NuLeptonSim: A practical use of a neutrino propagation code as an event generator

ARENA Conference,
Santiago de Compostela, Spain

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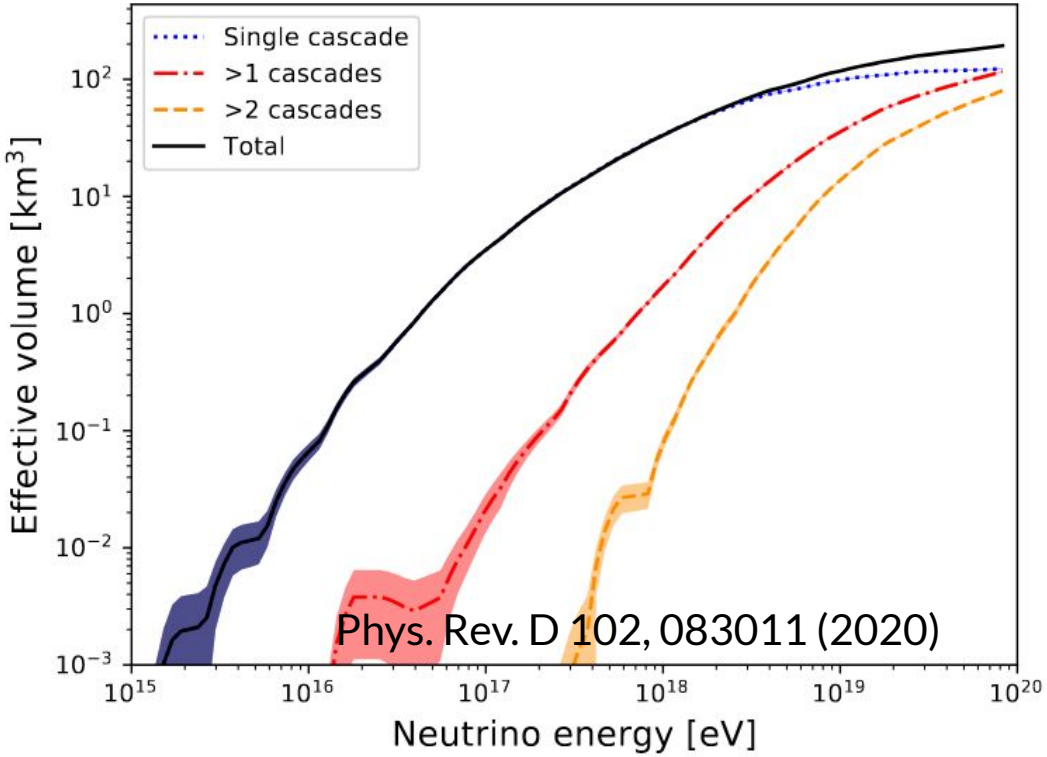
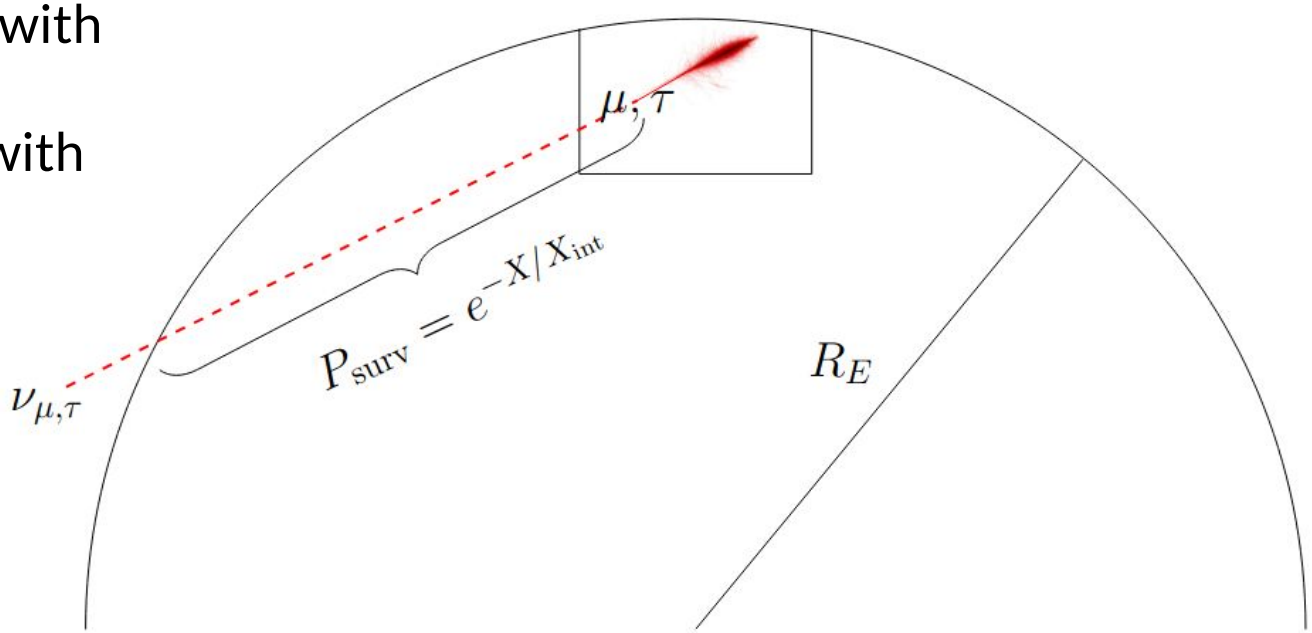
ASKARYAN RADIO ARRAY

What Has Been Done?

- Modelling of in-ice cascades induced by neutrino-sourced muons and τ-leptons
  - Events weighted by neutrino survival probability
  - Leptons propagated with PROPOSAL
  - NuRadioMC calculates radio emission from induced cascades

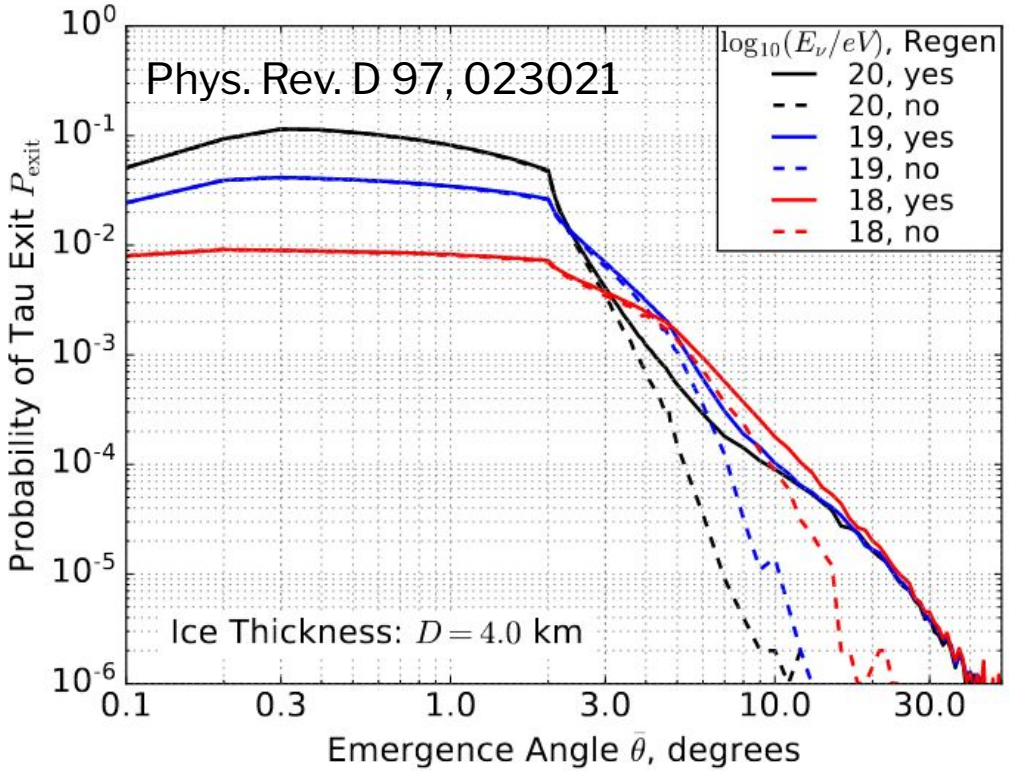
- Radiative losses improve instrument sensitivity with respect to purely neutrino interactions
  - Increasing number of observable cascades with increasing energy

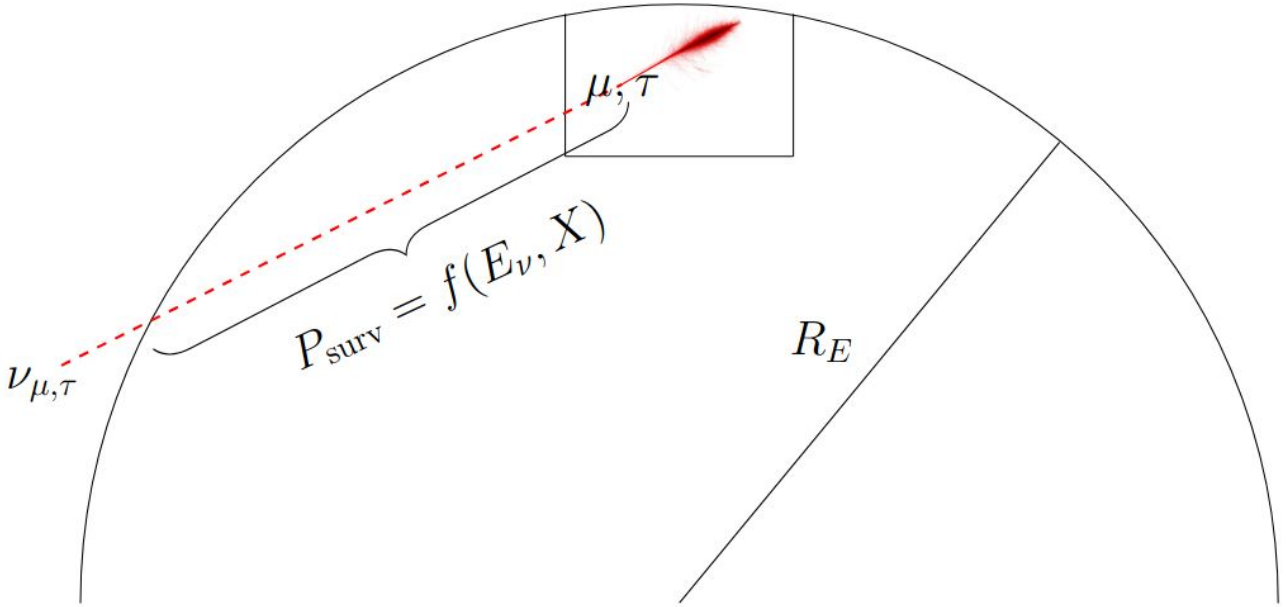




Further Improvements?

- Full propagation of neutrinos inside the Earth
  - Energy losses due to neutral current interactions
  - Potential $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ regeneration





