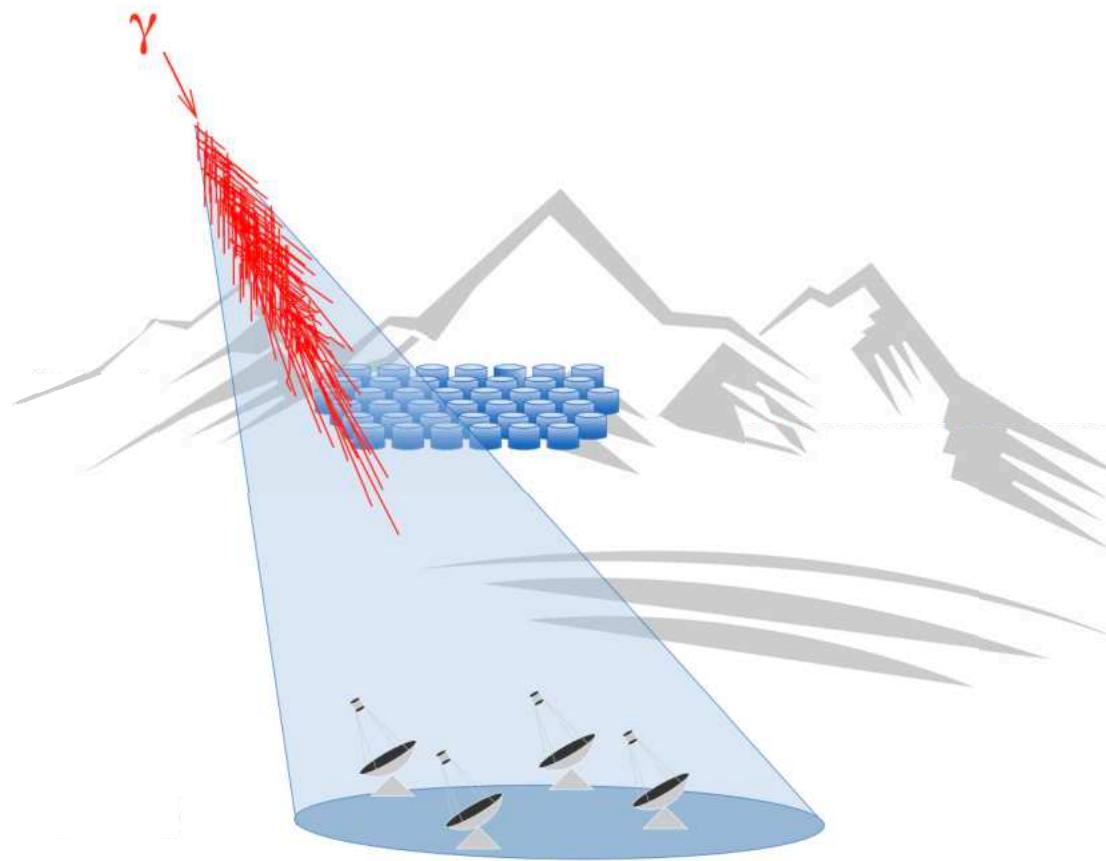


Detection and reconstruction of extensive air showers

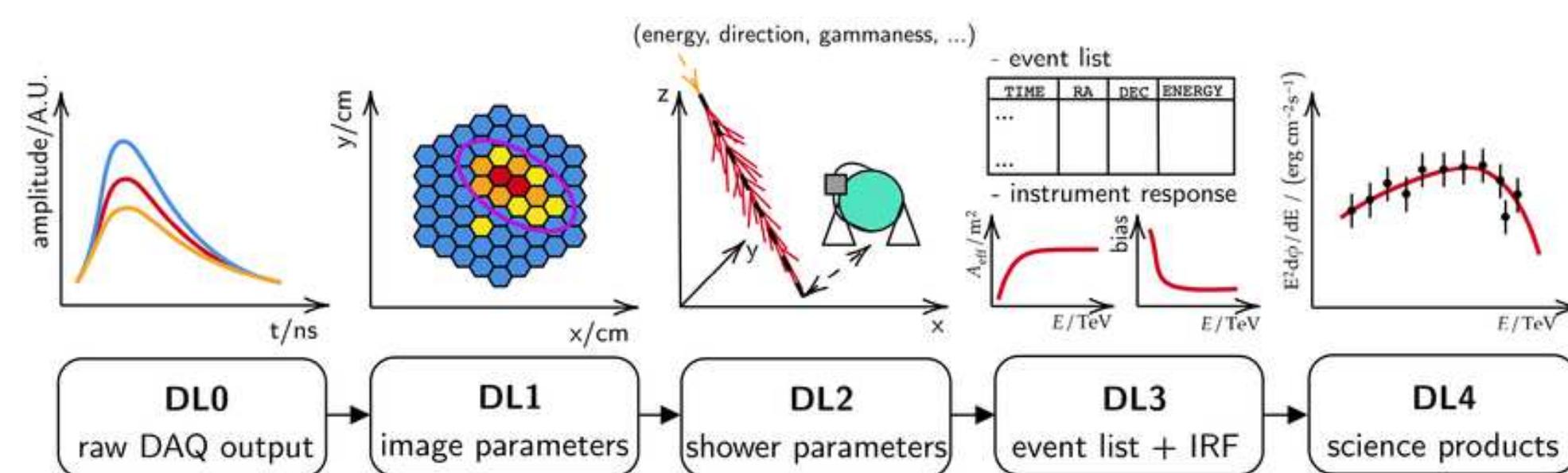
Federica Bradascio (IJCLab – Université Paris-Saclay)
CADS School - October 2024

Outline

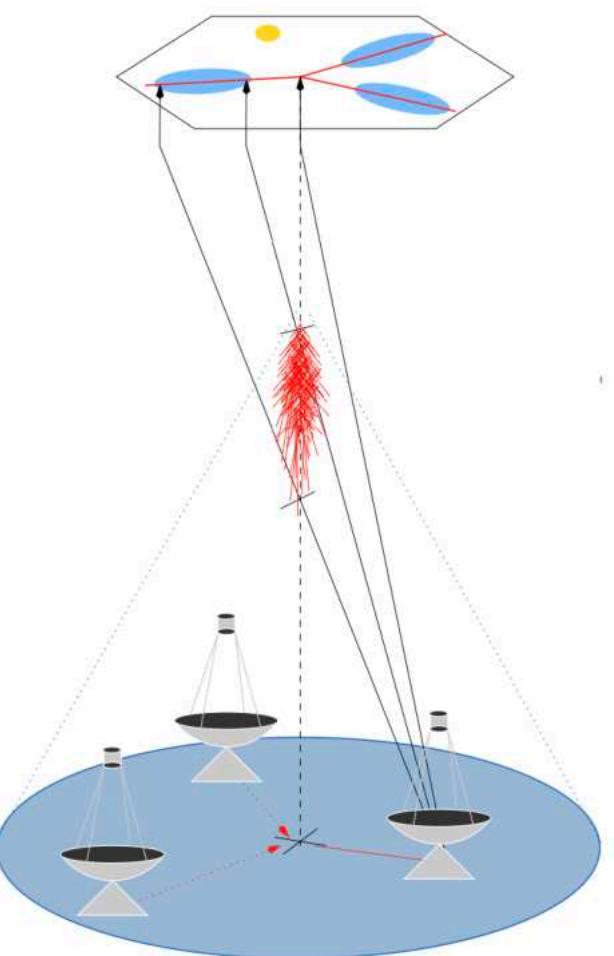


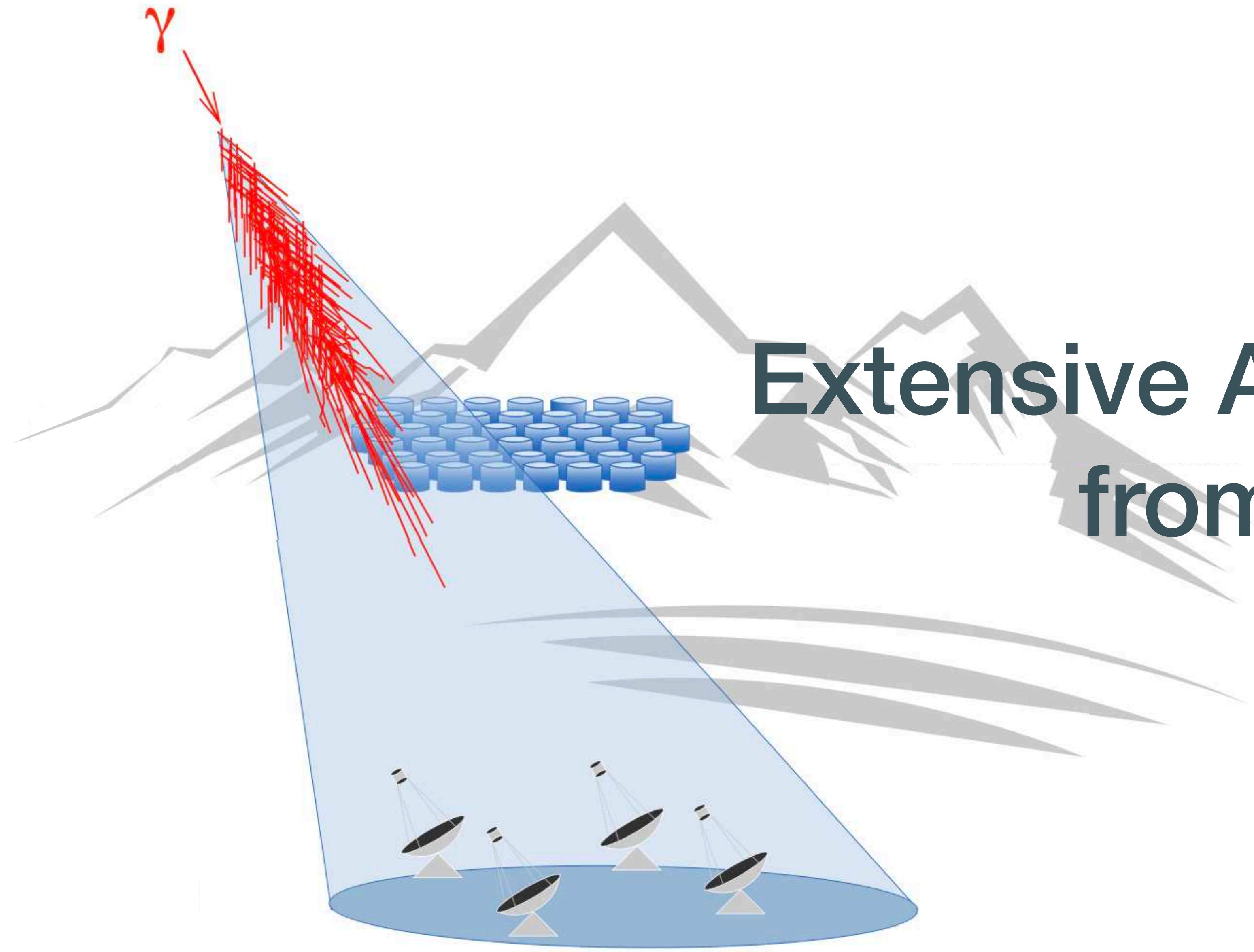
1. Extensive Air Showers: from sources to telescopes

2. IACTs: detection principles



3. From low-level to high-level IACTs data





Extensive Air Showers: from sources to telescopes

Very High Energy gamma-rays astrophysics

DEFINITIONS:

- Medium-Energy Gamma Rays (MeV)
- High-Energy (HE) Gamma Rays (100 MeV – 50 GeV)
- Very-High-Energy (VHE) Gamma Rays (50 GeV – 100 TeV)

ASTROPHYSICAL GAMMA RAYS:

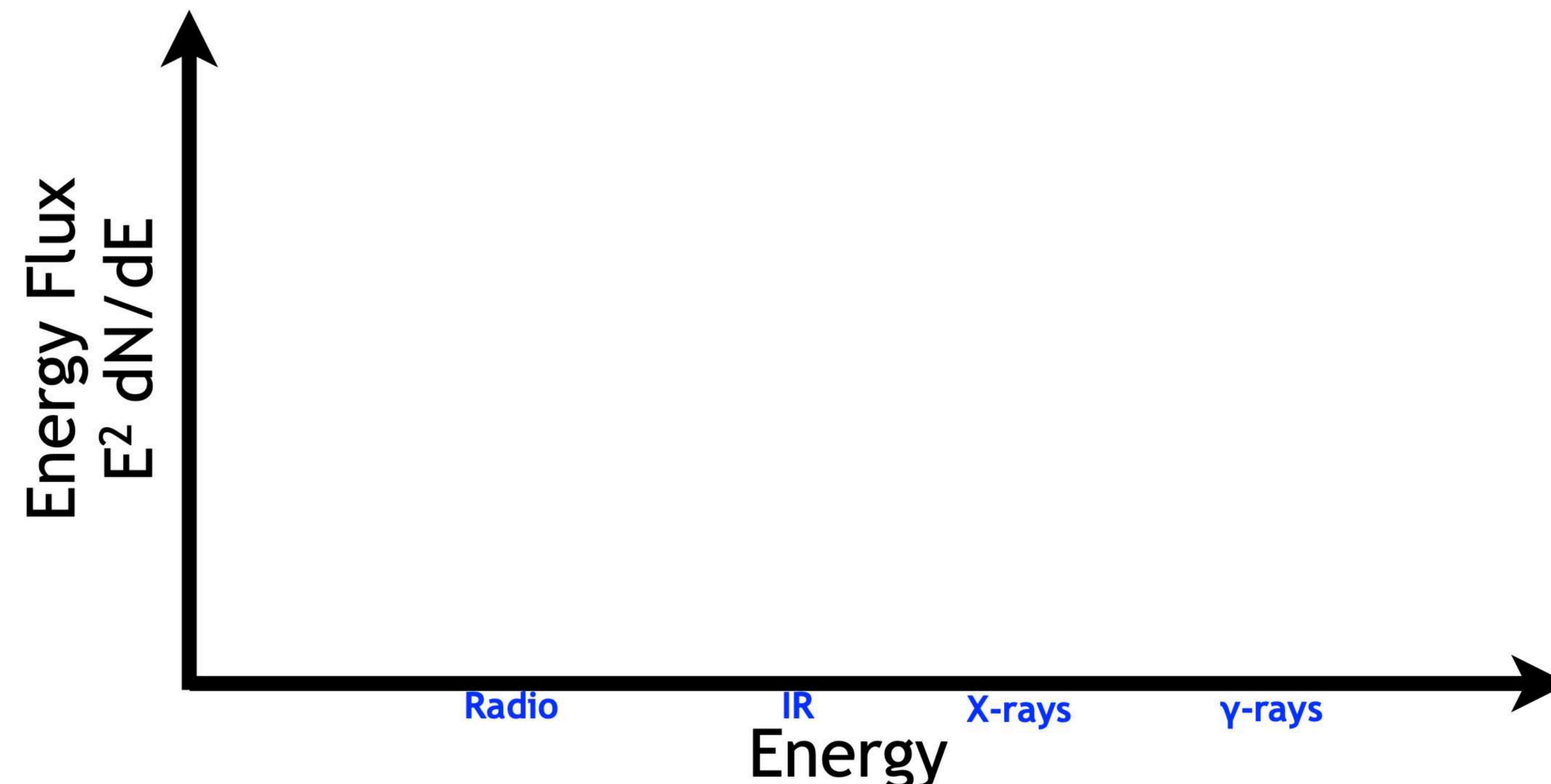
- Indicate the presence of a parental population of high-energy massive particles
- Little effect from absorption in the galaxy
- Carry information directly from the sites of acceleration

Very High Energy gamma-rays

Only produced by non-thermal processes

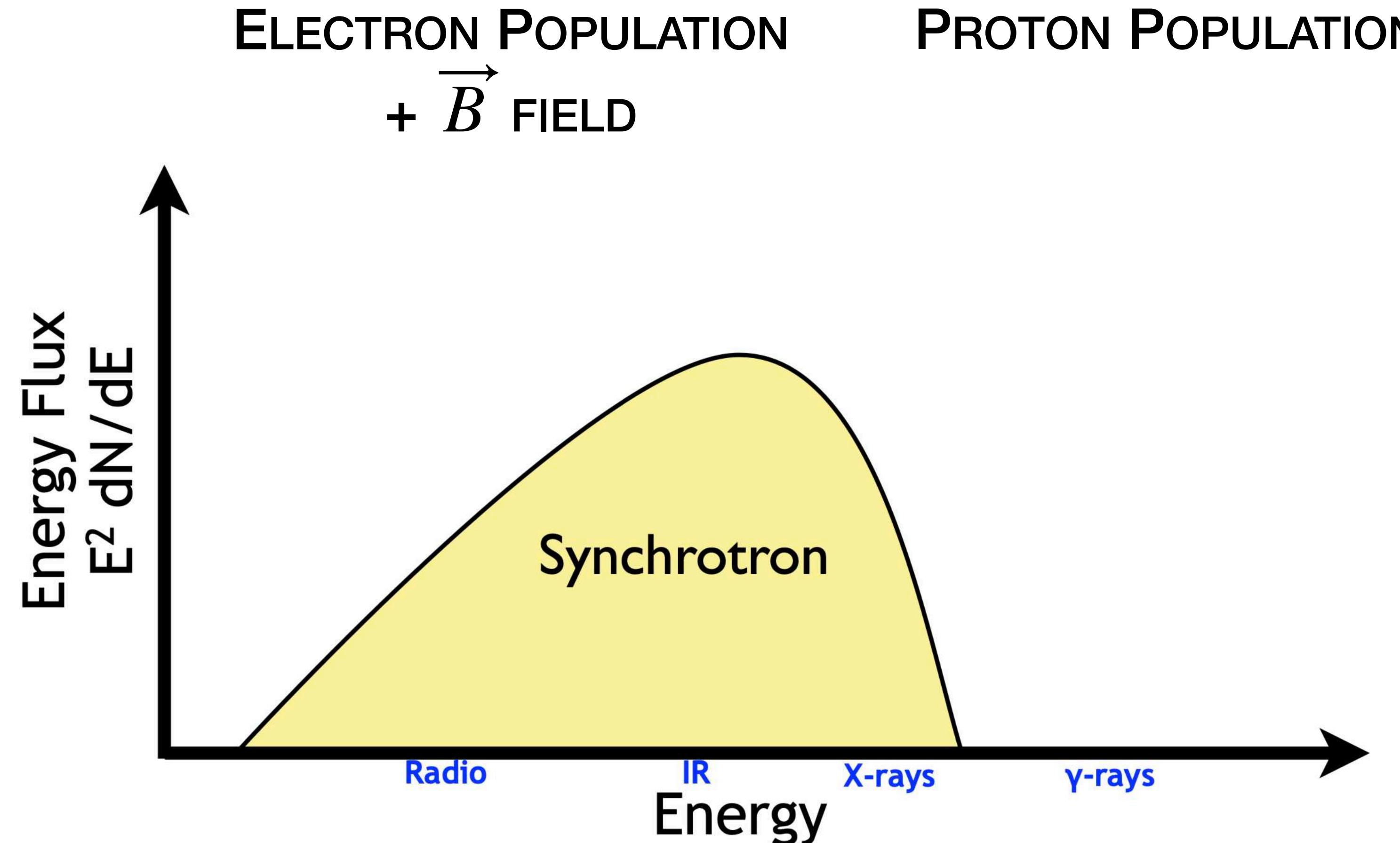
ELECTRON POPULATION

PROTON POPULATION



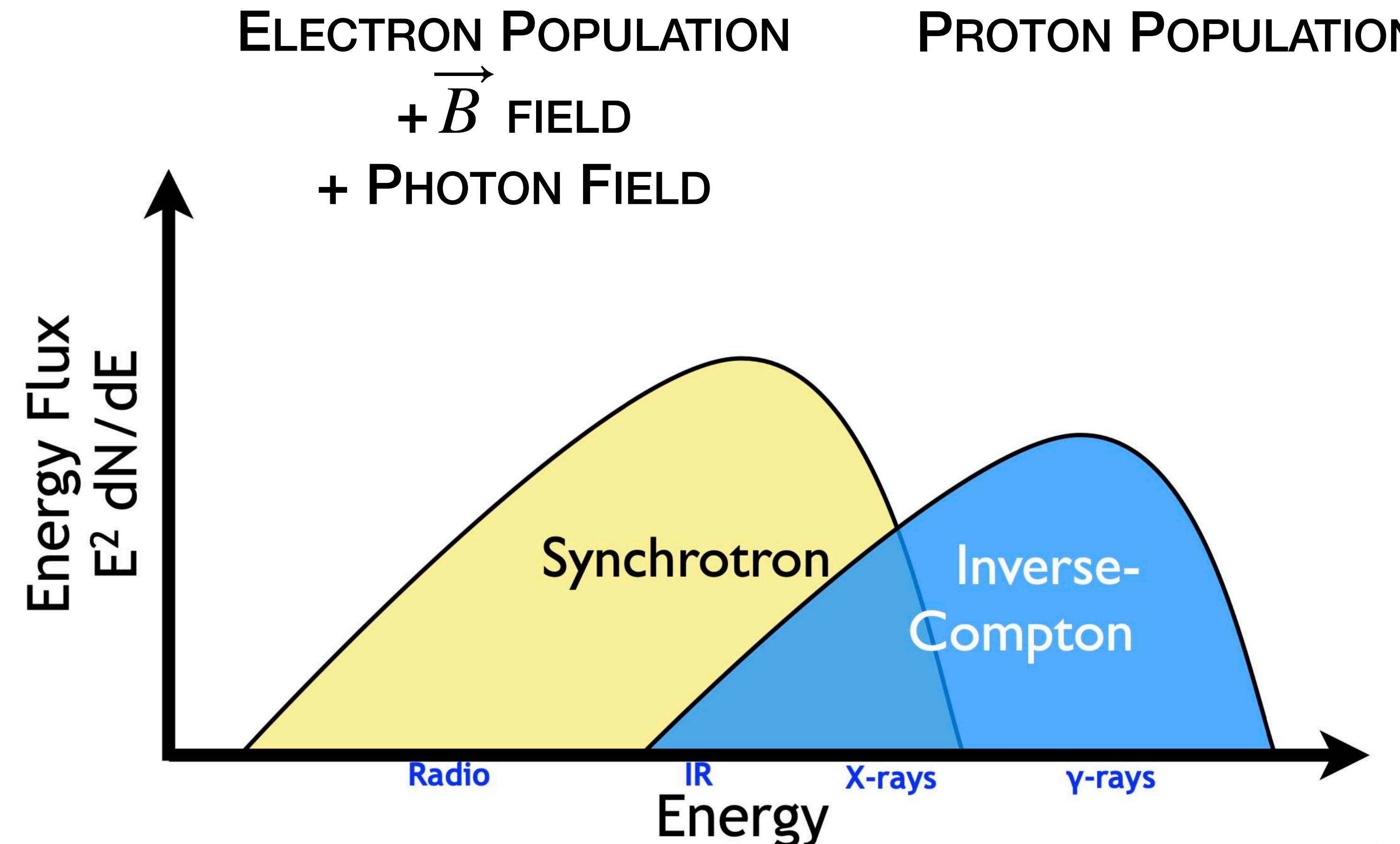
Very High Energy gamma-rays

Only produced by non-thermal processes



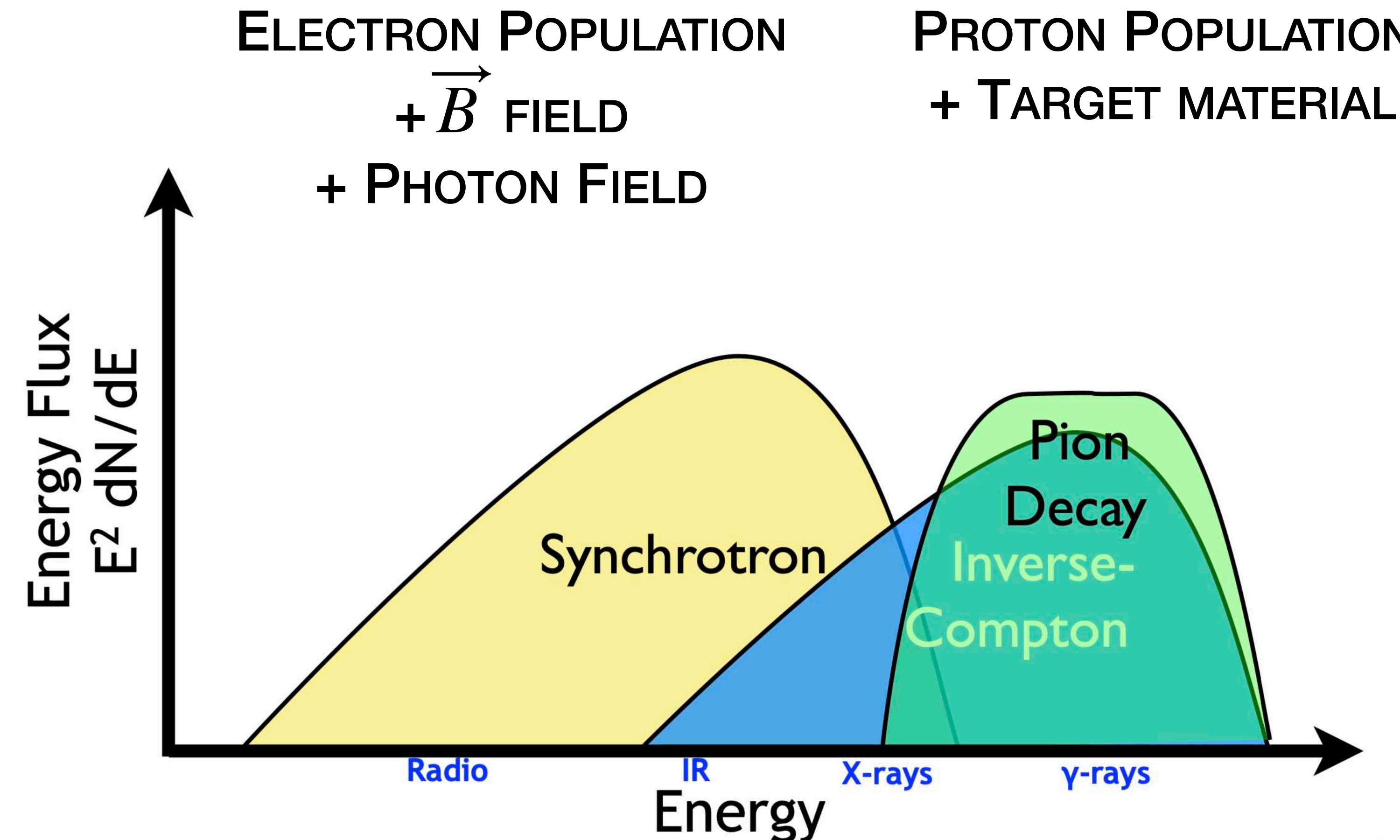
Very High Energy gamma-rays

Only produced by non-thermal processes



Very High Energy gamma-rays

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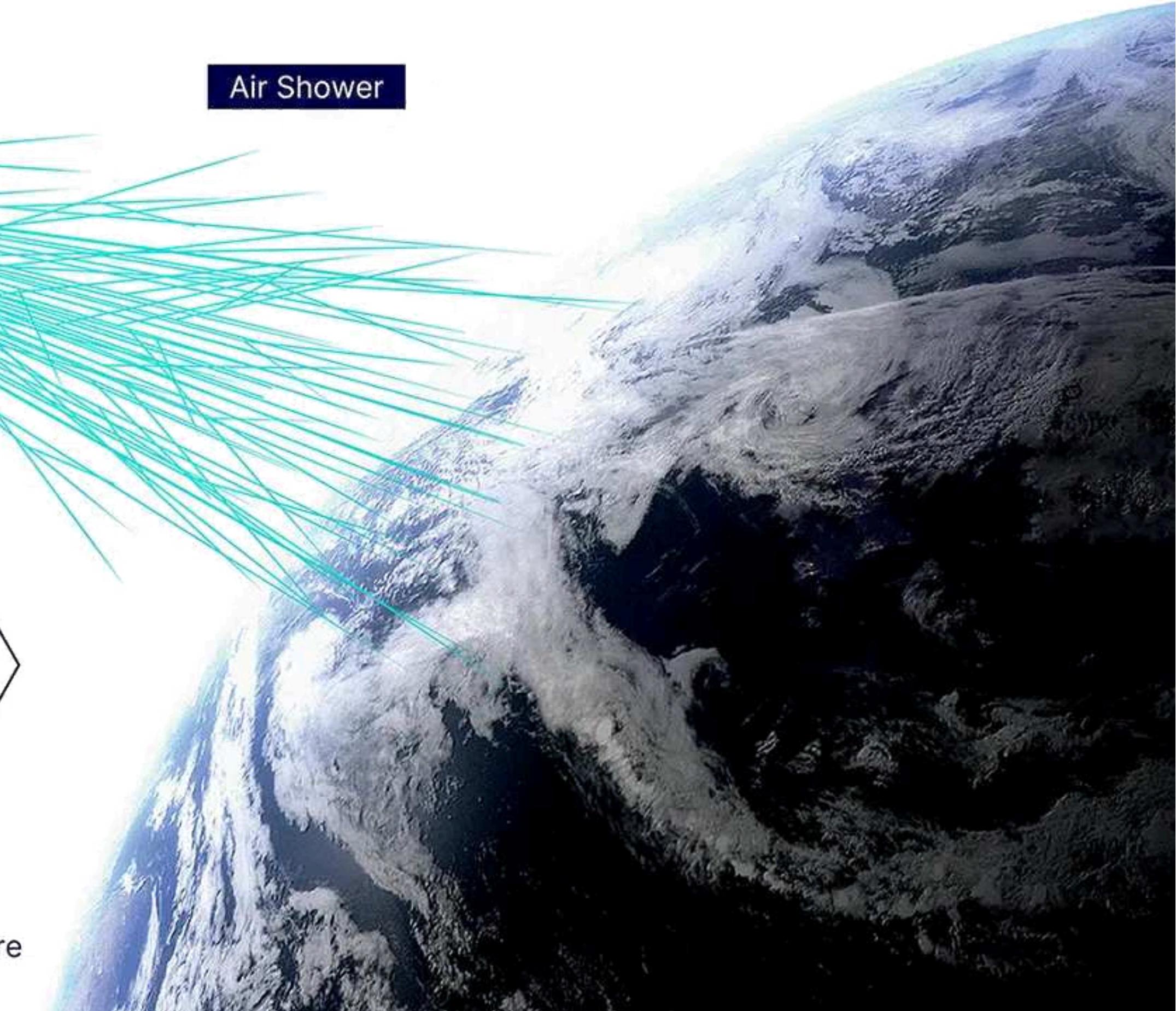
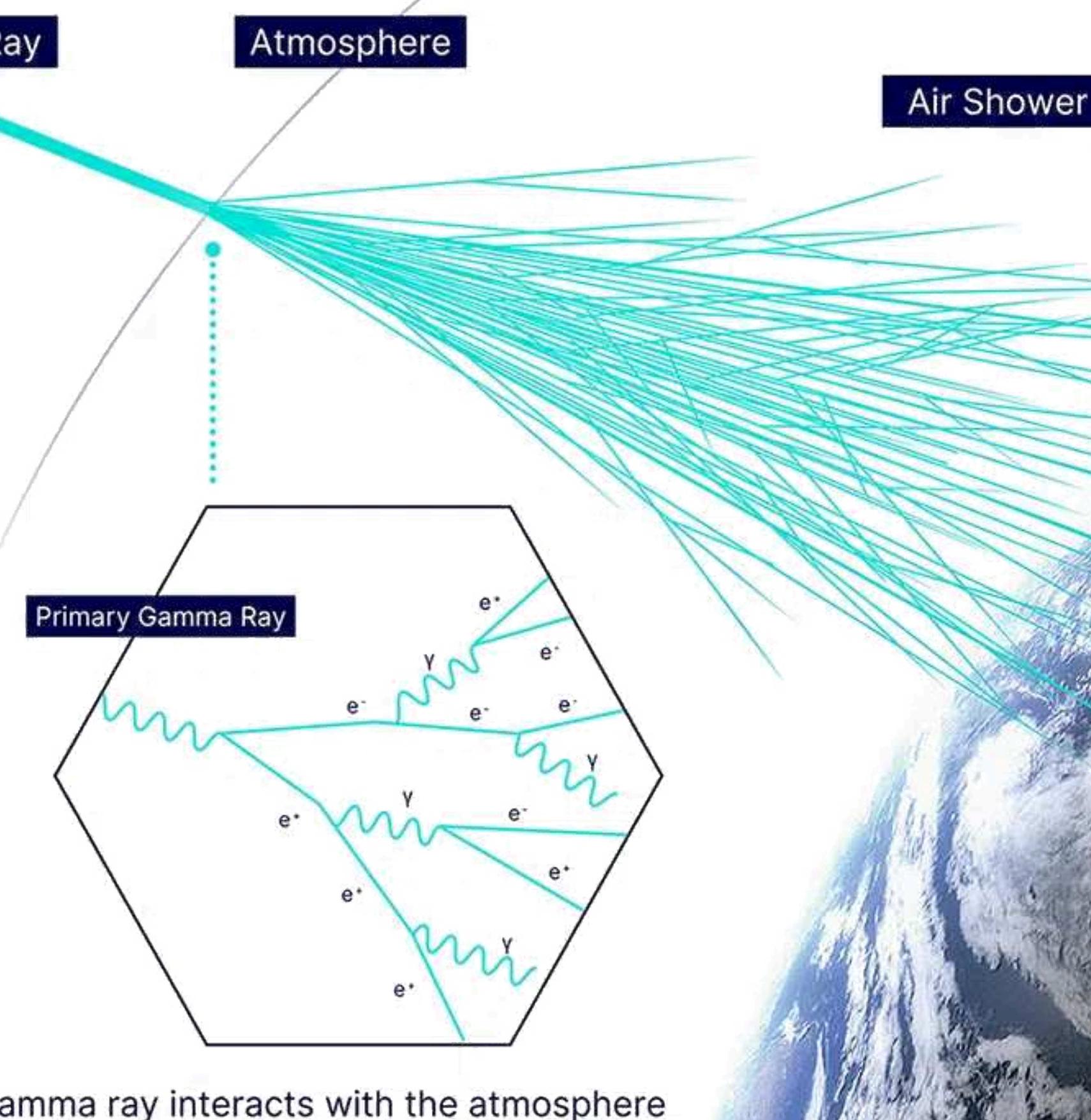




Extensive Air Showers

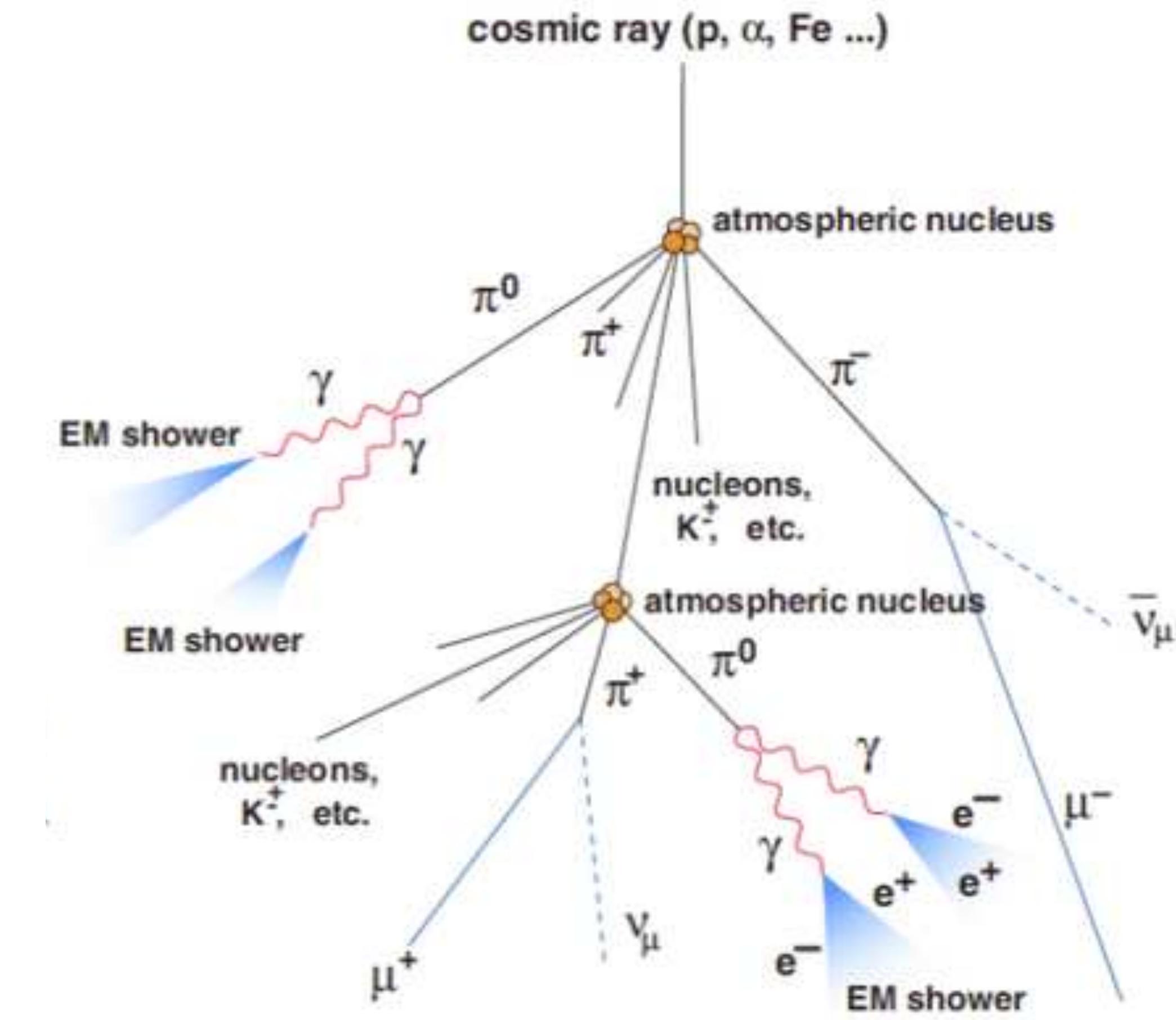
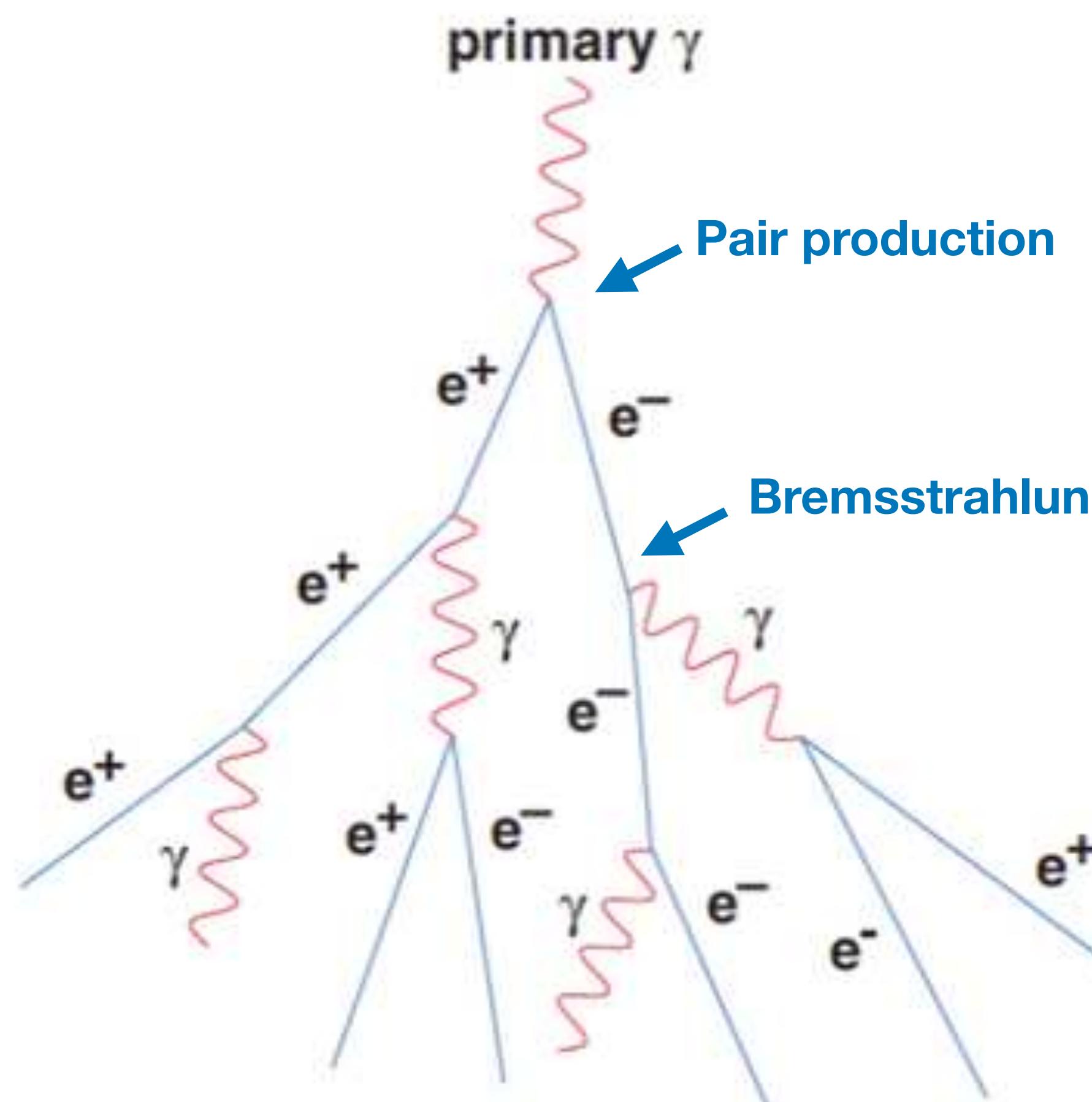
Interaction of primary particle in the high atmosphere
⇒ showers of secondary particles

