nuSpaceSim: An End-to-End Simulation Package for Modeling the Sensitivity of UHECR Experiments to Upward-moving Extensive Air Showers sources by Cosmic Neutrinos in the Earth

Jorge Caraça-Valente[5] for the νspacesim Collaboration: John Krizmanic[1], Yosui Akaike[2], Luis Anchordoqui[3], Douglas Bergman[4], Isaac Buckland[4], Austin Cummings[6], Johannes Eser[7], Fred Angelo Batan Garcia[8], Diksha Garg[9], Claire Guépin[10], Tobias Heibges[5], Luke Kupari[9], Andrew Ludwig[11], Simon Mackovjak[12], Eric Mayotte[5], Sonja Mayotte[5], Angela Olinto[7], Thomas Paul[3], Alex Reustle[1], Andrew Romero-Wolf[11], Mary Hall Reno[9], Fred Sarazin[5], Tonia Venters[1], Lawrence Wiencke[5], Stephanie Wissel[6]

Abstract

Neutrinos act as probes of hadronic processes and offer a distinctive view into their astrophysical origins at high energies (Fig 1). When reaching energies ≳PeV, ν_τ interactions within the Earth can produce a significant flux of τ-leptons. These tau-leptons subsequently decay, generating upward-moving extensive air showers (EAS). Using the Earth as a target for neutrinos and the atmosphere to generate signals effectively creates a detector with a mass >> gigaton. **νSpaceSim** is a comprehensive simulation developed to model all the relevant physical processes that describe the neutrino-induced Earth-emergent lepton chain to help design the next generation of balloon- and space-based experiments, estimate the exposure of ground-based experiments to these showers, as well as understand the data from recent experiments such as EUSO-SPB2 and ANITA (Fig 2). The simulation includes the modeling of neutrino interactions inside the Earth that produce leptons, the propagation of the leptons through the Earth into the atmosphere and their decay, forming composite EAS, generating the air optical Cherenkov and radio signals, modeling their propagation and attenuation through the atmosphere (including clouds and ionosphere effects) and modeling the response of detectors at a user-defined altitude.

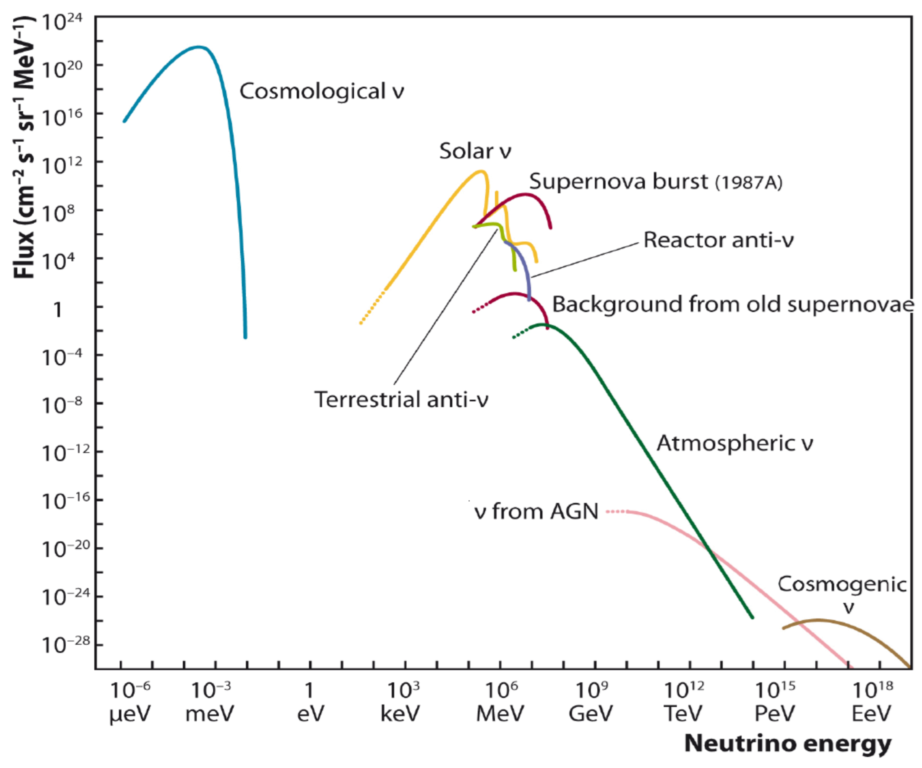


Fig 1: Neutrino flux spectrum and their sources. Spiering, C. 2012, The European Physical Journal H, 37, 515

