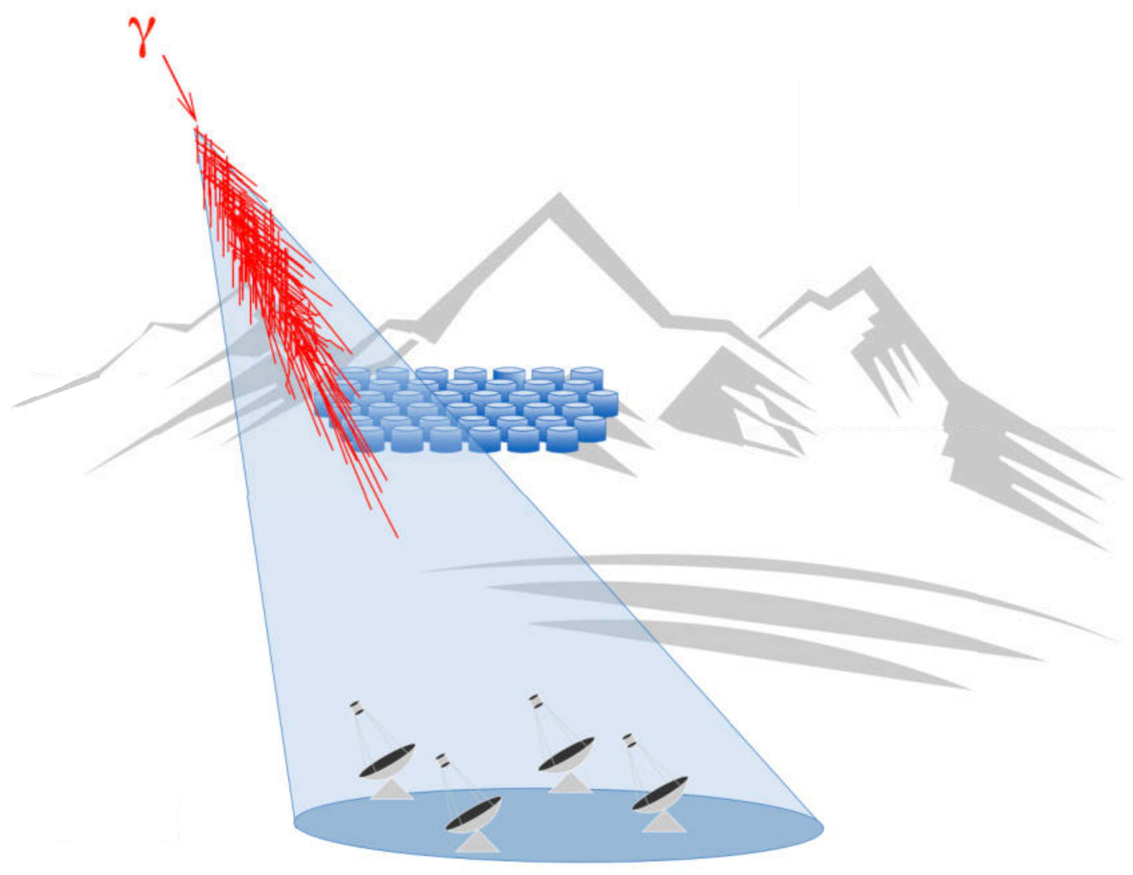
Detection and reconstruction of extensive air showers

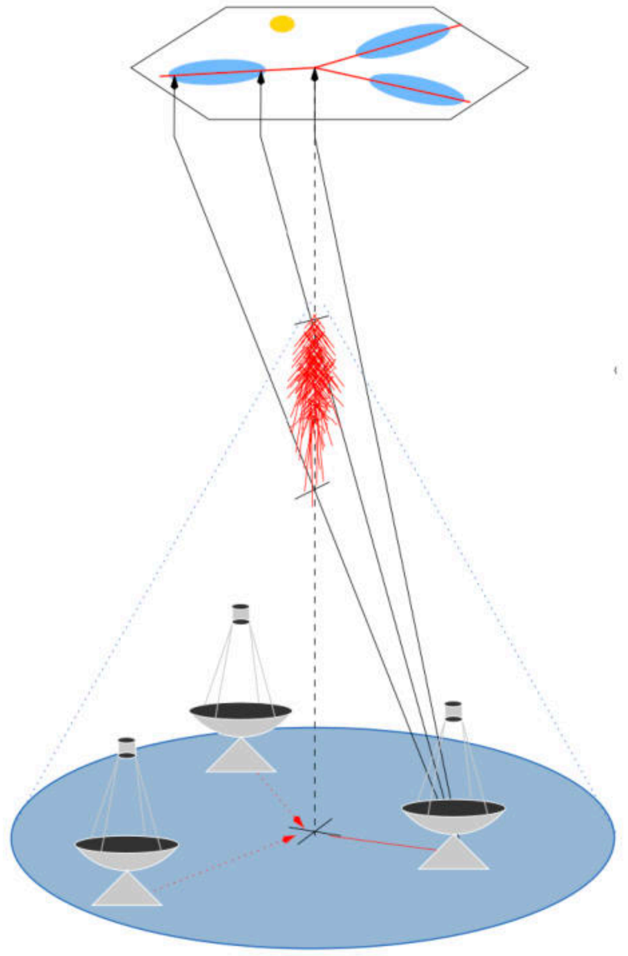
Federica Bradascio (IJCLab, Université Paris-Saclay)

CADS School - November 2025

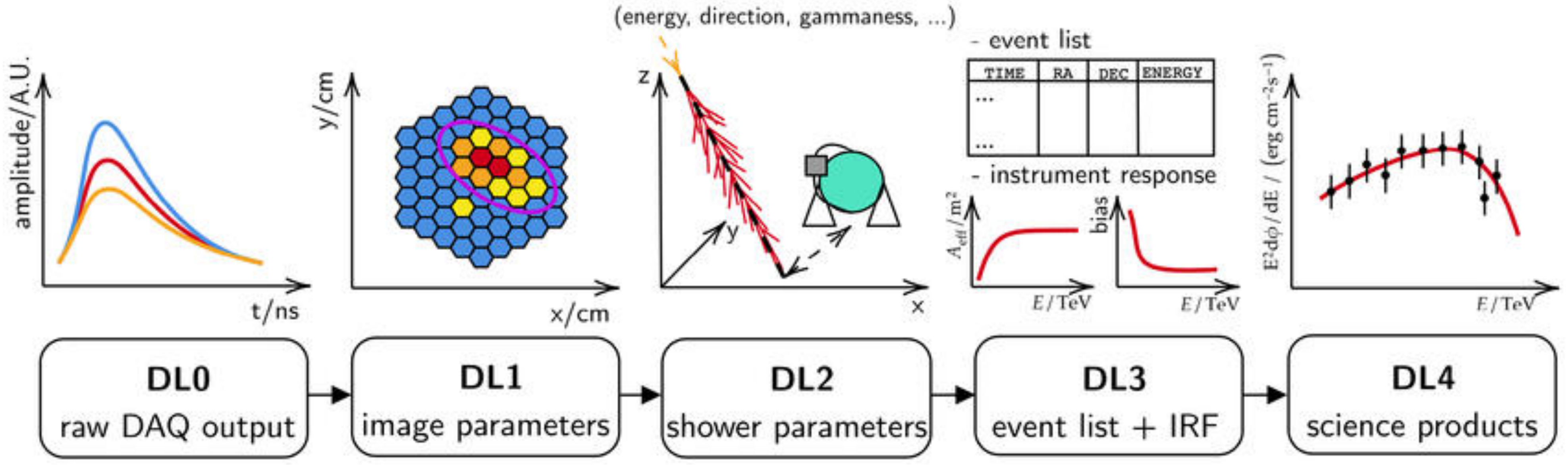
Outline



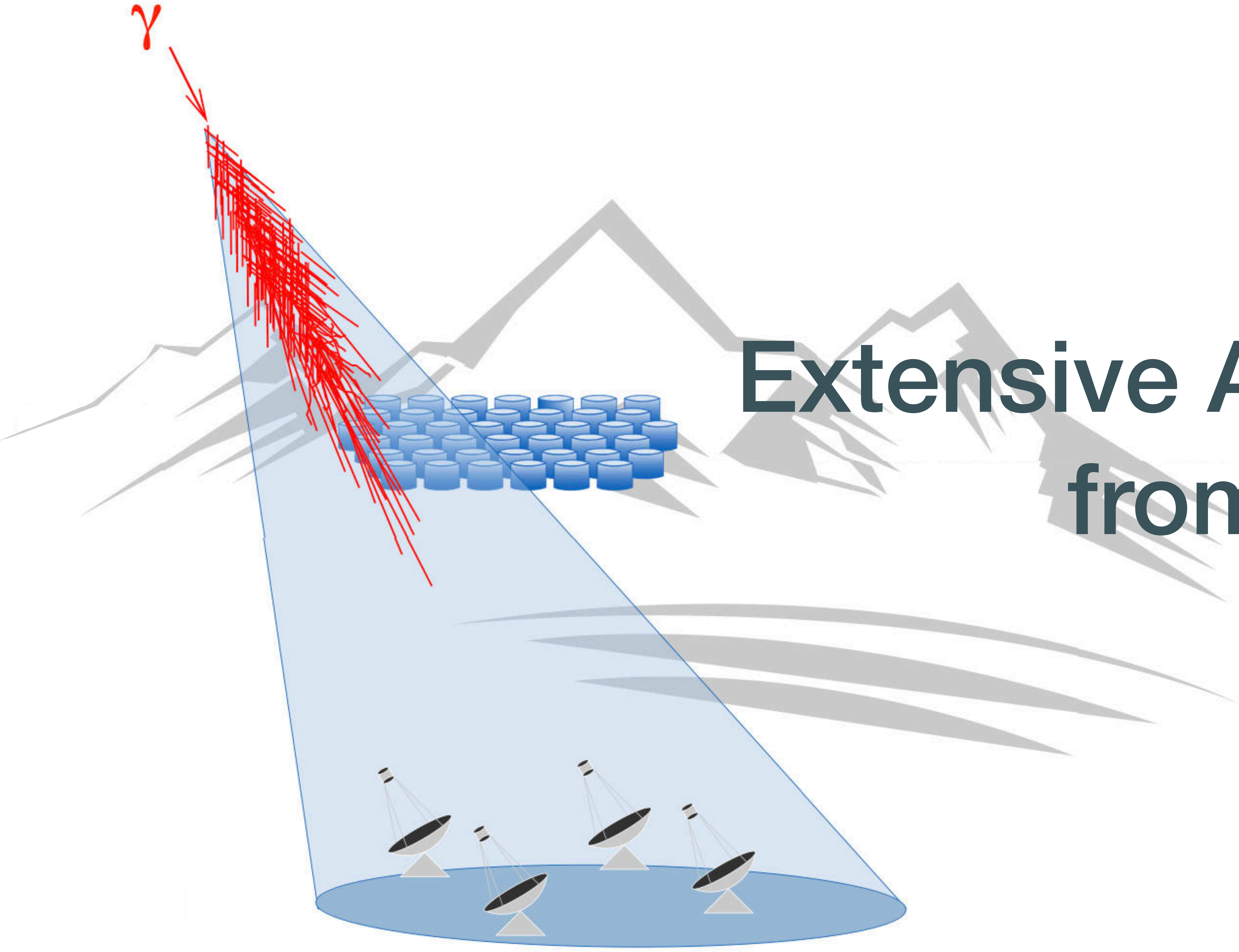
1. Extensive Air Showers:
from sources to telescopes



2. IACTs: detection principles



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



Extensive Air Showers: from sources to telescopes

Gamma-rays astrophysics

What are they and why studying them?

DEFINITIONS:

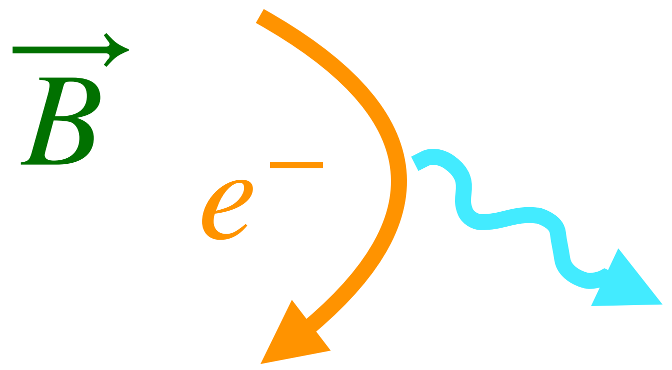
- Medium-Energy Gamma Rays (MeV)
- High-Energy (HE) Gamma Rays (100 MeV — 50 GeV)
- Very-High-Energy (VHE) Gamma Rays (50 GeV — 100 TeV)

ASTROPHYSICAL GAMMA RAYS:

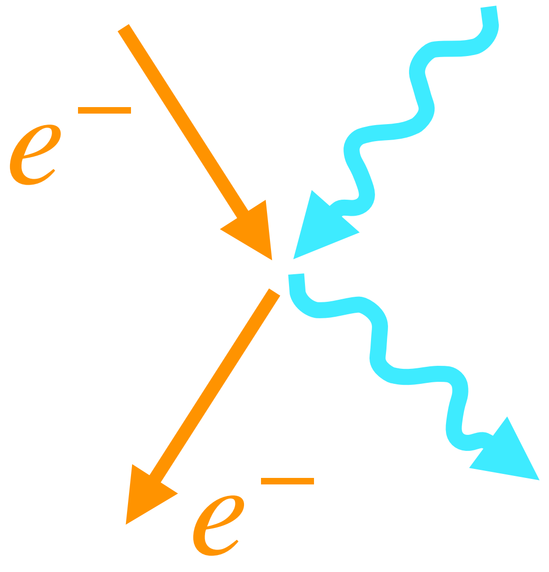
- Indicate the presence of a parental population of high-energy massive particles
- Little effect from absorption in the galaxy
- Carry information directly from the sites of acceleration

γ-rays: how are they produced?

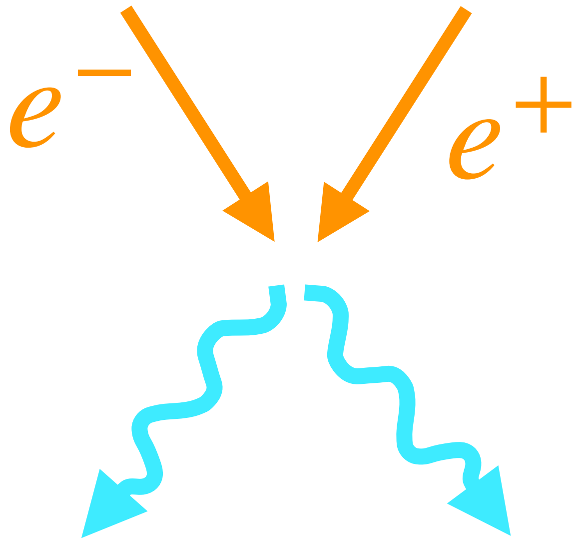
LEPTONIC PROCESSES



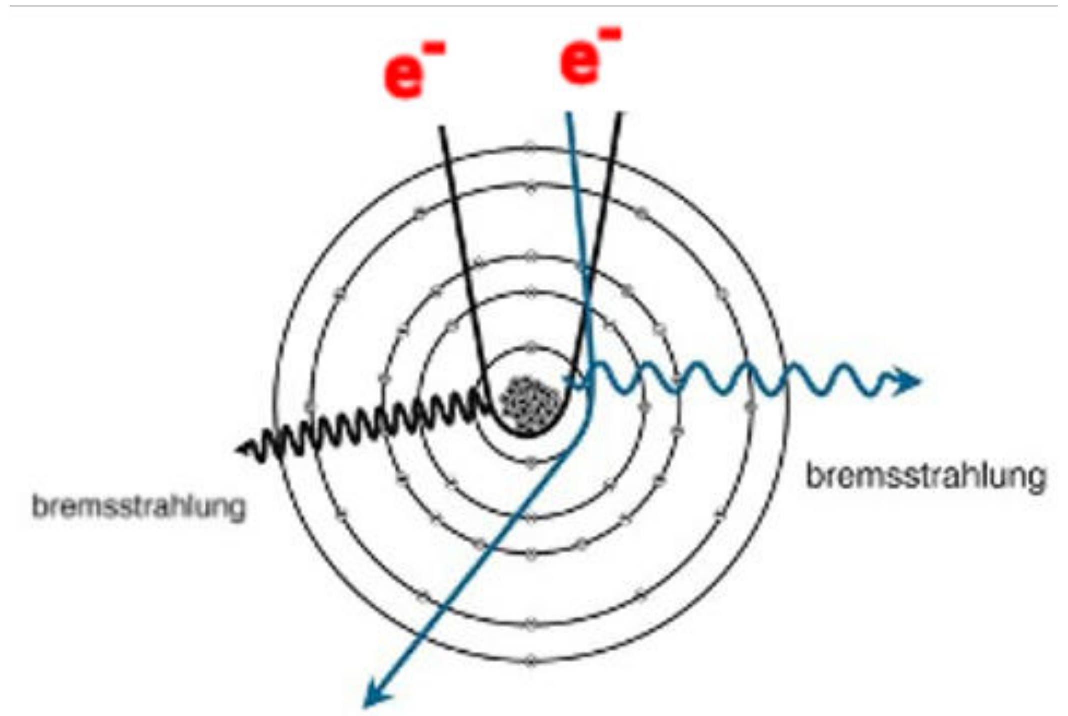
ELECTRON SYNCHROTRON



INVERSE COMPTON SCATTERING

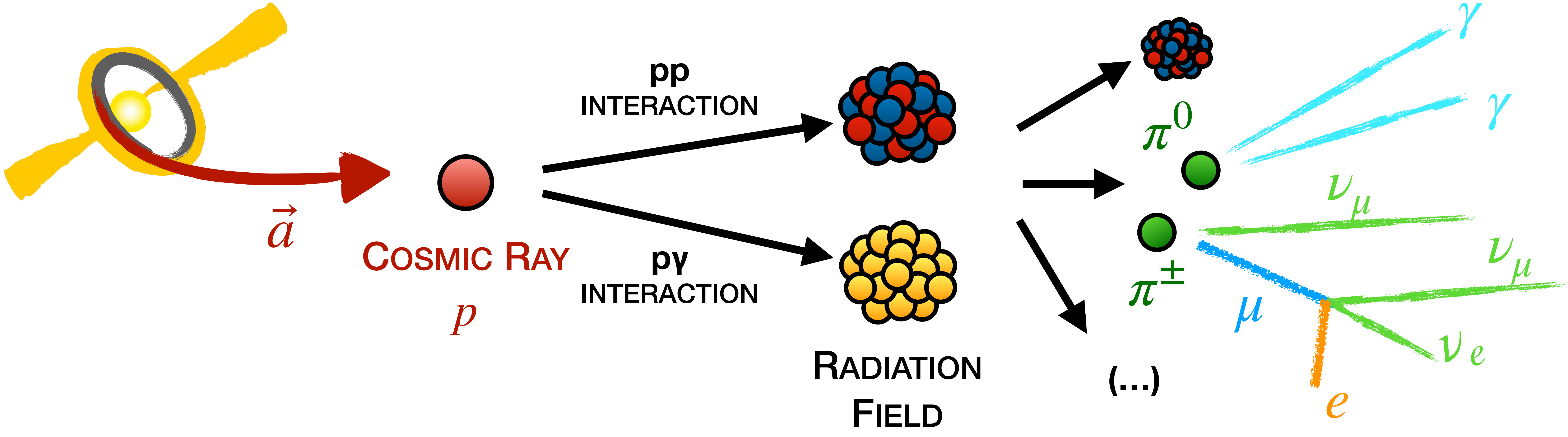


ELECTRON-POSITRON ANNIHILIATION



BREMSSTRAHLUNG

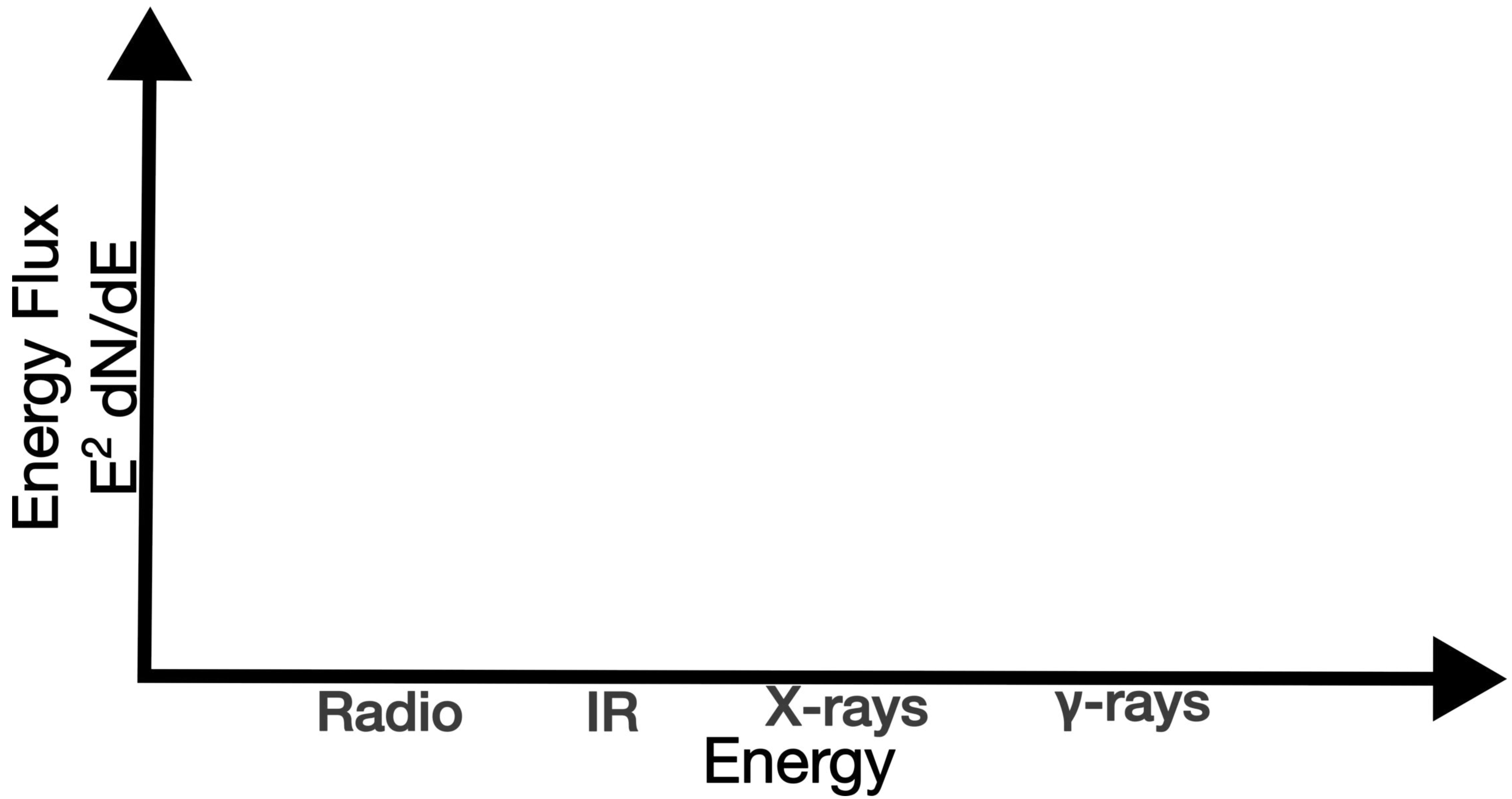
HADRONIC PROCESSES



γ-rays: how are they produced?

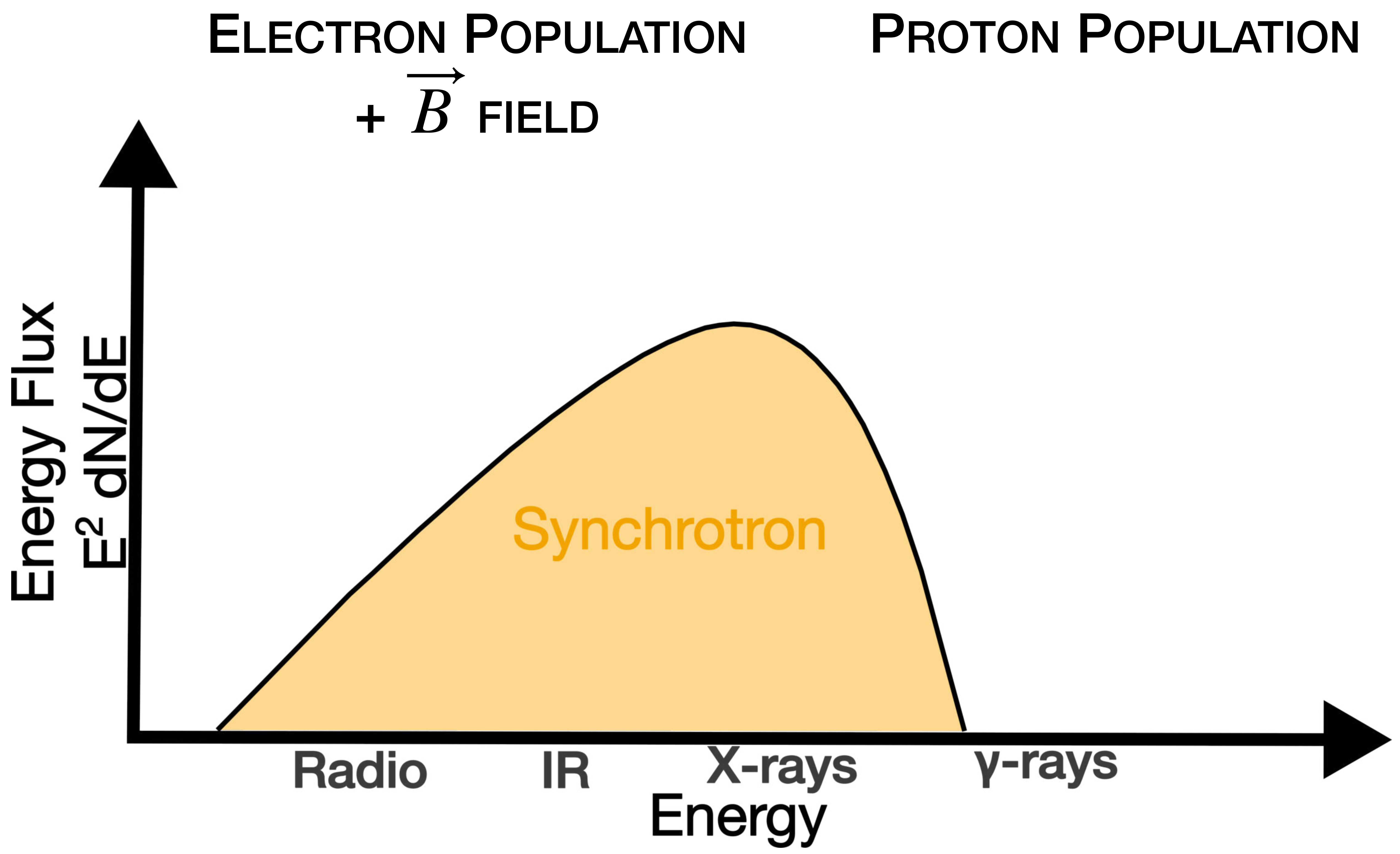
Only produced by non-thermal processes

ELECTRON POPULATION **PROTON POPULATION**



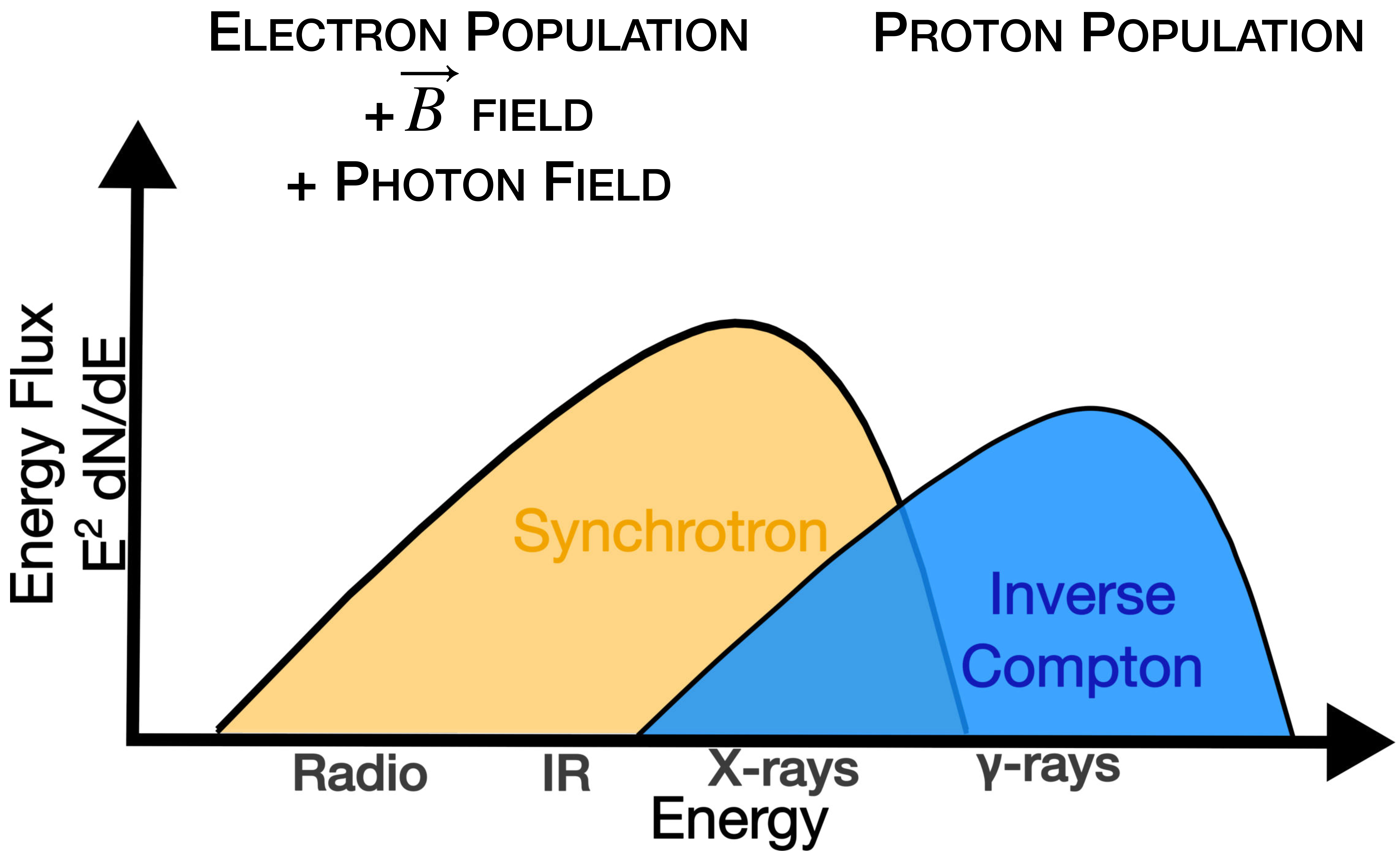
γ-rays: how are they produced?

Only produced by non-thermal processes



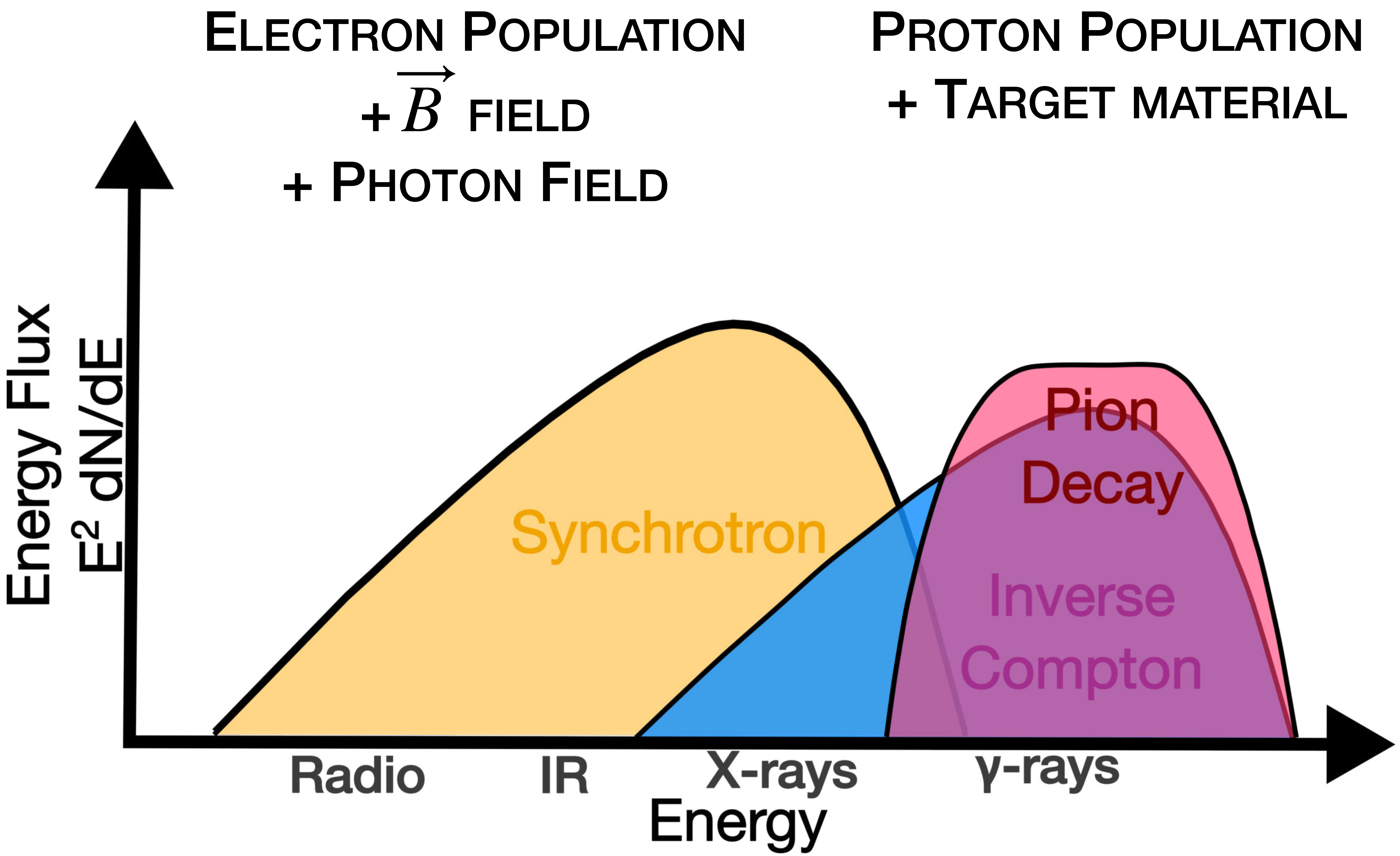
γ-rays: how are they produced?

Only produced by non-thermal processes



γ-rays: how are they produced?

Only produced by non-thermal processes



γ-rays: how to detect them?

- Medium-Energy Gamma Rays (MeV)

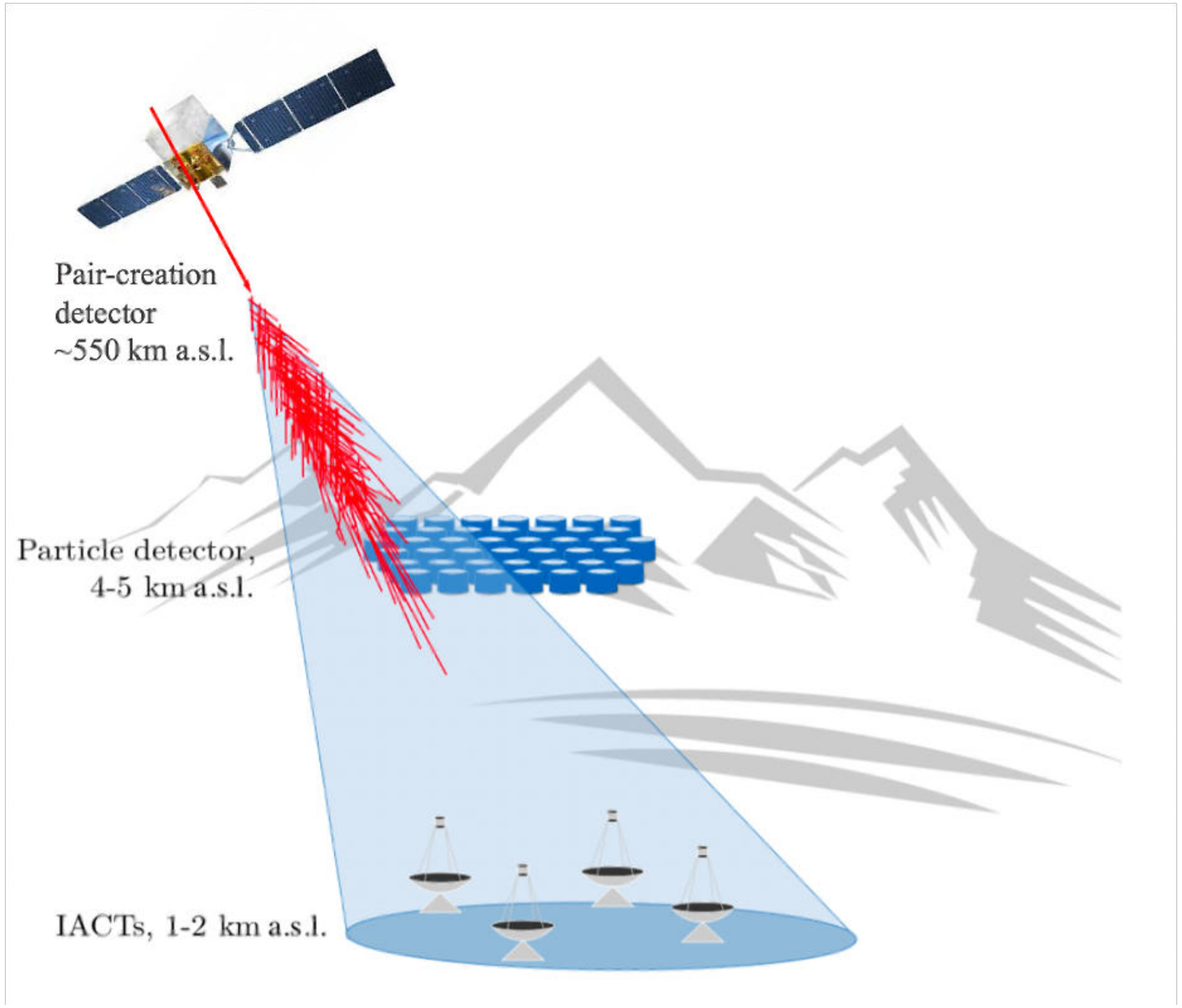
  → 🛰️ Detected from space

- High-Energy (HE) Gamma Rays (100 MeV — 50 GeV)

  → 🛰️ & 🌍 Detected from space and ground-based experiments

- Very-High-Energy (VHE) Gamma Rays (50 GeV — 100 TeV)

  → 🌍 Detected from ground-based experiments



γ-rays: how to detect them?

