Probing Neutrino Flavor Composition with the Glashow Resonance at Tau Air Shower Neutrino Telescopes

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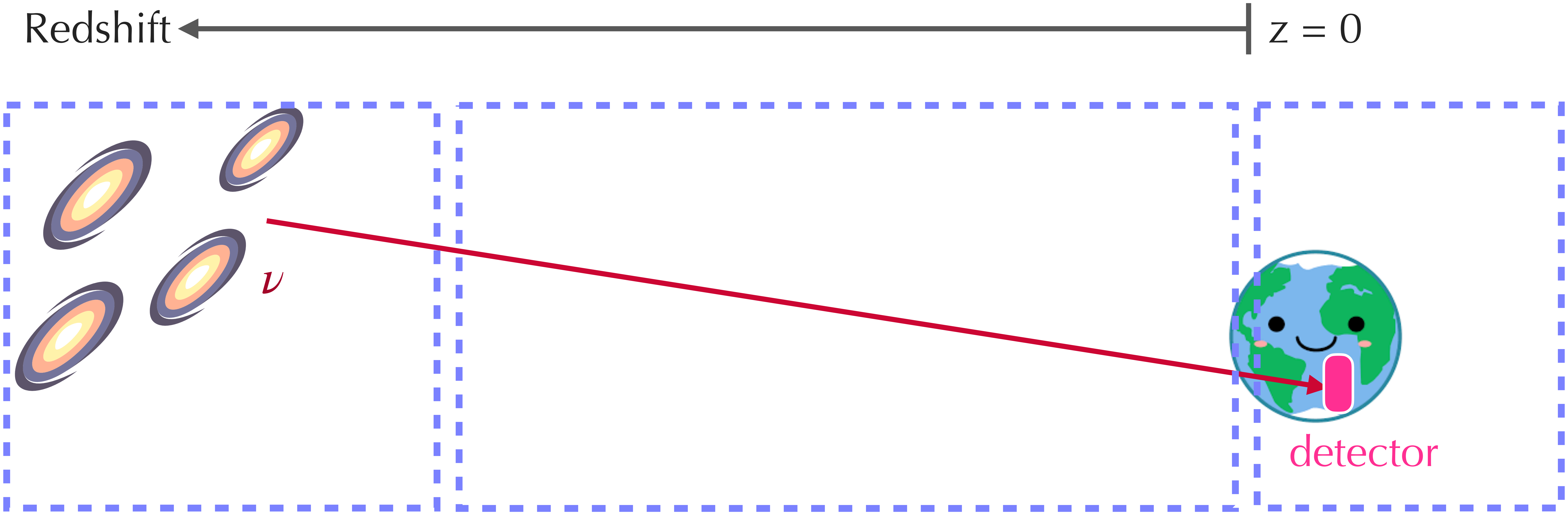
Compared to other messengers, neutrinos carry an extra piece of information: **flavor!**



Neutrinos are produced at the sources with a flavor composition.

Neutrino oscillations change the flavor composition.

Neutrinos are measured on Earth with a flavor composition.

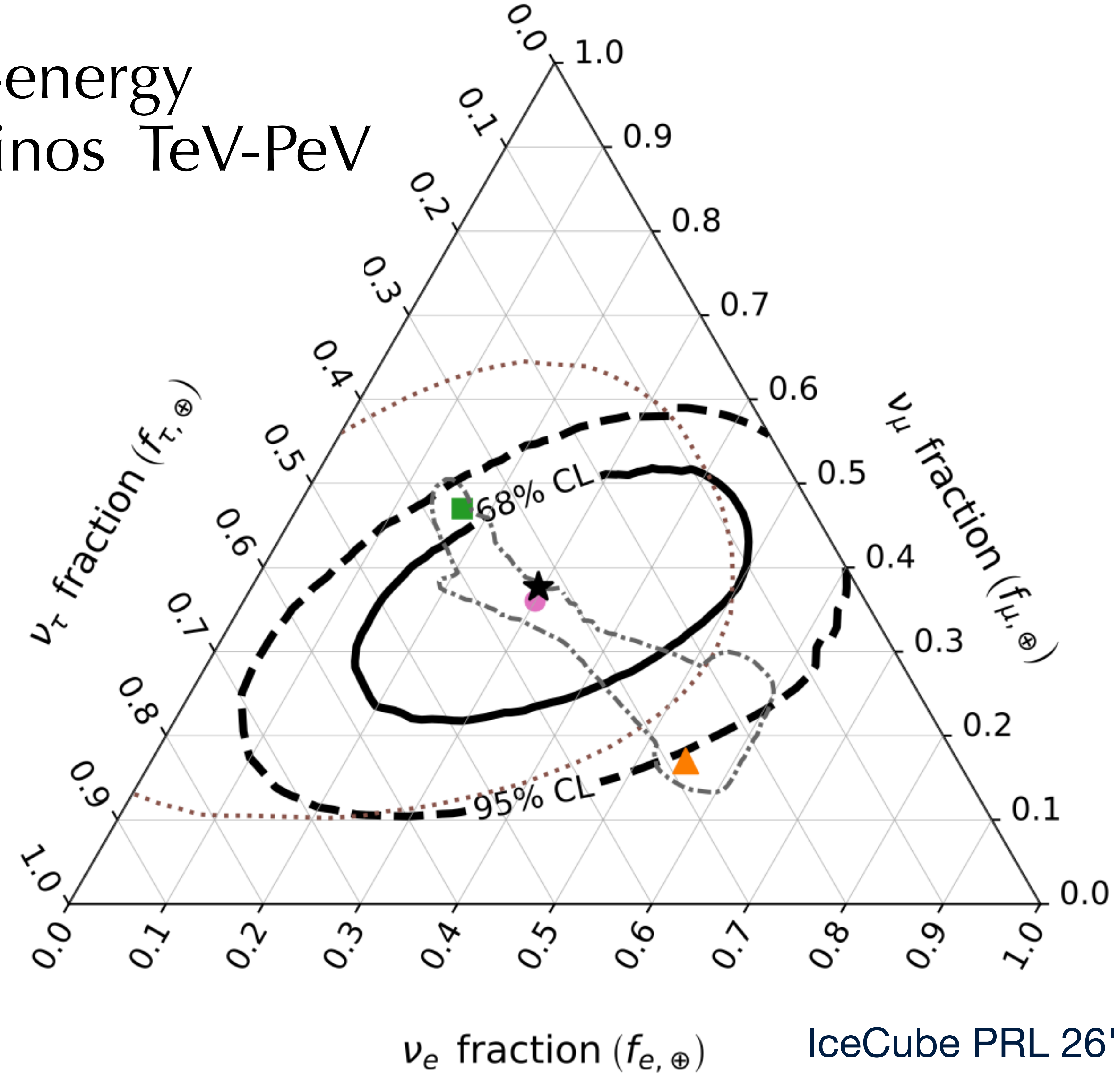
A way to infer neutrino production, propagation, and detection.

Neutrino Flavor Composition Measurements

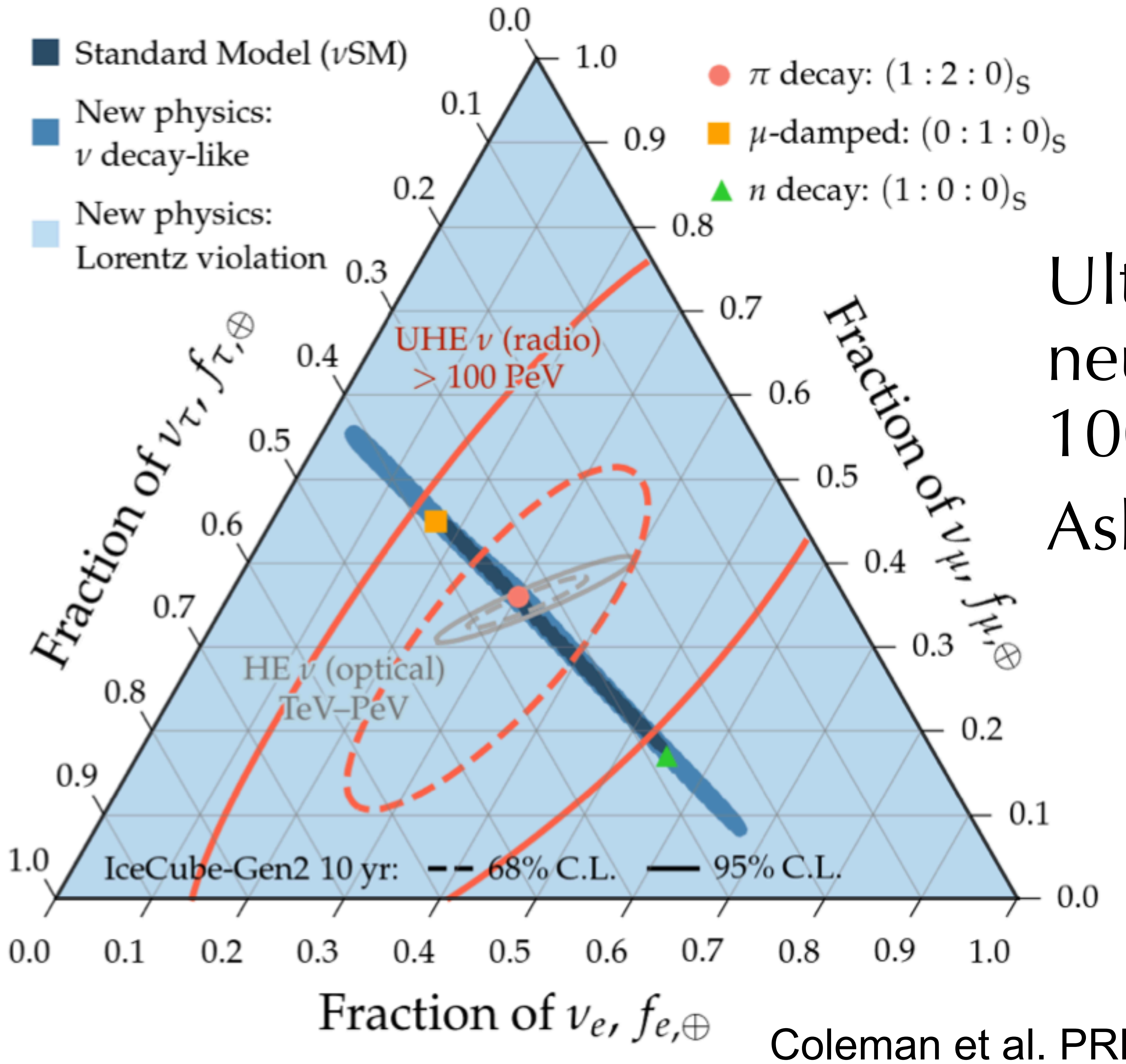
		$f_{e,s} : f_{\mu,s} : f_{\tau,s}$	$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$
• Pion decay	$\pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$\{1:2:0\}$	$\{0.34 : 0.33 : 0.33\}$
• Muon-damped	$\pi^+ \rightarrow \nu_\mu + \cancel{\mu}^+$	$\{0:1:0\}$	$\{0.24 : 0.37 : 0.39\}$
• Neutron decay	$n \rightarrow p + e^- + \bar{\nu}_e$	$\{1:0:0\}$	$\{0.55 : 0.23 : 0.22\}$

$\longrightarrow$ neutrino oscillations

High-energy neutrinos TeV-PeV



IceCube PRL 26'



Ultra-high-energy neutrinos above 100 PeV

Askaryan detectors

Coleman et al. PRD 24'

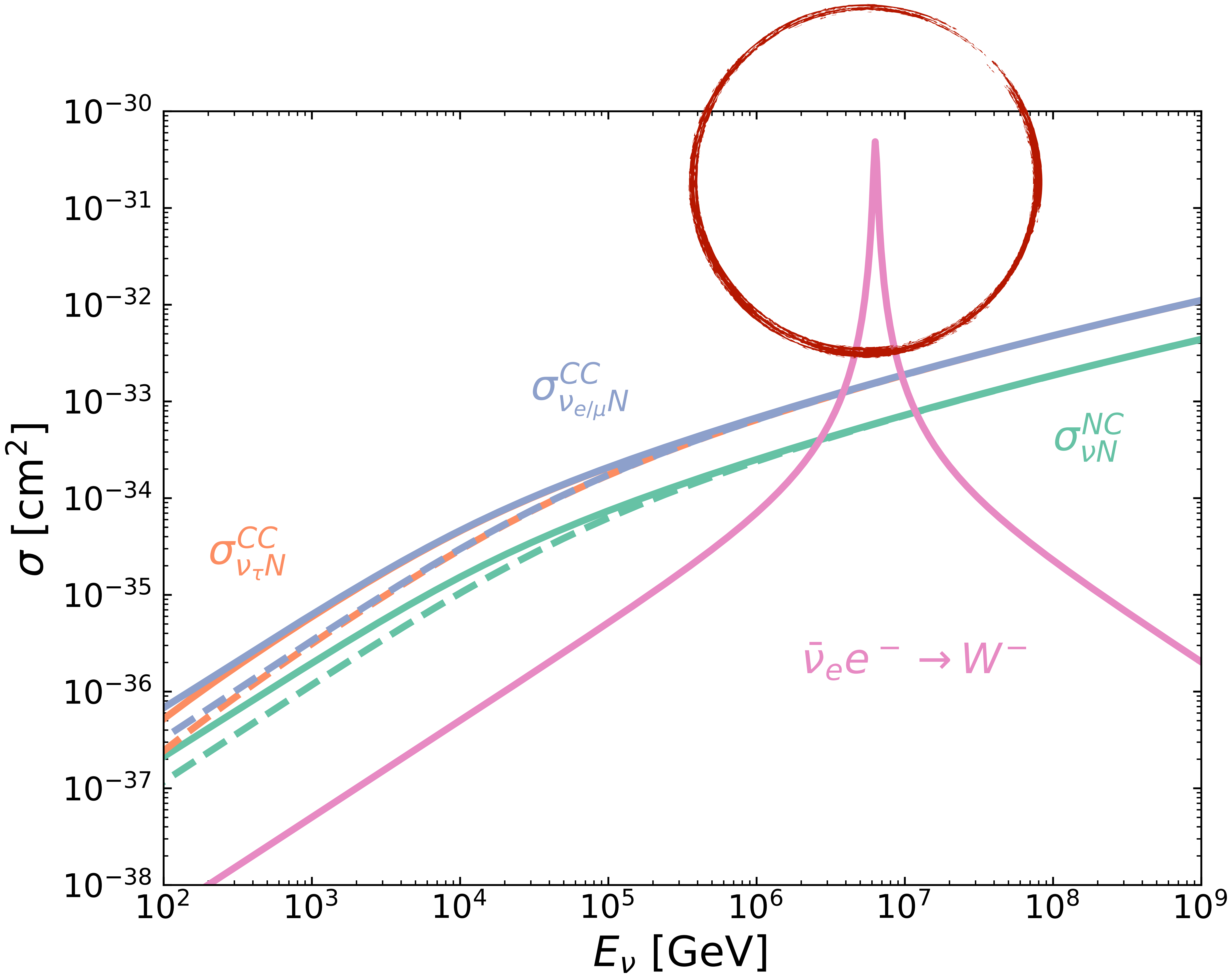
Glashow Resonance

Neutrino telescopes are blind to neutrinos and antineutrinos, but $\bar{\nu}_e$ can be disentangled with resonant interactions

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

6.3 PeV 511 KeV 80.38 GeV

S. Glashow *Phys.Rev.* 1960



The only way to differentiate the antineutrino flux from the total flux at high energies.

The first candidate was observed by IceCube as a hadronic shower.

Tau Air Shower Neutrino Telescopes

- Tau neutrino only observation for PeV and above: tau decays create extensive air showers (EAS) in the atmosphere that can be observed.
- Therefore, flavor composition measurements by such experiments alone were not discussed.

TAMBO

PIERRE AUGER OBSERVATORY

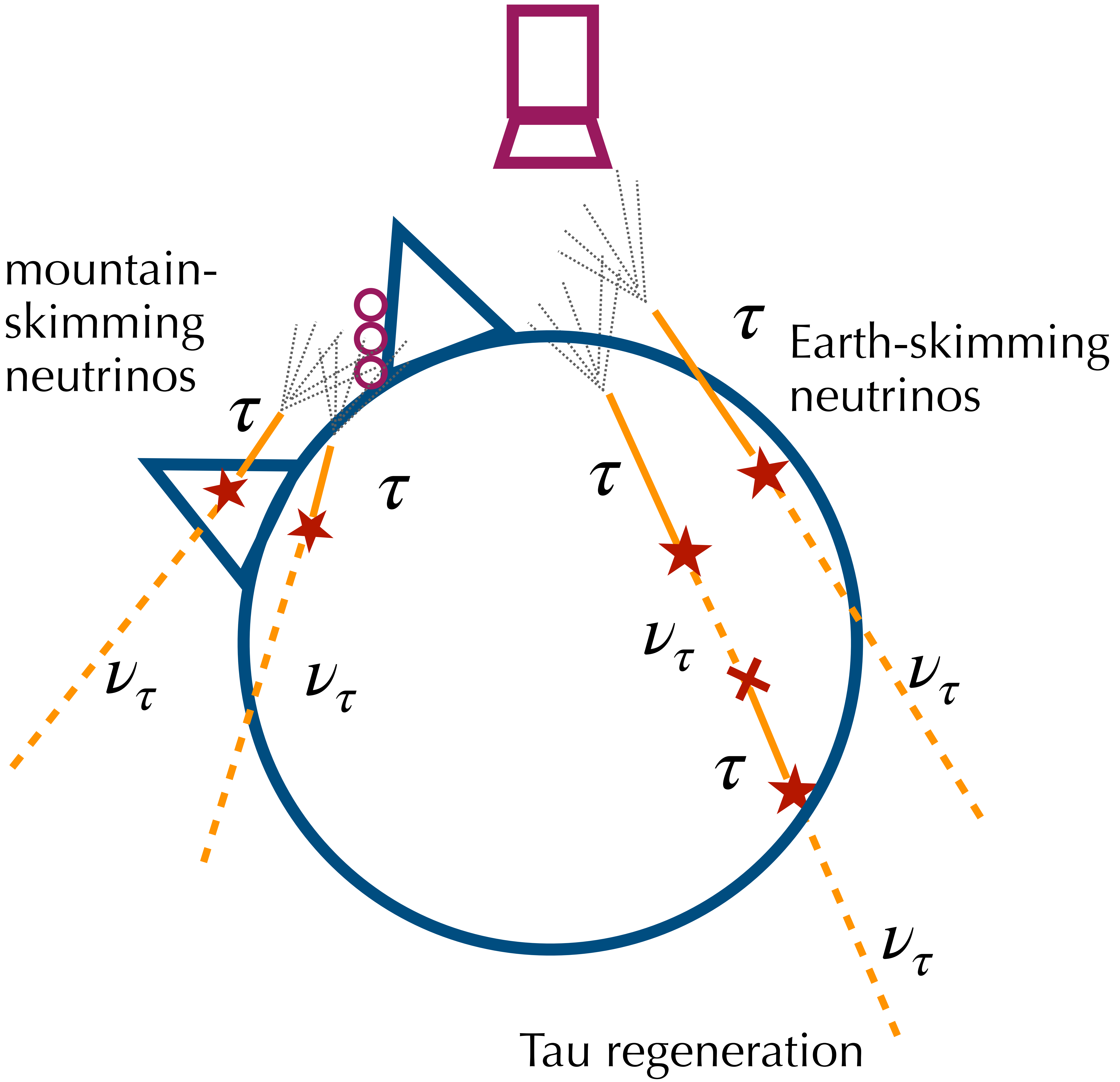
GRAND

Trinity

POEMMA

BEACON

PUEO



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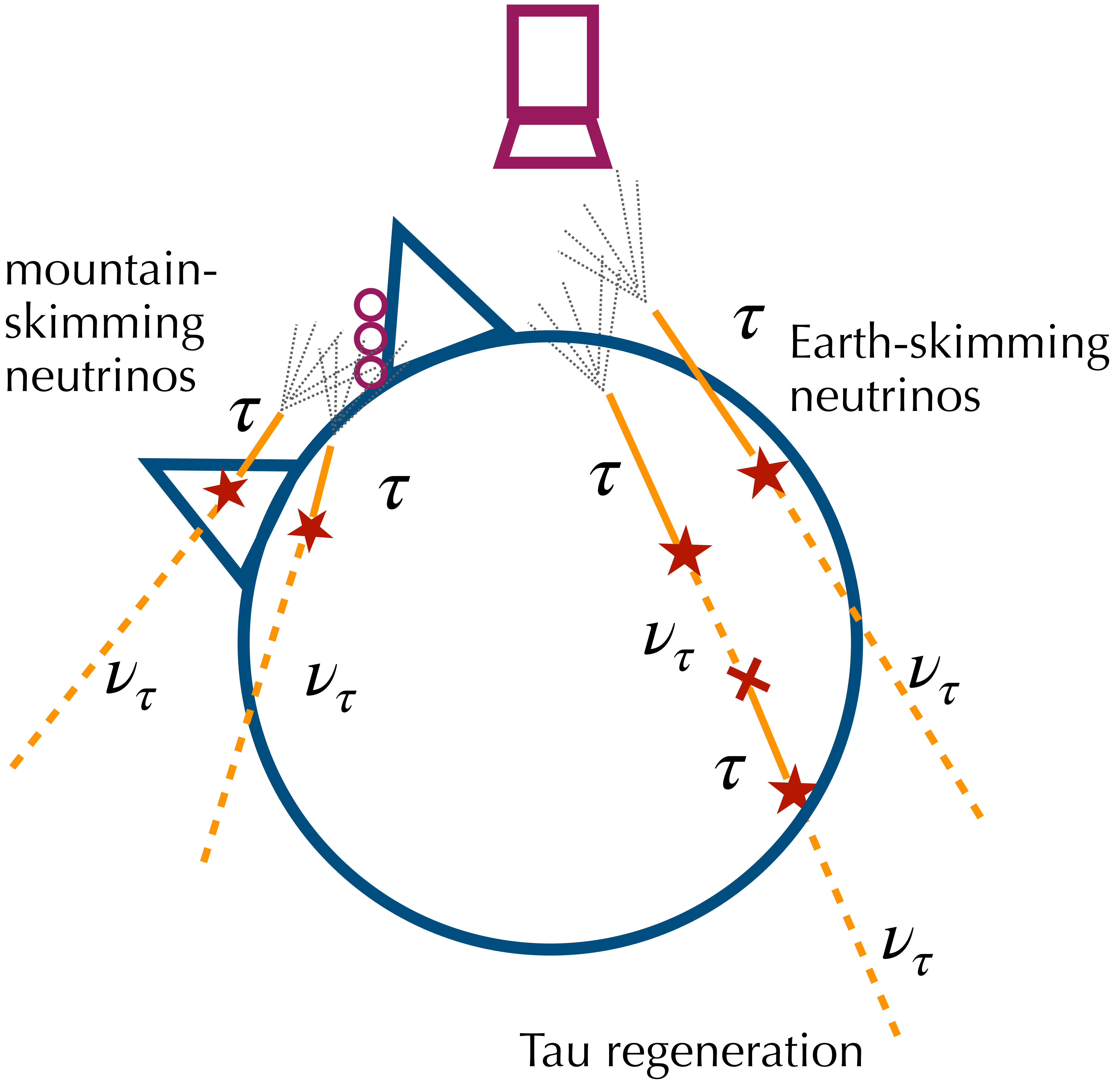
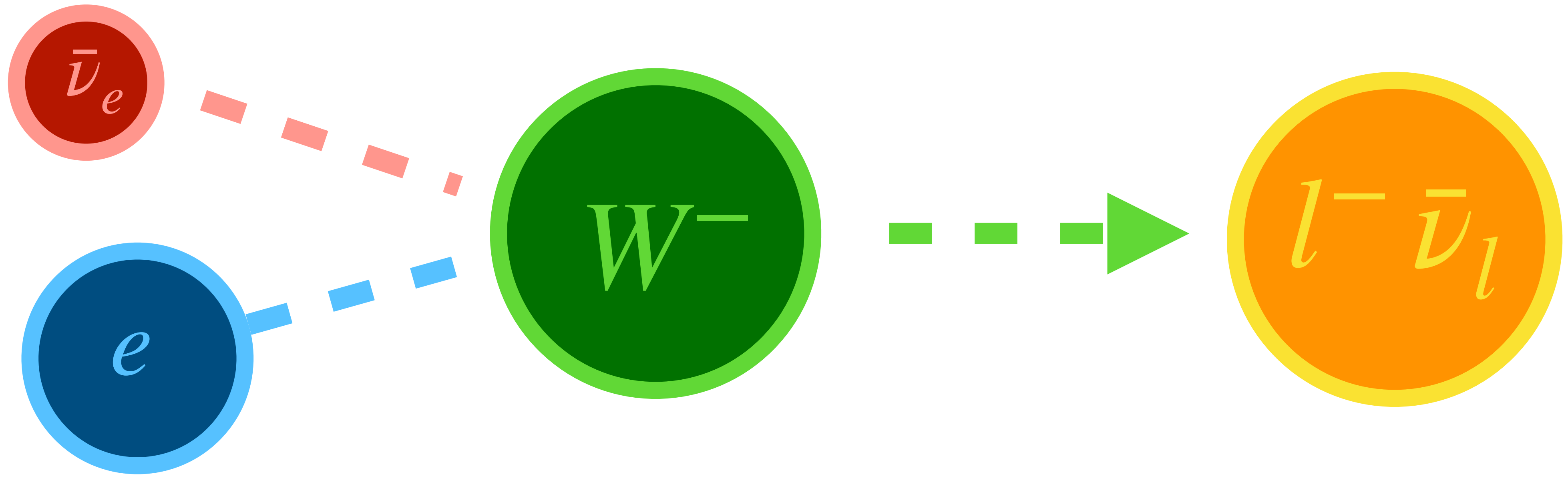


Can we observe more than tau neutrinos?

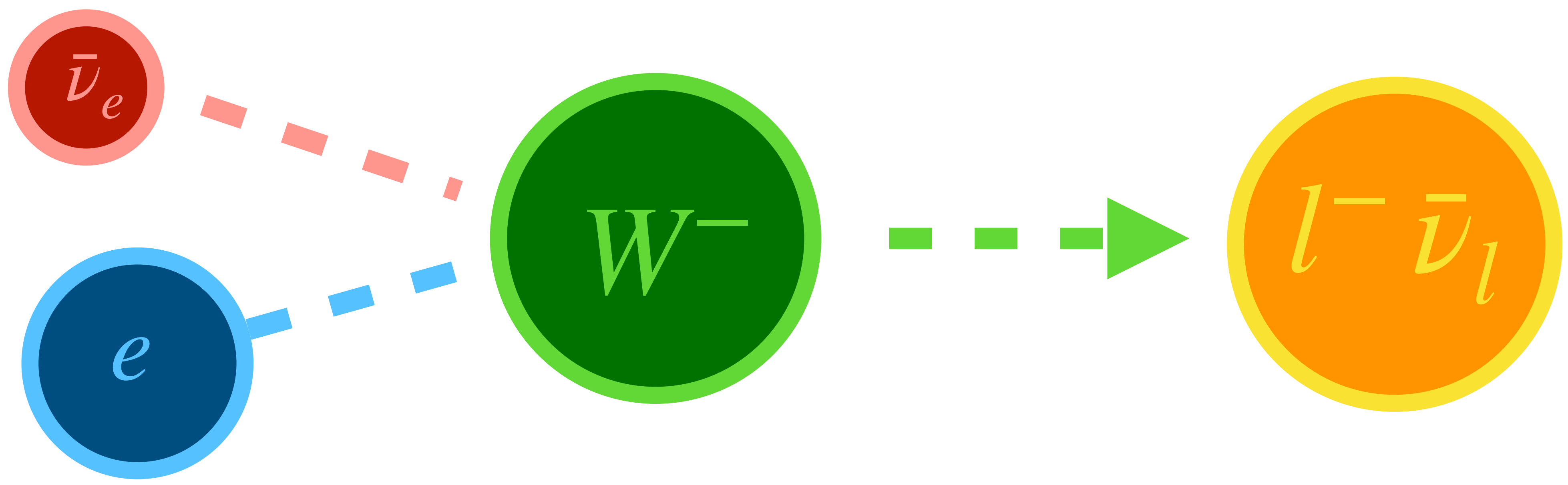
Glashow Resonance at Tau Air Shower Neutrino Telescopes



BR ~11 % for each flavor

- $\bar{\nu}_\tau$ and τ^- can be produced from the Glashow resonance, which will enter the $\tau/\bar{\nu}_\tau$ propagation chain — charged-current (CC)/neutral-current (NC) interactions and the tau regeneration.
- $\mathscr{R} = f_{\bar{\nu}_e}/f_{\nu_\tau+\bar{\nu}_\tau}$ may be measured statistically, making a standalone measurement possible.

Glashow Resonance at Tau Air Shower Neutrino Telescopes



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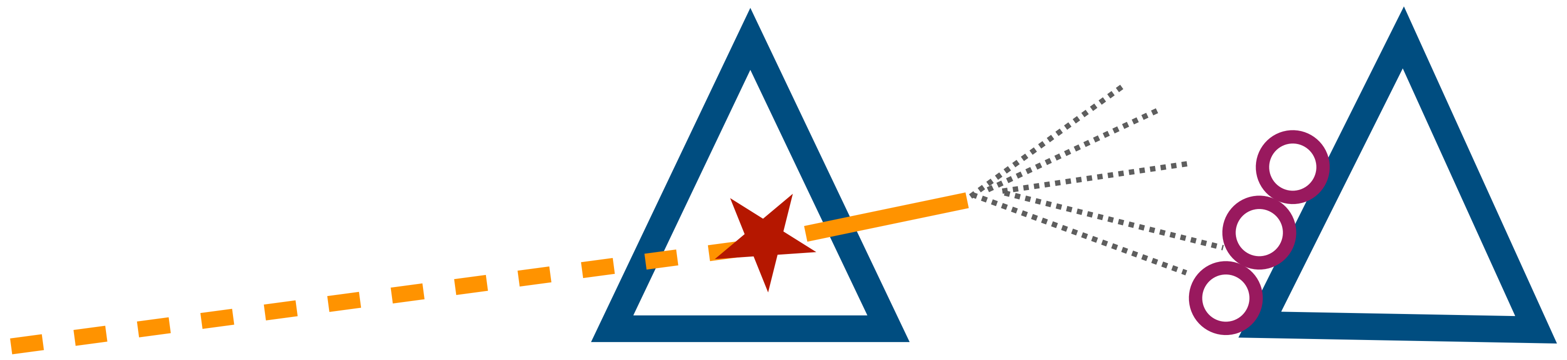
$\bar{\nu}_e$, ν_τ and $\bar{\nu}_\tau$ fluxes can contribute to the final observed EAS. We add the Glashow resonance-related terms into neutrino & τ propagation simulations to compute the signal.

- The mean free path in rock: $\lambda_{\mathrm{GR}} \simeq 26$ km; $\lambda_{\mathrm{CC}} \sim 10^3$ km.

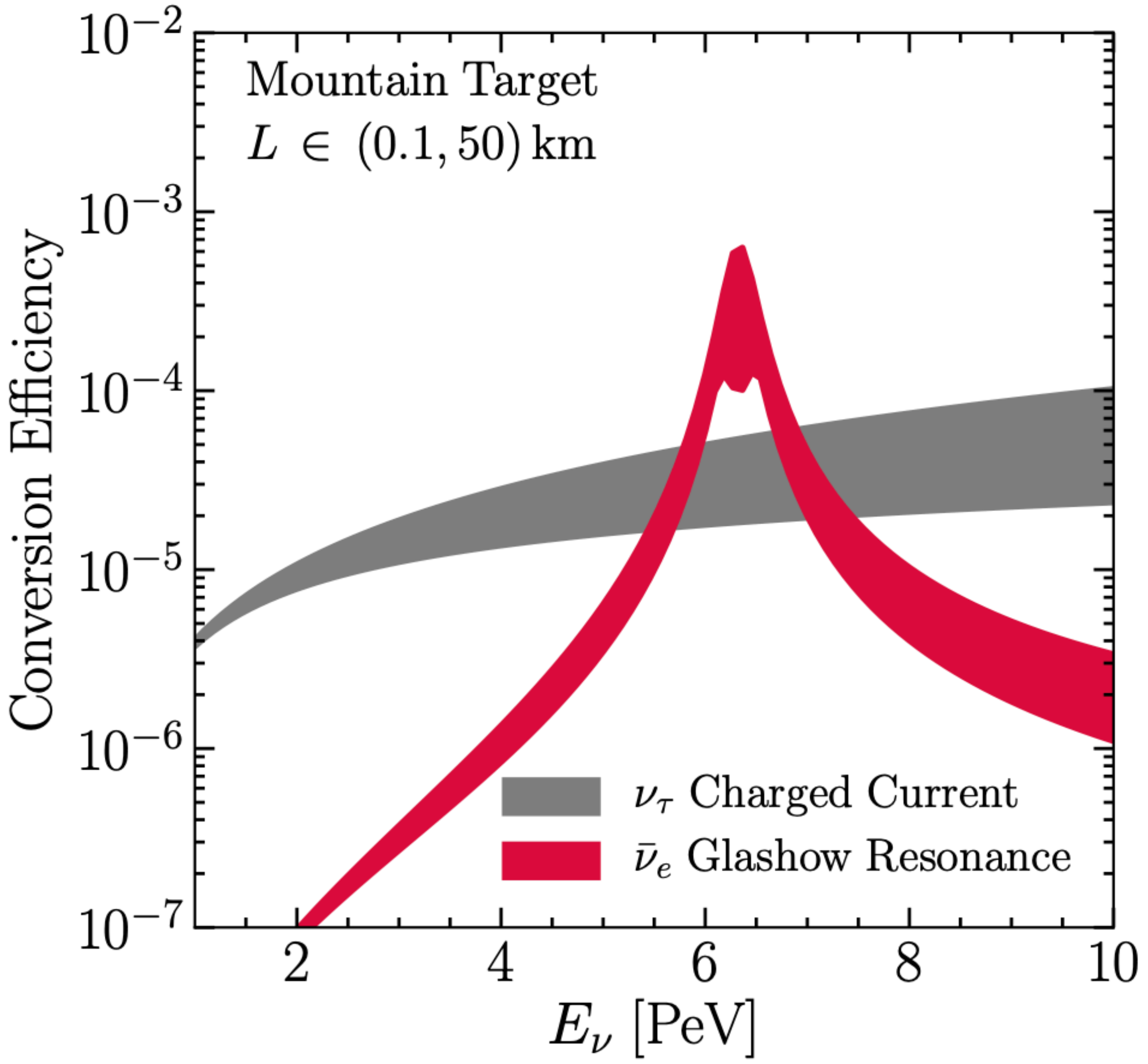
  Decay length: $\lambda^\tau_{\mathrm{decay}} \simeq 50\,\mathrm{m}\left(E_\tau/\mathrm{PeV}\right)$.

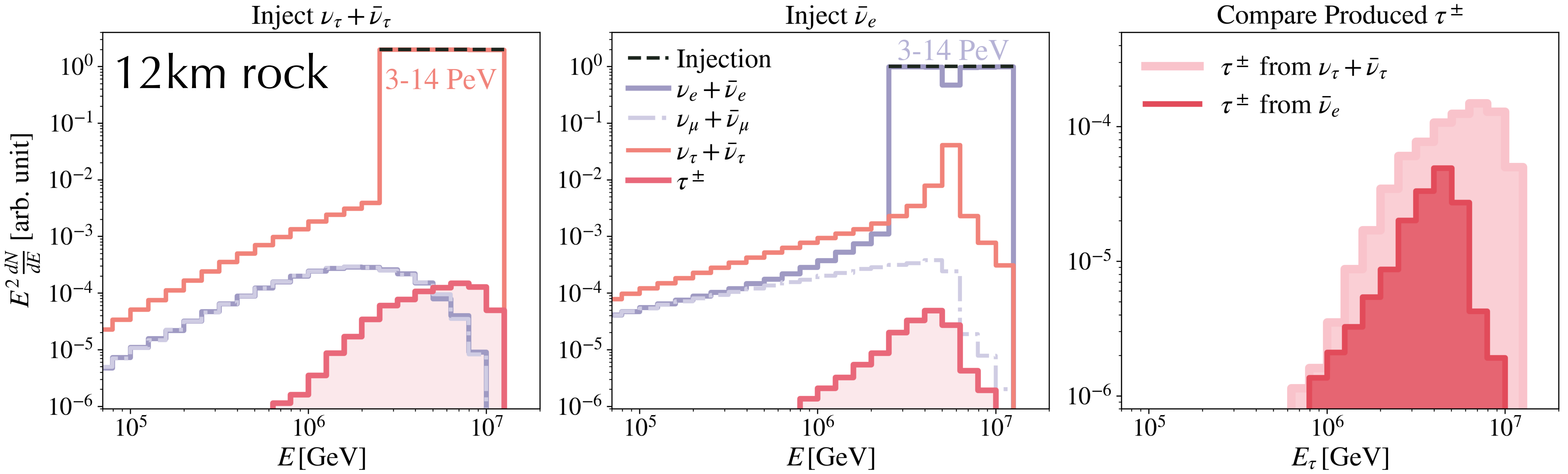
  The yield of $\bar{\nu}_e$ induced τ depends largely on the geometry - competition between the $\bar{\nu}_e$ attenuation and the production & survival of the τ afterwards.

Mountain-Skimming Neutrinos



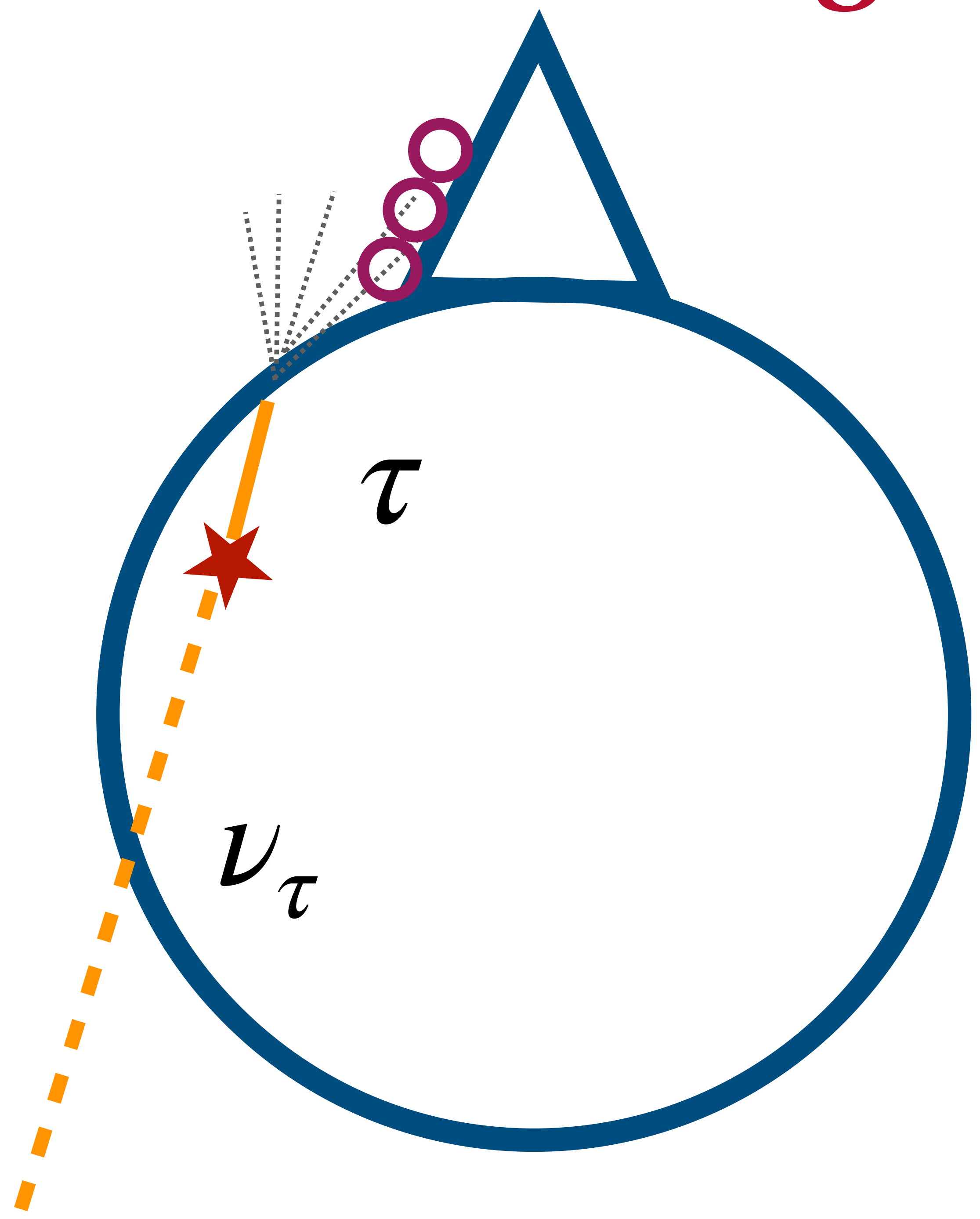
Huang & QL, JCAP 20′

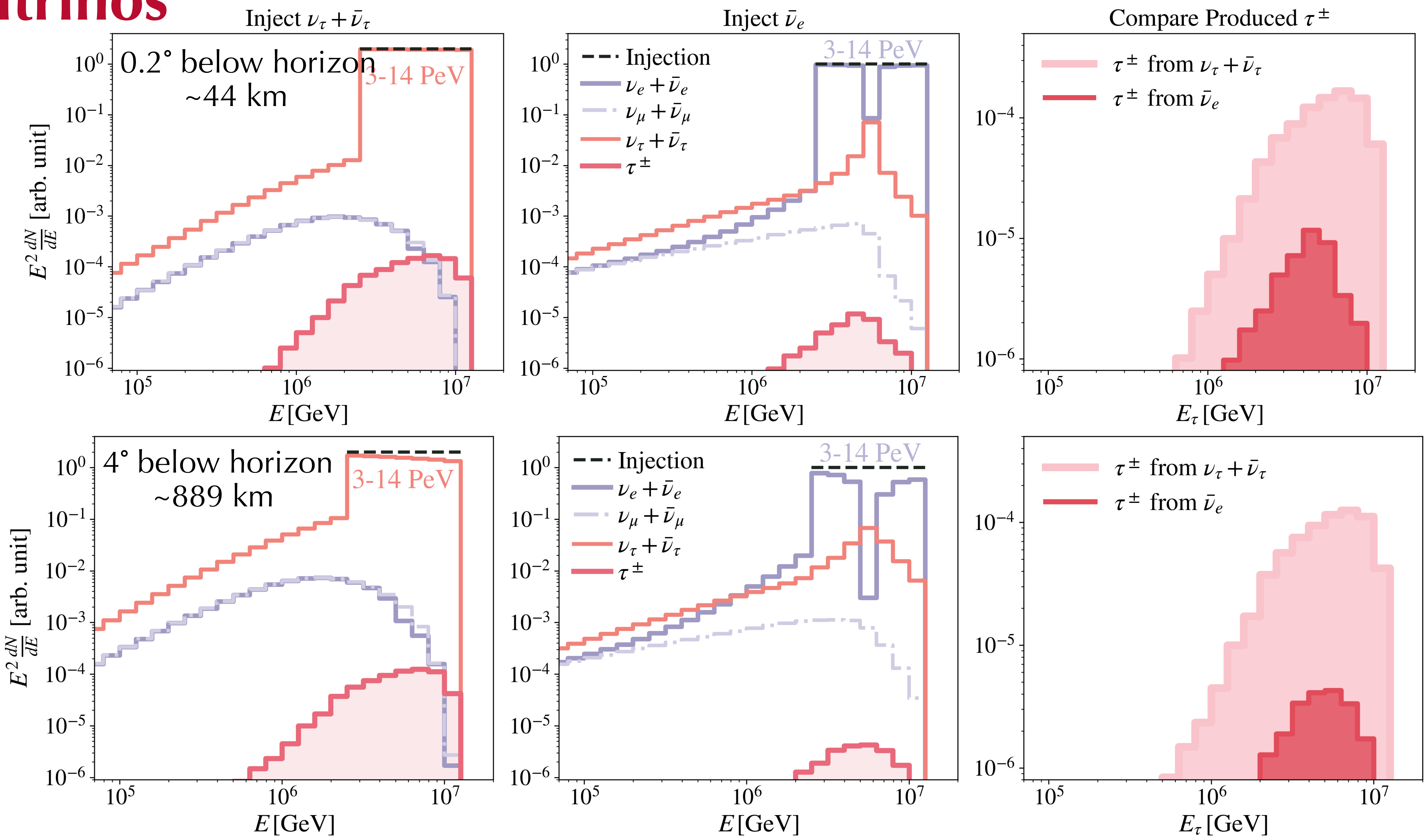




- The thickness of a mountain is $\lesssim \mathcal{O}(10\,\mathrm{km})$, of the same order as the Glashow resonance's mean free path — efficient $\bar{\nu}_e \to \tau$ before the $\bar{\nu}_e$ flux is attenuated.
- A large fraction of τ produced can escape.
- $\bar{\nu}_e$ and $\nu_\tau/\bar{\nu}_\tau$ generate comparable τ fluxes in the Glashow resonance energy window.

Earth-Skimming Neutrinos

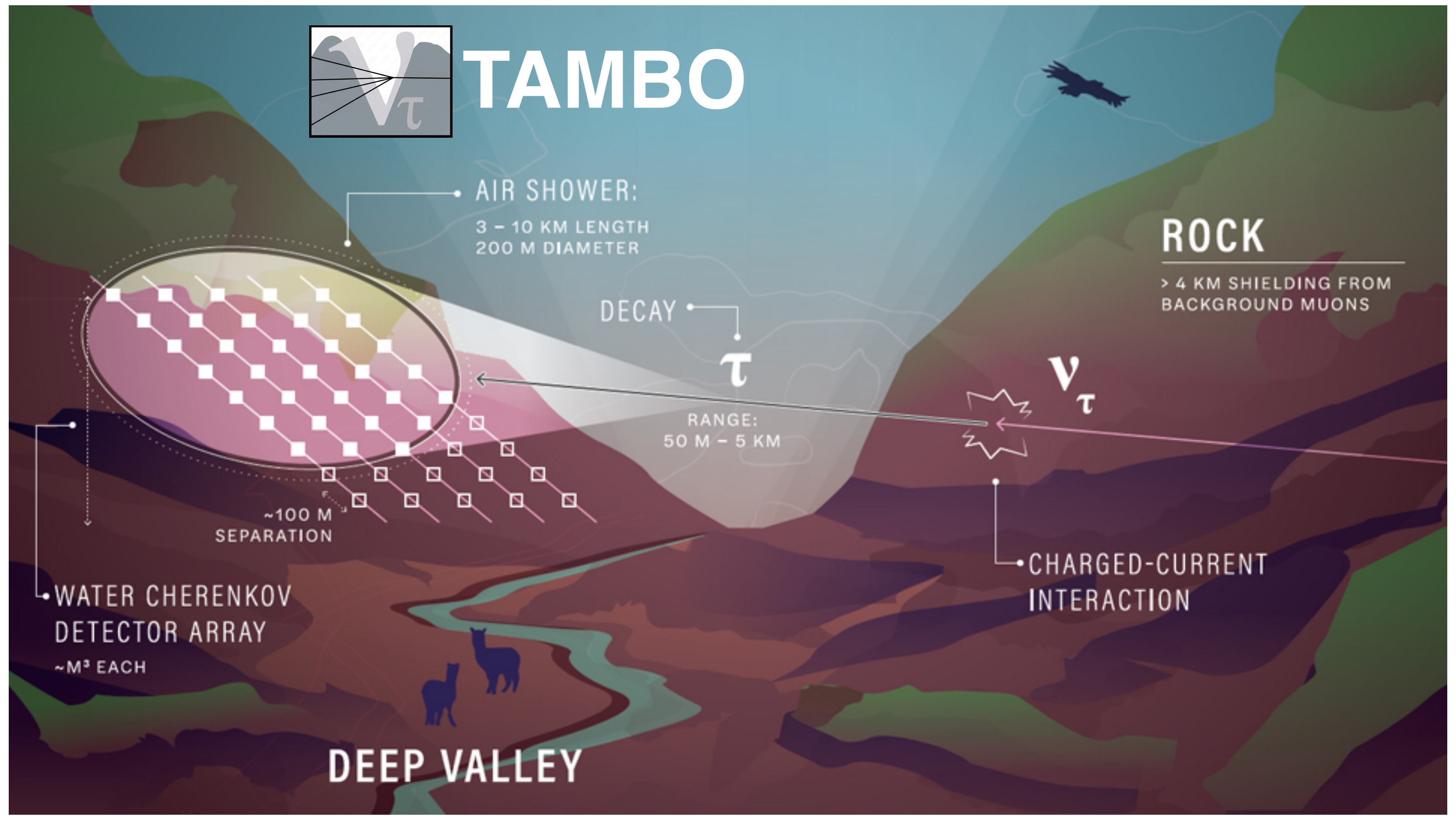




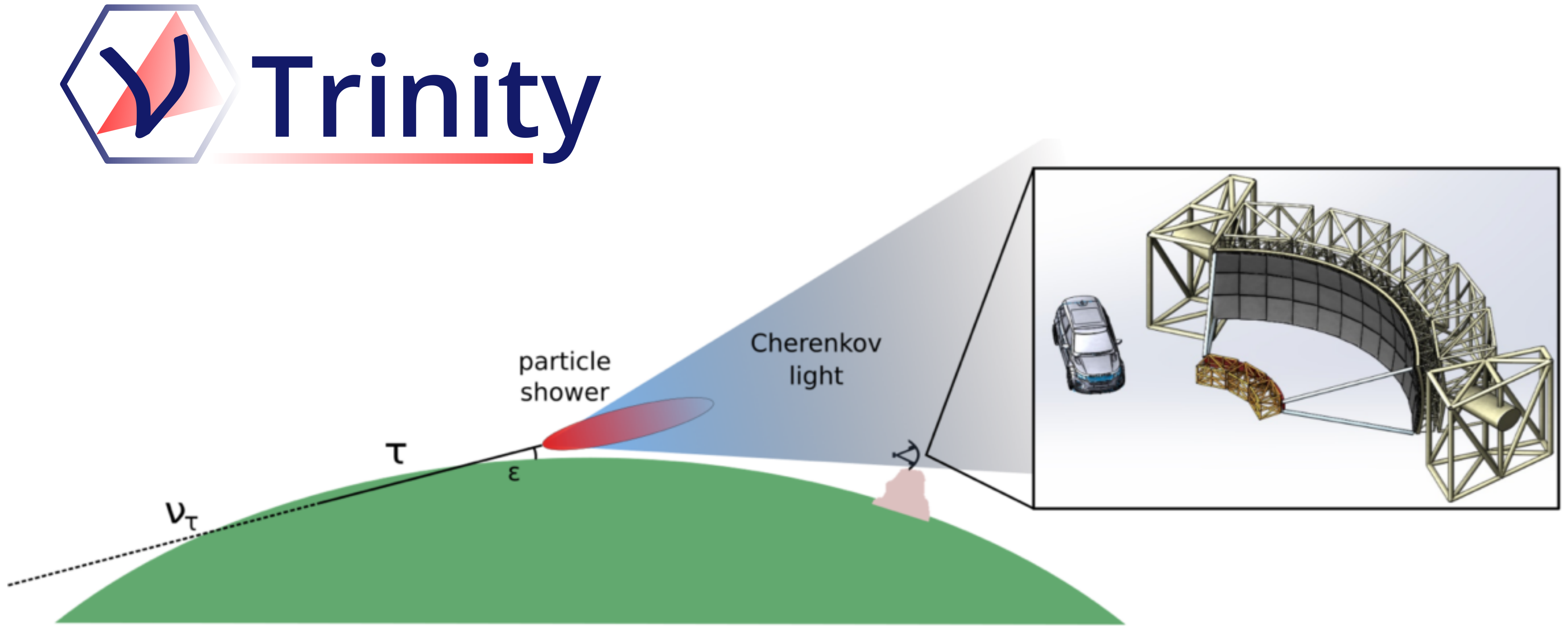
- The travel distance inside Earth increases rapidly from 20km —1000km from 0.1° — 5°.
- Primary $\bar{\nu}_e$ attenuates quickly near the incident location. Most produced τ decays before escaping the surface, while $\bar{\nu}_\tau$ does not have enough distance to interact — inefficient tau regeneration at PeV.
- Relatively large τ yield is expected only to be very close to the horizon.

TAMBO & TRINITY

Mountain-skimming:
TAMBO (water Cherenkov)



Earth-skimming: TRINITY (IACT)

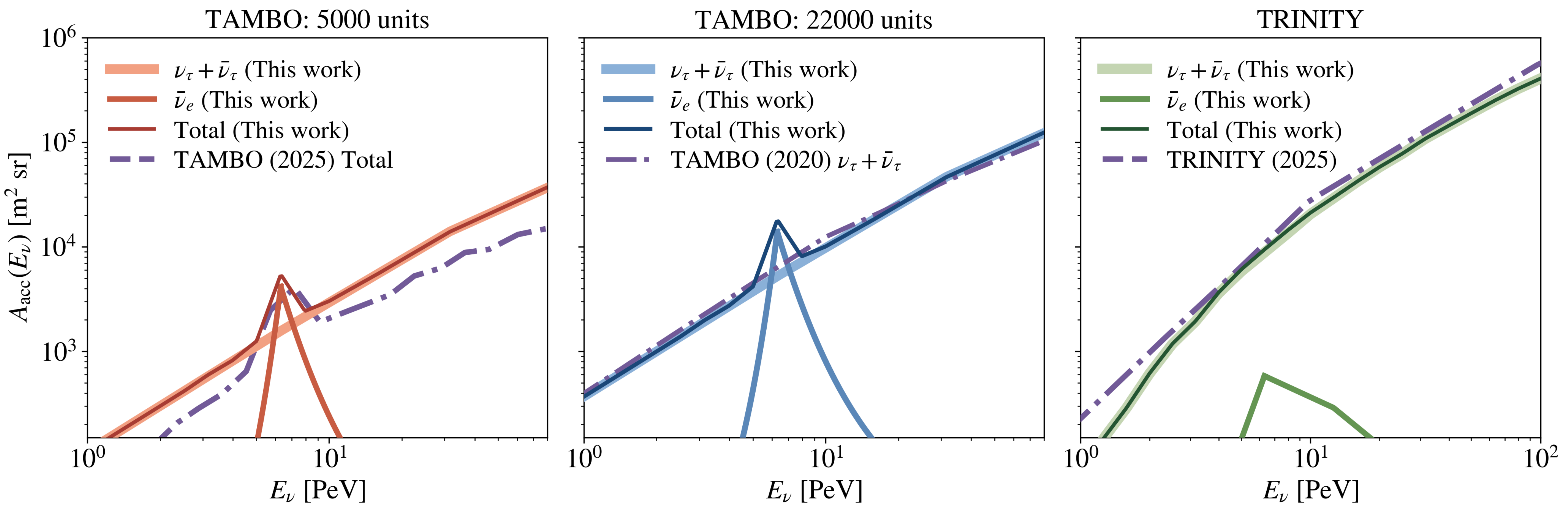


They focus on PeV - 100 PeV, bridging high-energy and ultra-high-energy detections, while other tau air shower experiments aim for ultra-high-energies.

Acceptance

$$A^{\nu_\alpha}_{\rm acc}\left(E_\nu\right) = \int_0^{E_\nu}\int_{A_{\rm geo}}\int_\Omega \underbrace{\frac{dP_{\rm exit}}{dE_\tau}(E_\nu, E_\tau)}_{\text{Probability of getting an exiting }\tau\text{ computed from simulations}} \cdot \underbrace{P^{\rm visible}_{\rm decay}\left(E_\tau\right)}_{} \cdot \underbrace{\epsilon_{\rm det}\left(E_\tau\right)}_{\text{efficiency}} \, dA\, d\Omega\, dE_\tau$$

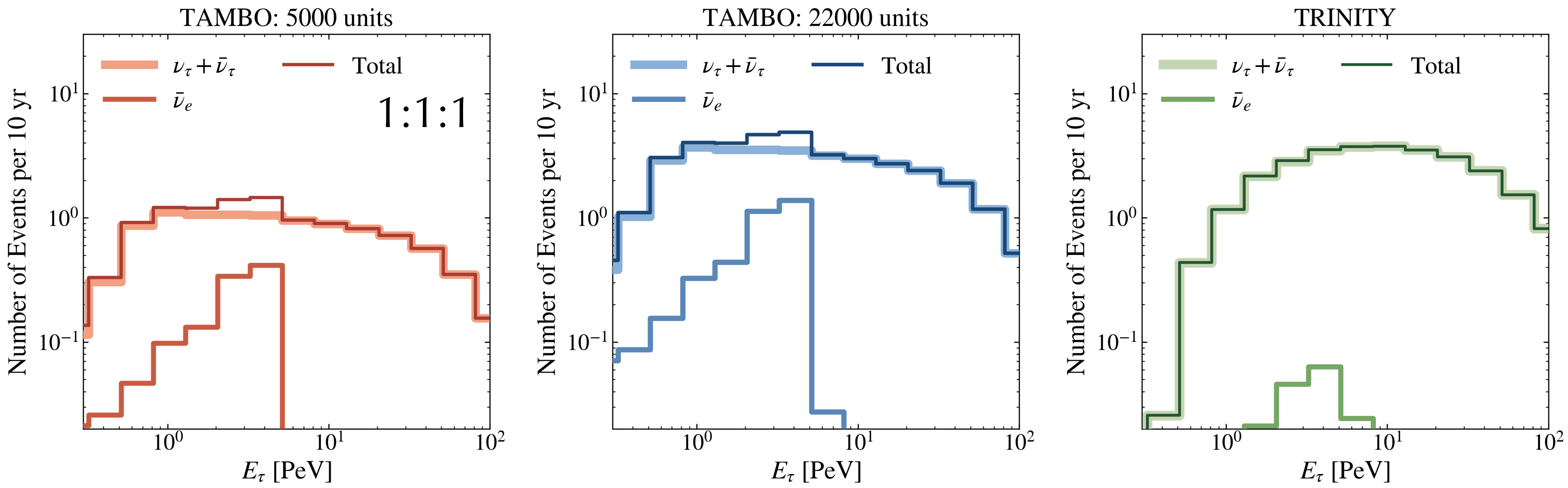
$$P^{\rm visible}_{\rm BR} \cdot \left[1 - \exp\left(-D/\lambda^\tau_{\rm decay}\right)\right]$$



A mountain-skimming geometry yields substantially higher $\bar{\nu}_e$ acceptance than an Earth-skimming one due to the shorter path length.

Event Numbers

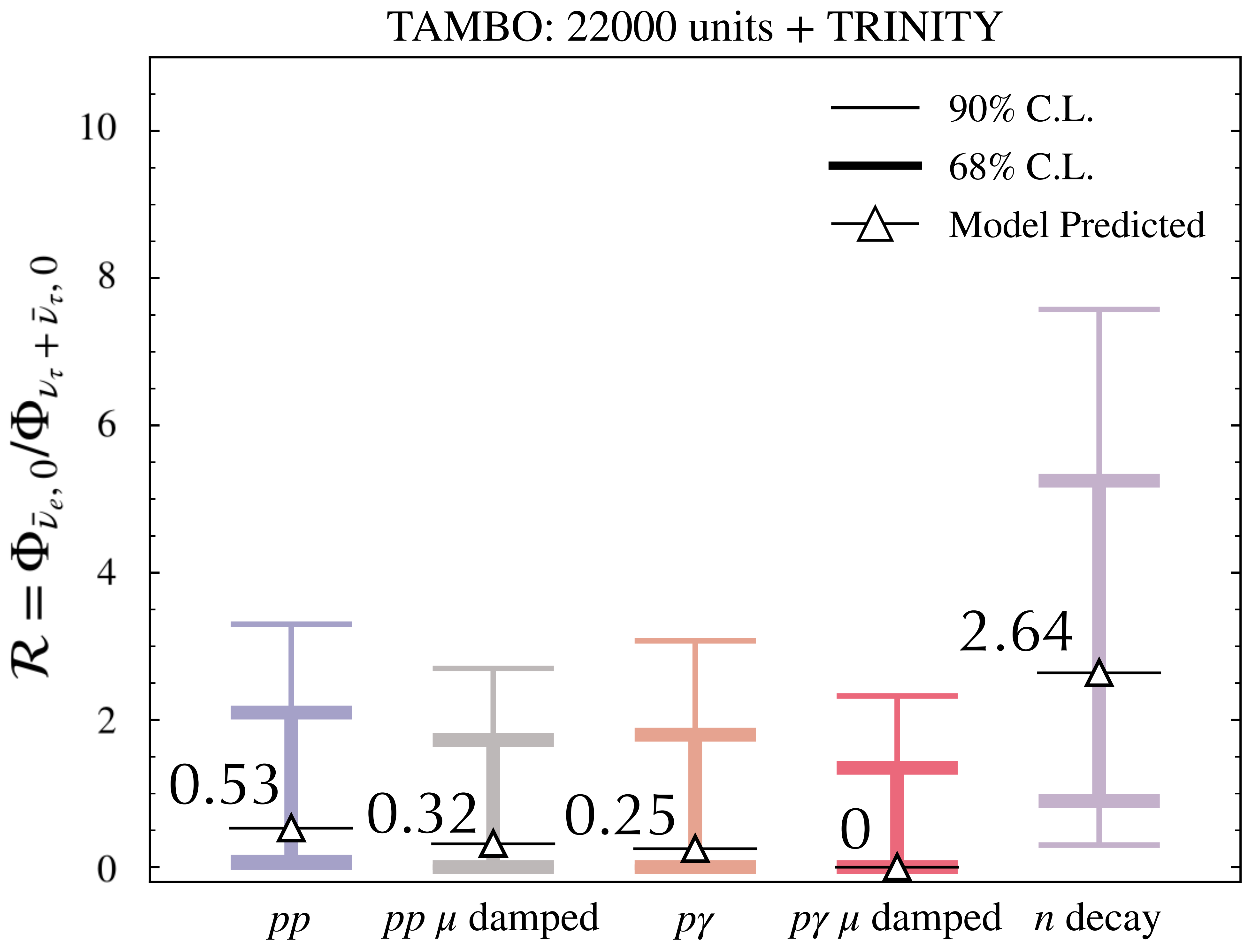
$$\frac{dN_\tau}{dE_\tau}(E_\tau) = T_{\rm obs} \int_{E_\nu} \Phi_{\nu_\alpha}\left(E_\nu\right) \cdot \frac{dA^{\nu_\alpha}_{\rm acc}}{dE_\tau}(E_\nu, E_\tau)\, dE_\nu,$$

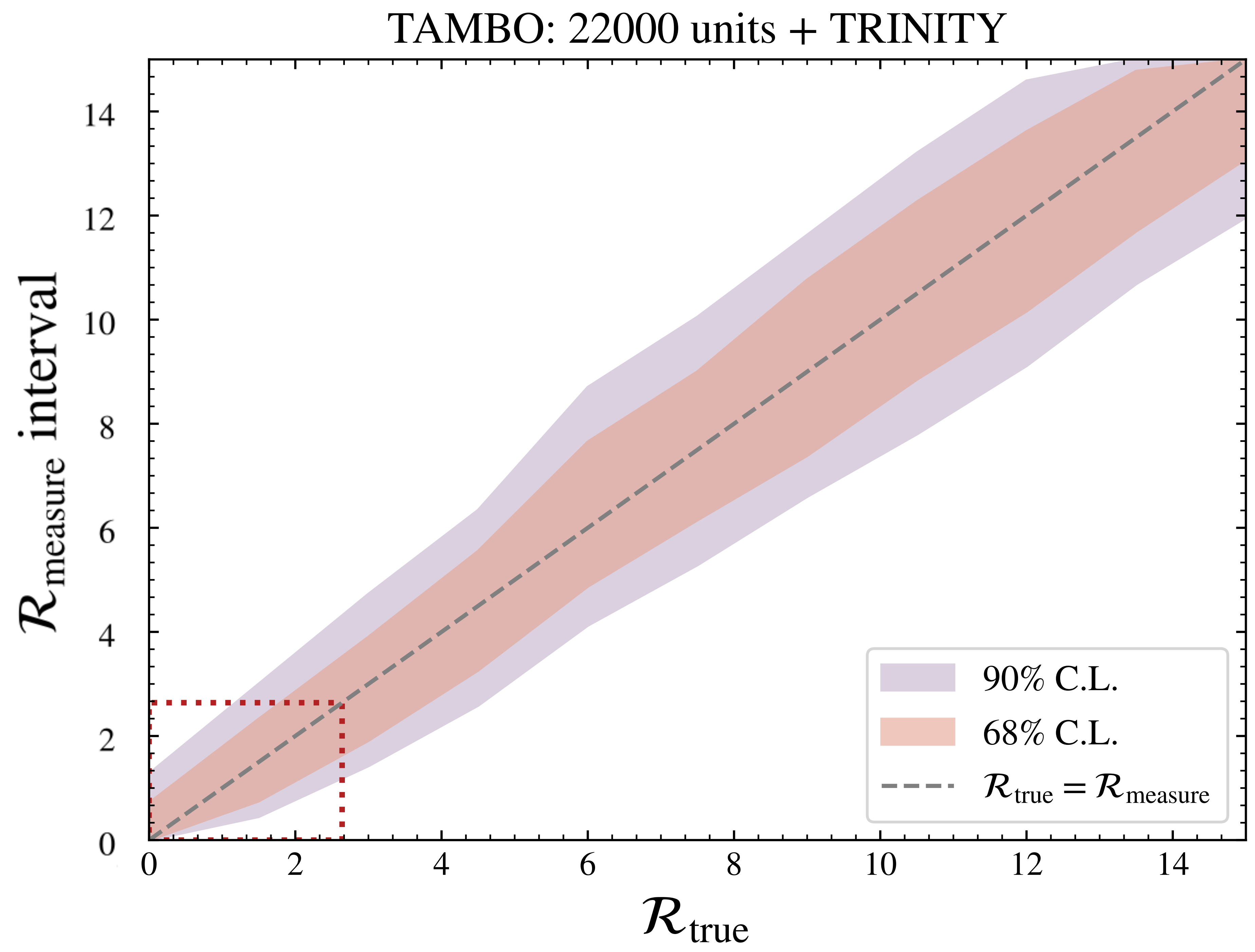


- Excess at several PeV from $\bar{\nu}_e$ is expected in TAMBO while $\bar{\nu}_e$ contributes less in TRINITY. But TRINITY has a larger $\nu_\tau/\bar{\nu}_\tau$ event rate at higher energies.
- $E^{-2.5}$ spectrum is assumed. Event numbers can be affected largely by the spectrum assumption in this low-statistics regime.

Projected Flavor Measurement Sensitivity

$\mathscr{R} = f_{\bar{\nu}_e}/f_{\nu_\tau+\bar{\nu}_\tau}$ is used to represent the flavor composition, as we cannot infer the fluxes of other flavors in a standalone measurement.





- Differentiating pion production scenarios is challenging in a standalone $\mathscr{R}$ measurement, but optimistically we can exclude a $\bar{\nu}_e$ rich scenario at $> 1\sigma$.
- Conversely, if we expect a $\bar{\nu}_e$ rich scenario such as neutron decay, we optimistically can exclude pion production scenarios at ~90%.
- If a new physics model predicts a large $\mathscr{R}$, it would be easier to differentiate.
- Combining the measurement with other experiments can mutually enhance the sensitivity/obtain a more comprehensive picture of each flavor/hint at possible energy-dependent features.

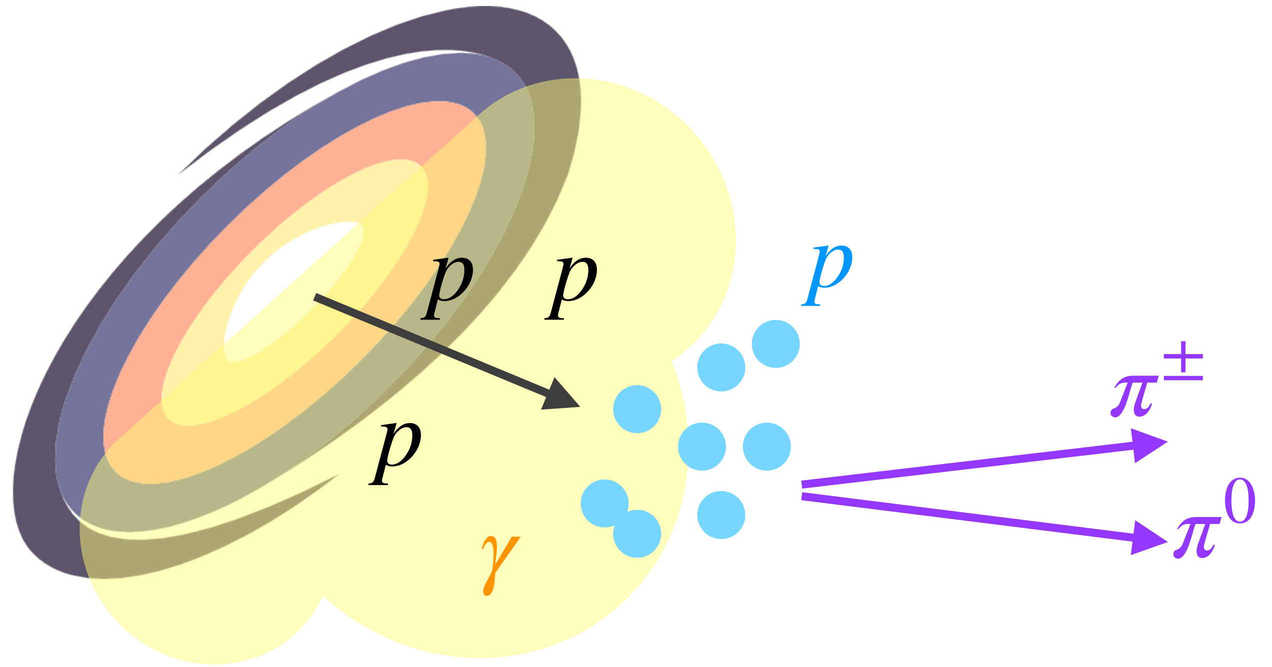
Summary

- The flavor composition of astrophysical neutrinos encodes important information about their production, propagation, and detection.
- The Glashow resonance provides a unique way to distinguish $\bar{\nu}_e$ from the neutrino flux.
- Due to the decay mode $W^- \to \bar{\nu}_\tau + \tau^-$, tau air shower neutrino experiments are expected to detect $\bar{\nu}_e$ statistically in addition to tau neutrinos, which therefore enables flavor composition studies.
- Mountain-skimming geometries yield substantially higher $\bar{\nu}_e$ acceptance than Earth-skimming ones.
- It can be challenging to differentiate pion production scenarios in a standalone measurement at tau air shower telescopes, while a $\bar{\nu}_e$ rich scenario such as neutron decay and specific new physics models would stand out or otherwise be constrained.
- Flavor composition measurements can be improved from combining neutrino observations sensitive to different flavors.

Thank you!

Bonus Slides

Astrophysical Processes Flavor Composition with Glashow Resonance



Accelerated cosmic ray beam (p) + gas(p)/ radiation(γ)

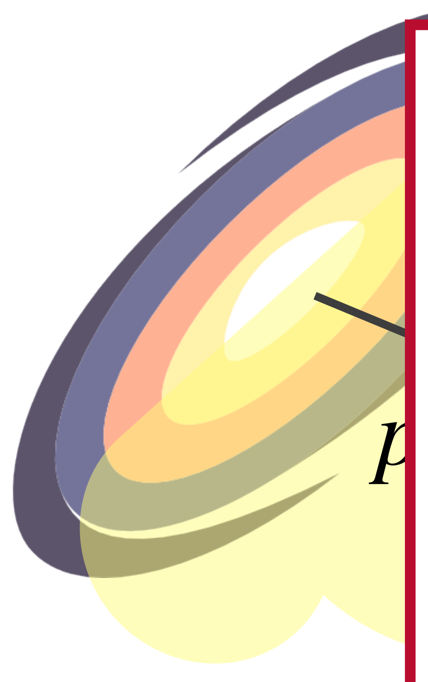
Hadronuclear $\quad p + p \rightarrow n_\pi \left[\pi^0 + \pi^+ + \pi^-\right]$

Photohadronic $\quad p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$

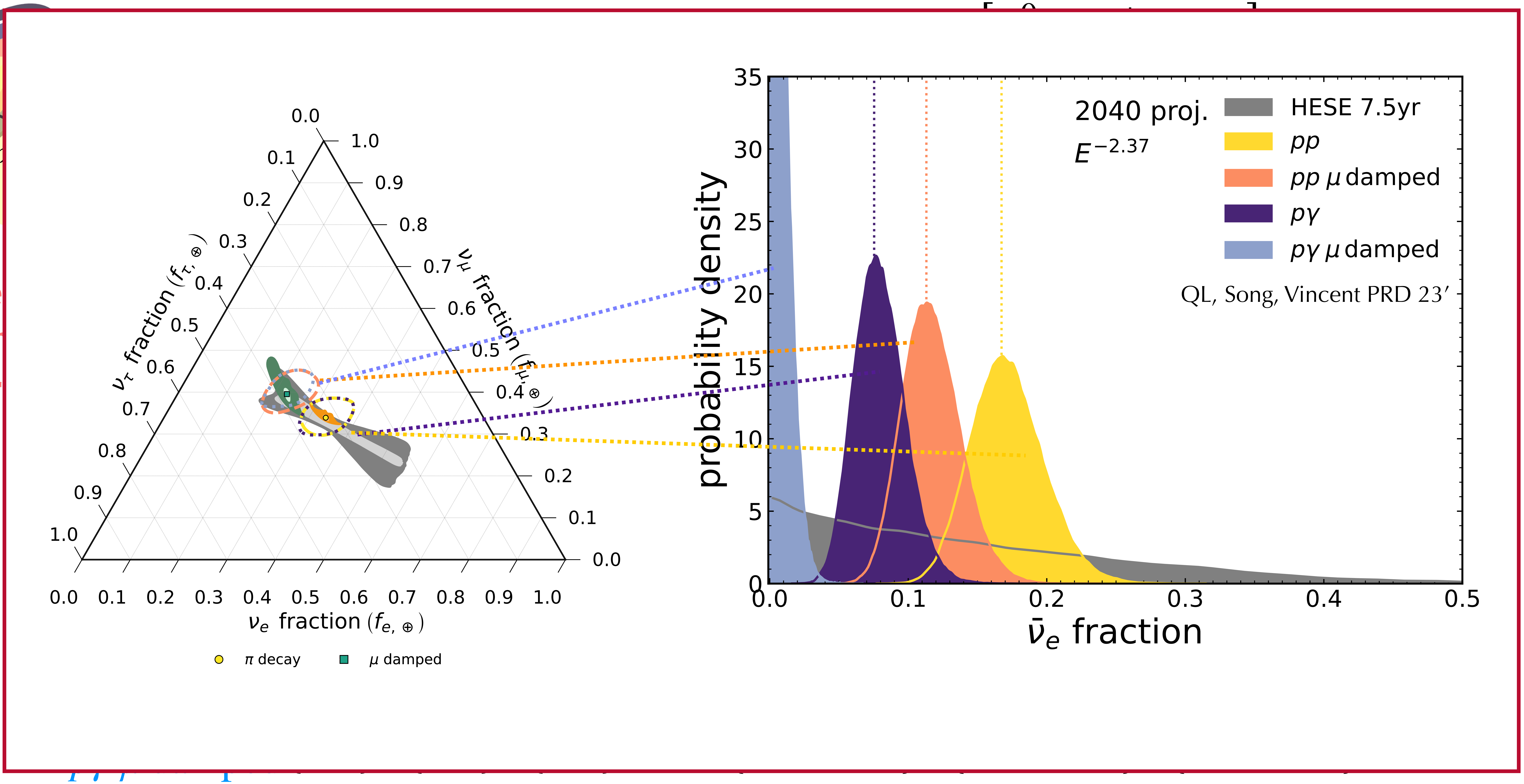
$$\begin{cases} \pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \rightarrow \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \end{cases}$$

	$\{f_{\nu_e,s}, f_{\bar{\nu}_e,s}\} : \{f_{\nu_\mu,s}, f_{\bar{\nu}_\mu,s}\} : \{f_{\nu_\tau,s}, f_{\bar{\nu}_\tau,s}\}$	$\longrightarrow$ $\{f_{\nu_e,\oplus}, f_{\bar{\nu}_e,\oplus}\} : \{f_{\nu_\mu,\oplus}, f_{\bar{\nu}_\mu,\oplus}\} : \{f_{\nu_\tau,\oplus}, f_{\bar{\nu}_\tau,\oplus}\}$
pp	$\{1,1\} : \{2,2\} : \{0,0\}$	$\{0.17,0.17\} : \{0.16,0.16\} : \{0.16,0.16\}$
$p\gamma$	$\{1,0\} : \{1,1\} : \{0,0\}$	$\{0.26,0.08\} : \{0.20,0.12\} : \{0.20,0.13\}$
pp μ damped	$\{0,0\} : \{1,1\} : \{0,0\}$	$\{0.12,0.12\} : \{0.19,0.19\} : \{0.19,0.19\}$
$p\gamma$ μ damped	$\{0,0\} : \{1,0\} : \{0,0\}$	$\{0.24,0.00\} : \{0.37,0.00\} : \{0.39,0.00\}$
n decay	$\{0,1\} : \{0,0\} : \{0,0\}$	$\{0.00,0.55\} : \{0.00,0.24\} : \{0.00,0.21\}$

Astrophysical Processes Flavor Composition with Glashow Resonance

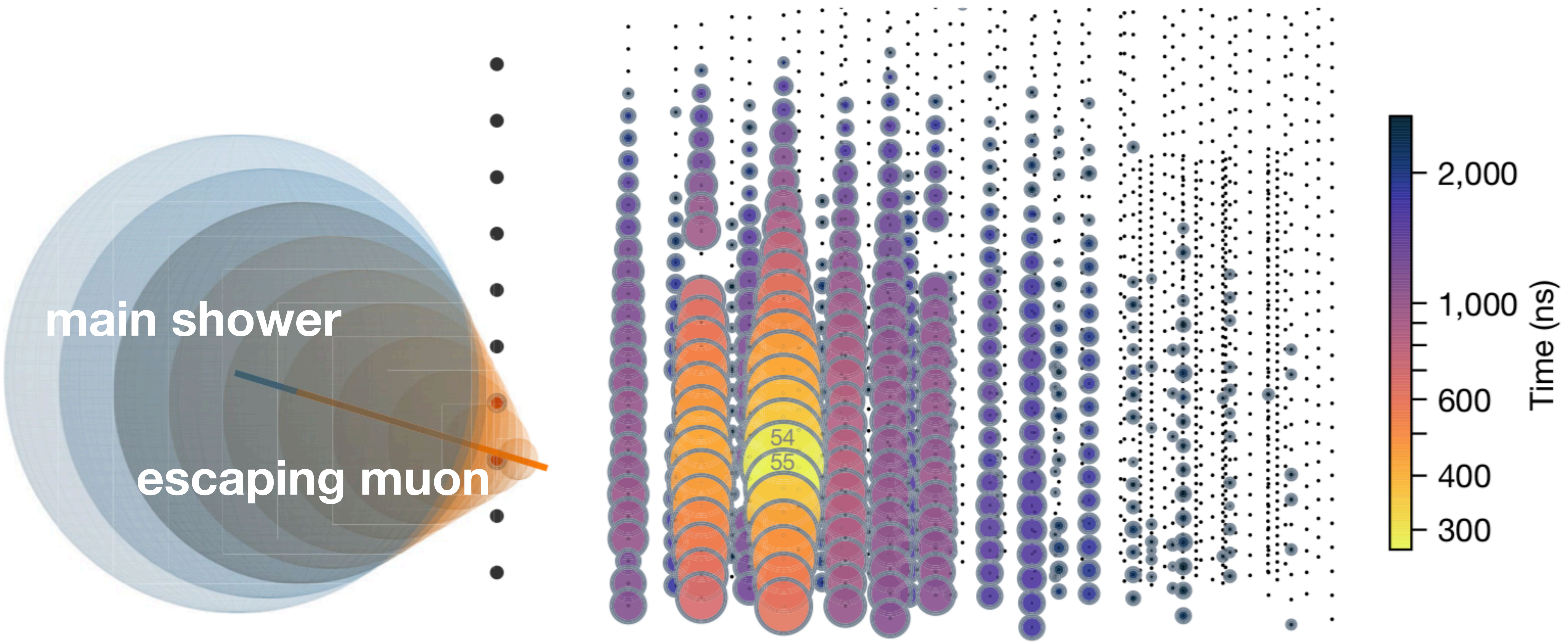


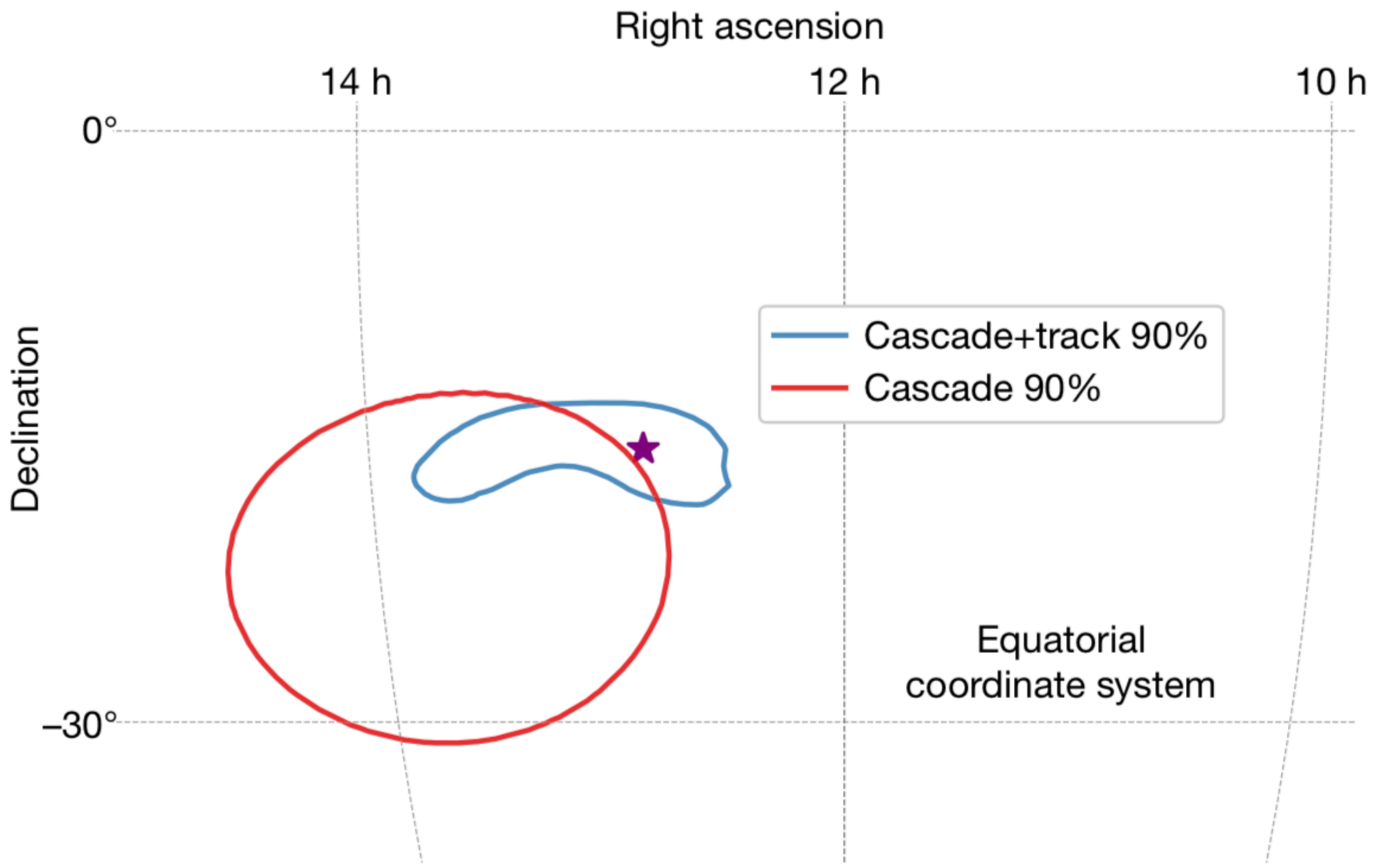
Accele
bear
r



n decay	{0,1} : {0,0} : {0,0}	{0.00,0.55} : {0.00,0.24} : {0.00,0.21}

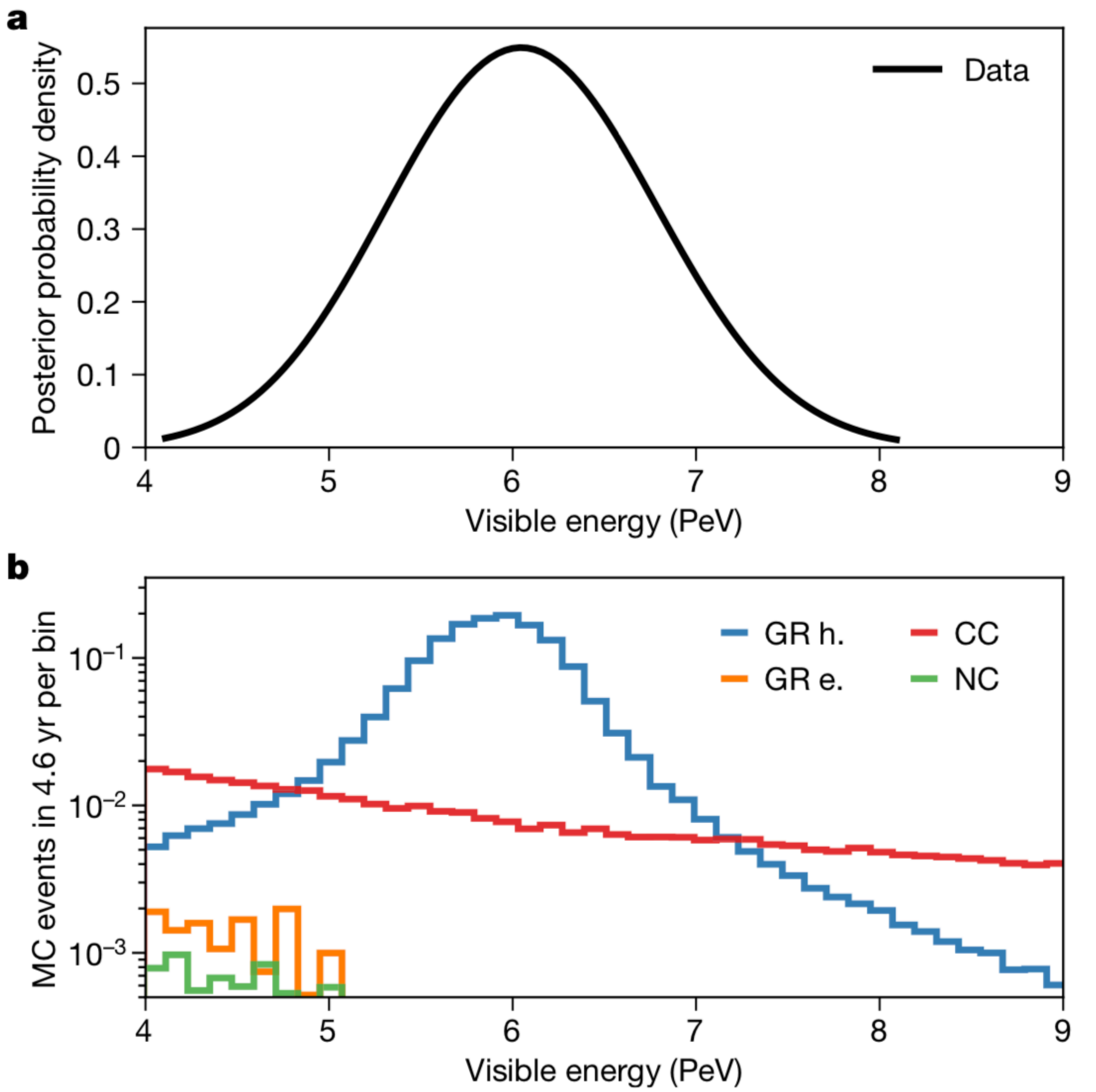
First Detection of Glashow Resonance





PeV energy partially-contained event selection

- The detectable escaping muons suggest it's a hadronic shower
- visible energy of 6.05 ± 0.72 PeV, 2.3σ assuming a $E^{-2.5}$ spectrum.



IceCube Nature 2021

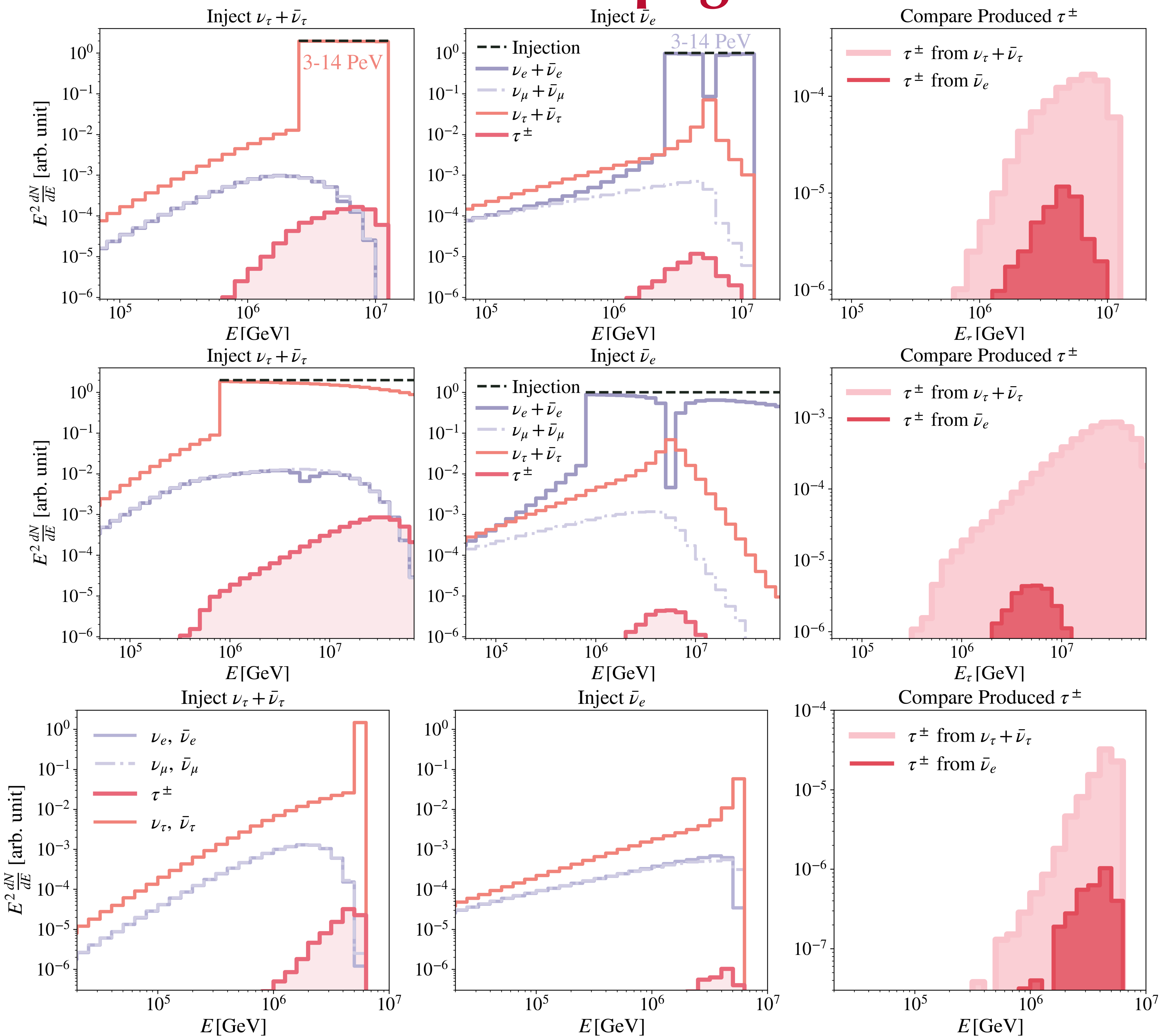
Neutrino Propagation Including Glashow Resonance

$$\frac{d^2\Phi_{\bar{\nu}_e}}{dxdE_\nu} = -\sum_{N=p,n} n_N(x)\left[\sigma_{\rm CC}(E_\nu)+\sigma_{\rm NC}(E_\nu)\right]\frac{d\Phi_{\bar{\nu}_e}}{dE_\nu} - n_e(x)\sigma_{\rm GR}(E_\nu)\frac{d\Phi_{\bar{\nu}_e}}{dE_\nu} + \sum_{N=p,n} n_N(x)\int_{E_\nu} dE'_\nu \frac{d\Phi_{\bar{\nu}_e}}{dE'_\nu}\frac{d\sigma_{\rm NC}}{dE_\nu}\left(E'_\nu, E_\nu\right) + \int_{E_\nu} dE'_\tau \frac{d\Phi_{\tau^\pm}}{dE'_\tau}\frac{1}{E'_\tau}\frac{dN_{\tau^-\to\bar{\nu}_e}}{dy} + n_e(x)\int_{E_\nu} dE'_\nu \frac{d\Phi_{\bar{\nu}_e}}{dE'_\nu}\sigma_{\rm GR}\left(E'_\nu\right)\frac{1}{E'_\nu}\frac{dN_{W^-\to\bar{\nu}_e}}{dy}$$

$$\frac{d^2\Phi_{\nu_\tau+\bar{\nu}_\tau}}{dxdE_\nu} = -\sum_{N=p,n} n_N(x)\left[\sigma_{\rm CC}(E_\nu)+\sigma_{\rm NC}(E_\nu)\right]\frac{d\Phi_{\nu_\tau+\bar{\nu}_\tau}}{dE_\nu} + \sum_{N=p,n} n_N(x)\int_{E_\nu} dE'_\nu \frac{d\Phi_{\nu_\tau+\bar{\nu}_\tau}}{dE'_\nu}\frac{d\sigma_{\rm NC}}{dE_\nu}\left(E'_\nu, E_\nu\right) + \int_{E_\nu} dE'_\tau \frac{d\Phi_{\tau^\pm}}{dE'_\tau}\frac{1}{E'_\tau}\frac{dN_{\tau\to\nu_\tau/\bar{\nu}_\tau}}{dy} + n_e(x)\int_{E_\nu} dE'_\nu \frac{d\Phi_{\bar{\nu}_e}}{dE'_\nu}\sigma_{\rm GR}\left(E'_\nu\right)\frac{1}{E'_\nu}\frac{dN_{W^-\to\nu_\tau/\bar{\nu}_\tau}}{dy}$$

$$\frac{d^2\Phi_{\tau^\pm}}{dxdE_\tau} = -\Gamma_\tau\frac{d\Phi_{\tau^\pm}}{dE_\tau} - g(E_\tau, x)\frac{d\Phi_{\tau^\pm}}{dE_\tau} + \int_{E_\tau} f(E'_\tau, E_\tau, x)\frac{d\Phi_{\tau^\pm}}{dE'_\tau}dE'_\tau + \sum_{N=p,n} n_N(x)\int_{E_\tau} dE'_\nu \frac{d\Phi_{\nu_\tau+\bar{\nu}_\tau}}{dE'_\nu}\frac{d\sigma_{\rm CC}}{dE_\tau}\left(E'_\nu, E_\tau\right) + n_e(x)\int_{E_\tau} dE'_\nu \frac{d\Phi_{\bar{\nu}_e}}{dE'_\nu}\sigma_{\rm GR}\left(E'_\nu\right)\frac{1}{E'_\nu}\frac{dN_{W^-\to\tau}}{dy}$$

Surface Fluxes after Propagation

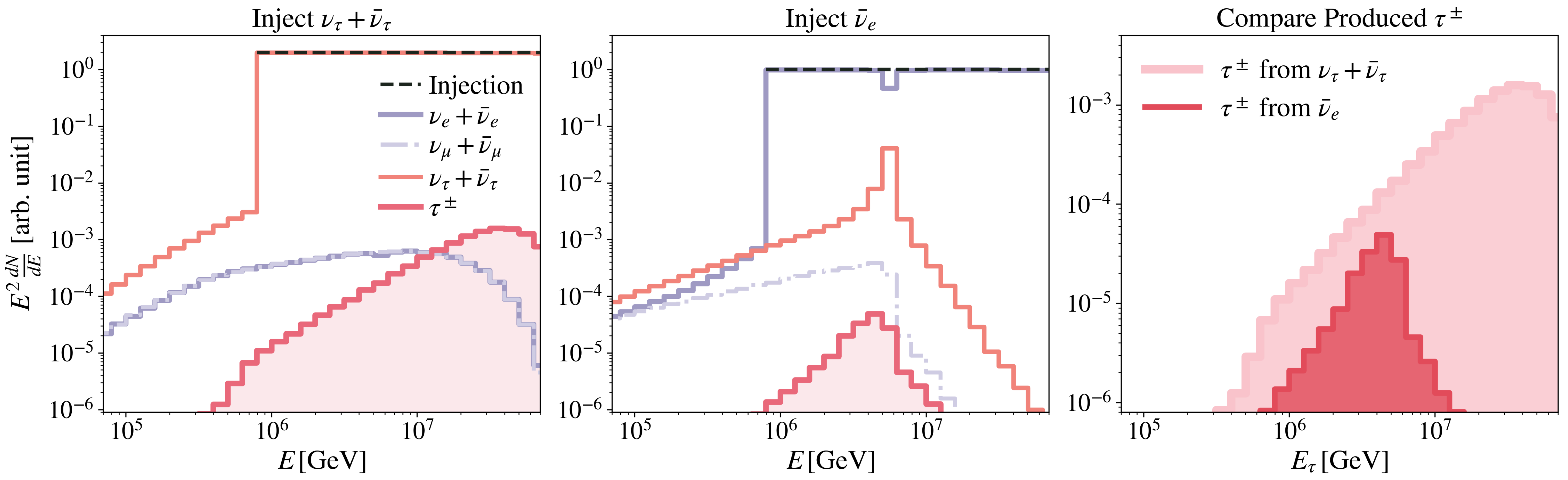


Earth-skimming: 0.2° below horizon, 3-14 PeV

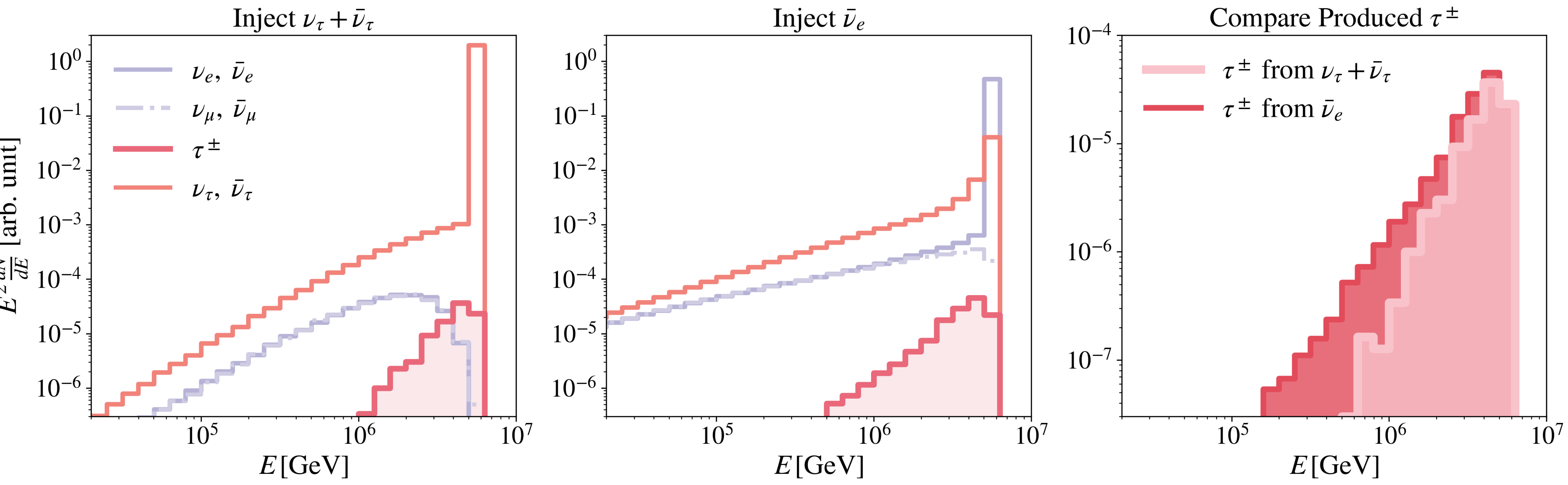
Earth-skimming: 4° below horizon, 1-100 PeV

Earth-skimming: 4° below horizon, mono-energetic 6.3 PeV

Surface Fluxes after Propagation



Mountain-skimming:
12km, 1-100 PeV



Mountain-skimming:
12km, mono-energetic
6.3 PeV