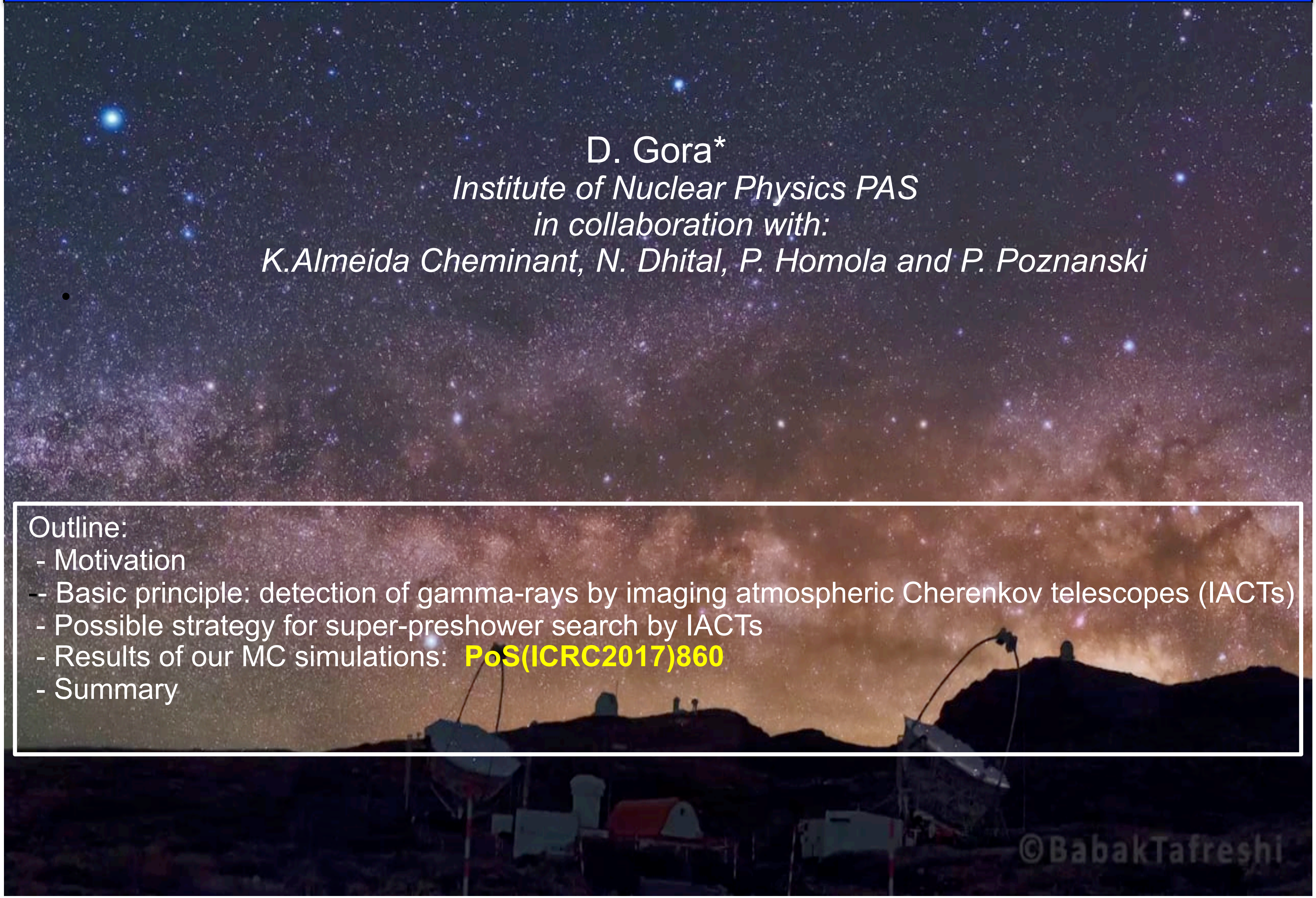
Multi-photon search in gamma-ray telescopes

D. Gora*
Institute of Nuclear Physics PAS
in collaboration with:
K.Almeida Cheminant, N. Dhital, P. Homola and P. Poznanski

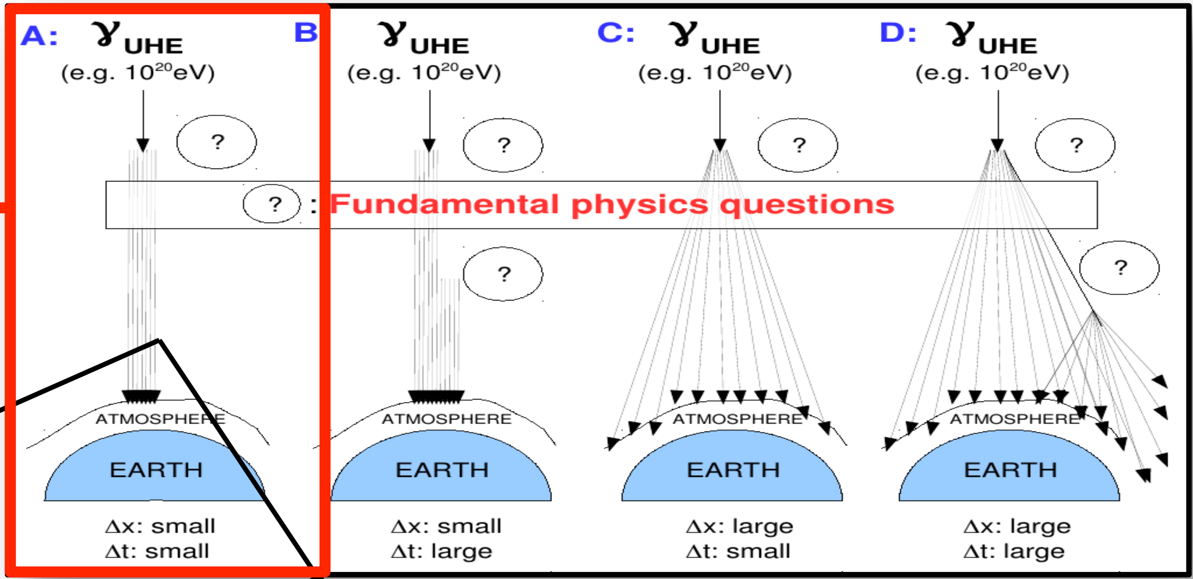
Outline:
- Motivation
- Basic principle: detection of gamma-rays by imaging atmospheric Cherenkov telescopes (IACTs)
- Possible strategy for super-preshower search by IACTs
- Results of our MC simulations: **PoS(ICRC2017)860**
- Summary

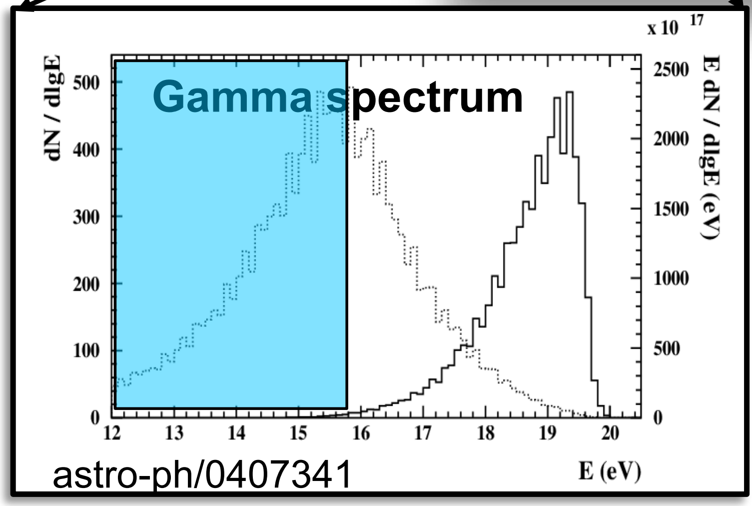


Introduction

> Super-preshower (SPS) is a cascade of electromagnetic particles originated above the Earth atmosphere, no matter the initiating process

This talk





Interesting energy range
for Cherenkov telescopes

> Various types of super-preshowers (SPS) based on time and spatial spread.

Basic principle: detection of high energies gamma-rays

(10 γ-rays/m²yr from the Crab nebula,
detection area about 50 000m^2, flux of > 1 γ-ray / min)