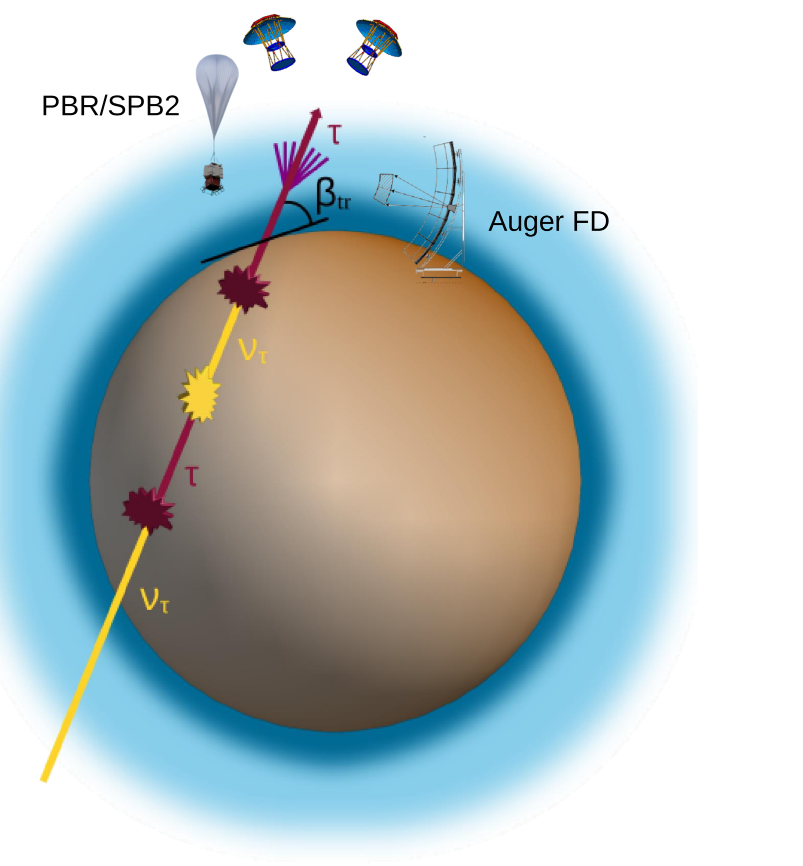


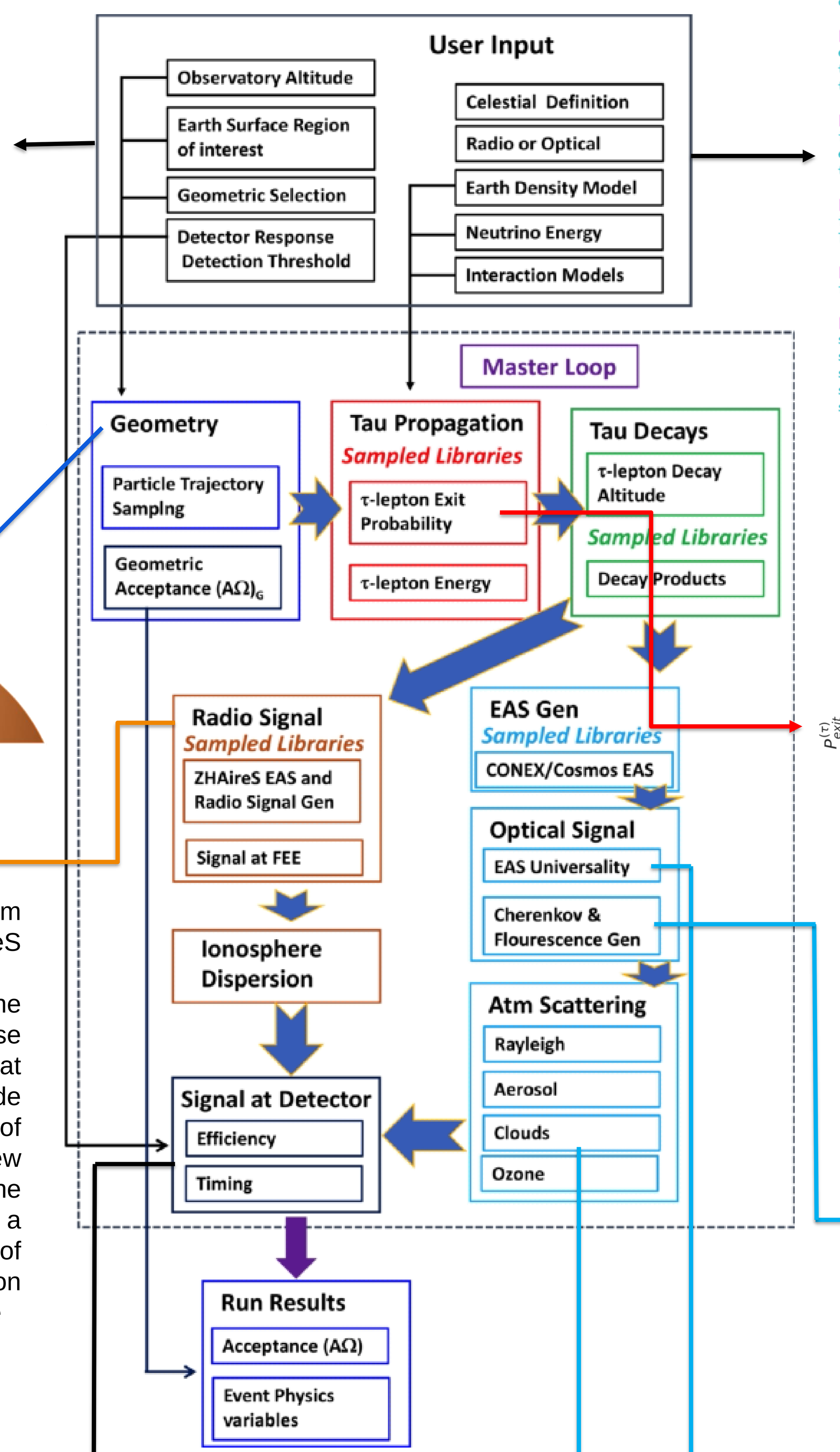
Fig 2: Sketch of the simulation process.

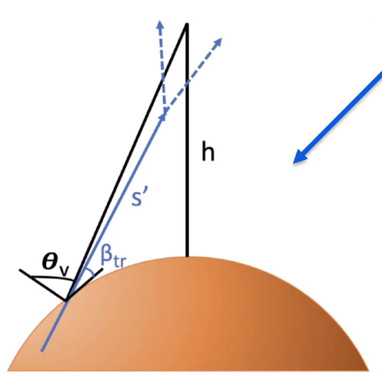
Simulation modeling

1. Inside the Earth
   τ neutrino flux, CC interactions, τ lepton propagation and energy loss, ν_τ regeneration
   Sampled Libraries: nuPyProp, nuTauSim, and any other with the appropriate input format
2. In the atmosphere
   τ propagation and decay, air shower, optical and radio generation, atmospheric attenuation and scattering of signals
   Sampled Libraries: Tau decay, EAS **(CONEX)**, Optical and Radio signals, MERRA-2 atmosphere
3. Instrument response
   Cherenkov and radio signal at instrument, including **spatial and temporal profile** and **wavelenght spectrum.** Instrument definition includes **height, orientation**, time and location of observation, and tools to define **threshold**


```
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 = "3.0 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
```


