

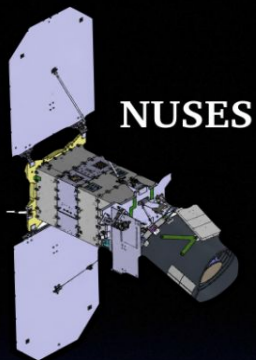
X-rays Emission: a novel tool to detect Extensive Air Showers

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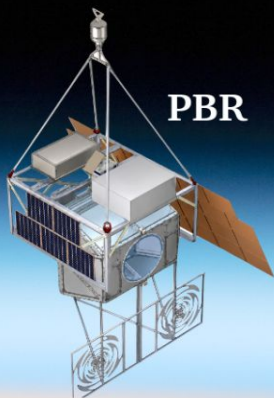
Supervisors: Prof. Roberto Aloisio, Prof. Adriano di Giovanni

Astroparticle PhD Passage of the Year
L'Aquila, Italy, Oct. 13, 2026

The detection principle: Look at the limb



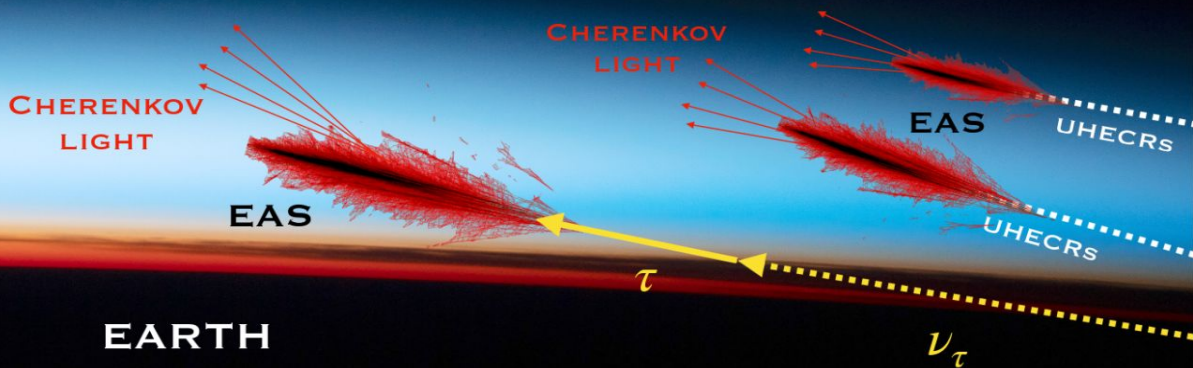
NUSES



PBR

Above: Cherenkov emission of air showers induced by CRs entering the atmosphere from above the Earth's limb

Below: Cherenkov emission produced by upward-moving EAS from tau decay or muon interactions.



Outline

The observation of **PeV Cosmic Rays** is key to understanding: sources, acceleration mechanisms, galactic–extragalactic transition...

- Currently, CRs above ~ 1 PeV detected only via **Extensive Air Showers (EAS)** with ground-based methods.
- Composition still uncertain (model dependencies, systematic errors).

New direction: High-altitude detection (~ 30 km)

- Advantages: larger acceptance, less absorption, higher efficiency.

Focus of this work:

- **Synchrotron X-ray emission from EAS** from e^-/e^+ secondaries in the geomagnetic field.
- Unique probe of **early EAS stages** (HE electrons, > 100 GeV).

Goals:

- Model the X-ray emission.
- Estimate the signal properties at the detector position.
- Estimate event rates.

Outline: PRD Publication

The first complete study based on this framework has now been published in the journal Physical Review D.

Publishing was also an opportunity to substantially expand and improve the original analysis following the referee comments.

- extension of the simulated photon energy range. The original study considered photons from 10 keV to 10 MeV, while the updated work extends the range up to 1 GeV.
- refined procedure to calculate the detector acceptance and event rate
- refined procedure to estimate the effect of the magnetic field on the photon footprint
- the simulation was additionally extended to detector altitude of 5 km and below.

Paper:



PHYSICAL REVIEW D **113**, 123067 (2026)

X-rays emission: A novel tool to detect extensive air showers

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We investigate the feasibility of detecting extensive air showers via their geo-synchrotron x-ray emission from high-altitude platforms. Starting from first principles, we derive a differential expression for the number of emitted photons per unit grammage and photon energy for an ensemble of gyrating shower electrons. The calculation uses noted parametrizations of the electron state variable distributions in the shower to establish a scale for the photon footprint and, further, takes into account the propagation of emitted photons in the atmosphere. The computed fluxes at the position of the detector are used to estimate the detector acceptance and event rate using a bootstrap Monte-Carlo procedure. For a 1 m-radius, 70° half-aperture circular detector at an altitude between 20 km to 30 km viewing the Earth's limb, we find acceptances at the $O(1 \text{ m}^2 \text{ sr})$ level and integral event rates of $O(10)$ per month. These results indicate that x-ray geo-synchrotron emission is a promising, complimentary channel for high-altitude indirect cosmic ray detection in the PeV regime.

DOI: 10.1103/physrevd.113.123067

Outline: The Master Formula

For an ensemble of particles in the incoherent radiation regime, the number of photons emitted by an EAS is given by:

- the convolution of the single-particle spectrum with the electron energy distribution,
- integrated over the entire shower development.

$$\left(\frac{dN_\gamma}{dE_\gamma} \right)^{\text{EAS}} = \int_{X_0}^{X_1} \frac{dX}{\rho(X)c} \text{Tr}(E_\gamma, \Delta X) N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma)$$

Number of
Photons

Geometry

Absorption

Longitudinal
Development

Electron Energy
Distribution

Single Particle
Emission

Earth's Atmosphere

EAS Physics

Geomagnetic
Synchrotron

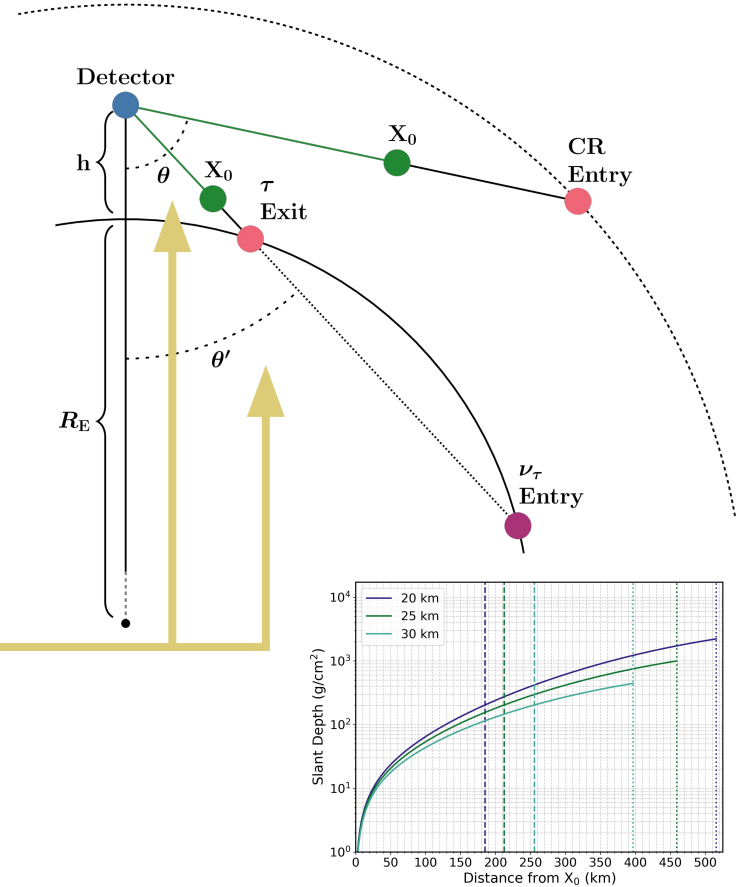
Outline: Geometry

The photon emission integral is computed along the **line of sight**:

- from a **reference point** (CR entry or charged lepton exit point)
- to the position of a **fixed detector**.

The geometry is fixed by the detector position and a **viewing angle**

For a detector at high-altitudes, the observed showers develop over scales of 100 – 1000 km.



Photon Emission From EAS

$$\left(\frac{dN_\gamma}{dE_\gamma}\right)^{\text{EAS}} = \int_{X_0}^{X_1} \frac{dX}{\rho(X)c} \text{Tr}(E_\gamma, \Delta X) \left[N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma) \right]$$

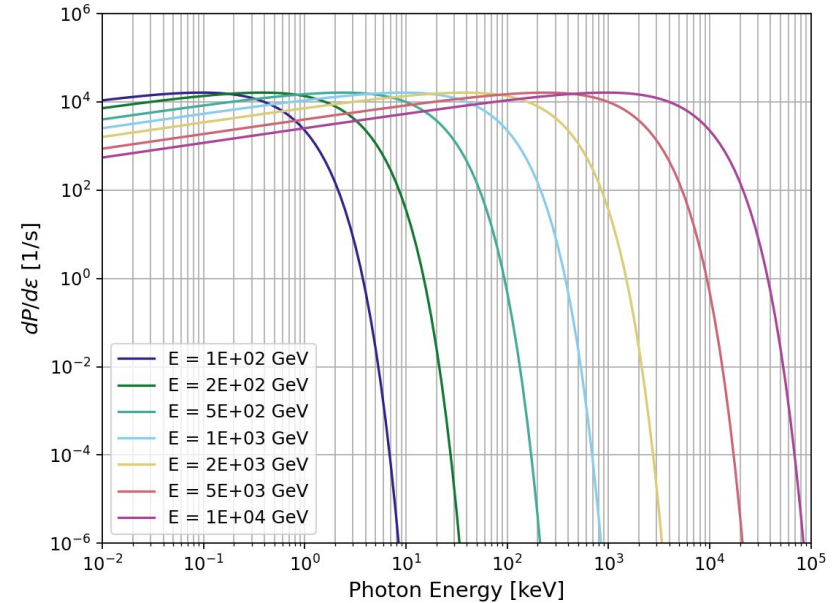
Emission: Single Electron

- The power spectrum is universal and proportional to the synchrotron function $\mathbf{F}(\mathbf{x})$, where $\mathbf{x} = \omega / \omega_c$

$$\frac{dN_\gamma}{dt dE_\gamma} = \frac{1}{E_\gamma} \frac{dP}{dE_\gamma} \propto F\left(\frac{E_\gamma}{\hbar\omega_c}\right)$$

$$\omega_c \propto \gamma^2 \|\vec{B}\| \sin(\alpha_p)$$

- In the geo-magnetic field, emission in the X- / gamma-ray bands requires electron energies $\gtrsim 100$ GeV.



