νSpaceSim: A Comprehensive Simulation for the Modeling of Optical and Radio Signals from Extensive Air Showers Induced by Cosmic Neutrinos for Space-based Experiments

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νSpaceSim

νSpaceSim **is a comprehensive end-to-end simulation package to model the optical and radio signals from extensive air showers (EAS) induced by cosmic neutrino interactions. The development has initially focused on modeling the upward-moving EASs sourced from tau neutrino interactions within the Earth that employs a new modeling package, *nuPyProp*. *νSpaceSim* is designed to model all aspects of the processes that lead to the neutrino-induced EAS signals, including the modeling of the neutrino interactions inside the Earth, propagating the leptons into the atmosphere, modeling the τ-lepton decays, forming composite EAS, generating the air optical Cherenkov and radio signals, modeling their propagation through the atmosphere, including using a MERRA-2 database driven application to generate cloud maps, and modeling detector responses. *νSpaceSim* uses a vectorized Python implementation of a sampled library approach to efficiently simulate neutrino-induced and background signals at a specific orbit or balloon altitude. A detector response module, based on user-inputted response parameters, subsequently is used to record the events and determine acceptance. The framework will allow for the calculation of the sky coverage and the pointing requirements needed for target-of-opportunity (ToO) follow-up observations of transients, as well as the assessment of the effects of dark-sky airglow and UHECR backgrounds. *νSpaceSim* will provide an efficient and practical cosmic neutrino EAS signal generation modeling package to aid in the development of future sub-orbital and space-based experiments.**

Software Architecture & User Input

Vectorized Python wrapper than schedules modules written in higher-level languages, C, C++, Fortran.

- Inherent multi-core processing via Dask
- XML input format and HDF5 library and output format
- Libraries pre-generated, with code to re-generate libraries