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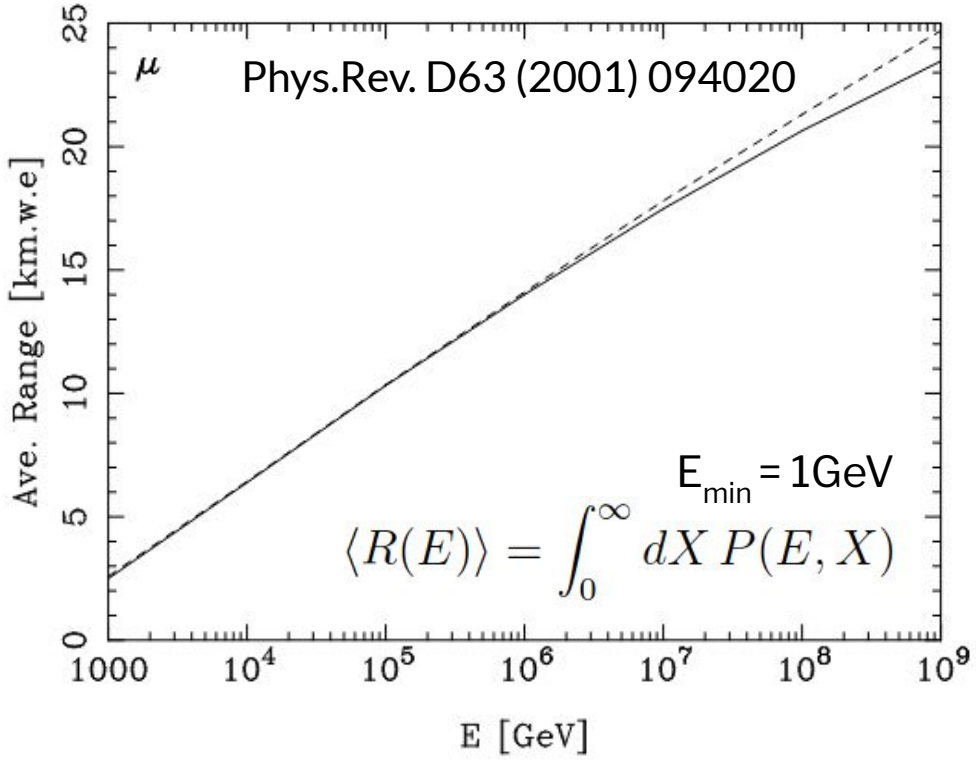
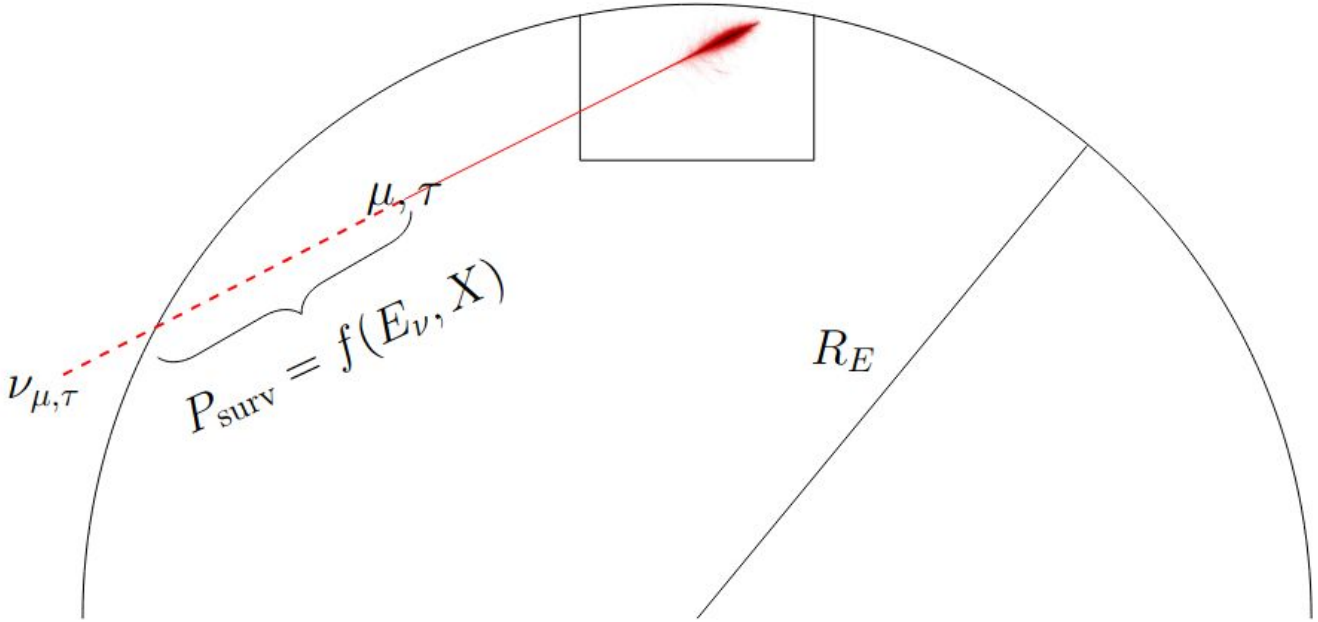
  - Propagation ranges increase significantly with increasing energy





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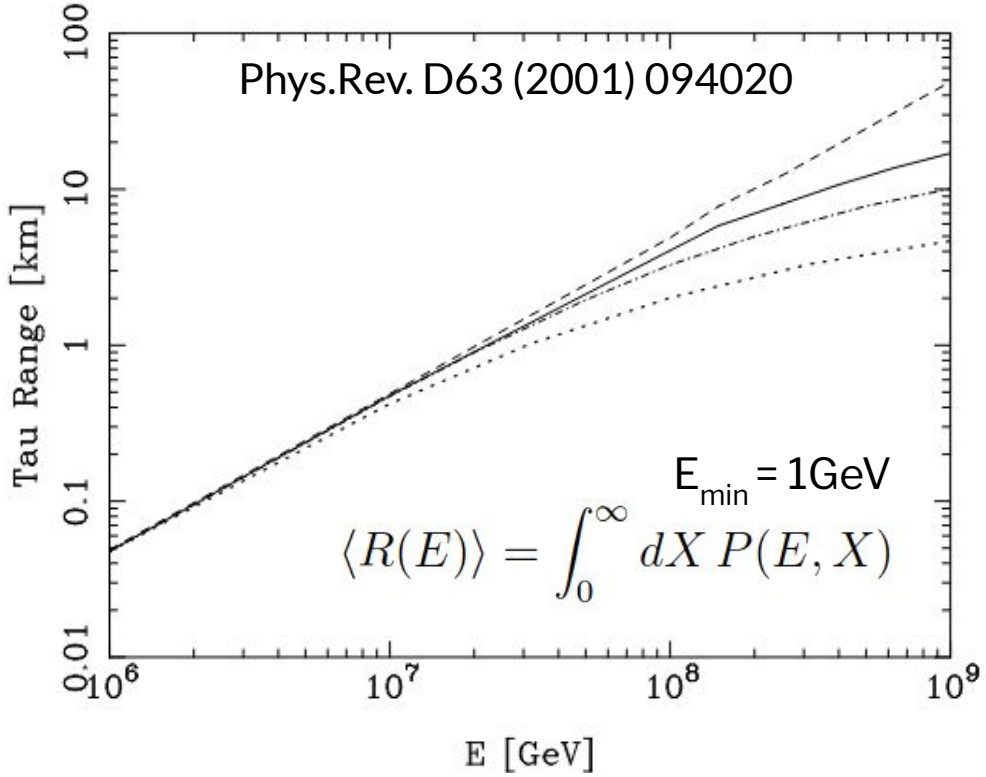

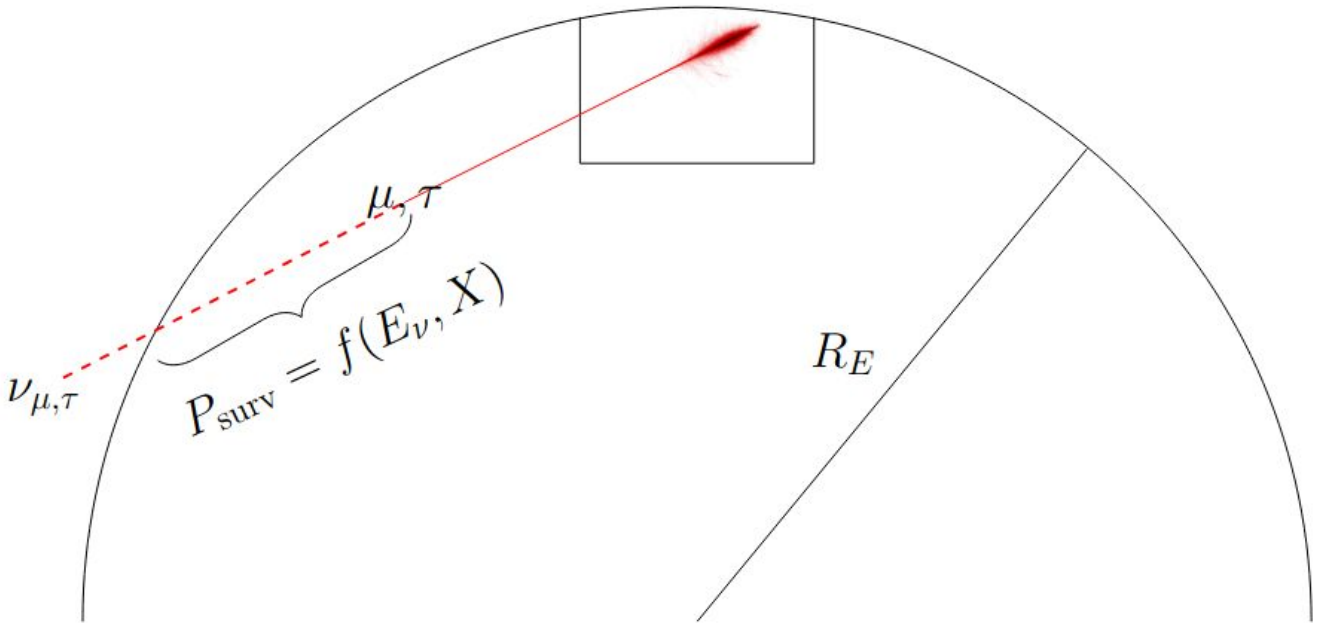

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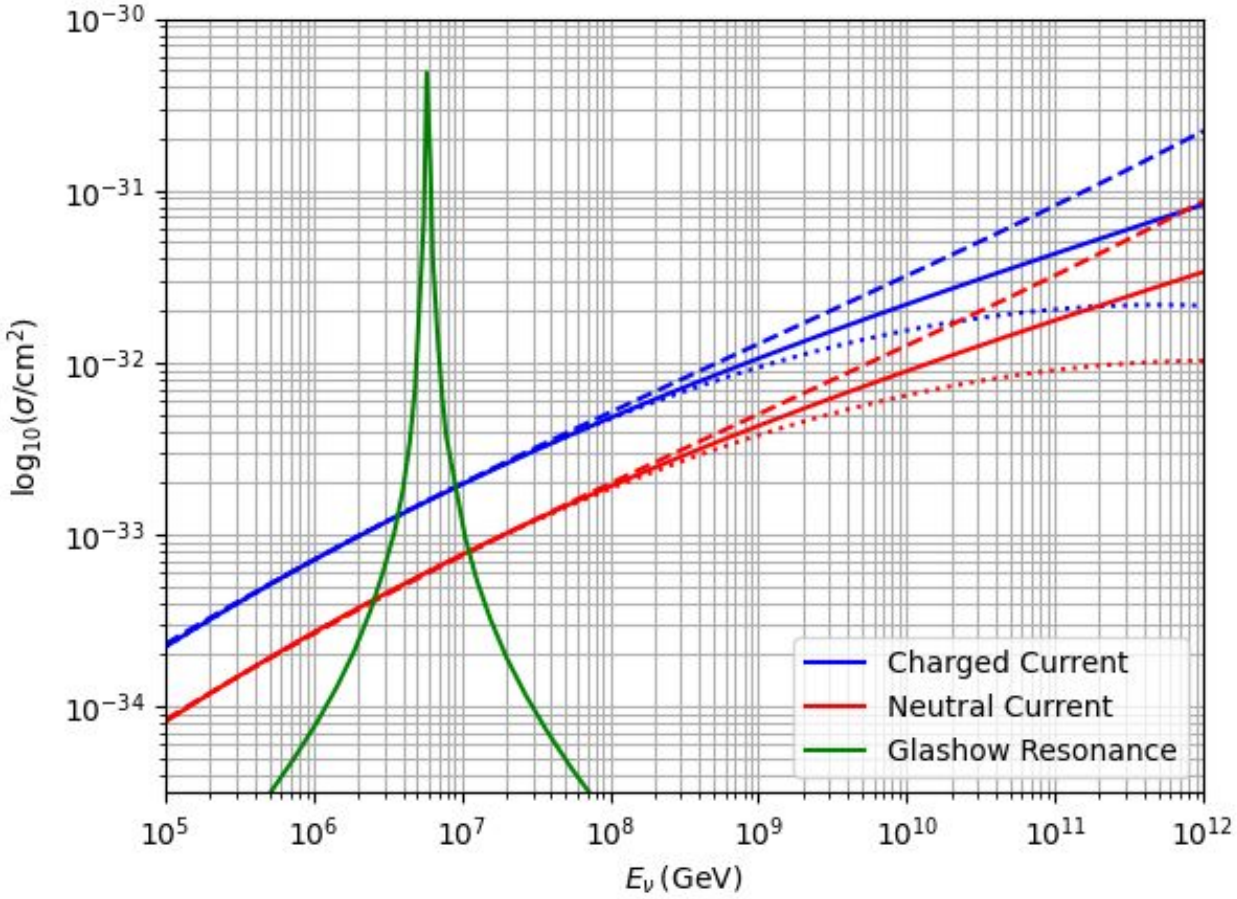
- Charged leptons sourced from secondary channels:
  - $\nu_\tau \rightarrow \tau \rightarrow \mu + \nu_\tau + \overline{\nu_\mu}$
  - $\overline{\nu_e} + e^- \rightarrow W^-$
    - $W^- \rightarrow \ell^- + \overline{\nu_\ell}$



Existing Neutrino Propagation Tools

Software	Medium	Cross-Section	Energy Loss	Decay	Secondaries
`NuPropEarth`	PREM*	DIS+Others (GENIE)	PROPO./TAUSIC	TAUOLA	ν(all), τ
`TauRunner`	PREM, Sun*	DIS (Table)	PROPOSAL	Param.	ν(all), τ, μ
`nuPyProp`	PREM*	DIS (Table)	Table	Param.	τ
`NuTauSim`	PREM	DIS (Param.)	Param.**	Table	ν, τ
`Danton`	PREM*	DIS+GLRES (ENT)	PUMAS	TAUOLA (Alouette)	ν(all), τ

