Extremely High Energy Cosmic Neutrinos and Relic Neutrinos

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Fermilab & CERN

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I Neutrino Observatories: Expectations

Cosmic ν flux may exceed atmospheric background at $E_\nu \approx$ few TeV

prospect for sources · characterize sources · study ν properties

Sources include AGN (at $\sim 10^2$ Mpc) $\quad$ 1 Mpc $\approx 3.1 \times 10^{22}$ m

pp or $p\gamma \Rightarrow\ \approx$ numbers of $\pi^+\ \pi^0\ \pi^-$

$$\pi^+ + \pi^0 + \pi^- \Rightarrow 2\gamma + 2\nu_\mu + 2\bar{\nu}_\mu + 1\nu_e + 1\bar{\nu}_e$$

$$\boxed{\Phi^0_{\rm std} = \{\varphi^0_e = \tfrac{1}{3}, \varphi^0_\mu = \tfrac{2}{3}, \varphi^0_\tau = 0\} \quad (\nu = \bar{\nu})}$$

Detection (in volumes $\to 1$ km^3)

$$\boxed{(\nu_\mu, \bar{\nu}_\mu)N \to (\mu^-, \mu^+) + \text{anything}}$$

Can we achieve efficient, calibrated $(\nu_e, \bar{\nu}_e)$ detection?

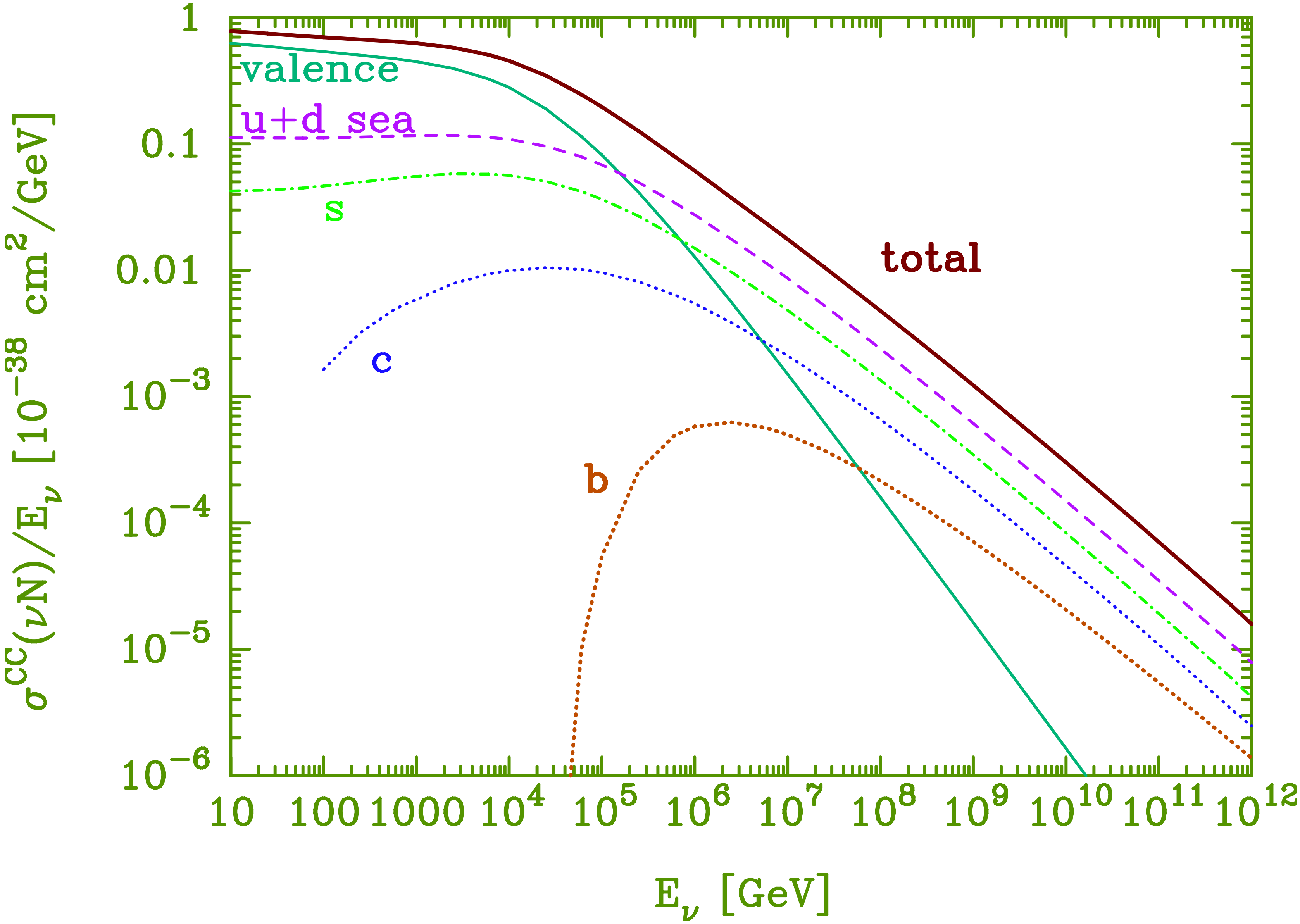
Good $(\nu_\tau, \bar{\nu}_\tau)$ detection, NC capability desirable

$\nu_\mu N \to \mu^- +$ anything

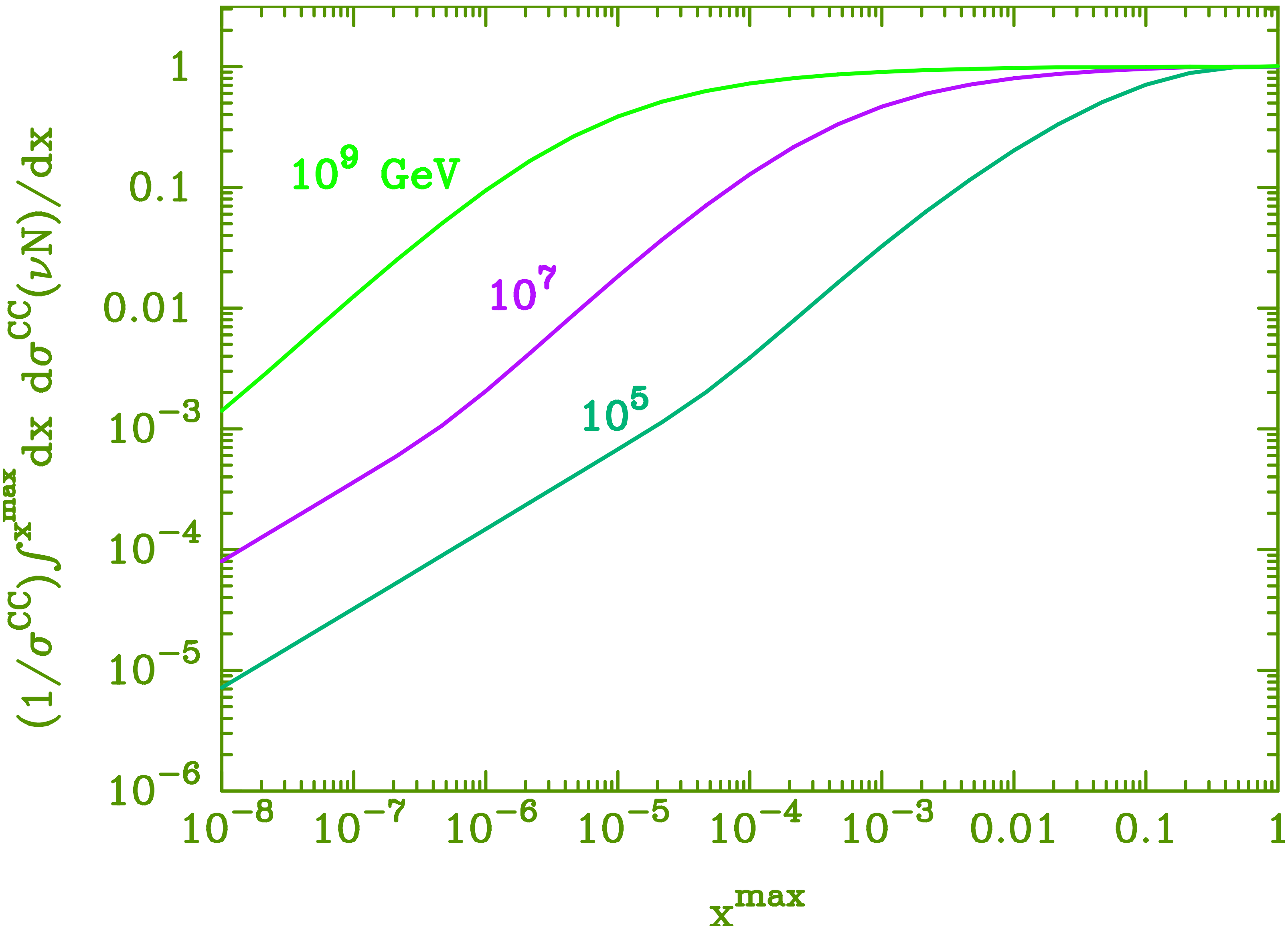
$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2\right]$$

$$\begin{aligned} q(x,Q^2) &= \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} \\ &\quad + s_s(x,Q^2) + b_s(x,Q^2) \\ \bar{q}(x,Q^2) &= \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + c_s(x,Q^2) + t_s(x,Q^2), \end{aligned}$$