- Atmosphere acts as an inhomogeneous calorimeter and a tracking medium
- Spread on a wide area, distant detection ⇒ large effective area, can be used at high energies ($\geq 100 \text{ TeV}$) where flux are very low
- Cascades initiated by:
 - Photons
 - Charged particles



Extensive Air Showers

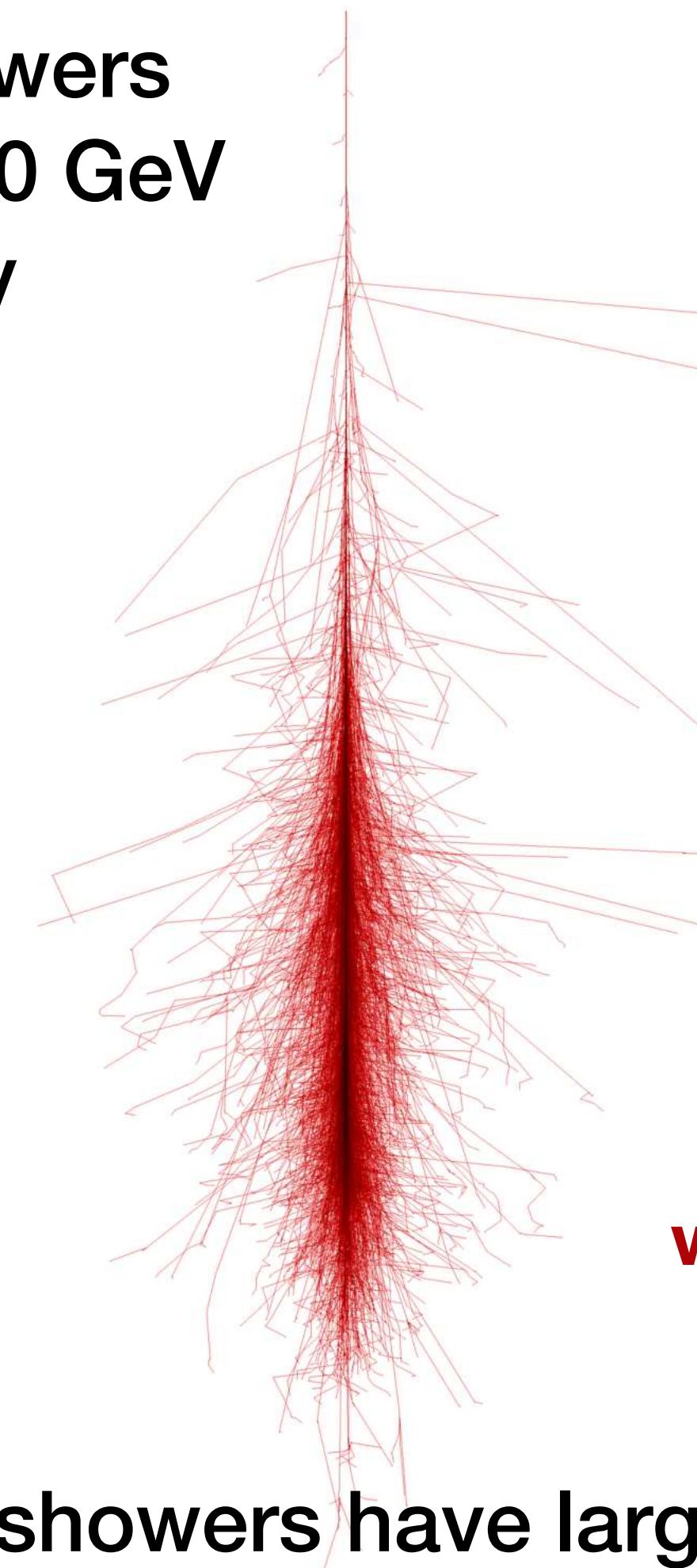
Electromagnetic vs Hadronic showers



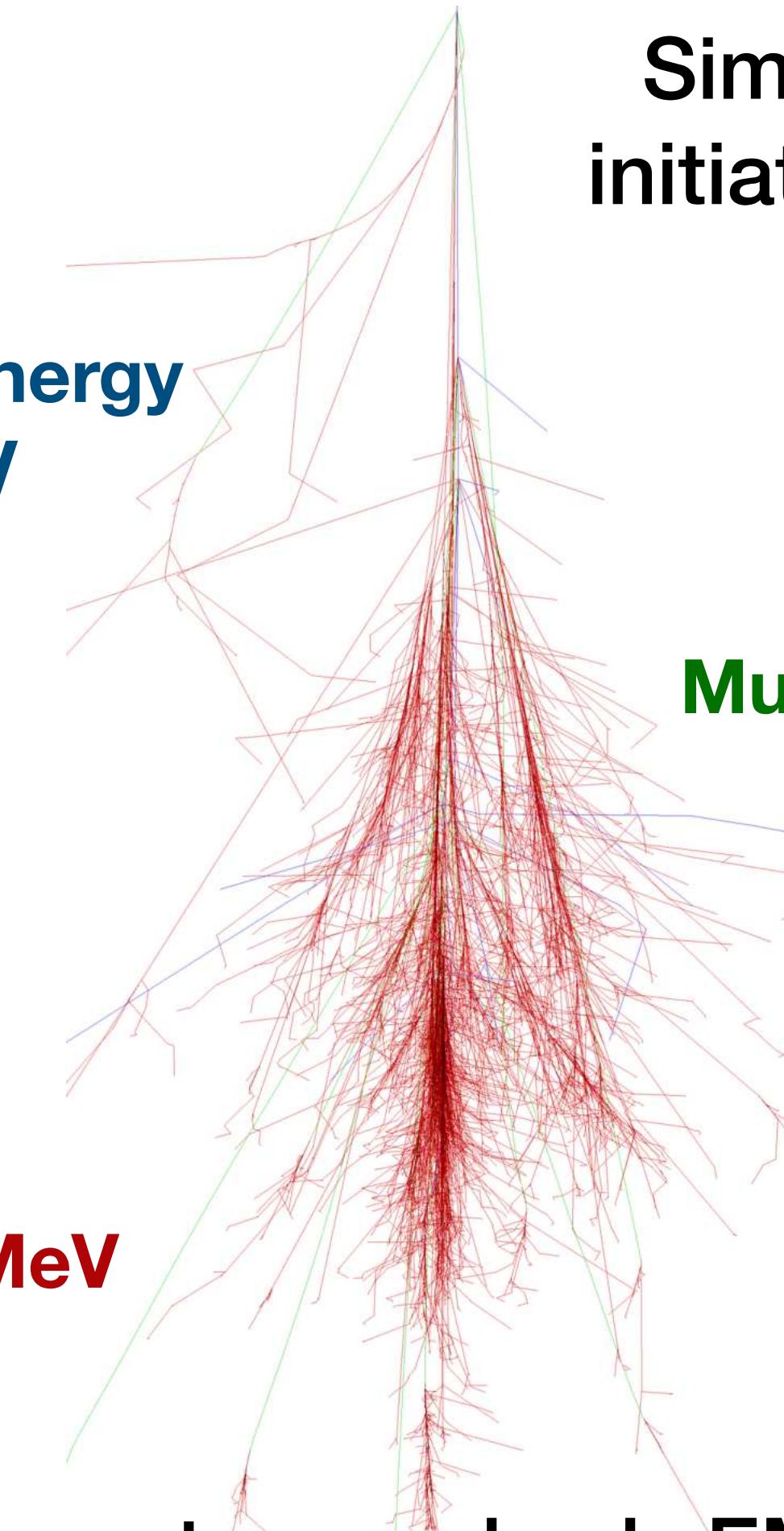
Extensive Air Showers

Electromagnetic vs Hadronic showers

Simulated showers
initiated by a 100 GeV
gamma ray



Simulated showers
initiated by a 100 GeV
proton



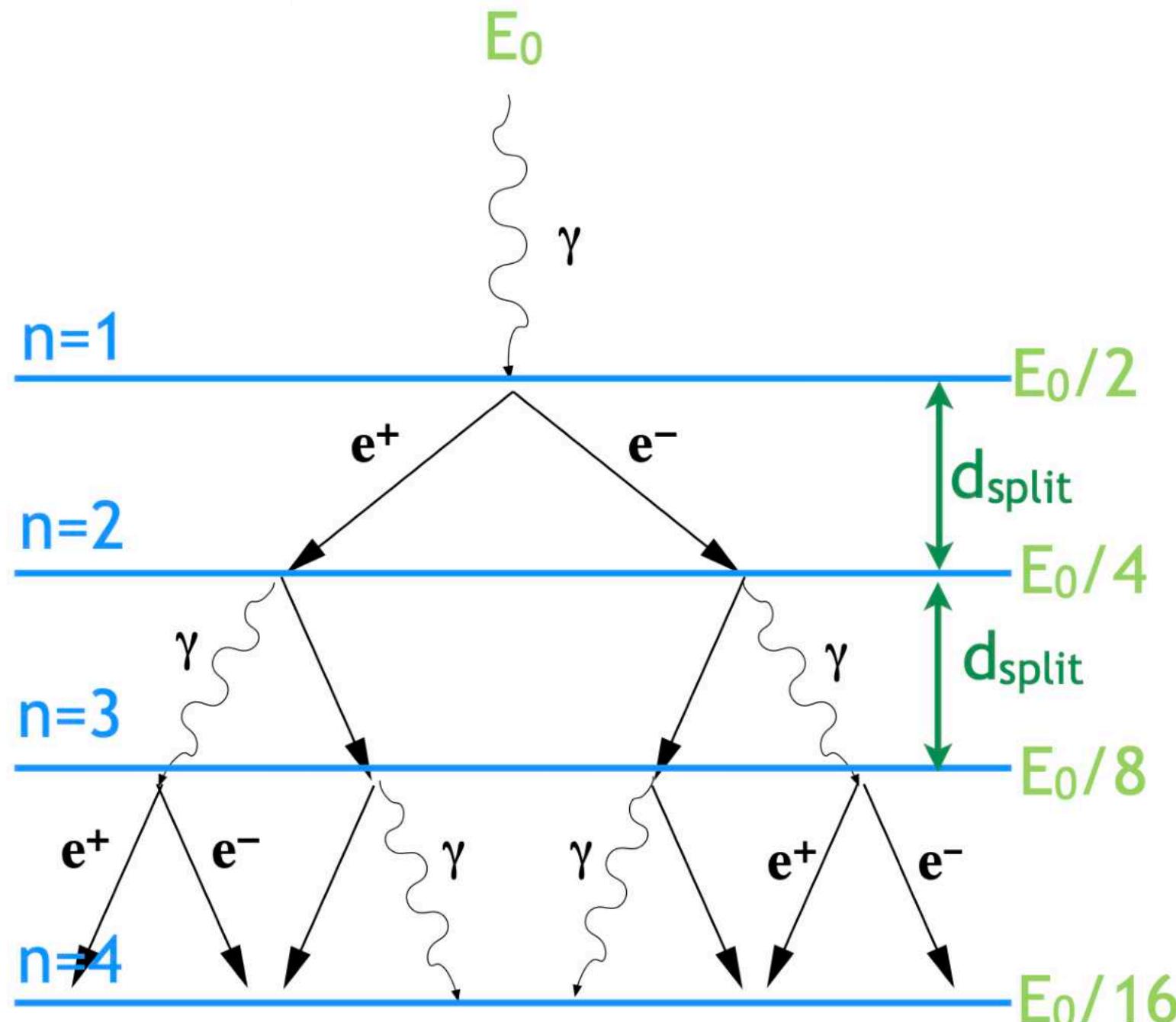
Hadrons with energy
 $E > 0.1 \text{ GeV}$

e^+, e^-, γ
with energy $E > 0.1 \text{ MeV}$

Hadronic showers have larger transverse momentum and sub-EM showers

The Heitler model

A simplified model for EM showers



- Two processes: *pair production + single-particle bremsstrahlung*
- Initial energy E_0 , radiation length X_0
- Distance between both interactions is a fixed length $d_{\text{split}} = X_0 \ln 2$
- Any interaction leads to two new particles of energy $E/2$
- When the energy of a particle drops below a critical energy E_{crit} , the cascade stops abruptly

$$\text{Shower depth: } x = n d_{\text{split}} = n X_0 \ln 2$$

$$\text{Total \# particles } (e^\pm, \gamma): \quad N = 2^n = e^{x/X_0}$$

$$\text{Maximum \# particles: } N_{\text{max}} = E_0/E_{\text{crit}}$$

$$\Rightarrow x_{\text{max}} = X_0 \ln \left(\frac{E_0}{E_{\text{crit}}} \right)$$

The Heitler model

How good is it?

- Doesn't account for particle loss
- Assumes abrupt stop of shower after E_{crit}
- Particle interactions are stochastic processes
- Assumes single-photon emitted during bremsstrahlung
 - In reality is several, so overestimates lepton fraction
 - Approximately: $N_\gamma \approx 10N_e$ (can be used as a simple correction factor)
- Atmosphere is complicated (e.g., density profile)

Effect of Earth's atmosphere

Longitudinal development of electromagnetic air showers

The number N of secondary electrons and positrons at a given atmospheric depth x :

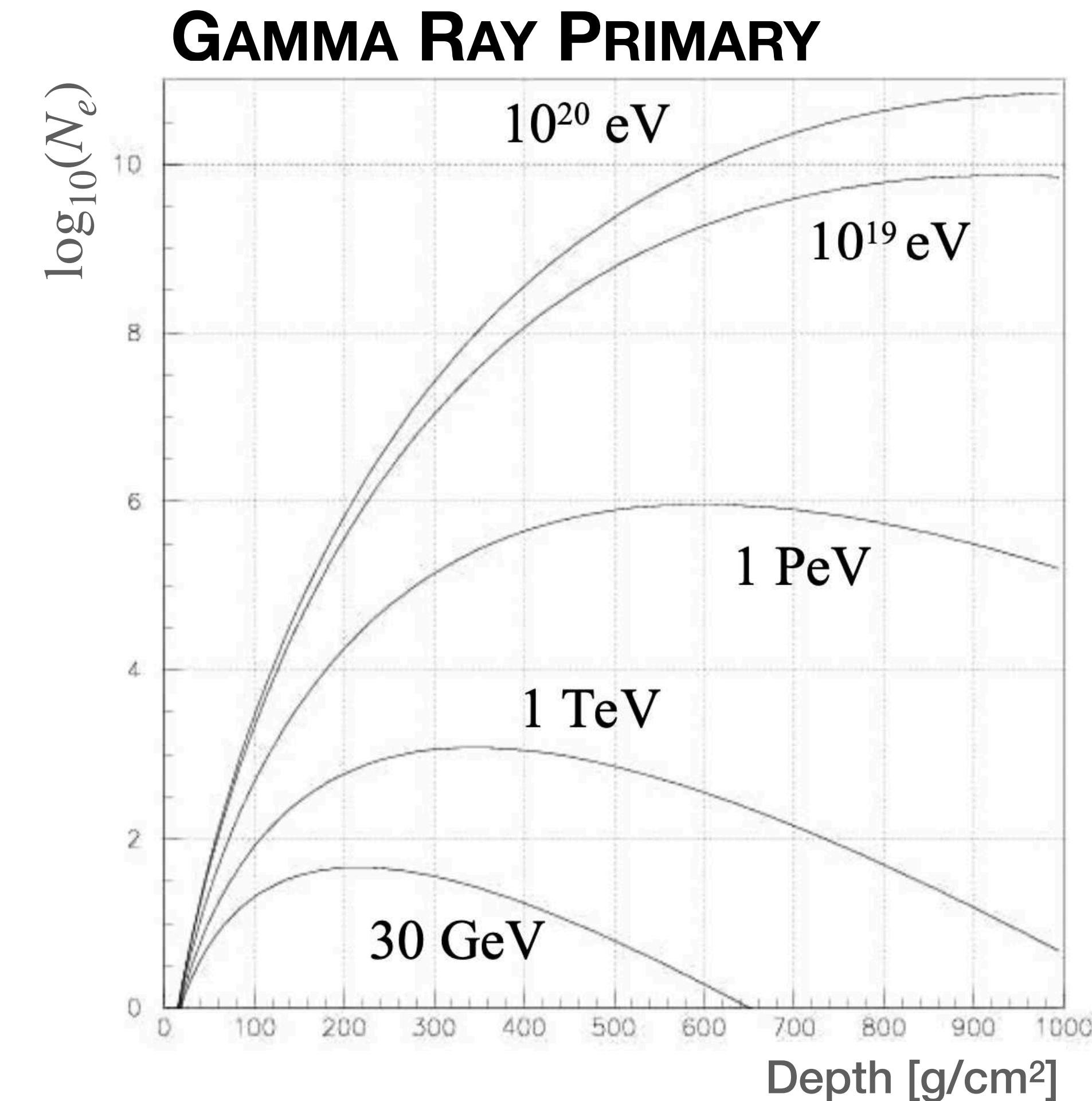
$$N(x) = \frac{0.31}{\sqrt{\ln(E_\gamma/E_c)}} \exp\left[\frac{x}{X_0}(1 - 1.5 \ln s)\right]$$

where s is the shower age parameter that describes the stage of development of the shower

$$s = \frac{3}{1 + 2 \ln(E_\gamma/E_c)/(x/X_0)}$$

At the shower maximum, the total number of particles is approximately:

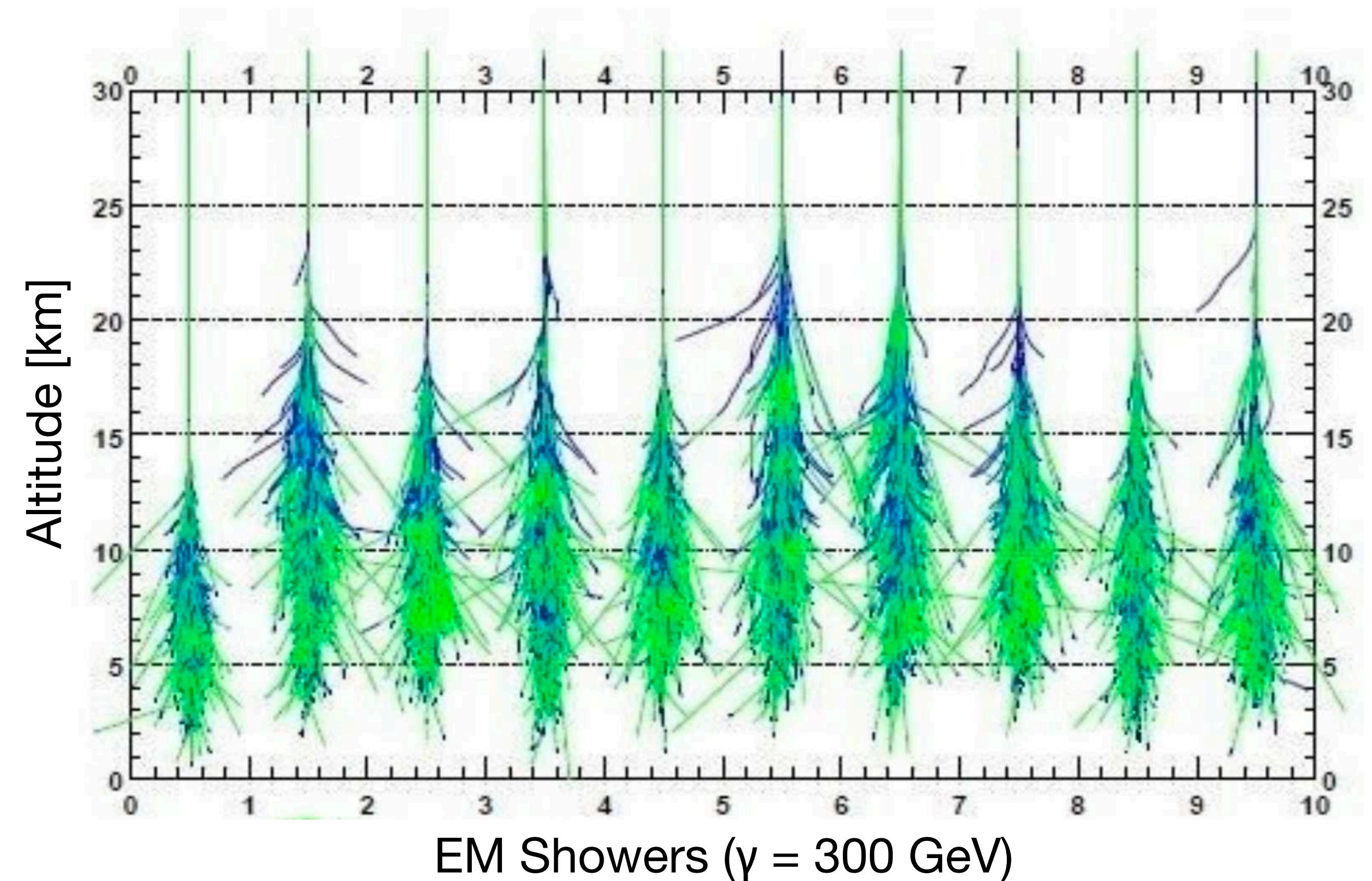
$$N(x_{\max}) \sim 10^3 E_\gamma / \text{TeV}$$



Shower variability

10 simulated EM showers initiated by a 300 GeV photon

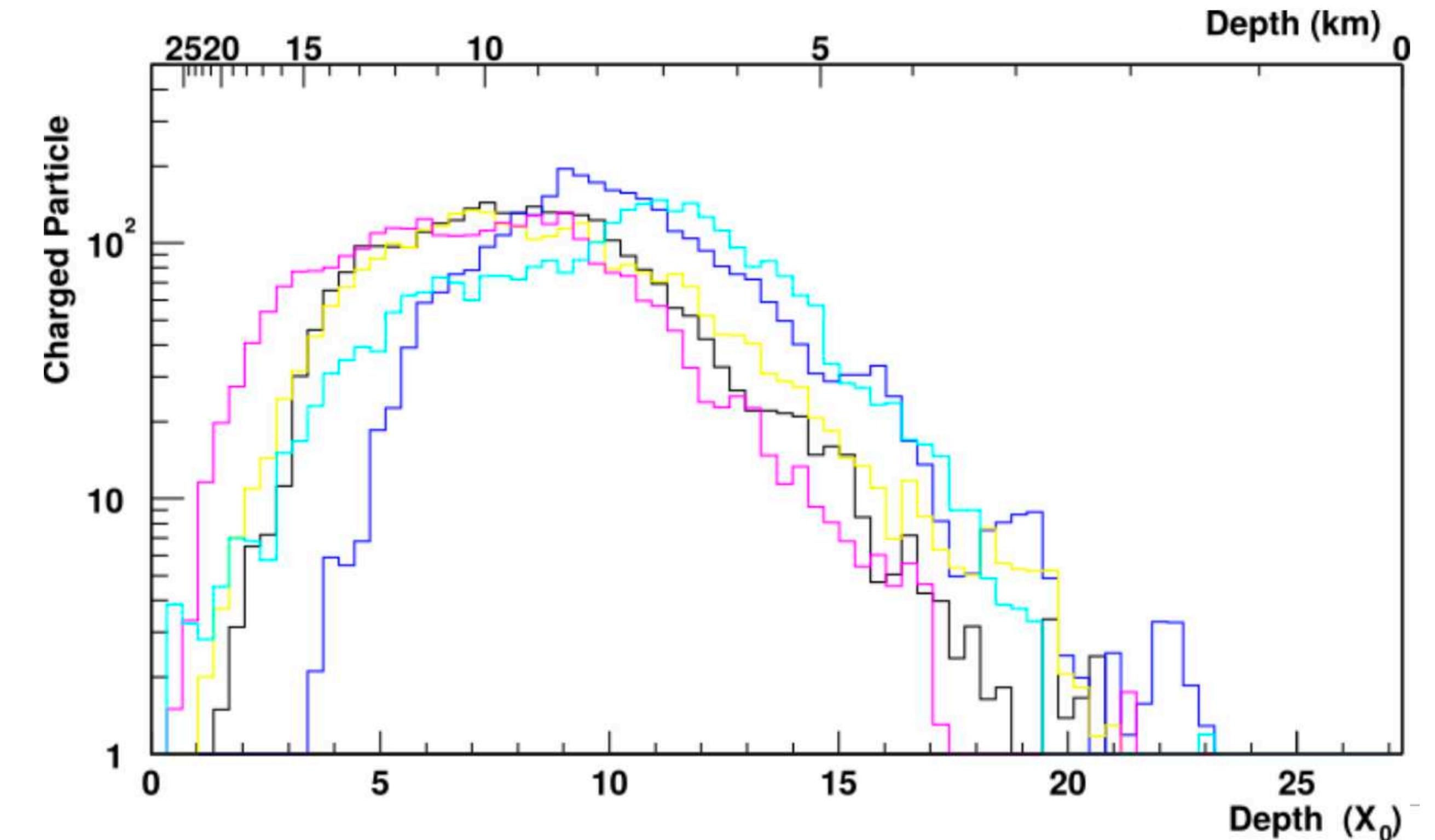
- Large fluctuations in showers, especially at low energy
- Fluctuations mainly due to the first interaction depth
- At high altitude, one radiation length \sim several km \rightarrow first point of interaction can vary by > 5 km
- At lower altitudes, radiation length < 1 km \rightarrow shower development becomes similar



Shower variability

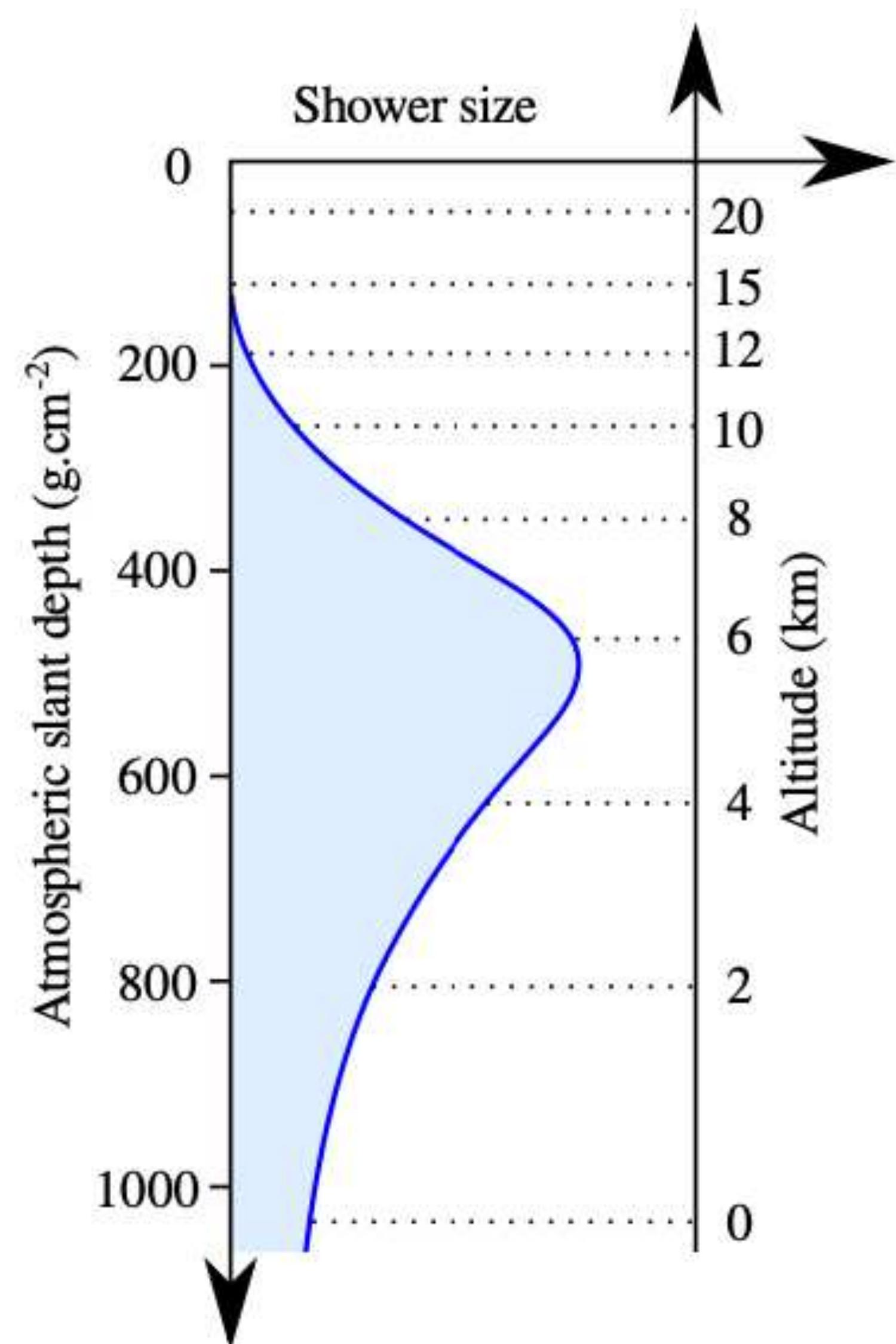
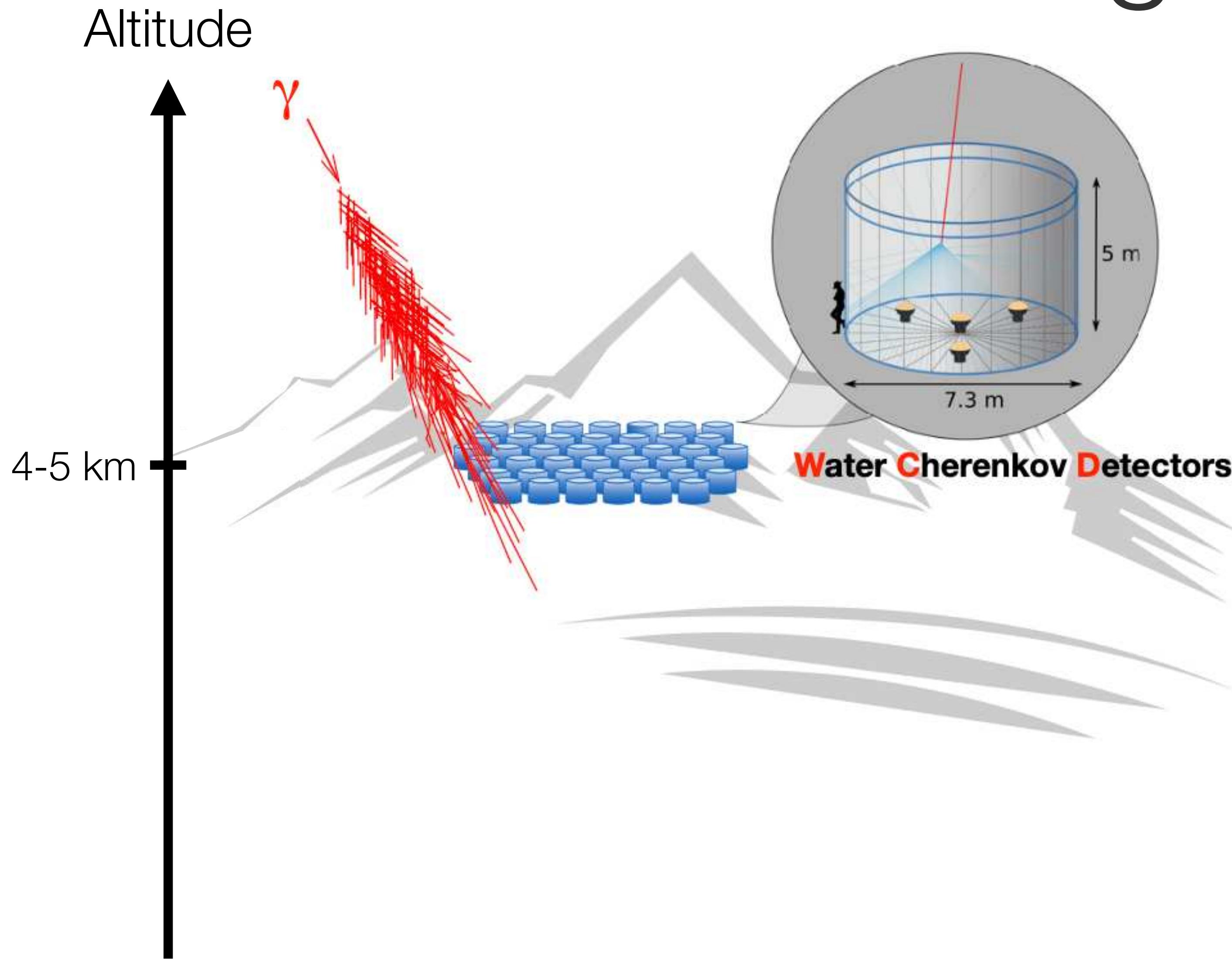
10 simulated EM showers initiated by a 300 GeV photon

- Large fluctuations in showers, especially at low energy
- Fluctuations mainly due to the first interaction depth
- At high altitude, one radiation length ~several km → first point of interaction can vary by > 5 km
- At lower altitudes, radiation length <1km → shower development becomes similar

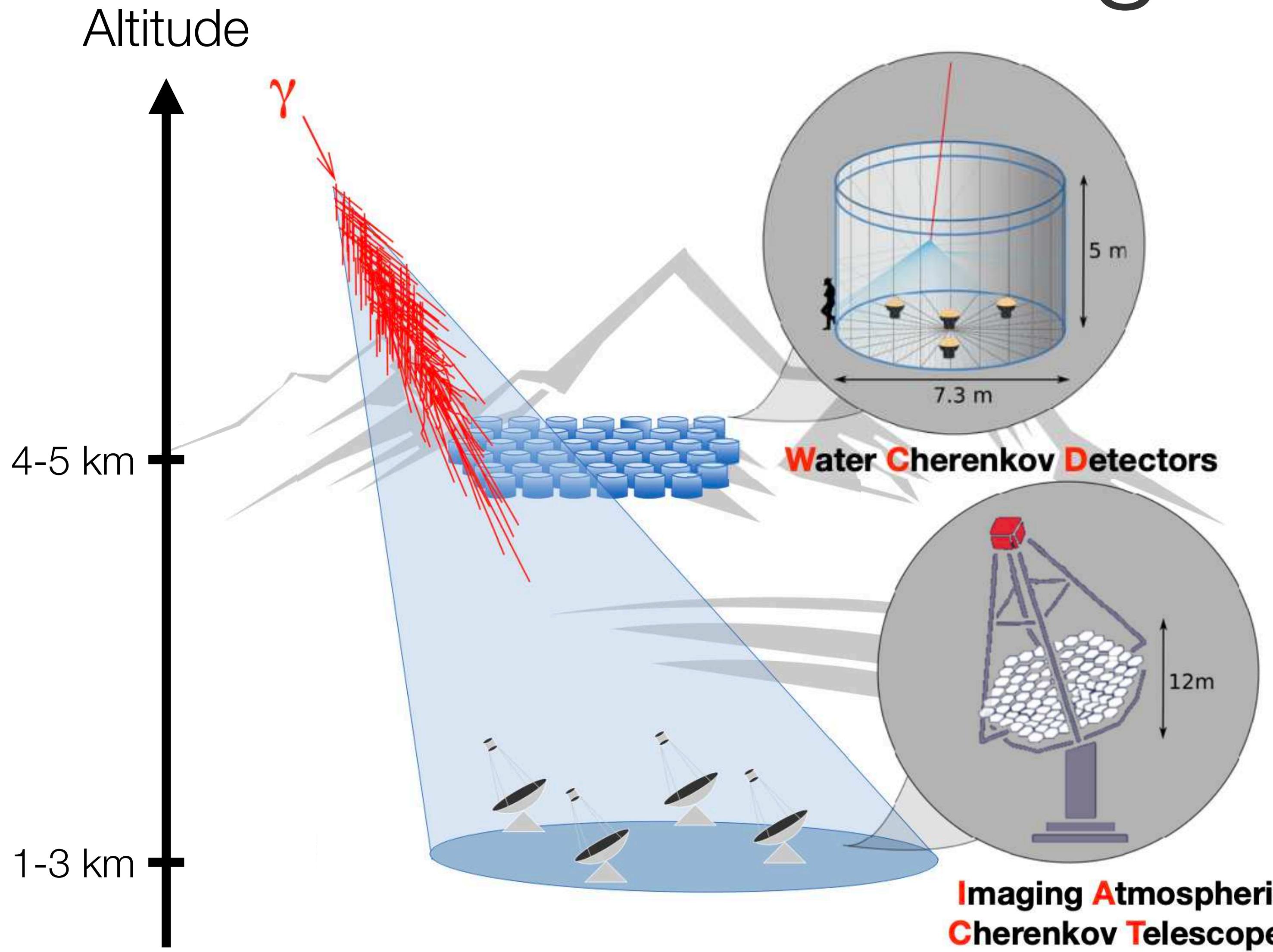


**Similar shower profiles, only shifted by few radiation lengths
→ relevant parameter is altitude**

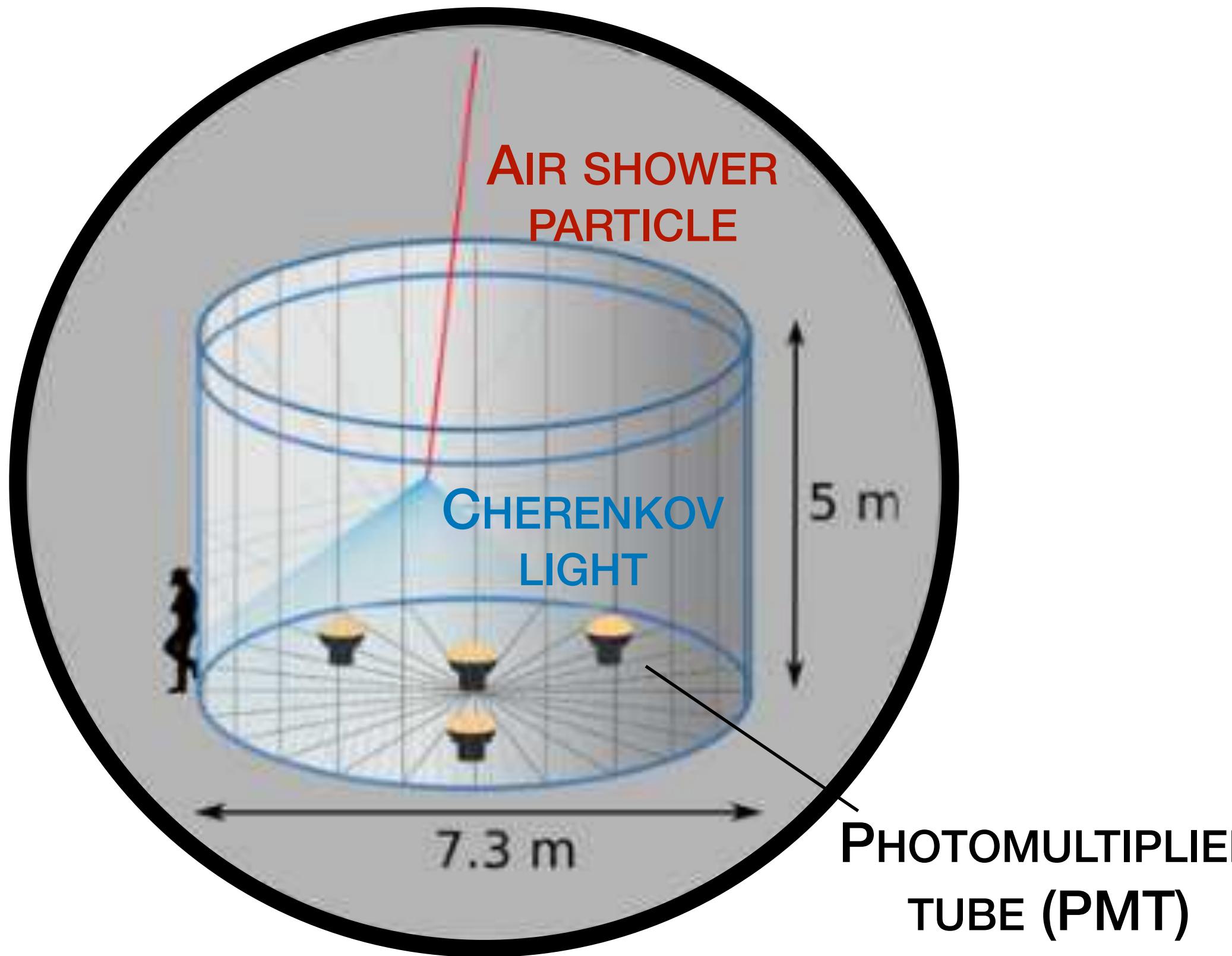
Detecting EASs



Detecting EASs



Water Cherenkov Detectors



Detecting method: showers particles reaching the ground ($\mu^\pm, e^\pm, \gamma, \nu$), in water, ground-based

