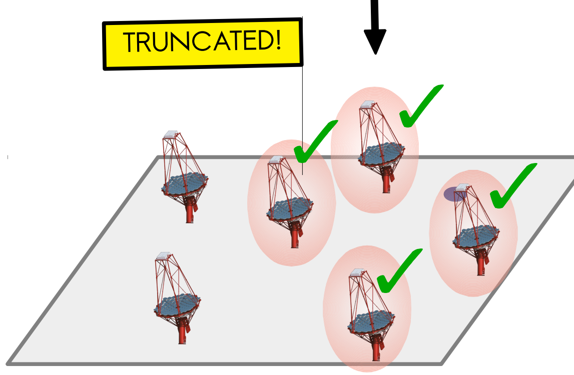
I. standard Hillas

II. 2D Fit

— Reconstructed Shower Events





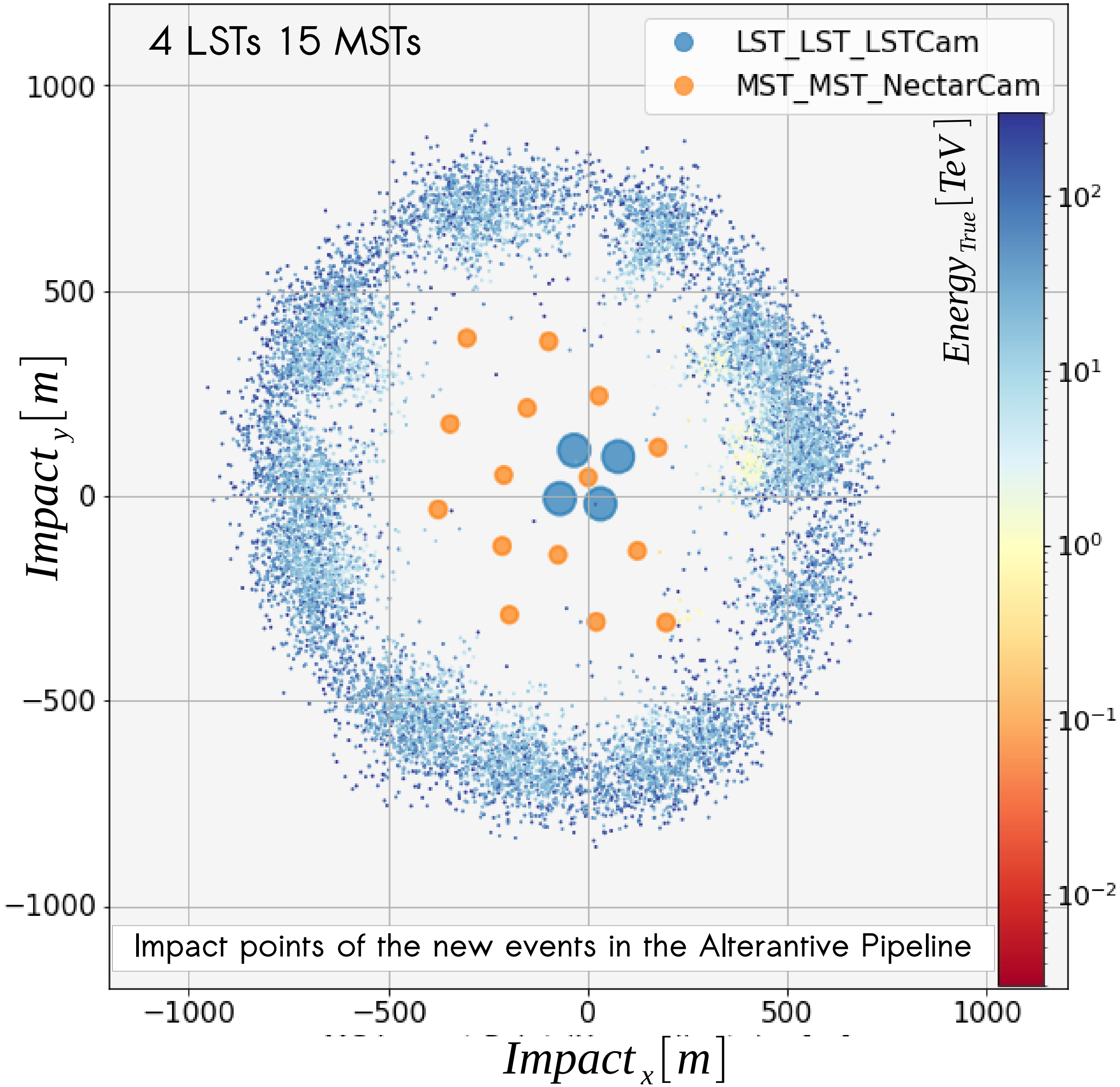


Different quality cut on truncated images were tested: on # pixels, size, ...

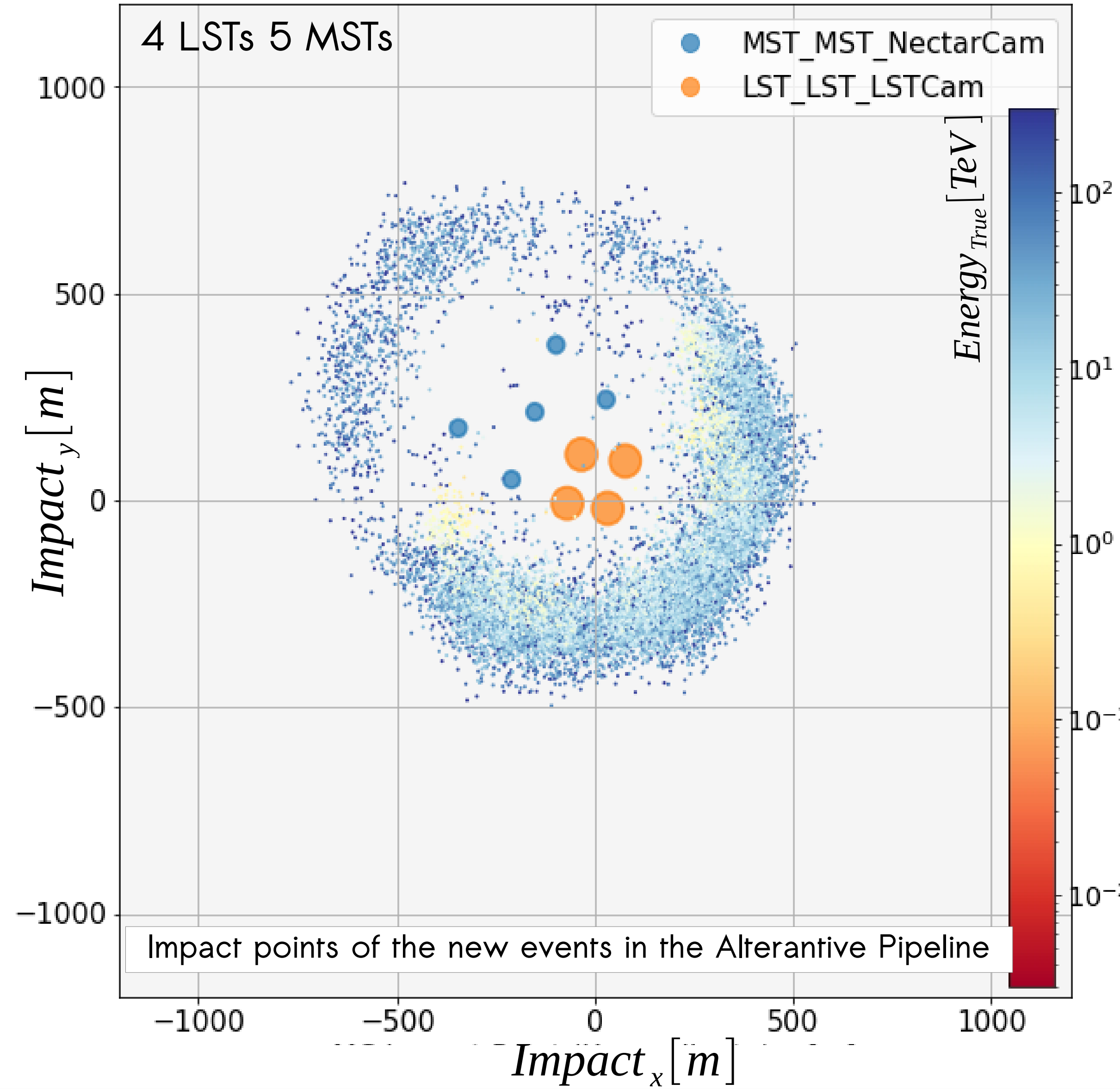
II. Inclusion of truncated images: new reconstructed events