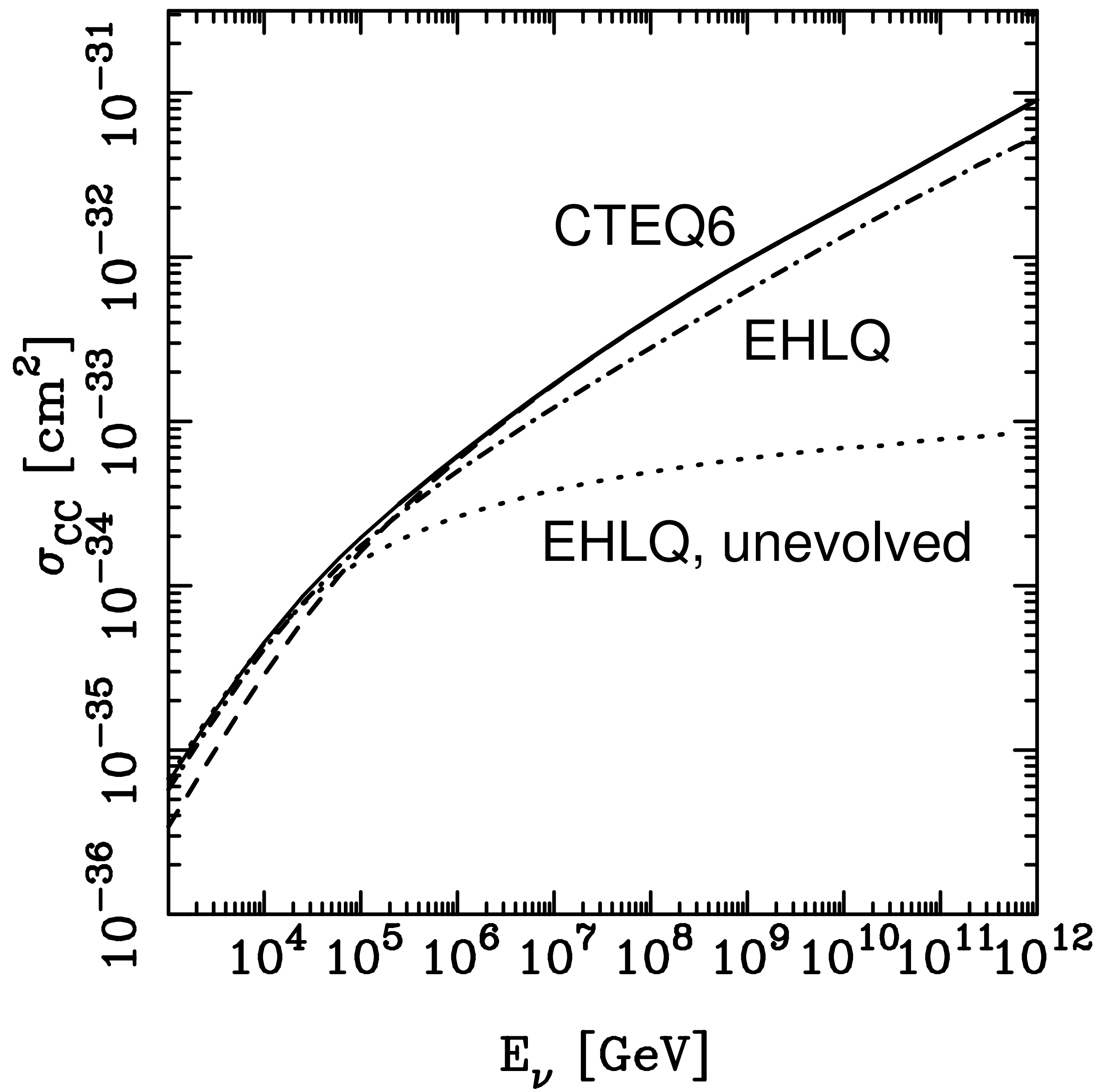
. . . isoscalar nucleon



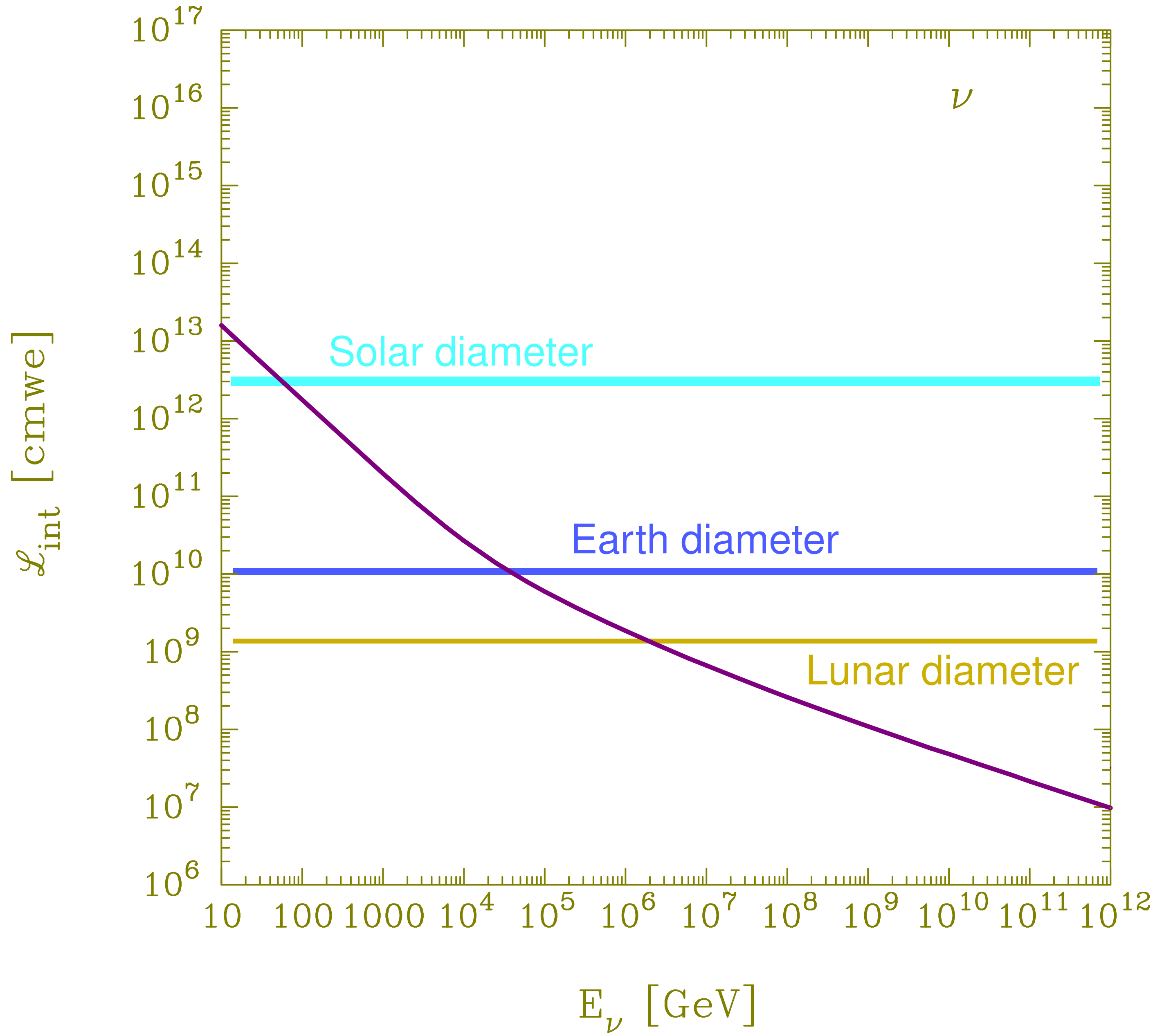
valence
u+d sea
s
c
b
total
$\sigma^{CC}(\nu N)/E_\nu$ [10^{-38} cm^2/GeV]
E_ν [GeV]
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}



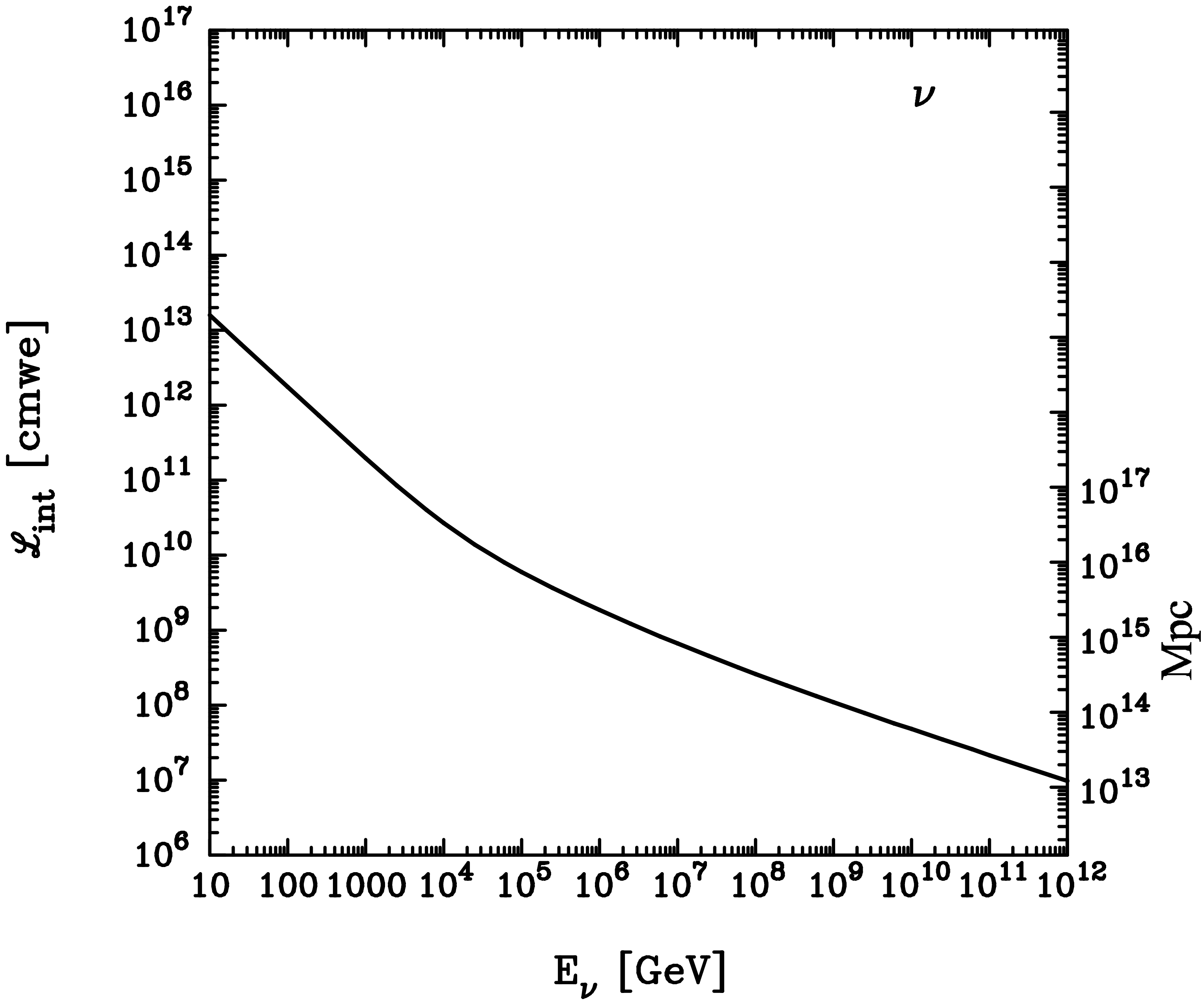
$(1/\sigma^{CC})\int^{x^{max}} dx\, d\sigma^{CC}(\nu N)/dx$
x^{max}
10^9 GeV
10^7
10^5
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1


CTEQ6
EHLQ
EHLQ, unevolved
σ_{CC} [cm^2]
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
E_ν [GeV]

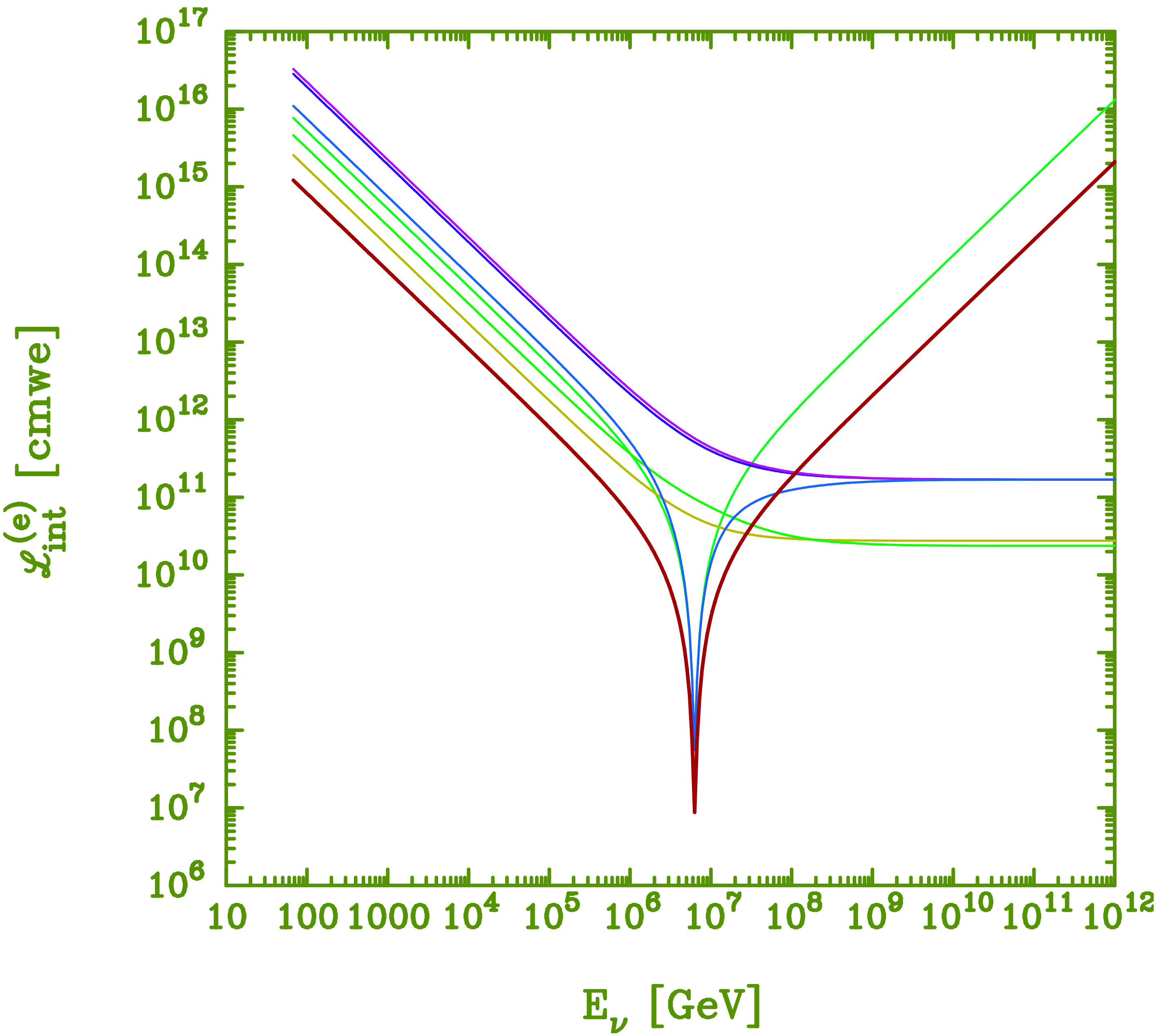
M. H. Reno



ν
Solar diameter
Earth diameter
Lunar diameter
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
$\mathscr{L}_{\mathrm{int}}$ [cmwe]
10 100 1000 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}
E_{ν} [GeV]



ν
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
$\mathscr{L}_{\text{int}}$ [cmwe]
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
Mpc
10 100 1000 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}
E_ν [GeV]



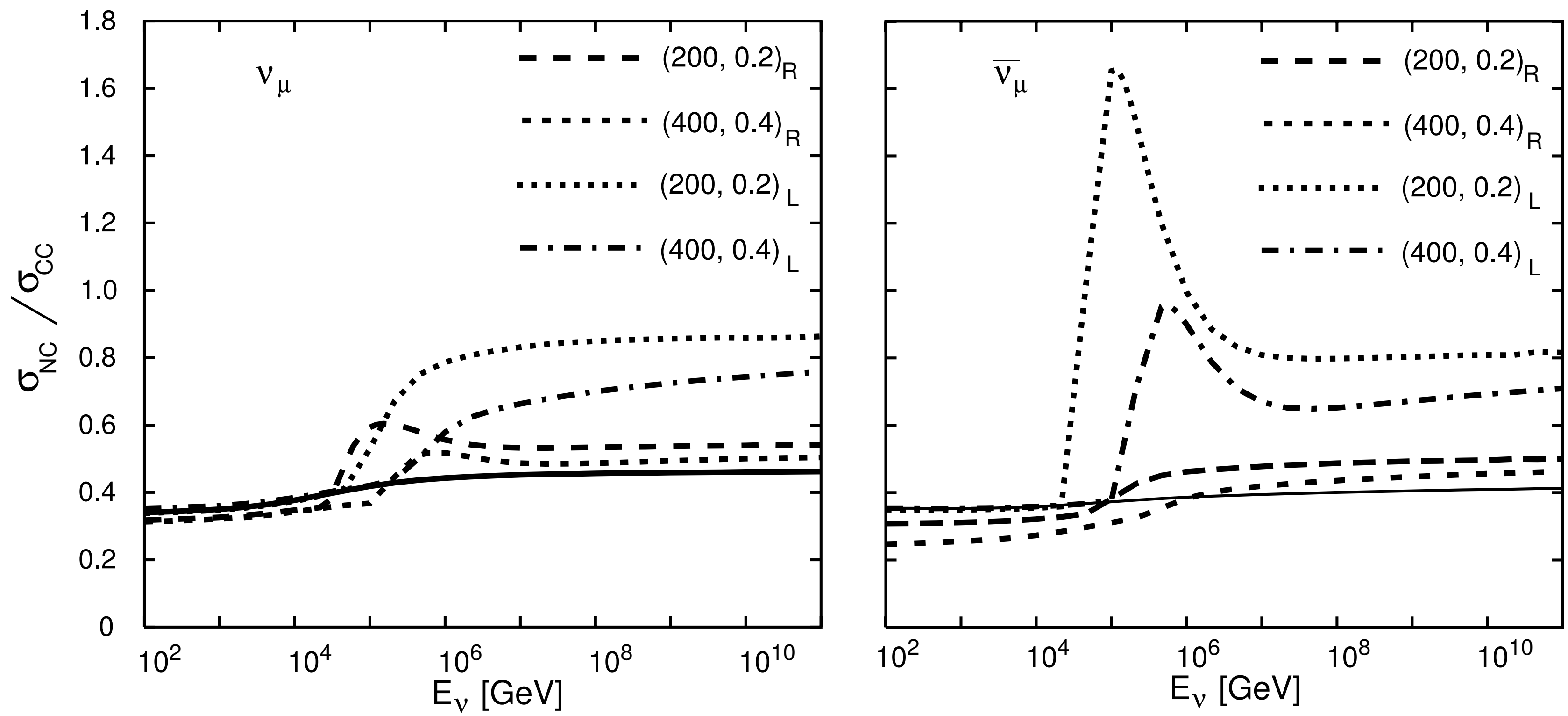
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
$\mathcal{L}_{\rm int}^{(e)}$ [cmwe]
10
100
1000
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
E_ν [GeV]

$(\nu, \bar{\nu})e$

II New Physics in νN interactions?

