Queen's University

Centre Canadien de Recherche en Physique des Astroparticules
Arthur B. McDonald
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The future of high-energy neutrino flavour and the search for new physics

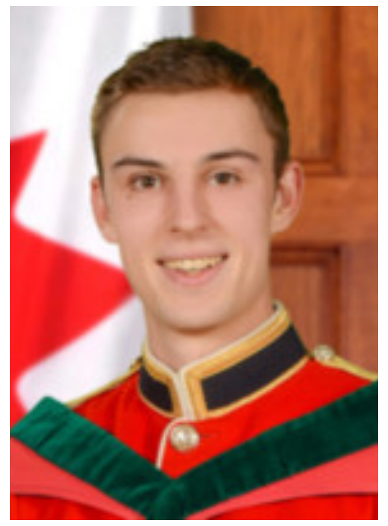
Aaron C. Vincent

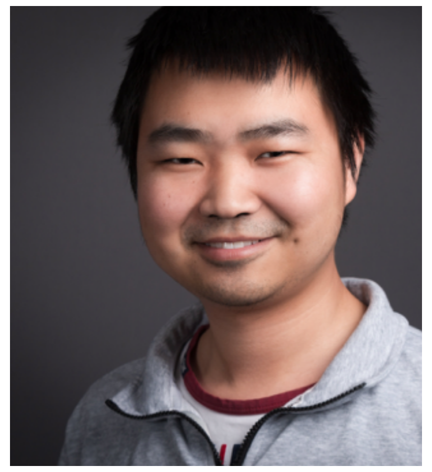
CAP 2021 Neutrino Symposium — June 8 2021

Featuring


Carlos Argüelles
Harvard


Ali Kheirandish
Penn State


Adam
McMullen


Ningqiang
Song


Mauricio Bustamante
Niels Bohr Institute


Shirley Weishi Li
Fermilab


Andrés Olivares-del-Campo
IPPP Durham


Alejandro Diaz
MIT


Katie Mack
NCSU


Ibrahim Safa
Harvard/UW
Madison

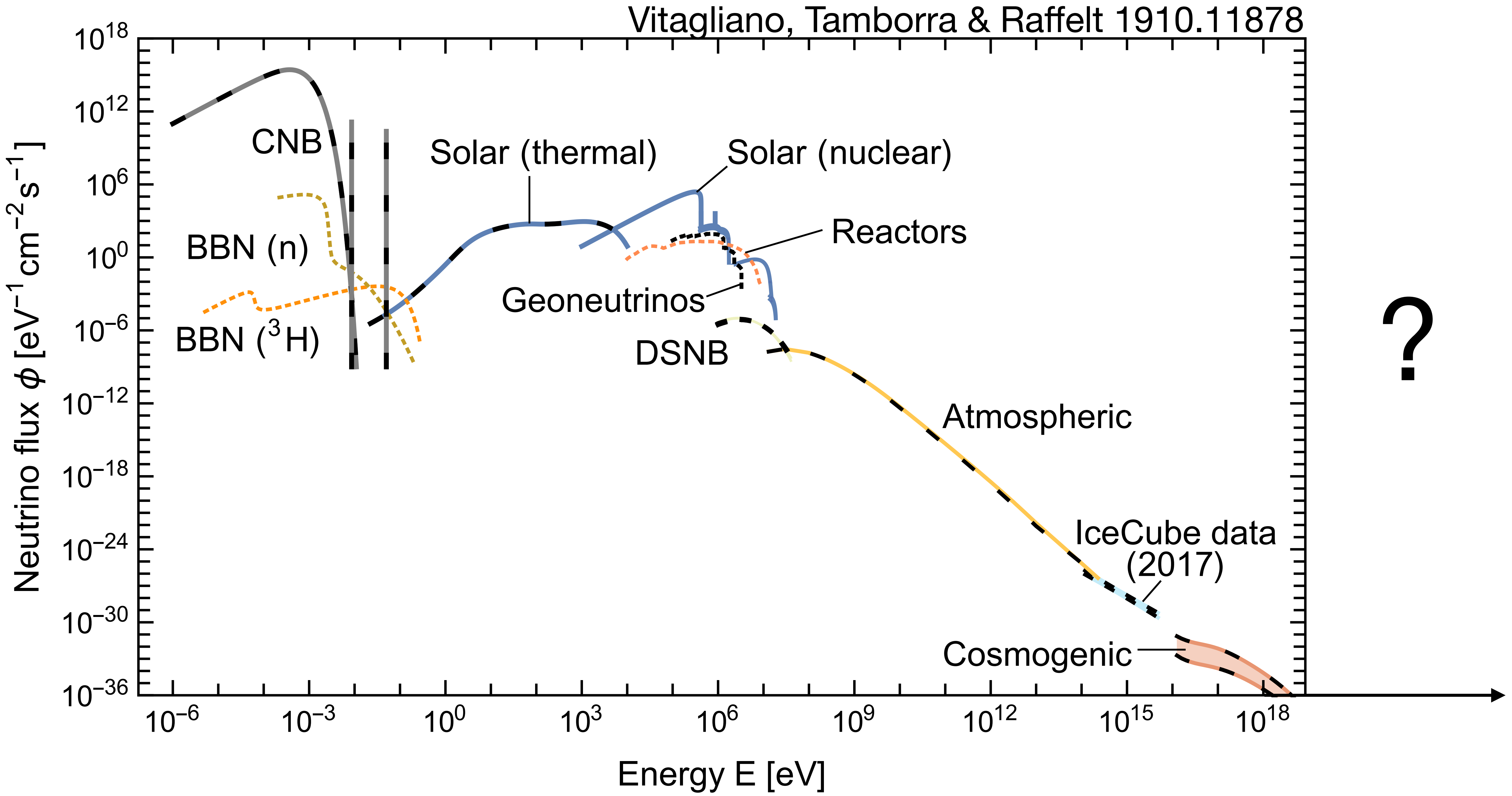
Overview

1. The neutrino sky today & in the future
2. New physics
    i. Neutrino decay
    ii. Dark matter
    iii. Large extra dimensions
3. Conclusions

The neutrino sky

Neutrinos from space carry:

- Directional information
- Timing information
- Energy
- **Flavour:** ν_e, ν_μ, ν_τ


Vitagliano, Tamborra & Raffelt 1910.11878

Now have experiments that cover this entire range.
What can we learn from extraterrestrial neutrinos?
Where do we go?

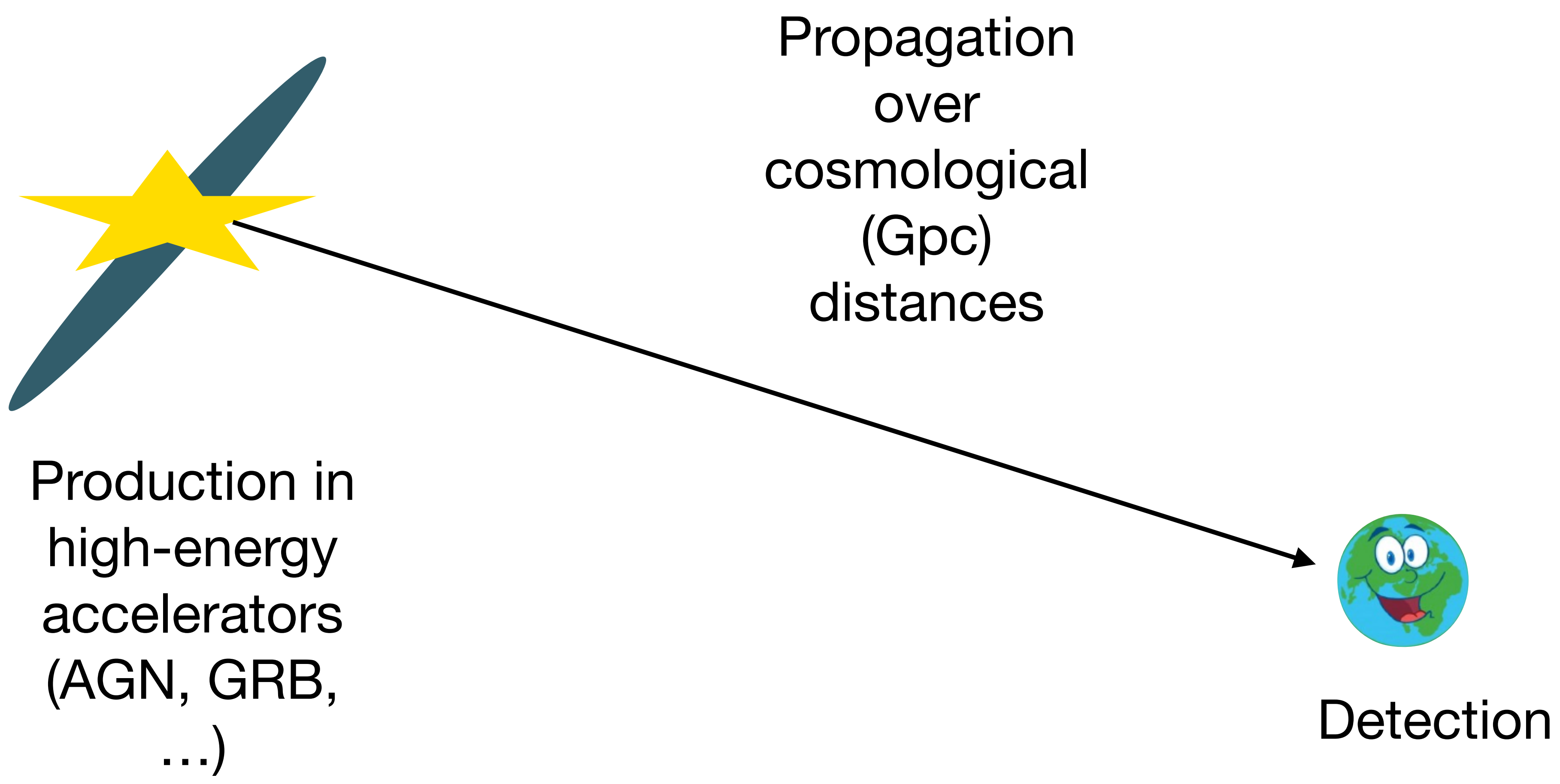
High energies & Flavour

The Future of High-Energy Astrophysical Neutrino Flavor Measurements

Ningqiang Song, Shirley Weishi Li, Carlos A. Argüelles, Mauricio Bustamante, Aaron C. Vincent