Truncated n_pix > 10 N_tels > 3

Baseline Array



Threshold Array

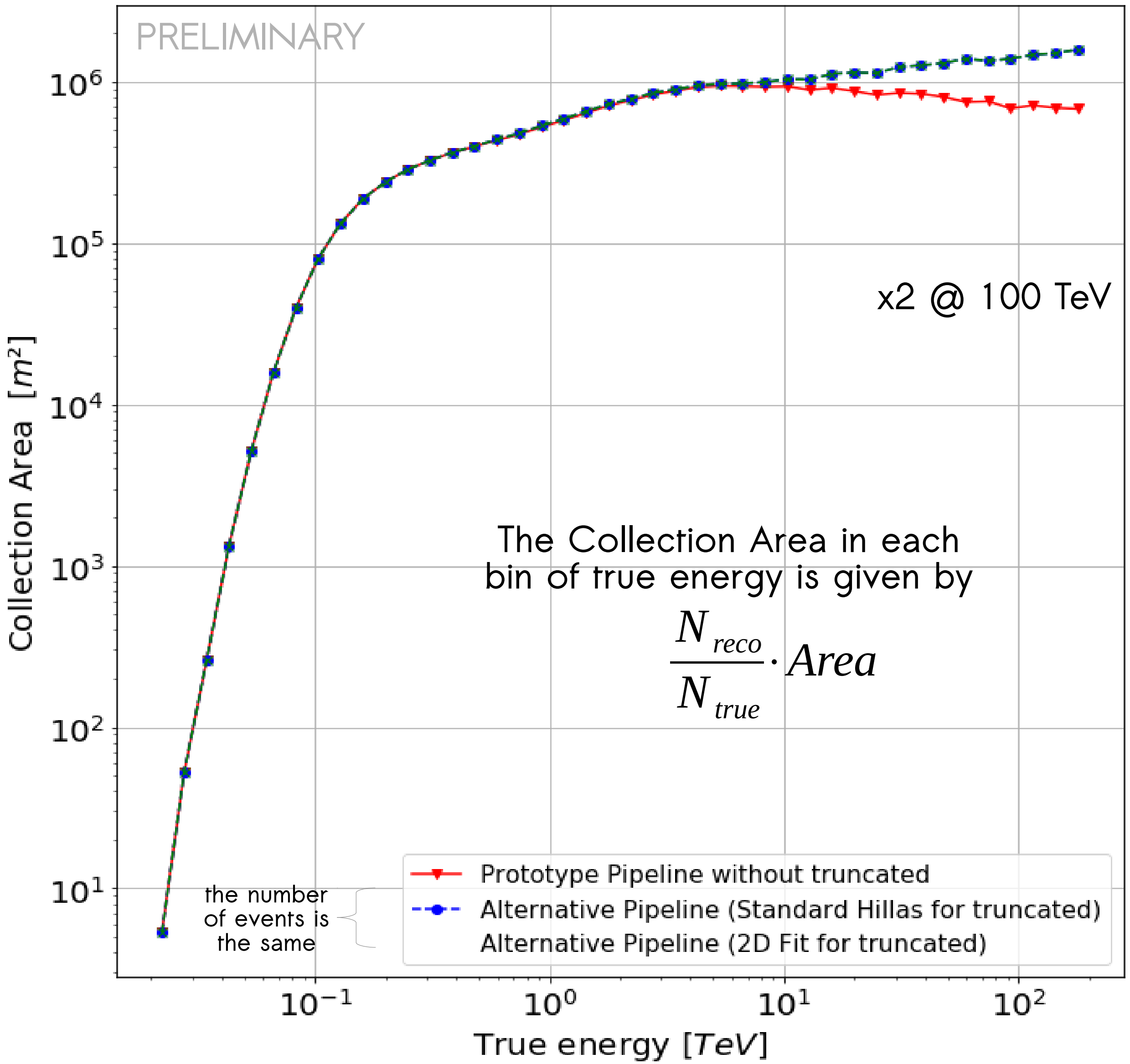


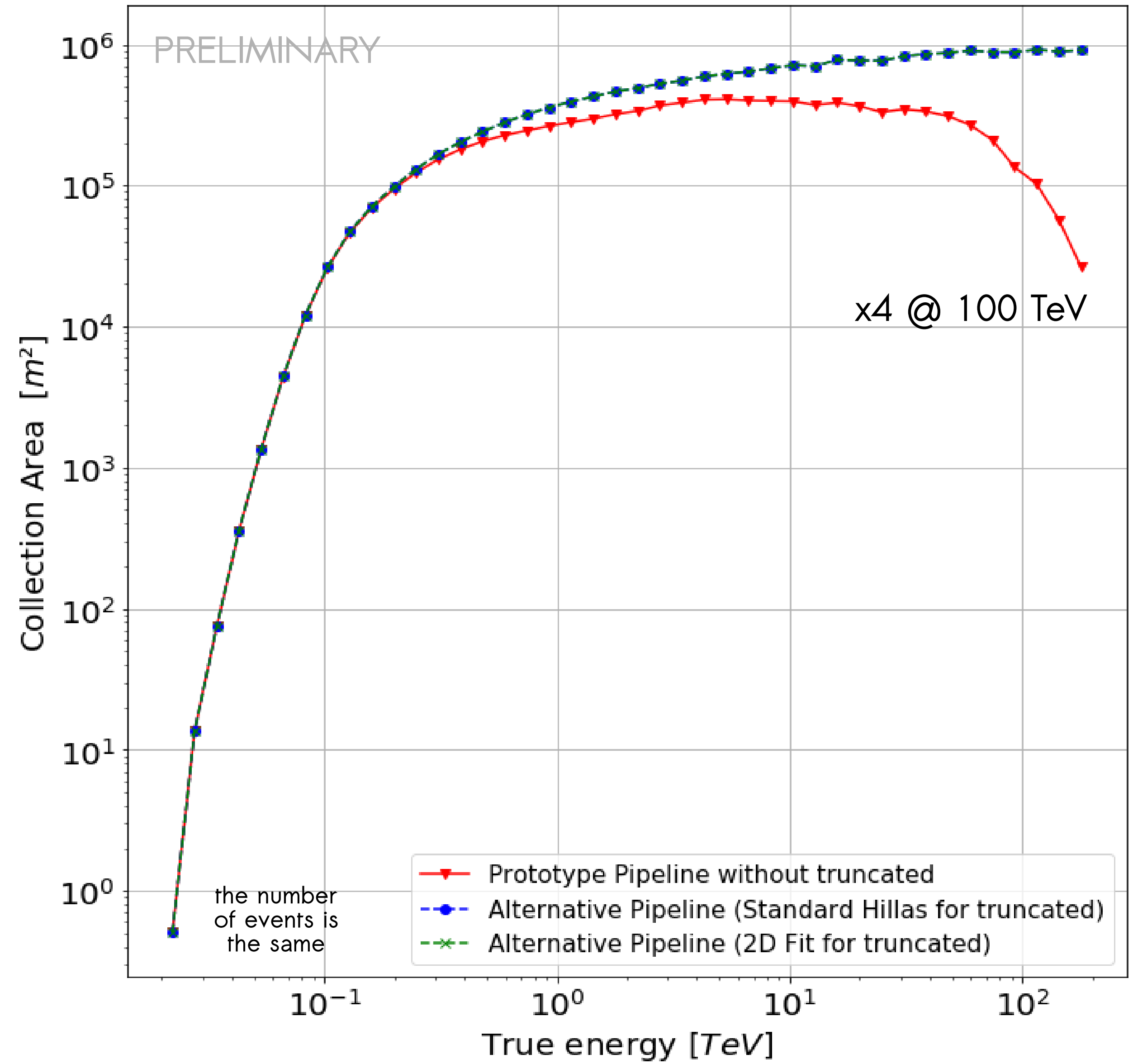
II. Inclusion of truncated images: Collection Areas

Baseline Array

Truncated n_pix > 10 N_tels > 3

Threshold Array



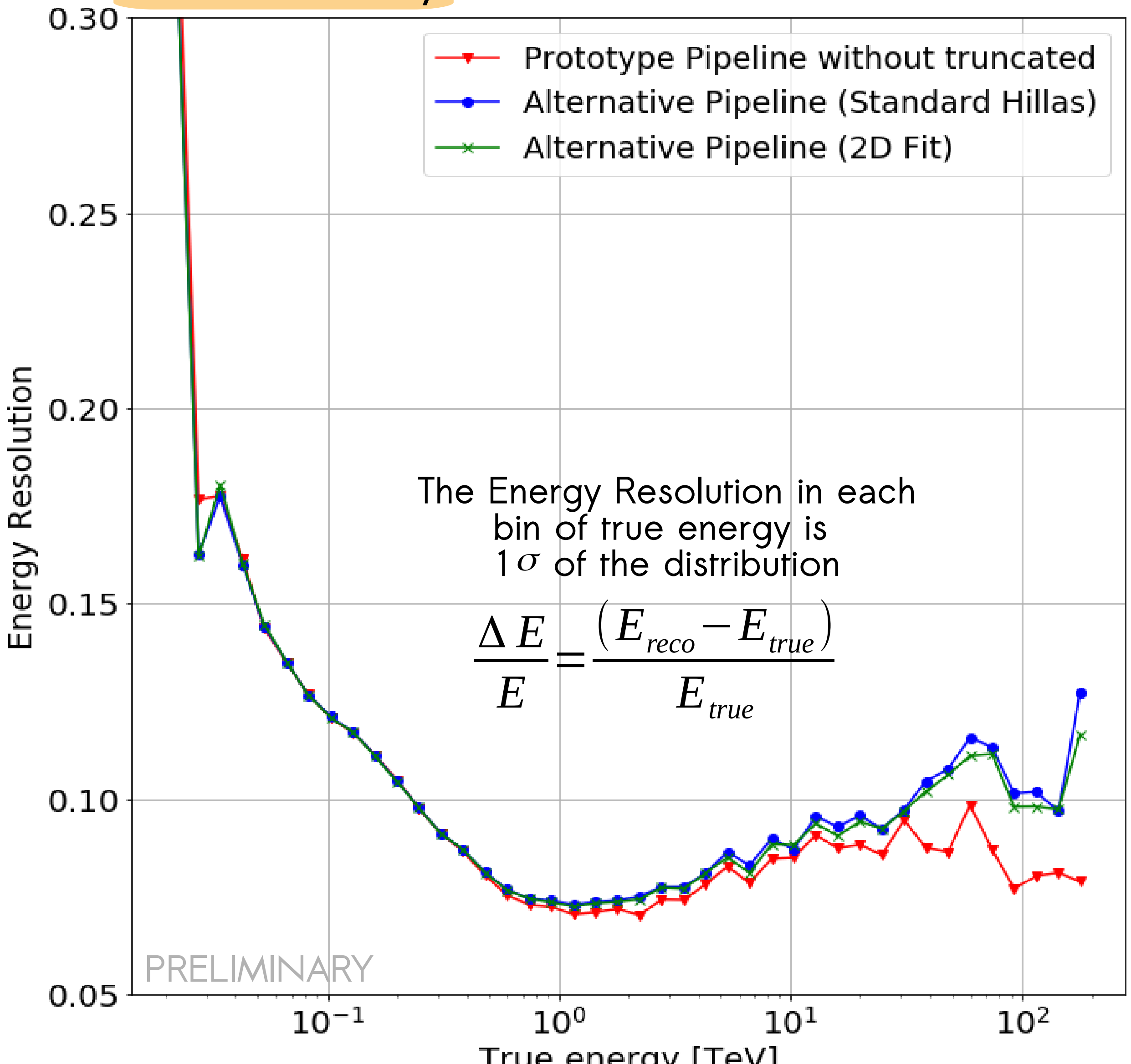


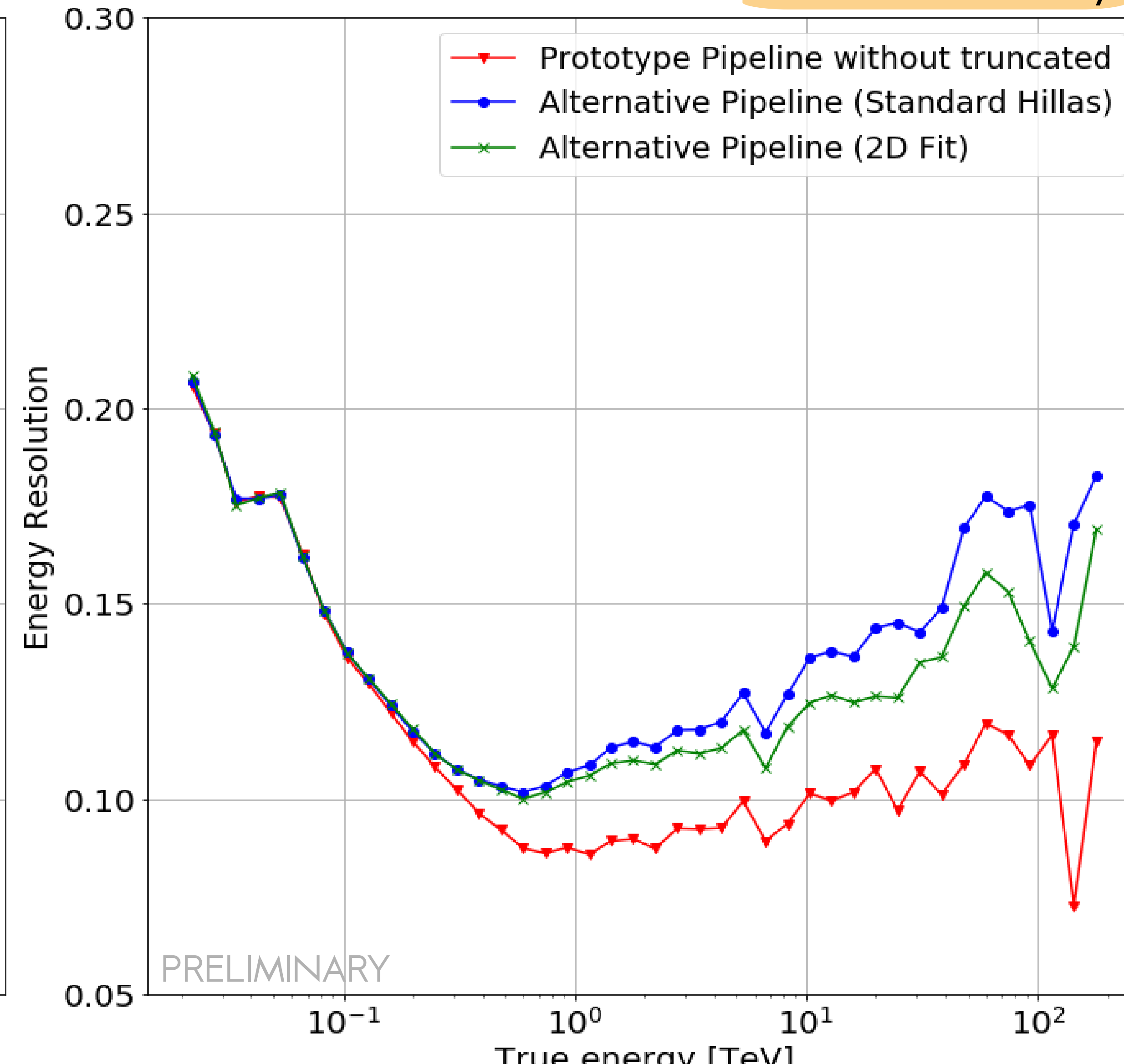
II. Inclusion of truncated images: Energy Resolution

