cherenkov telescope array

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
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CTA Data analysis and Performance

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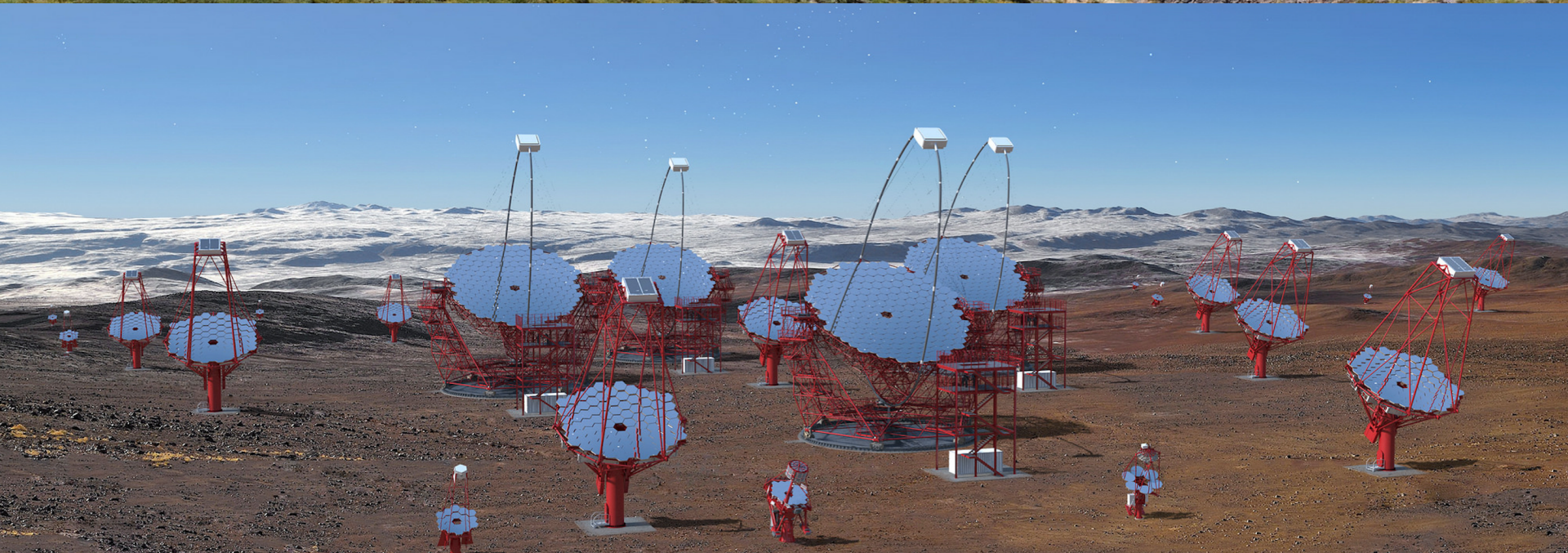
for the CTA Consortium

Outline

- CTA Arrays and design choices based on performance
- Data analysis
  - Calibration
  - Image cleaning and image parameters calculation
  - Stereo paramenter reconstruction
  - Gamma/hadron separation
  - Energy and direction reconstruction

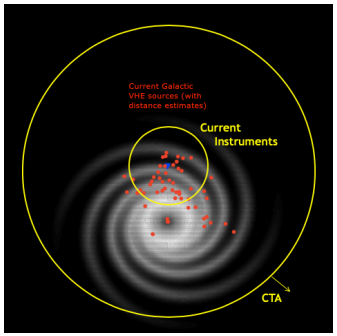
- Performance figures
  - Collection area
  - Angular and energy resolution
  - Sensitivity

CTA arrays



CTA Design

DESIGN
DRIVERS

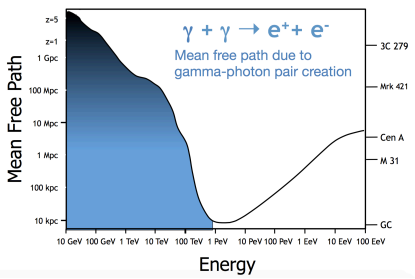


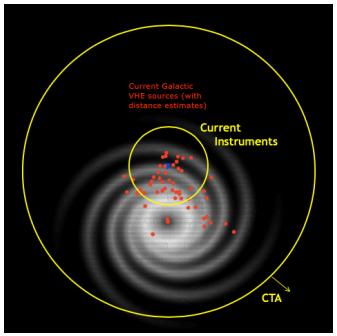
10 x Sensitivity,
Large Collection
Area

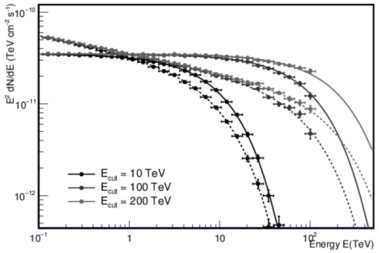
→ all topics

CTA Design

DESIGN DRIVERS







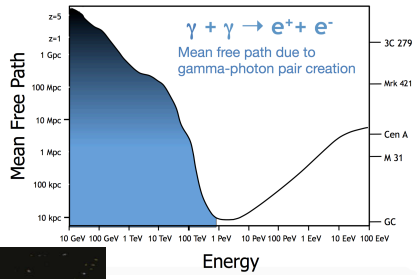
Energies down to 20 GeV
→ Cosmology++

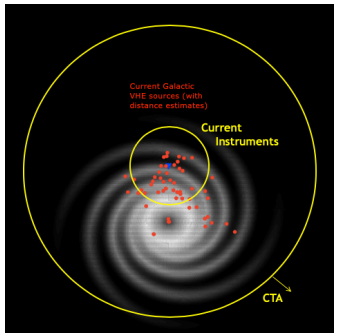
10 x Sensitivity, Large Collection Area
→ all topics

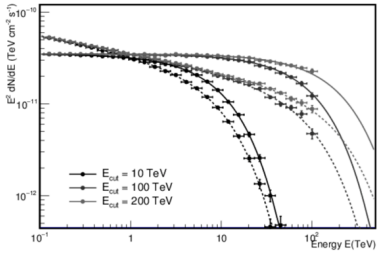
Energies up to 300 TeV
→ Pevatrons

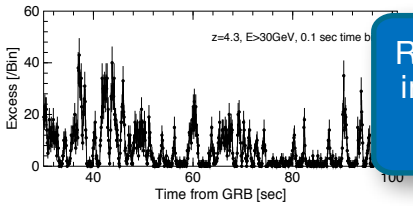
CTA Design

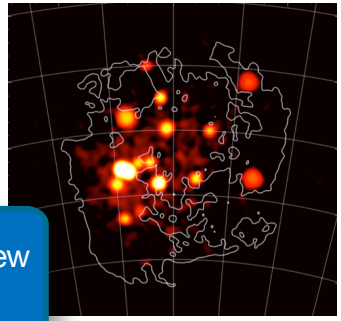
DESIGN DRIVERS











10 x Sensitivity, Large Collection Area → all topics

Energies down to 20 GeV → Cosmology++

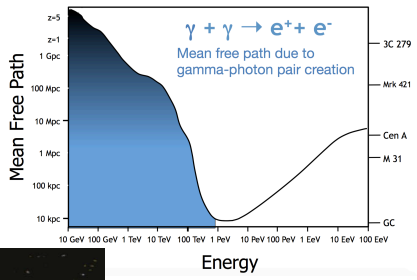
Energies up to 300 TeV → Pevatrons

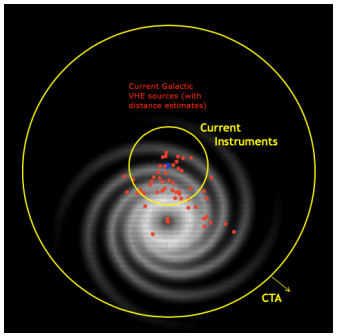
Rapid Slewing in 20 seconds → transients

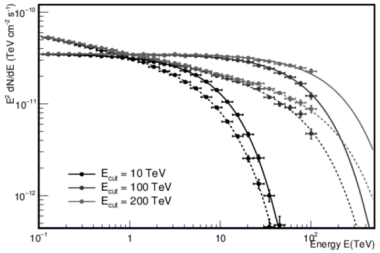
8° Field of View → surveys, extended objects

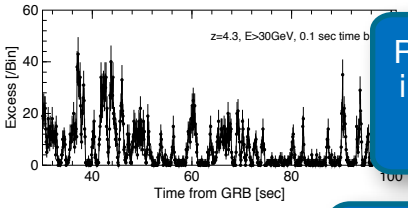
CTA Design

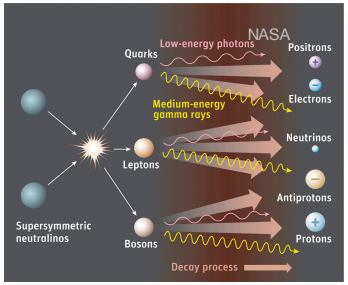
DESIGN DRIVERS











10 x Sensitivity, Large Collection Area → all topics

Energies down to 20 GeV → Cosmology++

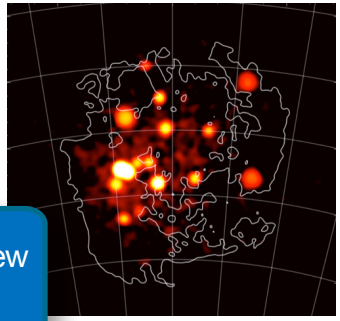
Energies up to 300 TeV → Pevatrons

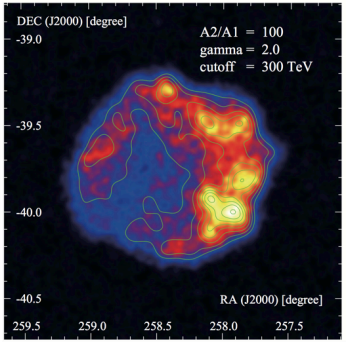
Rapid Slewing in 20 seconds → transients