- Medium-Energy Gamma Rays (MeV)

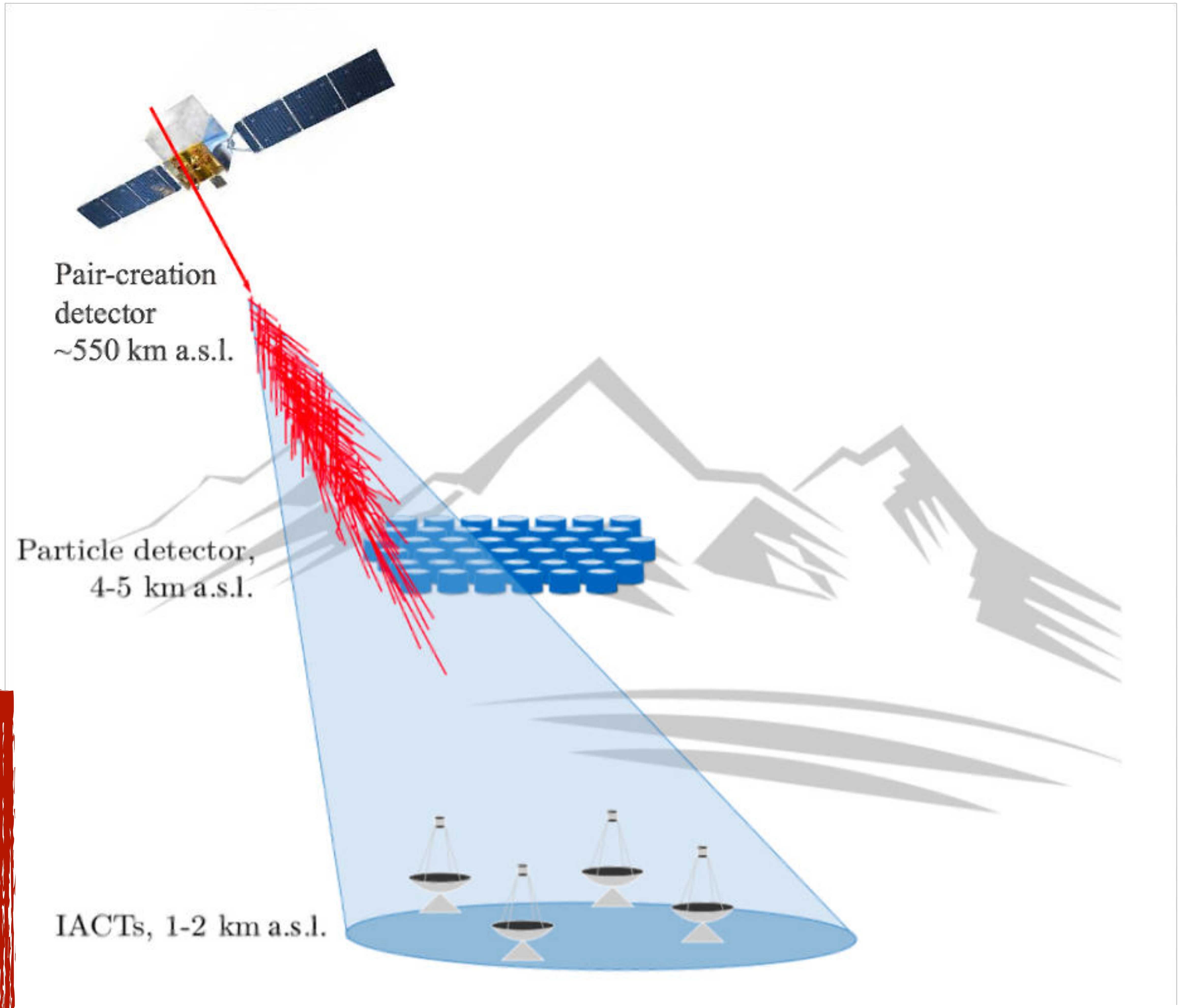
  → 🛰️ Detected from space

- High-Energy (HE) Gamma Rays (100 MeV — 50 GeV)

  → 🛰️ & 🌍 Detected from space and ground-based experiments

- Very-High-Energy (VHE) Gamma Rays (50 GeV — 100 TeV)

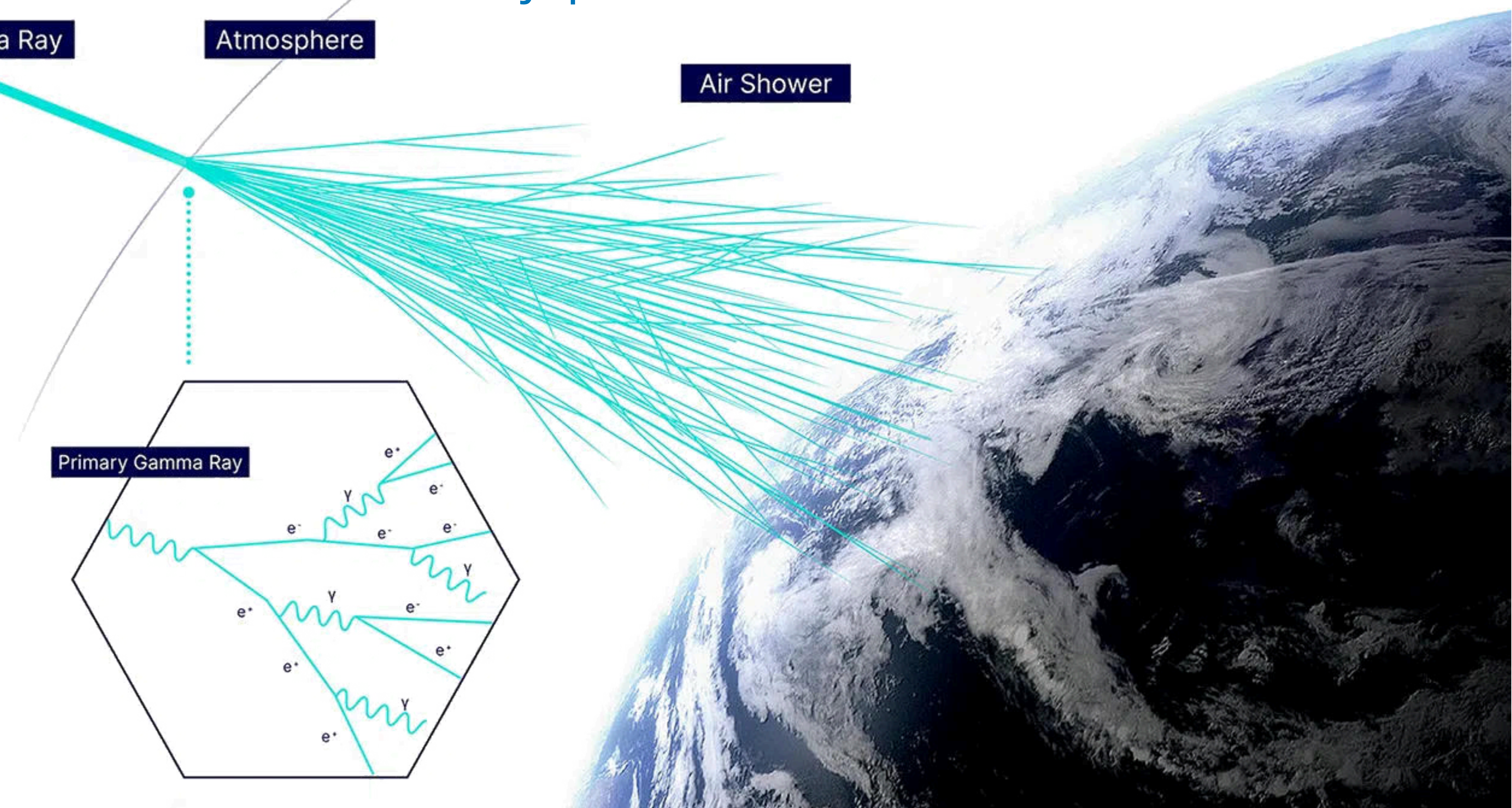
  → 🌍 Detected from ground-based experiments



Extensive Air Showers

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

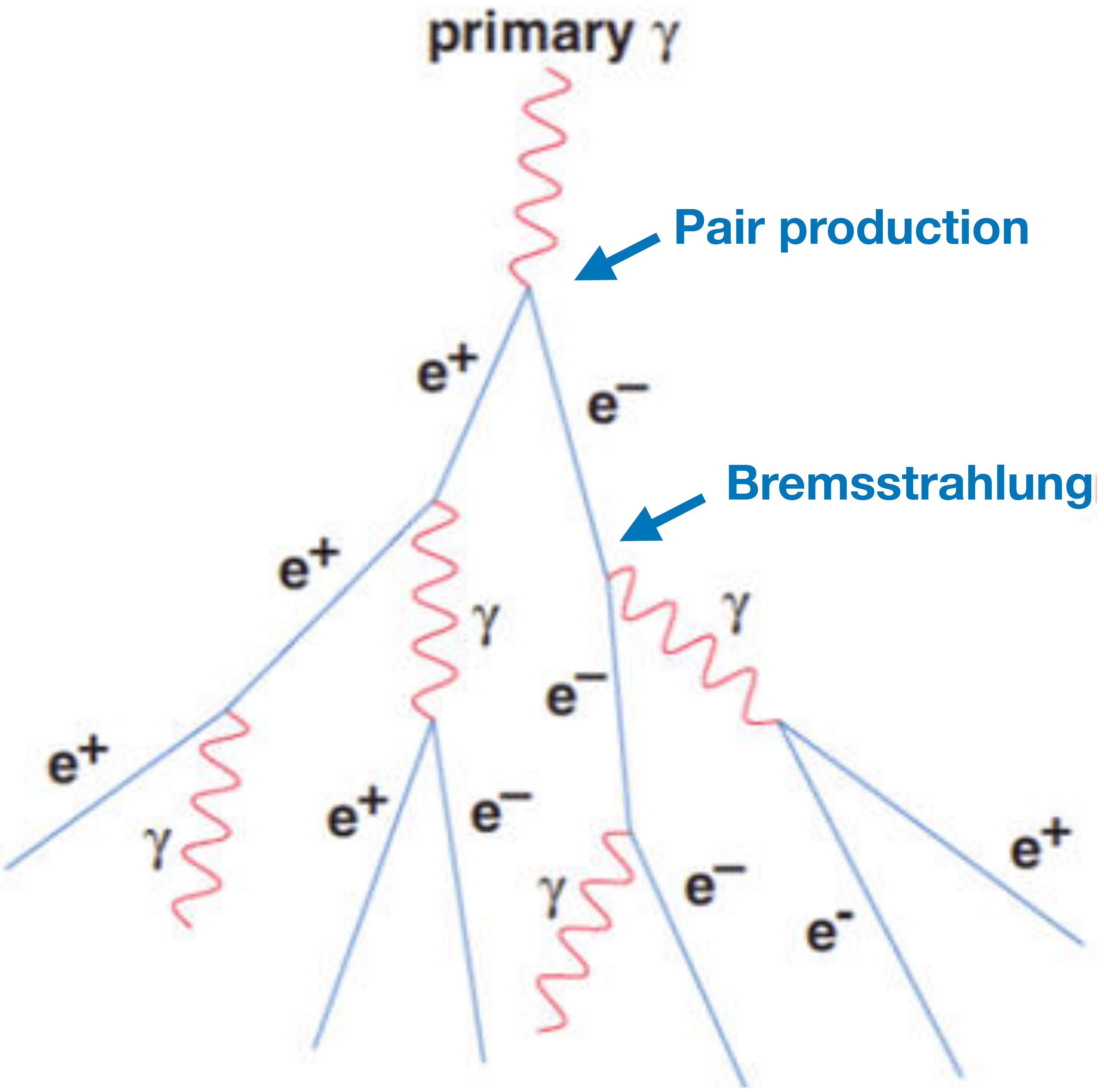
- Atmosphere acts as an inhomogeneous calorimeter and a tracking medium
- Spread on a wide area, distant detection ⇒ large effective area, can be used at high energies (≥ 100 TeV) where flux are very low
- Cascades initiated by:
  - Photons
  - Charged particles

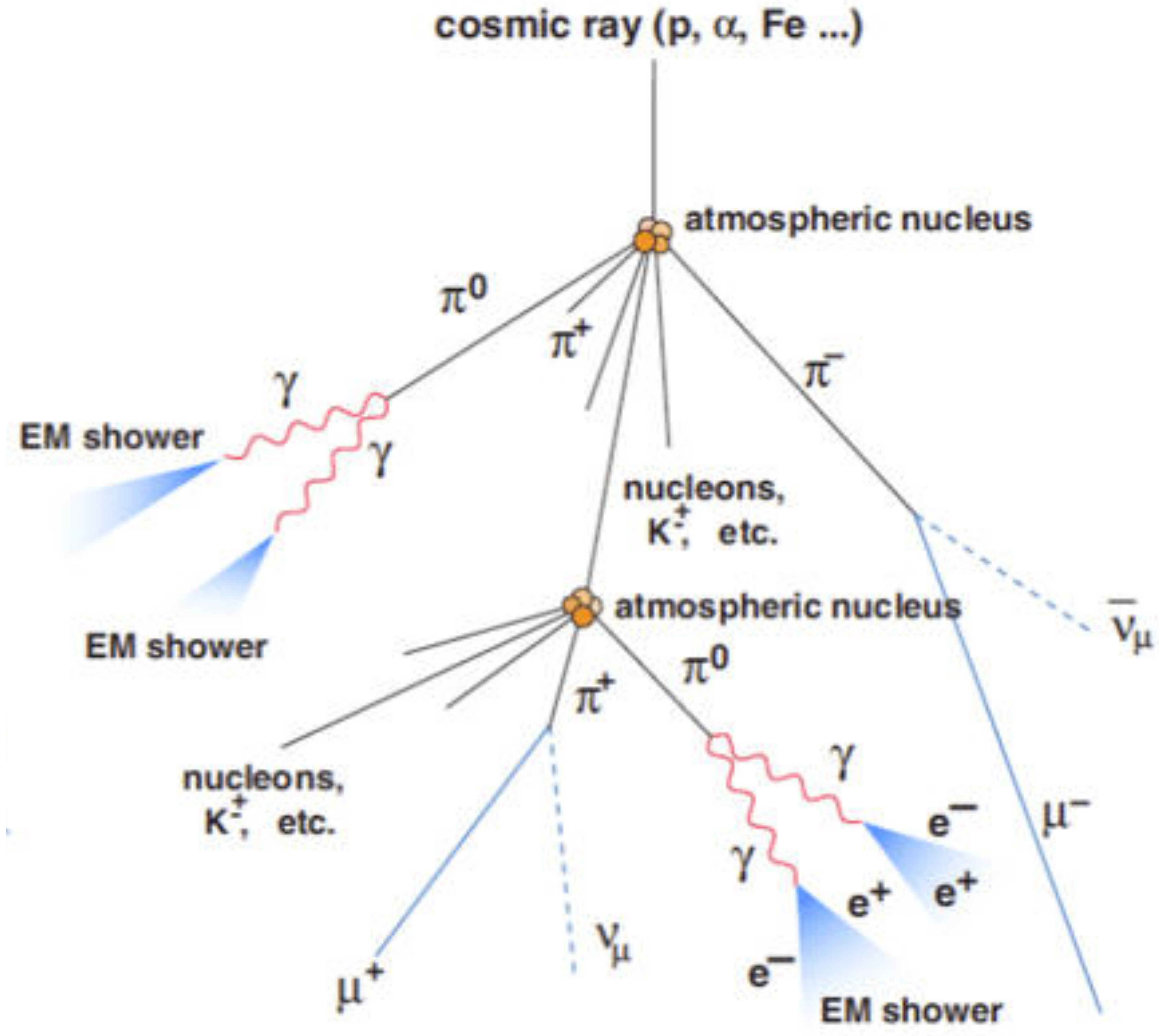


gamma ray interacts with the atmosphere

Extensive Air Showers

Electromagnetic vs Hadronic showers



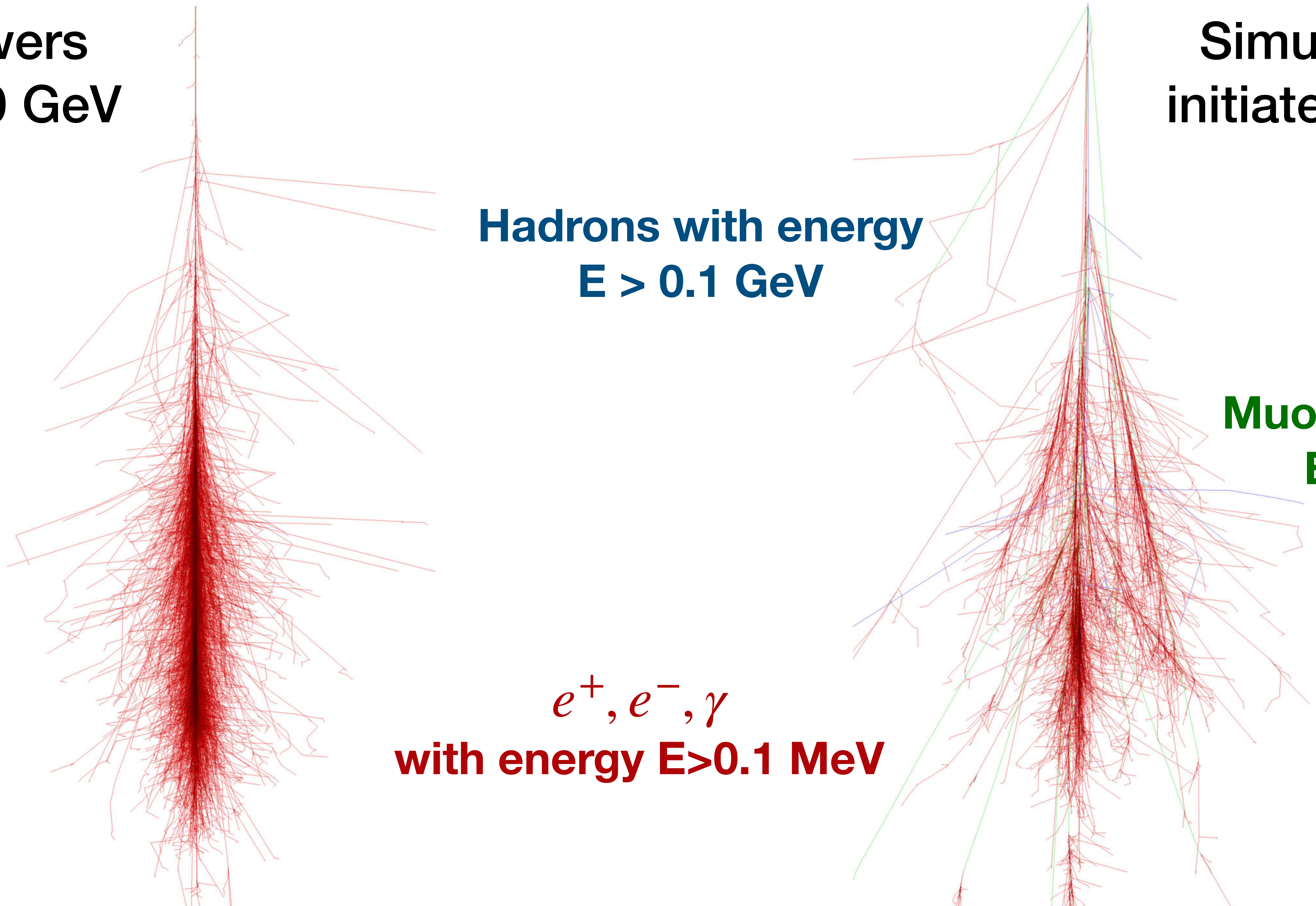


Extensive Air Showers

Electromagnetic vs Hadronic showers

Simulated showers initiated by a 100 GeV gamma ray

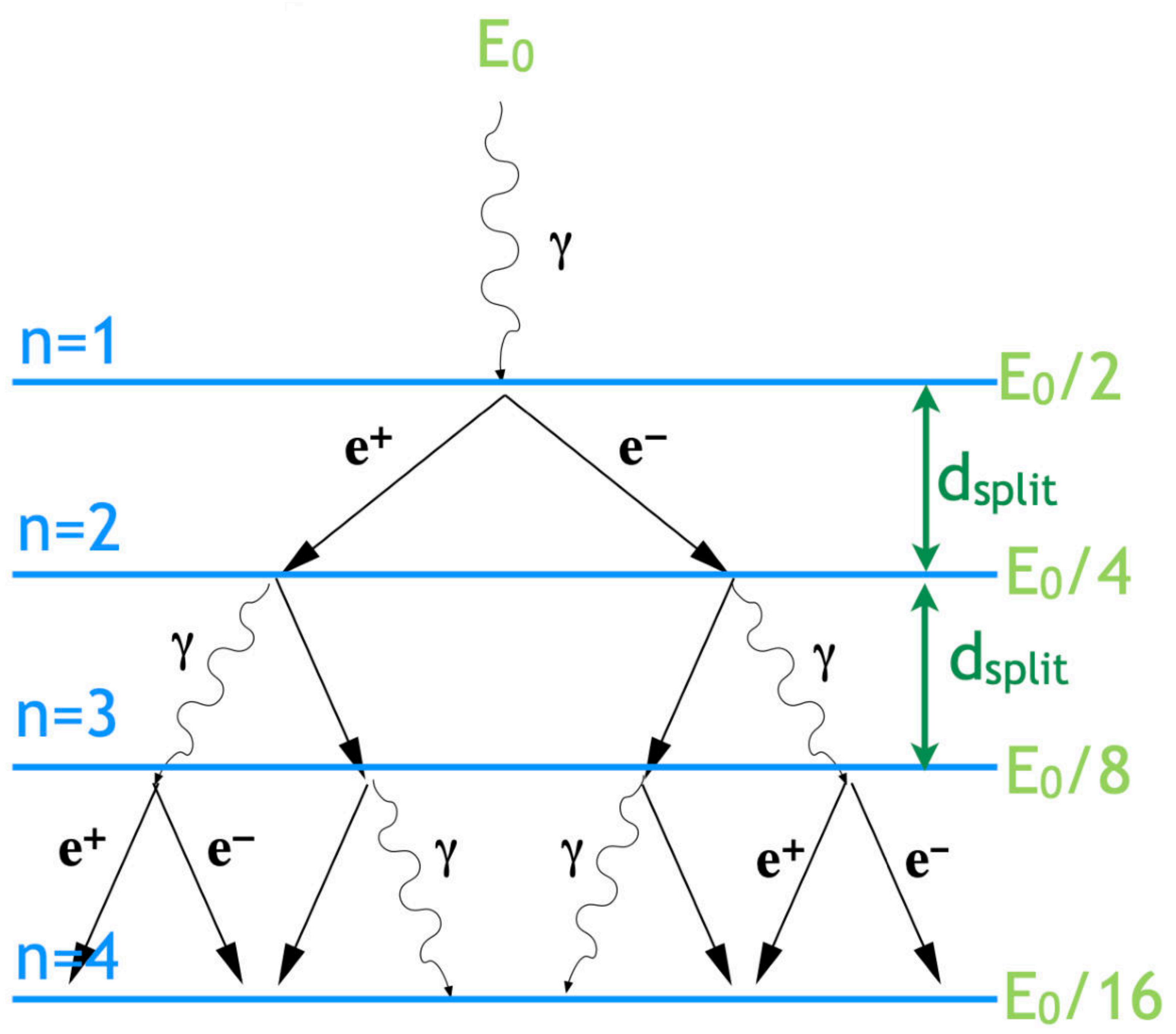
Simulated showers initiated by a 100 GeV proton



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

Shower depth: $x = nd_{\text{split}} = nX_0 \ln 2$

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

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

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

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***:

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

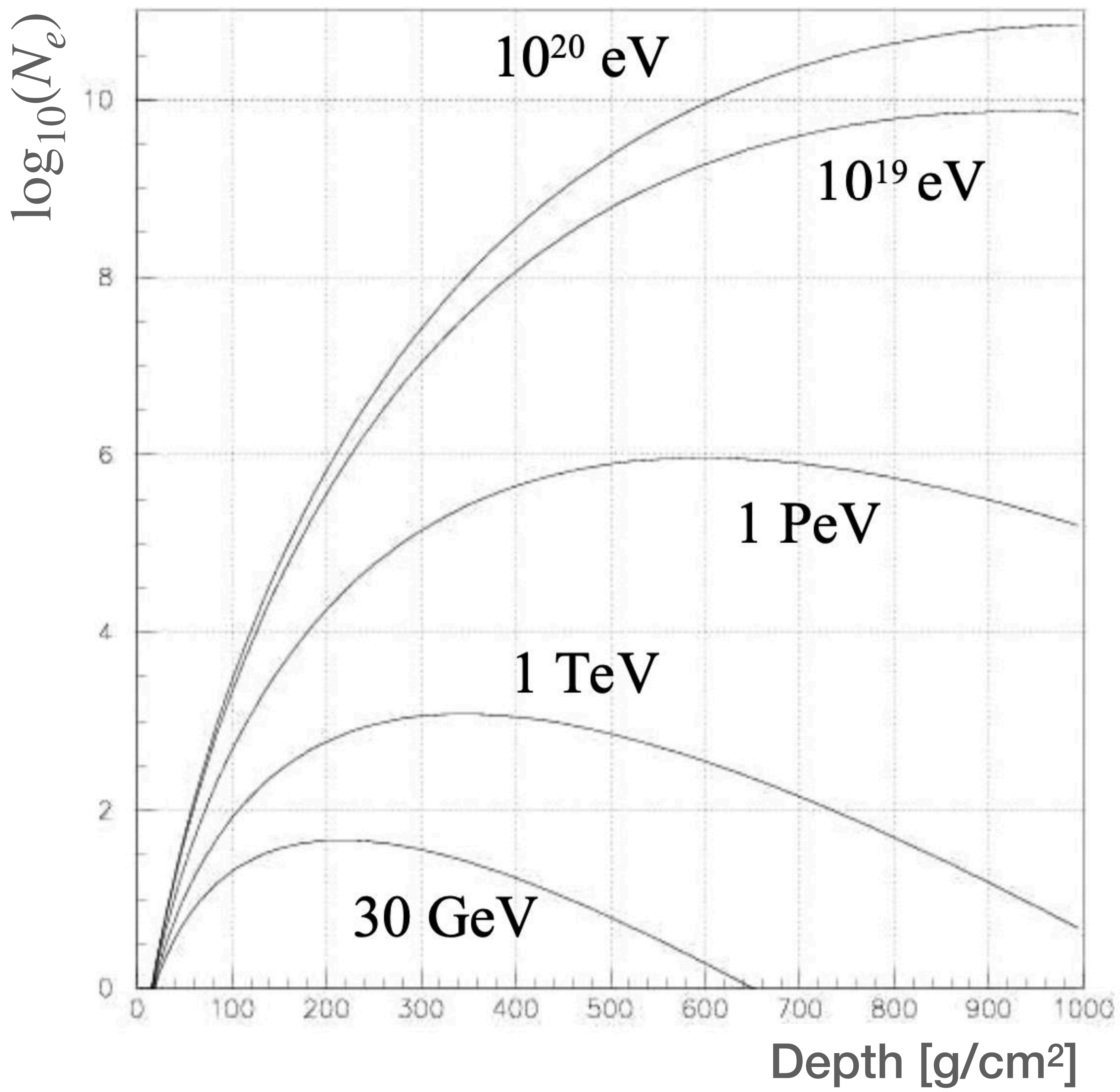
where ***s*** is the shower age parameter that describes the stage of development of the shower

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

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

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

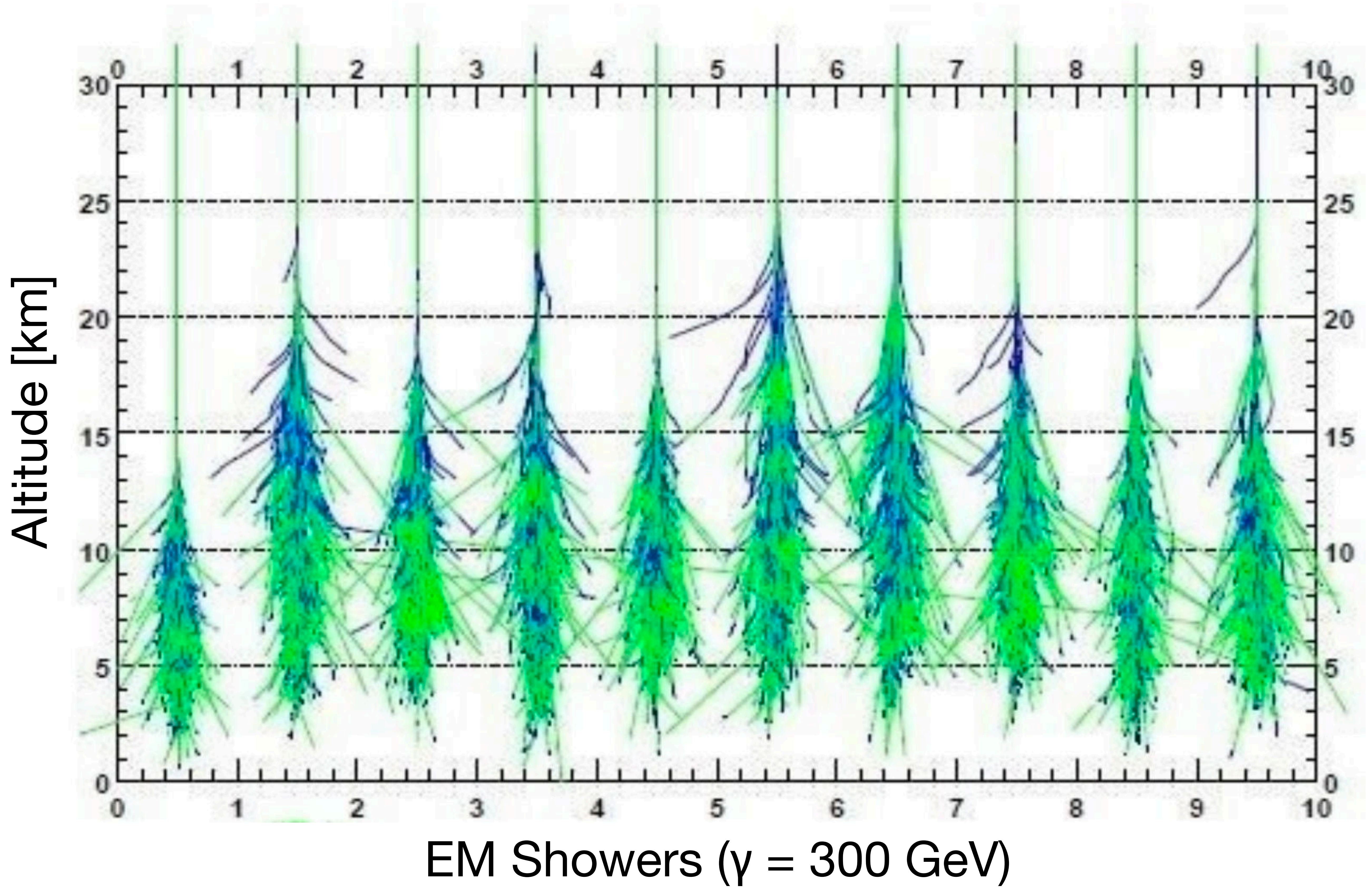
GAMMA RAY PRIMARY



Shower variability

10 simulated EM showers initiated by a 300 GeV photon

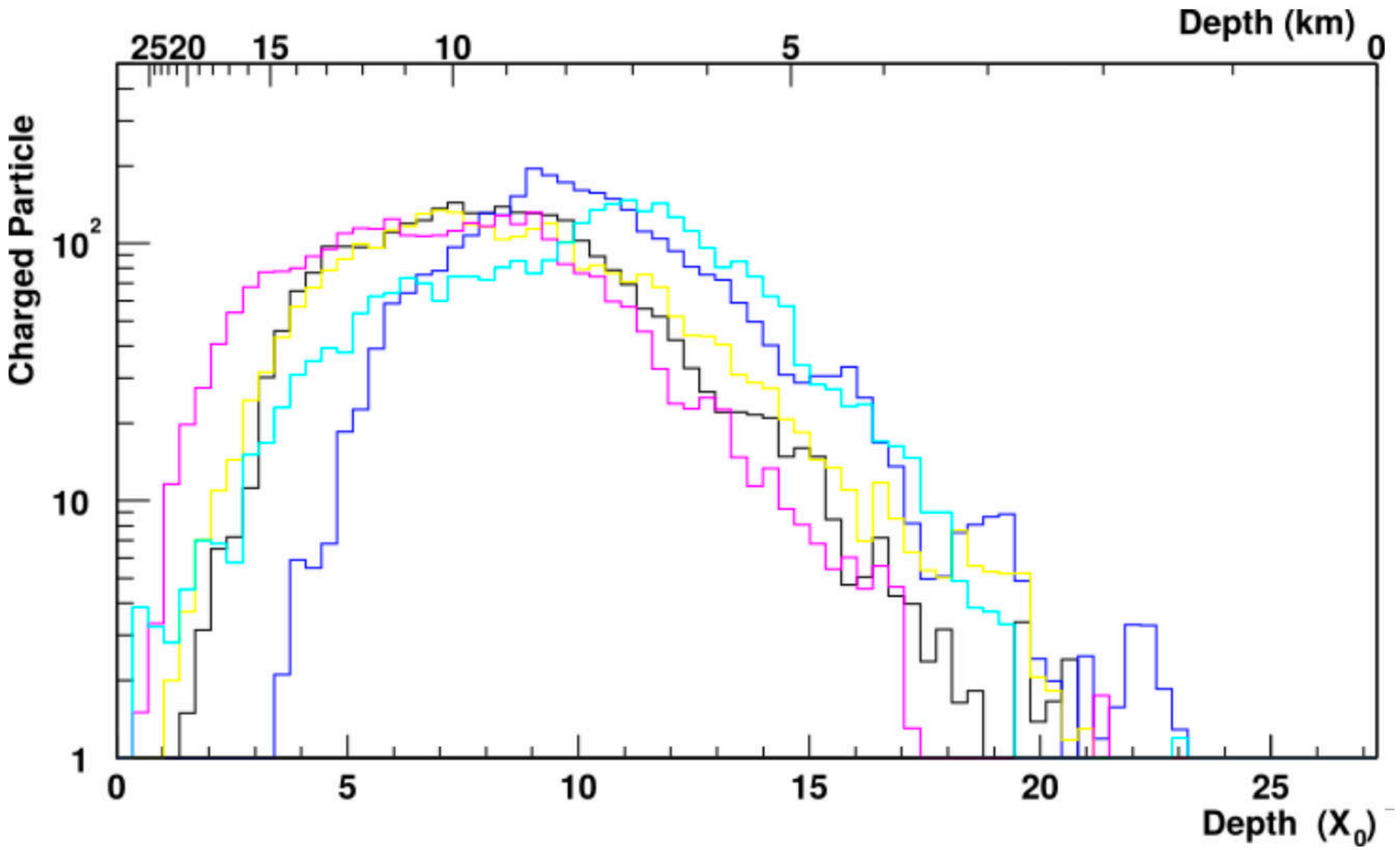
- Large fluctuations in showers, especially at low energy
- Fluctuations mainly due to the first interaction depth
- At high altitude, one radiation length ~several km → first point of interaction can vary by > 5 km
- At lower altitudes, radiation length <1km → shower development becomes similar



Shower variability

10 simulated EM showers initiated by a 300 GeV photon

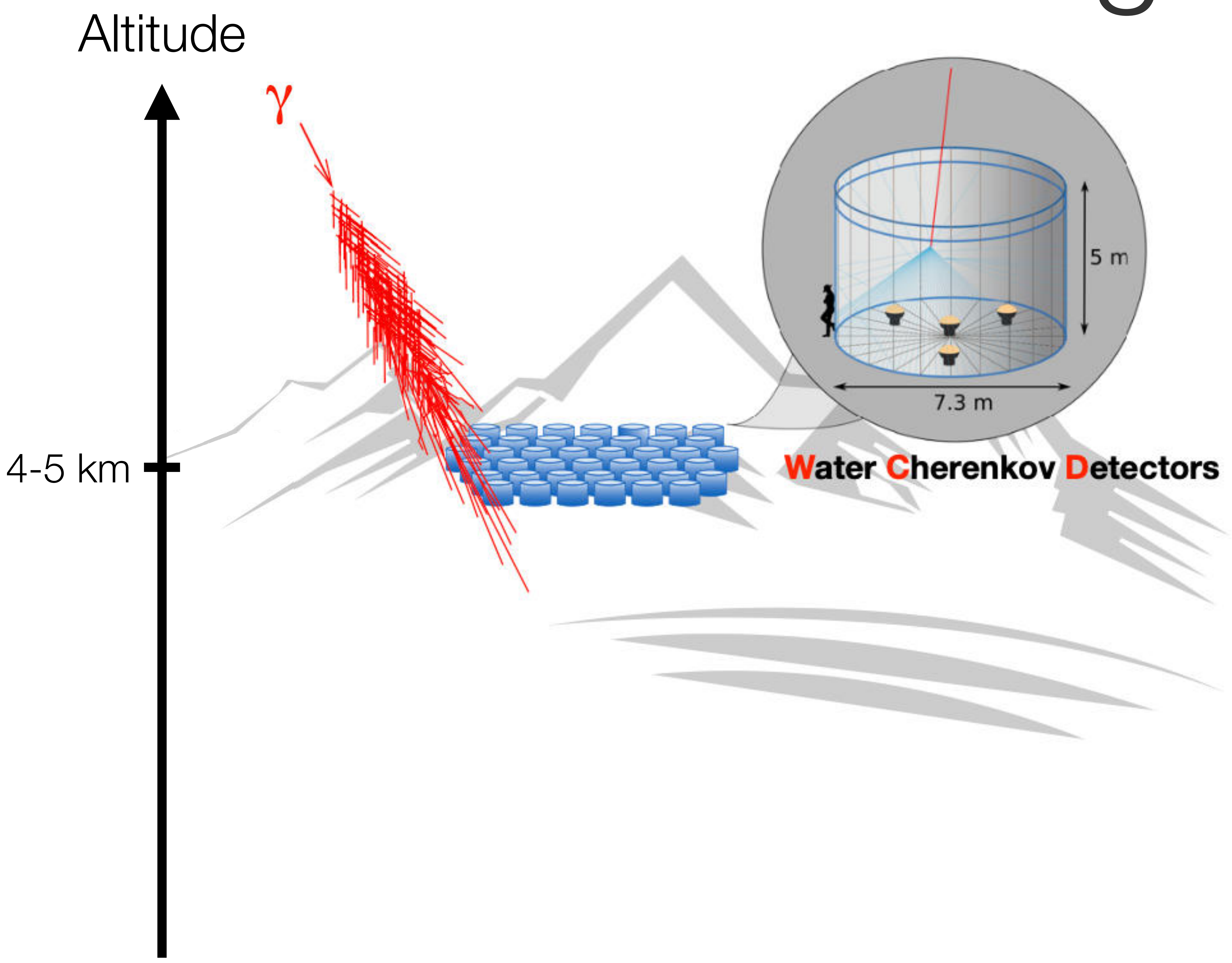
- Large fluctuations in showers, especially at low energy
- Fluctuations mainly due to the first interaction depth
- At high altitude, one radiation length ~several km → first point of interaction can vary by > 5 km
- At lower altitudes, radiation length <1km → shower development becomes similar

