Cherenkov telescopes hunting for super-preshowers

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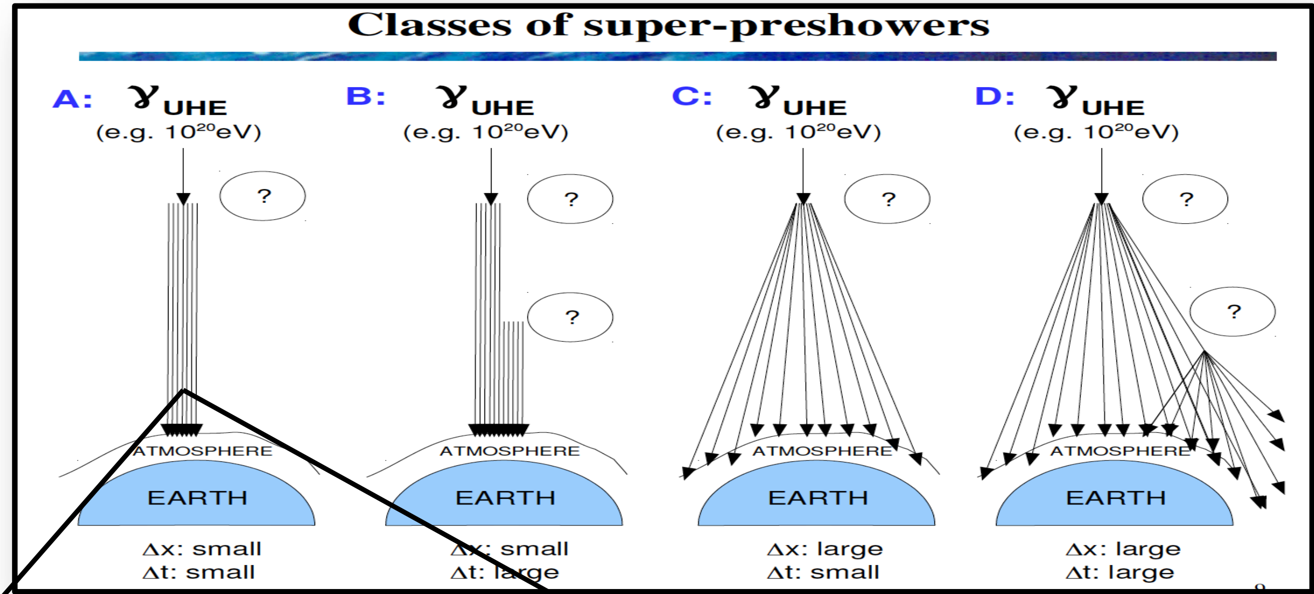
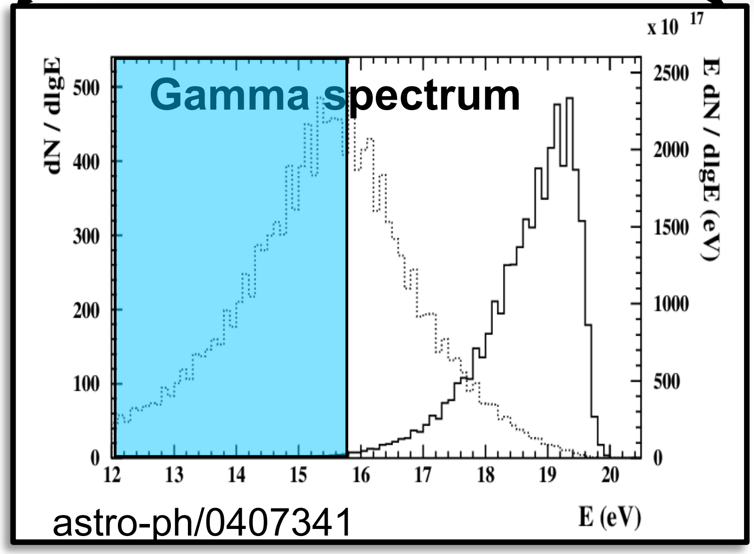
Outline:
- Motivation
- Basic principle: detection of gamma-rays by imaging atmospheric Cherenkov telescopes (IACTs)
- Background reduction and control in IACTs
- Possible strategy for super-preshower search by IACTs
- Mutli-messenger approach
- Summary

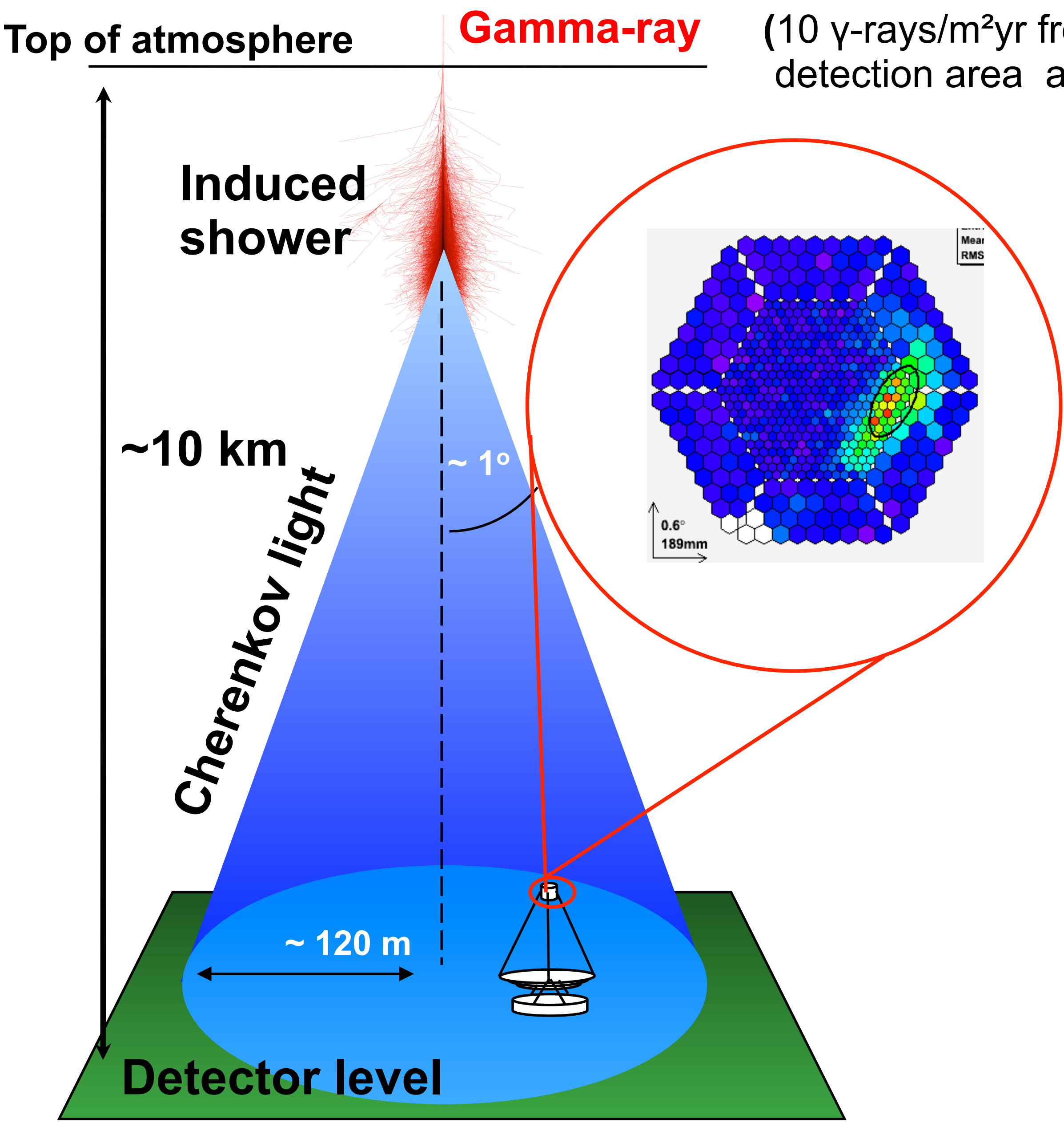
Introduction





Interesting energy range for Cherenkov telescopes

Basic principle: detection of high energies gamma-rays



(10 γ-rays/m²yr from the Crab nebula,
detection area about 50 000m², flux of > 1 γ-ray / min)