8° Field of View → surveys, extended objects

10% Energy Resolution → lines, features

Few ' Angular Resolution → morphology

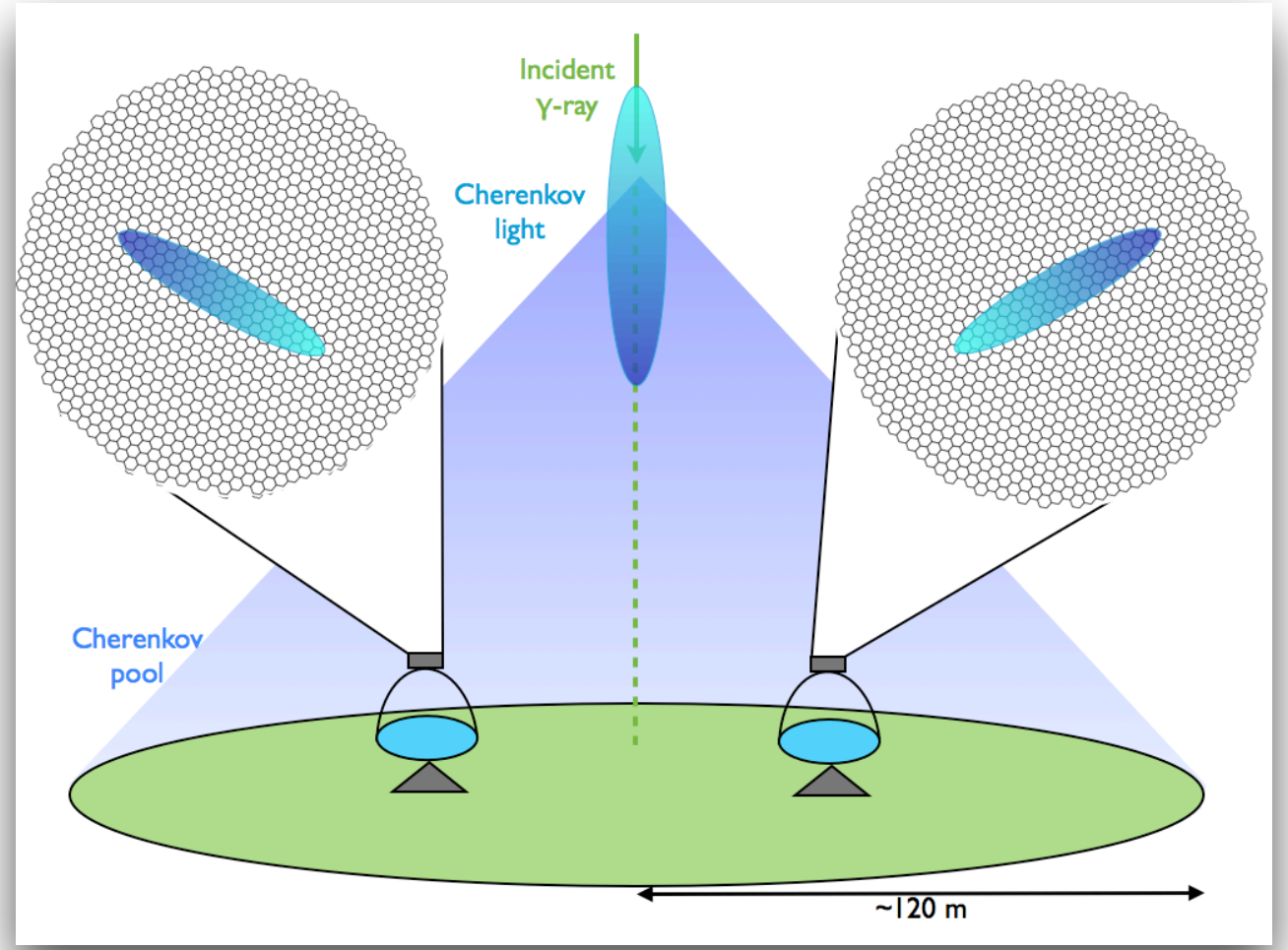




cherenkov telescope array

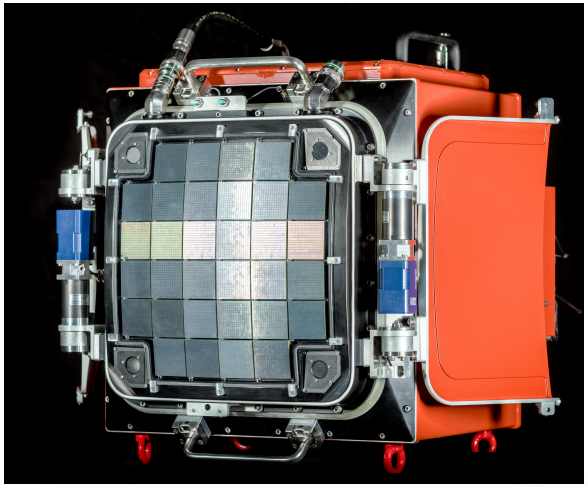
Data analysis

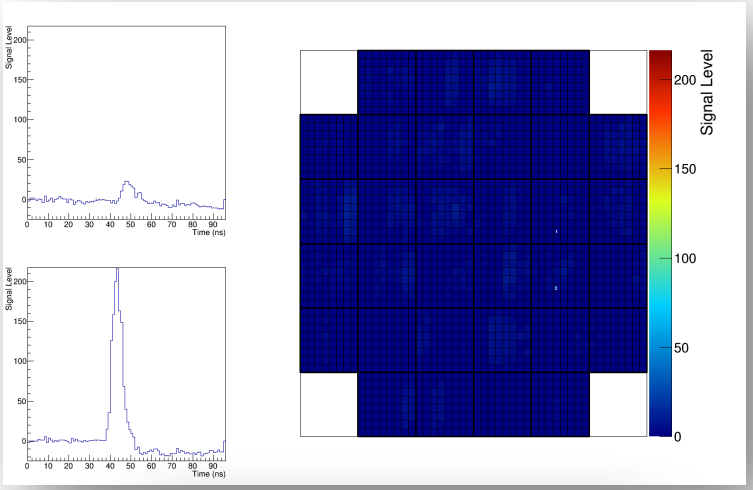
Atmospheric showers

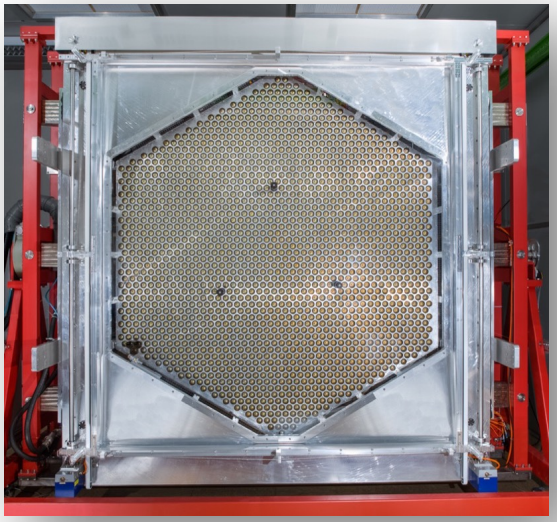


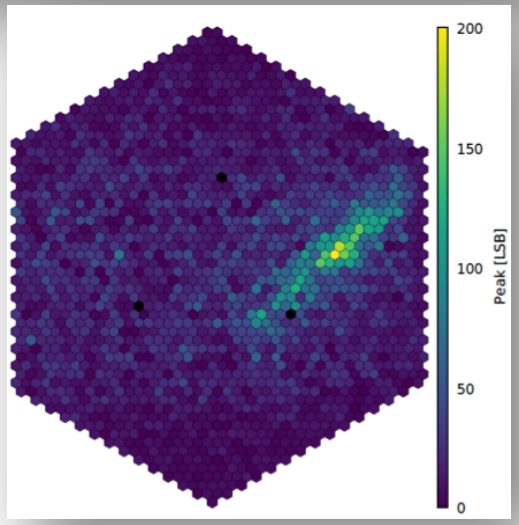
- We detect the Cherenkov light emitted by atmospheric showers using the imaging atmospheric Cherenkov technique

Signal detection and processing

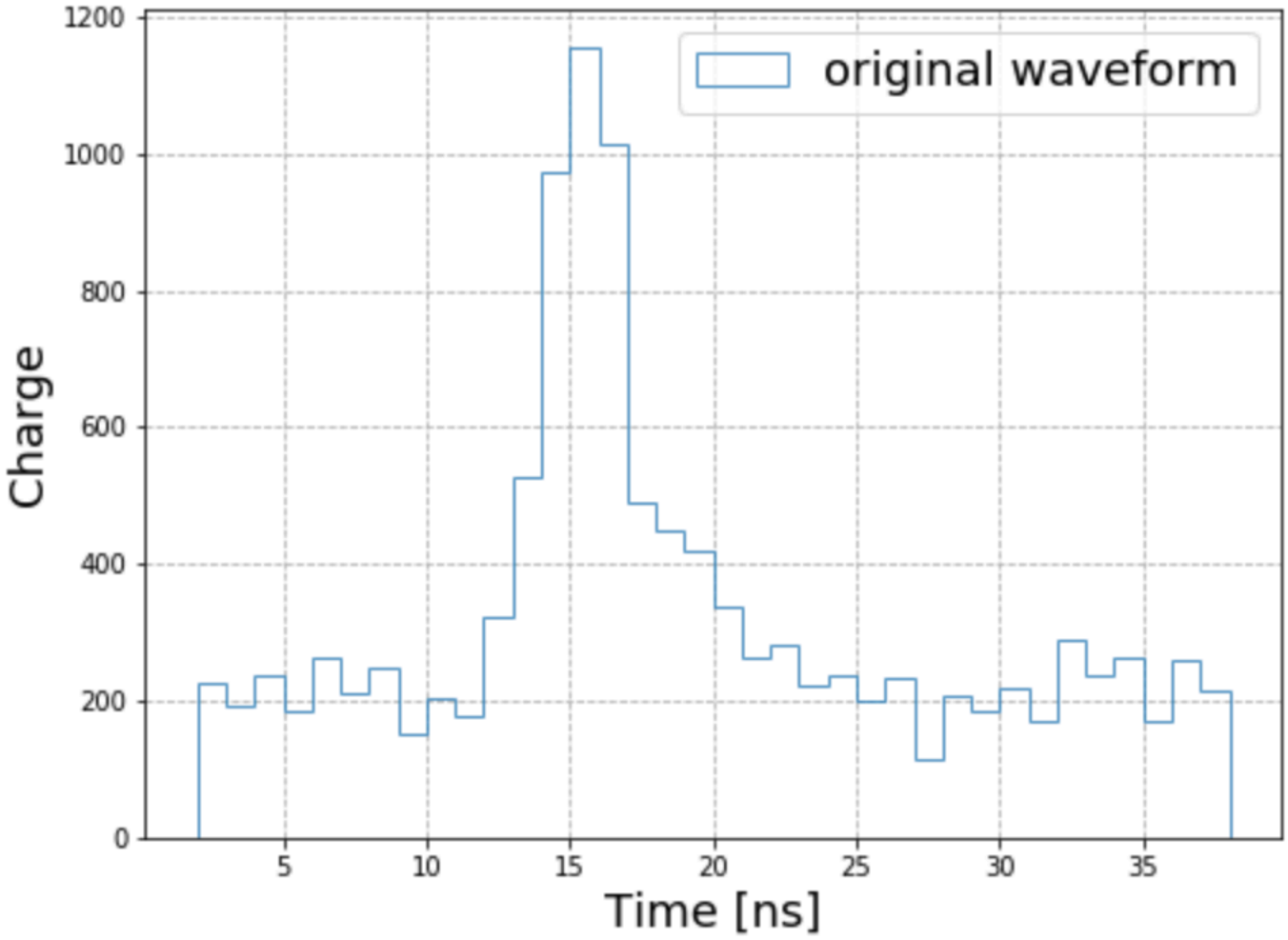








Calibration



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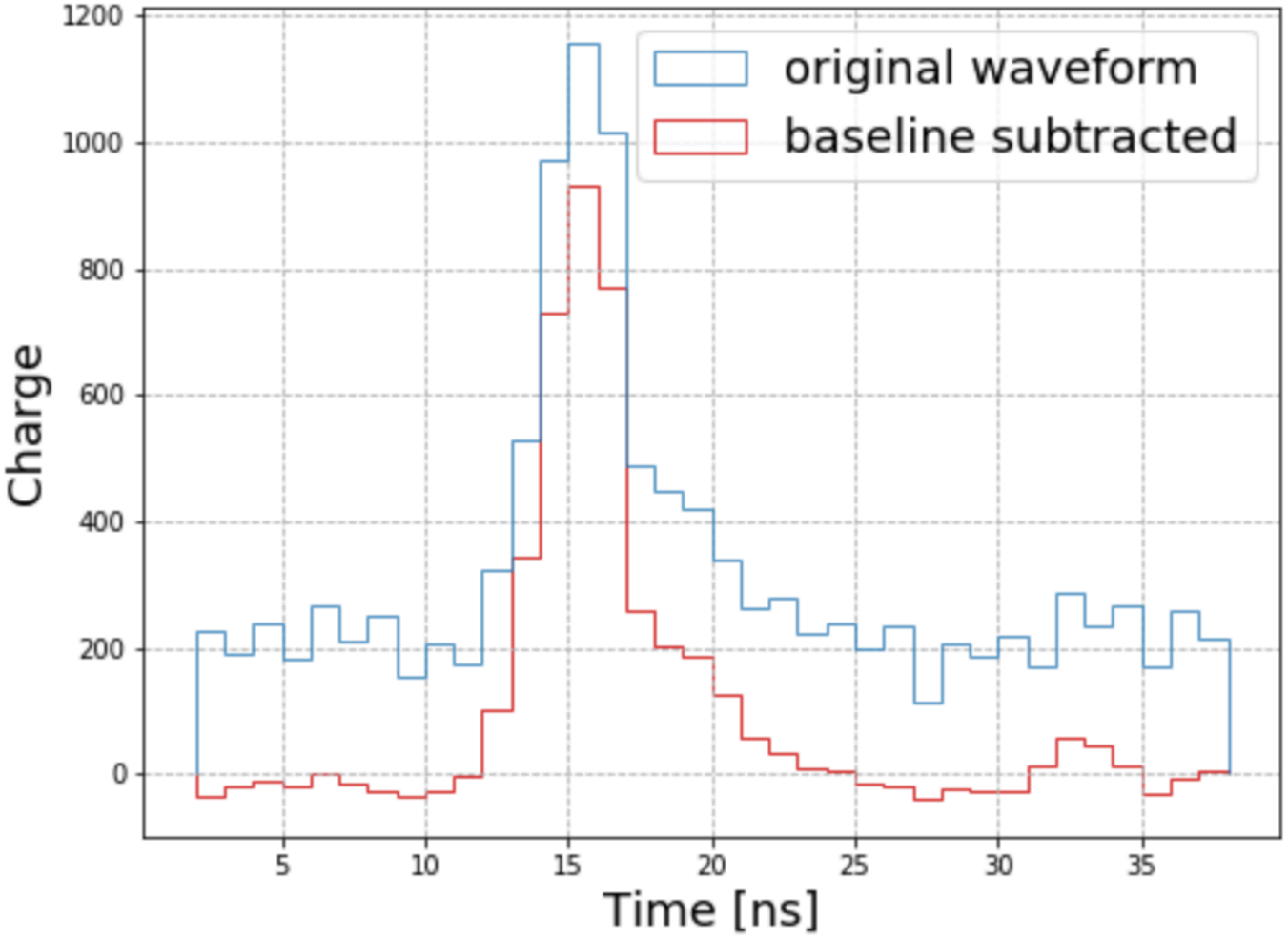