NC/CC an important diagnostic

$\tilde{d}^k_{\mathrm{L,R}}$ production through $\not{R}$ interactions:



$(\widetilde{m}, \lambda')$

III Influence of Neutrino Oscillations

Flux at Earth $\Phi = \{\varphi_e, \varphi_\mu, \varphi_\tau\} \neq \Phi^0 = \{\varphi_e^0, \varphi_\mu^0, \varphi_\tau^0\}$ source fluxes

Vacuum oscillation length is short; for $|\Delta m^2| = 10^{-5}$ eV^2,

$$L_{\mathrm{osc}} \;=\; 4\pi E_\nu/|\Delta m^2| \approx 2.5 \times 10^{-24}\ \mathrm{Mpc} \cdot (E_\nu/1\ \mathrm{eV})$$

. . . a fraction of Mpc even for $E_\nu = 10^{20}$ eV

ν oscillate many times between cosmic source and terrestrial detector

Also, over long paths, cosmic neutrinos are vulnerable to decay processes that would not affect terrestrial or solar experiments.

. . . Neutrino Oscillations

(flavor) $\nu_\alpha = \sum_i U_{\beta i} \nu_i$ (mass)

Idealize $\sin\theta_{13} = 0$, $\sin 2\theta_{23} = 1$, write $x = \sin^2\theta_{12}\cos^2\theta_{12}$.

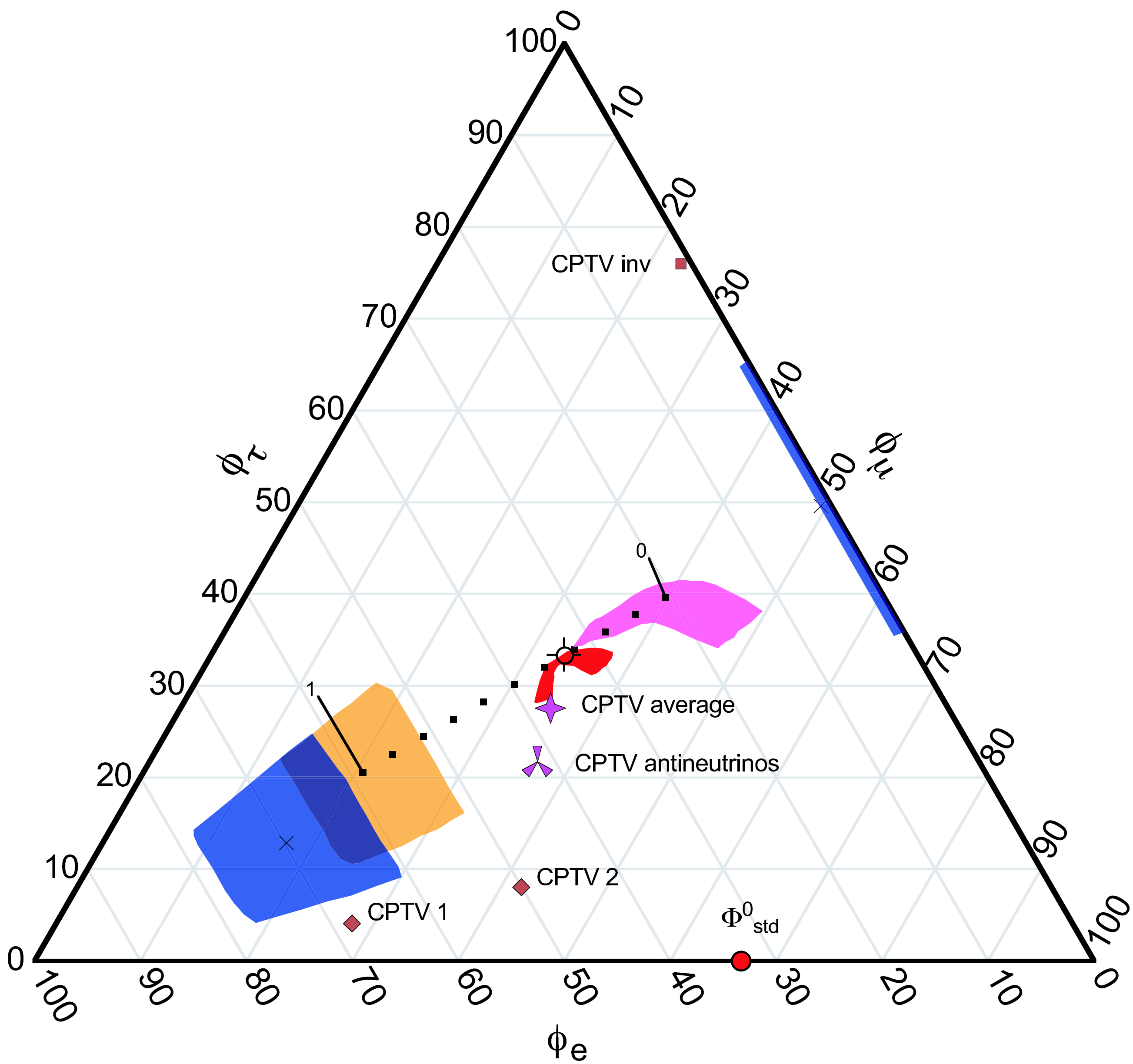
$$U_{\text{ideal}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

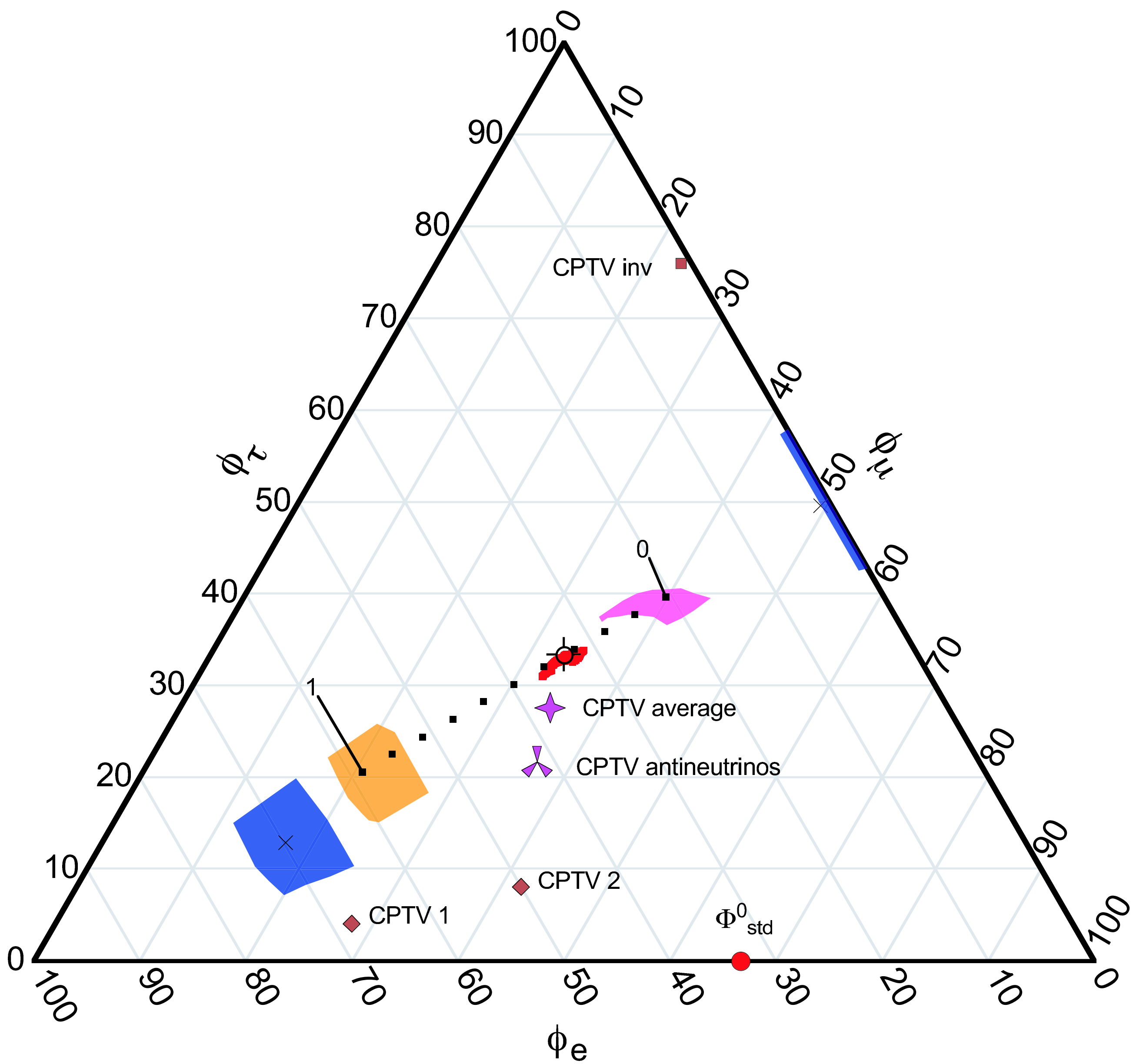
Transfer matrix $\mathcal{X}$: Φ^0 (source) $\rightarrow \Phi$ (detector); Over many oscillations,

$$\mathcal{X}_{\text{ideal}} = \begin{pmatrix} 1-2x & x & x \\ x & \frac{1}{2}(1-x) & \frac{1}{2}(1-x) \\ x & \frac{1}{2}(1-x) & \frac{1}{2}(1-x) \end{pmatrix}$$

Parke

$$\boxed{\mathcal{X}_{\text{ideal}} : \Phi^0_{\text{std}} \rightarrow \{\varphi_e = \tfrac{1}{3}, \varphi_\mu = \tfrac{1}{3}, \varphi_\tau = \tfrac{1}{3}\}}$$


CPTV inv
CPTV average
CPTV antineutrinos
CPTV 2
CPTV 1
Φ^0_{std}
ϕ_τ
ϕ_μ
ϕ_e
0
1

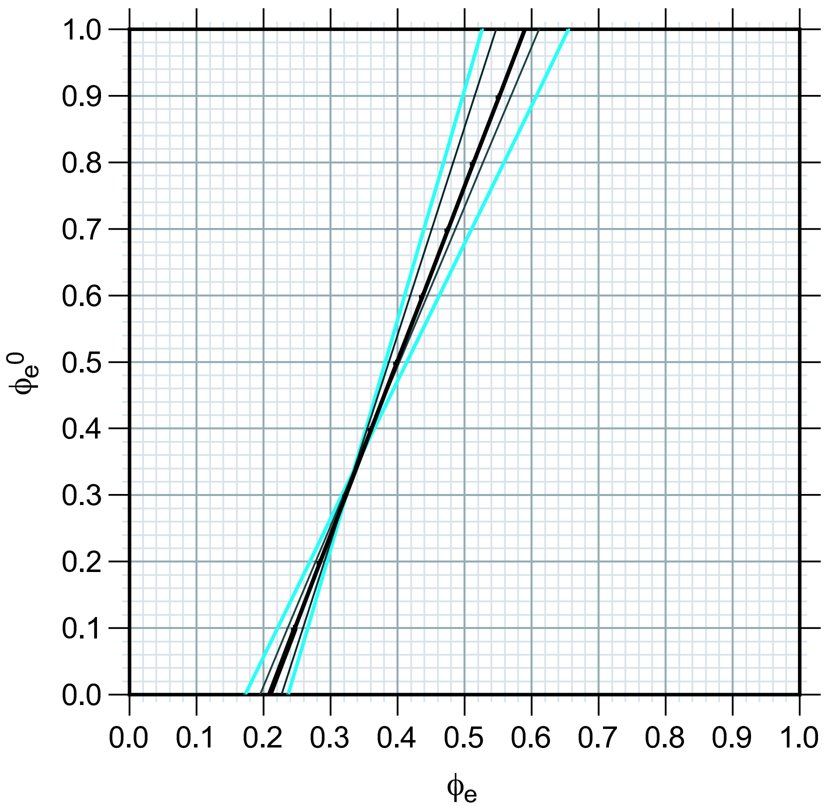


CPTV inv
CPTV average
CPTV antineutrinos
CPTV 2
CPTV 1
Φ^0_{std}
0
1
ϕ_τ
ϕ_μ
ϕ_e

IV Reconstructing the ν Mixture at the Source

ν_μ, ν_τ fully mixed $\Rightarrow$ can't fully characterize Φ^0

Reconstruct ν_e fraction at source using $\mathcal{X}_{\text{ideal}}$: $\varphi_e^0 = (\varphi_e - x)/(1 - 3x)$



Extreme φ_e implicates unconventional physics

V Influence of Neutrino Decays

Nonradiative decays $\nu_i \to (\nu_j, \bar{\nu}_j) + X$ not very constrained:

$\tau/m \gtrsim 10^{-4}$ s/eV

If only lightest neutrino survives, flavor mix at Earth is independent of composition at source

Normal hierarchy

$m_1 < m_2 < m_3$:

$\varphi_\alpha = |U_{\alpha 1}|^2$

$\Phi_{\text{normal}} \approx \{0.70, 0.17, 0.13\}$

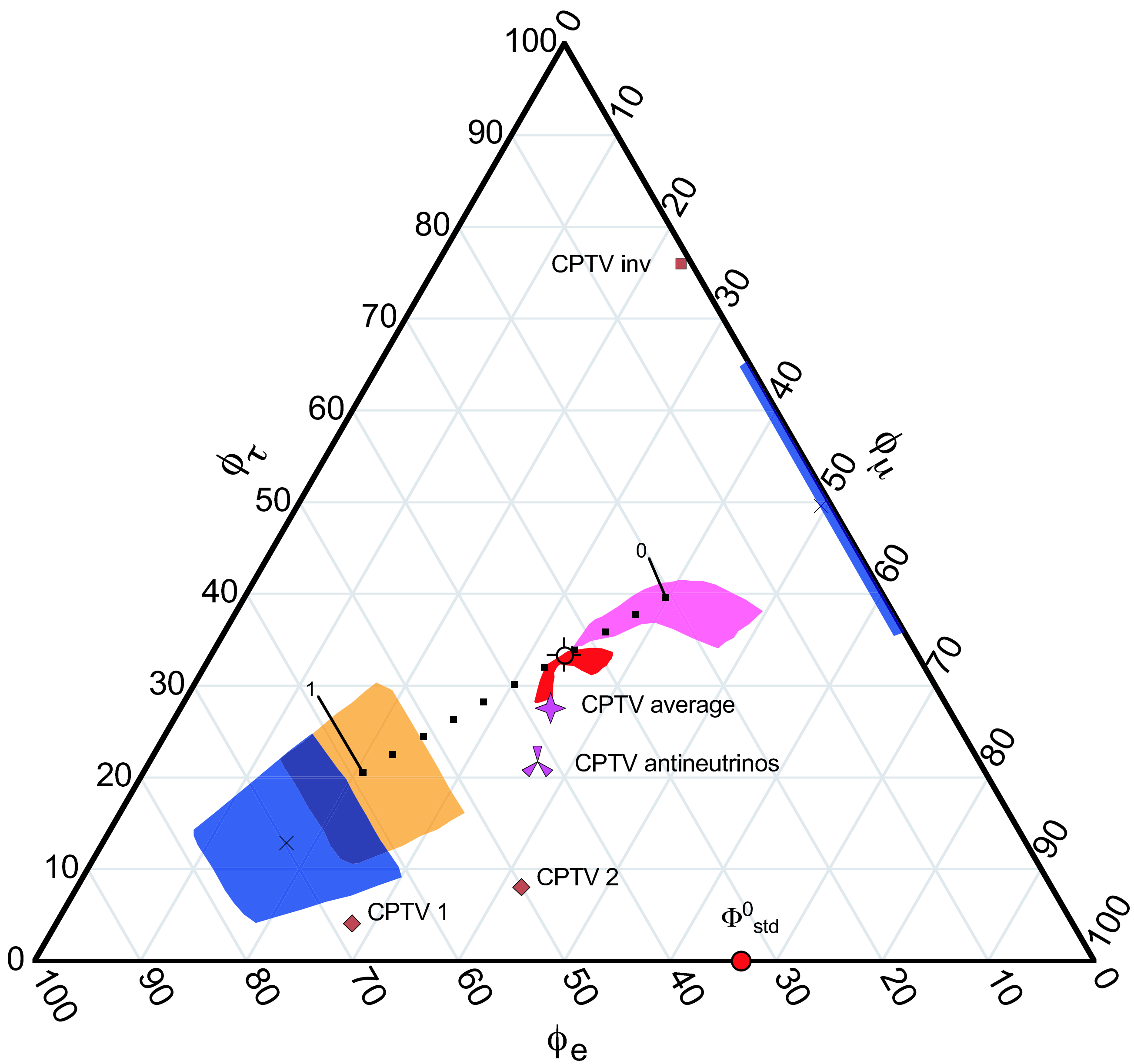
Inverted hierarchy

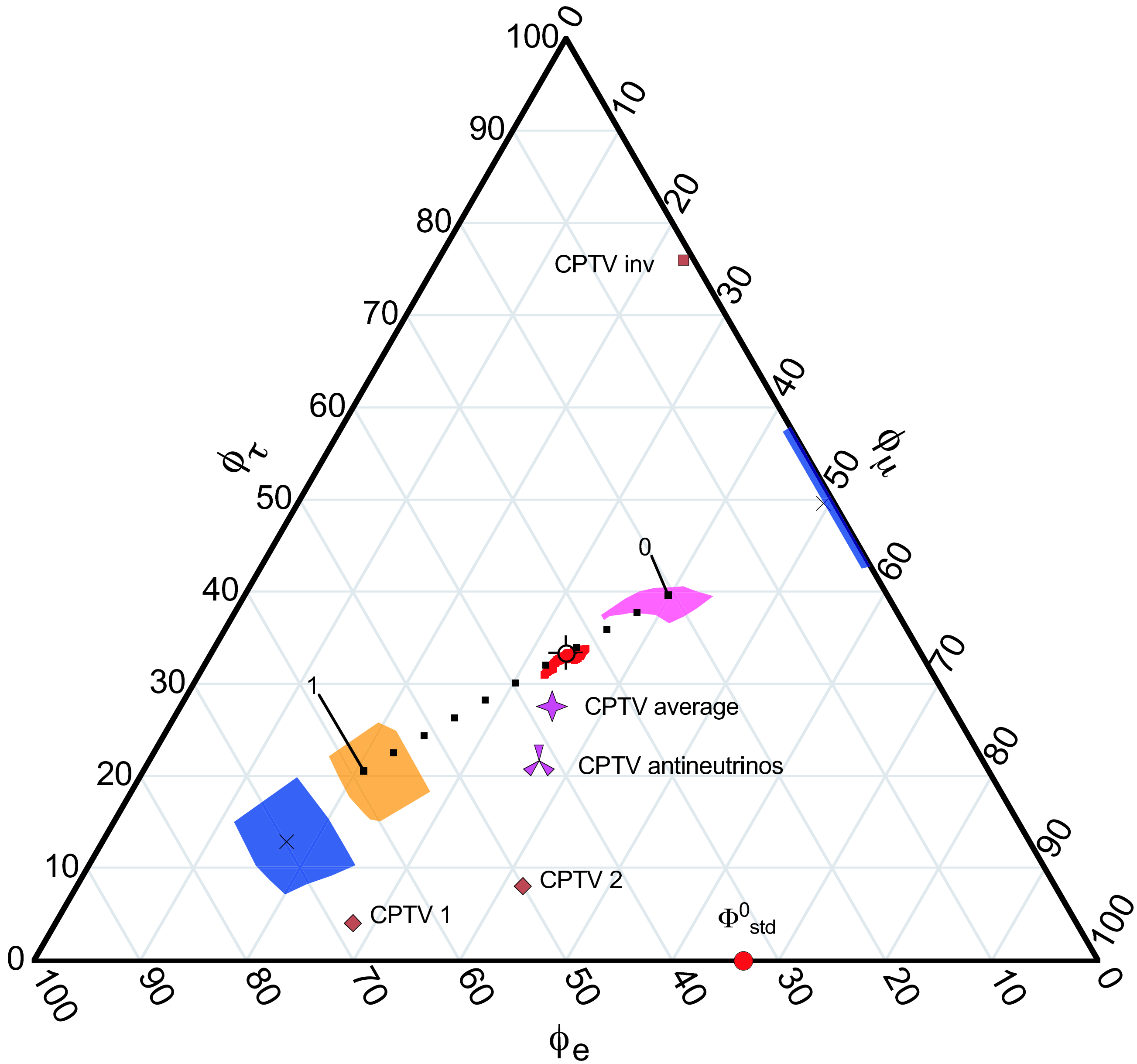
$m_1 > m_2 > m_3$:

$\varphi_\alpha = |U_{\alpha 3}|^2$

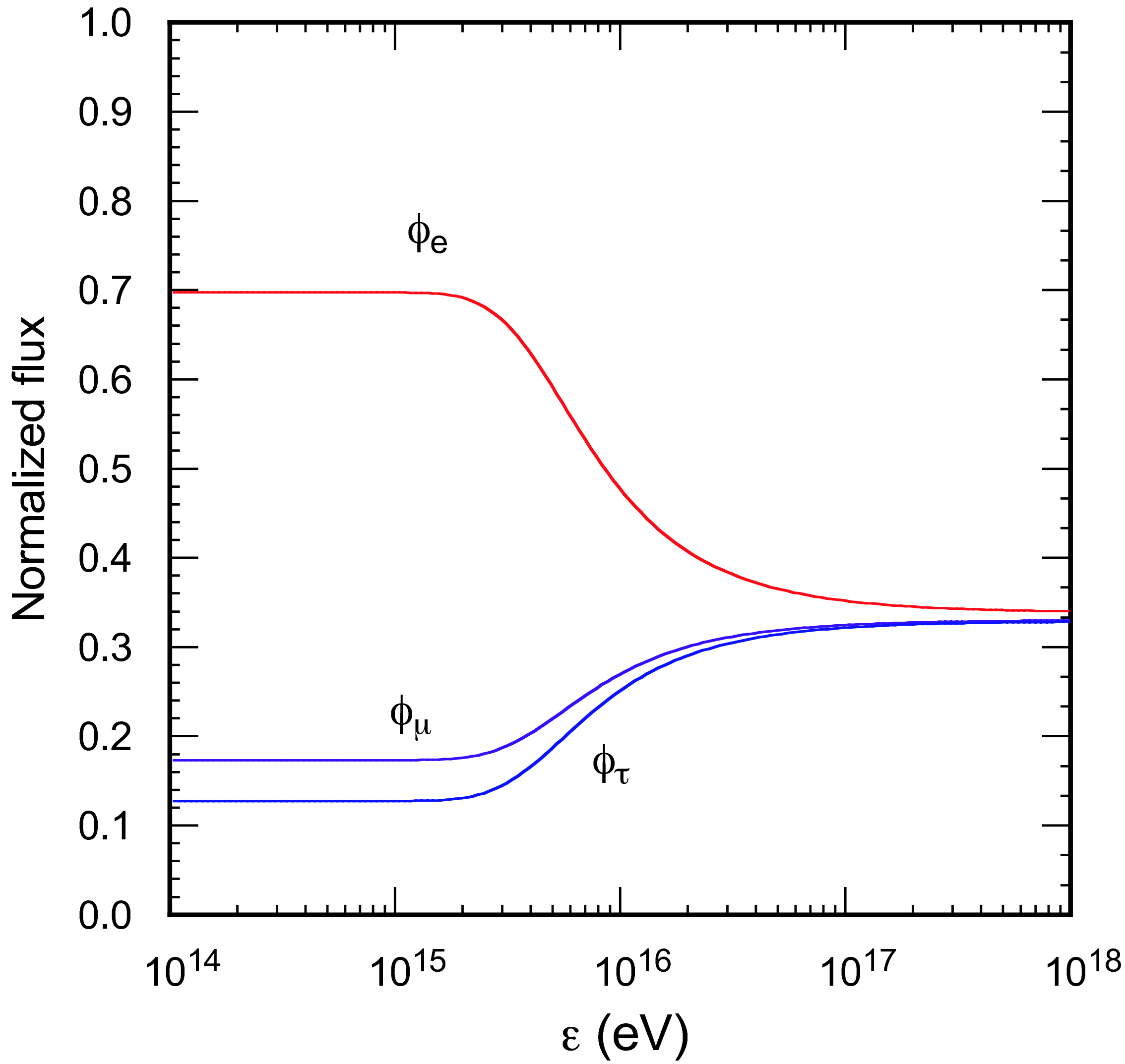
$\Phi_{\text{inverted}} \approx \{0, 0.5, 0.5\}$

far from $\Phi_{\text{std}} = \{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$


CPTV inv
CPTV average
CPTV antineutrinos
CPTV 2
CPTV 1
Φ^0_{std}
ϕ_τ
ϕ_μ
ϕ_e
0
1

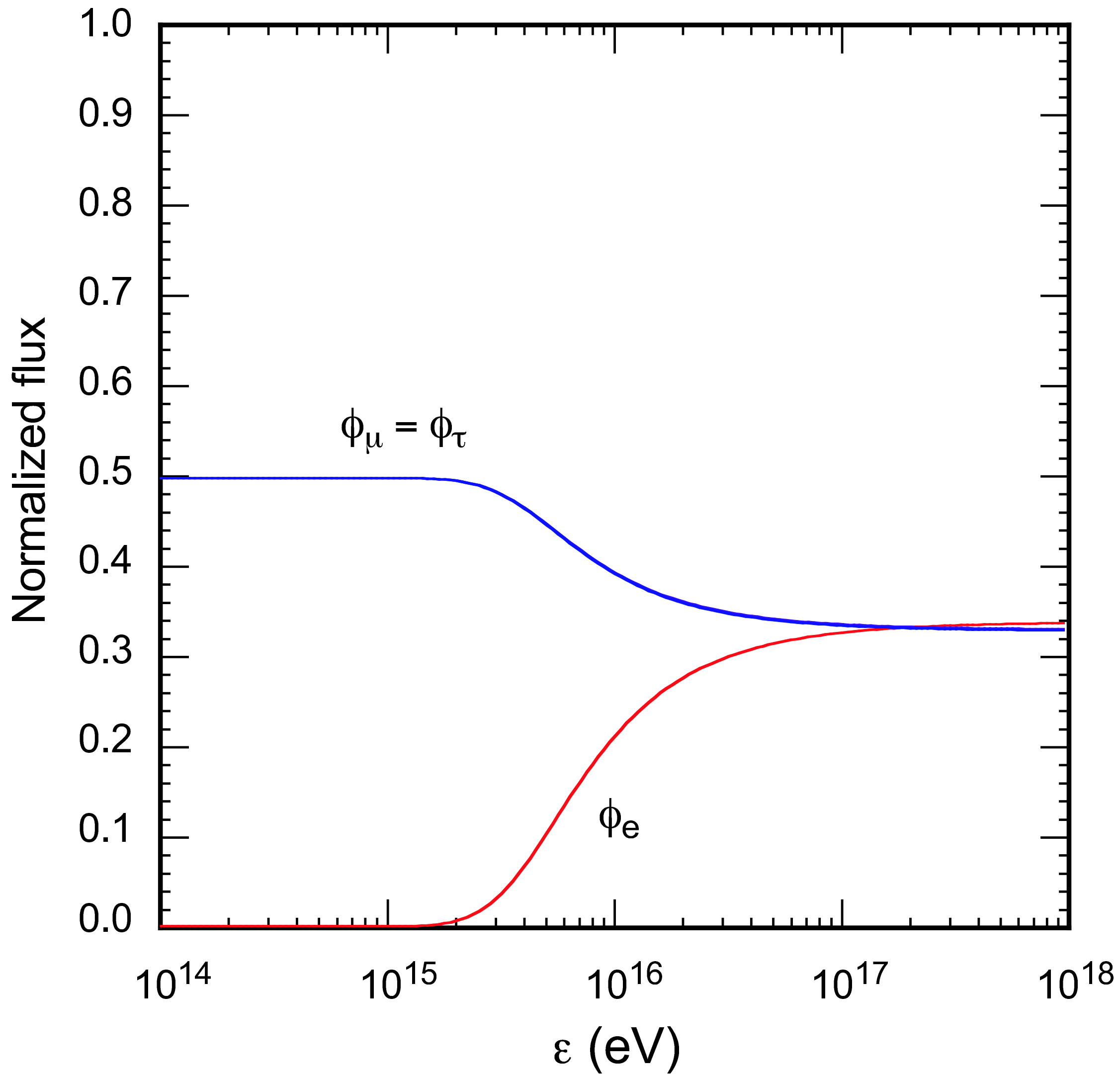


CPTV inv
0
CPTV average
CPTV antineutrinos
1
CPTV 2
CPTV 1
Φ^0_{std}
ϕ_τ
ϕ_μ
ϕ_e



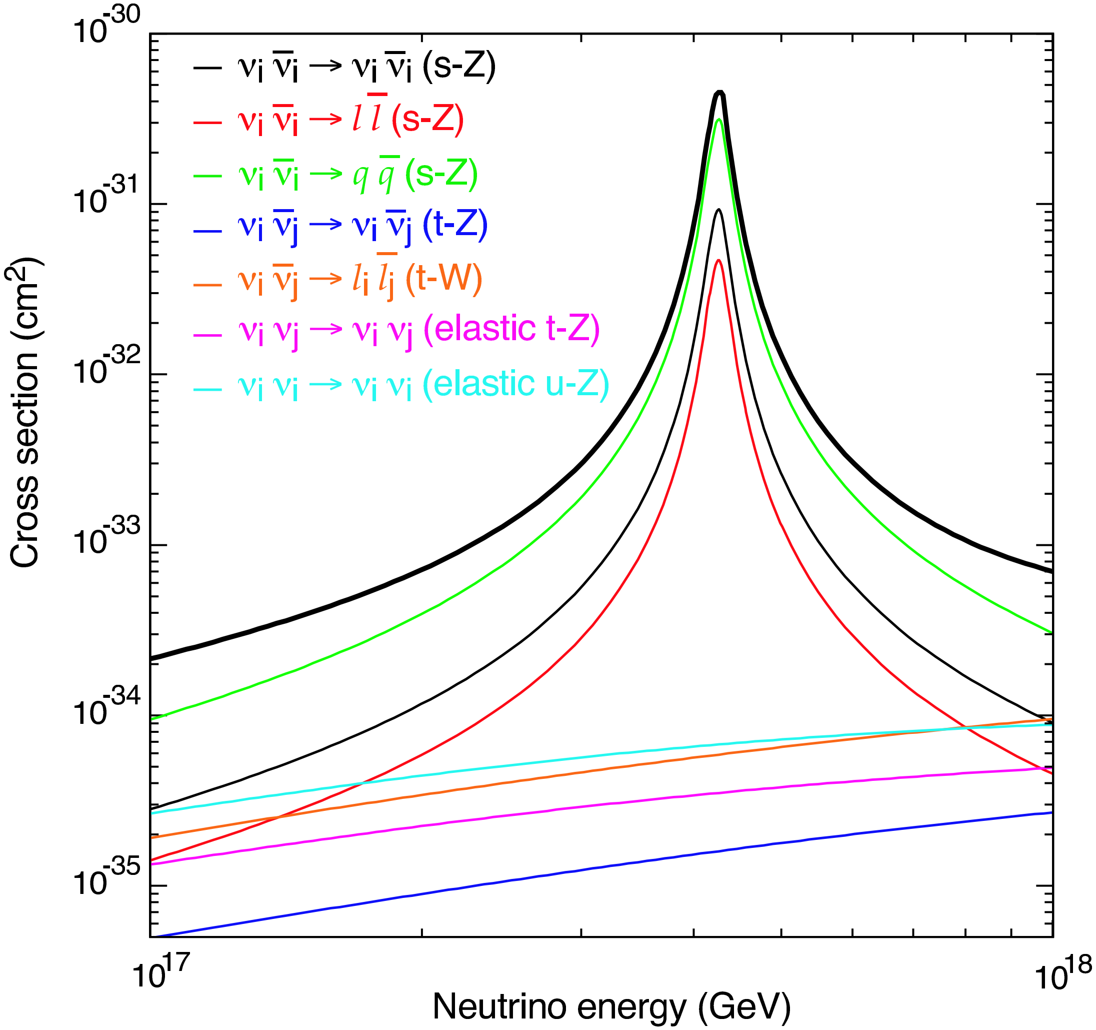
$E_\nu = \varepsilon(1\ \mathrm{s/eV})/(\tau_\nu/m_\nu) \cdot L/(100\ \mathrm{Mpc})$

Normal hierarchy



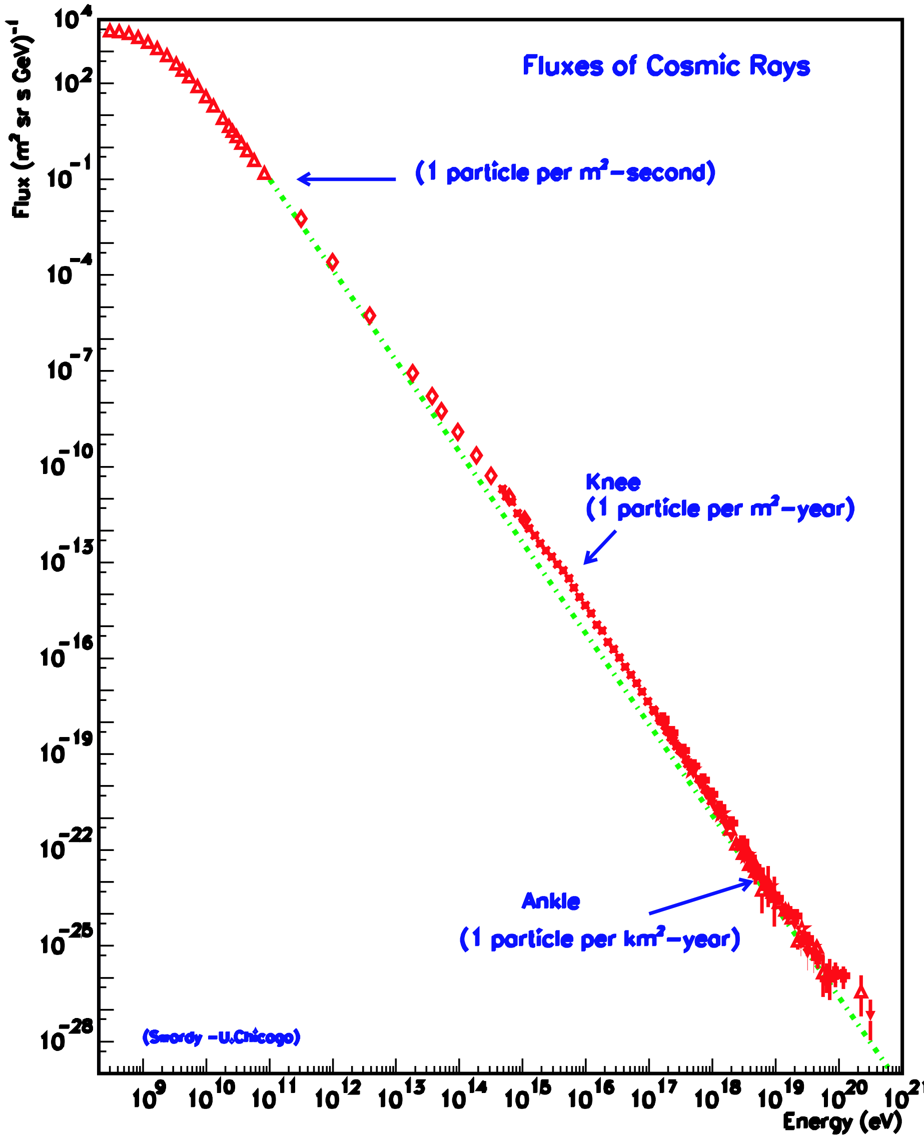
$E_\nu = \varepsilon(1\ \text{s/eV})/(\tau_\nu/m_\nu) \cdot L/(100\ \text{Mpc})$ Inverted hierarchy

VI UHE ν annihilation on ν relics

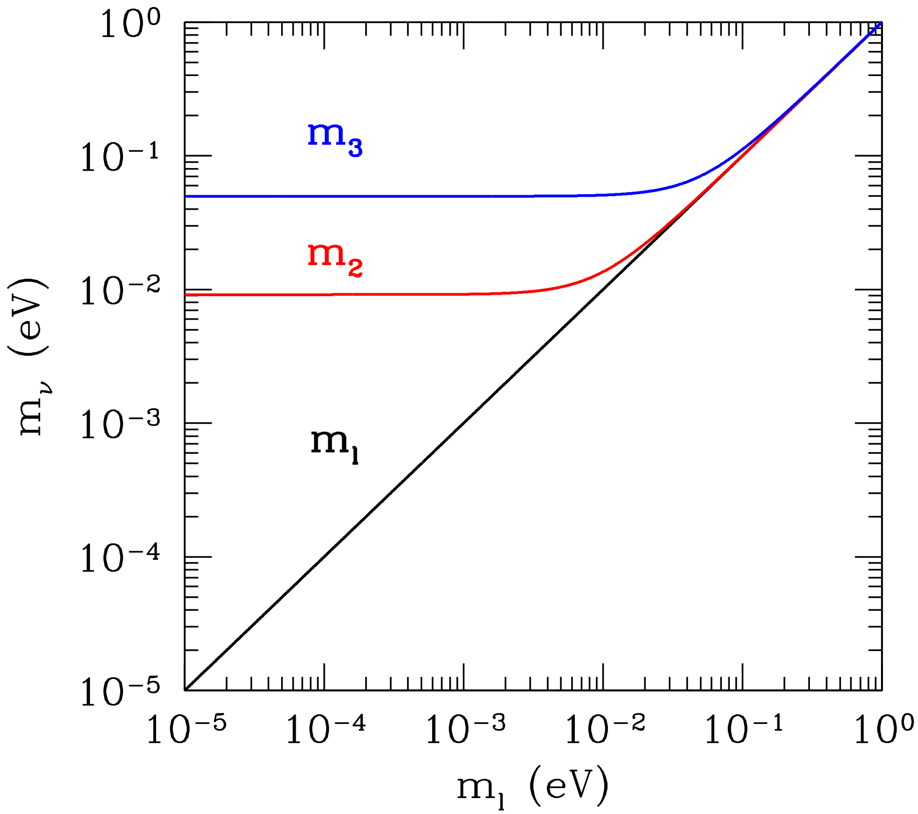


$m_\nu = 10^{-5}$ eV

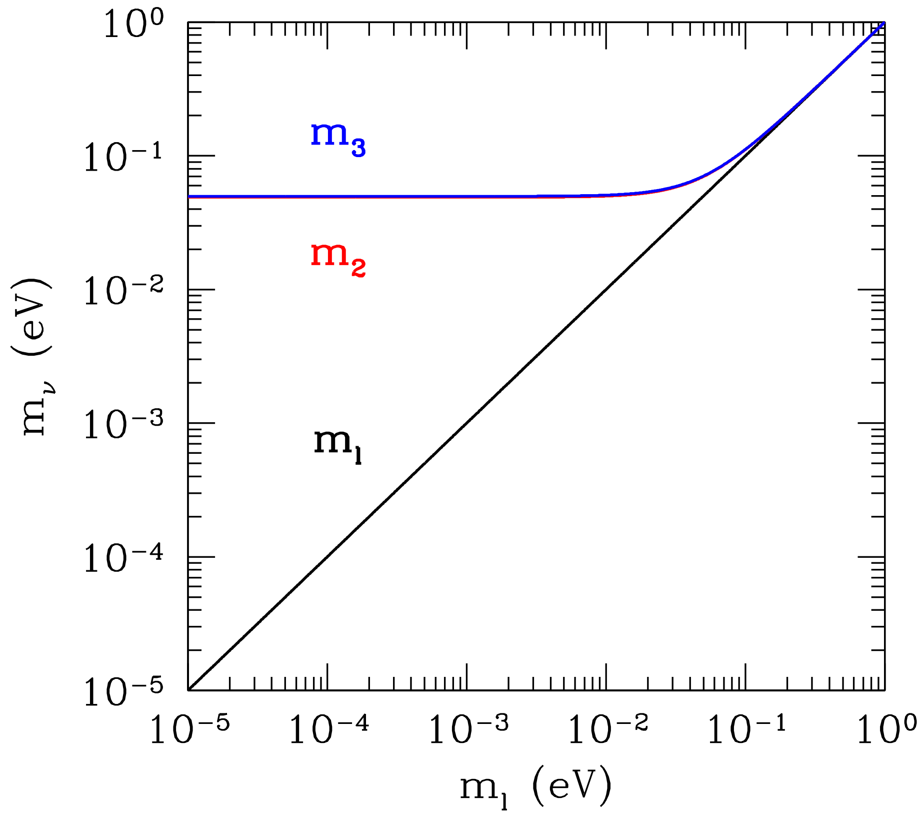
Pierre Auger Observatory should clarify trans-GZK regime soon



