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INFN LNGS

Geo-synchrotron X-ray emission from extensive air showers

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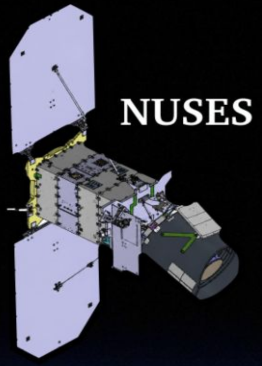
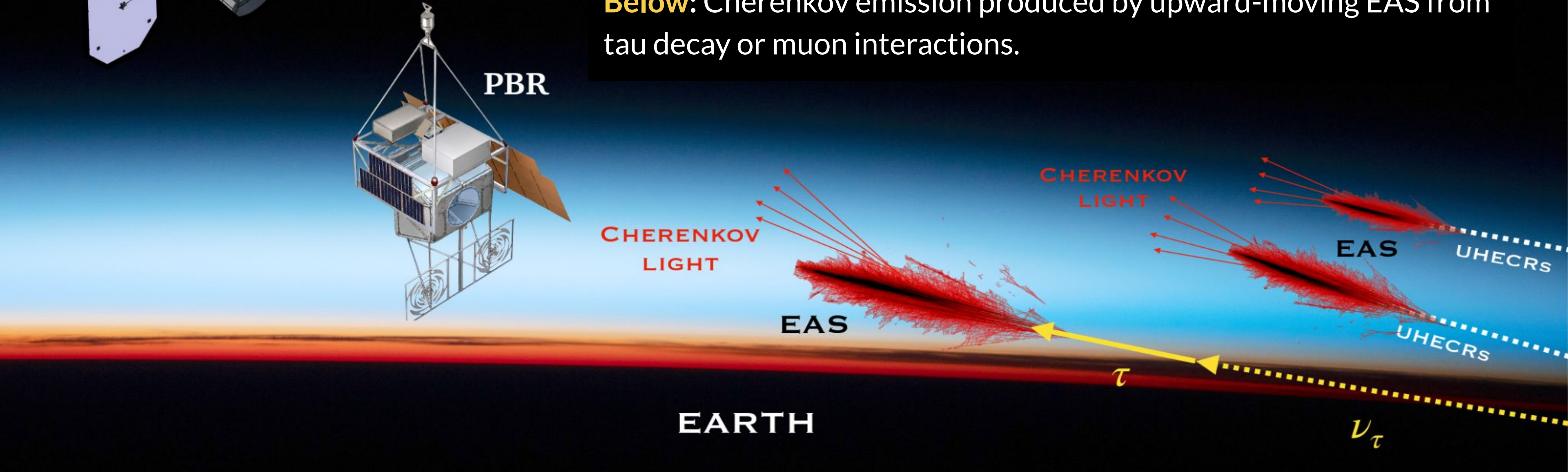
Tendo, Japan, Sep. 1st, 2026

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.



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 photon fluxes at the detection plane.
- Estimate event rates.

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.

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

Number of Photons	Geometry	Absorption	Longitudinal Development	Electron Energy Distribution	Single Particle Emission

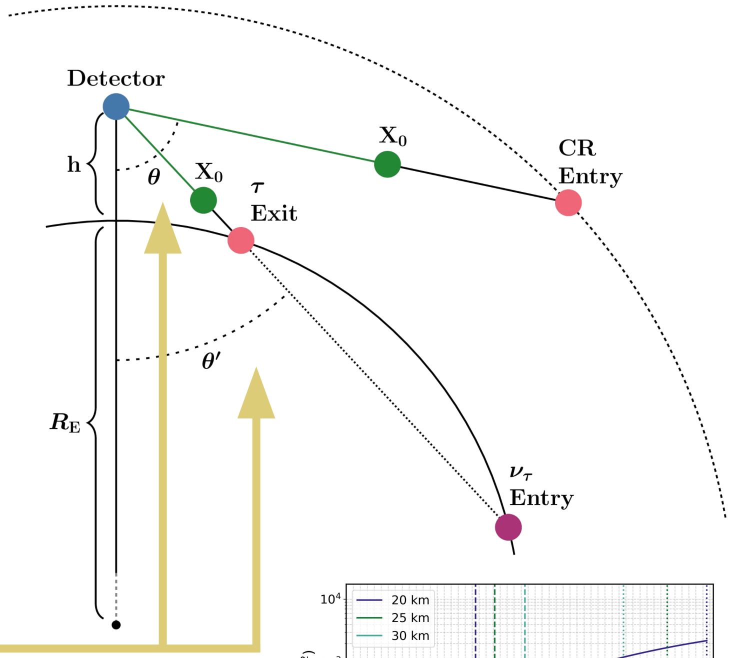
Earth's Atmosphere	EAS Physics	Geomagnetic Synchrotron

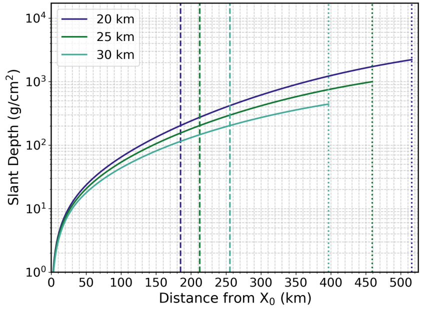
Outline: Geometry

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

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

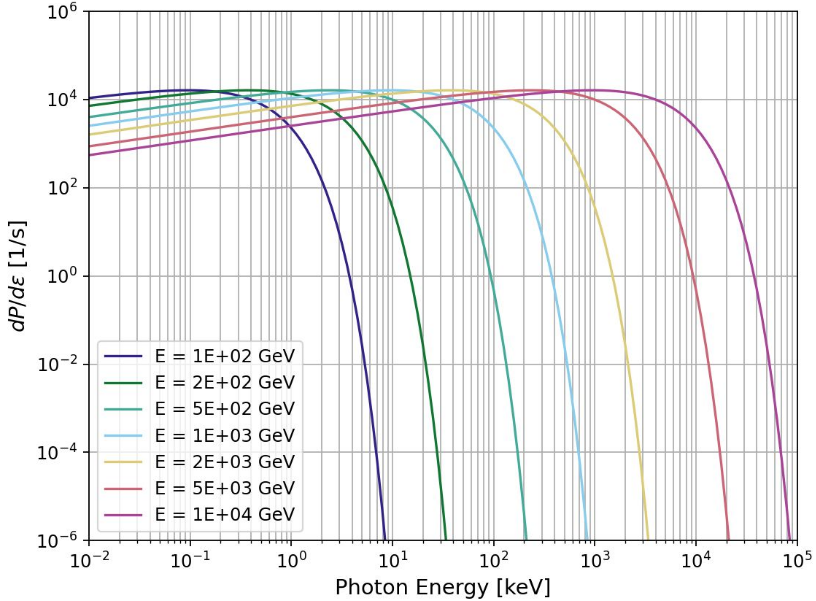
Emission: Single Electron

- The power spectrum is universal and proportional to the synchrotron function **F(x)**, where **x** = **ω** / **ω**$_c$

