νSpaceSim: A Comprehensive Simulation Package for Modeling the Measurement of Cosmic Neutrinos using the Earth as the Neutrino Target and Space-based Detectors

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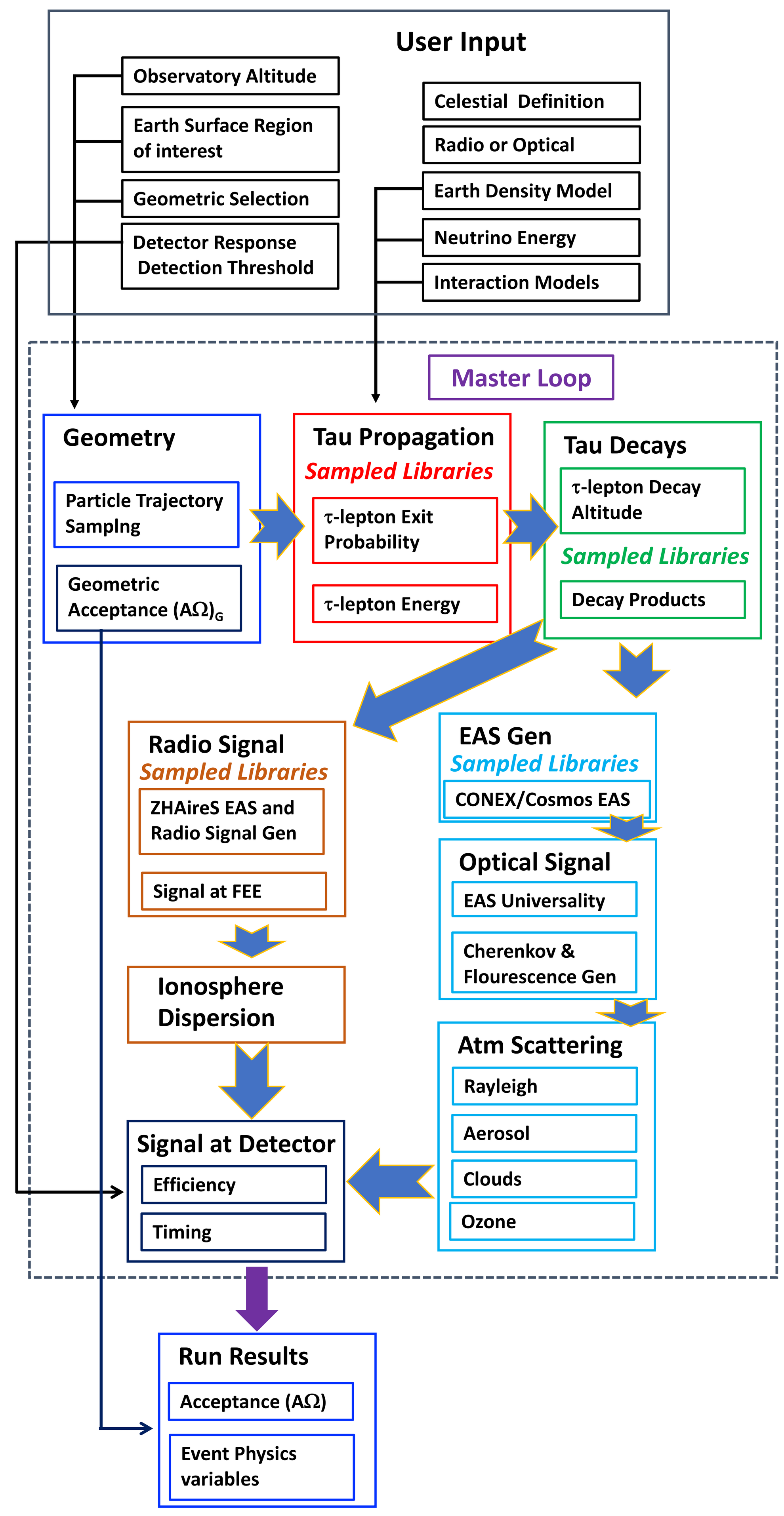
SpaceSim NASA Goddard SPACE FLIGHT CENTER