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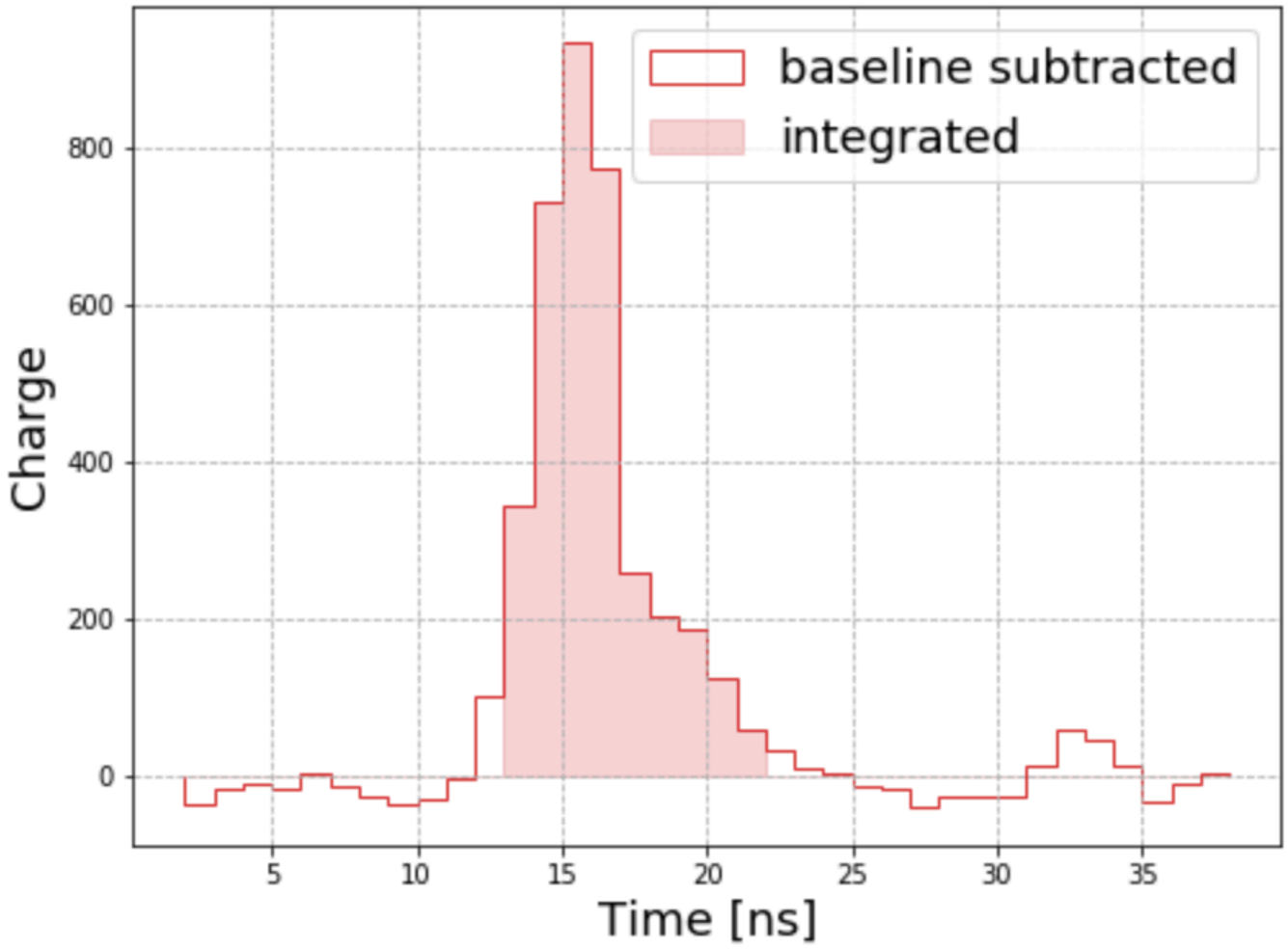

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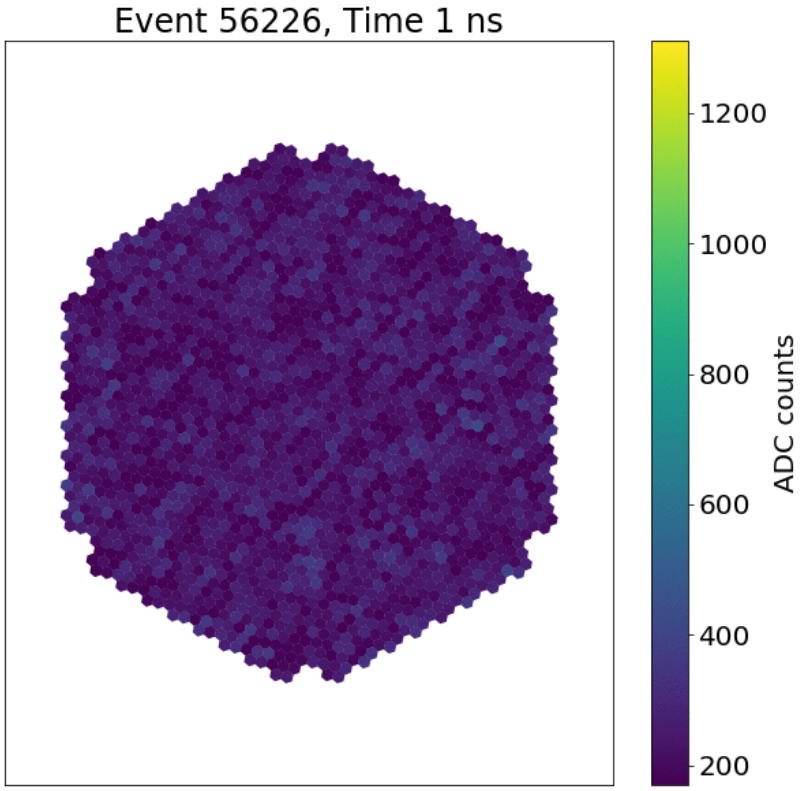

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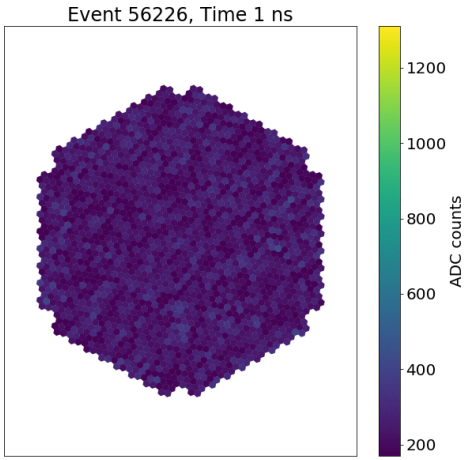

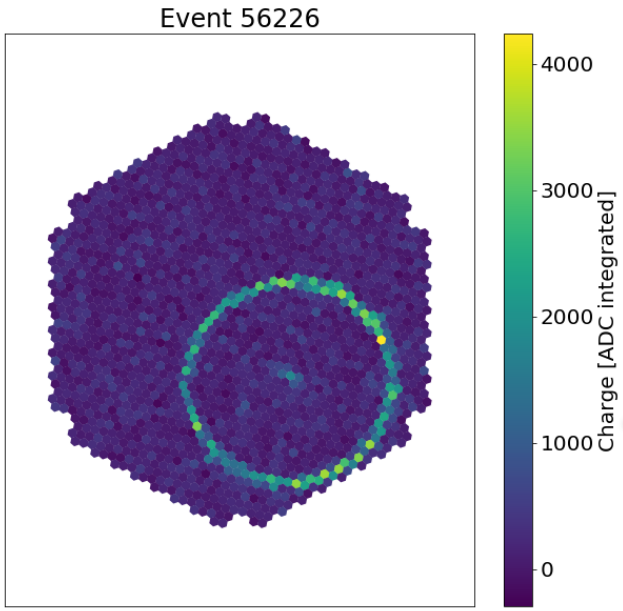

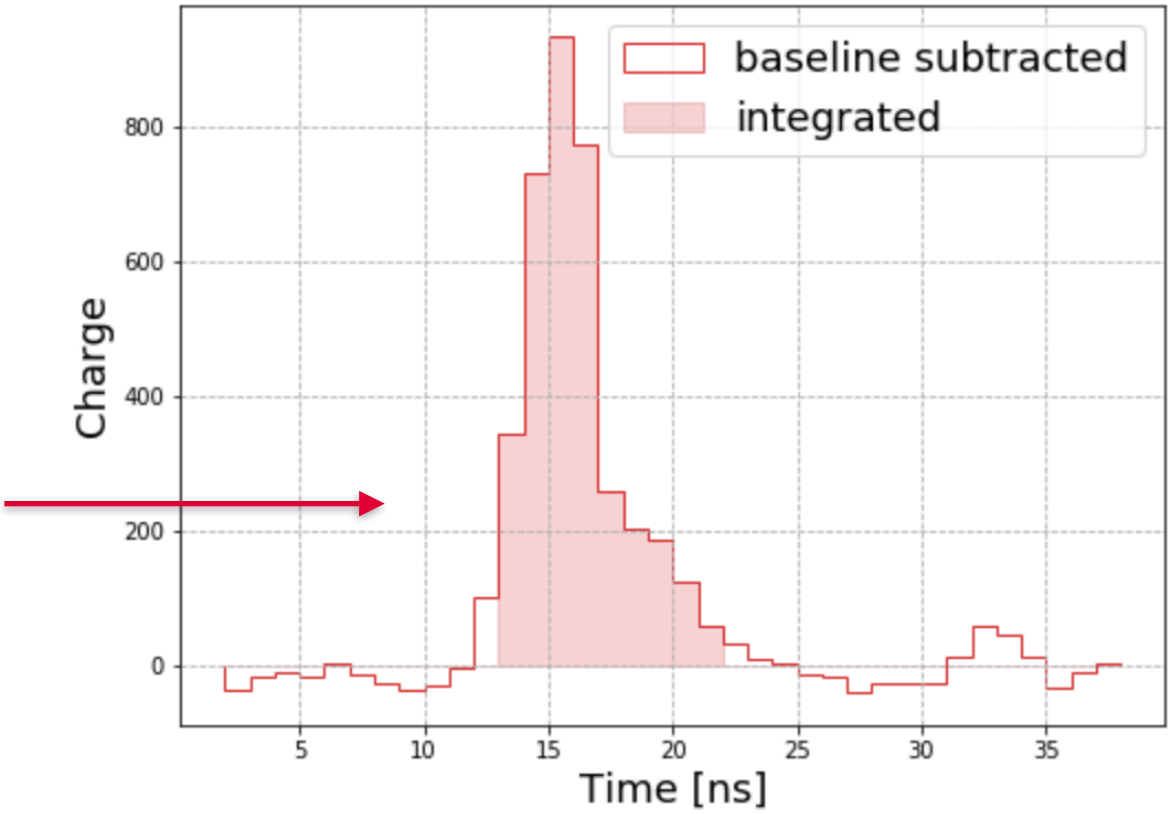

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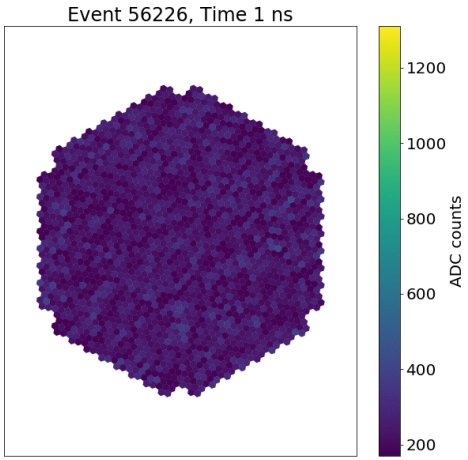
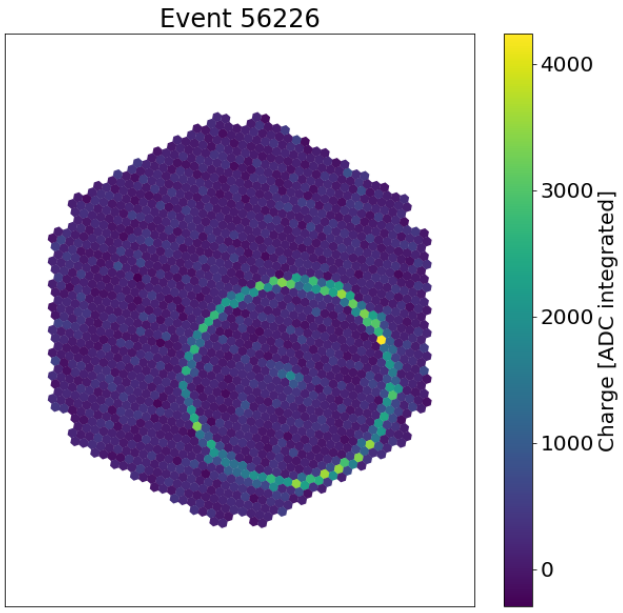




ADC to phe

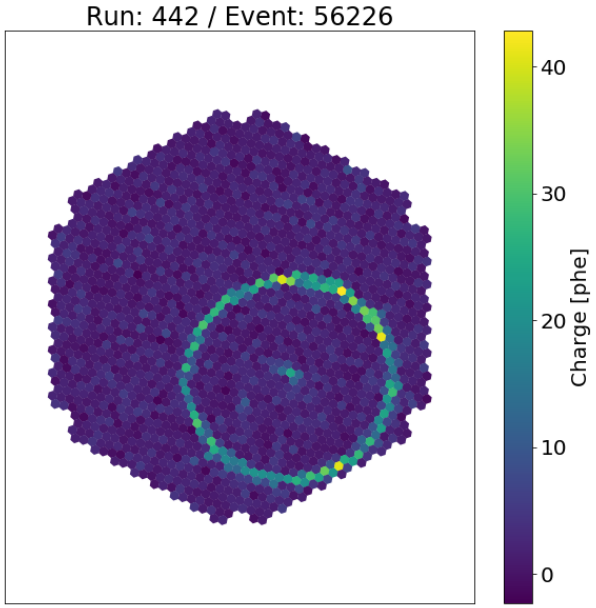
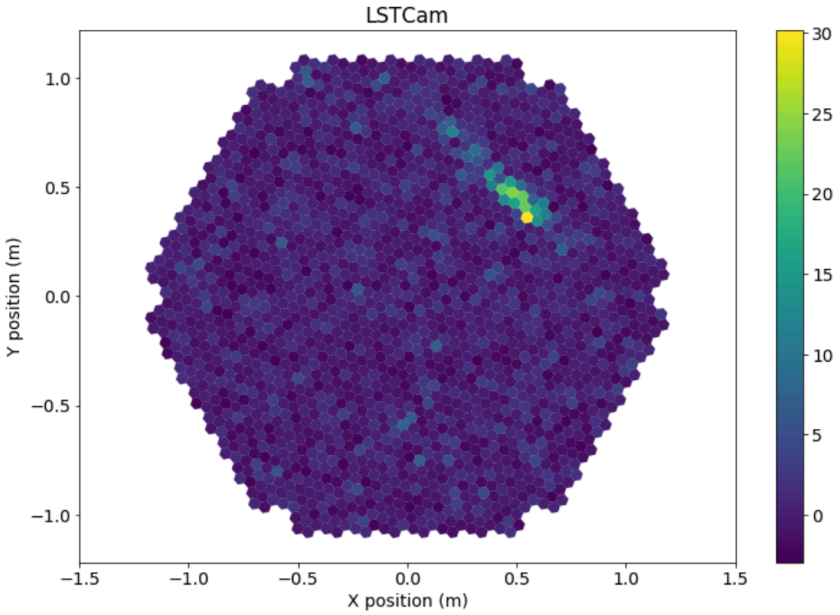