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

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

- In the geo-magnetic field, emission in the X- / gamma-ray bands requires electron energies ≳ 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.

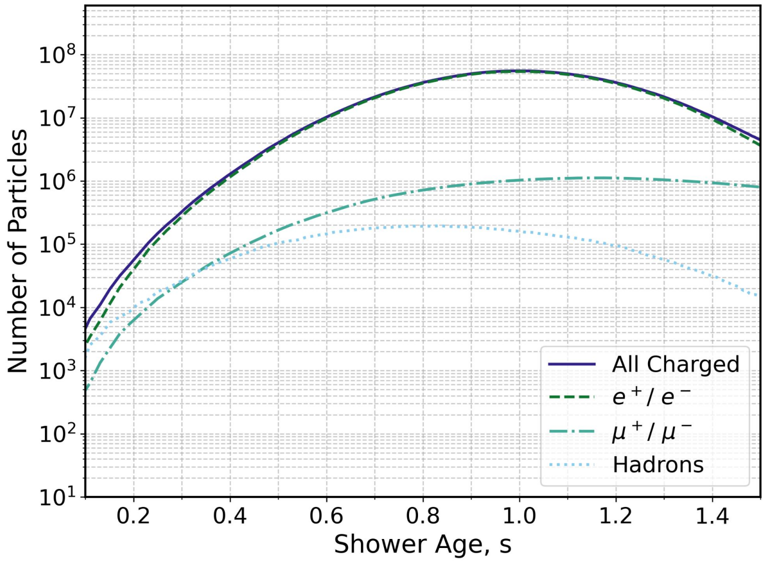
Emission: Air Showers

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

$$\left(\frac{dN_\gamma}{dt\, dE_\gamma}\right)^{EAS} = N_\mathrm{e}(X) \int_{E_0}^{E_1} dE_\mathrm{e} \frac{dn_\mathrm{e}}{dE_\mathrm{e}}(E_\mathrm{e}, s(X)) \times \frac{dN_\gamma}{dt\, dE_\gamma}(E_\mathrm{e}, E_\gamma)$$

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

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

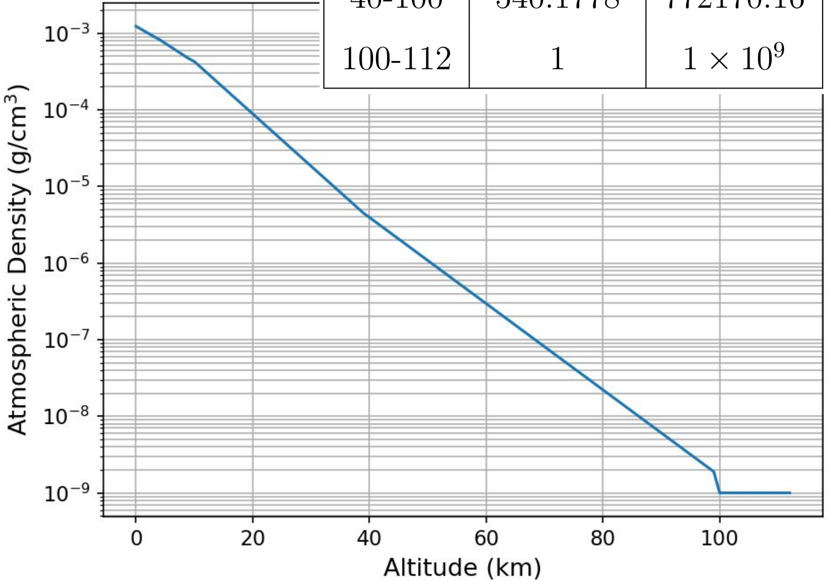
Atmosphere: Density

- 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).

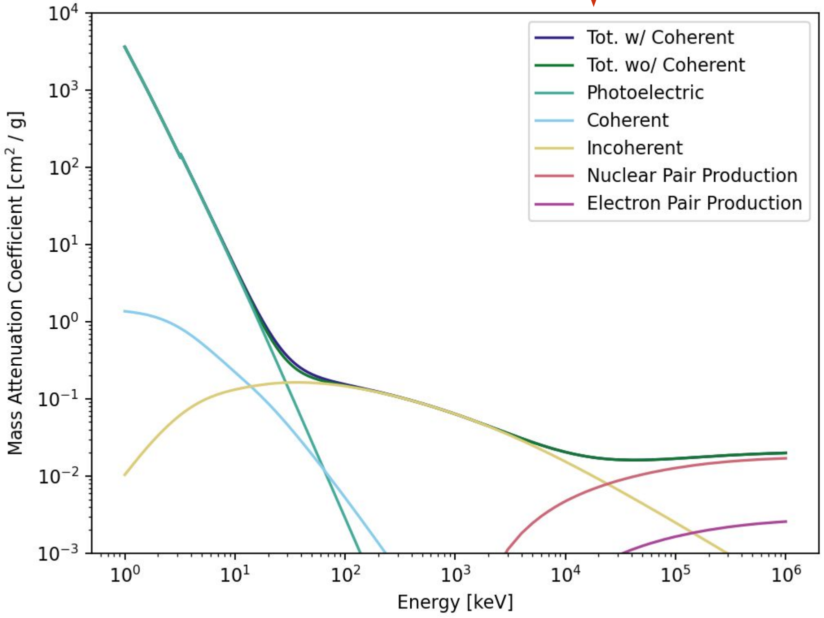
z(km)	b(g/cm^2)	c(cm)
0-4	1222.6562	994186.38
4-10	1144.9069	878153.55
10-40	1305.5948	636143.04
40-100	540.1778	772170.16
100-112	1	1×10^9