Simulation chain

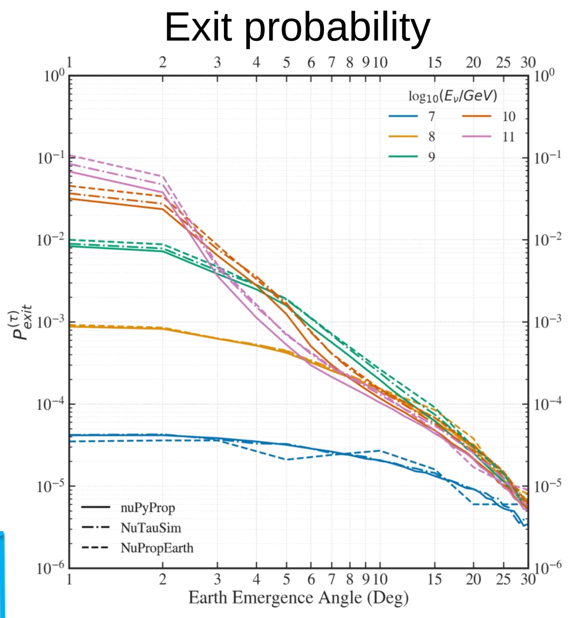




Features

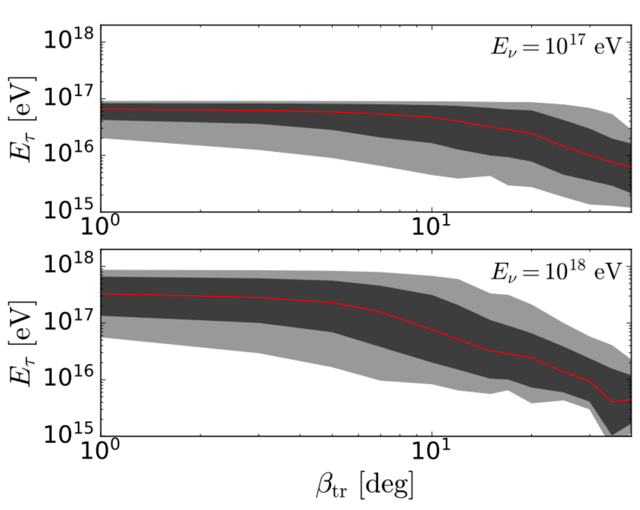
- Current Version: **νSpaceSim 1.5.1**
- **Vectorized Python** wrapper
- **Fast**: 10^6 generated events in ~4 min
- Dask **multi core**
- **TOML Input** format
- **HDF5+FITS** and **CONEX** output format
- Modelling of **cosmic diffuse** neutrinos
- Modelling of **transient** neutrino **sources**
- **Optical** and **radio** signals modeling
- Scattering, aerosol, ozone and clouds