Normal hierarchy

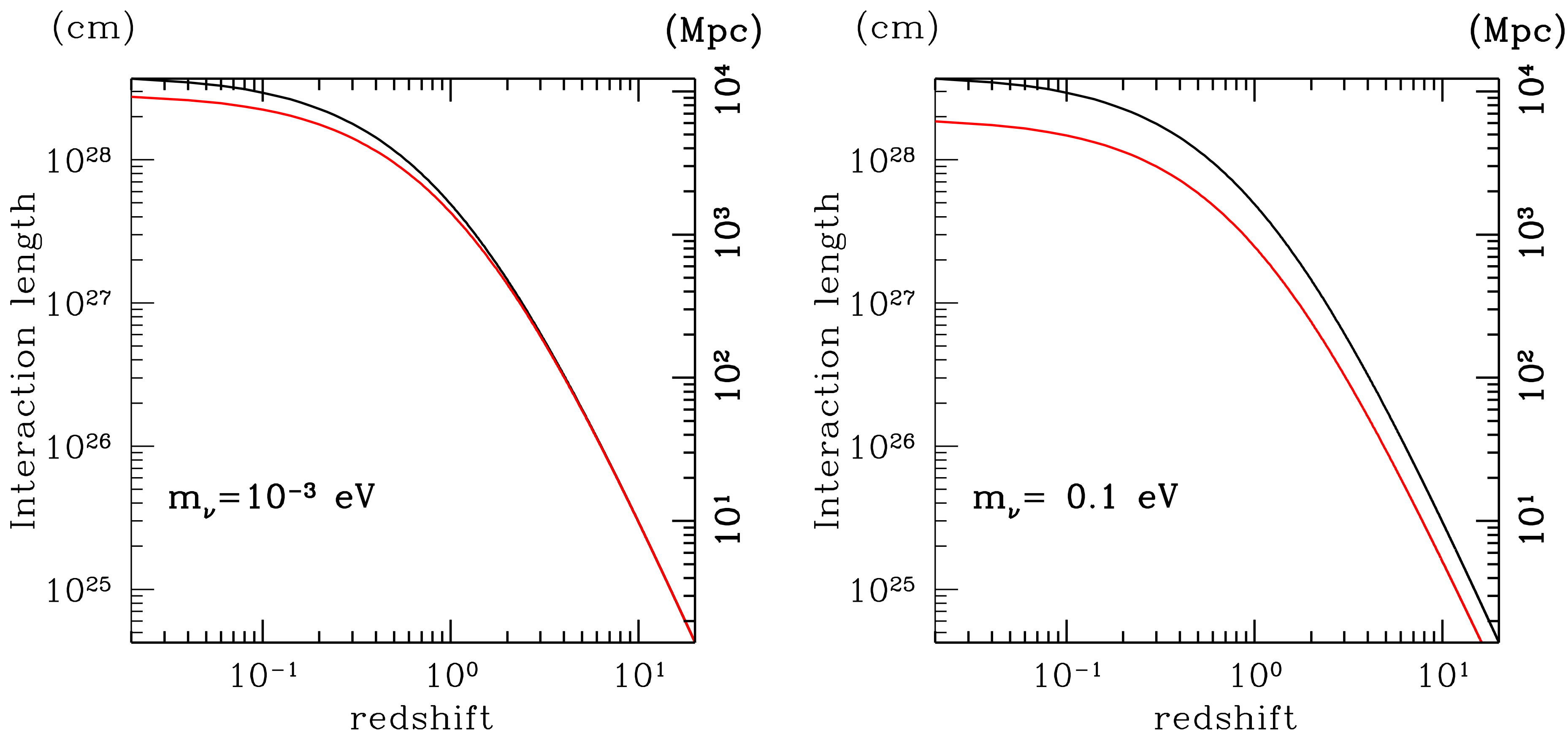


Inverted hierarchy



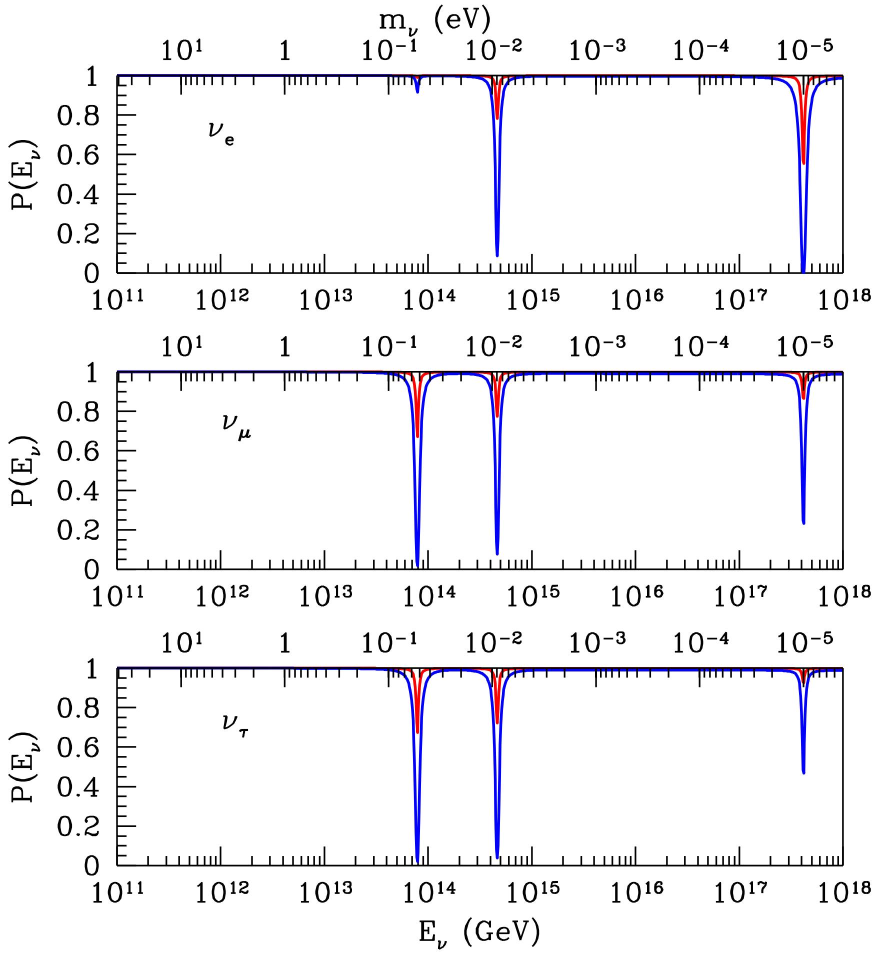
Animation

Interaction lengths on Z^0 resonance: Dirac Majorana

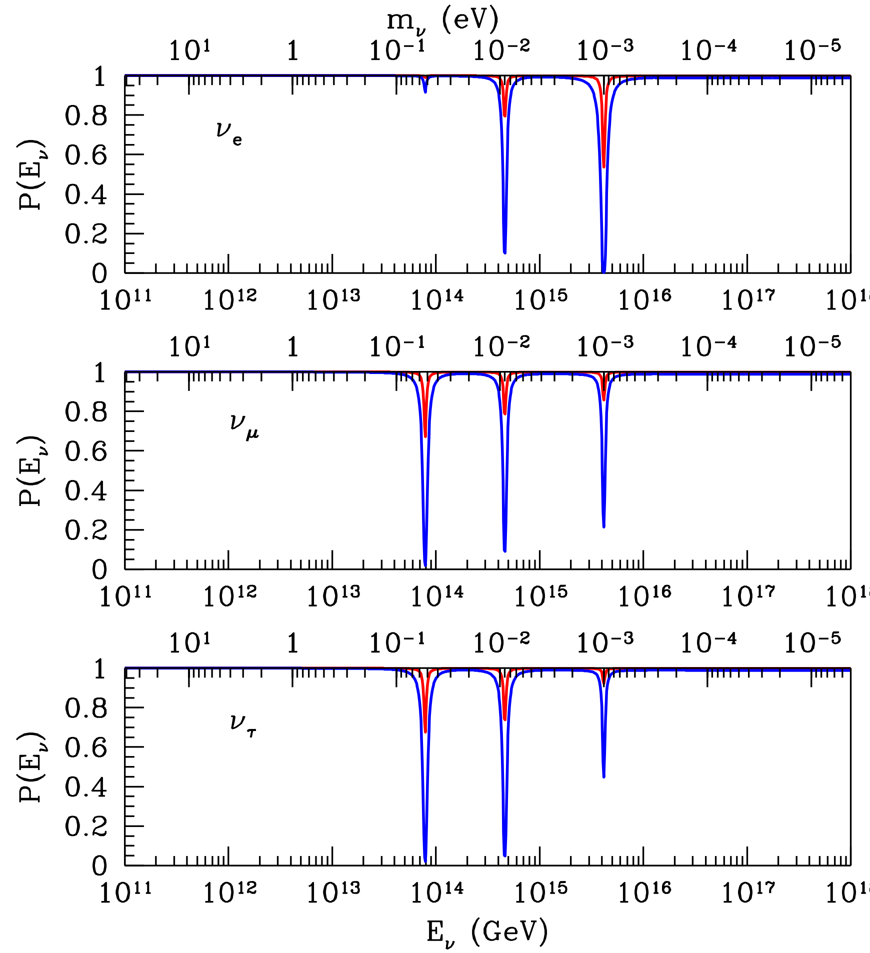


ν number density now: 56 cm^{-3}, $\propto (1+z)^3$

Fable: *l-o-o-o-o-n-g* path (10^4 or 10^5 Mpc) in current Universe

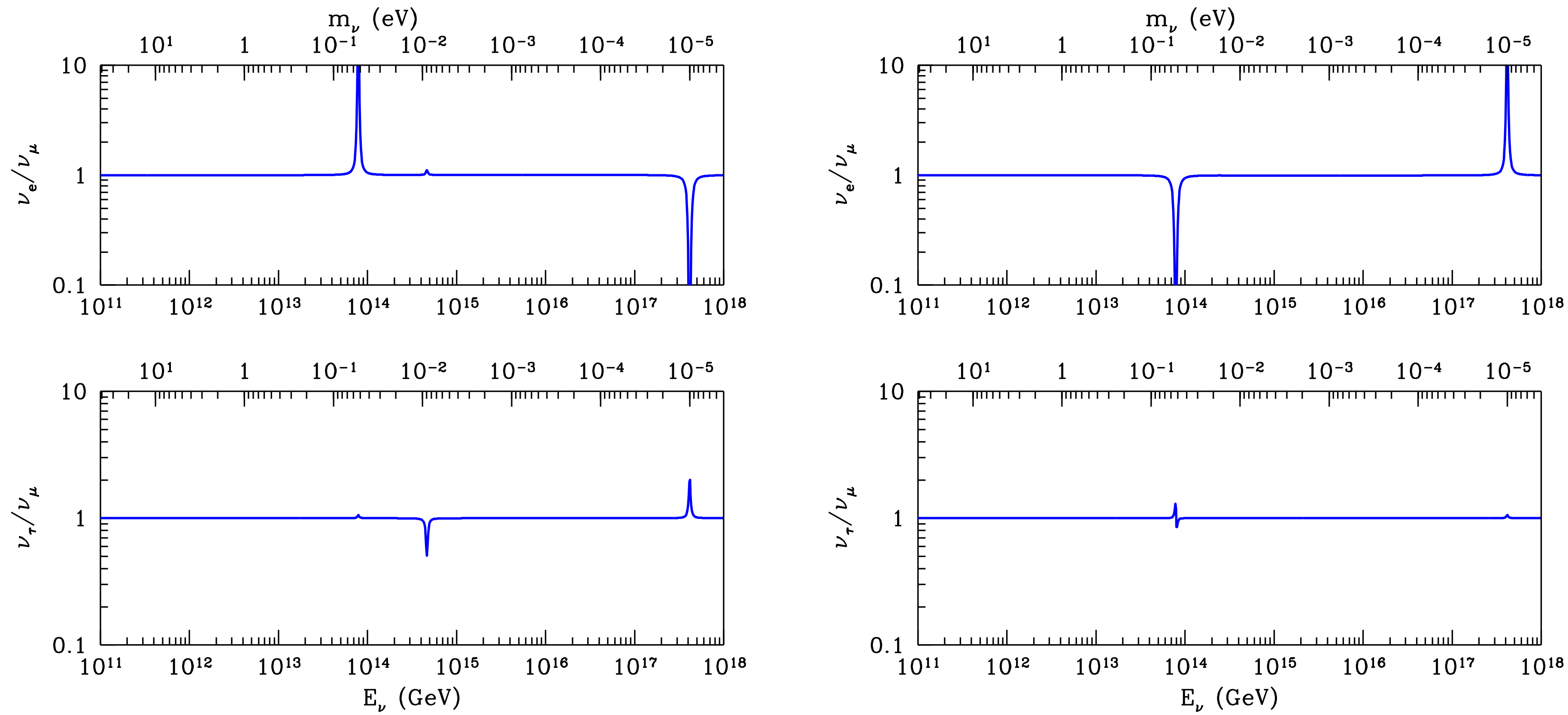


$m_\ell = 10^{-5}$ eV



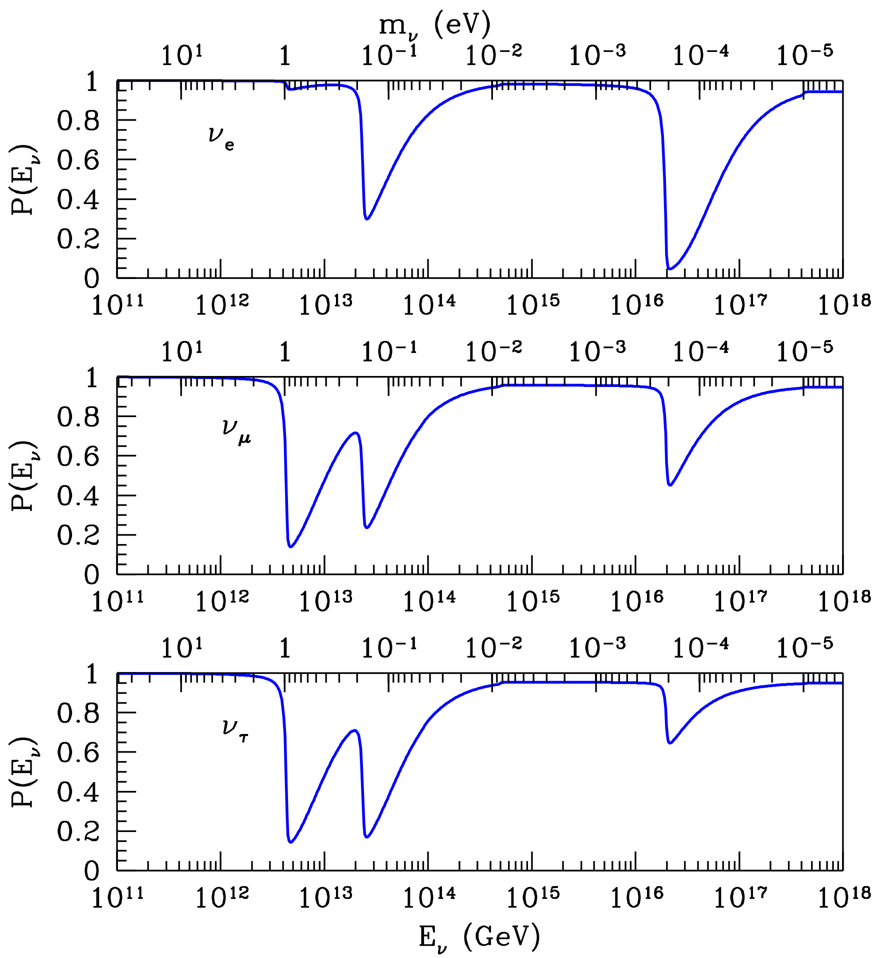
$m_\ell = 10^{-3}$ eV

Flavor ratios probe the mass hierarchy . . .

