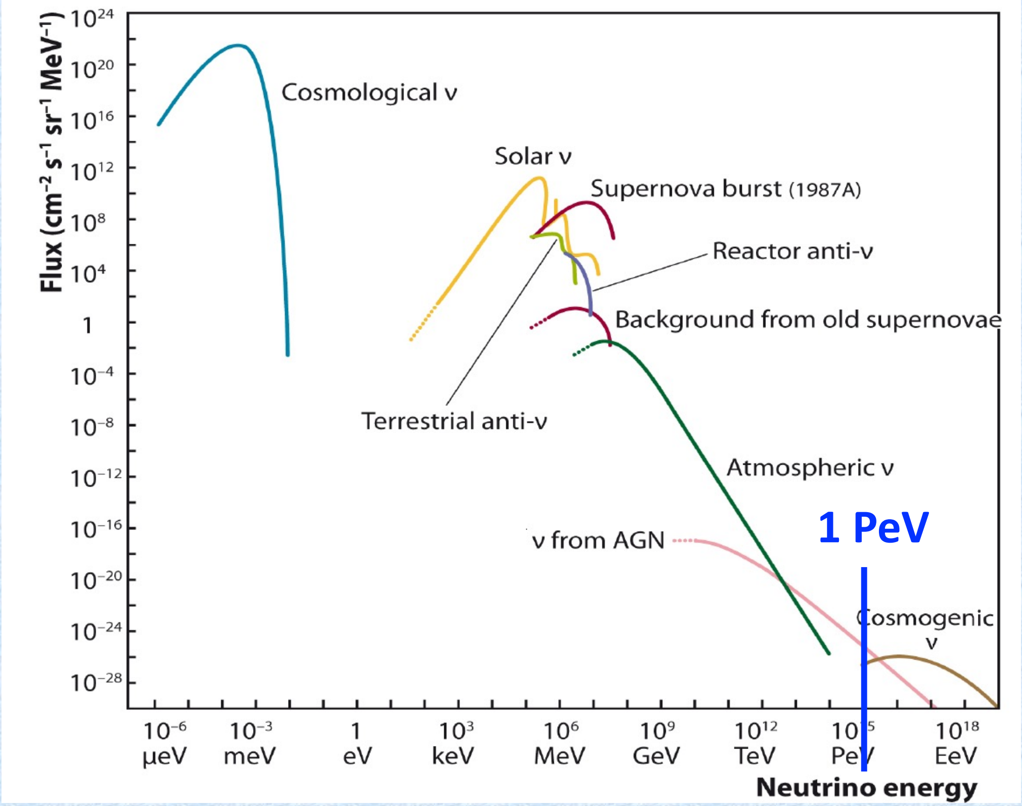
# νSpaceSim: Comprehensive Simulation Package for Modeling the Response of Space-based Experiments to Upward-moving Extensive Air Showers sources by Cosmic Neutrinos in the Earth


## νSpaceSim : End-to-end modeling package for Earth-emergent $\nu_\tau$ – induced upward EAS generating optical Cherenkov and radio signals to guide instrument design and analysis


John Krizmanic (NASA/GSFC)
for the νSpaceSim Collaboration

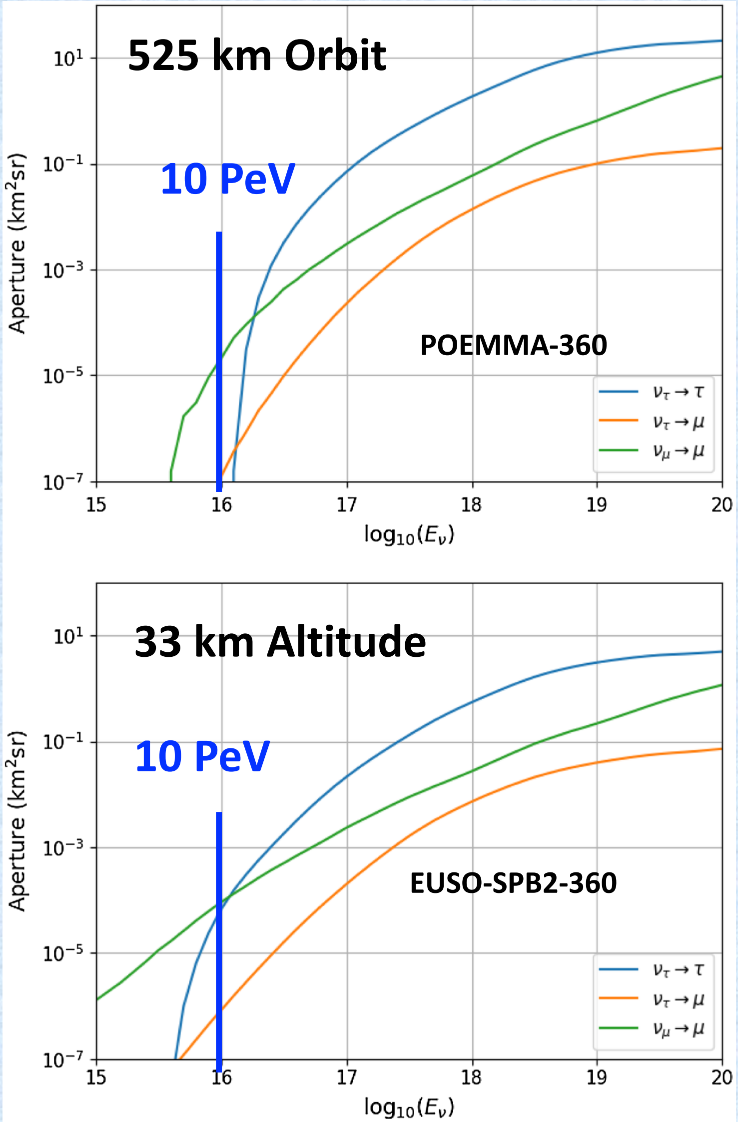
# νSpaceSim motivation: Low $\nu_\tau$ Energy Threshold via Ĉ

Spiering, C. 2012, The European Physical Journal H, 37, 515




Upward τ-lepton induced EAS provide a **beamed optical Cherenkov signal** that leads to **< 10 PeV tau-neutrino detection threshold** in space-based or balloon-based experiments, which is at energies above the atm bkgnd.

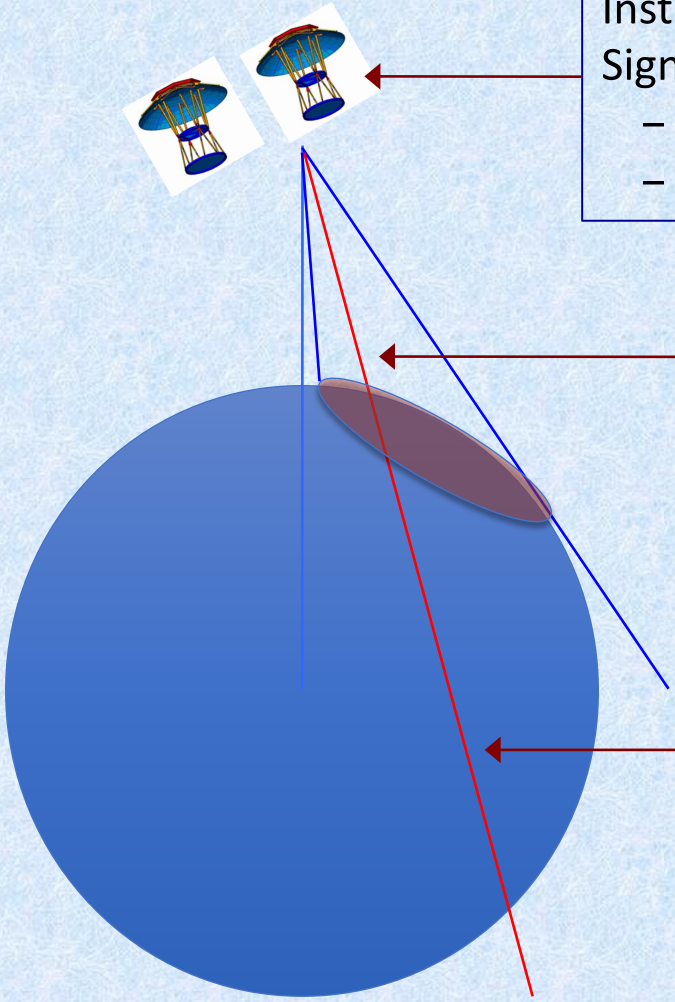
PHYS. REV. D **103,** 043017 (2021)




**Use the Earth and Atmosphere as large neutrino target & detector using extensive air showers (EAS)**

- $\sigma_\nu \approx \sigma_{\nu bar}$ for $E_\nu \gtrsim$ PeV
  - y-dependence similar for charge-current (CC) and neutral-current (NC) interactions

# Simulation Modeling : Simplified Picture



Instrument Response
Signal at Instrument:
- Cherenkov/radio Spatial and temporal profile
- Cherenkov/radio wavelength spectrum

**Detailed definition of instrument**
- **Orientation of viewed Earth/atmosphere**
- **Time/location of observation**
- **Tools to define threshold, eg optical dark-sky background**

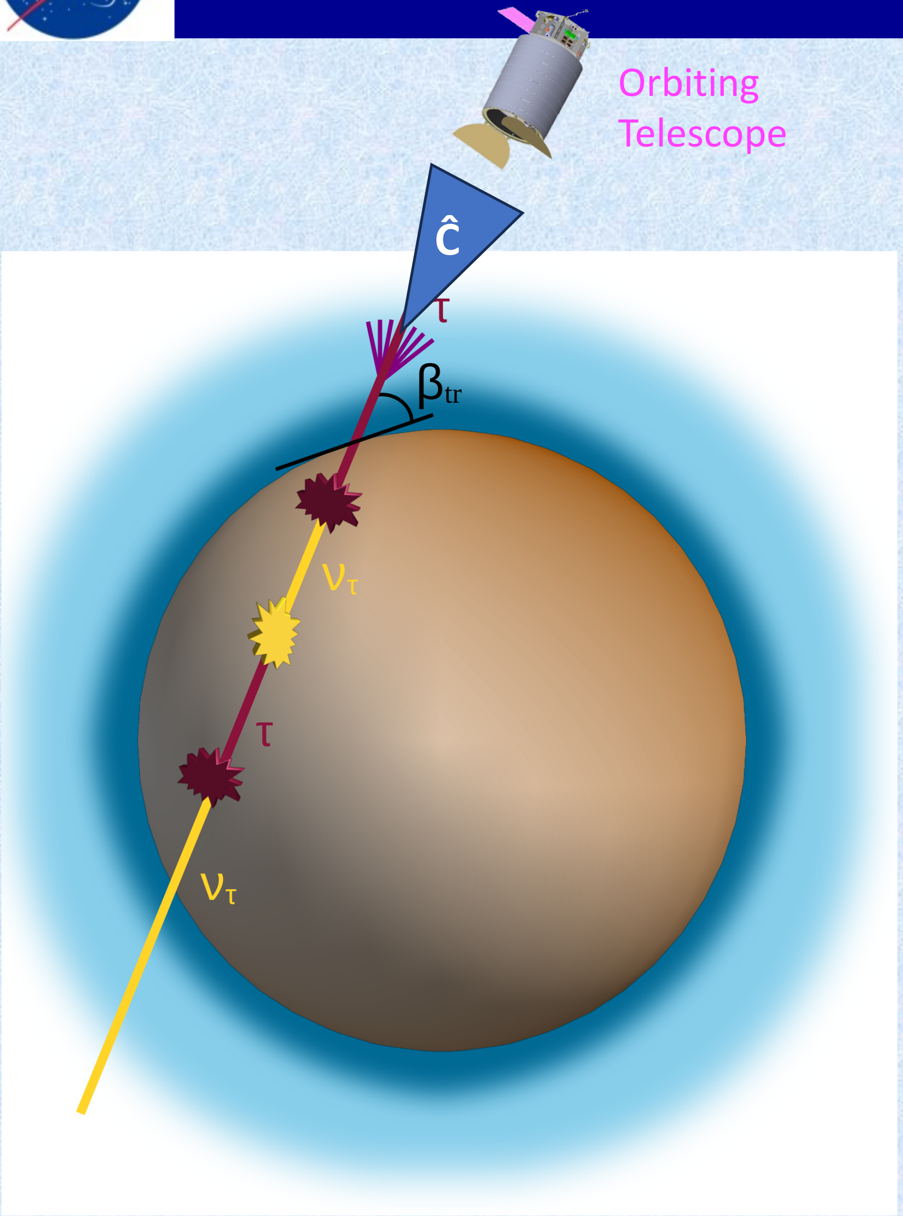
Atmospheric attenuation and scattering of Cherenkov & dispersion of radio signals
Air Shower & Optical and Radio Generation
Tau propagation and decay