- τ-lepton Earth-exit Probability (nuPyProp, nuTauSim)
- τ-lepton decay tables (Pythia)
- EAS longitudinal profiles (CONEX)
- Optical Cherenkov properties via EAS age
- Atmosphere Attenuation: Baseline for Rayleigh scattering, aerosol & ozone absorption
- Cloud and Aerosol libraries from MERRA-2 database
- Detailed Optical Detector modeling
- Radio: based on ZHAireS simulated libraries and standard antennae designs

Example xml User Input File

```xml
<NuSpaceSimParams>
<DetectorCharacteristics Type="Satellite" Method="Optical">
<QuantumEfficiency>0.2</QuantumEfficiency>
<TelescopeEffectiveArea
Unit="Sq.Meters">2.5</TelescopeEffectiveArea>
<PhotoElectronThreshold Preset="True">
<NPE>10</NPE>
</PhotoElectronThreshold>
<DetectorAltitude Unit="km">525.0</DetectorAltitude>
<InitialDetectorRightAscension
Unit="Degrees">0.0</InitialDetectorRightAscension>
<InitialDetectorDeclination
Unit="Degrees">0.0</InitialDetectorDeclination>
</DetectorCharacteristics>
<SimulationParameters DetectionMode="Diffuse">
<MaximumCherenkovAngle
Unit="Degrees">3.0</MaximumCherenkovAngle>
<AngleFromLimb Unit="Degrees">7.0</AngleFromLimb>
<TauShowerType Preset="True">
<FracETauInShower>0.5</FracETauInShower>
</TauShowerType>
<NuTauEnergySpecType SpectrumType="Mono">
<NuTauEnergy>8.0</NuTauEnergy>
</NuTauEnergySpecType>
<AzimuthalAngle Unit="Degrees">360.0</AzimuthalAngle>
<NumTrajs>1000000</NumTrajs>
</SimulationParameters>
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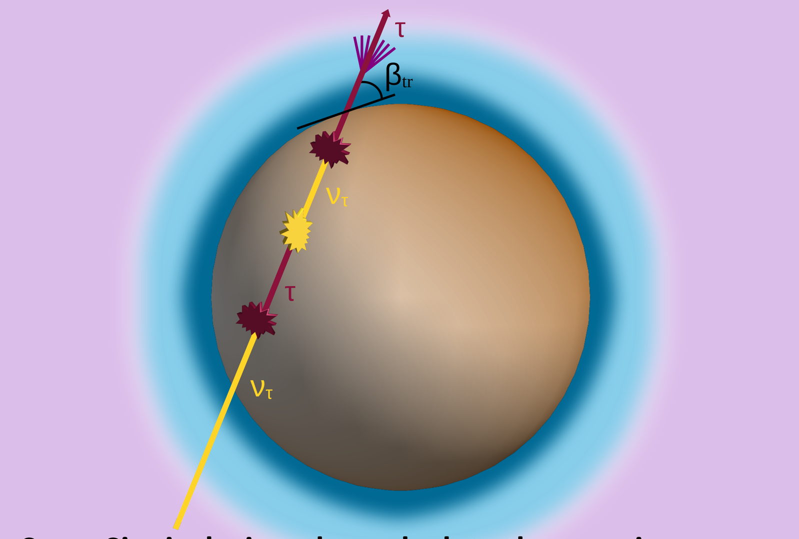
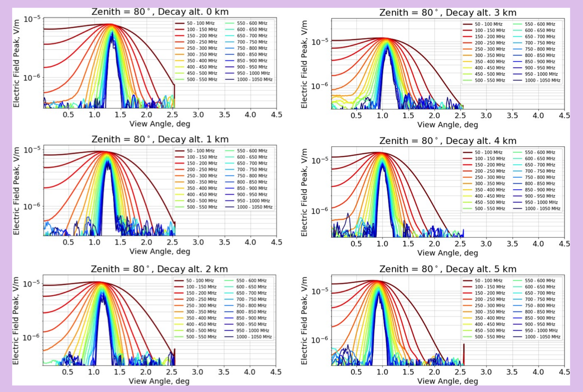
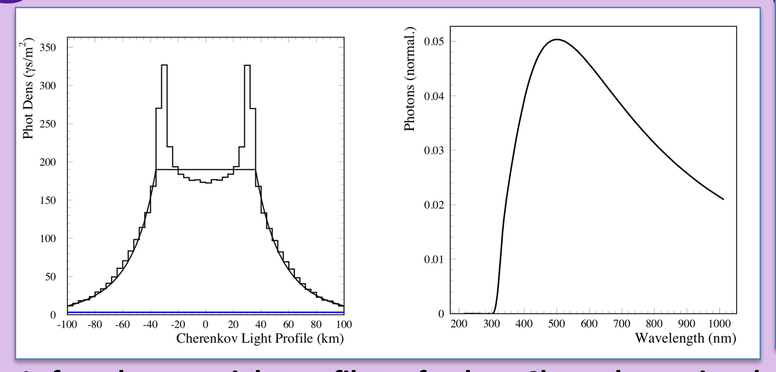


νSpaceSim is designed to calculate the cosmic neutrino sensitivity for space-based experiments fmeasuring the optical Cherenkov and radio EAS signals from Earth-interacting neutrinos. Figure from Patel & Reno: NU ID#482.

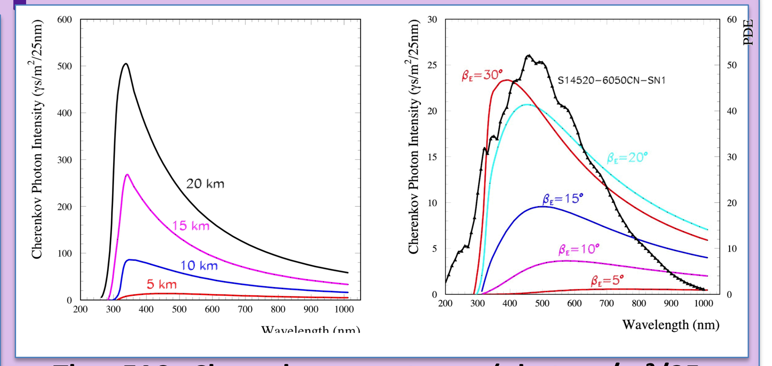
Upward-moving EAS Radio and Optical Cherenkov



Results from the ZHAireS simulation showing the radio pulse spectra at 525 km altitude as a function of observer view angle of the shower for β_{tr} = 10° vs τ-lepton decay altitude for 100 PeV EAS, ignoring ionosphere dispersion.



