

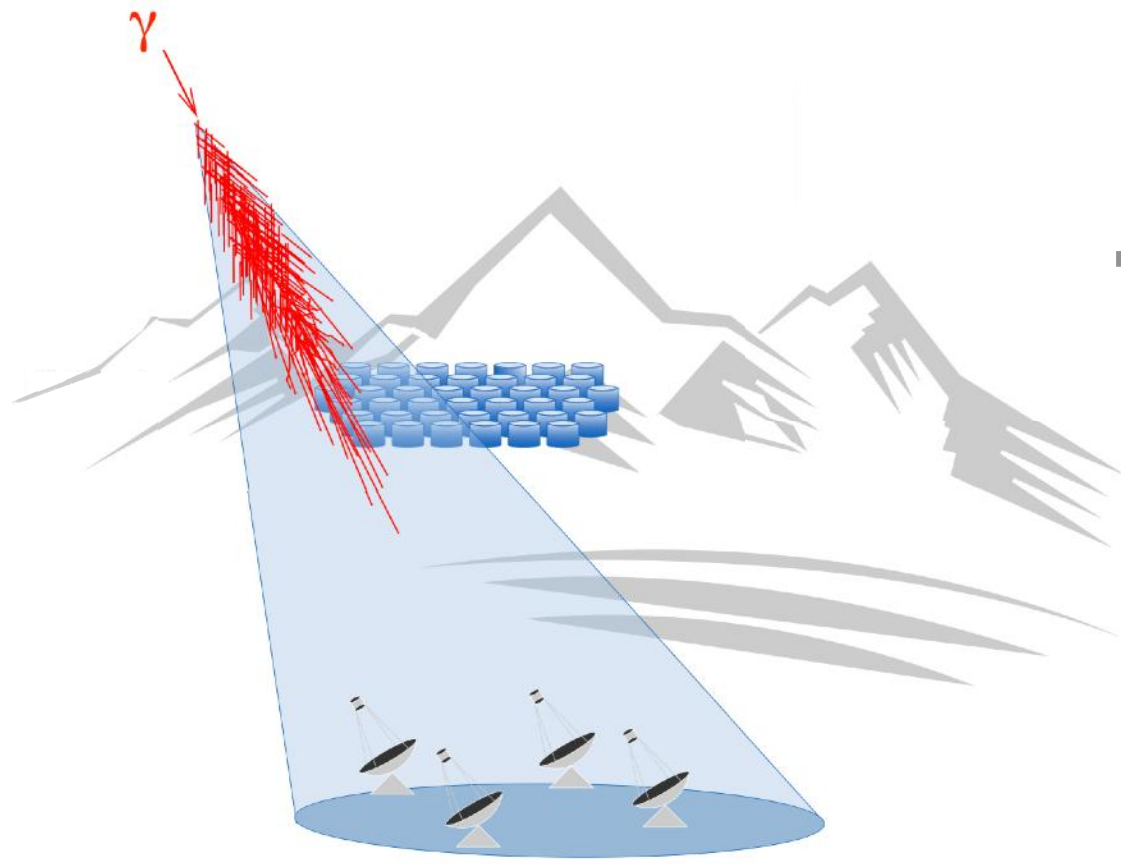
A stylized, colorful illustration of a night cityscape. The background is a dark blue sky filled with small white stars. Numerous windows of various shapes and sizes are scattered across the scene, each glowing with a different color (yellow, orange, green, purple, pink) and showing silhouettes of people or objects inside. A large, bright green beam of light, composed of several parallel lines, originates from the bottom left and extends diagonally towards the top right, passing behind the main title. The overall style is reminiscent of a children's book illustration or a digital art piece.

Ground-Based Gamma Ray Detection

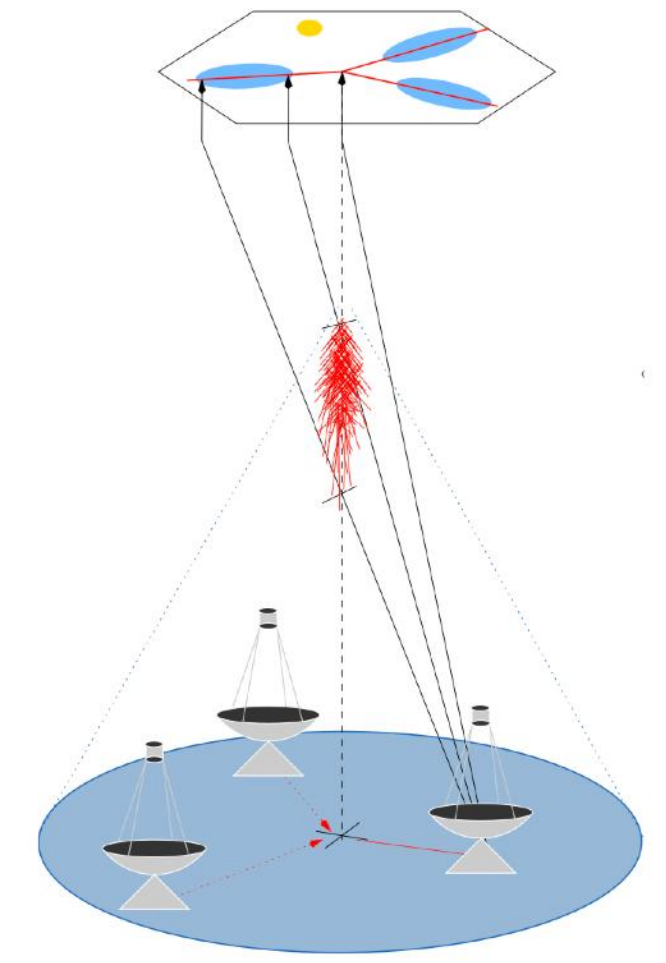
Federica Bradascio (IJCLab, Université Paris-Saclay)
ISAPP School - June 2026

Outline

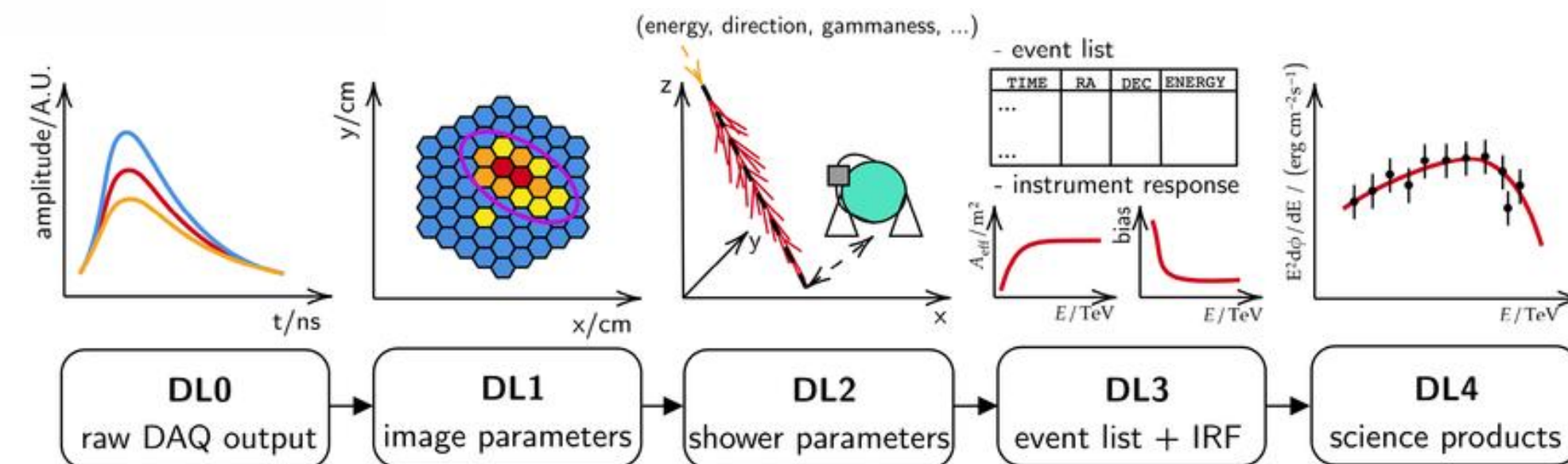
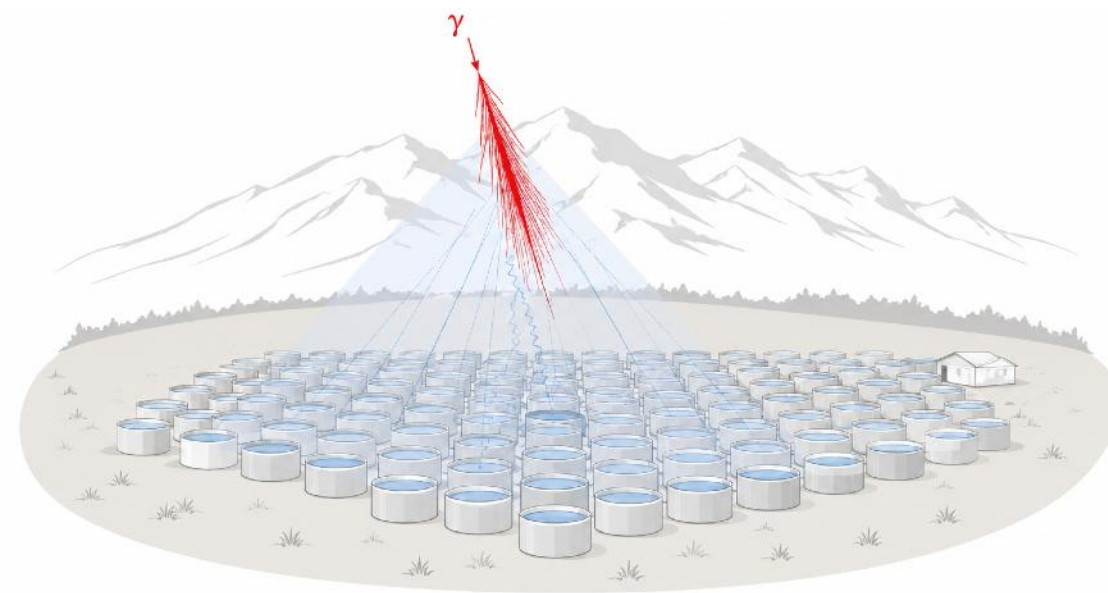
1. EAS: from sources to telescopes



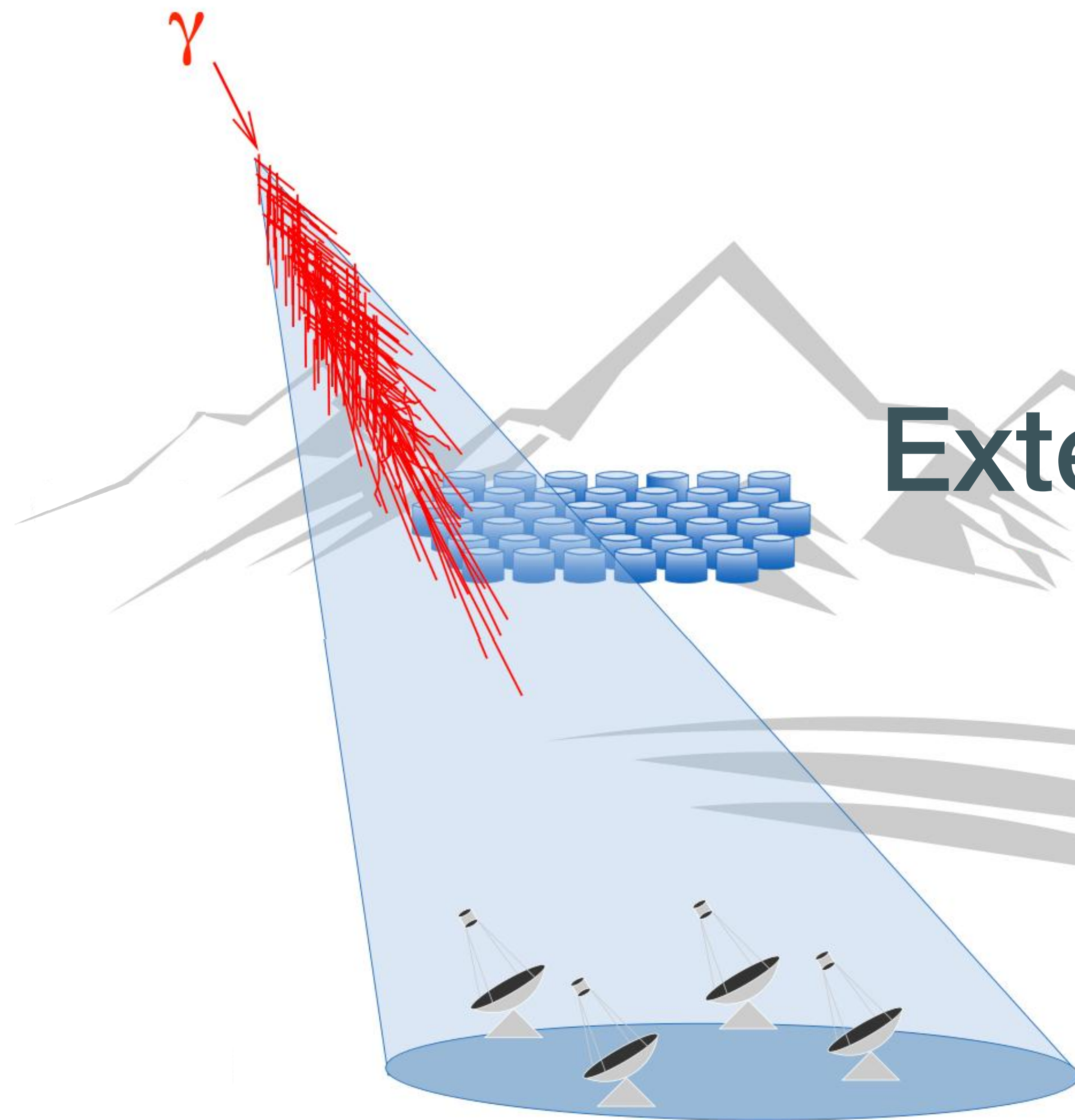
2. IACTs: detection principles



3. WCDs: detection principles



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



Extensive Air Showers: from sources to telescopes

Gamma-rays astrophysics

What are gamma-rays 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)
- Ultra-High-Energy (UHE) Gamma Rays (≥ 100 TeV)

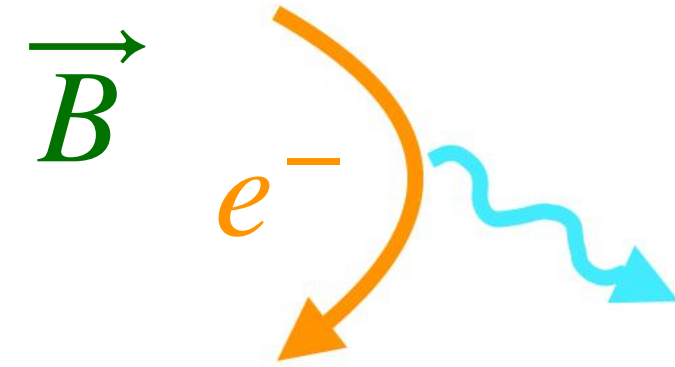
ASTROPHYSICAL GAMMA RAYS:

- 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

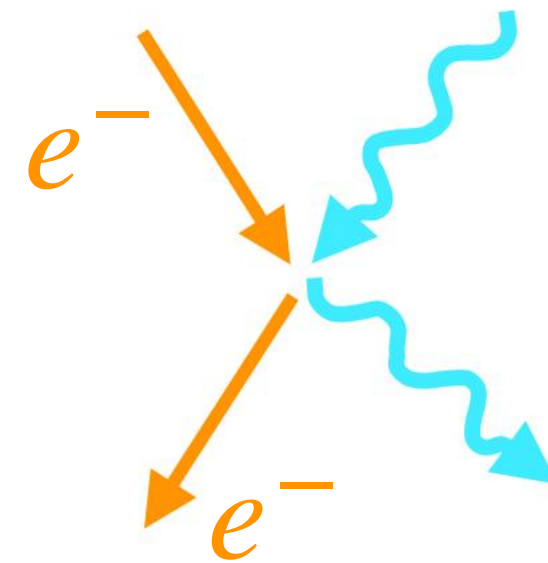
γ -rays: how are they produced?

γ rays show the sites of cosmic-ray acceleration

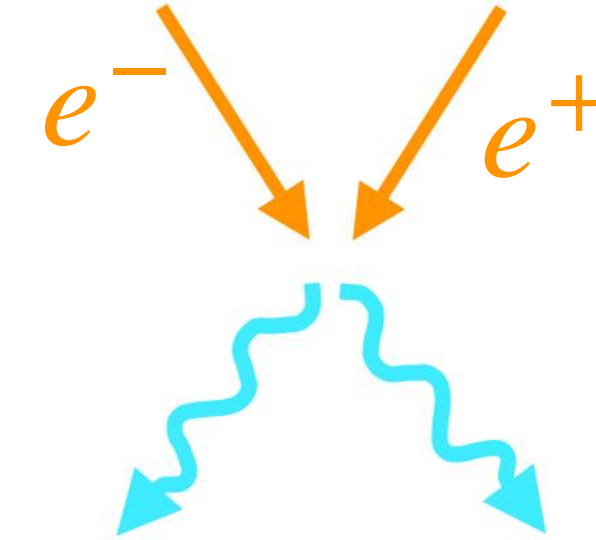
LEPTONIC PROCESSES



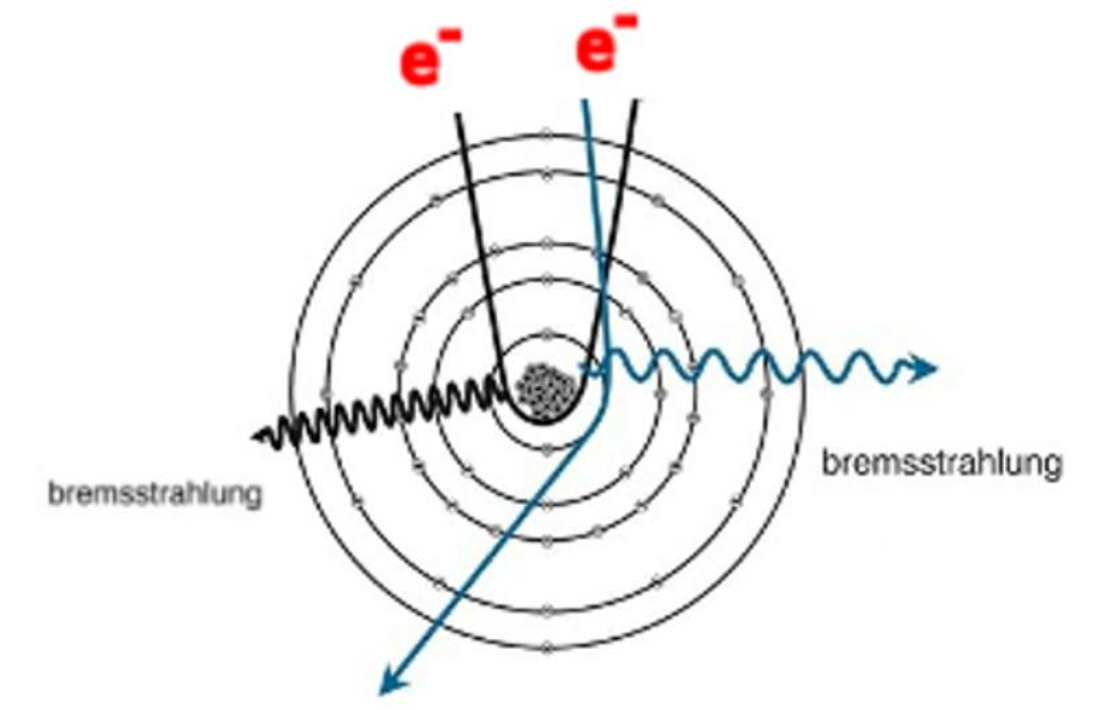
ELECTRON
SYNCHROTRON



INVERSE COMPTON
SCATTERING

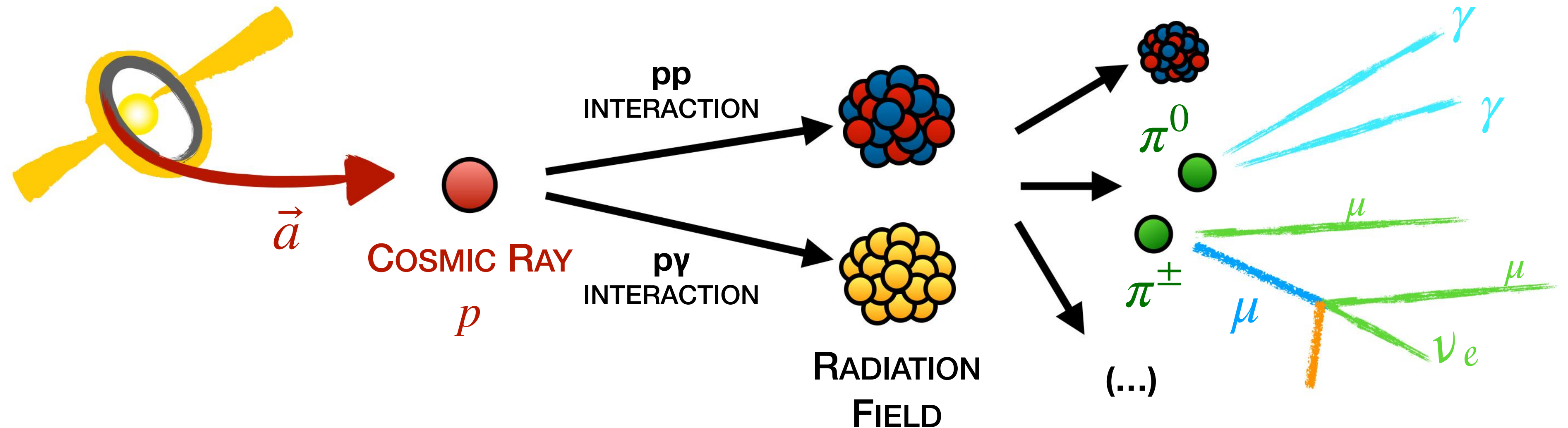


ELECTRON-POSITRON
ANNIHILATION



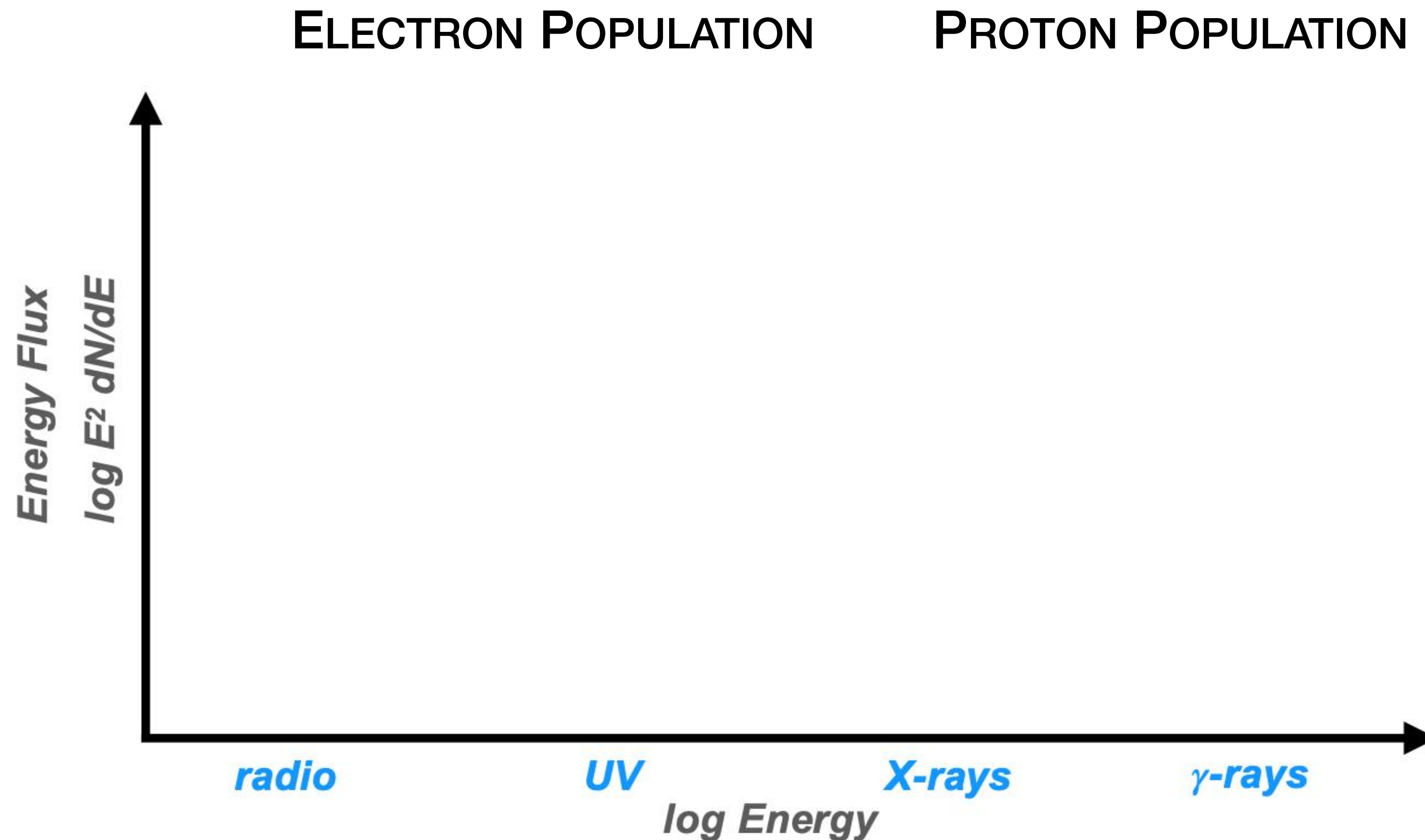
BREMSSTRAHLUNG

HADRONIC PROCESSES



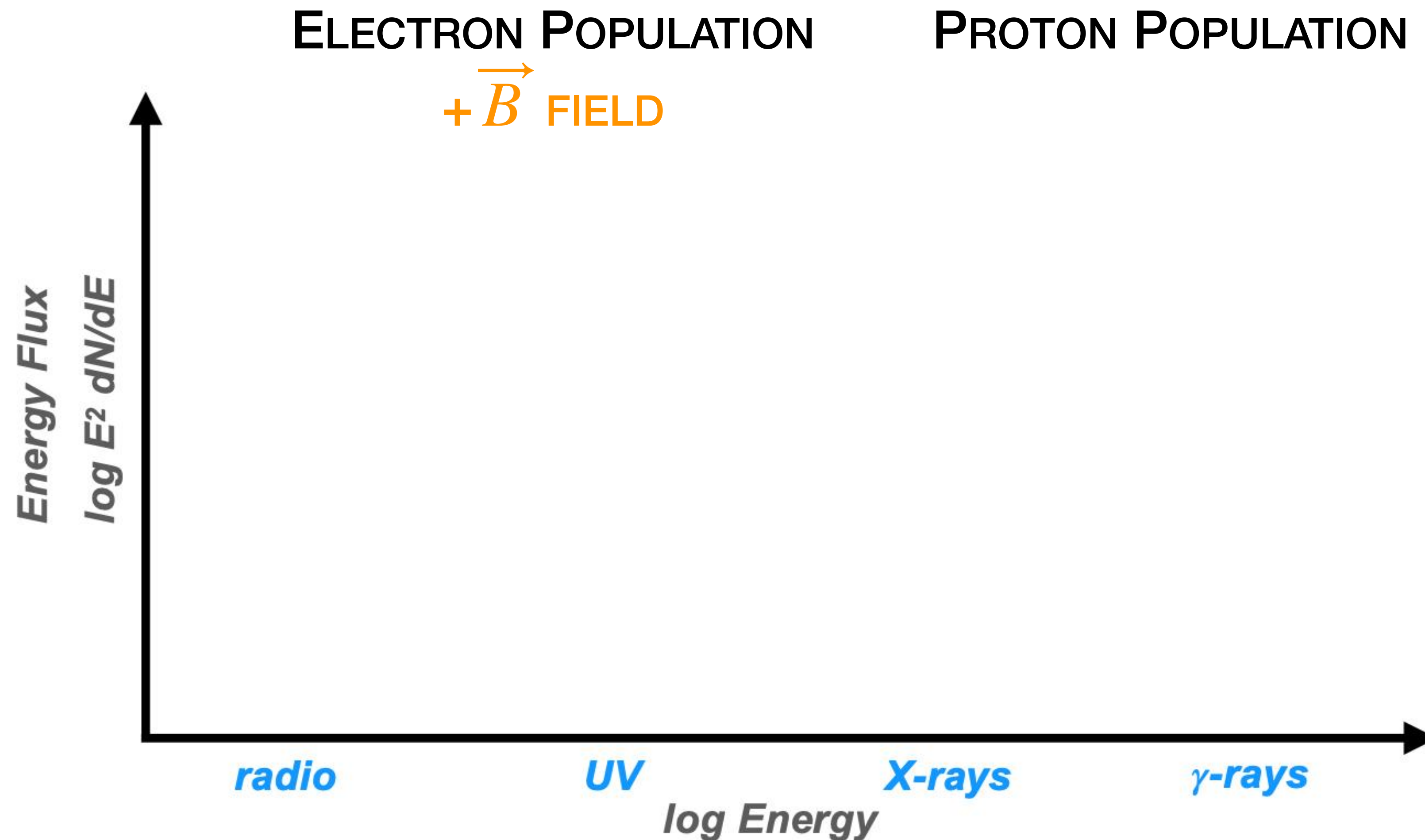
γ -rays: how are they produced?

Only produced by non-thermal processes



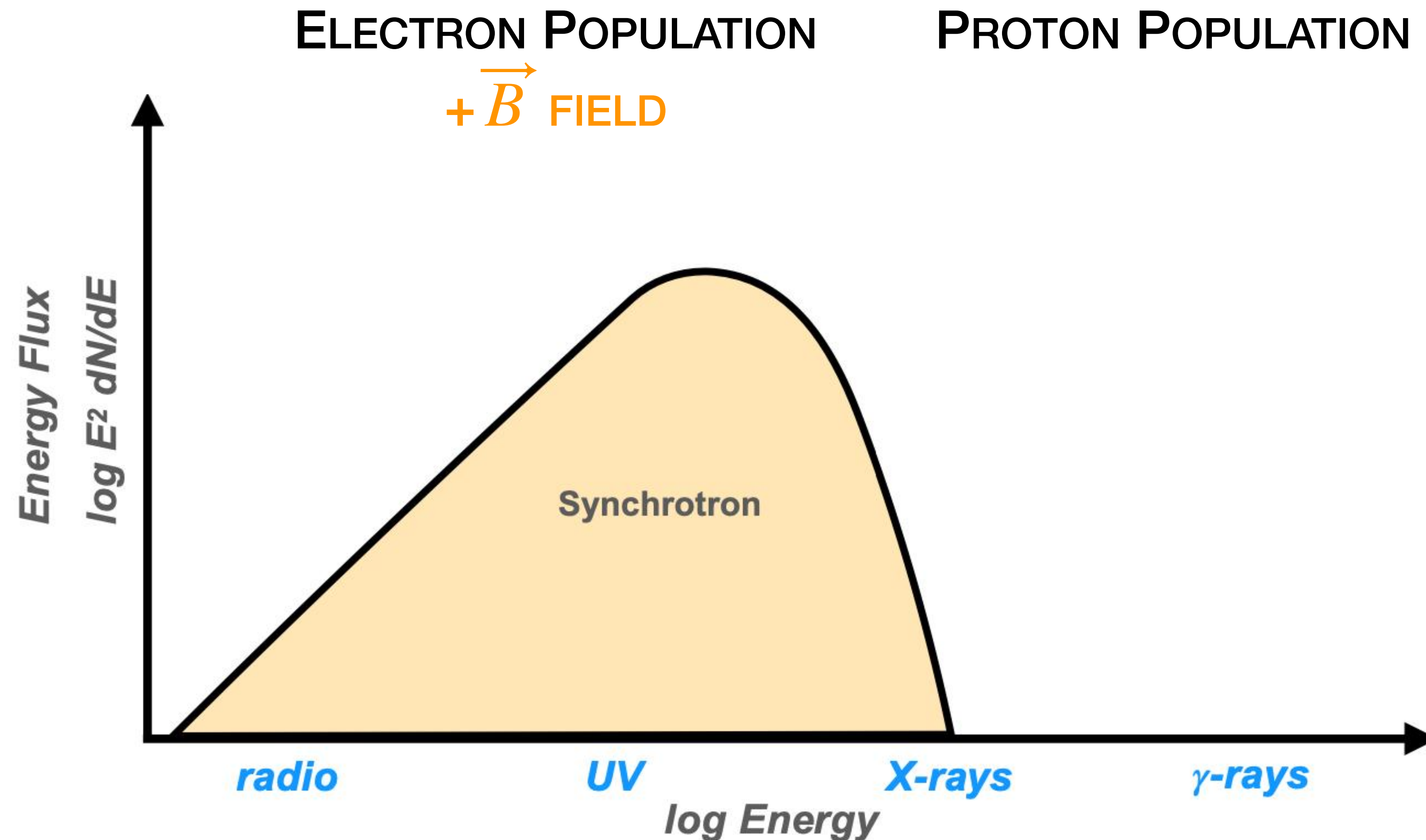
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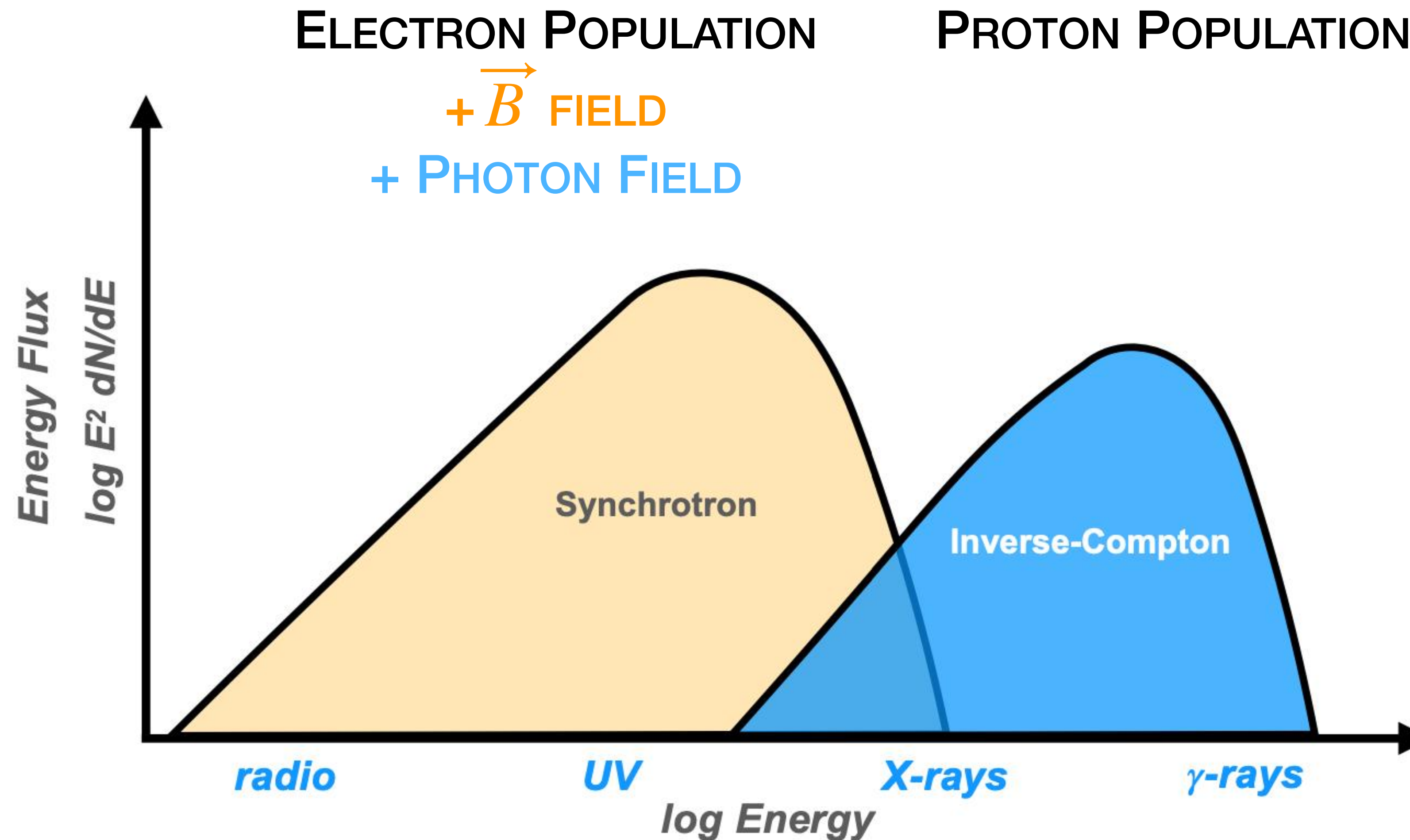
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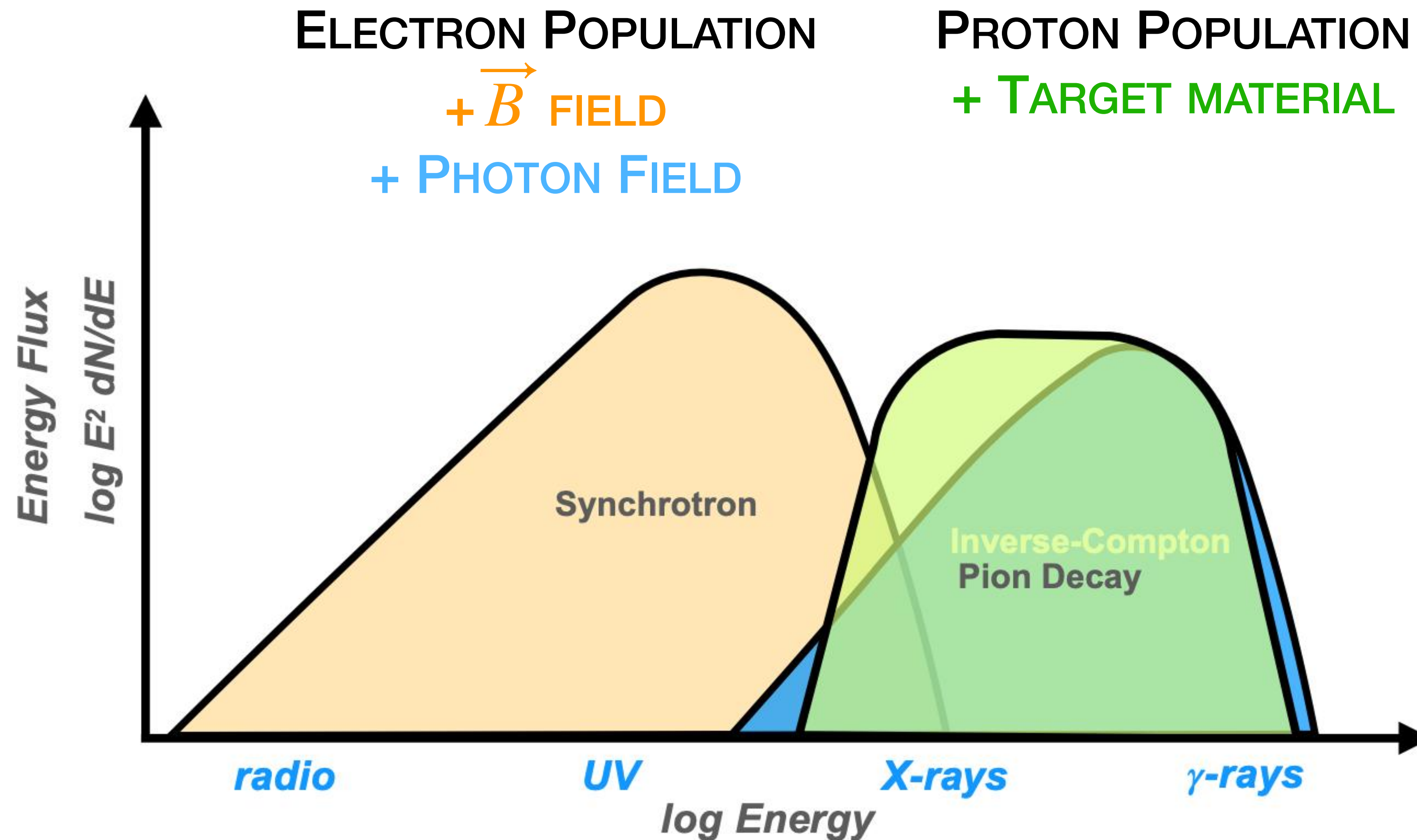
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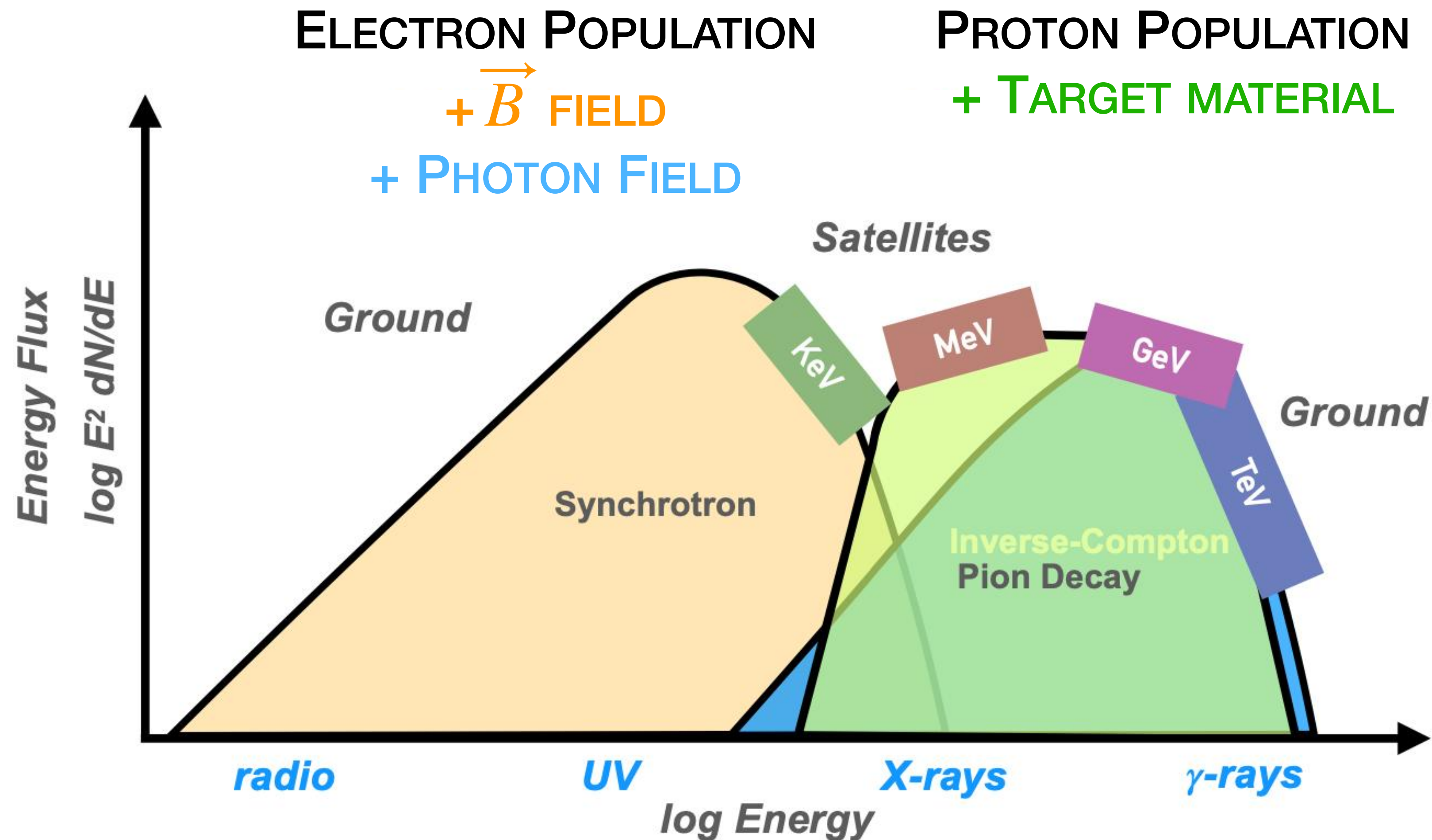
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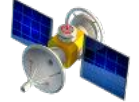
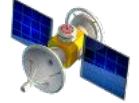


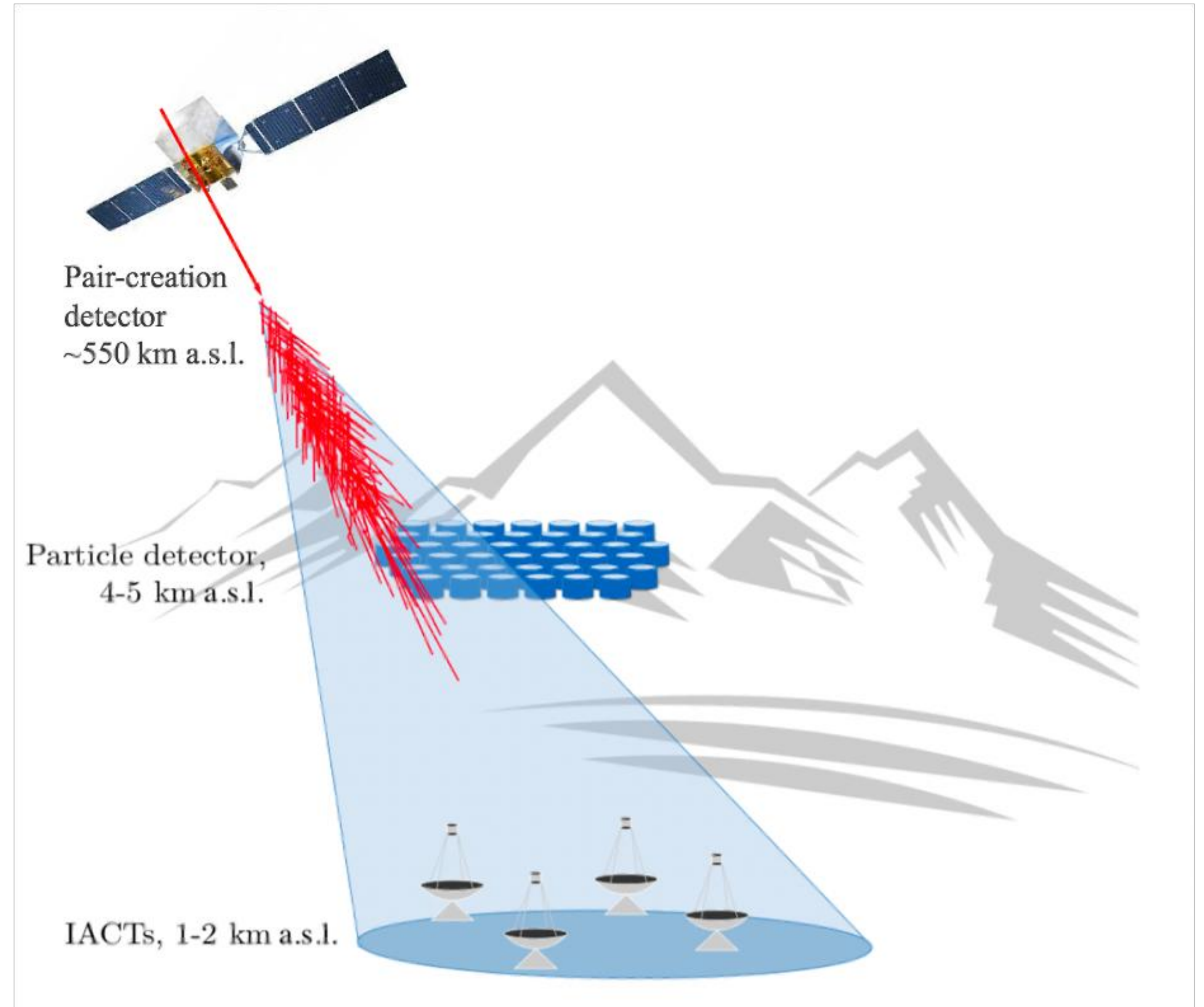
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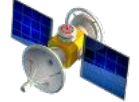
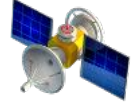


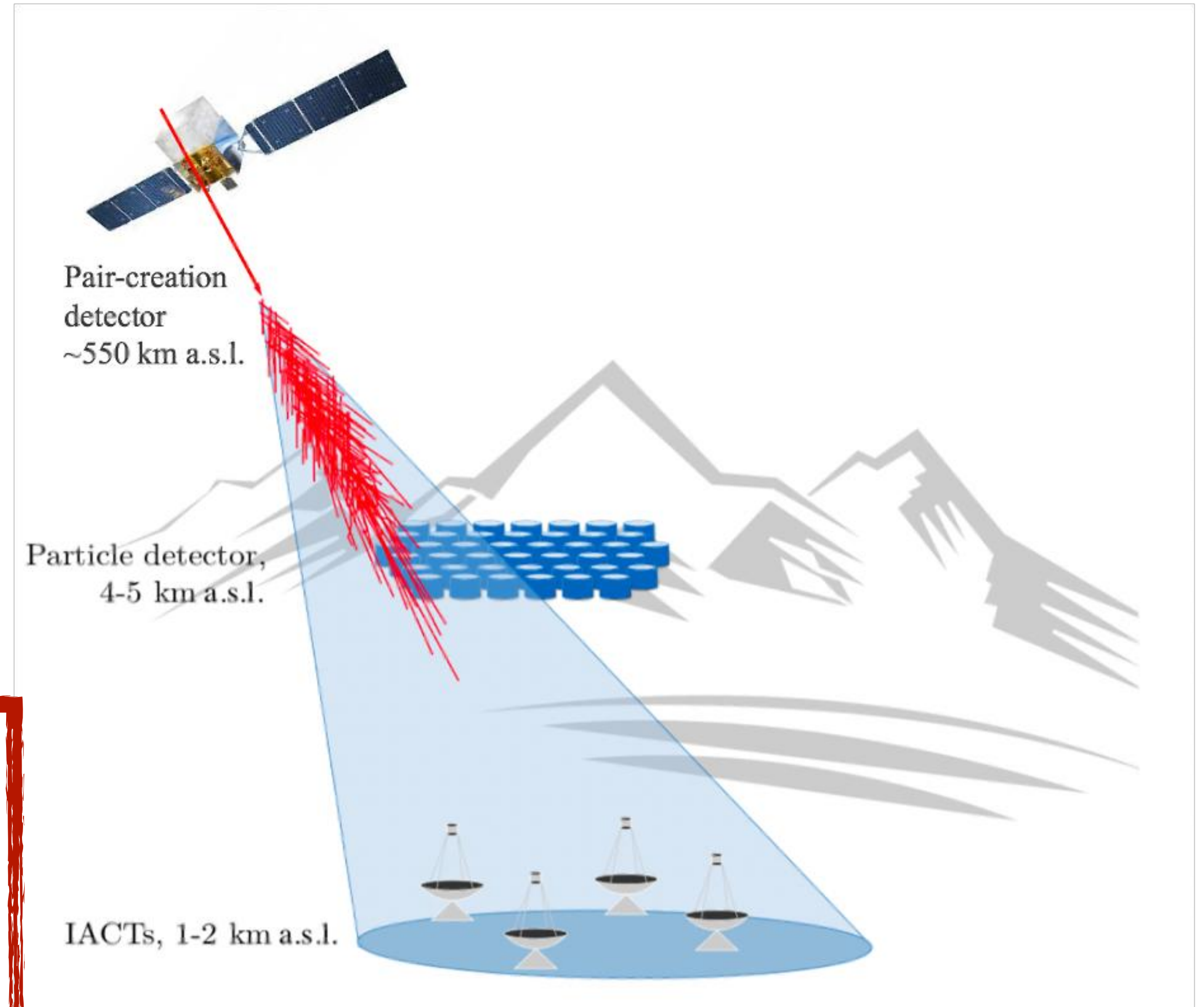
γ -rays: how to detect them?