Image on camera

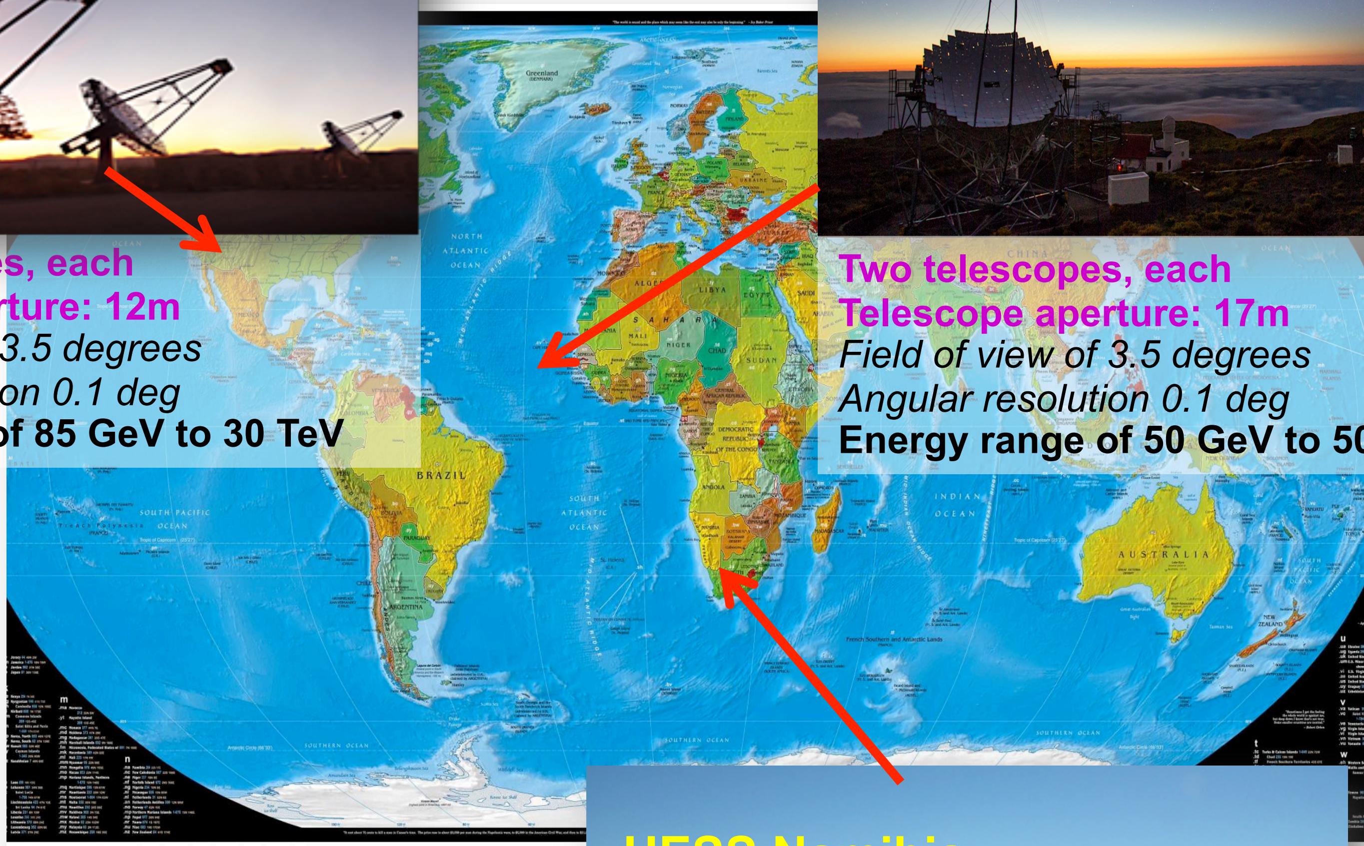
- Image intensity ➔ gama-ray energy
- Image form ➔ background reduction
- Image orientation ➔ gamma-ray direction

> **Stereo reconstruction**
- improved direction
- background reduction
- low energy threshold

Current IACTs locations

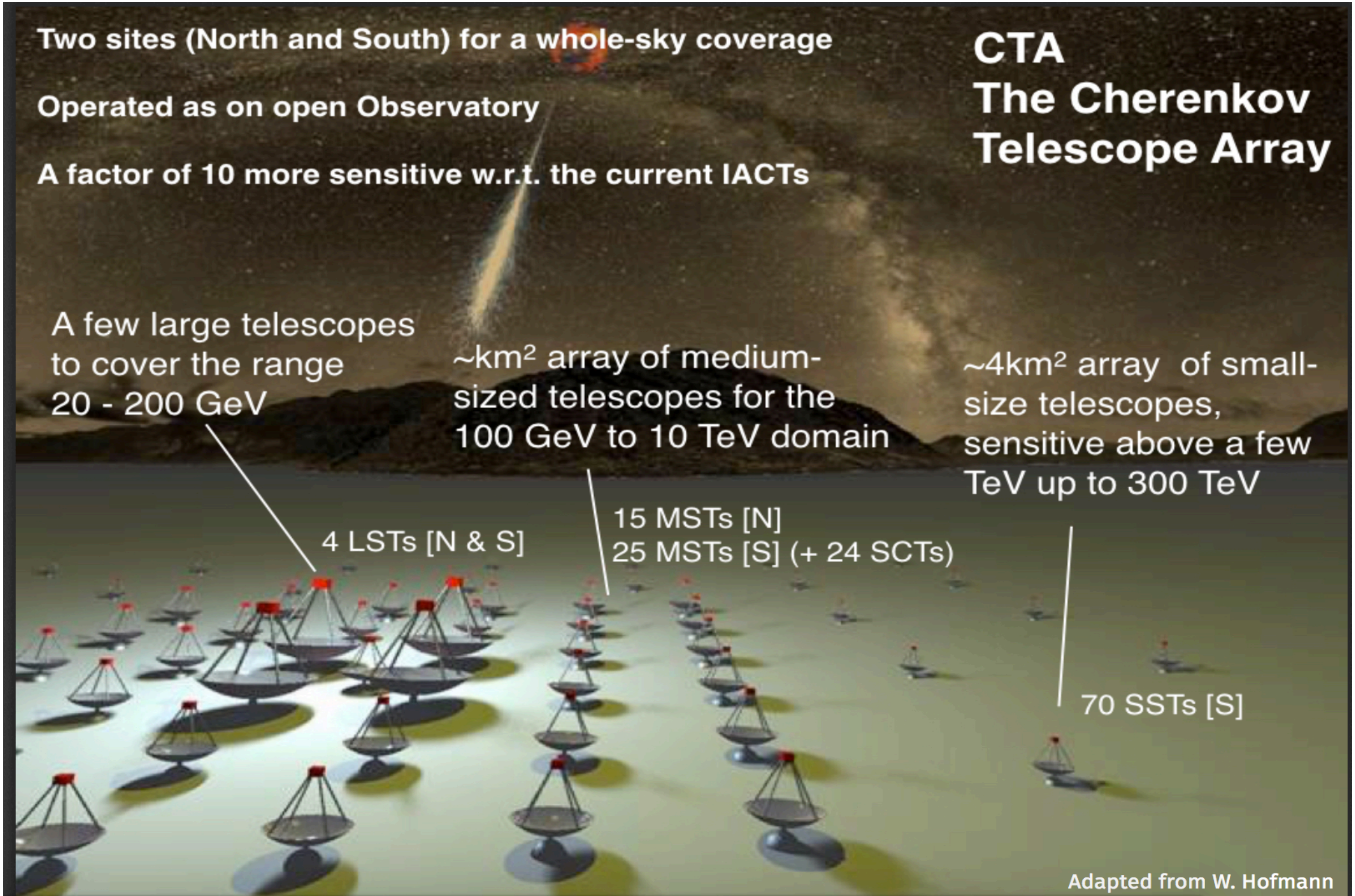
Four telescopes, each
Telescope aperture: 12m
Field of view of 3.5 degrees
Angular resolution 0.1 deg
Energy range of 85 GeV to 30 TeV

Two telescopes, each
Telescope aperture: 17m
Field of view of 3.5 degrees
Angular resolution 0.1 deg
Energy range of 50 GeV to 50 TeV



Five telescopes,
Four telescope aperture: 12m + one 28 m
Field of view of 5 degrees/3.5 degrees
Angular resolution 0.08 deg
Energy range of 10 GeV to 10 TeV

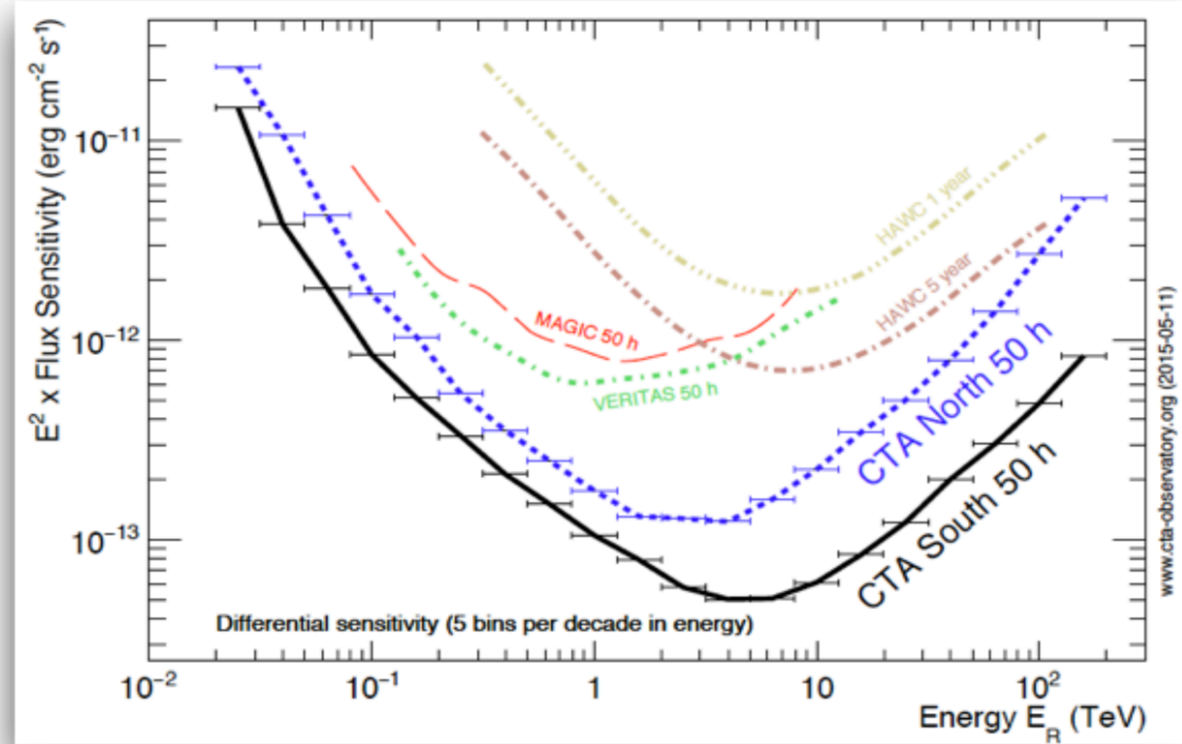
The next generation Cherenkov telescopes observatory