**Sampled Libraries:**
- **Tau decay**
- **EAS, eg CONEX**
- **Optical and radio signals**
- **MERRA-2 Data-driven atmosphere model**

Tau propagation & energy loss in Earth, $\nu_\tau$ regeneration
Tau neutrino CC interaction
Tau neutrino flux

**Sampled Libraries:**
- **nuPyProp:**
- **nuTauSim**
- **Any other if defined appropriate input format.**

# Modeling Software Status




## Current Version: νSpaceSim 1.5.1

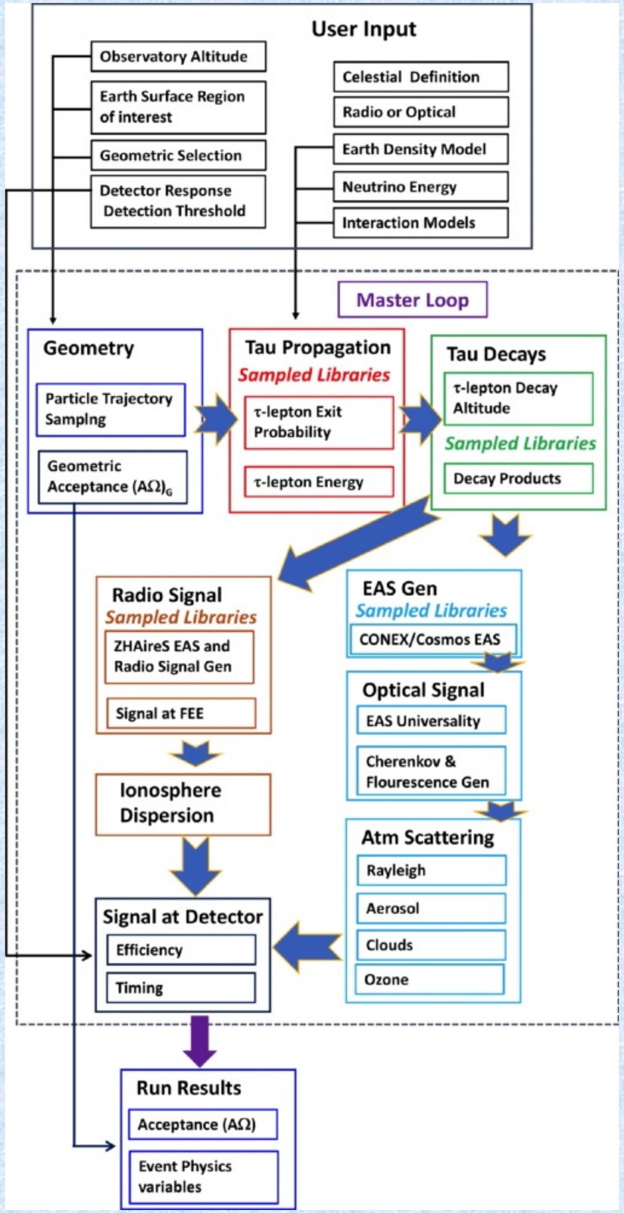
**Features: FAST! $10^6$ Generated events in ~6 min (M2 Mac)**

- nuPyProp $\nu_\tau \rightarrow \tau$-lepton $P_{EXIT}$ generator
- Modeling of optical Cherenkov emission from extensive air showers and Cherenkov light detection
- Modeling of geomagnetic radio emission from EAS, ionospheric dispersion, and radio detection
- Modeling of cosmic diffuse neutrinos
- Modeling of transient neutrino sources
- Cloud attenuation of optical signals based on MERRA-2 database
- User input format in TOML format
- Upward EAS output in CONEX format (Beta)
- Incorporation of CHASM Ĉ light generator (in progress)

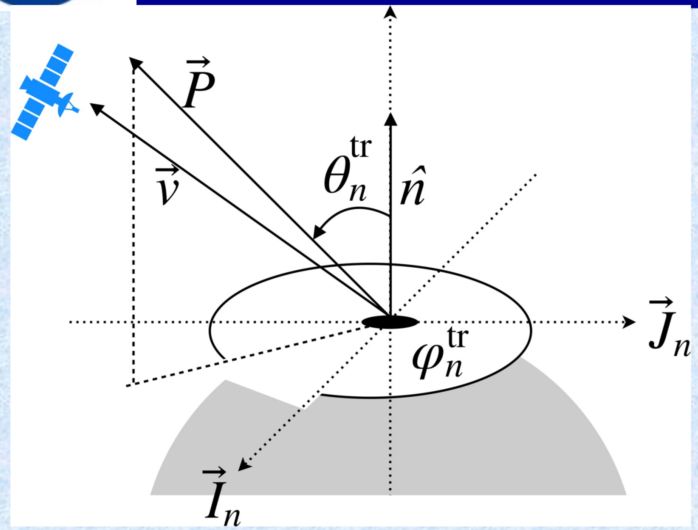
# Simulation Architecture

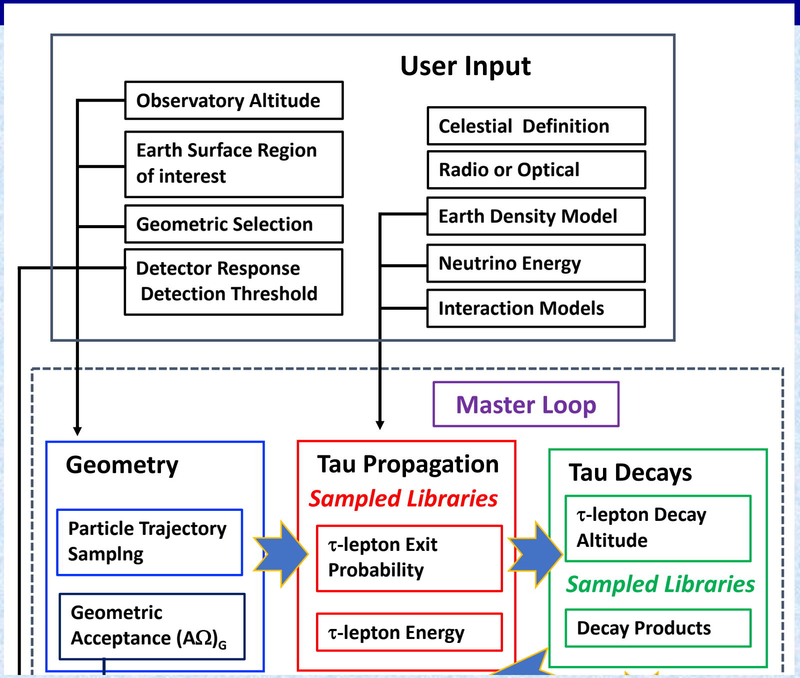
SpaceSim

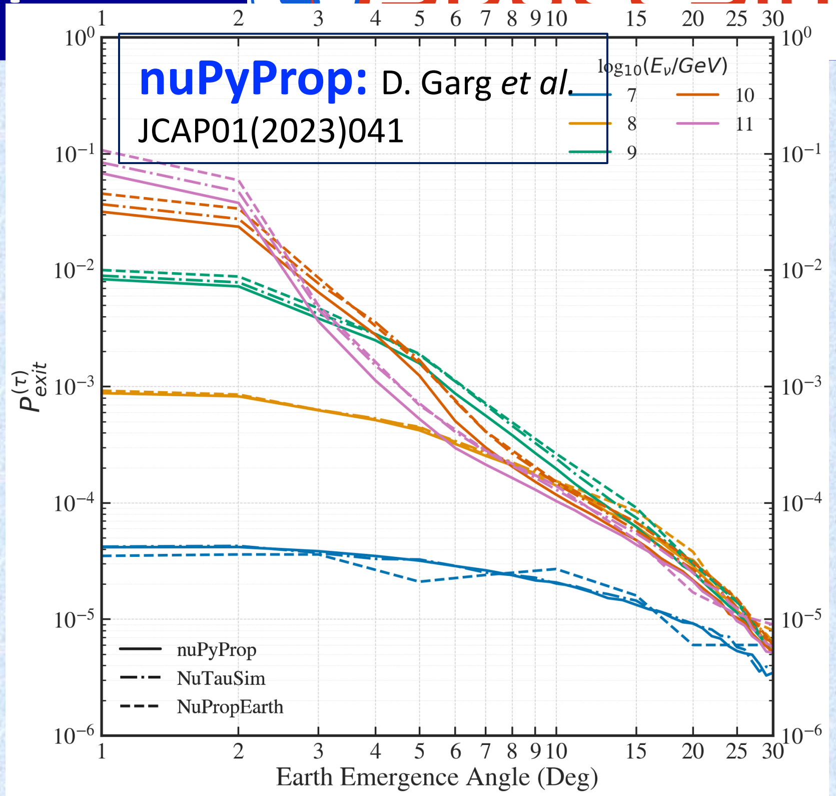
- **Vectorized Python wrapper than schedules modules also written in Python**
  - Inherent multi-core processing via *Dask*
  - TOML input format and HDF5 library and output format
- **Libraries pre-generated, with code of user to re-generate:**
  - $\tau$-lepton exit Probability: nuPyProp (nuLeptonSim *in progress*)
  - $\tau$-lepton decay products: 50% in EAS (Pythia-based *in progress*)
  - EAS longitudinal profiles: Greisen param , Gaisser-Hillas with and without full EAS longitudinal fluctuations in Beta testing
- **Optical:**
  - Optical Cherenkov properties via EAS age (CHASM *in progress*)
  - Atmosphere definition:
    - Baseline for Rayleigh scattering, aerosol & ozone absorption
    - Cloud libraries from MERRA-2 database, time and location dependent
    - Aerosol & Ozone from MERRA-2 (*in progress*)
  - Baseline Detector modeling (more detailed modeling *in progress*)
- **Radio: based on ZHAireS simulated libraries**
  - upgrade in progress 'Accurate&Efficient' method developed by Austin Cummings
  - Modeling of optical and radio correlation (near future)