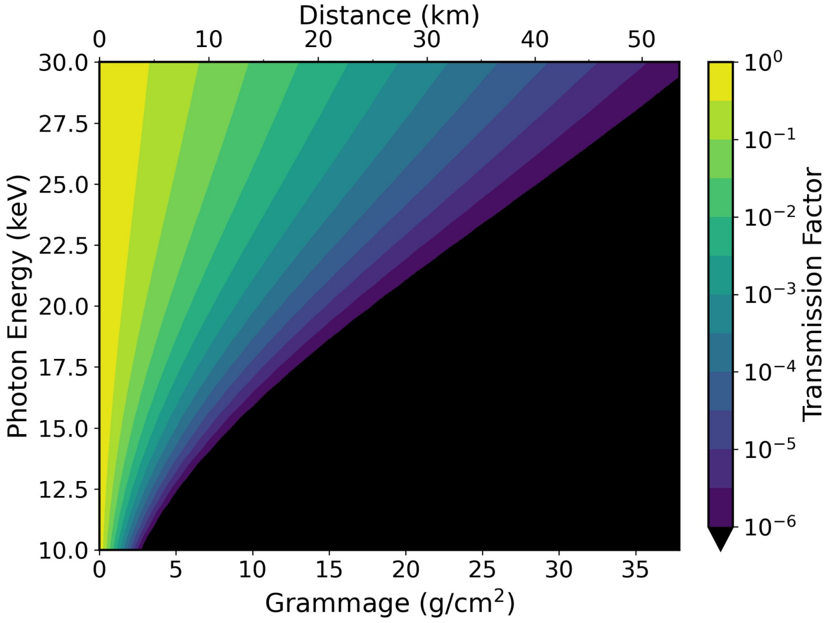
Atmosphere: Attenuation

$$\mathrm{Tr}(E_\gamma) = \exp\left[-\int_0^L \mu_\mathrm{a}(E_\gamma)\,\rho(l)\,dl\right]$$

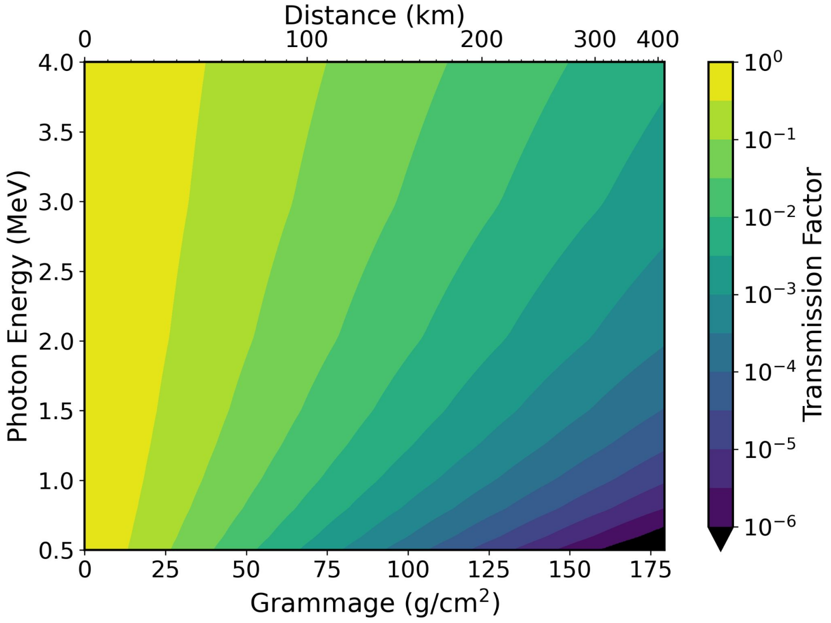
- Photons interact with the atmosphere along their path to the detector.
- The transmission factor depends on the line-of-sight integral of an attenuation coefficient.
- For a single element, this attenuation coefficient is inversely proportional to the interaction cross-section
- The NIST XCOM database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