DESY-22-040, LA-UR-21-32255

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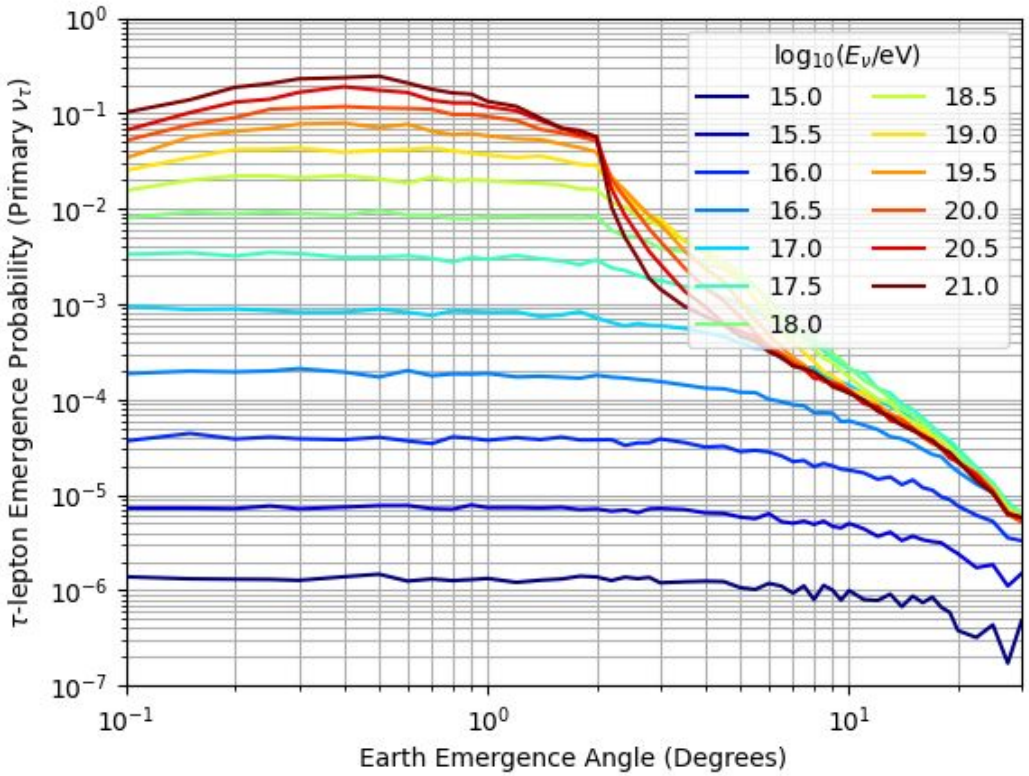
NuTauSim

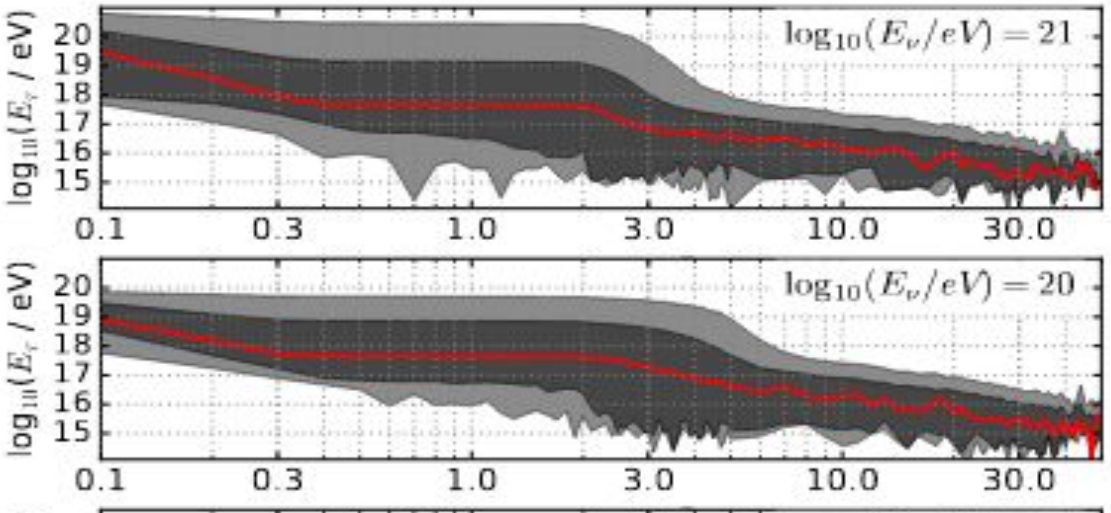
- C++ based monte carlo that models the Earth-emergent flux of tau leptons given monoenergetic fluxes of primary tau neutrinos and Earth emergence angles
  - Earth emergence probability
  - Energy distribution

- Includes NC and CC neutrino interactions, tau decays, regeneration

- Using average energy losses along a propagation step allows for comparatively fast speeds

- Physical models are modular and can be easily changed

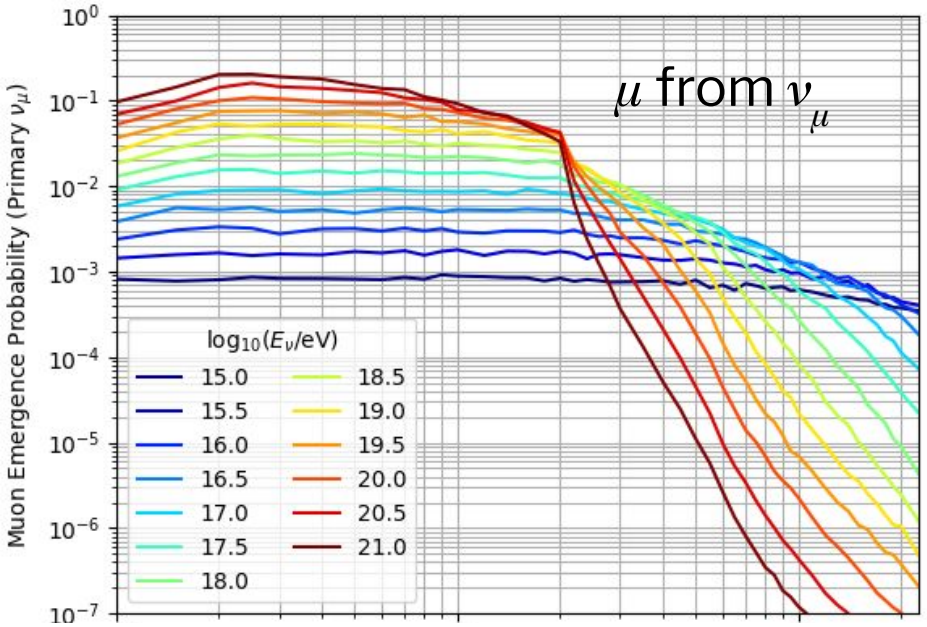


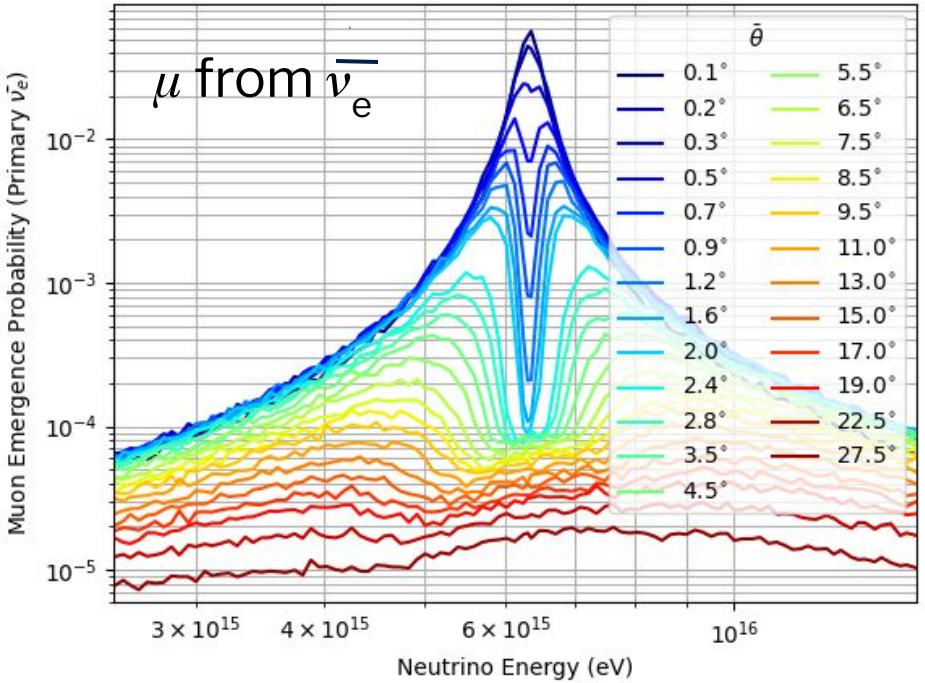


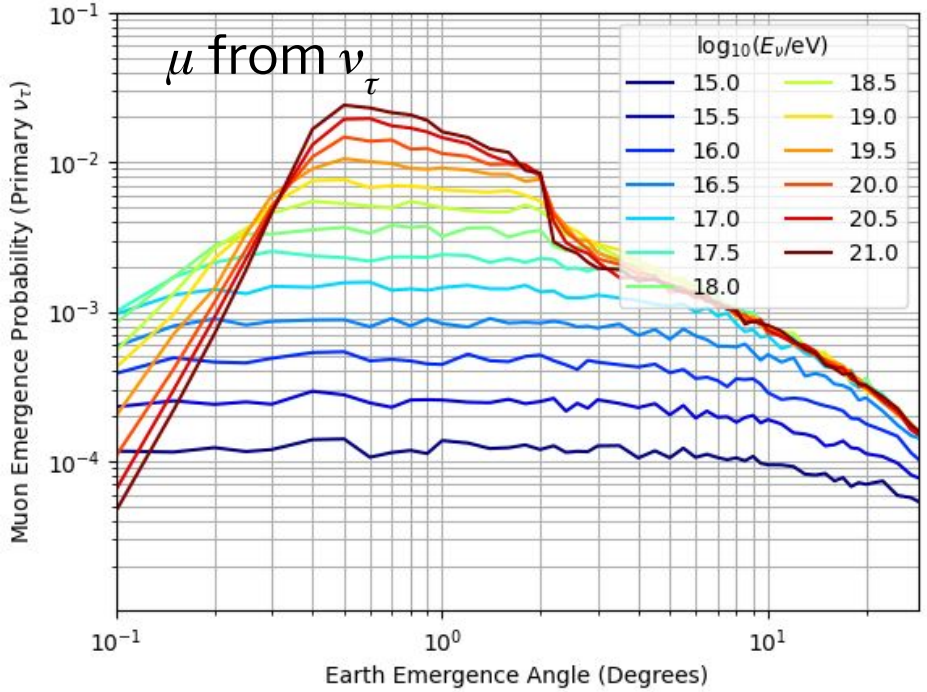
NuLeptonSim

- Upgrade to NuTauSim, but same basic layout

- New features:
  - Muon & muon neutrino propagation
  - Glashow Resonance events
  - Multiple particle tracking
  - Inclusion of detector volumes and arbitrary trajectories







Propagation of Charged Leptons (without PROPOSAL)

- From particle starting point, sample interaction length from exponential with mean:

$$X_{\text{int}} = \frac{A\, m_N}{\sigma}$$

  - Propagated distance:

$$\Delta R = X_{\text{int}}/\rho$$

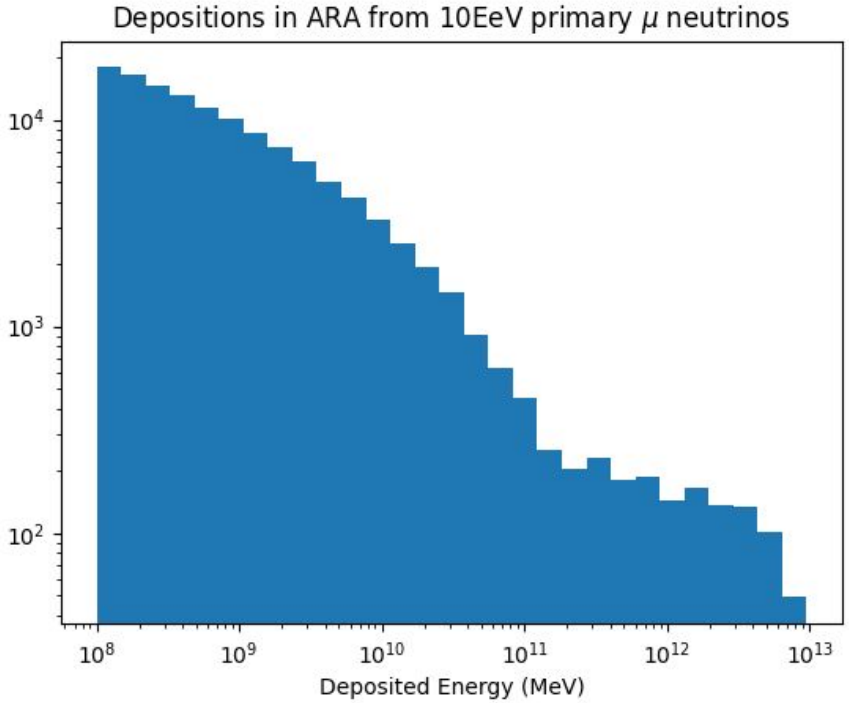
- Determine interaction type by ratio of cross sections at particle energy and a random number

