GRAN SASSO
SCIENCE INSTITUTE

PhD Defense: Sub-Orbital and Orbital Detection of High-Energy Astrophysical Radiation via Cherenkov Emission

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L'Aquila, Italy (remote)

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www.gssi.it

Outline

- Introduction (UHECRs, Neutrinos, and the Earth-skimming Detection Technique)
- Neutrino Propagation in the Earth
- Shower Modeling (Cherenkov Emission)
- Neutrino Detection Capabilities and Outlook
- Above-the-Limb Cosmic Ray Detection Capabilities and Outlook
- Summary and Future Perspectives

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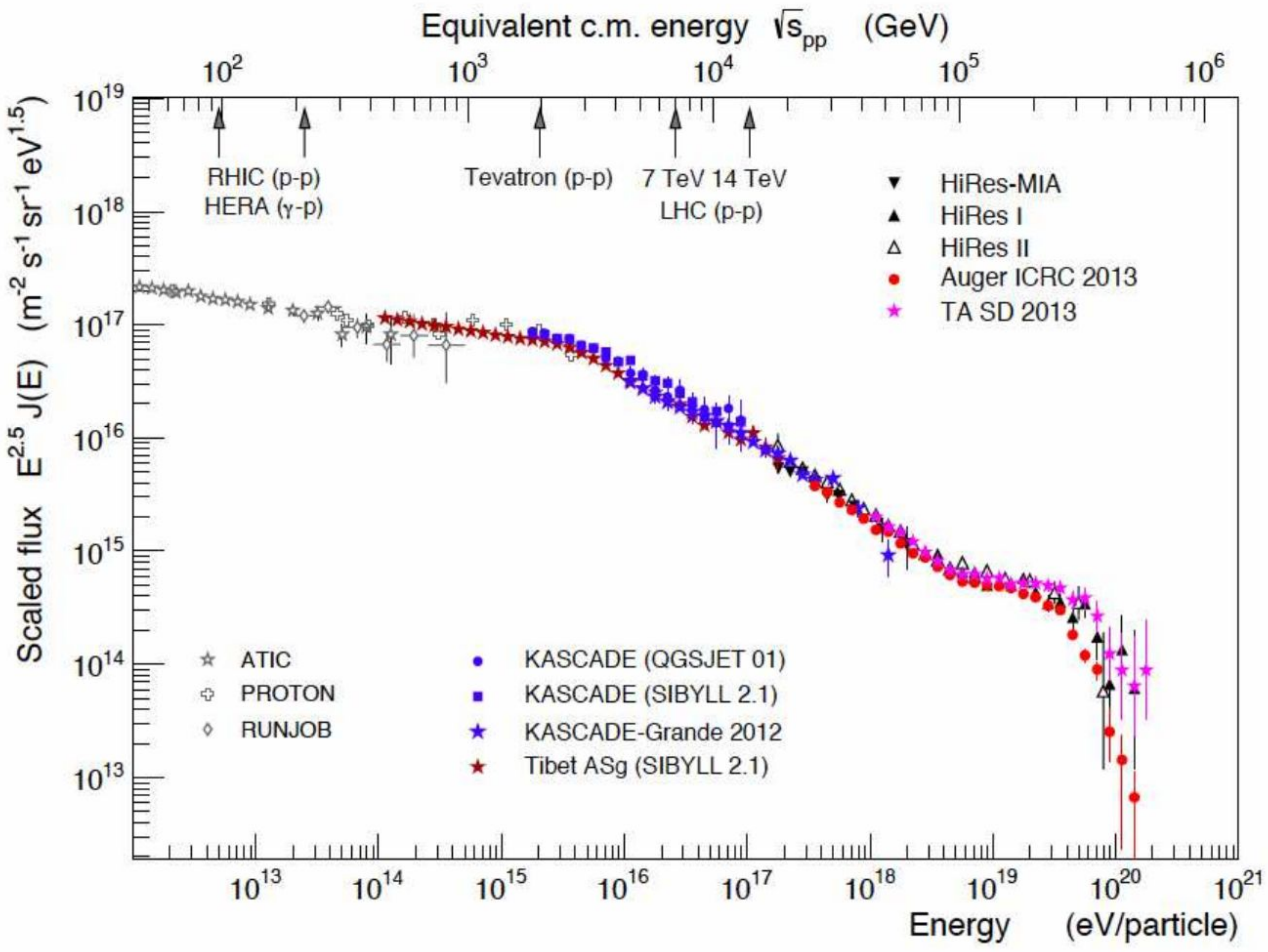
Ultra-High Energy Cosmic Rays (UHECR)

- Mostly protons and helium, with small fractions of heavier nuclei, electrons, and positrons

- Flux spans many orders of magnitude in energy, going from ~10^4/m²s at 10^9 eV to ~1/km²century at 10^{20} eV
  - Features in the flux curve can answer fundamental astrophysical questions

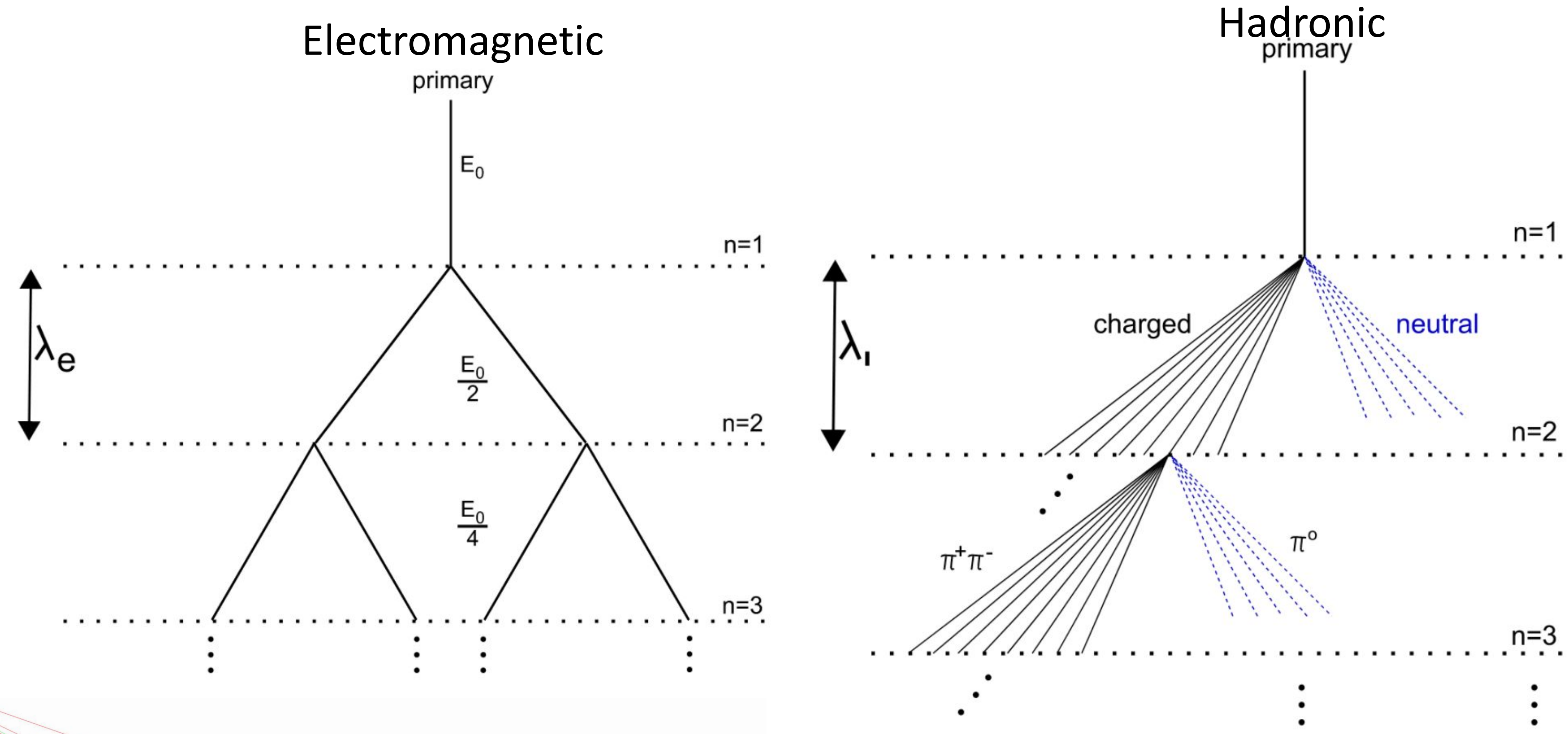
- Many questions regarding the sources, acceleration mechanisms, and propagation effects of cosmic rays are largely open



T. K. Gaisser, Cosmic Rays and Particle Physics: 2nd Edition

Extensive Air Showers (EAS)

- Primary cosmic ray interacts with atmospheric molecules
  - Produces many secondaries
- The majority of the shower energy is transferred to electrons, positrons, and photons
- The secondaries can be detected either directly or through emission:
  - Fluorescence
  - Radio
  - Optical Cherenkov



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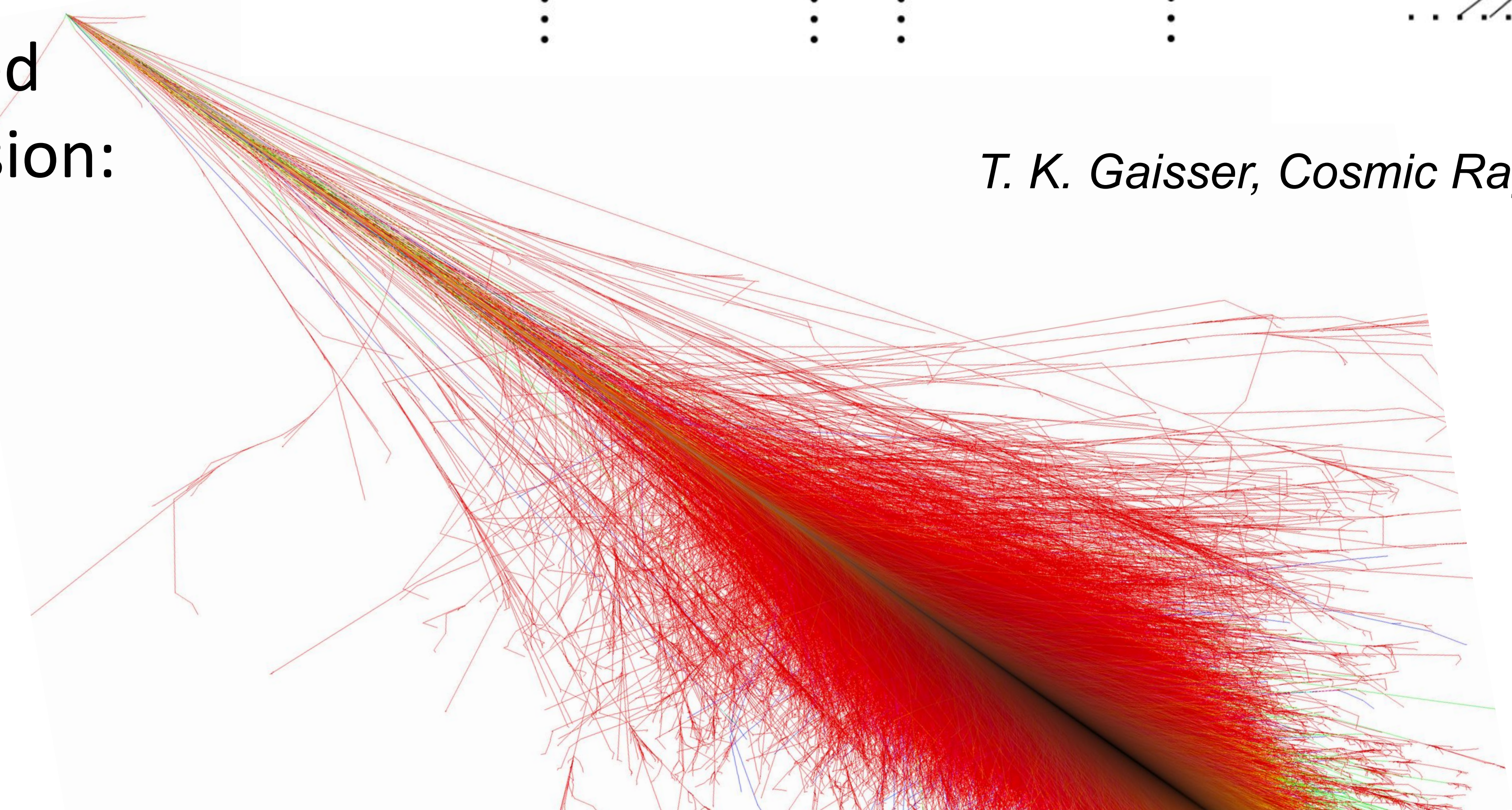

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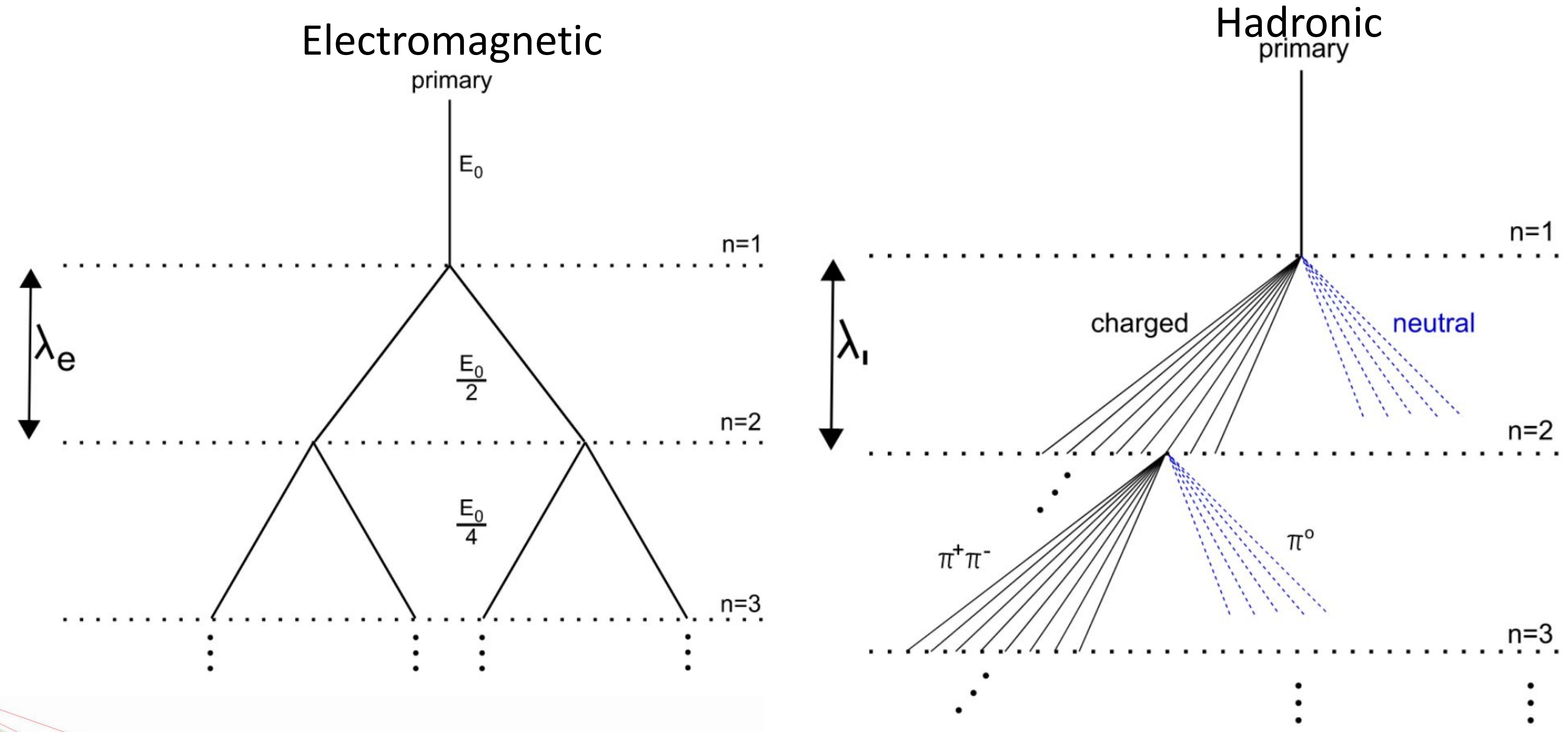
  - **Optical Cherenkov**



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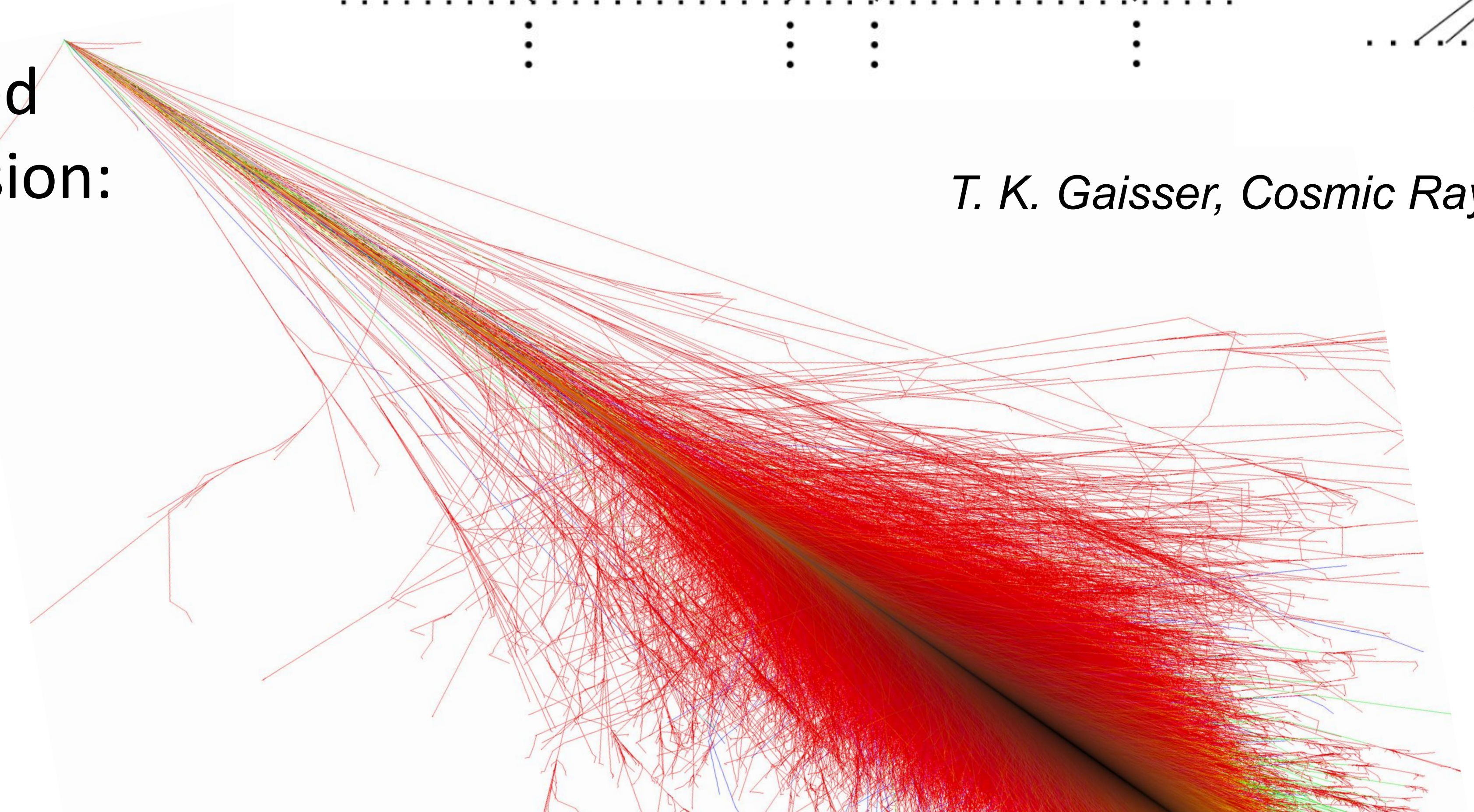
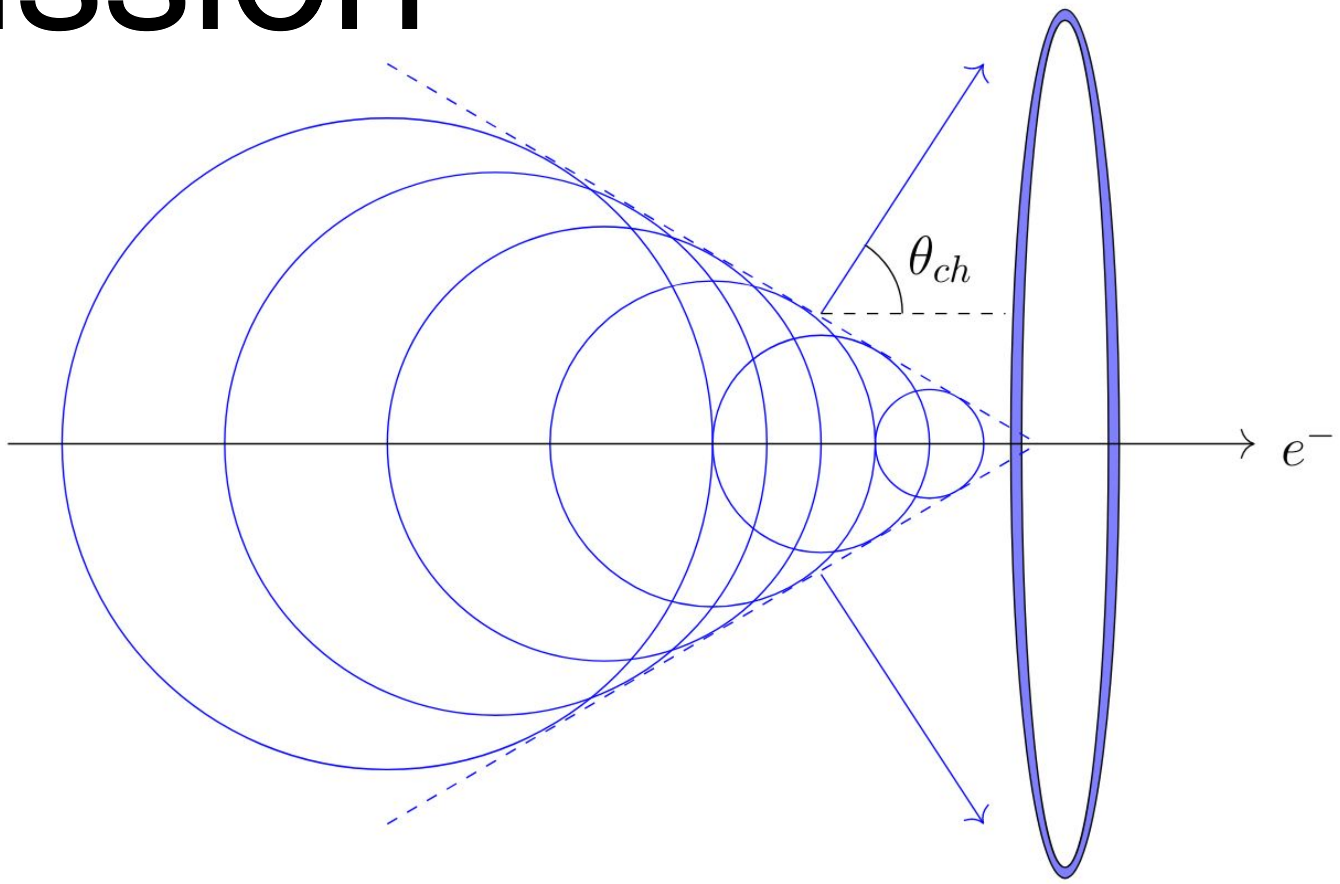


Optical Cherenkov Emission



- Occurs when a charged particle passes through a dielectric medium faster than the phase velocity of light

$$\beta > \frac{1}{n}$$

Energy threshold: 0.8 MeV in water
22 MeV in air

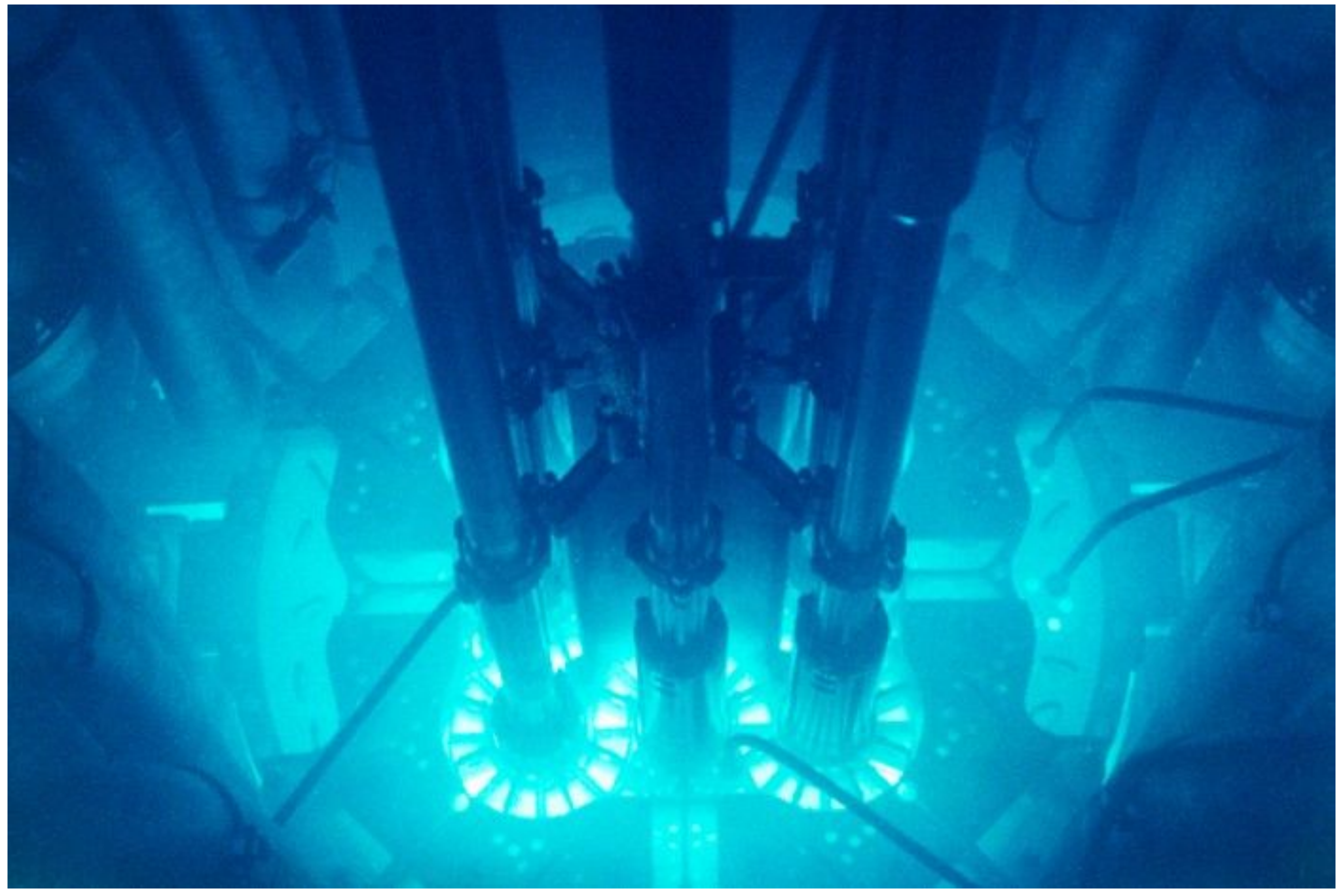
- Emission forms a coherent, narrow, forward projected ring

$$\cos(\theta_{ch}) = \frac{1}{\beta n}$$

Opening angle: 41° in water
1.4° in air

- Emission peaks at smaller wavelengths

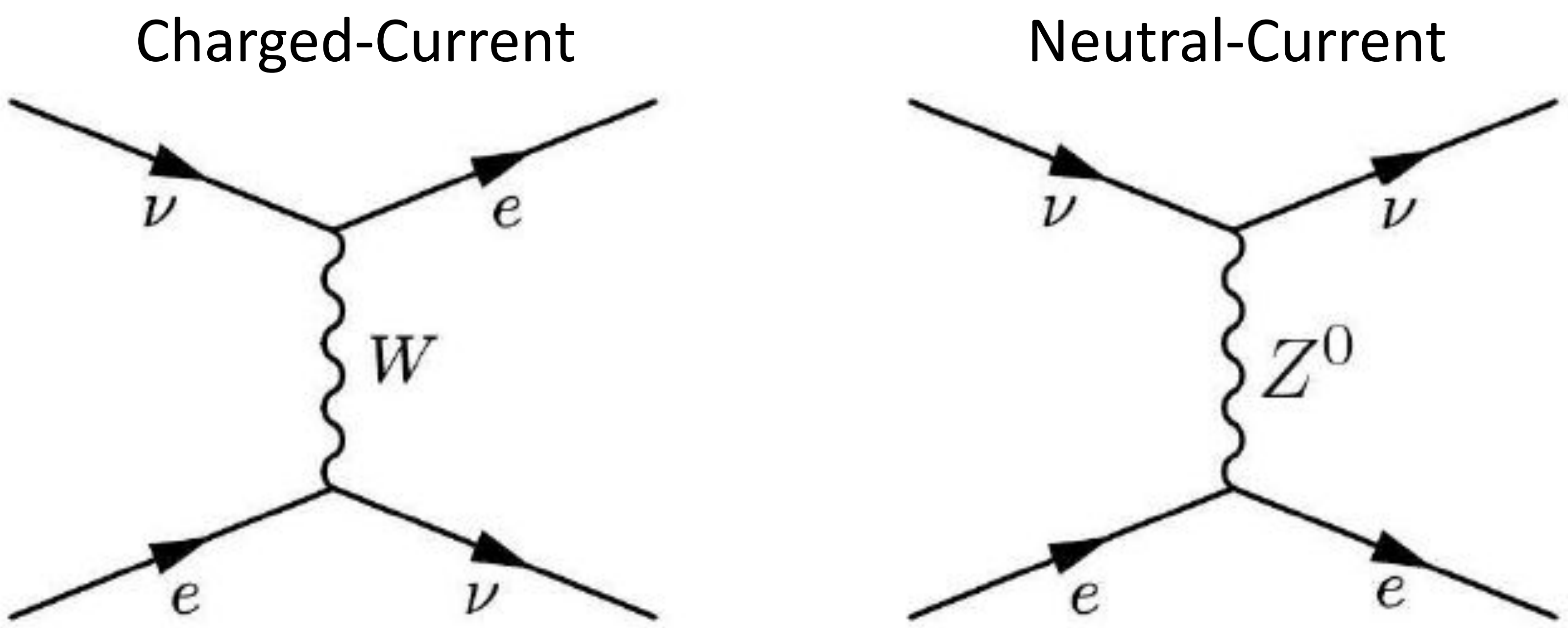
$$\frac{d^2 N_\gamma}{dz d\lambda} = 2\pi\alpha \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{1}{\lambda^2}$$

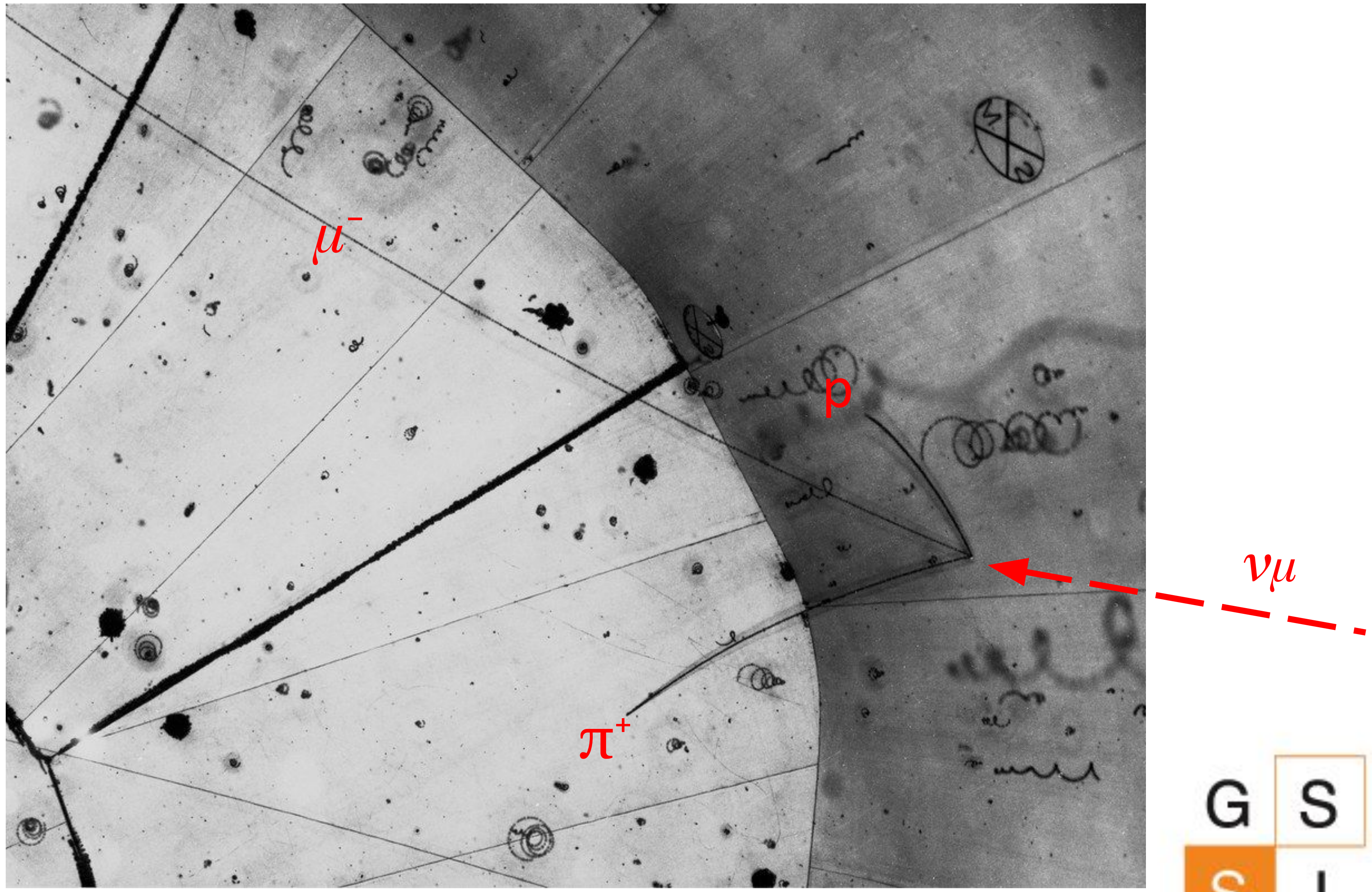


US Department of Energy/SPL

What are Neutrinos?

- Neutrinos are fundamental particles that couple only via the weak interaction force
  - Interactions are very rare
- 3 species of neutrinos:
  - Electron (e)
  - Muon (μ)
  - Tau (τ)
- Neutrinos undergo oscillation between the 3 different flavors
- Neutrinos have mass!
  - Cosmological limits give $\sum_i m_{\nu_i} < 0.12$ eV





Physics Today ***24****, 1, 21 (1971)*

How are High Energy Neutrinos Created?

- Neutrinos are created in nuclear decays of unstable particles
  - Relativistic (standard) particles
  - Beyond standard model (superheavy particles)

- UHECR can interact with background photon fields via:

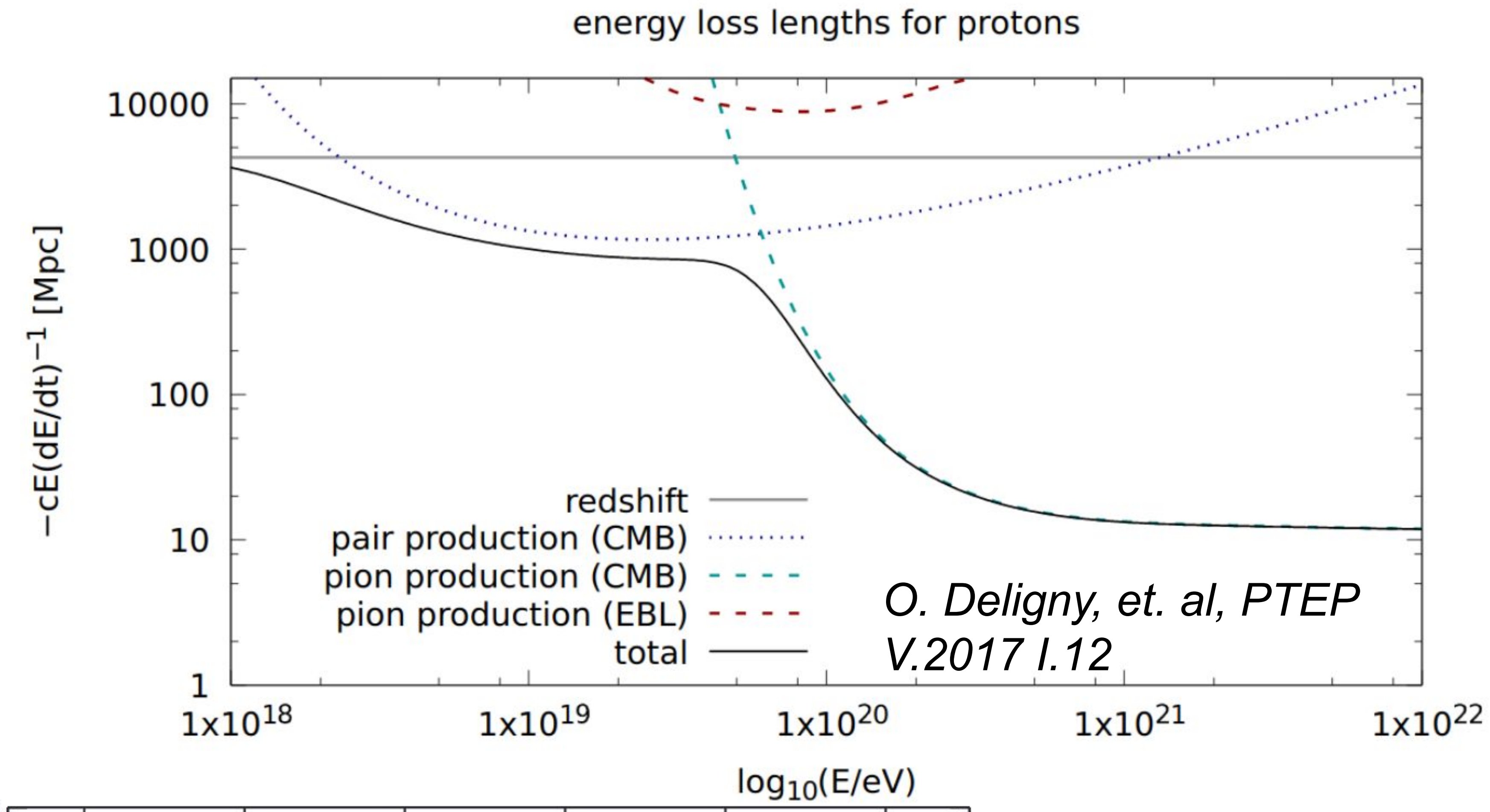
$$p(n) + \gamma \rightarrow n(p) + \pi^{\pm}$$

where the charged pions decay via:

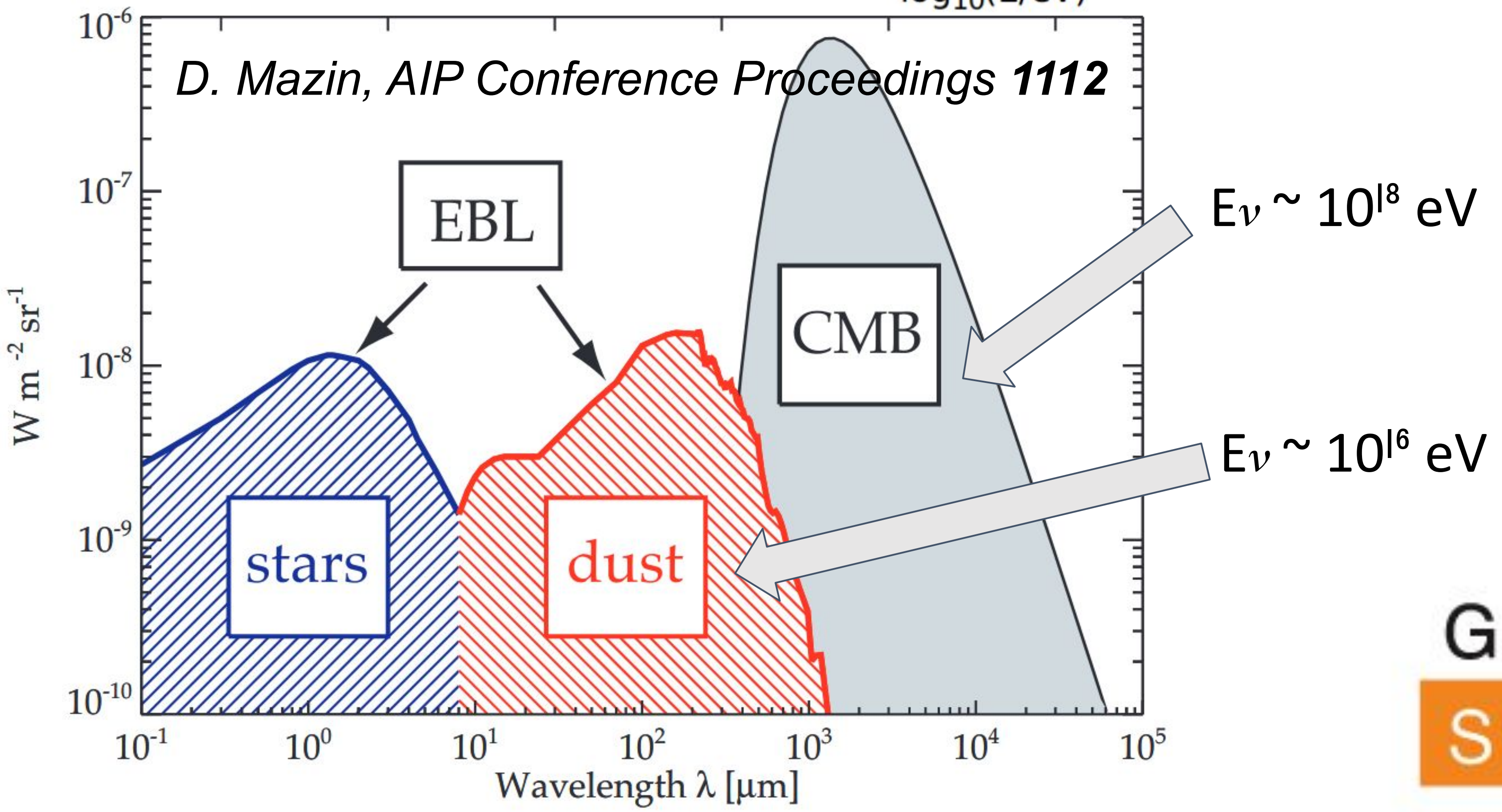
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu_{\mu}})$$

- Inherent link to hadronic acceleration/interactions

- Two primary background photon fields:
  - Cosmic Microwave Background (CMB)
  - Extragalactic Background Light (EBL)



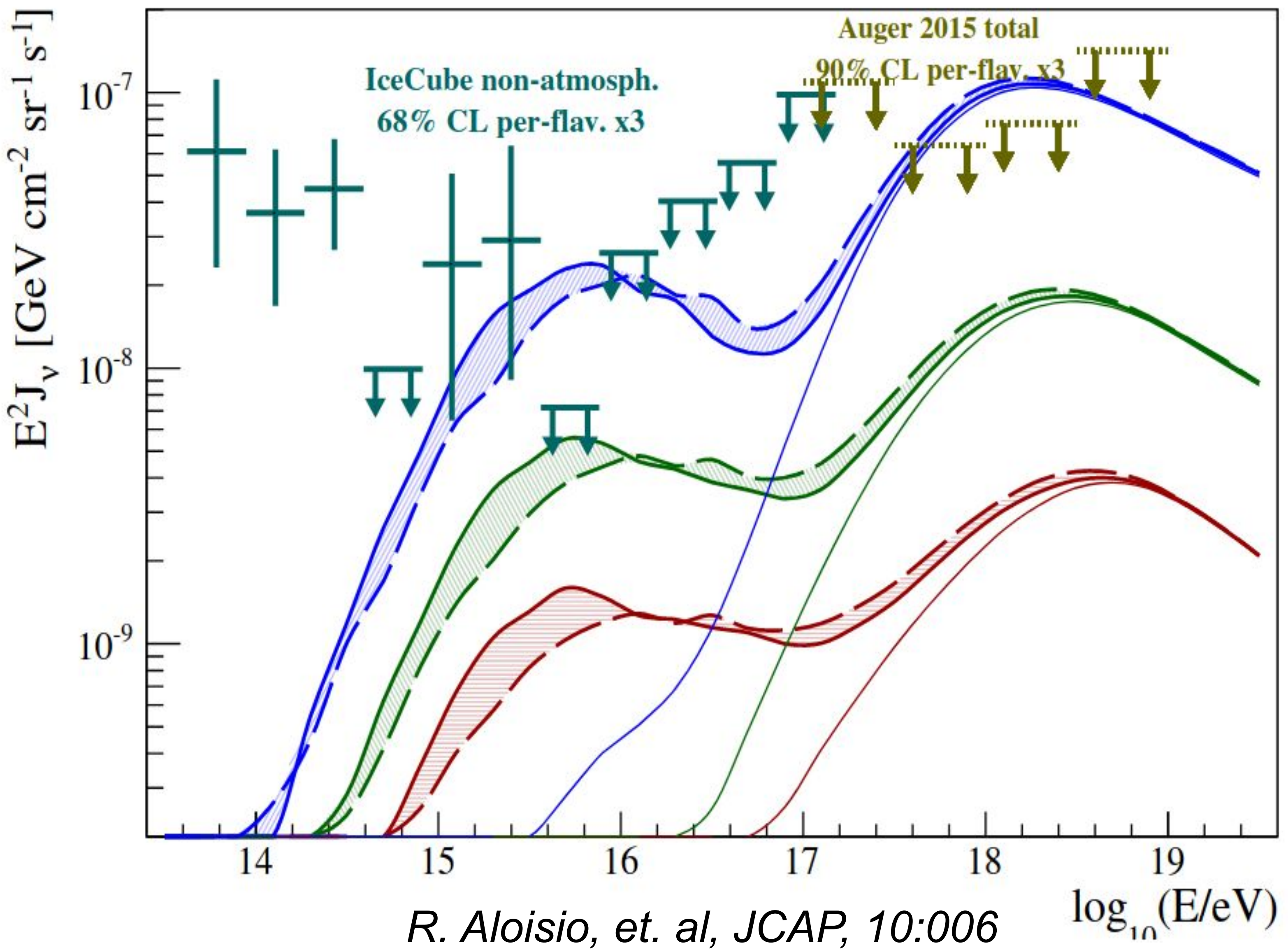
O. Deligny, et. al, PTEP V.2017 I.12



D. Mazin, AIP Conference Proceedings ***1112***

Neutrino Propagation to Earth

- Negligible interactions due to miniscule cross sections, even at cosmological scales
    - UHECR with energy> 50 EeV can only be observed within 100 Mpc
- No magnetic deflection because of electrical neutrality
    - Points back to sources
- Flavor oscillation results in a nearly 1:1:1 ratio of e, μ, and τ neutrinos at Earth
    - Deviation from this ratio can help determine acceleration mechanisms
- Neutrinos are ideal cosmic messengers of high energy astrophysical phenomena