Atmosphere: Transmission Factors



X-rays

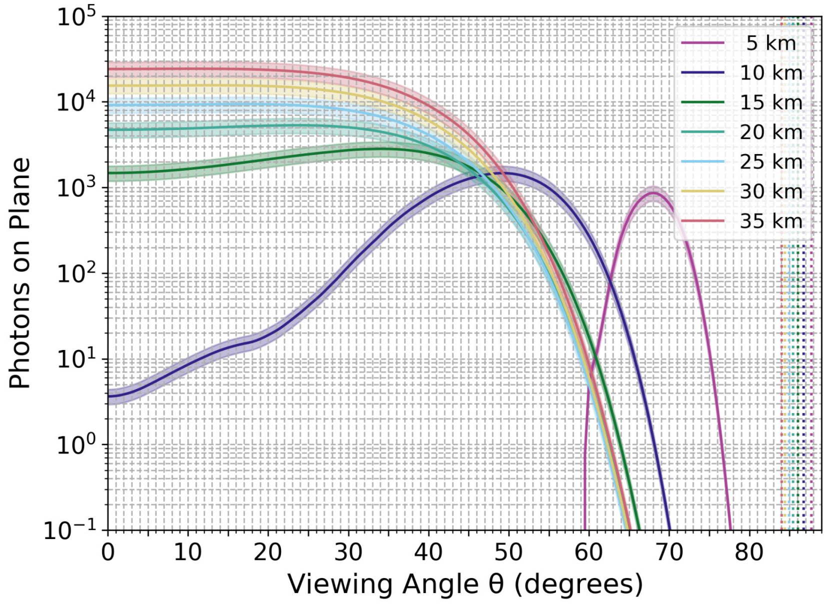


Gamma Rays

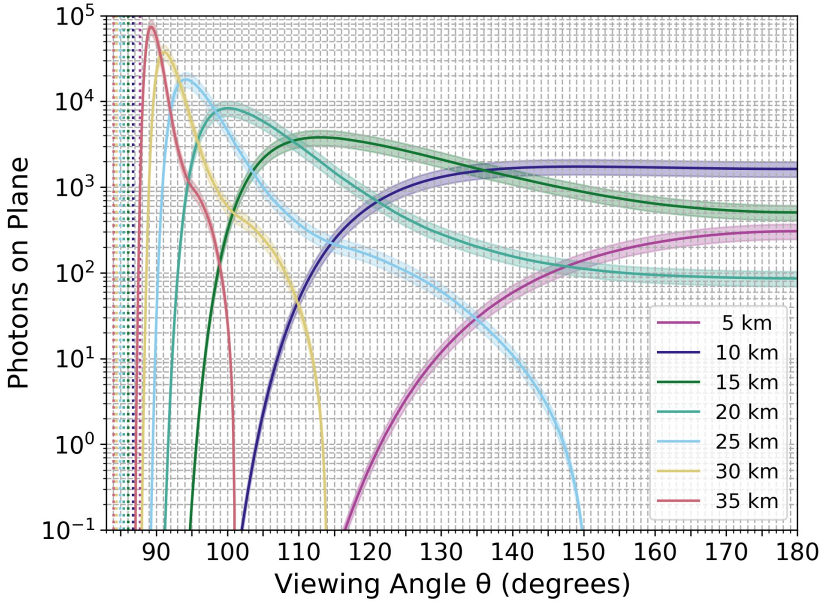
Photon Counts

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

Photon Counts: 100 PeV

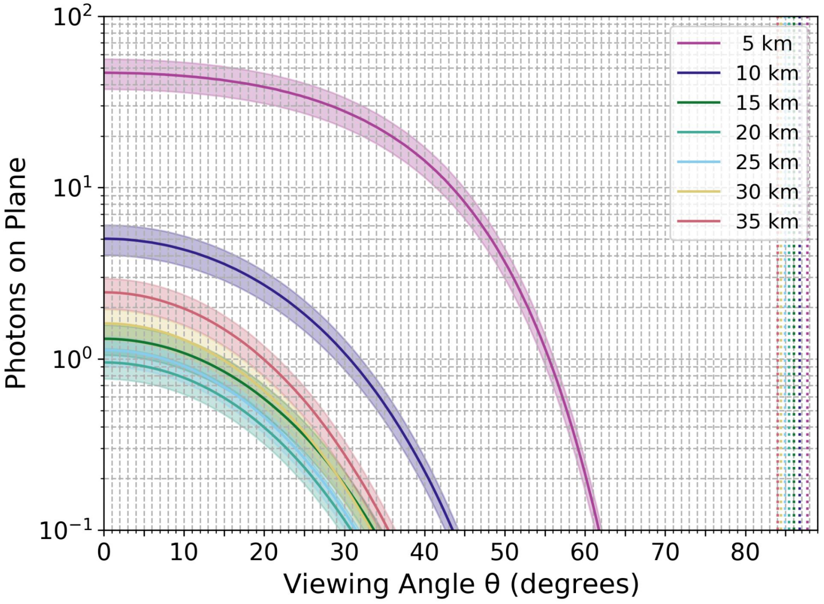


Below-limb

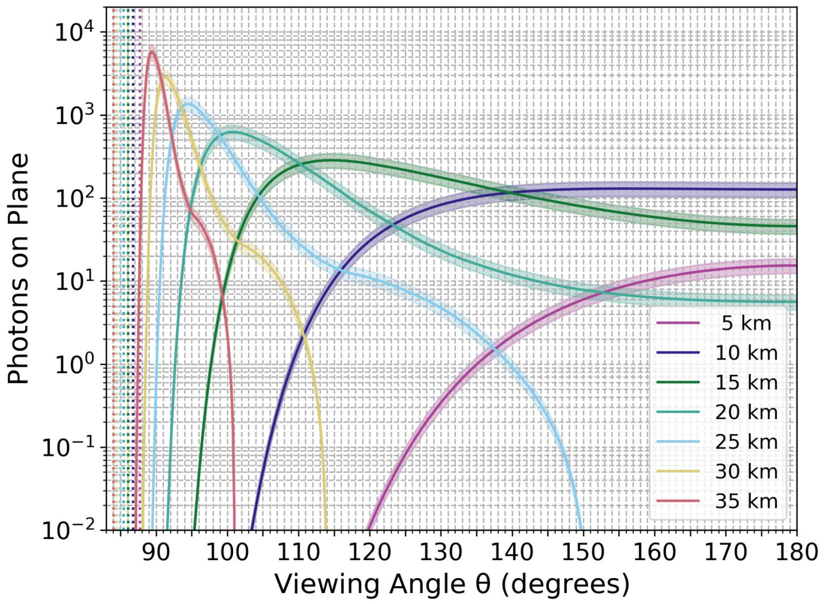


Above-limb

Photon Counts: 10 PeV



Below-limb



Above-limb

Emission Footprint & Fluxes

Emission Footprint

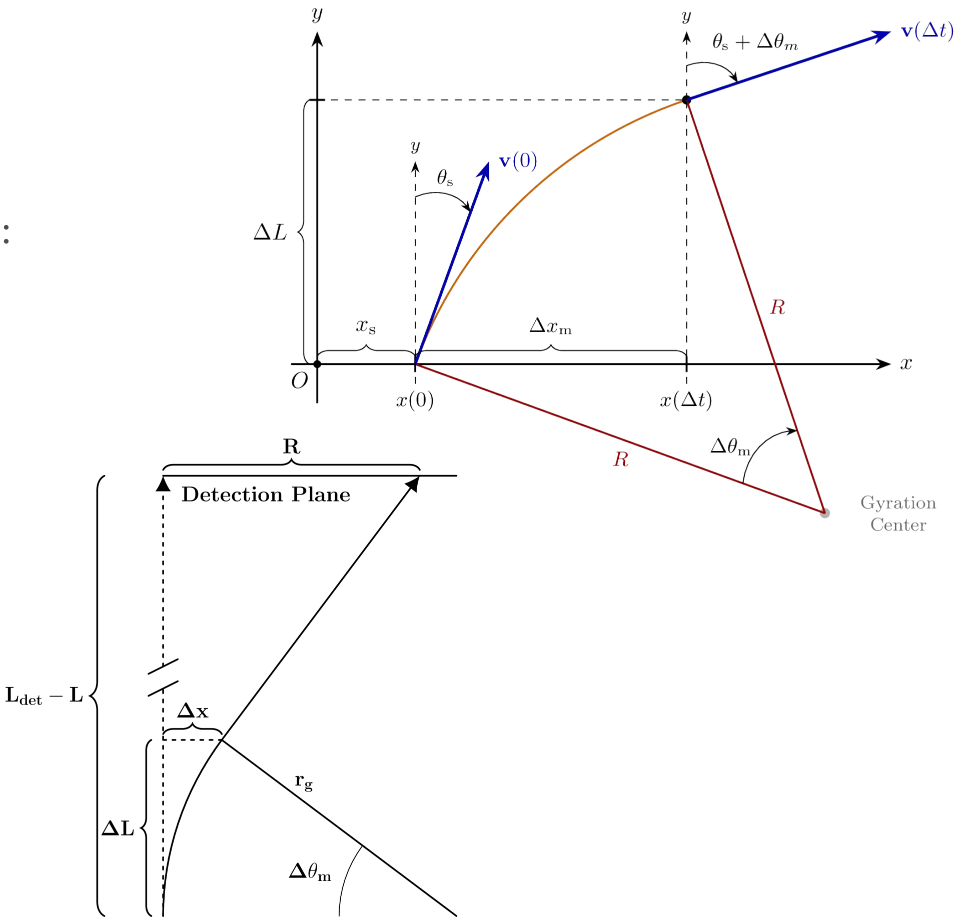
