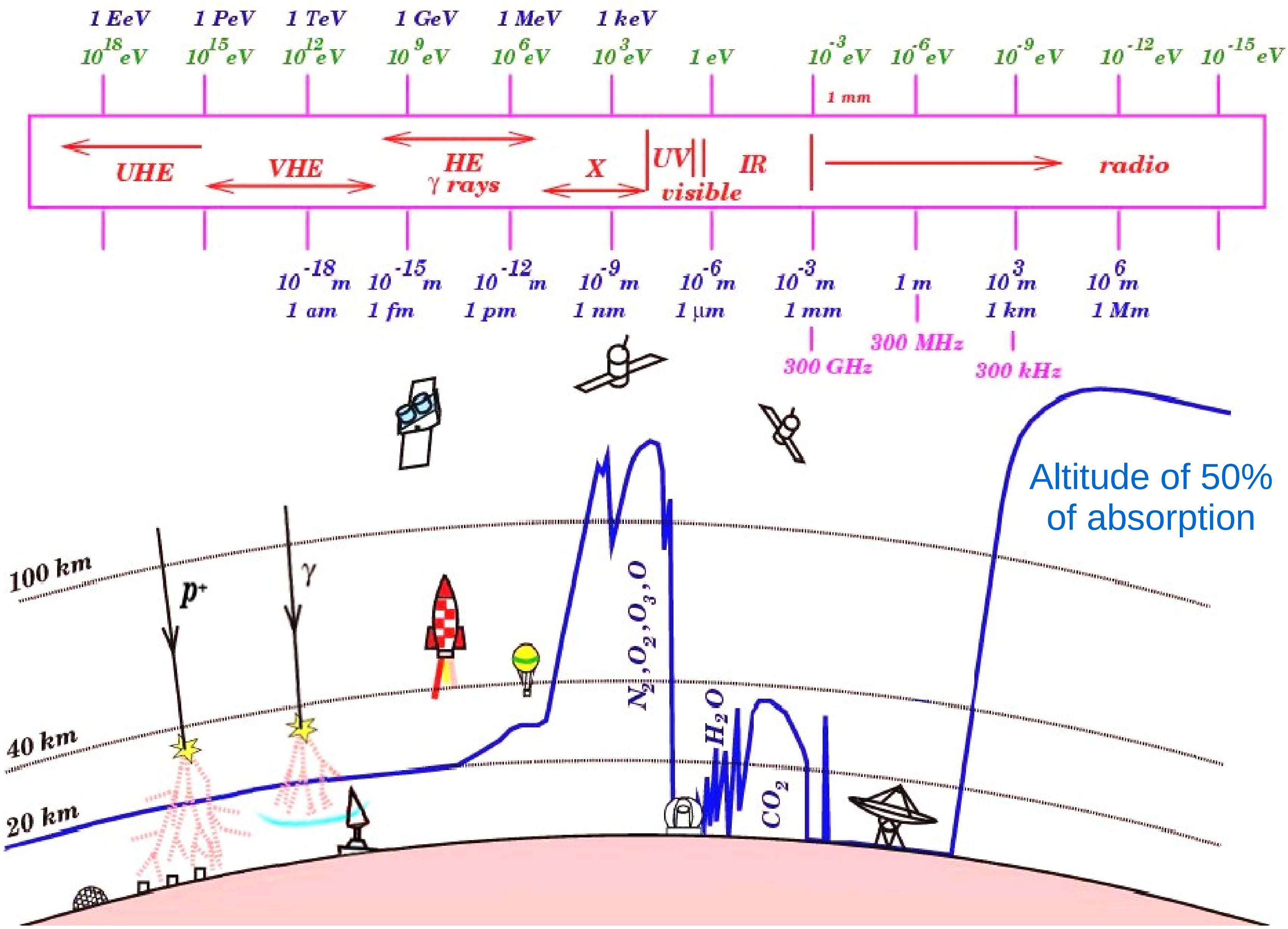
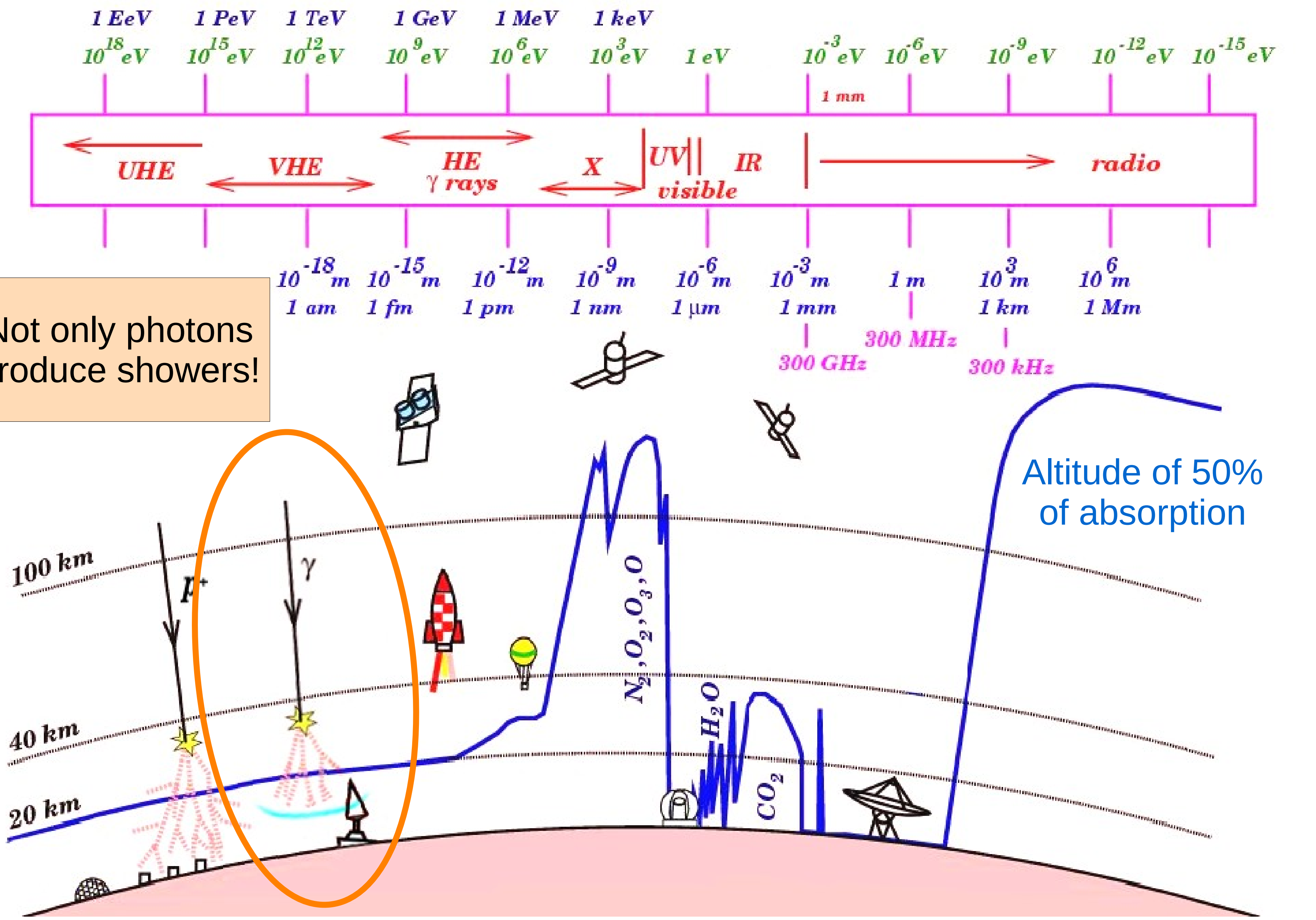
Imaging Atmospheric Cherenkov Telescopes:
Analysis I(I)

Tarek Hassan
DESY

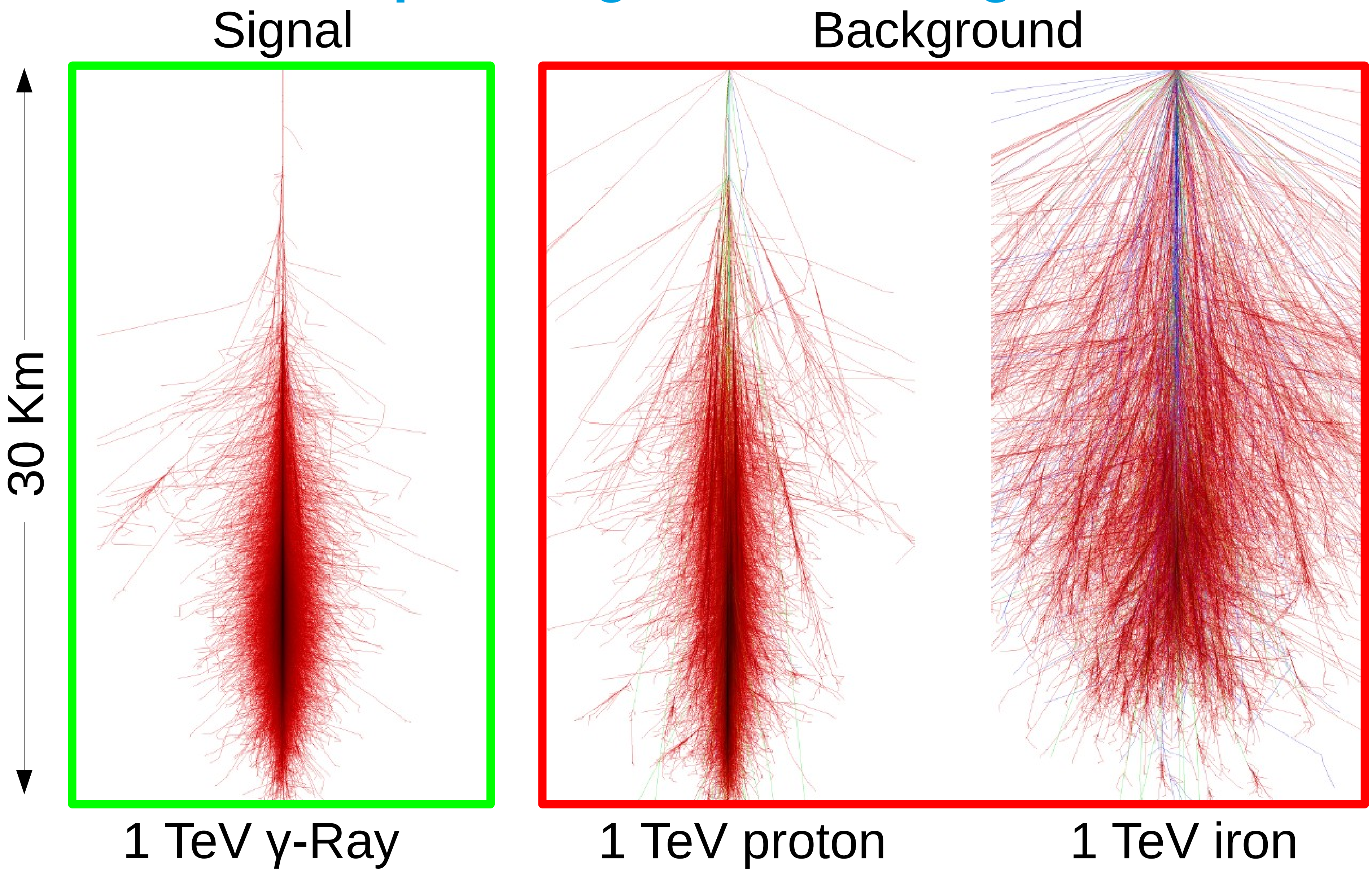


1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
10^18 eV
10^15 eV
10^12 eV
10^9 eV
10^6 eV
10^3 eV
1 eV
10^-3 eV
10^-6 eV
10^-9 eV
10^-12 eV
10^-15 eV
1 mm
UHE
VHE
HE
γ rays
X
UV
IR
visible
radio
10^-18 m
1 am
10^-15 m
1 fm
10^-12 m
1 pm
10^-9 m
1 nm
10^-6 m
1 µm
10^-3 m
1 mm
1 m
10^3 m
1 km
10^6 m
1 Mm
300 GHz
300 MHz
300 kHz
Altitude of 50%
of absorption
100 km
40 km
20 km
p+
γ
N2,O2,O3,O
H2O
CO2

Not only photons produce showers!