- $E_\gamma < \hbar\omega_c$: power grows as a power law.
- $E_\gamma > \hbar\omega_c$: power falls off exponentially.
- Emission is concentrated in a narrow band about ω_c .

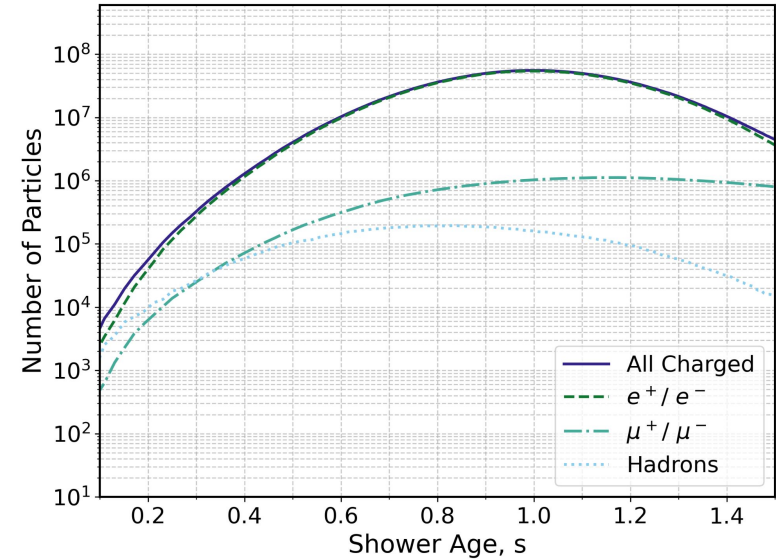
Emission: Air Showers

The instantaneous photon emission is the **single-particle spectrum** integral over the **shower electrons' energy distribution**:

$$\left(\frac{dN_\gamma}{dt dE_\gamma} \right)^{EAS} = N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \times \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma)$$

This work uses:

- **Nerling electron spectrum** model.
- **CORSIKA longitudinal profiles**.



CORSIKA showers give the # of electrons at arbitrary stages of shower development, above:

- 100 PeV proton shower
- QGSJETII-04 (high energies)
- GHEISHA 2002d (low energies)

Atmospheric Effects

$$\left(\frac{dN_\gamma}{dE_\gamma}\right)^{\text{EAS}} = \int_{X_0}^{X_1} \boxed{\frac{dX}{\rho(X)c} \text{Tr}(E_\gamma, \Delta X)} N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma)$$

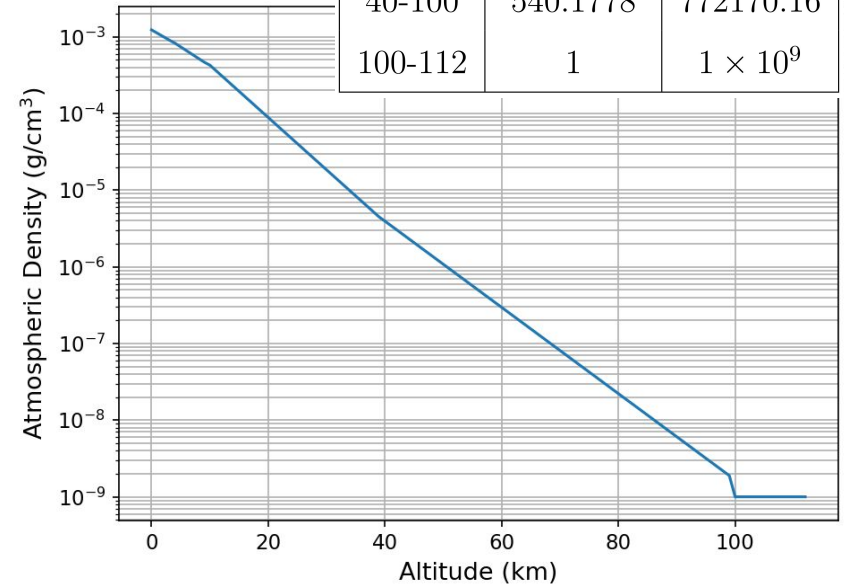
Atmosphere: Density

- The atmospheric density profile is based on the 1976 **US Standard Atmosphere**.

$$\rho(z) = \begin{cases} \frac{b}{c} e^{-z/c} & \text{if } z \leq 100 \text{ km} \\ \frac{b}{c} & \text{if } z > 100 \text{ km} \end{cases}$$

- It is a multi-layer exponential model (above) with parameters depending on the atmosphere layer (upper right).

$z(\text{km})$	$b(\text{g}/\text{cm}^2)$	$c(\text{cm})$
0-4	1222.6562	994186.38
4-10	1144.9069	878153.55
10-40	1305.5948	636143.04
40-100	540.1778	772170.16
100-112	1	1×10^9

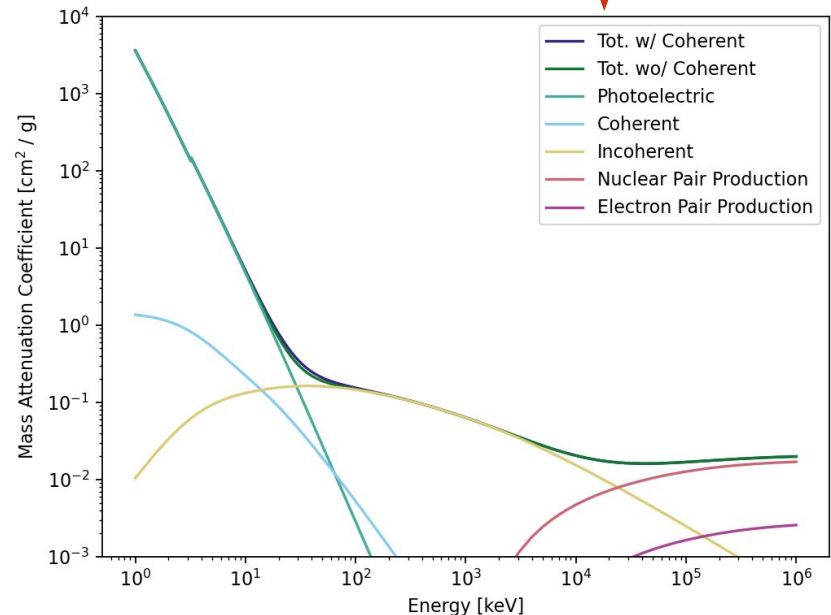


Atmosphere: Attenuation

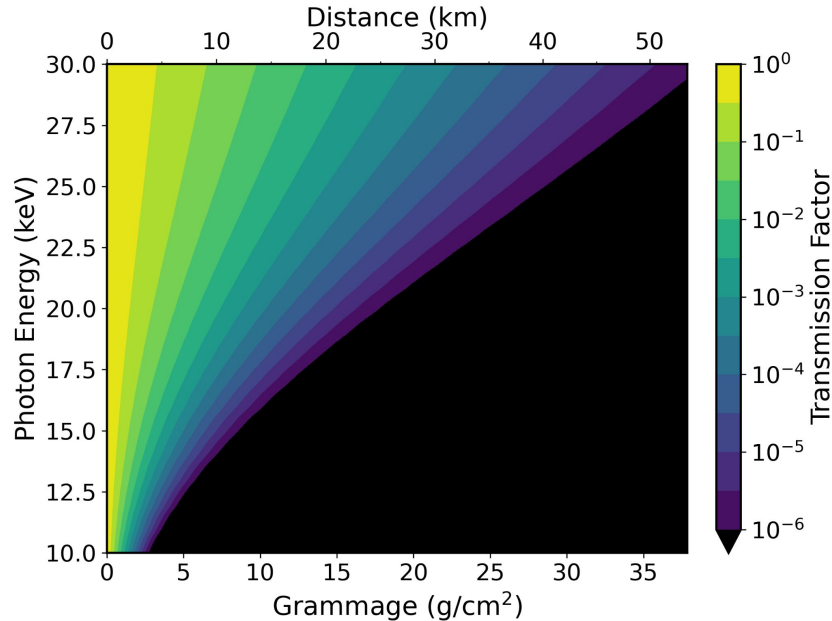
- Photons interact with the atmosphere along their path to the detector.
- The transmission factor depends on the line-of-sight integral of an attenuation coefficient.
- For a single element, this attenuation coefficient is inversely proportional to the interaction cross-section
- The NIST XCOM database was queried to obtain the attenuation coefficients.

$$\text{Tr}(E_\gamma) = \exp \left[- \int_0^L \boxed{\mu_a(E_\gamma)} \rho(l) dl \right]$$