The photon spatial distribution at the detector (and flux) depends on the high-energy electrons':

- lateral distribution (w.r.t shower core),
- angular distribution (w.r.t shower axis),
- photon emission cone (~ 1 / ɣ)

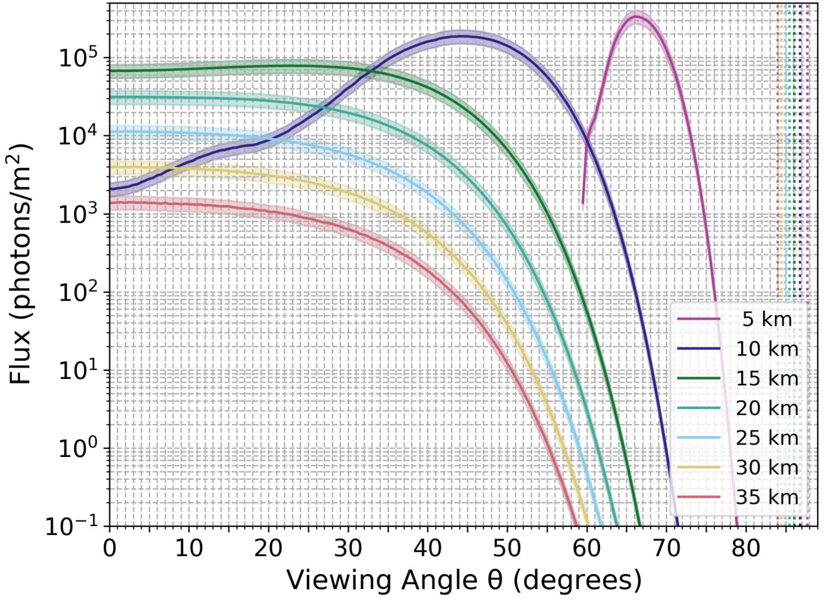
Geomagnetic field effects:

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

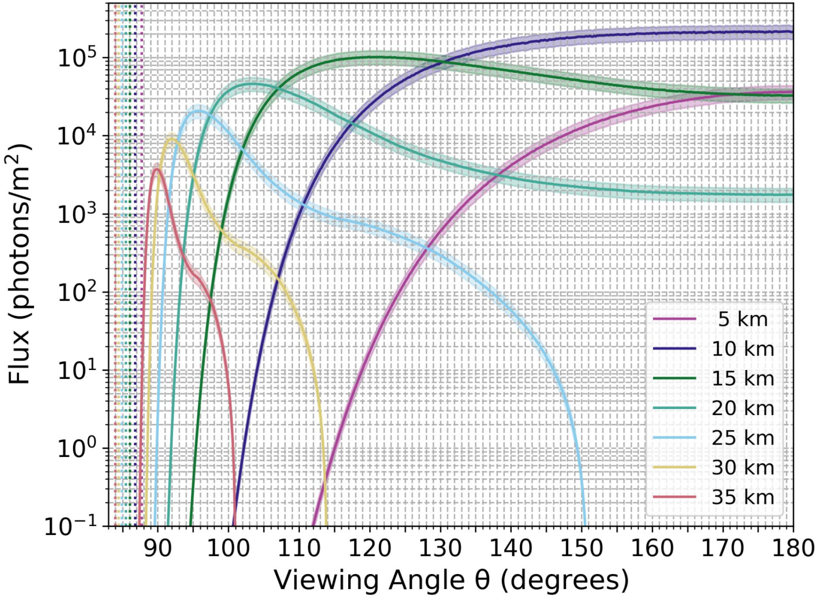
Plus, propagation and projection effects alter footprint between emission and detection.



Photon Flux On Detection Plane (100 PeV)