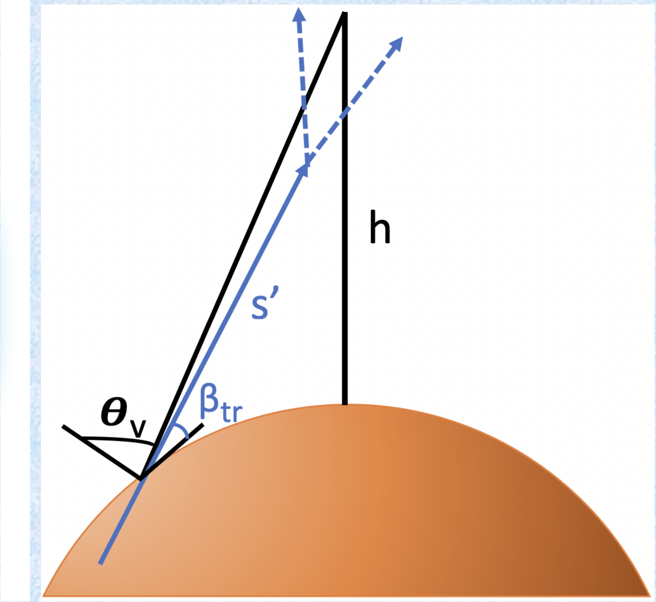


# User Input, Geometry, Tau Yield, EAS Generation

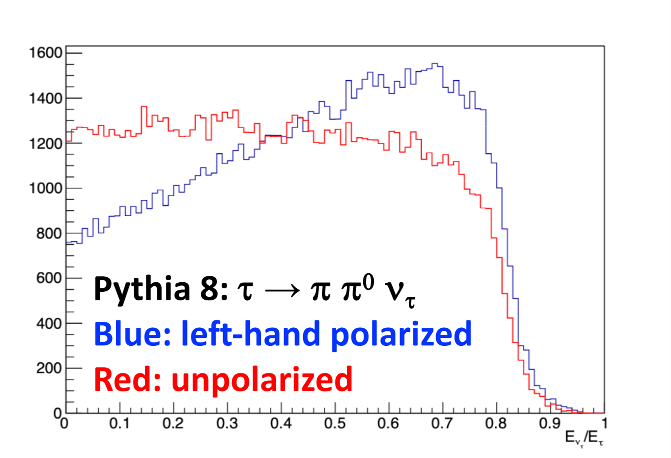


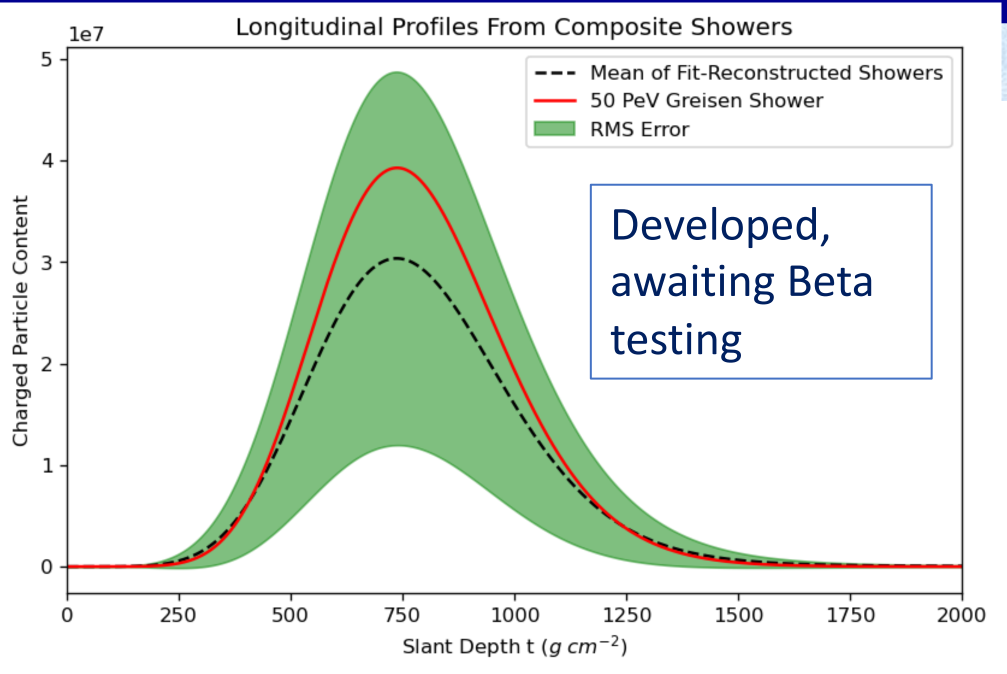




| | Altitude [km] | | |
|---|---|---|---|
| | 3 | 33 | 525 |
| HorizAng [deg] | 88.24 | 84.18 | 67.50 |
| HorizAng -Alpha [deg] | Earth Emerg An [deg] | | |
| 1 | 2.13 | 3.56 | 6.97 |
| 3 | 4.42 | 6.64 | 12.33 |
| 5 | 6.53 | 9.14 | 16.24 |
| 7 | 8.58 | 11.44 | 19.60 |
| 10 | 11.63 | 14.74 | 24.09 |
| 15 | 16.67 | 20.02 | 30.83 |
| 25 | 26.70 | 30.32 | 43.01 |
| 35 | 36.72 | 40.47 | 54.44 |



# Optical Cherenkov Light Generation & Detection




Developed, awaiting Beta testing

**EAS Gen**

***Sampled Libraries***

- **CONEX/Cosmos EAS**

**Optical Signal**

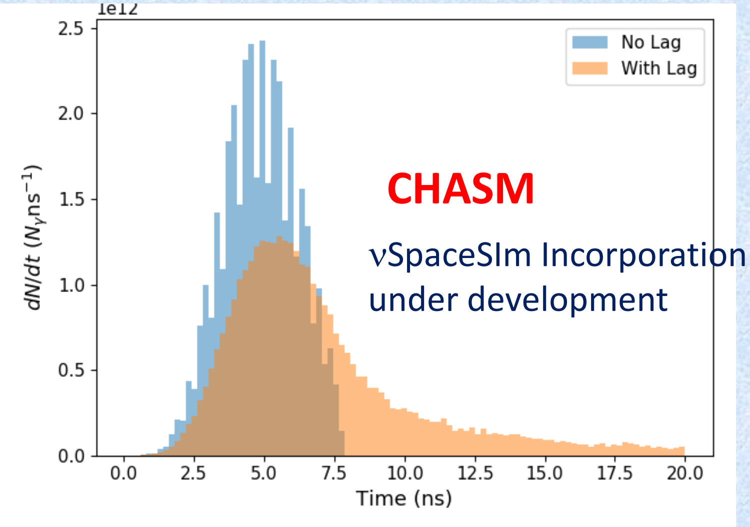
- **EAS Universality**
- **Cherenkov & Flourescence Gen**

**Atm Scattering**

- **Rayleigh**
- **Aerosol**
- **Clouds**
- **Ozone**

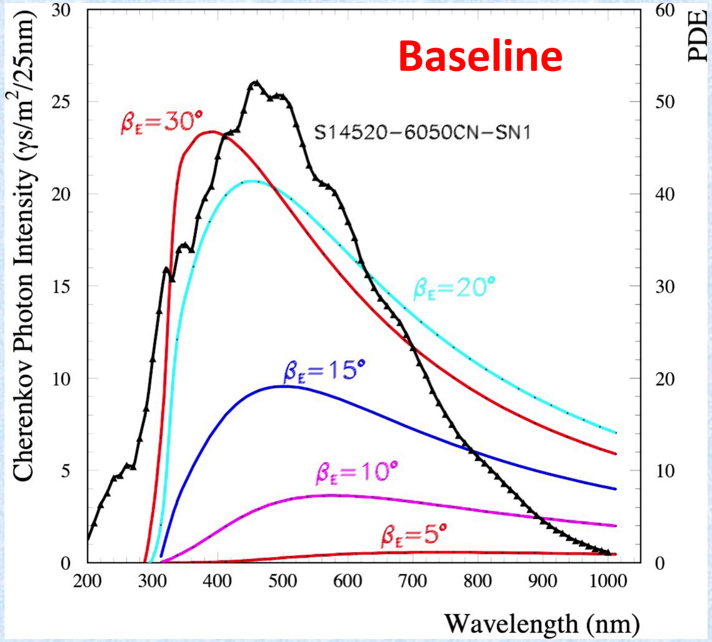
**Signal at Detector**

- **Efficiency**
- **Timing**




**CHASM**

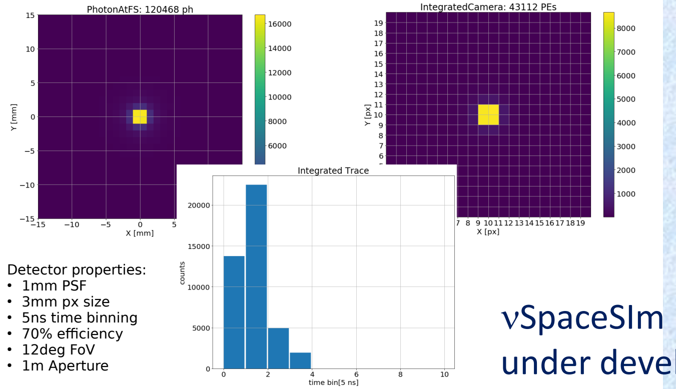
νSpaceSIm Incorporation under development




**Baseline**

## Detector Response Example

- **Shower detector distance 1.5km**




Detector properties:

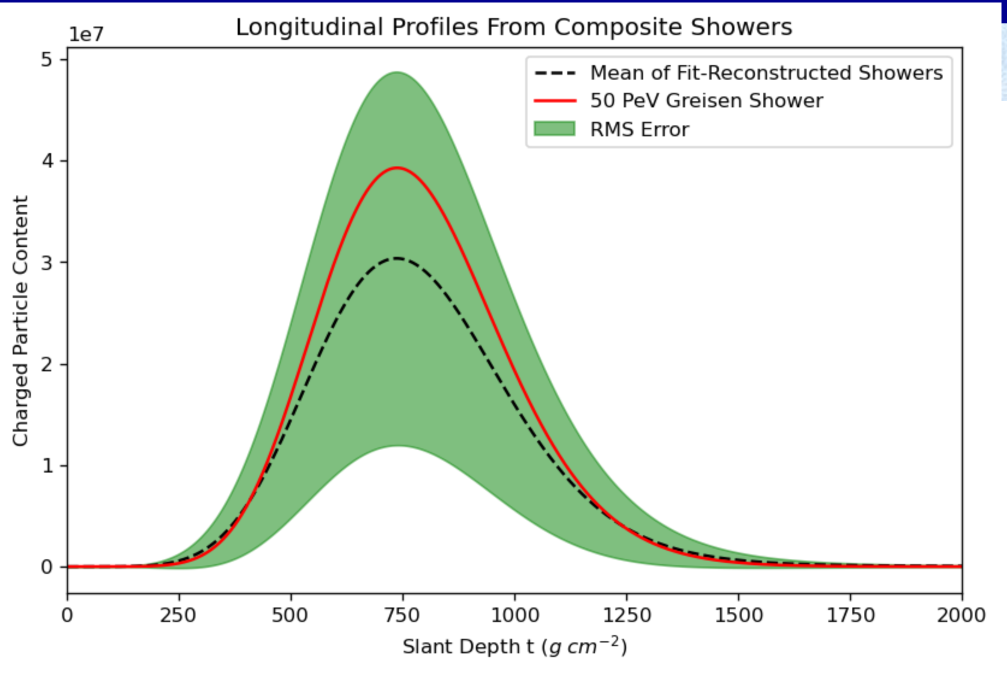
- 1mm PSF
- 3mm px size
- 5ns time binning
- 70% efficiency
- 12deg FoV
- 1m Aperture

νSpaceSIm Incorporation under development

**2021JCAP...06..007P:**

# Optical Cherenkov Light Generation & Detection

SpaceSim



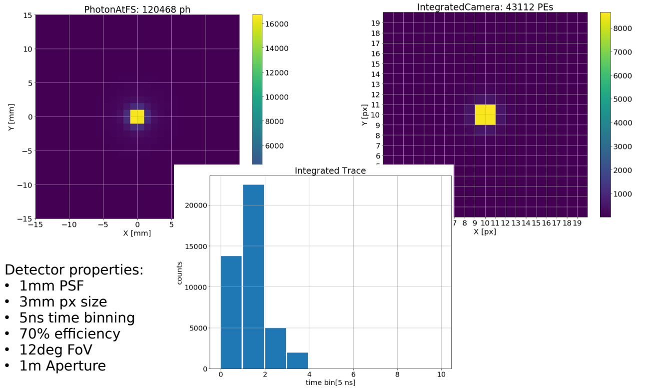

## EAS Gen
***Sampled Libraries***
- CONEX/Cosmos EAS

## Optical Signal
- EAS Universality
- Cherenkov & Flourescence Gen

## Atm Scattering
- Rayleigh
- Aerosol
- Clouds
- Ozone

## Signal at Detector
- Efficiency
- Timing

## Detector Response Example
- **Shower detector distance 1.5km**




Detector properties:
- 1mm PSF
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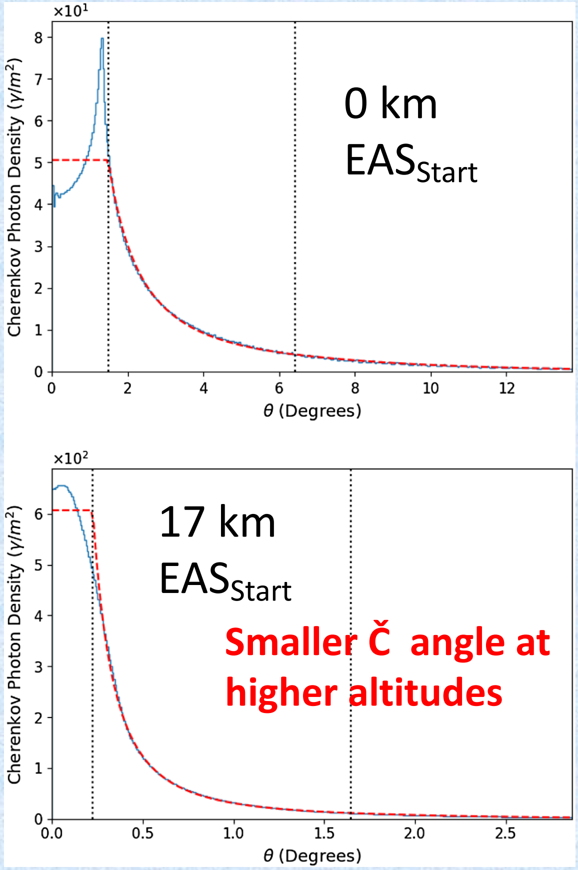



FIG. 17. Upper panel: Cherenkov light distribution for 100 PeV proton shower with 10° Earth emergence angle initiated at 0 km altitude as seen by POEMMA, with profile fits described in the text. Vertical lines show the transition from constant to power law to exponential behaviors. Lower panel: Shower initiated at 17 km altitude.

**PhysRevD.103.043017:**
**A.L. Cummings, R, Aloisi, J.F. Krizmanic**

# Upward-moving EAS: unique development and Radio & Optical Cherenkov signal formation

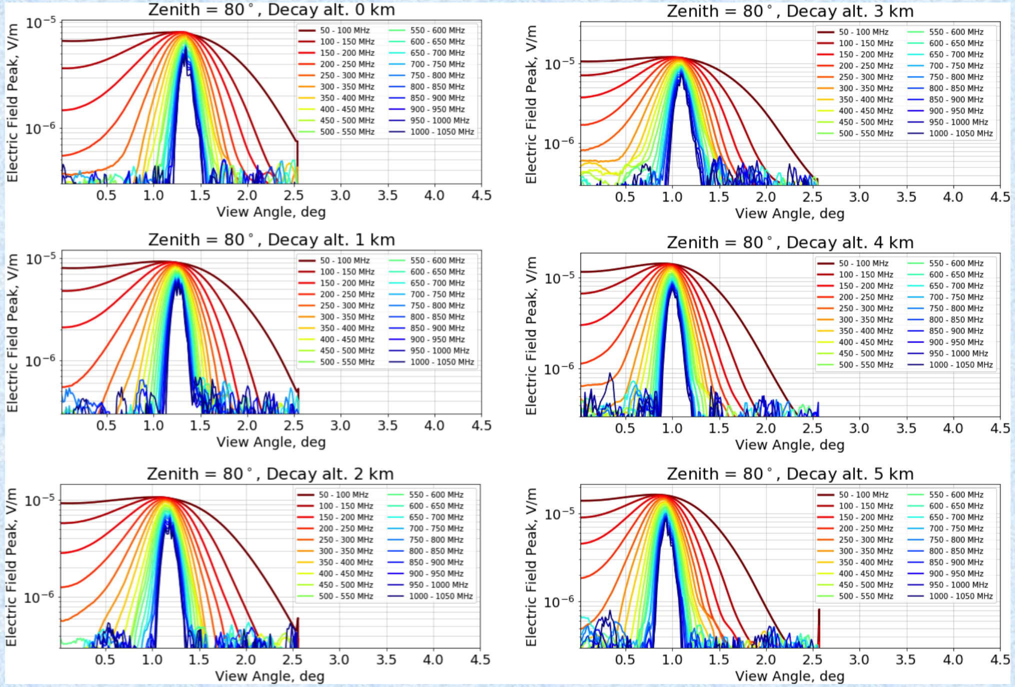
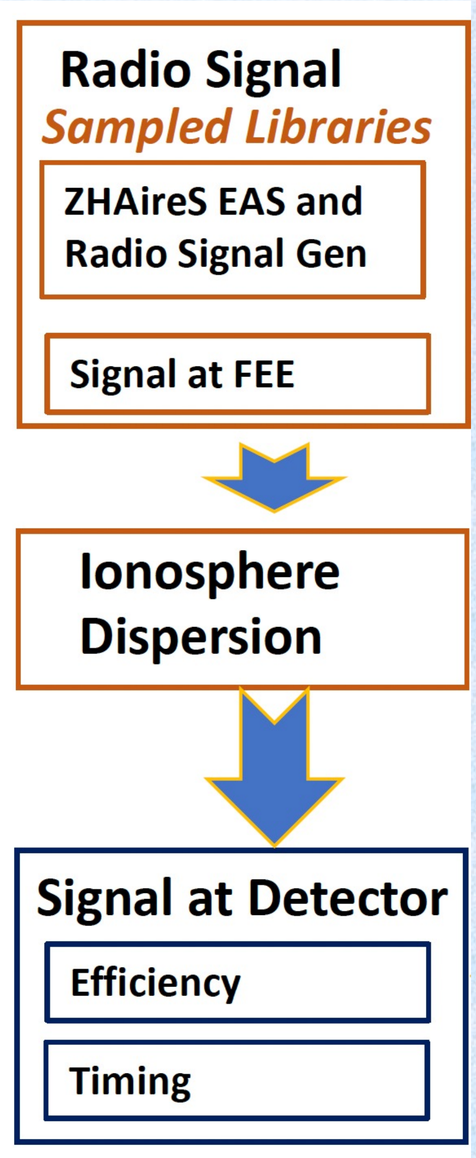



**Figure 4:** Results from the ZHAireS simulation showing the radio pulse spectra at 525 km altitude as a function of observer view angle of the shower for a zenith angle of 80° $\tau$-lepton decay altitude.