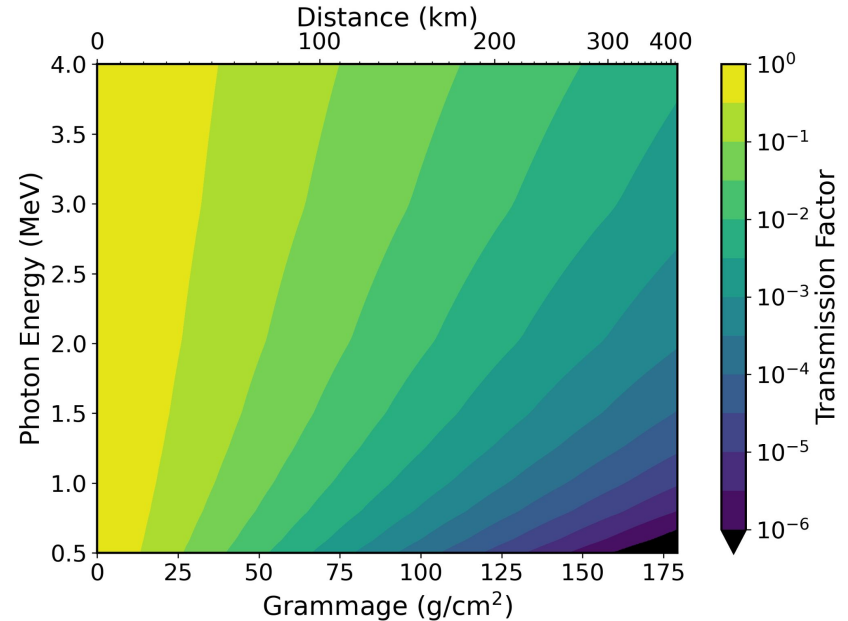
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Atmosphere: Transmission Factors



X-rays

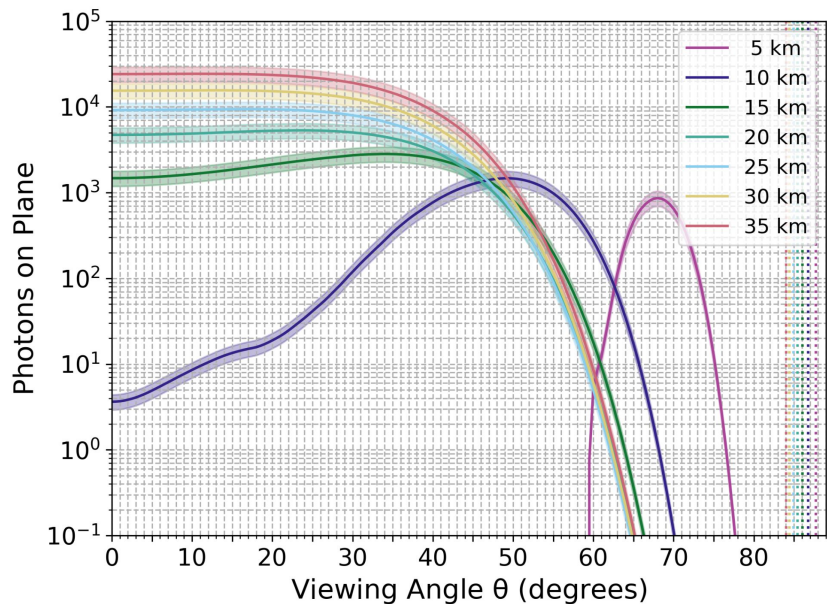


Gamma Rays

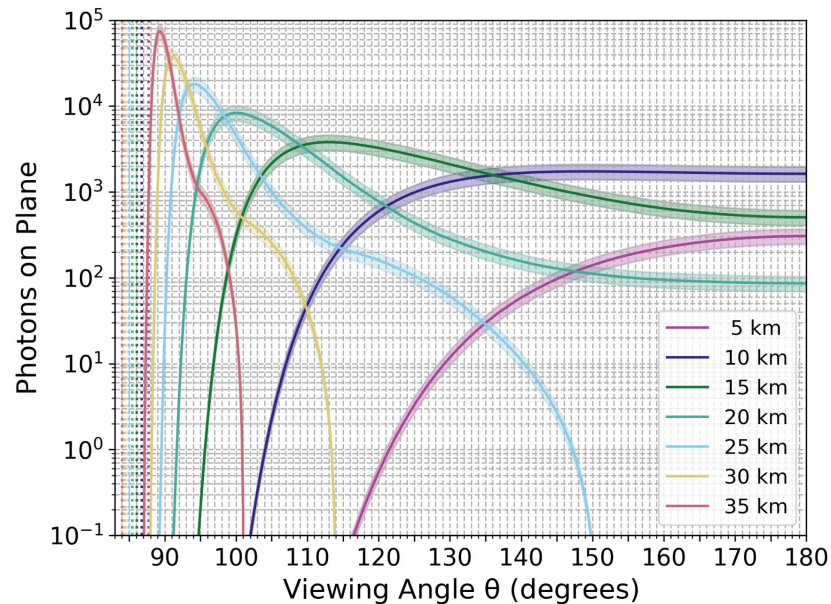
Photon Counts

$$\boxed{\left(\frac{dN_\gamma}{dE_\gamma}\right)^{\text{EAS}} = \int_{X_0}^{X_1} \frac{dX}{\rho(X)c} \text{Tr}(E_\gamma, \Delta X) N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma)}$$

