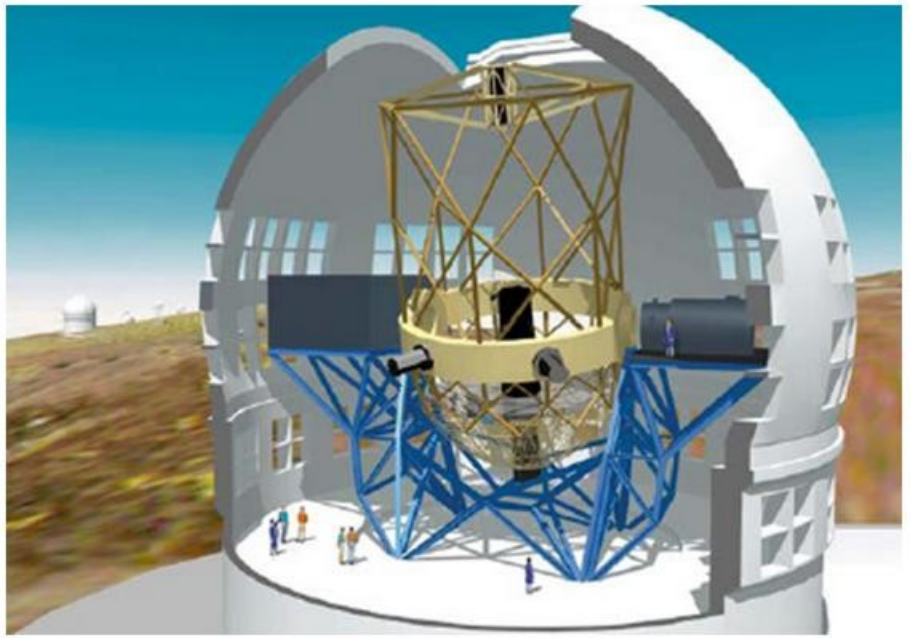
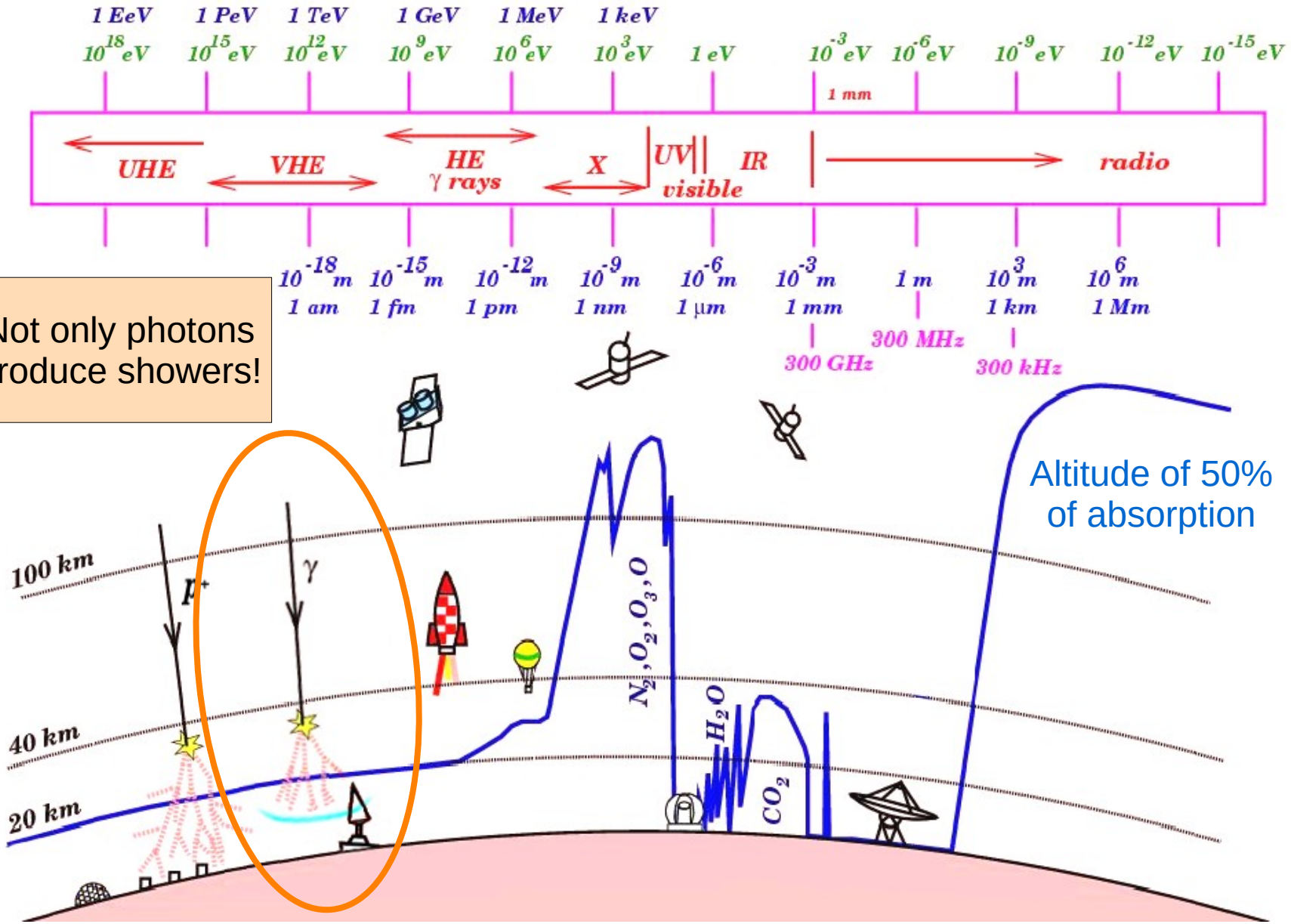
Imaging Atmospheric Cherenkov Telescopes:
Analysis I

Tarek Hassan
DESY

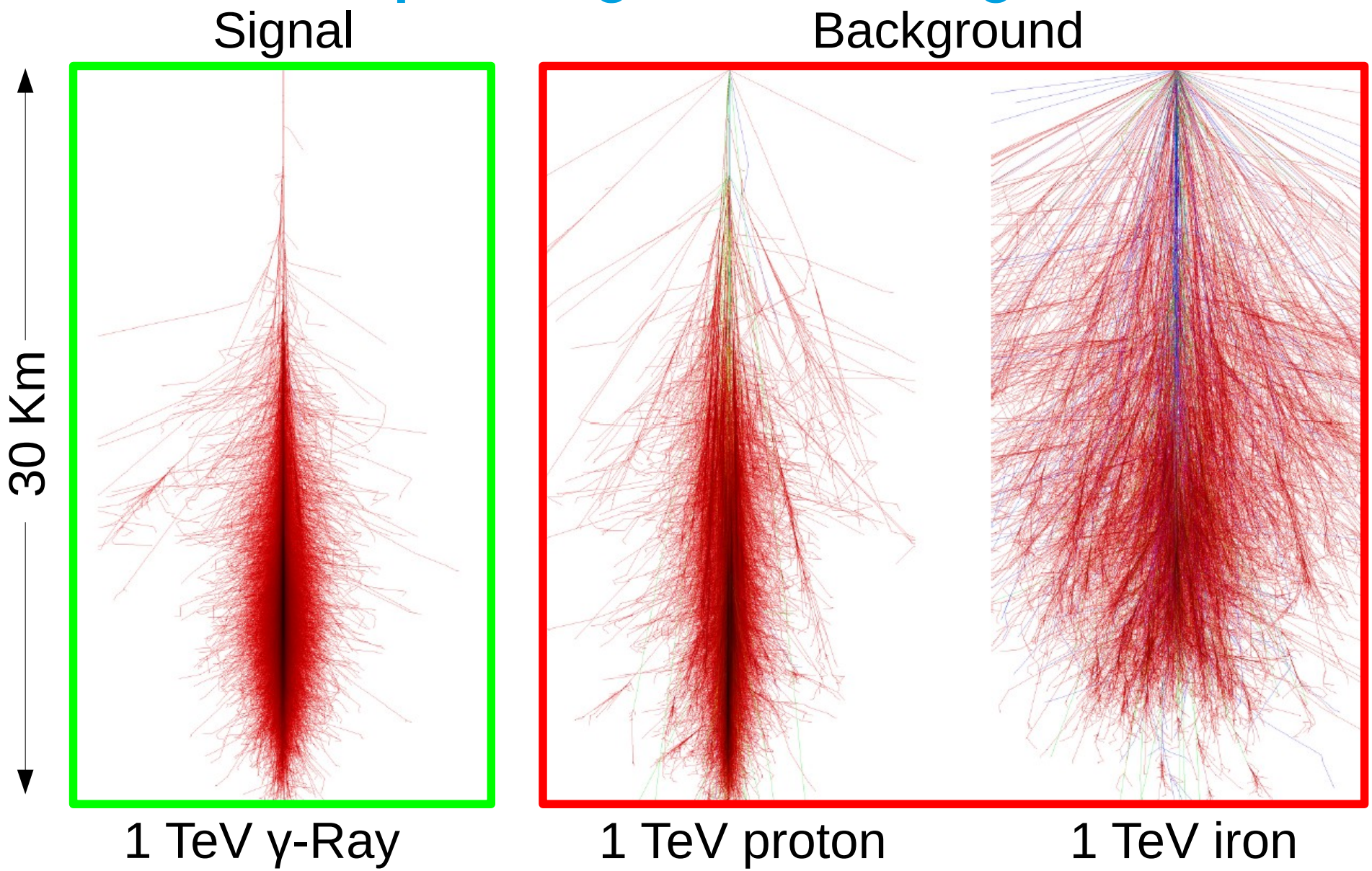
IACT technique – Overview

- Imaging Atmospheric Cherenkov Telescopes (IACTs) are very similar to normal optical telescopes