- 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



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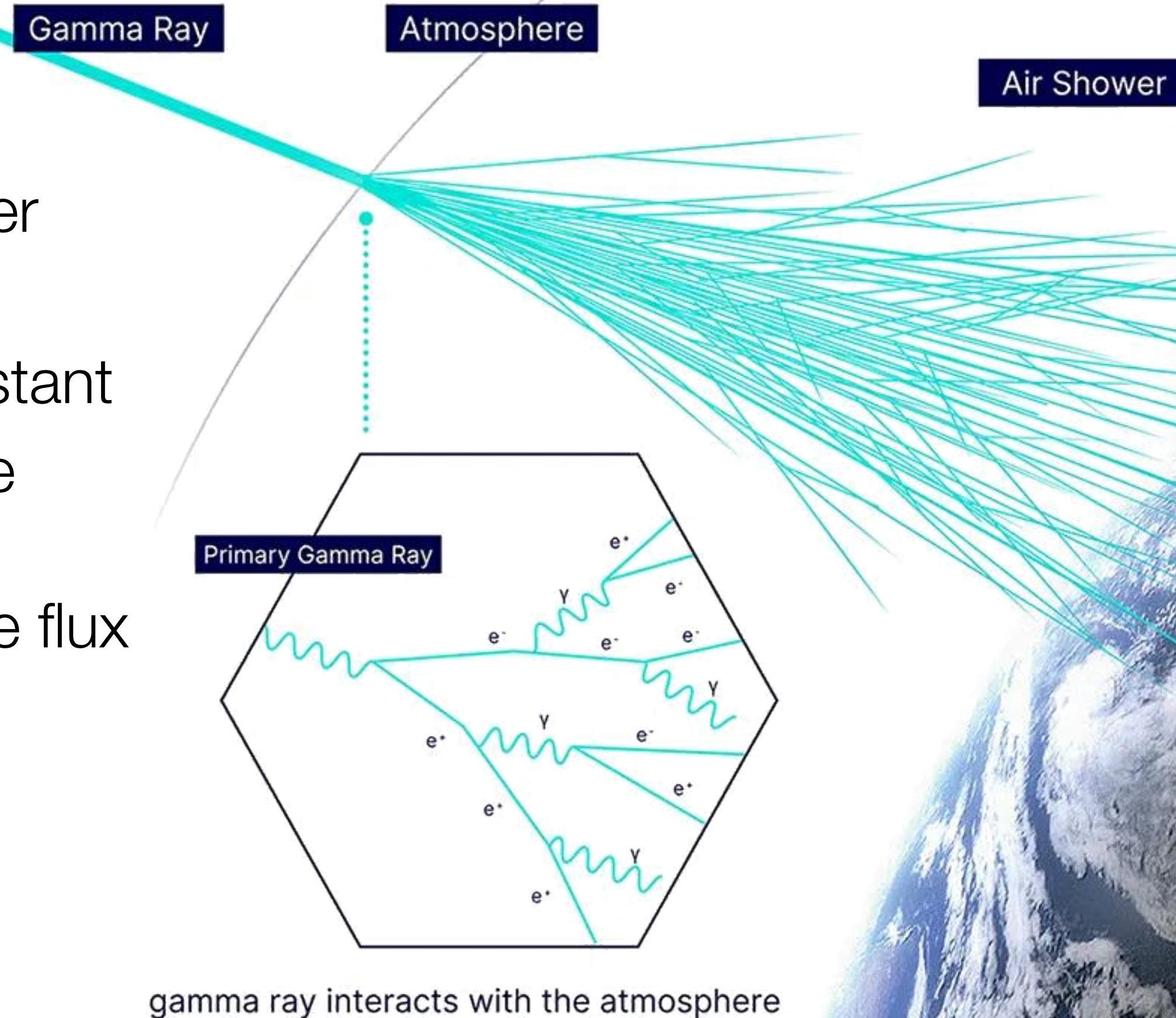


Extensive Air Showers

Interaction of primary particle in the high atmosphere

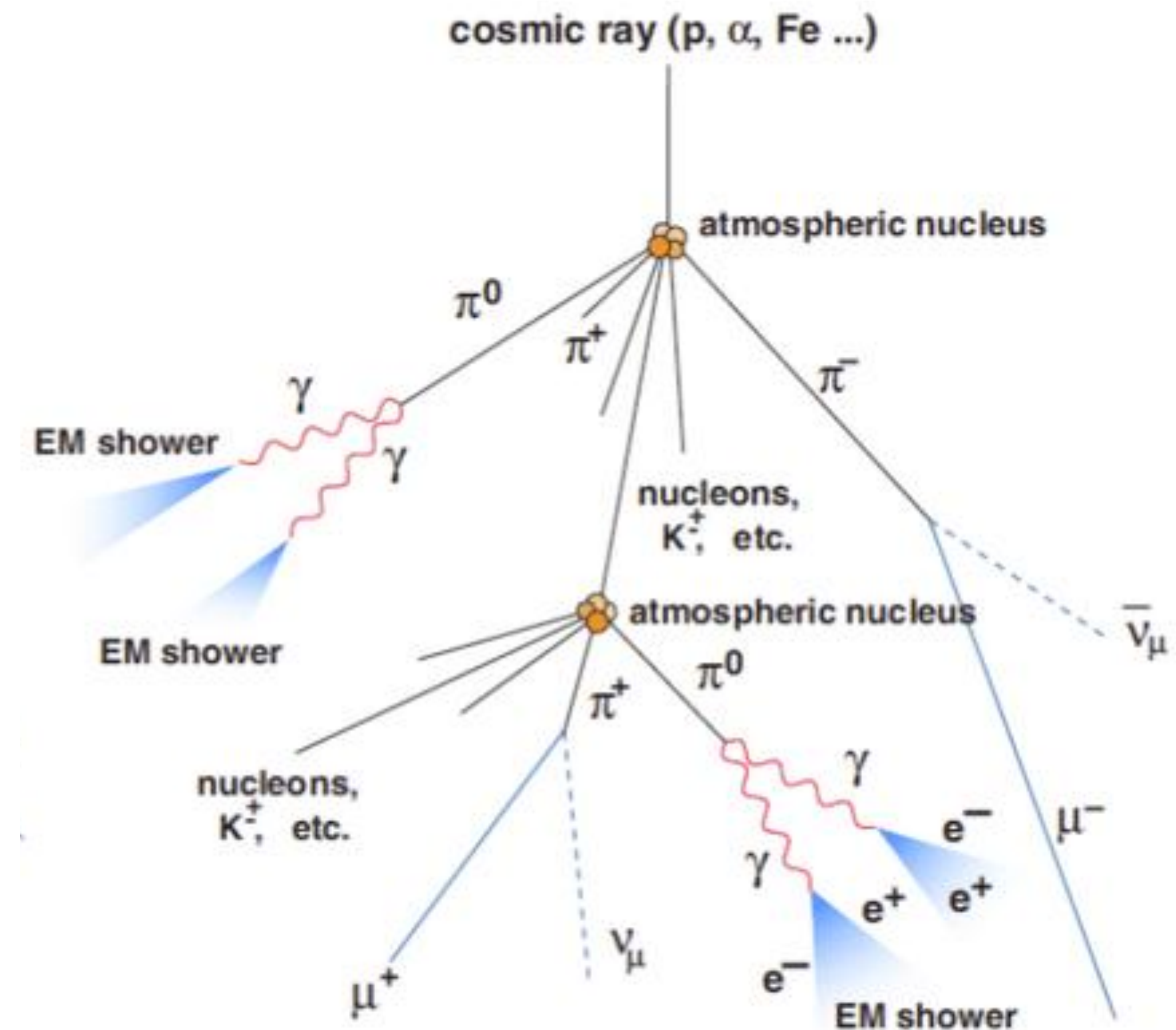
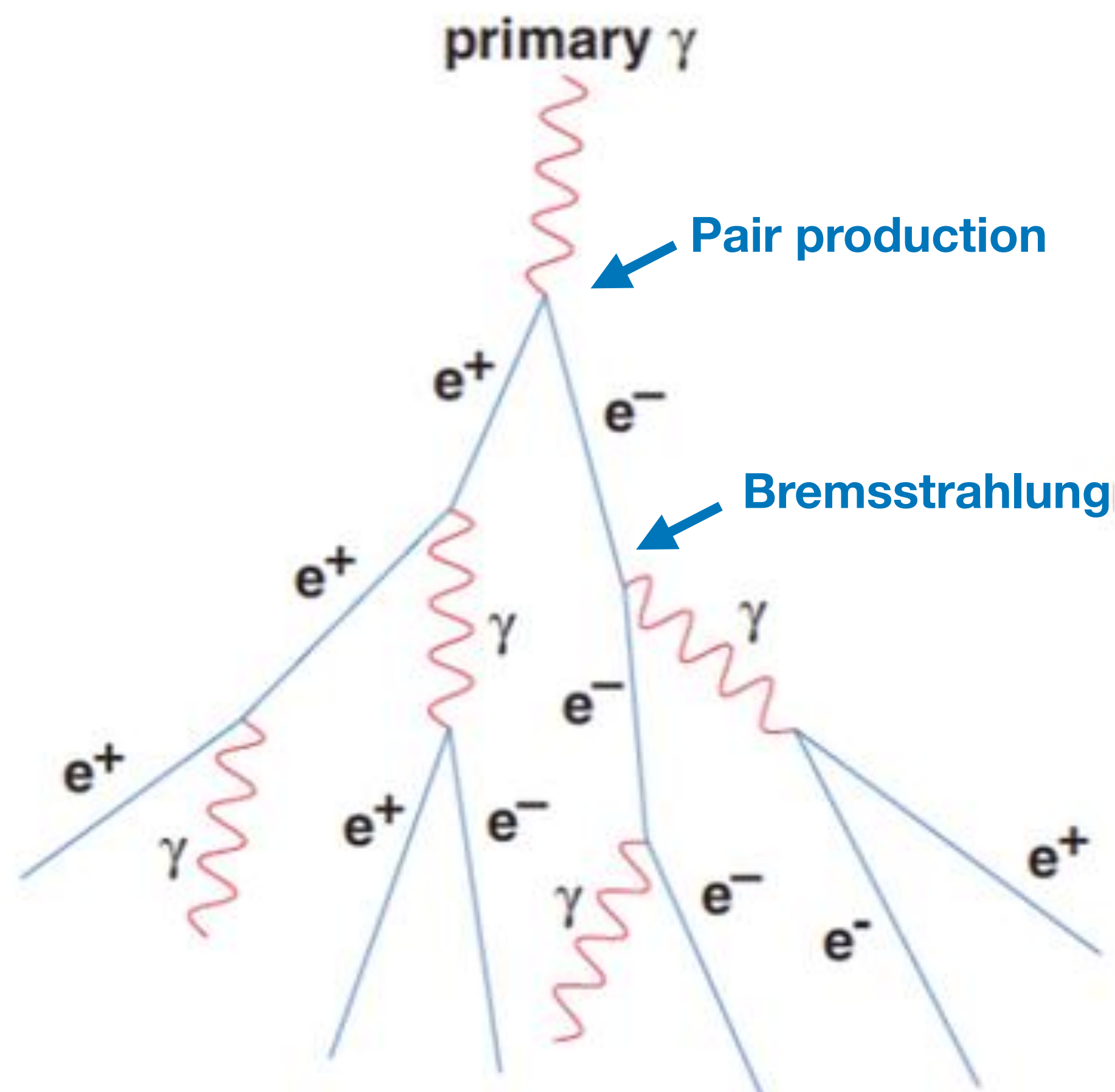
⇒ showers of secondary particles

- 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 (≥ 100 TeV) where flux is very low
- Cascades initiated by:
 - Photons
 - Charged particles



Extensive Air Showers

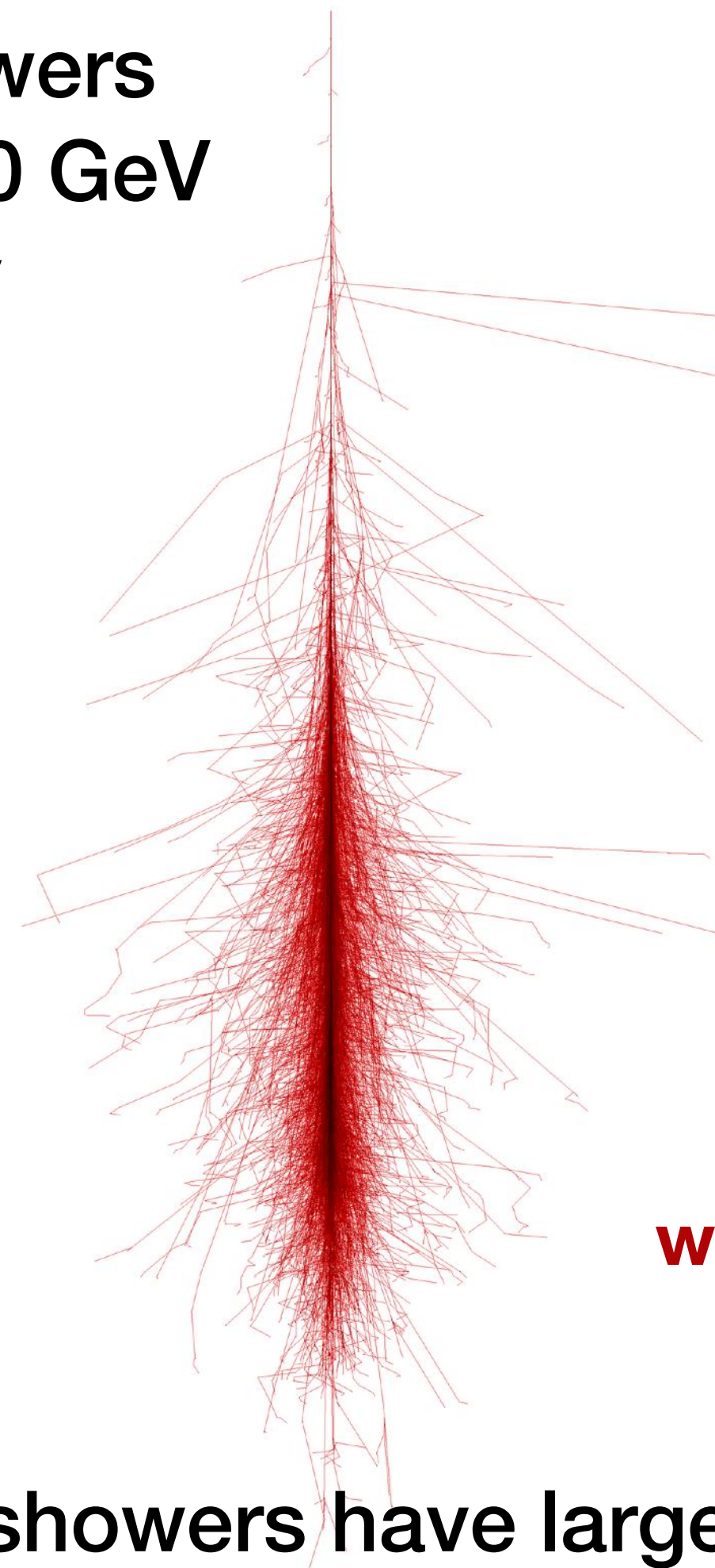
Electromagnetic vs Hadronic showers



Extensive Air Showers

Electromagnetic vs Hadronic showers

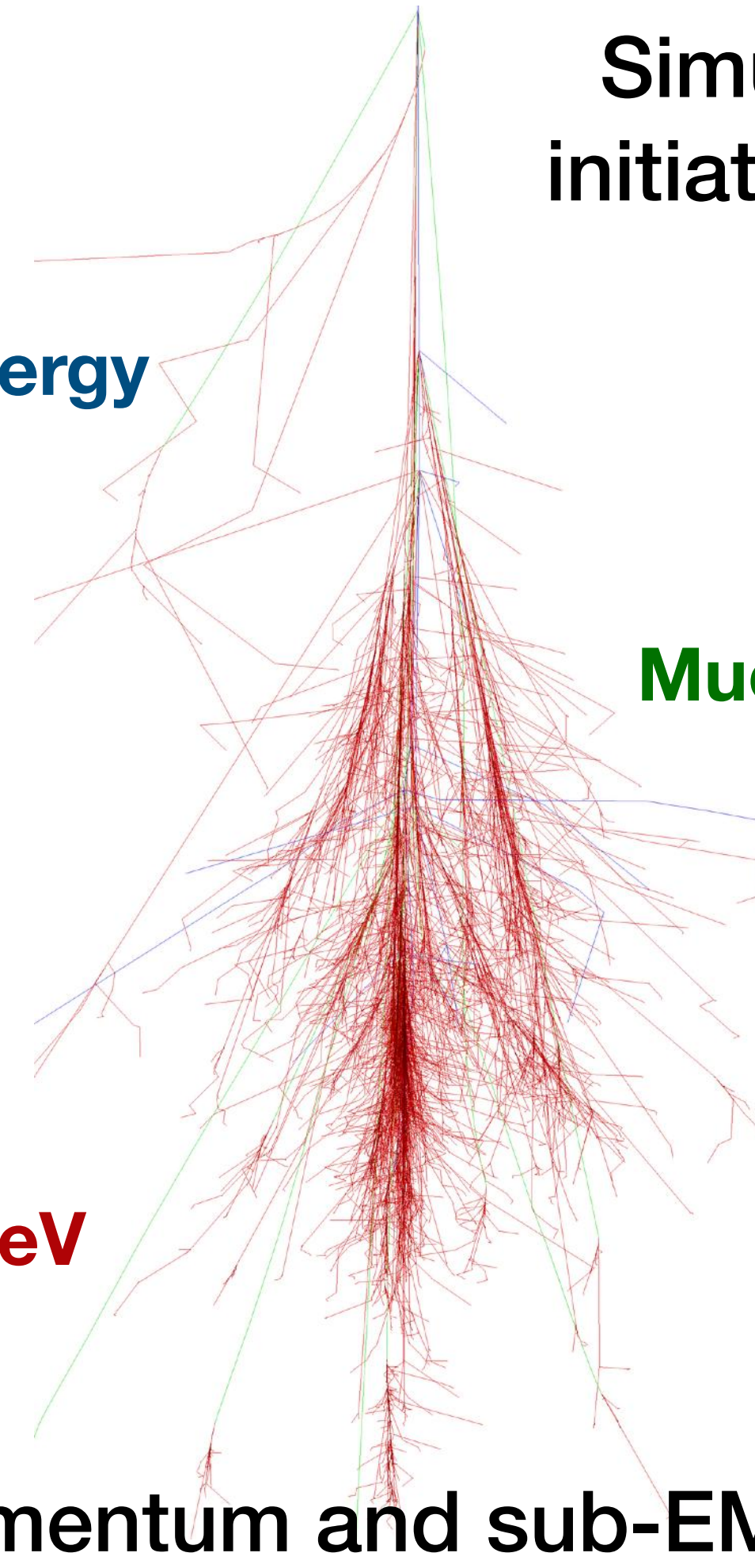
Simulated showers
initiated by a 100 GeV
gamma ray



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

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

Simulated showers
initiated by a 100 GeV
proton

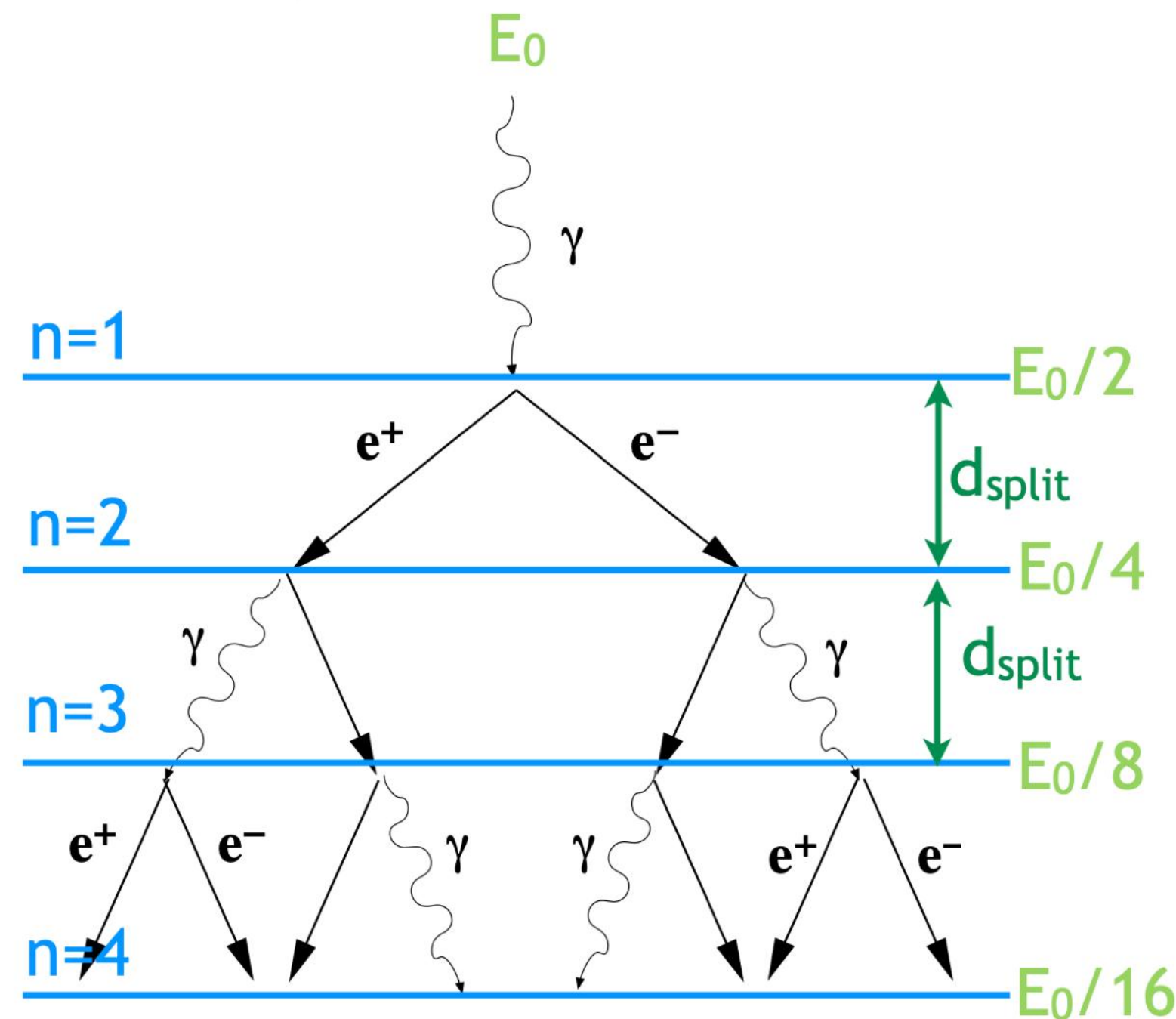


Muons with energy
 $E > 0.1 \text{ GeV}$

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 ($e^\pm, \gamma$): $N = 2^n = e^{x/X_0} \Rightarrow x_{\text{max}} = X_0 \ln \left(\frac{E_0}{E_{\text{crit}}} \right)$

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

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***:

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

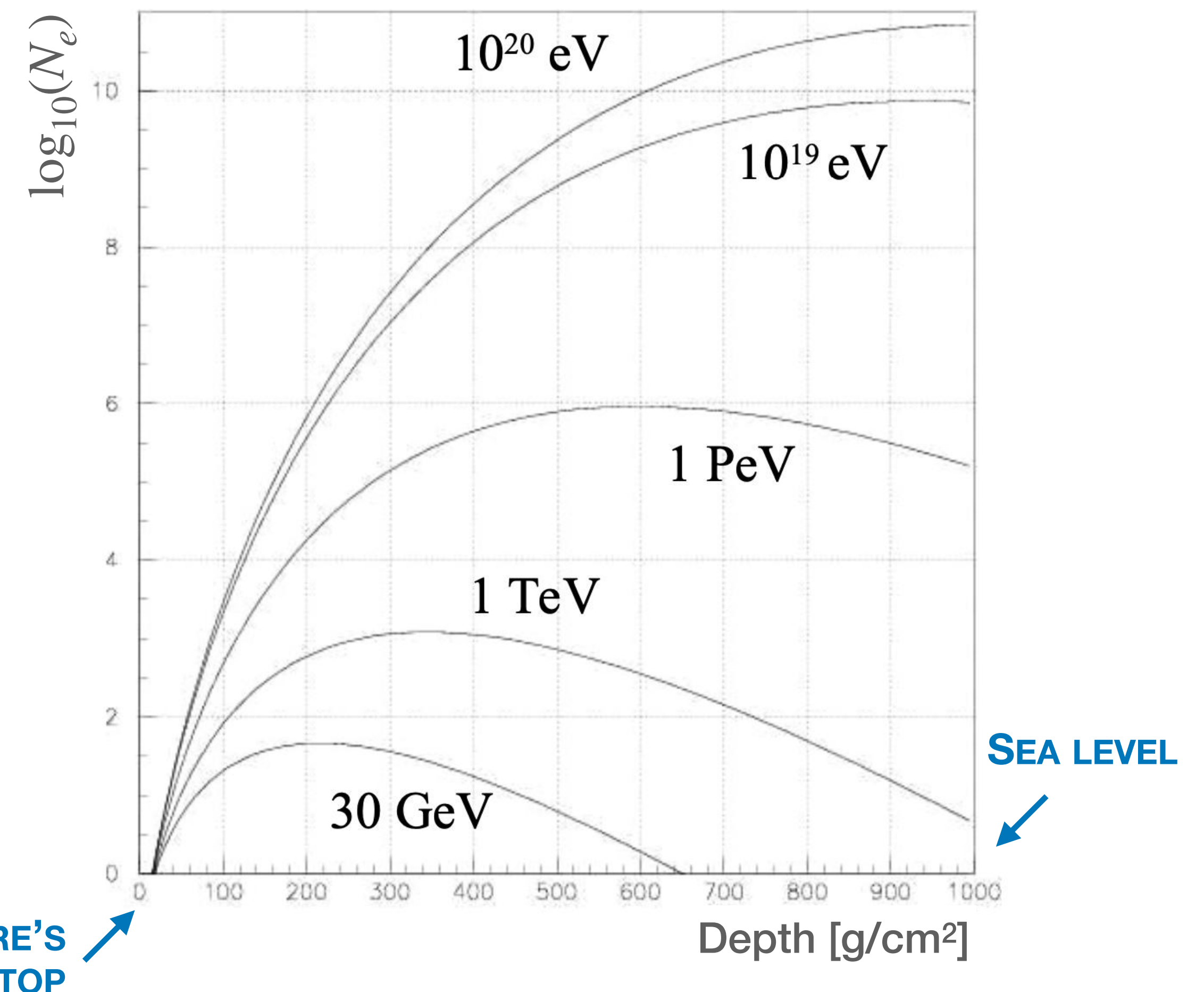
where ***s*** is the shower age parameter that describes the stage of development of the shower

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

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

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

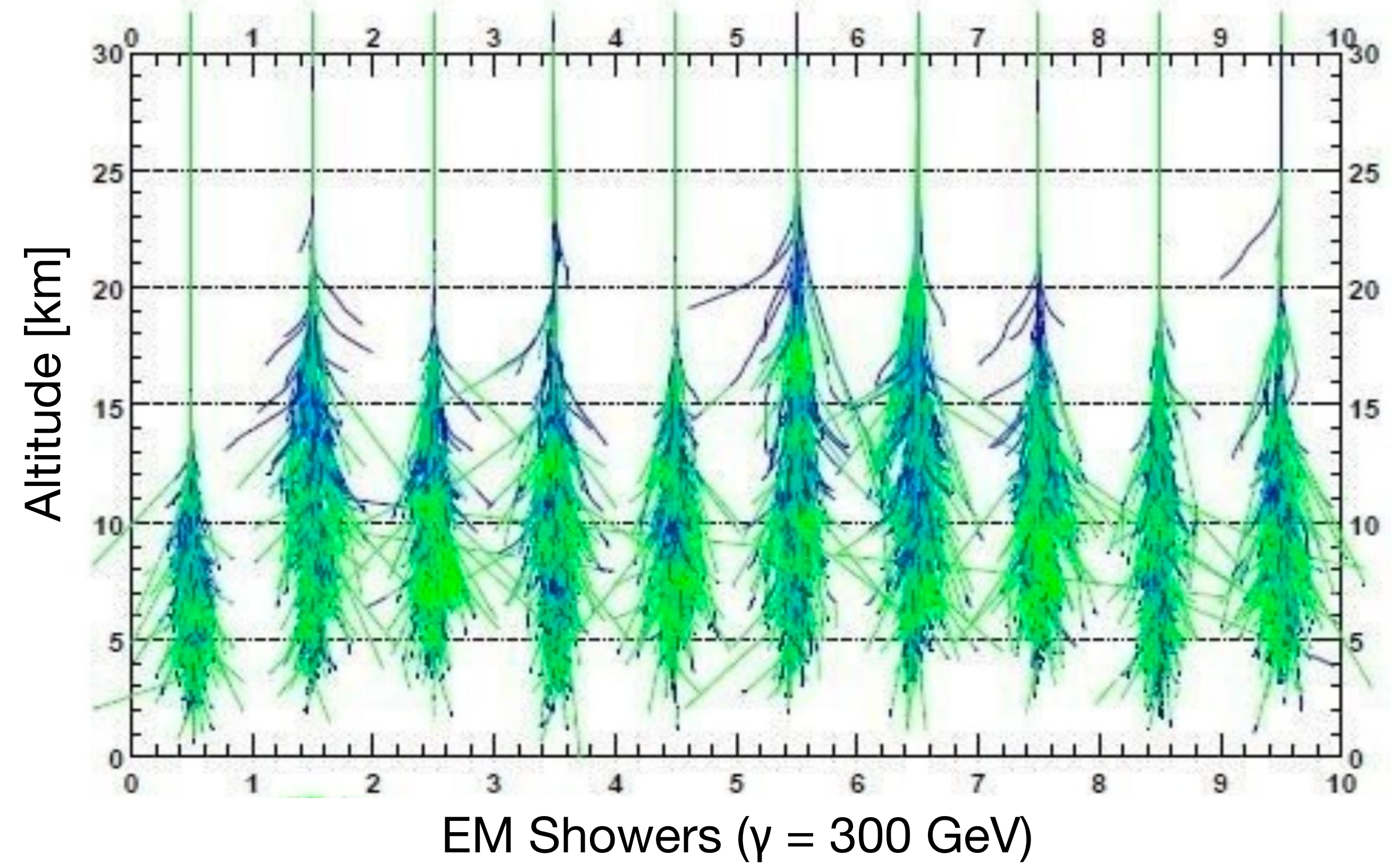
GAMMA RAY PRIMARY



Shower variability

10 simulated EM showers initiated by a 300 GeV photon

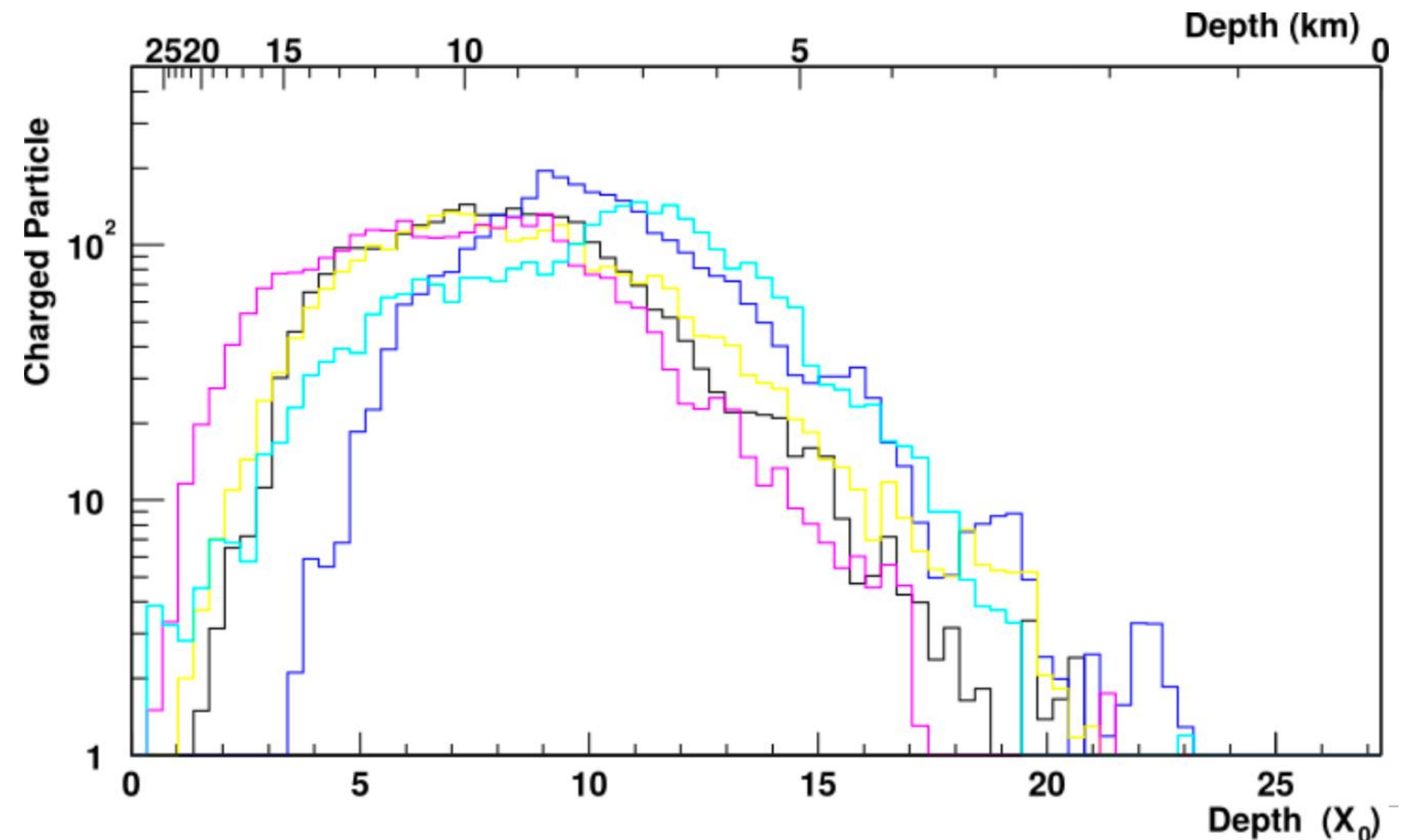
- Large fluctuations in showers, especially at low energy
- Fluctuations mainly due to the first interaction depth
- At high altitude, one radiation length ~several km $\rightarrow$ first point of interaction can vary by > 5 km
- At lower altitudes, radiation length < 1 km $\rightarrow$ shower development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



Shower variability

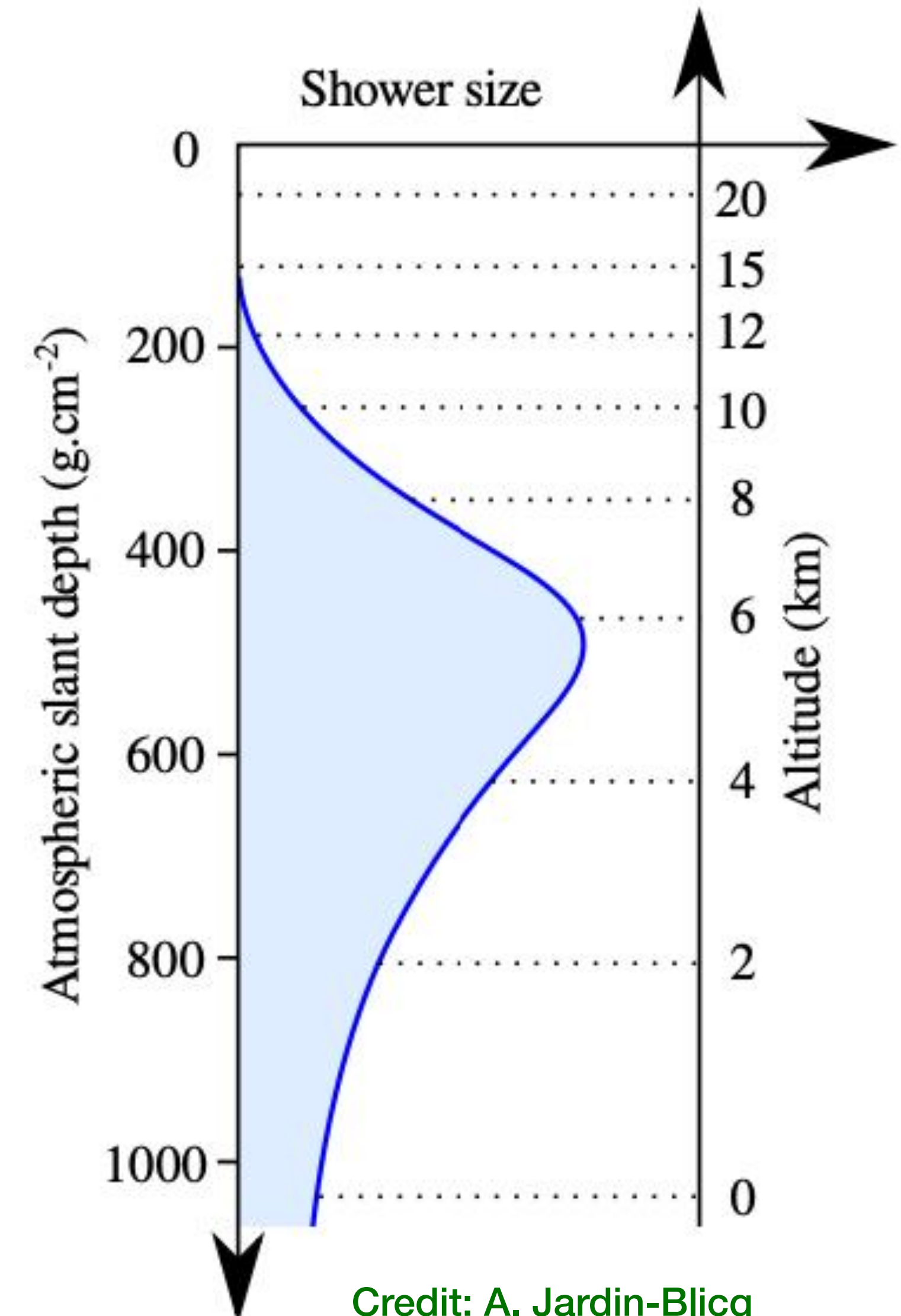
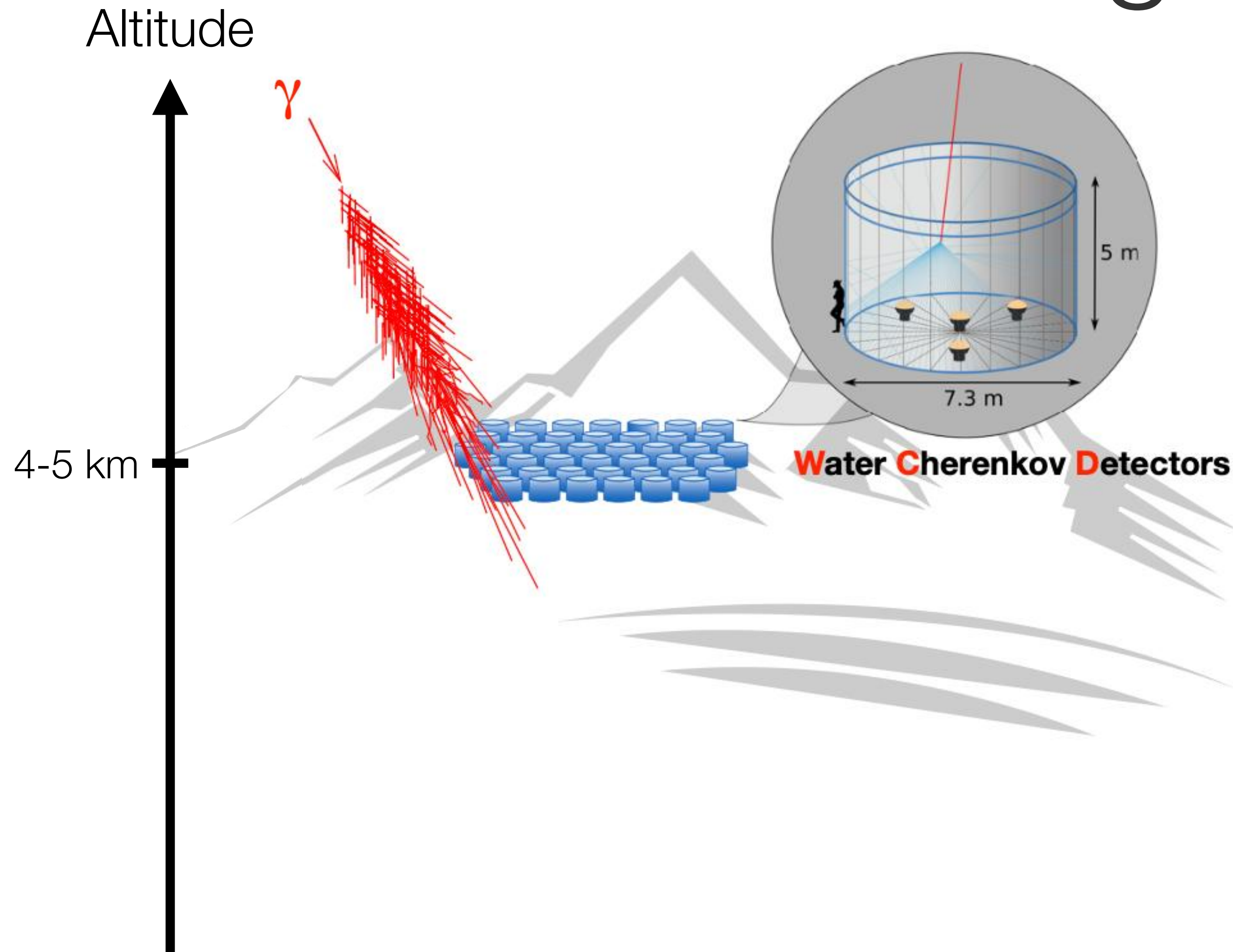
10 simulated EM showers initiated by a 300 GeV photon

- Large fluctuations in showers, especially at low energy
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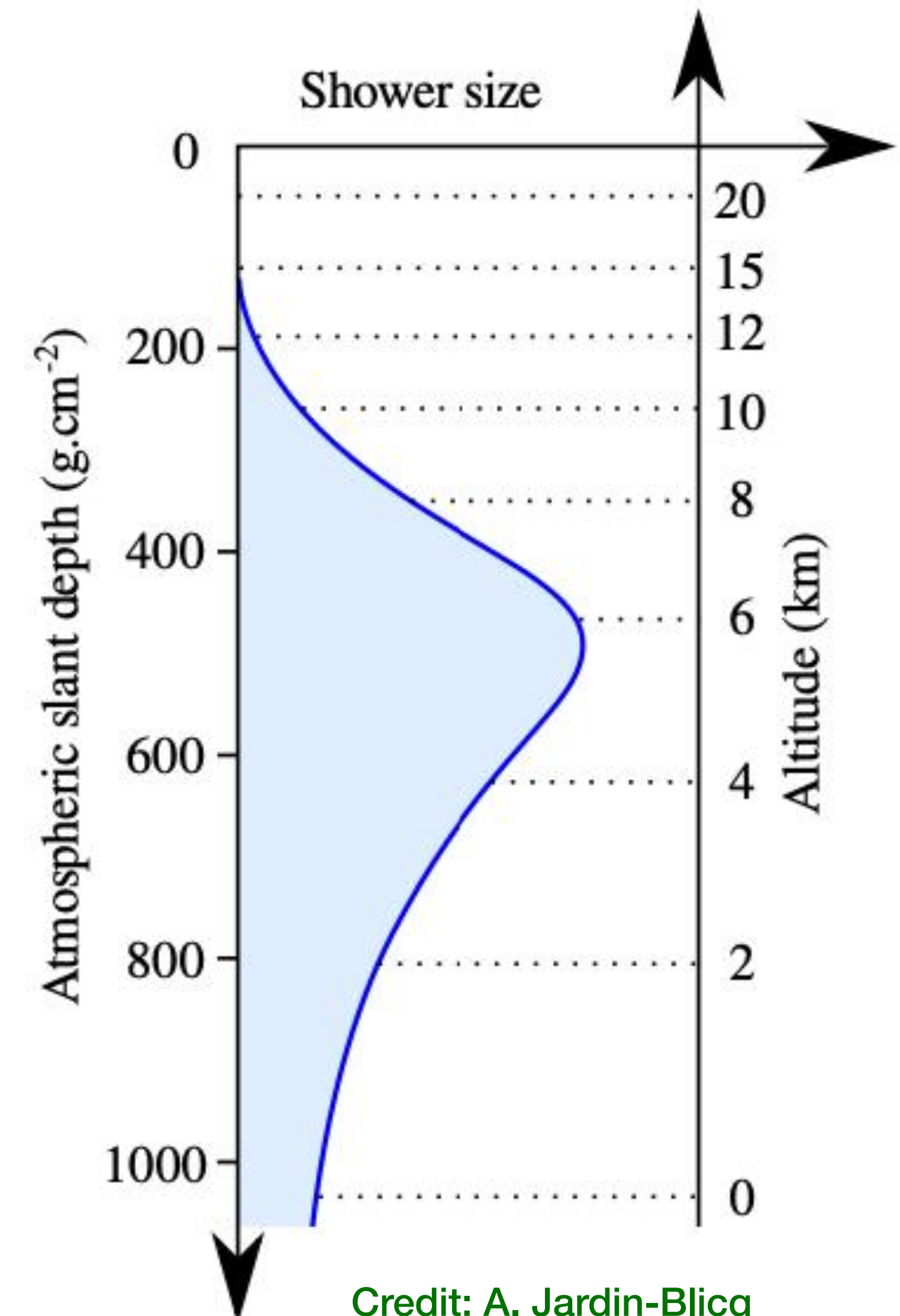
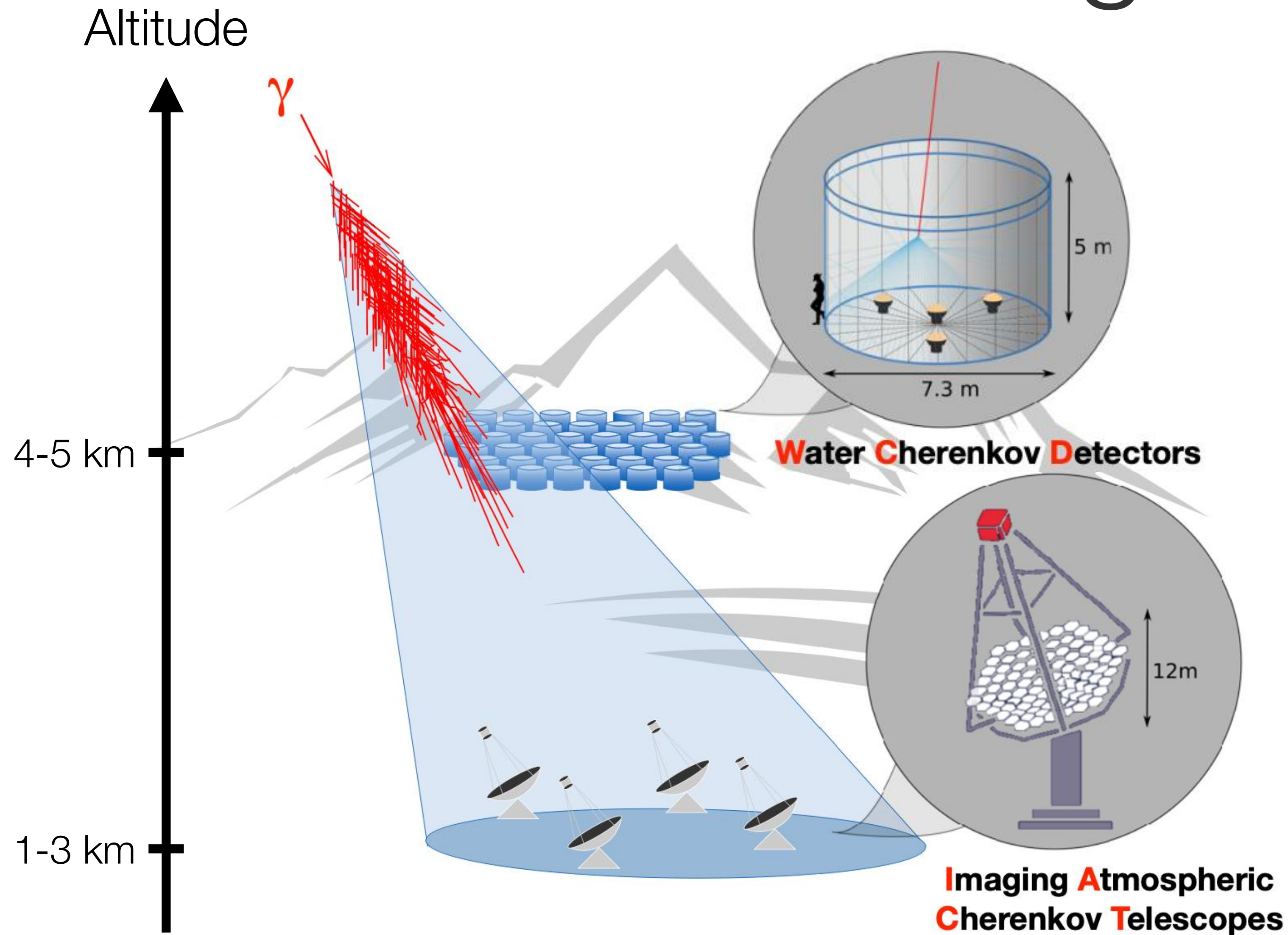
**Similar shower profiles, only shifted by few radiation lengths
 $\rightarrow$ relevant parameter is altitude**

Detecting EASs

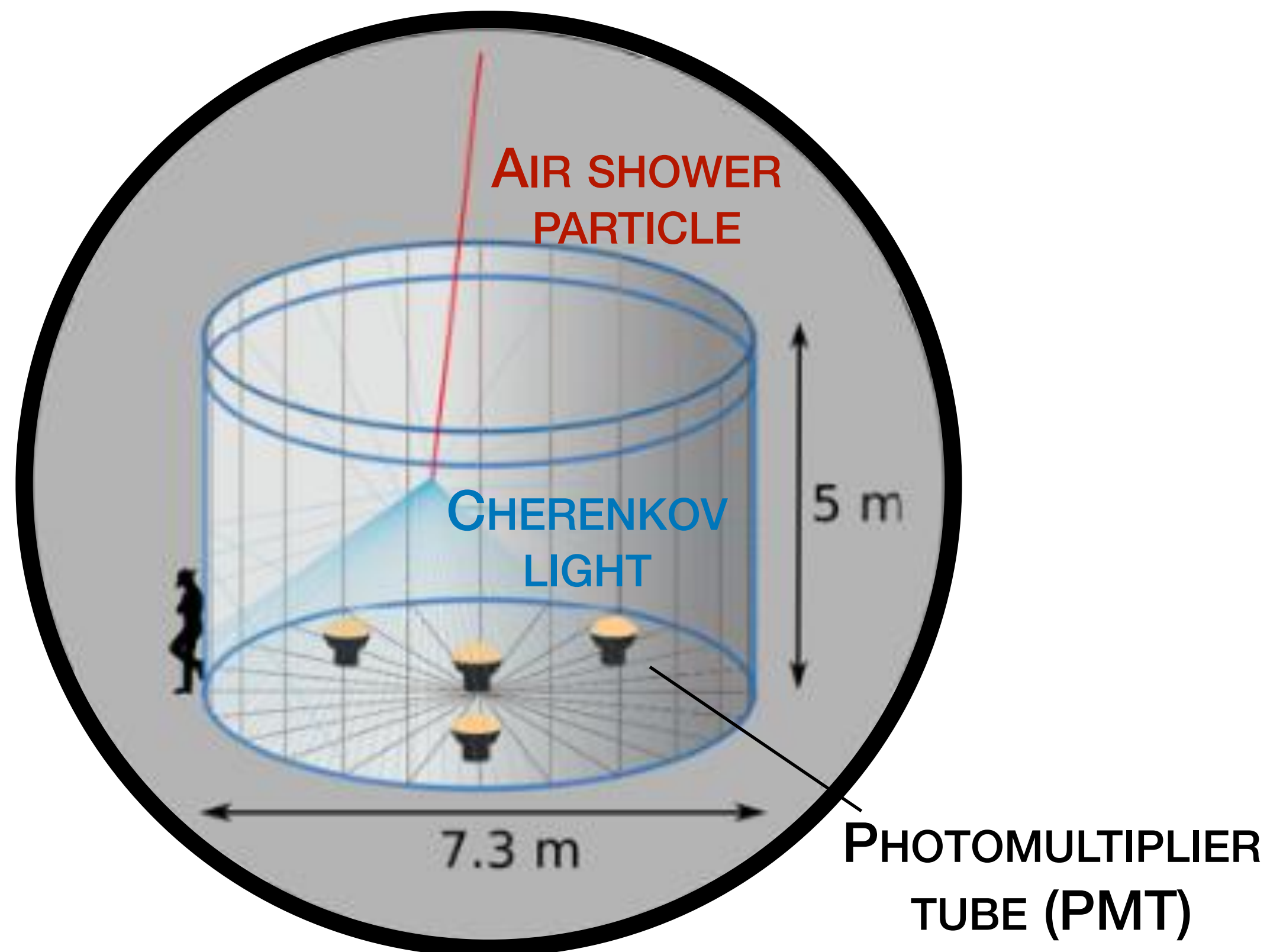


Credit: A. Jardin-Blicq

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: 95% (operates in daylight too)

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

Energy resolution: $\sim 30\%$

Effective area: $\sim 10^4 - 10^5 \text{ m}^2$

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

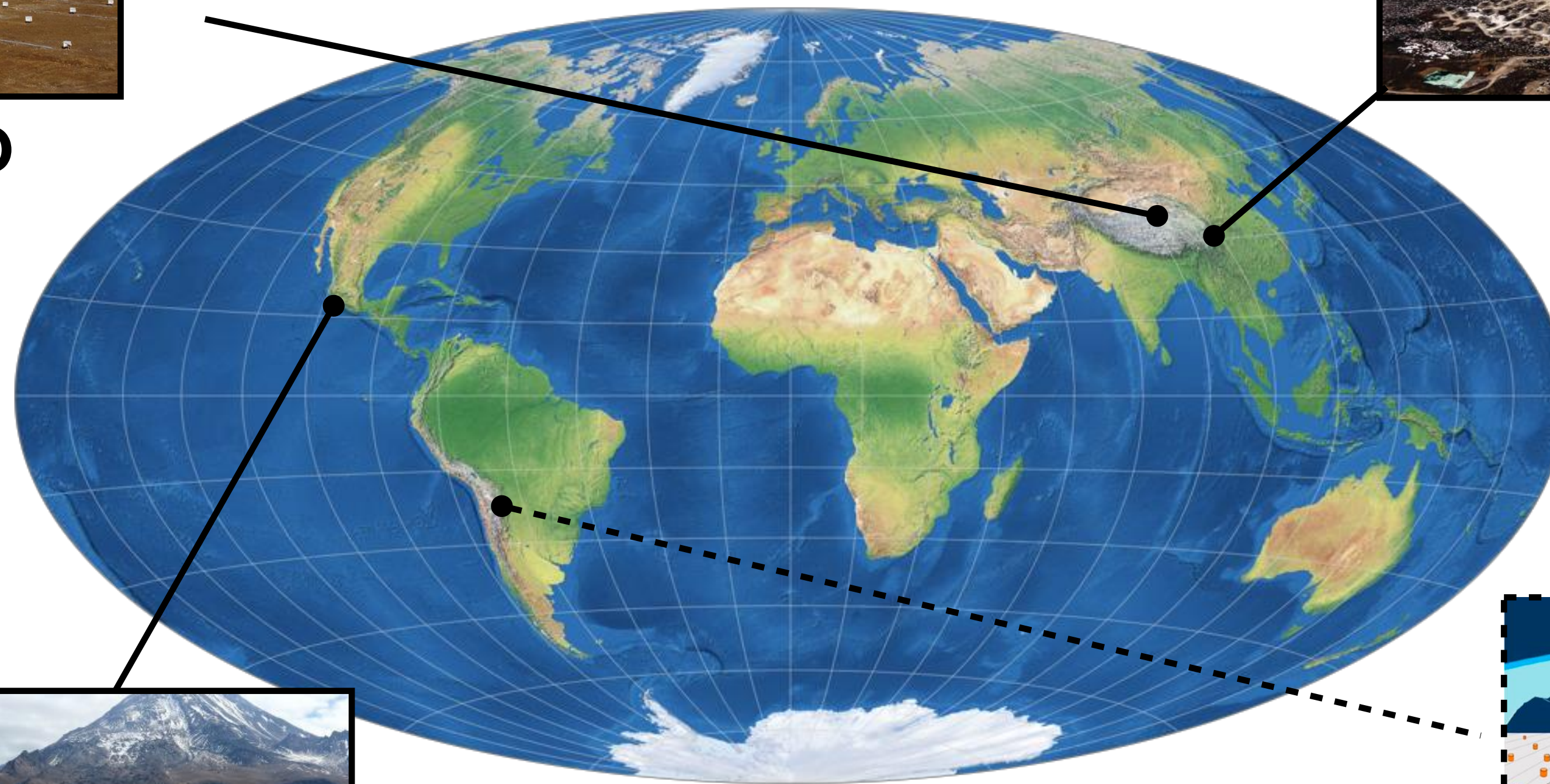
Current and future generation of WCDs



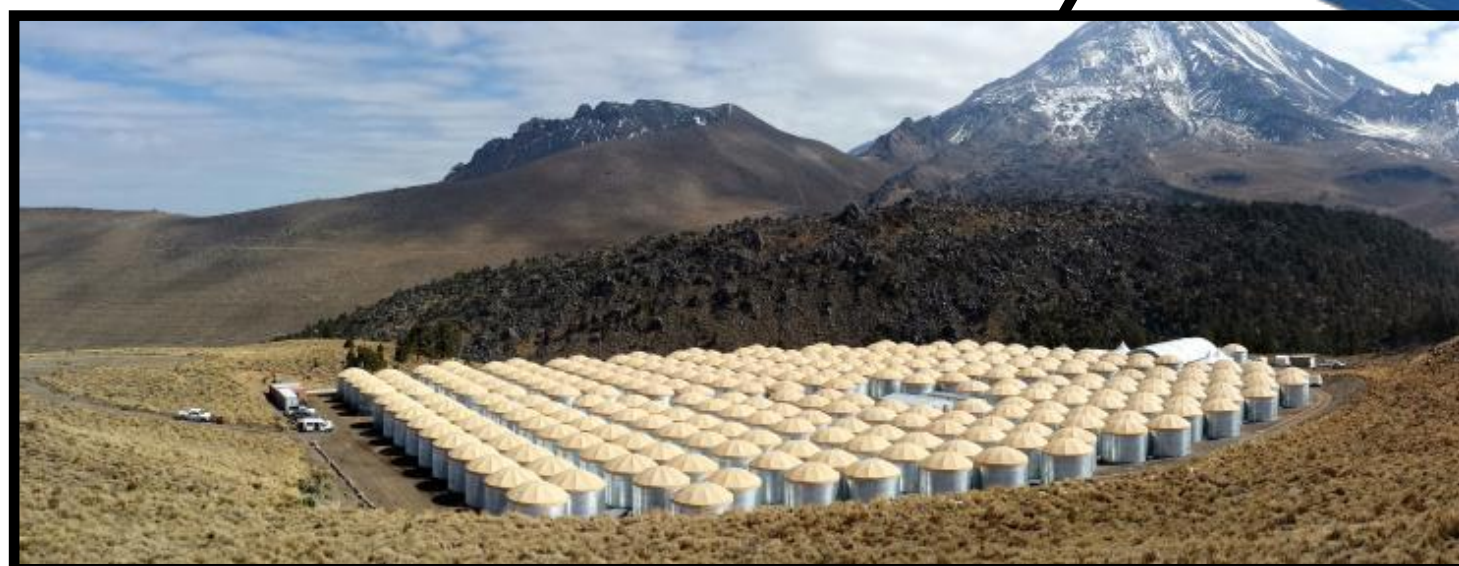
Tibet AS γ +ARGO (1990s)
Tibet (4300 m)