Left: the spatial profile of the Cherenkov signal (photons/m²) at 525 km altitude for a 100 PeV upward EAS for β_{tr} = 15°. Right: the simulated Cherenkov spectrum at 525 km for the EAS. Ref: JCAP V2021, I06, id007.



The EAS Cherenkov spectrum (photons/m²/25 nm) at 525 km altitude for a 100 PeV upward EAS for β_{tr} = 10°. Left: versus EAS starting altitude Right: versus β_{tr}. . The measured PDE curve of a representative SiPM is overlaid. Ref: JCAP V2021, I06, id007.

Acknowledgements:

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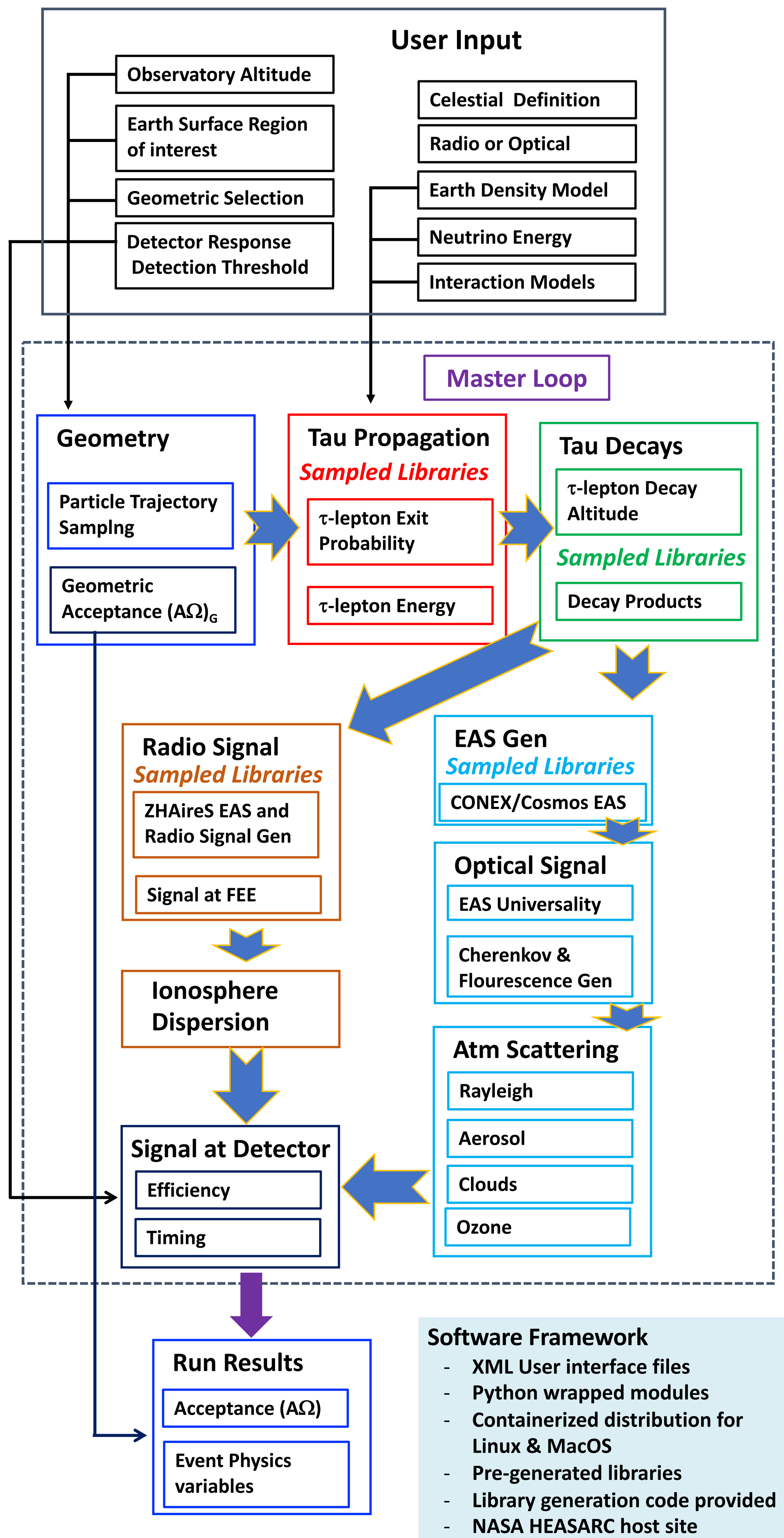
References to related ICRC2021 Papers:

- Sameer Patel: NU ID#482