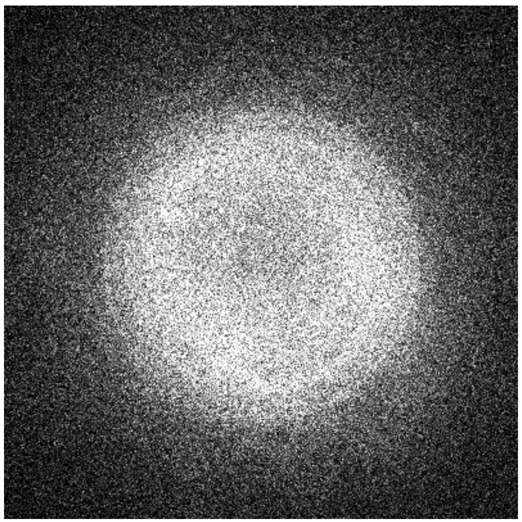


IACT technique – Signal and background

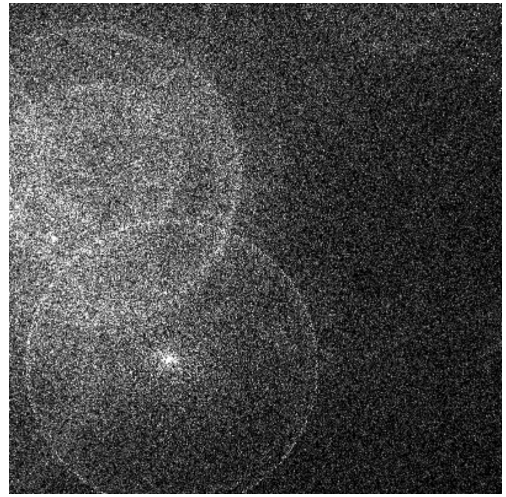


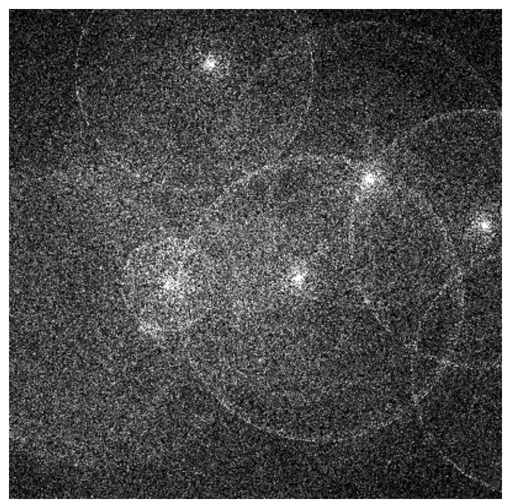
IACT technique – Signal and background

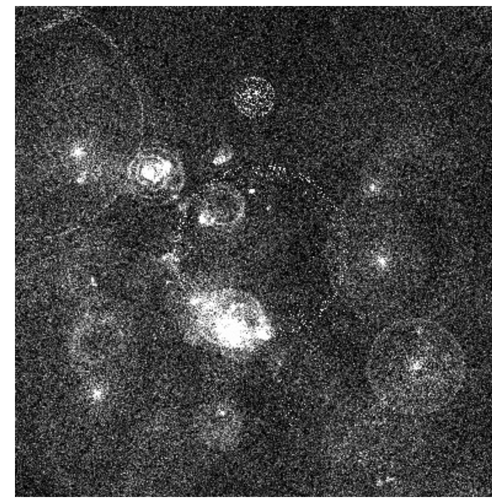
Signal



Background



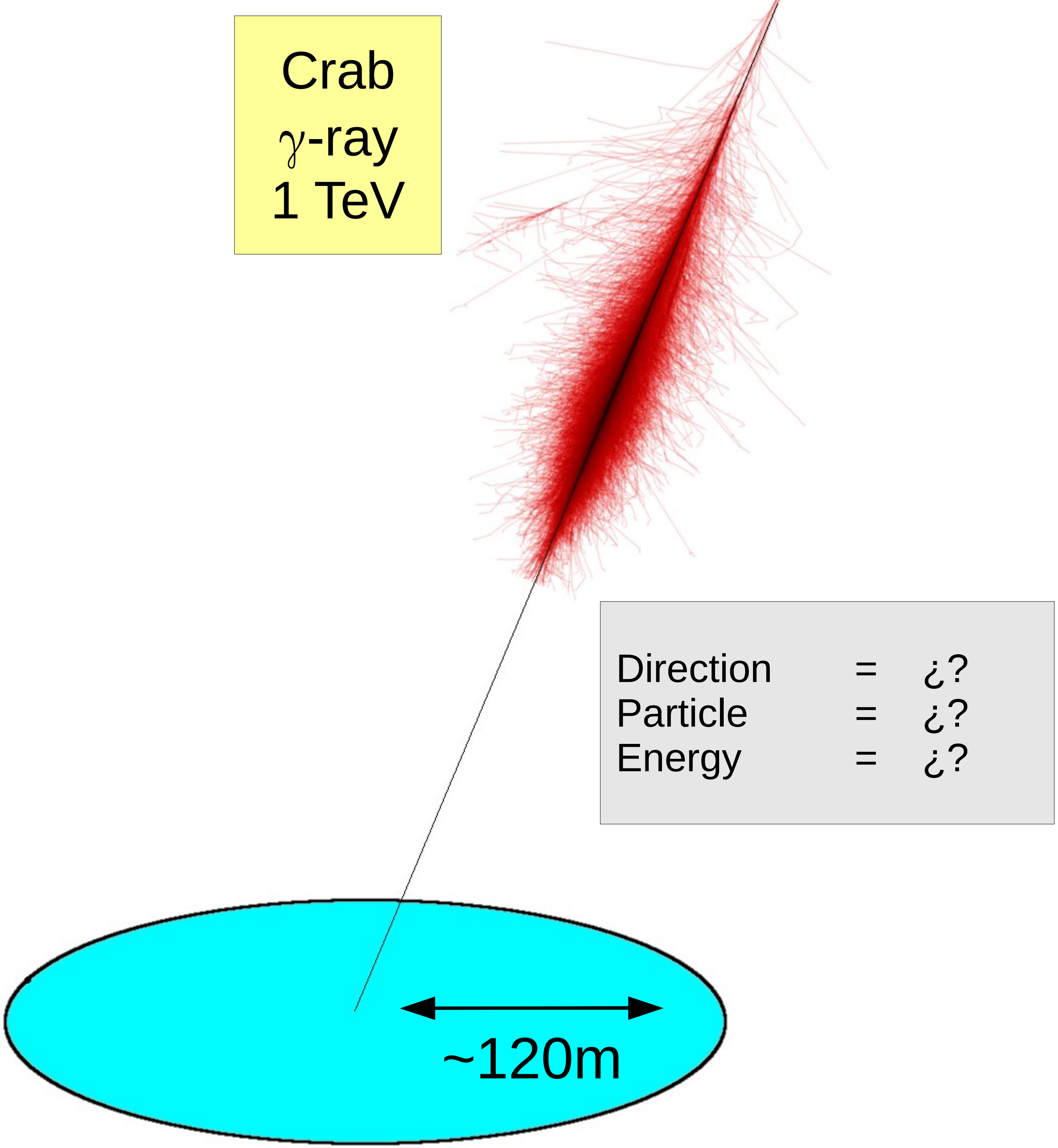




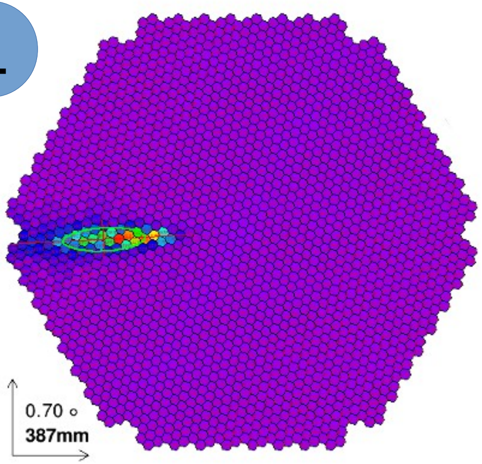
1 TeV γ-Ray

1 TeV proton

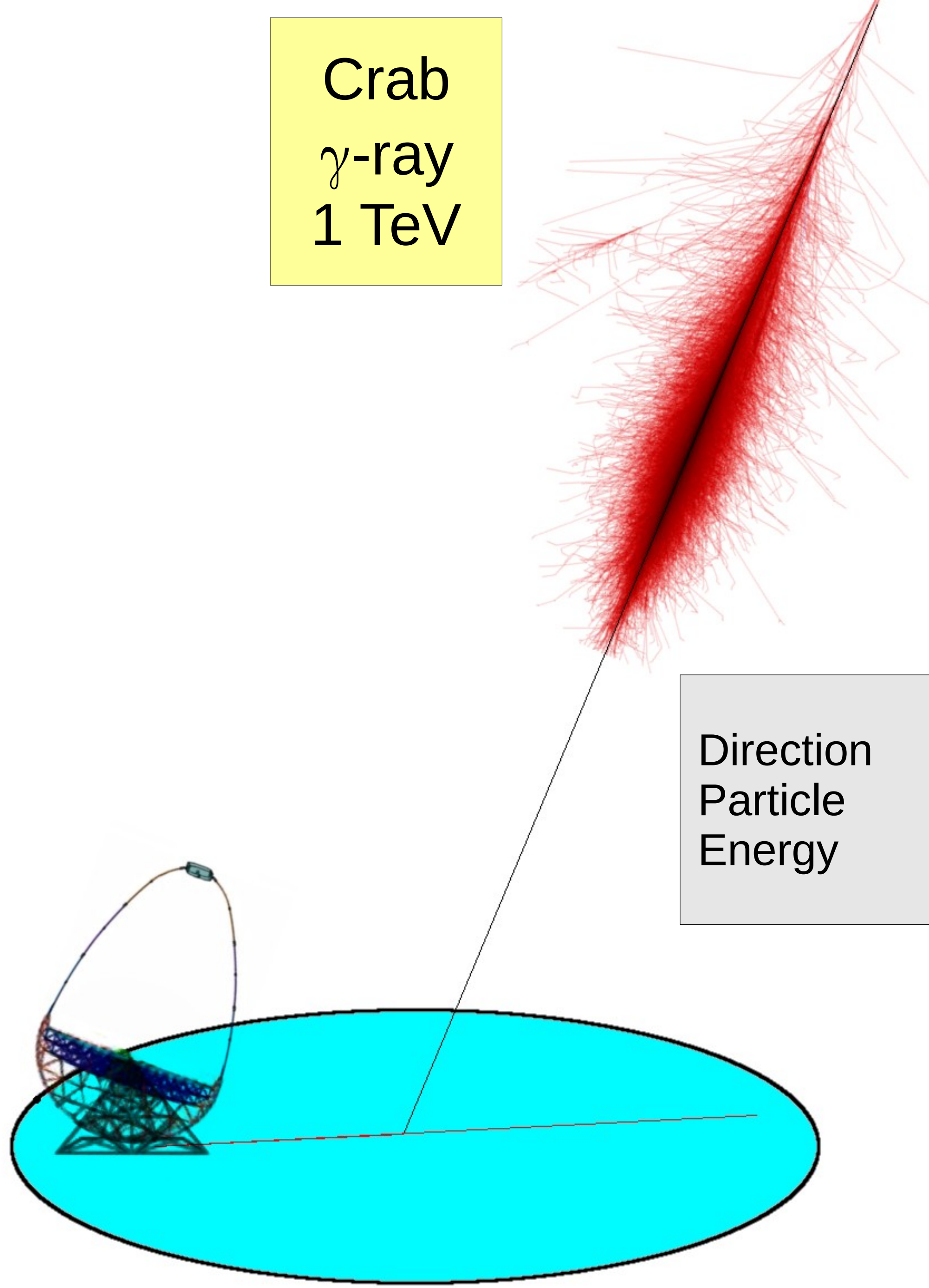
1 TeV iron


Crab
γ-ray
1 TeV
Direction = ¿?
Particle = ¿?
Energy = ¿?
~120m

1

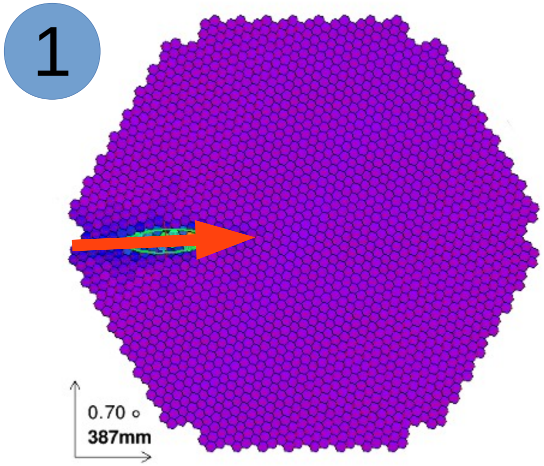


Crab
γ-ray
1 TeV



1

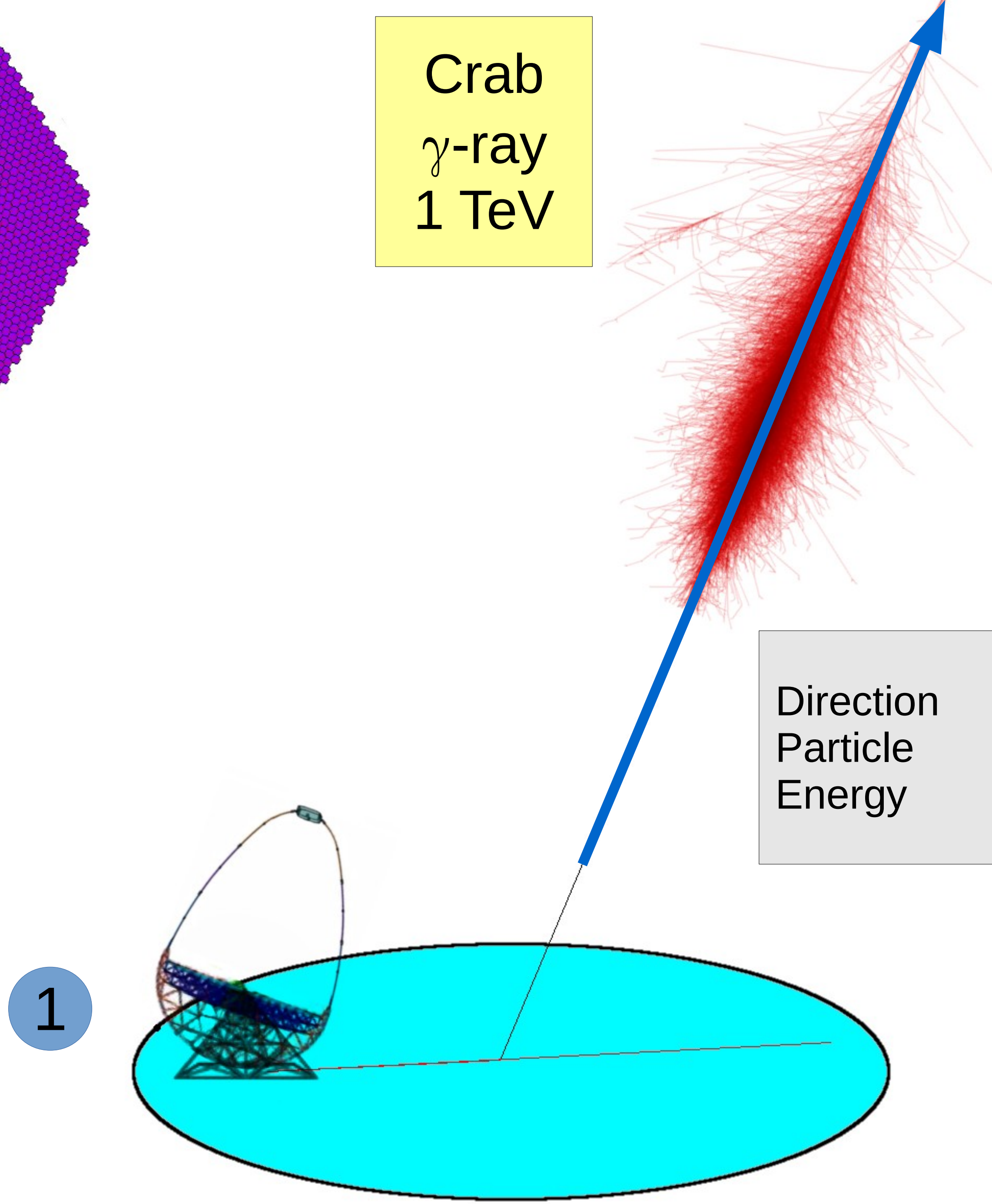
Direction = ¿?
Particle = ¿?
Energy = ¿?



Crab

γ-ray

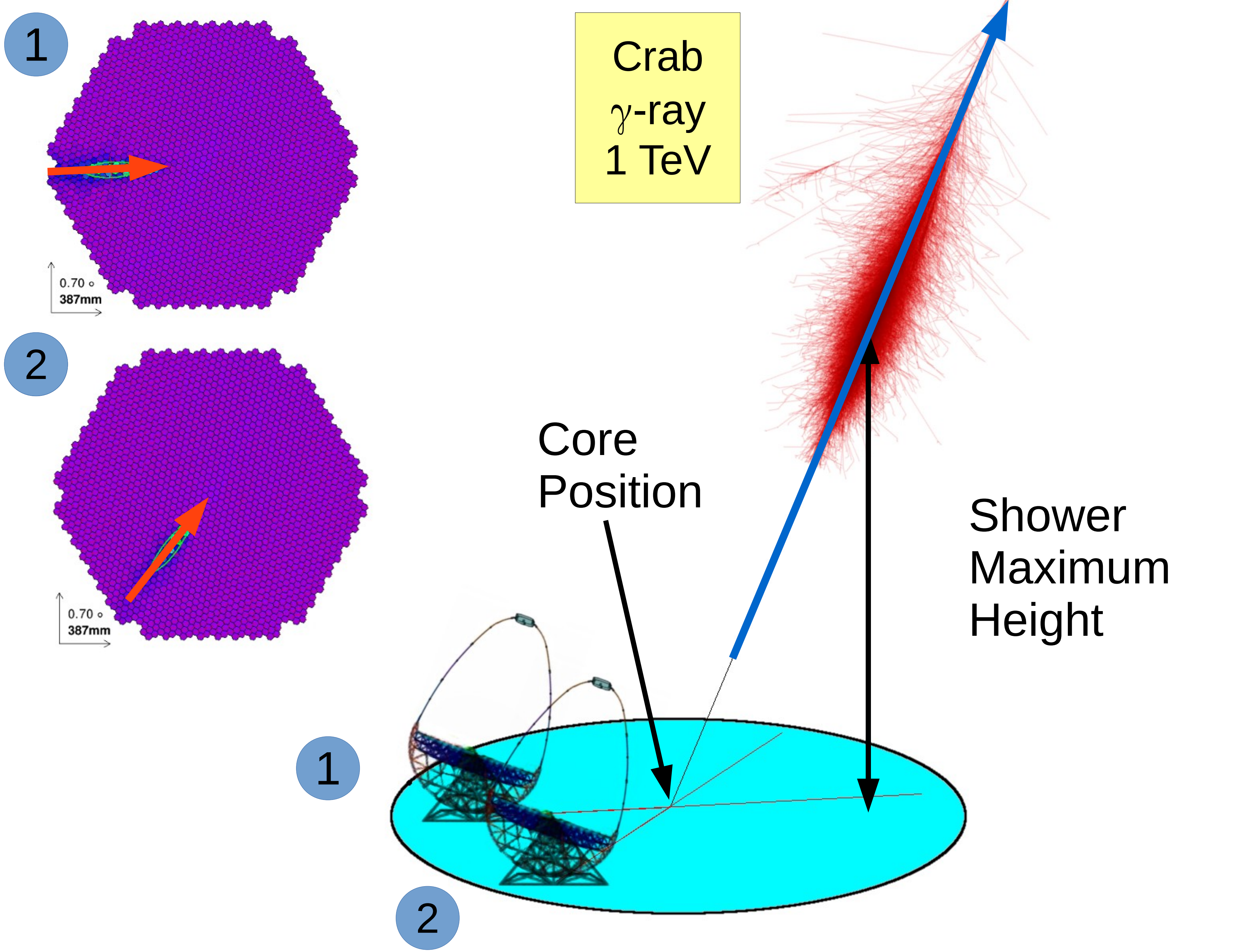
1 TeV



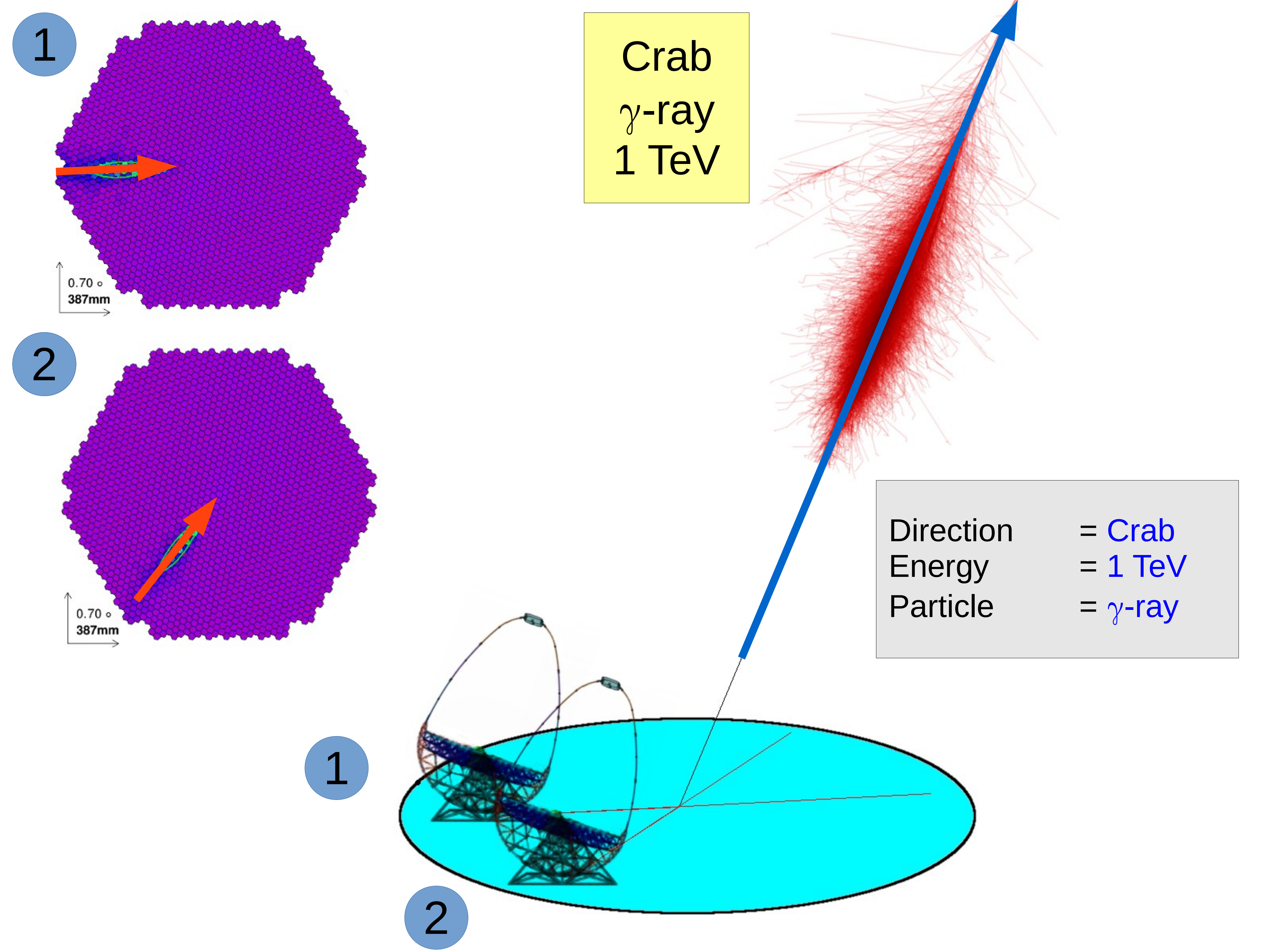
Direction = ¿?

Particle = ¿?

Energy = ¿?



1
0.70 °
387mm
2
0.70 °
387mm
Crab
γ-ray
1 TeV
Core
Position
Shower
Maximum
Height
1
2


1
0.70 ∘
387mm
2
0.70 ∘
387mm
Crab
γ-ray
1 TeV
Direction = Crab
Energy = 1 TeV
Particle = γ-ray
1
2

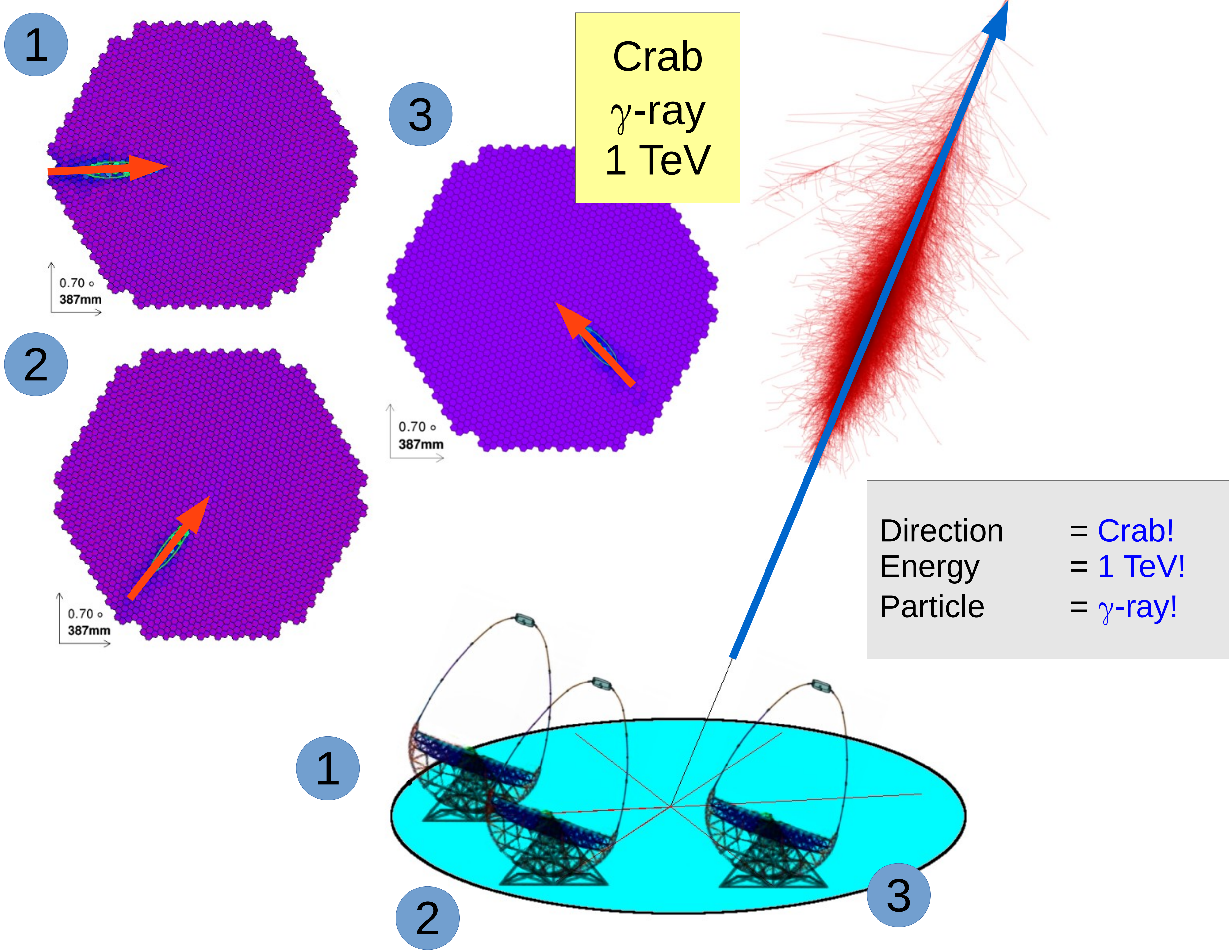
IACT technique – The MAGIC telescopes

2 IACTs – 17 m diameter

Dominated by hadronic background

FoV = ~3.5º

Eff Area ~ 10^5 m²



1
0.70 ∘
387mm
2
0.70 ∘
387mm
3
0.70 ∘
387mm
Crab
γ-ray
1 TeV
Direction = Crab!
Energy = 1 TeV!
Particle = γ-ray!
1
2
3

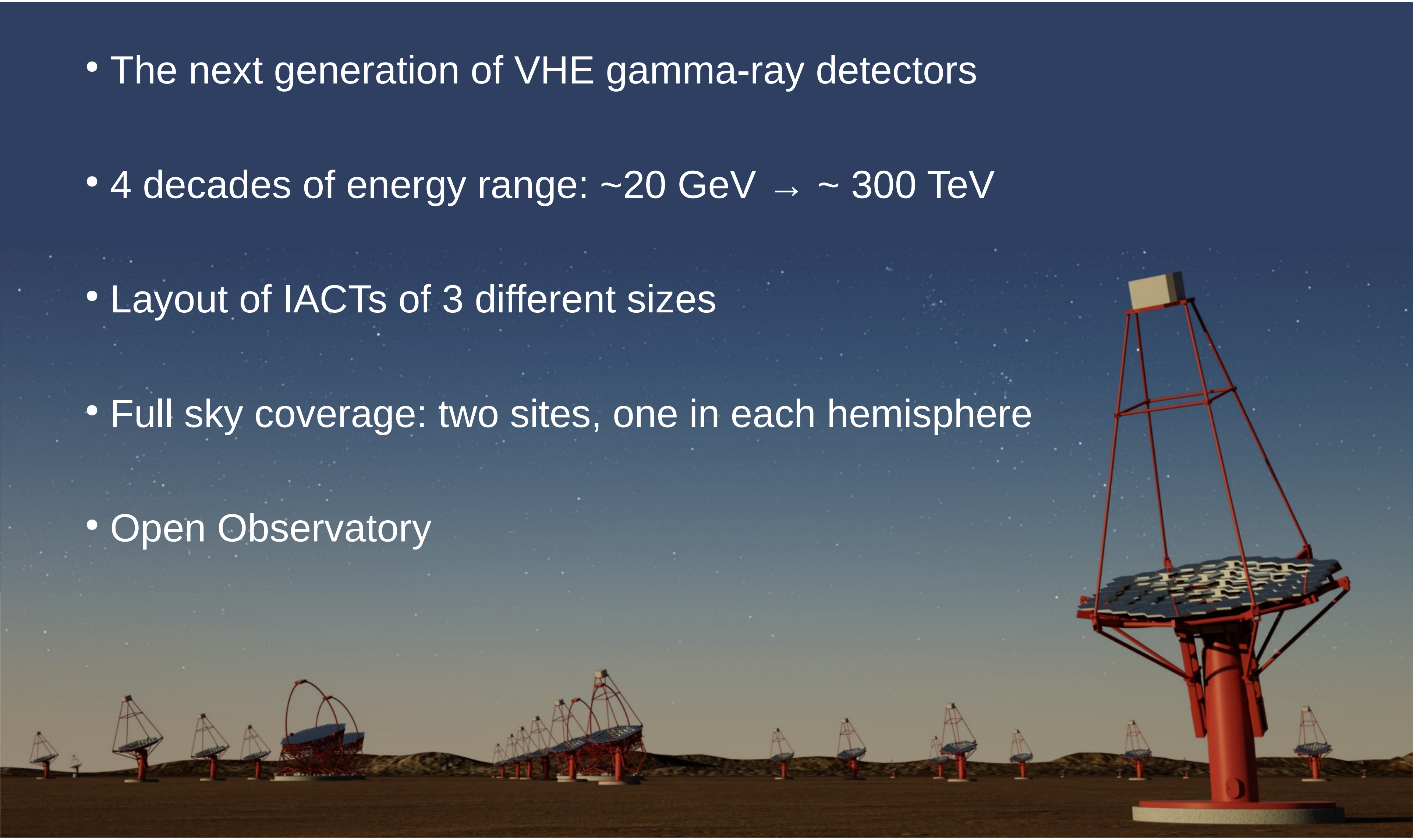
IACT technique – HESS and VERITAS

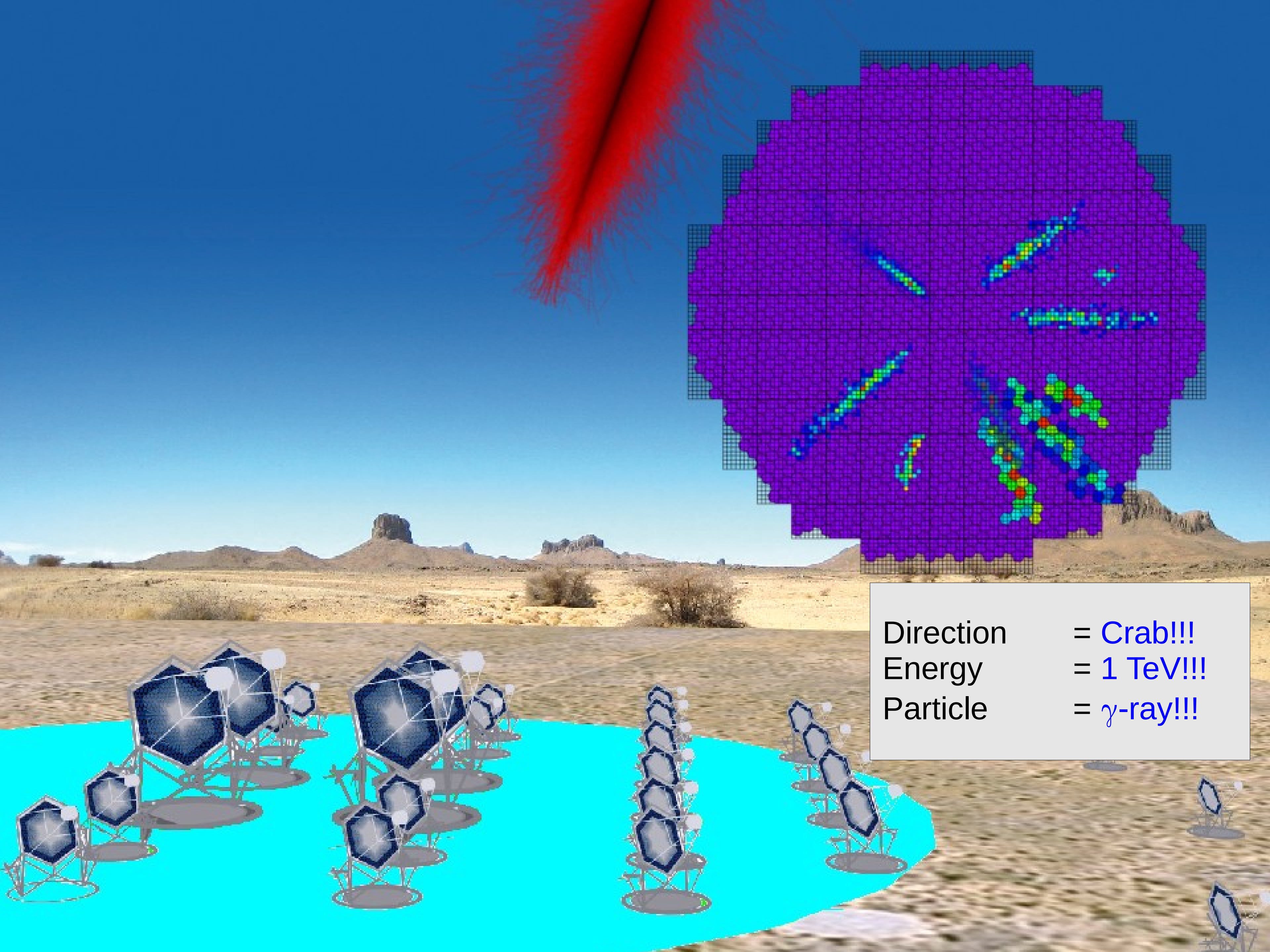
H.E.S.S.