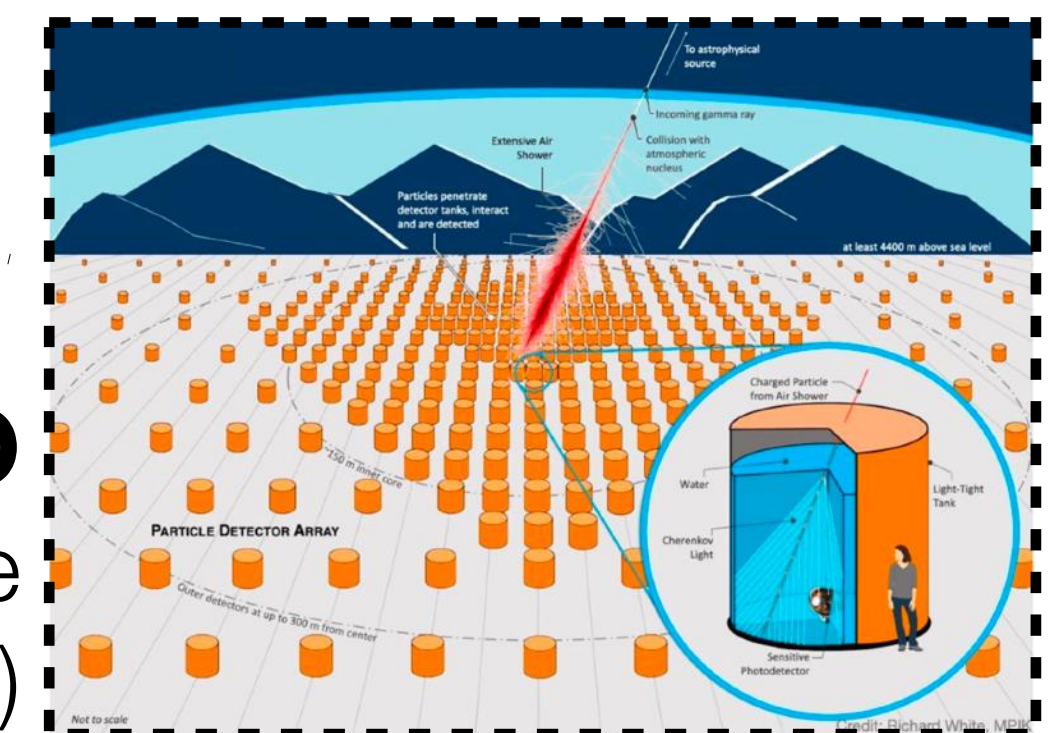
LHAASO (2021)
Daocheng, China
(4410 m)



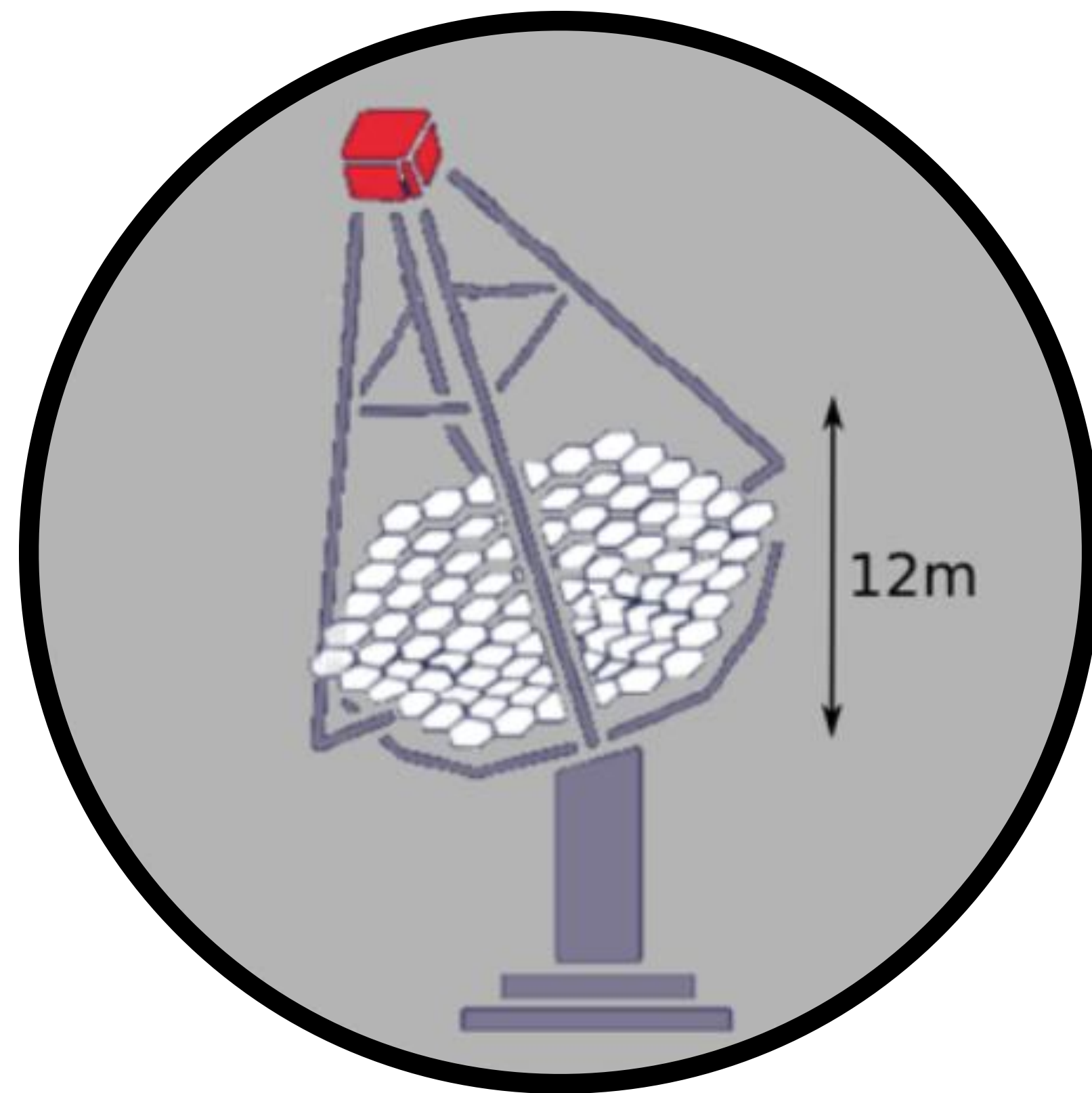
HAWC (2015)
Puebla, Mexico
(4100 m)



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]°

Energy resolution: ~15%

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

Energy range: wide (50-100 TeV)

Current and future generation of IACTs

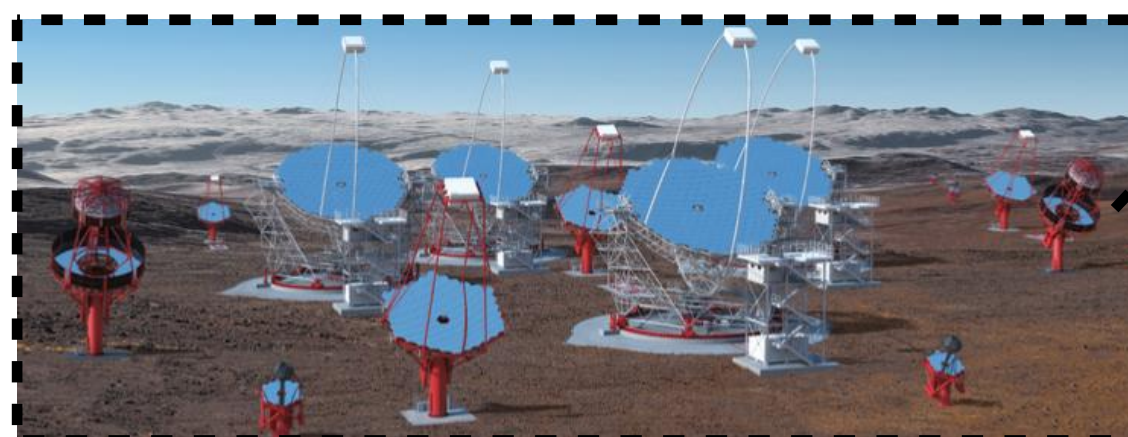


VERITAS

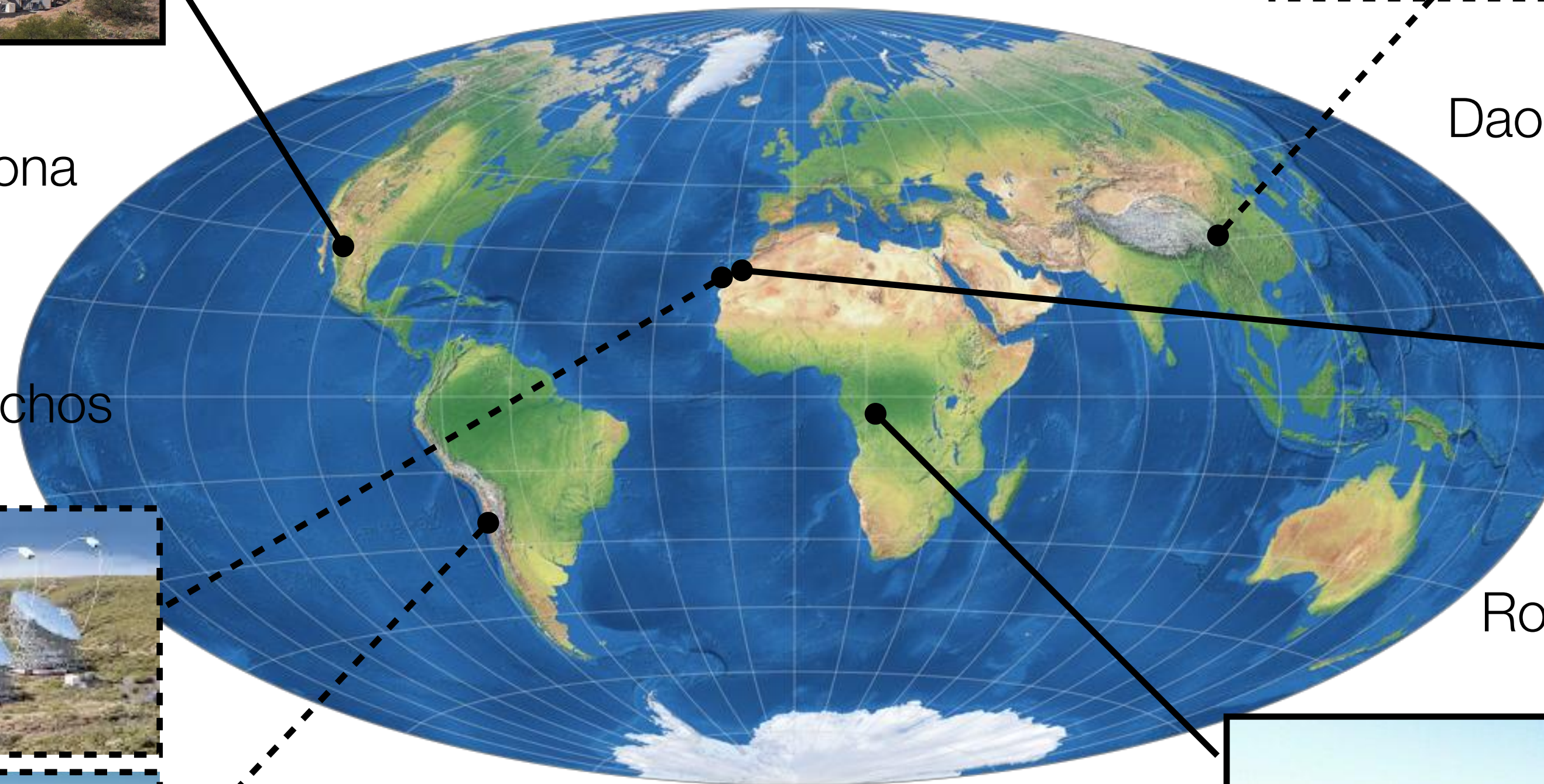
Mount Hopkins, Arizona

CTAO - North

Roche de los Muchachos
Canary Island

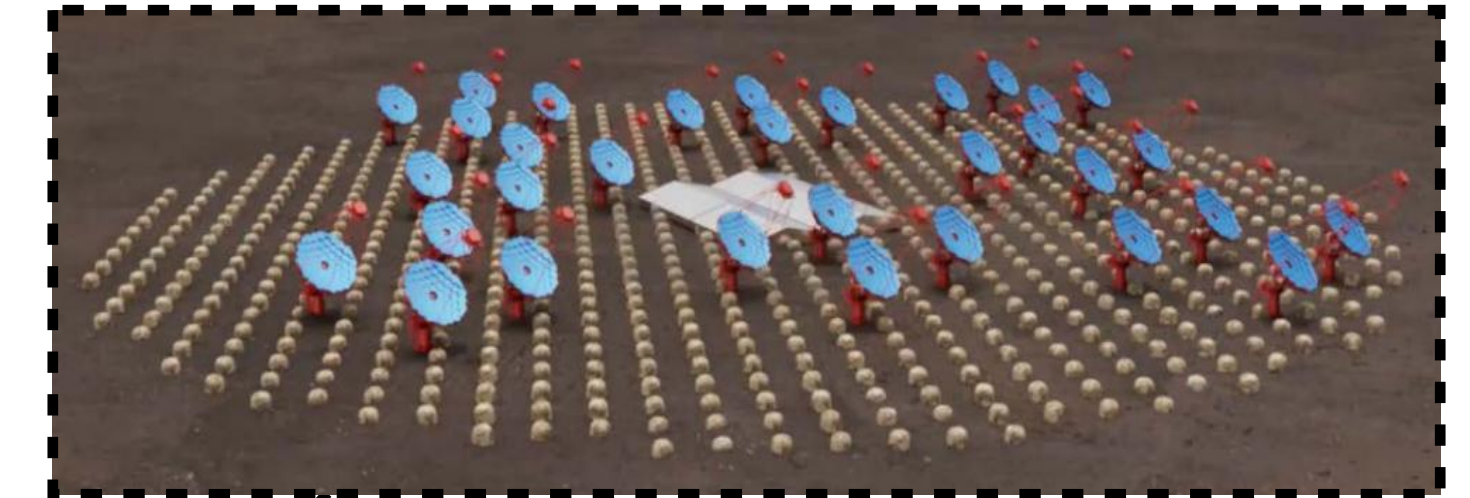


CTAO - South
Atacama, Chile



H.E.S.S. (2002)

Khomas Highland,
Namibia



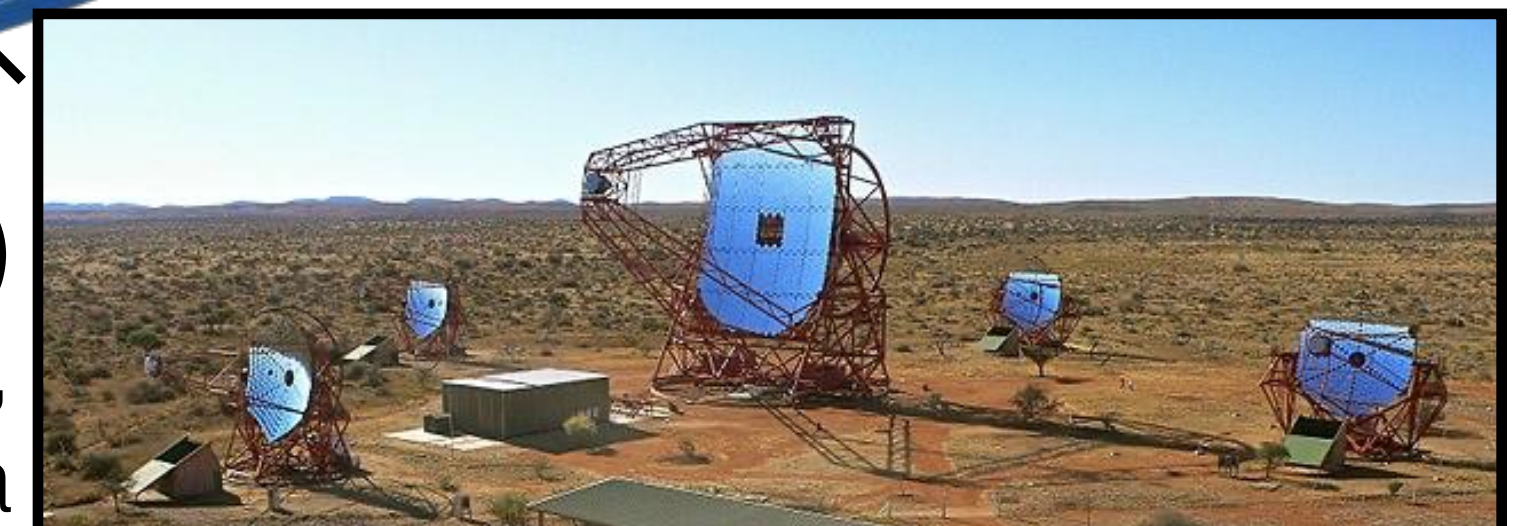
LACT

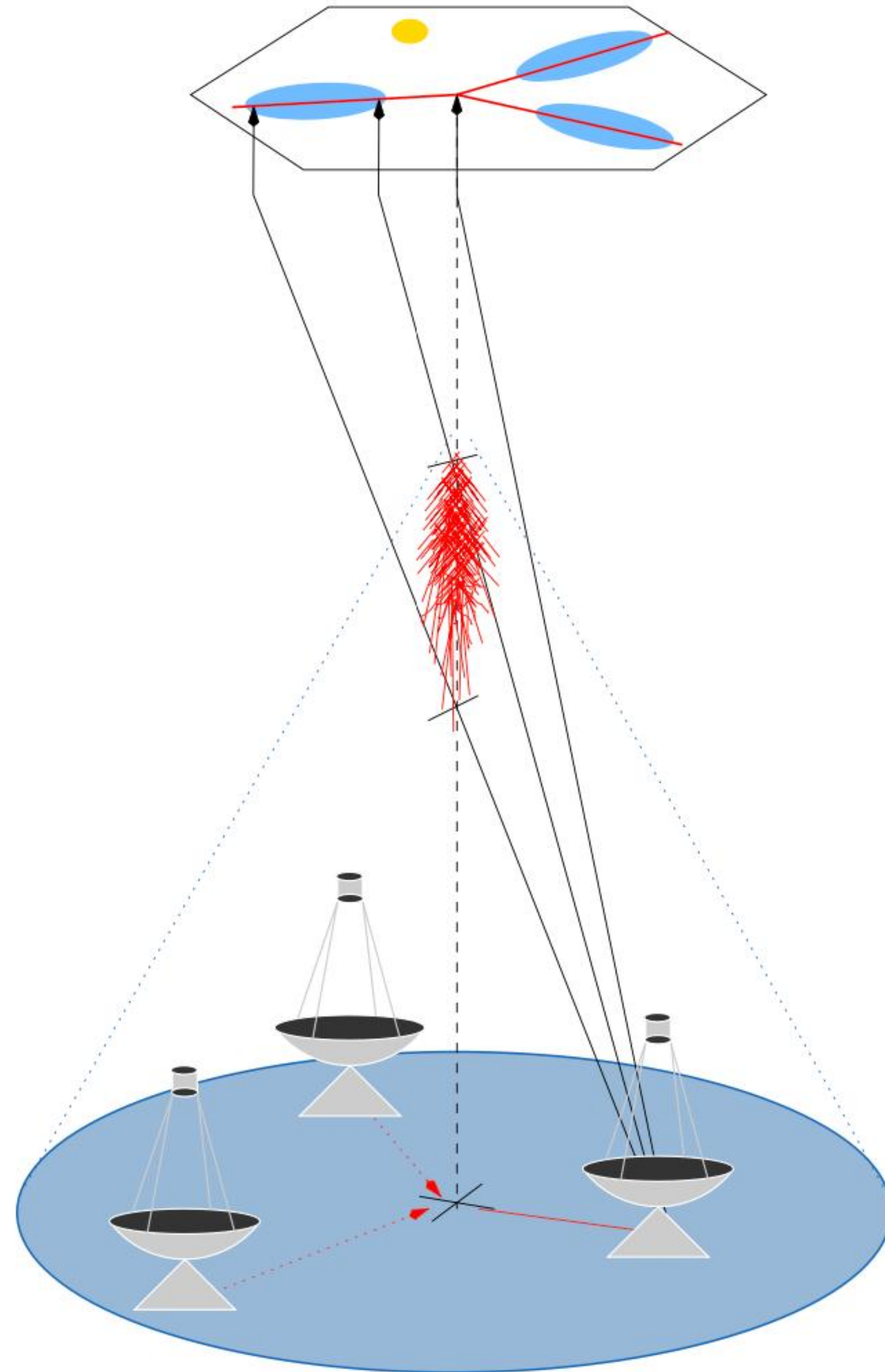
Daocheng, China (4410 m)



MAGIC

Roche de los Muchachos
Canary Island





IACTs: detection principles

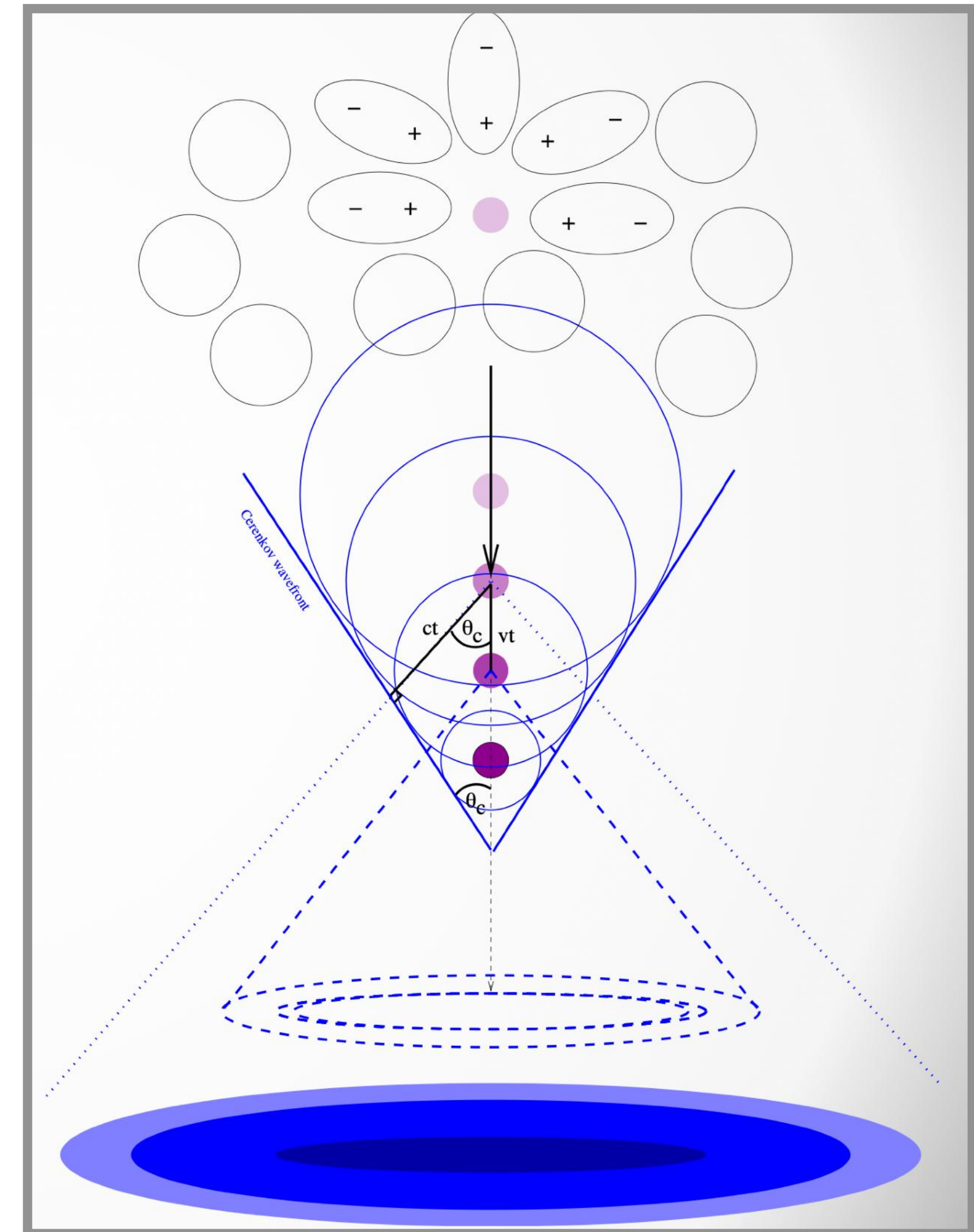
Cherenkov radiation

- 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 :

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



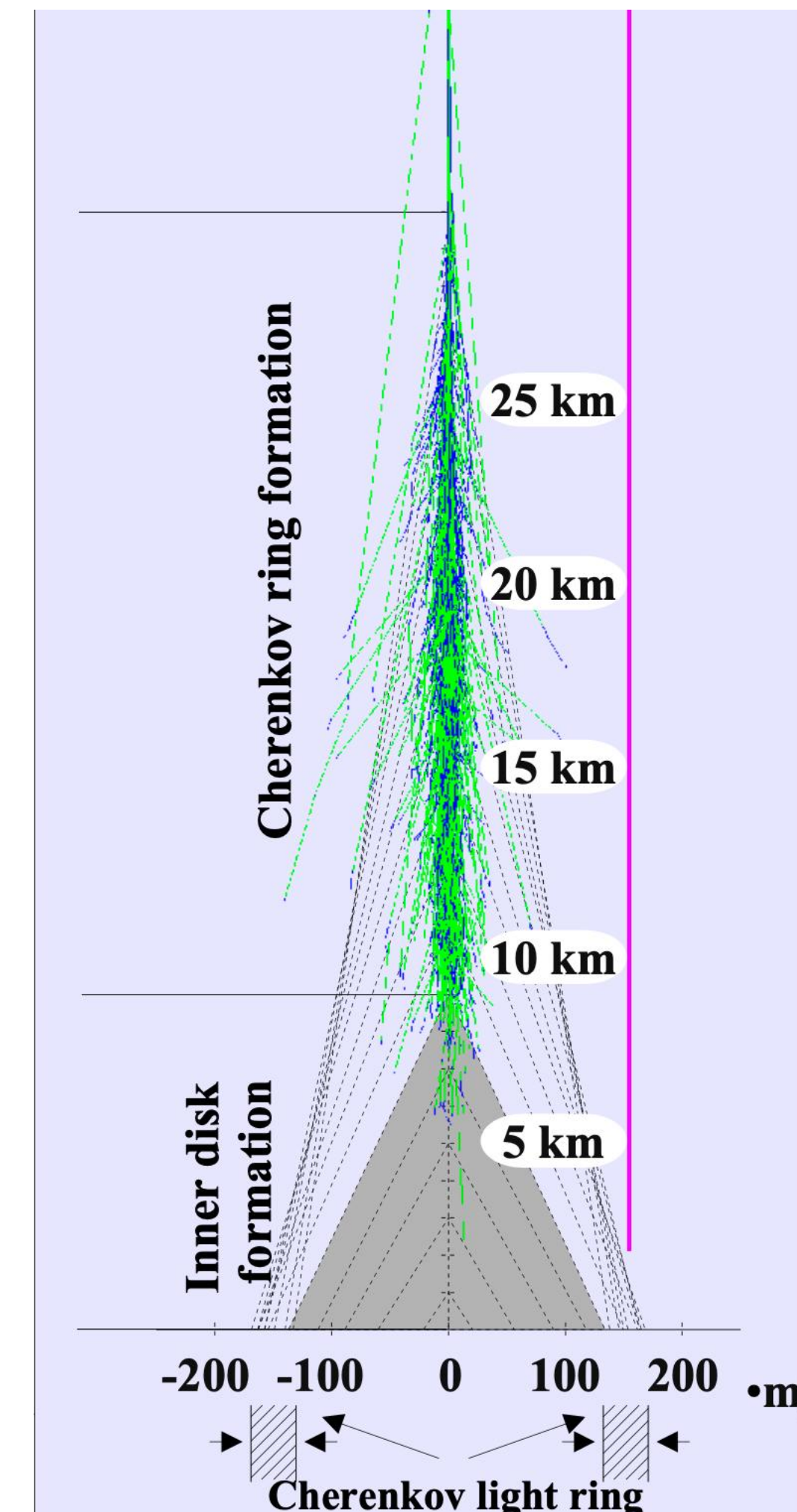
Cherenkov radiation

In the atmosphere

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

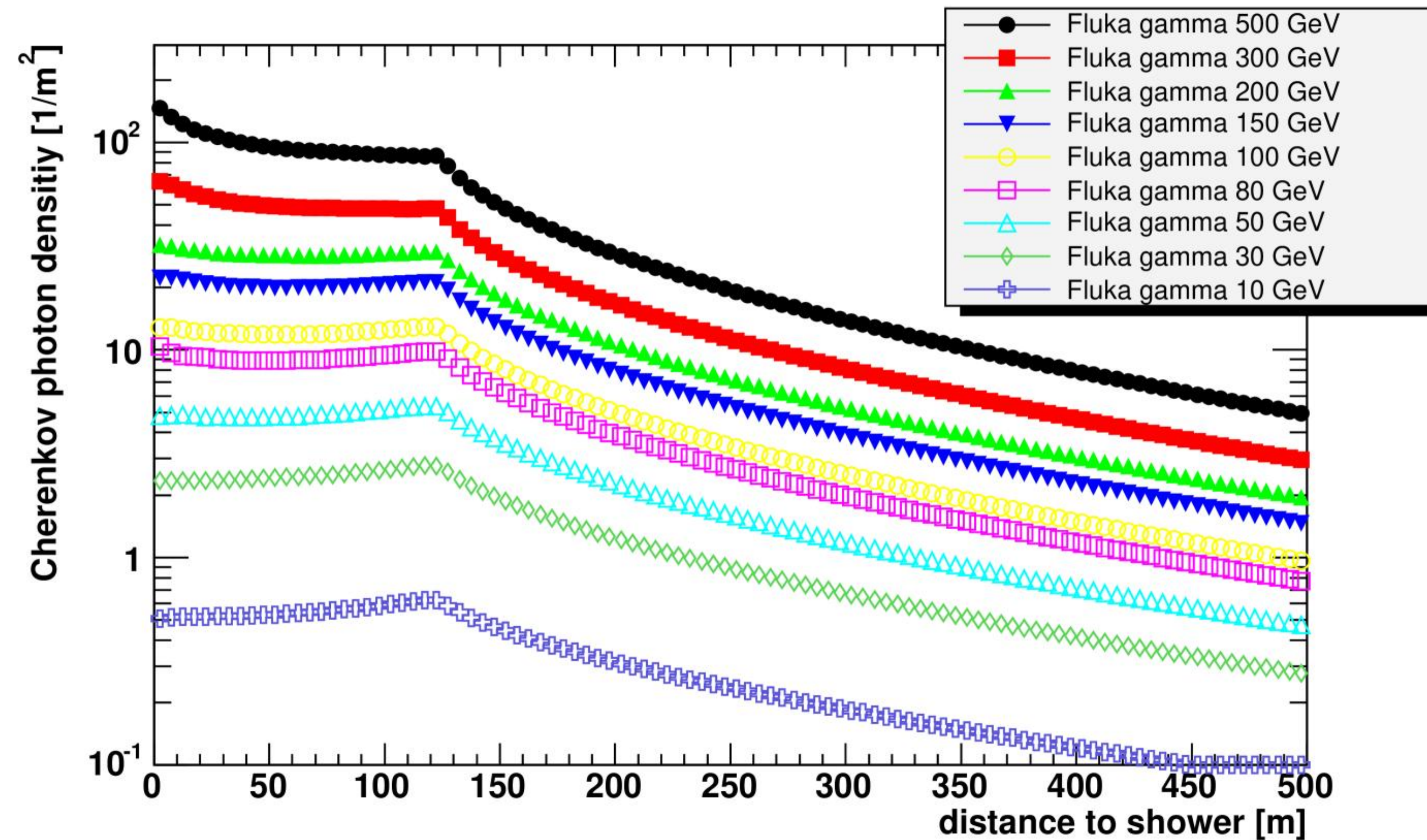
$$\rho(z) \propto \rho_0 \exp\left(-\frac{z}{z_0}\right)$$

- Evolution of the Cherenkov angle with altitude z :



Cherenkov radiation

Cherenkov photon density on ground

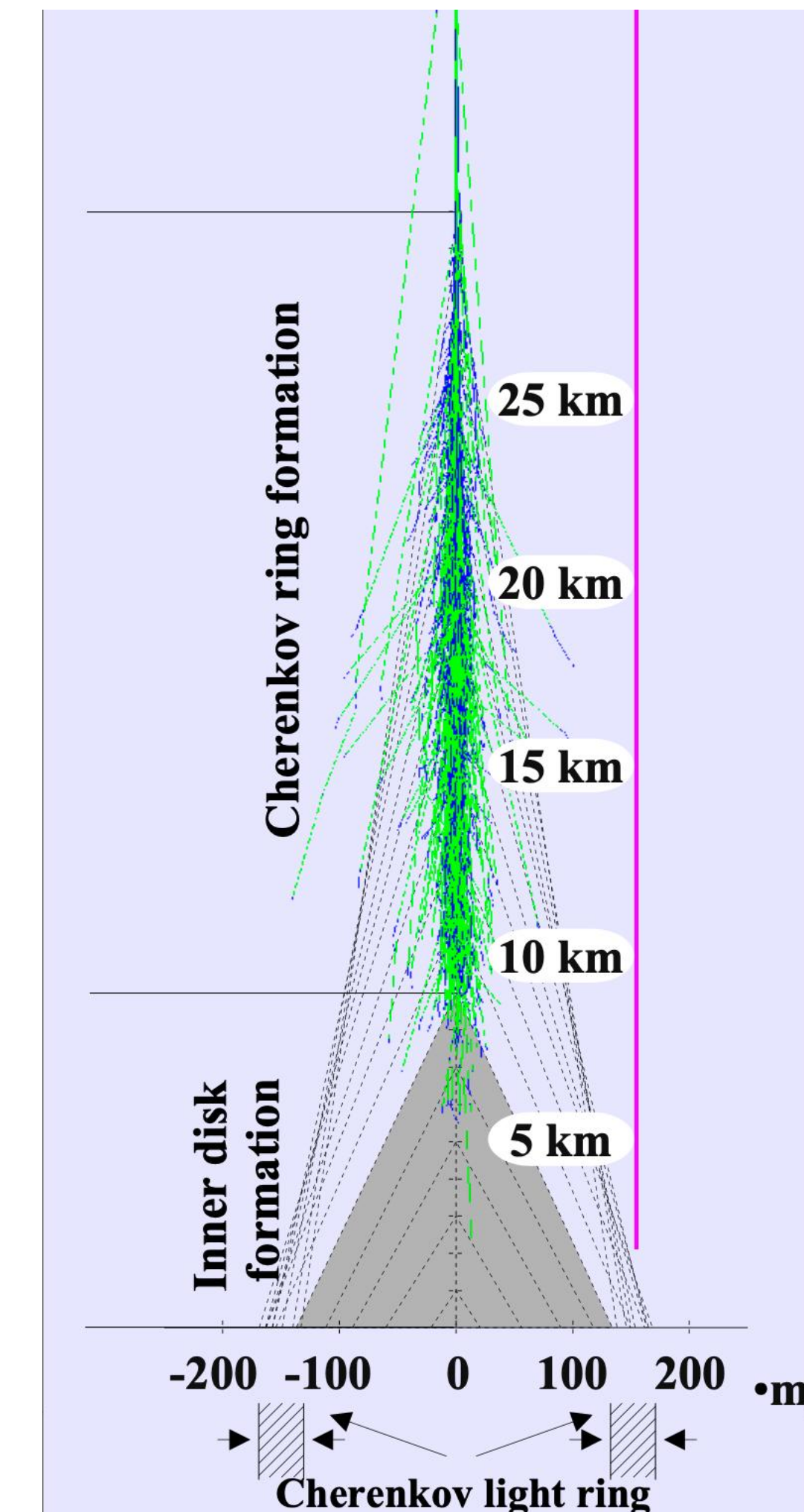
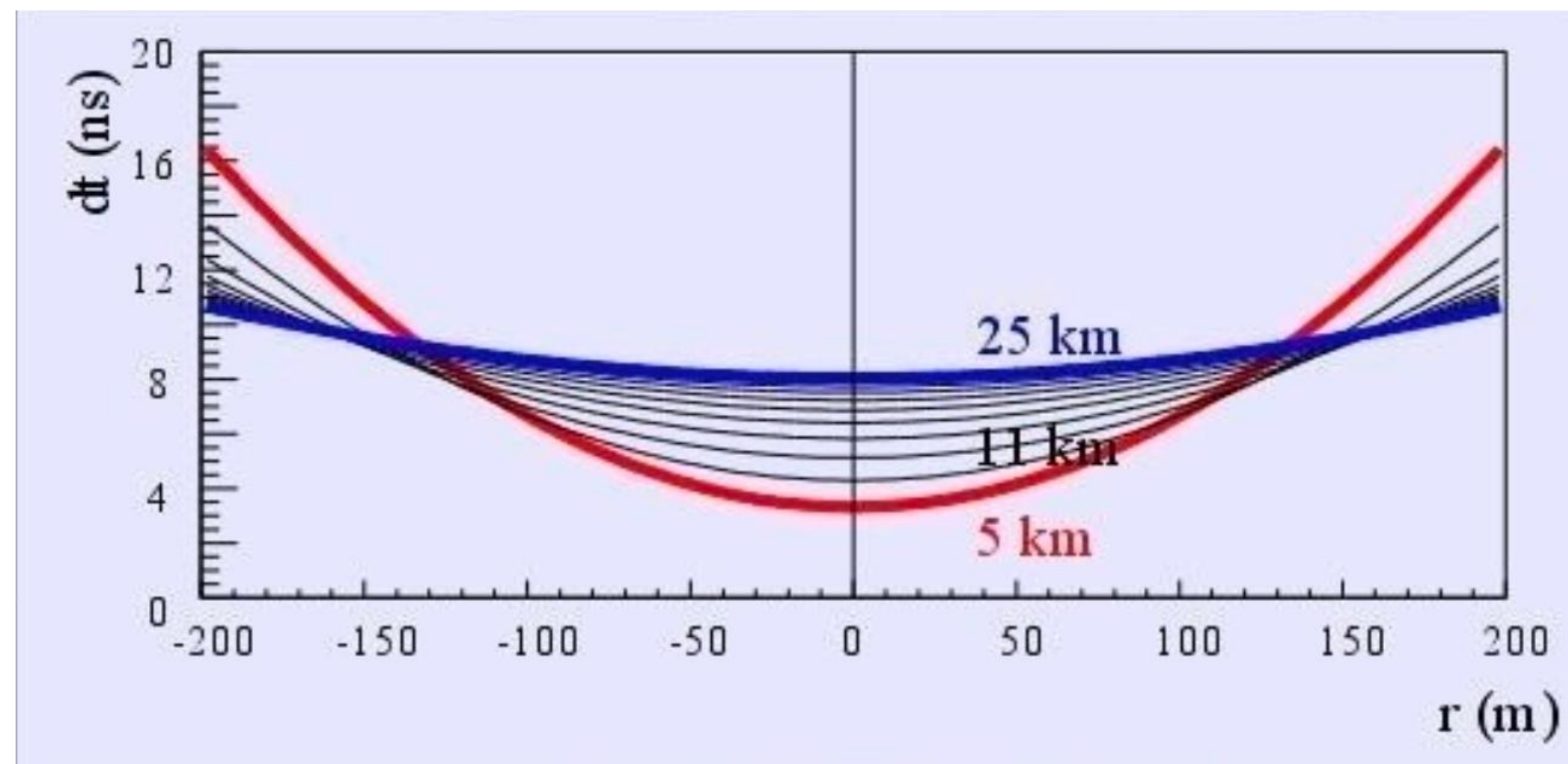


Cherenkov radiation

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:

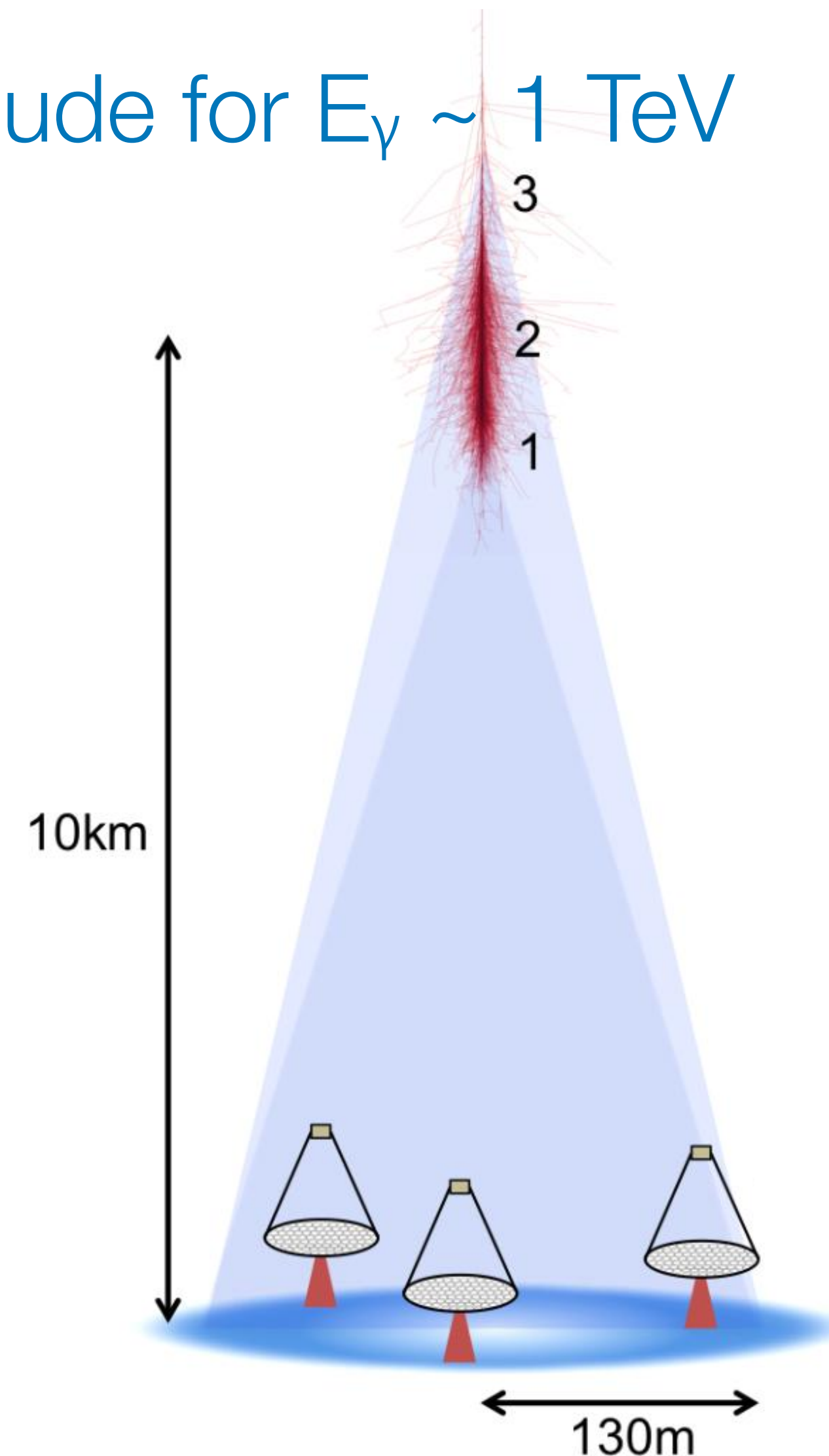
- Altitude $\sim 10 \text{ km}$
- $\sim 10^3$ charged particles

Cherenkov emission:

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

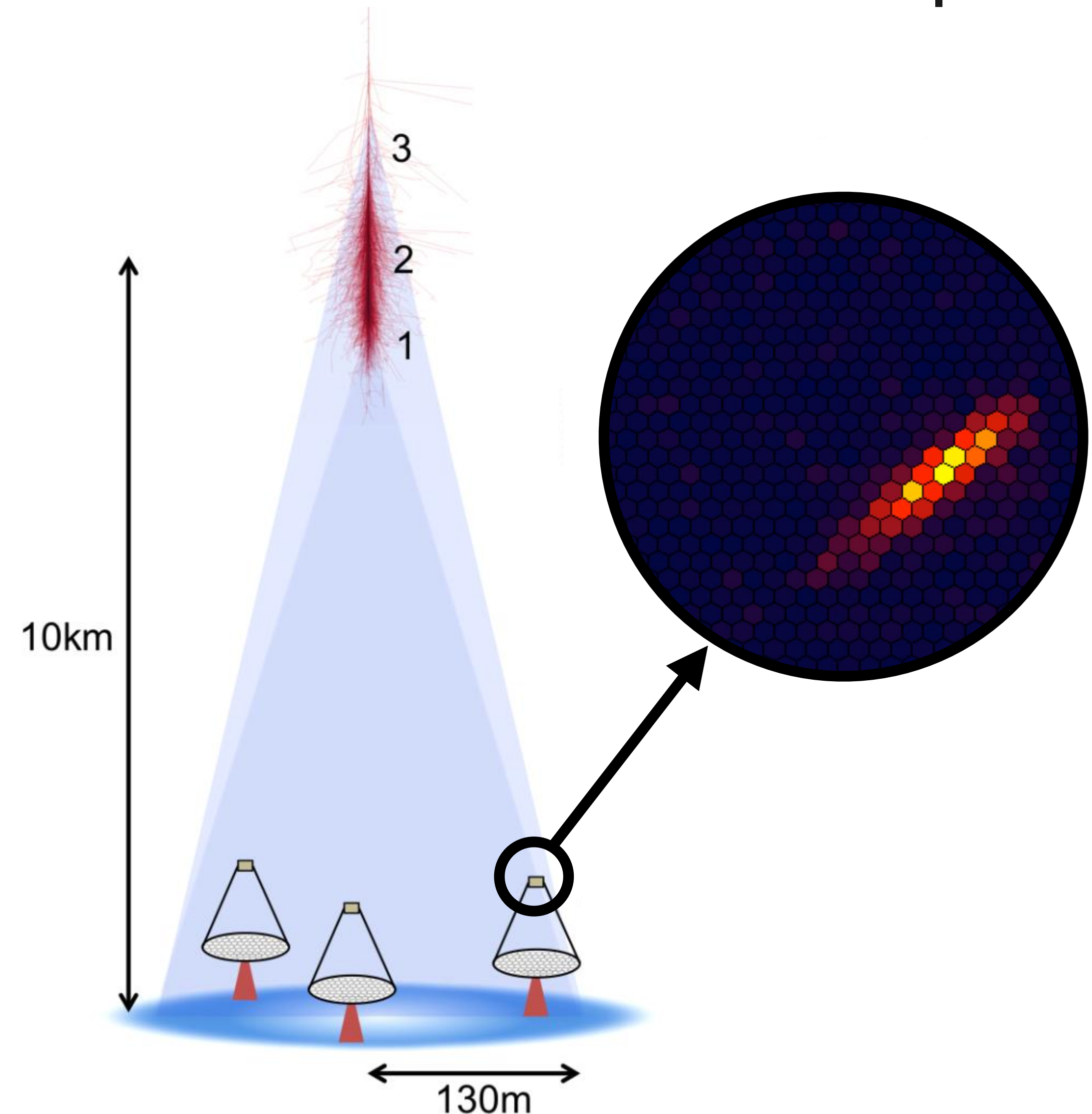
Cherenkov light-pool on ground:

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



Imaging Atmospheric Cherenkov Telescopes

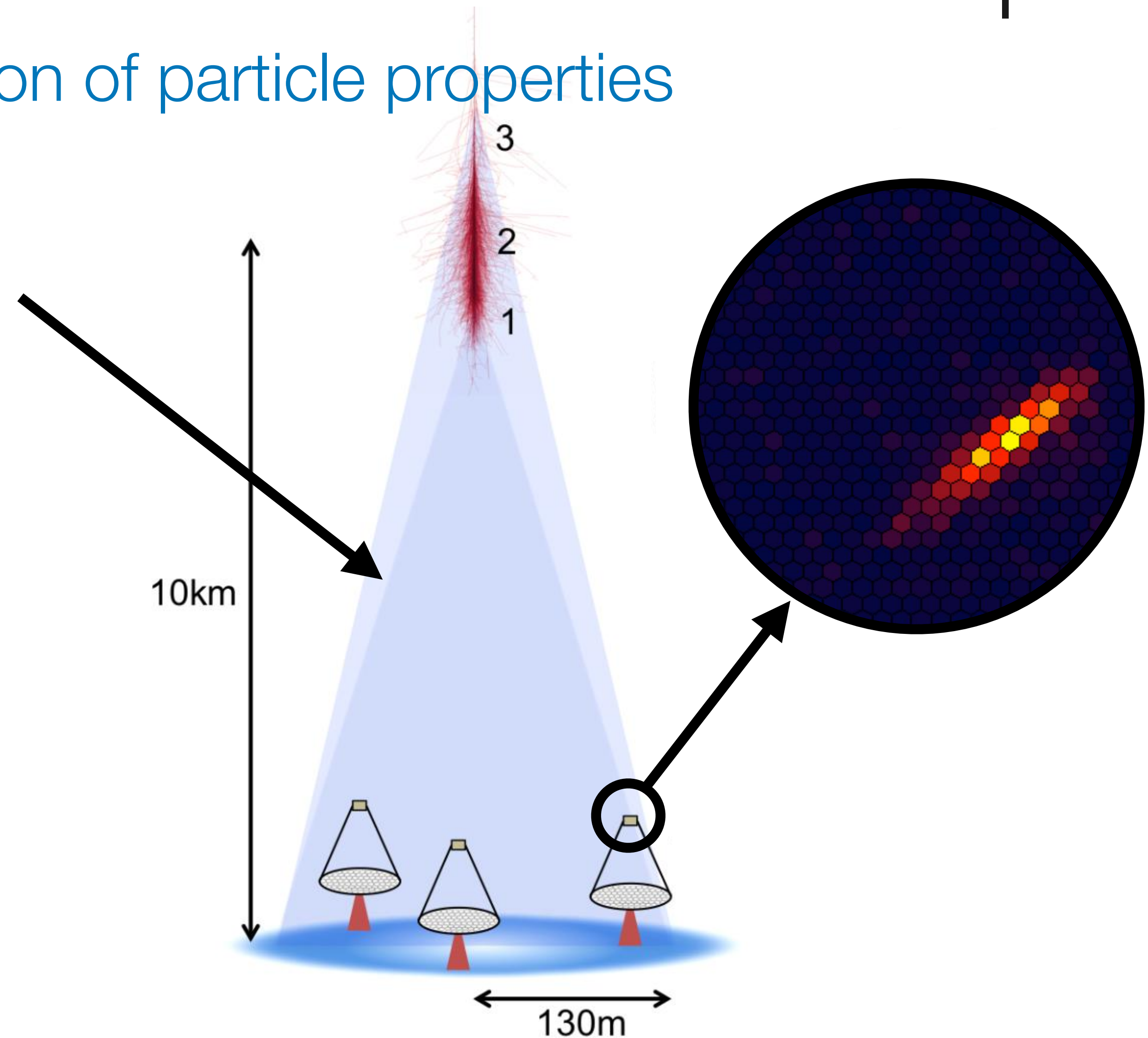
- Cherenkov light-pool ~120 m
- Image the shower on a fast camera ($\Delta t \sim 2\text{ns}$)
- Large effective area (10^5 m^2) even with modest reflector
- Change in Cherenkov angle + multiple Coulomb-scattering washes out the ring shape of the Cherenkov light $\rightarrow$ faint elliptical shaft of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



Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light
(calorimeter)