Field of View (FOV): 50°

Duty cycle: 100% (operates in daylight too)

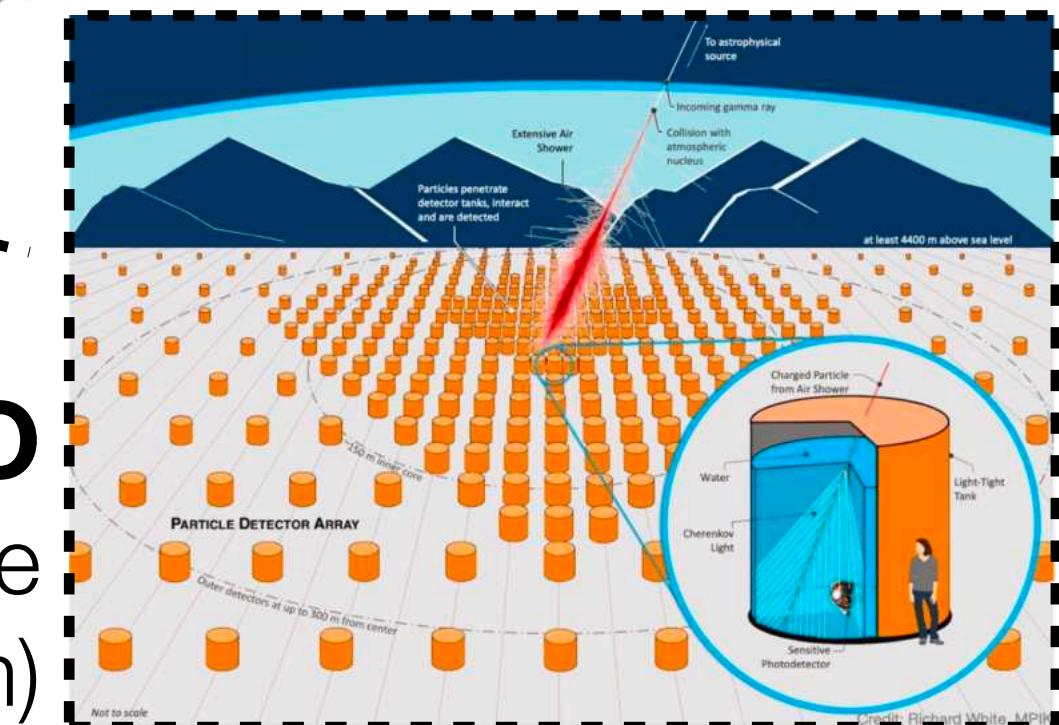
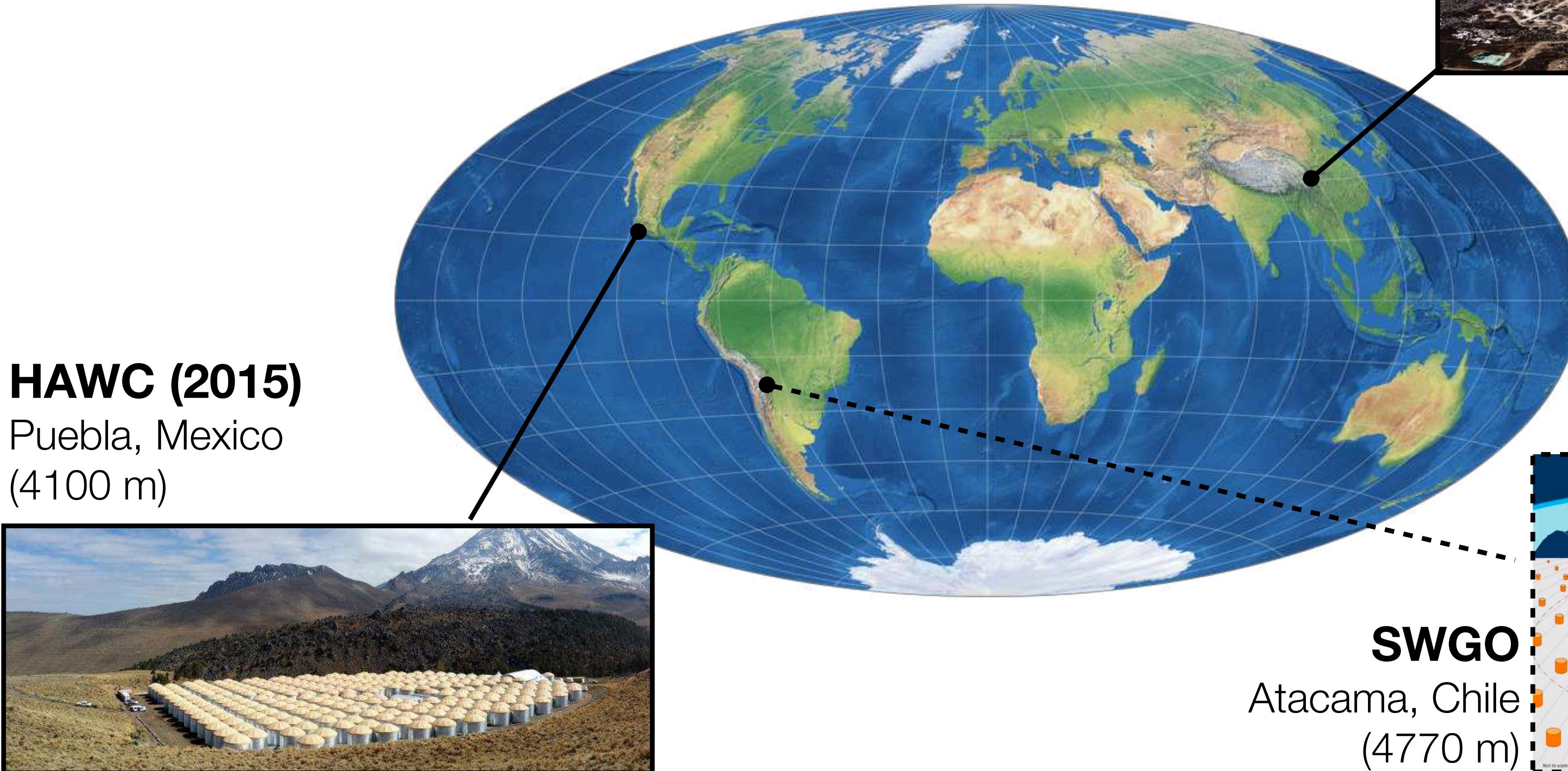
Angular resolution: $[0.1, 1]^\circ$

Energy resolution: ~30%

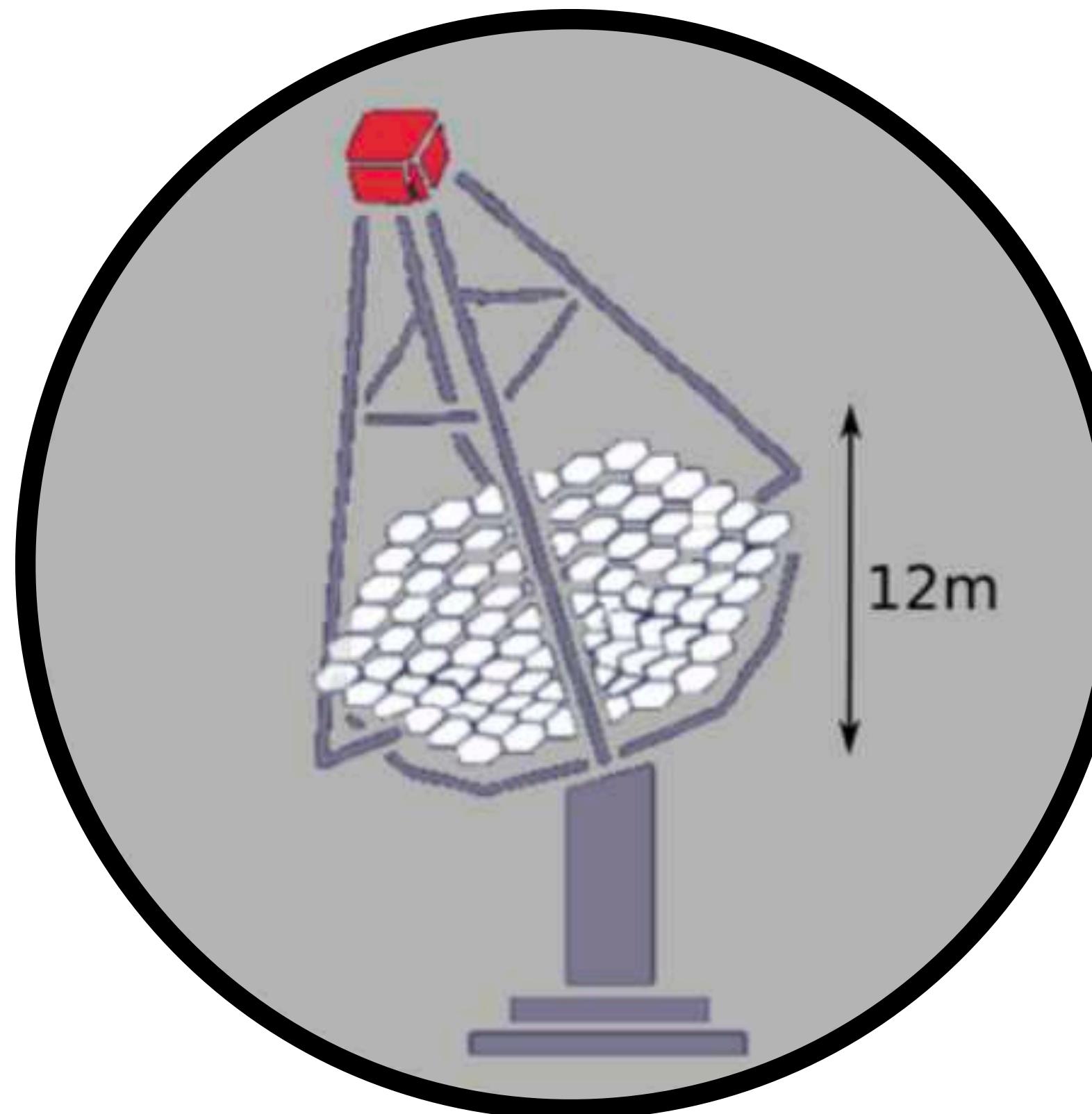
Effective area: $\sim 10^5 \text{ m}^2$

Energy range: ultra-high-energy regime (UHE, $E > 100 \text{ TeV}$)

Current and future generation of WCDs



Imaging Atmospheric Cherenkov Telescopes (IACTs)



Detecting method: Cherenkov radiation induced by EAS in atmosphere, ground-based, pointing

Field of View (FOV): 2-6°

Duty cycle: 10-15% (clear, moonless nights)

Angular resolution: [0.04,1]°

Energy resolution: ~15%

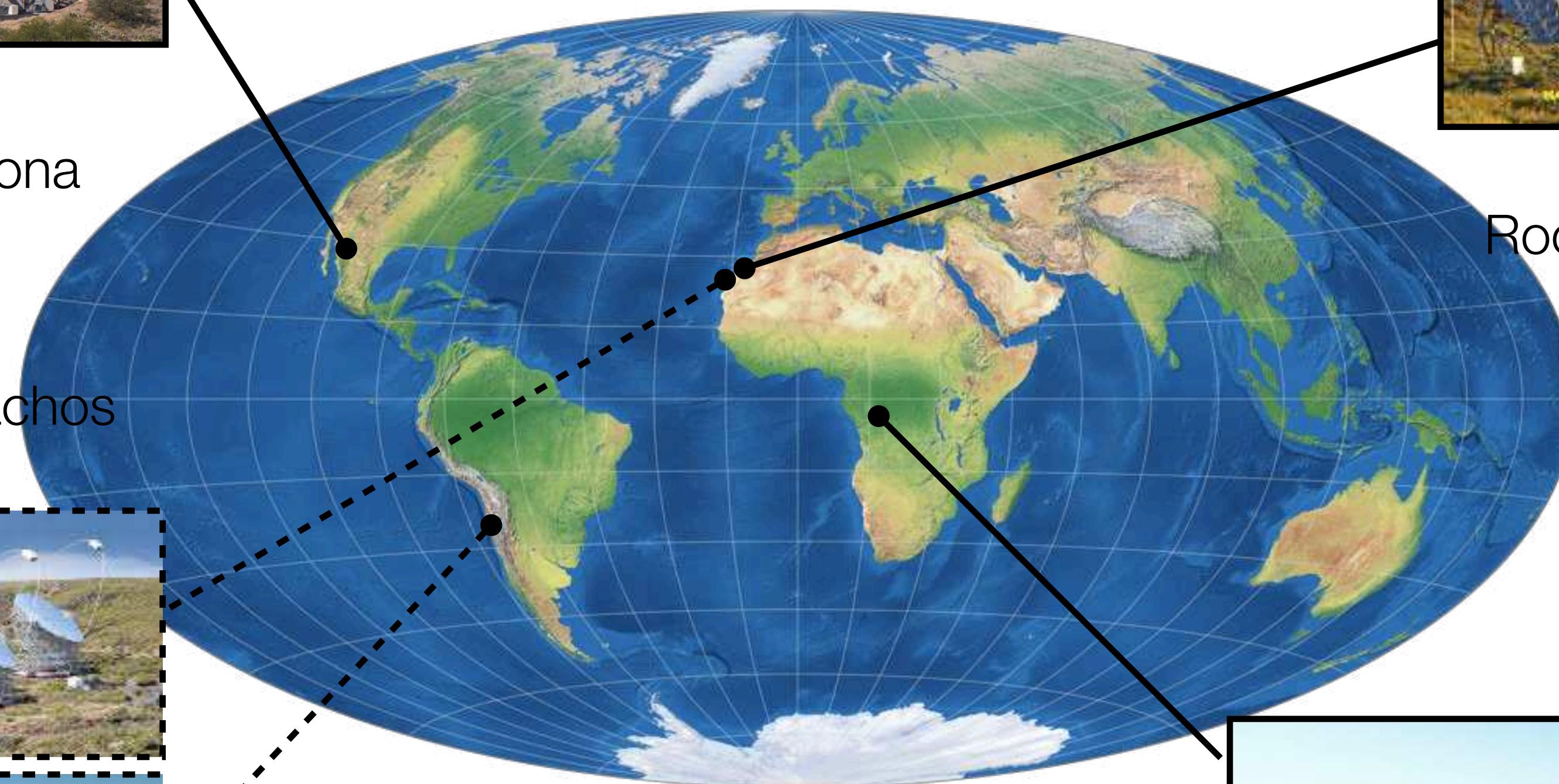
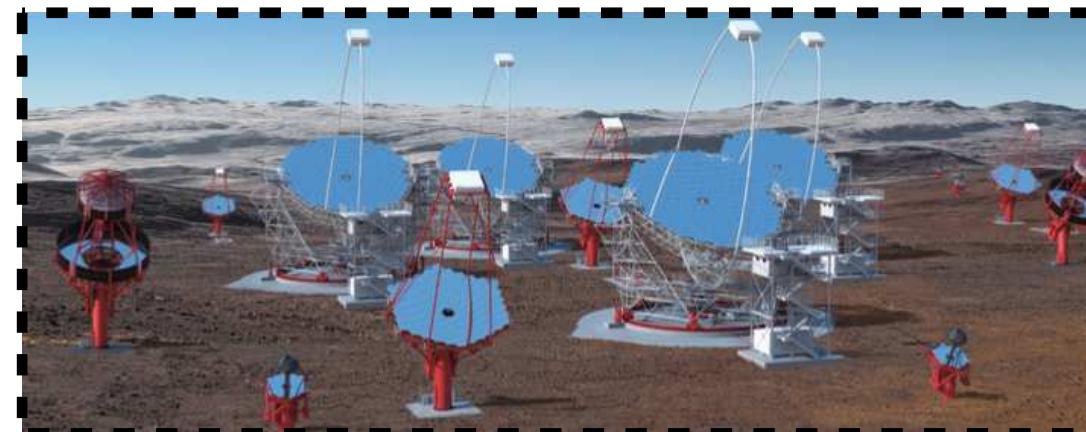
Effective area: ~ 10^5 m²

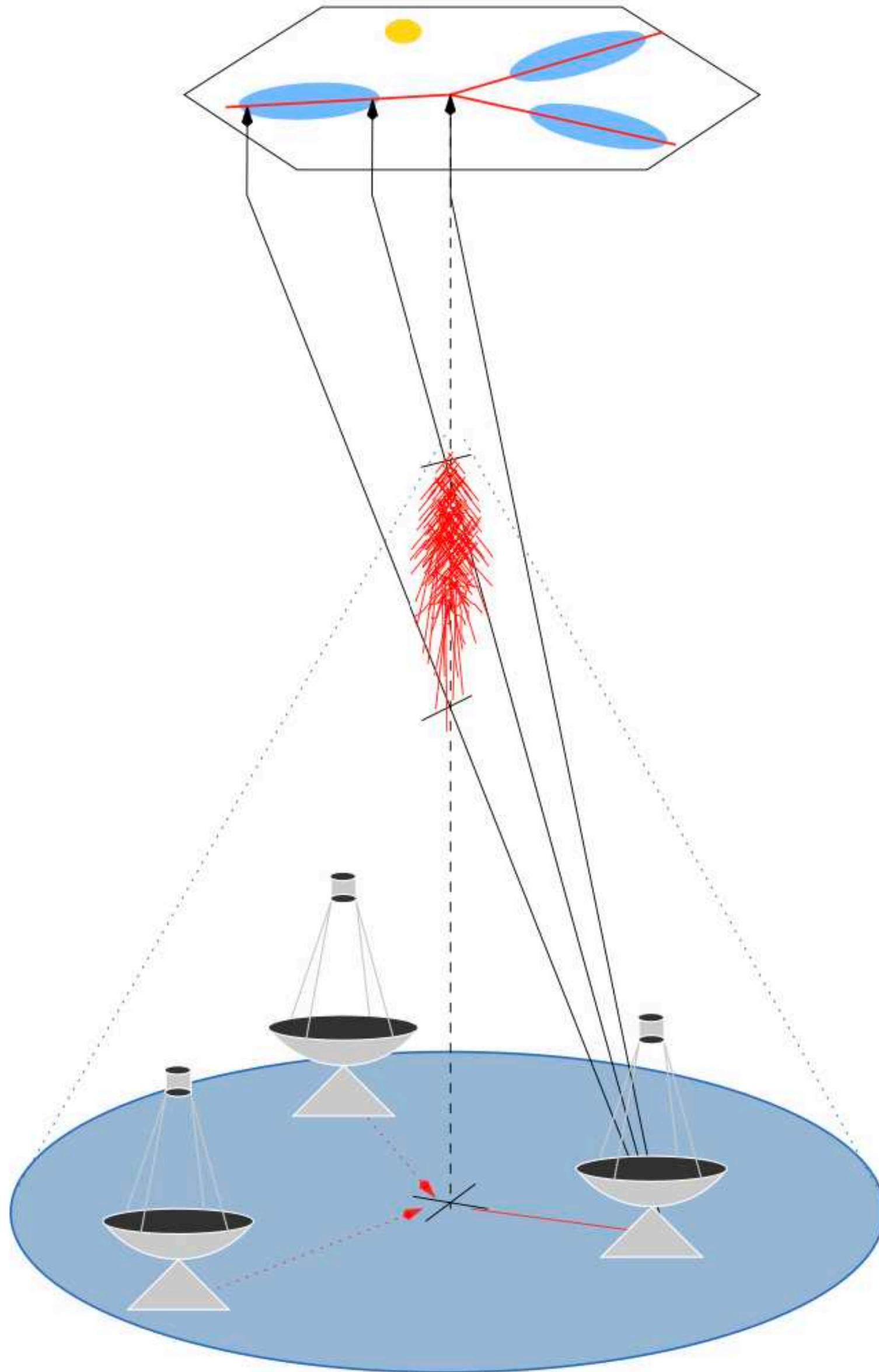
Energy range: wide (50-100 TeV)

Current and future generation of IACTs

**VERITAS**

Mount Hopkins, Arizona

**MAGIC**Roche de los Muchachos
Canary Island**CTAO - North**Roche de los Muchachos
Canary Island**H.E.S.S. (2002)**Khomas Highland,
Namibia



IACTs: detection principles

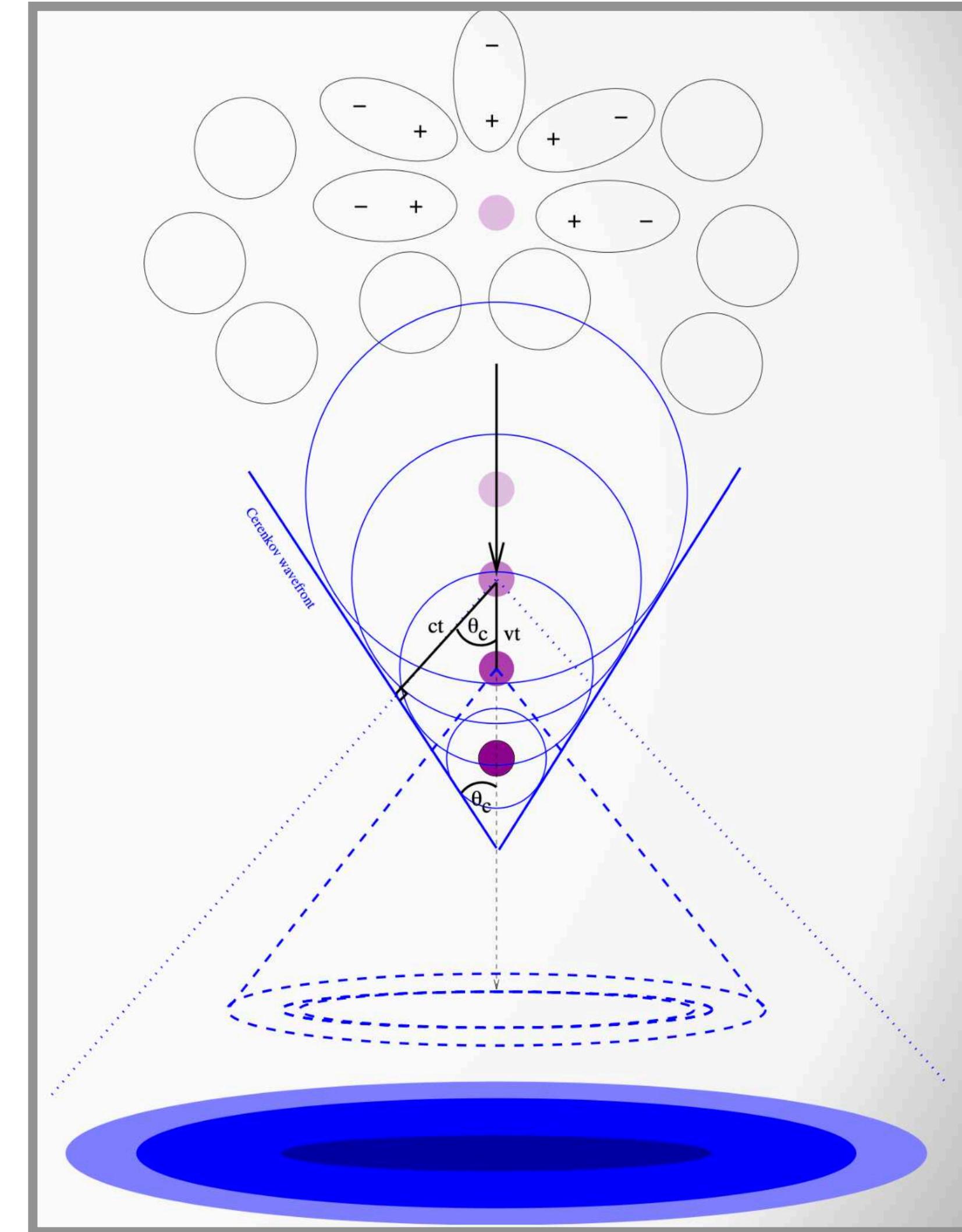
Cherenkov radiation

- Polarization of dielectric medium by charged particles
- Constructive interference when particle is faster than the emitted radiation (c/n)
- Emission in a cone with respect to the particle direction

Cherenkov condition: $n\beta > 1$

Light is emitted along a cone with half opening angle θ :

$$\cos \theta = \frac{1}{n\beta}$$



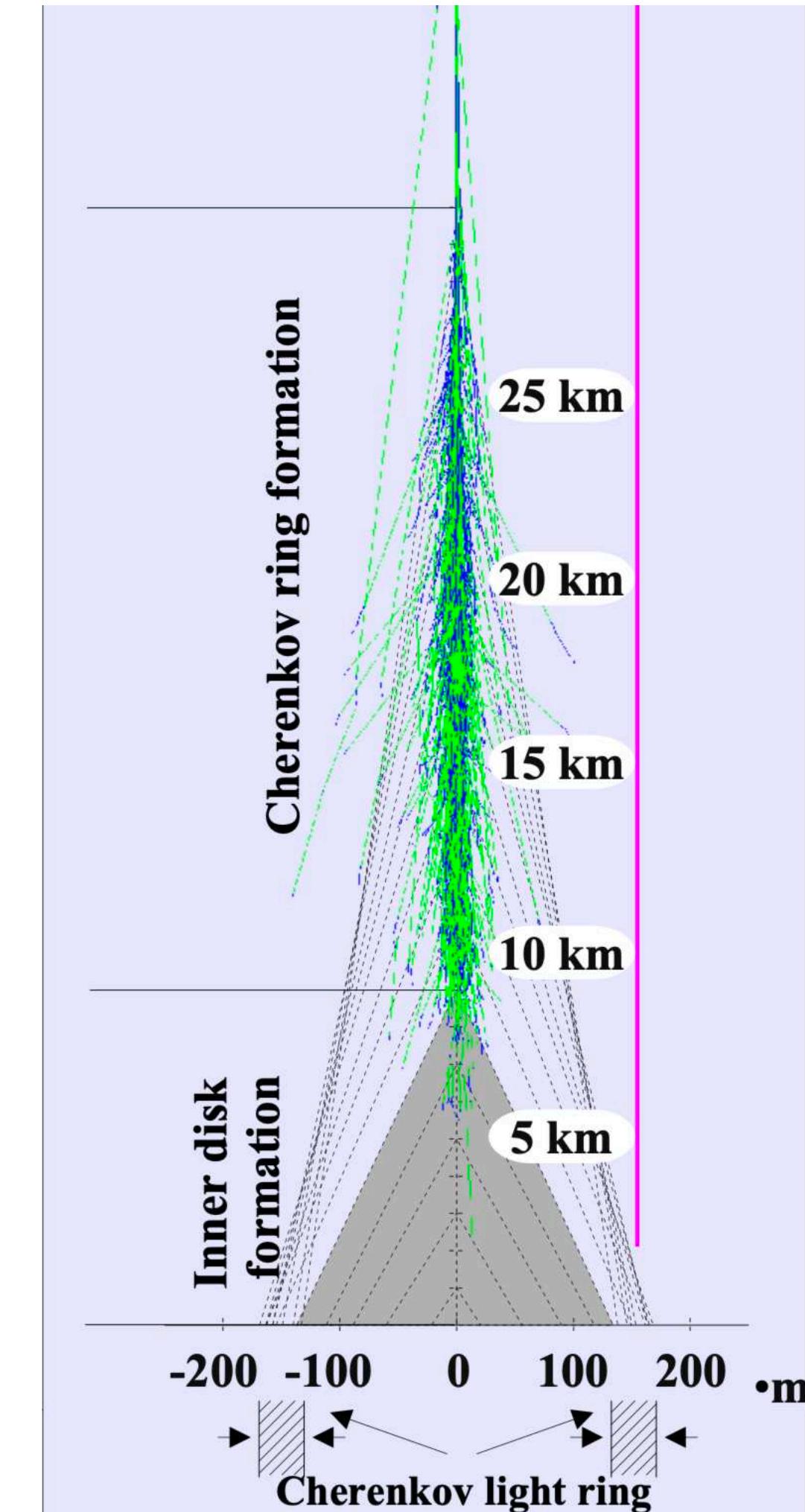
Cherenkov radiation

In the atmosphere

- Refractive index: $n - 1 \propto \rho(z)$
- Atmospheric density profile:

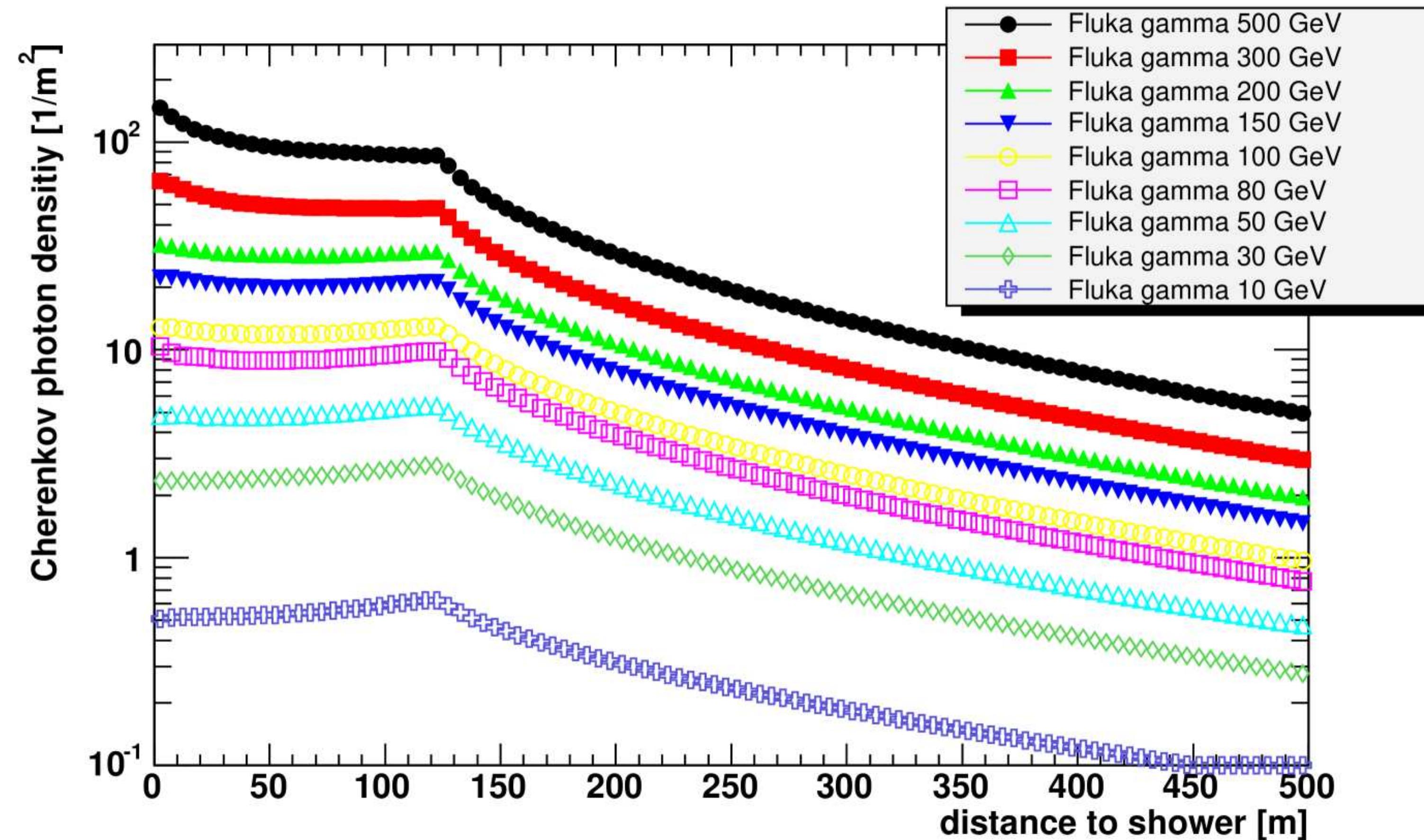
$$\rho(z) \propto \rho_0 \exp\left(-\frac{z}{z_0}\right)$$

- Evolution of the Cherenkov angle with altitude z :



Cherenkov radiation

Cherenkov photon density on ground

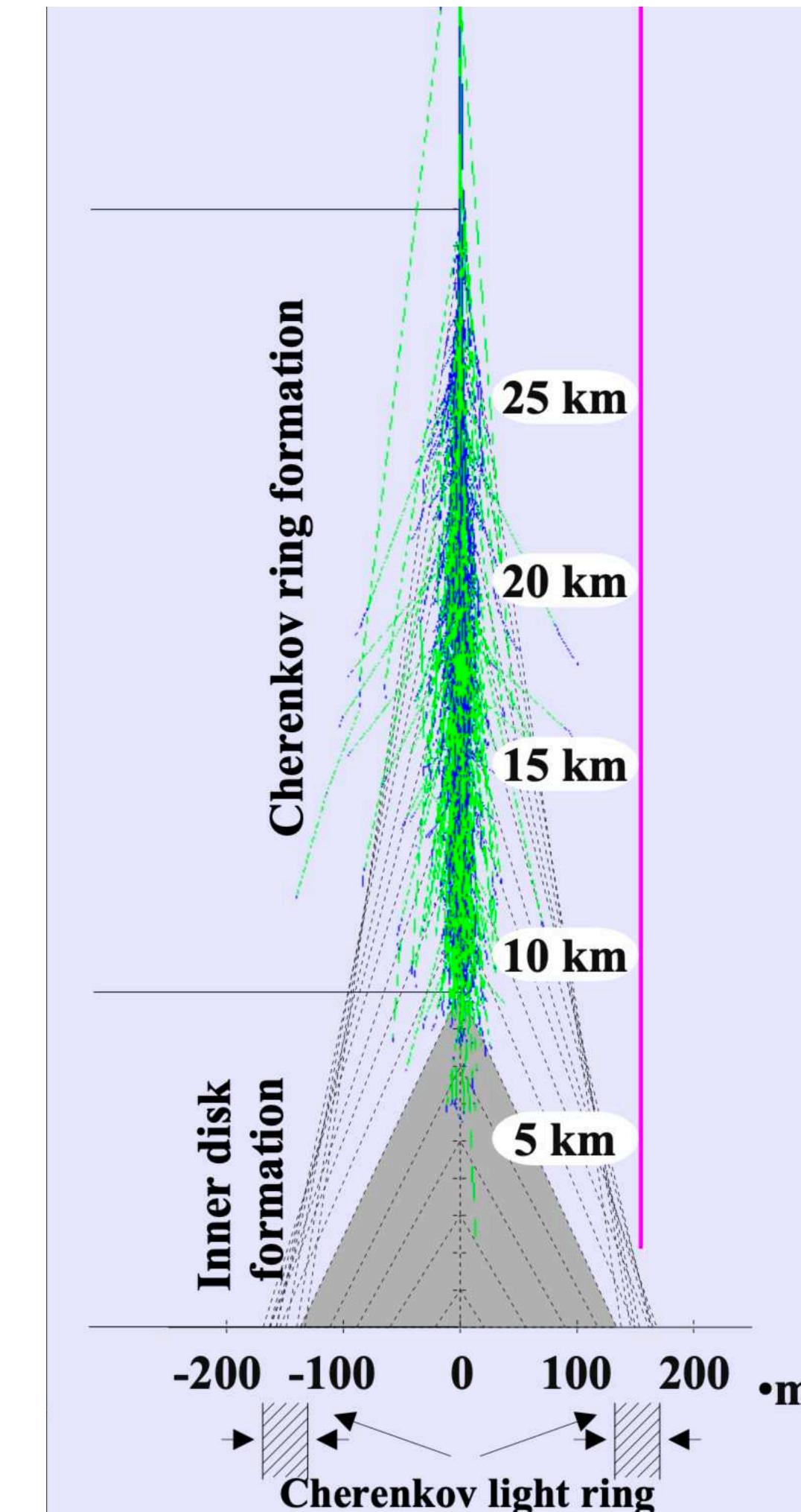
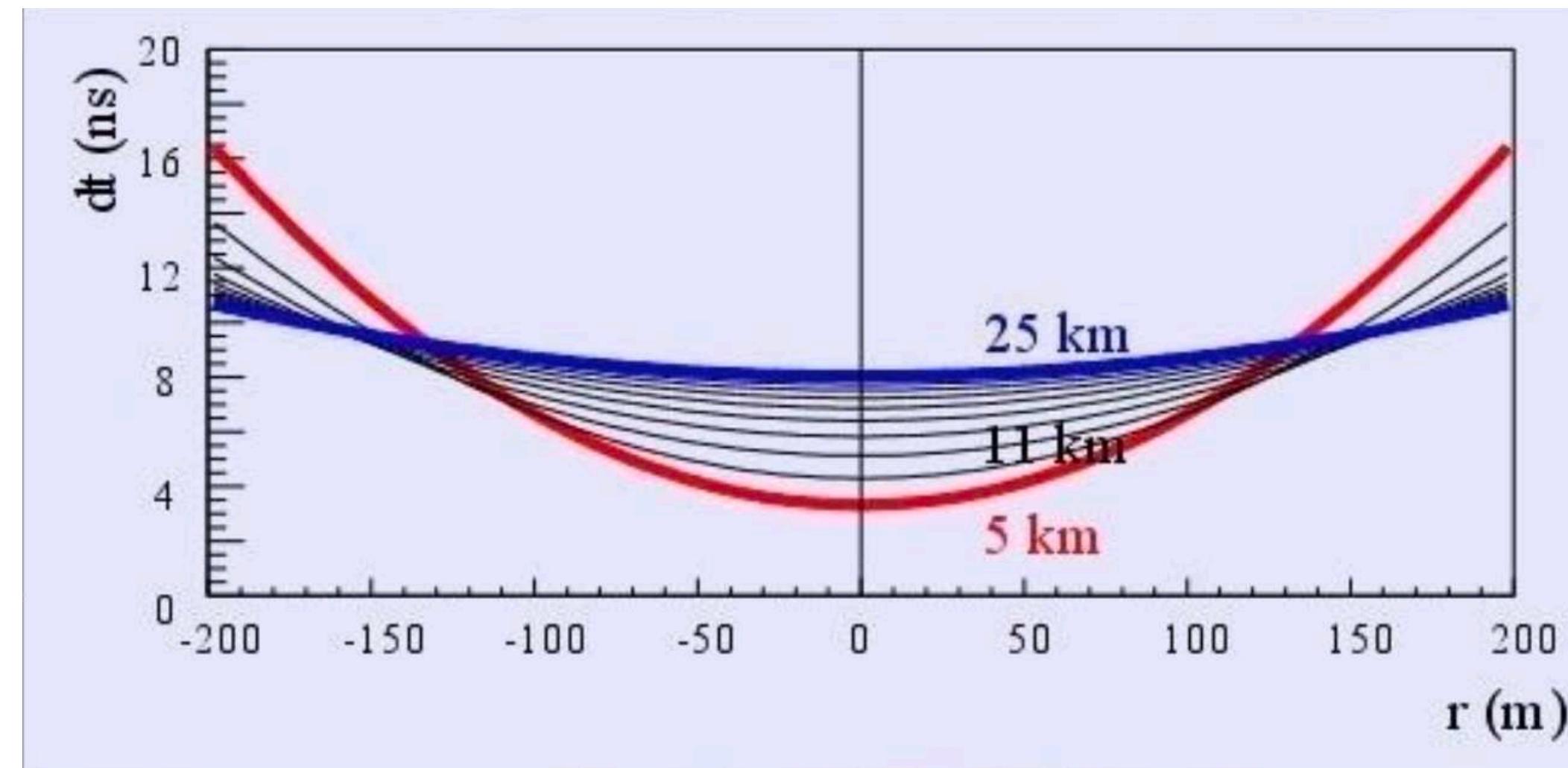