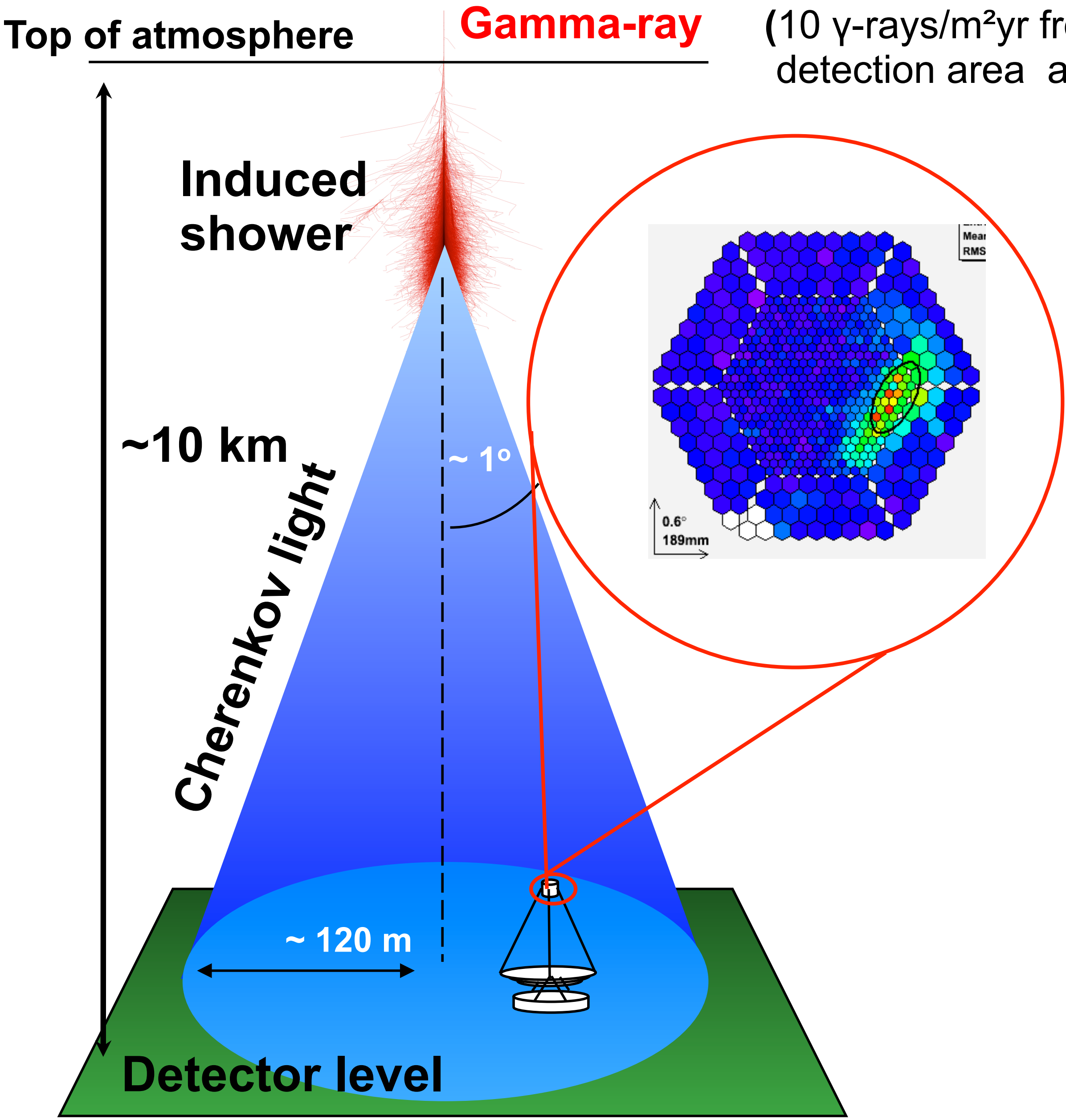


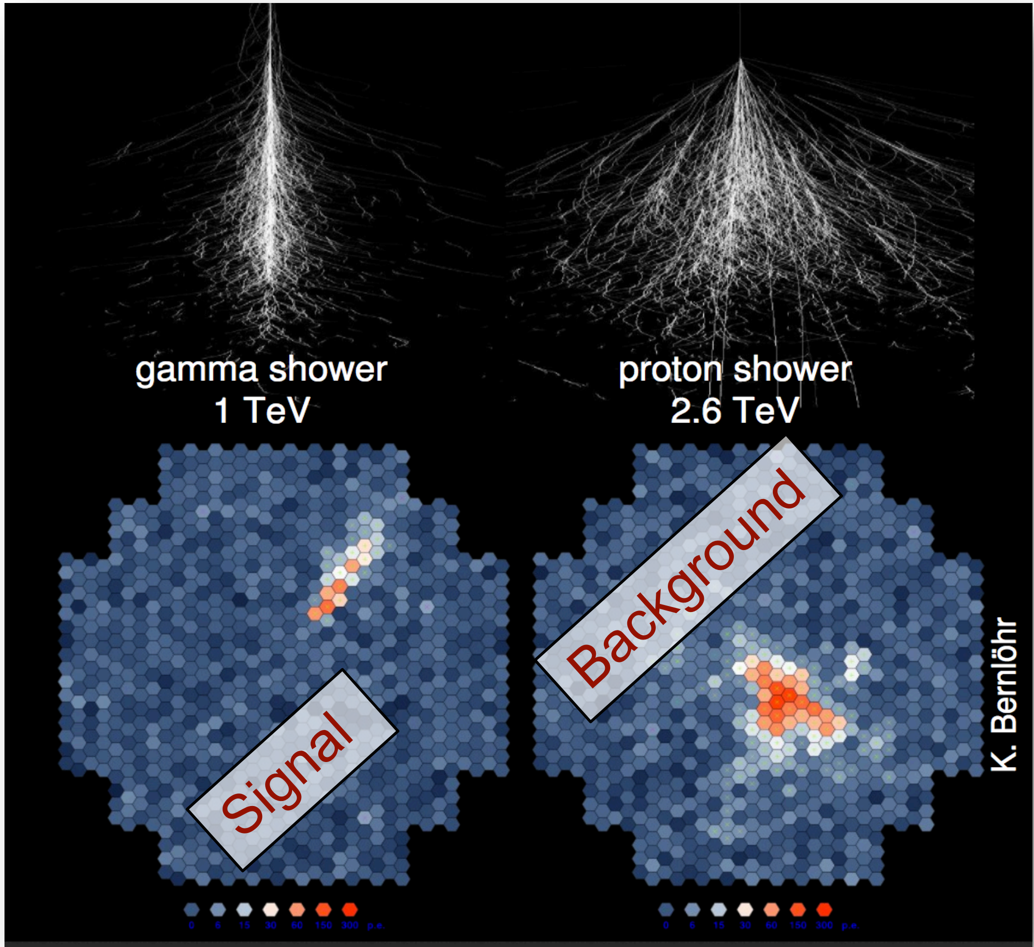
Image on camera

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

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

Gamma-hadron separation

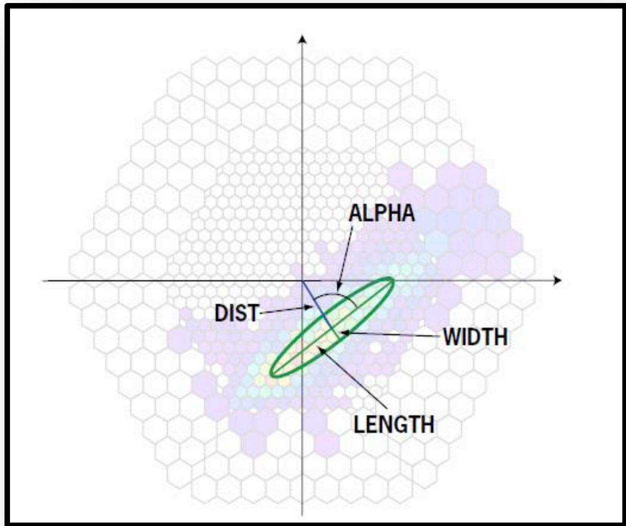
> **Background reduction by image shape analysis**
... Cosmic Rays main background for Cherenkov astronomy



> *Protons create hadronic showers with irregular images*

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

> Hillas parameters:



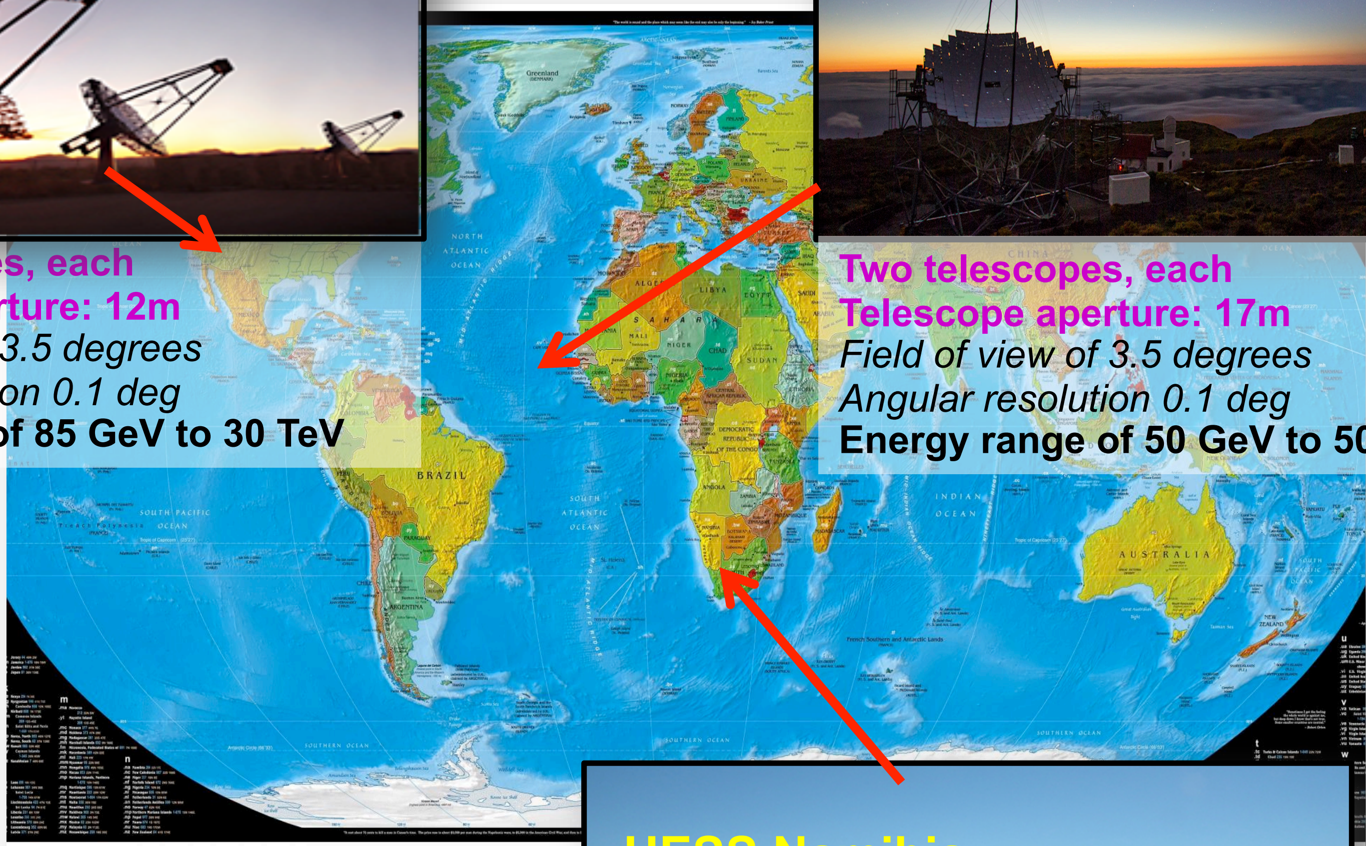
A.M. Hillas,Nucl. Phys. Proc. Suppl.52B (1997) 29

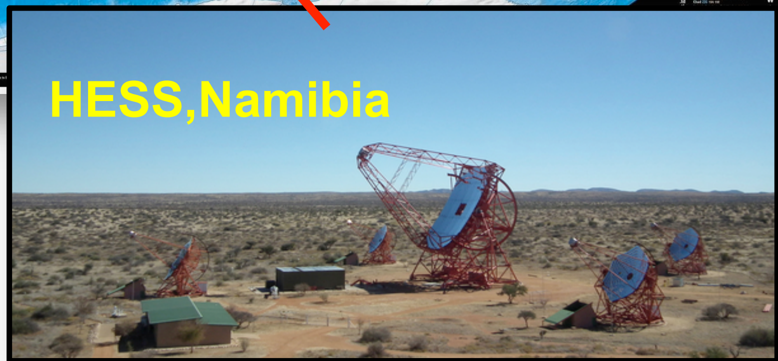
SIZE parameter: the total amount of detected light (in p.e.) in all camera pixels

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

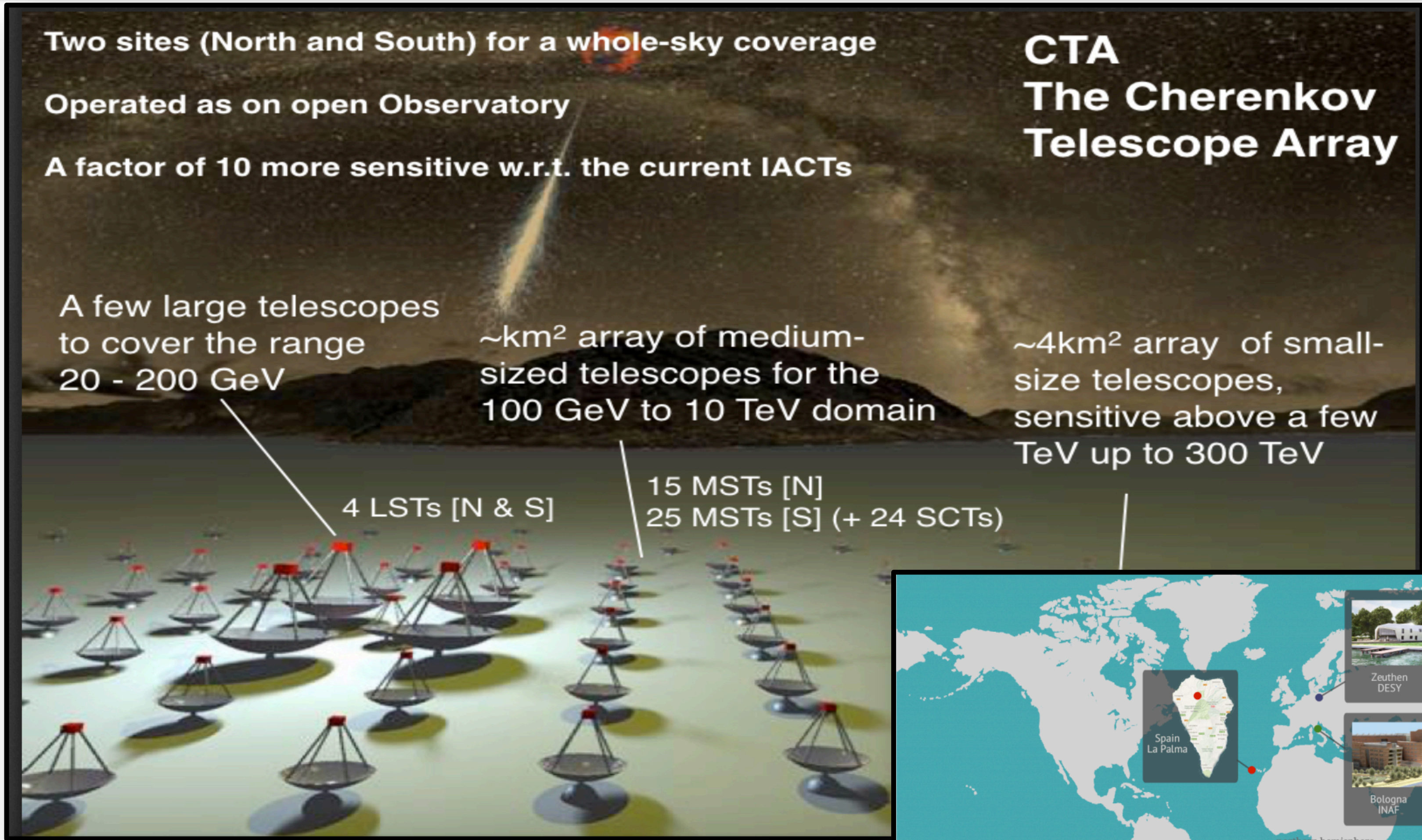
Two telescopes, each
Telescope aperture: 17m
Field of view of 3.5 degrees
Angular resolution 0.1 deg
Energy range of 50 GeV to 50 TeV

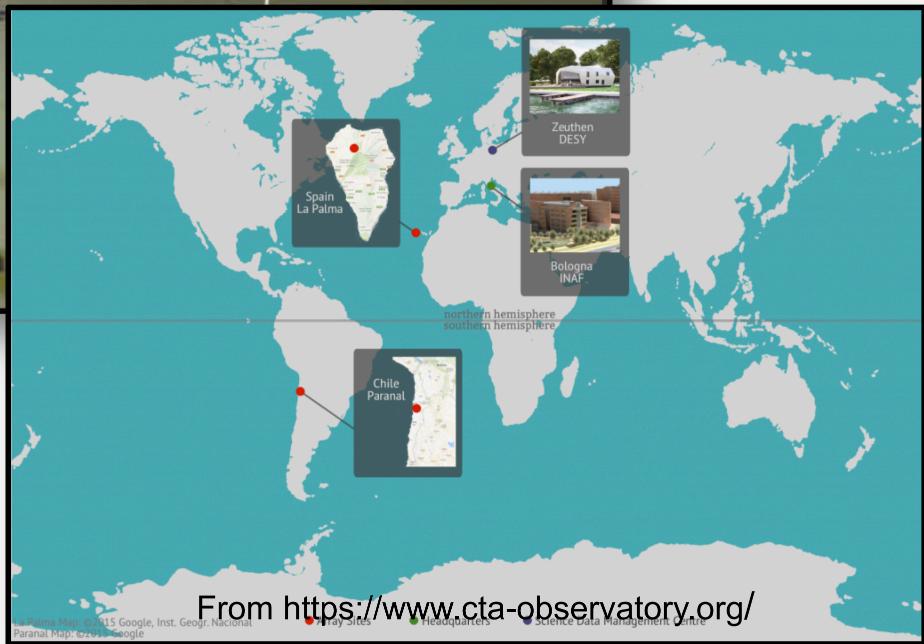




Five telescopes,
Four telescope aperture: 12m + one 28 m
Field of view of 5 degrees/3.5 degrees
Angular resolution 0.08 deg
Energy range of 10 GeV to 10 TeV