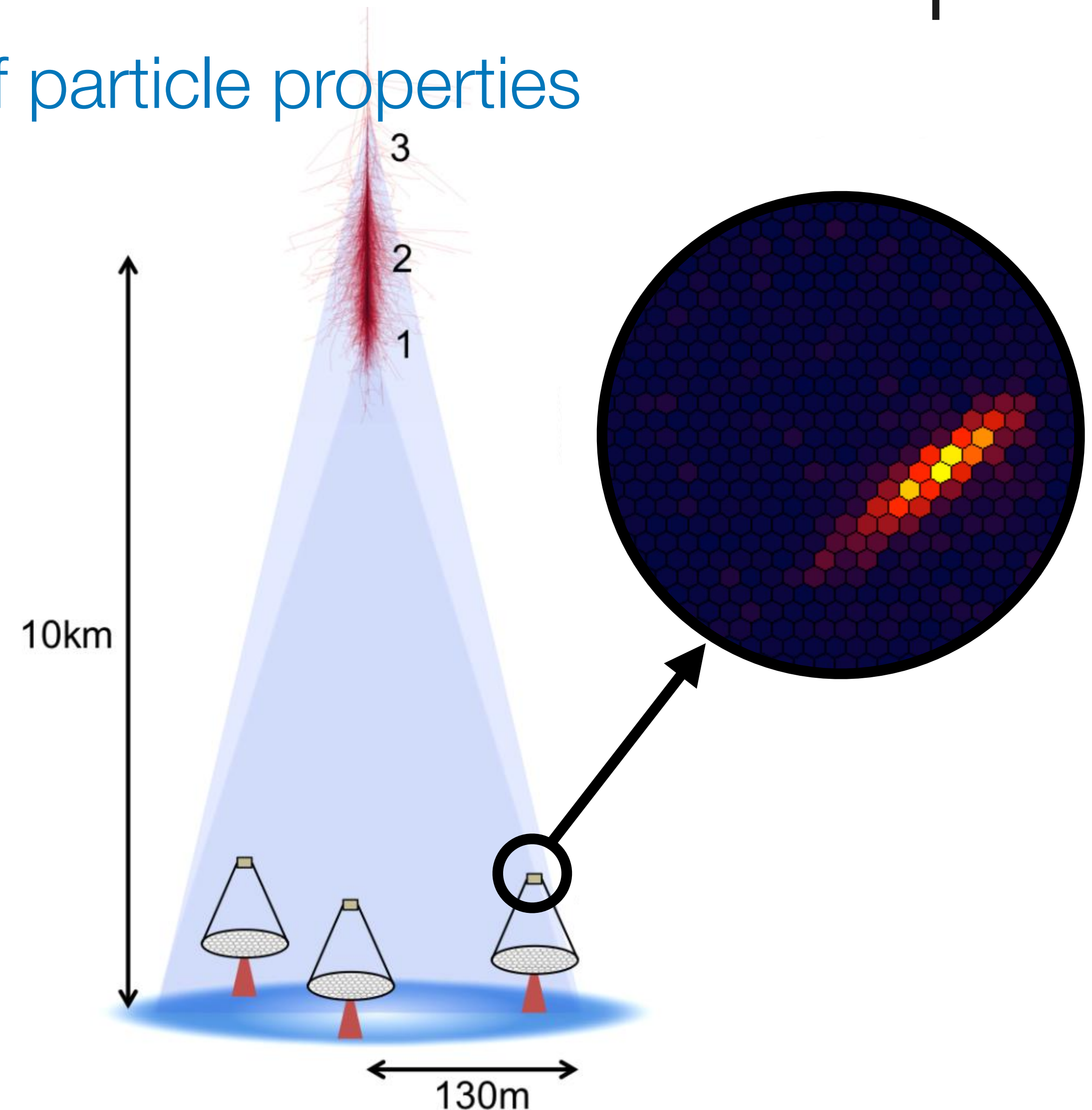
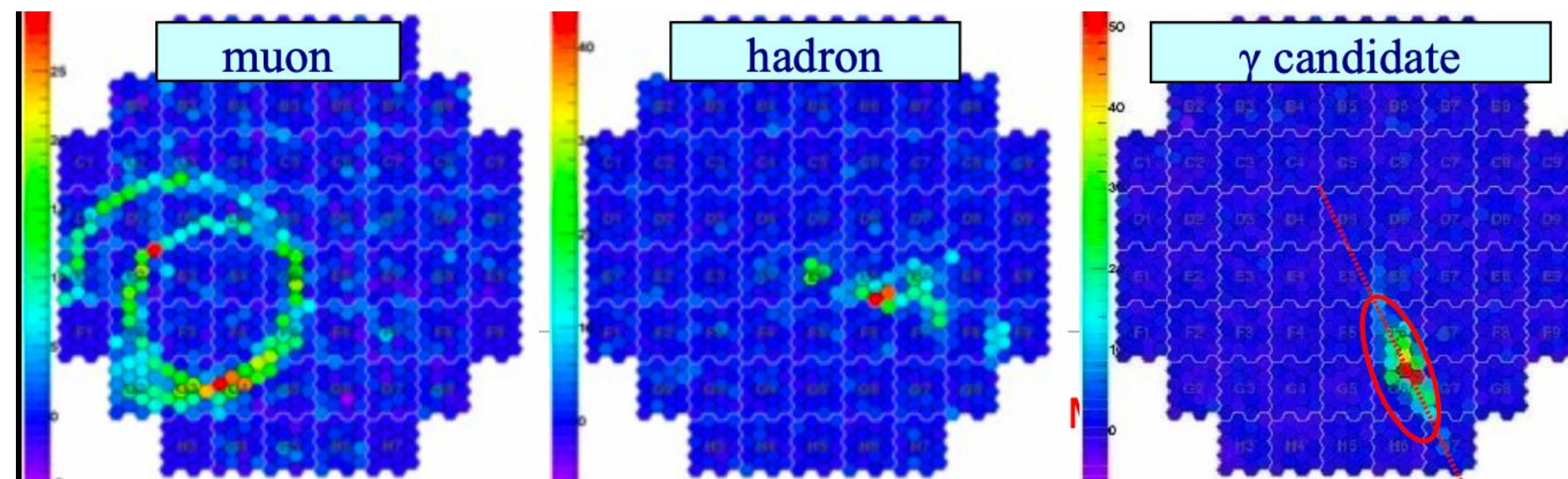


Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

Energy: amount of Cherenkov light
(calorimeter)

Nature: shape of the shower



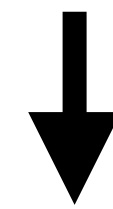
Imaging Atmospheric Cherenkov Telescopes

Reconstruction of particle properties

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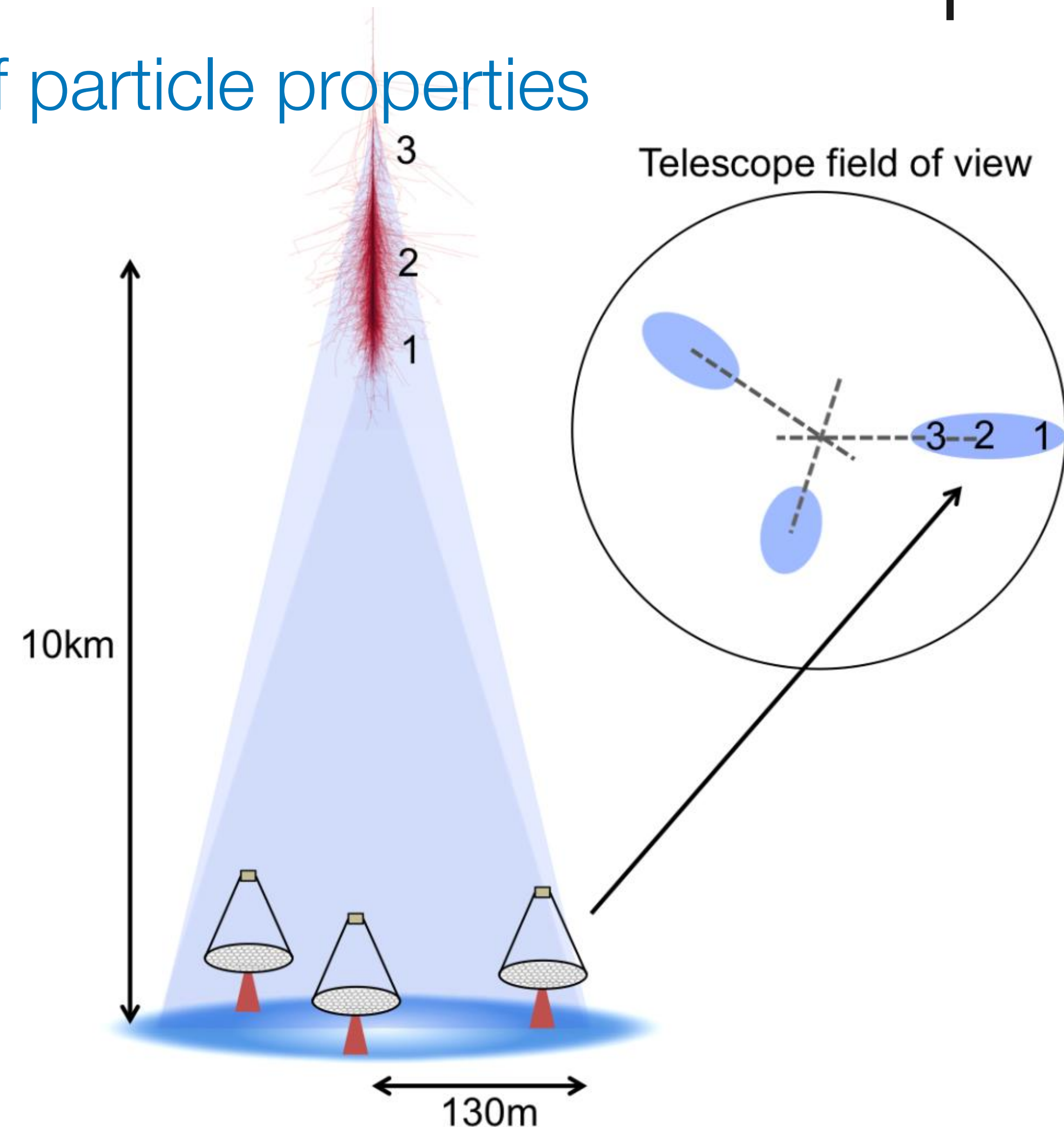
Nature: shape of the shower

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

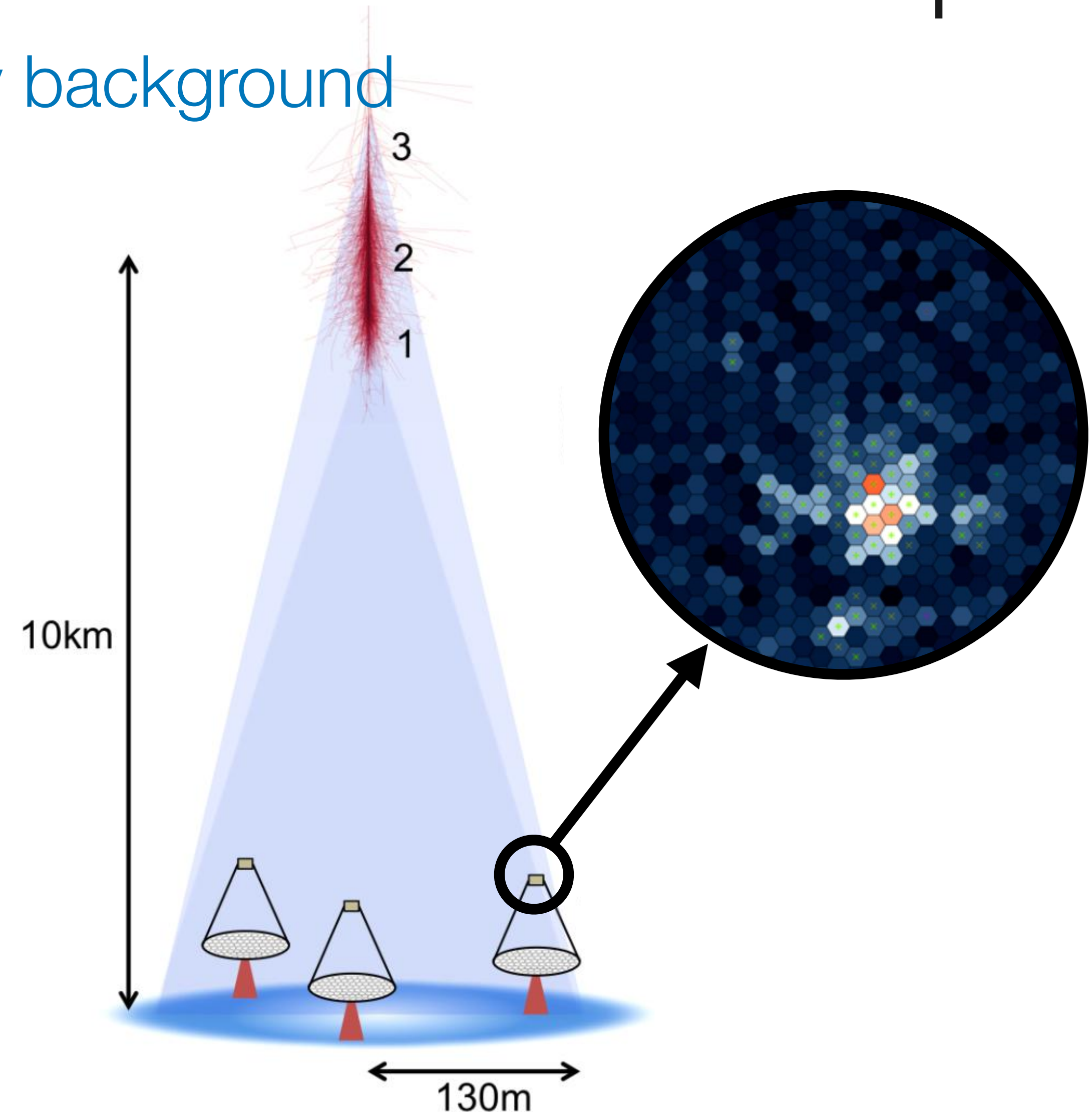
Cosmic-ray background

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

Stereo trigger: $\approx 1/4$

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

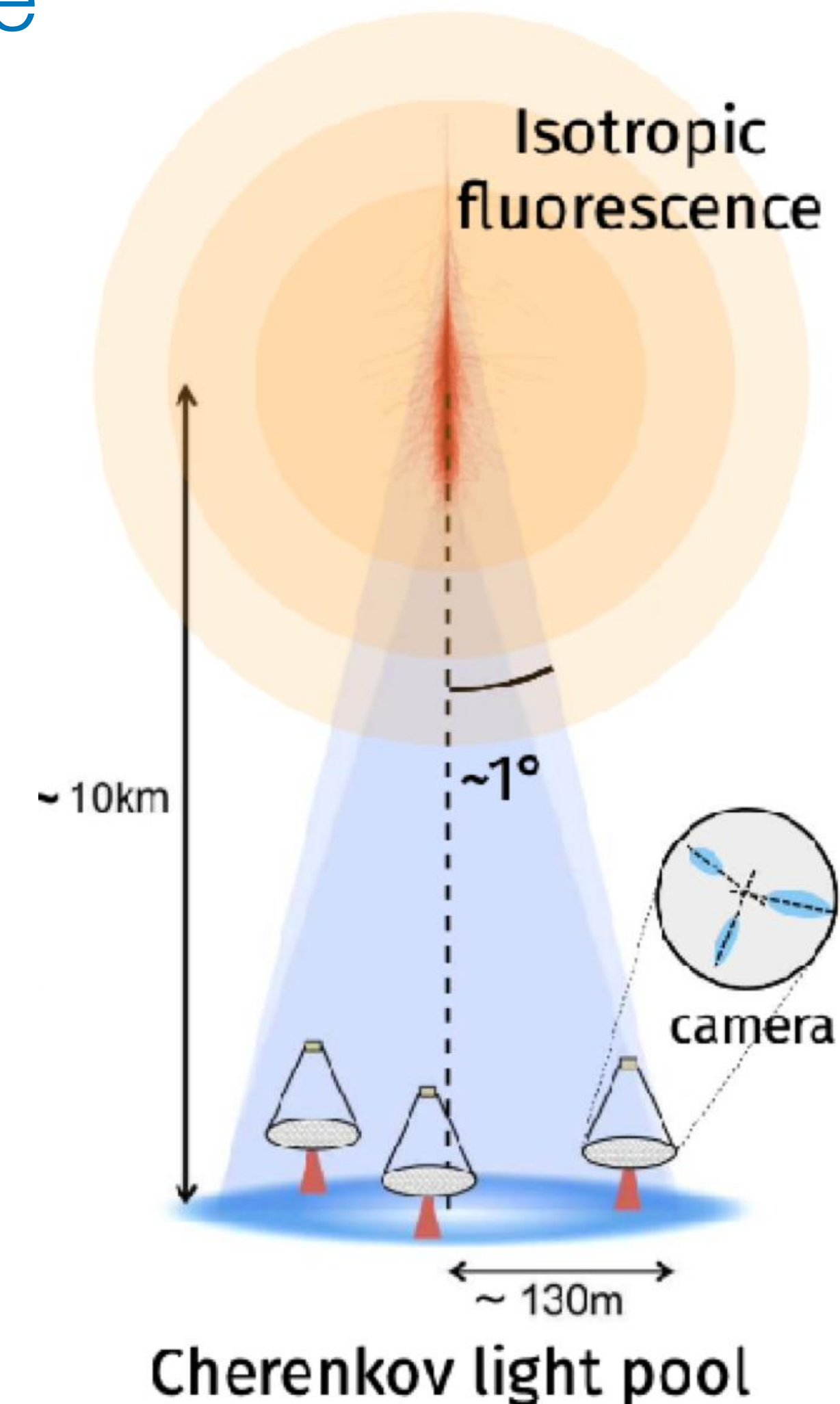
Arrival direction: $\approx 1/100$



Backgrounds

Fluorescence

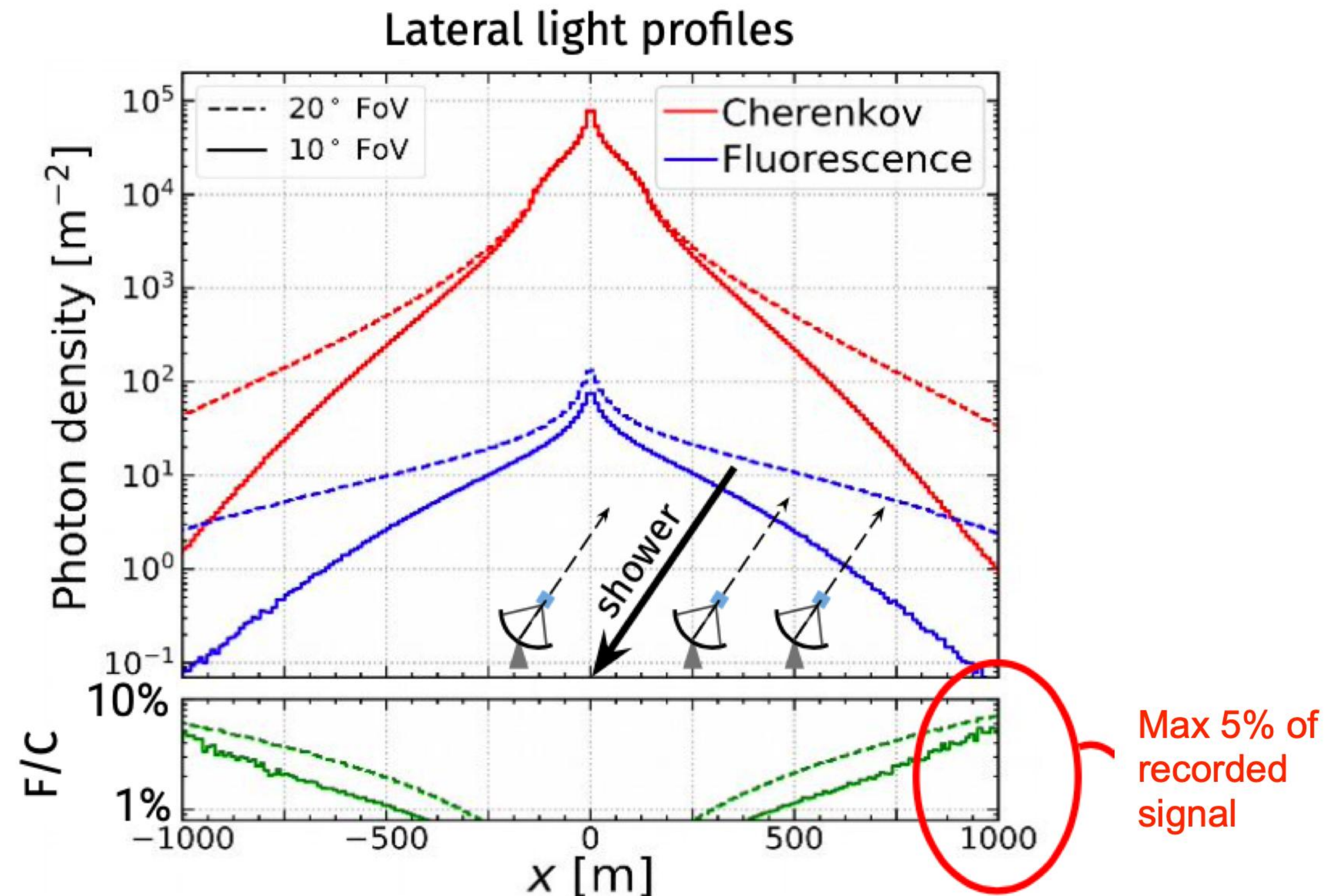
- Fluorescence emission from de-excitation of N_2 states (290-430 nm)
- Less efficient light emission:
 - For 1 GeV electron near ground, 30 photons from Cherenkov light vs 4 photons from fluorescence light (per m track length)
- Longer time profile: microseconds vs 10s of nanoseconds



Backgrounds

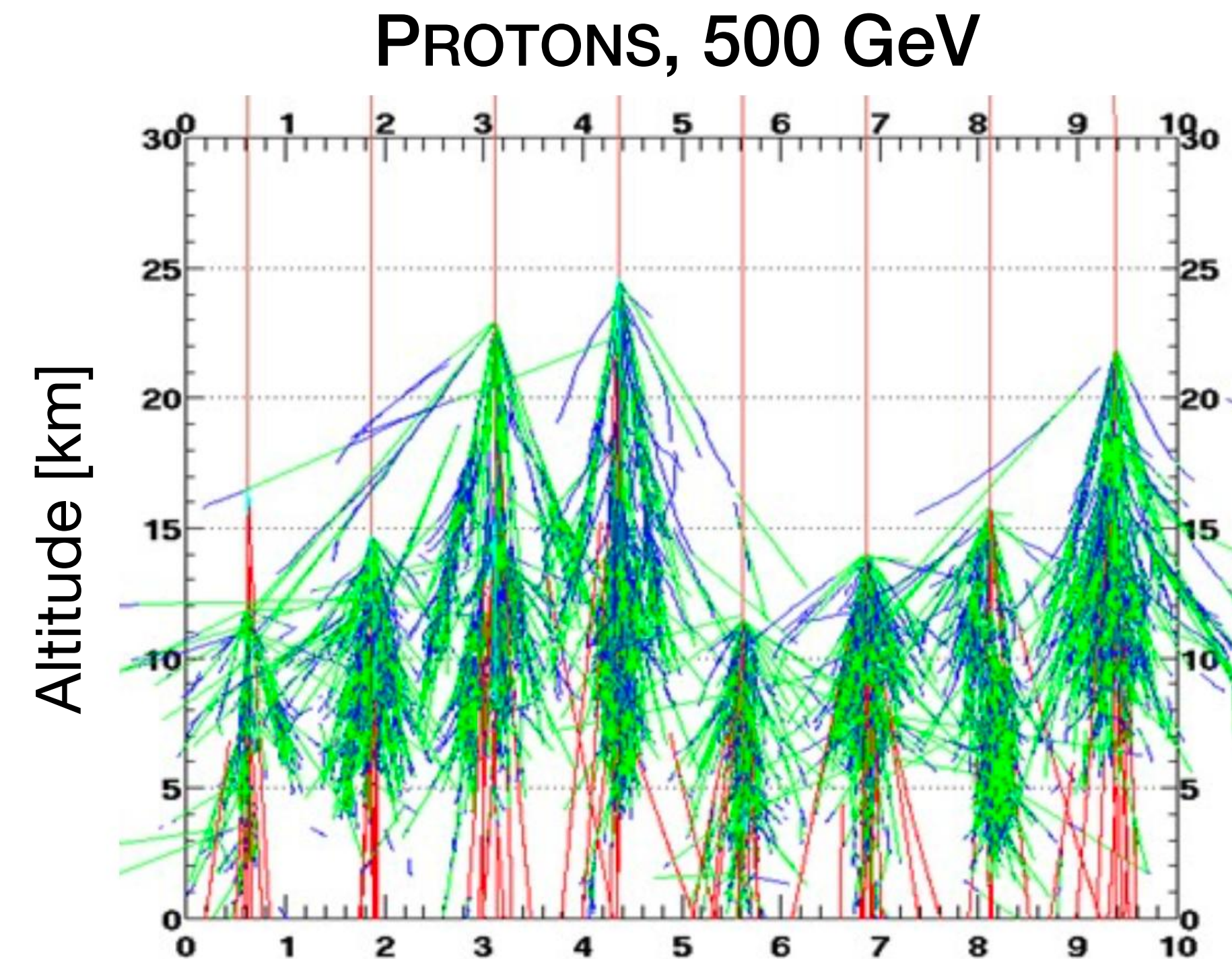
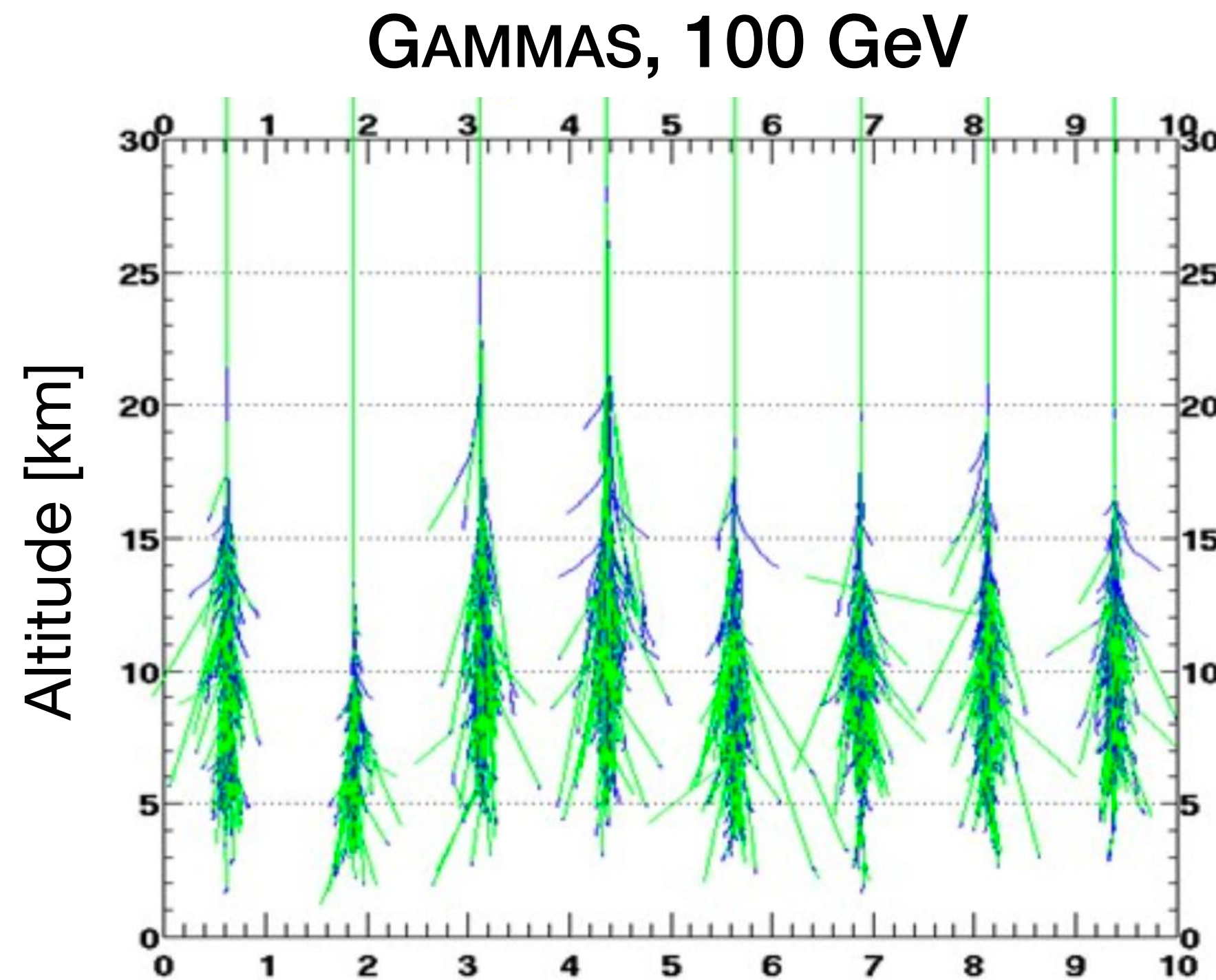
Fluorescence

- 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

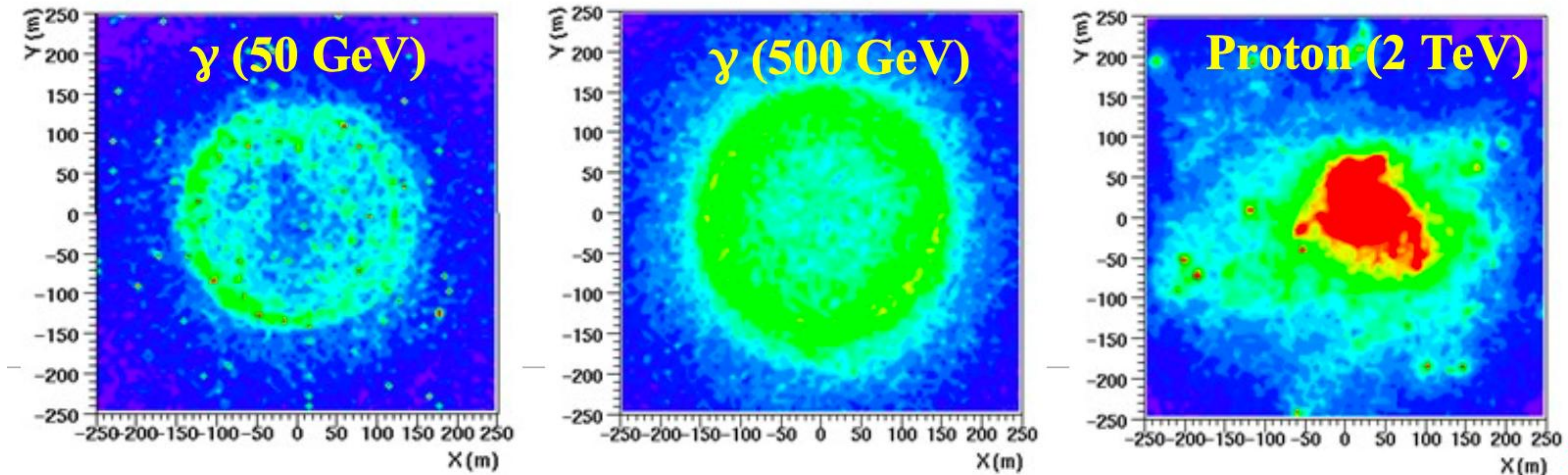


For hadronic showers, the higher transverse momentum from pion production and sub-showers produce a wider shower

→ 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

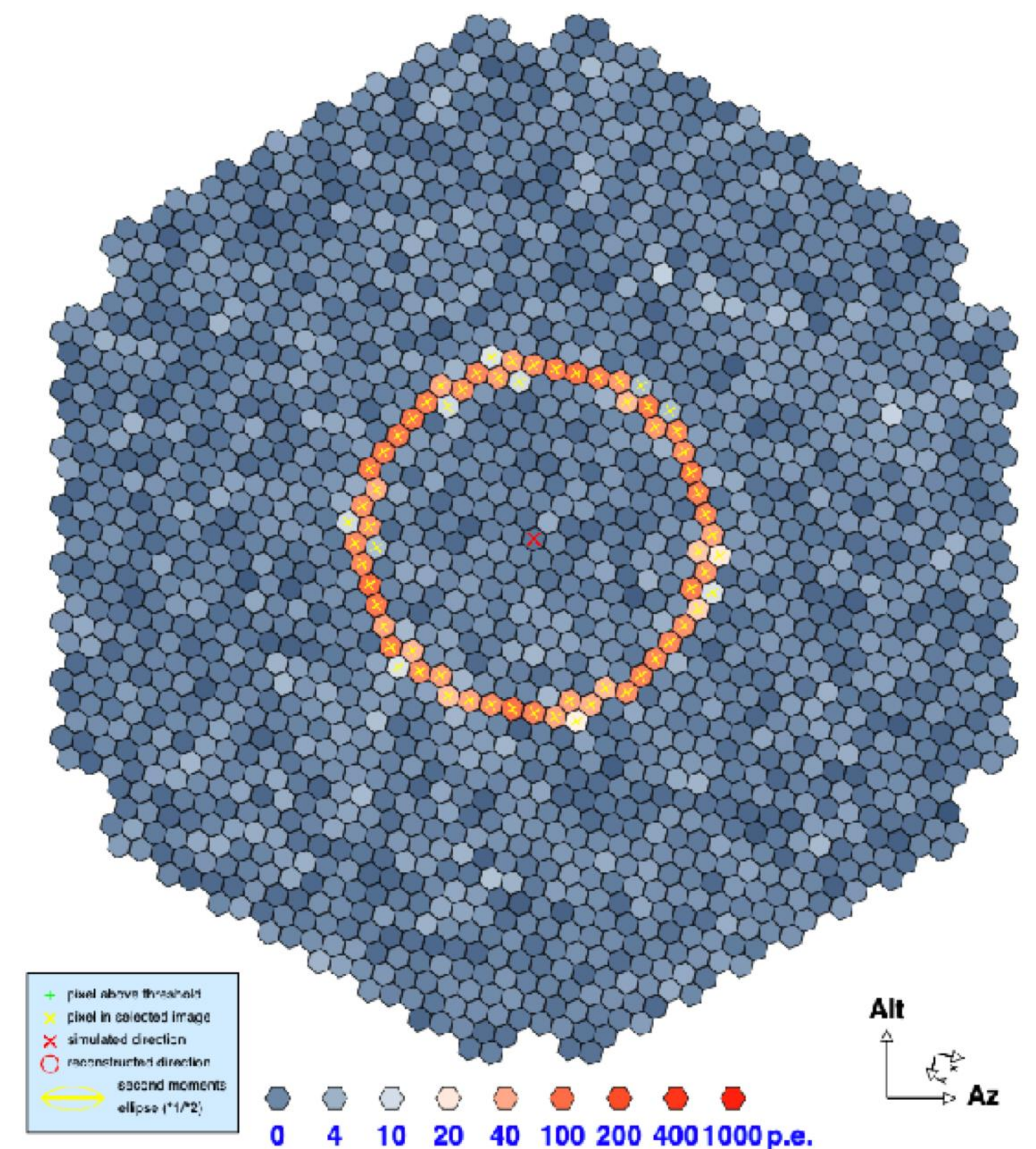
→ **the width of the shower can be used to discriminate gammas from hadrons**

Backgrounds

Hadronic showers: muons

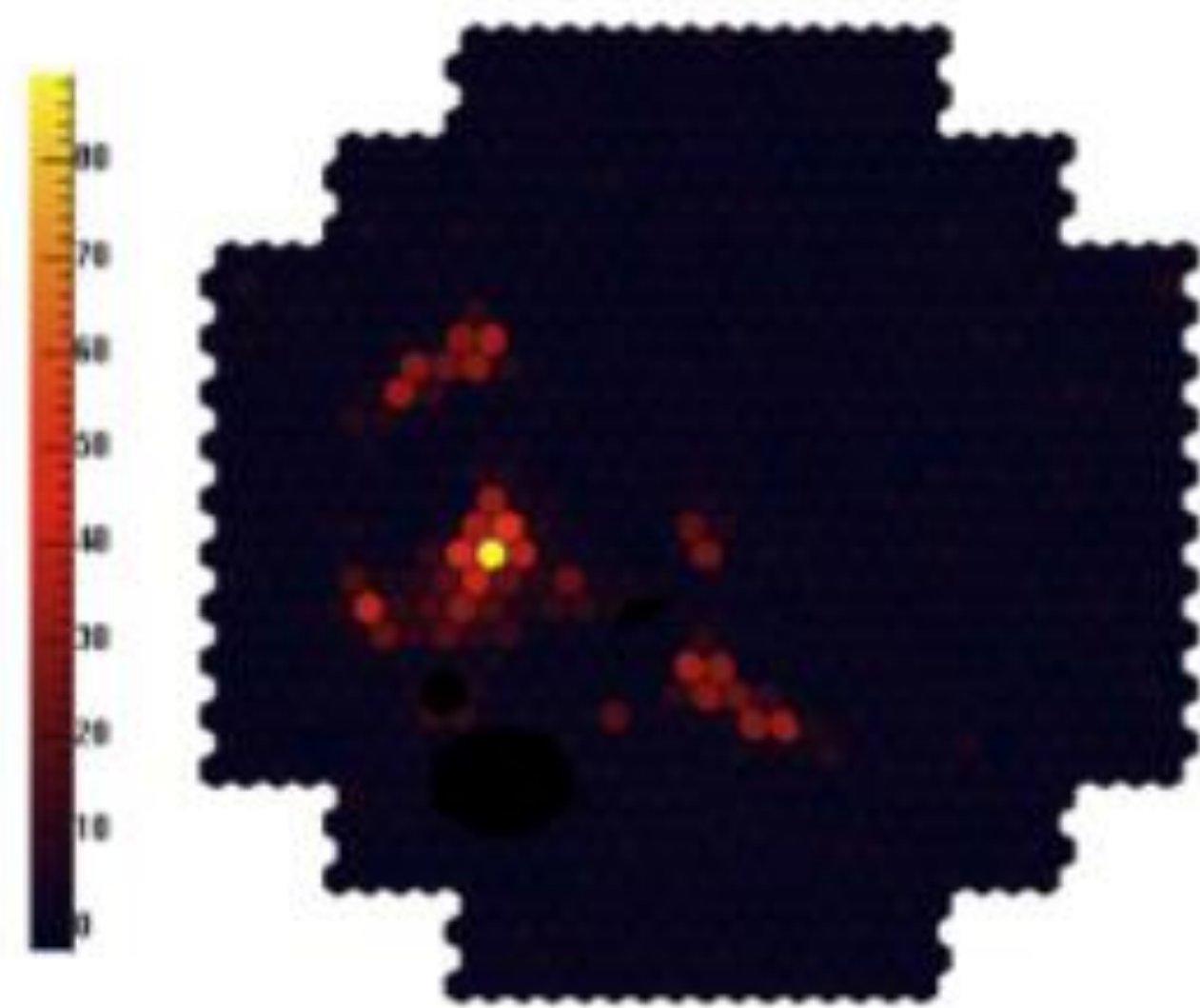
- **Produced in hadronic sub-showers**
- Most muons detected by IACTs are minimum ionizing particles with a long lifetime → large penetration depth
- Travel in straight lines towards the ground with Cherenkov radiation emitted under constant opening angle in a cone around the muon direction of travel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

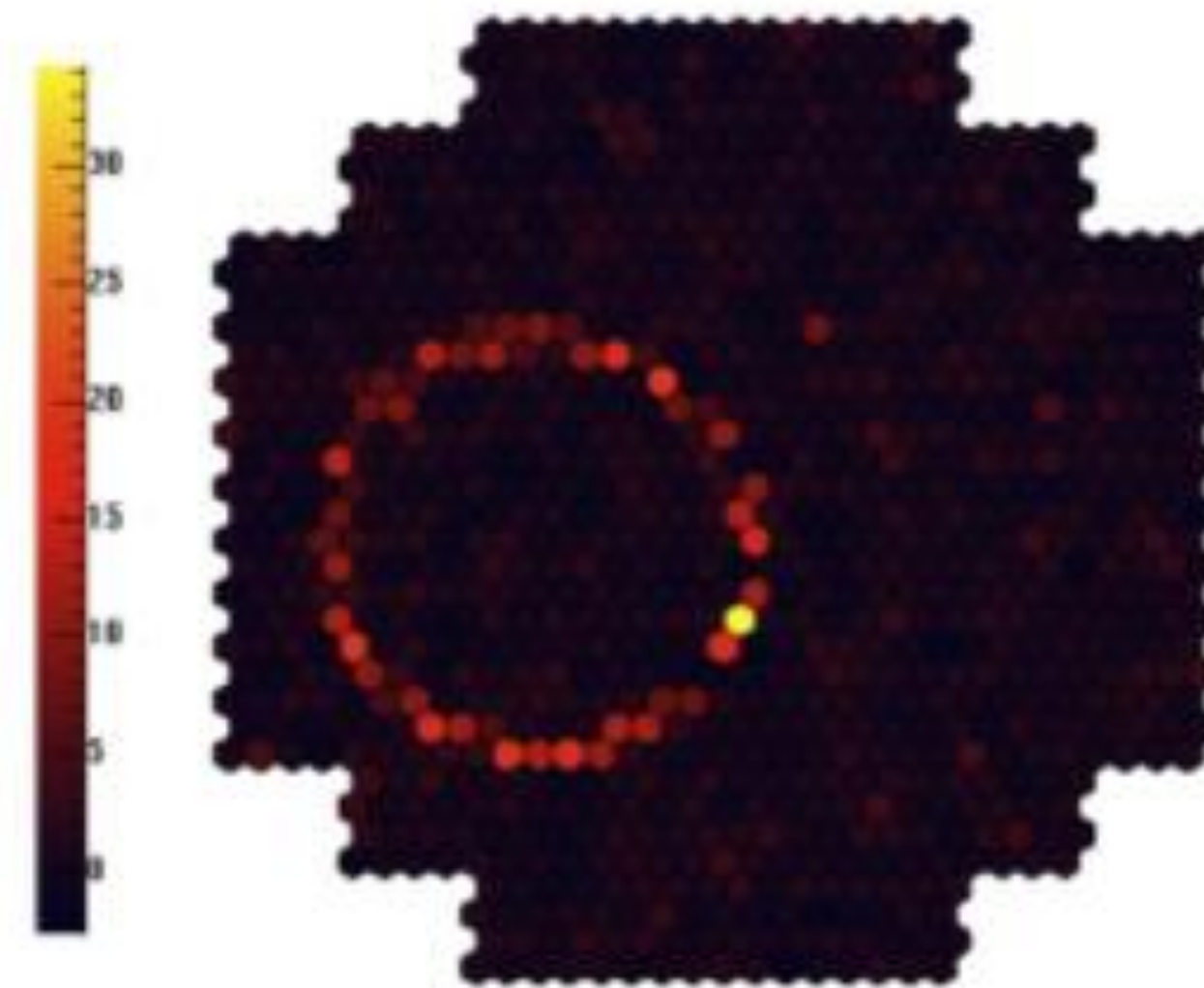


Backgrounds

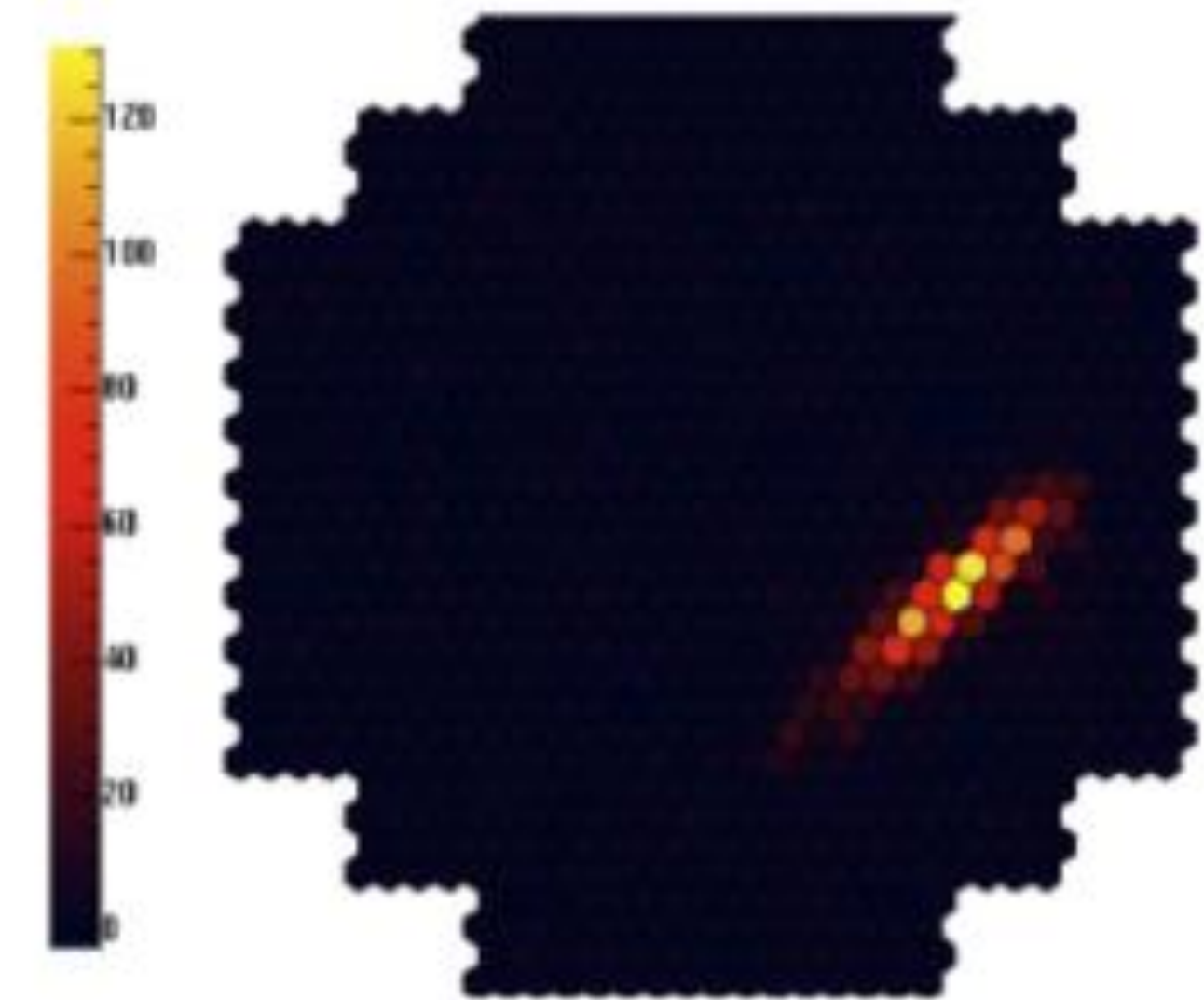
Hadronic showers and muons



Hadronic shower



Isolated muon



Gamma-like event

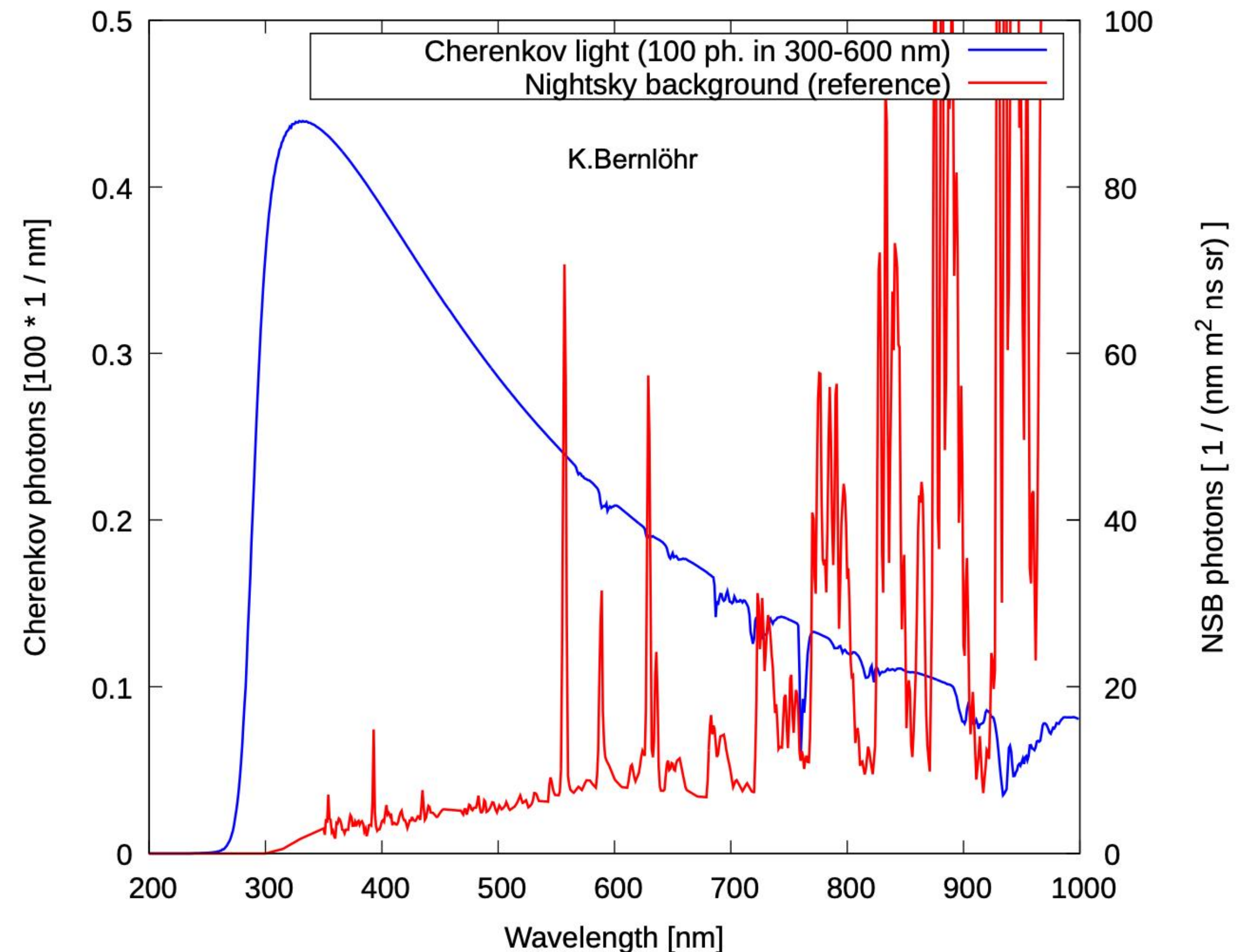
Gamma / hadron discrimination through image topology

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



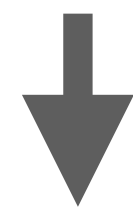
How to build an IACT?

General astronomical requirements

ANGULAR RESOLUTION

What is the smallest object we can resolve?

→ Ability to resolve two nearby objects

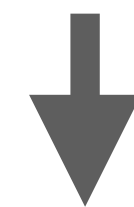


**Telescope optics,
camera pixel sizes**

LIGHT COLLECTING POWER

What is the faintest object we can detect?

→ Ability to detect weak Cherenkov flashes

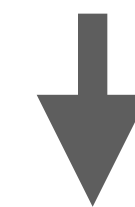


**Mirror area and reflectivity,
camera sensitivity**

FIELD OF VIEW (FOV)

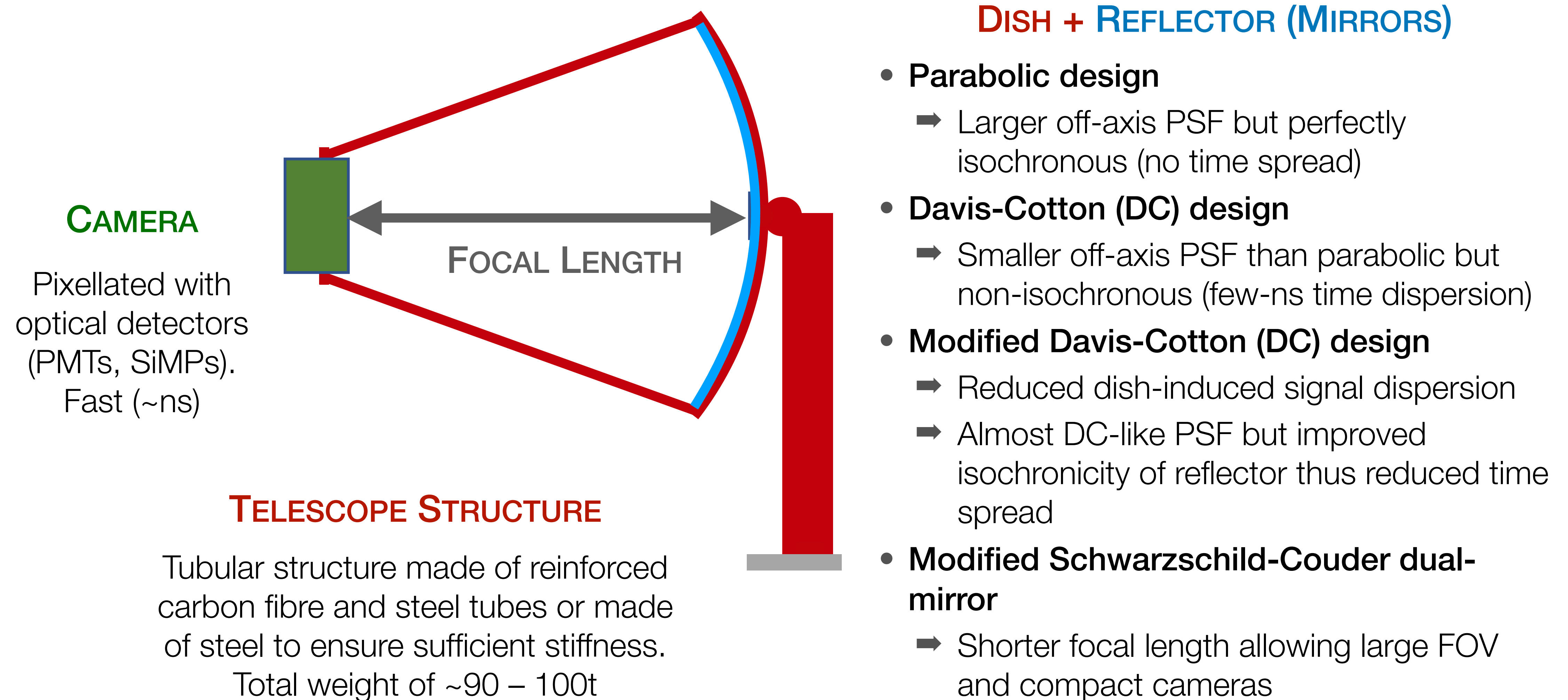
What is the largest object we can image?

