B13.003

Characterizing Neutrino Properties and Cosmic Sources with Neutrino Observatories

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Fermilab

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Characterizing Neutrino Properties and Cosmic Sources with Neutrino Observatories

CQ & Gabriela Barenboim

Neutrino telescopes that measure relative fluxes of ultrahigh-energy ν_e, ν_μ, ν_τ can give information about the location and characteristics of sources, about neutrino mixing, and can test for neutrino instability and for neutrino-sector CPT violation.

John Beacom, P9.010 (ν decays)
Gabriela Barenboim, U1.001 (CPTV)

I Neutrino Observatories: Expectations

UHE cosmic ν flux may exceed atm bgd at few TeV

prospect for sources

characterize sources

study ν properties

Sources include AGN (at $\sim 10^2$ Mpc)

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

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

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

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

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

Need efficient, calibrated $(\nu_e, \bar{\nu}_e)$ detection

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

II Influence of Neutrino Oscillations

Fluxes 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

$$\begin{aligned} L_{\rm osc} &= 4\pi E_\nu / |\Delta m^2| \\ &\approx 2.5 \times 10^{-24}\ \text{Mpc} \cdot (E_\nu / 1\ \text{eV}) \end{aligned}$$

. . . 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 $\sin\theta_{13} = 0$, $\sin 2\theta_{23} = 1$:

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

Transfer matrix $\mathcal{X}$: Φ^0 (source) $\rightarrow \Phi$ (detector)

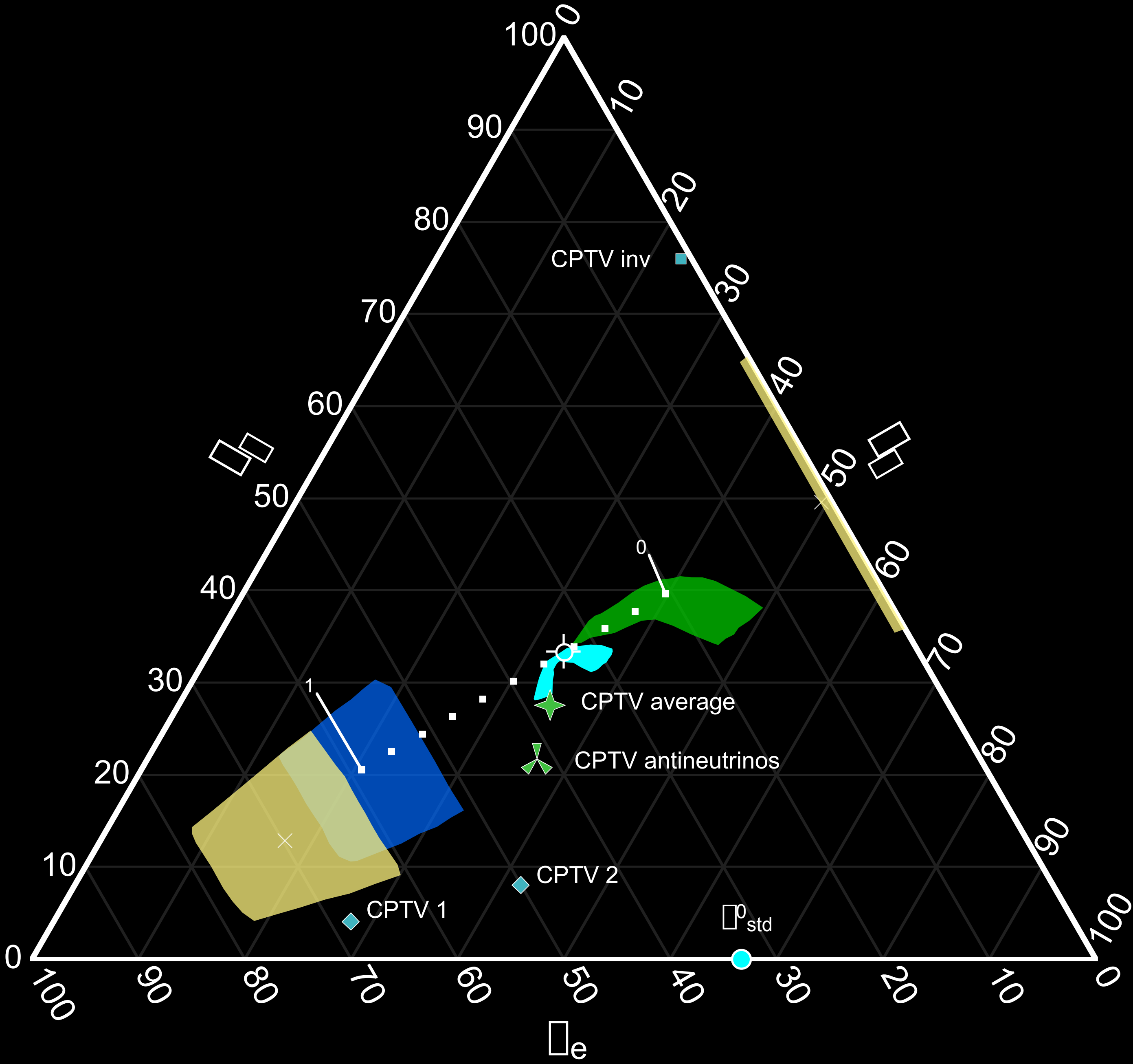
Averaged over many oscillations,

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

$$x = \sin^2\theta_{12}\cos^2\theta_{12}.$$

$\varphi_\mu = \varphi_\tau$;

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



CPTV inv
CPTV average
CPTV antineutrinos
CPTV 2
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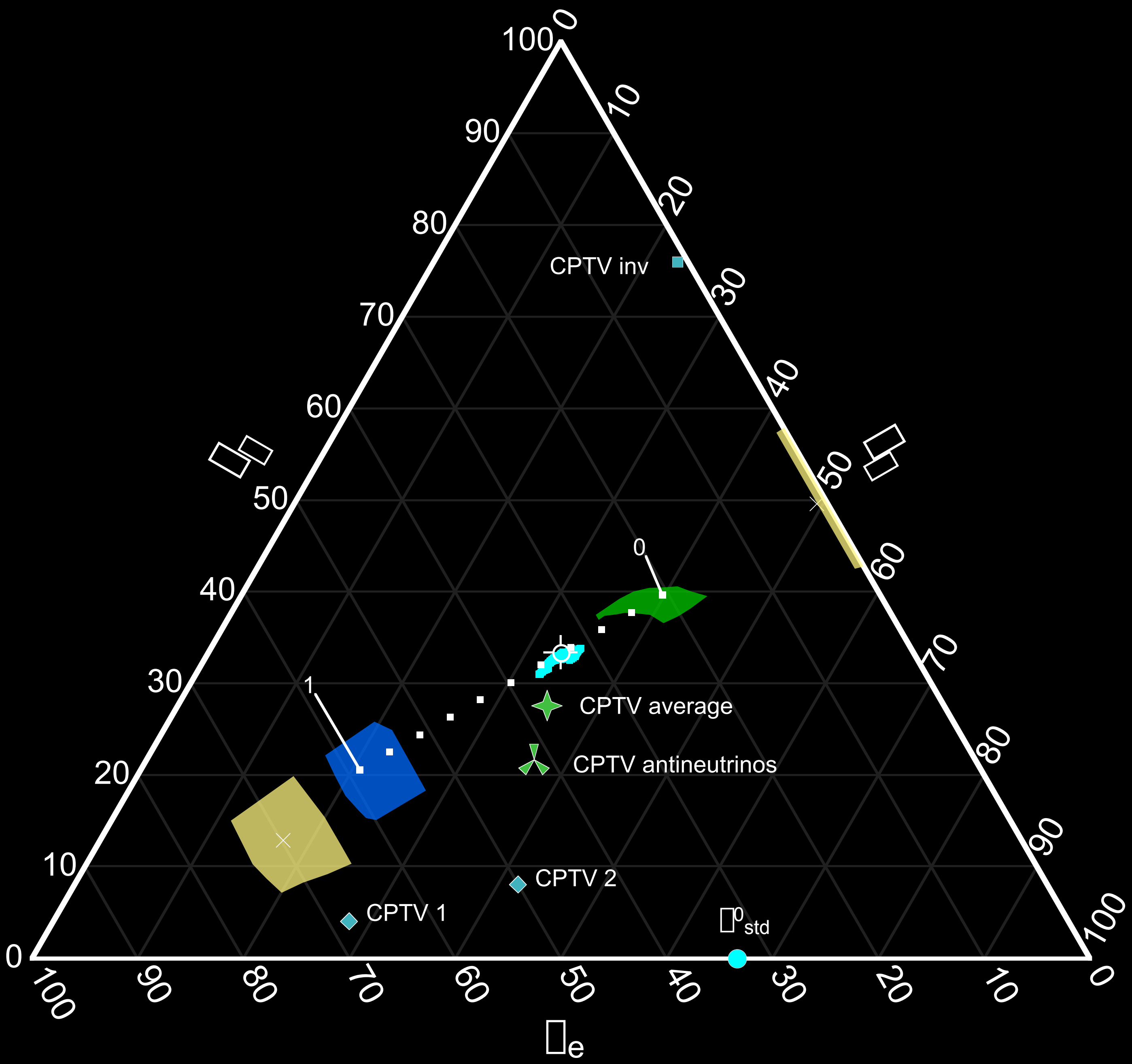

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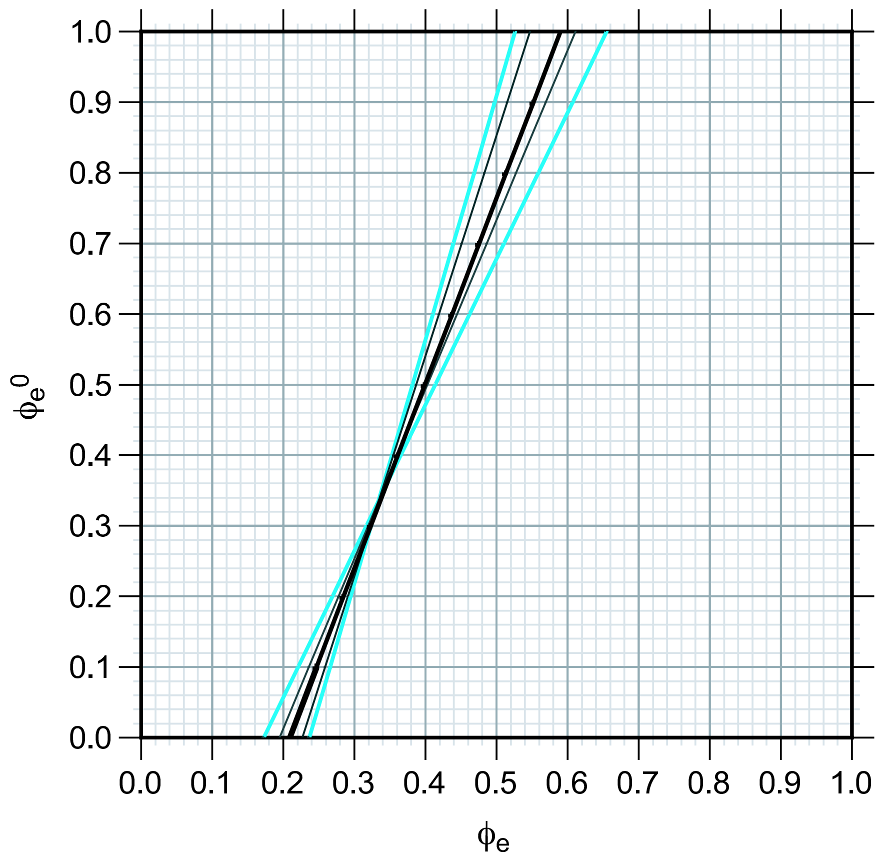
100

III 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 the source using $\mathcal{X}_{\text{ideal}}$:

$$\varphi_e^0 = \frac{\varphi_e - x}{1 - 3x}$$



Measure ν_e/ν_μ, provisonally *assume* $\nu_\mu = \nu_\tau$

Extreme φ_e implicates unconventional physics

IV Influence of Neutrino Decays

Nonradiative decays — Beacom P9.010

$$\nu_i \to (\nu_j, \bar{\nu}_j) + X$$

not very constrained

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

Normal hierarchy

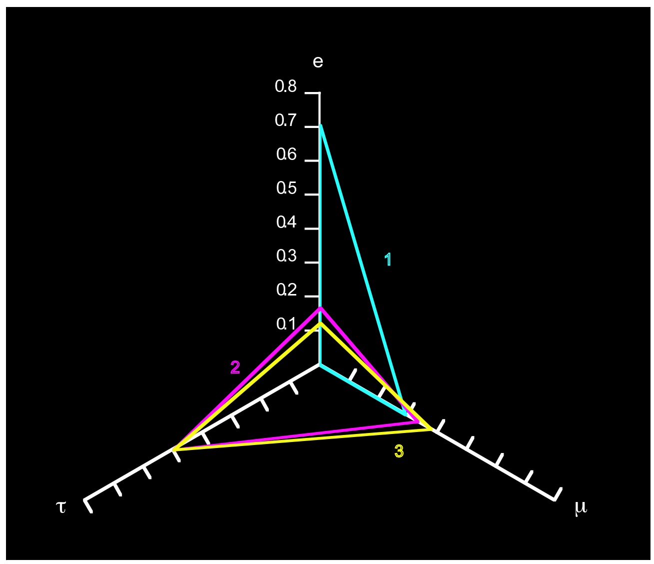
$m_1 < m_2 < m_3$:

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

Inverted hierarchy

$m_1 > m_2 > m_3$:

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

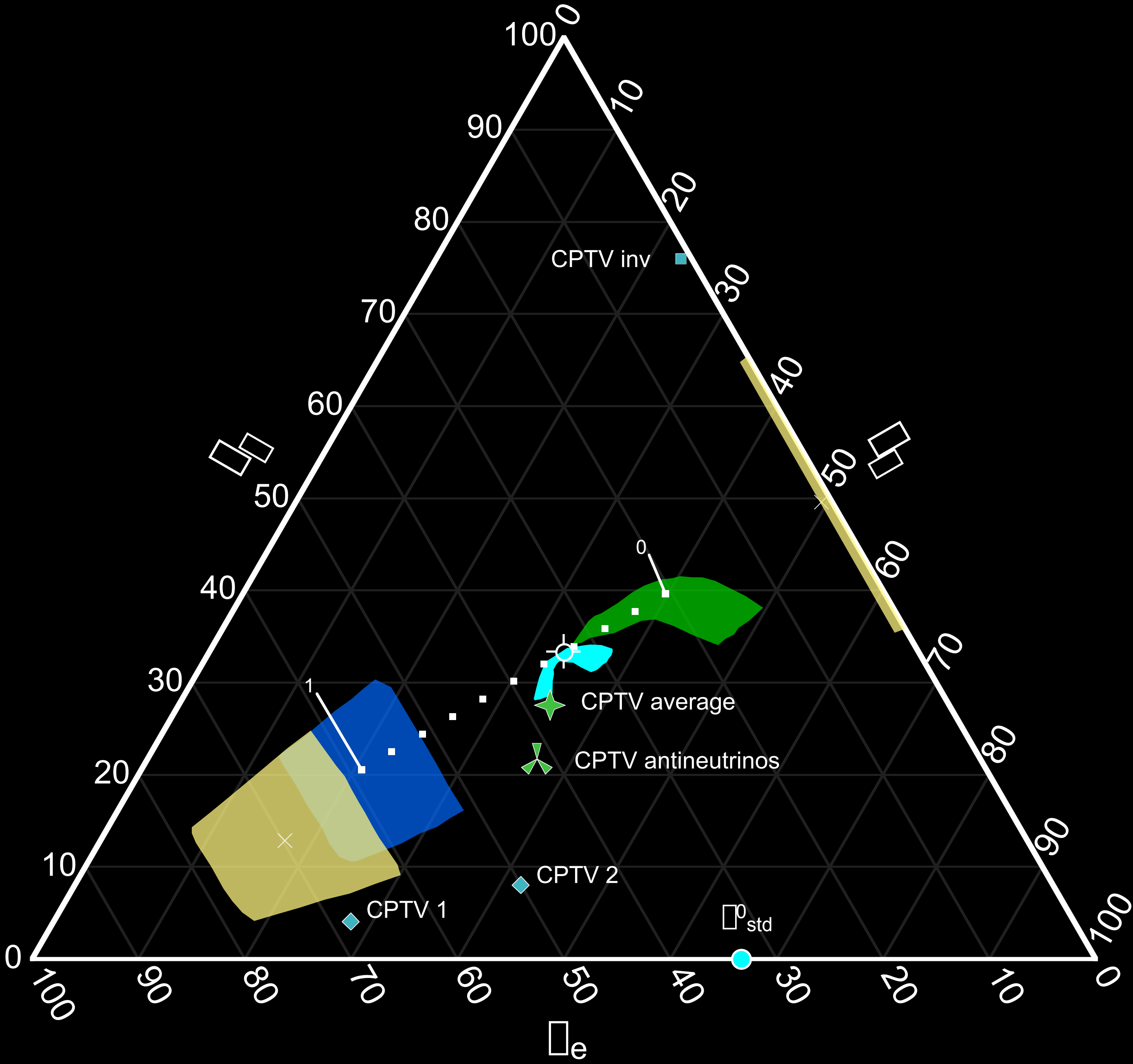


Central values:

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

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

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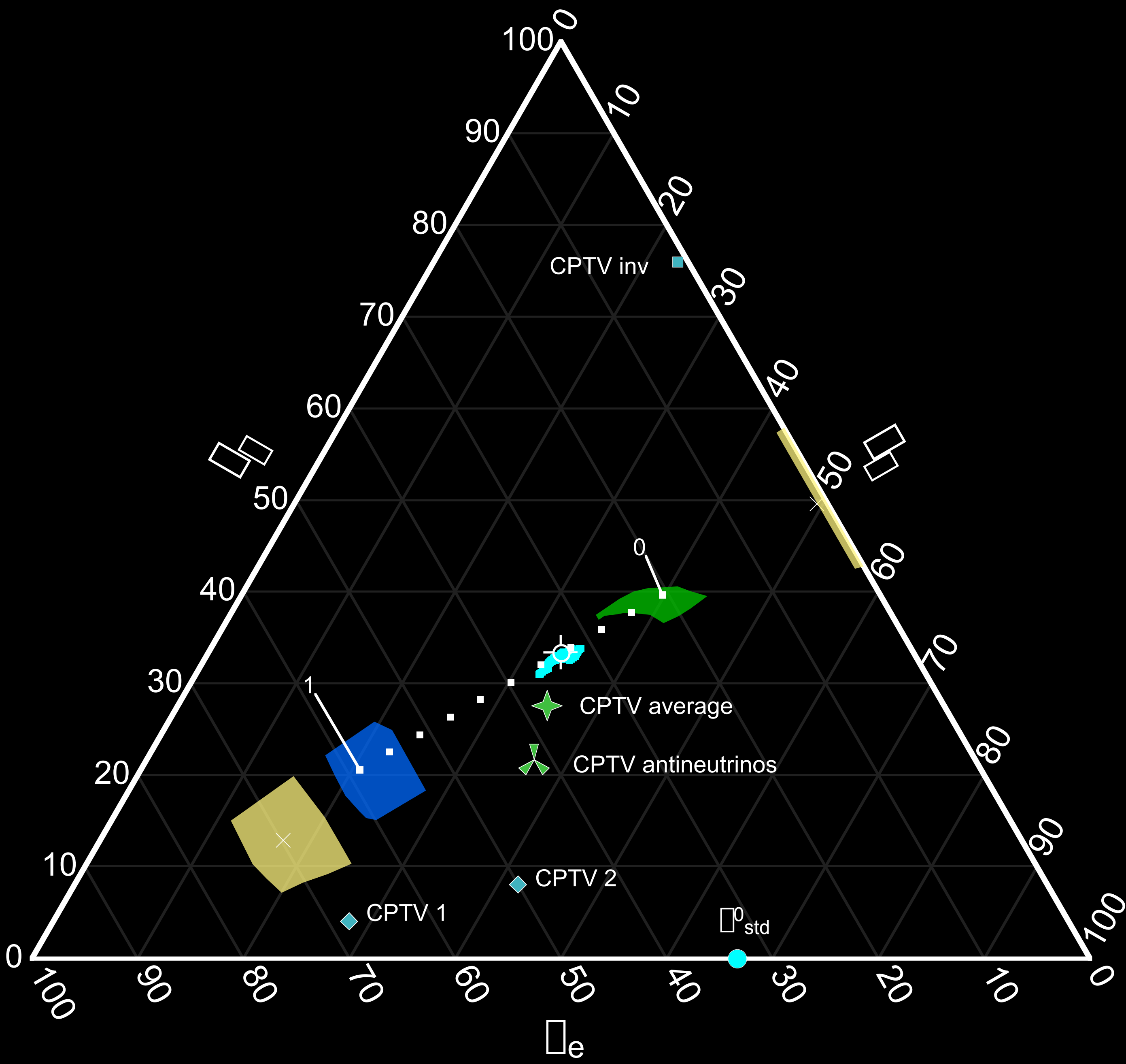

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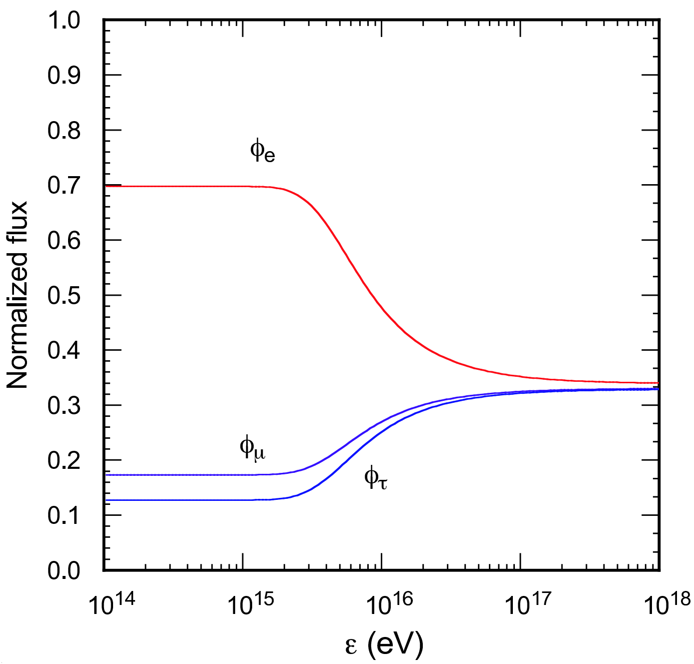
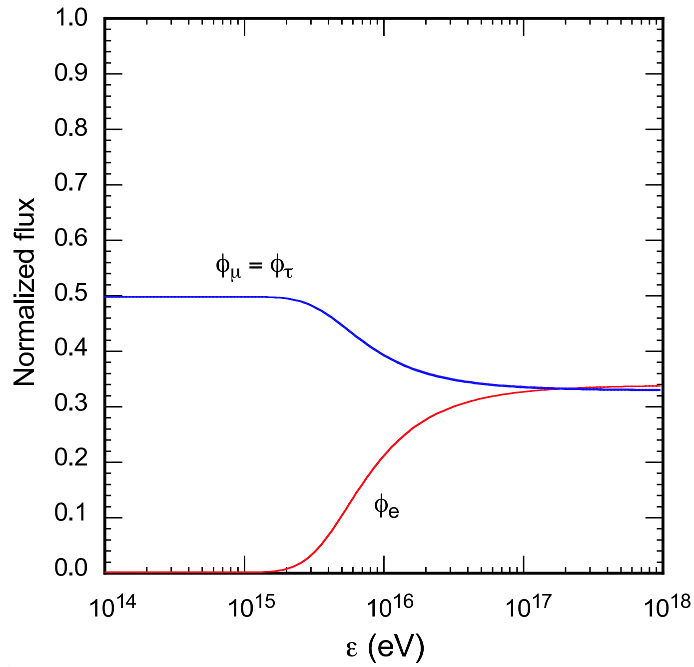
See decays to survivors transition, measure lifetime?

- ▷ Solar ν: $\tau/m \gtrsim 10^{-4}$ s/eV
- ▷ Distances range over one order of magnitude
- ▷ Energies range over several orders of magnitude



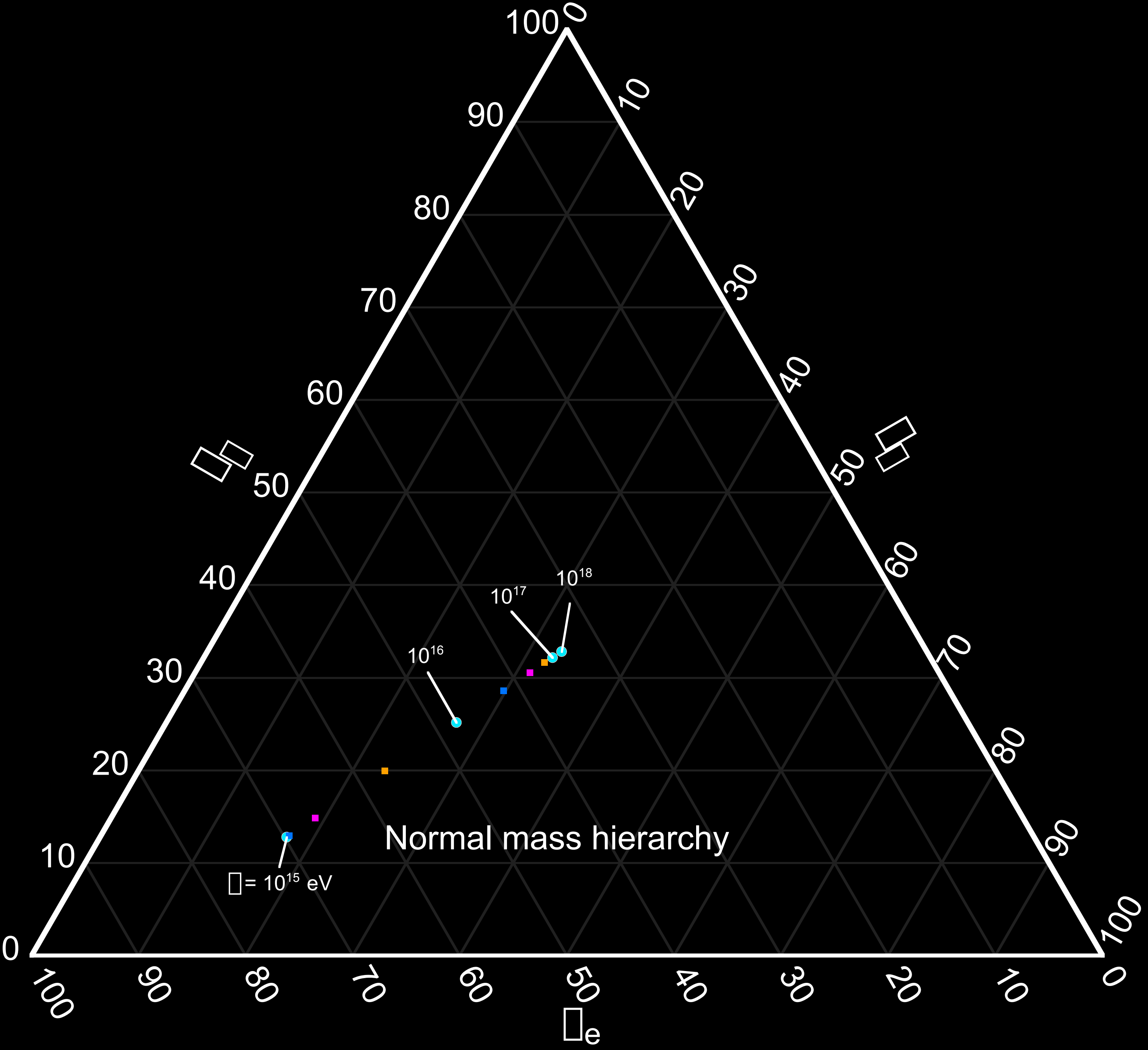


$$\text{Rescale: } E_\nu = \varepsilon \left(\frac{1 \text{ s/eV}}{\tau/m}\right)\left(\frac{L}{100 \text{ Mpc}}\right)$$

Transition at $E^\star \Rightarrow$

$$\tau/m \approx 100 \text{ s/eV} \cdot \left(\frac{L}{1 \text{ Mpc}}\right)\left(\frac{1 \text{ TeV}}{E^\star}\right)$$

Φ_{std} @ 10 TeV, 100 Mpc: improves $\tau/m \times 10^7$



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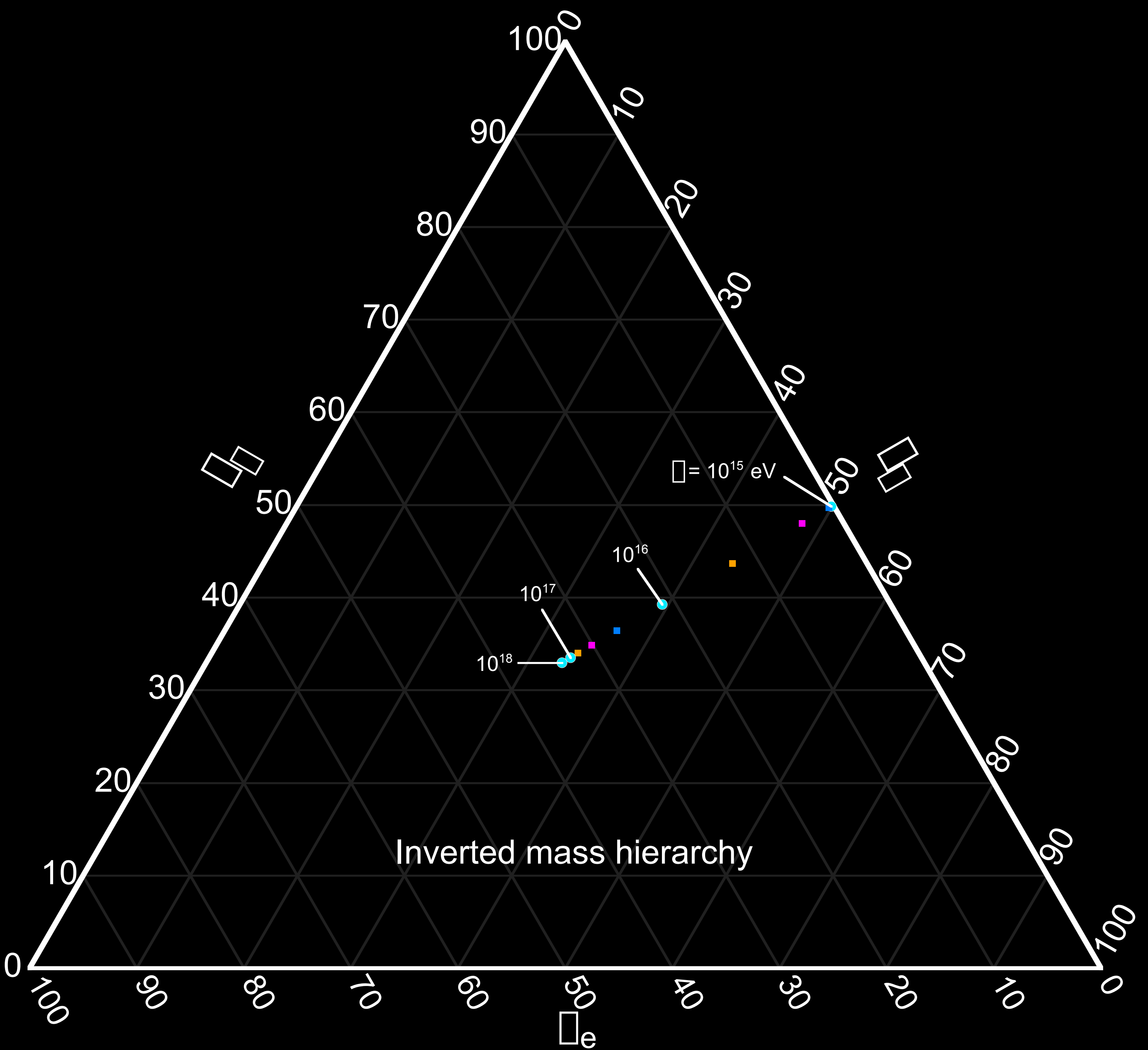
90
100
10^{18}
10^{17}
10^{16}
= 10^{15} eV
Normal mass hierarchy
e



= 10^15 eV
10^16
10^17
10^18
Inverted mass hierarchy
e

V Assessment: ν oscillations enrich UHE ν science

Standard $1\nu_e : 2\nu_\mu : 0\nu_\tau$ production + oscillations:

$\approx \nu_e, \nu_\mu, \nu_\tau$ fluxes at Earth

Uncertainties (now and +5 years) better appreciated

Detecting equal fluxes strengthens ν lifetime bounds

Deviation $\Rightarrow$ revised conception of source

OR unexpected ν behavior

Measure fraction φ_e to characterize source

ν decay: mixtures incompatible with standard source

distinguish from unconventional sources

possibility to estimate lifetime

Departure from $\varphi_\mu \approx \varphi_\tau$ is marker for exotic physics

Distinguish ν, $\bar{\nu}$ for best CPTV test

Adds motivation to identify ν_e, ν_μ, ν_τ interactions and measure ν energies in km^3 ν observatories

Brief Bibliography

This talk: G. Barenboim & C. Quigg, "Neutrino Observatories Can Characterize Cosmic Sources and Neutrino Properties," $\longrightarrow$ *Phys. Rev. D* [arXiv:hep-ph/0301220].

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CPT *violation:* G. Barenboim, L. Borissov, J. Lykken, and A. Yu. Smirnov, *JHEP* **0210**, 001 (2002) [arXiv:hep-ph/0108199]; G. Barenboim, L. Borissov, and J. Lykken, *Phys. Lett.* **B534**, 106 (2002) [arXiv:hep-ph/0201080]; "CPT Violating Neutrinos in the Light of KamLAND," [arXiv:hep-ph/0212116]. U1.001

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

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$ 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):

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