PoS(ICRC2021)1205 : J.F Krizmanic, for νSpaceSim

POS(ICRC2021)1031 : A. Romero-Wolf et al. & νSpaceSim

**Geomag Radio: more ω (sterads) for lower frequency signals**




**Radio TOML Input**

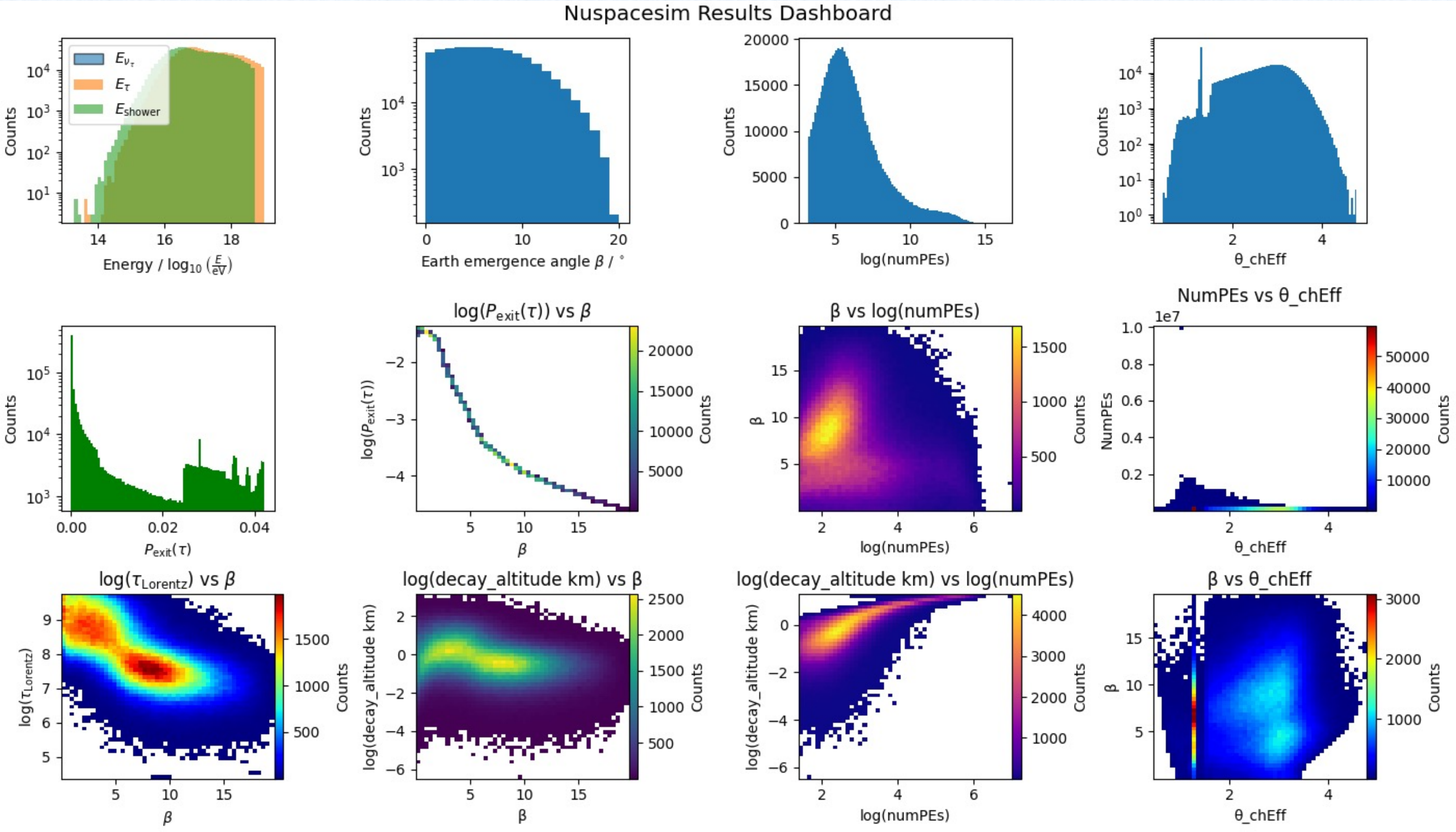
```
[detector.radio]
enable = true
low_frequency = "30.0 MHz"
high_frequency = "300.0 MHz"
snr_threshold = 5.0
nantennas = 10
gain = "1.8 dB"

[simulation]
mode = "Diffuse"
thrown_events = 100
max_cherenkov_angle = "9.0 deg"
max_azimuth_angle = "360.0 deg"
angle_from_limb = "6.4 deg"
cherenkov_light_engine = "Default"

[simulation.ionosphere]
enable = true
total_electron_content = 10.0
total_electron_error = 0.1
```

# Optical Ĉ Results Dashboard Plots: $10^{8.5}$ GeV $\nu_\tau$ Isotropic Flux

SpaceSim

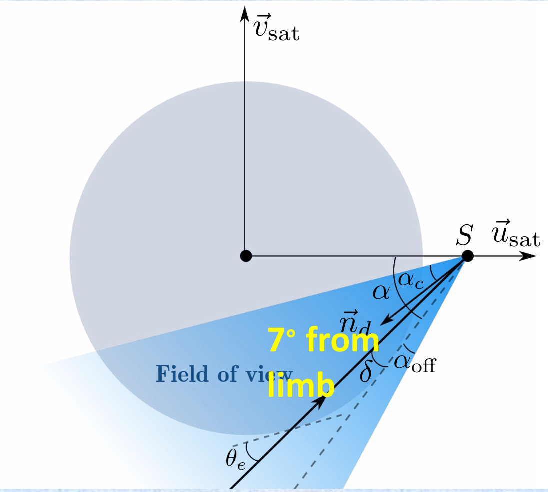
## Example Balloon Mission:

```
title = "NuSpaceSim"

[detector]
name = "Default Name"

[detector.initial_position]
altitude = "33.0 km"
latitude = "-44.6943 deg"
longitude = "169.1417 deg"

[detector.sun_moon]
sun_moon_cuts = true
sun_alt_cut = "-18.0 deg"
moon_alt_cut = "0.0 deg"
moon_min_phase_angle_cut = "150.0 deg"

[detector.optical]
enable = true
telescope_effective_area = "0.625 m2"
quantum_efficiency = 0.2
photo_electron_threshold = 25

[detector.radio]
enable = true
low_frequency = "30.0 MHz"
high_frequency = "300.0 MHz"
snr_threshold = 5.0
nantennas = 10
gain = "1.8 dB"

[simulation]
mode = "Diffuse"
thrown_events = 100
max_cherenkov_angle = "9.0 deg"
max_azimuth_angle = "360.0 deg"
angle_from_limb = "6.4 deg"
cherenkov_light_engine = "Default"

[simulation.ionosphere]
enable = true
total_electron_content = 10.0
total_electron_error = 0.1

[simulation.tau_shower]
id = "nupyprop"
etau_frac = 0.5
table_version = "3"

[simulation.spectrum]
id = "monospectrum"
log_nu_energy = 8.0

[simulation.cloud_model]
id = "no_cloud"

[simulation.target]
source_RA = "0.0 deg"
source_DEC = "0.0 deg"
source_date = "2022-06-02T01:00:00"
source_date_format = "isot"
source_obst = 86400
```



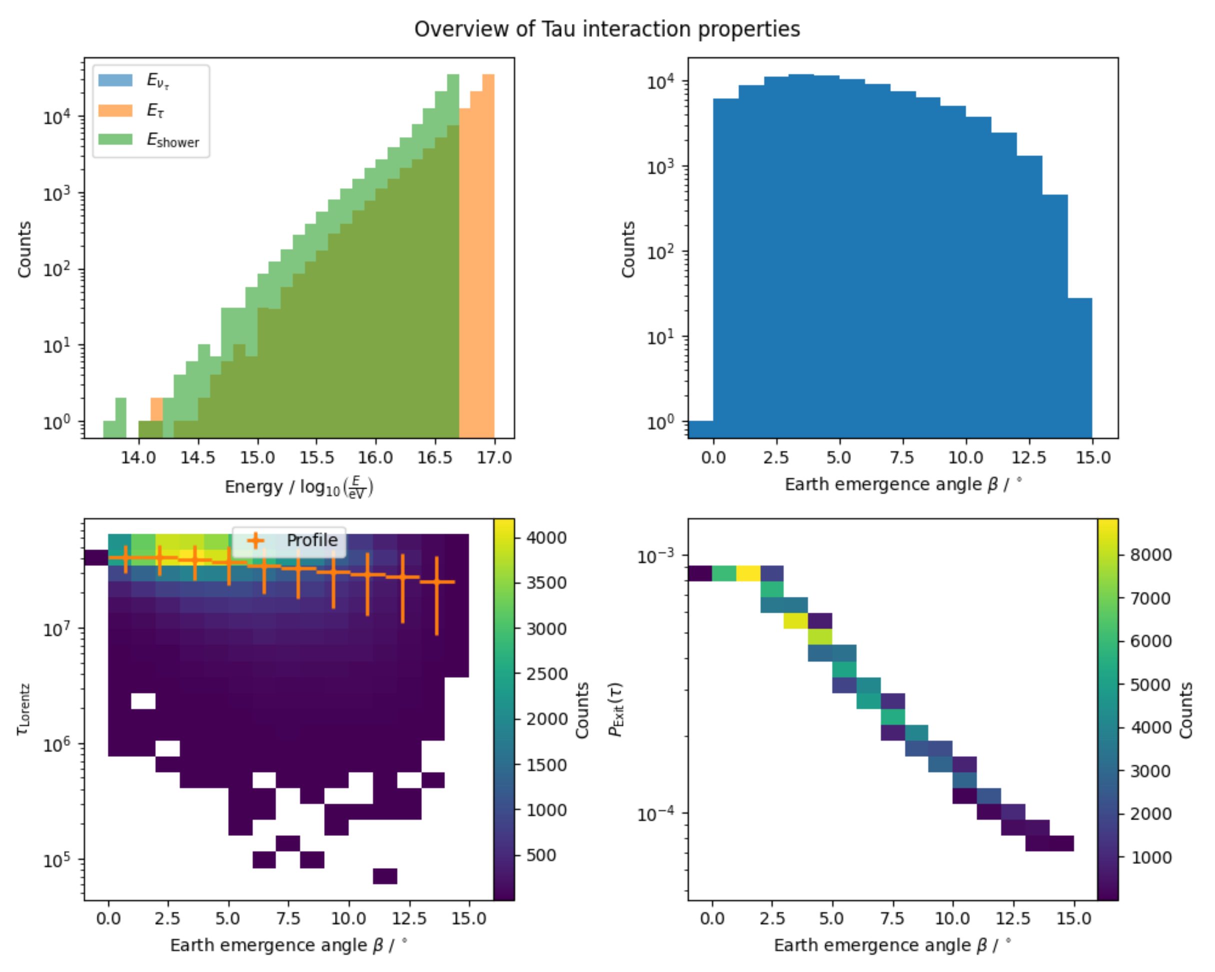

Standard Analysis Plots & Event-by-Event data variables available for each run -> needed to answer questions such as what is the $\nu_\tau$ energy resolution?

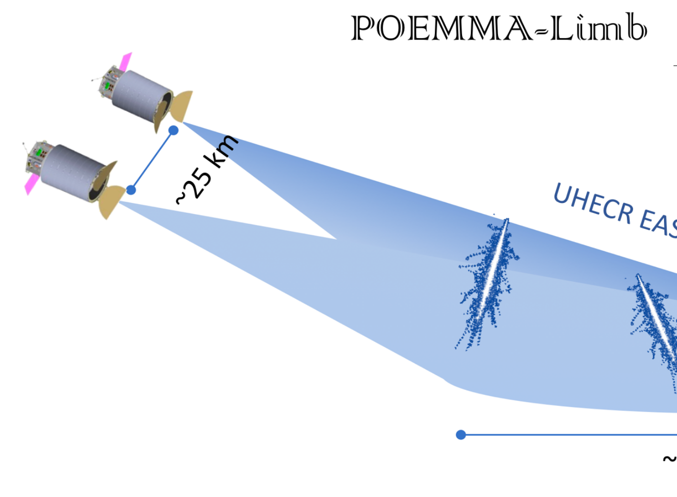
# Optical Cherenkov Example: $E^{-2}$ $\nu_\tau$ Spectrum to