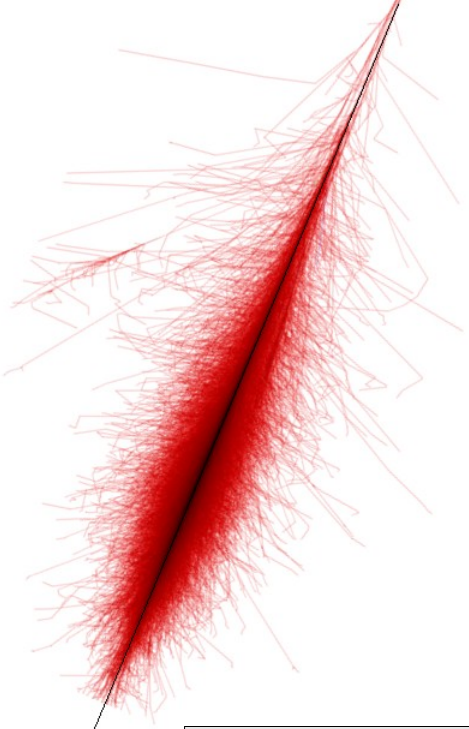



1 EeV
10^18 eV
1 PeV
10^15 eV
1 TeV
10^12 eV
1 GeV
10^9 eV
1 MeV
10^6 eV
1 keV
10^3 eV
1 eV
10^-3 eV
1 mm
10^-6 eV
10^-9 eV
10^-12 eV
10^-15 eV
UHE
VHE
HE
γ rays
X
UV
visible
IR
radio
10^-18 m
1 am
10^-15 m
1 fm
10^-12 m
1 pm
10^-9 m
1 nm
10^-6 m
1 μm
10^-3 m
1 mm
1 m
10^3 m
1 km
10^6 m
1 Mm
300 GHz
300 MHz
300 kHz
Not only photons produce showers!
Altitude of 50% of absorption
100 km
40 km
20 km
p+
γ
N2,O2,O3,O
H2O
CO2

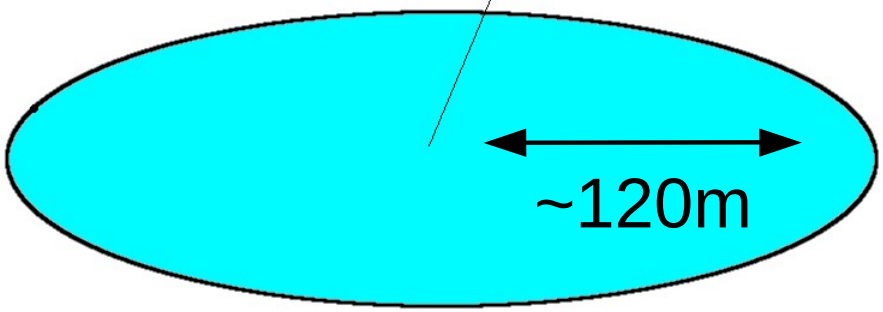
IACT technique – Signal and background



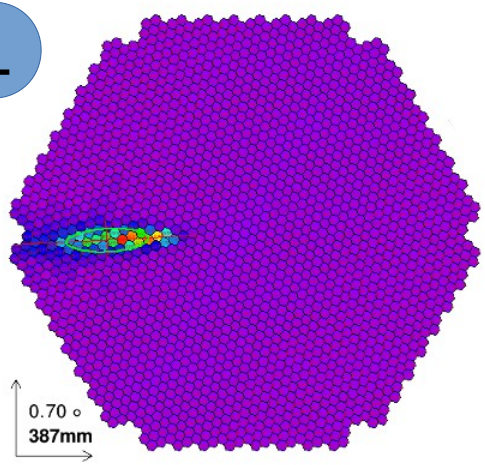
Crab
γ-ray
1 TeV



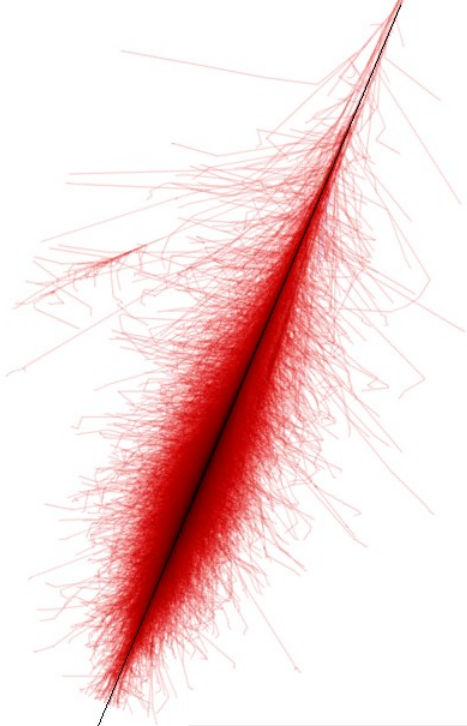
Direction = ¿?
Particle = ¿?
Energy = ¿?



1

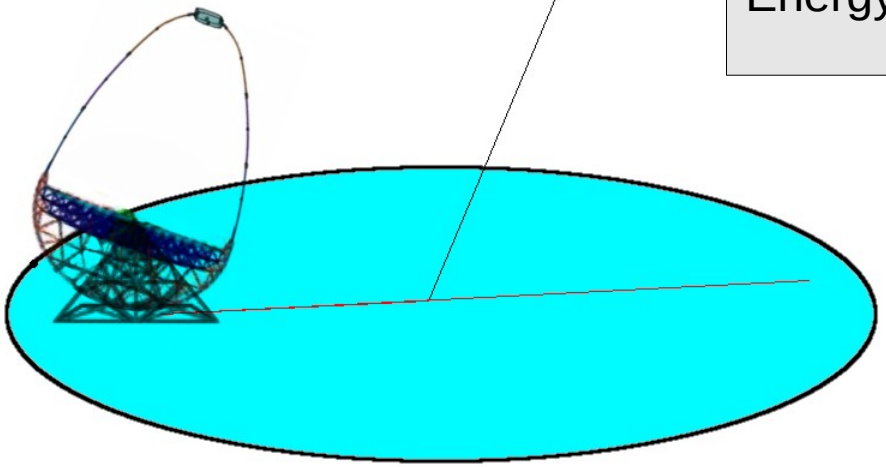


Crab
γ-ray
1 TeV

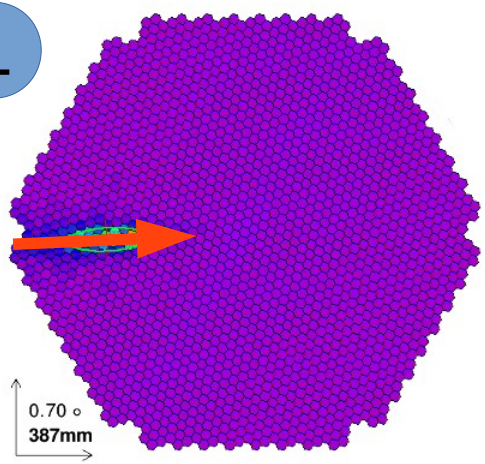


Direction = ¿?
Particle = ¿?
Energy = ¿?