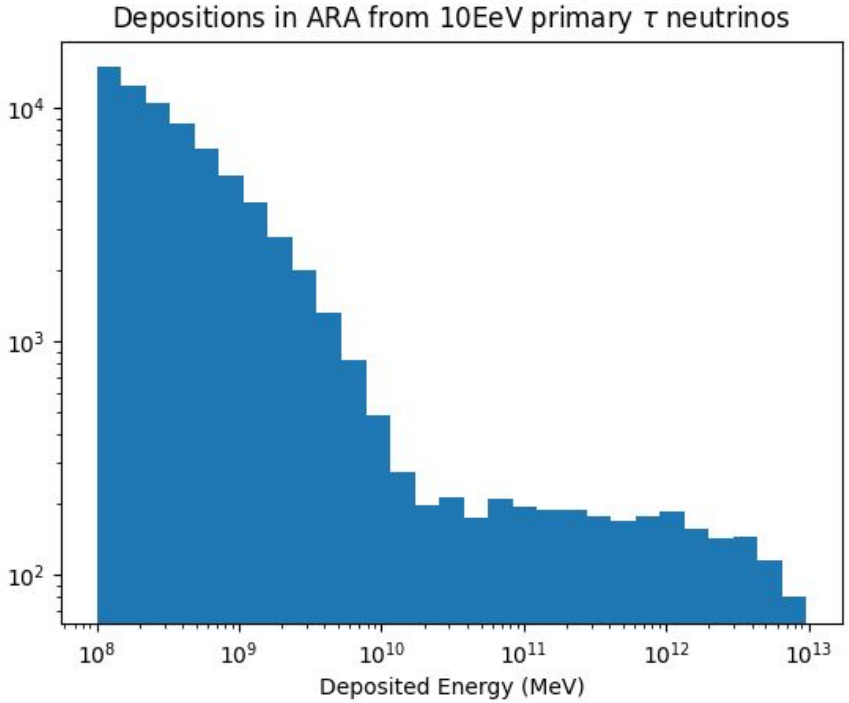
- Sample energy of interaction ΔE
  - Using inverse transform sampling on CDFs of interaction cross sections (see bonus slide)

- Increment energy:

$$E = E - \Delta E$$

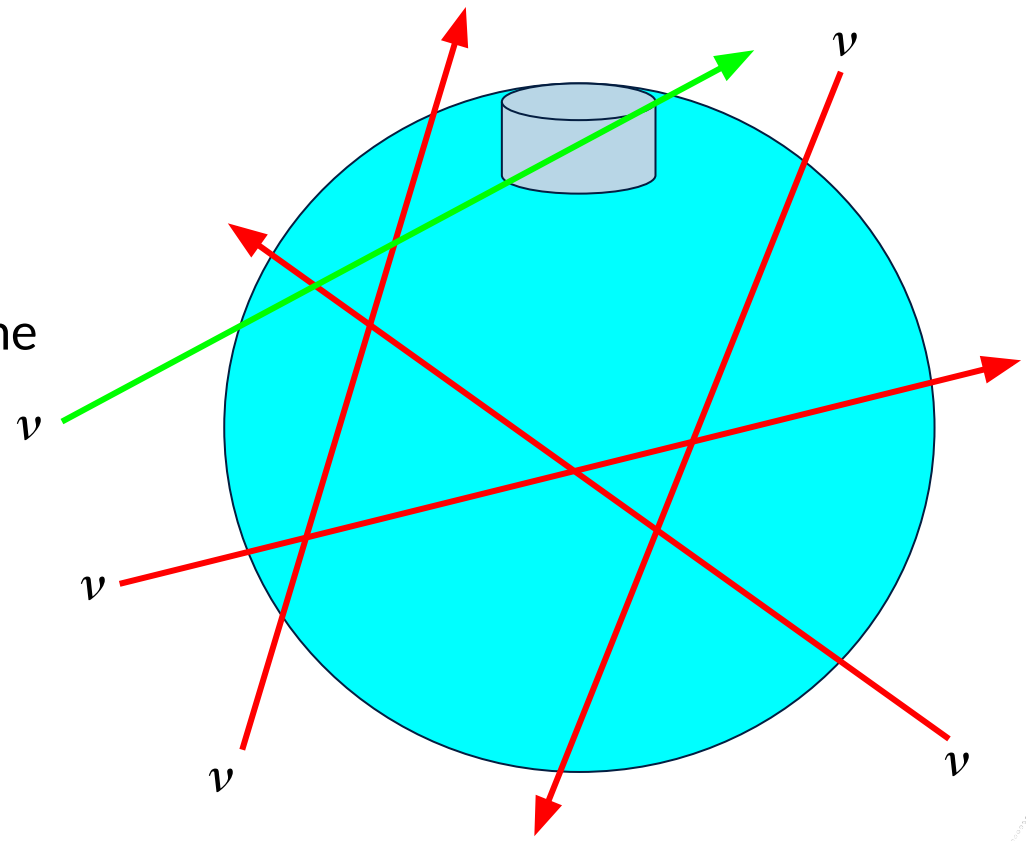
- Continue until exiting volume or reaching threshold





Event Generation for ARA

1. Isotropically throw trajectories through the Earth
2. Accept trajectories that pass through the cylinder
   - For ARA: 15km radius, 2.8km depth
3. For each passing trajectory, throw N_ν neutrinos using NuLeptonSim and save events which occur inside the volume
   - Charged current
   - Neutral current
   - τ decays
   - Glashow Resonance
   - Charged leptons
     - Propagate further using custom code
4. Output passing events:
   [E(shower)+inelasticity, x, y, x, V_x, V_y, V_z, type, weight]

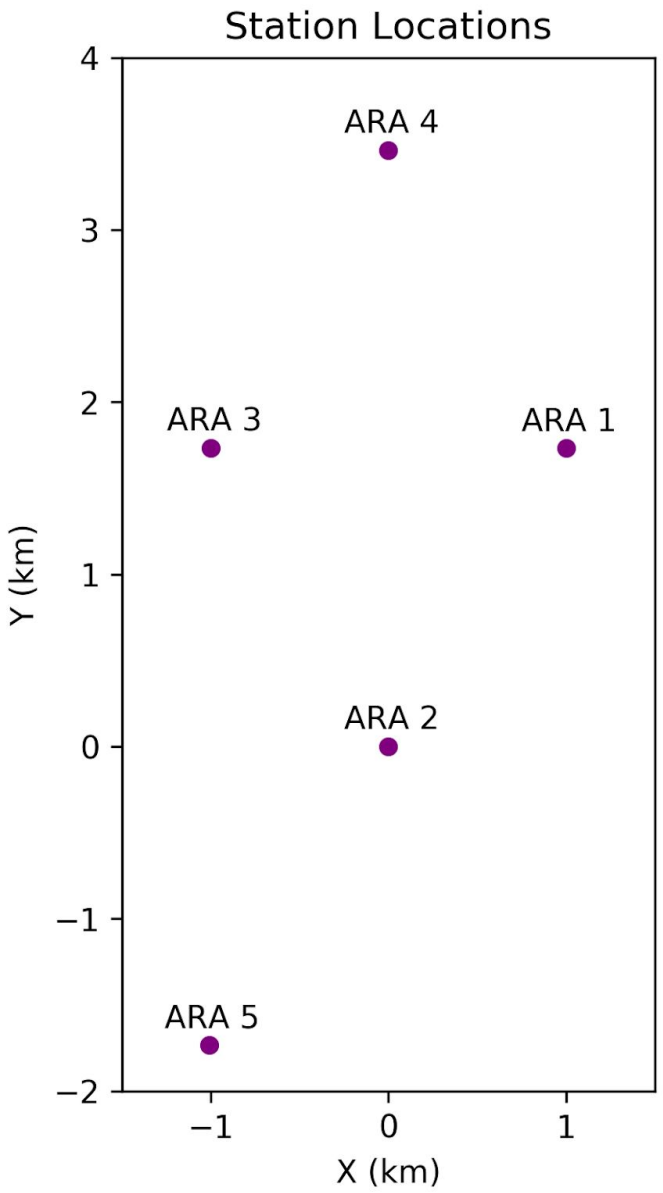


Characteristics of showers can be approximated by:

- γ's (e's from CC, e's and π^0s from decays, e's from GR, e's from pair production, γ's from Bremsstrahlung)
- Hadrons (CC, NC, $\pi^{\mp}$s from decays, nucleons from photonuclear interactions)

5-Station ARA Layout

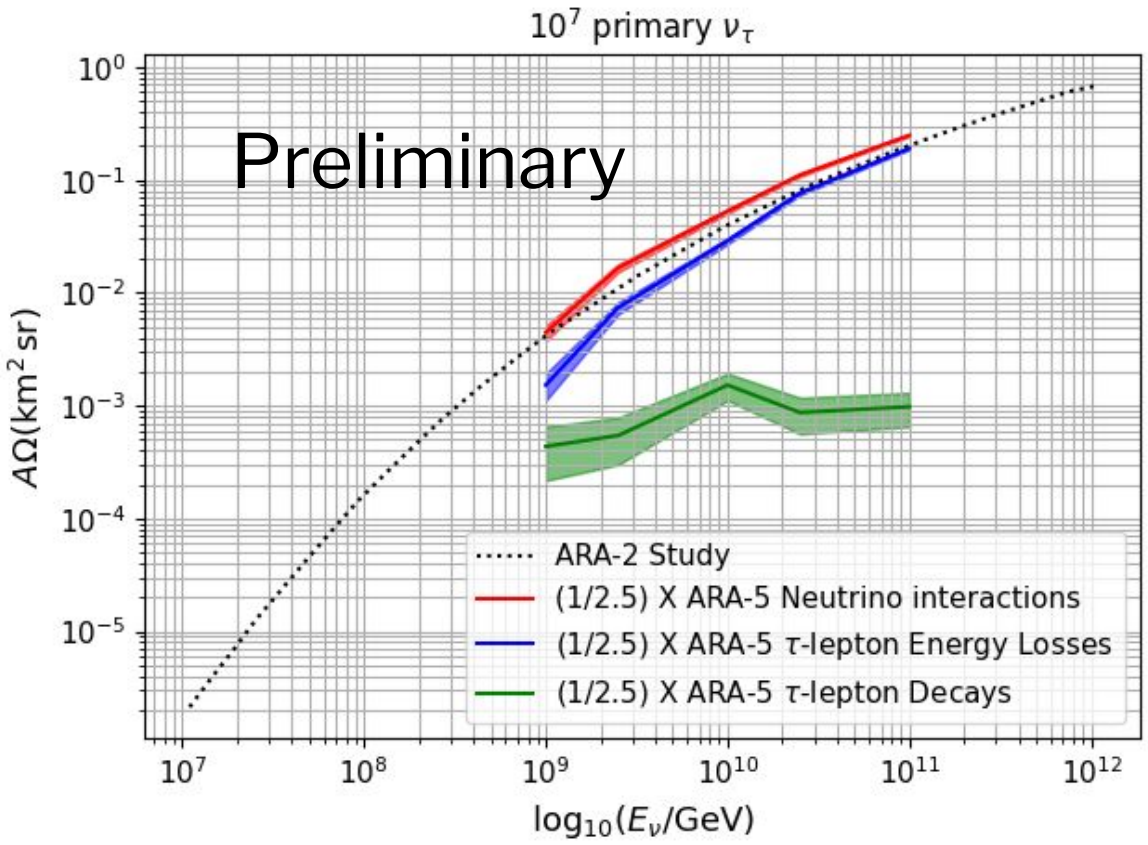
- 5 stations simulated in deployed positions
- Radio emission from showers initialized by neutrino interactions or charged lepton radiative losses are calculated and propagated by PYREX
  - Event detection considered for 3 triggered antennas with 3-6σ
- Searching for:
  - Coincident events for potential lowered thresholds
  - Effect of regeneration on effective volume
  - Effect of secondaries on effective volume



5-Station ARA Performance

- Effective volume calculated only using primary neutrino interaction vertices matches well to A2 (2 station ARA) in Phys. Rev. D 102, 043021 (2020)

- Effect of τ-leptons matches well to results of Phys. Rev. D 102, 083011 (2020)
  - Decay topology makes up a few percent of observed events (stronger effect at lower energies)
  - Radiative losses ~⅓ of neutrino curve at 1EeV, increases to ~⅔ at 100EeV
    - Closer to ~½ in PRD at 100EeV



Conclusion

- Robust simulation pipeline:
  - Isotropically throw trajectories
  - Propagating neutrinos through the Earth (NuLeptonSim)
    - Record any interactions
  - Propagate showers and calculate radio emission using PYREX

- Initial results match well with previous studies
  - First hints of an increase in effective area from radiative losses due to increased propagation range at high energies

- Muon neutrinos currently running

- Higher statistics runs coming soon

Discussion & Questions

Bonus Slide: Neutrino Interaction in the Earth

- Calculate grammage profile along neutrino trajectory:

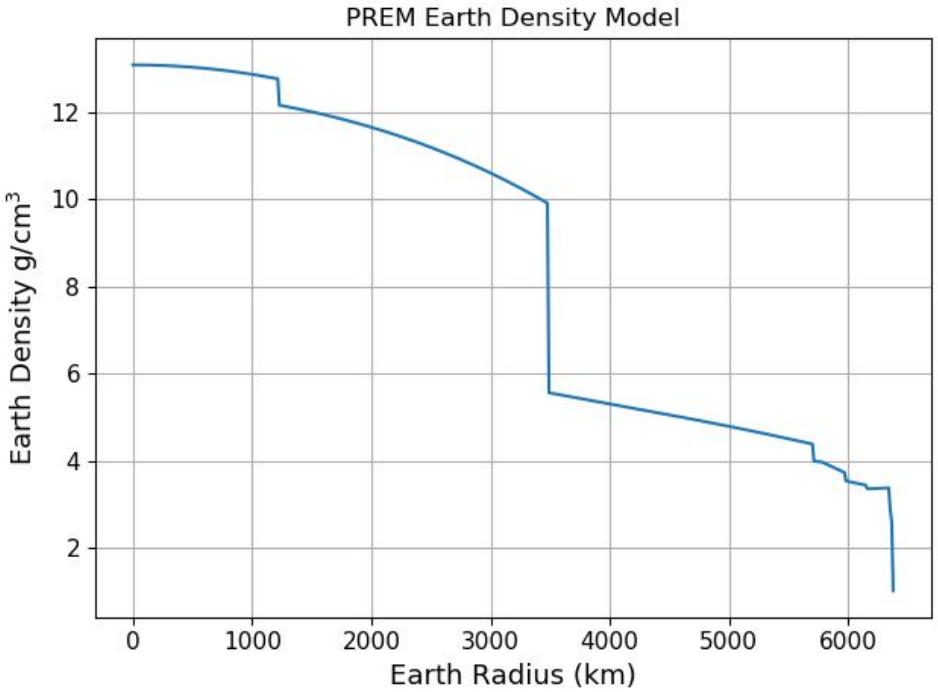
$$X_E(L) = \int_0^L \rho(r(L))dL$$

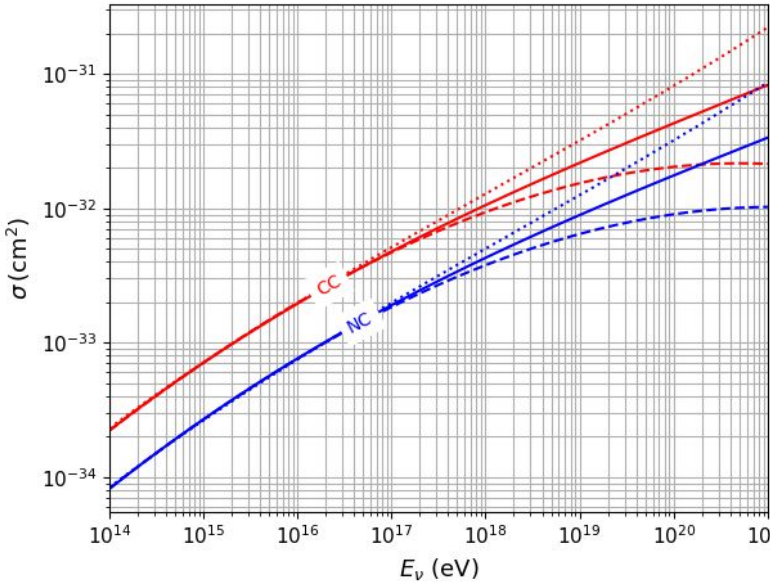
- Sample neutrino interaction grammage from exponential distribution with mean:

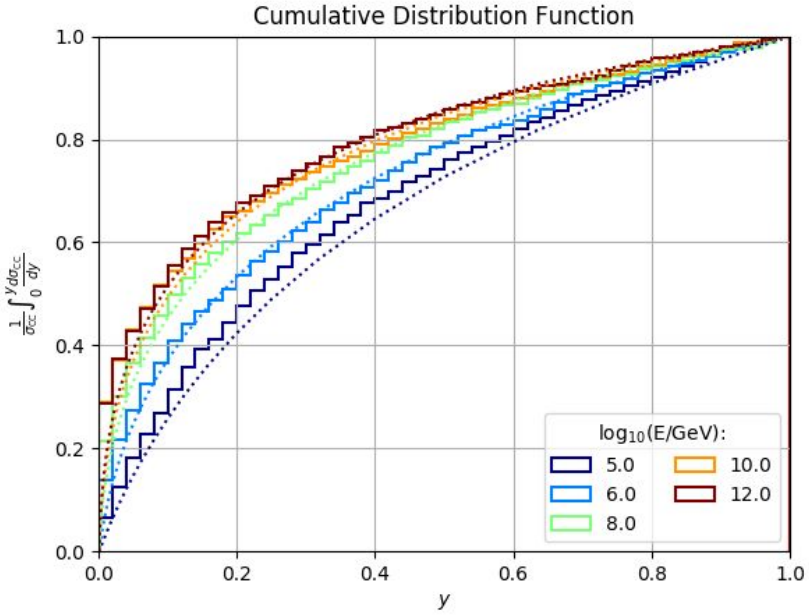
$$X^{\nu}_{int}(E_\nu) = \frac{m_N}{\sigma_{\rm CC}(E_\nu) + \sigma_{\rm NC}(E_\nu)}$$

  - σ_{CC}/σ_{NC} ≈ 2.6

- Charged lepton energy = (1-y) Eν
  - Average y ≈ 20%







Bonus Slide: Charged Lepton Propagation (continuous)

- Assume continuous energy losses inside the Earth:

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

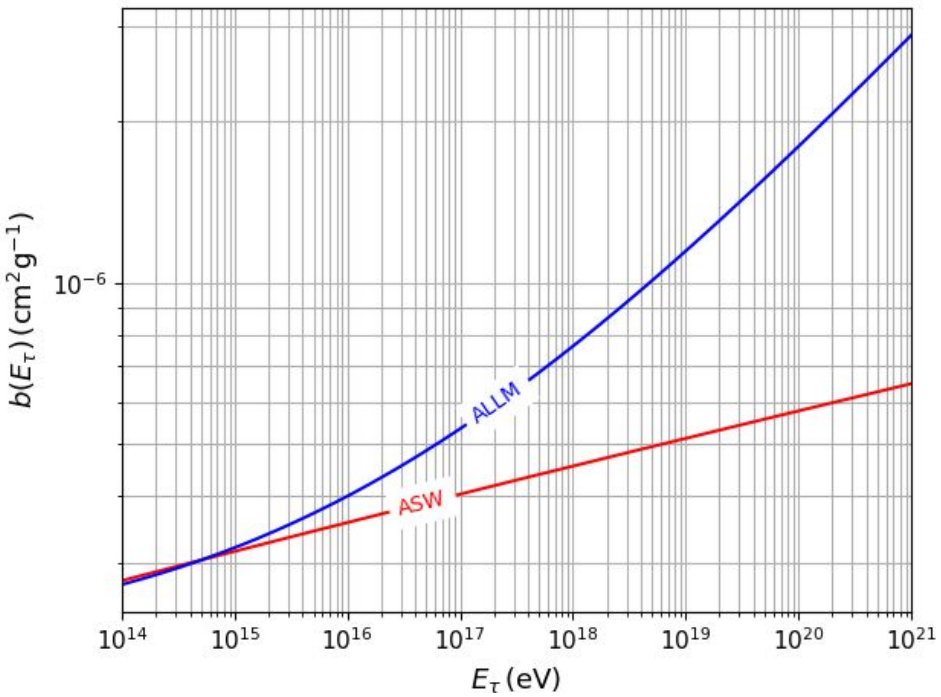
a(Eτ) corresponds to constant ionization losses
b(Eτ) corresponds to radiative losses
  - Bremsstrahlung
  - Electron-positron pair production
  - Photonuclear interactions

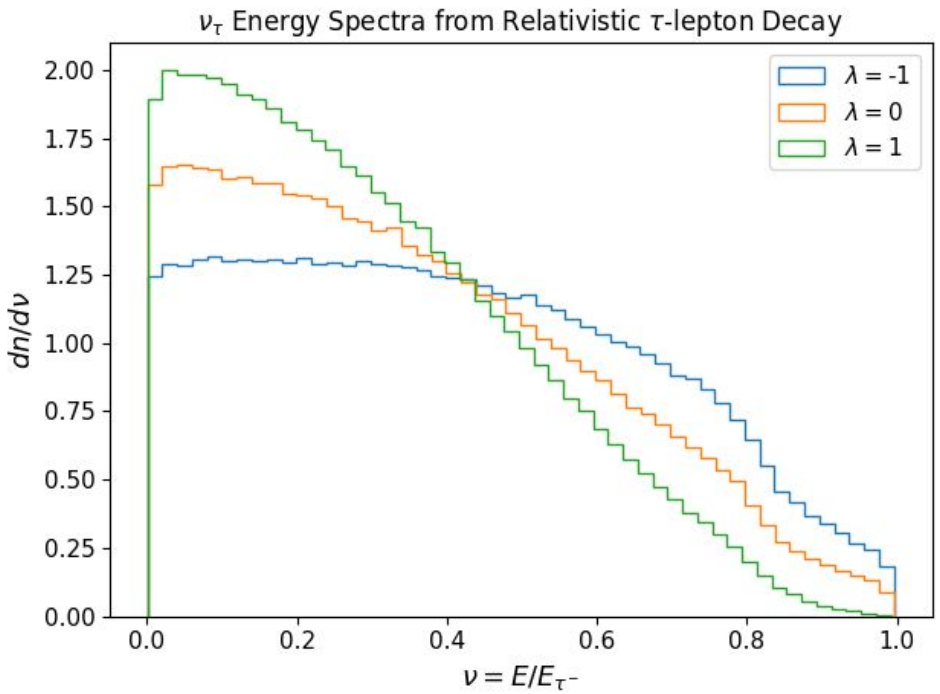
- Propagated in steps ΔL such that 0.1% of the primary energy is lost

- Check for decay with probability:

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

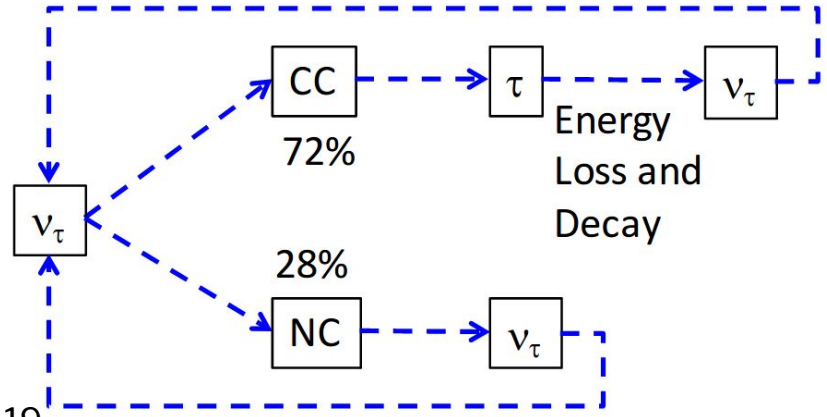
  - Sample neutrino energy from decay spectra

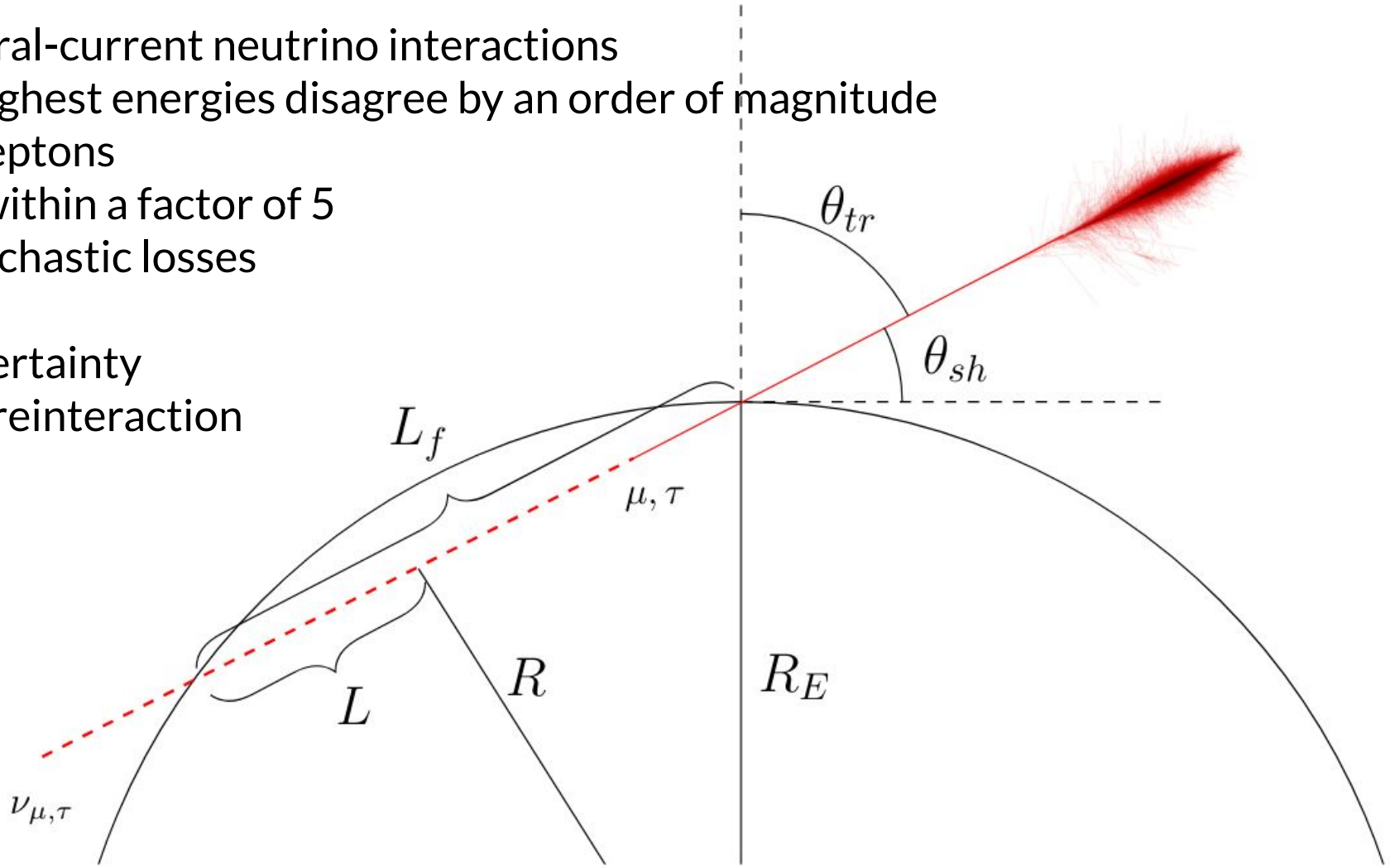




Bonus Slide: Modeling Neutrino Propagation

- Must properly consider:
  - Charged-current and neutral-current neutrino interactions
    - Uncertainties at the highest energies disagree by an order of magnitude
  - Energy losses of charged leptons
    - Similar uncertainties within a factor of 5
    - Continuous versus stochastic losses
  - Charged lepton decay
    - Polarization state uncertainty
  - Multiple particle tracking/reinteraction