Baseline Array

Truncated n_pix > 10 N_tels > 3

Threshold Array

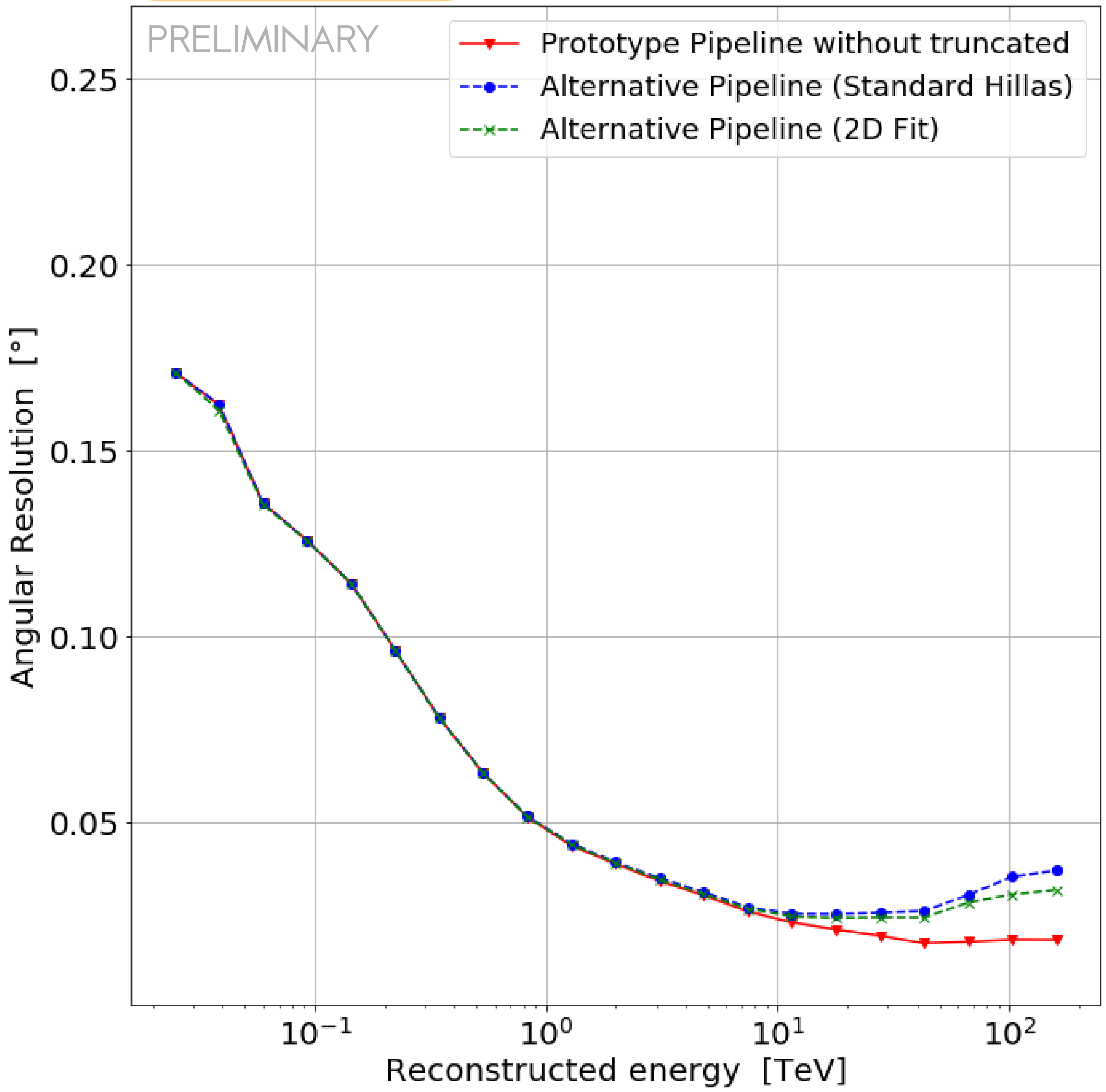




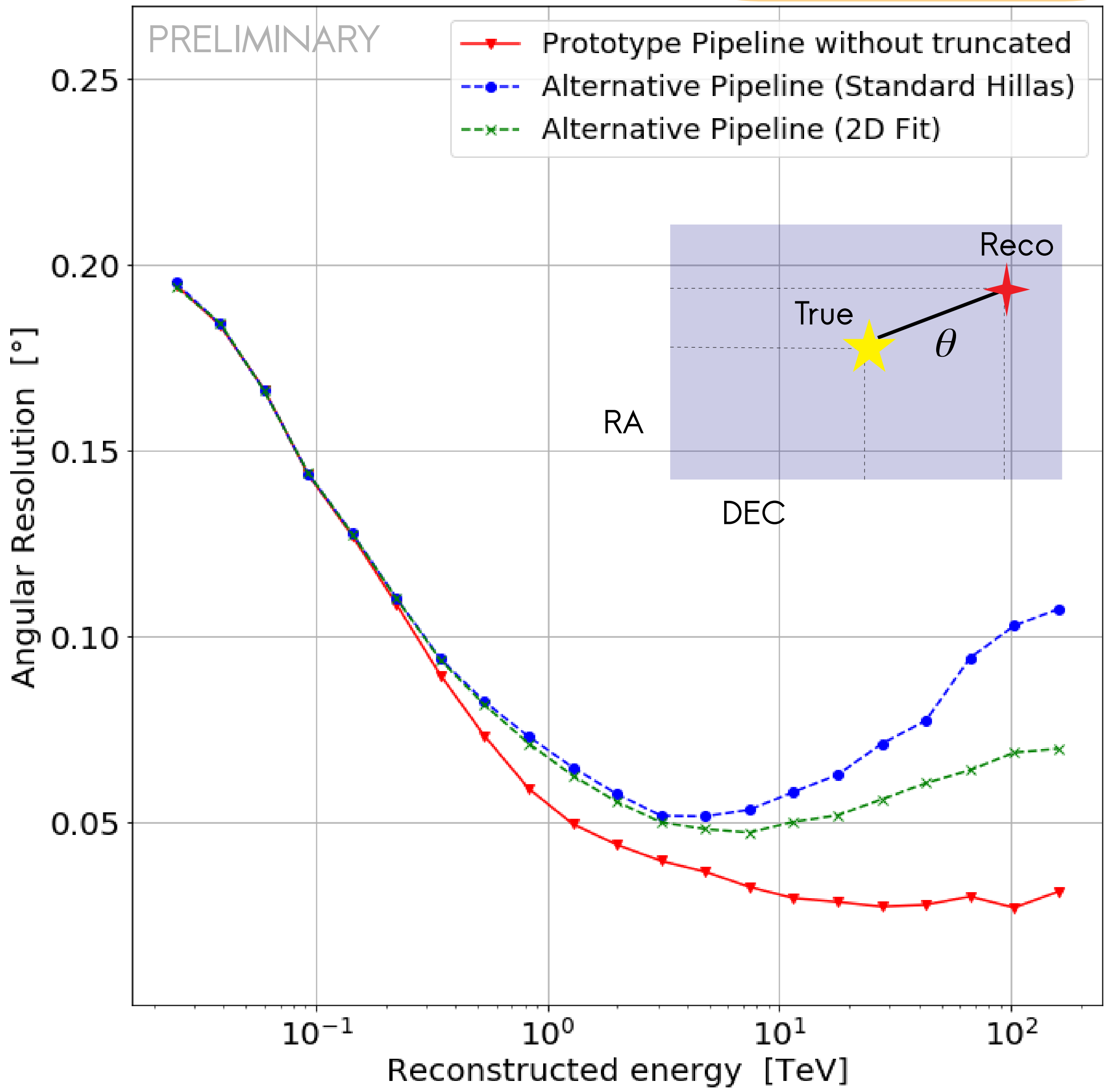
II. Inclusion of truncated images: Angular Resolution

Truncated n_pix > 10 N_tels > 3

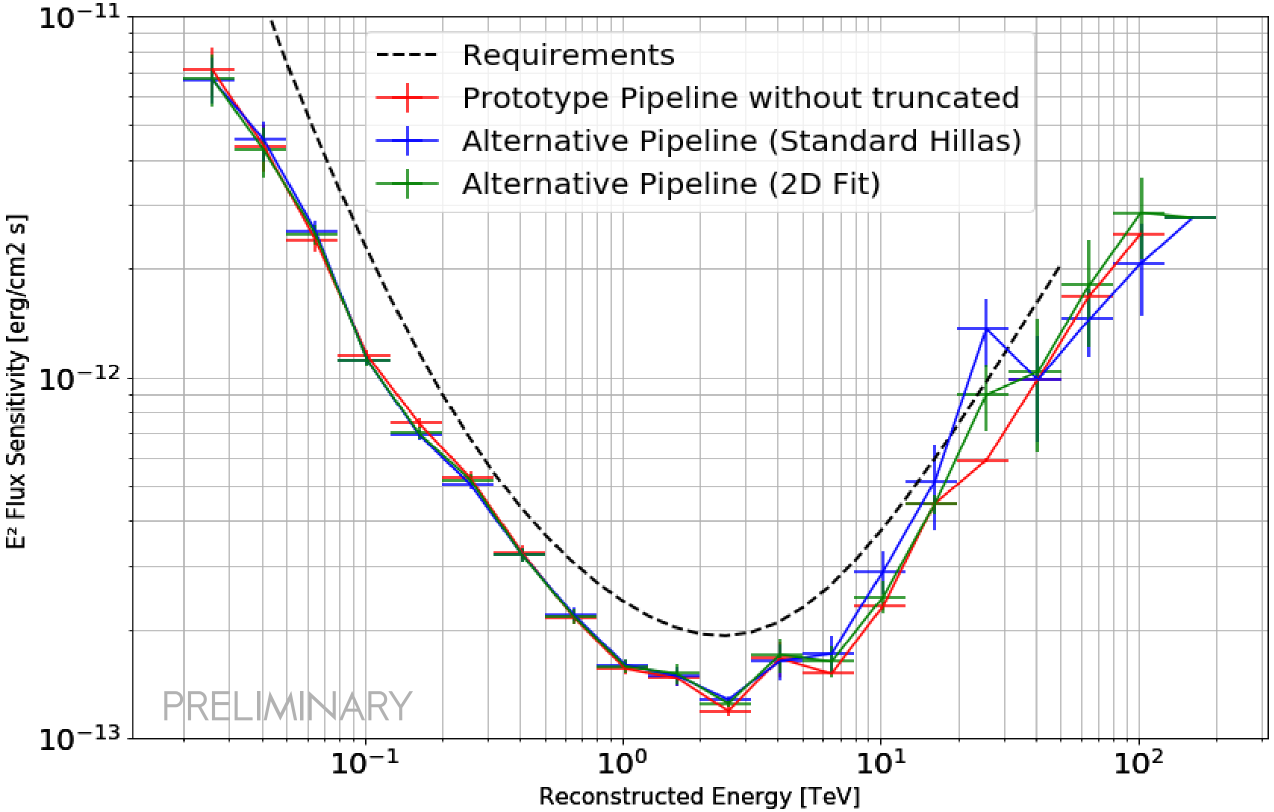
Baseline Array



Threshold Array



II. Inclusion of truncated images: new reconstructed events



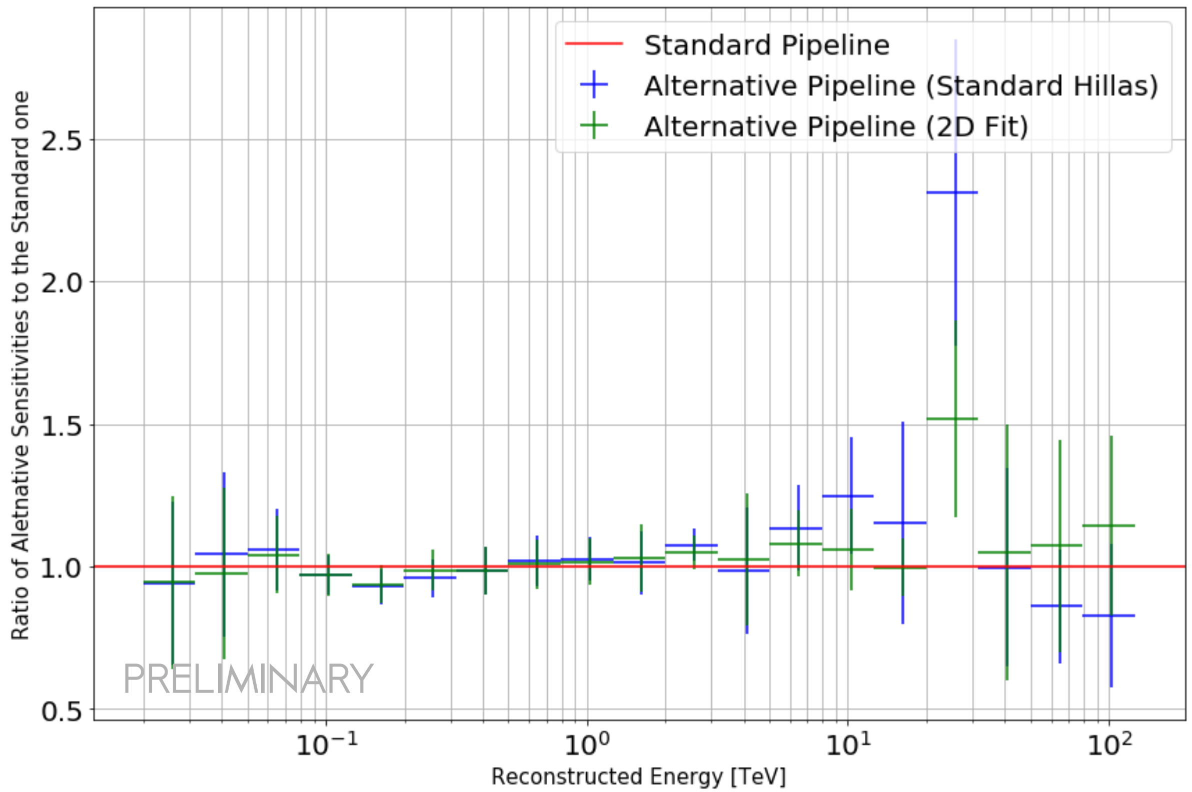
The **Sensitivity** is defined as the minimal gamma ray flux satisfying the requirements for 50 hours:

In each energy bin:

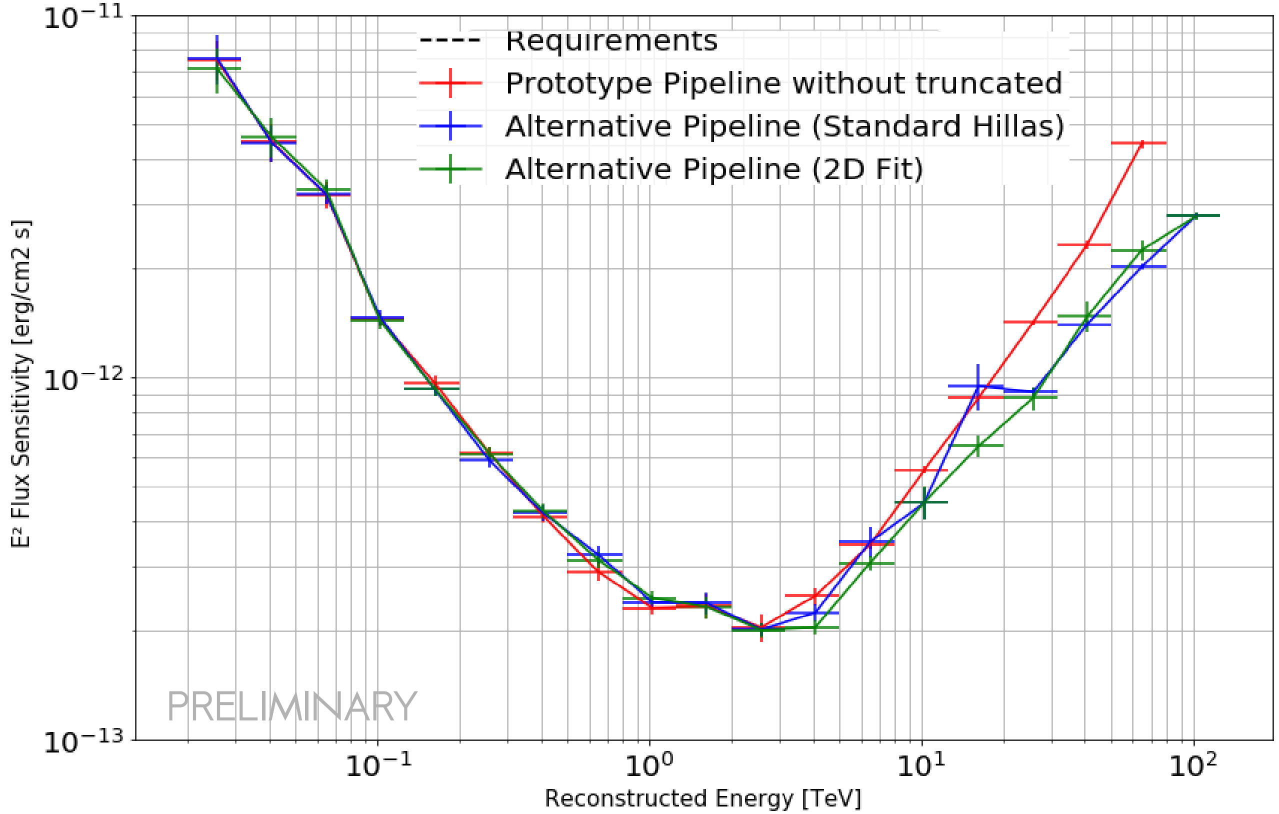
$$5\sigma$$
$$N_\gamma \geq 10$$
$$N_\gamma \geq 5\% \, N_{bkg}$$

Baseline Array

Statistical uncertainties on the sensitivity curve are derived through the boostrap method



II. Inclusion of truncated images: new reconstructed events



The **Sensitivity** is defined as the minimal gamma ray flux satisfying the requirements for 50 hours:

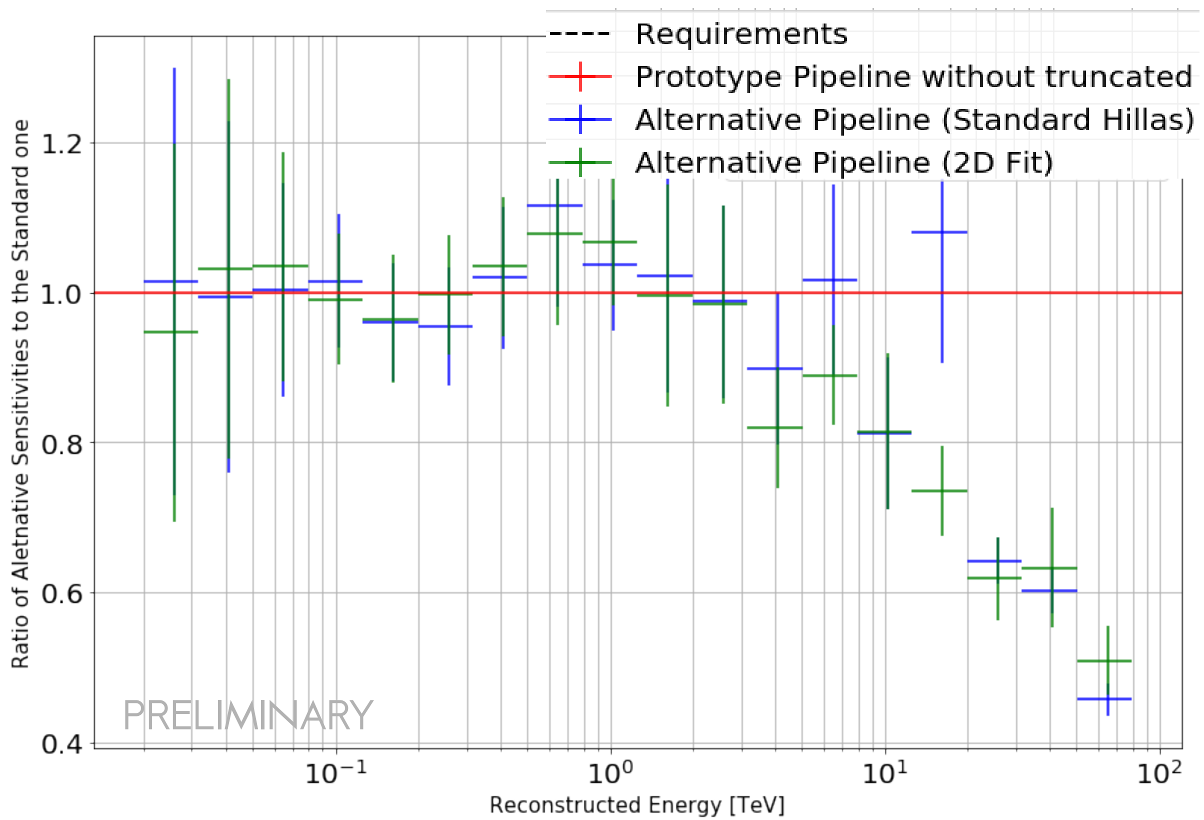
In each energy bin: 5σ

$$N_\gamma \geq 10$$

$$N_\gamma \geq 5\%\, N_{bkg}$$

Threshold Array

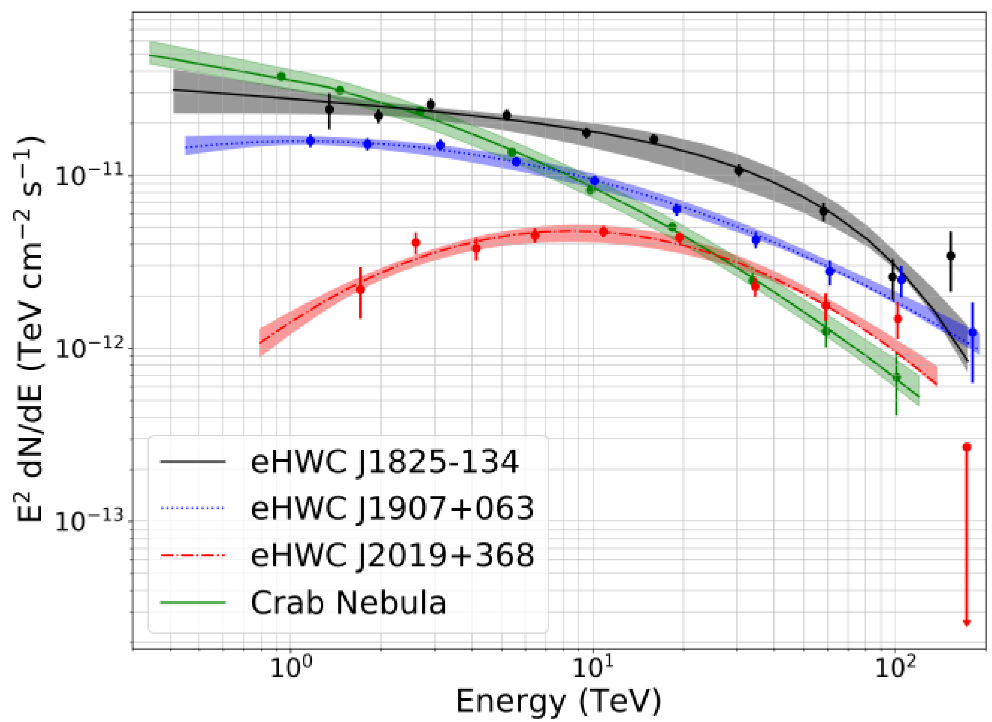
Statistical uncertainties on the sensitivity curve are derived through the boostrap method



III. PeVatron candidates for the North array: J1907

New (January 2020) catalog of gamma-ray sources emitting above 56 and 100 TeV from the High Altitude Water Cherenkov (**HAWC**) Observatory.

HAWC Collaboration June 2020 doi:10.3847/2041-8213/ab96cc



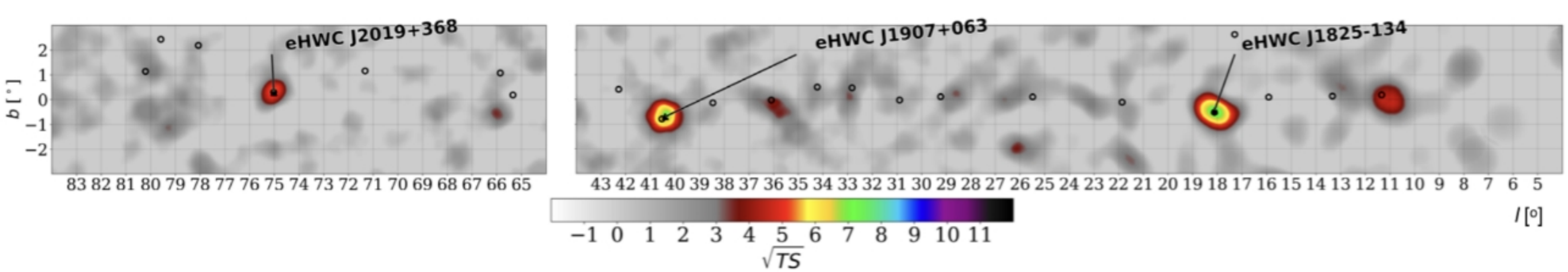
J1907

- Data avaible from
  - HAWC [1]
  - HESS [2]
  - VERITAS [3]
  - Fermi
  - VLA (radio maps)
  - IceCube

- Better visibility in the northern hemisphere

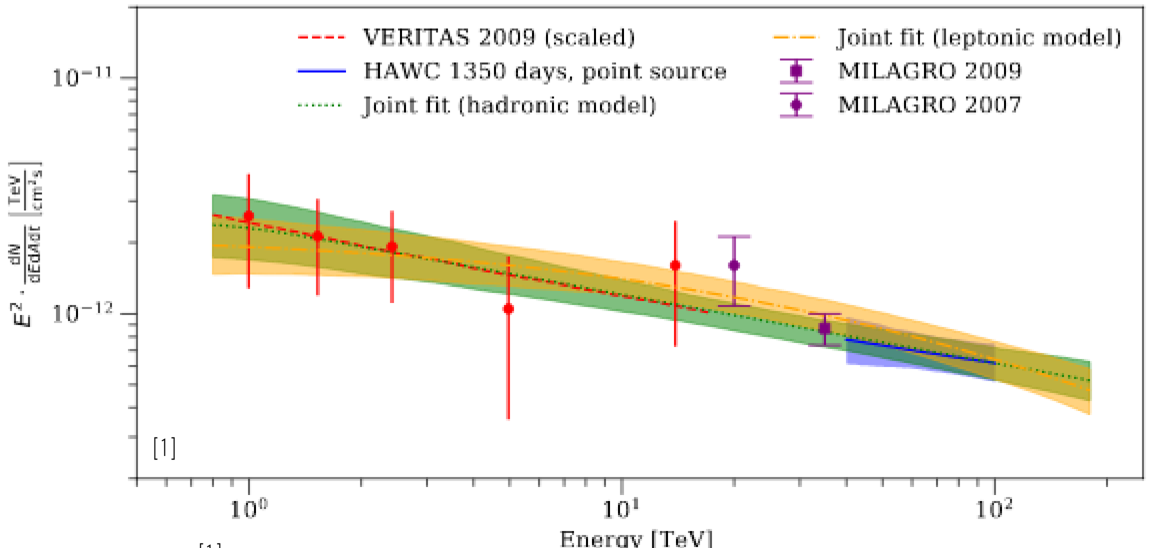
[1] HAWC Collaboration June 2020 doi: 10.3847/2041-8213/ab96cc
[2] HESS Collaboration April 2018 doi: 10.1051/0004-6361/201732098
[3] VERITAS Colaboration June 2019 doi:10.1088/0004-637X/787/2/166
[4] IceCube Colaboration Febrary 2019

