Centre Canadien de Recherche en
Physique des Astroparticules
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The flavour of high-energy neutrinos

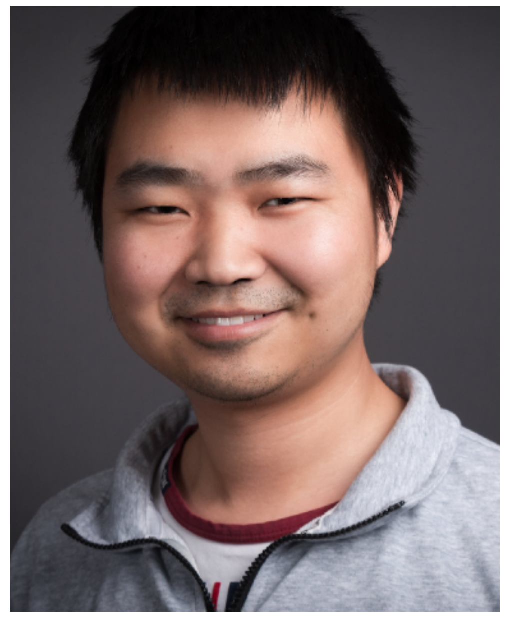
Aaron Vincent

Neutrinos in Cosmology and Astrophysics | TRIUMF | Mar 8 2024

Featuring


Carlos Argüelles
Harvard


Mauricio Bustamante
Niels Bohr Institute


Ningqiang Song
CN Yang ITP

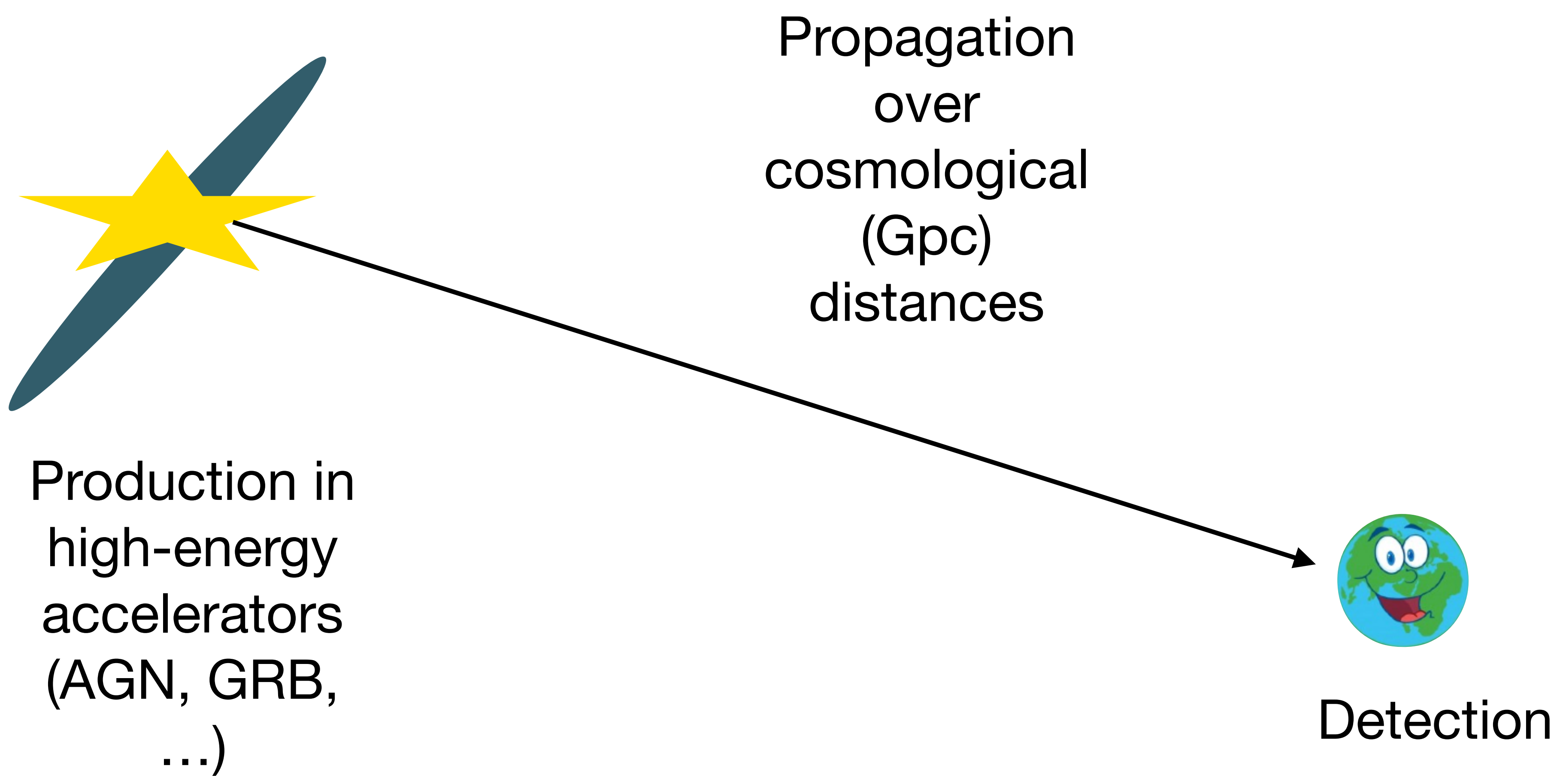

Ali Kheirandish
Las Vegas


Shirley Li
UC Irvine


Damiano
Fiorillo
NBI

Qinrui Liu
Queen’s

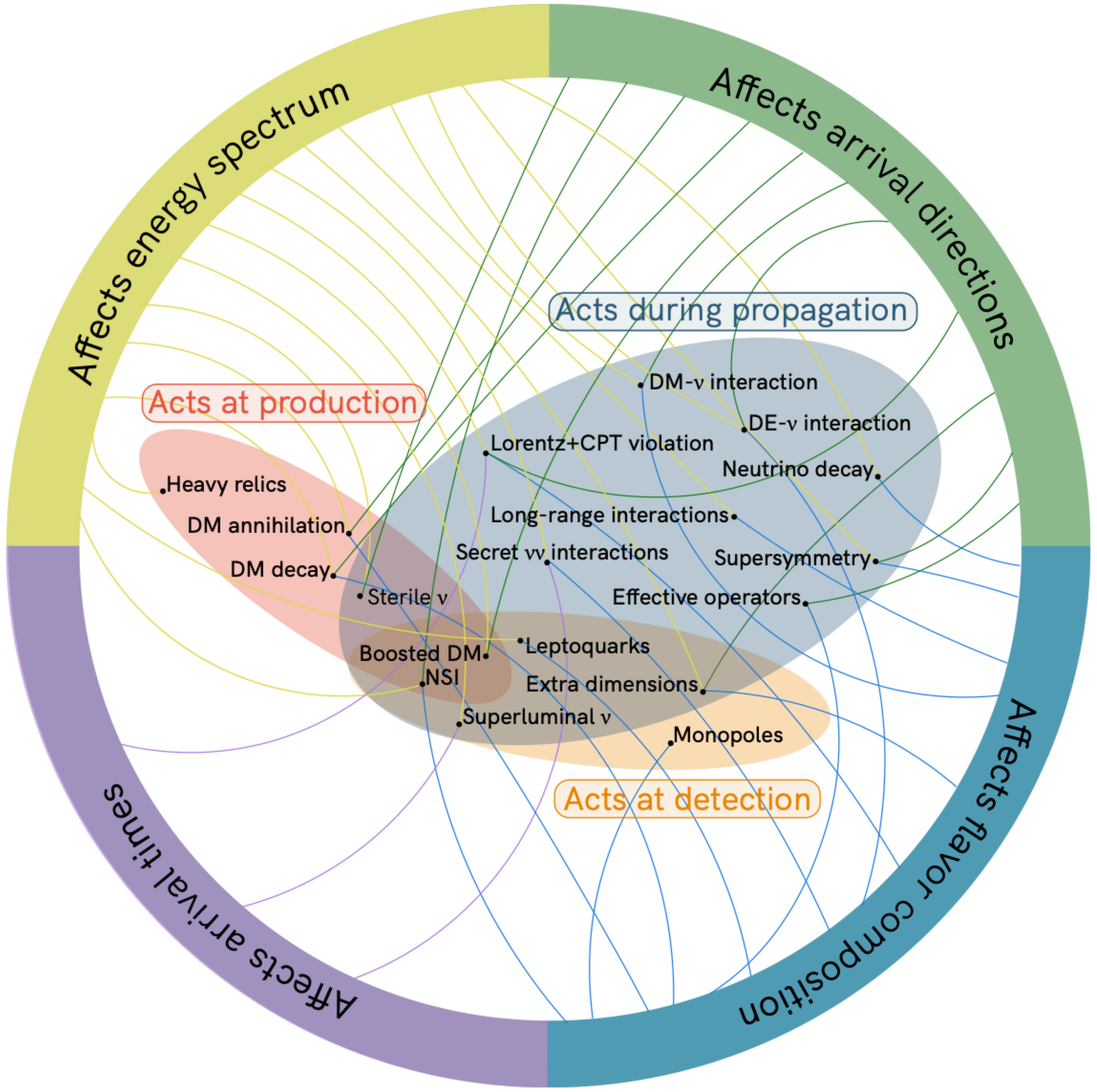
High-energy neutrinos



Propagation over cosmological (Gpc) distances

Production in high-energy accelerators (AGN, GRB, …)

Detection



Neutrinos can tell us about "standard model" physics:

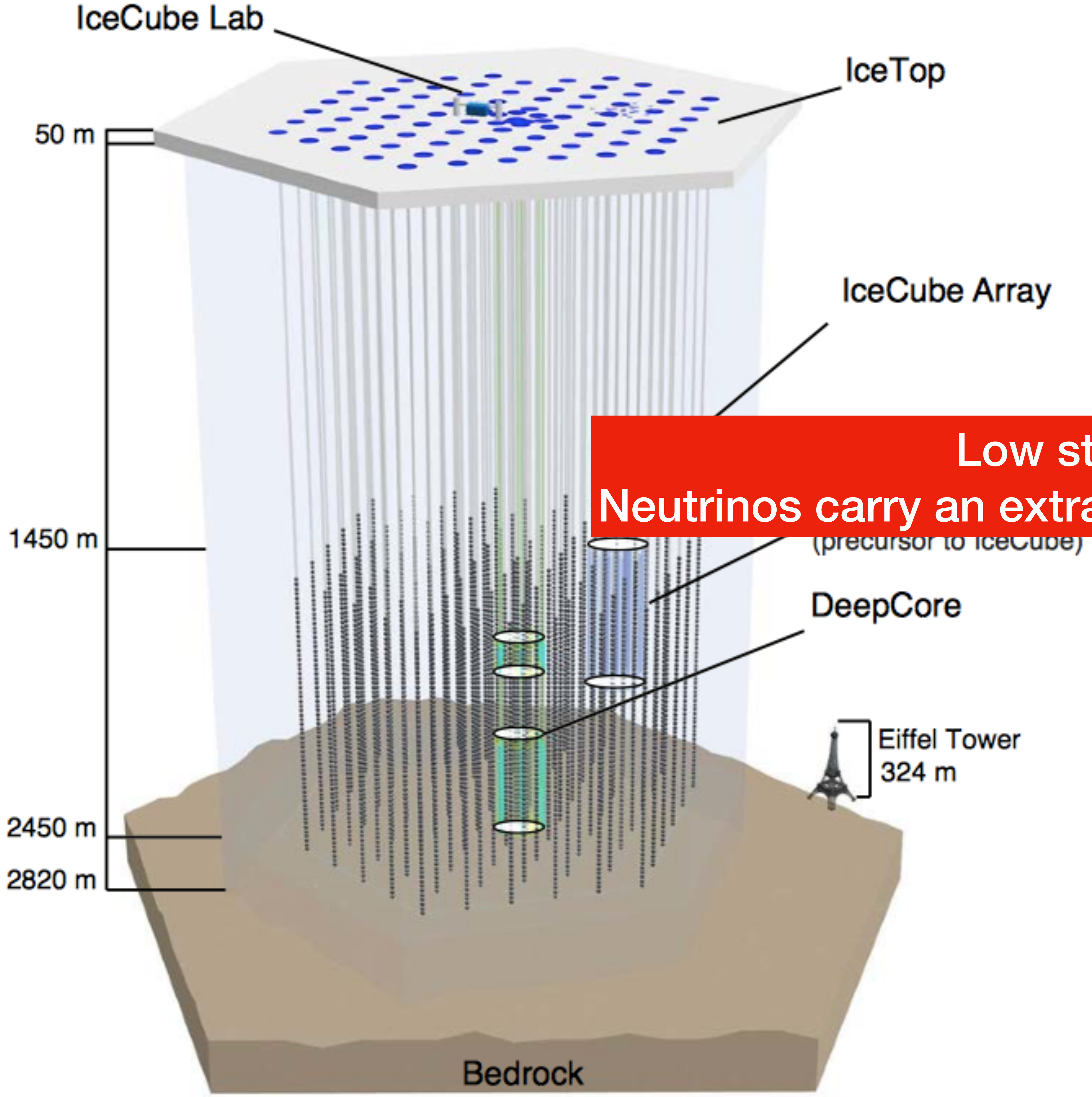
- Nature of these accelerators
- Oscillation, interaction with intergalactic medium
- Detection: high-energy neutrino-nucleus cross sections

New Physics?

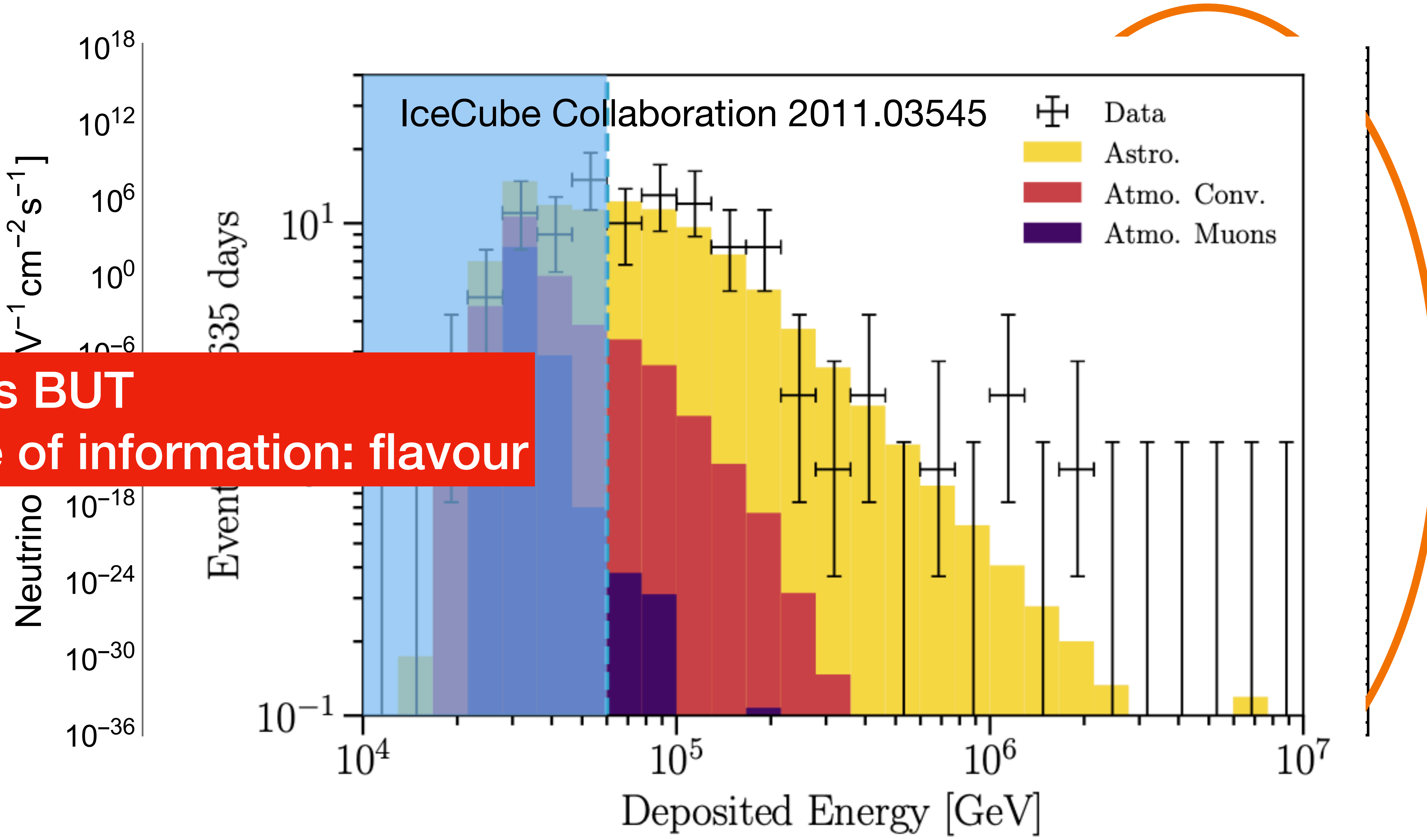
1907.08690 Argüelles,Bustamante,Kheirandish,Palomares-Ruiz,Salvado, ACV

Current observations: IceCube (south pole)

Effective volume $\sim 1\,\mathrm{km}^3$



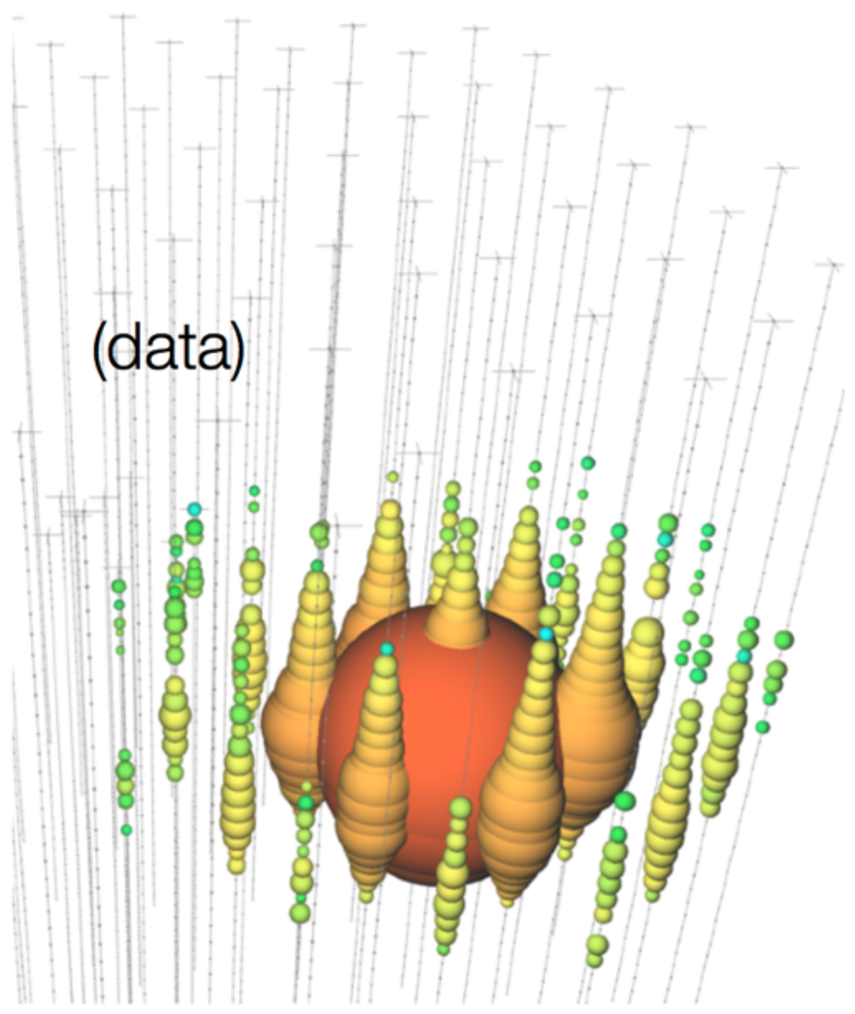
Low statistics BUT
Neutrinos carry an extra piece of information: flavour


IceCube Collaboration 2011.03545

large exposures necessary
due to low fluxes

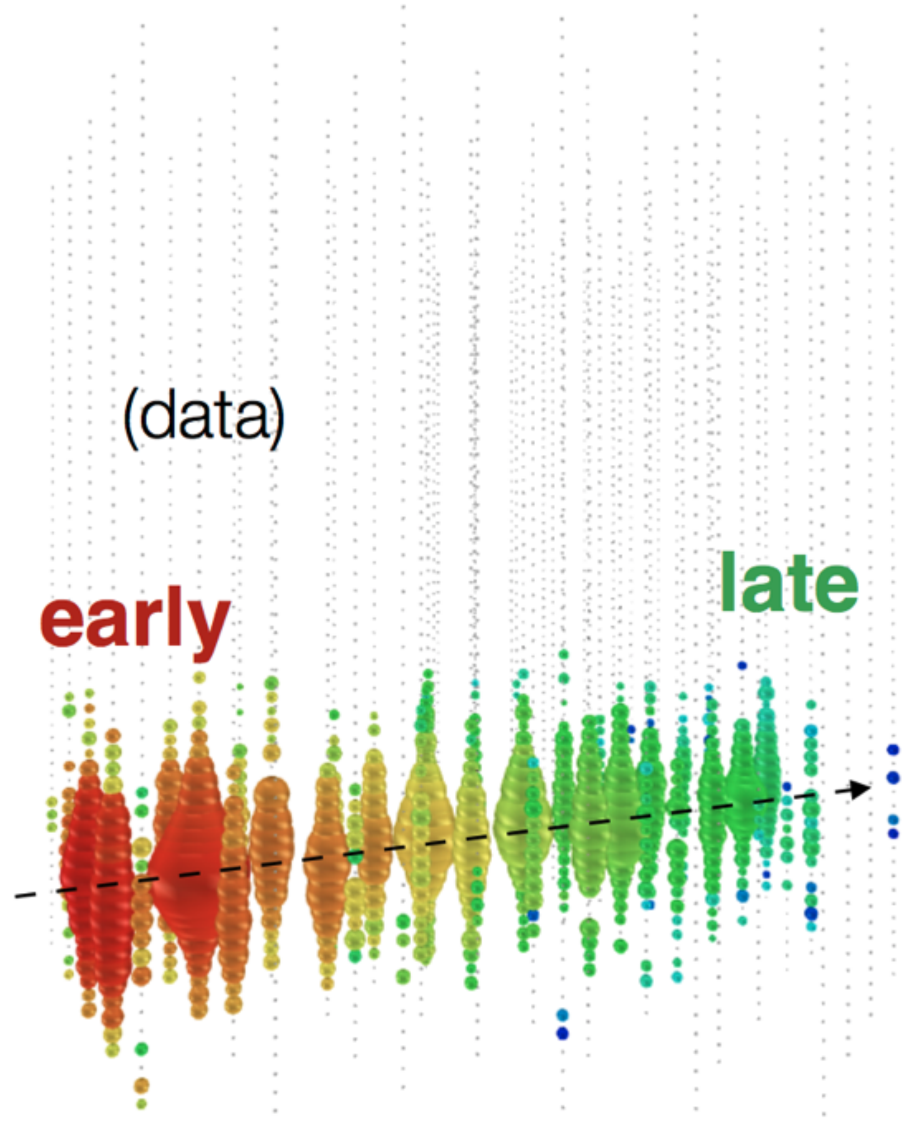
Flavour: event morphology

Neutral-current / ν_e



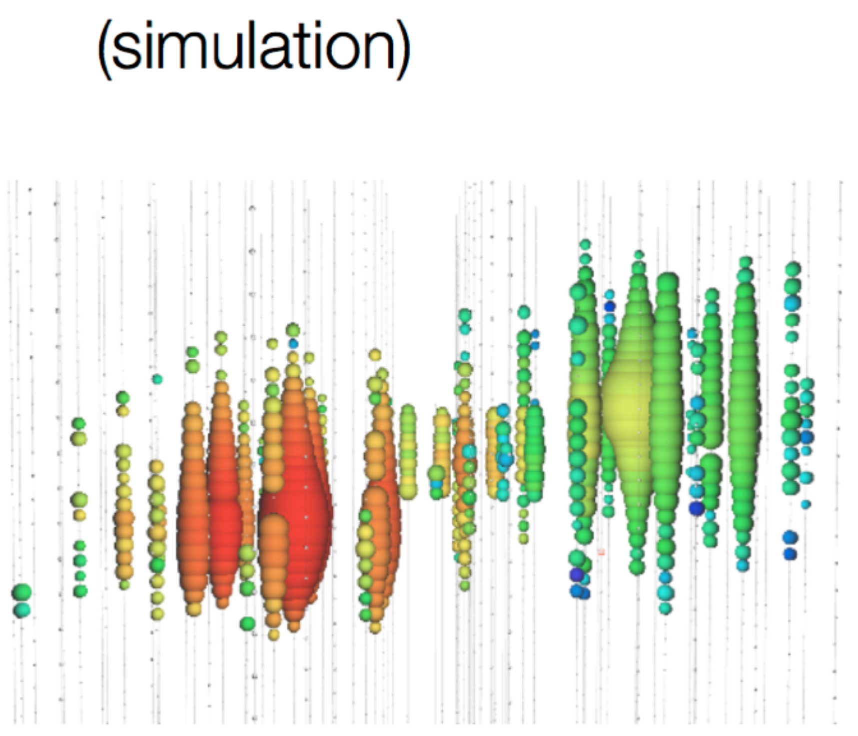
Isolated energy deposition (cascade) with no track

