The Future of Neutrino Telescopes: Neutrino Sources and New Physics

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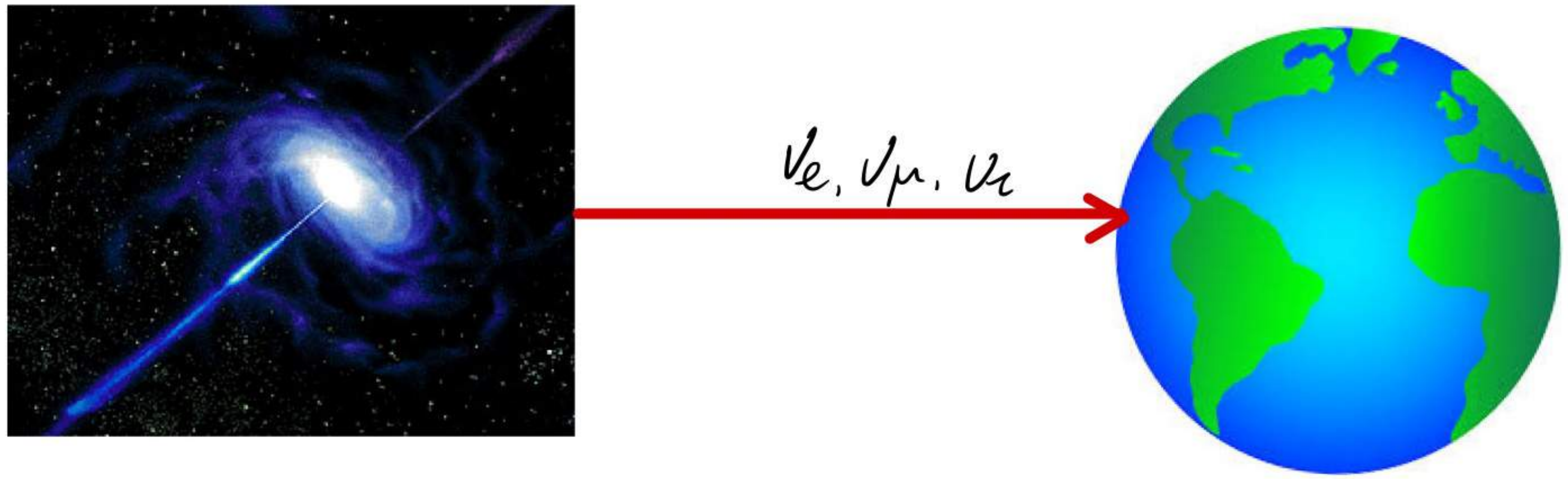
High Energy Neutrinos



- Pion decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

- Muon-damped $(\nu_e : \nu_\mu : \nu_\tau) = (0 : 1 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$

~~μ^+~~ $\to e^+ + \nu_\mu + \bar{\nu}_e$

- Neutron decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 0 : 0)$

$$n \to p + e^- + \bar{\nu}_e$$

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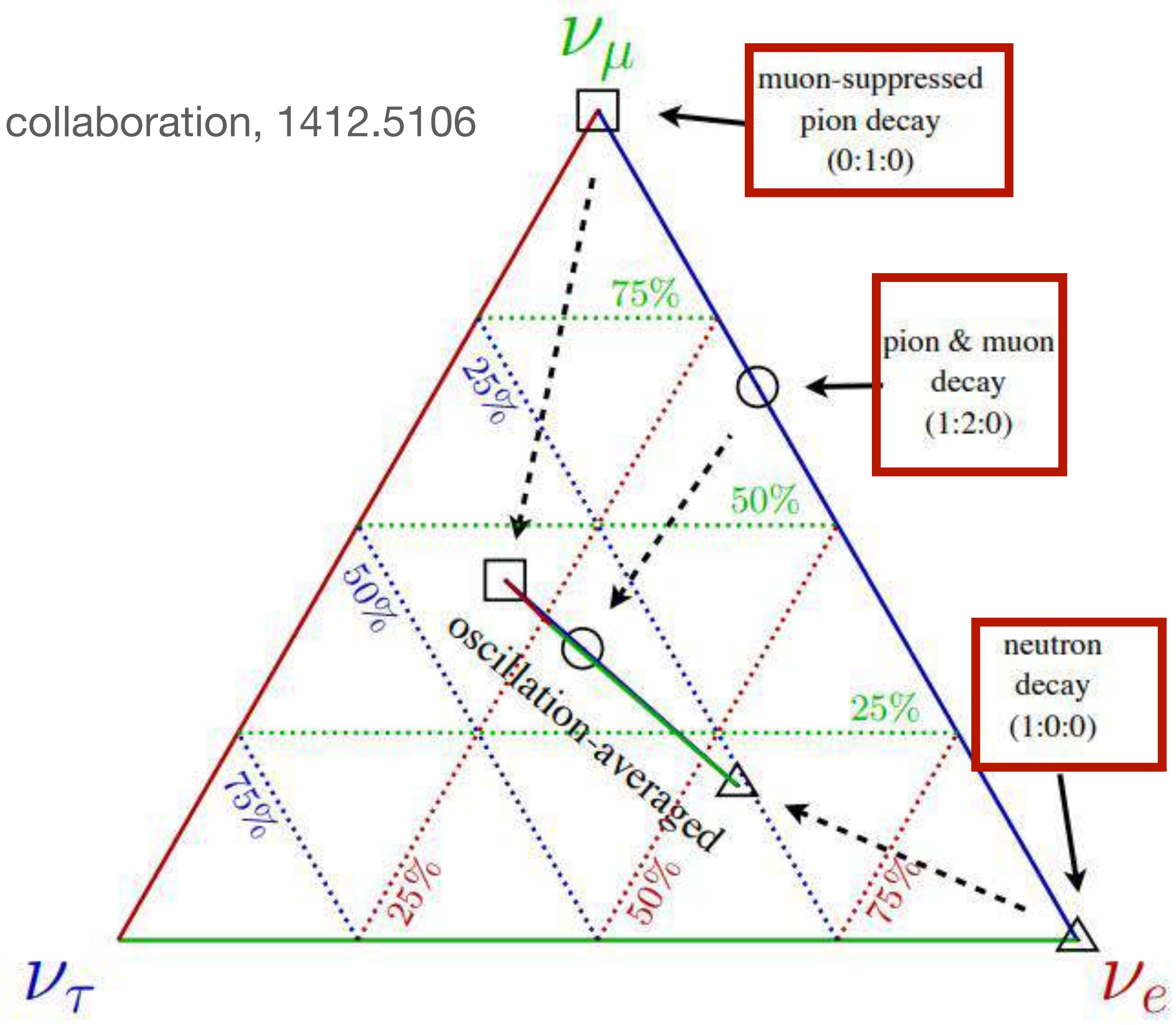
Neutrino Flavor at Earth

IC-Gen2 collaboration, 1412.5106

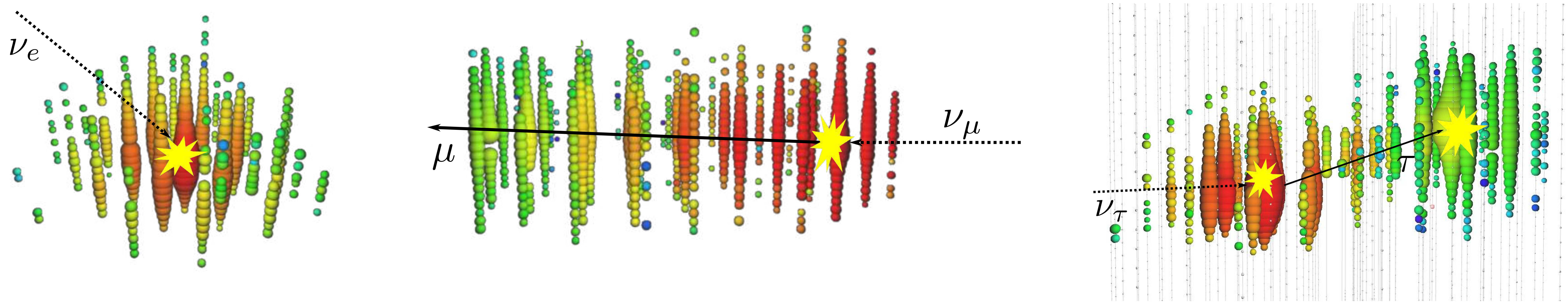


- Neutrinos oscillate from source to Earth

$$P_{\alpha\beta}^{s\to\oplus} = \sum_{ij} U_{\beta i}U^*_{\beta j}U_{\alpha j}U^*_{\alpha i}\exp(-i\frac{\Delta m^2_{ij}L}{2E})$$

$$= \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- $f_S = (1/3,\ 2/3,\ 0) \to f_\oplus = (0.3,\ 0.36,\ 0.34)$



Showers/Cascades

Tracks

Double bangs

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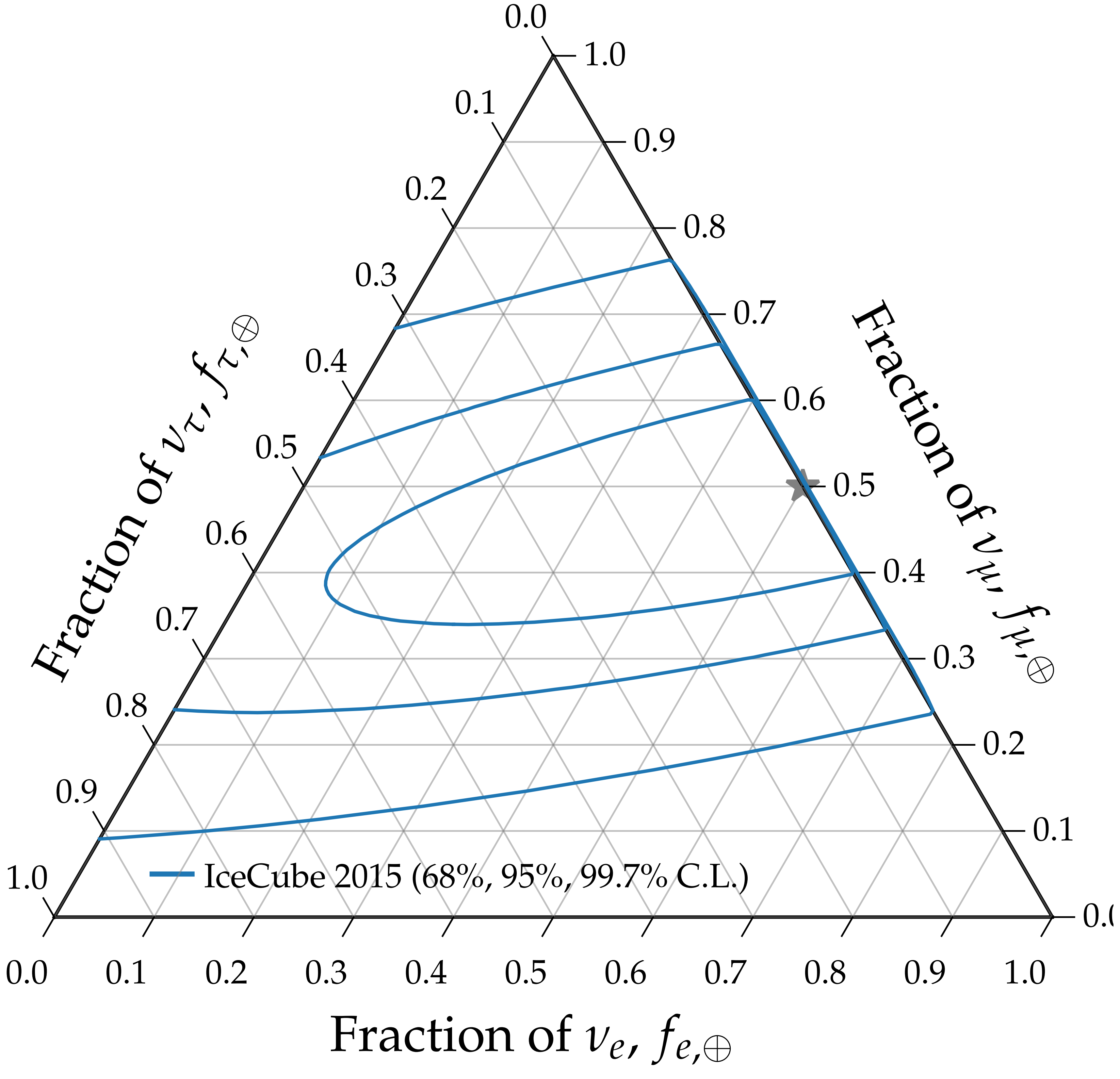
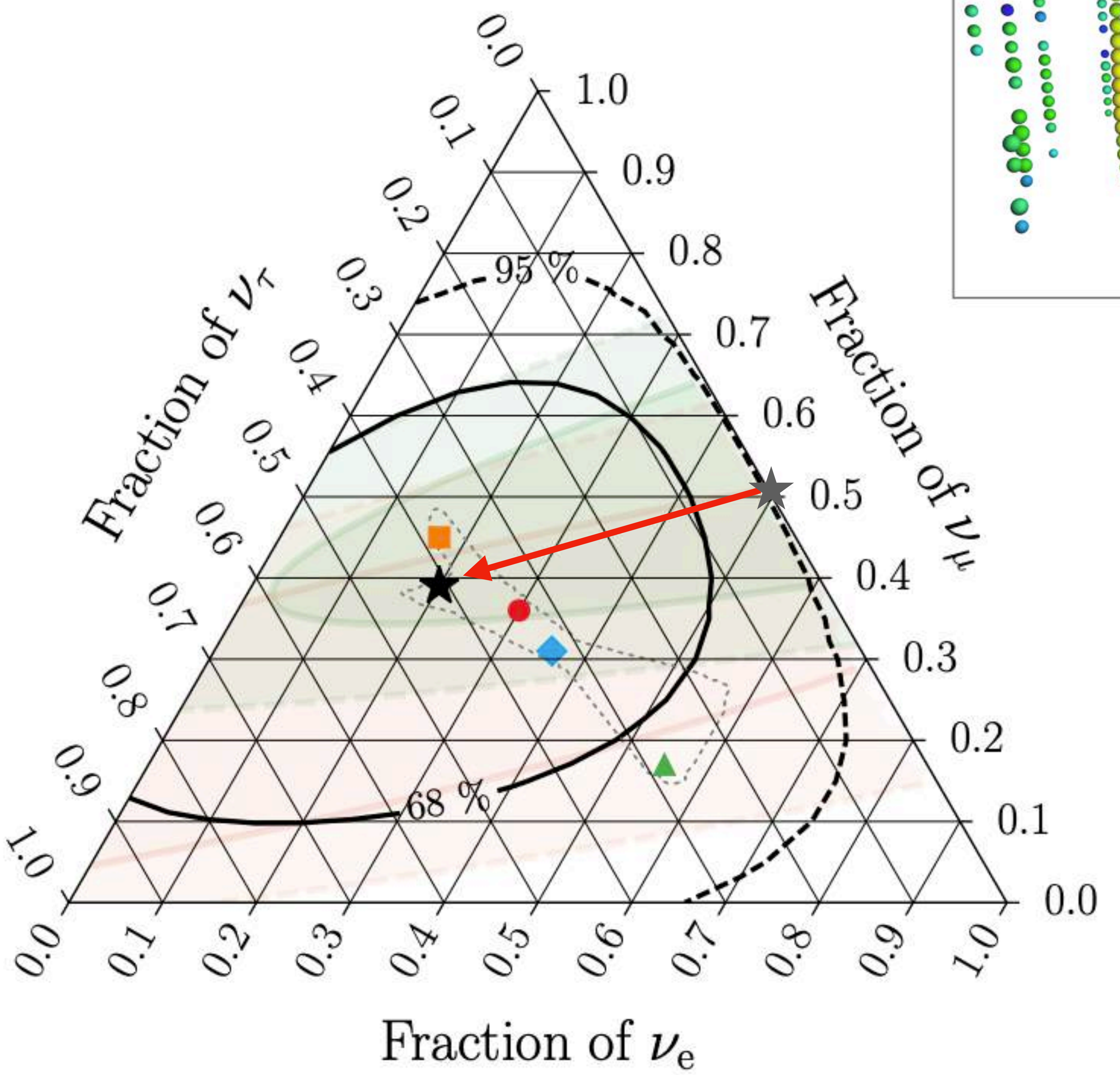
Neutrino Flavor Measurements: Status