The next generation Cherenkov telescopes observatory



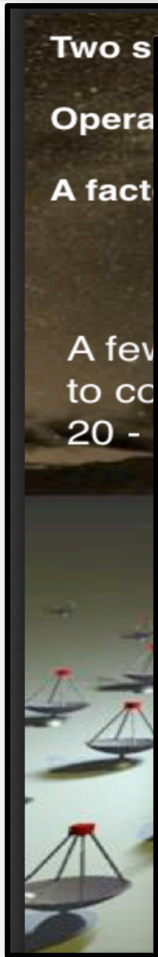


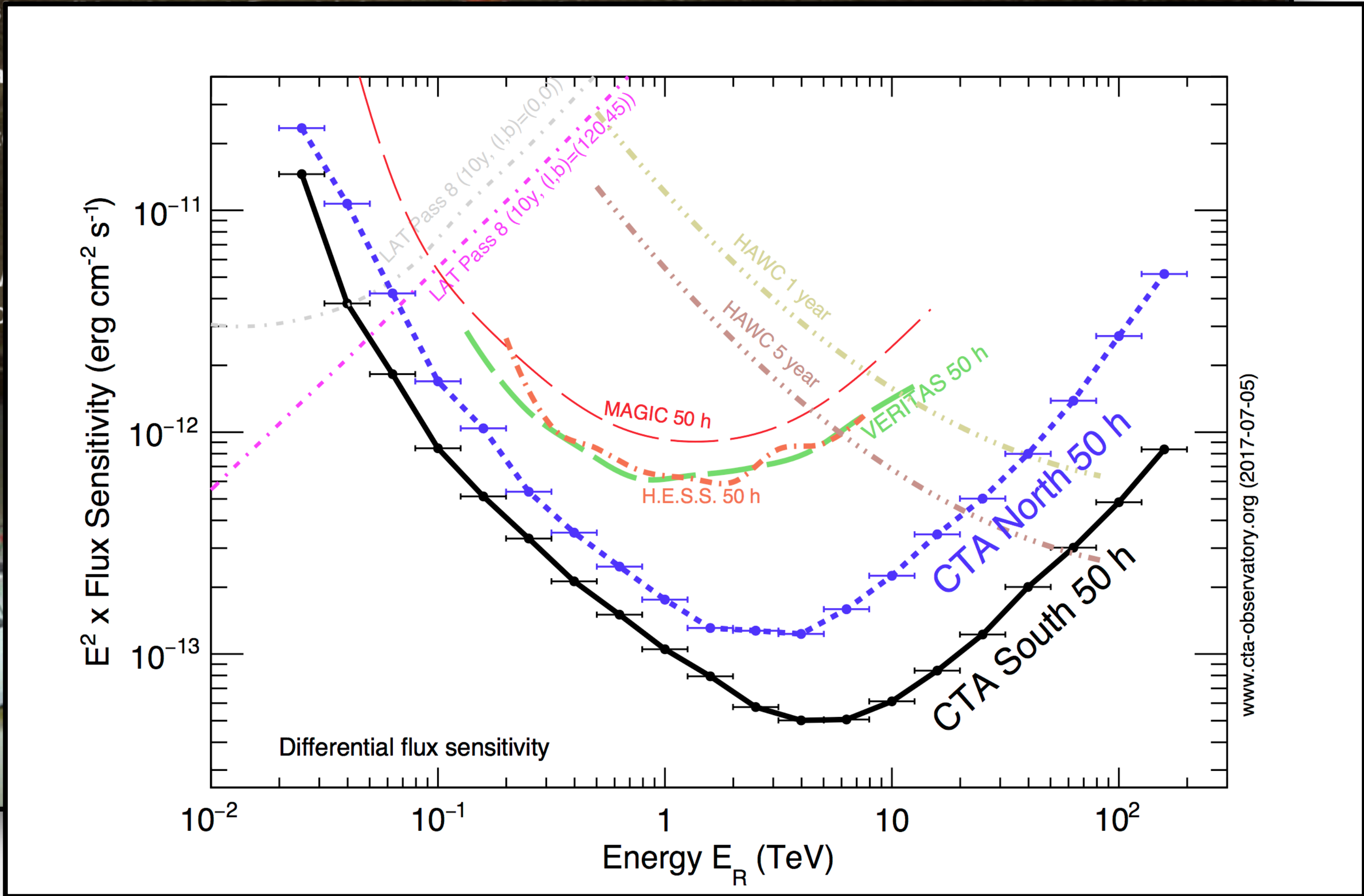
From https://www.cta-observatory.org/

Two array locations:

La Palma (north) and Chile (South)

The next generation Cherenkov telescopes observatory





Two array locations:

La Palma (north) and Chile (South)

From https://www.cta-observatory.org/

Monte Carlo simulation chain

(1) Simulation of eletromagnetic particle by interaction with geomagnetic field (Preshower effect)

(2) Simulation of shower in air at high zenith angles

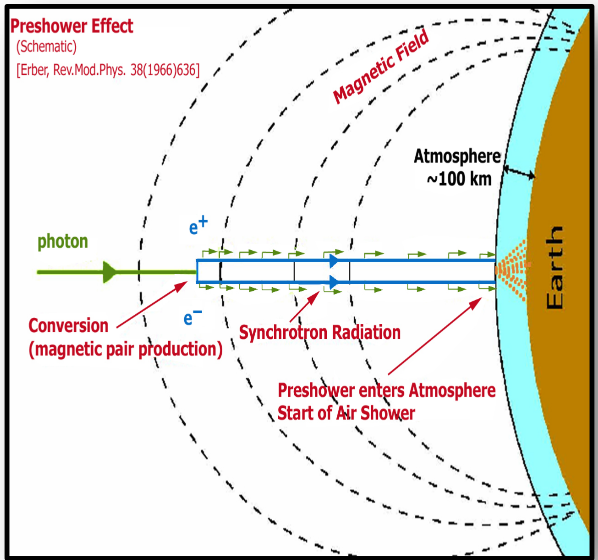
(3) Simulation of CTA responce

PRESHOWER ➔ ***CORSIKA*** ➔ ***Sim_telarray***

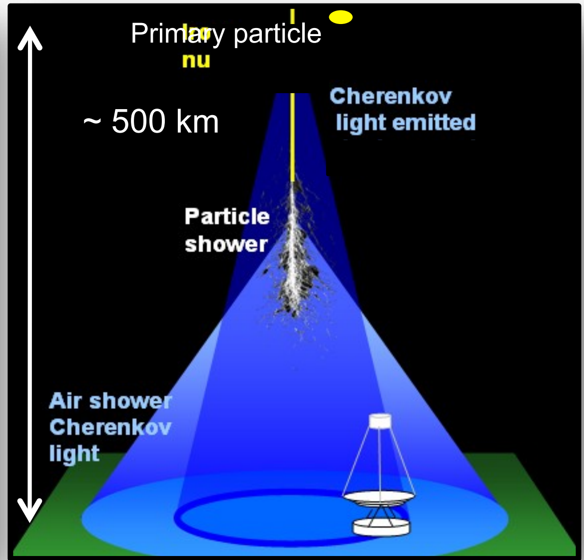
Homola et al., Computer Physics Commun. 184 (2005), 1468

D. Heck, et al., FZKA Report, 6019 (1998)

K. Bernlöhr, Astropart. Phys. 30 (2008), 149



PRESHOWER linked with **CORSIKA**



Compiled: with **CURVED-EARTH**, **CHERENKOV/IACT, THIN** option

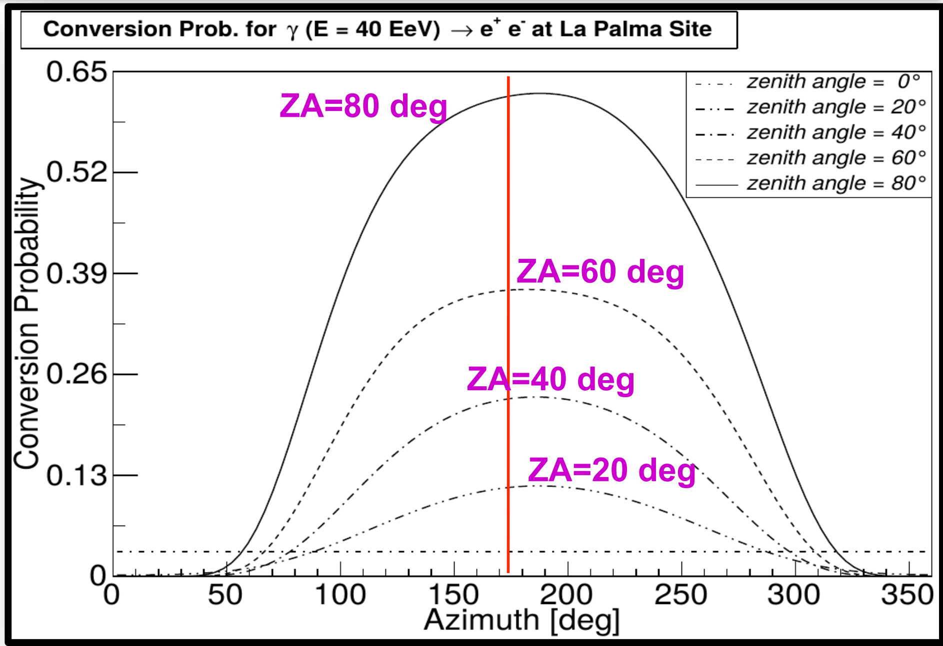
Miror optics/camera electronics simulations, with public ***Production-1* settings**

Simulation conditions

> The simulation were performed in the direction of the largest gamma conversion probability at the La Palma site

PRESHOWER photon primary: E=40 EeV, θ=80°, φ=180°

.. and for the northern site of CTA (La Palma)