Charged-current ν_μ



Up-going track

Charged-current ν_τ

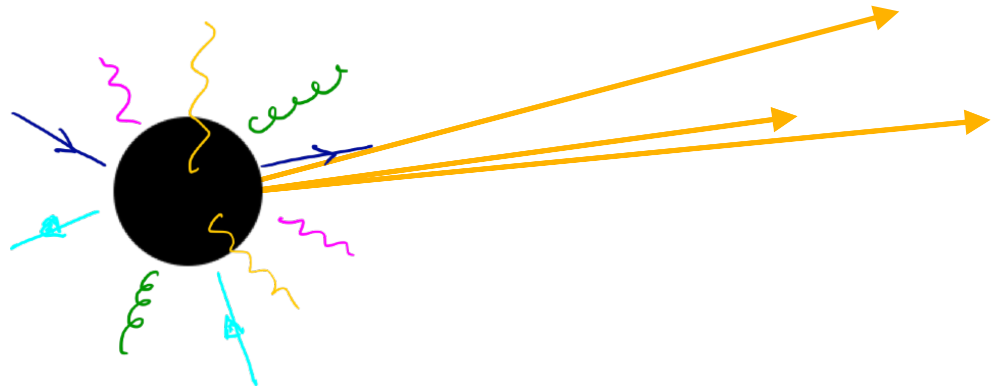


Double cascade

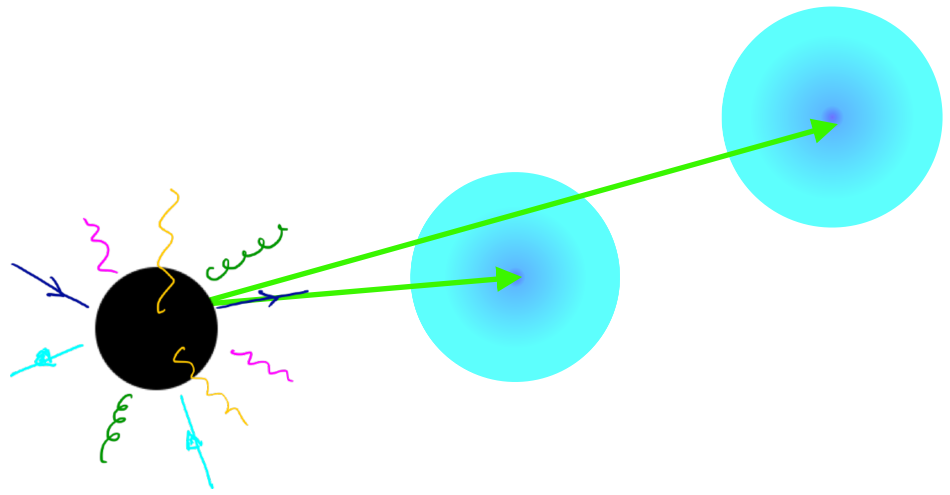
Images: icecube.wisc.edu

Aside: new physics can give new morphologies

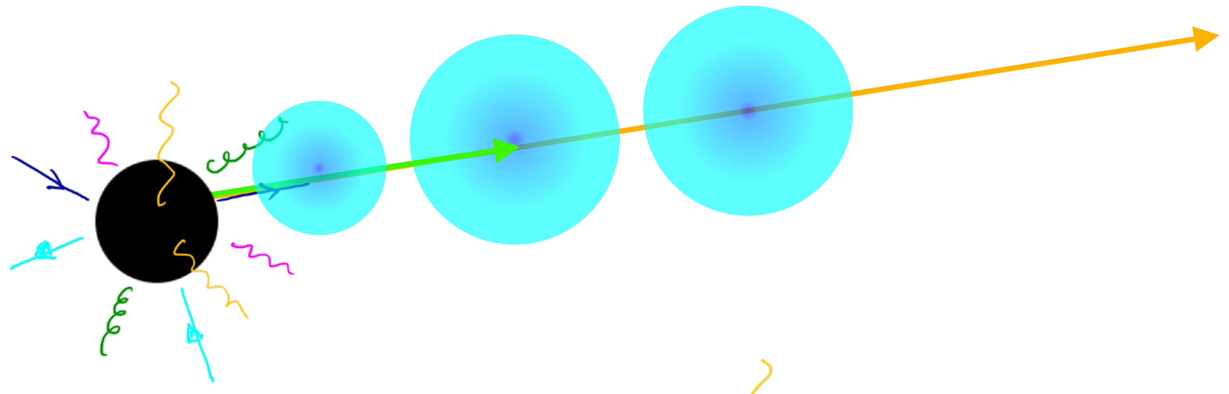
Microscopic black hole signatures: Mack, Song, ACV 1912.06656



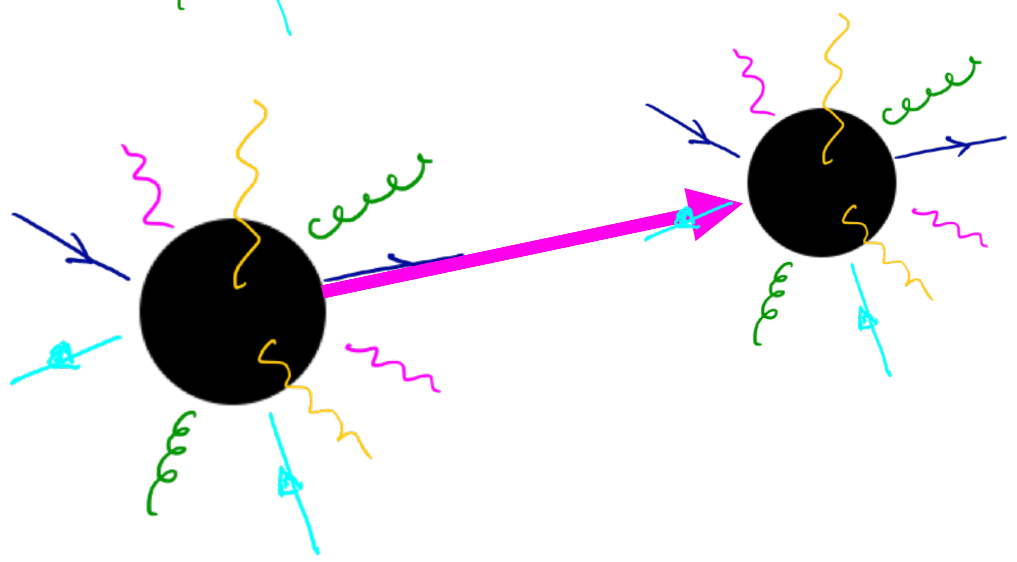
Multitrack (hard to see)



n-bang (*only* 0.2% of black hole events)



Kebab**:** (About 3% of cases)



Double black hole bang**:** (very rare!!)

Flavour composition in astrophysical sources

(GRBs, AGNs, blazars, pulsars…)

$(\alpha_e : \alpha_\mu : \alpha_\tau)$

● **Pion sources**

(c.c. for π^-)

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

(1 : 2 : 0)

■ **“muon-damped”**

(c.c. for π^-)

$$\pi^+ \to \cancel{\mu^+} + \nu_\mu$$

(0 : 1 : 0)

◆ **“muon source”**

(c.c. for π^-)

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

(1 : 1 : 0)

▲ **Neutron source**

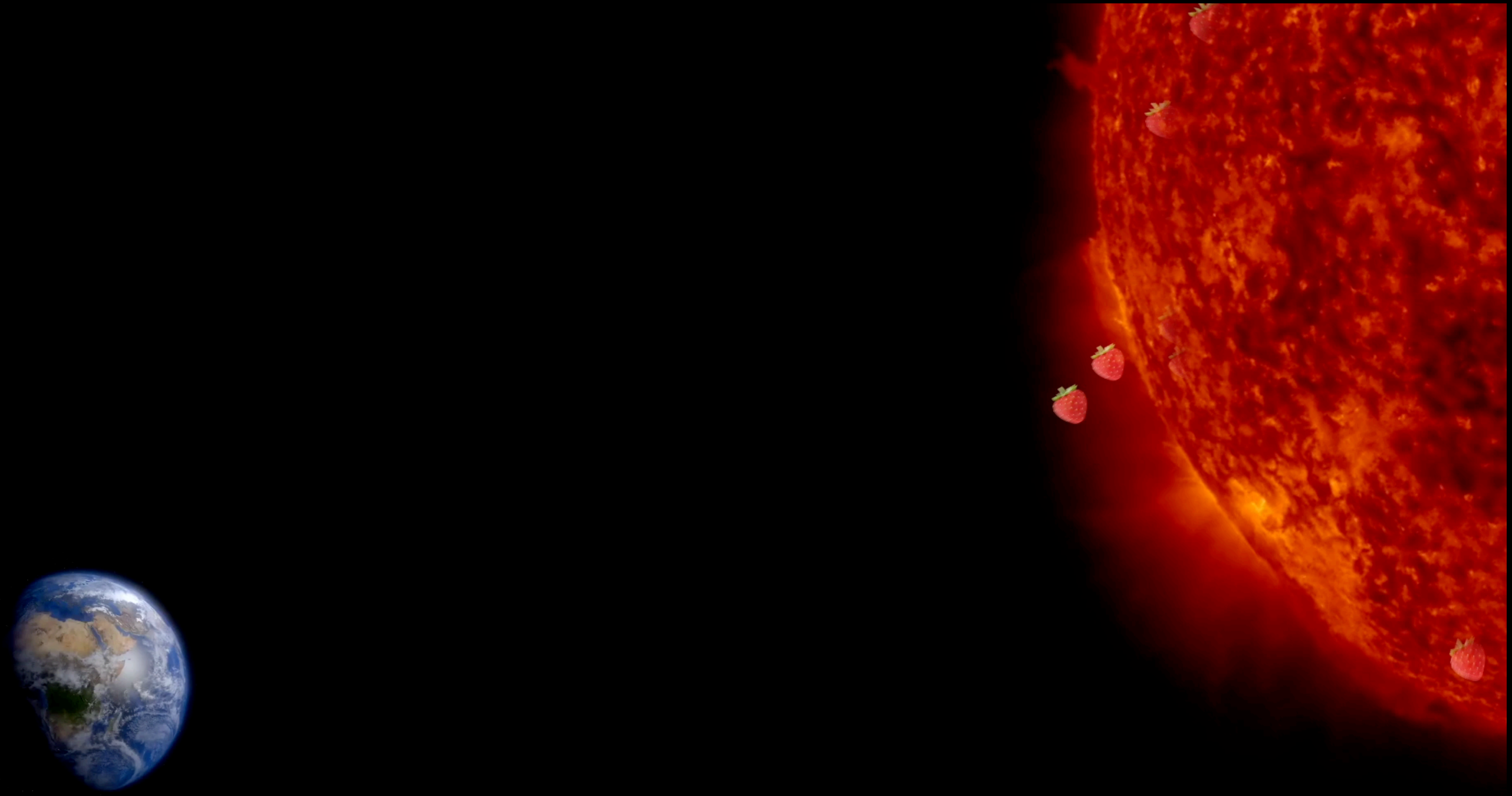
$$n \to p + e^- + \bar{\nu}_e$$

(1 : 0 : 0)

Different scenarios: different production environments

Flavour can be distinguished **statistically** in neutrino detectors: different charged-current interactions lead to different event **morphologies** (there is some degeneracy)

Can we learn the flavour composition at the source to understand the production of astrophysical neutrinos?



Stan Yen

Oscillation

Flavour eigenstates ($\alpha = e, \mu, \tau$) are not eigenstates of the Hamiltonian ($i = 1{,}2{,}3$)

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle,$$

Flavour basis

PMNS mixing matrix

mass basis

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

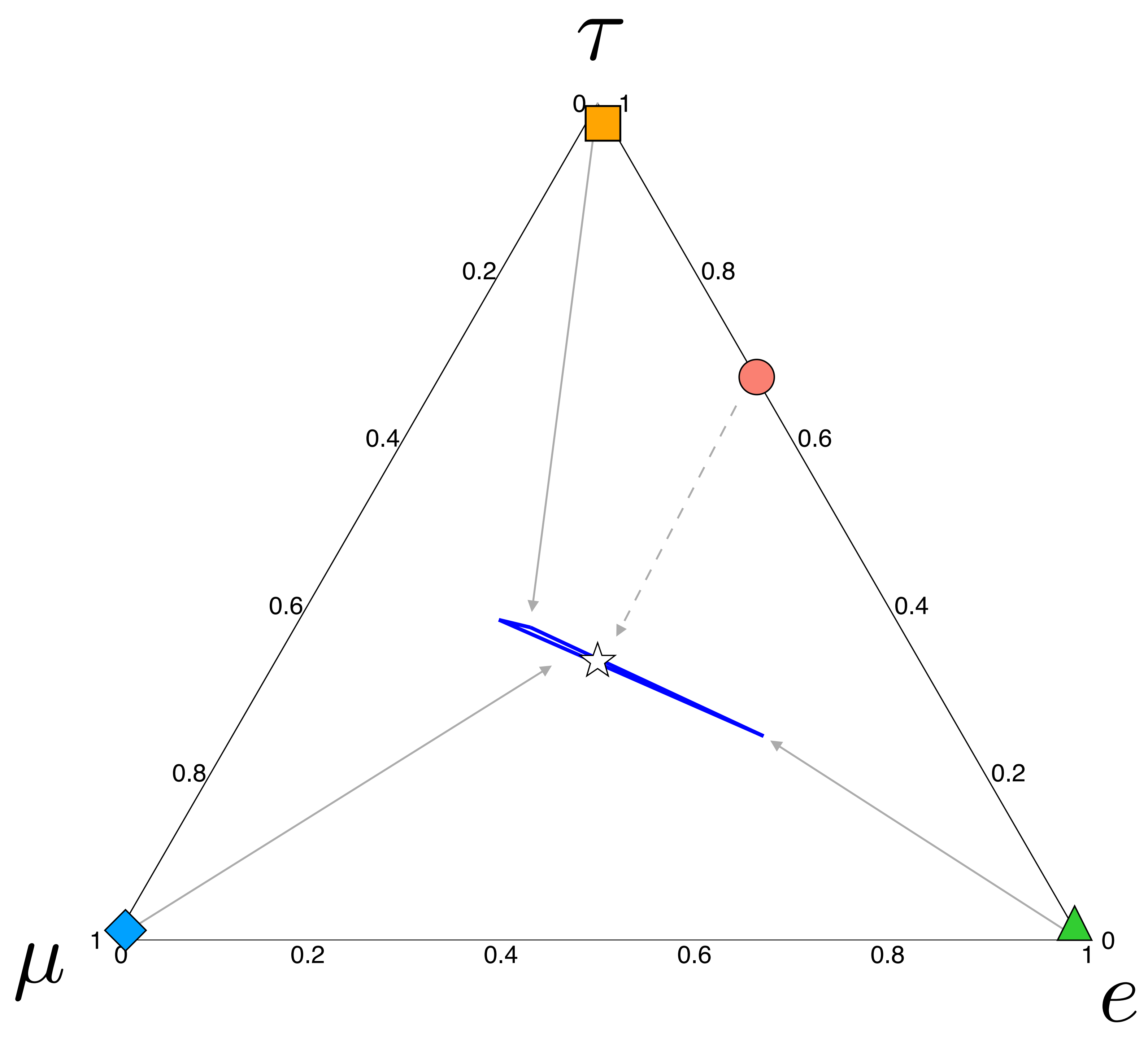
Distances are **large and uncorrelated** -> mixing **averages out:**

$$P_{\alpha\to\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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

flavour composition at Earth

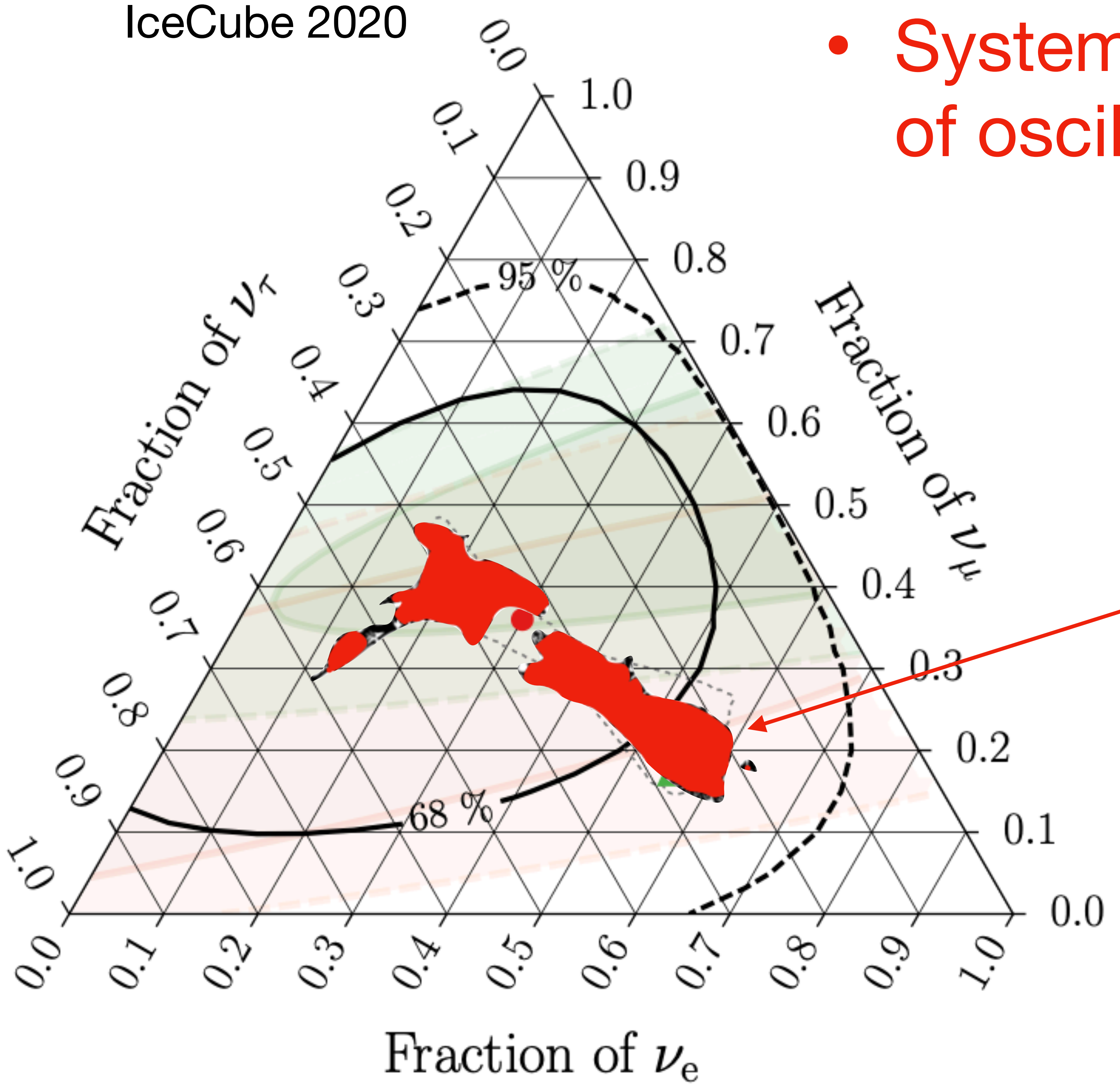
flavour composition at source



Flavour composition at Earth

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix}$$

IceCube 2020



Two limits:

- Statistics (astrophysical neutrinos)
- Systematics: precise knowledge of oscillation parameters

A flavour composition outside of this region = new physics (or you messed up)