The next generation Cherenkov telescopes observatory

CTA Performance

Differential Sensitivity



A factor of **5-10 improvement** in sensitivity in the domain of **about 100 GeV to some 10 TeV.**

Extension of the accessible energy range from **well below 100 GeV to above 100 TeV.**

Credits: The CTA Consortium

Adapted from W. Hofmann

Background Reduction and Control

- (one of) the most critical issue for analysis
- vital for significance calculation
- vital for flux determination

> **Two types of background:**

- **Cosmic-rays hadrons**
    - produce air shower somewhat similar to gamma-rays
    - about 10^4 more hadrons tha gamma-rays
- **Cosmic ray electrons**
    - shower very similar to gamma-rays
    - flux suppressed at TeV energies

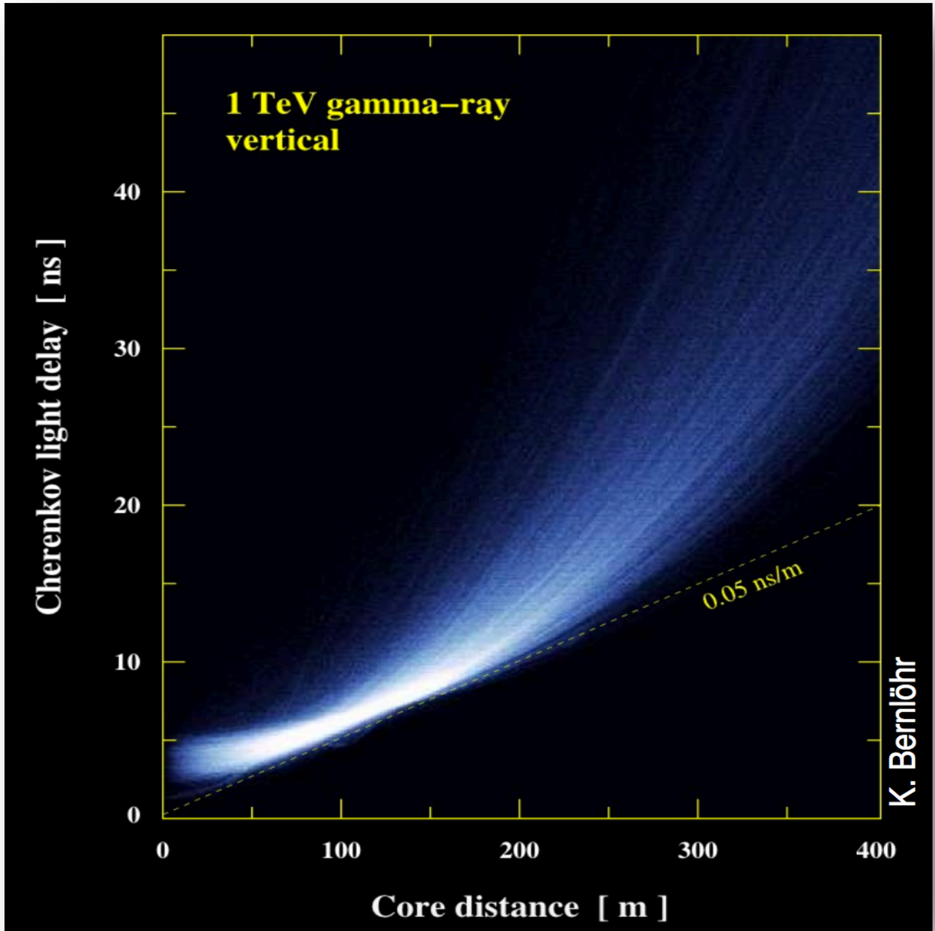
> **Three stages of background reduction:**

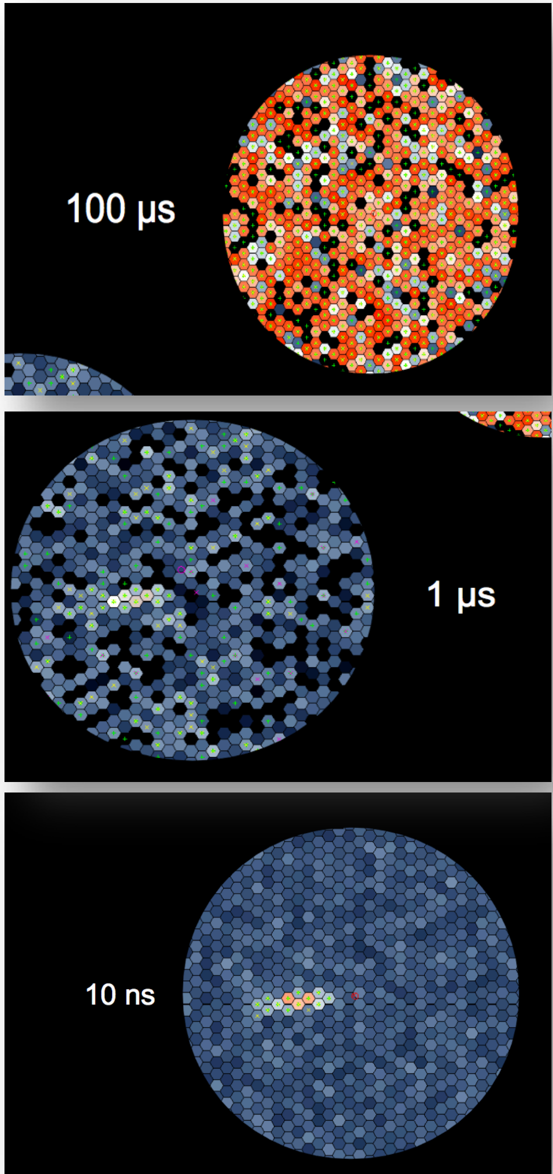
(I) suppresion at trigger level
(II) reduction by image shape analysis
(III) substraction by background modeling

Background Reduction

(I) Need for short exposures

... to reduce the night-sky background

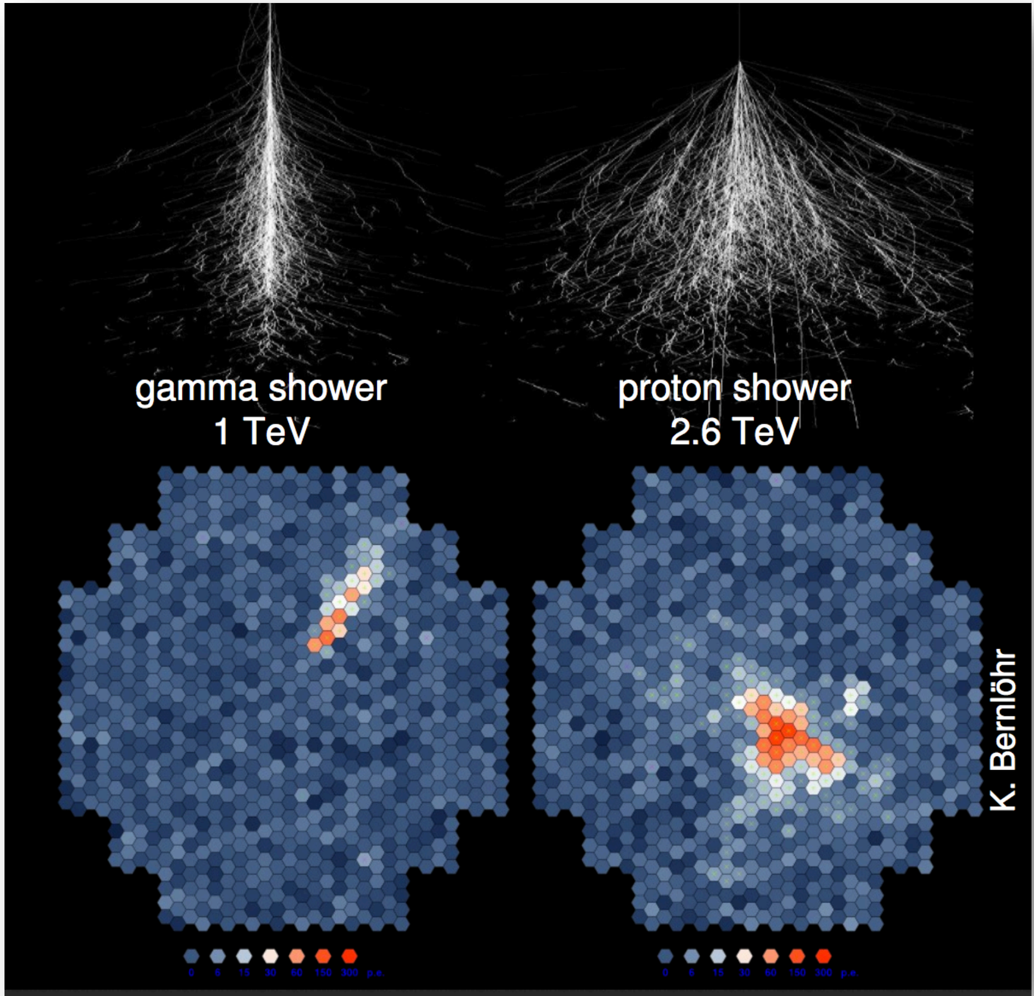




Background Reduction and Control

(II) Reduction by image shape so-called gamma/hadron separation

... Cosmic Rays main background for Cherenkov astronomy



> Protons create hadronic showers with irregular images

> Electrons, positrons, gammas produce electro-magnetic shower, shower image is elongated ellipse