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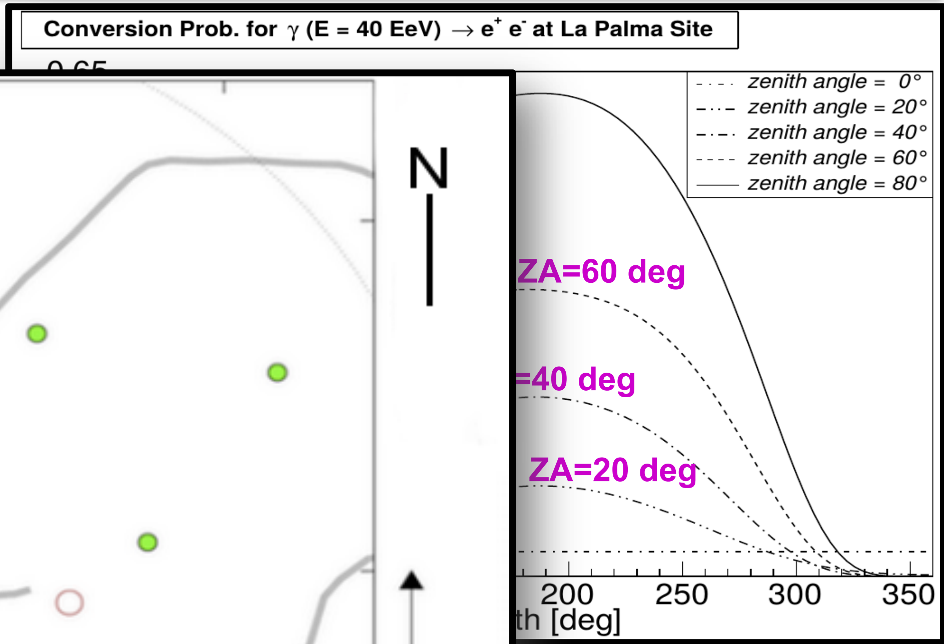
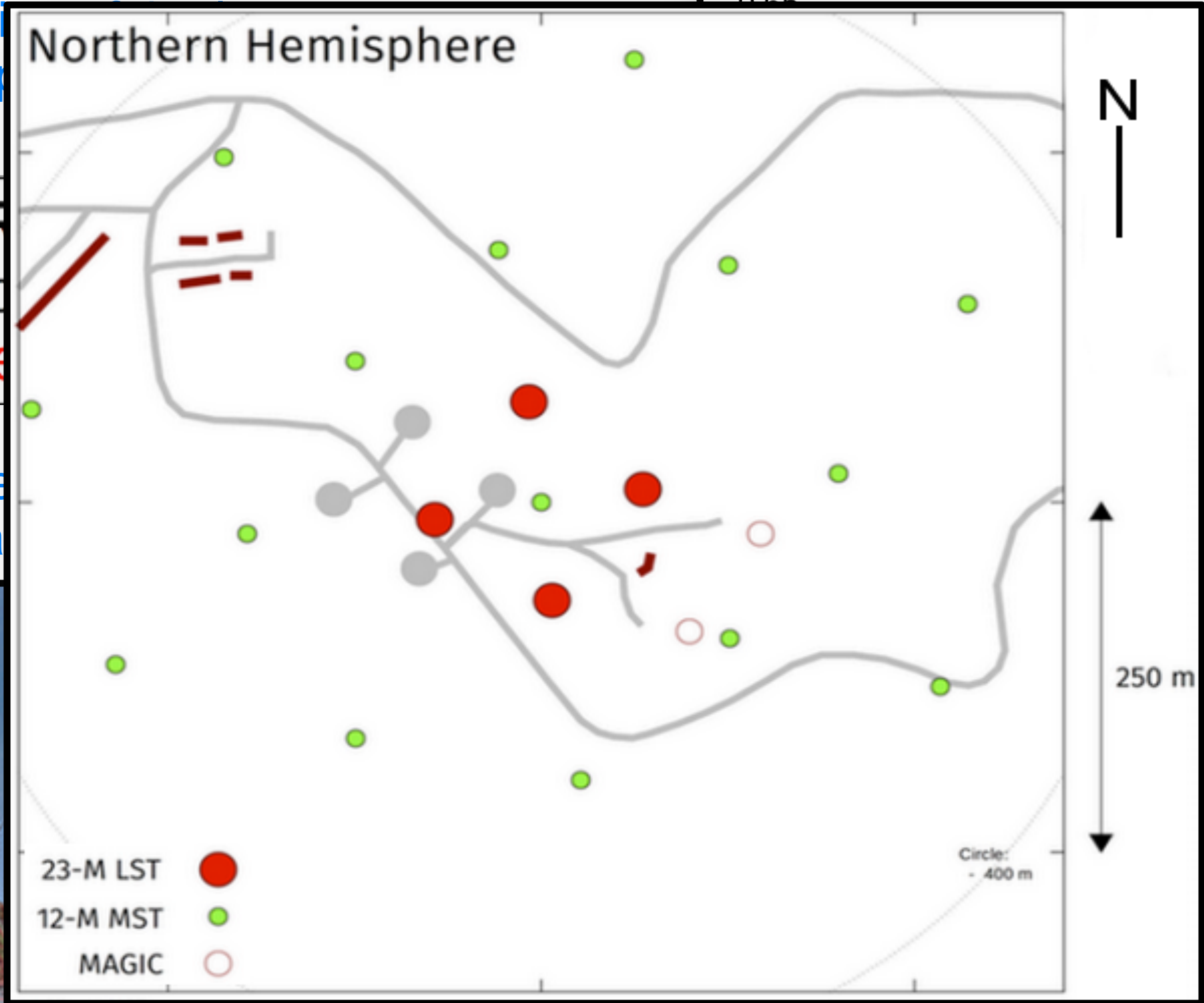
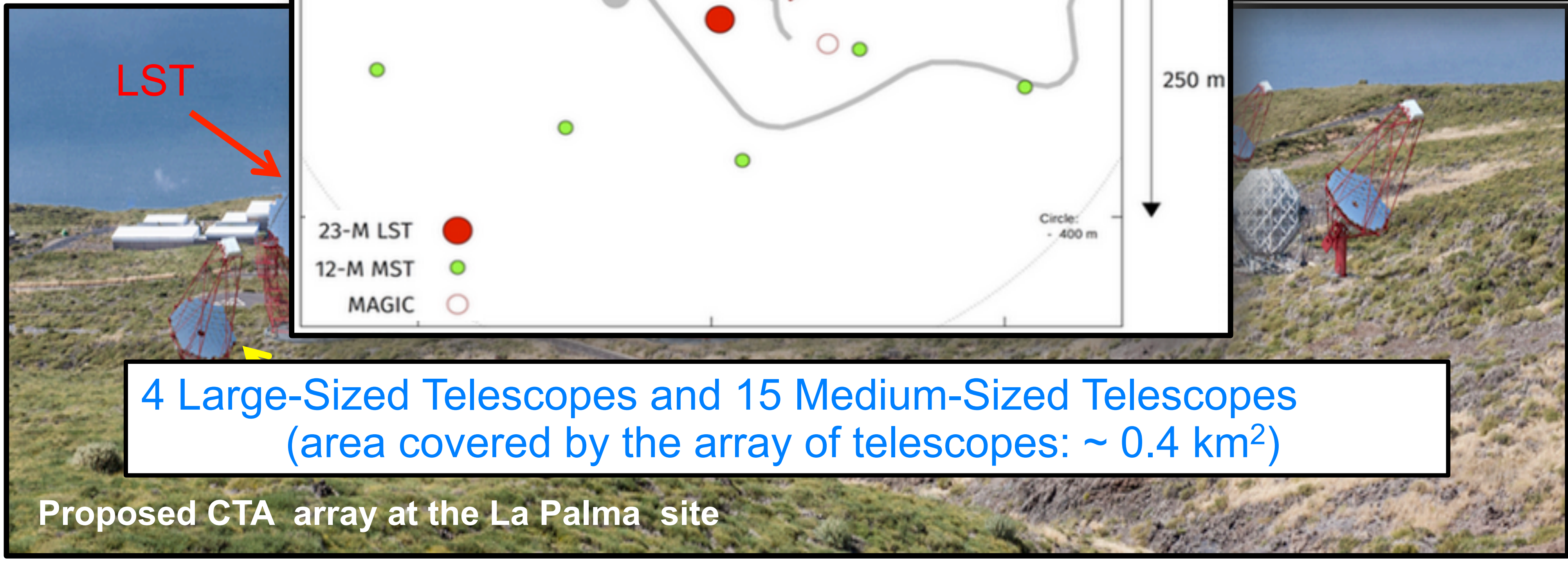






4 Large-Sized Telescopes and 15 Medium-Sized Telescopes
(area covered by the array of telescopes: ~ 0.4 km^2)

Proposed CTA array at the La Palma site

Inclined showers

> In this work, a special attention is given to nearly horizontal showers

Advantage:

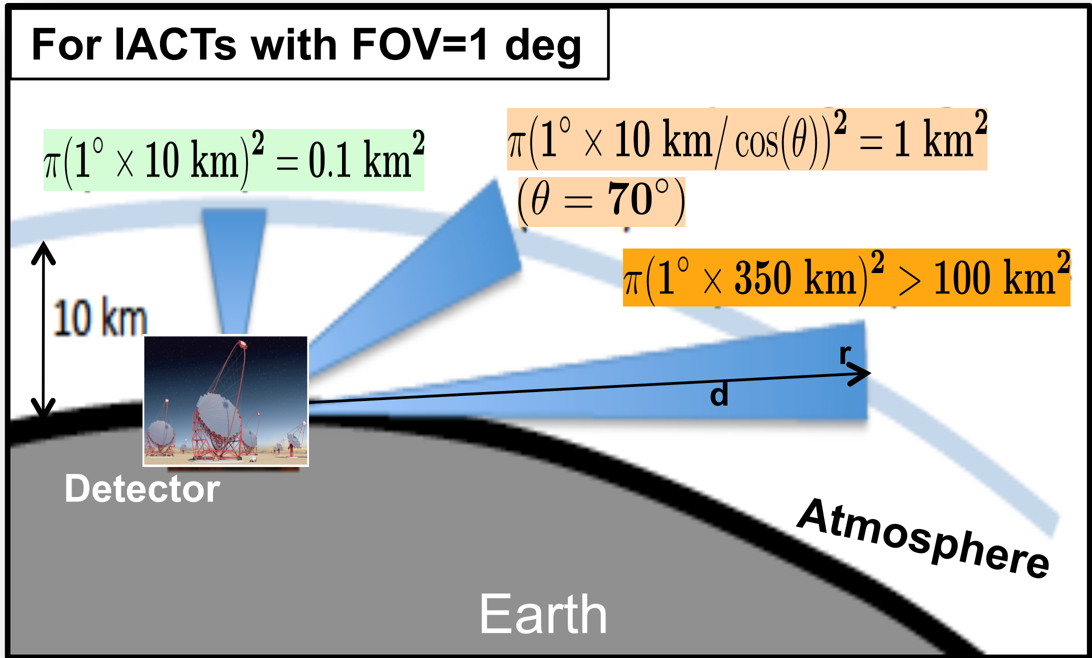
- large expected aperture

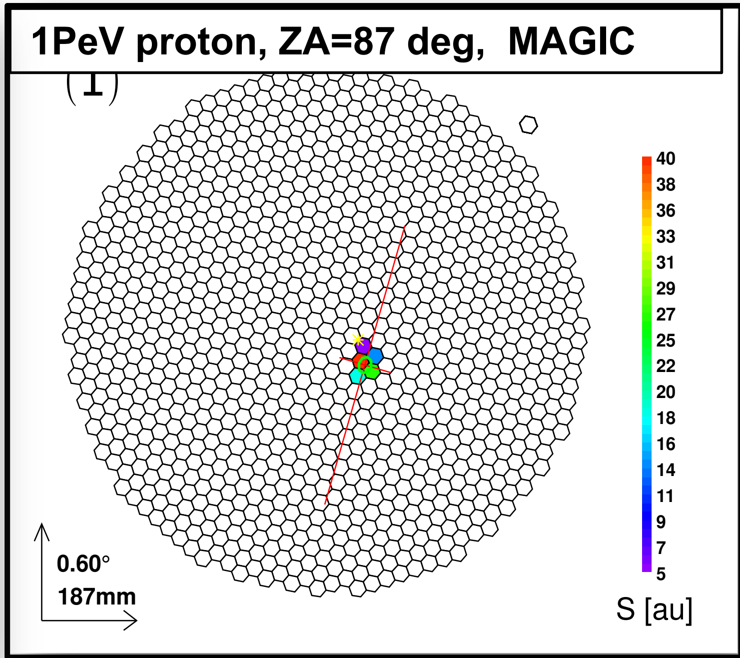
$$\text{Aperture} = \pi r^2 \simeq d \times \alpha_{FOV}[\text{rad}]/2$$

Disadvantage:

- worse gamma/hadron separations

due to large thickness of the atmosphere, (~1000 km at ZA=87 deg), shower images are almost inside a single pixel