NuFit 5.0 global fit

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

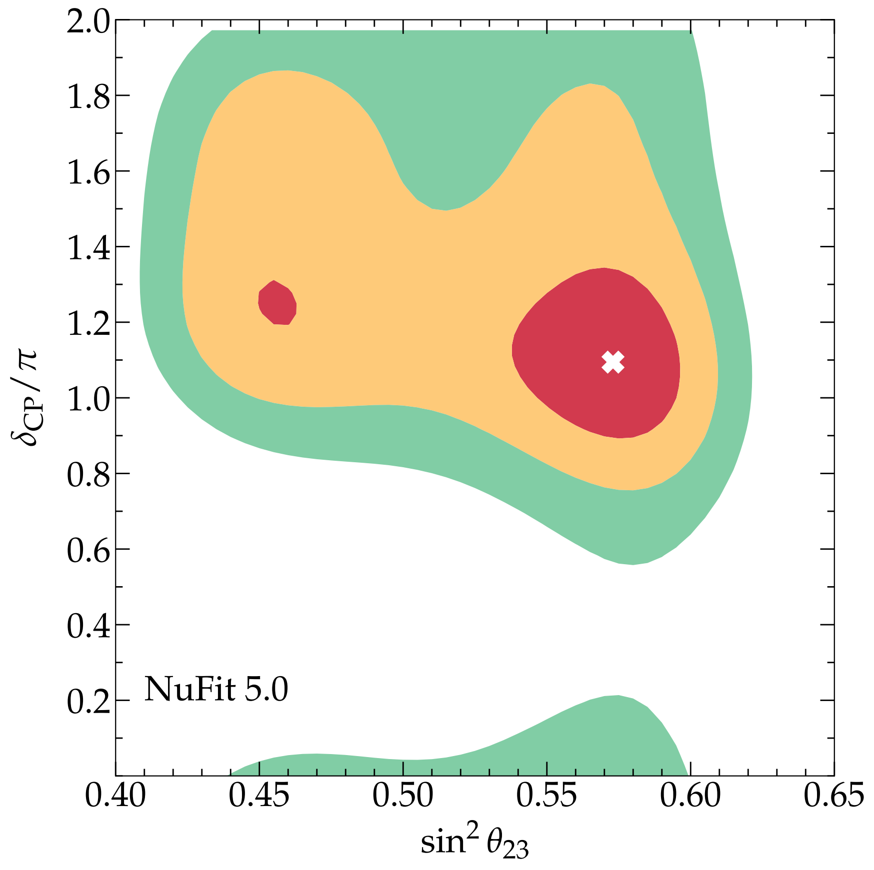
θ_{12} ("solar angle"): Solar, reactor experiments

θ_{23} ("atmospheric angle") Atmospheric, long-baseline

θ_{13} Reactor experiments

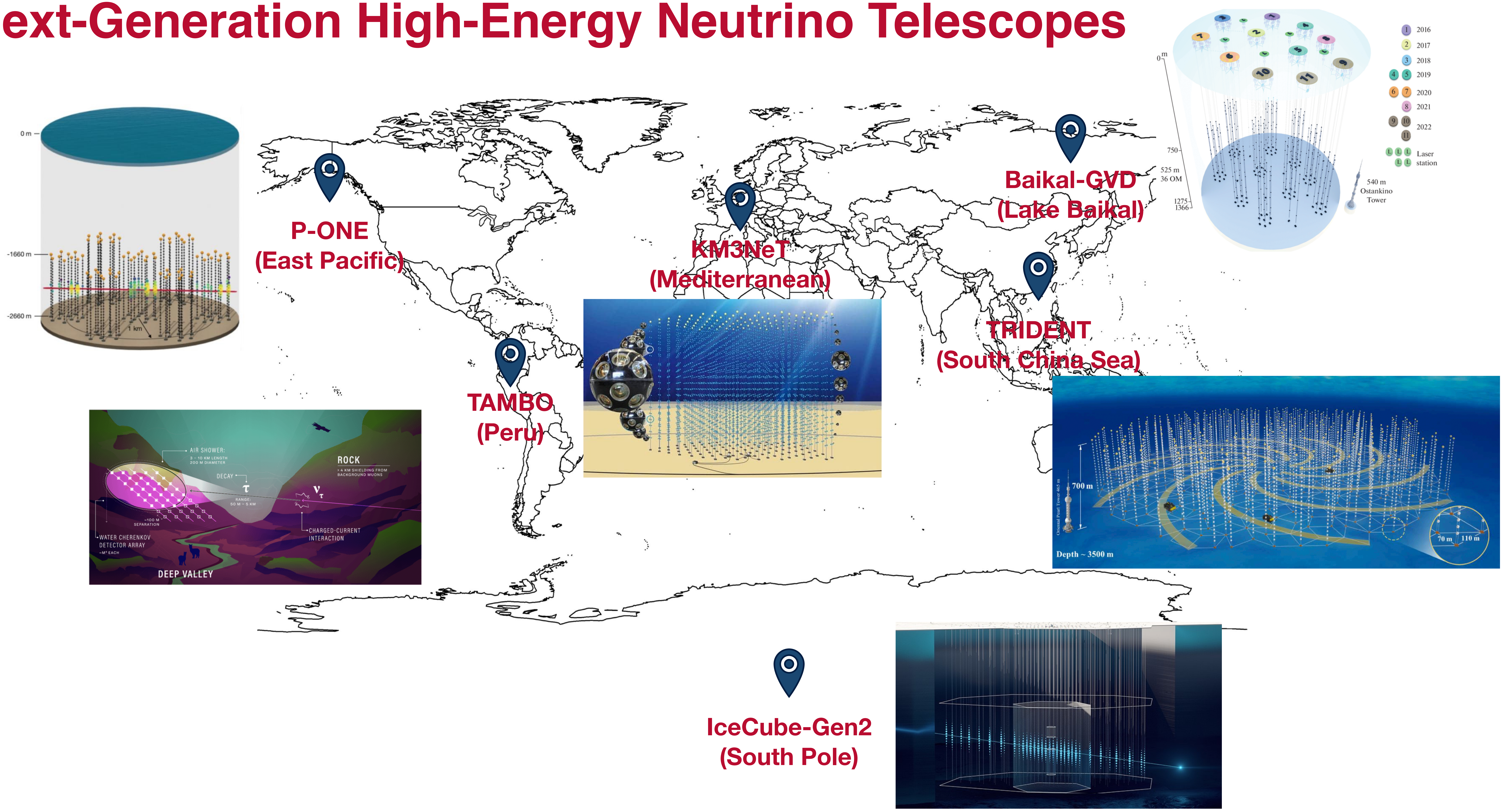
δ_{CP} Long-baseline experiments

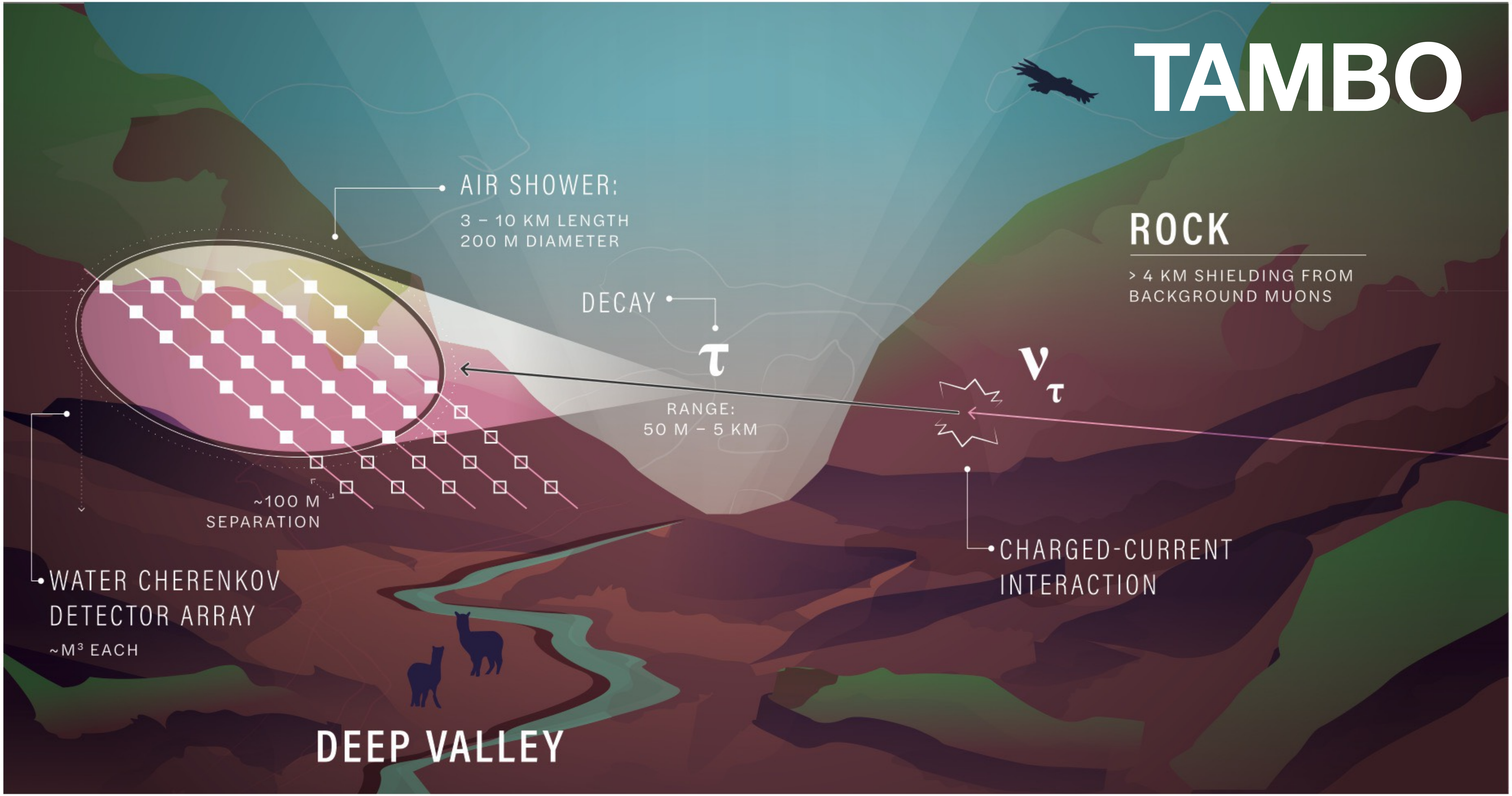
Mostly uncorrelated except:



What does the future say about this?

Next-Generation High-Energy Neutrino Telescopes





TAMBO

AIR SHOWER:
3 – 10 KM LENGTH
200 M DIAMETER

DECAY

τ

RANGE:
50 M – 5 KM

ROCK

> 4 KM SHIELDING FROM BACKGROUND MUONS

ν_τ

CHARGED-CURRENT INTERACTION

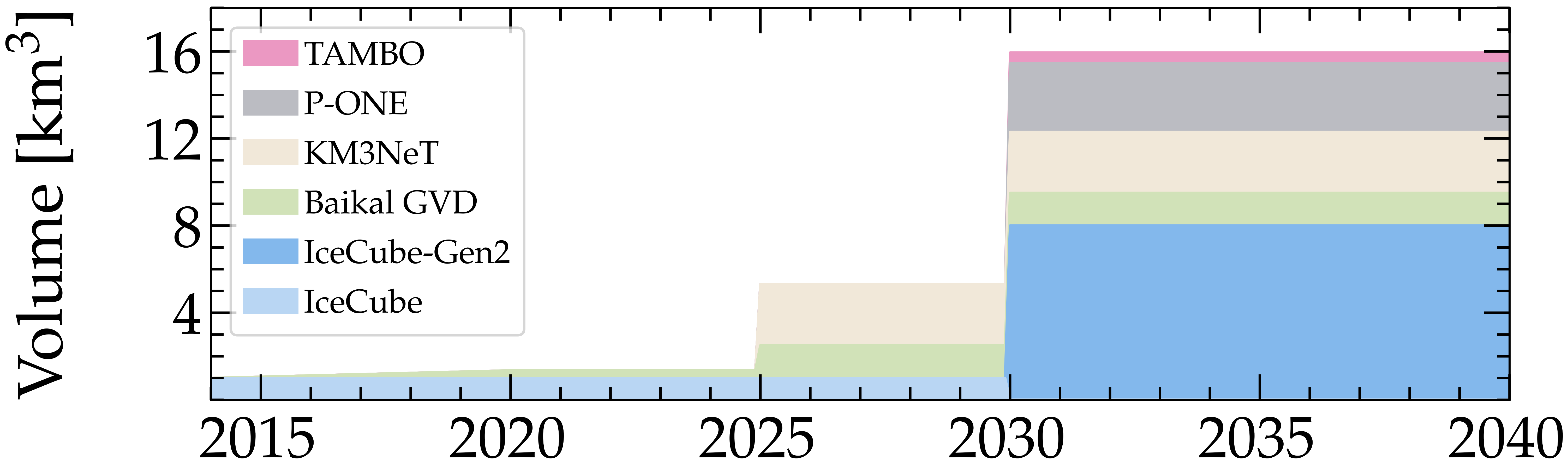
~100 M SEPARATION

WATER CHERENKOV DETECTOR ARRAY
~M³ EACH

DEEP VALLEY

TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Statistics: need more Cherenkov telescopes!



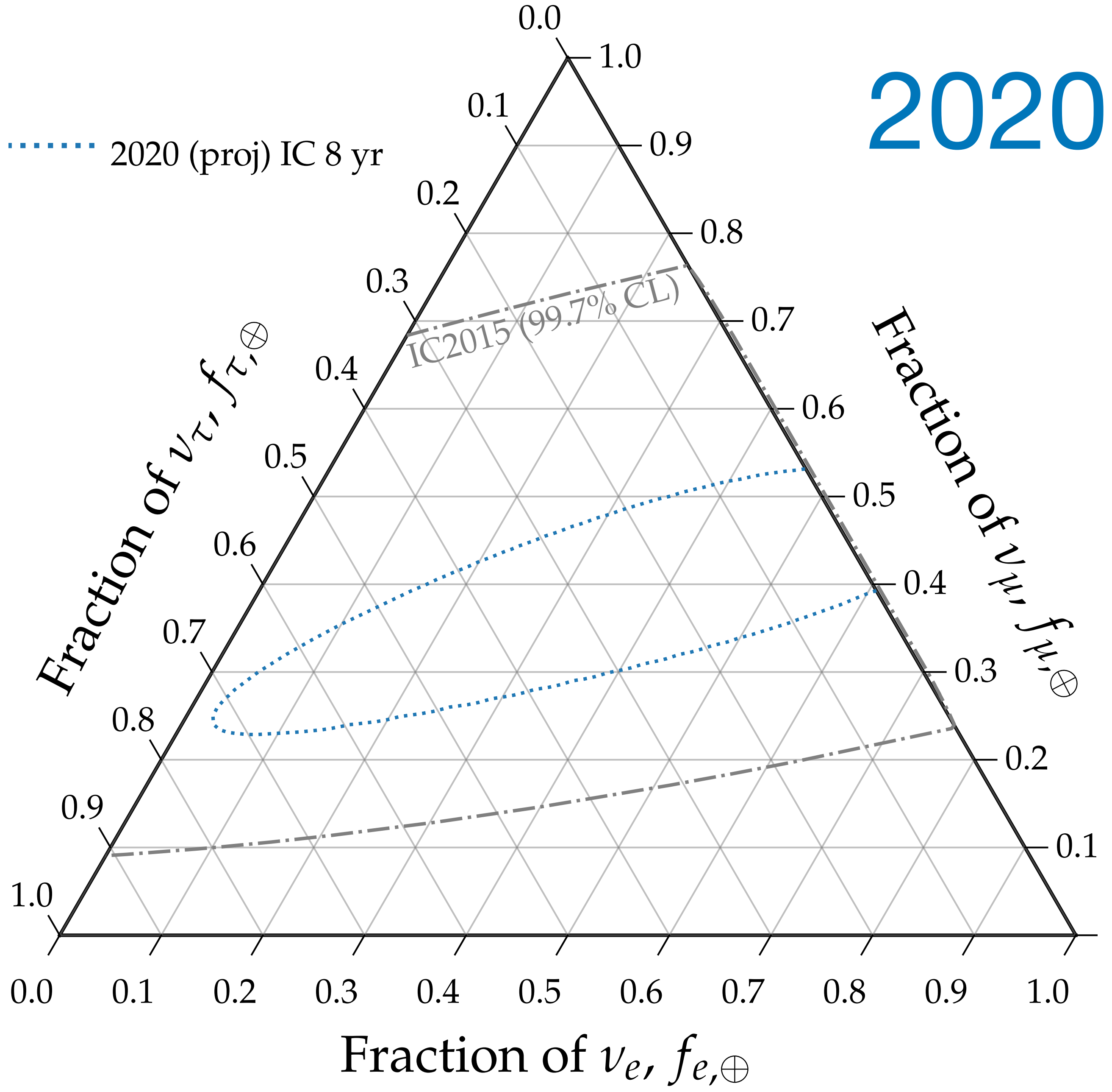
Telescope	Medium	Location	Exposure (km^3)
IceCube-Gen2	Ice	South pole (HE upgrade of IceCube)	~6-9
KM3NeT	Seawater	Mediterranean Sea (successor to ANTARES)	~2-3
GVD	Freshwater	Lake Baikal	1.5
P-ONE	Seawater	Cascadia Basin (Pacific Ocean)	π
TAMBO	Rock/air/water Cherenkov	Peru	~10 (very high E, tau only)

Song, Li, Argüelles, Bustamante, ACV 2012.12893

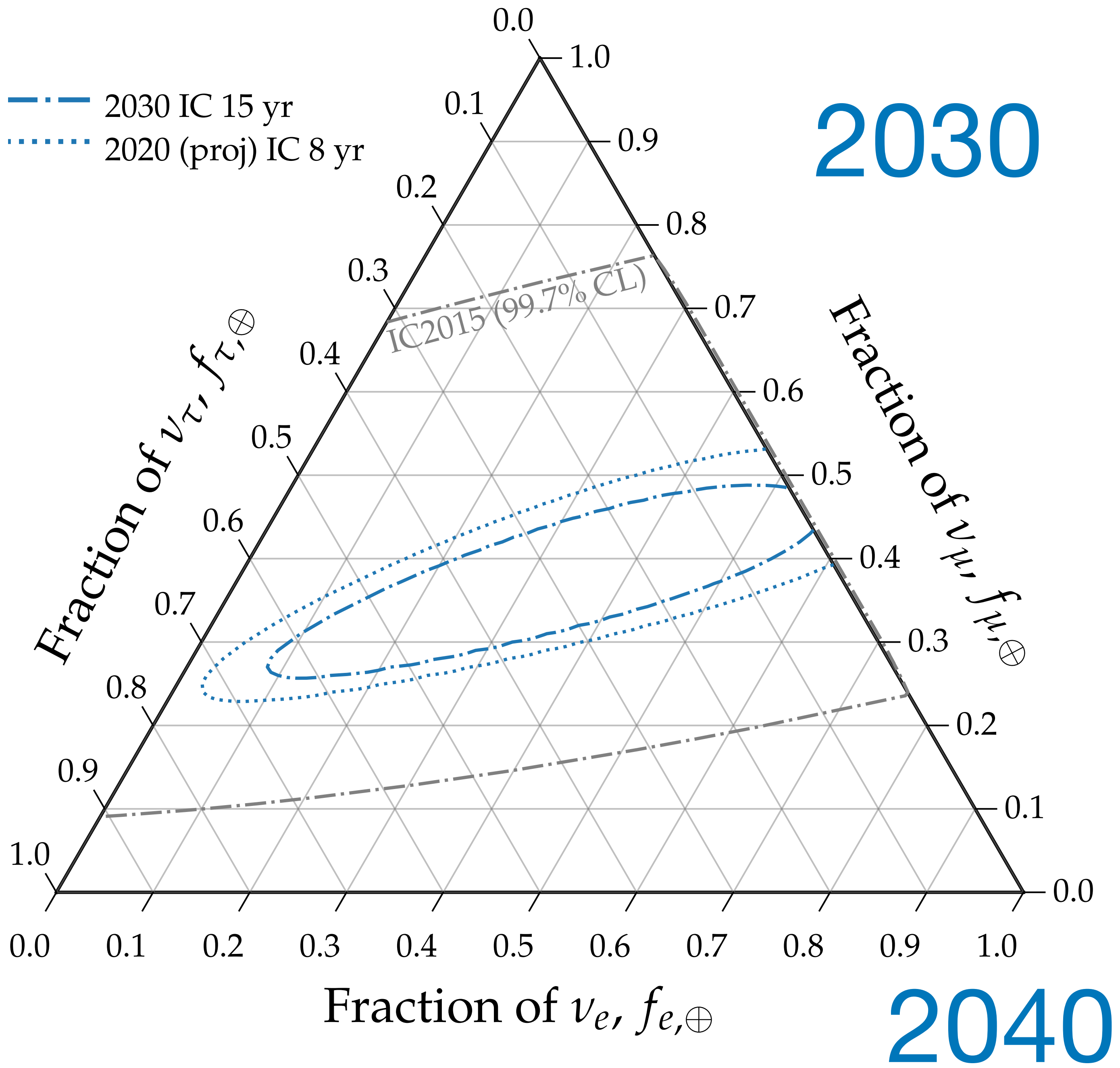
Song, Li, Argüelles, Bustamante, ACV 2012.12893