**Space-based Example:**

**POEMMA in $\nu_\tau$ Limb-viewing mode**

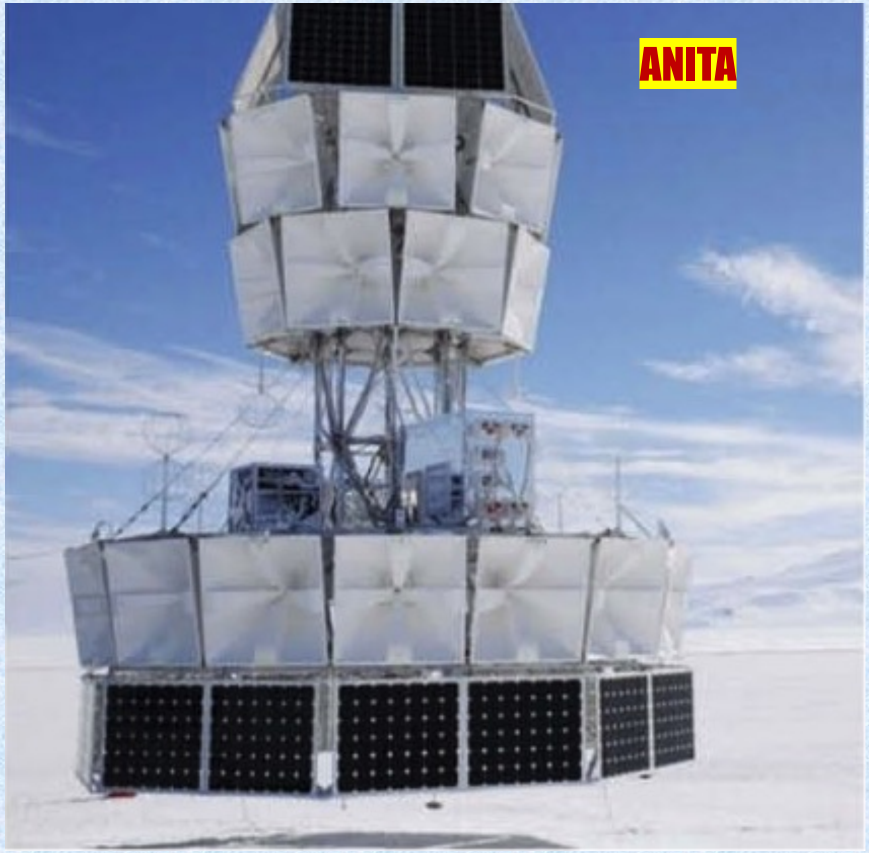


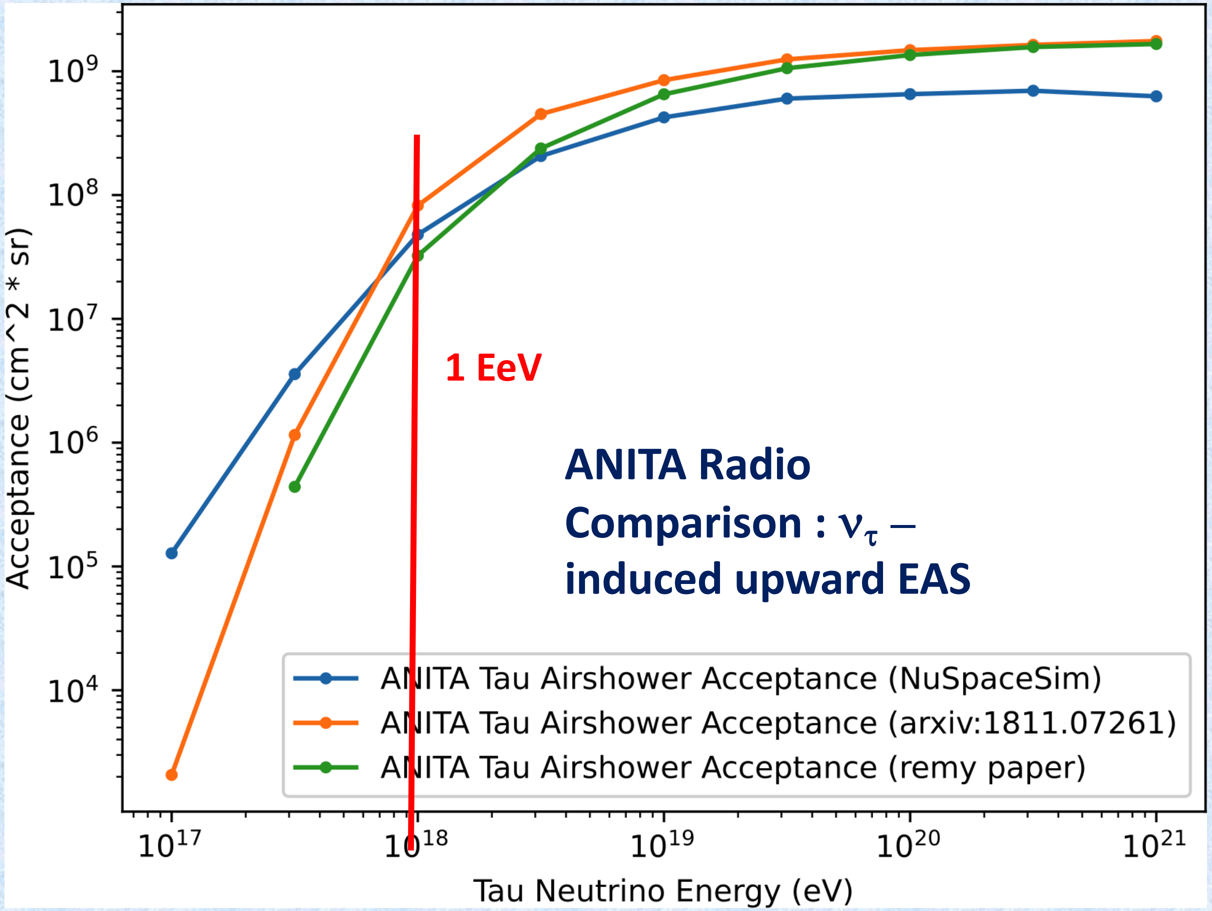




| Optics | Schmidt | 45° full FoV |
|---|---|---|
| | Primary Mirror | 4 m diam. |
| | Corrector Lens | 3.3 m diam. |
| | Focal Surface | 1.6 m diam. |
| | Pixel Size | 3 × 3 mm² |
| | Pixel FoV | 0.084° |

Standard Analysis Plots & Event-by-Event data variables available for each run -> needed to answer questions such as what is the $\nu_\tau$ energy resolution?

