# CREDO and gamma astronomy

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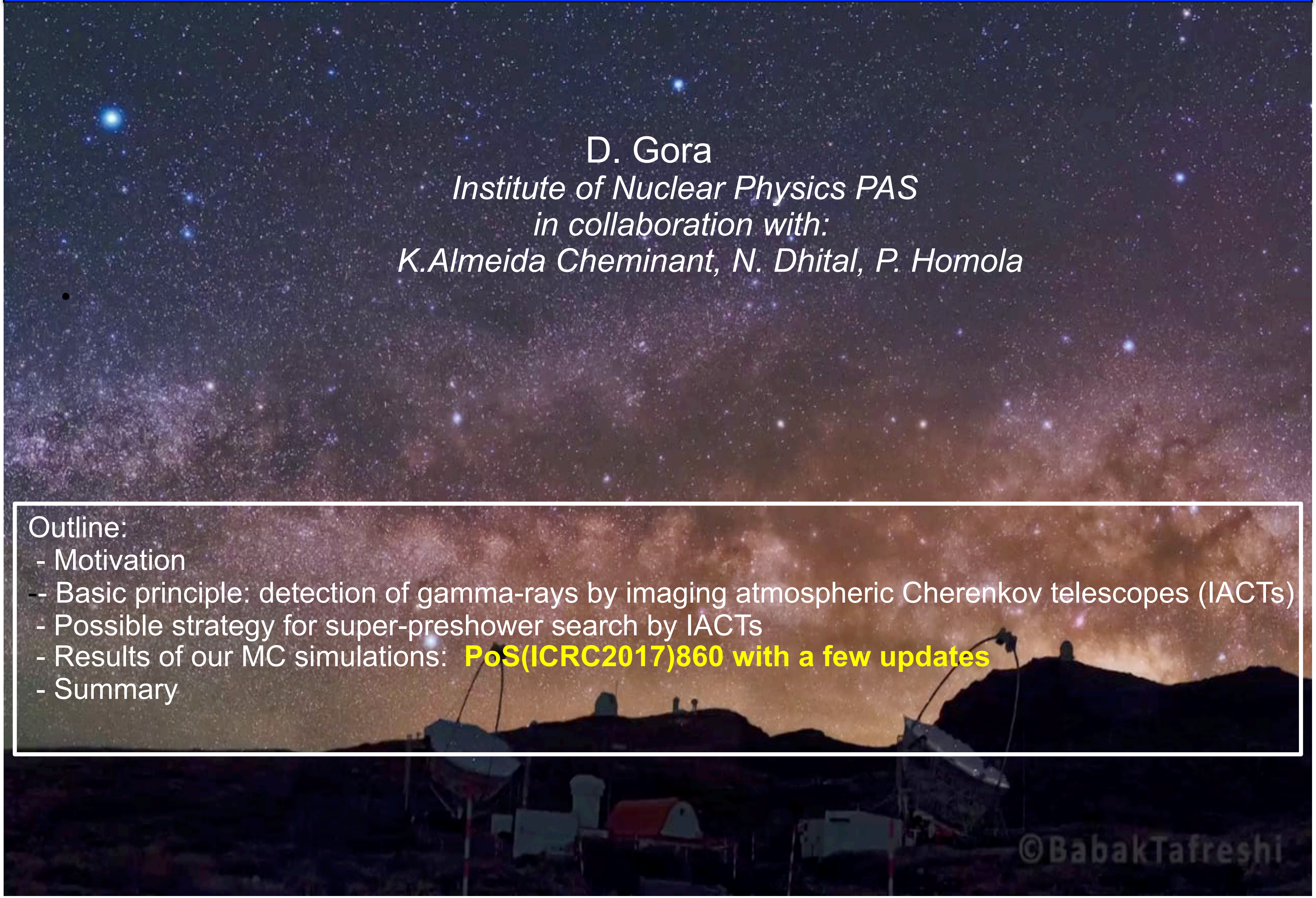
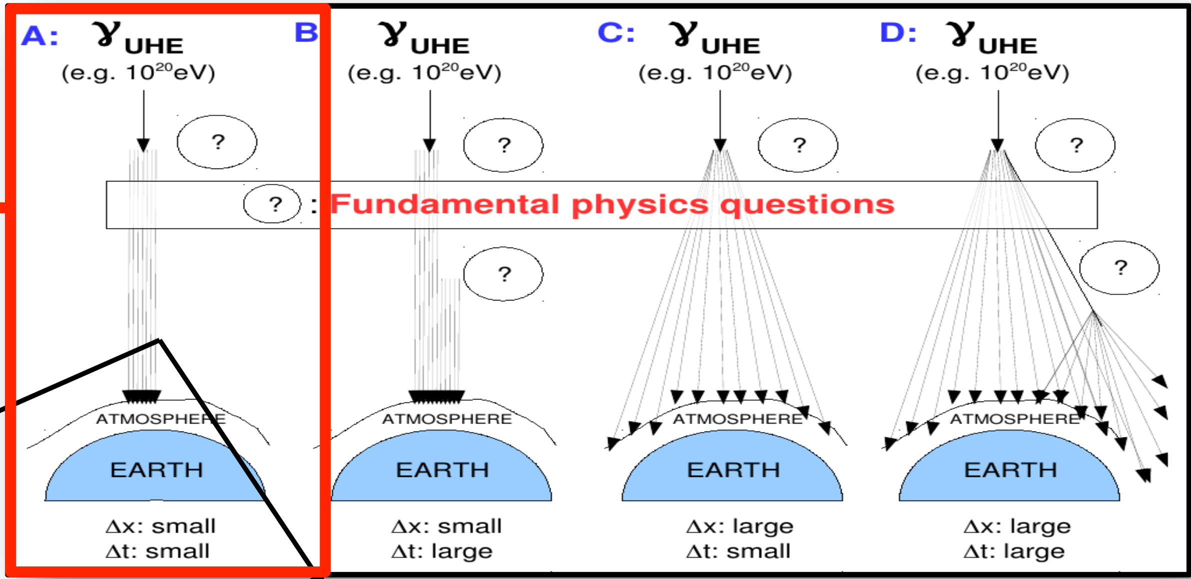
Outline:
- Motivation
- Basic principle: detection of gamma-rays by imaging atmospheric Cherenkov telescopes (IACTs)
- Possible strategy for super-preshower search by IACTs
- Results of our MC simulations: **PoS(ICRC2017)860 with a few updates**
- Summary

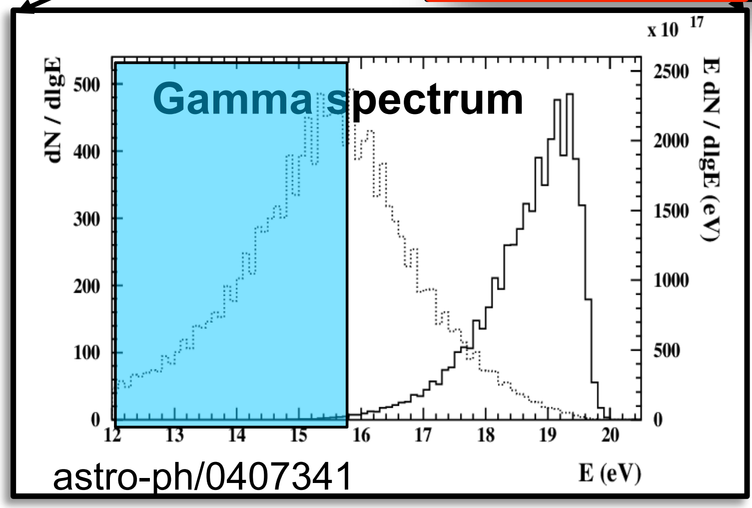


# Introduction

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

This talk



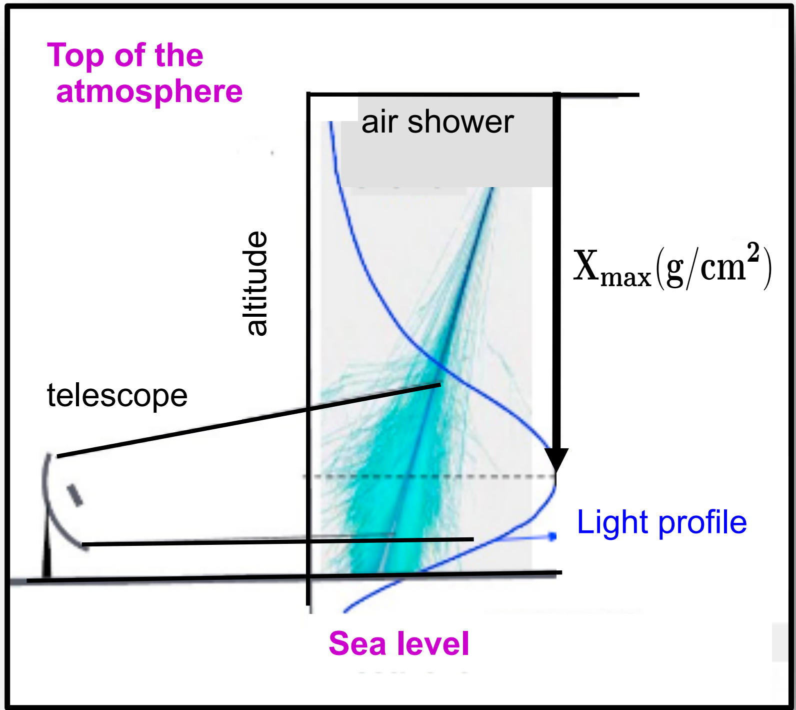



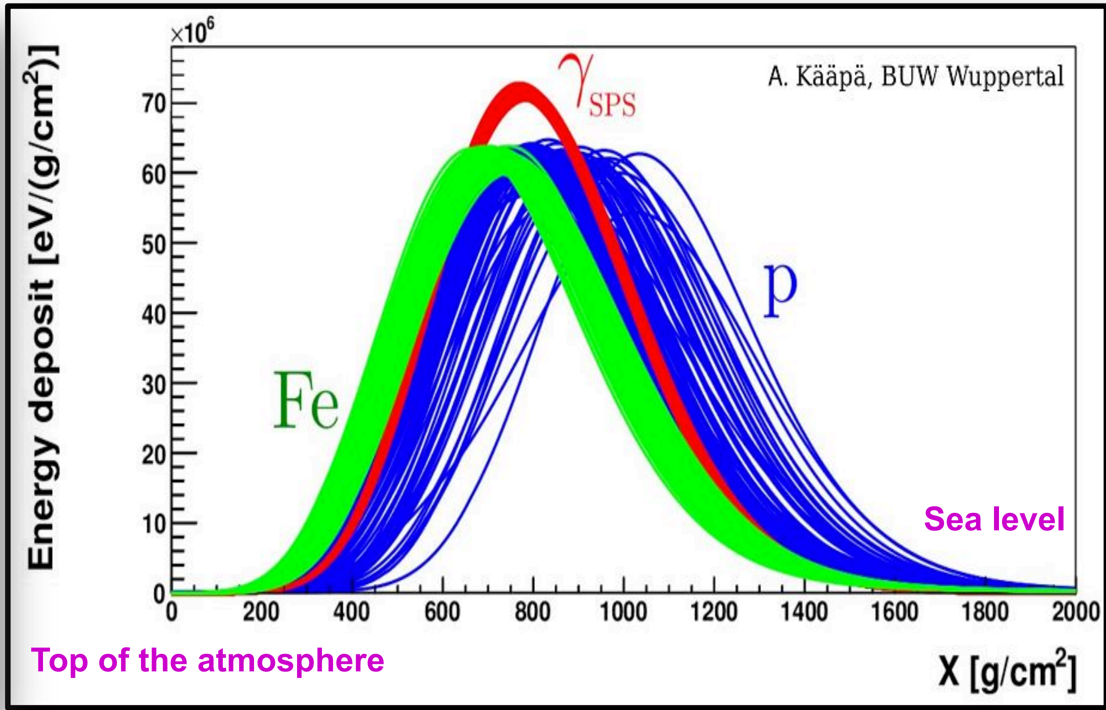

Interesting energy range for Cherenkov telescopes

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

# Introduction

> Existing techniques can have a problem with distinguishing SPS induced showers from hadronic shower induced by cosmic-rays.