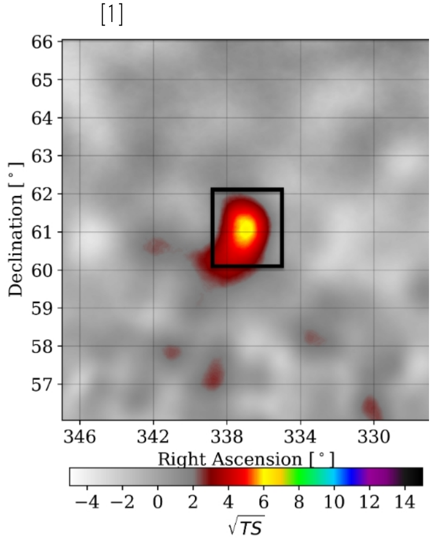
E > 100 TeV



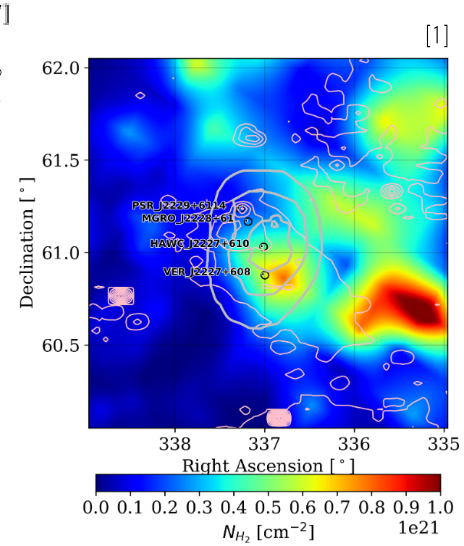
III. PeVatron candidates for the North array: J2227

New (July 2020) gamma-ray source wich is a PeVatron candidate for High Altitude Water Cherenkov (**HAWC**) Observatory.





RA = 336.96°
Dec = 61.05°



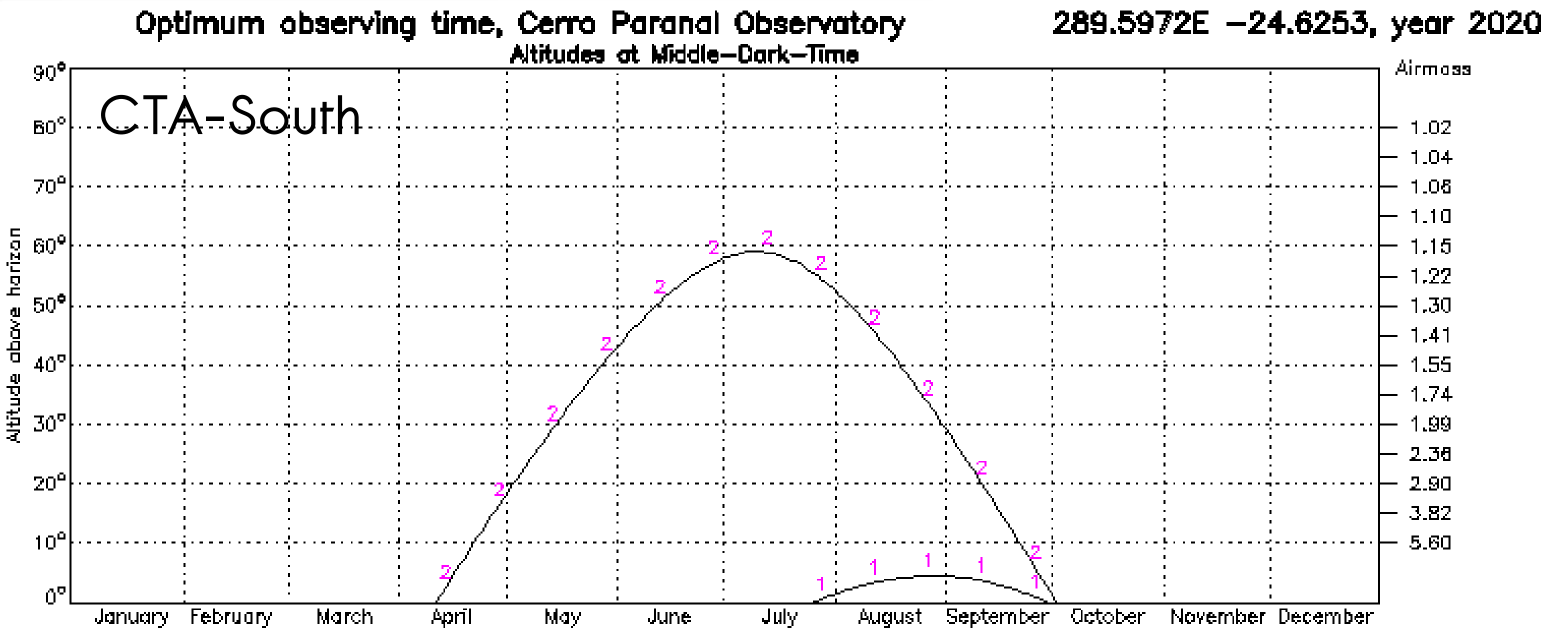
J2227

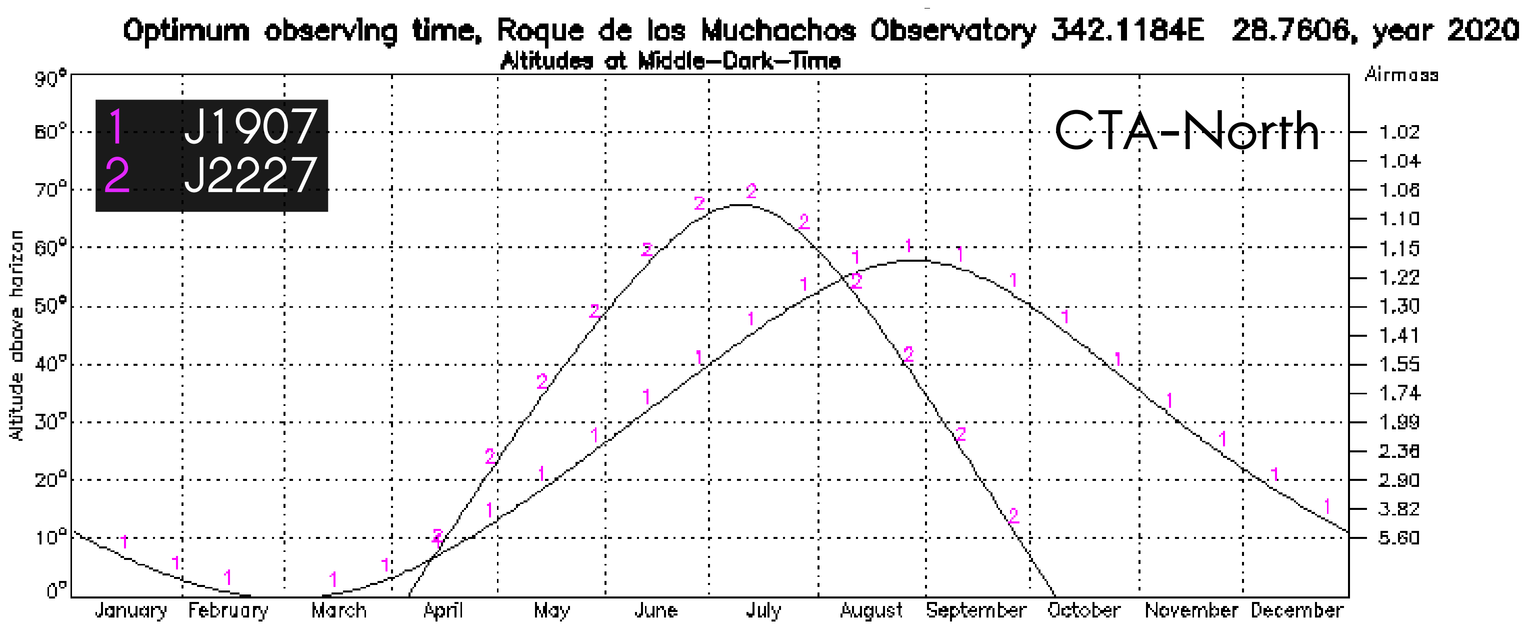
- Data avaible from
  - HAWC [1]
  - VERITAS [2]
  - CO emission
  - GeV data
  - X-ray data
- Modelization [3]:
  - in the **pure leptonic** model for the gamma-ray emission can be marginally ruled out by the X-ray and TeV data [6]
  - in the **hadronic model** gamma-ray data suggest that the emission may be Powered by the Pulsar wind nebula Instead of shocks of the SNR

- visible only in the northern hemisphere

[1] HAWC Collaboration June 2020 doi: 10.3847/2041-8213/ab96cc
[2] VERITAS Collaboration September 2009 doi: 10.1088/0004-637X/703/1/L6
[3] Xin et al. November 2019 doi: 10.3847/1538-4357/ab48ee

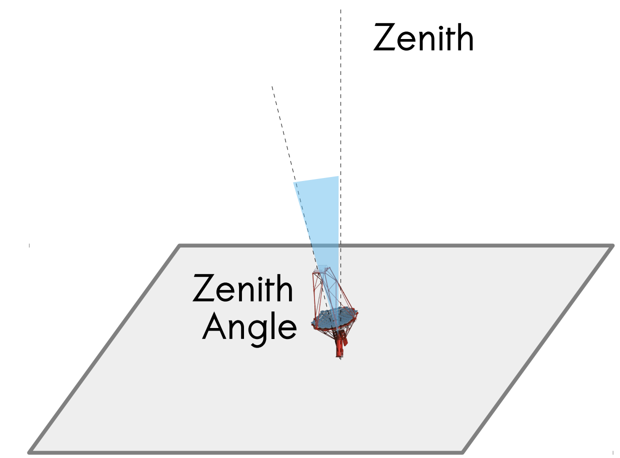
III. Sources visibility in the CTA's sites





Visibility

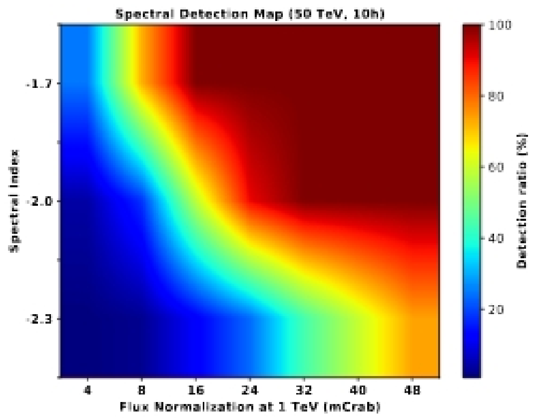
CTA-North	CTA-South
Min Zenith Angle	Min Zenith Angle
J1907: ~ 35°	J1907: ~ 85°
J2227: ~ 45°	J2227: ~ 40°



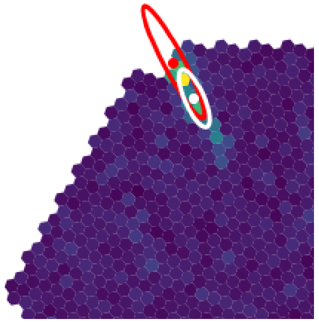
Zenith Angle = 90° - Altitude above horizon

Conclusions and outlooks

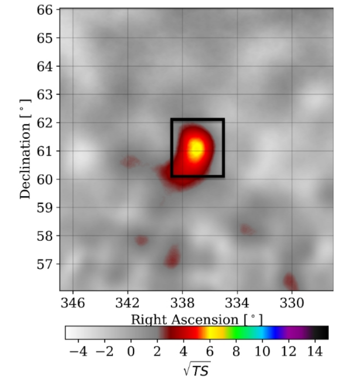
- **Potentiality of CTA in the detection of a spectral cutoffs:**
  we have created spectral cutoff detection maps for simulated high energy sources in order to find the cutoff detection probability in the multi-parameter space of a simple power law exponential cutoff spectral model