Photon Counts: 100 PeV

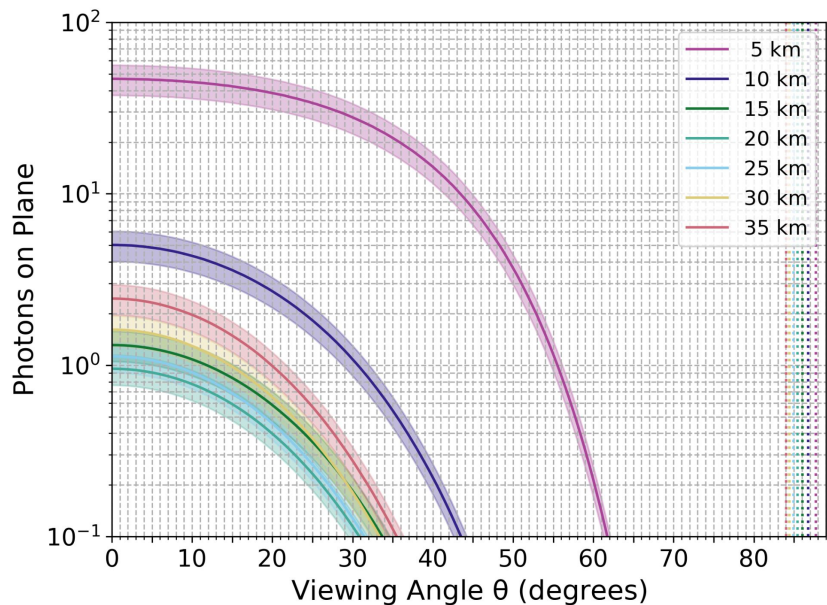


Below-limb

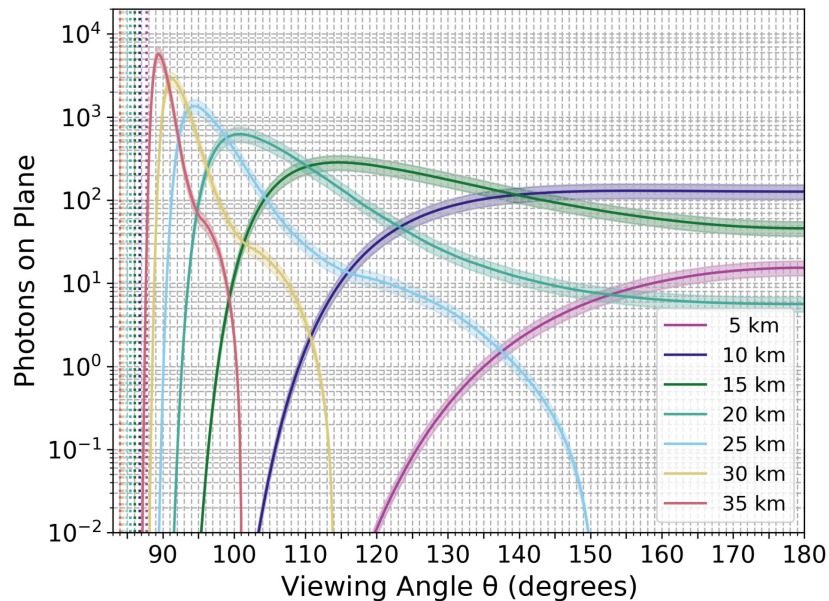


Above-limb

Photon Counts: 10 PeV



Below-limb



Above-limb

Emission Footprint & Fluxes

Emission Footprint

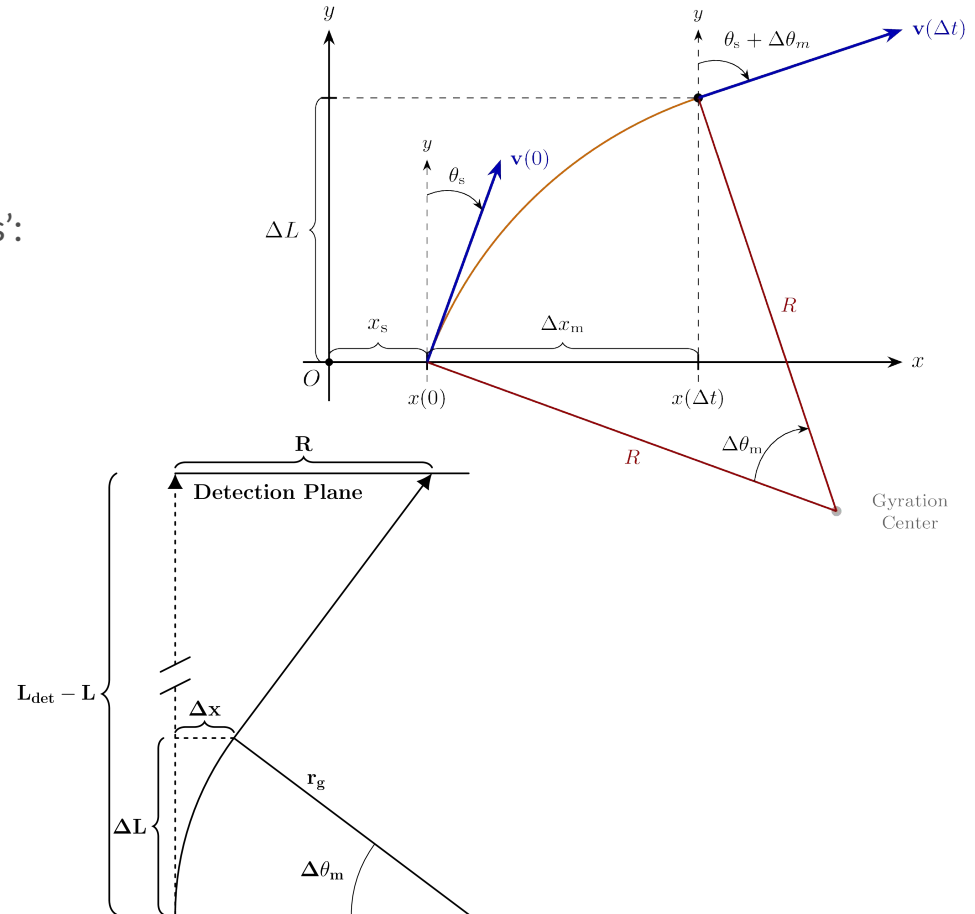
The photon spatial distribution at the detector (and flux) depends on the high-energy electrons':

- lateral distribution (w.r.t shower core),
- angular distribution (w.r.t shower axis),
- photon emission cone ($\sim 1/\gamma$)

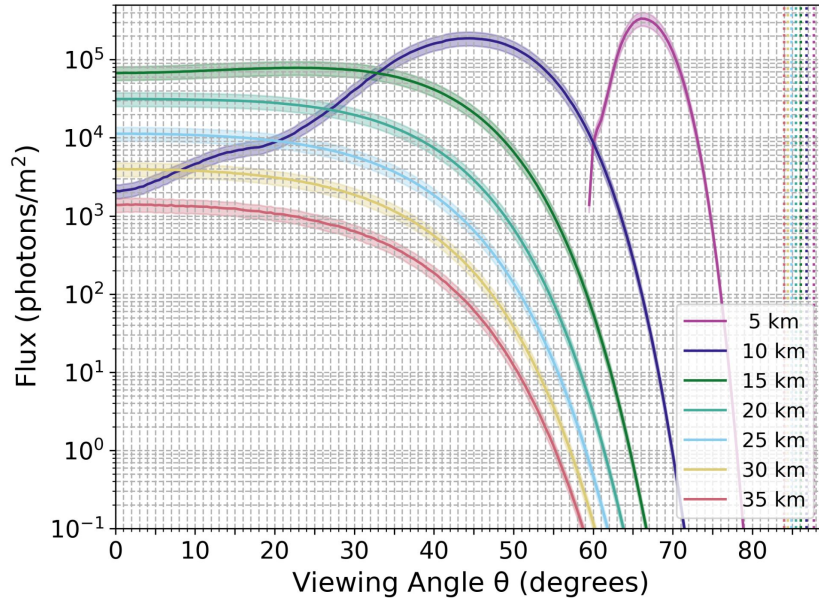
Geomagnetic field effects:

- Larmor radii $\sim 10^4$ km in Earth's B
- showers develop over $\sim 10^3$ km

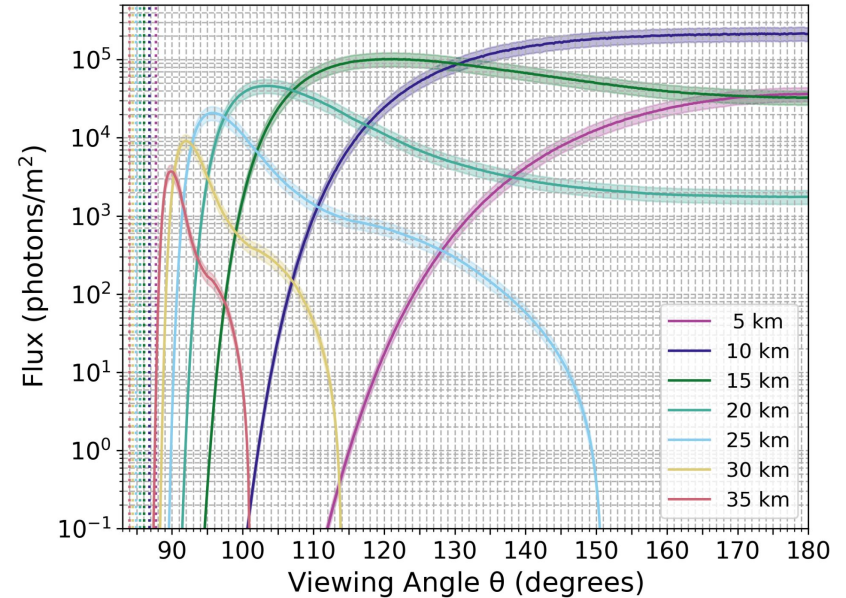
Plus, propagation and projection effects alter footprint between emission and detection.



Photon Flux On Detection Plane (100 PeV)

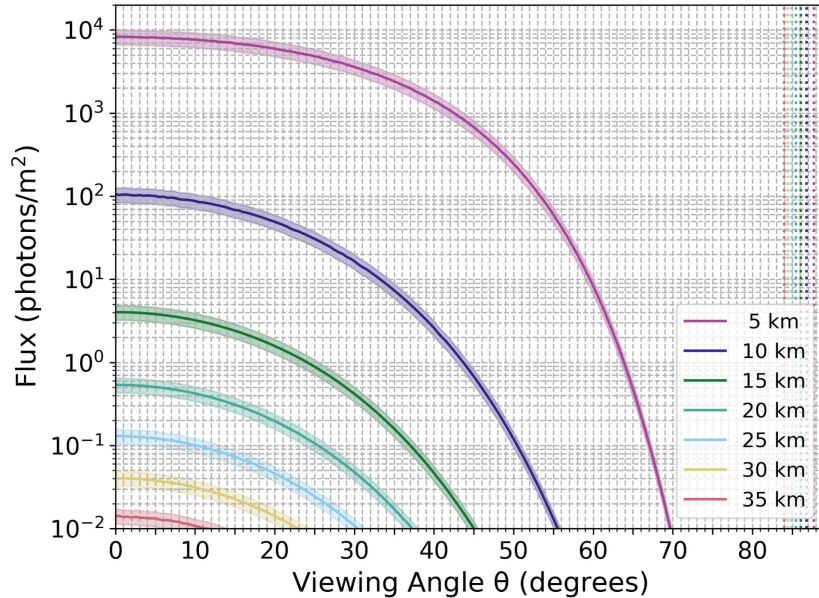


Below-limb

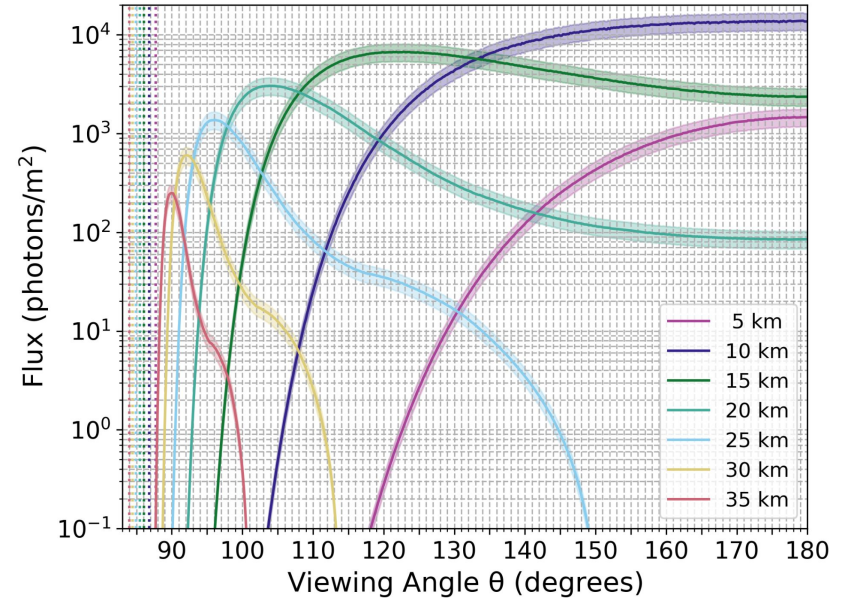


Above-limb

Photon Flux On Detection Plane (10 PeV)