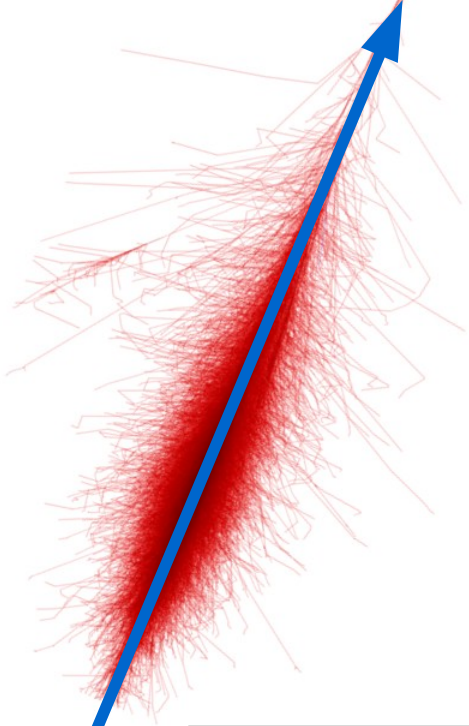
1



1

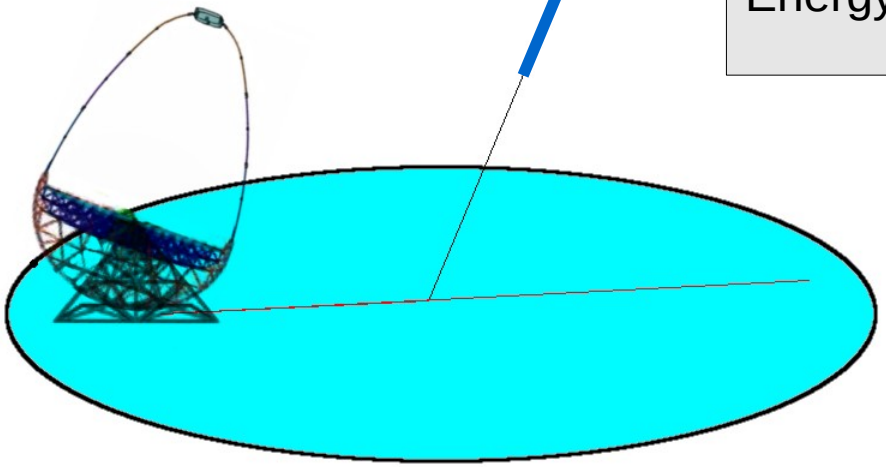


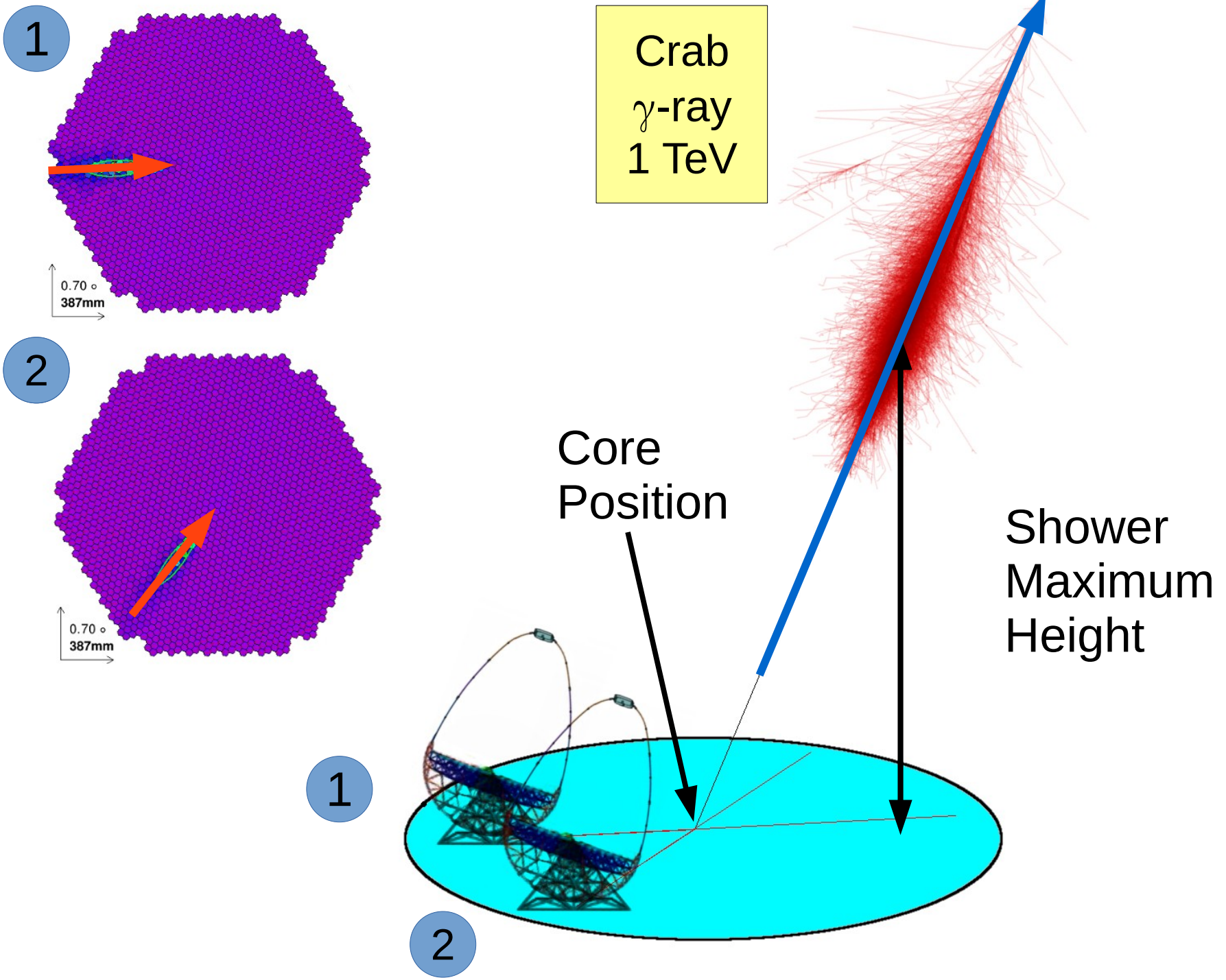
Crab
γ-ray
1 TeV

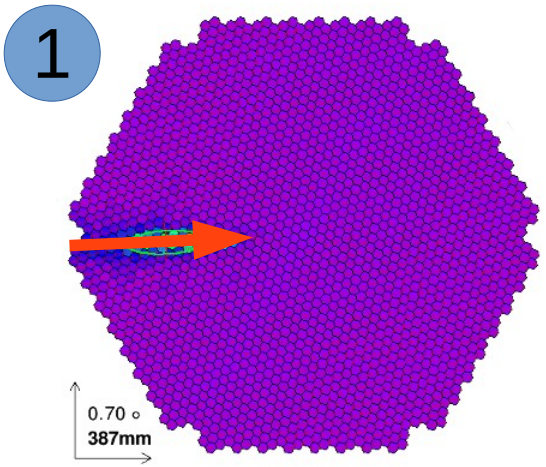


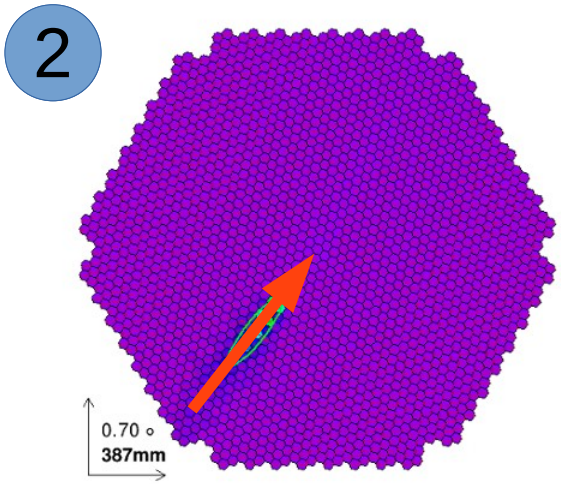
Direction = ¿?
Particle = ¿?
Energy = ¿?

1

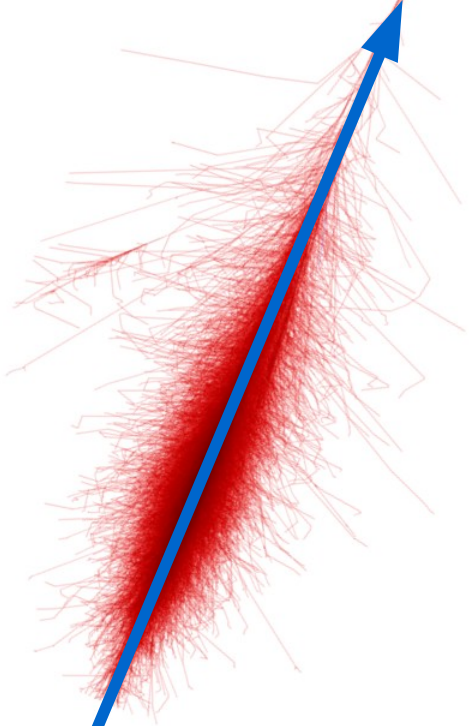



1
0.70 ∘
387mm
2
0.70 ∘
387mm
Crab
γ-ray
1 TeV
Core
Position
Shower
Maximum
Height
1
2

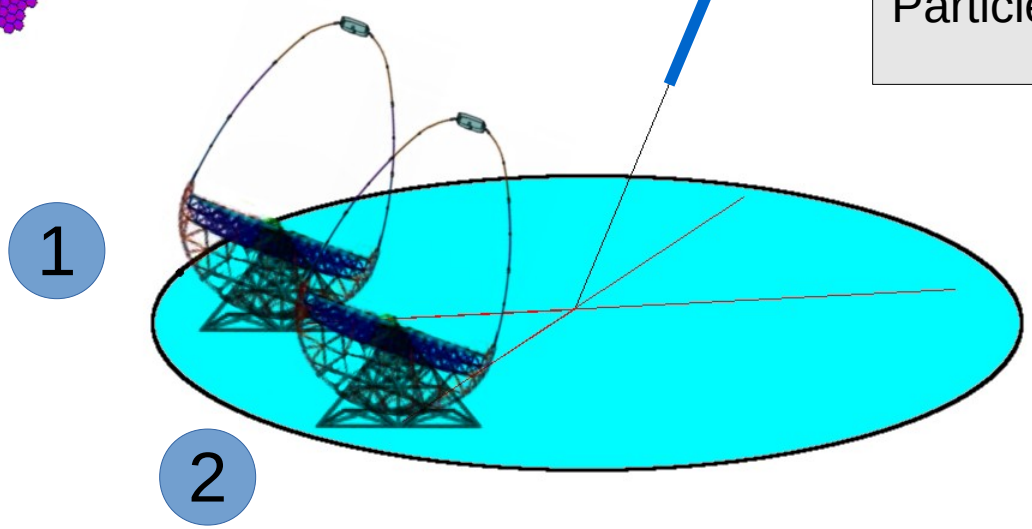


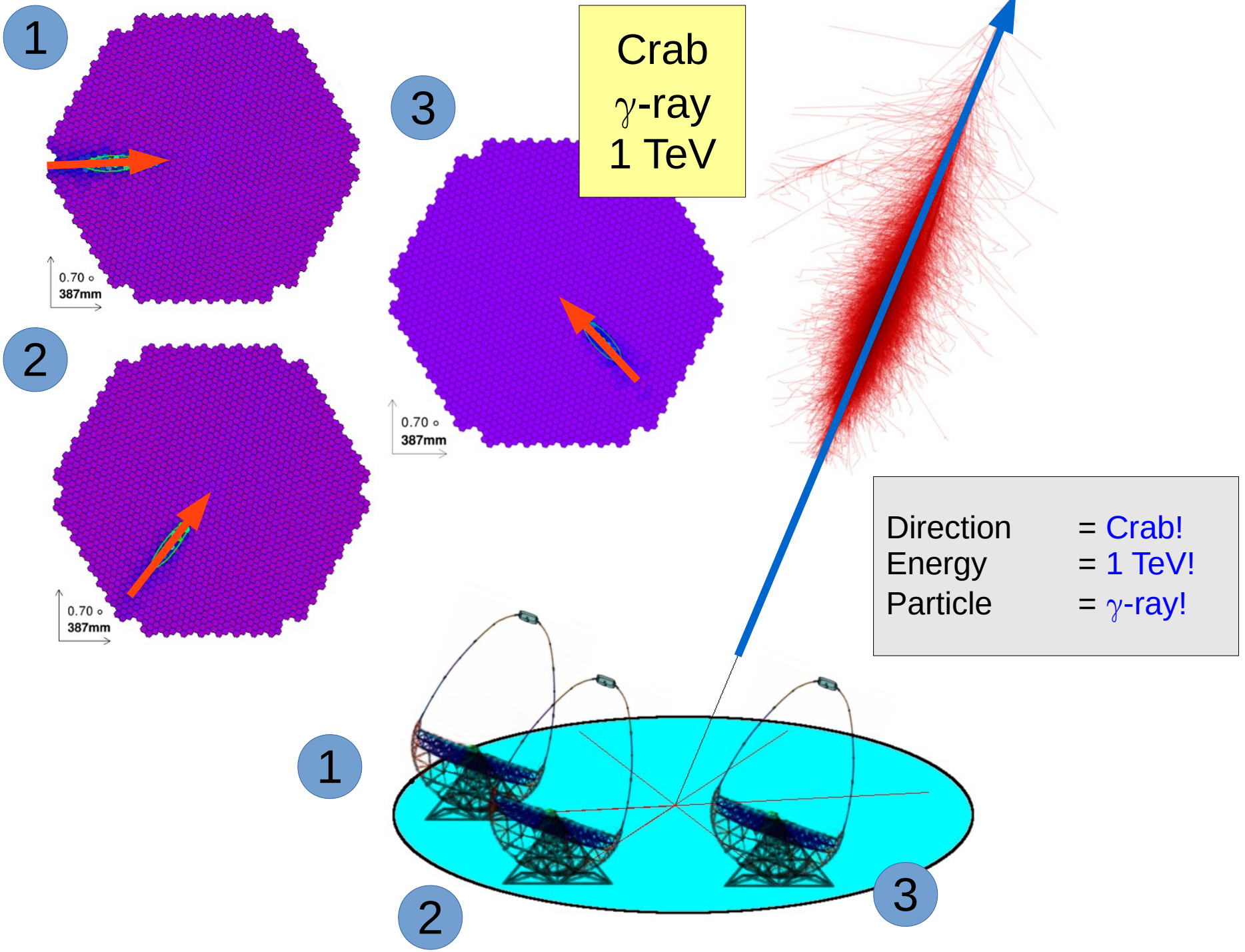


Crab
γ-ray
1 TeV



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




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

IACT technique – Overview

- Imaging Atmospheric Cherenkov Telescopes (IACTs) are very similar to normal optical telescopes