# $\nu$SpaceSim: Example Radio Detector Sensitivity Calculation

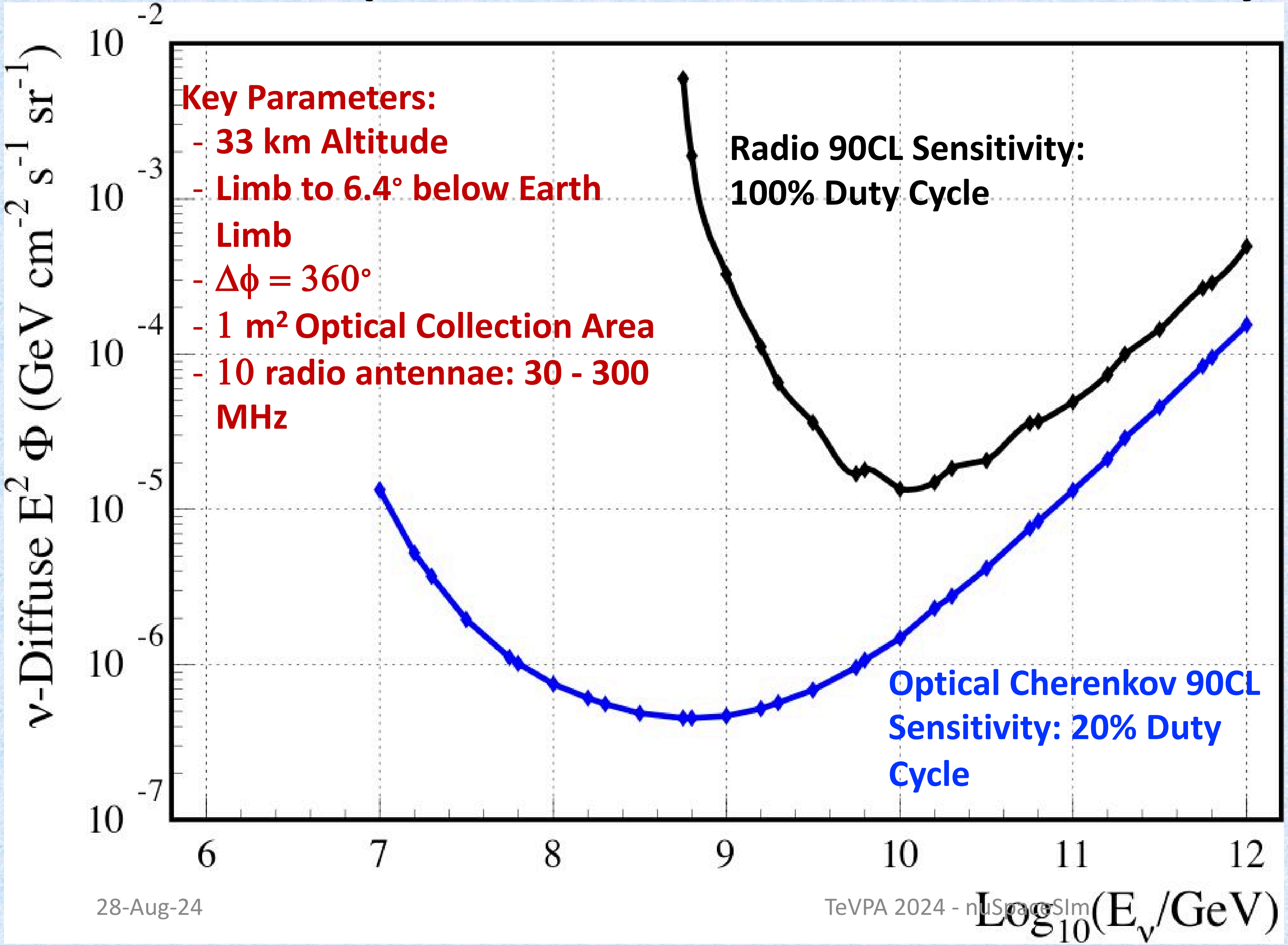



**Plot by Andrew Ludwig:**
**Ref: Remy Prechelt: arXiv:2112.07069**

# Combined EAS Cherenkov and Radio

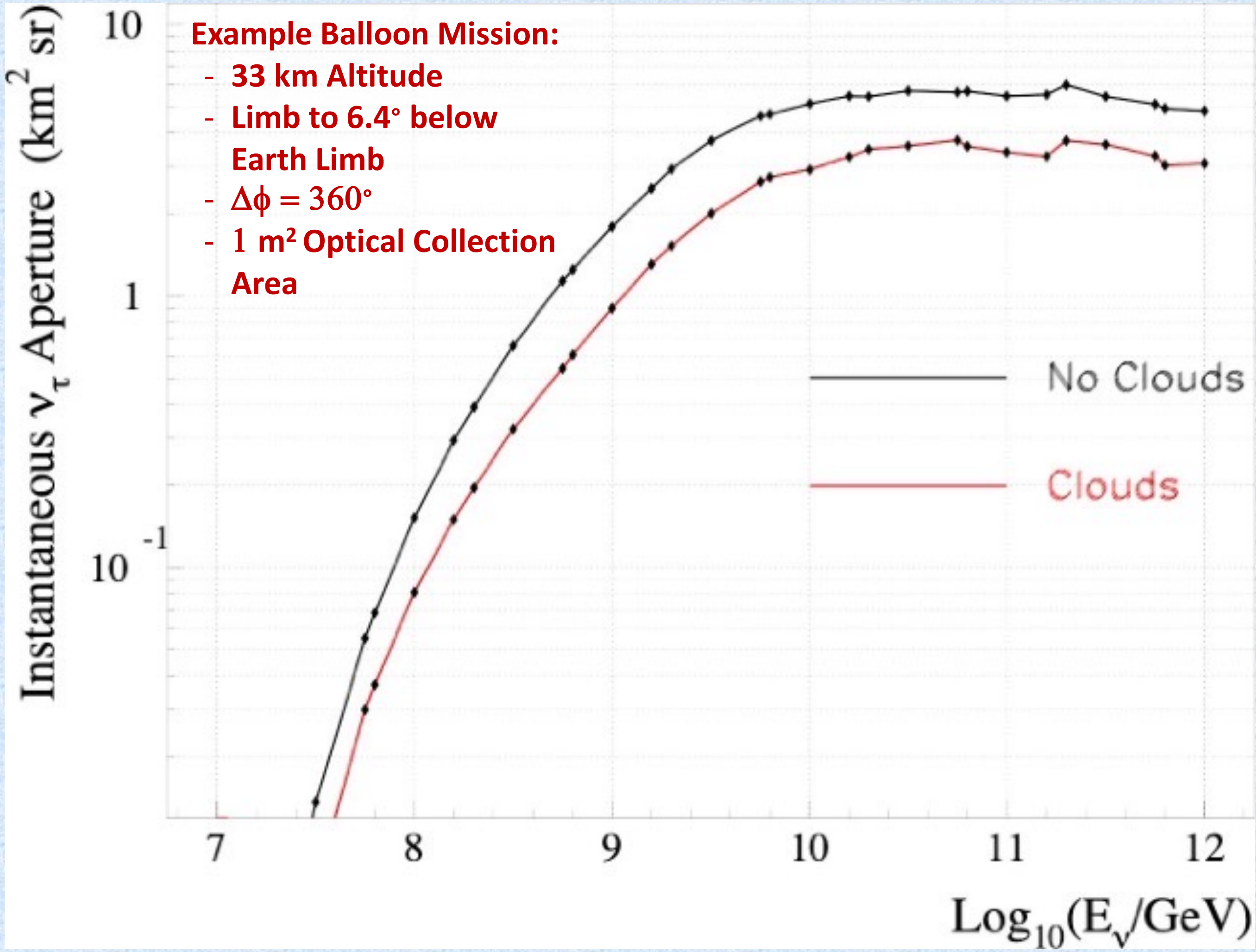
## All-flavor Optical w/ Radio Simulated Sensitivity




### TOML input File

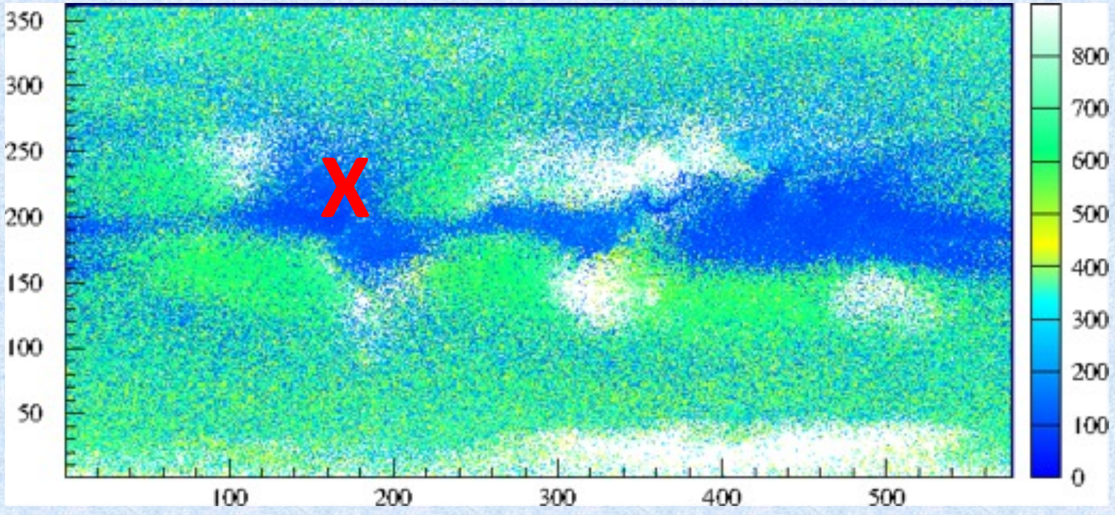
```
title = "NuSpaceSim"

[detector]
name = "Default Name"

[detector.initial_position]
altitude = "33.0 km"
latitude = "-44.6943 deg"
longitude = "169.1417 deg"

[detector.sun_moon]
sun_moon_cuts = true
sun_alt_cut = "-18.0 deg"
moon_alt_cut = "0.0 deg"
moon_min_phase_angle_cut = "150.0 deg"

[detector.optical]
enable = true
telescope_effective_area = "0.625 m2"
quantum_efficiency = 0.2
photo_electron_threshold = 25

[detector.radio]
enable = true
low_frequency = "30.0 MHz"
high_frequency = "300.0 MHz"
snr_threshold = 5.0
nantennas = 10
gain = "1.8 dB"

[simulation]
mode = "Diffuse"
thrown_events = 100
max_cherenkov_angle = "9.0 deg"
max_azimuth_angle = "360.0 deg"
angle_from_limb = "6.4 deg"
cherenkov_light_engine = "Default"

[simulation.ionosphere]
enable = true
total_electron_content = 10.0
total_electron_error = 0.1

[simulation.tau_shower]
id = "nupyprop"
etau_frac = 0.5
table_version = "3"

[simulation.spectrum]
id = "monospectrum"
log_nu_energy = 8.0

[simulation.cloud_model]
id = "no_cloud"

[simulation.target]
source_RA = "0.0 deg"
source_DEC = "0.0 deg"
source_date = "2022-06-02T01:00:00"
source_date_format = "isot"
source_obst = 86400
```

# Effects of Clouds using MERRA-2 Database

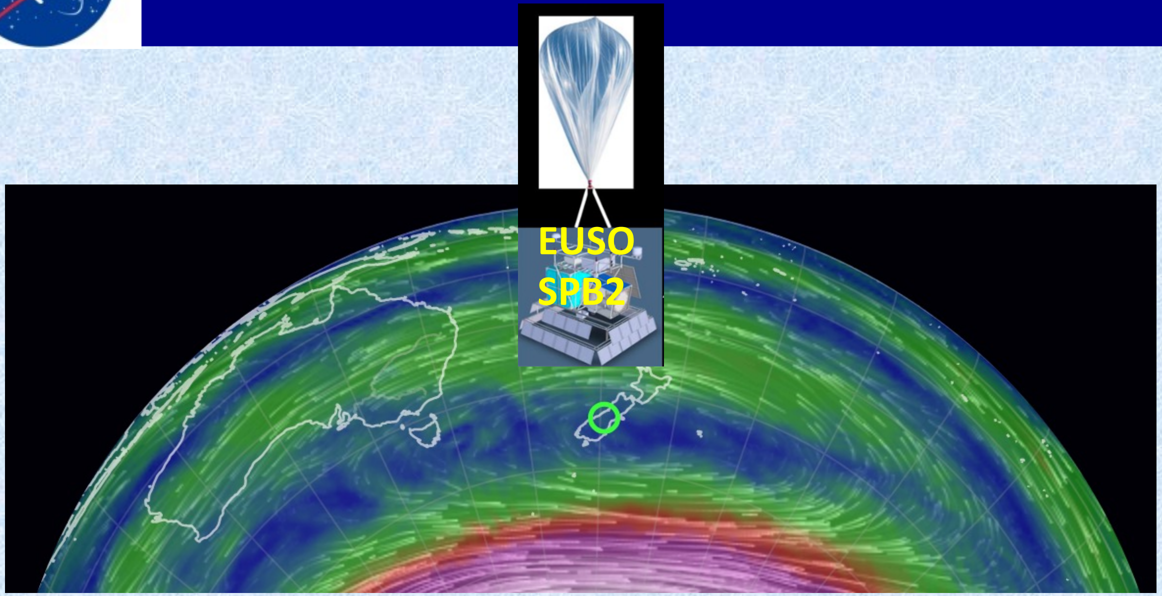



**Effects of cloud height distribution over Baltimore**

**MERRA-2 Cloud Map: <June 2023>**



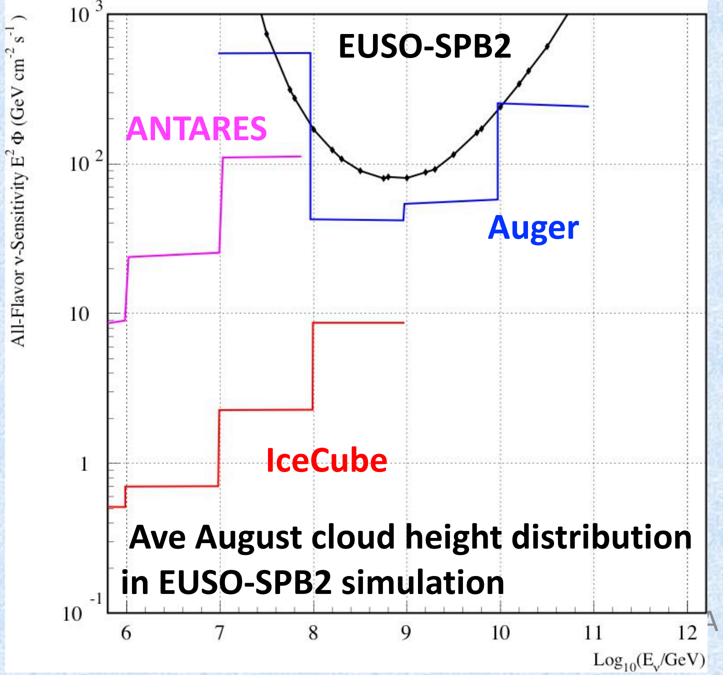
# GW170817 Transient Neutrino Sensitivity Example