Image cleaning

- We get rid of pixels containing non significant signals
  - Cuts using different threshold levels in the number of photoelectrons
  - Arrival time also used

Original image



Cleaned image

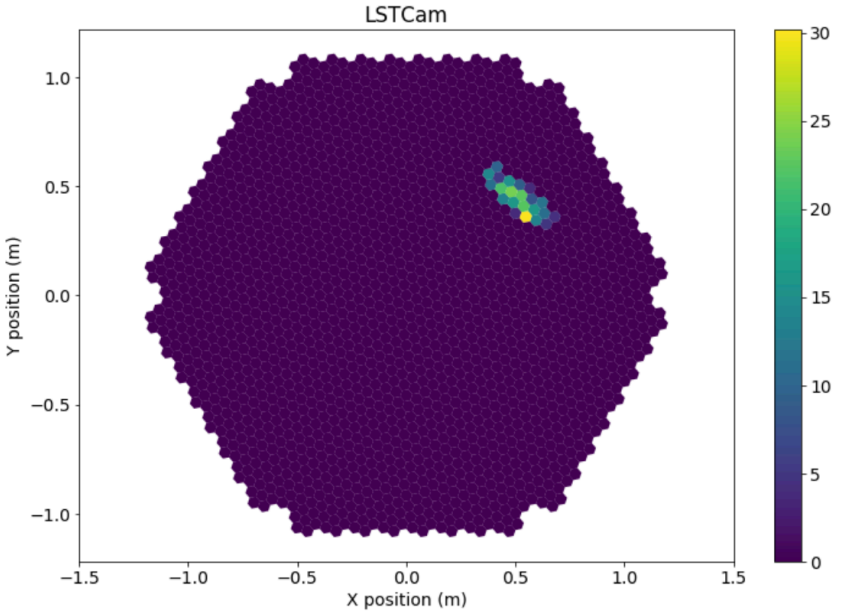
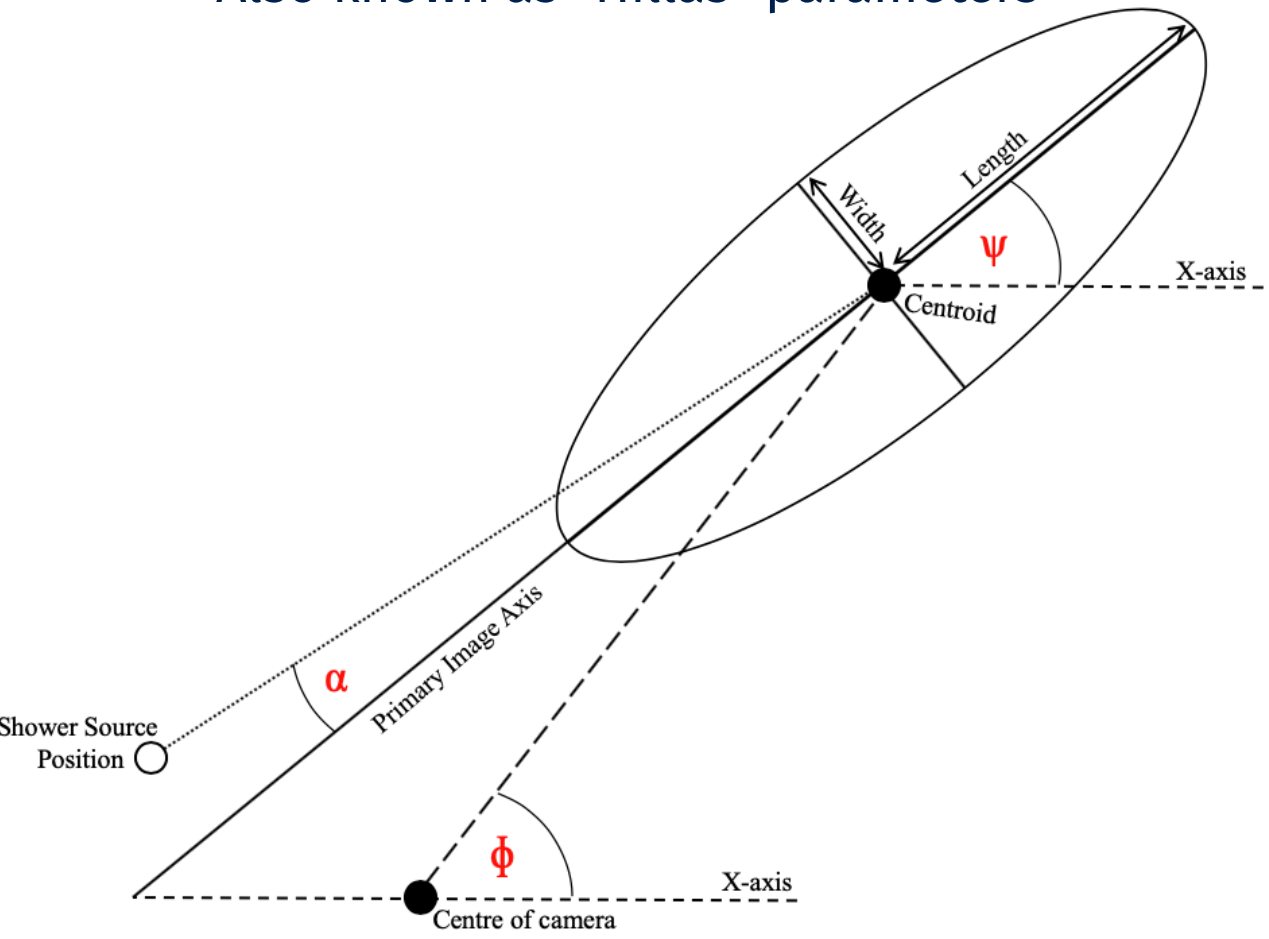


Image parameter calculation

- Also known as “Hillas” parameters



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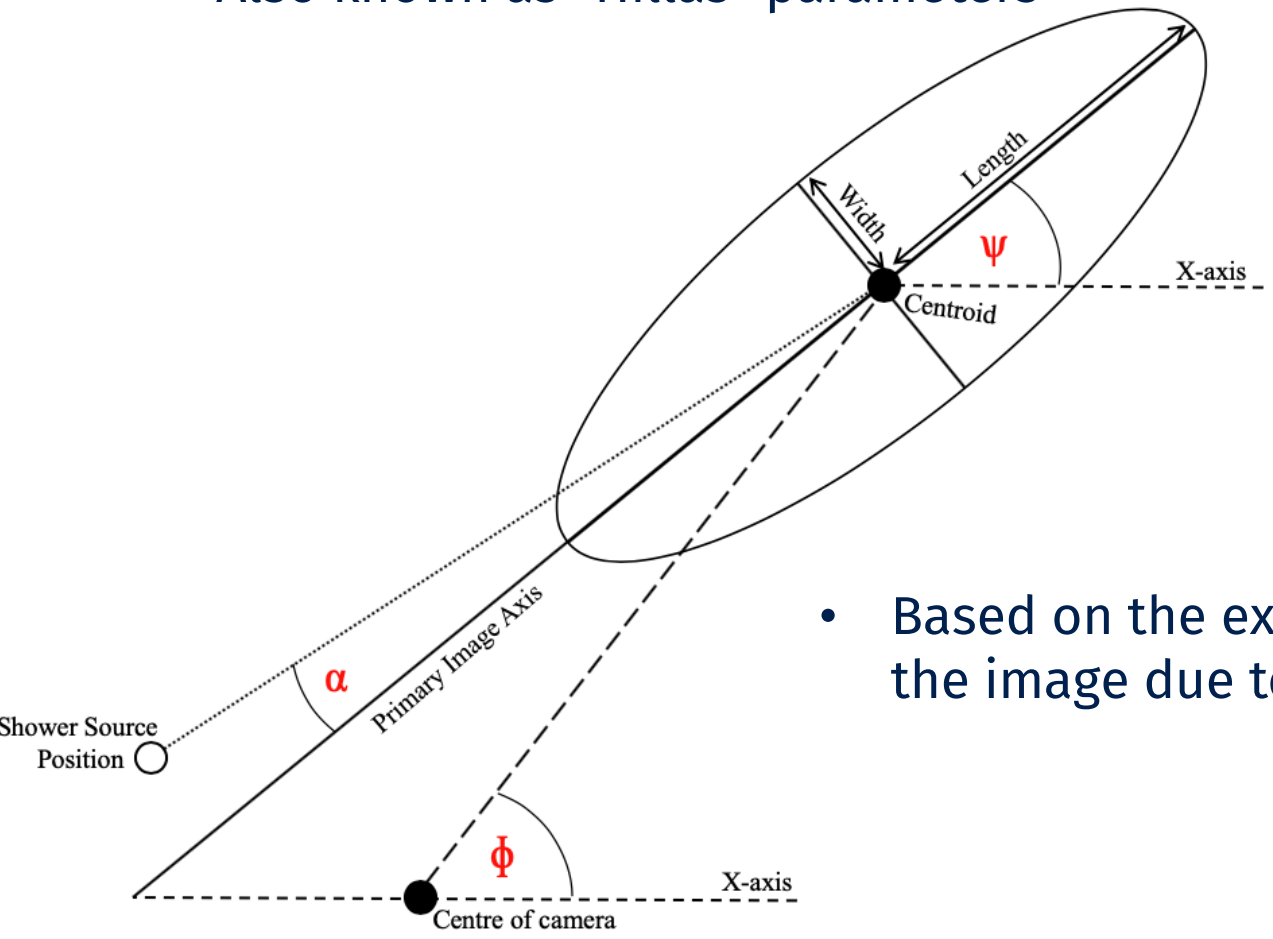
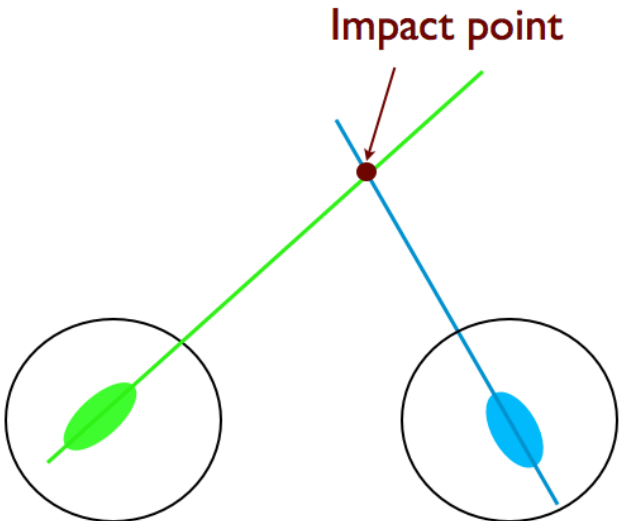
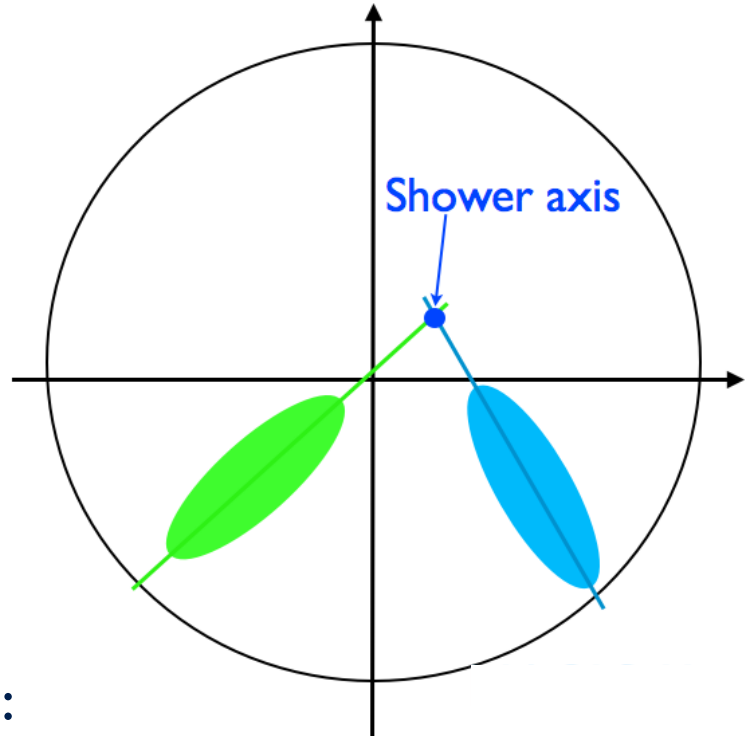