- **Optimization of CTA-North's sensitivity at very high energies:**
  - I've compared the prototype pipeline (without truncated images) with two alternative ones in which truncated images were paramtrized with a standard method (Hillas) or a 2D fit
  - including truncated images seems to significantly benefit the sensitivity at high energies (> 10 TeV) only for CTA-North threshold configuration (4LSTs 5 MSTs)

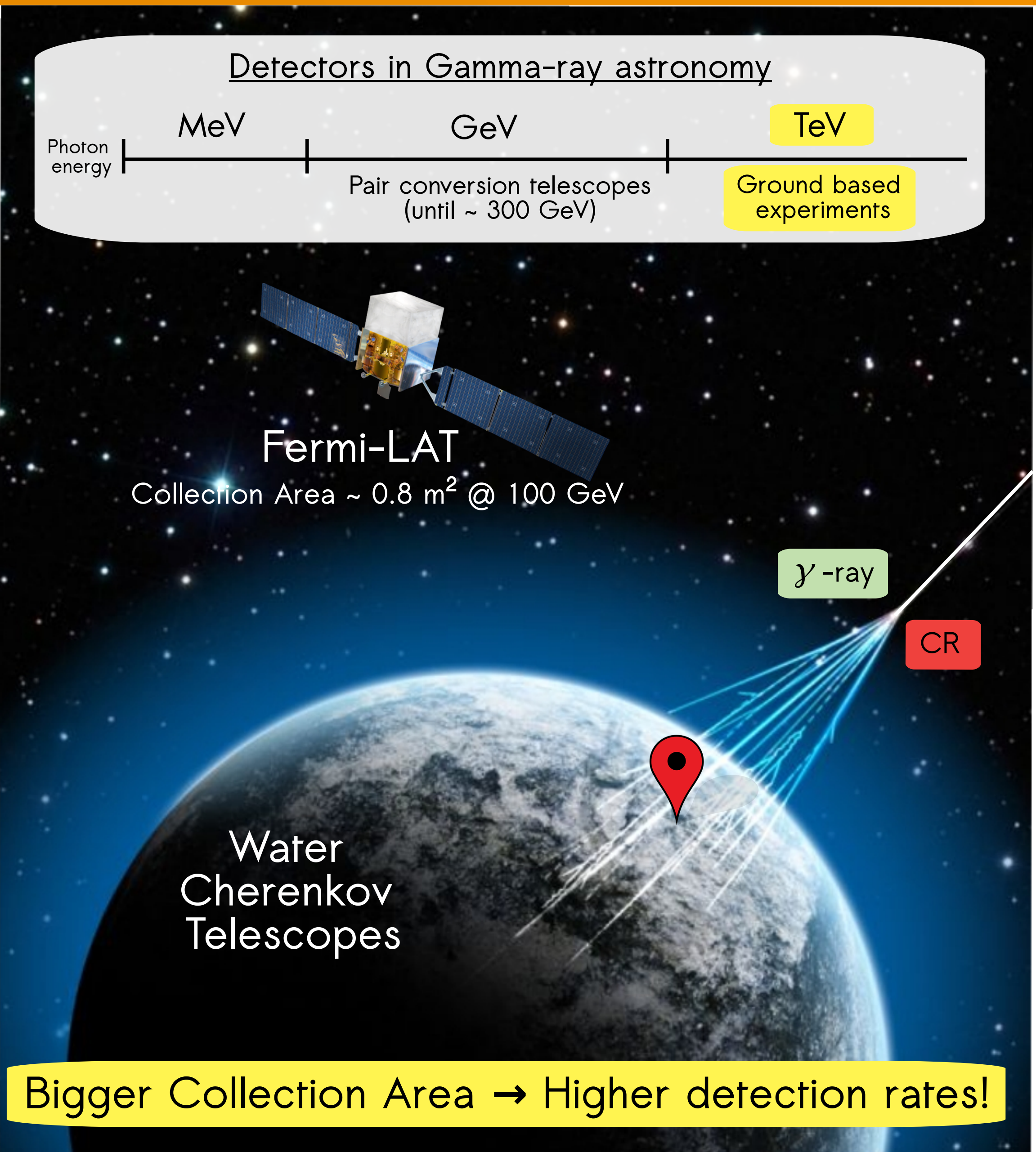


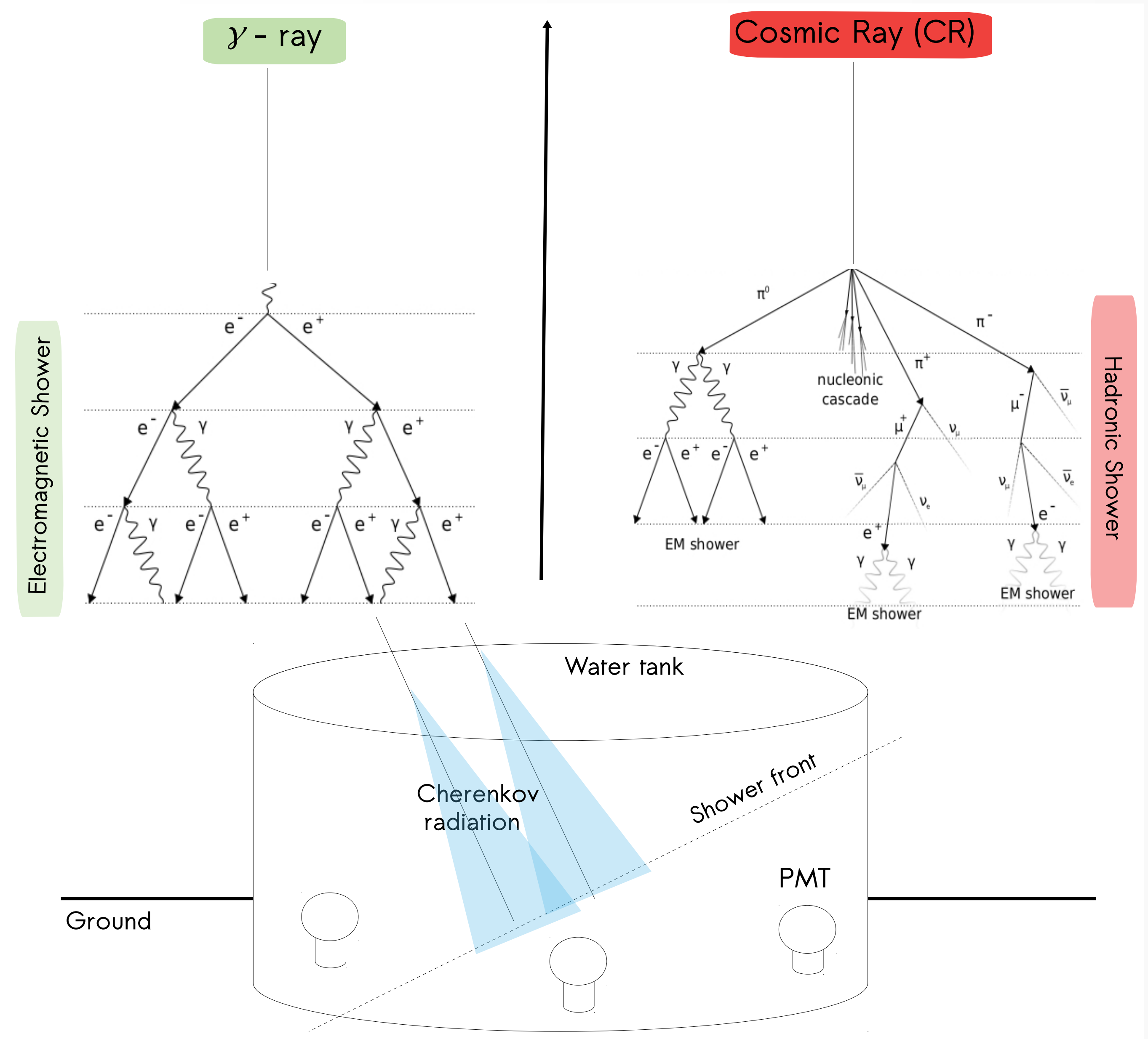
- **Perspectives for the future observation of existing PeVatron candidates:**
  an improvement of the Sensitivity at high energies for CTA-North would increase the chances of detecting PeVatrons in the Northern hemisphere and a specific study on **J2227** and **J1907** will be perform in the last part of my project



Thanks for your attention

Gamma-ray astronomy and water Cherenkov telescopes





Steps to obtain the final performance

1. Dataset of **gammas**:
   - image parametrization
   - direction reconstruction

   Energy Regressor

2. Dataset of **gammas** + **protons**:
   - image parametrization
   - direction reconstruction
   - energy reconstruction

   Particle Classifier

3. Dataset of **gammas** + **protons** + **electrons**:
   - direction reconstruction
   - energy reconstruction
   - particle classification “gammaness”

Optimization of the:
- angular cut
- “gammaness” cut

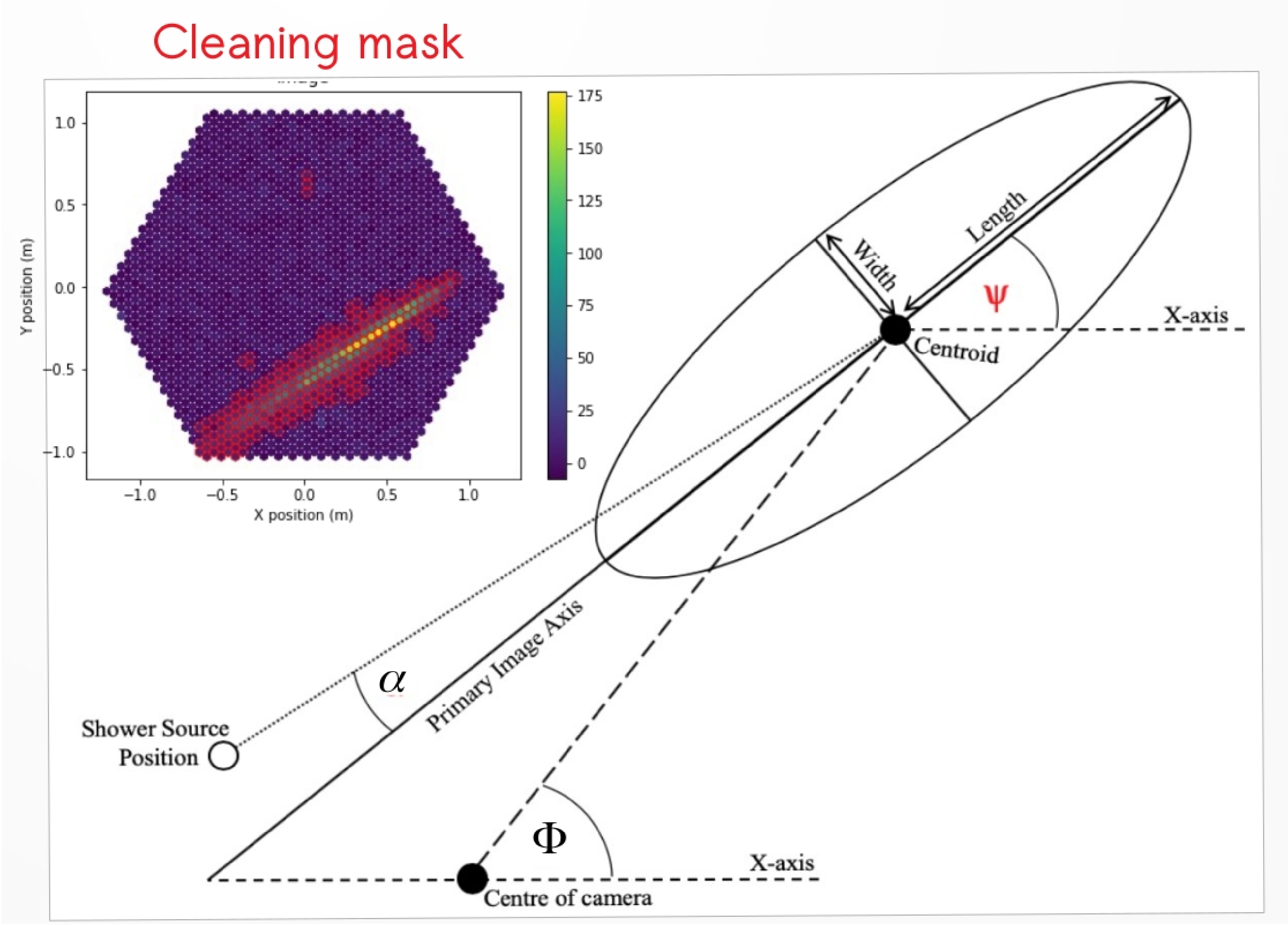
In order to obtain the **best point source sensitivity in a given observation time**

Instrument Response Functions

Effective Area
Background rate
Energy Resolution
Point Spread Function

Sensitivity curve

Std Method



Cleaning mask
Y position (m)
X position (m)
1.0
0.5
0.0
−0.5
−1.0
175
150
125
100
75
50
25
0
Length
Width
ψ
X-axis
Centroid
Primary Image Axis
α
Shower Source Position
Φ
X-axis
Centre of camera

