The Future of Neutrino Telescopes: Neutrino Sources and New Physics

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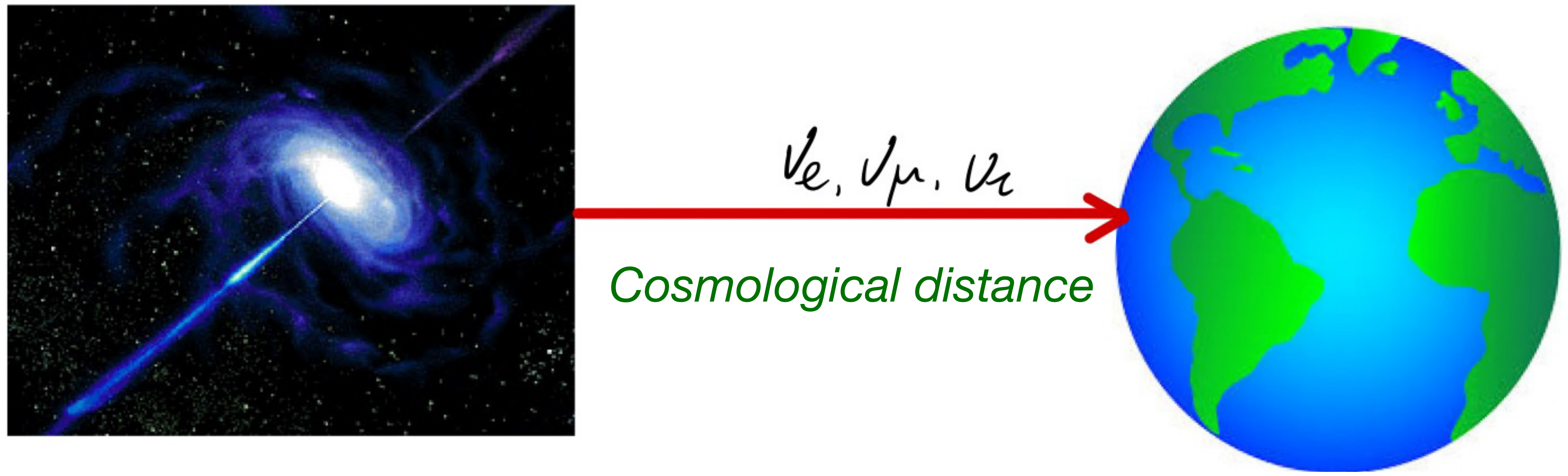
July 12, 2021

Code available at https://github.com/songningqiang/FANFIC

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University

High Energy Astrophysical Neutrinos



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

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

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

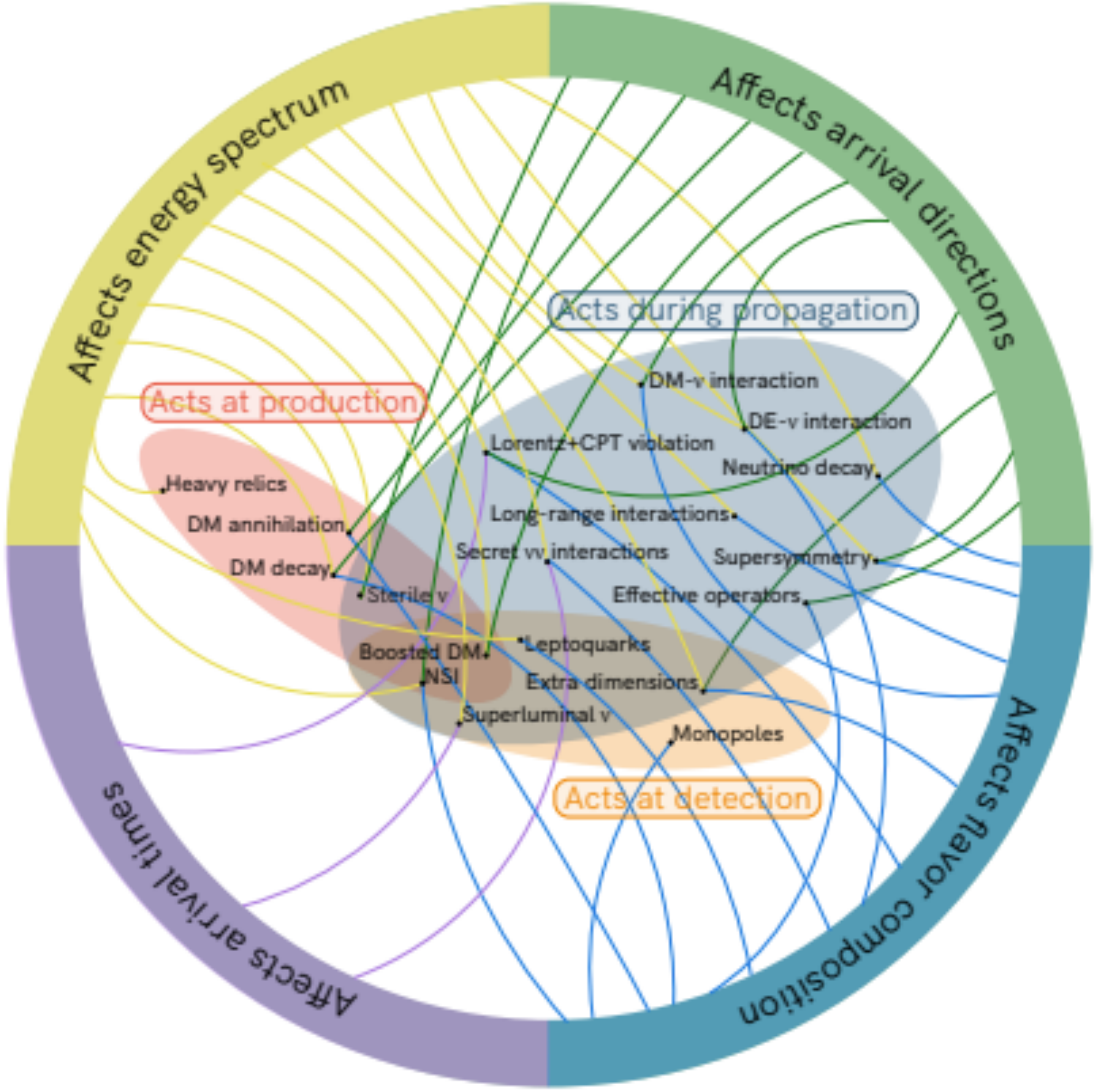
- Muon-damped $(\nu_e : \nu_\mu : \nu_\tau) = (0 : 1 : 0)$

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

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

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

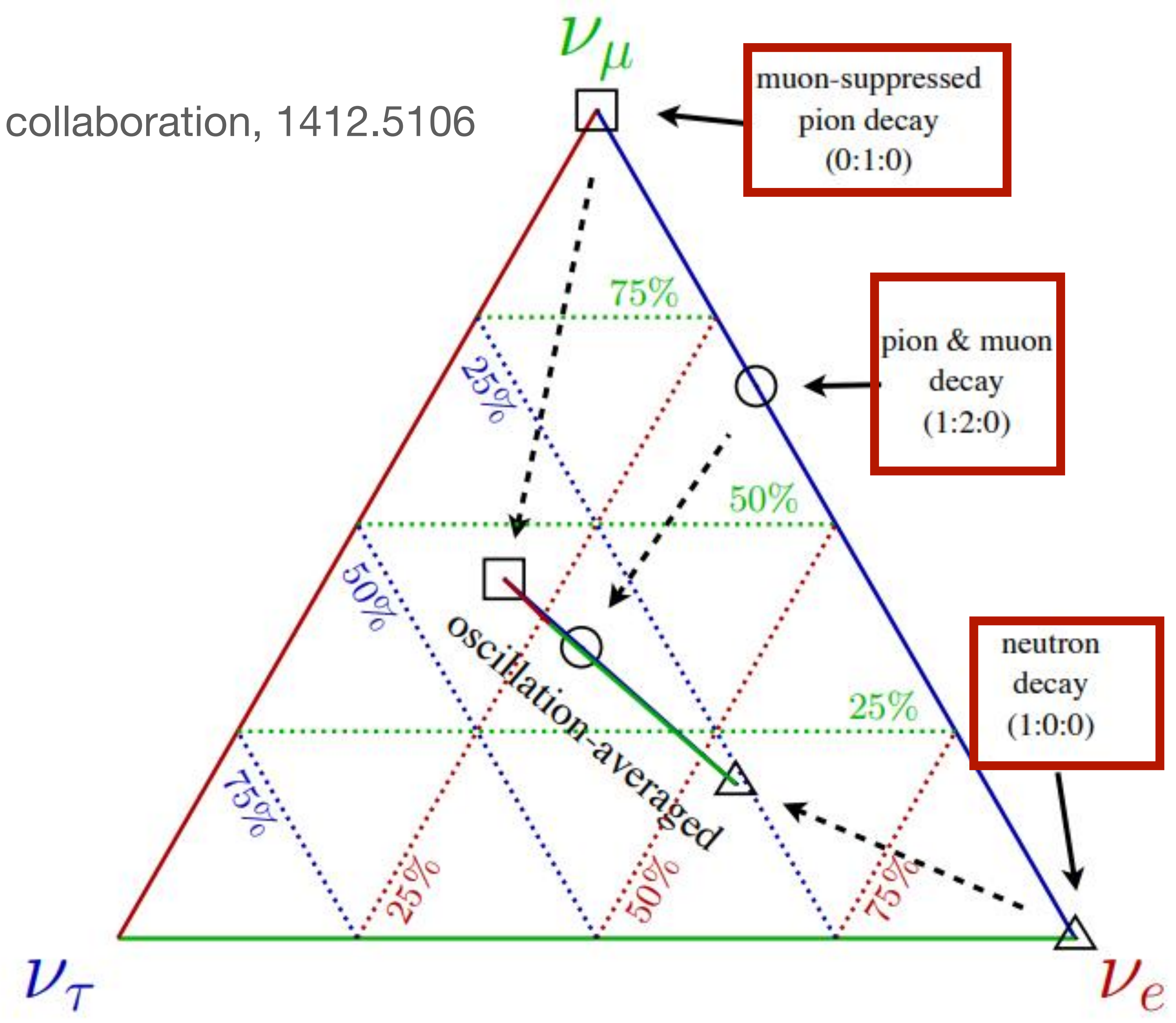
$$n \to p + e^- + \bar{\nu}_e$$



Argüelles *et al*, 1907.08690

Neutrino Flavor at Earth

IC-Gen2 collaboration, 1412.5106

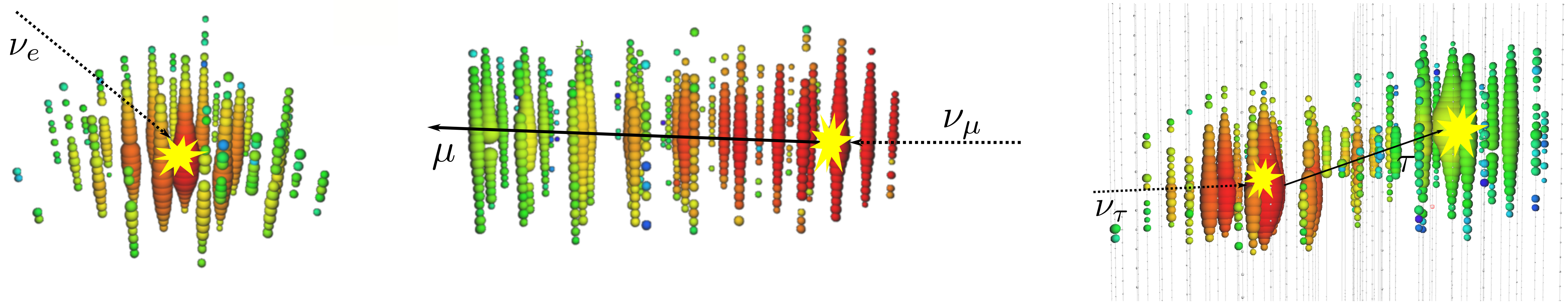


- Neutrinos oscillate from source to Earth

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

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

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



Showers/Cascades

Tracks

Double bangs

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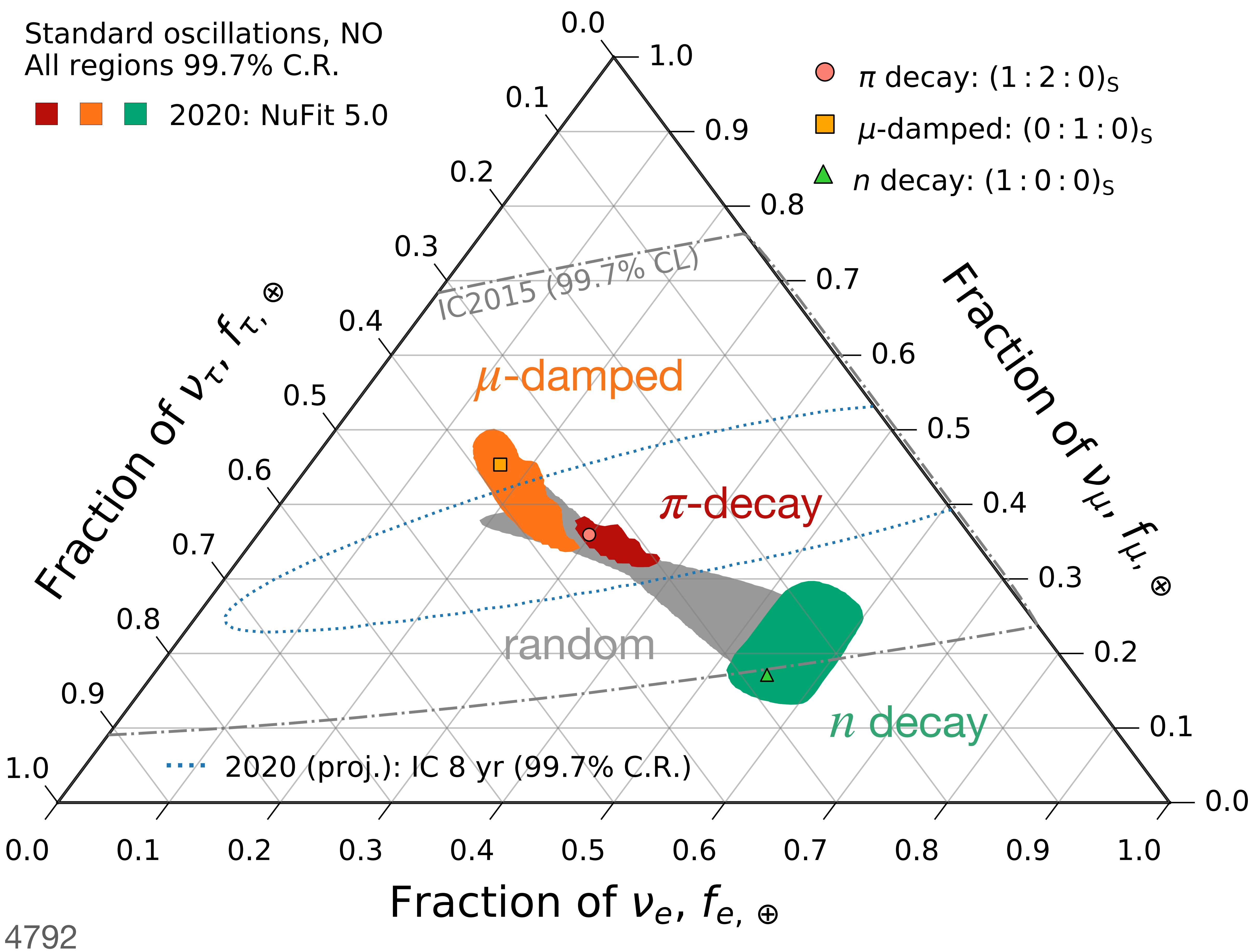
Source Discrimination? Hard!