> Cuts on image parameters ➔ 99.9% background reduction

Background Reduction and Control

(III) Background modeling

> Remaining background is substracted based on statistical basis:

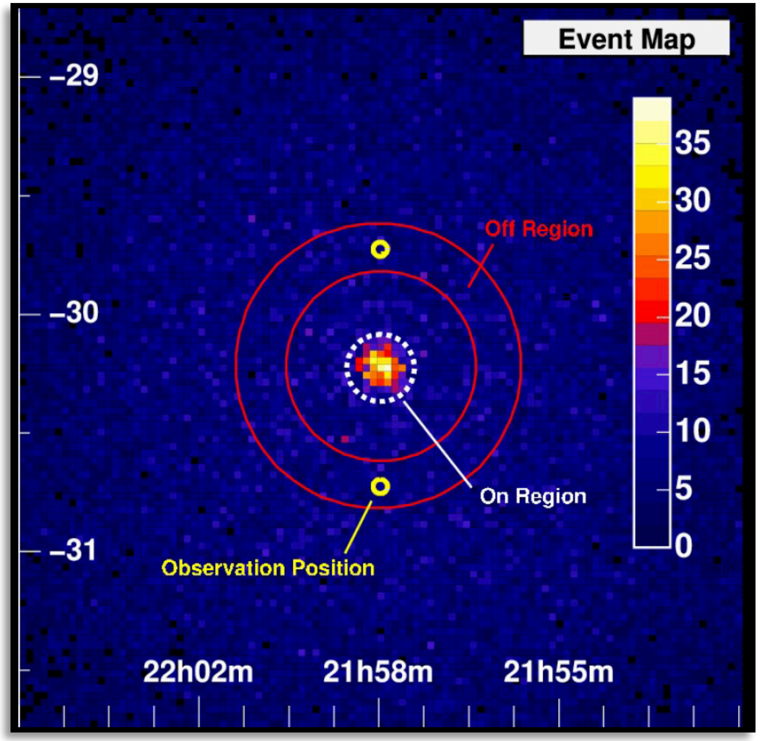
$$N_\gamma = N_{\rm on} - \alpha\, N_{\rm off}$$

- ideally, control background is taken
- same position in camera
- same sky region
- with large event statistics
- same image-parameter phase space

> not all criteria can be met at the same time

> favoured background model depends on type of analysis
(detection, morphology, spectrum...)

- Ring Background -



Off-Region: ring around On-Region
Off-Events subtracted from On-Events
- proper area factor
- acceptance correction

Background Reduction and Control

(III) Background modeling

> **Off-Region:** ring of circular regions around observation position (same distance as **On-Region**)

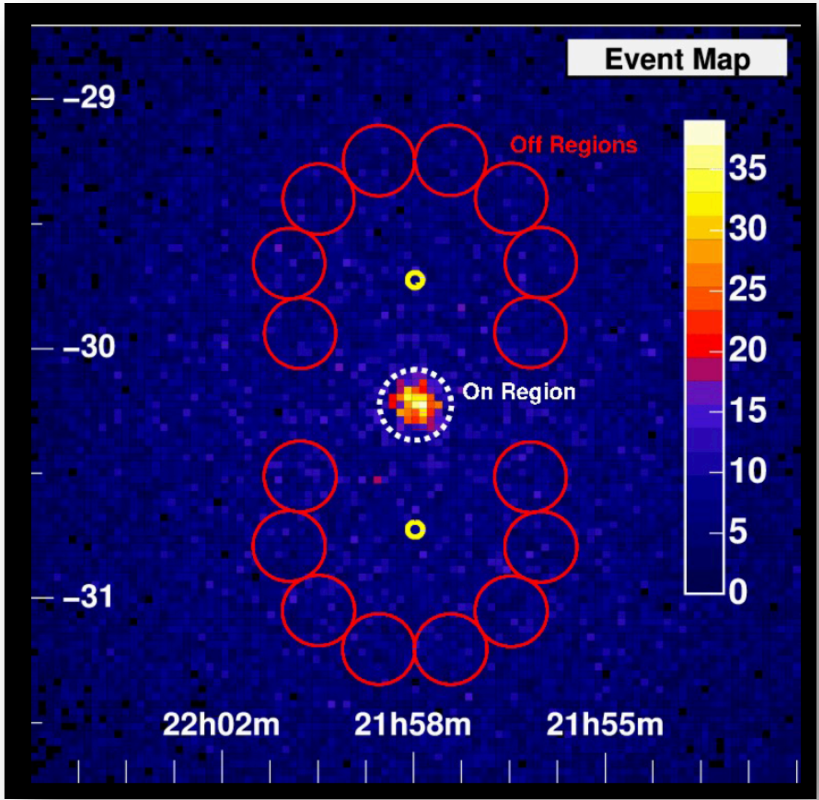
> Observation position must be outside the On-Region

> no acceptance correction needed assuming radially symmetric acceptance

> insensitive to systematics of acceptance determination

> very well suited for spectra

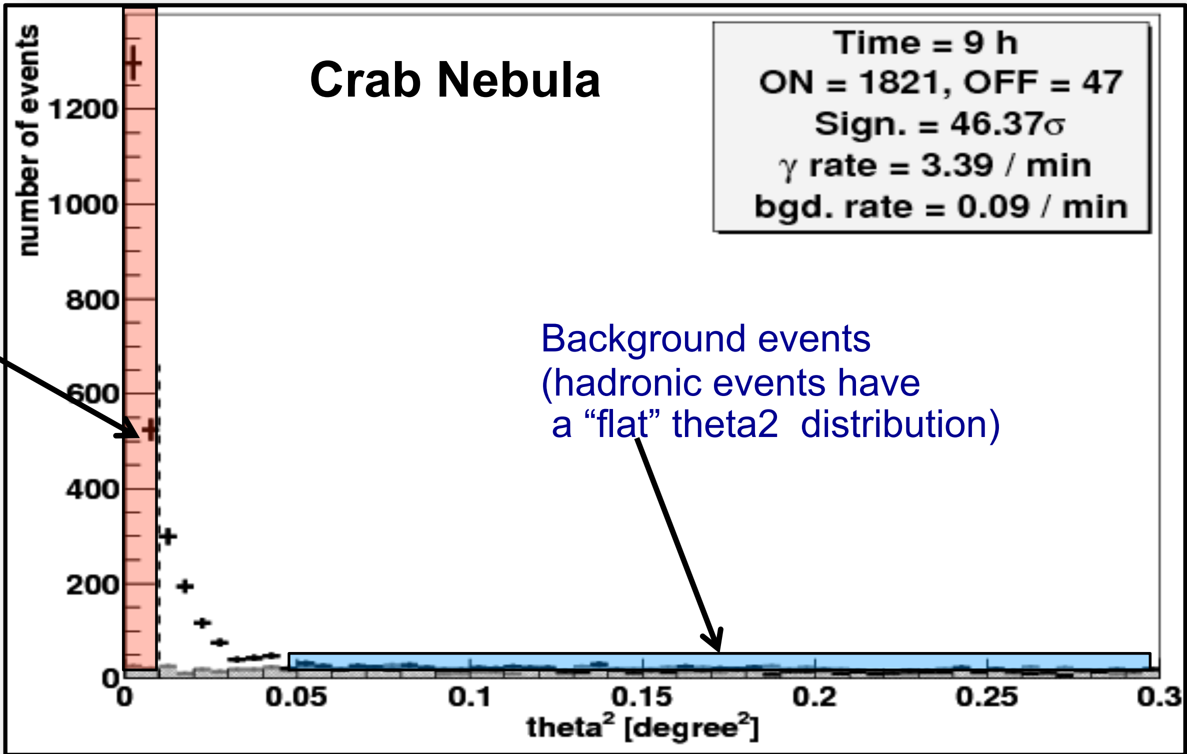
- Reflected Region Background -



Significance calculation

> use the so-called theta^2 parameter – defined as squared distance between the true and the reconstructed source position.

Excess events (gamma events characterized by the small theta^2 value)



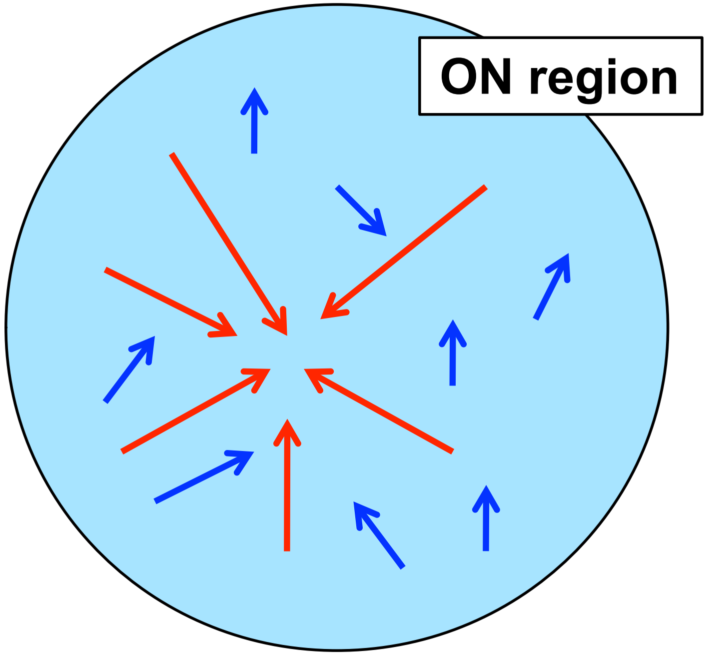
The significance is defined by the expression (Li, T. & Ma, Y. 1983, ApJ, 272, 317):

$$S_{LM} = \sqrt{2}\left(N_{on}\cdot\ln\left(\frac{(1+\alpha)\,N_{on}}{\alpha\,(N_{on}+N_{off})}\right)+N_{off}\cdot\ln\left(\frac{(1+\alpha)N_{off}}{N_{on}+N_{off}}\right)\right)^{1/2} \cdot \quad \alpha = \frac{\kappa_{on}\cdot t_{on}\cdot A_{on}}{\kappa_{off}\cdot t_{off}\cdot A_{off}} \, .$$

where $\boldsymbol{N_{on}}$ and $\boldsymbol{N_{off}}$ are the numbers of **ON** and **OFF** events in the signal region and **alpha** is given by the ratio of the sizes of the two regions, the ratio of the exposure times for both regions and the respective acceptances.