Statistics

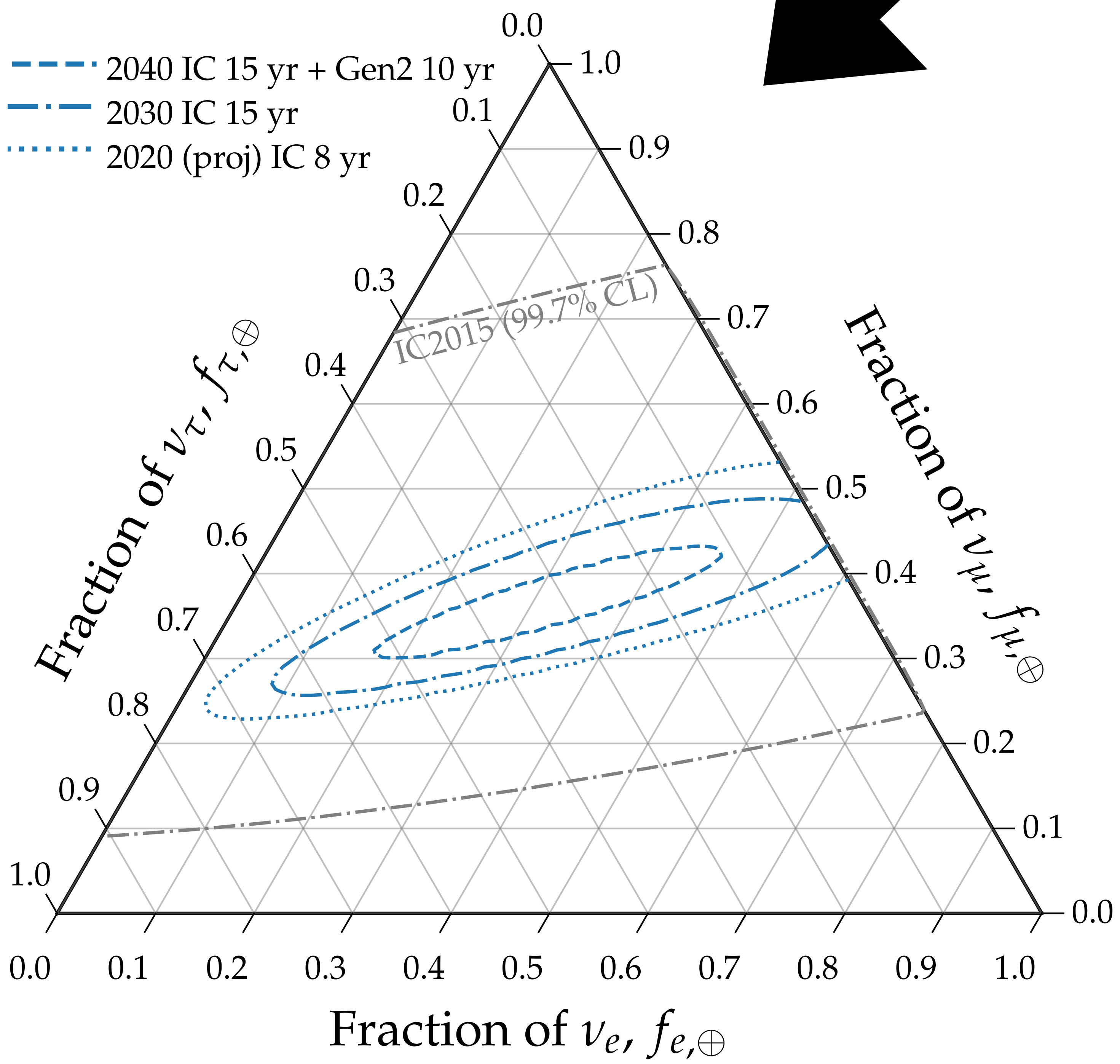
2020



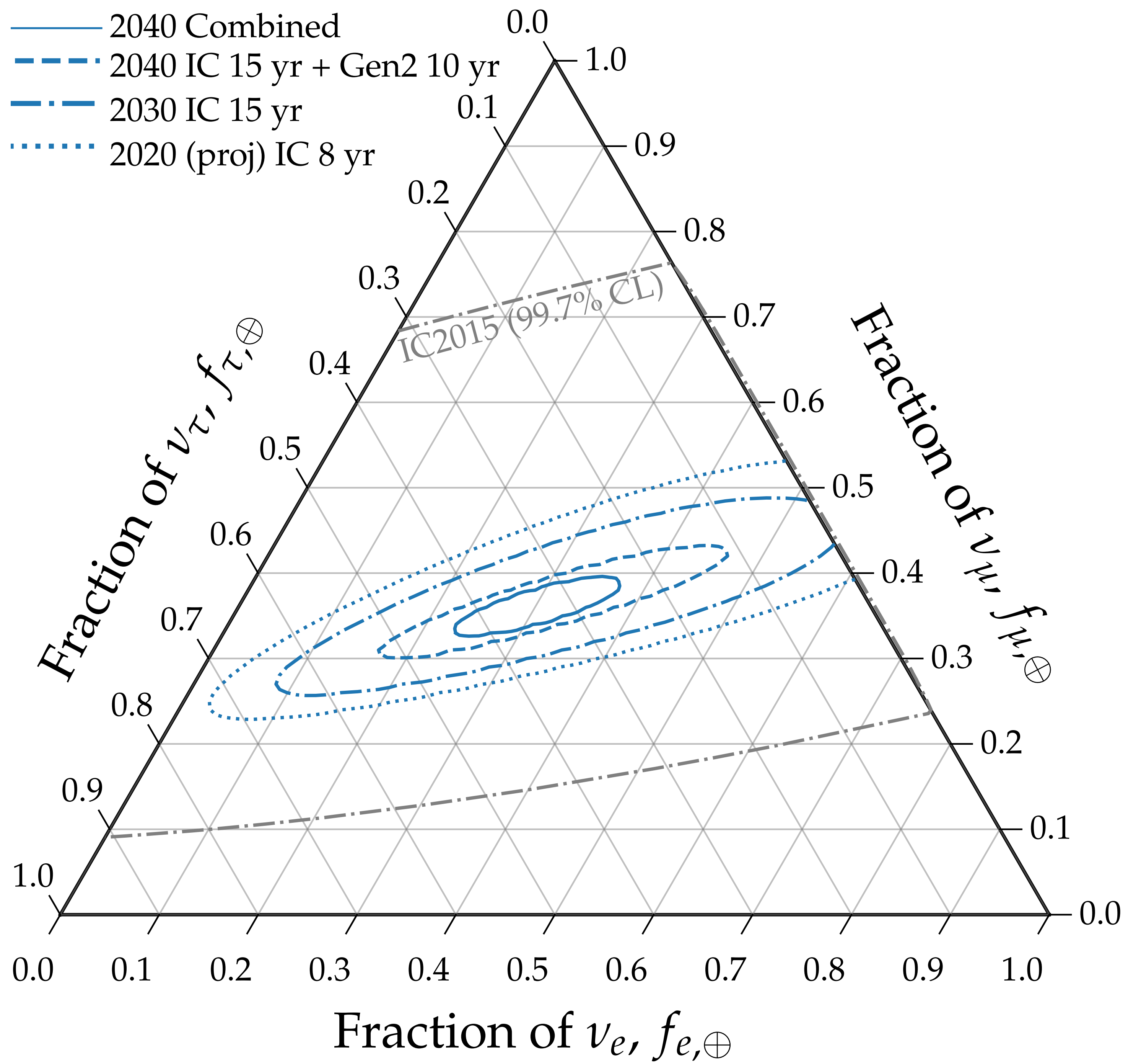
2030



2040 (IceCube-Gen2)

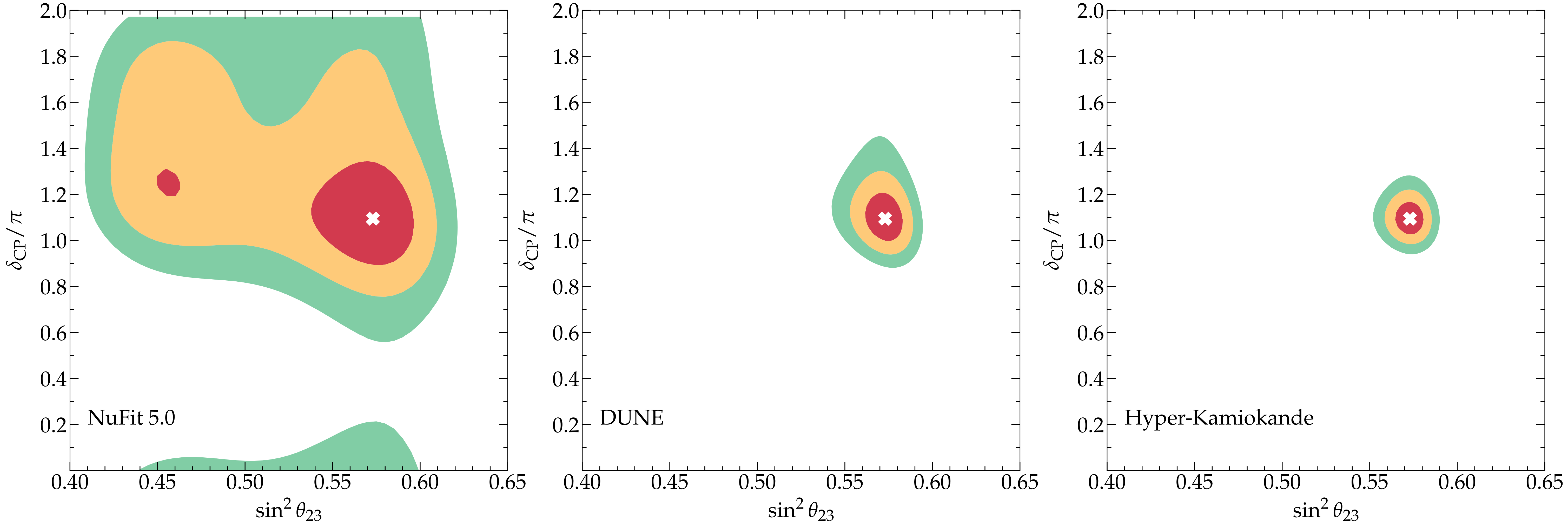


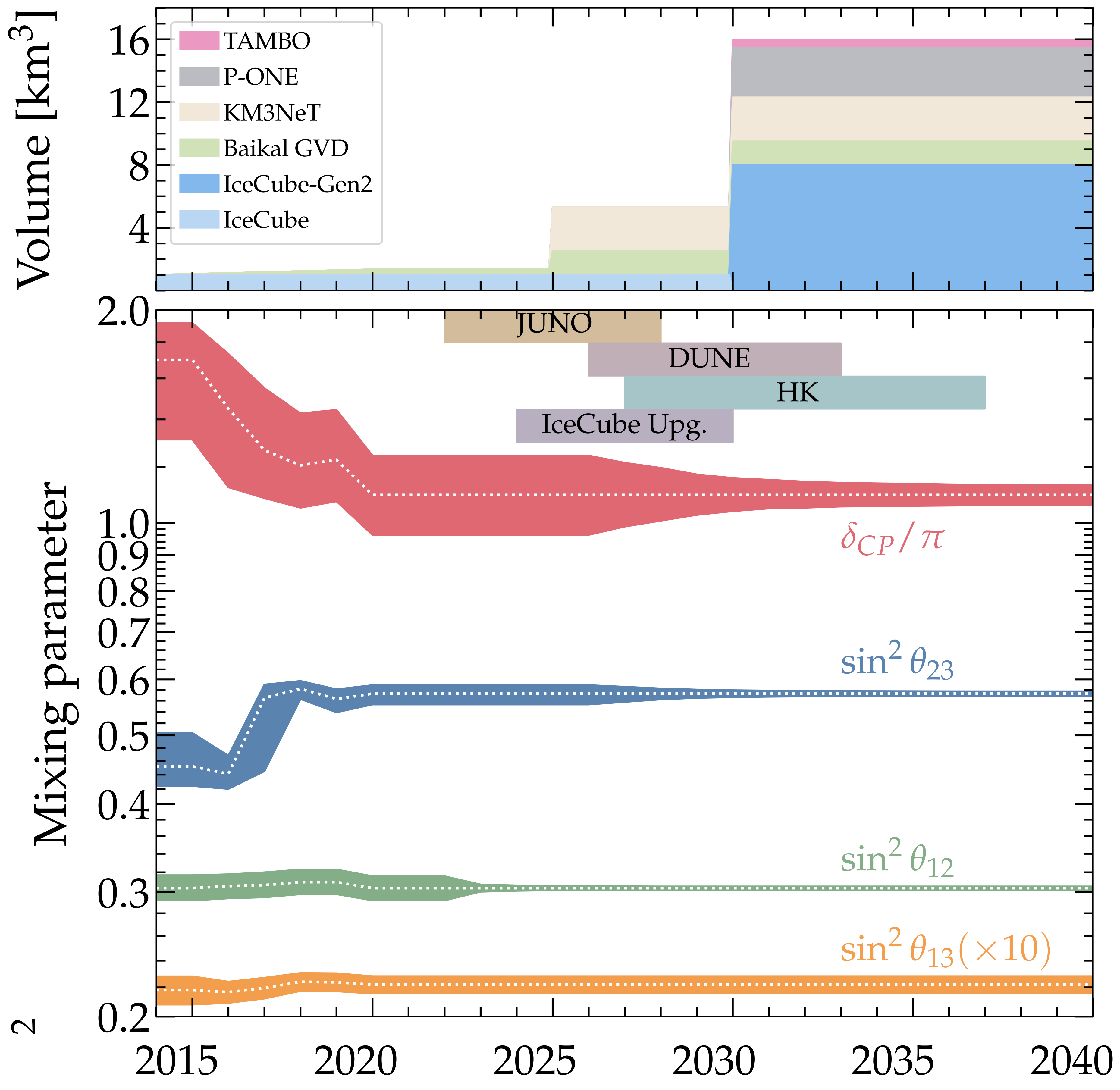
2040(all experiments)



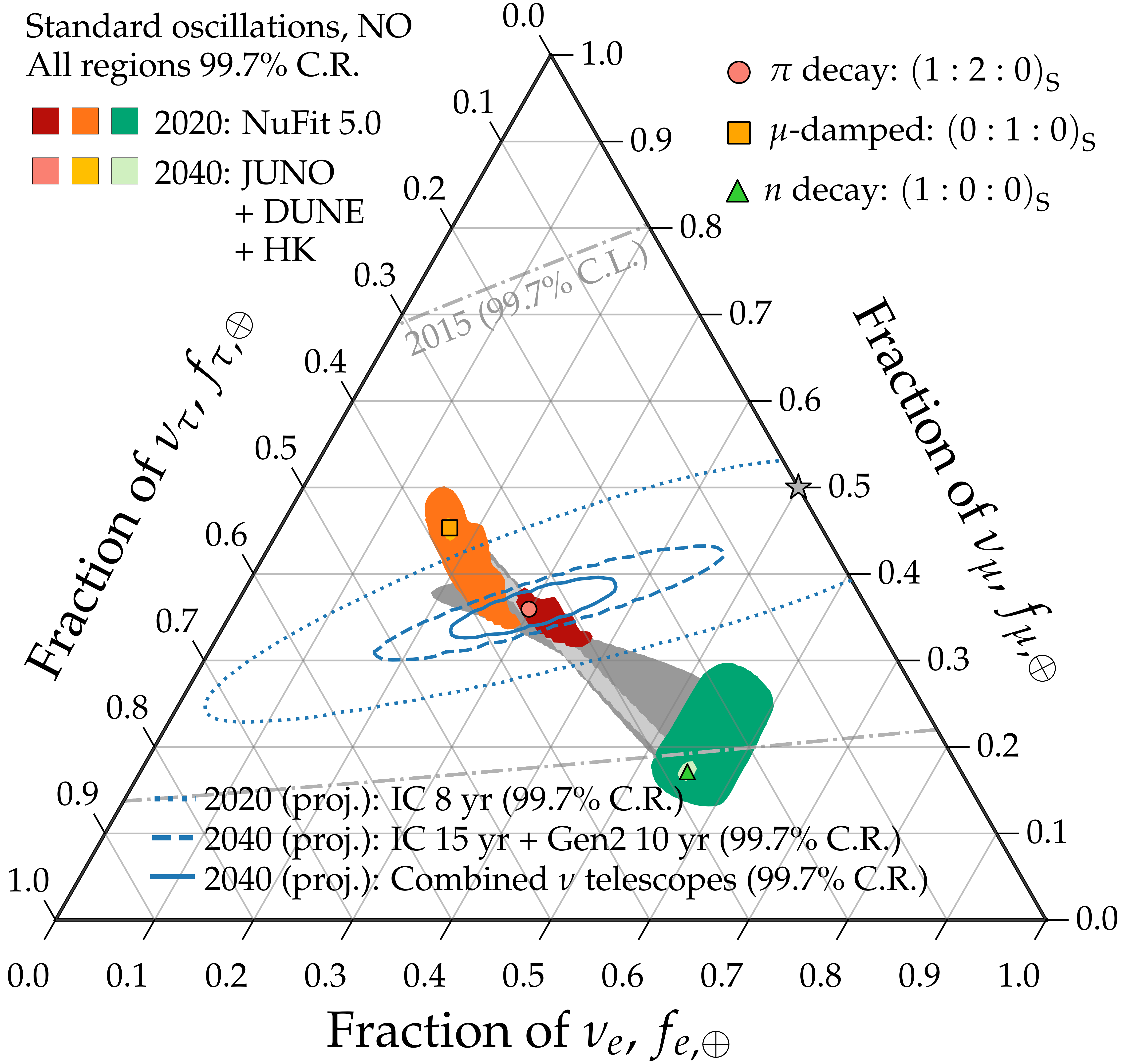
Systematics: terrestrial experiments

- JUNO (Jiangmeng): 2022-2028: 20kt liquid scintillator reactor measurement. 0.52% uncertainty on $\sin^2\theta_{12}$
- DUNE (US): ~2026-2033: 40kt liquid argon long baseline experiment. θ_{23} & δ_{CP}
- Hyper-Kamiokande: 187 kt water Cherenkov. θ_{23} & δ_{CP}
- IceCube Upgrade: dense instrumentation: constrain unitarity





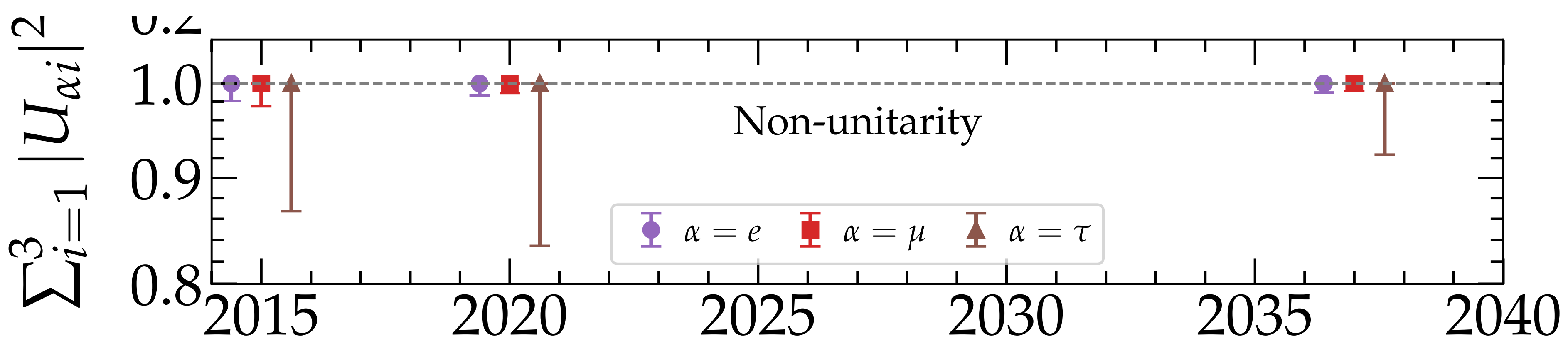
Song, Li, Argüelles, Bustamante, ACV 2012.12893

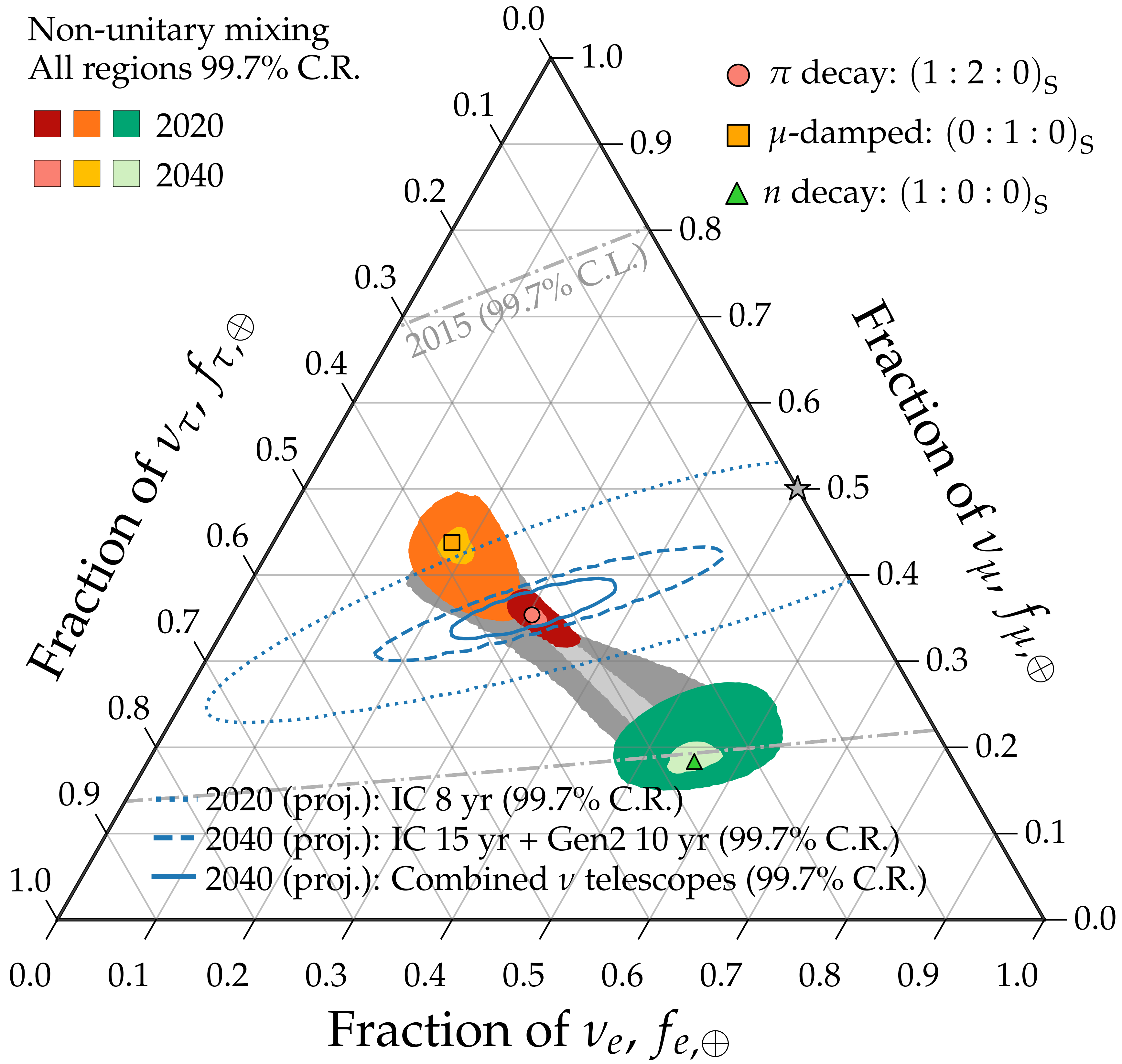


Grey: allowed region within the standard model
Colours: allowed region assuming a single source composition

$$|\nu_\alpha\rangle = \frac{1}{\sqrt{N_\alpha}}\sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

Without assuming unitary 3x3 PMNS matrix?