Cherenkov radiation

Temporal aspect

Competition between geometrical path and particle speed:

- Close to shower axis, light emitted at the bottom is first
- Far away, light emitted at high altitude arrives first
- Transition ~ 125 m (depends on altitude), short duration flash (~ 2 ns)



Cherenkov radiation at IACTs

Orders of magnitude for $E_\gamma \sim 1 \text{ TeV}$

Shower maximum:

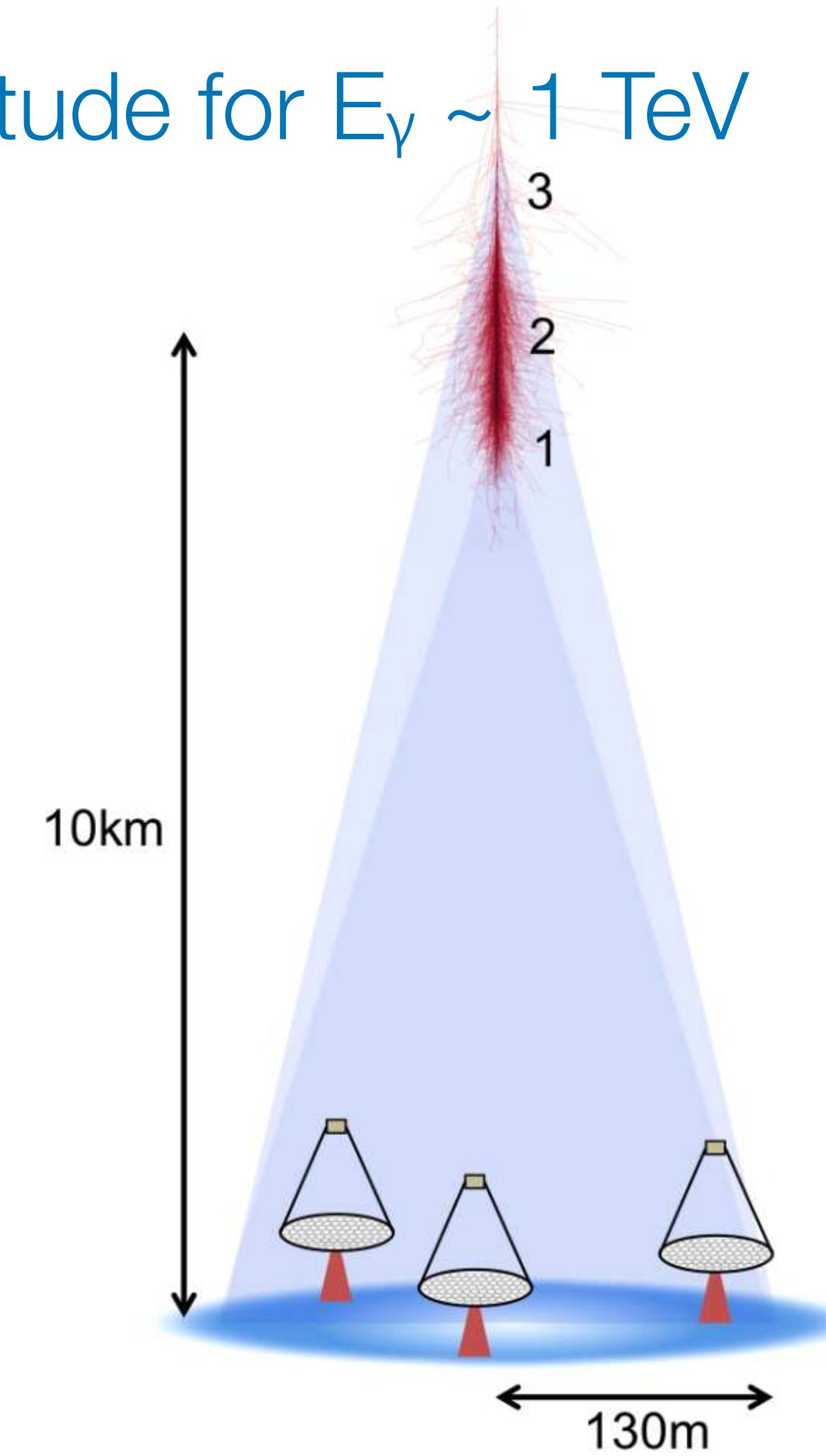
- Altitude $\sim 10 \text{ km}$
- $\sim 10^3$ charged particles

Cherenkov emission:

- Altitude $\theta_{\text{Cherenkov}} \sim 1^\circ$
- Duration $< 10 \text{ ns}$
- UV light

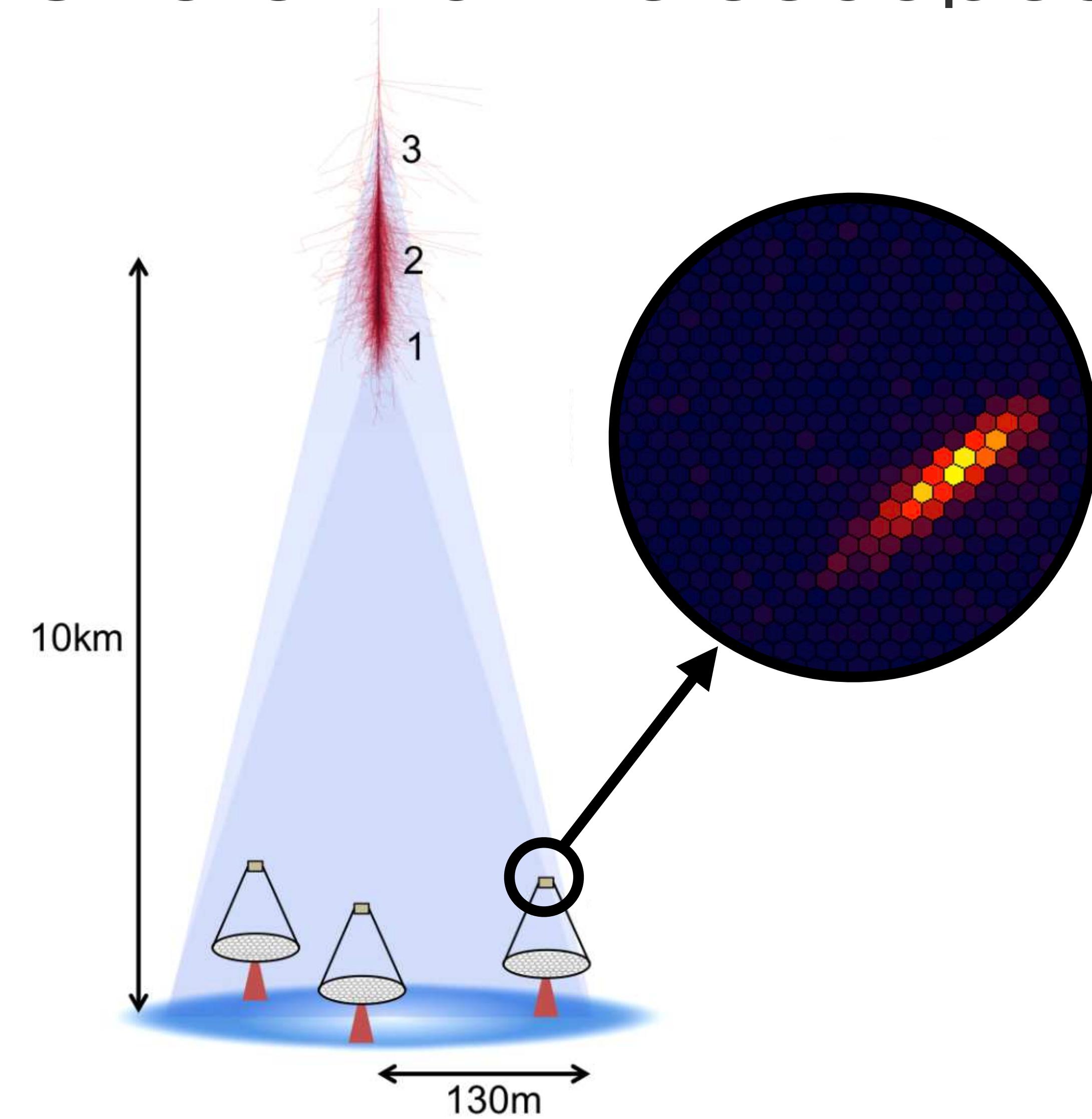
Cherenkov light-pool on ground:

- $R \sim 100 \text{ m}$
- $\sim 100 \text{ } \gamma_{\text{Cherenkov}}/\text{m}^2$



Imaging Atmospheric Cherenkov Telescopes

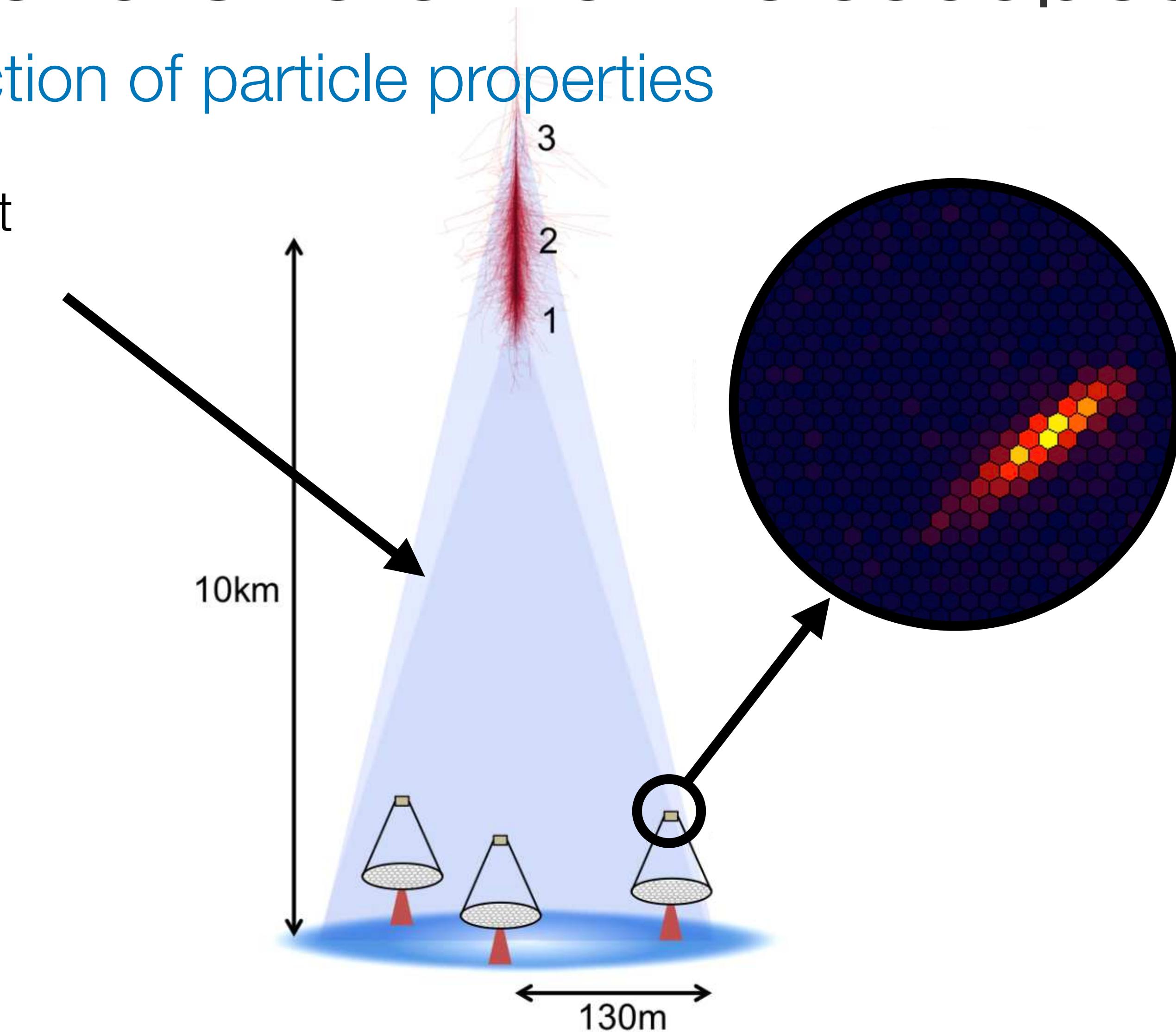
- Cherenkov light-pool ~120 m
- Image the shower on a fast camera ($\Delta t \sim 2\text{ns}$)
- Large effective area (10^5 m^2) even with modest reflector
- Change in Cherenkov angle + multiple Coulomb-scattering washes out the ring shape of the Cherenkov light \rightarrow faint elliptical shaft of UV light



Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light
(calorimeter)

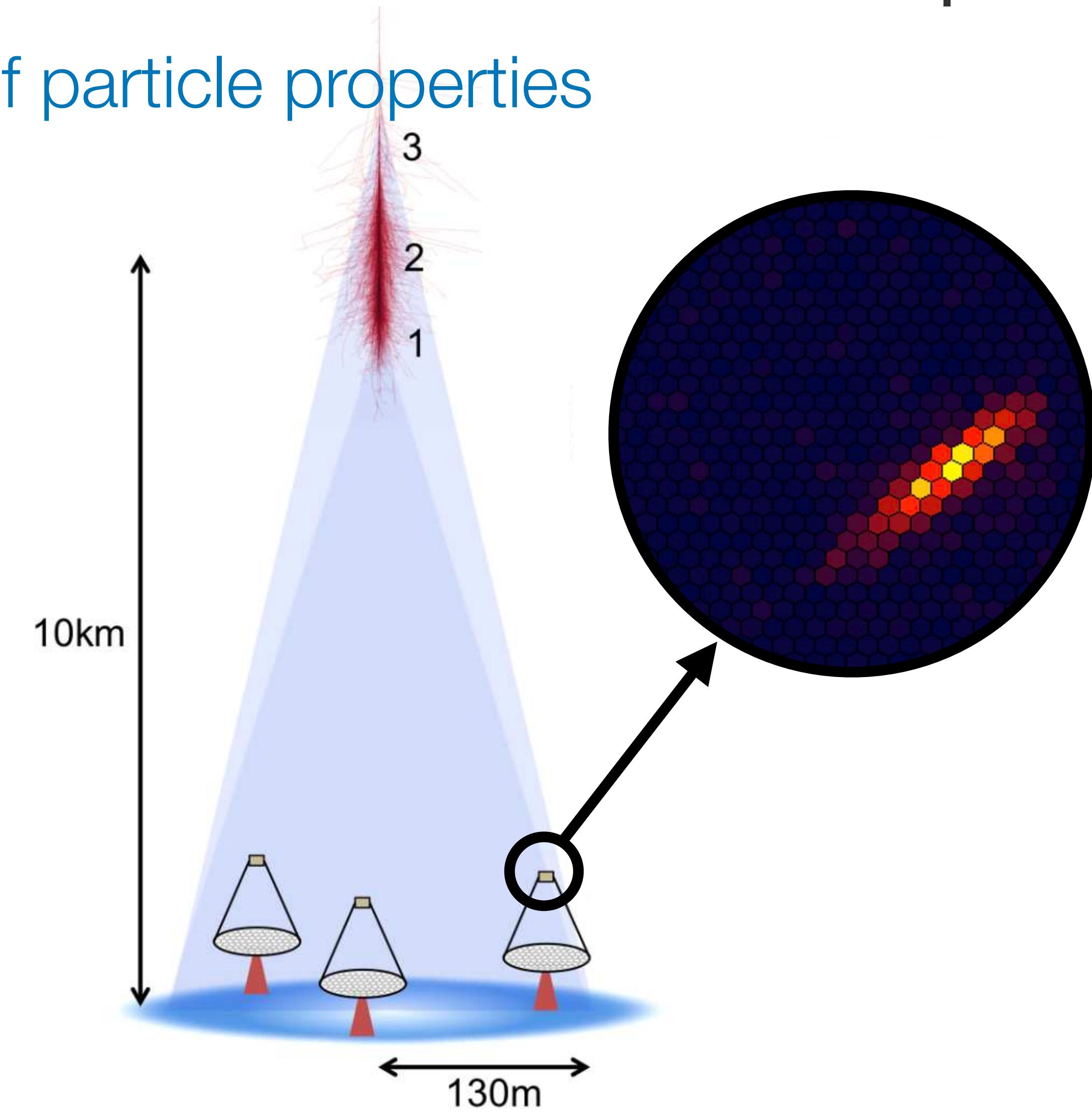
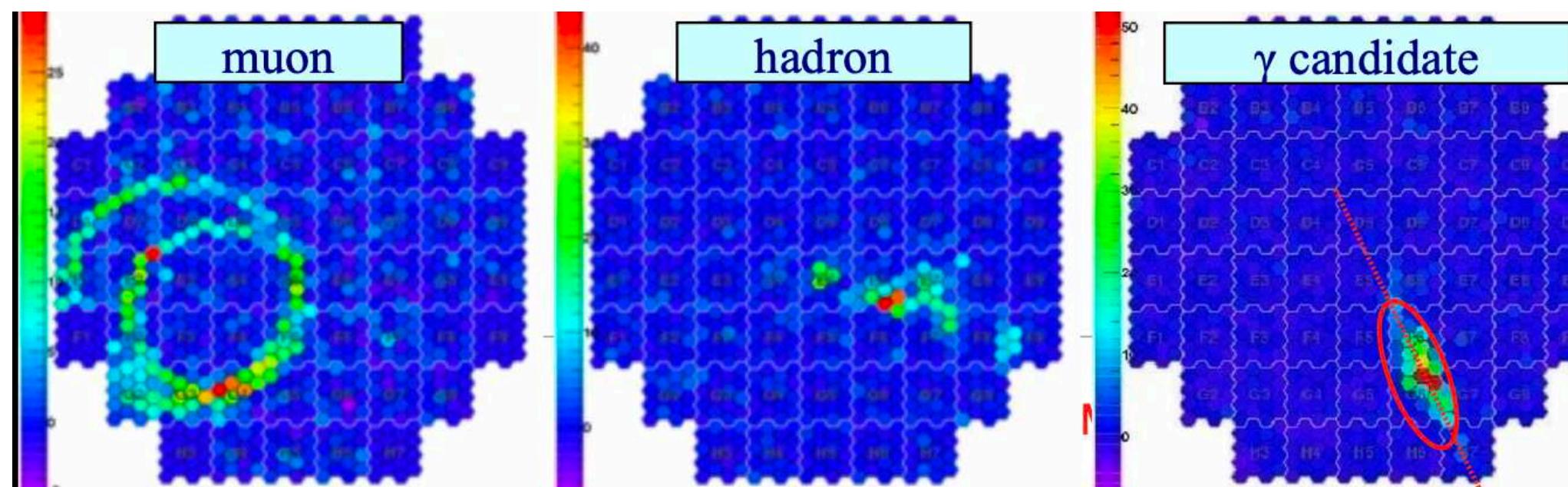


Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light
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Nature: shape of the shower



Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light
(calorimeter)

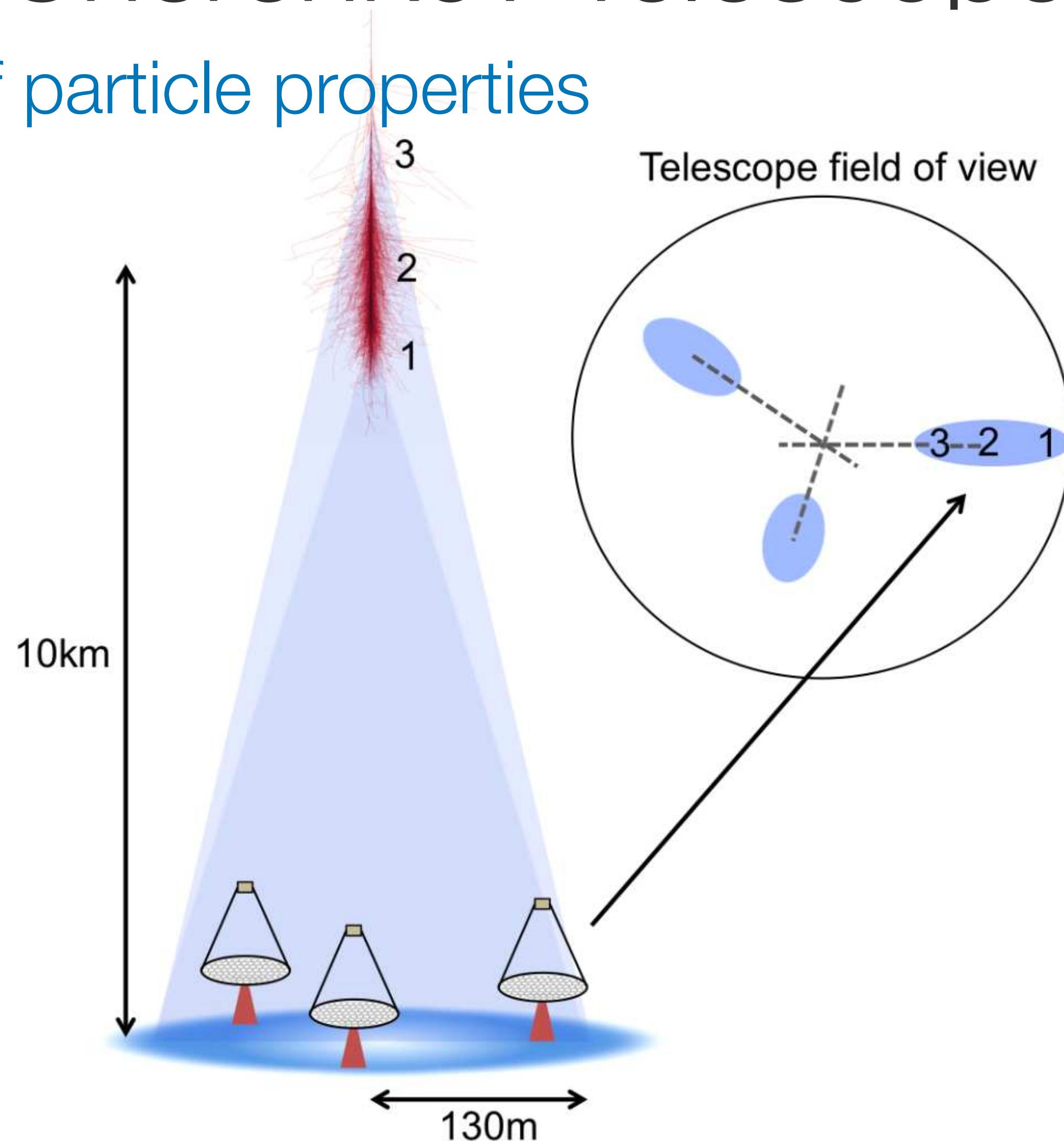
Nature: shape of the shower

Direction: stereoscopic observation



Directional reconstruction by geometrical
intersection of image main axes

- Greatly reduces the background at the trigger level (requiring 2-tel coincidence)
- Significantly improves shower reconstruction, PSF, etc



Imaging Atmospheric Cherenkov Telescopes

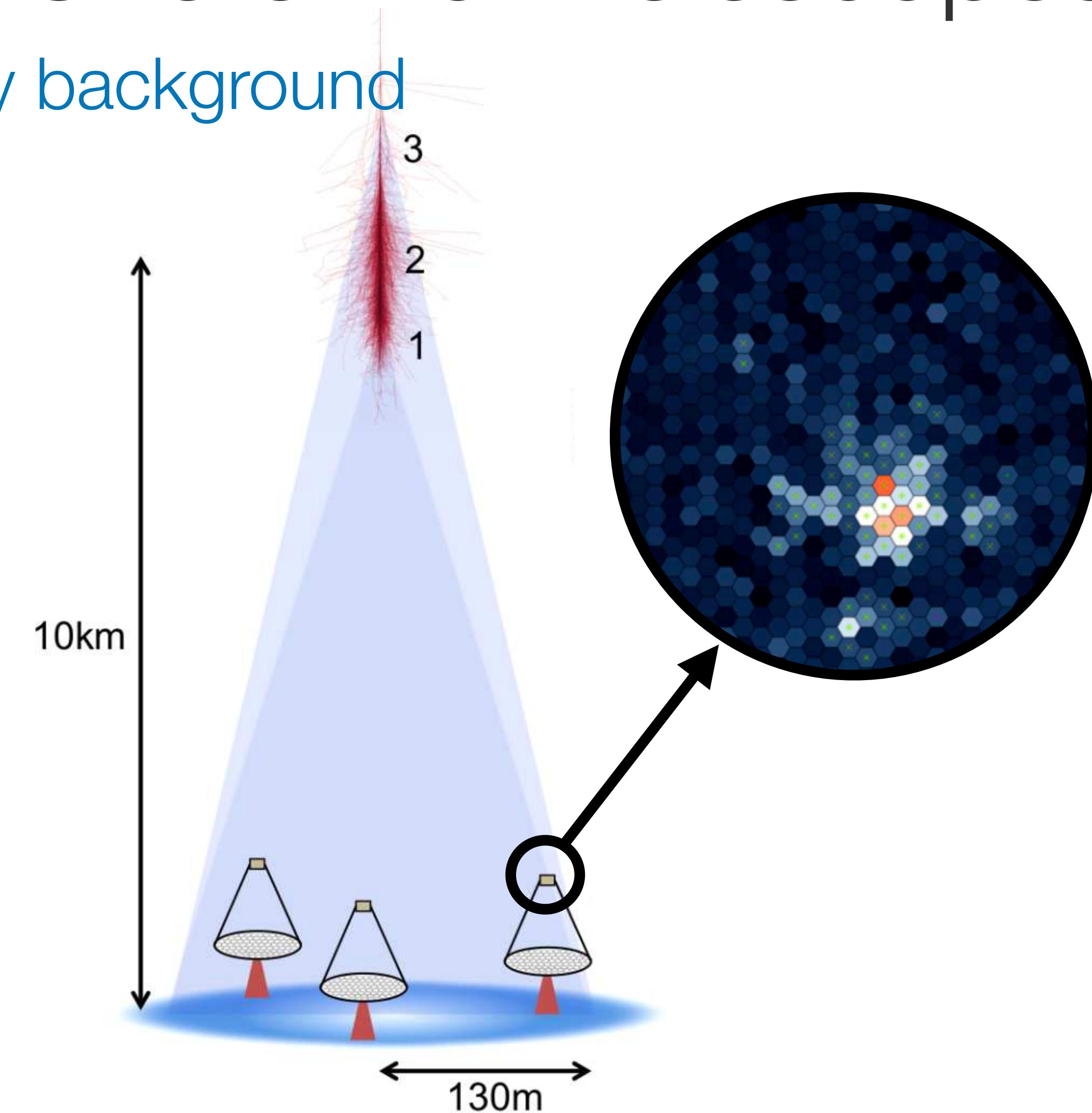
Cosmic-ray background

$10^4 - 10^5$ more cosmic rays than gamma rays

Stereo trigger: $\approx 1/4$

Image analysis/shape: $\approx 1/250$

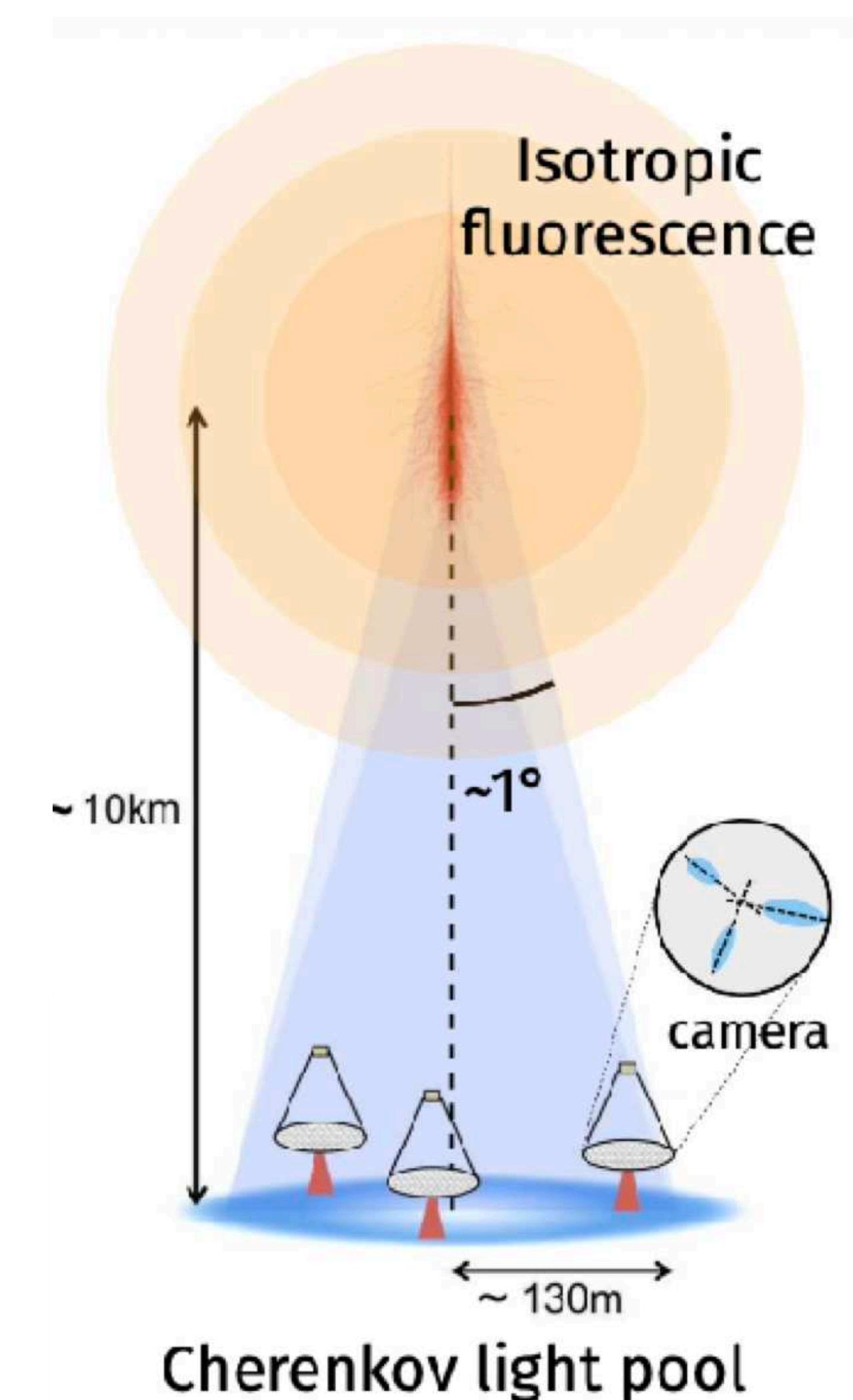
Arrival direction: $\approx 1/100$



Backgrounds

Fluorescence

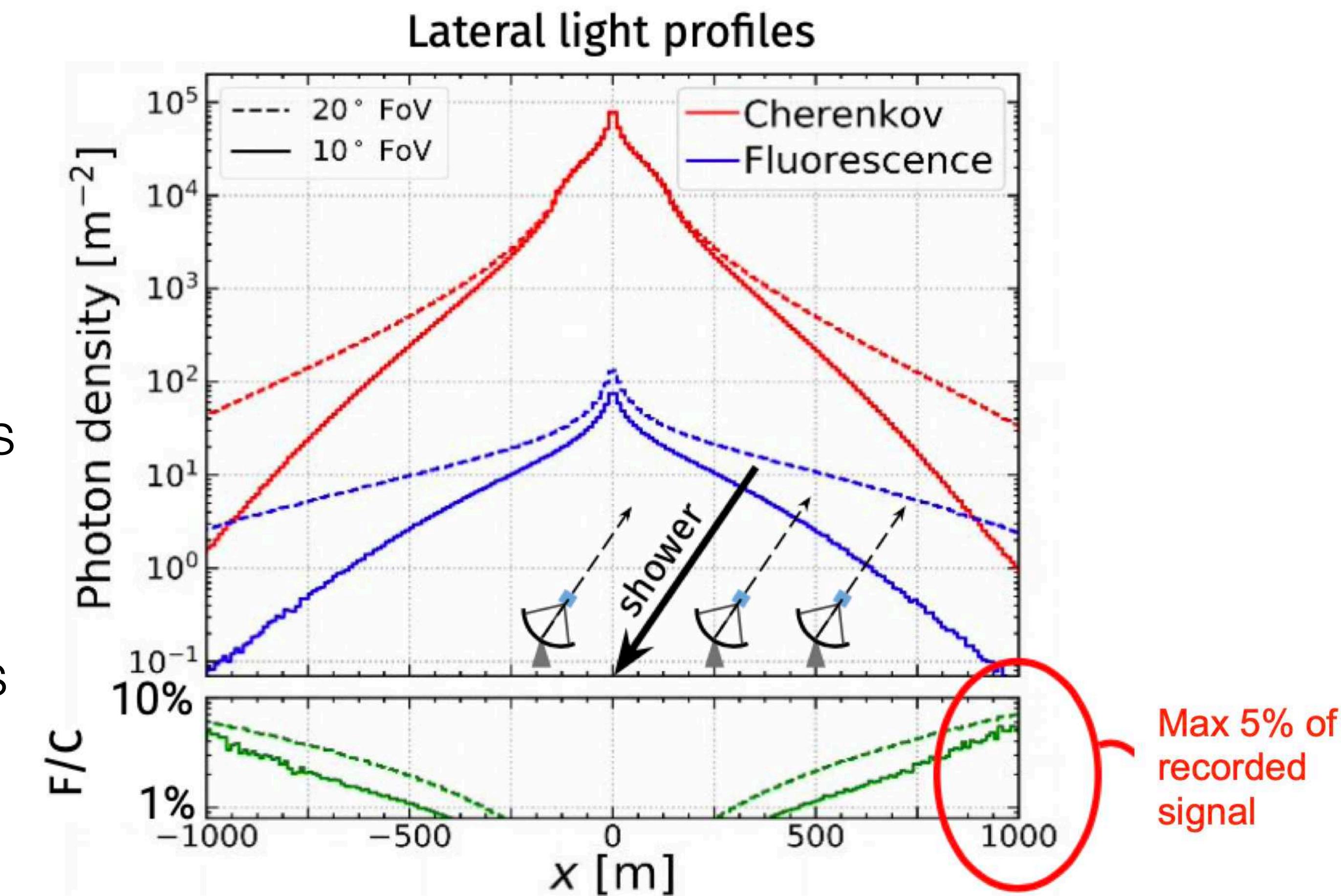
- Fluorescence emission from de-excitation of N₂ states (290-430 nm)
- Less efficient light emission:
 - For 1 GeV electron near ground:
30 photon from Cherenkov light vs
4 photons from fluorescence light
(per m track length)
 - Longer time profile: microseconds vs
10s of nanoseconds