- Based on the expected shape of the image due to shower physics

Stereo Image parameters

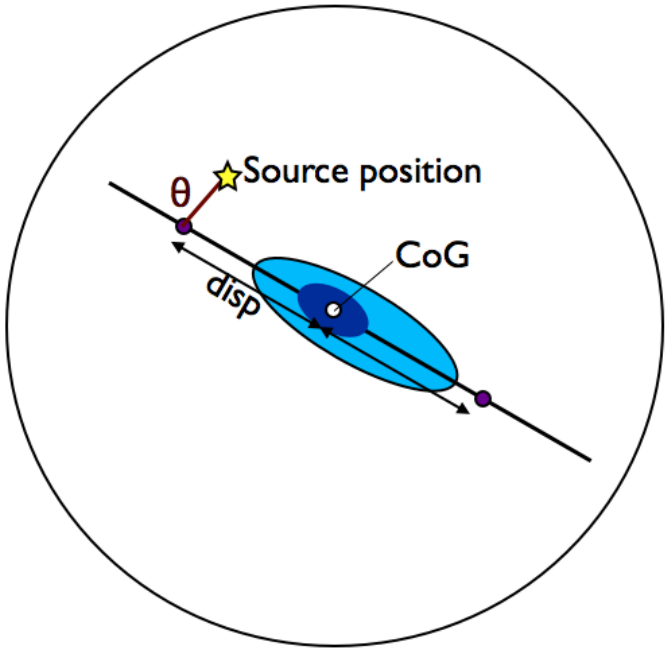


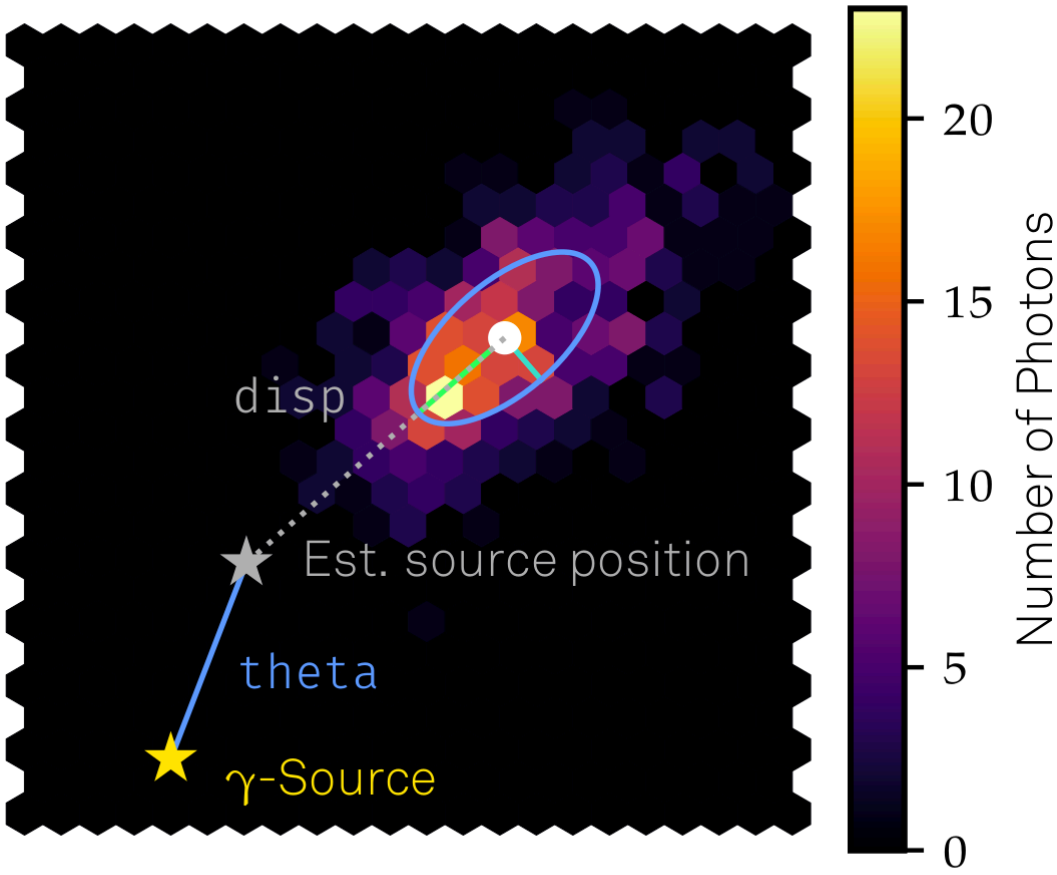


- Stereo image reconstruction helps on:
  - Energy and Direction reconstruction
  - Gamma/hadron separation

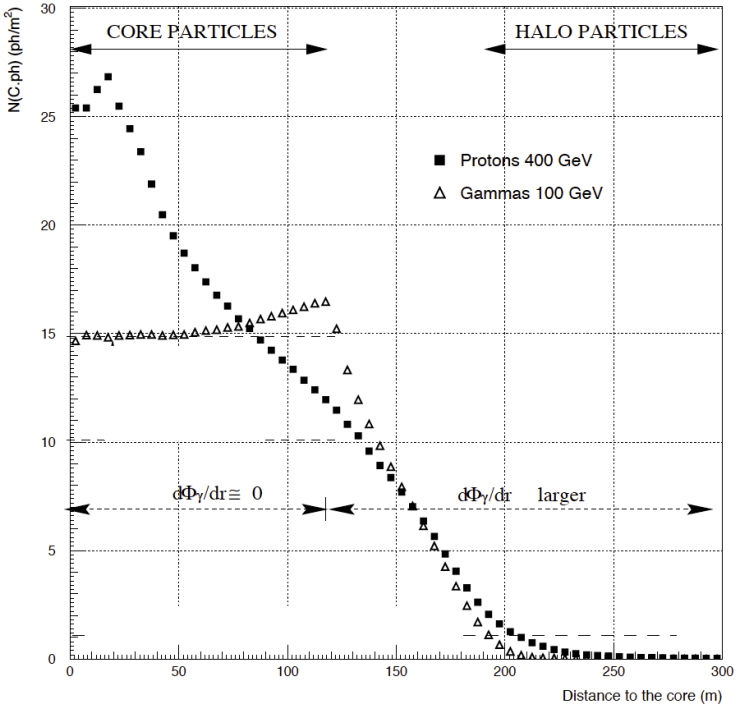
Direction reconstruction

- Disp method usually used
- The “disp” is the distance between the image CoG and the estimated source position

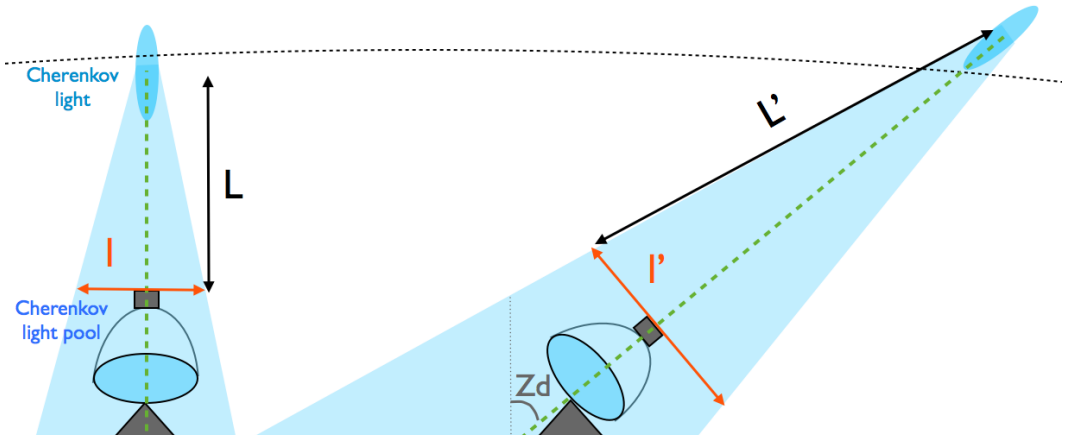




Energy estimation dependence

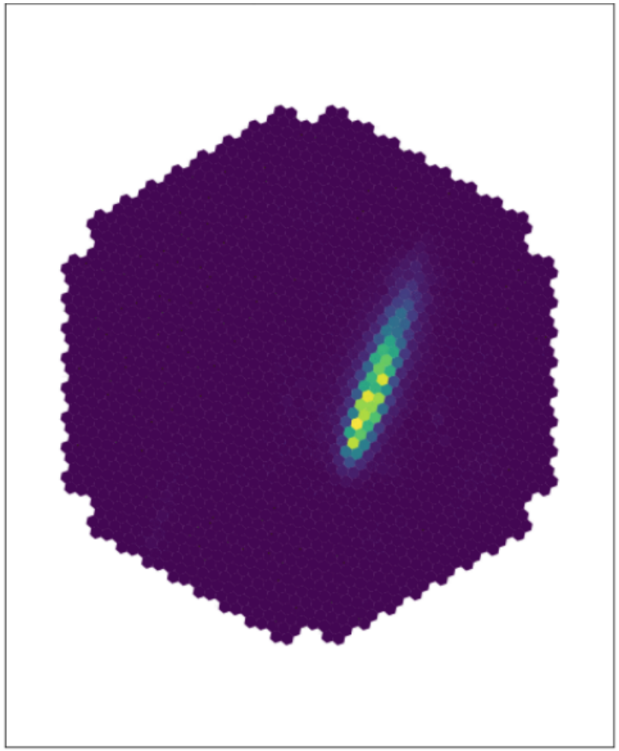


- Energy depends on several parameters:
  - Impact parameter
  - Zenith angle of the observation
  - Hmax (height of maximum of the shower)
  - Azimuth (due to geomagnetic field effects)

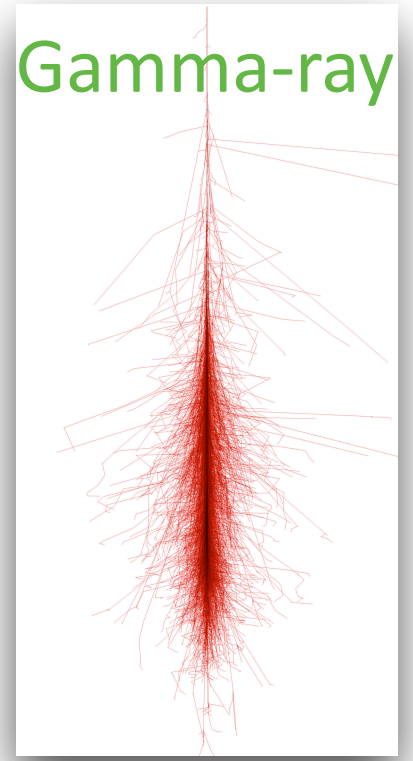


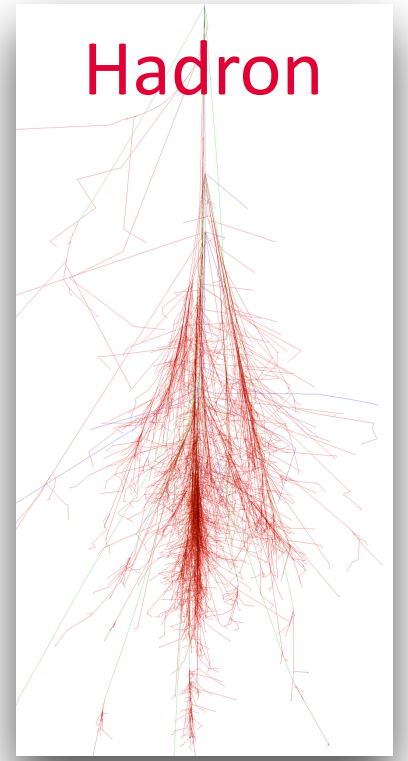
Energy estimation

- Related to the intensity detected by the telescope
  - (For a given impact parameter)
- Estimated using Machine Learning methods such as Random Forest
- Train dataset are MC gamma-ray simulations covering the whole energy range of interest