Exit probability

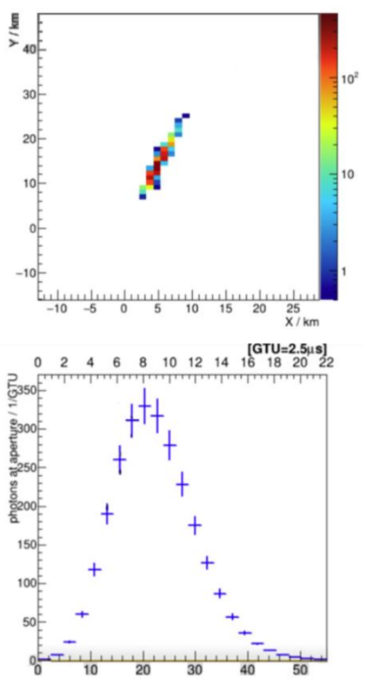


nuPyProp: D. Garg *et al.* JCAP01(2023)041

τ-lepton energy

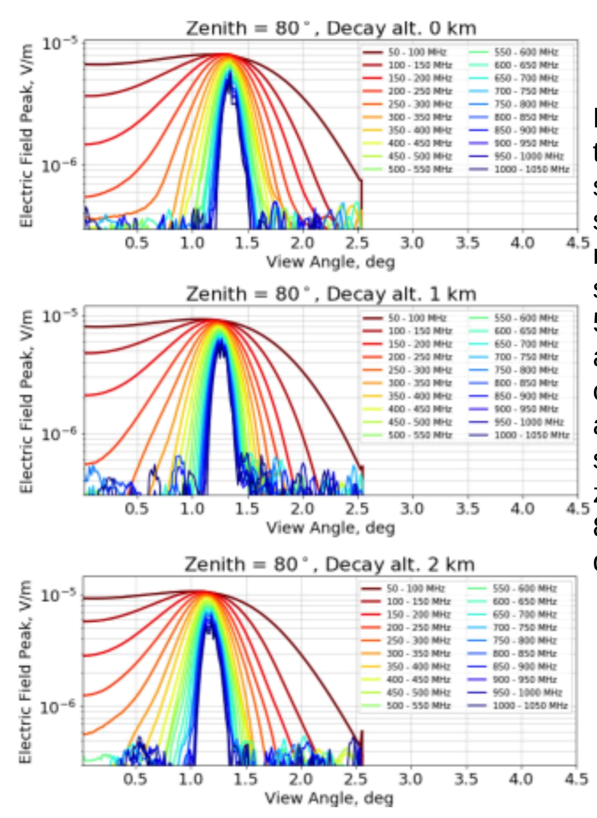


Average energy of the outgoing τ-lepton (red line) and range of energies within 68% and 95% of values. Reno, M.H. et al. Physical Review D, 2019, vol. 100, no 6, p. 063010.



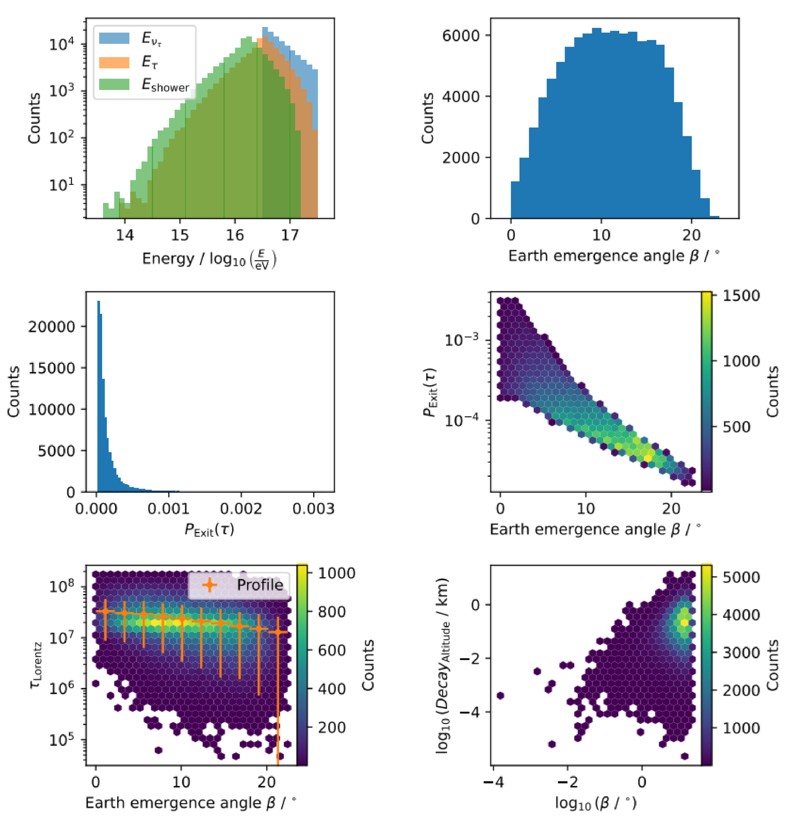
Fluorescence simulation of a 100 EeV shower with 5º emergence angle, generated with vSpaceSim.