R. Aloisio, et. al, JCAP, 10:006

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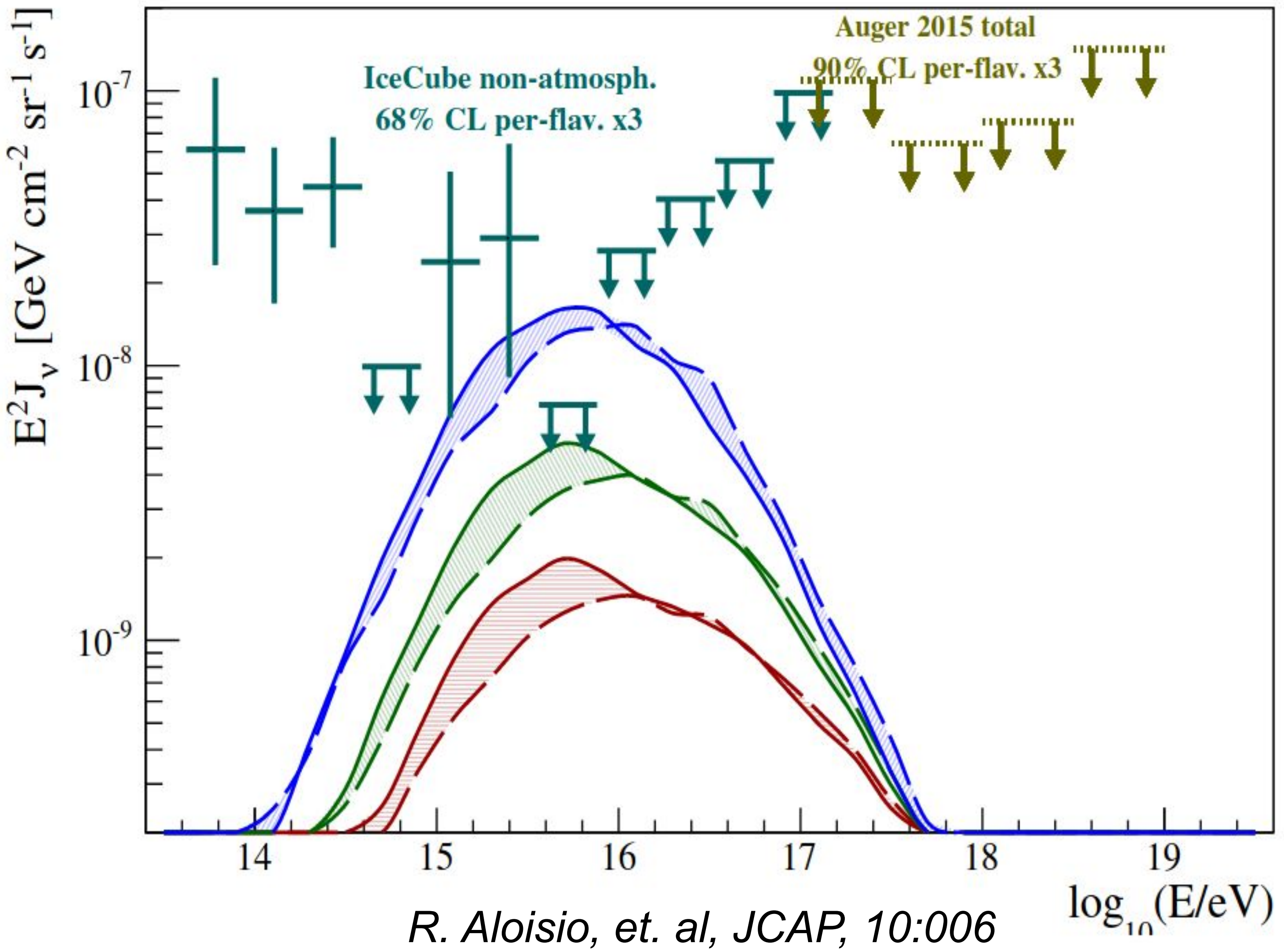


R. Aloisio, et. al, JCAP, 10:006

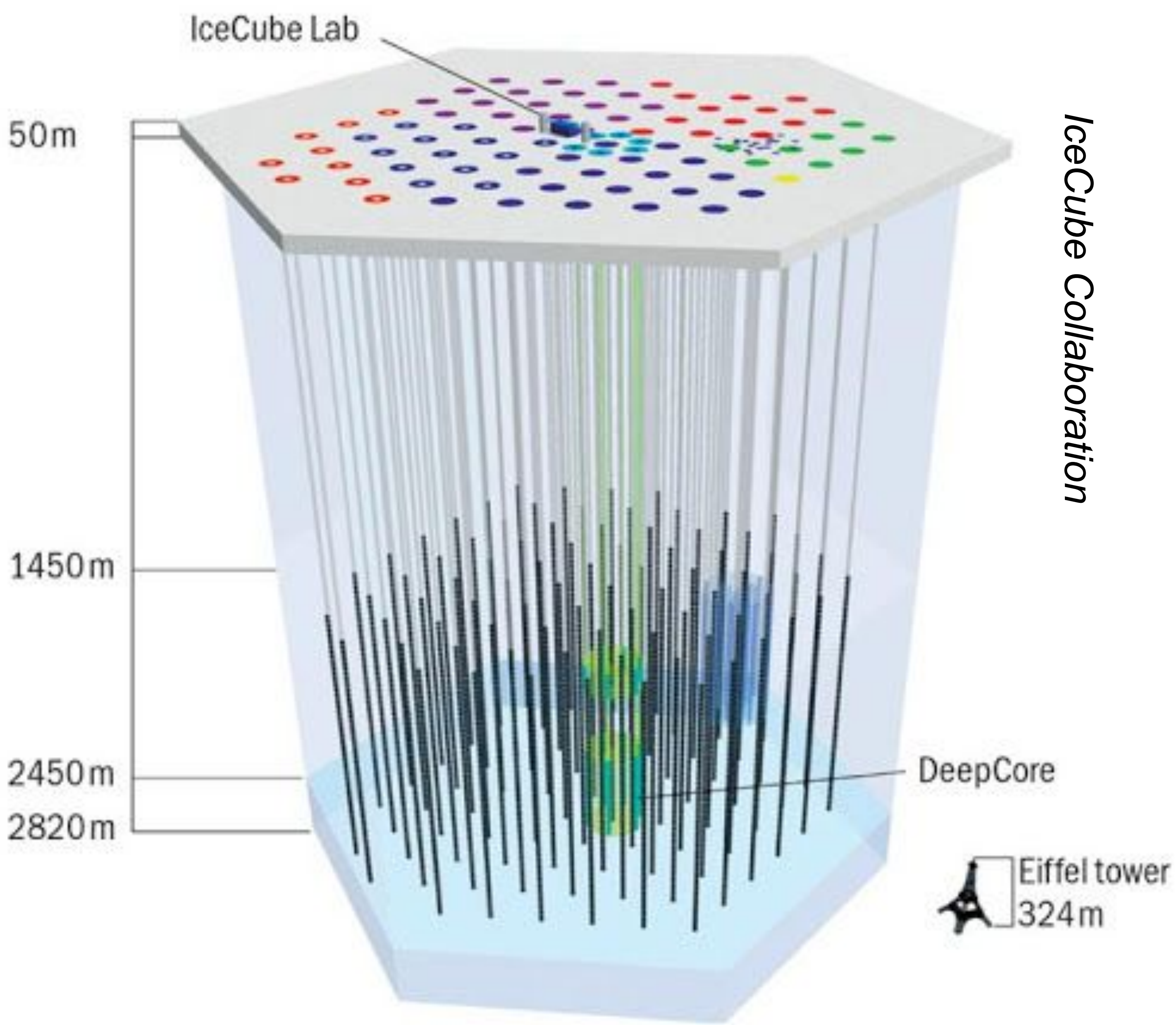
High Energy Neutrino Detection

- Because neutrinos rarely interact, it's necessary to instrument large detection volumes

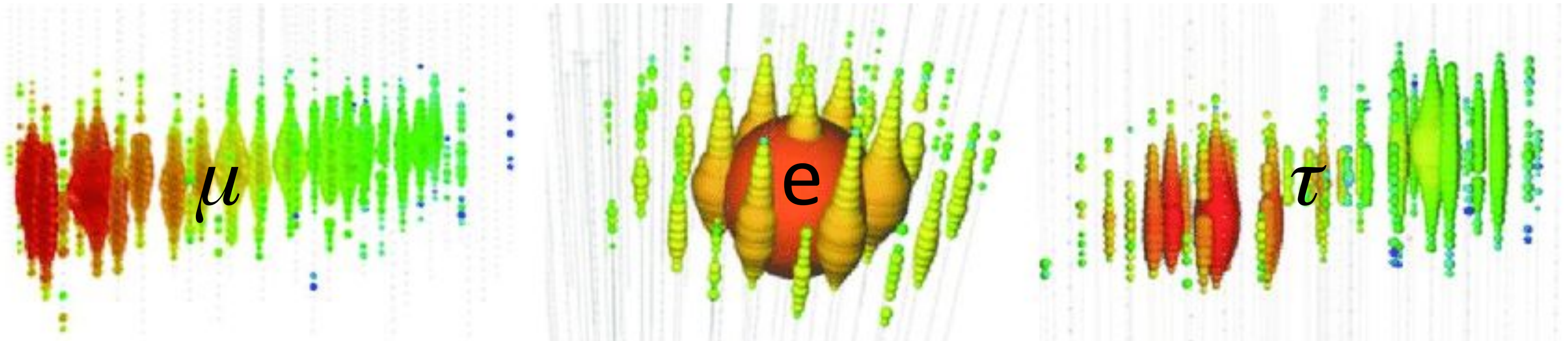
- IceCube is a 1 km^3 neutrino detector located in the South Pole
  - Instrumented with 5160 Digital Optical Modules (DOMs) 1.5 km under the ice
  - Can measure energy, direction, and flavor of the incident neutrino

- In addition to characterizing the atmospheric neutrino flux, IceCube has measured the cosmic neutrino flux from ~10 TeV to ~PeV

- For higher energy measurements, larger detector volumes are needed
  - The in-ice Cherenkov method becomes cost prohibitive to make these measurements



IceCube Collaboration



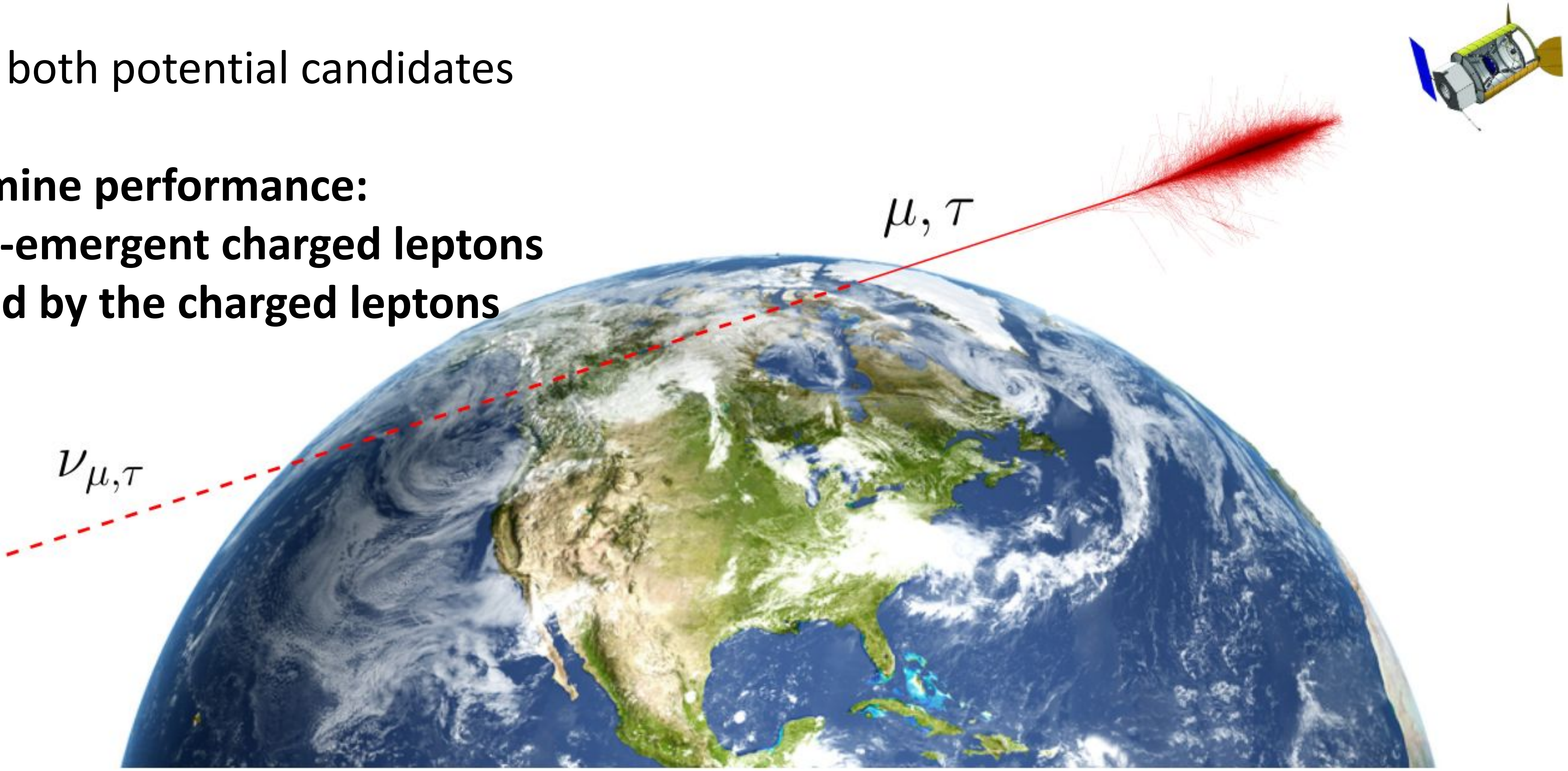
Earth-Skimming Neutrino Technique

- Using the Earth and its atmosphere as the instrumental volume allows for huge geometric apertures

- We consider the optical Cherenkov detection regime
    - Cherenkov angle ~1.4° in atmosphere, projected to sub-orbital and orbital altitudes yields signal diameters ~10-100 km

- Tau and muon neutrinos are both potential candidates

- **2 things necessary to determine performance:**
    - **Characterization of Earth-emergent charged leptons**
    - **Properties of EAS initiated by the charged leptons**



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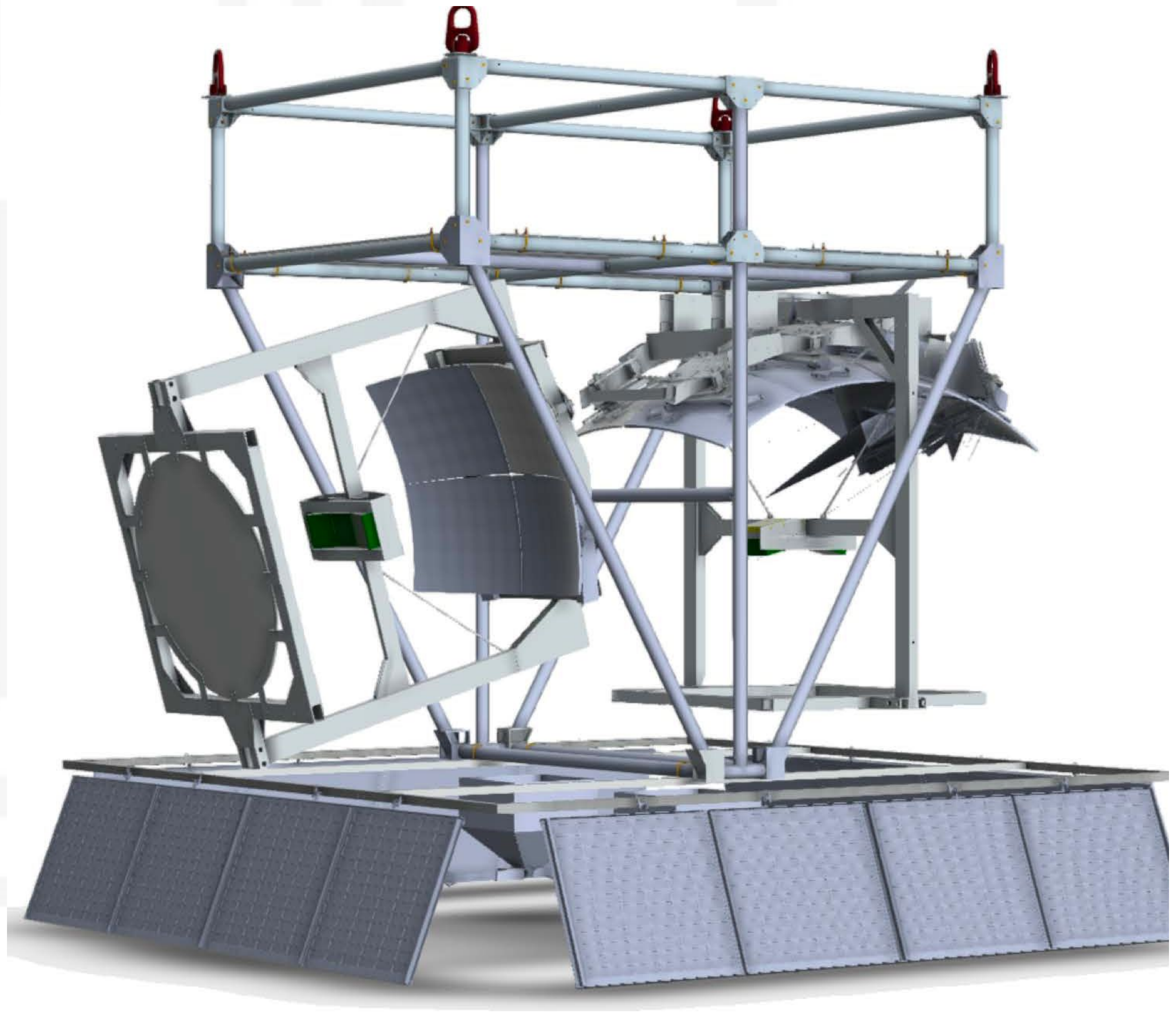

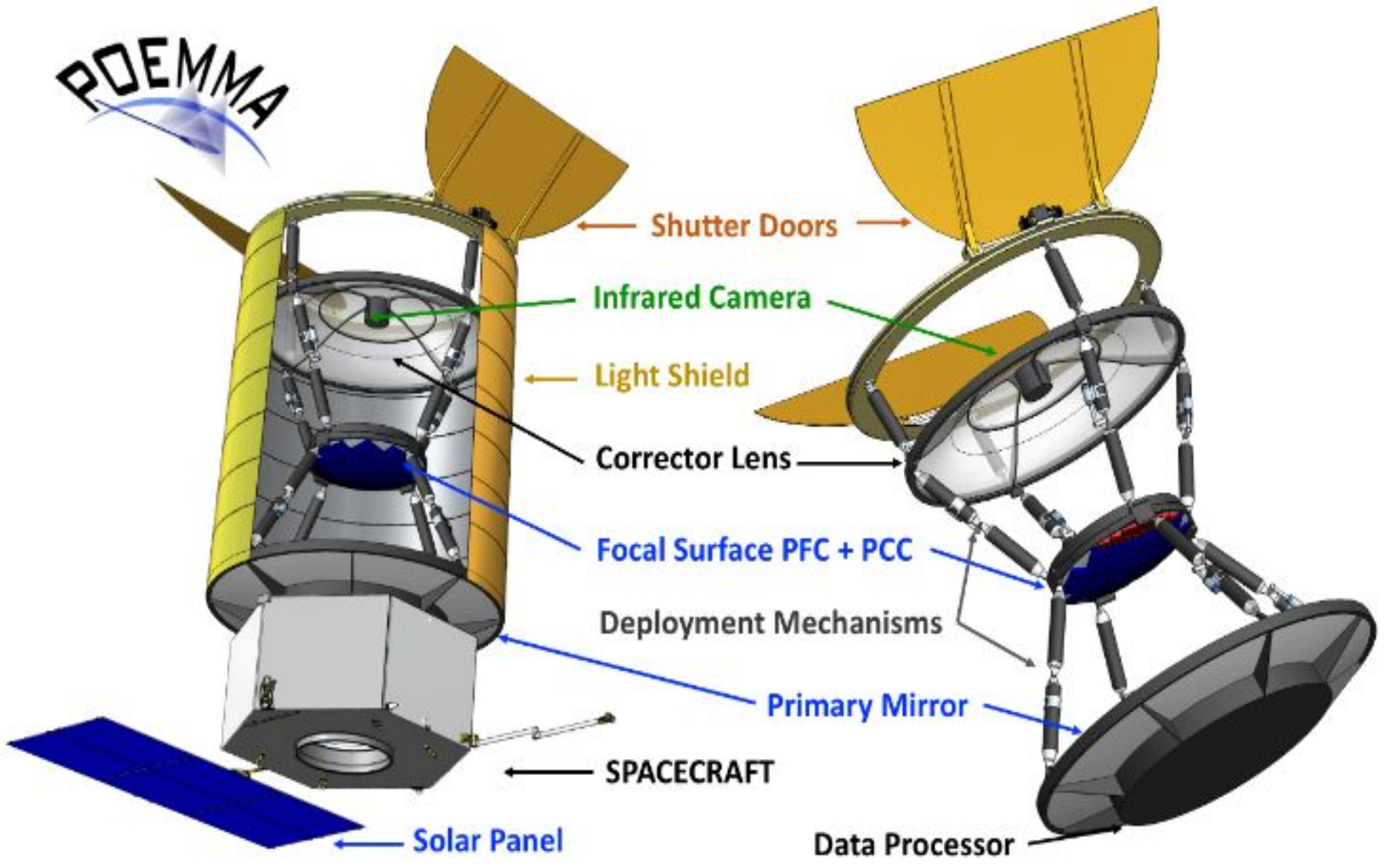

- Orbiting altitude: 33 km
- Mission lifetime: ~100 days
- Fluorescence Camera: 6912 pixels
- Cherenkov Camera: 512 pixels, 12.8°x7° FOV

- Orbiting altitude: 525 km
- Mission lifetime: 3 year (5 year goal)
- Fluorescence Camera: 126,720 pixels
- Cherenkov Camera: 15,360 pixels, 30°x7° FOV

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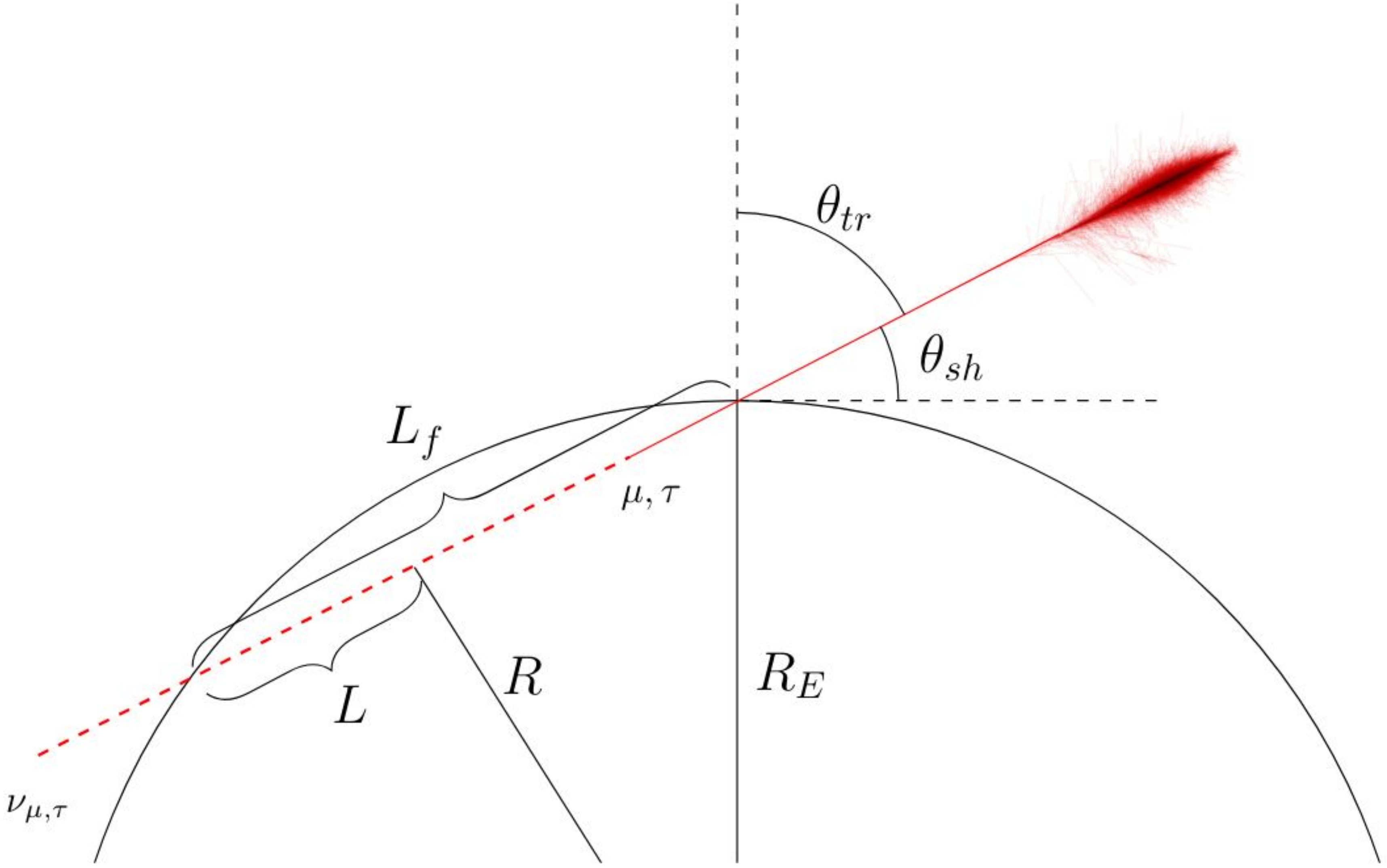
Neutrino Propagation

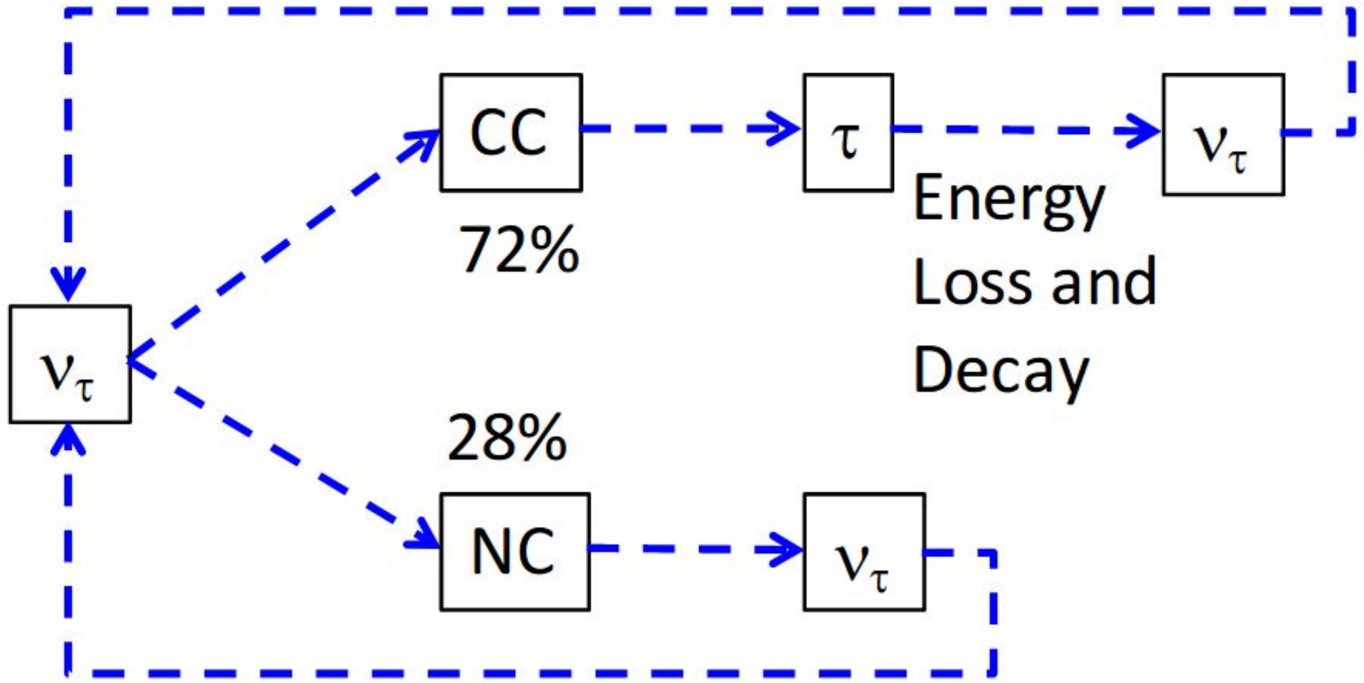
J. Alvarez-Muniz, et. al, Phys. Rev. D 97

- **Goal:** Follow high-energy neutrinos as they propagate through the Earth and qualify the properties of any emerging charged leptons

- Must properly consider:
  - Charged-current and neutral-current neutrino interactions
  - Energy losses of charged leptons
  - Charged lepton decay
  - Possible neutrino re-interaction

- Monte Carlo computation scheme: NuTauSim
  - Added propagation of muons to the scheme





A.M. Dziewonski and D.L. Anderson, Phys. Earth Planet. Interiors, 25:297–356

Neutrino Interaction in Earth

- Calculate grammage profile along neutrino trajectory:

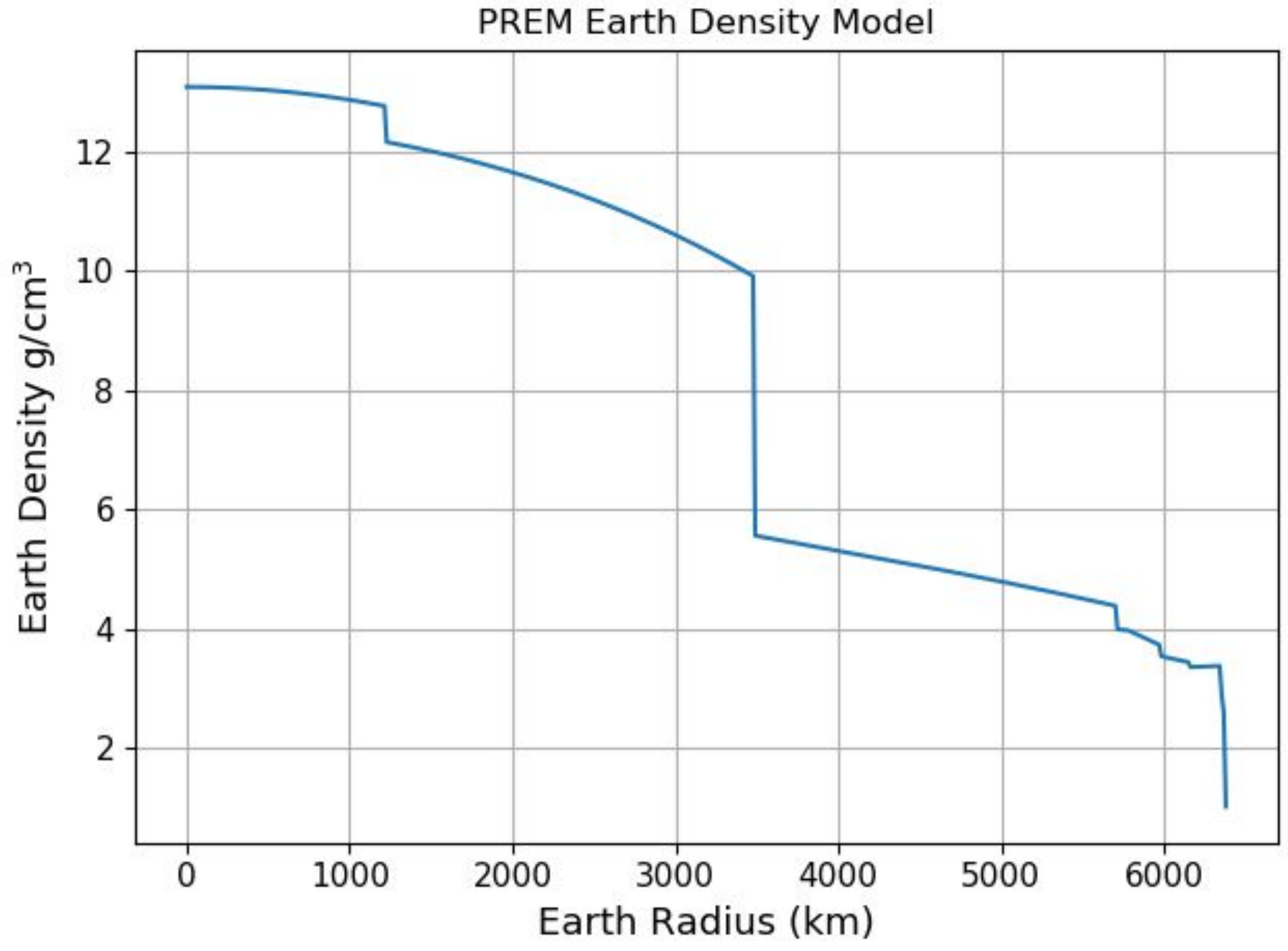
$$X_E(L) = \int_0^L \rho(r(L))dL$$

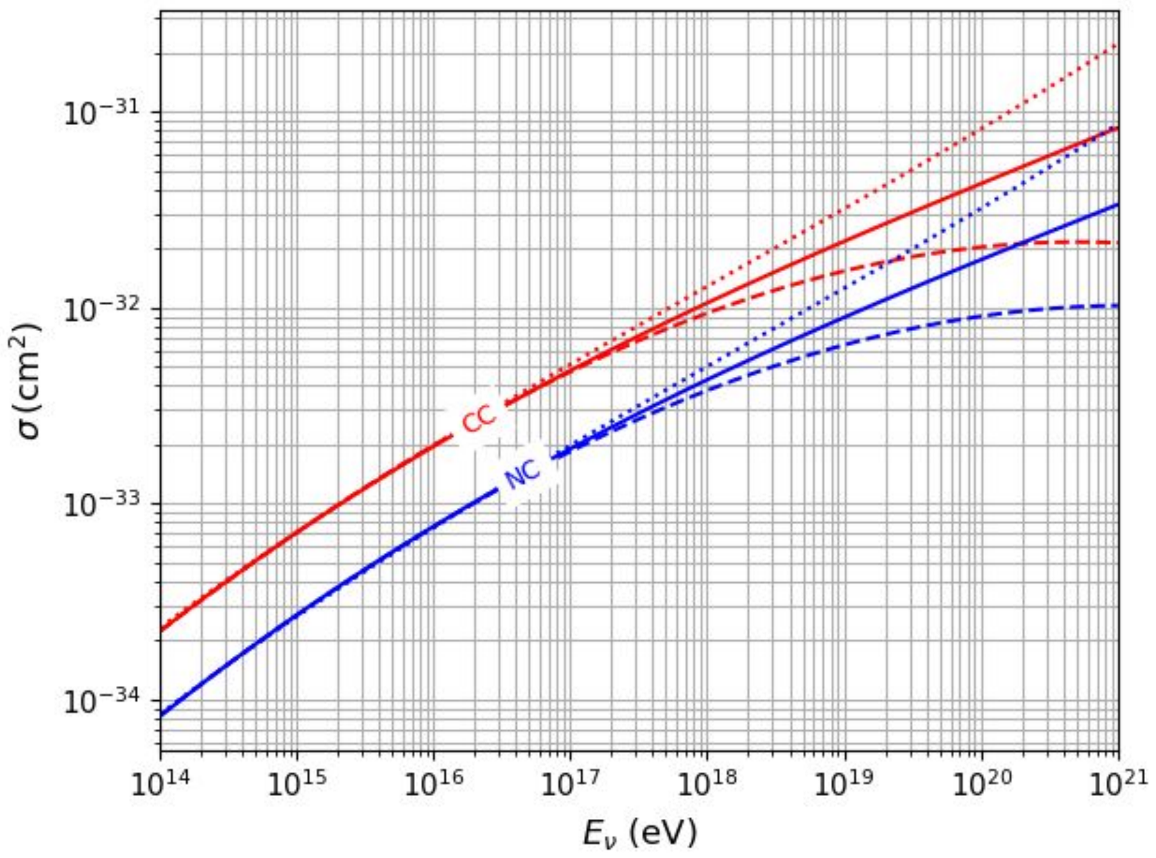
- Sample neutrino interaction grammage from exponential distribution with mean:

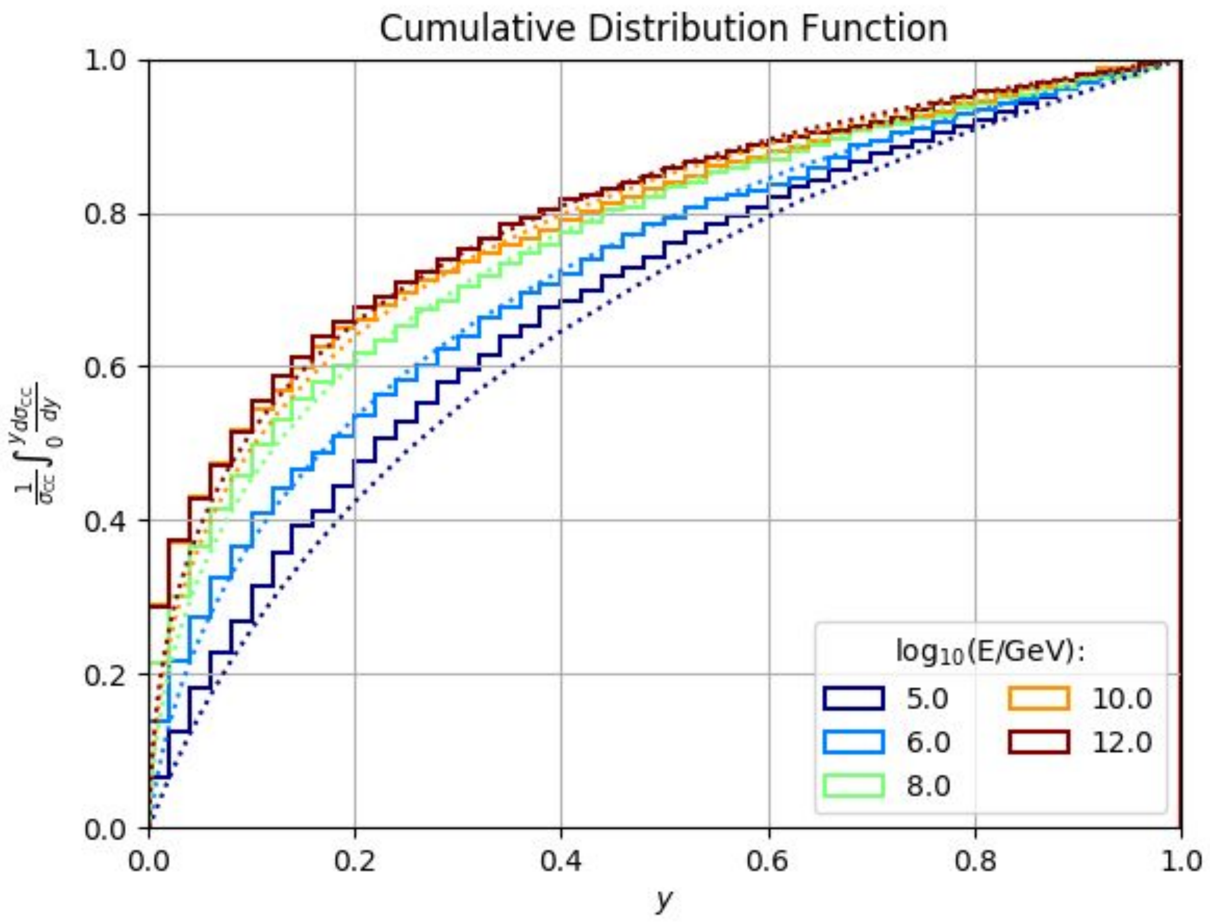
$$X^{\nu}_{int}(E_\nu) = \frac{m_N}{\sigma_{\rm CC}(E_\nu) + \sigma_{\rm NC}(E_\nu)}$$

  - $\sigma_{\rm CC}/(\sigma_{\rm CC} + \sigma_{\rm NC})$ probability of becoming a charged lepton
  - σ_{CC}/σ_{NC} ≈ 2.6 for E>10^{12} eV

- Charged lepton energy = (1-y) E_ν
  - y is called the inelasticity
  - Average y ≈ 20%







Charged Lepton Propagation

- Assume continuous energy losses inside the Earth:

$$\left\langle \frac{dE_\tau}{dX} \right\rangle = -a(E_\tau) - b(E_\tau)E_\tau$$

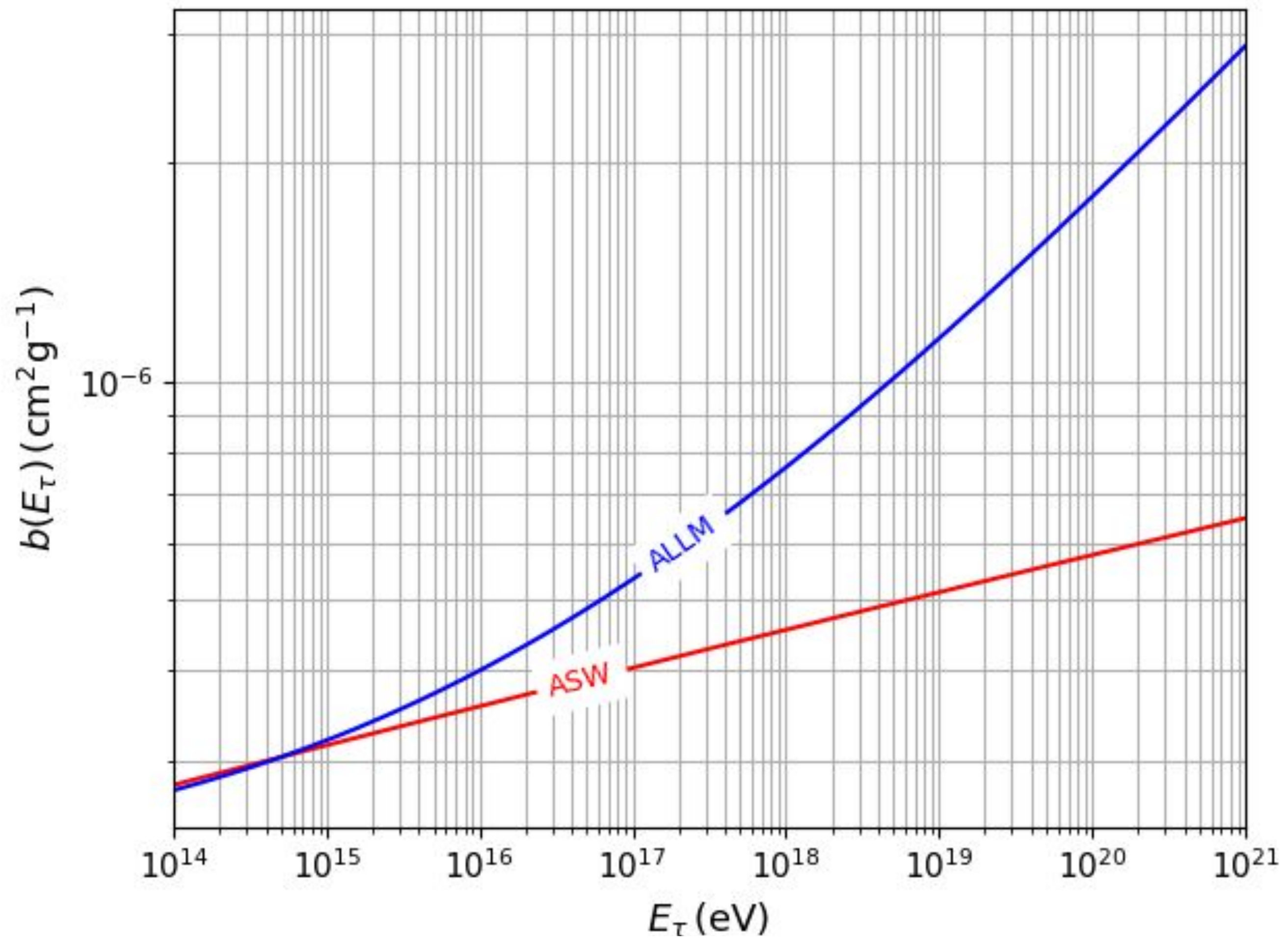
$a(E_\tau)$ corresponds to constant ionization losses
$b(E_\tau)$ corresponds to radiative losses
  - Bremsstrahlung
  - Electron-positron pair production
  - Photonuclear interactions

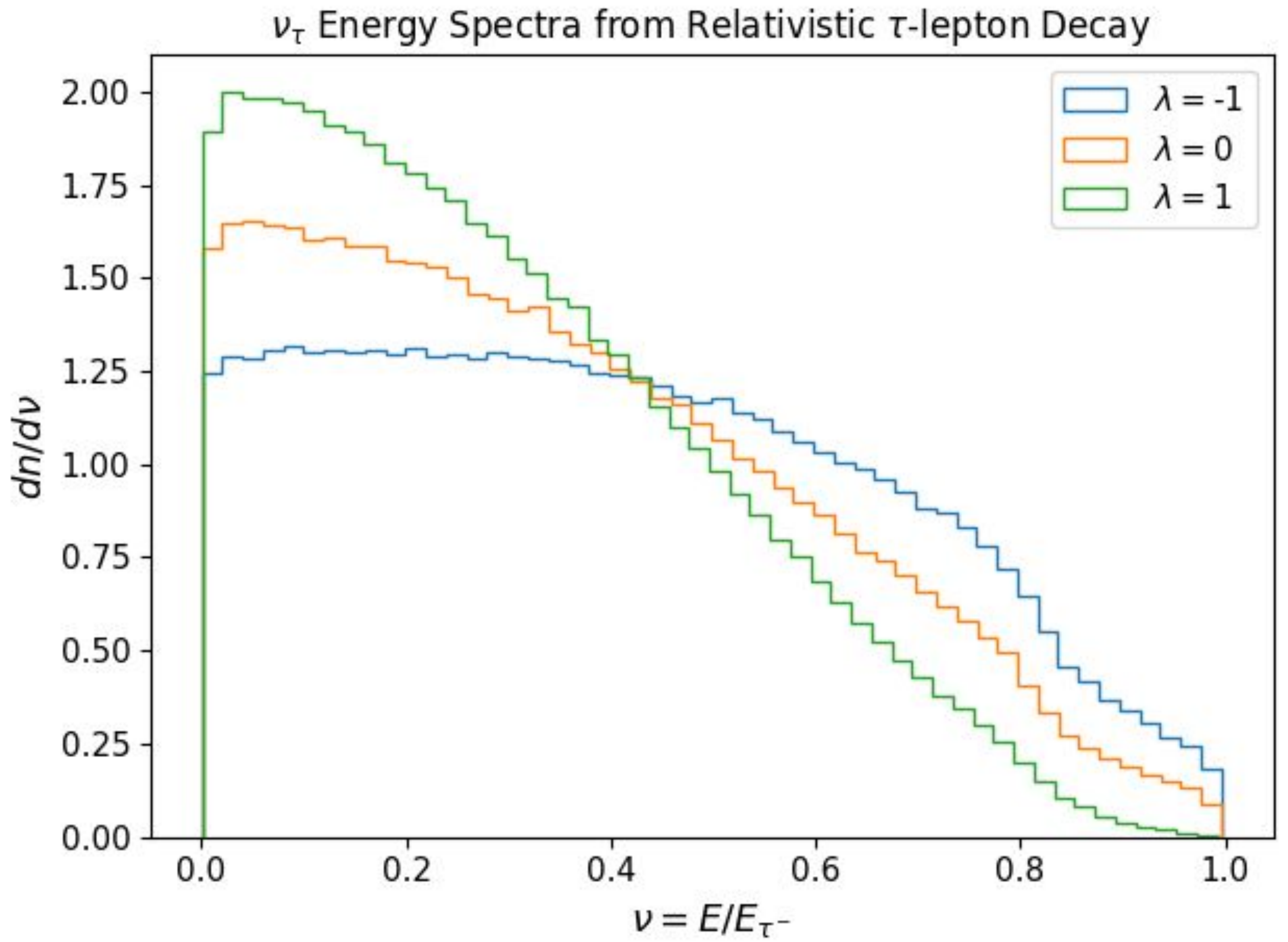
- Propagated in steps ΔL such that 0.1% of the primary energy is lost

- Check for decay with probability:

$$P_{\text{decay}}(E_\tau) = 1 - e^{-\Delta L/\gamma(E_\tau)ct_\tau}$$

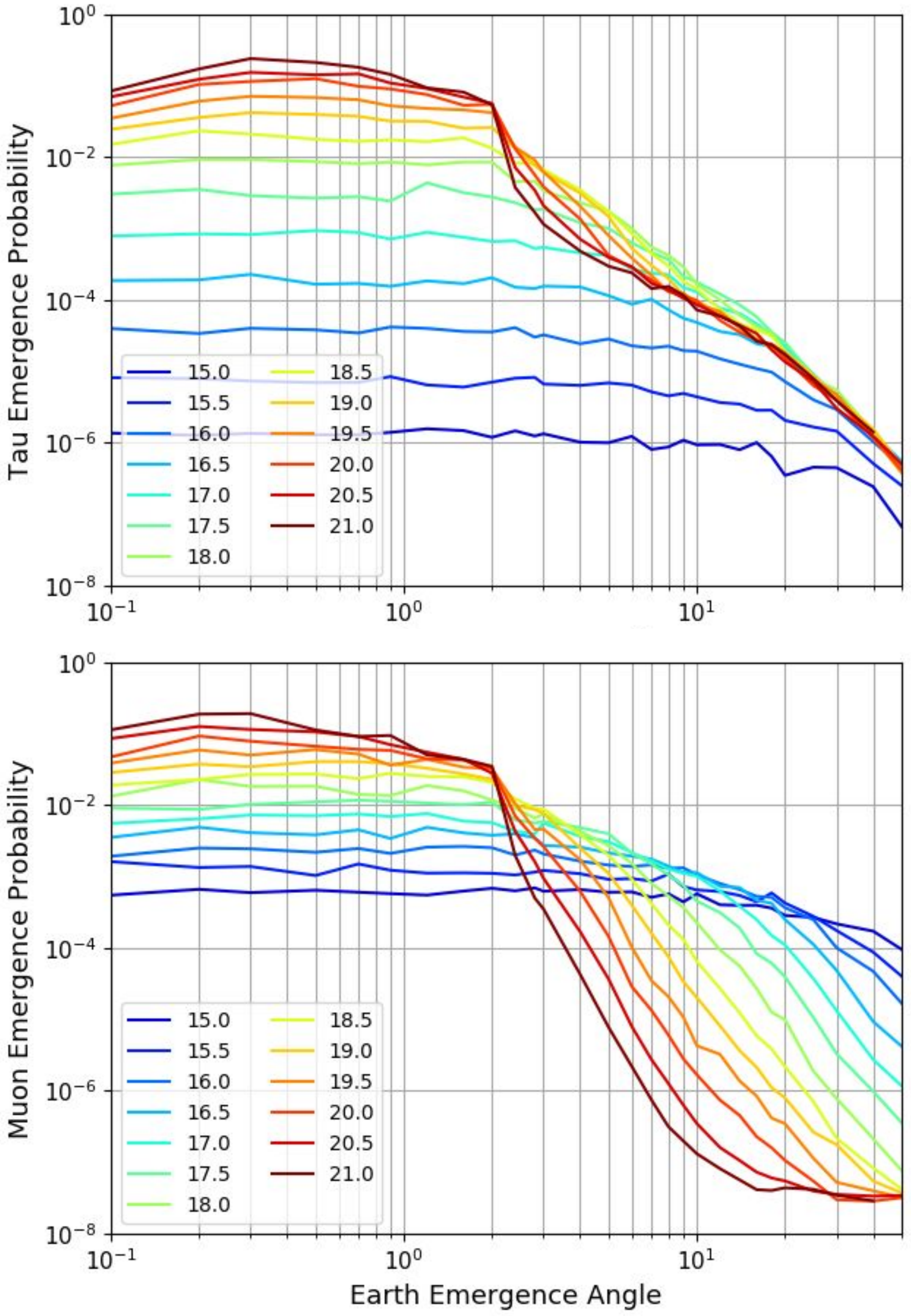
  - If decayed, sample neutrino energy from decay spectra