→ Solid angle of the sky covered



**Telescope optics,
camera pixel sizes**

An IACT's prototype



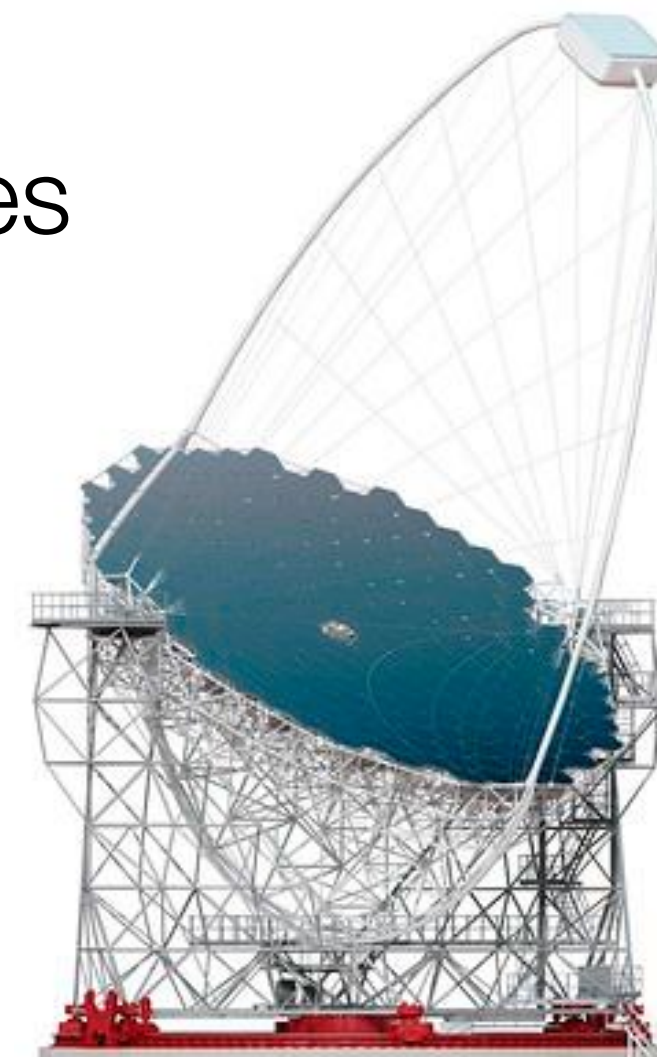
IACTs: how big? How many?

A compromise between size and number...

Bigger dishes:

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

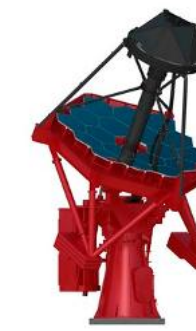
LST



MST

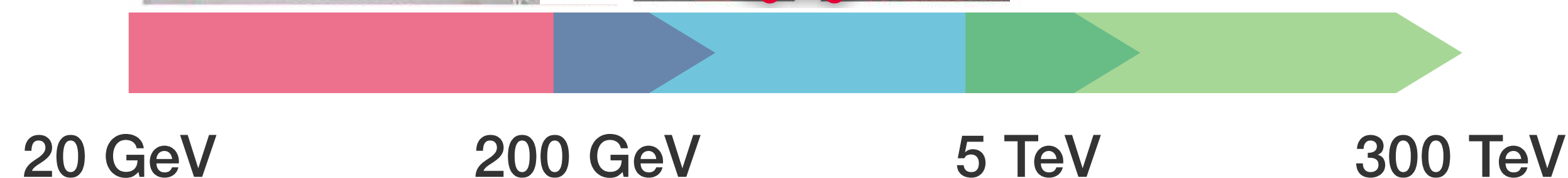


SST



Smaller dishes:

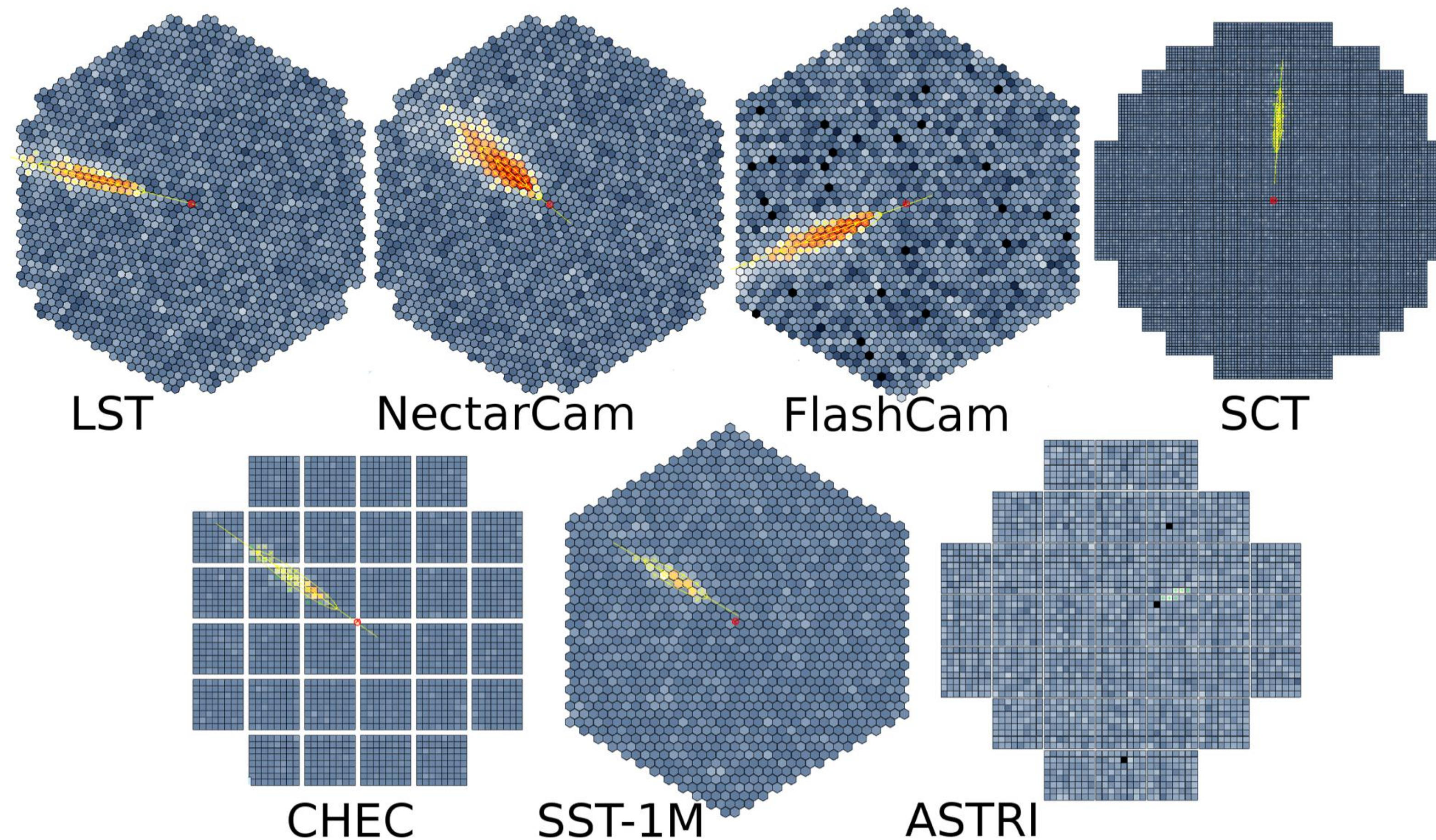
- Greater sensitivity at medium to high energies
- Larger FOV ($\sim 9^\circ$)



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

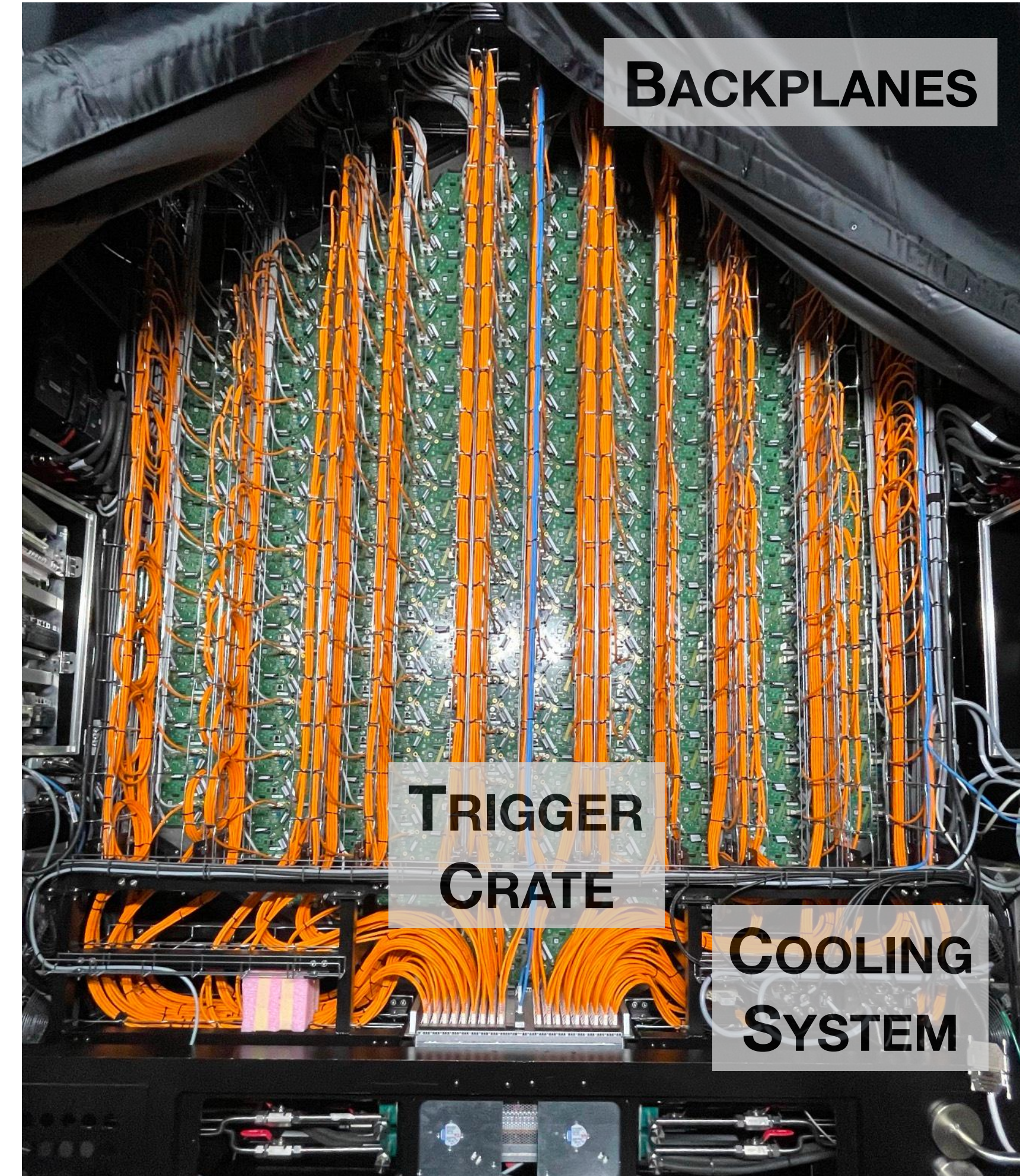
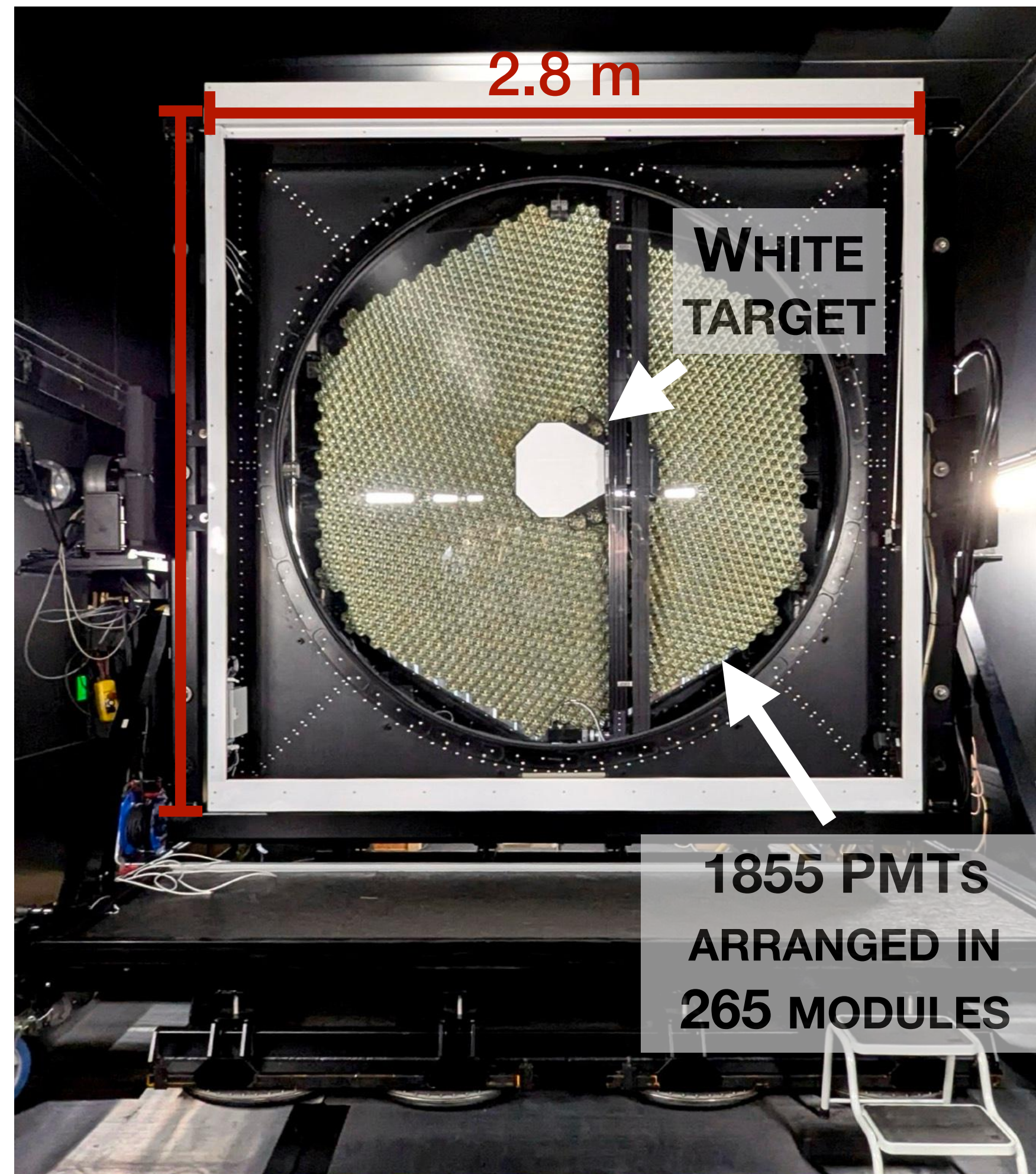
IACT cameras

The CTAO designs



IACT cameras

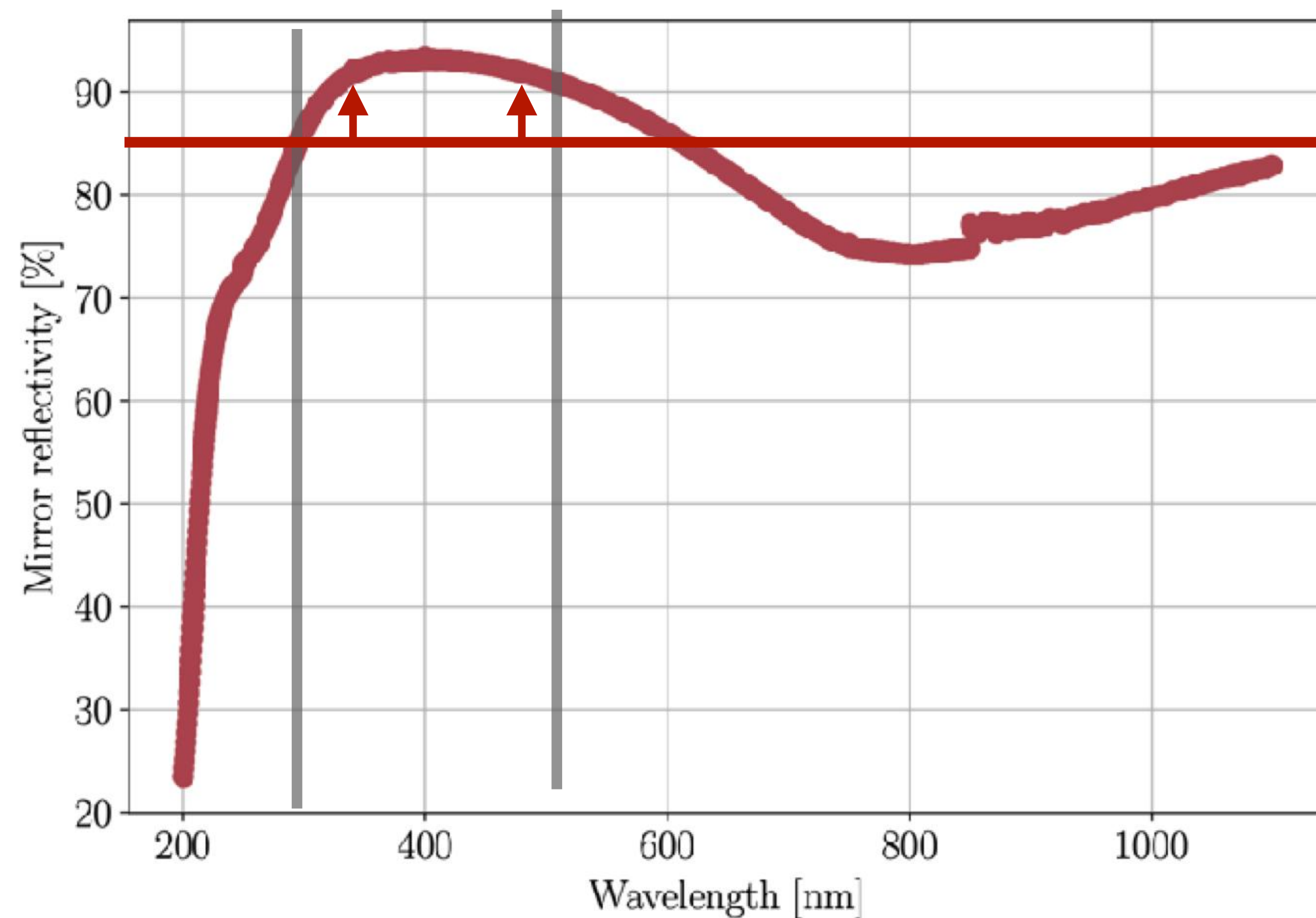
NectarCAM camera at IRFU/CEA Paris-Saclay



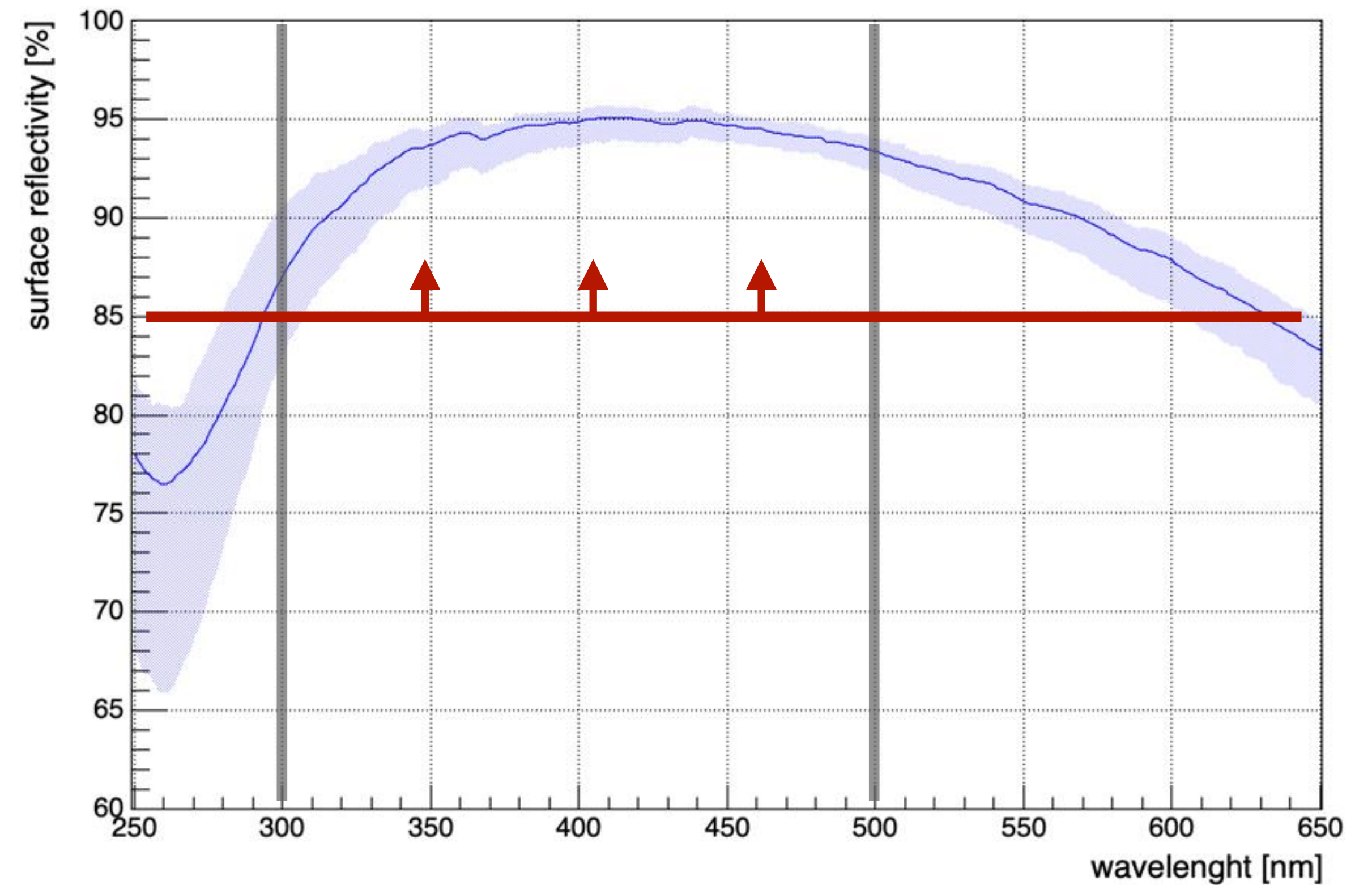
IACT mirrors

Reflectivity > 85% in [300, 500] nm

LST



MST

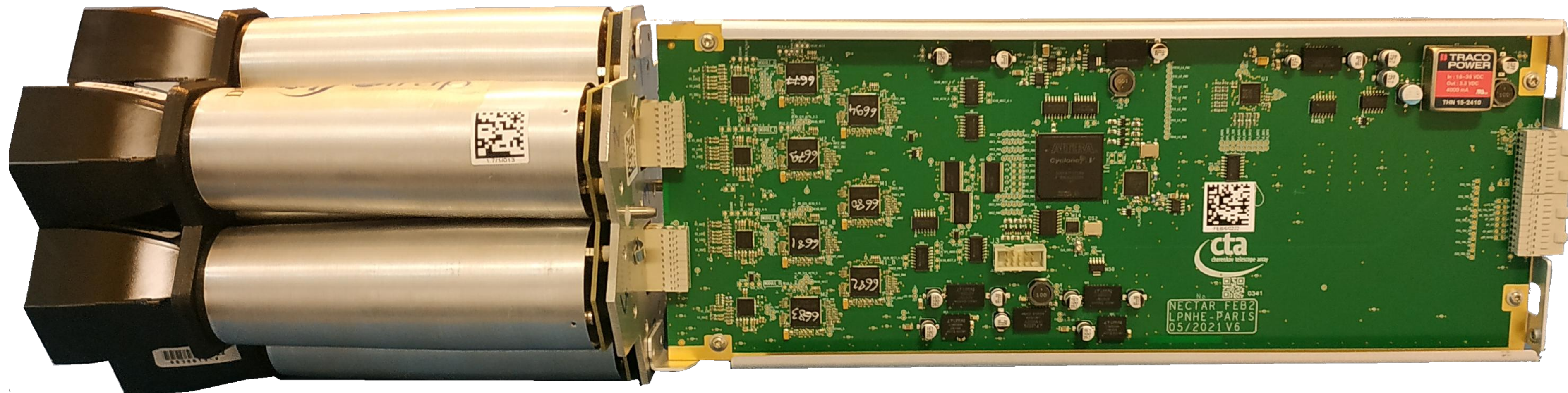


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

FRONT END BOARD

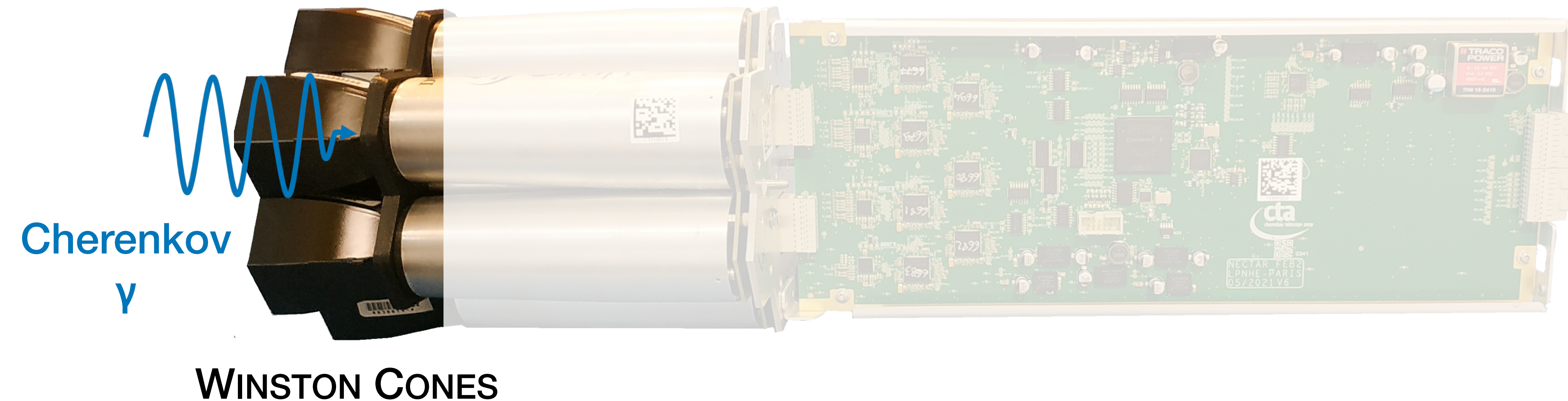


From photons to photoelectrons

Formation of the electric signal

FOCAL PLANE MODULE

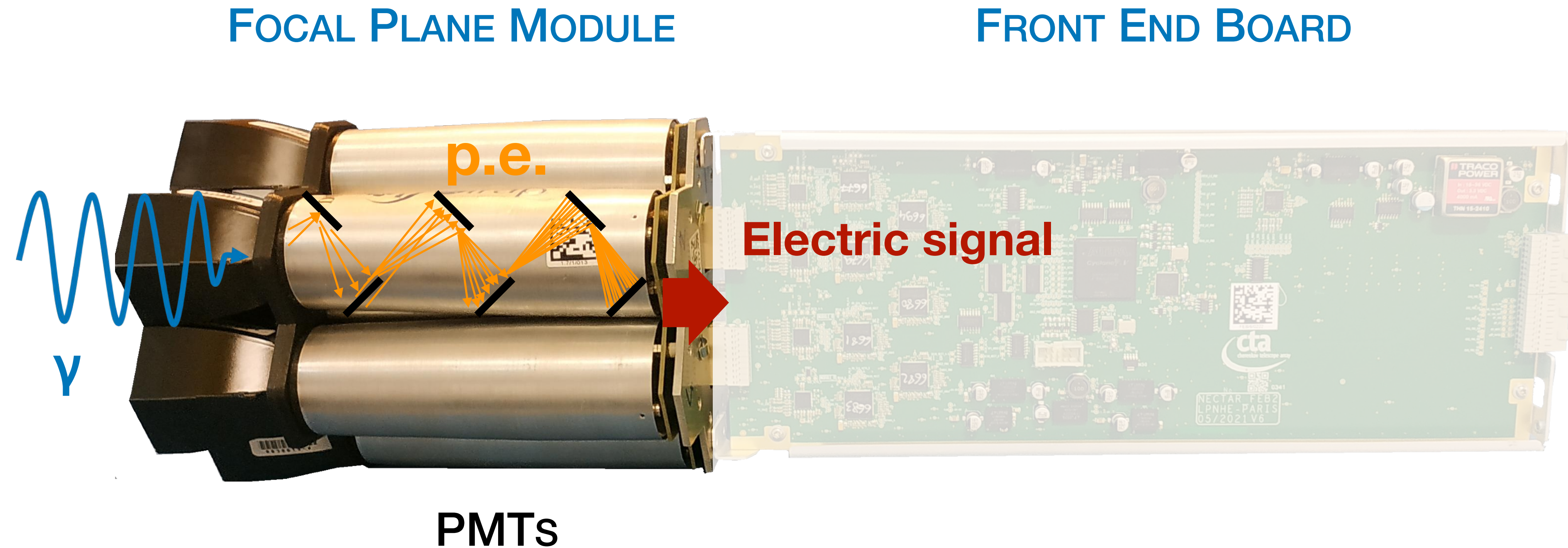
FRONT END BOARD



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

From photons to photoelectrons

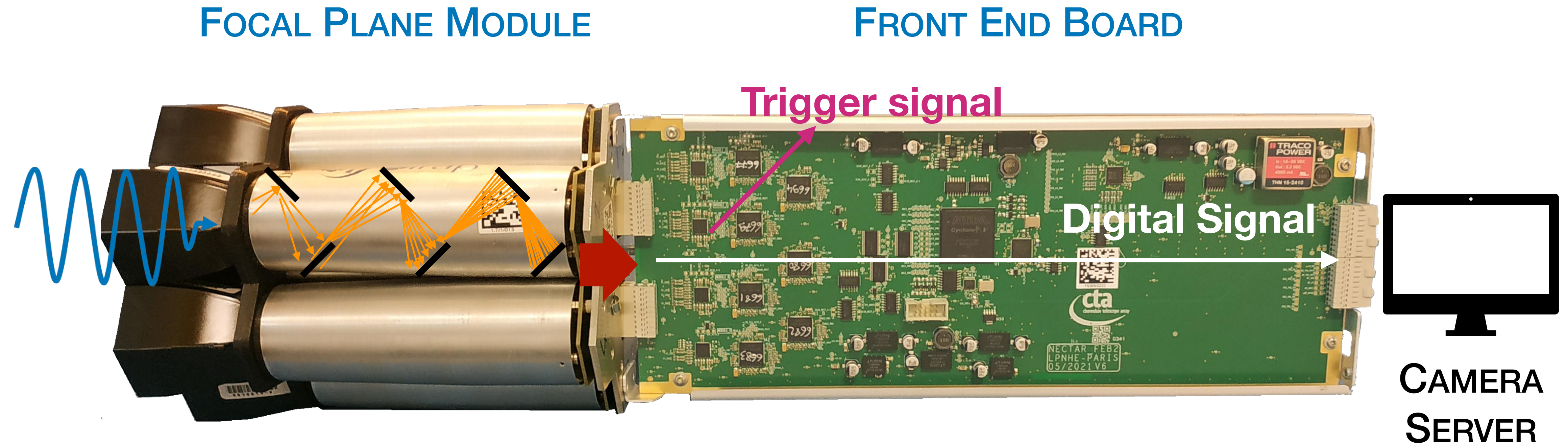
Formation of the electric signal



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

From photons to photoelectrons

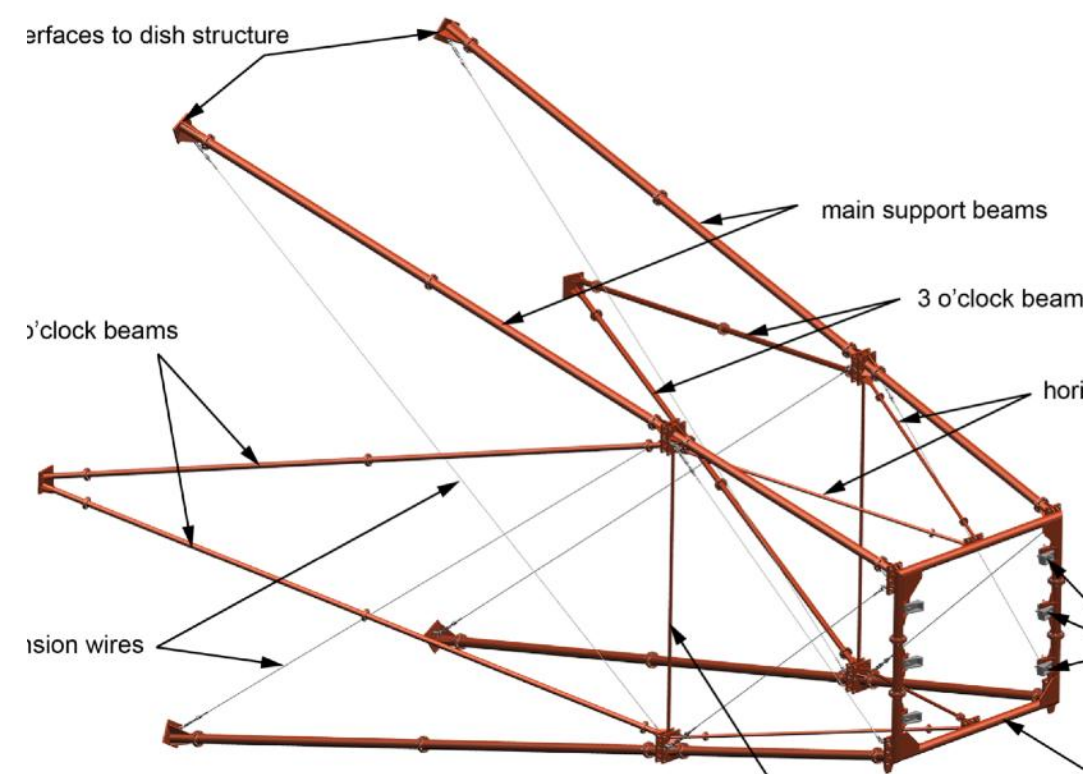
Formation of the electric signal



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

From photons to photoelectrons

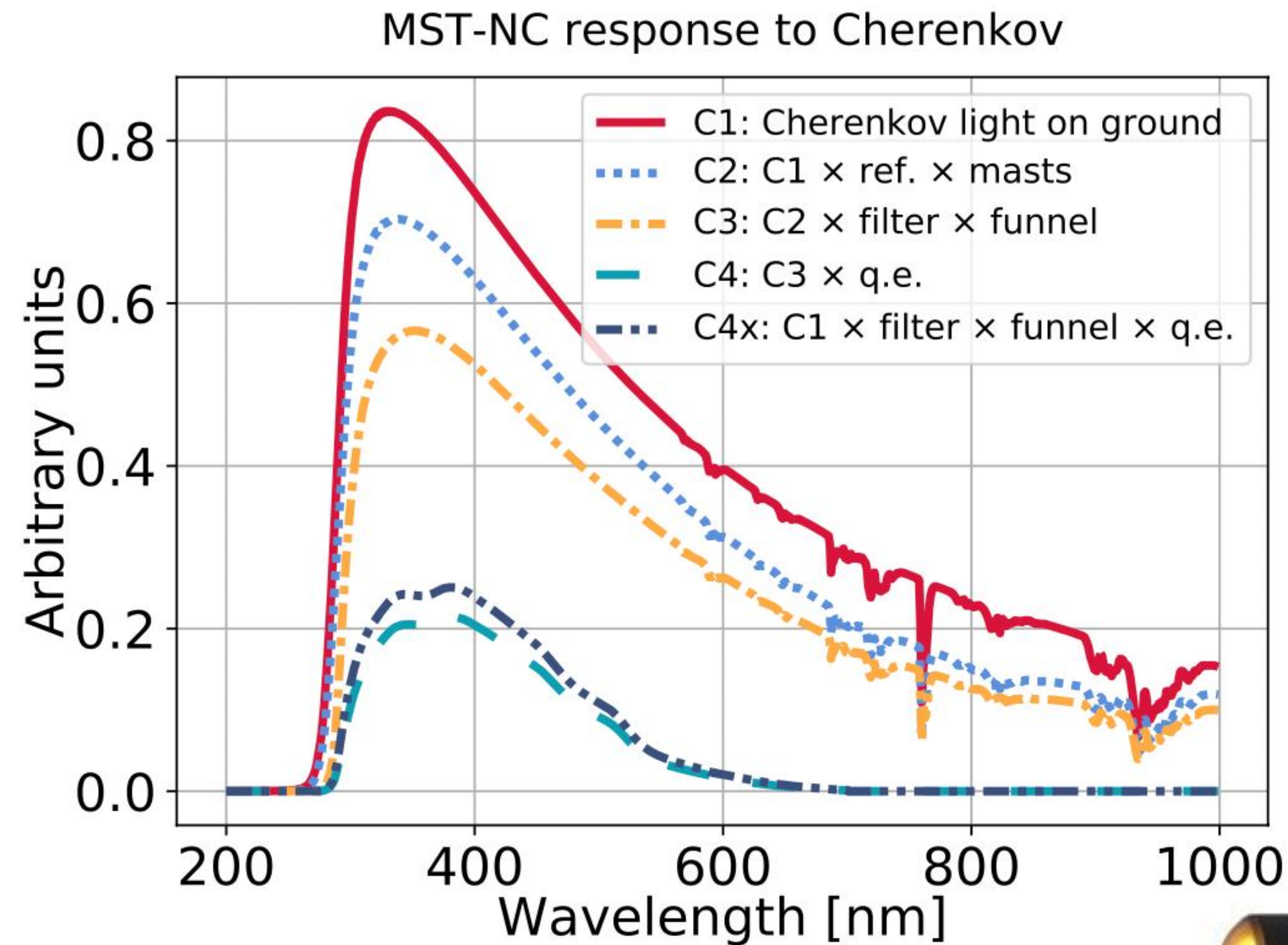
Impact of components on Cherenkov light detection efficiency



**TELESCOPE
STRUCTURE**



MIRRORS



Credit: J.F. Glicenstein



ENTRANCE WINDOW



**LIGHT
GUIDES**

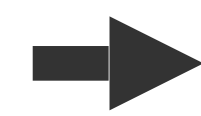


**HAMAMATSU
PMT**

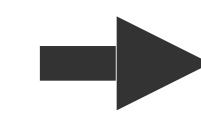
Triggering an IACT array

From the single pixels to an array trigger

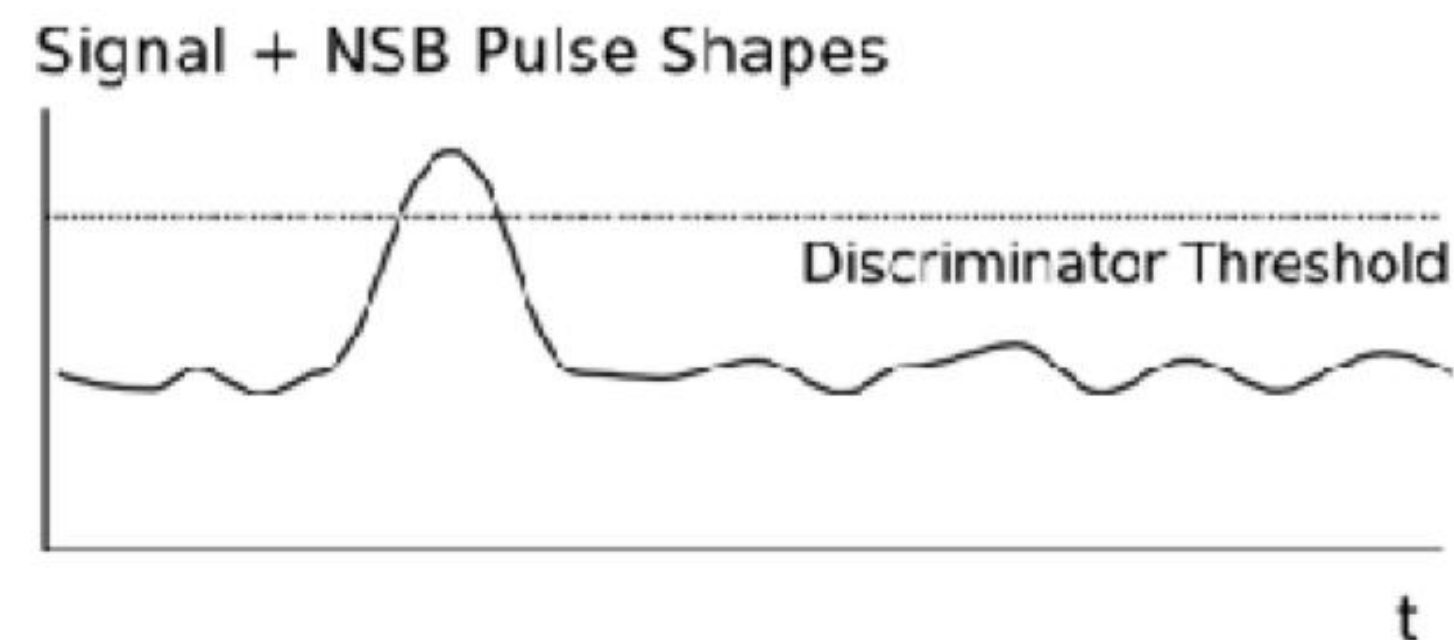
L1: pixel trigger



L2: telescope trigger



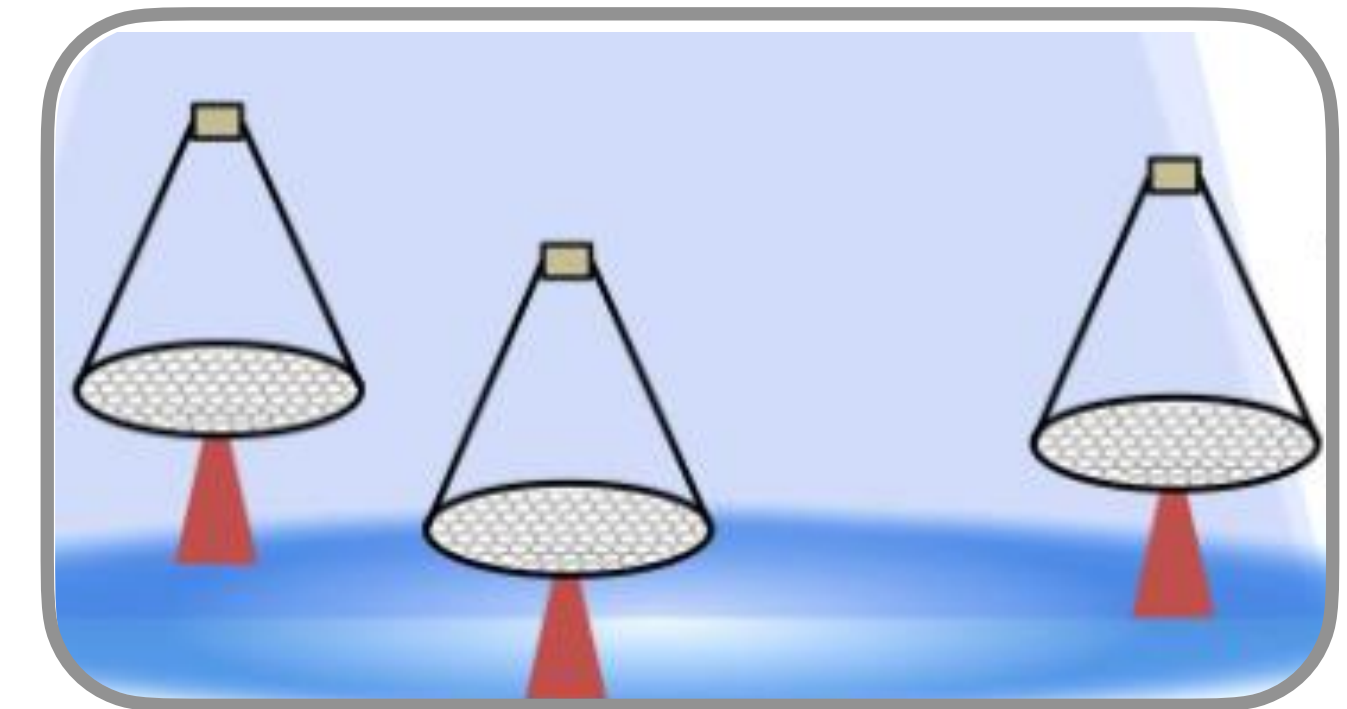
L3: array trigger



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

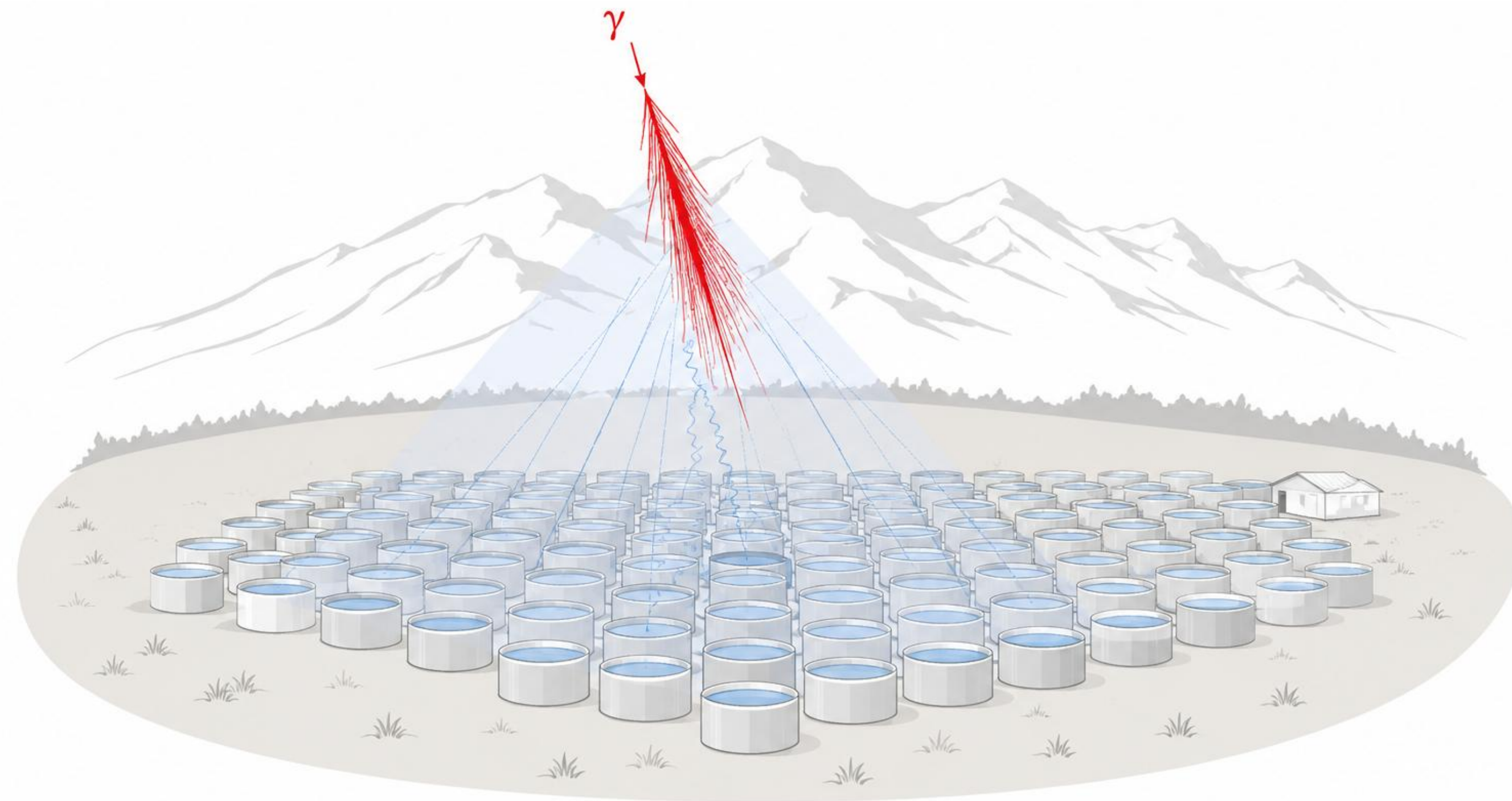
Summary of IACTs

ADVANTAGES

- High angular ($<0.1^\circ$) and energy ($<15\%$) resolution
- Very good sensitivity
 - Many orders of magnitude better than *Fermi*-LAT in overlapping energy range
 - Great for short-term variability
- Cheap! (ground-based)
- Upgradable!
 - e.g. add more telescopes to get larger effective area

DISADVANTAGES

- Small(ish) Field-Of-View (3° - 10°)
 - Non uniform exposure $\rightarrow$ must know where to look
- Small duty cycle
 - Can't observe in day or with bright moon!
 - ≈ 1000 - 1400 hours/year
- No full-sky coverage for single instrument
 - Limitation of being on Earth
- Limited by atmosphere quality and ambient light conditions



WCDs: detection principles

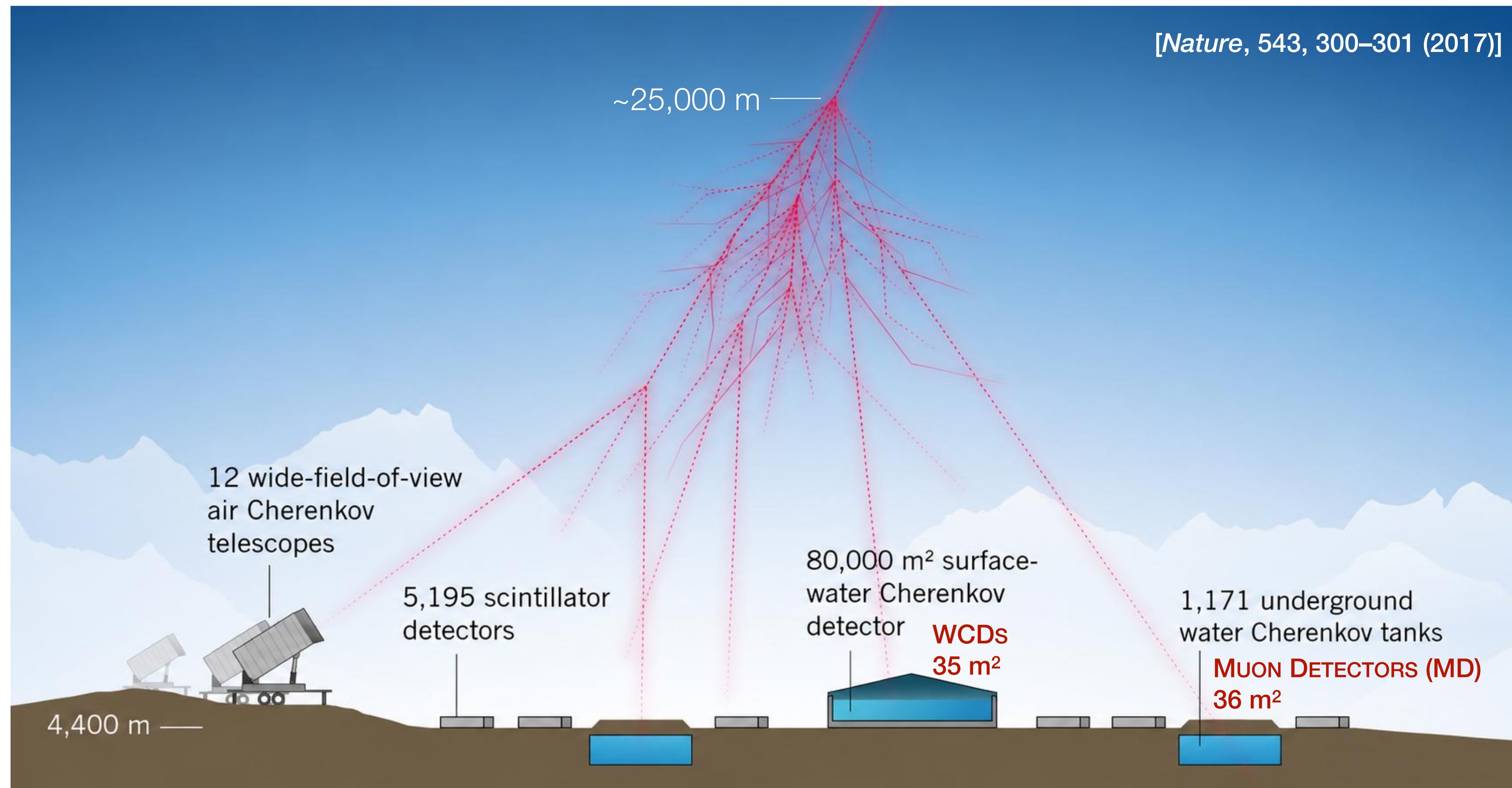
Water Cherenkov Detectors

Detectors: HAWC (4100 m)



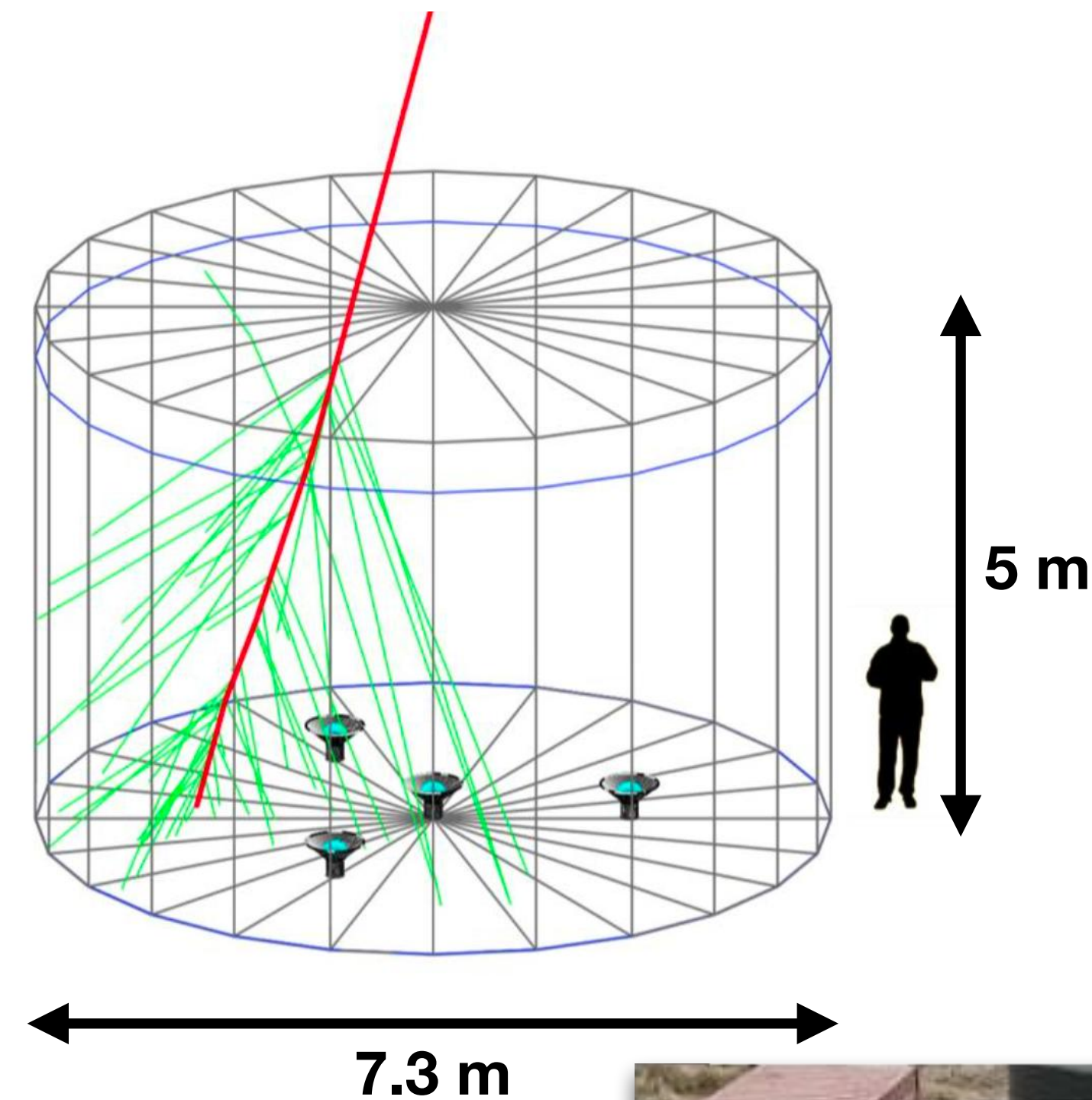
Water Cherenkov Detectors

Detectors: LHAASO (4400 m)