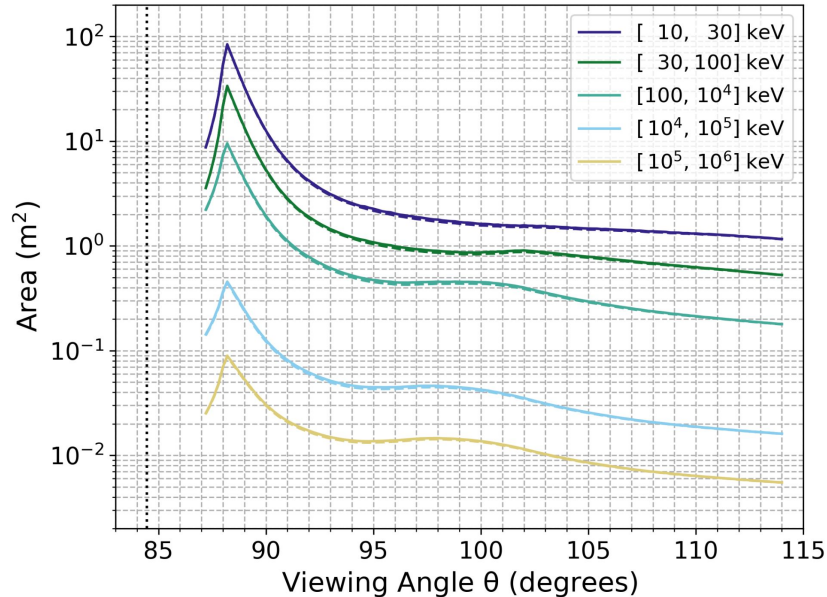


Below-limb

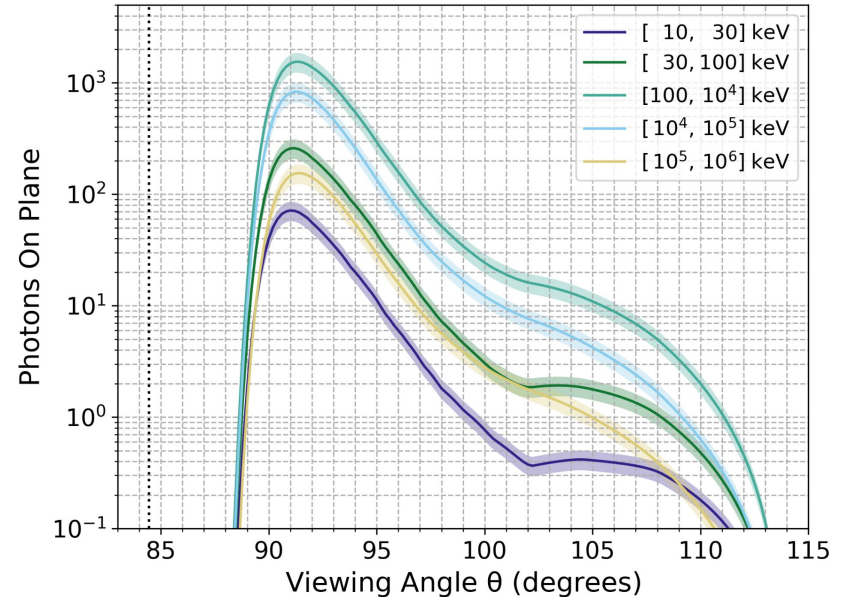


Above-limb

Signal Properties On Detection Plane (10 PeV)



Per-band Footprint
Areas @ 30 km



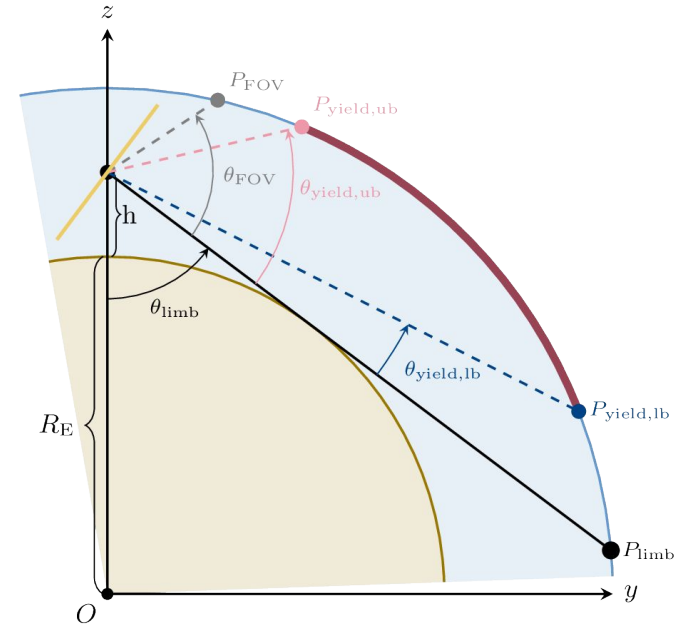
Per-band Photon
Counts @ 30 km

Event Rate & Acceptances

Bootstrap MC Approach: Sky Scan

For every point on our generation area:

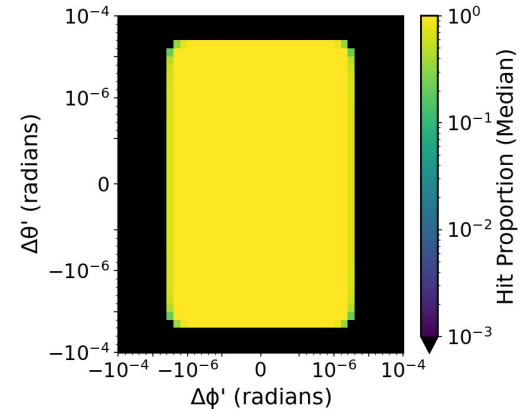
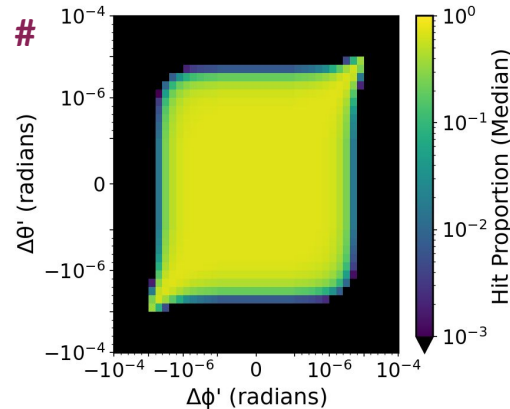
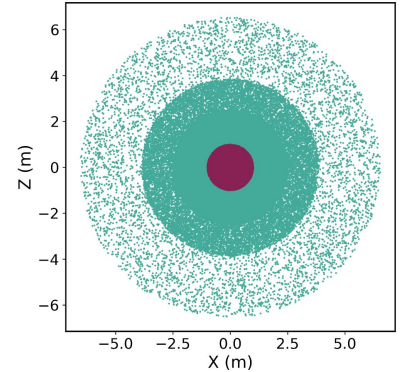
- connect the point to the detector center
- **define direction grid** about point using angular deviations ($\Delta\theta'$, $\Delta\phi'$)
- **generate and project positions** from shower plane to detector plane
- **compute the hit proportion** as the ratio: #
inside geometry / # outside geometry
- **built hit proportion distribution** via bootstrapping
- **extract median and 95 % confidence interval**



Bootstrap MC Approach: Sky Scan

For every point on our generation area:

- connect the point to the detector center
- **define direction grid** about point using angular deviations ($\Delta\theta'$, $\Delta\phi'$)
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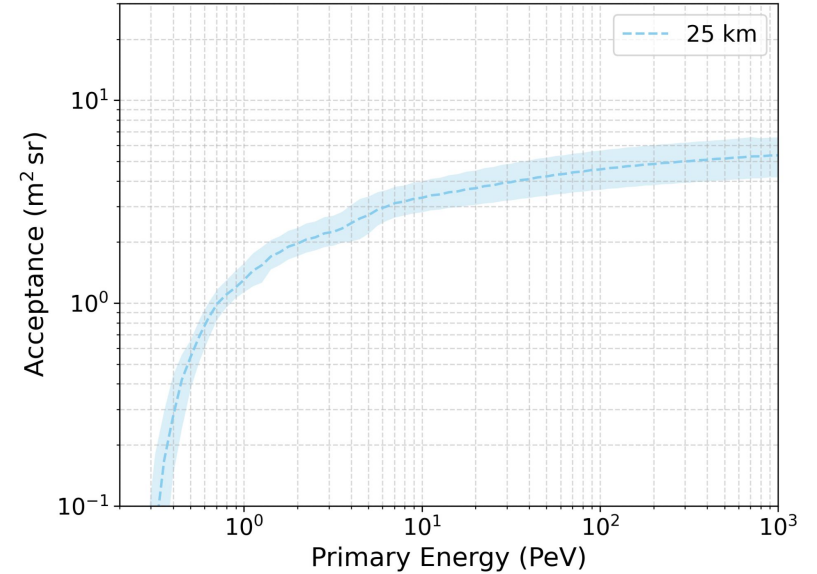
Acceptance & Event Rates: CRs

From the single hit probabilities, we compute an efficiency factor for every position in the sky as:

$$\xi_i(E) = \sum_{m,n} P(N_{\text{hit}} \geq N_{\text{threshold}}; N_{\gamma,i}(E), p_{m,n}) \times \left(\frac{\Delta\theta'_m \Delta\phi'_n}{4\pi} \right)$$

And we compute the acceptance as:

$$\begin{aligned} G(E) &= (A_{\text{geo}} \Omega_{\text{geo}}) \times \frac{1}{N_{\text{gen}}} \sum_i \frac{N_{\text{gen}}}{N_{\text{cells}}} \xi_i(E) \\ &= (A_{\text{geo}} \Omega_{\text{geo}}) \times \frac{1}{N_{\text{cells}}} \sum_i \xi_i(E) \end{aligned}$$



Circular Detector. Looking at limb.
FoV = 70°. R = 1 m.