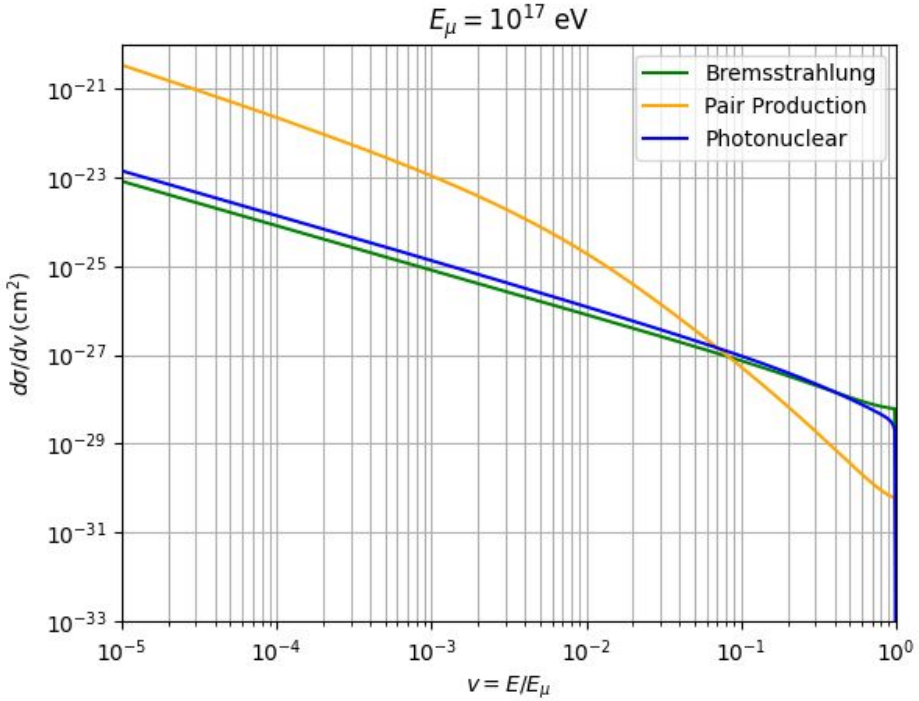


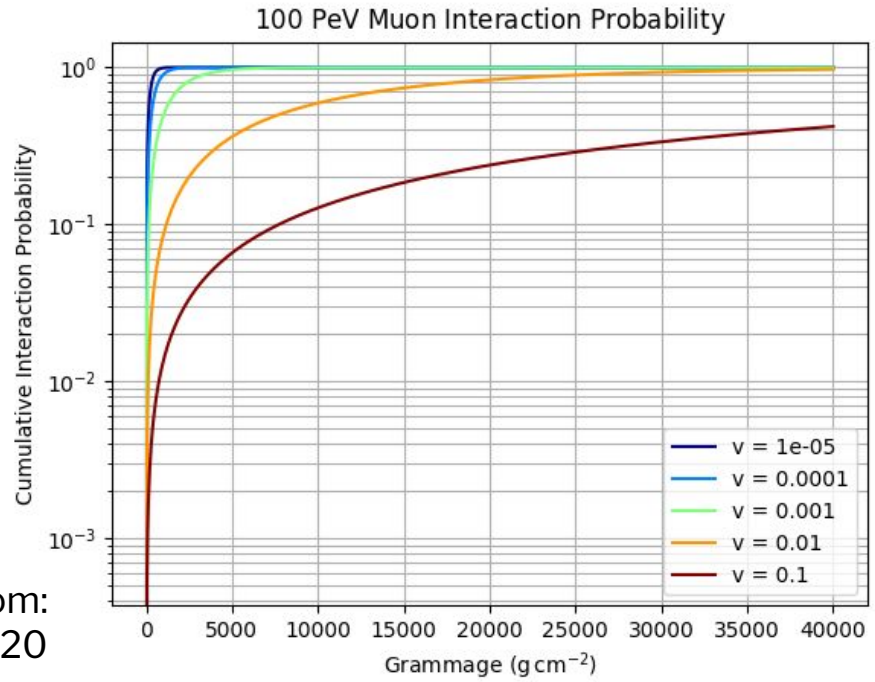
Bonus Slide: Shower Initiation via Radiative Energy Losses

- Radiative energy losses proportional to primary energy
  - Even a small fraction lost can trigger a detectable shower if the primary is energetic enough
  - Tau losses ~1/10 Muon losses, but have characteristically higher primary energies

- Losses to consider:
  - Pair production (model as γ shower)
  - Bremsstrahlung (model as γ shower)
  - Photonuclear (model as hadronic shower)

- For each Earth-emergent charged lepton, provide:
  - Energy of deposition
  - Location of deposition
  - Interaction type





Parameterizations taken from:
Phys.Rev. D63 (2001) 094020

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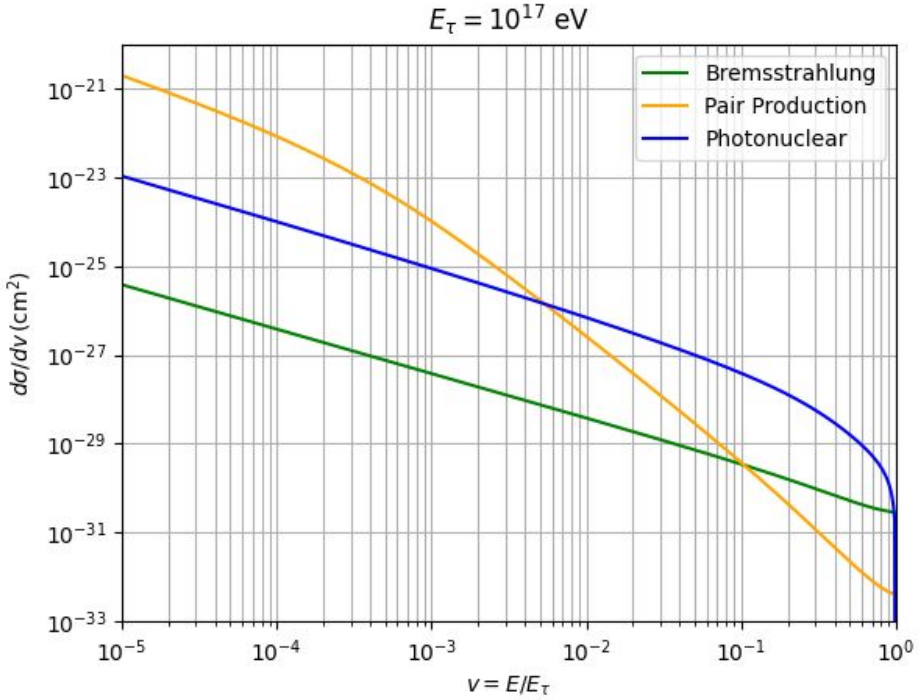