- Mary Hall Reno: NU ID#248
- Toni Venters: MM ID#1337
- Andres Romero-Wolf: NU ID#205
- Austin Cummings: CRI ID#1002
- Luis Anchordoqui: MM ID#187

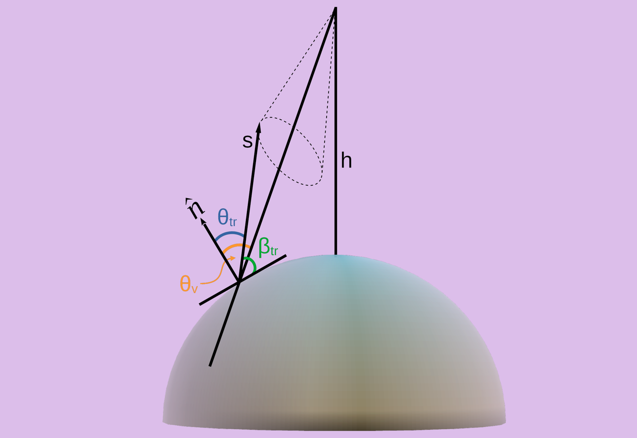
Earth-interacting $\nu_\tau \rightarrow \tau$ EAS Simulation FlowChart



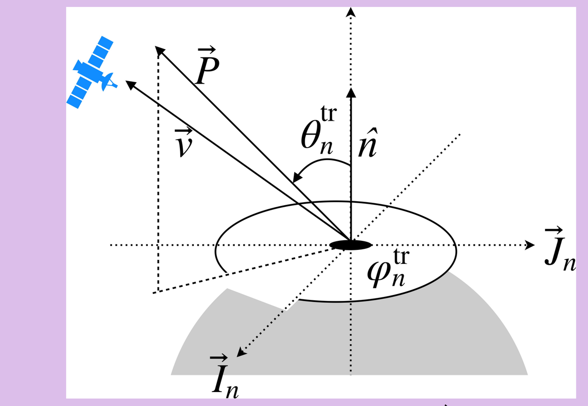
Software Framework

- XML User interface files
- Python wrapped modules
- Containerized distribution for Linux & MacOS
- Pre-generated libraries
- Library generation code provided
- NASA HEASARC host site

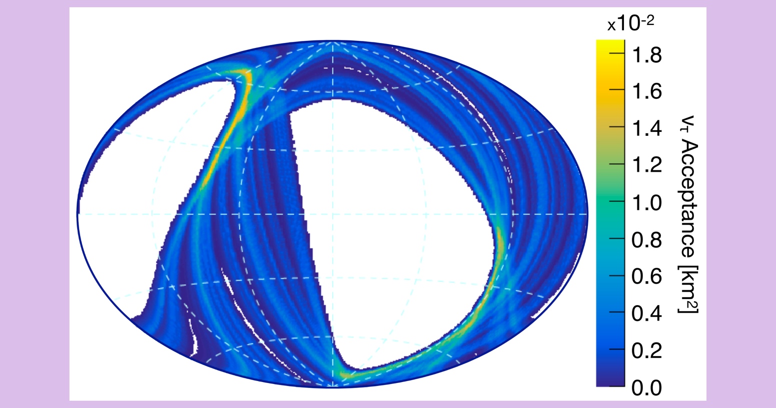
Geometry and Celestial Sky Mapping



The geometry for observing a τ–lepton induced EAS from a detector at altitude h. See NU ID#482.