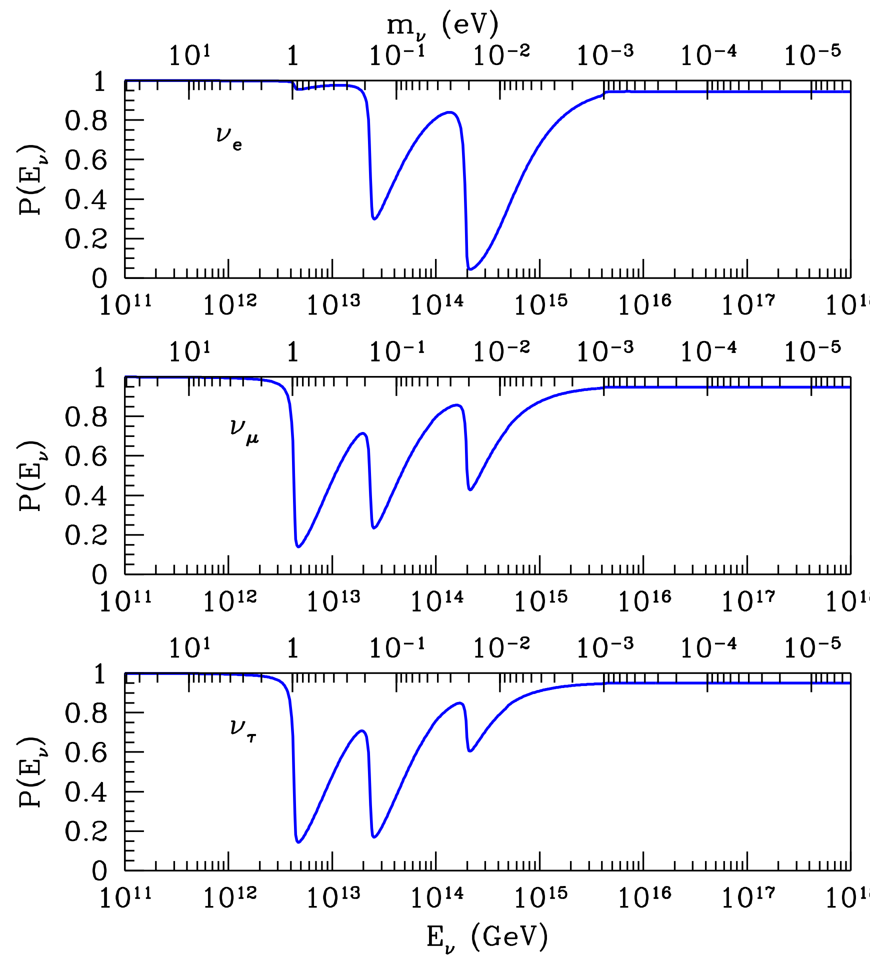


Normal $m_\ell = 10^{-5}$ eV Inverted

Incorporate evolution of Universe back to $z = 20$

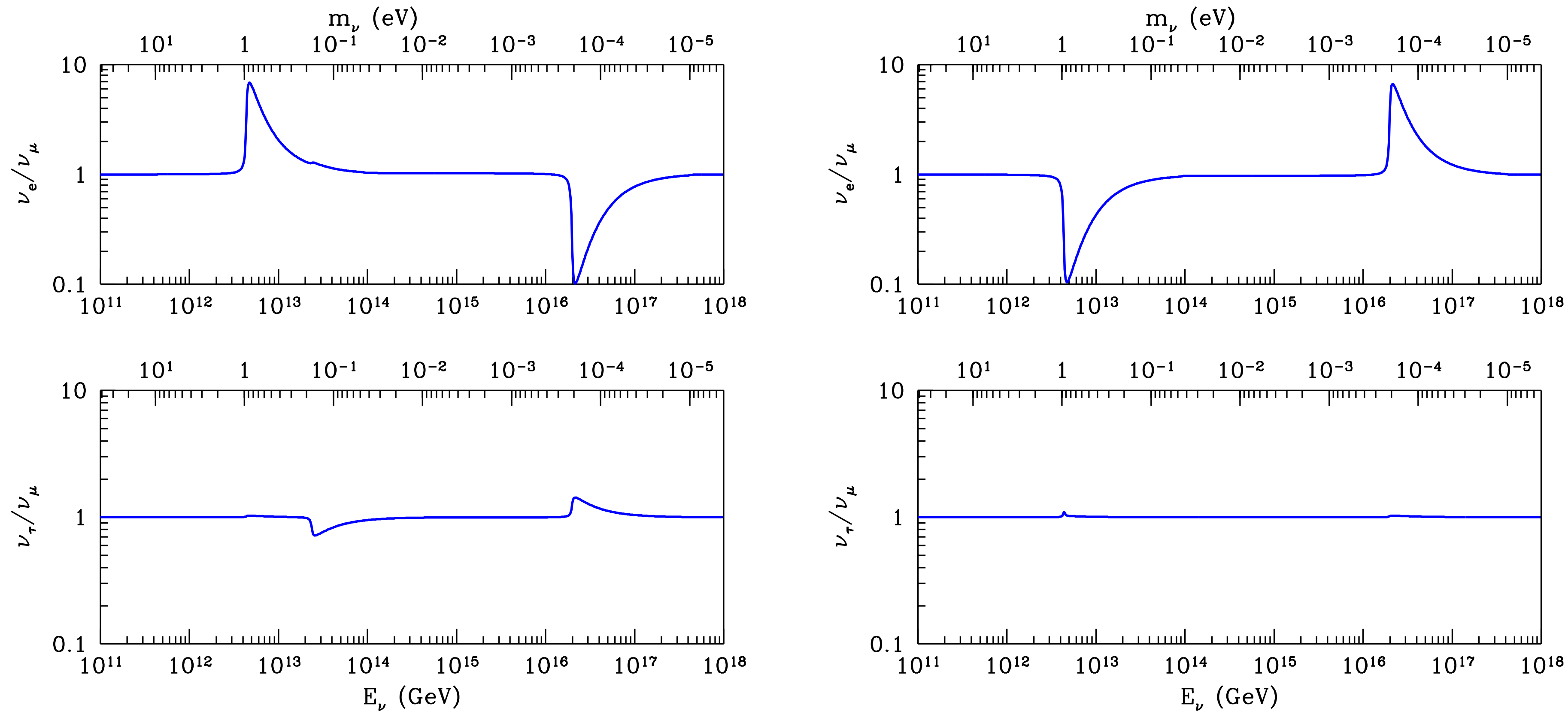


$m_\ell = 10^{-5}$ eV



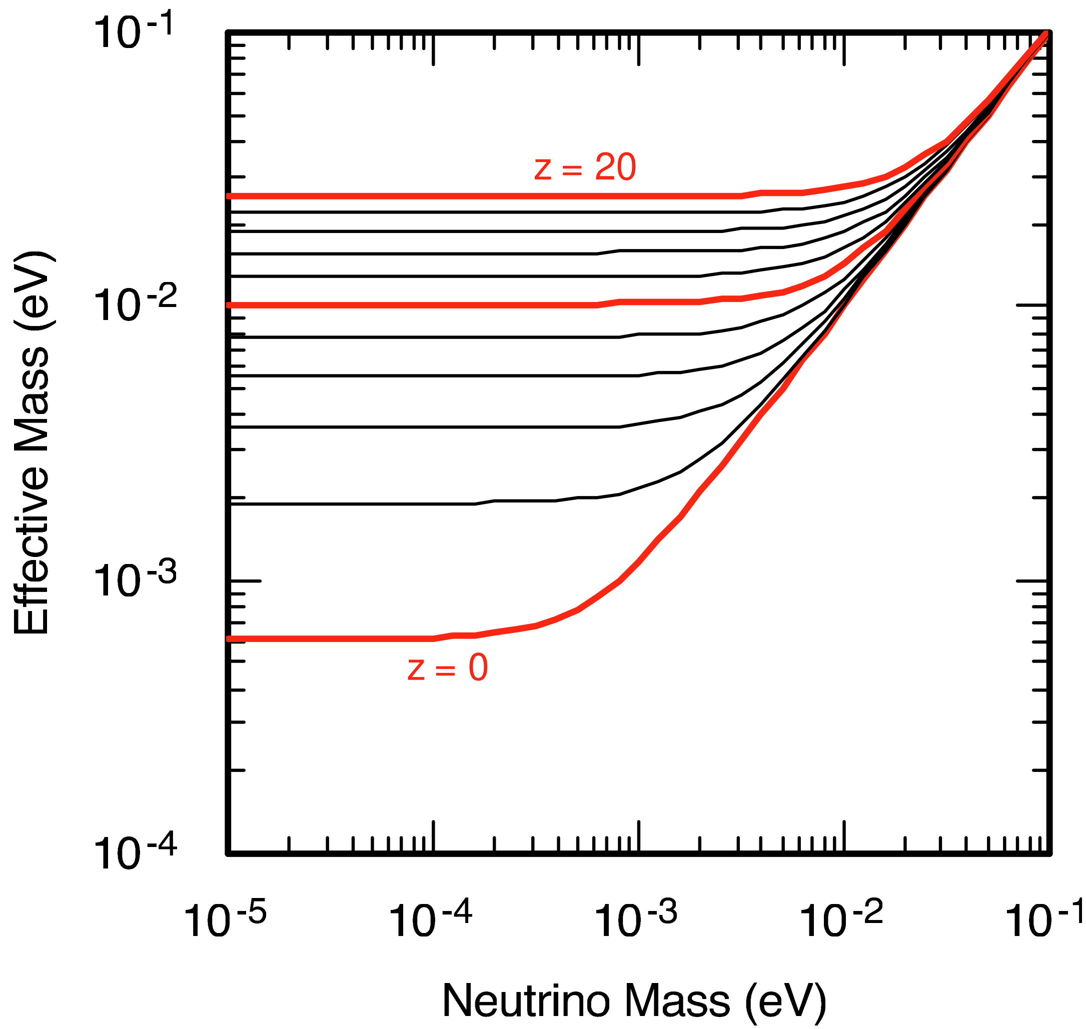
$m_\ell = 10^{-3}$ eV

Flavor ratios probe the mass hierarchy $(z \lesssim 20)$



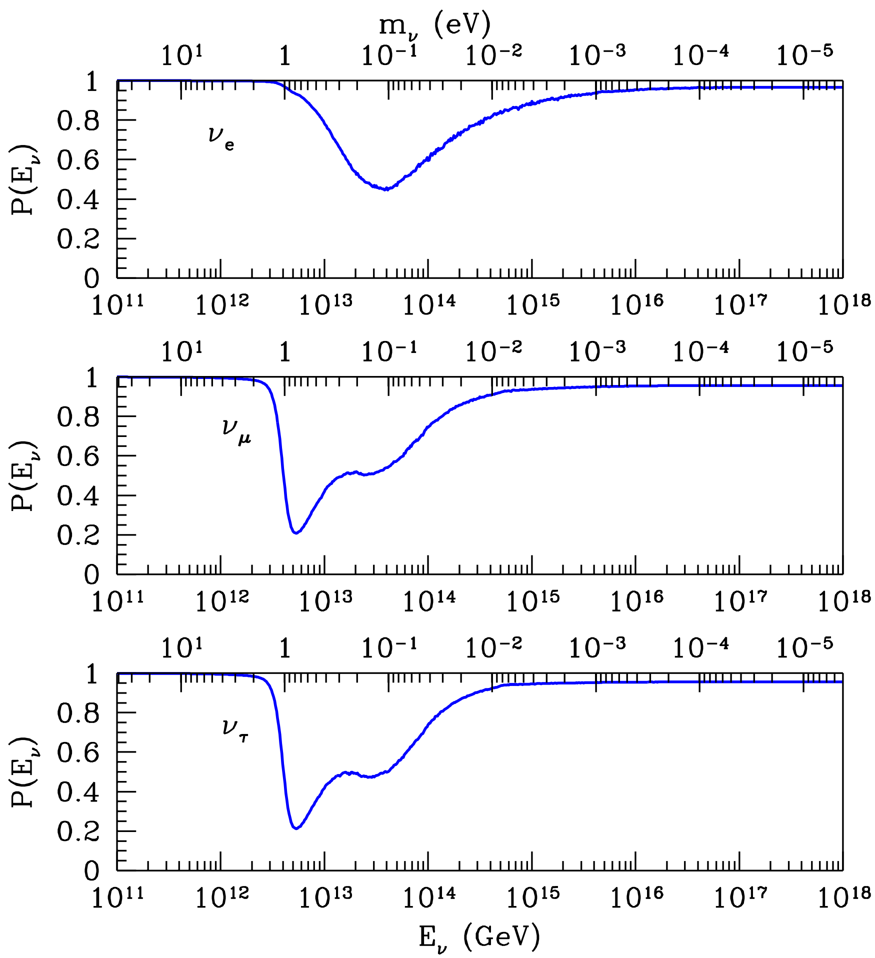
Normal $m_\ell = 10^{-5}$ eV Inverted

Neutrinos are moving targets . . .