Backgrounds

Fluorescence

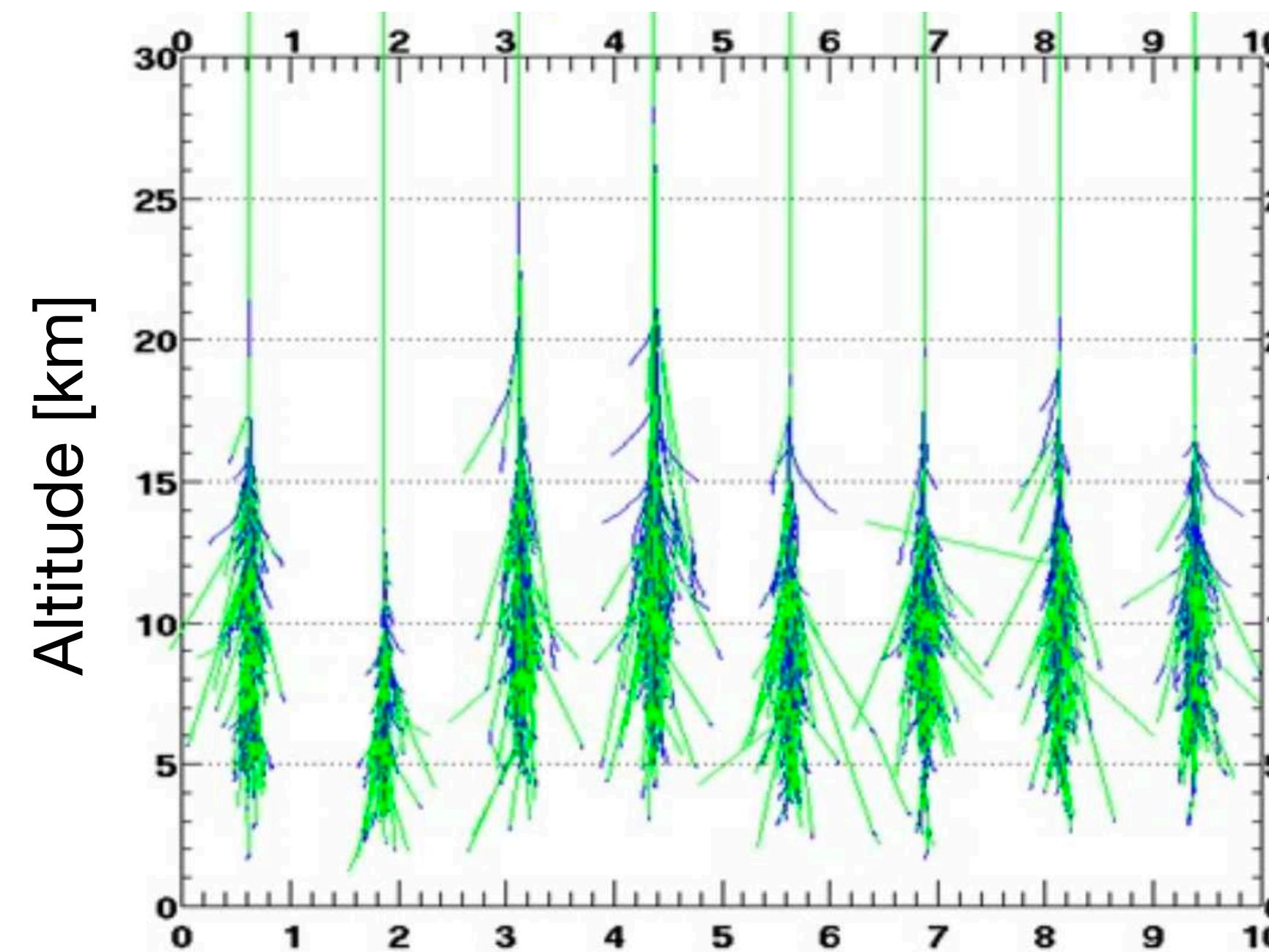
- Fluorescence emission from de-excitation of N_2 states (290-430 nm)
- Less efficient light emission:
 - For 1 GeV electron near ground: 30 photons from Cherenkov light vs 4 photons from fluorescence light (per m track length)
- Longer time profile: microseconds vs 10s of nanoseconds



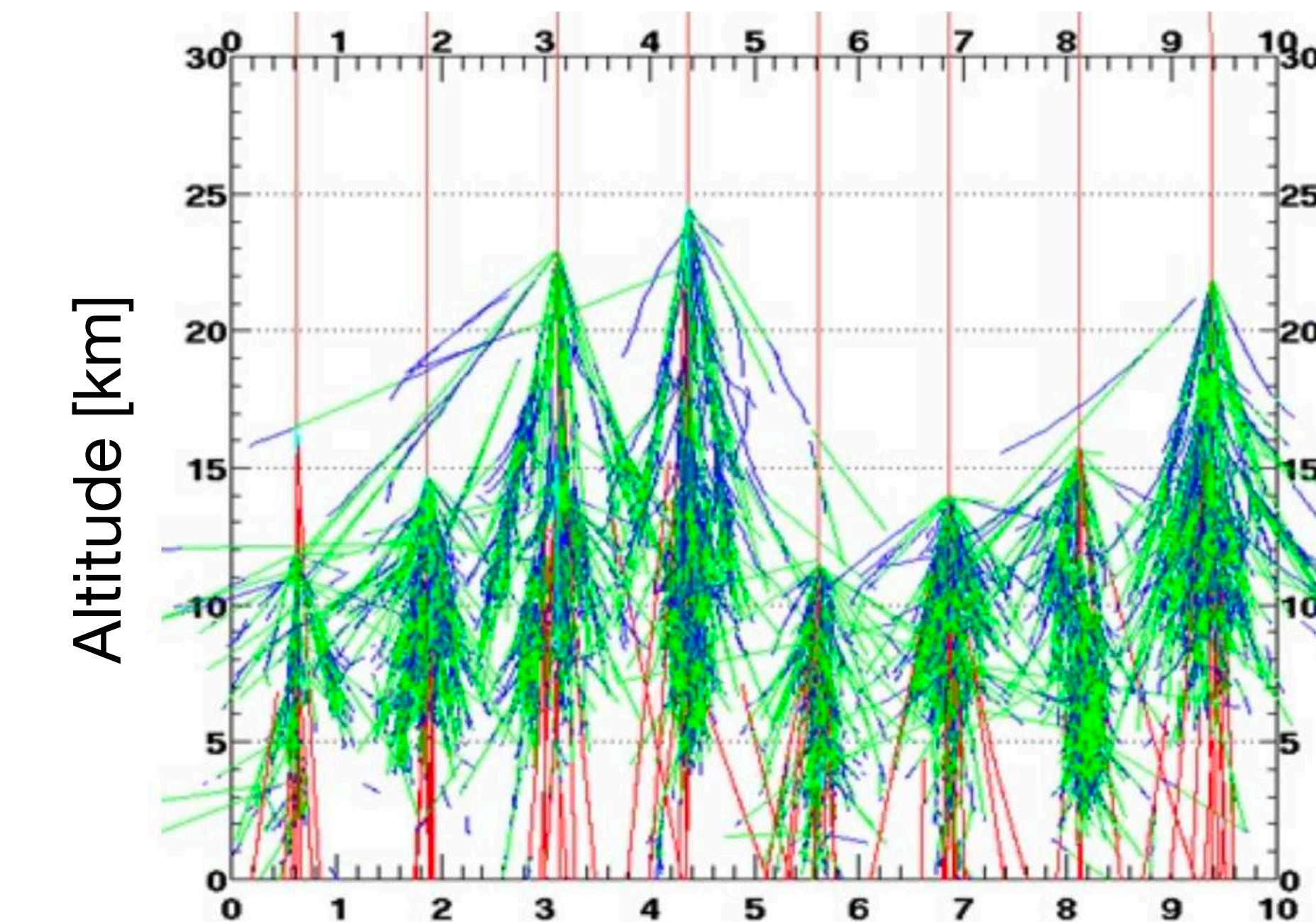
Backgrounds

Hadronic showers

GAMMAS, 100 GeV



PROTONS, 500 GeV

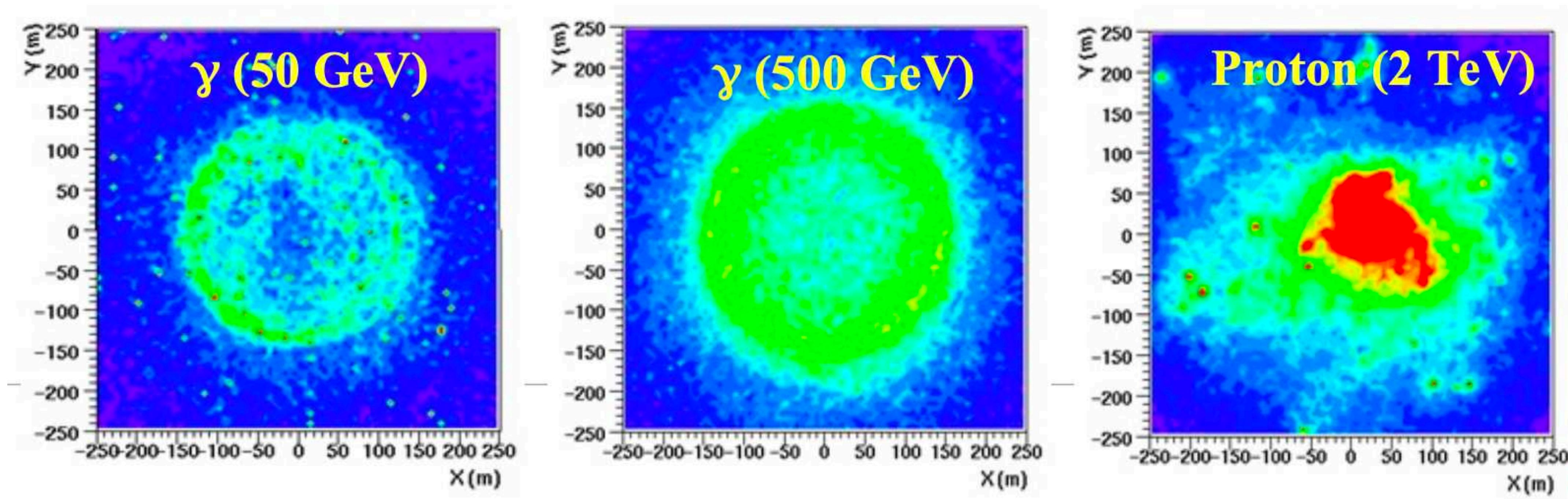


For hadronic showers, the higher transverse momentum from pion production and sub-showers produce a wider shower

→ the width of the shower can be used to discriminate gammas from hadrons

Backgrounds

Hadronic showers



For hadronic showers, the higher transverse momentum
from pion production and sub-showers produce a wider shower

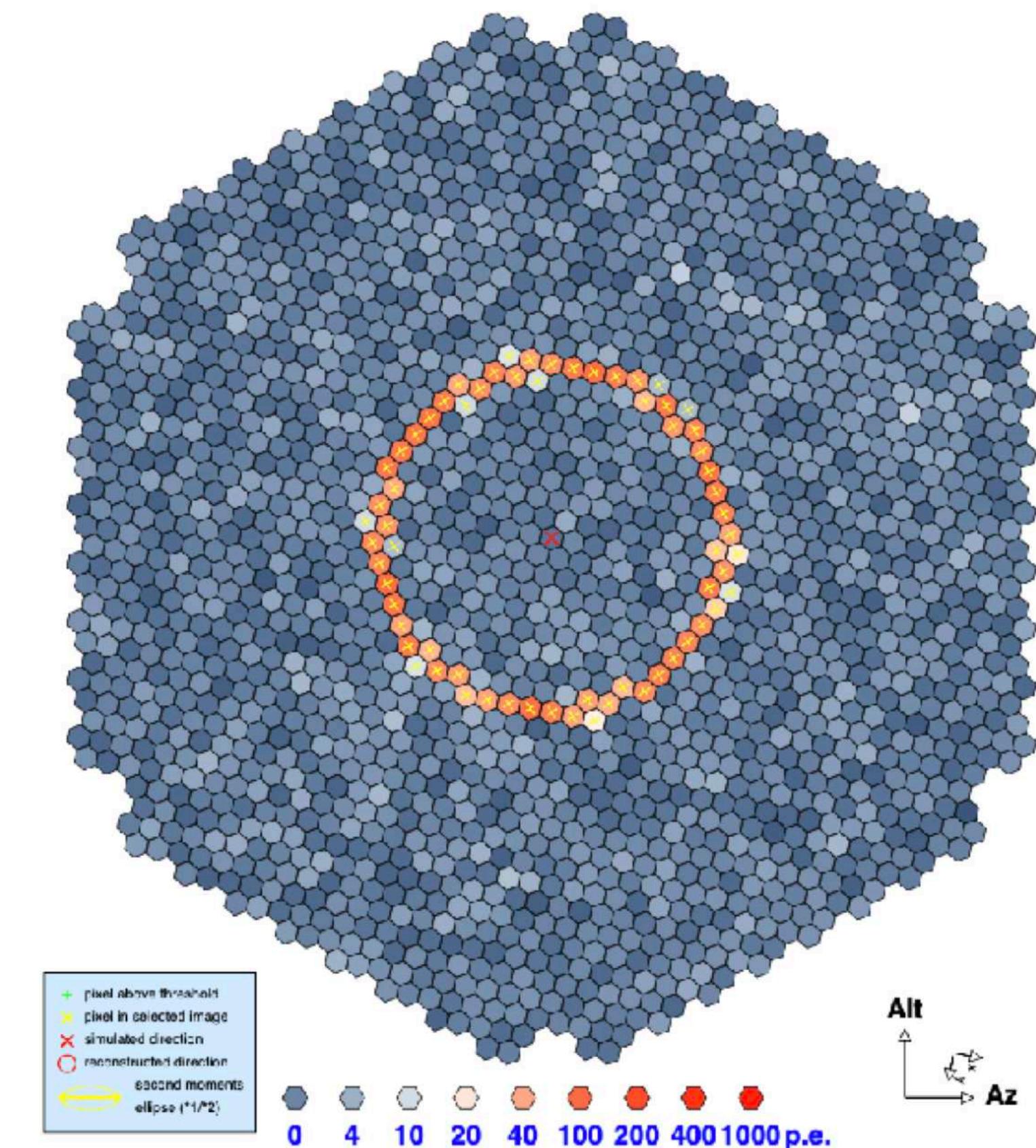
→ the width of the shower can be used to discriminate gammas from hadrons

Backgrounds

Hadronic showers: muons

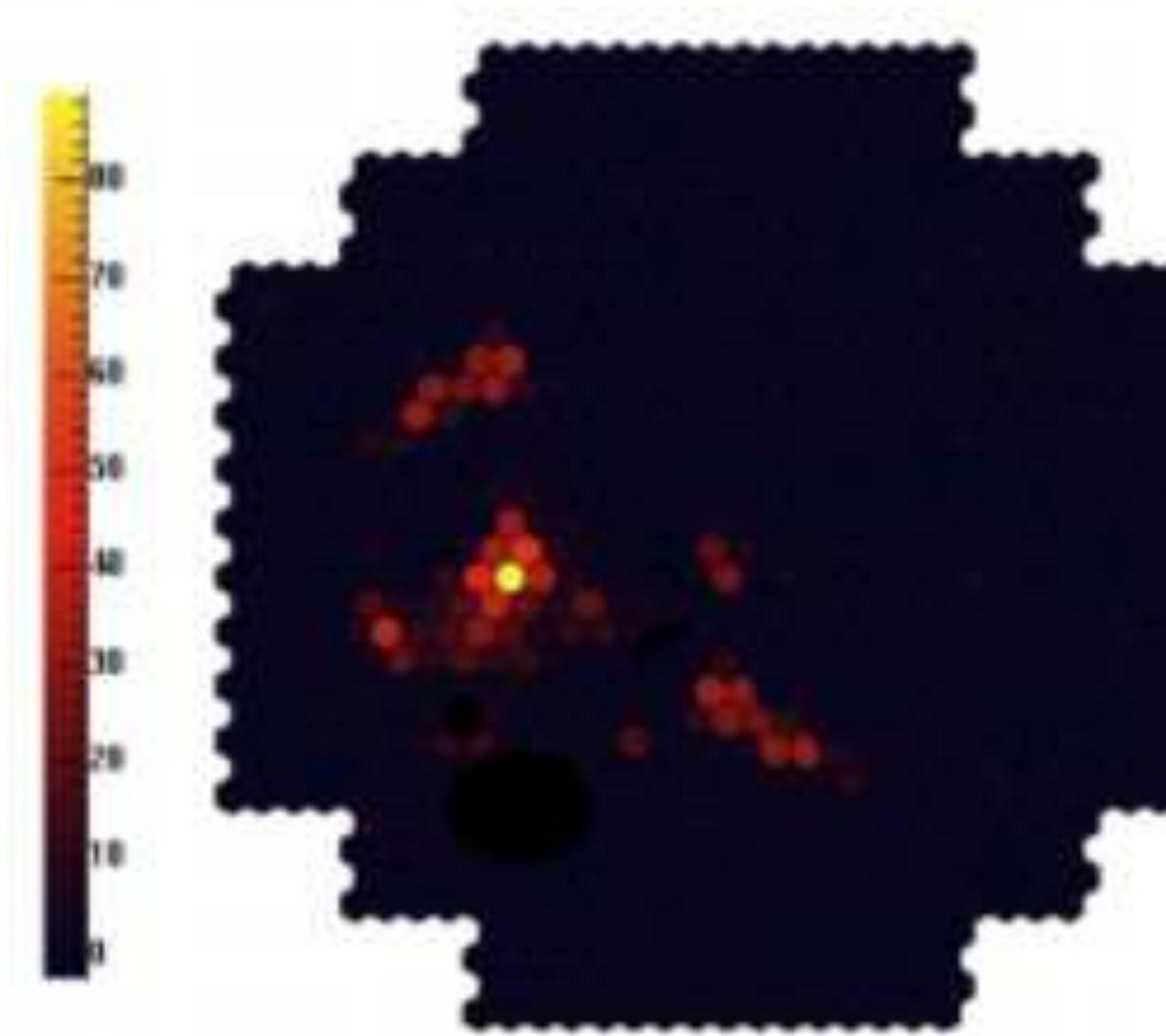
- Produced in hadronic sub-showers
- Most muons detected by IACTs are minimum ionizing particles with a long lifetime → large penetration depth
- Travel in straight lines towards the ground with Cherenkov radiation emitted under constant opening angle in a cone around the muon direction of travel
- As IACTs image in angular space, the Cherenkov light from muons traveling parallel to the telescope's optical axis forms a **ring-shaped image in the camera**

⇒ Partial muon arcs look much like EM showers,
particularly a problem at ≈ 100 GeV

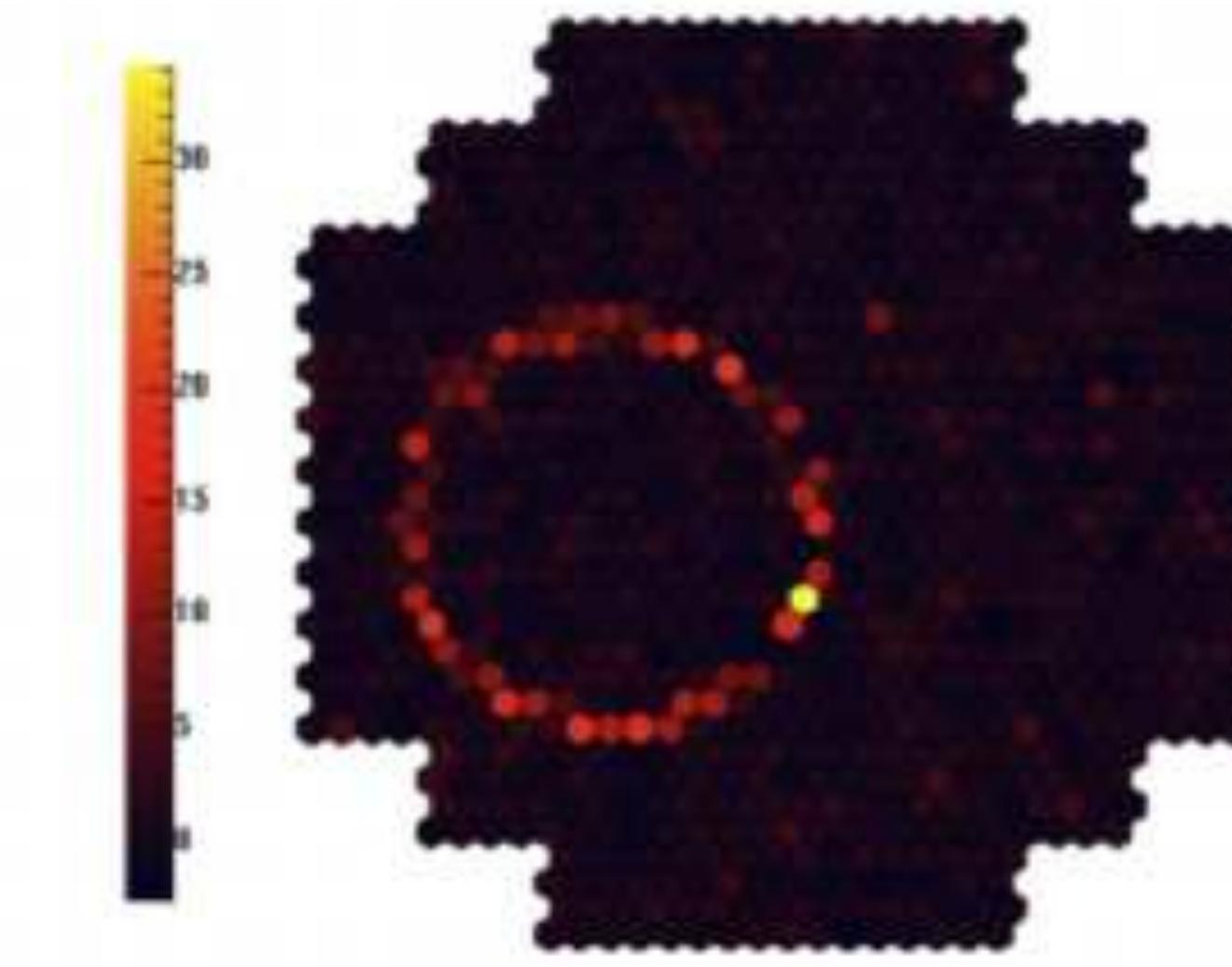


Backgrounds

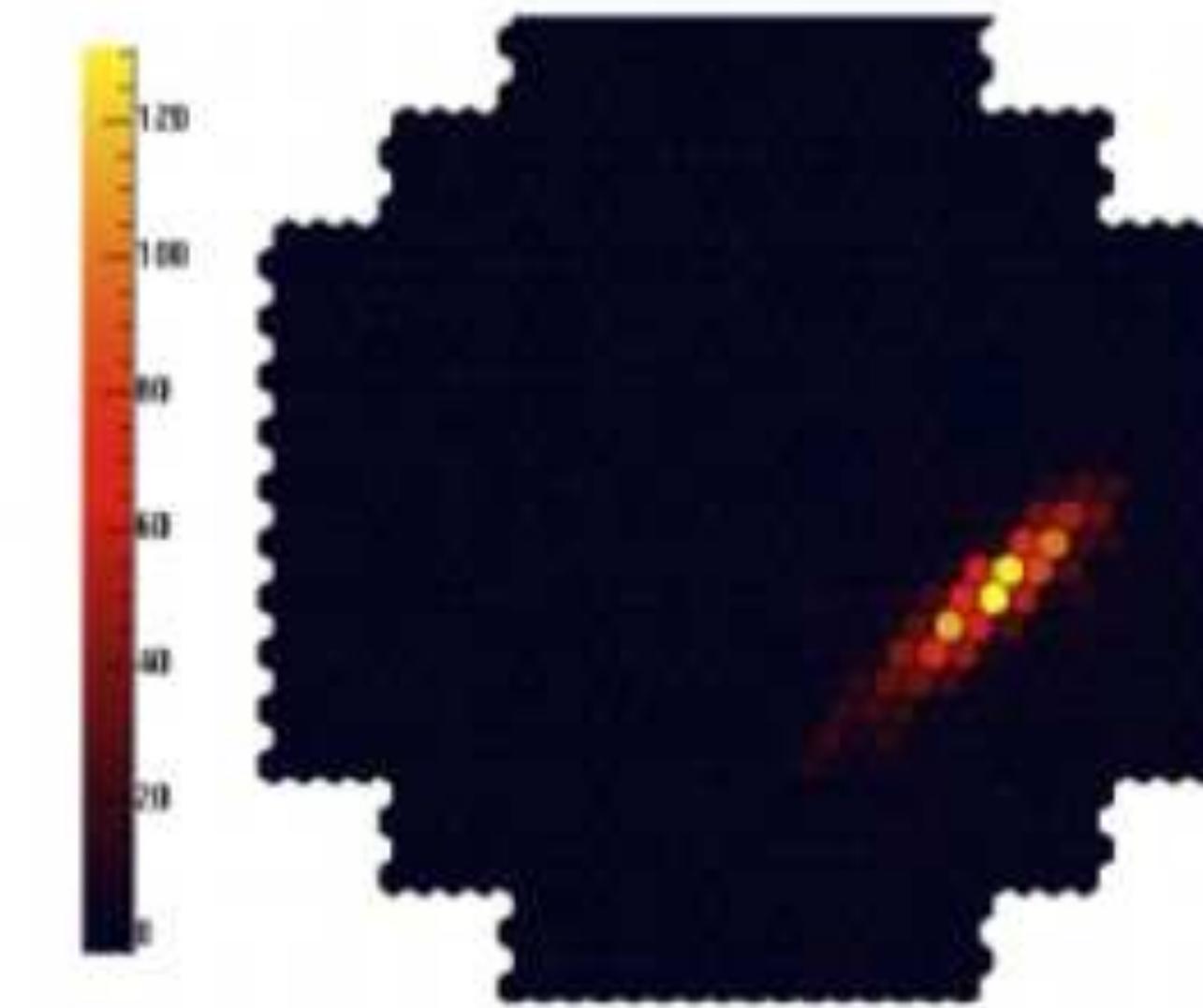
Hadronic showers and muons



Hadronic shower



Isolated muon



Gamma-like event

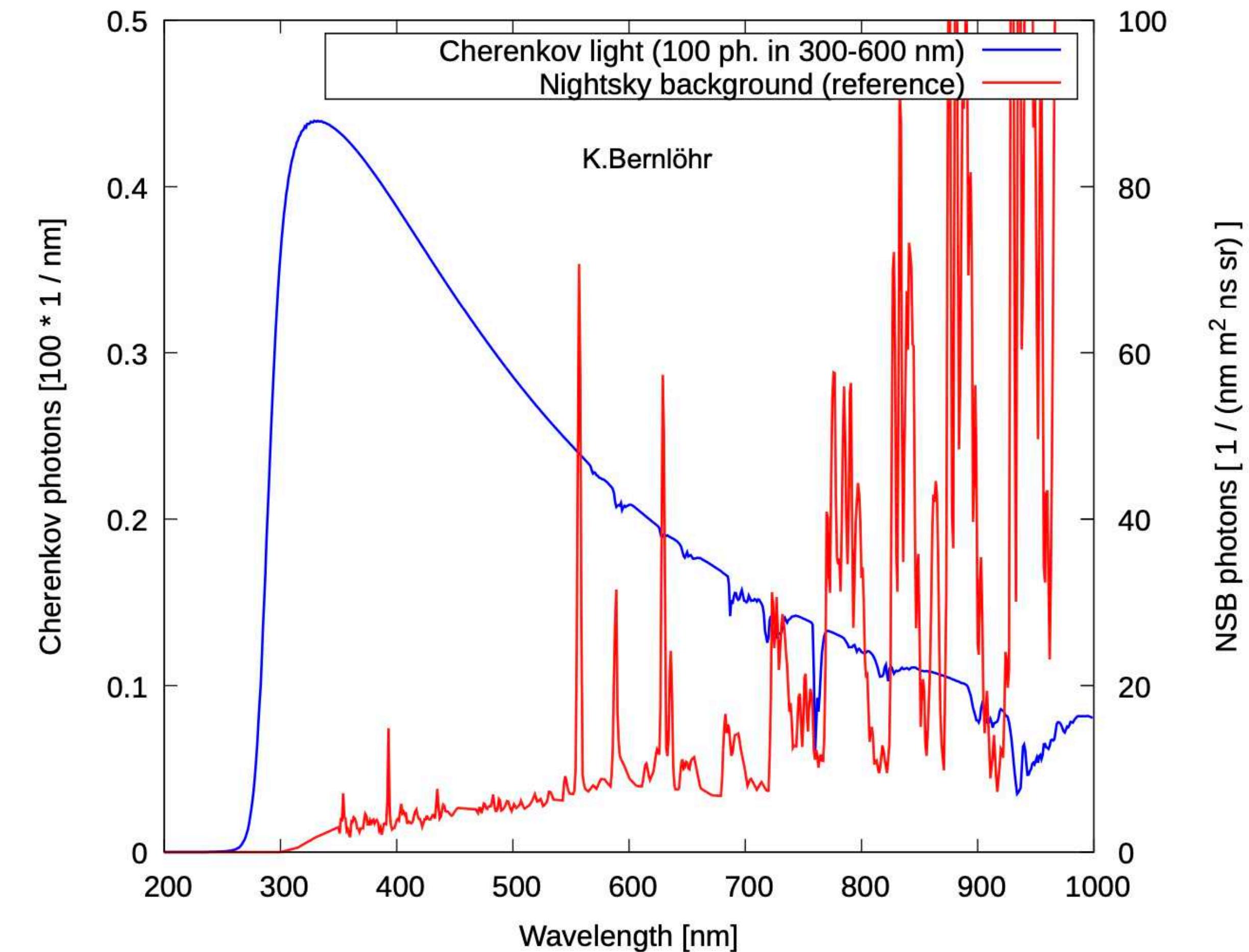
Gamma / hadron discrimination through image topology

Backgrounds

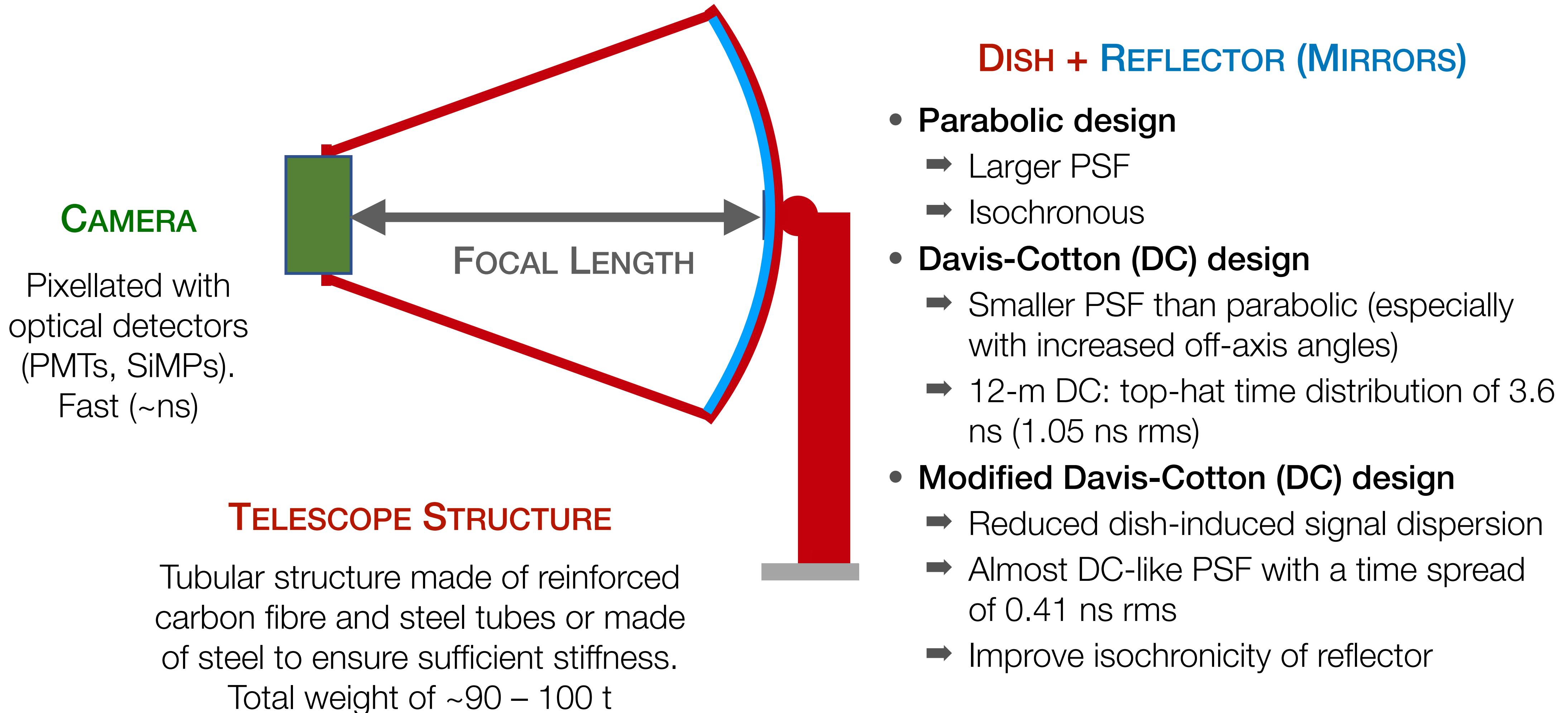
NSB

Even ignoring stars, the sky is not dark:

- Night Sky Background (NSB)
light is always present
- Collective unresolved visible/UV
light from optical sources (stars,
Milky Way, etc)
- Glow from moon, nearby light
pollution



An IACT's prototype



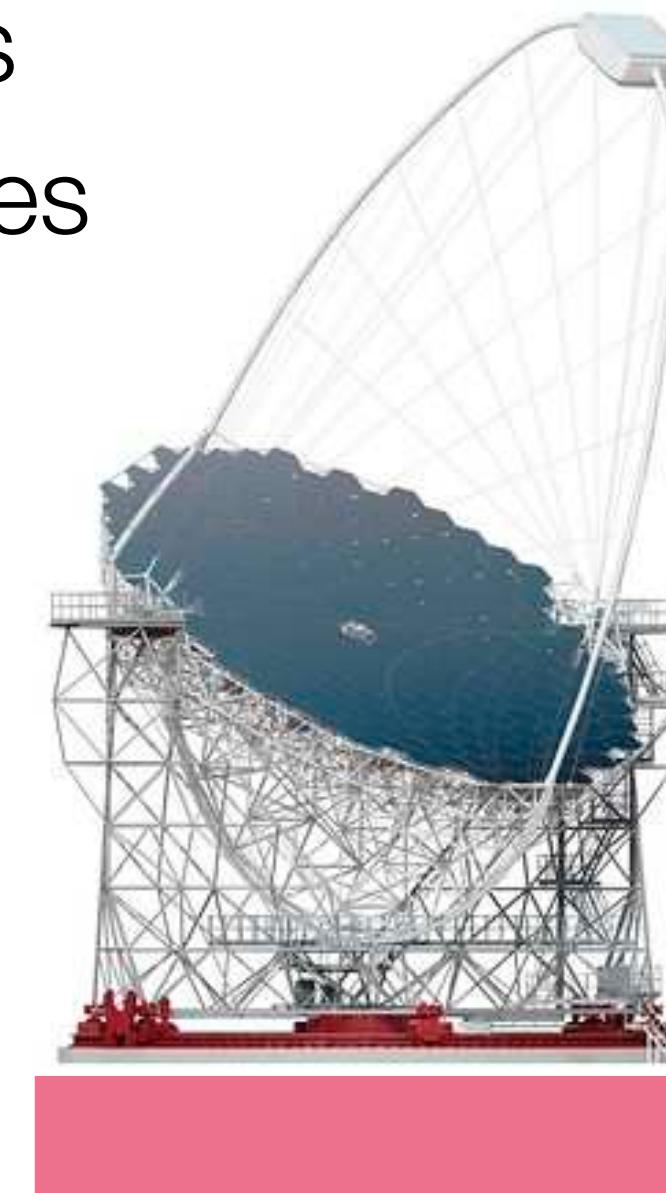
IACTs: how big? How many?

A compromise between size and number...