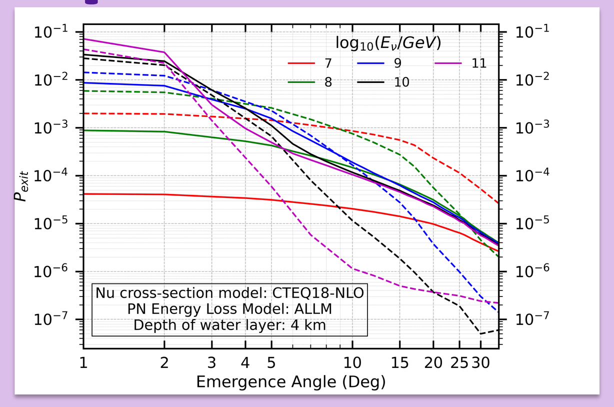


Neutrino trajectory vector ($\vec{\nu}$) in relation to equatorial celestial coordinate: $\hat{I}$ is the vernal equinox direction and $\hat{n}$ is the north pole direction).

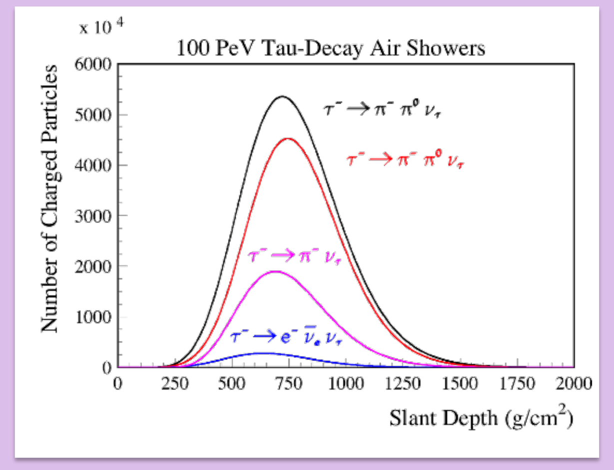


Sky map of the sensitivity to transient neutrino fluxes for the EUSO-SPB2 ULDB instrument assuming observations in astronomical night near new moon. *implementation in progress*, see MM ID#1337.

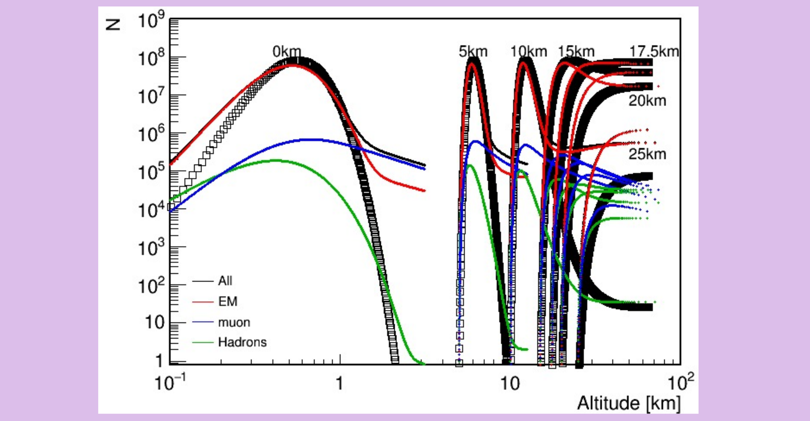
τ-leptons from Earth ν_τ Interactions & EAS Models



τ-lepton P_{exit} versus tau neutrino energy and Earth-emergence angles using CT18-NLO ν cross-sections and ALLM photonuclear τ-lepton energy loss model: $\nu_\tau \rightarrow \tau$ (solid); $\nu_\mu \rightarrow \mu$ (dashed). See NU ID#482.