JCAP 24 (2021) 054 https://arxiv.org/abs/2012.12893

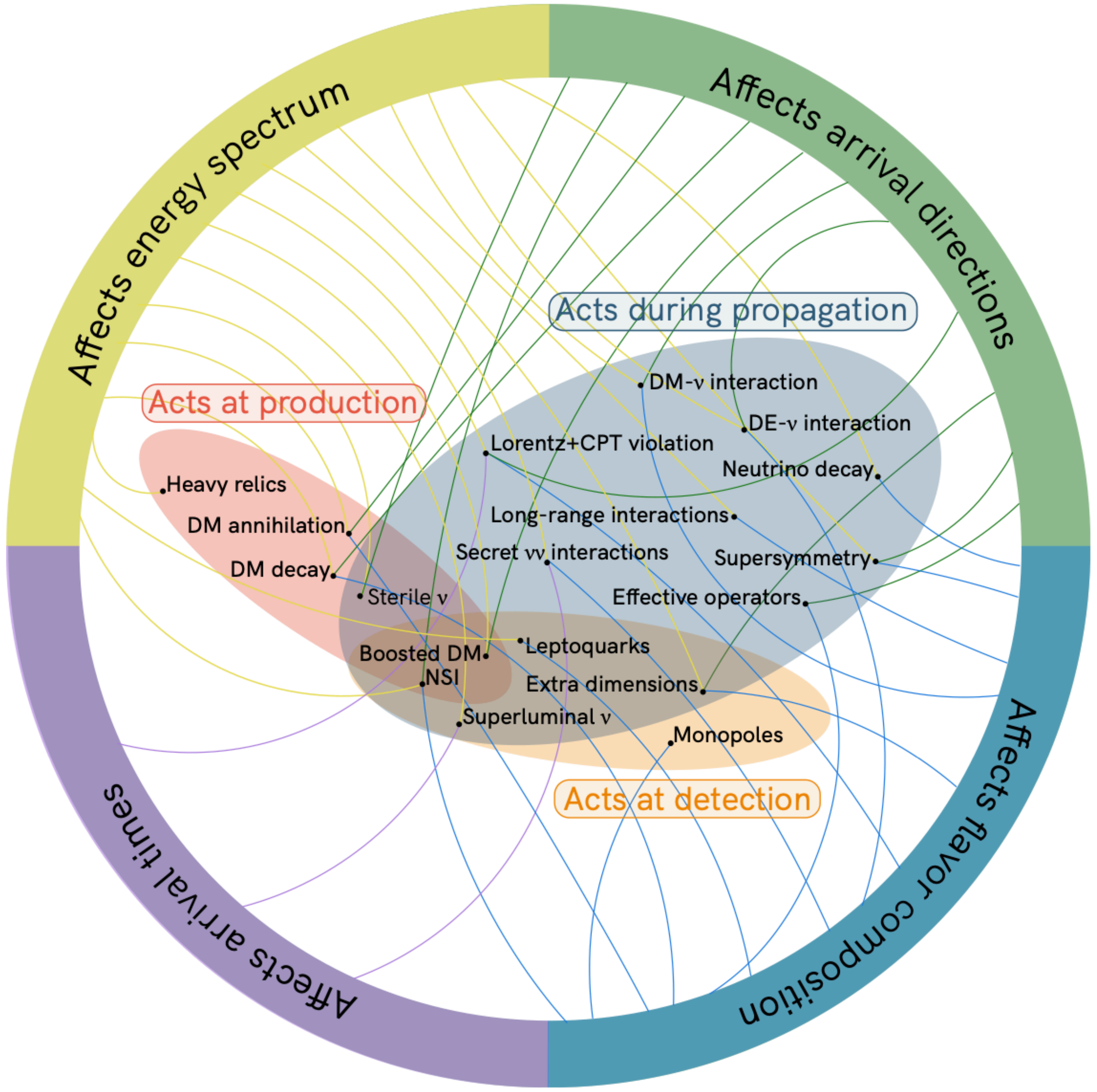
High-energy neutrinos



Propagation over cosmological (Gpc) distances

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

Detection



New Physics?

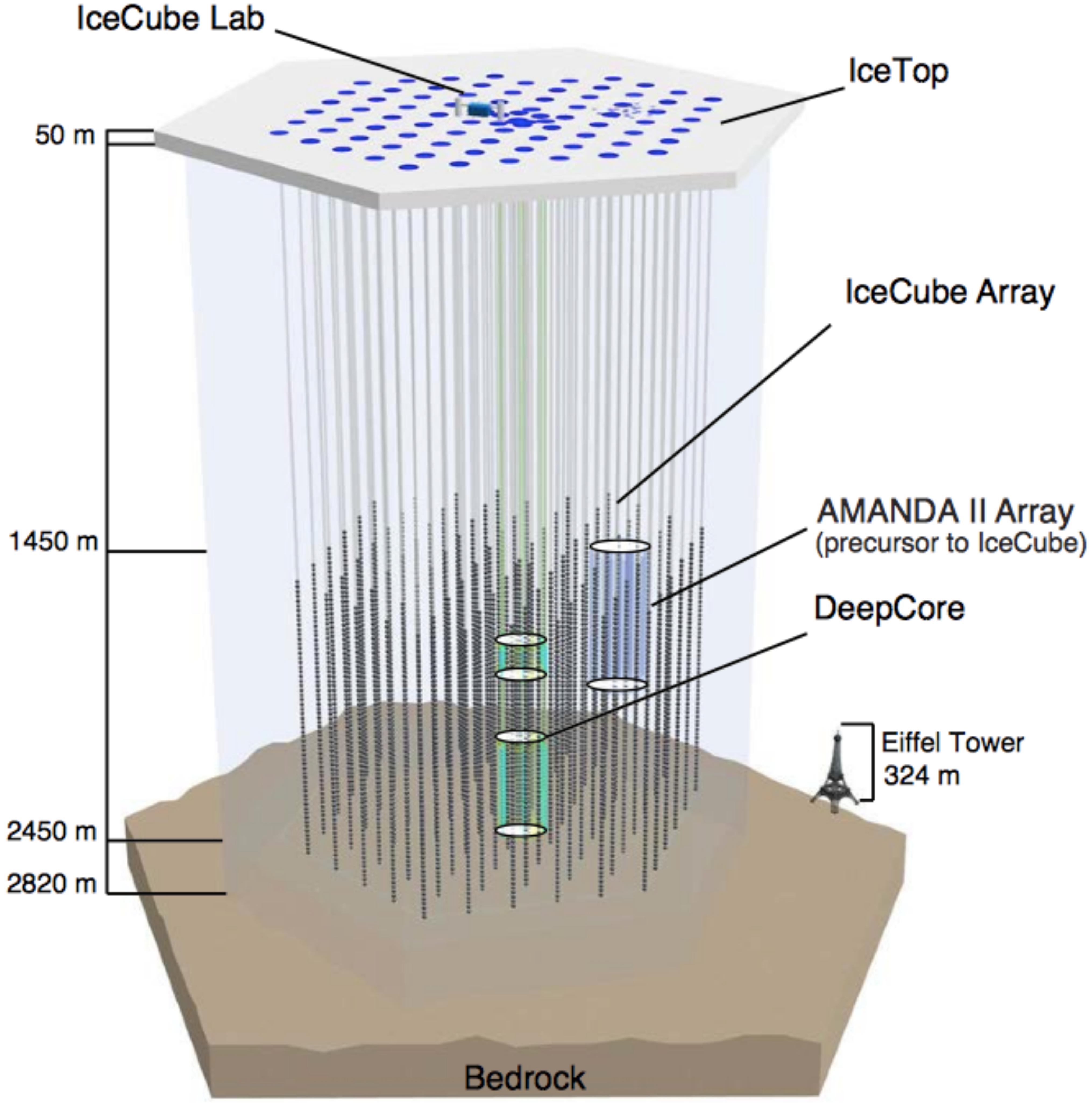
Neutrinos can tell us about "standard model" physics:

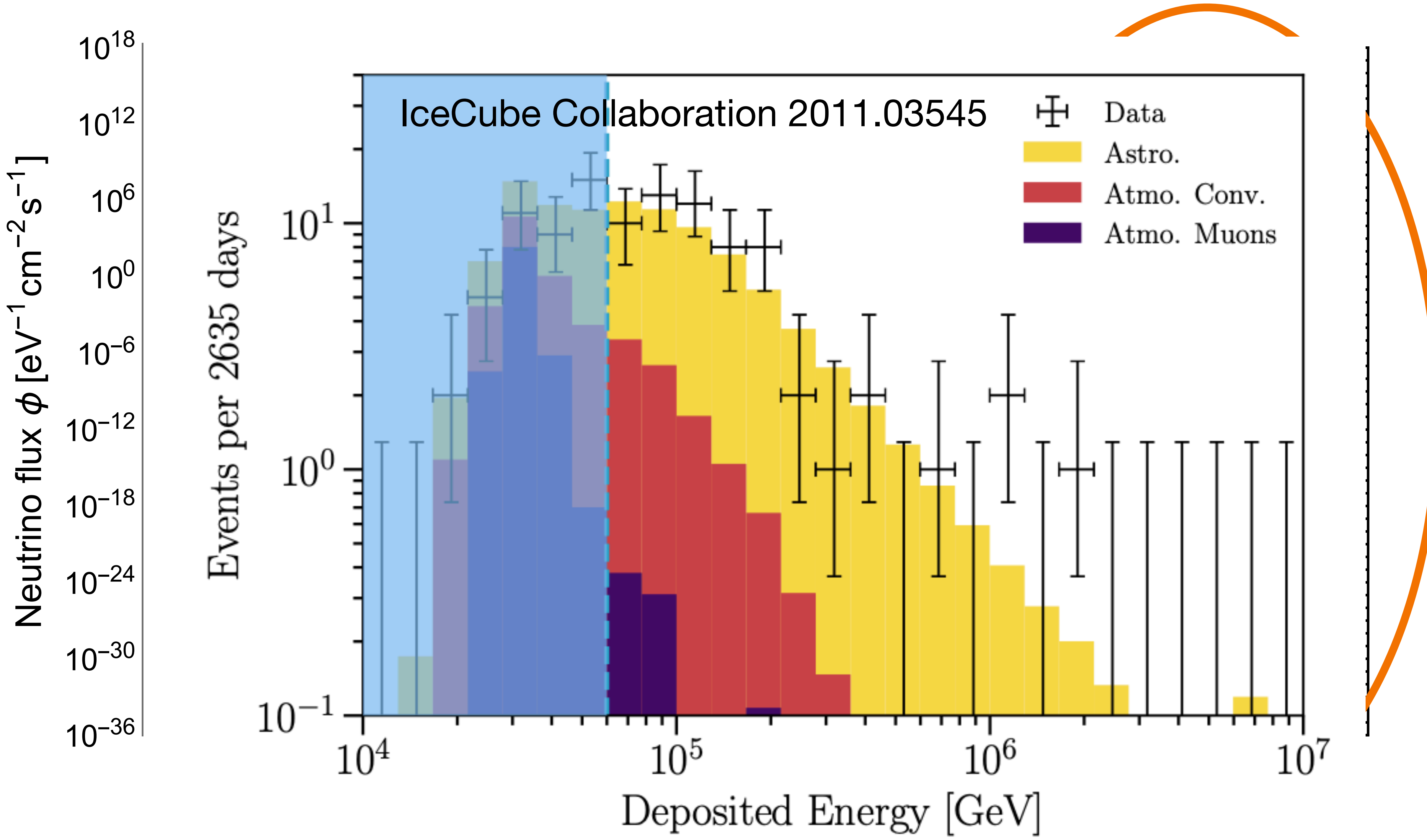
- Nature of these accelerators
- Oscillation, interaction with intergalactic medium
- Detection: high-energy neutrino-nucleus cross sections

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

Current observations: IceCube (south pole)