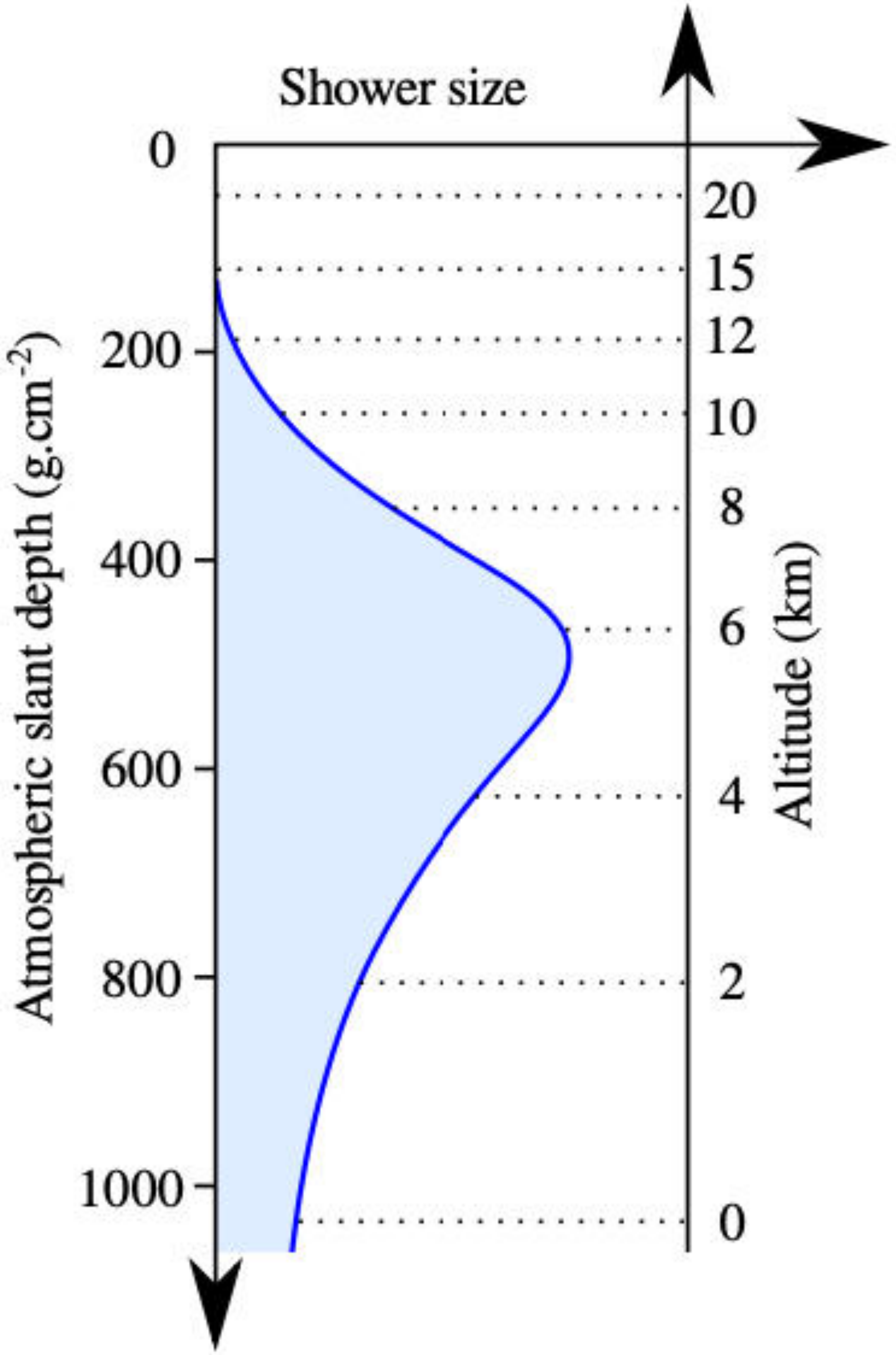


Similar shower profiles, only shifted by few radiation lengths

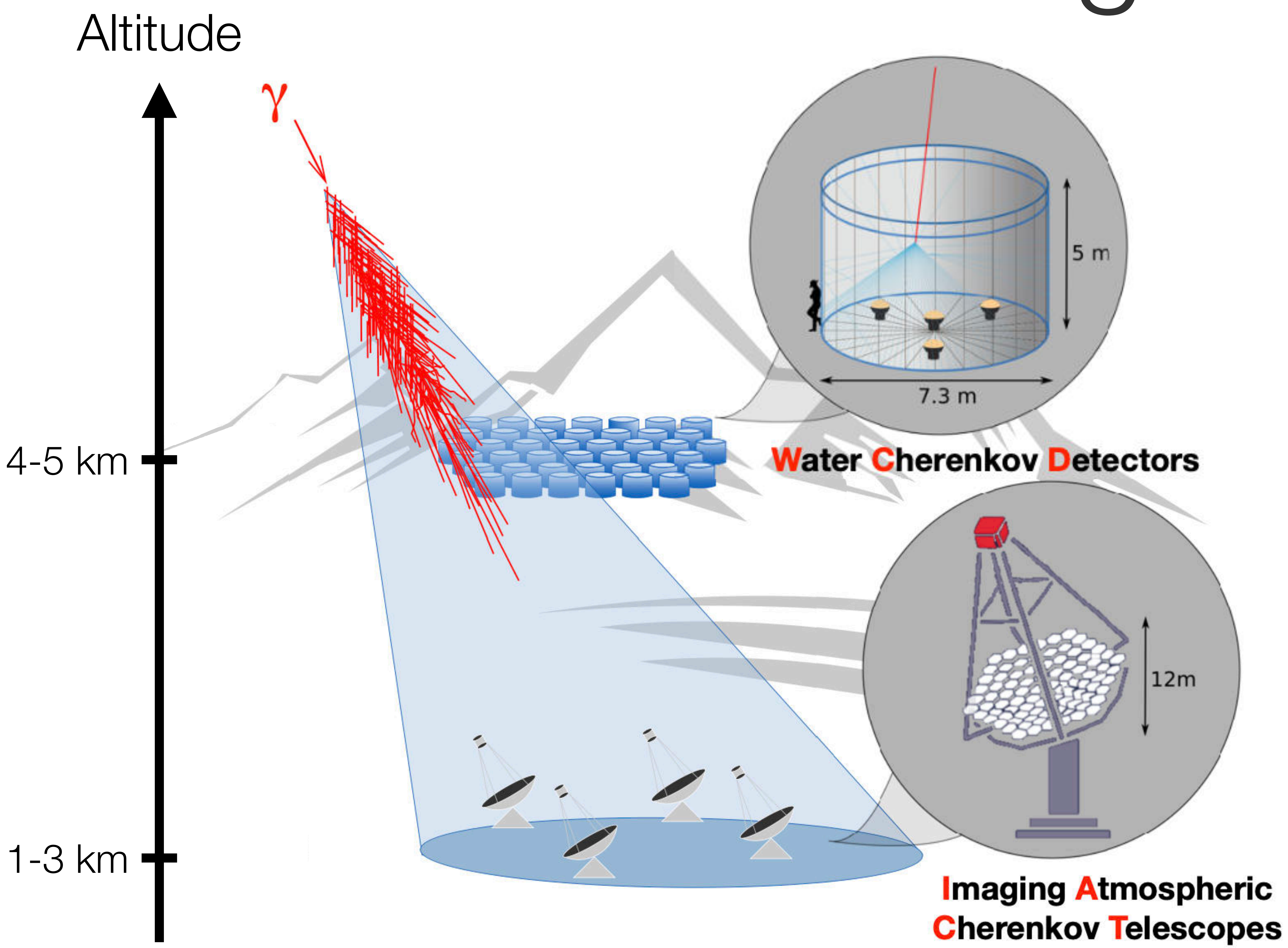
→ relevant parameter is altitude

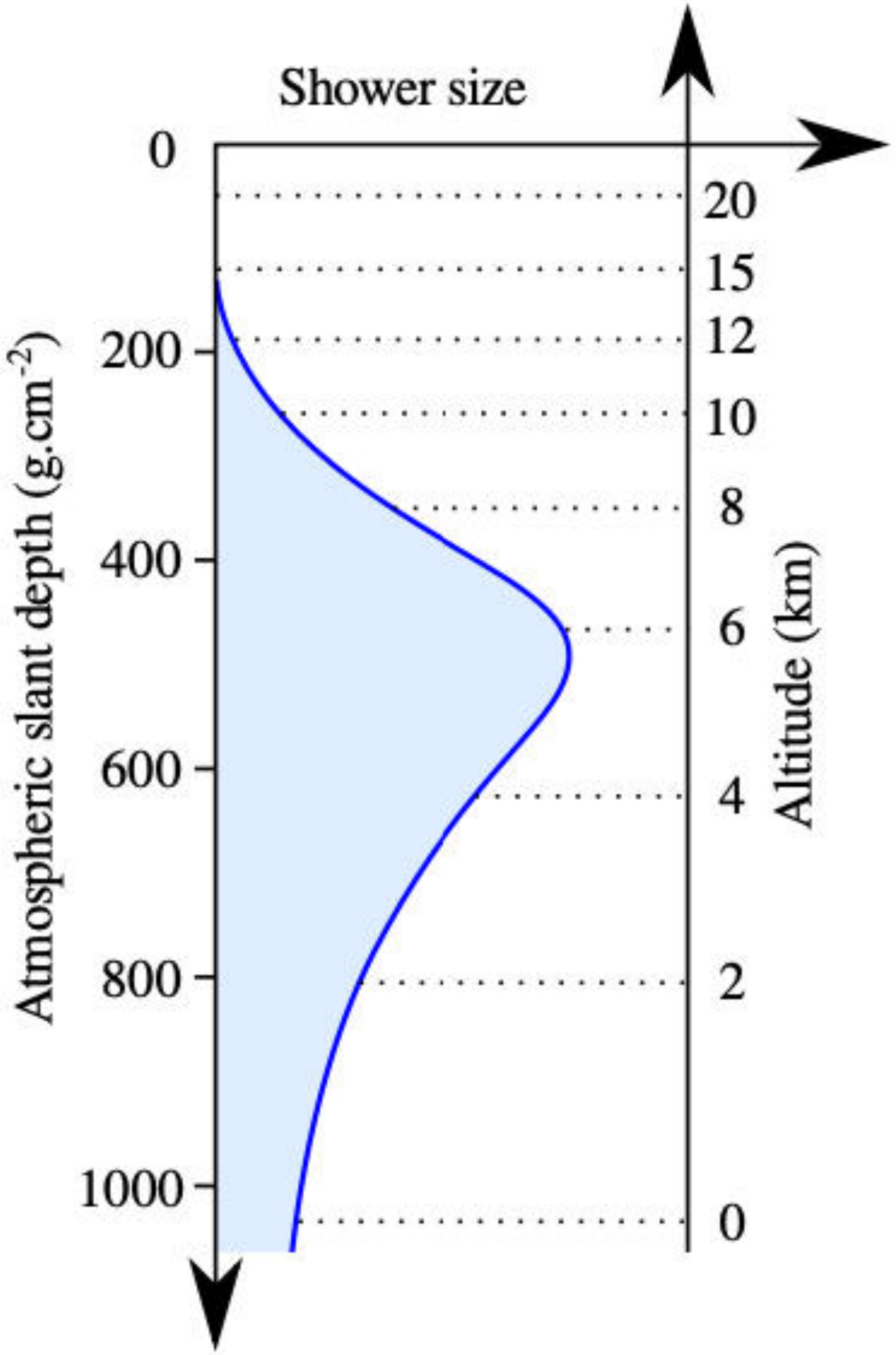
Detecting EASs



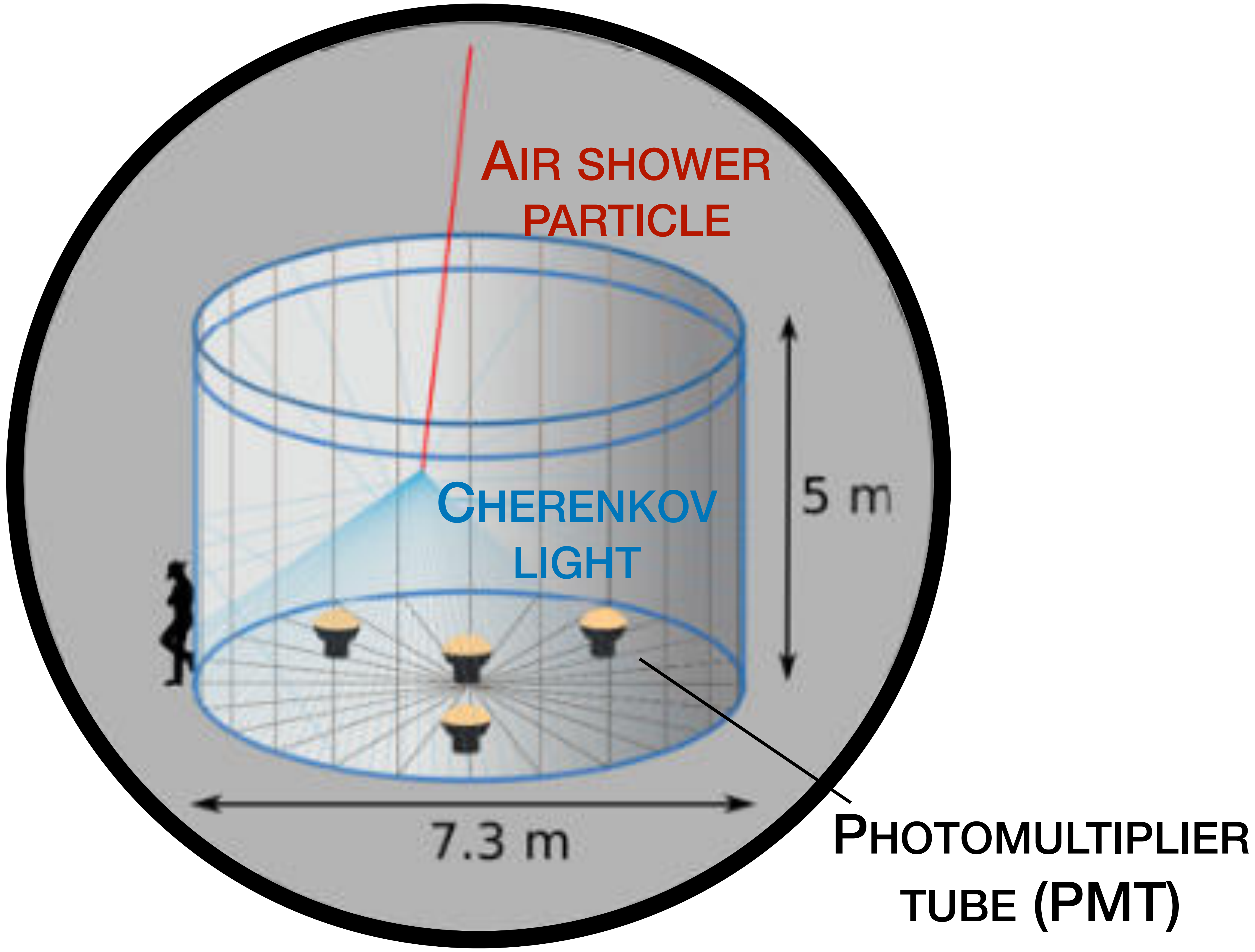


Detecting EASs





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 aerea: ~10^5 m^2

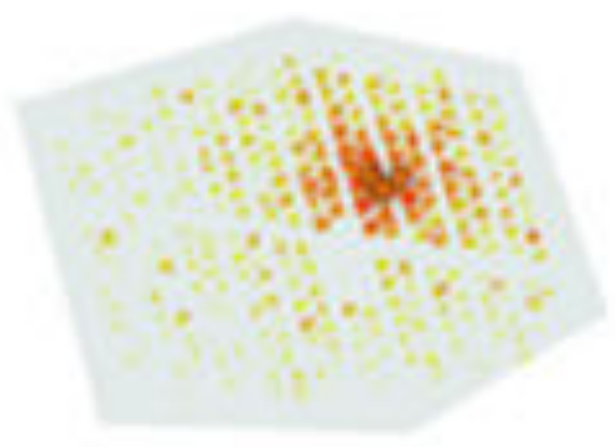
Energy range: ultra-high-energy regime (UHE, E > 100 TeV)

Water Cherenkov Detectors

Reconstruction

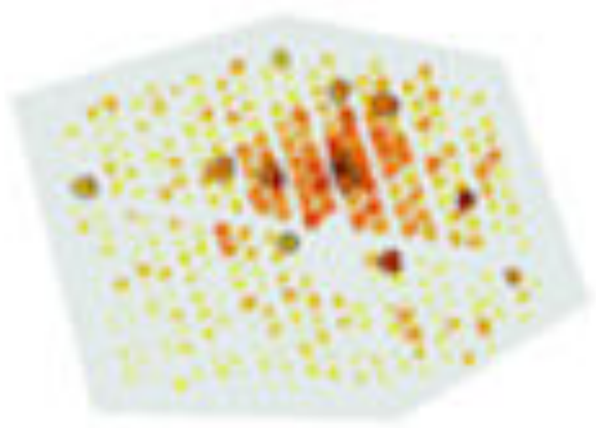
- **Timing** → Direction (determined by arrival time differences recorded at different detectors as the shower front sweeps through the detector plane)
- **Size** → Energy
- **Shape** → Nature

GAMMA-RAY SHOWER

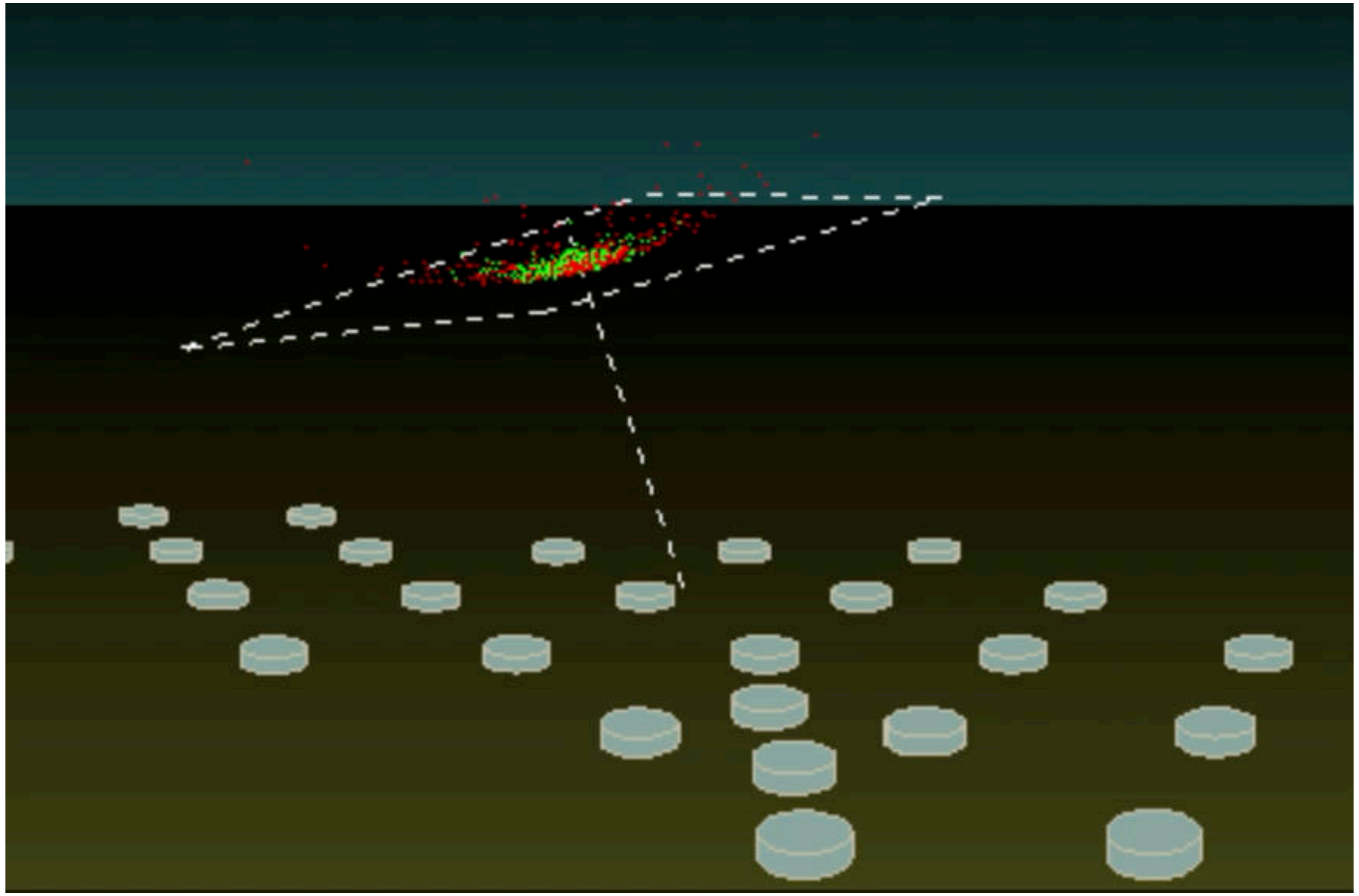


"Hot" spots concentrate around the core

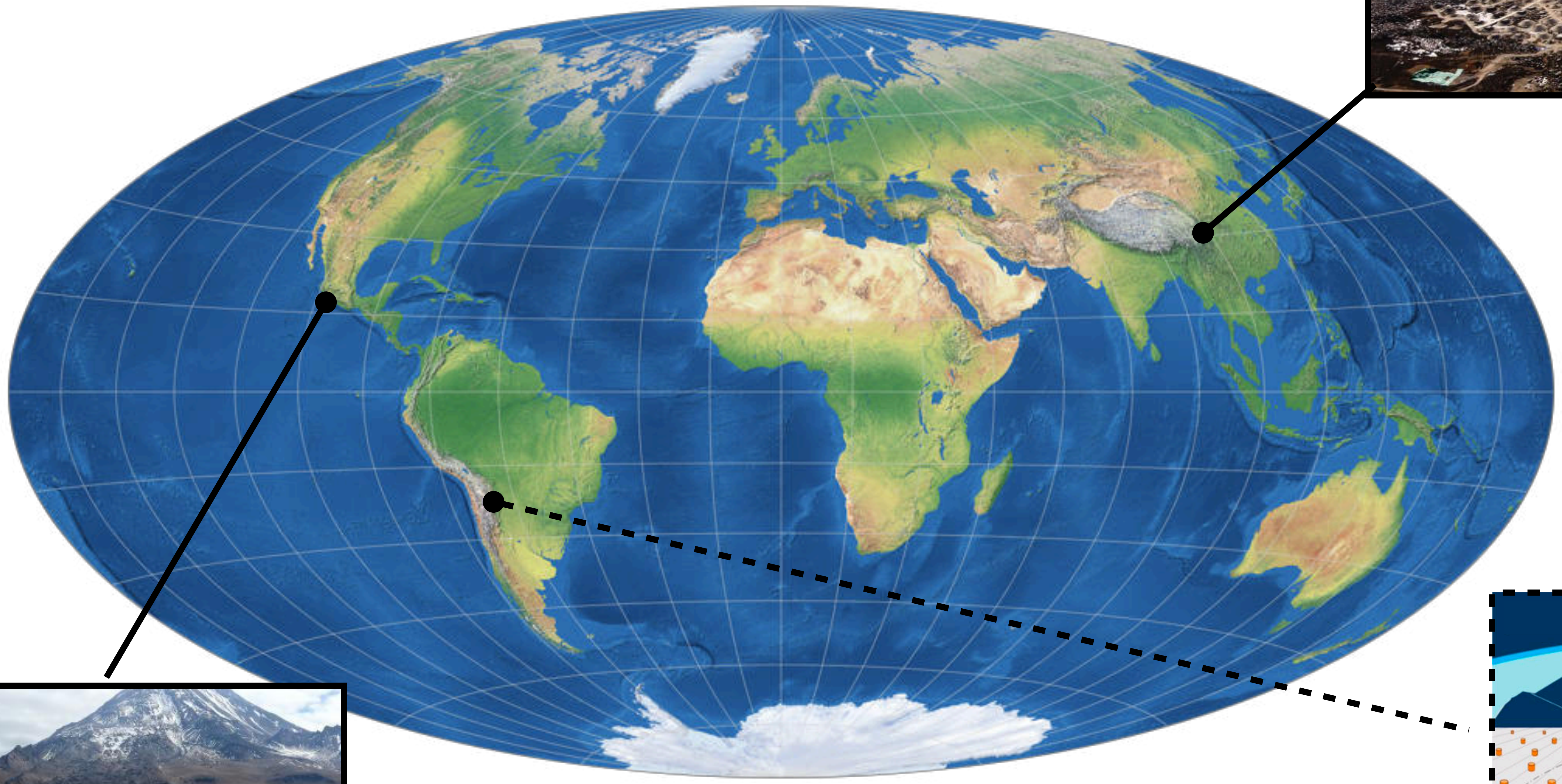
COSMIC-RAY SHOWER



"Hot" spots are more dispersed

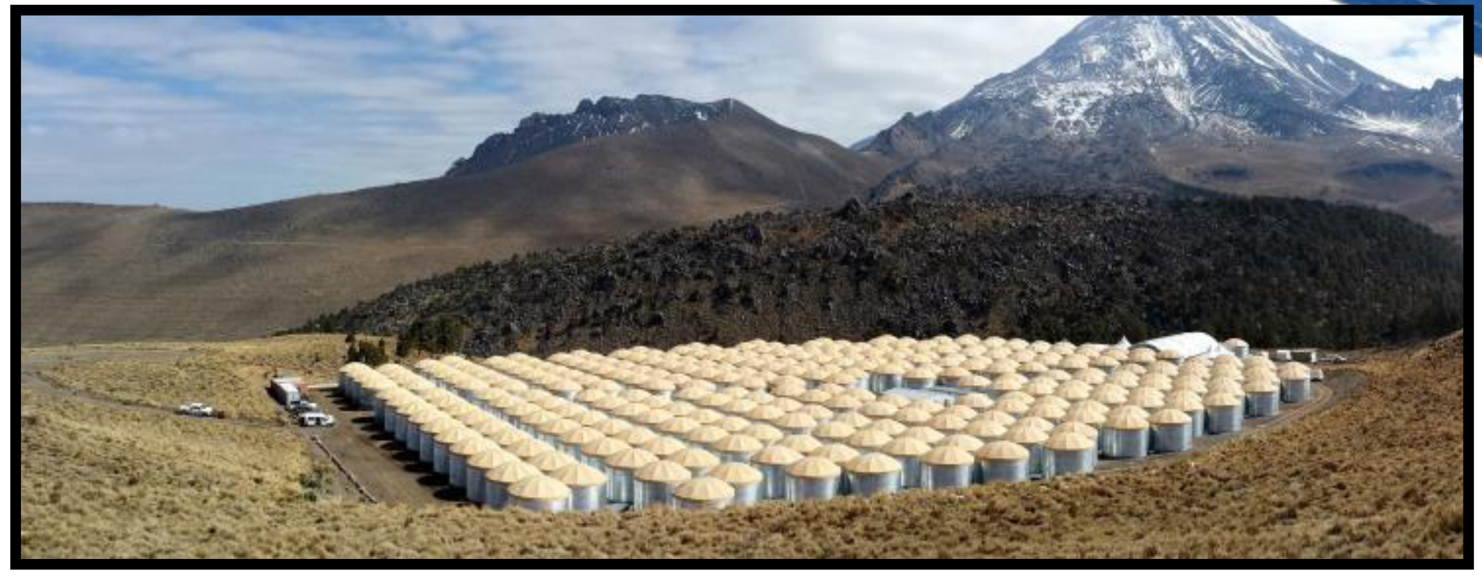


Current and future generation of WCDs

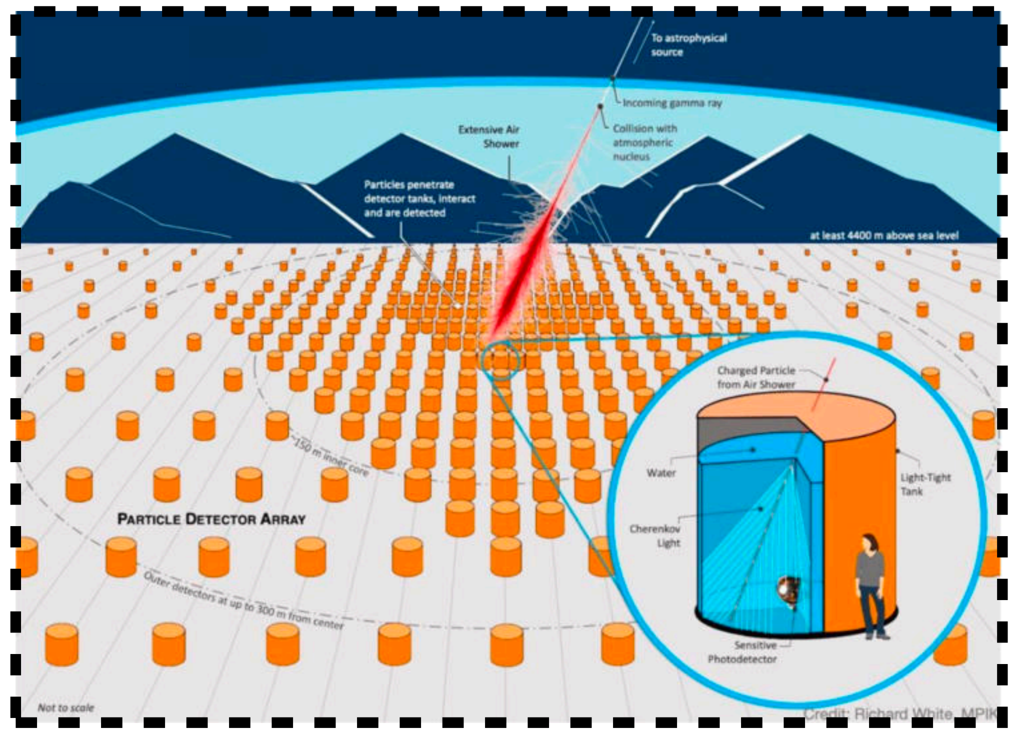


LHAASO (2021)
Daocheng, China
(4410 m)

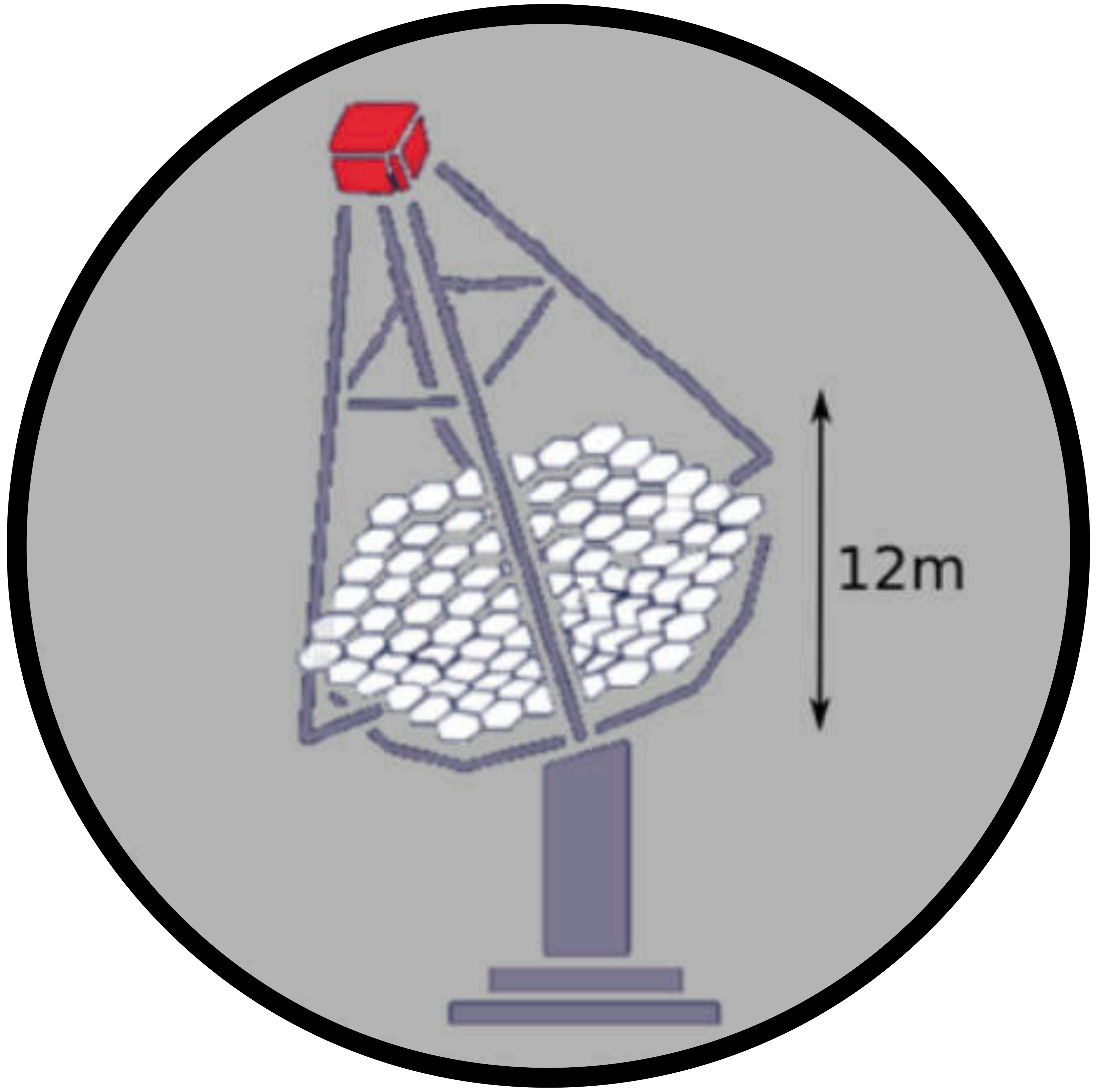
HAWC (2015)
Puebla, Mexico
(4100 m)



SWGO
Atacama, Chile
(4770 m)



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: $[0.04, 1]^{\circ}$

Energy resolution: ~15%

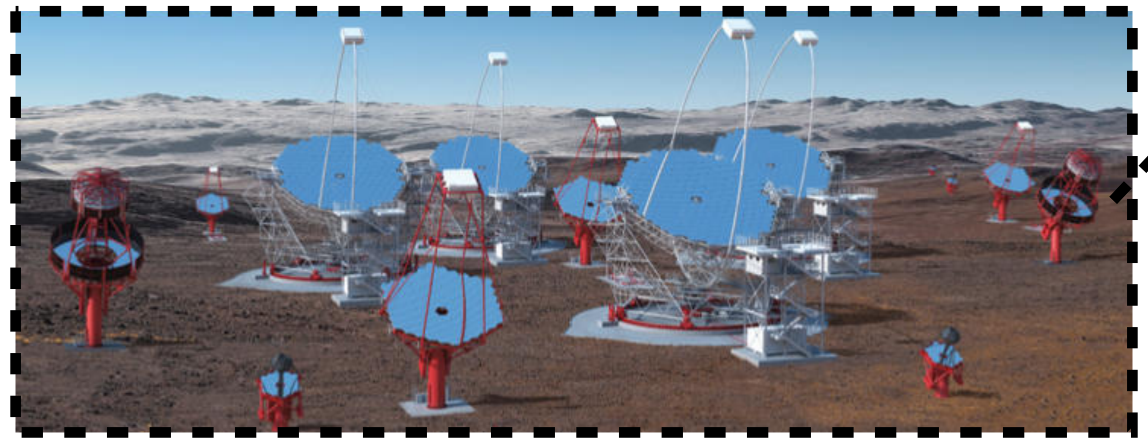
Effective aerea: ~10^5 m^2

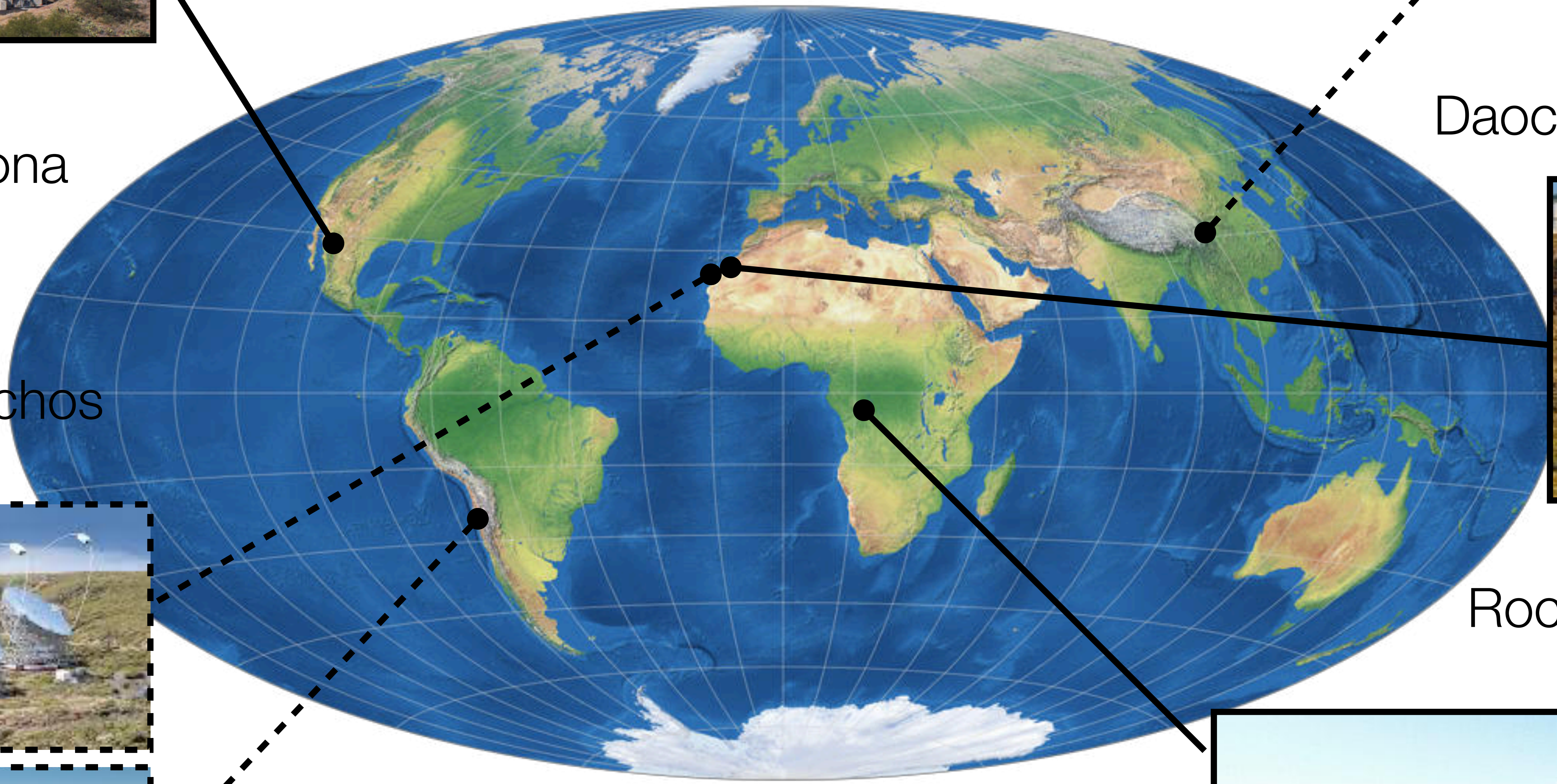
Energy range: wide (50-100 TeV)

Current and future generation of IACTs

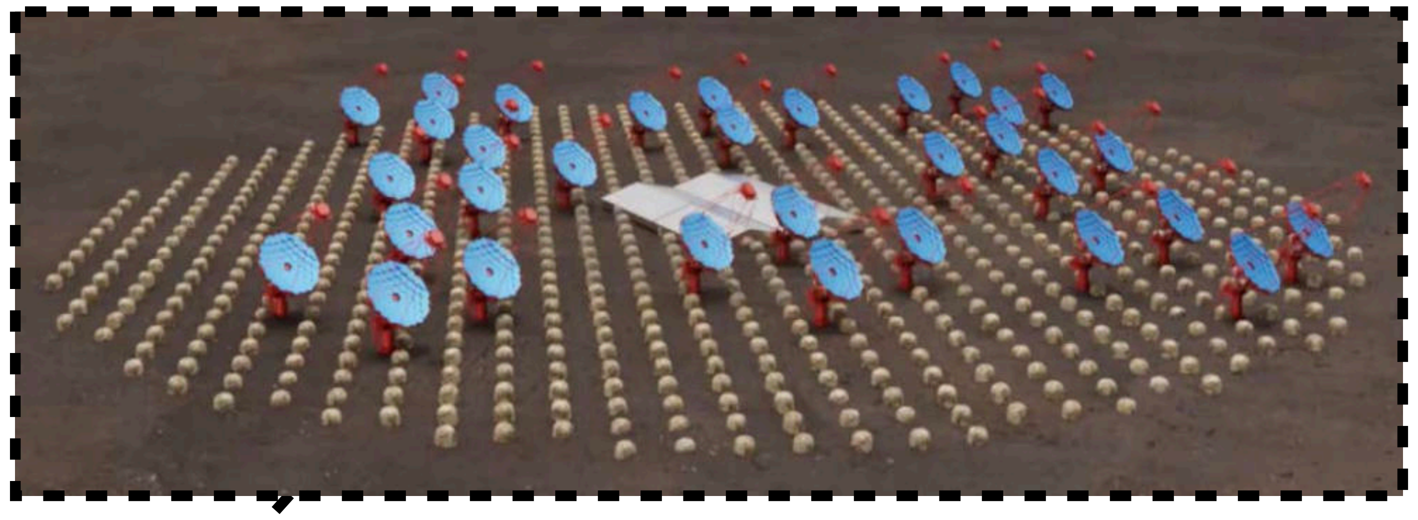
VERITAS
Mount Hopkins, Arizona

CTAO - North
Roche de los Muchachos
Canary Island





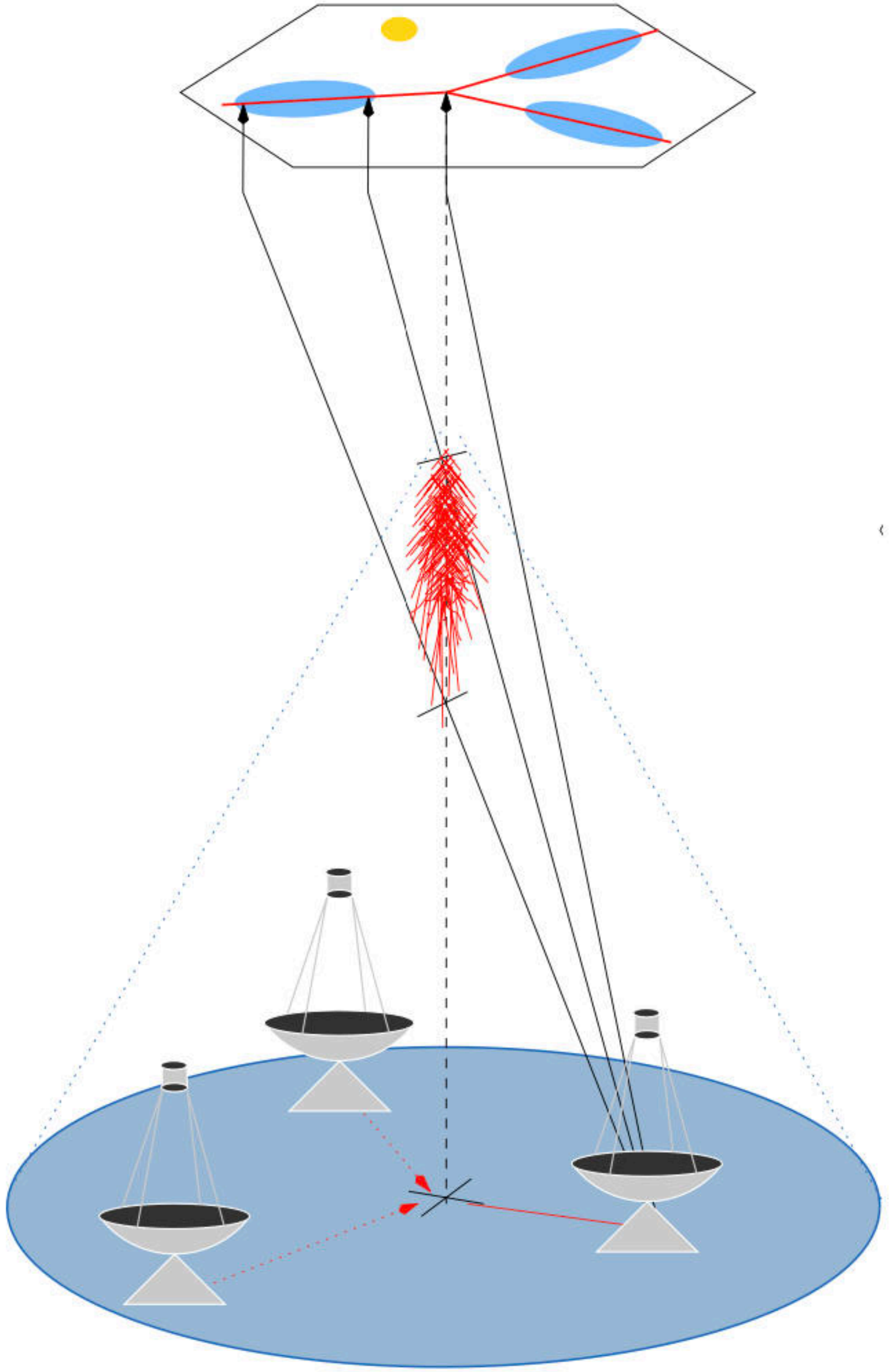
CTAO - South
Atacama, Chile



LACT
Daocheng, China (4410 m)