VERITAS

IACT technique – CTA

- The next generation of VHE gamma-ray detectors
- 4 decades of energy range: ~20 GeV → ~ 300 TeV
- Layout of IACTs of 3 different sizes
- Full sky coverage: two sites, one in each hemisphere
- Open Observatory




Direction = Crab!!!
Energy = 1 TeV!!!
Particle = γ-ray!!!

IACT technique – Analysis

- Low-level analysis: Infer from the measured "light flashes":
  - **Classify** the shower as a gamma-ray
  - The original **energy** of the gamma-ray
  - The original **direction** of the gamma-ray

- High-level analysis: infer from the measured photons, of "known" direction and energy…
  - Detection of VHE sources
  - Measured flux (spectrum, lightcurves)
  - Morphology (skymaps)

IACT technique – Analysis

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  - The original **energy** of the gamma-ray
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- High-level analysis: infer from the measured photons, of "known" direction and energy…
  - Detection of VHE sources
  - Measured flux (spectrum, lightcurves)
  - Morphology (skymaps)

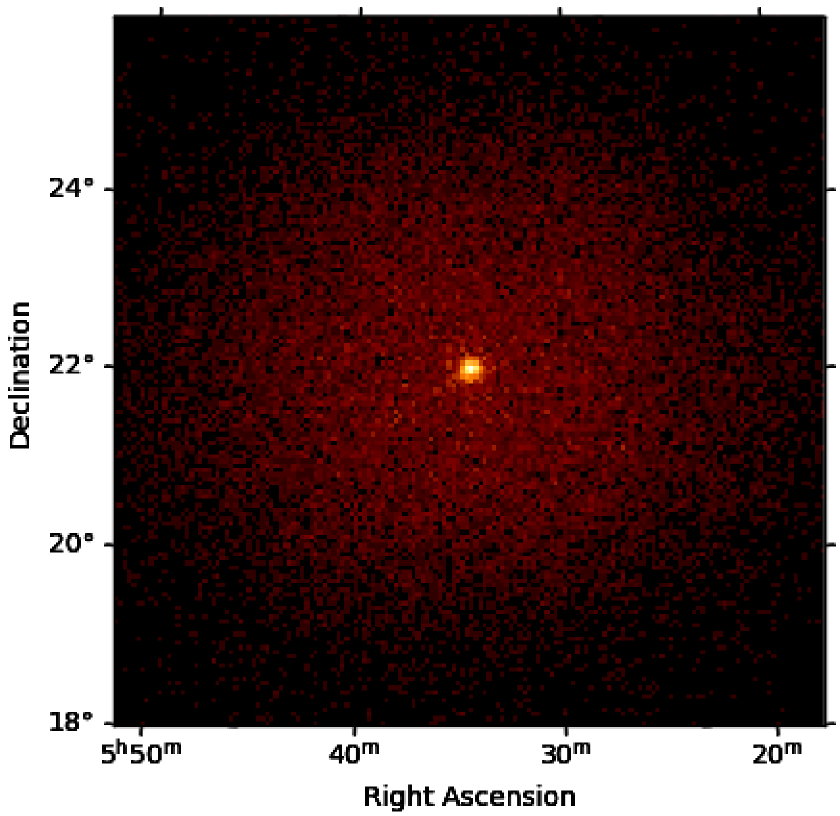
This talk is focused on this analysis!

IACT technique – Low-level analysis

- Outline of a classical IACT analysis:
  - Signal extraction from measured charge
  - Image cleaning and parameterization
  - Estimate the **direction** of the gamma-ray
  - **Classify** the shower (gamma/hadron separation)
  - Estimate the **energy** of the shower

IACT technique – High-level data products

- After the low-level analysis, we get something like this:



IACT technique – High-level data products

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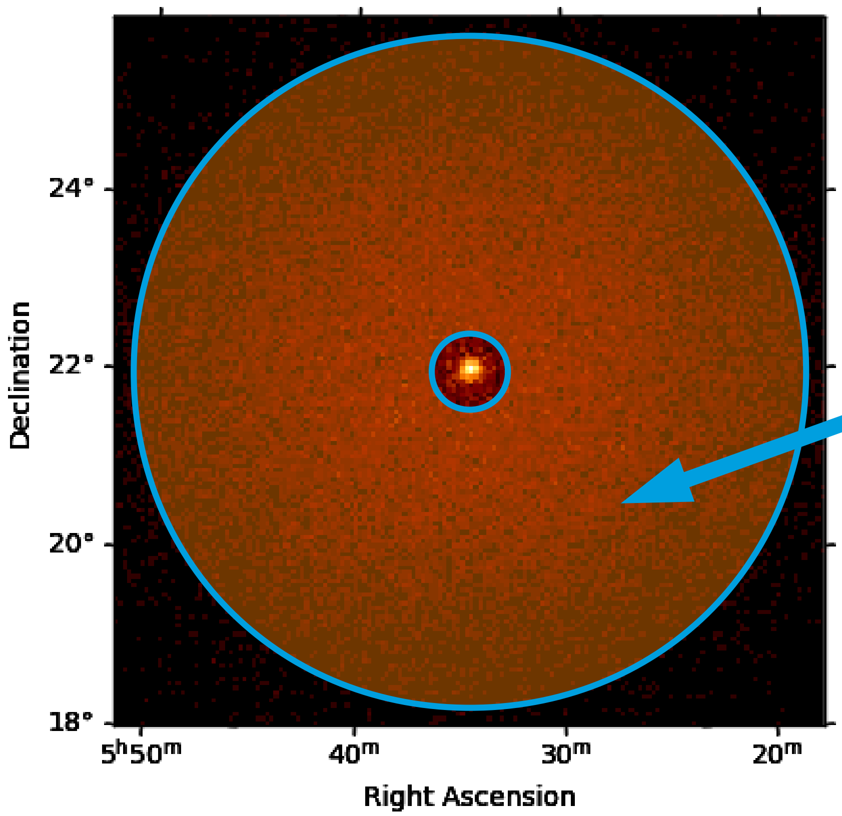
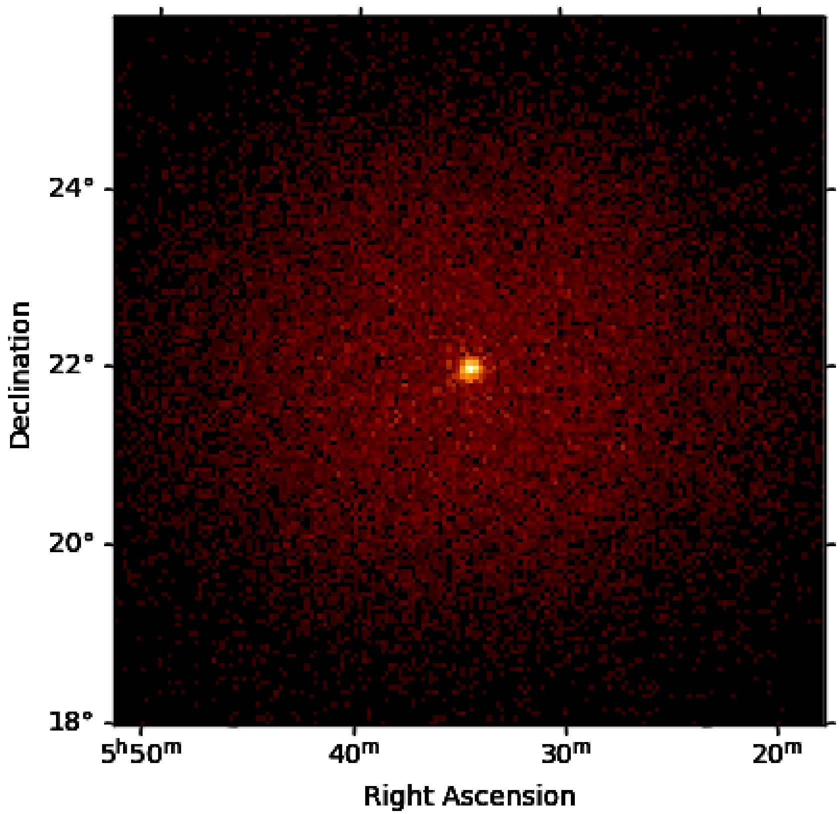


- First question: What is **all this**?

IACT technique – High-level data products

- After the low-level analysis, we get something like this:



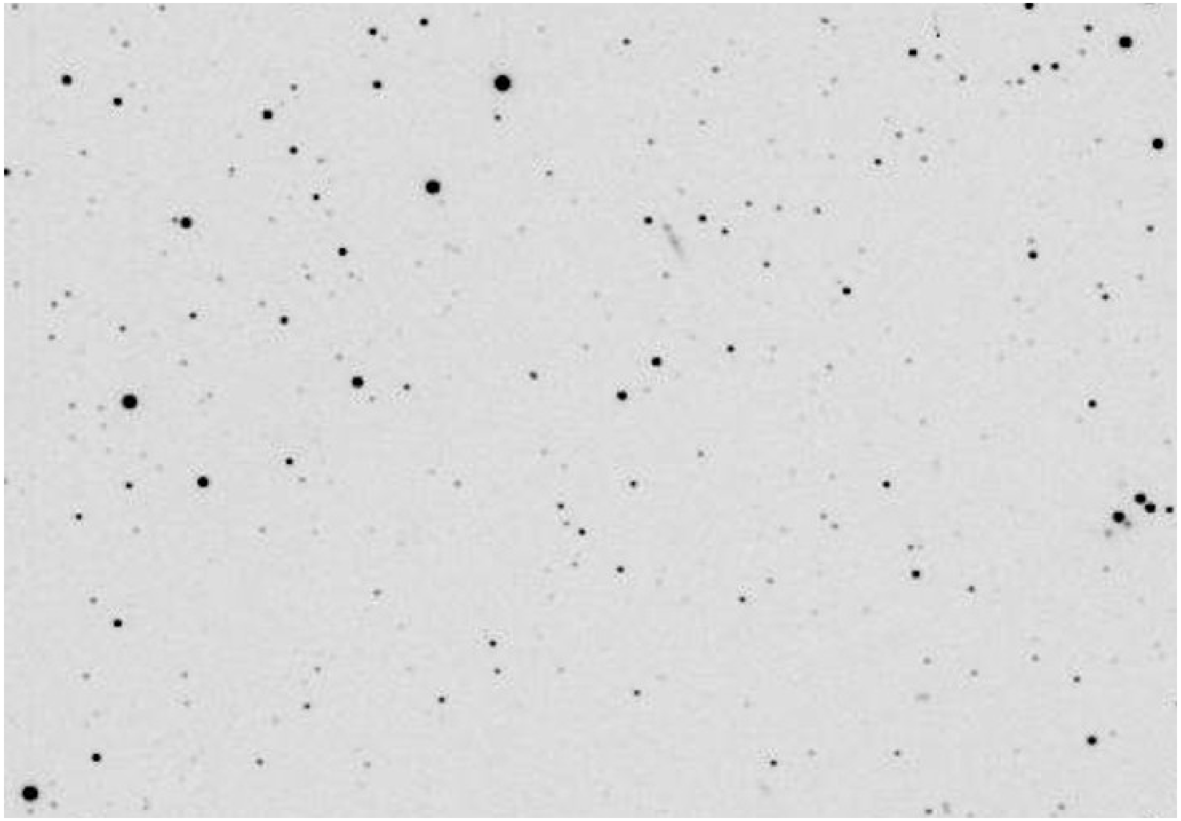
- First question: What is **all this**?

cosmic-ray background dominates many of our observations (specially at low energies)

Even if our gamma-hadron rejection power is good, there will be many cosmic-rays that will look identical to gamma-ray showers

Analysis in astronomy – Optical

- In classical photometry analysis, the following method is usually used:



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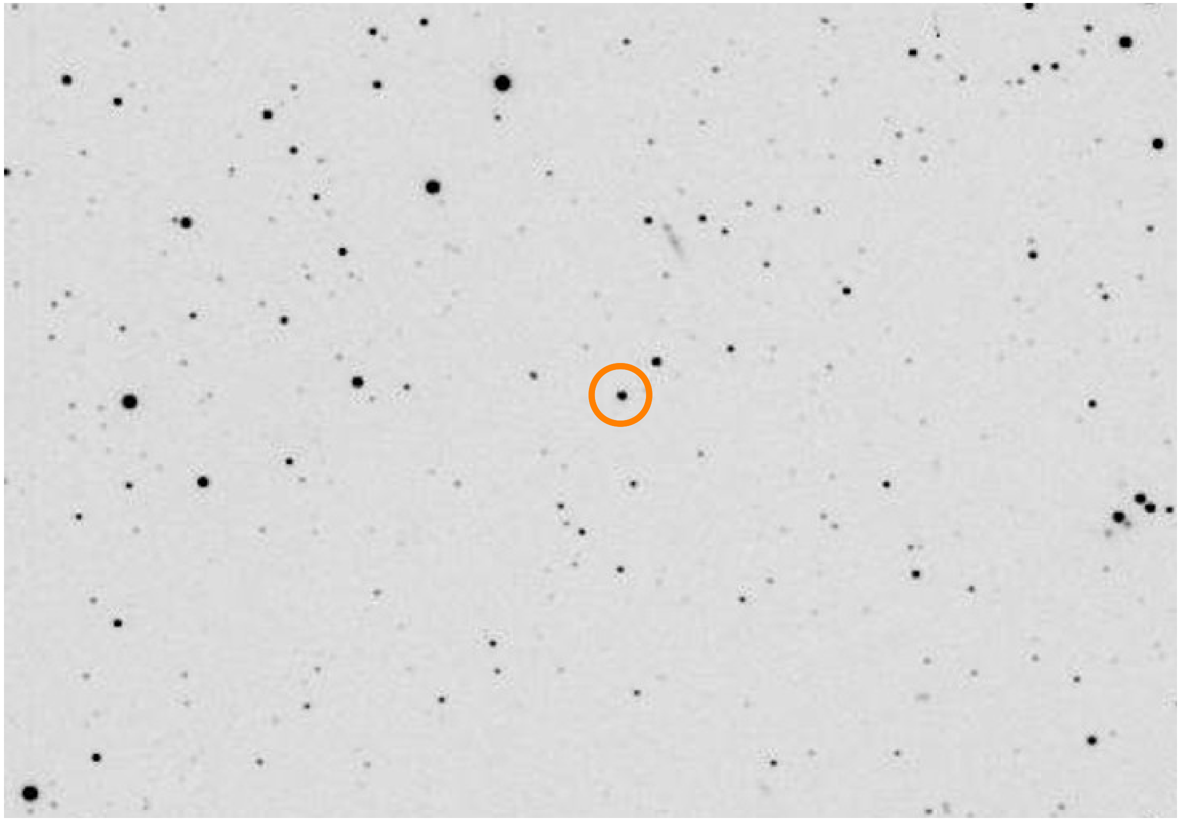

- Decide the size of your ON-region

Analysis in astronomy – Optical

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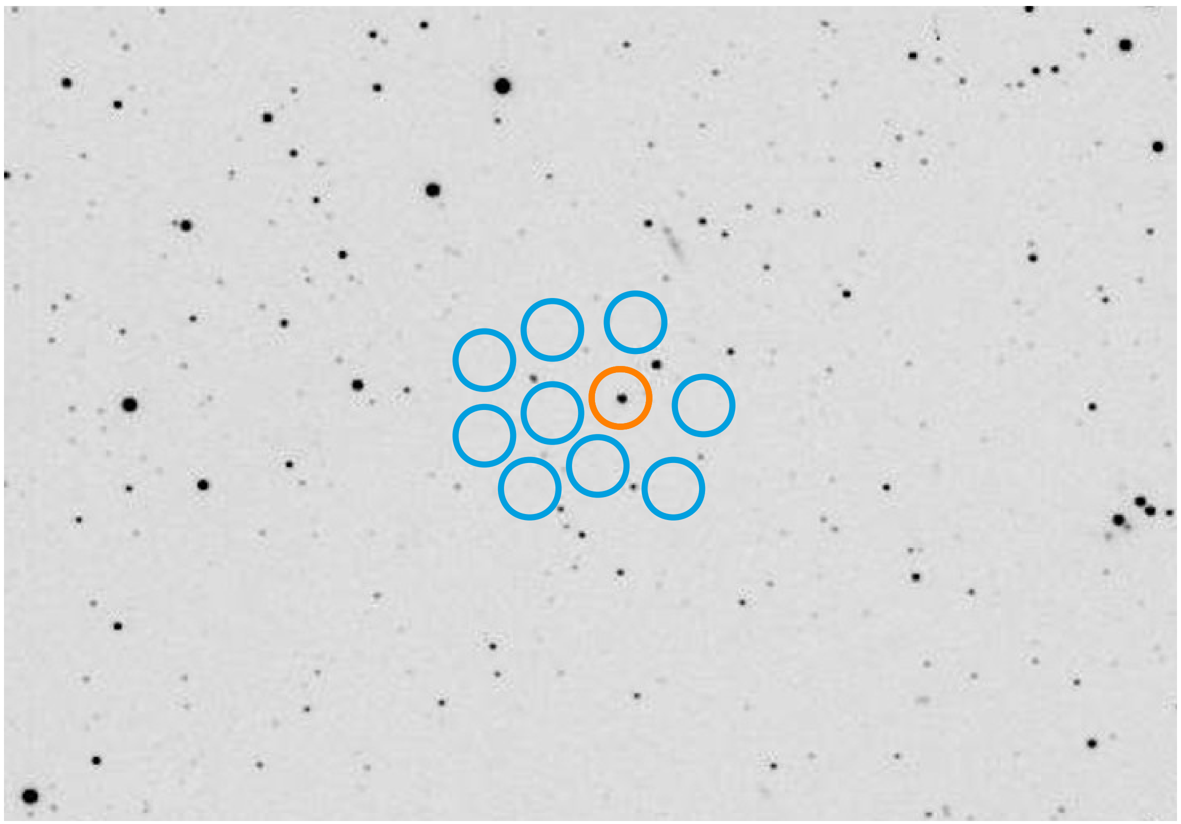

- Decide the size of your **ON region**

- Calculate the expected background from star-free **OFF regions**

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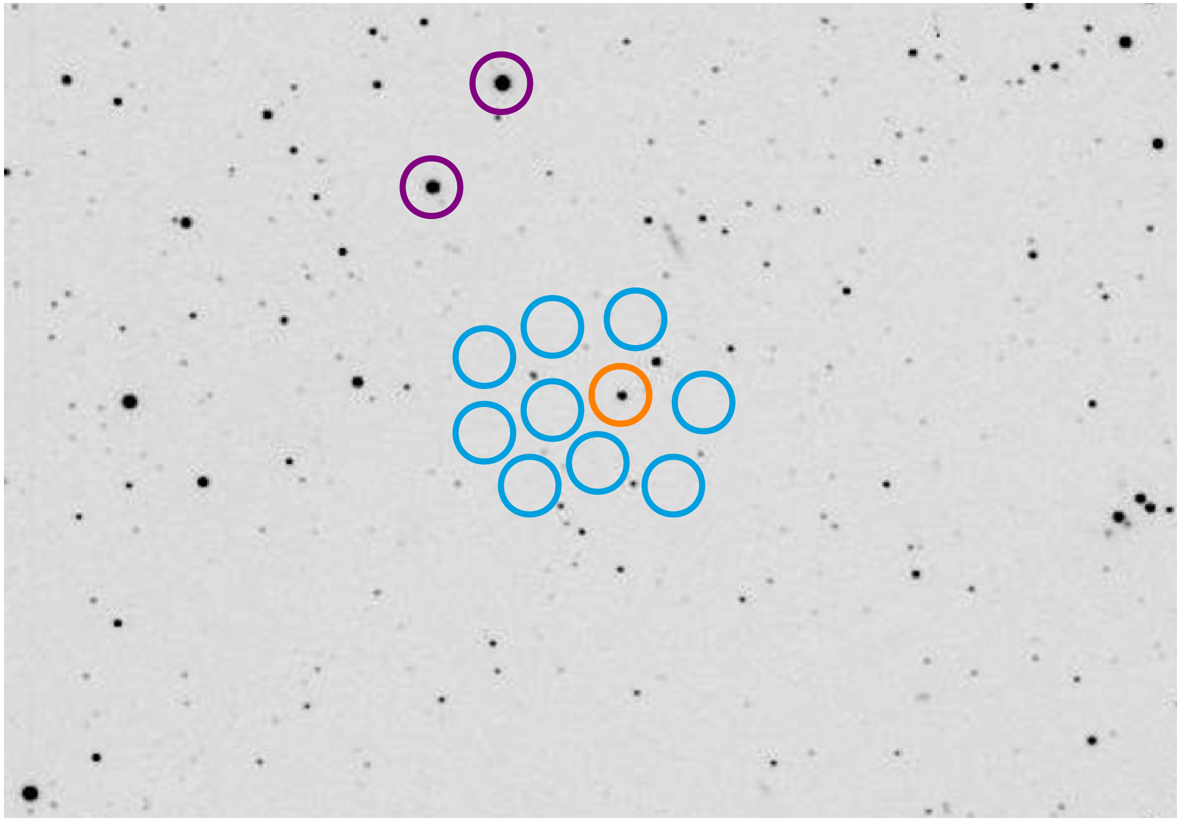

- Decide the size of your **ON region**

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- Flux is usually calculated by comparing counts with respect to known **reference stars** in the FoV

Analysis in astronomy – Optical

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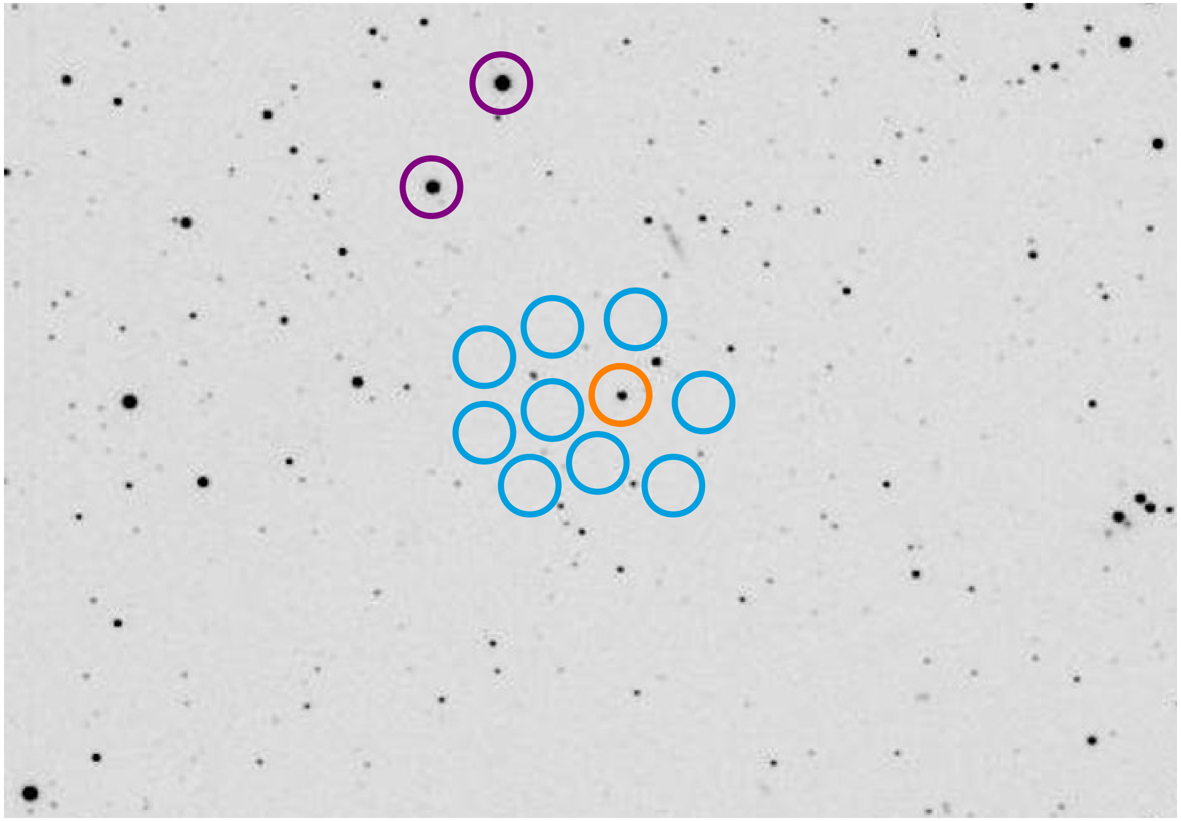


Why so easy?!?