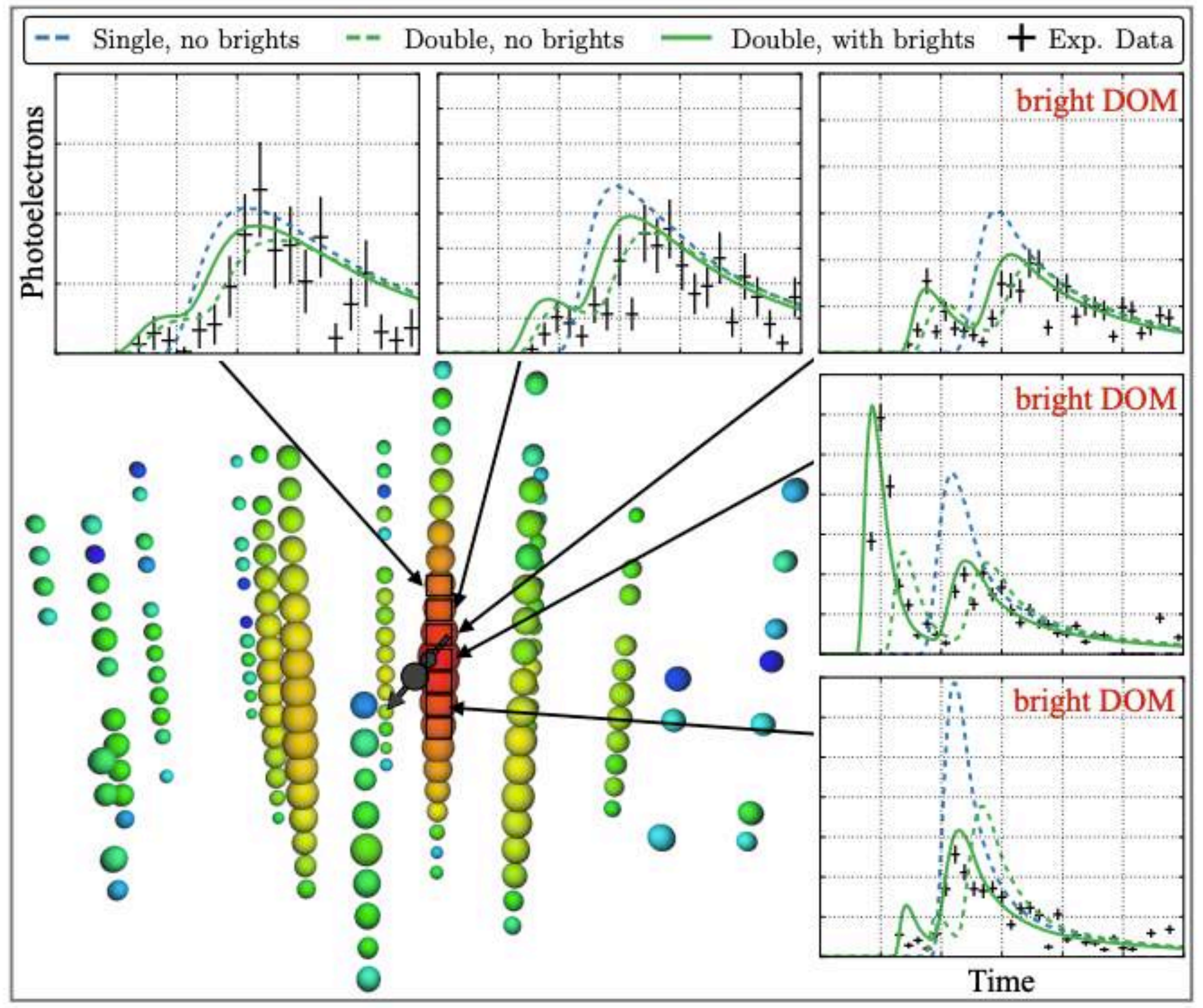
- HESE data + through-going muons



IceCube Collaboration, 1507.03991



IceCube Collaboration, 2011.03561



First detection of tau neutrino double bangs

$$\Phi \propto E^{-\gamma}$$

$$\gamma_{\rm astro} = 2.87^{+0.20}_{-0.19}$$

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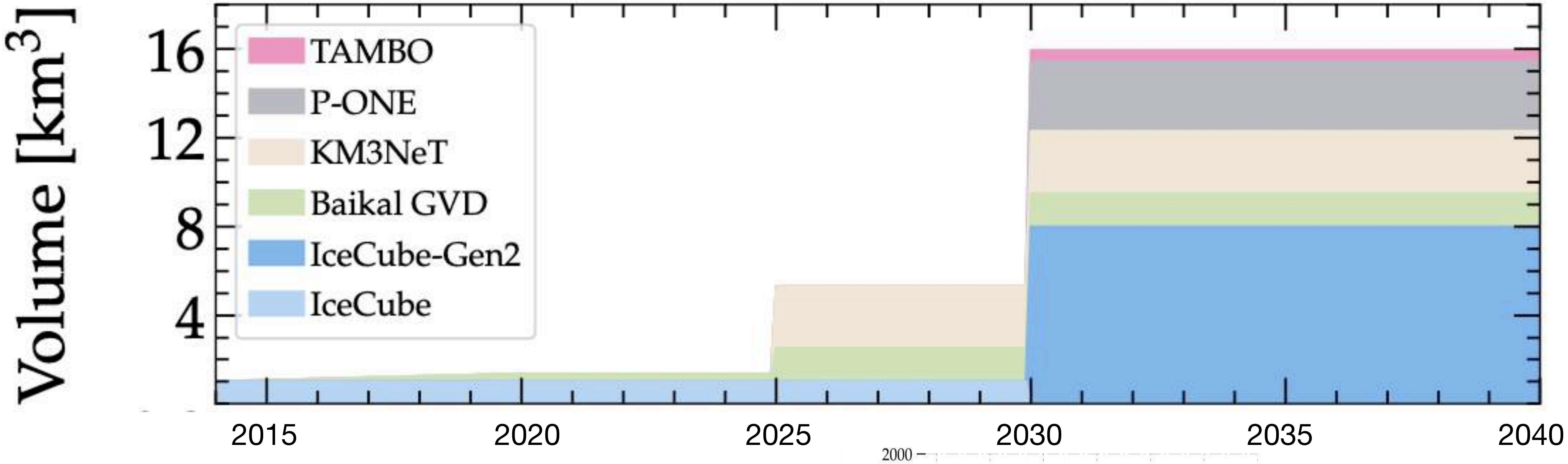
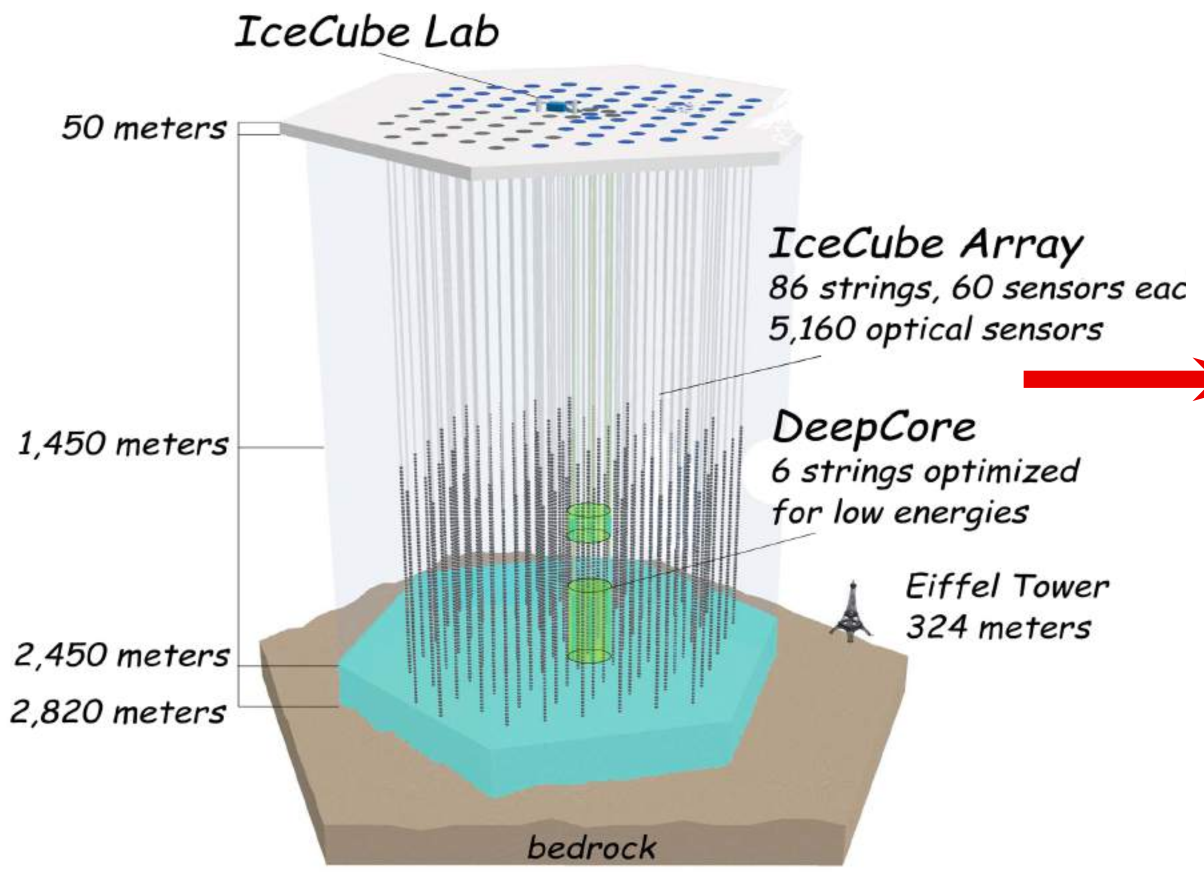
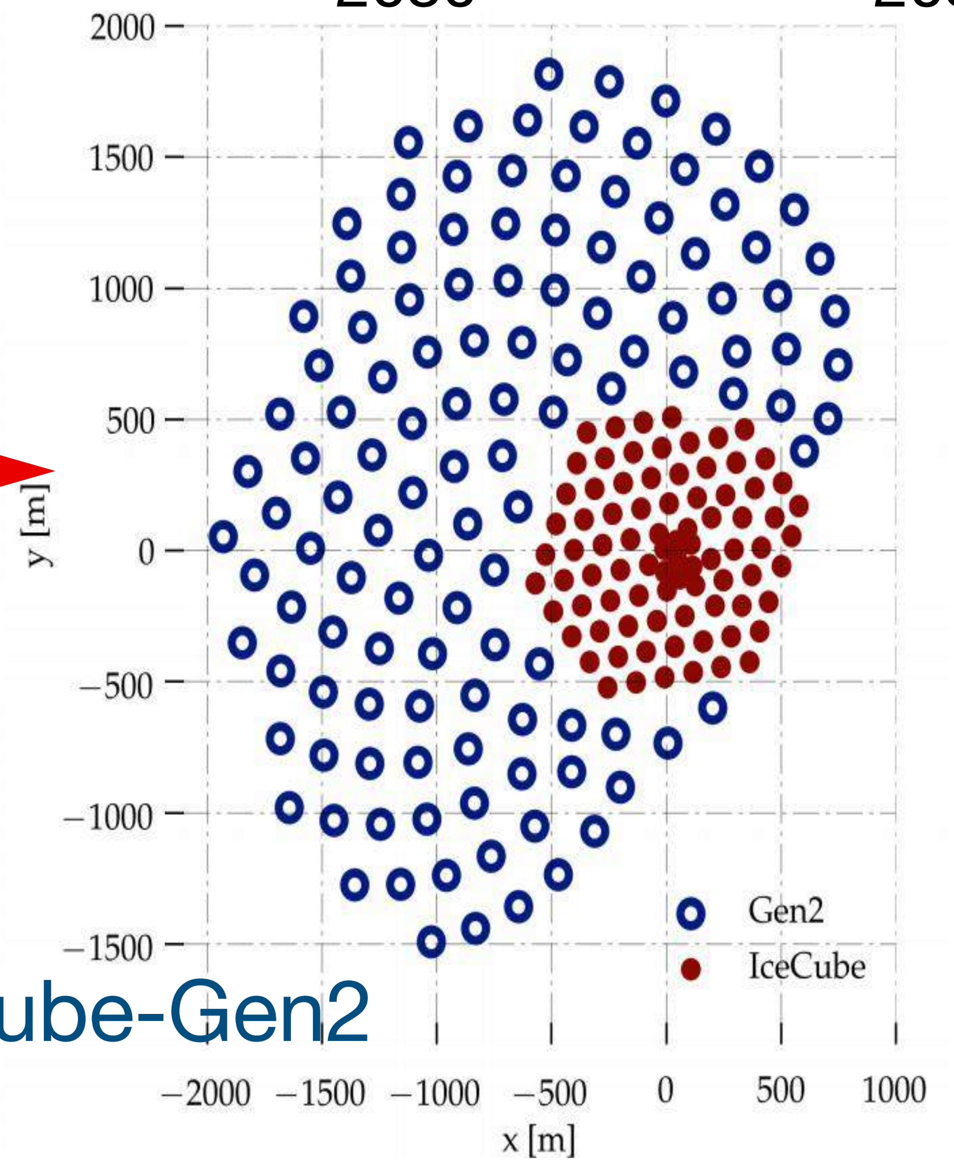
Future Neutrino Telescopes