Abstract: νSpaceSim is a highly-efficient (e.g., fast) module-based, end-to-end simulation package that models the physical processes of cosmic neutrino interactions that leads to detectable signals for sub-orbital and space-based instruments. Starting with an input flux of neutrinos incident on a user-specified geometry in the Earth, the flux of Earth-emergent leptons are calculated followed by their subsequent extensive air showers (EAS). Next, the EAS optical Cherenkov and radio emission, signal attenuation to the detector, and the detector response are modeled to determine the sensitivity to both the diffuse cosmic neutrinos and transient neutrino sources. Using the Earth as a tau neutrino target and the atmosphere as the signal generator effectively forms a detector with a mega-gigaton mass. Furthermore, t-lepton decays and neutrino neutral-current interactions within the Earth (re)generates a flux of lower energy tau neutrinos that can also interact in the Earth thus enhancing the detection probability. νSpaceSim provides a tool to both understand the data from recent experiments such as EUSO-SPB2 as well as design/understand the performance the next generation of balloon- and space-based experiments, including POEMMA Balloon with Radio (PBR) and the Payload for Ultrahigh Energy Observations (PUEO). In this poster, the νSpaceSim software, physics modeling, and the cosmic neutrino measurement capabilities of example sub-orbital and space-based experimental configurations are presented as well as status of planned modeling upgrades.

Software Architecture

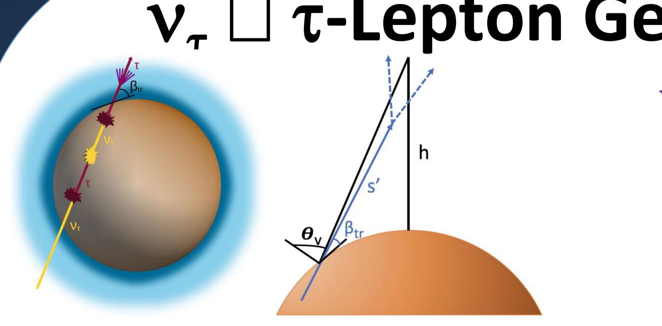
Hosted at https://heasarc.gsfc.nasa.gov/docs/nuSpaceSim/



Vectorized Python wrapper than schedules physics software modules :

- Inherent multi-core processing via Dask
- TOML input format and HDF5 & FITS library and output format
- Lookup Table Libraries pre-generated,: code provided to re-generate libraries
- τ-lepton Earth-exit Probability: nuPyProp ALLM or BHDM, or nuLeptonSim as options
- EAS profile based on parameterized models as well as CONEX libraries options
- τ-lepton decay properties with model based on Pythia decay tables in near future
- Optical Cherenkov model based on Hillas parameterization Optical Cherenkov properties via CHASM in near future
  Ref: I. Buckland & D. Bergman, AstroparPhys. id 102832 (2023)
- Atmosphere Attenuation: Baseline for Rayleigh scattering, aerosol & ozone absorption
- Cloud and Aerosol libraries from MERRA-2 database being implemented: Ref: nuSpaceSim HEASARC webpage
- Radio: based on ZHAireS simulated libraries and standard antennae designs incluing model of ionospheric dispersion