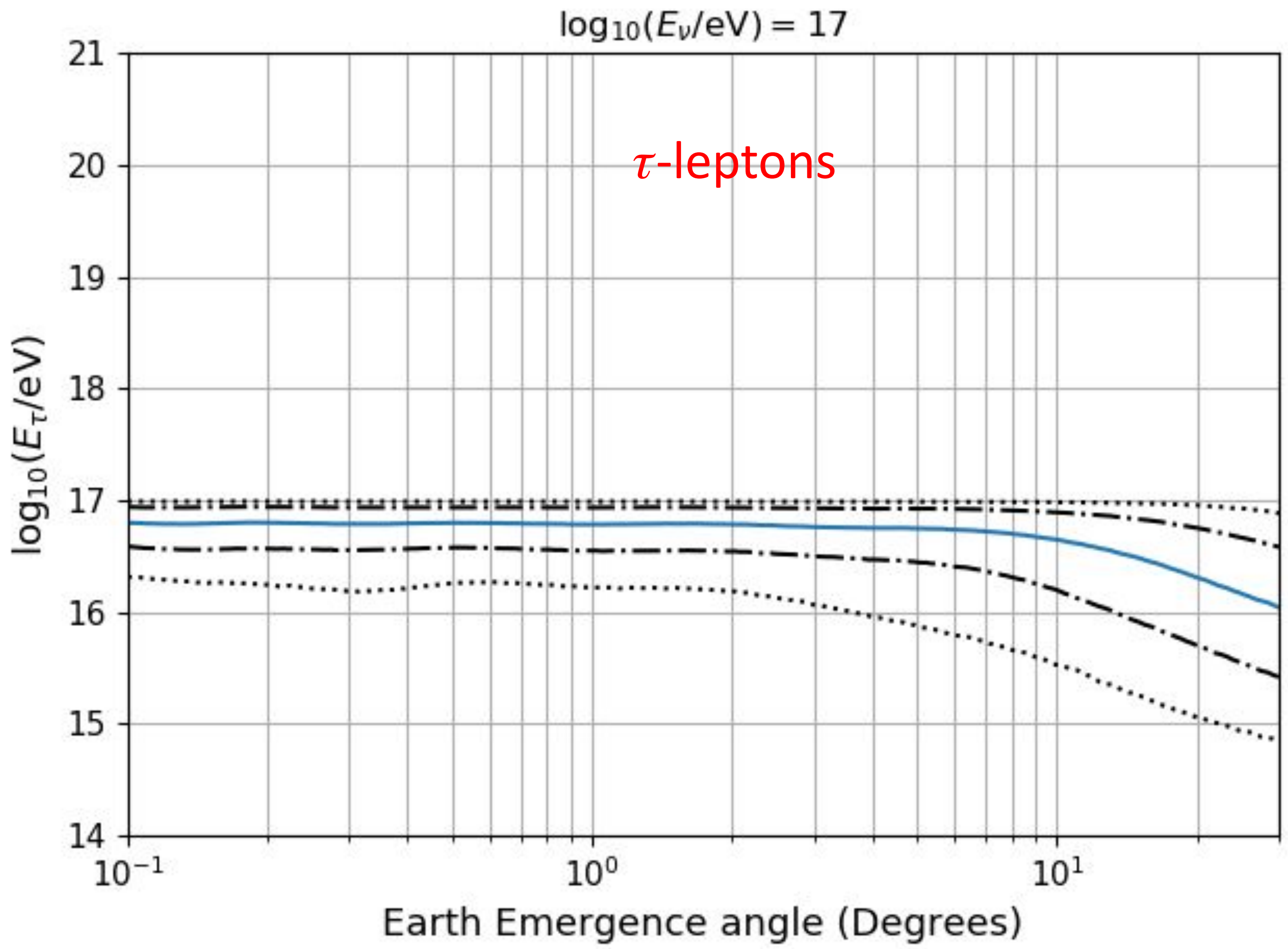


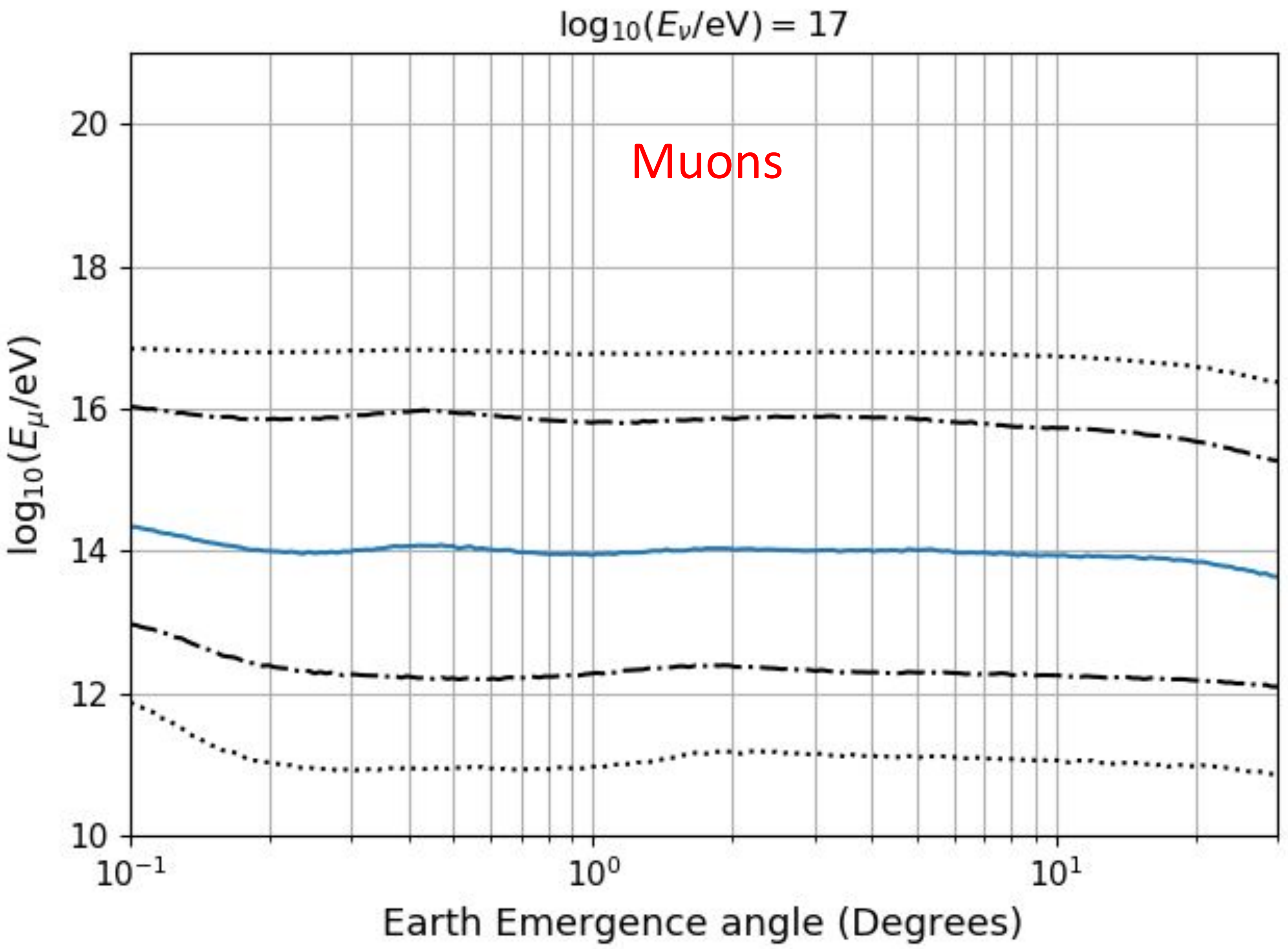
Earth Emergence Probability

- Defined as the number of charged leptons emerging from the Earth divided by the number of simulated neutrinos
- Muon Earth emergence probability exceeds τ-lepton Earth emergence probability until parent neutrino energies of about 100 PeV
  - At PeV energies, factor of 600!
- While τ-leptons experience $\nu_\ell \rightarrow \ell \rightarrow \nu_\ell$ regeneration, muons do not, as muon decays happen at characteristically small energies



Earth-Emergent Charged Lepton Energy Distributions





Energy reconstruction inherently limited by the physics of propagation

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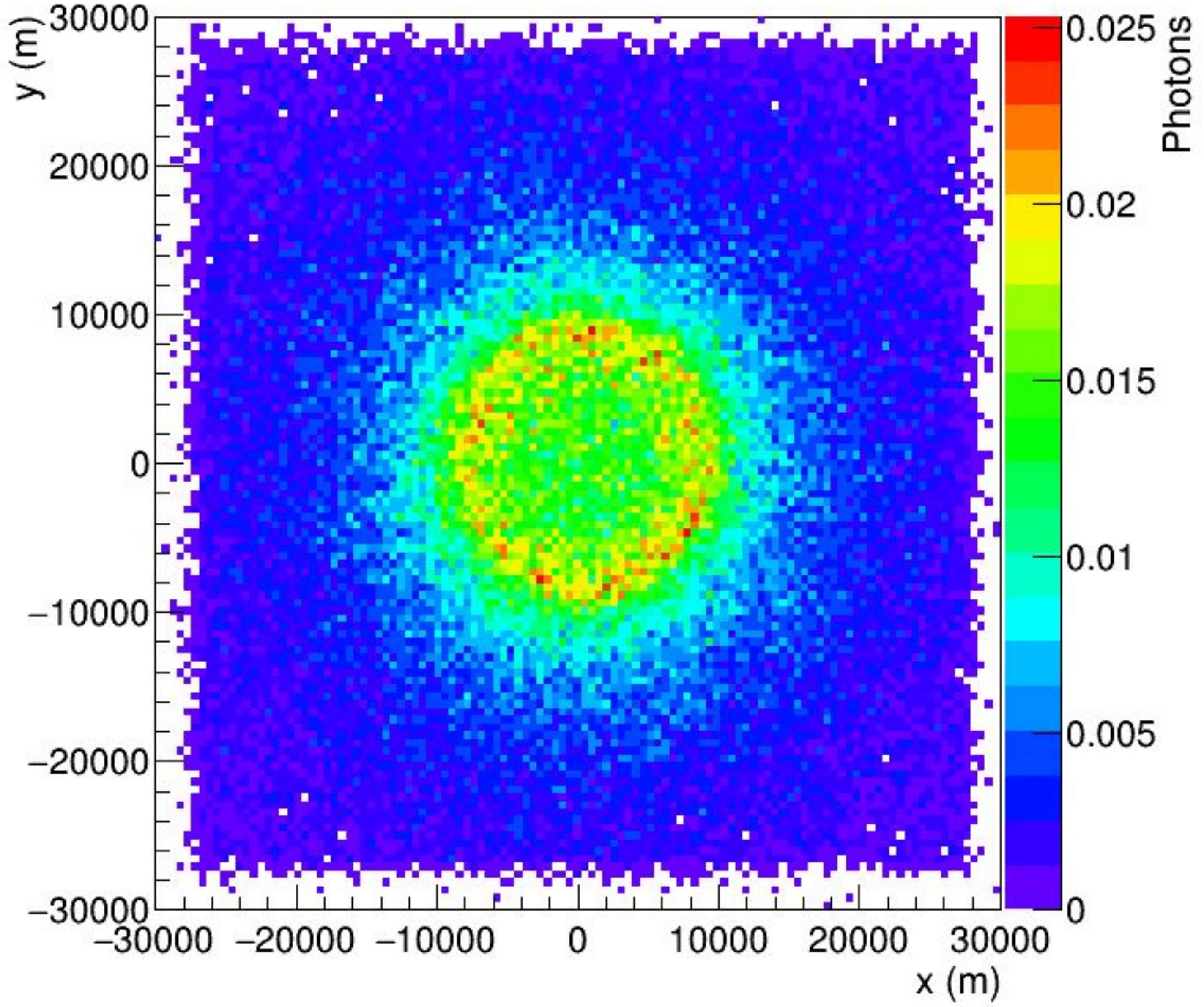
Optical Cherenkov Simulation

- **Goal:** return the properties of arriving Cherenkov photons on a predefined detection plane, from a given shower:
  - Spatial
  - Wavelength
  - Timing
  - Angular

- Taking into account:
  - Underlying charged particle properties
  - Atmospheric Effects

- Current simulations are unequipped to handle upward going showers, except in the case of a flat atmosphere
  - Unreliable arrival times of arriving photons

1TeV proton EAS with θ_{sh} = 90° (perfectly vertical), 350 nm < λ <450 nm, observed from 400km



CORSIKA 7 run provided by F. Bisconti

τ-lepton Induced EAS

- τ-lepton decay branches:

$$\tau^{\mp} \rightarrow \text{hadrons} + \nu_\tau(\bar{\nu}_\tau) \approx 64.79\%$$

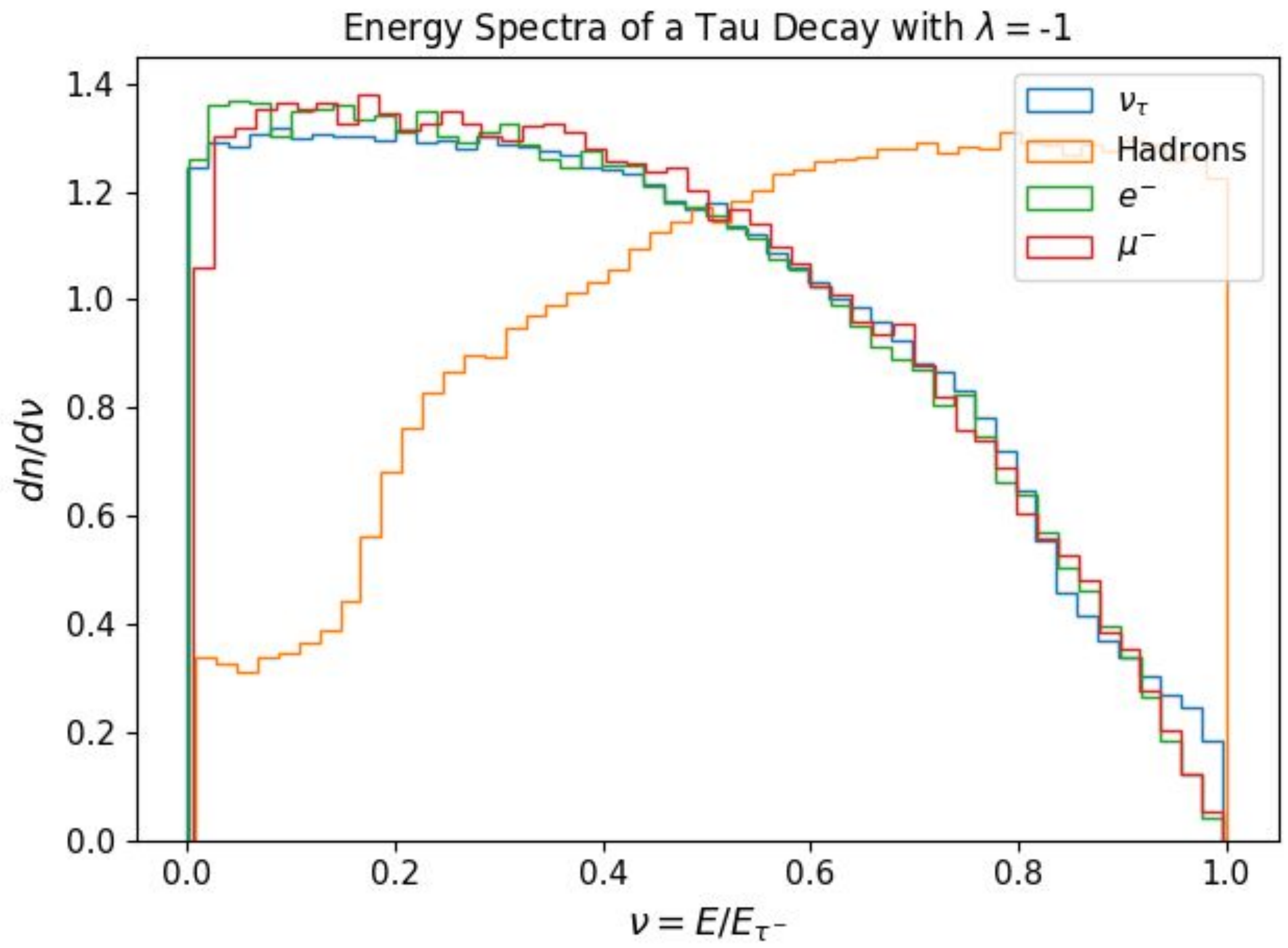
$$\tau^{\mp} \rightarrow e^{\mp} + \bar{\nu}_e(\nu_e) + \nu_\tau(\bar{\nu}_\tau) \approx 17.82\%$$

$$\tau^{\mp} \rightarrow \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu) + \nu_\tau(\bar{\nu}_\tau) \approx 17.39\%$$

  Average fractional energy of e/μ ≈ 42%
  Average fractional energy deposited into hadrons ≈ 58%

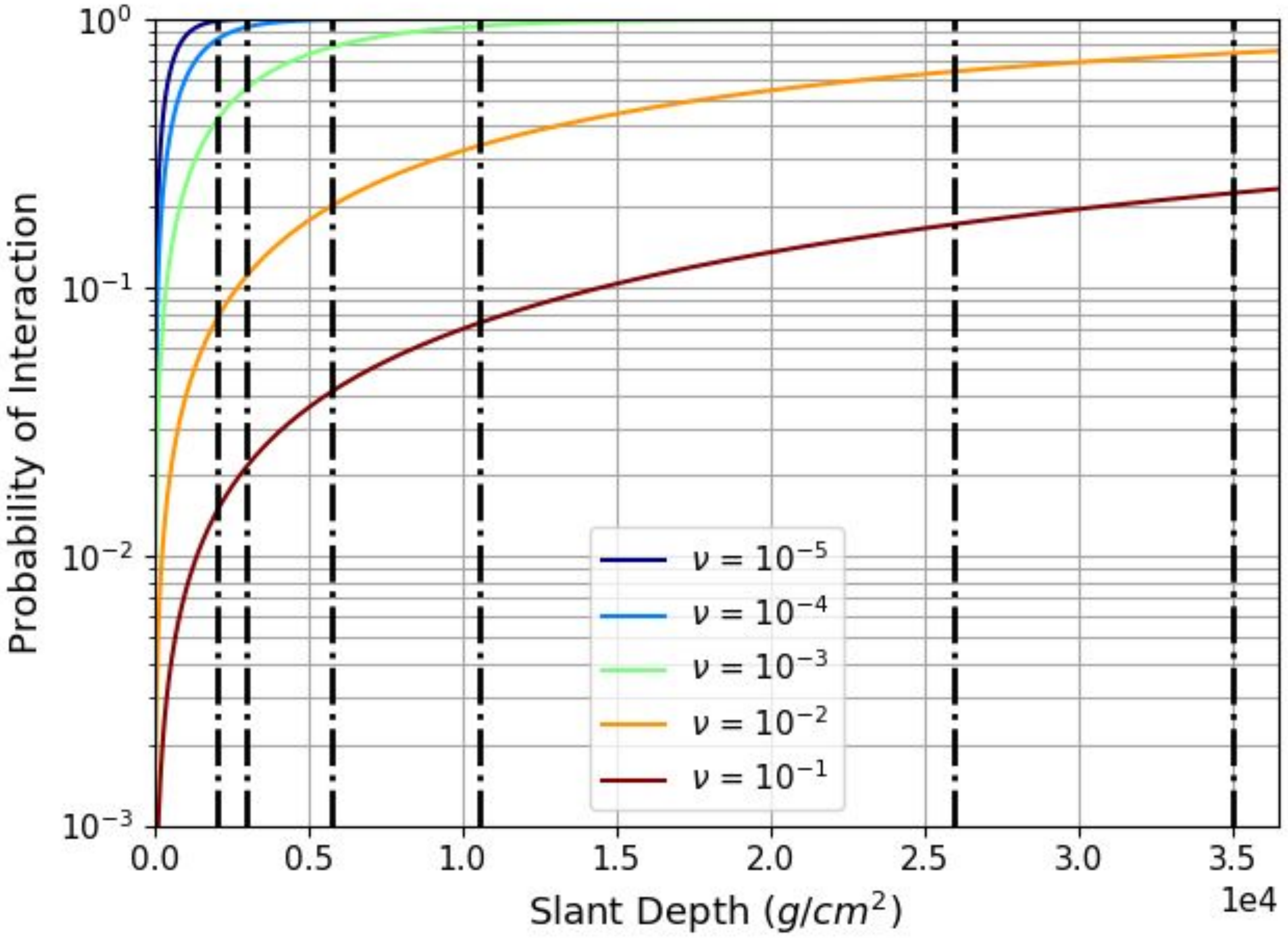
- Well justified in approximating longitudinal profile with that of a proton induced EAS

- Long decay length:
  $4.9 \times (E_\tau / 10^{17}\ \text{eV})$ km



Muon Induced EAS

- Large one-time energy depositions
  - Bremsstrahlung
  - Pair-production
  - Photonuclear interactions
- In near-limb trajectories, a significant fraction of muons can interact:
  - Below θ_{sh} = 5°, ~10% chance a muon deposits 10% or more of its energy into a single interaction
- Due to long interaction lengths, muons can initiate EAS anywhere along their trajectories
- Can approximate longitudinal profile with that of a proton induced EAS
  - Most significant energy loss process corresponds to photonuclear interactions

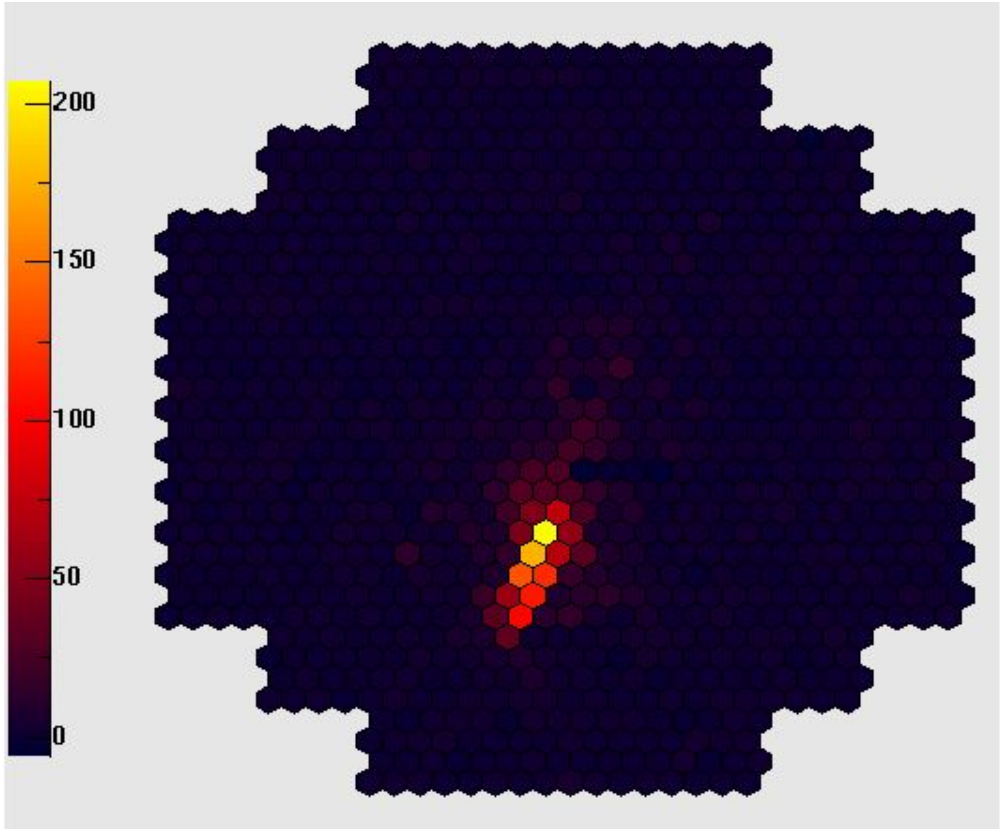


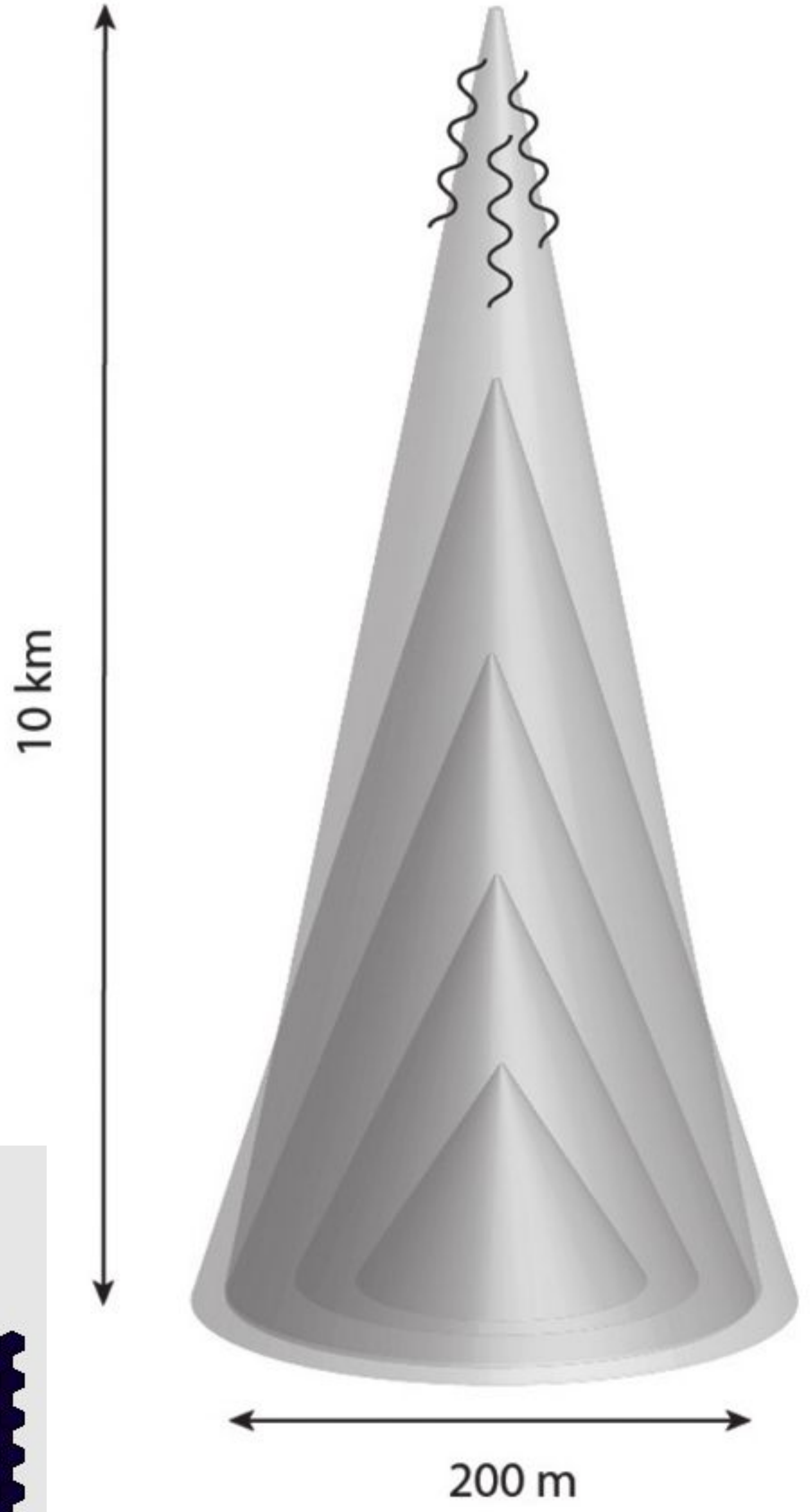
*Dot-dashed lines correspond to total thickness of atmosphere provided for trajectories of Earth-emergence angle: 30°, 20°, 10°, 5°, 1°, 0°

Cherenkov Emission from EAS

- Charged particles in the EAS generate Cherenkov emission
- Superposition of all particle emission forms the measurable signal
- Consider only electrons within the EAS
  - EAS is e^+/e^- dominant
  - Cherenkov threshold of π^+/π^-, μ is >200x larger
- Electron properties:
  - Energy
  - Angular
  - Lateral
  - Timing
  - Geomagnetic deflection

HESS Collaboration

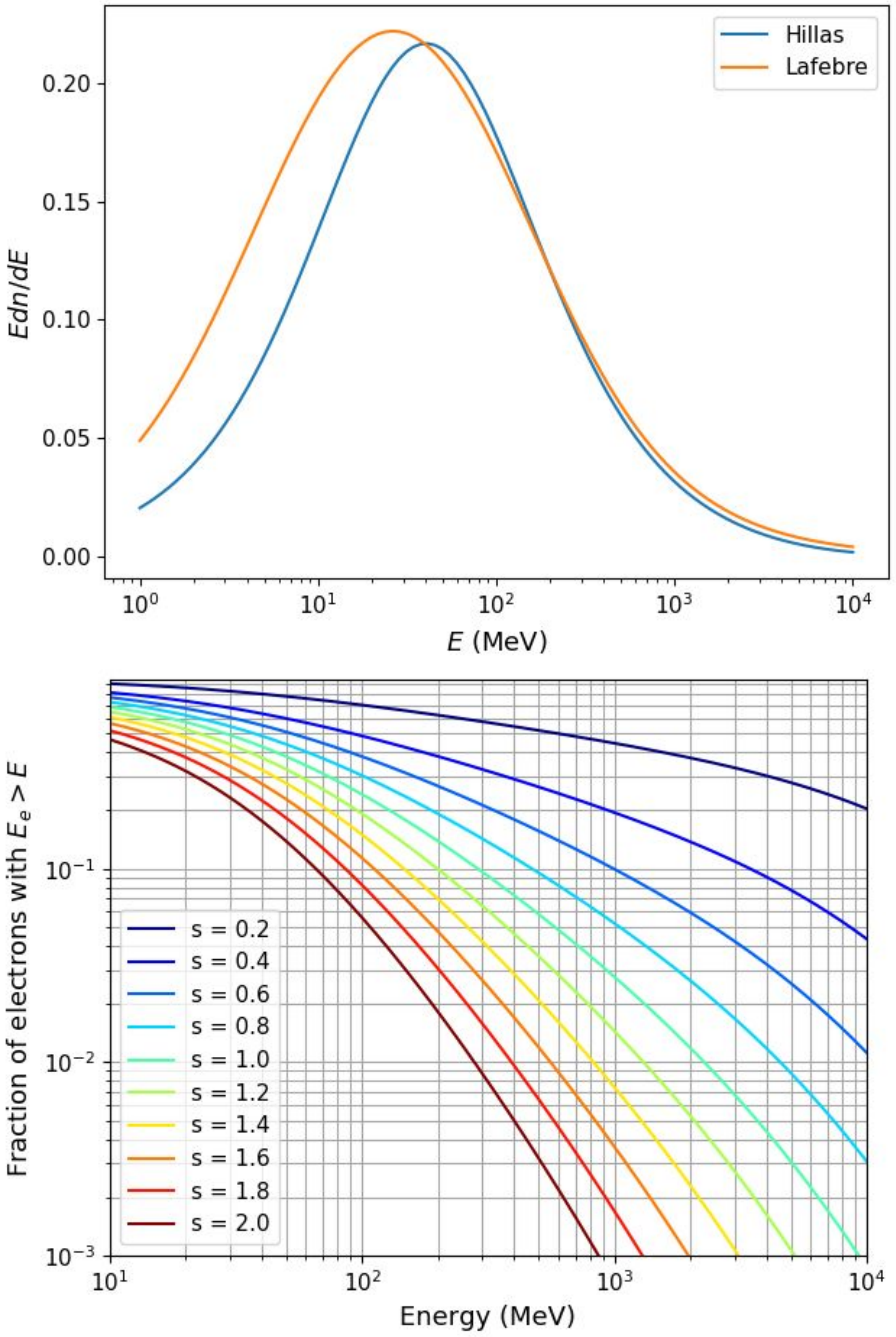




T. K. Gaisser, Cosmic Rays and Particle Physics: 2nd Edition

M. Hillas, J. Phys. G : Nucl. Phys. 8 (1982) 1461-1473.

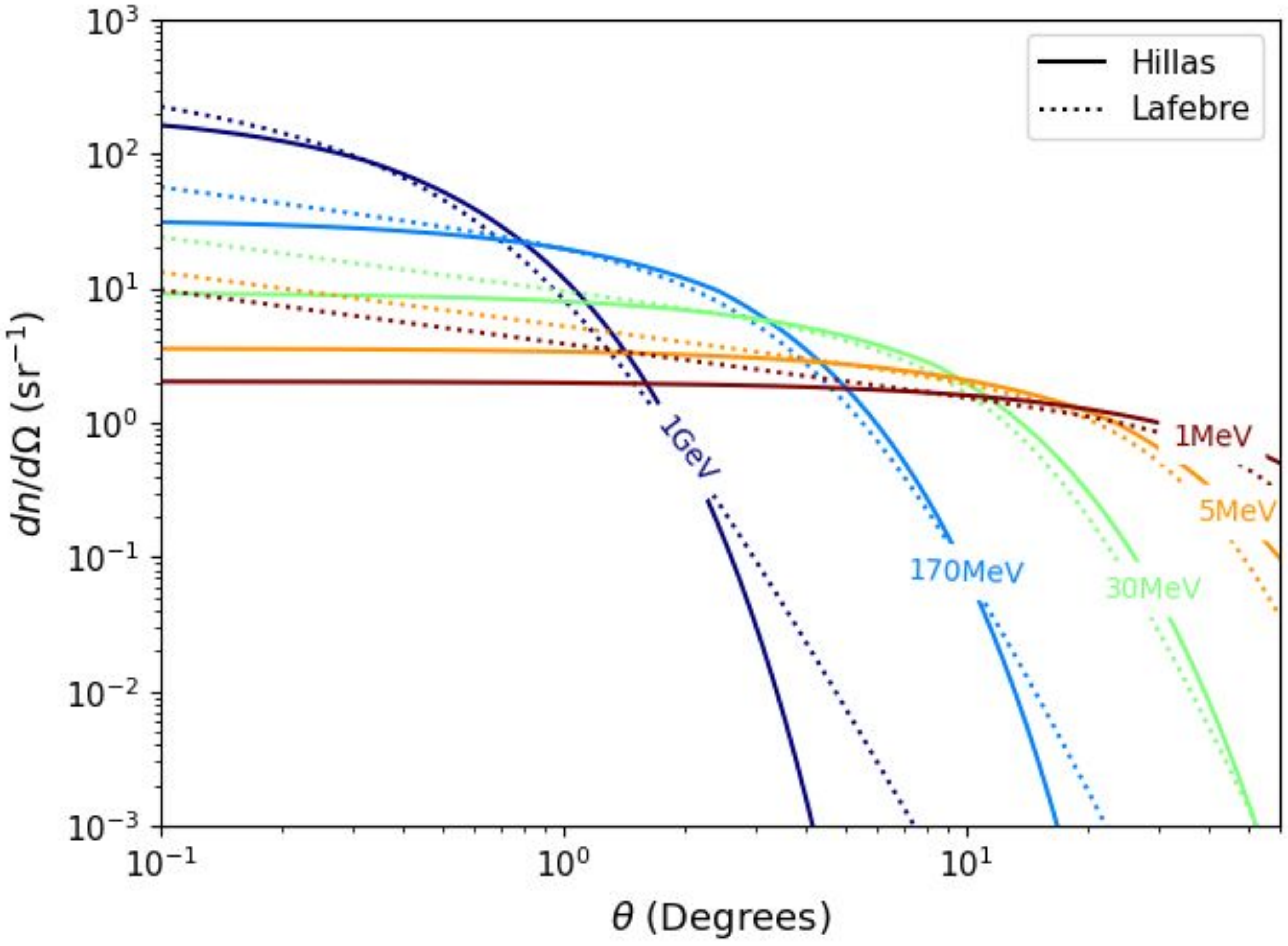
Electron Energy Distribution



- Electrons have a nontrivial distribution in energy that changes with shower evolution
- Overall, electrons which propagate during late shower ages are of characteristically lower energies
- For the purpose of this work, we implement the model of Hillas (1982)

Electron Angular Distribution

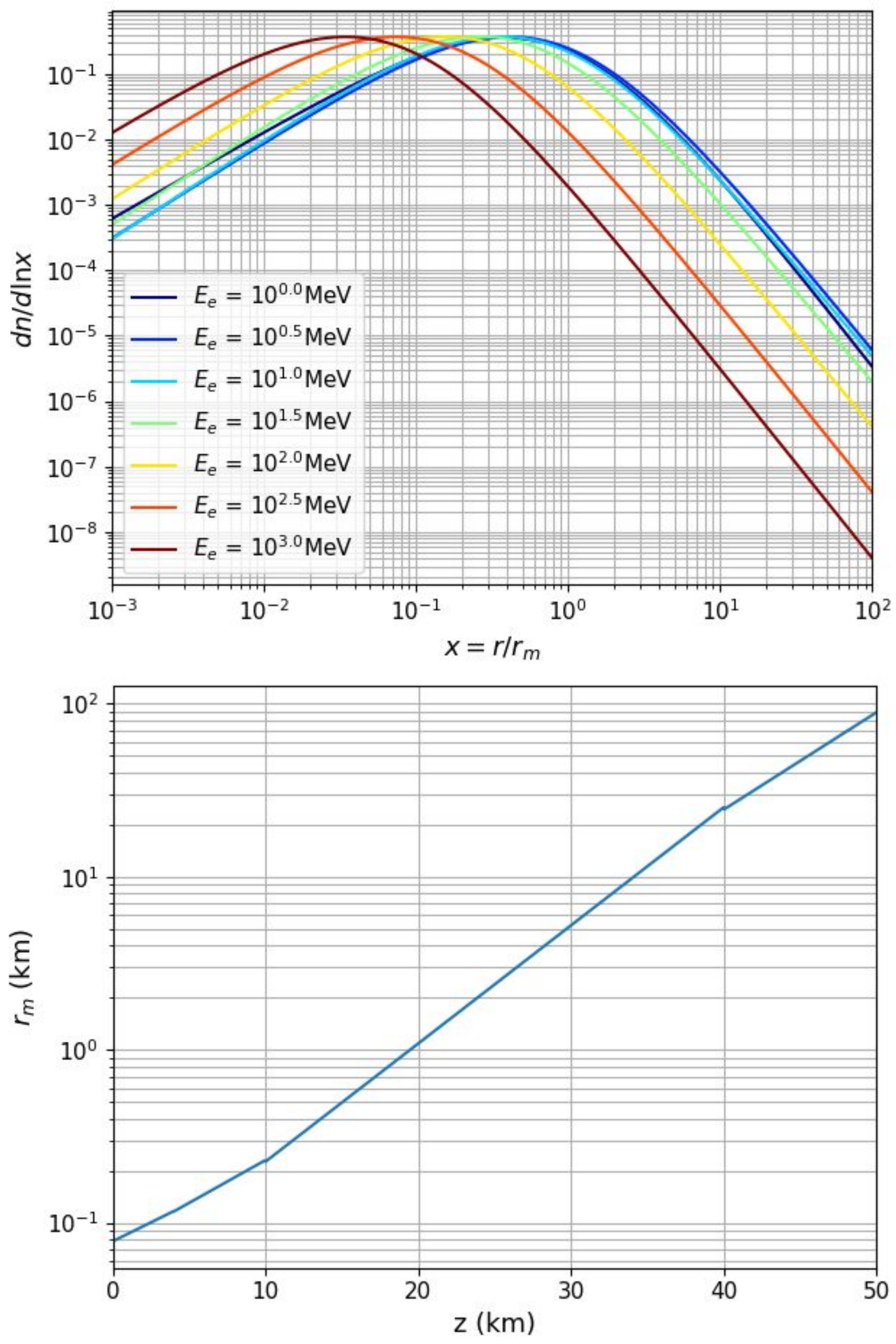
M. Hillas, J. Phys. G : Nucl. Phys. 8 (1982) 1461-1473.



- The angular distribution of electrons in the shower varies strongly with the electron energy and minimally with the shower age
  - Although, the average electron energy **does** change with shower development
- High energy electrons are typically confined near the shower axis, while low energy electrons are able to spread much further
- For the purpose of this work, we implement the model of Hillas (1982)

Electron Lateral Distribution

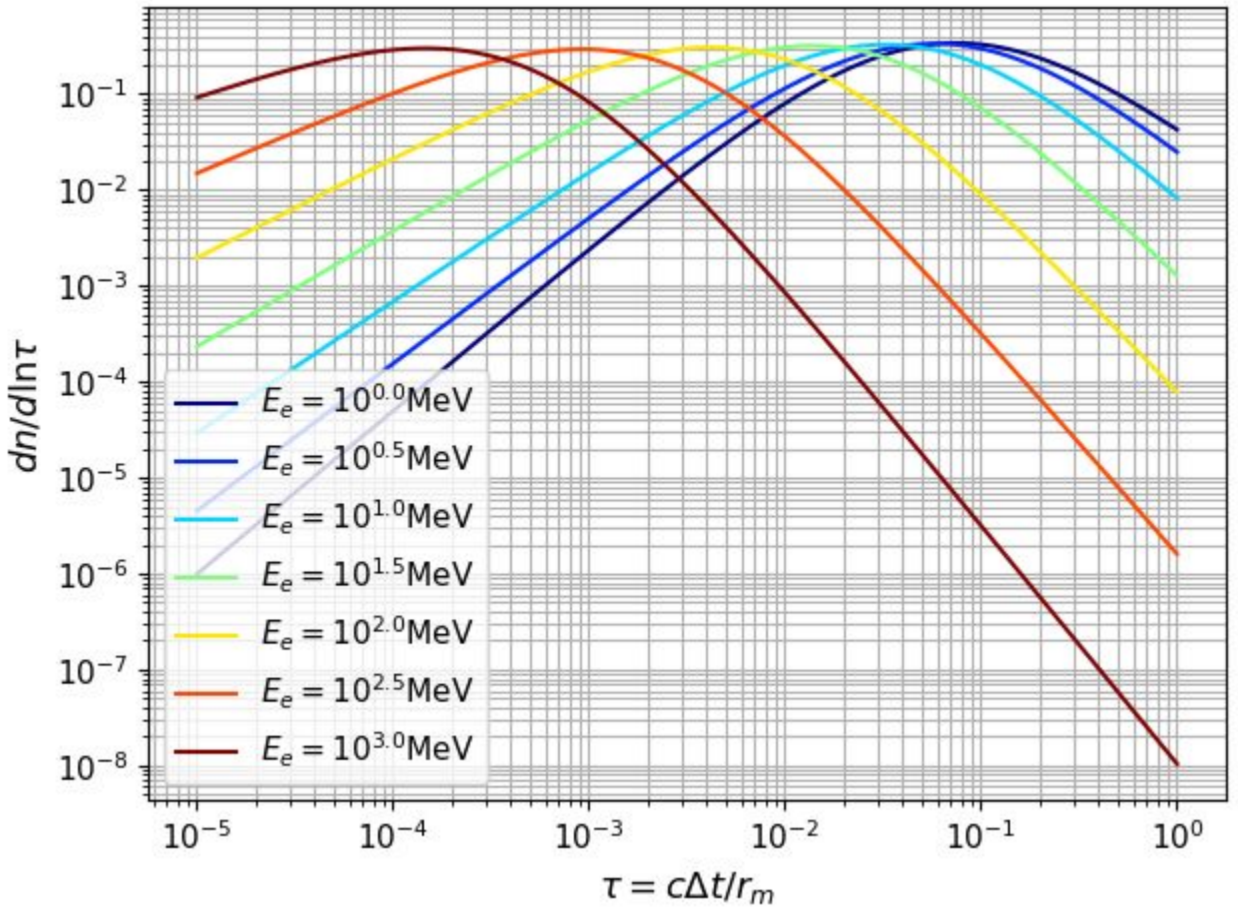
S. Lafebre, Astropart.Phys.31:243-254

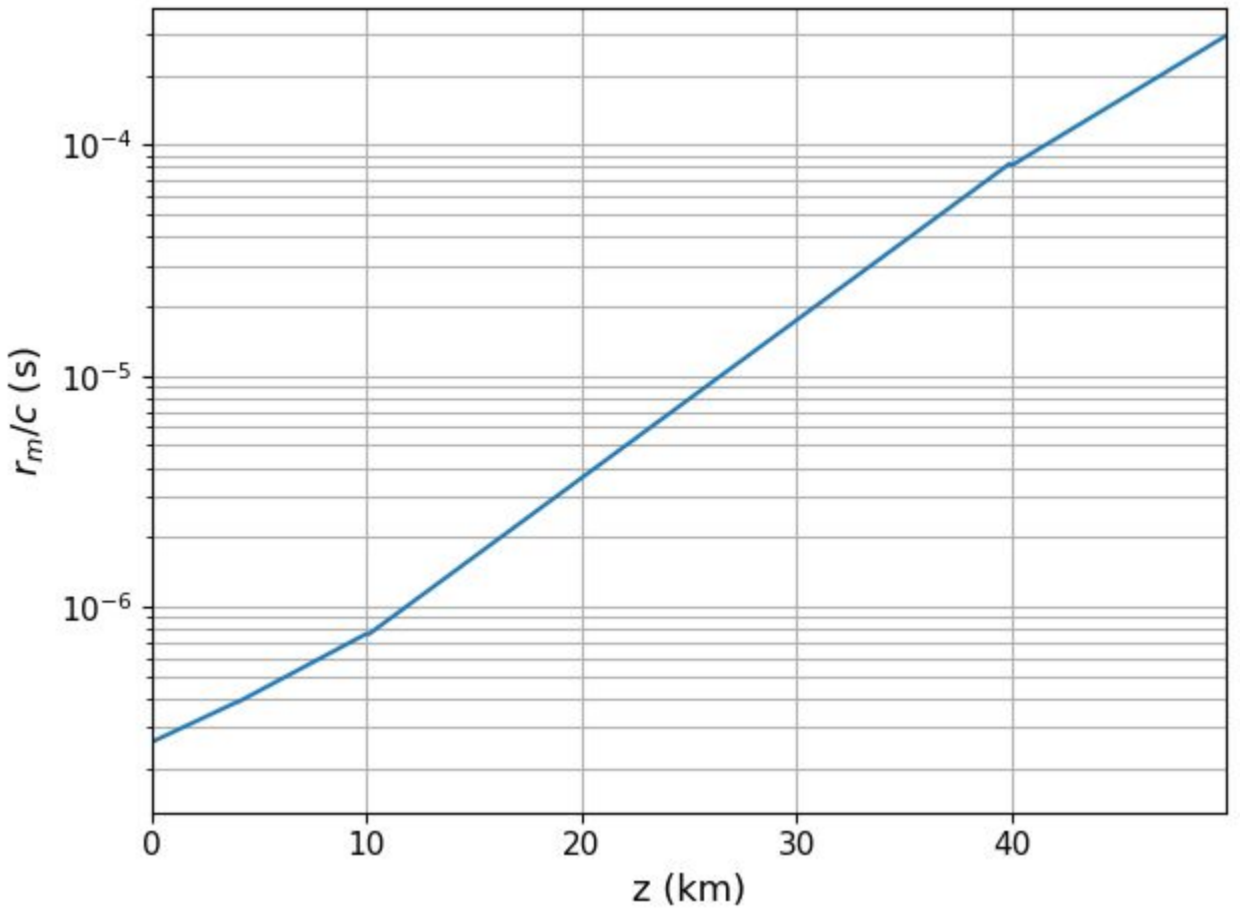


- The lateral distribution of electrons has a poor universality throughout the shower and can be rescaled by the Moliere Radius
- High energy electrons have smaller lateral spreads than low energy electrons
- Electrons generated at higher altitudes have larger lateral spreads
  - Competes with Cherenkov scale above 30 km altitude
- For the purpose of this work, we implement the model of Lafebre, et. al. (2009)