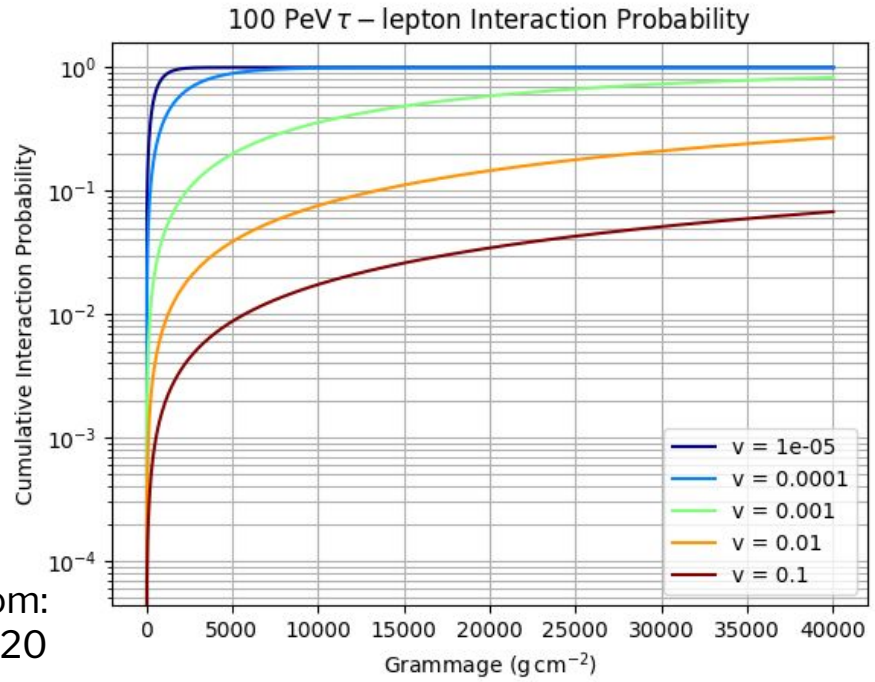

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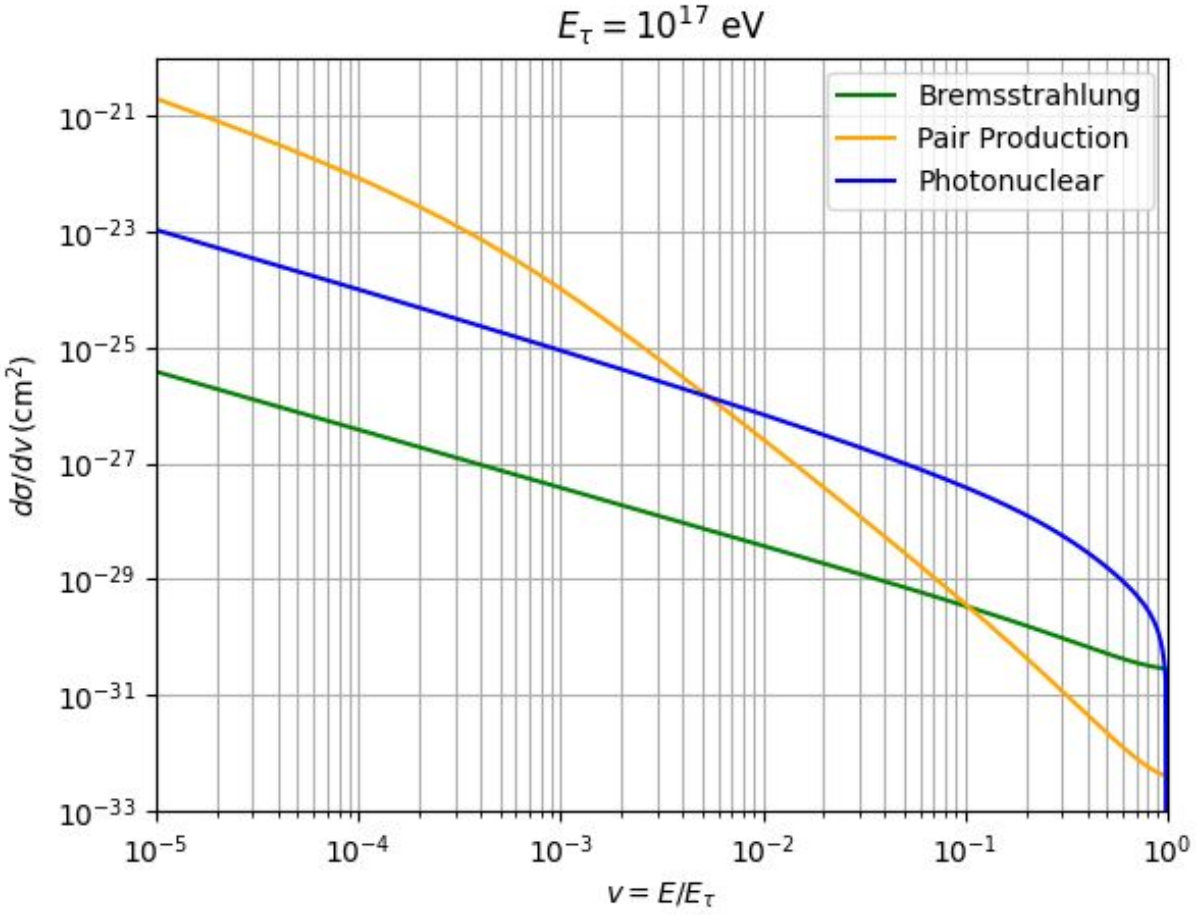
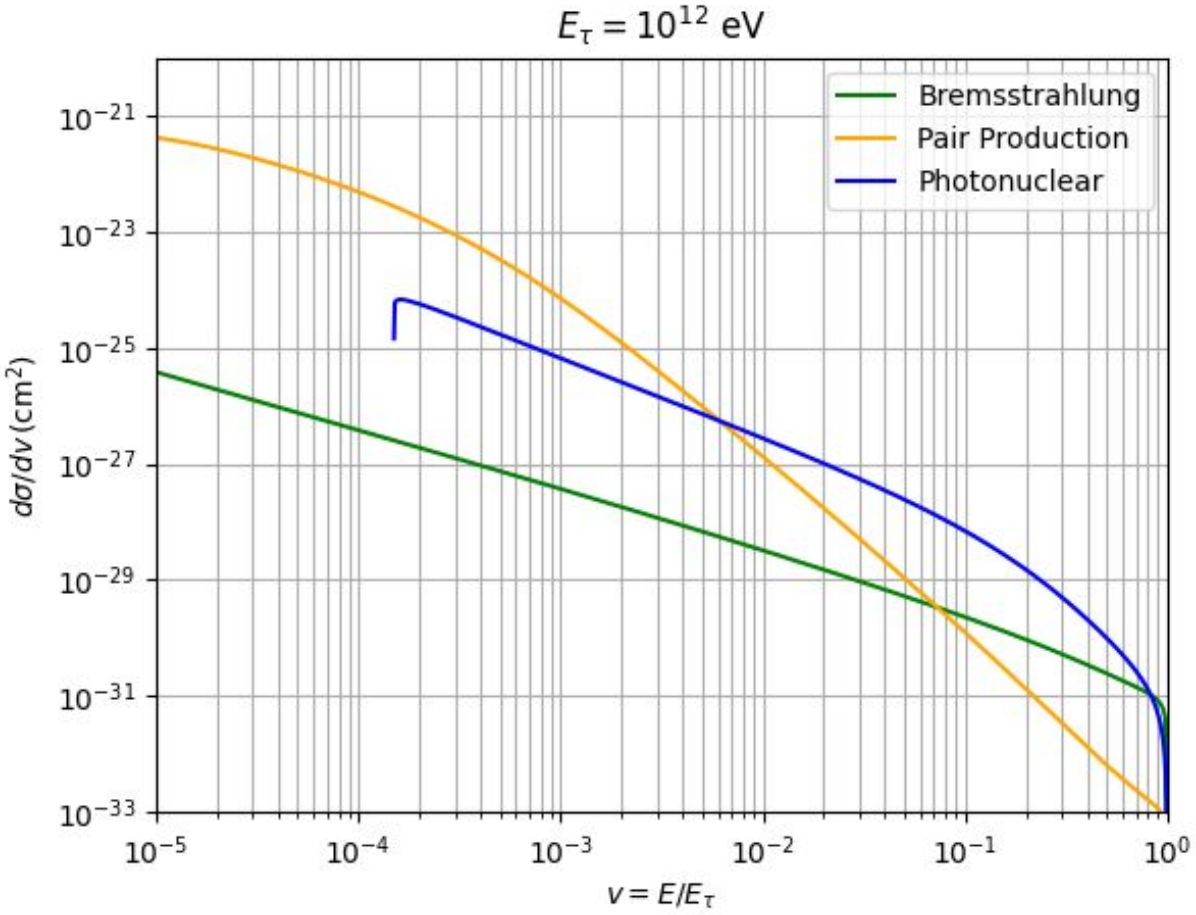
Bonus Slide: Cross Section Behavior

- Must consider energy dependence of cross sections



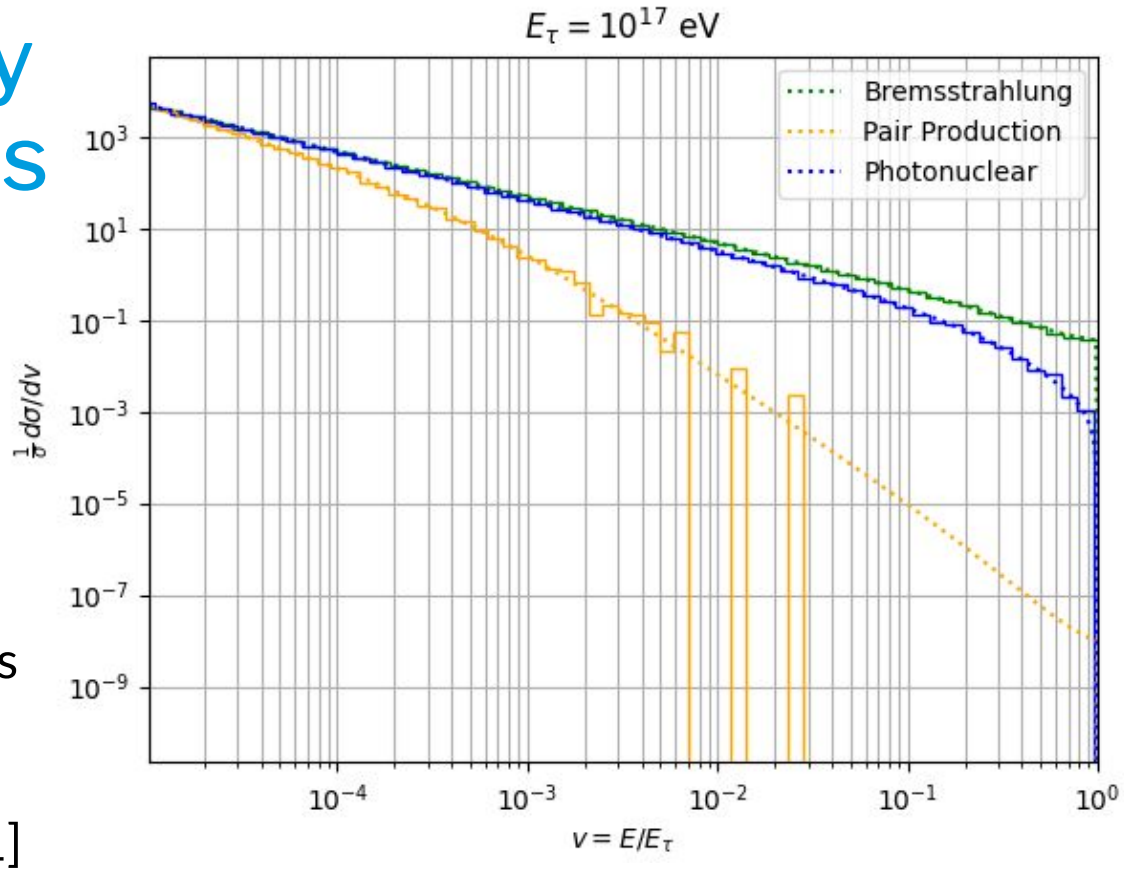


Bonus Slide:Radiative Energy Sampling of Charged Leptons

- Integrate cross sections to recover cumulative distribution function:

$$\mathrm{CDF}(v) = \int_{v_{\min}}^{v} \frac{d\sigma}{dv} \Big/ \int_{v_{\min}}^{v_{\max}} \frac{d\sigma}{dv}$$

- Use inverse transform sampling to recover depositions in an interaction
- Resample the CDF values over a regular grid from [0,1]
- Build 2-D interpolation table (charged lepton energy, random sample)



Curves are normalized! Only shape is important

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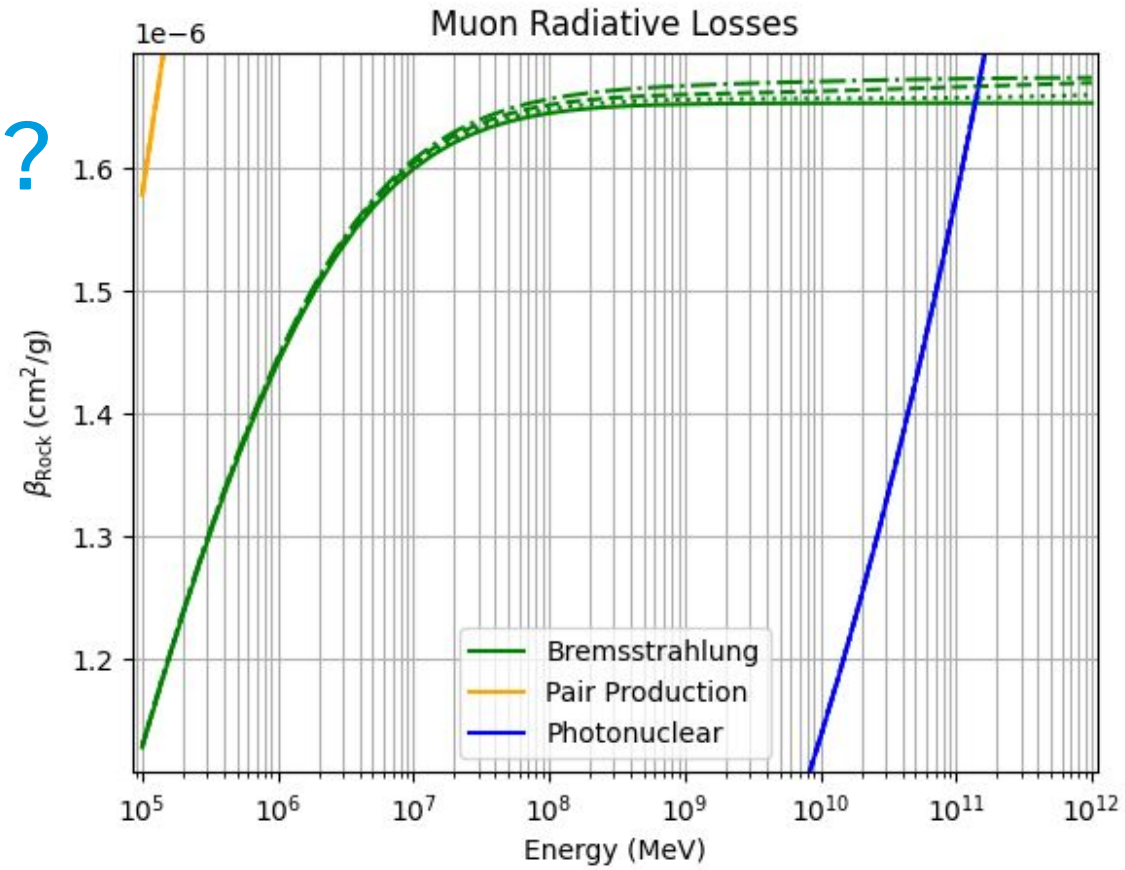
Bonus Slide: Cutoff for low inelasticities?