Diffuse method - Basics

Point-source search

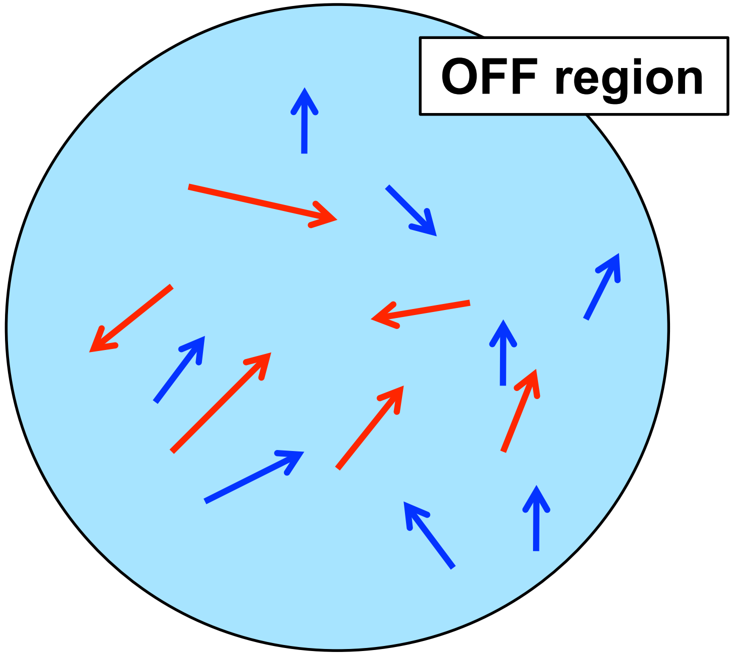


→ : background events on camera FOV

→ : signal events on camera FOV

> Direction information as strong discriminator between signal and background as seen for example, in the theta^2 plot

Diffuse search



> No direction information

> No background measurement possible

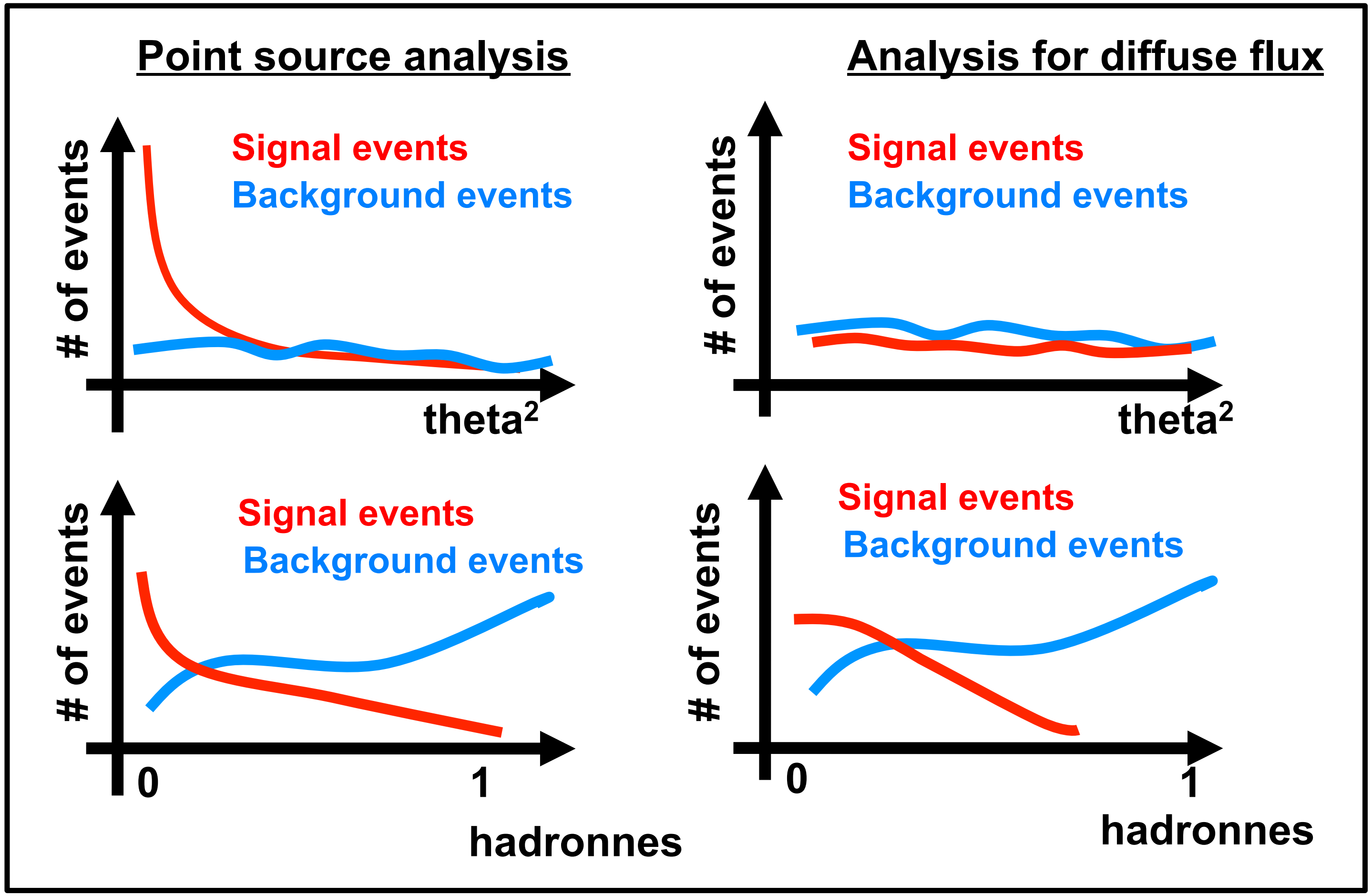
> We need Monte Carlo to model the background/signal

> Different analysis method required

Method – Random forest

Random forest (multidimensional classification method):

- assigns value between 0 and 1 called **hadronness**
- classifies the hadron likeness of an event
- Image & shower parameter used for training
- trained on MC protons & electrons/photons from super pre-showers



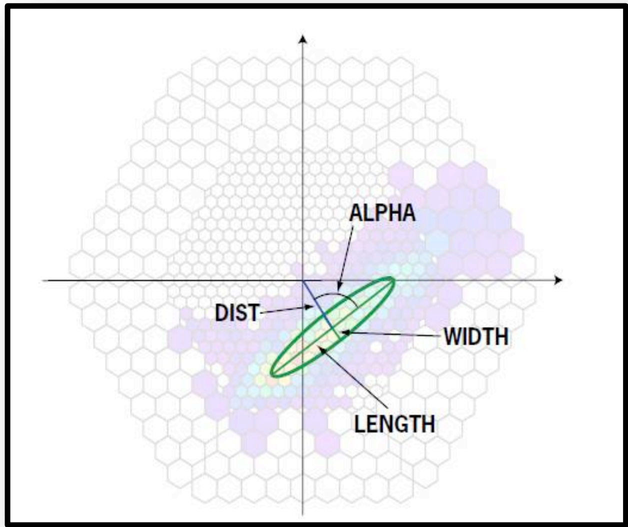
HADRONNESS:

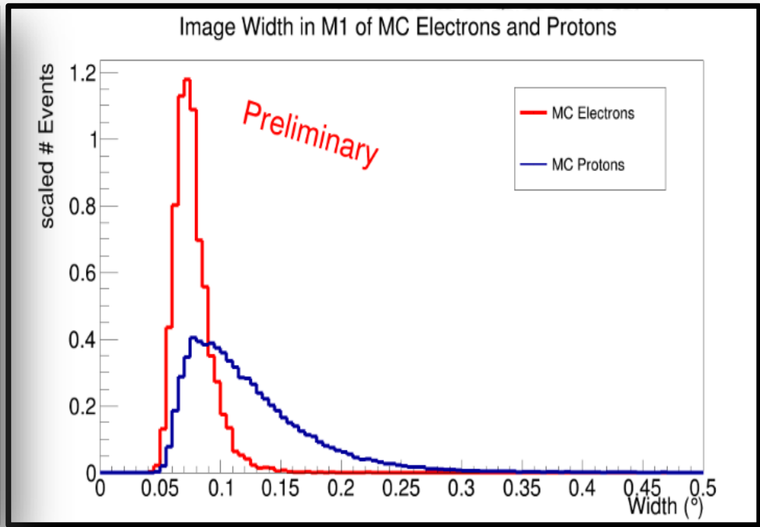
0 - gamma-like event
1 - hadron-like event