- The “only” difference is that optical telescopes **directly** detect photons from the emitting source (stars, galaxies…) while IACTs detect **indirectly** the incoming gamma-rays

- IACTs detect the very-brief **blue** Cherenkov optical flashes produced within extended air showers

    - Telescopes optimized to measure ultra-fast signals (~ ns)

IACT technique – Analysis

- This technique is relatively new:

Whipple	1968 → 2006	MAGIC	2004 → ongoing
HEGRA	1987 → 2002	H.E.S.S.	2003 → ongoing
CANGAROO	2004 → 2008	VERITAS	2007 → ongoing

- The IACT technique imposes a **very different** treatment of collected data as the one used in other wavelengths

- Low-level analysis (covered in this talk)

  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

IACT technique – 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 – Analysis

- Outline of a classical IACT analysis:
  - Signal extraction from measured charge
  - Image cleaning and parameterization

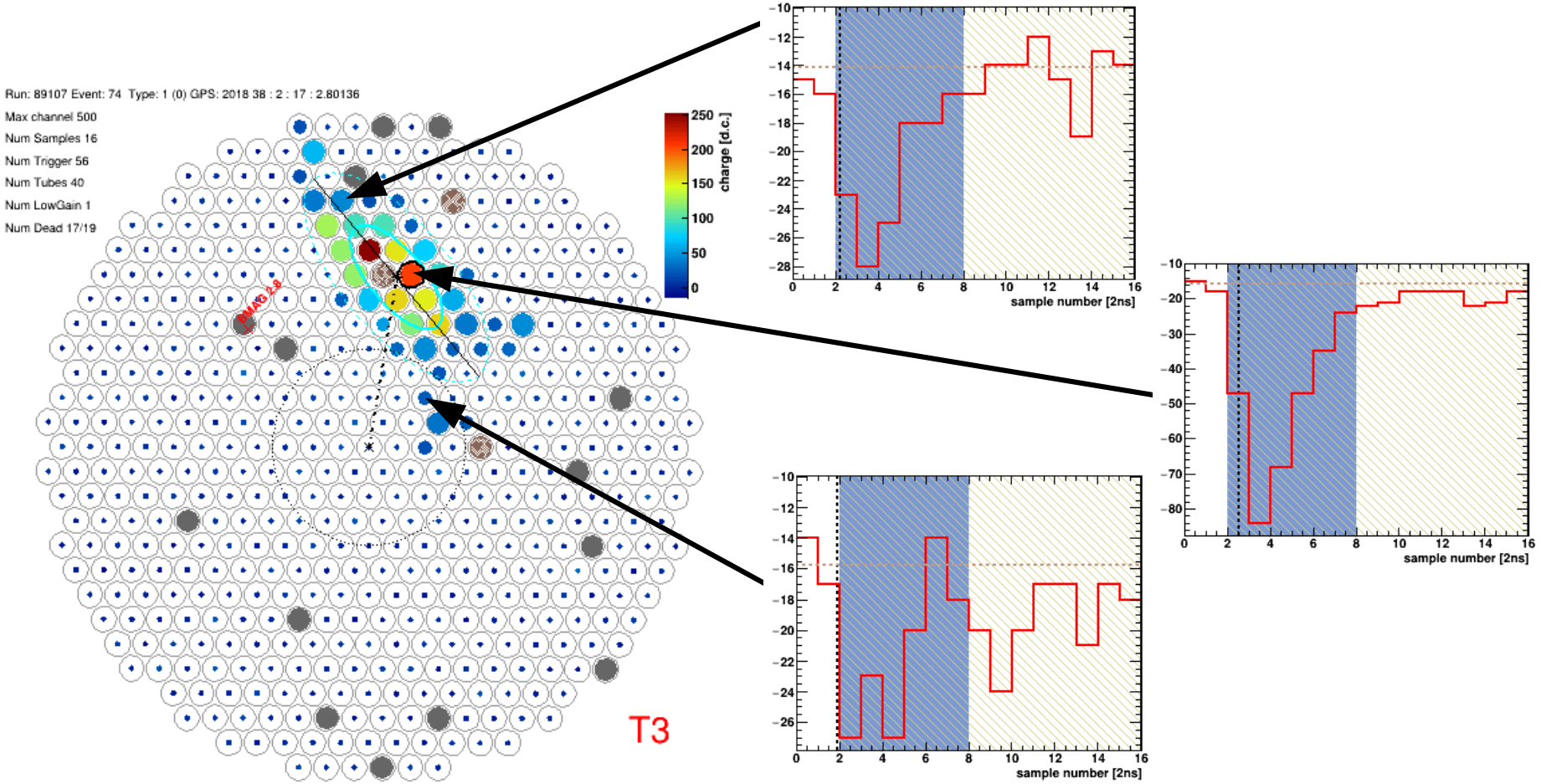
  } Image-wise (one for each triggered telescope)

  - Estimate the direction of the gamma-ray
  - Classify the shower (gamma/hadron separation)
  - Estimate the energy of the shower

  } Shower-wise (one for each stereo event)

IACT Analysis – Signal extraction

- For each triggered event, signal vs time is stored.
  That signal needs to be extracted maximizing Cherenkov photons



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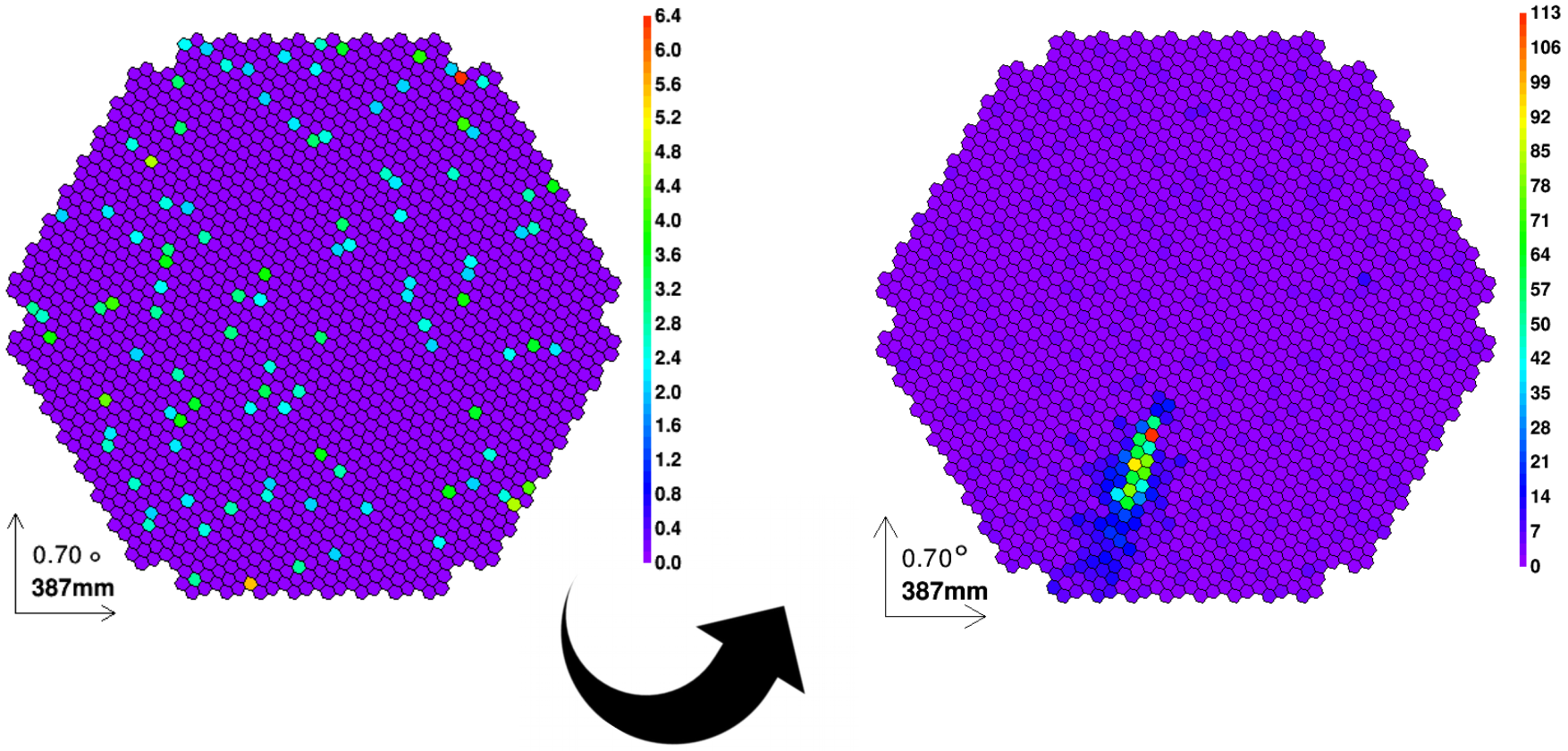