Water Cherenkov Detectors

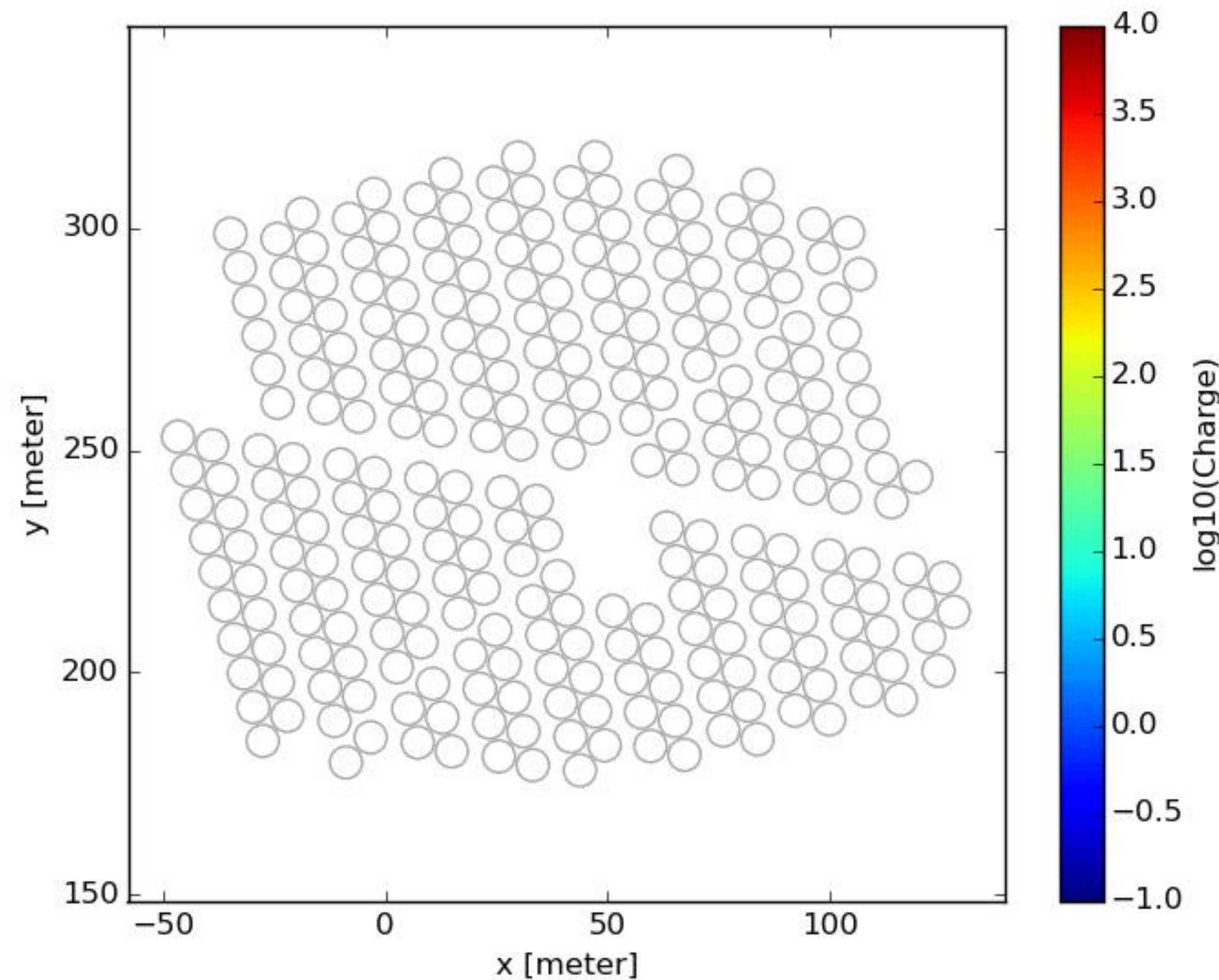
Detectors



- 5m tank $\rightarrow$ 12 radiation lengths ($X_0 \sim 40 \text{ g/cm}^2$)
 - Gamma conversion
 - EM showers near top of tank except for highest energy shower particles
- Muons pass through without interaction – long path length
- Cherenkov light
 - Angle $\sim 41^\circ$
 - Yield: 300 photons / cm

Water Cherenkov Detectors

Event reconstruction



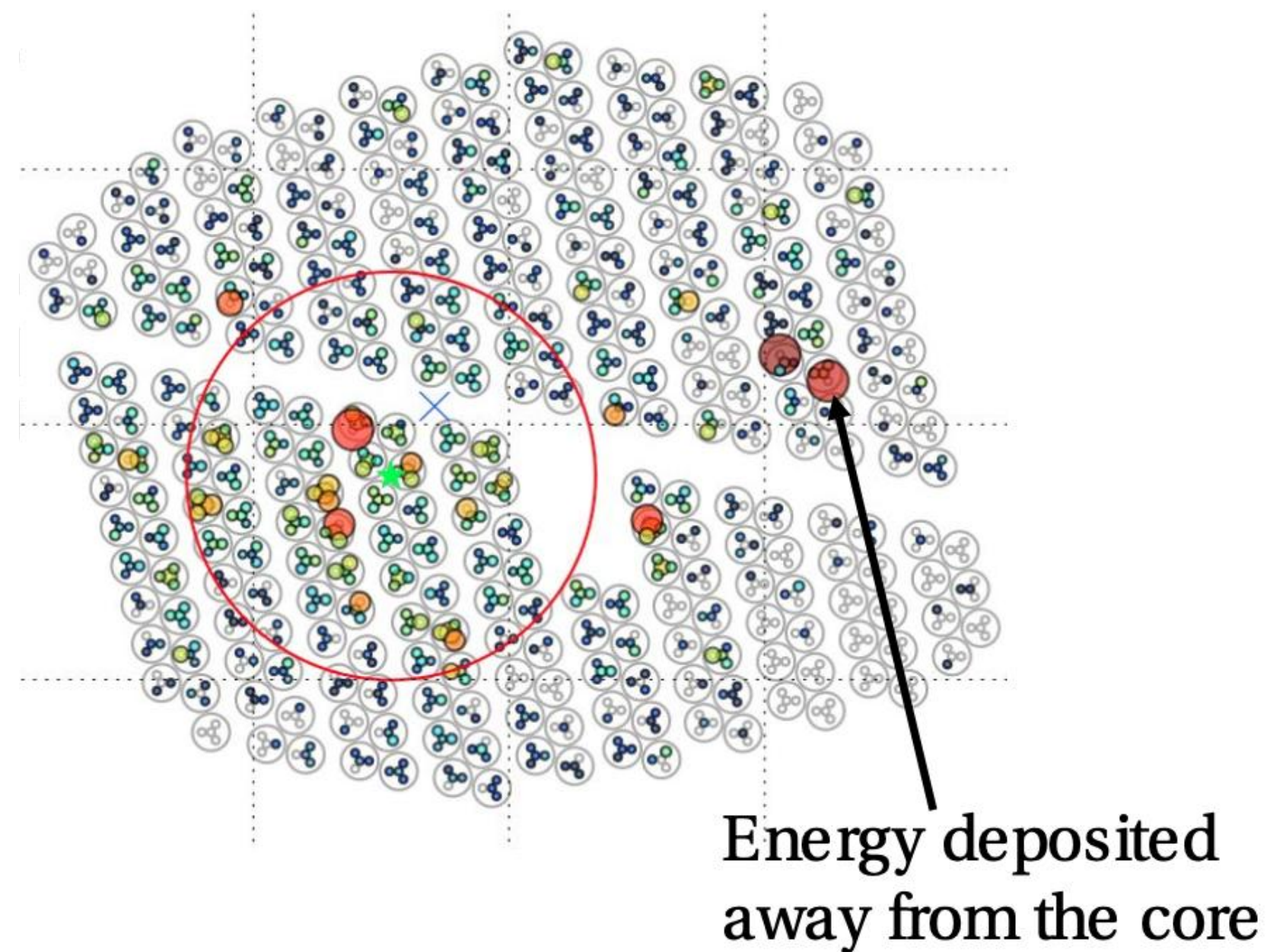
- **Direction** → **Timing**
 - Determined by arrival time differences recorded at different detectors as the shower front sweeps through the detector plane
 - Time resolution ~ 1 ns over 100 m lever-arm → angular resolution $\sim 0.2^\circ$
- **Energy** → **Size**
 - Ground-level size but big fluctuations doing to $X_{\max}$ differences / shower development
- **Nature = gamma/hadron separation** → **Shape**

Water Cherenkov Detectors

Shower classification: gamma/hadron separation

COSMIC-RAY SHOWERS

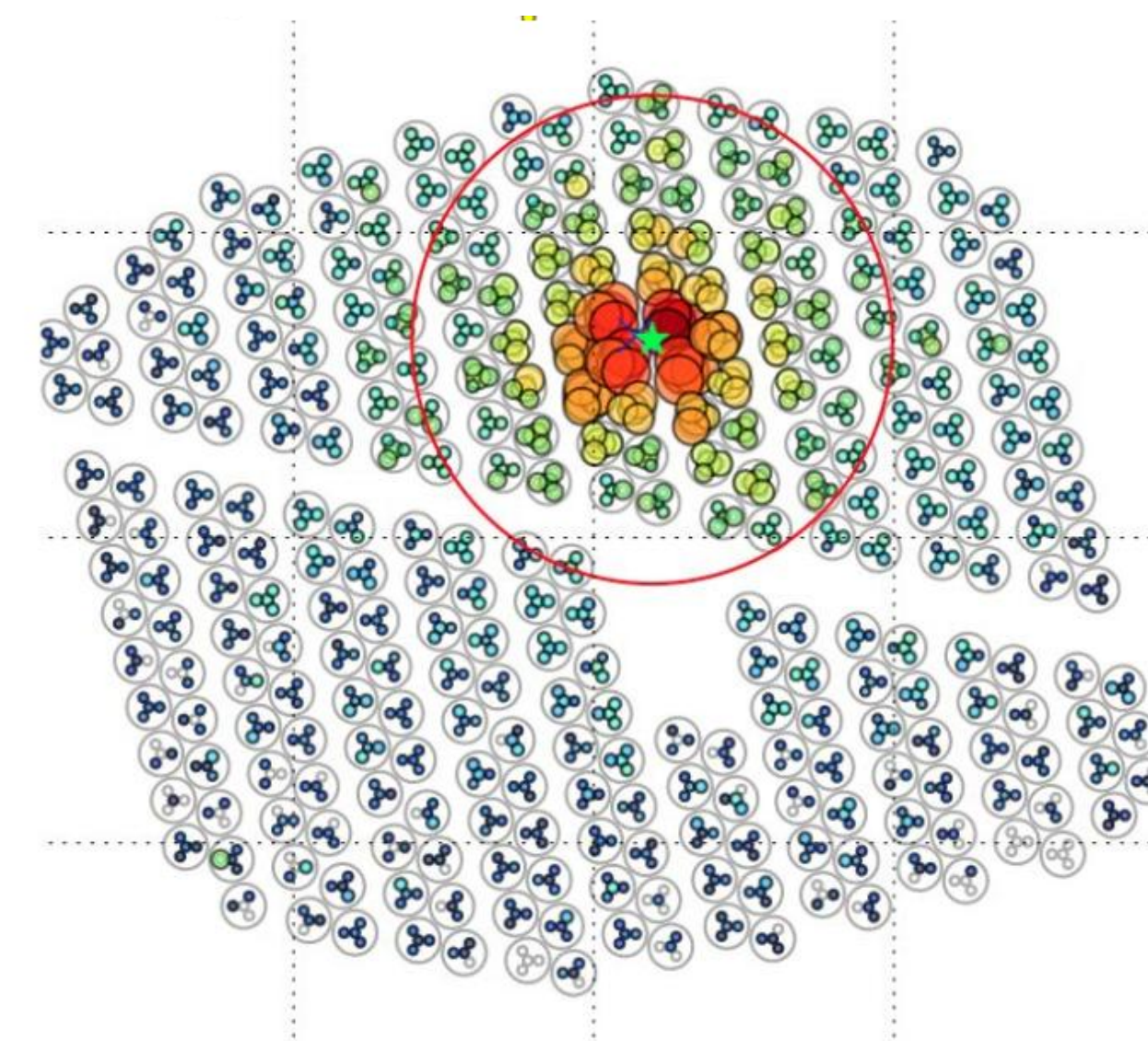
Simulated proton with $E = 24 \text{ TeV}$, $\theta=44^\circ$
837 hit PMTs



“Hot” spots are more dispersed

GAMMA-RAY SHOWERS

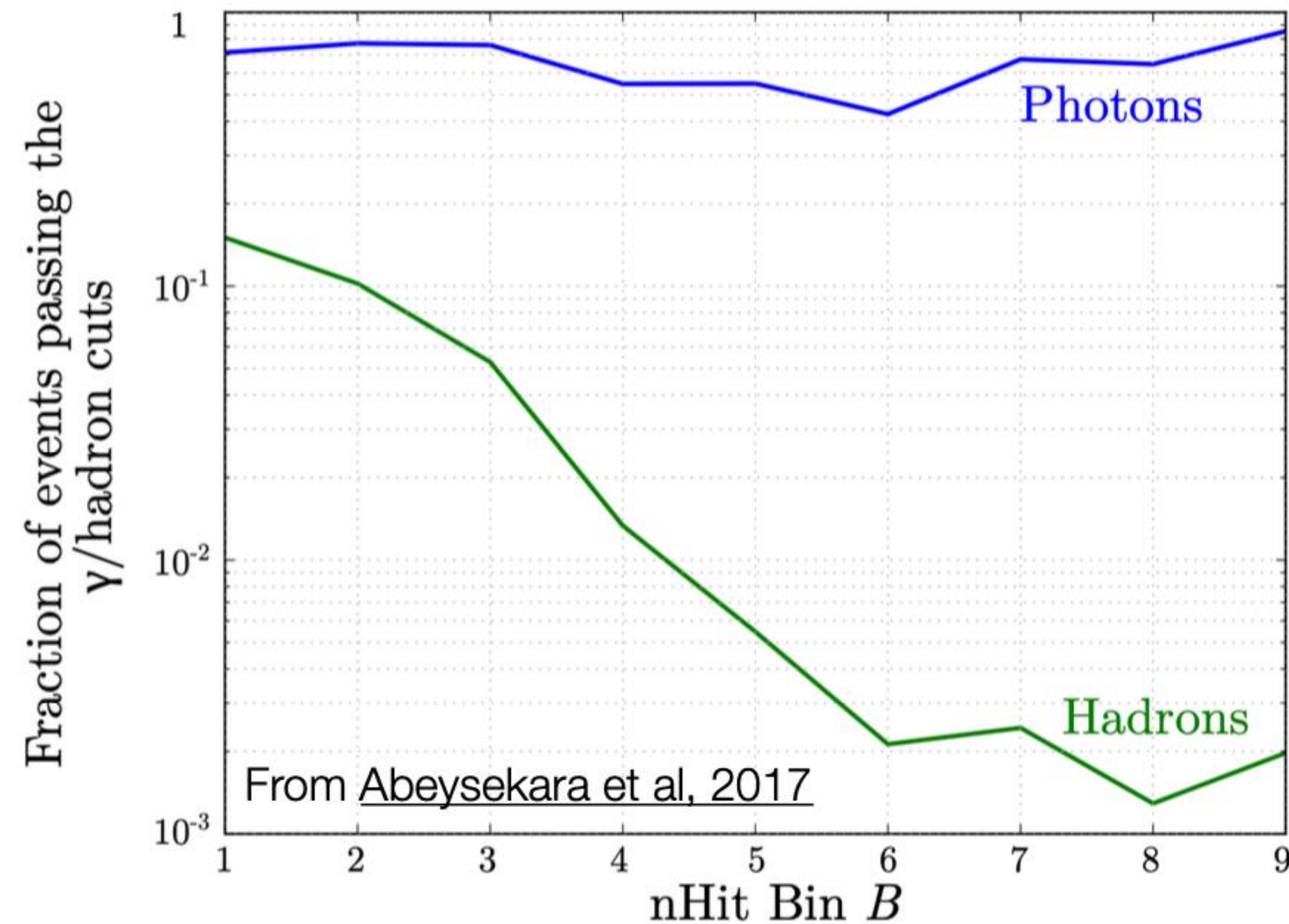
Simulated γ -ray with $E = 21 \text{ TeV}$, $\theta=21^\circ$
1131 hit PMTs



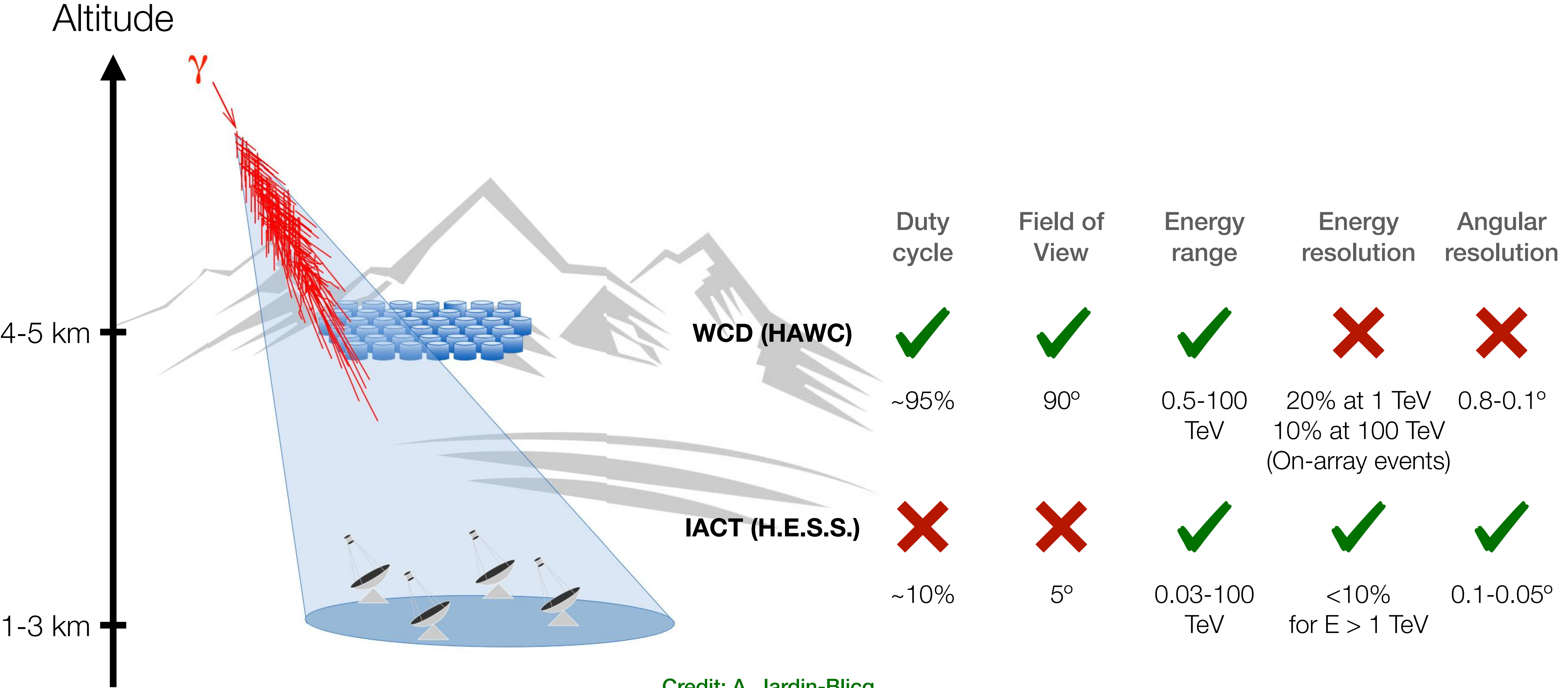
“Hot” spots concentrate around the core

Water Cherenkov Detectors

Shower classification: gamma/hadron separation



WCDs vs IACTs

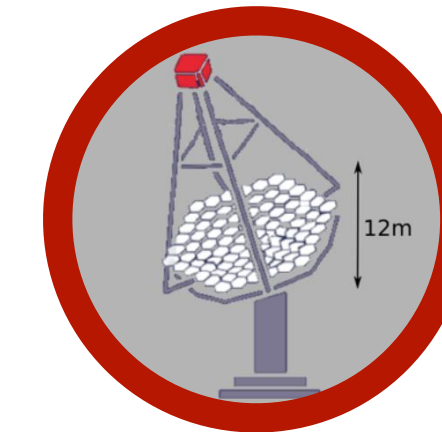
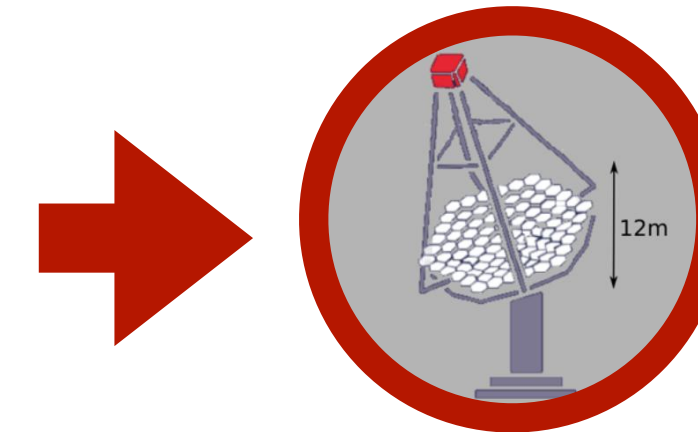
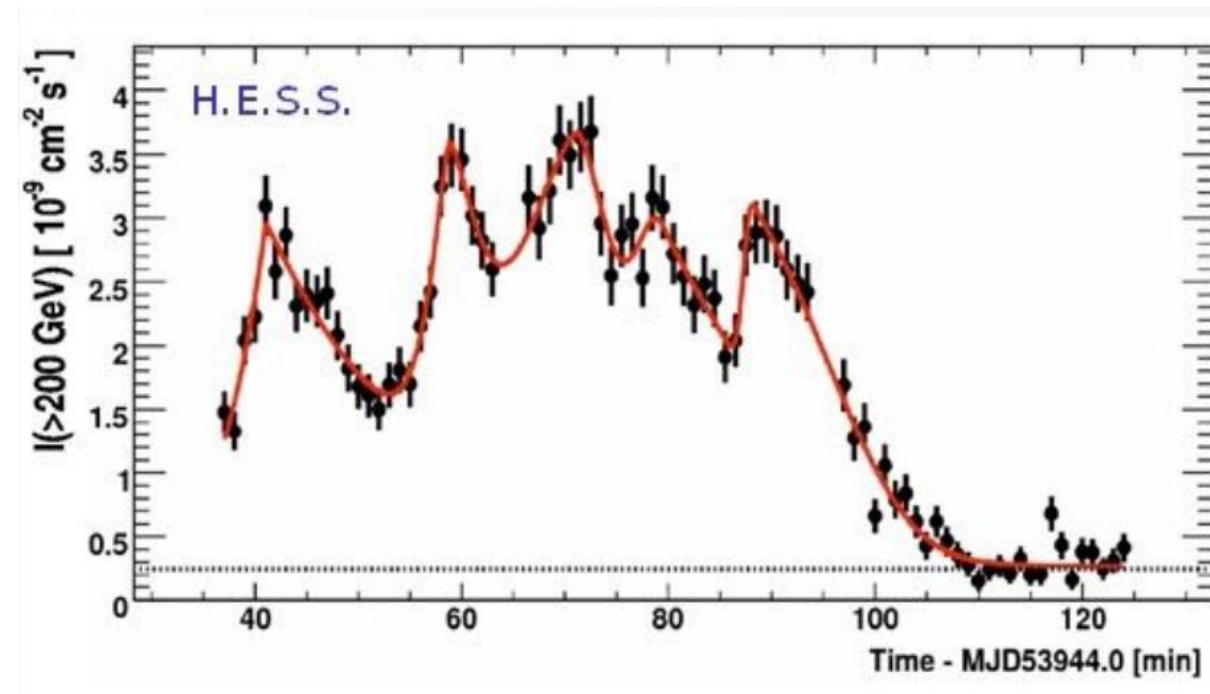


WCDs vs IACTs

Science cases: observation time

Transient and Periodic Sources

- Flares of Active Galactic Nuclei
- Black-Hole / Neutron-Star merger events (GWs)
- Microquasars (star - compact object binaries)
- Gamma Ray Bursts (GRBs)

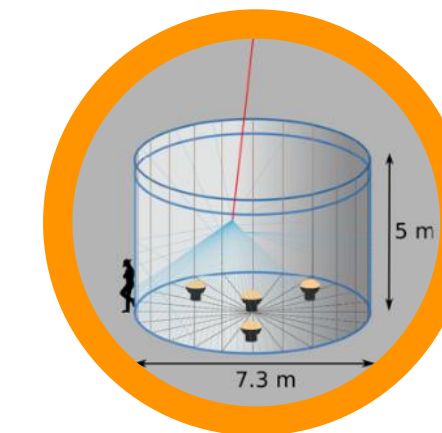
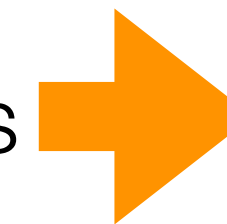
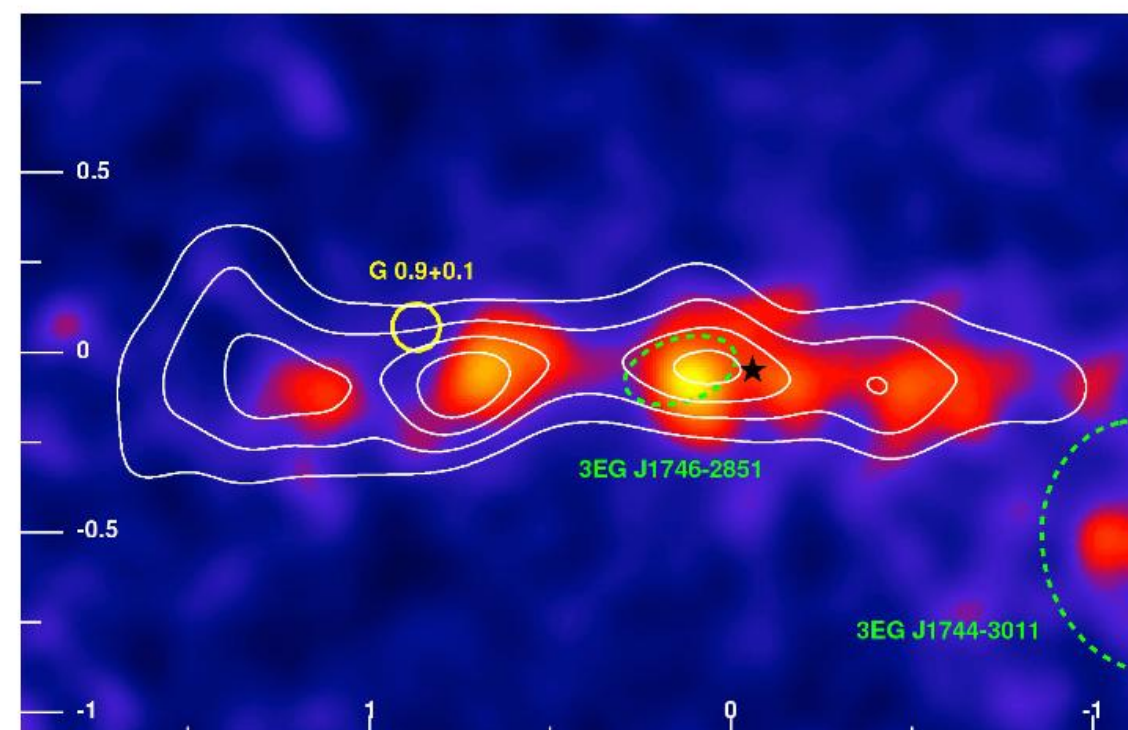


IACTs

with high short-term sensitivity and lower energy threshold provided that we know where to look! (need *multiwavelength alerts*)

Steady or Periodic Sources

- Pulsar Wind Nebulae
- Supernova Remnants
- AGN quiescent states, radio galaxies
- Gamma-ray Binary Systems
- Dark Matter
- Illuminated Molecular Clouds

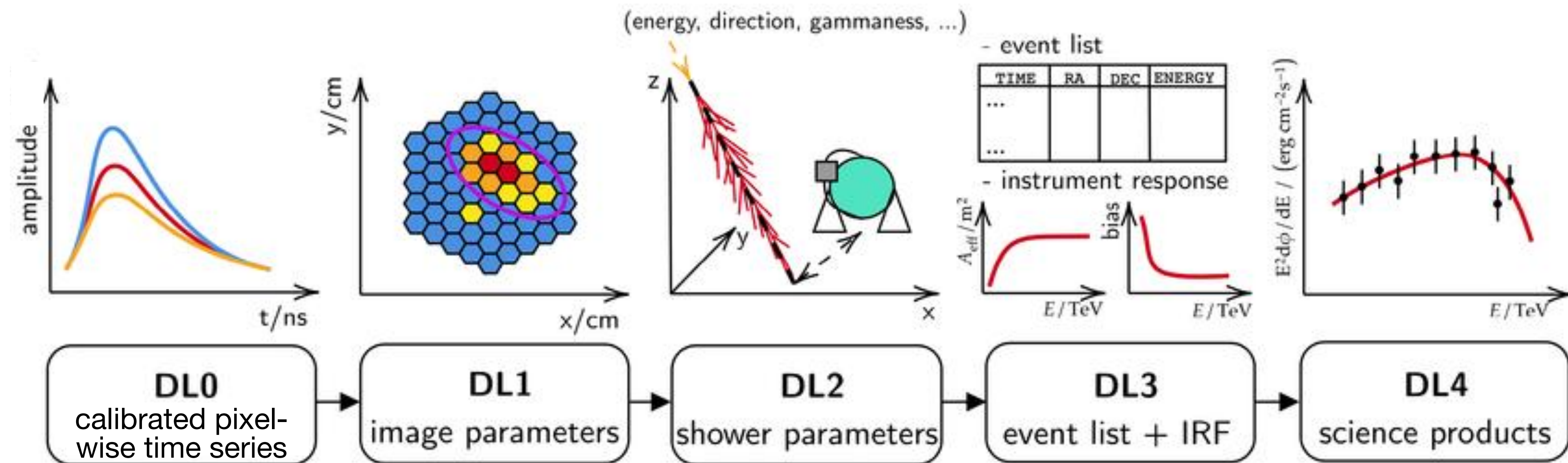


WCDs

become competitive on long timescales, while IACTs maintain superior angular and energy resolution in overlapping energy range

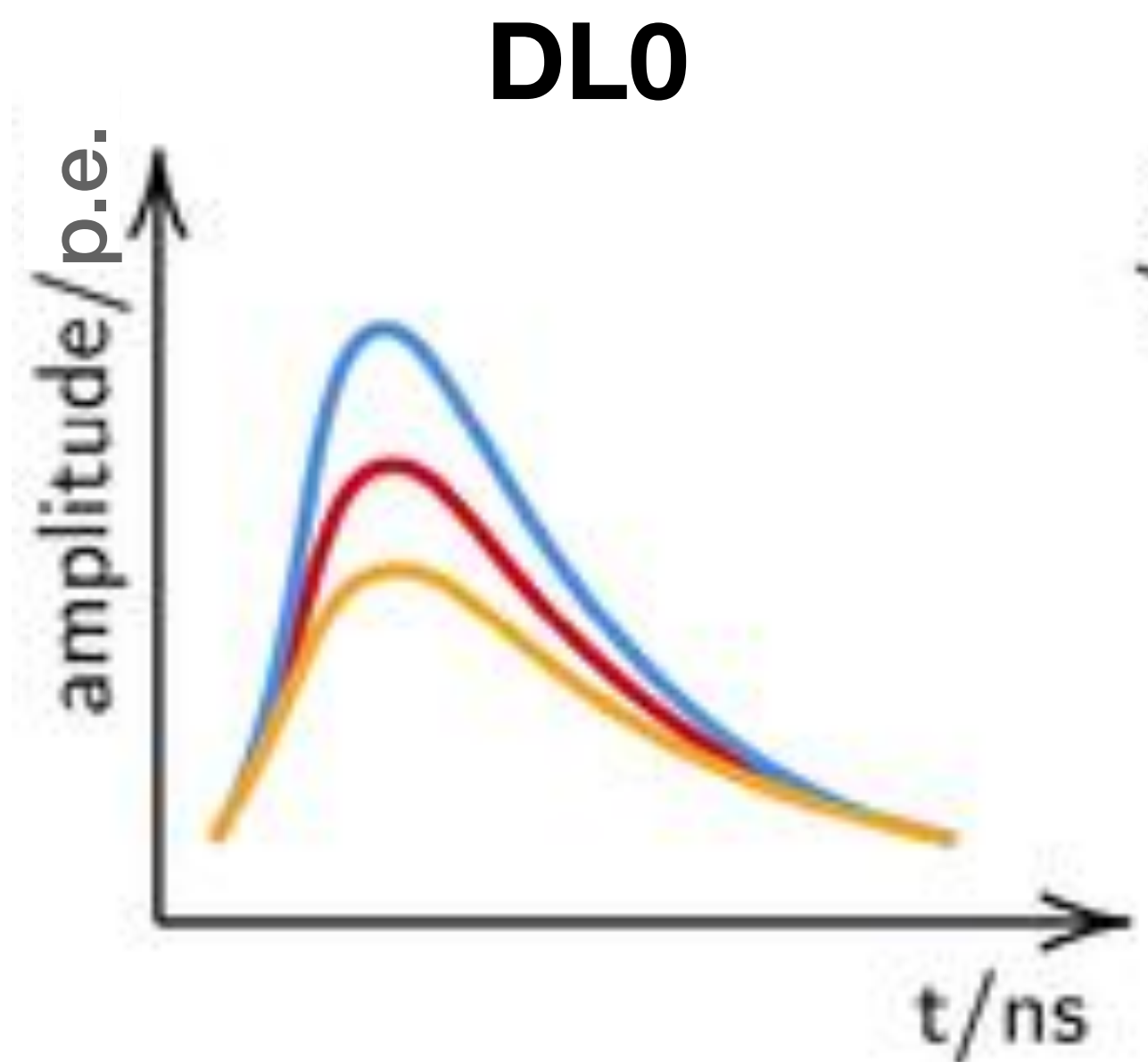
Credit: K. Kosack

From low-level to high-level IACTs data



Data levels

Definition of data levels (DL) foreseen for CTAO



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

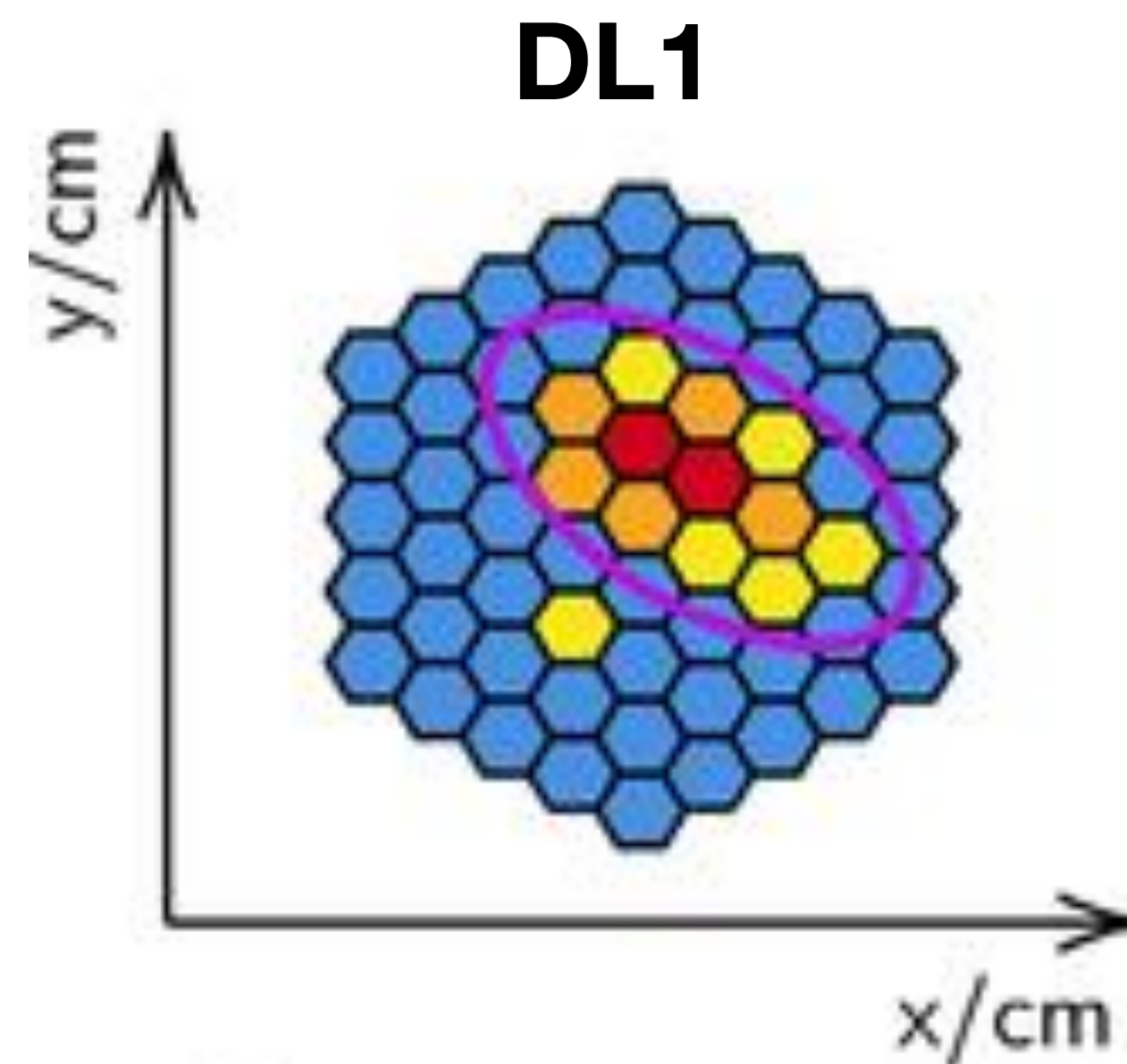
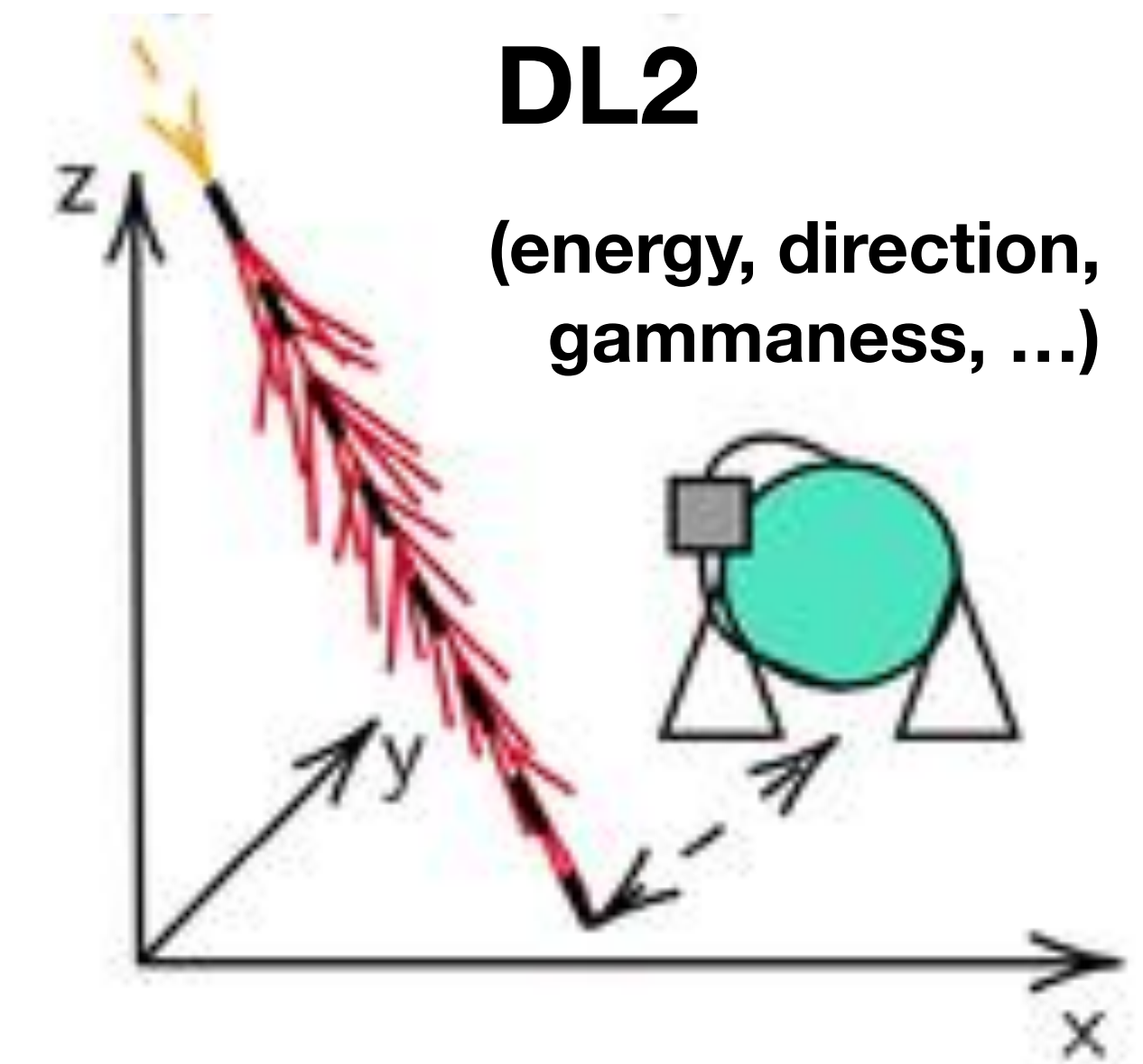


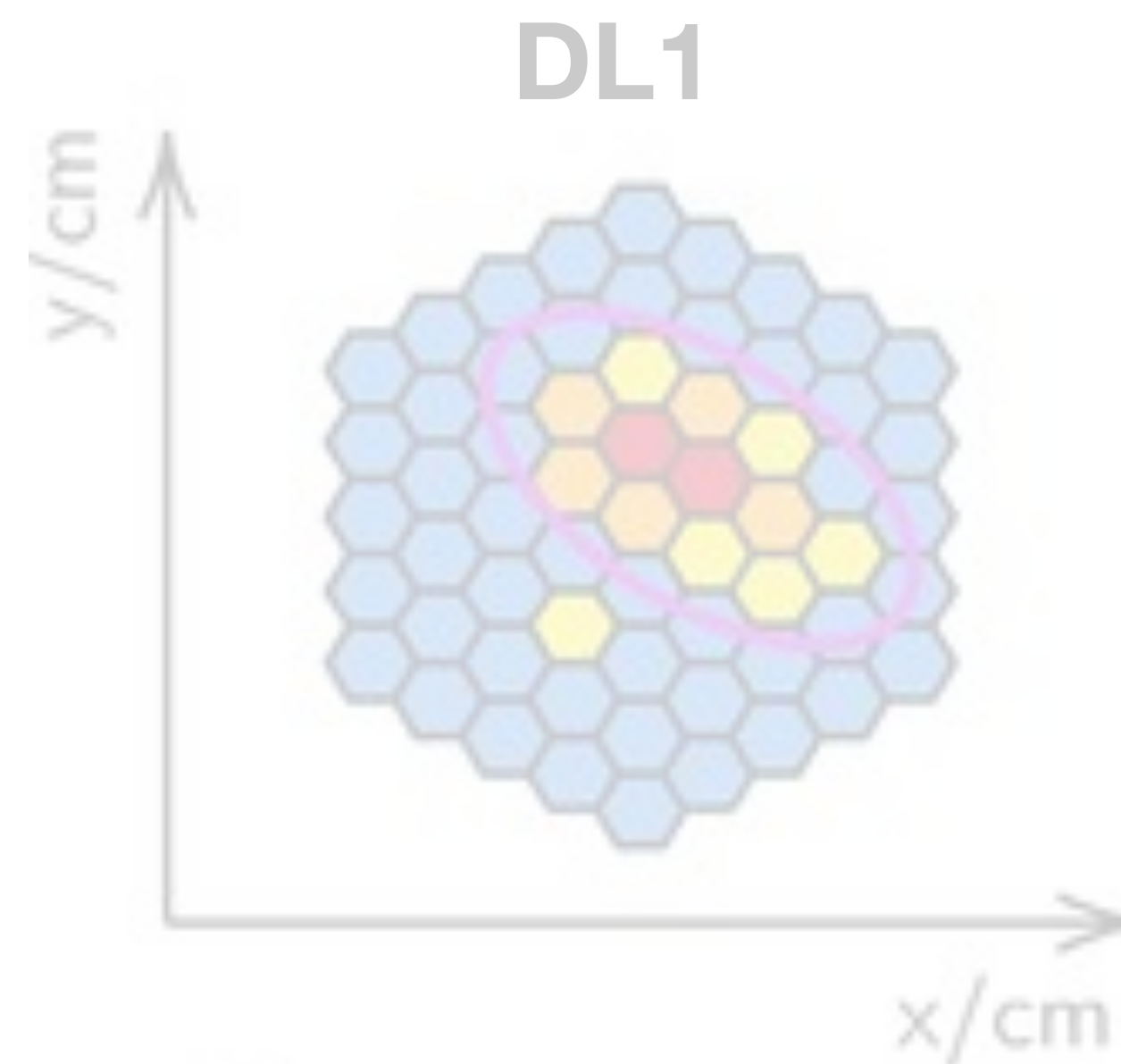
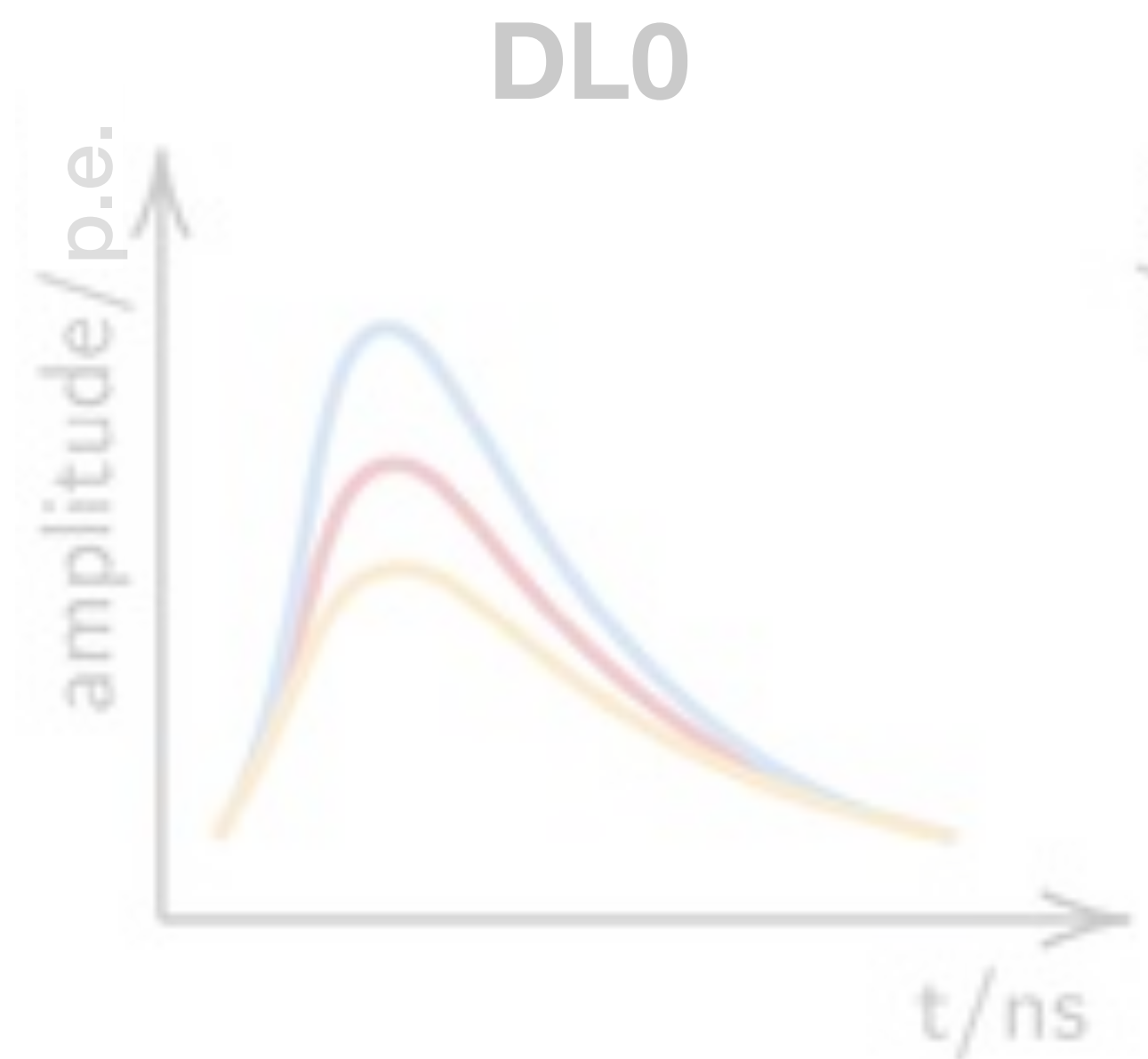
Image extraction and cleaning, and derived per-telescopes parameters.
Camera image parameters (Hillas parameters)



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)

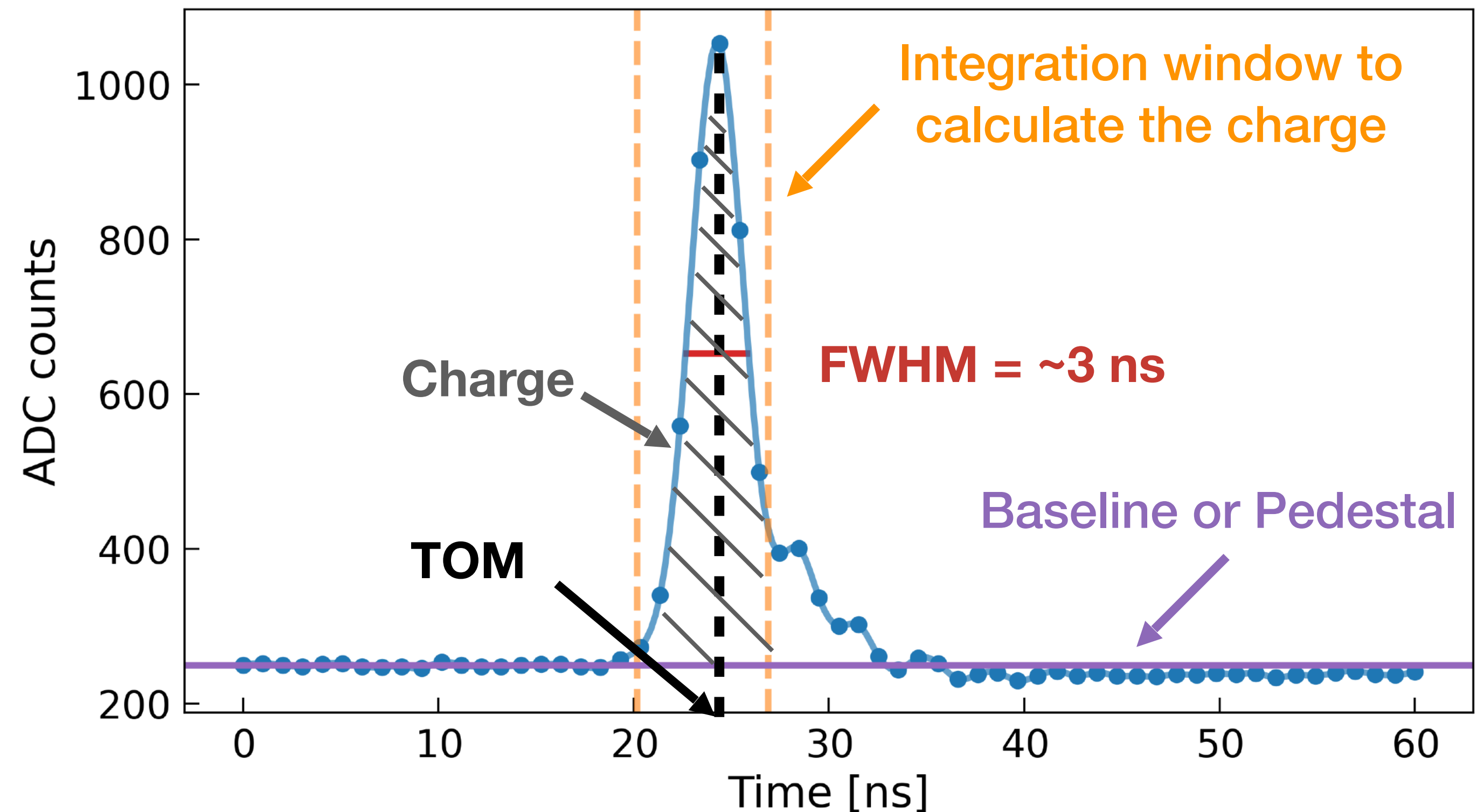
→ Calibration (R0) and data volume reduction (R1): transition to DL0