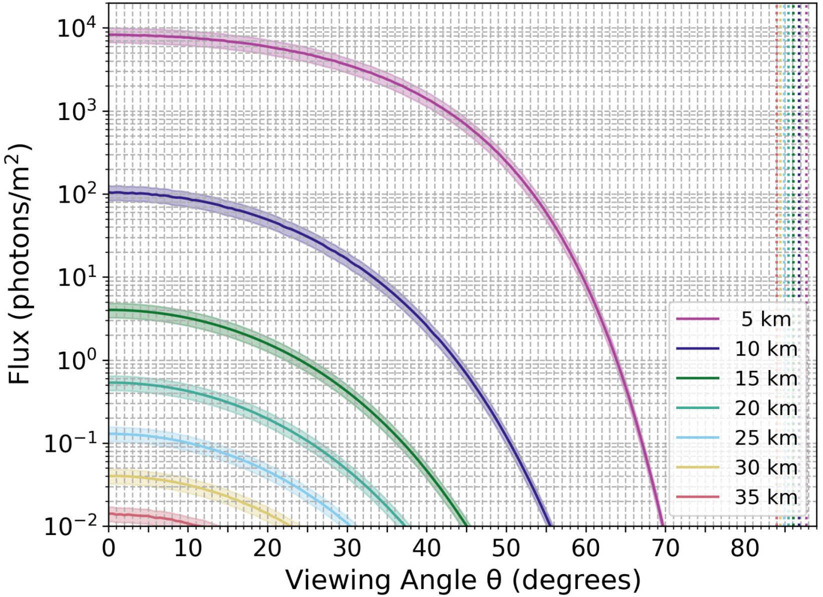


Below-limb

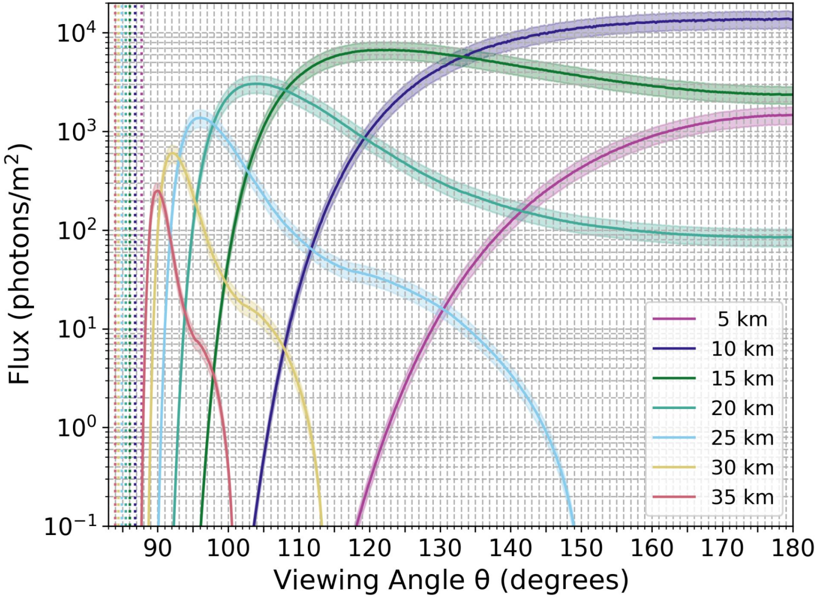


Above-limb

Photon Flux On Detection Plane (10 PeV)

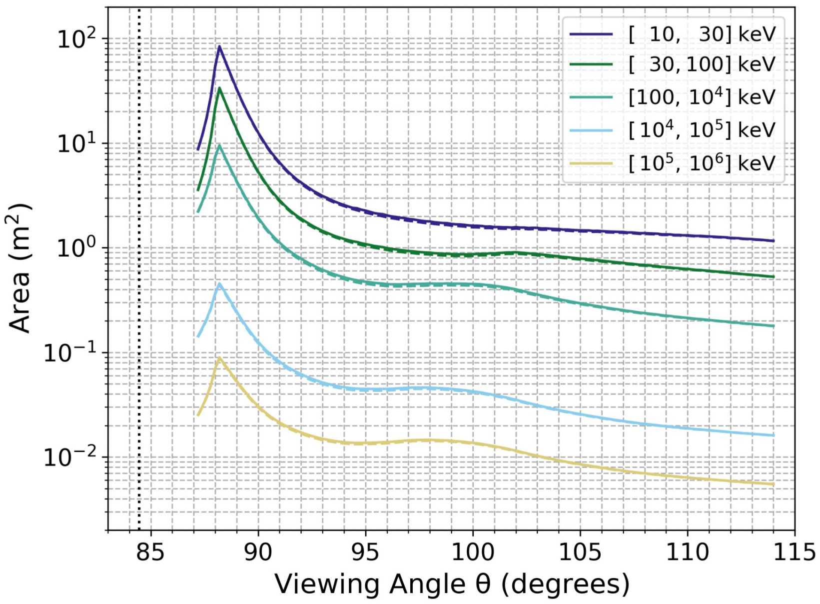


Below-limb

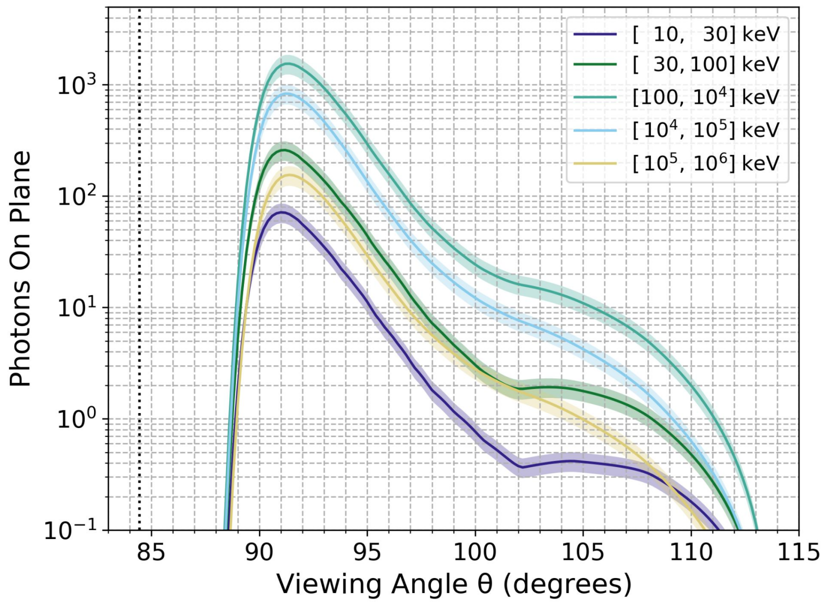


Above-limb

Signal Properties On Detection Plane (10 PeV)