Fit Method

$$A = \frac{C}{2\pi \sigma_{length} \sigma_{width}}$$

$$G(x_i, y_i) = A \exp\left(-\frac{1}{2}\left(\frac{(x_i - x_c)\cos\theta - (y_i - y_c)\sin\theta}{\sigma_{length}}\right)^2 - \frac{1}{2}\left(\frac{(x_i - x_c)\sin\theta + (y_i - y_c)\cos\theta}{\sigma_{width}}\right)^2 \right)$$

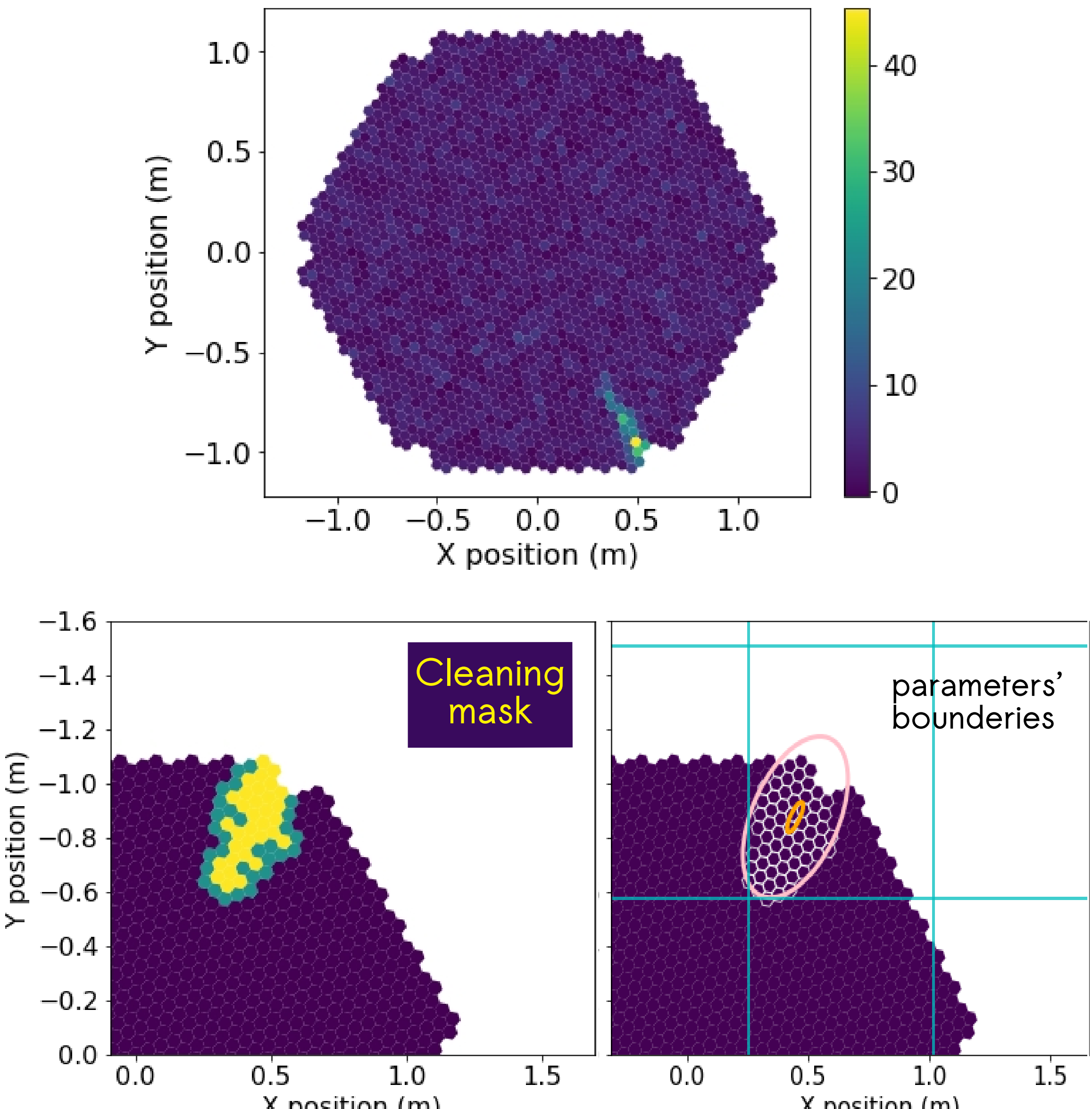
$$\chi^2 = \frac{1}{N_{DOF}}\left(\sum_{\text{all pixels}} \frac{(S_i - G(x_i, y_i))^2}{\sigma_i^2} \right)$$

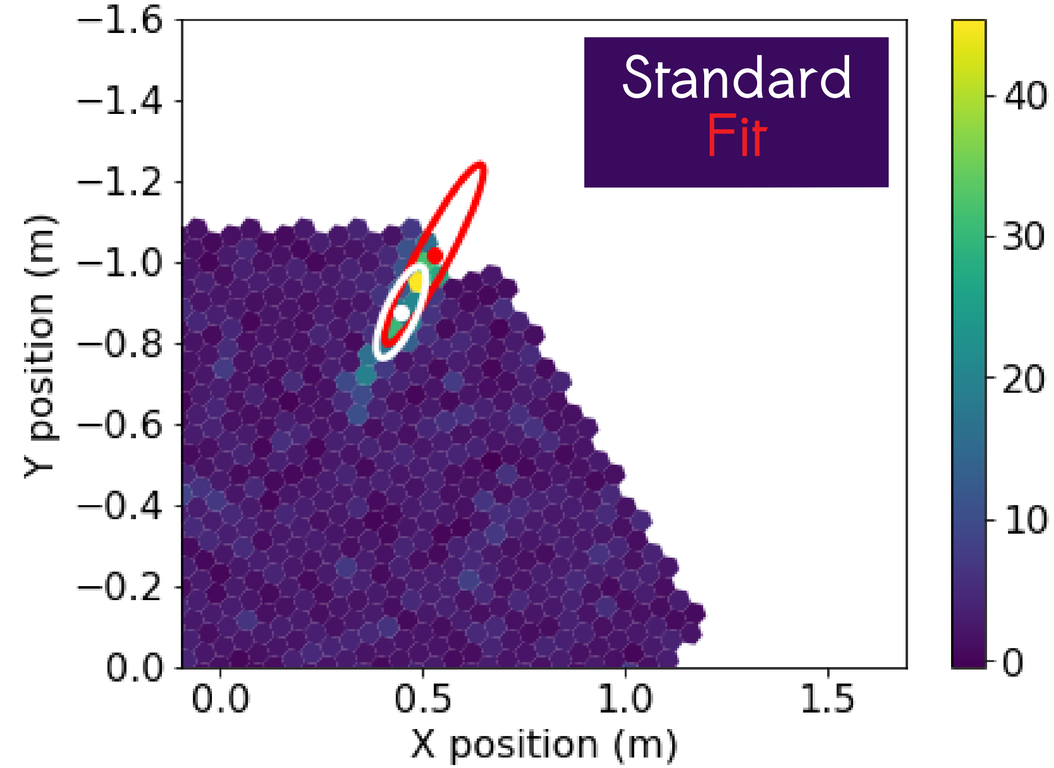
→ Minimizer (Minuit) → Best estimations of the 6 hillas parameters

$$\sqrt{G + \sigma_{ped}^2}$$

(~ 2 pe)

Standard and alternative image parametrization





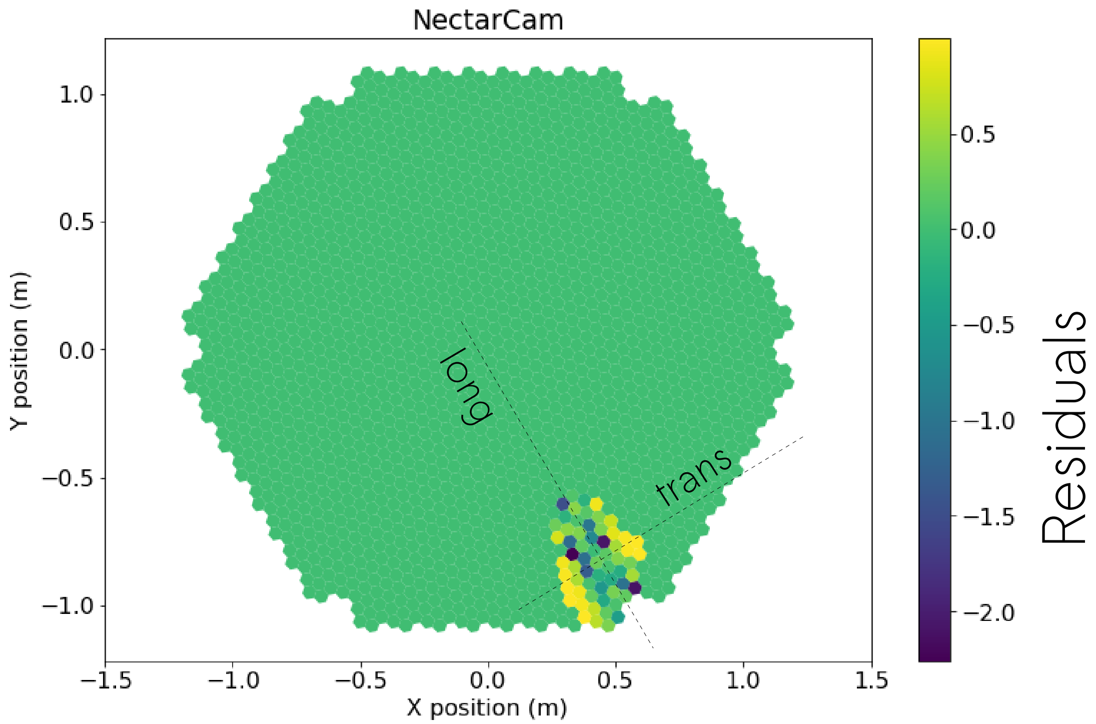
Standard parameters:

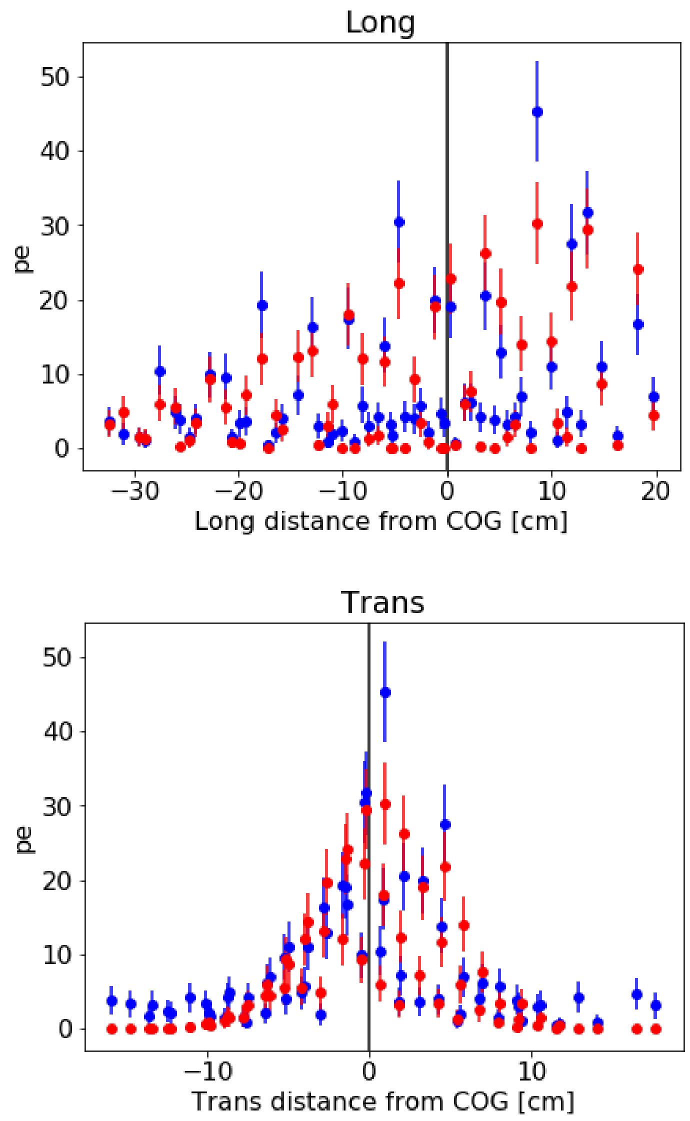
intensity = 423.45 pe
$\bar{x}$ = 0.45 m
$\bar{y}$ = -0.87 m
length = 0.123 m
width = 0.039 m
psi = -1.15 rad

Fit parameters

intensity = 1131 pe
$\bar{x}$ = 0.53 m
$\bar{y}$ = -1.02 m
length = 0.27 m
width = 0.047 m
psi = -1.08 rad