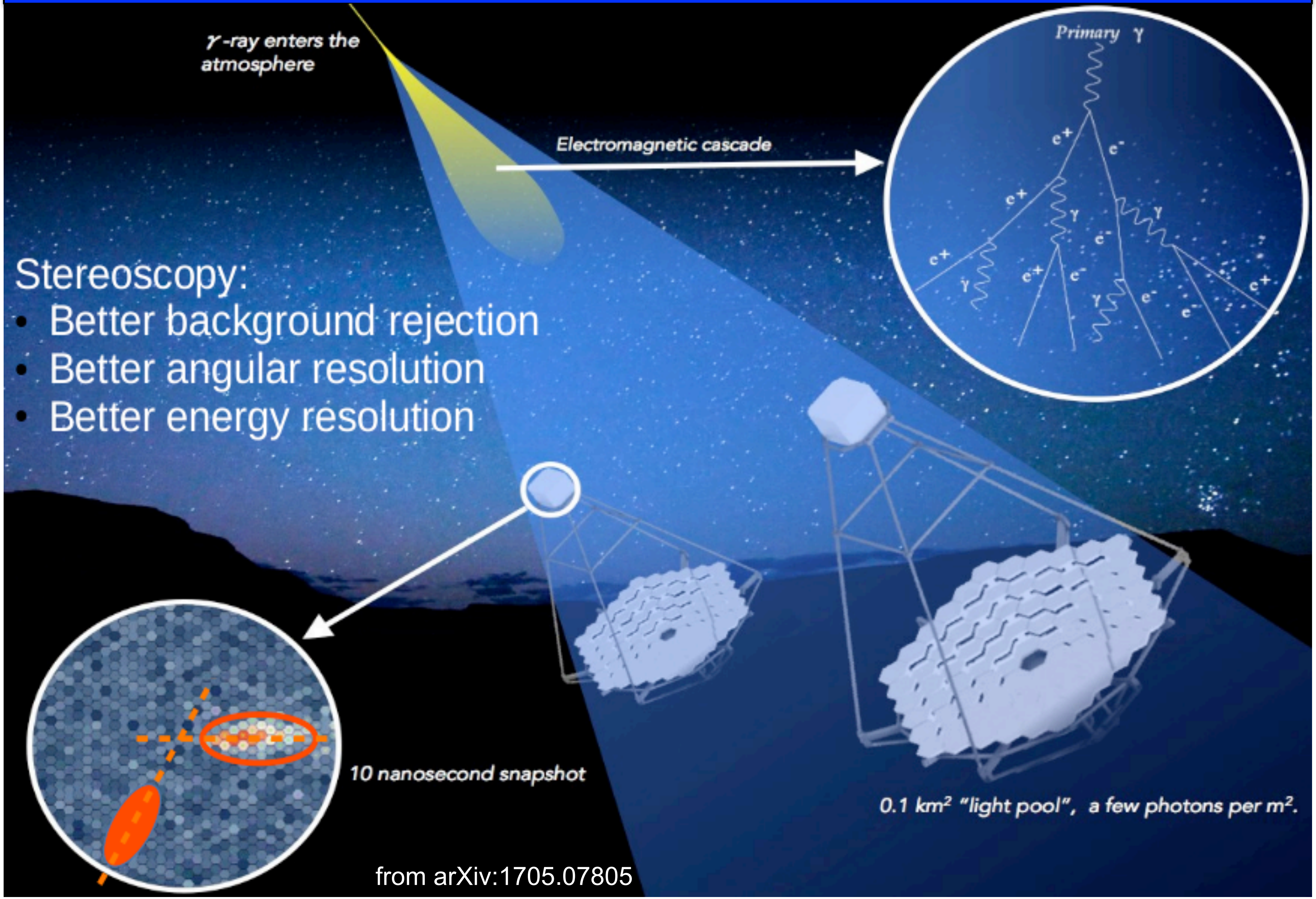




**$X_{max}$ : atmospheric depth of shower maximum development**

> $X_{max}$ is one of main parameters used in UHECR research to study the mass composition, it is prudent to perform the UHE photon search using an alternative approach for a better inference on the mass

Imaging Atmospheric Cherenkov Telescopes (IACTs)

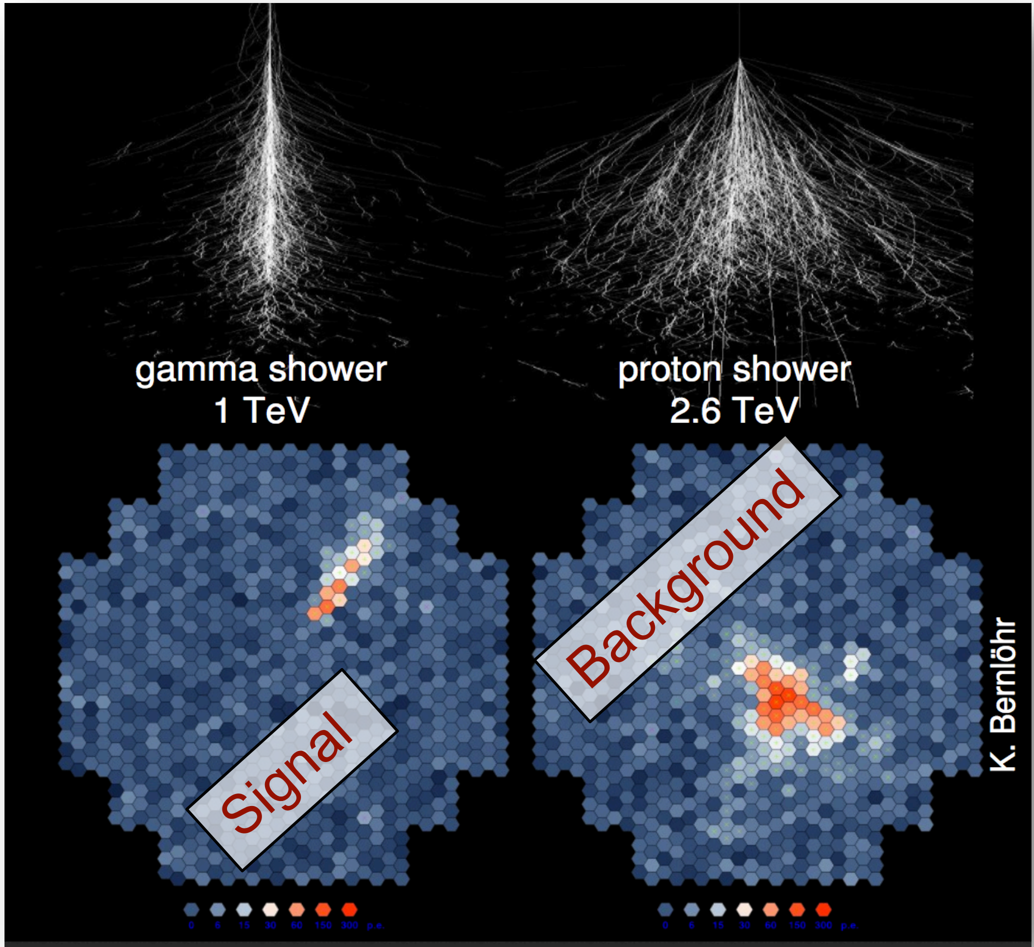
# Basic principle: detection of high energies gamma-rays




from arXiv:1705.07805

# Gamma-hadron separation

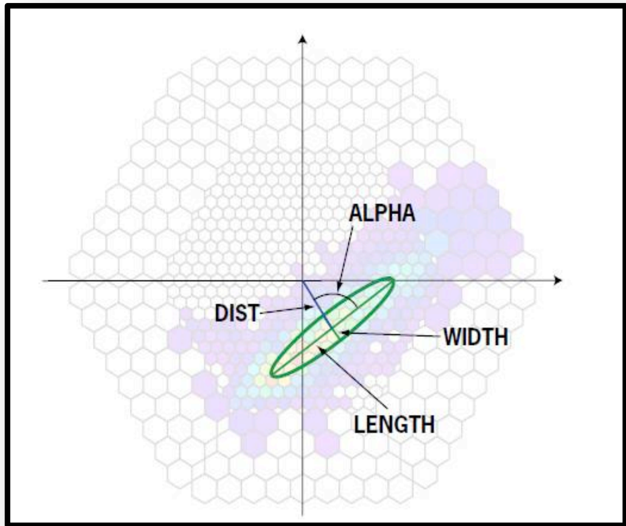
> **Background reduction by image shape analysis**
... Cosmic Rays main background for Cherenkov astronomy




> *Protons create hadronic showers with irregular images*

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

> Hillas parameters:

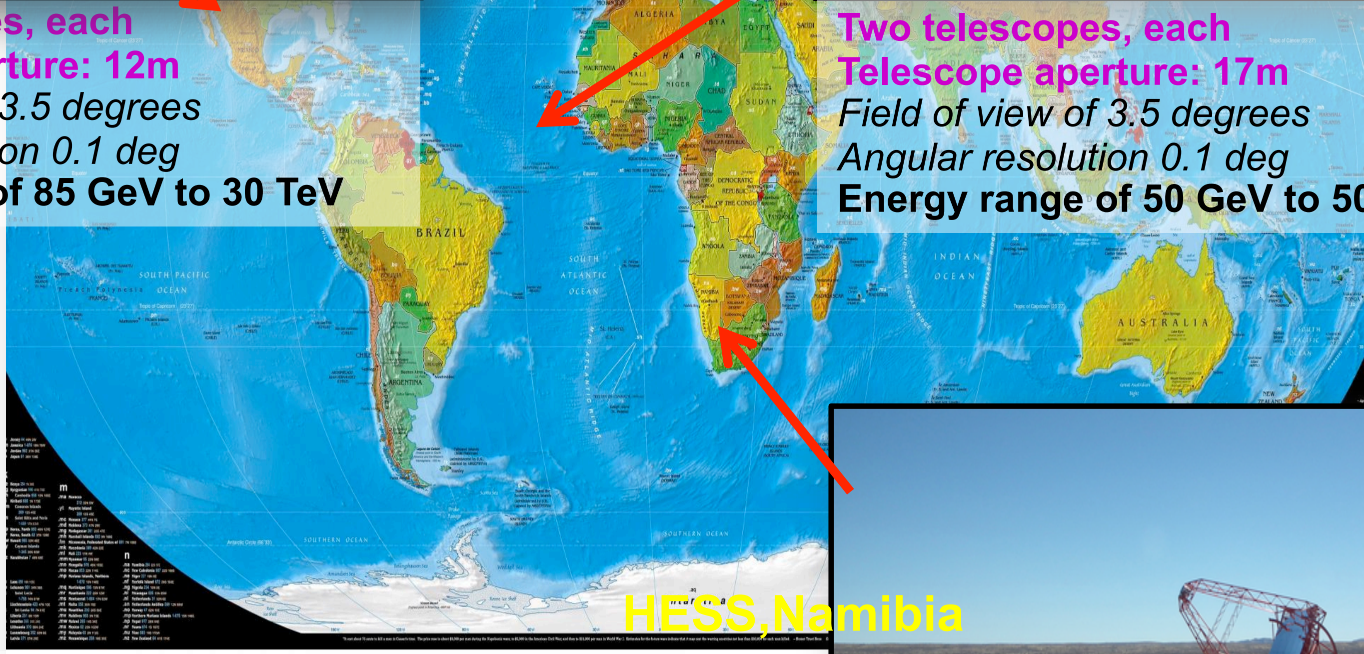



A.M. Hillas,Nucl. Phys. Proc. Suppl.52B (1997) 29

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**

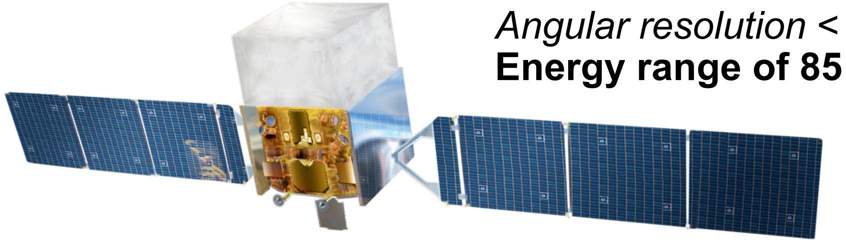
HESS,Namibia

**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**

# Other players

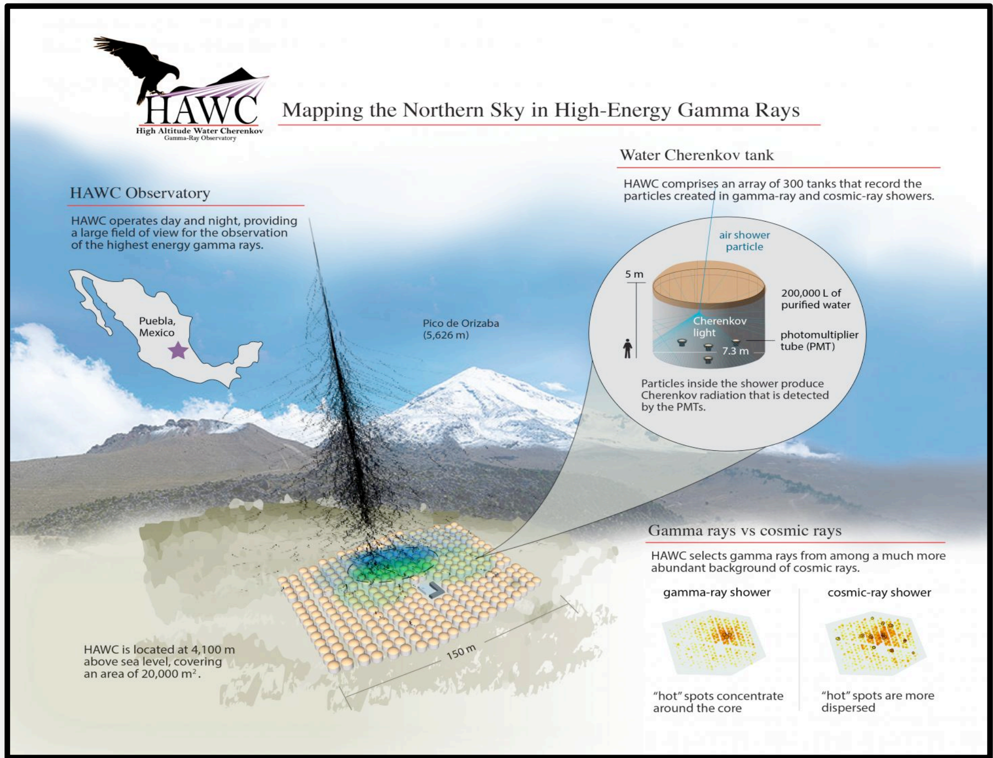
> Satelites; Fermi-Lat, Agille ...