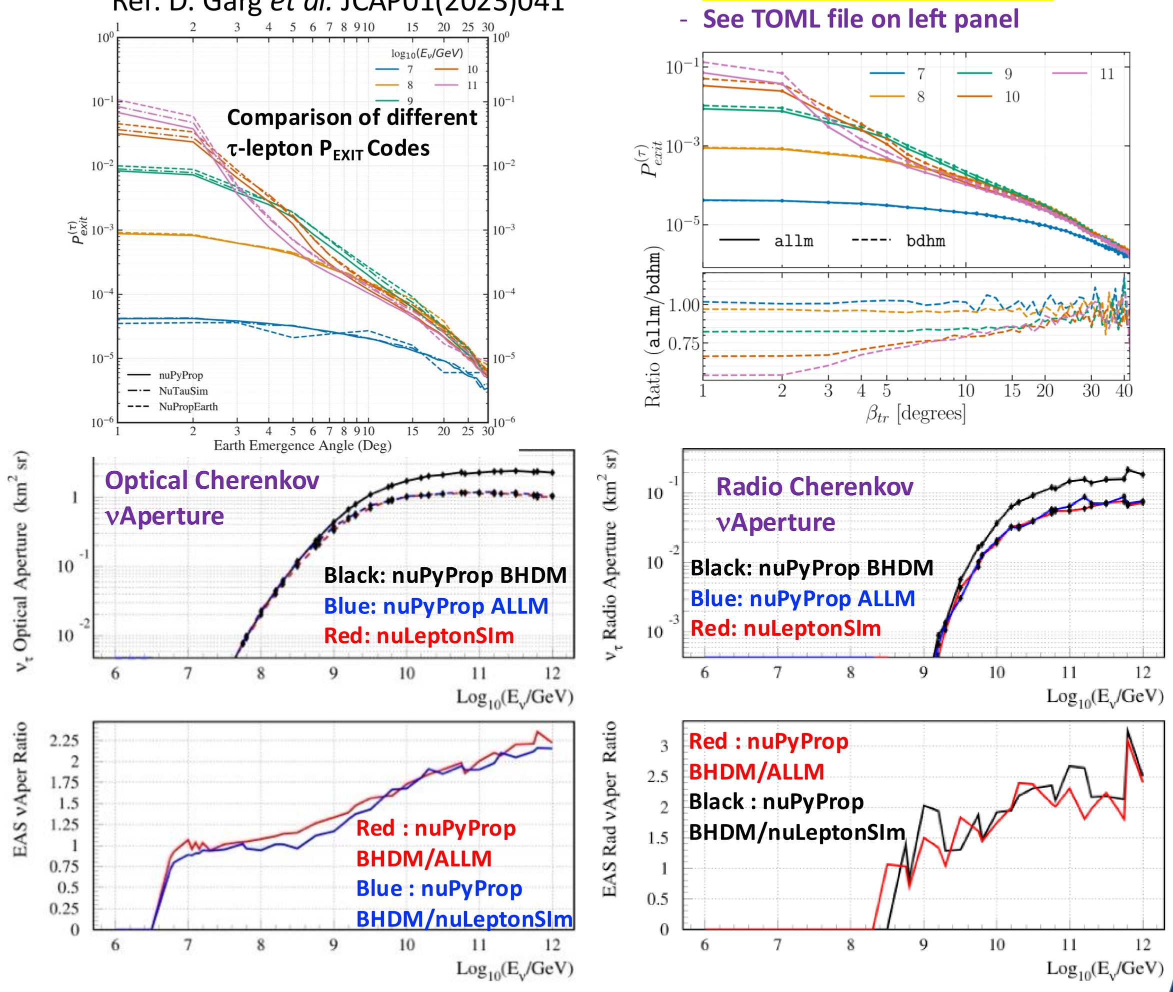
ν_τ □ τ-Lepton Generation



Geometry of a ν_τ interaction leading to an Earth-emergent τ-lepton with an emergence angle β_{tr}
Ref: D. Garg *et al.* JCAP01(2023)041

νSpaceSim Input Parameters:

- 33 km Altitude
- View to 6.4° below Earth Limb
- $\Delta\phi = 360°$
- 1 m² Optical Collection Area
- 10 radio antennae: 50 - 500 MHz
- No Clouds
- Greissen EAS model
- Diffuse neutrino flux
- 3 Different Lepton Generators
- See TOML file on left panel



Optical w/ Radio Simulation

νSpaceSim TOML Input Parameter File

```
title = "NuSpaceSim"

[detector]
name = "SPB2 360 Diffuse"

[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 = "0.6255 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"
eas_long_profile = "Greisen"
cherenkov_light_engine = "nuspacesim"

[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
~
```