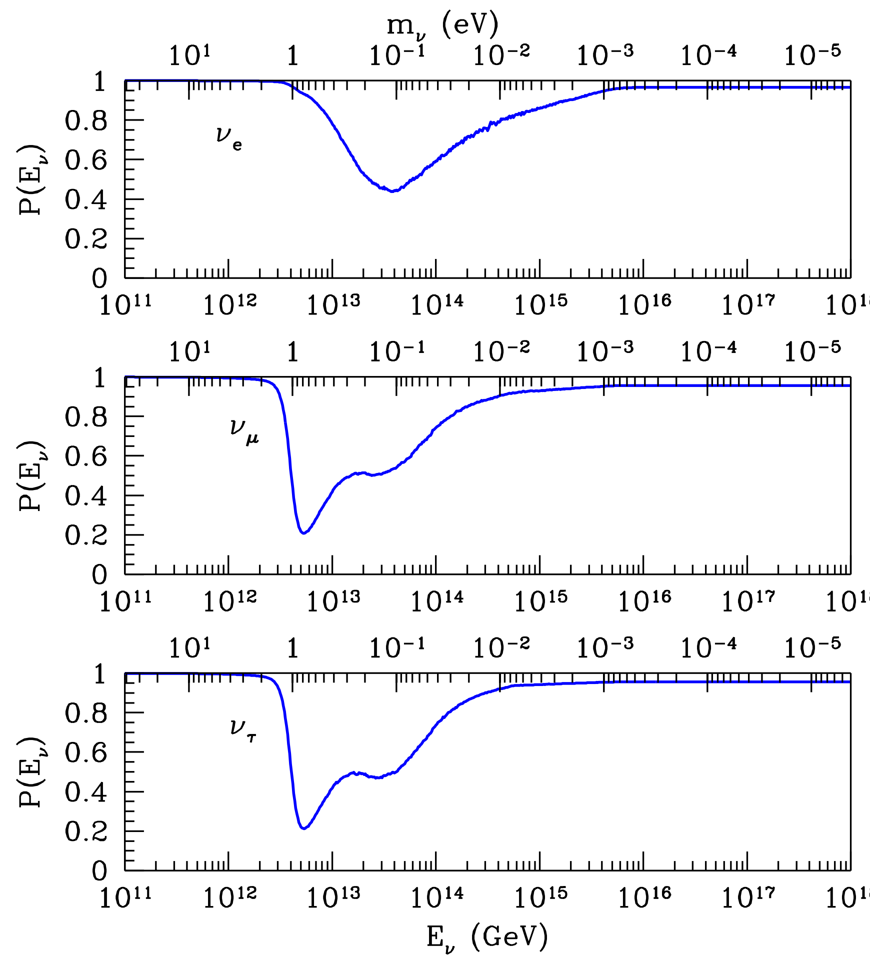


$$T_{\nu 0} = 1.945 \text{ K} = 1.697 \times 10^{-4} \text{ eV} \quad T_\nu \propto (1+z)$$

Incorporate evolution of Universe back to $z = 20$, Fermi motion

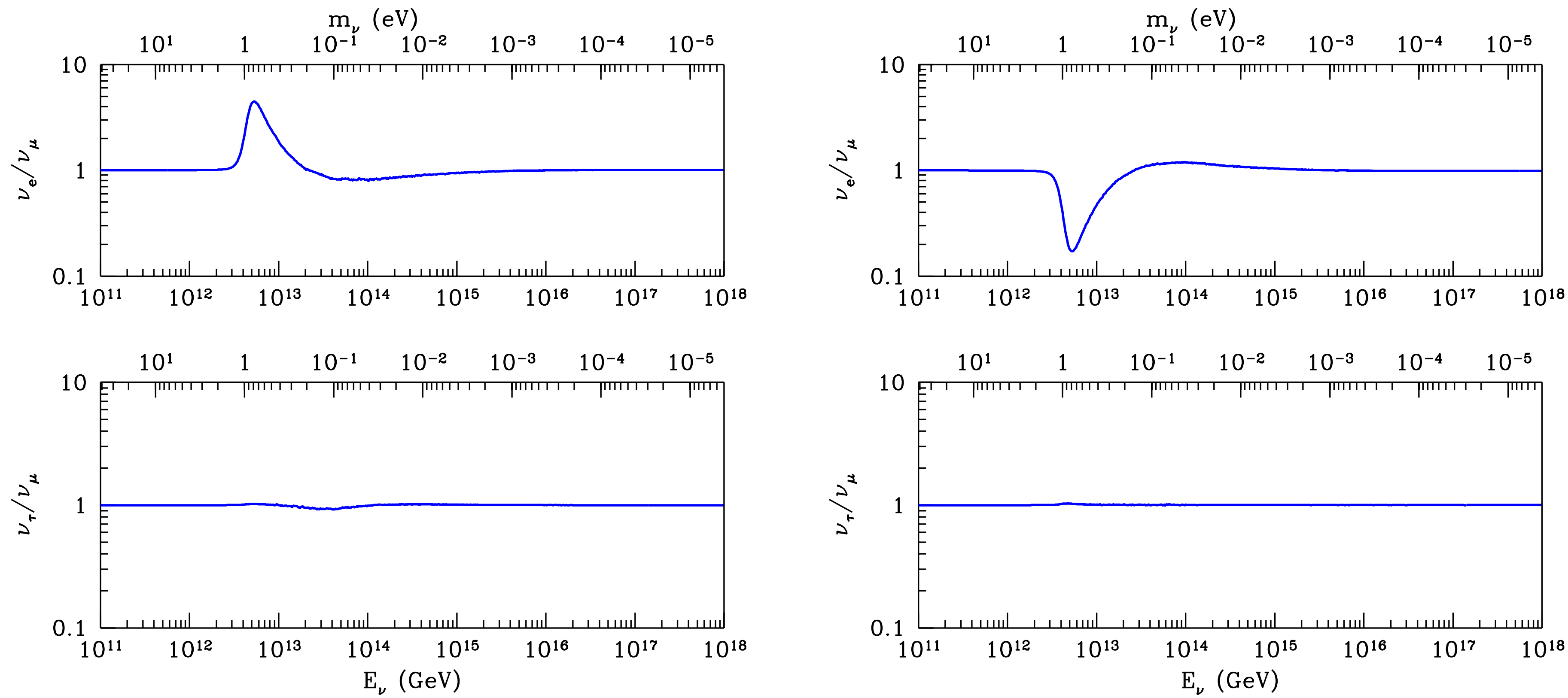


$m_\ell = 10^{-5}$ eV



$m_\ell = 10^{-3}$ eV

Flavor ratios probe the mass hierarchy $(z \lesssim 20)$, Fermi motion



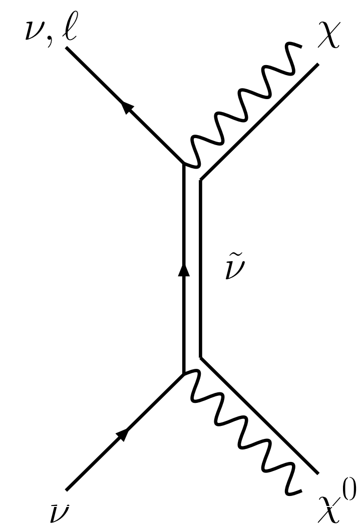
Normal $\quad m_\ell = 10^{-5}$ eV $\quad$ Inverted

Cosmic-neutrino absorption spectroscopy . . .

- ▷ Must establish ν flux exists in GZK regime and beyond
- ▷ Will require vast effective volumes, long observation times
- ▷ To probe neutrino properties (beyond mass scale), need (at least) e/μ comparison
- ▷ Earlier the sources (higher redshift), the lower the energy of absorption lines, the greater the sensitivity to thermal history of the Universe
- ▷ Nonacceleration sources at early times could plant dips at unexpectedly low energies

VII Neutrino Coannihilation on Dark-Matter Relics?

Consider neutralino dark matter, $M_{\chi_1^0} \approx 150$ GeV



Good news: $E_\nu^{\text{res}} \approx 400$ GeV ($\tilde{\nu}$ formation);
cross section 10% of $\nu\bar{\nu} \to Z$

Bad news: relic χ^0 much rarer than relic ν

Universe at large: $56\ \nu$ cm^{-3}, $\lesssim 10^{-8}\ \chi^0$ cm^{-3}

Interaction length for $\tilde{\nu}$ formation: 10^{15} Mpc

Our location in galaxy [NFW]: $\lesssim 10^{-3}\ \chi^0$ cm^{-3}

Barenboim, Mena, CQ

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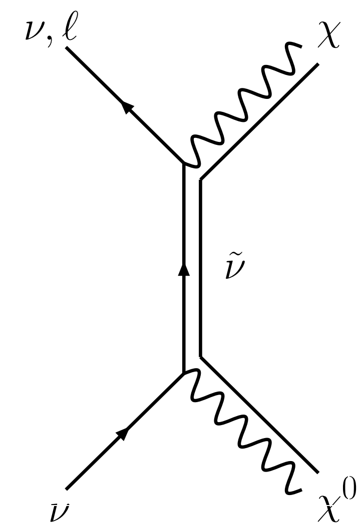

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Interaction length for $\tilde{\nu}$ formation: 10^{15} Mpc

Our location in galaxy [NFW]: $\lesssim 10^{-3}\ \chi^0$ cm^{-3}

Solar system, inside Earth orbit [Khriplovich & Pitjeva]: $< 10^3\ \chi^0$ cm^{-3}

$\rightsquigarrow \quad < 10^{-6}\ \tilde{\nu}$ y^{-1} in Earth's atmosphere (ATM ν)

. . . but up to $O(600)\ \tilde{\nu}$ y^{-1} inside Earth's orbit (AGN ν)

Barenboim, Mena, CQ

Datta, Fargion, Mele: UHE χ^0 on relic ν

$\ldots \nu\chi_1^0 \to \tilde{\nu}$

Entire galaxy would contain $\sim 10^{65}$ neutralinos (NFW profile)

With reasonable ν flux, $dN_\nu/dE_\nu \approx 5 \times 10^{-18}$ [GeV cm^2 s sr]$^{-1}$,
expect $O(10^{24})$ coannihilations per year in the galaxy

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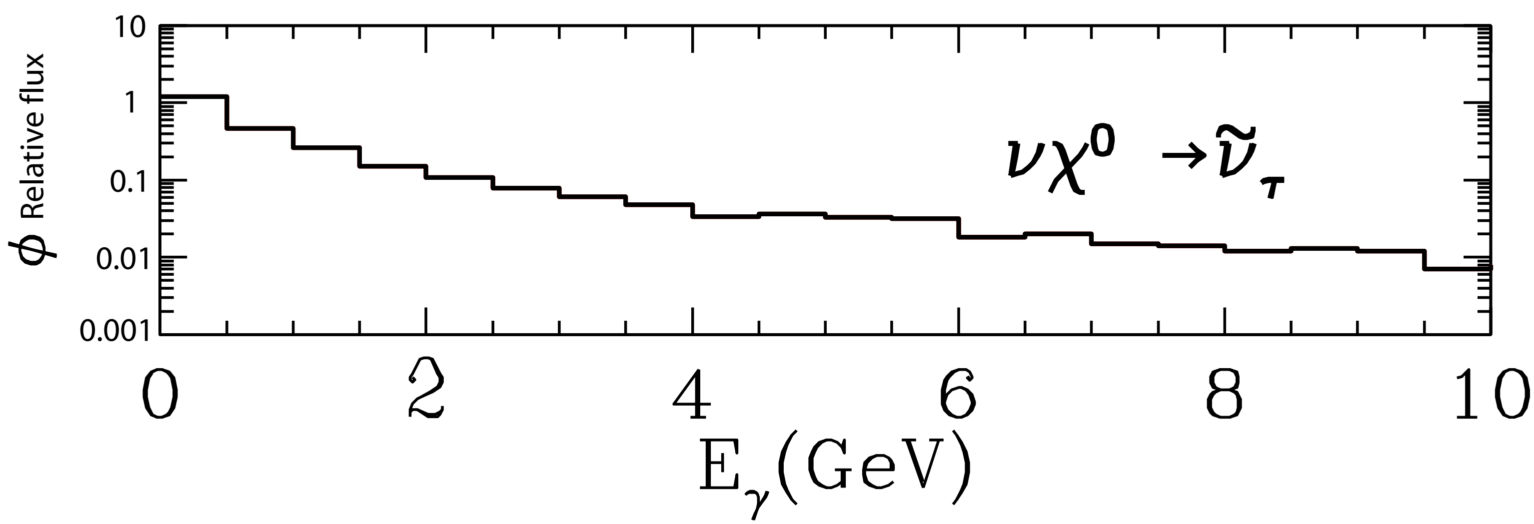
Few-GeV γ signals from inelastic decay channels, *most prominent for ν_τ*
...for the right kind of neutralino dark matter (GLAST regime)



VIII Gravitational Lensing of Neutrinos?

How demonstrate that neutrinos have normal gravitational interactions?

Analogue of Pound–Rebka experiment exploiting Mössbauer effect?

Arrival time of SN1987A neutrinos, photons   Longo, Krauss & Tremaine

Lack steady sources, angular resolution to see deflection by the Sun

Lensing Supernova neutrinos by black hole at galactic center:
significant amplification, time dispersion

Mena, Mocioiu, CQ

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"It is a part of probability that many improbable things will happen."
George Eliot (after Aristotle), *Daniel Deronda*

Mena, Mocioiu, CQ

From Neutrino Astronomy to Particle Physics

Prospects for probing particle physics in neutrino telescopes will be greatly enhanced by

- recording, characterizing energy of NC events
- neutrino flavor tagging, with energy measurement
- attention to surprises (e.g., misplaced absorption lines)
- sensitivity to TeV-γ signals from ν coannihilation (γ-ray telescopes)
- SN neutrino bursts from other side of our galaxy

Thanks to . . .

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Marcela Carena, Magda Lola,

Debajyoti Choudhury, Vu Anh Tuan,

Gabriela Barenboim, Olga Mena,

Irina Mocioiu, Stephen Parke

$$
\begin{aligned}
U &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \\
&= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}
\end{aligned}
$$

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$ and δ is a CP-violating phase.

$$
\begin{aligned}
\mathcal{X}_{\beta\alpha} &= \delta_{\alpha\beta} - 2\Re \sum_{i>j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \\
&= \sum_j \mid U_{\alpha j} \mid^2 \; \mid U_{\beta j} \mid^2 ,
\end{aligned}
$$

(does not depend on phase δ)

Idealized case: $\theta_{12} = 0.57$, $x = 0.21$

Current knowledge (95% CL):

$$0.49 < \theta_{12} < 0.67$$
$$\frac{\pi}{4} \times 0.8 < \theta_{23} < \frac{\pi}{4} \times 1.2$$
$$0 < \theta_{13} < 0.1$$

After next round (95% CL):

$$0.54 < \theta_{12} < 0.63$$
$$\frac{\pi}{4} \times 0.9 < \theta_{23} < \frac{\pi}{4} \times 1.1$$
$$0 < \theta_{13} < 0.1$$