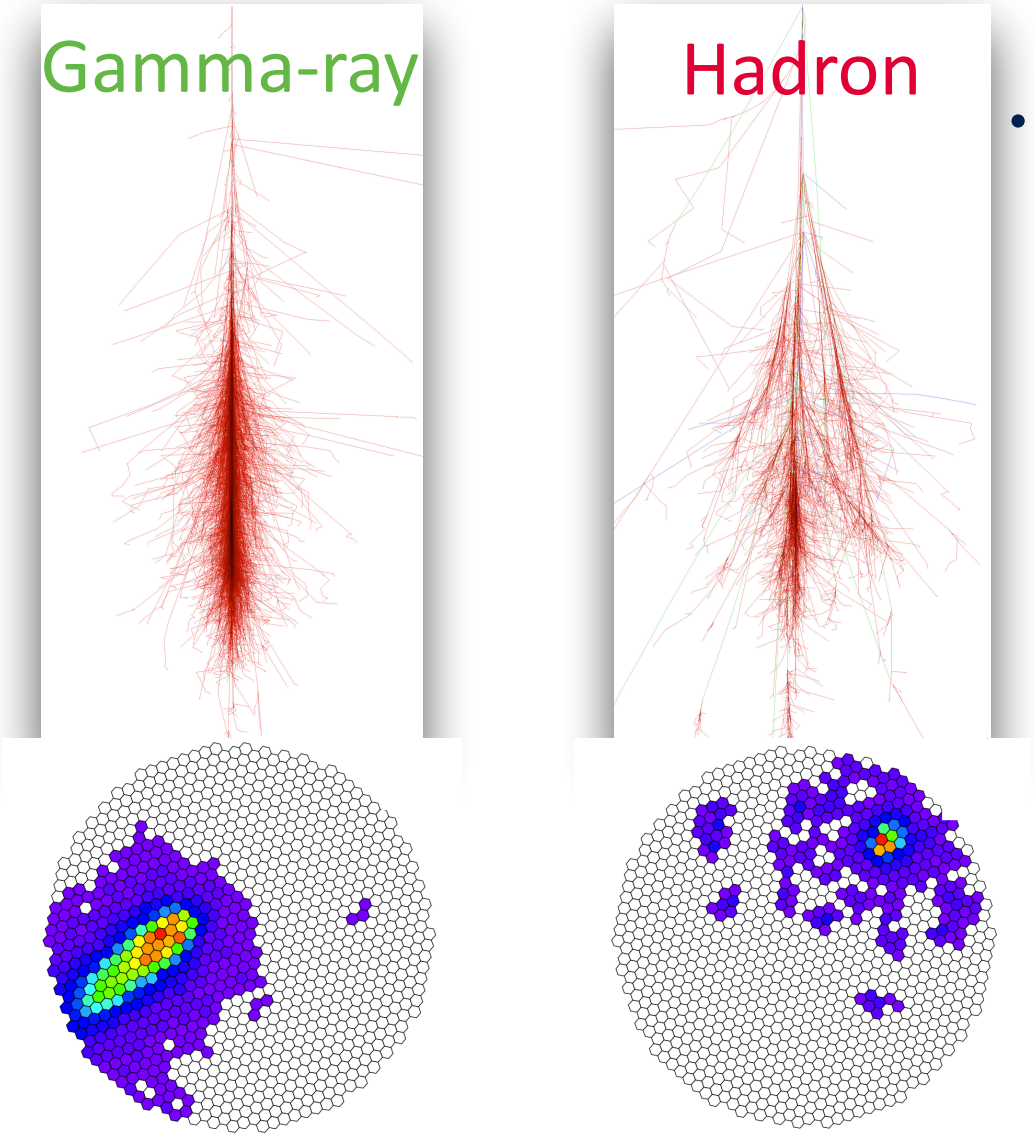
Importance: gamma/hadron separation





- Gamma and hadron-initiated showers have different shapes
  - Gamma-initiated showers are smoother and more compact
    - They produce elliptical images
  - Hadron-initiated showers are clumpier and less compact
    - They produce irregular images

Importance: gamma/hadron separation



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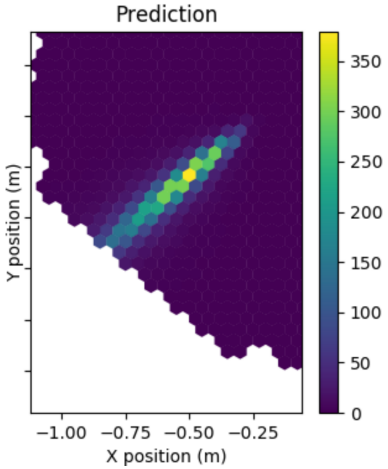
Gamma/hadron separation: techniques

- Machine learning techniques such as Random Forest, Boosted Decision trees
  - They give a good performance in all the currently existing IACTs

- Full reconstruction: Further than the “classic”
  - Template-based methods:
    - Semi-Analytical templates (HESS analysis)
    - MC-filled templates (ImPACT, also used in HESS)
  - Deep Learning methods:
    - Convolutional Neural Networks for a full reconstruction of the energy, direction and type of particle
      - Usage of public software (PyTorch, TensorFlow)
      - Dedicated task group in CTA



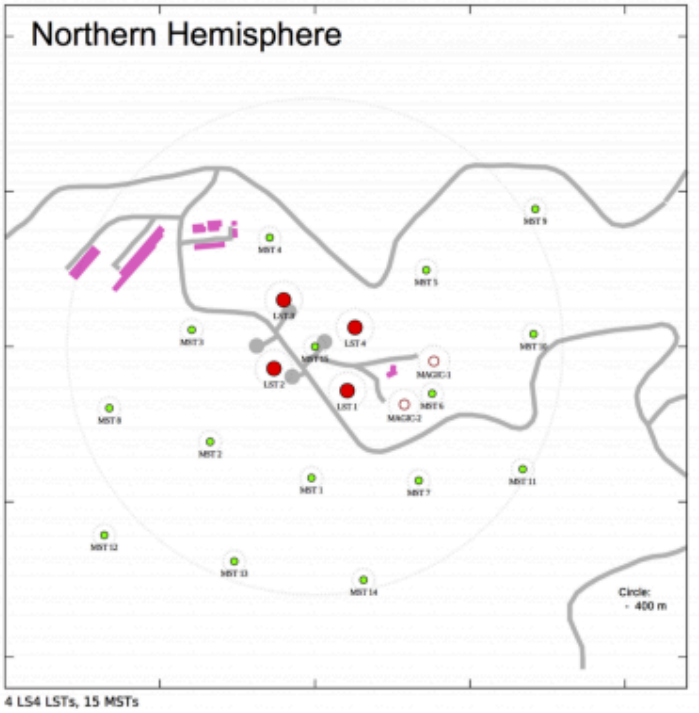
cherenkov telescope array

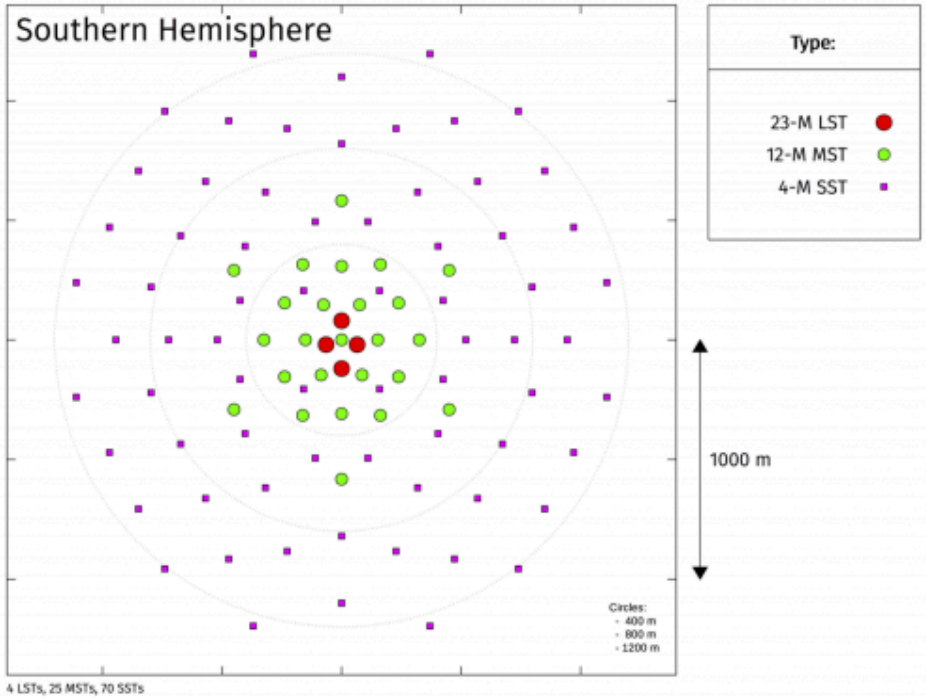
Figures of merit - Instrument Response Functions

what you need to plot to check the performance of your system

Layout

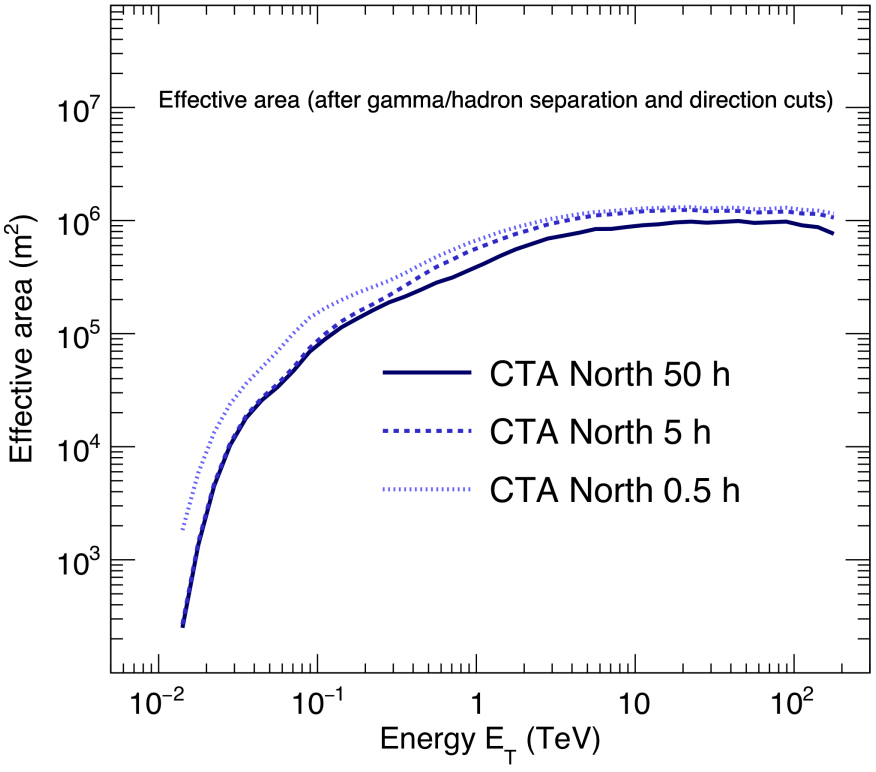
- After you have the energy and direction reconstructed and you have separated your data, it is time to calculate the figures of merit that will tell you the performance of your telescope.
- I will show the different figures of merit of CTA for the layouts described below

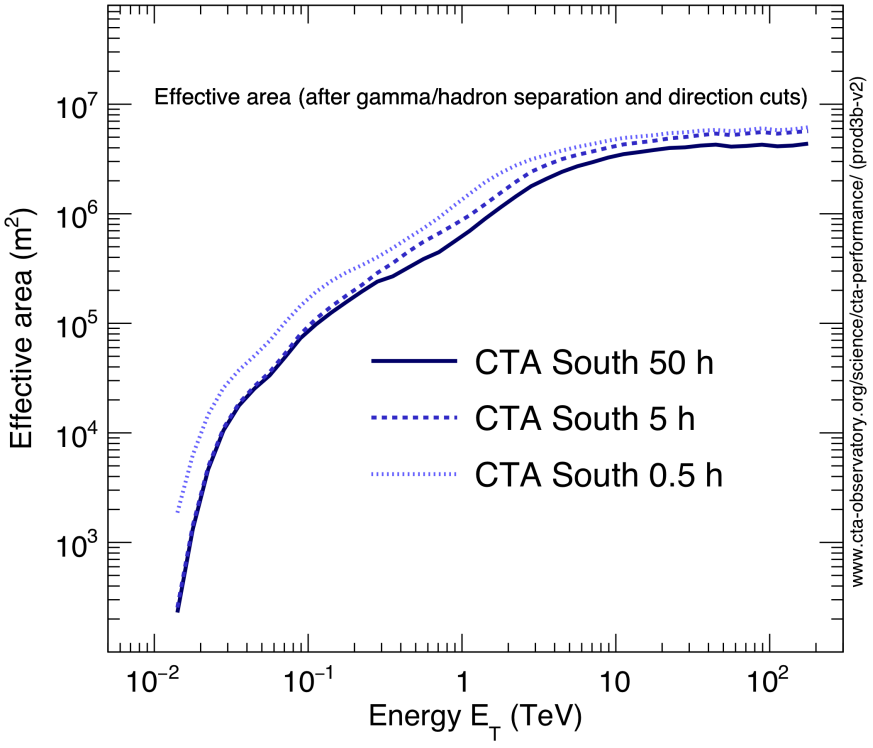




Collection area

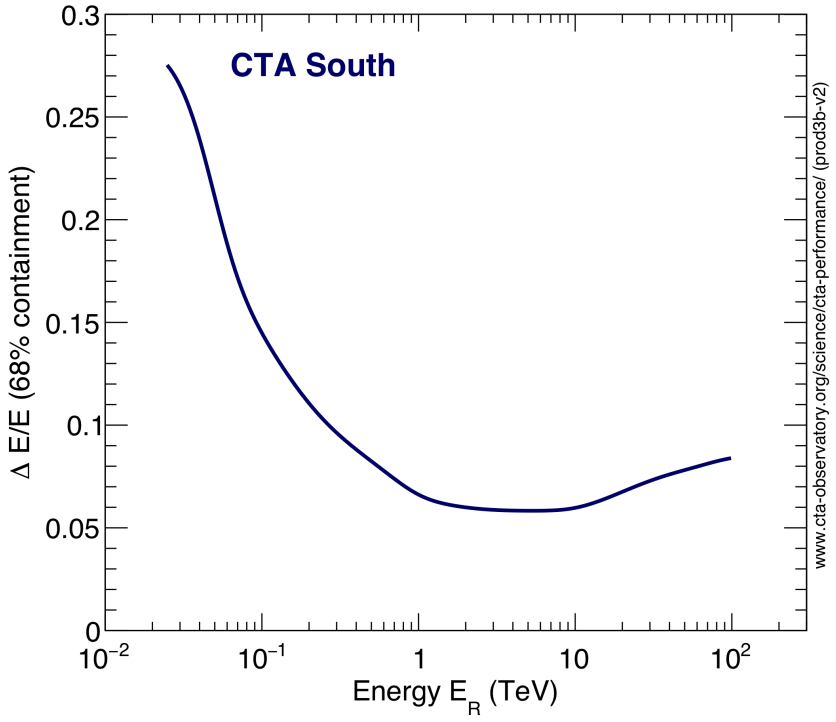
- It indicates up to which distance your array effectively work
- Calculated using the number of simulated events, those that survive the reconstruction cuts and the simulated area