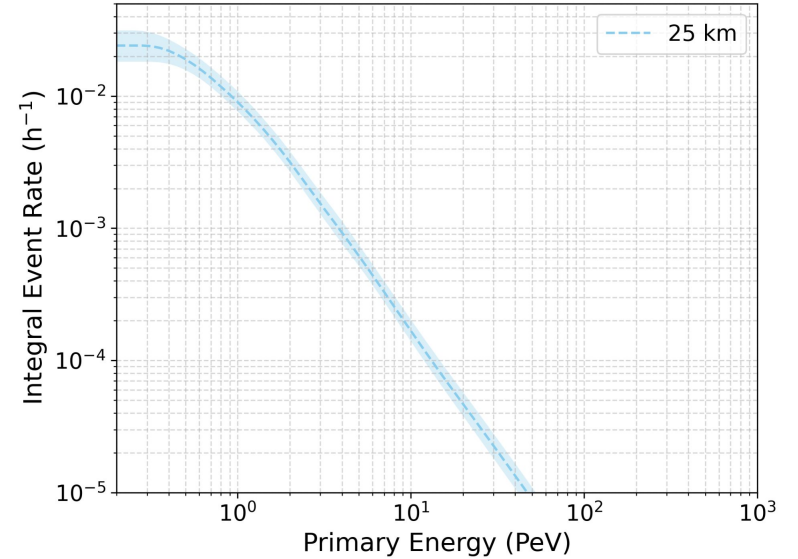
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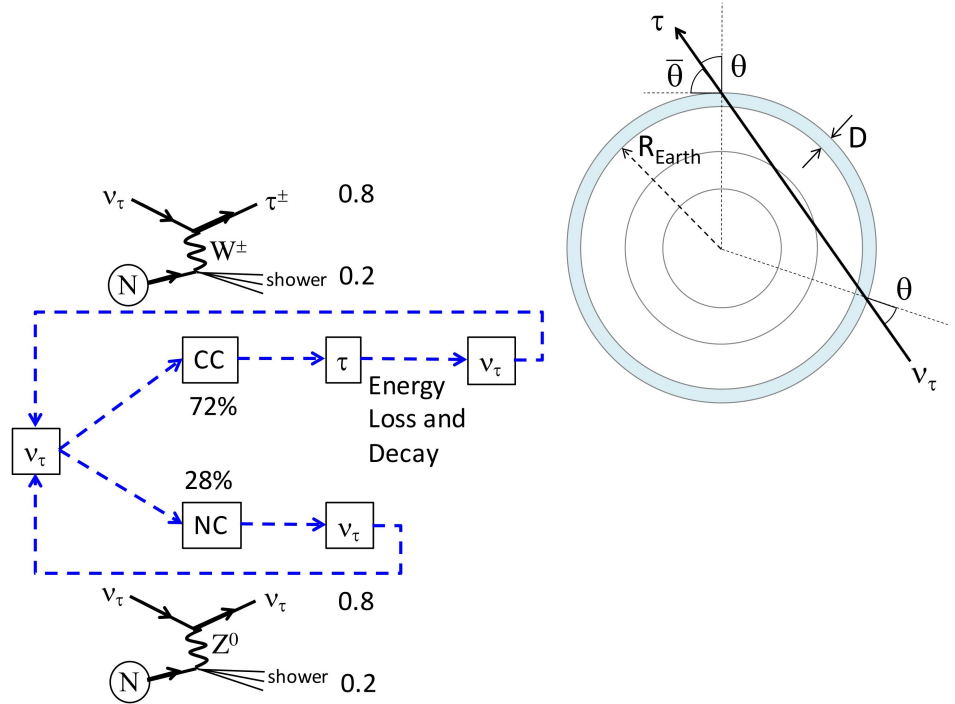
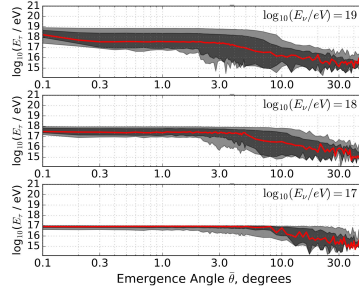
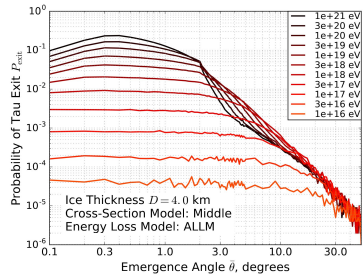


Circular Detector. Looking at limb.
FoV = 70°. R = 1 m.

Acceptance & Event Rates: Neutrinos

Full modeling of the earth-skimming neutrino events requires simulating of several additional processes, including the neutrino interaction inside the Earth, its propagation as well as the lepton interactions and their propagation.

This work uses **NuTauSim** as part of the simulation chain.



Acceptance & Event Rates: Neutrinos

Earth-skimming neutrinos introduce additional physical processes to the chain:

1. neutrino Earth propagation and lepton emergence:
 - a. lepton exit probability
 - b. lepton energy distribution
2. lepton atmospheric propagation before interaction/decay
3. lepton energy deposition into the hadronic shower

The **detector efficiency** must be integrated over these stochastic processes.

$$\begin{aligned}\xi_i(E_\nu) &= P(\text{trigger} \mid E_\nu, \alpha_i) = P_{\text{exit}}(E_\nu, \alpha_i) \\ &\times \int dE_\tau P(E_\tau \mid E_\nu, \alpha_i, \text{exit}) \\ &\times \int dL' P(L' \mid E_\tau) \\ &\times \int dE_{\text{sh}} P(E_{\text{sh}} \mid E_\tau) \\ &\times \xi(E_\tau, L', E_{\text{sh}})\end{aligned}$$

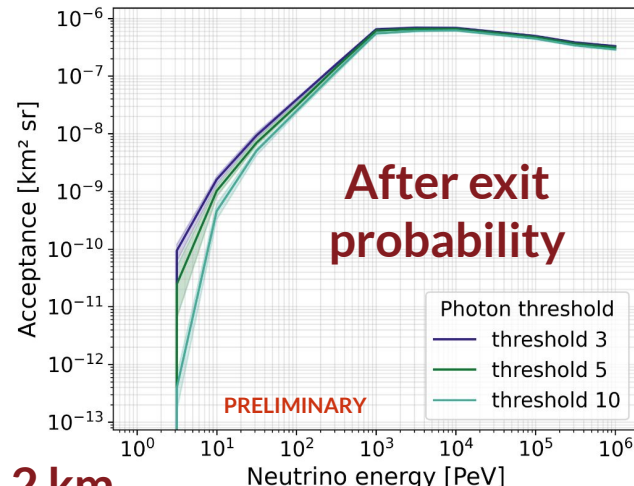
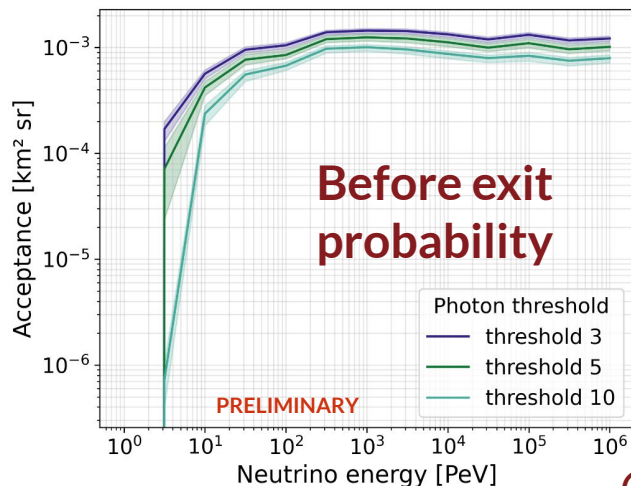
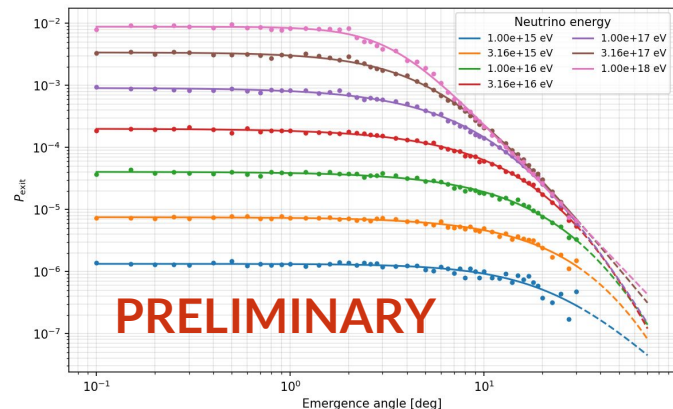
This work uses **NuTauSim** to compute and tabulate the lepton exit probabilities and energy distributions as a function of the emergence angle, α_i .

Acceptance: Neutrinos

The emergence probability is the dominant factor, suppressing events at large emergence angles.

- large emergence angles equal long Earth chords
- suppressed lepton emergence
- the EAS develops upwards -> more absorption
- smaller altitudes are favored

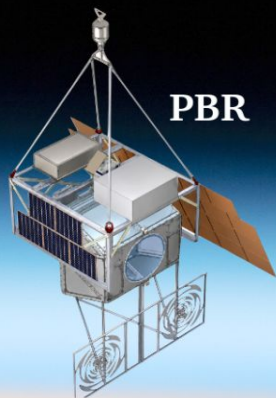
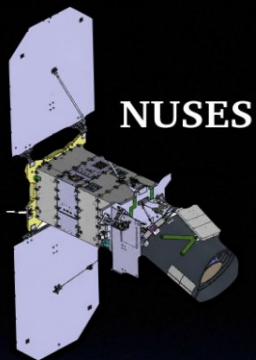
Exploring alternative geometries is crucial to recover acceptance.