Fit Method

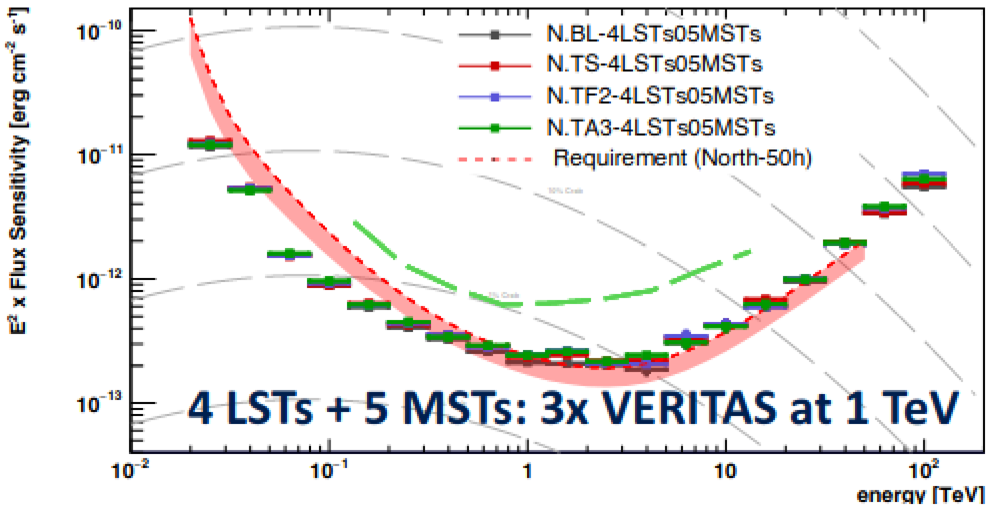


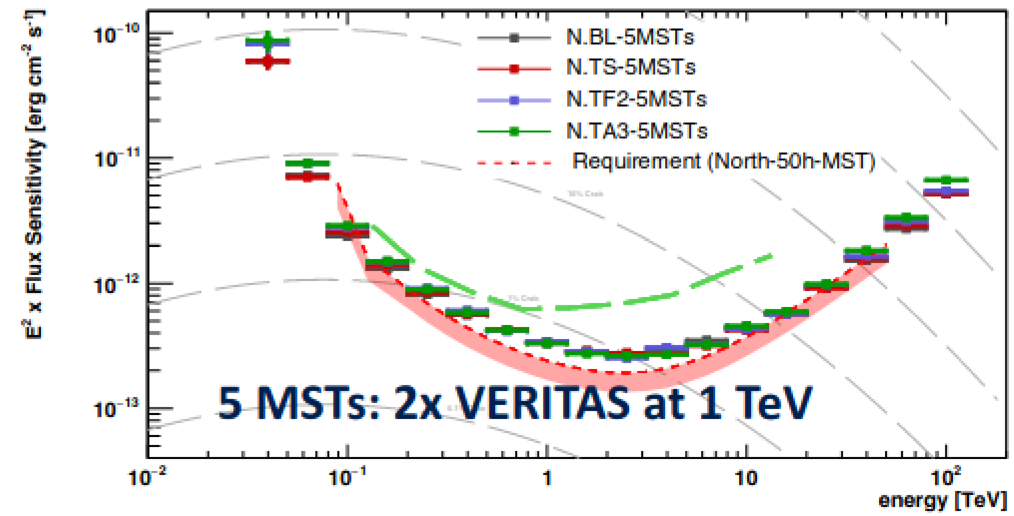


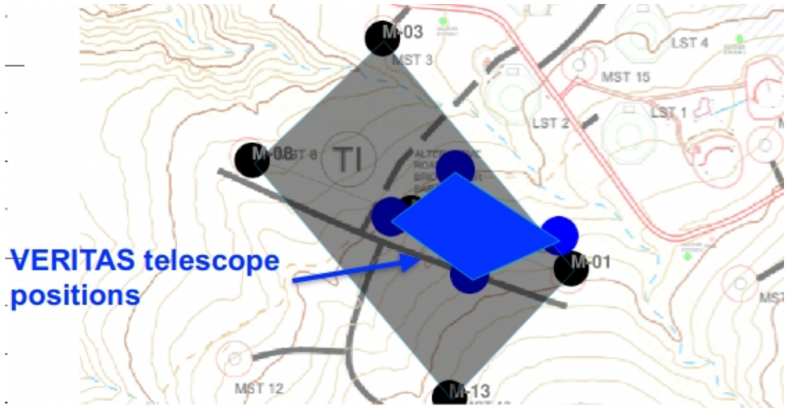
Predicted counts

Observed counts

CTA North significantly better than VERITAS



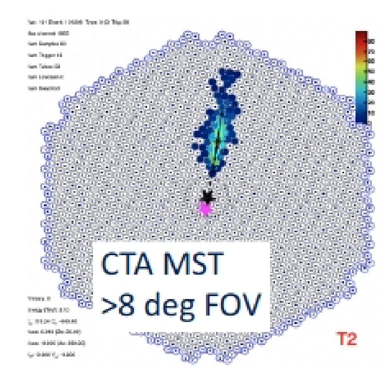


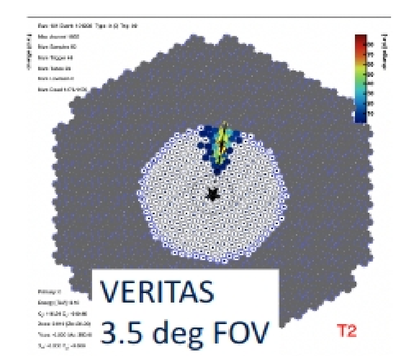


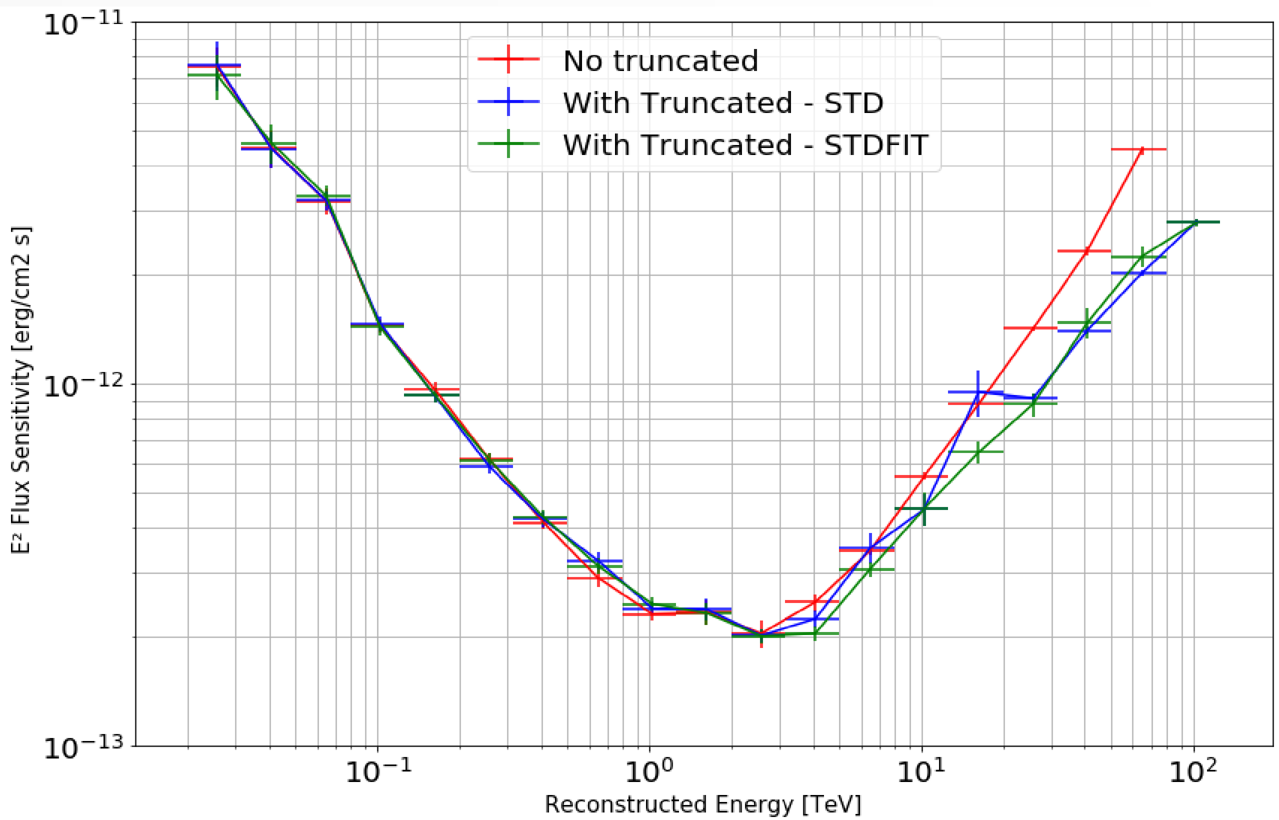
Large differences in telescope distances:
- VERITAS: ~100 m
- CTA MSTs: ~175 m

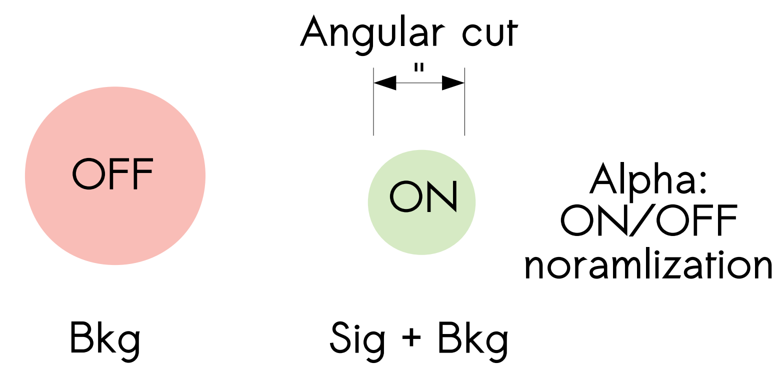
Footprint of CTA-5MST array is more than 4x that of VERITAS

Combination of **large FOV** and **larger telescope distances** explain significant improvement of CTA over VERITAS









Significance_Li&Ma (Non, Noff, alpha)

$$\sqrt{2}\left\{N_{on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right]+N_{off}\ln\left[(1+\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{1/2}.$$

The **Sensitivity** is defined as the minimal gamma ray flux satisfying the requirements for 50 hours:

In each energy bin: 5σ

$N_{\gamma} \geq 10$

$N_{\gamma} \geq 5\% N_{bkg}$

HAWC

The HAWC Gamma-ray Observatory is a wide field of view, continuously operating, TeV gamma-ray telescope

HAWC monitors the northern sky and makes coincident observations with other wide field of view observatories.

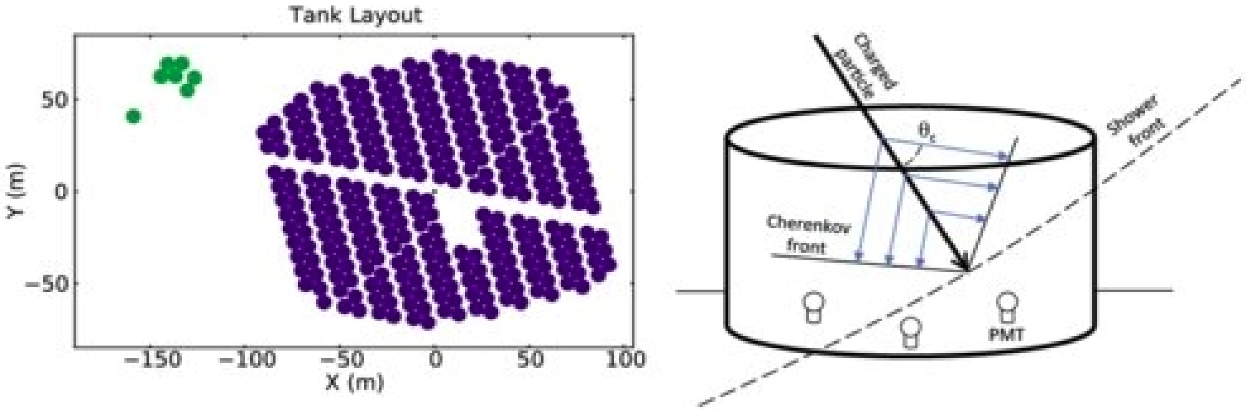
Have a 2 steradian (sr) instantaneous field of view to allow observations of diffuse gamma-ray emission from the plane of the Galaxy over a broad range of Galactic longitudes reaching to the Galactic centerOperate for at least

five years with >90% duty cycle

Have a >95% hadronic background rejection for E >10 TeV

Energy resolution

angular resolution of <0.5° for E >1 TeV and 0.25° for E >10 TeV



(a) HAWC tank layout.

(b) Water Cherenkov Detection Principle.

Performance