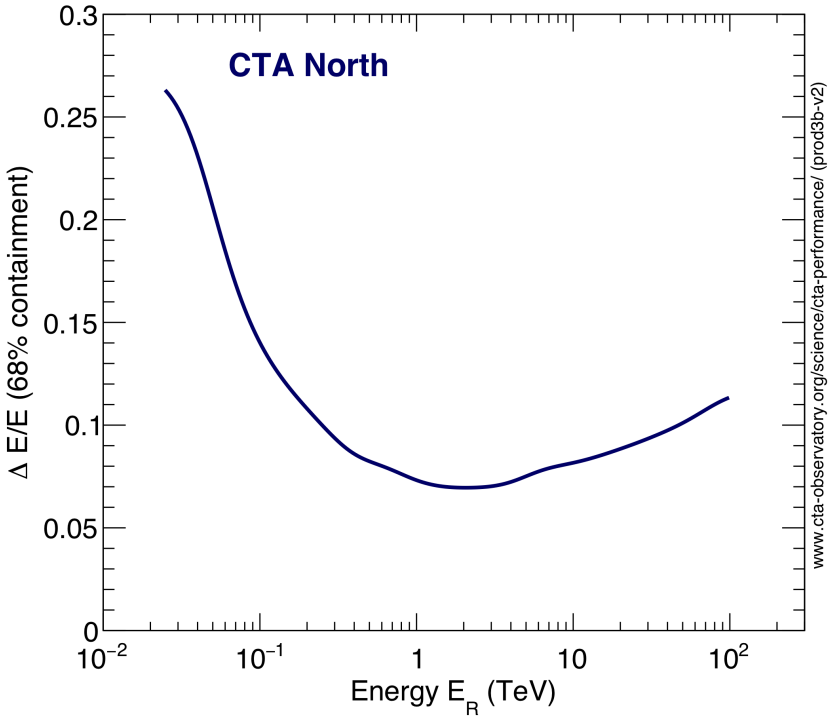




Energy resolution

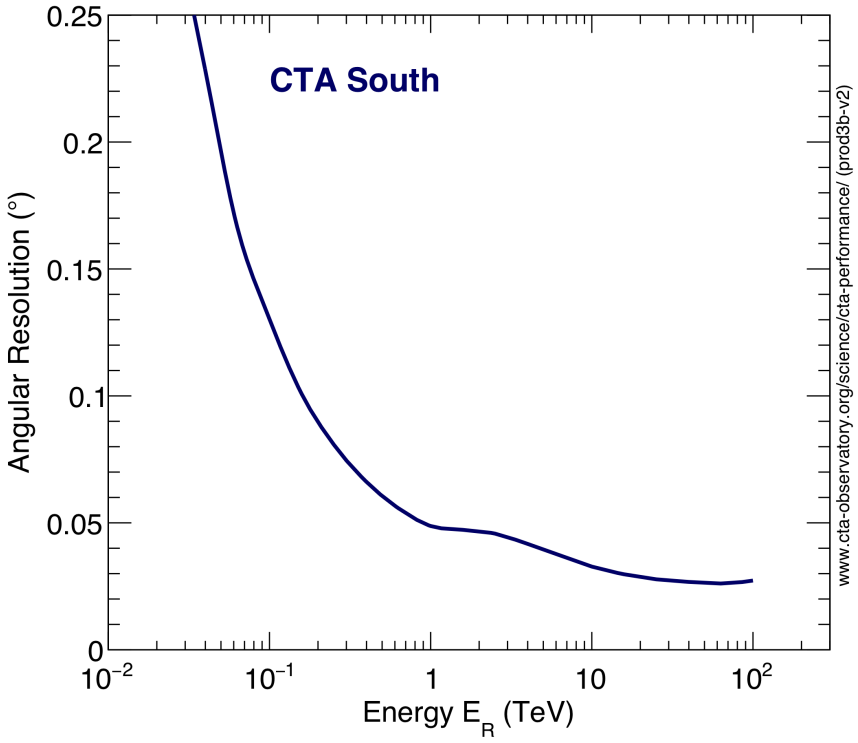
- Defined as the sigma of the gaussian of the relative error between the reconstructed and the true energy
- A lower energy resolution implies a better spectral reconstruction

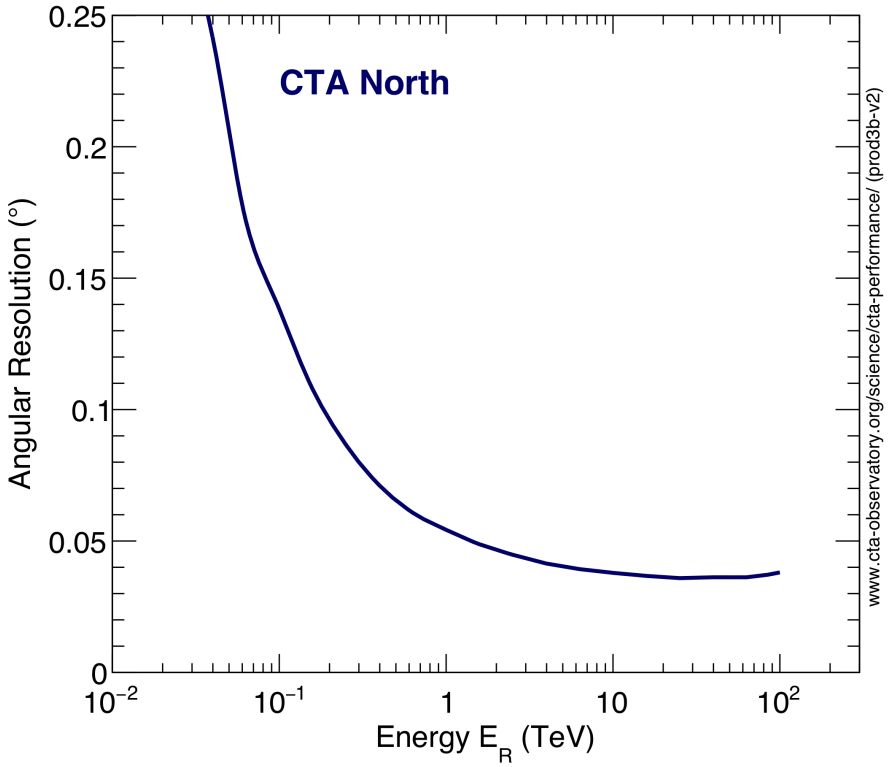




Angular resolution

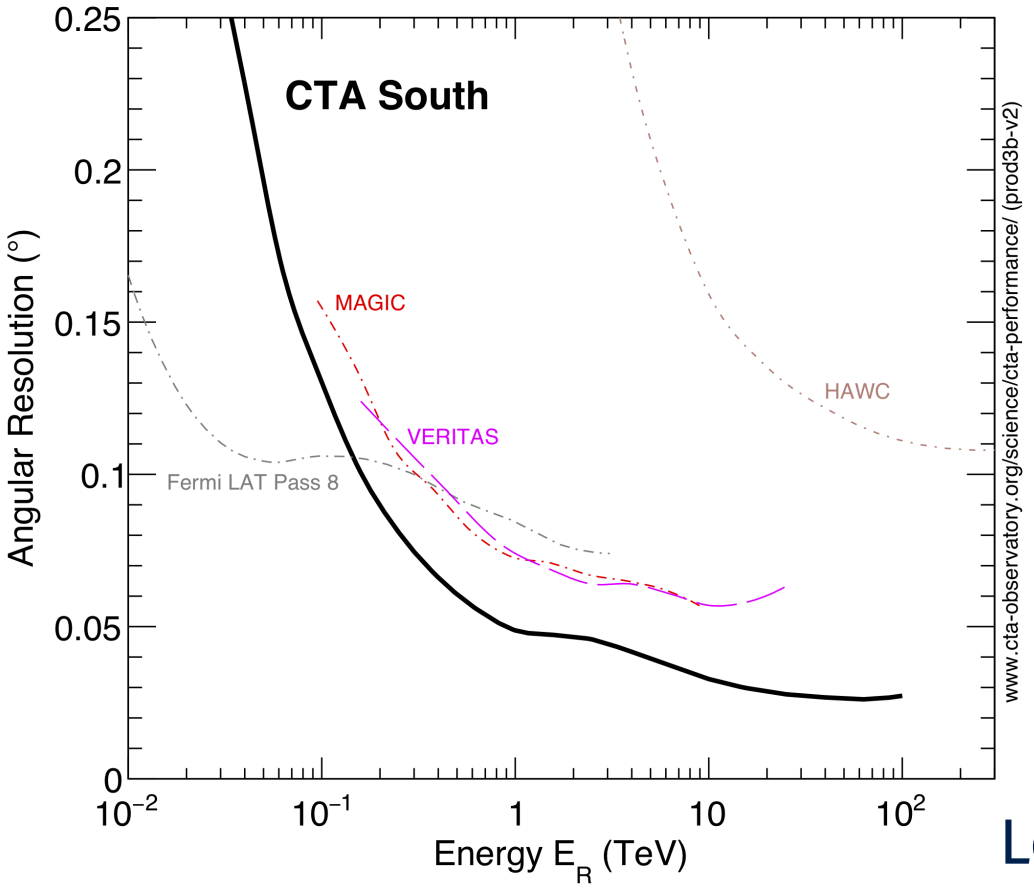
- Usually defined as the 68% containment radius of well reconstructed events in an energy bin
- It evaluates the ability of your instrument to resolve a source





Angular resolution comparison

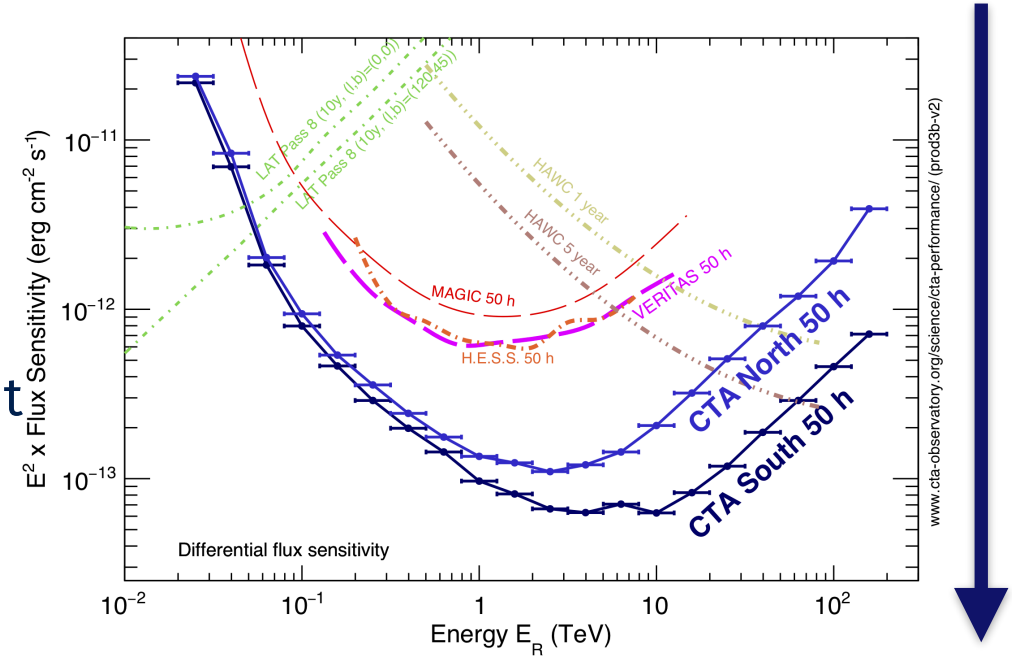
- Significant improvement with respect to the currently existing facilities
- CTA will be able to resolve most of the known galactic sources