*Field of view ~20% of the sky at any time*
*Angular resolution* < 0.15° (>10 GeV), 5.8° (100 MeV)
**Energy range of 85 GeV to 30 TeV**

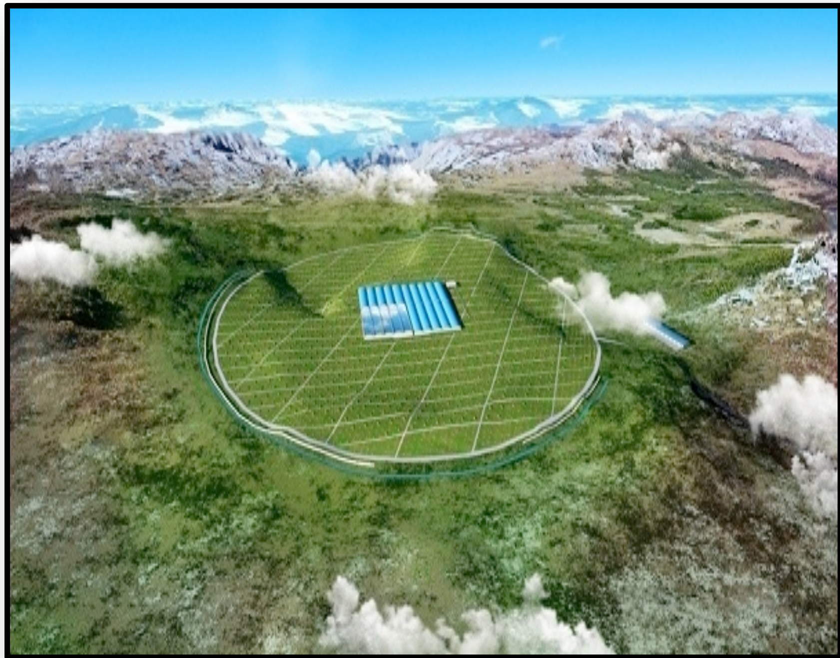


> The High-Altitude Water Cherenkov Observatory (HAWC)

*Field of view 2π sky coverage*
*Angular resolution ~ 0.5 deg*
**Energy range of 1 TeV to 100 TeV**

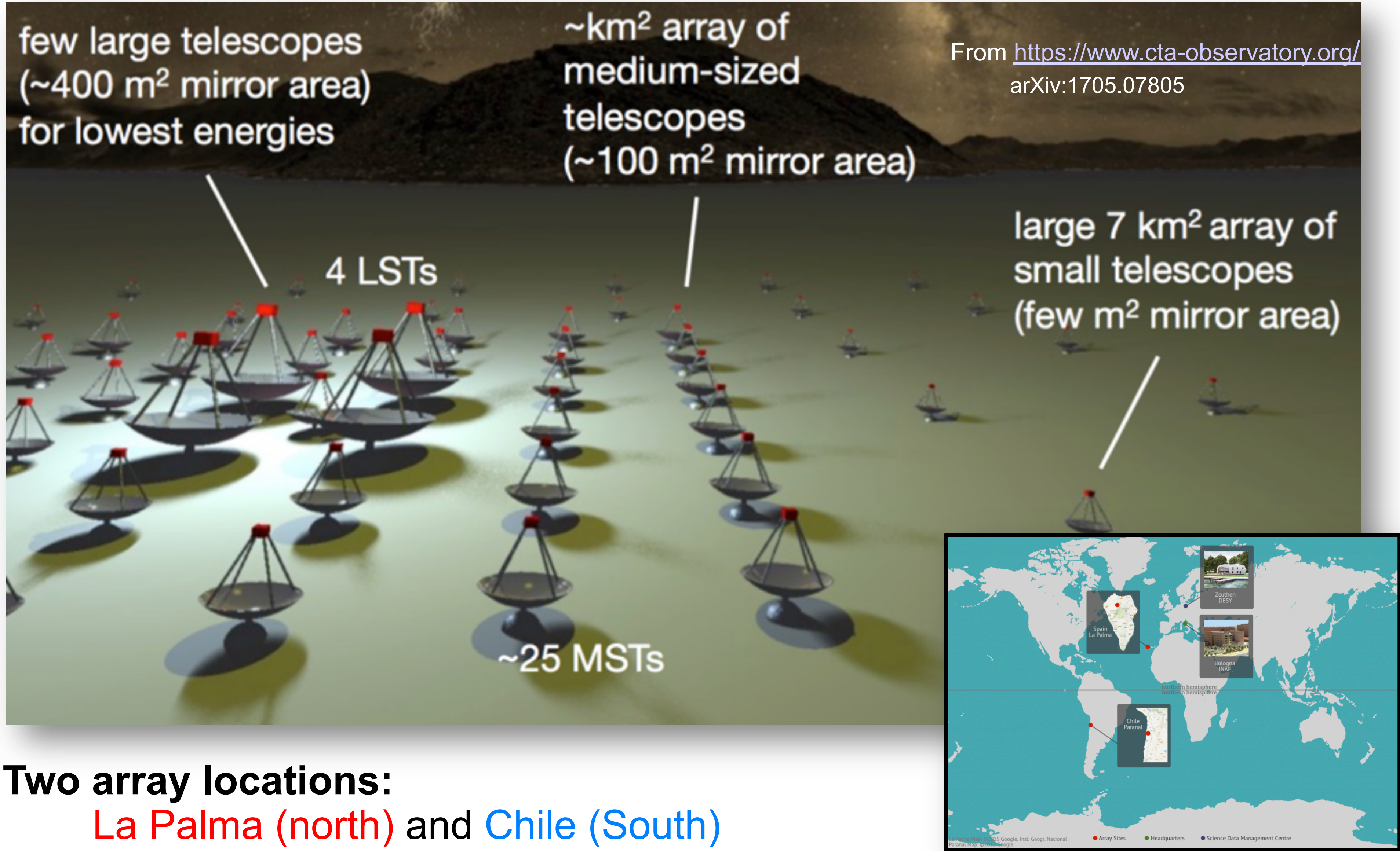



> Large High Altitude Air Shower Observatory (LHASO) Sichuan,China, 4410 asl.



# The next generation Cherenkov telescopes observatory

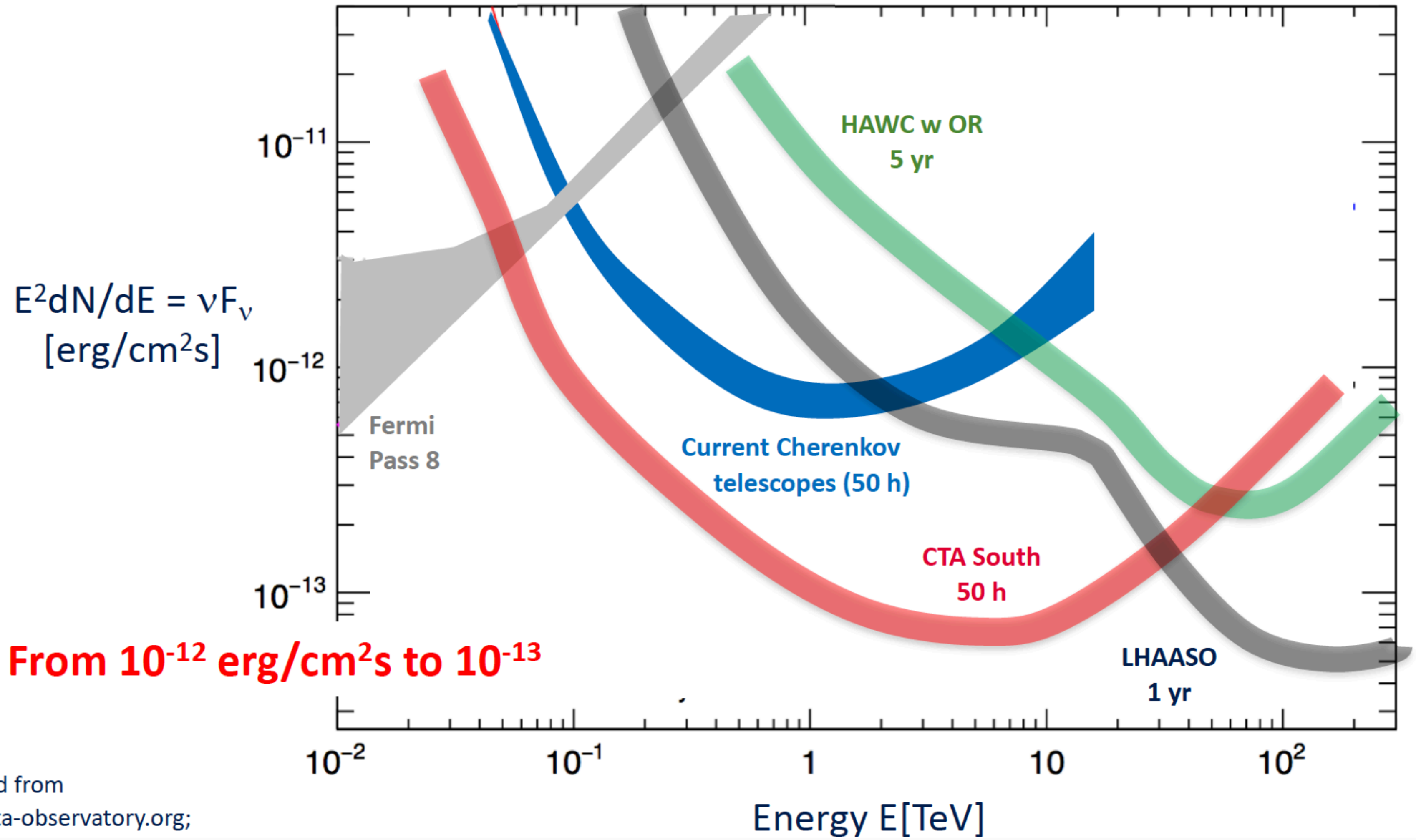
## Cherenkov Telescope Array (CTA)




**Two array locations:**

La Palma (north) and Chile (South)

# Energy flux sensitivity




**From $10^{-12}$ erg/cm²s to $10^{-13}$**

adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

CREDO and gamma-ray astronomy

... example of search for SPS with IACTs

# Inclined showers

> … but you can increase sensitivity for 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

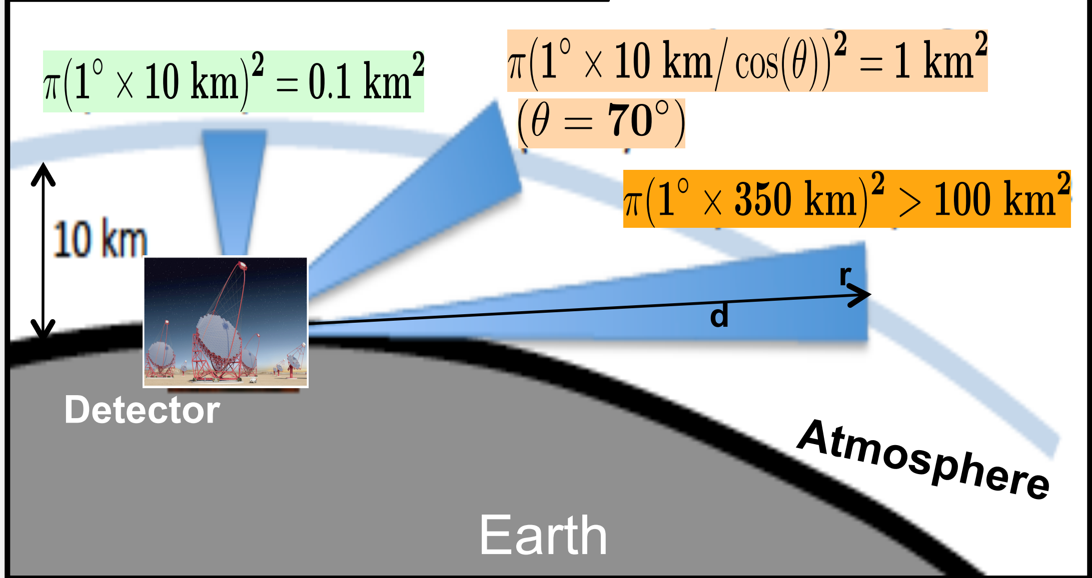
due to large thickness of the atmosphere,
( ~1000 km at ZA=87 deg),
shower images are almost inside a single pixel

**For IACTs with FOV=1 deg**

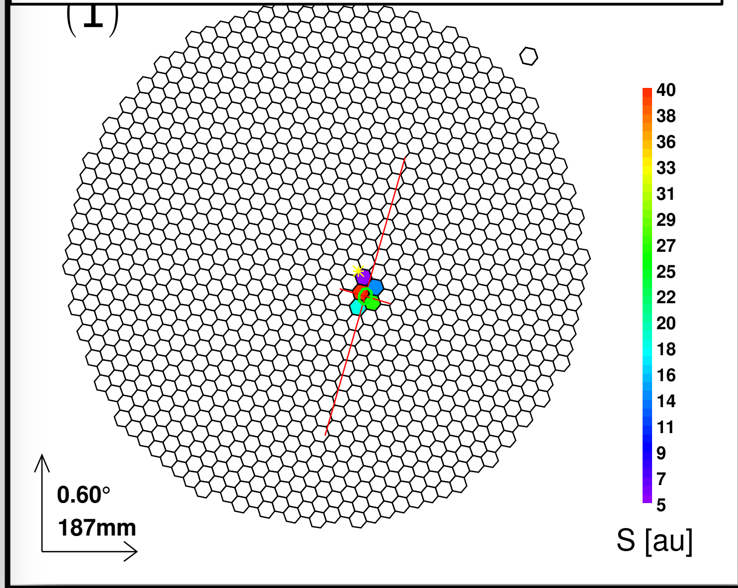
$$\pi(1^\circ \times 10\ \text{km})^2 = 0.1\ \text{km}^2$$

$$\pi(1^\circ \times 10\ \text{km}/\cos(\theta))^2 = 1\ \text{km}^2 \quad (\theta = 70^\circ)$$