MAGIC
Roche de los Muchachos
Canary Island

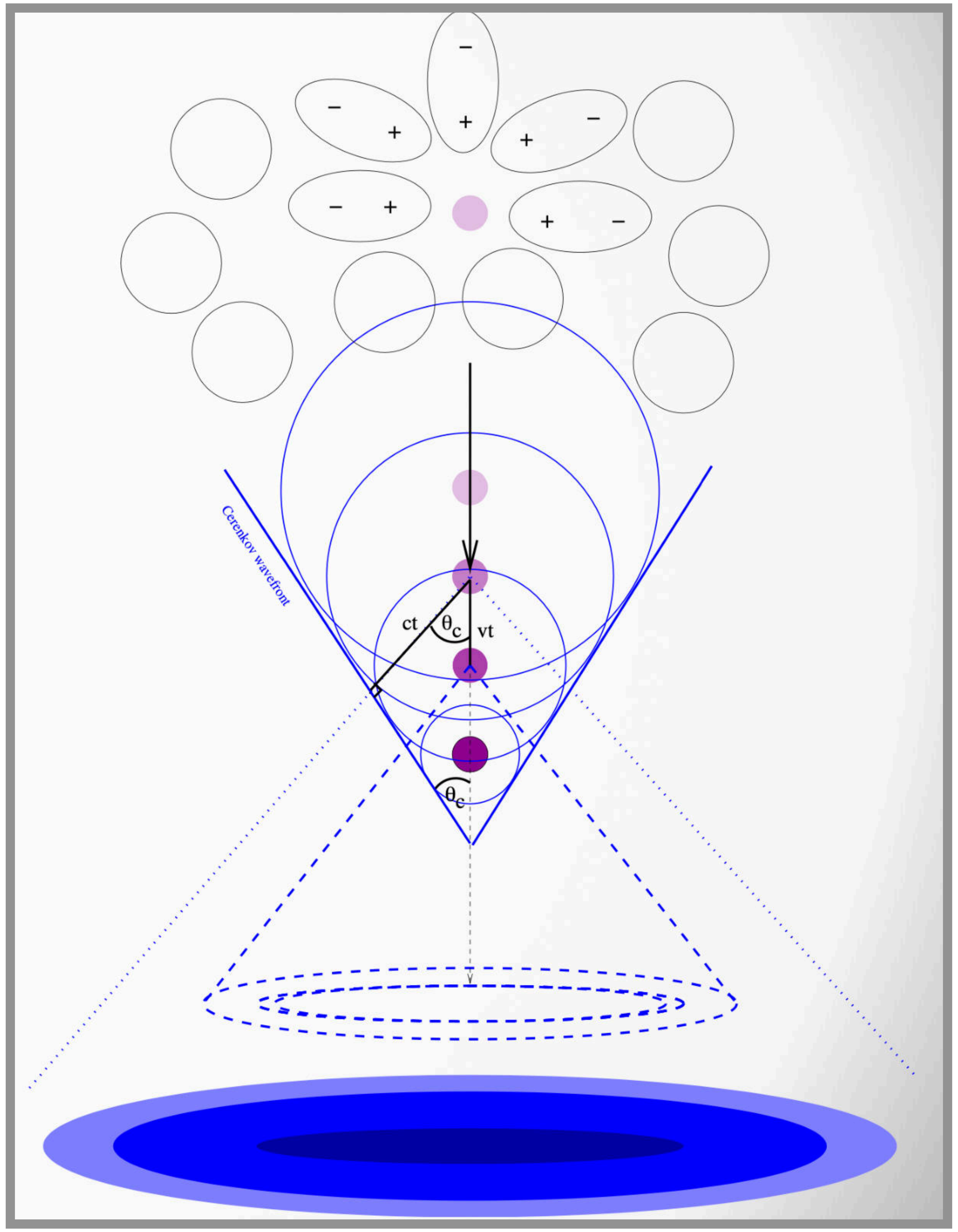
H.E.S.S. (2002)
Khomas Highland,
Namibia



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:

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

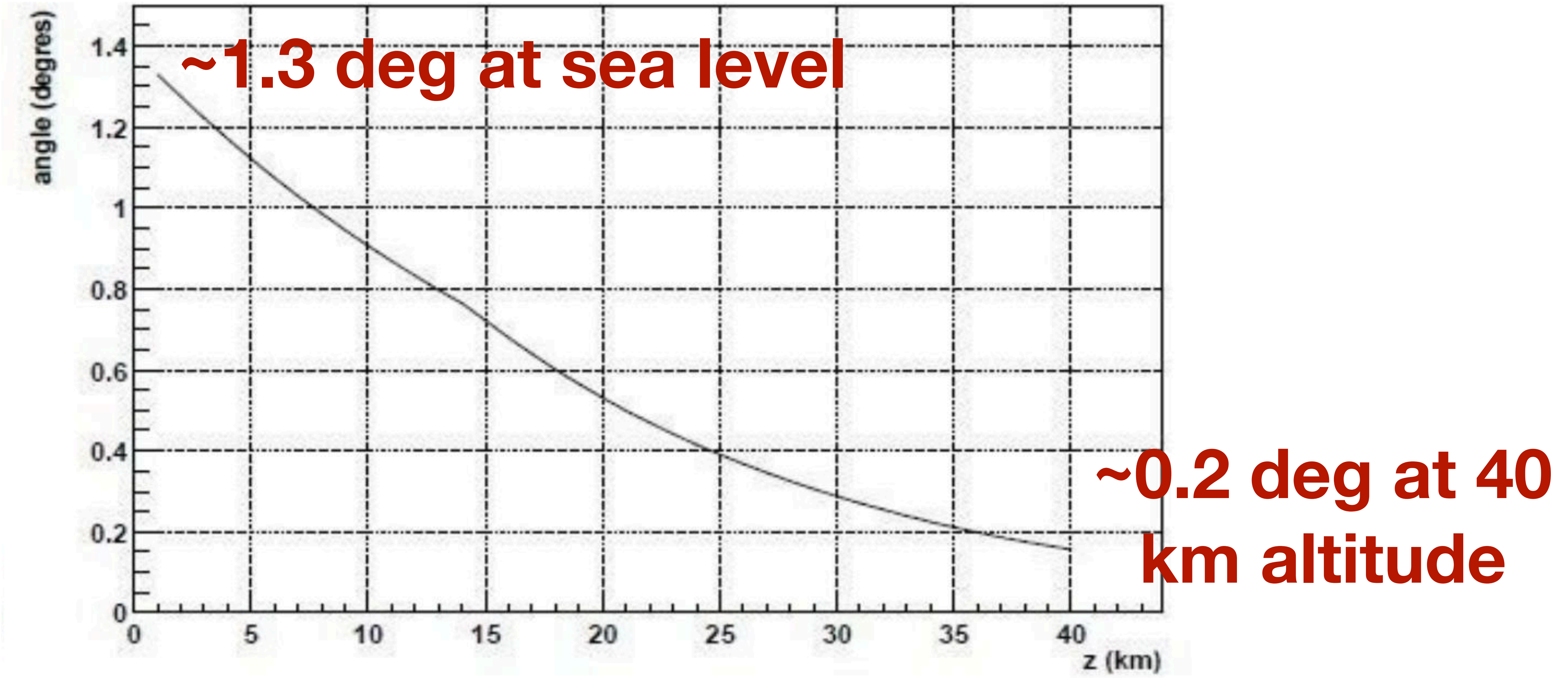
Cherenkov radiation

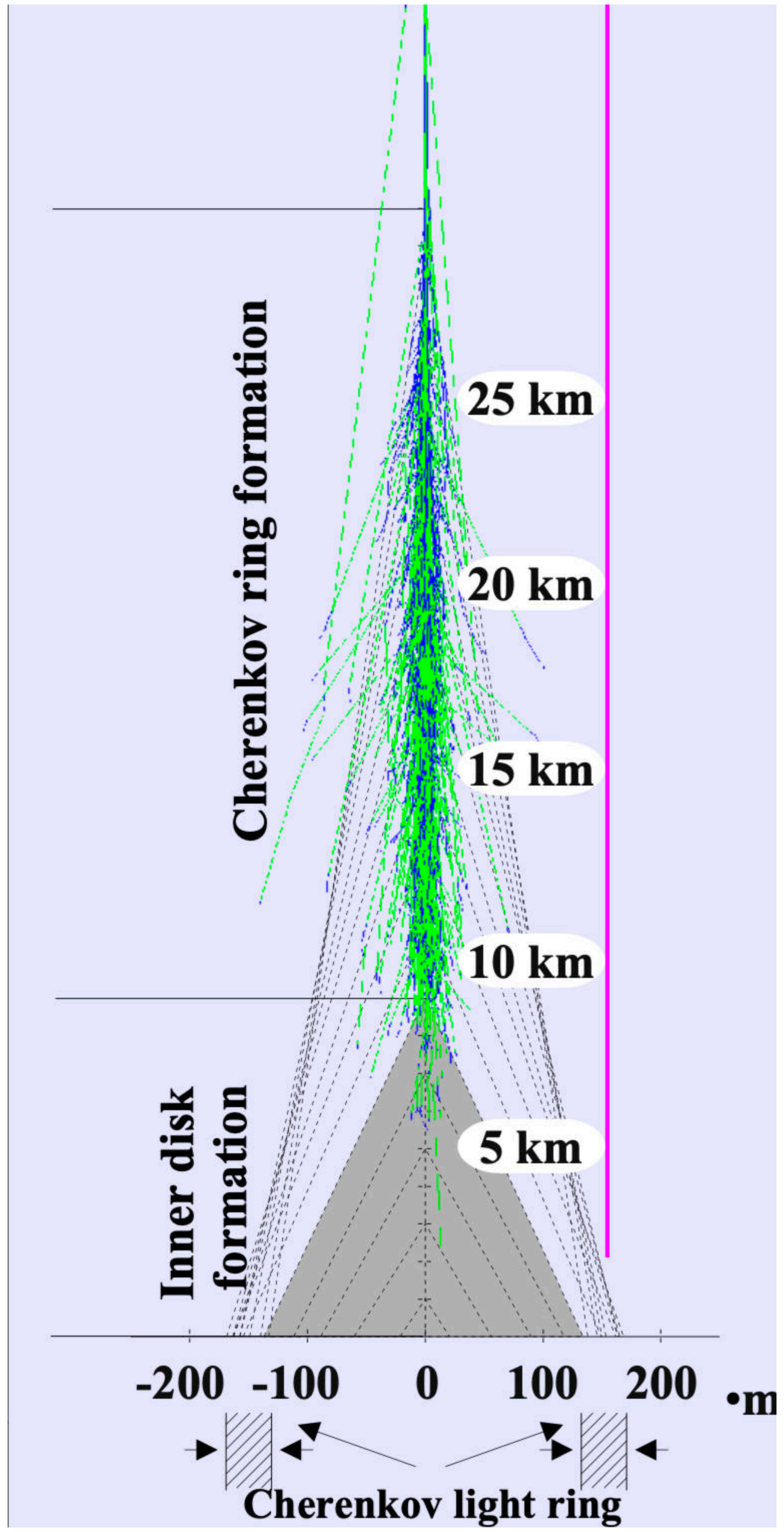
In the atmosphere

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

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

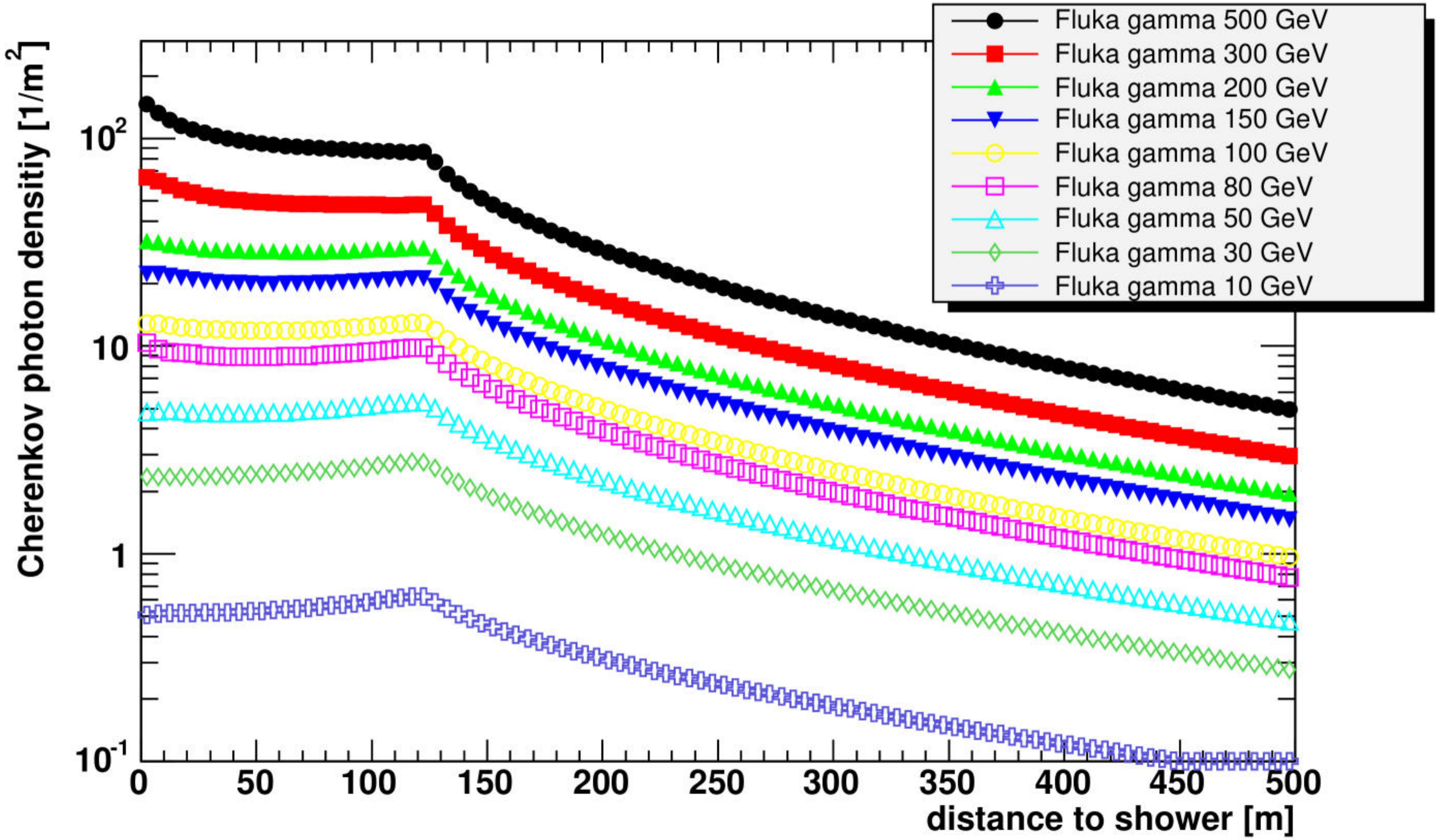
- Evolution of the Cherenkov angle with altitude ***z***:





Cherenkov radiation

Cherenkov photon density on ground

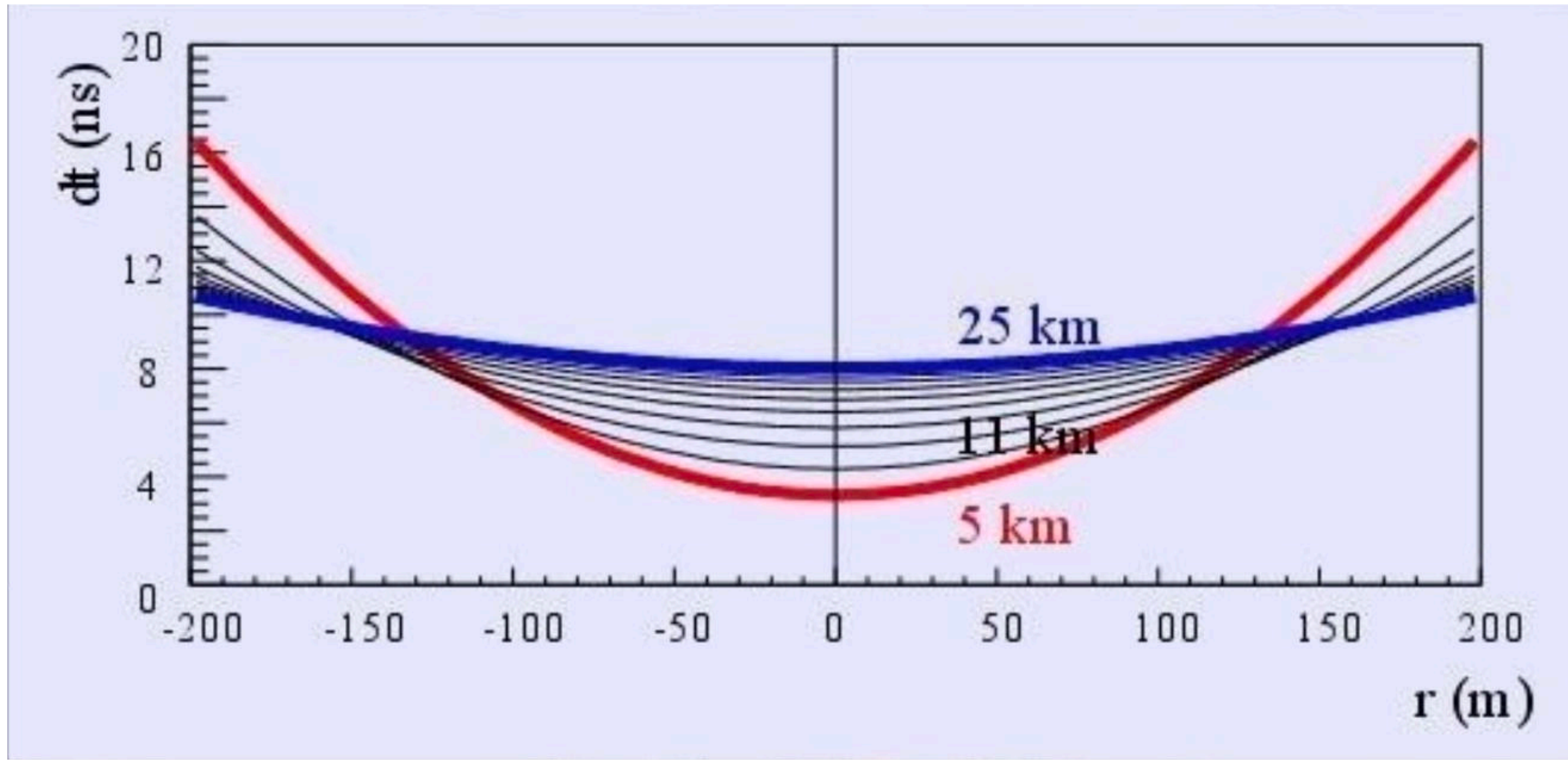


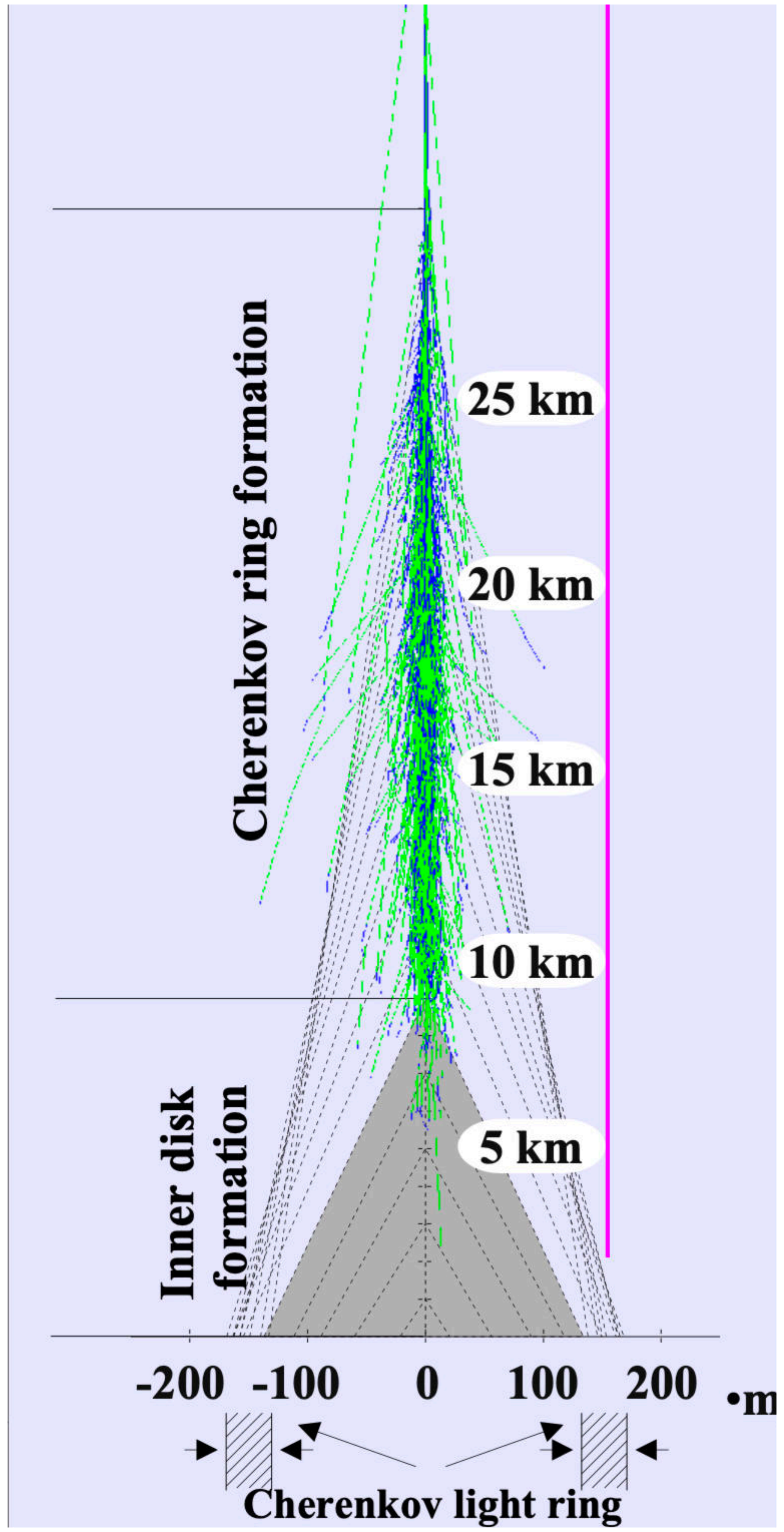
Cherenkov radiation

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_γ ~ 1 TeV

Shower maximum:

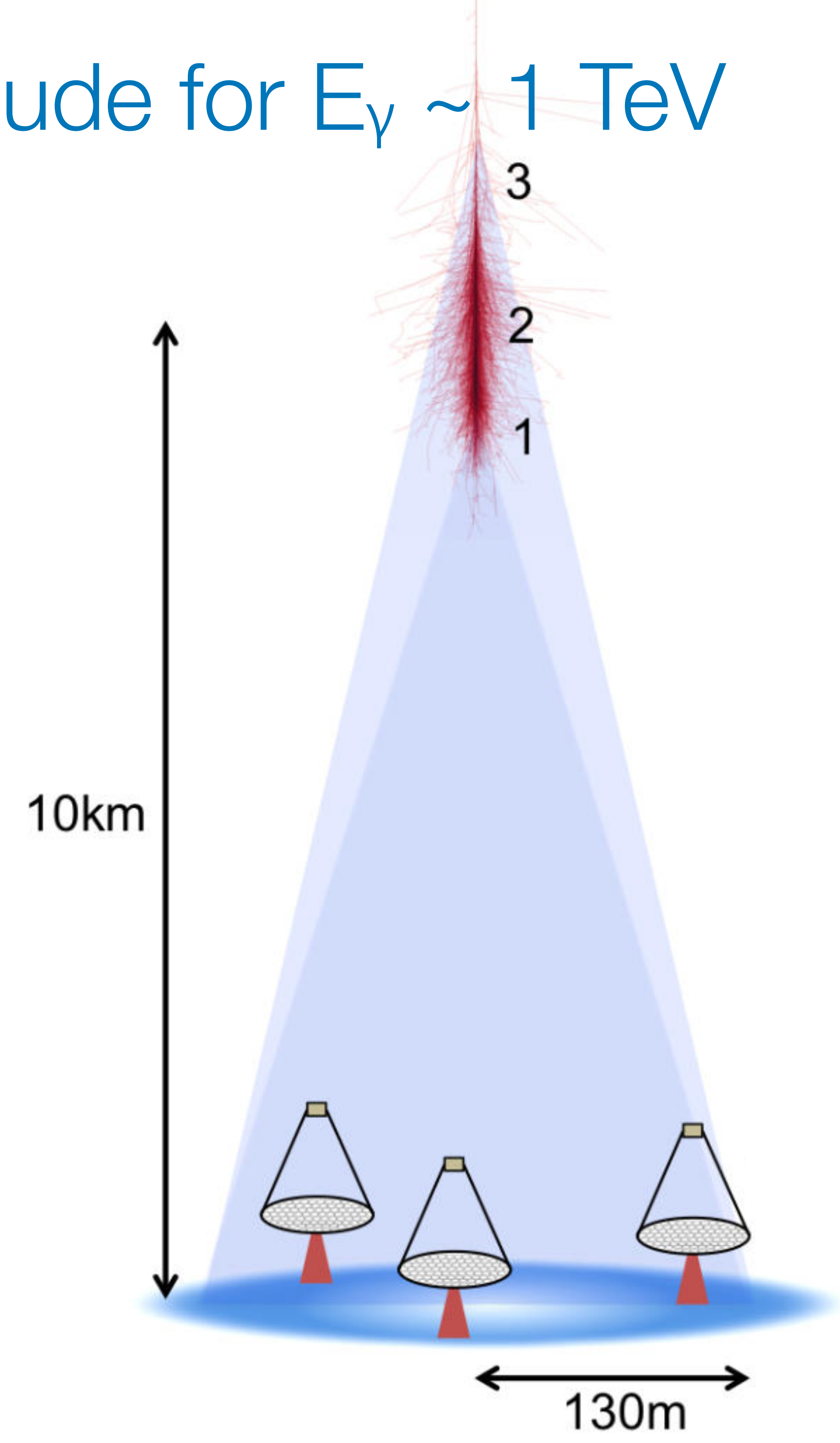
- Altitude ~10 km
- ~10^3 charged particles

Cherenkov emission:

- Altitude $\theta_{Cherenkov}$ ~1°
- Duration < 10 ns
- UV light

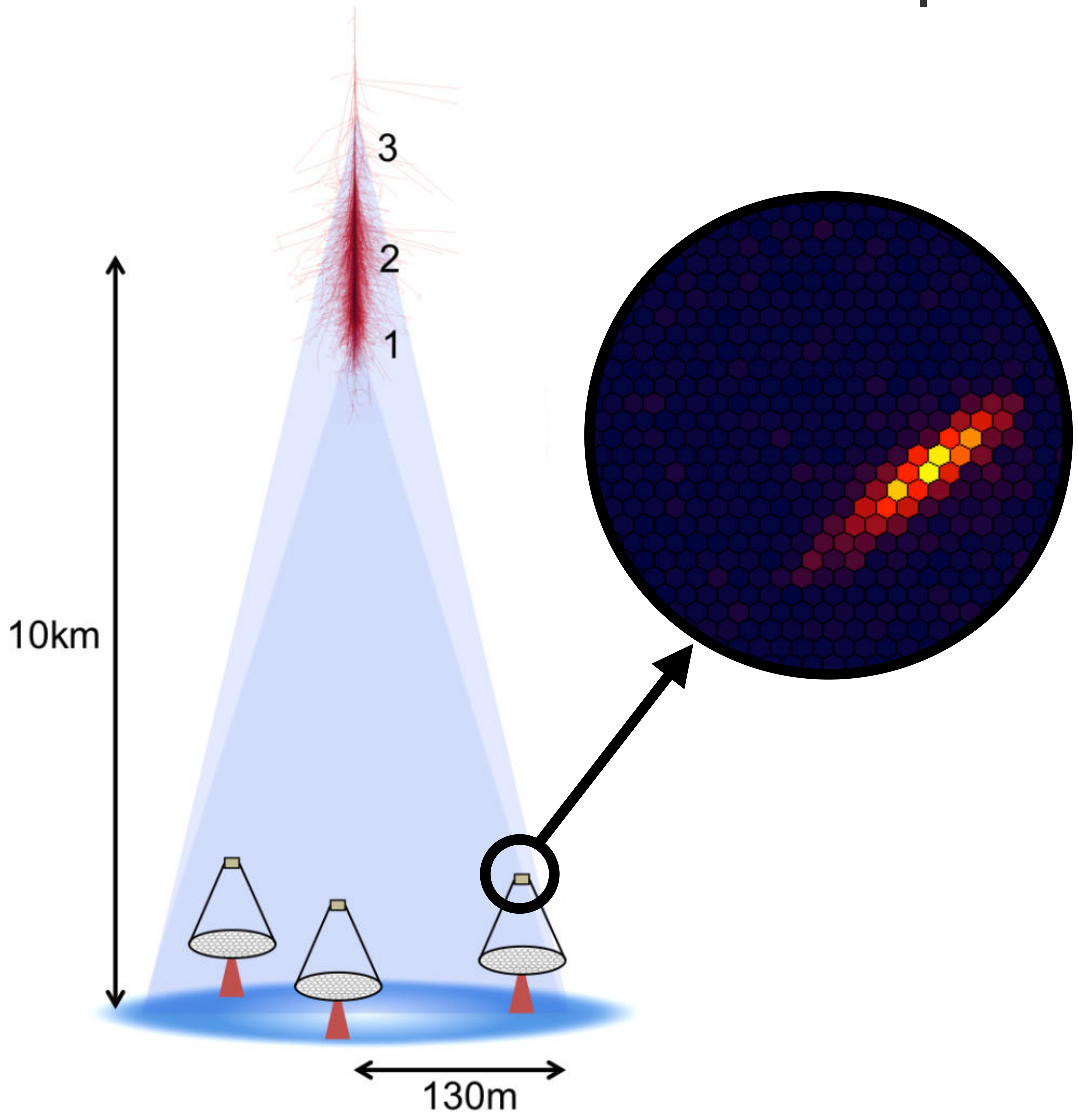
Cherenkov light-pool on ground:

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



Imaging Atmospheric Cherenkov Telescopes

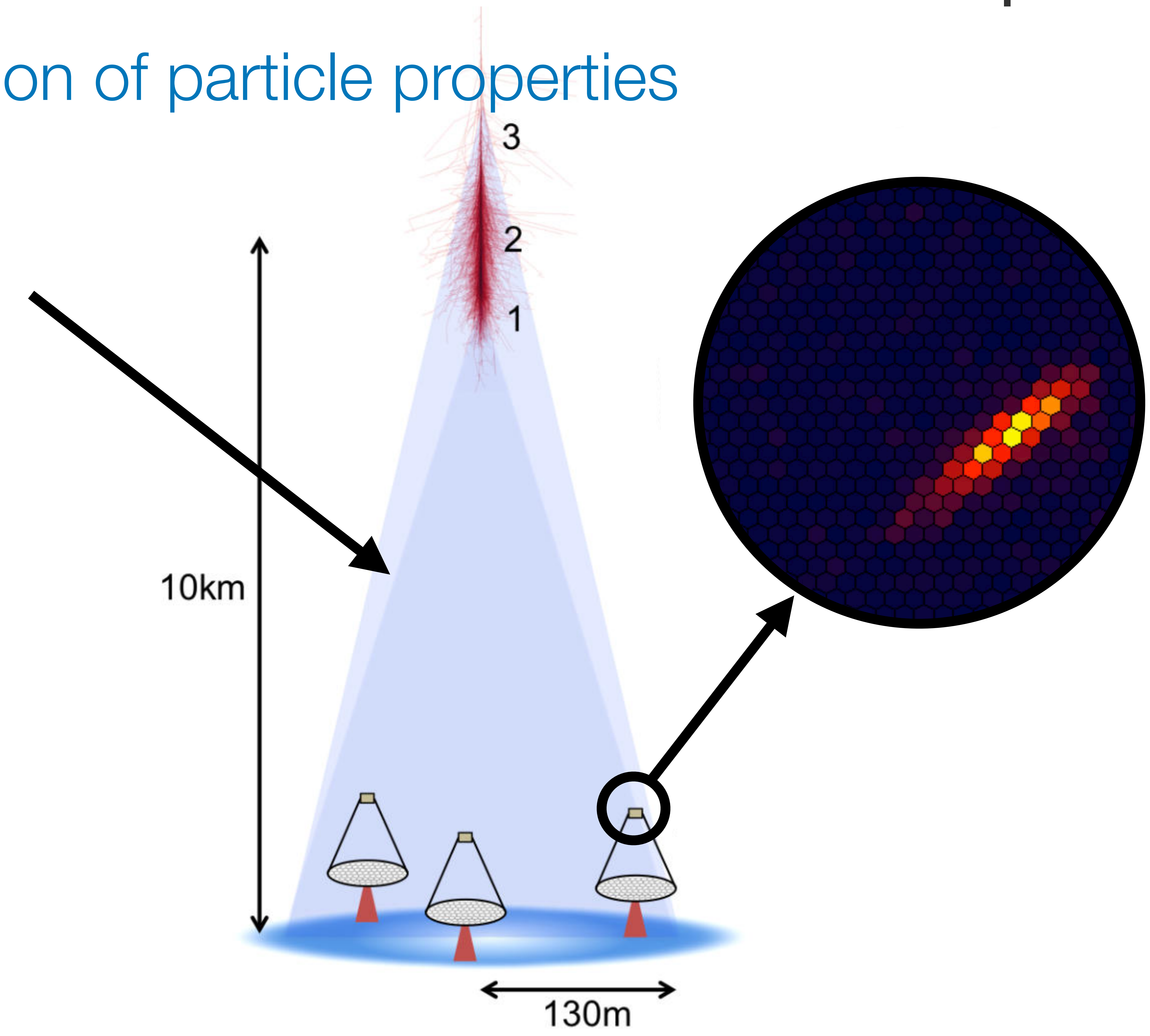
- Cherenkov light-pool ~120 m
- Image the shower on a fast camera (Δt ~2ns)
- Large effective area (10^5 m^2) even with modest reflector
- Change in Cherenkov angle + multiple Coulomb-scattering washes out the ring shape of the Cherenkov light → faint elliptical shaft of UV light



Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light (calorimeter)

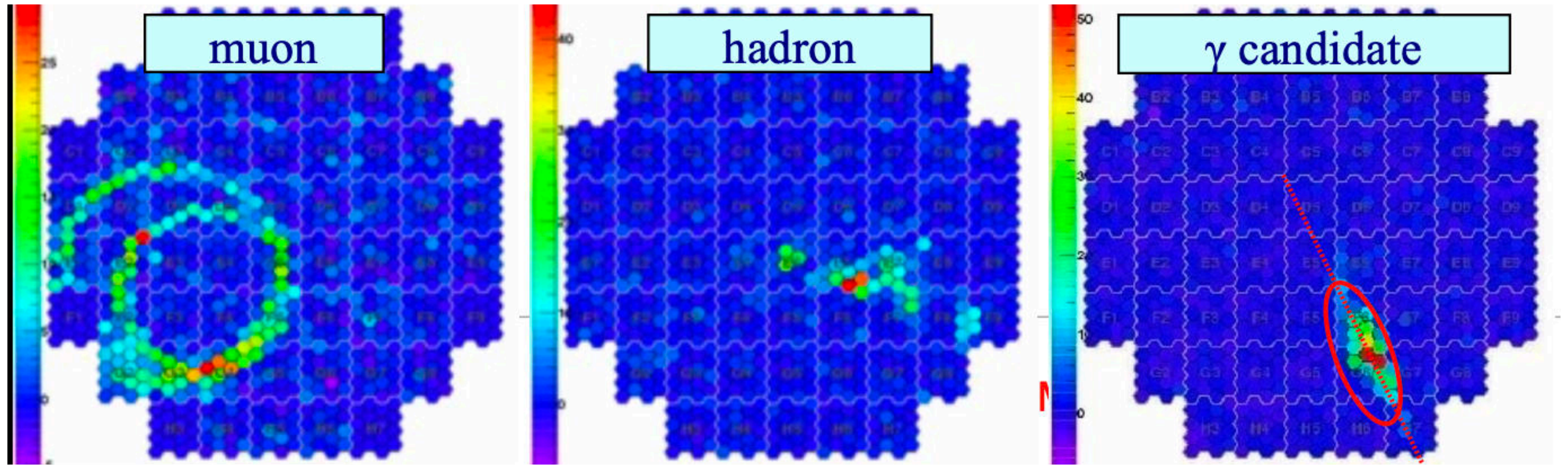


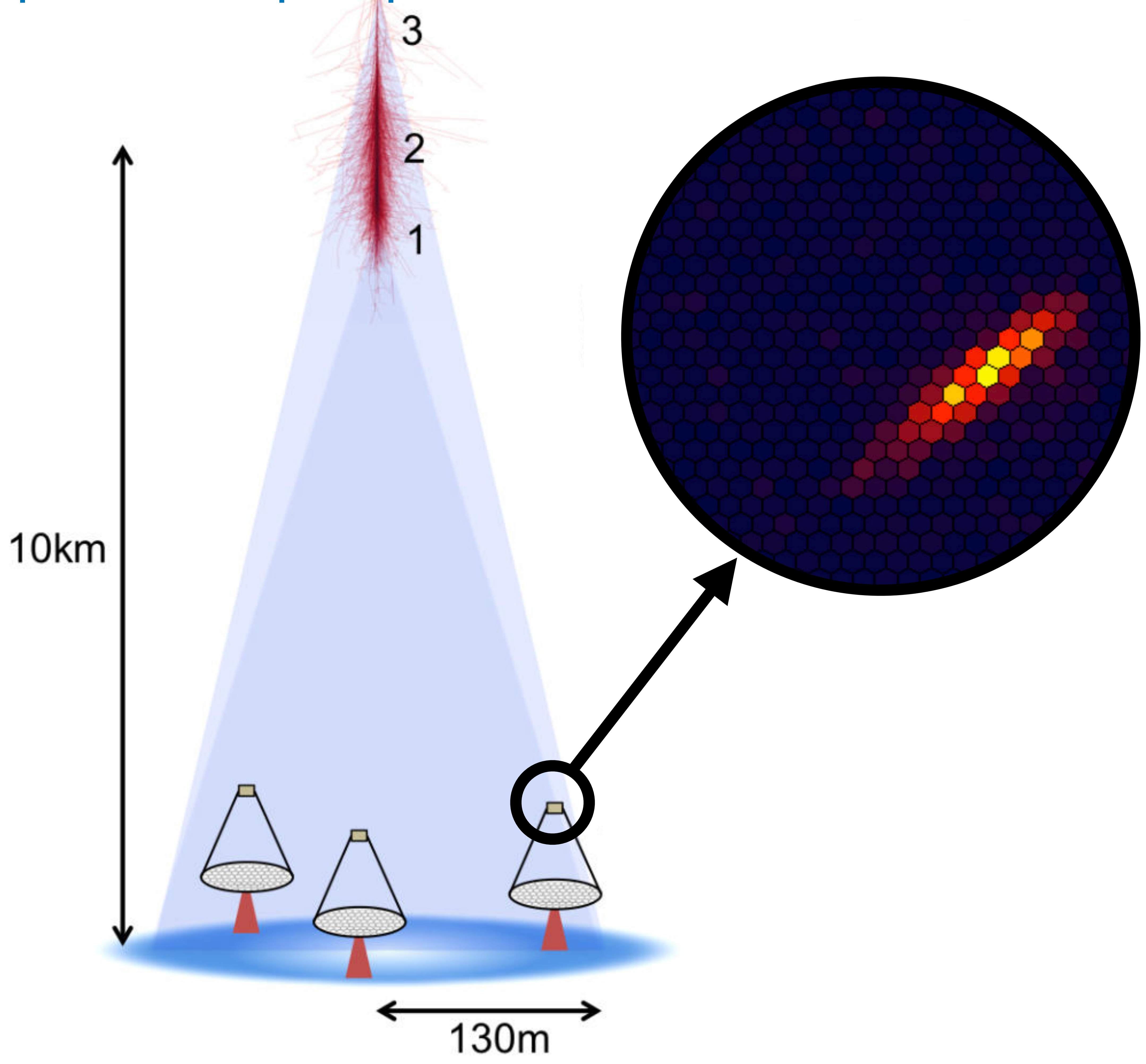
Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light (calorimeter)

Nature: shape of the shower





Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light (calorimeter)