Electron Delay Time Distribution

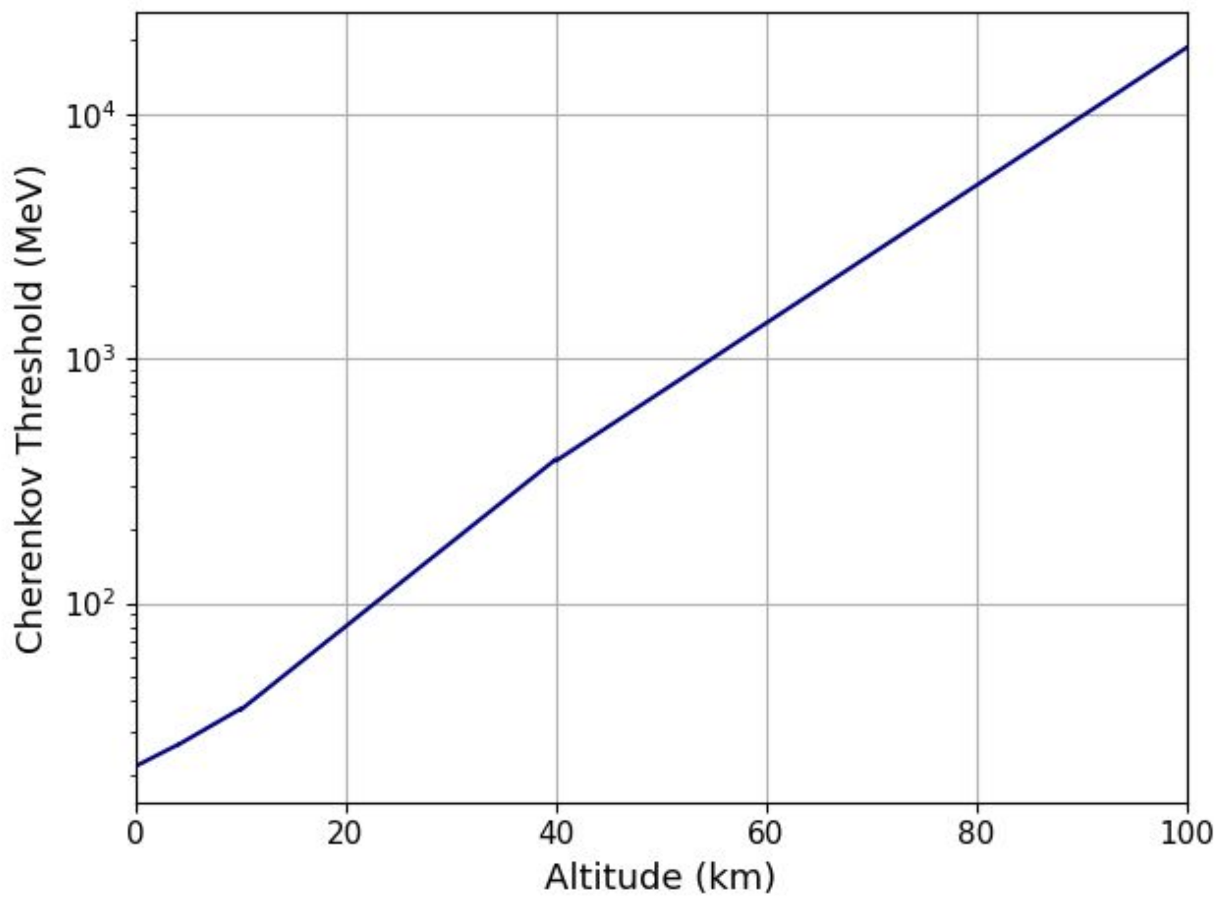
S. Lafebre, Astropart.Phys.31:243-254

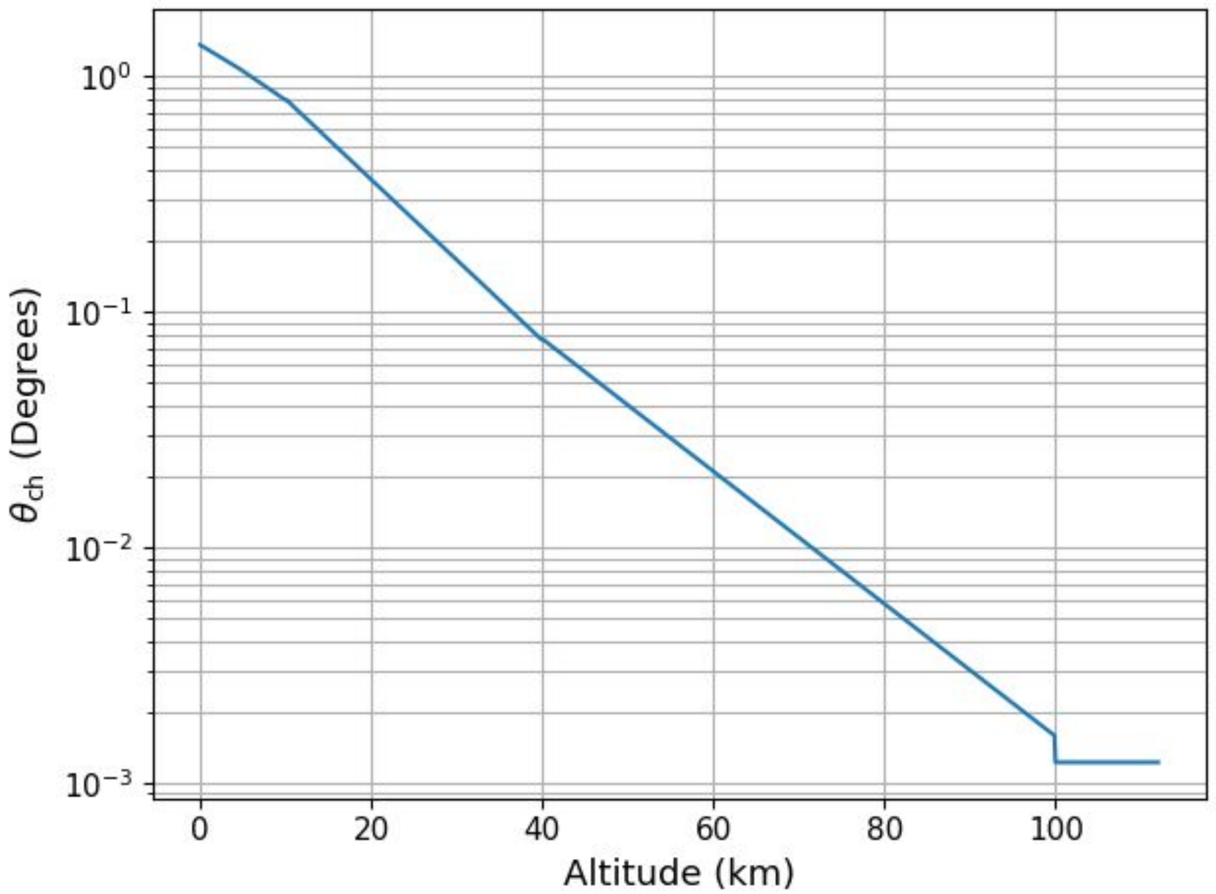




- Lag time measures how much an electron lags an imaginary particle traveling at the speed on light along the shower axis
- The timing distribution of electrons has a poor universality throughout the shower and can be rescaled by the Moliere Radius
- High energy electrons travel closer to the speed of light than low energy electrons
- Electrons generated at higher altitudes have greater time lags
- For the purpose of this work, we implement the model of Lafebre, et. al. (2009)

Atmospheric Effects: Index of Refraction





- Index of refraction model given by:

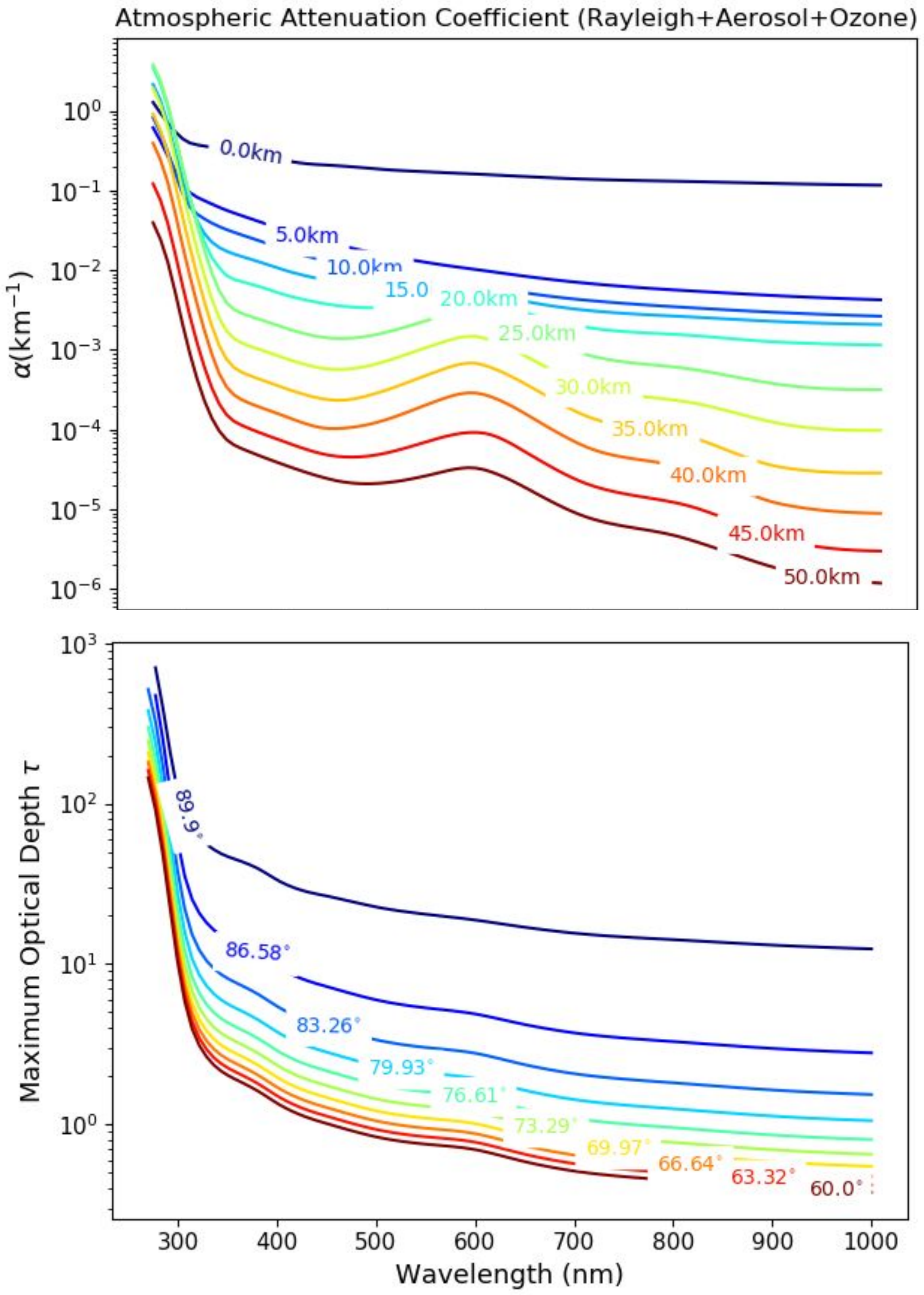
$$n(z) = 1 + 0.283 \times 10^{-3} \frac{\rho(z)}{\rho(0)}$$

We use the standard US atmosphere to describe ϱ(z)

- This choice influences:
  - The energy threshold for emission
  - The angle of the emission θ_{ch}
  - The propagation time of photons through the atmosphere:

$$t_\gamma(z(L)) = \int_L^{L_{det}} \frac{n(z(L'))}{c} dL'$$

Atmospheric Effects: Light Extinction



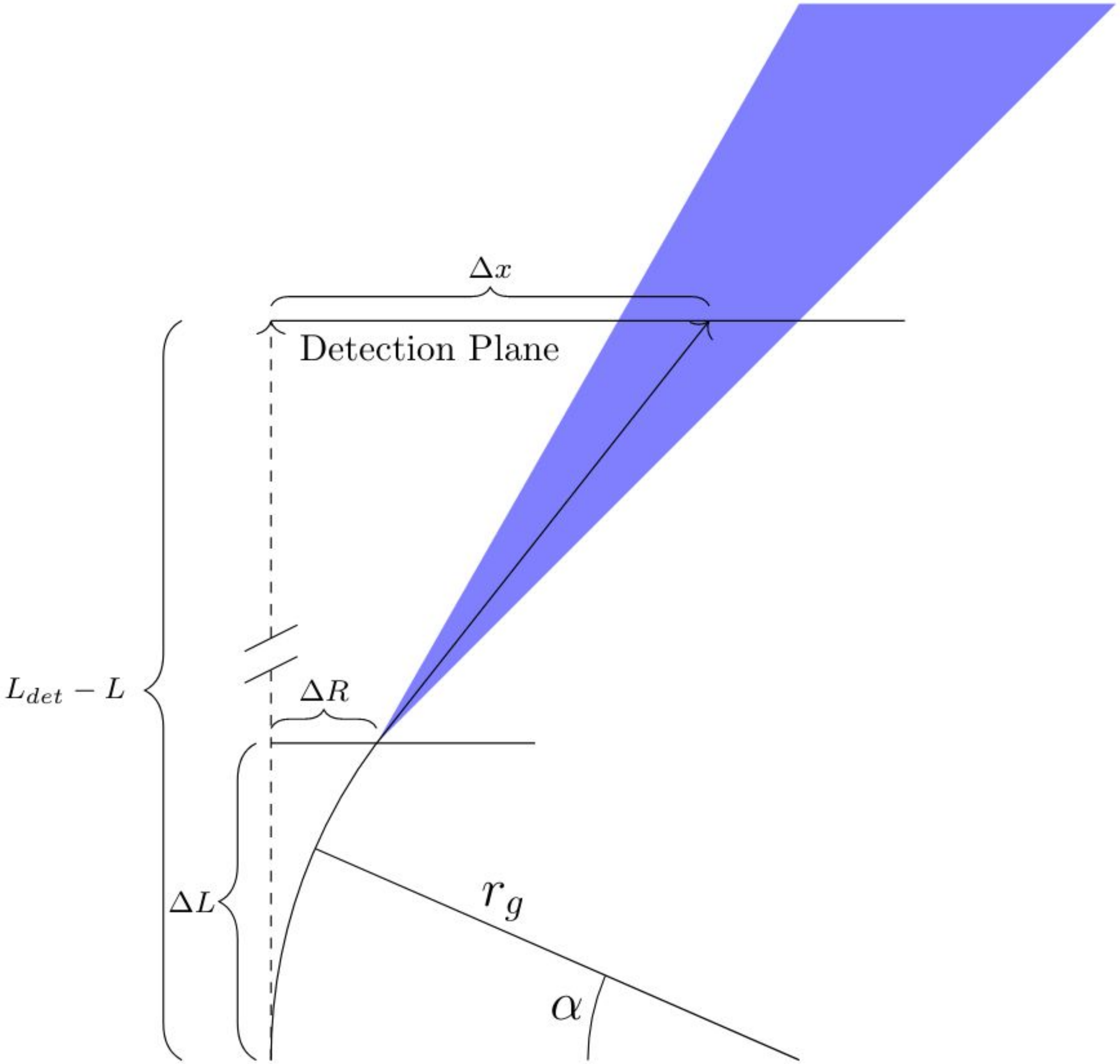
L. Elterman, AFCRL-68-0153, 1968

- The extinction coefficient corresponds to the inverse of the distance light travels to attenuate by a factor of e, and is calculated as:

$$\alpha(z, \lambda) = \sigma(\lambda)\rho_N(z)$$

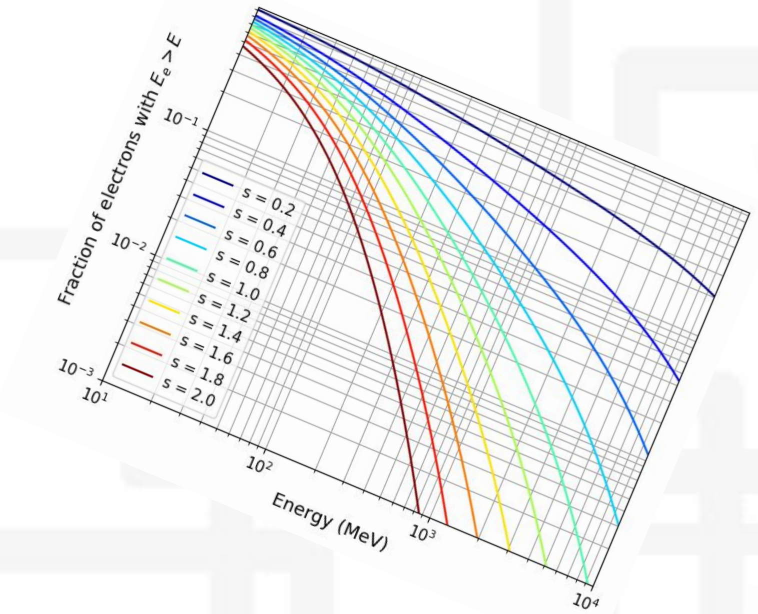
- 3 main components:
  - Rayleigh Scattering (Molecular)
  - Aerosol Scattering (Mie)
  - Ozone Absorption
- Scattering strong for low altitudes and for $\lambda<350$ nm
- Small Earth emergence angles result in extreme atmospheric attenuation

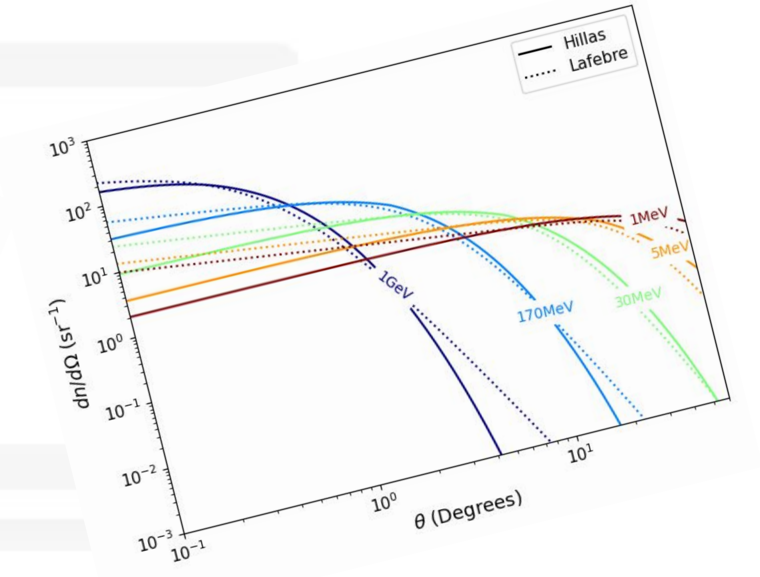
Geomagnetic Separation

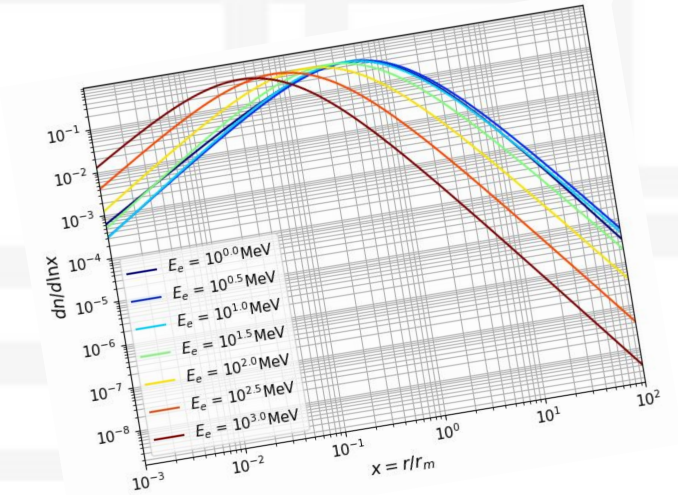


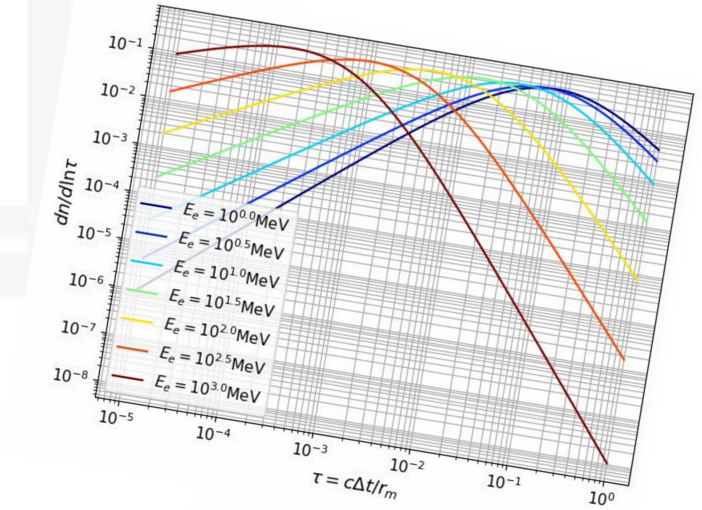
- Electrons and positrons can be separated from one another via Earth's magnetic field
- Length scales of the electron radiation length and gyration radius compete for z>25 km at the Cherenkov threshold
  - Effect is mainly important at very high altitudes
- We assume:
  - Fairly strong geomagnetic field (50 µT)
  - Field oriented perpendicular to the shower axis
  - No negative charge excess

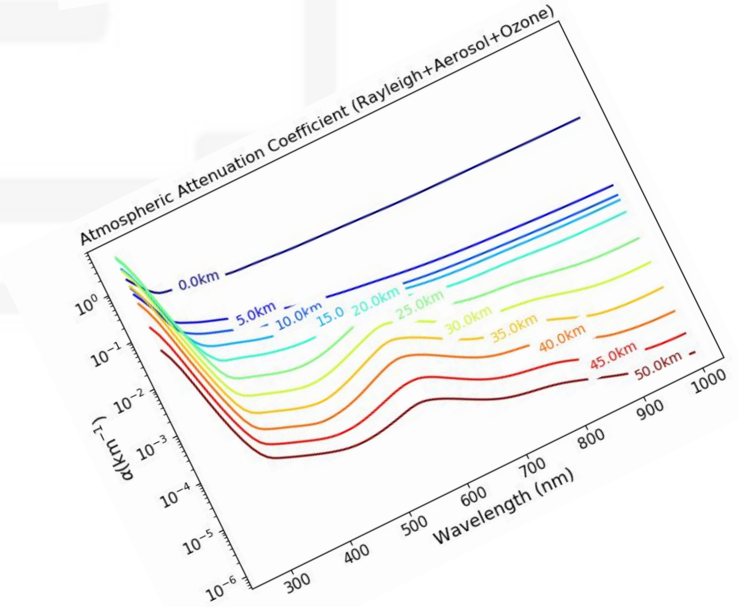
First Results:

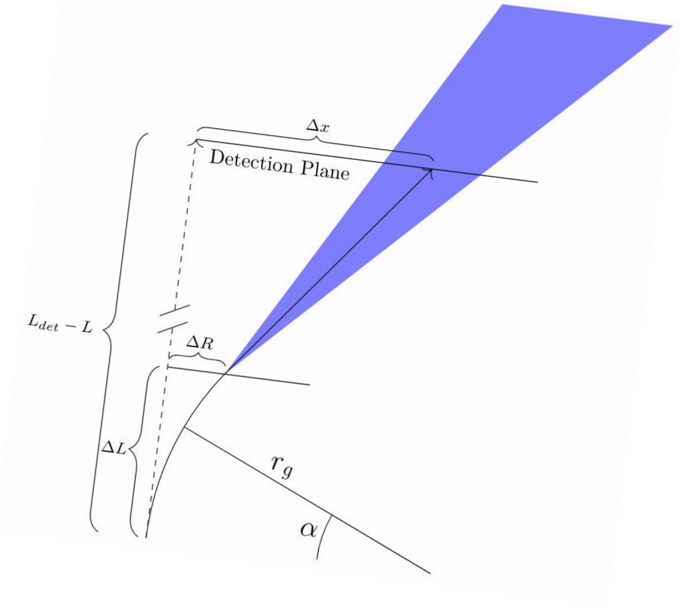


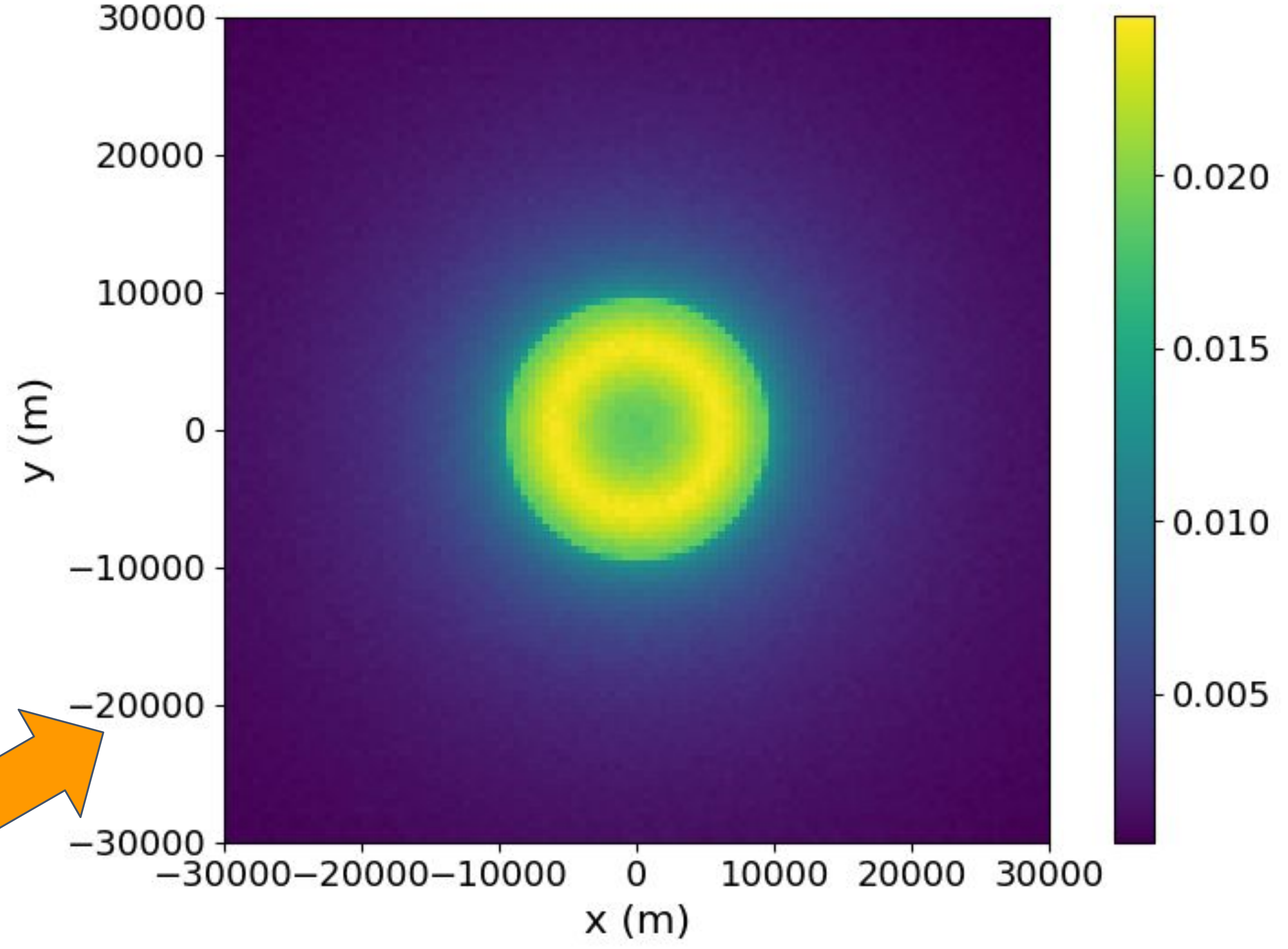


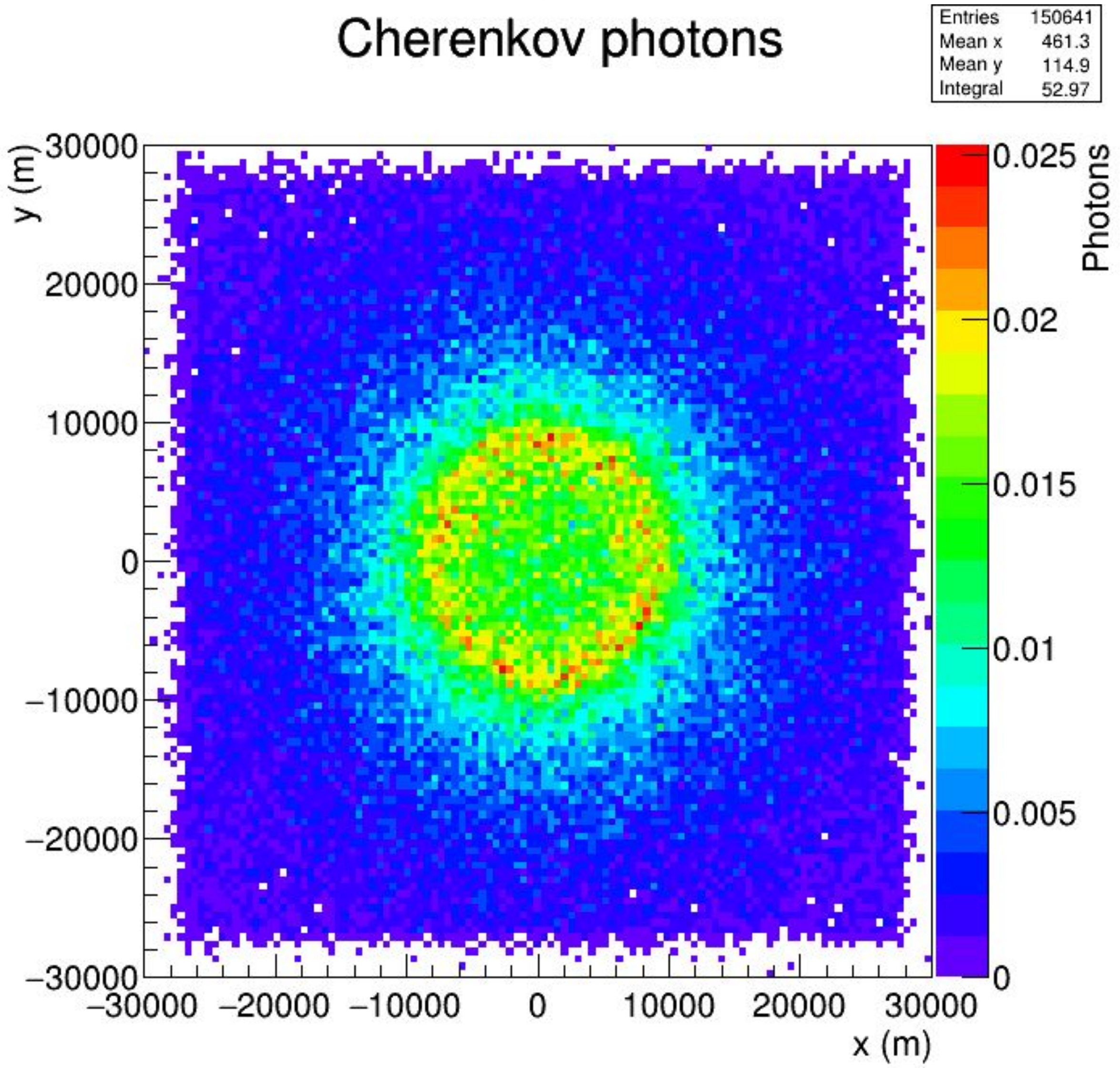






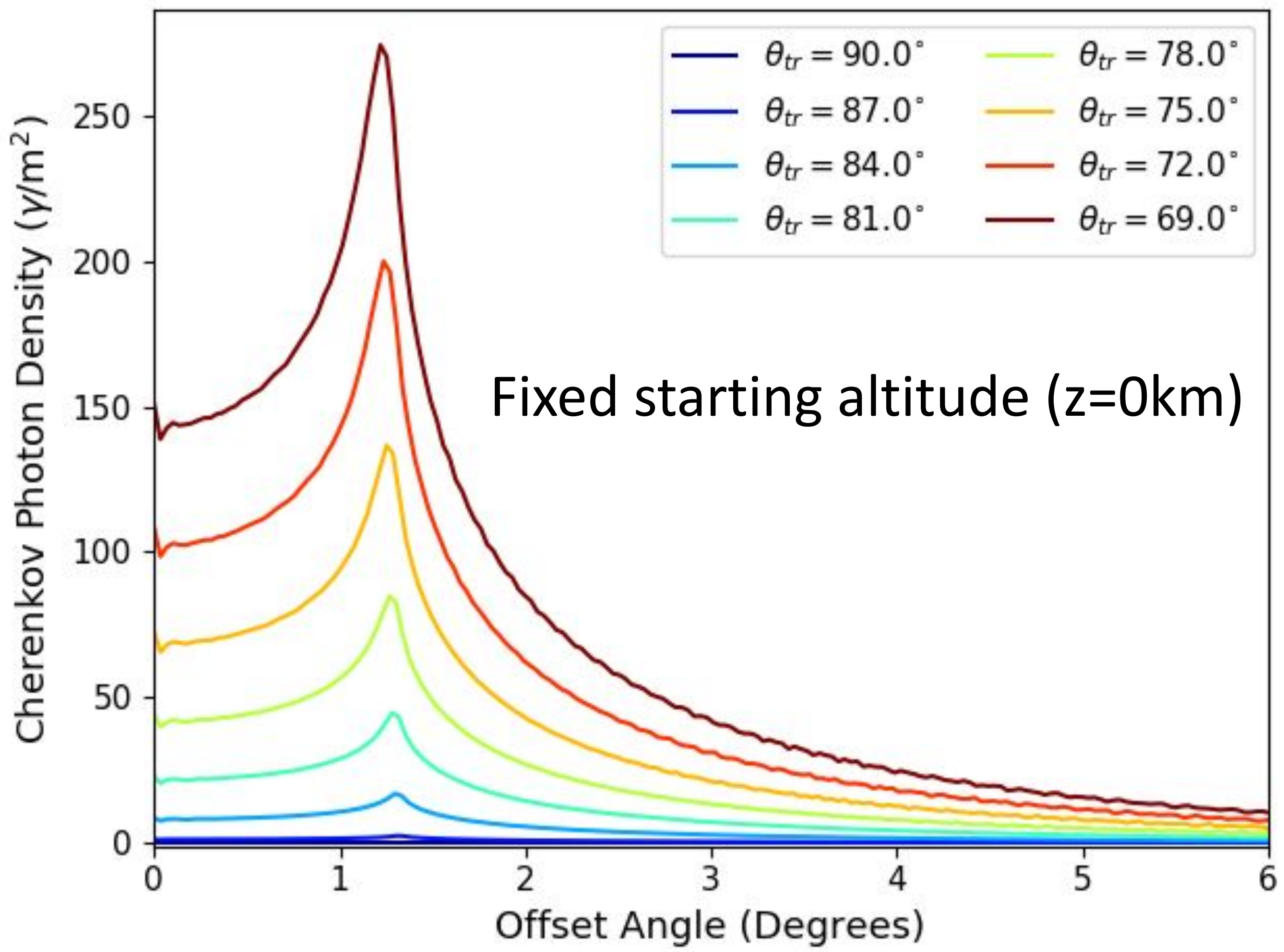


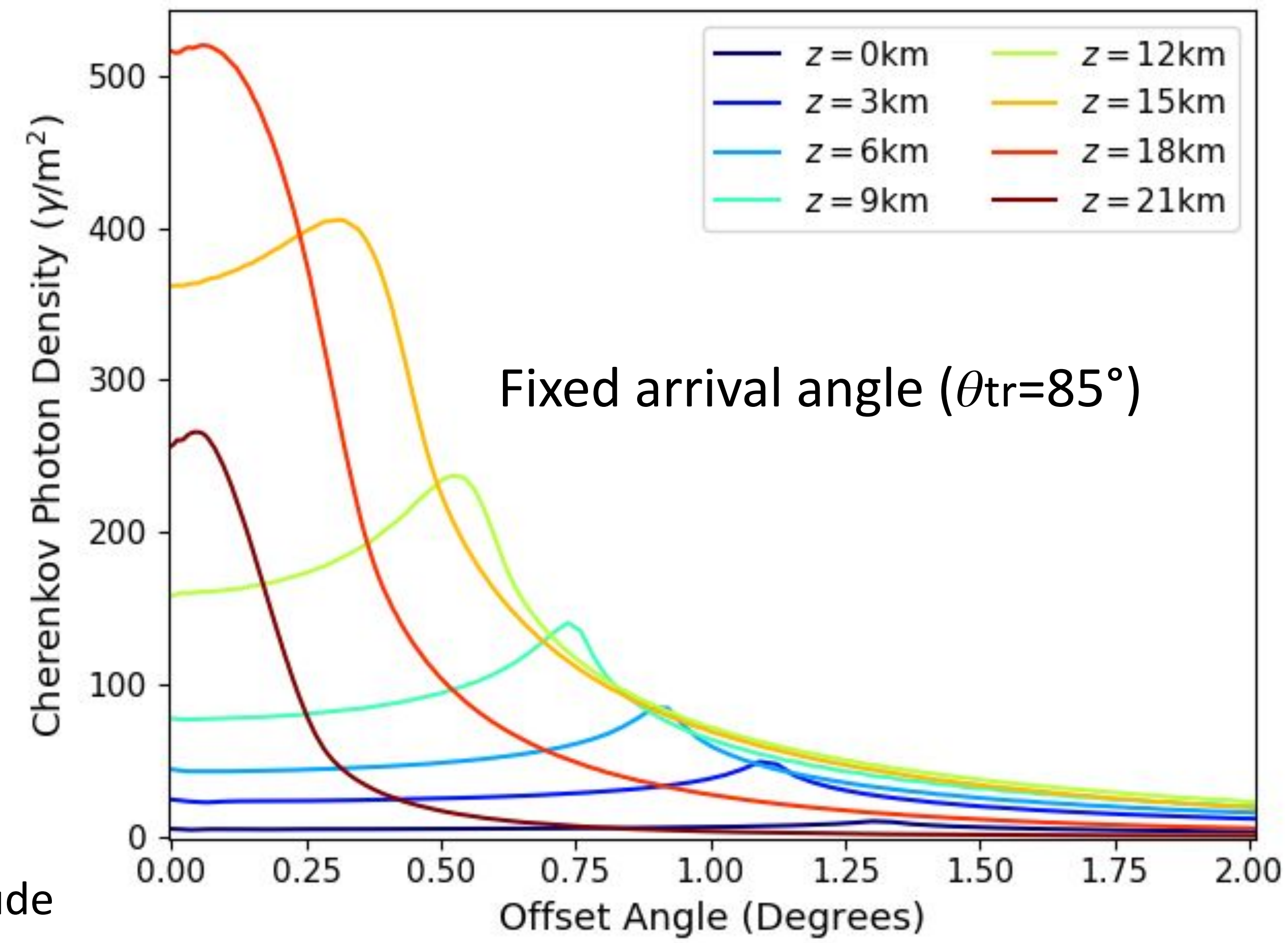




Cherenkov Spatial Distribution

- Increasing the emergence angle and starting altitude avoids atmospheric attenuation of the Cherenkov light
- For showers which begin close to the limb ($\theta_{sh} < 5°$), the gains in intensity with increasing starting altitude grow dramatically
  - High energy τ-leptons
  - Muons of any energy
- In principle, muons can mimic τ-leptons of higher energy

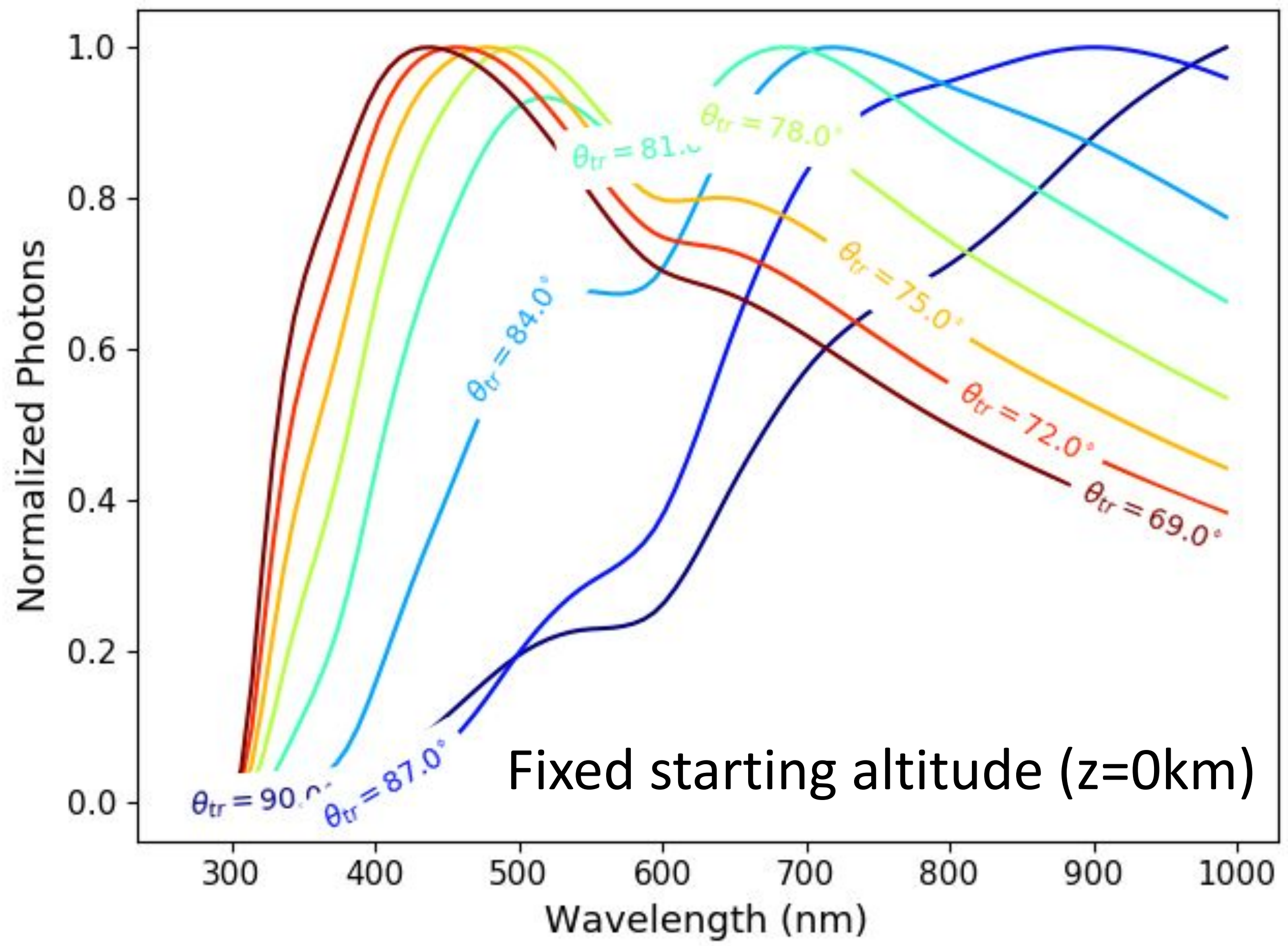


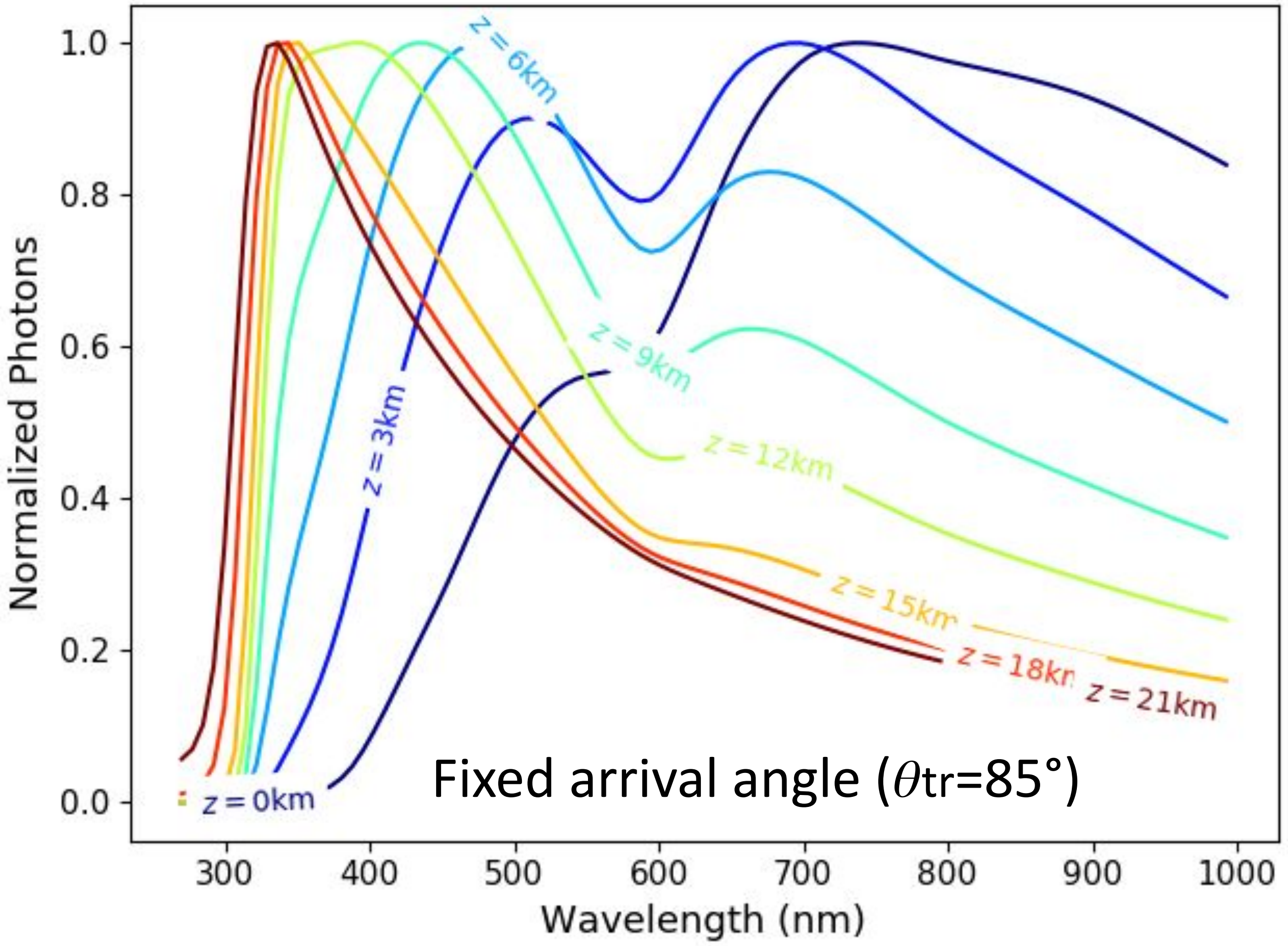


*Cherenkov profile generated using 100 PeV proton shower, observed from 525km altitude

Cherenkov Wavelength Distribution

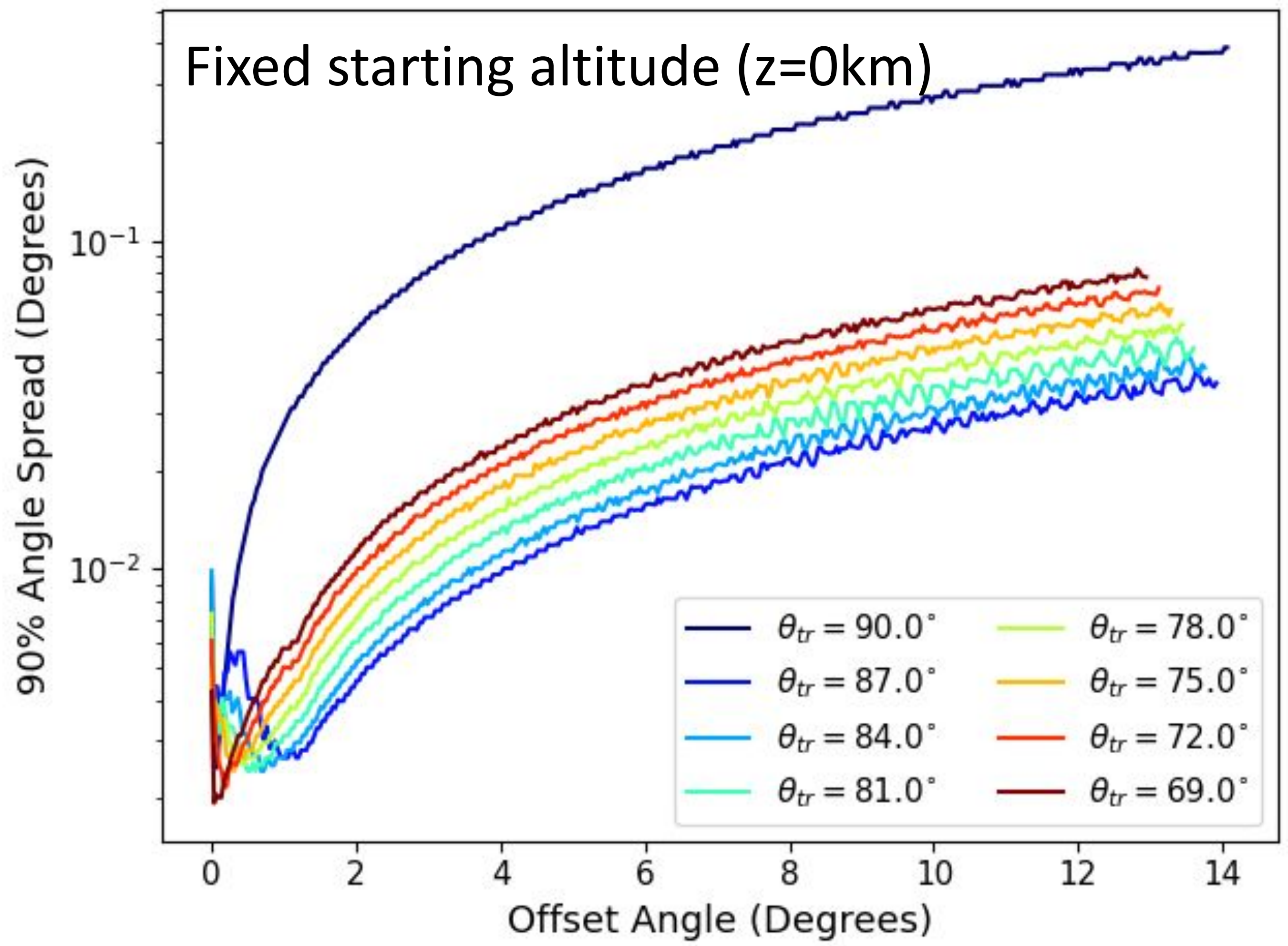
- Increasing the emergence angle and starting altitude avoids atmospheric attenuation of the Cherenkov light
- Wavelength spectrum of Cherenkov photons is “blue-shifted” towards smaller wavelengths
  - Original Cherenkov spectrum $\propto 1/\lambda^2$
- Strong attenuation below 300 nm from Ozone attenuation
  - Dip near 600 nm due to Ozone scattering cross section
- Typical spectrum within 300 nm-1000 nm