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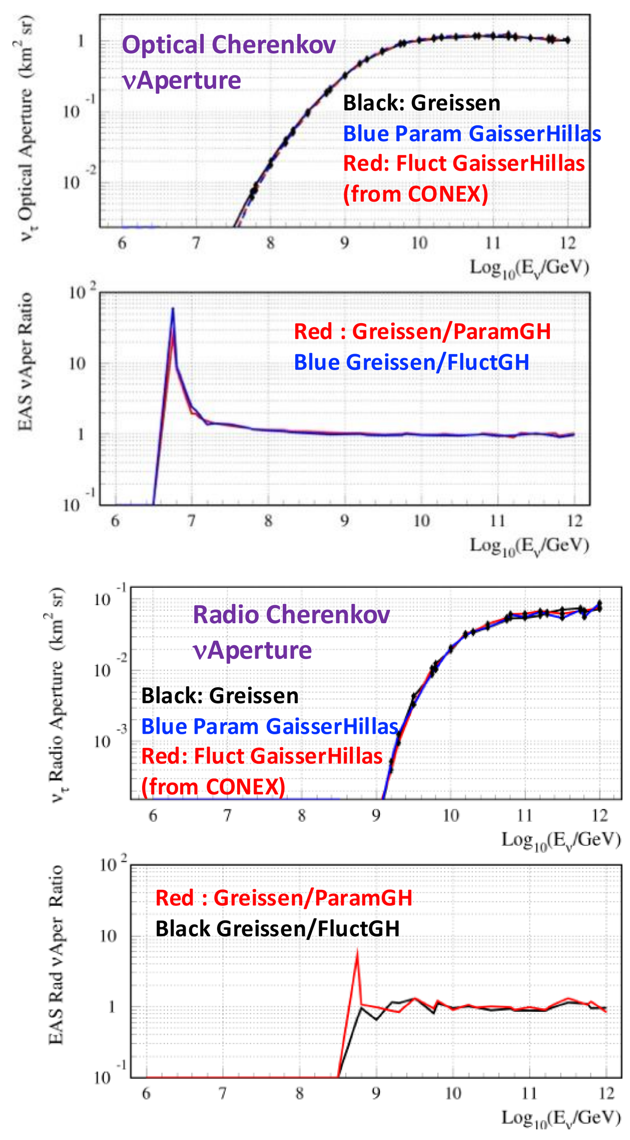
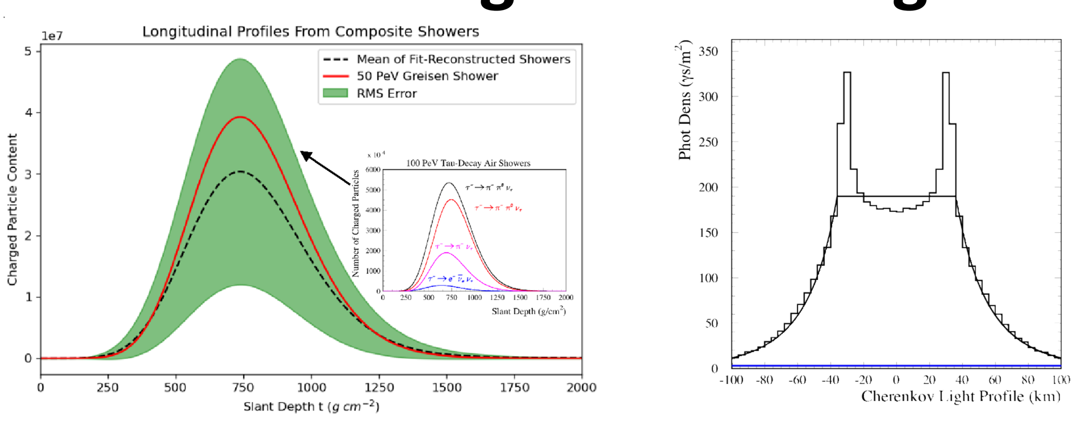
- 10 radio antennae: 50 - 500 MHz
- No Clouds
- 3 different EAS models
- Diffuse neutrino flux