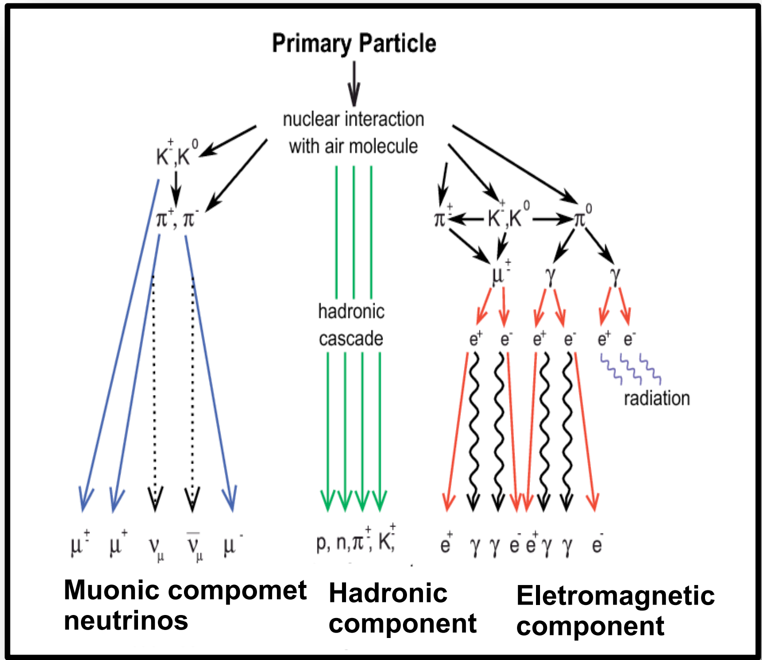




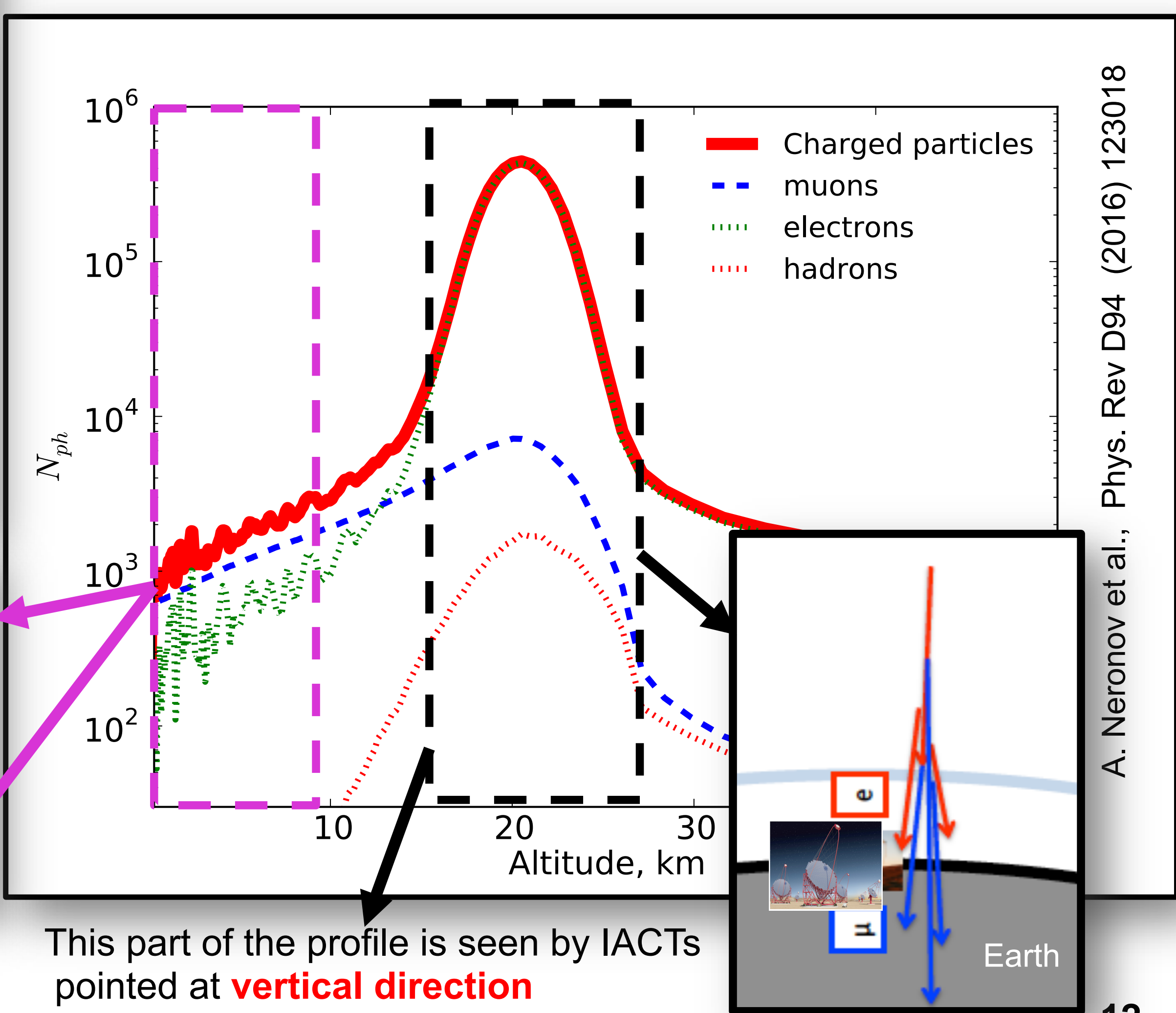
> However, we are working at ~ EeV energies not TeVs, so at these energies gamma/hadron separation can be recovered again

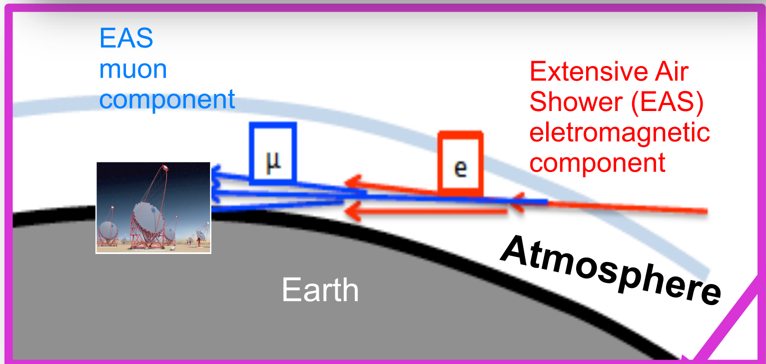
Muon component of air shower

> Muon component is largely sub-dominant in the shower maximum region but it starts to dominate at large depth (small altitudes) in the atmosphere.



Longitudinal profiles of charged particle distribution in an EAS initiated by a 1 PeV energy proton inclined at 87 deg



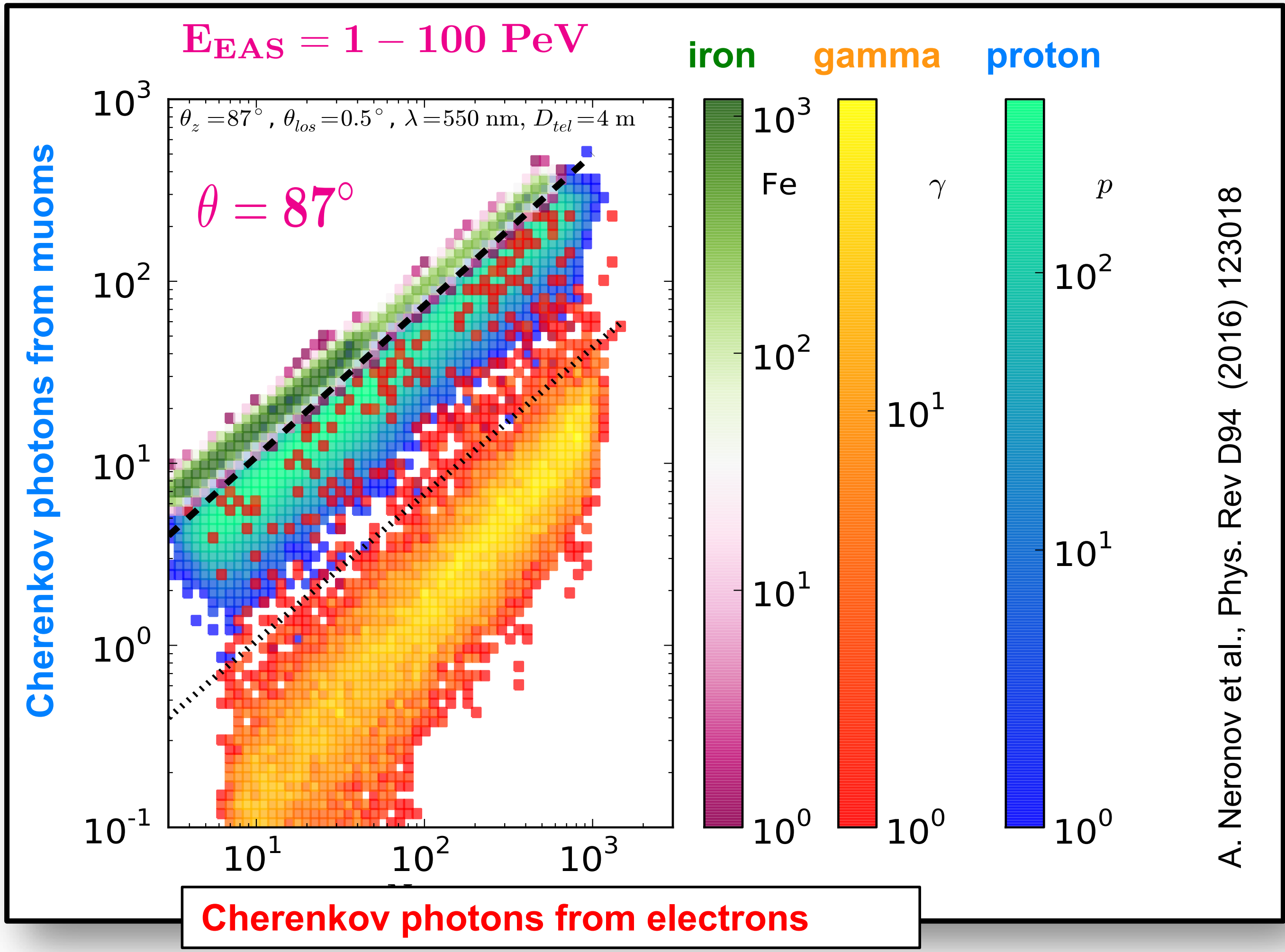


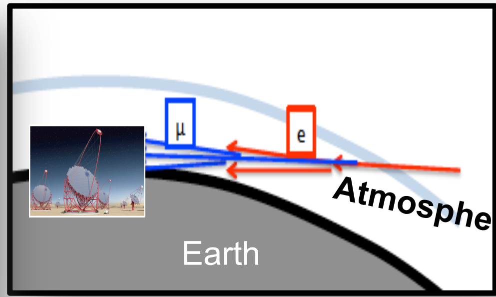
This part of the profile is seen by IACTs pointed at **horizontal direction**

This part of the profile is seen by IACTs pointed at **vertical direction**

Cherenkov light from muon component of air showers

- Measurement of Cherenkov emission from muons could provide primary particle ID but only for inclined air showers (A. Neronov et al., Phys. Rev D94 (2016) 123018, [astro-ph/1610.01794])



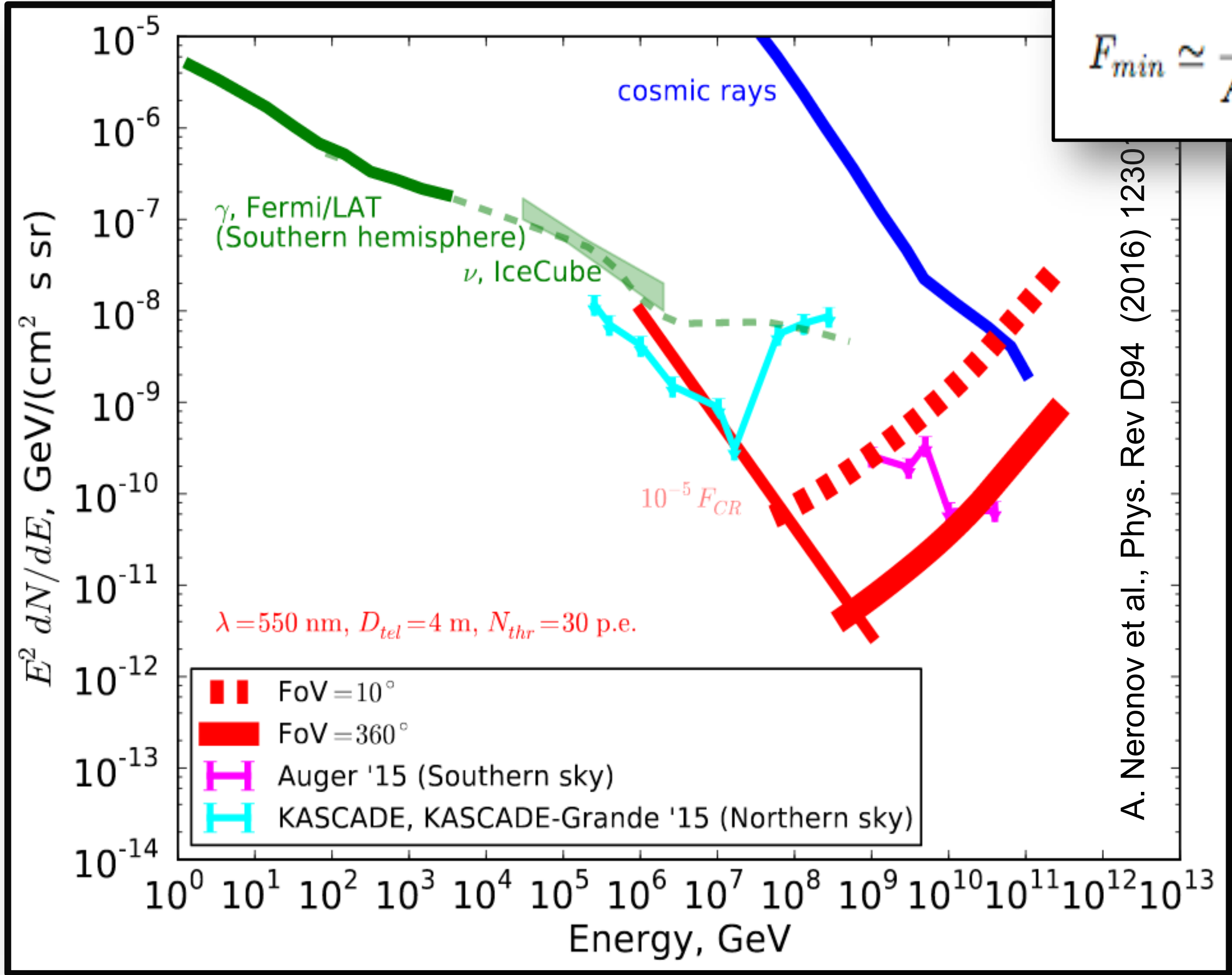


- This provides a possibility for exploration of the PeV gamma-ray sky in background-free regime

Expected sensitivity of Cherenkov telescopes

> The differential sensitivity corresponding to one event per energy decade:

$$F_{min} \simeq \frac{E}{A\Omega\kappa T_{exp}} \simeq 10^{-11}\left[\frac{E}{10^8\ \mathrm{GeV}}\right]\frac{\mathrm{GeV}}{\mathrm{cm}^2\ \mathrm{s\ sr}}$$