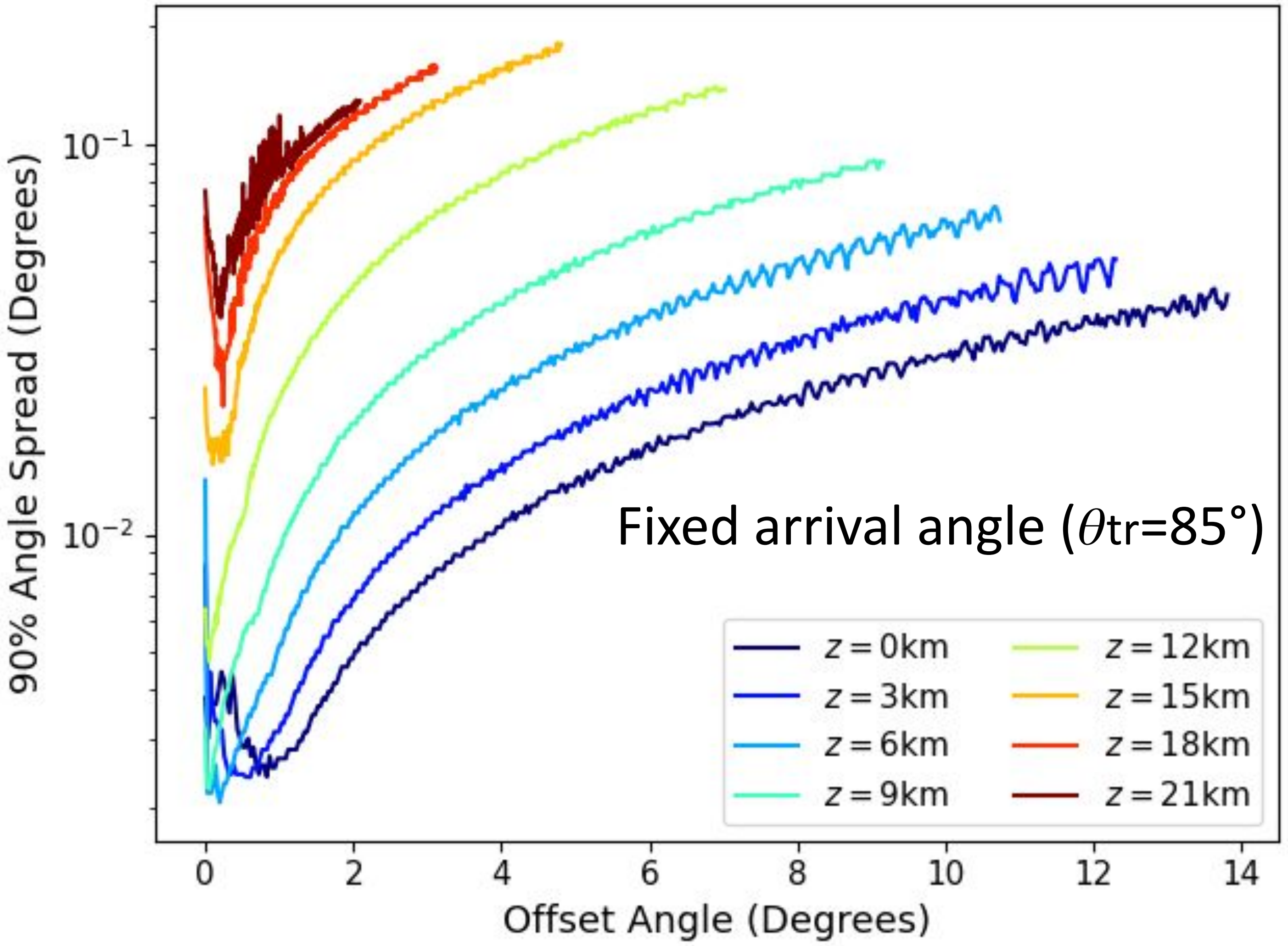




Cherenkov Angular Distribution

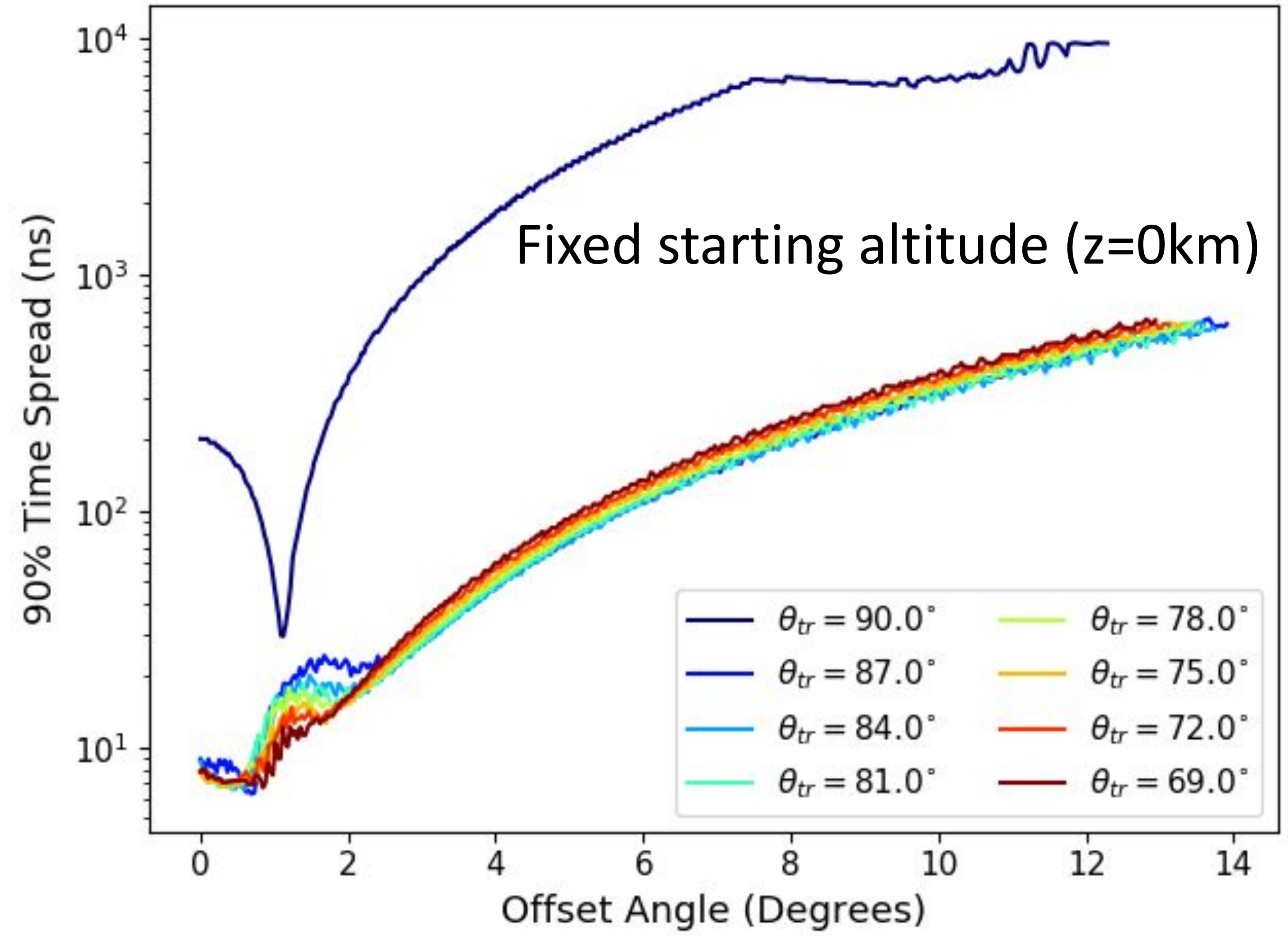
- The further away from the Cherenkov angle the photons are observed, the larger angular spread they have
  - Later shower ages are sampled measuring further from the shower axis
- Most Cherenkov emission is observed within scales of 0.1°
- The pixel FOV of POEMMA is 0.084° x 0.084° while EUSO-SPB2 has 0.4° x 0.4°
  - Light is well constrained within a single pixel (well focused)

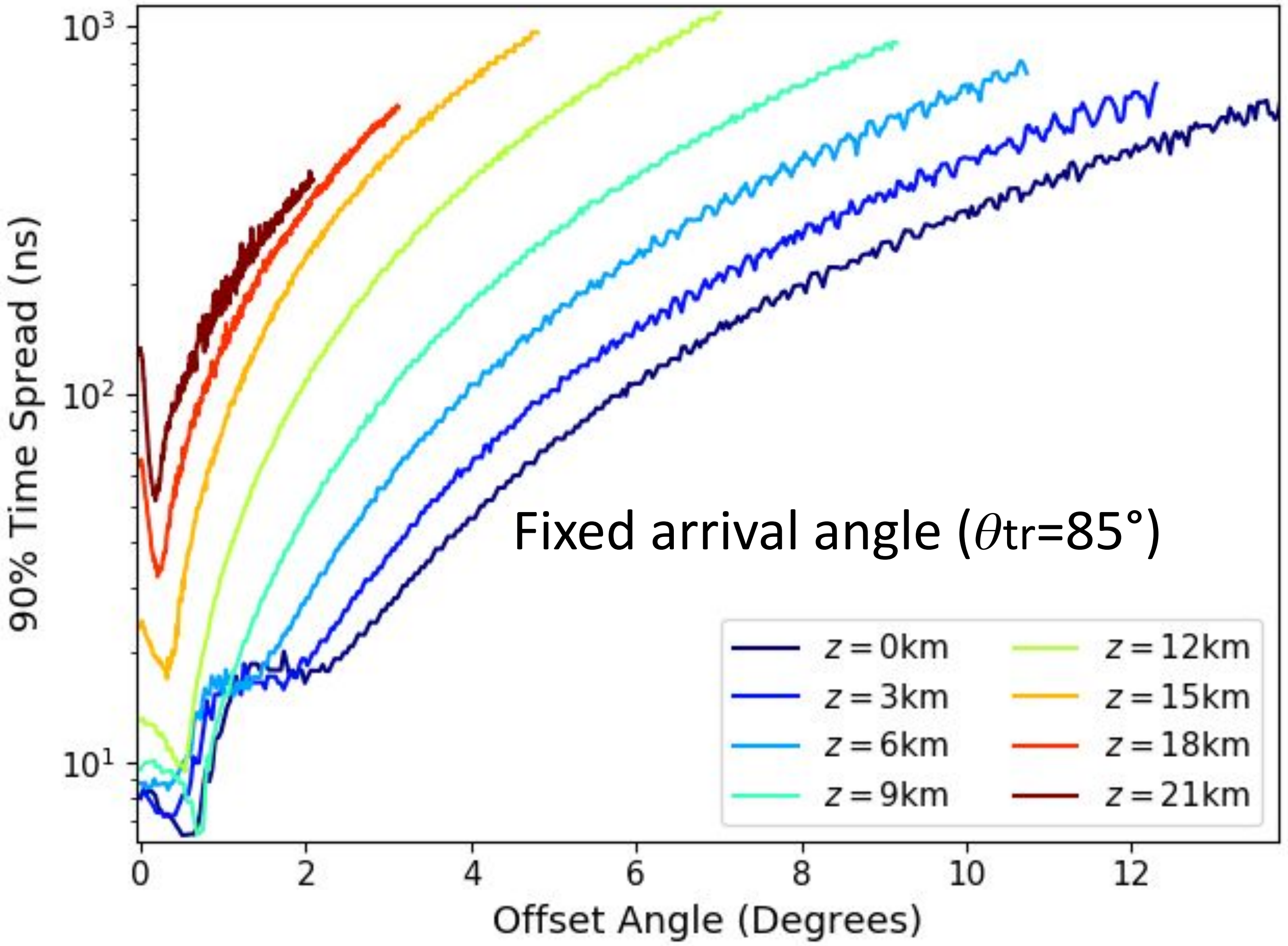




Cherenkov Time Distribution

- The further away from the Cherenkov angle the photons are observed, the larger time spread they have
- Time width of the arriving Cherenkov pulse grows from ~20 ns near shower axis up to ~1 µs
- The electronic integration time of POEMMA/EUSO-SPB2 is 20/10 ns to optimize on-axis observations
  - Larger time spreads result in decreased SNR for observations in the tails of the distribution





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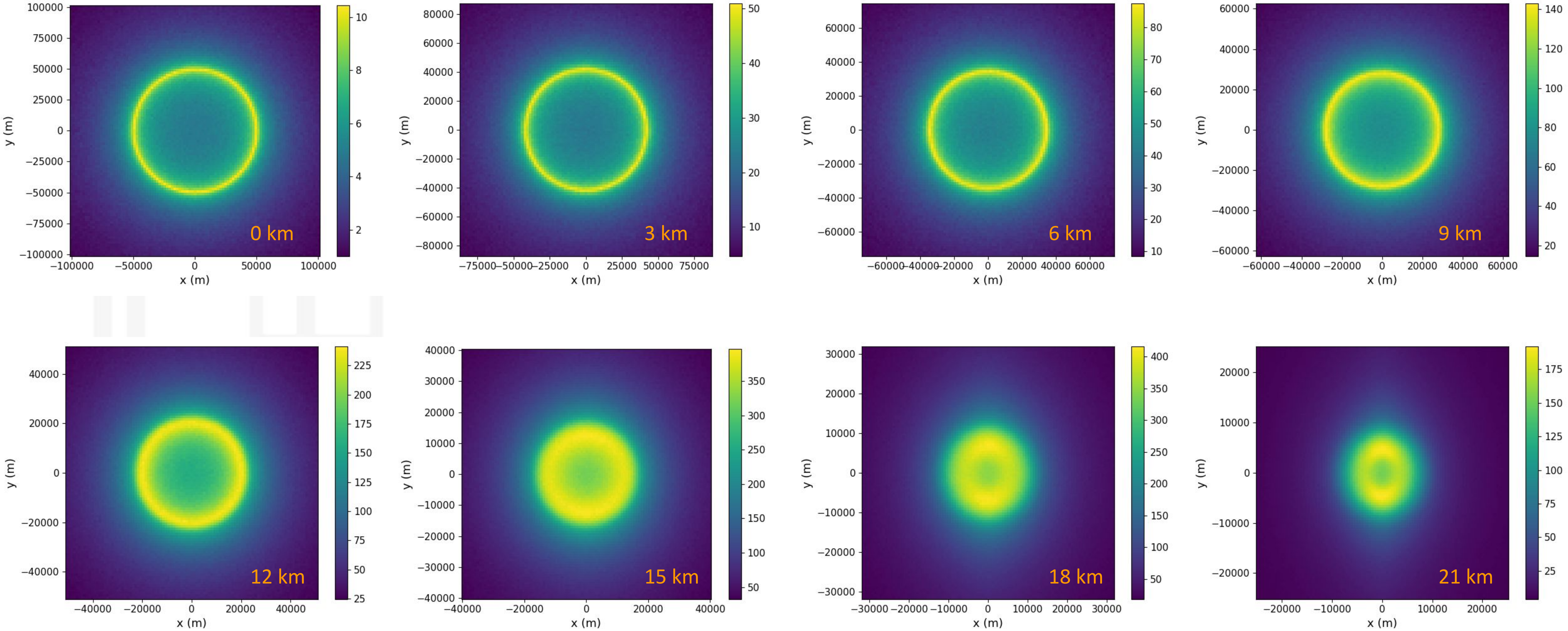
Geomagnetic Effects

Fixed arrival angle (θtr=85°)



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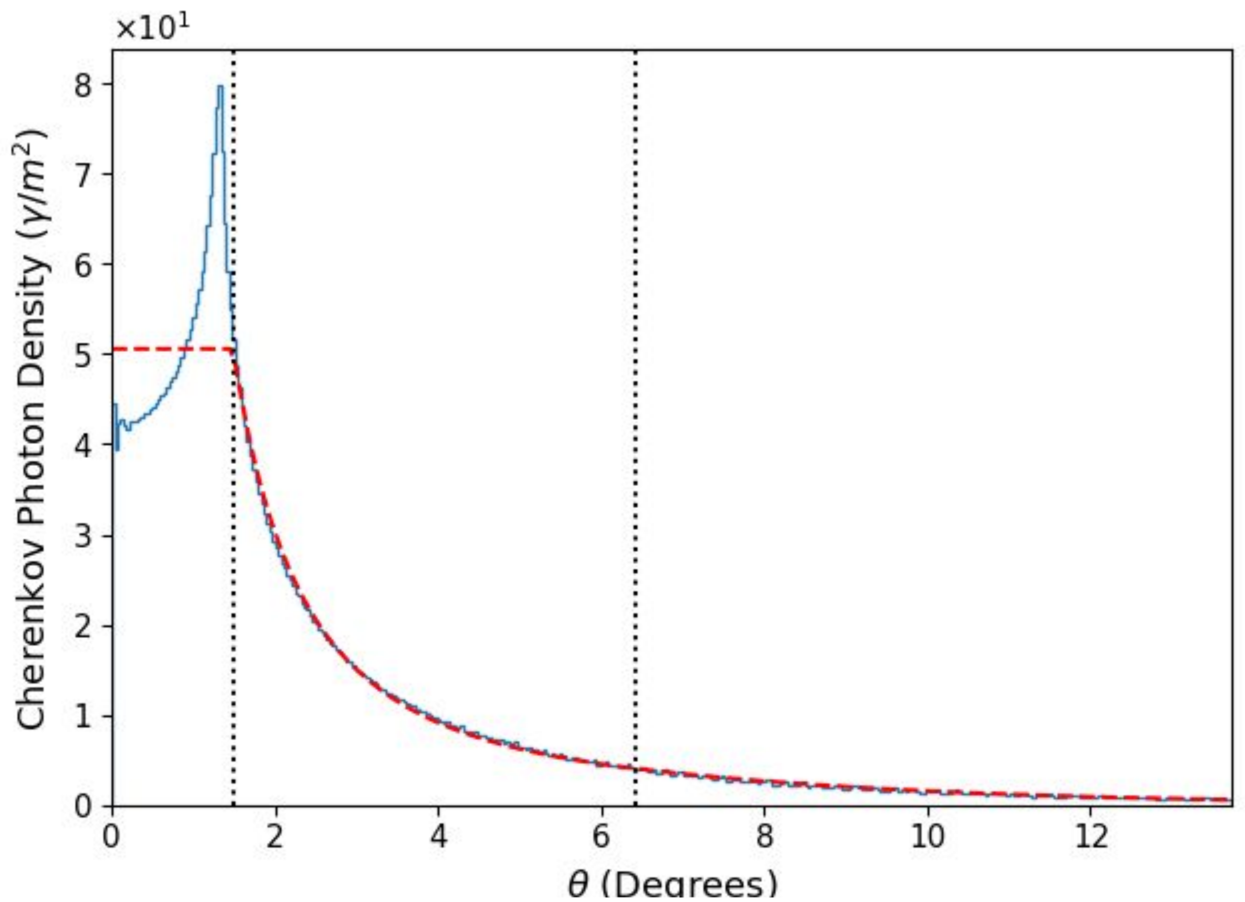
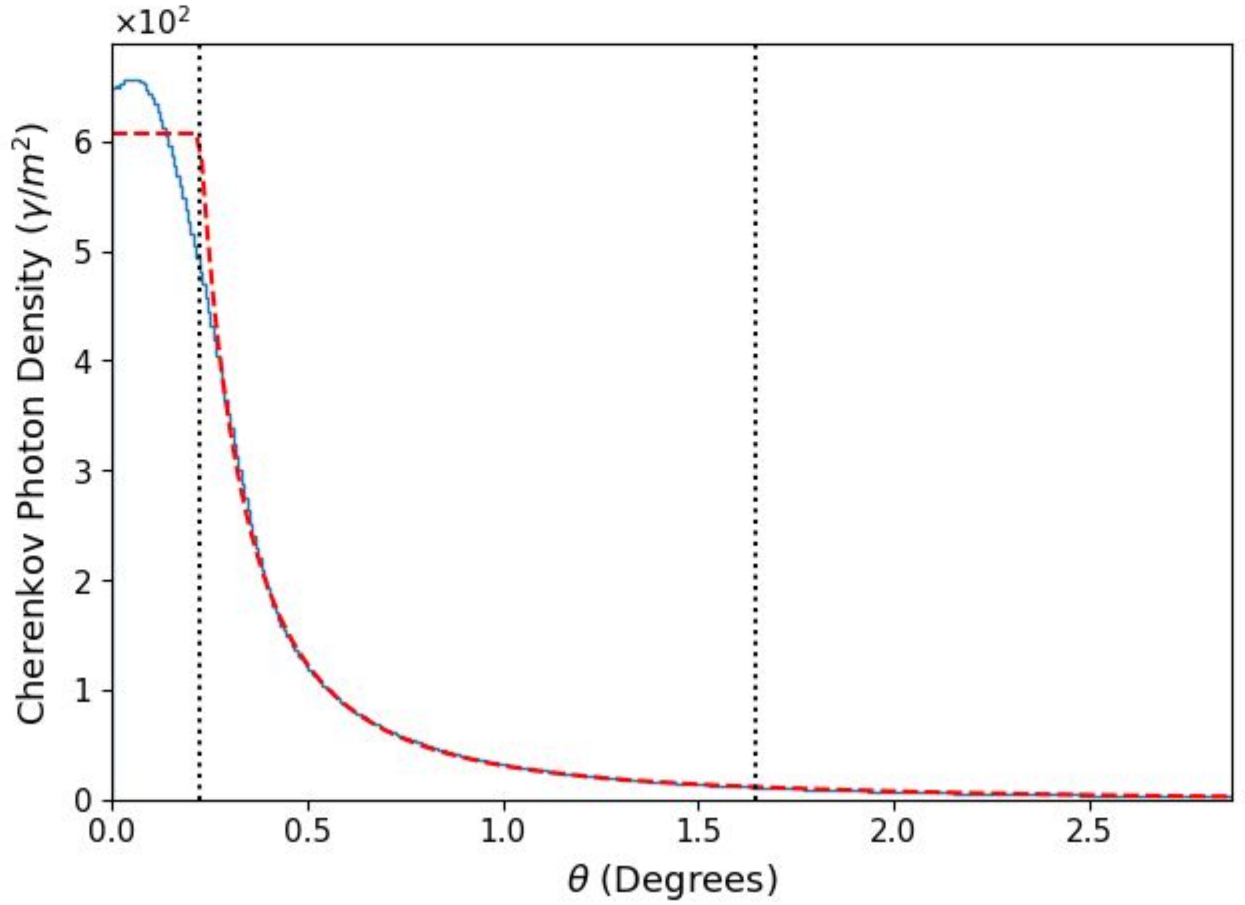
1-Dimensional Fitting



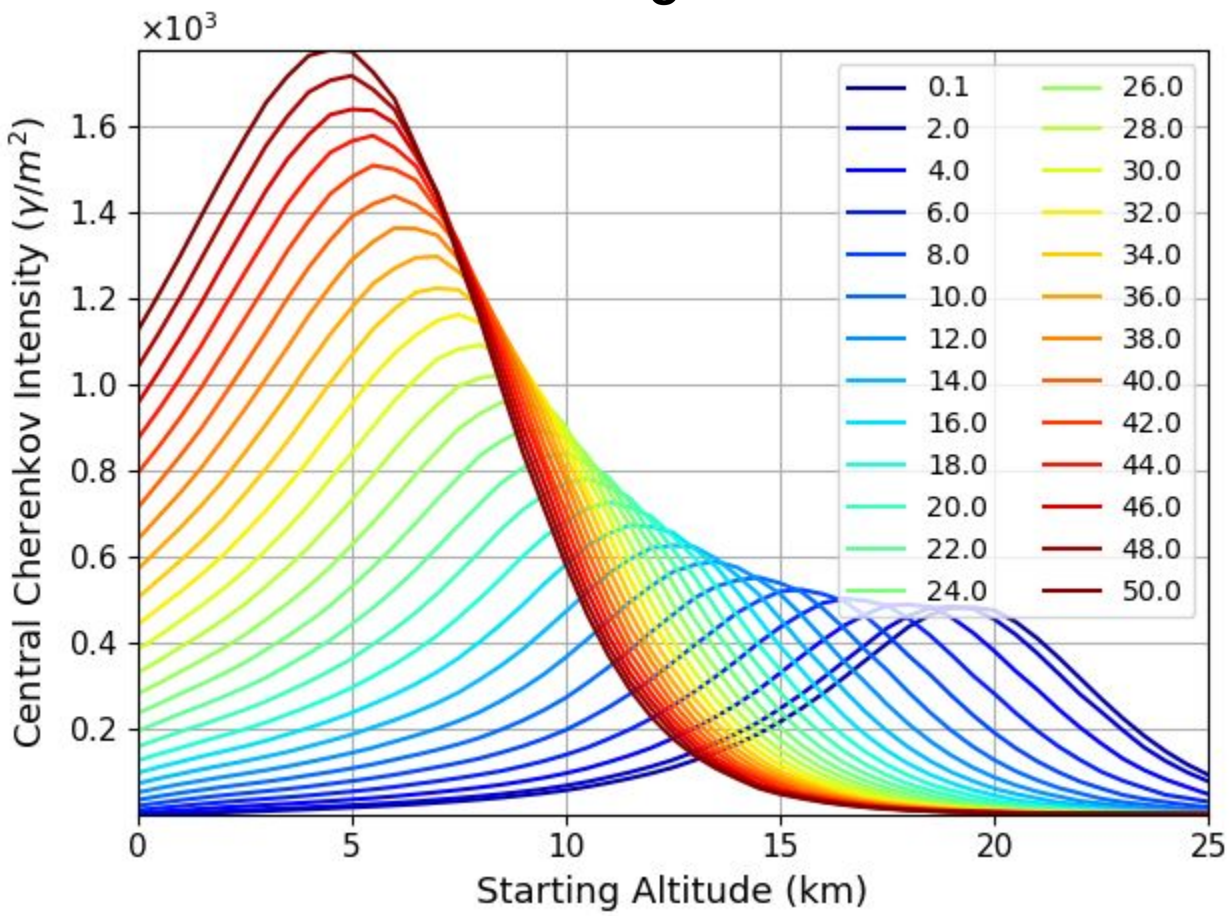


- Simulation of a single shower takes a significant amount of computational time
- Useful to fit the shower parameters over a wide geometric parameter space
  - Earth emergence angle, decay altitude
- As a first estimate, we assume:
  - No wavelength dependence
  - Optimal focusing
  - Geomagnetic separation of e^+/e^- negligible
  - *Time spread of photons ≈ 20 ns*
- Fit the spatial distribution of the arriving Cherenkov photons on the detection plane with:

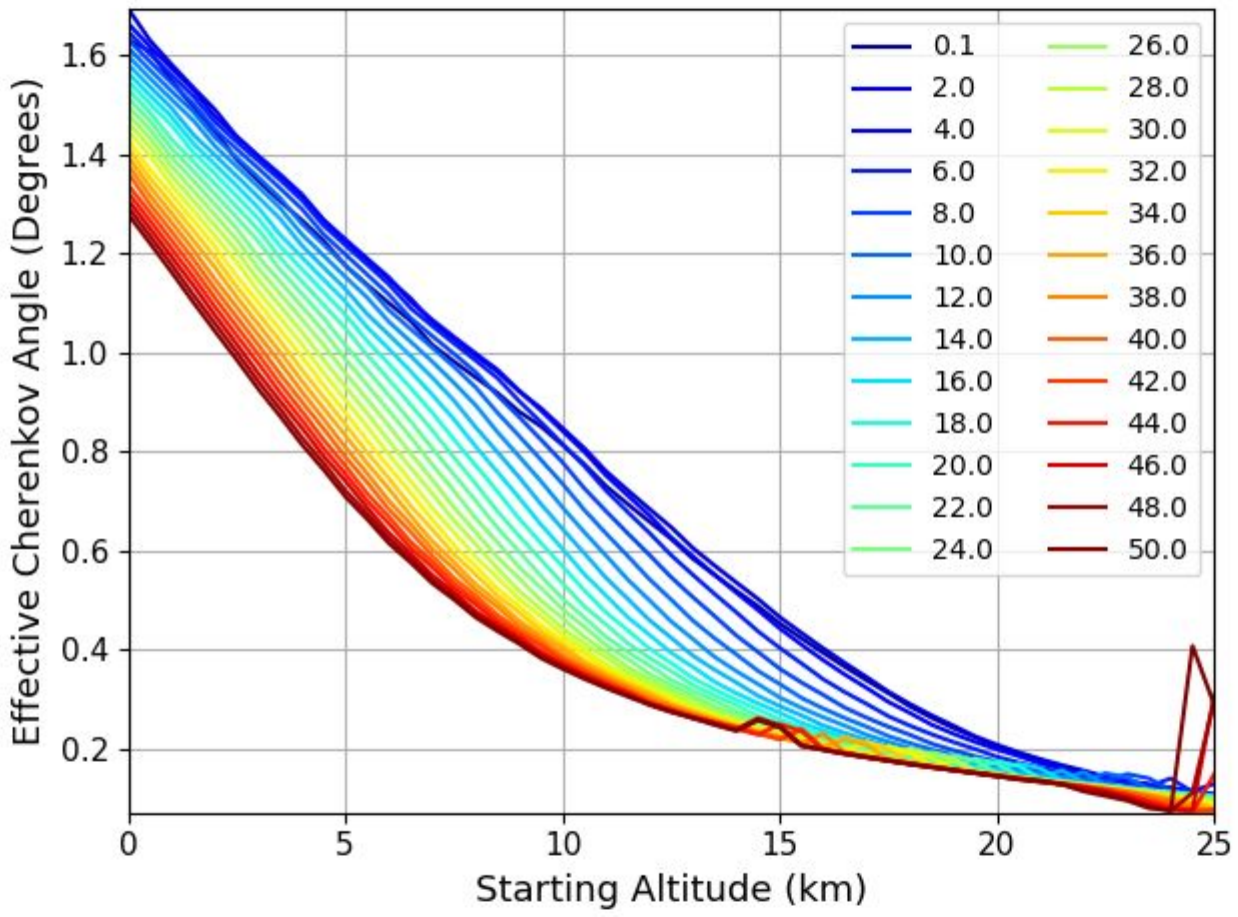
$$\rho_{ch} = \begin{cases} \rho_0 & \theta \leq \theta_{ch} \\ \rho_0 \left(\frac{\theta}{\theta_{ch}}\right)^{-\beta} & \theta_{ch} \leq \theta \leq \theta_1 \\ \rho_1 e^{-(\theta-\theta_1)/\theta_2} & \theta \geq \theta_1 \end{cases}$$

POEMMA Parameters

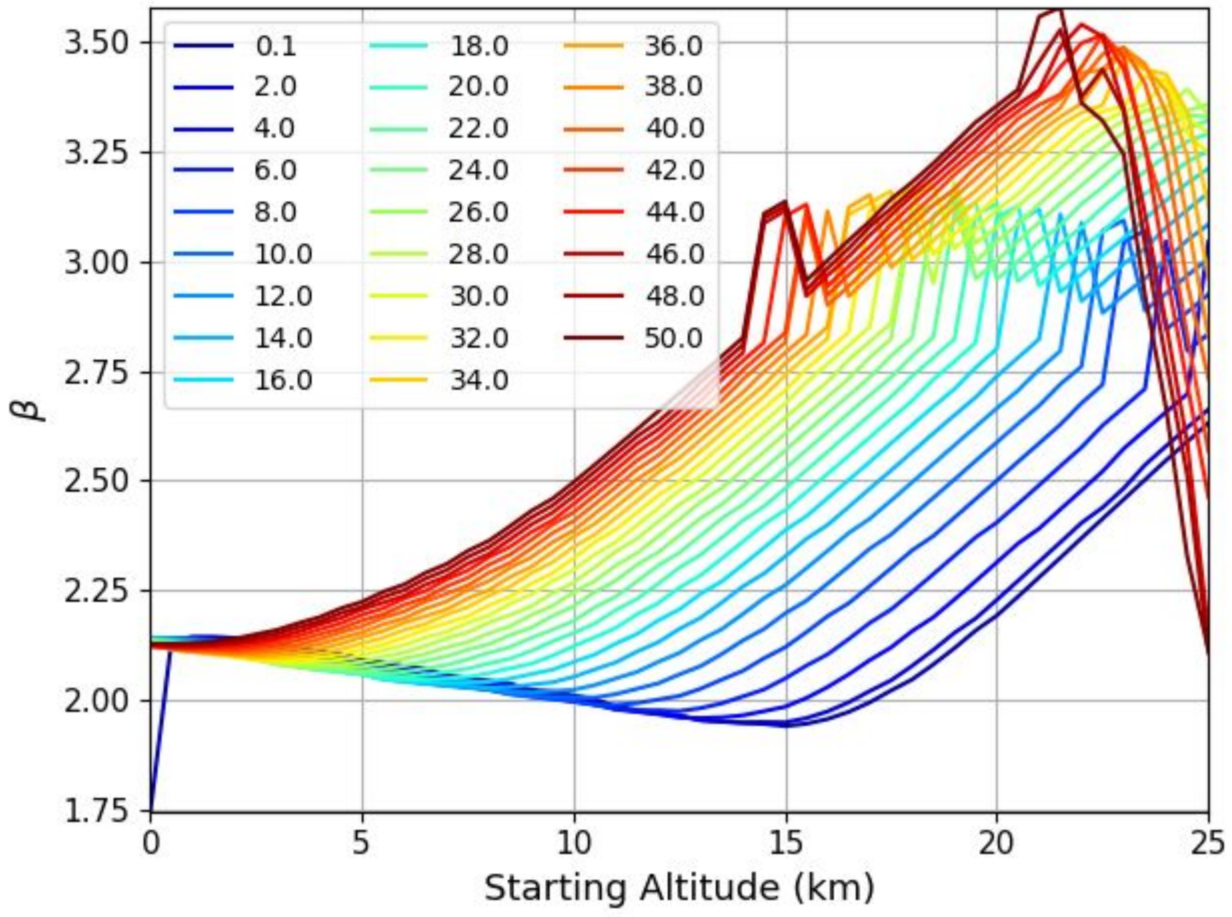
ϱ_0



θ_{ch}

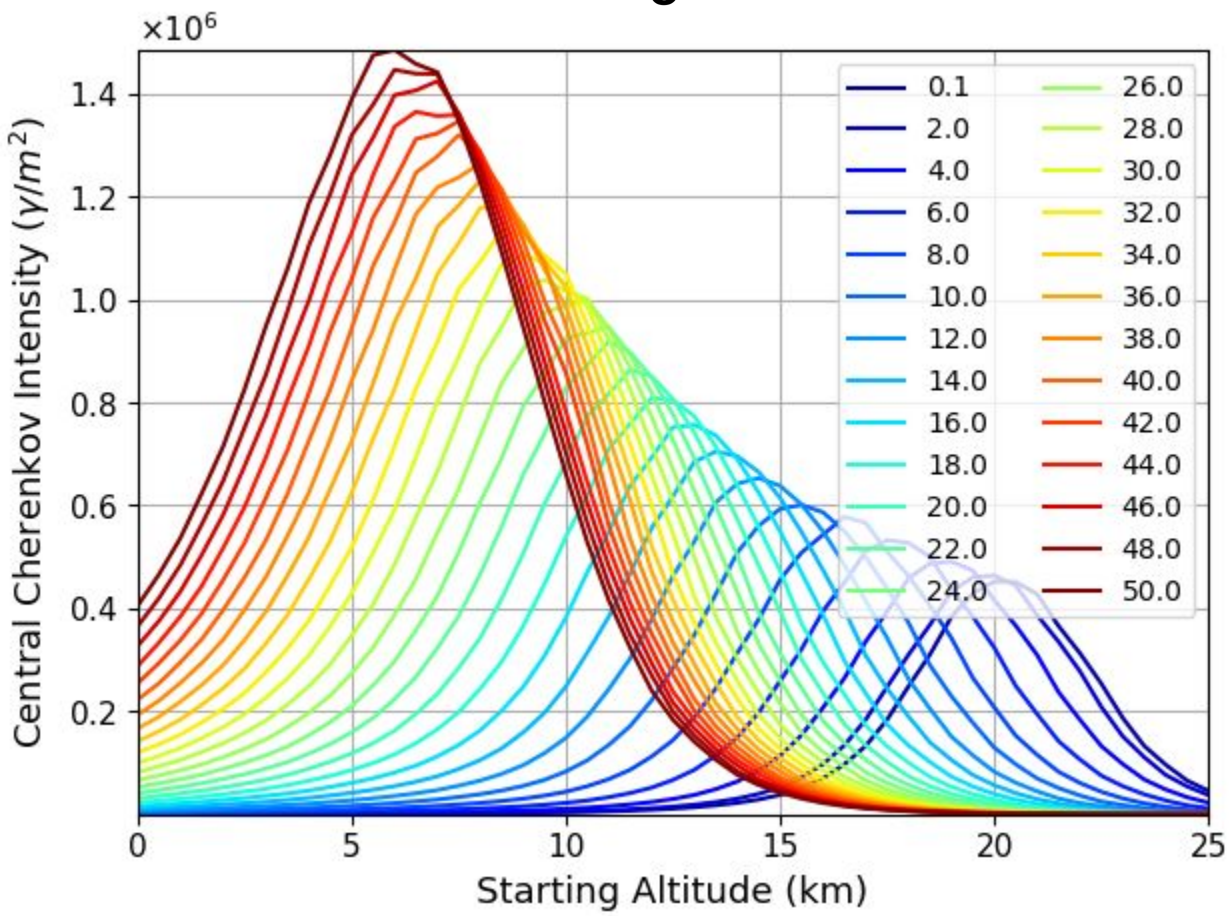


β

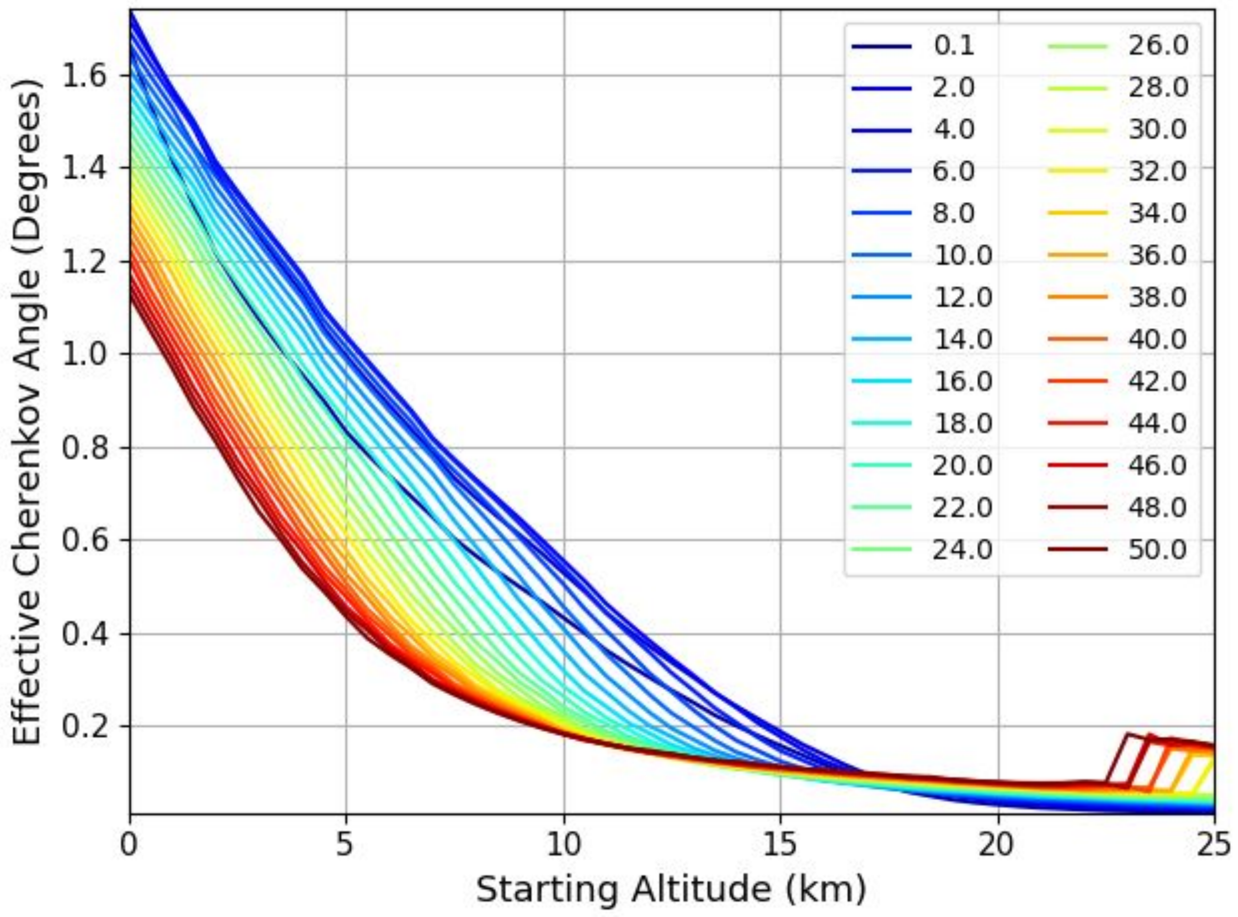


EUSO-SPB2 Parameters

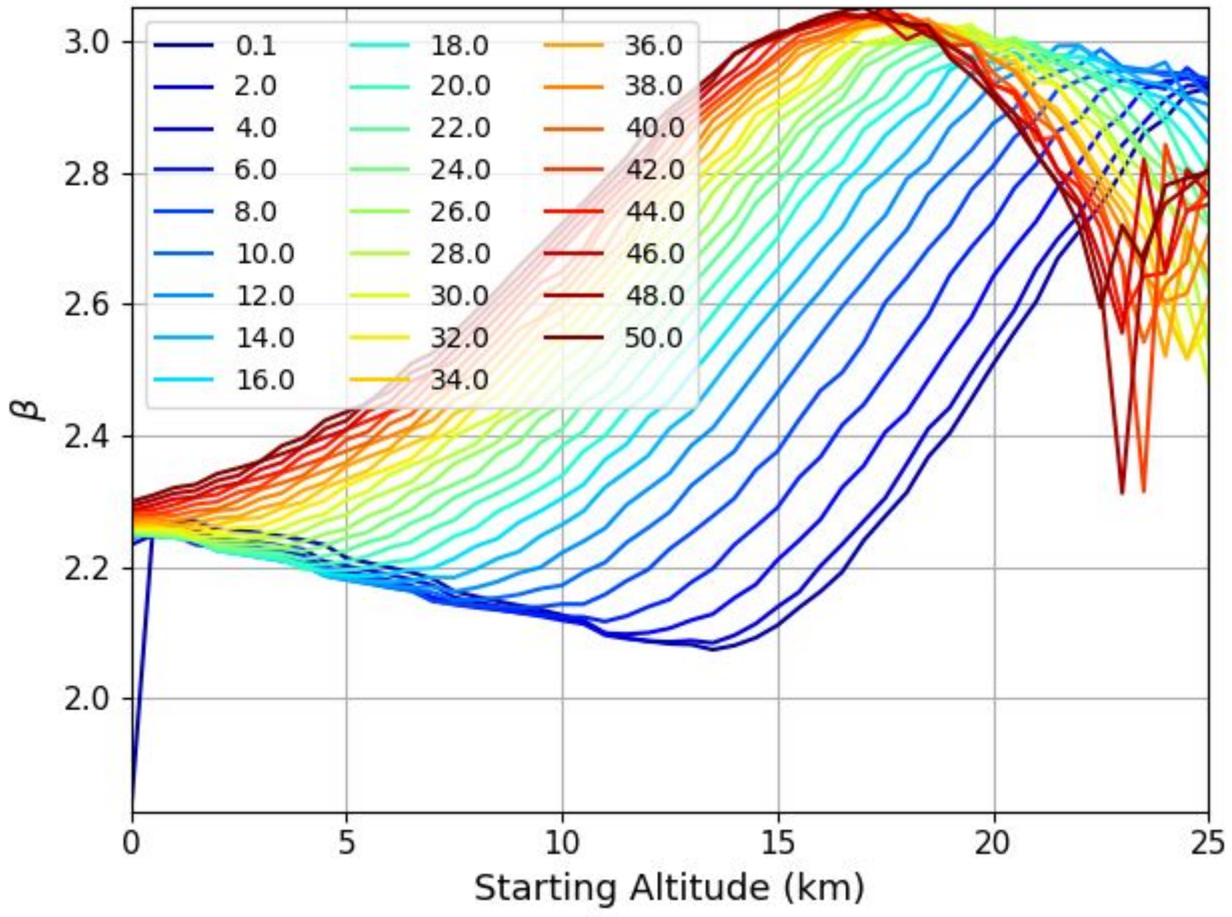
ϱ_0



θ_{ch}



β

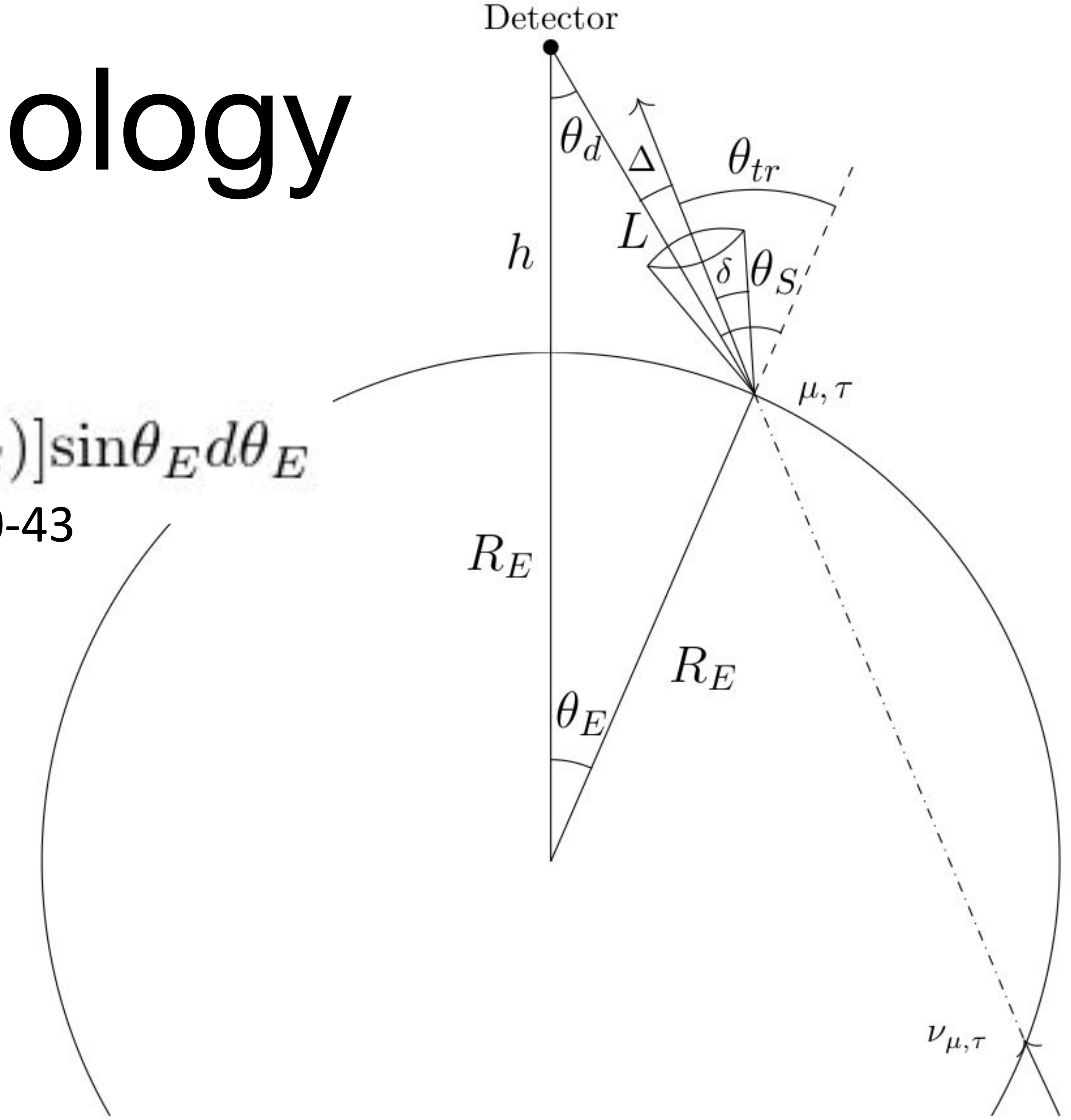


Monte Carlo Methodology

- Analytical estimate of geometry factor given by:

$$\langle A\Omega\rangle(E_\nu) = \pi R_E^2 \Delta\phi_E \int P_{obs}[E_\nu, \theta_s(\theta_E)] \times \cos[\theta_s(\theta_E)] \sin^2[\delta(\theta_E)] \sin\theta_E d\theta_E$$