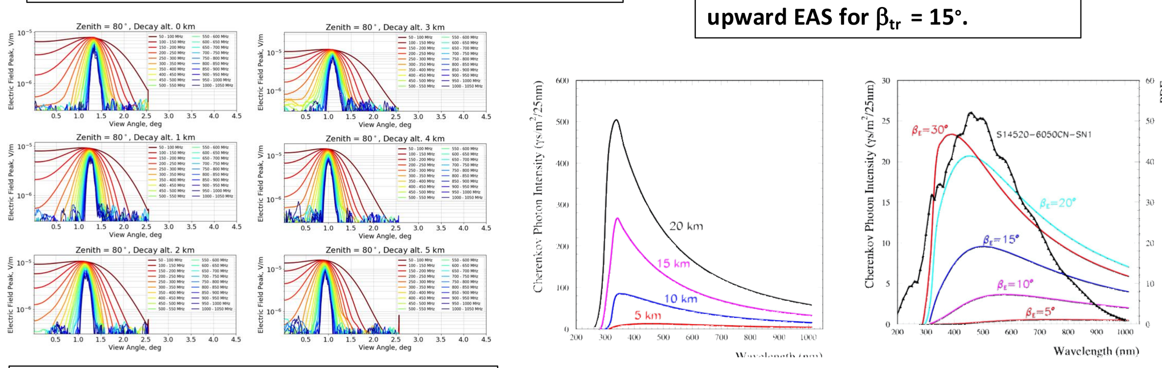


EAS Optical Cherenkov and Radio Signal Modeling



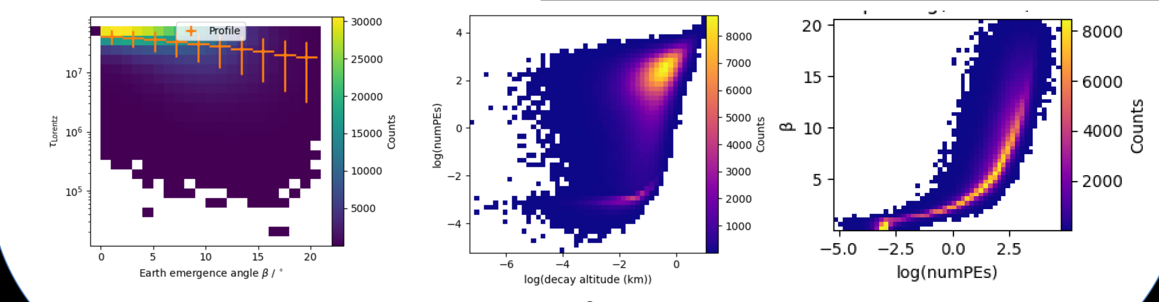
The profiles of composite for 100 POeV upwrd-moving EAS from τ-lepton decays. The inset shows the variability for several different decay channel (implementation in progress)..

The spatial profile of the Cherenkov signal (photons/m²) at 525 km altitude for a 100 PeV upward EAS for $\beta_{tr} = 15°$.