$$\pi(1^\circ \times 350\ \text{km})^2 > 100\ \text{km}^2$$



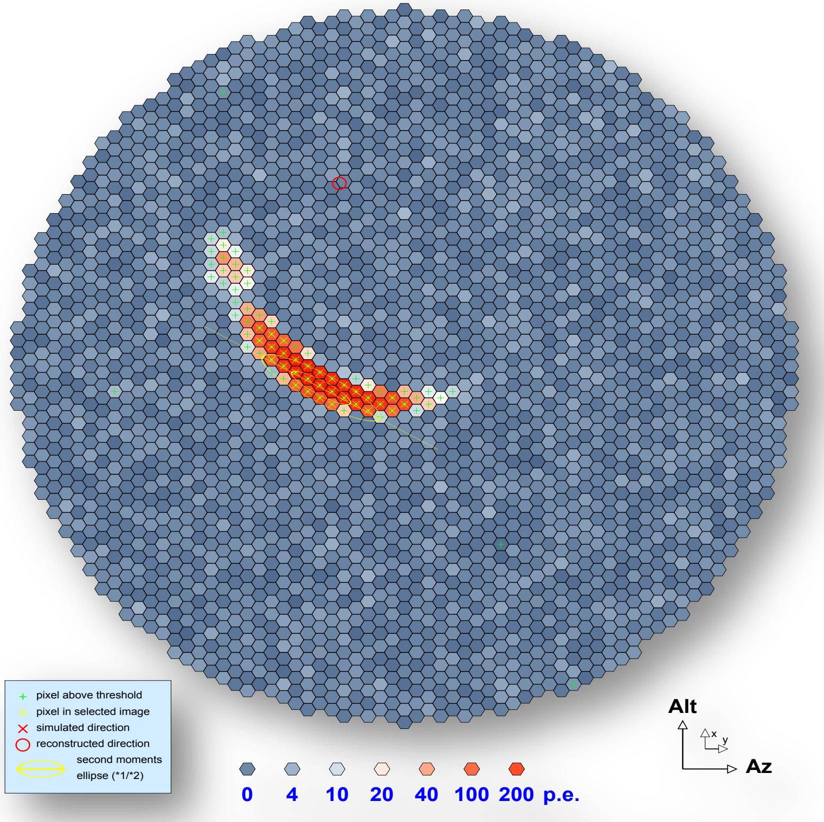

**1PeV proton, ZA=87 deg, MAGIC**



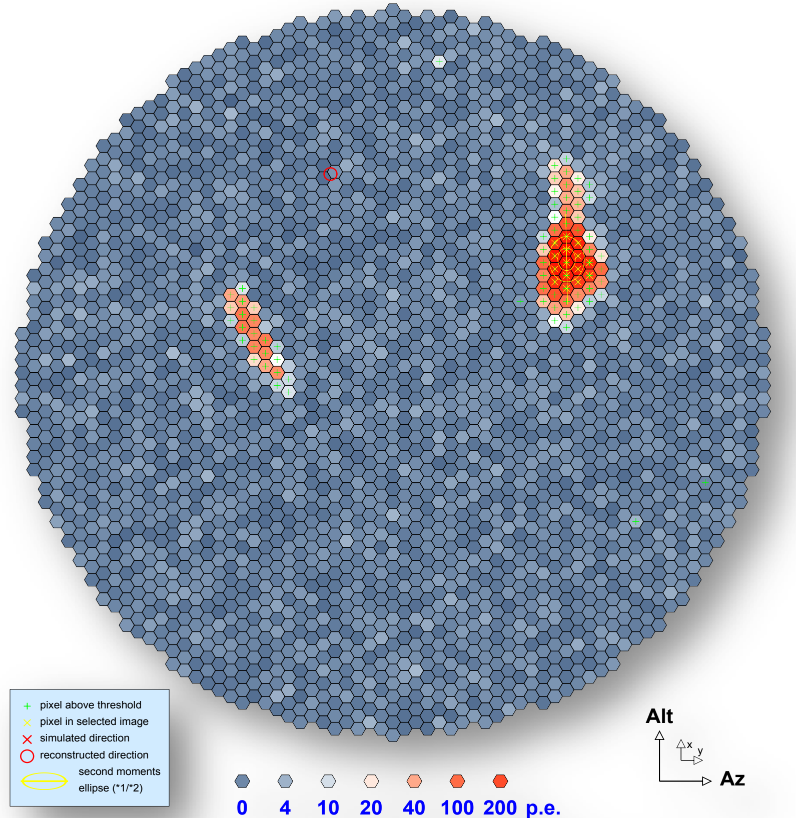

> However, we are working at ~ EeV energies not TeVs,
> so at these energies gamma/hadron separation can be recovered again

# Image for inclined SPS shower induced by 40 EeV photon

> Example of camera images for SPS primaries with E=40 EeV, θ=80 deg
  the first interaction pint about 400 km




Primary: gamma of 40000000.000 TeV energy at 100 m distance

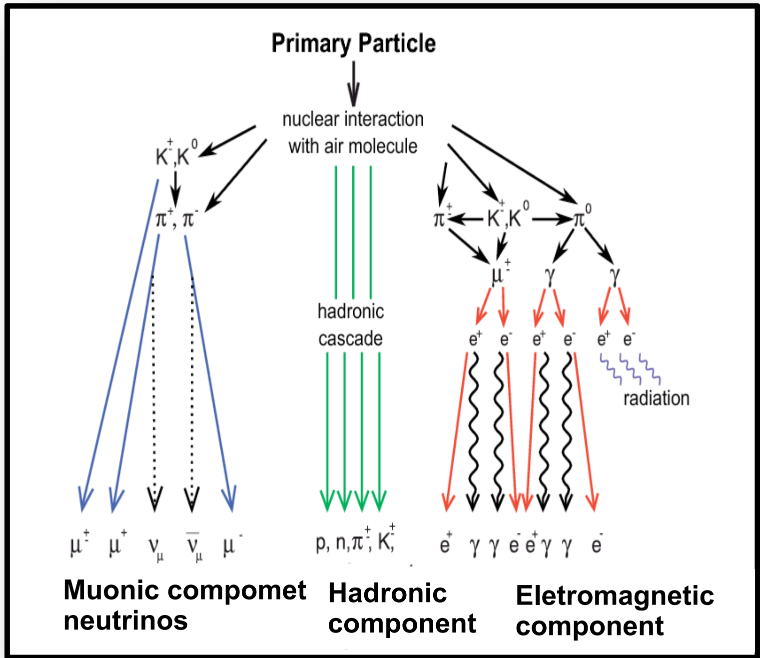



Primary: gamma of 40000000.000 TeV energy at 171 m distance

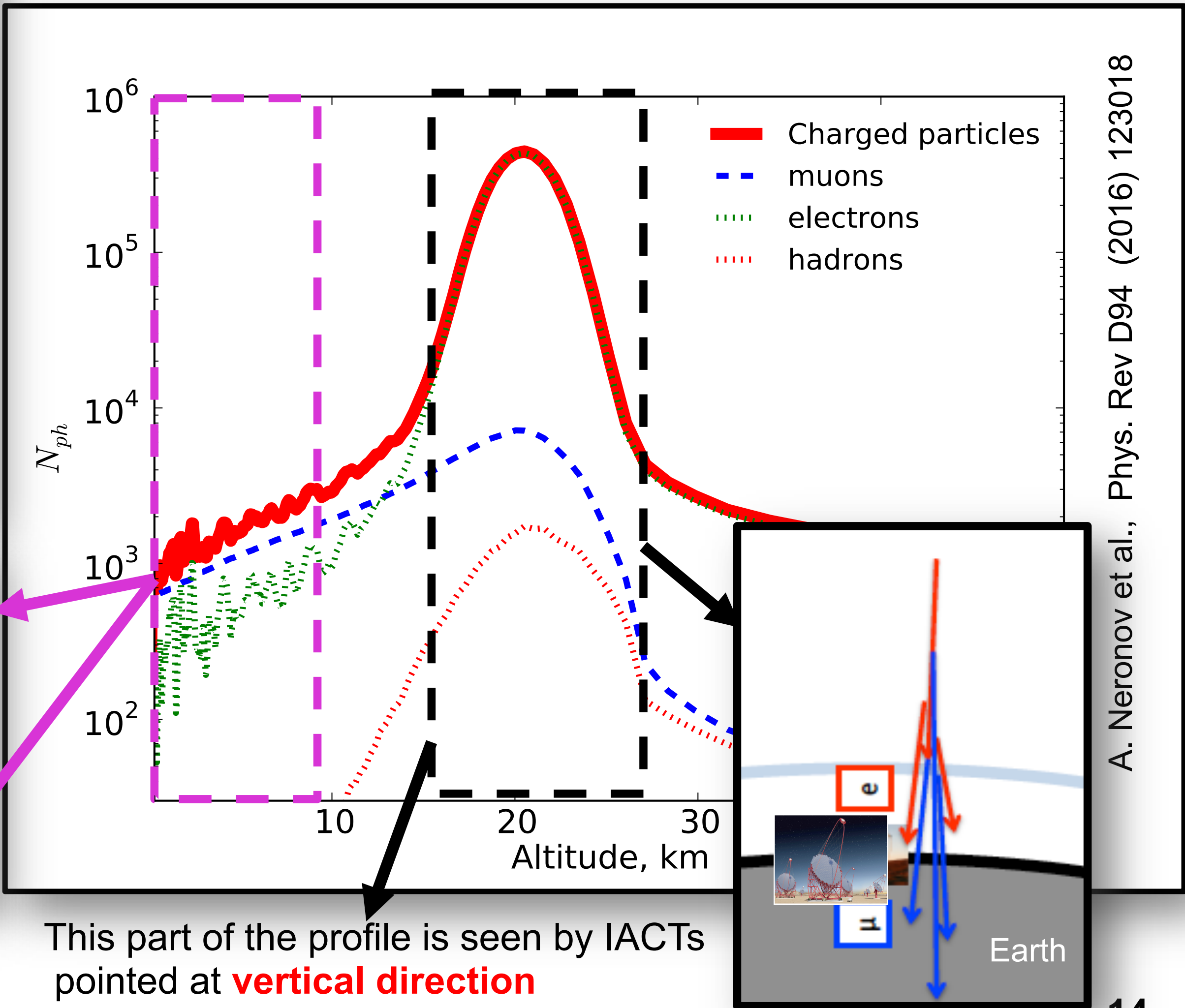
So even with existing facilities we can search for SPSs showers