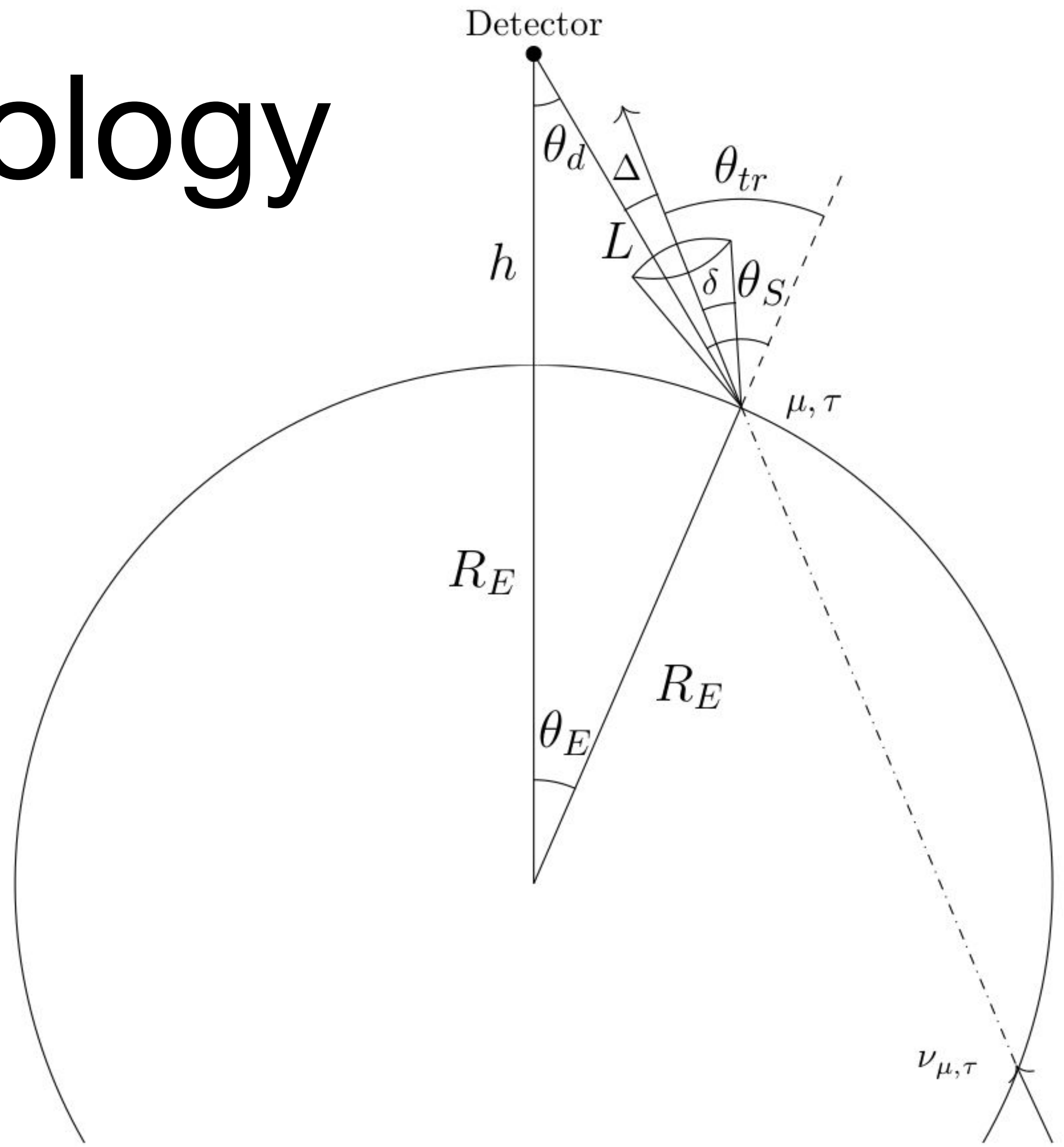
* *P. Motloch, Astropart.Phys.* 54 (2014) 40-43



For Tau-Leptons:

1. Interpolate Pobs, the Earth emergence probability from NuTauSim
2. Sample charged lepton energy given distribution at [E_ν,θ_s] using kernel density estimation
3. Sample decay altitude and fractional energy
4. Interpolate Cherenkov parameters from generated lookup table
5. Calculate δ(θ_E)
   - EUSO-SPB2 threshold: 200 γ/m²
   - POEMMA threshold: 20 γ/m²

Monte Carlo Methodology

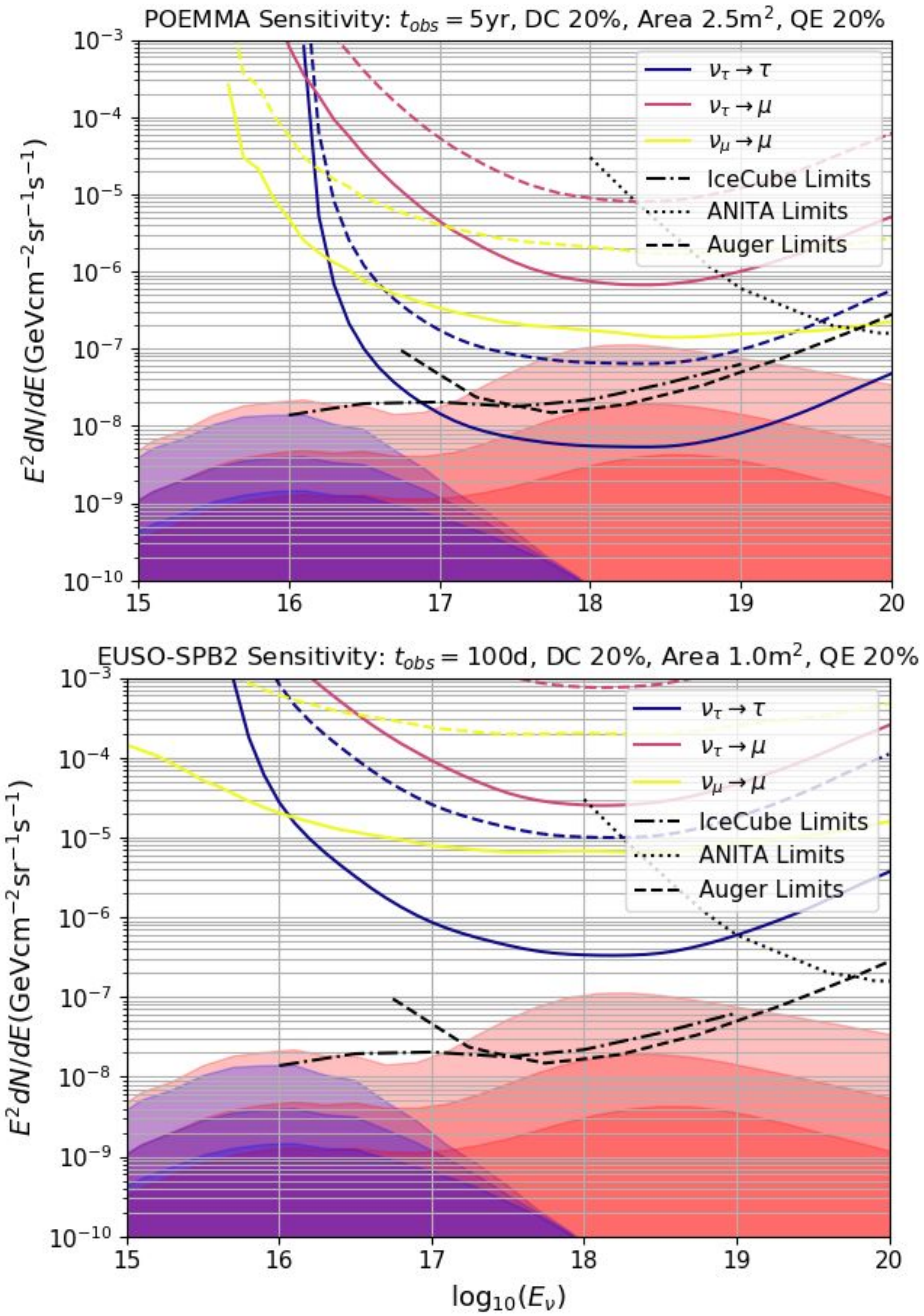


For Muons:

1. Interpolate P_{obs}, the Earth emergence probability from NuTauSim
2. Sample charged lepton energy given distribution at [E_ν, θ_s] using kernel density estimation
3. Sample interaction length from exponential distribution with mean dX inelasticity $y=E/E_\mu$ from differential muon cross sections
   - dX = ⅕ X_{tot}, the total atmospheric slant depth provided by the trajectory
4. Interpolate parameters from lookup table
5. Calculate $\delta(\theta_E)$
6. Continue propagation through atmosphere, keeping only the most significant interaction (highest δ)
   - Doesn't consider the superposition of multiple interactions

Neutrino Sensitivities

- Including the muon channels extends sensitivity below 10PeV
  - Muon neutrino channel more relevant than muons from tau decay due to Earth emergence probability
- The POEMMA and EUSO-SPB2 instruments remain most sensitive to the tau neutrino flux
- Even under the most optimistic conditions, neither POEMMA nor EUSO-SPB2 compete with limits set by existing experiments on the diffuse neutrino flux
- **Energy reconstruction very difficult**

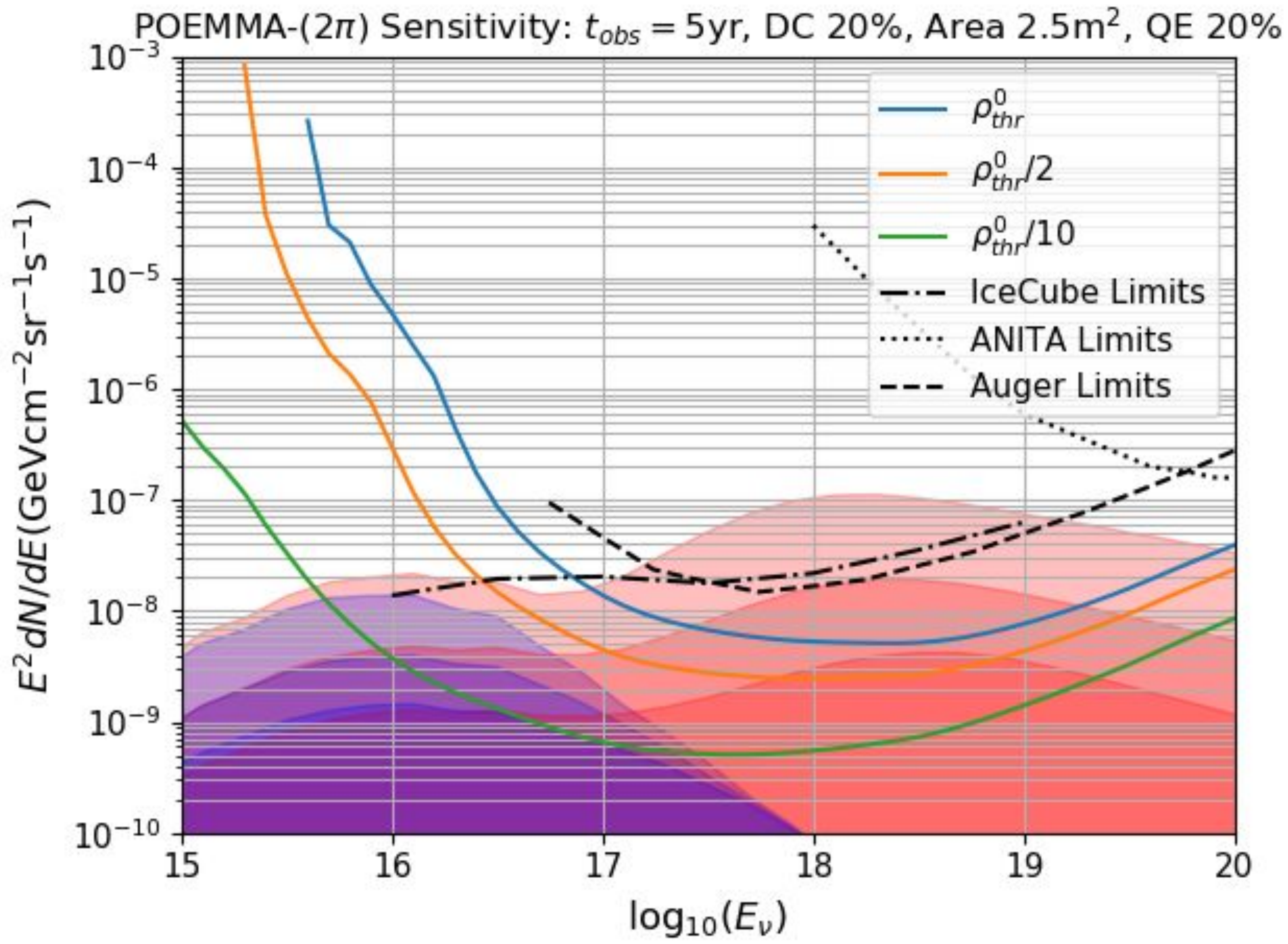


Cummings, Aloisio, Krizmanic Phys. Rev. D. 103, 043017

*Solid lines correspond to 360° azimuth, while dashed lines are current designs

How Can We Target the Diffuse Flux?

- Assume optimistic 2π azimuth, POEMMA optics and observation altitude
- Consider lowered detection thresholds
- Consider the most optimistic cosmological evolution of UHECR sources not yet ruled out by existing neutrino limits
  - For a pure proton composition model, assume the evolution of the Stellar Formation Rate (SFR)
  - For a mixed composition, assume the evolution of Active Galactic Nuclei (AGN)



Pure Proton Composition, SFR

	$\nu_\tau \to \tau$	$\nu_\tau \to \mu$	$\nu_\mu \to \mu$
ρ^0_{thr}	7.06	5.23×10^{-2}	3.05×10^{-1}
$\rho^0_{thr}/2$	14.46	1.20×10^{-1}	6.62×10^{-1}
$\rho^0_{thr}/10$	61.59	6.83×10^{-1}	3.51

Mixed Composition, AGN

	$\nu_\tau \to \tau$	$\nu_\tau \to \mu$	$\nu_\mu \to \mu$
ρ^0_{thr}	2.07×10^{-1}	8.12×10^{-4}	1.54×10^{-2}
$\rho^0_{thr}/2$	7.99×10^{-1}	2.82×10^{-3}	6.31×10^{-2}
$\rho^0_{thr}/10$	8.86	3.28×10^{-2}	1.03

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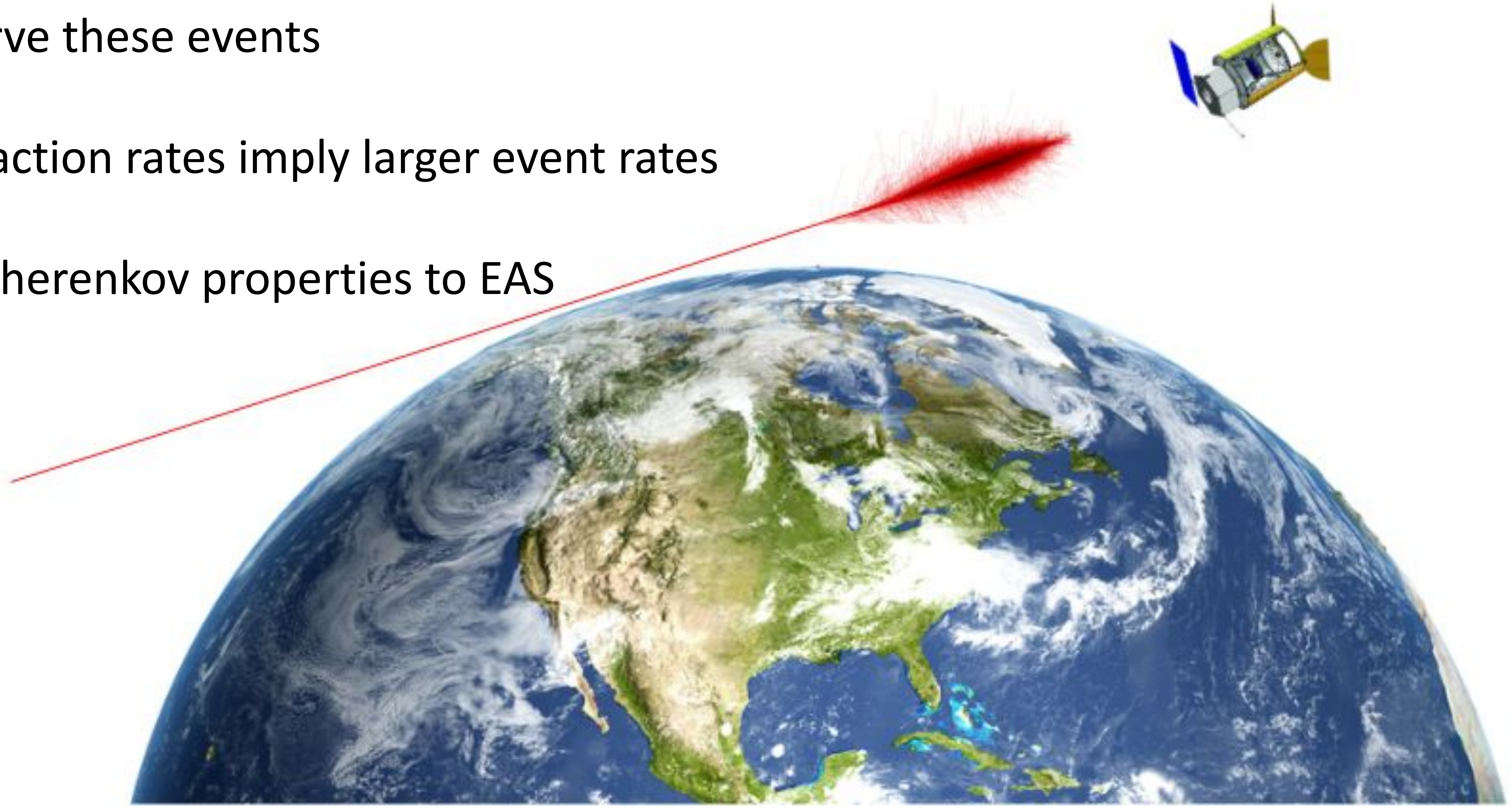
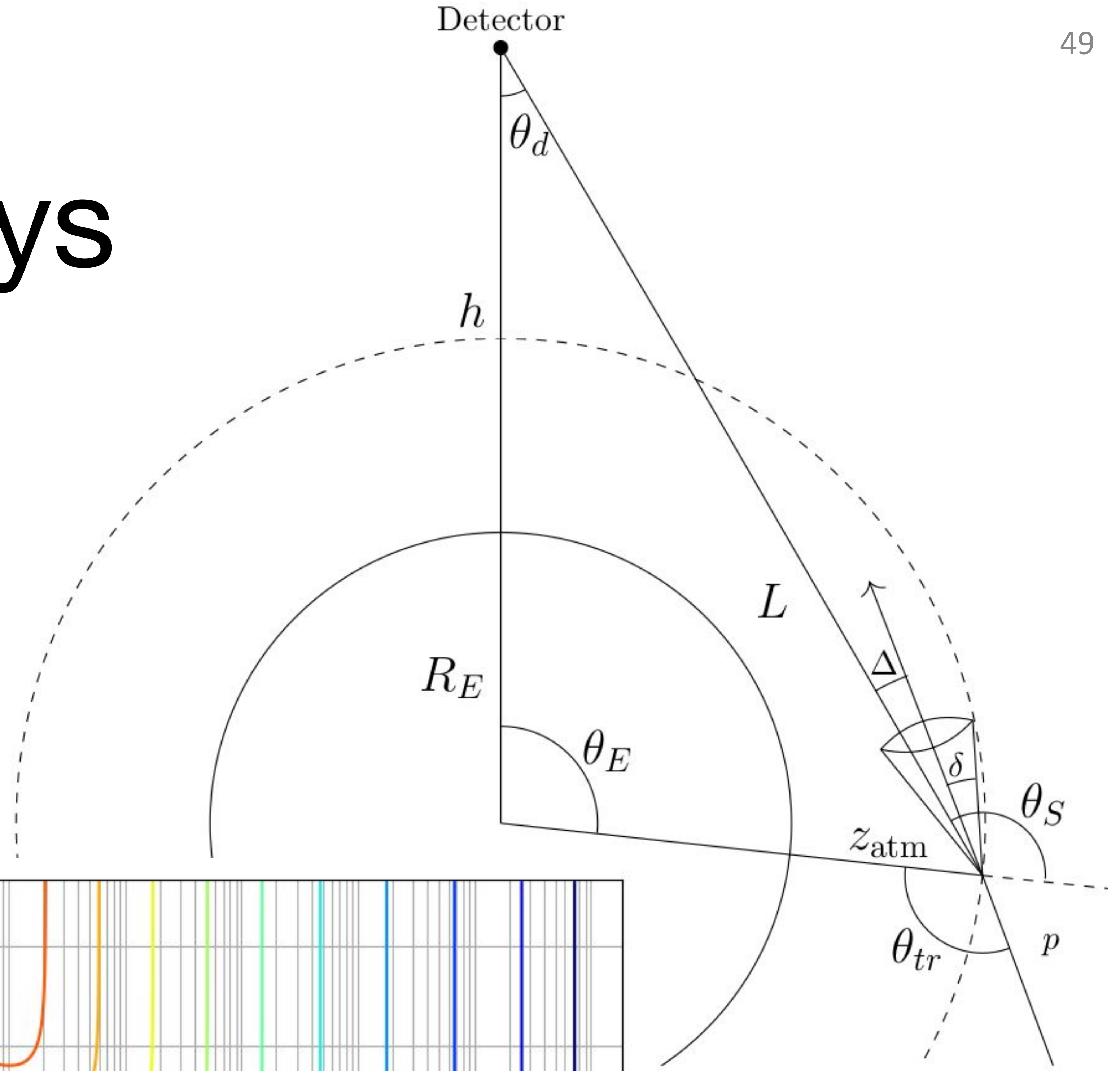
Above the Limb Observation

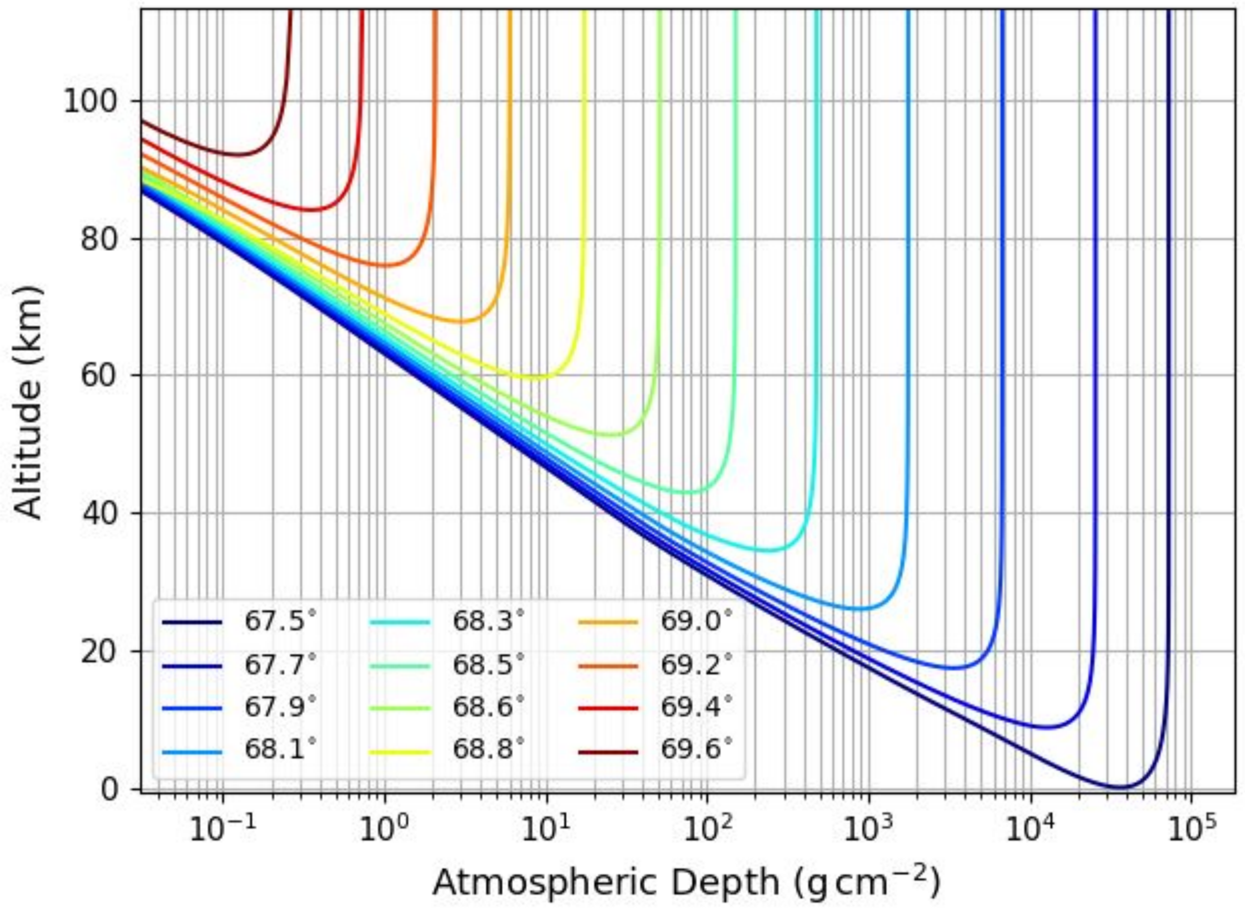
- Cosmic rays can skim the atmosphere and initiate upward going EAS like neutrinos
- The Cherenkov cameras of POEMMA and EUSO-SPB2 can look above the Earth and observe these events
- Increased fluxes and interaction rates imply larger event rates
- Expected to have similar Cherenkov properties to EAS initiated by neutrinos



Above the Limb Cosmic Rays

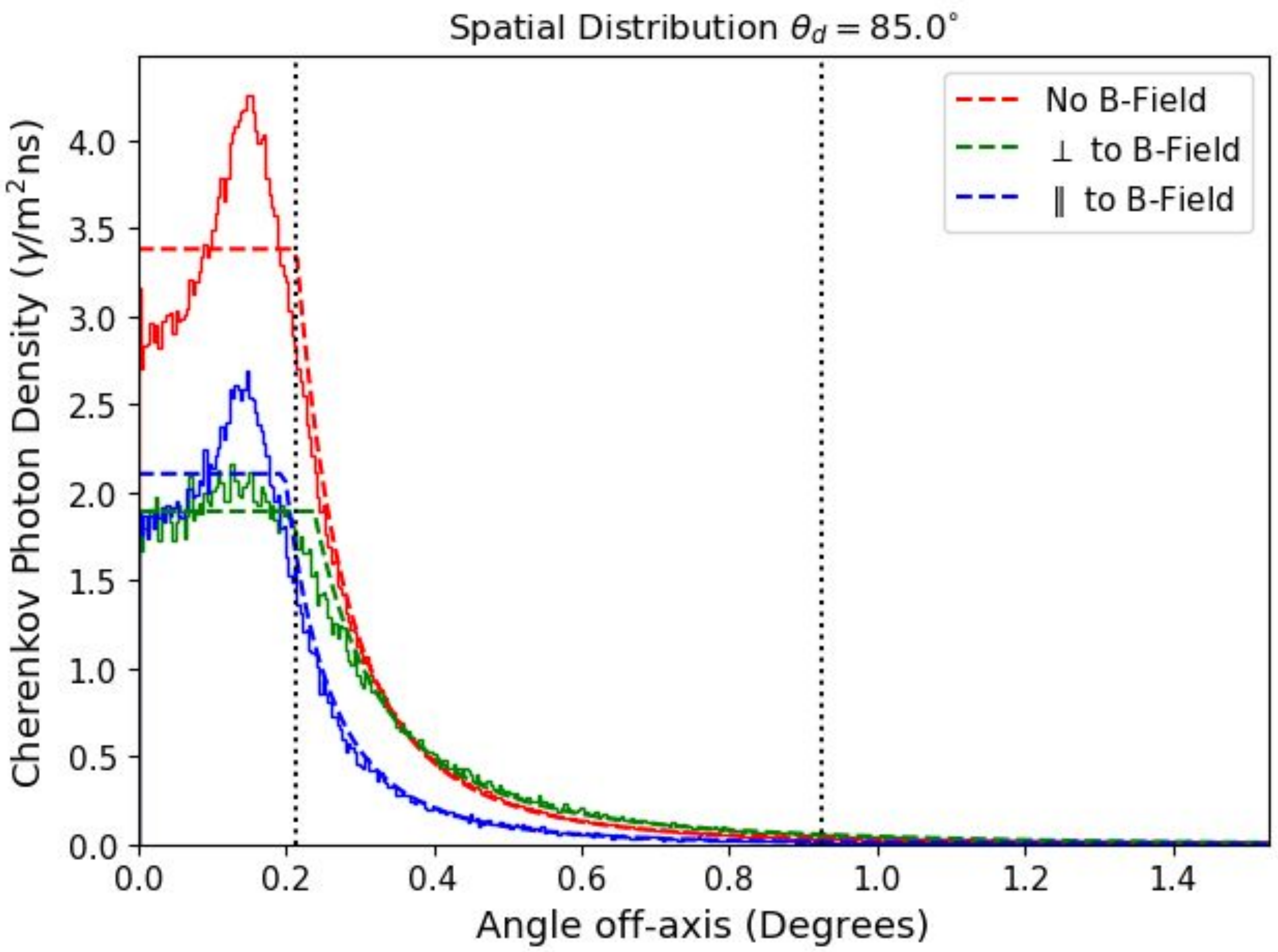
- Cosmic rays from above the Earth limb develop at characteristically high altitudes
  - X_{max} occurs close to 25 km
- Cosmic rays deposit the majority of their energy into EAS
- Trajectories near the limb will experience extremely strong atmospheric extinction
- Must now consider:
  - Geomagnetic separation of electrons/positrons
  - The time spread of the arriving photons





Above-the-Limb 1-D Profile Fitting

Example Cherenkov spatial distribution of a 100 PeV shower with 85° viewing angle, observed from 33 km altitude



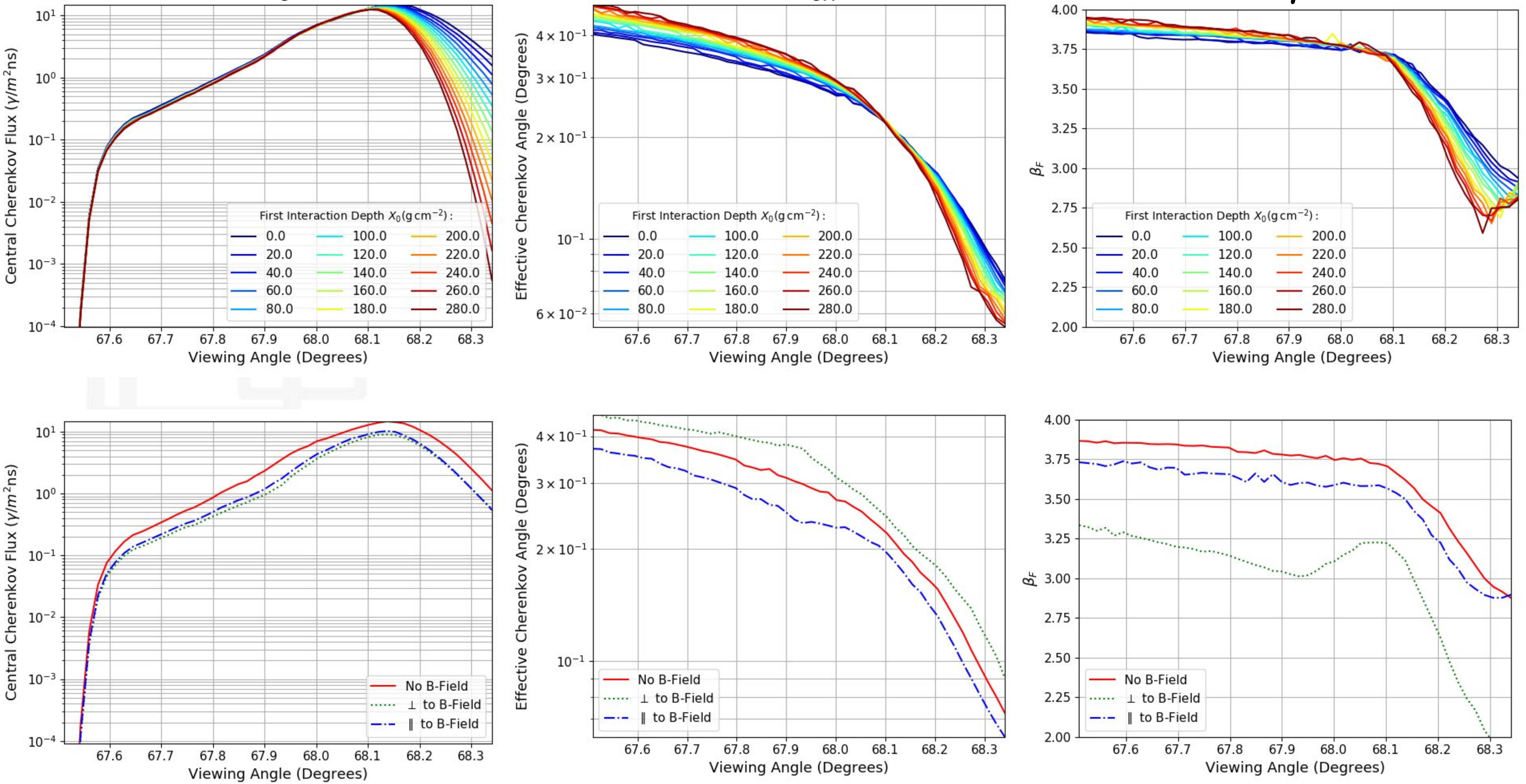
- Spatial distributions fit with:

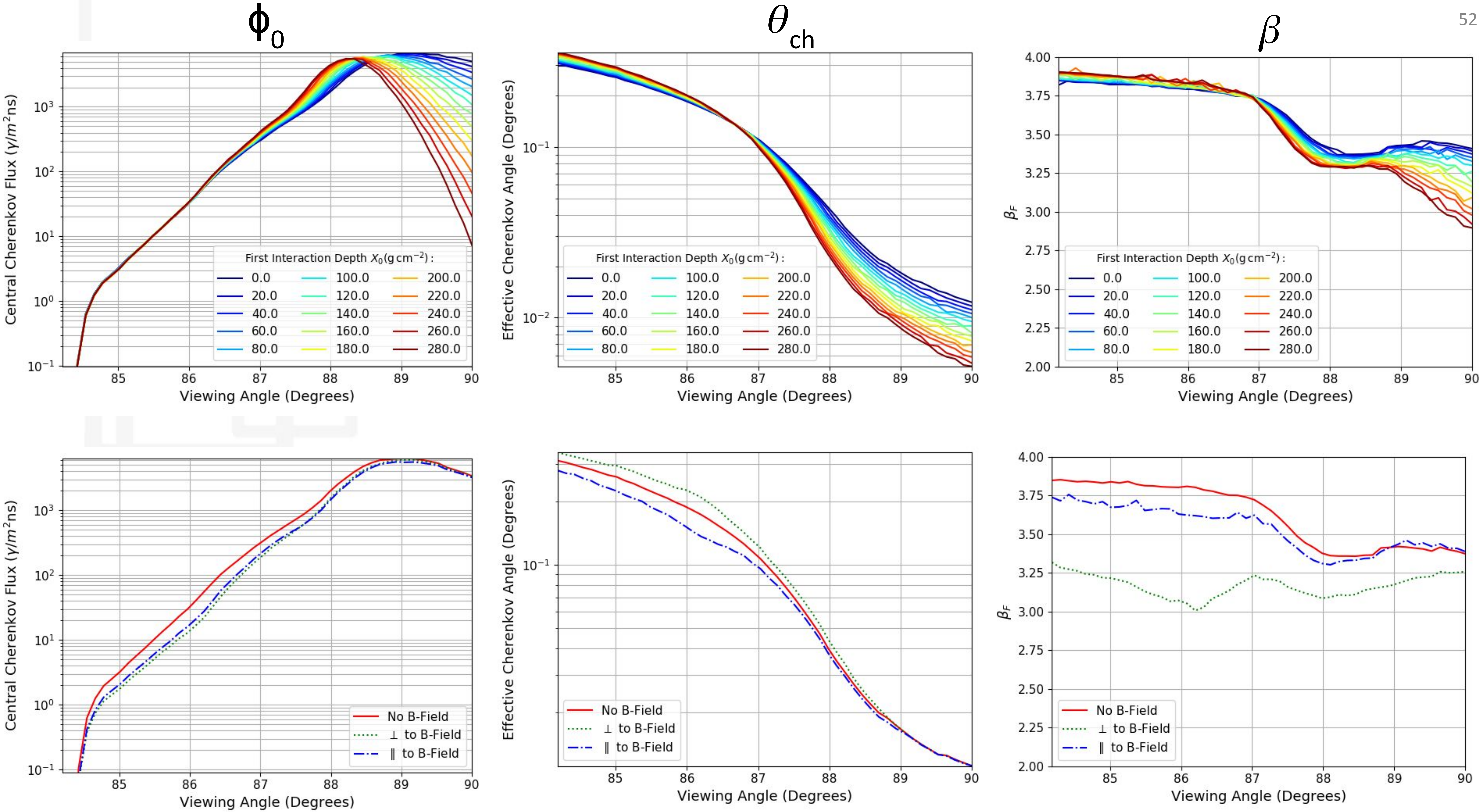
$$\Phi_{ch} = \begin{cases} \Phi_0 & \theta \leq \theta_{ch} \\ \Phi_0 \left(\frac{\theta}{\theta_{ch}}\right)^{-\beta} & \theta_{ch} \leq \theta \leq \theta_1 \\ \Phi_1 e^{-(\theta-\theta_1)/\theta_2} & \theta \geq \theta_1 \end{cases}$$

- To bound the maximum effects of the geomagnetic field:
  - Fit the spatial distributions parallel and perpendicular to the B field

- Simulate showers over the parameter space θ_d from limb to 300 g/cm² and X_0 from 0 to 280 g/cm²

ϕ_0 θ_{ch} β



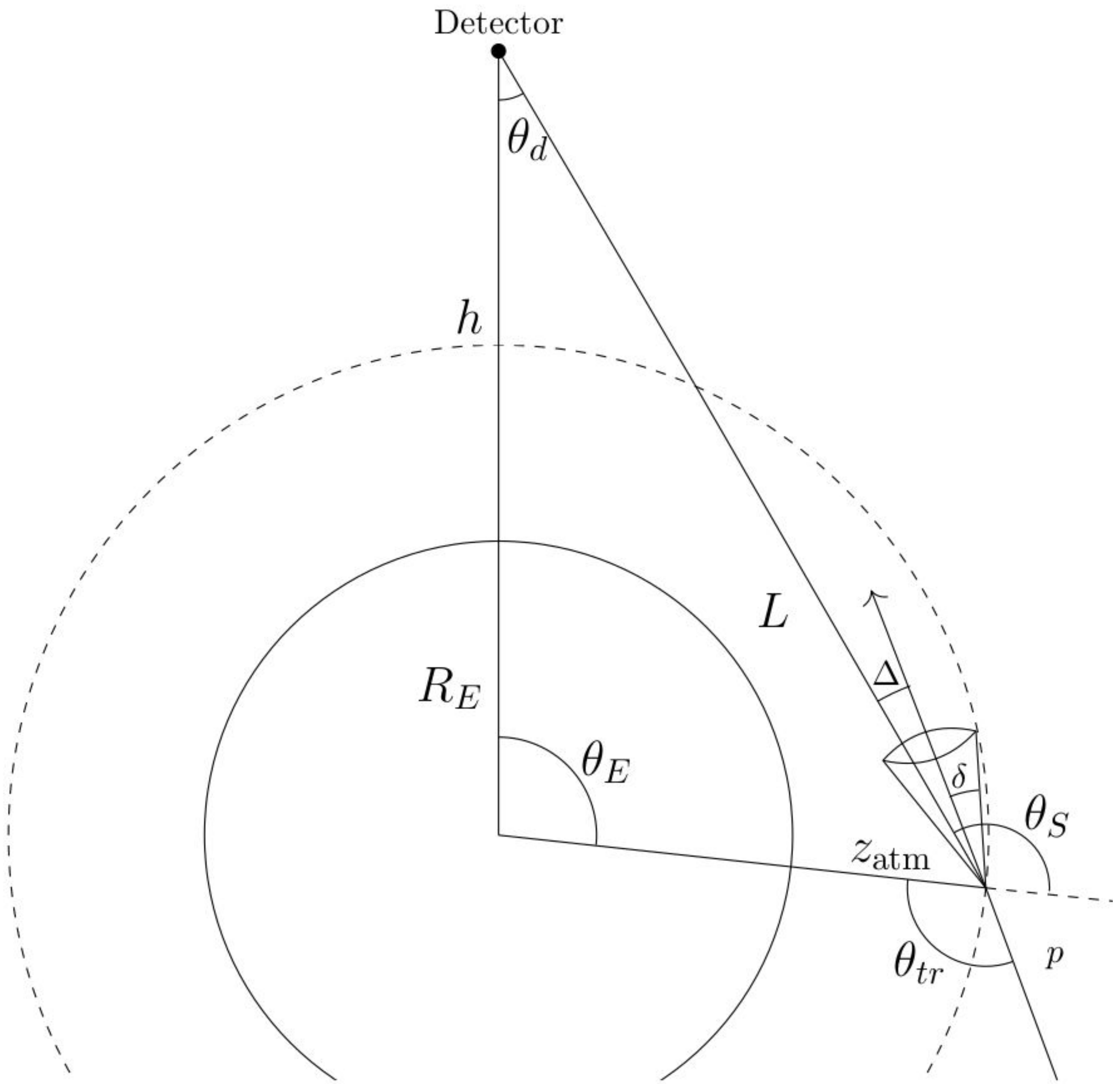


ϕ_0
θ_{ch}
β
Central Cherenkov Flux (γ/m^2ns)
Effective Cherenkov Angle (Degrees)
β_F
Viewing Angle (Degrees)
First Interaction Depth X_0(g cm^{-2}) :
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
220.0
240.0
260.0
280.0
No B-Field
⊥ to B-Field
∥ to B-Field

Above Limb Monte Carlo

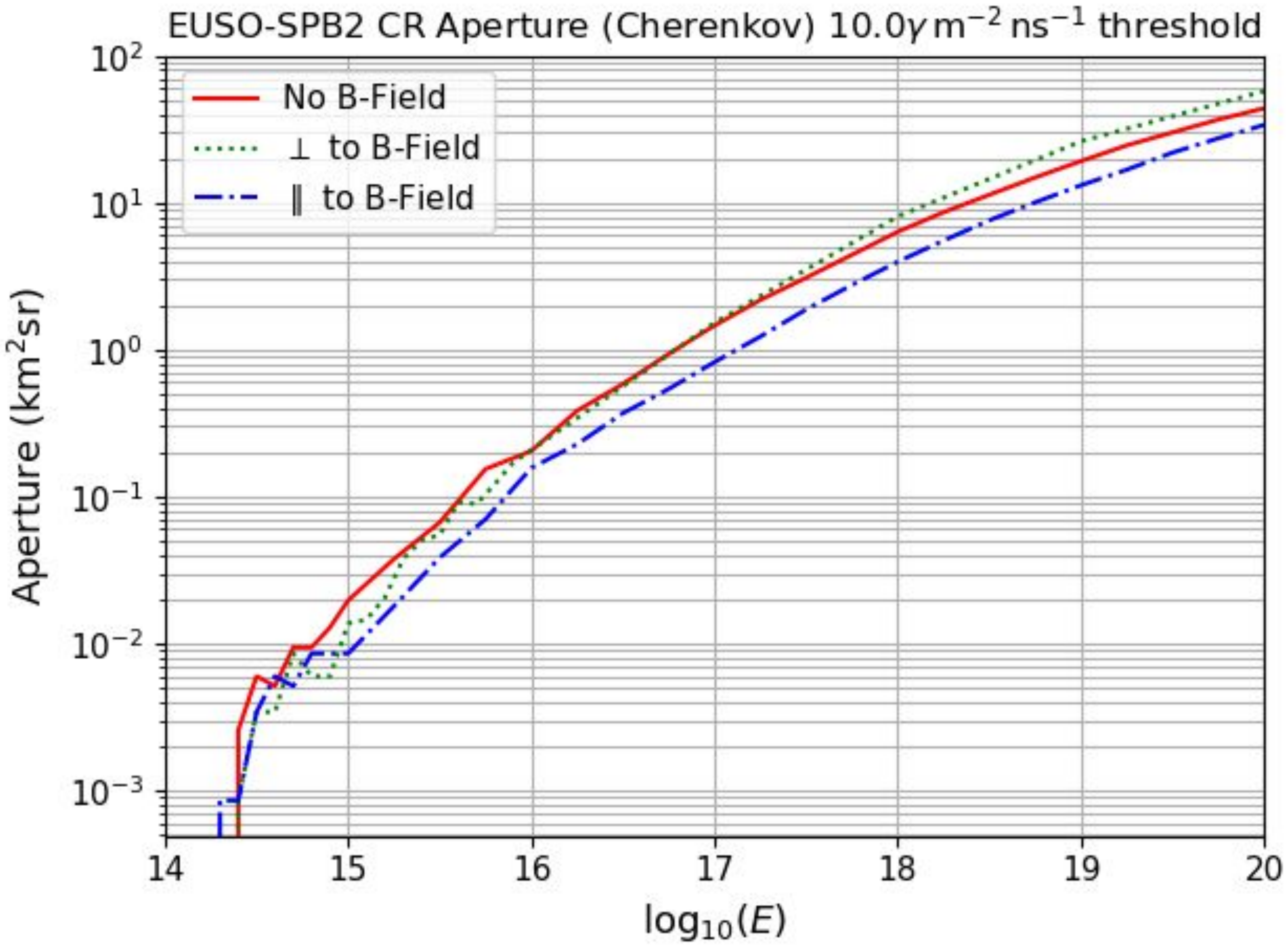
- For shower starting point: sample θ_E flat in cos(θ) constrained by FOV, and Φ_E uniformly from 0-2π
- For shower trajectory: sample θ_s flat in cos²θ, and Φ_s uniformly from 0-2π
- Calculate angle between shower trajectory and detector
- Sample interaction length from exponential
- Take Cherenkov spatial profile from lookup table, and calculate the Cherenkov photon density at detector--if higher than threshold, event is accepted
  - EUSO-SPB2 threshold: 200 γ/m²/20 ns
  - POEMMA threshold: 20 γ/m²/20 ns
- Geometry factor estimated as:

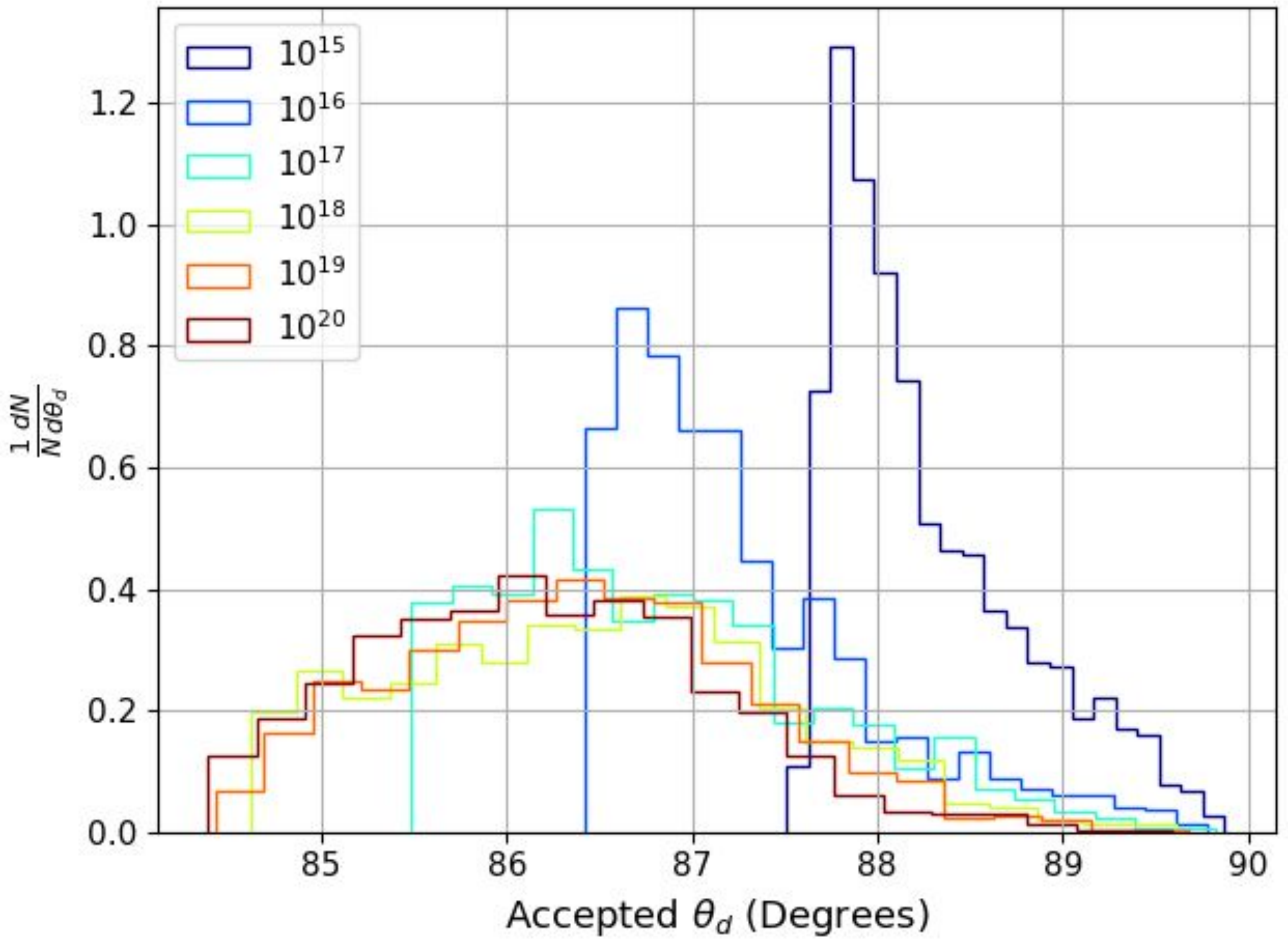
$$A(E) = \pi A_S \frac{N_{\text{accepted}}}{N_{\text{thrown}}}$$