- The detection efficiency across the CCD camera FoV is ~ constant

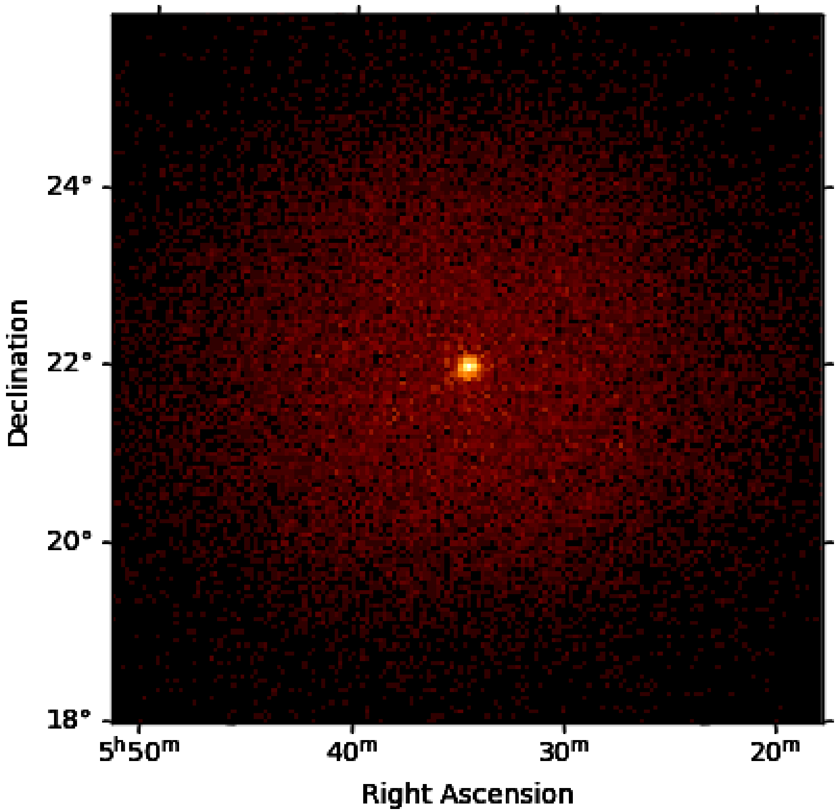
- CCD cameras operate under **very stable** conditions

- CCD cameras are calibrated in the lab

- Great knowledge we have on standard candles allow calibration

Analysis in astronomy – VHE energy

- In VHE, it's not so simple!



Why **not** so easy?!?

- The detection efficiency across an IACT FoV is **definitely** not constant

Analysis in astronomy – VHE energy

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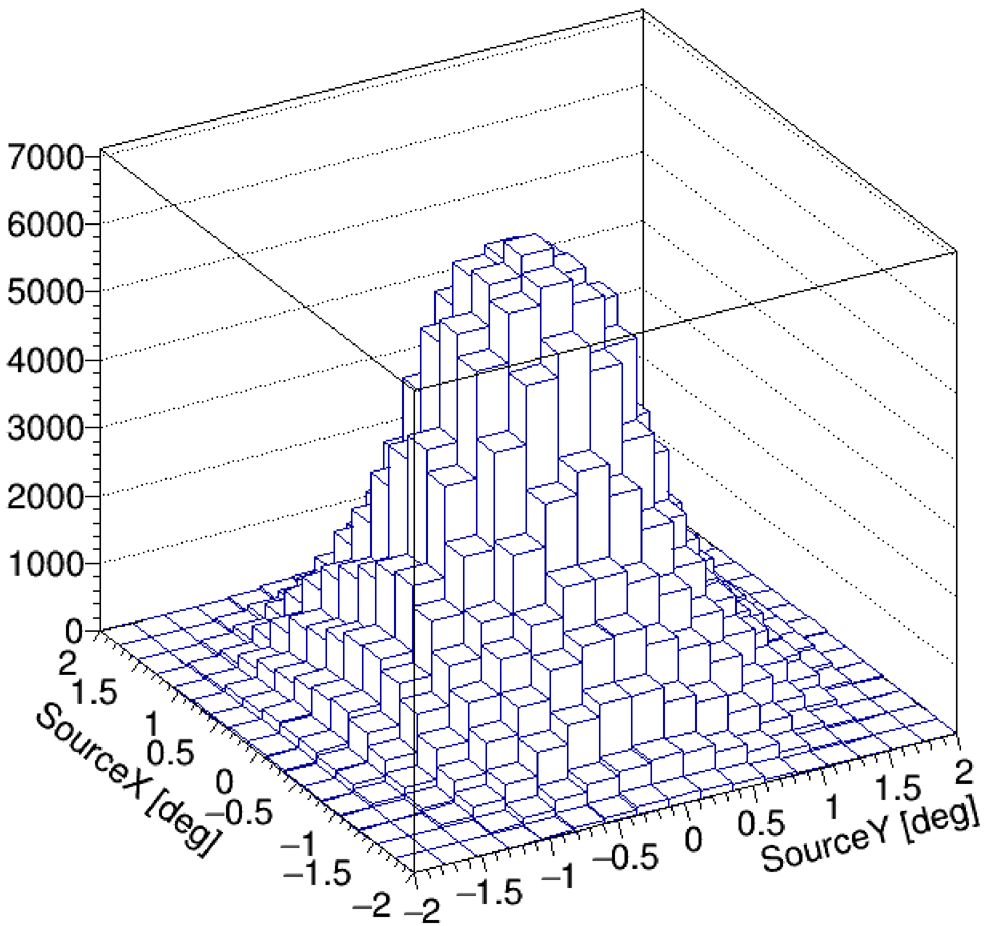

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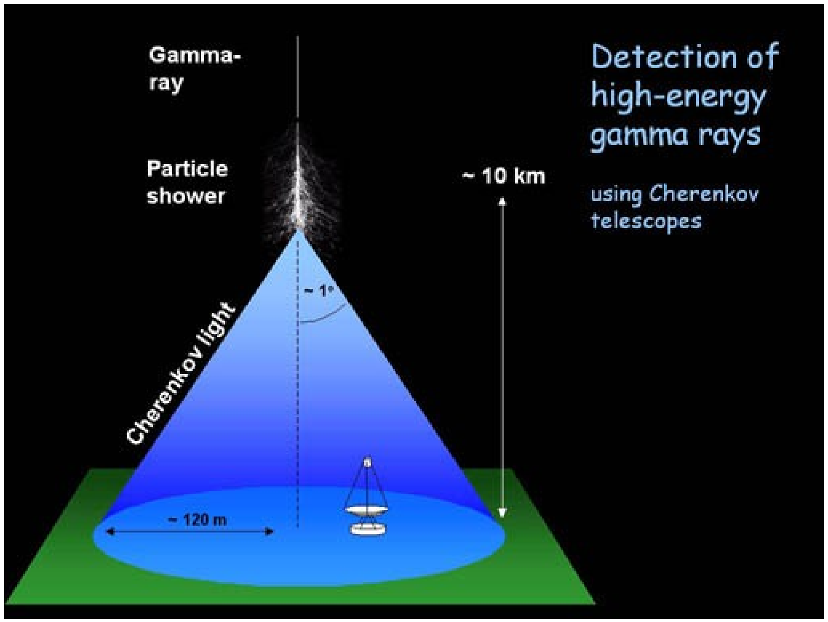

Why **not** so easy?!?

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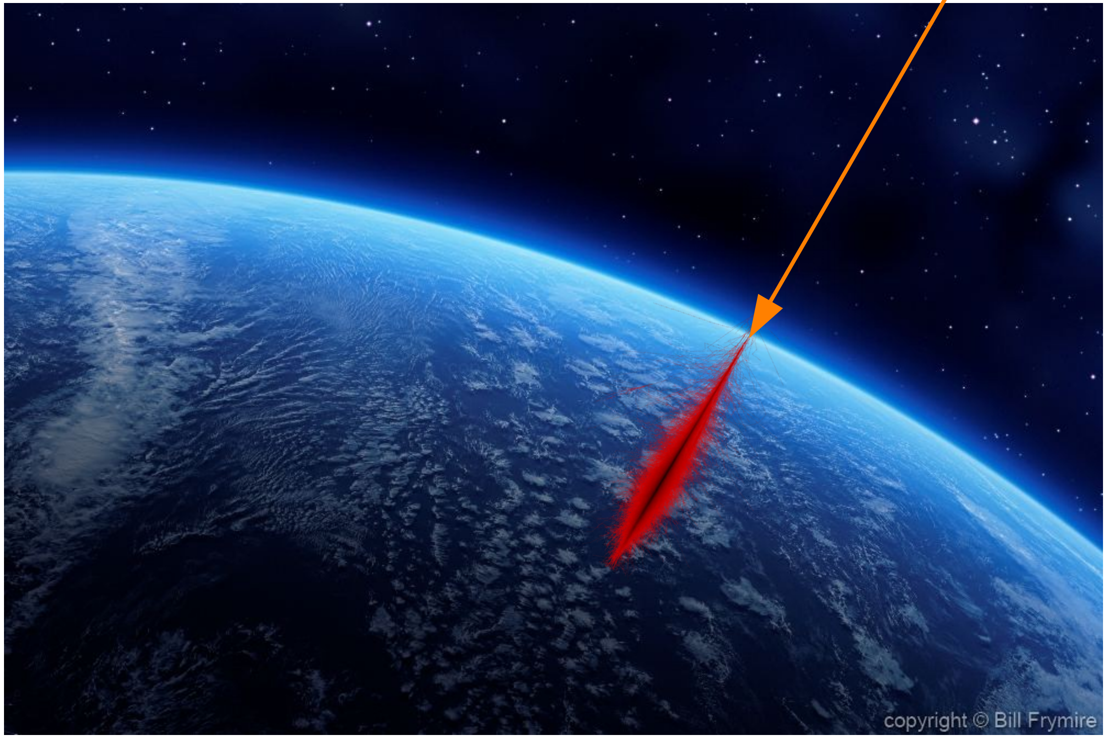
- IACTs operate under **very unstable** conditions

- The atmosphere is part of our detector, and it heavily influences our performance. We are also affected by the moon, the weather…

- Performance also depends on the direction we look at (zenith and azimuth), as well as the night sky background intensity

Analysis in astronomy – VHE energy



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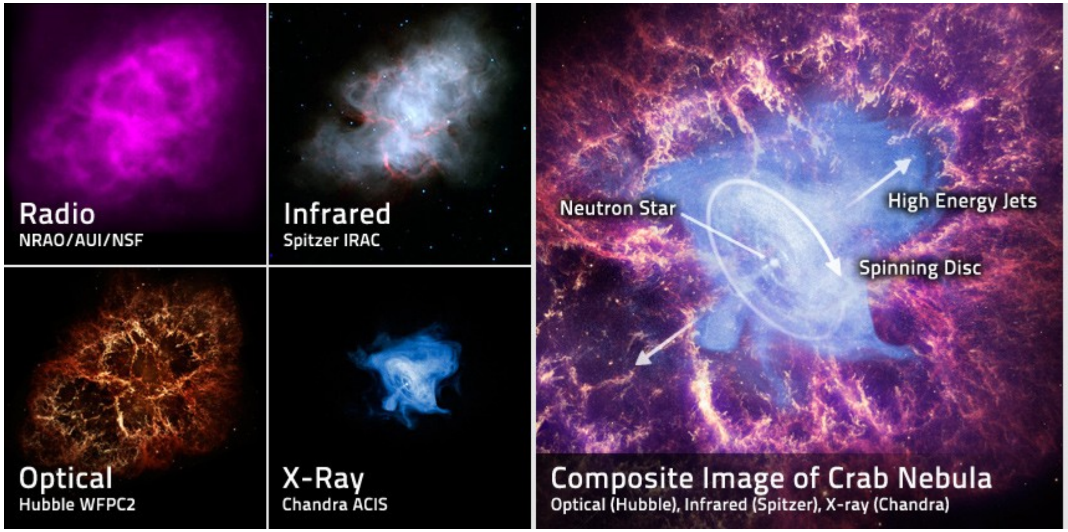
Analysis in astronomy – VHE energy



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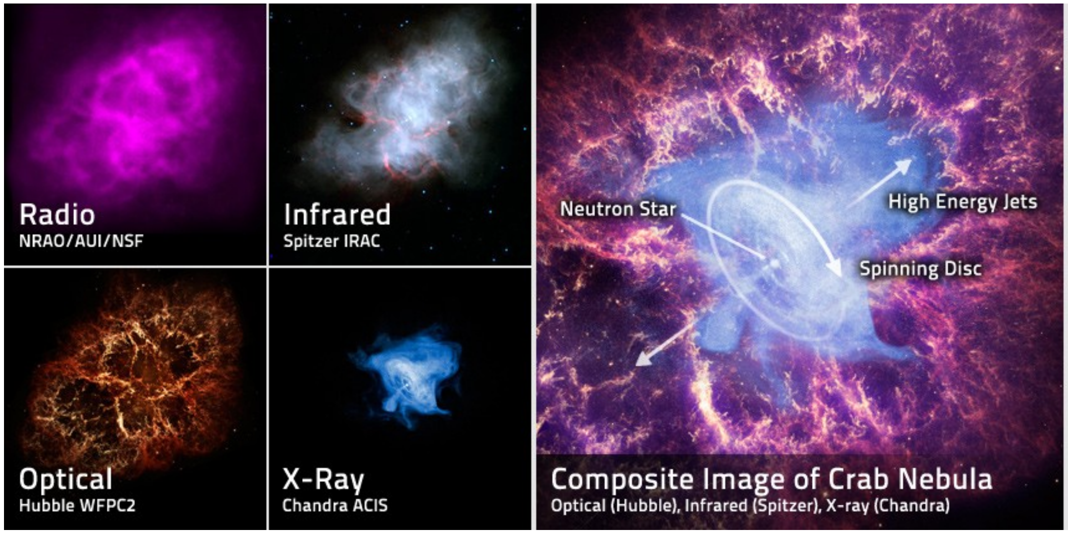
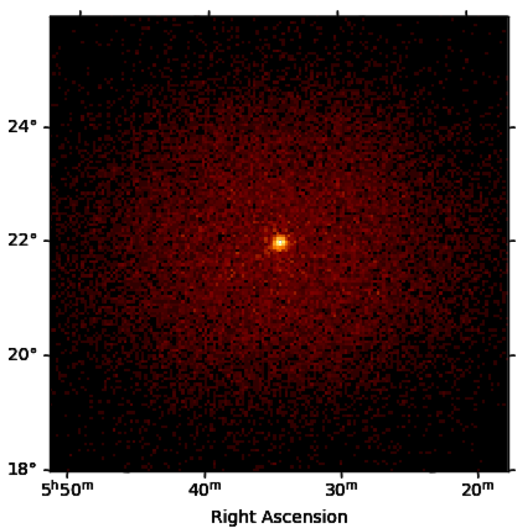
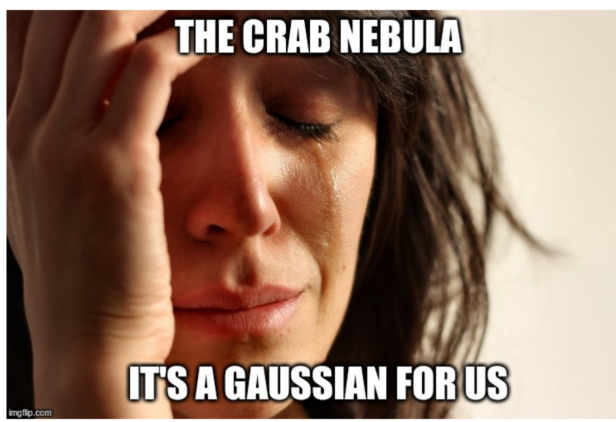
Analysis in astronomy – VHE energy







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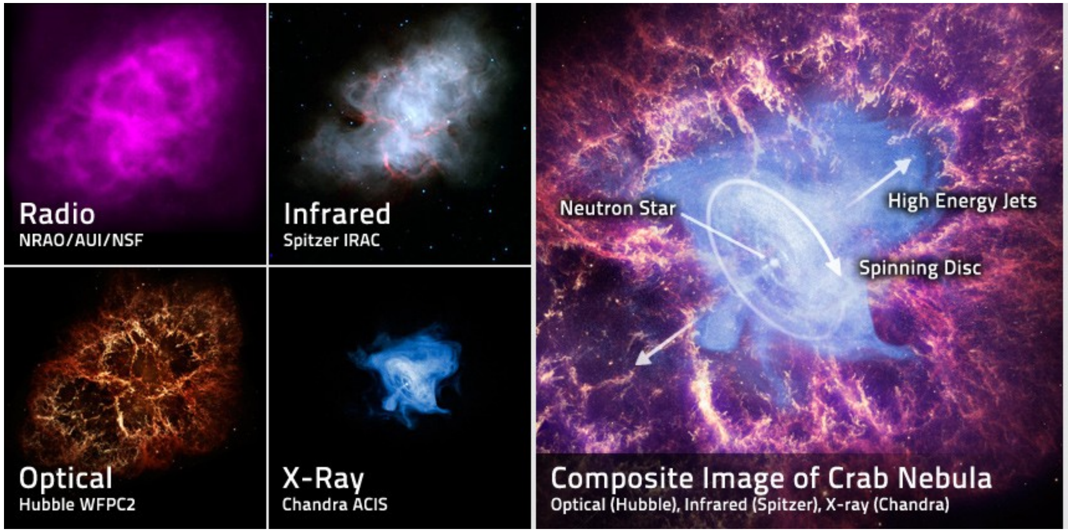

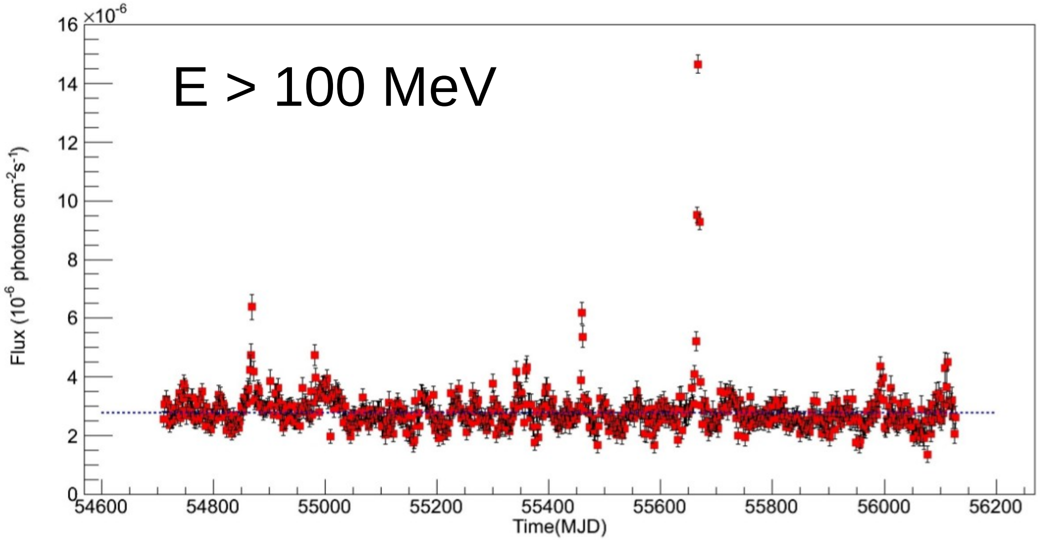

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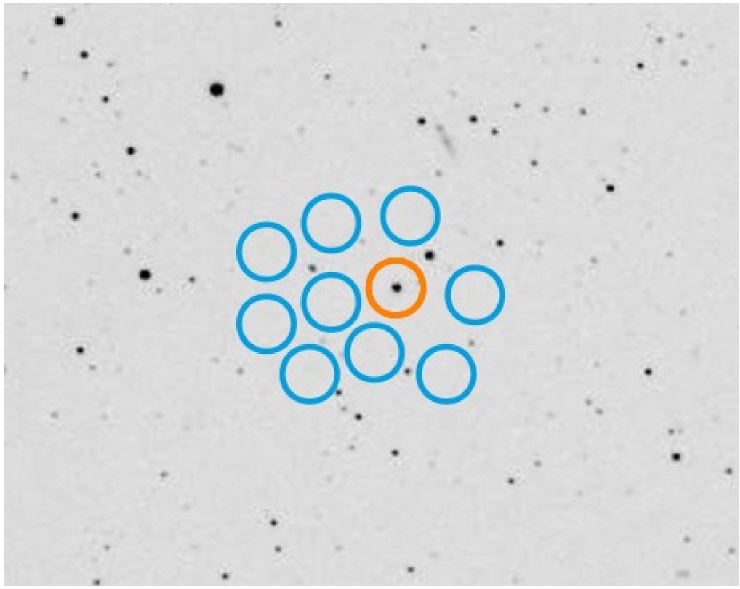
- Hey, it's not so bad! We do have a **standard candle**! Remembering it is also a **variable source**...

Analysis in VHE – Source detection

- The simplest analysis in VHE astronomy is to detect sources:
  - Statistically prove with **confidence** that in a given position, there is a gamma-ray source above the cosmic-ray background



- In other wavelengths, statistical treatment may be simpler, mainly because the quantity of photons

- A high confidence detection in VHE astronomy may come from just **10 excess events**!