- Lower bound for inelasticity for Bremsstrahlung emission is 0
- Consider a lower bound cutoff for inelasticity where interactions below do not contribute significantly to energy loss processes
- Energy losses can be approximated as:

$$-\langle \frac{dE}{dX} \rangle = \alpha + \beta E$$

where

$$\beta^i(E) = \frac{N}{A} \int_{y_{min}}^{y_{max}} dy \; y \frac{d\sigma^i(y,E)}{dy}$$

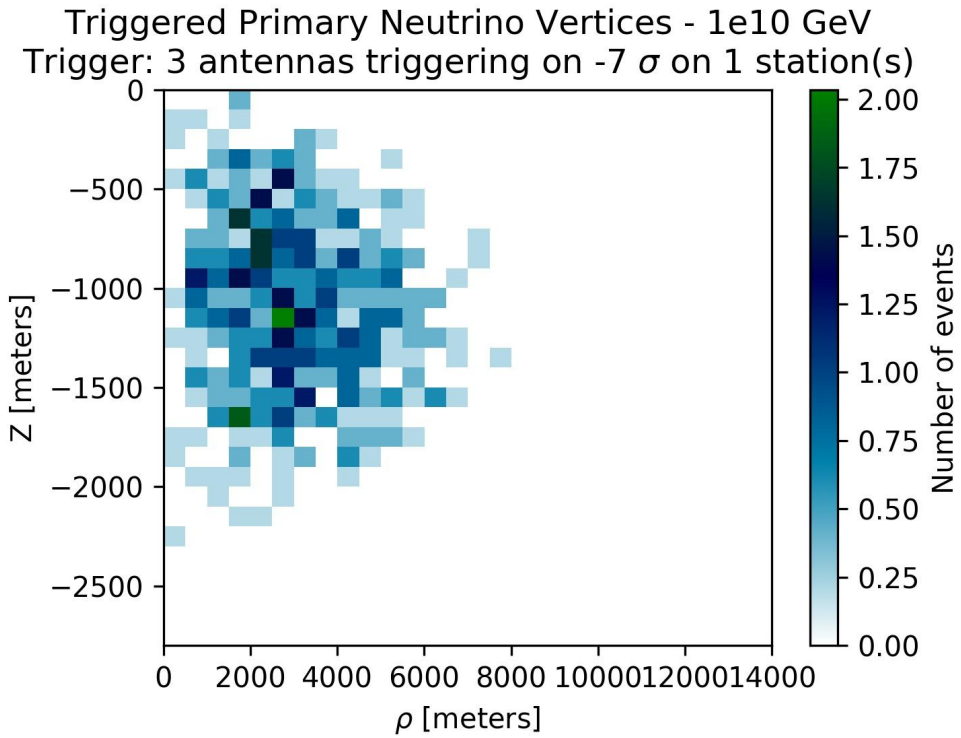


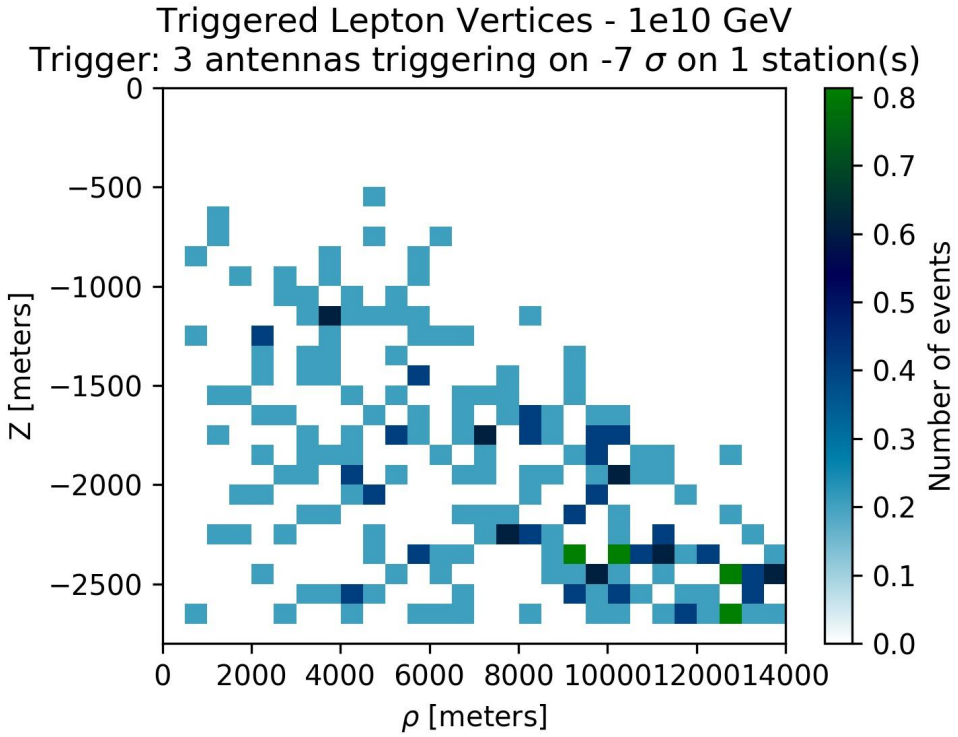
Lines correspond to values of lower bound cutoff inelasticity:

- Solid: 1×10^{-11}
- Dotted: 1×10^{-9}
- Dashed: 1×10^{-7}
- Dot-dashed: 1×10^{-5}

$y = 1\times10^{-9}$ is a good approximation for the lower bound!

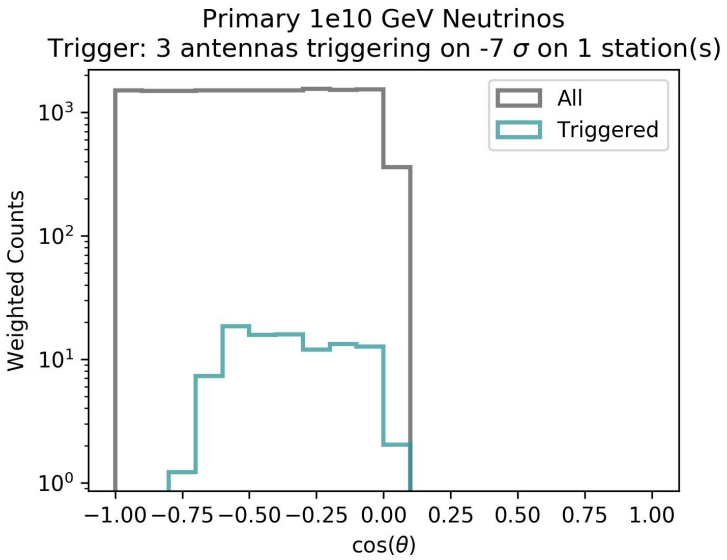
5-Station ARA Performance

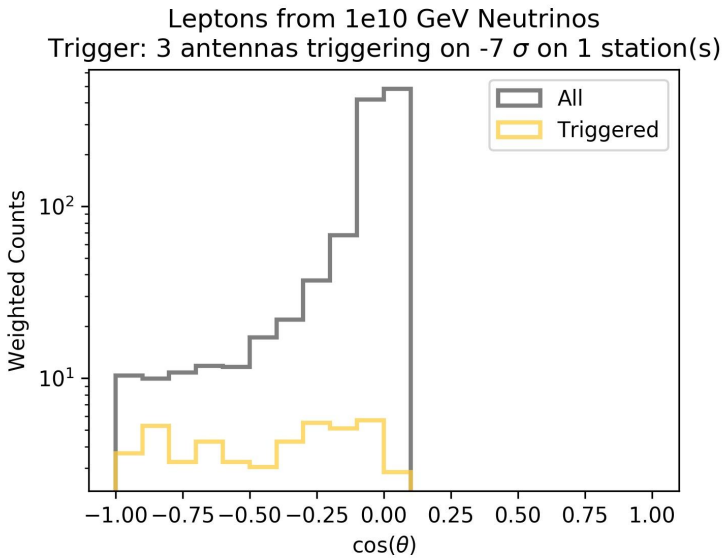


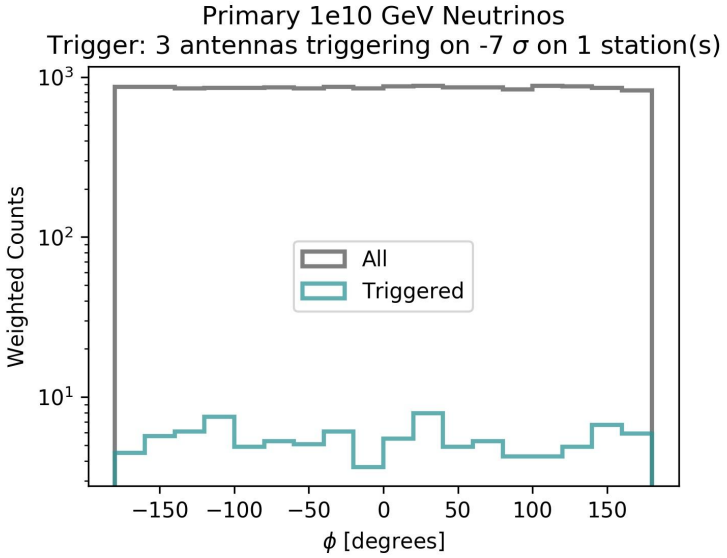


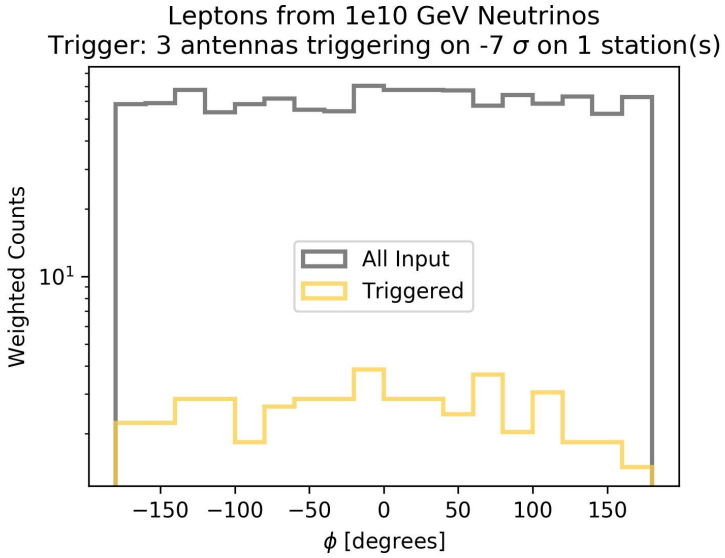
- Input leptons cluster near bedrock at the bottom of the viewing region whereas primary neutrinos cluster near the surface at the top of the viewing region.

5-Station ARA Performance - Angular

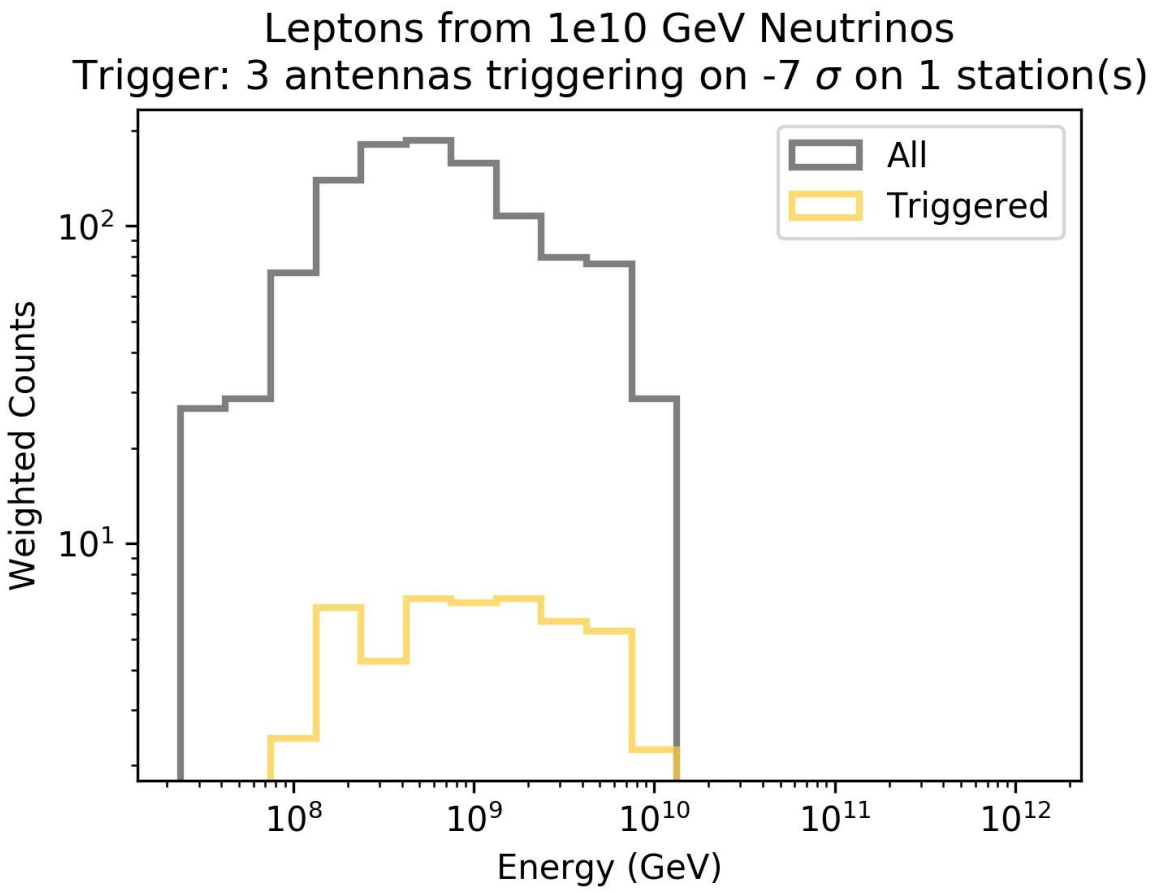








5-Station ARA Performance - Lepton Energies



PyREx Detector Simulations

- Simulates Askaryan radiation from neutrino interactions with the Askaryan model developed by Jamie Alvarez-Muñiz, Andrés Romero-Wolf, and Enrique Zas: https://arxiv.org/abs/1106.6283
- Using an south pole based ice model based on south pole ice properties parameterized by Matt Newcomb
- Noiseless simulations were used in this study (no additional noise was added to signals, thermal noise was only simulated to calculate trigger thresholds)

- Triggering:
  - ARA uses tunnel diodes in their signal chain
  - An antenna triggers if signal is **below** $\bar{n} - P\sigma_n$ where $\bar{n}$ is the average noise signal, σ_n is the RMS value of noise in the antenna, and *P* is an integer

- Code used in this study is open source and can be found here: https://github.com/abigailbishop/pyrex/tree/secondaries/analyses/secondaries