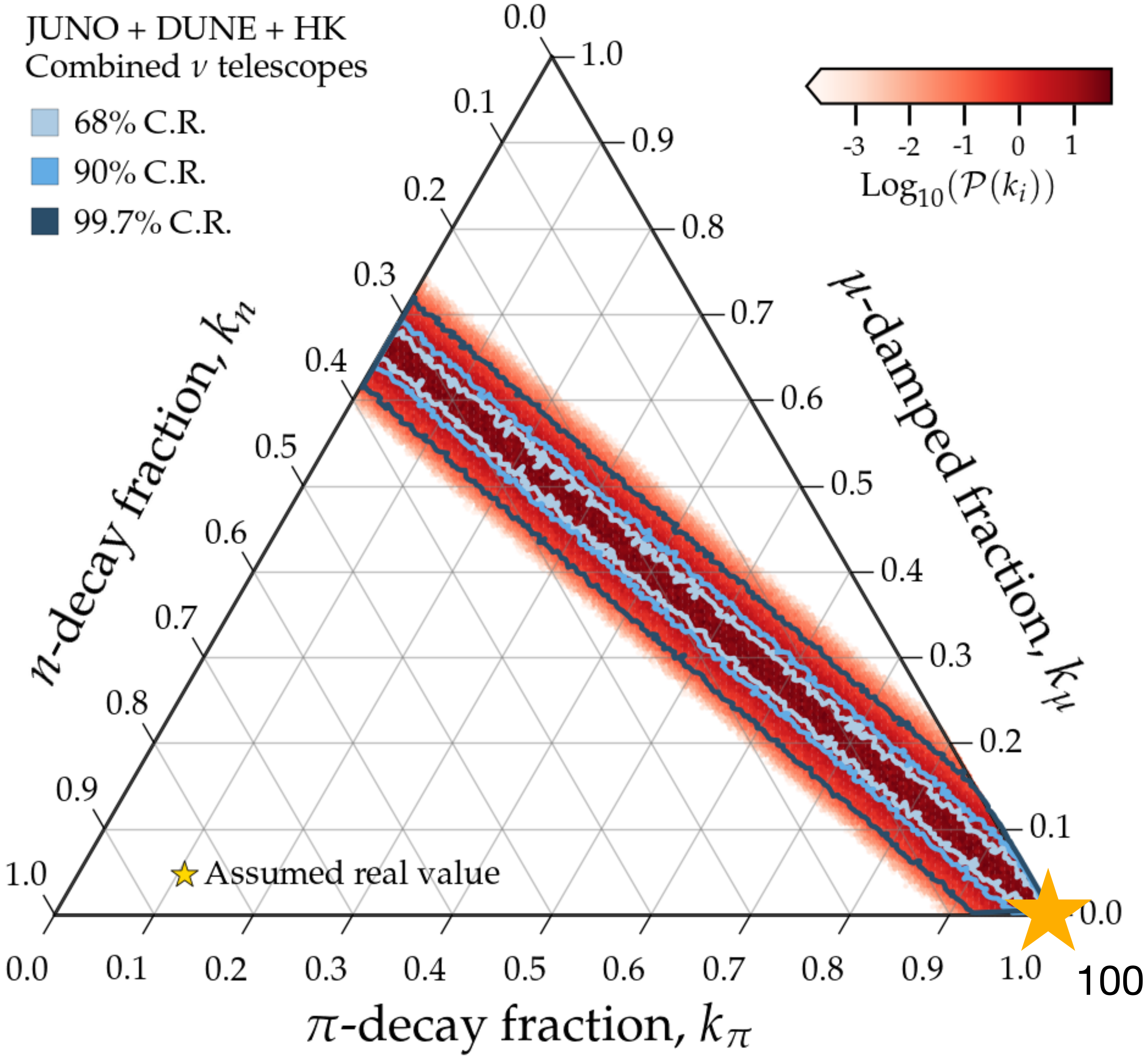




Song, Li, Argüelles, Bustamante, ACV 2012.12893

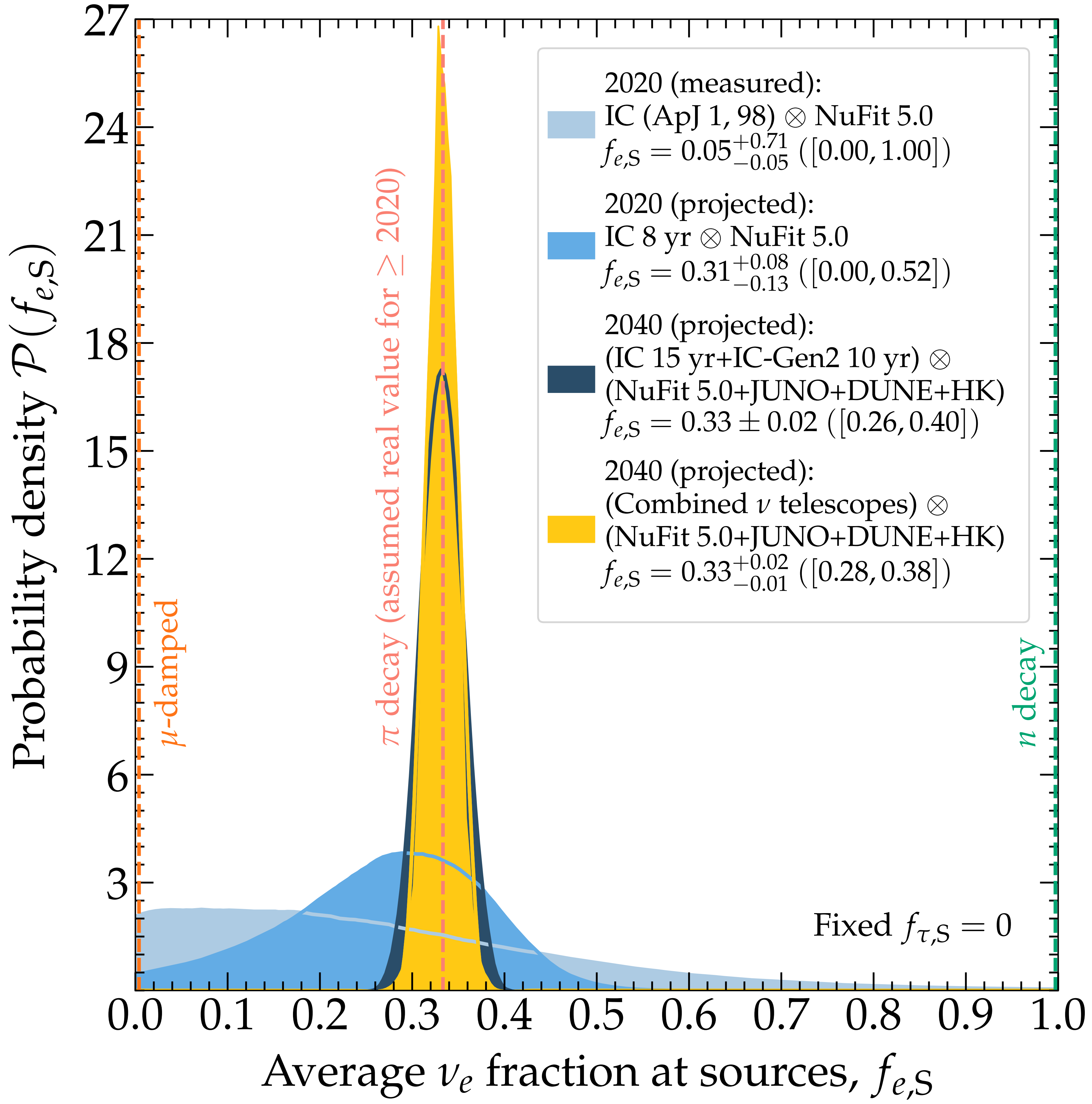
Flavour composition at the source?

100% μ damped (pions but no muons)



100% Neutron decay

100% Pions

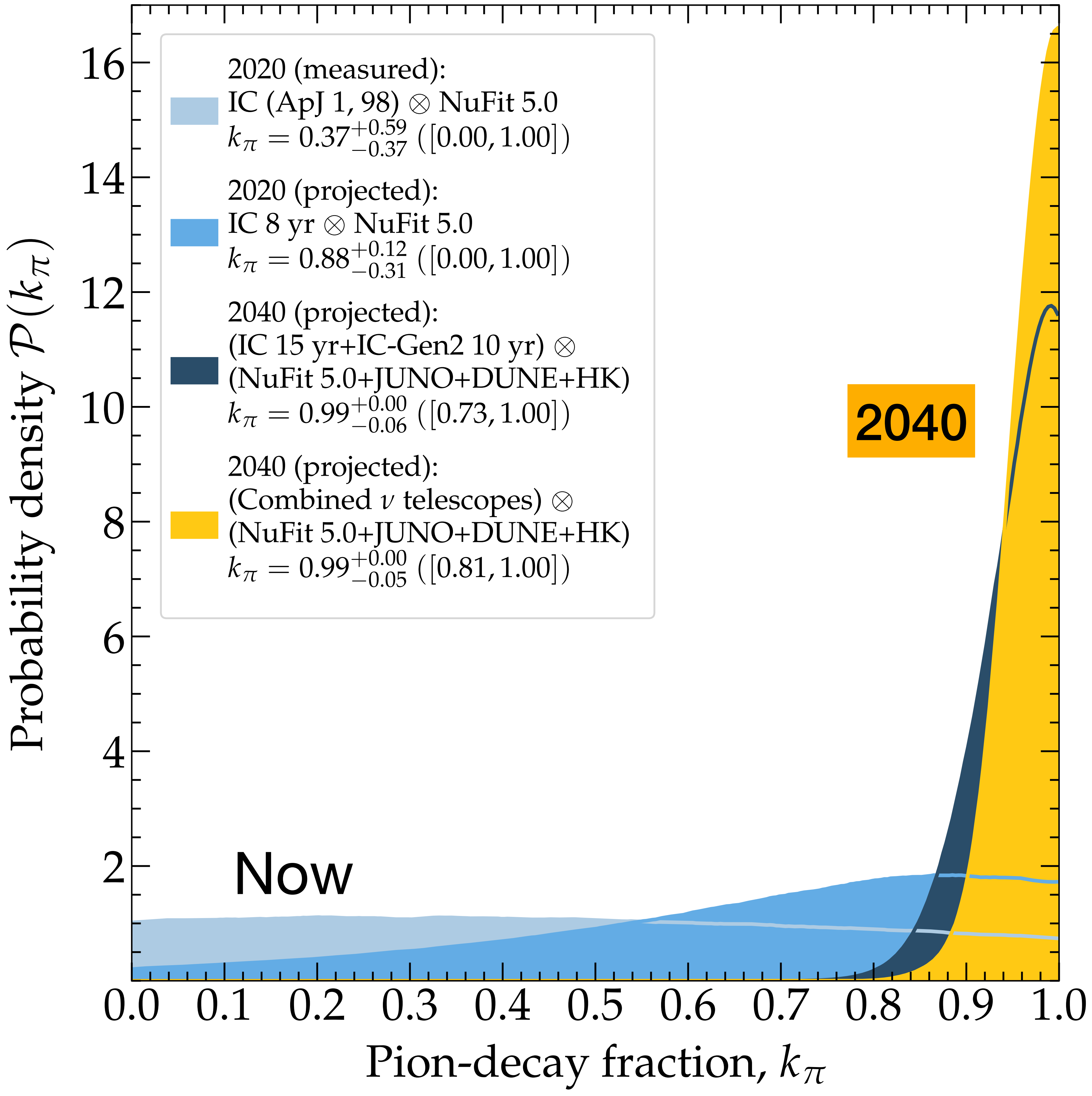


Song, Li, Argüelles, Bustamante, ACV 2012.12893

Flavour composition at the source

Dominant production mechanism can be pinned down to within 20% *using neutrino flavour alone*.

Assuming no neutron decay



Song, Li, Argüelles, Bustamante, ACV 2012.12893

New physics: neutrino decay

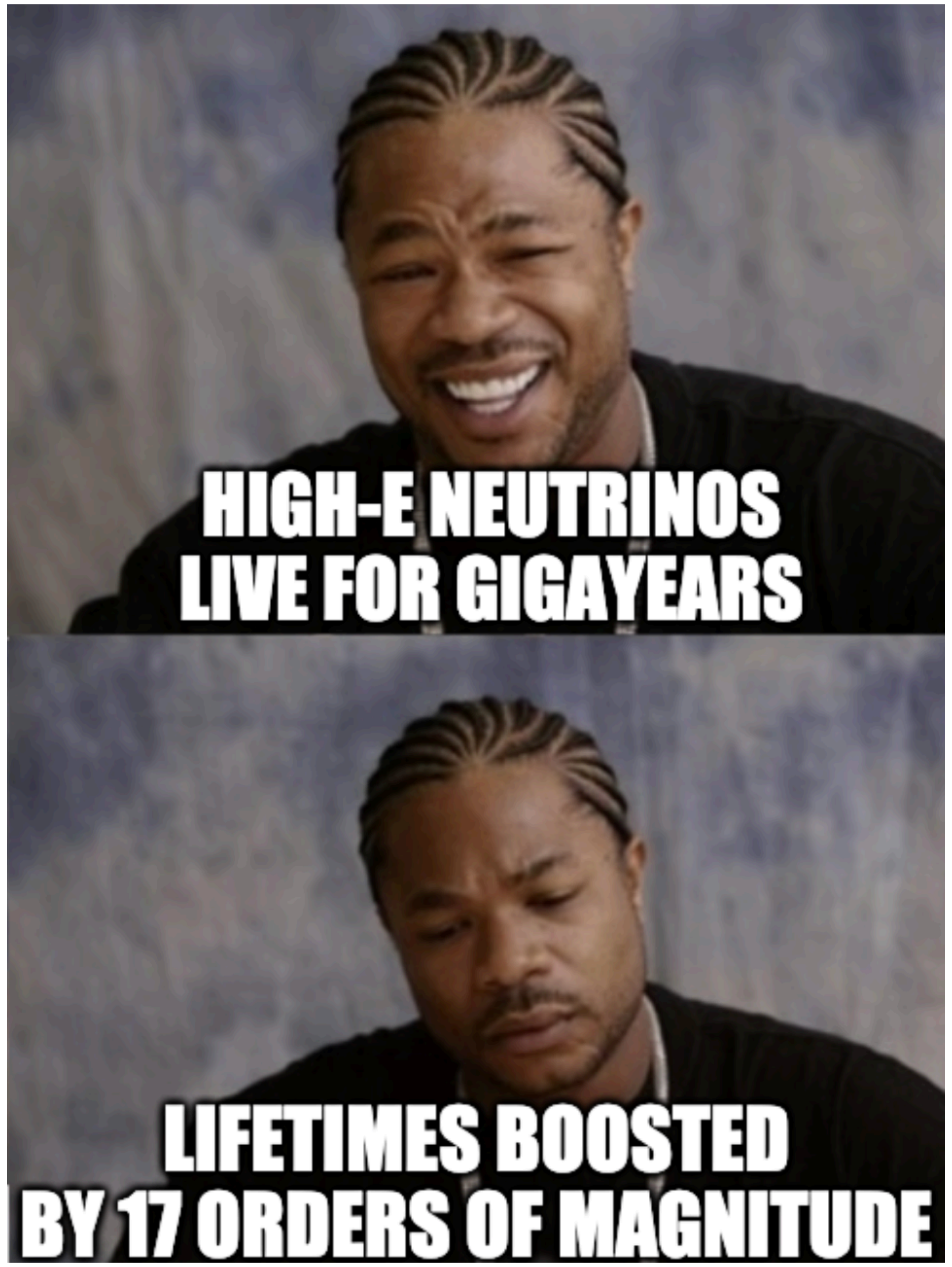
Neutrino decay

Invisible decay: all but one mass eigenstate decays to invisible species.

$$N_\nu = N(z_0)\exp\left\{ -\frac{m_\nu}{\tau E_\nu}\int_0^{z_0} \frac{dz}{(1+z)^2 H_0\sqrt{\Omega(z)}} \right\}$$