Analysis in VHE – Source detection

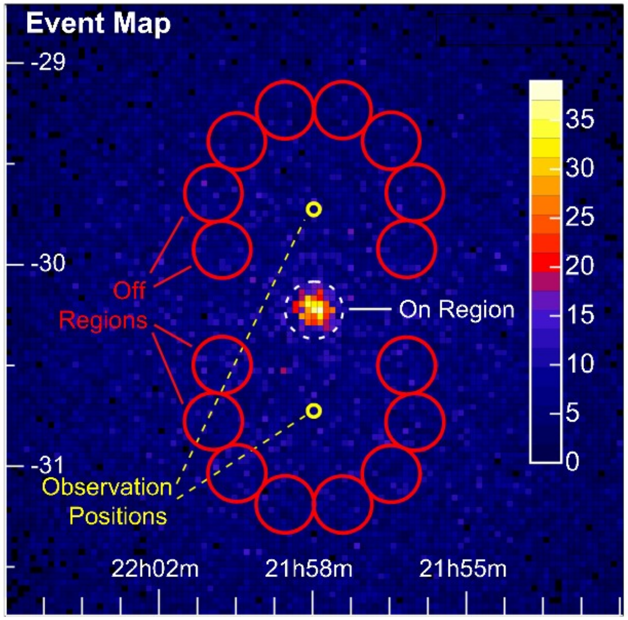
- The simplest analysis in VHE astronomy is to detect sources:
  - Statistically prove with **confidence** that in a given position, there is a gamma-ray source above the cosmic-ray background
  - The most generalized statistical method for source detection is described in Li & Ma 1983
    - Calculate the probability of observing X amount of events assuming there is only background
    - The simplest method to understand it is by plotting the θ^2 distribution

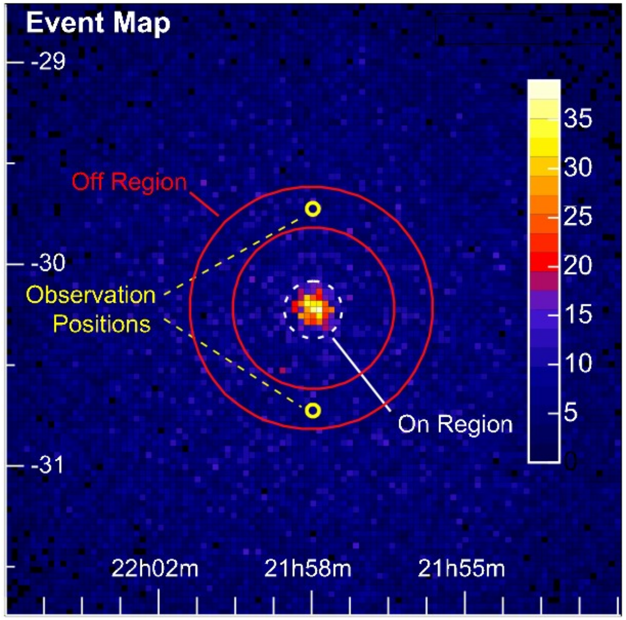
Analysis in VHE – Source detection

- The detection efficiency across an IACT FoV is not constant

Make sure your OFF regions have identical acceptance

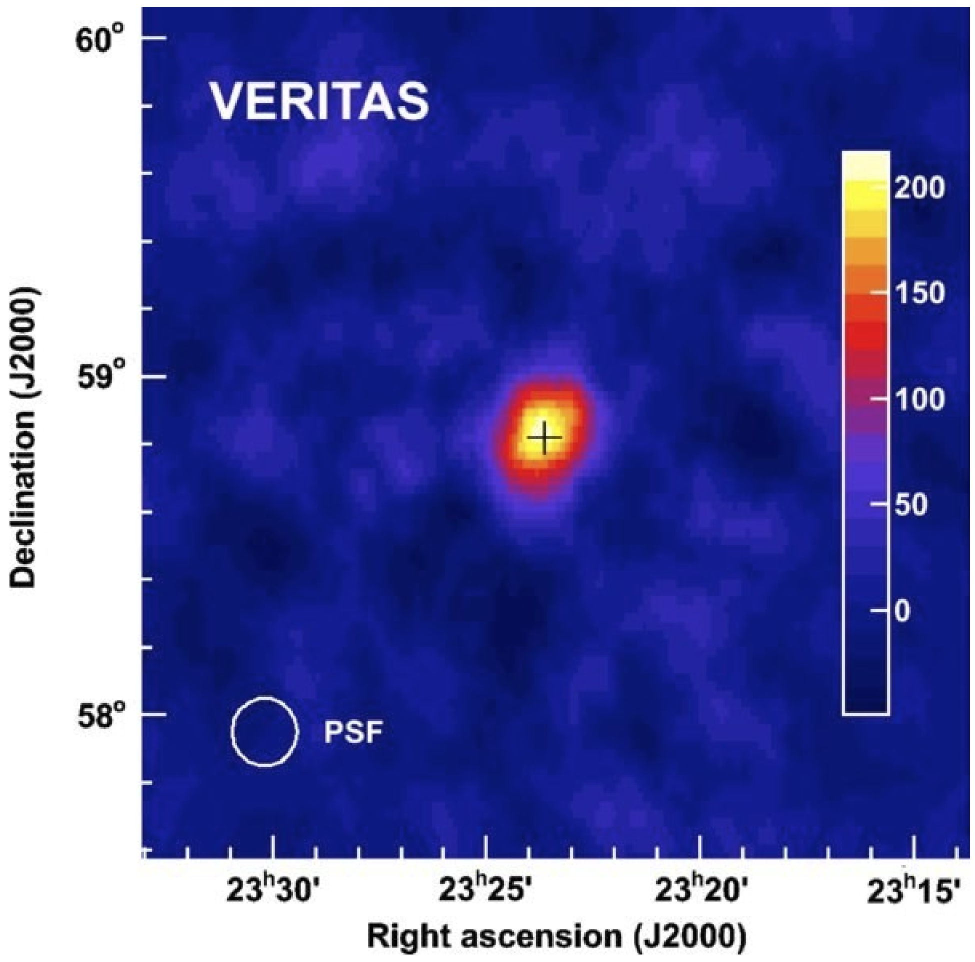
Understand how acceptance changes over the FoV





Analysis in VHE – Source detection

- An easy way to understand this is the θ^2 plot



- Counts for a ring around the source, of constant area

Analysis in VHE – Source detection

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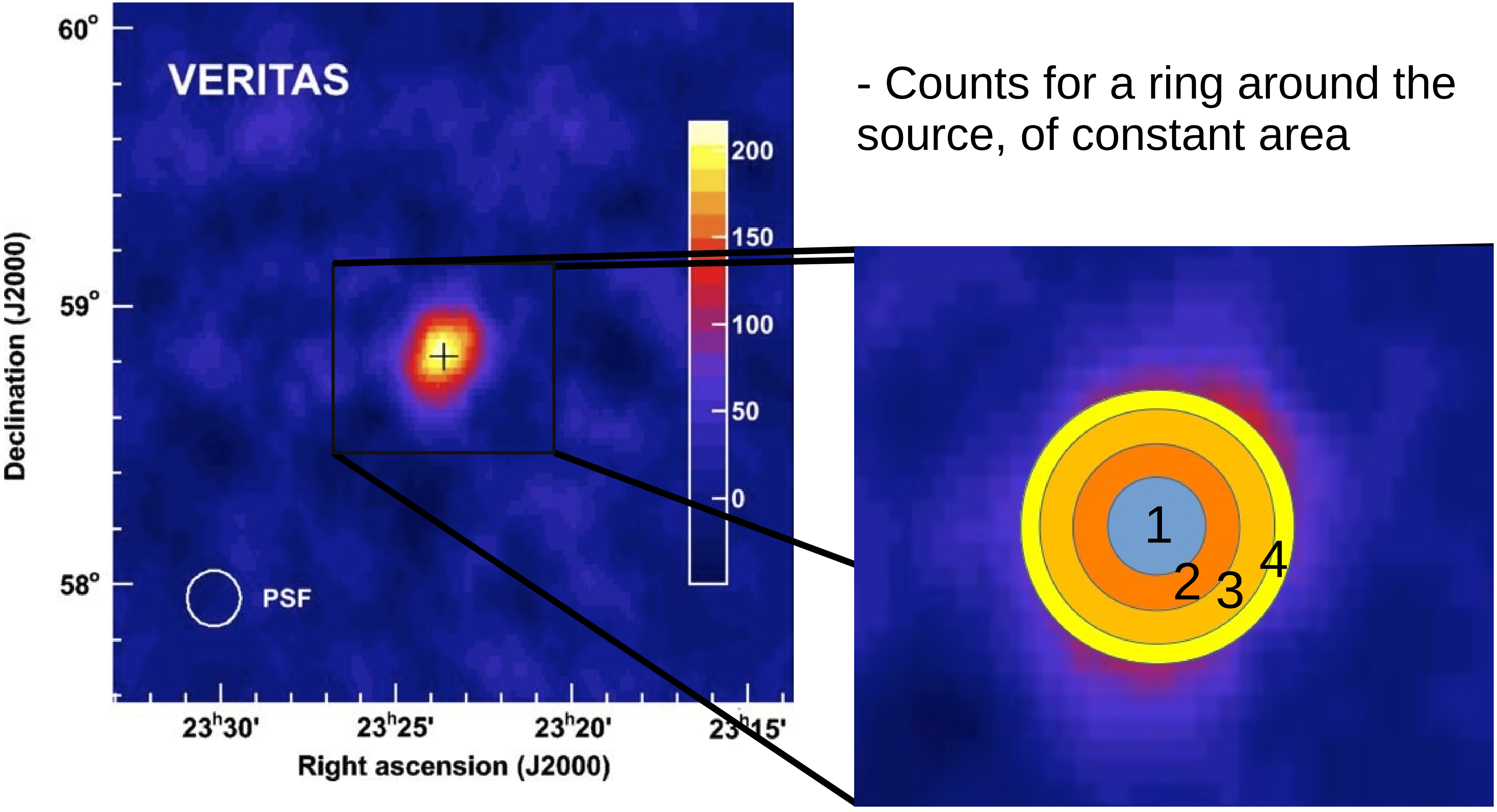

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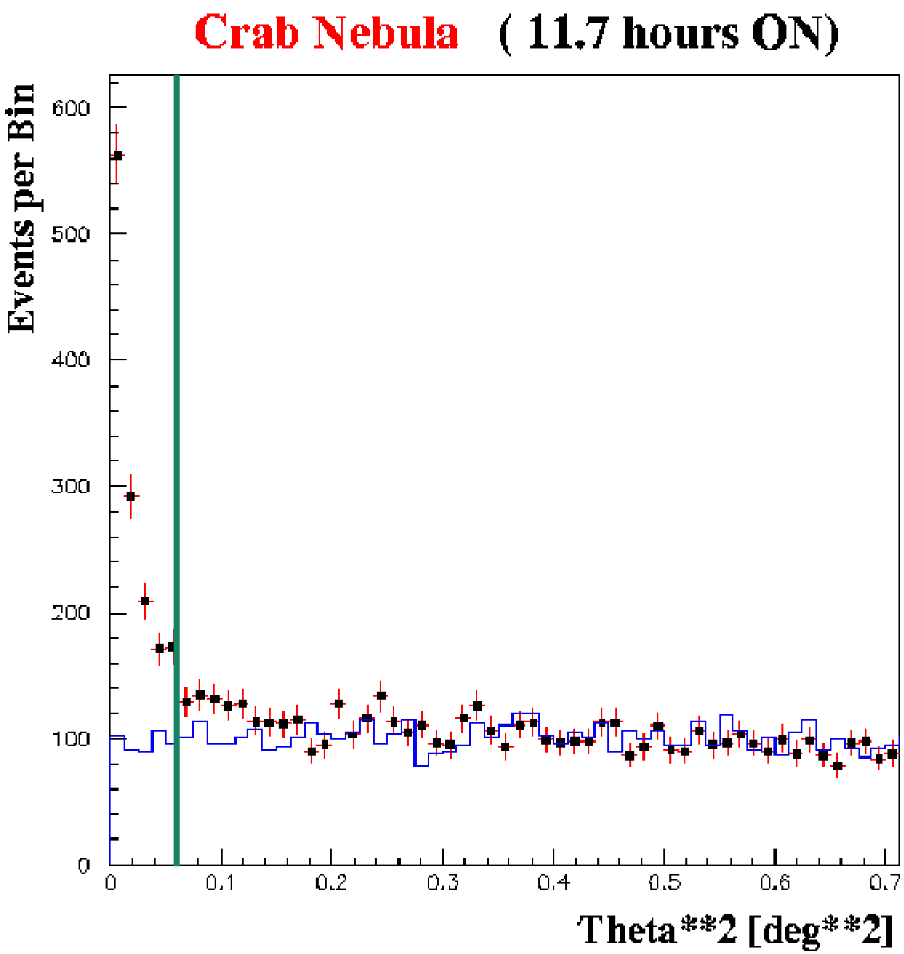


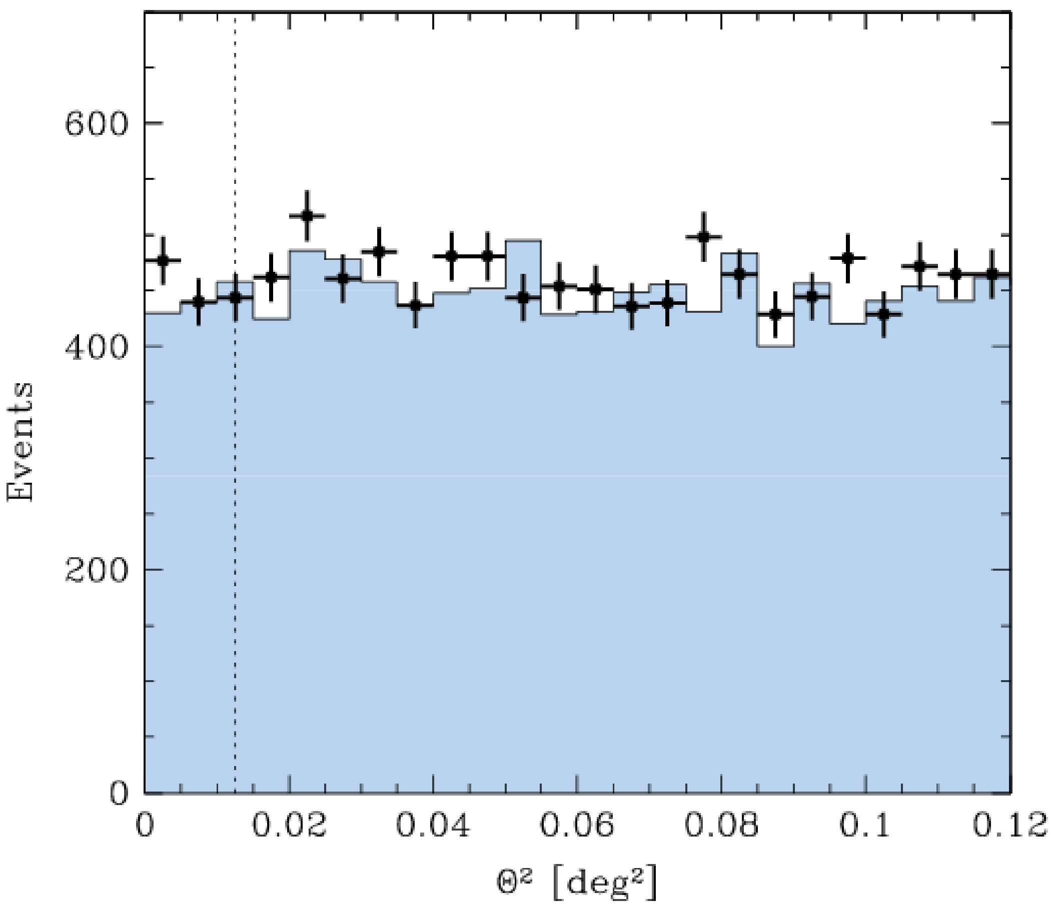
- Counts for a ring around the source, of constant area

- The same done around **OFF regions**

- Test, after applying a **pre-defined cut**, the significance of detection

Analysis in VHE – Source detection

- An easy way to understand this is the θ^2 plot



- Counts for a ring around the source, of constant area

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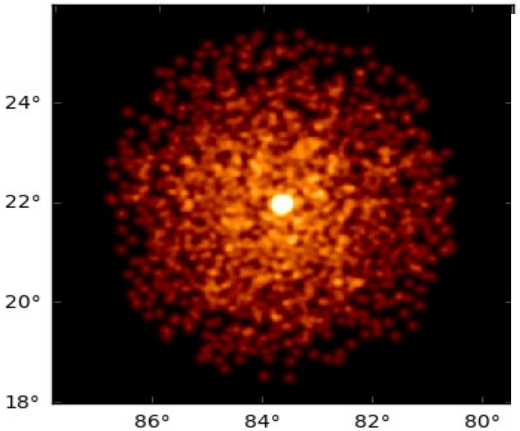
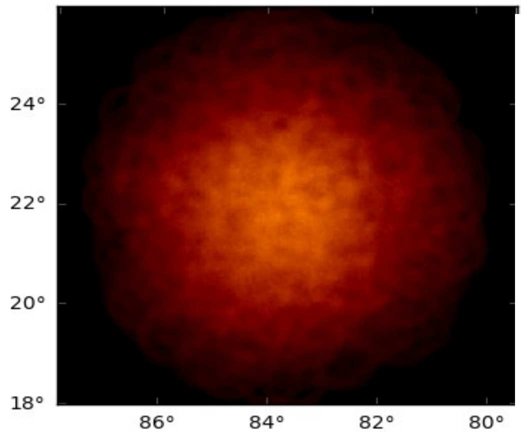
Analysis in VHE – Source detection

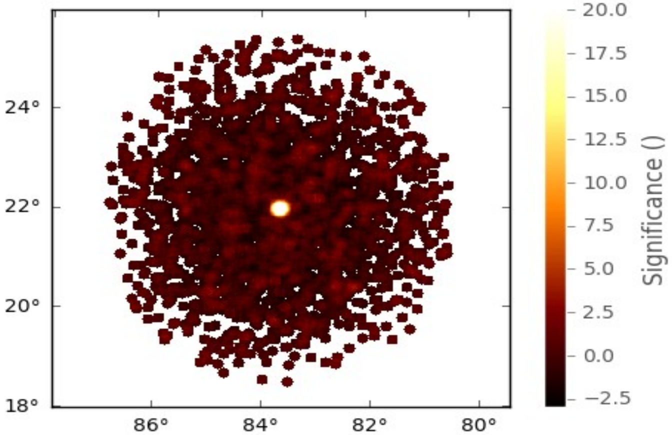
- If you do that for every point of an observation: skymap



ON counts (data)



Background model



Skymap

- Not as easy to calculate flux (e. g. a spectrum, integral flux...)
- Also, not easy to study morphology

Analysis in astronomy – VHE energy

Remember our problems?!?

- Direct calibration is **not possible**

- IACTs operate under **very unstable** conditions

Analysis in astronomy – VHE energy

Remember our problems?!?

- Direct calibration is **not possible**

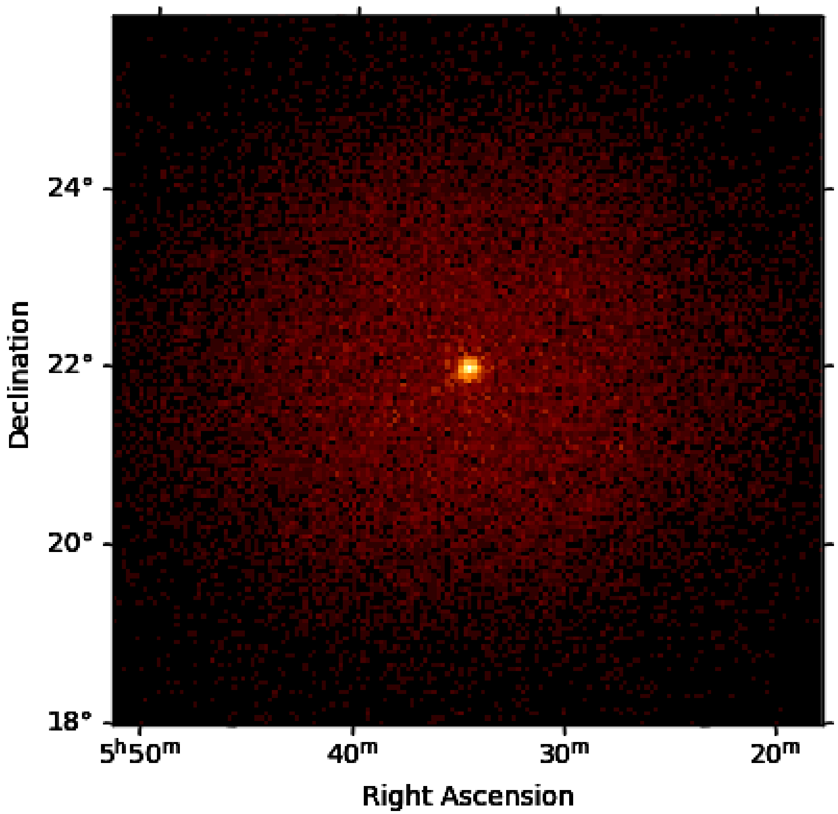
Monte Carlo simulations

- IACTs operate under **very unstable** conditions

More Monte Carlo simulations!

IACT technique – MC simulations

- After a normal IACT observation, we get this data (direction, time of arrival and energy of gamma-like events)



- How do we convert from **observed** number of photons to **flux**, if we cannot calibrate our instrument and the conditions are changing?

- We define the **Instrument Response Function** that relates "reconstructed" quantities with the "true" emitted photons

IACT technique – MC simulations

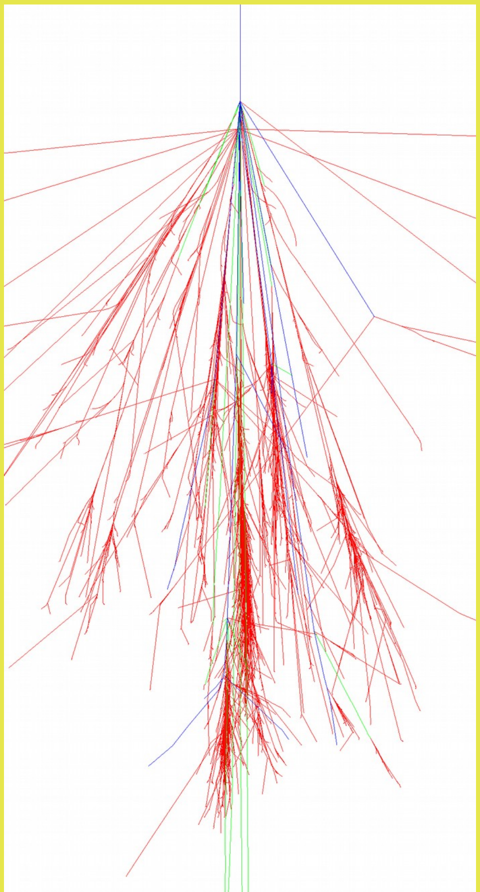
- The Instrument Response Function relates the array reconstructed quantities with the parameters of the source emitted photons

$$R_\gamma(\theta', \phi', E' | \theta, \phi, E) = A_\gamma(\theta, \phi, E) \times PSF(\theta', \phi' | \theta, \phi, E) \times D(E' | \theta, \phi, E)$$

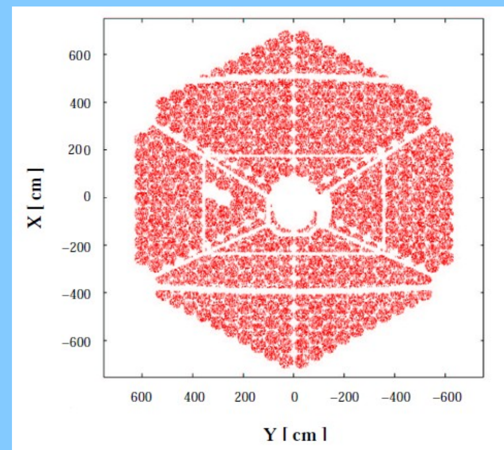
- The IRF elements are:
  - Effective area
  - Energy dispersion
  - Direction dispersion (PSF)
  - Hadronic background “acceptance”