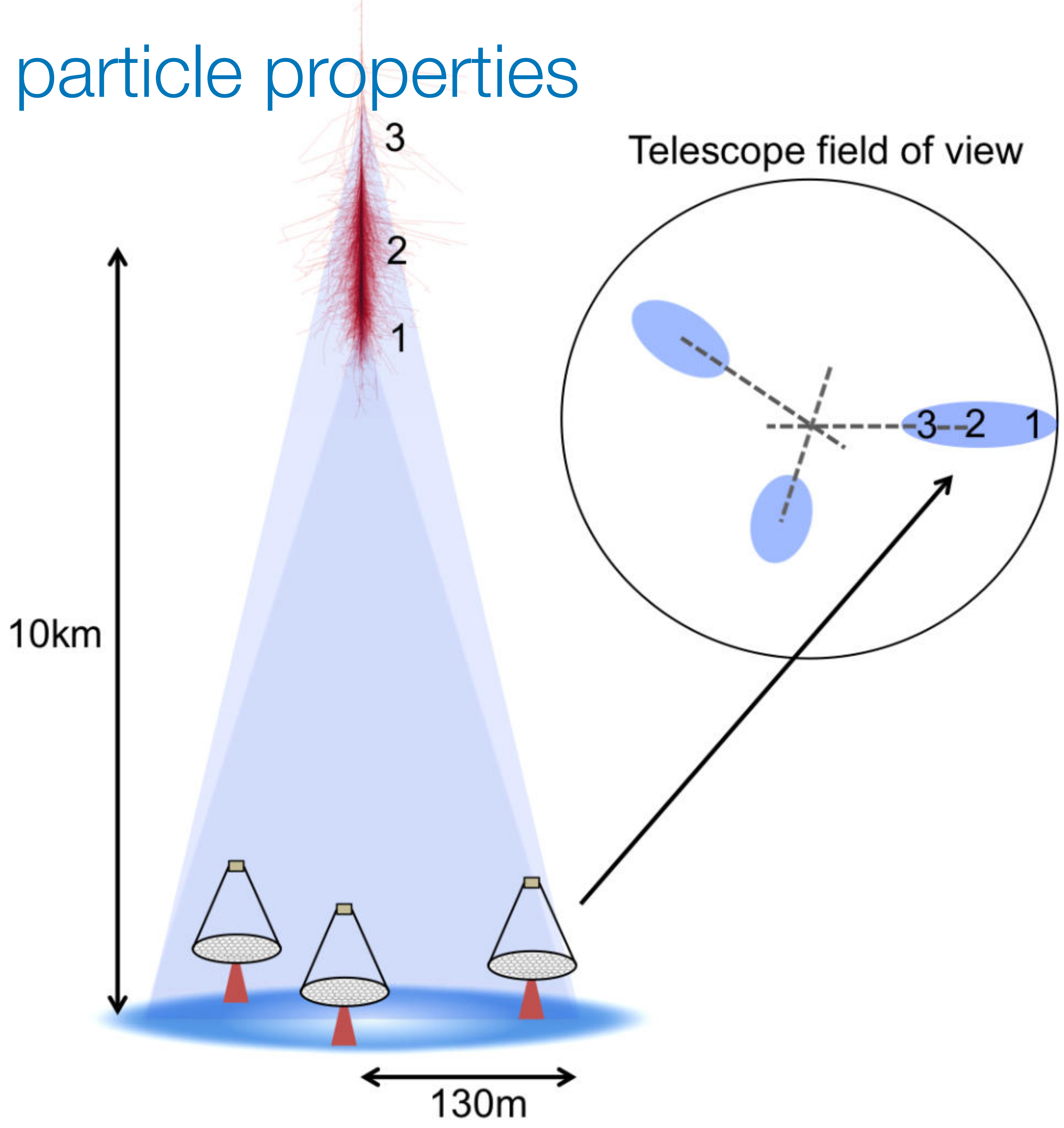
Nature: shape of the shower

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

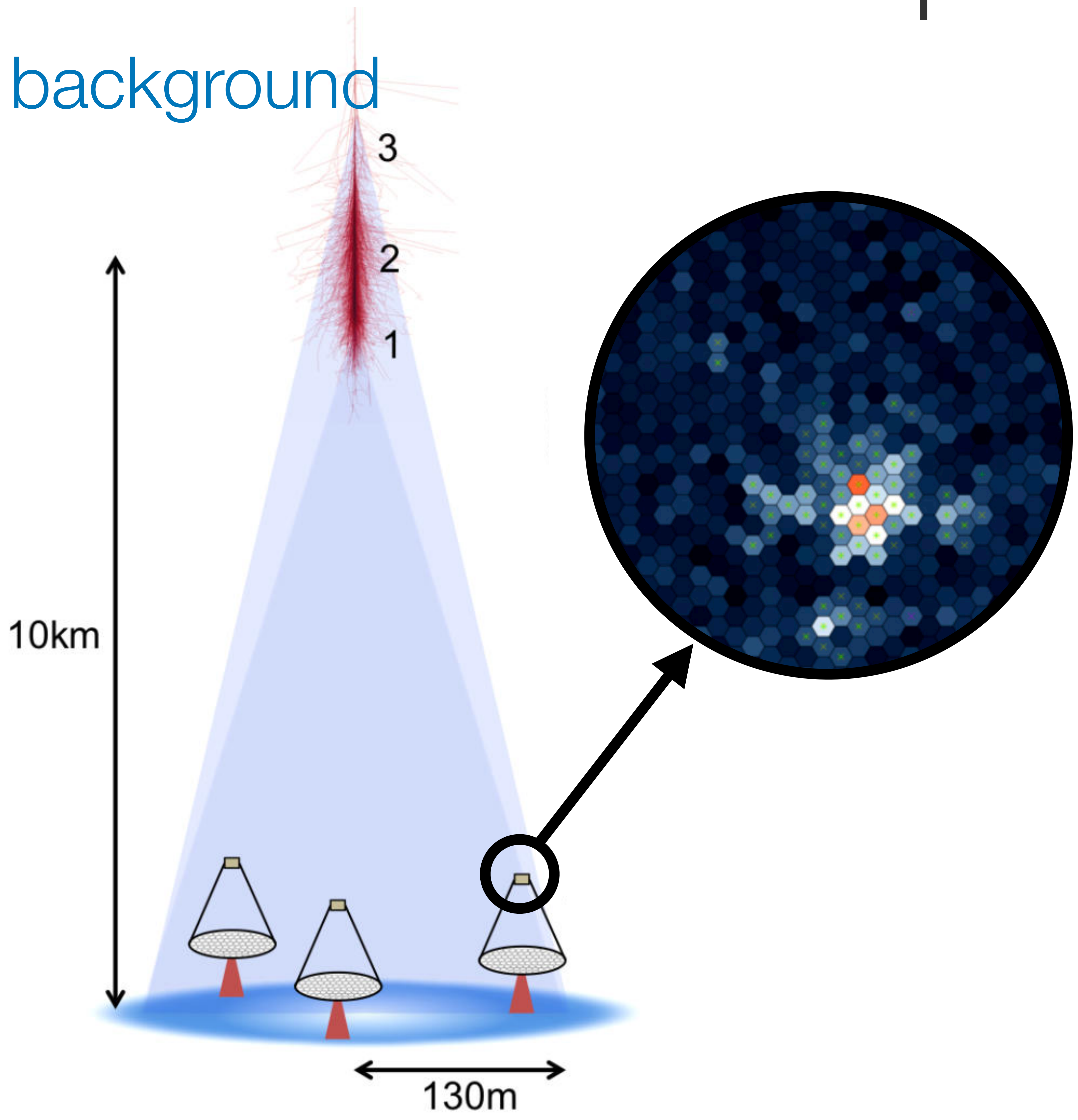
Cosmic-ray background

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

Stereo trigger: $\approx 1/4$

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

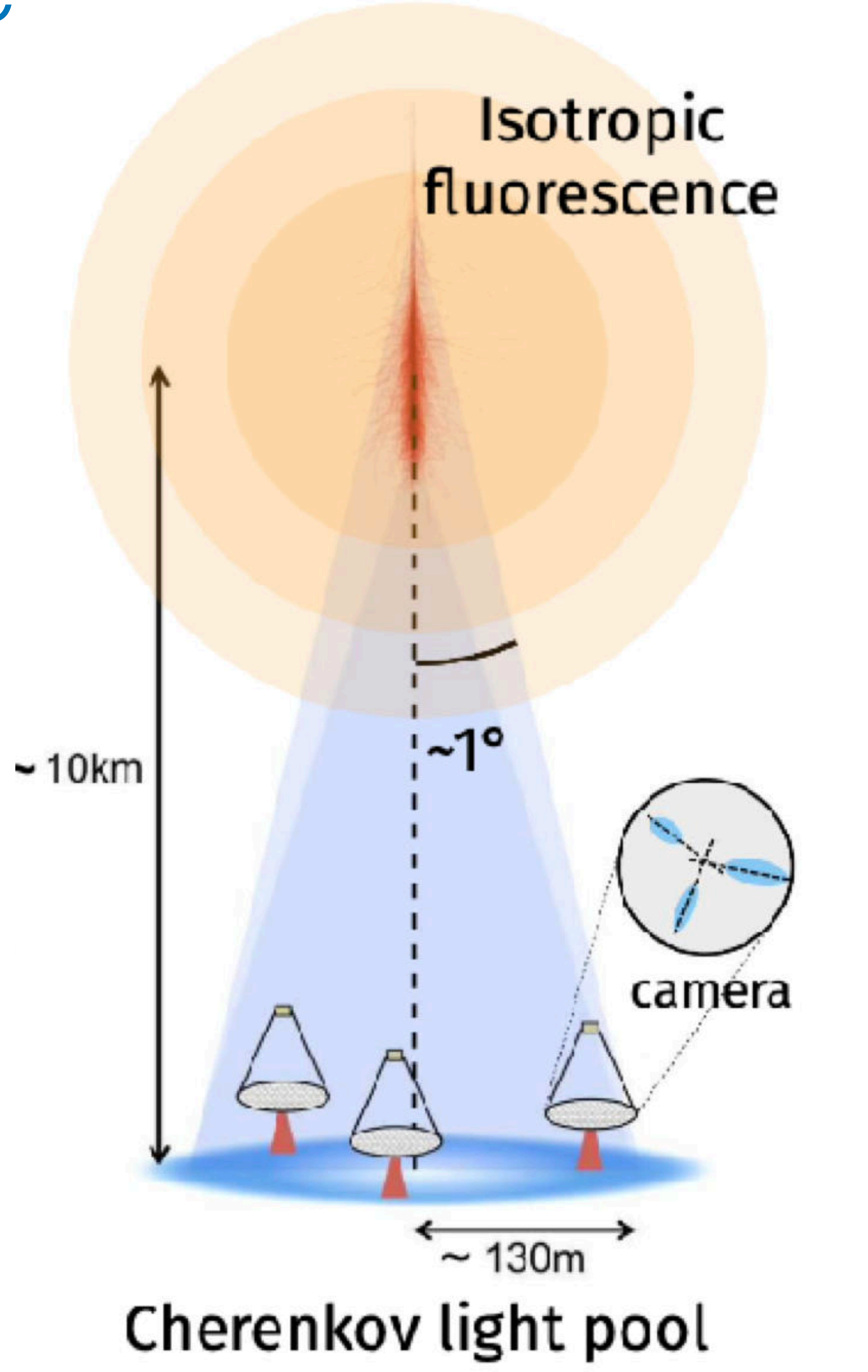
Arrival direction: $\approx 1/100$



Backgrounds

Fluorescence

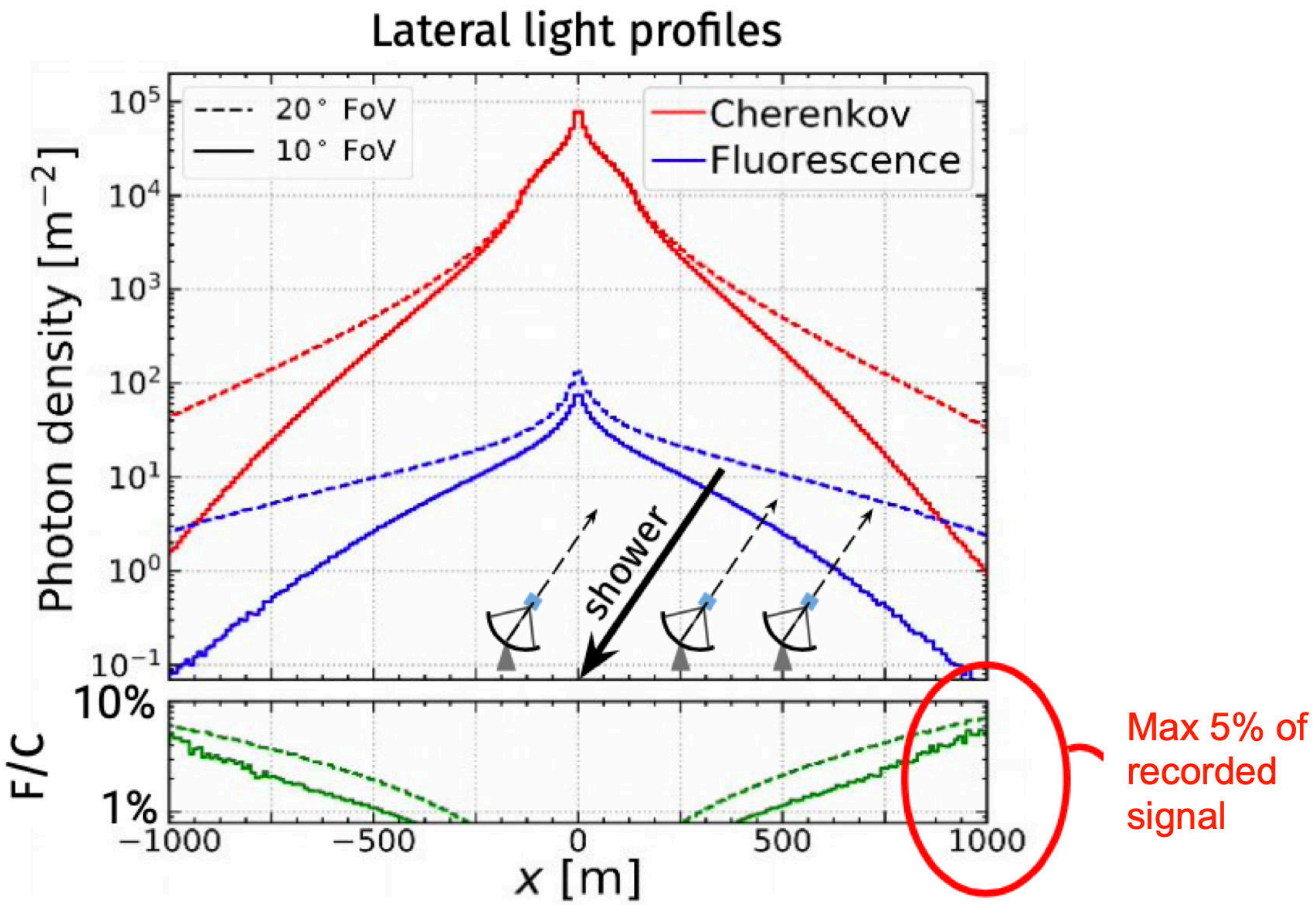
- Fluorescence emission from de-excitation of N_2 states (290-430 nm)
- Less efficient light emission:
  - For 1 GeV electron near ground, 30 photons from Cherenkov light vs 4 photons from fluorescence light (per m track length)
- Longer time profile: microseconds vs 10s of nanoseconds



Backgrounds

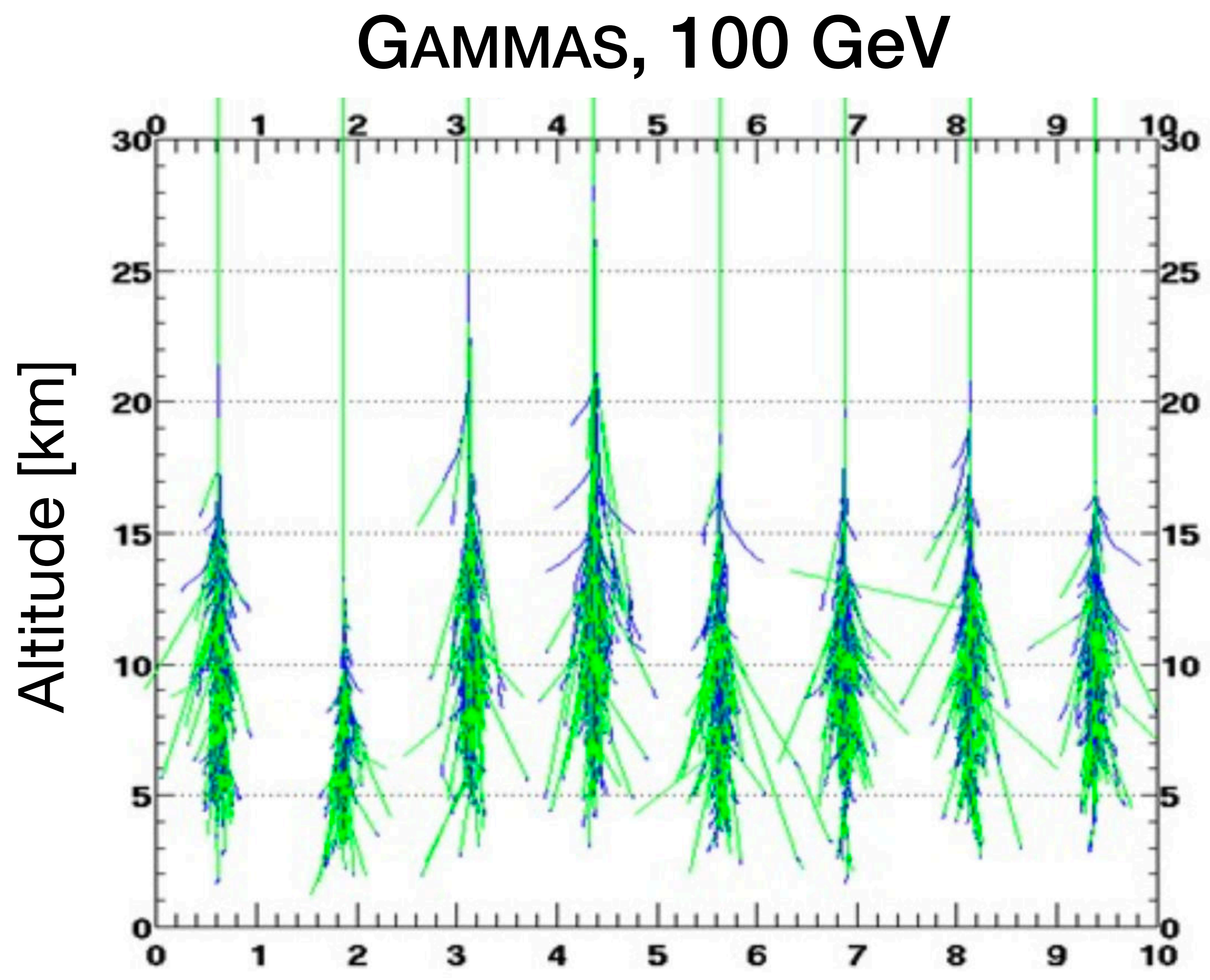
Fluorescence

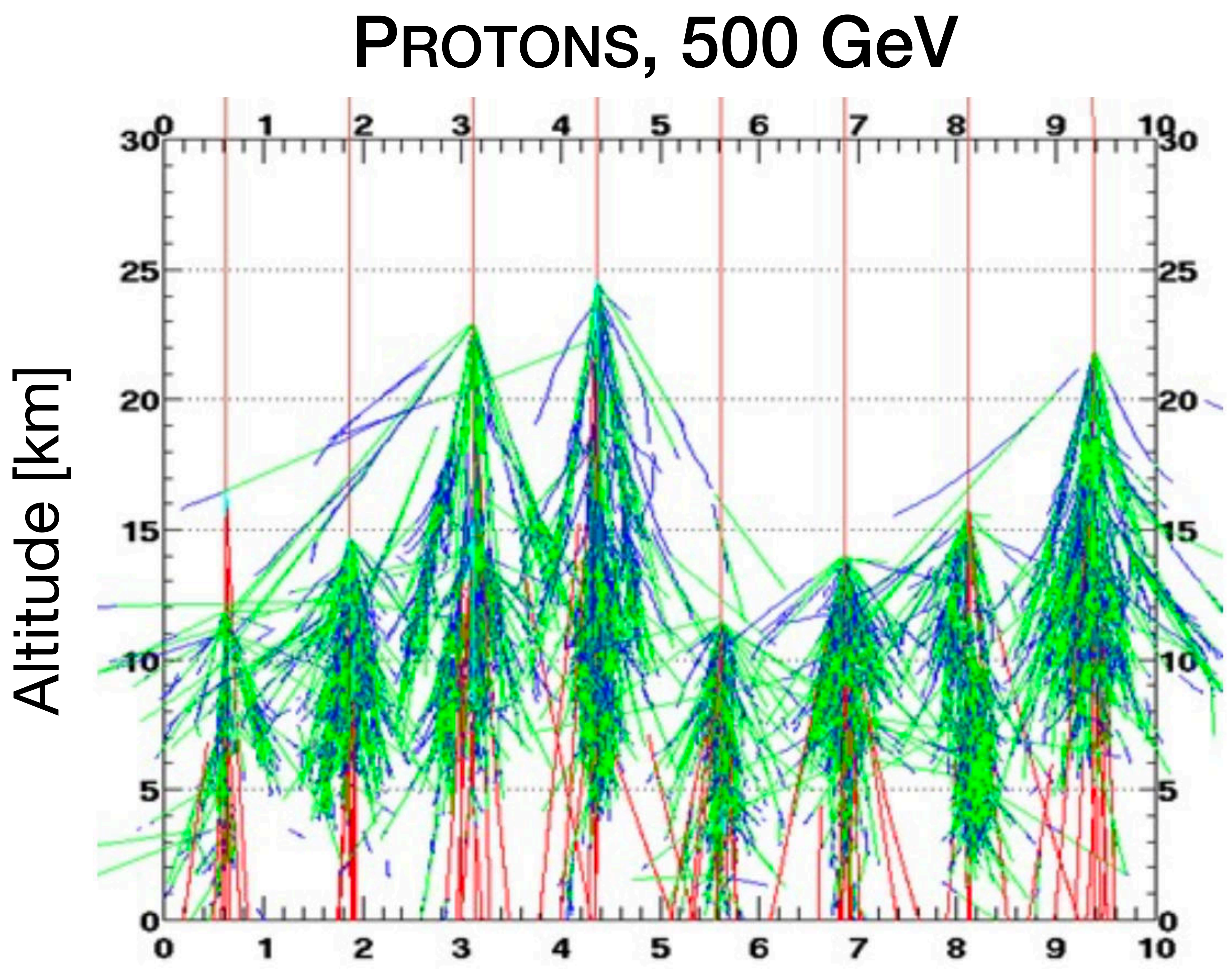
- Fluorescence emission from de-excitation of N_2 states (290-430 nm)
- Less efficient light emission:
  - For 1 GeV electron near ground, 30 photons from Cherenkov light vs 4 photons from fluorescence light (per m track length)
- Longer time profile: microseconds vs 10s of nanoseconds



Backgrounds

Hadronic showers



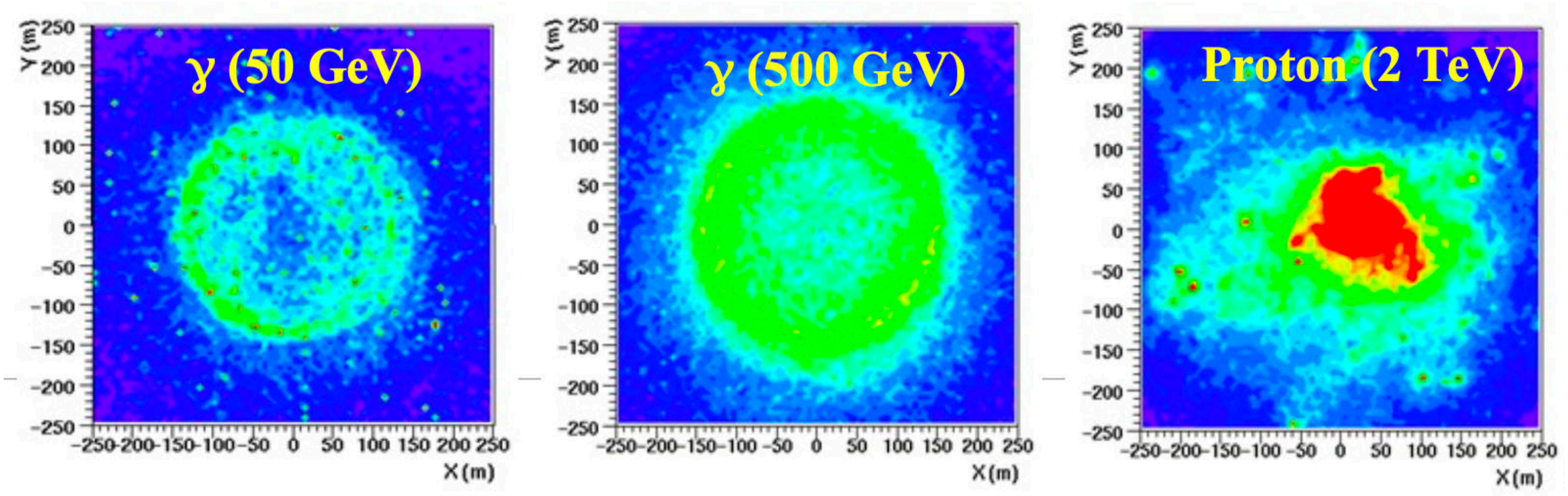


For hadronic showers, the higher transverse momentum
from pion production and sub-showers produce a wider shower

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

Backgrounds

Hadronic showers



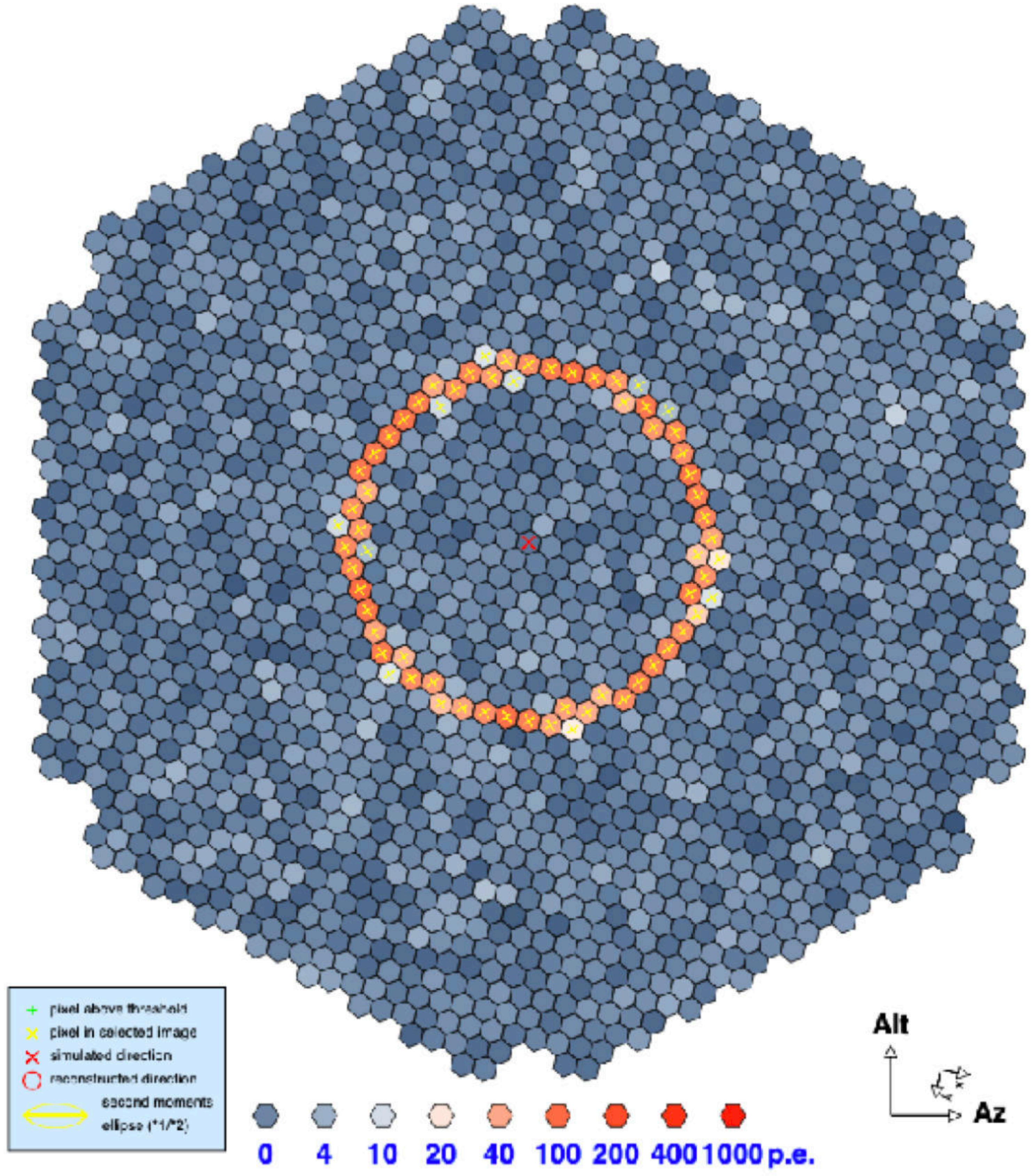
For hadronic showers, the higher transverse momentum
from pion production and sub-showers produce a wider shower

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

Backgrounds

Hadronic showers: muons

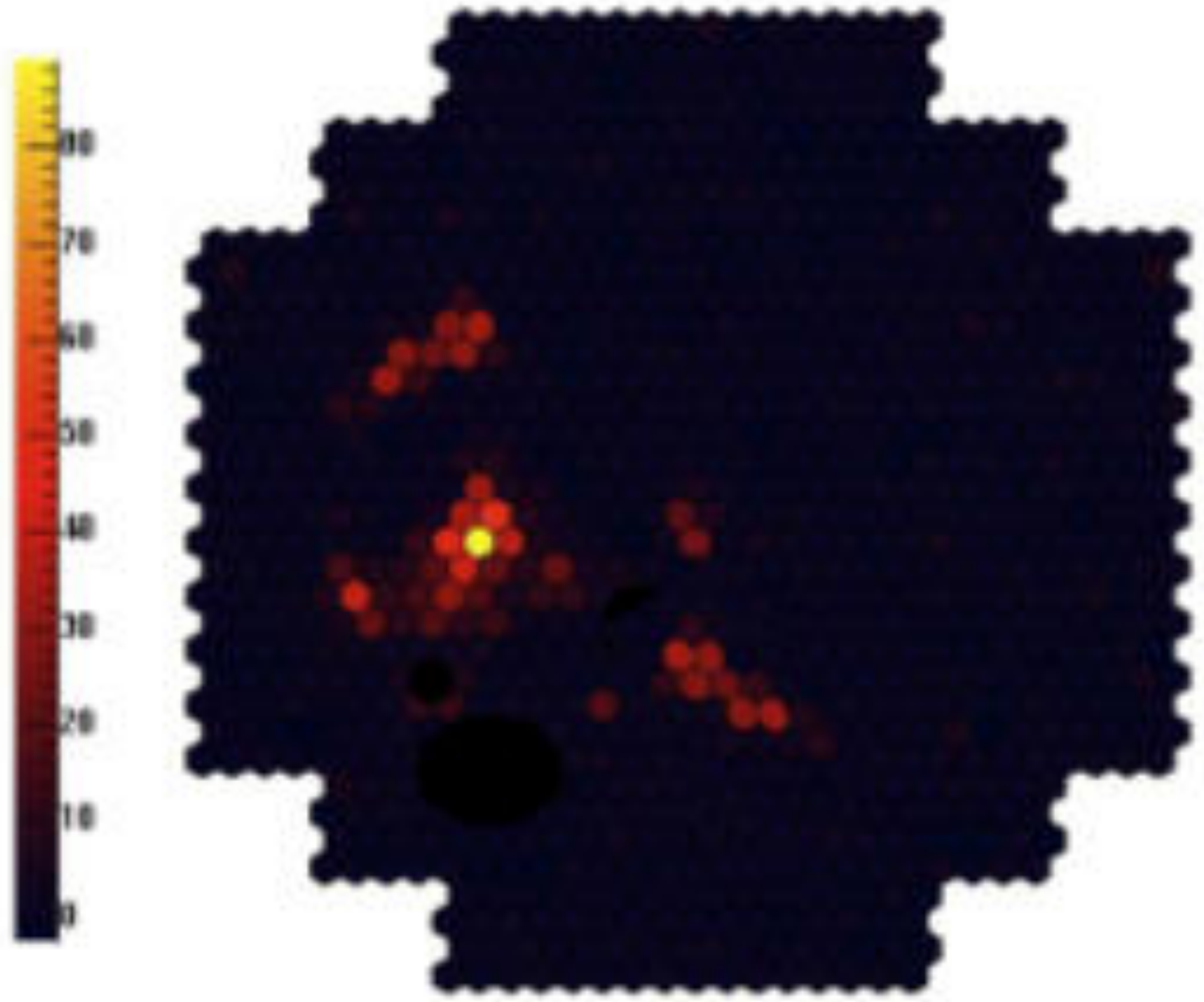
- **Produced in hadronic sub-showers**
- Most muons detected by IACTs are minimum ionizing particles with a long lifetime → large penetration depth
- Travel in straight lines towards the ground with Cherenkov radiation emitted under constant opening angle in a cone around the muon direction of travel
- 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**



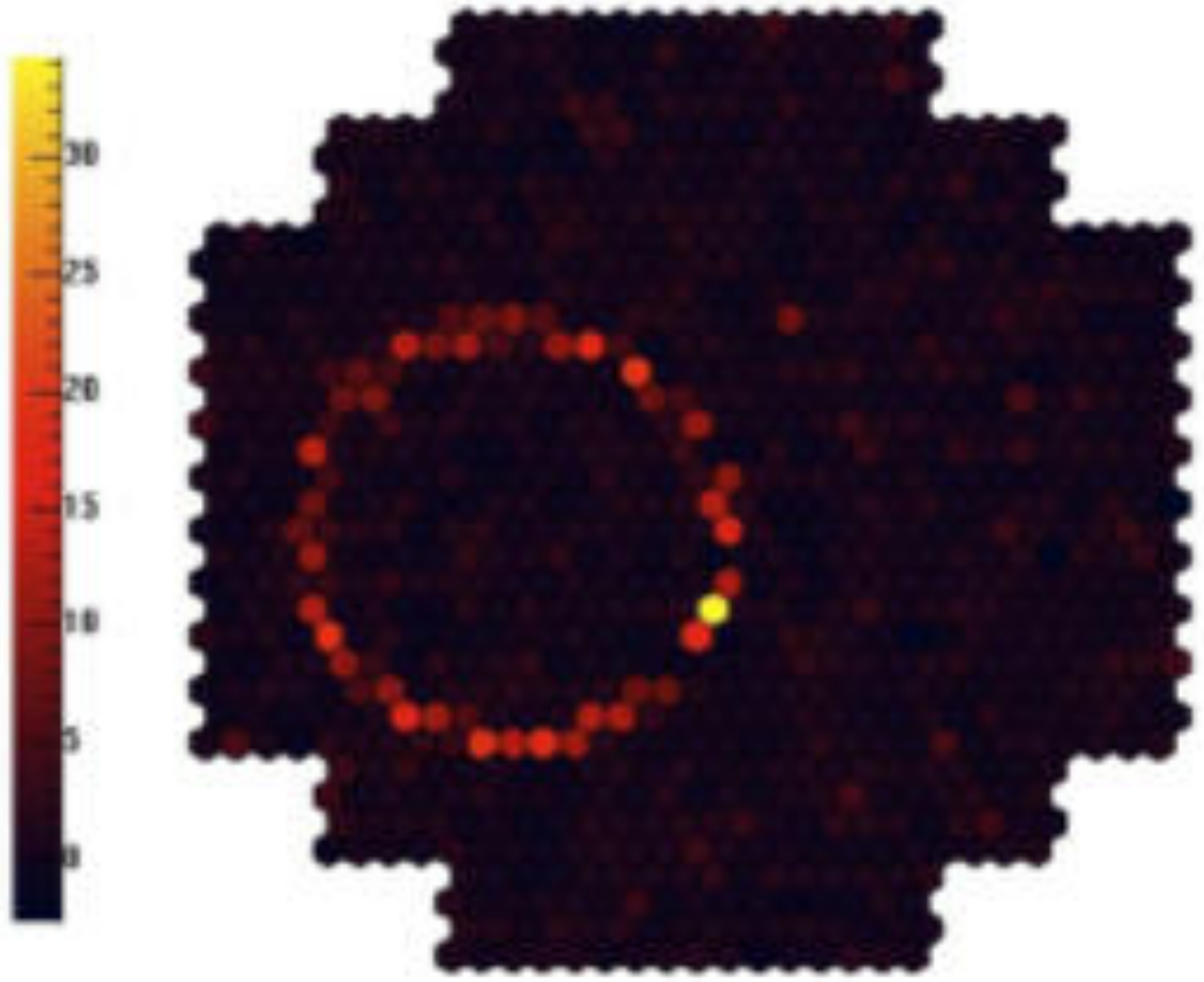
⇒ Partial muon arcs look much like EM showers, particularly a problem at ≈100 GeV

Backgrounds

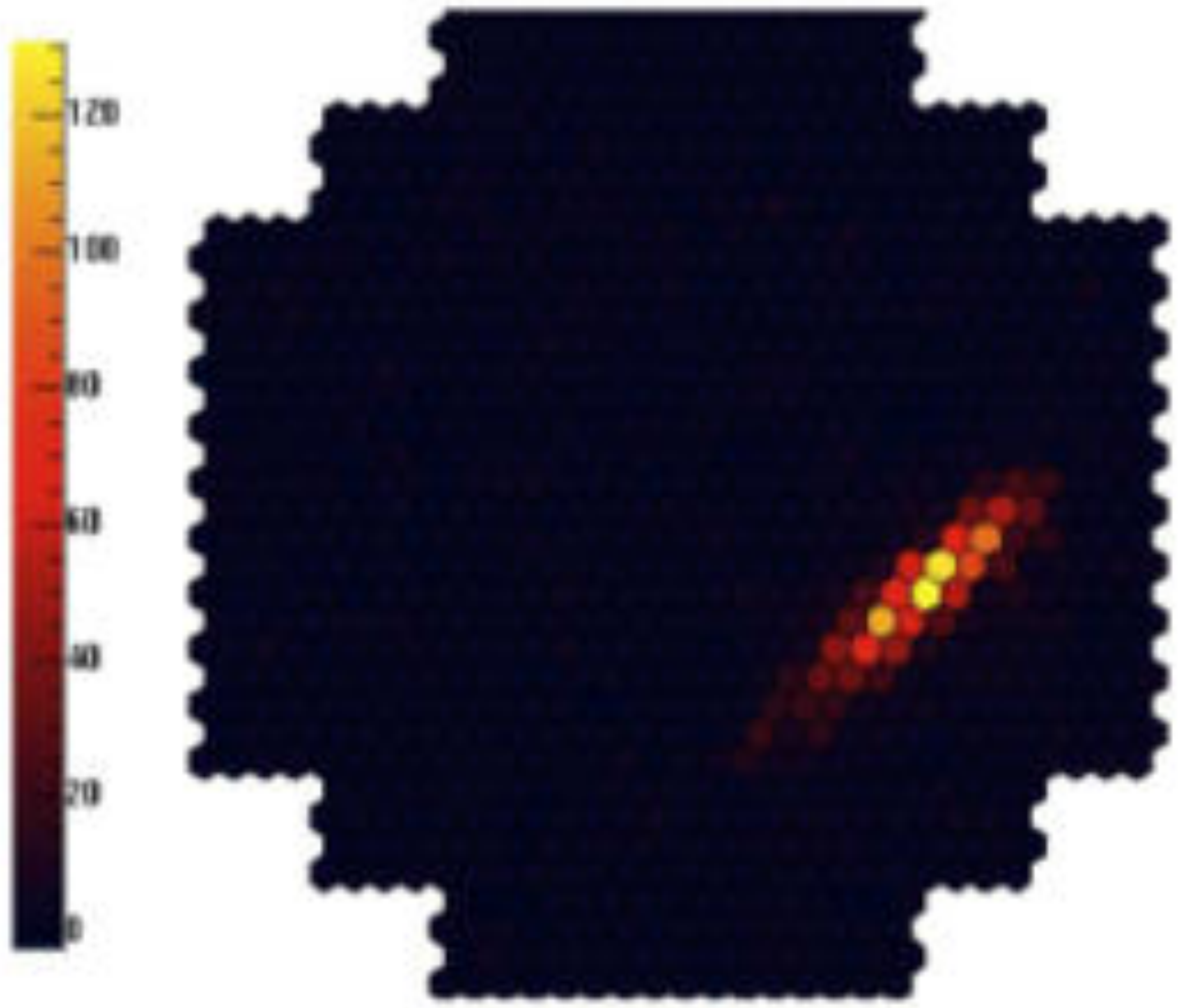
Hadronic showers and muons



Hadronic shower



Isolated muon



Gamma-like event

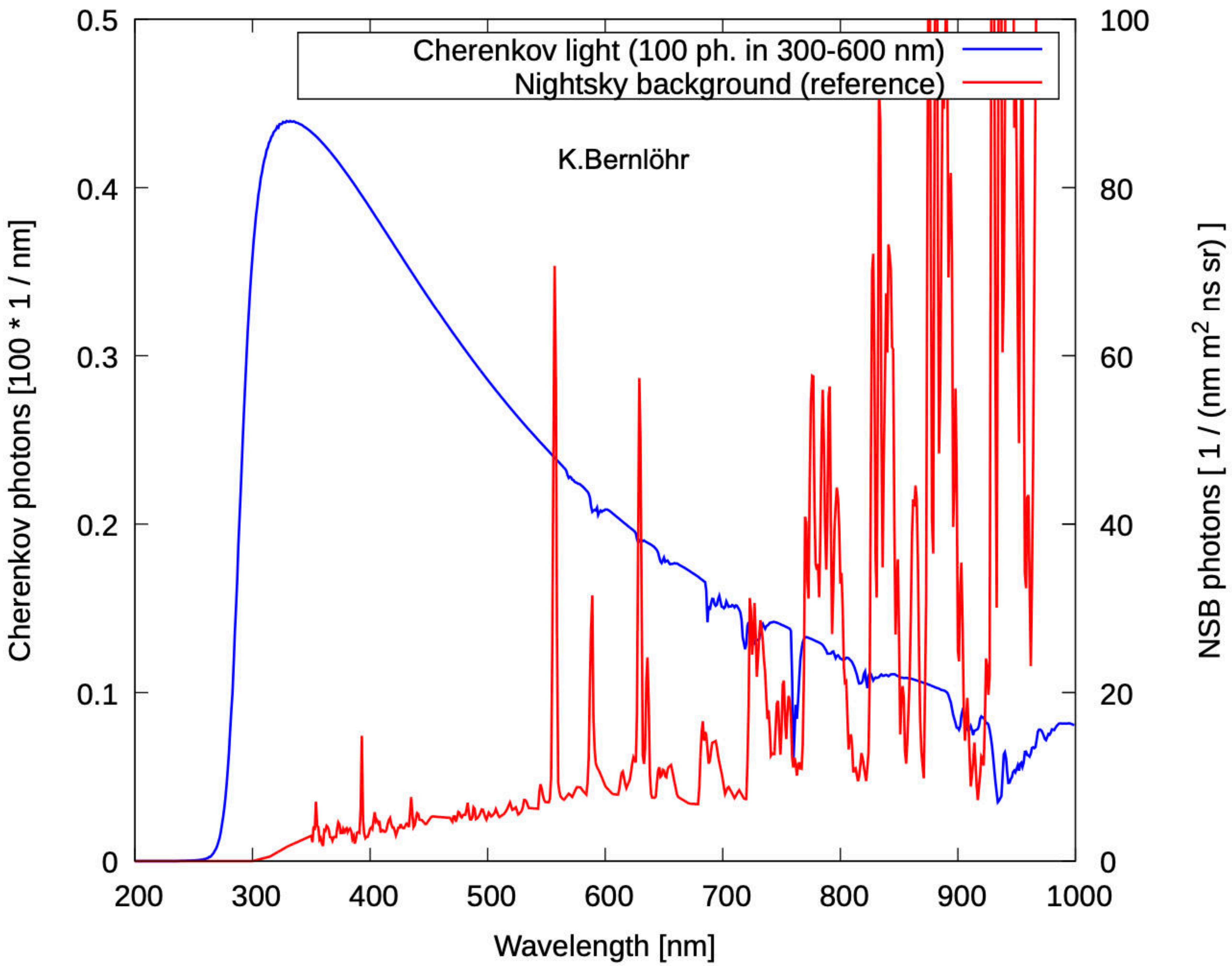
Gamma / hadron discrimination through image topology

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



How to build an IACT?