Low-level data processing

Raw 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

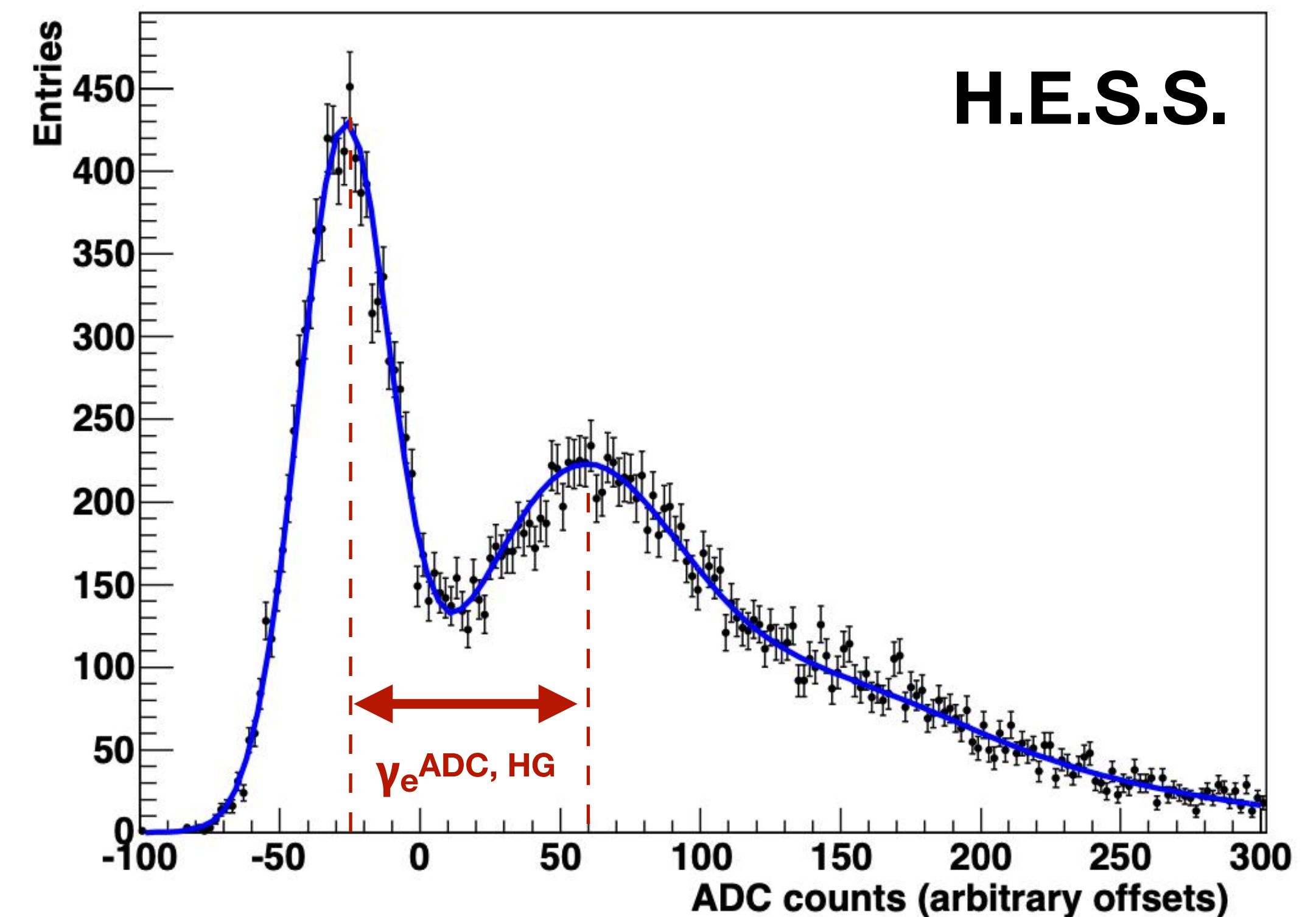
From ADC counts to p.e. + data volume reduction

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

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

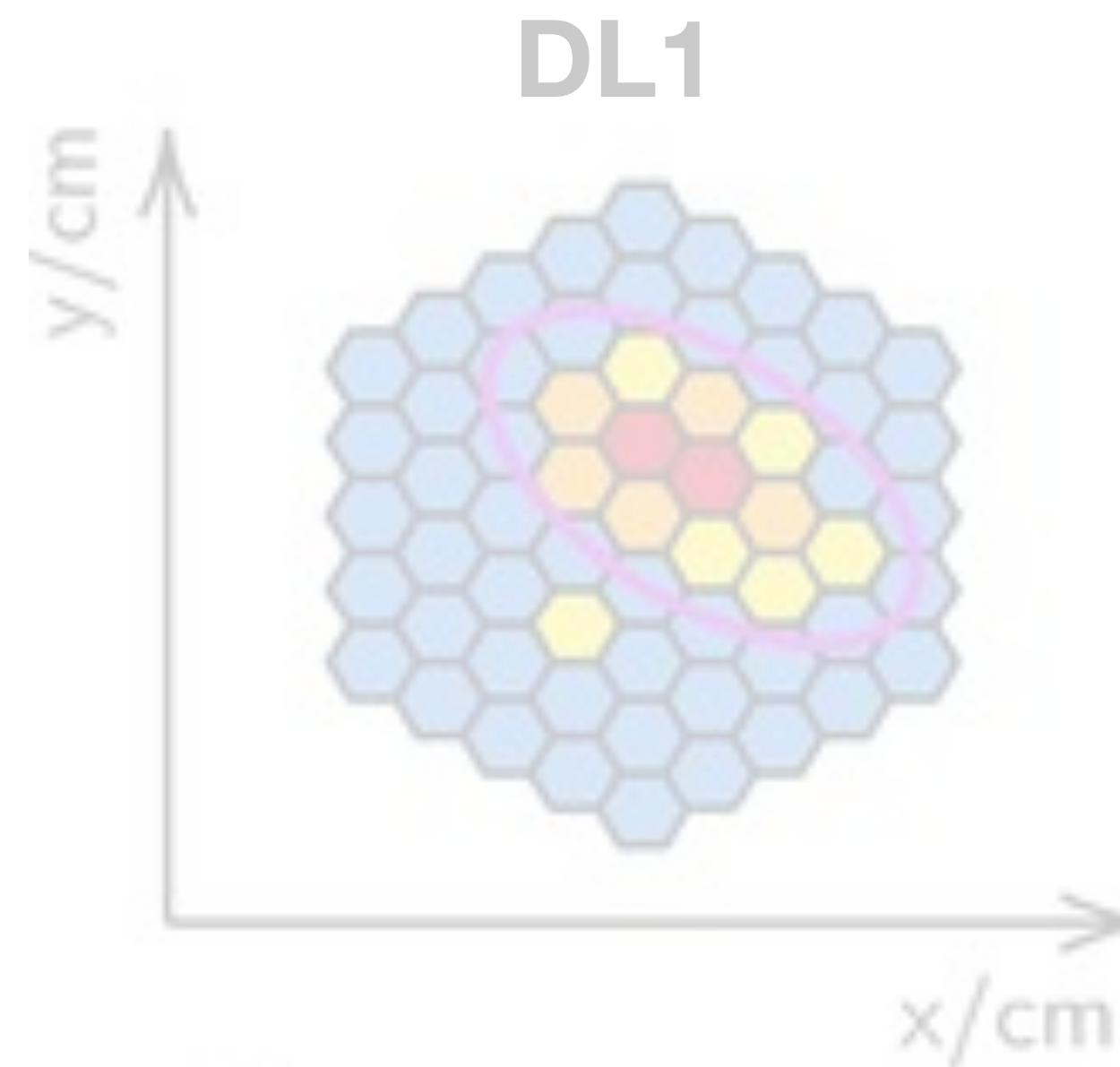
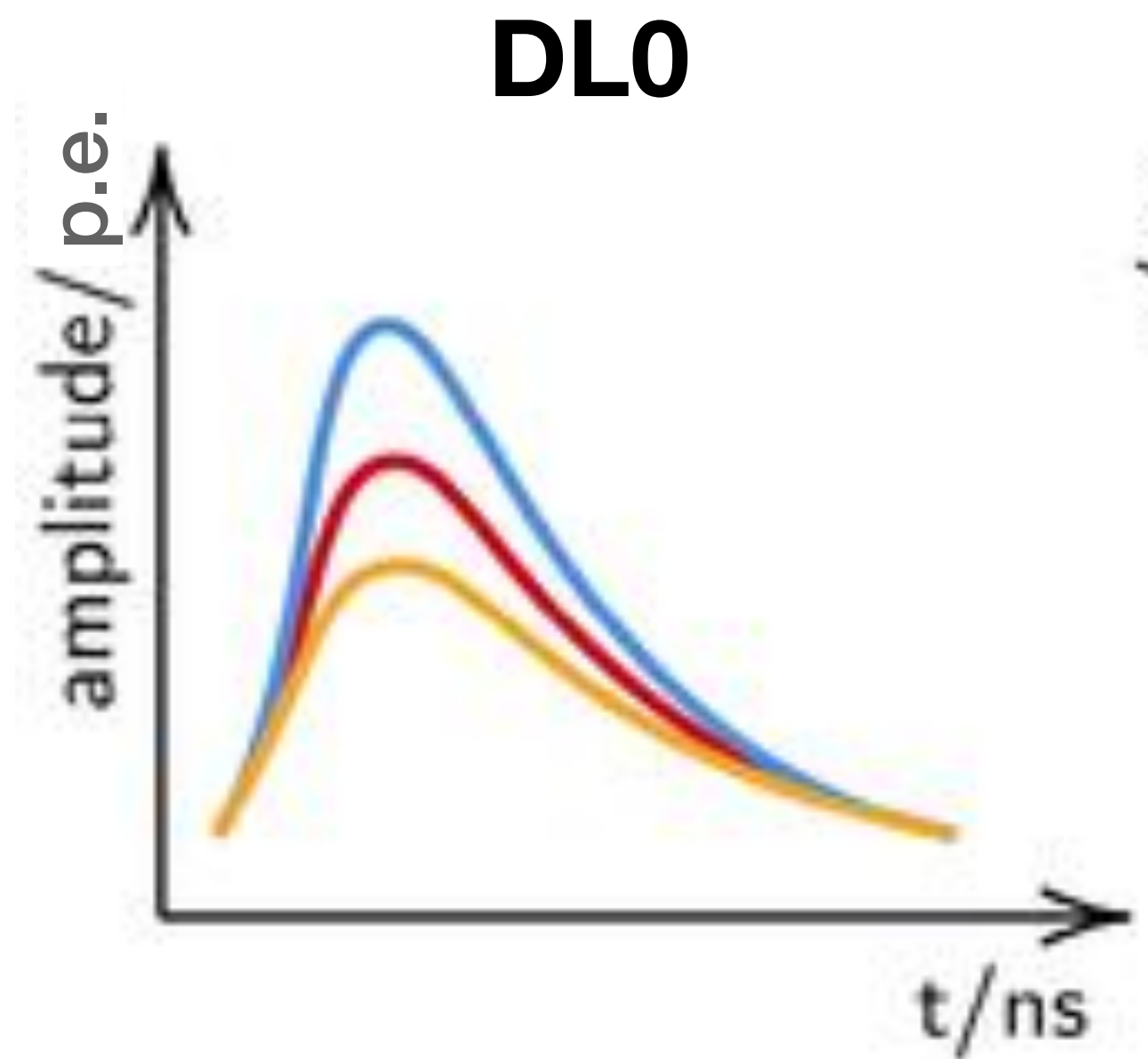
$$A^{\text{LG}} = \frac{ADC^{\text{LG}} - P^{\text{LG}}}{\gamma^{\text{ADC,HG}}} \times (HG/LG) \times FF$$

- 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, stars, highly illuminated pixels



Data levels

We are now at DL0!



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

→ Now image extraction: transition to DL1

DLO data processing

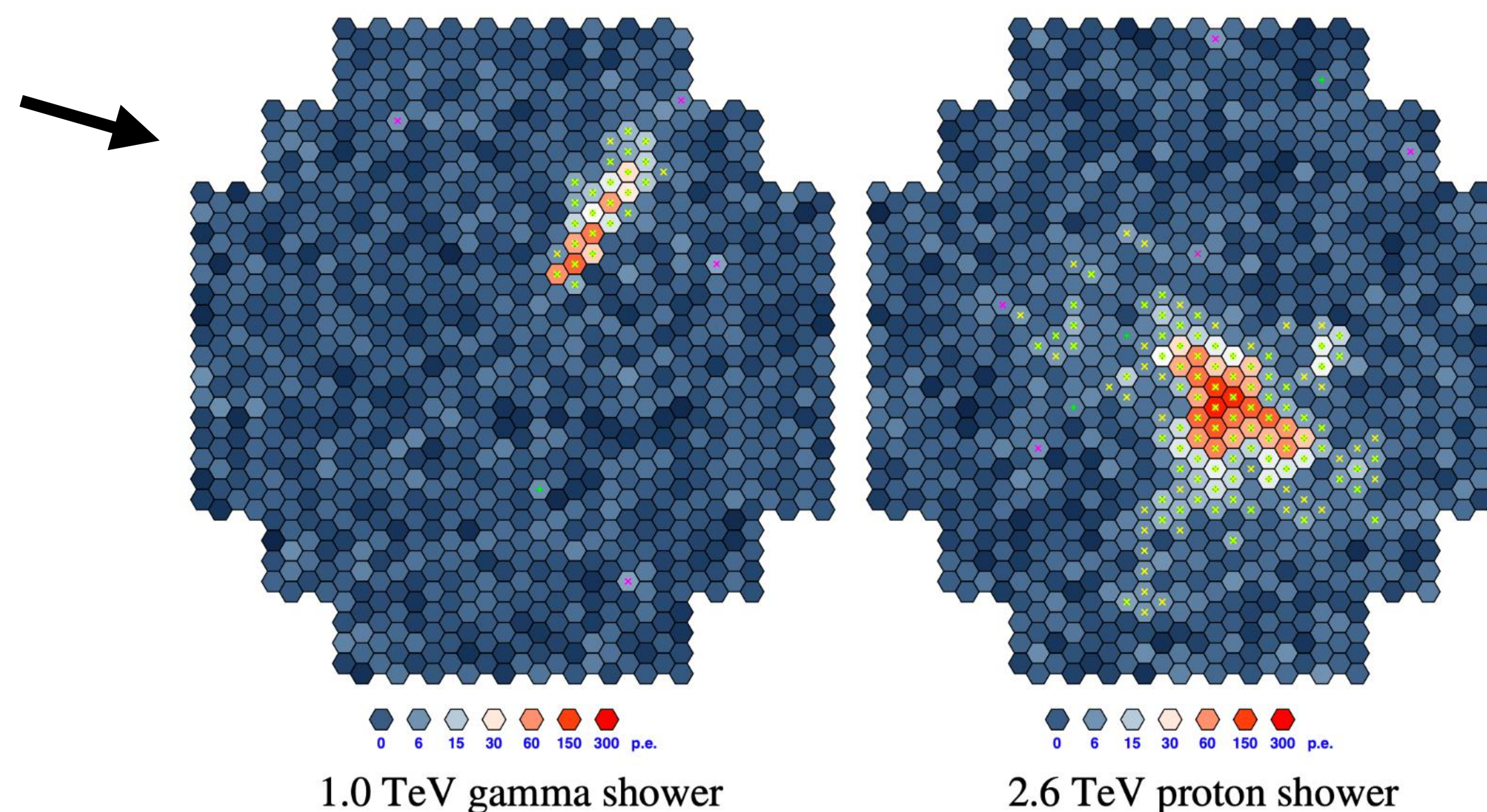
Image cleaning

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:

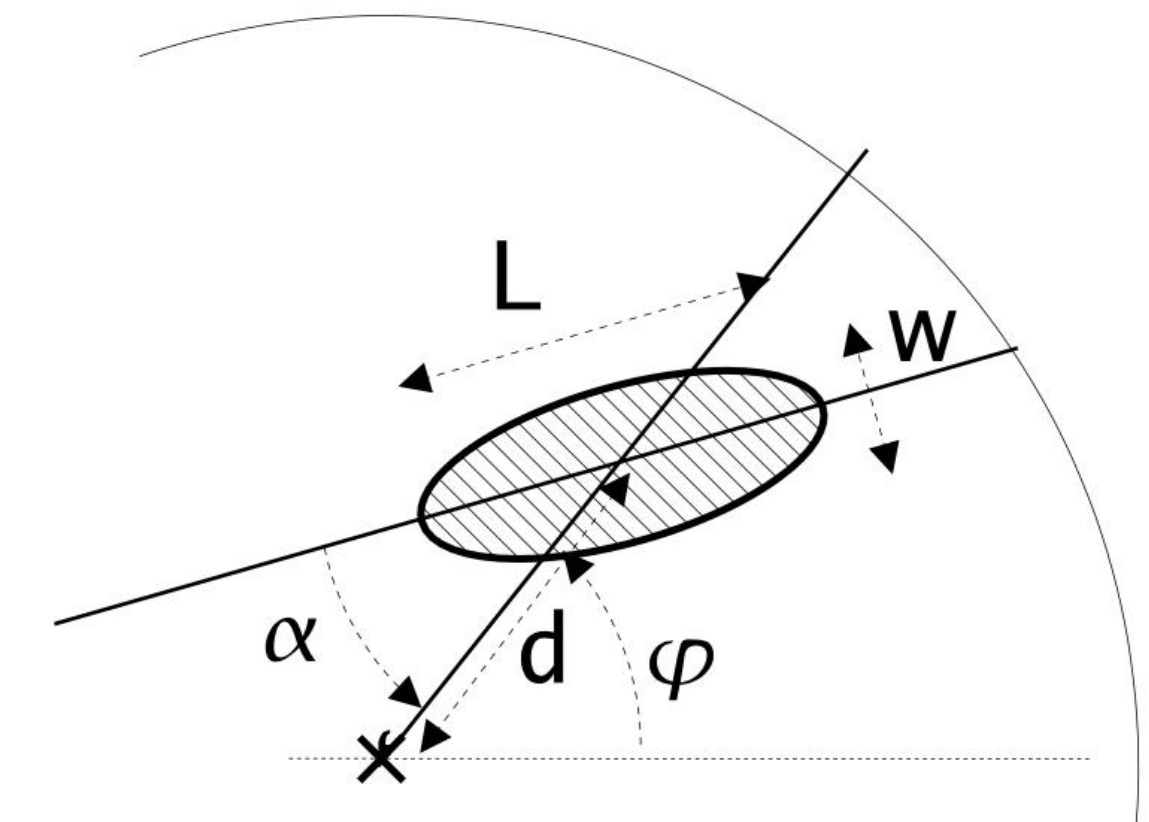
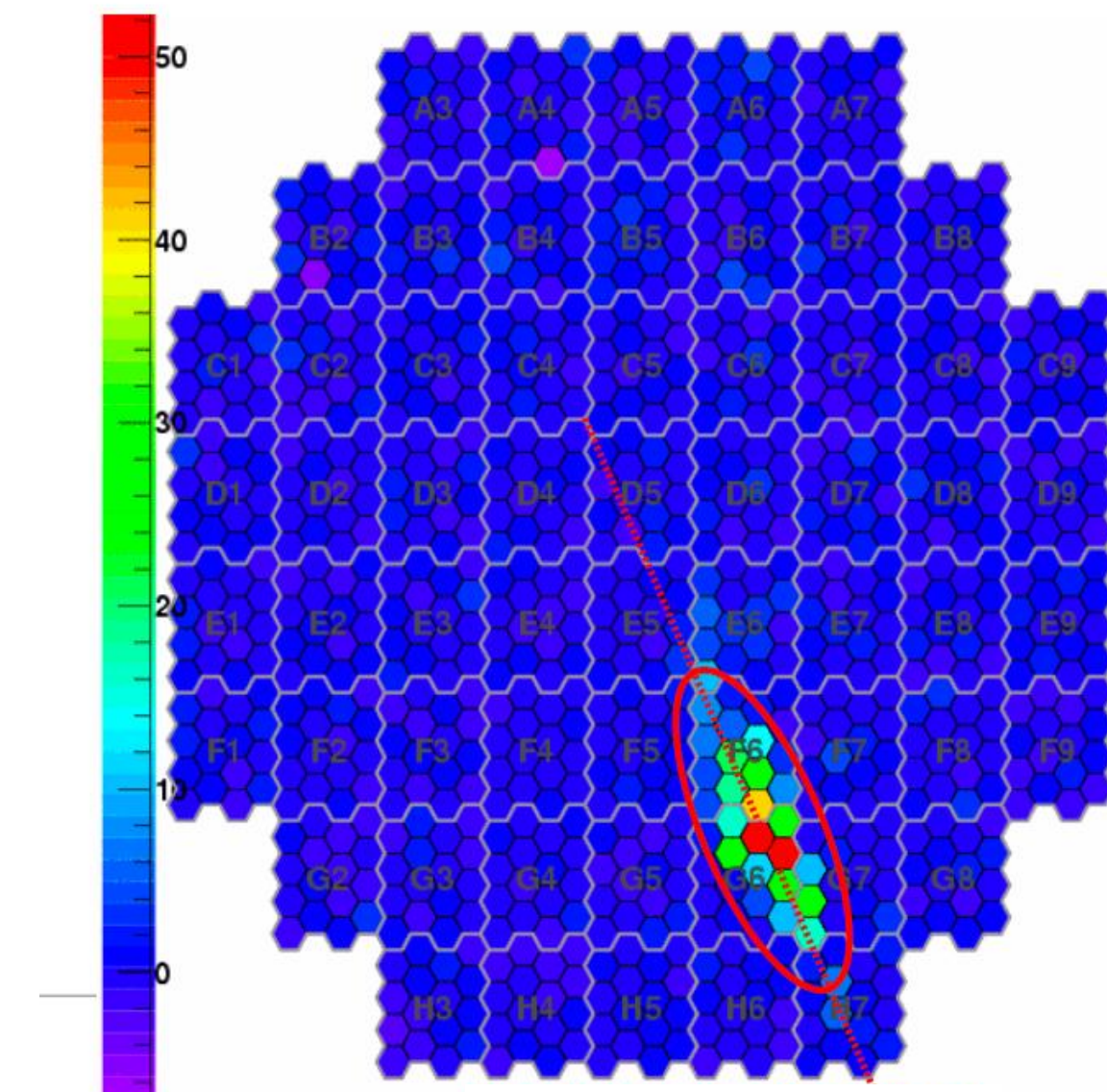
- Shower signal stick out from NSB (more of high energies)
- Shower signals are bundled in neighboring pixels
- Shower signals have time structure



DL0 data processing

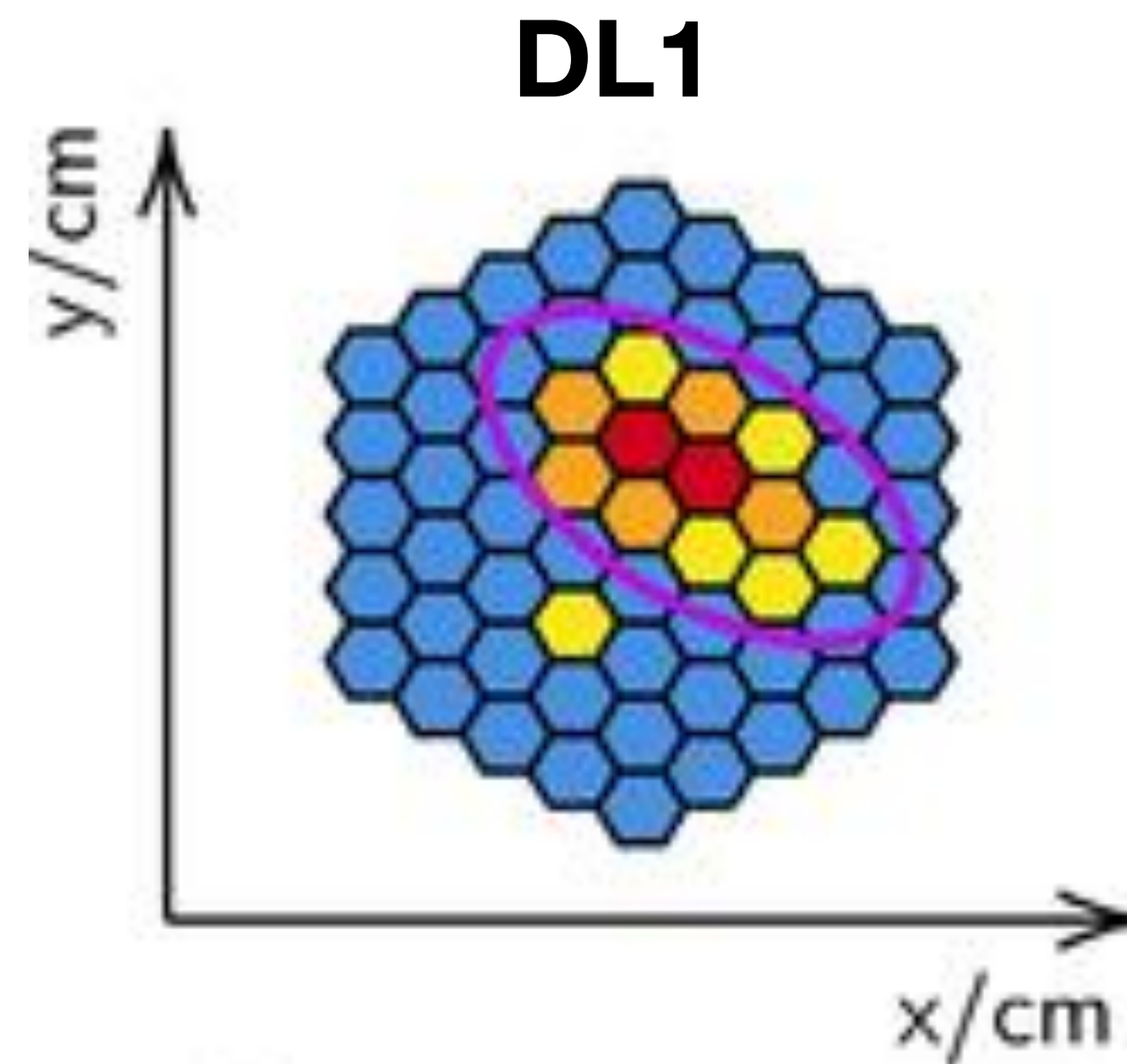
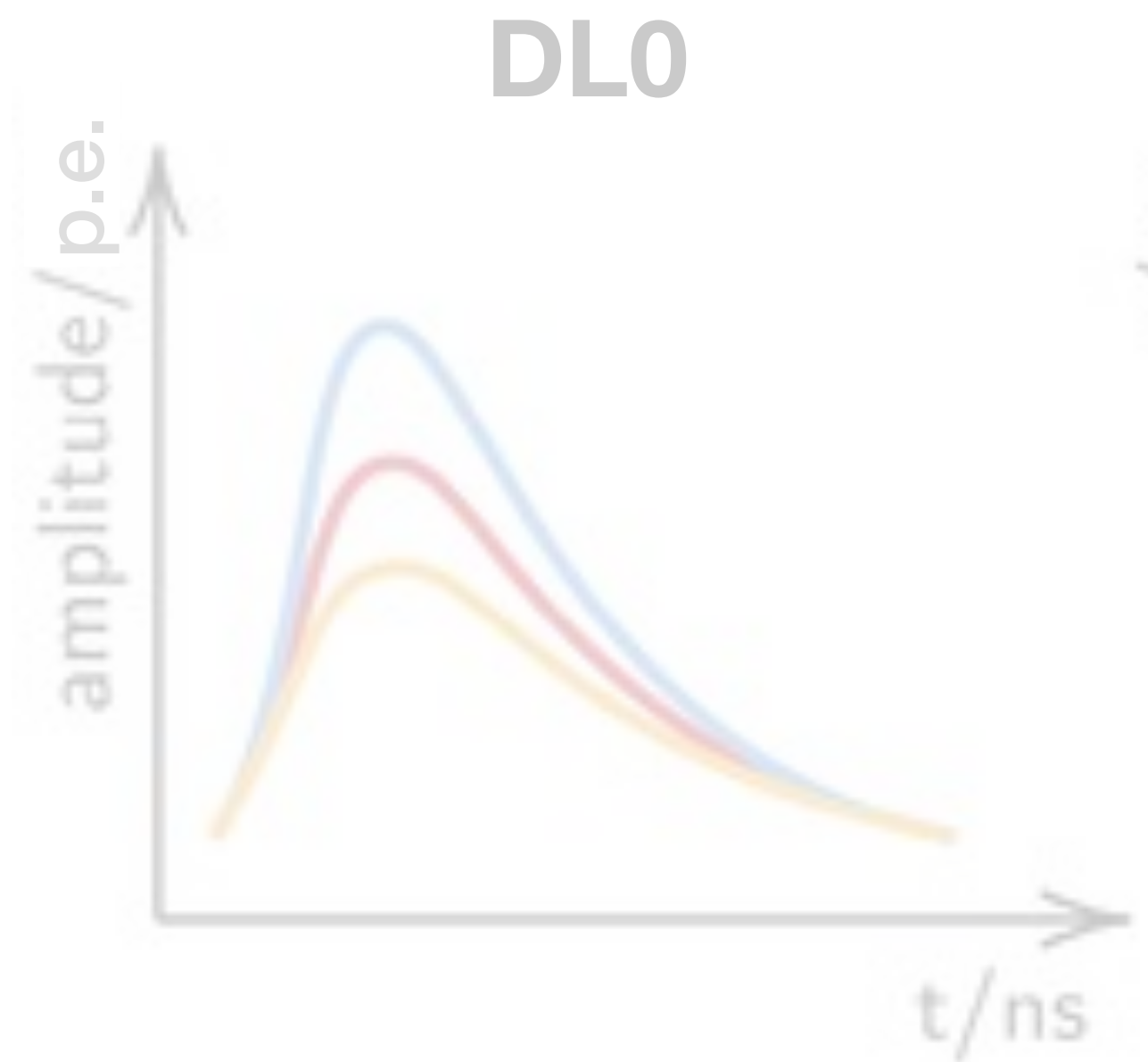
Hillas parameters

- 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 (***amplitude*** 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!

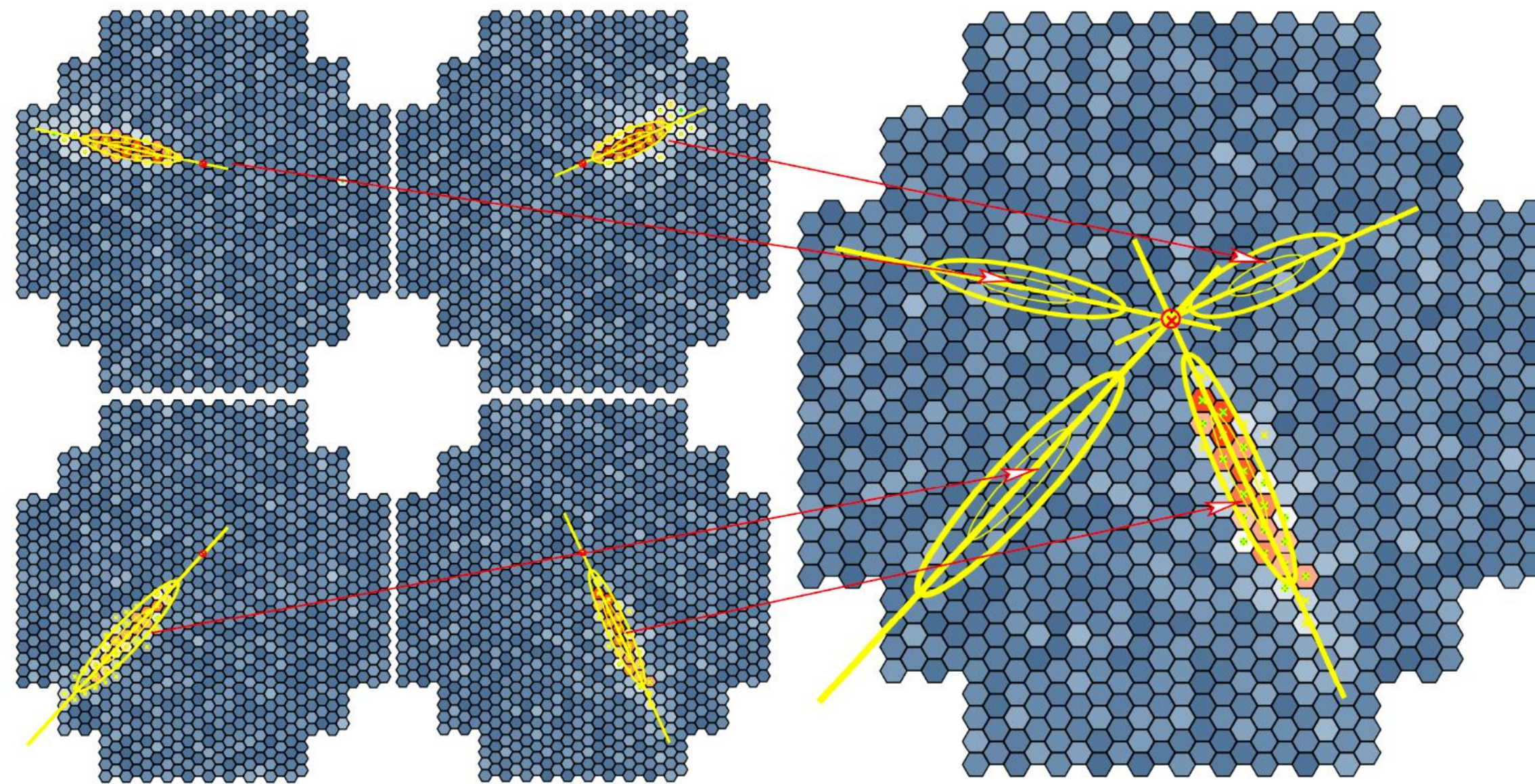


We have images and they are cleaned and parameterized

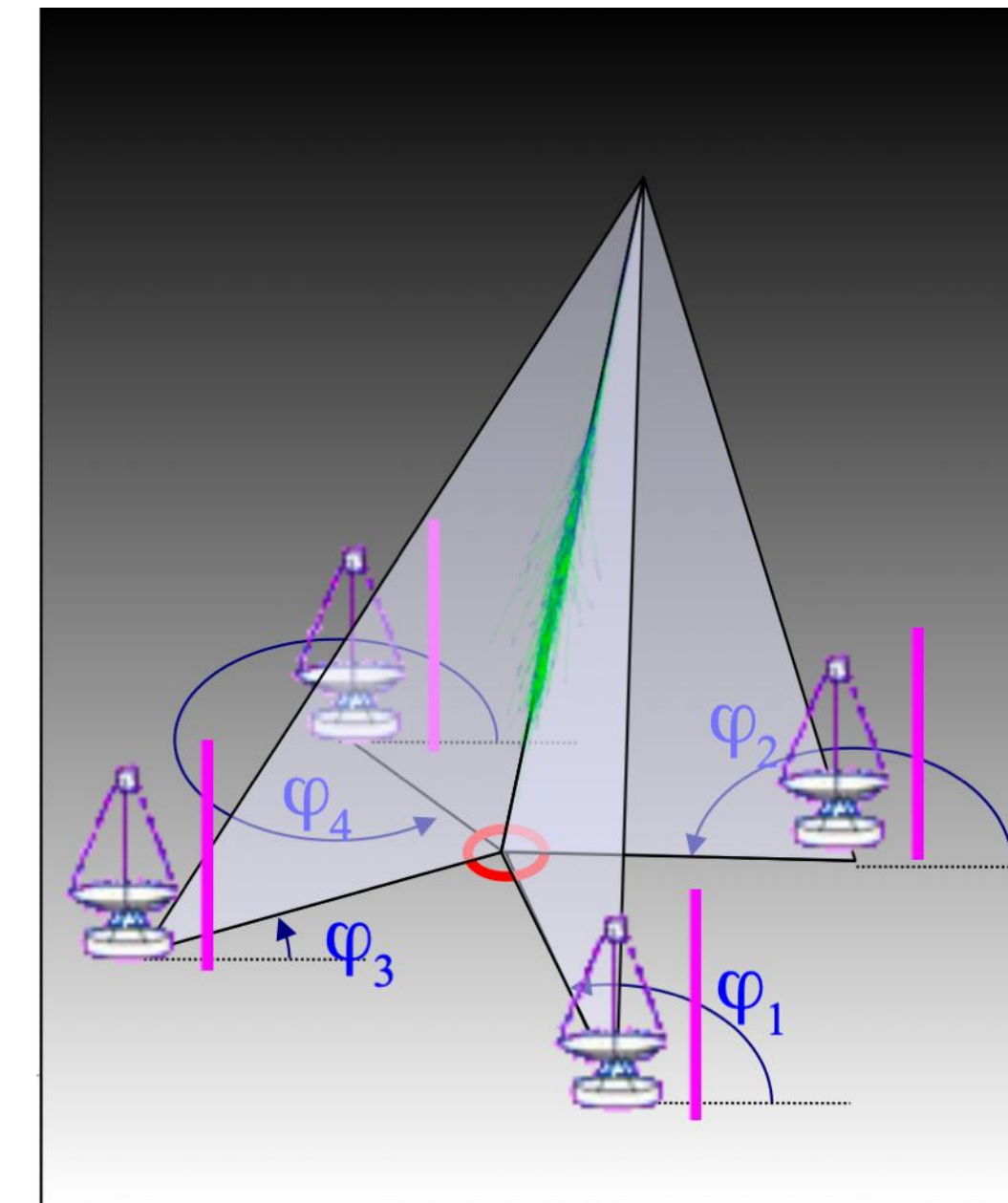
→ transition to DL2

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, $E \approx \text{size}$
- 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)

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

Signal, gamma rays $\Leftrightarrow$ 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

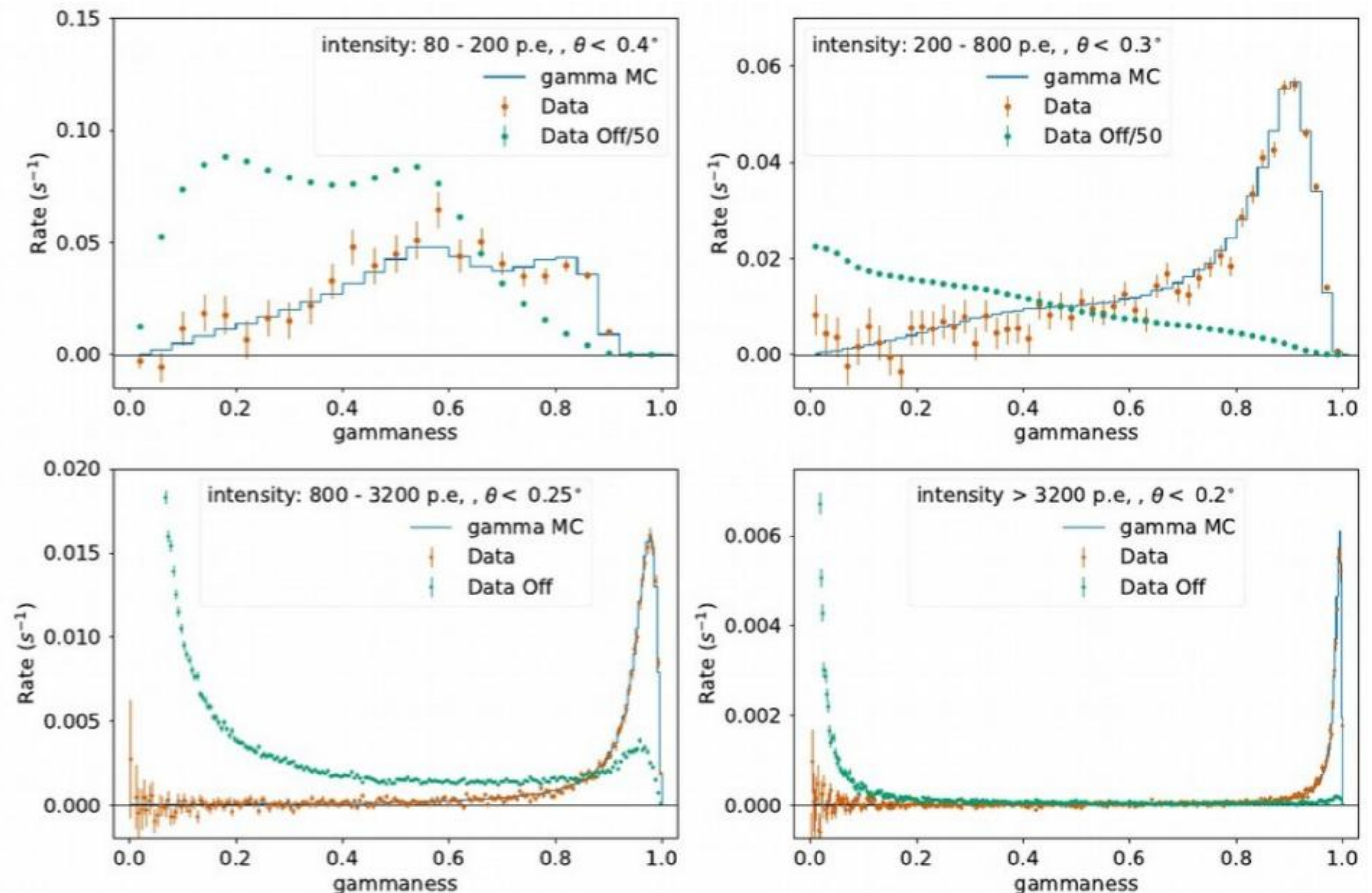
Gammaness

- 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

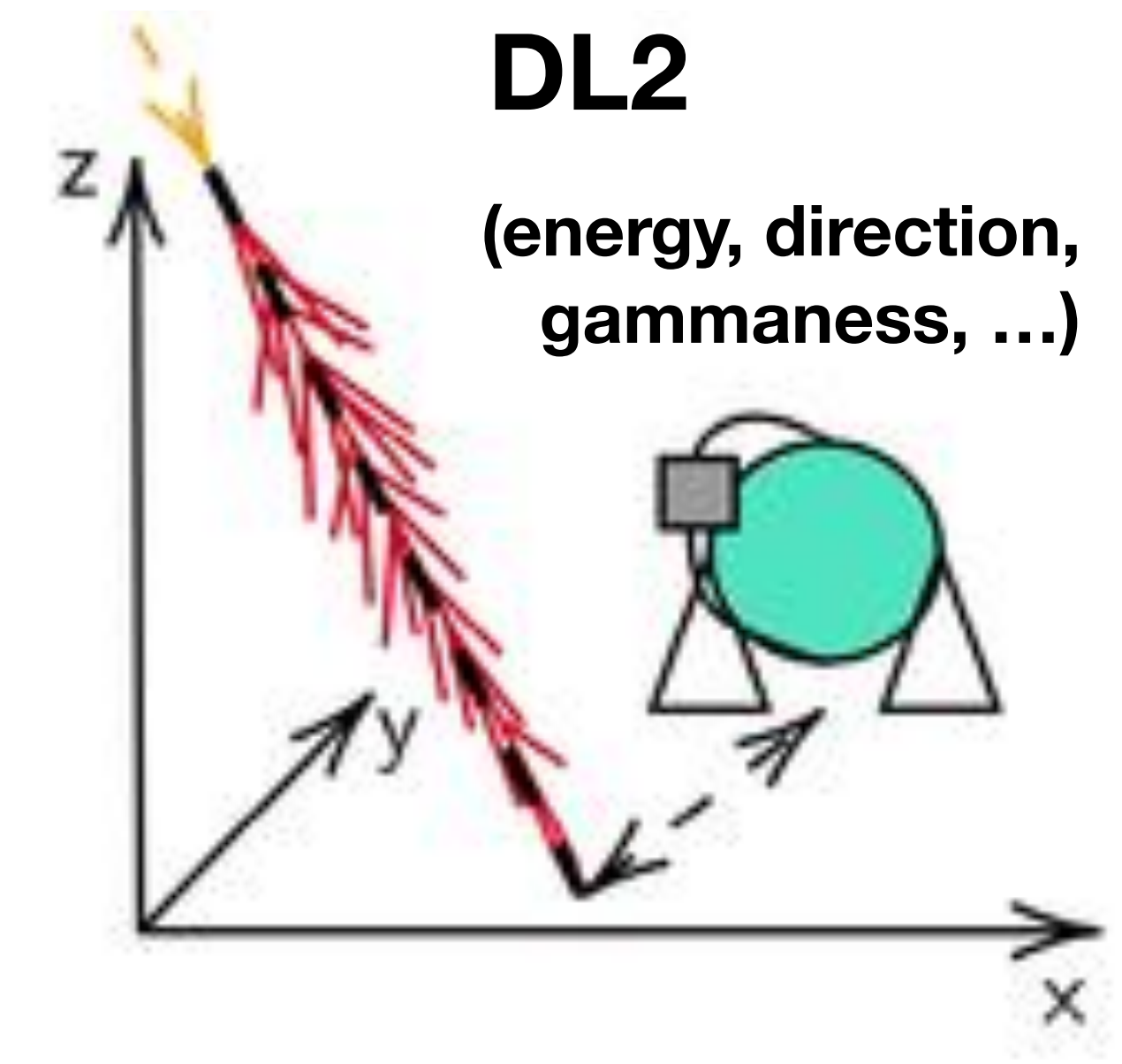
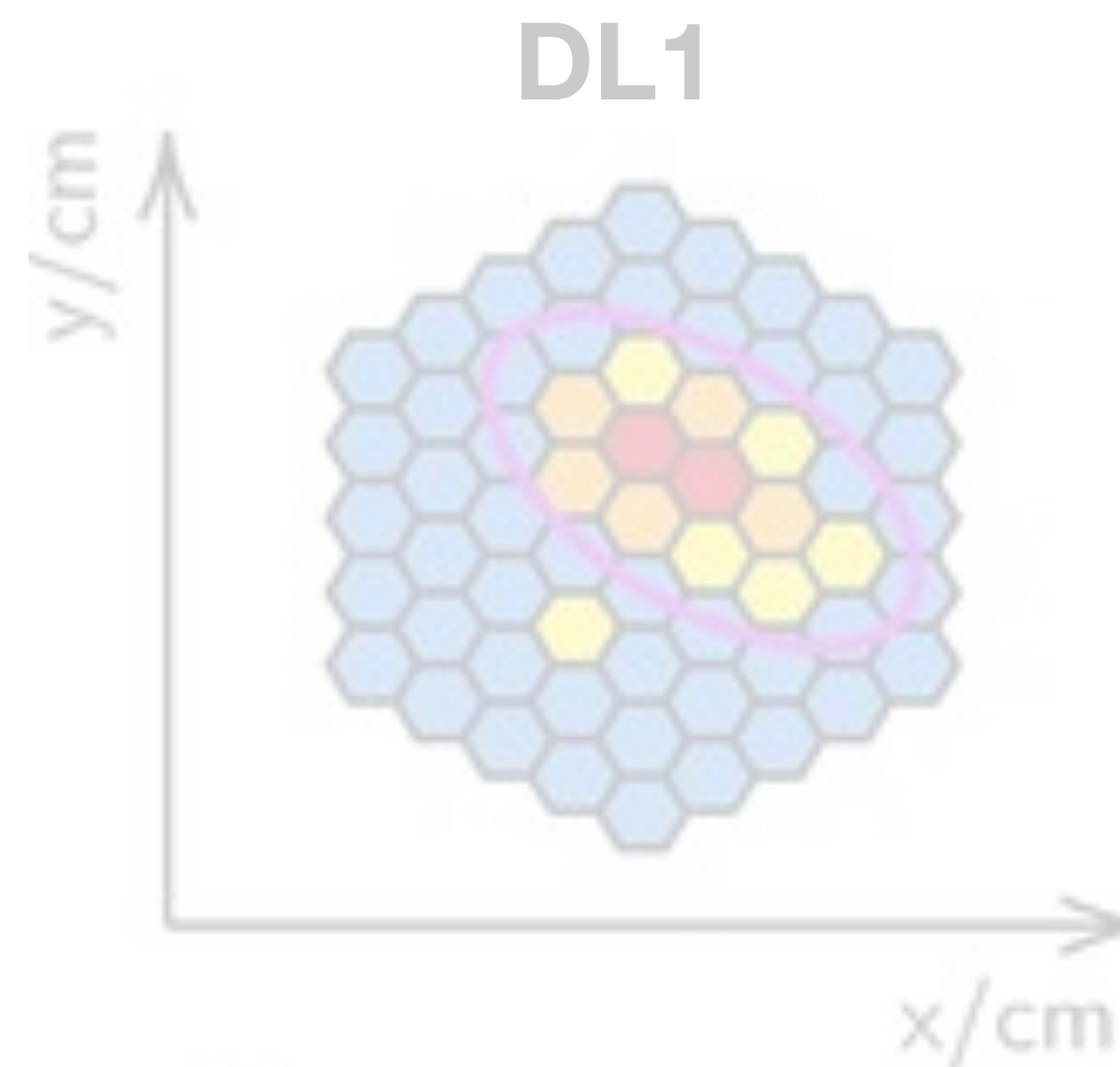
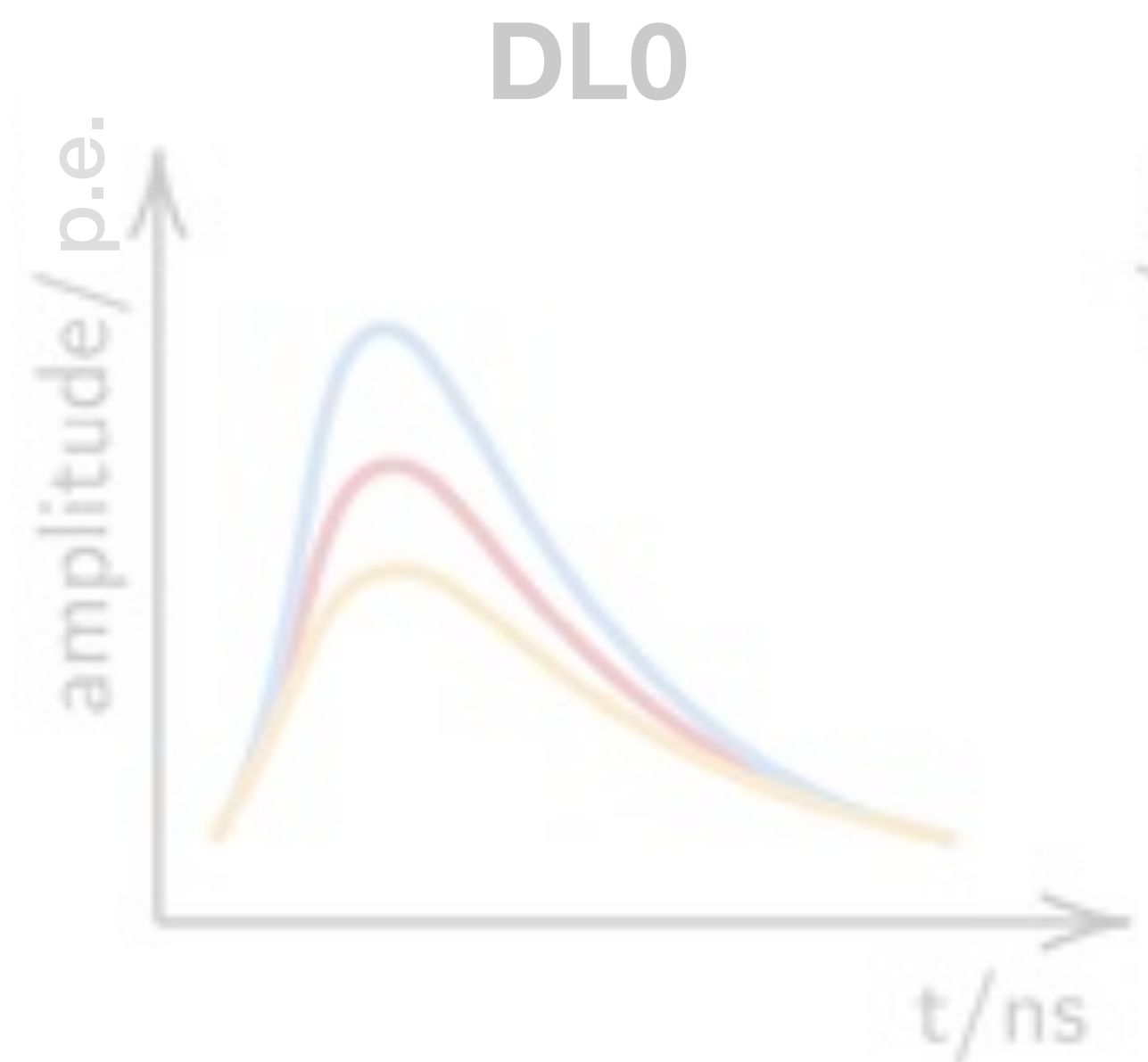
Gammaness

- 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!