@ 2 km

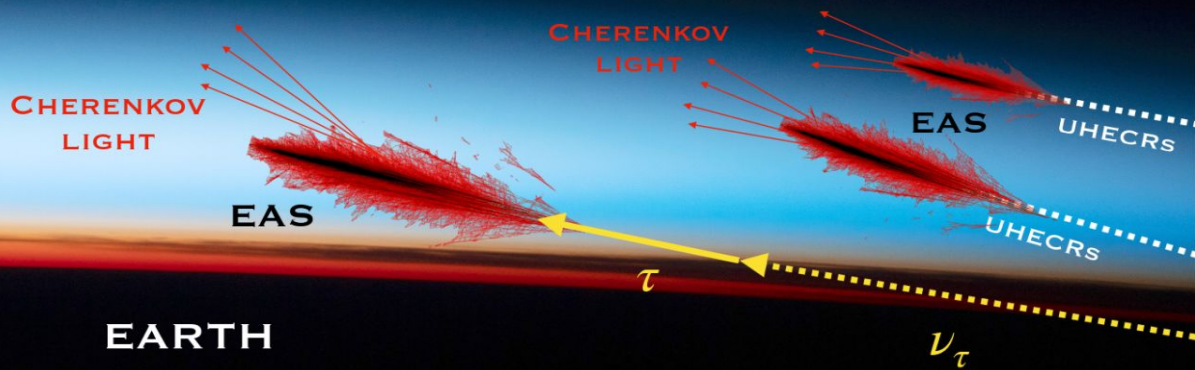
The Terzina Cherenkov Telescope

The detection principle: Look at the limb



Above: Cherenkov emission of air showers induced by CRs entering the atmosphere from above the Earth's limb

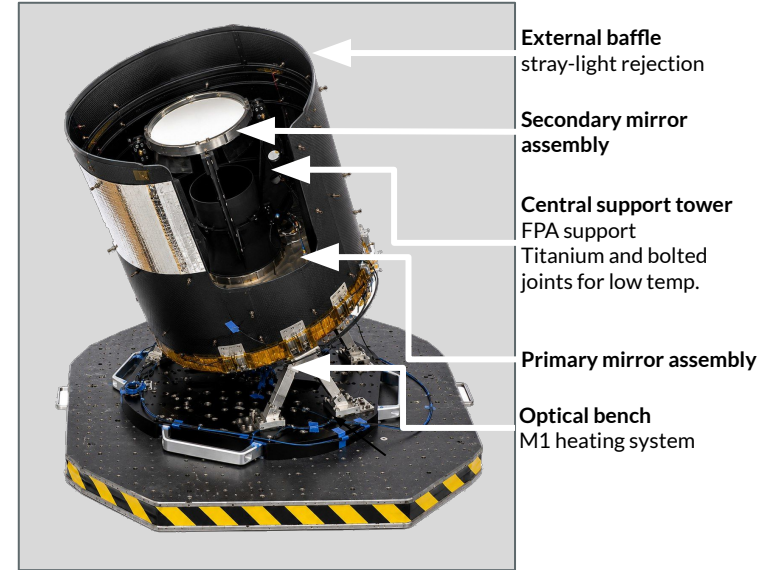
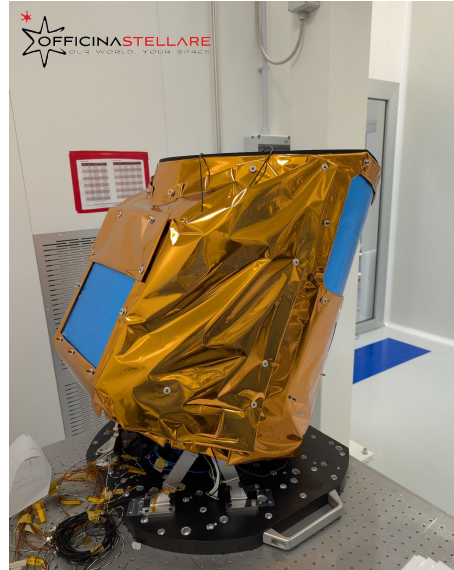
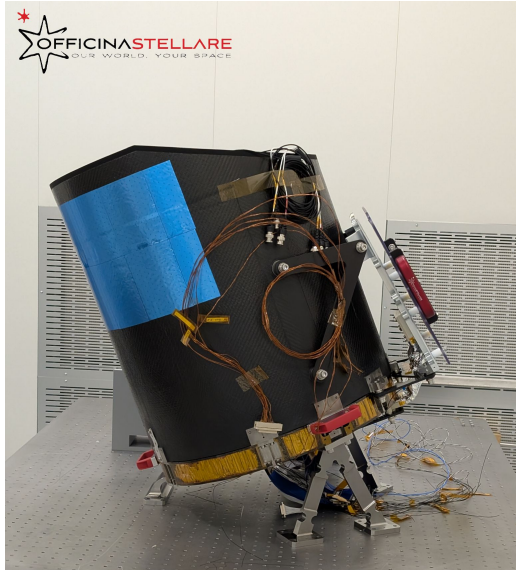
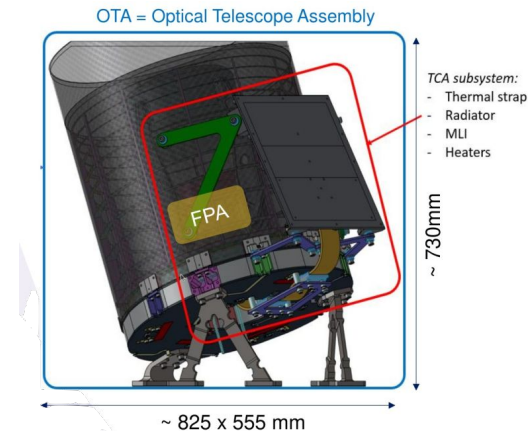
Below: Cherenkov emission produced by upward-moving EAS from tau decay or muon interactions.



Terzina Payload Overview

Terzina is a double mirror telescope composed by:

- the Optical Telescope Assembly (OTA)
- the Focal Plane Assembly (FPA)
- the Thermal Control Assembly (TCA)
- the front-end electronics (FEE) and data acquisition (DAQ) boards



Terzina: Background from photons

Previous simulation work:

1. The **Night Glow Background (NGB)** of visible lights.

$$R_{\text{pix}}^{\text{NGB}} = \eta \cdot \Delta\Omega \cdot \phi_{\text{NGB}} \cdot S \cdot PDE_{\text{eff}}$$

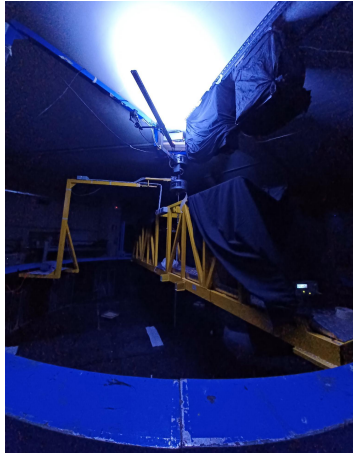
$$S = 0.1 \text{ m}^2 - PDE_{\text{eff}} = 0.1 - \Delta\Omega \simeq (FoV_{\text{pix}})^2 - \phi_{\text{NGB}} = 1.55 \cdot 10^4 \text{ m}^{-2}\text{sr}^{-1}\text{ns}^{-1} - \eta = 6$$

2. Preliminary study for city lights using **DMSP** and Moonlight with LIME.

On going work and next steps:

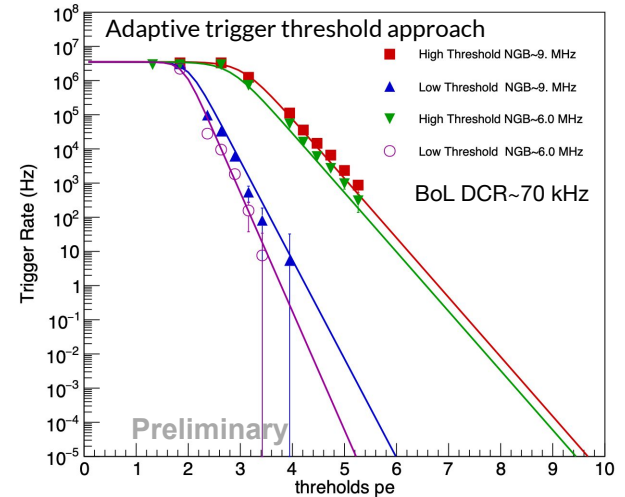
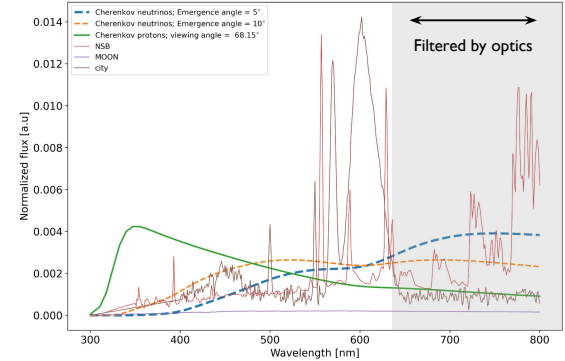
- Simulate the background rate measured by Mini-EUSO
- Compare with the CITIROC raw data at **TurLab**

TurLab Setup



See also: <https://arxiv.org/abs/2510.02844>

PoS-ICRC2025-337 & PoS-ICRC2025-418



Terzina: Background from photons

Cherenkov Signal Calibration and Trigger Studies

The FPA was calibrated using an LED source reproducing the expected Cherenkov signal from a ~ 100 -300 PeV event.