General astronomical requirements

Angular Resolution

What is the smallest object we can resolve?

→ Ability to resolve two nearby objects

↓

Telescope optics, camera pixel sizes

Light Collecting Power

What is the faintest object we can detect?

→ Ability to detect weak Cherenkov flashes

↓

Mirror area and reflectivity, camera sensitivity

Field of View (FOV)

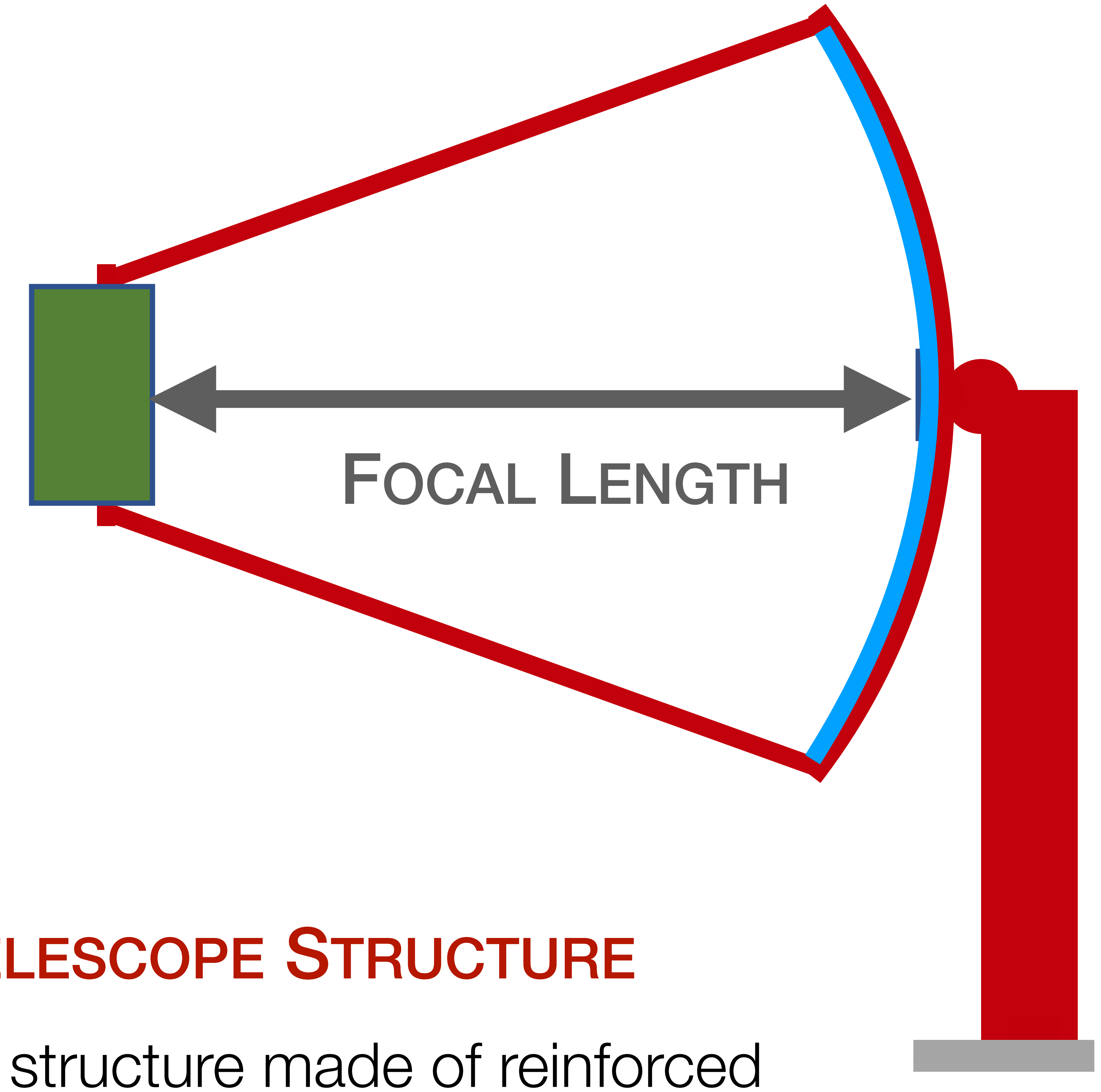
What is the largest object we can image?

→ Solid angle of the sky covered

↓

Telescope optics, camera pixel sizes

An IACT's prototype



CAMERA

Pixellated with optical detectors (PMTs, SiMPs). Fast (~ns)

TELESCOPE STRUCTURE

Tubular structure made of reinforced carbon fibre and steel tubes or made of steel to ensure sufficient stiffness. Total weight of ~90 – 100t

DISH + REFLECTOR (MIRRORS)

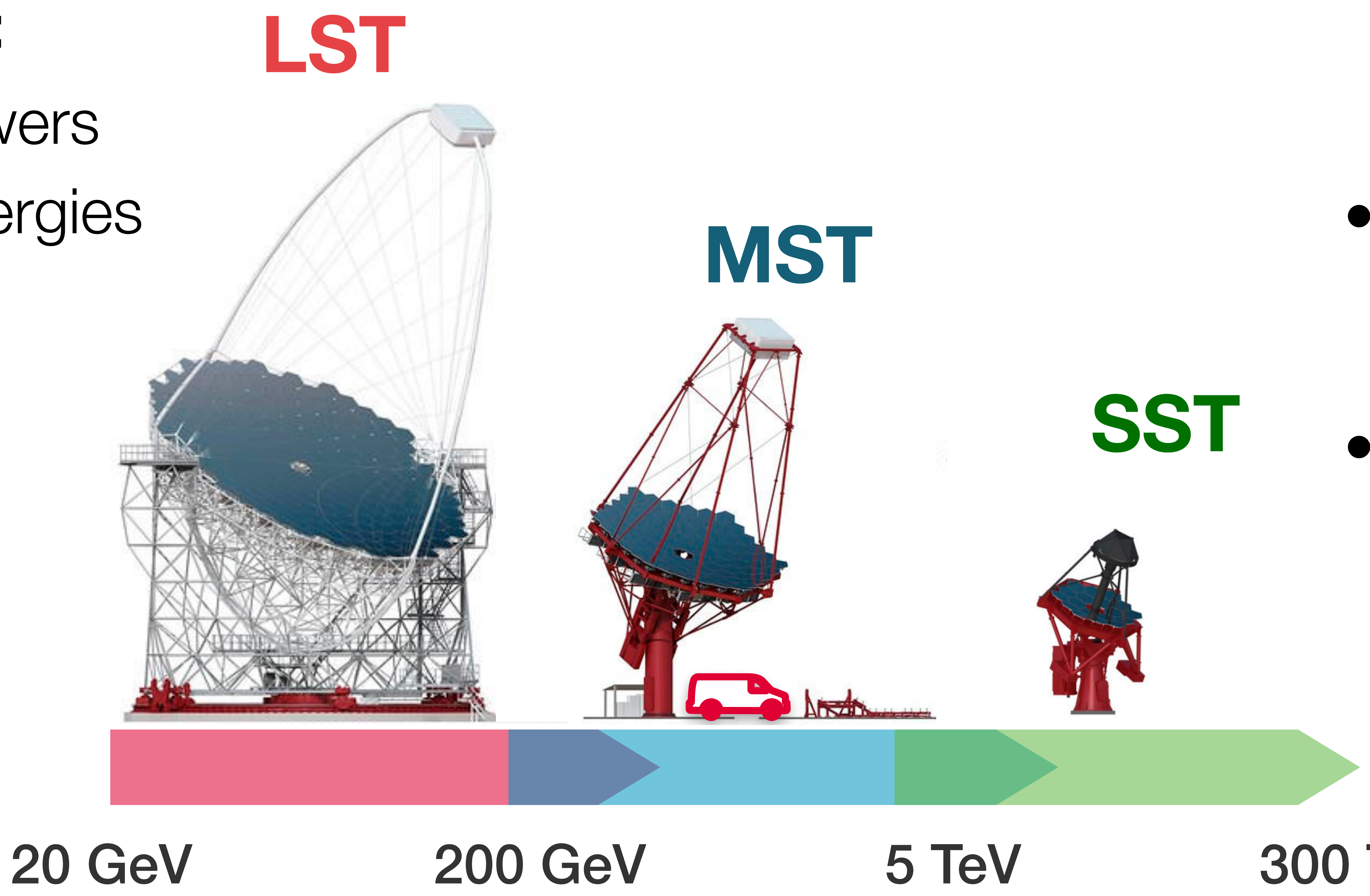
- **Parabolic design**
  - ➡ Larger off-axis PSF but perfectly isochronous (no time spread)
- **Davis-Cotton (DC) design**
  - ➡ Smaller off-axis PSF than parabolic but non-isochronous (few-ns time dispersion)
- **Modified Davis-Cotton (DC) design**
  - ➡ Reduced dish-induced signal dispersion
  - ➡ Almost DC-like PSF but improved isochronicity of reflector thus reduced time spread
- **Modified Schwarzschild-Couder dual-mirror**
  - ➡ Shorter focal length allowing large FOV and compact cameras

IACTs: how big? How many?

A compromise between size and number…

Bigger dishes:

- Image fainter showers
  → go to lower energies
- Smaller FOV (~4º)



Smaller dishes:

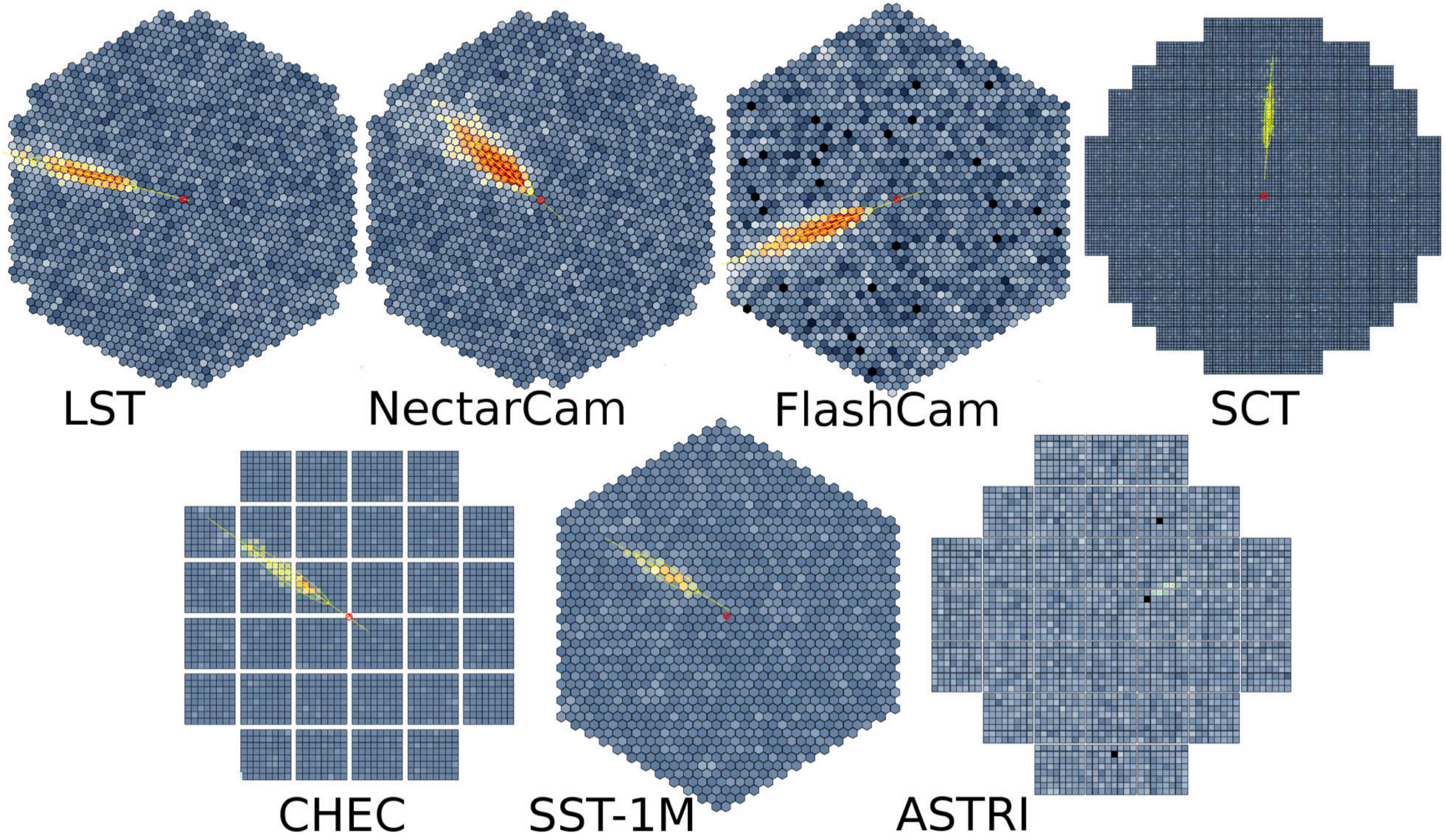
- Grater sensitivity at medium to high energies
- Larger FOV (~9º)

Ideally: Lots of big-dish telescopes, but money is always a limitation!