Solid angle:

$$\Omega \sim \pi(\alpha_{Ch} + \gamma_{Ch}^{-1})^2 \simeq 6 \times 10^{-3}$$

Aperture:

$$A \sim 2\pi r_{horizontal} H_{atm} \simeq 2 \times 10^4\ \mathrm{km}^2$$

Observation time:

$$T_{exp} \sim 1\ \mathrm{yr}$$

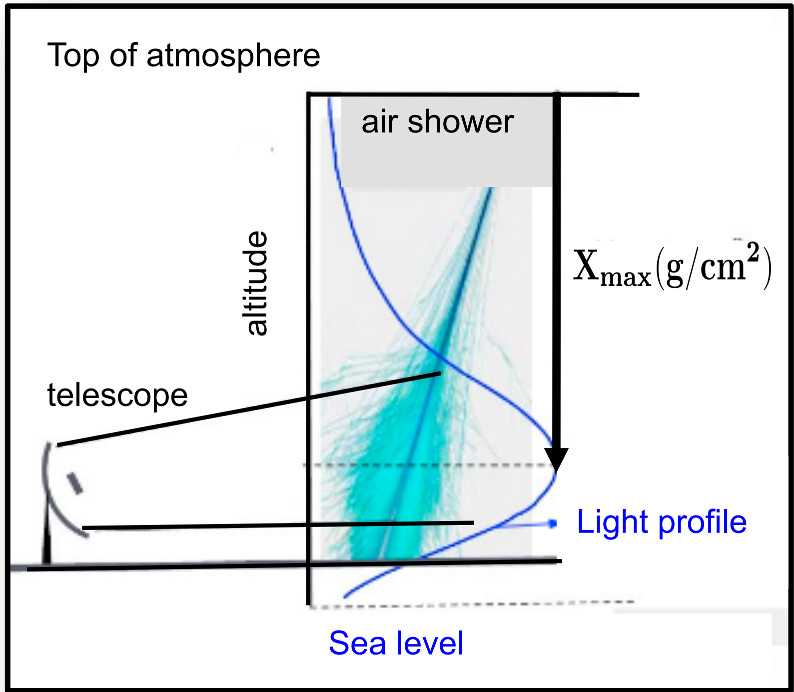
Duty cycle:

$$\kappa \simeq 0.1$$

> The differential sensitivity is comparable to the large cosmic rays experiments like Kaskade, Kasade-Grande or even the Pierre Auger Observatory.

Results of SPS simulations

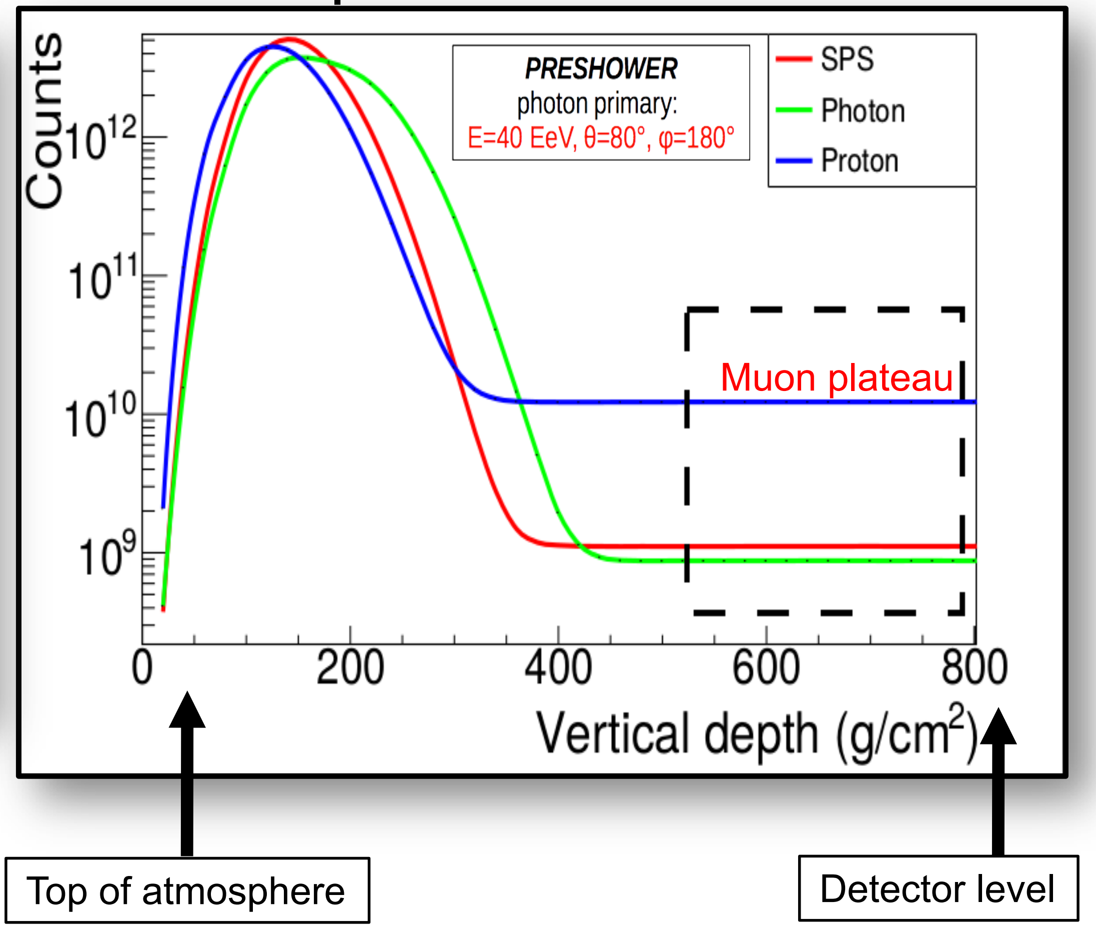
Longitudinal profiles of Cherenkov light



X_{max} : **atmospheric depth of shower maximum development**

$$\langle \mathbf{X_{max}(p)} \rangle > \langle \mathbf{X_{max}(\gamma)} \rangle$$

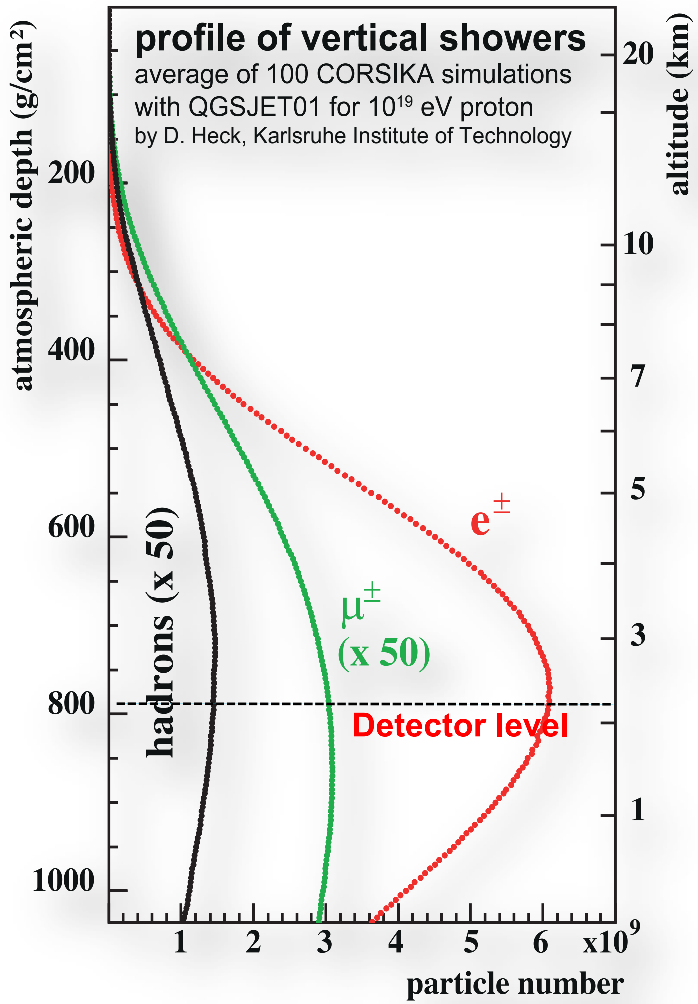
Cherenkov profile for inclined shower

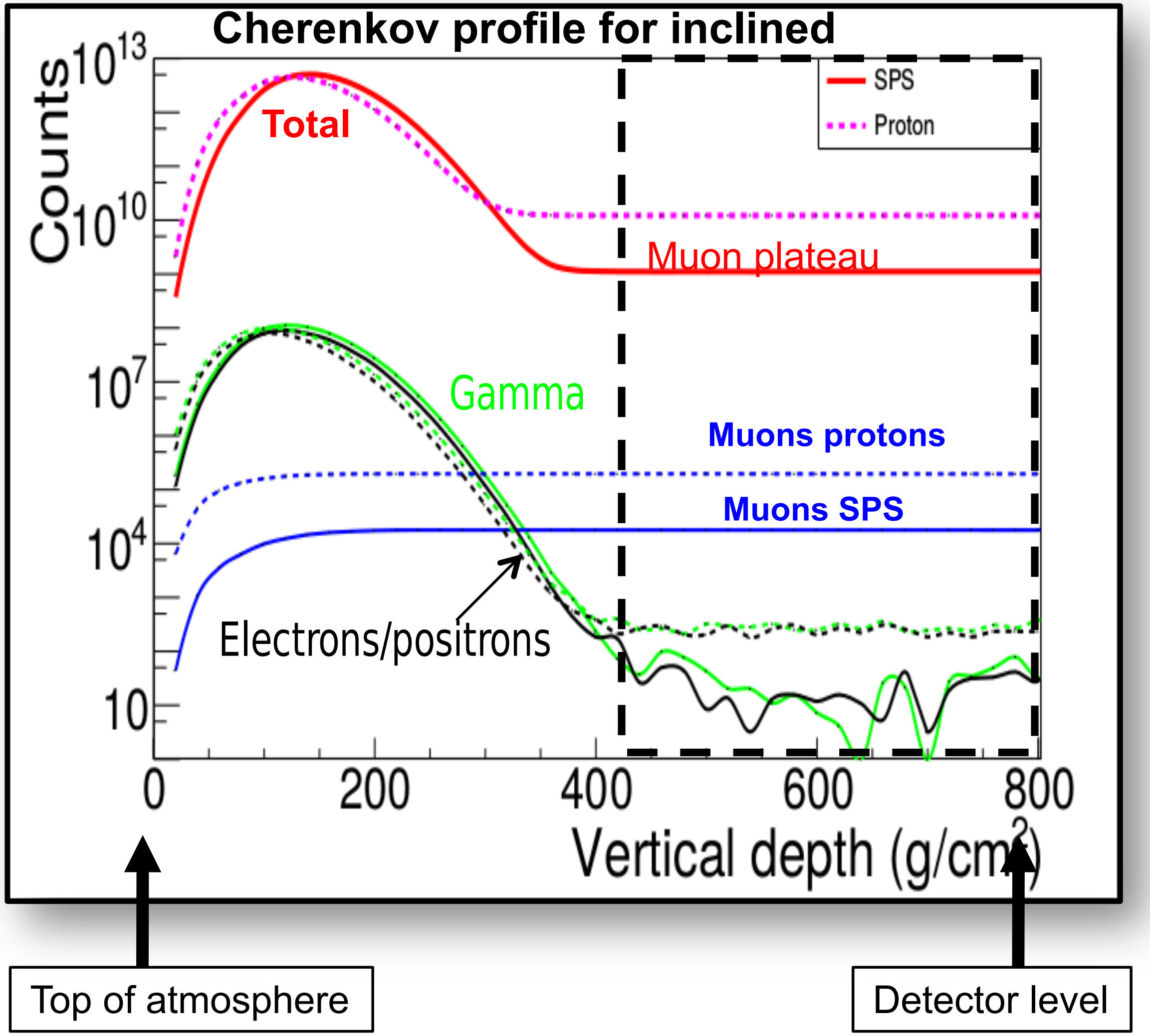


> Maxima of photon-induced showers deeper in the atmosphere than proton-induced showers (for similar interaction point) due to Landau–Pomeranchuk–Migdal (LPM) effect

> SPSs with higher interaction point (multiple photons): air shower maxima shifted towards proton showers maxima → **difficulties in identifying SPSs with current observation modes** i.e. looking at small zenith angle range (< 60 deg)