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

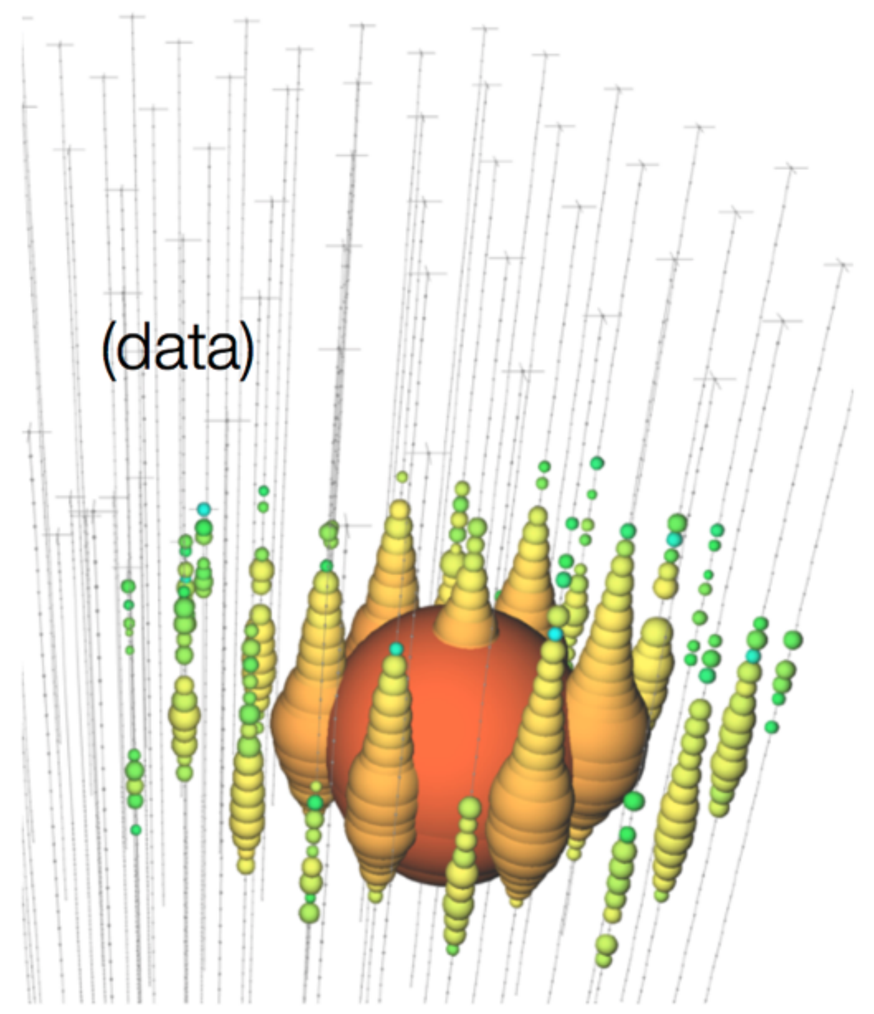




large exposures necessary
due to low fluxes

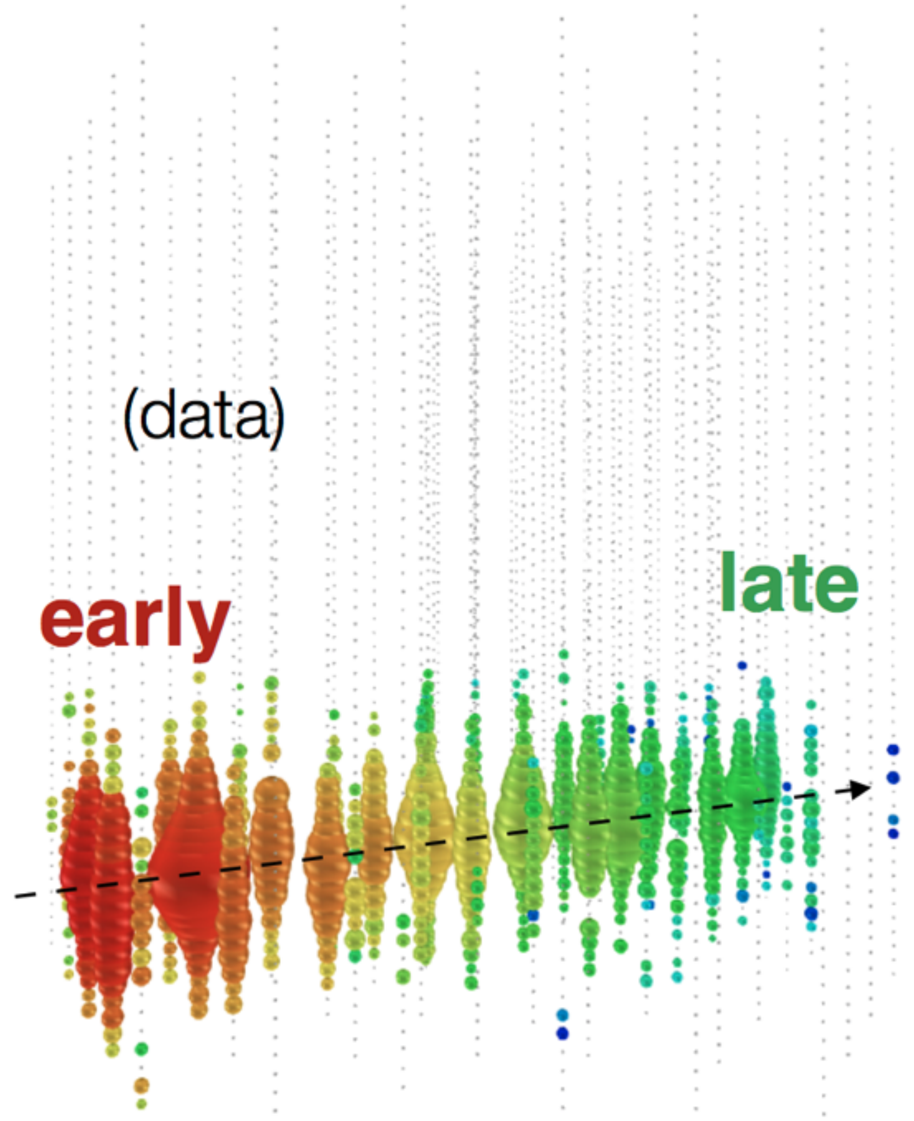
Flavour: event morphology

Neutral-current / ν_e



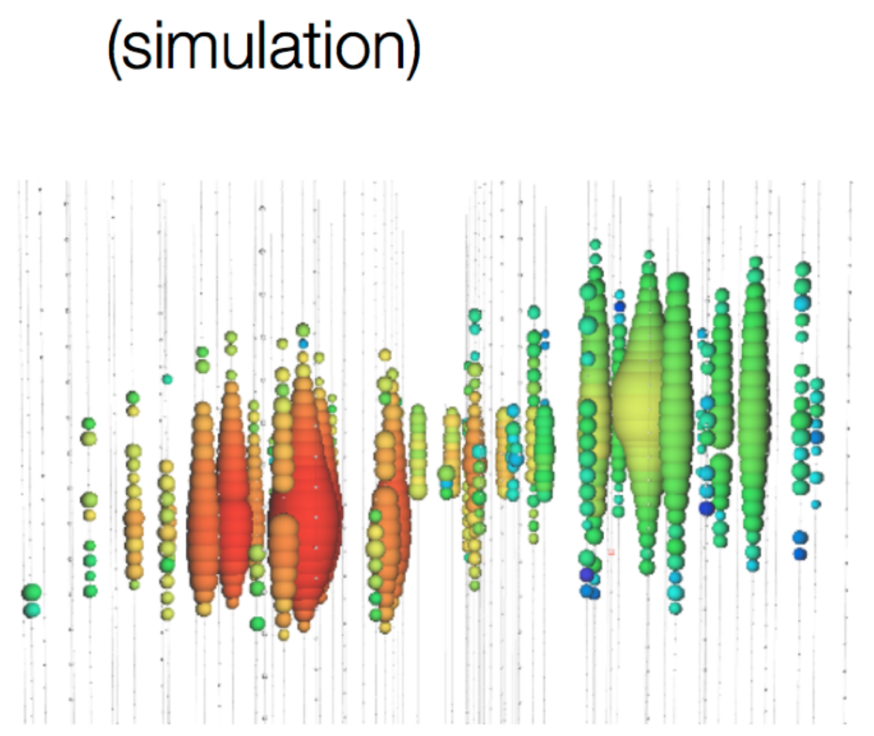
Isolated energy deposition (cascade) with no track

Charged-current ν_μ



Up-going track

Charged-current ν_τ



Double cascade

Images: icecube.wisc.edu

Flavour composition in astrophysical sources

(GRBs, AGNs, blazars, pulsars…)

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

● **Pion sources** (c.c. for π^-)

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

(1 : 2 : 0)

■ **“muon-damped”** (c.c. for π^-)

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

(0 : 1 : 0)

◆ **“muon source”** (c.c. for π^-)

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

(1 : 1 : 0)

▲ **Neutron source**

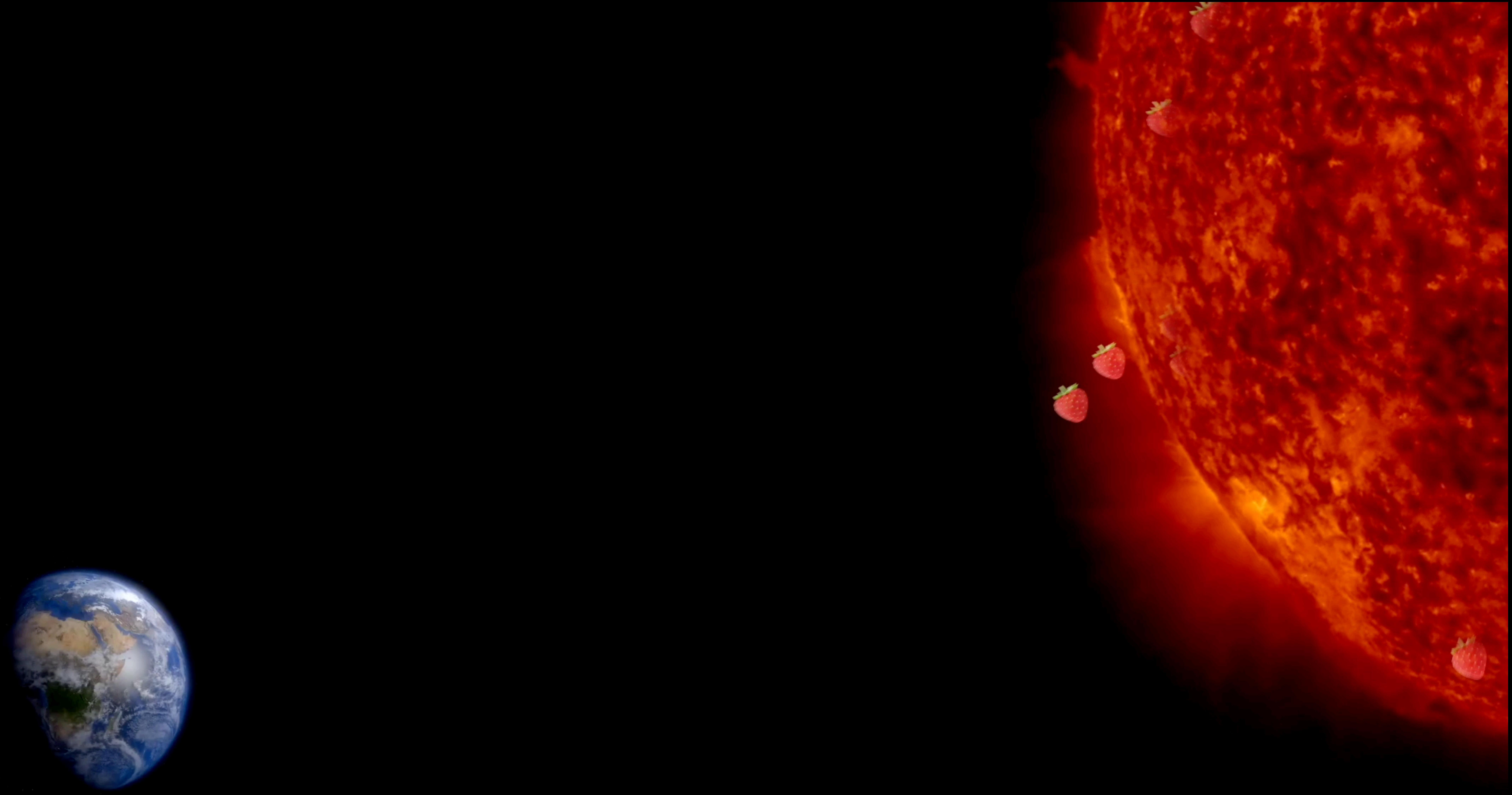
$$n \to p + e^- + \bar{\nu}_e$$

(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 ($i = 1{,}2{,}3$)

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

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

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

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

Flavour basis

PMNS mixing matrix

mass basis

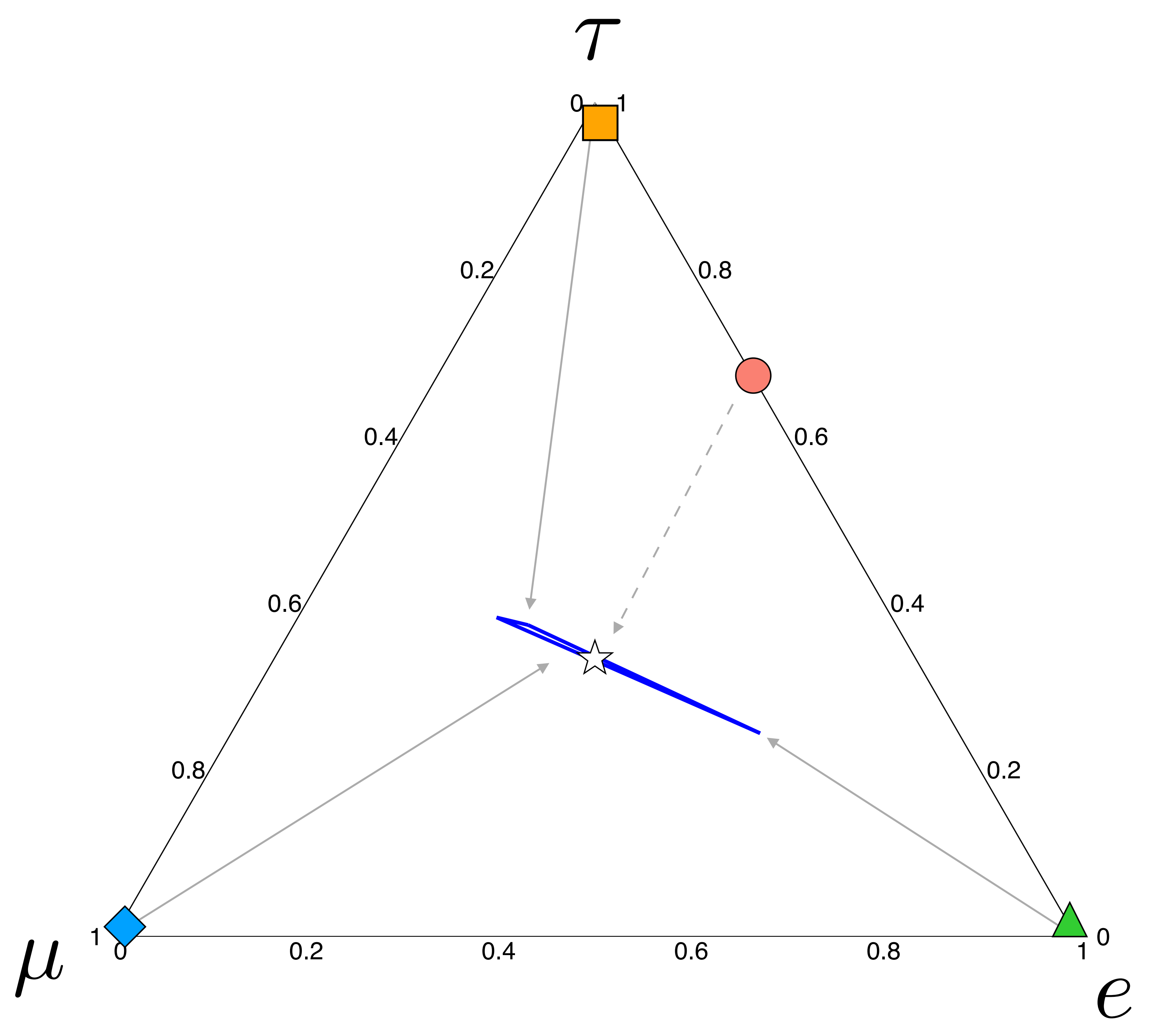
Distances are **large and uncorrelated** -> mixing **averages out:**