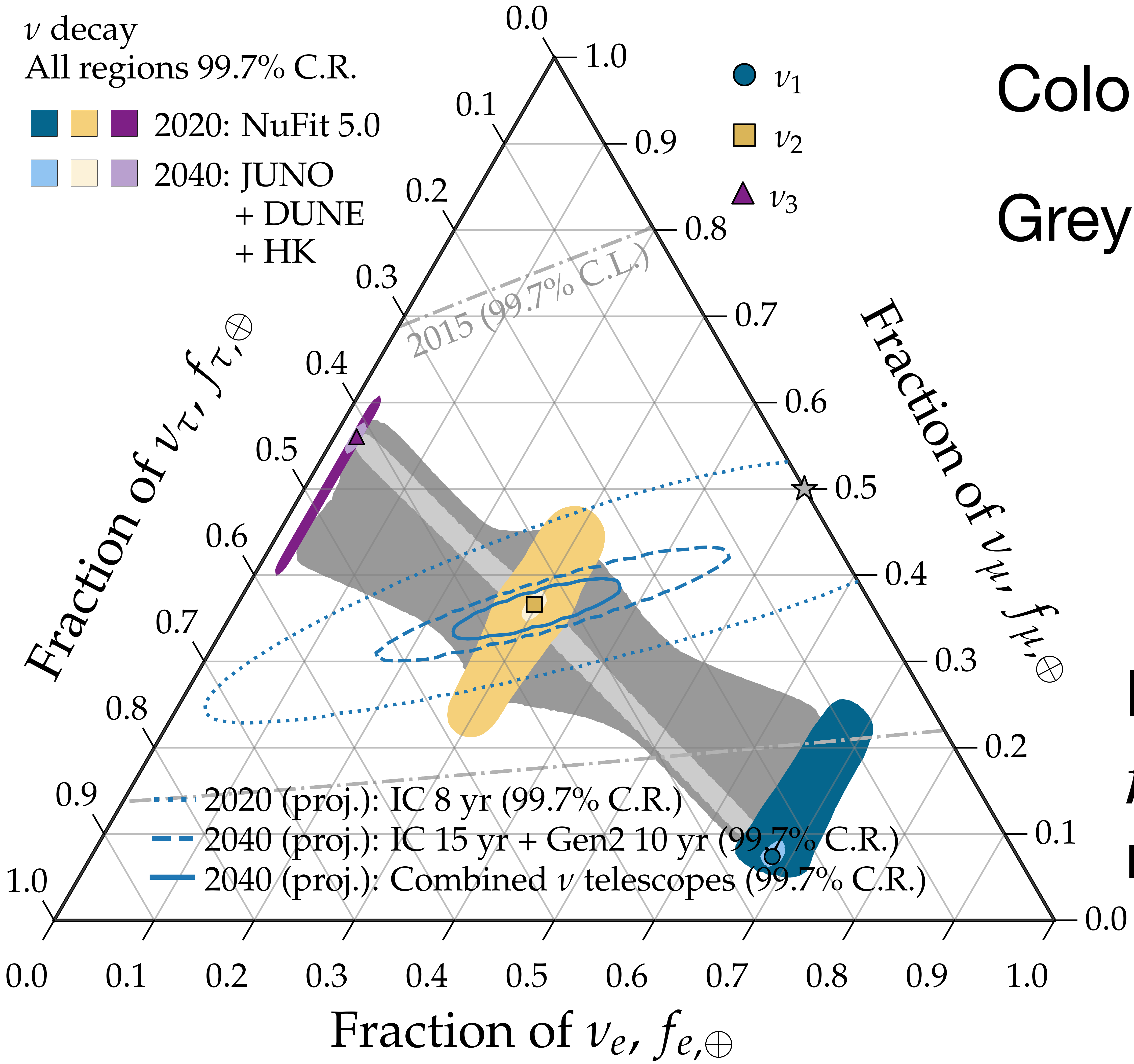
neutrino lifetime at rest

Must be integrated over distribution of cosmic sources



See Abdullah & Denton 2005.07200 for a complete treatment of *visible* decay

Song, Li, Argüelles, Bustamante, ACV 2012.12893



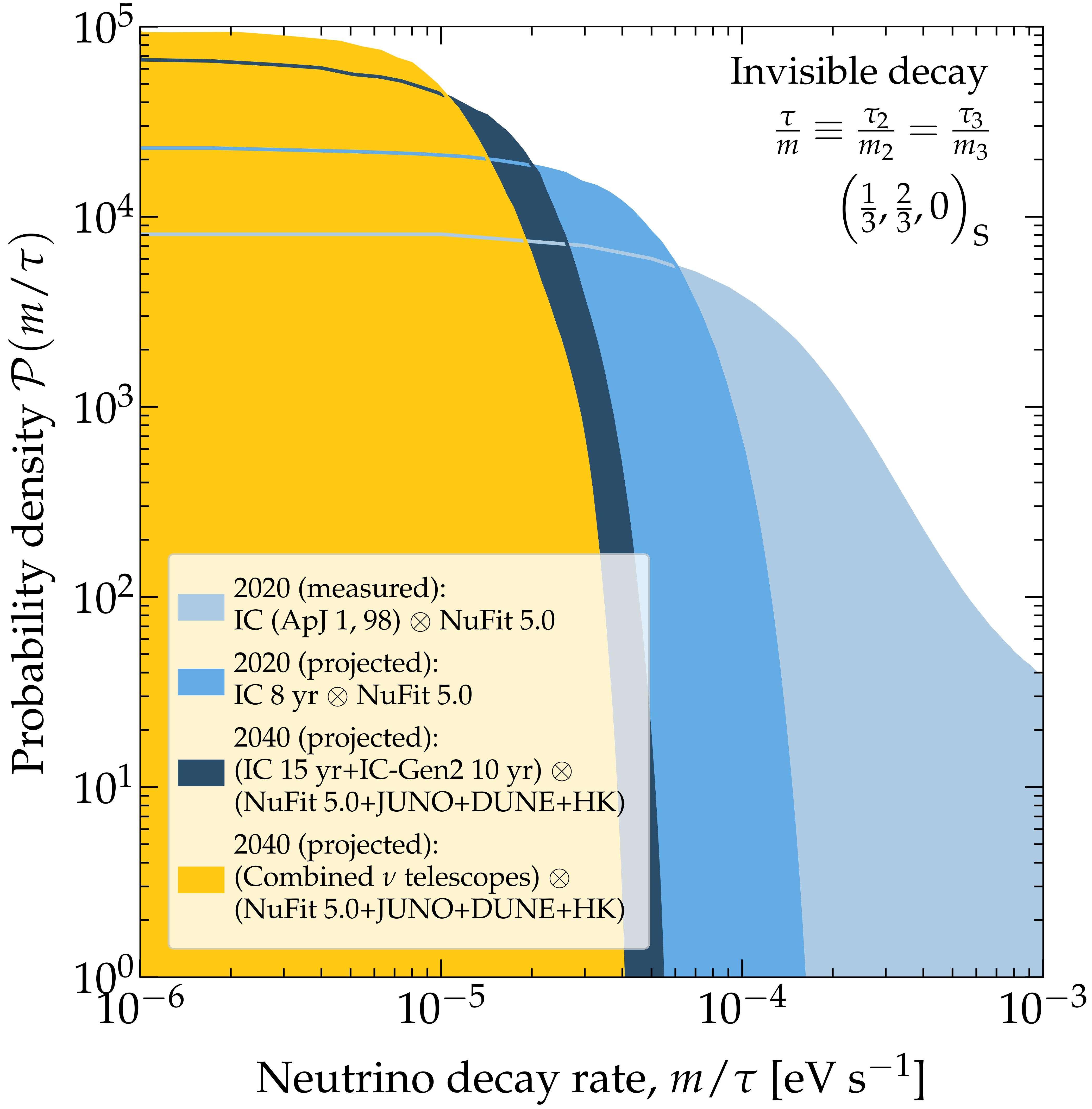
Colour: full decay

Grey: partial decay

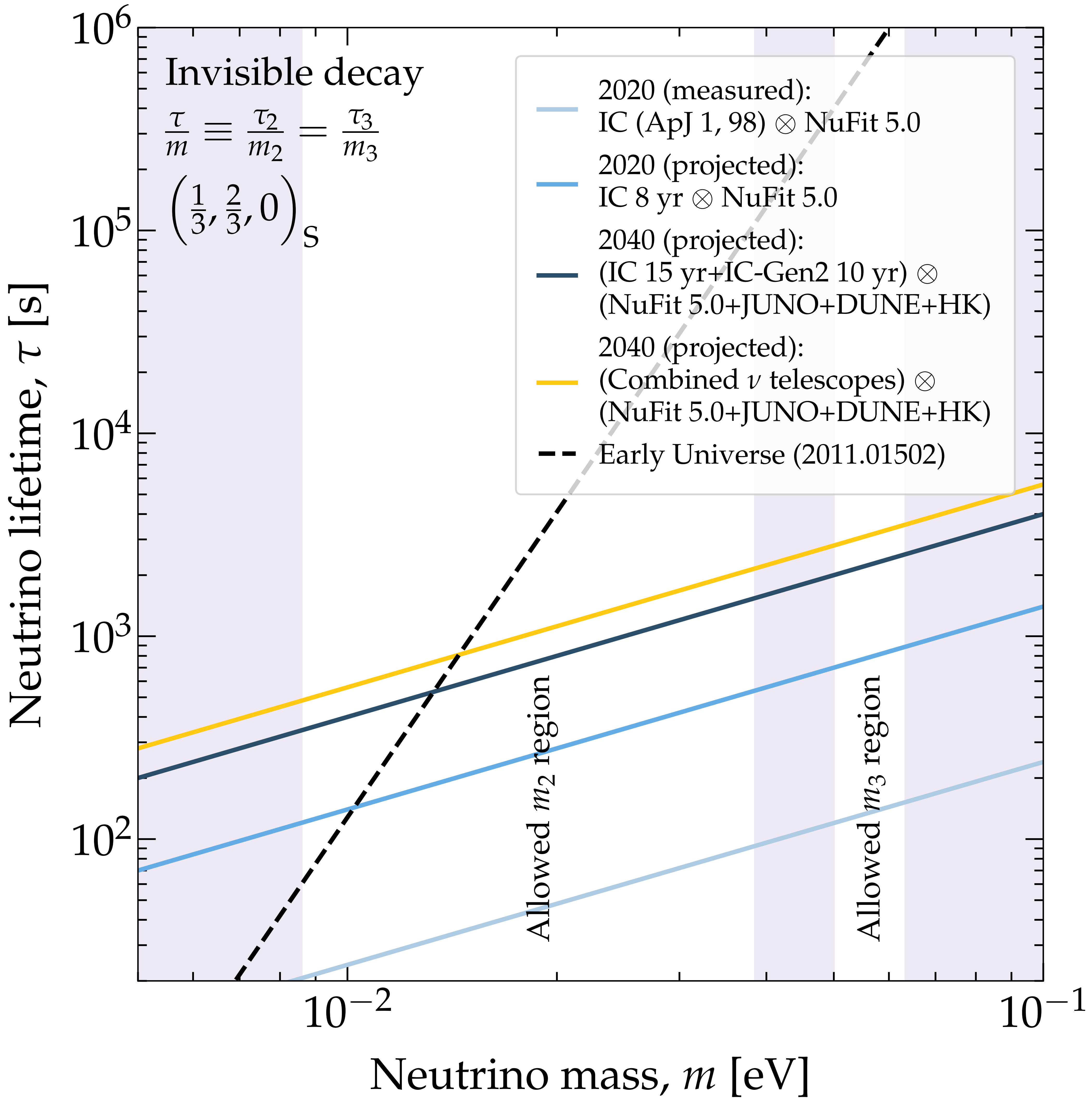
Full decay of m_2 and m_3 almost excluded now

Sensitivity to single mass eigenstates

Song, Li, Argüelles, Bustamante, ACV 2012.12893



Cosmology bounds didn't compute phase space correctly, see 2203.09075 for weaker limits

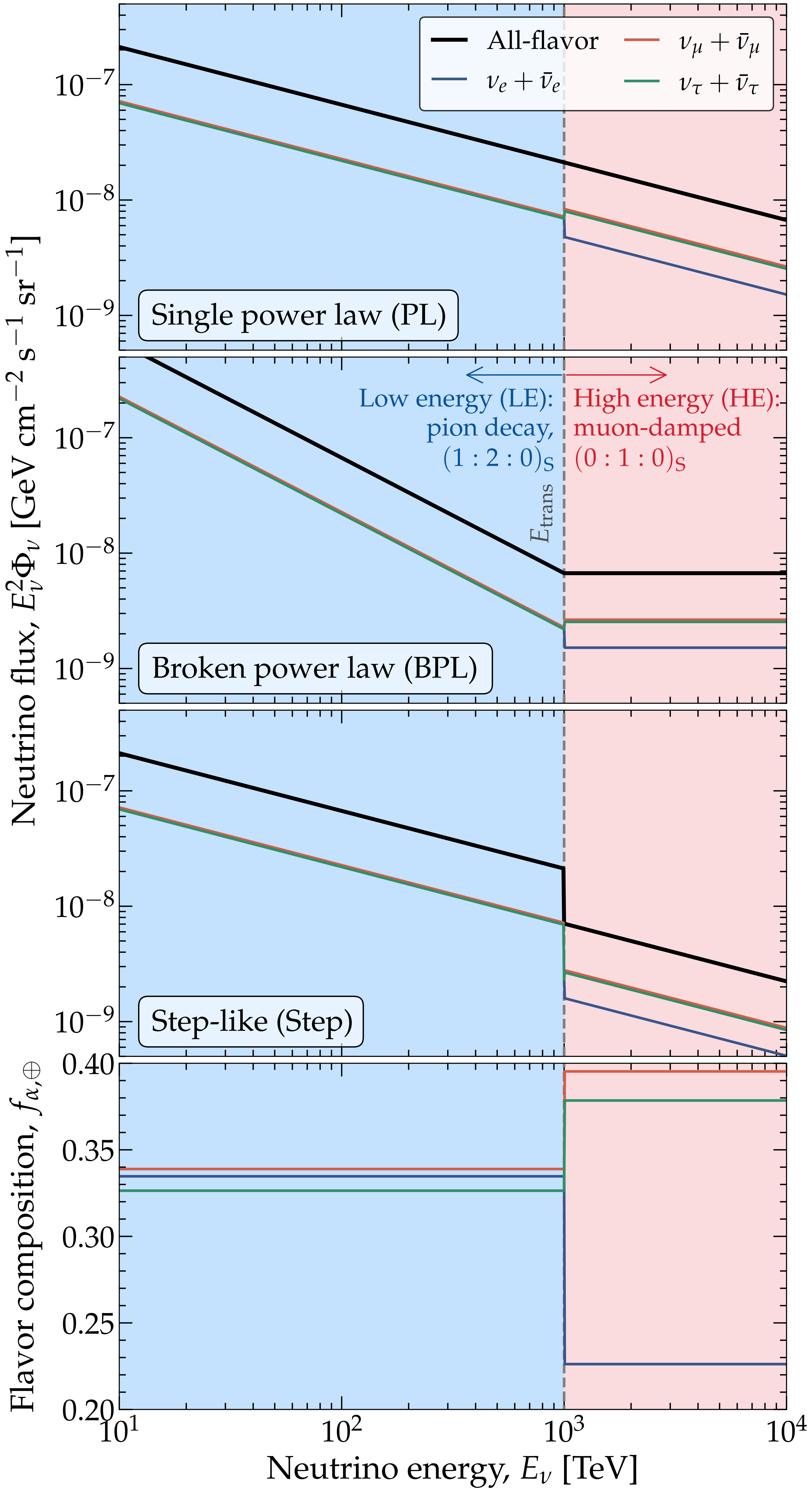


Song, Li, Argüelles, Bustamante, ACV 2012.12893

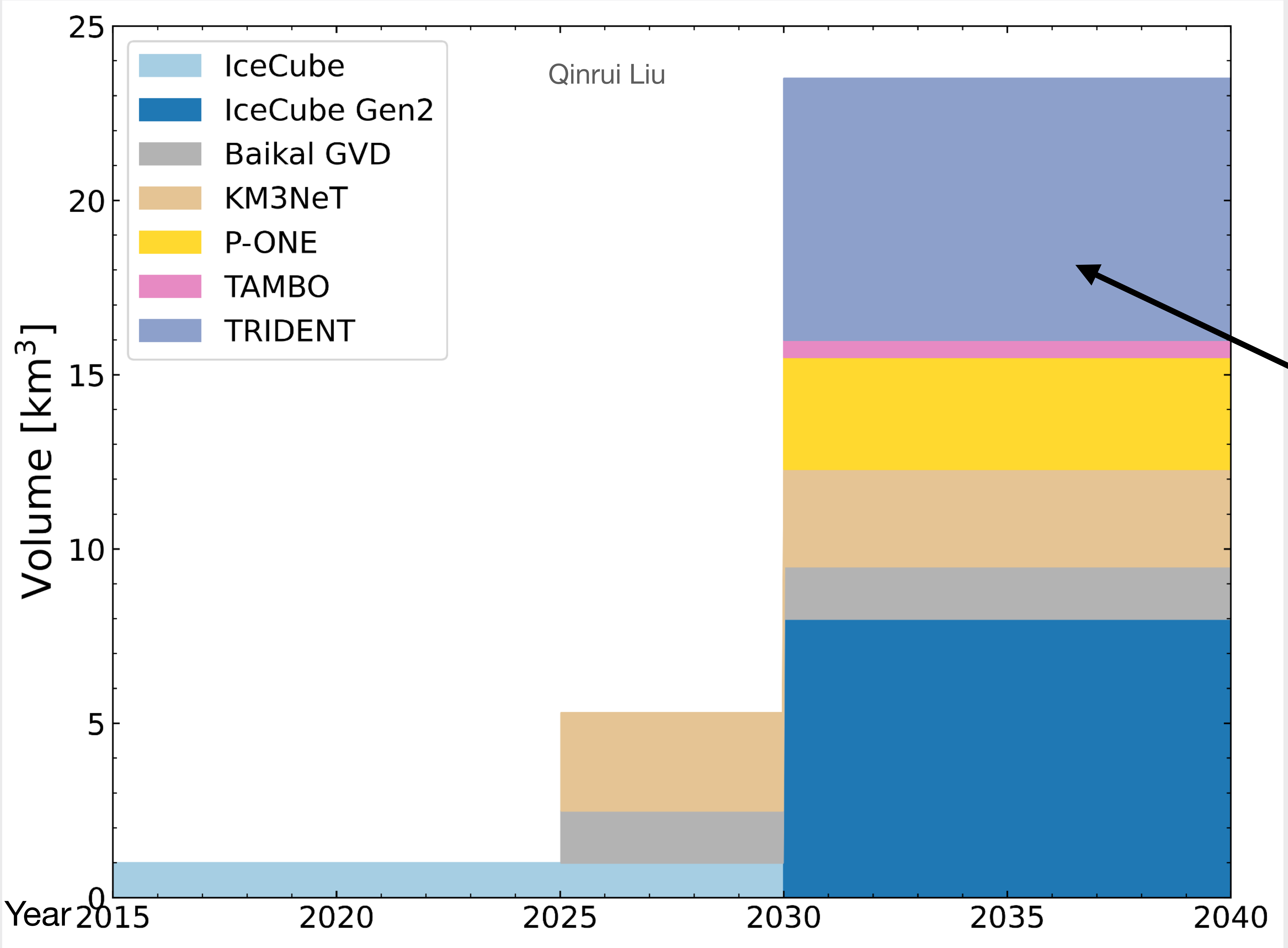
But these don’t include energy dependence

The flavour composition can depend on energy

- Muon-damping: we see the neutrinos from the pion at high-energy, and from the muon at lower energy
- Neutrino decay, Lorentz-invariance violation can give an E-dependent step
- Different sources could dominate at different energy ranges
- We test three generic **benchmark scenarios:**
    - **Single power law with a flavour transition**
    - **Broken power law, transition at the break**
    - **Step, transition at the step**

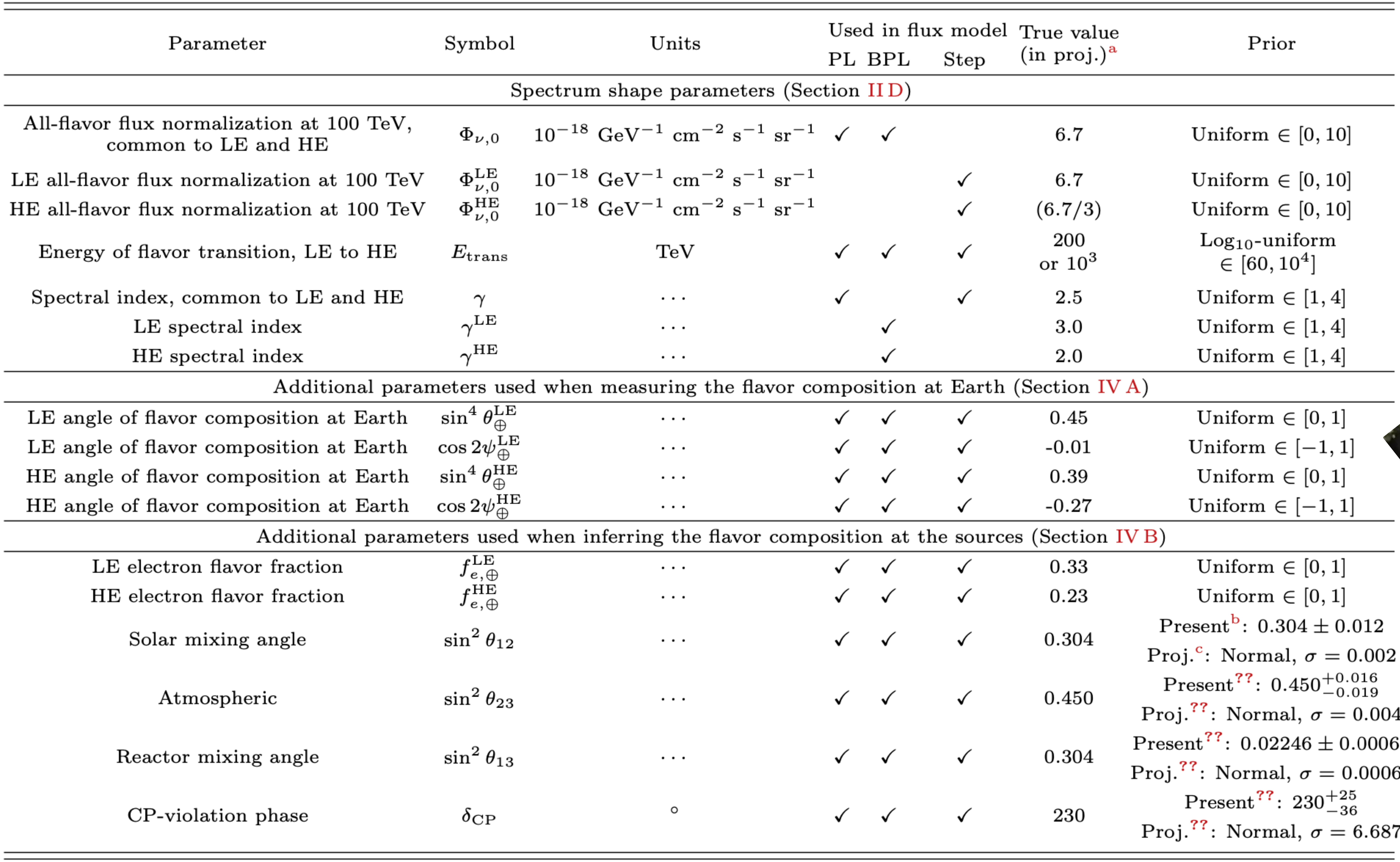


Liu, Fiorillo, Argüelles, Bustamante, Song, ACV 2304.06068



We've added TRIDENT to the mix

More telescopes with larger exposure!
Combine the exposure to reach the optimal sensitivity.



Parameter	Symbol	Units	Used in flux model PL	BPL	Step	True value (in proj.)[a]	Prior
Spectrum shape parameters (Section II D)							
All-flavor flux normalization at 100 TeV, common to LE and HE	$\Phi_{\nu,0}$	10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}	✓	✓		6.7	Uniform $\in [0, 10]$
LE all-flavor flux normalization at 100 TeV	$\Phi_{\nu,0}^{\rm LE}$	10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}			✓	6.7	Uniform $\in [0, 10]$
HE all-flavor flux normalization at 100 TeV	$\Phi_{\nu,0}^{\rm HE}$	10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}			✓	(6.7/3)	Uniform $\in [0, 10]$
Energy of flavor transition, LE to HE	$E_{\rm trans}$	TeV	✓	✓	✓	200 or 10^3	Log$_{10}$-uniform $\in [60, 10^4]$
Spectral index, common to LE and HE	γ	···	✓		✓	2.5	Uniform $\in [1, 4]$
LE spectral index	$\gamma^{\rm LE}$	···		✓		3.0	Uniform $\in [1, 4]$
HE spectral index	$\gamma^{\rm HE}$	···		✓		2.0	Uniform $\in [1, 4]$
Additional parameters used when measuring the flavor composition at Earth (Section IV A)							
LE angle of flavor composition at Earth	$\sin^4\theta_\oplus^{\rm LE}$	···	✓	✓	✓	0.45	Uniform $\in [0, 1]$
LE angle of flavor composition at Earth	$\cos 2\psi_\oplus^{\rm LE}$	···	✓	✓	✓	-0.01	Uniform $\in [-1, 1]$
HE angle of flavor composition at Earth	$\sin^4\theta_\oplus^{\rm HE}$	···	✓	✓	✓	0.39	Uniform $\in [0, 1]$
HE angle of flavor composition at Earth	$\cos 2\psi_\oplus^{\rm HE}$	···	✓	✓	✓	-0.27	Uniform $\in [-1, 1]$
Additional parameters used when inferring the flavor composition at the sources (Section IV B)							
LE electron flavor fraction	$f_{e,\oplus}^{\rm LE}$	···	✓	✓	✓	0.33	Uniform $\in [0, 1]$
HE electron flavor fraction	$f_{e,\oplus}^{\rm HE}$	···	✓	✓	✓	0.23	Uniform $\in [0, 1]$
Solar mixing angle	$\sin^2\theta_{12}$	···	✓	✓	✓	0.304	Present[b]: 0.304 ± 0.012 Proj.[c]: Normal, $\sigma = 0.002$
Atmospheric	$\sin^2\theta_{23}$	···	✓	✓	✓	0.450	Present[??]: $0.450^{+0.016}_{-0.019}$ Proj.[??]: Normal, $\sigma = 0.004$
Reactor mixing angle	$\sin^2\theta_{13}$	···	✓	✓	✓	0.304	Present[??]: 0.02246 ± 0.00062 Proj.[??]: Normal, $\sigma = 0.00062$
CP-violation phase	$\delta_{\rm CP}$	°	✓	✓	✓	230	Present[??]: 230^{+25}_{-36} Proj.[??]: Normal, $\sigma = 6.687$