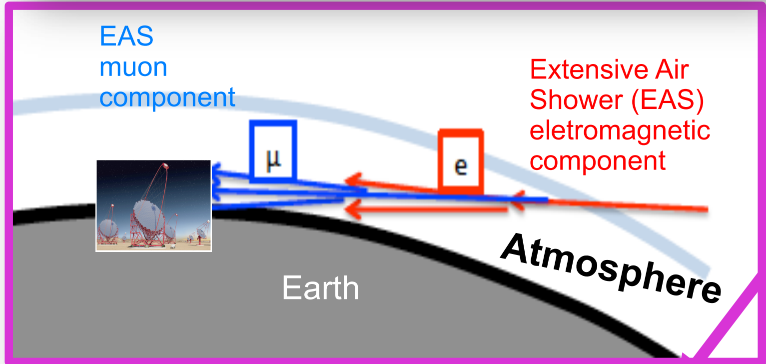
# Muon component of air shower

> 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**

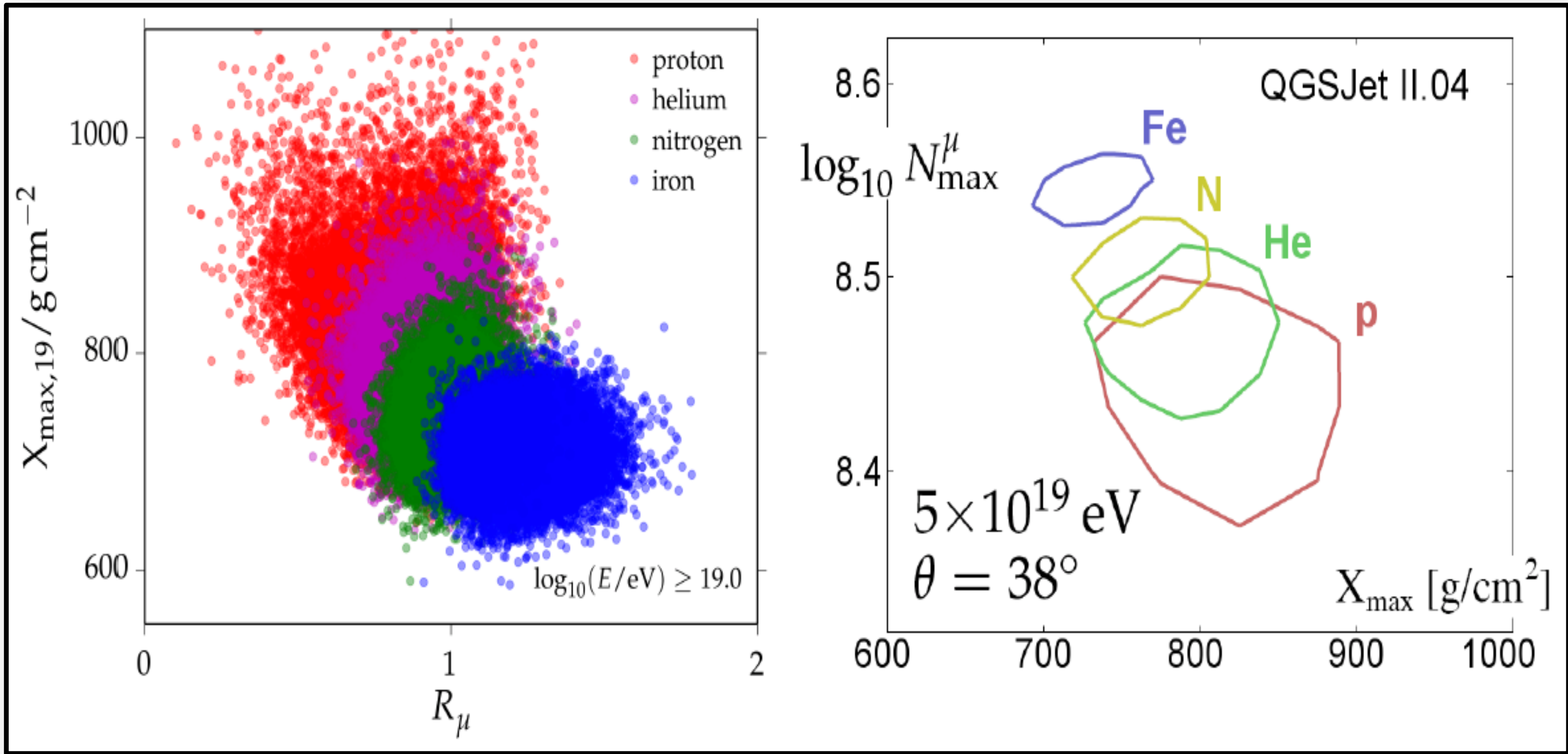



This part of the profile is seen by IACTs pointed at **horizontal direction**

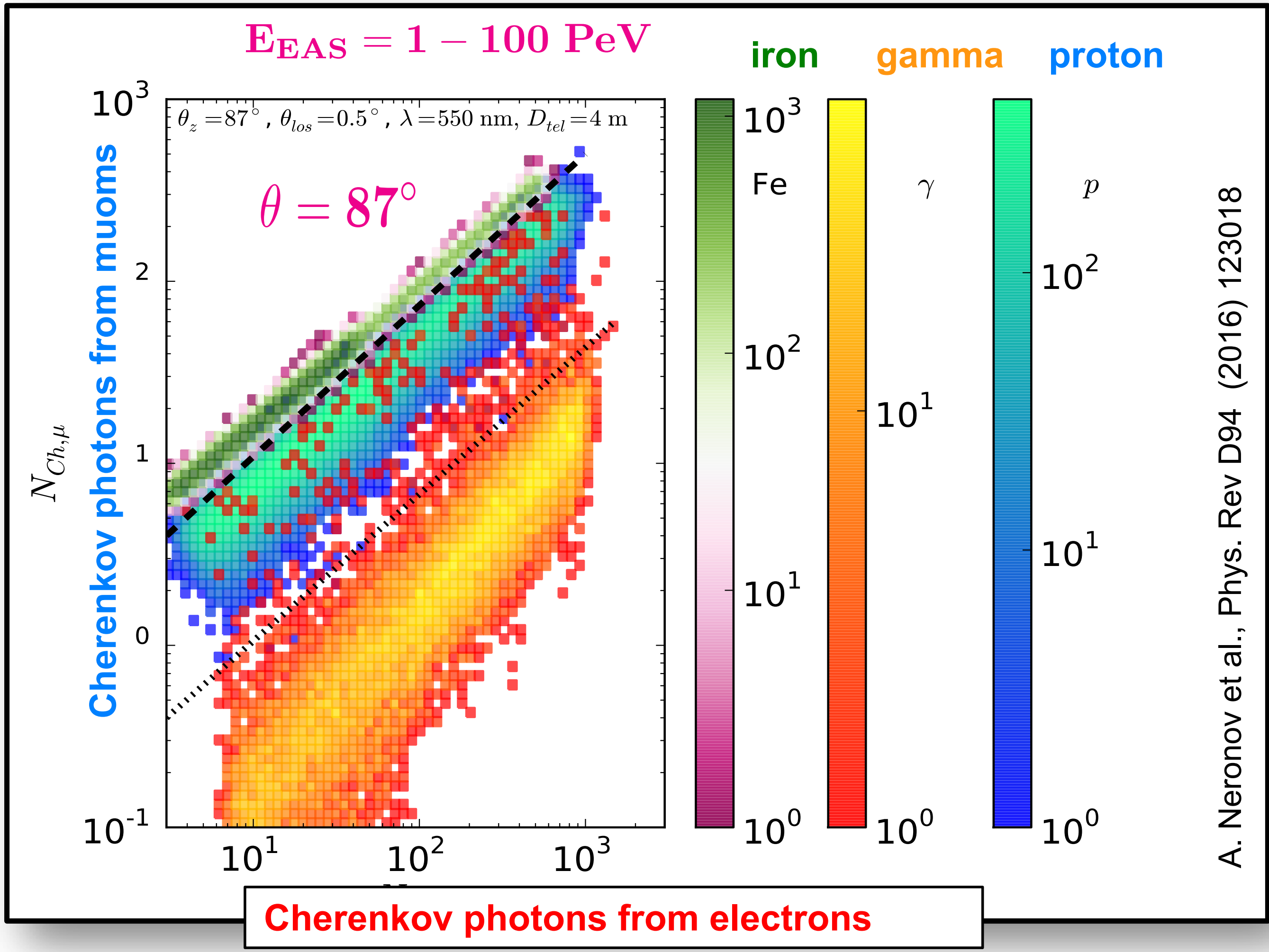
This part of the profile is seen by IACTs pointed at **vertical direction**

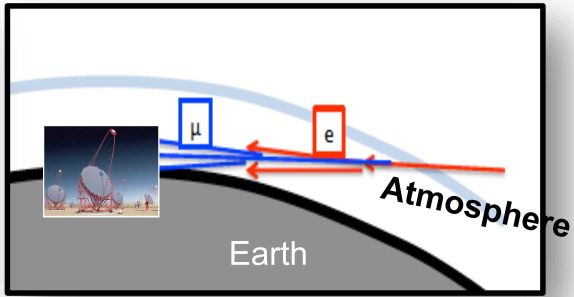
# Muon component of air shower



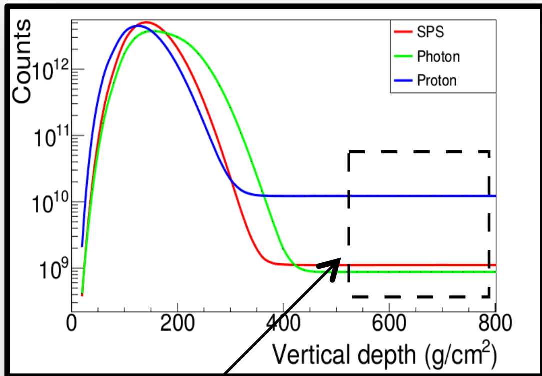
# Cherenkov light from muon component of air showers

> 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 ])




Distribution of Cherenkov photons for 40 EeV, θ=80 deg




Part seen when pointing telescope to the inclined directions

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

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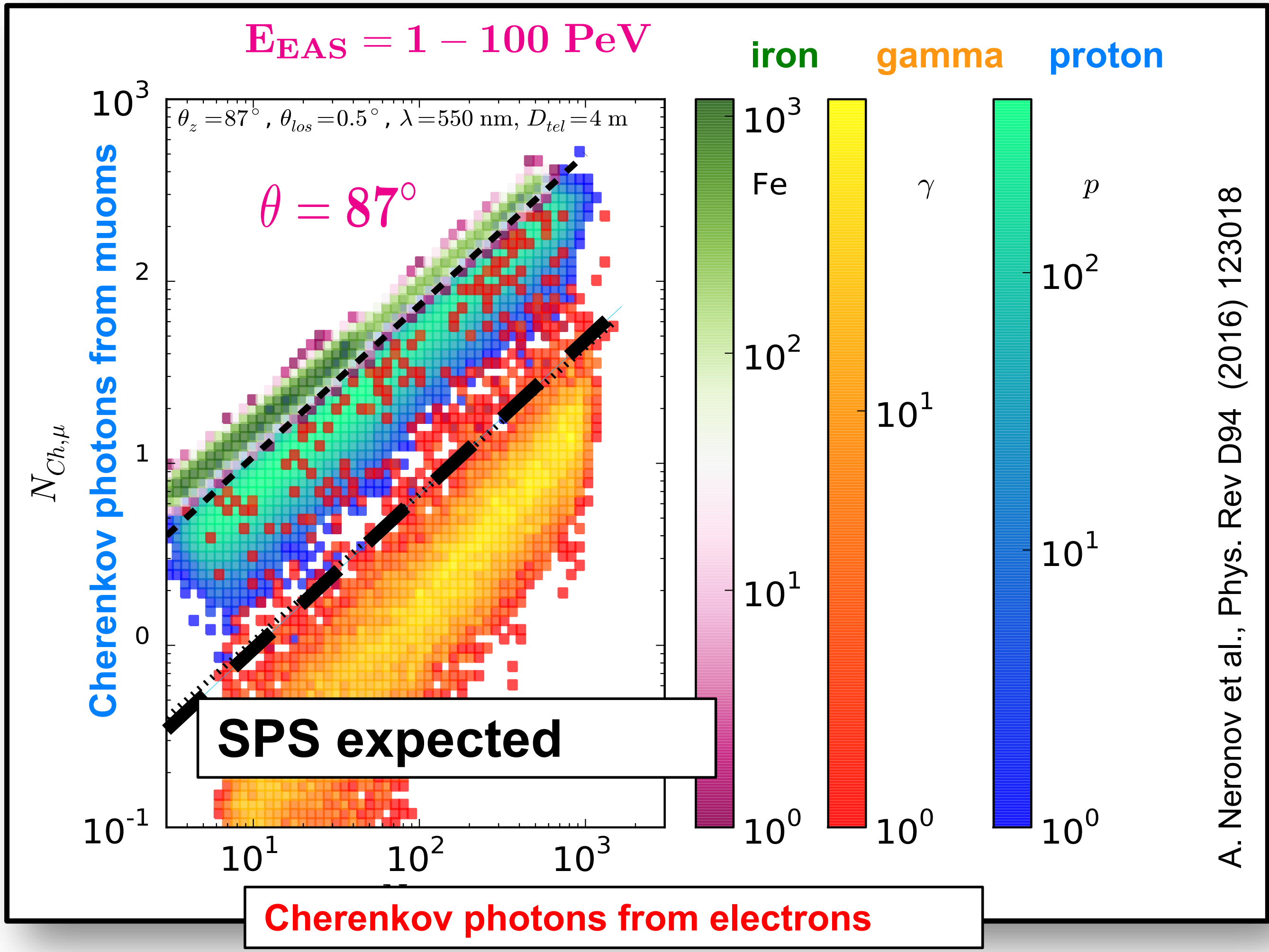


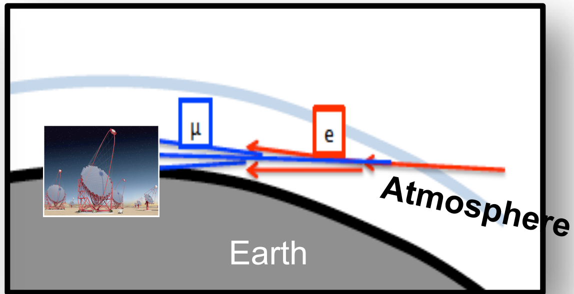


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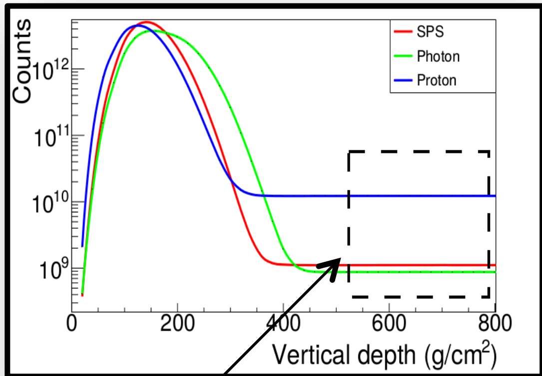
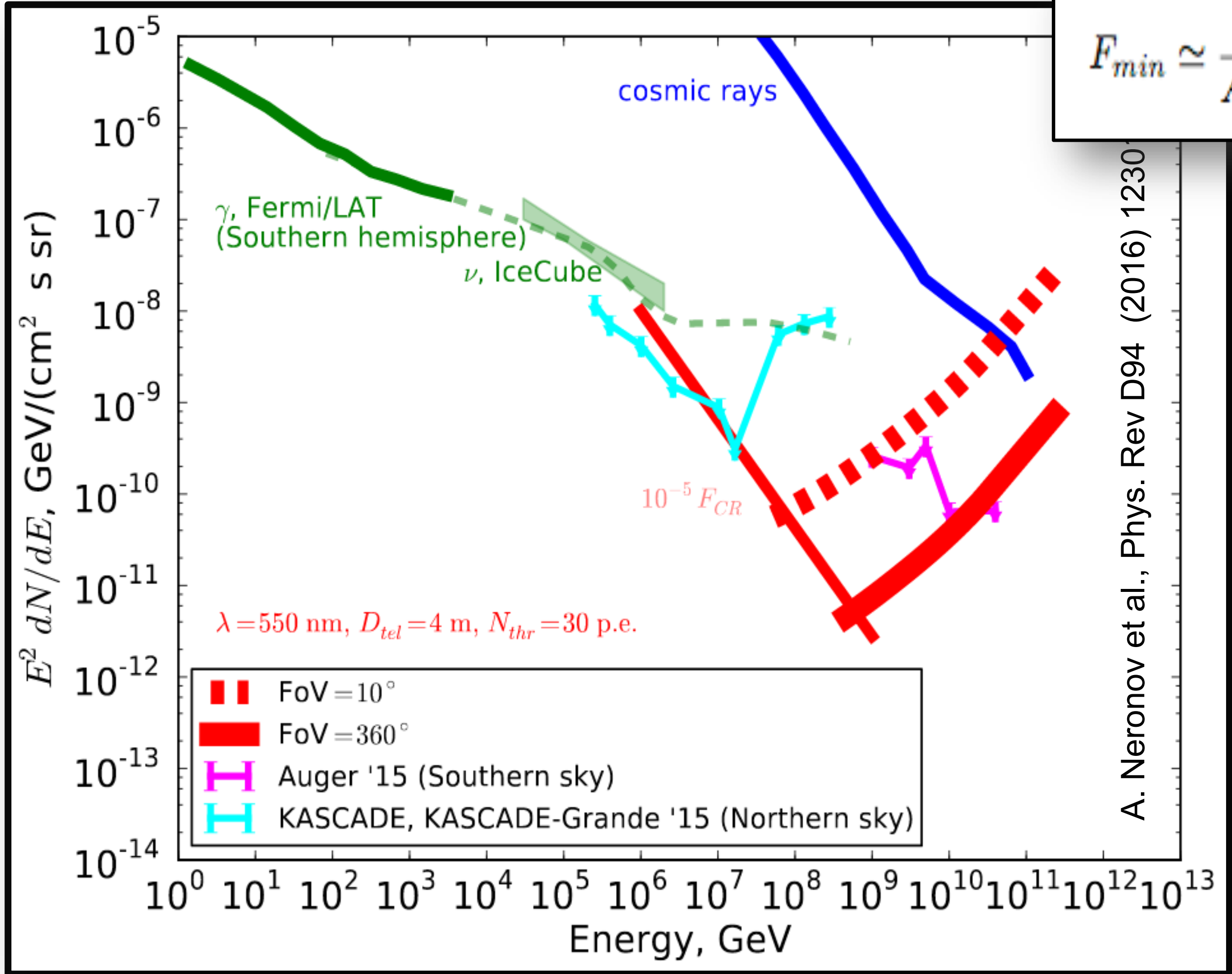