Longitudinal profiles of Cherenkov light

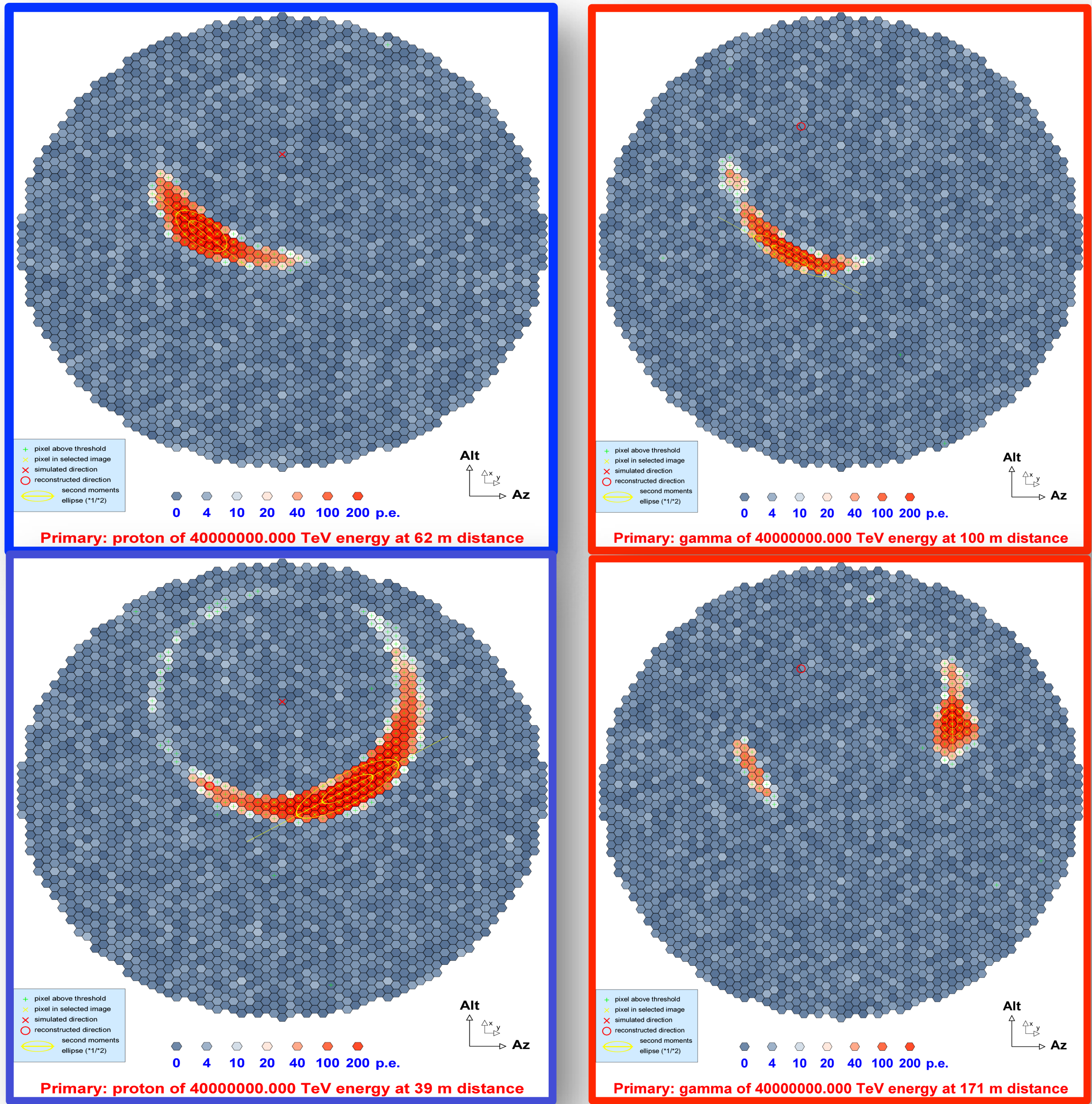




> Large zenith angles allow the observation of the **muon plateau**.
→ **possible identification of SPSs**.

Images on camera

proton **SPS**



PRESHOWER
photon primary:
E=40 EeV, θ=80°, φ=180°

> SPSs higher interaction point and muon poor:

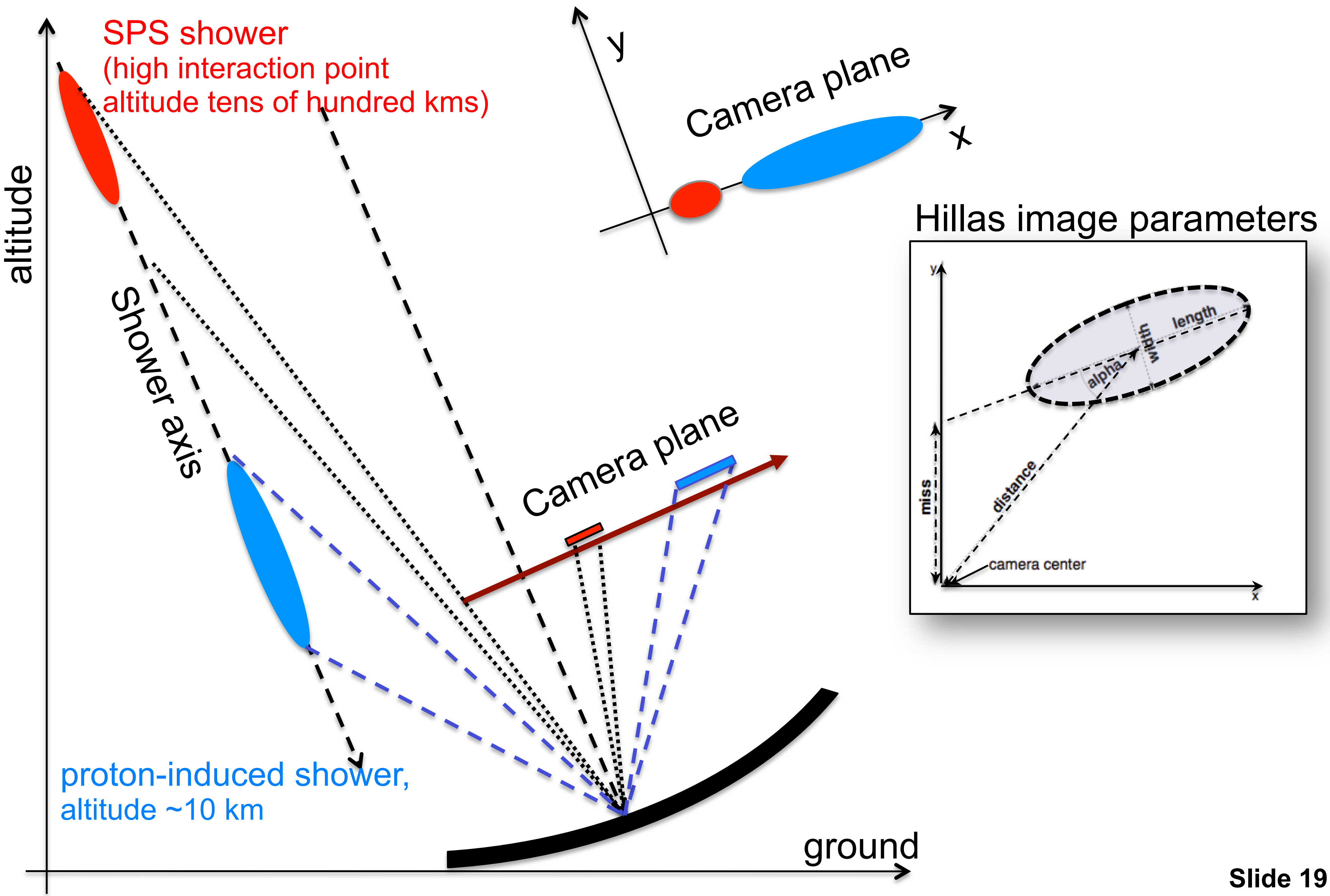
→ images are dimmer and smaller in size than in the proton case.

→ less muon rings.

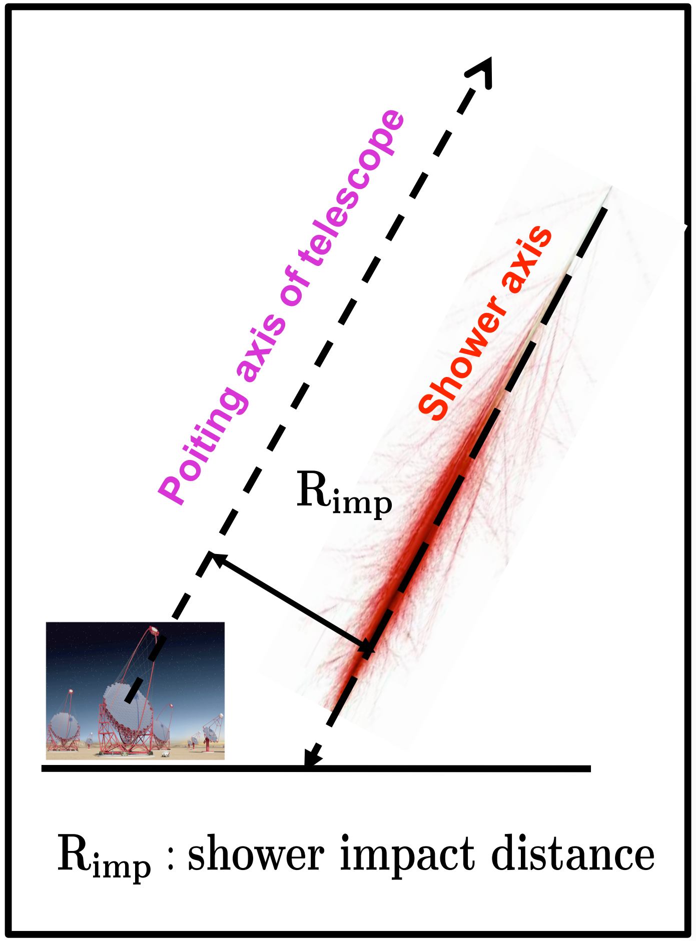
> Multiple air showers initiated by SPSs

→ new class of events are expected.

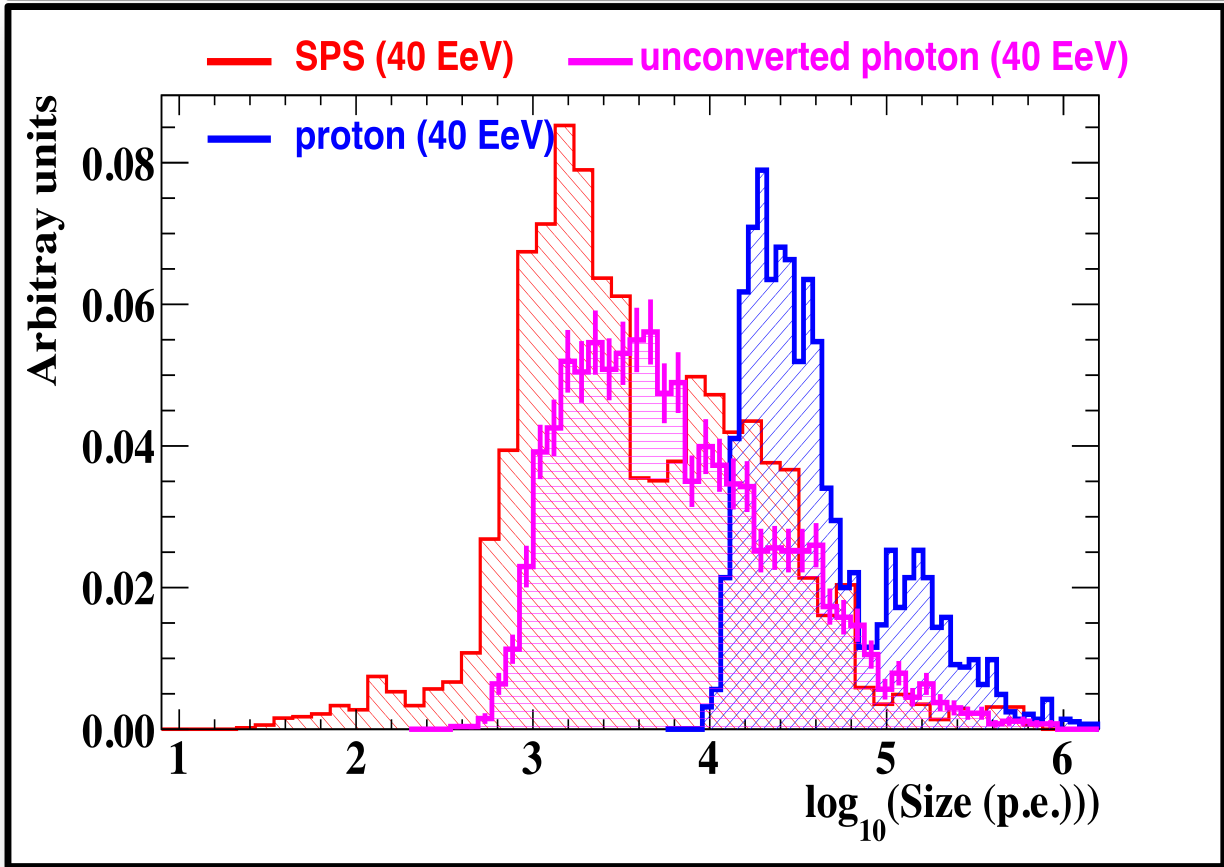
Towards SPS identification



Hillas parameters: preliminary results



for the impact distance $R_{imp} < 50$m and zenith angle : $\theta = 80^\circ$



The same geometry for different primaries in CORSIKA simulations was used. The diffuse signal from CRs, was mimic by proton simulations with VIEWCONE option activated in CORSIKA