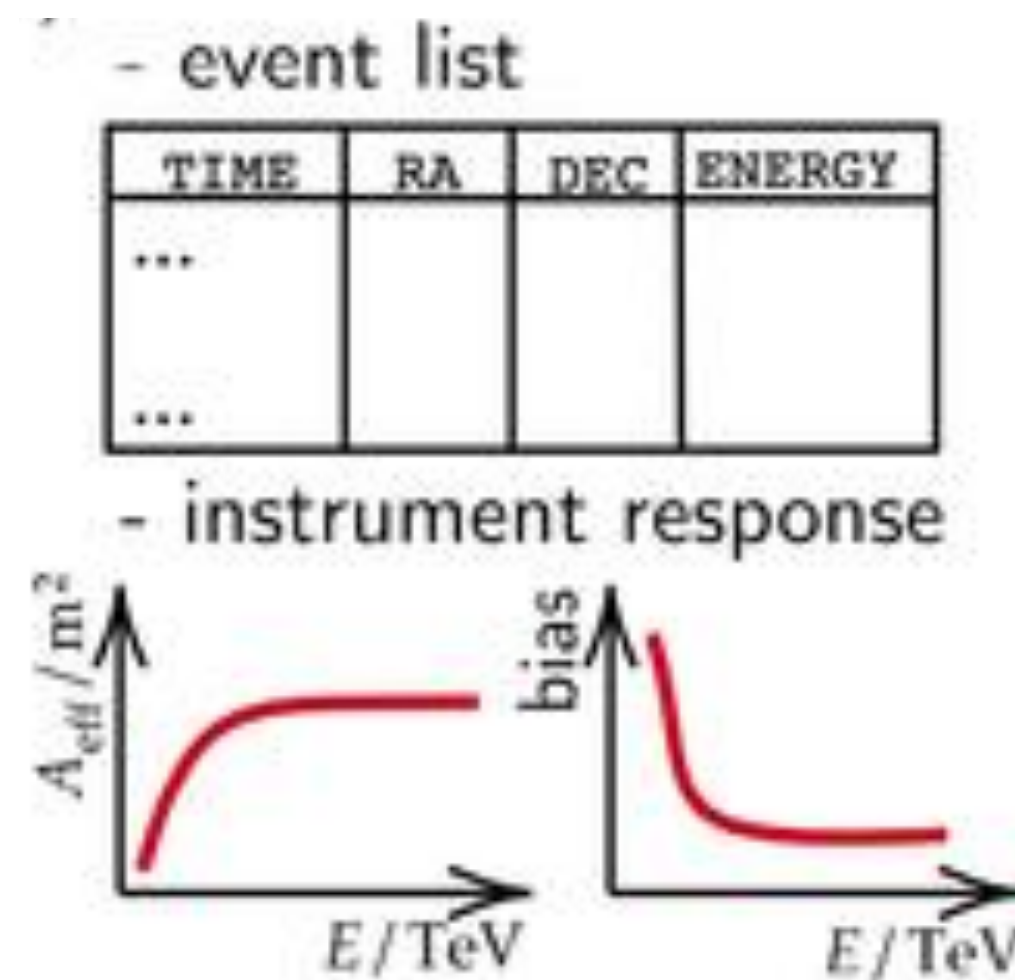


**Data reconstruction of the intrinsic gamma-ray event parameters:
energy, direction and gammaness**

Data levels

From gamma-ray events to science

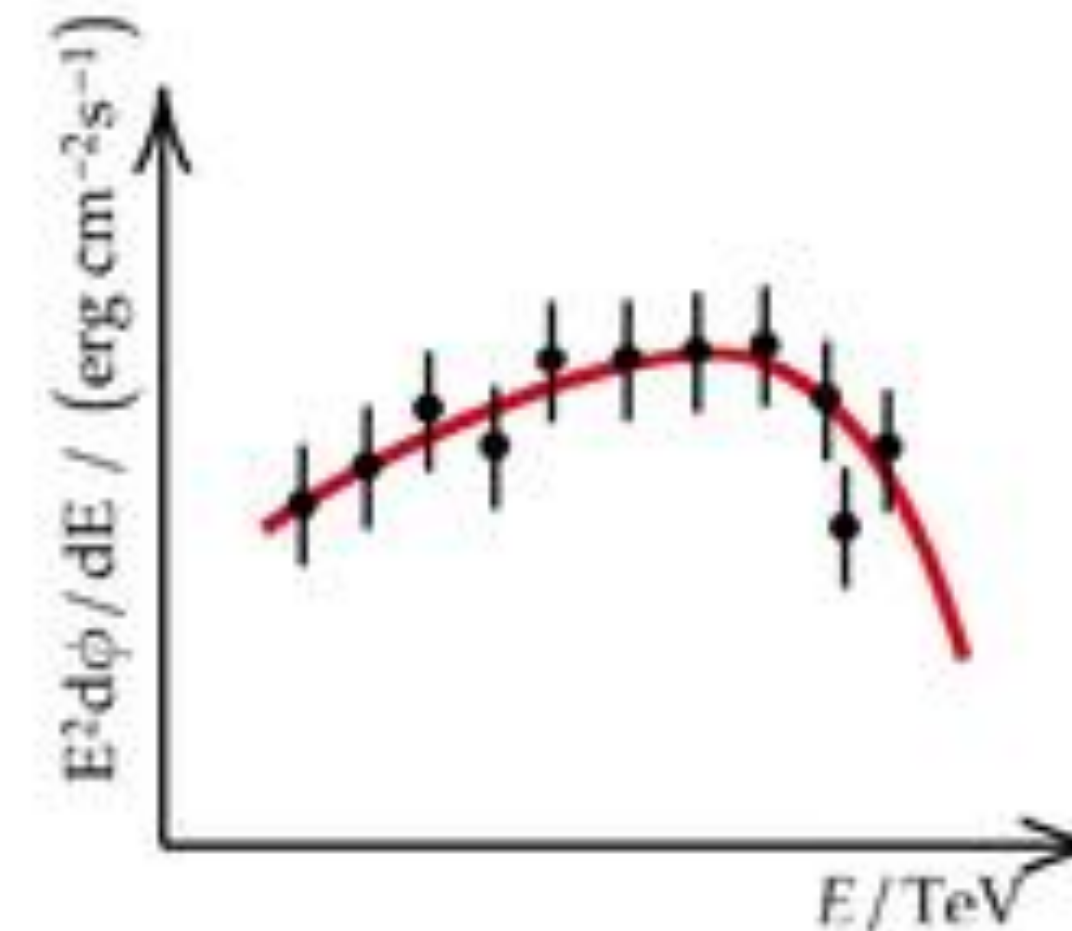
DL3



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

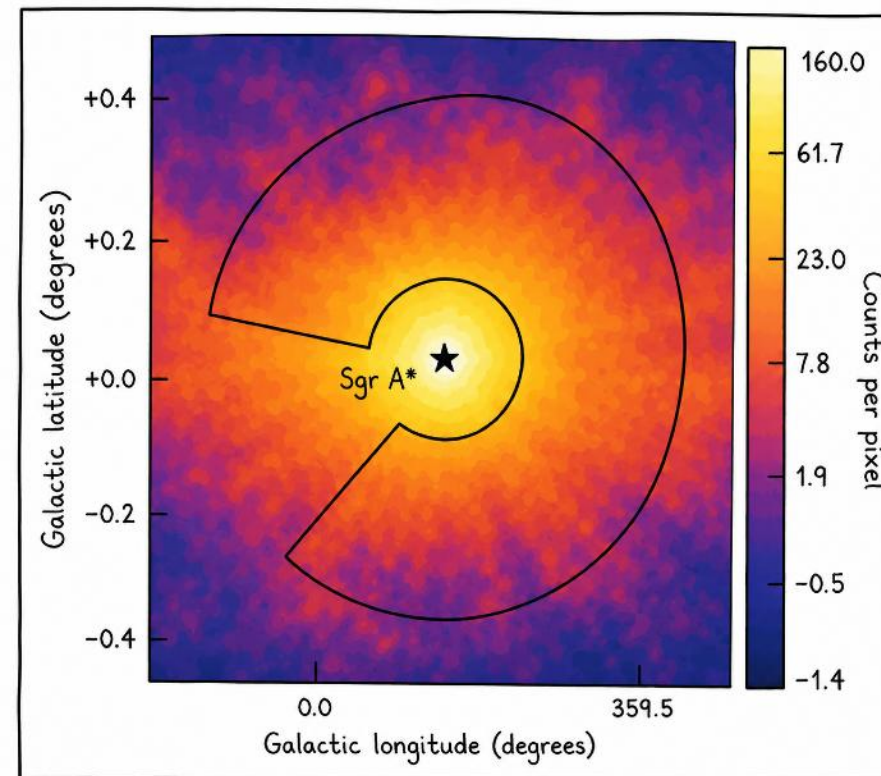
What do we have?

Gamma-like events

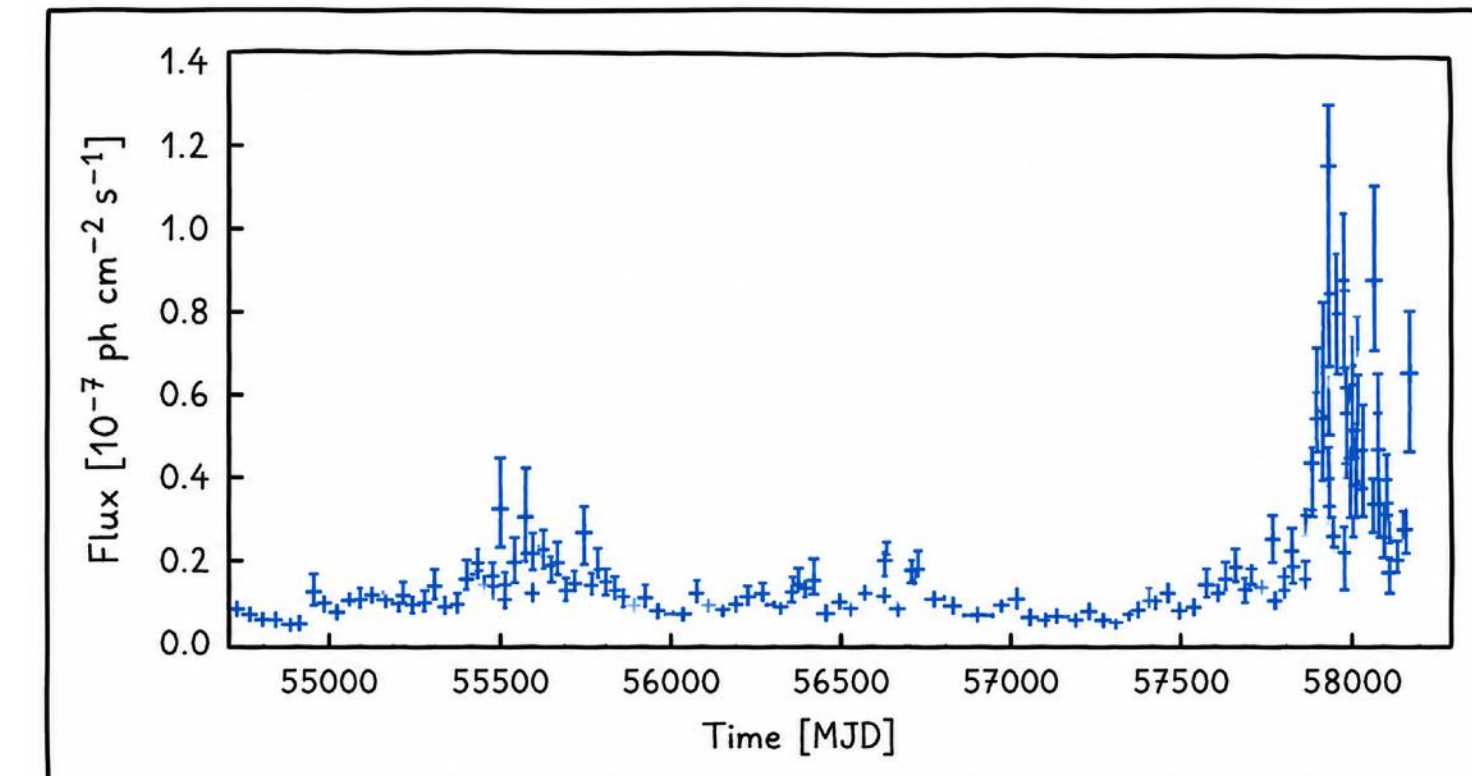
Points in space, time, and estimated energy that may be **gamma rays**
or may be **mis-reconstructed cosmic rays**

event id	time	ra	dec	E _{reco}
1	12	87.6	-23.7	5.6
2	150	87.2	-22.1	0.32
3	190	86.5	-23.4	0.45
4	2000	82.0	-23.2	0.57
5	7029	88.6	-24.1	2.4

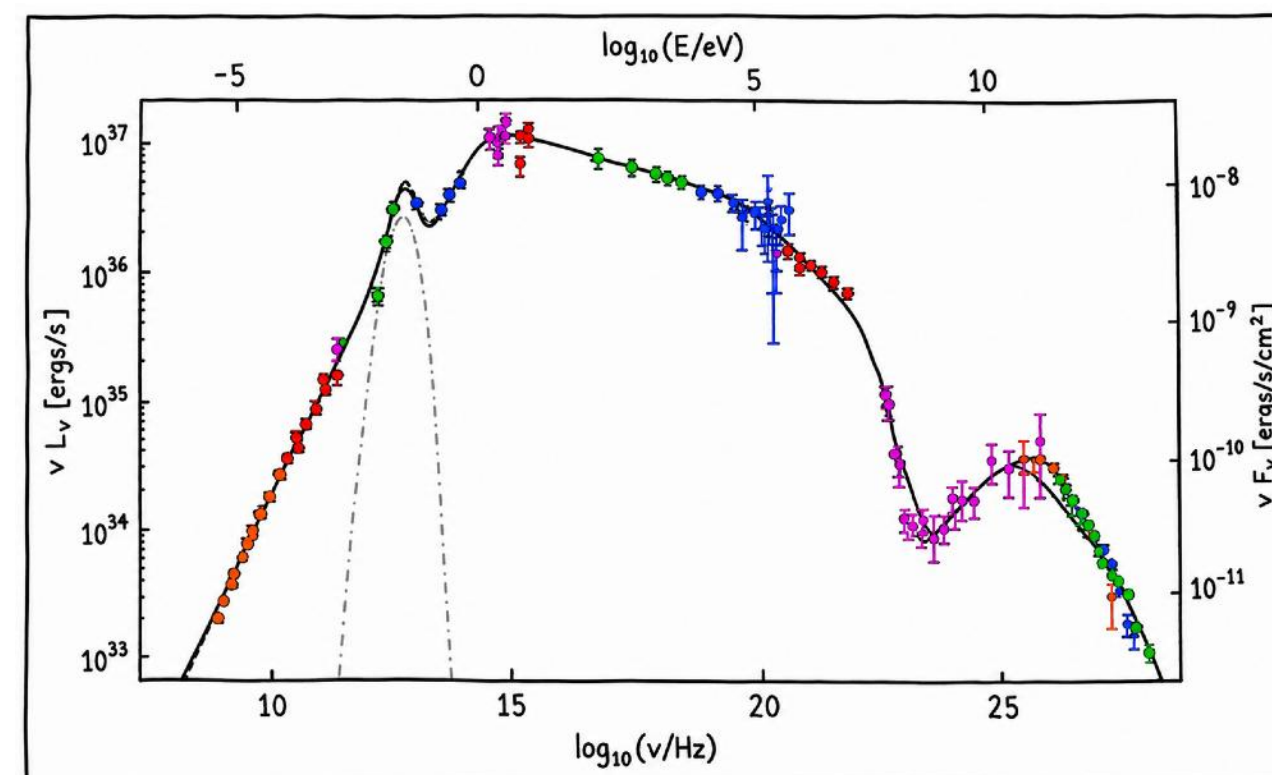
What do we want?



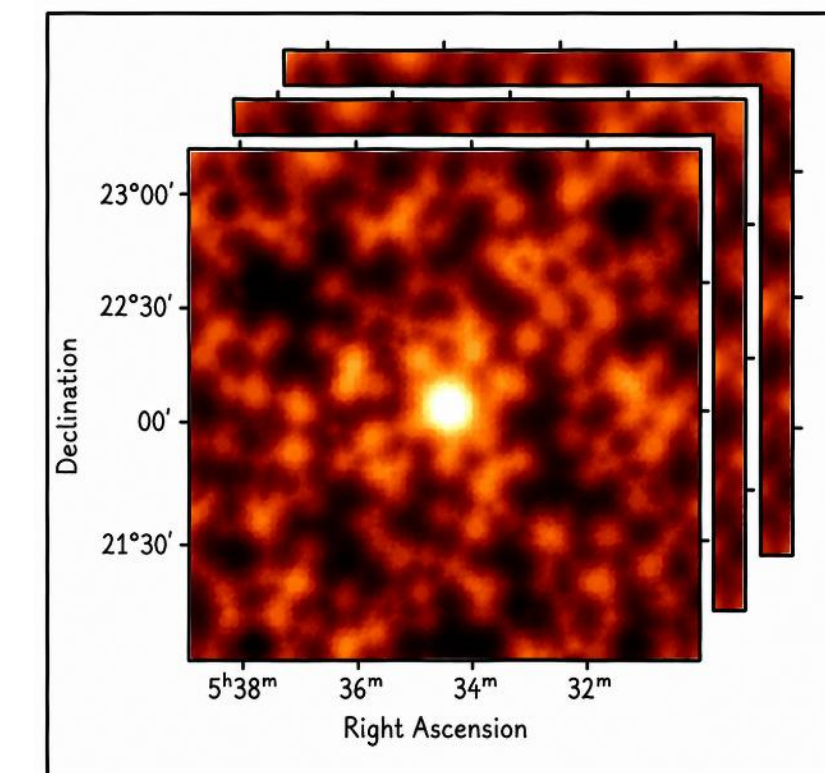
Images: γ -ray flux as a function of **spatial coordinates**



Light Curves: γ -ray flux from a region as a function of **time**



Spectra: γ -ray flux from a region as a function of **energy**

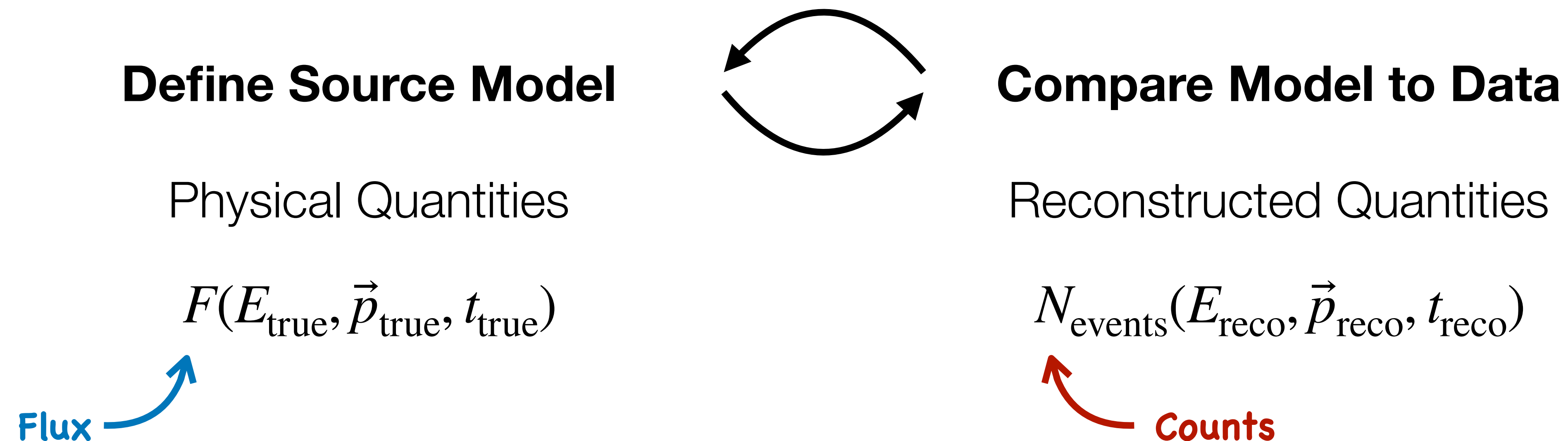


Or their combination (**data cubes**)

What do we *really* want?

To understand the source of emission

We make a hypothesis about the gamma-ray emission
in a region of the sky and test that hypothesis



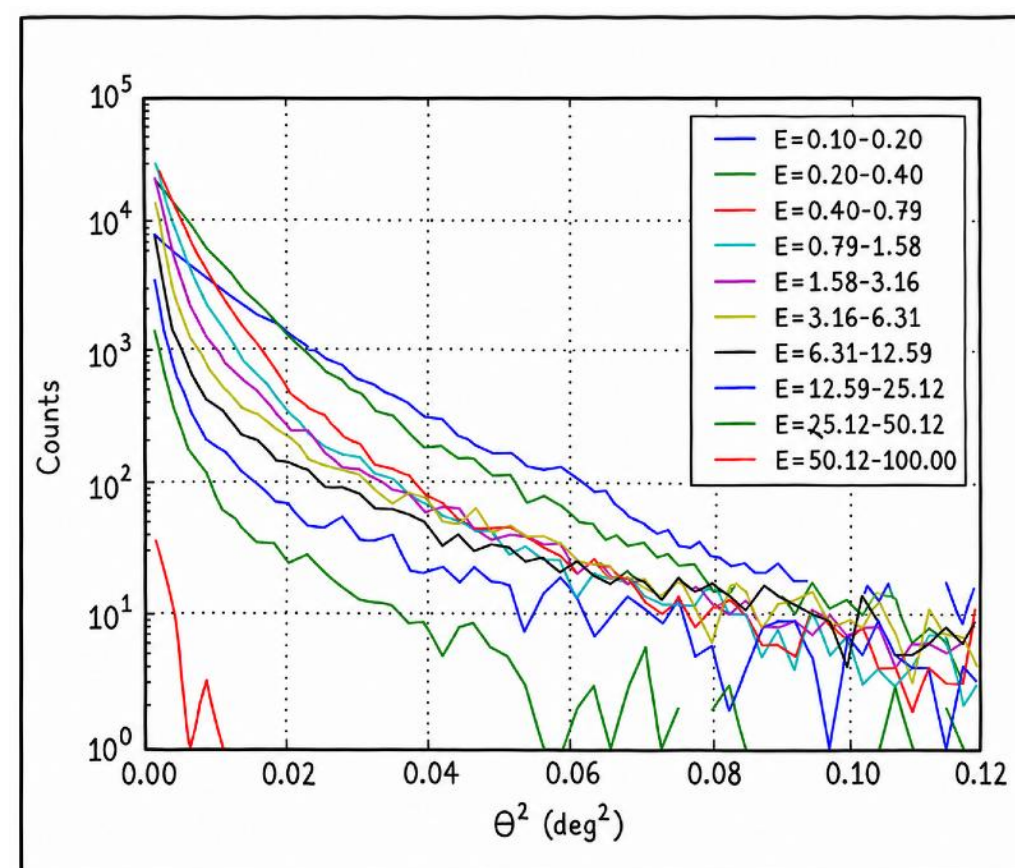
How to go between true and measured (reconstructed) quantities?

Credit: K. Kosack

Instrumental Response Function

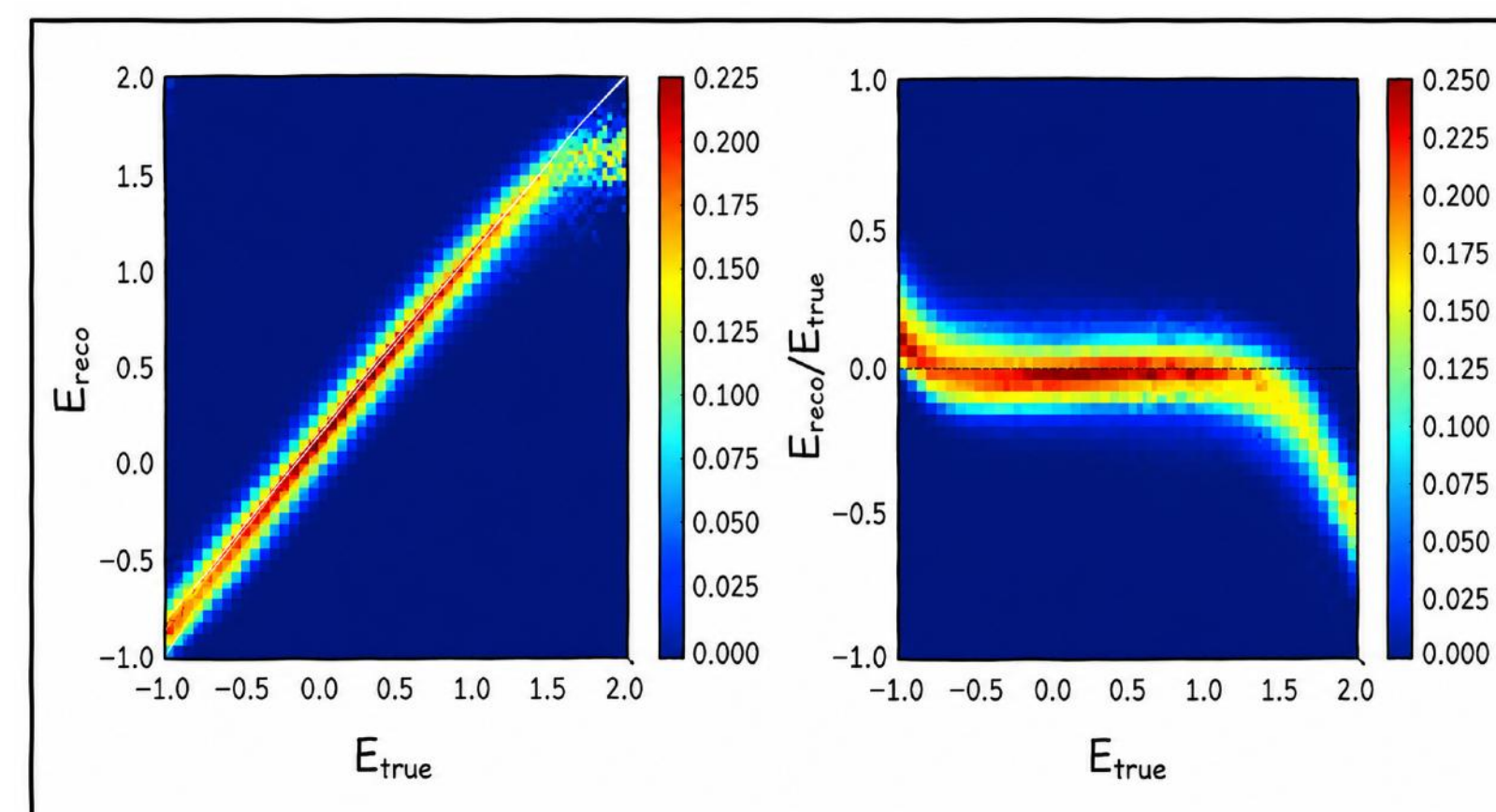
Generated from detailed air-shower simulations where both *true* and *reconstructed* quantities are known

Point Spread Function (PSF)



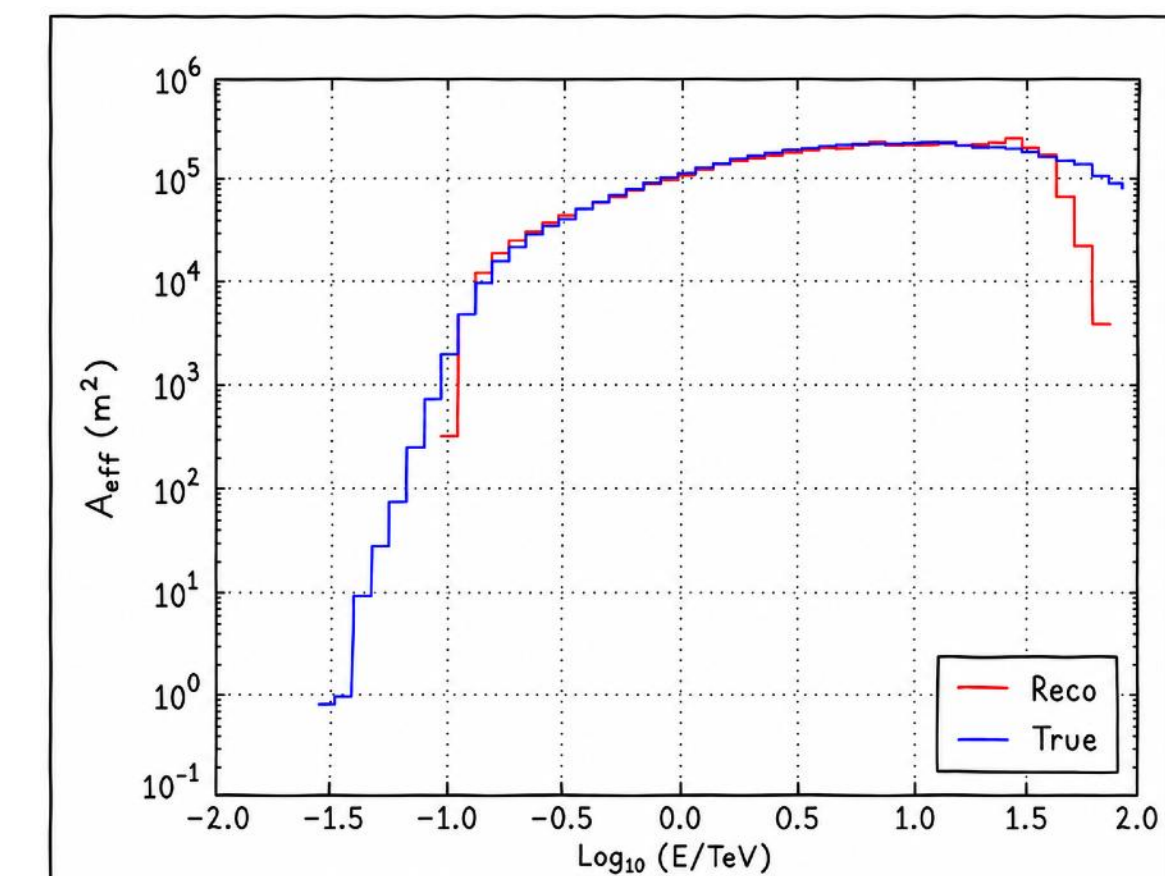
System response to perfect point in space: $P(\vec{p}_{\text{reco}} | \vec{p}_{\text{true}})$
Usually no translation, only dispersion

Energy-Migration Matrix



System response to a mono-energetic source: $P(E_{\text{reco}} | E_{\text{true}})$
Takes into account both energy resolution and energy bias

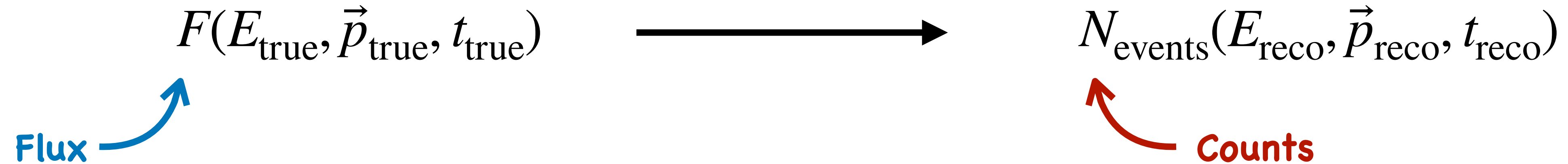
Effective Collection Area (A_{eff})



How likely it is to detect a γ -ray shower wrt the number of true showers times the true area simulated on the ground:
 $P(N_{\text{reco}} | N_{\text{true}}) \cdot A_{\text{true}}$

Credit: K. Kosack

From true flux to predicted counts



Assume: IRFs are independent factors (no cross-terms)

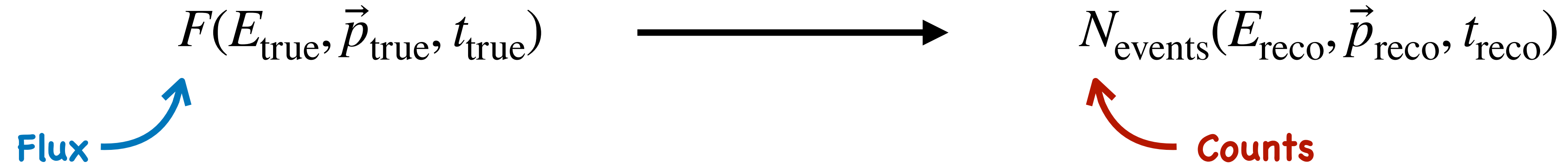
Given: flux model F that is a function of true energy, time, space

$$N_{\text{predicted}}^{\text{signal}} = F_{\text{true}} \circledast \left(A_{\text{eff}} \cdot PSF \cdot E_{\text{mig}} \right)$$

$$\Rightarrow N_{\text{predicted}}^{\text{observed}} = N_{\text{predicted}}^{\text{signal}} + N_{\text{predicted}}^{\text{background}}$$

Credit: K. Kosack

From true flux to predicted counts



Assume: IRFs are independent factors (no cross-terms)

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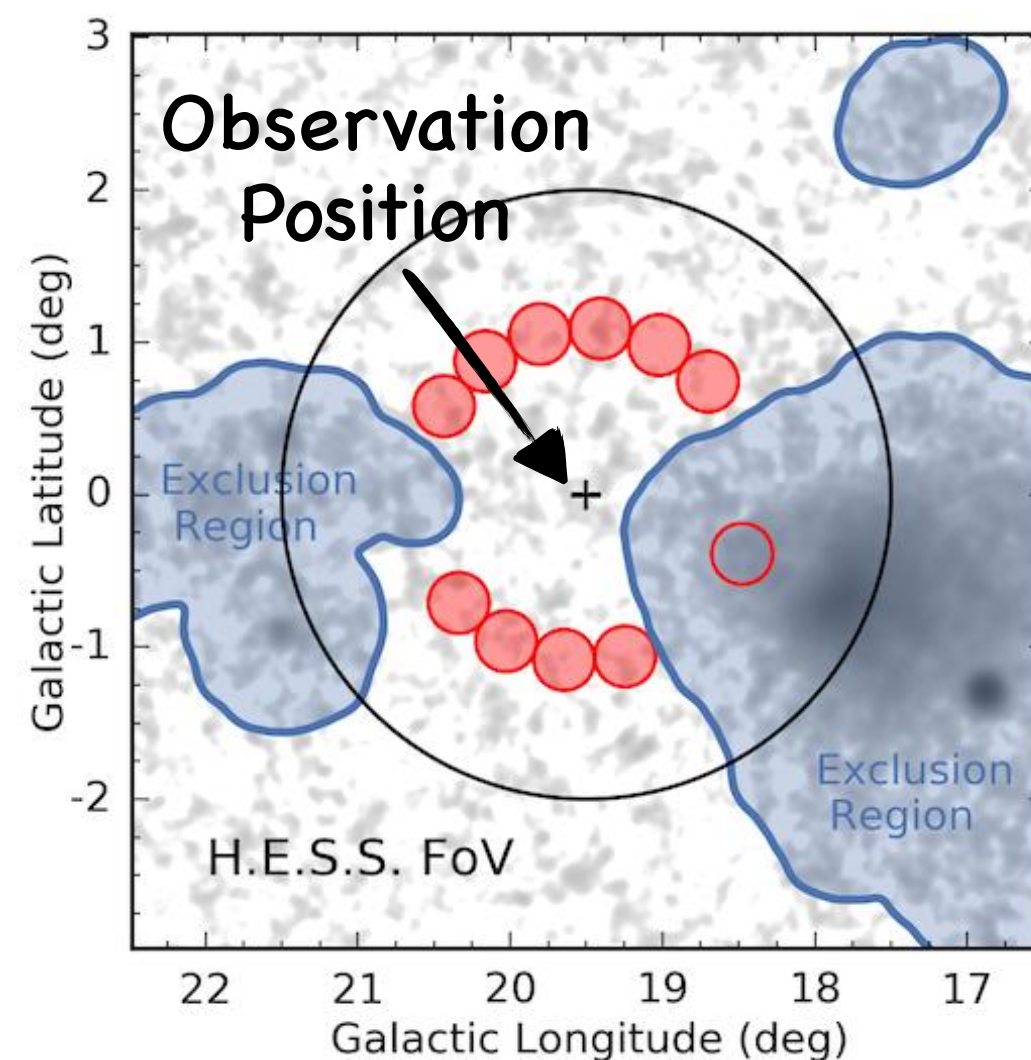
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Credit: K. Kosack

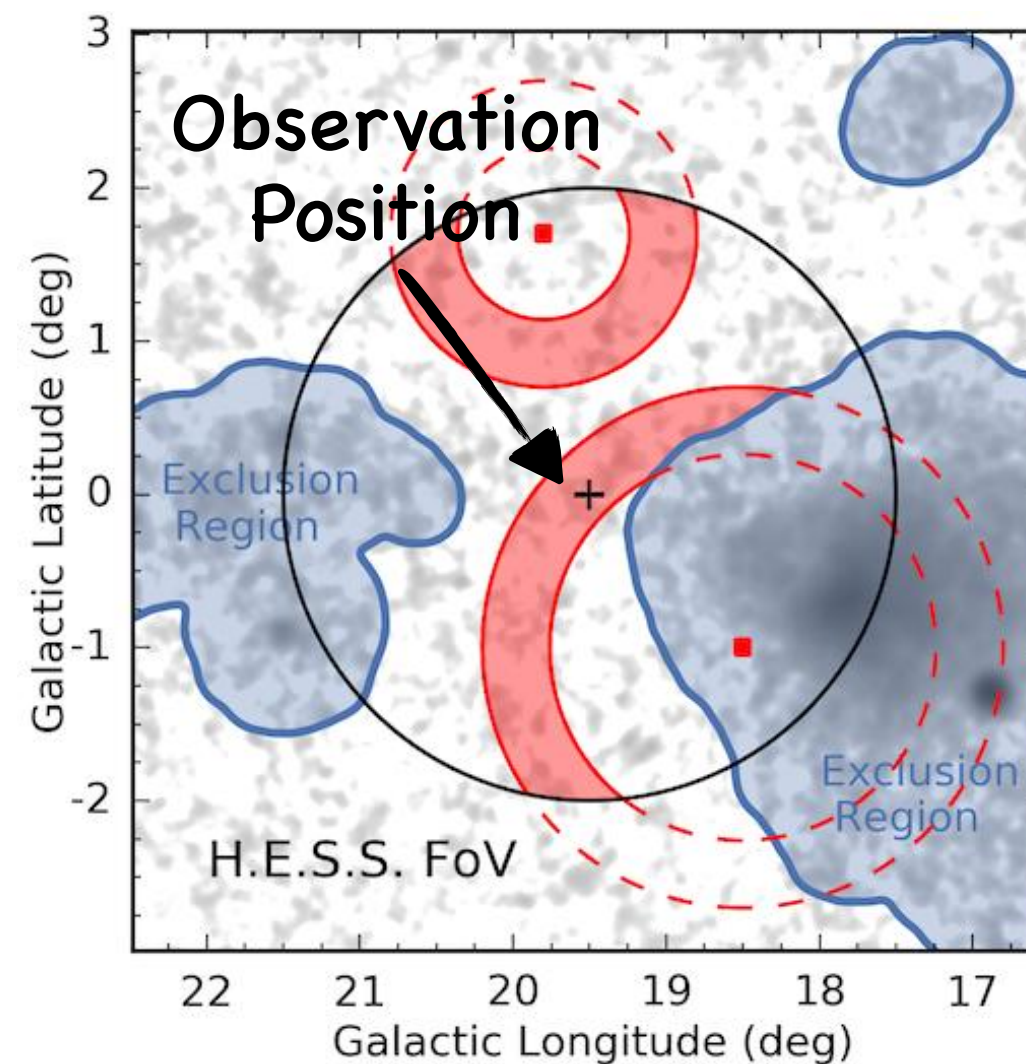
Background Model

- **Simulation:** difficult (uncertainties in hadronic physics) and computationally expensive.
- **Data-driven:** estimate background from γ -ray-free regions in the FoV or from dedicated observations (but systematics!)



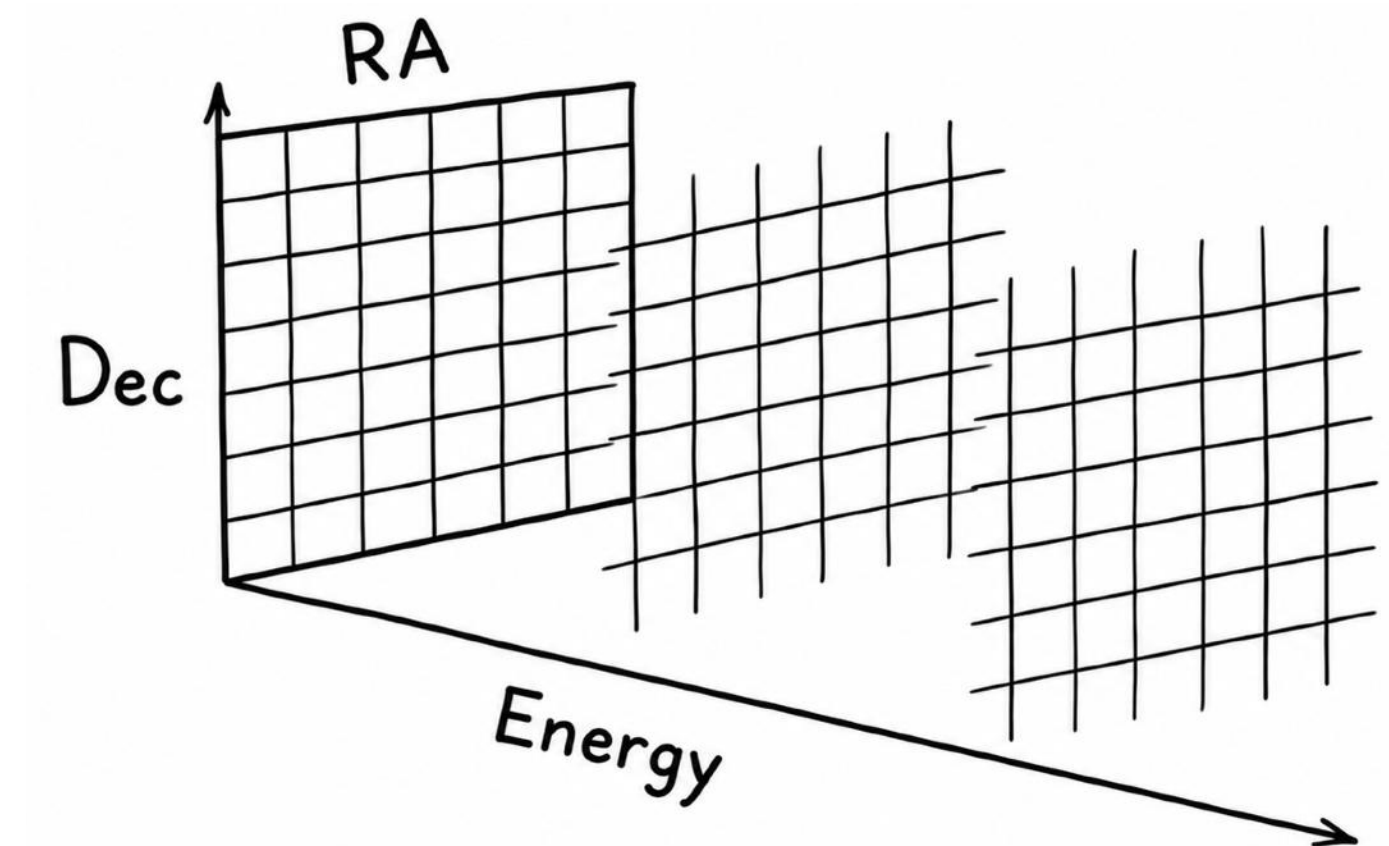
Reflected Region method

Bkg estimated from multiple OFF regions at the same camera offset as the source, minimizing acceptance systematics. Preferred for **spectra** and **light curves**.



Ring method

Bkg estimated from an annulus around each sky position, suppressing large-scale gradients and enabling sky-map production. Preferred for **source detection** and **significance maps**.

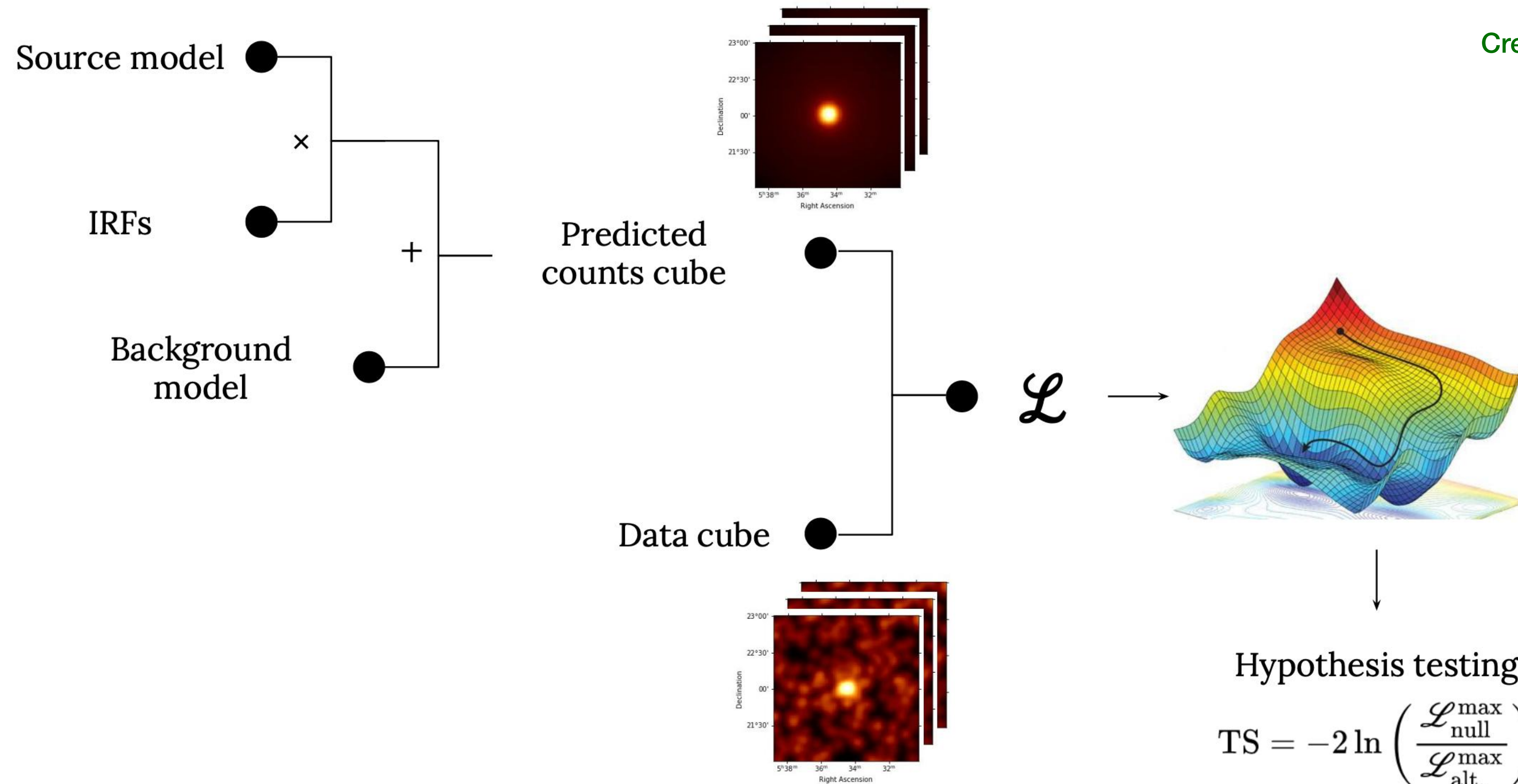


Field of View (FoV) method

An IRF-based background model is normalized using γ -ray-free regions of the FoV, providing an accurate estimate for 3D analyses. Preferred for **extended sources** and **stacked datasets**.

What is next?

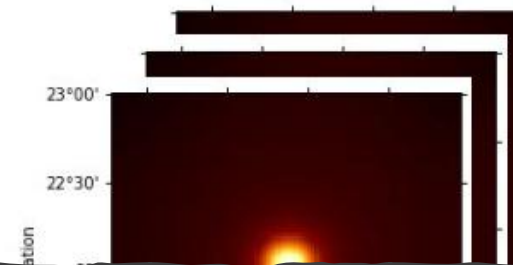
Likelihood minimization to get a source model in physical units



What is next?

Likelihood minimization to get a source model in physical units

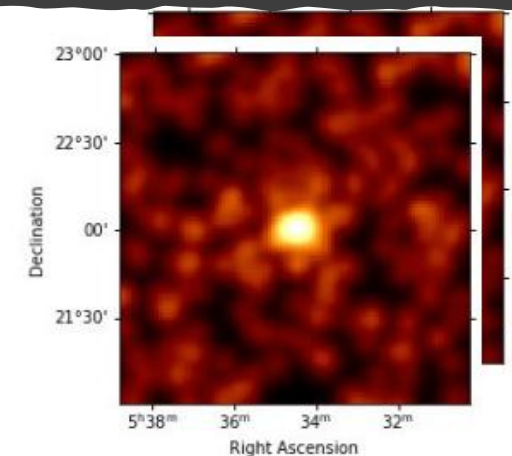
Source model



Credit: L. Giunti

$\gamma\pi$ A **Python** package for
gamma-ray astronomy

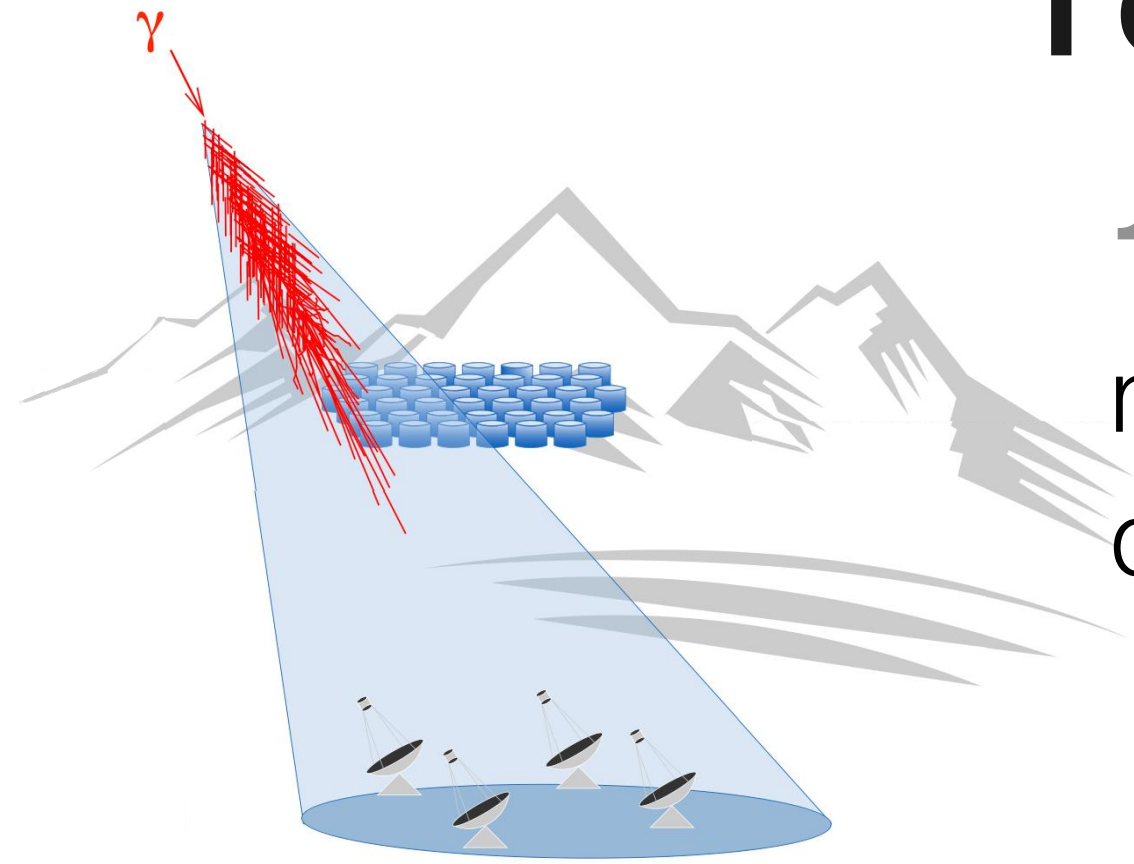
Hands-on session next Wednesday: you try!



Hypothesis testing

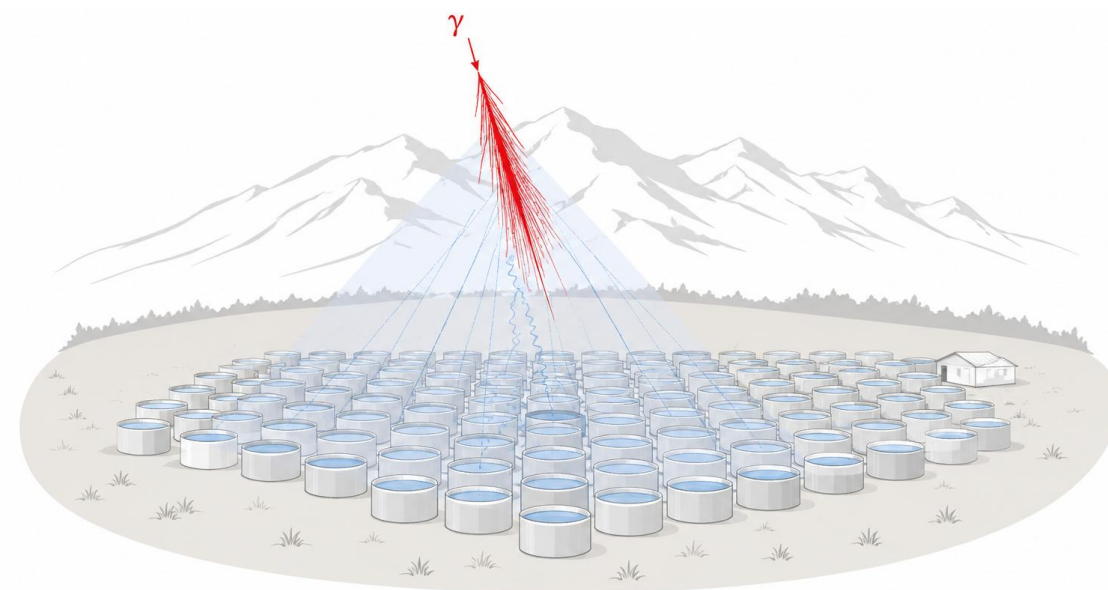
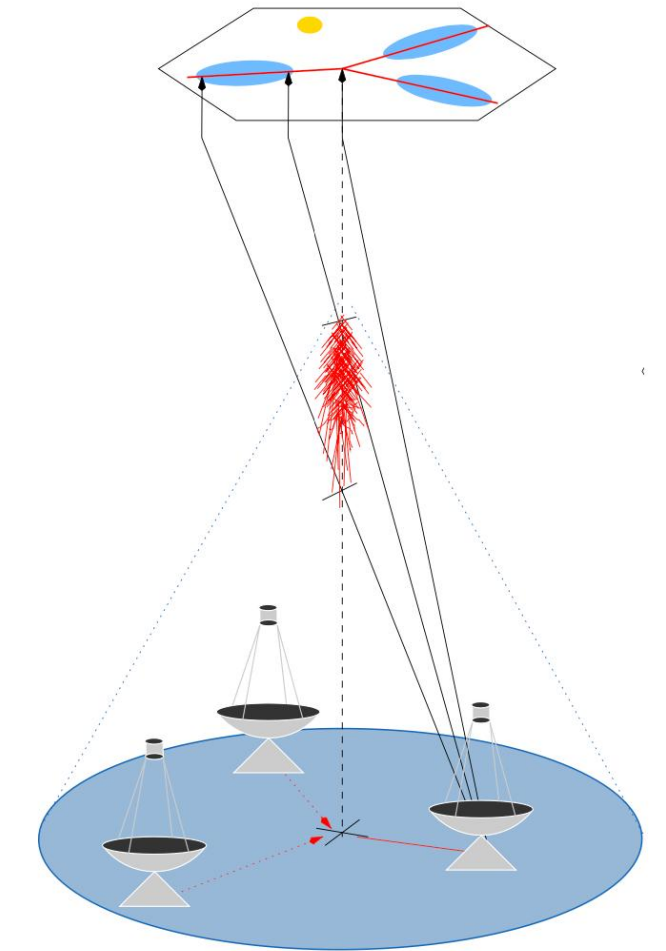
$$TS = -2 \ln \left(\frac{\mathcal{L}_{\text{null}}^{\text{max}}}{\mathcal{L}_{\text{alt.}}^{\text{max}}} \right)$$

Take home messages



1. VHE gamma-rays produced in astrophysical source via non-thermal processes create atmospheric EM showers detectable on the ground by WCDs and IACTs

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



3. Charged particles in the EM showers detected by WCDs at high altitude

4. From camera raw data to ready-to-analyze data: waveform calibration $\rightarrow$ single telescope reconstruction $\rightarrow$ stereoscopic reconstruction $\rightarrow$ γ -ray events $\rightarrow$ γ -ray flux