Cost increases with size of dish or number of telescopes

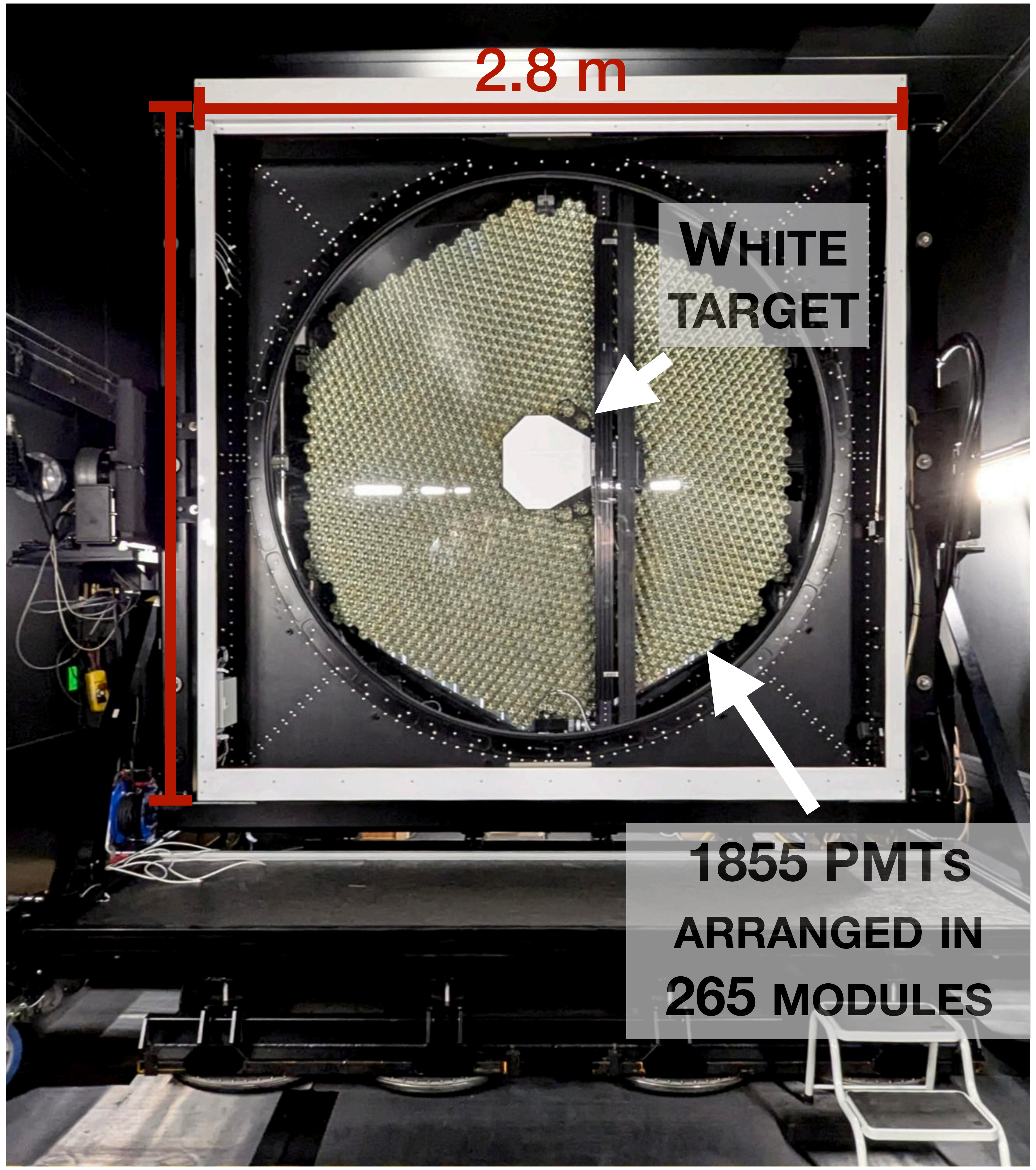
IACT cameras

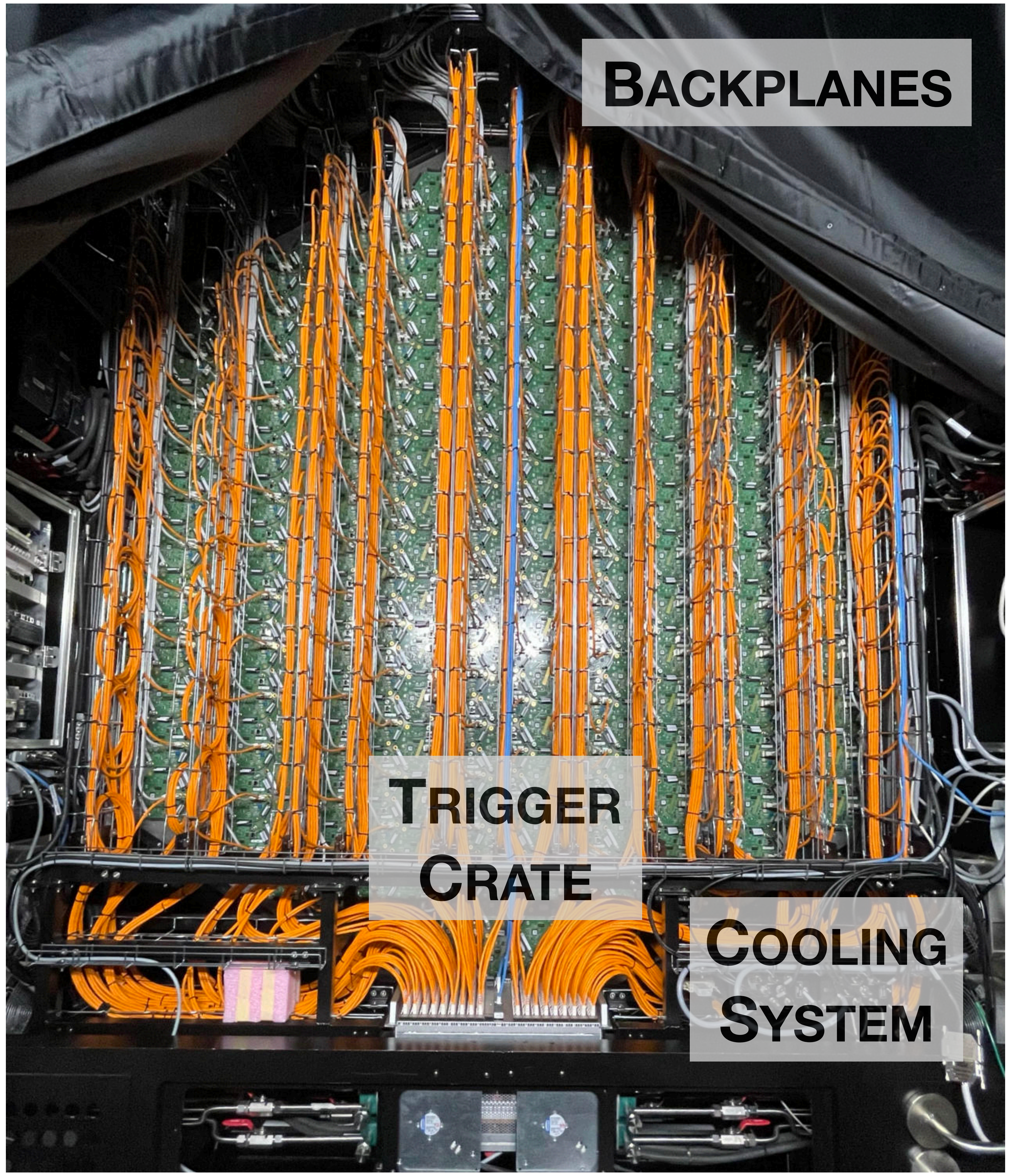
The CTAO designs



IACT cameras

NectarCAM camera at IRFU/CEA Paris-Saclay

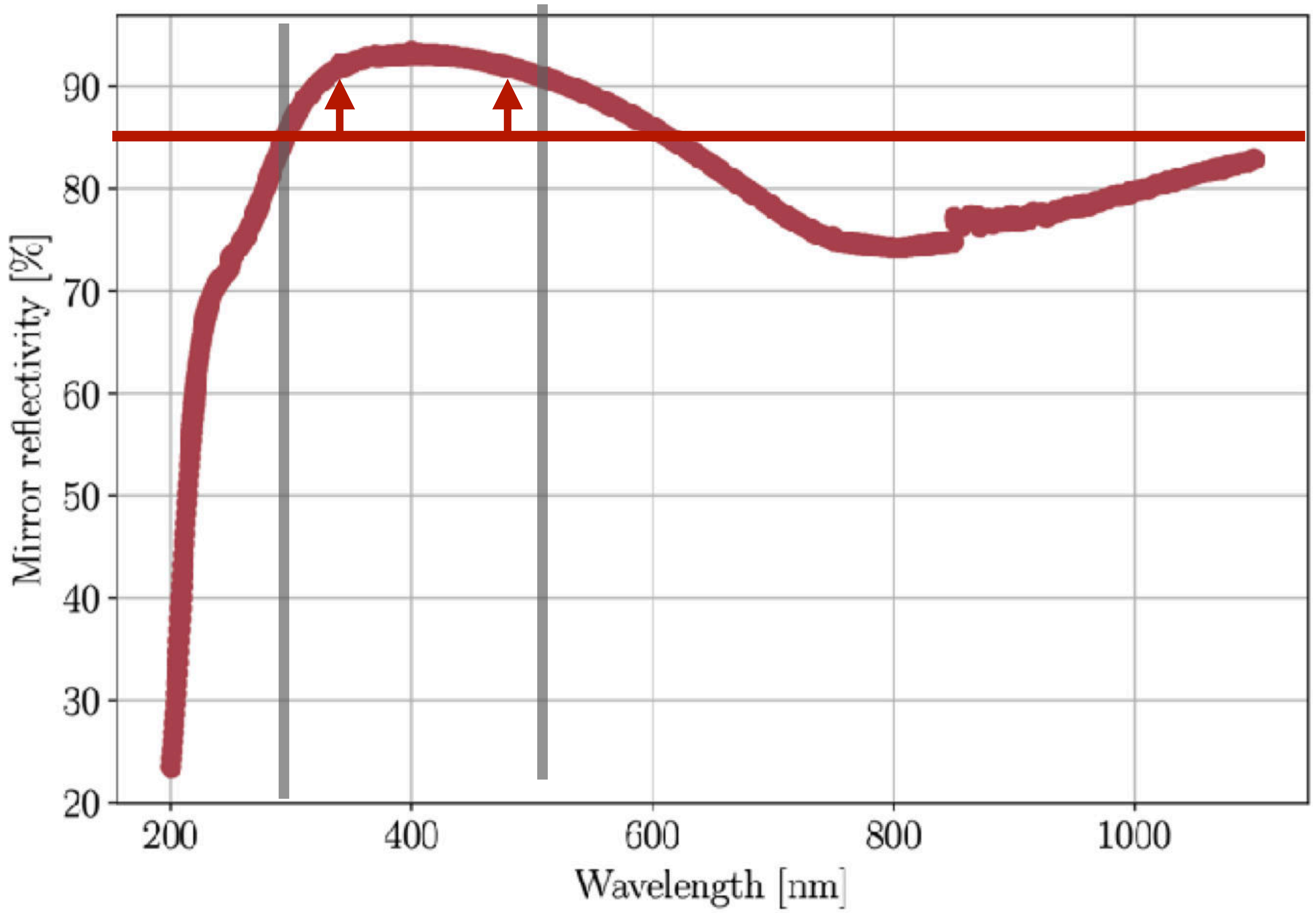




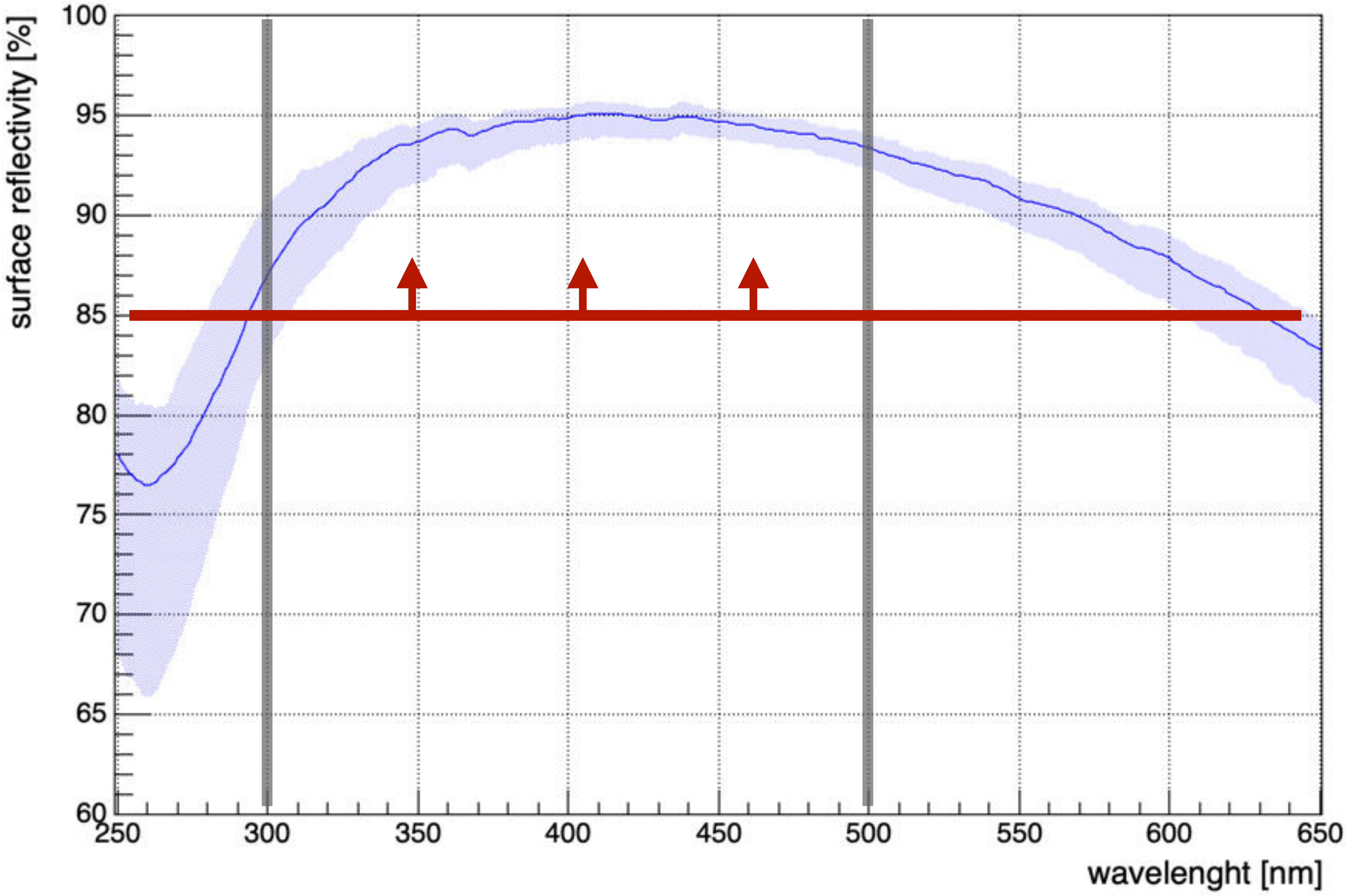
IACT mirrors

Reflectivity > 85% in [300, 500] nm

LST



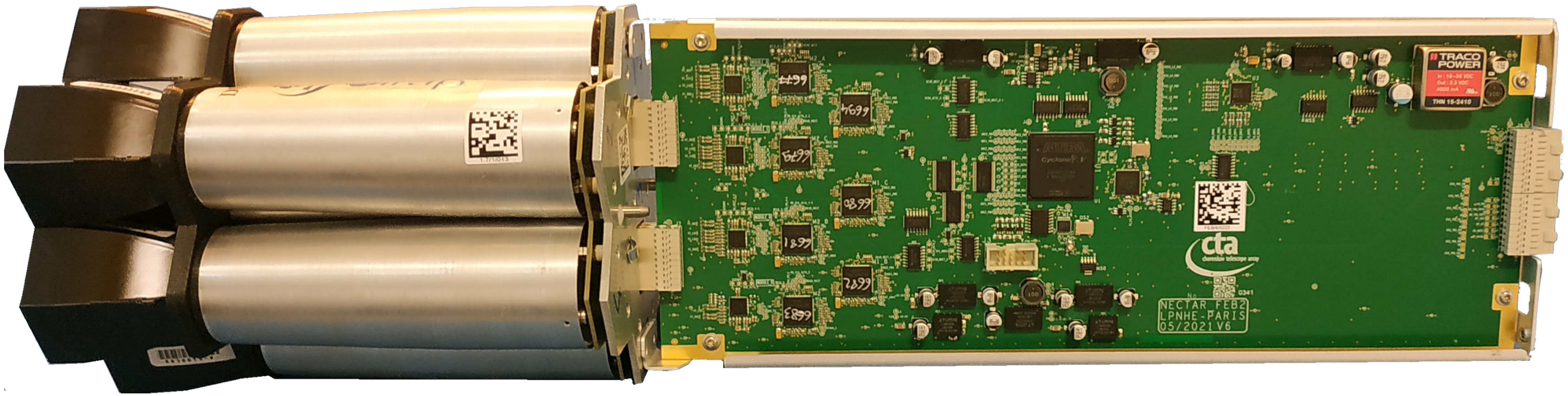
MST



From photons to photoelectrons

Formation of the electric signal

Focal Plane Module **Front End Board**

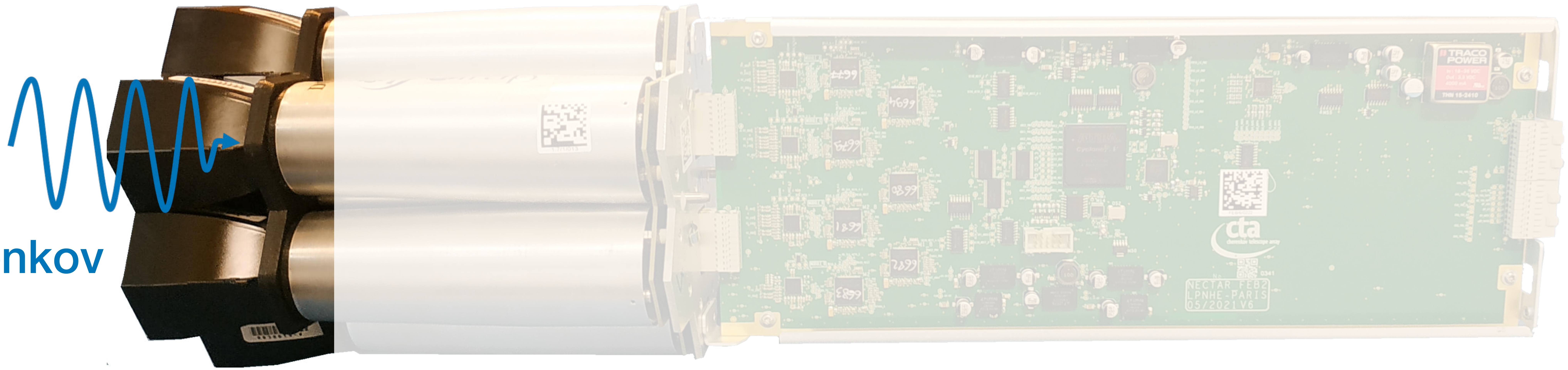


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE FRONT END BOARD

Cherenkov γ

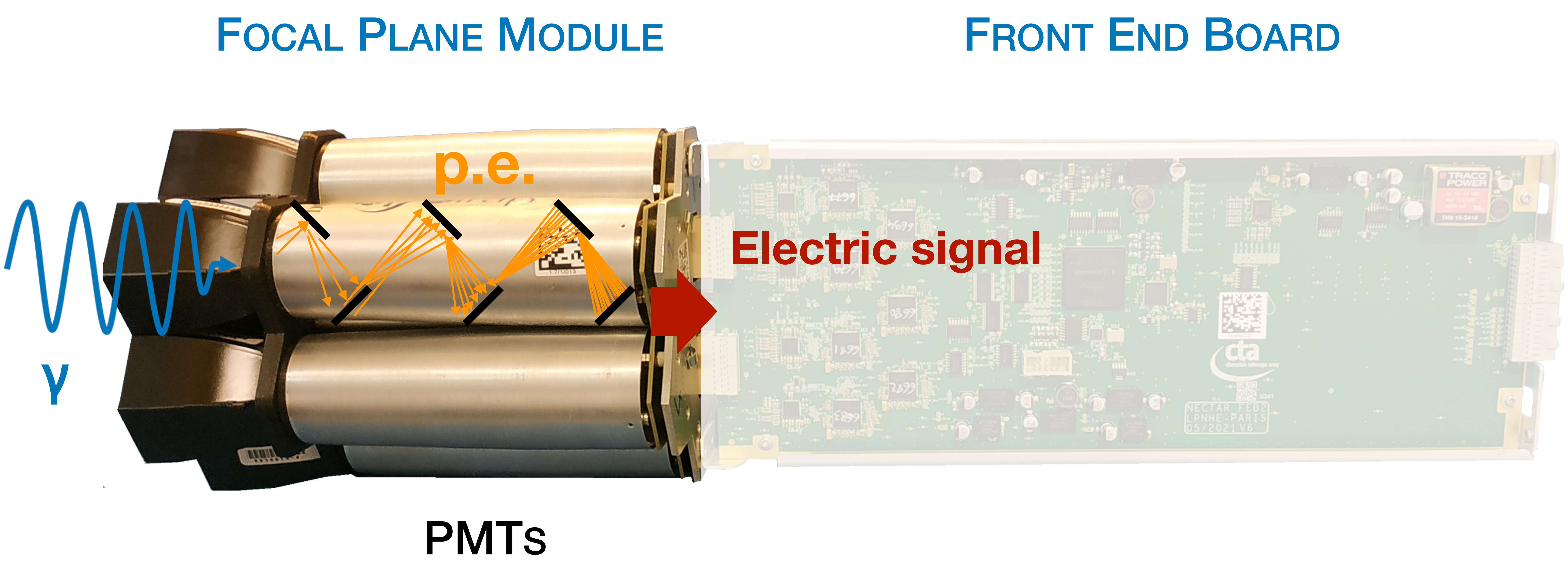


WINSTON CONES

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

From photons to photoelectrons

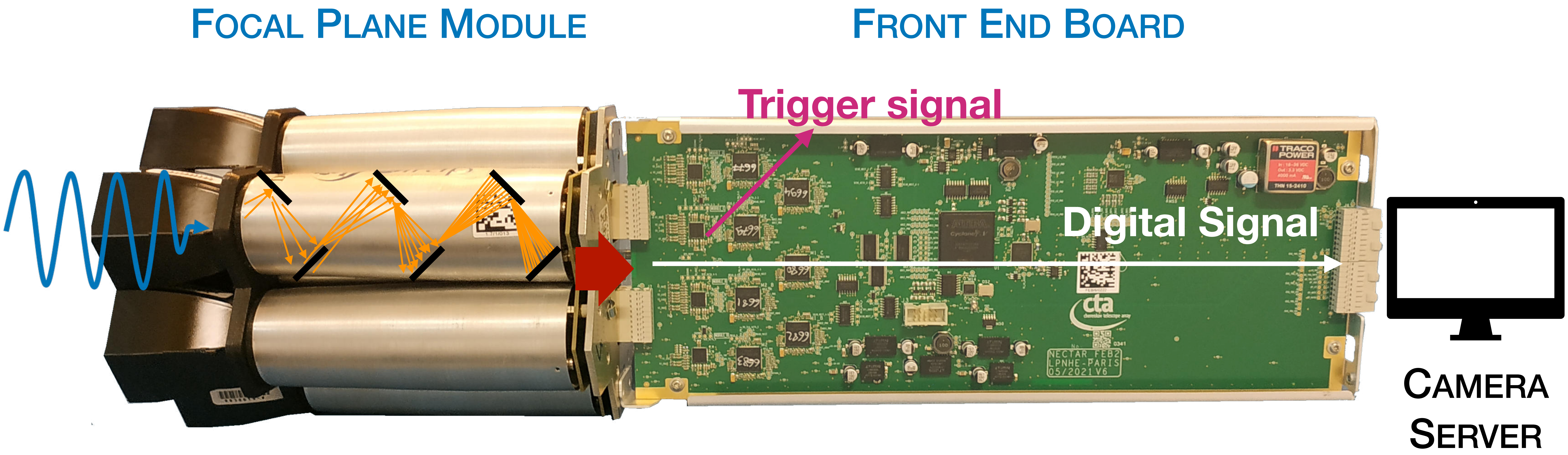
Formation of the electric signal



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

From photons to photoelectrons

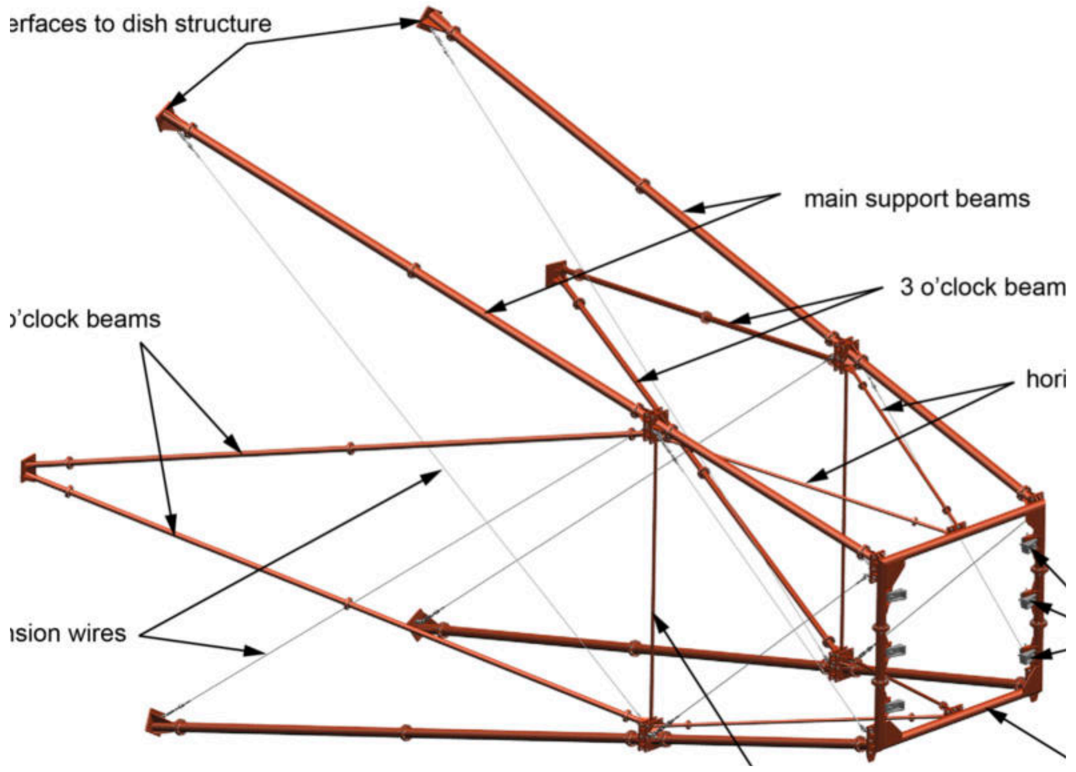
Formation of the electric signal



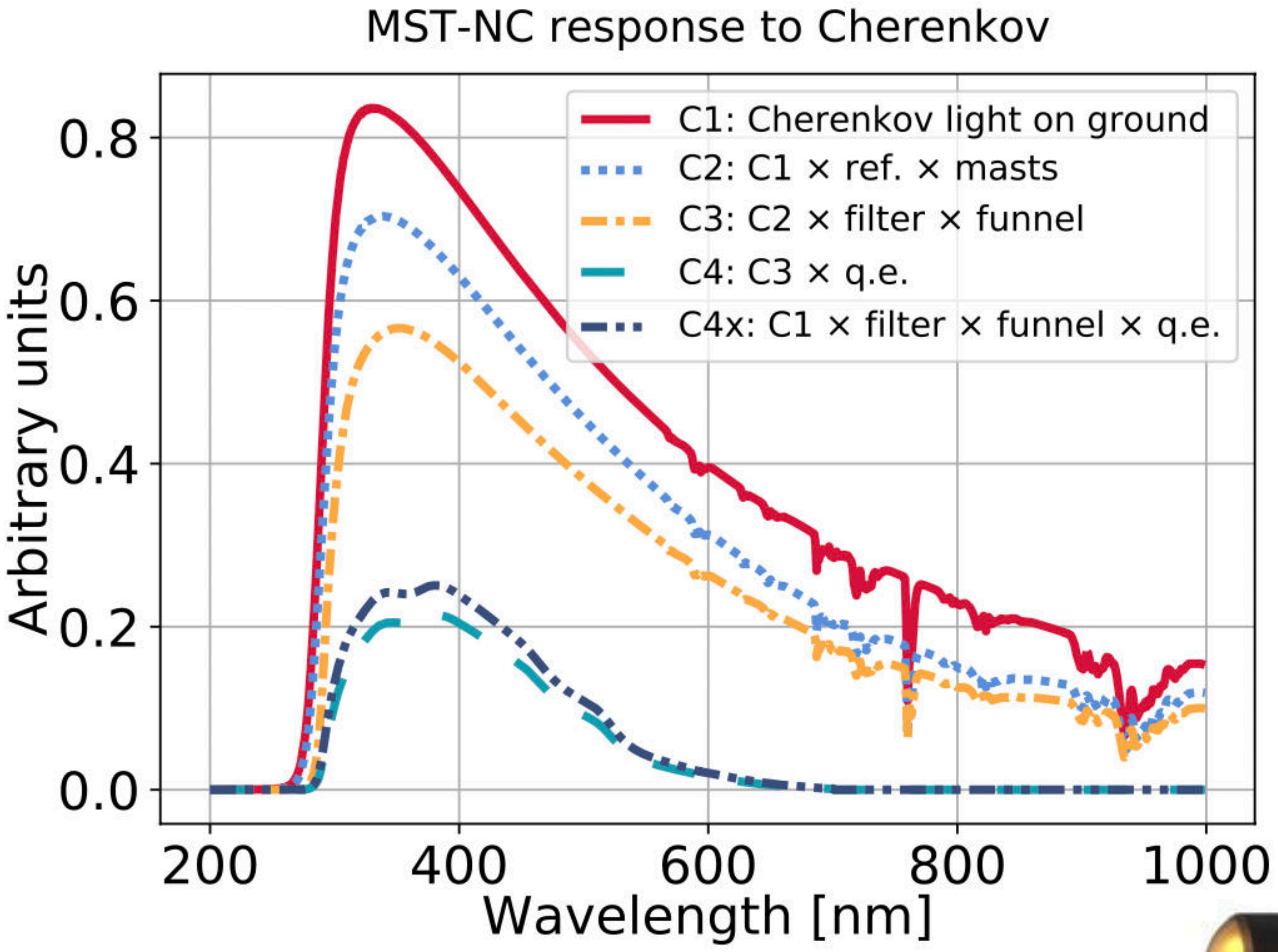
3. Signal is amplified, sampled and digitized + formation of trigger signal

From photons to photoelectrons

Impact of components on Cherenkov light detection efficiency



TELESCOPE STRUCTURE



ENTRANCE WINDOW

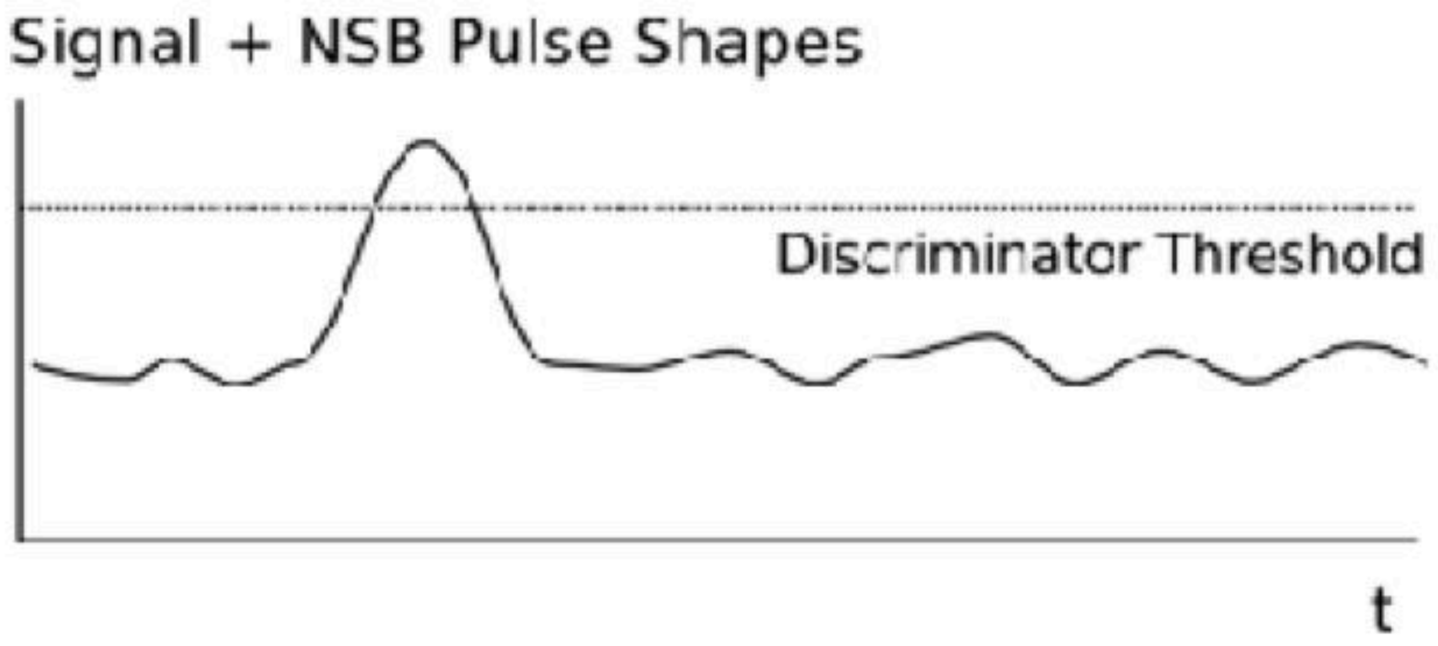
LIGHT GUIDES

HAMAMATSU PMT

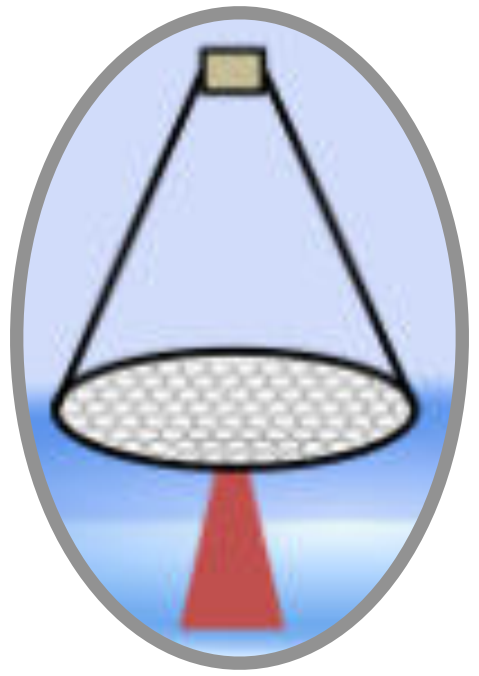
Triggering an IACT array

From the single pixels to an array trigger

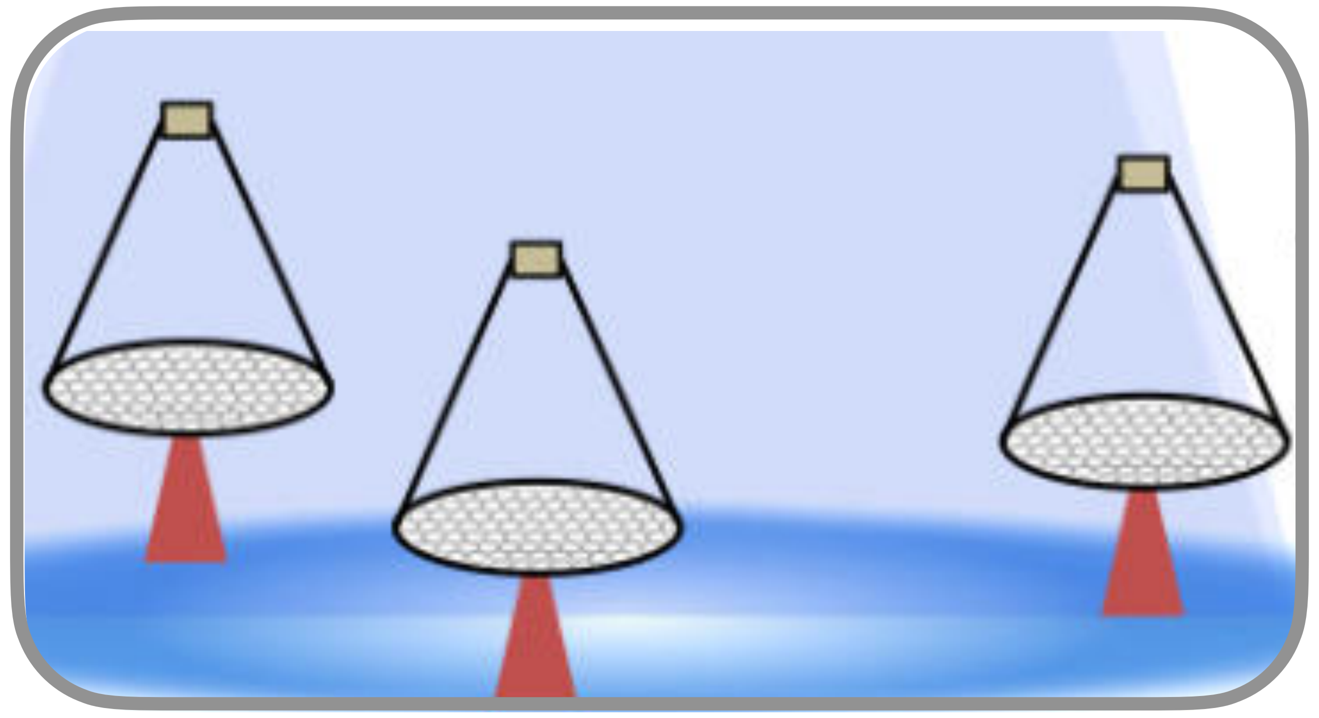
L1: pixel trigger ➡ **L2: telescope trigger** ➡ **L3: array trigger**



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



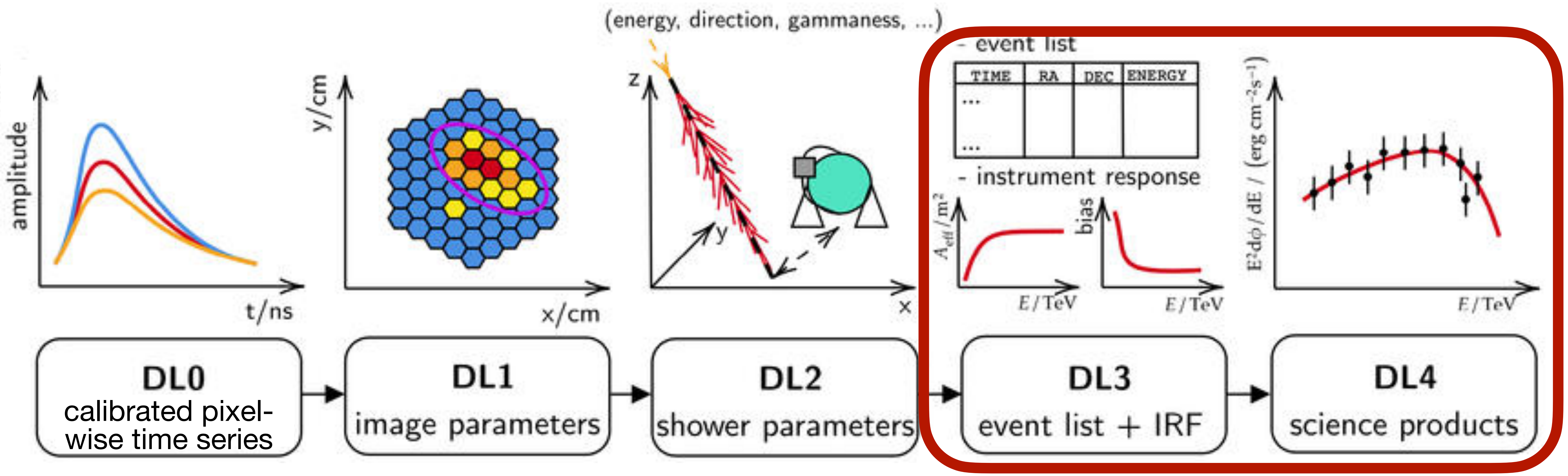
Have enough pixels/ sectors triggered?



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

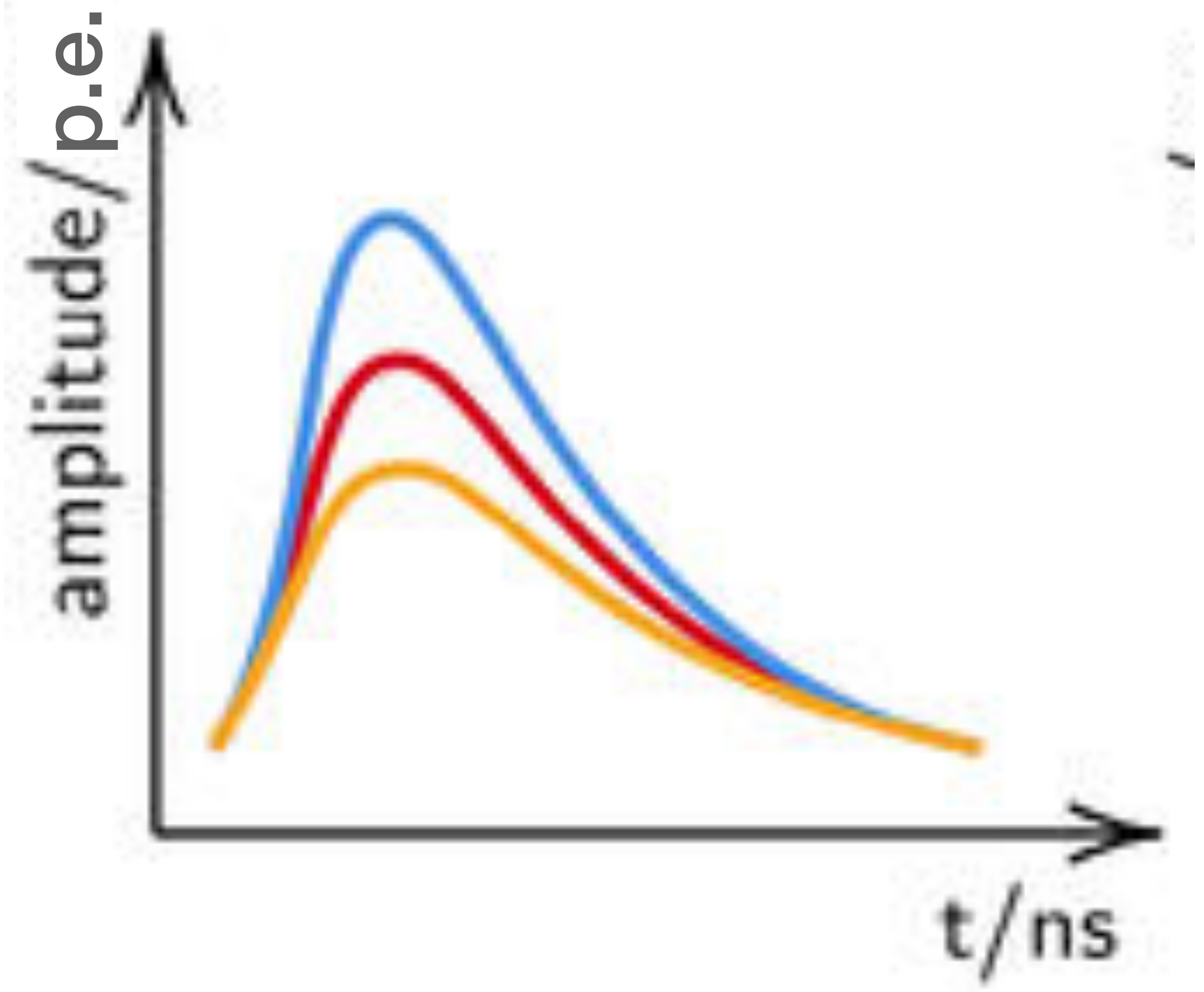


→ Jonathan's talk yesterday!

Data levels

Definition of data levels (DLs) foreseen for CTAO

DL0



First level of calibrated data written to disk and long-term preserved.
Pixel-wise time series for each telescope.

DL1

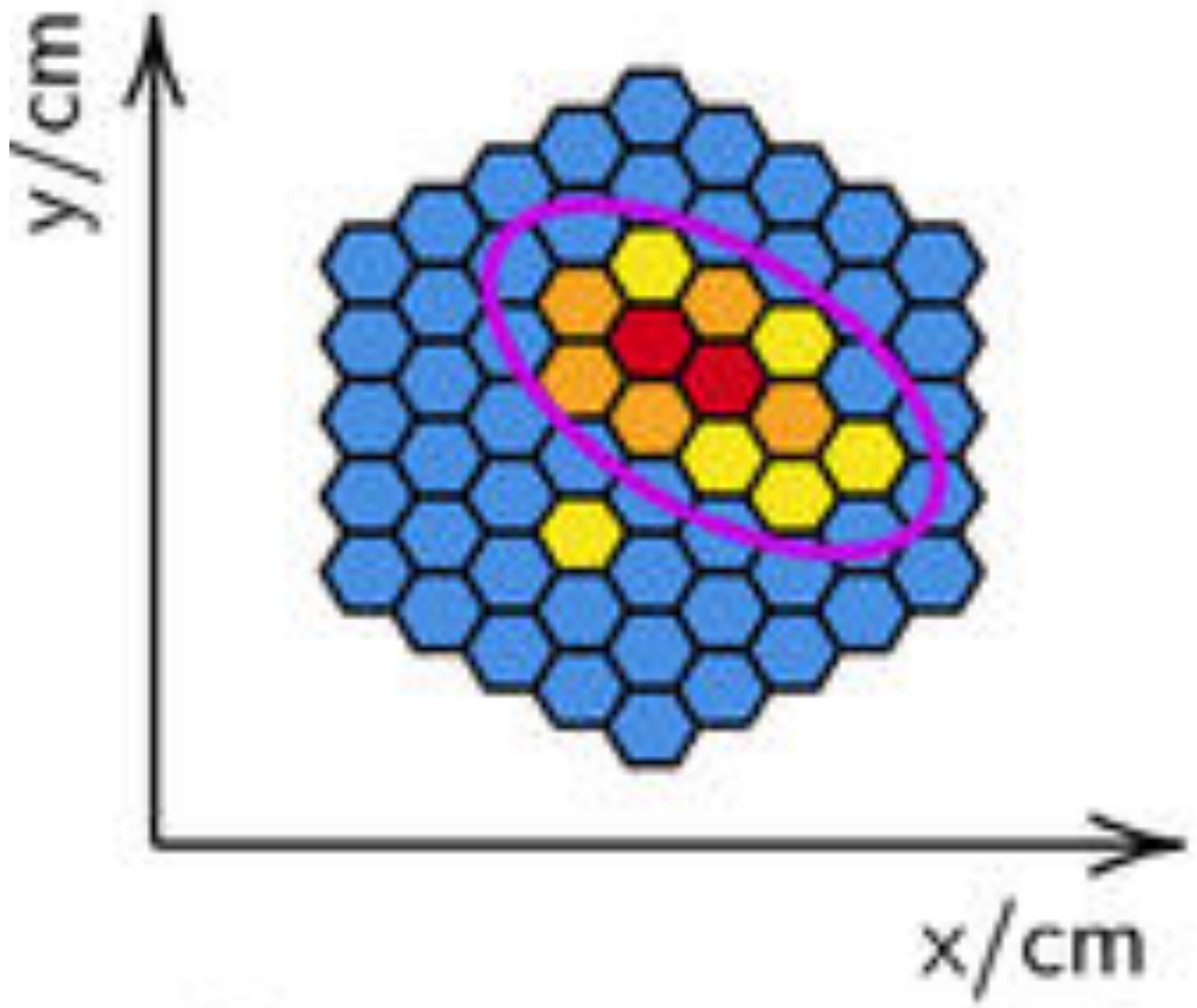
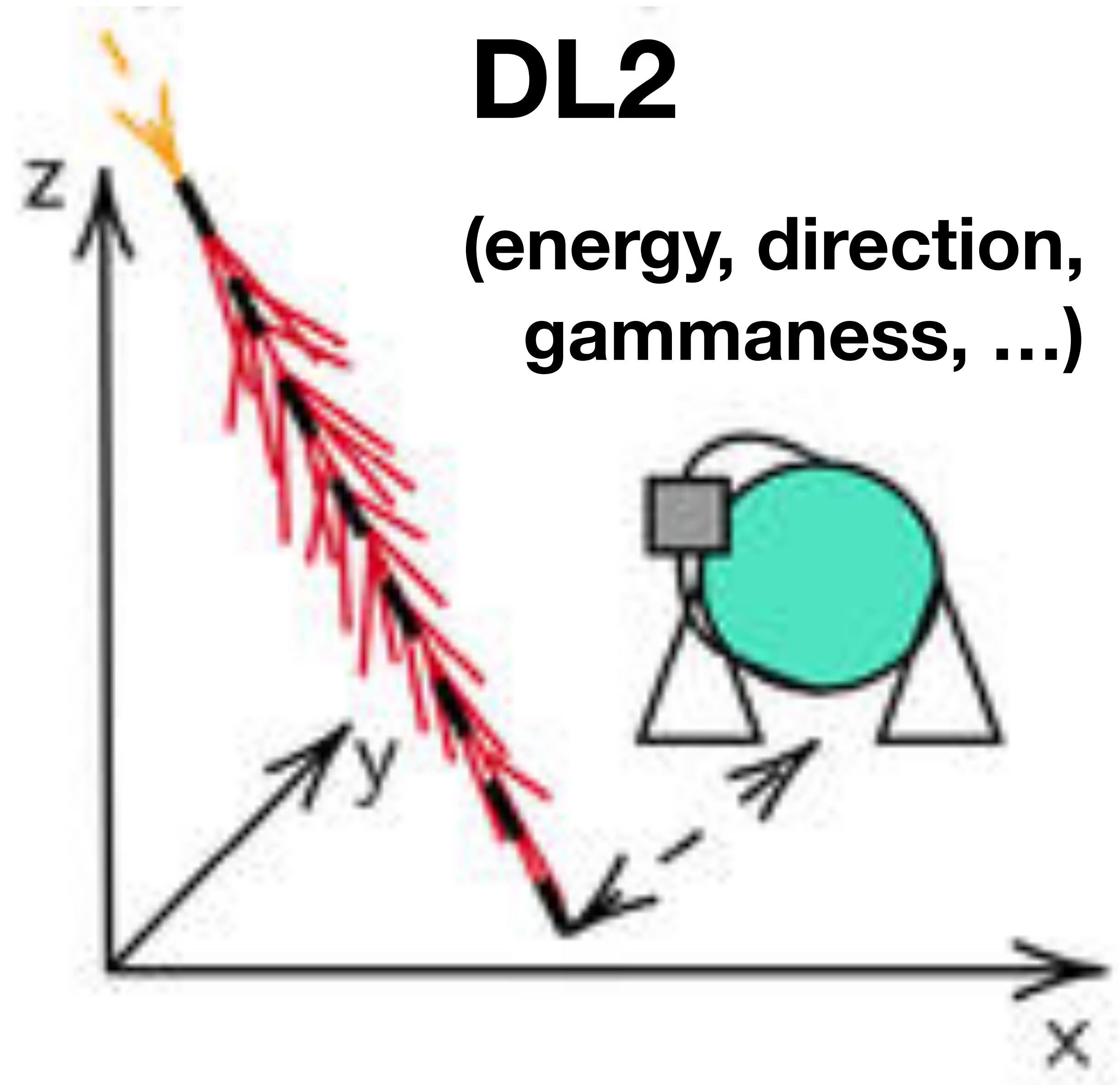


Image extraction and cleaning, and derived per-telescopes parameters.
Camera image parameters (Hillas parameters)

DL2

(energy, direction, gammaness, ...)



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

Data levels

From R0, through R1 to DL0

We still have uncalibrated waveforms in units of ADC counts (R0)

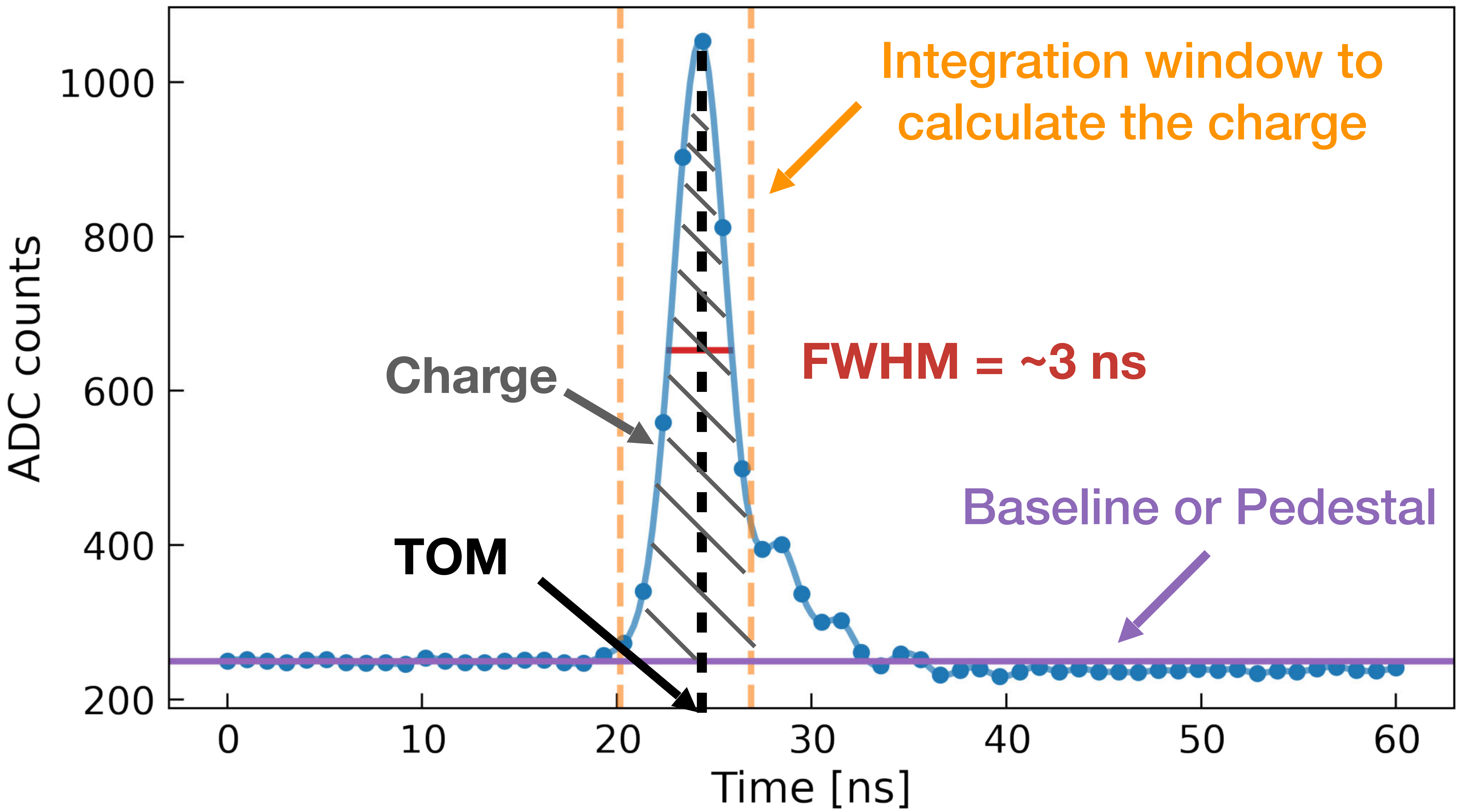
→ Calibration (R0) and data volume reduction (R1): transition to DL0

Low-level data processing

Row data calibration: charge [ADC counts] and arrive time

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)

Typical waveform of a light pulse event (NectarCAM)



Low-level data processing

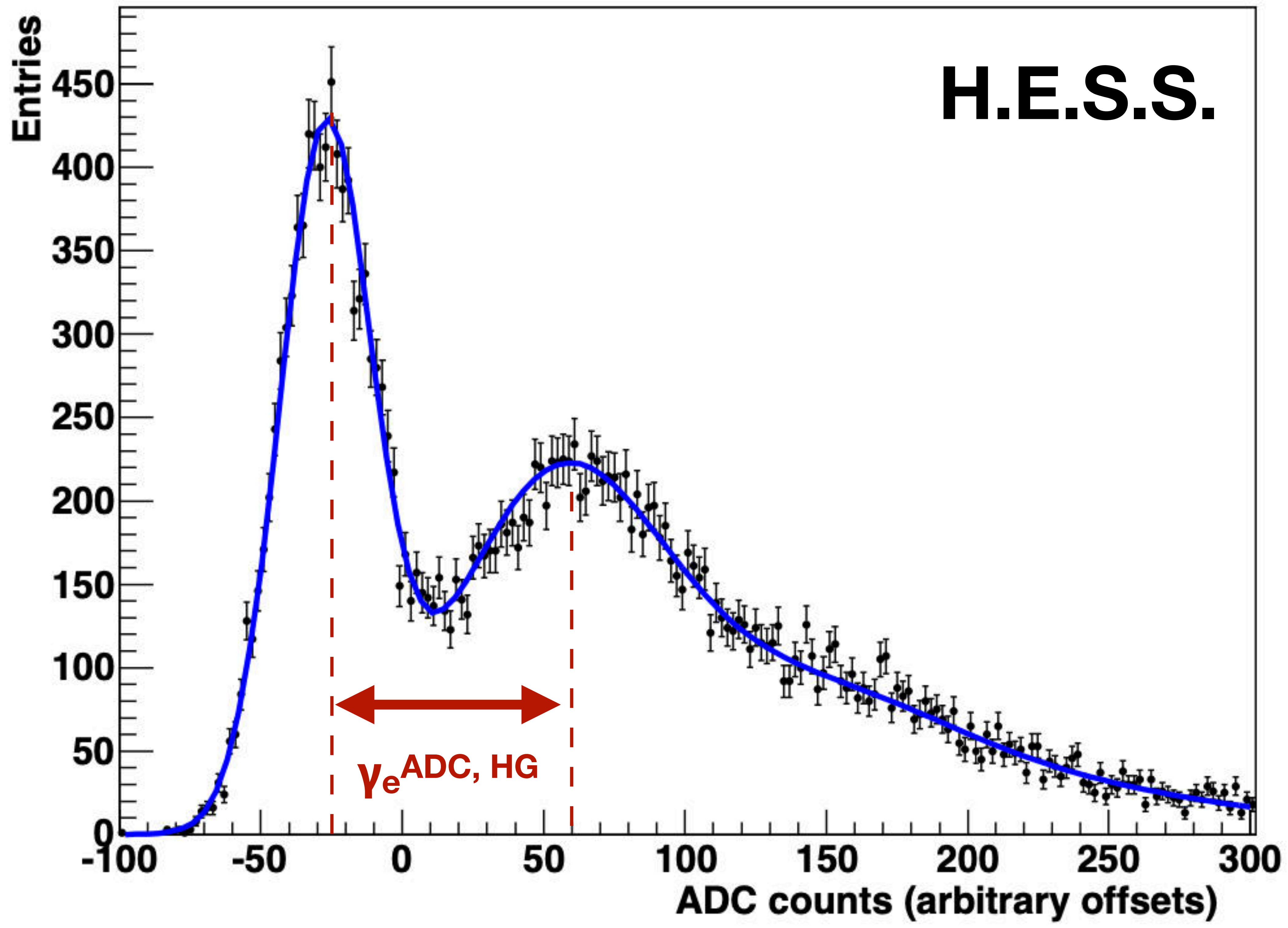
From ADC counts to p.e. + data volume reduction

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

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

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

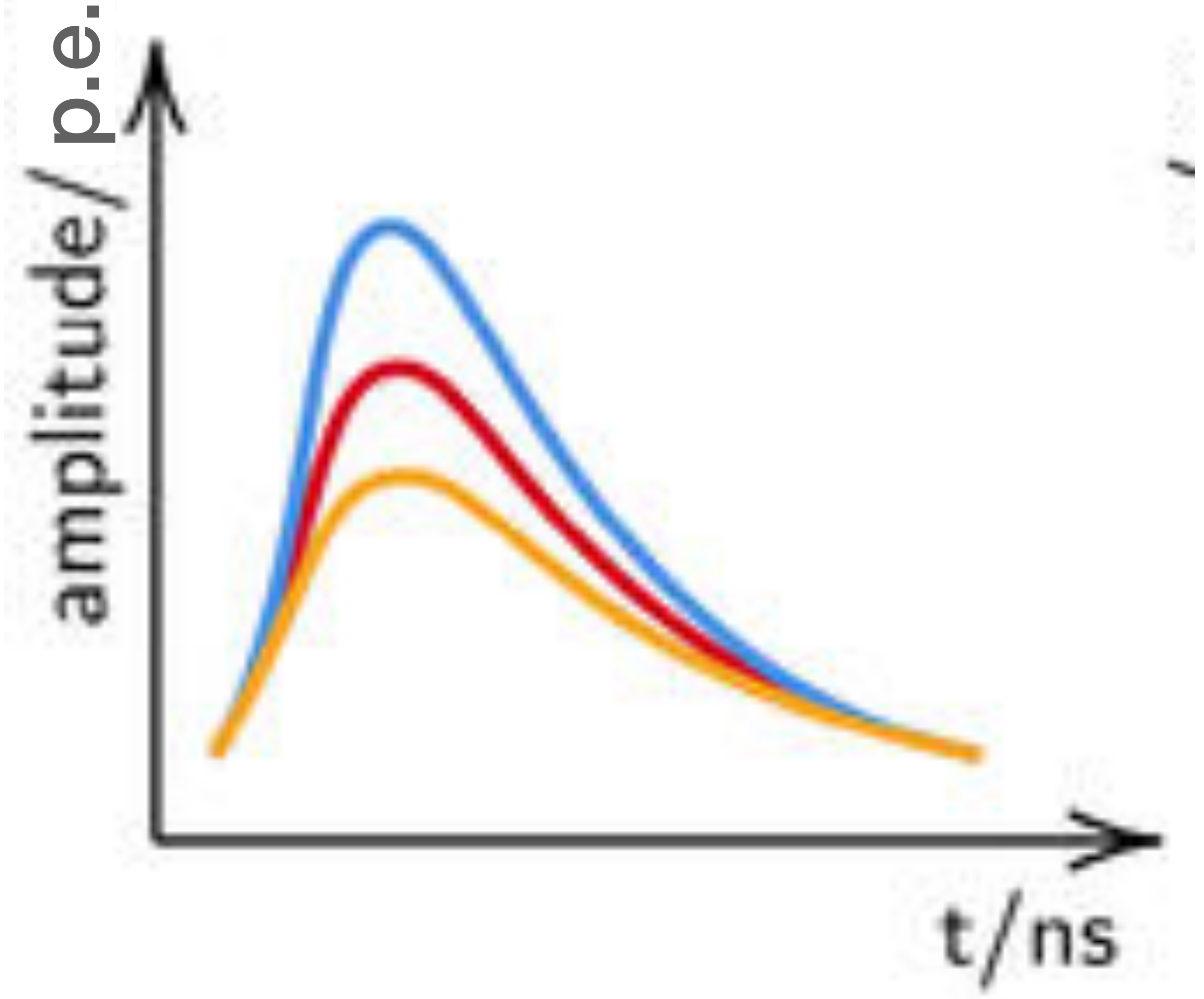
- Ratio High/Low gain
- Flat-fielding corrections ***FF*** to homogenize the response of the sensors across the camera
- Exclusion of “Broken” pixels because HV off/ unstable, PMT without signal, stars, highly illuminated pixels



Data levels

We are now at DL0!

DL0



DL1

DL2

(energy, direction, gammaness, ...)