IACT Analysis – Signal extraction

- For each triggered event, signal vs time is stored.
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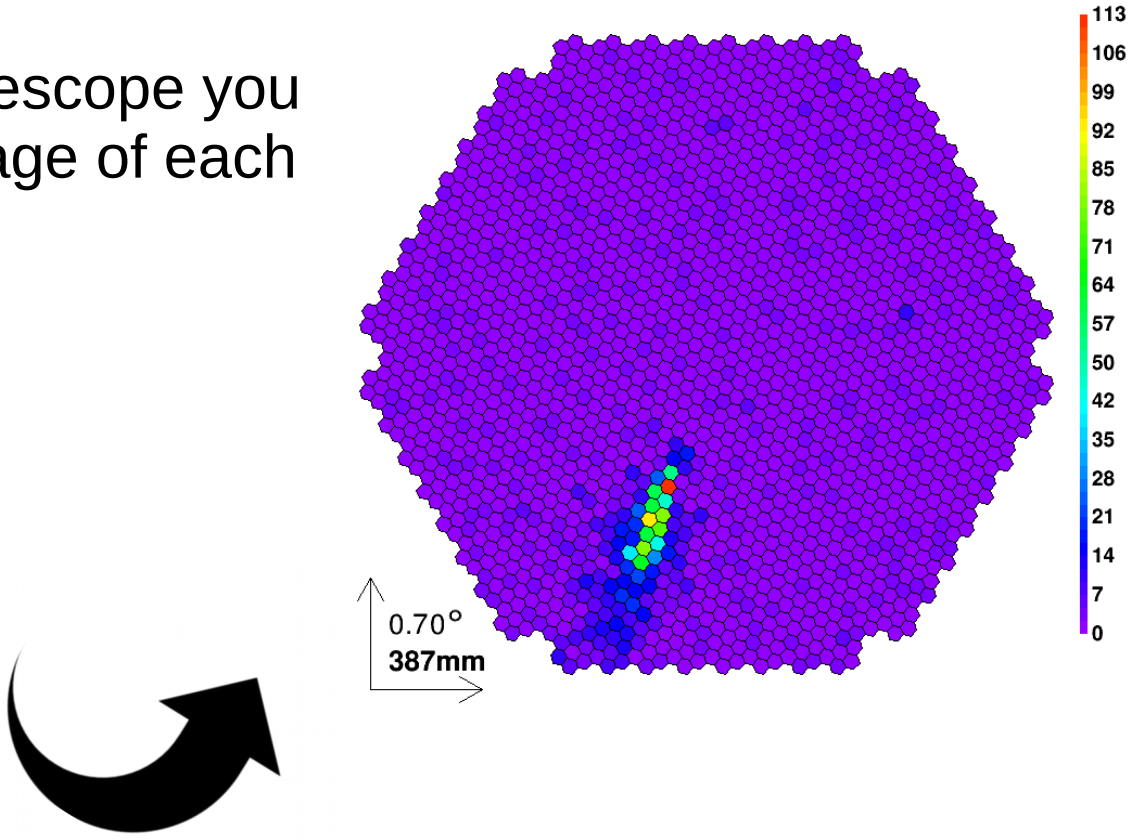
- For each triggered telescope you need to extract an image of each event

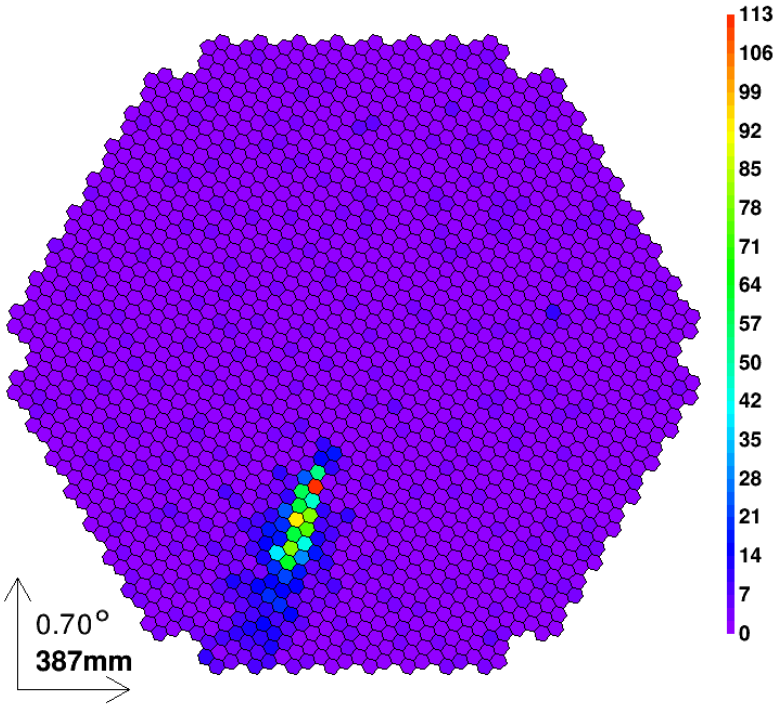


IACT Analysis – Signal extraction

- For each triggered event, signal vs time is stored.
  That signal needs to be extracted maximizing Cherenkov photons

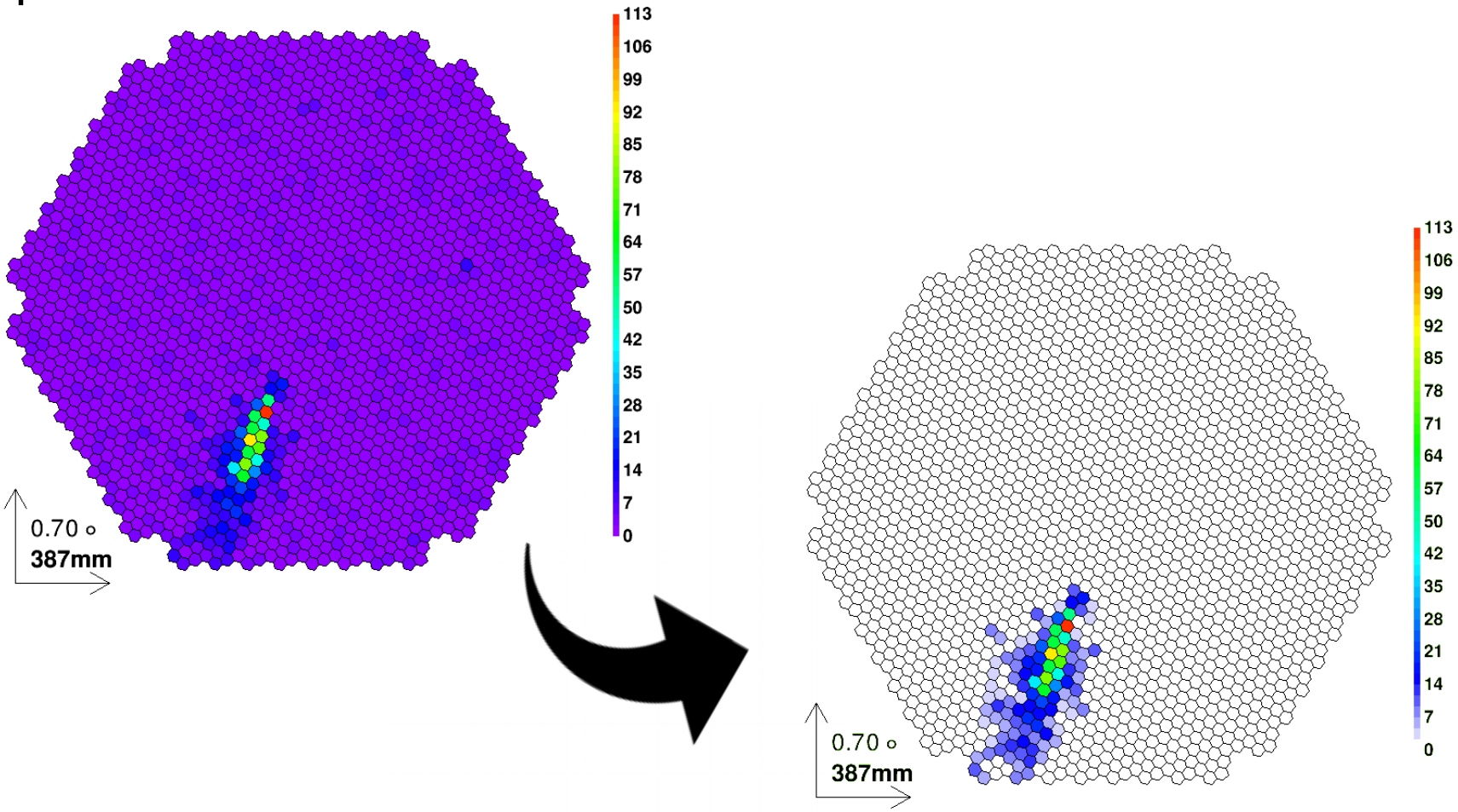
- For each triggered telescope you need to extract an image of each event

- These images are noisy! First we need to clean them a bit



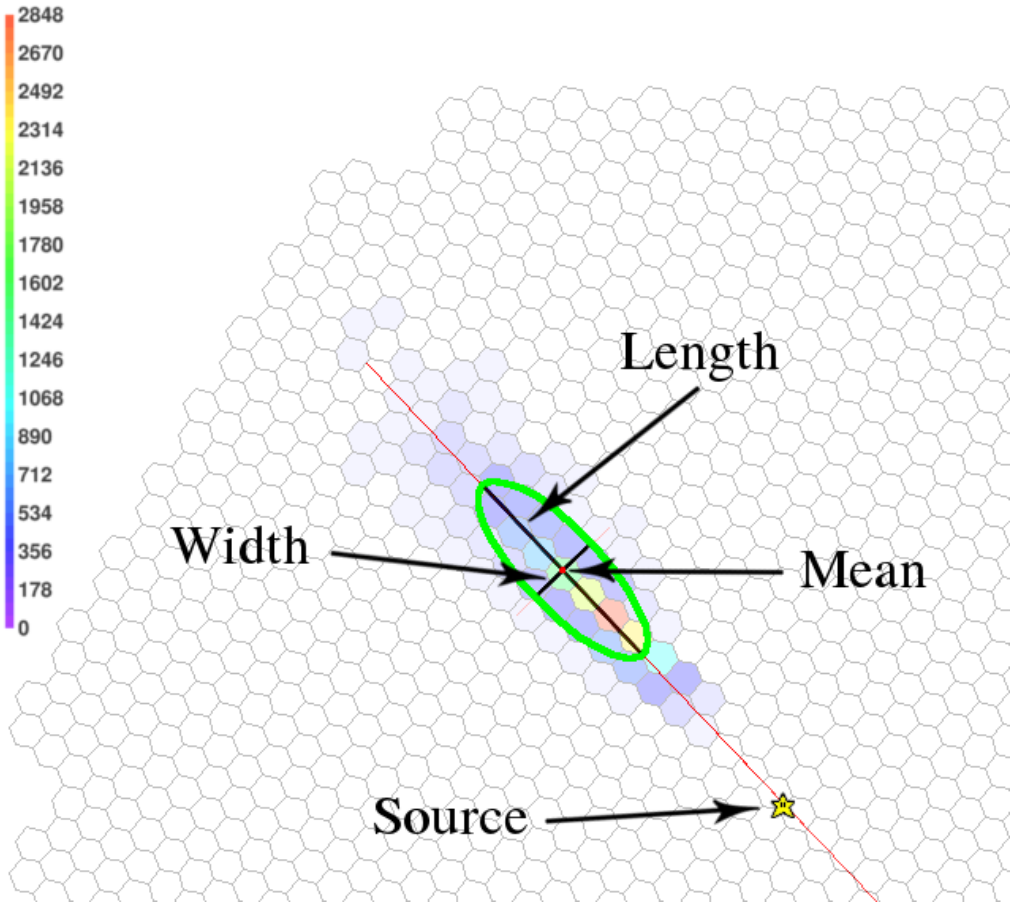
IACT Analysis – Image cleaning

- Image cleaning algorithms remove as many noise (NSB) photons as possible, trying to leave as many Cherenkov photons as possible



IACT Analysis – Image parameterization

- With the cleaned images, we parameterize the images with the classical “Hillas parameters”:



IACT Analysis – Stereoscopic reconstruction

- Once all images are cleaned and parameterized, we combine all the available images of each shower

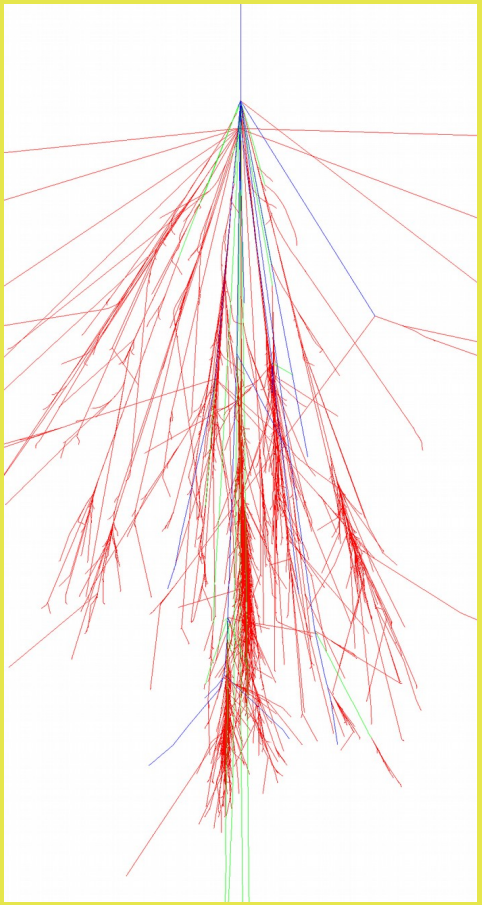
- Using all the available images, we reconstruct:

  - Direction
  - Evaluate how likely the event “seems like” a gamma (vs hadron)
  - Energy

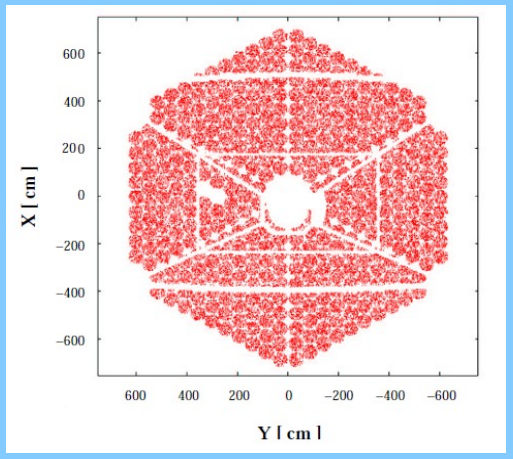
All methods improved with both **Monte Carlo** simulations and **machine learning**

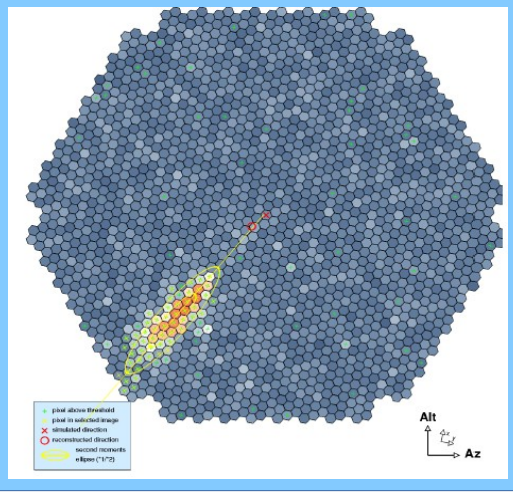
IACT technique – MC simulations reminder

Shower simulation

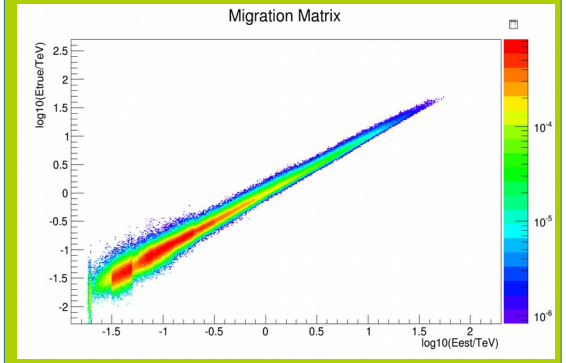


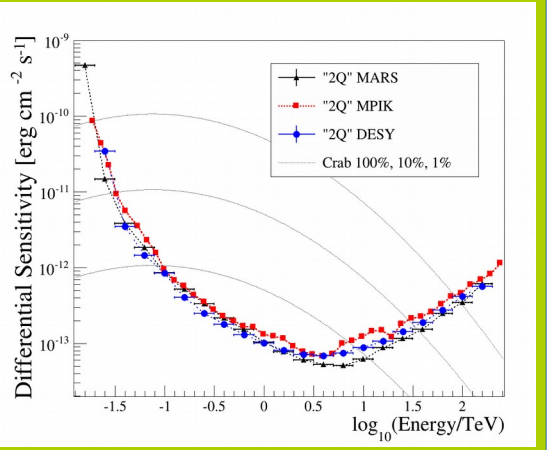
Telescope simulation





Analysis identical to the one performed to the data





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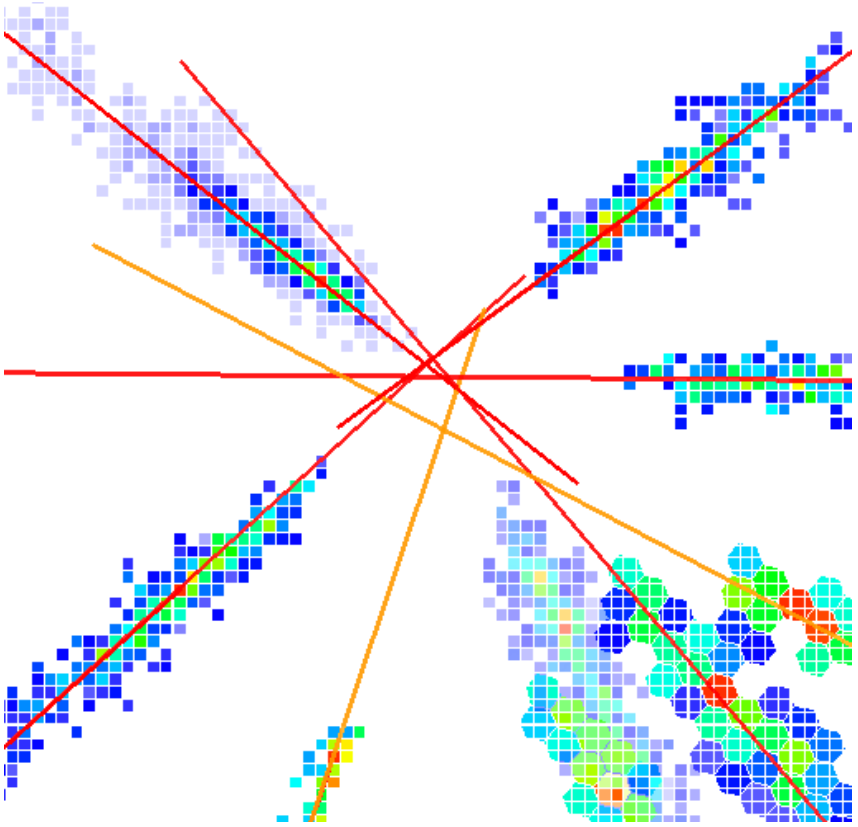

IACT Analysis – Stereoscopic reconstruction

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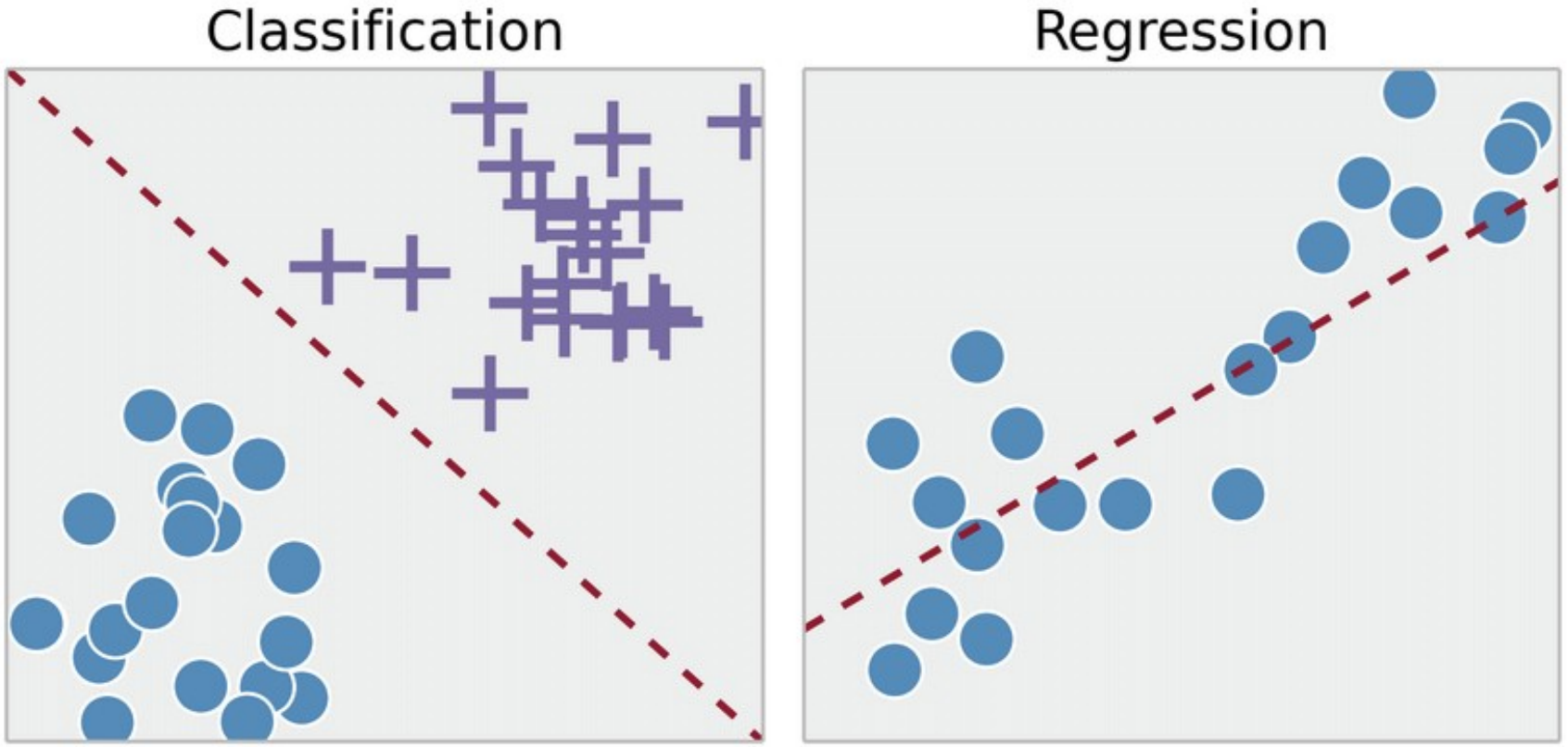
Specifically these 2 cases, are **excellent** examples to explain **machine learning**!

IACT Analysis – Machine Learning basics

- There are few things more useful than understanding how machine learning works

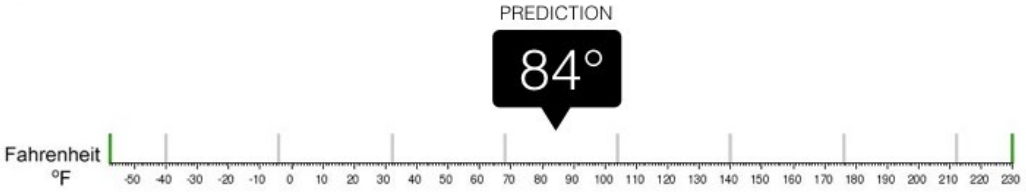


IACT Analysis – Machine Learning basics

- There are few things more useful than understanding how machine learning works

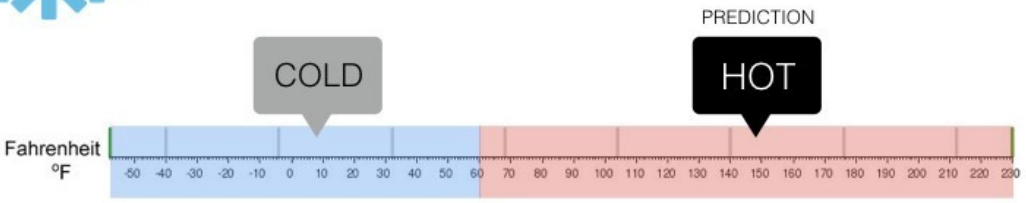
Regression

What is the temperature going to be tomorrow?



Classification

Will it be Cold or Hot tomorrow?



IACT Analysis – Machine Learning basics

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Regression

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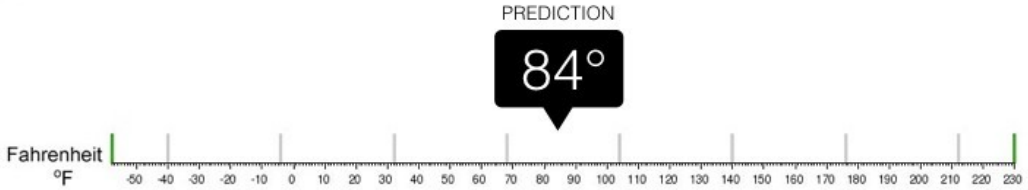
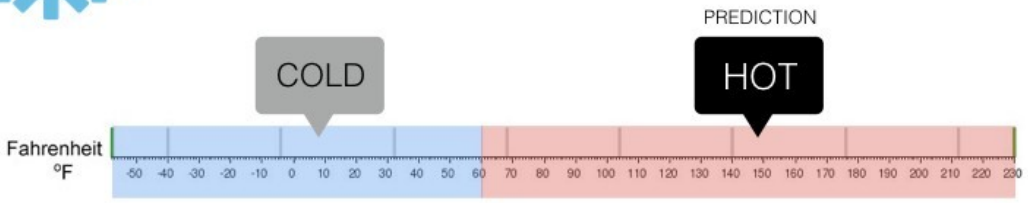


What is the **energy** of this event?

Classification

Will it be Cold or Hot tomorrow?



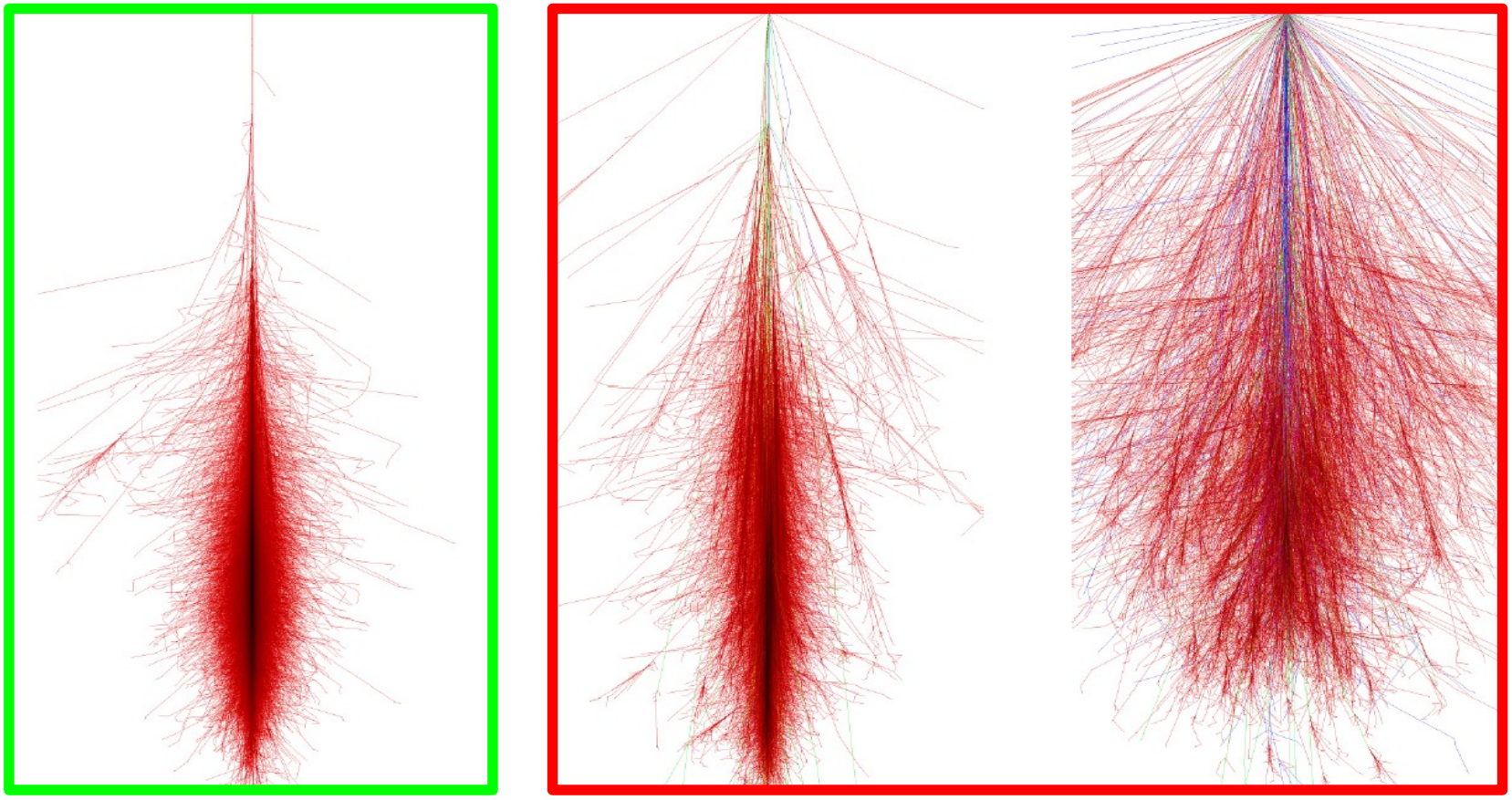
Is this a gamma-ray?
Or a cosmic-ray?

IACT Analysis – Gamma-hadron separation

- Gamma-hadron separation is an obvious classification problem:

Signal

Background



1 TeV γ-Ray

1 TeV proton

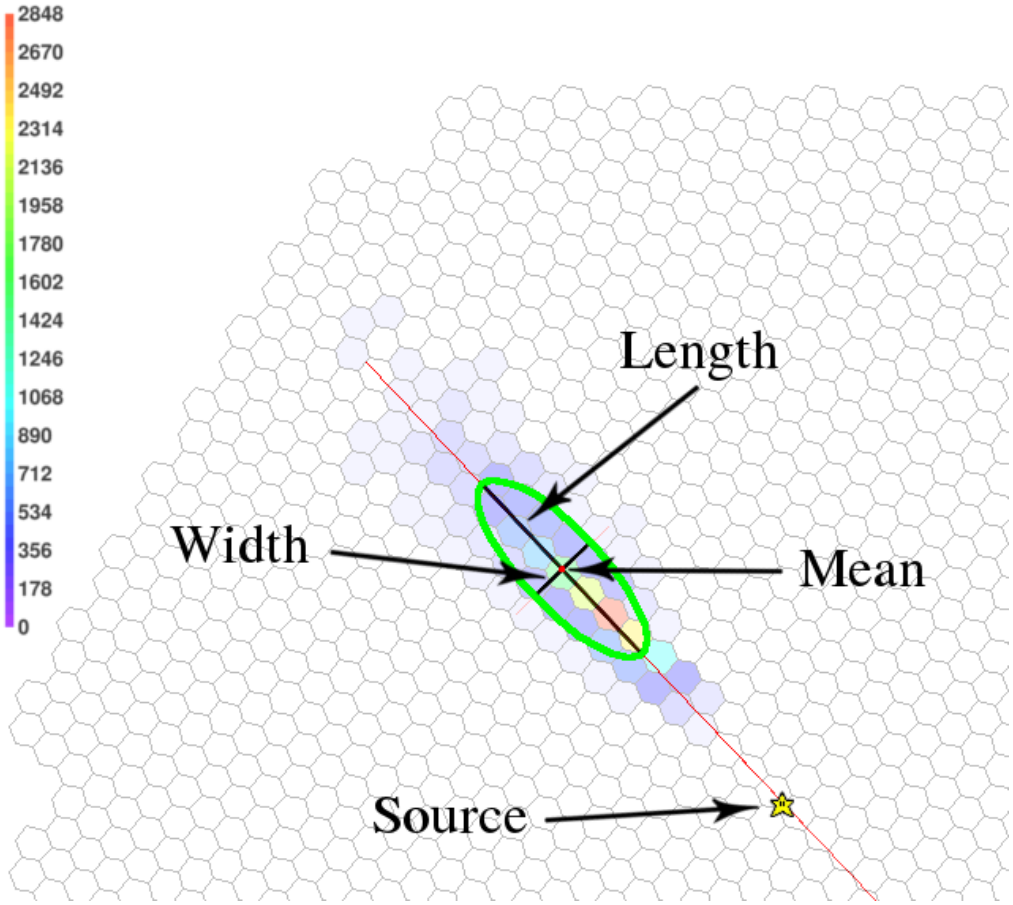
1 TeV iron

IACT Analysis – Gamma-hadron separation

- Gamma-hadron separation is an obvious classification problem:

- We **train** our machine learning algorithm with parameterized:
  - Monte Carlo gammas
  - Cosmic-rays (data)

- We test their performance with Monte Carlo and data, maximizing sensitivity



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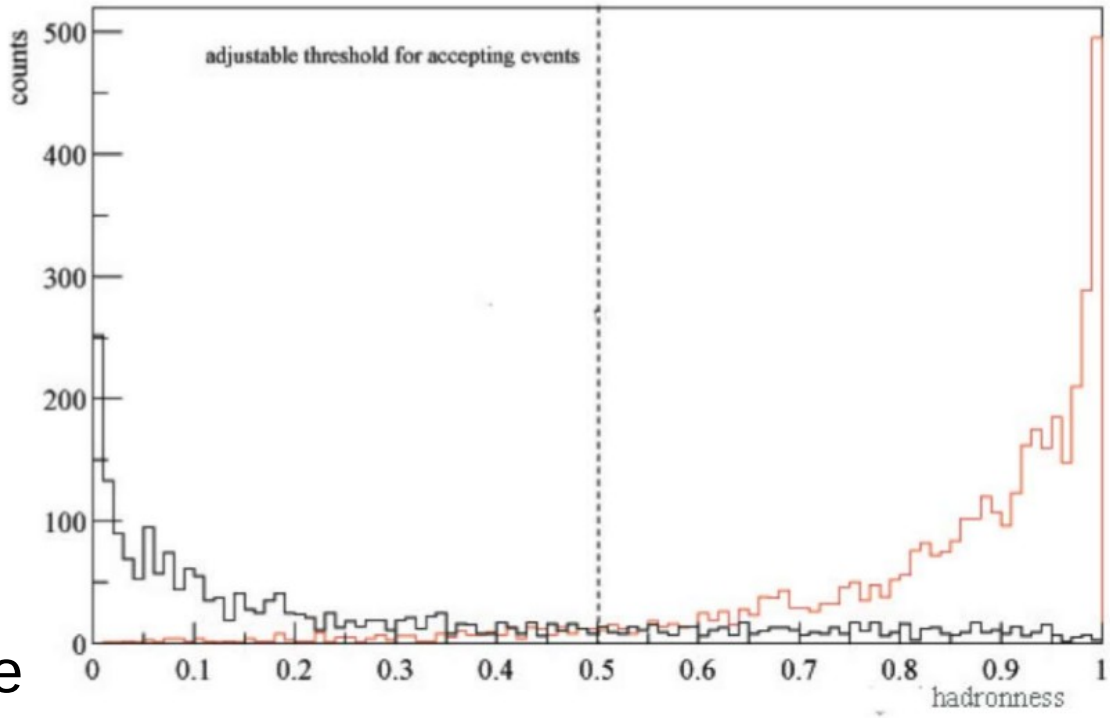
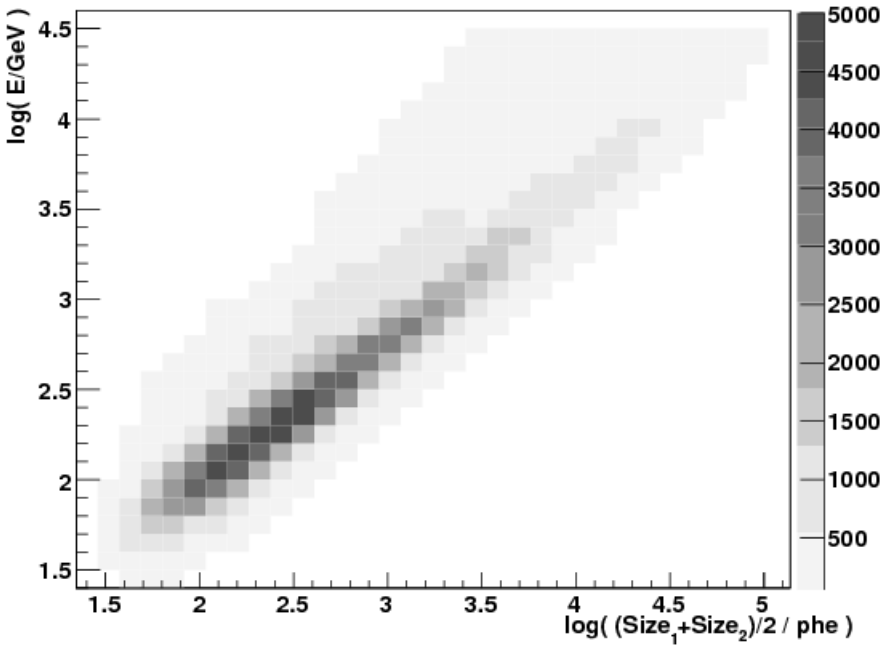


gammas protons

J. Albert et al 2007

IACT Analysis – Energy evaluation

- Energy evaluation is an obvious regression problem:



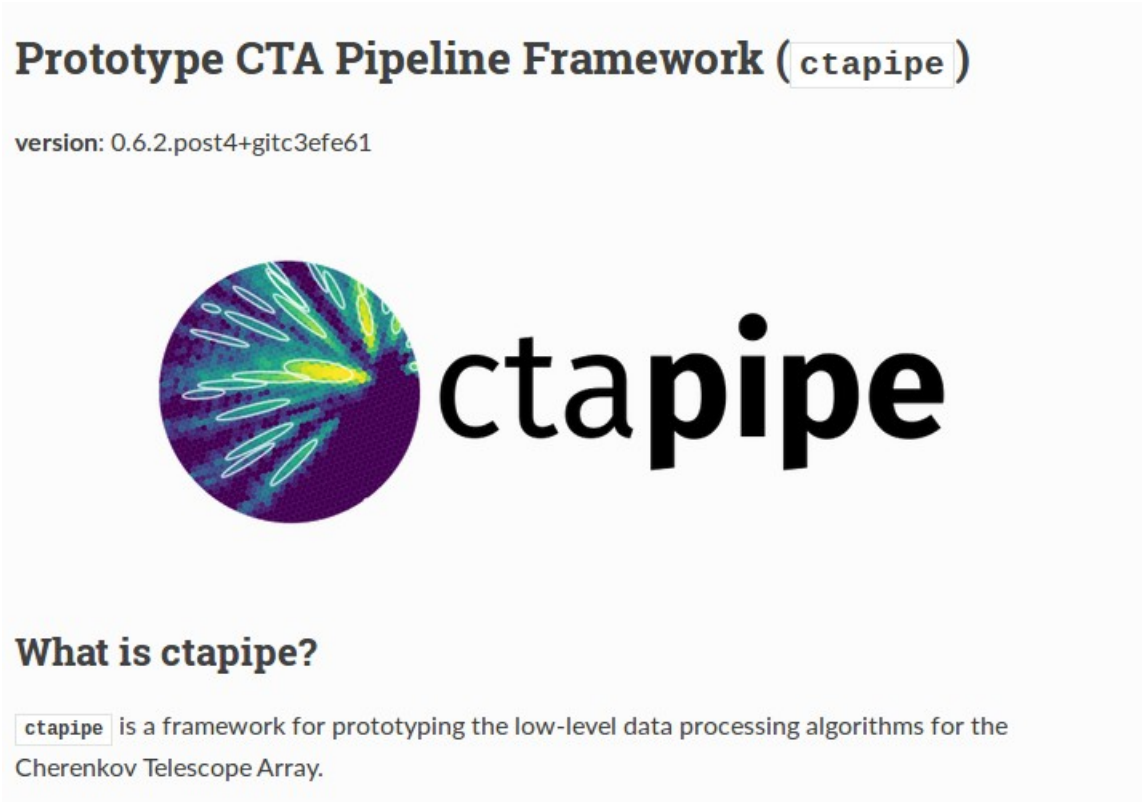
Look-up table method

J. Aleksic et al 2012

- Classically look-up tables have been used to evaluate the energy
- Machine learning allows to add many parameters to the evaluation “equation”, and finds the solution that provides a better energy evaluation
- Becoming the standard method for all experiments

CTA Analysis – ctapipe

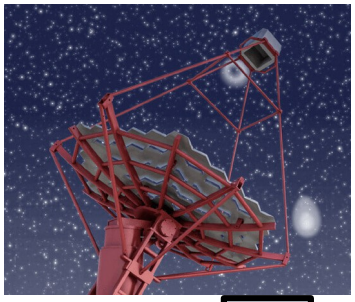
- The low level analysis pipeline of CTA is under development



- The whole package is open source, and you can find it here: https://github.com/cta-observatory/ctapipe/

CTA Analysis – ctapipe

- The low level analysis pipeline of CTA is under development



Prototype CTA Pipeline Framework (`ctapipe`)

version: 0.6.2.post4+gitc3efe61

ctapipe

What is ctapipe?

`ctapipe` is a framework for prototyping the low-level data processing algorithms for the Cherenkov Telescope Array.

DL3 data

CTA MC simulations

ctools cherenkov telescope array

- The whole package is open source, and you can find it here:

IACTs low-level analysis – Summary

- The low-level analysis of IACTs comprises all the methods used to infer from the measured Cherenkov flashes:
  - Classification of gamma-rays over the cosmic-ray background
  - Estimate their **direction** and **energy**
- The analysis pipeline of CTA is under development, and there is **a lot** of work to be done
- Understanding the details (and specially, the limitations) of the low-level analysis of CTA will be key for understanding its scientific possibilities


BACKUP