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

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

flavour composition at Earth

flavour composition at source



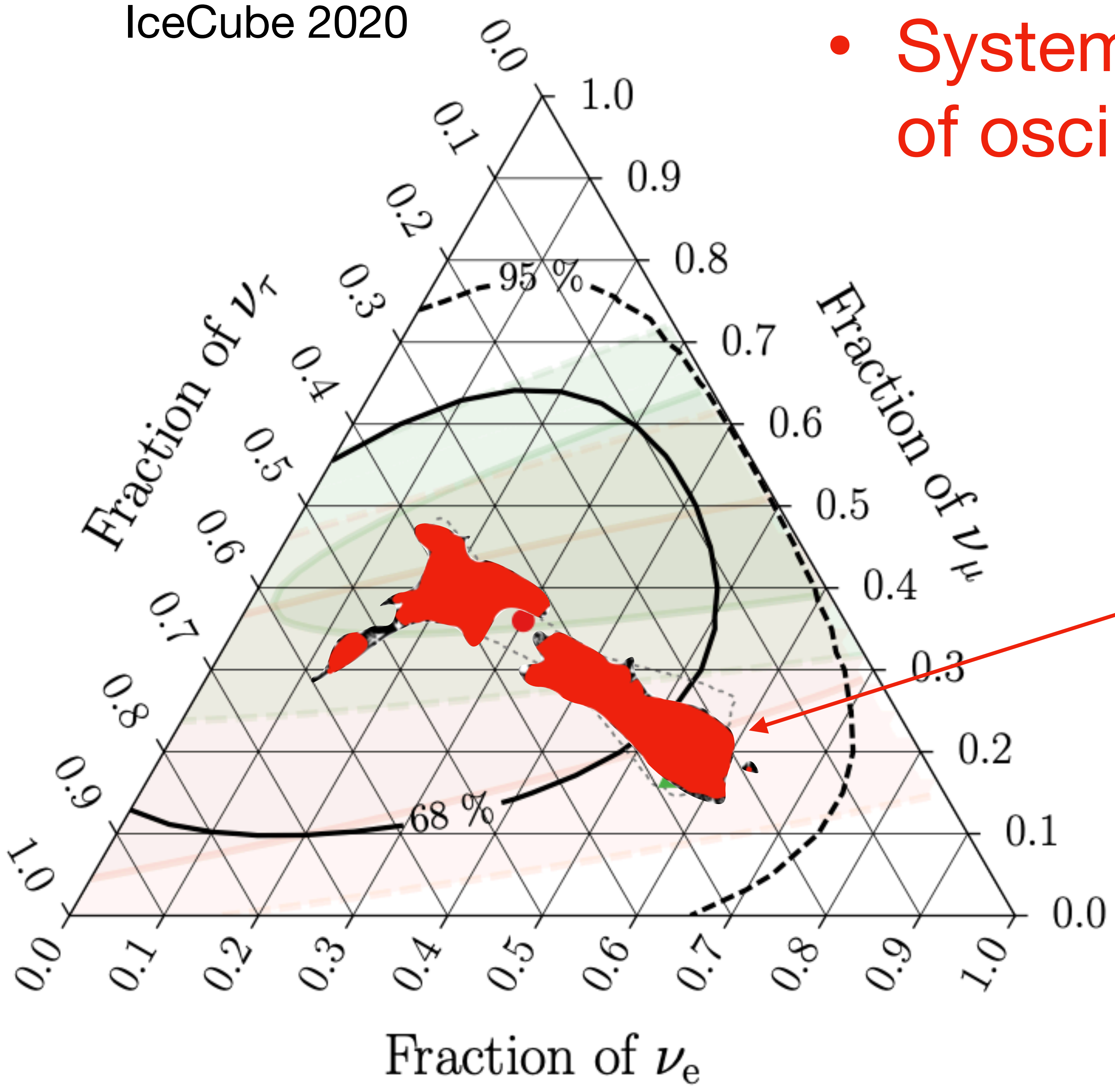
Flavour composition at Earth

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

Two limits:

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

IceCube 2020



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

NuFit 5.0 global fit

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

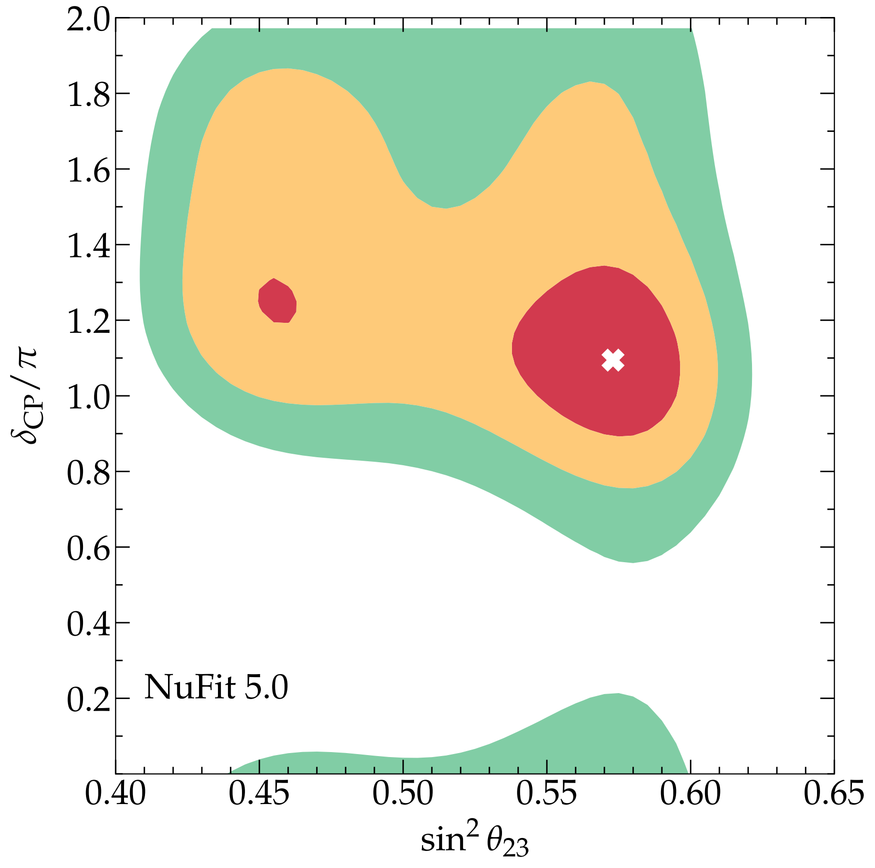
θ_{12} (“solar angle”): Solar, reactor experiments

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

θ_{13} Reactor experiments

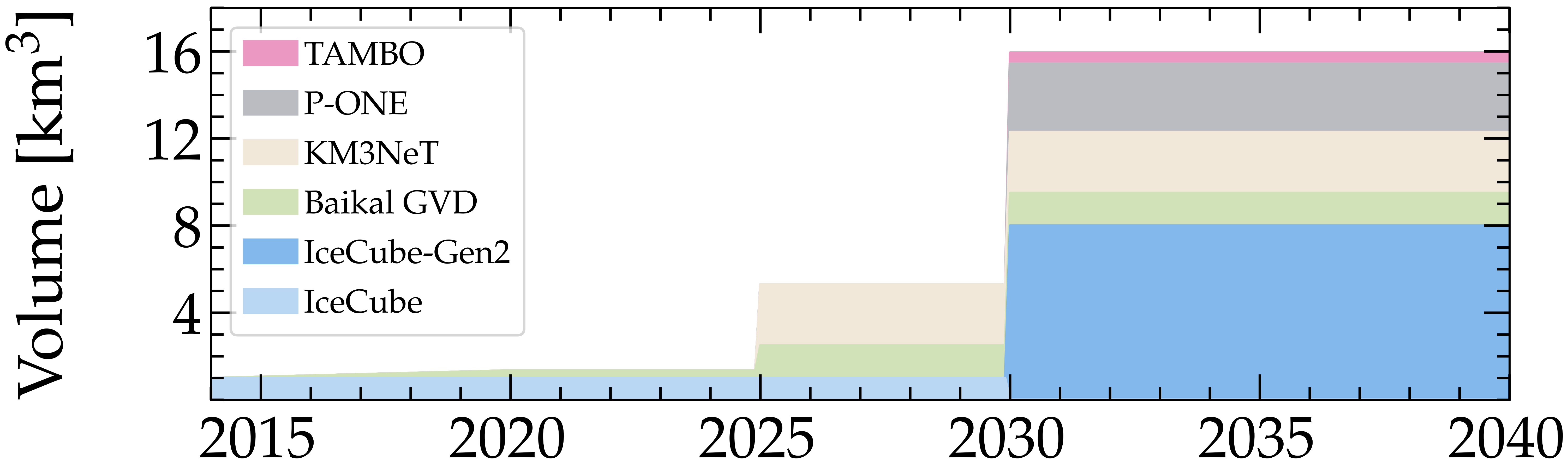
δ_{CP} Long-baseline experiments

Mostly uncorrelated except:



What does the future say about this?