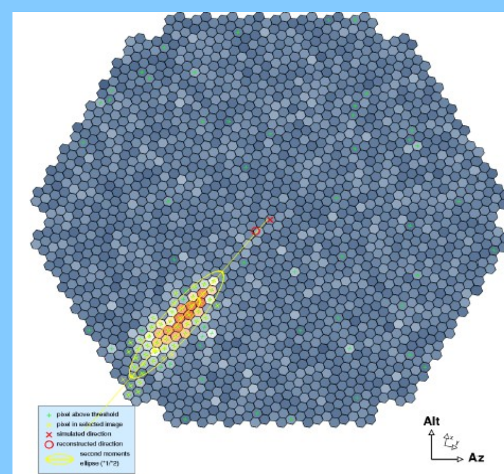
IACT technique – MC simulations

1 Shower simulation

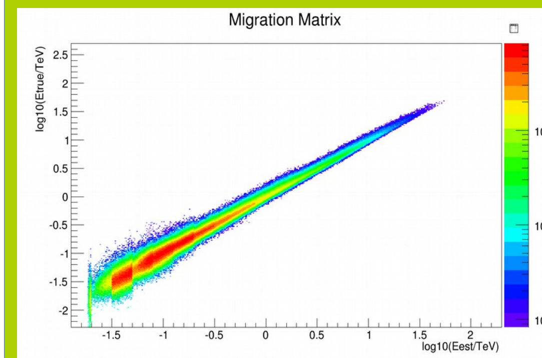


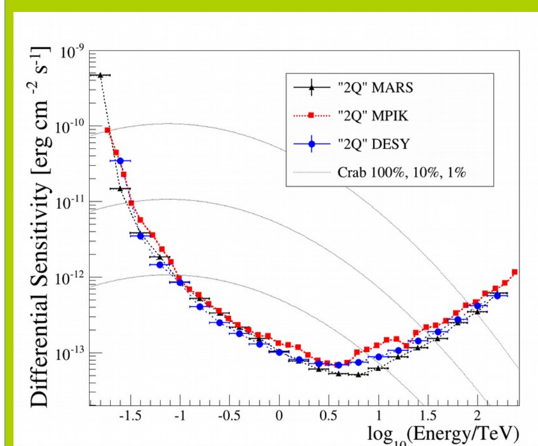
2 Telescope simulation





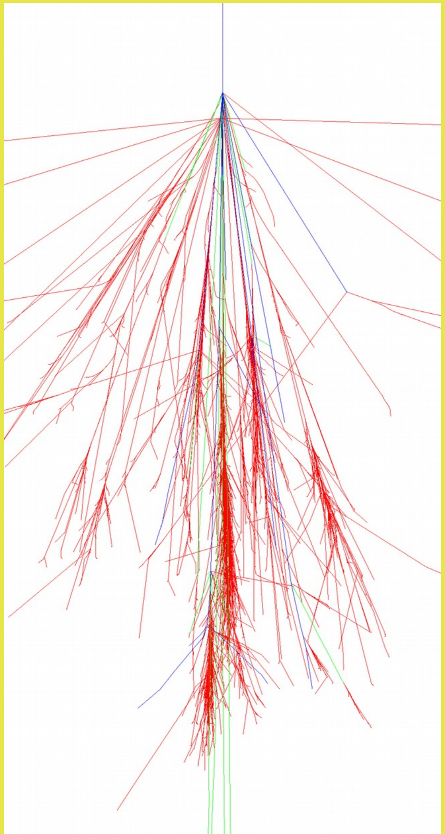
3 Performance analysis



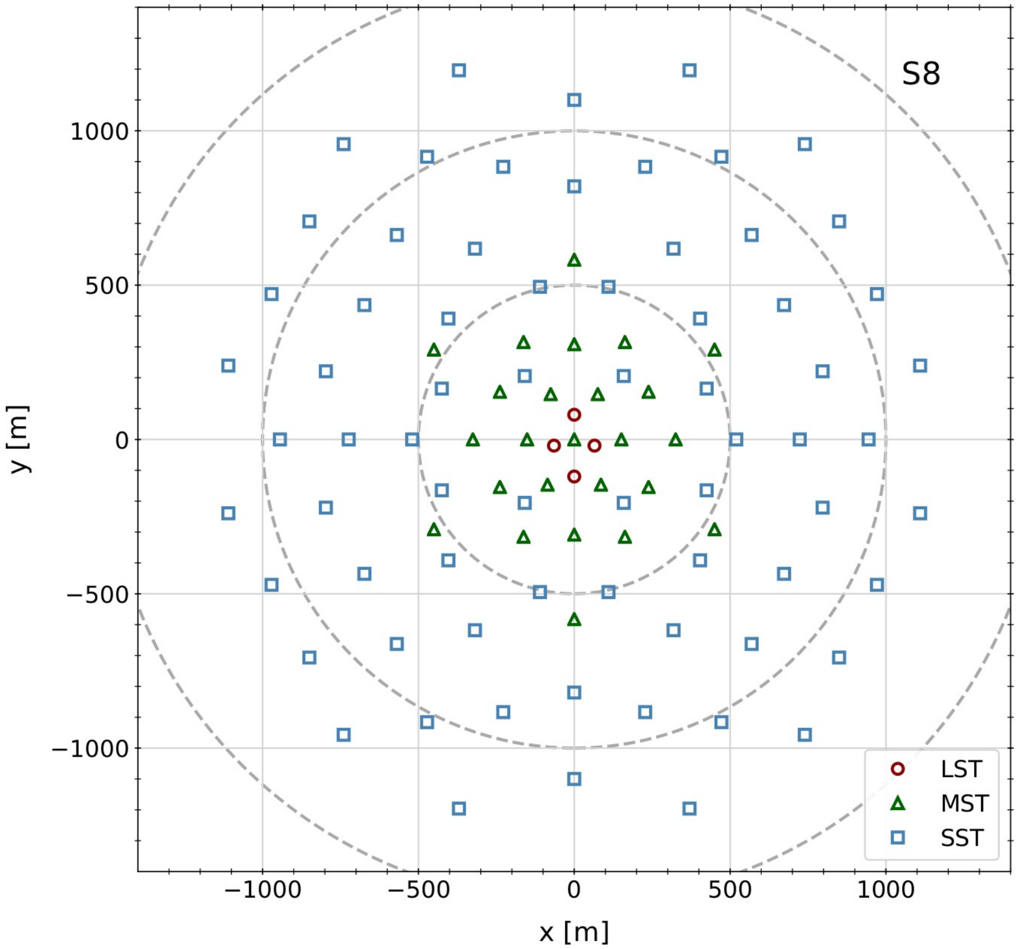


IACT technique – MC simulations

Shower simulation



- First, define a layout of telescopes



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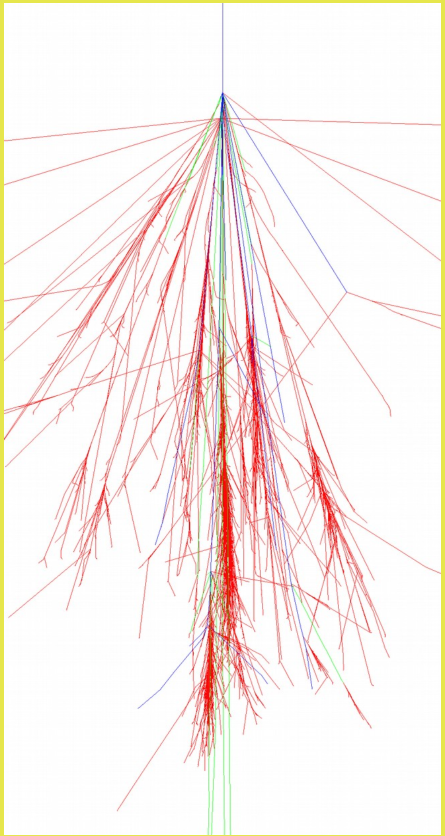
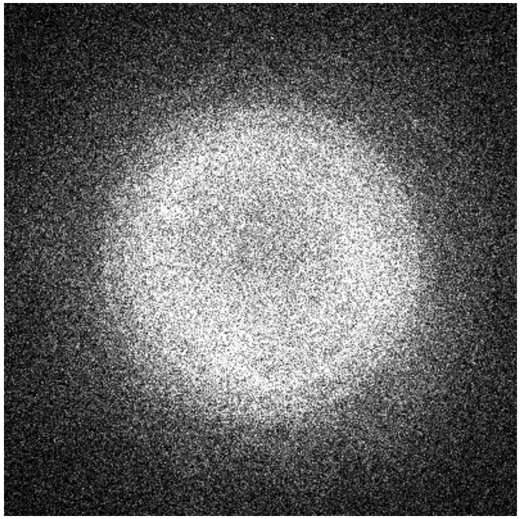
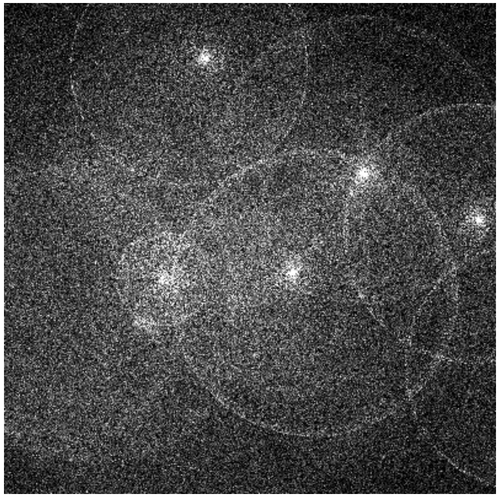


- First, define a layout of telescopes

- Gamma, cosmic-ray nuclei and electron showers are generated (CORSIKA)





IACT technique – MC simulations

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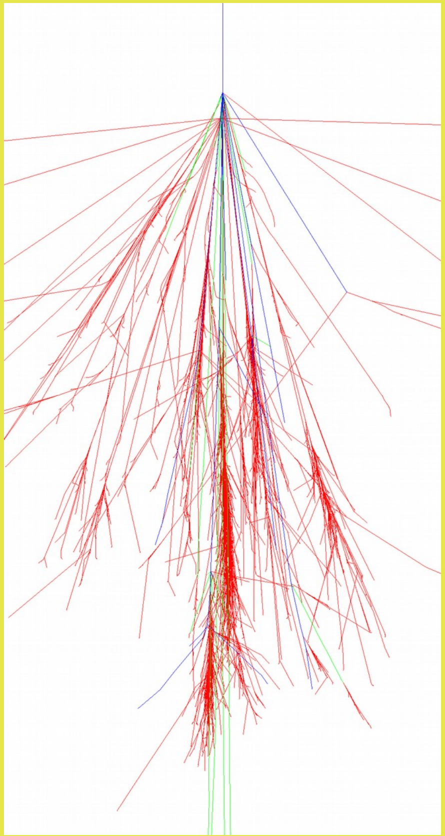
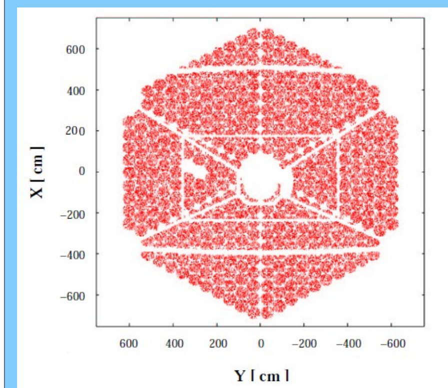
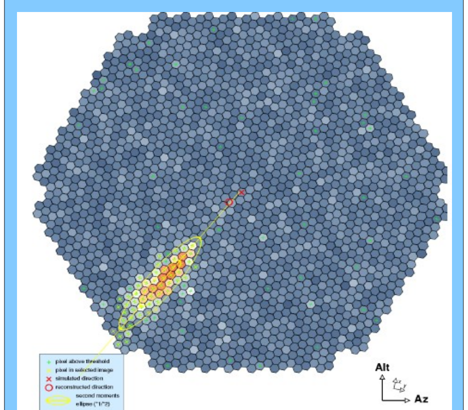


- First, define a layout of telescopes
- Gamma, cosmic-ray nuclei and electron showers are generated (CORSIKA)
- With the direction and timing of all photons from the air showers, the **telescope simulation** begins

IACT technique – MC simulations

Telescope simulation

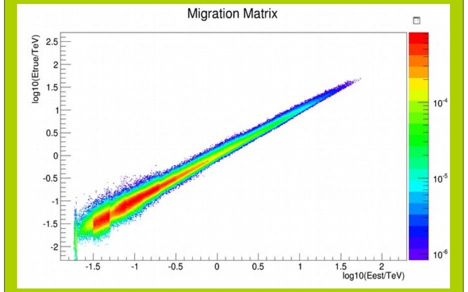


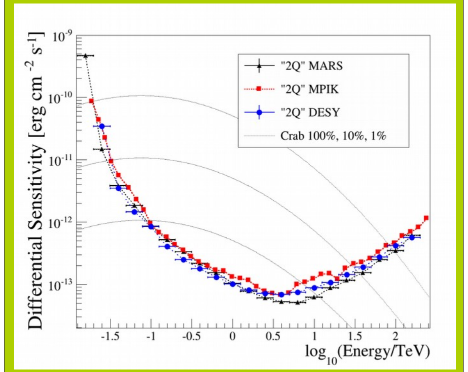


- Each IACT uses their own simulation software to mimic their optical system and ray tracing, electronics, trigger system, camera response…
- In CTA, telescope response is simulated using `sim_telarray` (K. Bernlöhr)
- Simulates the ray tracing, electronics and camera response of several telescope types

IACT technique – MC simulations

Performance analysis





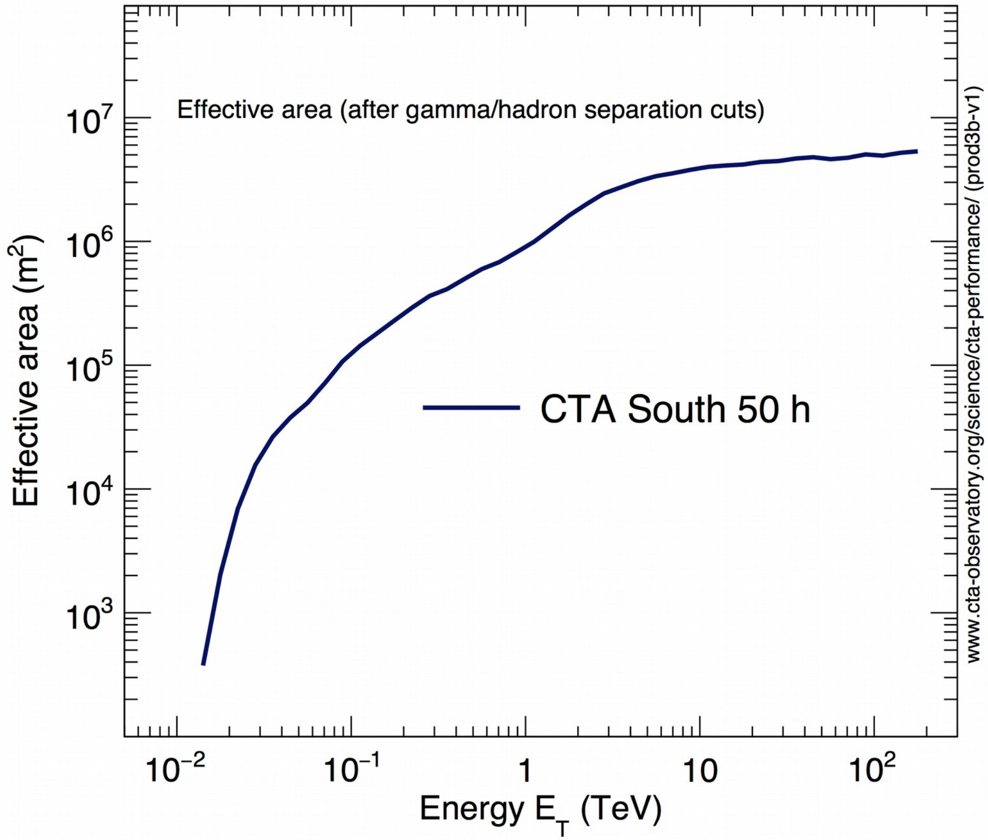
- MC generated data should be as close as possible to real data
- The IACT technique relies on MC simulations for both the low and high-level analyses:
  - Gamma-hadron separation
  - Energy reconstruction
  - Direction reconstruction
  - Performance evaluation (IRFs)

IACT IRFs – Effective area

- If we detect X amount of gammas during Y amount of time… What is the flux of the source? → Need effective area

- $A_{sim} * N_{analysis}(E) / N_{sim}(E)$

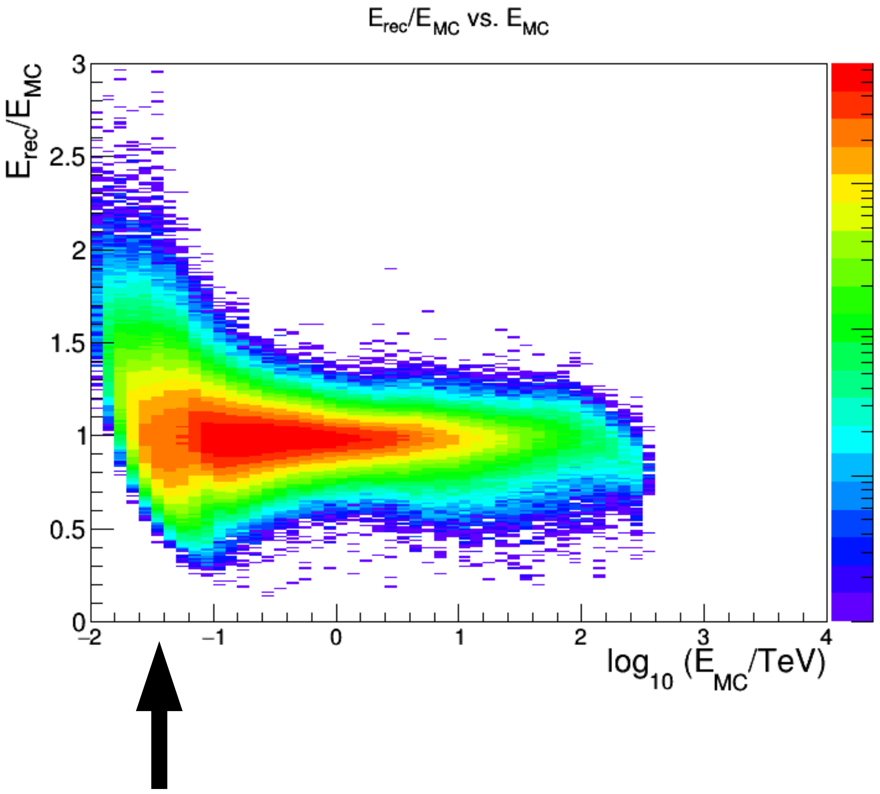
- Strongly affected by the low-level analysis

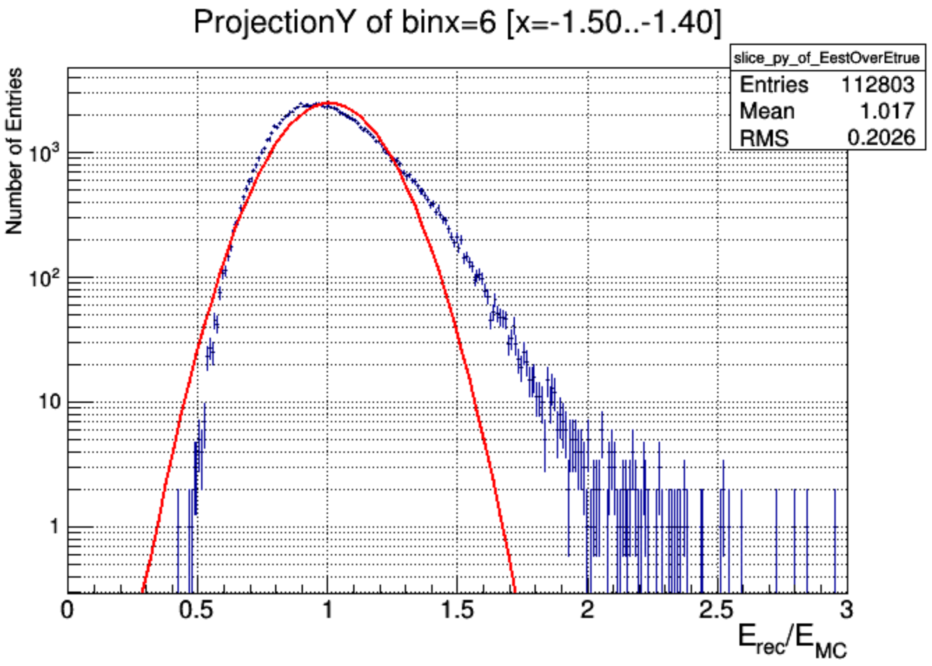


IACT IRFs – Energy migration

- Energy reconstruction is not perfect (actually, it's pretty bad…)

- Need to take into account it's dispersion in the analysis





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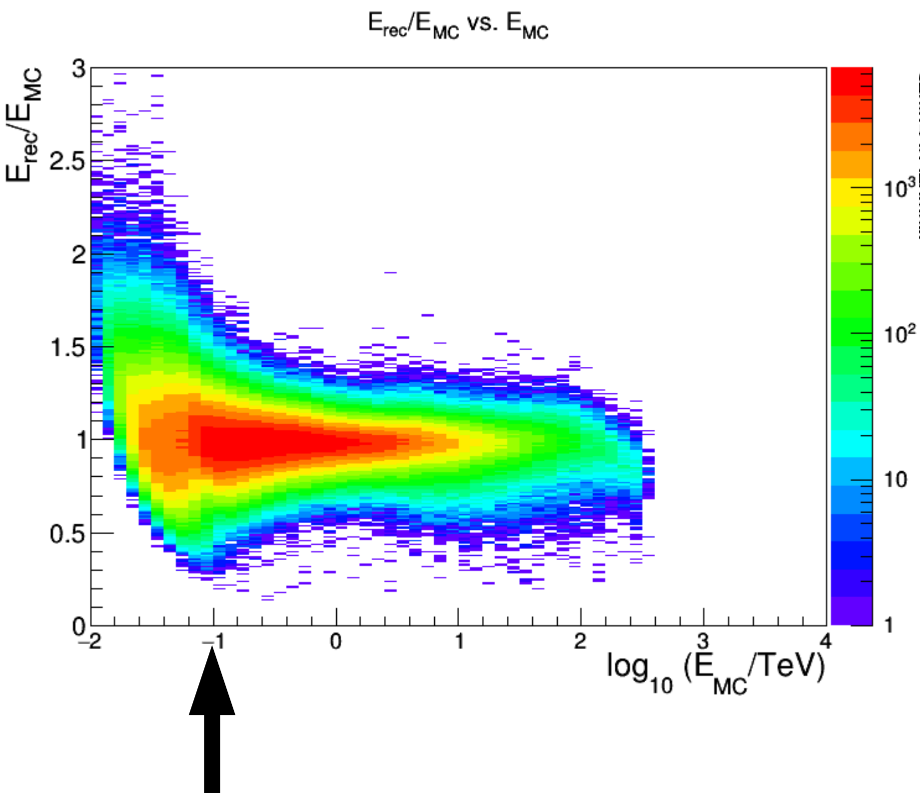