Part seen when pointing telescope to the inclined directions

> 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:**

$$\Omega \sim \pi(\alpha_{Ch} + \gamma_{Ch}^{-1})^2 \simeq 6\times10^{-3}$$

**Aperture:**

$$A \sim 2\pi r_{horizontal} H_{atm} \simeq 2\times10^4\ \mathrm{km}^2$$

**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.

... example of search for SPS with IACTs
(Monte Carlo results)

# Monte Carlo simulation chain

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

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

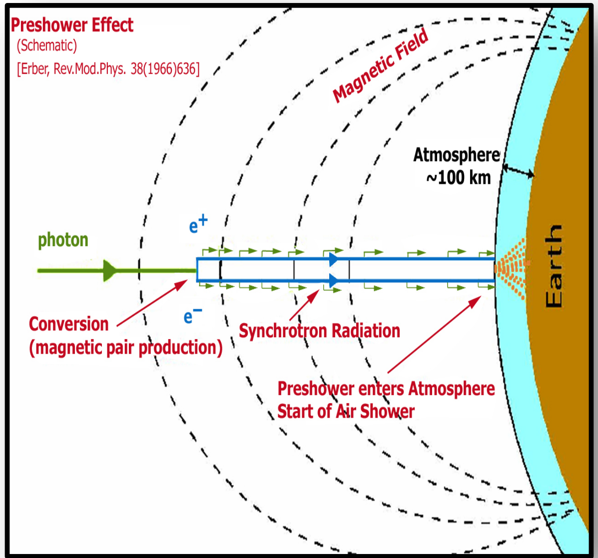
(3) Simulation of CTA responce

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

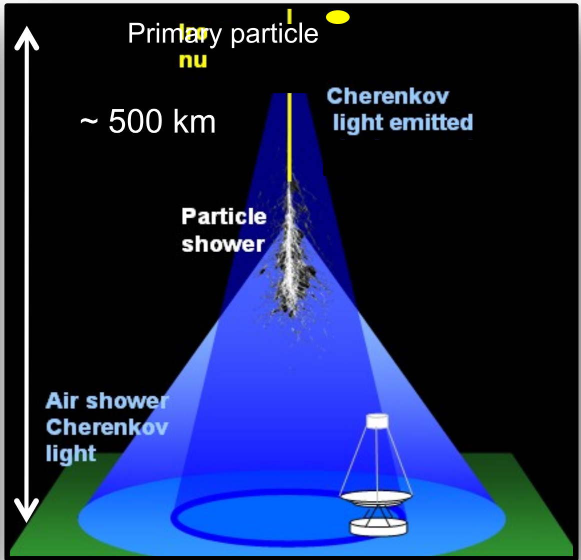
**PRESHOWER**
Homola et al., Computer Physics Commun. 184 (2005), 1468

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

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




**PRESHOWER** linked with **CORSIKA**




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

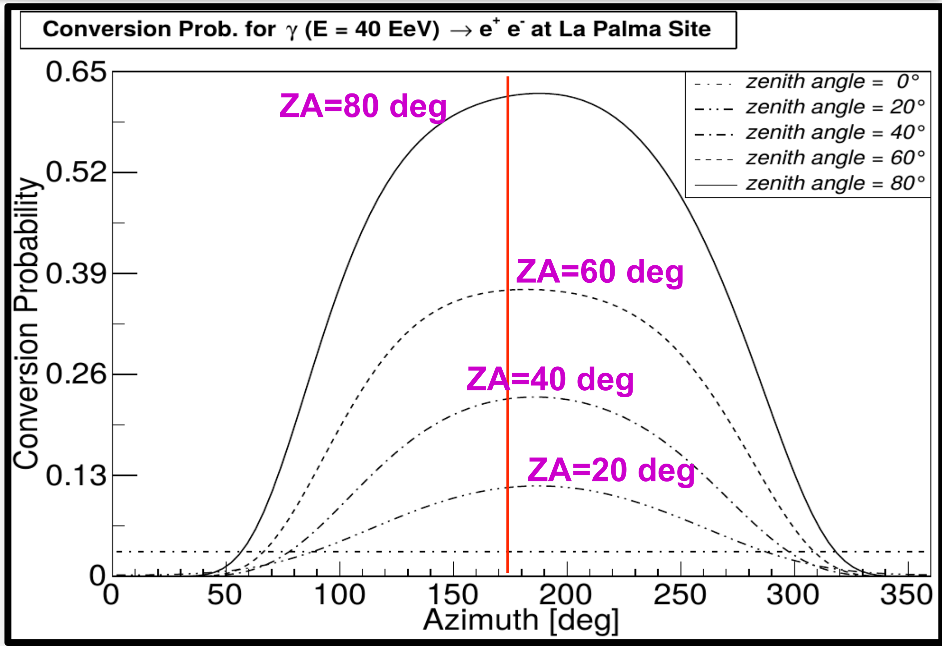

Miror optics/camera electronics simulations, with public ***Production-1* settings**

# Simulation conditions

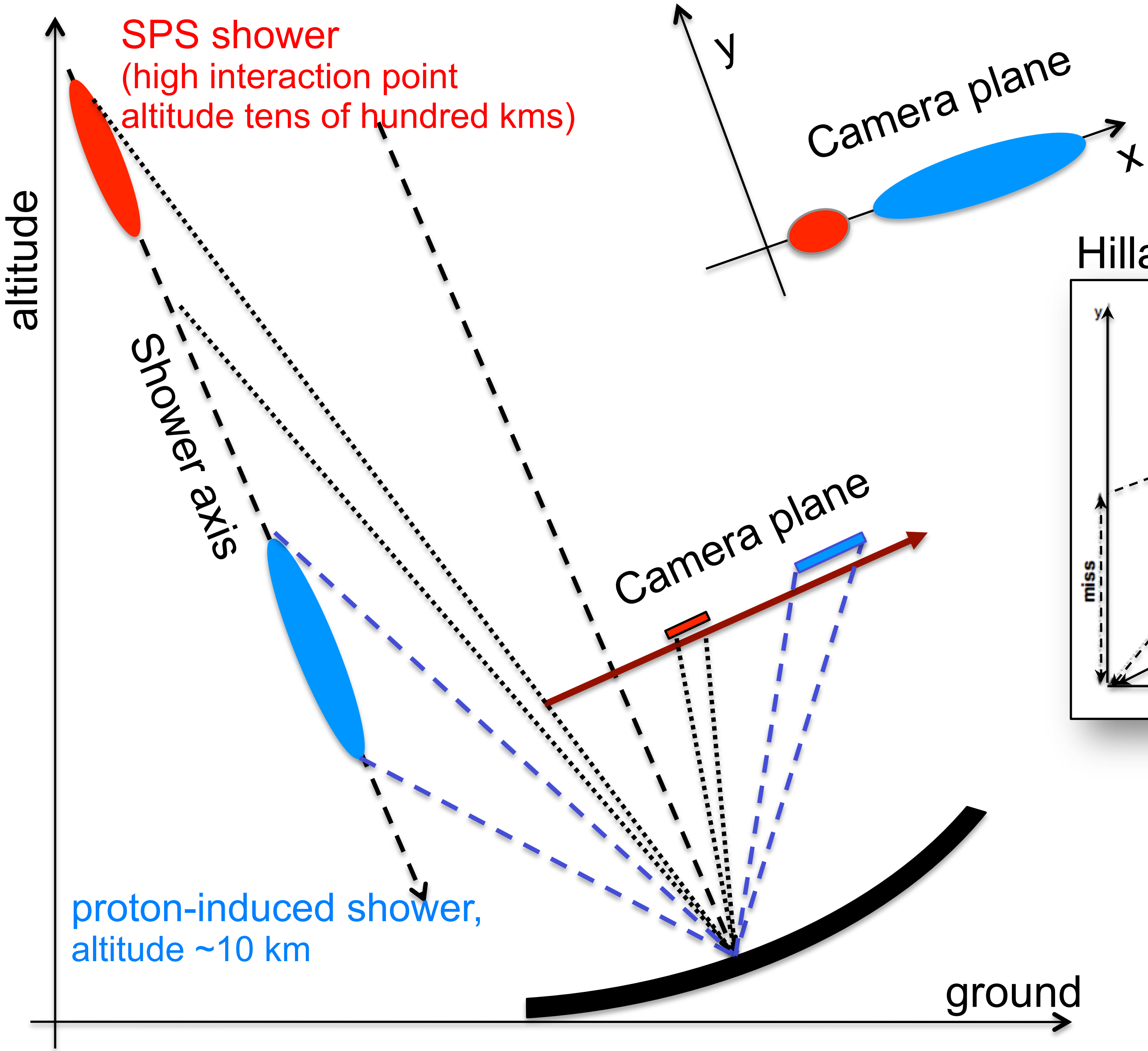
> The simulation were performed in the direction of the largest gamma conversion probability at the La Palma site

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

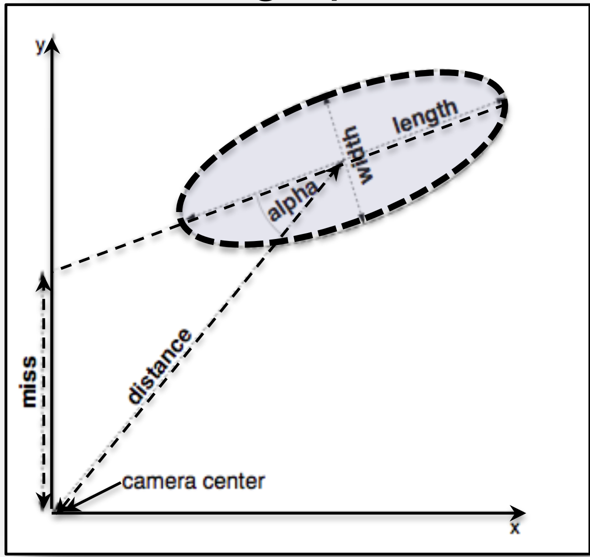
.. and for the northern site of CTA (La Palma)