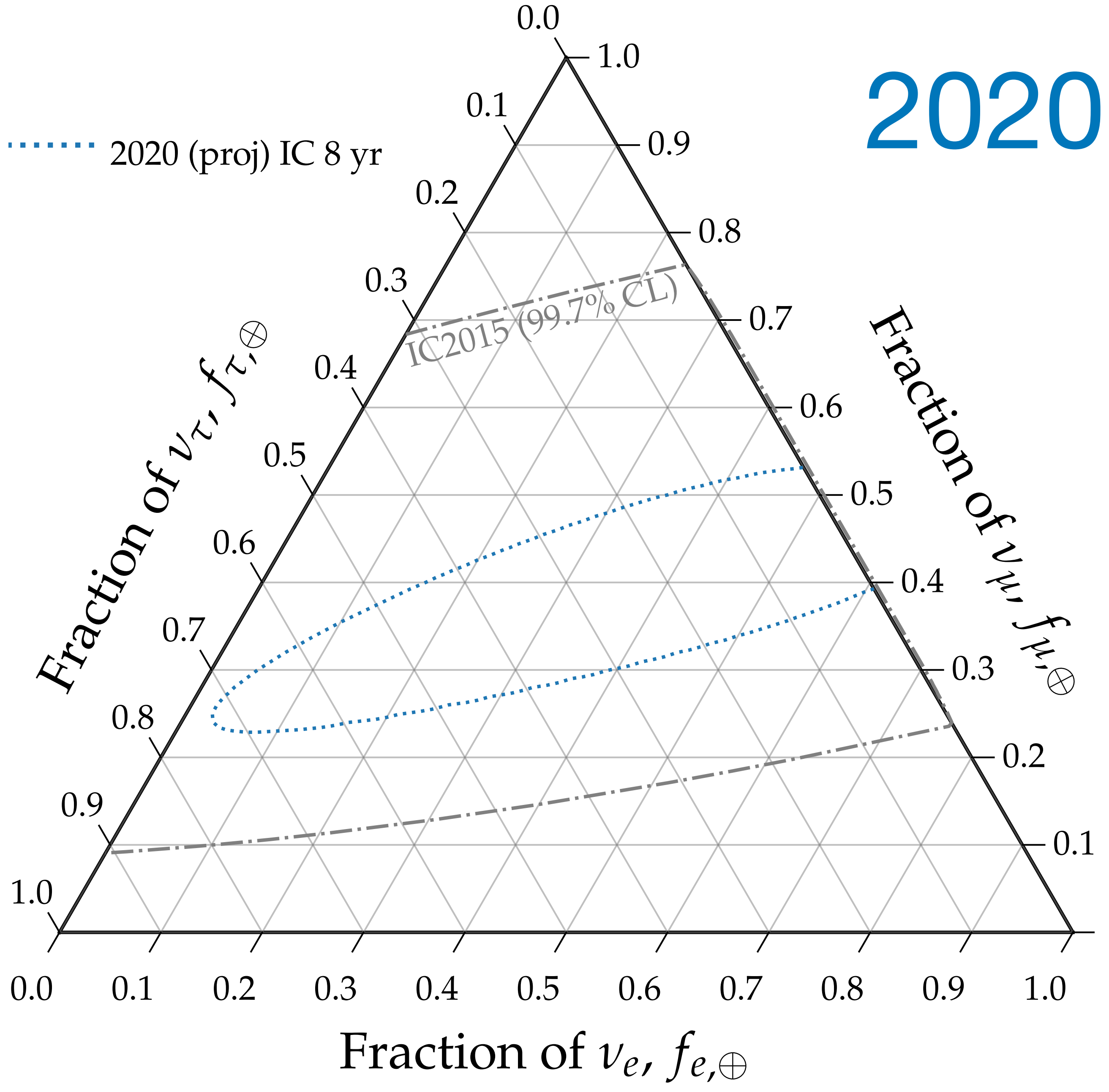
Statistics: need more Cherenkov telescopes!



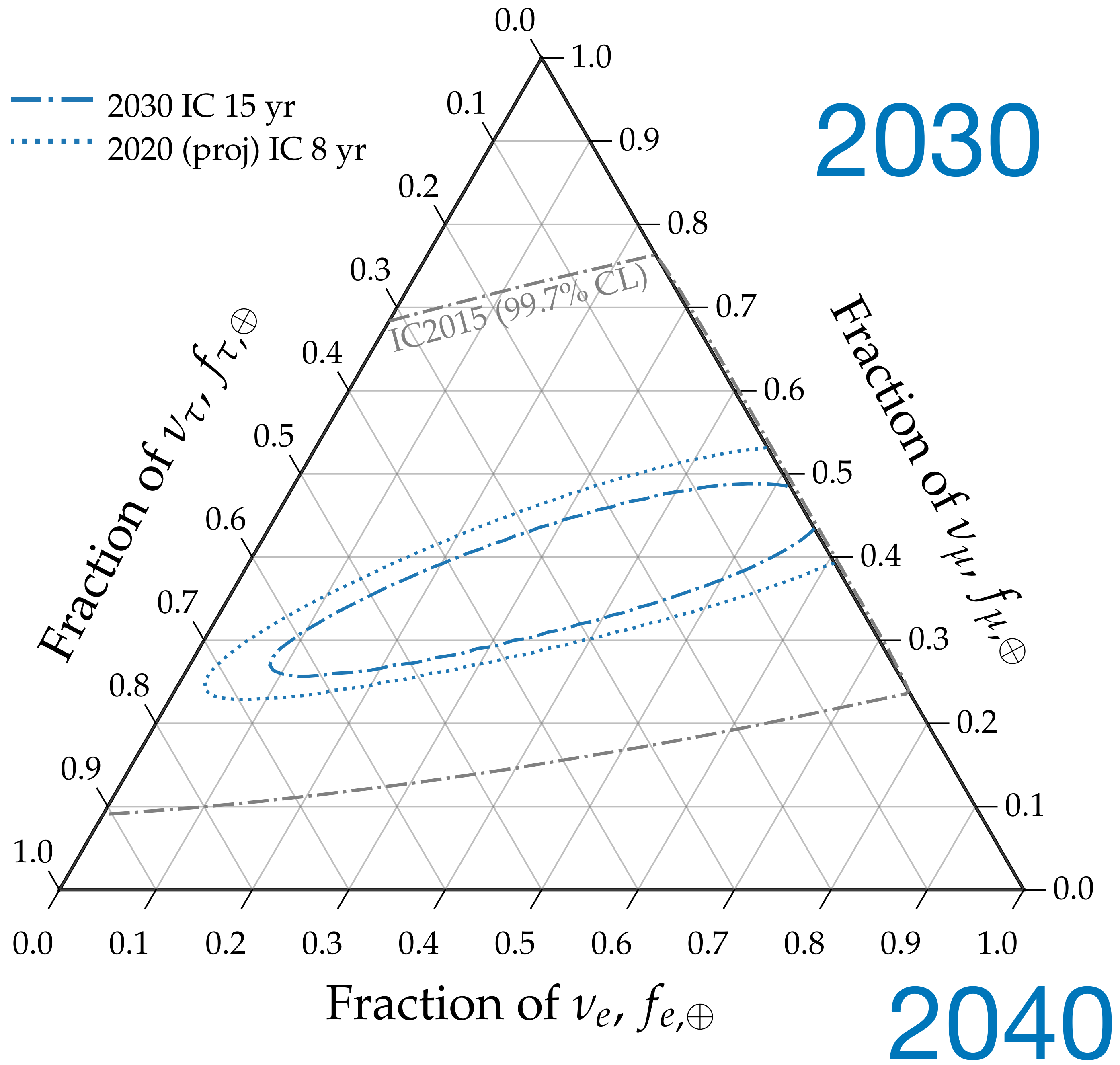
Telescope	**Medium**	**Location**	**Exposure** (km^3)
IceCube-Gen2	Ice	South pole (HE upgrade of IceCube)	~6-9
KM3NeT	Seawater	Mediterranean Sea (successor to ANTARES)	~2-3
GVD	Freshwater	Lake Baikal	1.5
P-ONE	Seawater	Cascadia Basin (Pacific Ocean)	π
TAMBO	Rock/air/water Cherenkov	Peru	~10 (very high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