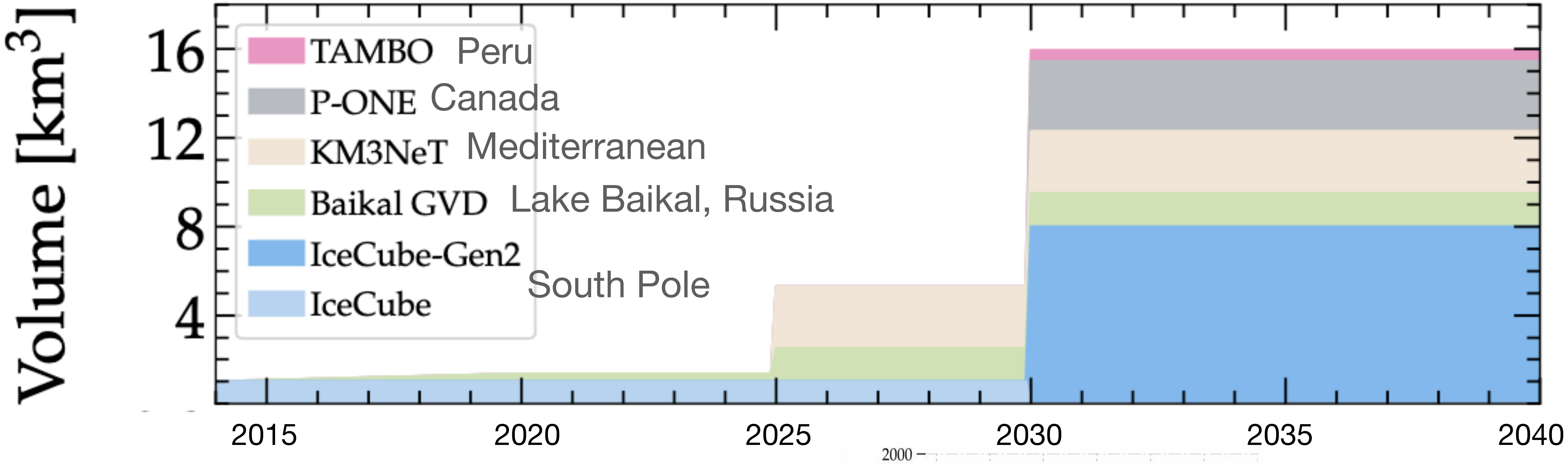
- Limitations
  - Statistical: flux measurement
  - Systematical: precise oscillation parameters

Parameter	Normal ordering	Inverted ordering
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.575^{+0.016}_{-0.019}$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02238^{+0.00063}_{-0.00062}$
δ_{CP} (°)	197^{+27}_{-24}	282^{+26}_{-30}

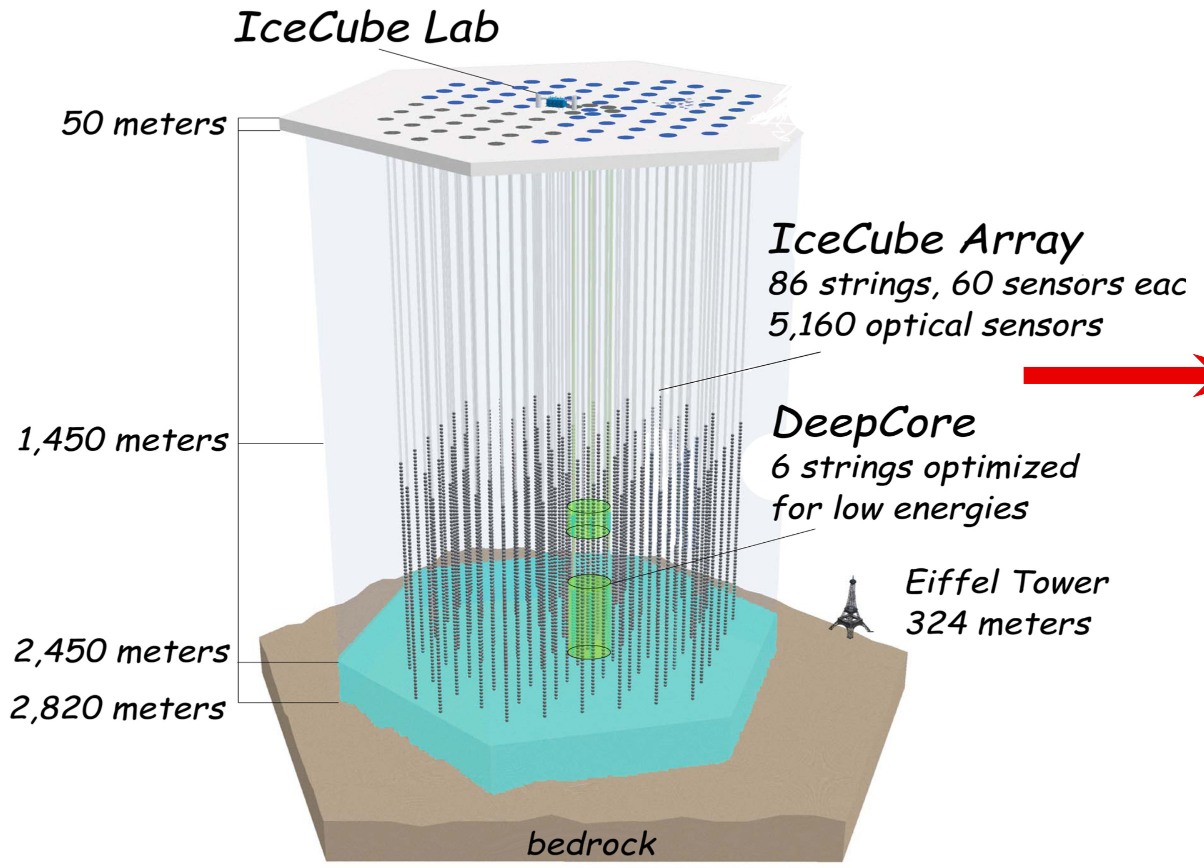
NuFit 5.0 global fit, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

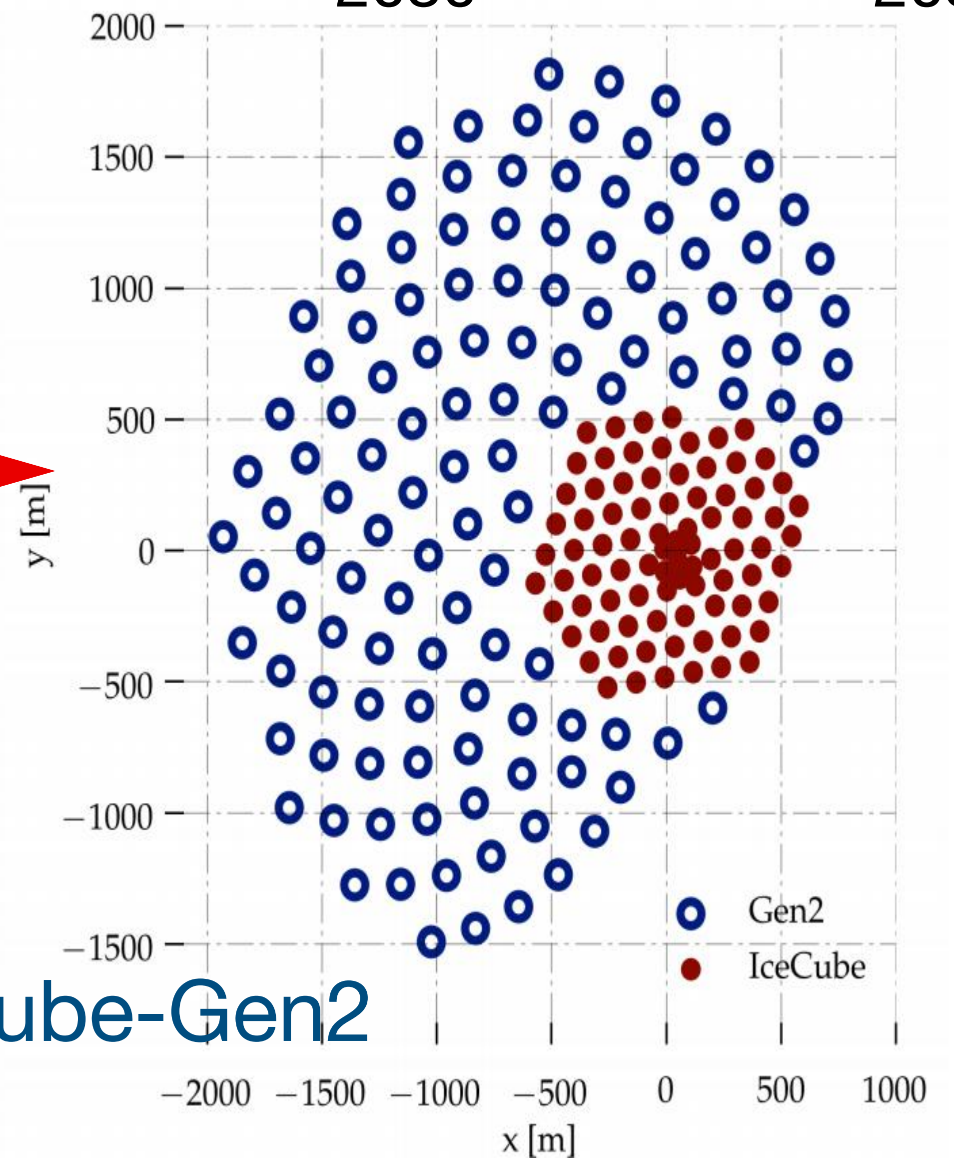


Future Neutrino Telescopes

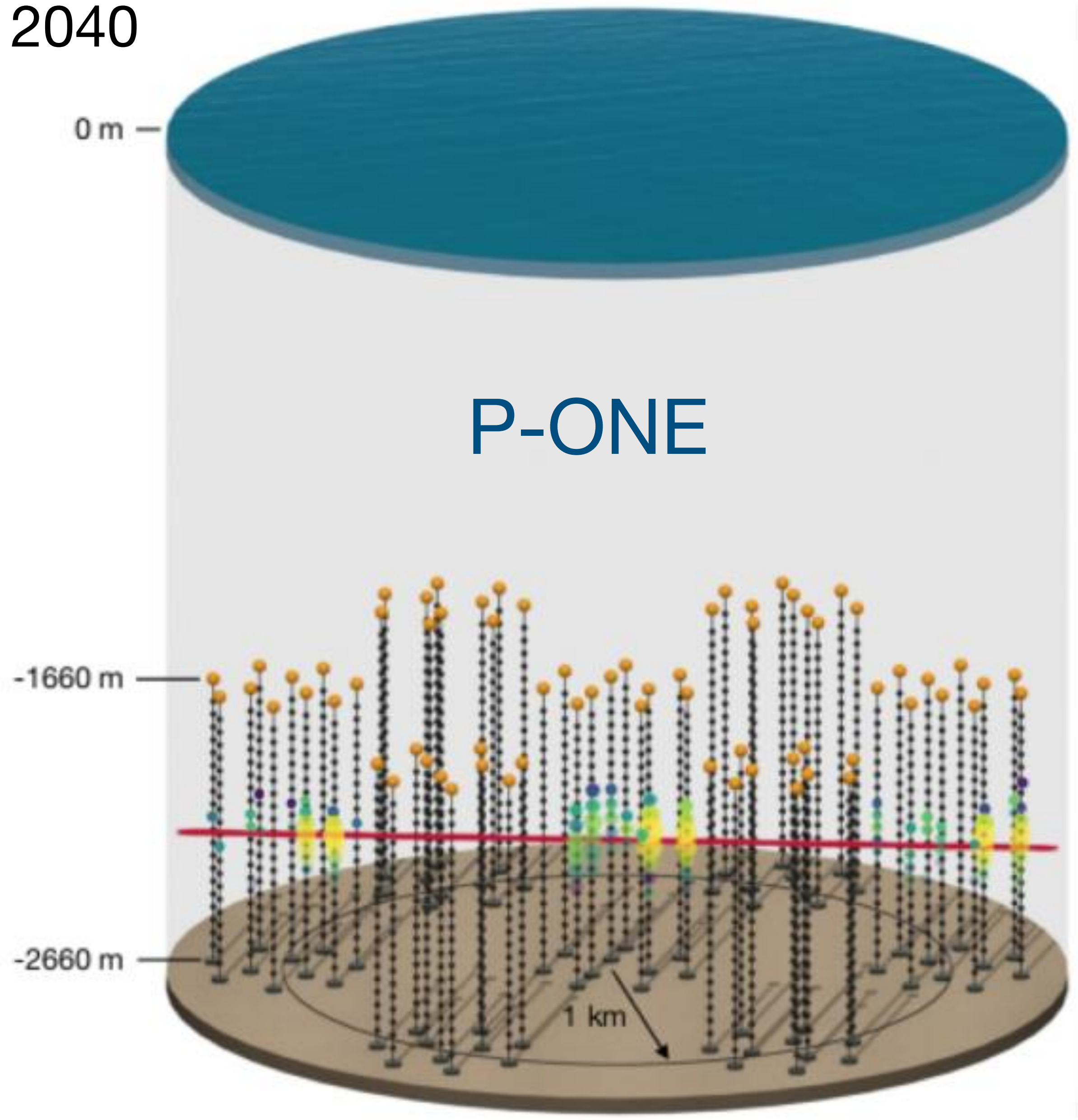


Combination of IC-Gen2, P-ONE, KM3NeT, GVD, TAMBO offers ~20 times more exposure by 2040 than IceCube

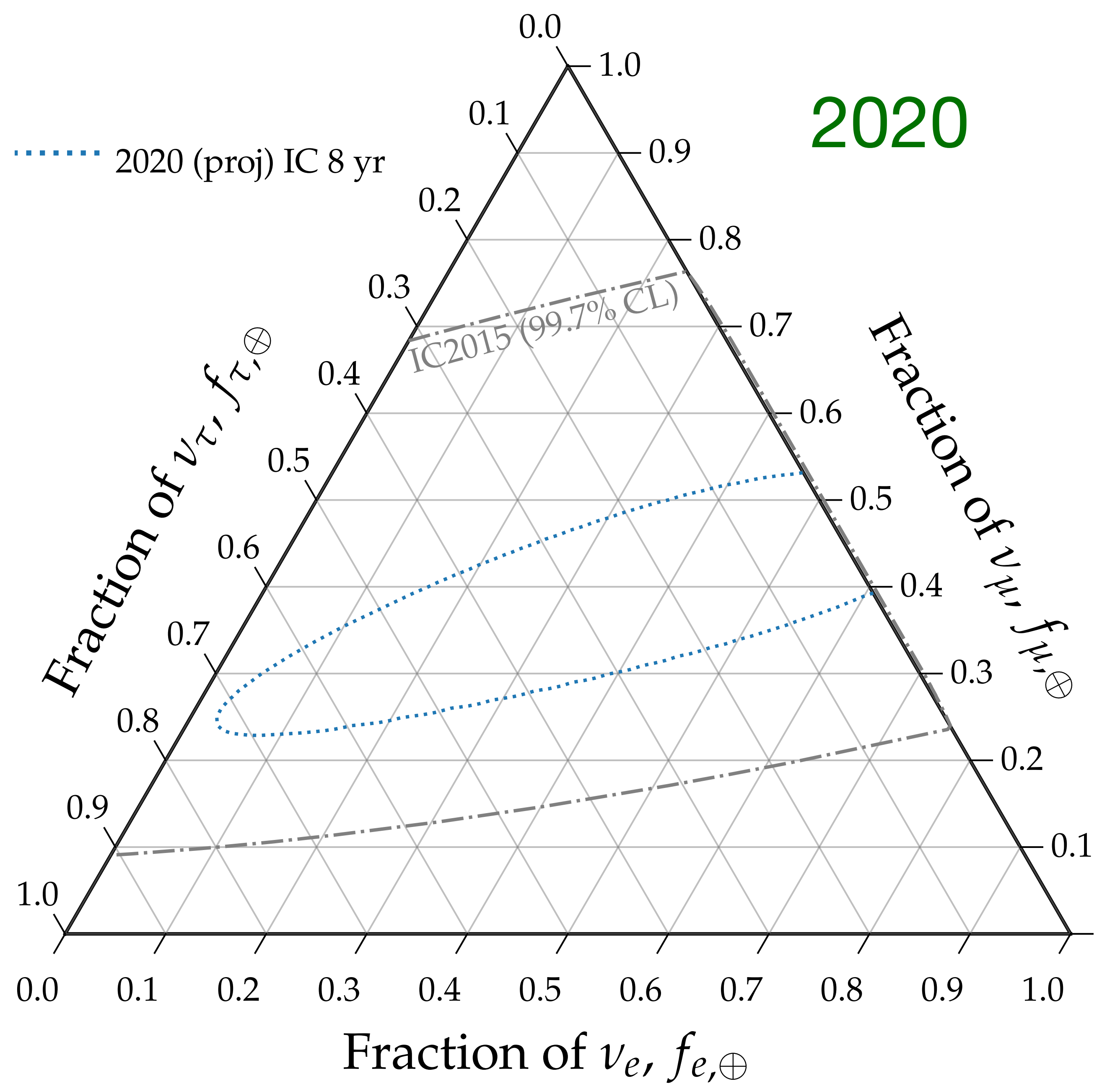


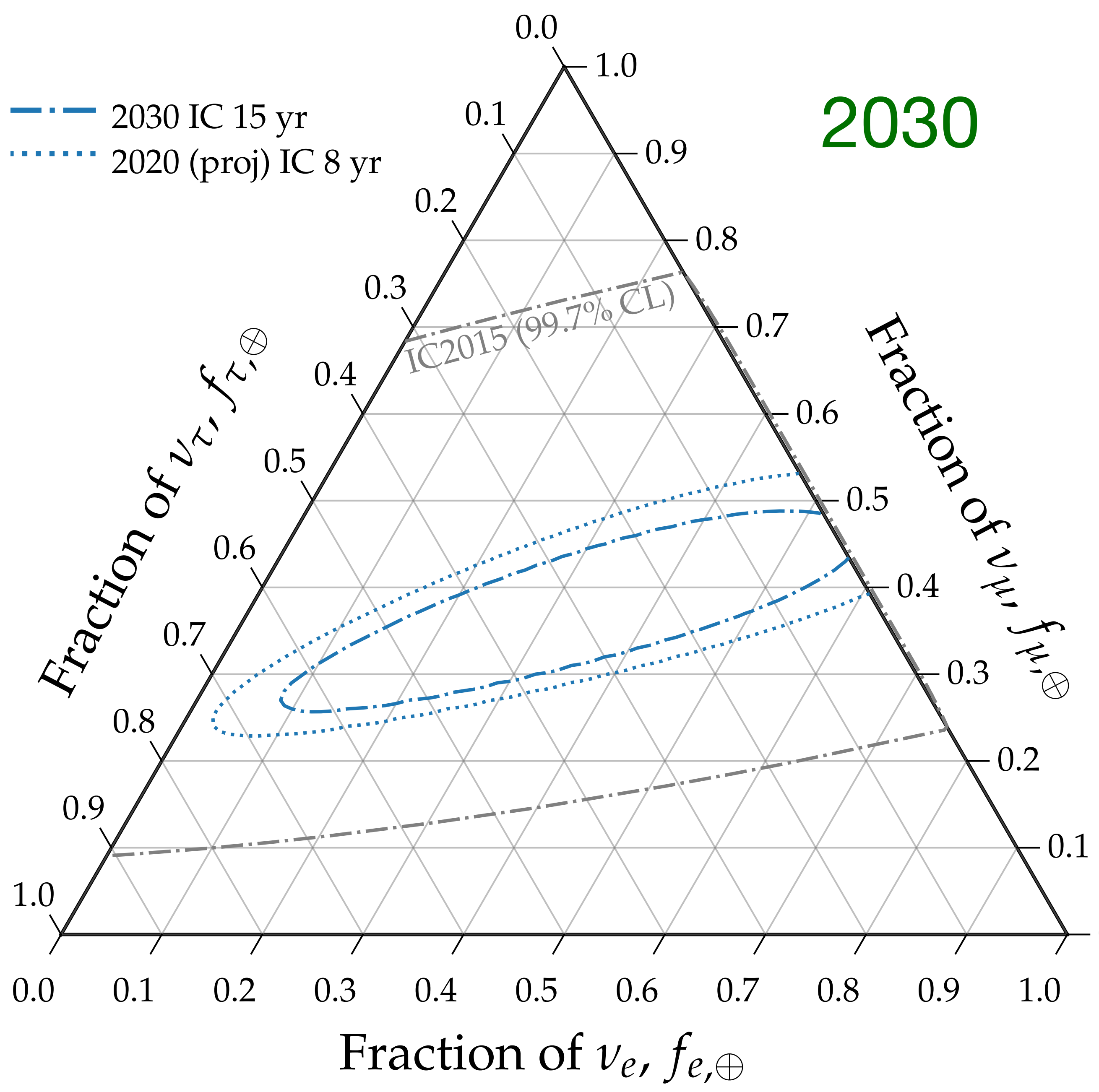


IceCube-Gen2

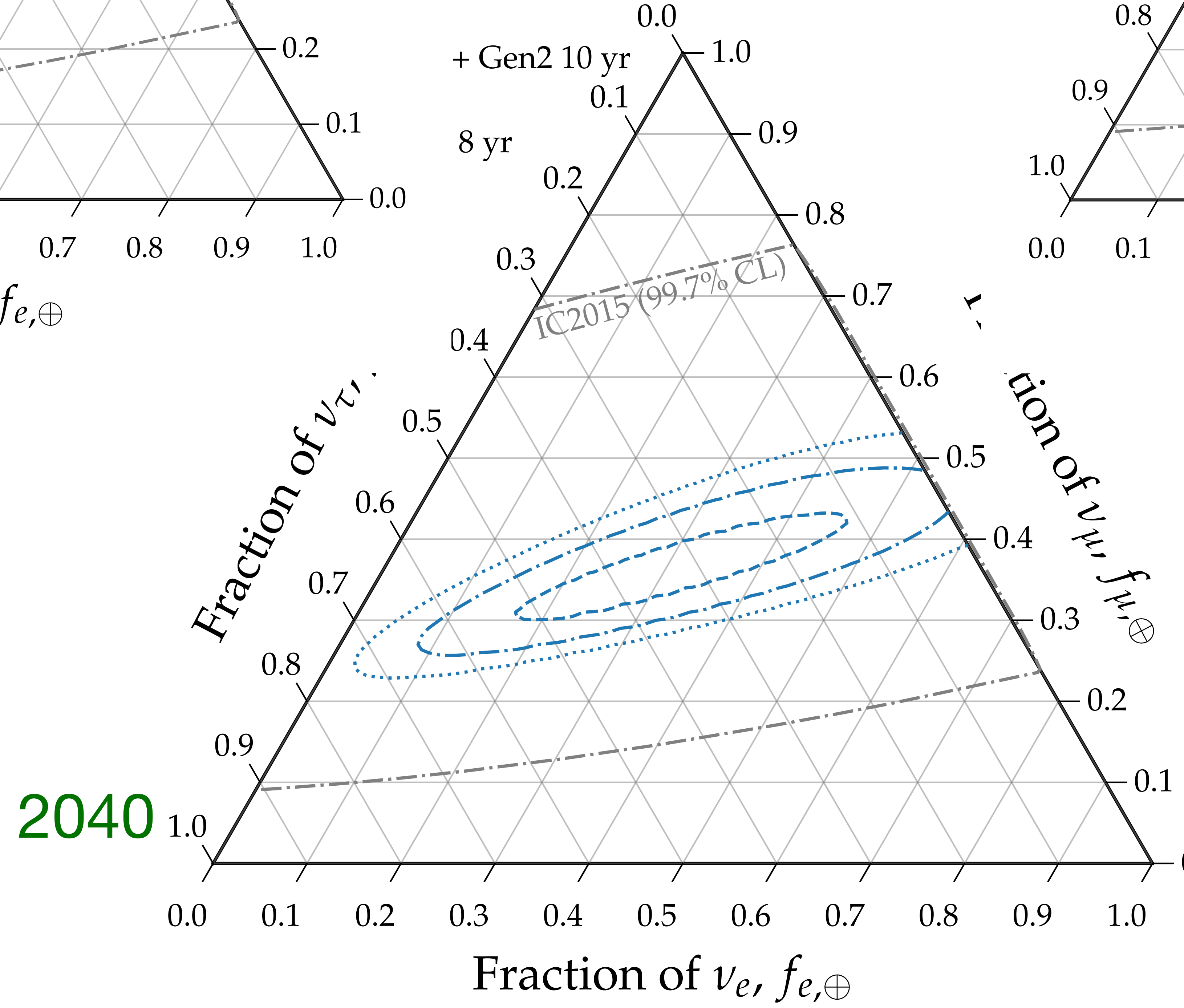


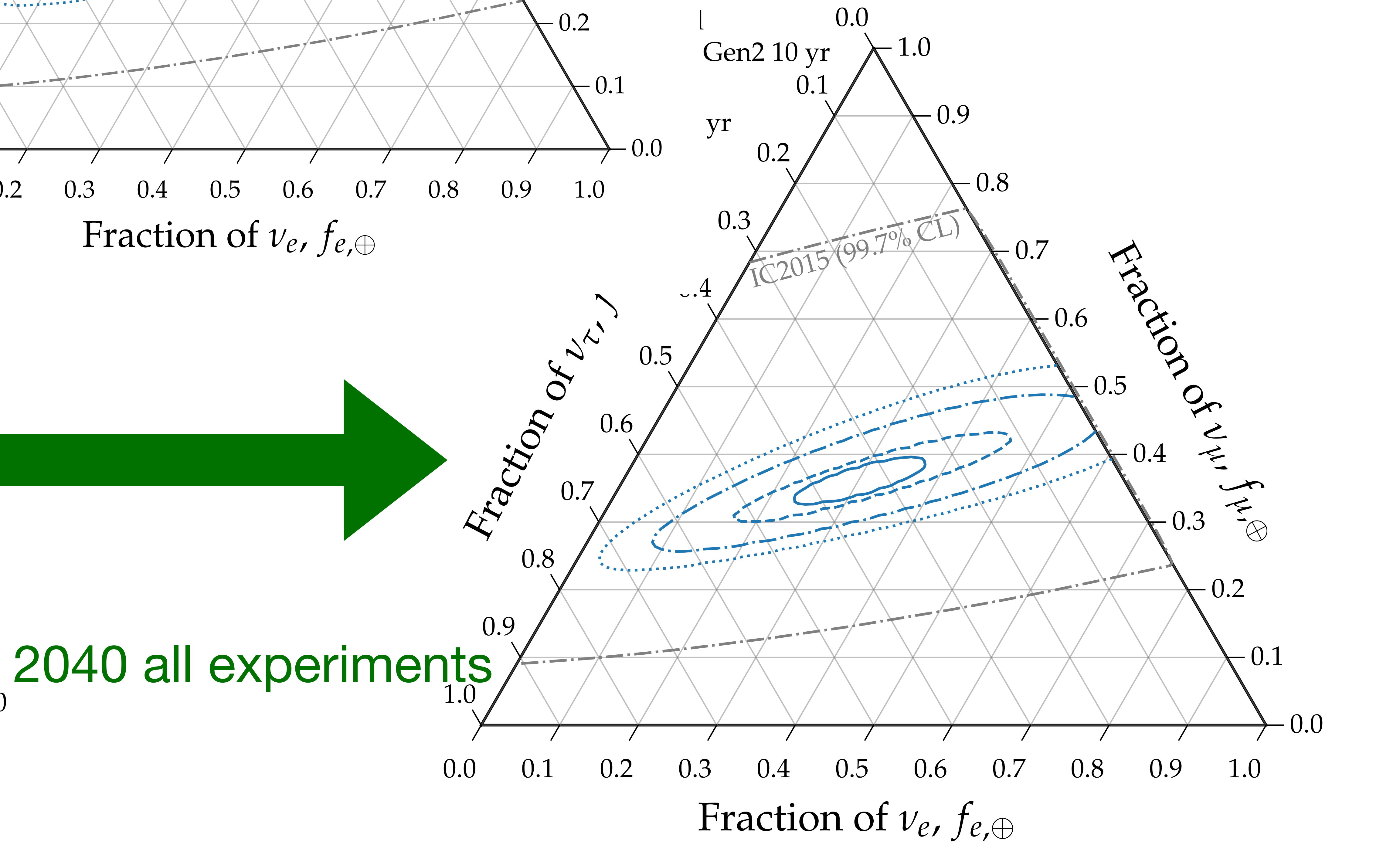
Neutrino Flavor Measurements: Future





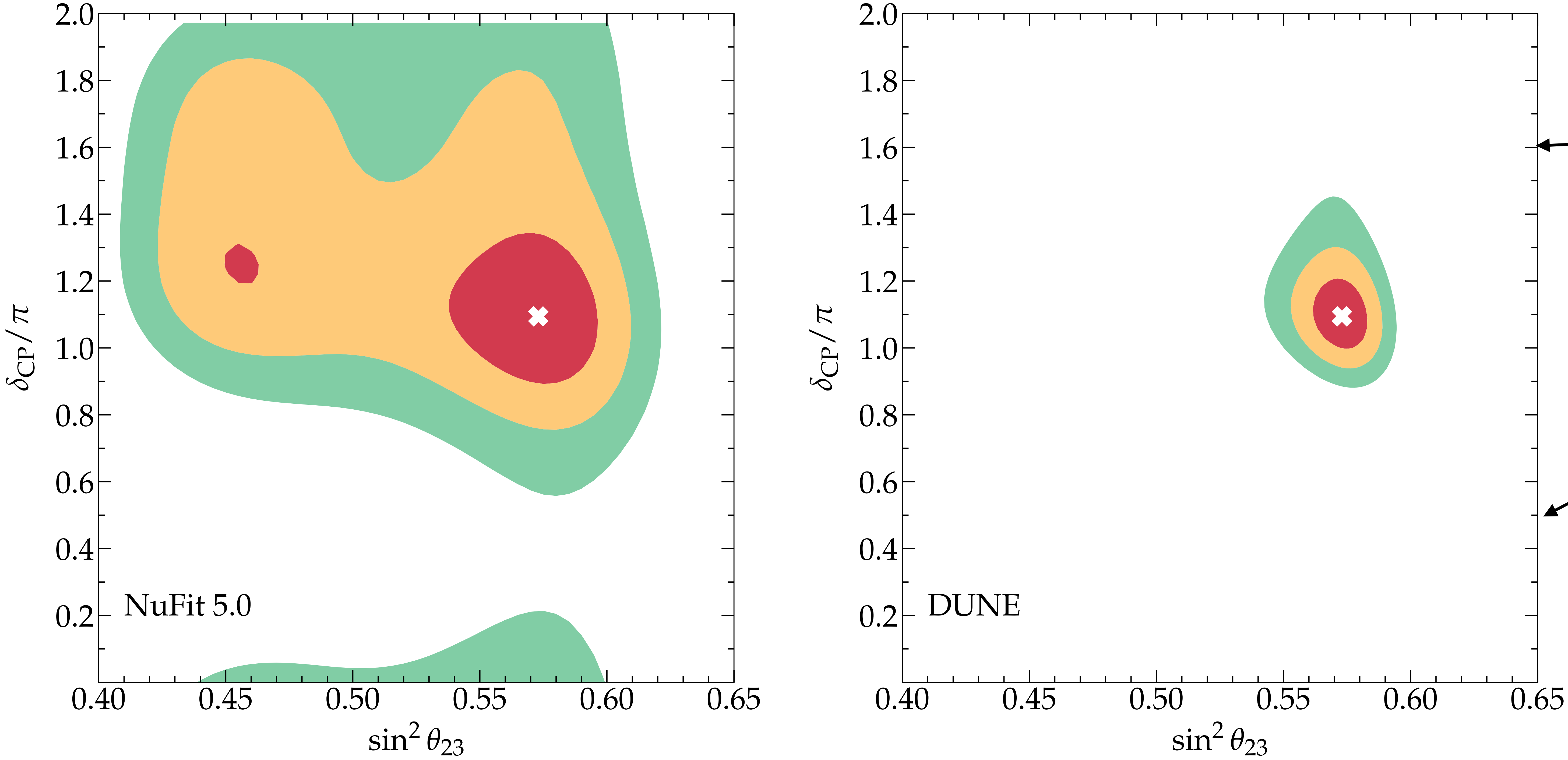
	Flavor ratios at Earth		
	$f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$
2020	$0.30^{+0.13}_{-0.11}$	$0.36^{+0.059}_{-0.053}$	$0.34^{+0.16}_{-0.18}$
2040	$0.30^{+0.039}_{-0.037}$	$0.36^{+0.017}_{-0.016}$	$0.34^{+0.049}_{-0.050}$
2040 all	$0.30^{+0.030}_{-0.027}$	$0.36^{+0.011}_{-0.011}$	$0.34^{+0.037}_{-0.039}$



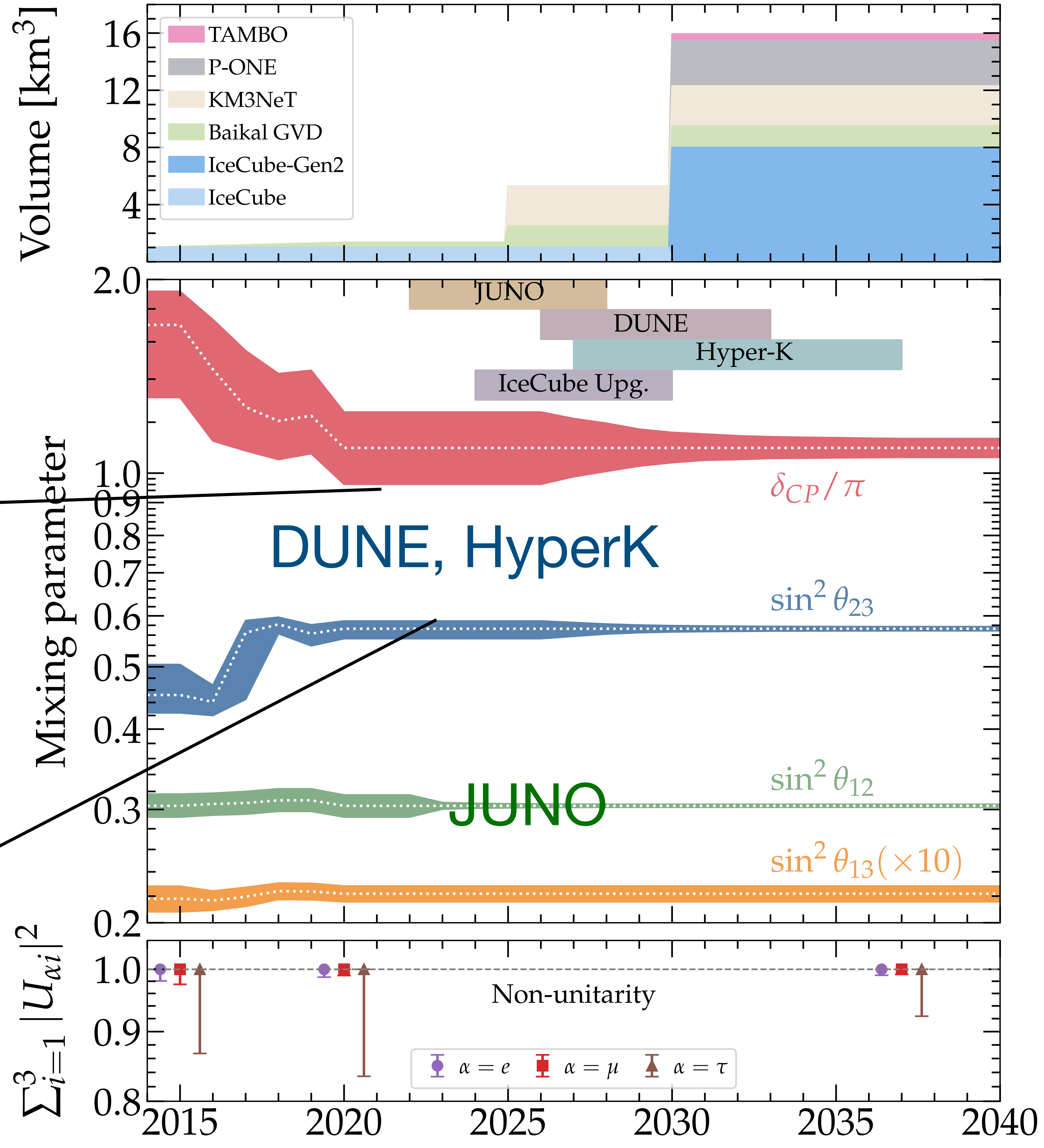


Neutrino Oscillation Measurements

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



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



Non-Unitarity

NS, Li, Argüelles, Bustamante, Vincent, JHEP/2012.12893

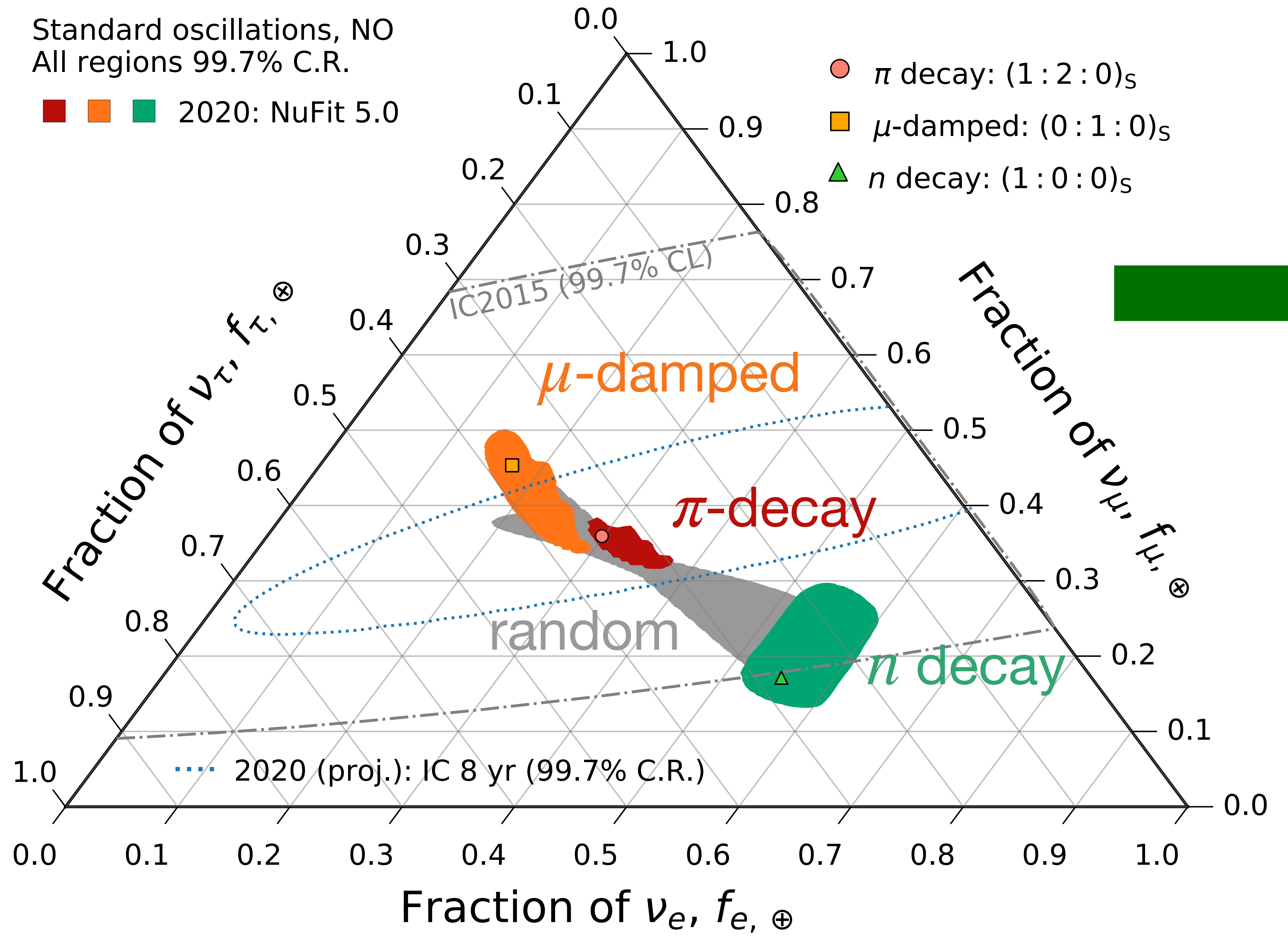
Source Discrimination? **Yes!**

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

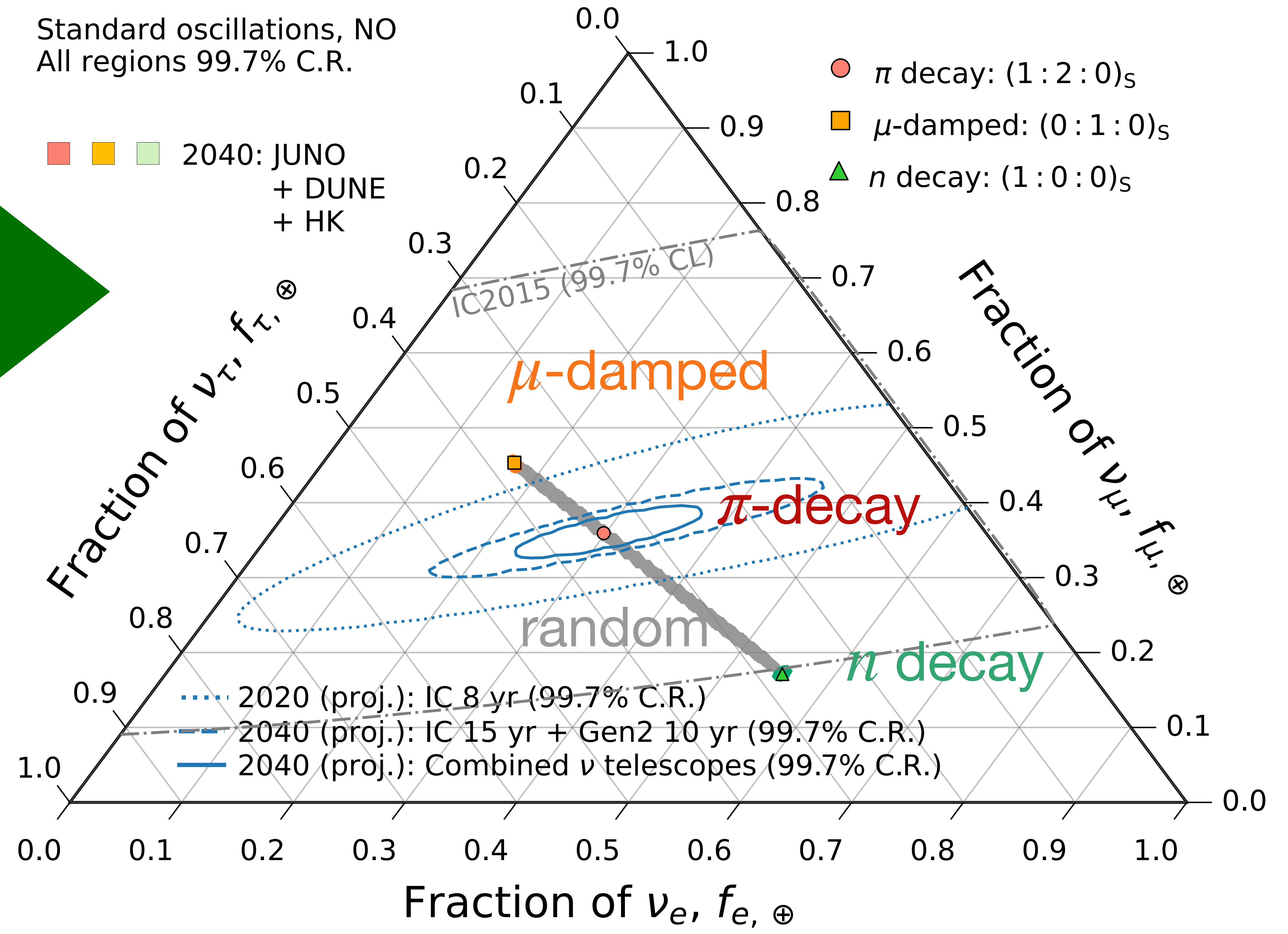
$$P_{\alpha\beta}^{s\to\oplus} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Pion decay well separated from muon damped by 2040

2020



2040



NS, Li, Argüelles, Bustamante, Vincent, JHEP/2012.12893

Flavor Composition at Source

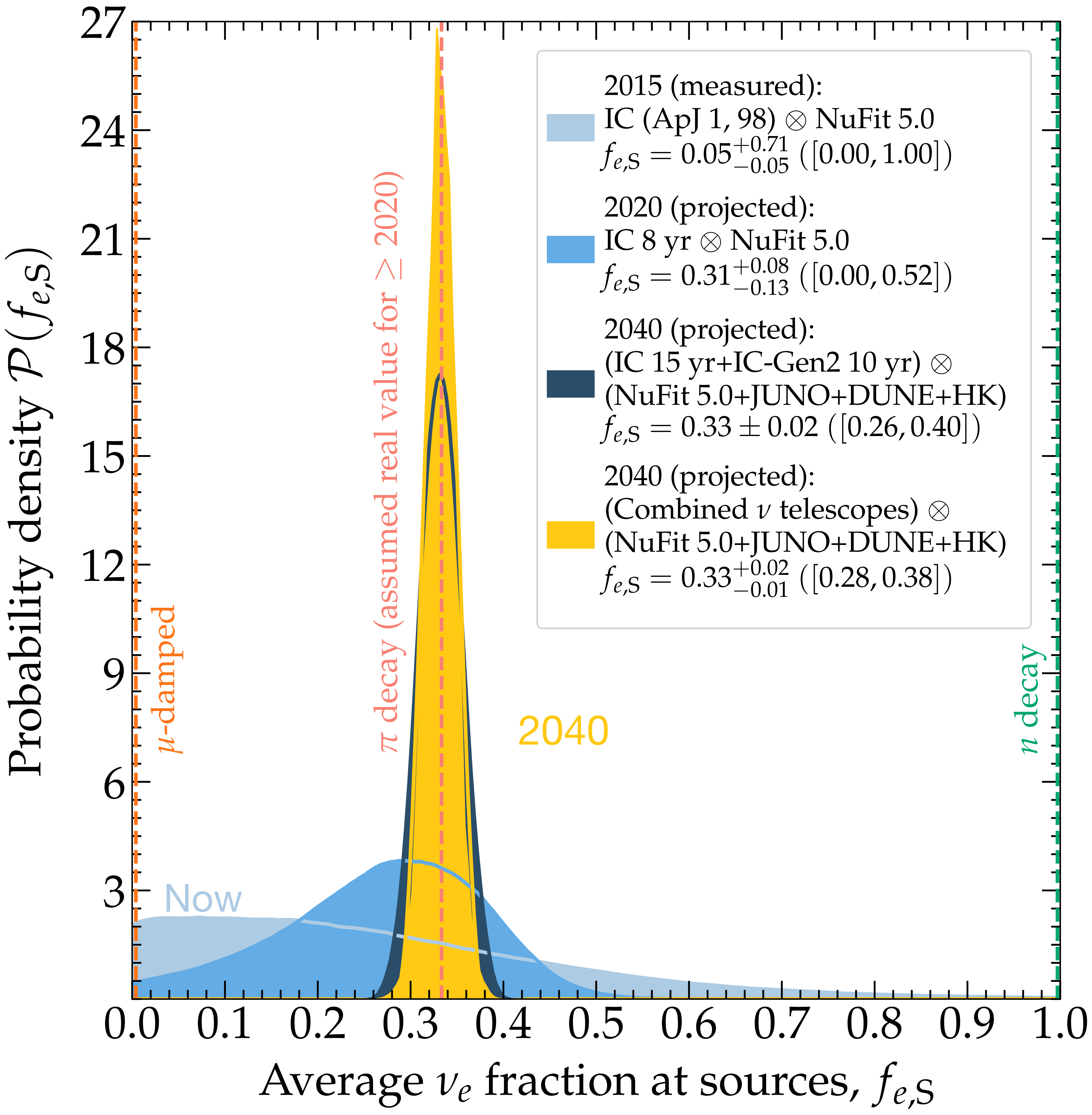
- Assume no ν_τ at source $f_{\tau,S} = 0$
- Combine the information from neutrino oscillation experiments and neutrino telescopes

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

uniform prior

See 1404.0017, 1502.02649, 1605.01556,1901.10087 for source inference

NS, Li, Argüelles, Bustamante, Vincent, JHEP/2012.12893



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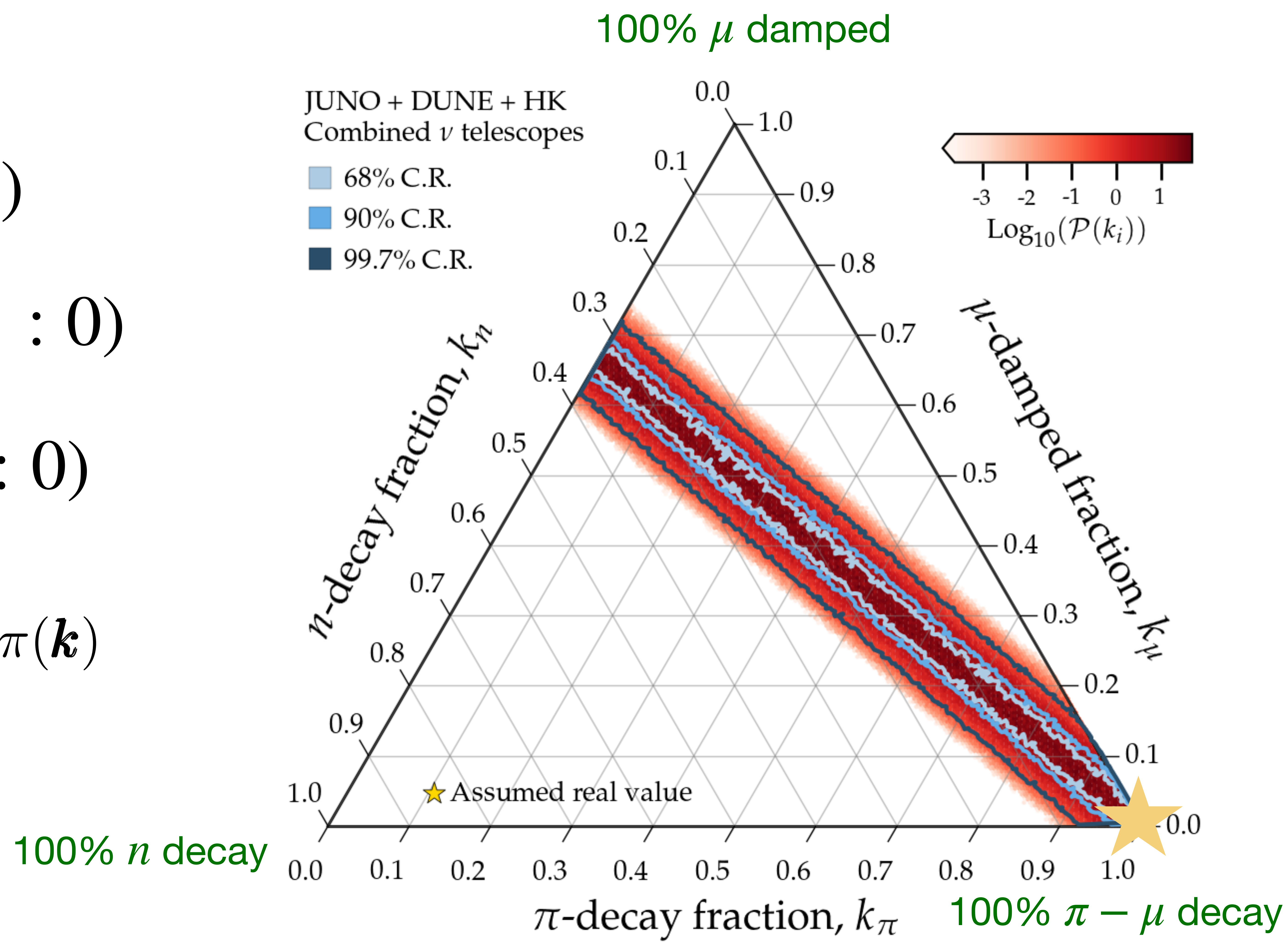
Flavor Composition at Source

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

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



NS, Li, Argüelles, Bustamante, Vincent, JHEP/2012.12893

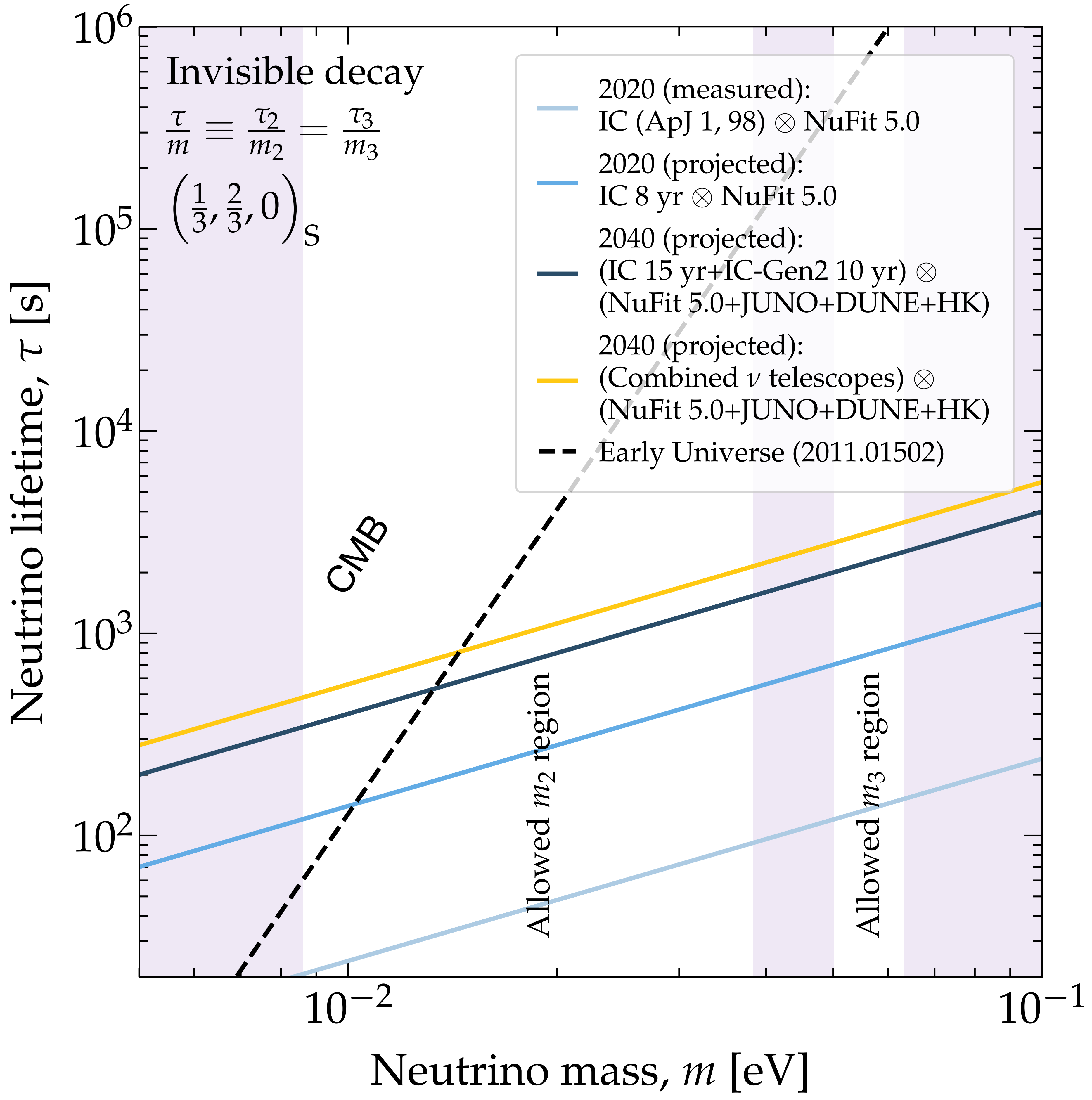
Neutrino Decay

NS, Li, Argüelles, Bustamante, Vincent, JHEP/2012.12893

- 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

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

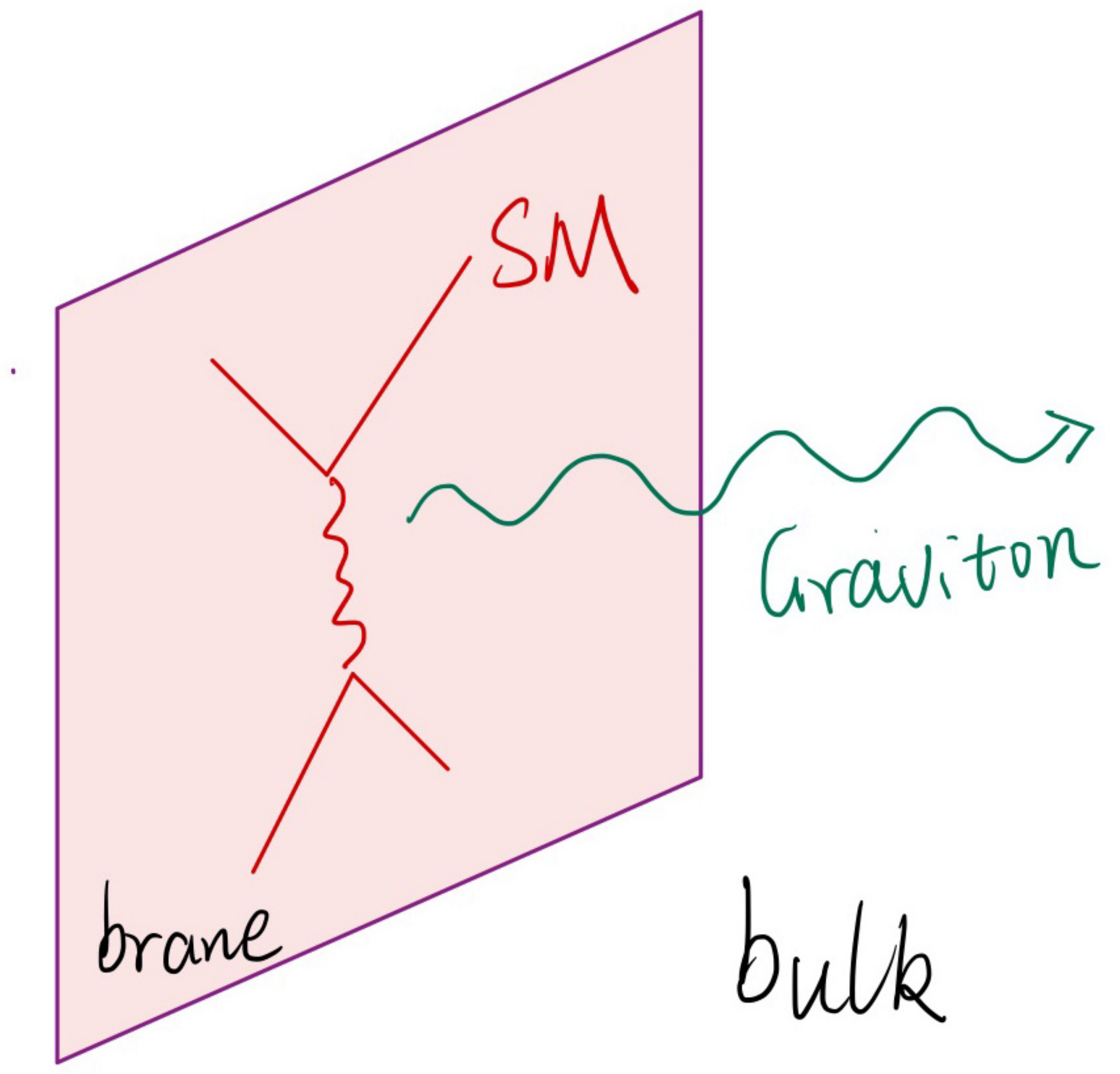
ν telescopes $\otimes$ oscillation experiments	m_ν/τ_ν (eV s^{-1})
2015 (measured): IC $\otimes$ NuFit 5.0	4.1×10^{-4}
2020 (projected): IC 8 yr $\otimes$ NuFit 5.0	7.4×10^{-5}
2040 (projected): IC 15 yr + IC-Gen2 10 yr $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	2.5×10^{-5}
2040 (projected): All ν telescopes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

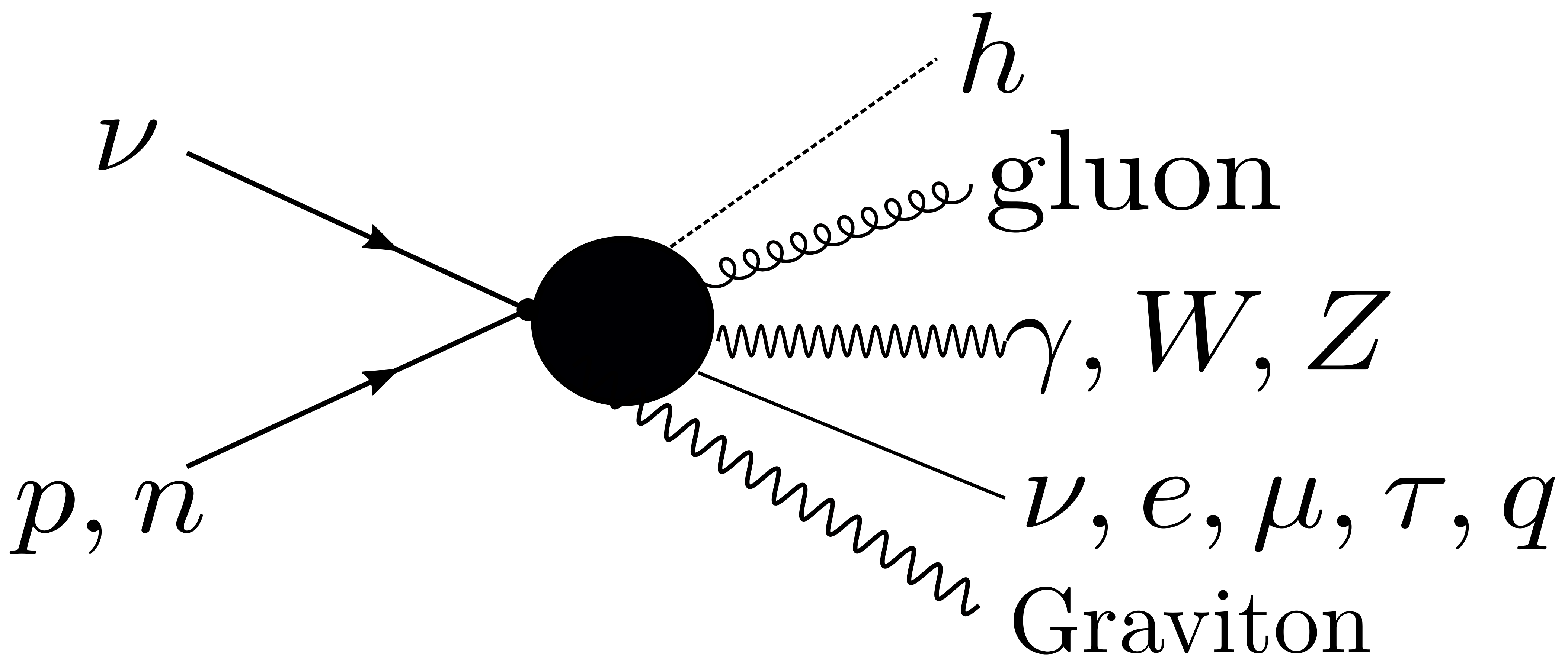


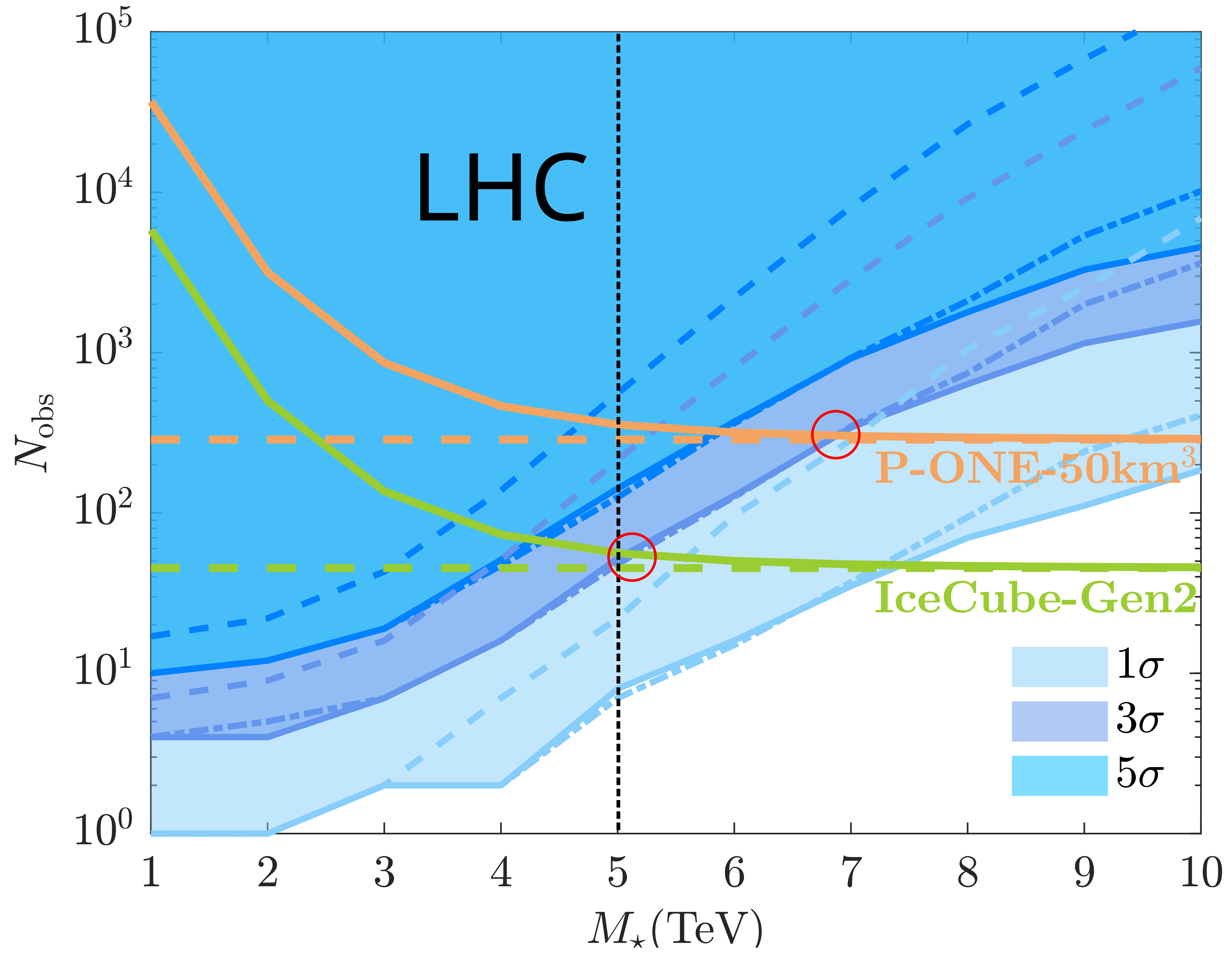
Large Extra Dimensions

$$M_{pl}^2 \sim M_\star^{2+n} R^n$$

Mack, **NS**, Vincent, JHEP/1912.06656







Summary

Code available at https://github.com/songningqiang/FANFIC

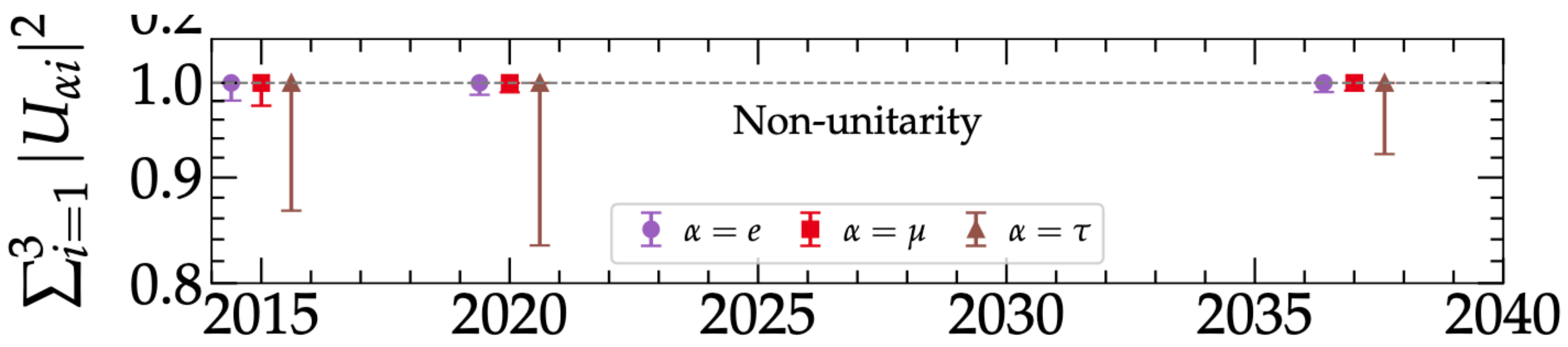
- More precise mixing parameters: JUNO, DUNE, HK…
- Better flavor ratio measurement: IceCube-Gen2, P-ONE, KM3NeT, GVD, TAMBO…
- Pin down the production mechanism at source, robust against non-unitarity
- Constrain neutrino decay and neutrino lifetime

To do:

- More new physics: leptoquarks, Z', microscopic BHs, long-lived particles
- Energy spectral analysis

Backup Slides

Leptonic Non-unitarity



Ellis, Kelly, Li, 2012.12893

Source determination is robust against non-unitarity

- Assuming non-unitarity

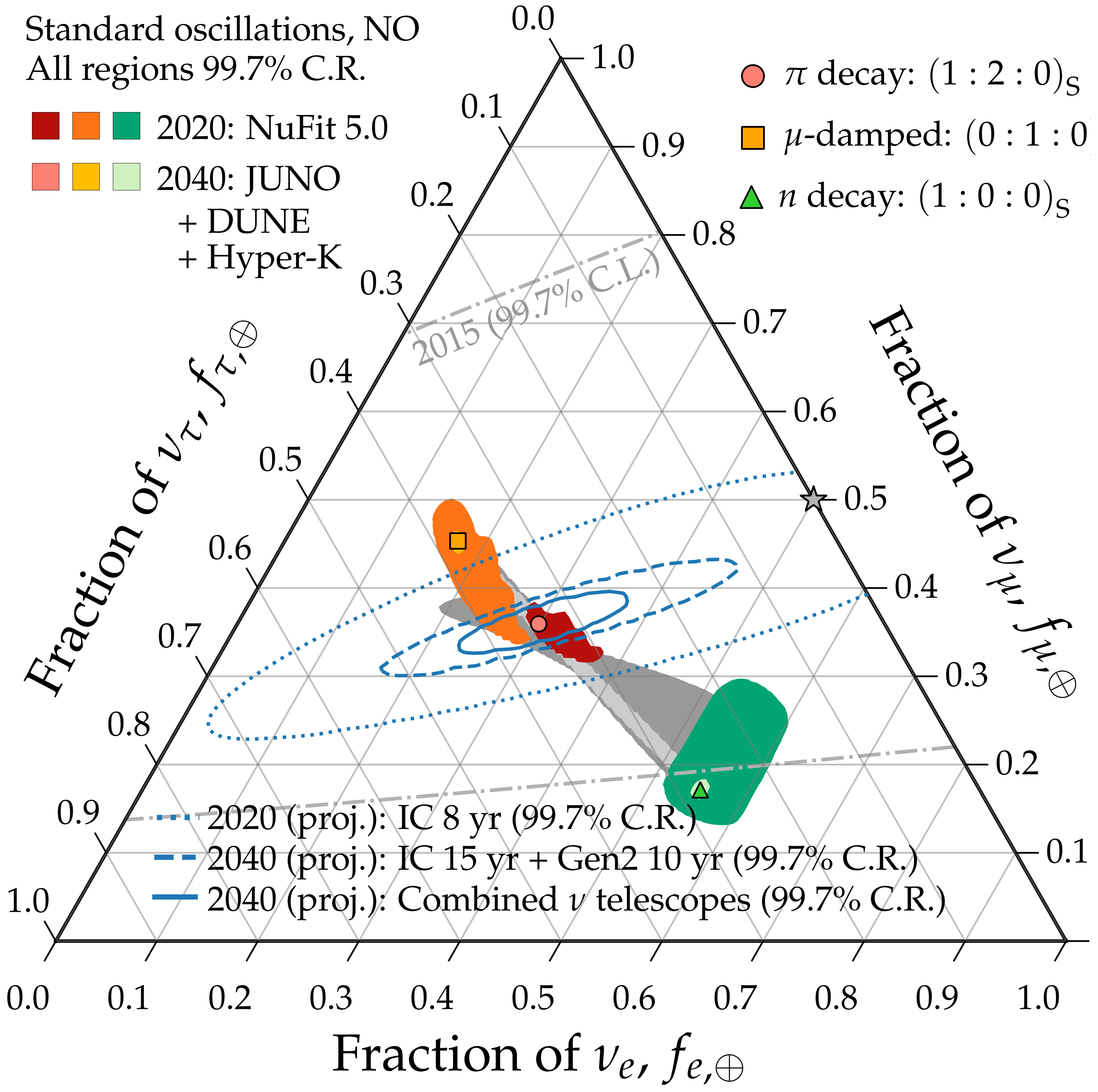
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- Oscillation probability

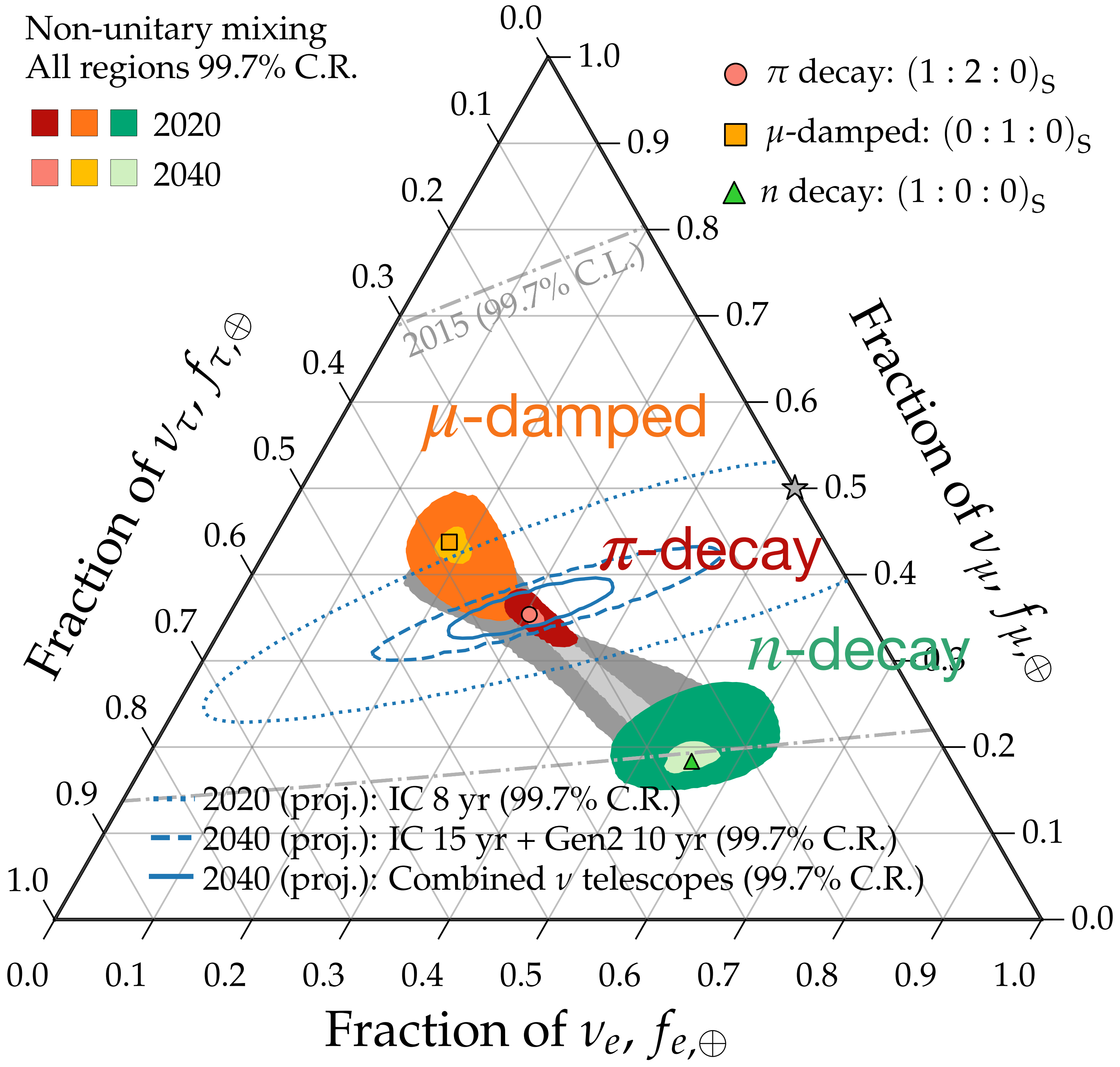
$$P_{\alpha\beta}^{\text{NU}} = \frac{1}{N_\alpha N_\beta} \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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

Standard Oscillation



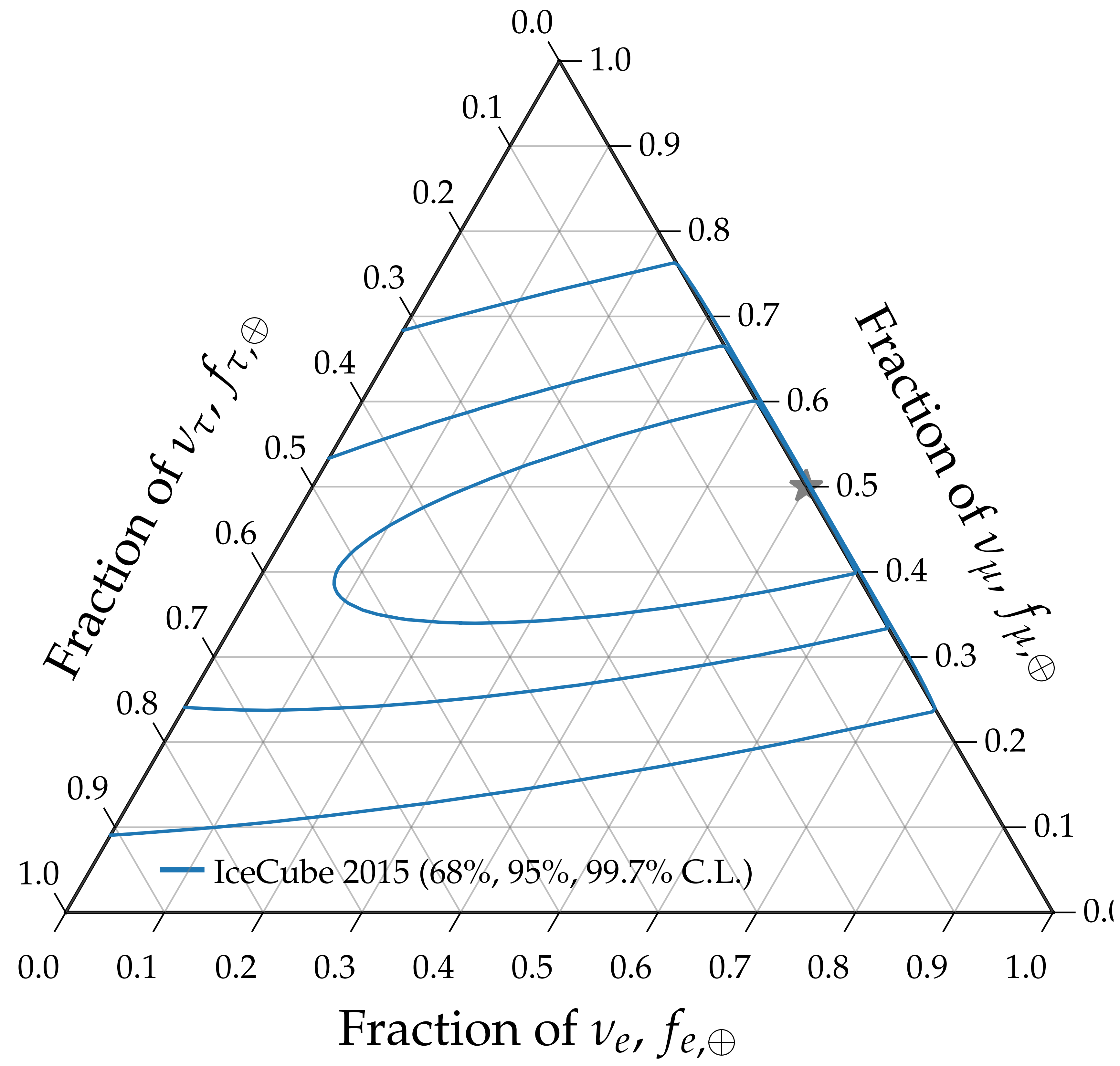
Non-unitarity



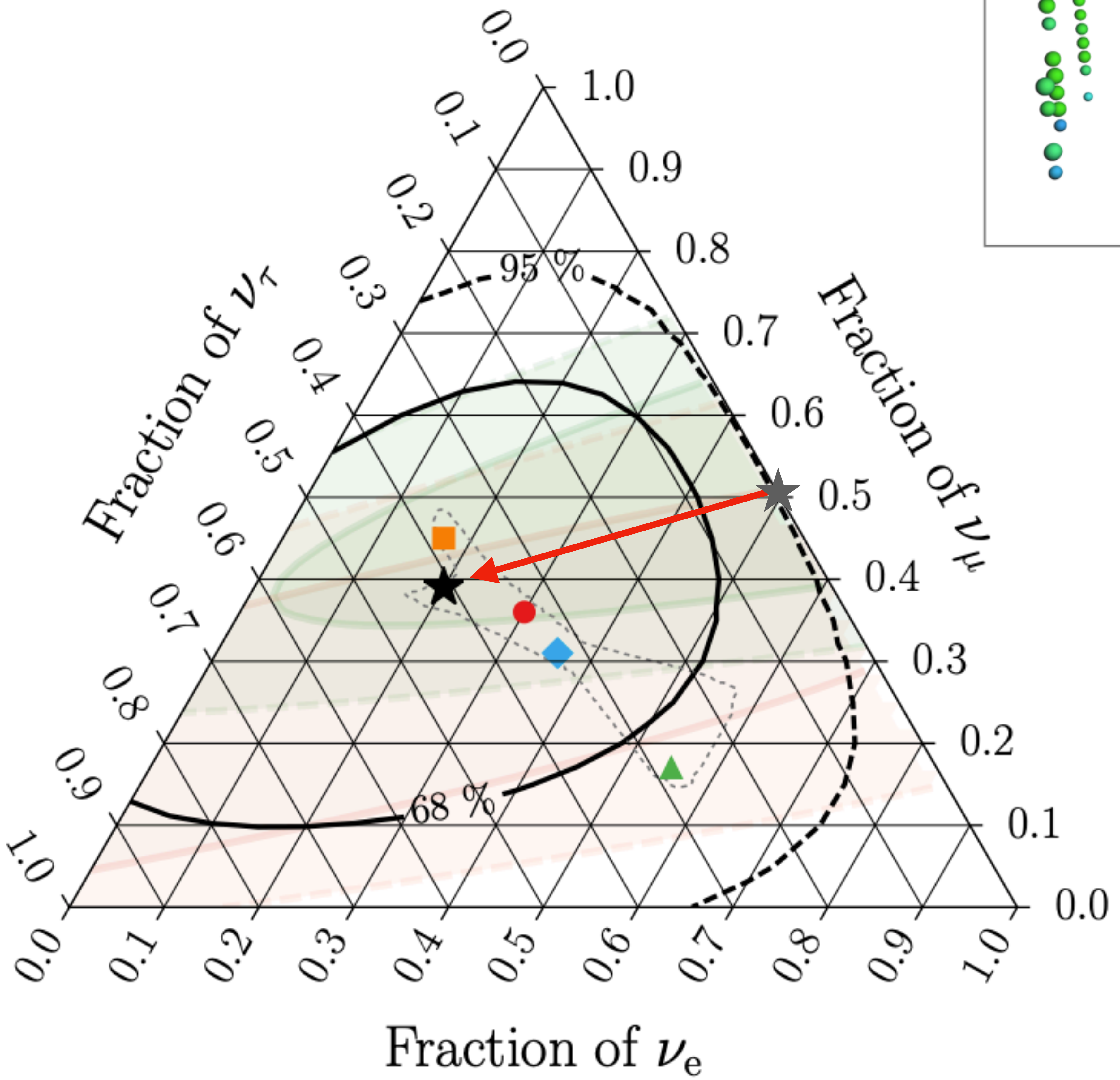
NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Astrophysical Neutrino Measurements

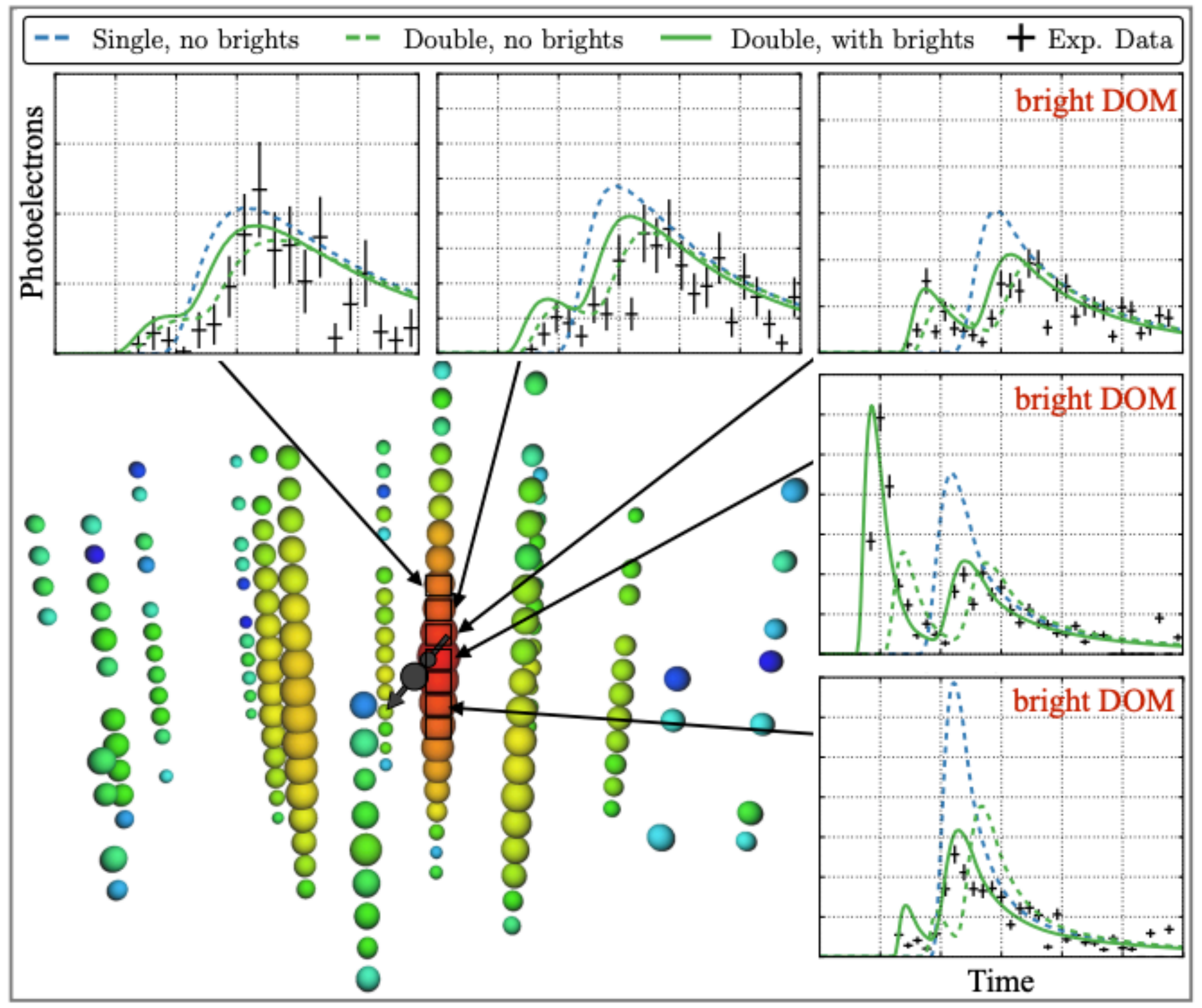
- HESE data + through-going muons



IceCube Collaboration, 1507.03991



IceCube Collaboration, 2011.03561



First detection of tau neutrino double bangs

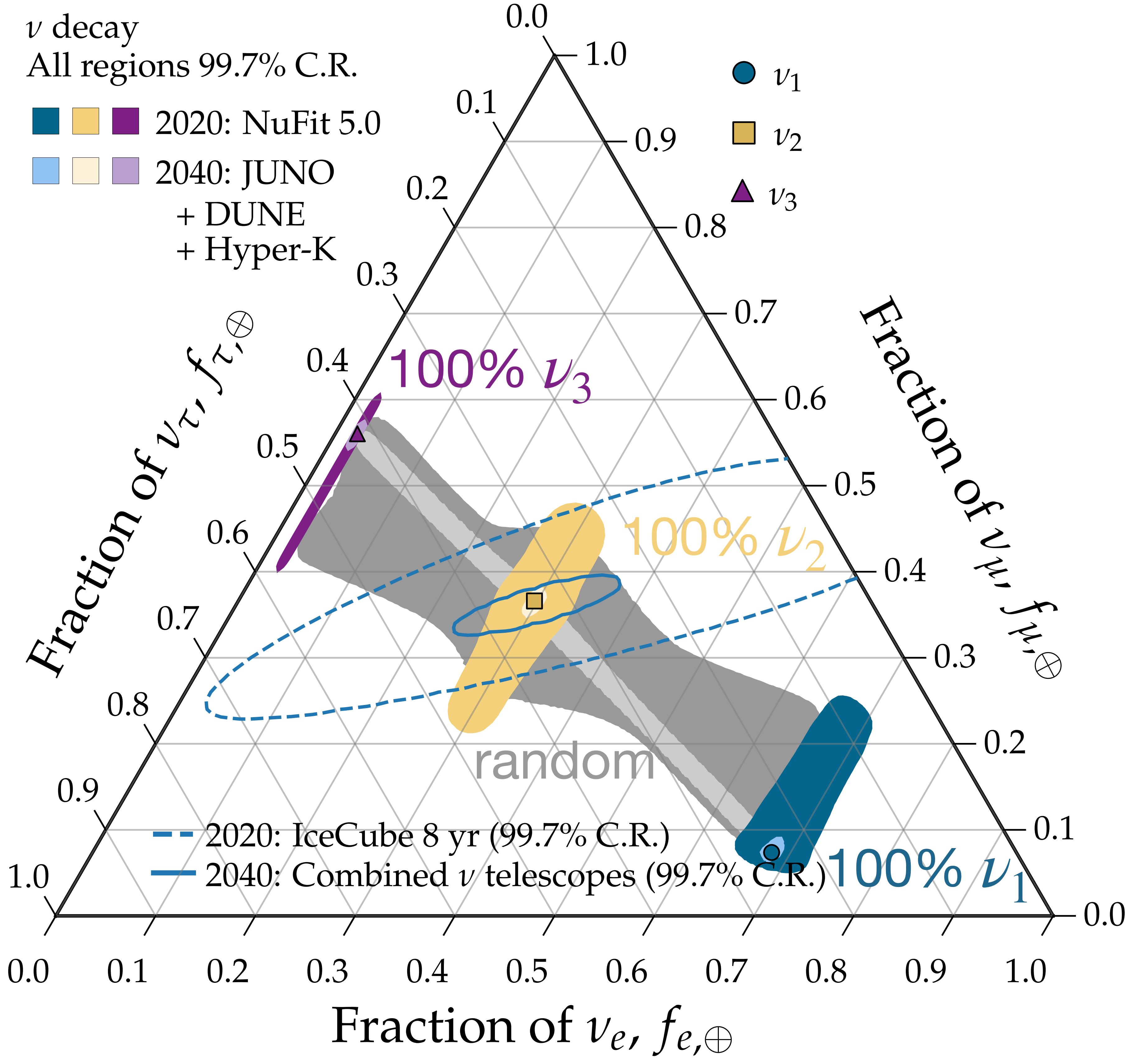
$$\Phi \propto E^{-\gamma}$$

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

New Physics: Neutrino Decay

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

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



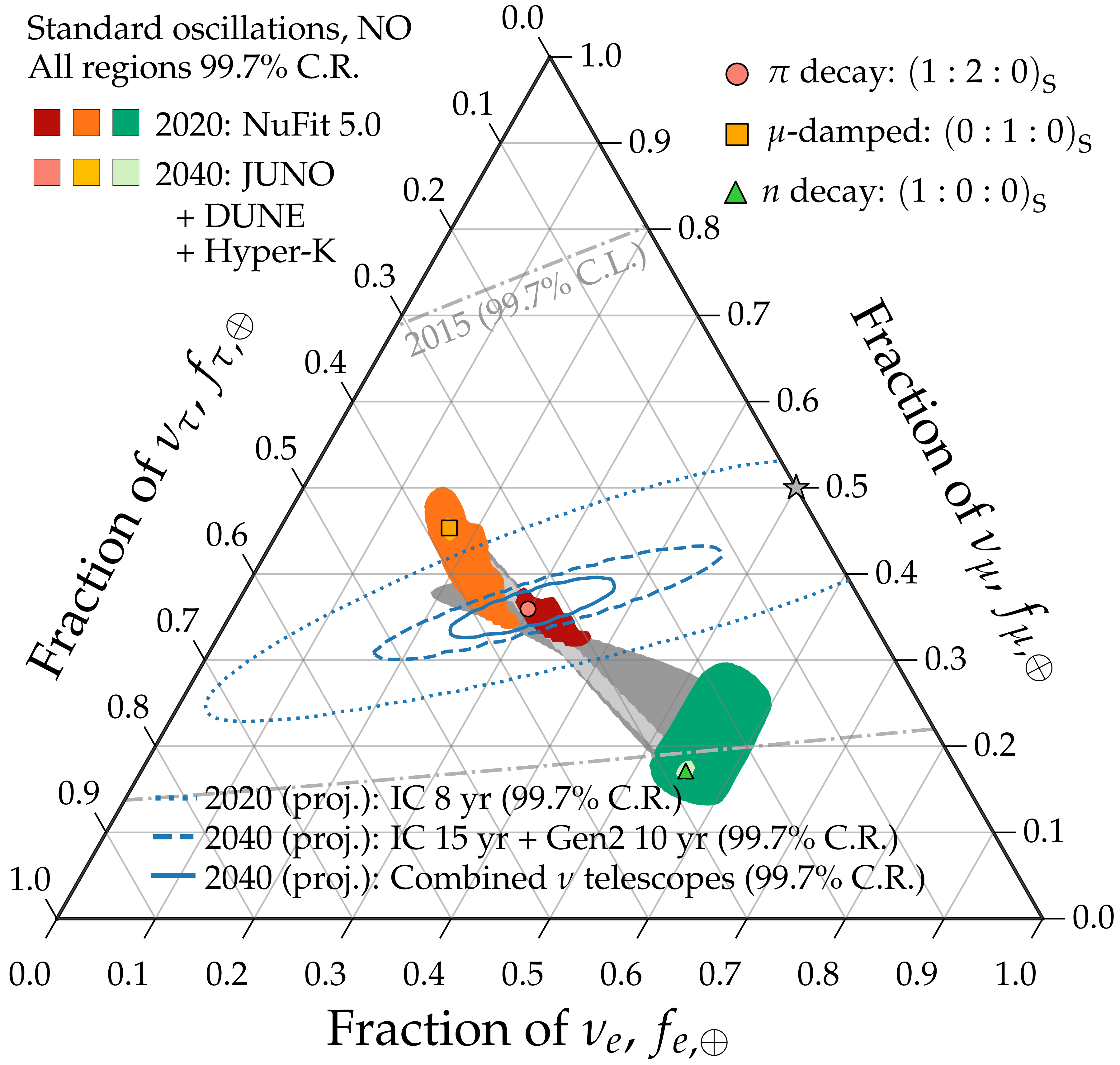
See 1506.02645, 2005.07200 for similar decay studies

See 1506.02043, 1506.02645 for other new physics

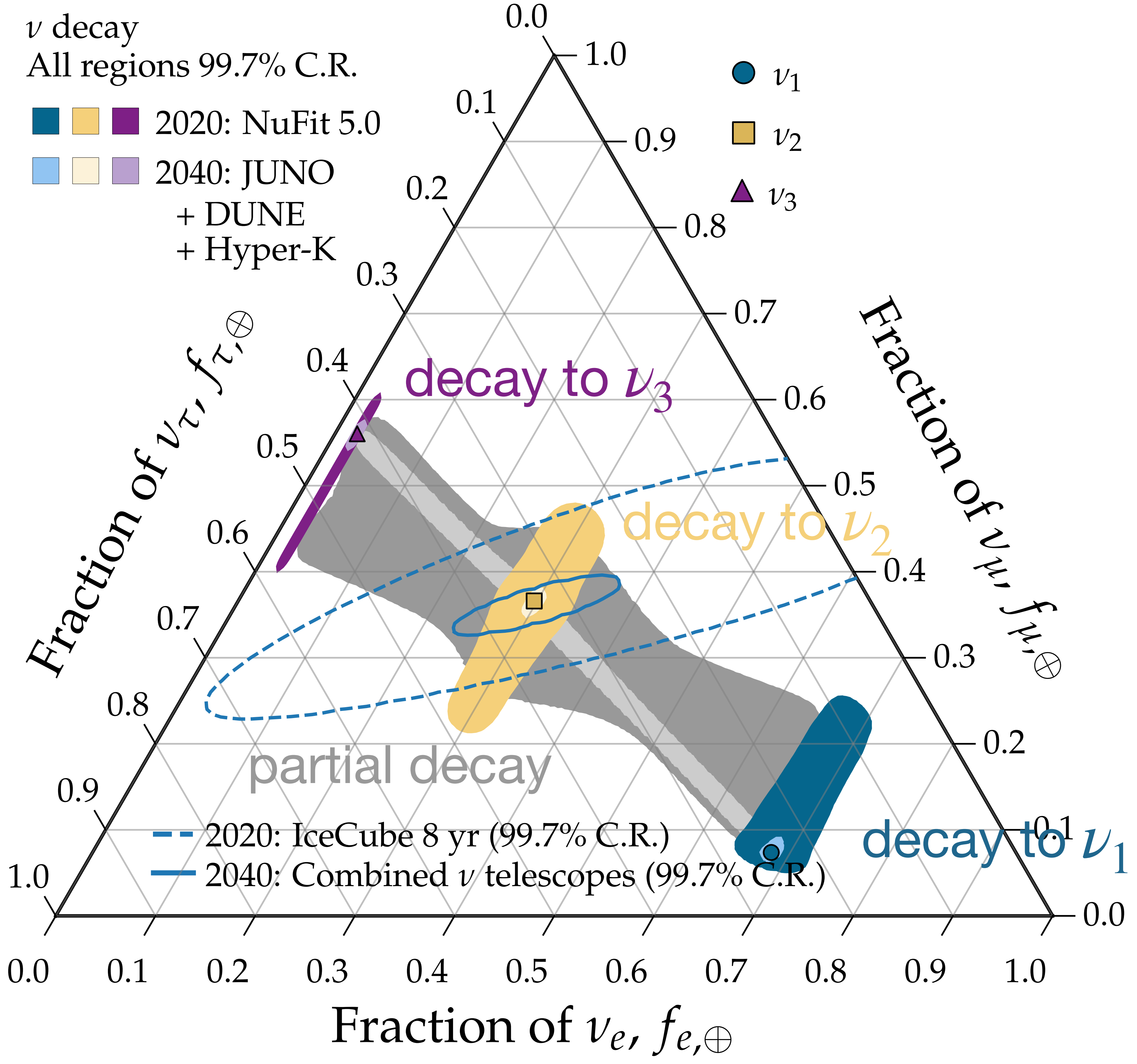
NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Neutrino Decay

Standard Oscillation



Neutrino Decay



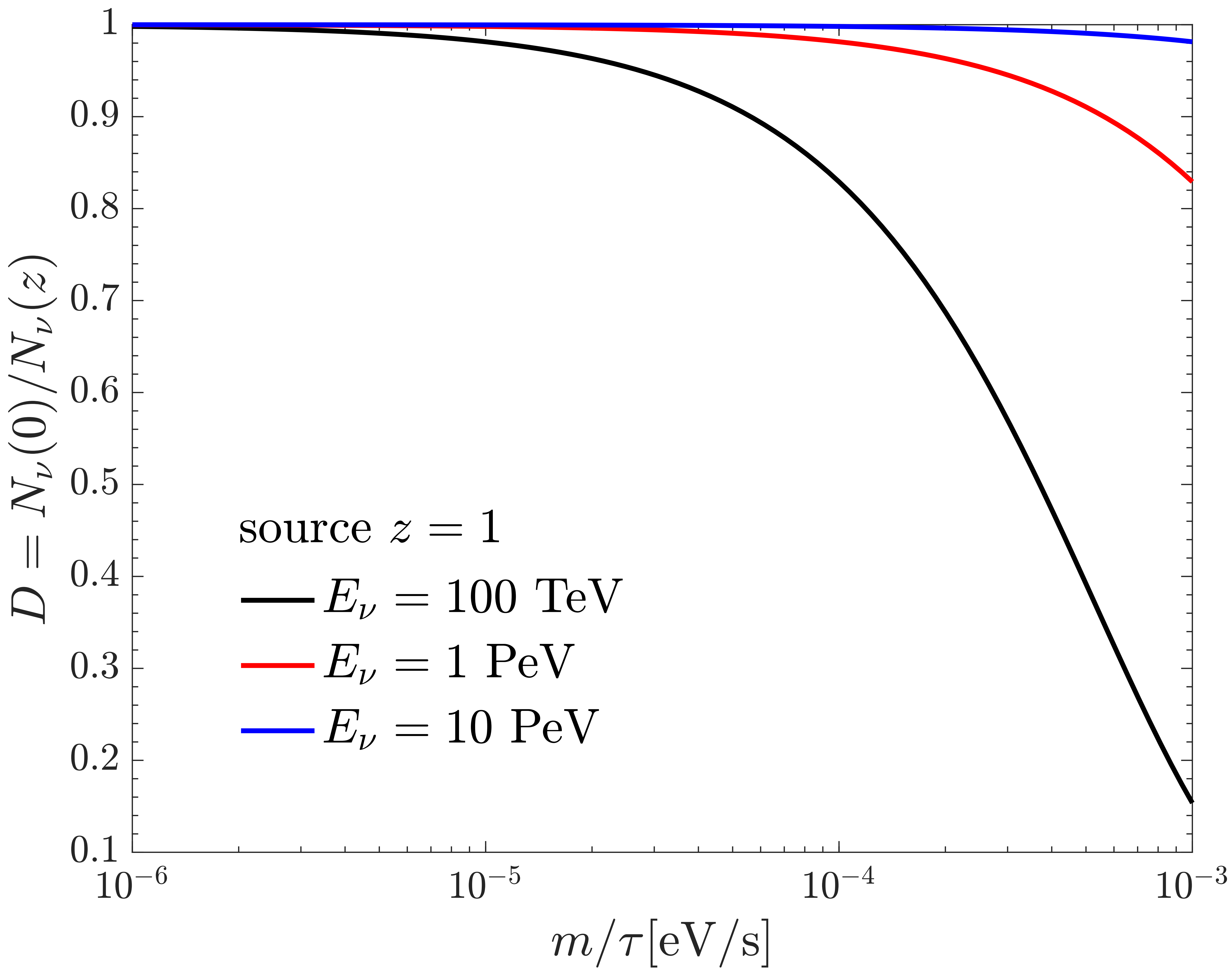
NS, Li, Argüelles, Bustamante, Vincent, 2012.12893

Neutrino Decay

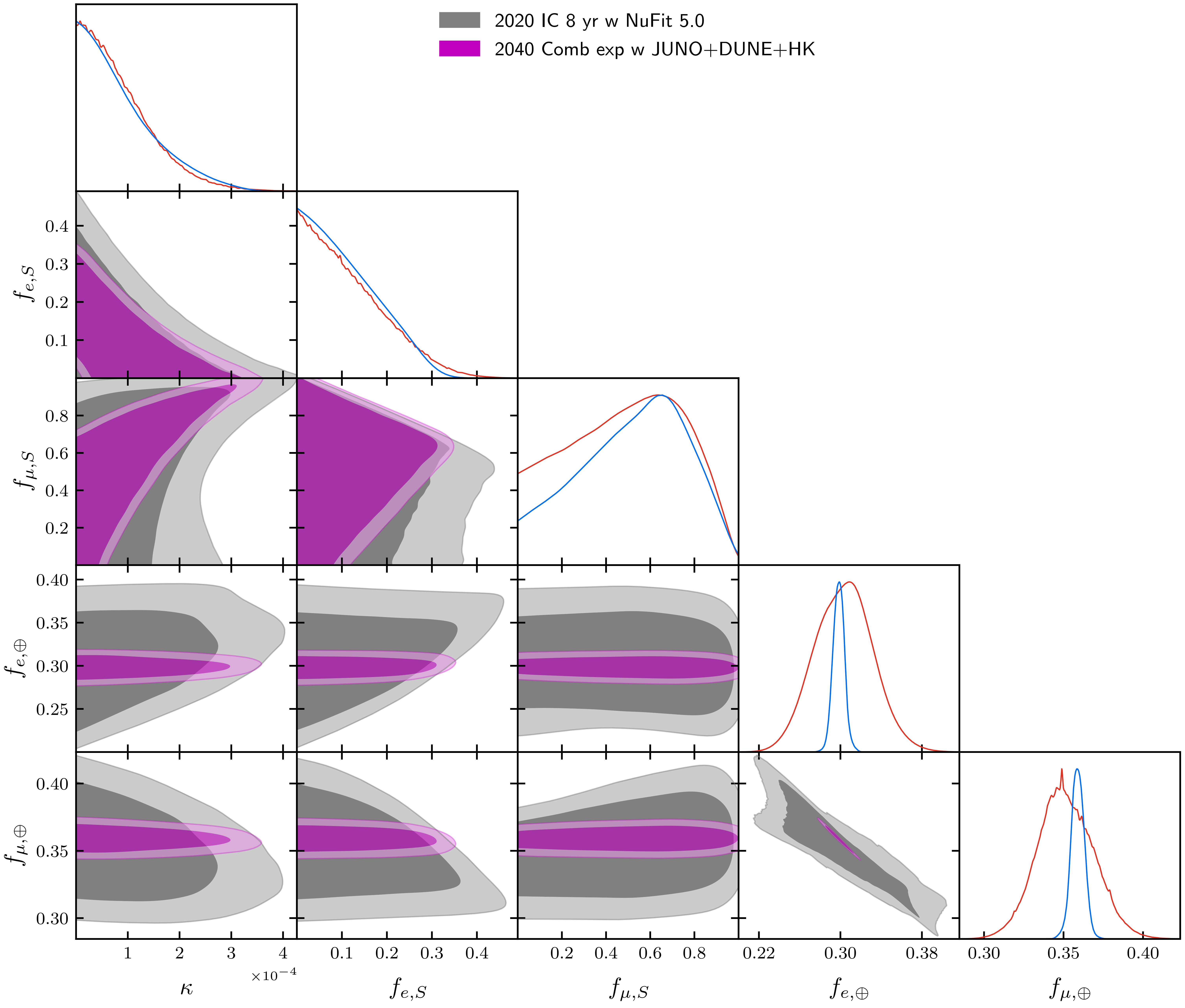
- Assume ν_2, ν_3 decay invisibly, ν_1 stable
- Assume pion decay at source $(f_e : f_\mu : f_\tau)_S = (1/3,\ 2/3,\ 0)$
- Sum up neutrinos sources at different redshifts

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

See 1208.4600, 1610.02096 for details



Neutrino Decay



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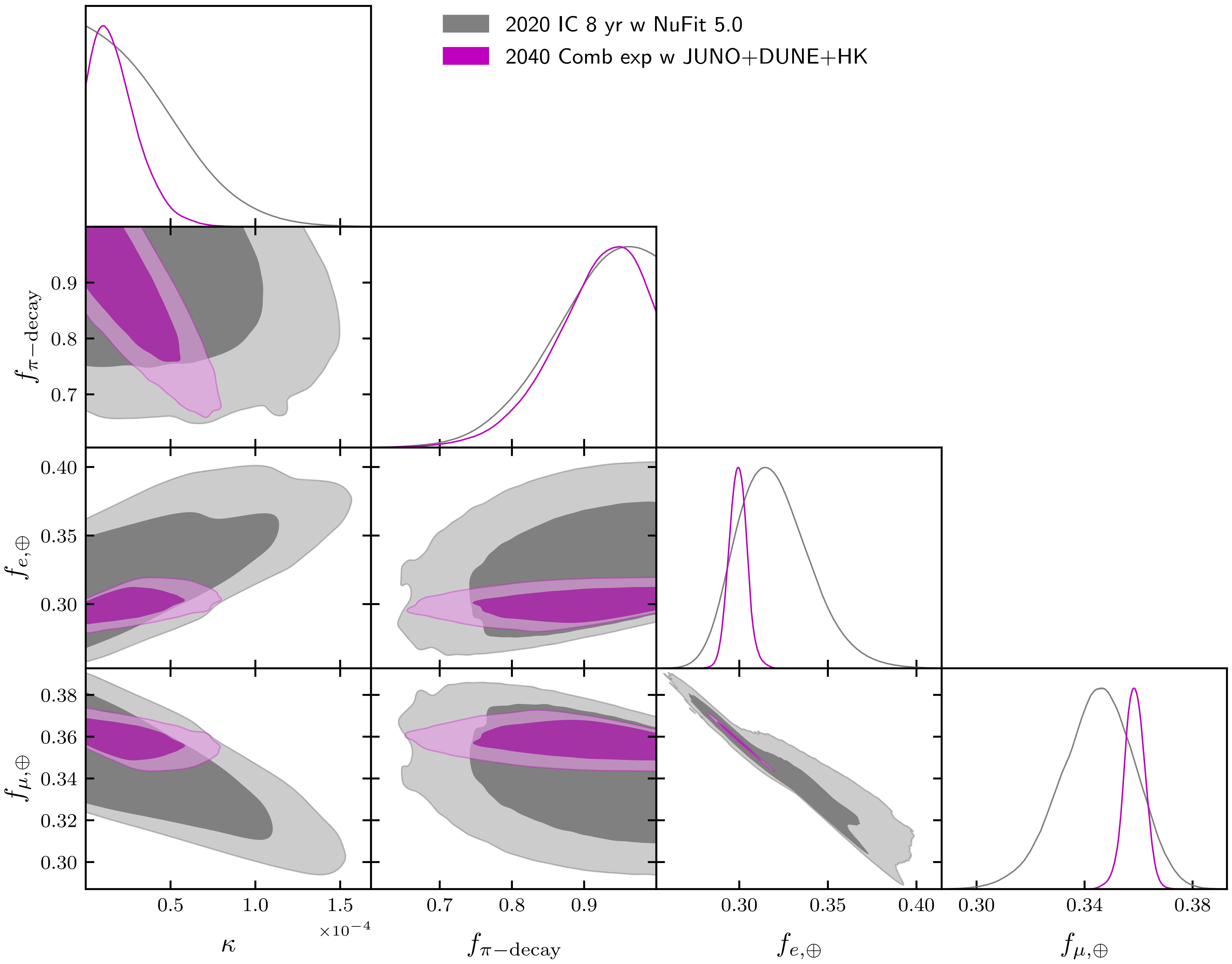
Neutrino Decay



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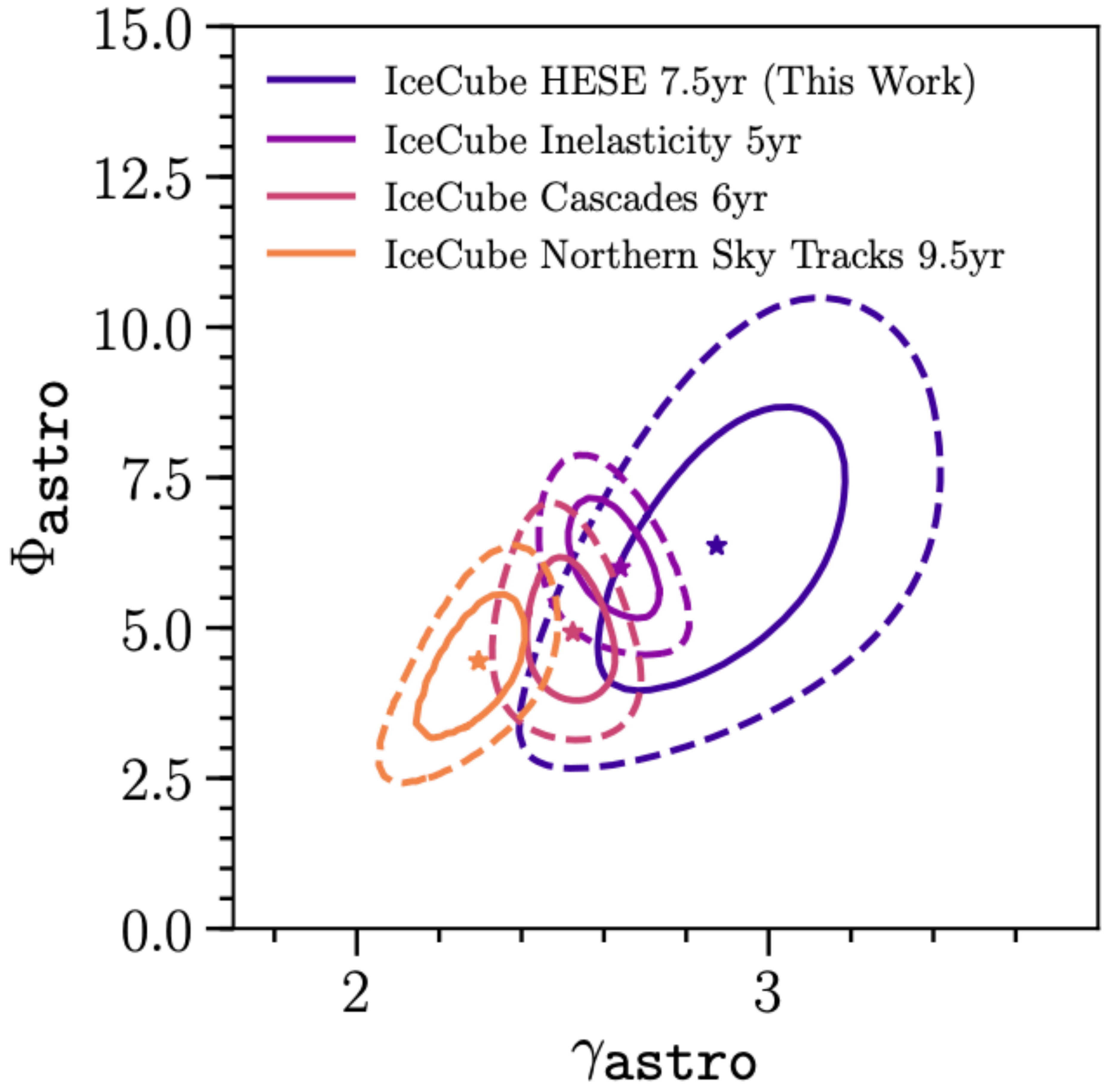
Astrophysical Neutrino Flux

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

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

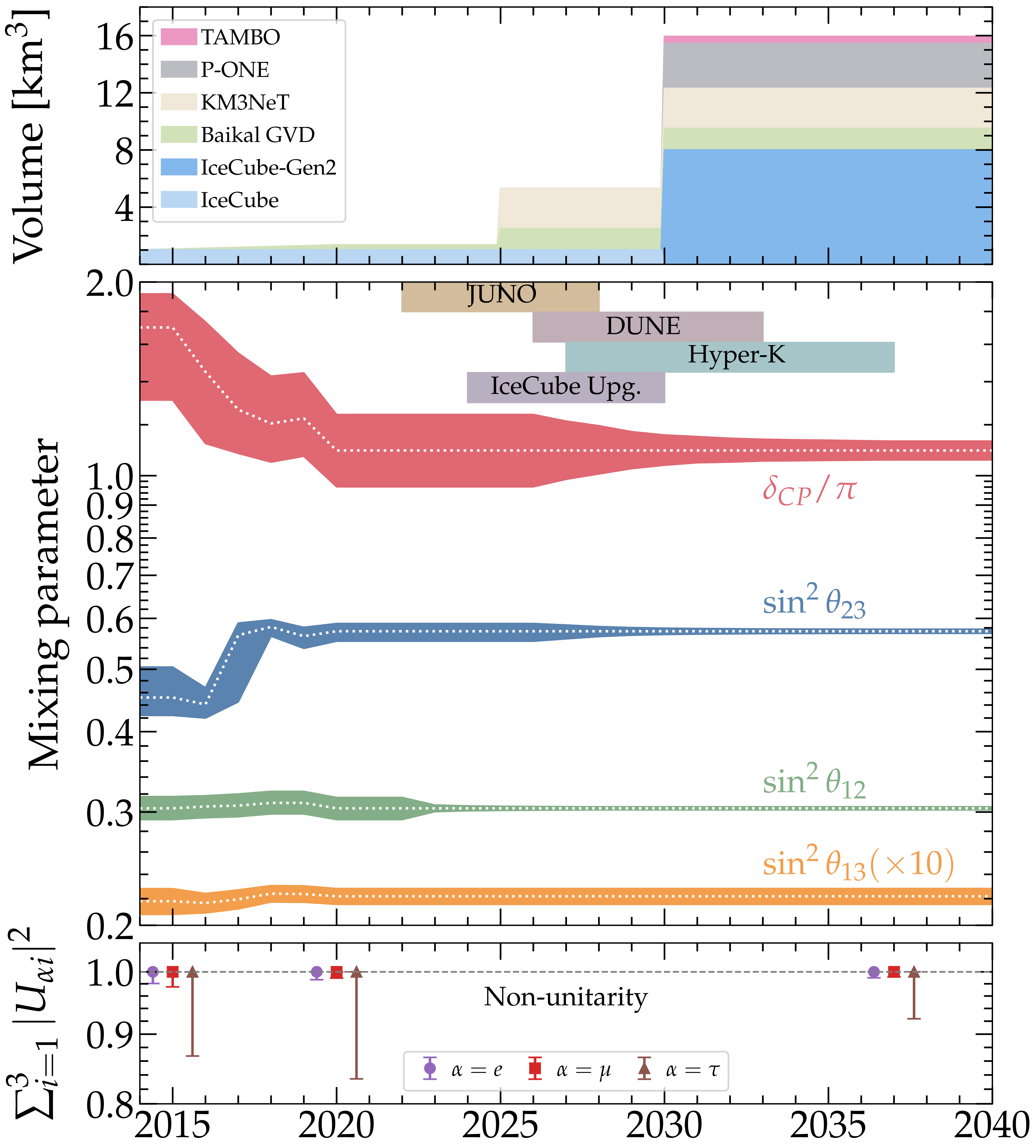
IceCube Collaboration, 2011.03561

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}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		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}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

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

What We Expect



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & \cdots \\ U_{\tau} & U_{\tau2} & U_{\tau3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

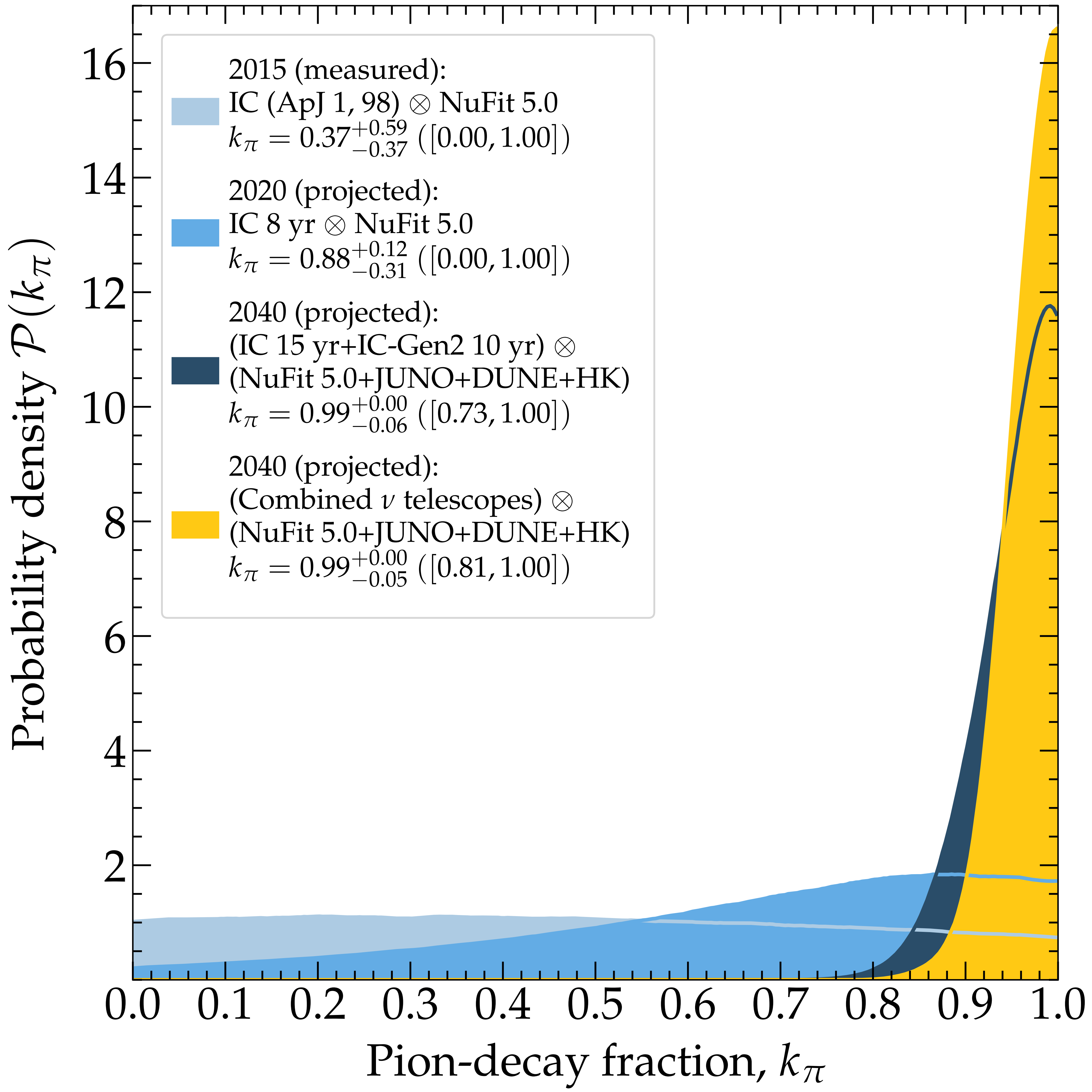
NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

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