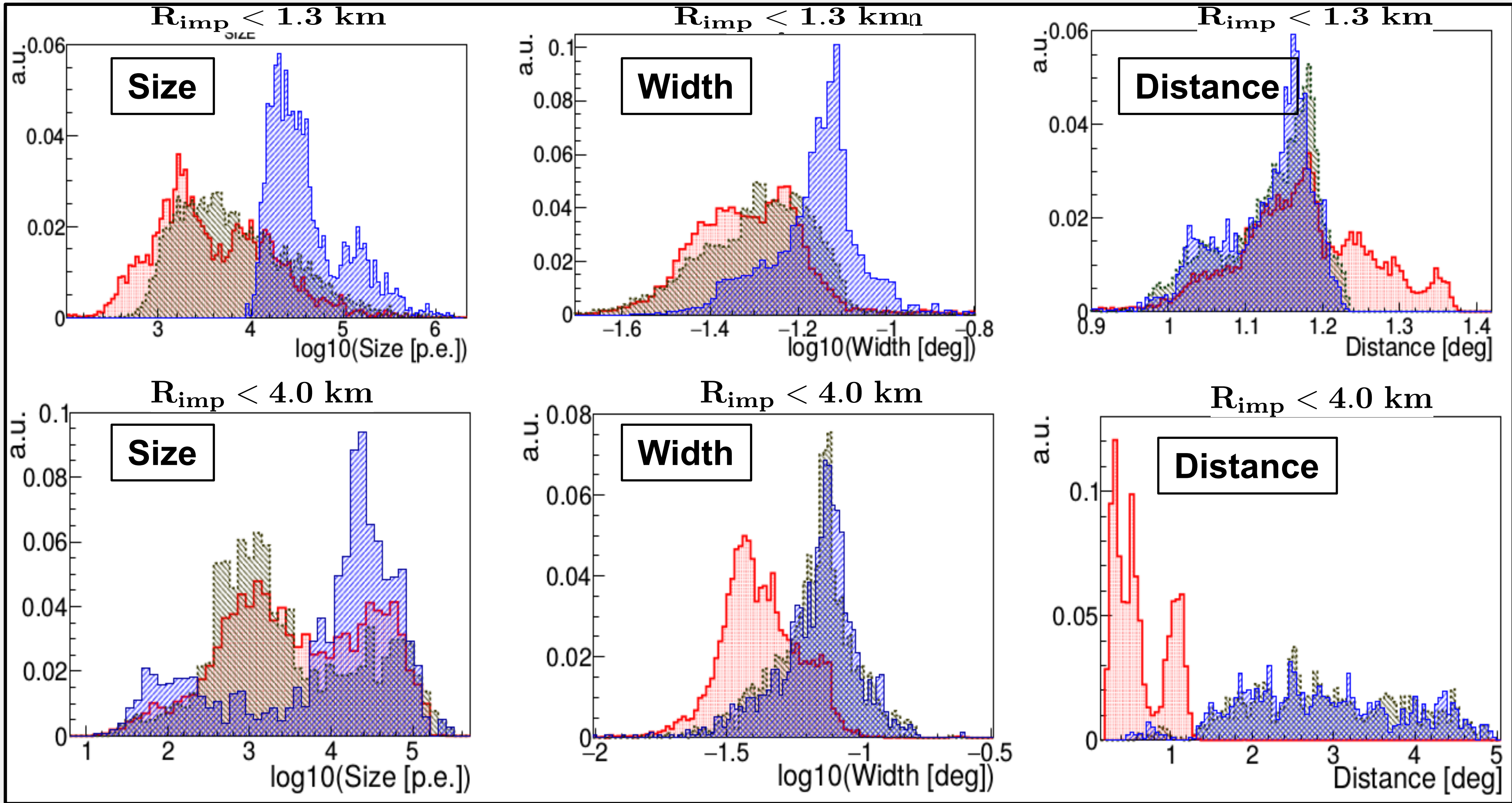
SIZE parameter: the total amount of detected light (in p.e.) in all camera pixels

> Very good separation between SPS, unconverted photon and proton induced showers for small values of the shower impact distance

Hillas parameters: preliminary results

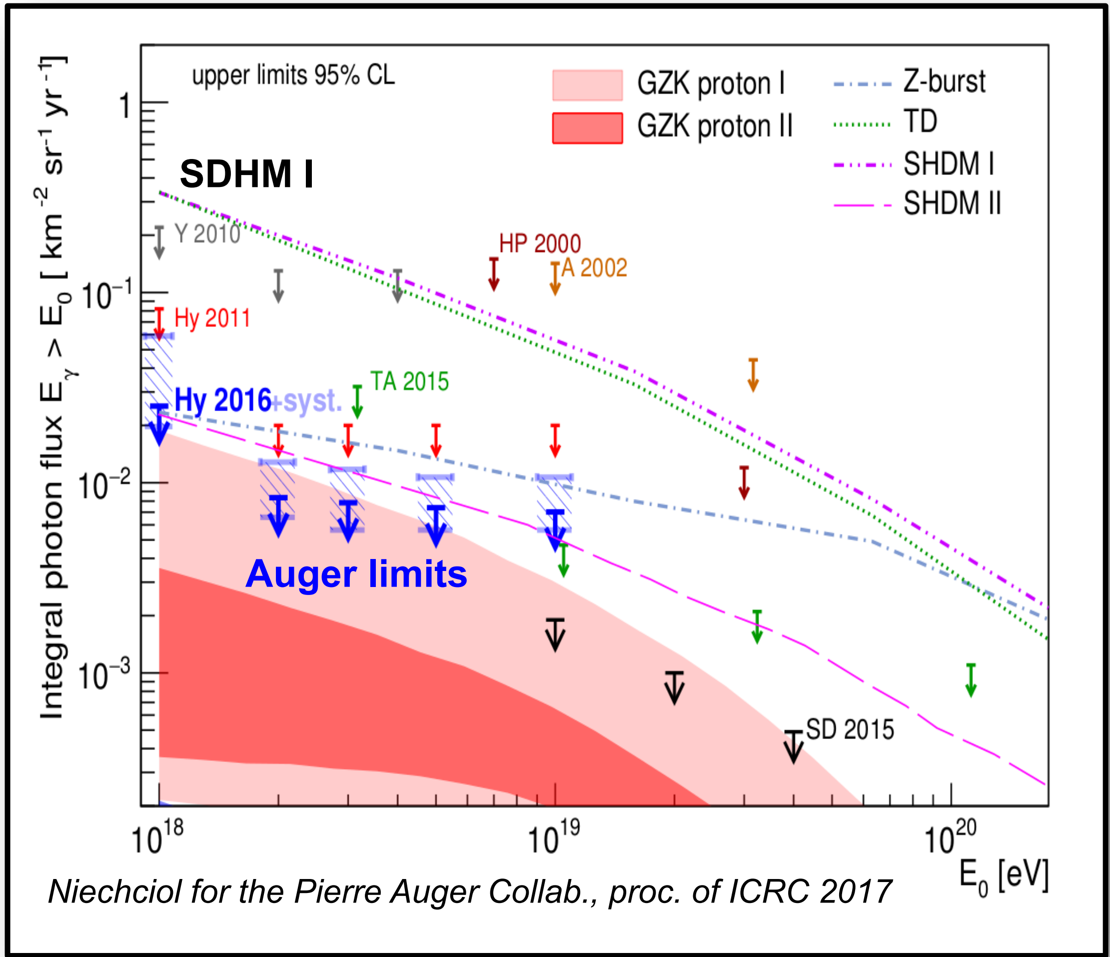
Top: R_{IMP}< 1.3 km ; bottom R_{IMP}< 4 km

SPS — PROTON — PHOTON —



> Potential for **event by event discrimination** for different impact distances R_{IMP} range
→ cut on multivariate analysis could allow discrimination with low statistics (how many events do we need/expect ?).

Event rate



> Event rate

$$\mathbf{N} = \phi(\mathbf{E} > \mathbf{E_0}) \times \mathbf{A} \times 4\pi$$

with $\mathbf{A} = \pi \mathbf{R}^2_{\mathbf{imp}}$ and $\mathbf{E_0} = 40$ EeV

$R_{imp} = 4$ km

a) Assuming flux from SHDM I model

$$\mathrm{N_{EXP}} = 0.002 \text{ events/hour}$$
$$\sim 17 \text{ events/year}$$

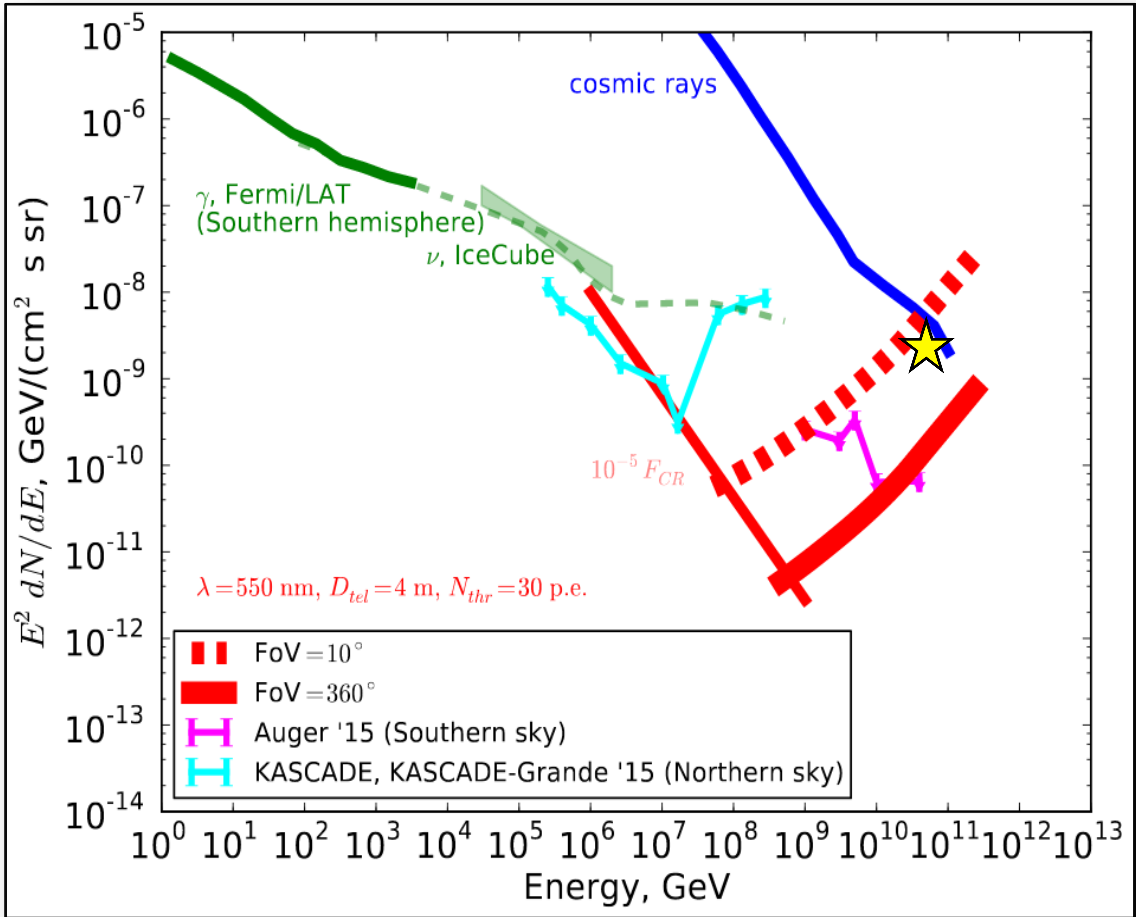
b) Flux at level of Auger limits:

$$\mathrm{N_{EXP}} = 0.00005 \text{events/hour}$$

Large time exposerue is needed !

> … but still possible during a few IACTs observation periods

Preliminary SPS sensitivity



> First estimation ☆
... using method from
Neronov et al. (2016)

$$\mathbf{F_{min}} = \frac{\mathbf{E_0}}{\mathbf{A\Omega_k T_{exp}}\kappa}$$

with

Number of CTA telescopes

$$\mathbf{A} = \pi \mathbf{R^2_{imp}} \times \mathbf{19}$$

in extended observation mode

$$\kappa = \mathbf{0.1} \quad \mathbf{T_{exp}} = \mathbf{1\ year}$$

$$\mathbf{R_{imp}} = \mathbf{4\ km}$$

$$\mathbf{F_{min}} = \mathbf{1.33 \times 10^{-9}\ [GeV cm^{-2} s^{-1} sr^{-1}]}$$

> Study of SPS type C and D would allow to go to lower energies (10^7-10^9 GeV) and reach more competitive sensitivity to Auger photon limits.

Summary and Outlook

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

> Possible discrimination between SPSs and CRs based on a multivariate analysis of Hillas parameters and nearly horizontal observations with IACTs.

> IACTs sensitivity to photons/SPS at large zenith angles can be comparable to Pierre Auger Observatory.
Study of SPS type C and D would allow to go lower in energy and reach better sensitivity.

> 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)

Thanks