Bigger dishes:

- Image fainter showers
→ go to lower energies
- Smaller FOV ($\sim 4^\circ$)

LST



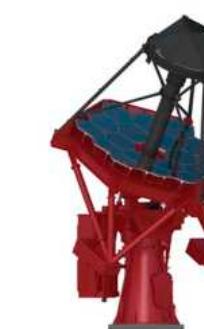
20 GeV

MST



200 GeV

SST



5 TeV

300 TeV

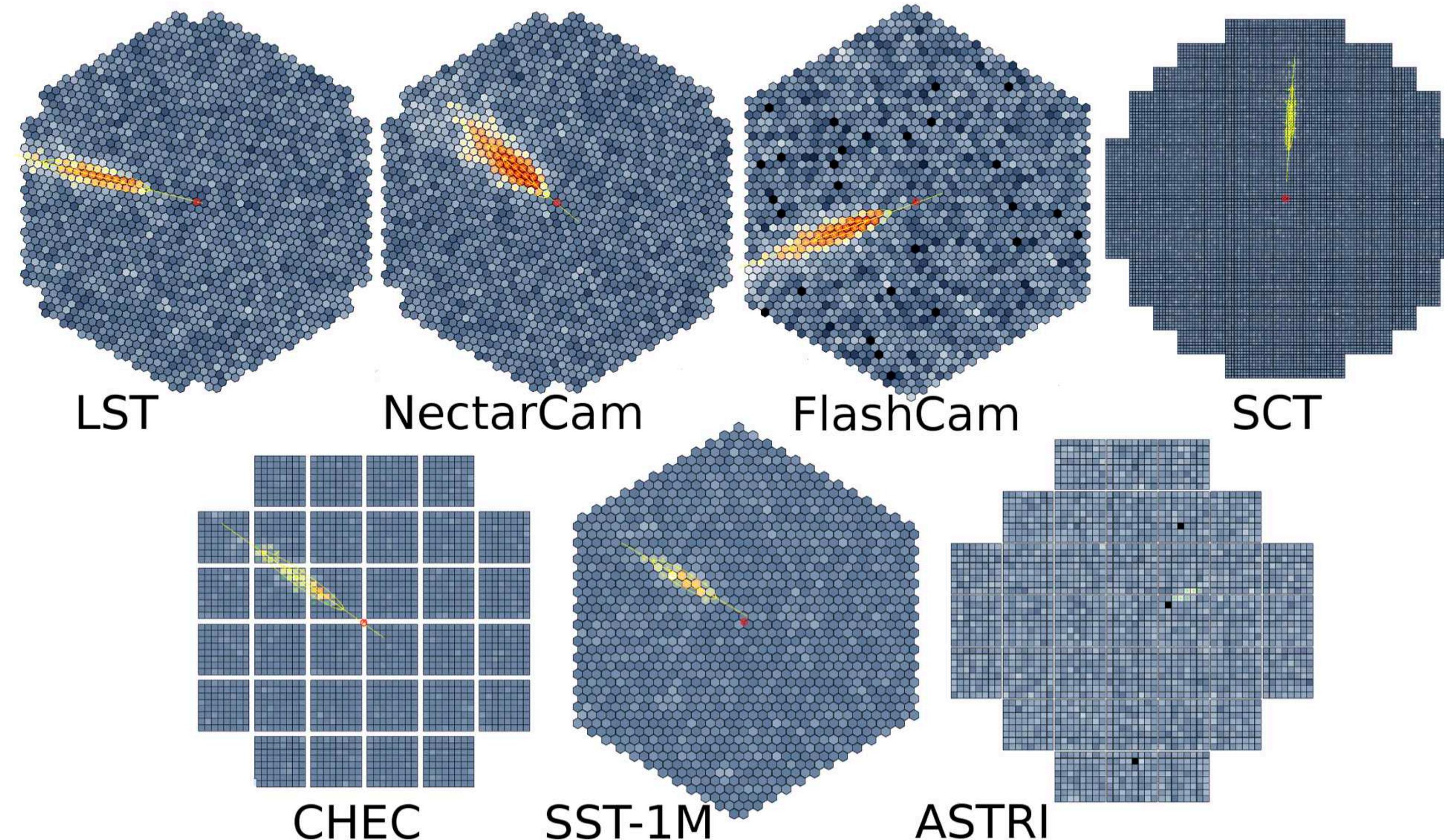
Smaller dishes:

- Greater sensitivity at medium to high energies
- Larger FOV ($\sim 8^\circ$)

Ideally: Lots of big-dish telescopes, but money is always a limitation!
Cost increases with size of dish or number of telescopes

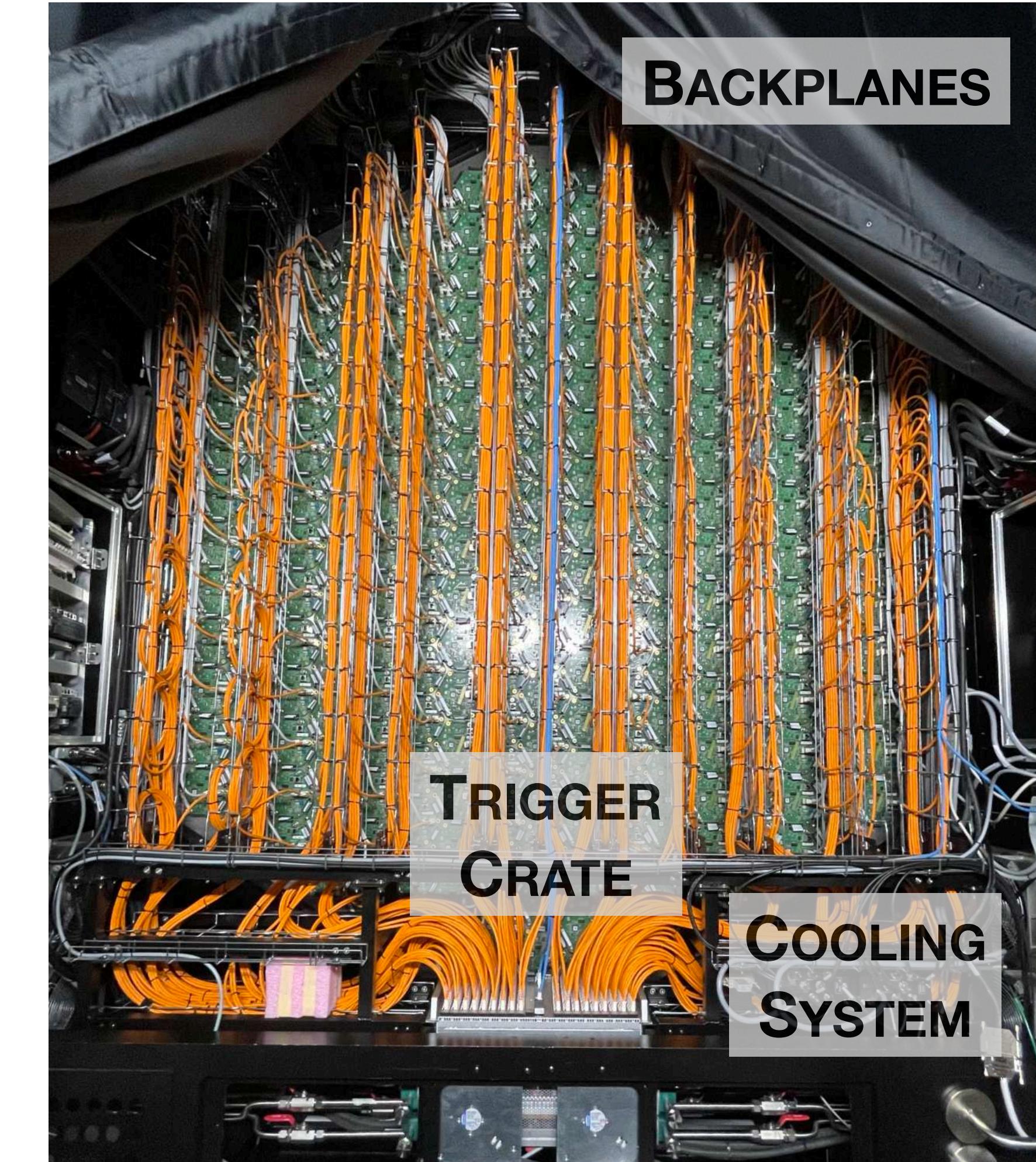
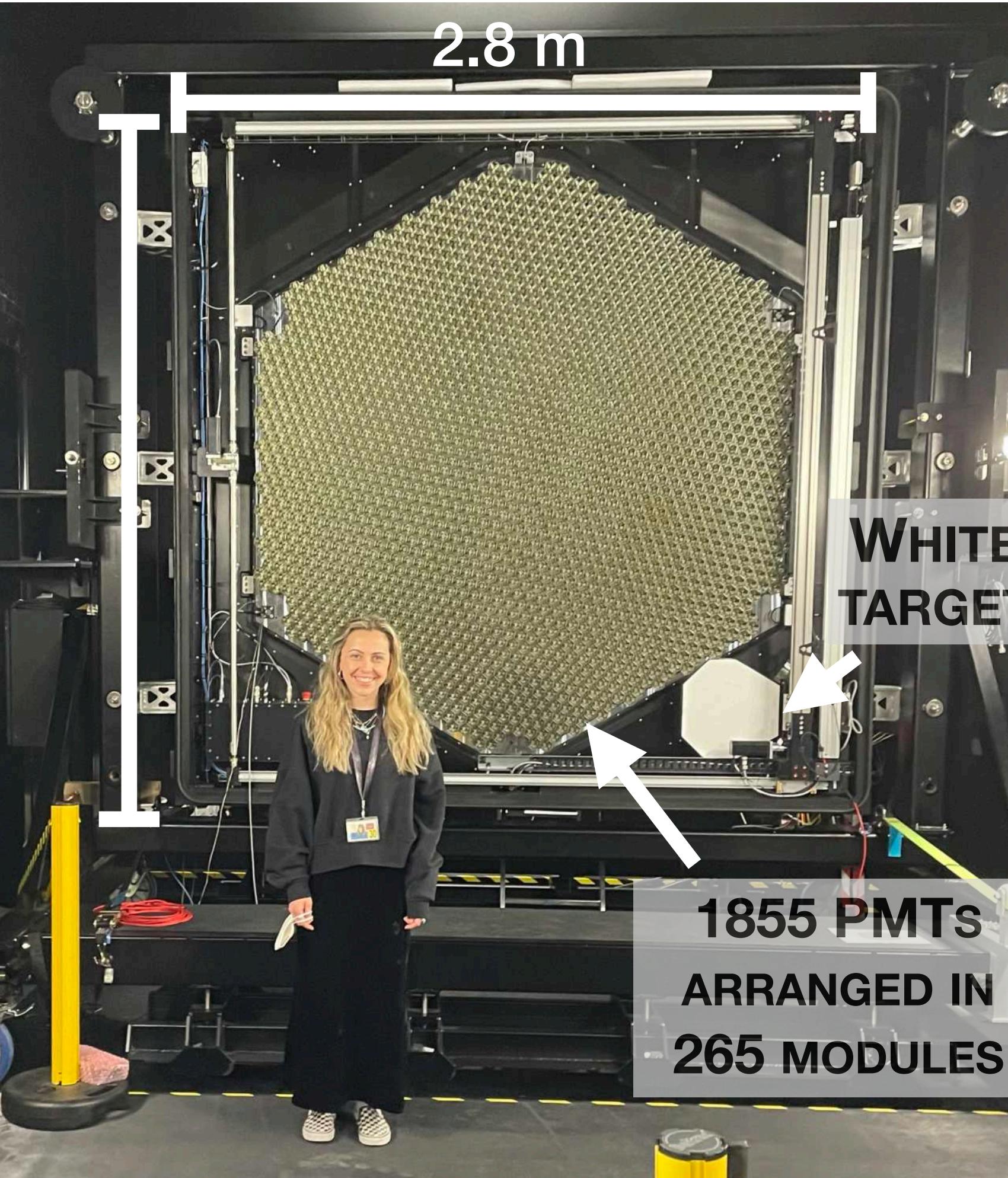
IACT cameras

The CTAO designs



IACT cameras

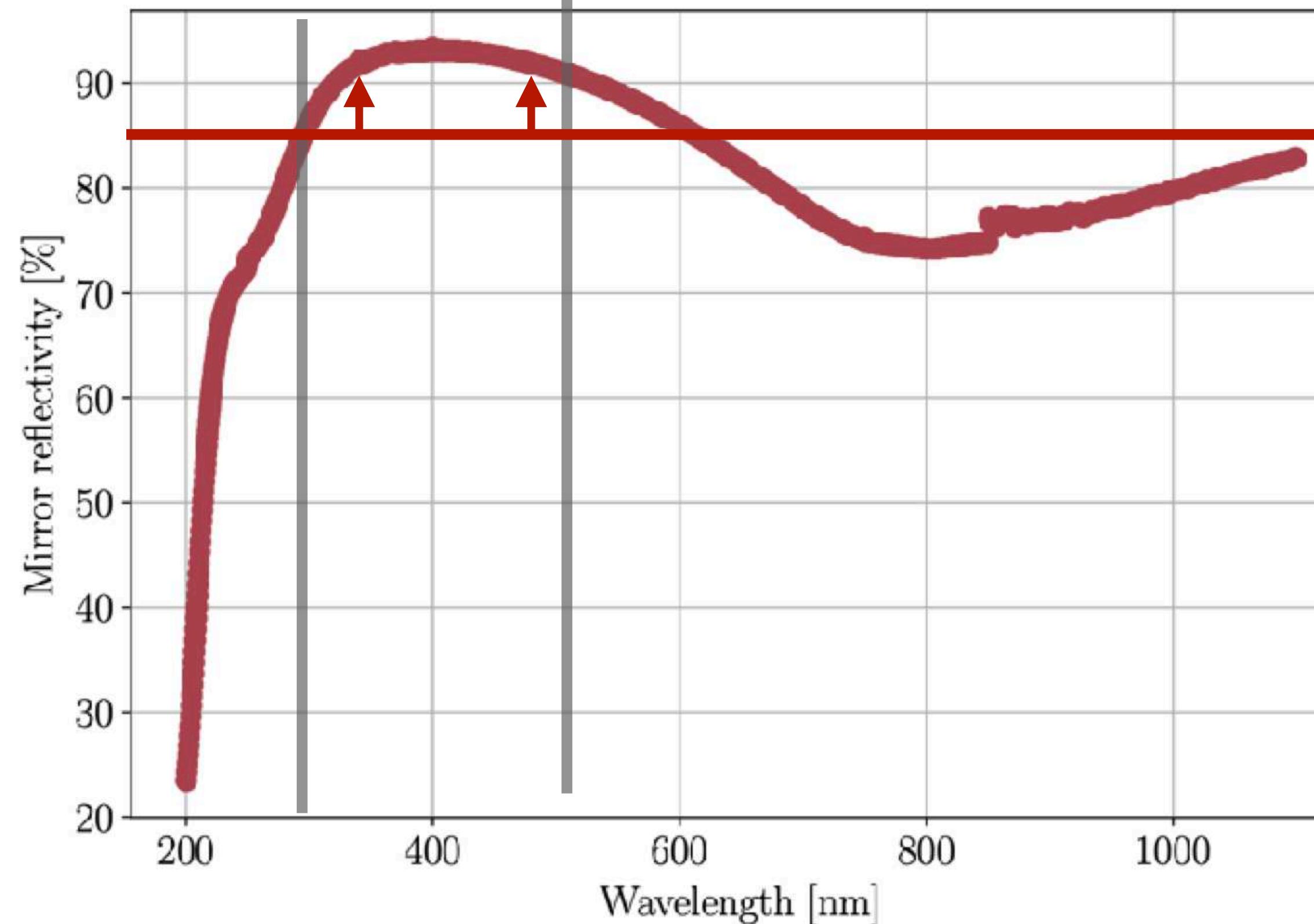
NectarCAM camera at IRFU/CEA Paris-Saclay



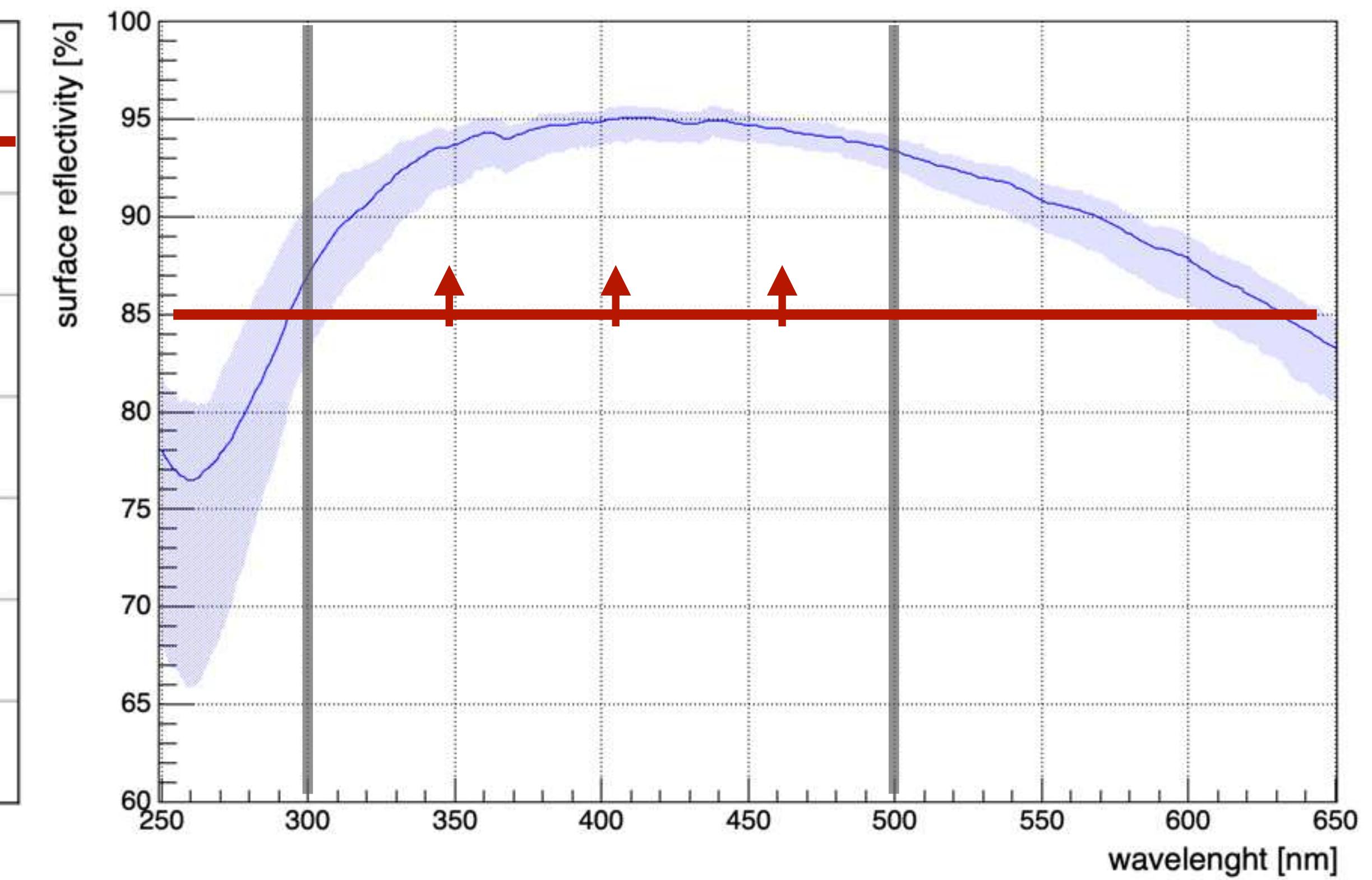
IACT mirrors

Reflectivity > 85% in [300, 500] nm

LST



MST

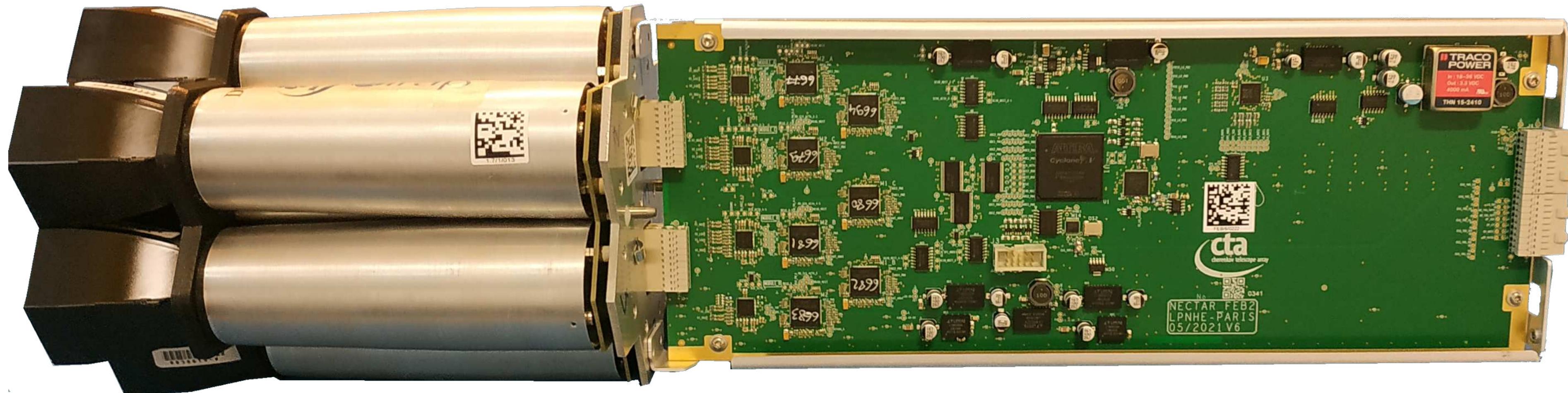


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

FRONT END BOARD

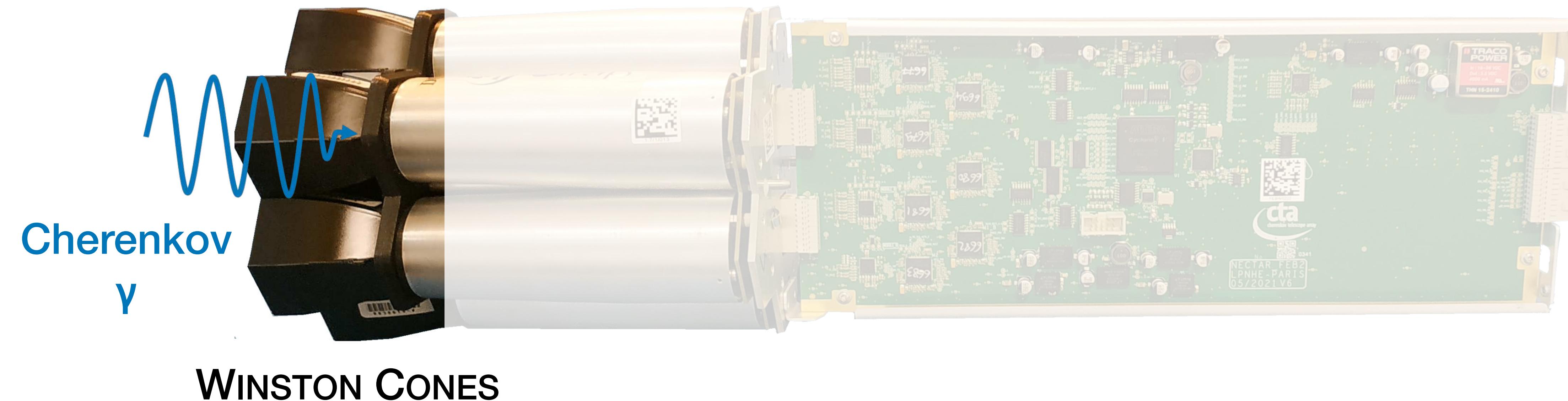


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

FRONT END BOARD

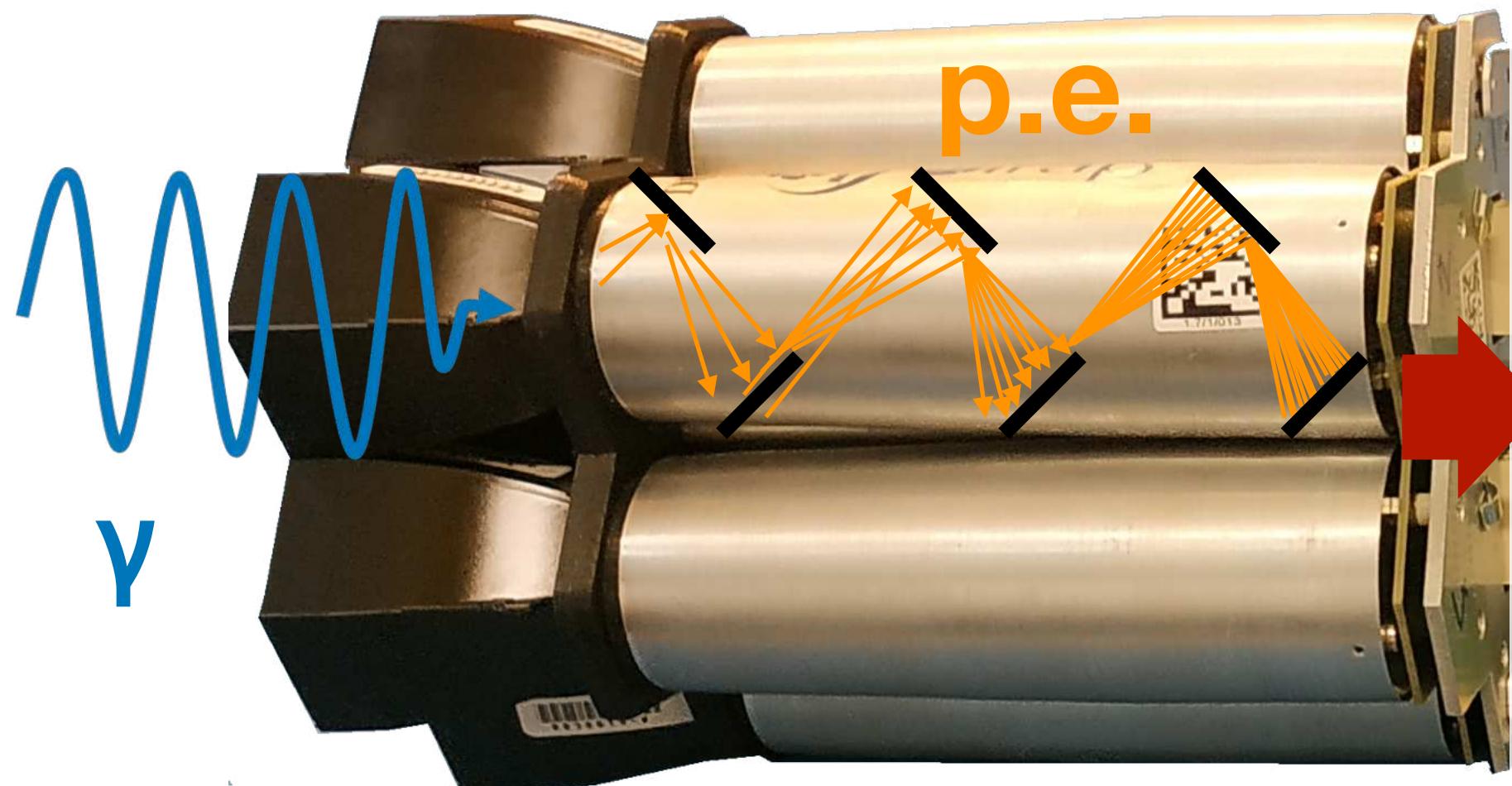


1. Light deposited in the camera is first collected in the **light guides** and detected in the focal plane

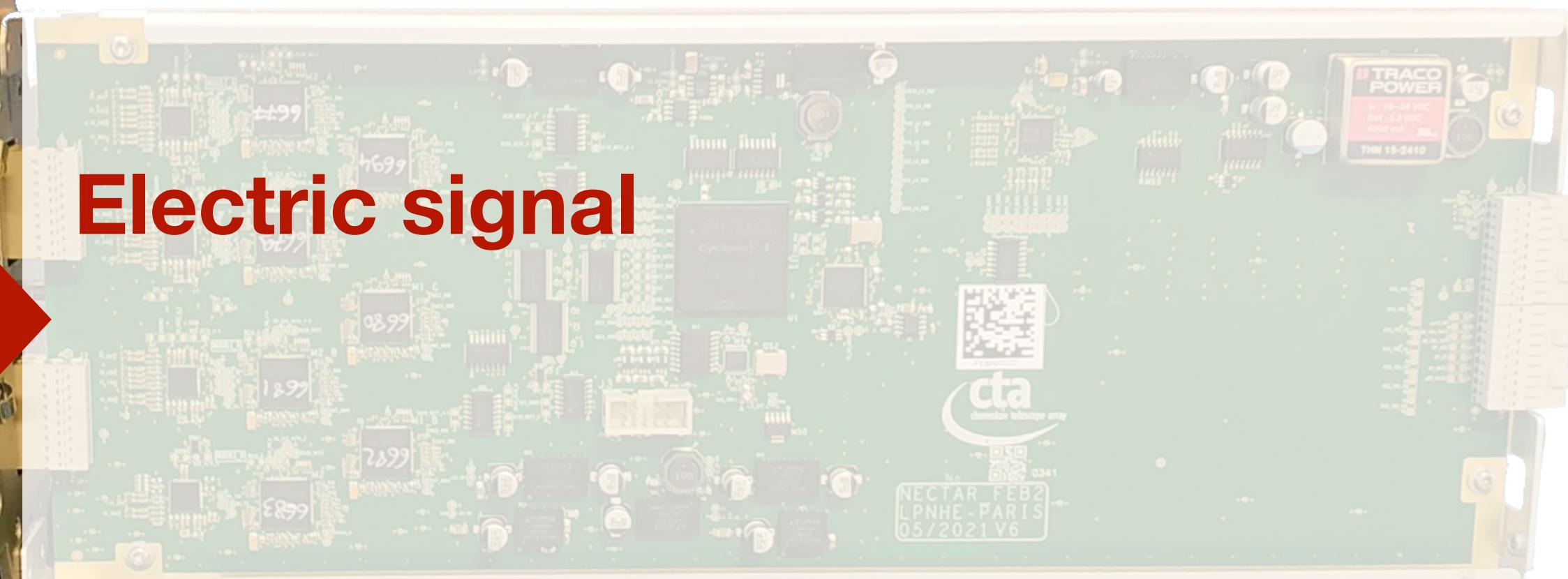
From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE



FRONT END BOARD



PMTs

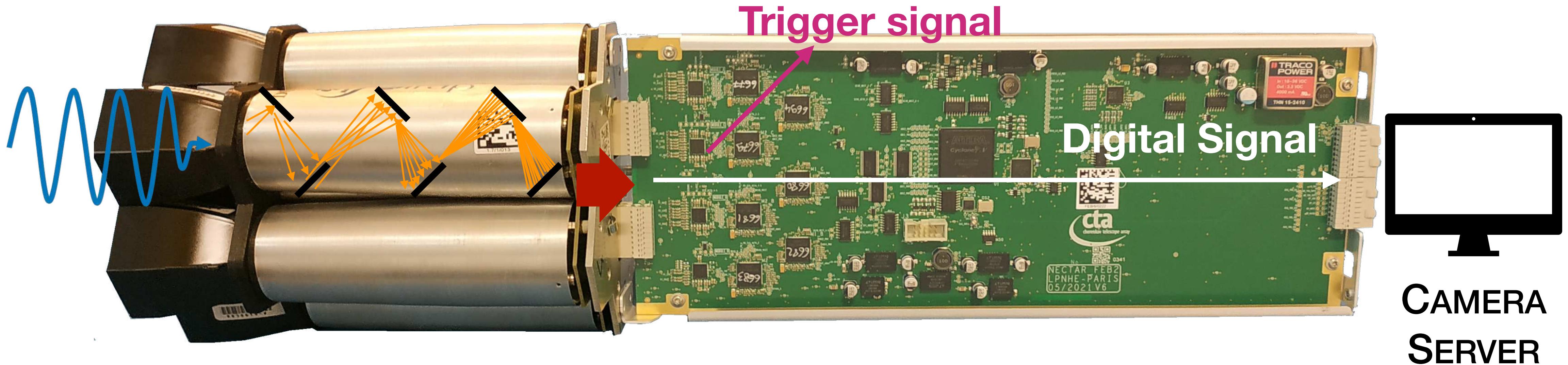
2. The signal is converted into electric signal by the **PMTs** and pre-amplified

From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

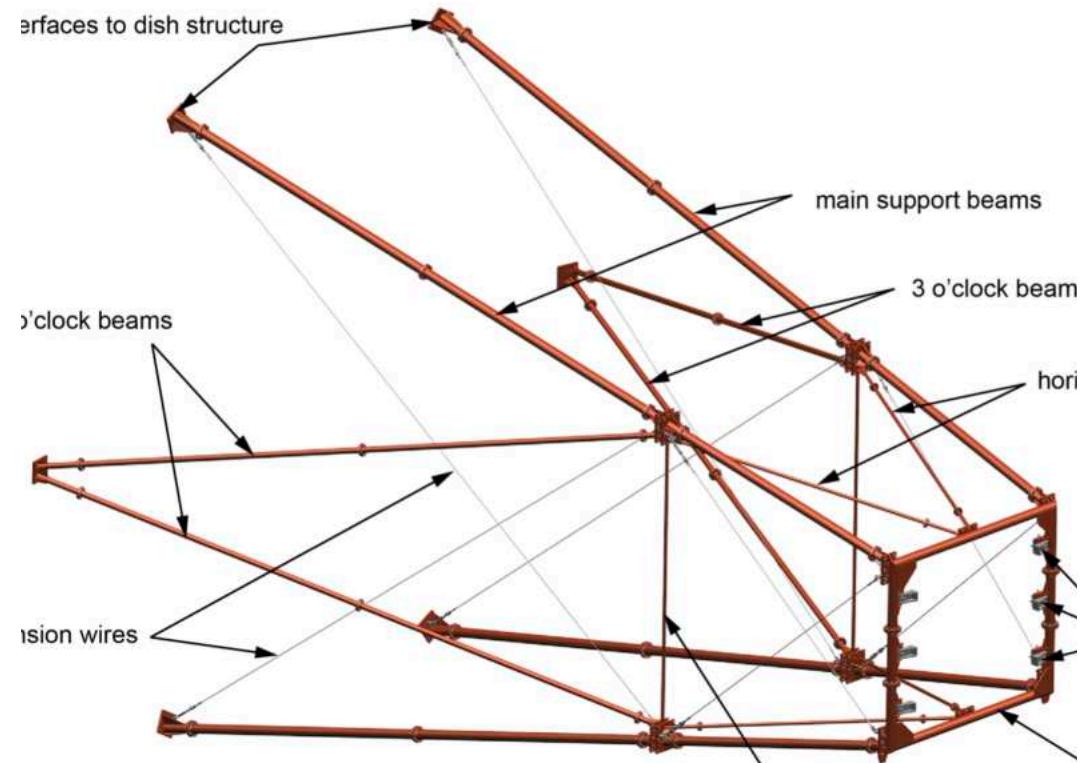
FRONT END BOARD



3. Signal is amplified, sampled and digitized + formation of trigger signal

From photons to photoelectrons

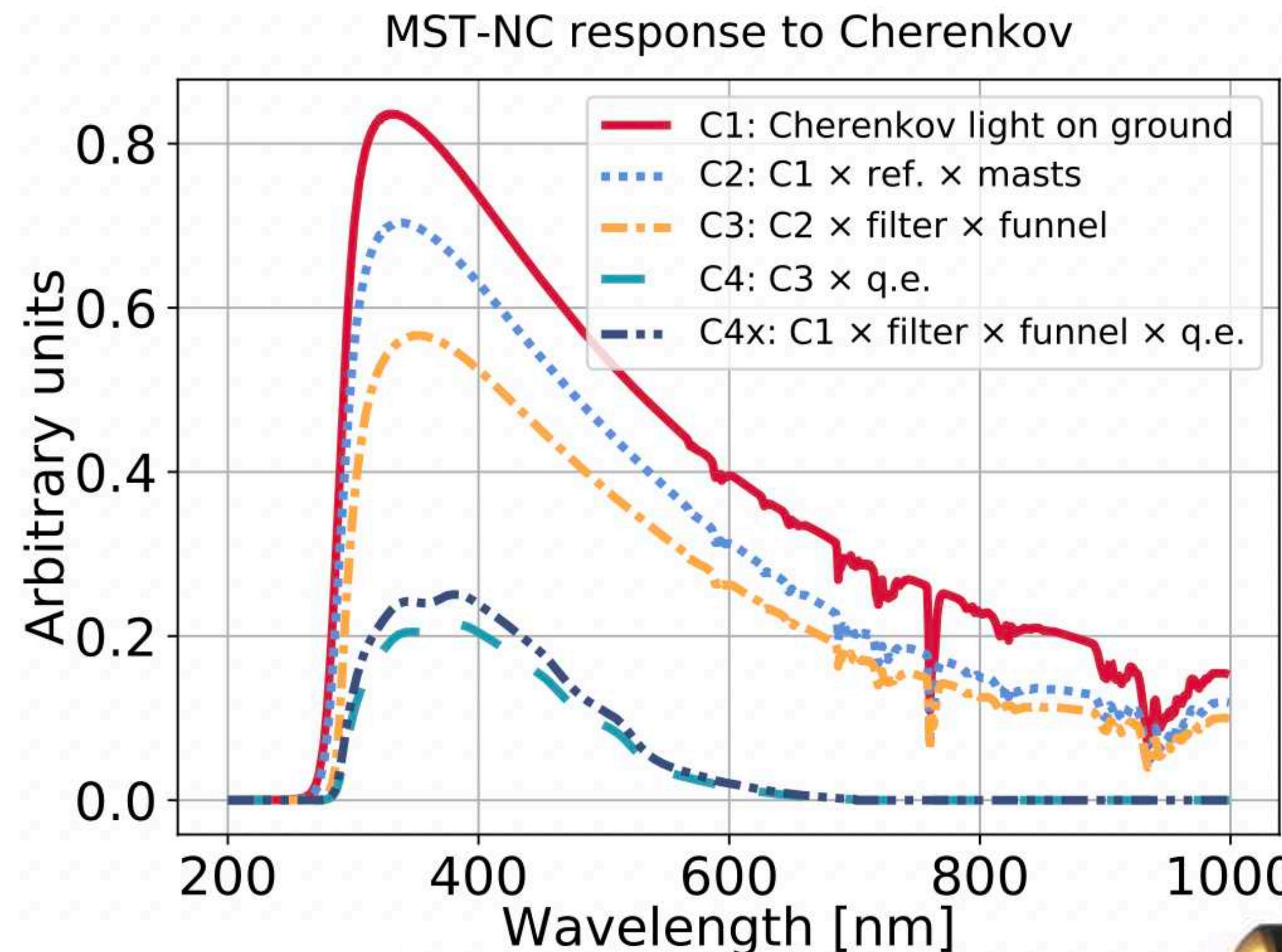
Impact of components on Cherenkov light detection efficiency



**TELESCOPE
STRUCTURE**



MIRRORS



ENTRANCE WINDOW



**LIGHT
GUIDES**

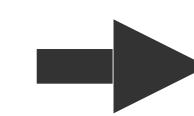


**HAMAMATSU
PMT**

Triggering an IACT array

From the single pixels to an array trigger

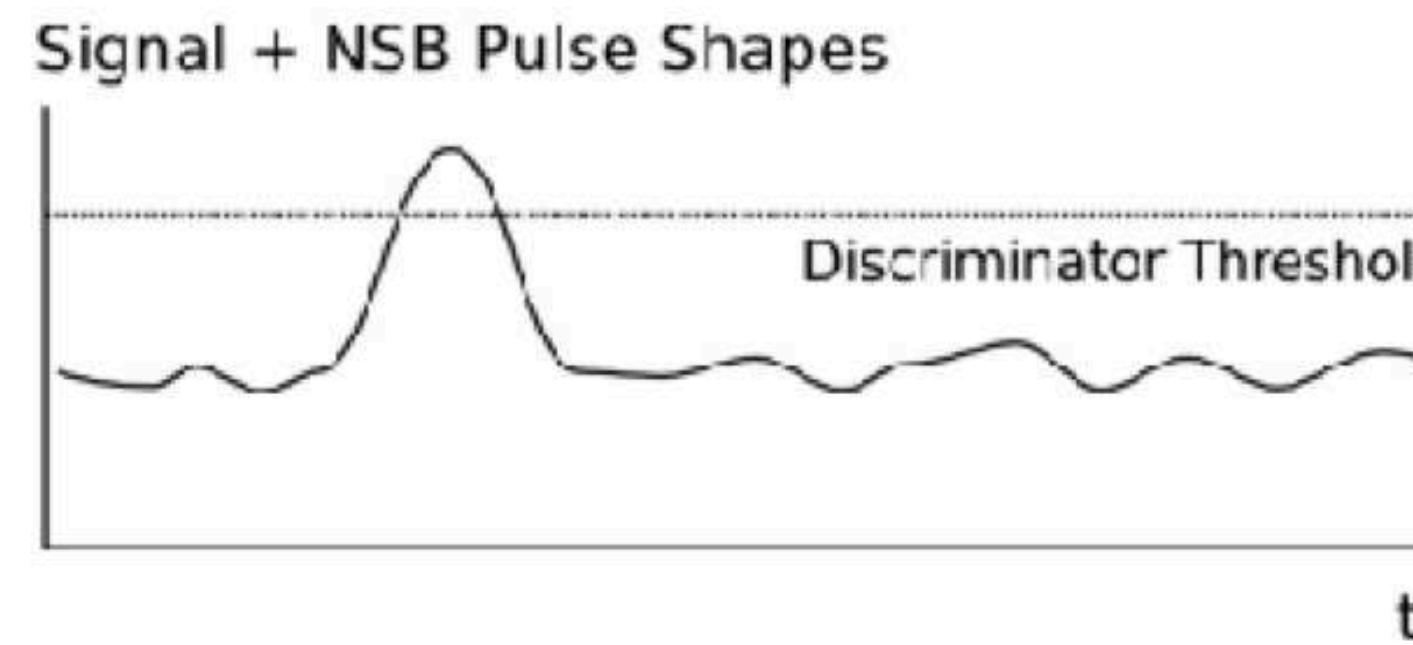
L1: pixel trigger



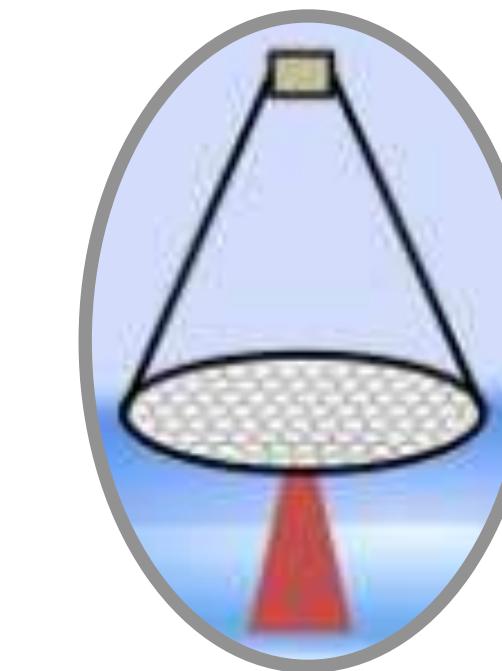
L2: telescope trigger



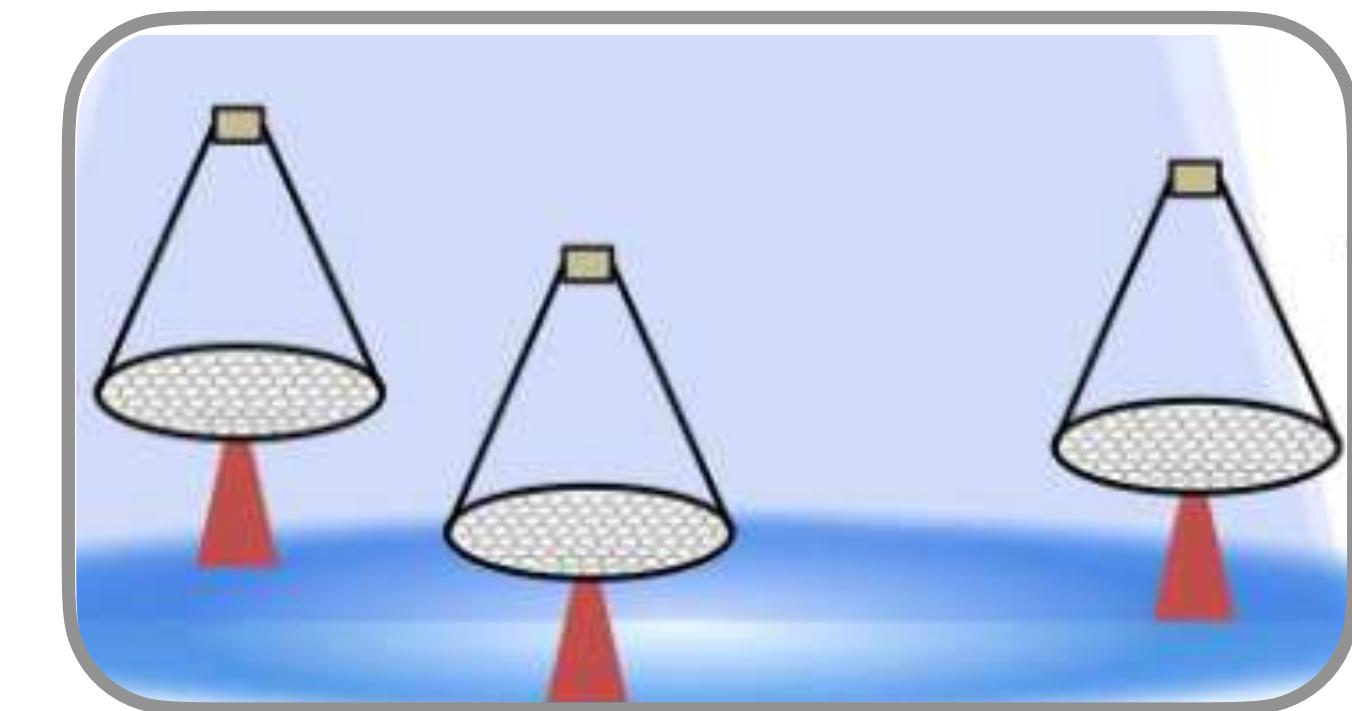
L3: array trigger



Is the signal in a single (or trigger sector) above a threshold?