Per-band Footprint Areas @ 30 km



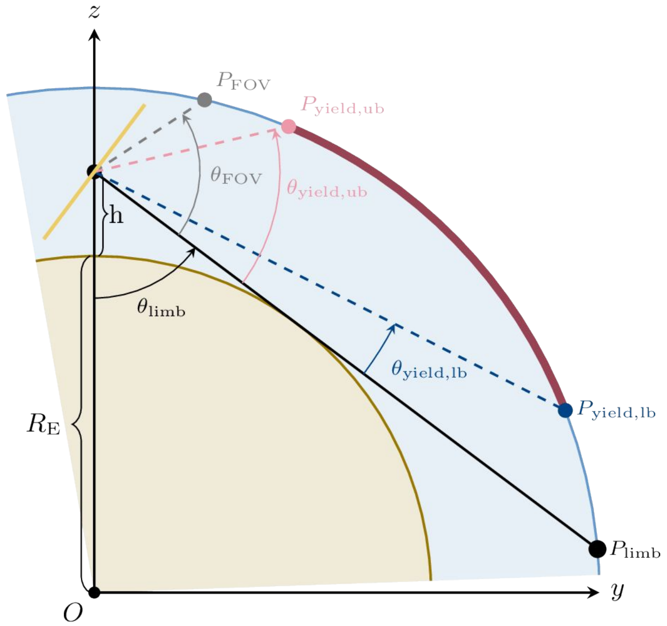
Per-band Photon Counts @ 30 km

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 (Δθ', Δφ')
- **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



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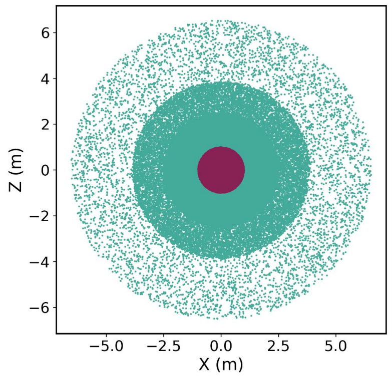
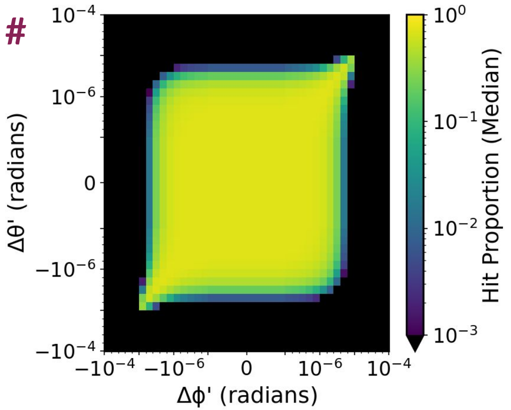
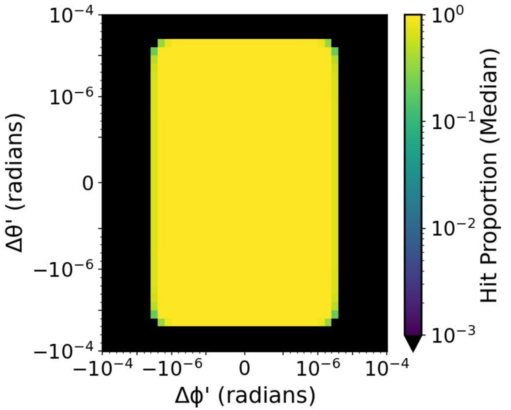






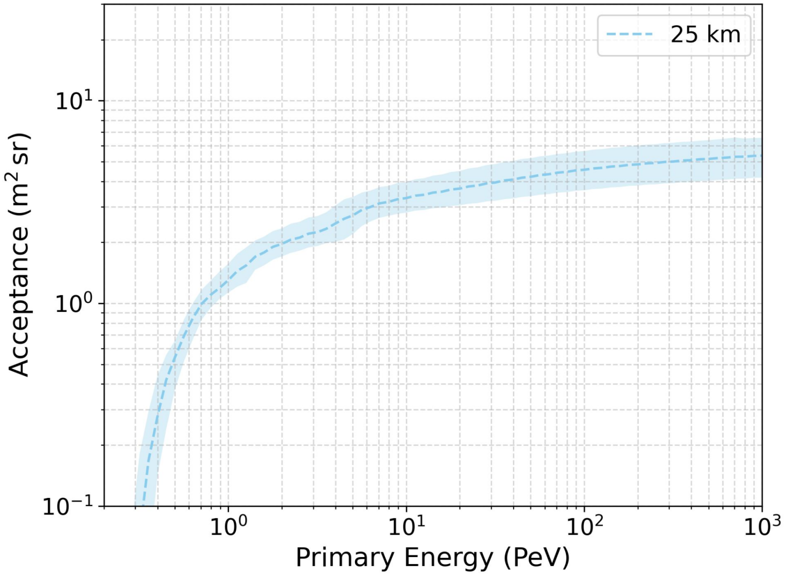
Acceptance & Event Rates: CRs

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

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

And we compute the acceptance as:

$$G(E) = (A_{\mathrm{geo}}\,\Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{gen}}} \sum_i \frac{N_{\mathrm{gen}}}{N_{\mathrm{cells}}}\,\xi_i(E)$$
$$= (A_{\mathrm{geo}}\,\Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{cells}}} \sum_i \xi_i(E)$$



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

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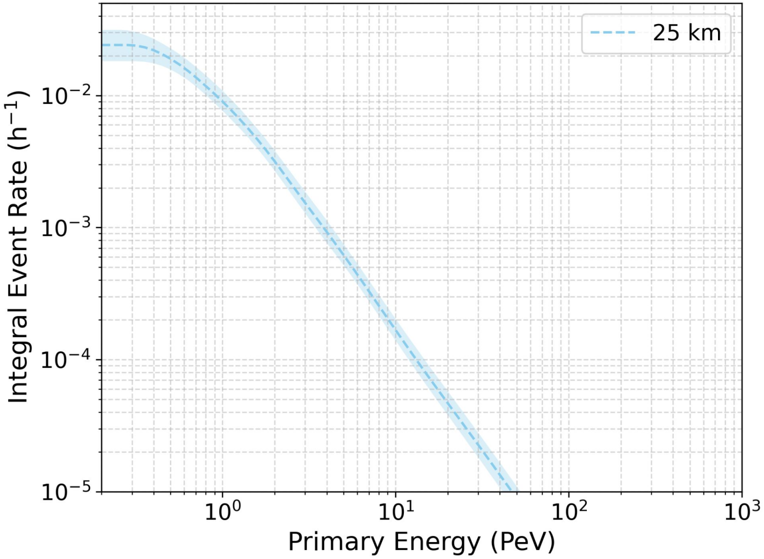
$$\begin{aligned} G(E) &= (A_{\mathrm{geo}}\,\Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{gen}}} \sum_i \frac{N_{\mathrm{gen}}}{N_{\mathrm{cells}}}\, \xi_i(E) \\ &= (A_{\mathrm{geo}}\,\Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{cells}}} \sum_i \xi_i(E) \end{aligned}$$