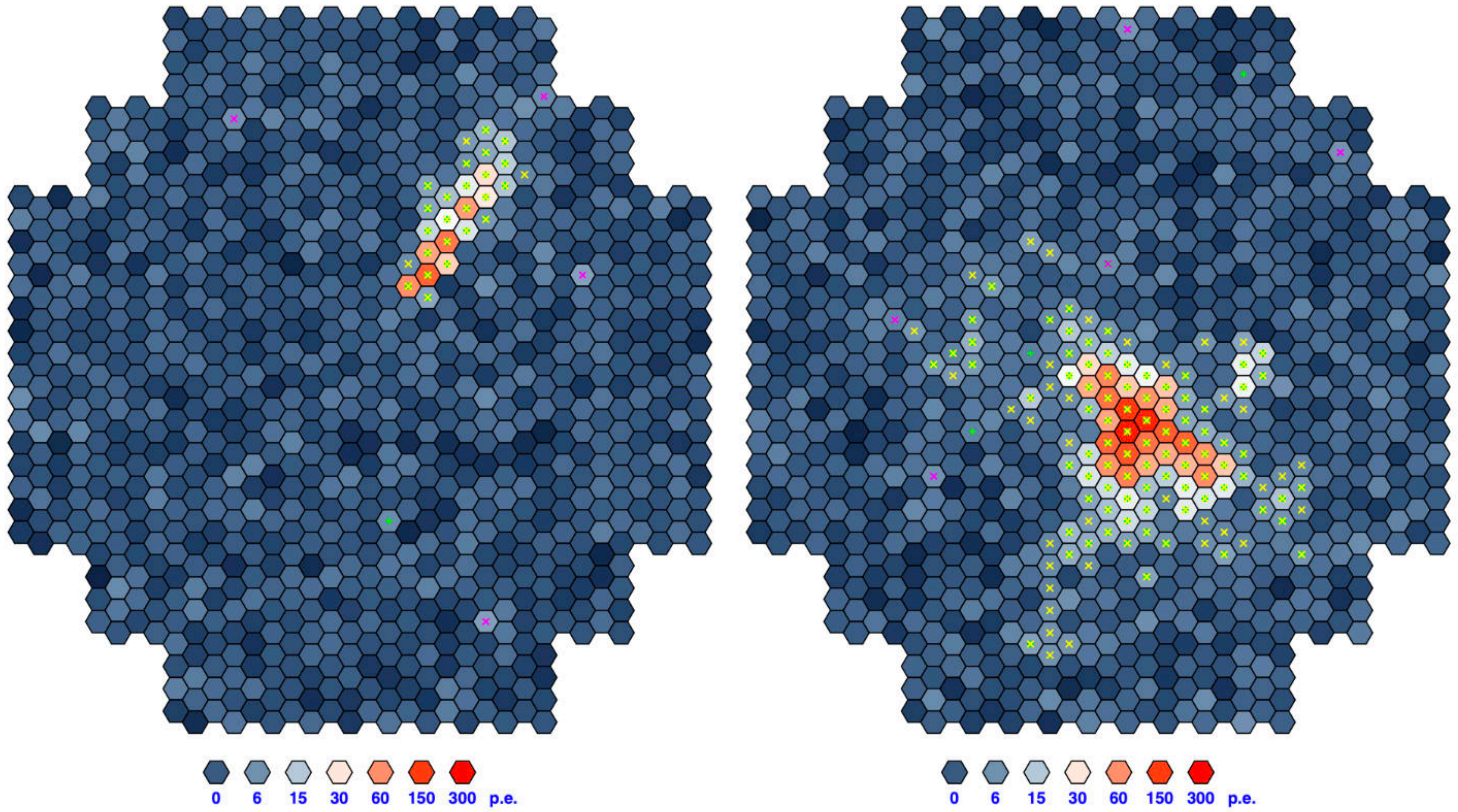
We have calibrated and filtered pixel-wise time-series in p.e. for each telescope

→ Now image extraction: transition to DL1

DL0 data processing

Image cleaning

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



1.0 TeV gamma shower 2.6 TeV proton shower

- 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

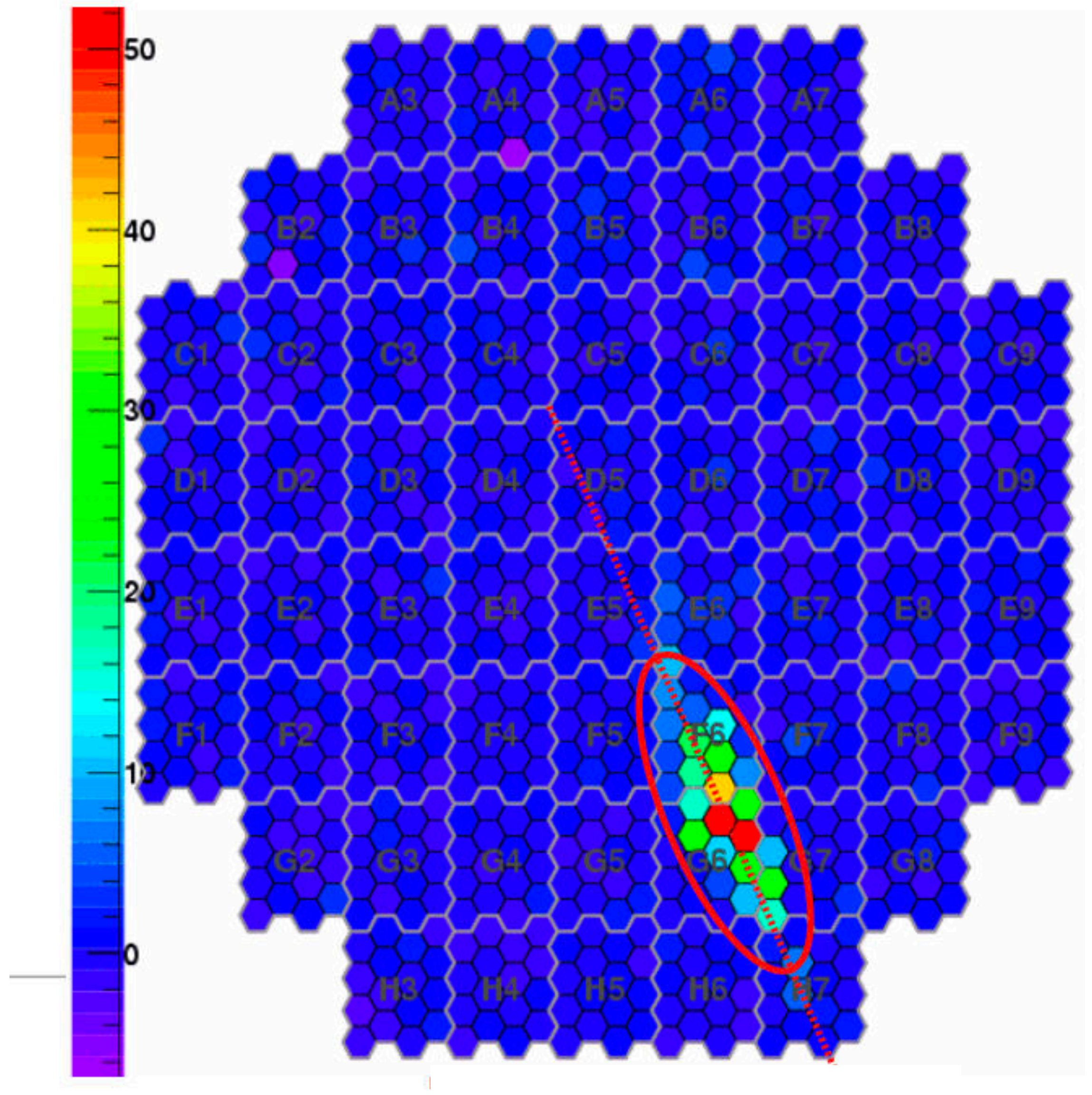
Cleaning algorithm profits from:

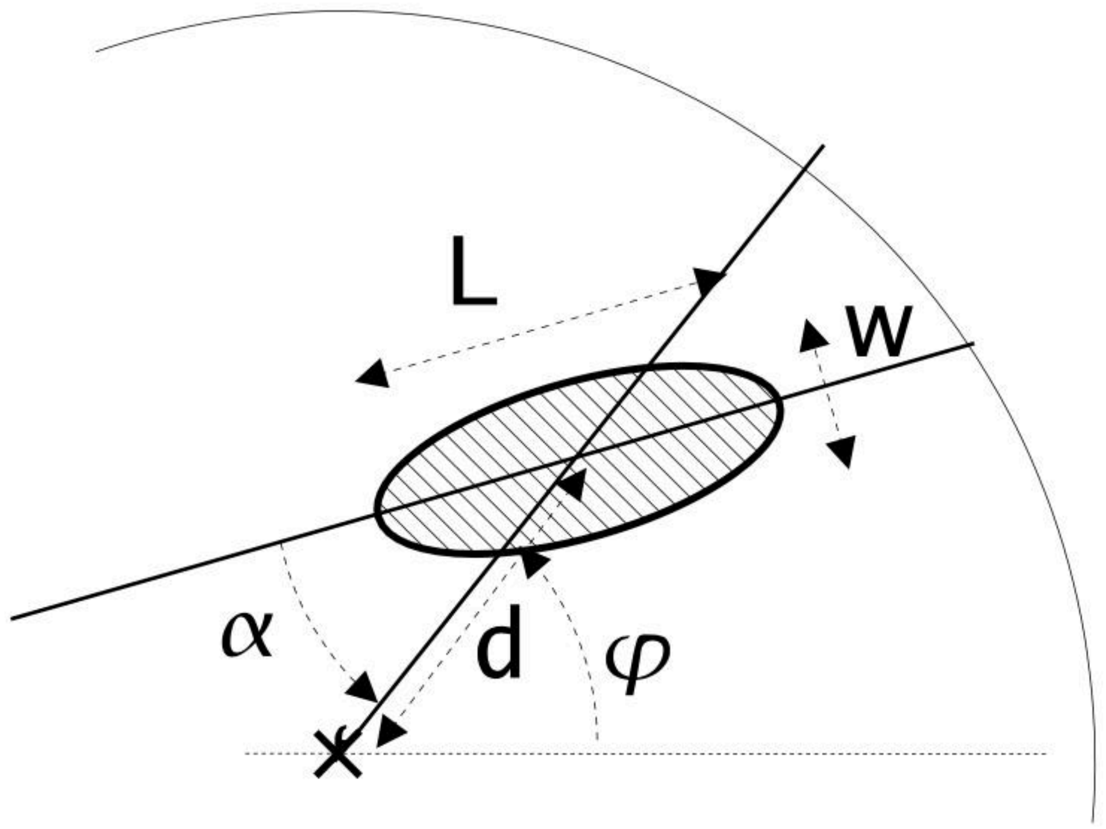
- Shower signal stick out from NSB (more of high energies)
- Shower signals are bundled in neighboring pixels
- Shower signals have time structure

DL0 data processing

Hillas parameters

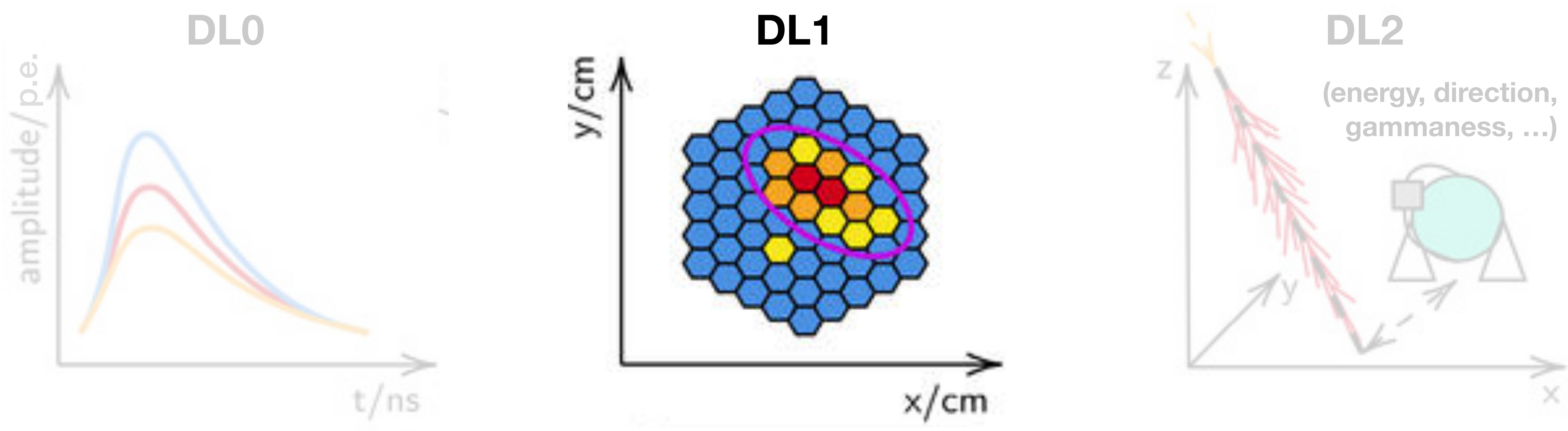
- Images of gamma rays are elongated ellipses
- Hillas parameters = analytical representation of the image as a 2D Gaussian:
  - Width (***W***) and length (***L***)
  - Total image amplitude = total number of photoelectrons (***size*** or ***intensity***)
  - Nominal distance ***d*** between the centre 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!

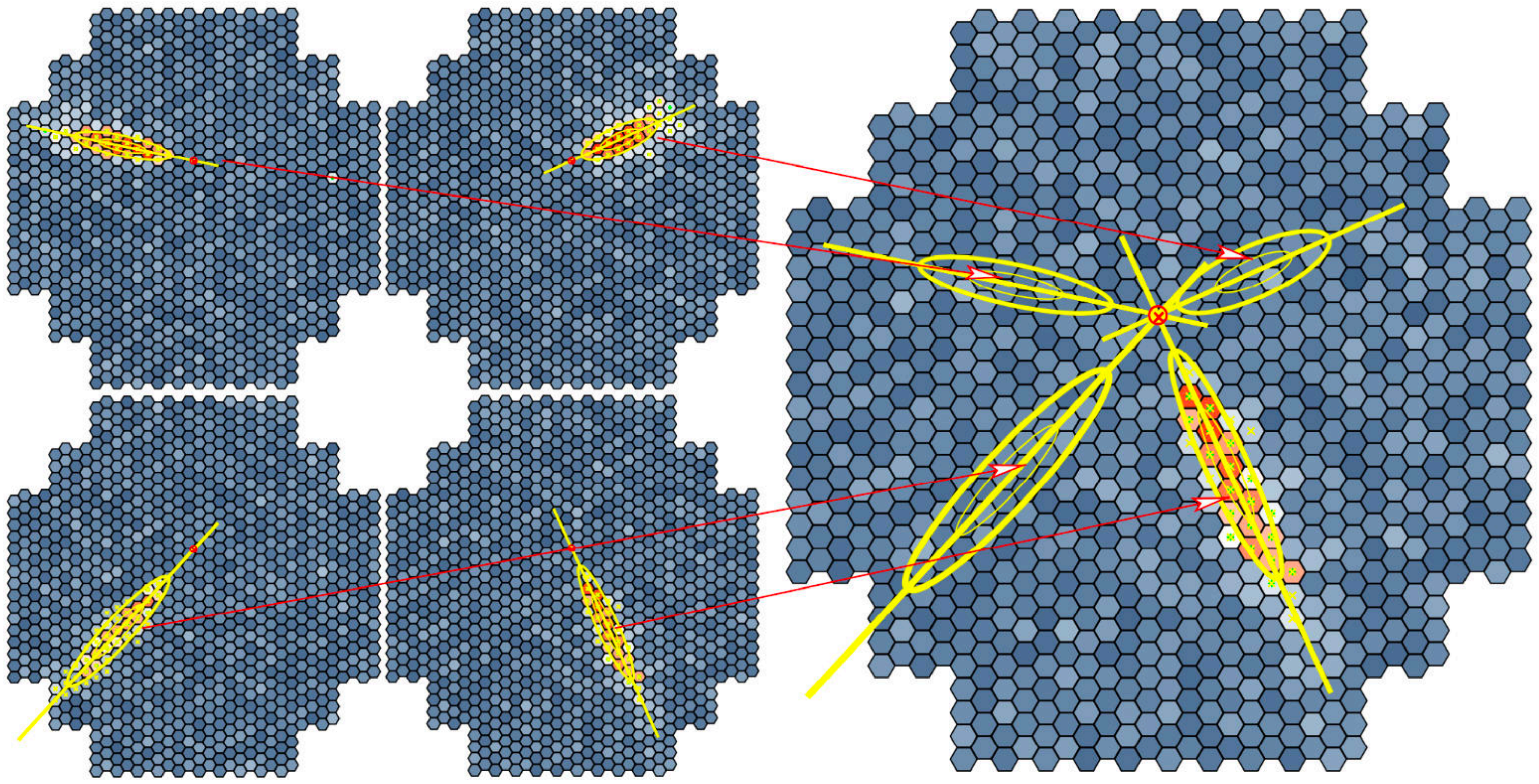


We have images and they are cleaned and parameterized

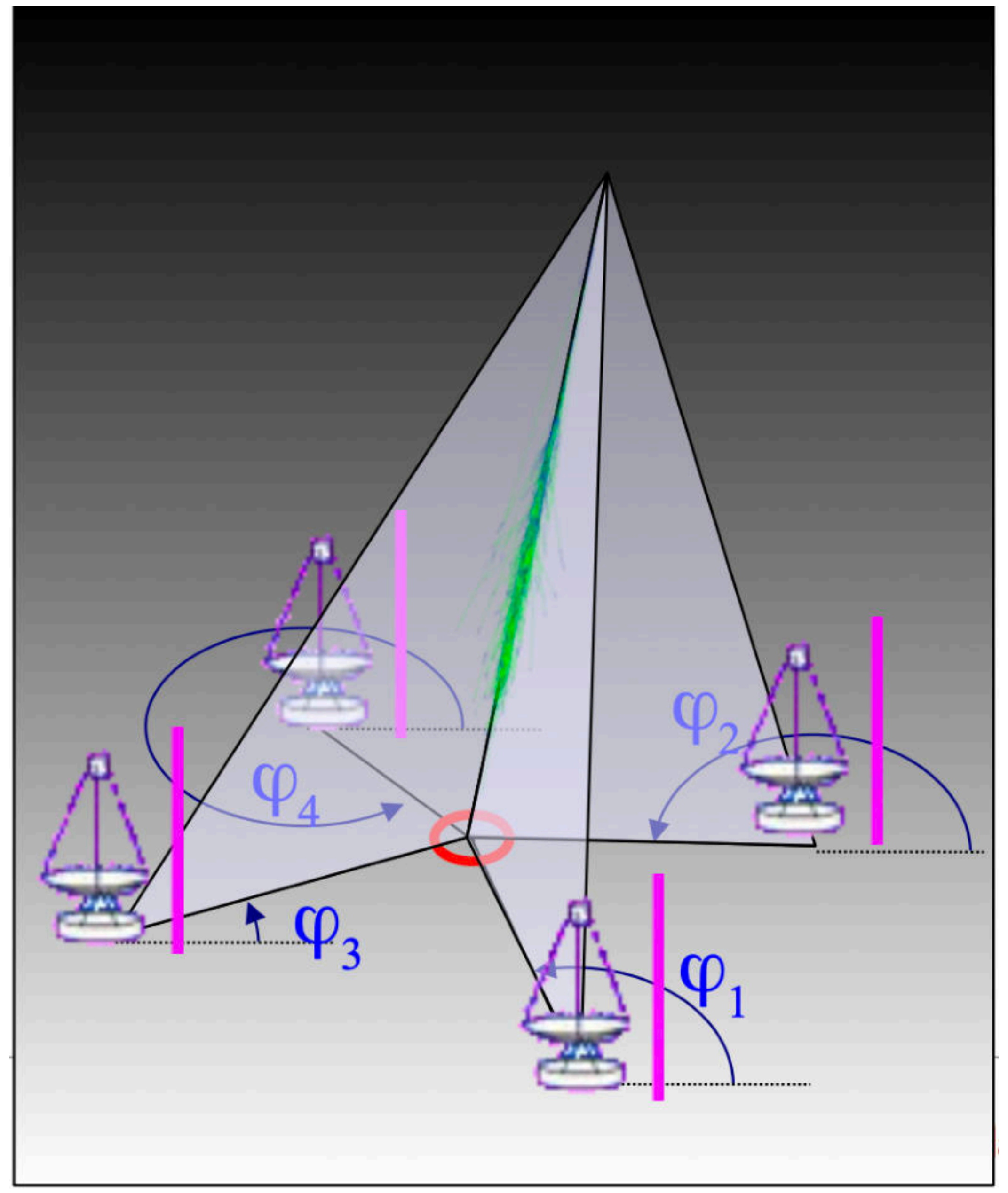
→ transition to DL2

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 ≈ 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)

- As a gamma-ray observatory, for almost all science cases we can simplify to binary classification:

Signal, gamma rays ⇔ background, everything else

- 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 for signal and background:
  - Signal is almost always taken from simulated gamma-ray events
  - Background can either be simulations as well or taken from observations of “dark spots”

Stereoscopic reconstruction

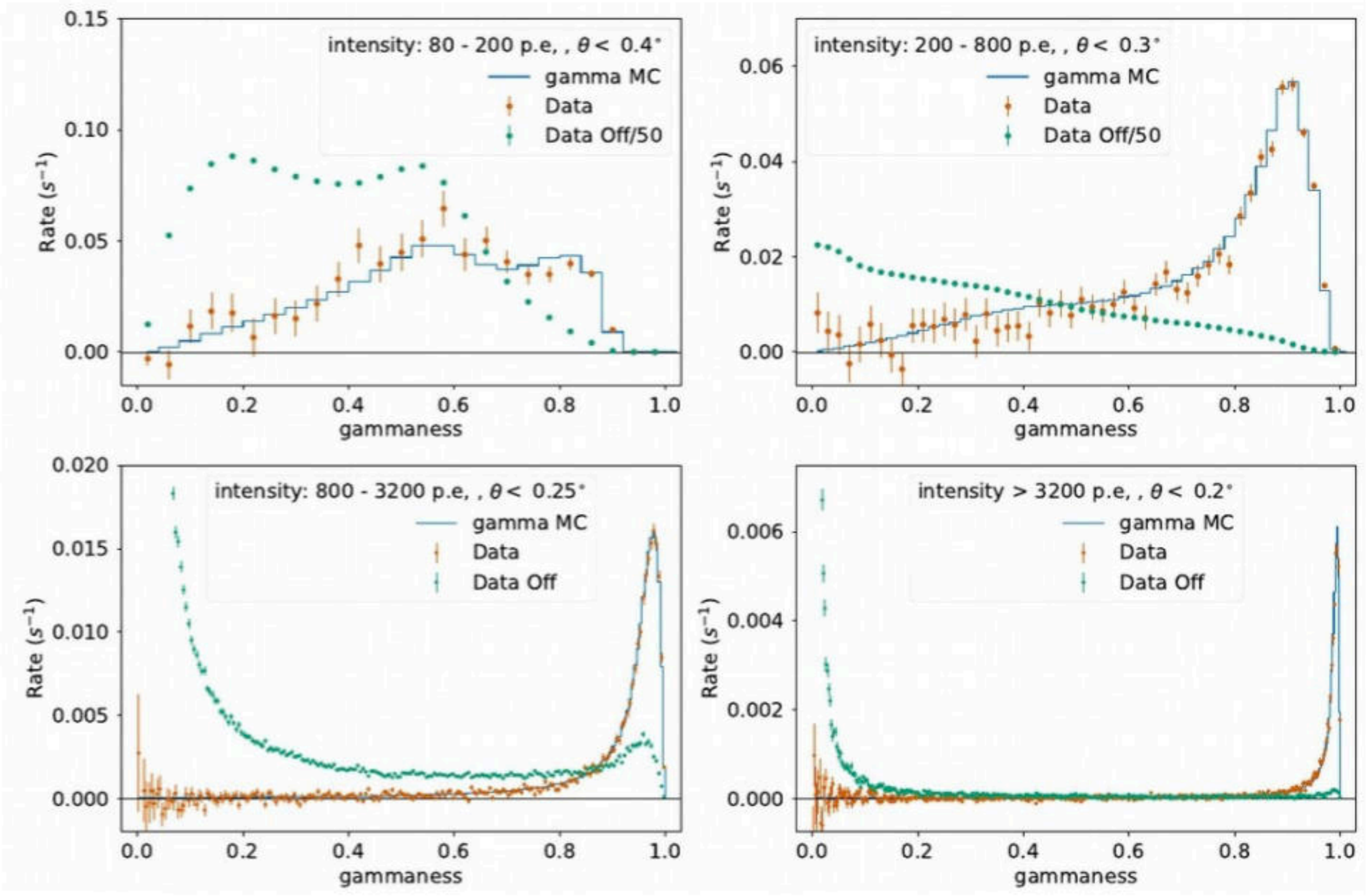
Gammaness

- 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

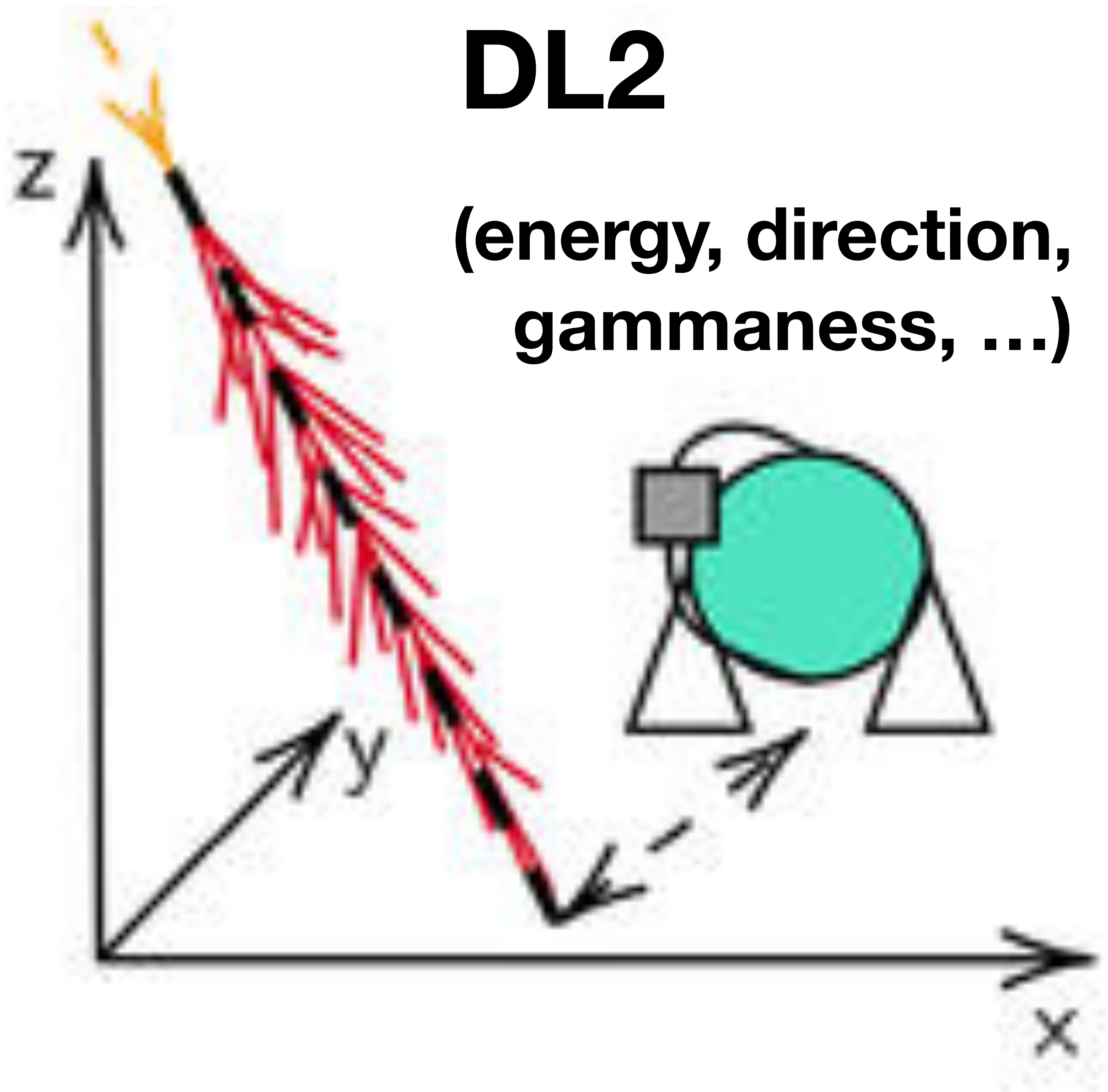
We are now at DL2!

DL0

DL1

DL2

(energy, direction, gammaness, ...)

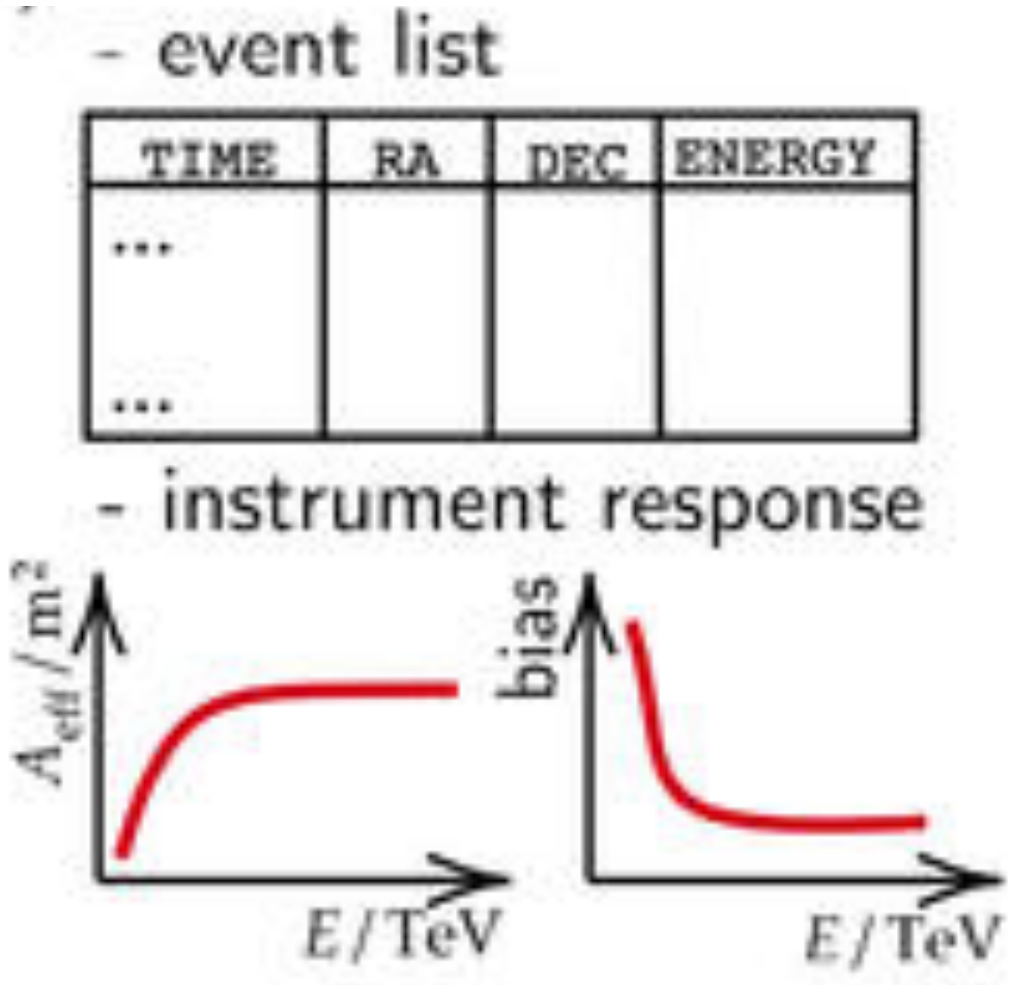


Data reconstruction of the intrinsic gamma-ray event parameters: energy, direction and gammaness

What is next?

You already know everything about this after Jonathan's talk!

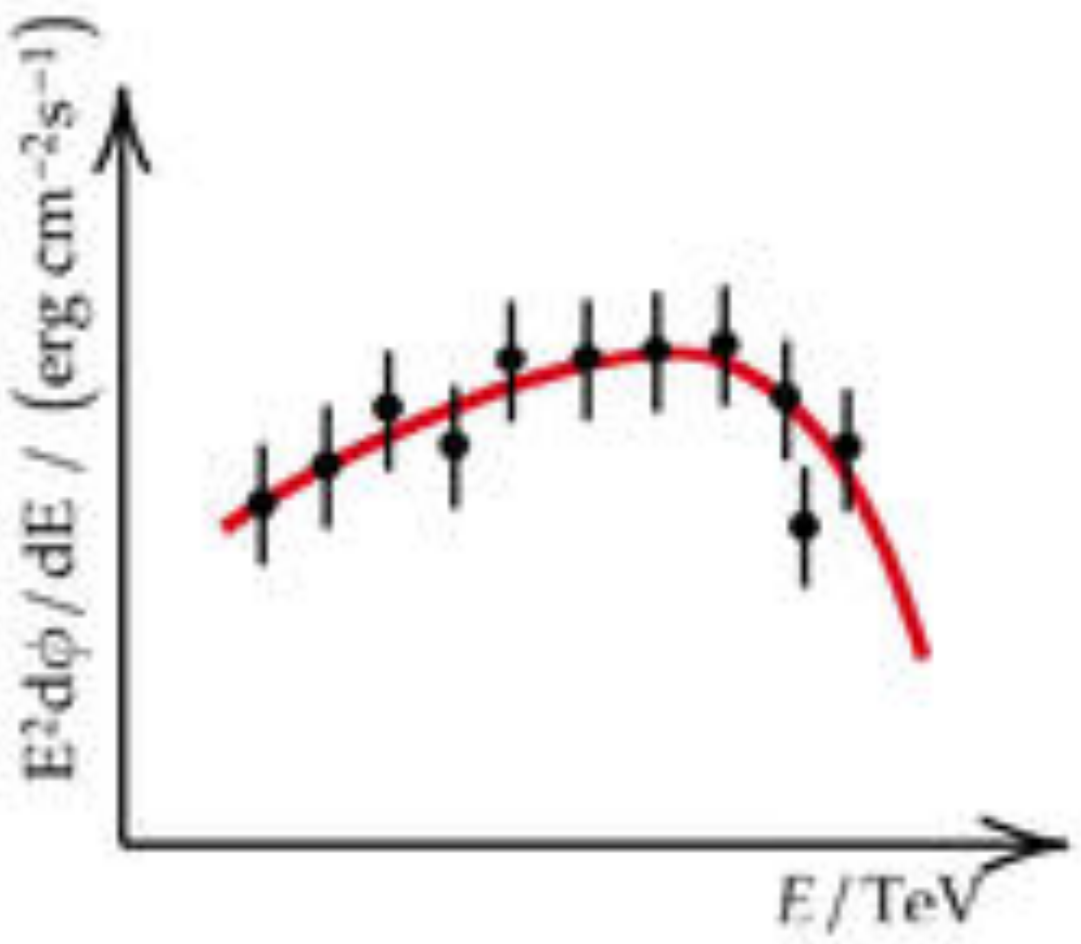
DL3



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

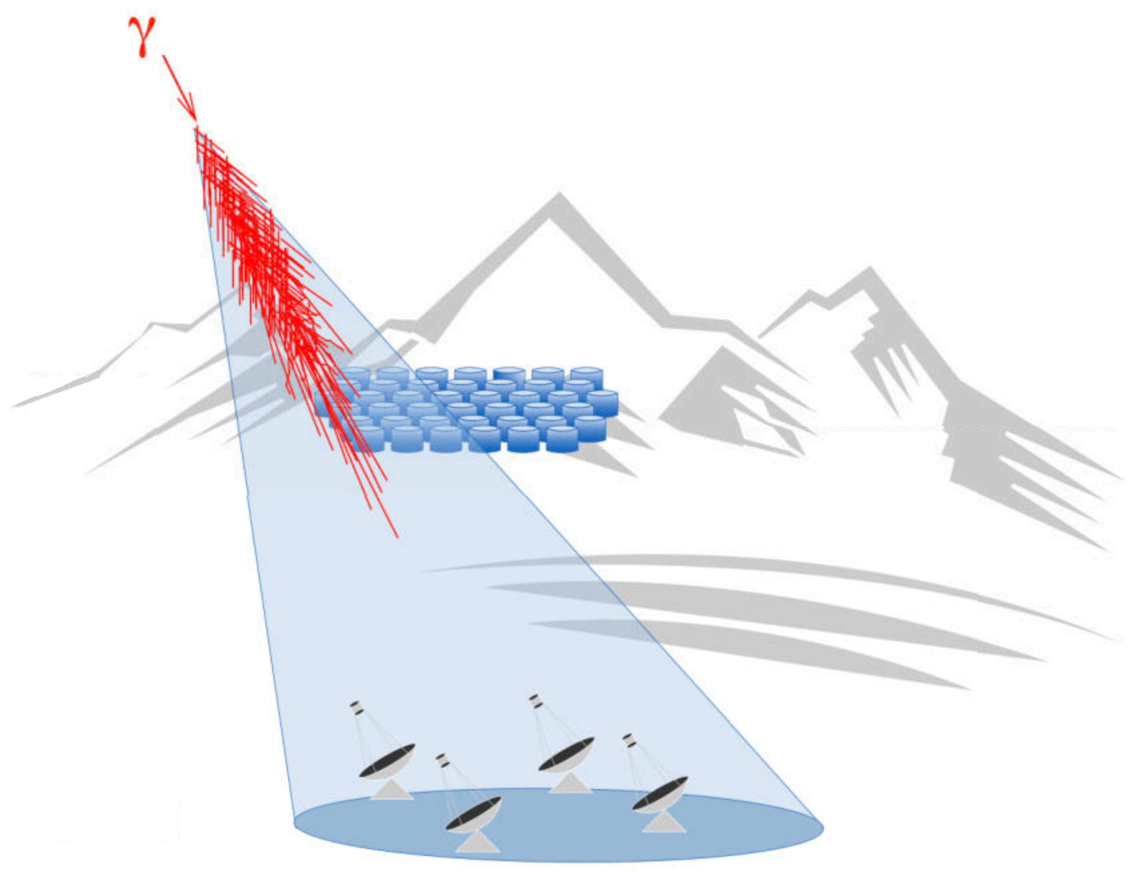
DL4



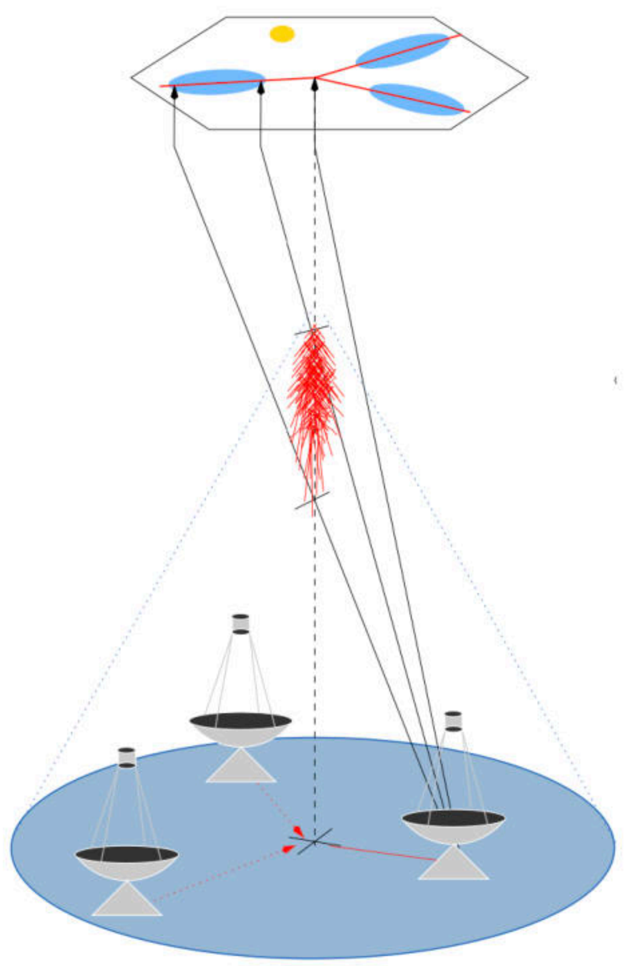
High-level science data products

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

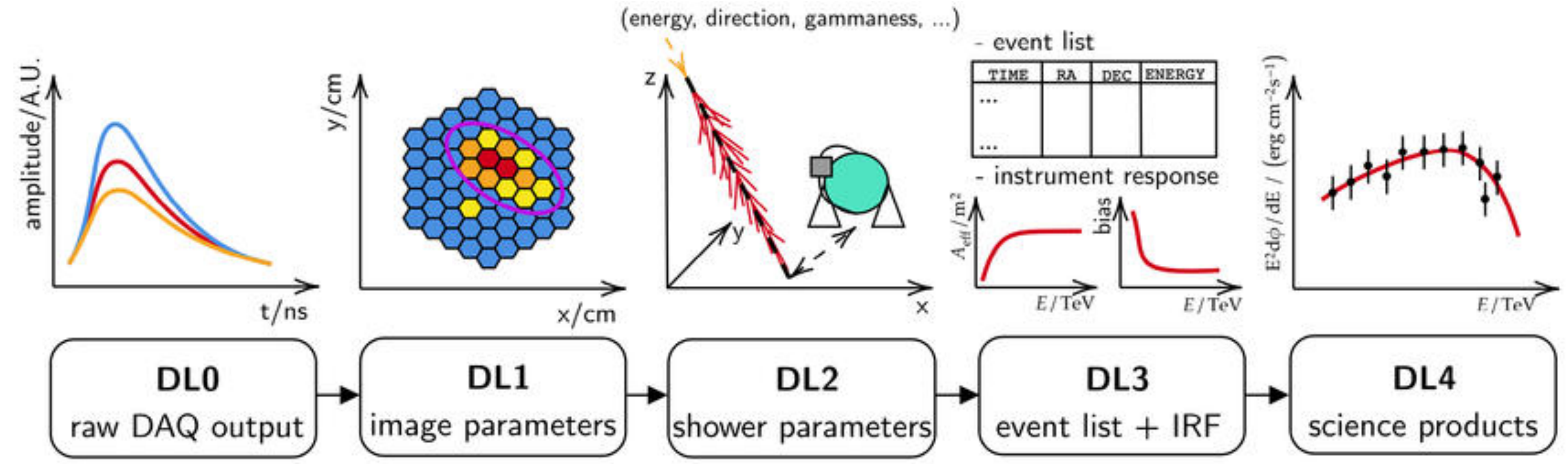
Take home messages



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 → single telescope reconstruction → stereoscopic reconstruction