Radio Signal

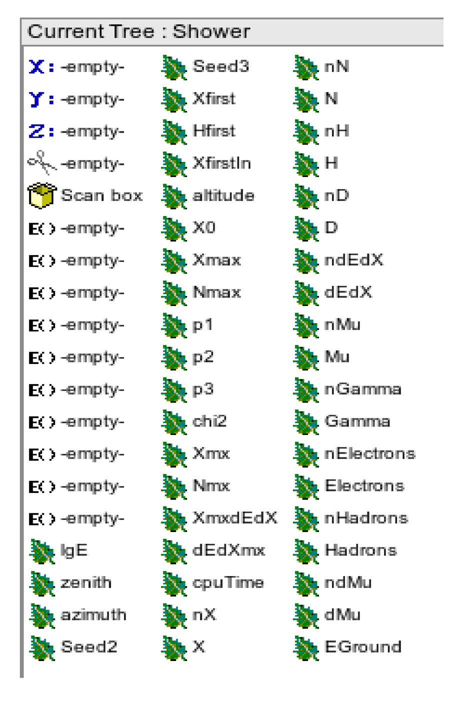


Results from the ZHAireS simulation showing the radio pulse spectra at 525km altitude as a function of observer view angle of the shower for a zenith angle of 80º τ-lepton decay altitude