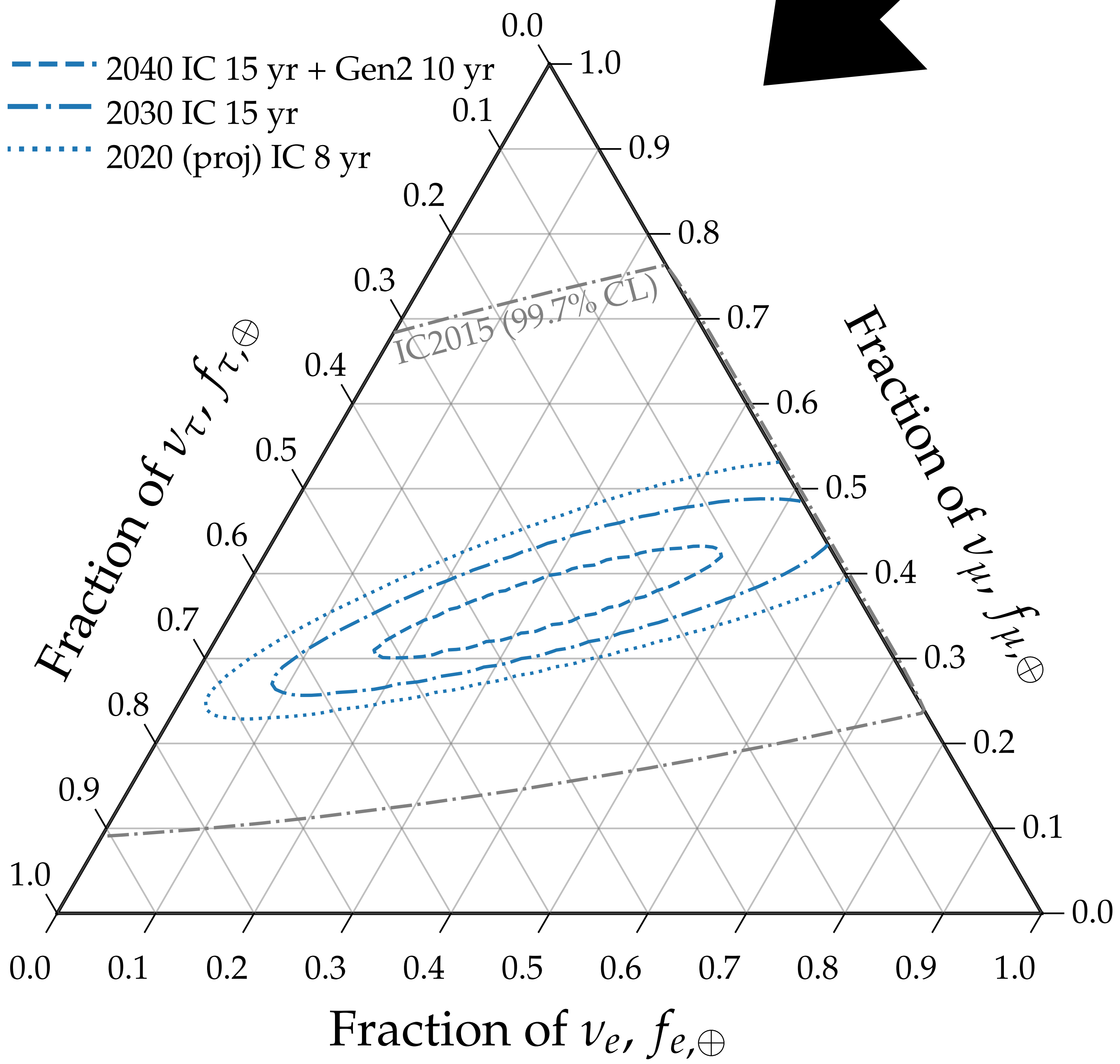
Statistics

2020



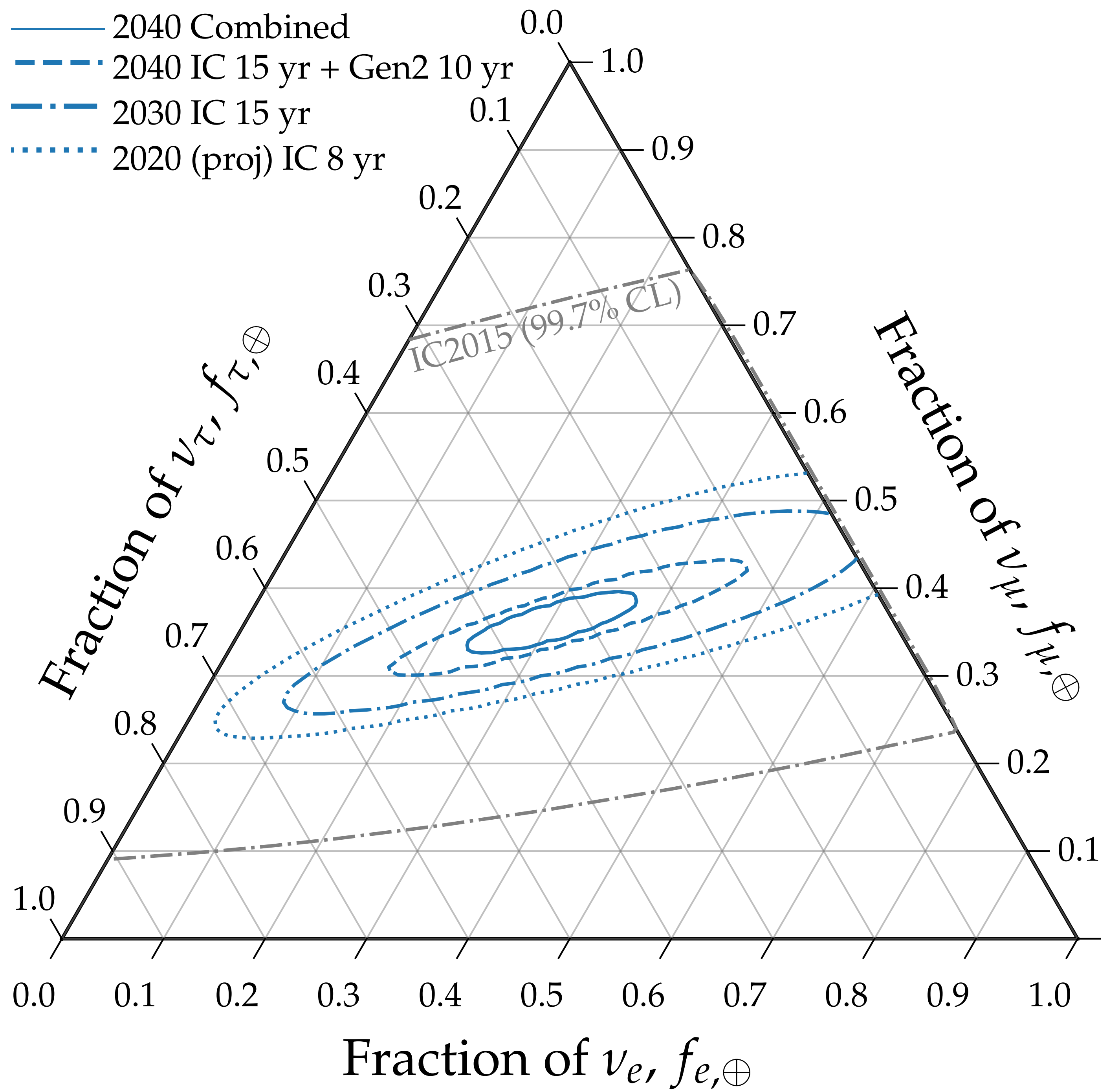
2030





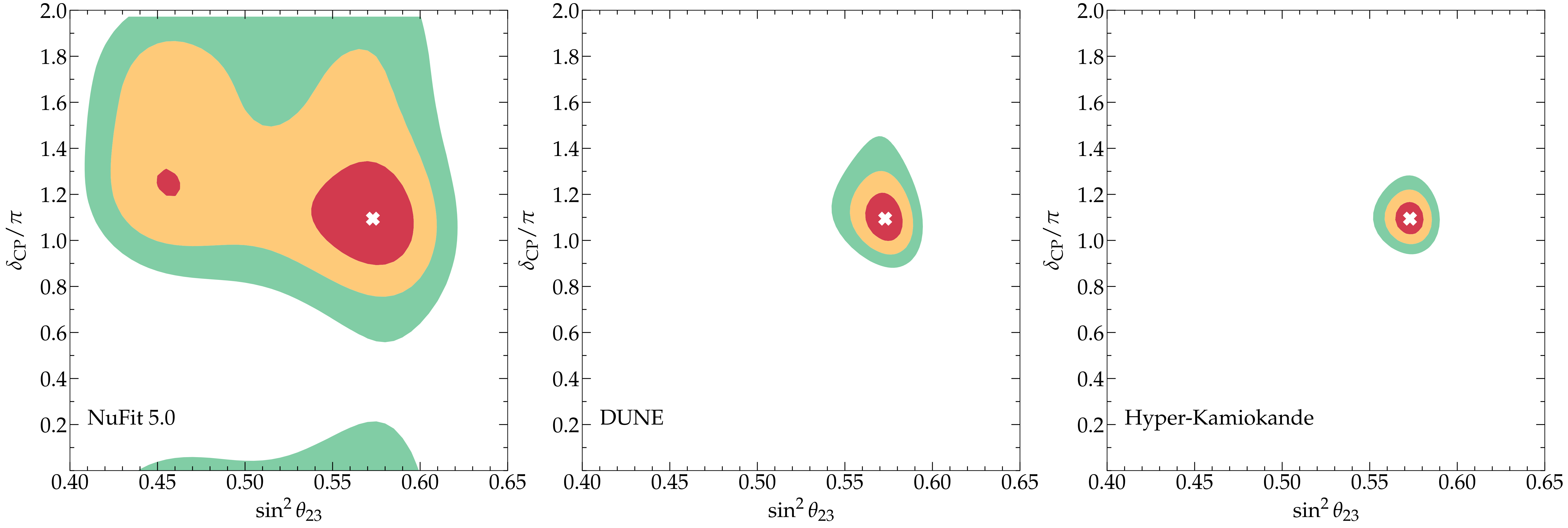
2040 (IceCube-Gen2)