Cosmic Ray Aperture (EUSO-SPB2)

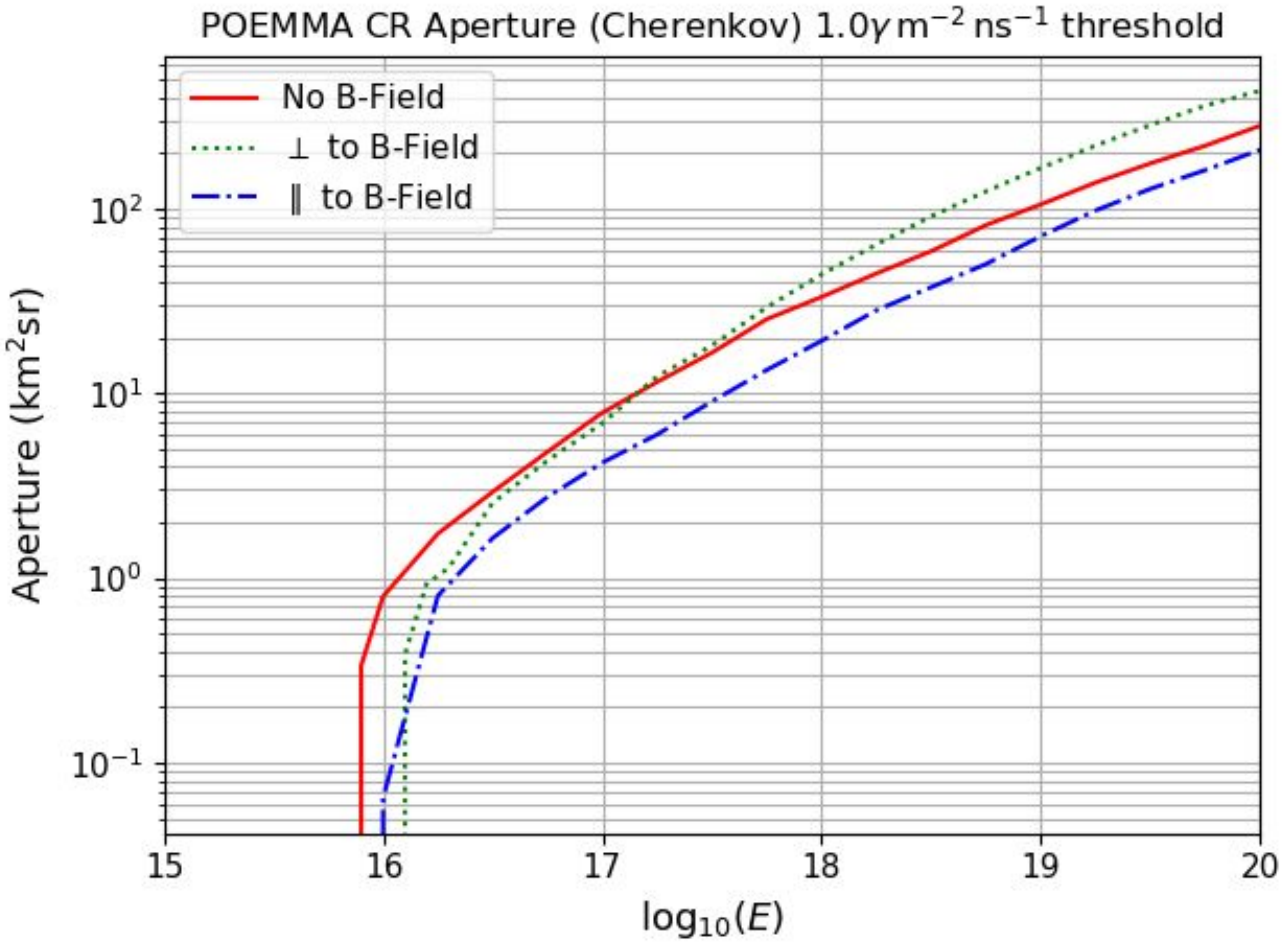
- Energy threshold below 1 PeV
- Higher energy events more visible near the limb
  - Due to atmospheric refraction, higher energy CR can be reconstructed as originating below limb (neutrino)

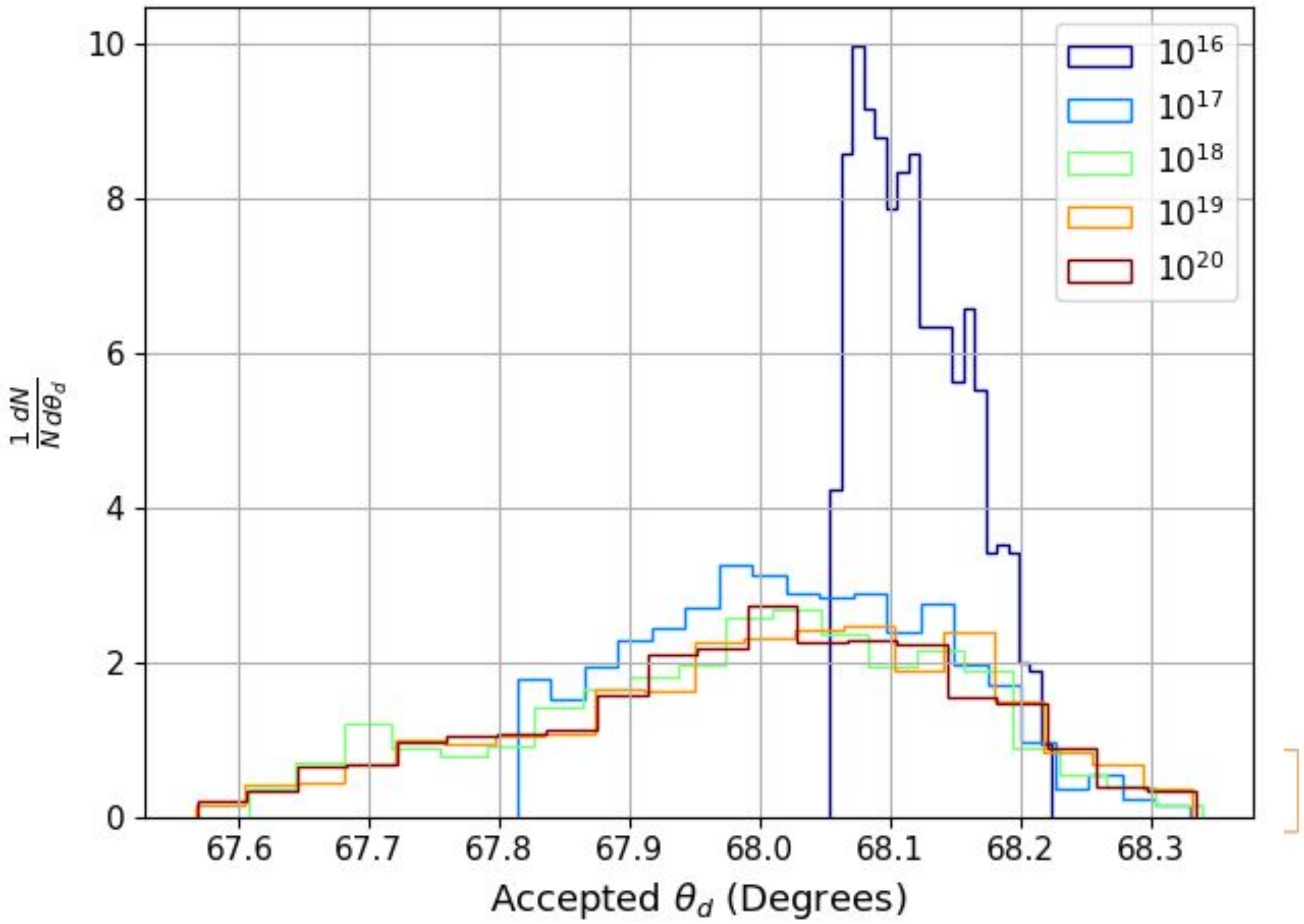




Cosmic Ray Aperture (POEMMA)

- Energy threshold below 10 PeV
- Higher energy events more visible near the limb
  - Due to atmospheric refraction, higher energy CR can be reconstructed as originating below limb (neutrino)



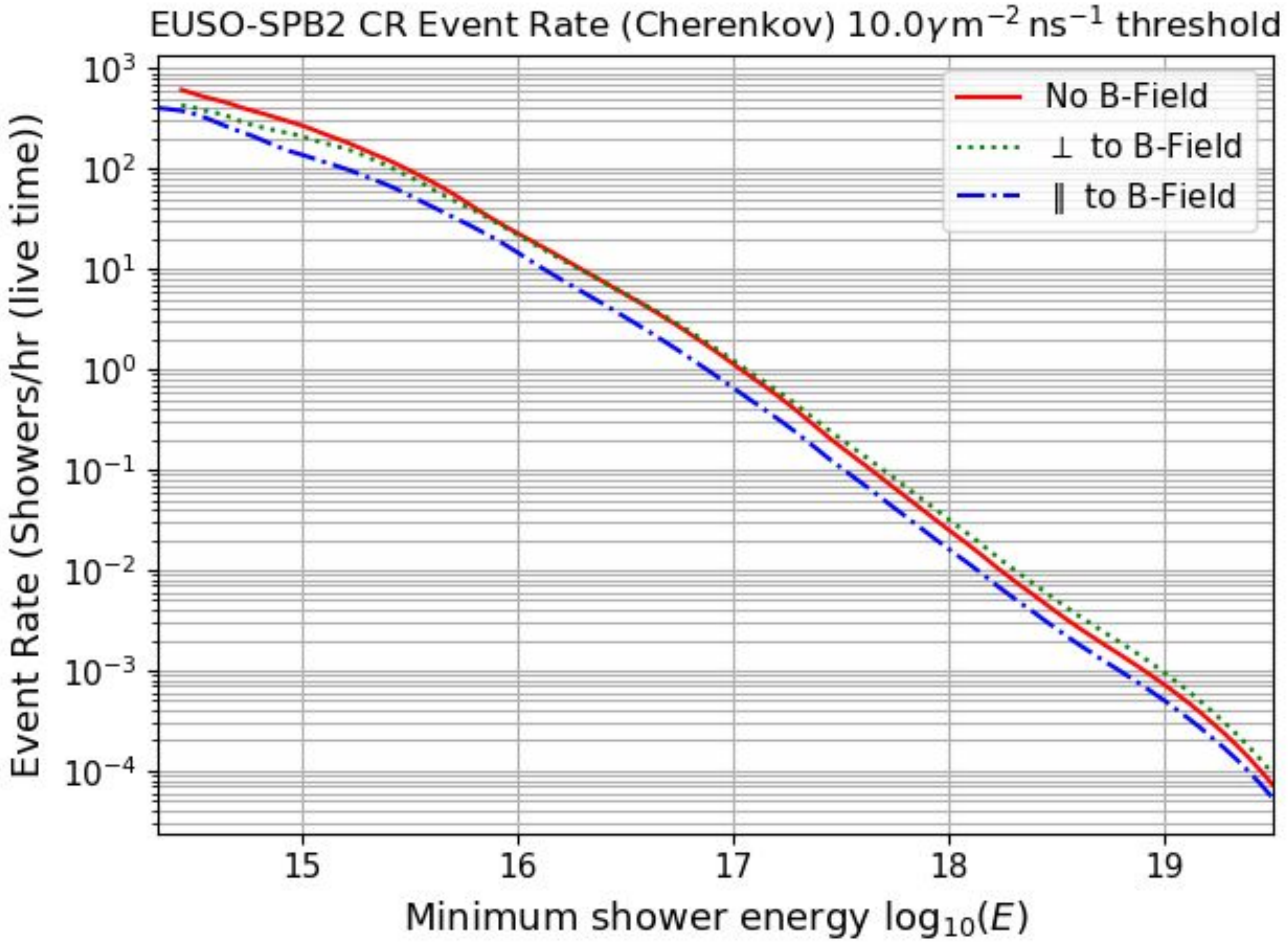


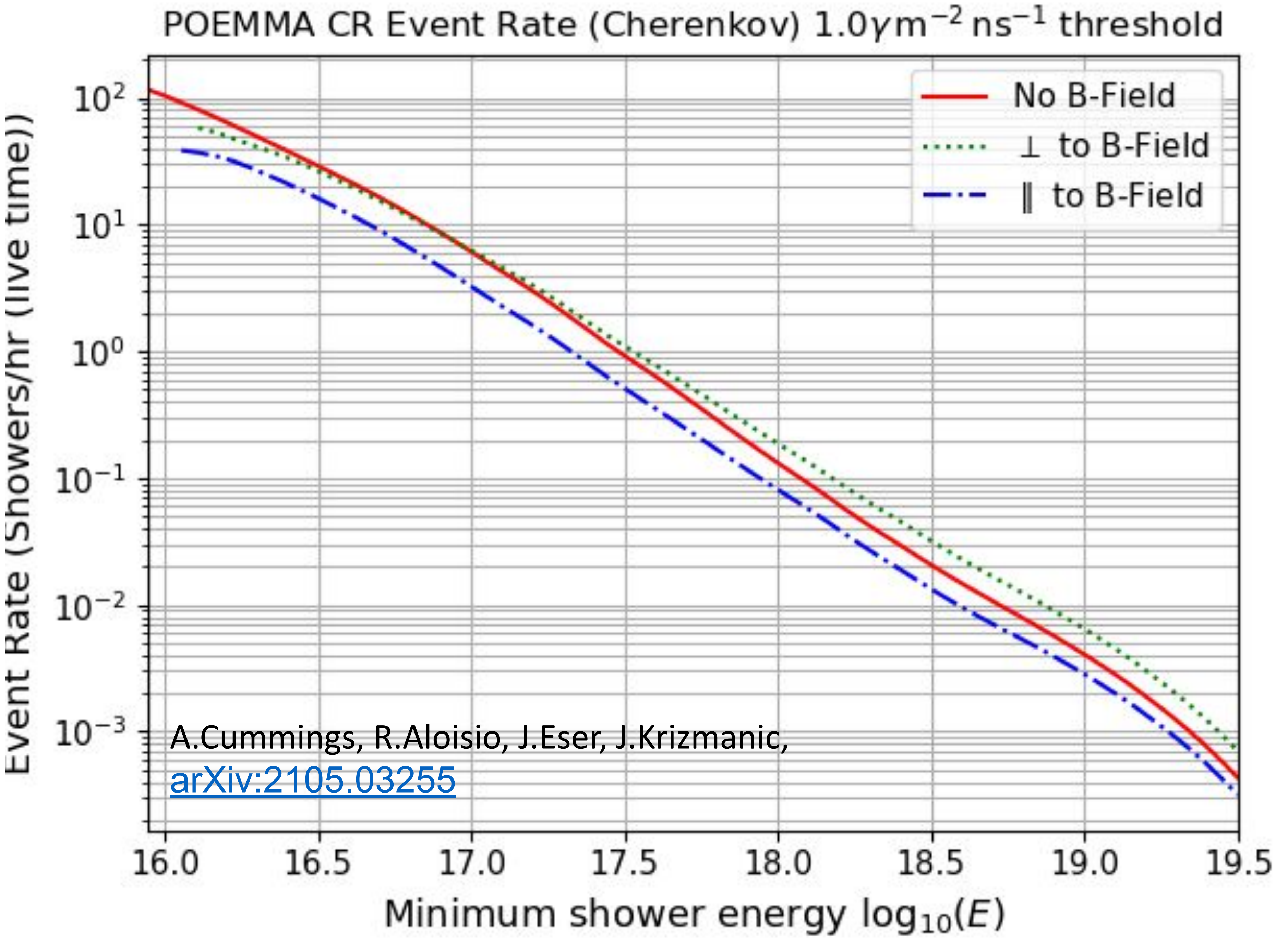
Cosmic Ray Event Rate

$$N = \int \int_E^\infty \langle A\Omega \rangle (E) \Phi_{CR}(E) dE dt$$

*Φ_{CR}(E): the all-particle flux measured by Kascade-Grande and Pierre-Auger

- High event rate
  - 100 events per hour of live time
  - Above EeV energies, similar event rates to radio detection (ANITA)
- **Definitive test of the optical Cherenkov detection technique from altitude**





Future Work:
Energy Reconstruction

- Angular scales are small
  - Good knowledge of arrival direction
- Time spread can quantify observation angle
- Signal intensity is proportional to primary energy
- Angular acceptance is energy dependent
  - Acceptance near limb could indicate higher primary energy, for example
- EUSO-SPB2 flight data will help to quantify reconstruction abilities

Future Work: Mass Composition

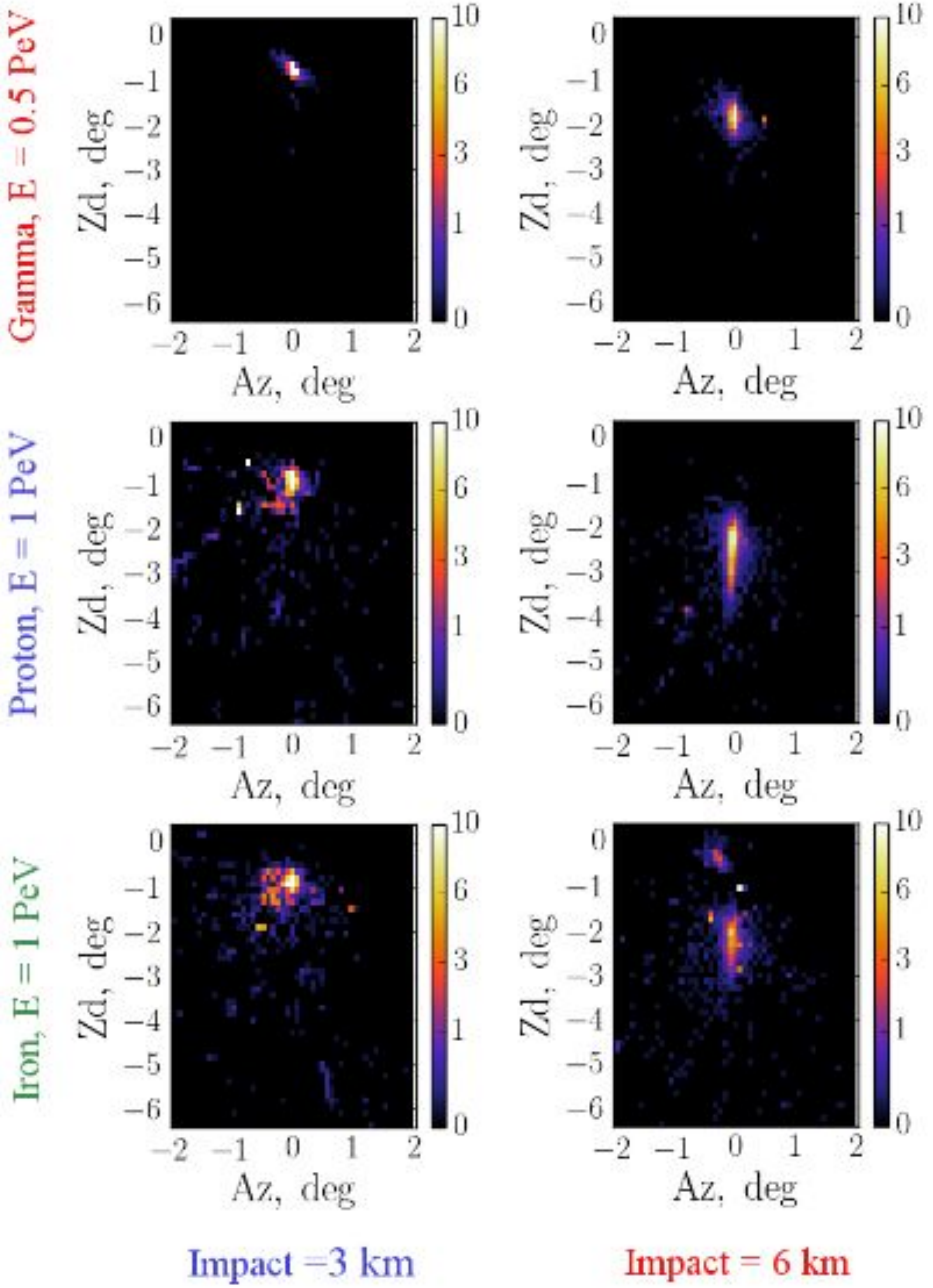
<u>Using Muons</u>

- Direct Cherenkov light from muons can be used to make composition measurements in ground-based optical Cherenkov telescopes

- Simulations necessary to determine the effect for high altitude observations

<u>Using Multiple Satellites</u>

- Structure within the effective Cherenkov angle can help resolve X_{max}
  - Tunka
  - NICHE



arXiv:1610.01794

A. Neronov, D.V. Semikoz, Ie.Vovk, R. Mirzoyan

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Summary and Future Perspectives

In this work:

- Characterized the Earth-emergent charged lepton flux given a parent flux of τ and μ neutrinos
- Characterized the optical Cherenkov signal from EAS induced by neutrinos and cosmic rays, considering also the muon induced EAS
- Showed that neither POEMMA nor EUSO-SPB2 is competitive with existing experiments for measuring the diffuse neutrino flux
  - The full sky coverage and slewing capability do allow for multi-messenger follow-up measurements
- Showed that both POEMMA and EUSO-SPB2 will measure copious amounts of cosmic rays. Because the properties of the emission are so similar, these cosmic rays provide an in-flight test source and a verification of the detection technique. Performing and optimizing energy and angular reconstructions on these events allows for readiness for neutrino observations.

What to expect in the near future:

- Simulation work will show whether mass composition measurements are feasible with high-altitude observations
- EUSO-SPB2 will launch from Wanaka, NZ in 2023 and make the first high-altitude observations of Cherenkov emission. EUSO-SPB2 will quantify backgrounds, verify the detection method, and help optimize future space-based missions.
- Terzina will measure backgrounds and UHECR from space-based altitudes for the first time

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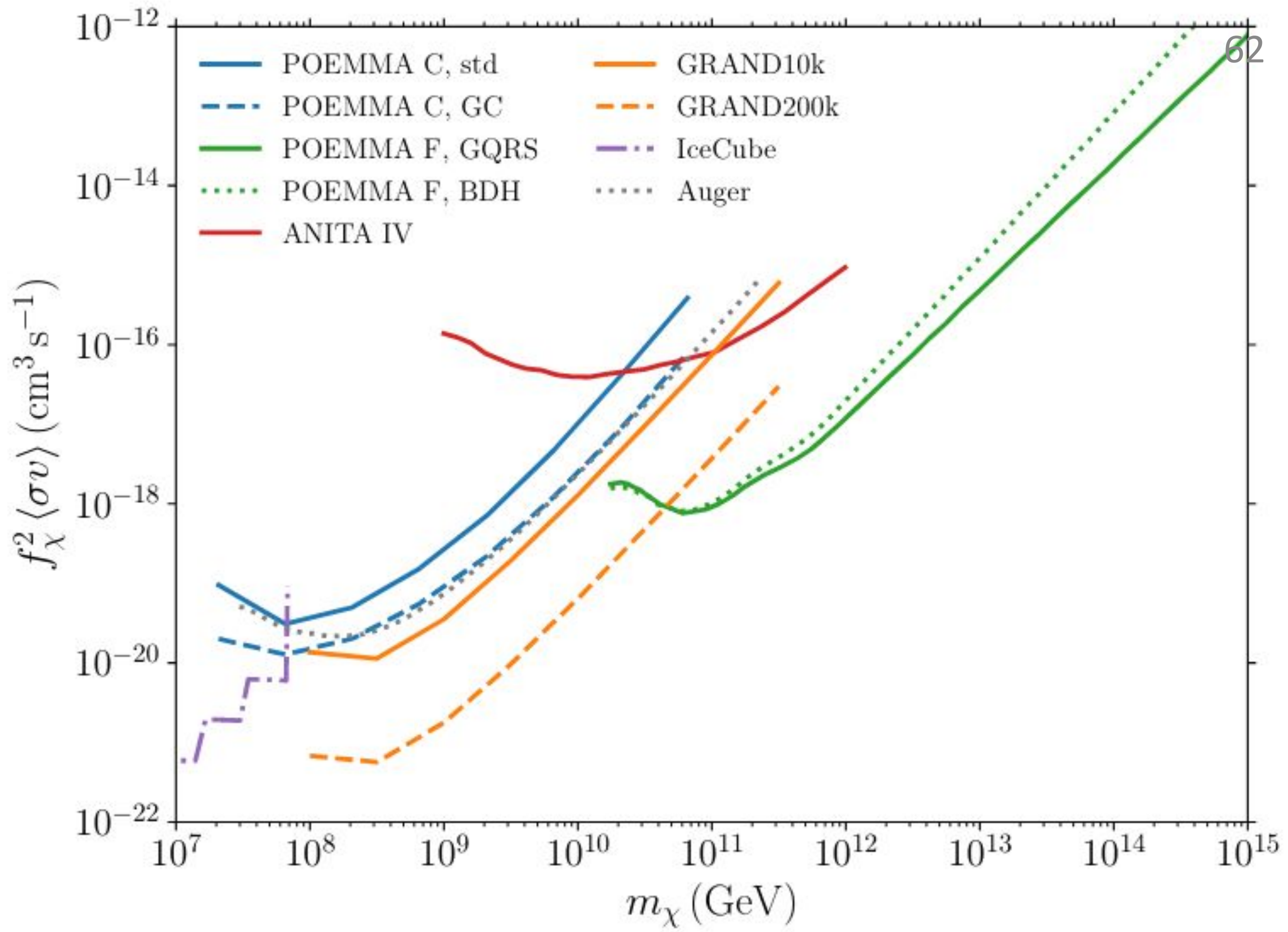
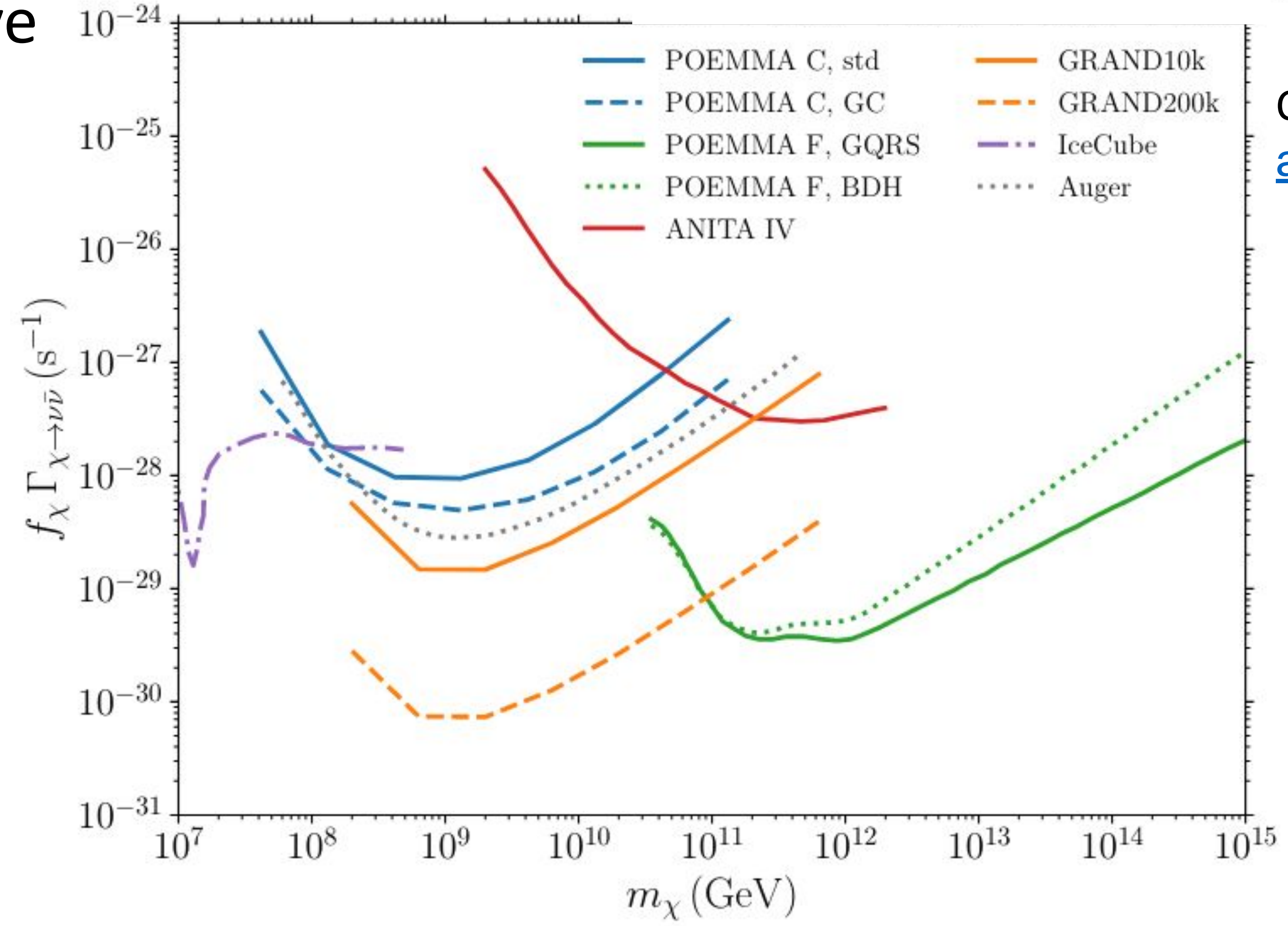
Indirect Dark Matter

- POEMMA sensitive to indirect dark matter via:
  - Annihilation $\chi\chi \rightarrow \nu\bar{\nu}$
  - Decay $\chi \rightarrow \nu\bar{\nu}$
- Probe of superheavy DM (E>10^{16} eV)
- Observations of the Galactic Center improve sensitivities
- Fluorescence channel vastly improves detection capabilities for E>10^{20} eV

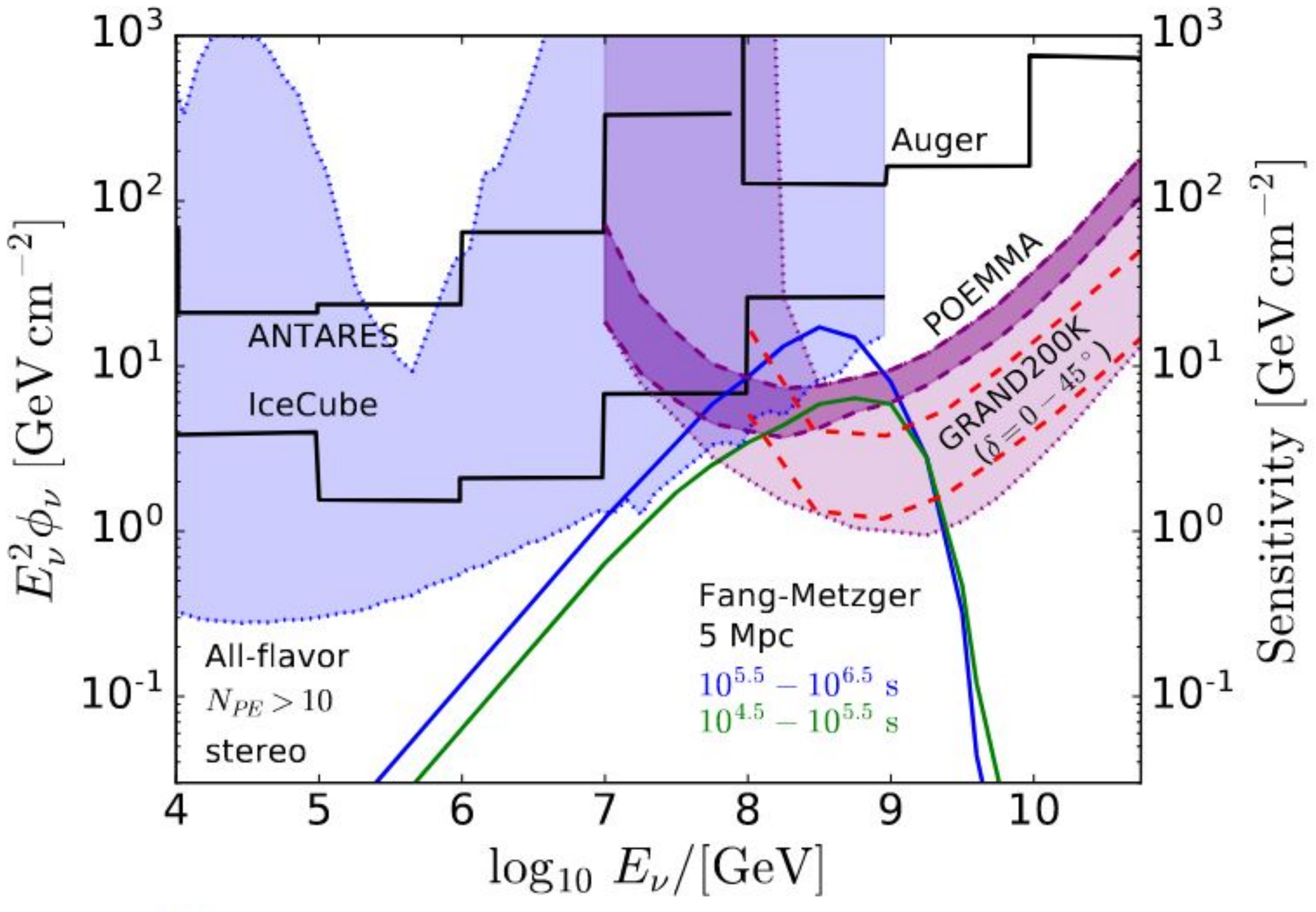


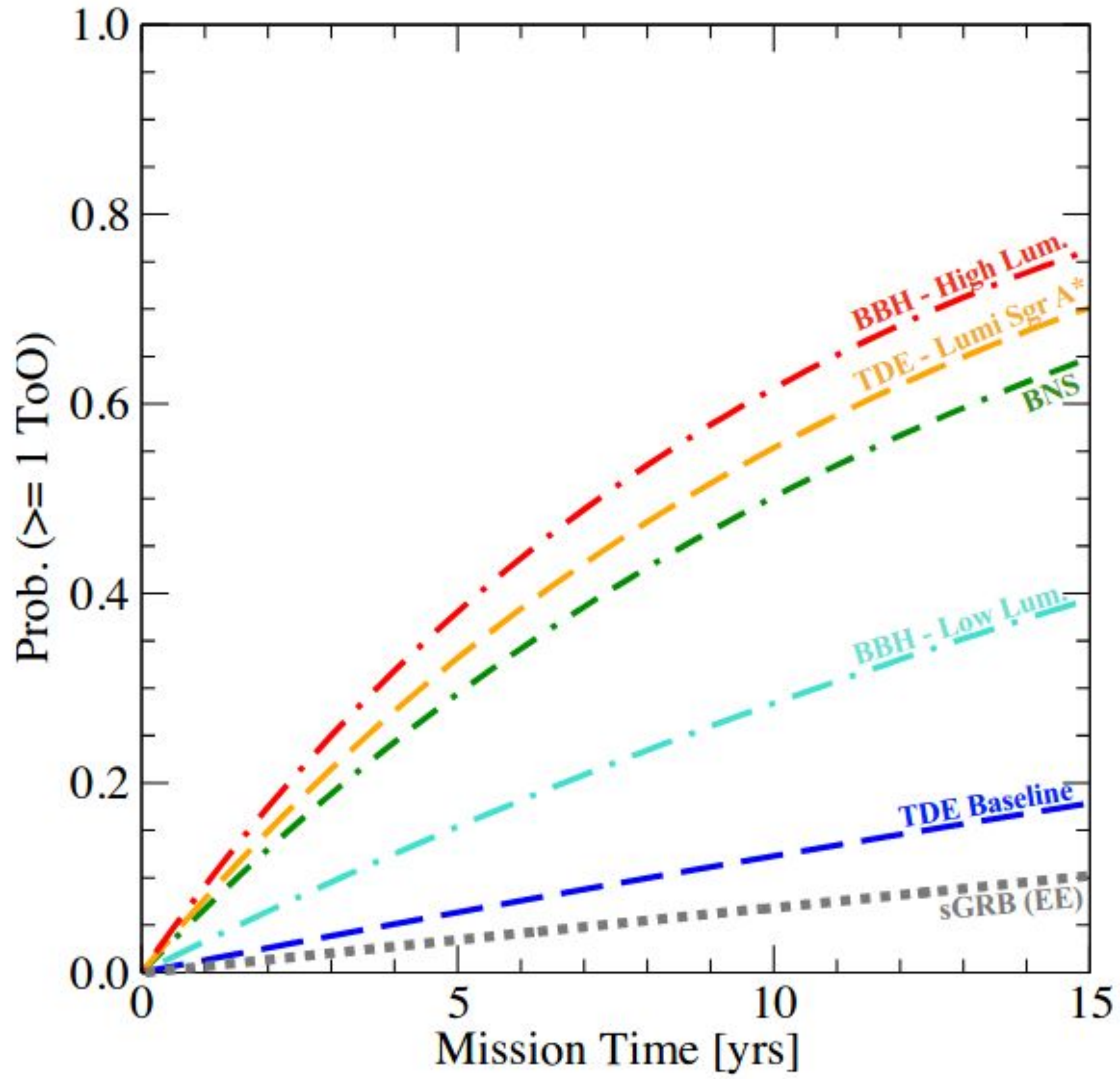


C. Guepin, et. al, arXiv:2106.04446

"Target of Opportunity"

- POEMMA has the ability to follow-up transient astrophysical events
  - Slew to target following multi-messenger alert
- Consider "long-burst" (>1000 s) and "short-burst" (<1000 s) events
- Full-sky view of POEMMA offers a good chance at observing one such event under many different models
- Most promising detection candidates:
  - Jetted Tidal Disruption Events (TDE)
  - Binary Neutron Star Mergers (BNS)
  - Binary Black Hole Mergers (BBH)





T. M Venters, et. al., Phys. Rev. D 102, 123013

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Detection Thresholds

- Average number of background photons per pixel:

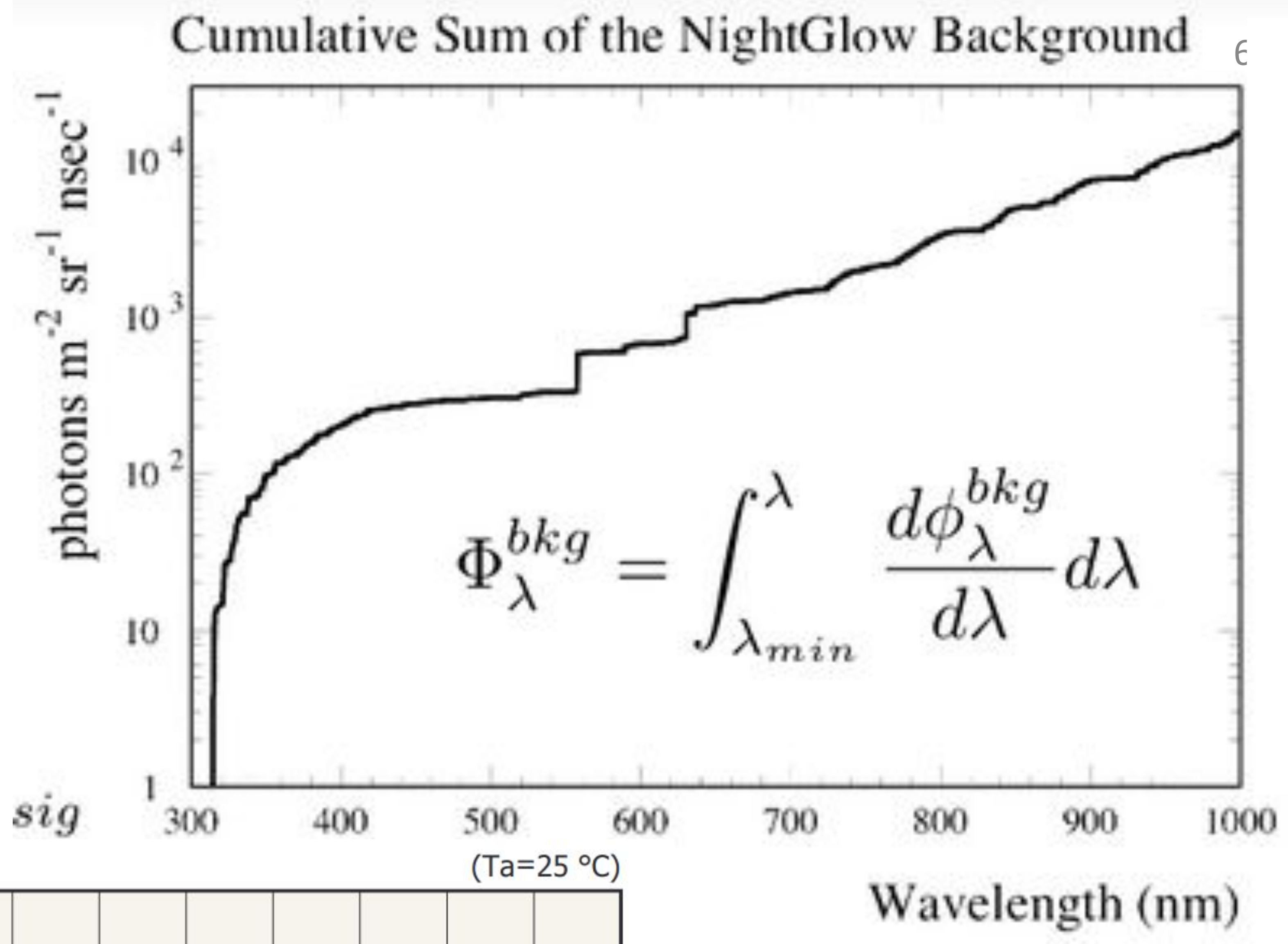
$$\mu = \langle N_{bkg} \rangle = \Phi_\lambda^{bkg} \epsilon_Q \Delta\Omega_{pix} \Delta S_{pix} \Delta t_{sig}$$

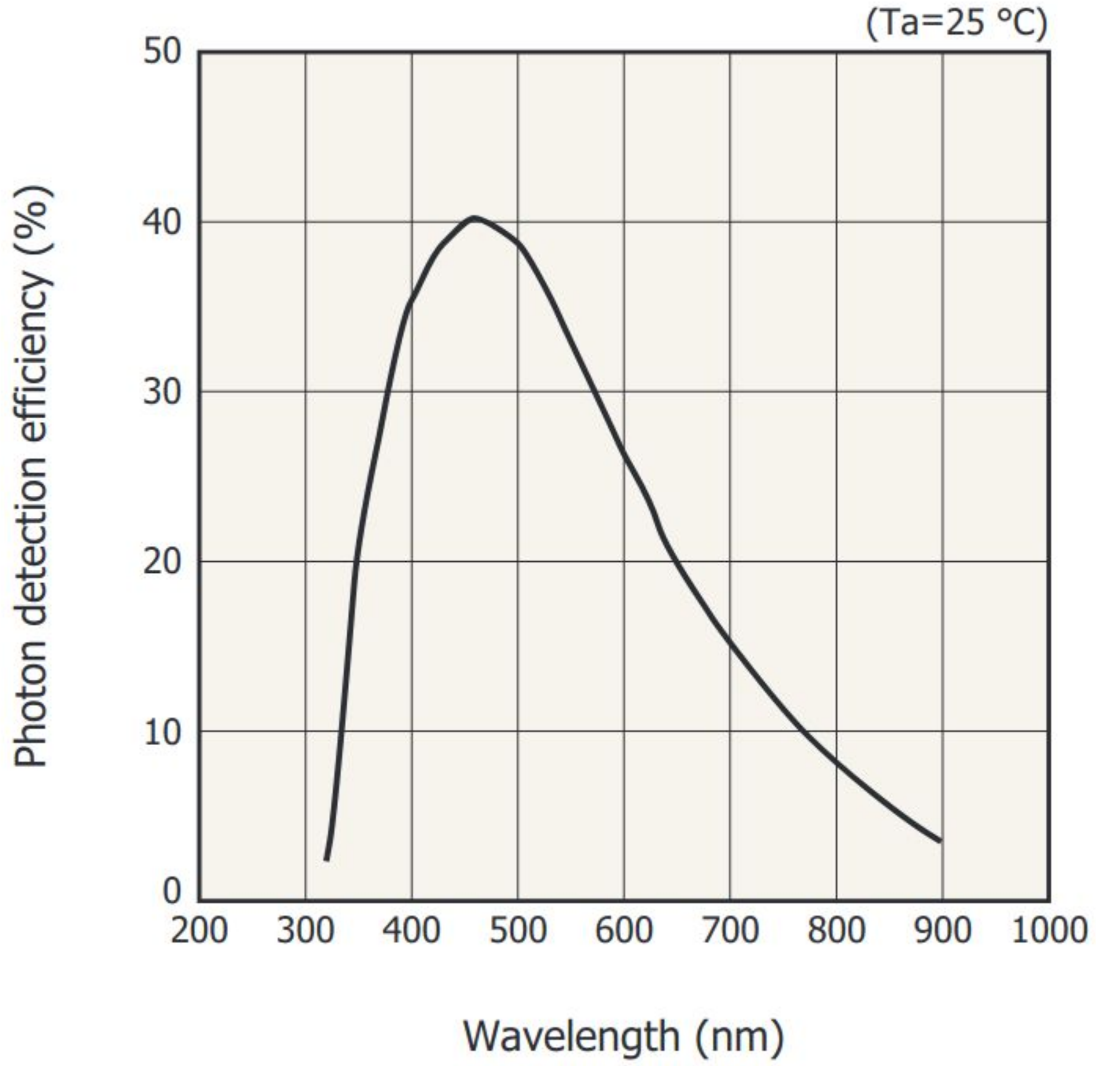
- Rate of false positive events due to background from Poisson statistics:

$$F(N_{PE}, \mu) = 1 - \sum_{k=0}^{N_{PE}-1} e^{-\mu} \frac{\mu^k}{k!}$$

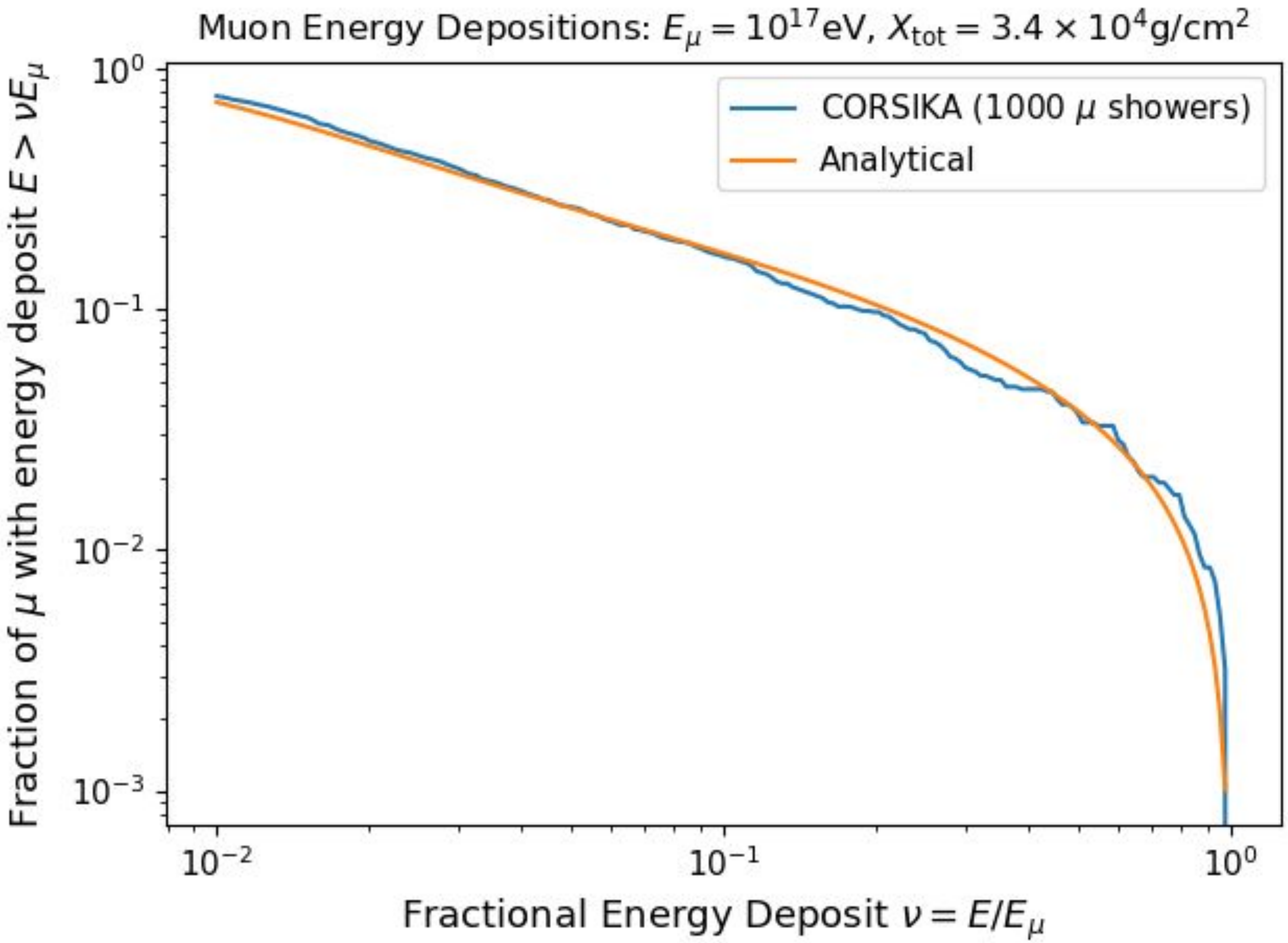
$$\eta = F(N_{PE}, \mu) N_{pix} \frac{\Delta t_{duty}}{\Delta t_{sig}}$$