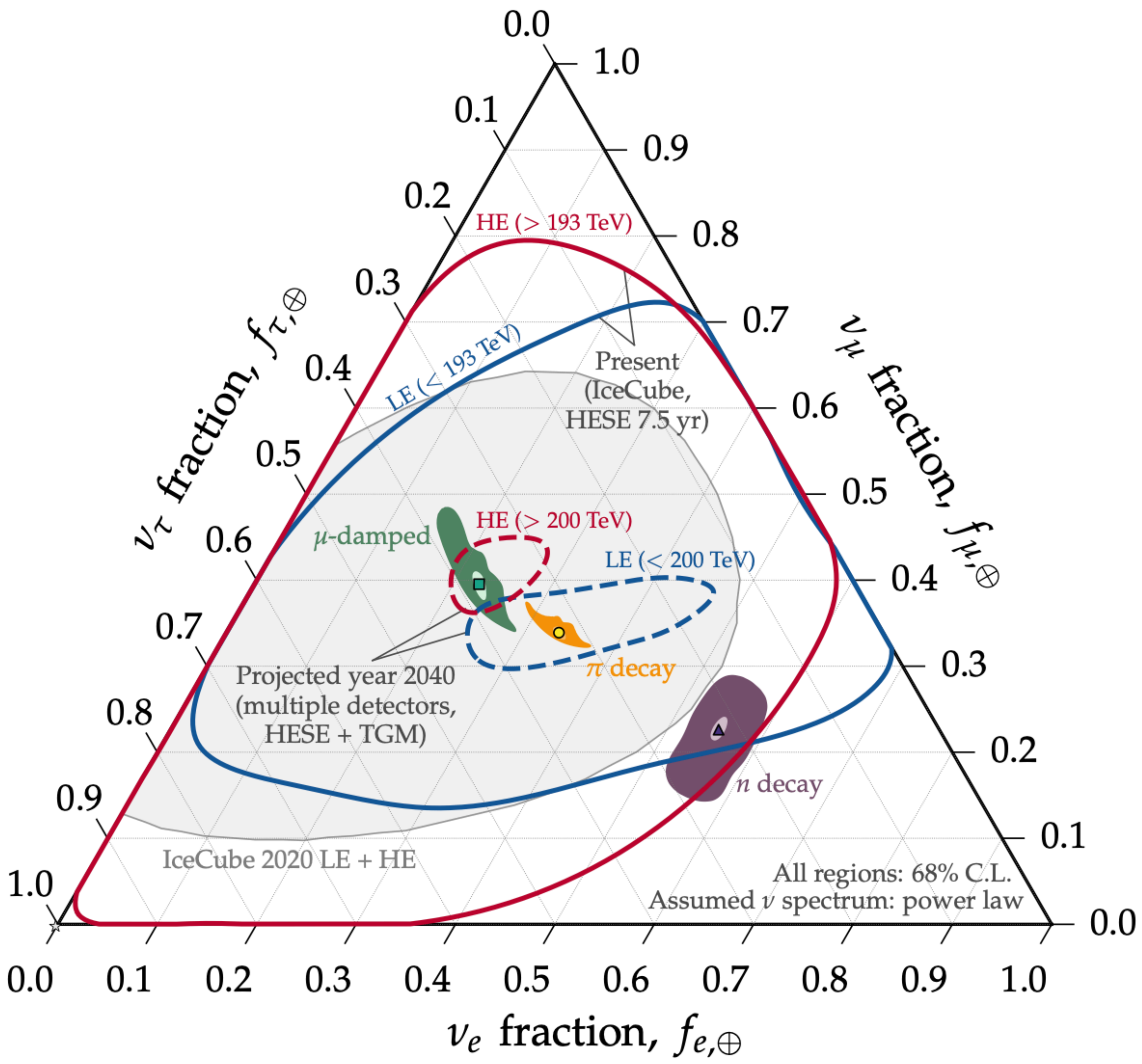
Very numbers

Much statistics

Liu, Fiorillo, Argüelles, Bustamante, Song, ACV 2304.06068

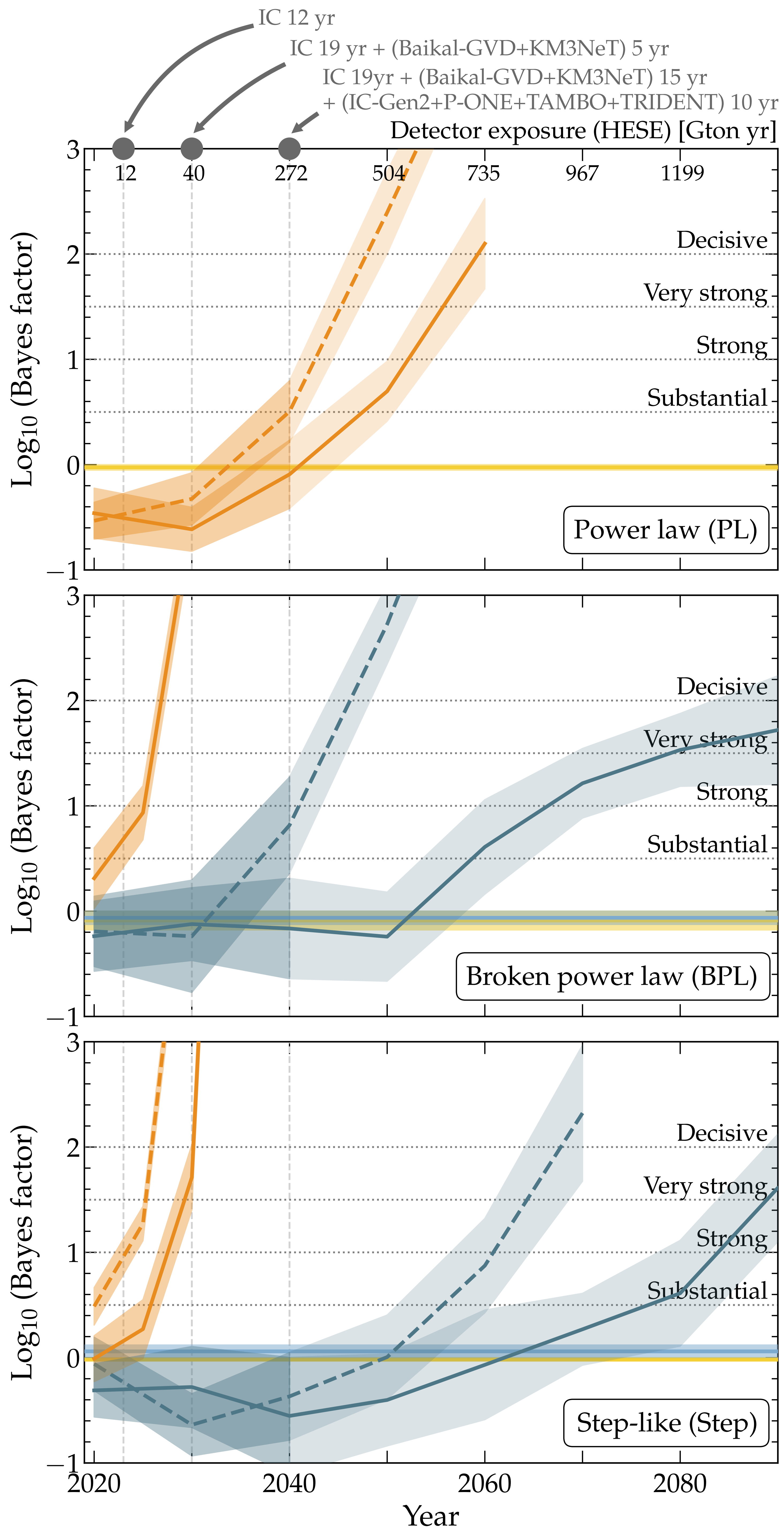
Flavor Transition Measurements

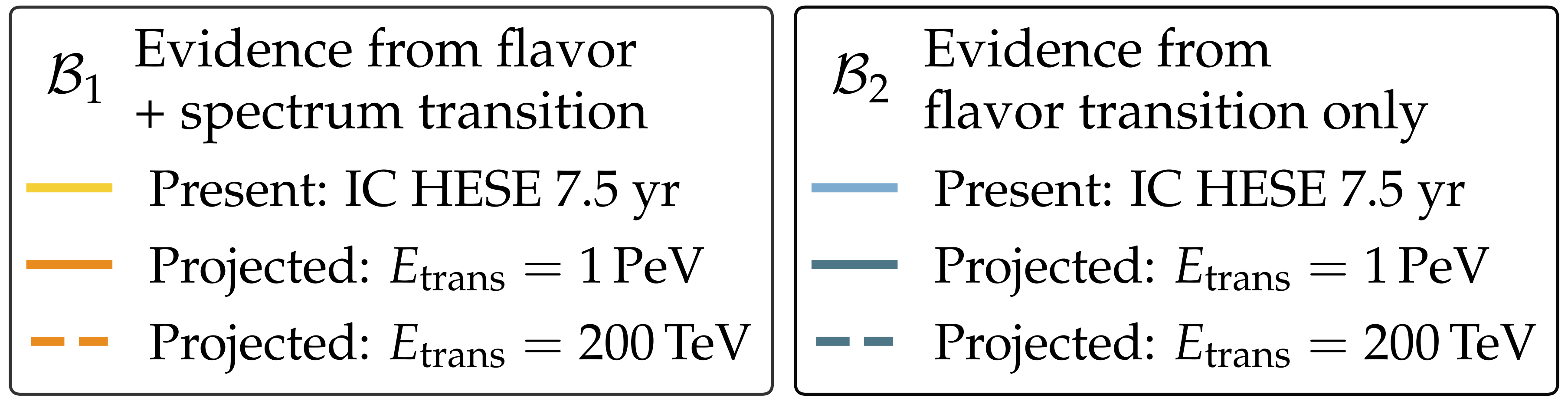
Liu, Fiorillo, Argüelles, Bustamante, Song, ACV 2304.06068



Future combined exposure: IceCube/IceCube-Gen2+KM3NeT+Baikal-GVD +P-ONE+TAMBO+TRIDENT

The HE flavor composition can be marginally distinguished from the LE composition at 1σ level by 2040





Bayes factor

$$\frac{\mathcal{Z}_{\text{transition}}}{\mathcal{Z}_{\text{no transition}}}$$

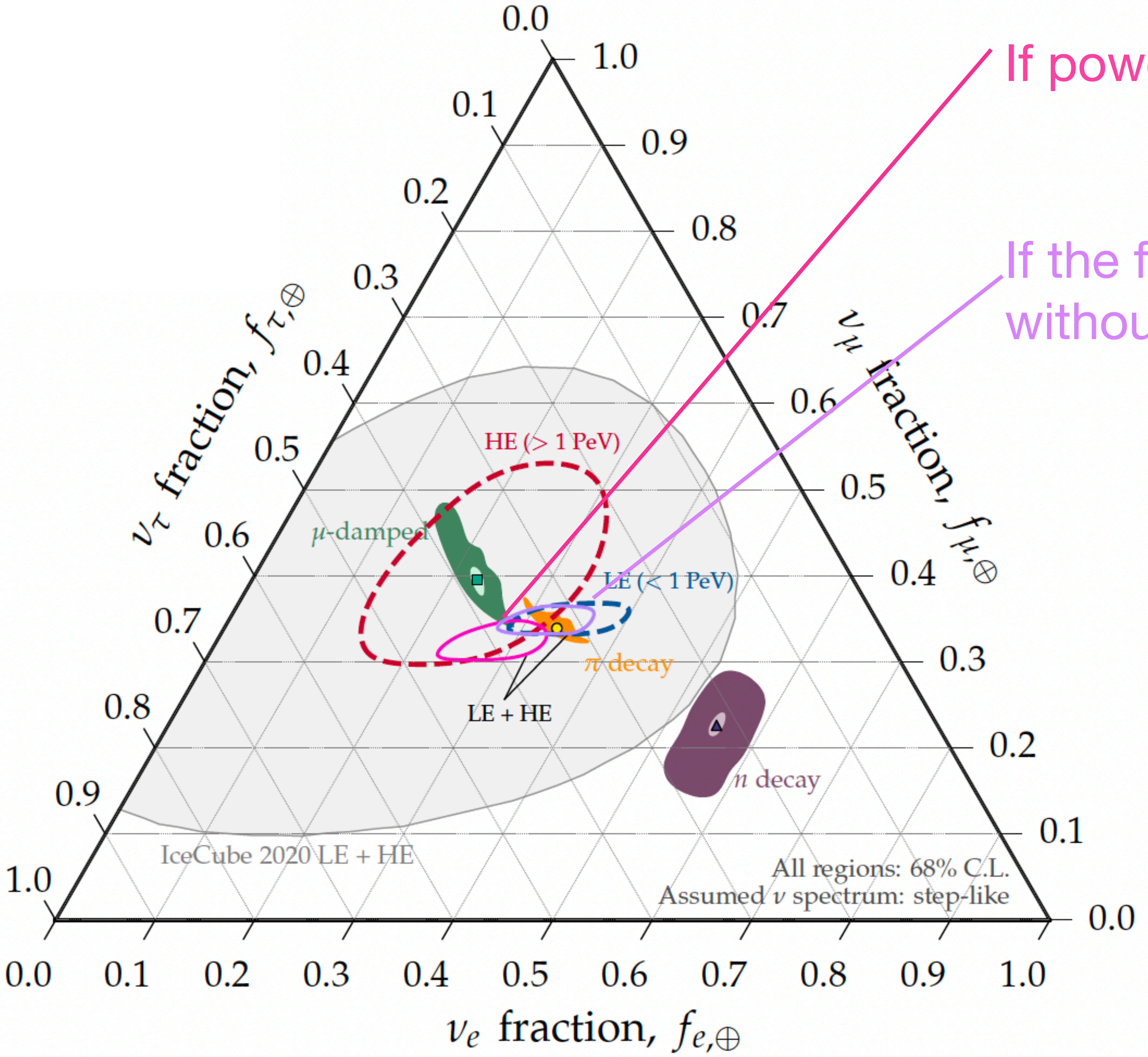
🟧 From Flavour + spectrum transition

▨ From Flavour transition only

Liu, Fiorillo, Argüelles, Bustamante, Song, ACV 2304.06068

Comparison with the General Approach

Liu, Fiorillo, Argüelles, Bustamante, Song, ACV 2304.06068



If power law spectrum + no flavor transition is fitted

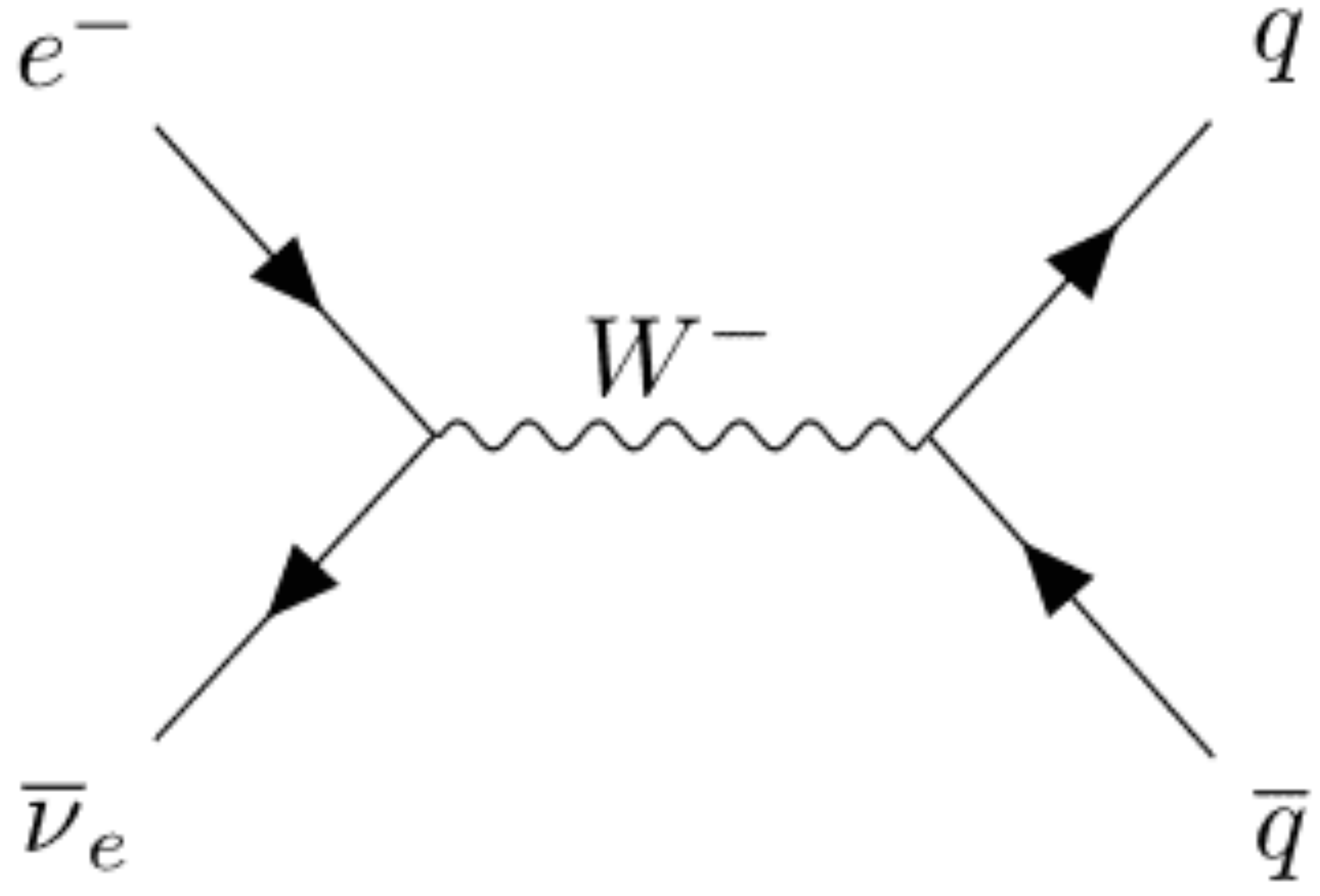
If the fitting assumption assumes the correct spectrum but without the flavor transition

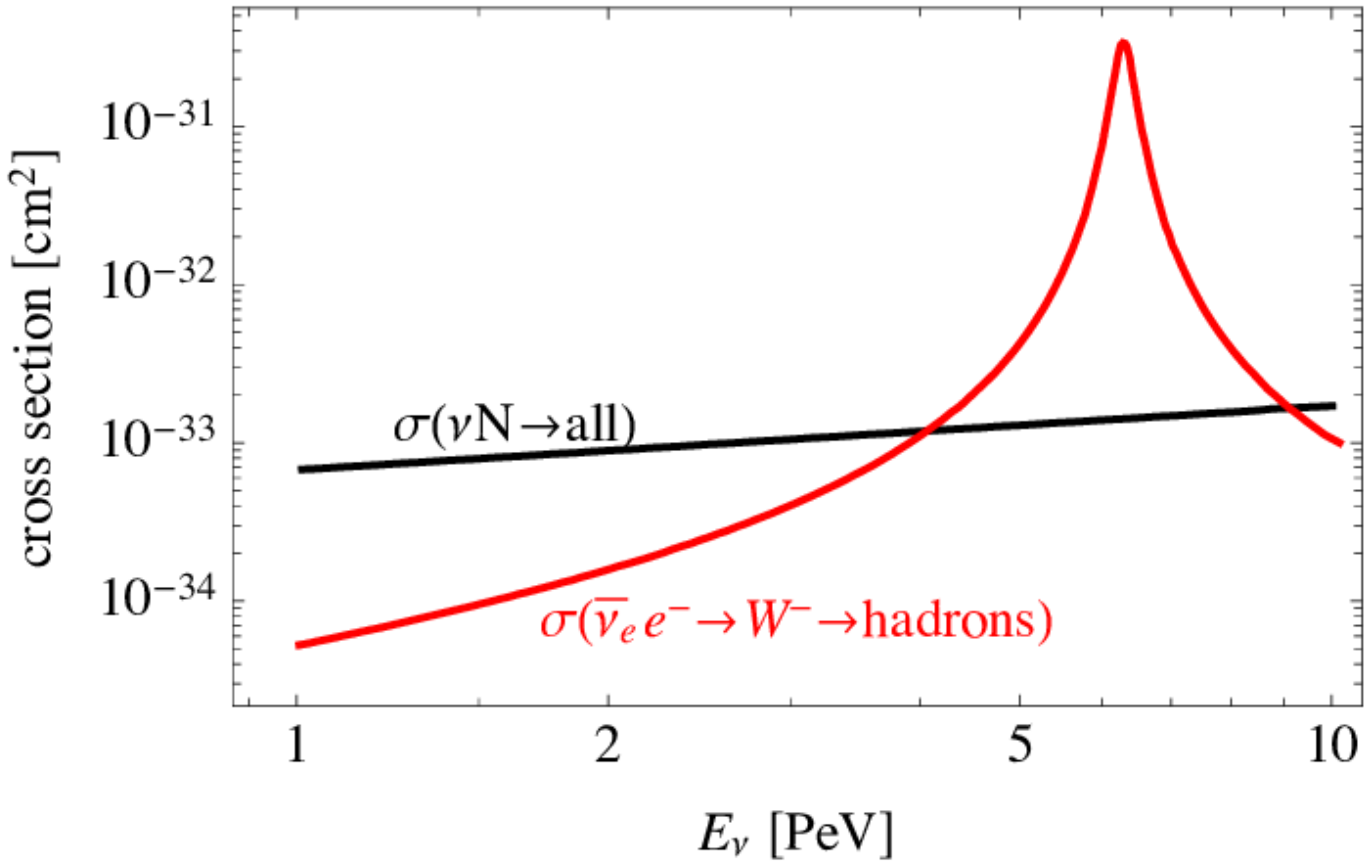
Assuming there is a flavor transition, if the measurement models that there is no flavor transition, more constrained contours can be obtained but no accurate detail is told.

Flavor measurements must use flexible descriptions of the neutrino spectrum to avoid reporting inaccurate flavor composition measurements.

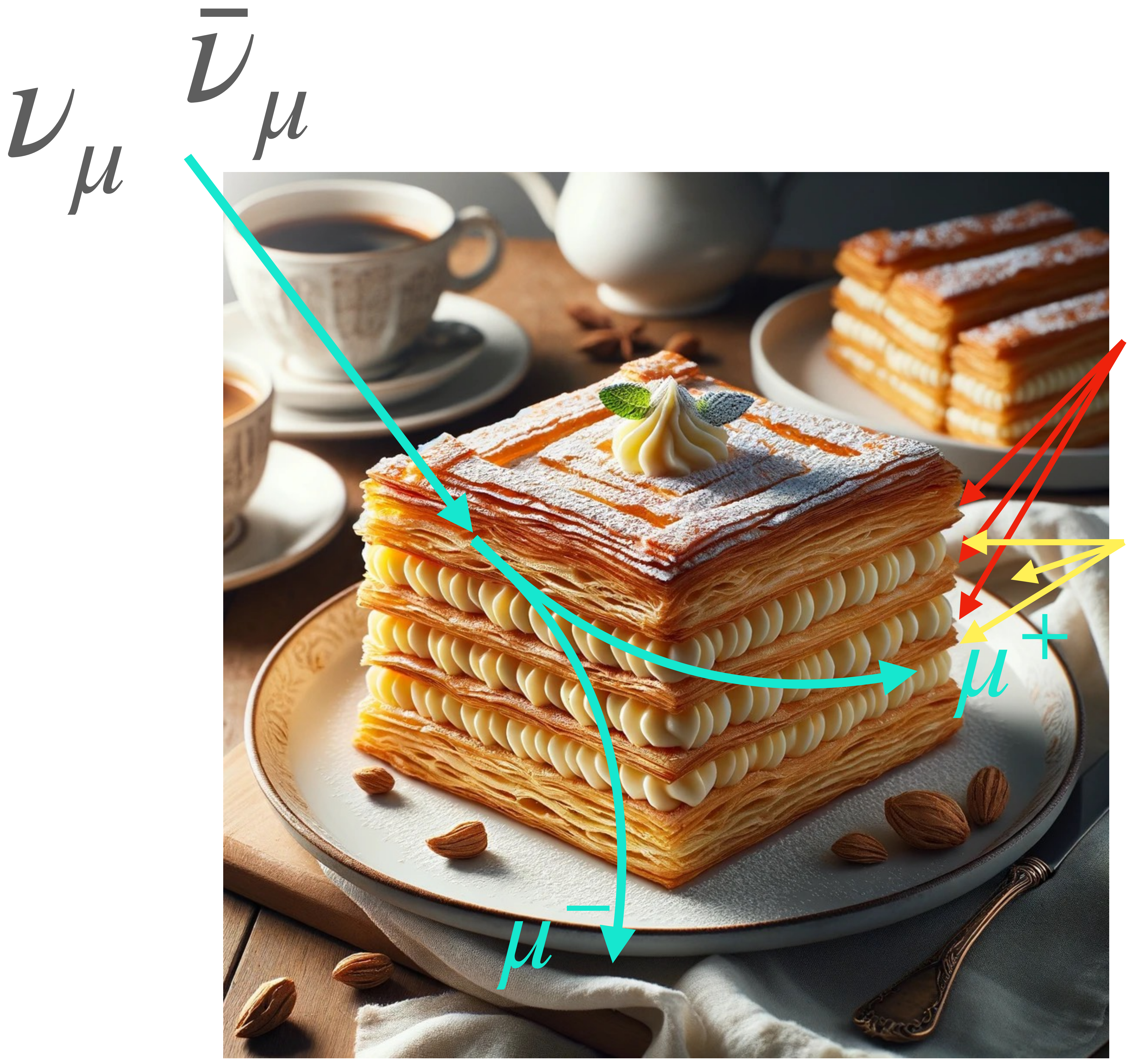
Distinguishing ν vs $\bar{\nu}$?

- At high energies, neutrino/antineutrino separation is almost impossible
- Exception: the Glashow resonance.
  At $E_{CM} = M_W$, or $E_\nu = 6.3$ PeV, can produce on-shell W for $\bar{\nu}_e$ only.





(Aside: India-based Neutrino Observatory proposal)



50,000 tons magnetized iron leaves

Resistive plate chambers

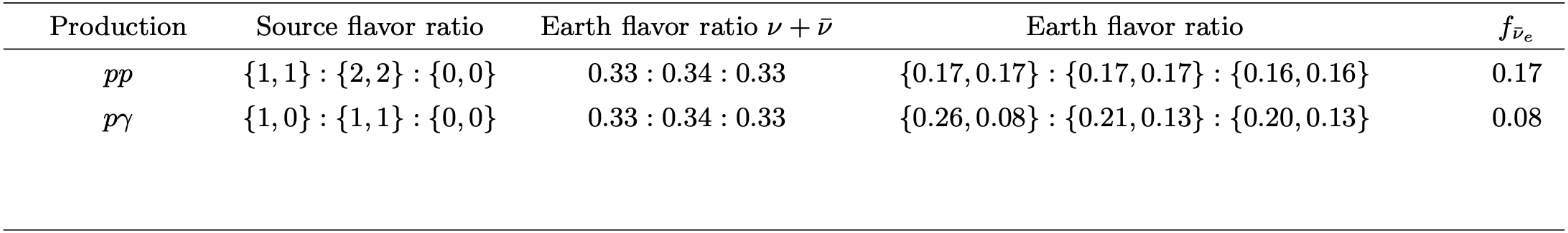
Currently stalled due to ecological concerns (blasting, excavation, …)

What does ν vs $\bar{\nu}$ do for you?