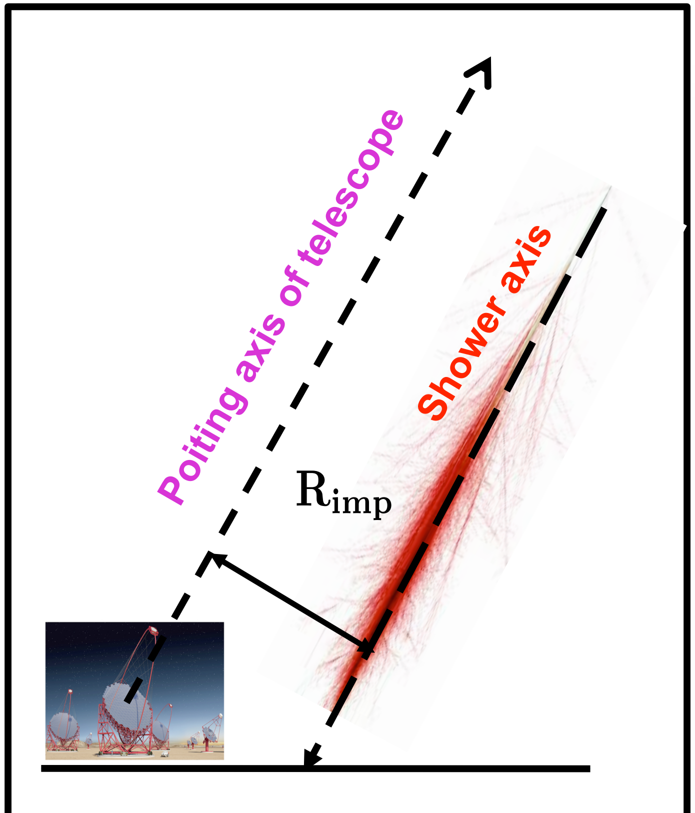

# Towards SPS identification




Hillas image parameters

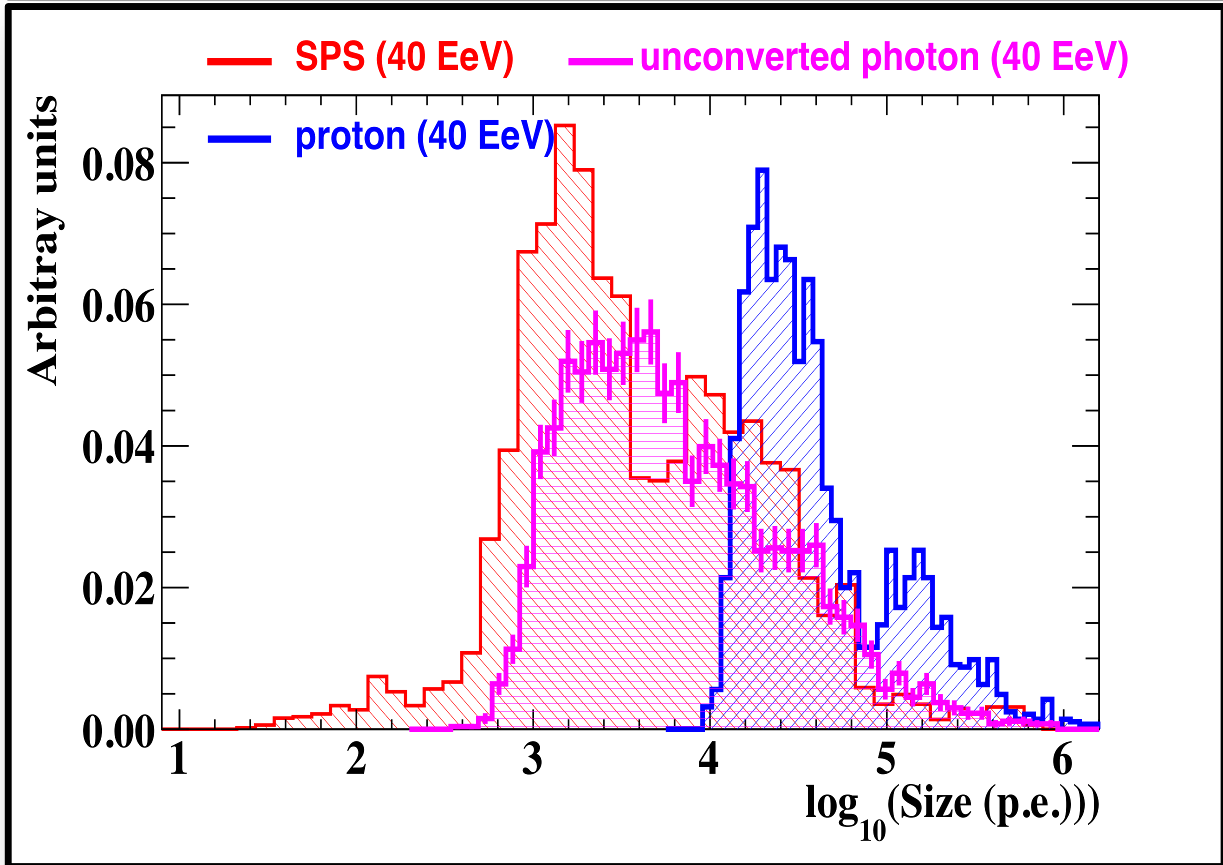


# Hillas parameters: preliminary results




$R_{imp}$ : shower impact distance

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

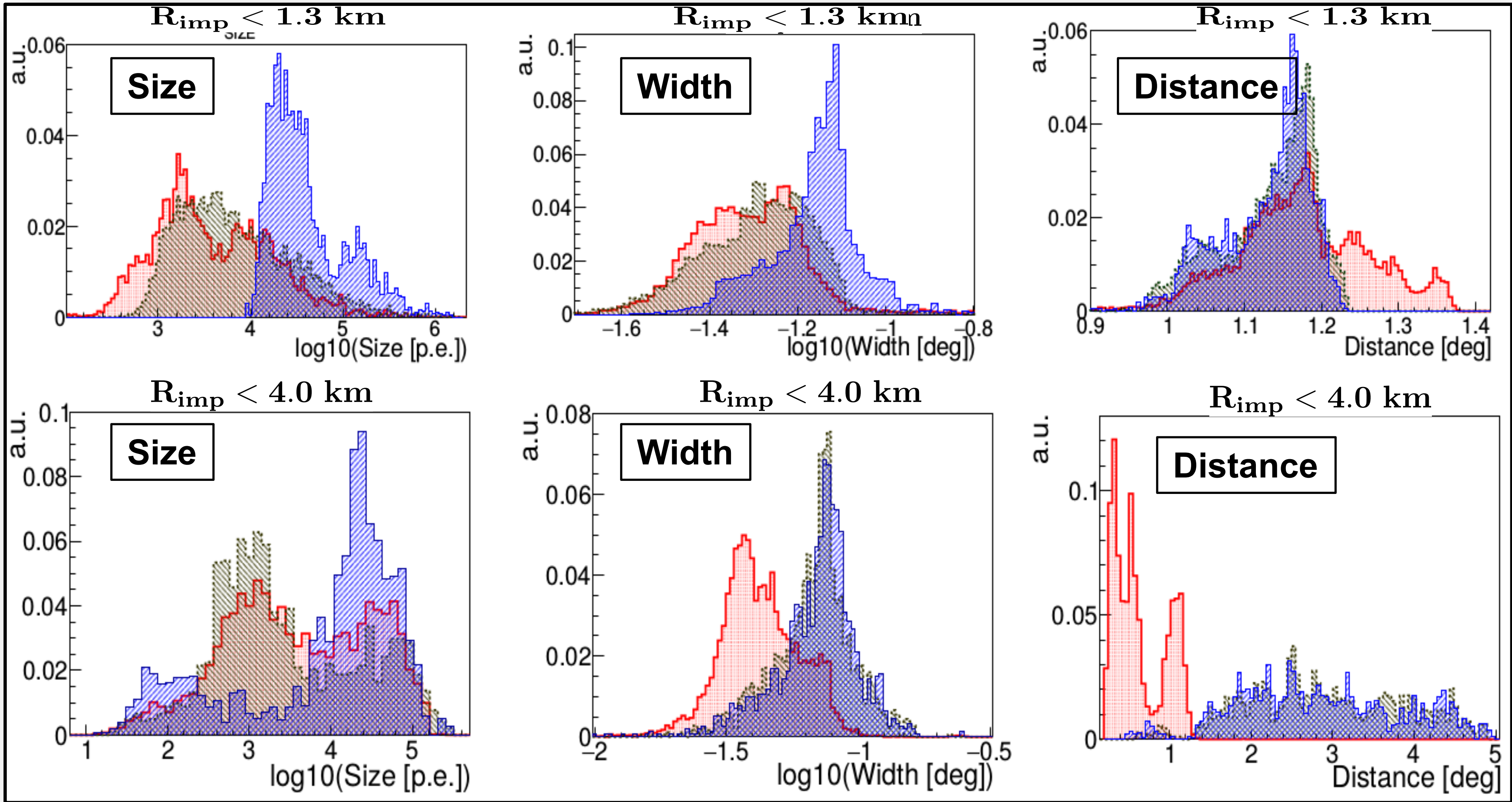
SIZE parameter: the total amount of detected light (in p.e.) in all camera pixels

> 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

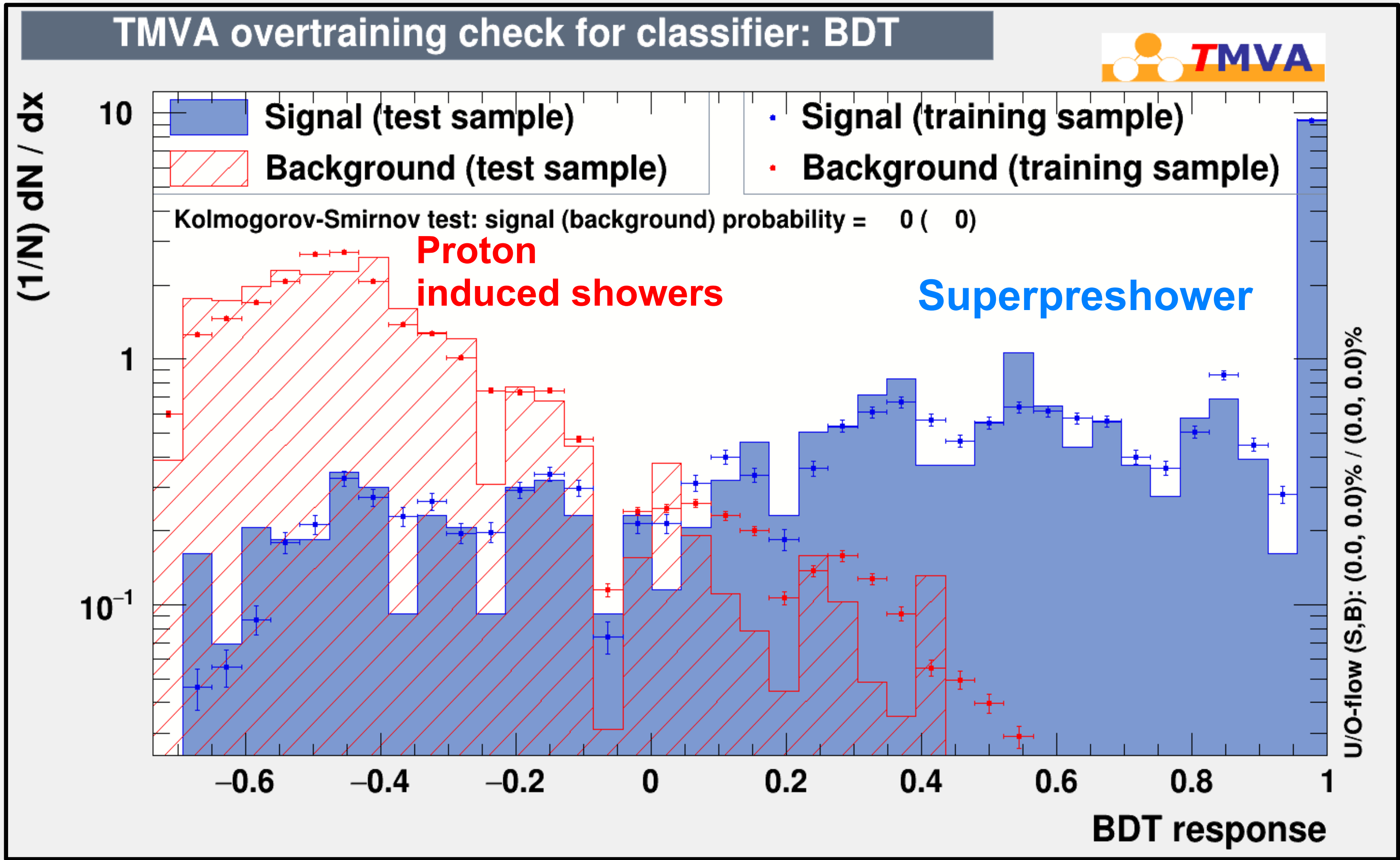
SPS — PROTON — PHOTON —



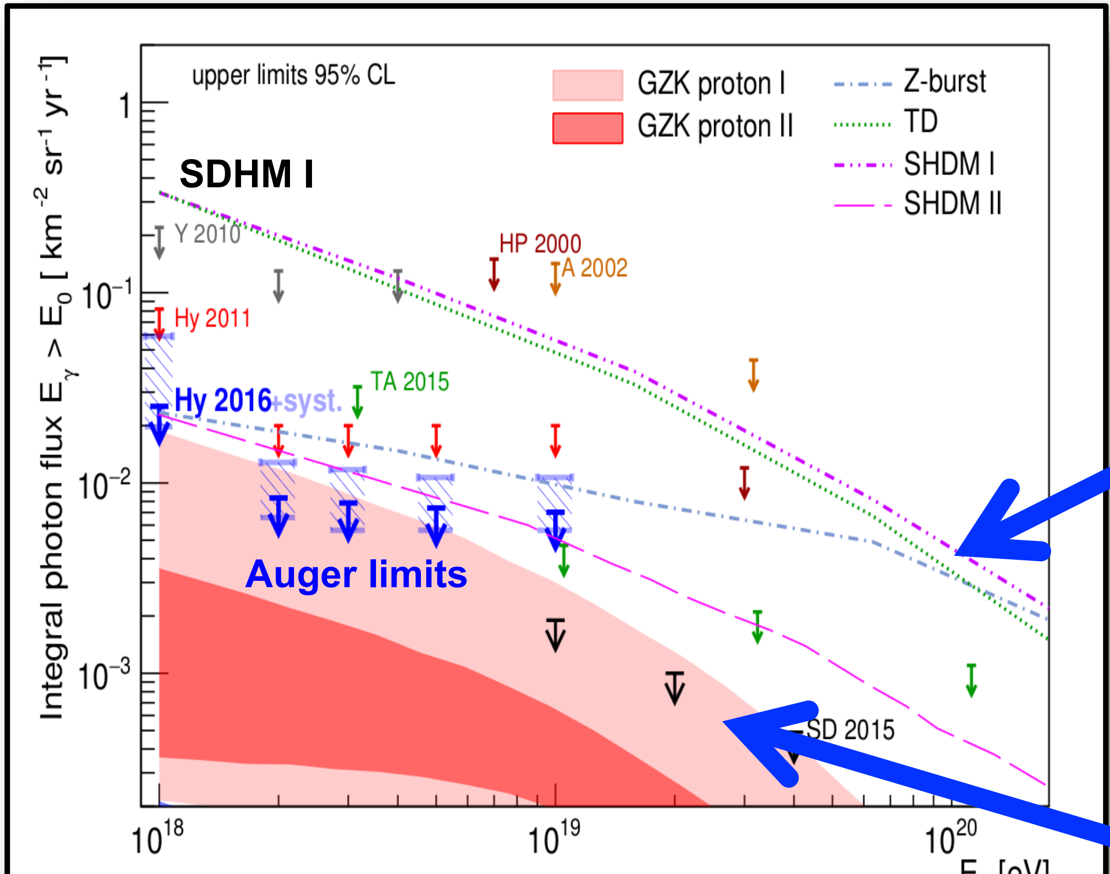

> Potential for **event by event discrimination** for different impact distances $R_{IMP}$ range
→ cut on multivariate analysis could allow discrimination with low statistics (how many events do we need/expect ?).

# Multivariante analysis for Super-preshower

> Cut on multivariate analysis (BDT score > 0.65) allow discriminate the SPS from cosmic-rays background.