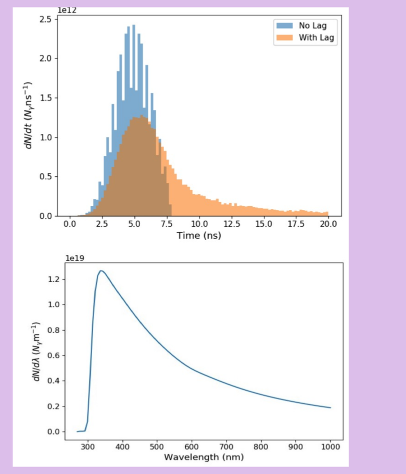


Example composite EAS profiles from various τ-lepton decay channels. *Implementation in progress.*

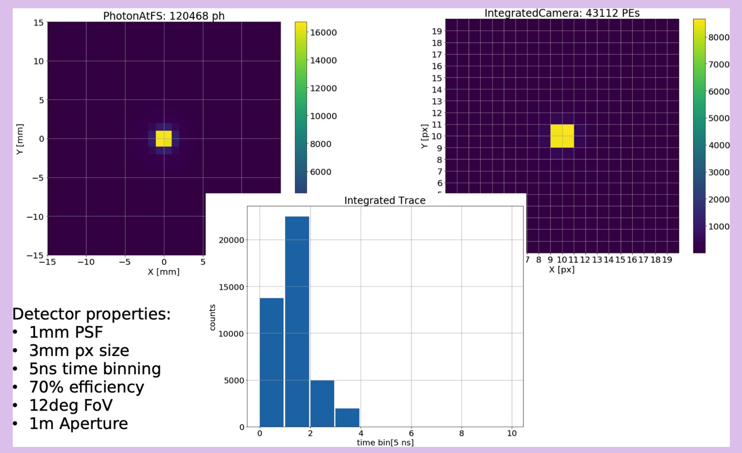


The average longitudinal EAS profiles from the CONEX simulation for 100 PeV pions for β_{tr} = 5° Earth-emergence angle vs of EAS starting altitudes. The various components are shown by the solid lines while the black boxes show the profile from the Greissen parameterization.

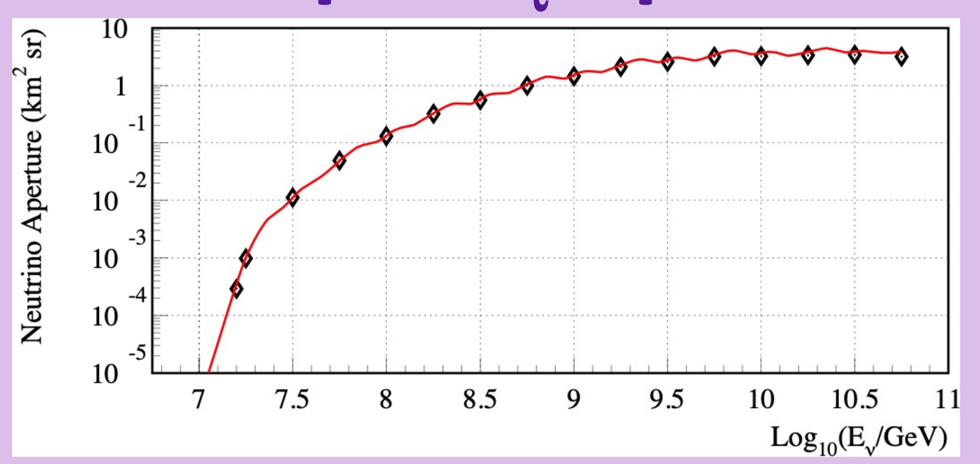
Optical Detector Modeling & Example ν_τ Aperture



Example Optical Chernkov signal properties for a 100 PeV upward-moving EAS. Ref: PhysRevD.103.043017



Example of the modeling of a pixelated optical Cherenkov detector. *Implementation in progress.*



The results of a νSpaceSim calculation of ν_τ aperture) for the diffuse ν_τ flux for a POEMMA-like detector viewing the surface of the Earth 7° below the limb and 360° in azimuth. The points are from νSpaceSim while the red curve is from that used in PhysRevD.100.063010