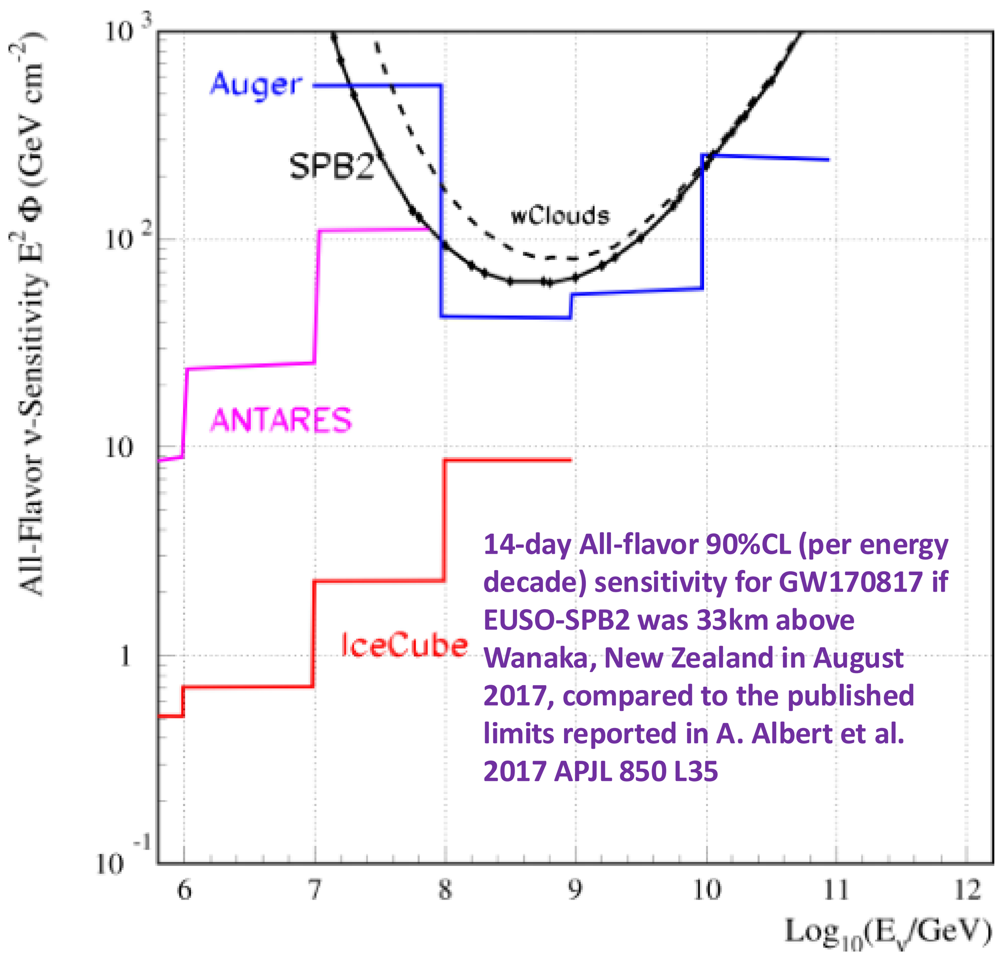
ZHAireS results showing the radio pulse spectra at 525 km altitude vs observer view angle of the shower for $\beta_{tr} = 10°$ vs τ-lepton decay altitude for 100 PeV EAS, ignoring ionosphere dispersion

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



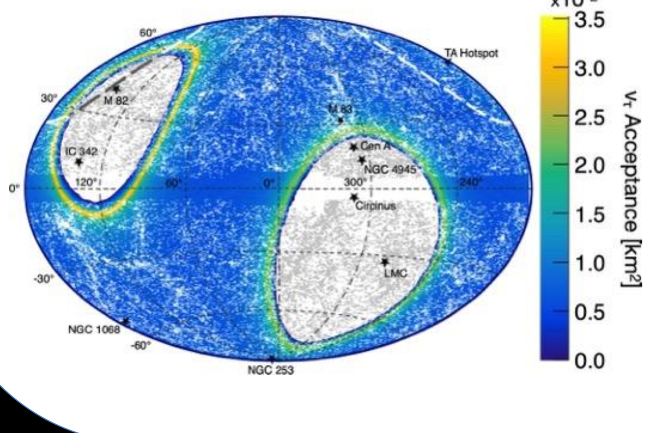
νSpaceSIm show-plot Results for 10^8 GeV ν_τ Flux to 6.4° below the Earth Limb for a balloon-borne 1 m² Cherenkov Telescope at 33 km altitude

Neutrino Source Modeling



14-day All-flavor 90%CL (per energy decade) sensitivity for GW170817 if EUSO-SPB2 was 33km above Wanaka, New Zealand in August 2017, compared to the published limits reported in A. Albert et al. 2017 APJL 850 L35

Neutrino Point Source Sensitivity



Sky map of the sensitivity to transient neutrino fluxes for EUSO-SPB2 for 100-day ULDB flight from Wanaka, New Zealand, assuming observations in astronomical night near new moon.

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