Random forest variables (example)

> Hillas parameters:

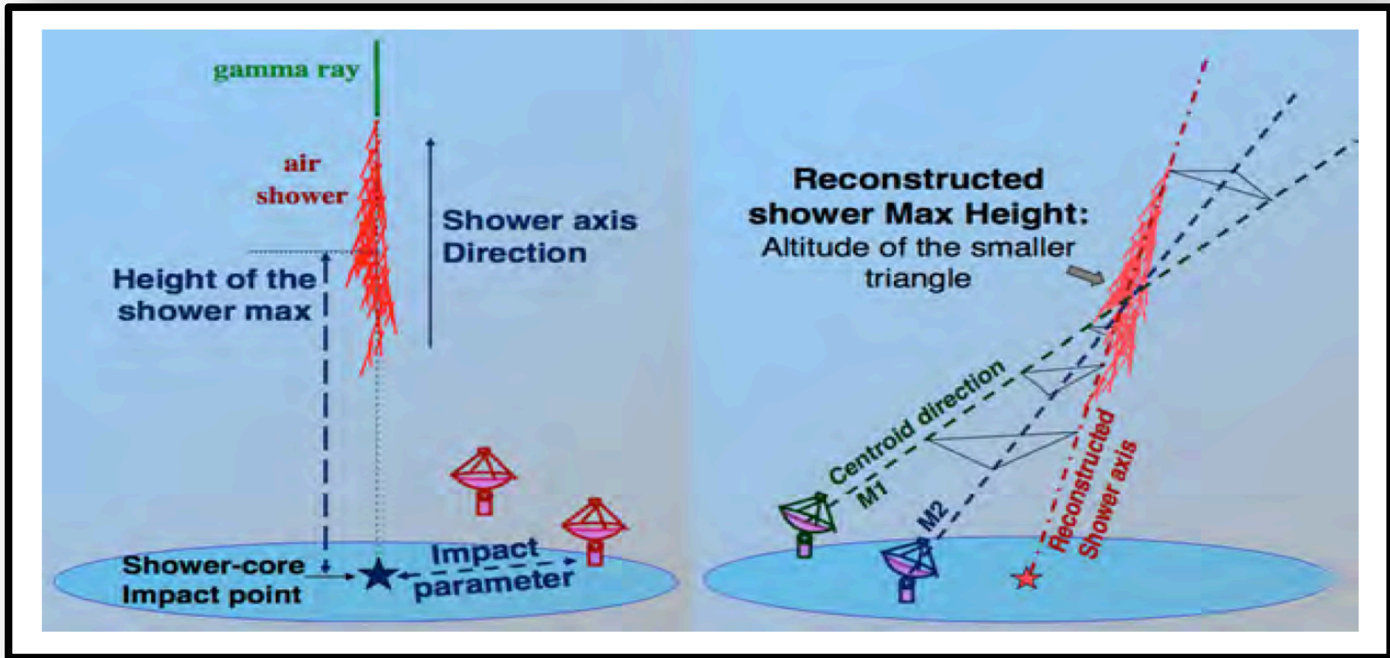
A.M. Hillas,
Nucl. Phys. Proc. Suppl.
52B(1997) 29





> Reconstructed height of shower maximum

- parameter sensitive to the type of primary particle



Monte Carlo simulations

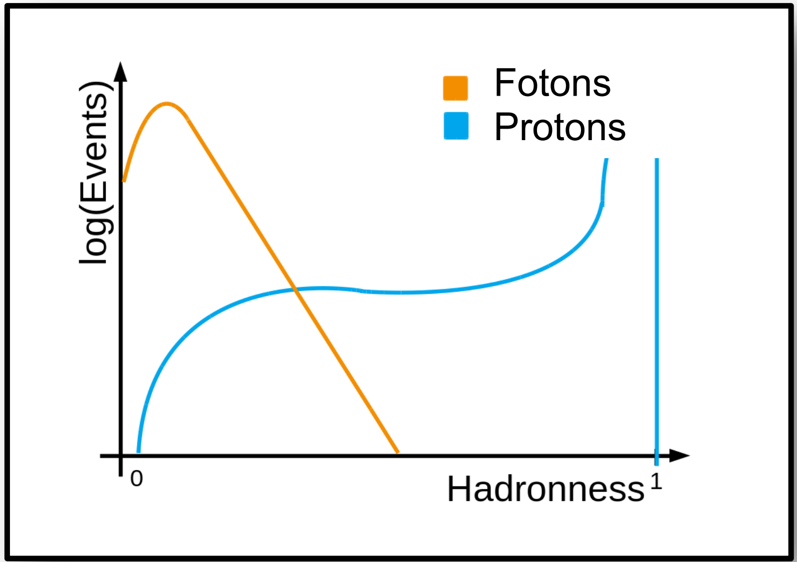
For super-preshower searches the signal is hidden in the diffuse background

... we need MC for signal substraction

{MCp} - diffuse proton simulation instead of {OFF}: BACKGROUND
{MCph} - diffuse super-preshower photon simulations*: SIGNAL

*Simulation of super-preshower could lead to non-standard images on camera: so RF will be train on ''strange''/non-standard images, at least in some cases.

Strategy:	Diffuse analysis	Point-source analysis
OFF data (RF)	{MCp}(train)	real data
Bkgd substraction	{MCp}(test)	real data
Excess computed by	hadronnes	theta^2
Assumption	α {MCph}+β {MCp}={ON}	theta^2 < value
MC signal	{MCph}	{MC$_\gamma$}
Significance	({ON}-β {MCp})/ΔN_{bgd}	Li & Ma



> Simulation software:
- CORSIKA compiled with the PRESHOWER, VIEVCONE option
- IACT/CTAs software (K. Bernlohr, *sim_telarray*)

Proof of concept

> The cosmic-ray electron spectrum measured by HESS (PRL101, (2008) 261104) and MAGIC (arXiv:1110.4008).

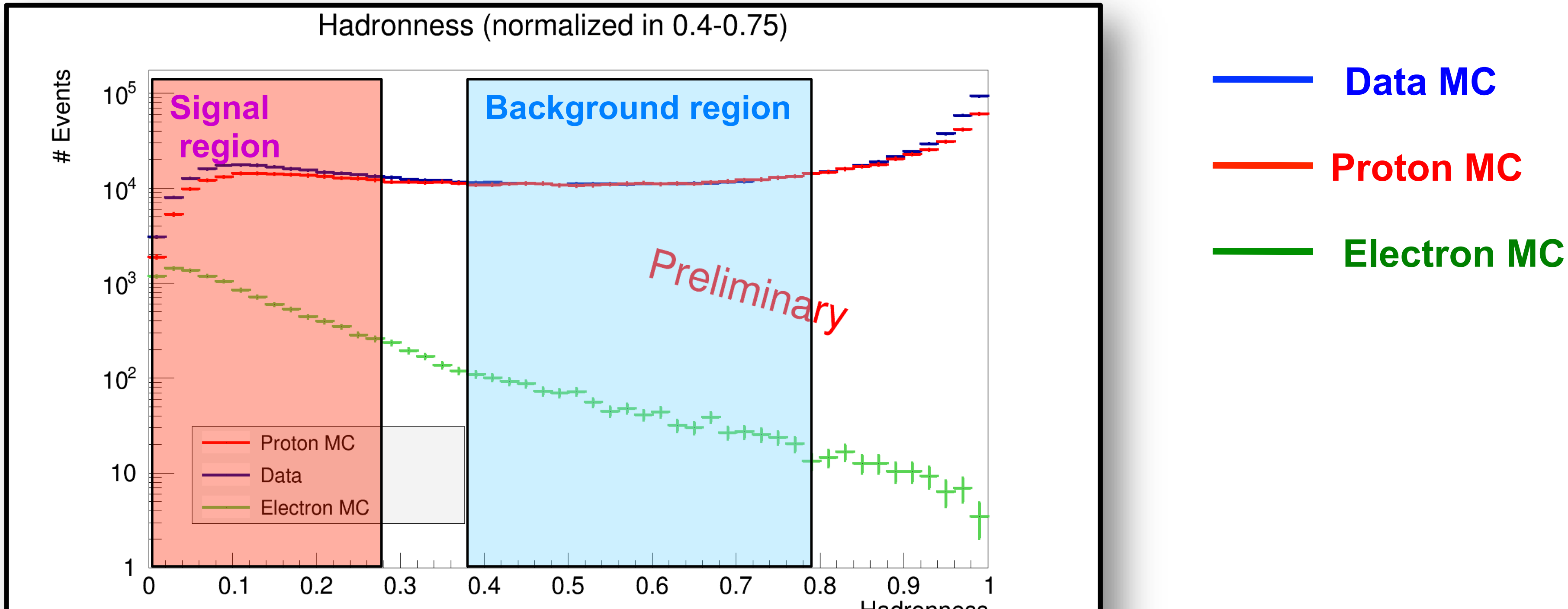
- Background region: mostly only hadron-like events to be present.

$$\{ON_b^{data}\} = \alpha\{MC_{e_b}\} + \beta\{MC_{p_b}\}$$

- Signal region: the fraction of expected CRe in the signal zone, extrap. from the {MCe} sample.