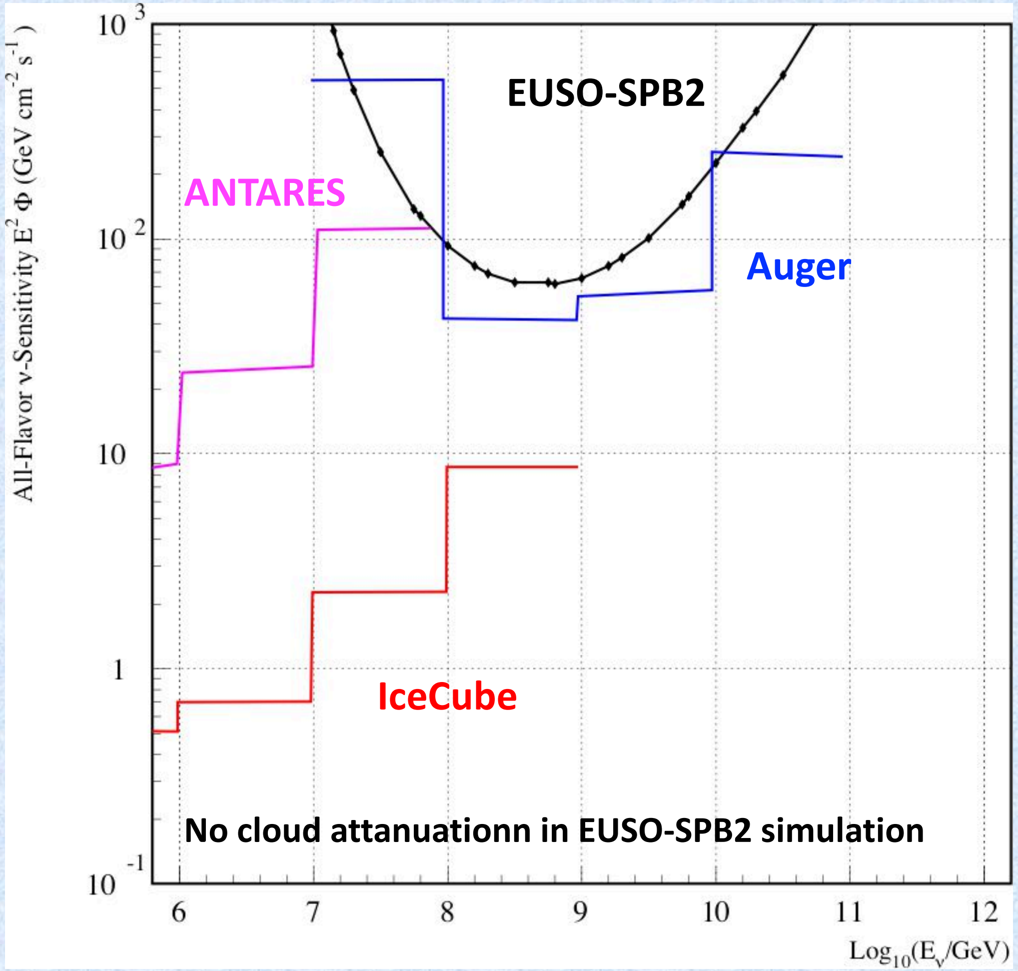

Assume EUSO-SPB2 was over Wanaka, NZ on 17Aug17

```
title = "NuSpaceSim"

[detector]
name = "SP2"

[detector.initial_position]
altitude = "33.0 km"
latitude = "-44.6943 deg"
longitude = "169.1417 deg"

[detector.sun_moon]
sun_moon_cuts = true
sun_alt_cut = "-23.819097 deg"
moon_alt_cut = "0.0 deg"
moon_min_phase_angle_cut = "150.0 deg"

[detector.optical]
telescope_effective_area = "0.625 m2"
quantum_efficiency = 0.2
photo_electron_threshold = 25
```

```
[simulation.cloud_model]
id = "no_cloud"

[simulation.too]
source_RA = "197.45 deg"
source_DEC = "22.38 deg"
source_date = "2017-08-17T01:41:00"
source_date_format = "isot"
source_obst = 1209600
```




## 14-day All-flavor 90% CL GW170817 Limits




THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed


Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

# https://heasarc.gsfc.nasa.gov/docs/nuSpaceSim/

- **νSpaceSim is designed to be a comprehensive, end-to-end simulation package for the development of space- and sub-orbital based experiments to detect the optical and radio EAS signals and interpret data:**
  - Provides a quantification of modeling systematics by choice of different libraries by user
  - Provide detailed analysis variables to aid definition and analysis of upward neutrino induced EAS missions using radio and optical signals
- **Available thru Github and pip (precompiled binaries)**
  - nuPyProp: τ-lepton $P_{exit}$ and Energy Distributions
  - νSpaceSim1.5.1 ver *1.6.0 in beta test*
    - *Implementation of EAS external CONEX libraries*
  - Future updates:
    - Atmosphere defined using MERRA-2 Database for Aerosol and Ozone Distributions
    - Full implementation of CHASM for optical Cherenkov generation
    - Update of EAS radio signal modeling

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Goddard Space Flight Center
Sciences and Exploration

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SpaceSim

The nuSpaceSim cosmic neutrino simulation software package that is designed as an end-to-end, neutrino flux to space-based signal detection, modeling tool for the design of sub-orbital and space-based neutrino detection experiments. nuSpaceSim is a comprehensive suite of physics modeling packages designed to accept an experimental design input and then model the experiment's sensitivity to both the diffuse, cosmogenic neutrino flux as well as astrophysical neutrino transient events, such as that postulated from binary neutron star (BNS) mergers. nuSpaceSim uses state-of-the art, vectorized and multi-threaded Python-based computer code to precisiely simulate neutrino interactions in the Earth using the new, nuPyProp tau neutrino and tau-lepton simulation package, then model the generation of extensive air shower (EAS) optical and radio emission signals from Earth-emergence tau-lepton decays. nuSpaceSim then models the EAS signal propagation through the atmosphere and subsequent detection by sub-orbital and space-based instruments. nuSpaceSim is the first neutrino simulation package that combines the neutrino-induced optical and radio signal modeling in a single package to facilitate the experimental design, observation strategy, and interpretation of data for space-based neutrino experiments. The initial public release of nuSpaceSim will be in 2021 to the neutrino research community. The nuSpaceSim collaboration includes astroparticle physicists and graduate students from NASA/GSFC, JPL, University of Iowa, University of Utah, Colorado School of Mines, University of Chicago, Pennsylvania State University, Lehman College, CUNY, and the Slovak Academy of Sciences.

***Software Products***

nuSpaceSim : Simulate upward-going extensive air showers.

- [Github]
- [PyPI]
- [Conda-Forge]

nuPyProp : Generate nu-tau propagation tables (optional)

- [Github]
- [PyPI]
- [Conda-Forge]

Atmospheric Data Model Generator: Web application (Beta)

***Data Libraries***

***Documentation and Academic Papers***

Links to papers
Links to software documentation

- [nuSpaceSim Documentation]
- [nuPyProp Documentation]

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## νSpaceSim Collaboration:

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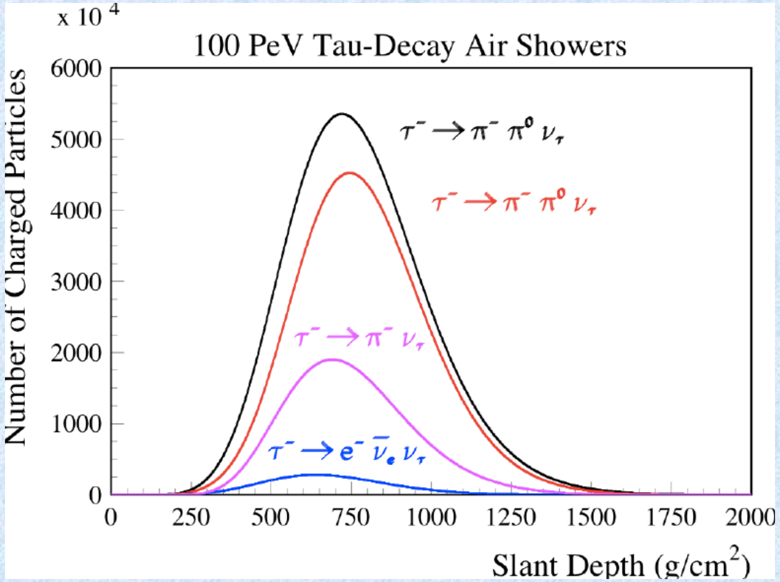
# Backup Slides

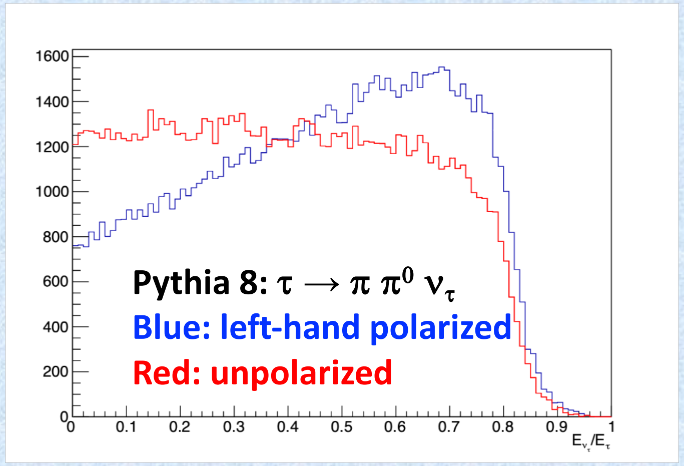
# Overview of τ–lepton EAS Signal Formation

**Tau decay channels (PDG)**

| | |
|---|---|
| Tau -> electron + nu_e + nu_tau | 18% BR |
| Tau -> h- + nu_tau | 12% BR |
| Tau -> h- + pi0 + nu_tau | 26% BR |
| Tau -> h- + 2pi0 + nu_tau | 11% BR |
| Tau -> h- + 3pi0 + nu_tau | 1% BR |
| Tau -> h- + h- + h+ + nu_tau | 10% BR |
| Tau -> h- + h- + h+ +pi0 + nu_tau | 5% BR |
| **Tau -> mu + neutrinos (special case)** | 17% BR |
| **Total** | **100%** |

**Both Optical Č and geomag radio signal dominated by $e^{\pm}$ in EAS with variability due to atmospheric properties**



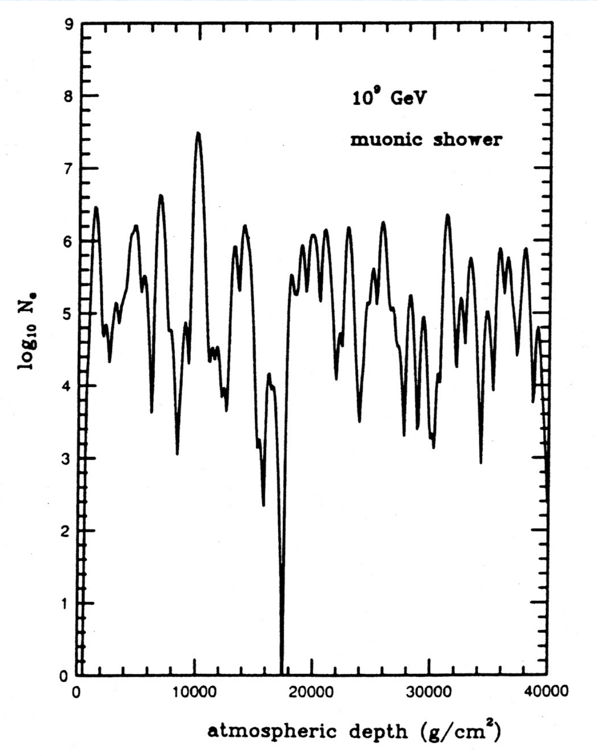




FIG. 2. A sample muon air shower. Shower size as a function of atmospheric depth. Muon energy $10^9$ GeV.

**Stanev and Vankov, Phys Rev D 40 (1989)**

**Charged particle yield ~$10^{-4}$ that for E&M or hadronic EAS**

**However, column depths are much larger than nominal 500 g/cm$^2$ EAS width for E&M and hadronic showers**