EAS results:
E^{-1} ν_τ Spectrum $10^{16.5} - 10^{17.5}$ eV

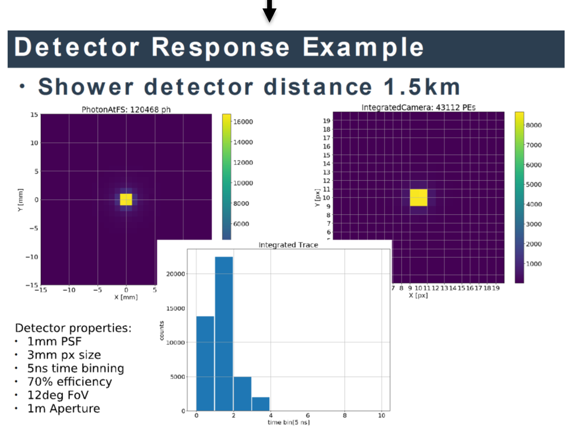


Conex-like Root output

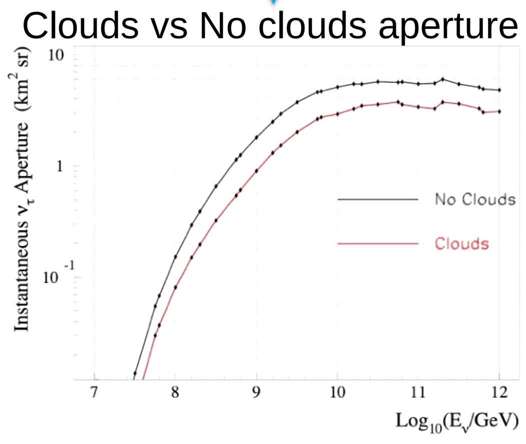


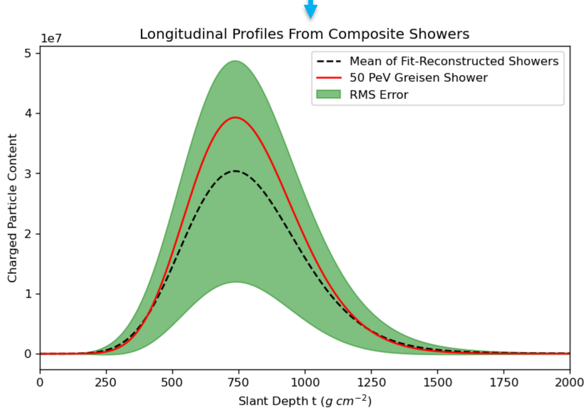
Detector Response Example

· Shower detector distance 1.5km



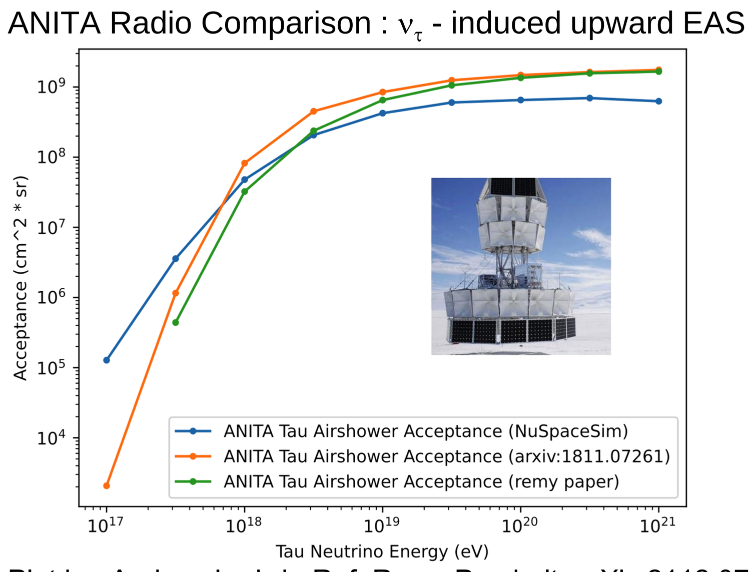
Clouds vs No clouds aperture





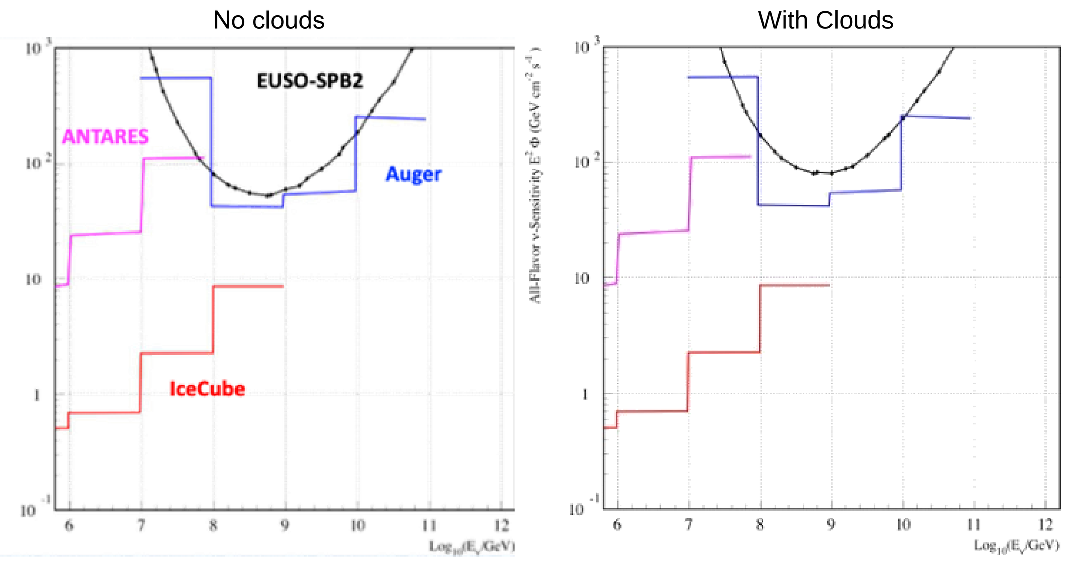
Example Results

ANITA Radio Comparison : ν_τ - induced upward EAS

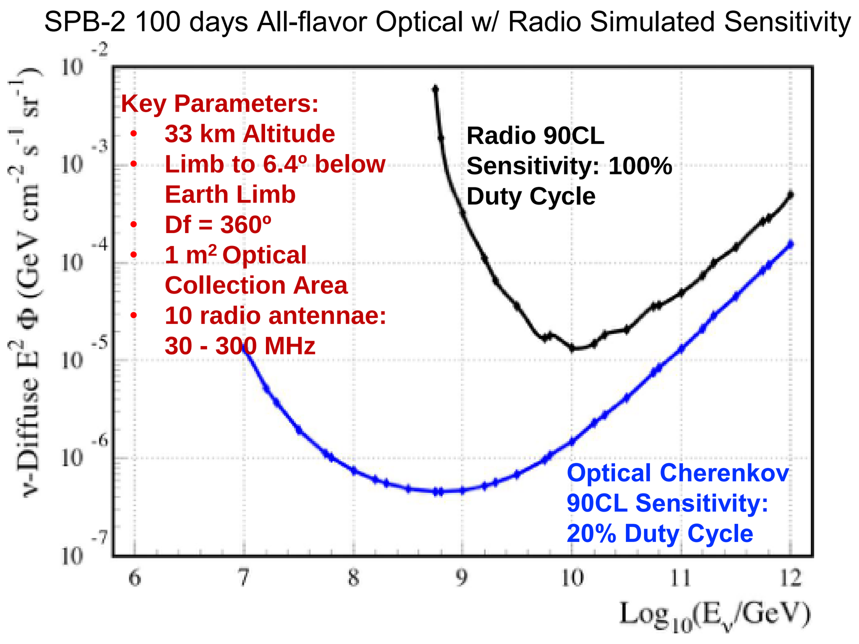


Plot by Andrew Ludwig Ref: Remy Prechelt: arXiv:2112.07069

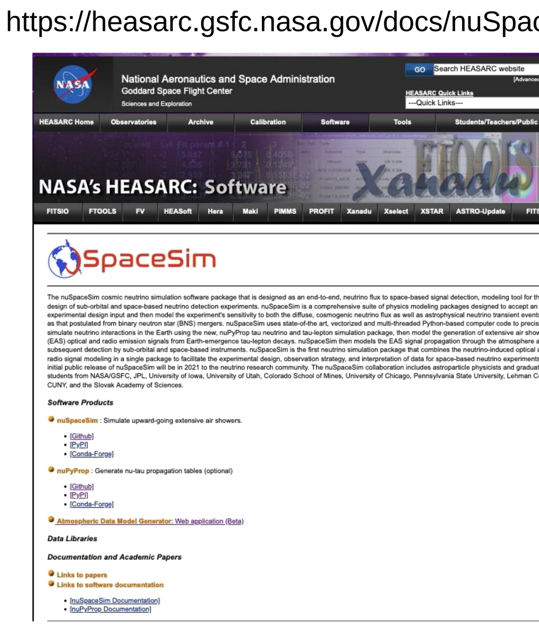
SPB-2 Neutrino sensitivity to GW170817 14-day All flavor 90% CL



SPB-2 100 days All-flavor Optical w/ Radio Simulated Sensitivity



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



References

[1] Krizmanic, J. et al (2019). nuSpaceSim: A Comprehensive Neutrino Simulation Package for Spacebased & Suborbital Experiments. *PoS Proc. ICRC*, *936*.
[2] Ackermann, M. et al (2022). High-energy and ultra-high-energy neutrinos: A Snowmass white paper. *Journal of high energy astrophysics*, *36*, 55-110.
[3] Wiencke, L., & Olinto, A. (2019). The extreme universe space observatory on a super-pressure balloon II mission. arXiv preprint arXiv:1909.12835.
[4] Olinto, A. V. (2023). POEMMA (Probe Of Extreme Multi-Messenger Astrophysics) Roadmap Update. arXiv preprint arXiv:2309.14561.
[5] Cummings, A. (2023). Analysis of above-the-limb cosmic rays for EUSO-SPB2. arXiv preprint arXiv:2310.07063.
[6] Buckland, I. J., & Bergman, D. R. (2023). Universality of Cherenkov light in EAS. Astroparticle Physics, 102832.

The νspacesim collaboration

1 NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771 USA 2 Waseda Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo, Japan 3 Department of Physics and Astronomy, Lehman College, City University of New York, New York, New York, 10468 USA 4 Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112 USA 5 Department of Physics, Colorado School of Mines, Golden, Colorado 80401 USA 6 Department of Physics, Pennsylvania State University, State College, Pennsylvania 16801 USA 7 Department of Astronomy and Astrophysics University of Chicago, Chicago, Illinois 60637 USA 8 Department of Physics, Columbia University, New York, New York USA 9 Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242 USA 10 Laboratoire Univers et Particules de Montpellier (LUPM) France 11 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA 12 Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia