

Energy-Dependent Astrophysical Neutrino Flavor Composition at High Energies

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w/ Mainak Mukhopadhyay

in prep



SFU

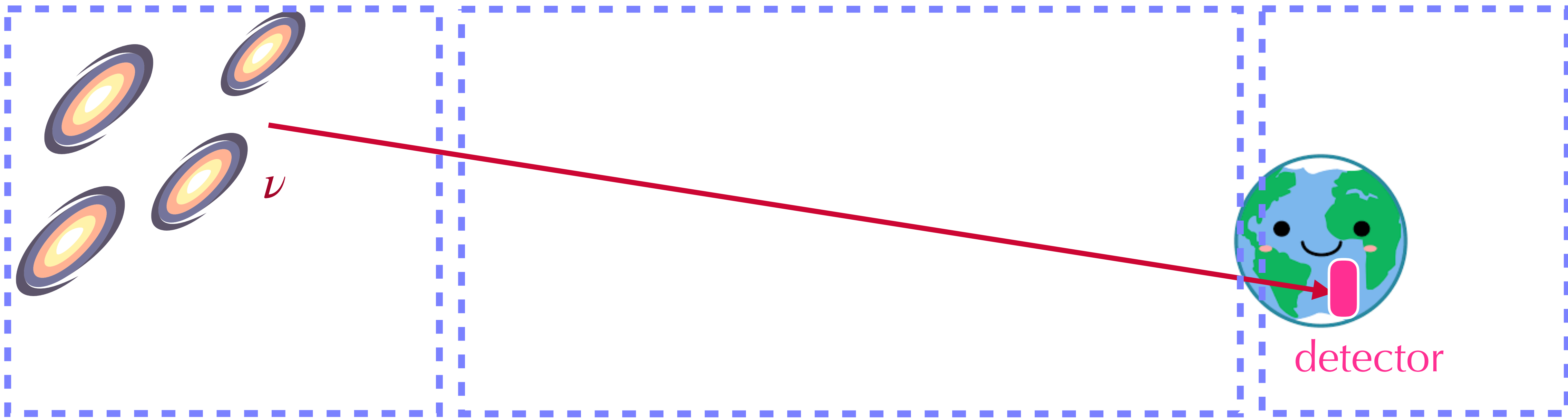
SIMON FRASER
UNIVERSITY



Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

IceCube Particle Astrophysics Symposium
IPA 2026
From the Upgrade to IceCube-Gen2

Redshift ← $z = 0$



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 and the Measurements

- Pion decay $\pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Muon-damped $\pi^+ \rightarrow \nu_\mu + \cancel{\mu^+}$
- Neutron decay $n \rightarrow p + e^- + \bar{\nu}_e$

$$f_{e,s} : f_{\mu,s} : f_{\tau,s}$$

$$\{1 : 2 : 0\}$$

$$\{0 : 1 : 0\}$$

$$\{1 : 0 : 0\}$$

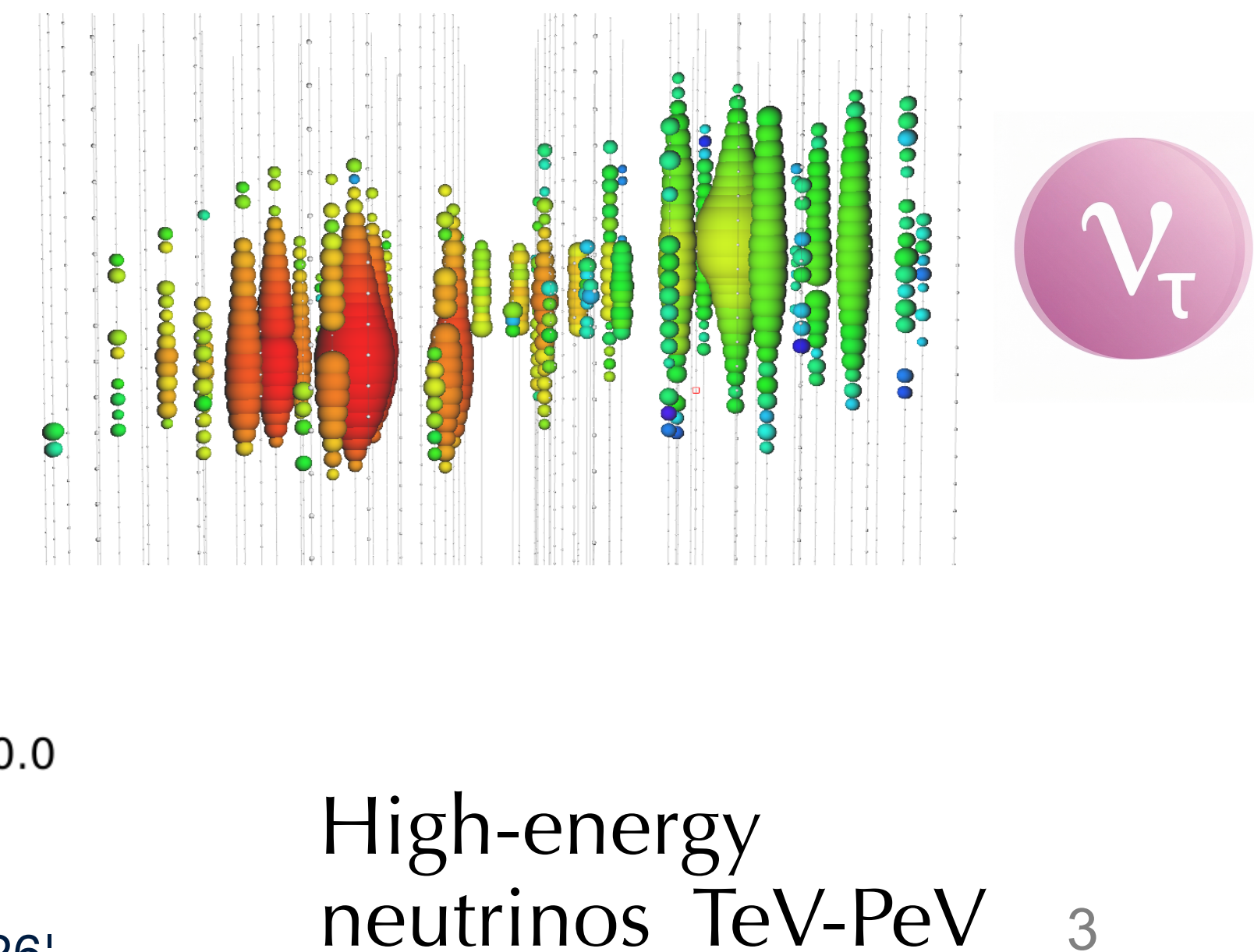
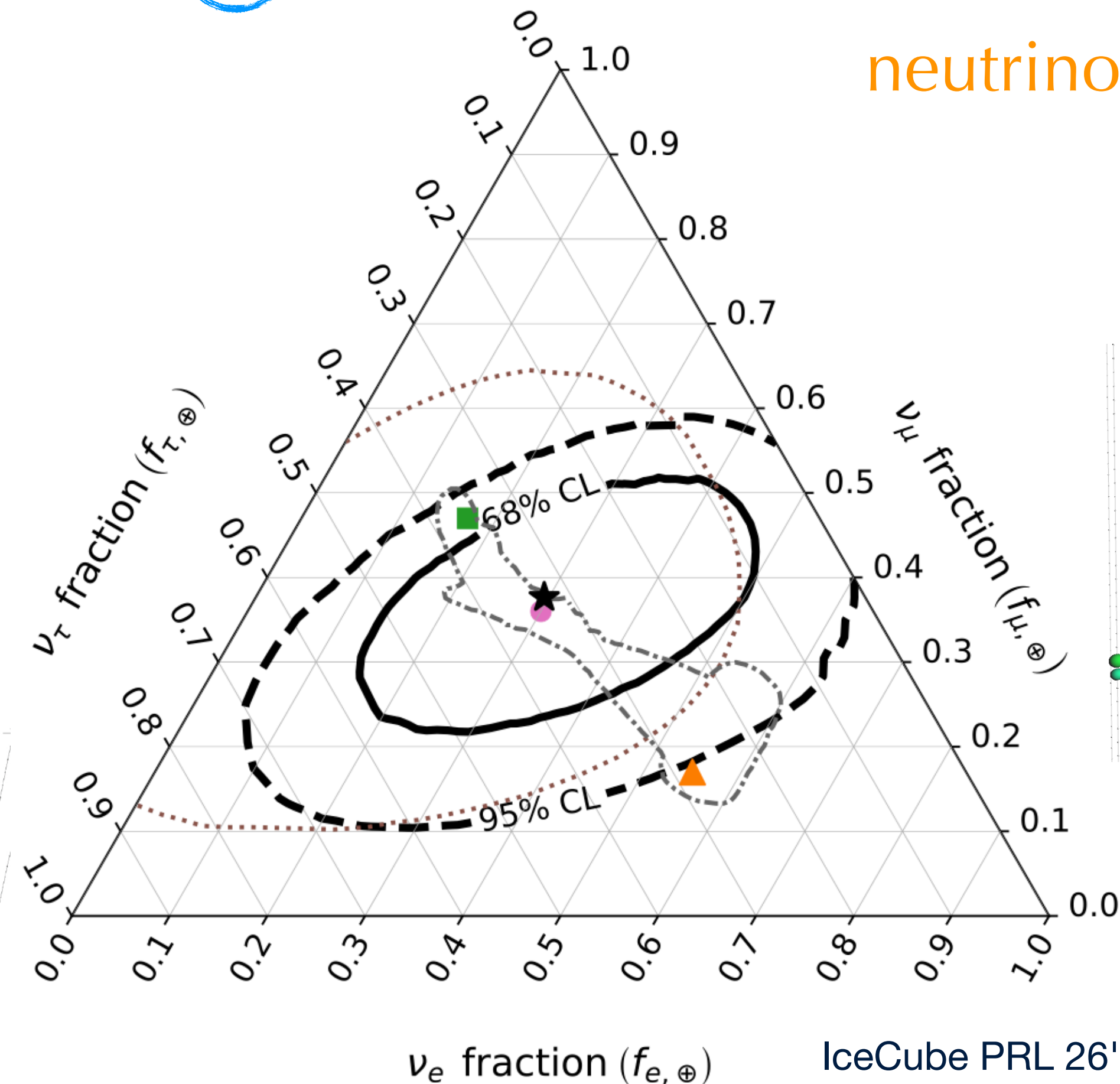
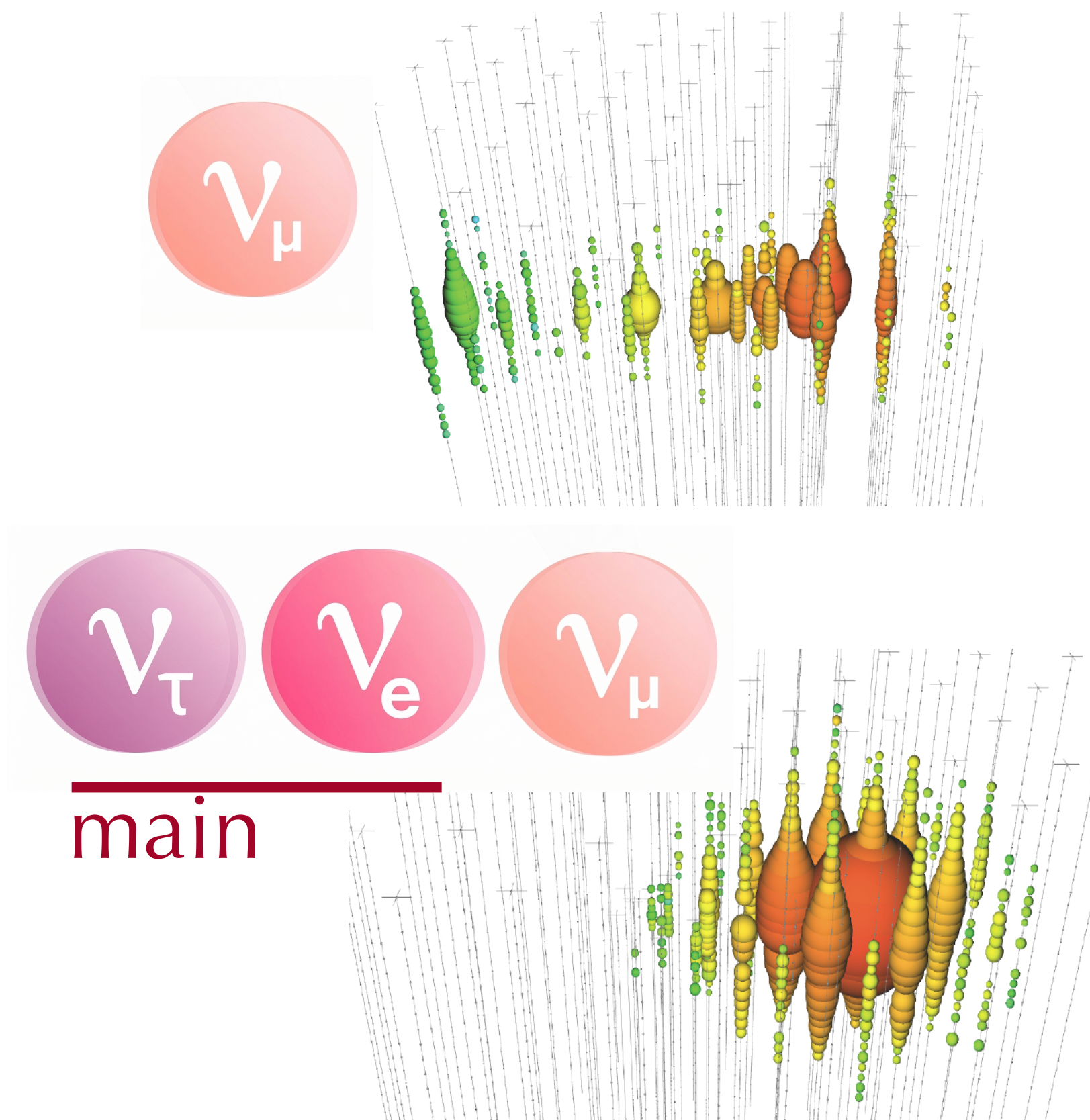
$$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$$

$$\{0.34 : 0.33 : 0.33\}$$

$$\{0.24 : 0.37 : 0.39\}$$

$$\{0.55 : 0.23 : 0.22\}$$

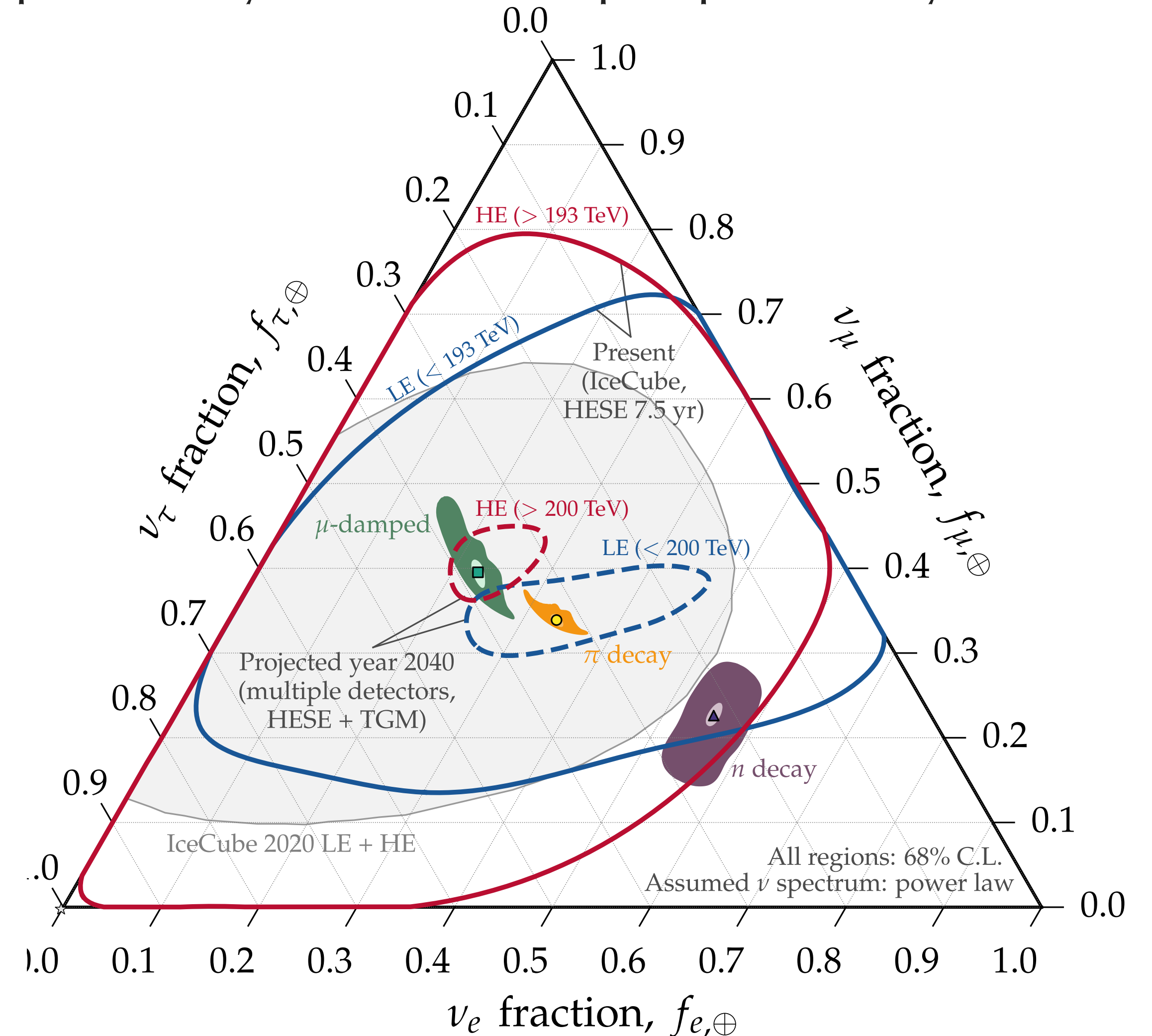
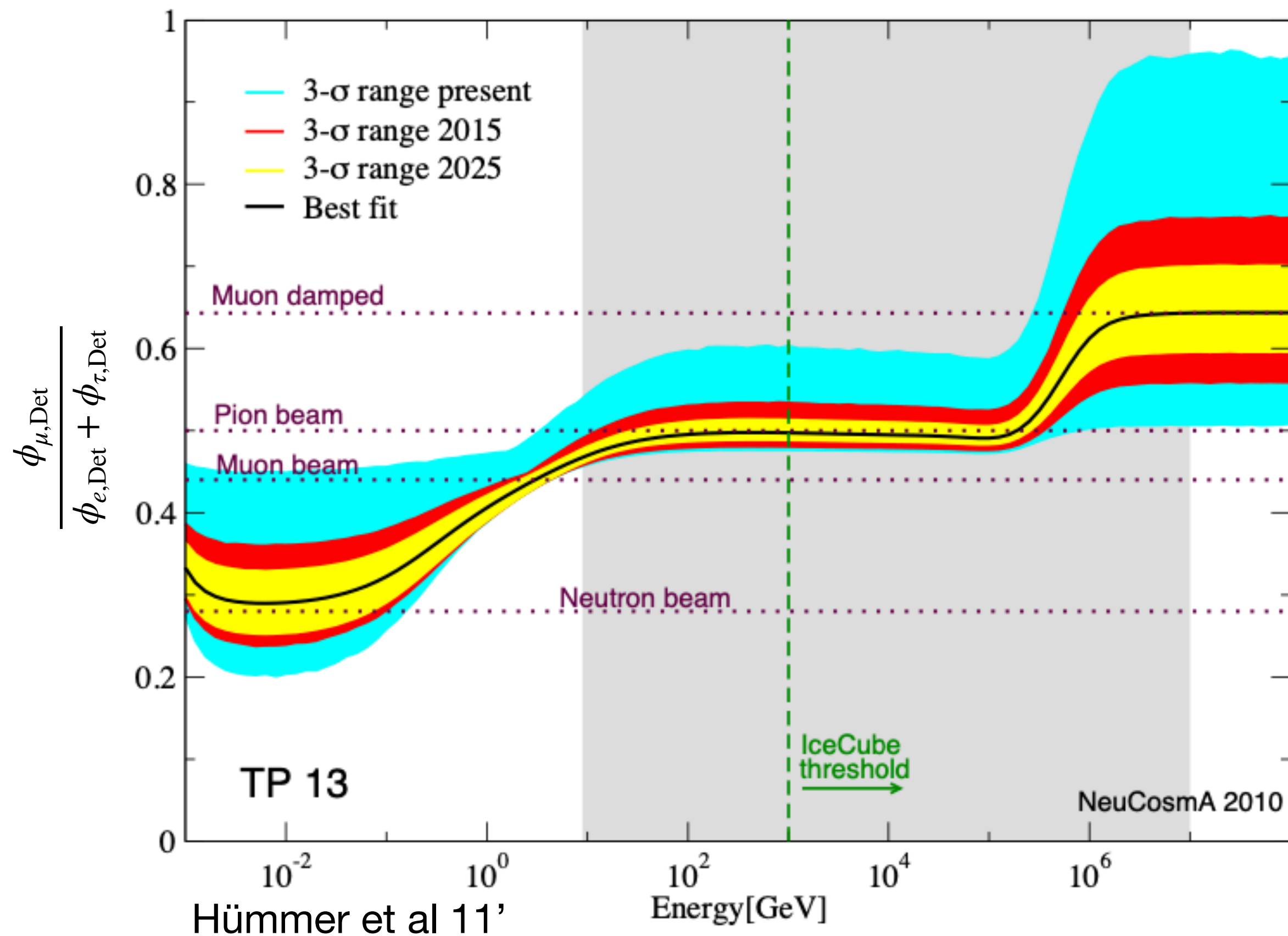
neutrino oscillations



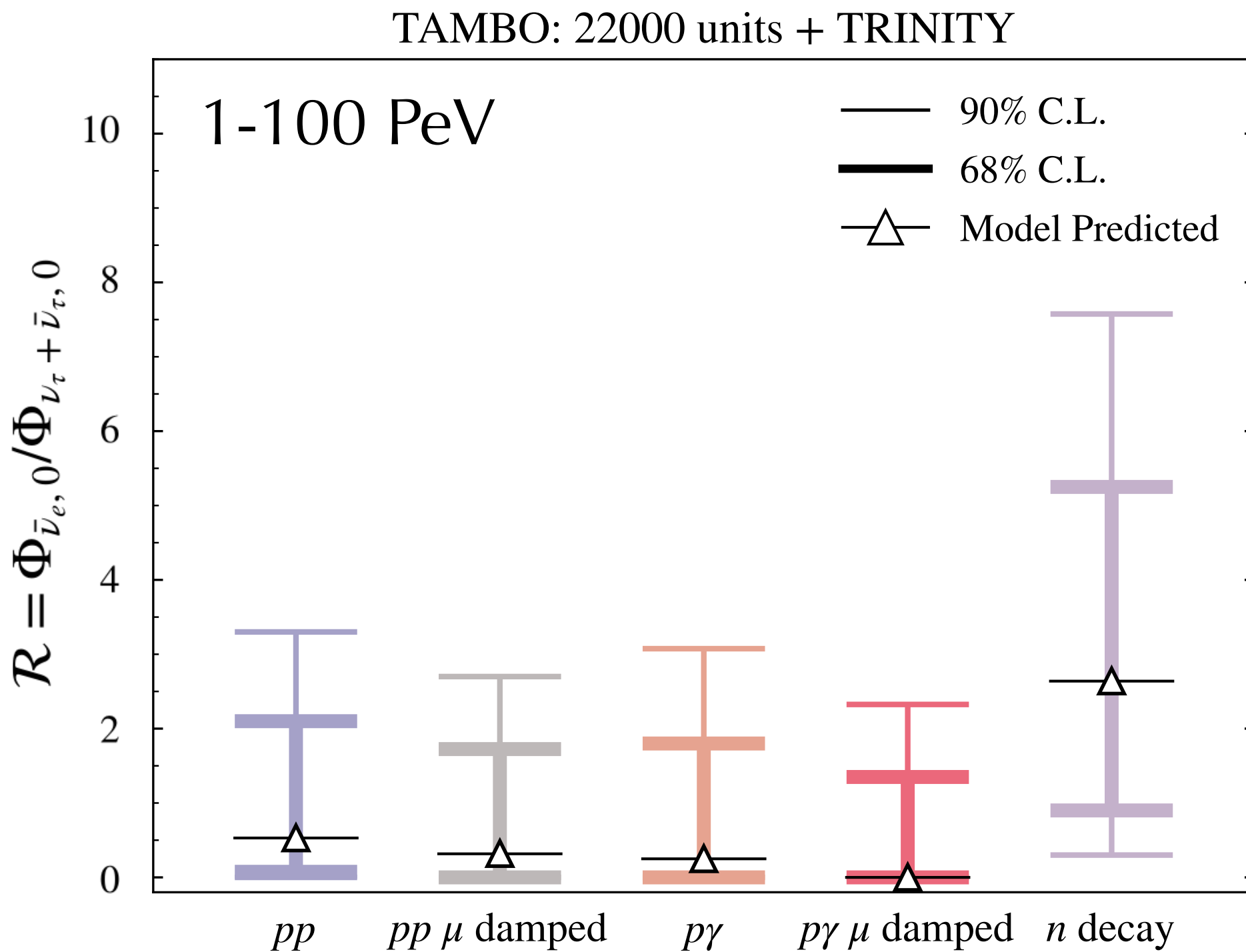
High-energy
neutrinos TeV-PeV

Energy-Dependent Neutrino Flavor Composition

- The Flavor composition is often taken to be an energy-independent constant.
- Even considering the simplest source models, due to the presence of the magnetic field, the flavor composition is expected to be energy-dependent - pion decay -> muon-damped pion decay.

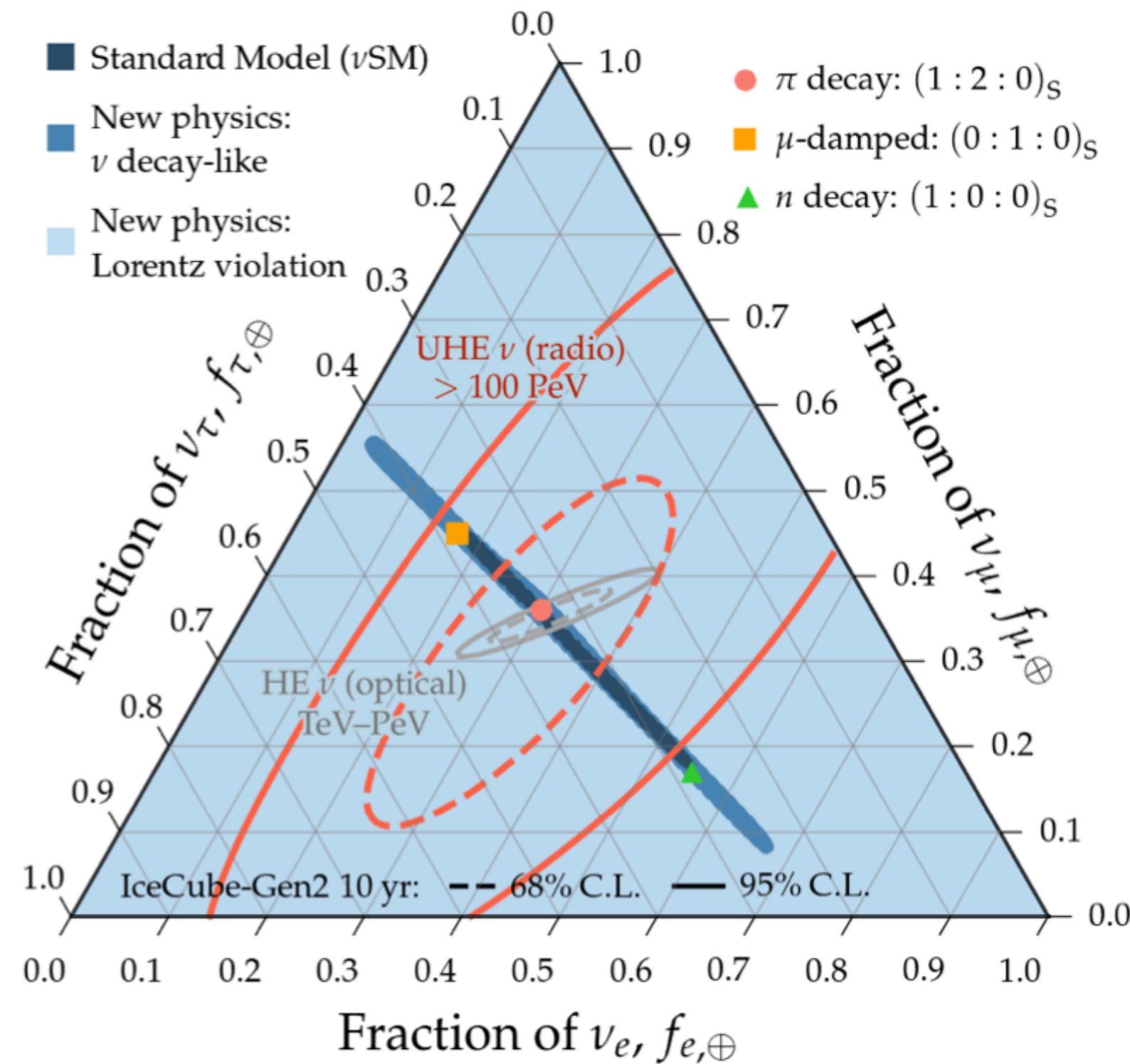


Flavor Composition Measurements: High Energies - Ultra-High Energies



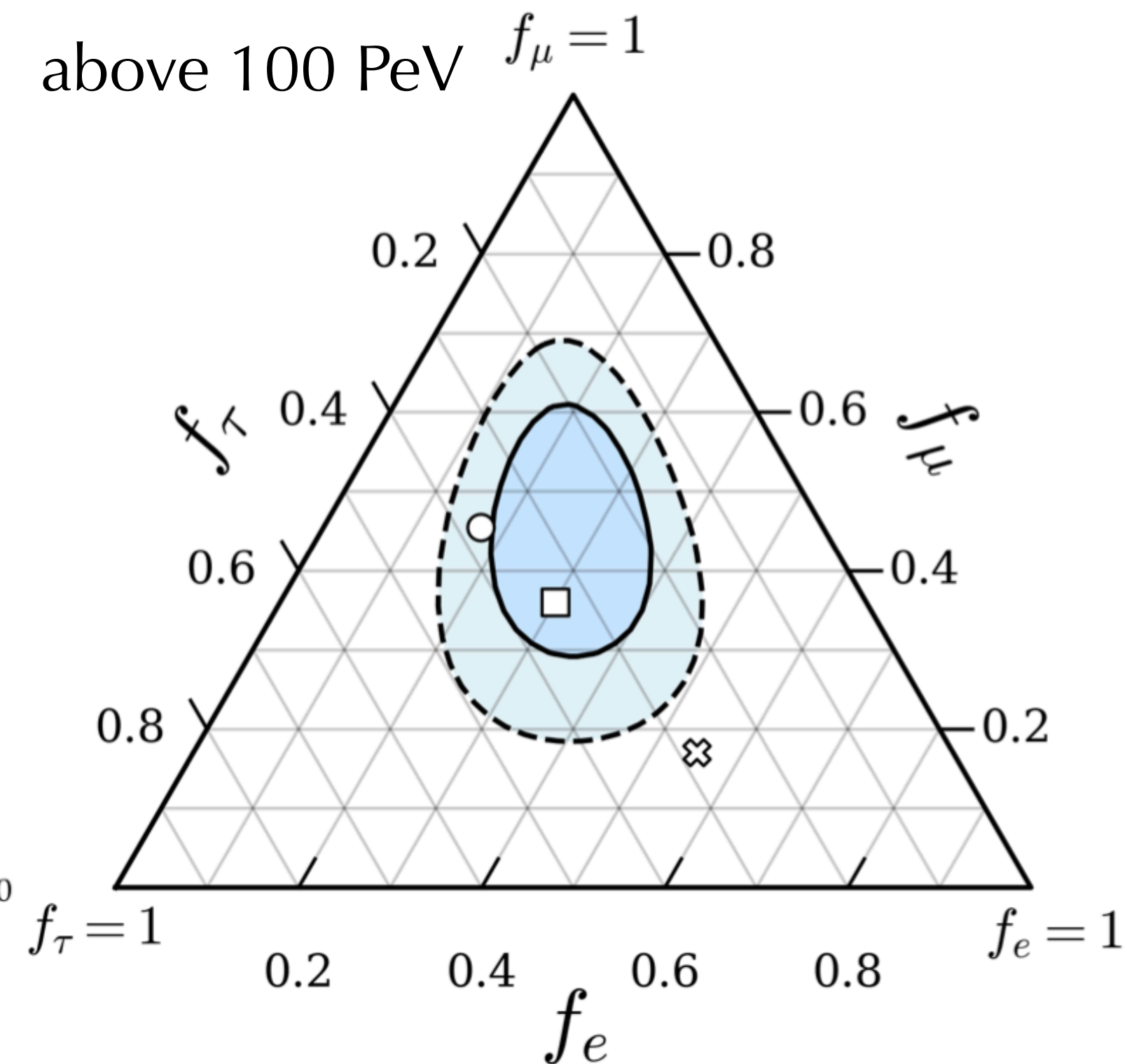
Ding & **QL** 2607.26128

See our poster!



Coleman et al. 24'

in-ice radio detectors



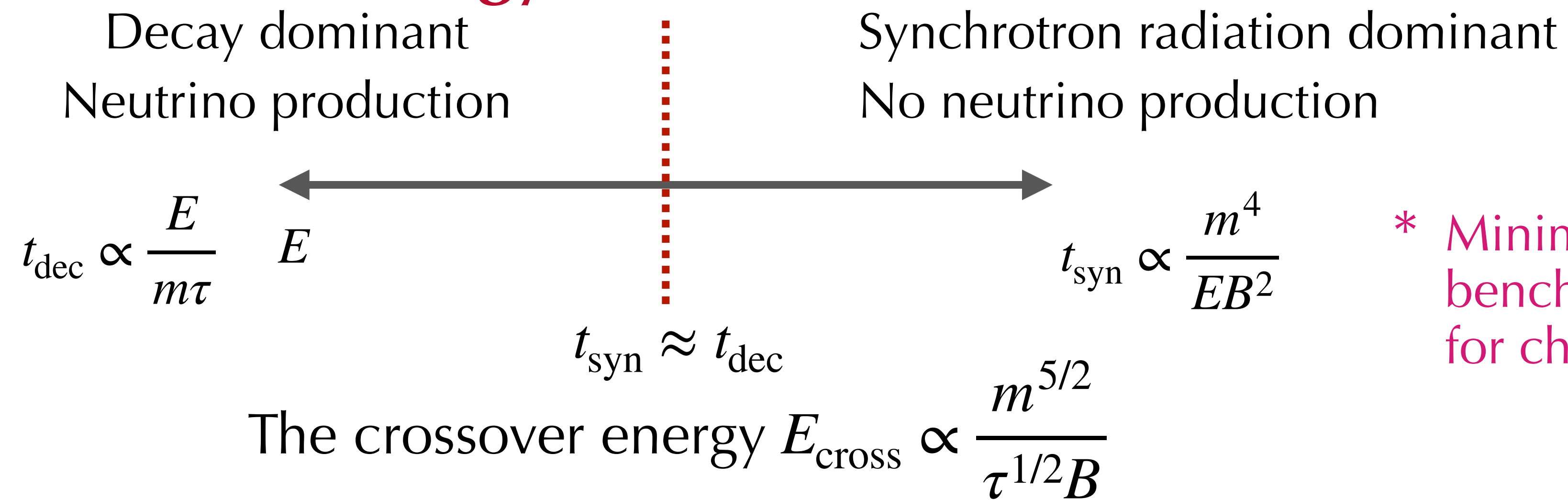
Burgos-Mondéjar, Thomson, Argüelles
2608.22556

Combining in-ice radio experiments & tau air shower neutrino experiments

Very-high-energy tau air shower neutrino experiments through detection of the Glashow resonance

More transitions at higher energies?

Decay vs. Synchrotron Energy Loss

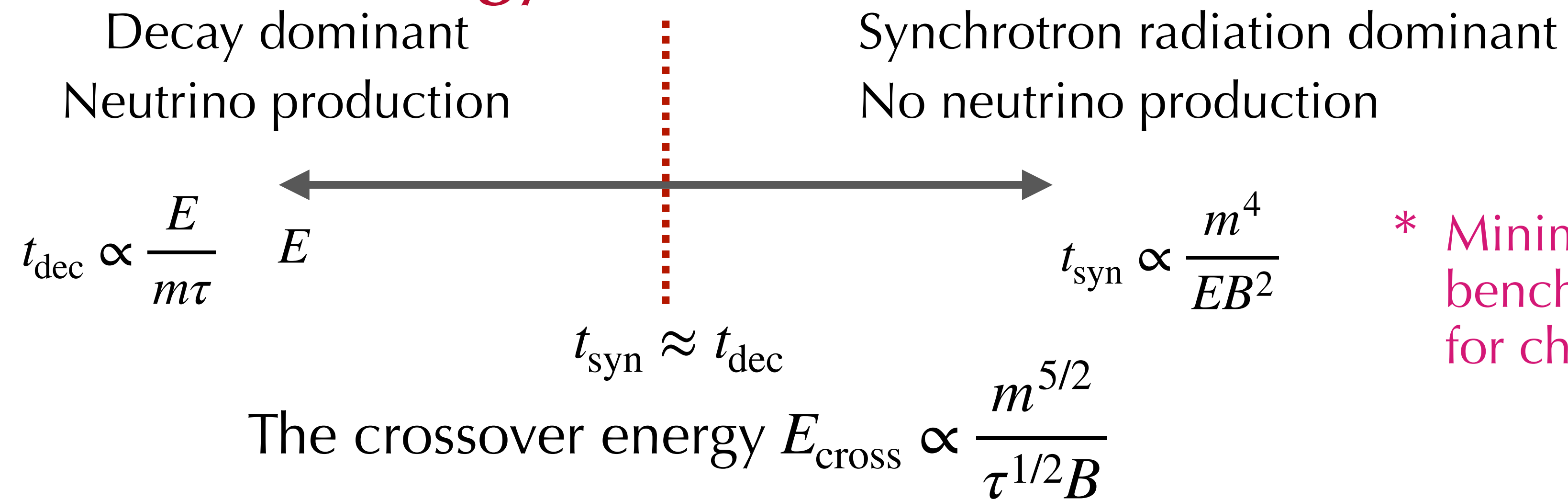


* Minimal-assumption benchmark. Guaranteed for charged parents.

The damping ladder:

$$E_{\text{cross}}^{\mu} : E_{\text{cross}}^{\pi} : E_{\text{cross}}^K : E_{\text{cross}}^c \approx 1 : 18 : 629 : 2 \times 10^6 \quad E_{\text{cross}}^{\mu} \approx \frac{6 \times 10^9}{B[\text{G}]} \text{GeV}$$

Decay vs. Synchrotron Energy Loss

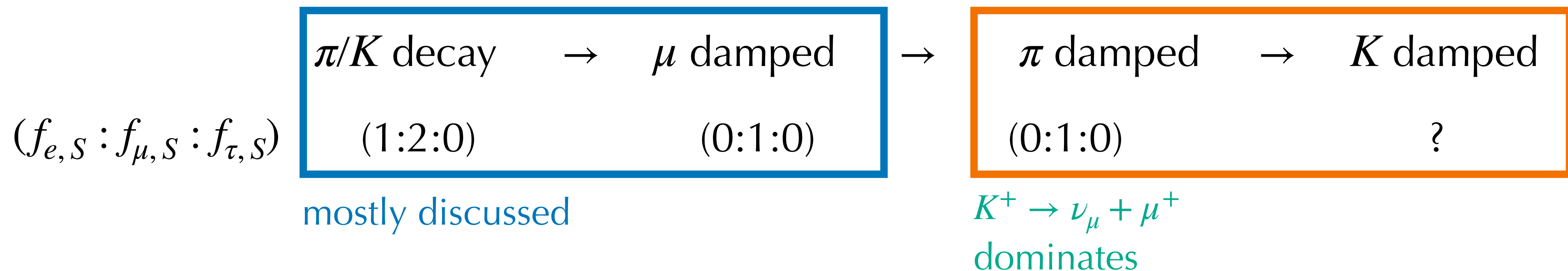


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This work



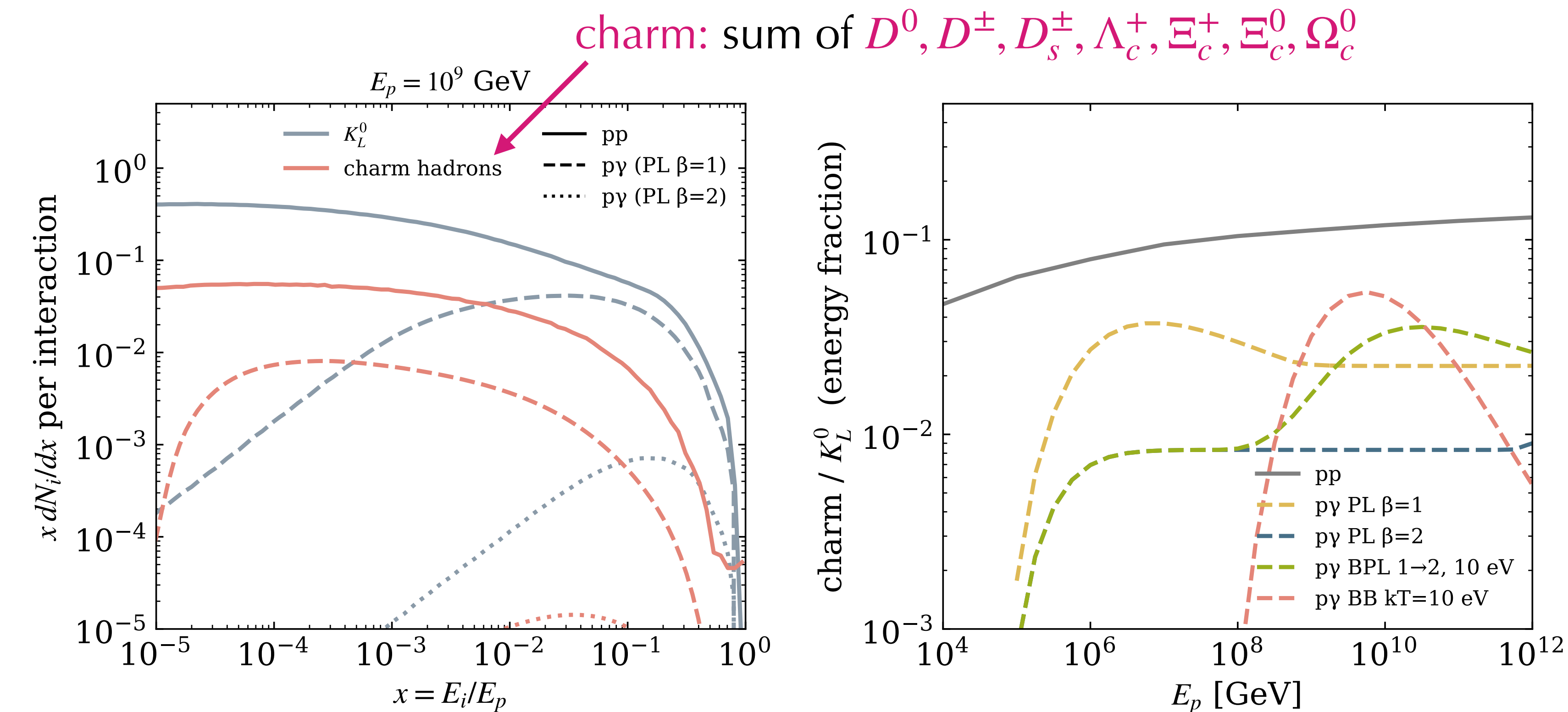
Charm Dominance?

- What happens after Kaons are damped? The natural answer is **charm**.
- Discussions on charm contribution from e.g., magnetars and slow-jet supernovae.

See Carpio et al. 20', Bhattacharya et al. 24'

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- Discussions on charm contribution from e.g., magnetars and slow-jet supernovae.
See Carpio et al. 20', Bhattacharya et al. 24'
- Charm dominance is conditional, depending on the cooling processes.
- Long-lived neutral meson K_L^0 sets a floor for the minimum assumption benchmark.



- For pp ,

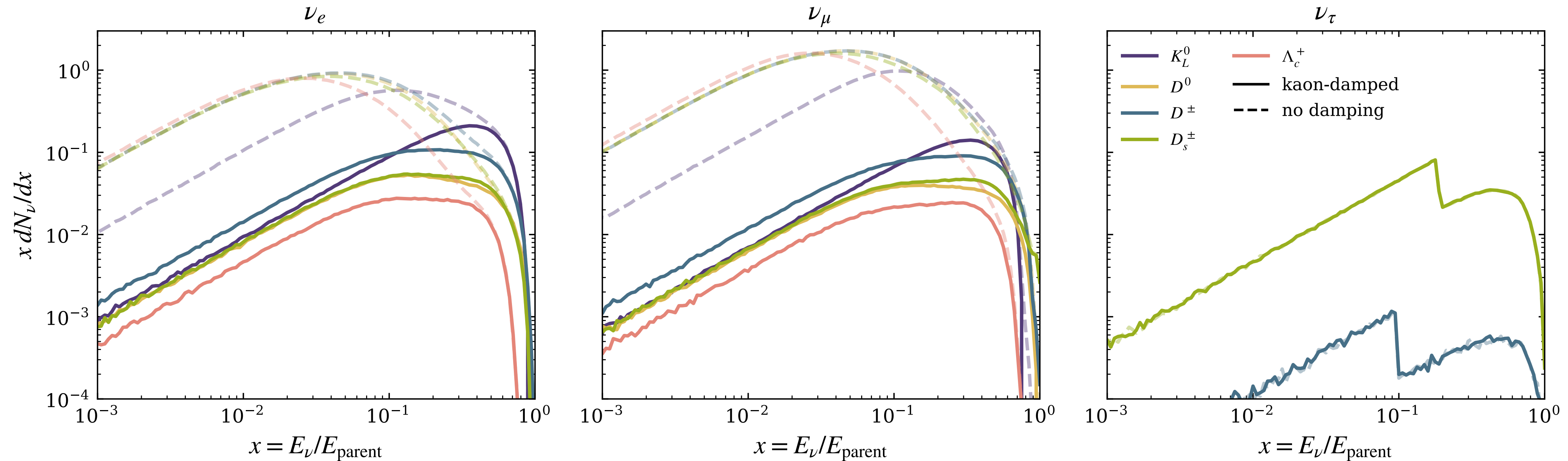
$$\frac{dN_c}{dx} \sim 10^{-1} \frac{dN_{K_L^0}}{dx} \sim 5 \times 10^{-2} \frac{dN_{K^\pm}}{dx} \sim 10^{-2} \frac{dN_{\pi^\pm}}{dx}$$

- For $p\gamma$, the target photon spectrum matters. In general less K_L^0 and charm can be produced.

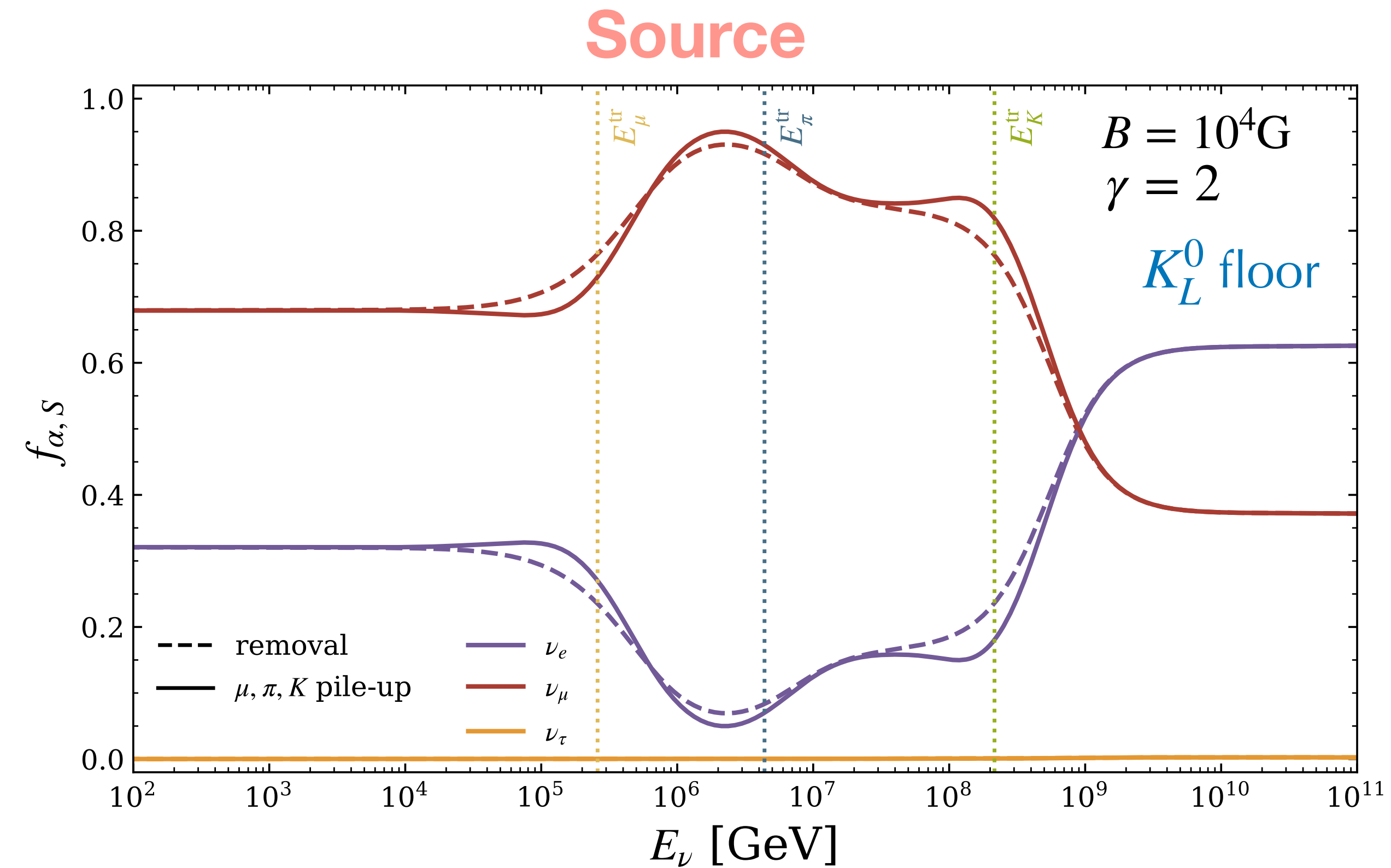
We focus on pp here and $p\gamma$ is the next step.

Flavor Composition from Decays

- Production $D^0 : D^\pm : D_s^\pm : \Lambda_c^+ \approx 0.57 : 0.23 : 0.1 : 0.1$
- The largest decay channels of charmed hadrons are to hadrons. Charged pions and kaons produce neutrinos at lower energies.
- Prompt neutrinos come from **semileptonic** and **leptonic decays** of charmed hadrons, at **$\sim 10\% - 17\%$** .
 $(f_{e,S} : f_{\mu,S} : f_{\tau,S}) \sim (0.51 : 0.44 : 0.04)$, including a few ν_τ from $D_s^\pm$ decay.
- $K_L^0 \sim 68\%$ semileptonic decay $(f_{e,S} : f_{\mu,S} : f_{\tau,S}) \sim (3:2:0)$

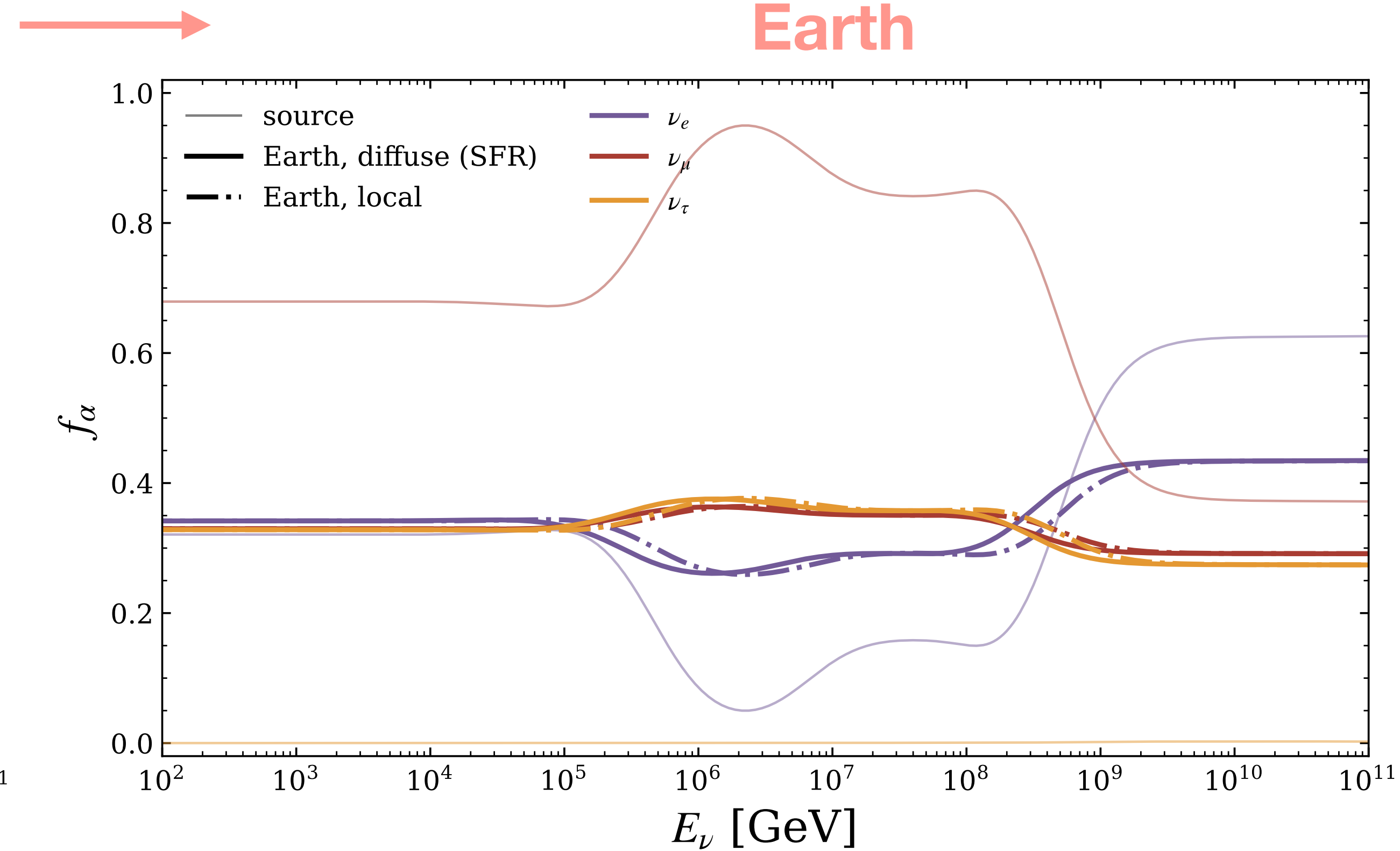
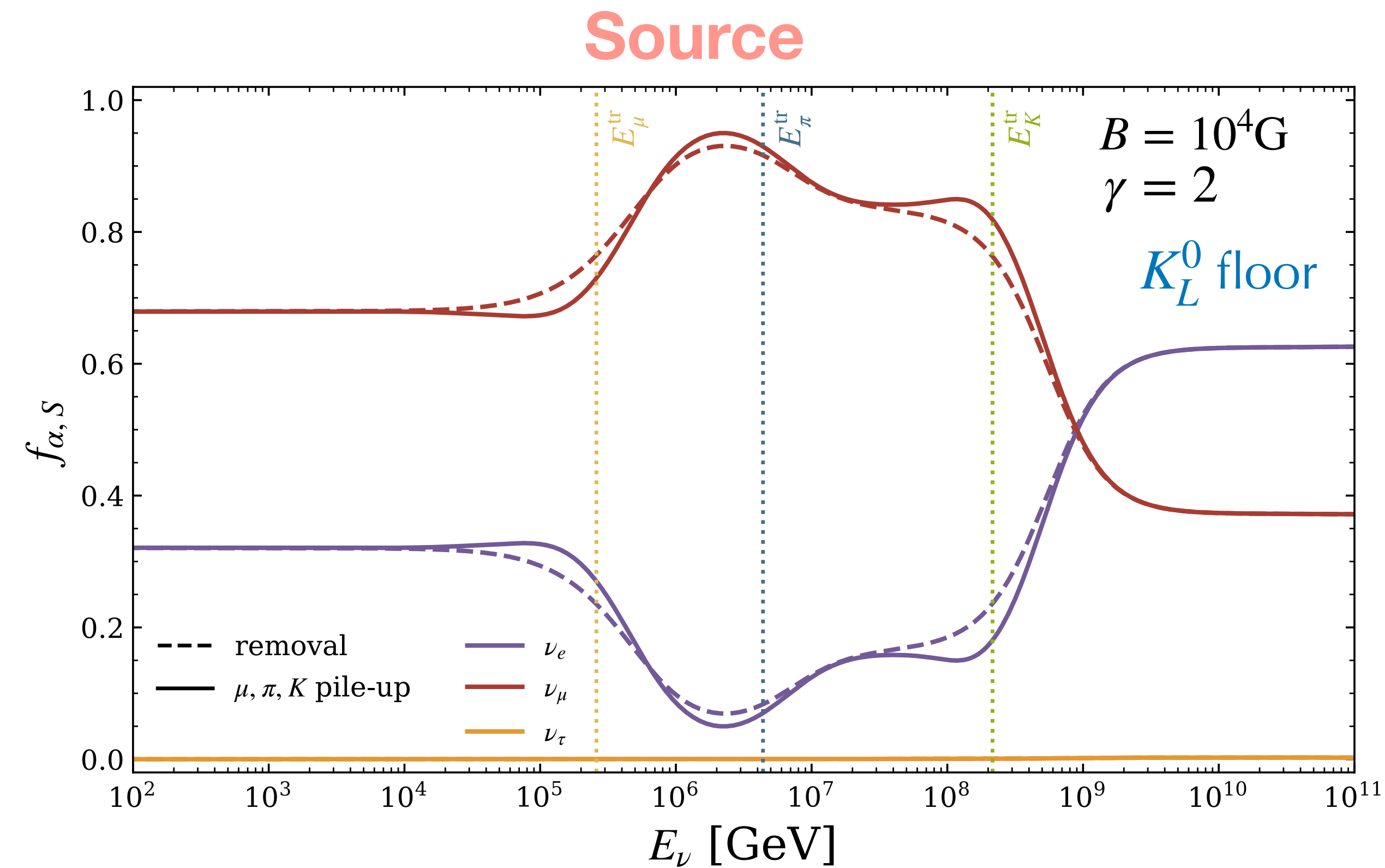


Flavor Composition



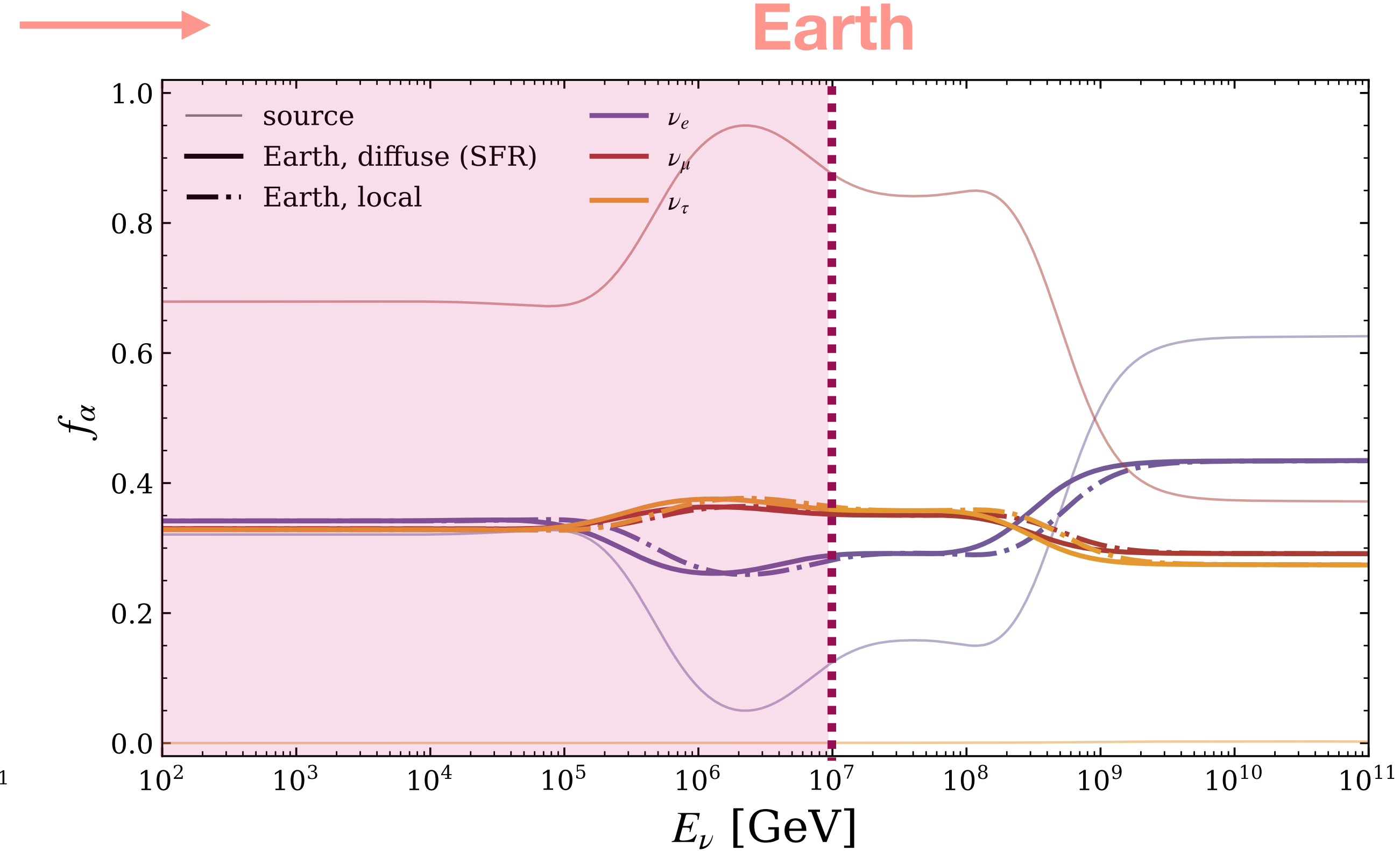
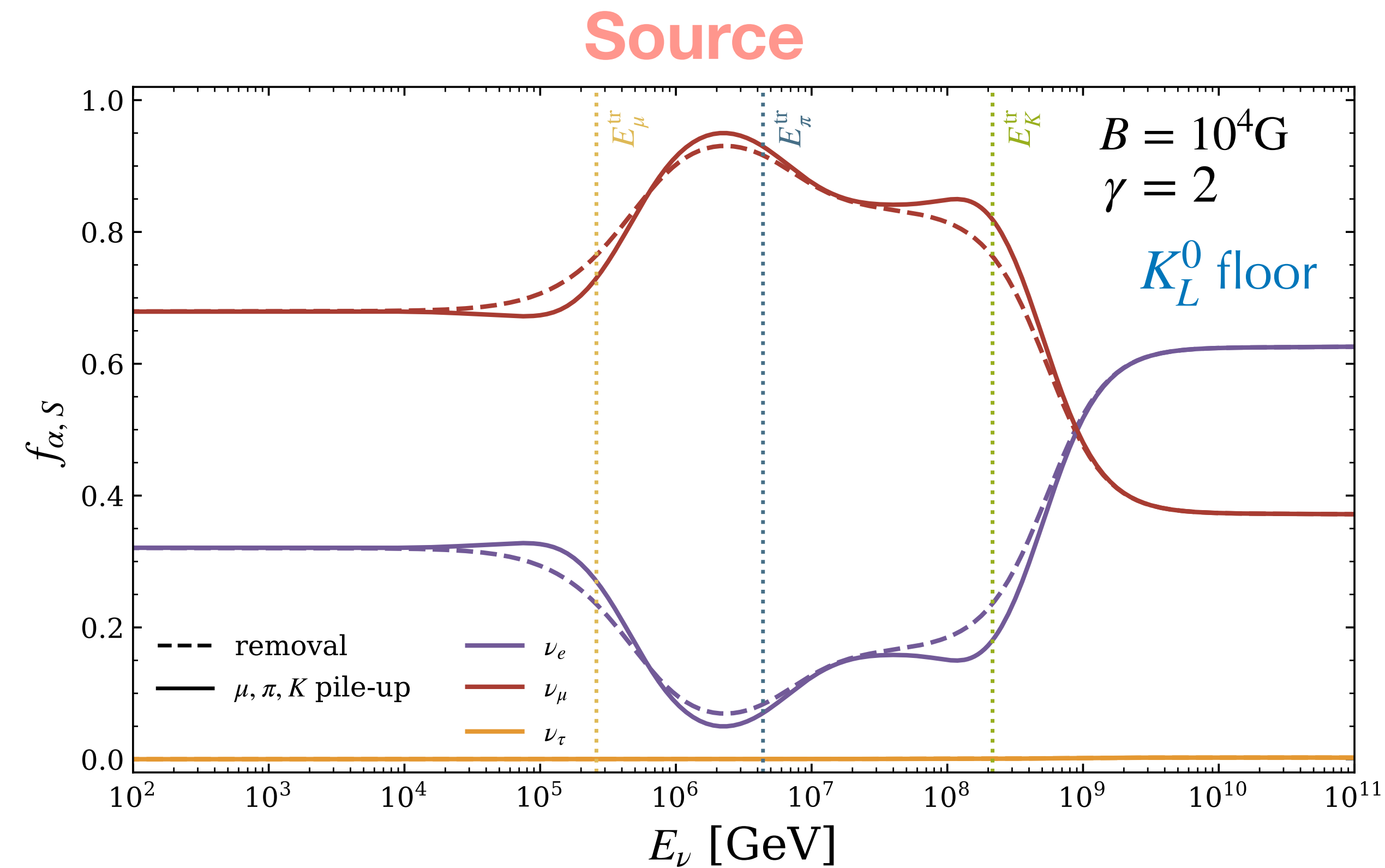
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- The injection proton spectrum affects the neutrino flux spectrum, while the flavor composition and transition energies change slightly.

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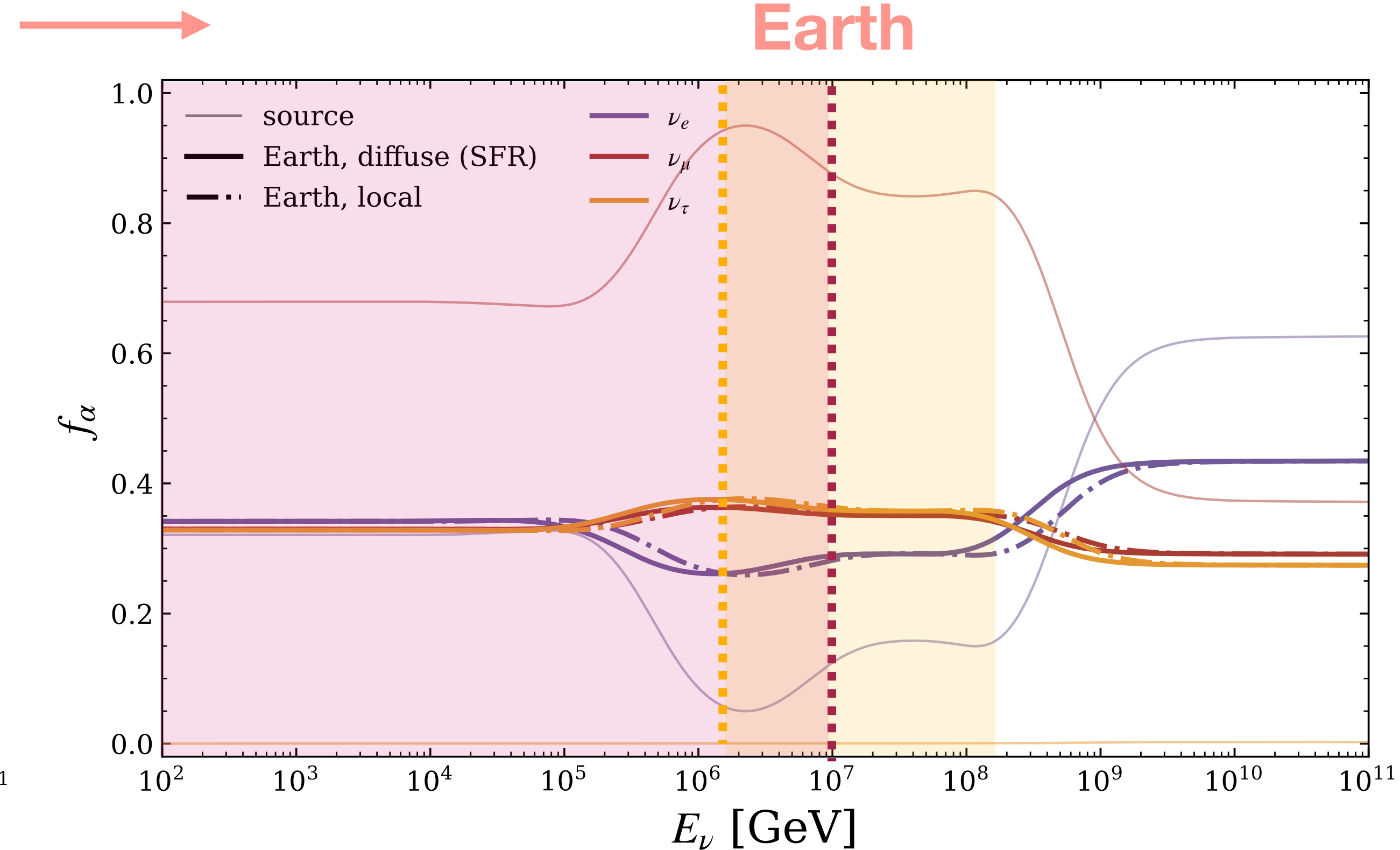
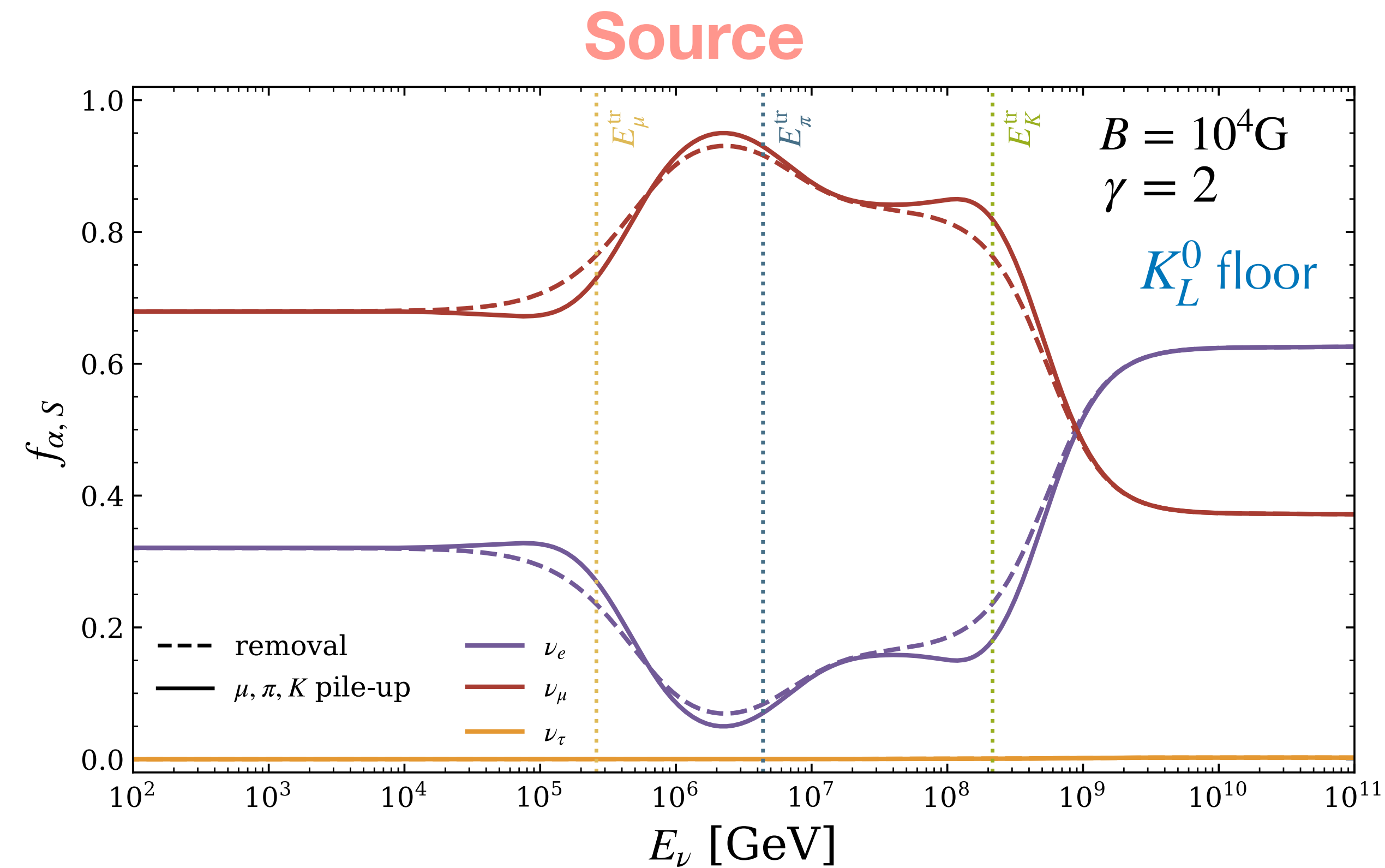
Flavor Composition



HE
TeV-10 PeV

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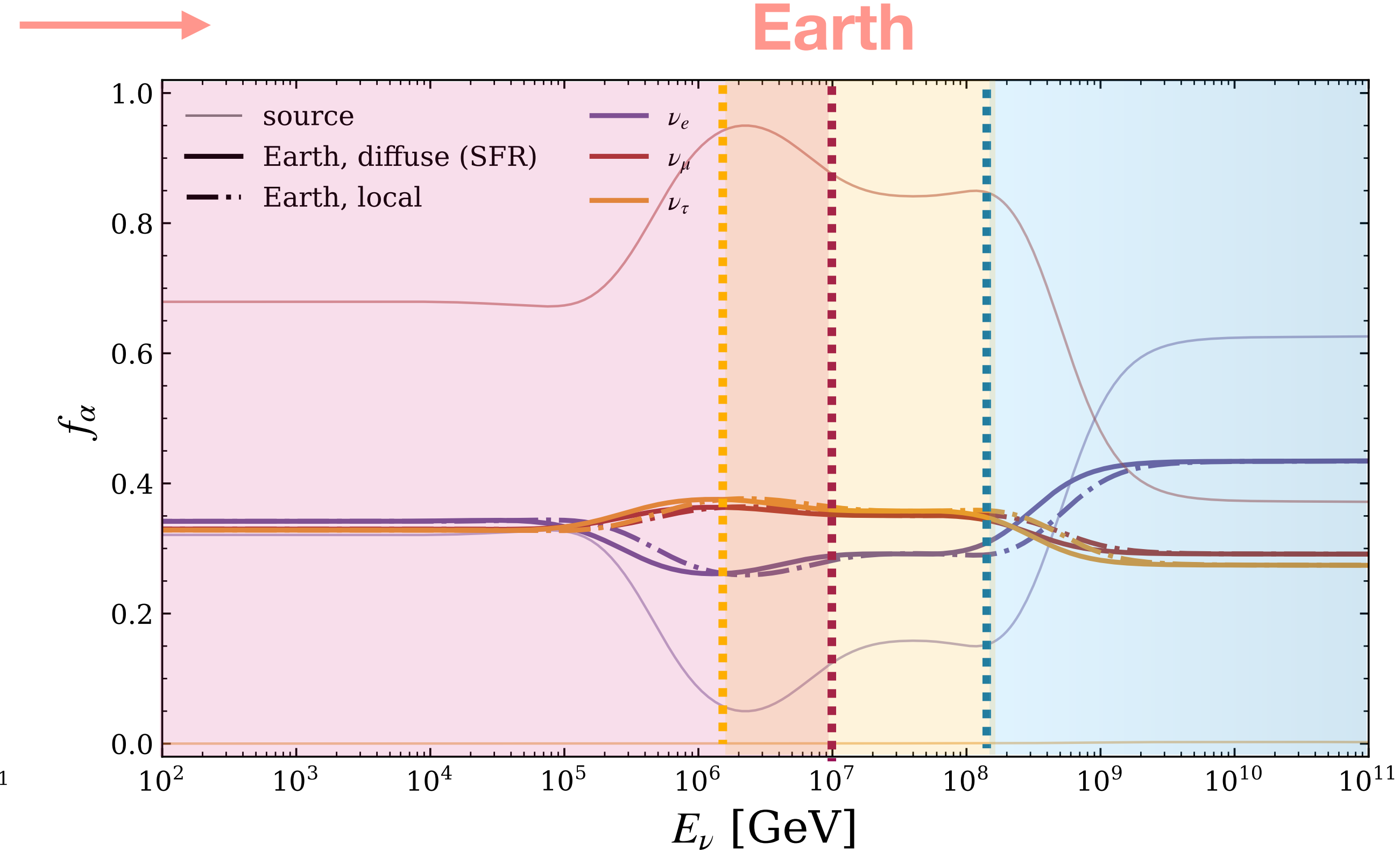
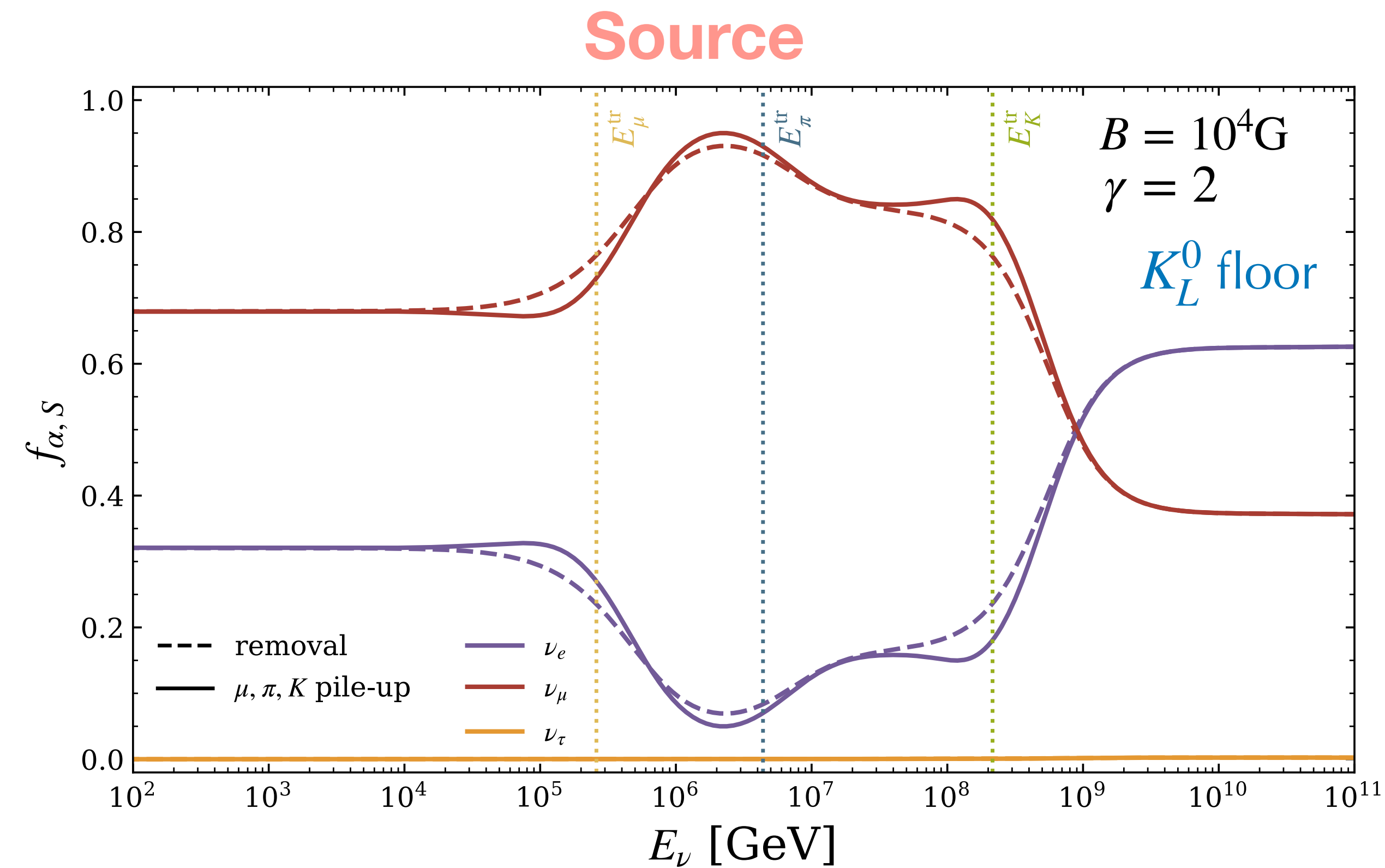
Flavor Composition



HE VHE
TeV-10 PeV PeV - 100 PeV

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Flavor Composition



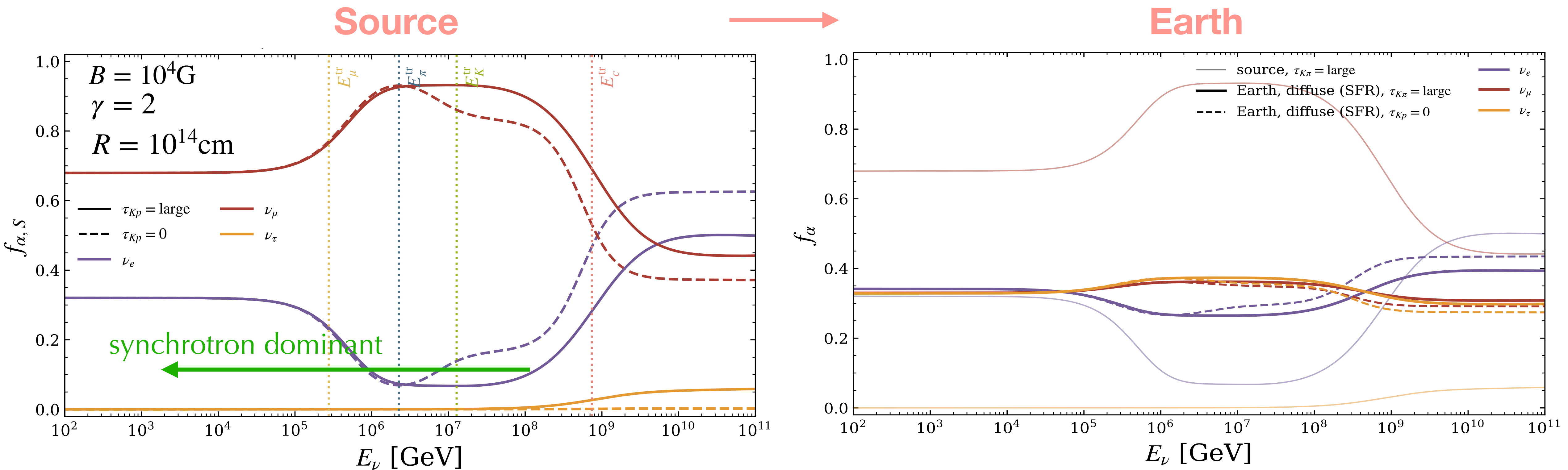
HE VHE UHE
TeV-10 PeV PeV - 100 PeV > 100 PeV

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Charm Dominance

Hadronic damping removes the K_L^0 floor in a thick target.

$$f_{\text{dec}} = \left[1 + (E/E_{\text{cross}}^{\text{syn}})^2 + \underbrace{E/E_{\text{cross}}^{\text{had}}}_{\text{hadron interactions}} \right]^{-1} \quad E_{\text{cross}}^{\text{had}} = \frac{m}{c\tau n\sigma} \quad \pi < K_L^0 < K^\pm \ll D$$



Charm Dominance

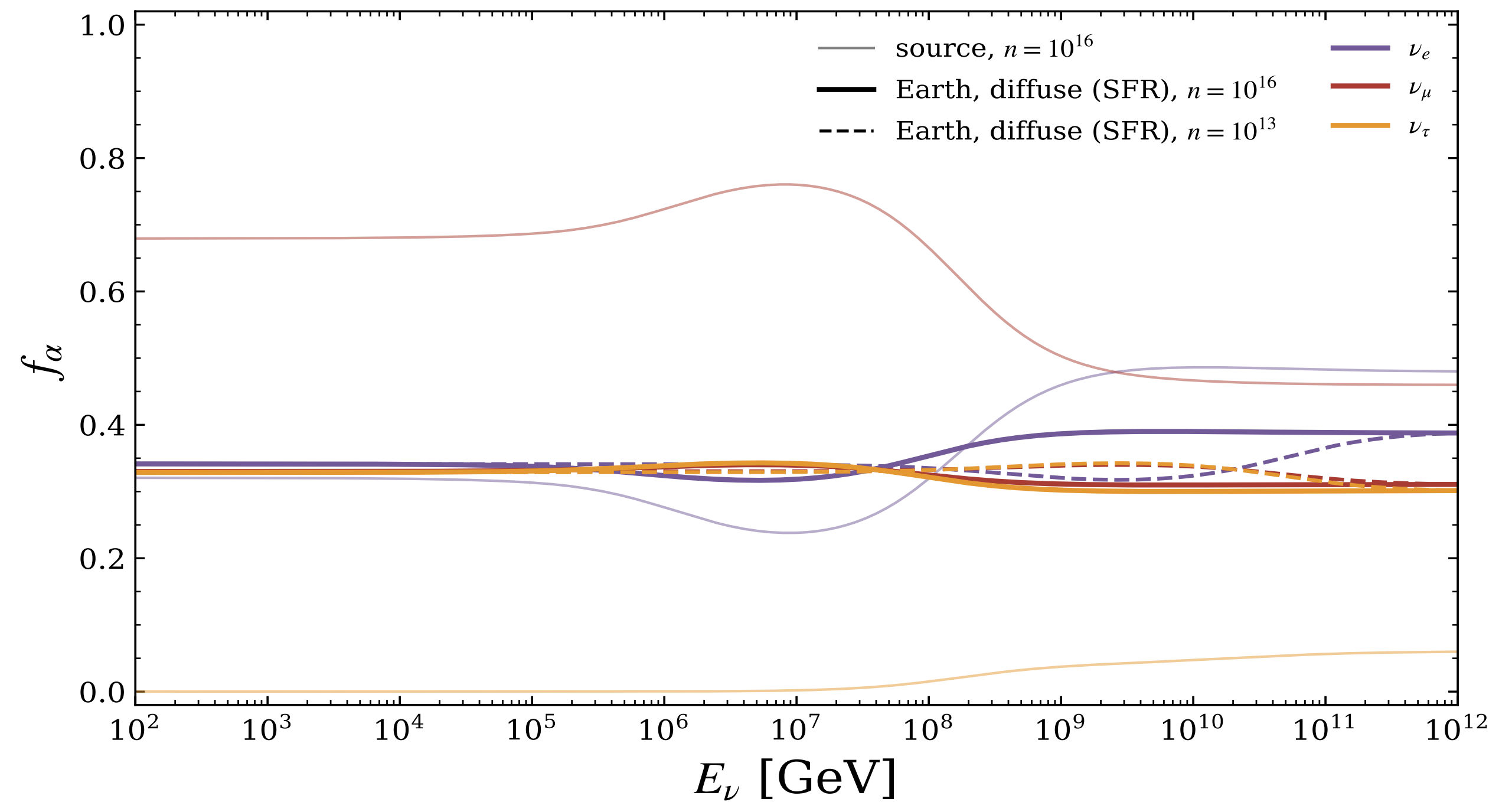
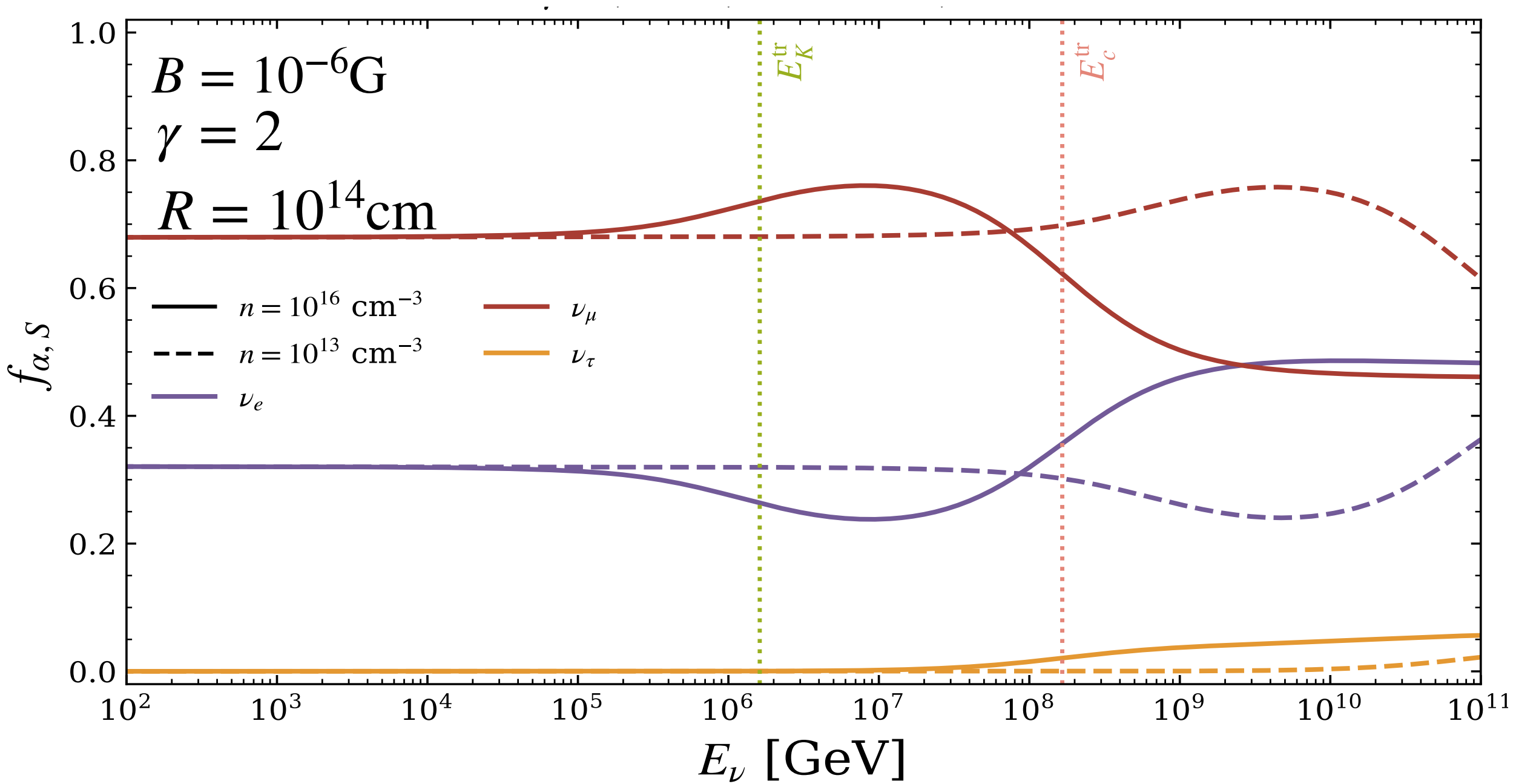
Hadronic damping removes the K_L^0 floor in a thick target.

If we consider a weak magnetic field $f_{\text{dec}} \approx \left[1 + E/E_{\text{cross}}^{\text{had}} \right]^{-1}$

Source

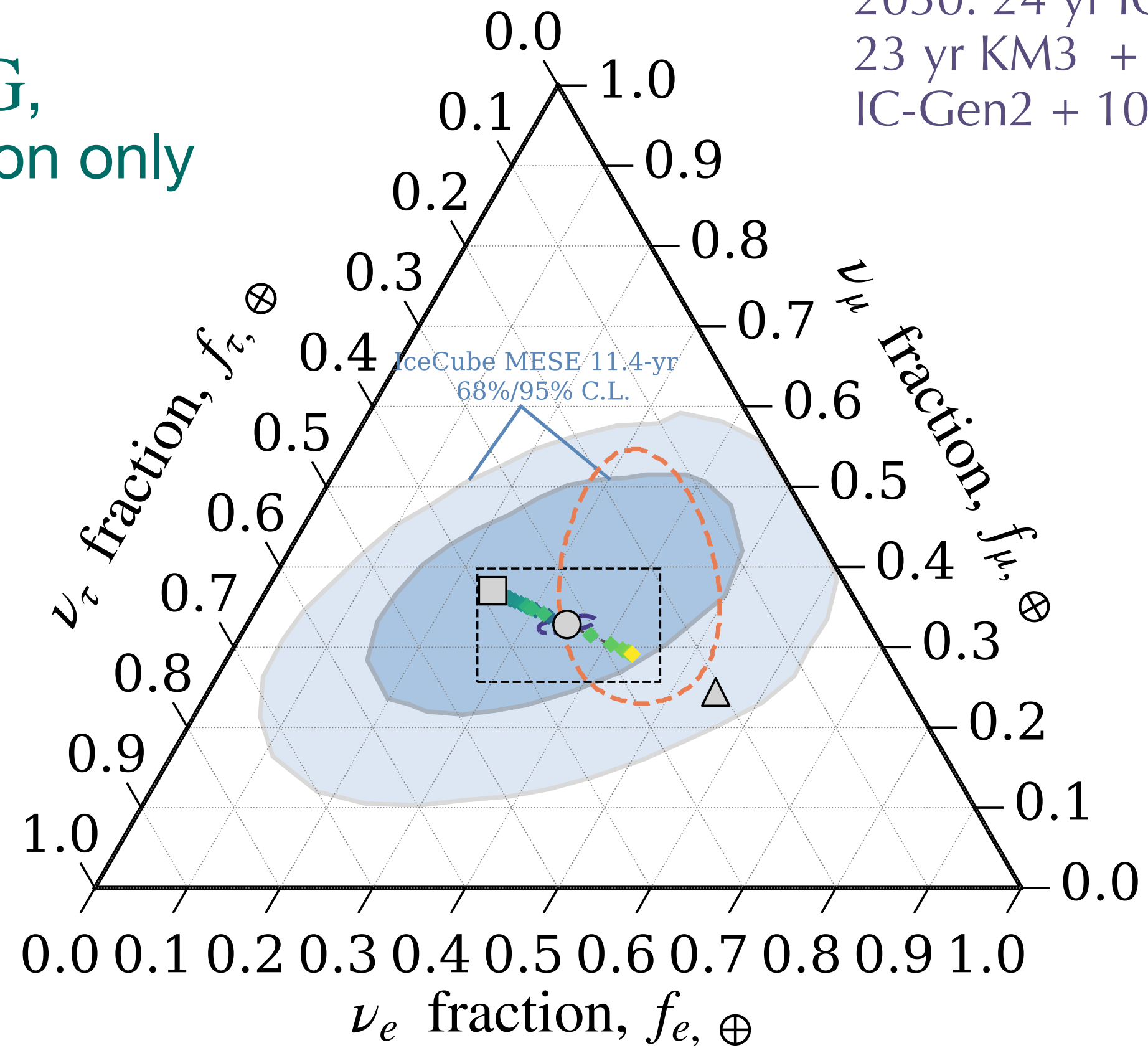


Earth



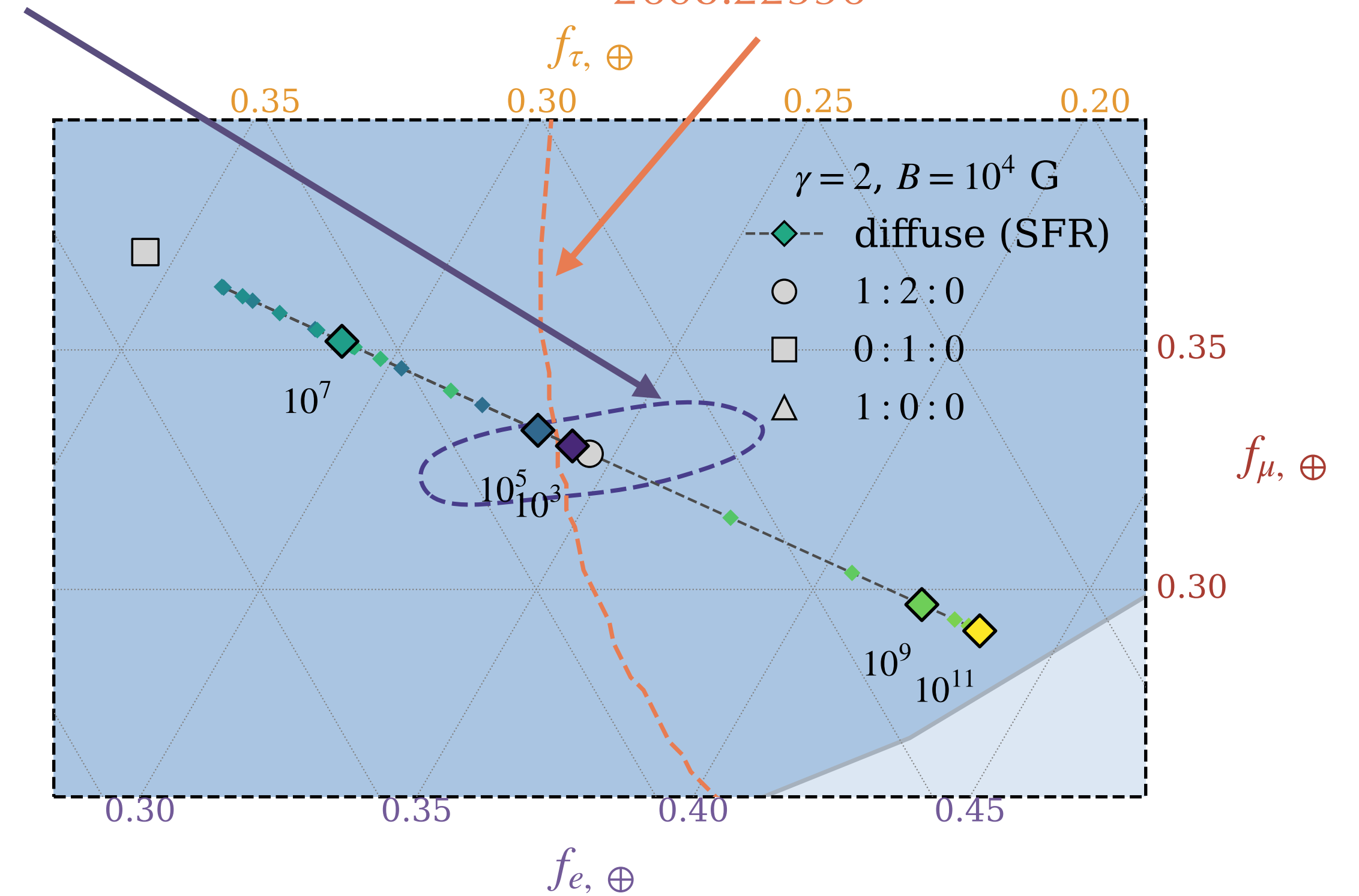
Energy-dependent Flavor Composition Measurements

$B = 10^4 \text{G}$,
synchrotron only



optical telescopes: 1σ sensitivity to
2050: 24 yr IC + 25 yr B-GVD +
23 yr KM3 + 19 yr P-ONE + 15 yr
IC-Gen2 + 10 yr TRIDENT/HUNT

combined UHE telescopes: 1σ
sensitivity shifted from Burgos-
Mondéjar, Thomson, Argüelles
2608.22556

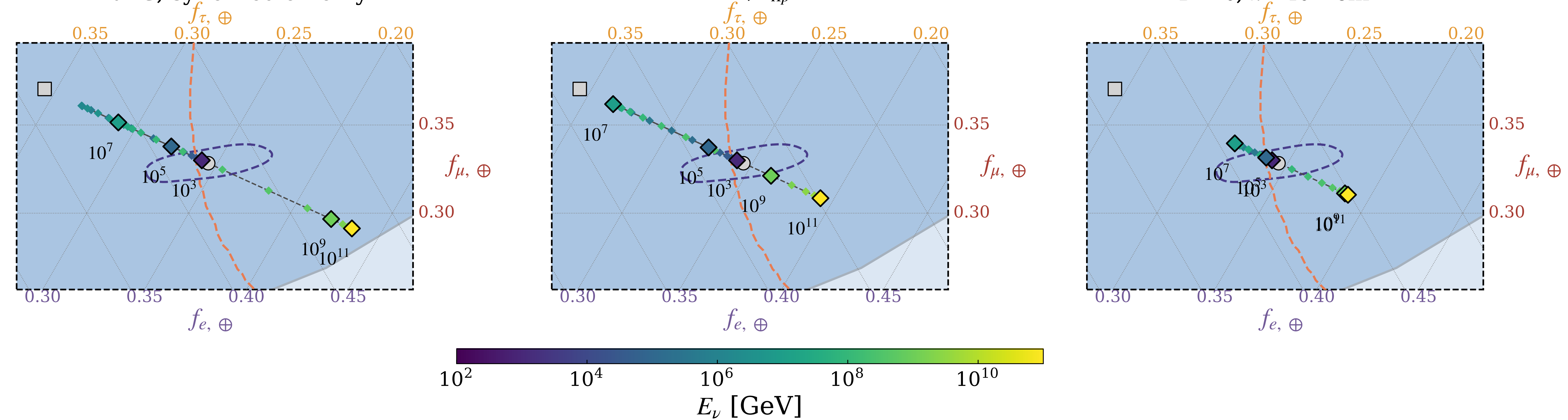


Energy-dependent Flavor Composition Measurements

$B = 10^4$ G, synchrotron only

$B = 10^4$ G, $\tau_{Kp} = 10^4$

$B \rightarrow 0$, $n = 10^{16}$ cm $^{-3}$



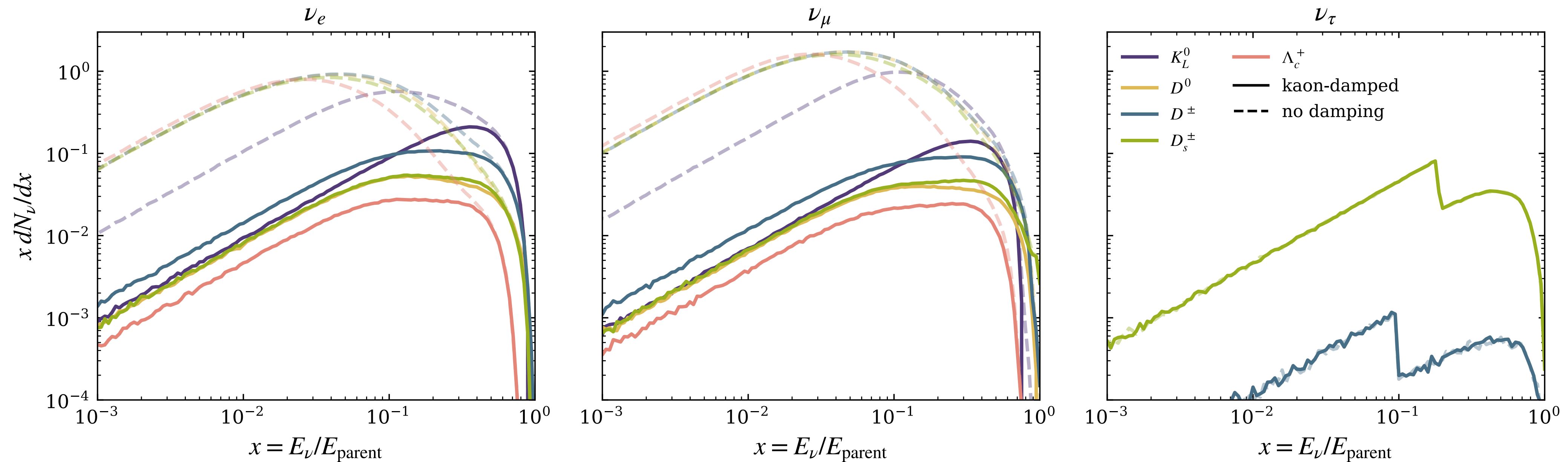
Summary

- The flavor composition of astrophysical neutrinos encodes important information about their **sources**.
- Neutrinos are expected to be produced with an **energy-dependent** flavor composition due to the presence of magnetic fields and environments in sources.
- In addition to the transition from pion decay to muon-damped pion decay, there could be another transition to the **K_L^0 -dominant** or **charmed-hadron-dominant** region at higher energies, predicting a different flavor composition but close to each other.
- We study features of energy-dependent transitions. **K_L^0** production and its neutrino generation are **more efficient** than **charmed hadrons**. **K_L^0** dominates if the source is **hadron-thin**, while **charmed hadrons dominate** if the source is **hadron-thick**. In a weak field, all damping is hadronic and a high-energy rise in ν_e points to charm.
- **Future neutrino telescopes** across high energies and ultra-high energies may enable us to **identify flavor transitions**. Combining the measurements will make it possible to **pin down source environments**.

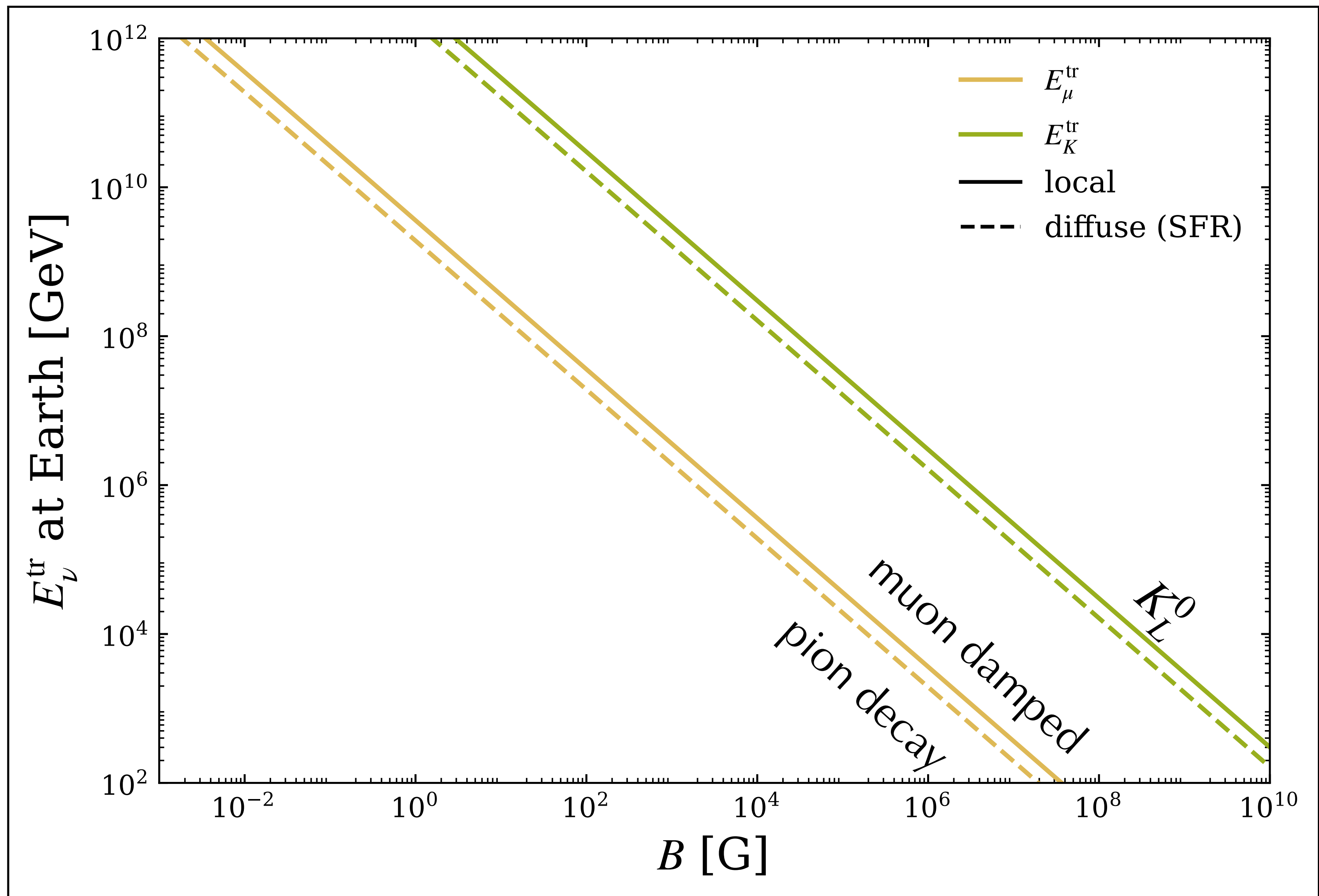
Bonus Slides

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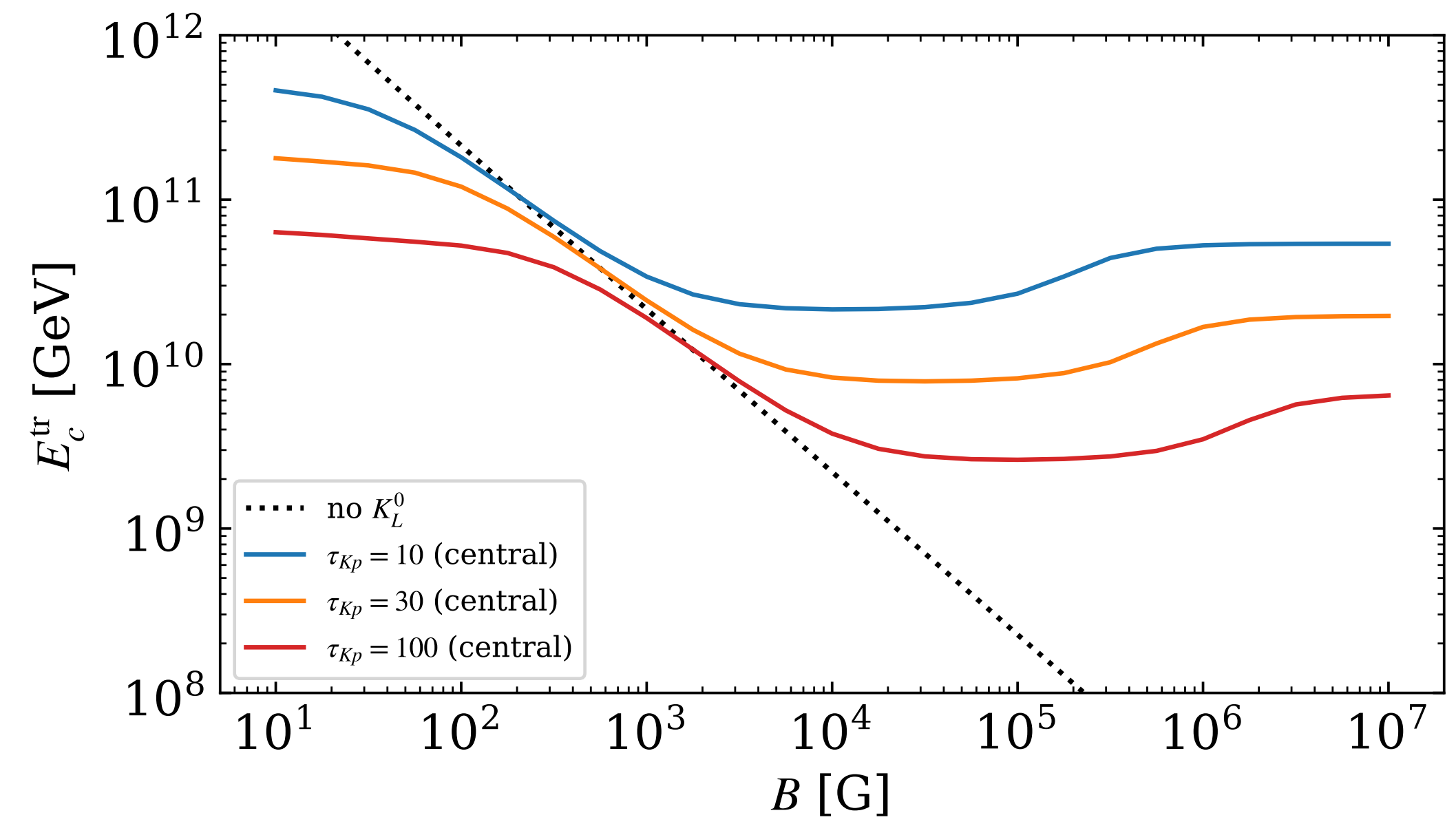
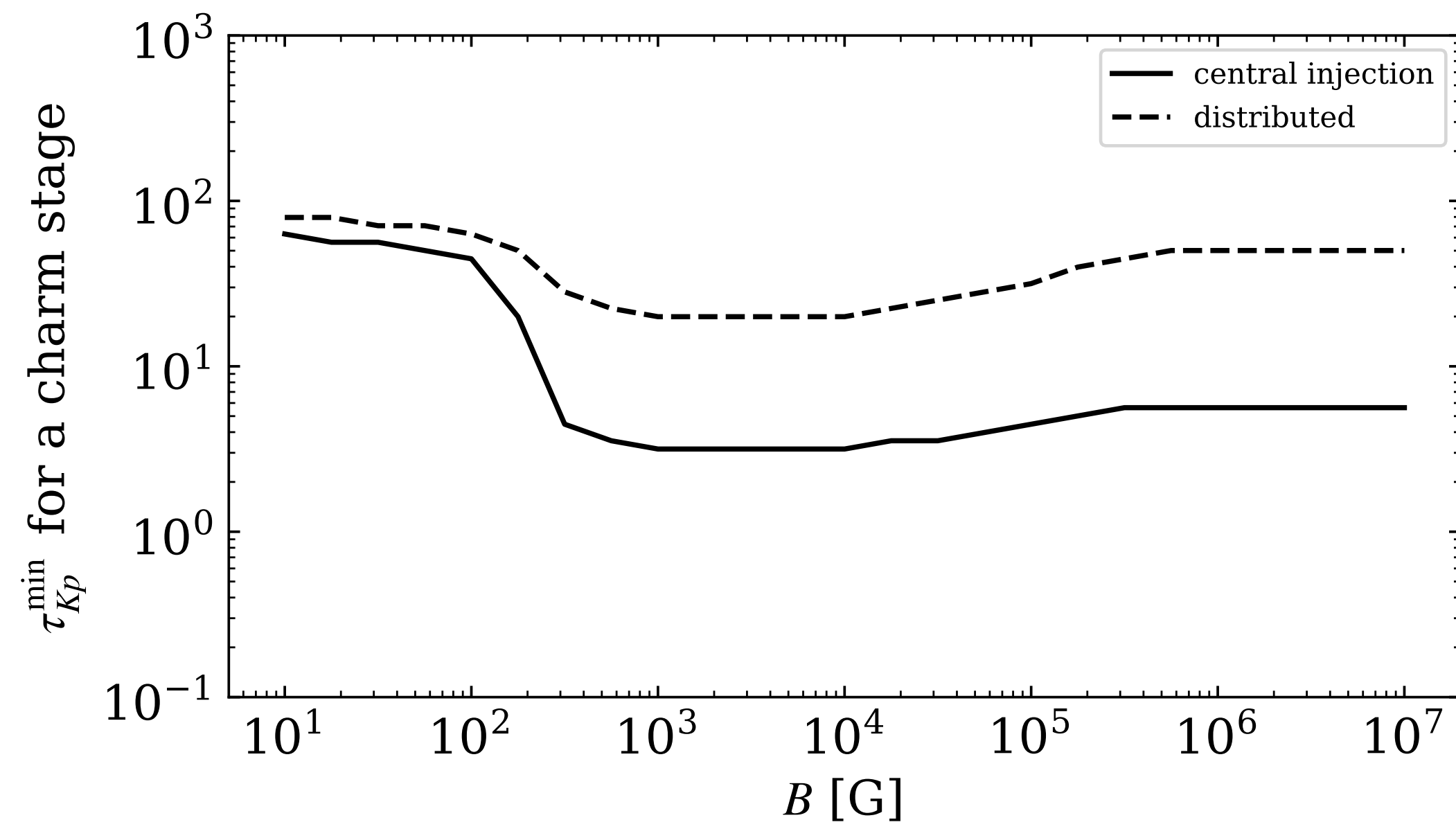


Transitions over B

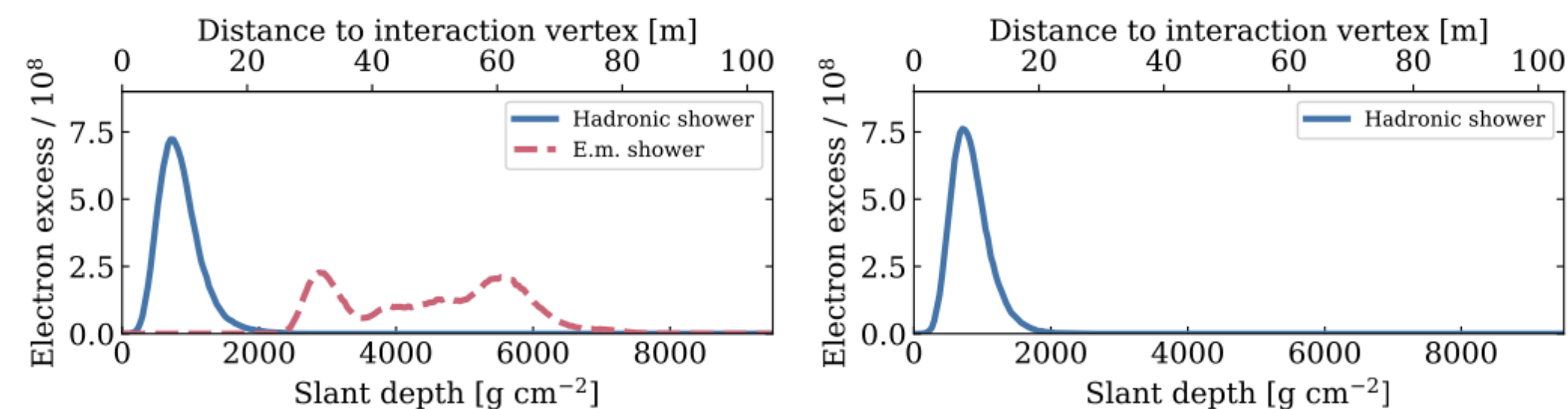
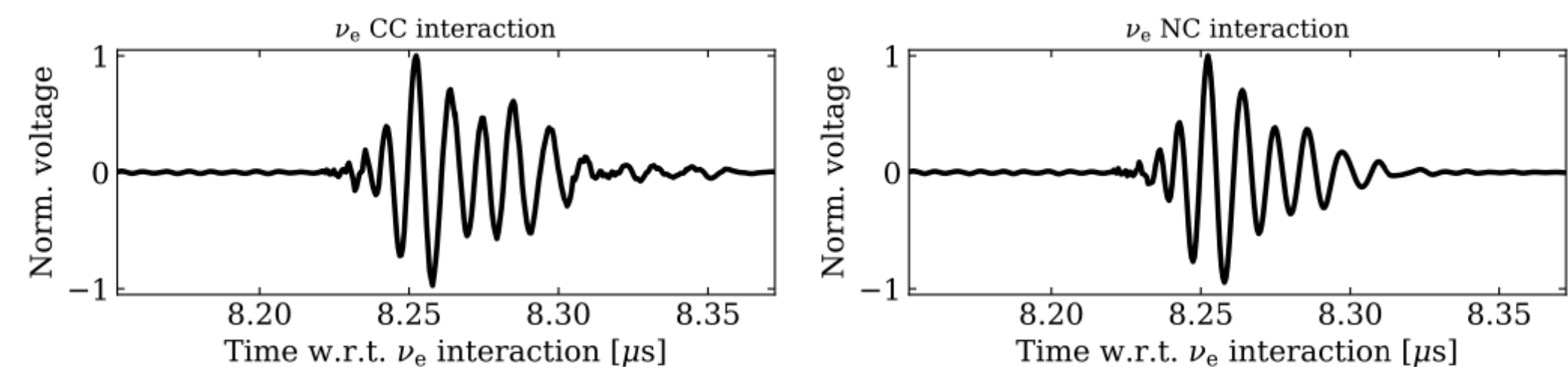
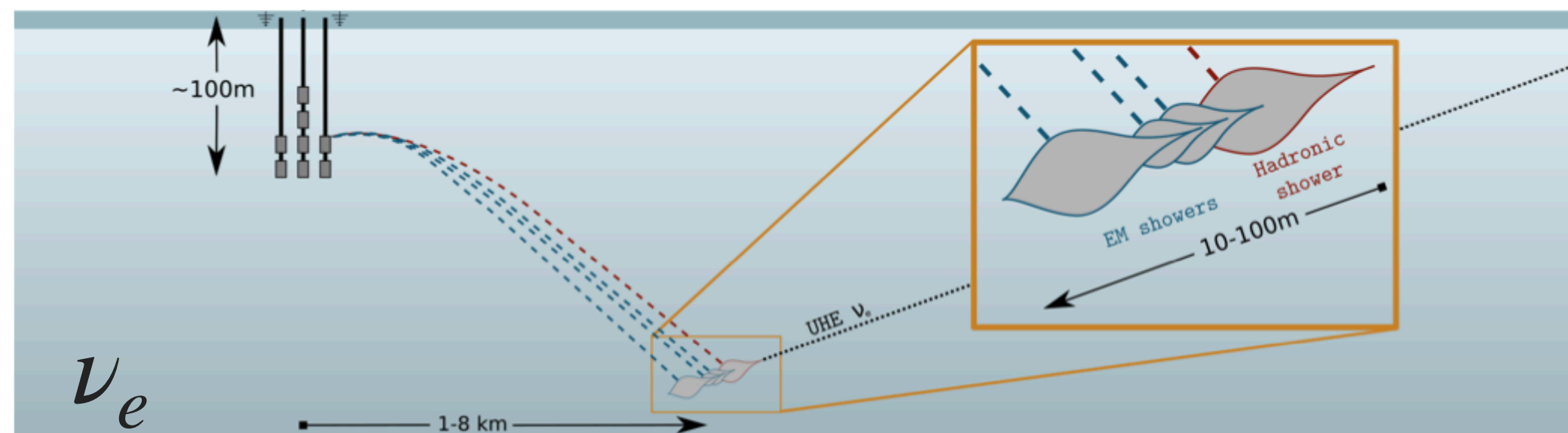
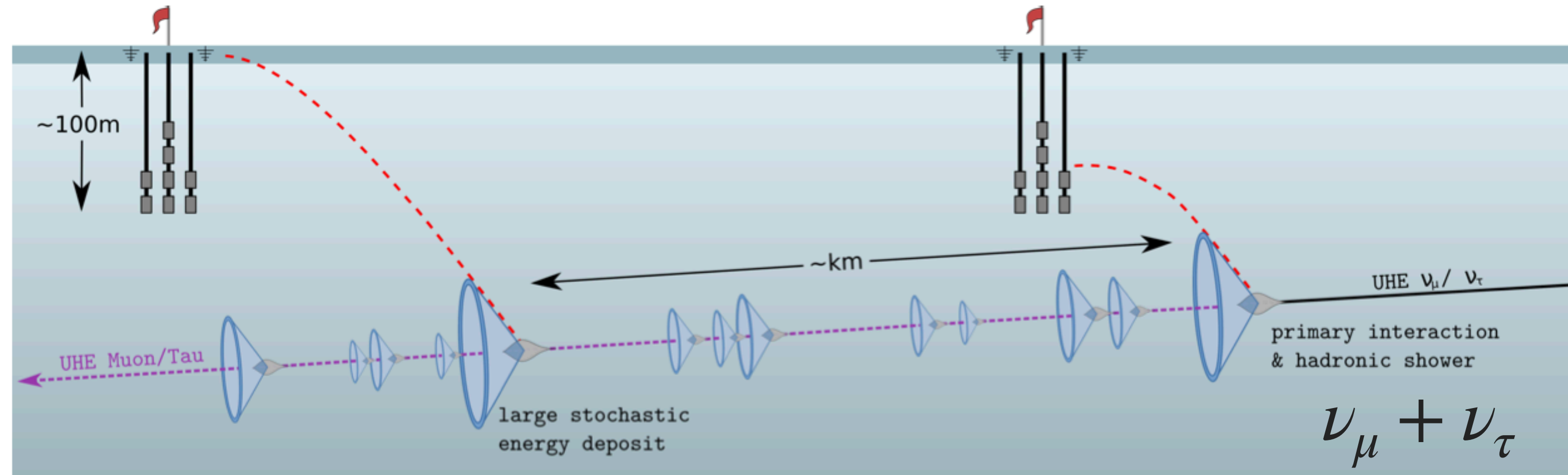


The Optical Depth Needed for a Charm Stage

$$R = 10^{14} \text{ cm}$$



Flavor Composition Measurement at Ultra-High-Energies



Landau-Pomeranchuk-Migdal (LPM) effect
elongated showers