$$\{ON_s^{data}\} = \alpha\{MC_{e_s}\} + \beta\{MC_{p_s}\}$$

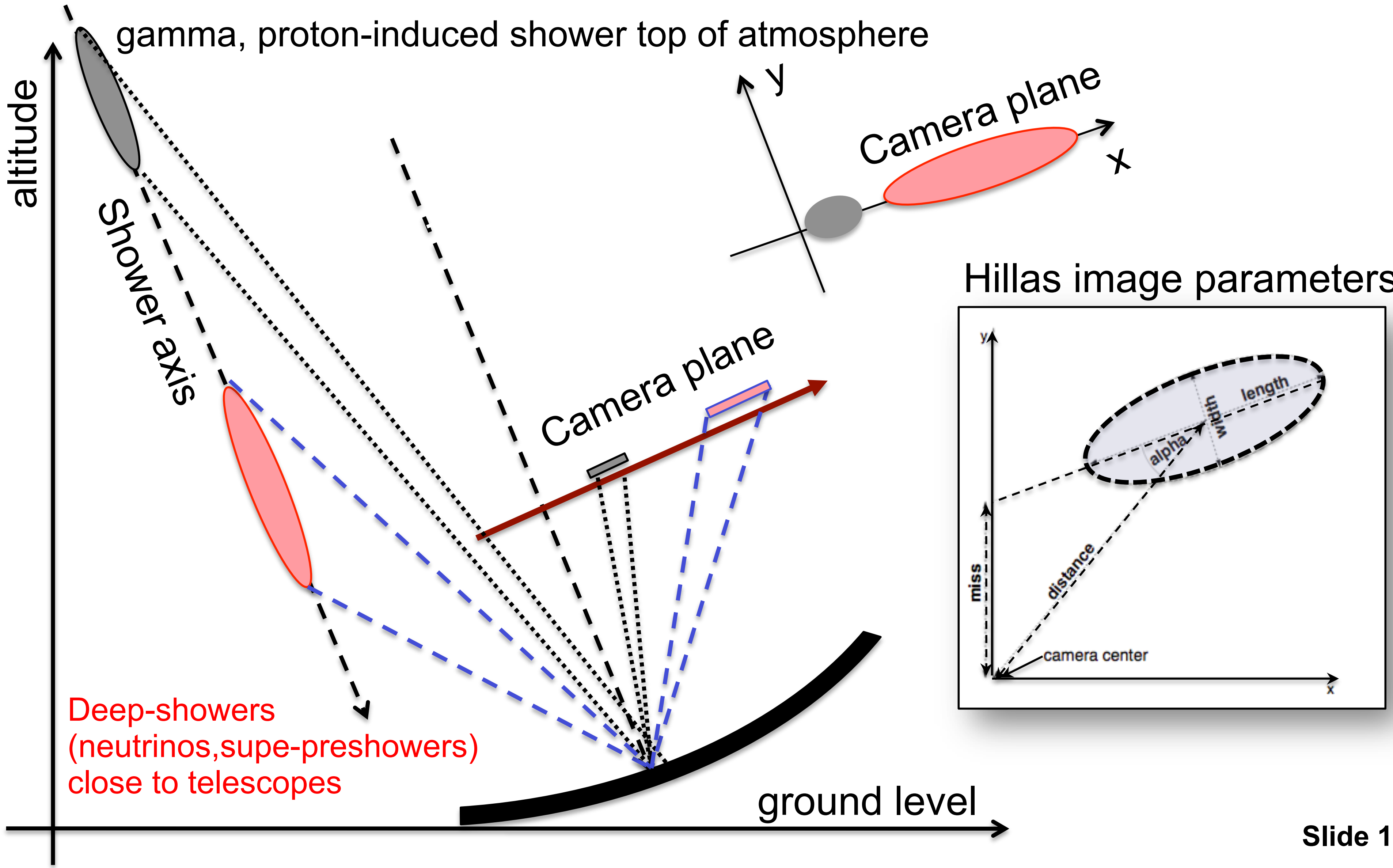
- Solution of these two equations give normalization factors ***α, β*** i.e. contribution of the signal/background to measured data.



Credits: K. Mallot for MAGIC Collaboration, TeVPa 2015

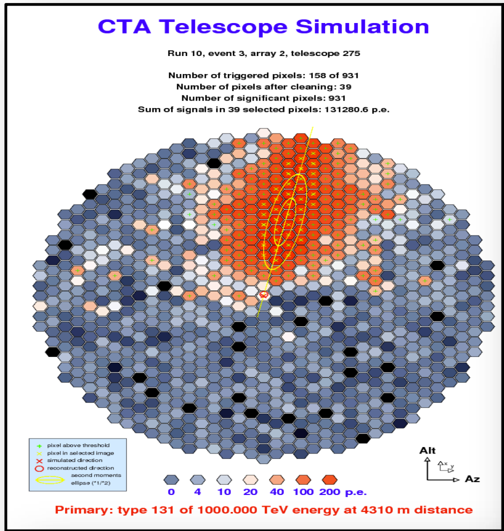
Analysis of shower images

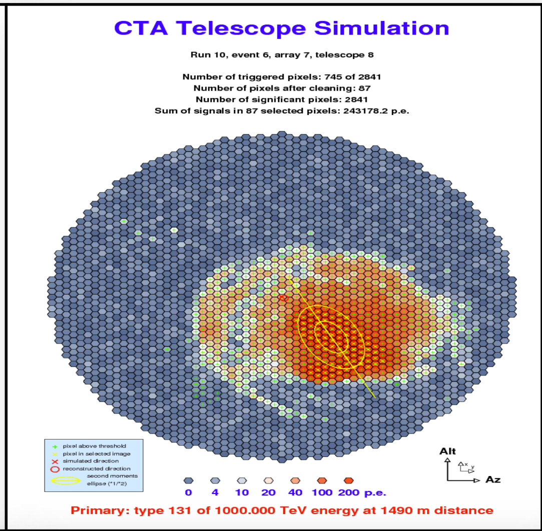
> Hillas parameters depend on the distance between the shower maximum and the detector i.e. the position of shower maximum in the atmosphere.



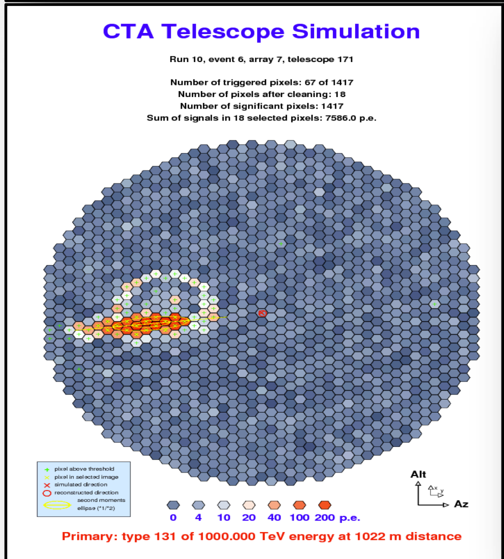
Example of non-standard shower images

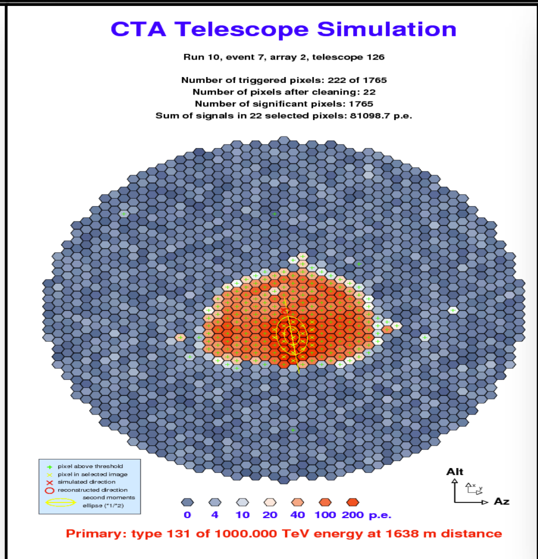
> A few PeV tau lepton decays to different channels and produce mixture of electromagnetic and hadronic sub-showers

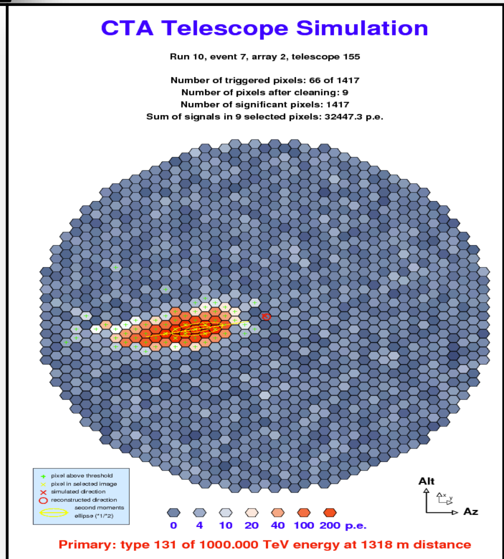




Decay	Secondaries	Probability	Air-shower
$\tau \to \mu^- \bar{\nu}_\mu \nu_\tau$	μ^-	17.39 %	[illegible]
$\tau \to e^- \bar{\nu}_e \nu_\tau$	e^-	17.85 %	1 e/m
$\tau \to \pi^- \nu_\tau$	π^-	11.08 %	1 hadr.
$\tau \to \pi^- \pi^0 \nu_\tau$	$\pi^-, \pi^0 \to 2\gamma$	25.37 %	1 hadr., 2 e/m
$\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$	$\pi^-, 2\pi^0 \to 4\gamma$	9.19 %	1 hadr., 4 e/m
$\tau \to \pi^- \pi^0 \pi^0 \pi^0 \nu_\tau$	$\pi^-, 3\pi^0 \to 6\gamma$	1.08 %	1 hadr., 6 e/m
$\tau \to \pi^- \pi^- \pi^+ \nu_\tau$	$2\pi^-, \pi^+$	8.98 %	3 hadr.
$\tau \to \pi^- \pi^- \pi^+ \pi^0 \nu_\tau$	$2\pi^-, \pi^+, \pi^0 \to 2\gamma$	4.30 %	3 hadr., 2 e/m