Are neutrinos coming from pp or $p\gamma$ collisions? These give different π^+/π^-ratios

$$\{\nu_e, \bar{\nu}_e\} : \{\nu_\mu, \bar{\nu}_\mu\} : \{\nu_\tau, \bar{\nu}_\tau\}$$

$$p + p \to n_\pi \left[\pi^0 + \pi^+ + \pi^-\right] \qquad p + \gamma \to \Delta^+ \to \pi^+ + n$$



Production	Source flavor ratio	Earth flavor ratio $\nu + \bar{\nu}$	Earth flavor ratio	$f_{\bar{\nu}_e}$
pp	$\{1,1\} : \{2,2\} : \{0,0\}$	$0.33 : 0.34 : 0.33$	$\{0.17, 0.17\} : \{0.17, 0.17\} : \{0.16, 0.16\}$	0.17
$p\gamma$	$\{1,0\} : \{1,1\} : \{0,0\}$	$0.33 : 0.34 : 0.33$	$\{0.26, 0.08\} : \{0.21, 0.13\} : \{0.20, 0.13\}$	0.08

Liu, Song, ACV 2304.06068/PRD

Event-Wise Identification

QL, Song, Vincent [2304.06068]

The case where Glashow resonant events can be identified on an event-by-event basis in the [4,10] PeV deposited energy window. Only consider $\bar{\nu}_e$ fraction.

$W^- \to \text{hadrons}$ **BR ~67 %** ★

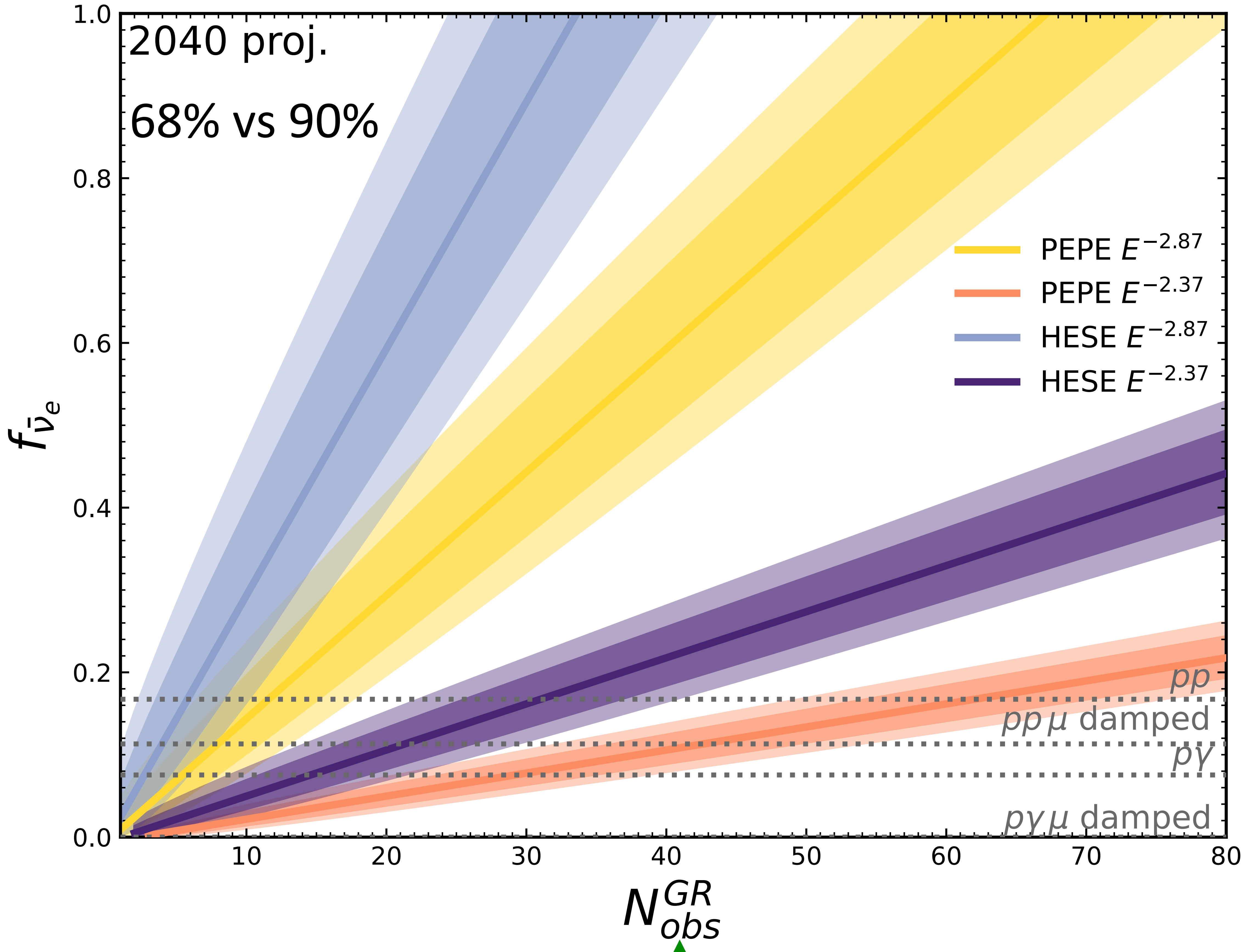
✓ escaping muons, the only irreducible background is from NCDIS events

$W^- \to e^-\bar{\nu}_e/\tau^-\bar{\nu}_\tau$ **BR ~11 %**

✗ Undistinguishable to a DIS cascade

$W^- \to \mu^-\bar{\nu}_\mu$ **BR ~11 %**

✓ track without the initial cascade comparing to ν_μ CCDIS



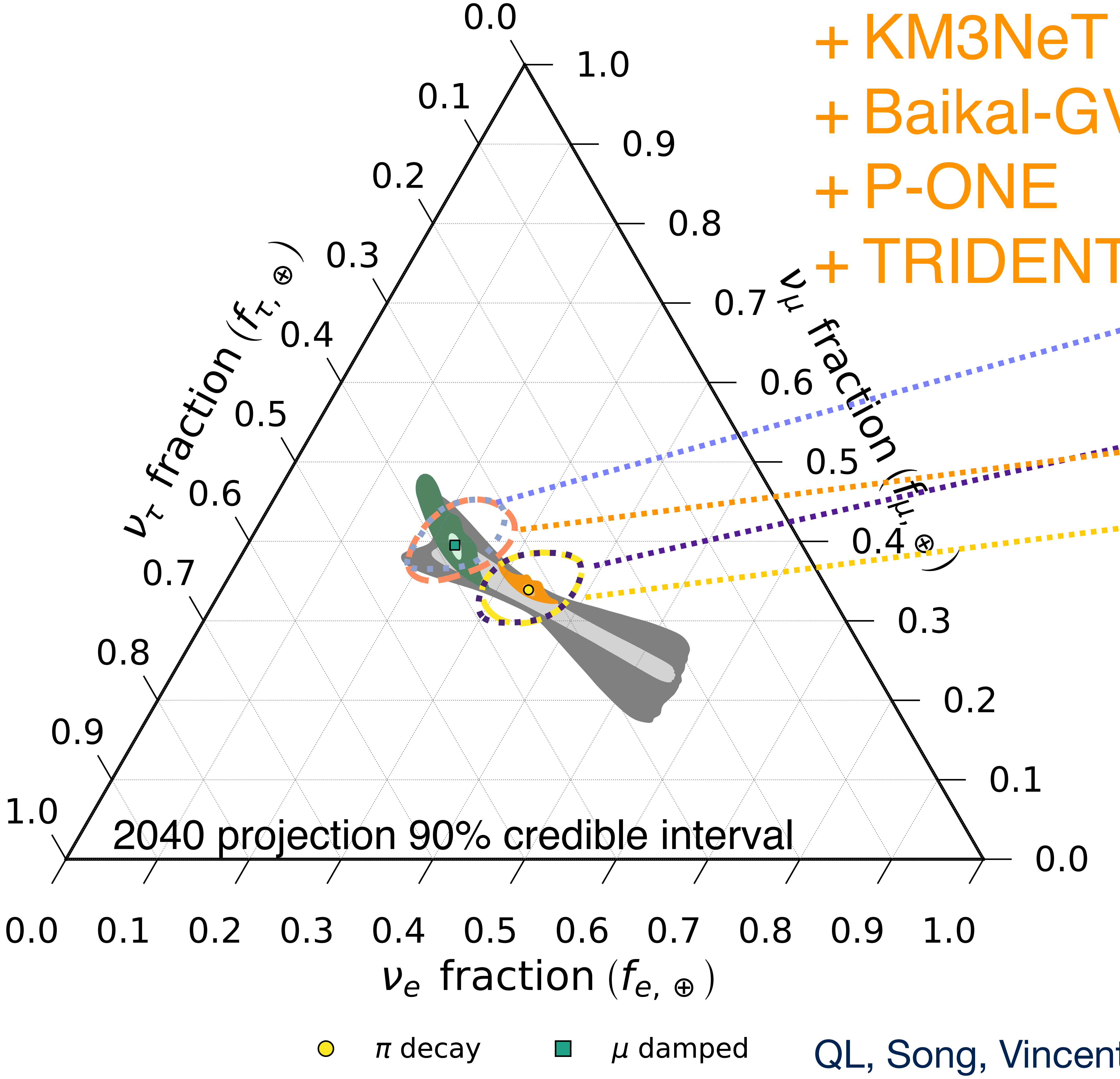
Number of Glashow resonant-like events observed

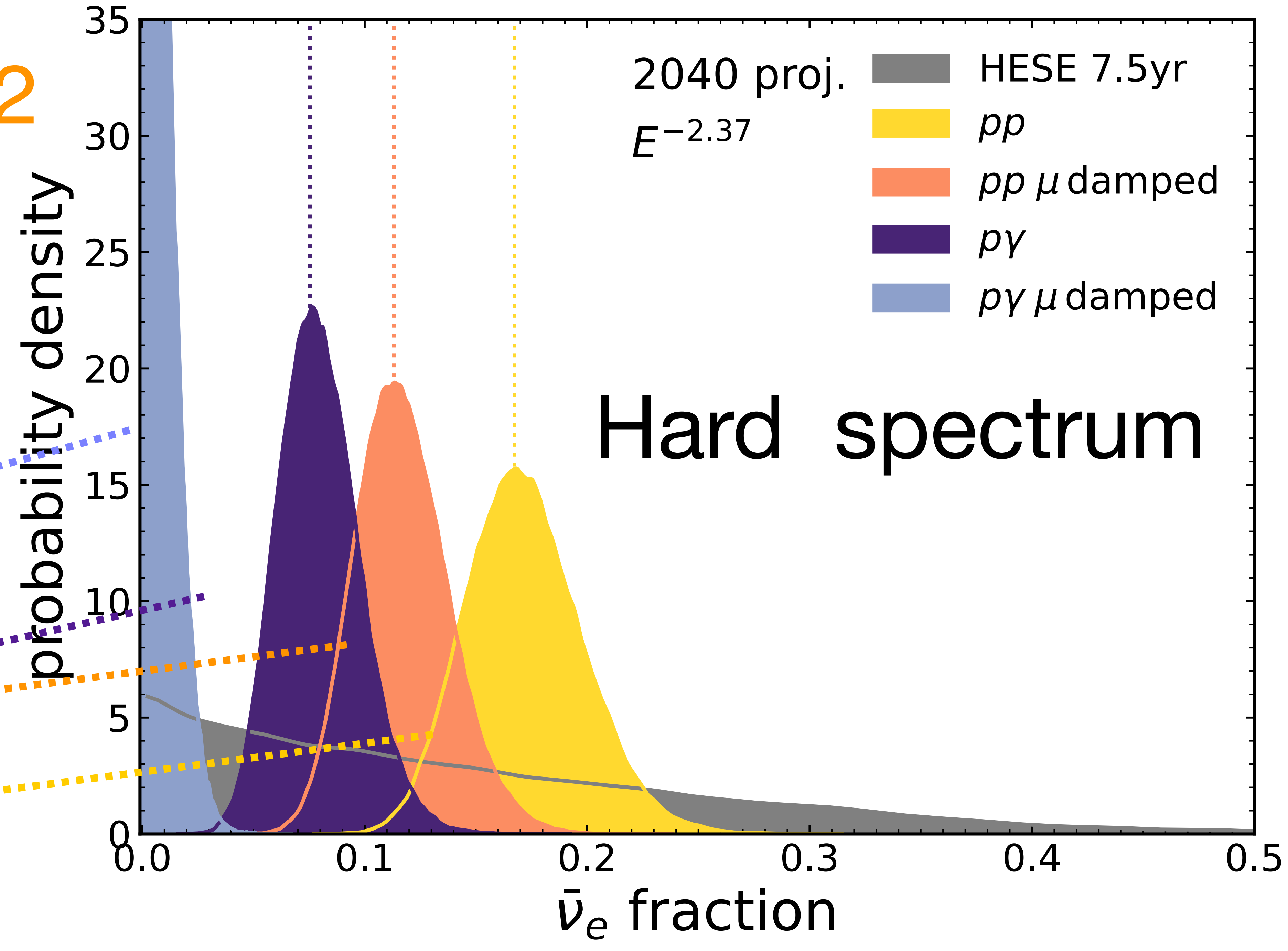
3-flavor degenerate scenarios can be distinguished at $\gtrsim 2\sigma$ w/ the soft spectrum assumption and $\sim 5\sigma$ w/ the hard spectrum assumption by 2040

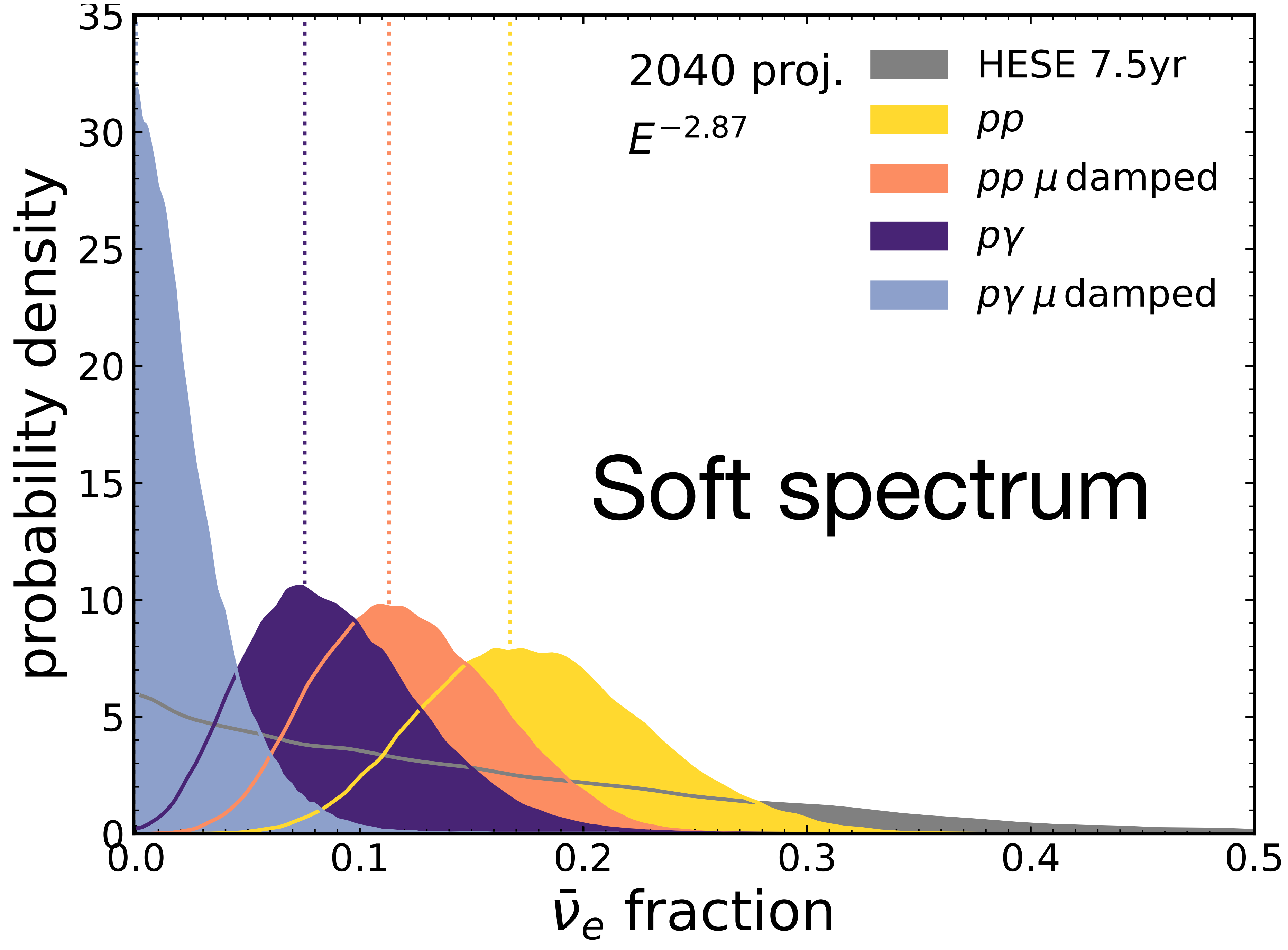
IceCube/IceCube-Gen2
+ KM3NeT
+ Baikal-GVD
+ P-ONE
+ TRIDENT

4-Flavor Analysis

IceCube/IceCube-Gen2
+ KM3NeT
+ Baikal-GVD
+ P-ONE
+ TRIDENT







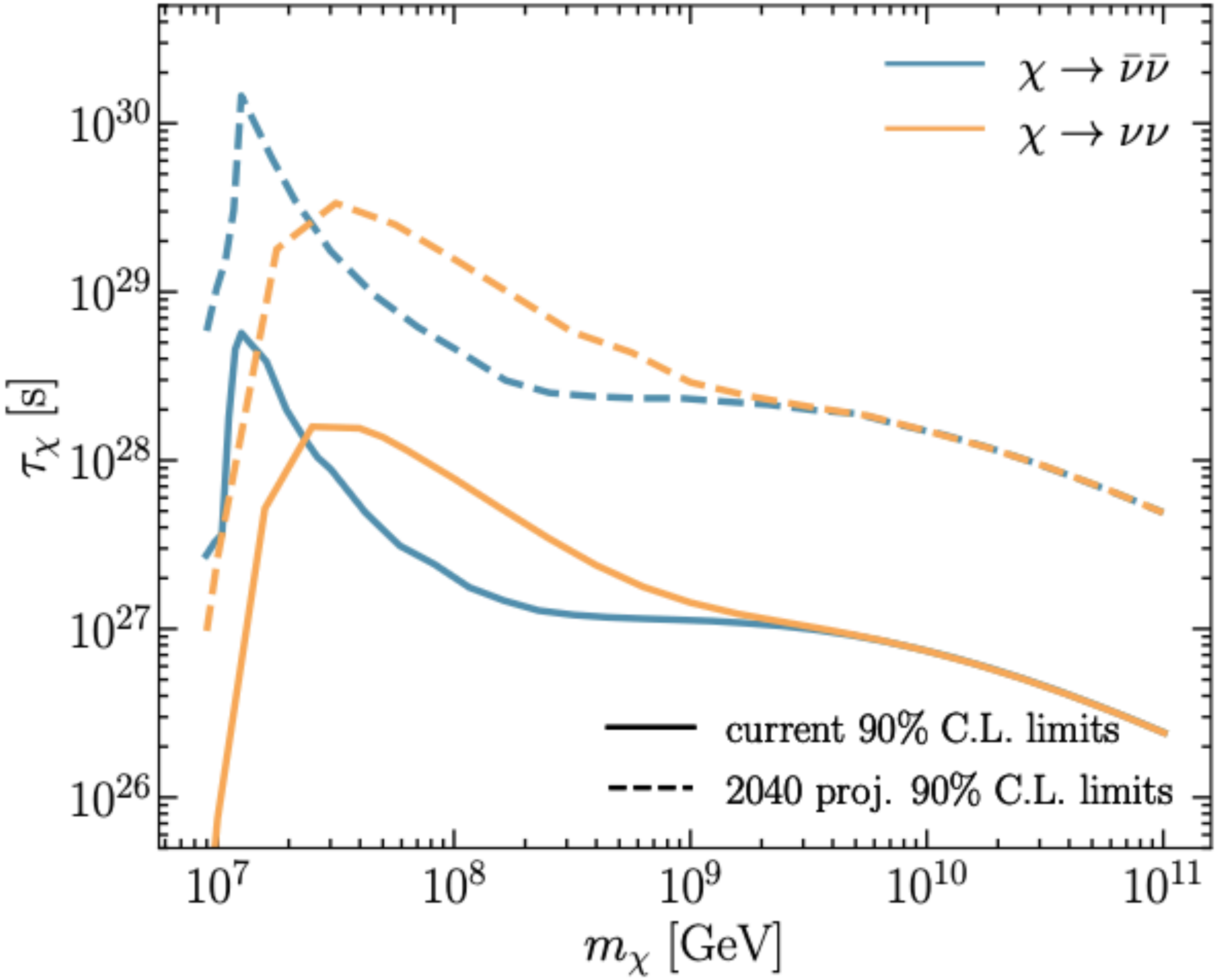
QL, Song, Vincent [2304.06068]

3-flavor can be reconstructed and degenerated scenarios can be distinguished at $\gtrsim 2\sigma$ w/ the soft spectrum assumption and $\gtrsim 4\sigma$ w/ the hard spectrum assumption by 2040

New Physics? Dark matter decay to neutrinos

- High mass (> PeV) decay to neutrinos produces an additional flux from **electroweak corrections**
- **The ν or $\bar{\nu}$** flux in the glashow window is different for asymmetric decay to $\nu\nu$ vs $\bar{\nu}\bar{\nu}$

Qinrui Liu, Ningqiang Song, ACV, in prep



Summary

- Our understanding of the high-energy neutrino sky will become **1-2 orders of magnitude more precise** over the coming two decades
- Neutrino telescopes cover at least **14 orders of magnitude in energy** & can say all sorts of things about the dark sector & new physics
  - neutrino decay
  - Dark matter
  - More!
- We can go beyond 3-flavours and break the neutrino-antineutrino degeneracy, and thus the pp-$p\gamma$ degeneracy, by looking at the glashow resonance. This also allows new interesting probes of new physics.