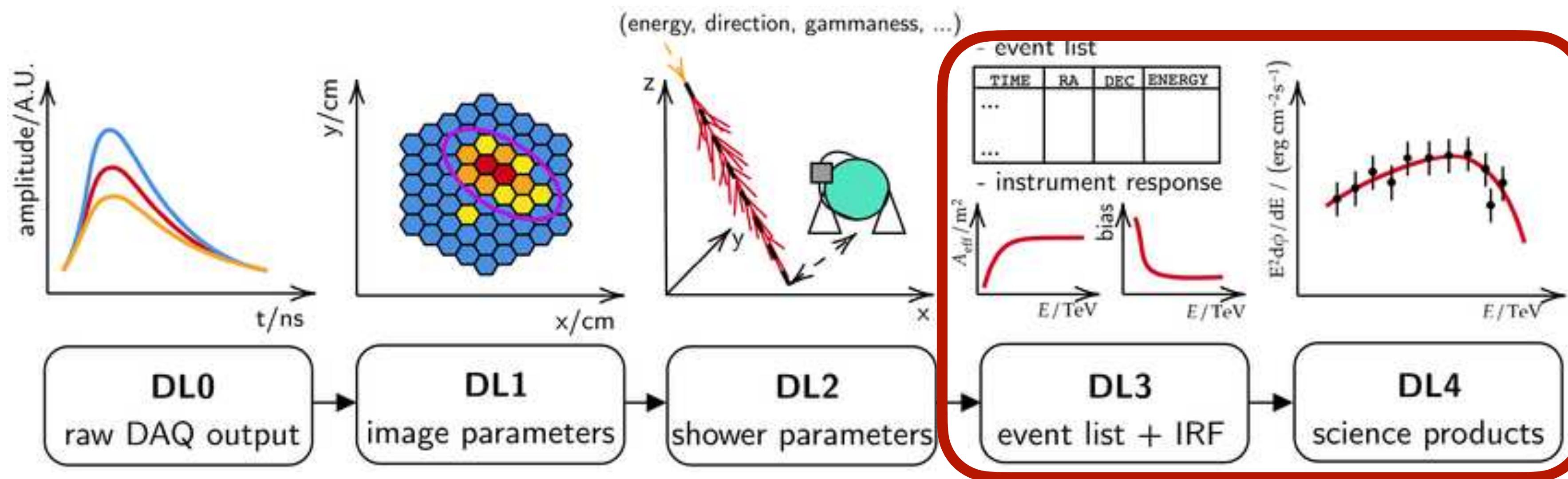
Have enough pixels/sectors triggered?



Has more than one telescope triggered within a small time window?

- ✓ Rejects most muons
- ✓ Drastically reduces triggers due to NSB fluctuations

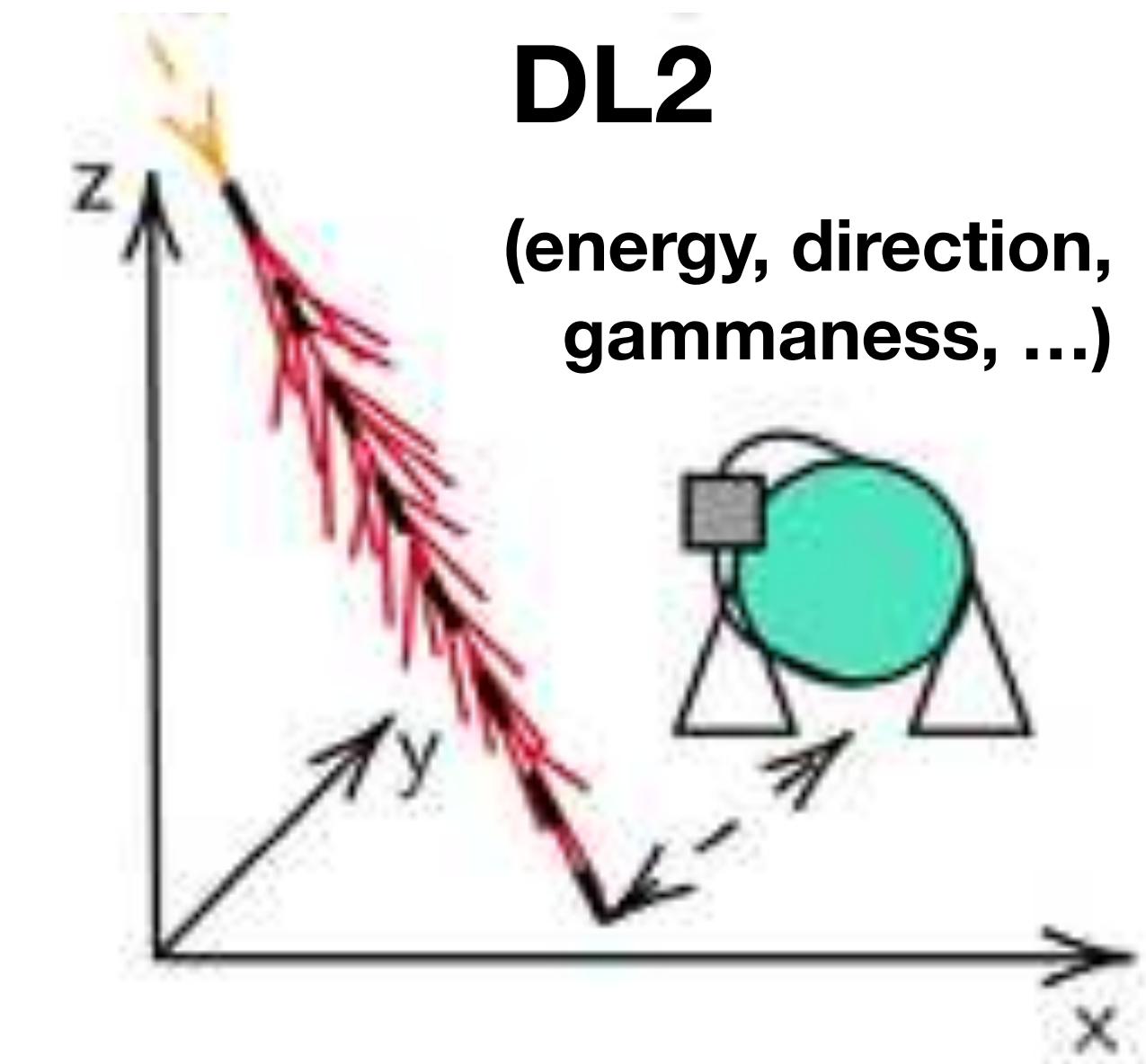
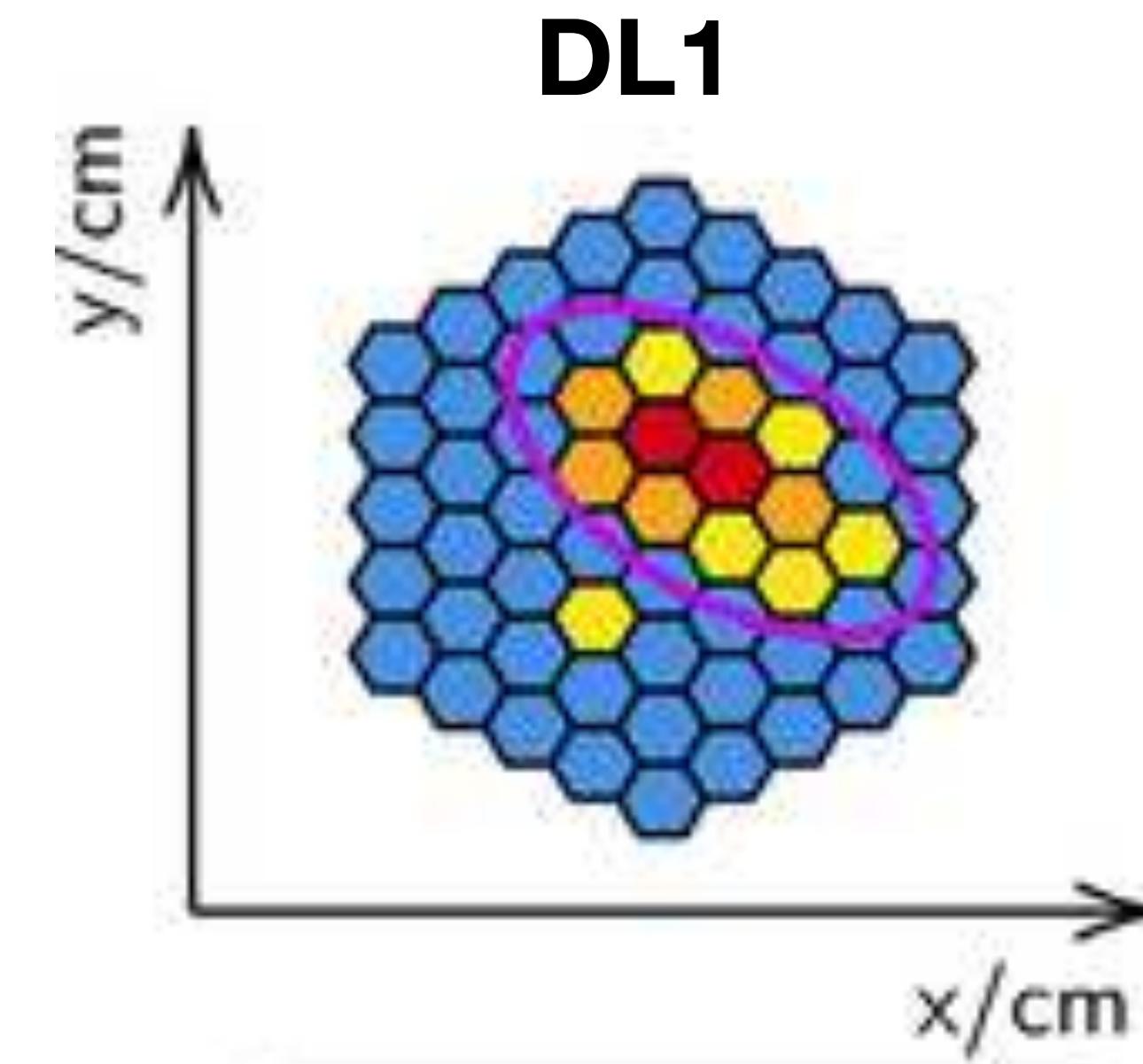
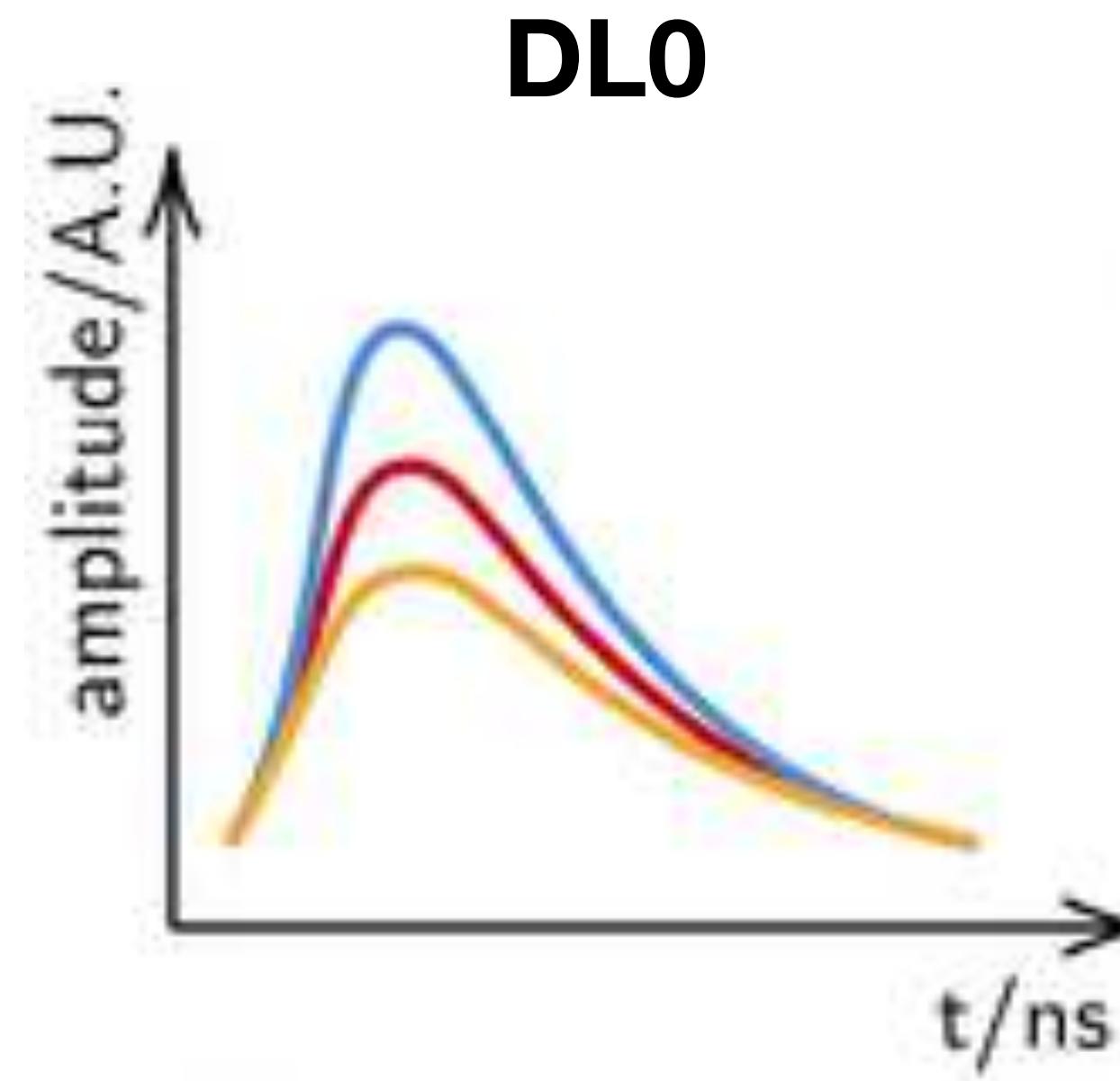
From low-level to high-level IACTs data



→ Jonathan's talk this afternoon!

Data levels

Definition of data levels (DLs) foreseen for CTA



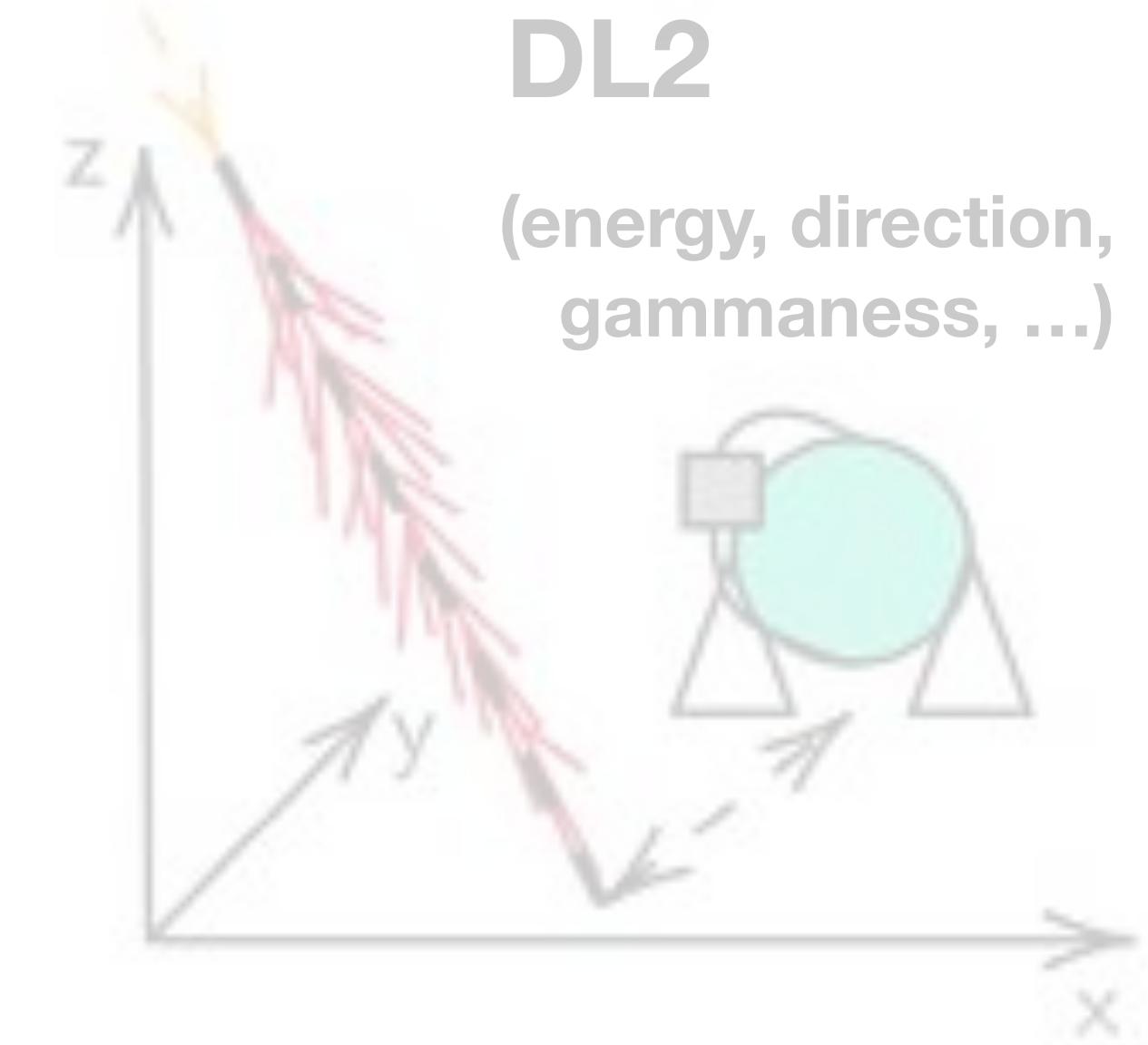
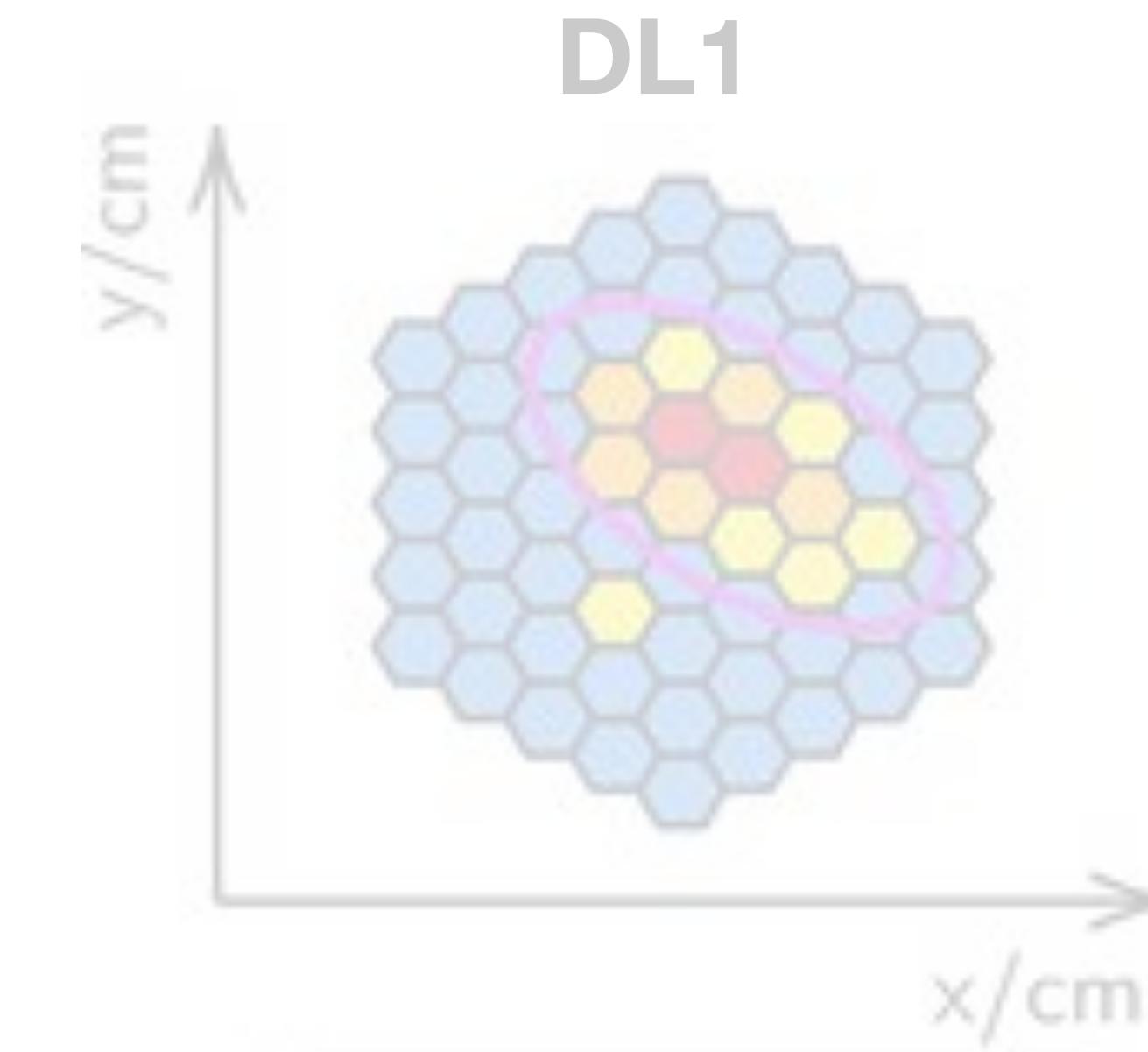
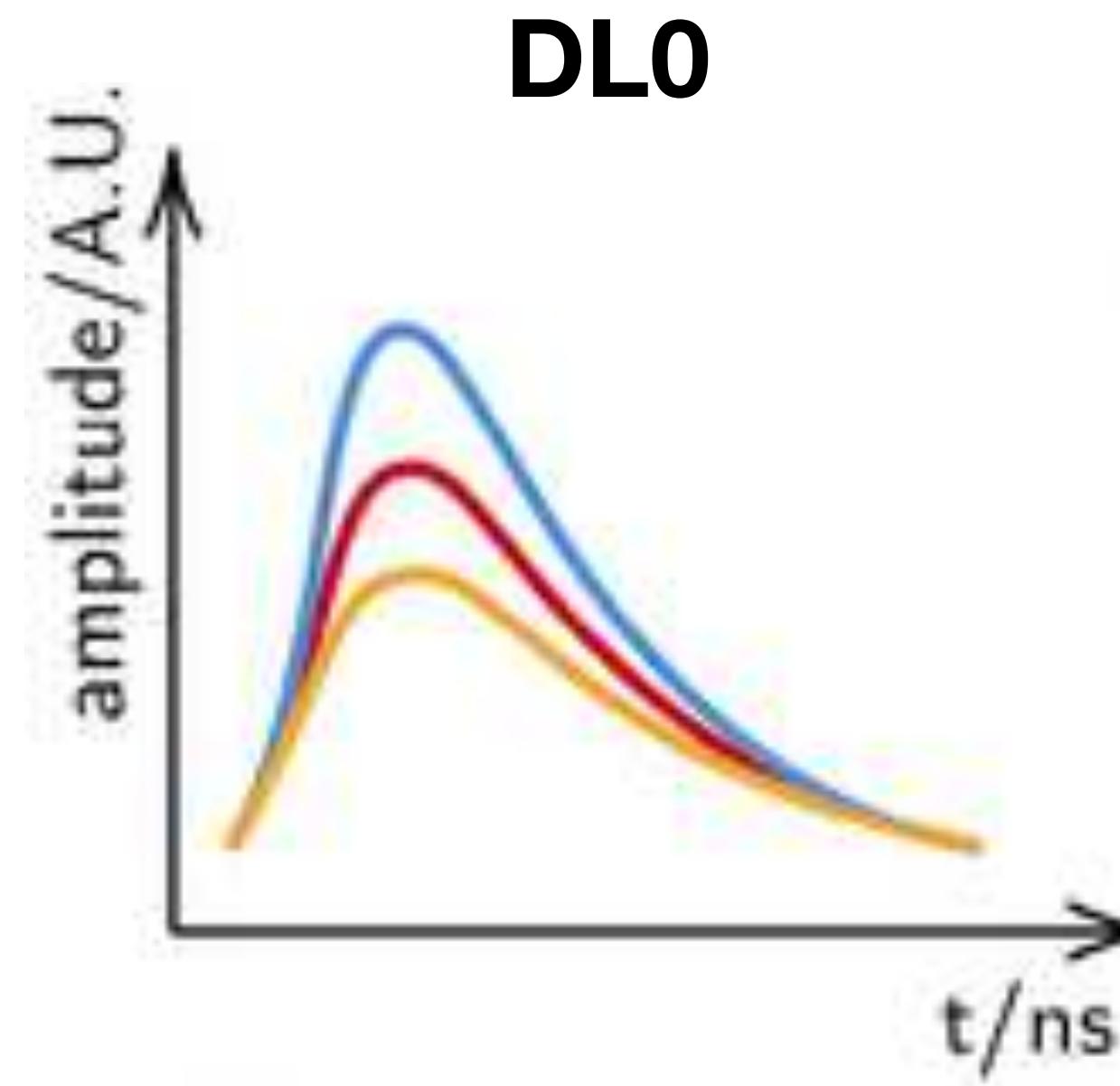
Raw output of the data acquisition system.
Uncalibrated signals measured in the photo-sensors in each camera pixel

Calibrated signals and derived per-telescopes parameters.
Pixel signals converted into physical quantities + camera image parameters

Reconstructed shower parameters.
Parameters from different telescopes combined to infer air shower properties

Data levels

We are at DL0!

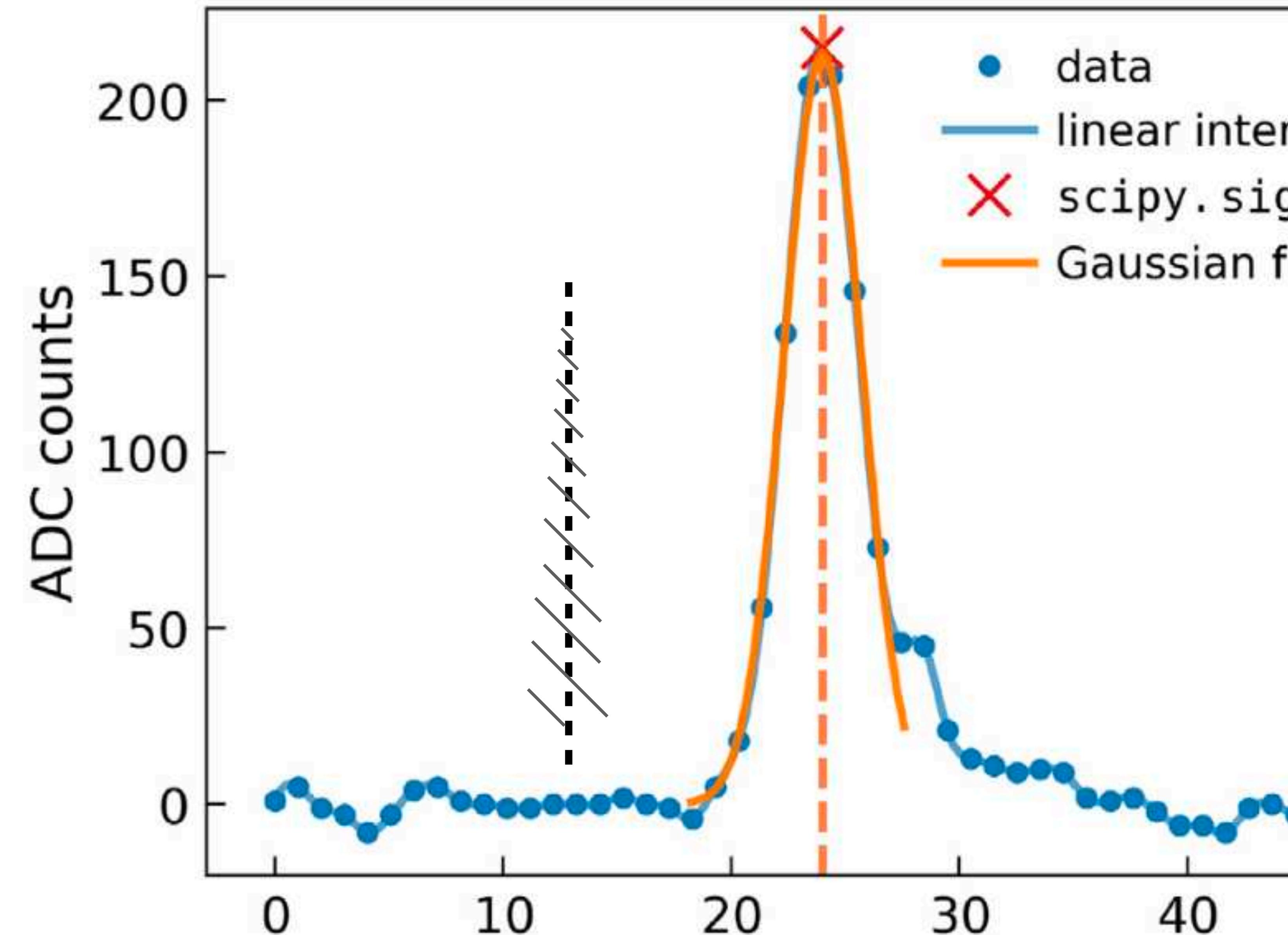


We still have uncalibrated waveforms in units of ADC counts
→ transition to DL1

Low-level data processing

Calibration

1. Subtraction of the baseline (NSB + electronic noise)
2. Integration of charge around mean peak in ADC counts
3. Calculation of the signal arrival time: time of maximum (TOM)



Low-level data processing

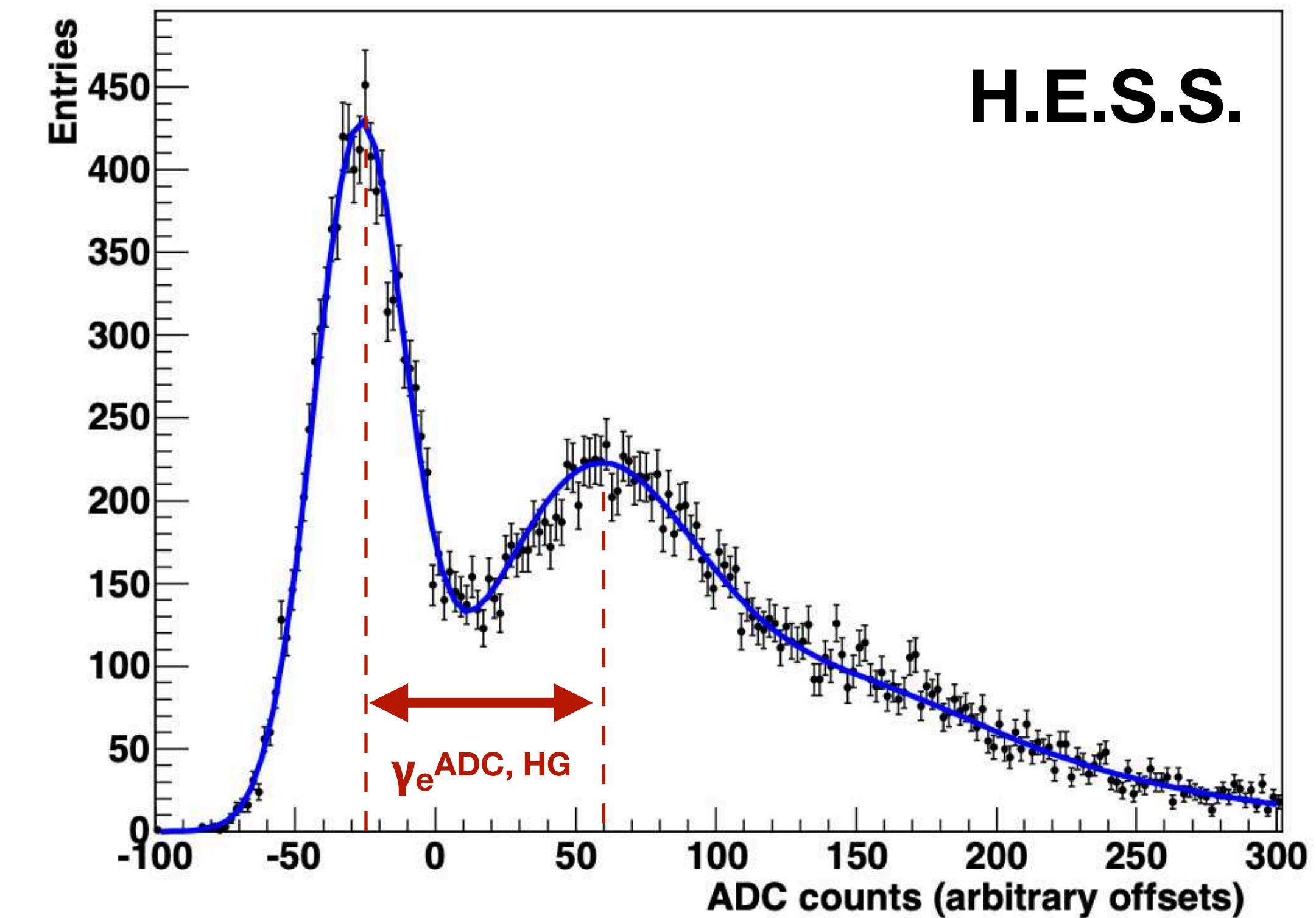
Calibration: from ADC counts to p.e.