# Event rate of SPS: simple estimation




*Niechciol for the Pierre Auger Collab., proc. of ICRC 2017*

> Event rate

$$\mathbf{N = \phi(E > E_0) \times A \times 4\pi}$$
$$\mathbf{with\ A = \pi R^2_{imp}\ and\ E_0 = 40\ EeV}$$
$$R_{imp} = 4\ \mathrm{km}$$

a) Assuming flux from SHDM I model

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

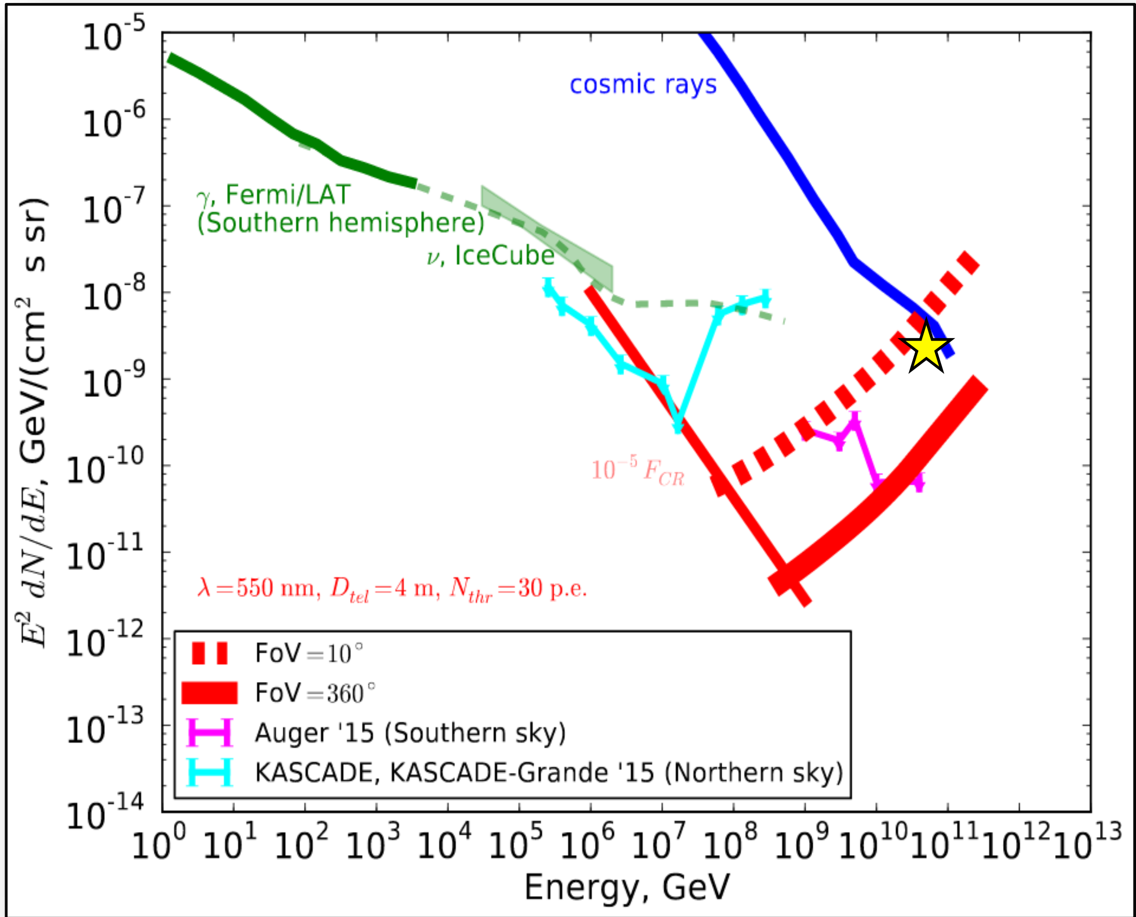
b) Flux at level of Auger limits:

$$N_{EXP} = 0.00005 \mathrm{events/hour}$$
$$\sim \mathbf{0.5\ events/year}$$

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

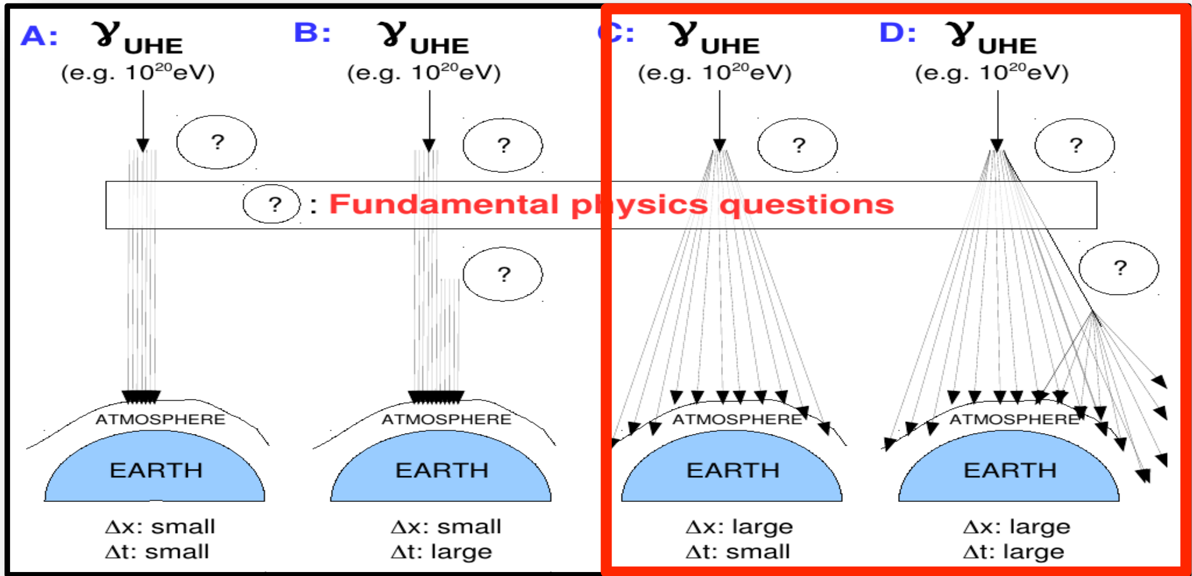
$$\kappa = \mathbf{0.1} \quad \mathbf{T_{exp}} = \mathbf{1\ year}$$

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

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

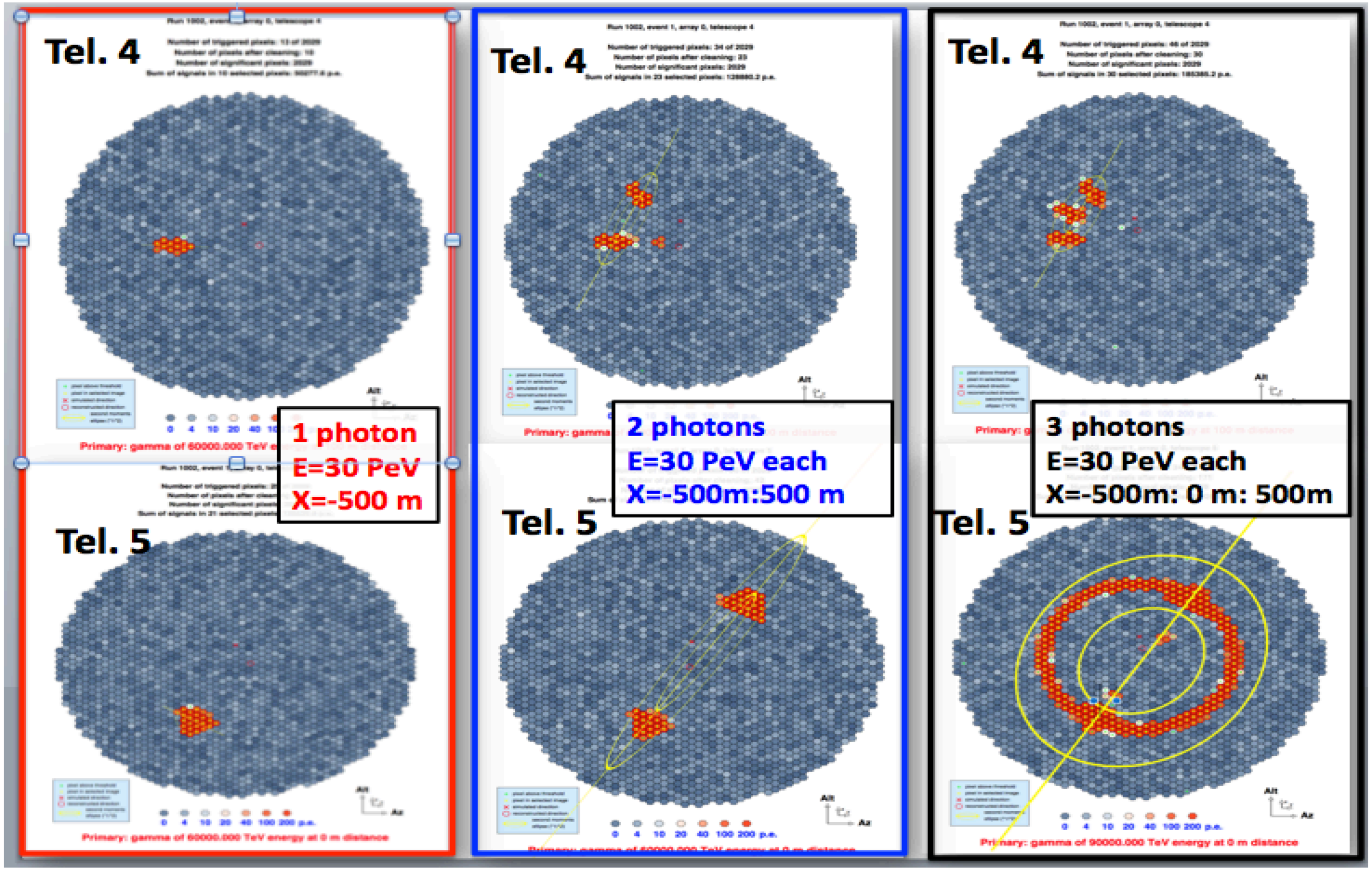
> Study of SPS type C and D would allow to go to lower energies ($10^7$-$10^9$ GeV) and reach more competitive sensitivity to Auger photon limits.

... example of search for SPS  type C or D



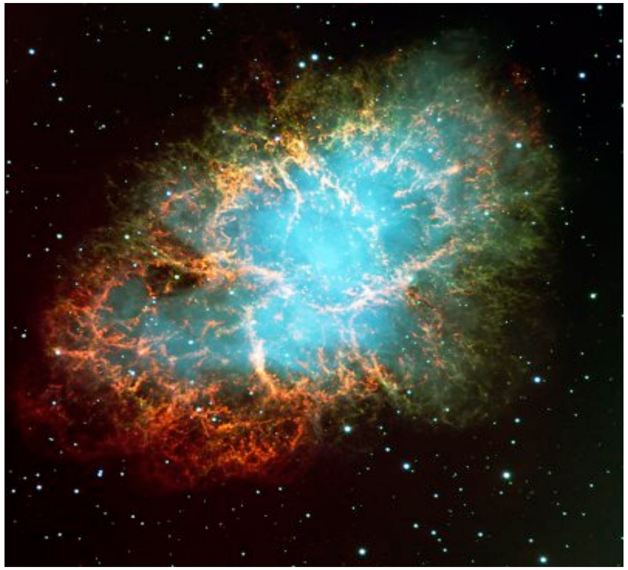
# Other classes of SPS

Example of simulated events see by Cherenkov telescope array: SPS type D




Unique signature for SPS shower

# Other ideas: coincident search by a few IACTs



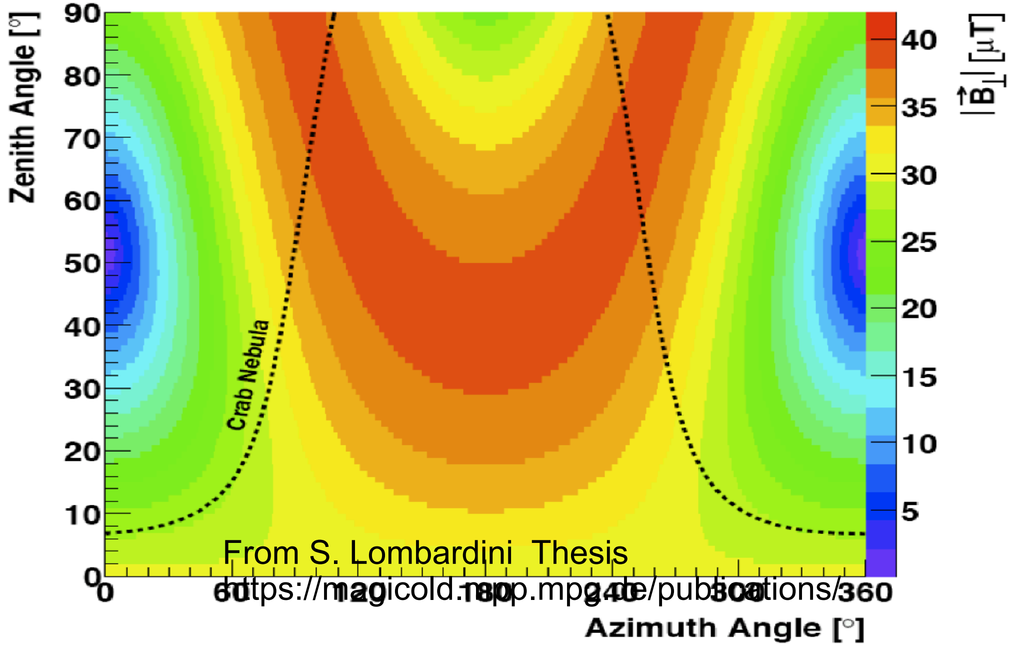
- **Coincident search by a few IACTs**

  *Already existing proposal betwen diffrent IACTs to observe Crab Nebula in order to compare the senstivity of these detectors (data from MAGIC, HESS, VERITAS)*

  In principle, the so-called OFF data, taken to estimate the background, can be used in search for SPS

- **Observation at inclined directions**

  Pointing at Crab Nebula we can also search for SPS signature.




From S. Lombardini Thesis
https://magicold.mpp.mpg.de/publications/

# 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 when looking for the direction of the maximum photon conversion probability.

> 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 can give different image than a single photon)

Thanks