Lower is better

Differential Sensitivity

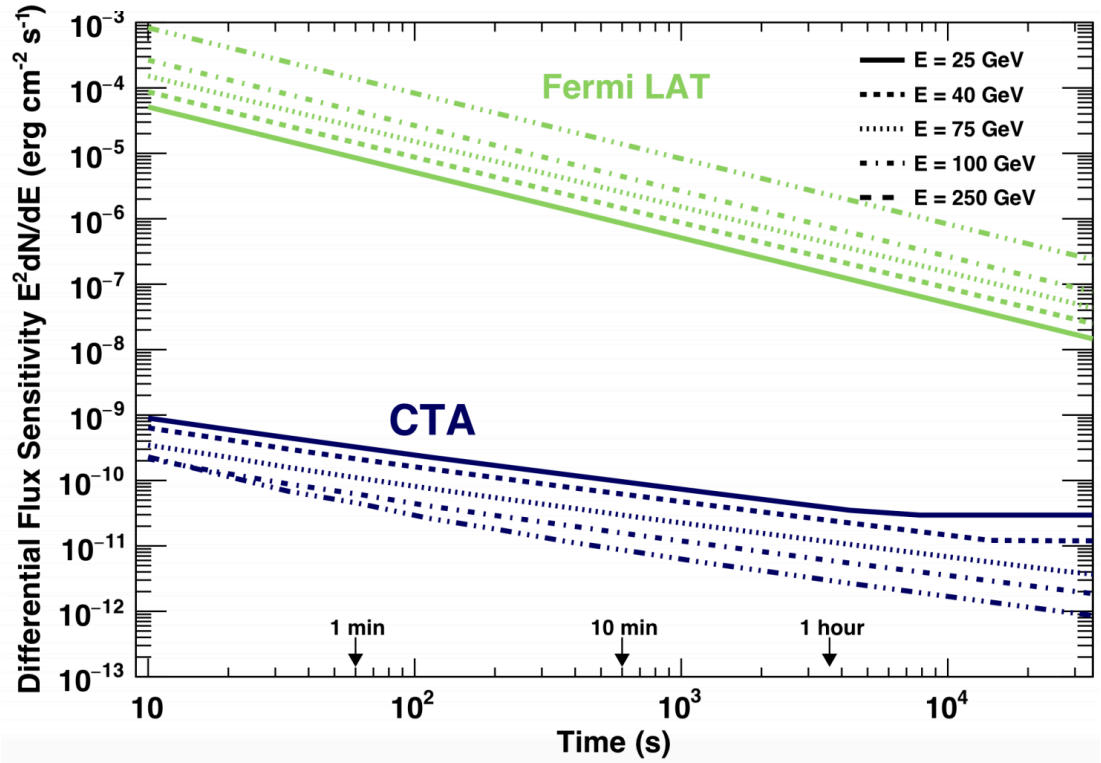
- One of the most important figures of merit that you will see
- It represents the lower differential flux an instrument is able to measure with 5σ significance
- The improvement of CTA with respect to the currently existing facilities is around one order of magnitude



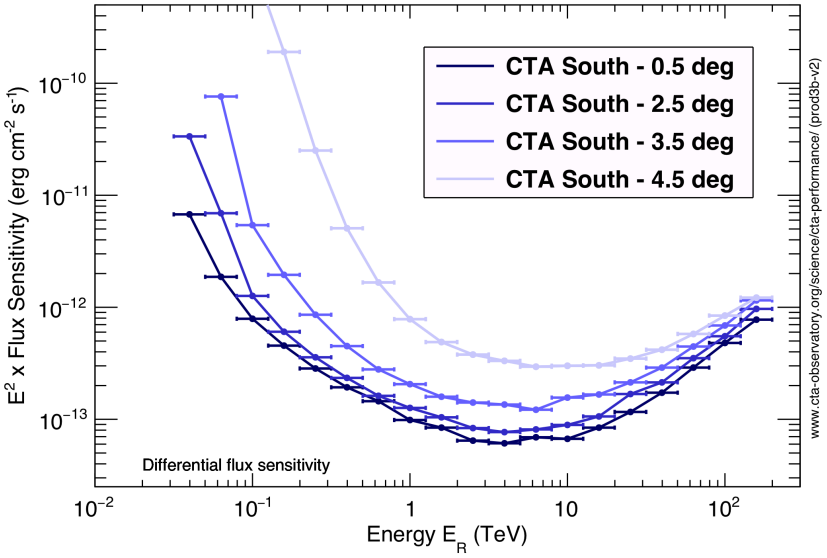
Lower is better

Sensitivity vs time

- Important for transient sources
- Sources (e.g. GRBs) emitting a very large flux for a short time at ~tens of GeV may produce one photon in Fermi-LAT, but thousands in CTA!

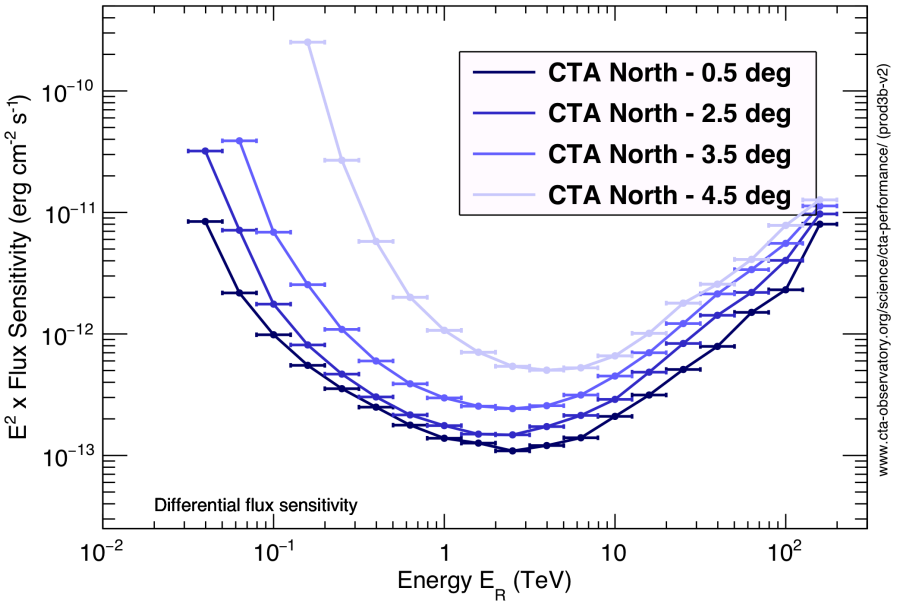


Off-axis performance



- Sensitivity rapidly degrades with the off-axis angle

- While performing scans, not only the sensitivity near the center of the cam is important



Summary

- IACT Analysis Summary:
  - Calibration and signal extraction
  - Image cleaning and parametrization
  - Stereo image reconstruction
  - High level products
    - Gamma/Hadron separation
    - Energy reconstruction
    - Direction reconstruction

- CTA performance has been shown. Important figures of merit:
  - Collection area, Angular and energy resolution and differential sensitivity
  - Also important: sensitivity vs time and off-axis sensitivity

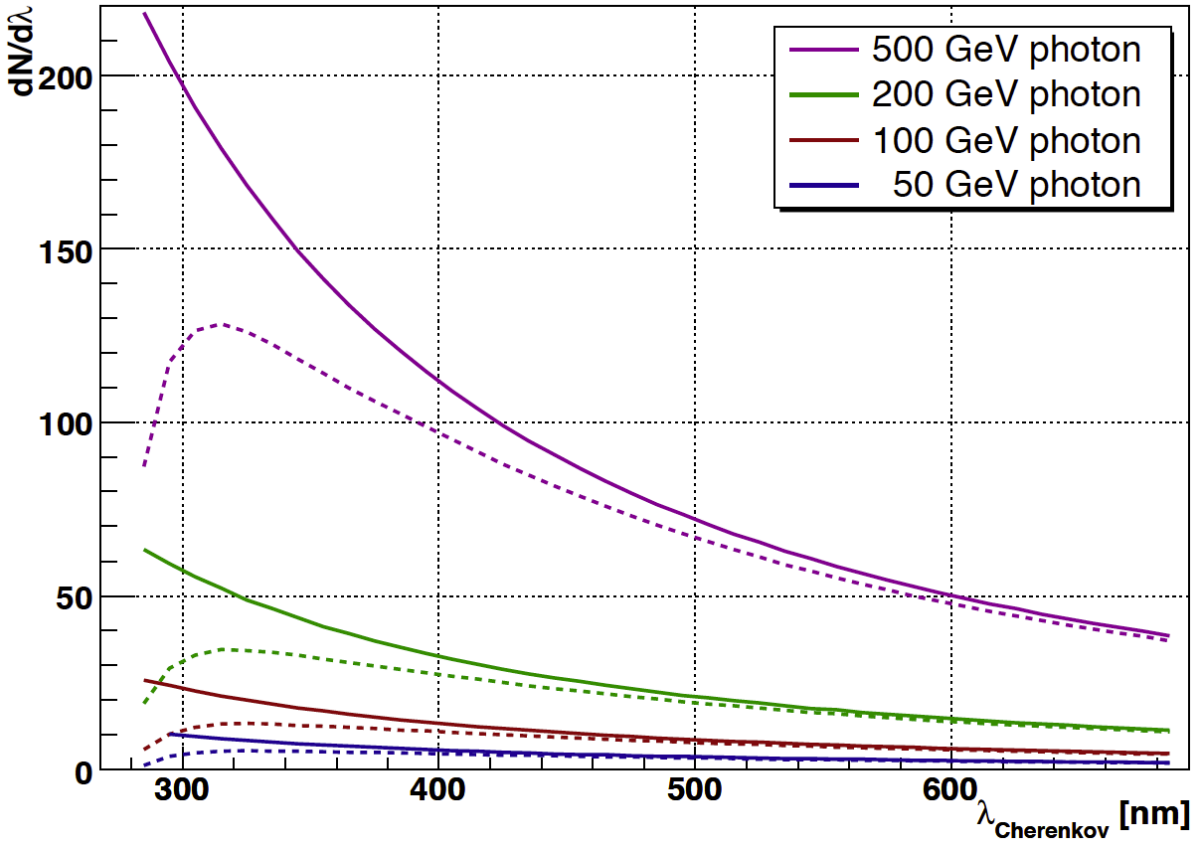
cherenkov telescope array

Thanks!

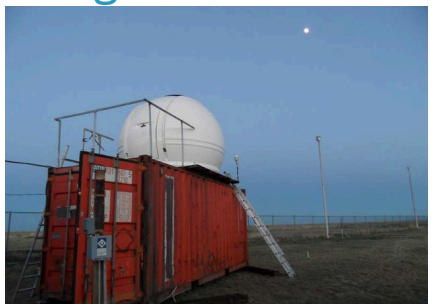
cherenkov telescope array

Backup

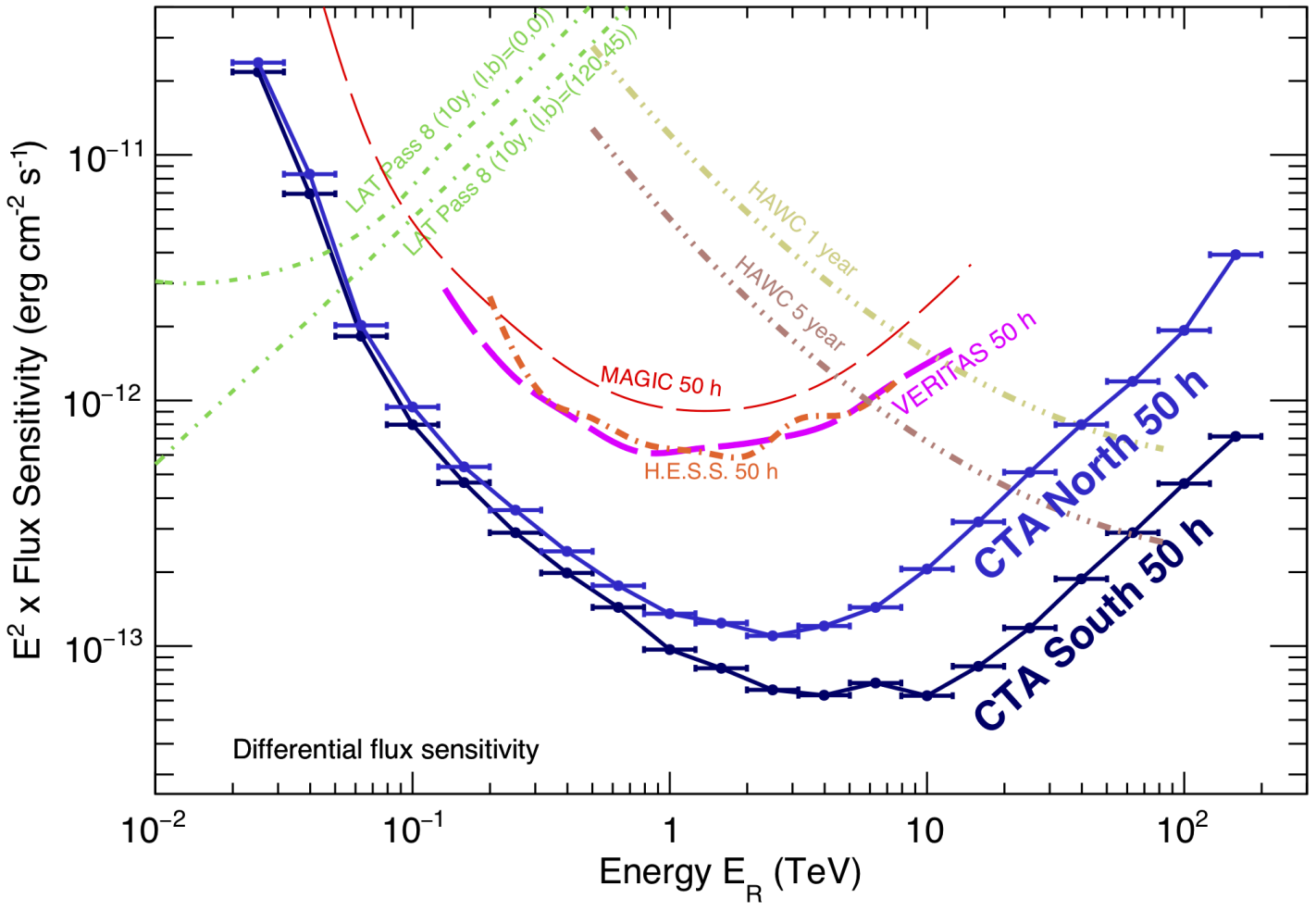
Calibration: Atmosphere absorption



- Solid lines are the emitted Cherenkov spectrum
- Dashed lines are the detected one at 2200 m
- The atmosphere transmission plays a very important role in energy estimation
  - it is modified by clouds, dust, aerosol...
  - Continuous monitoring using LIDARs



Sensitivity



Lower is better