- Determination of the amplification gain of the photo-sensors for a single photo-electron

$$A^{\text{HG}} = \frac{ADC^{\text{HG}} - P^{\text{HG}}}{\gamma^{\text{ADC,HG}}} \times FF$$

$$A^{\text{LG}} = \frac{ADC^{\text{LG}} - P^{\text{LG}}}{\gamma^{\text{ADC,HG}}} \times (HG/LG) \times FF$$

- Ratio High/Low gain
- Flat-fielding corrections **FF** to homogenize the response of the sensors across the camera
- Exclusion of “Broken” pixels because HV off/unstable, PMT without signal, starts, highly illuminated pixels



Low-level data processing

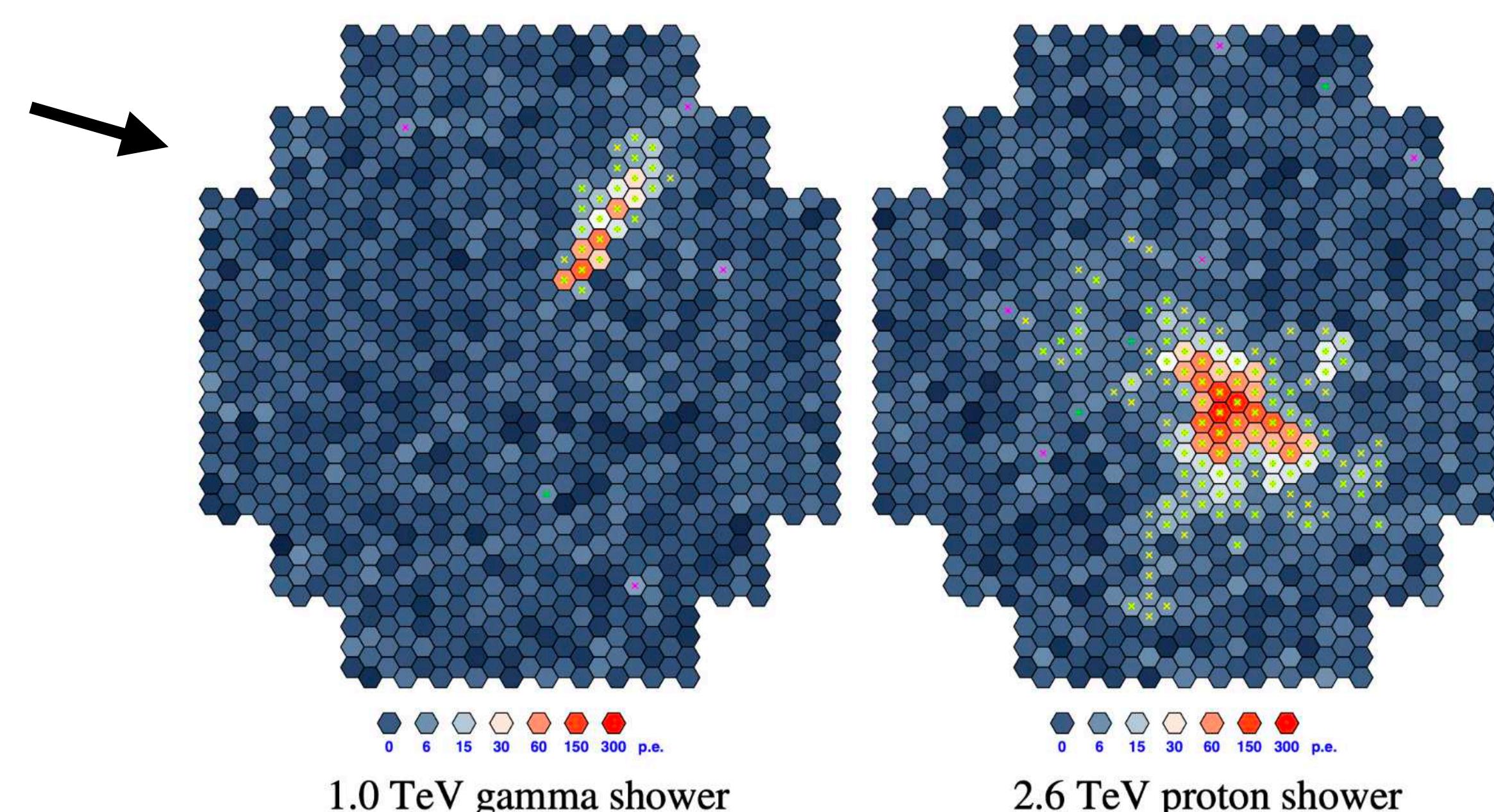
Image cleaning

After the calibration of the signals recorded in the individual camera pixels, a calibrated camera image is obtained

- Most of the shower images contained in a dozen - few tens of pixels
- Rest of the pixels have a mixture of electronic noise and NSB/afterpulses

Cleaning algorithm profits from:

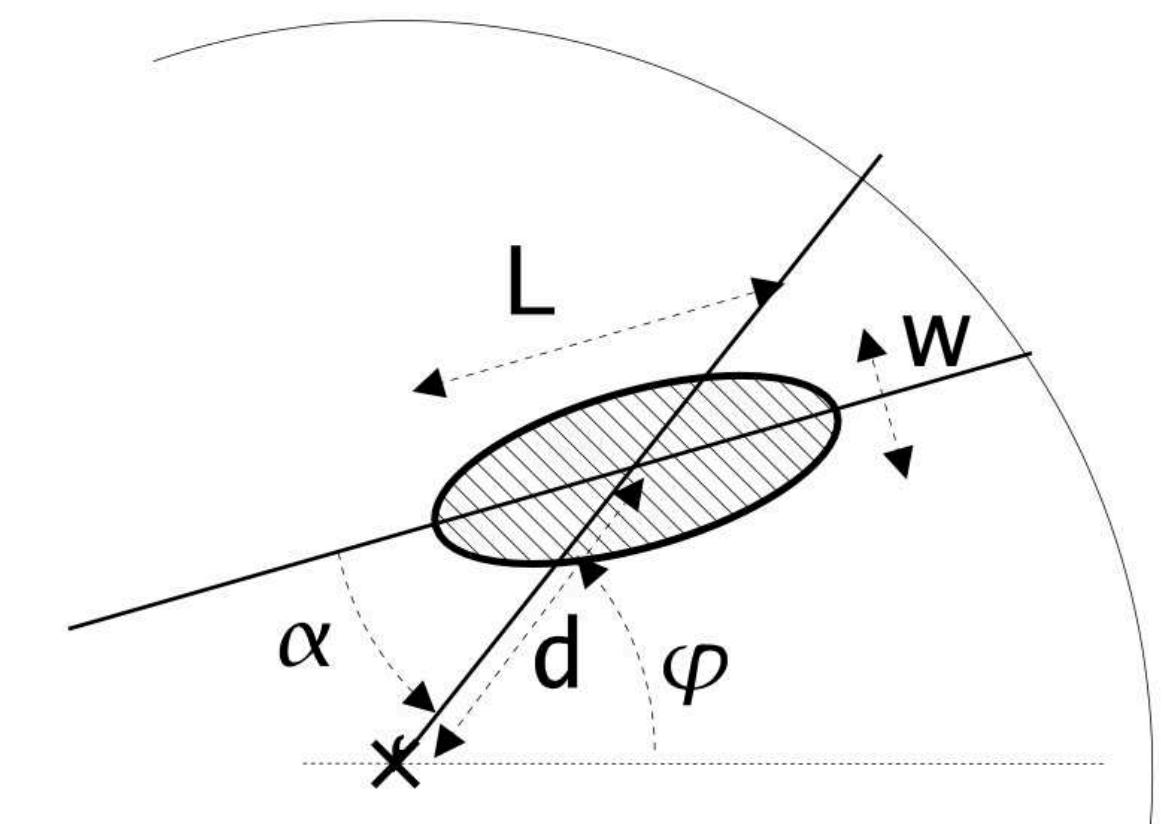
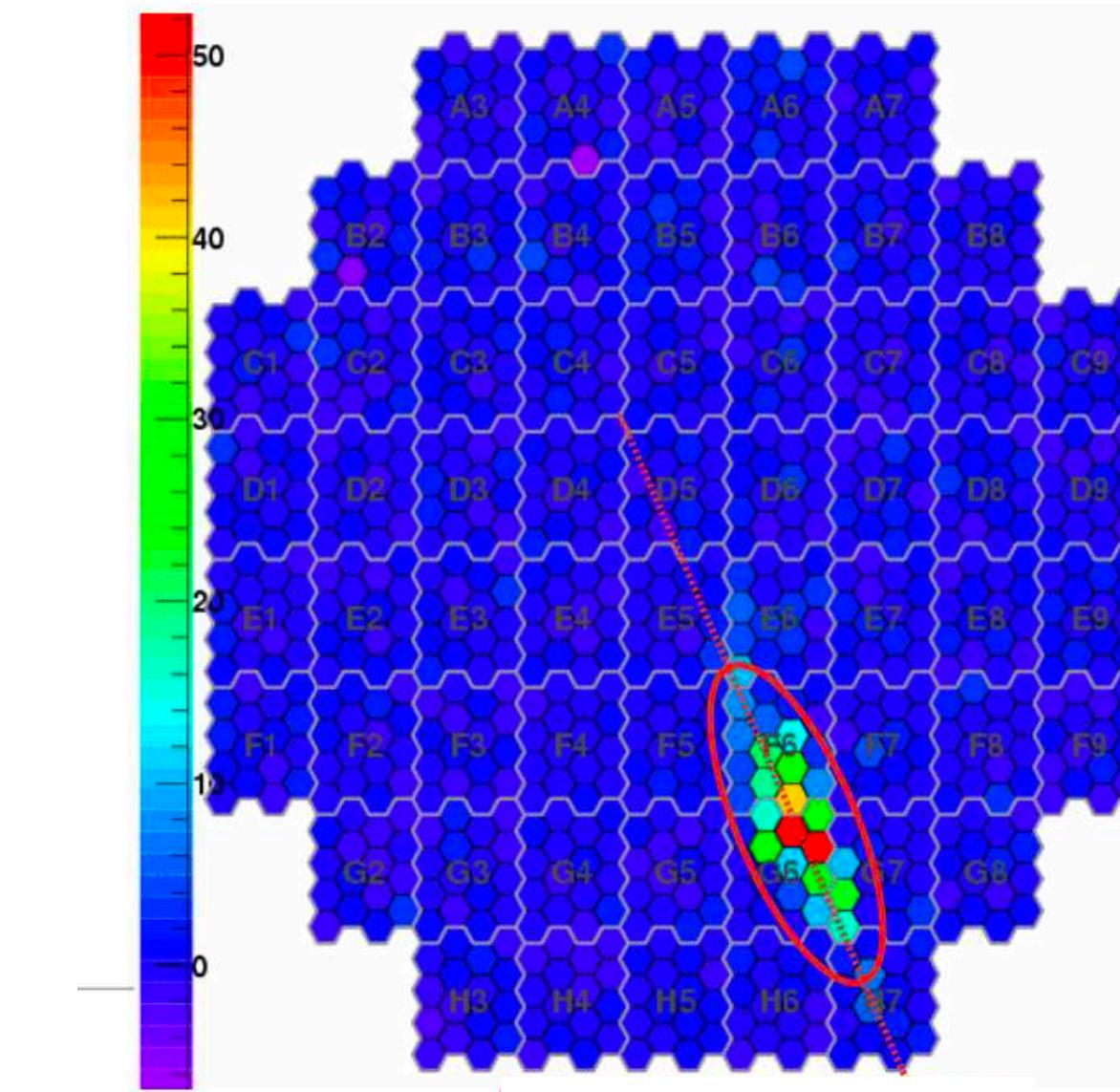
- Shower signal stick out from NSB (more of high energies)
- Shower signals are bundled in neighboring pixels
- Shower signals have time structure



Low-level data processing

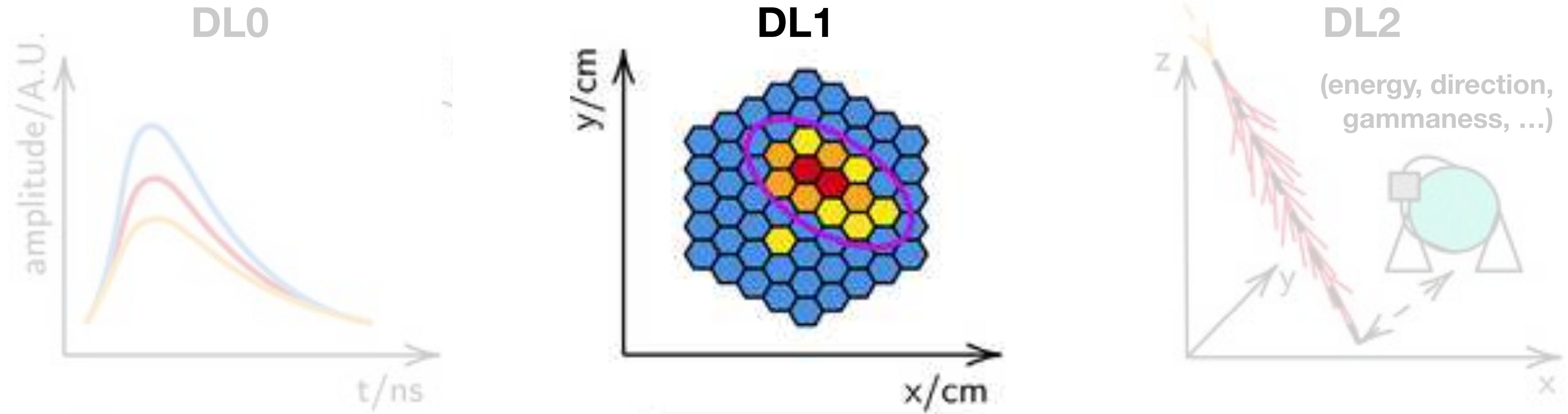
Hillas parameters

- Images of gamma rays are elongated ellipses
- Hillas parameters = analytical representation of the image as a 2D Gaussian:
 - Width (W) and length (L)
 - Total image amplitude (**size**)
 - Nominal distance d between the centre of the camera and the (amplitude-weighted) centroid of the image
 - Azimuthal angle φ of the image centroid with respect to the camera centre
 - Orientation angle α of the ellipse in the camera



Data levels

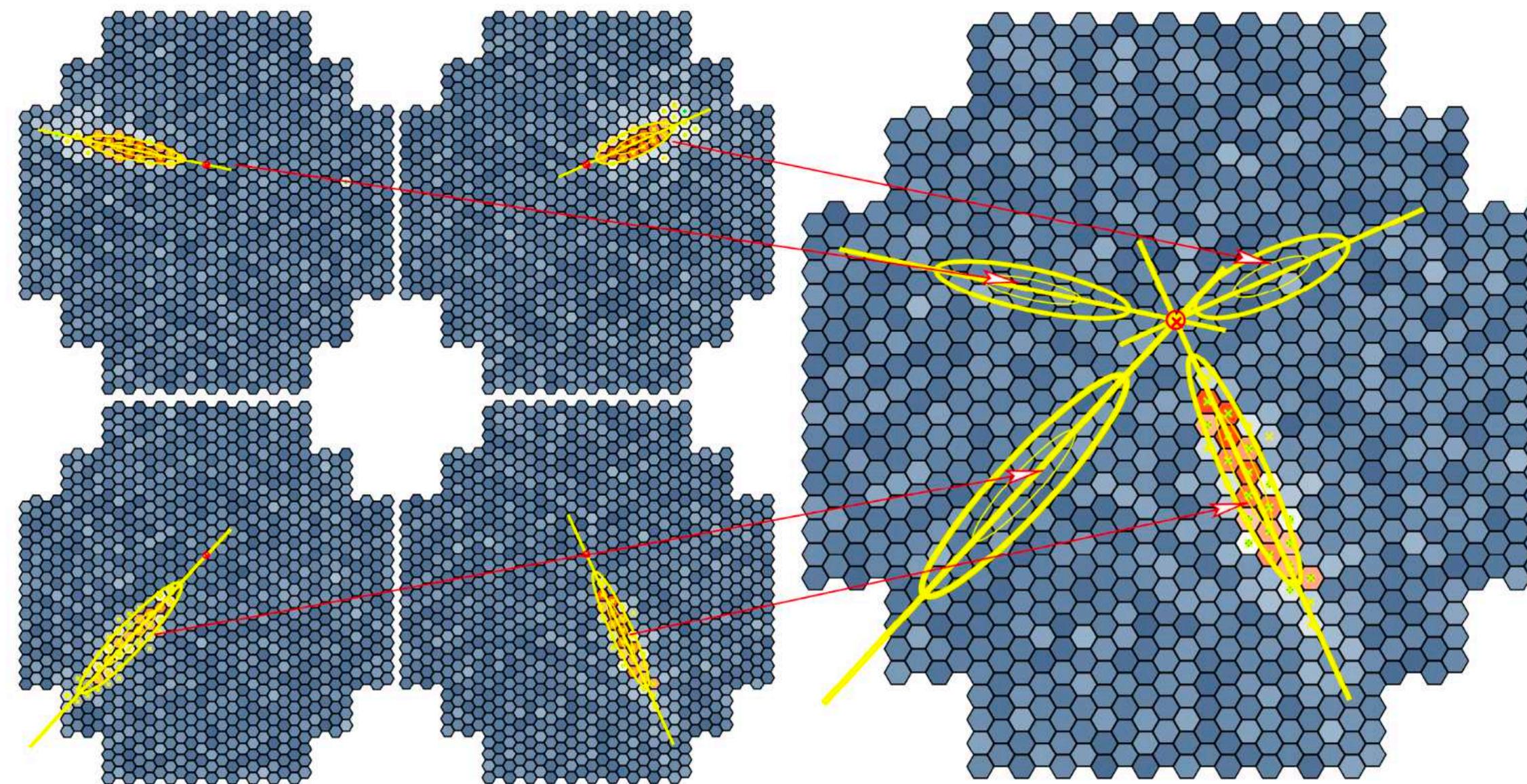
We are now at DL1!



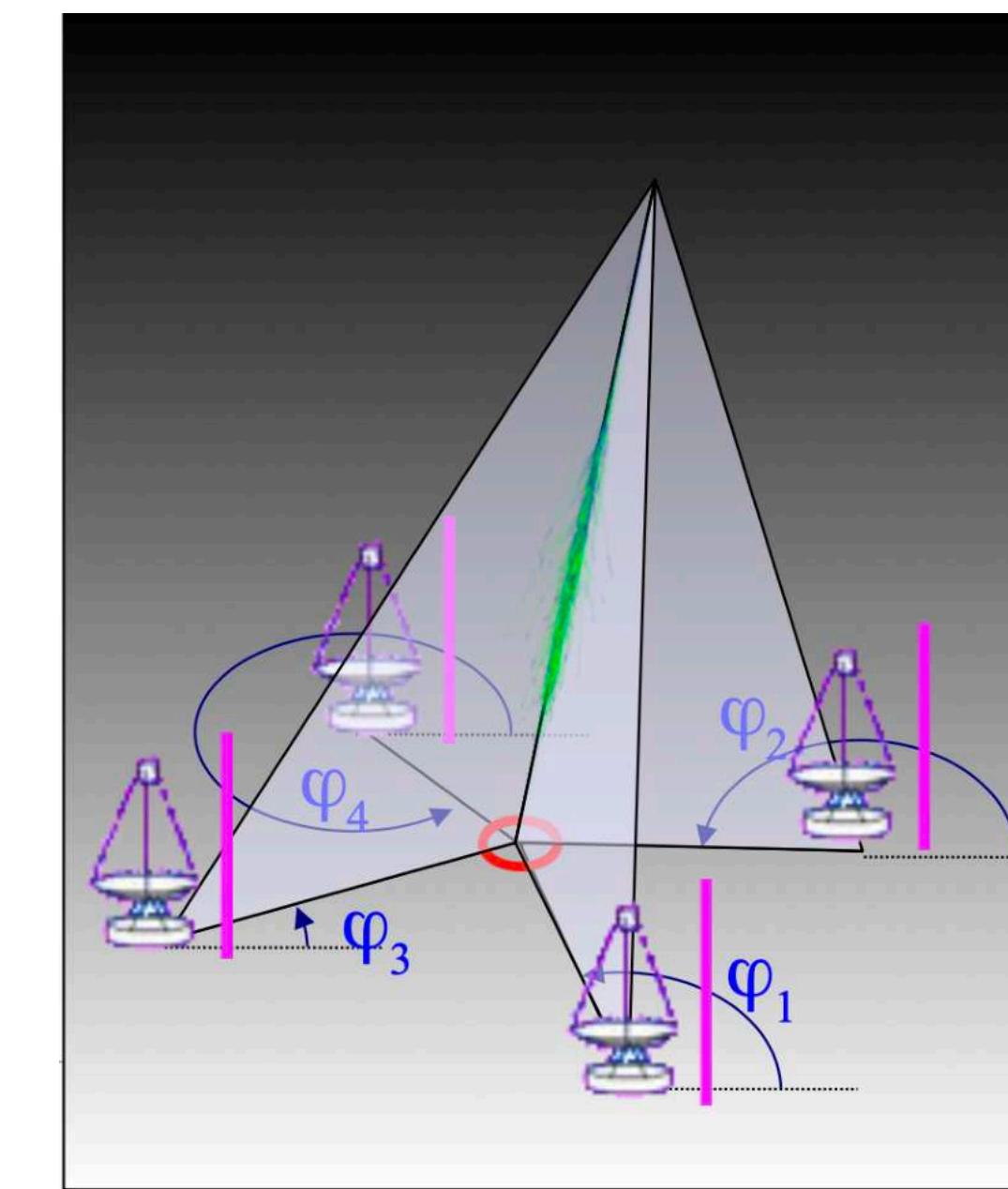
We have images and they are cleaned and parameterized
→ transition to DL2

Stereoscopic reconstruction

Event reconstruction: (improved) arrival direction



Shower direction given by intersection of major axes of the ellipses obtained in the different camera images



Shower axis given by intersection of planes corresponding to major axes of ellipses.
Impact parameter given by intersection of major axes on ground

Stereoscopic reconstruction

Event reconstruction: energy

- Hillas' parameters **size** and **distance** (which is proportional to impact parameter) can be used to determine the energy
- At fixed impact parameter, $E \approx \text{size}$
- Energy derived from image intensity compared to MC
 - Hillas parameters derived from MC simulations of gamma-ray showers
 - Quantities derived for multiple image amplitudes, zenith angle and impact position and stored in look-up tables

Stereoscopic reconstruction

Event reconstruction: particle type (γ /background)

- Hillas parameters can be used for gamma/hadron separation:
 - **Width:** primary hadron rejection parameter. Hadronic showers are wider due to larger transverse momentum and sub-showers
 - **Length/size:** good veto for muon ring images
- MC simulation of large library of showers with different energies, distribution of impact points, etc and use it as a label dataset for supervised learning

Stereoscopic reconstruction

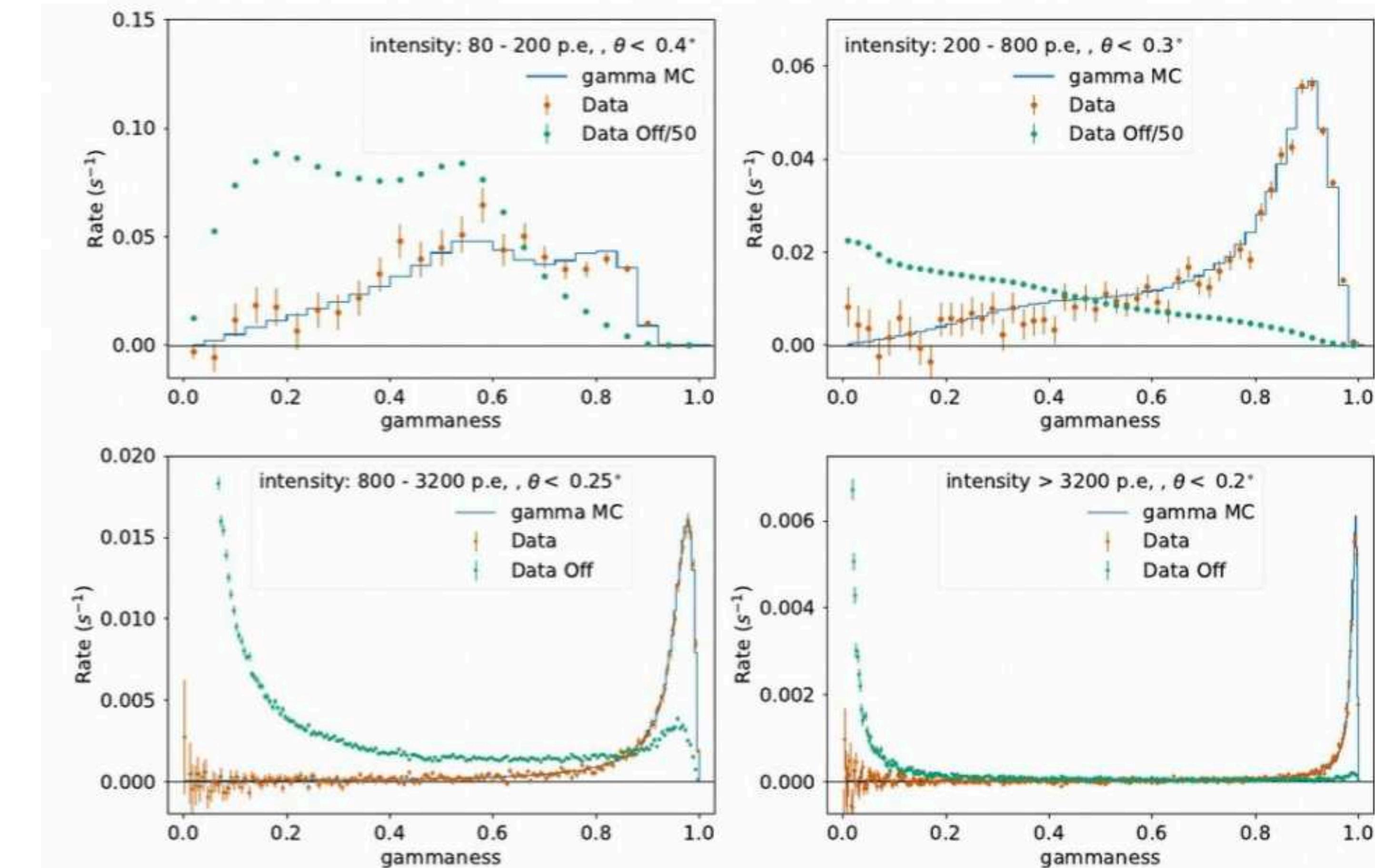
Gammaness

- By using training data (with known gamma-ray and cosmic-ray events), machine learning models or statistical methods (such as Random Forests or Boosted Decision Trees) are employed to develop a classifier that calculates the **probability that a given event is a gamma-ray**
- The classifier output is the **gammaness** parameter, typically ranging between 0 and 1, where:
 - Gammaness close to 1: Indicates a high probability of being a gamma-ray event.
 - Gammaness close to 0: Suggests a higher likelihood of being a cosmic-ray background event.
- No “physical” meaning — the values of gammaness will strongly depend on the training
- Efficiency of the cut = a cut that keeps a certain percentage of the gamma-rays

Stereoscopic reconstruction

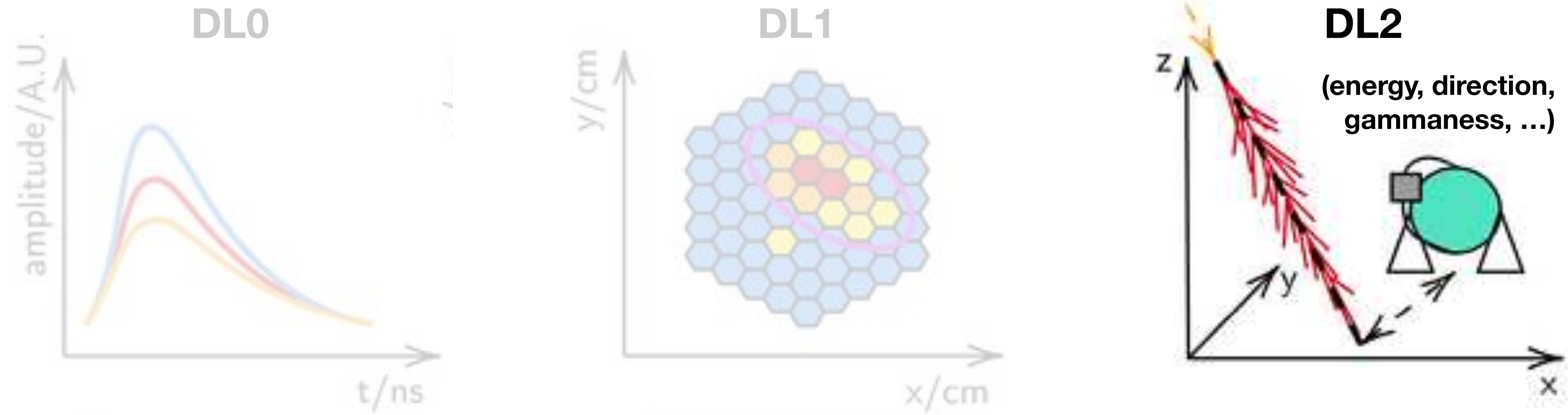
Gammaness

- High energies (larger images) separate better: a cut excludes most of the protons while keeping most of gammas
- At low energies the distributions heavily overlap



Data levels

We are now at DL2!

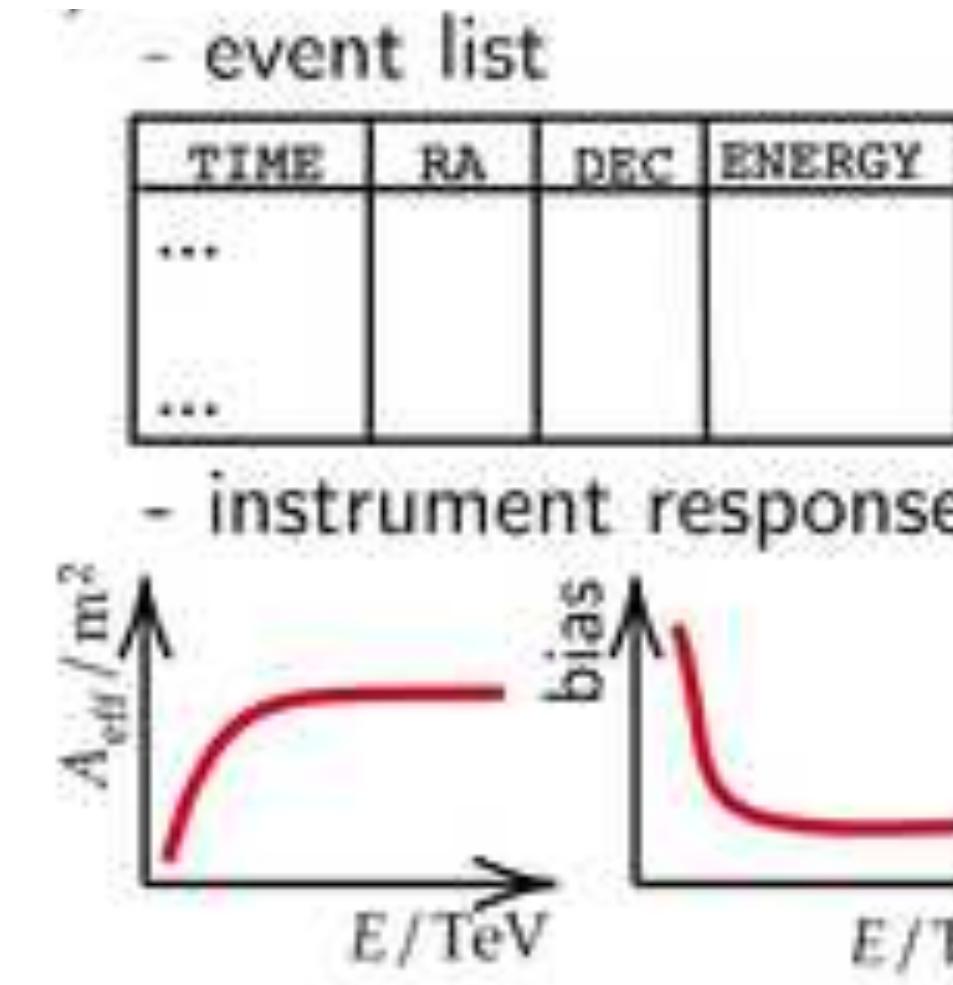


**Data reconstruction of the intrinsic gamma-ray event parameters:
energy, direction and gammaness**

What is next?

A small spoiler to Jonathan's talk...

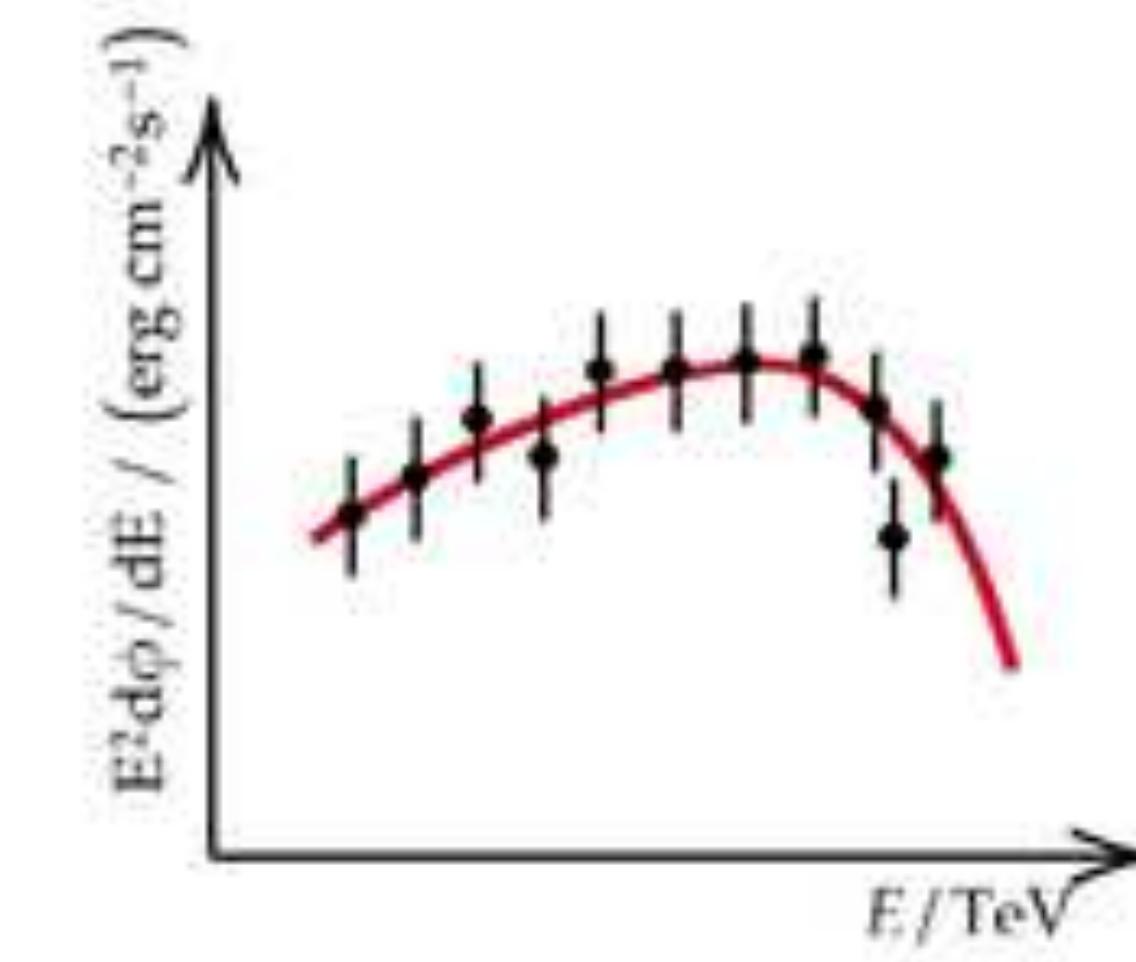
DL3



List of gamma-ray candidate events and associated IRFs

Reconstructed properties of events that pass certain event selection criteria, as well as the IRFs (effective area, PSF, etc. – typically obtained from MC) that detail the performance of the system

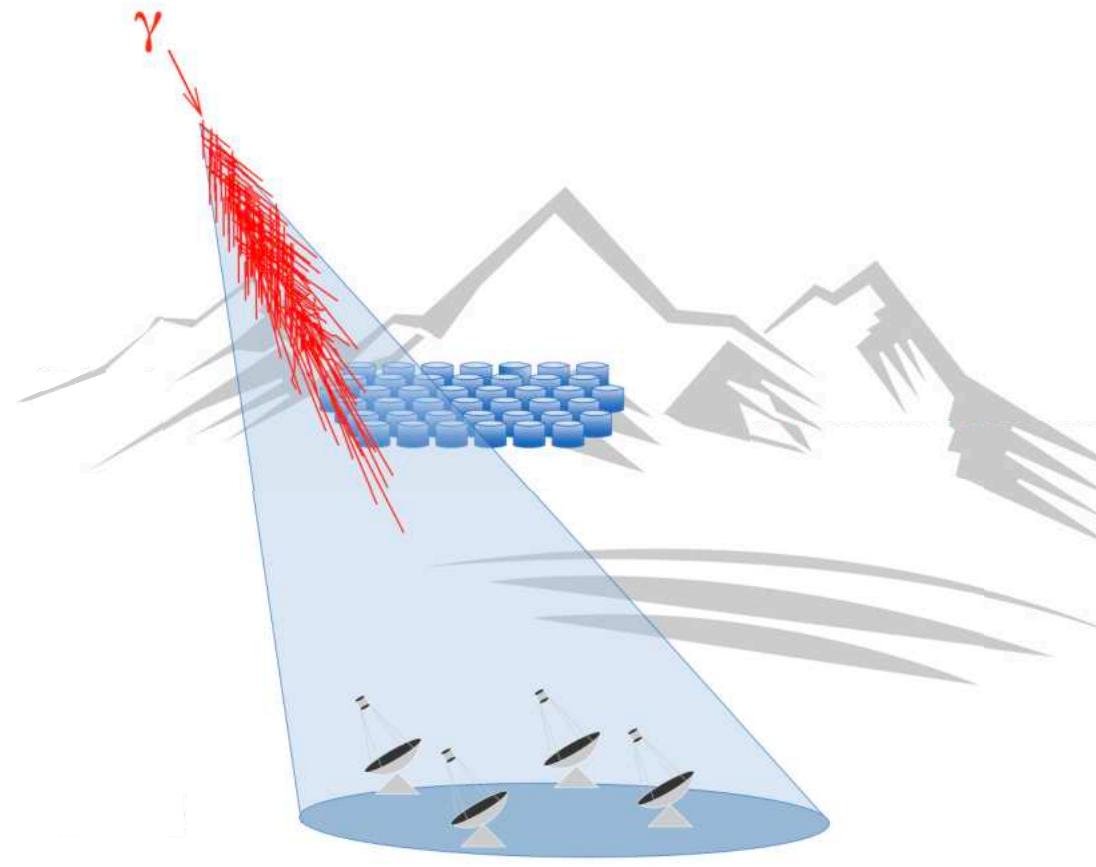
DL4



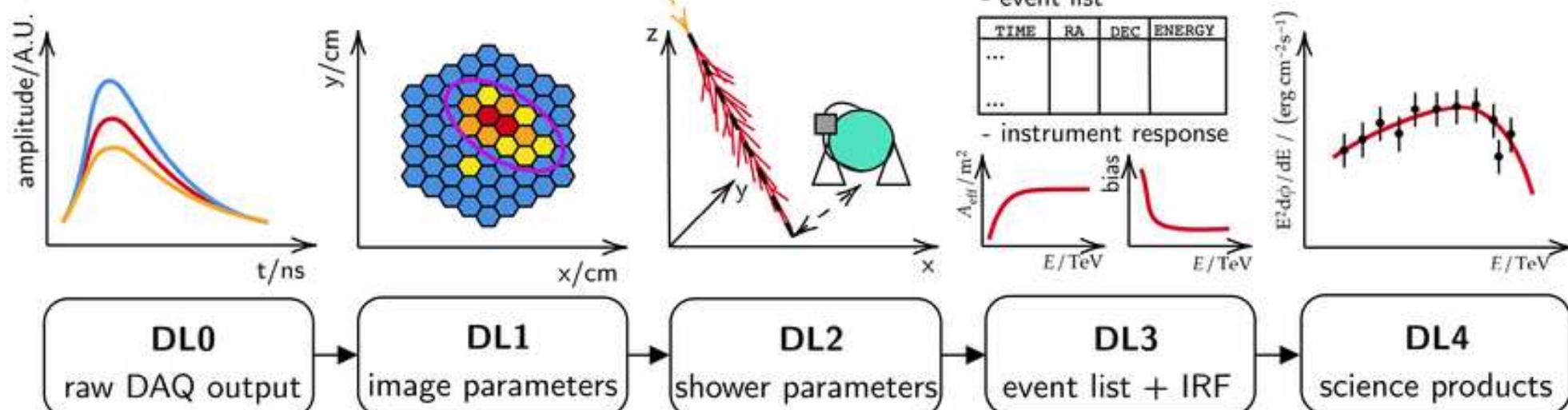
High-level science data products

From the list of selected events and the IRFs, “astronomical” science products such as sky maps, energy spectra, or light curves may be derived

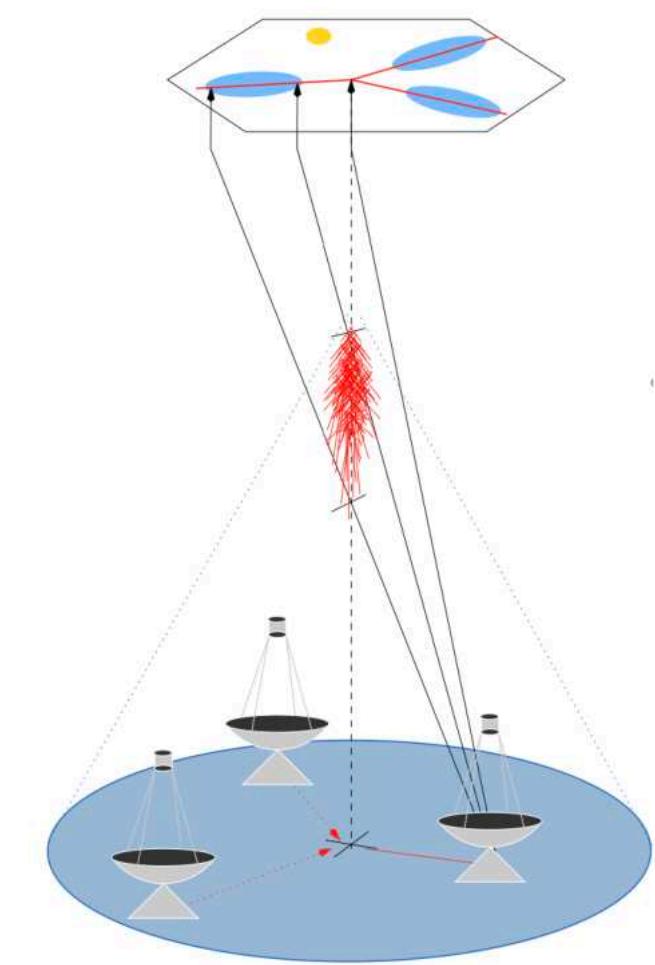
Take home messages



1. VHE gamma-ray produced in astrophysical source via non-thermal processes creates atmospheric EM showers detectable on the ground by WCD and IACTs



2. Cherenkov light produced by charged particles in the EM showers detected by IACTs via stereoscopic method



3. From camera raw data to ready-to-analyze data:
waveform calibration \rightarrow single telescope
reconstruction \rightarrow stereoscopic reconstruction