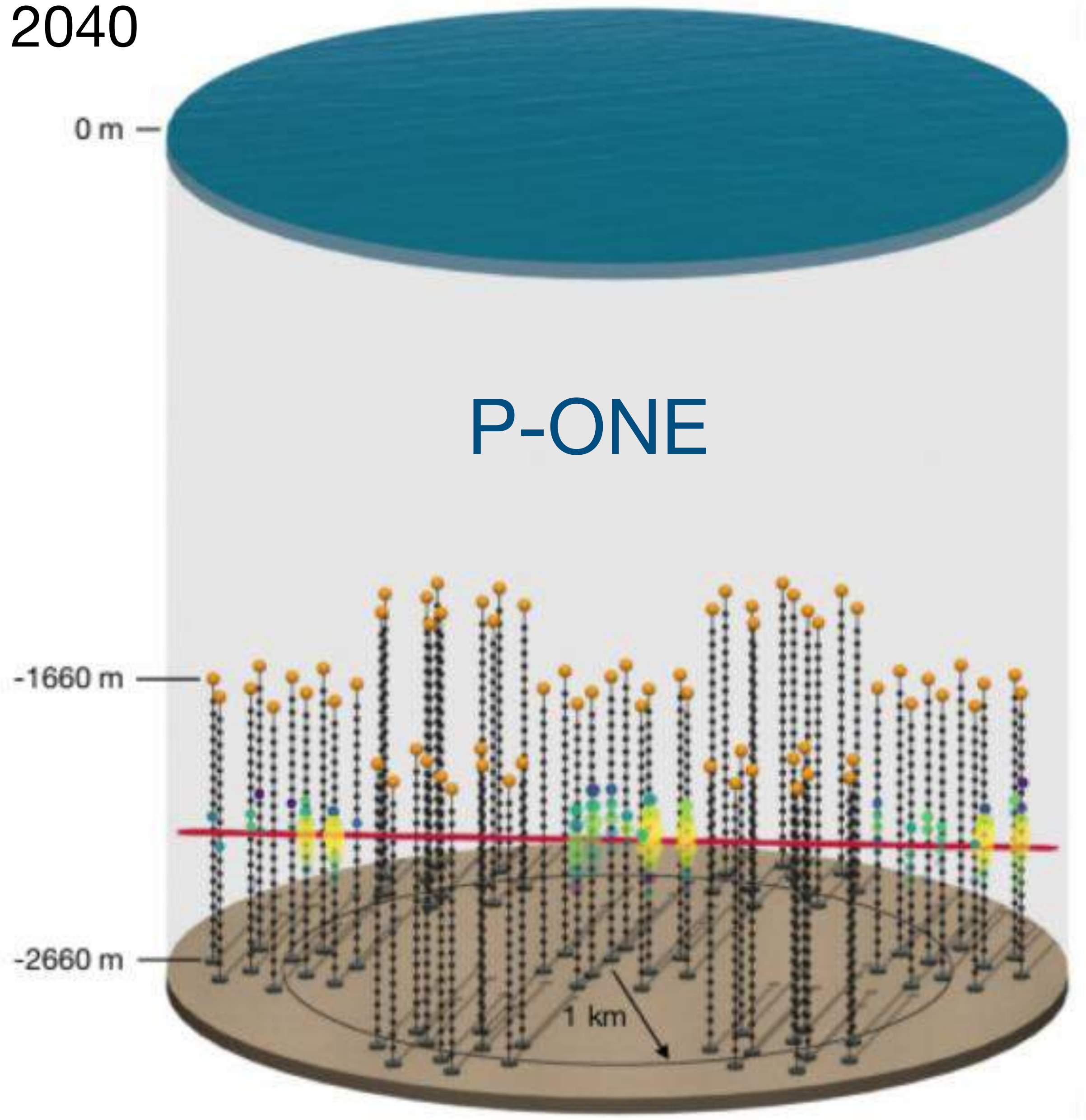


Combination of IC-Gen2, P-ONE, KM3NeT, GVD, TAMBO offers ~20 times more exposure by 2040 than IceCube



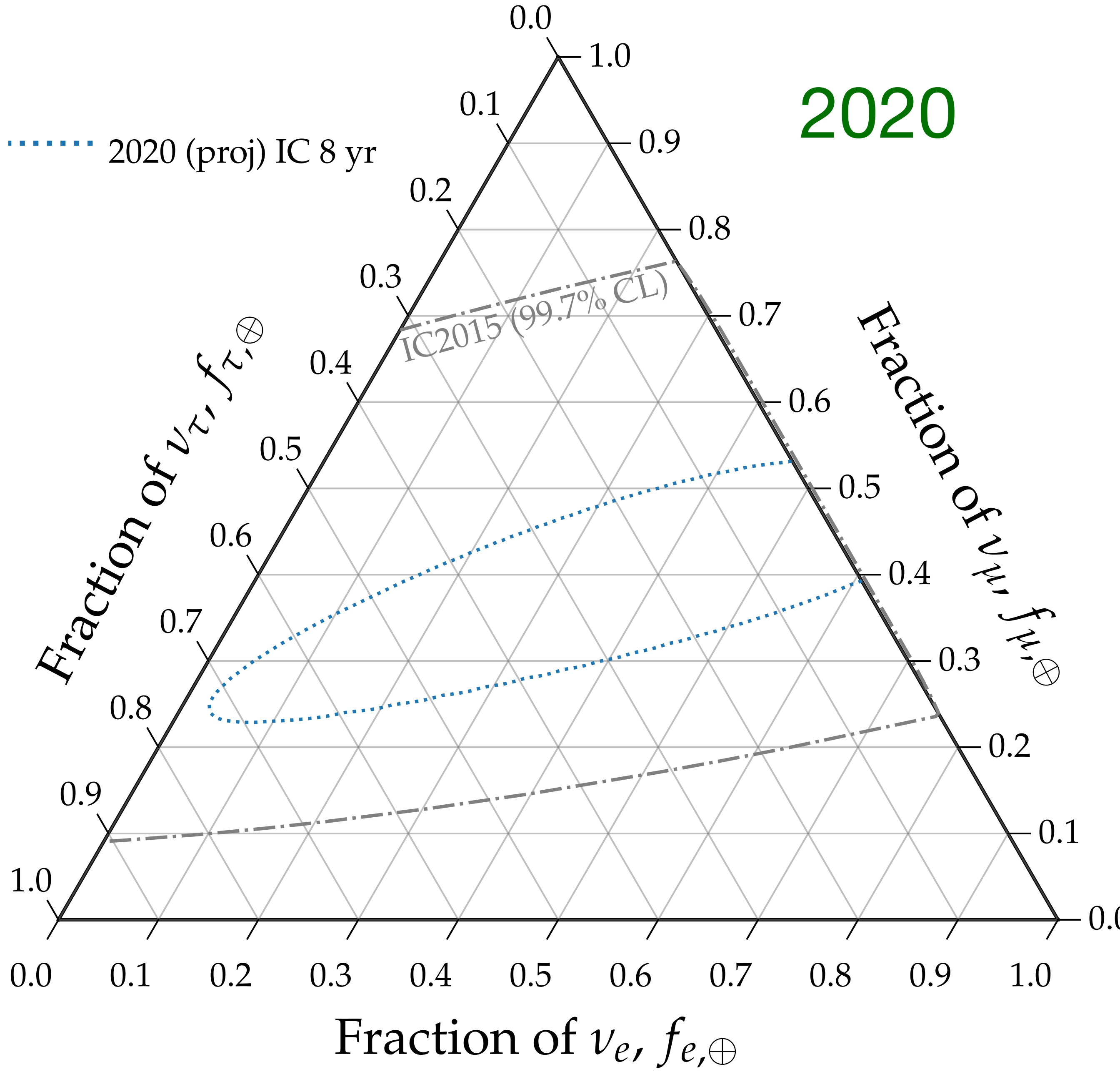


IceCube-Gen2

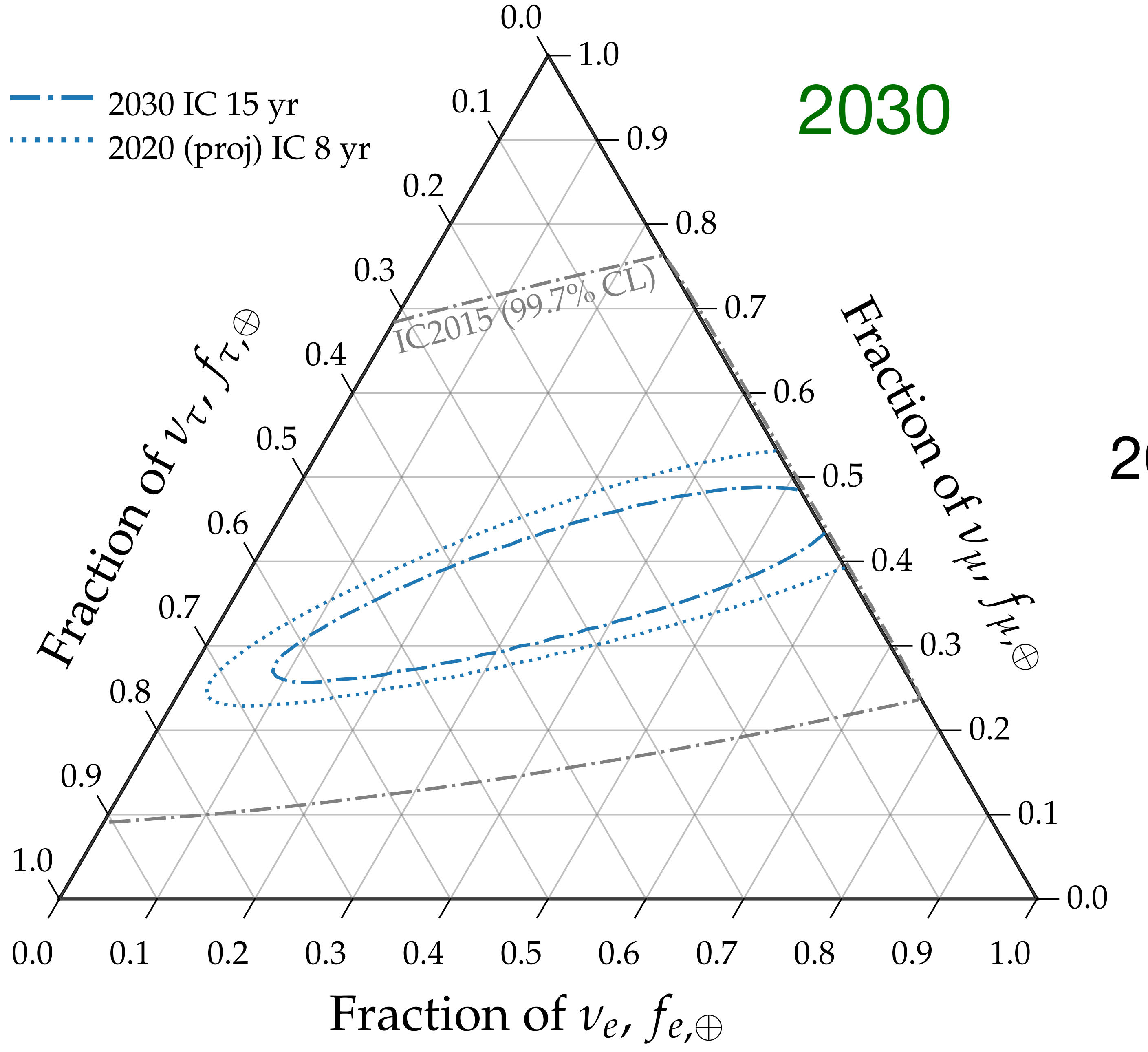


Neutrino Flavor Measurements: Future

2020

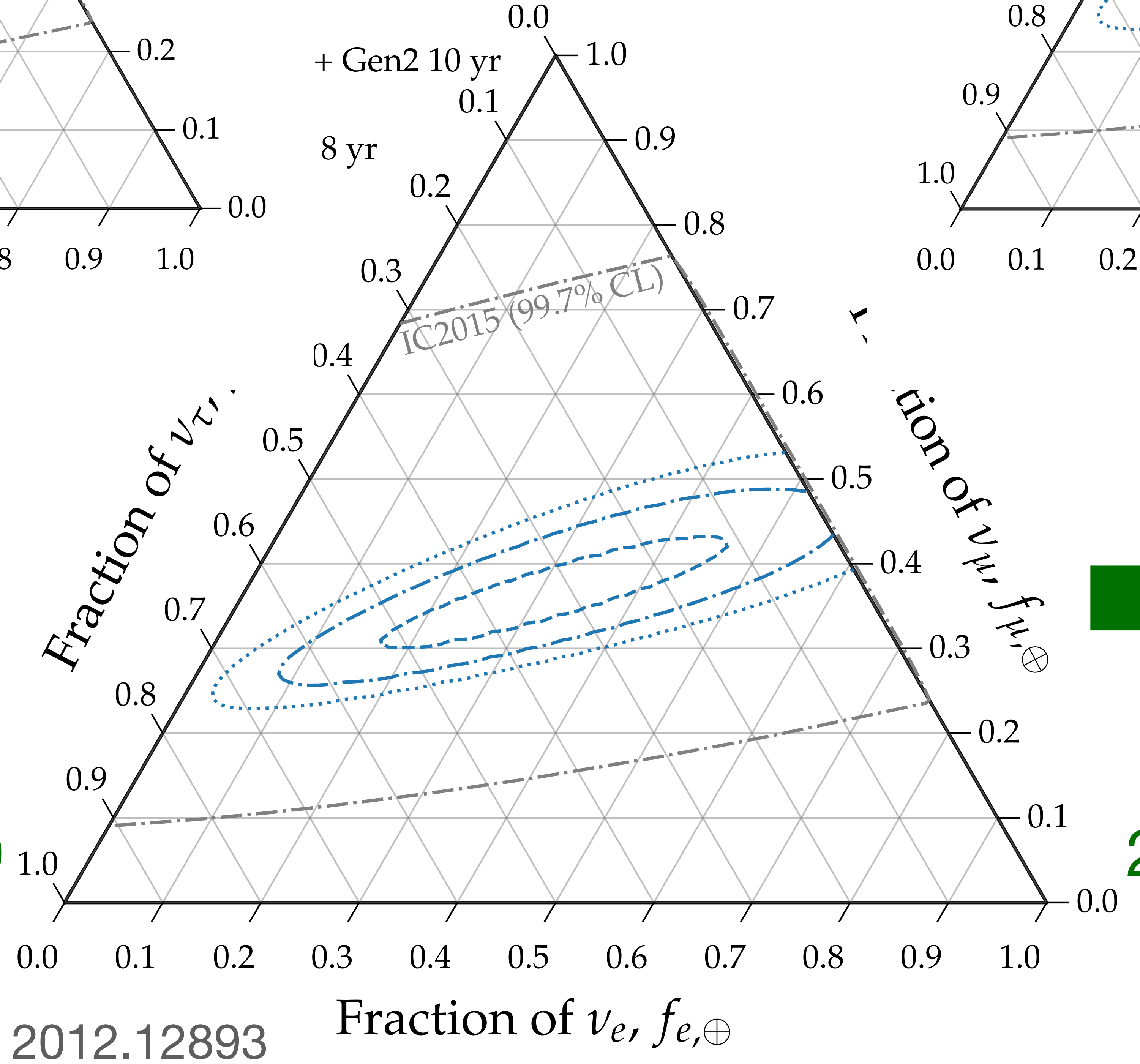


2030

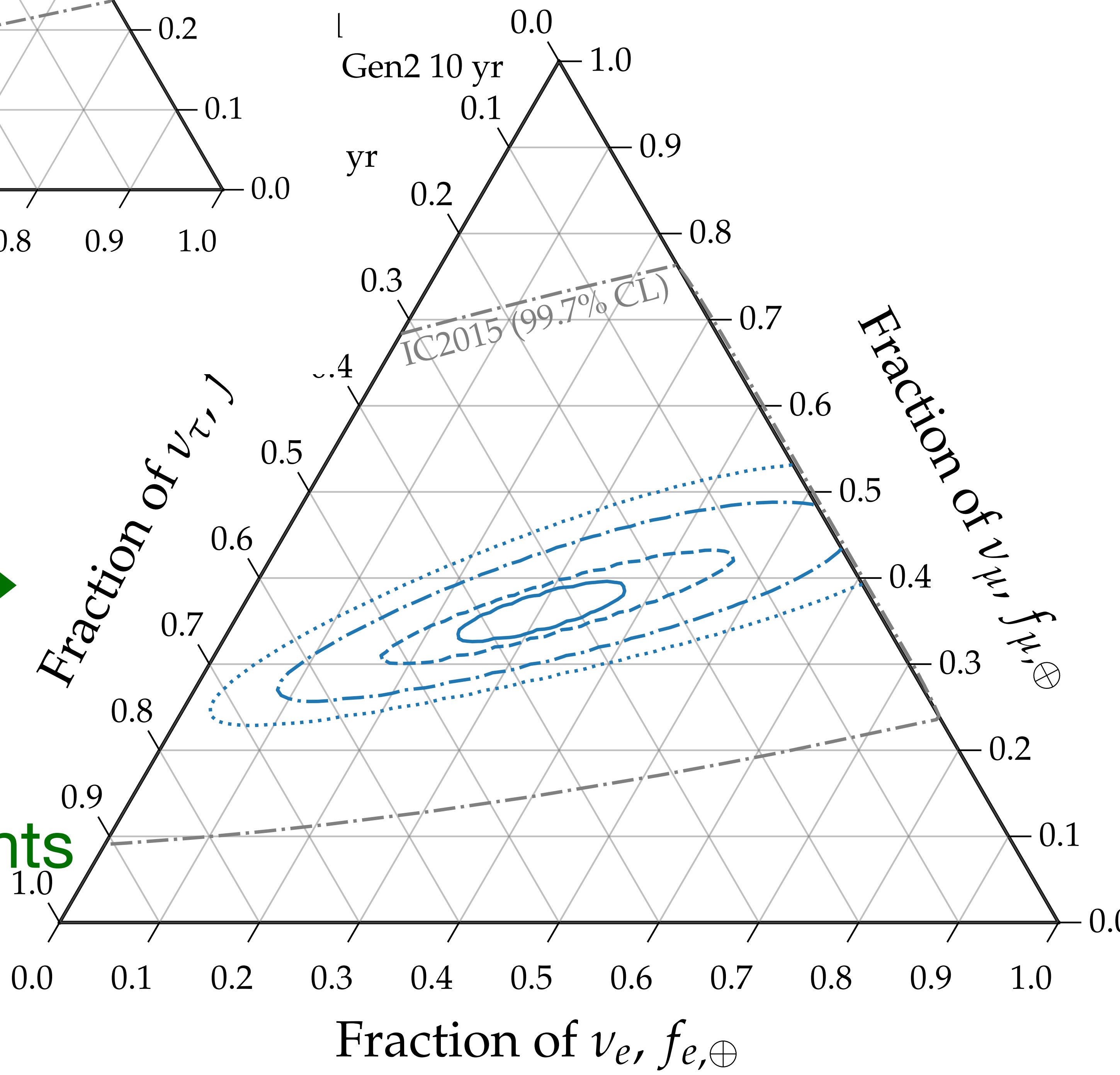


	$f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$
	Flavor ratios at Earth		
2020	$0.30^{+0.13}_{-0.11}$	$0.36^{+0.059}_{-0.053}$	$0.34^{+0.16}_{-0.18}$
2040	$0.30^{+0.039}_{-0.037}$	$0.36^{+0.017}_{-0.016}$	$0.34^{+0.049}_{-0.050}$
2040 all	$0.30^{+0.030}_{-0.027}$	$0.36^{+0.011}_{-0.011}$	$0.34^{+0.037}_{-0.039}$

2040



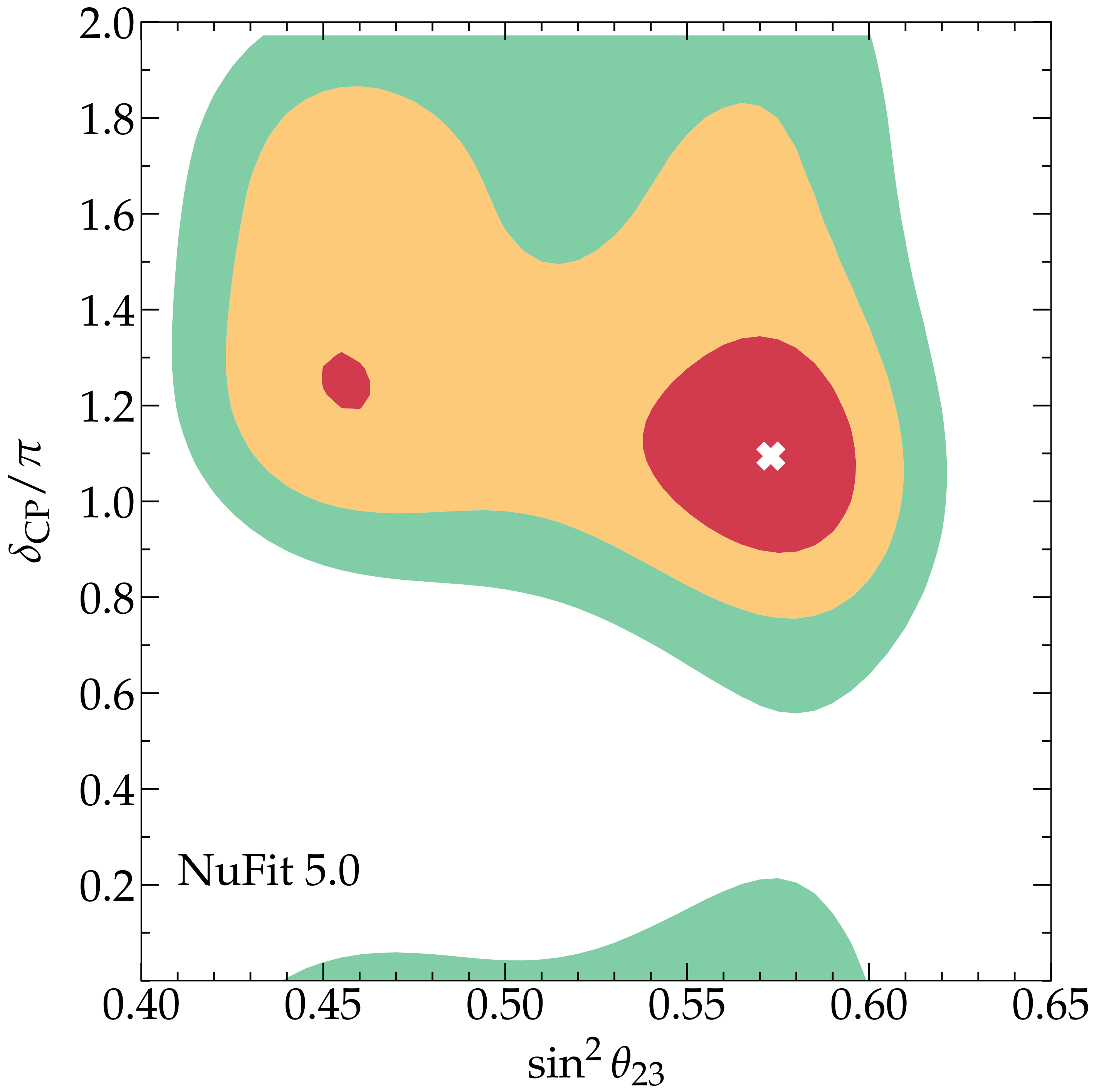
2040 all experiments

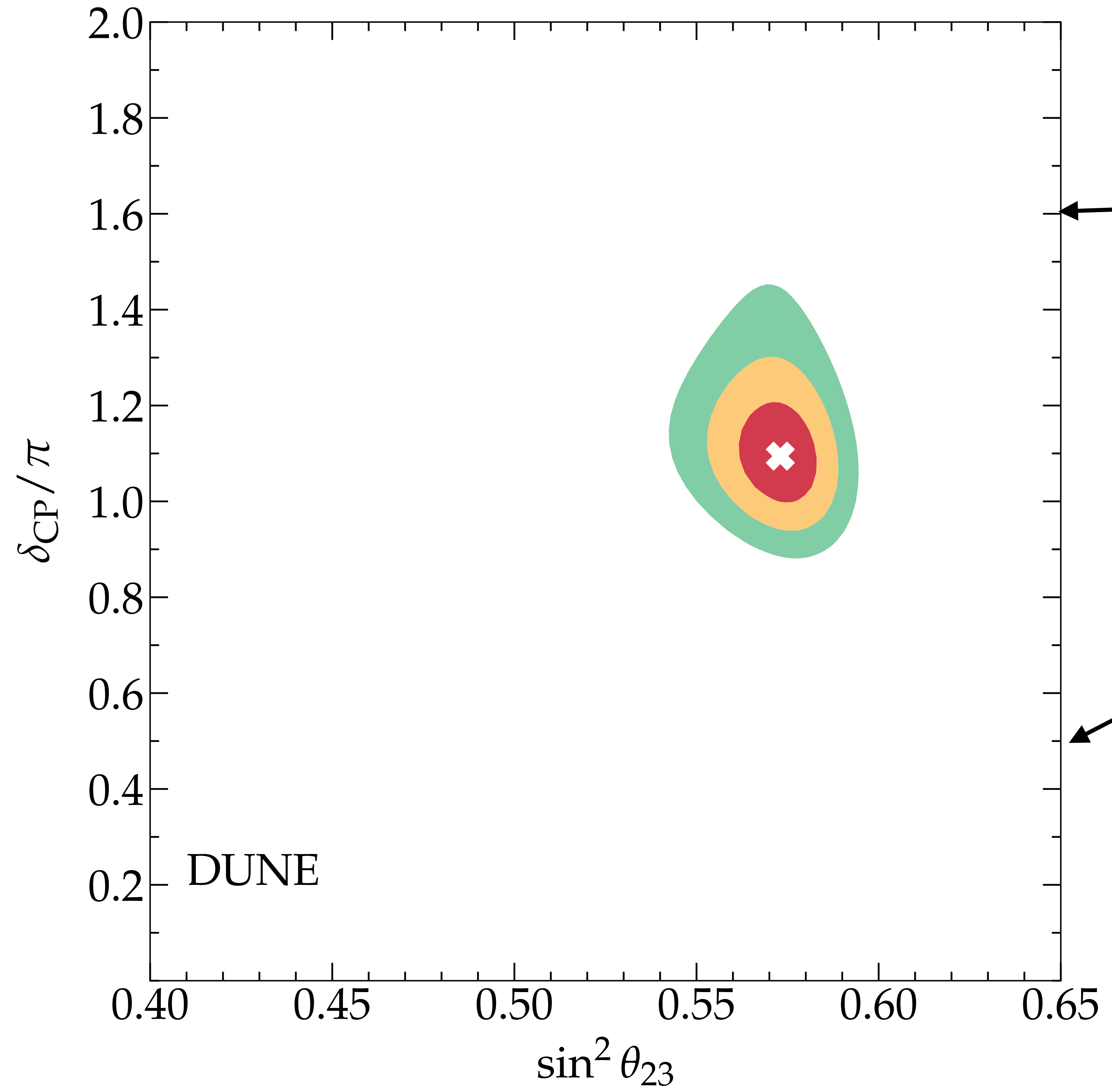


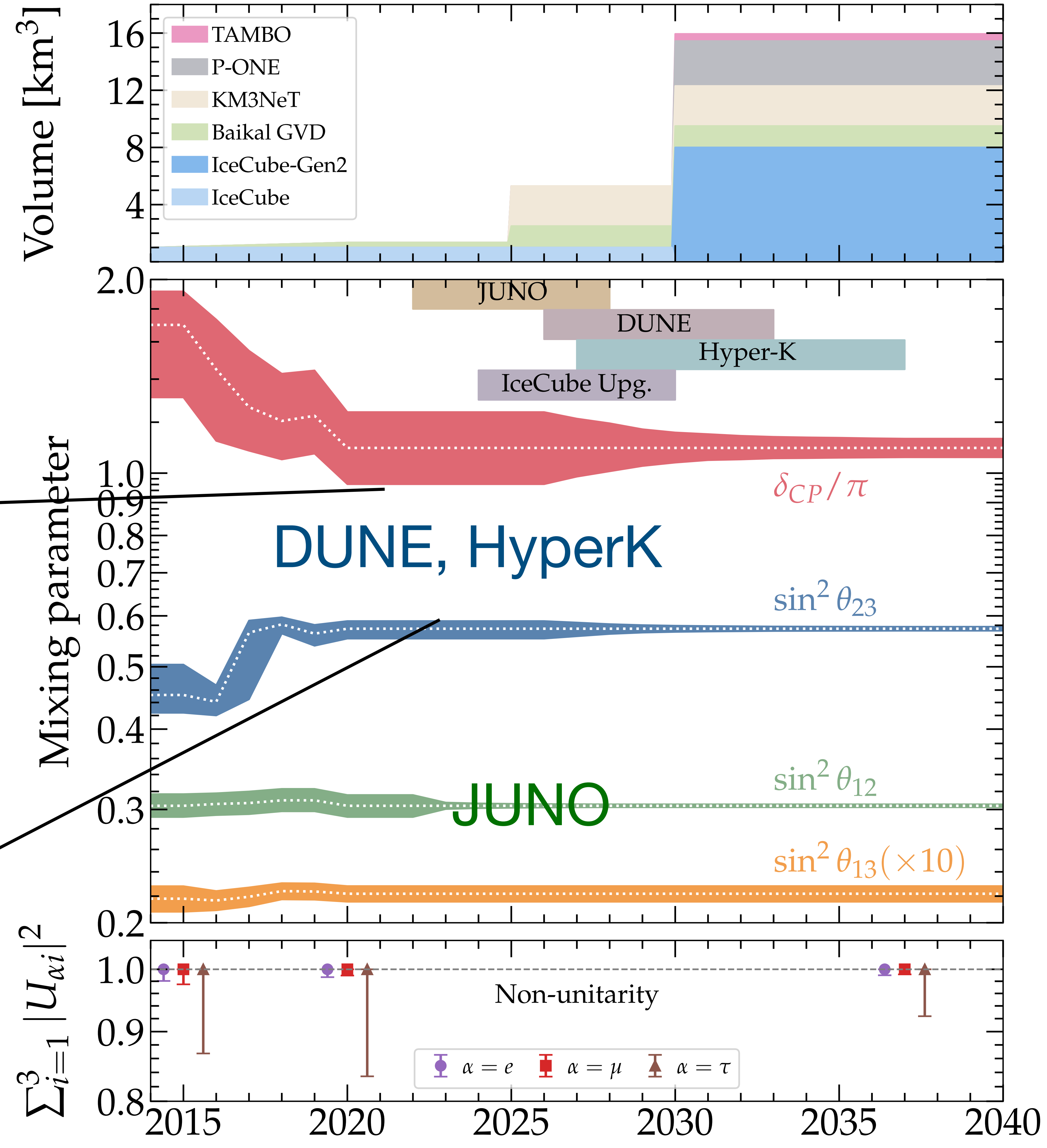
NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Neutrino Oscillation Measurements

- More precise oscillation parameters: JUNO, DUNE, Hyper-K





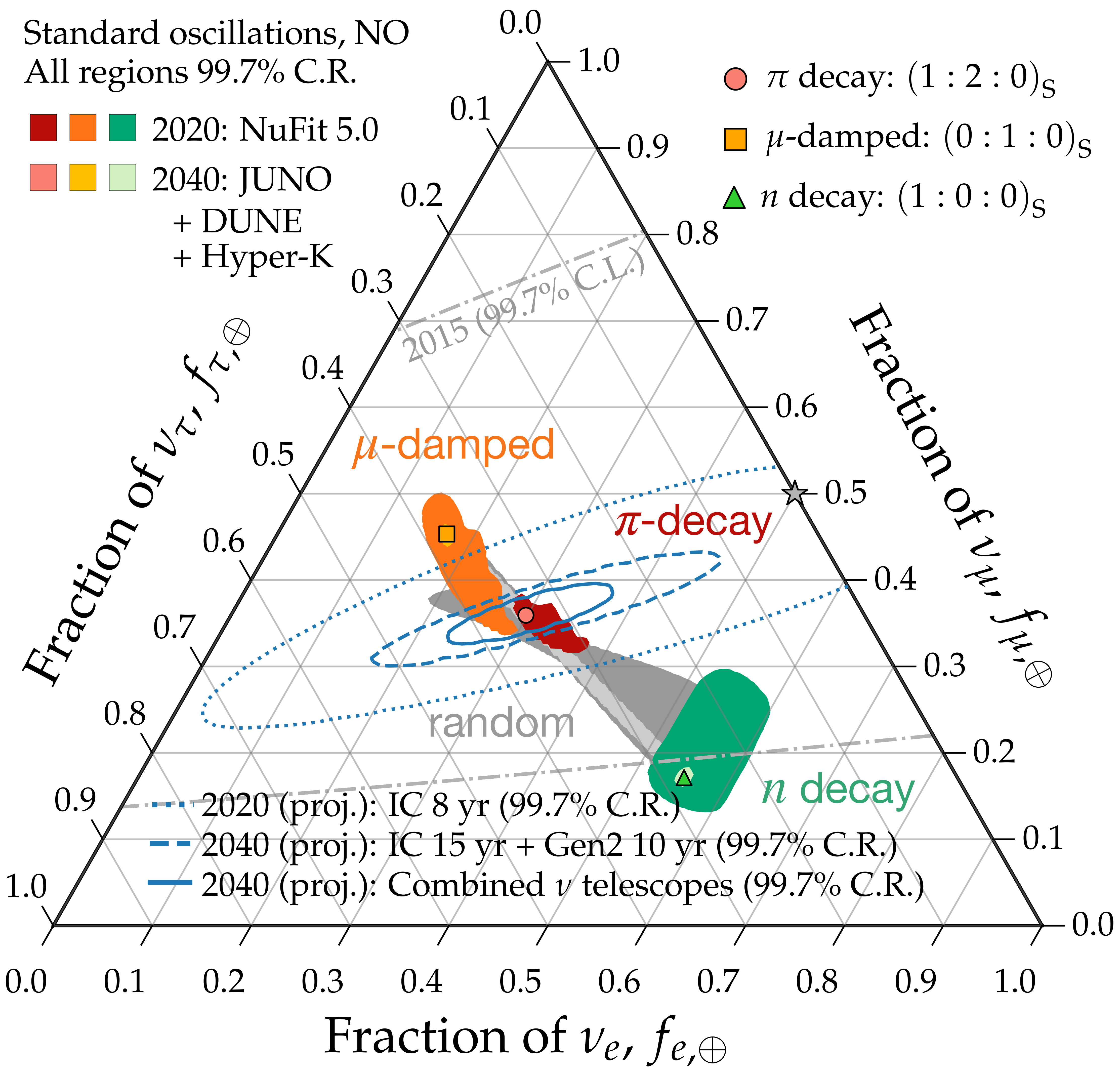


Non-Unitarity

$$P_{\alpha\beta}^{s\to\oplus} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Flavor Composition at Earth



$$P_{\alpha\beta}^{s\to\oplus} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$f_{\beta,\oplus} = \sum_{\alpha=e,\mu,\tau} P_{\alpha\beta}^{s\to\oplus} f_{\alpha,S}$$

Pion decay well separated from muon damped by 2040

NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Flavor Composition at Source

- Assume no ν_τ at source $f_{\tau,S} = 0$
- Combine the information from neutrino oscillation experiments and neutrino telescopes

$$\mathcal{P}(f_{e,\mathrm{S}}) = \int d\boldsymbol{\theta}\mathcal{L}(\boldsymbol{\theta})\mathcal{L}_{\mathrm{exp}}(\boldsymbol{f}_\oplus(f_{e,\mathrm{S}},\boldsymbol{\theta}))\pi(f_{e,\mathrm{S}})$$

uniform prior

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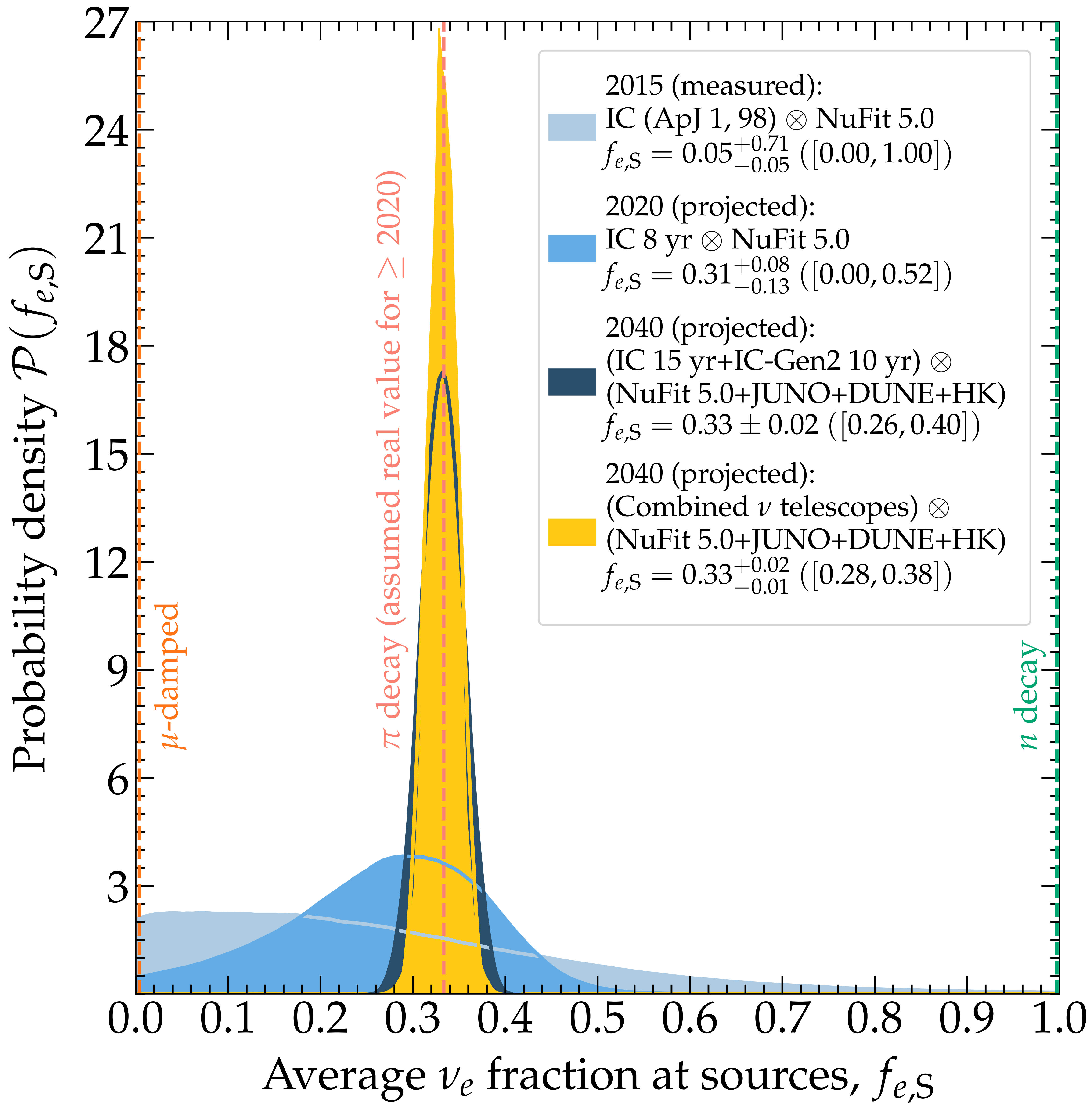
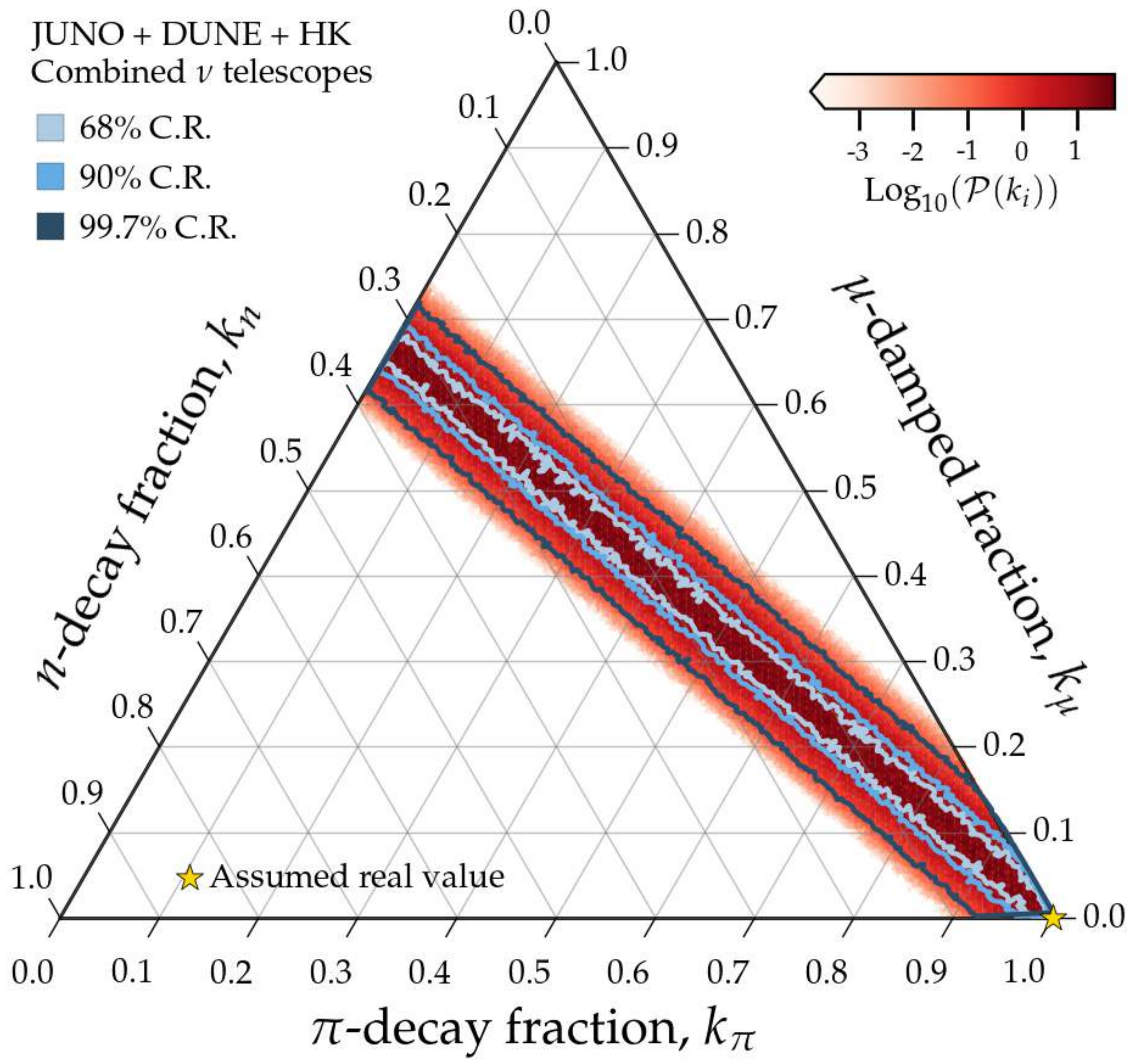


Flavor Composition at Source

- k_π: pion decay fraction $(1:2:0)$
- k_μ: muon-damped fraction $(0:1:0)$
- k_n: neutron decay faction $(1:0:0)$

$$\mathcal{P}(\boldsymbol{k}) = \int d\boldsymbol{\theta}\mathcal{L}(\boldsymbol{\theta})\mathcal{L}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}(\boldsymbol{k}),\boldsymbol{\theta}))\pi(\boldsymbol{k})$$



NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Leptonic Non-unitarity

Source determination is robust against non-unitarity

- Assuming non-unitarity

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- Oscillation probability

$$P^{\rm NU}_{\alpha\beta} = \frac{1}{N_\alpha N_\beta} \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$N_\alpha \equiv \sum_{i=1}^{3} |U_{\alpha i}|^2$$

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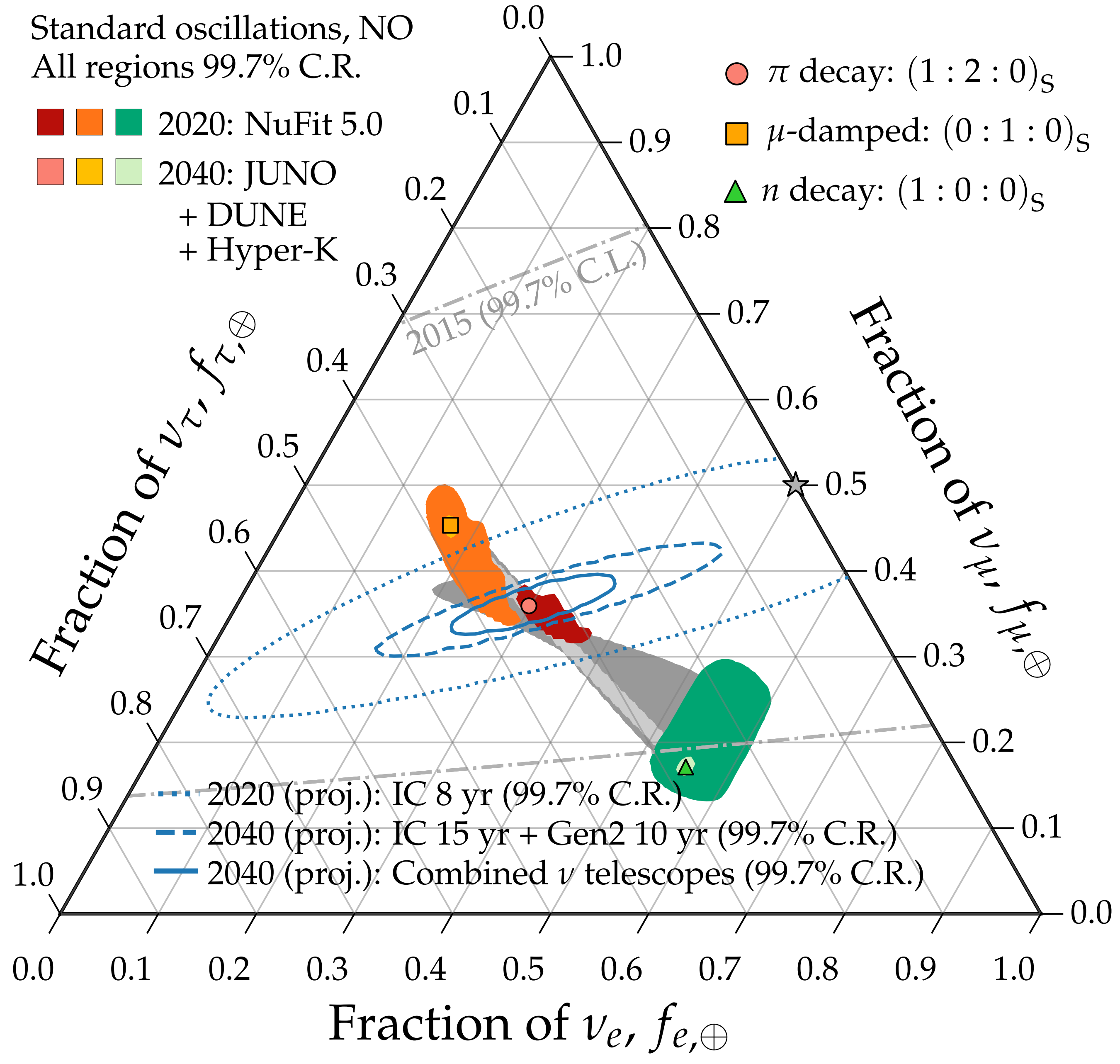
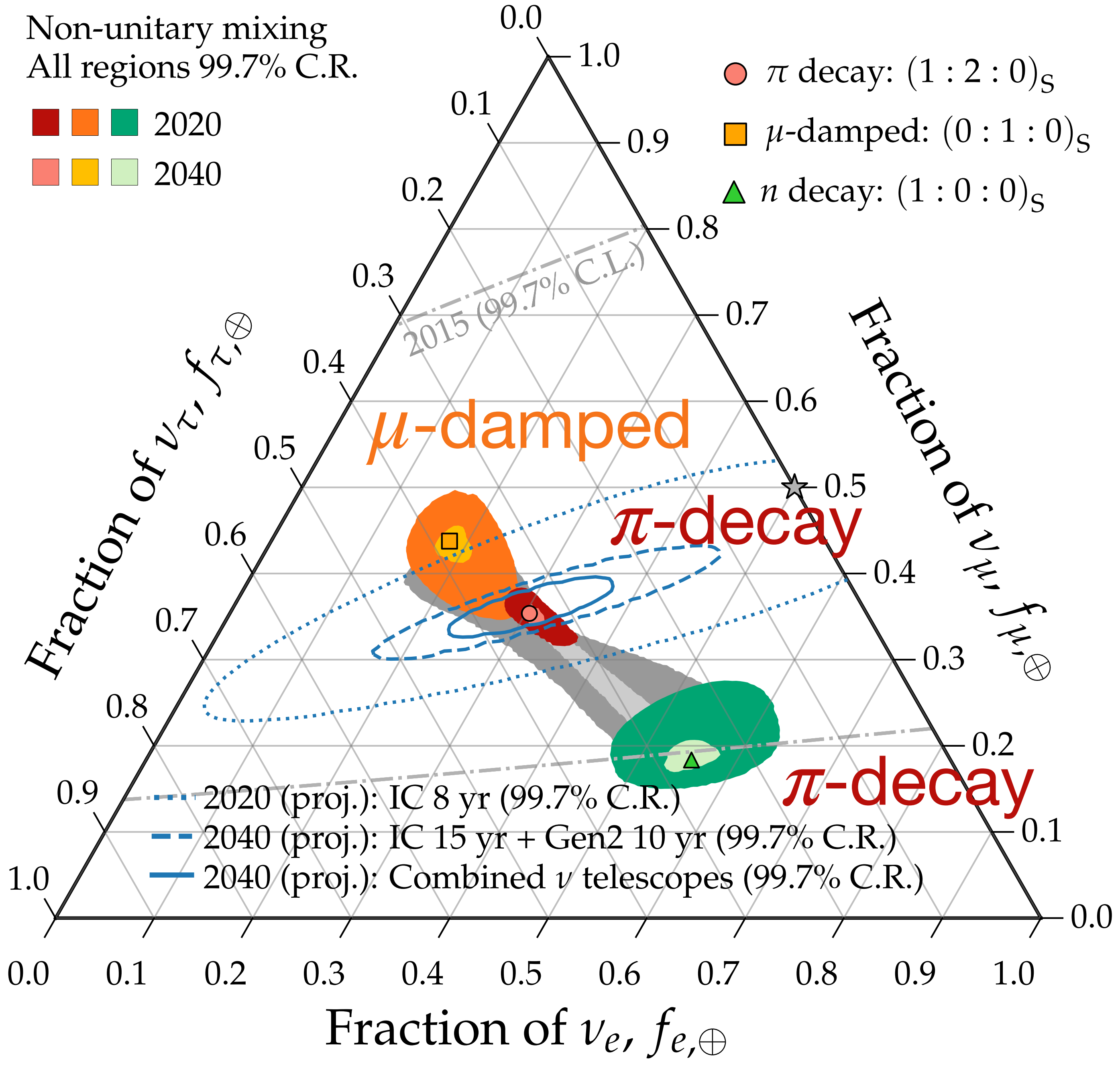


Standard Oscillation

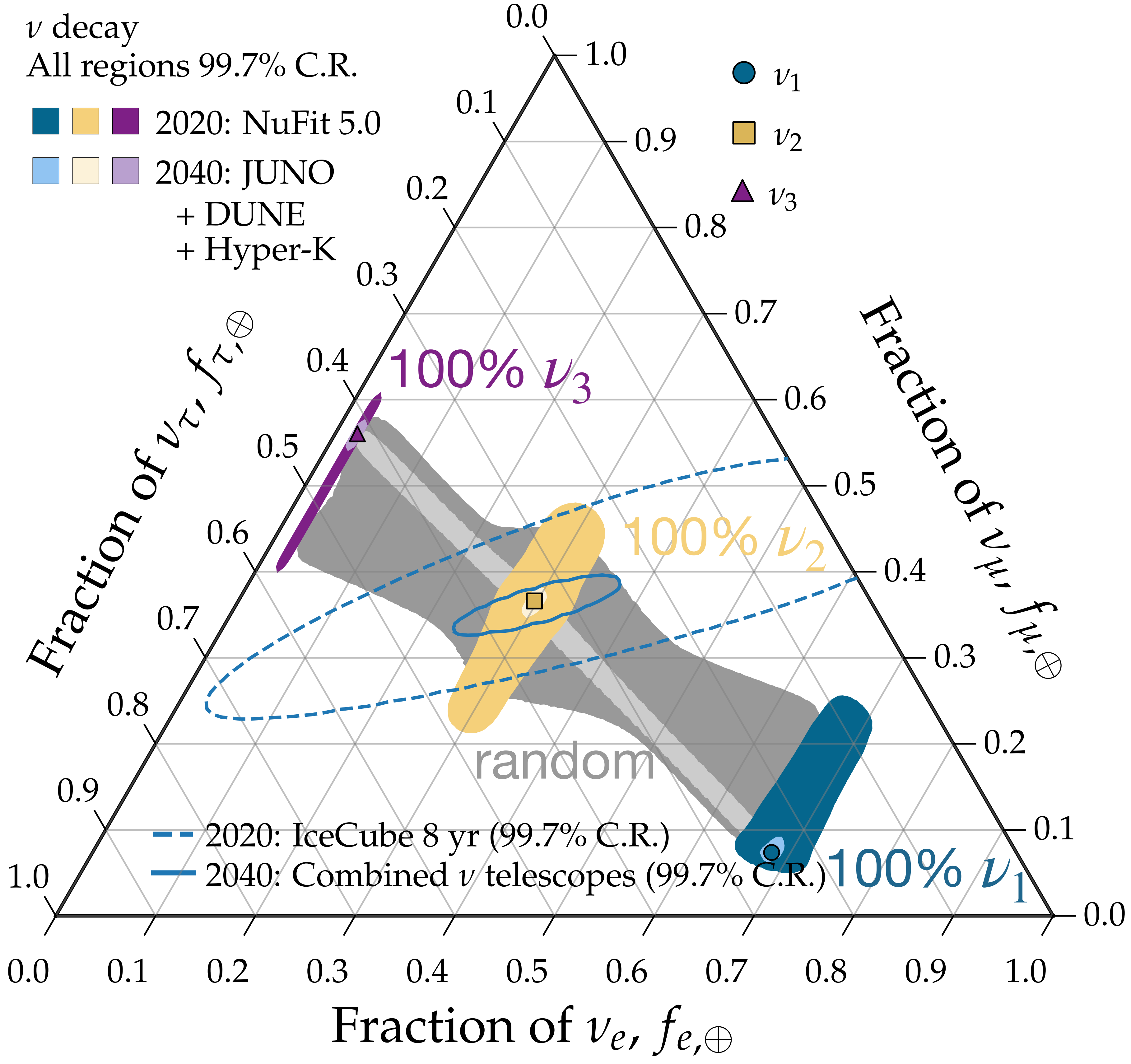


Non-unitarity

Neutrino Decay

- Neutrino decay is model dependent and mass-ordering dependent
- With decay

$$f_{\beta,\oplus} = \sum_{i=1}^{3} |U_{\beta i}|^2 f_{i,\oplus}$$



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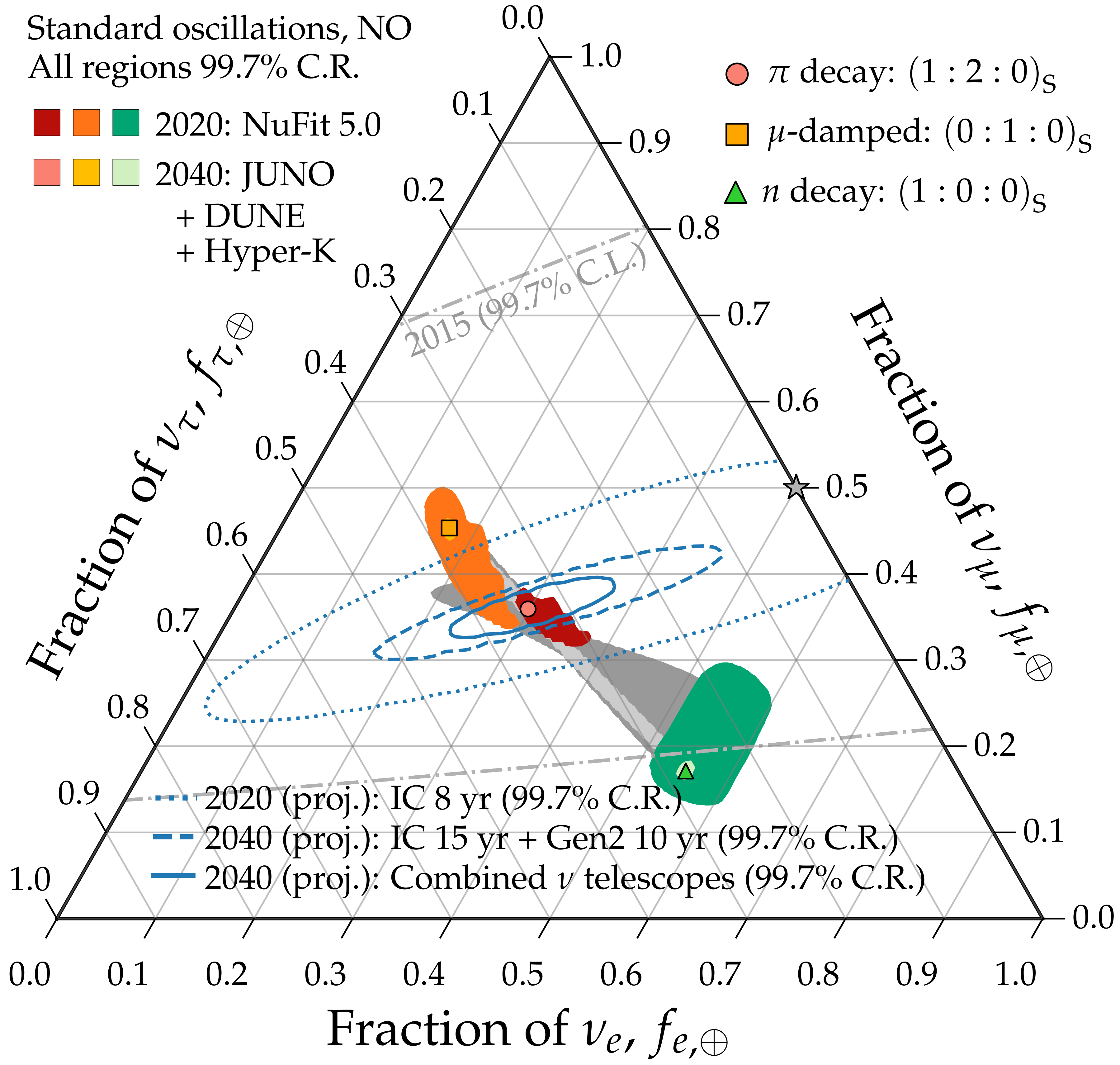
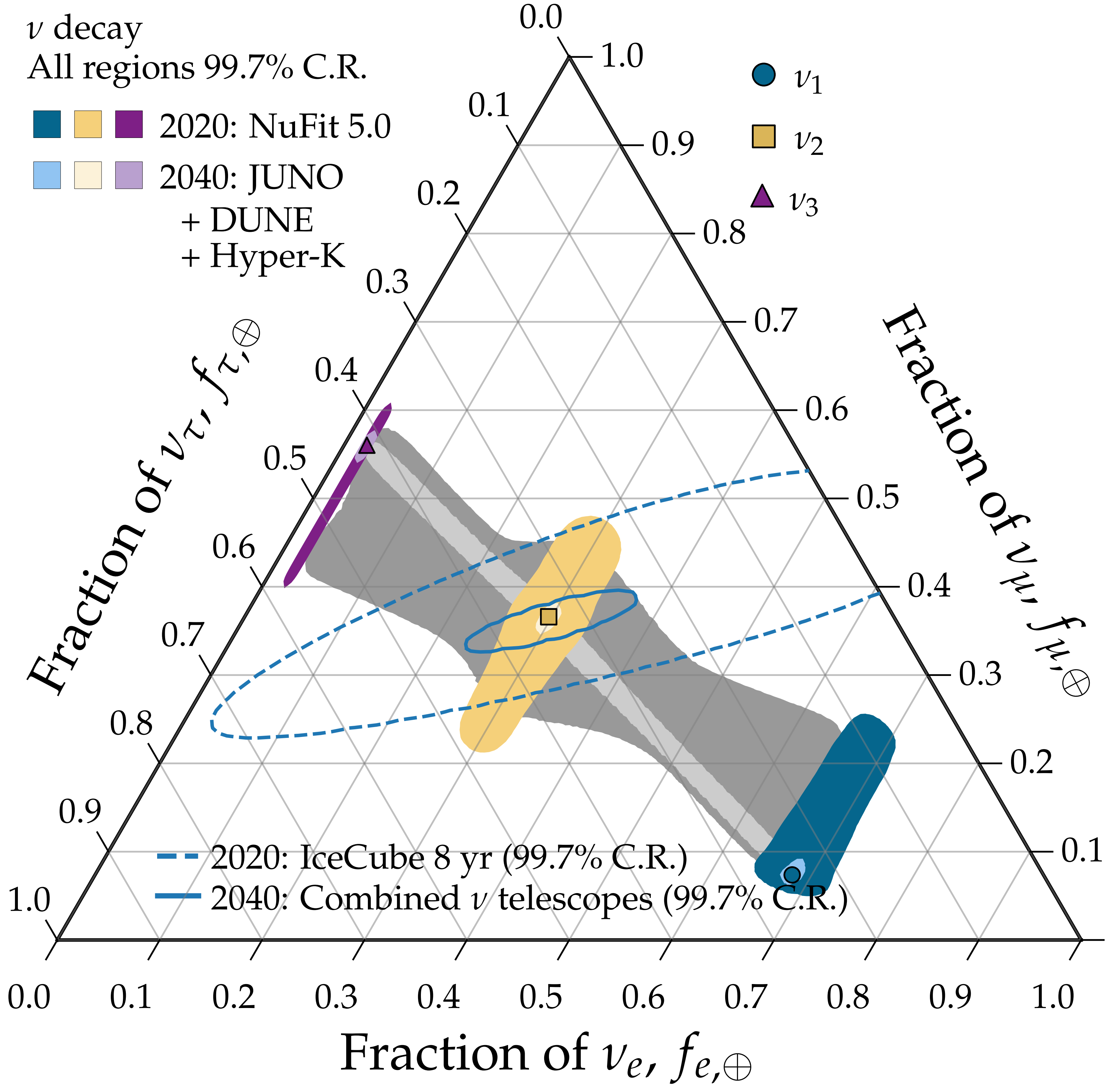
Neutrino Decay

Standard Oscillation



Neutrino Decay



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Neutrino Decay

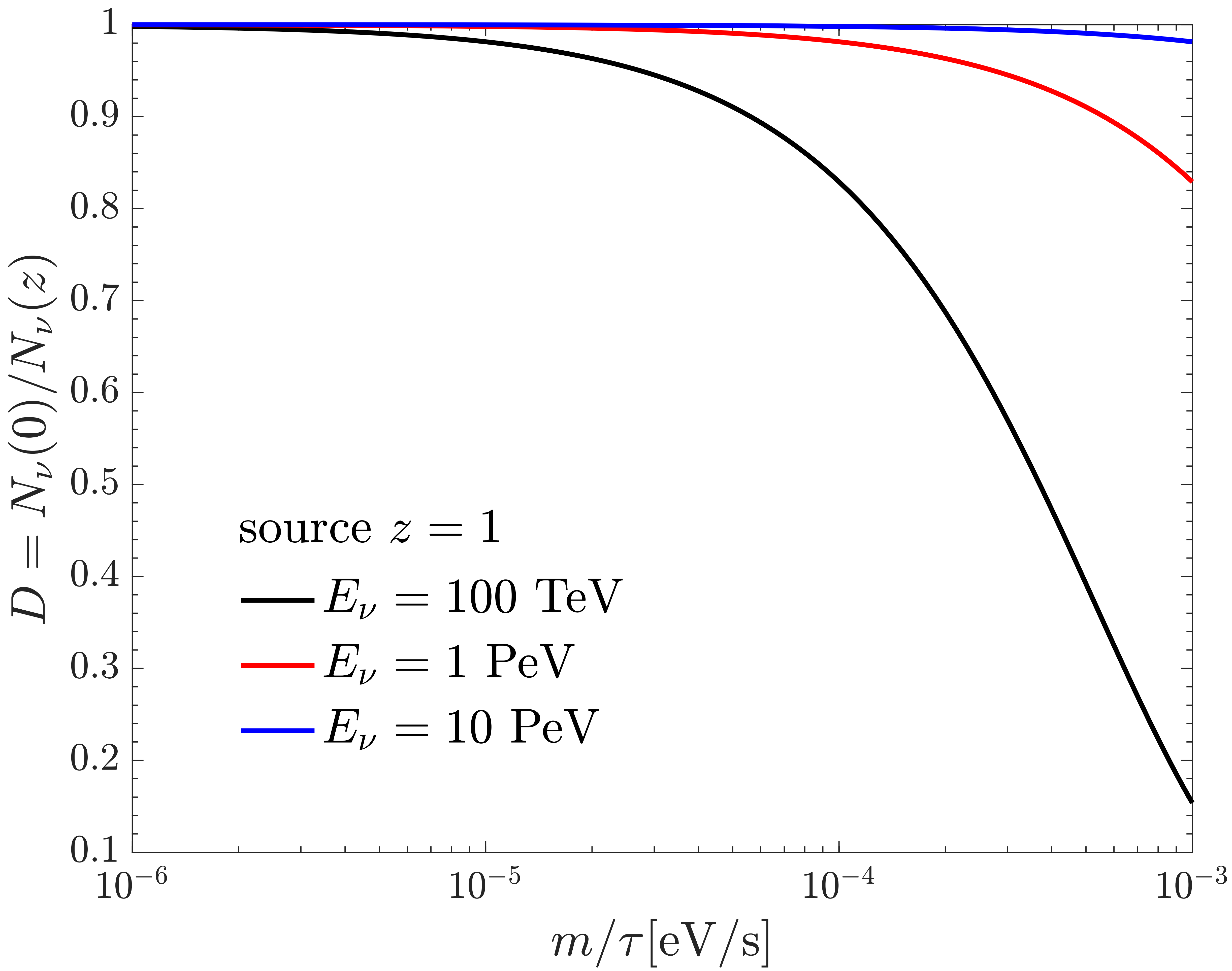
- Assume ν_2, ν_3 decay invisibly, ν_1 stable

- Assume pion decay at source $(f_e : f_\mu : f_\tau)_S = (1/3,\ 2/3,\ 0)$

- Sum up neutrinos sources at different redshifts

$$D_i = \frac{N_i(E,0)}{N_i(E,z)} = Z(z)^{-\frac{m_i}{\tau_i}\frac{1}{H_0 E}}$$

NS, Li, Argüelles, Bustamante, Vincent, 2012.12893



Neutrino Decay

ν telescopes $\otimes$ oscillation experiments	m_ν/τ_ν (eV s^{-1})
2015 (measured): IC $\otimes$ NuFit 5.0	4.1×10^{-4}
2020 (projected): IC 8 yr $\otimes$ NuFit 5.0	7.4×10^{-5}
2040 (projected): IC 15 yr + IC-Gen2 10 yr $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	2.5×10^{-5}
2040 (projected): All ν telescopes $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	1.8×10^{-5}

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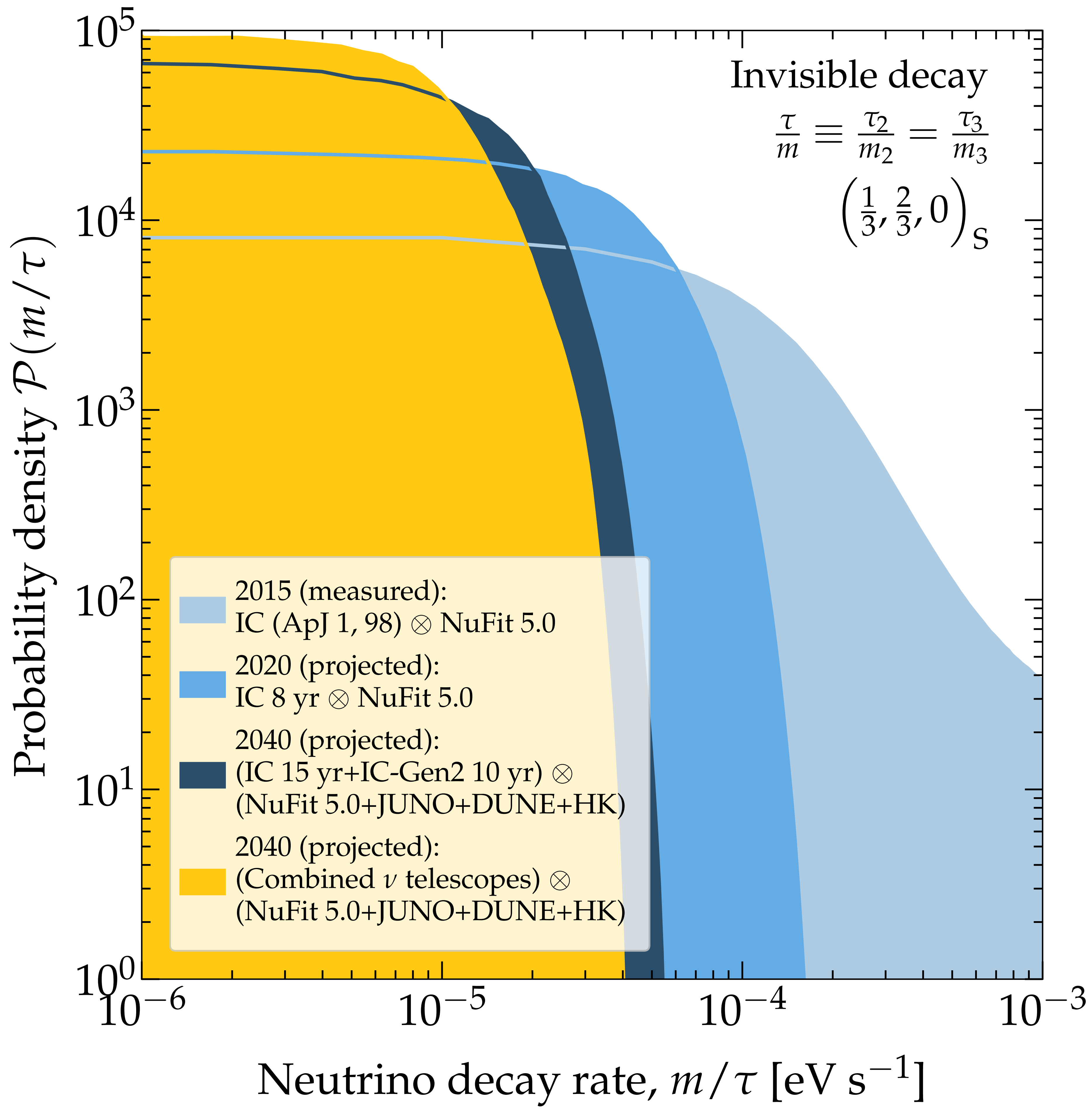

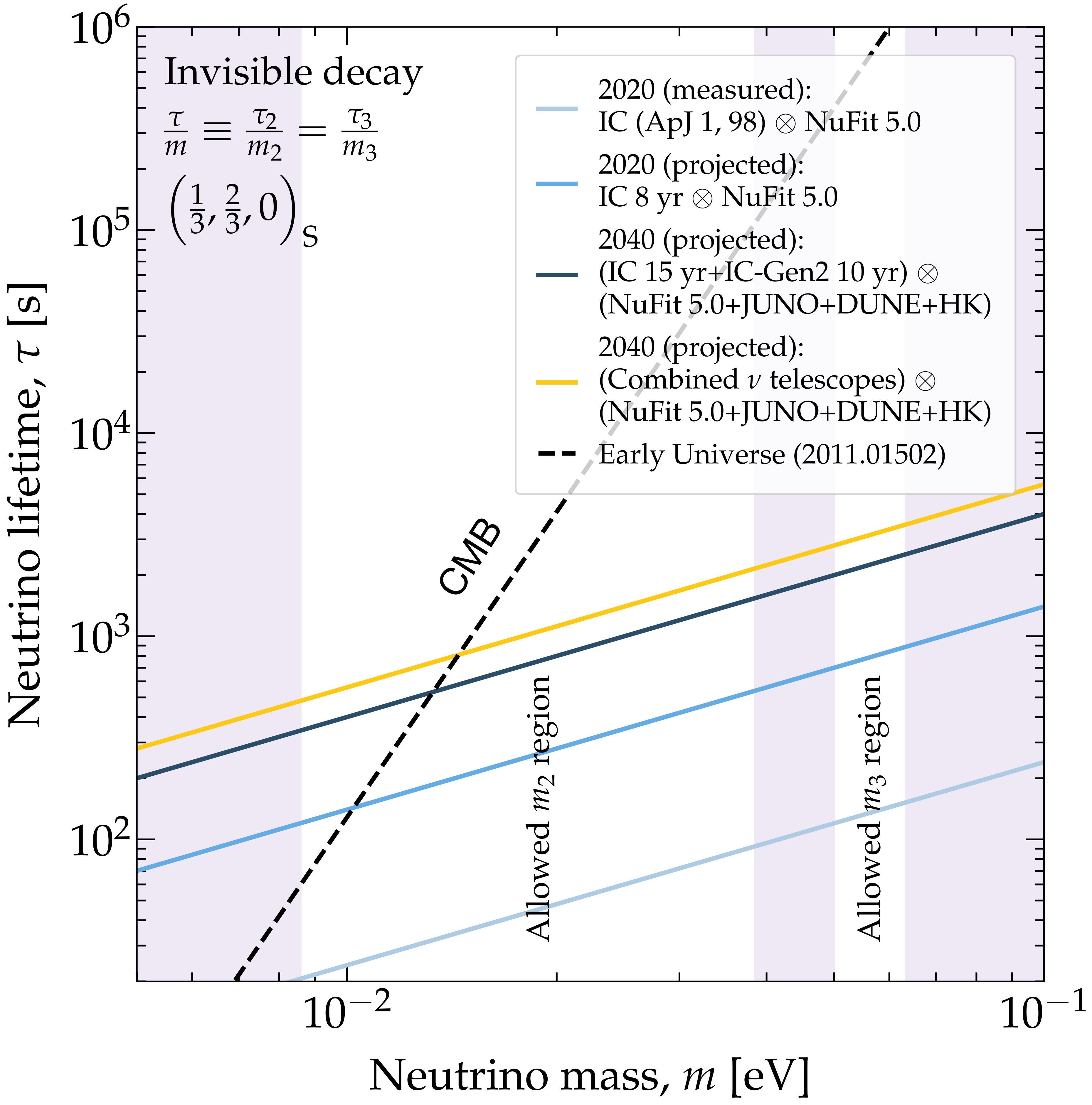

Summary

- More precise neutrino mixing parameters at oscillation experiments: JUNO, DUNE, HK…
- Better flavor ratio measurement with significantly more high energy neutrino events: IceCube-Gen2, P-ONE, KM3NeT, GVD, TAMBO…
- Pin down the production mechanism at source, robust against non-unitarity
- Constrain neutrino decay and neutrino lifetime
- More new physics at future neutrino telescopes: leptoquarks, Z', microscopic black holes, long-lived particles

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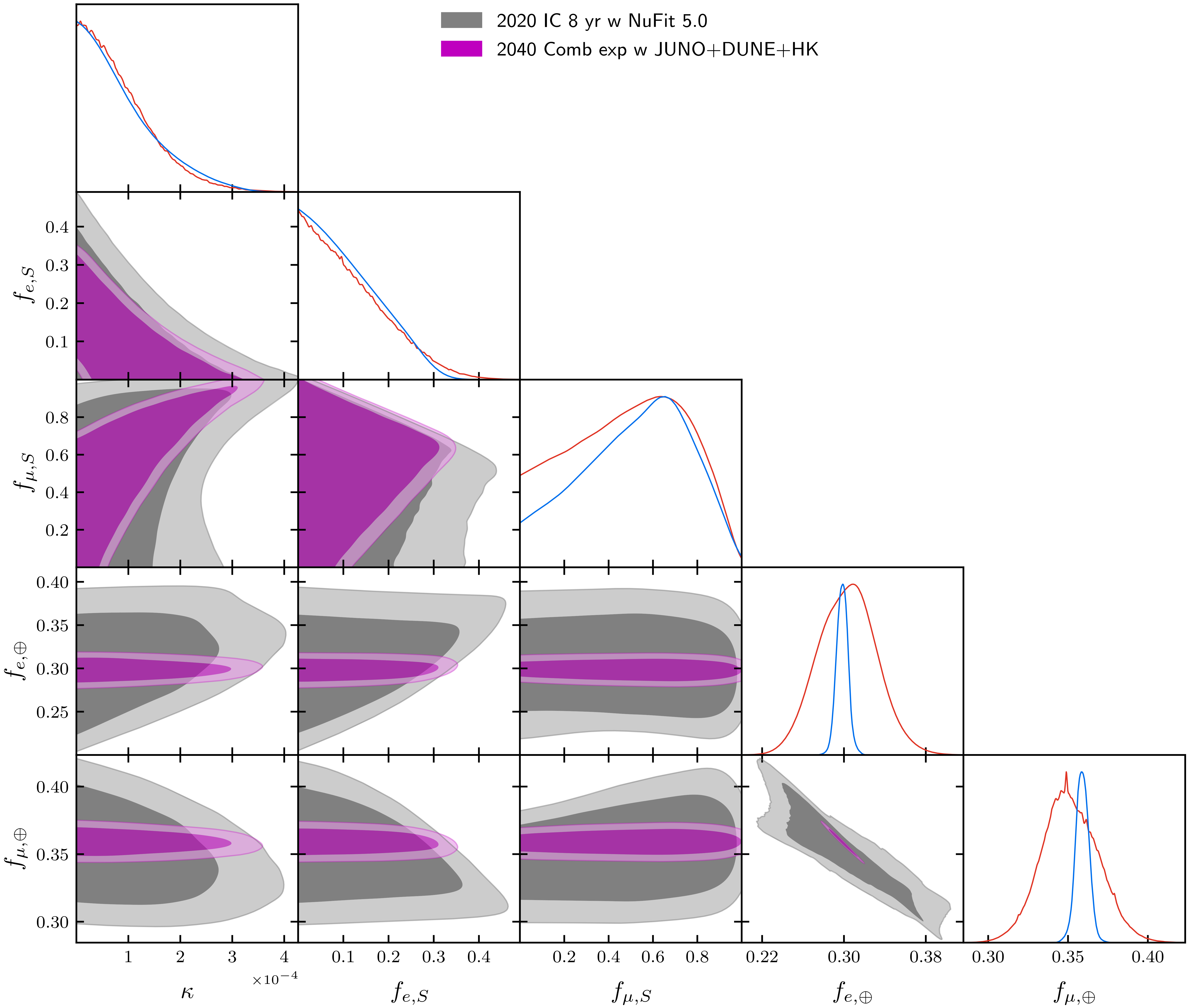
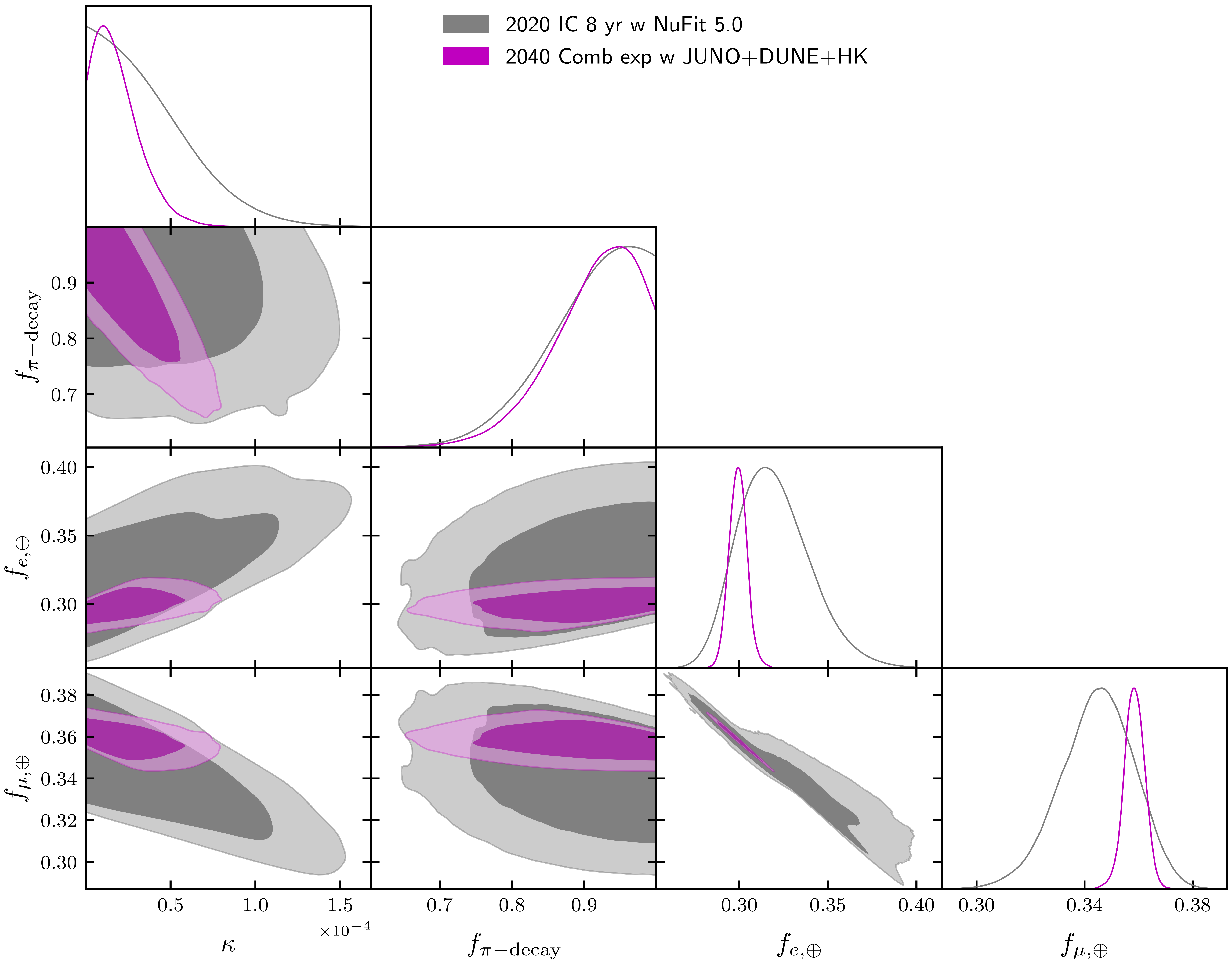
Backup Slides

Neutrino Decay



Neutrino Decay

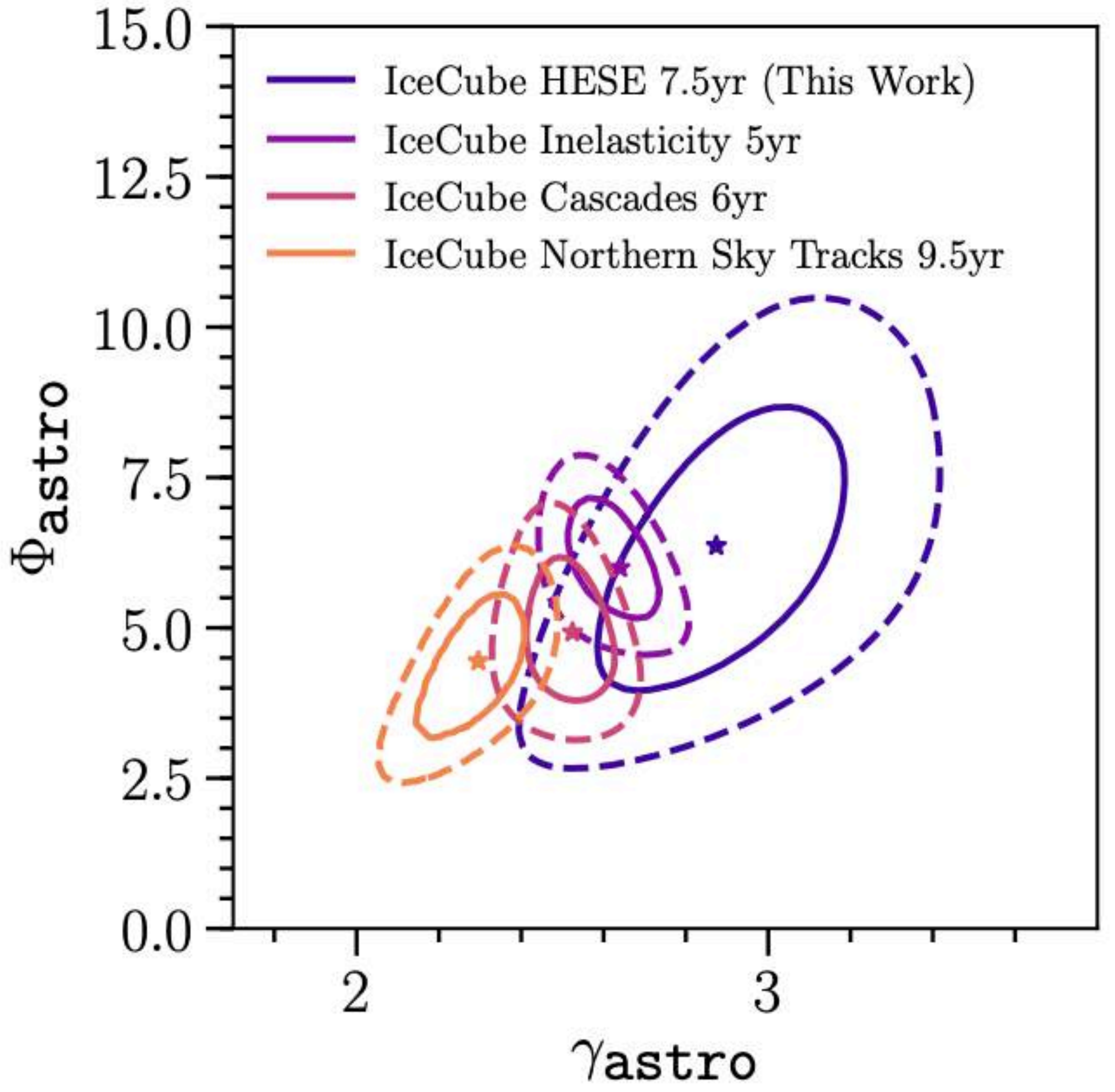


Astrophysical Neutrino Flux

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

$\gamma_{\text{astro}} = 2.87^{+0.20}_{-0.19}$ HESE 7.5 years

IceCube Collaboration, 2011.03545



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Where We Are

- Solar neutrinos + atmospheric neutrinos + reactor neutrinos + accelerator neutrinos
- $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ within 4%, $\sin^2\theta_{13}$ within 3%
- δ_{CP} and mass ordering less constrained

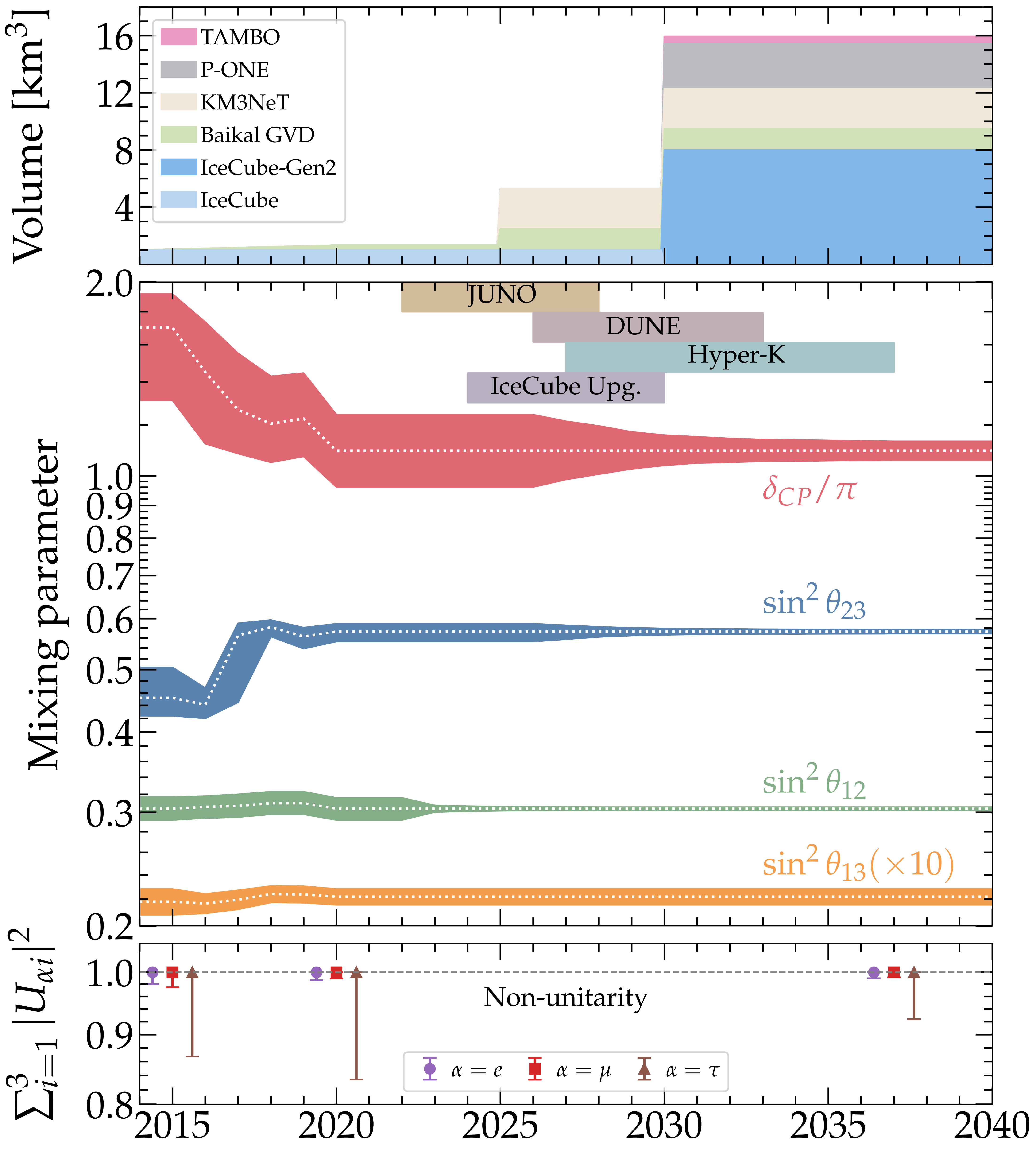
NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

IceCube Collaboration, 2011.03561

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

What We Expect



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

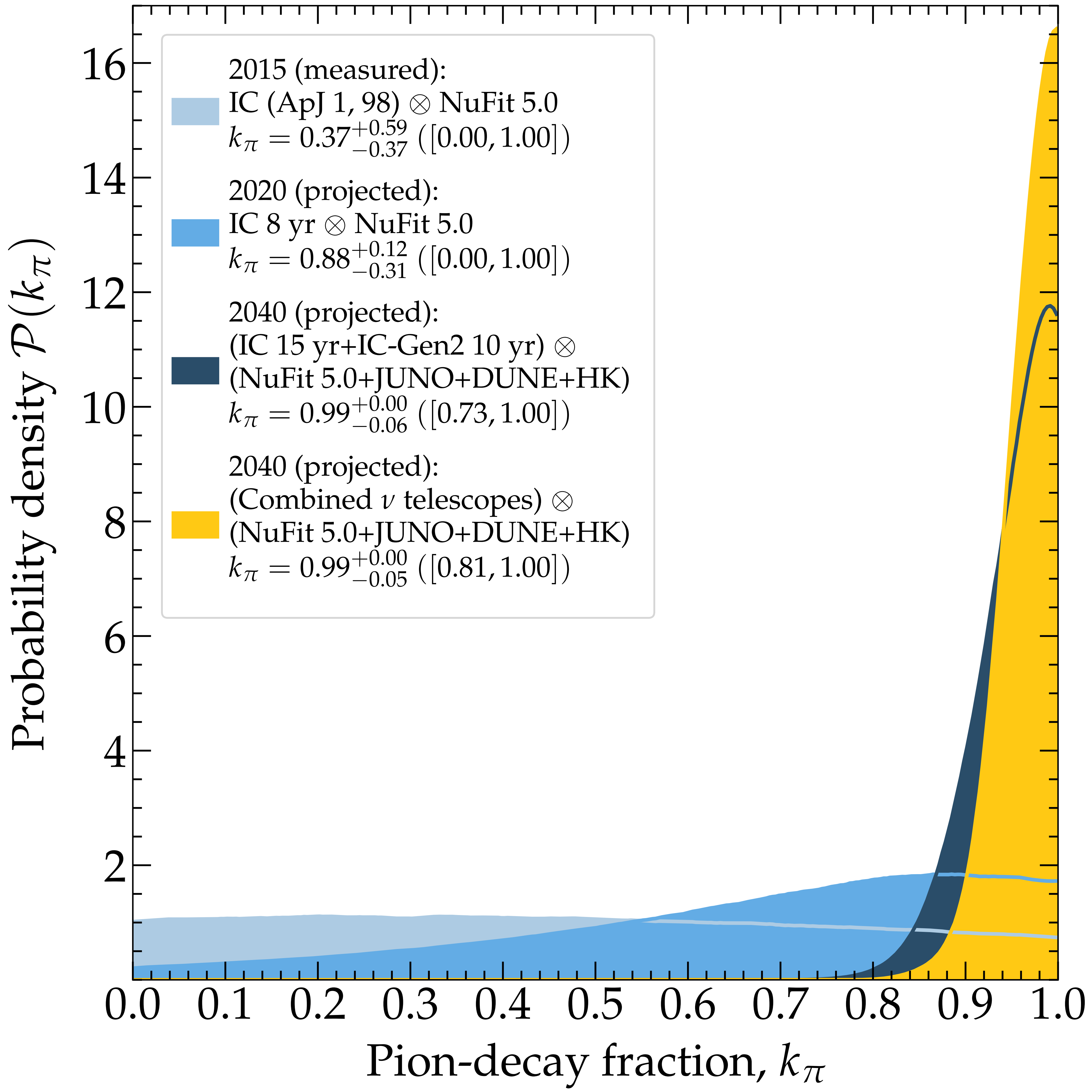
NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Flavor Composition at Source

- Neutron decay very subdominant
- Assume $k_n = 0$

$$\mathcal{P}(k_\pi) = \int d\boldsymbol{\theta} \mathcal{L}(\boldsymbol{\theta}) \mathcal{L}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}(k_\pi), \boldsymbol{\theta})) \pi(k_\pi)$$

Pion decay determined within 20% by 2040



NS, Li, Argüelles, Bustamante, Vincent, 2012.12893