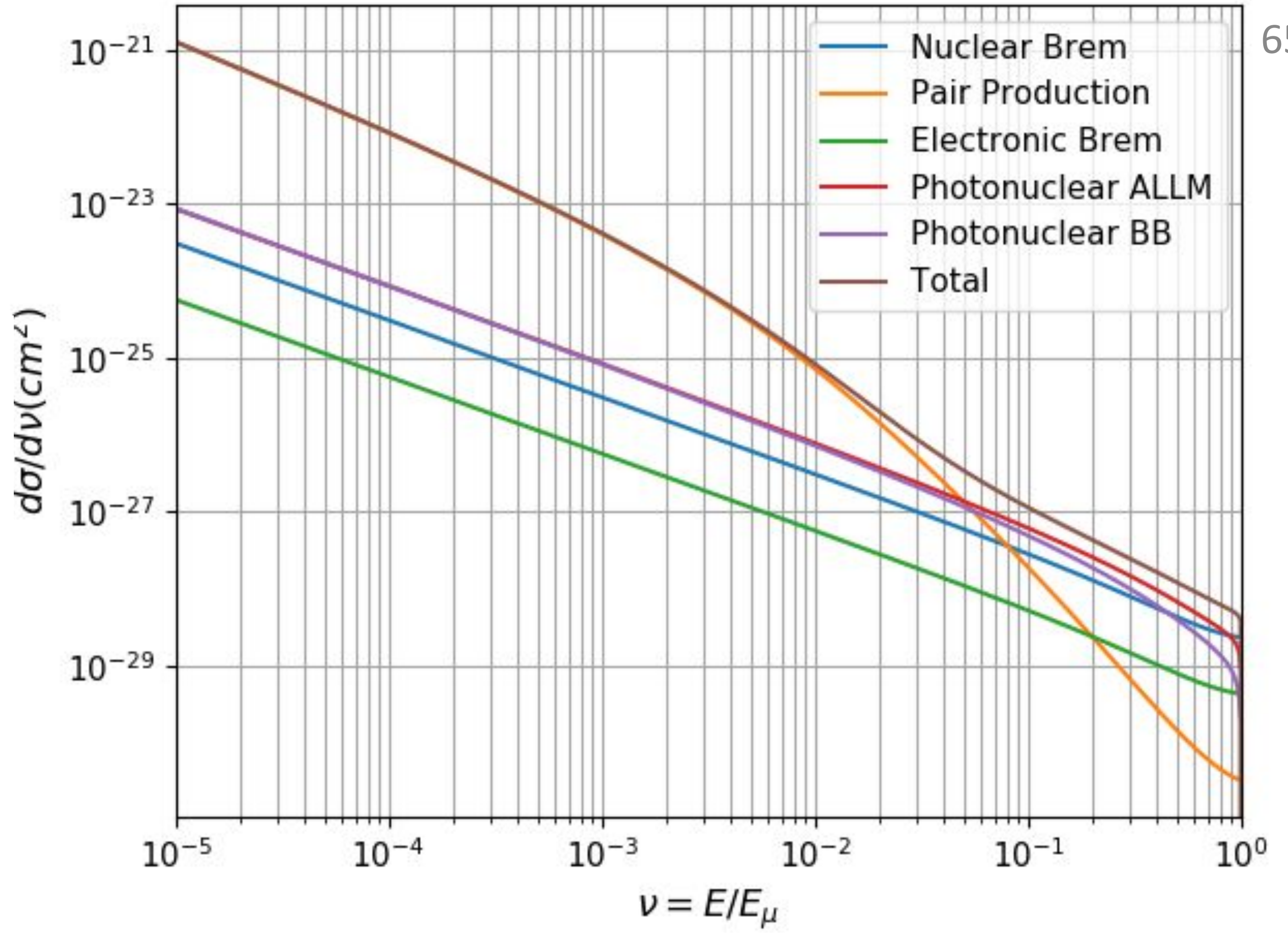
- Assuming an integration time of 20 ns, a quantum efficiency of 10%, and the spectrum of the night sky airglow emission, the threshold to allow for <0.01 false events per year
  - EUSO-SPB2: 40 PE
  - POEMMA: 10 PE

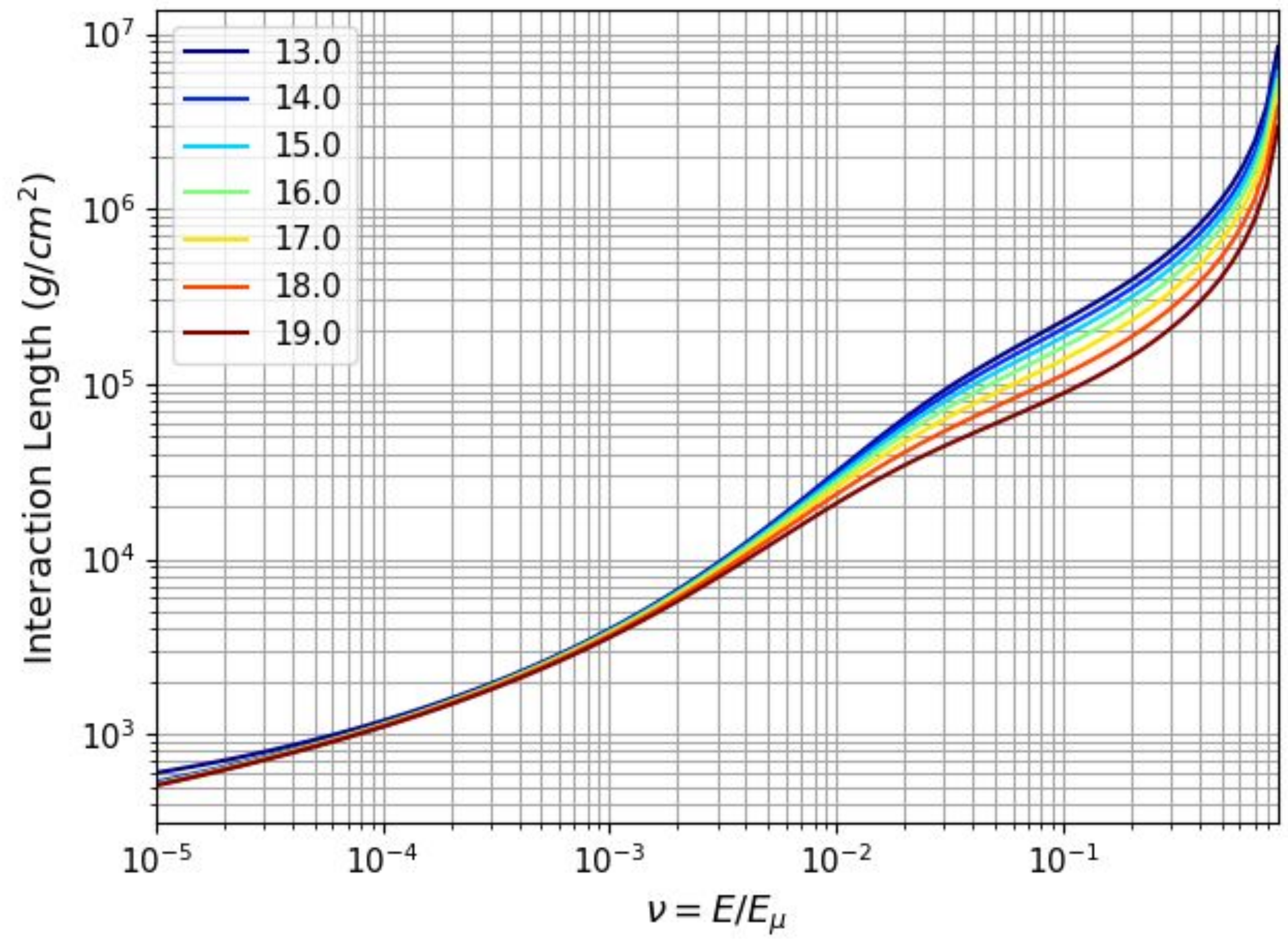




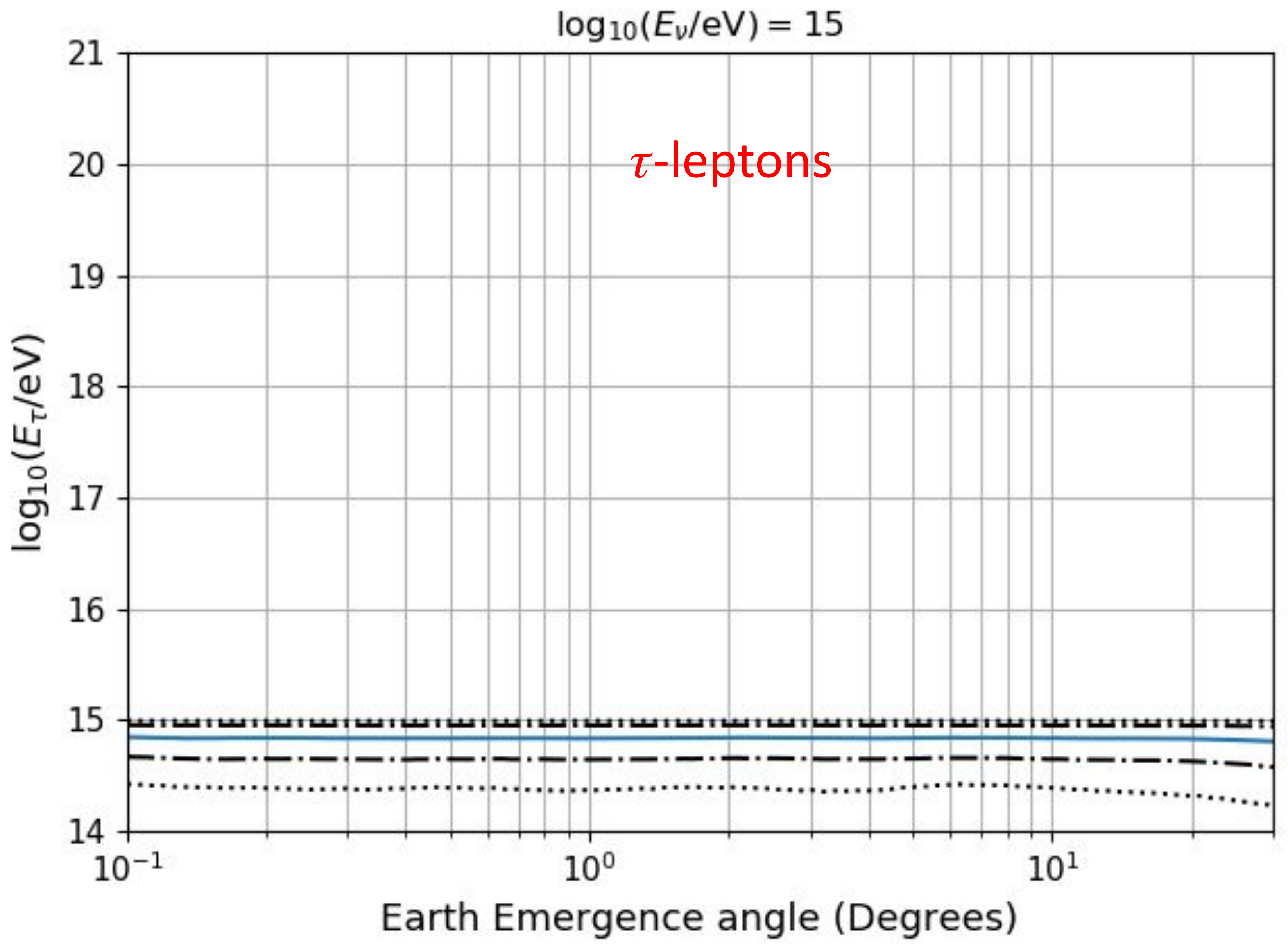
Muon Cross Sections

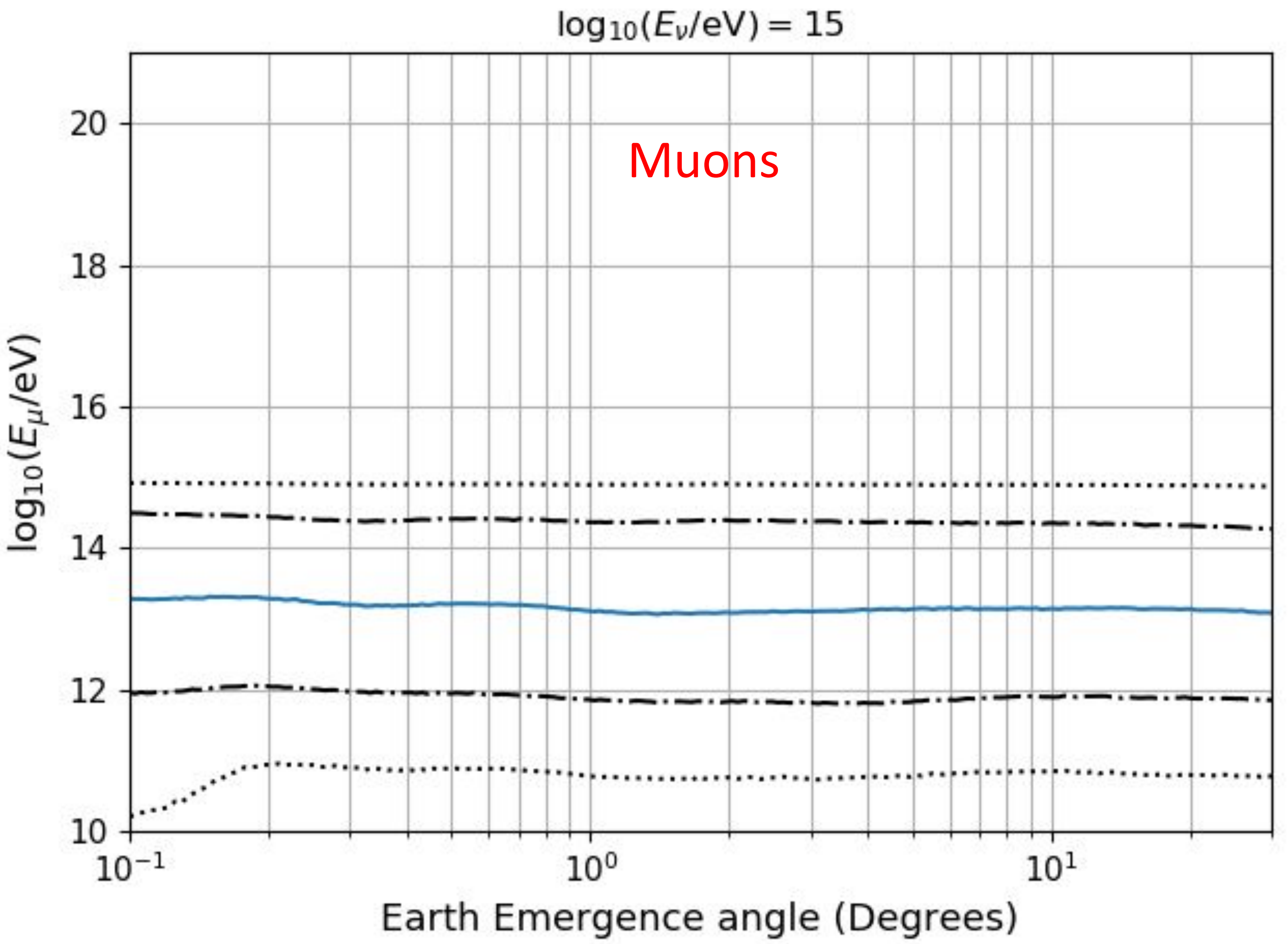






Earth-Emergent Charged Lepton Energy Distributions





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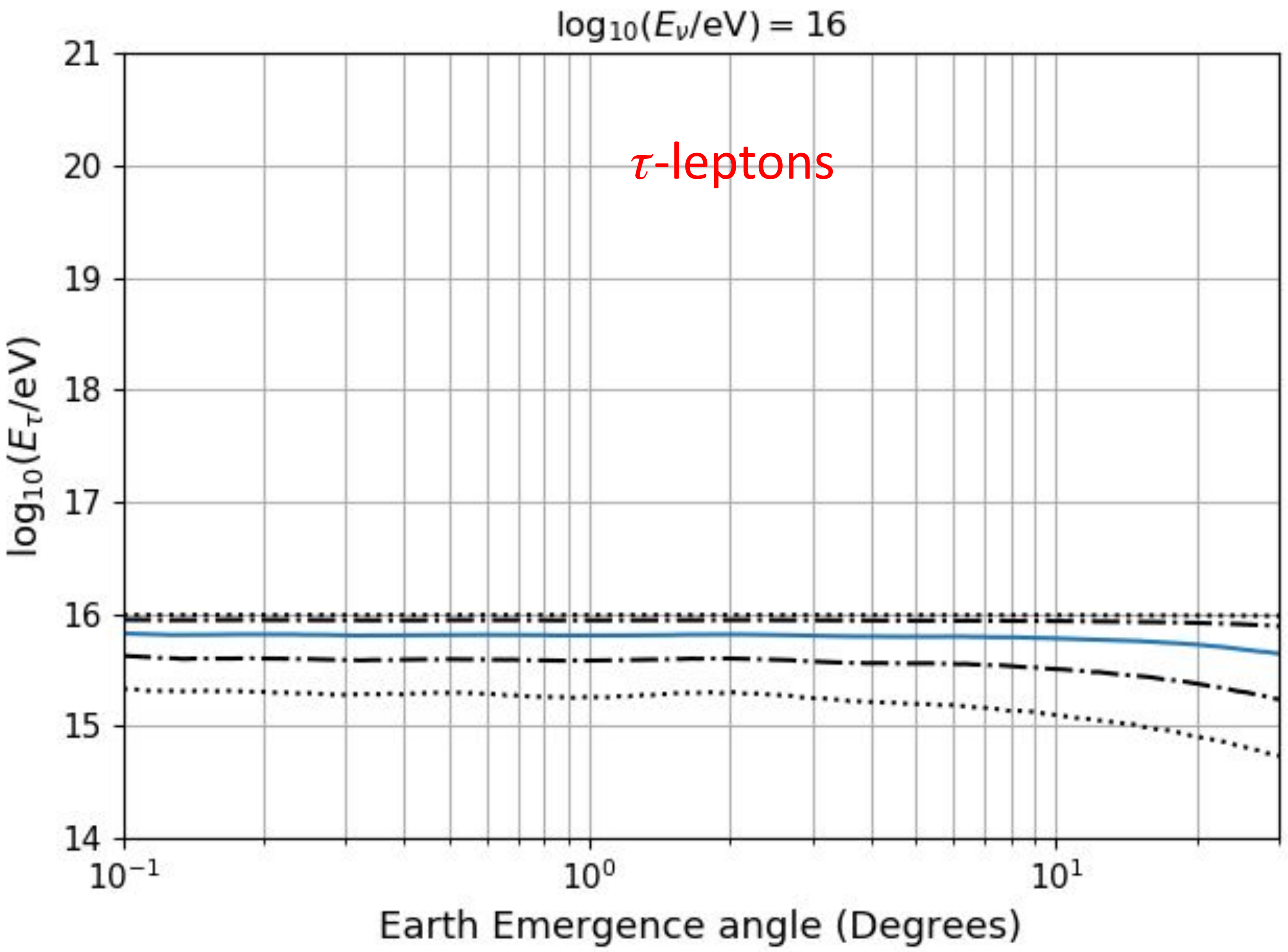

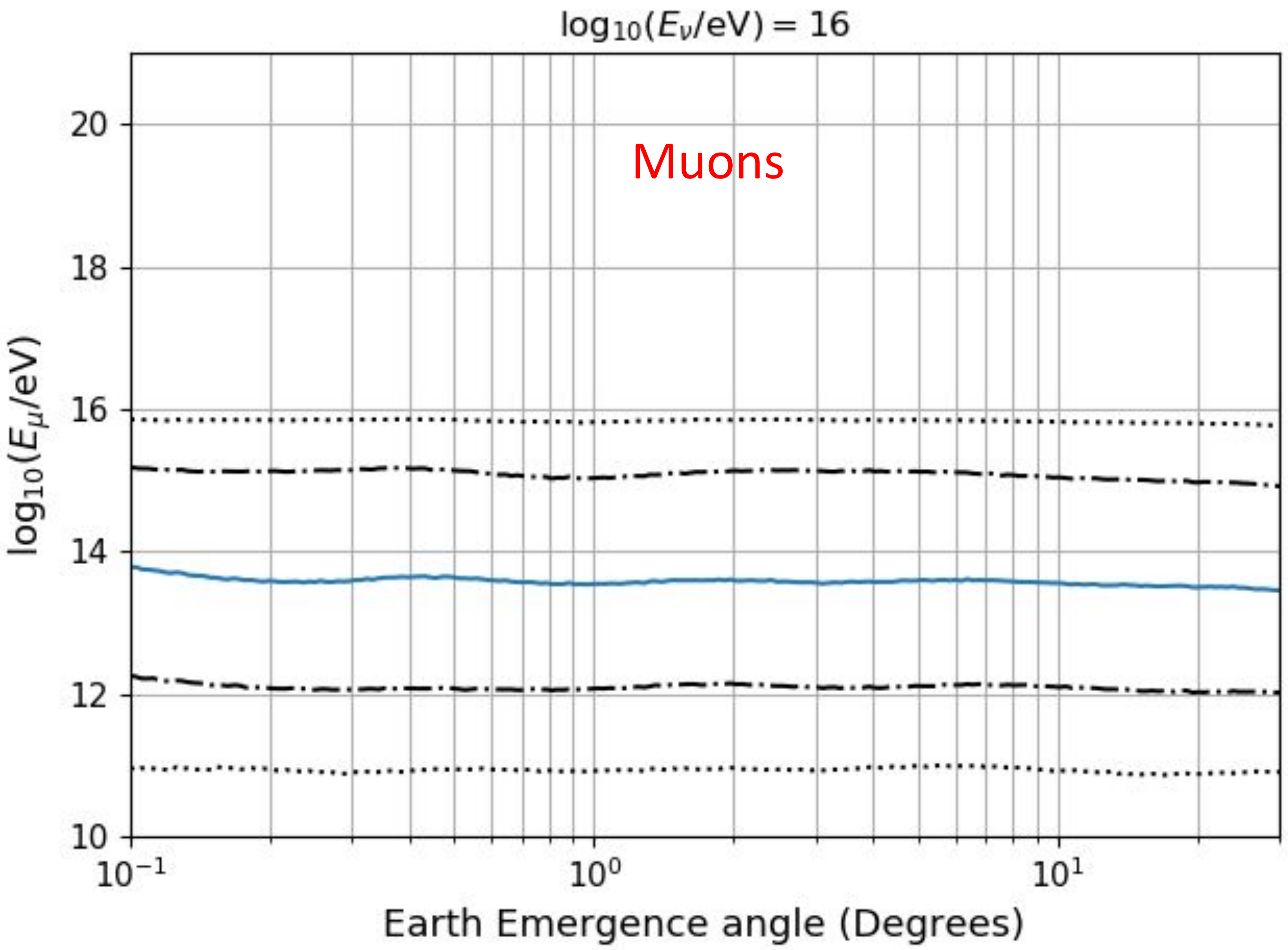

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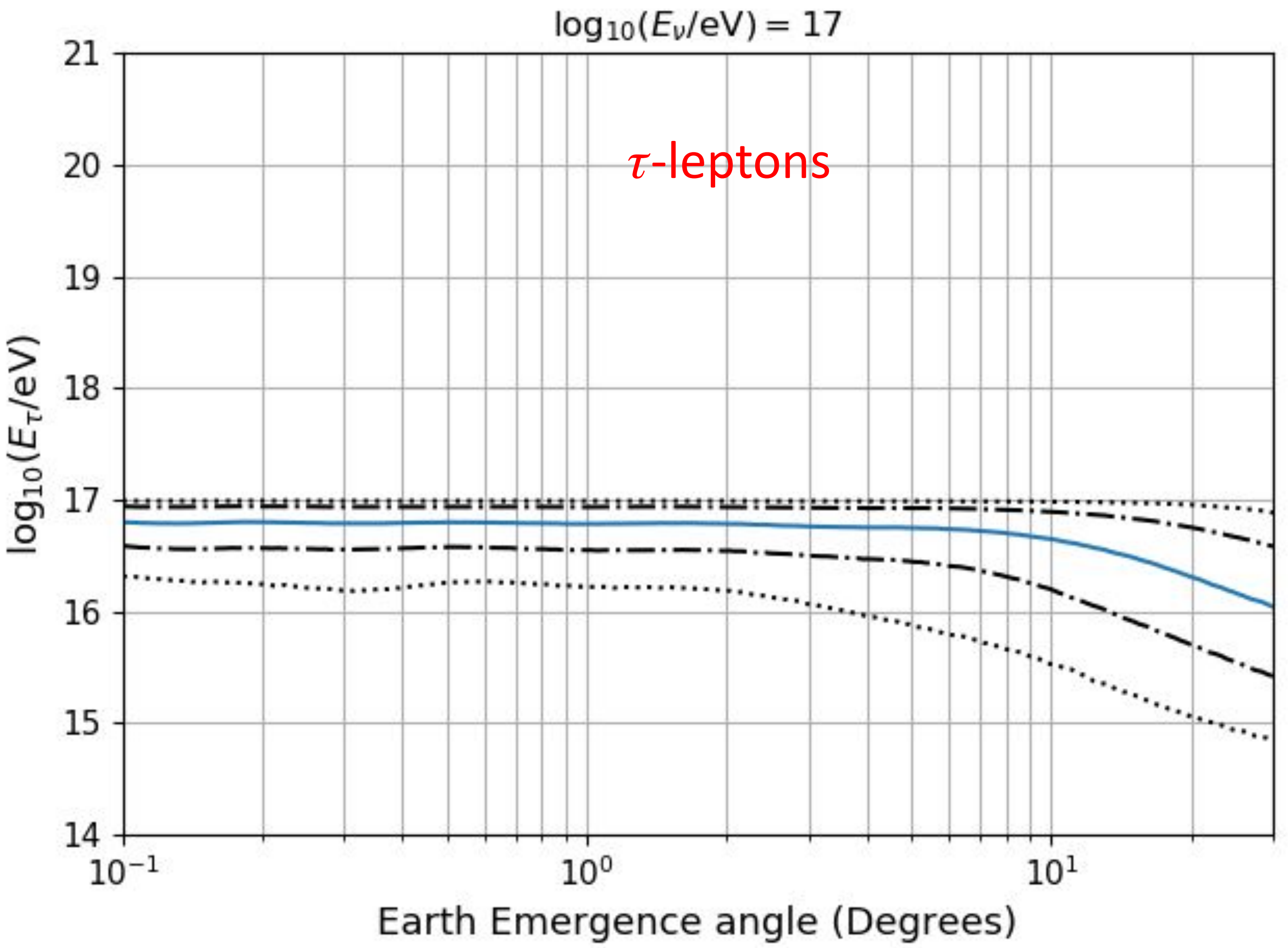

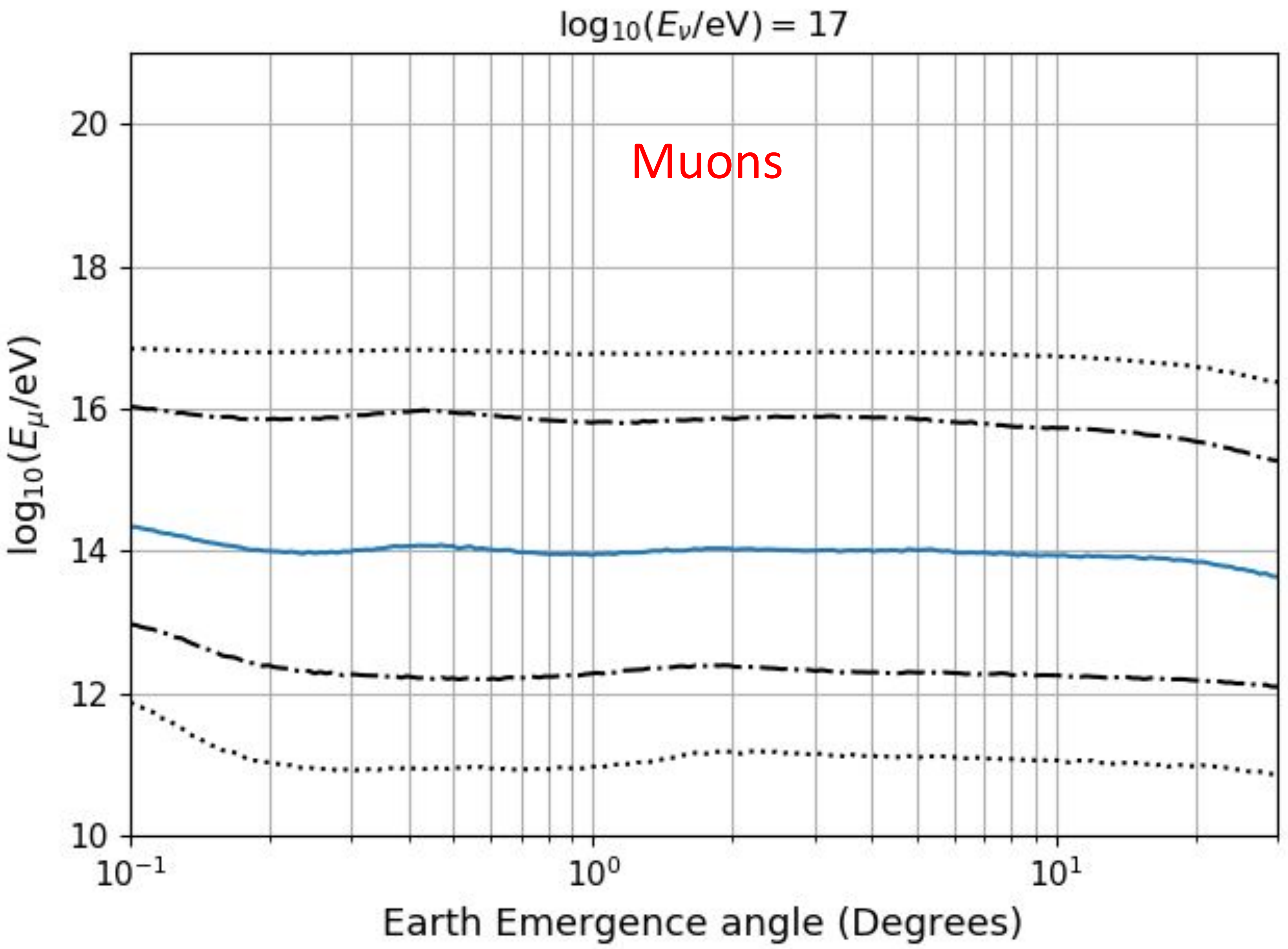

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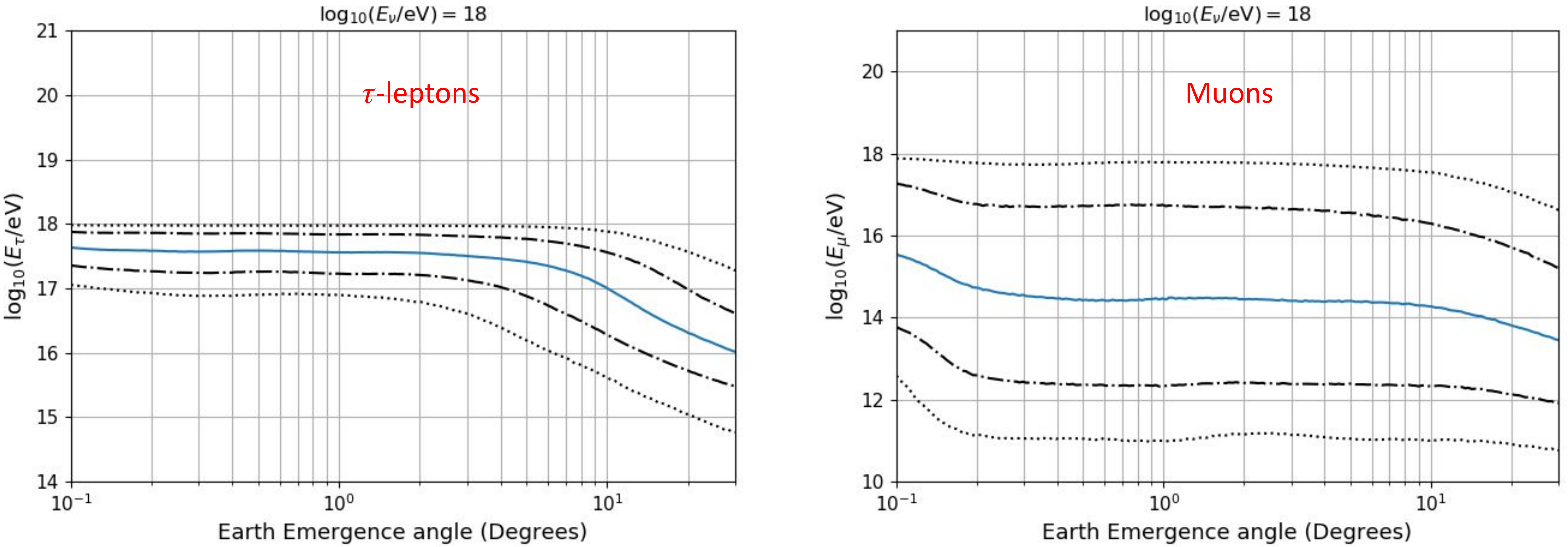

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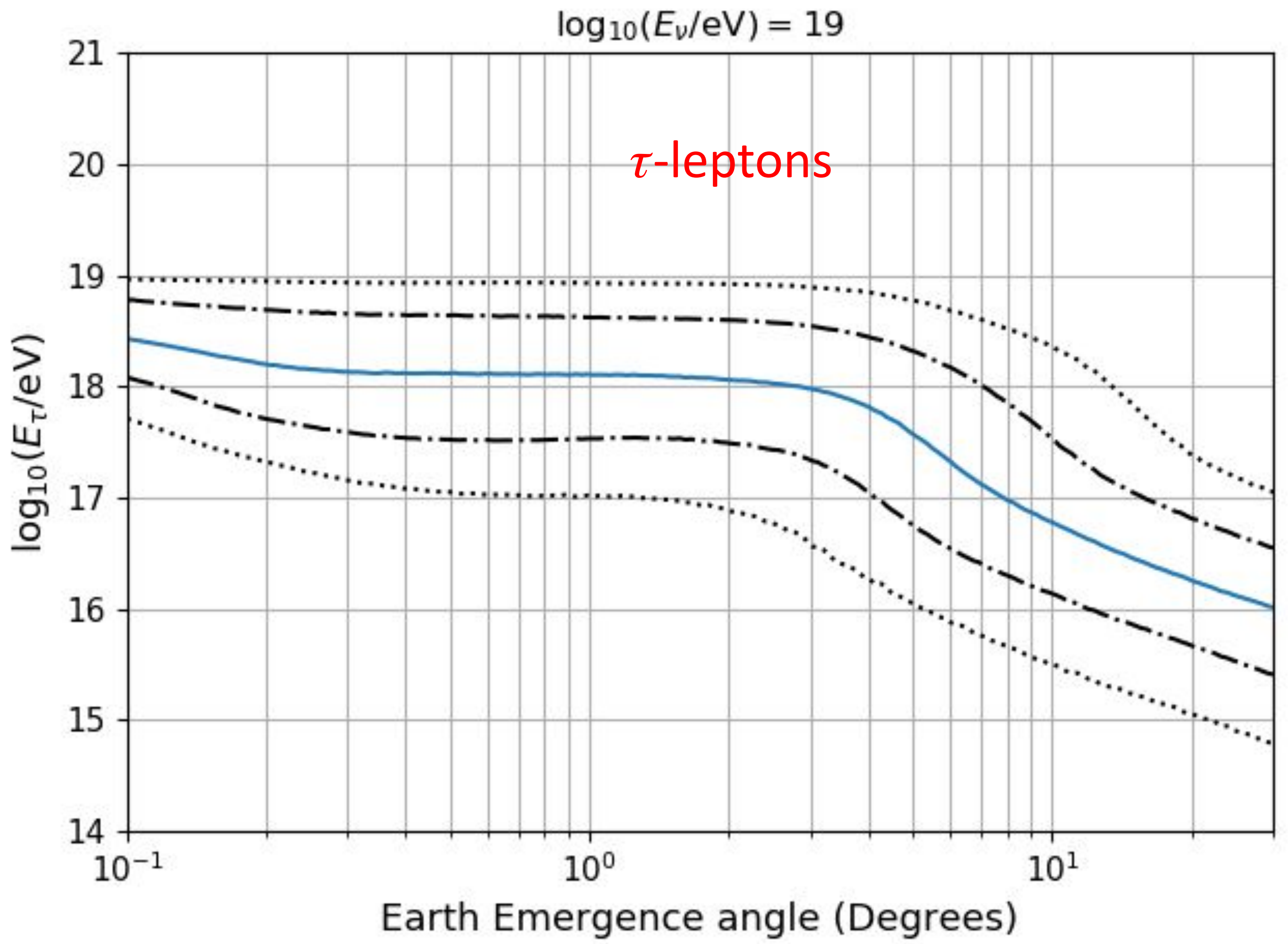

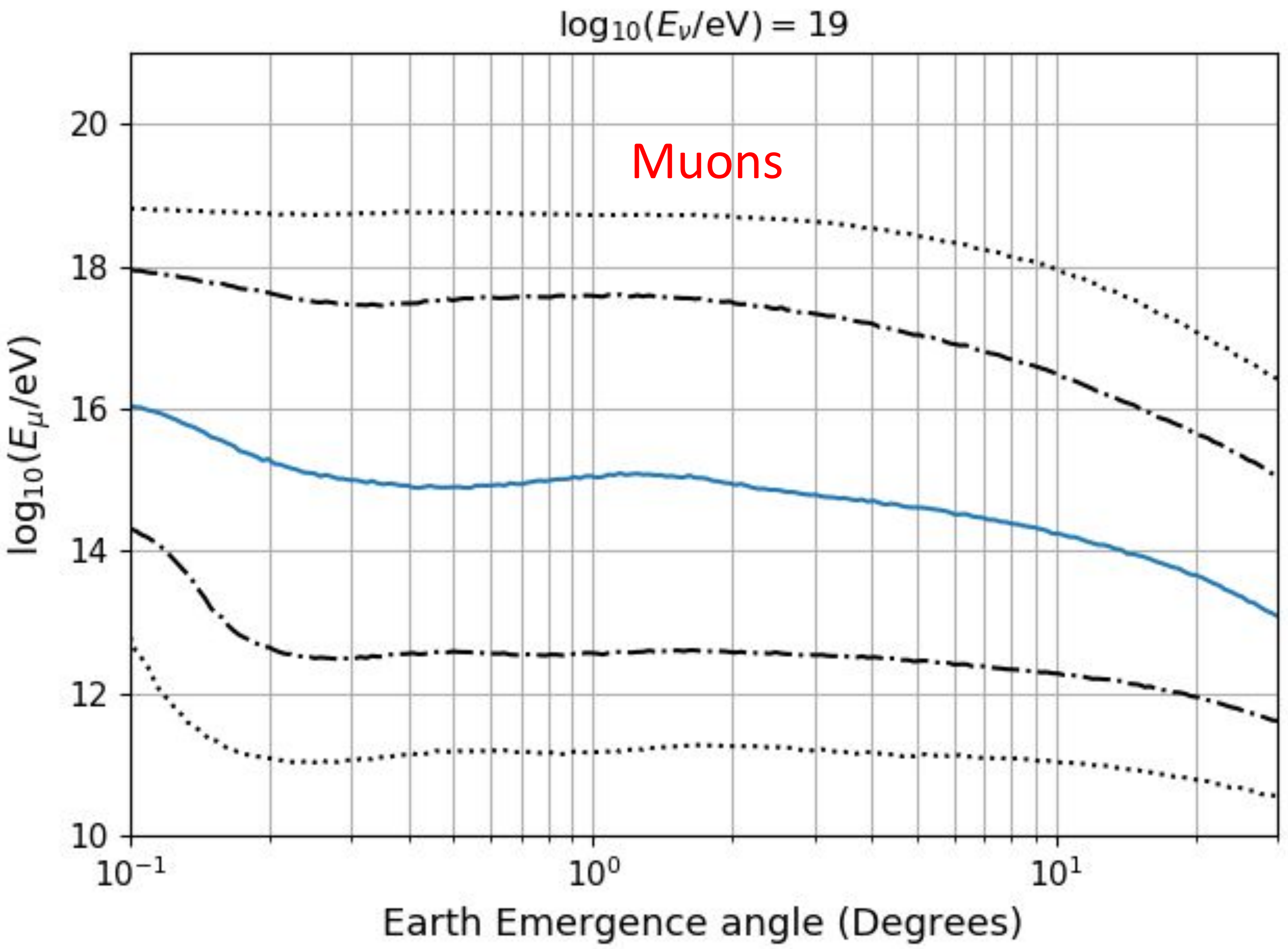

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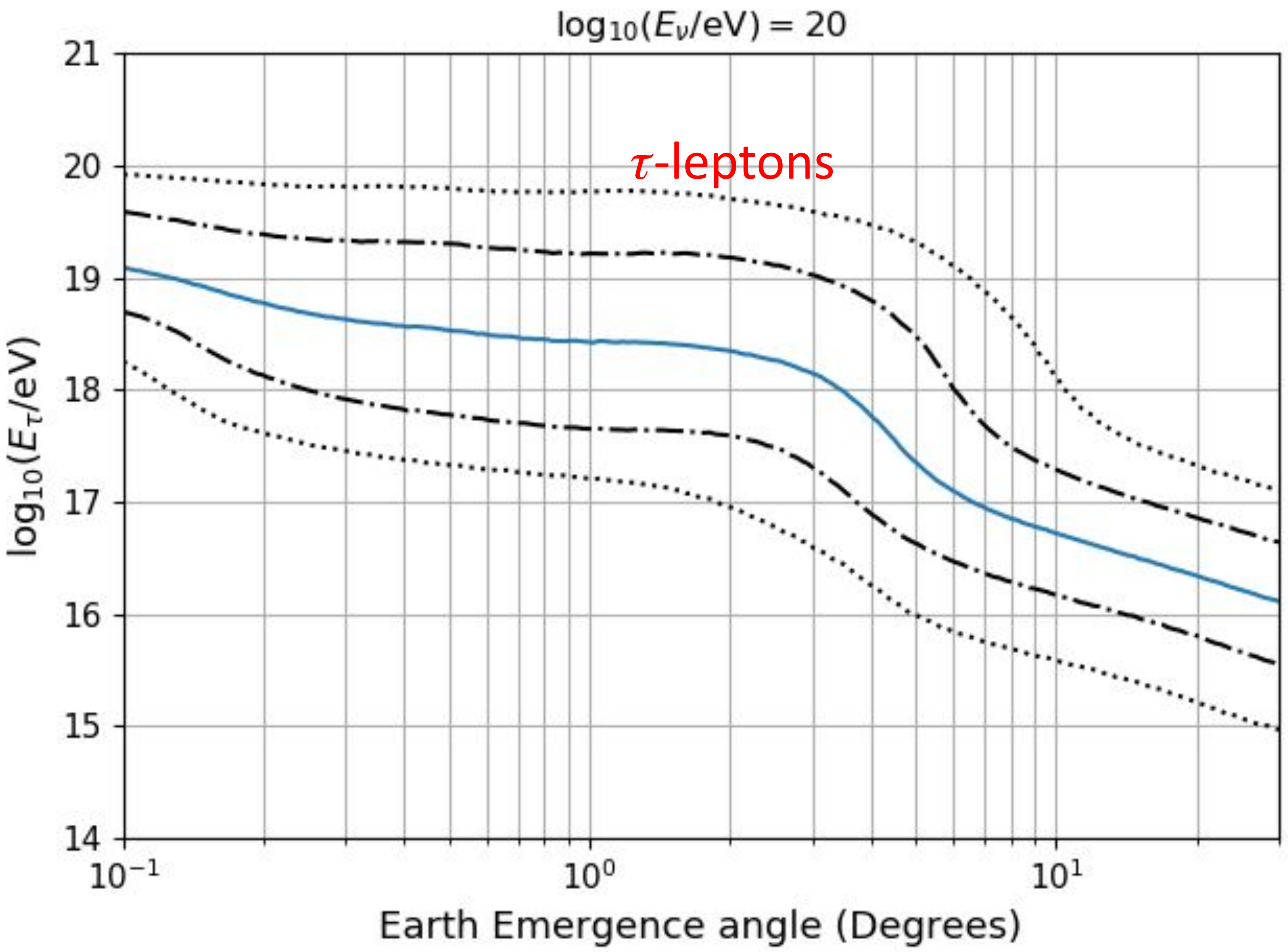

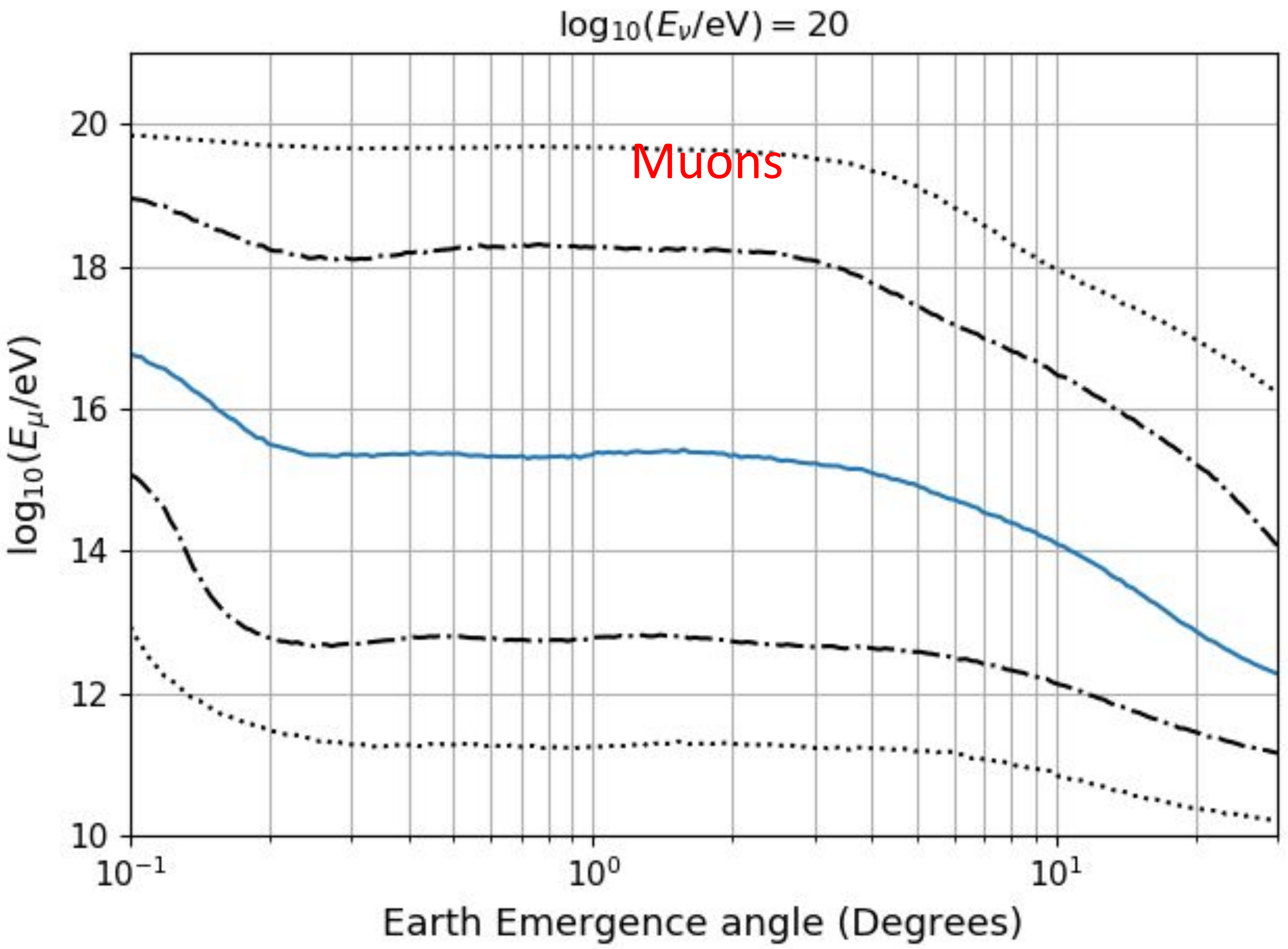

Kernel Density Estimation Example