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

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.

$$\xi_{\mathrm{i}}(E_\nu) = P(\mathrm{trigger} \mid E_\nu, \alpha_{\mathrm{i}}) = P_{\mathrm{exit}}(E_\nu, \alpha_{\mathrm{i}})$$
$$\times \int dE_\tau \, P(E_\tau \mid E_\nu, \alpha_{\mathrm{i}}, \mathrm{exit})$$
$$\times \int dL' \, P(L' \mid E_\tau)$$
$$\times \int dE_{\mathrm{sh}} \, P(E_{\mathrm{sh}} \mid E_\tau)$$
$$\times \xi(E_\tau, L', E_{\mathrm{sh}})$$

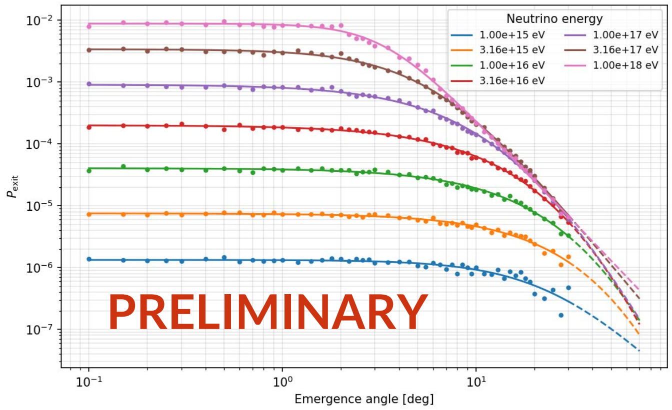
This work uses **NuTauSim** to compute and tabulate the lepton exit probabilities and energy distributions as a function of the emergence angle, $\boldsymbol{\alpha}_{\mathrm{i}}$.

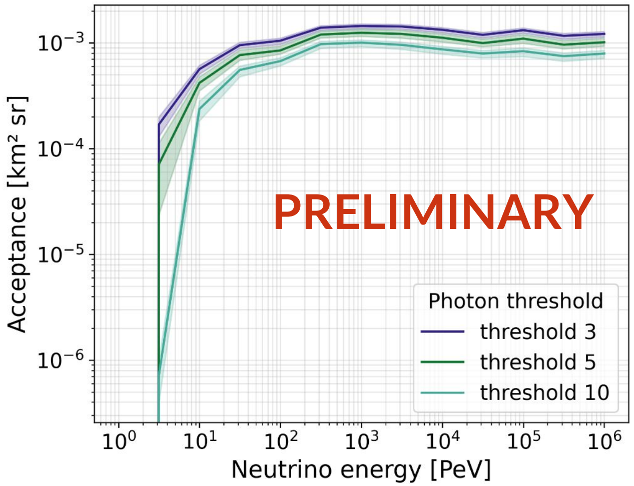
Acceptance: Neutrinos

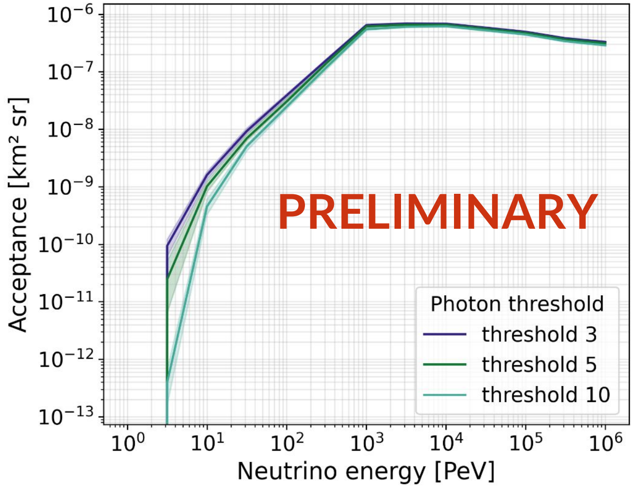
The emergence probability is the dominant factor, suppressing events at large emergence angles.

- 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.







Conclusions

The **results**:

- for below-the-limb trajectories, fewer photons arrive to the detection plane since the shower develops in a denser layer of the atmosphere. Further, the flux is appreciable at angles for which the emergence probability is small, suppressing the number of events.
- for above-the-limb trajectories, the number of photons is significantly larger, and the footprint is such that the signal could be detected by a sub-orbital experiment, flying at an altitude of 20 - 30 km with a detector with an area of few m^2 could observe this signal.

Future work:

- study of the expected event rates for alternative below-the-limb geometries
- study of the event rates for CR detectors on land
- dedicated CORSIKA simulations to study the shower electrons' distributions

Paper:

Backup

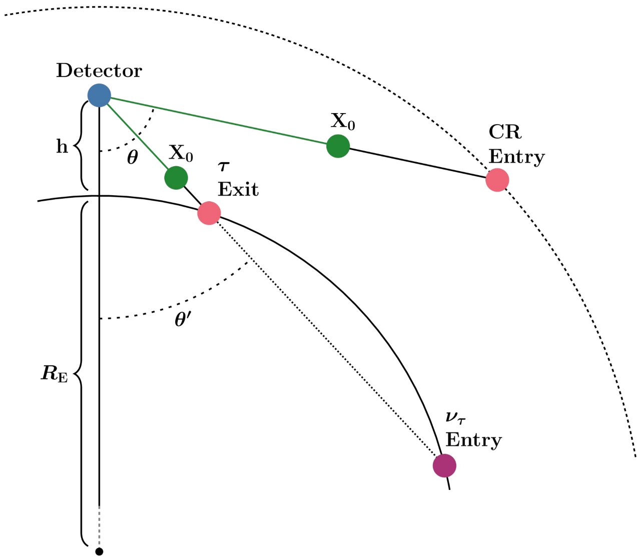
Photon Counts: Procedure

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

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 (~ 5km 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.