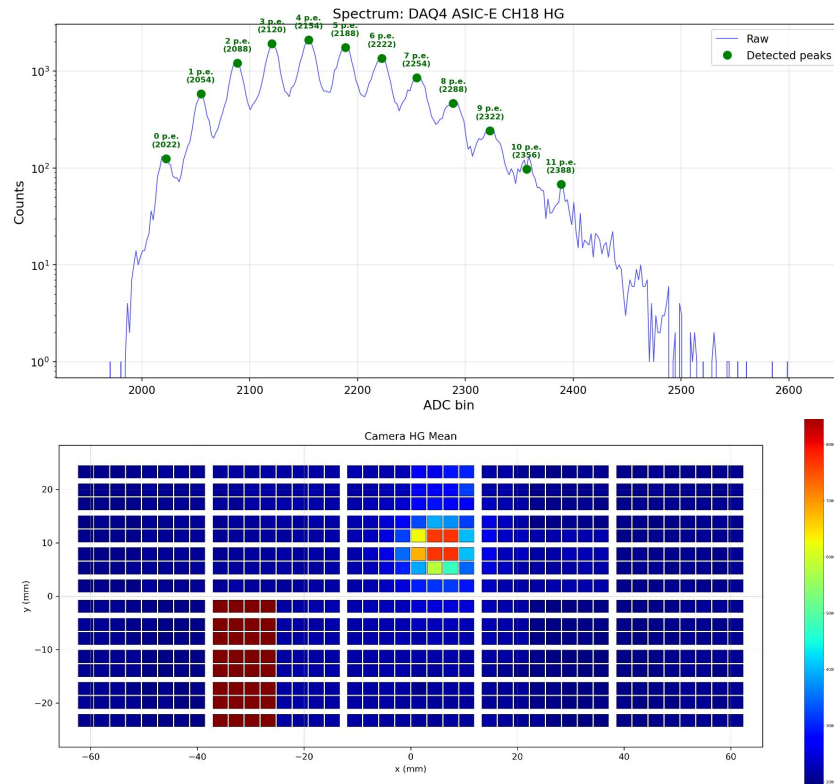
The injected signal was set according to the expected number of photoelectrons, with a slightly broader spatial distribution than in the Cherenkov simulations.

Cherenkov-like signals were acquired both on a controlled background and during the rotating-background measurements.

This provides a preliminary controlled test of the FPA response to signal + time-dependent background, under conditions representative of an orbital observation.

The measurements provide a first validation of the detector and trigger response and will be used to improve the adaptive-threshold trigger approach for future orbital operations

This test will be useful to improve and test the CITIROC software implementation. **Data analysis is ongoing.**

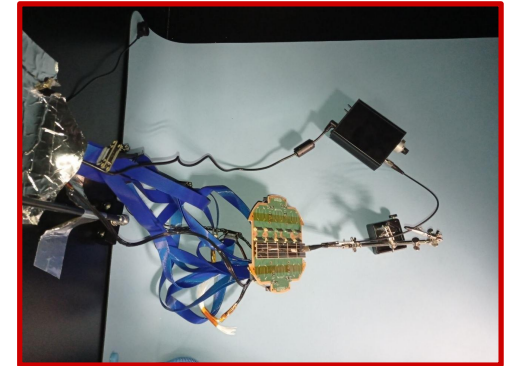
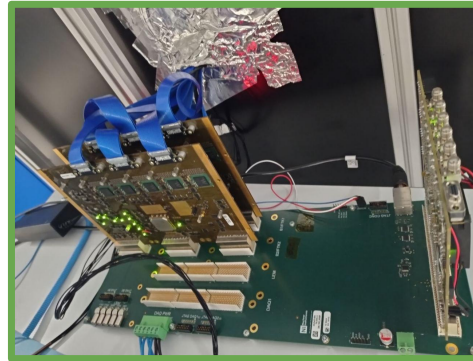


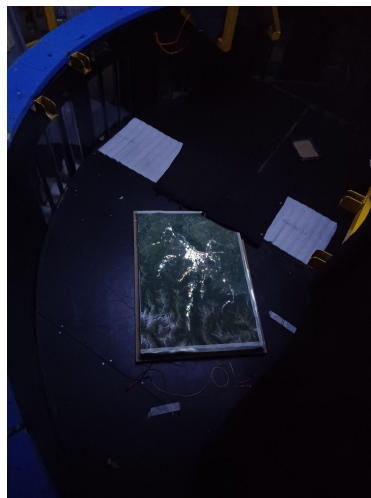
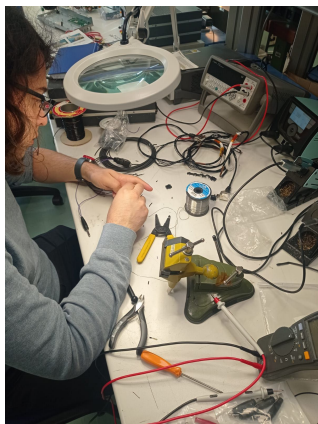
Terzina: Qualification tests

Ongoing preparation for the upcoming Terzina **qualification tests campaign**, including:

- encircled energy tests
- vibration tests
- TVAC

This has led to preparing and testing a mock-up of the final Terzina data acquisition chain on board.





Conclusions:

In a nutshell:

- refinement, verification and publishing of the simulation work on X-ray geo-synchrotron emission from EAS induced by CRs that started the previous year
- expanding of this simulation work to include the event rates from EAS induced by Earth-skimming neutrino events both for mountain top and flying geometries
- planning and participating in the the hardware tests campaigns for the Terzina Cherenkov telescope on board NUSES

Ongoing work:

- finalizing the EAS X-ray geo-synchrotron emission simulation work by implementing the full MC machinery and exploring additional geometries for Earth-skimming neutrino events
- further work on the Terzina test campaigns and simulation chain (particularly on the trigger module)

Publications:

- **Torres Saavedra, R. A.** et al, *X-rays emission: A novel tool to detect extensive air showers*, Phys. Rev. D, 113, 12 (2026)
- Abdullahi, M. et al, *Progress status of the NUSES Space Mission*, Advances in Space Research, 77, 8 (2026)
- Adams, J. et al, *POEMMA-Balloon with Radio: A multi-messenger, multi-detector balloon payload*, J. Cosmol. Astropart. Phys., 7, 1 (2026)
- **Torres Saavedra, R. A.** and Aloisio, R., PoS ICRC 2025, 417 (2025)
- several conference proceedings as part of the NUSES collaboration
- several conference proceedings as part of the JEM-EUSO & PBR collaboration

Conferences/Meetings/Schools/Outreach:

Abroad Stays:

- Université de Genève, October 27- December 5 2024.

Collaboration Meetings:

- Bari, Italy, June 15-19 2026, 39th JEM-EUSO Collaboration Meeting, **attended remotely**.
- Tokyo, Japan, December 8-12 2025, 38th JEM-EUSO Collaboration Meeting, **invited talk**.
- L'Aquila, Italy, December 16-18 2024, NUSES Collaboration Meeting, **attended**.
- Paris, France, June 2-6 2025, 37th JEM-EUSO Collaboration Meeting, **invited talk**.

Outreach:

- SHARPER, September 25 2026, L'Aquila.
- PhD orientation presentation to Ferrara students, March 3 2026, L'Aquila.
- SHARPER, September 26 2025, L'Aquila.

Conferences:

- Florence, Italy, September 7-11 2026, 112th National Congress of the SIF, **contributed talk**.
- Tendo, Japan, August 30 - September 4 2026, TeVPA 2026, **contributed talk**.
- Florence, Italy, August 1-9 2026, 46th COSPAR Scientific Assembly, **contributed talk**.
- Florence, Italy, January 26-28 2026, Space It Up! Days 2026, **attended**.
- L'Aquila, Italy, September 30 - October 3 2025, 14th YRM, **contributed talk**.
- Geneva, Switzerland, July 14-24 2025, ICRC 2025, **poster**.
- Girona, Spain, May 12-16 2025, ASAPP 2025, **contributed talk**.

Schools and Workshops:

- Perugia, Italy, October 27-29 2025, Advanced course to FPGA programming, **attended**.

Backup

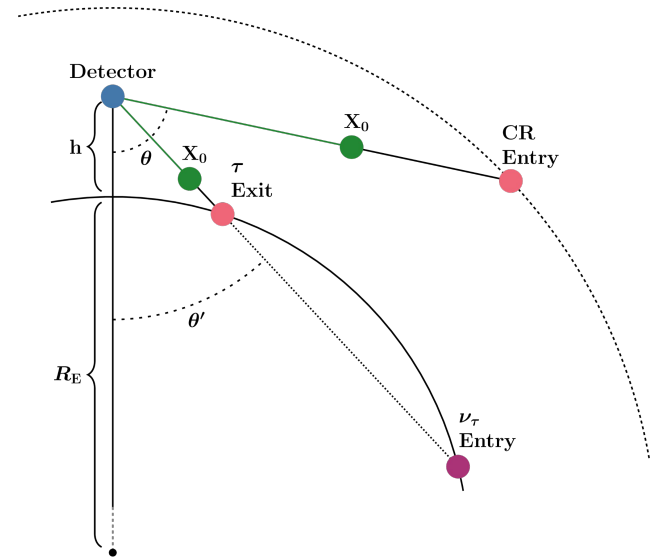
Photon Counts: Procedure

$$\left(\frac{dN_\gamma}{dE_\gamma} \right)^{\text{EAS}} = \int_{X_0}^{X_1} \frac{dX}{\rho(X)c} \text{Tr}(E_\gamma, \Delta X) N_e(X) \int_{E_0}^{E_1} dE_e \frac{dn_e}{dE_e}(E_e, s(X)) \frac{dN_\gamma}{dt dE_\gamma}(E_e, E_\gamma)$$

For a given trajectory (fixed by altitude and viewing angle), the photon count at the detector position is computed by solving the integral above numerically.

The initial interaction grammage assumptions are:

- For protons, X_0 is fixed at 30 g/cm^2 .
- For taus, X_0 is given by the expected tau decay length ($\sim 5 \text{ km}$ at 100 PeV).



Fluxes: Procedure

For every bin in grammage:

- Compute the expected angular deviations (angular RMS) from the Bergman distribution.
- Use this angular RMS in Hillas' formula for the expected lateral deviation as a function of s .
- Compute the magnetic deviation and add it to the normal lateral and angular deviations.

Then, perform:

- A weighted average of the areas using the electron energy distribution as a weighing function.
- A second weighted average of the areas over shower age, using the number of transmitted photons as a weighing factor.