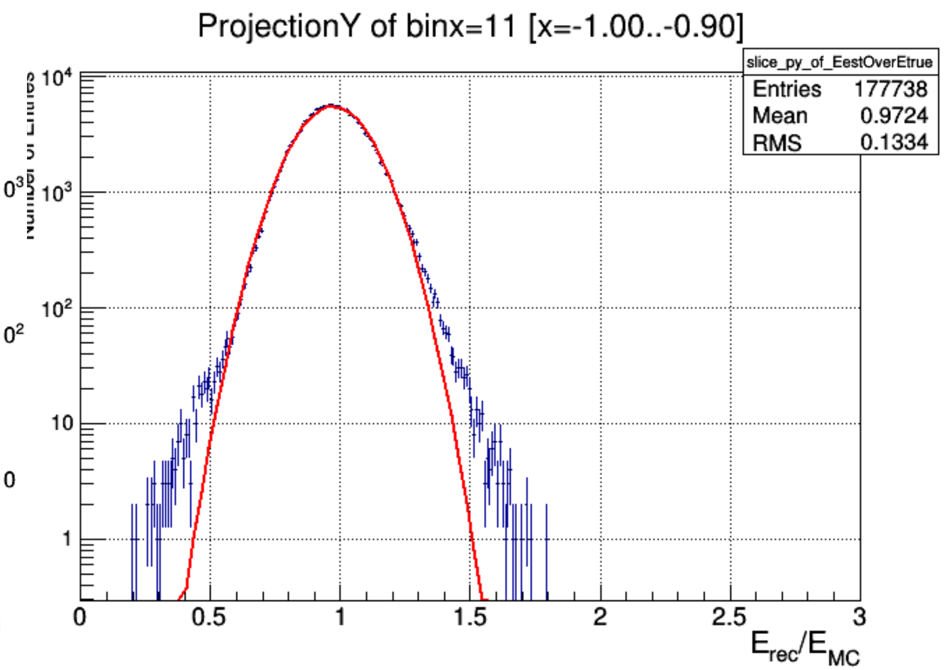

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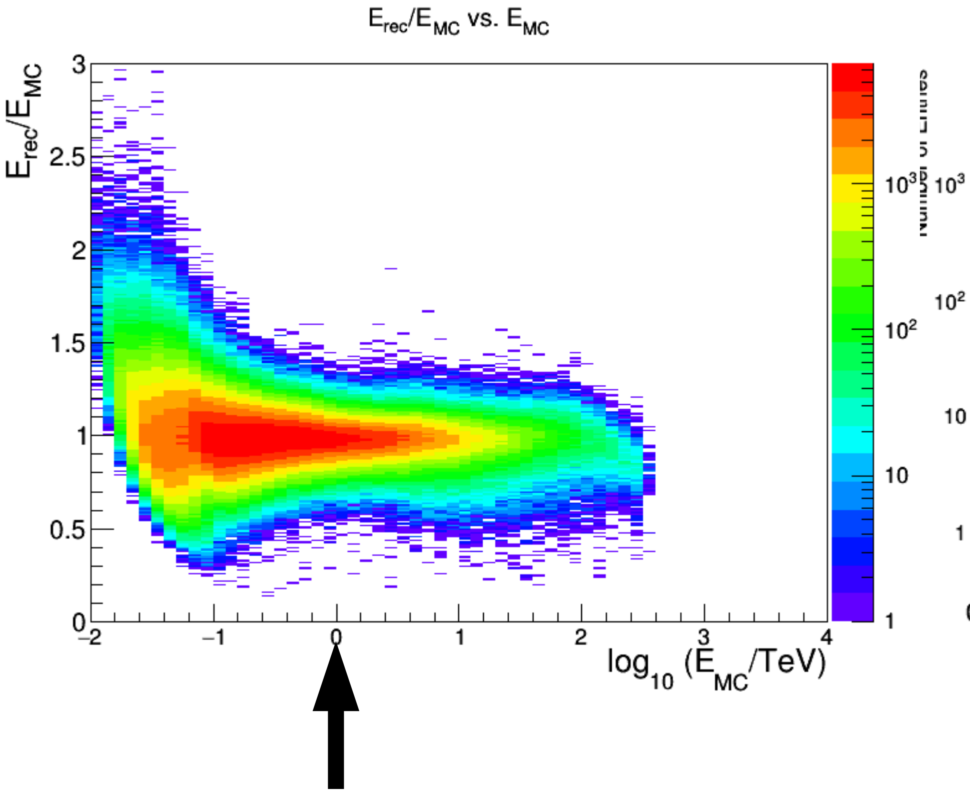

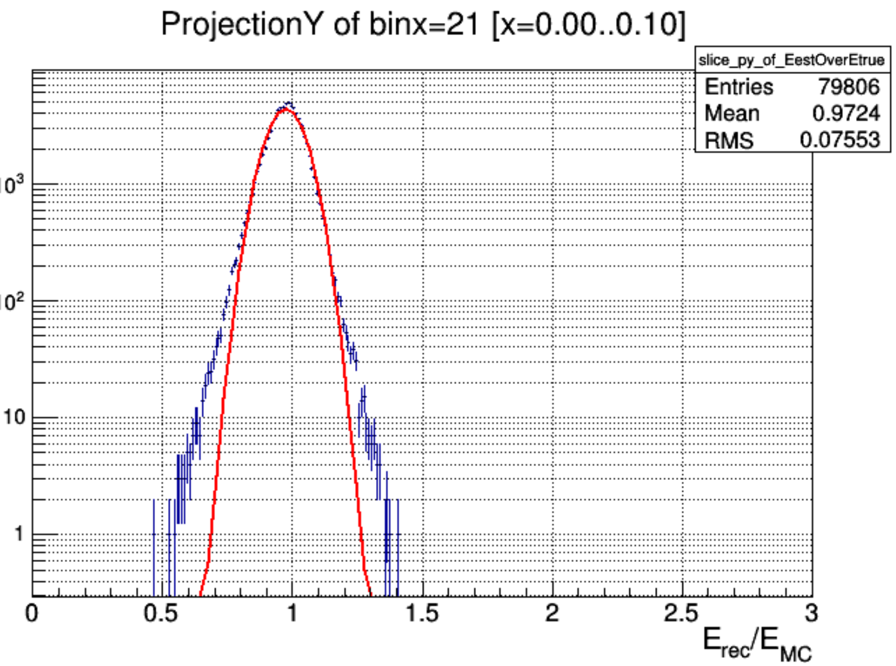

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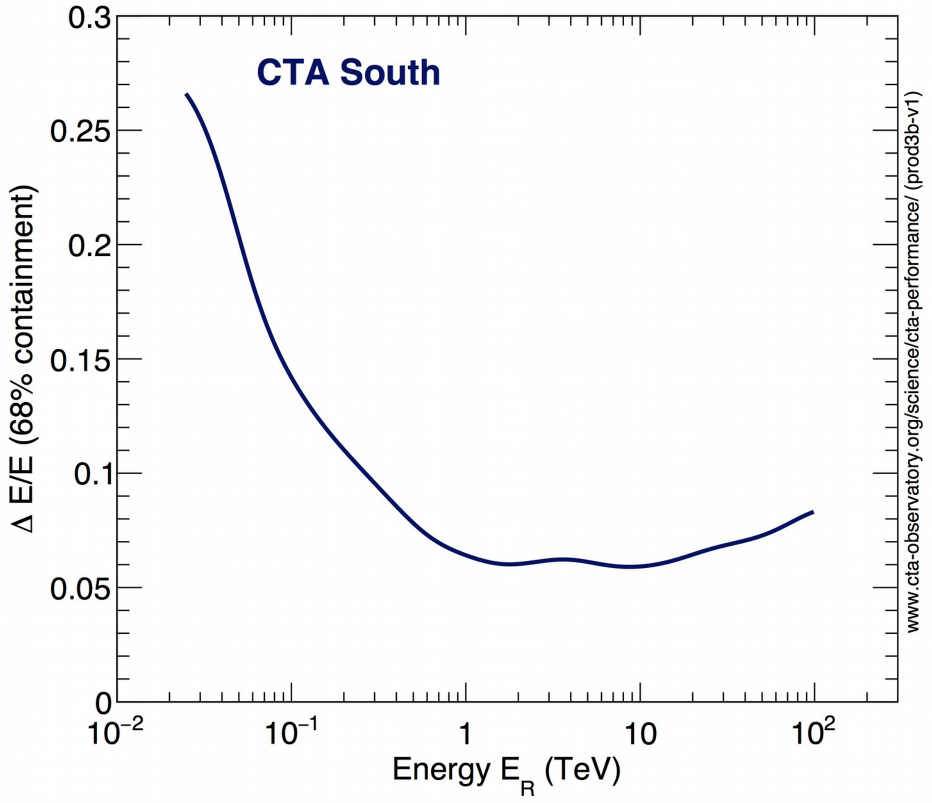
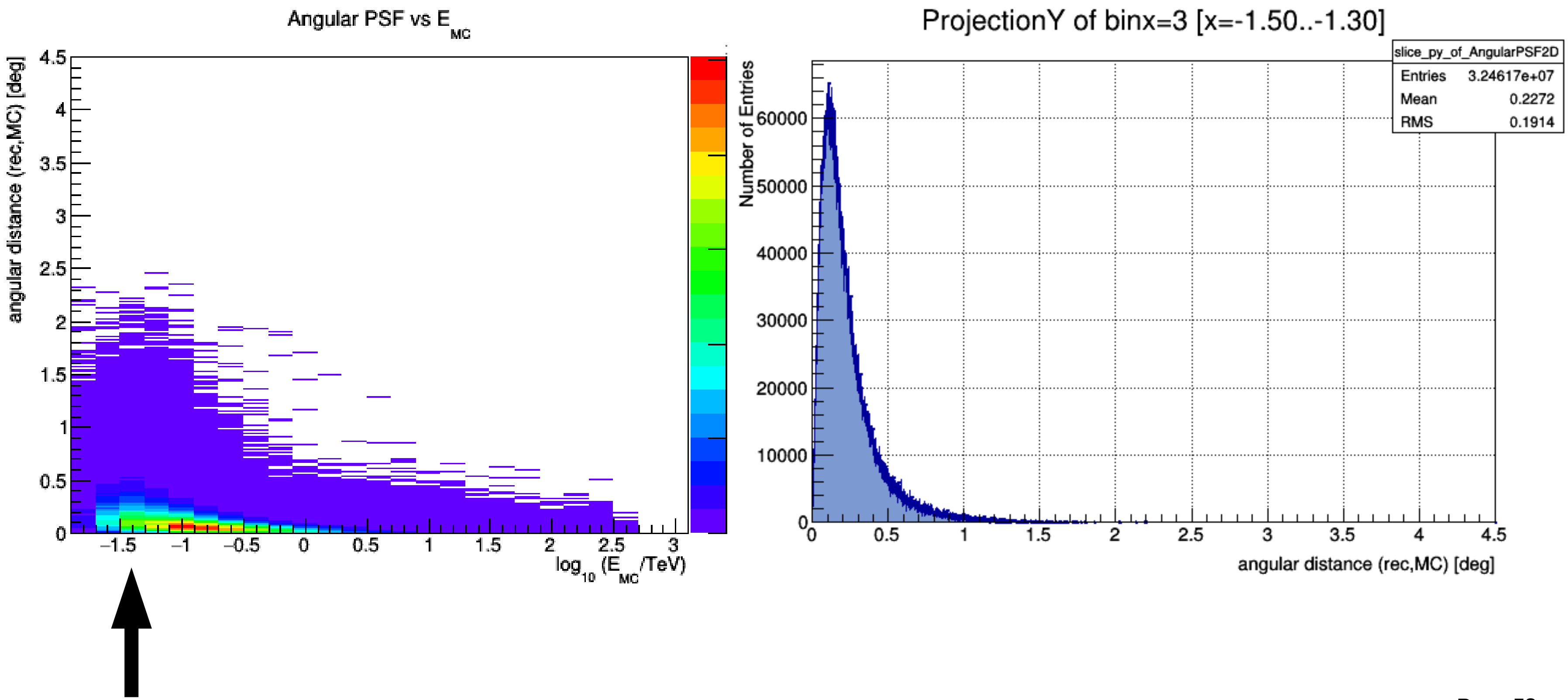


IACT IRFs – Direction reconstruction

- Direction reconstruction is not perfect either
- To study source morphology, it's crucial to understand our **point spread function** (PSF)



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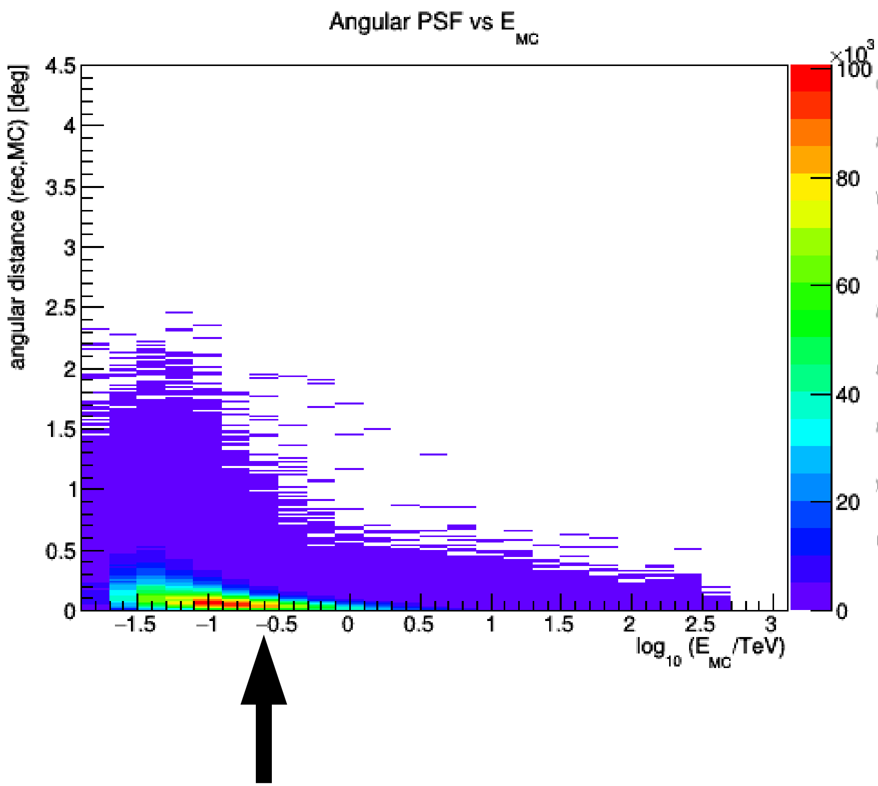

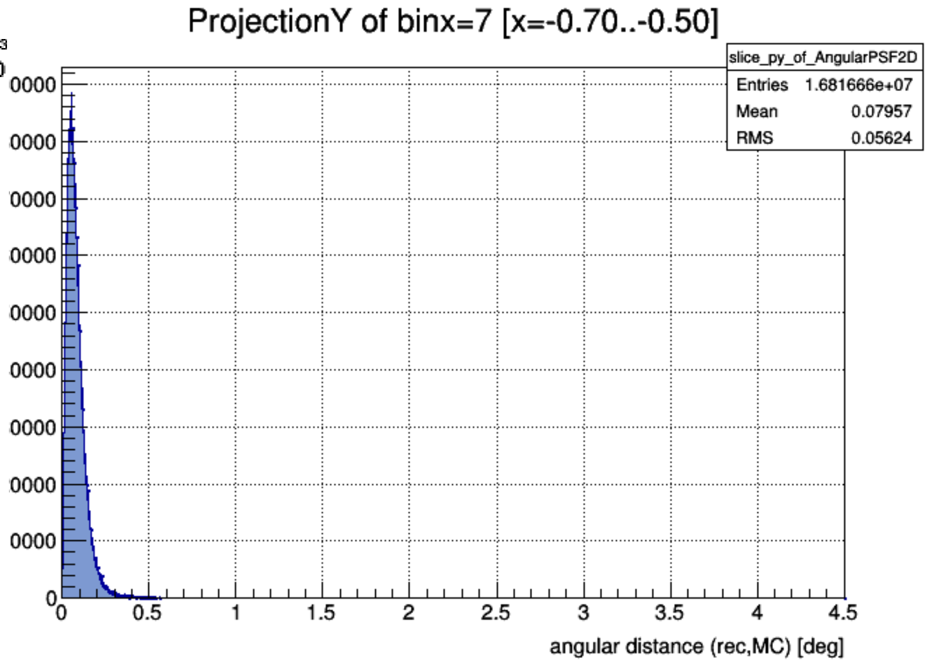

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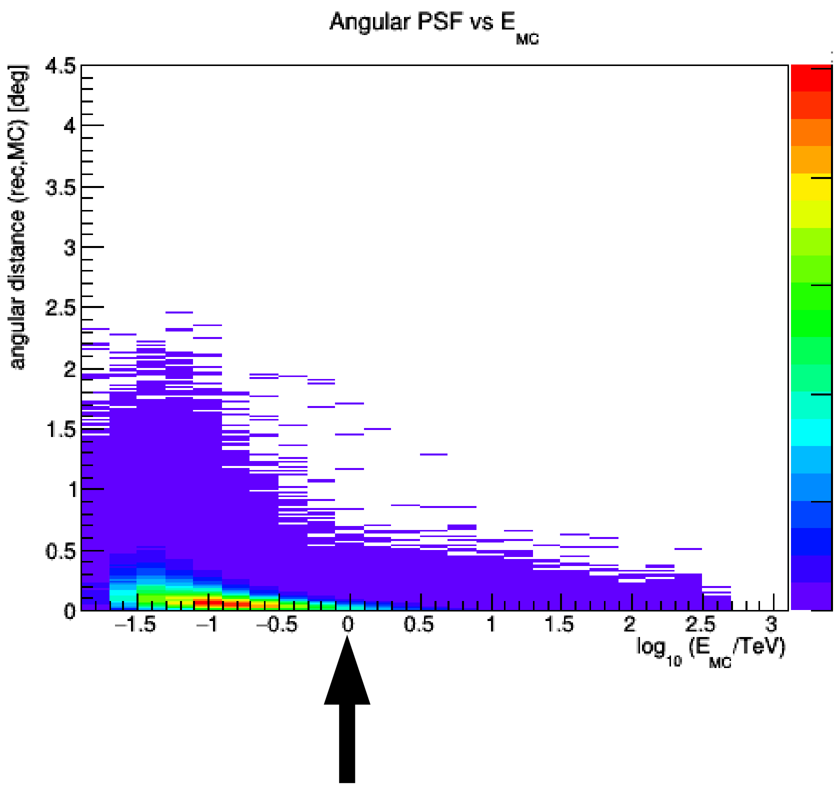
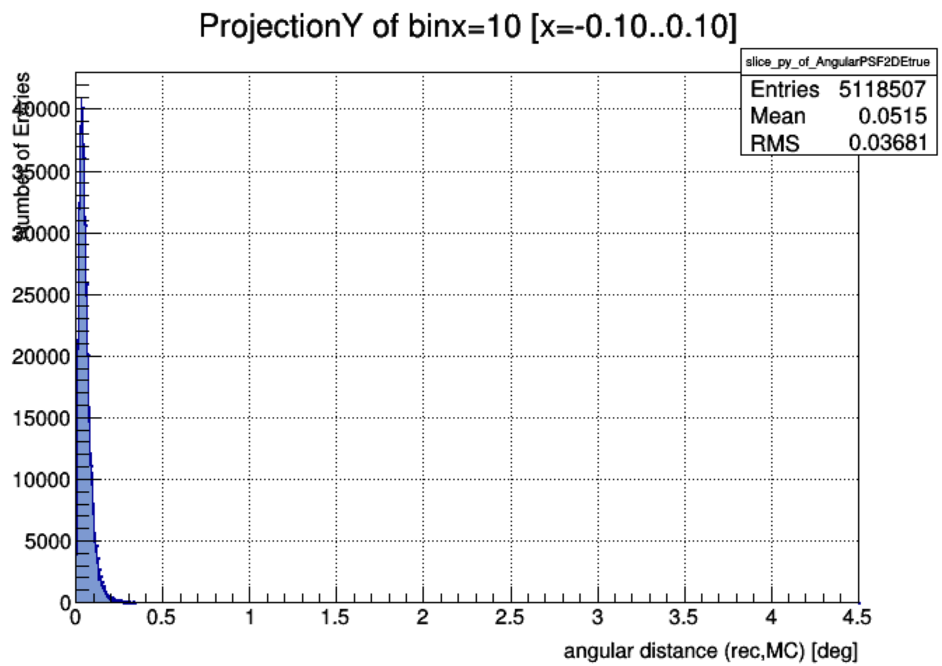
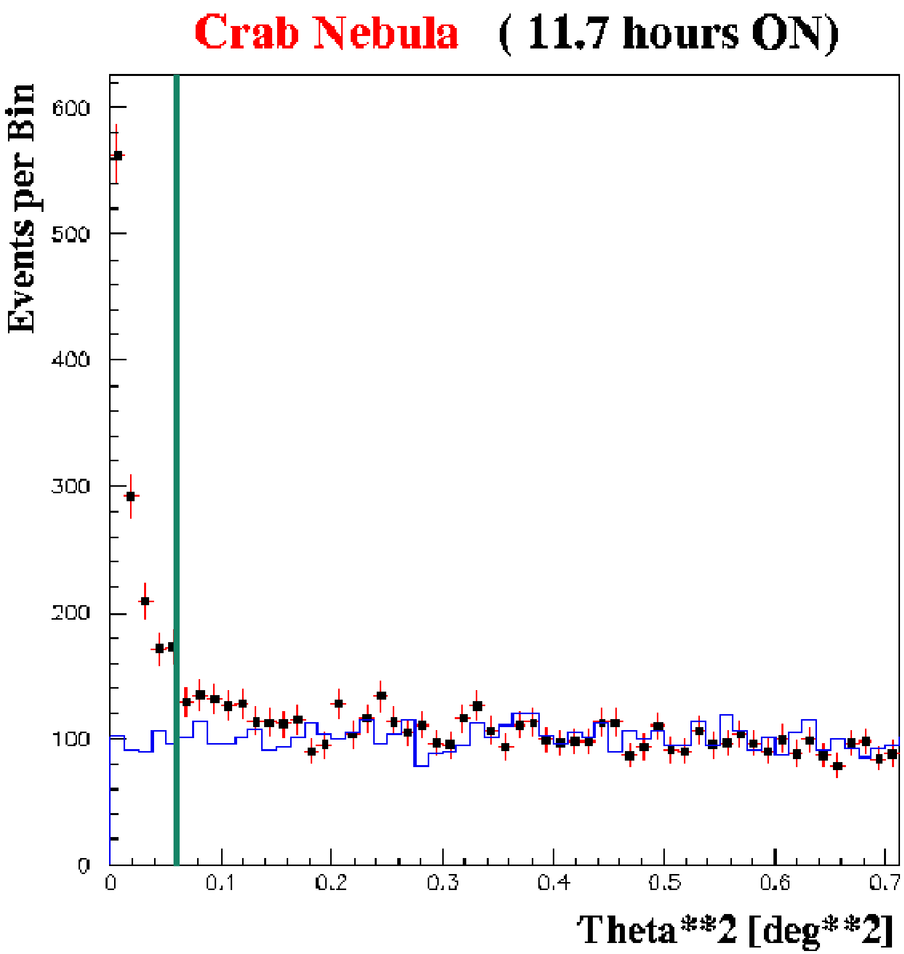




Analysis in VHE – Spectra

- Applying the same data analysis to our Monte Carlo events:



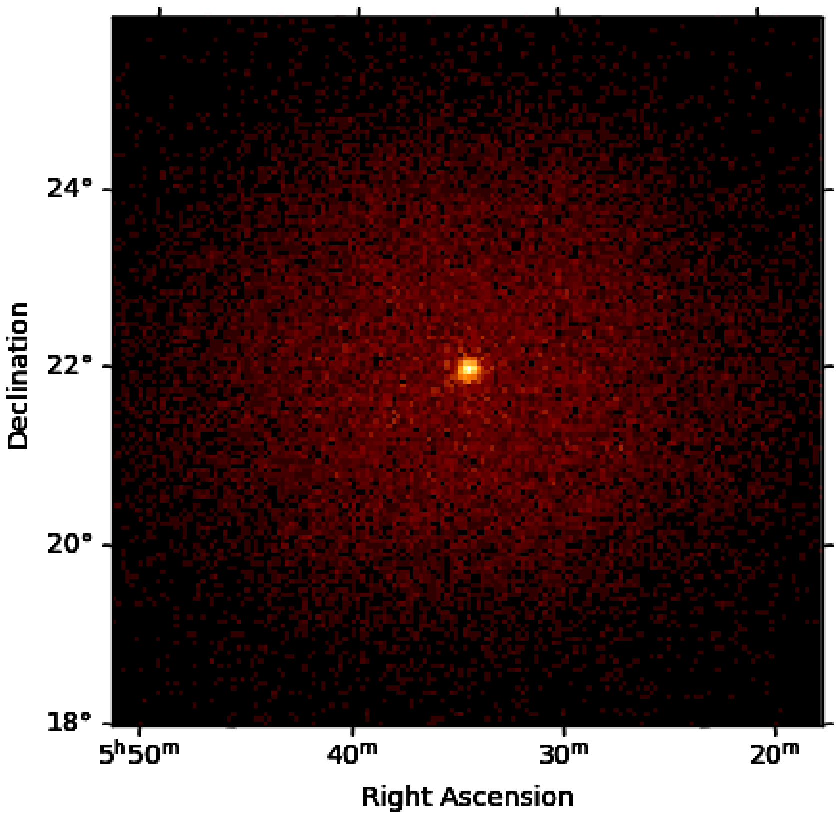
- Knowing the effective area, we can relate the number of gammas **we detect**, with the number of gammas that were emitted (vs energy)