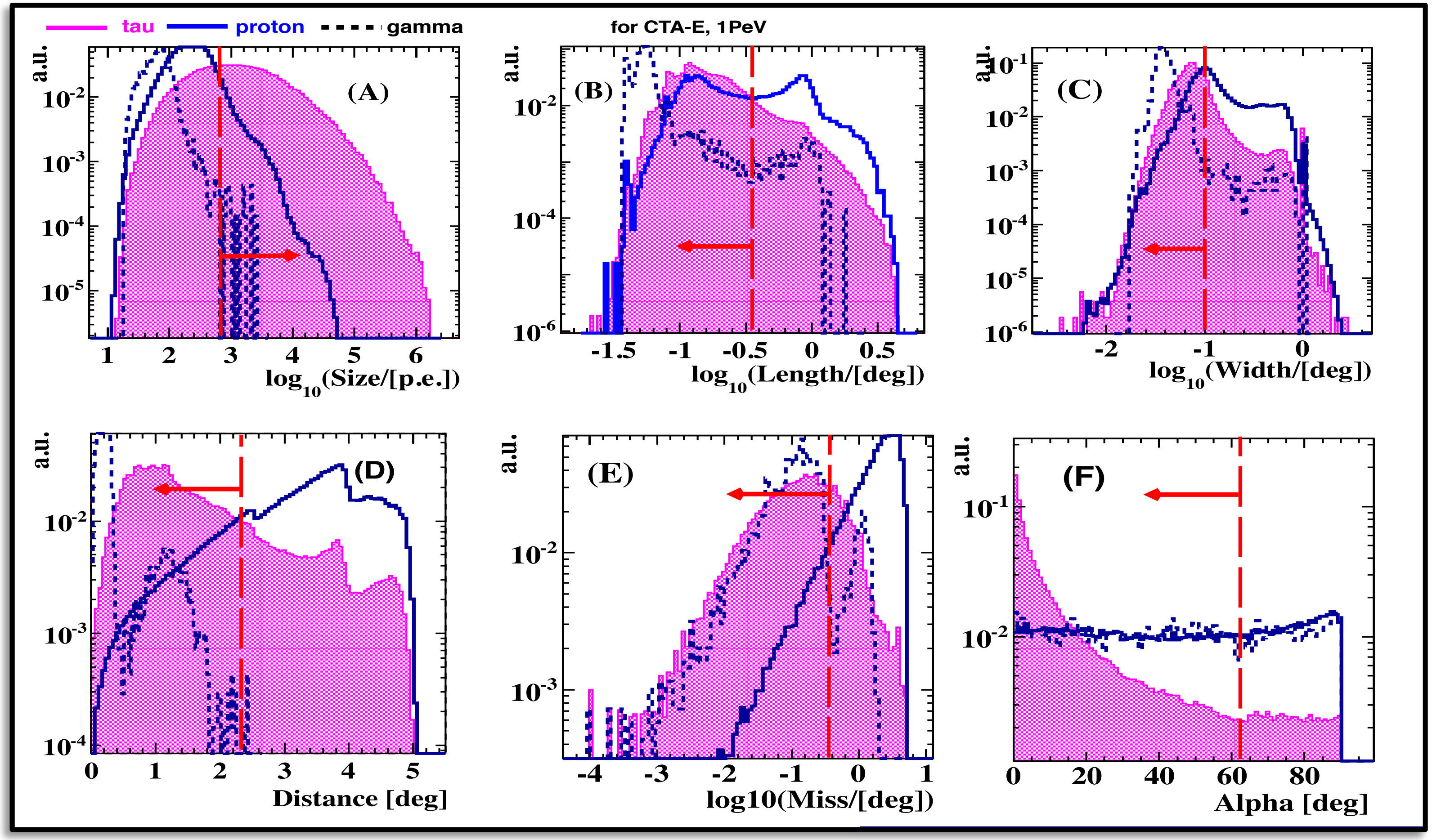




for 1 PeV lepton tau, injected deep in the atmosphere (780 g/cm^2, zenith angle=88 deg)

Analysis of shower images

…Thus analysis of Hillas distributions, especially at large zenith angles, give possibility to identify new types of rare events (as an example neutrinos by CTAs arXiv:1606.01676)

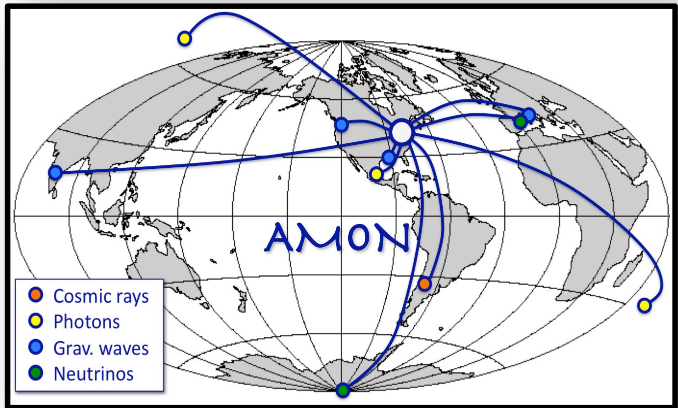


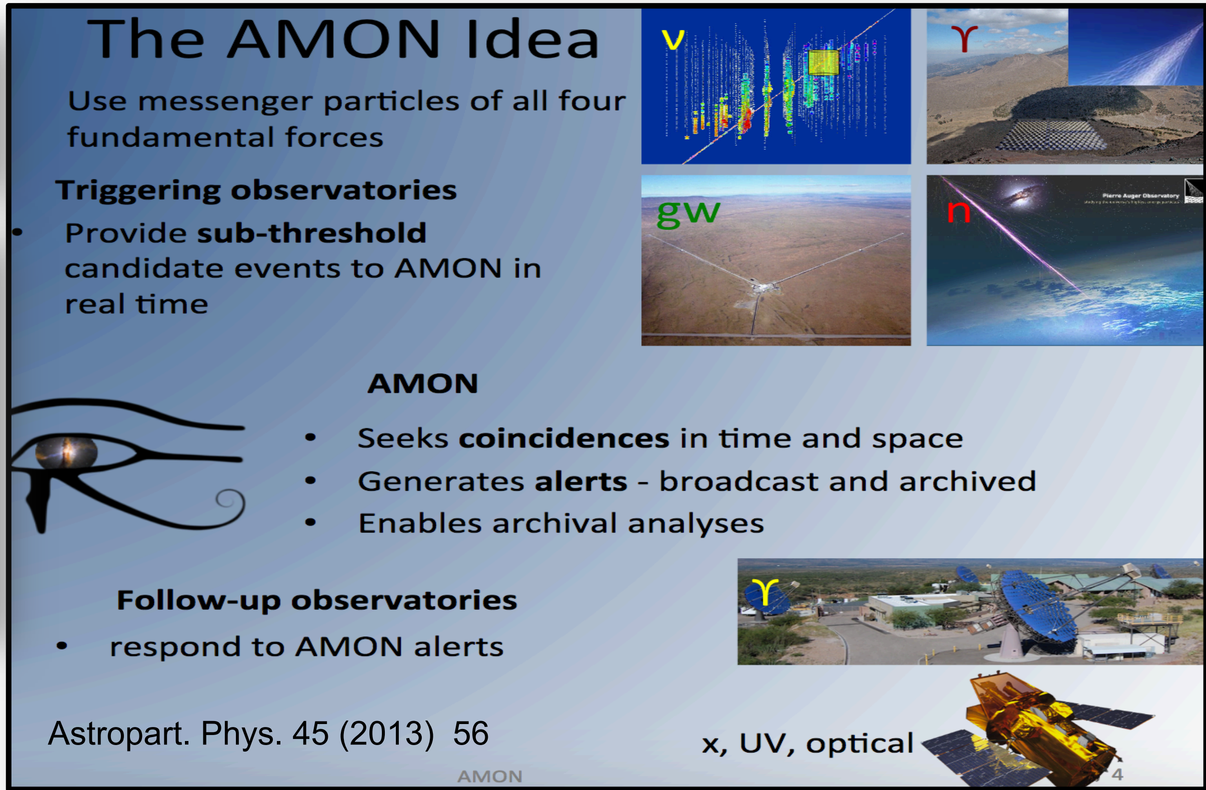
For IACTs large zenith angles means larger threshold (up to 300 TeV), and less background from cosmic-rays and photons.

Multi-messenger approach

> Discovery of astrophysical neutrinos by IceCube boosted the multi-messenger approach.
- analysis of online data from different observatories: IceCube, Antares, HAWC, IACTs, Fermi, Swift and triggering follow-up observations by broadcasting alerts.

AMON
Astrophysical Multimessenger Observatory Network





> CREDO will be fit to this strategy very well, in case of interesting event
- it could distribute alerts via AMON
- or sent to IACTs, if IACTs will be part of the CREDO collaboration

Summary and Outlook

> We shortly review detection technique of Cherenkov telescope, showing how they can be used for detection of super-preshowers

> Super-preshower approach to gamma ray data, in principle can use recently developed technique for diffuse searches in IACTs.

> Can also, focus on analysis strange/non standard/border images, in order to identify new types of rare events (eg. super-preshowers class A can give different image than a single photon)

> Gamma ray astronomers are also interested in CREDO strategy: (receiving alerts in case of interesting events seen by CREDO stations)

> ….

Thanks