- Knowing the energy dispersion, we correct the spectrum with the inferred energy migration

- If MC and real data are not matching, **systematic errors** will arise

IACT analysis – Classical spectral analysis

- The classical analysis for the last 20 years goes like this:



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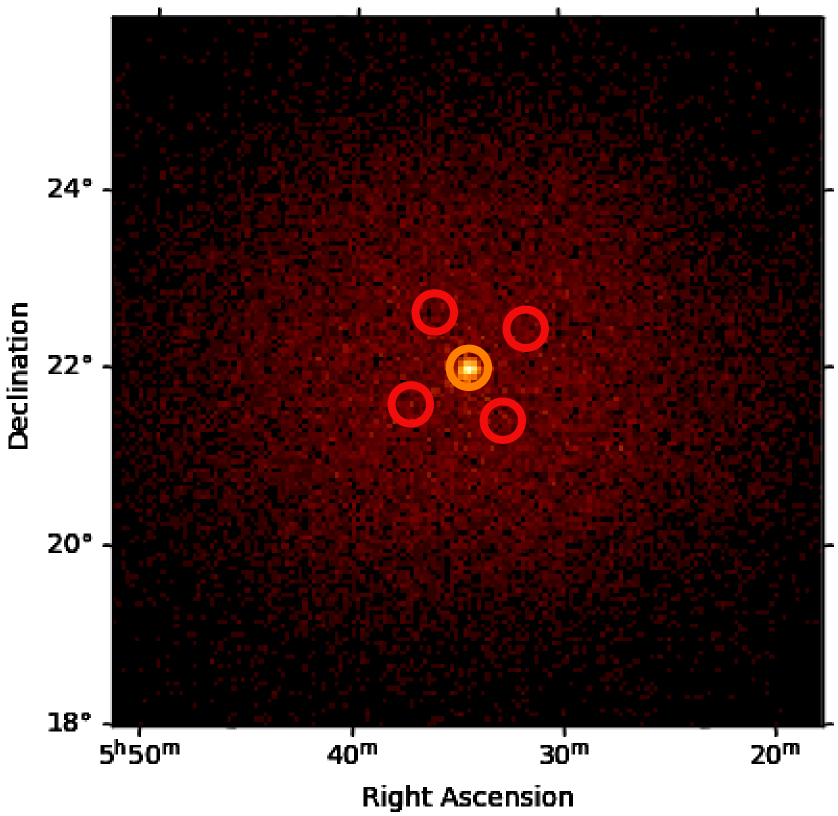

- **Fix** ON region, a background evaluation method, and calculate significance

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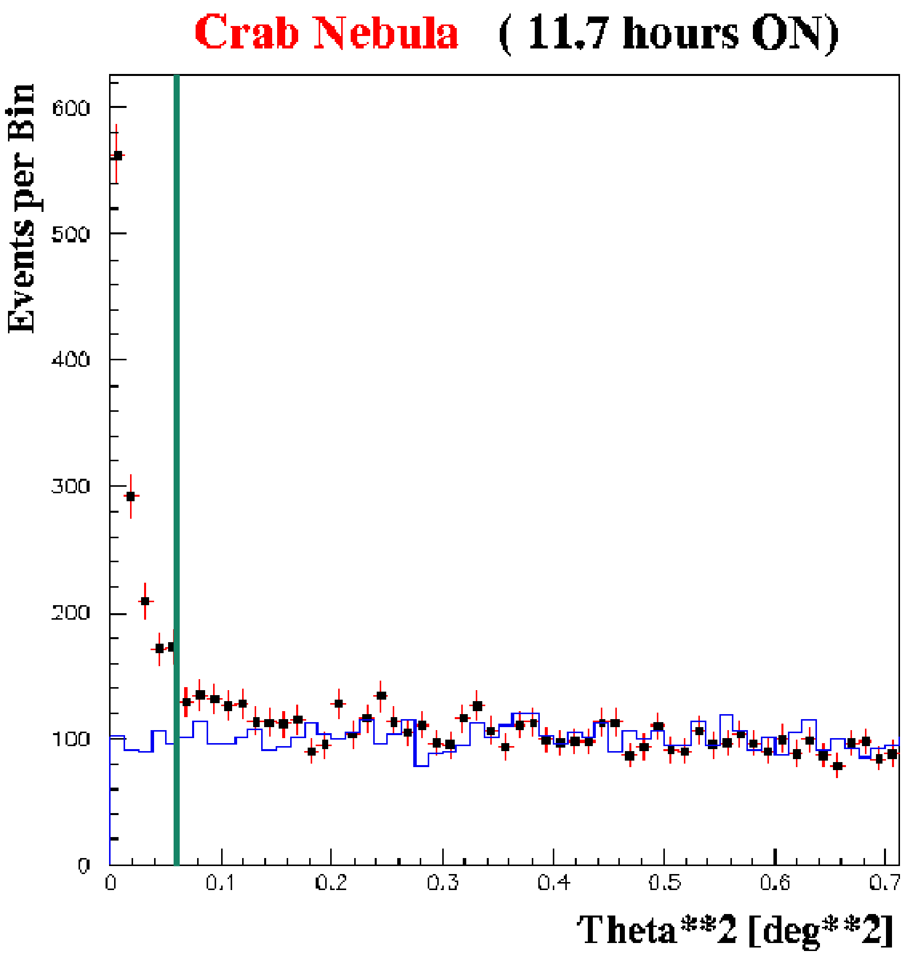

- **Fix** ON region, a background evaluation method, and calculate significance

- For **that ON region**, calculate IRFs through MC simulations

- With the effective area, we calculate flux vs energy

- With a known energy dispersion, we “correct” the spectrum

IACT analysis – Classical spectral analysis

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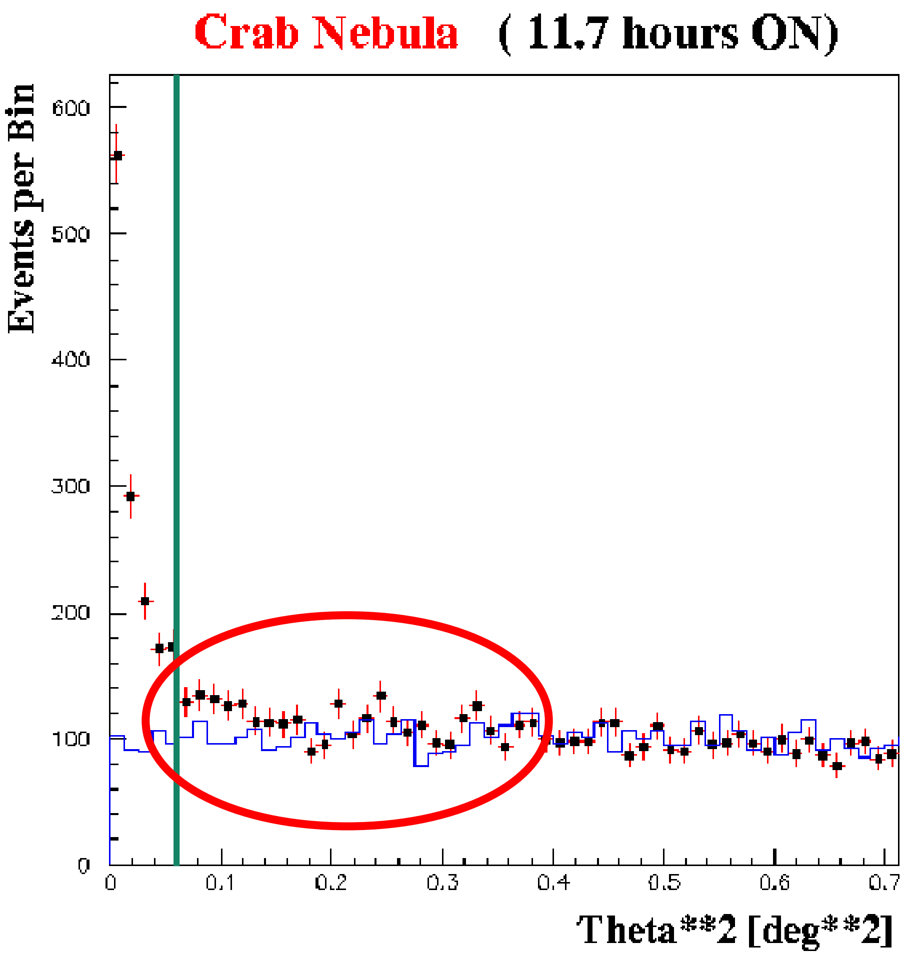


What can we improve?

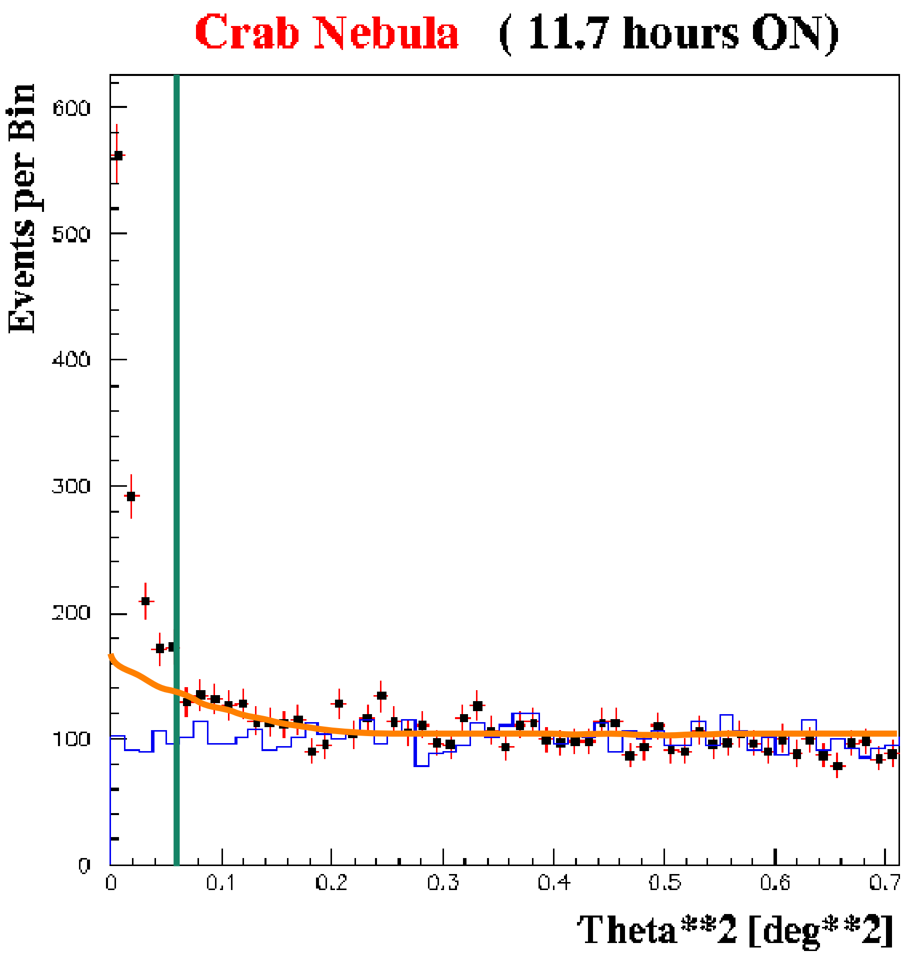
- By fixing the ON region, we “throw away” the rest

- Ignore the #events vs energy for testing detection significance

- Ignore our **understanding** of our instrument (e.g. the size of the PSF vs energy)

CTA analysis – Likelihood analysis

- The analysis currently proposed for CTA solved this problem:



1) Assume a model:
(e.g. point-like source)

2) **Simulate** the number of events + background

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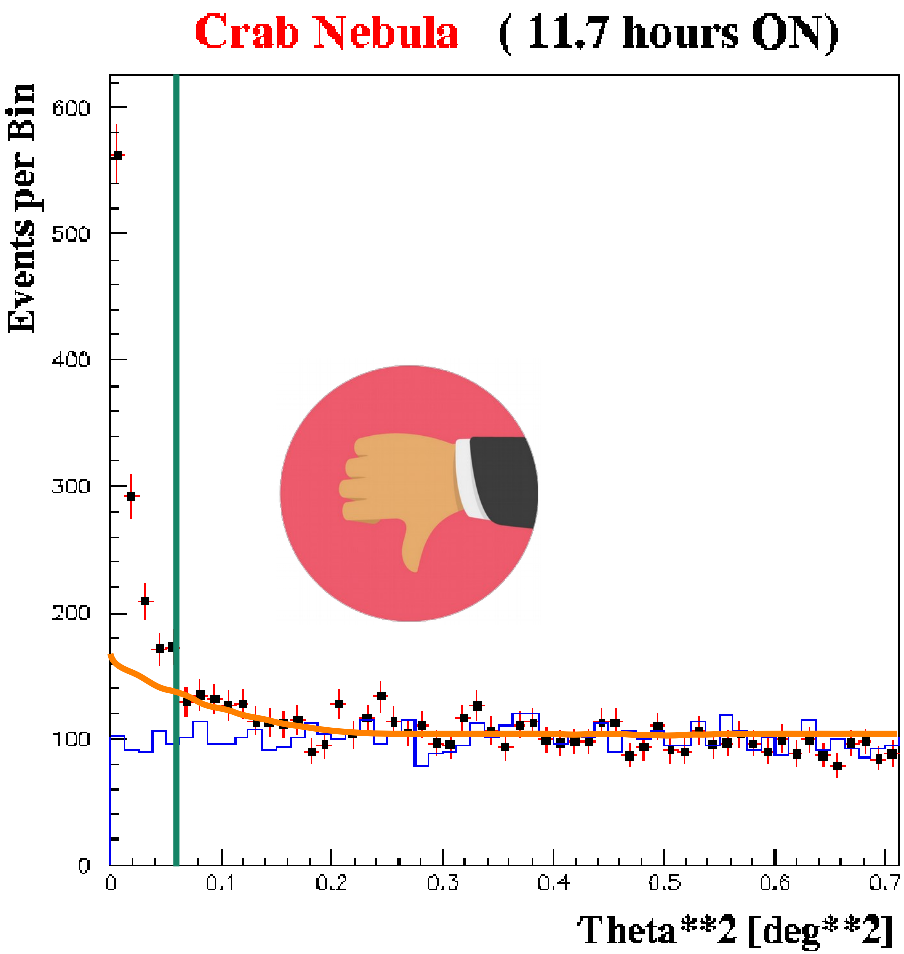

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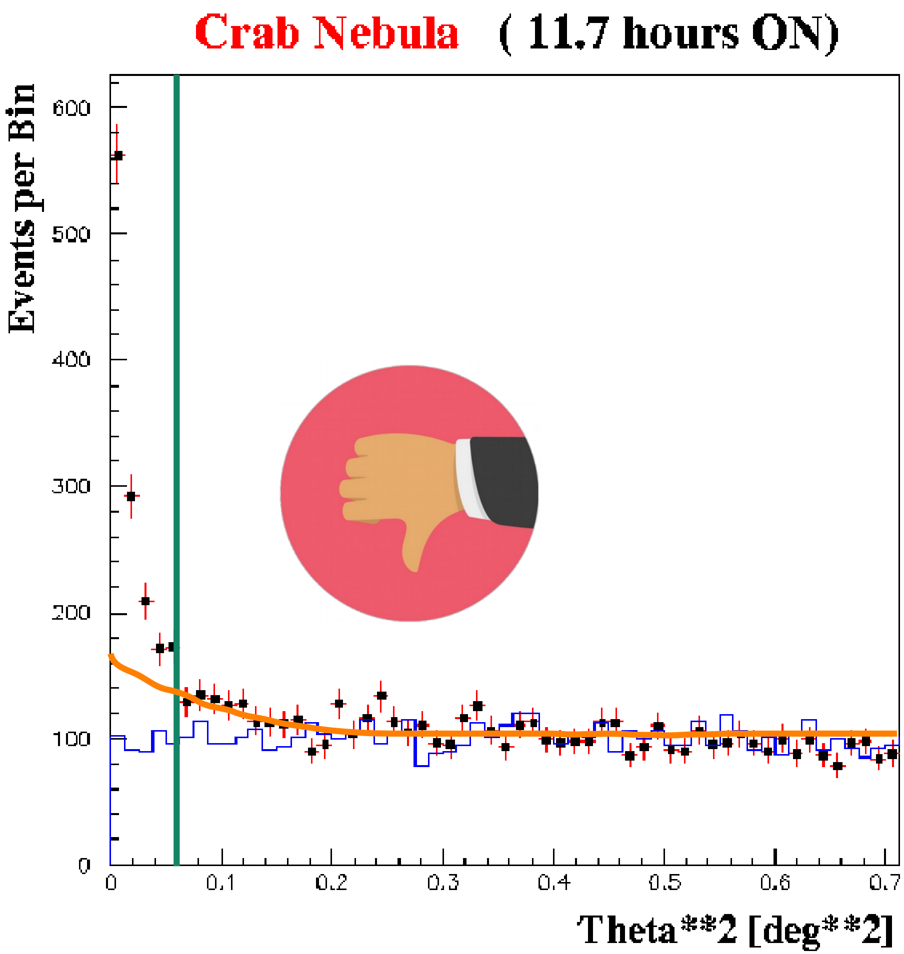

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4) Iteratively repeat steps 1, 2 and 3, until you find the model better matching the data

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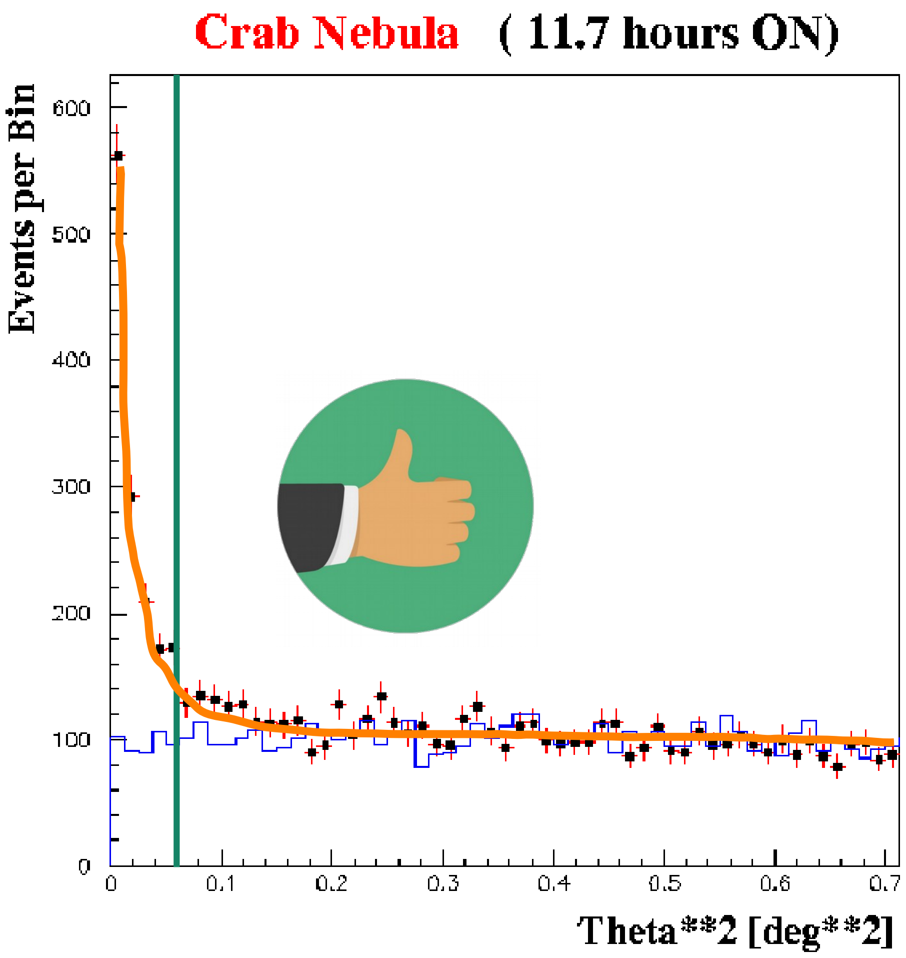

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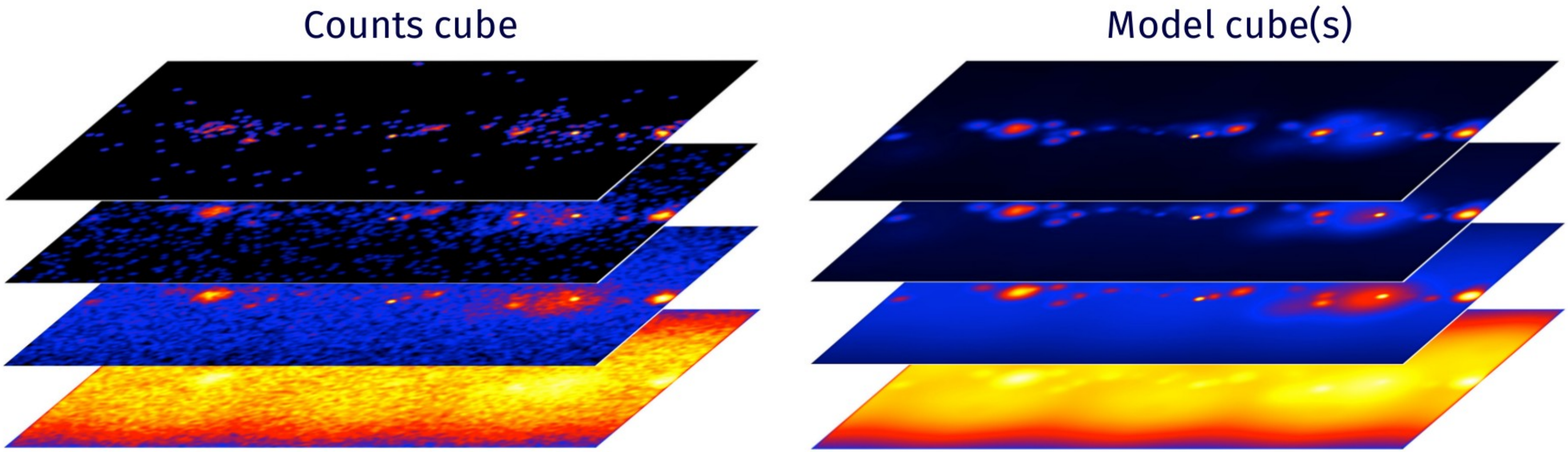

- Remember: For this analysis, understanding your instrument (correct IRFs) is key!

- Good news: CTA will take care of (almost!) everything

CTA analysis – Introduction to DL3

- DL3 is the "high-level" product (FITS format) resulting from the analysis of collected data containing:

  - Event lists (event-wise energy, RA, DEC, time) of **gamma-like events**

  - IRFs describing the instrument performance (Eff. Area, BG rate, direction/energy dispersion)

  - TECH data describing details of the observations (pointing, obs. conditions, etc..)

DL3 = EVT3 + IRF3 + TECH3

CTA analysis – Introduction to DL3

DL3

Fermi-LAT

+

ctools
cherenkov telescope array

By J. Knödlseder et al.

Science tools

By C. Deil et al.

- Data Selection
  - Light Curves
    Counts Maps
    Spectra
  - Likelihood Analysis
  - Timing Analysis

IACTs high-level analysis – Summary

- The high-level analysis of IACTs comprises all the methods used to study source properties from the measured (reconstructed) events:
  - Source detection, skymaps and studying morphology, spectra, lightcurves...
- The high-level analysis planned for CTA is similar to other operating instruments (X-rays and gamma-rays)
- The main differences:
  - Very limited event statistics (every photon is important!)
  - Instrument with time evolving performance


BACKUP


2.4
HH
4.7