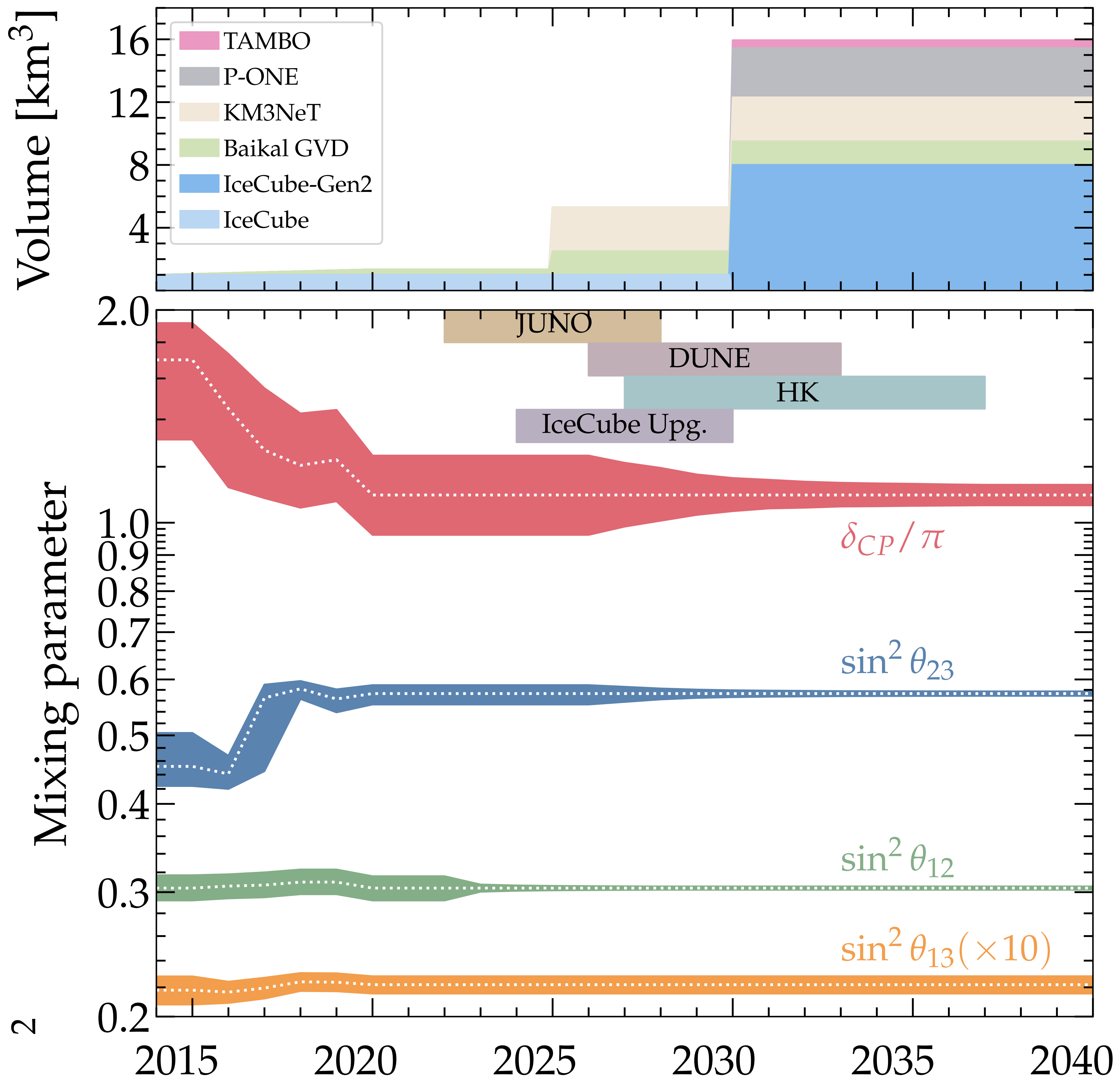
2040(all experiments)

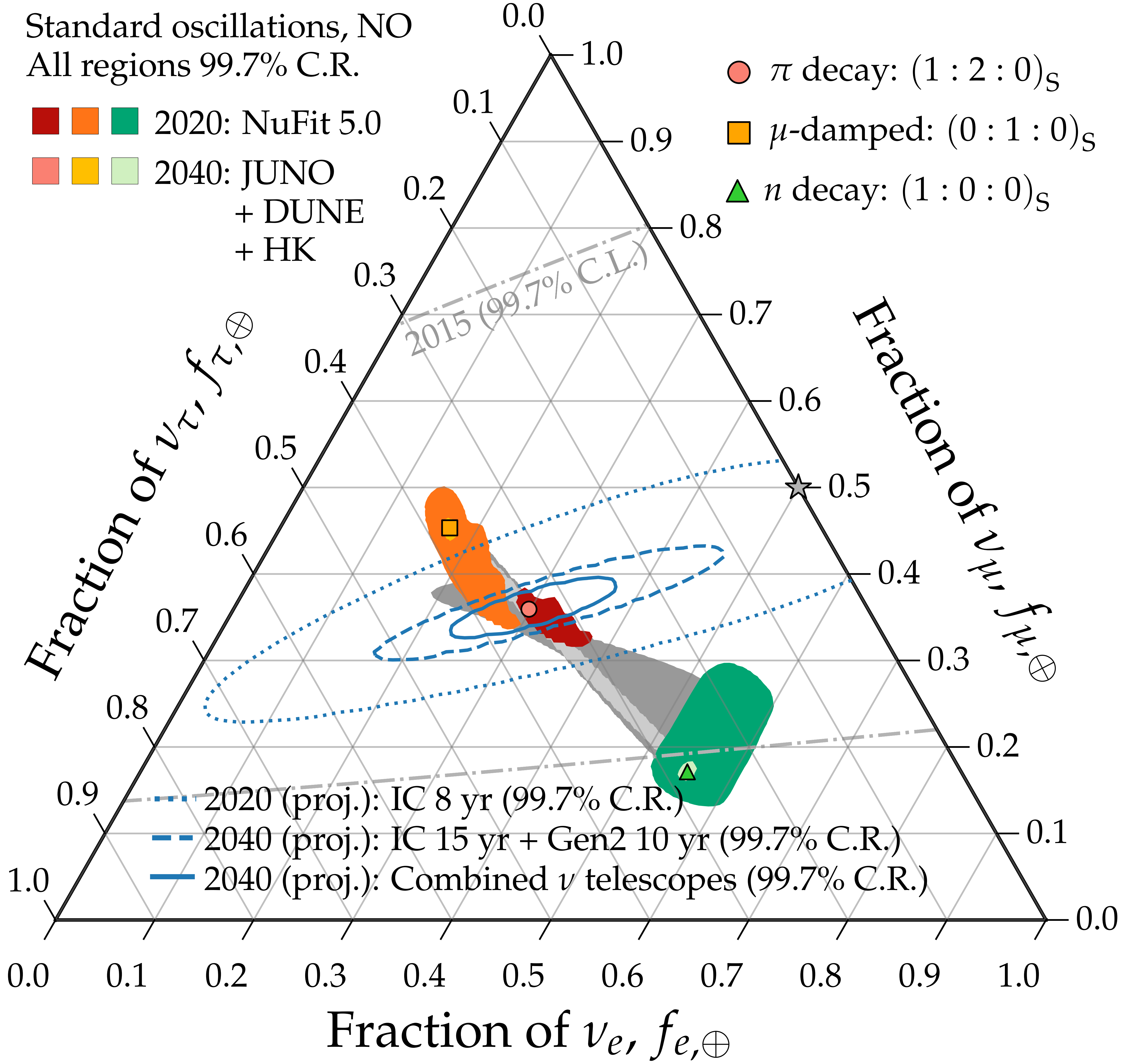


Systematics: terrestrial experiments

- 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



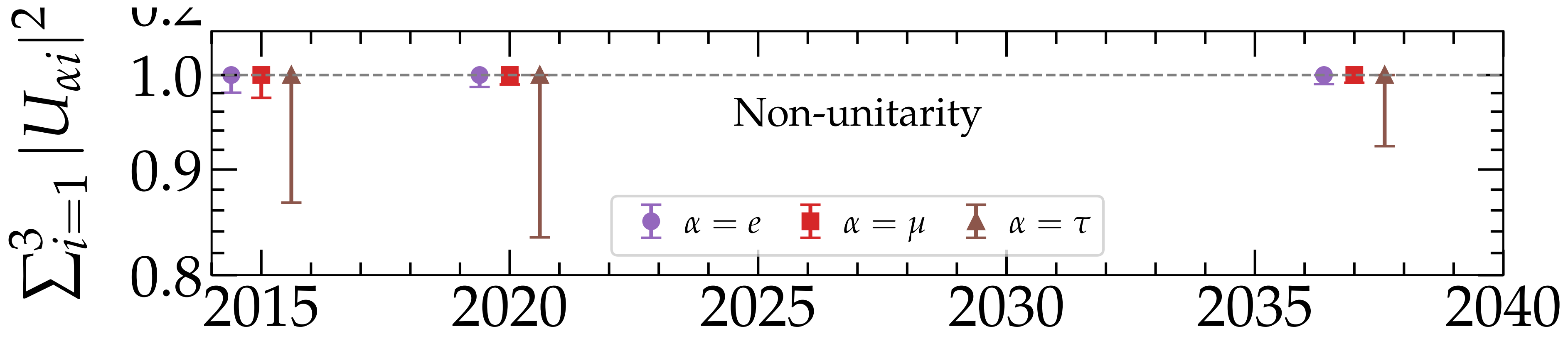


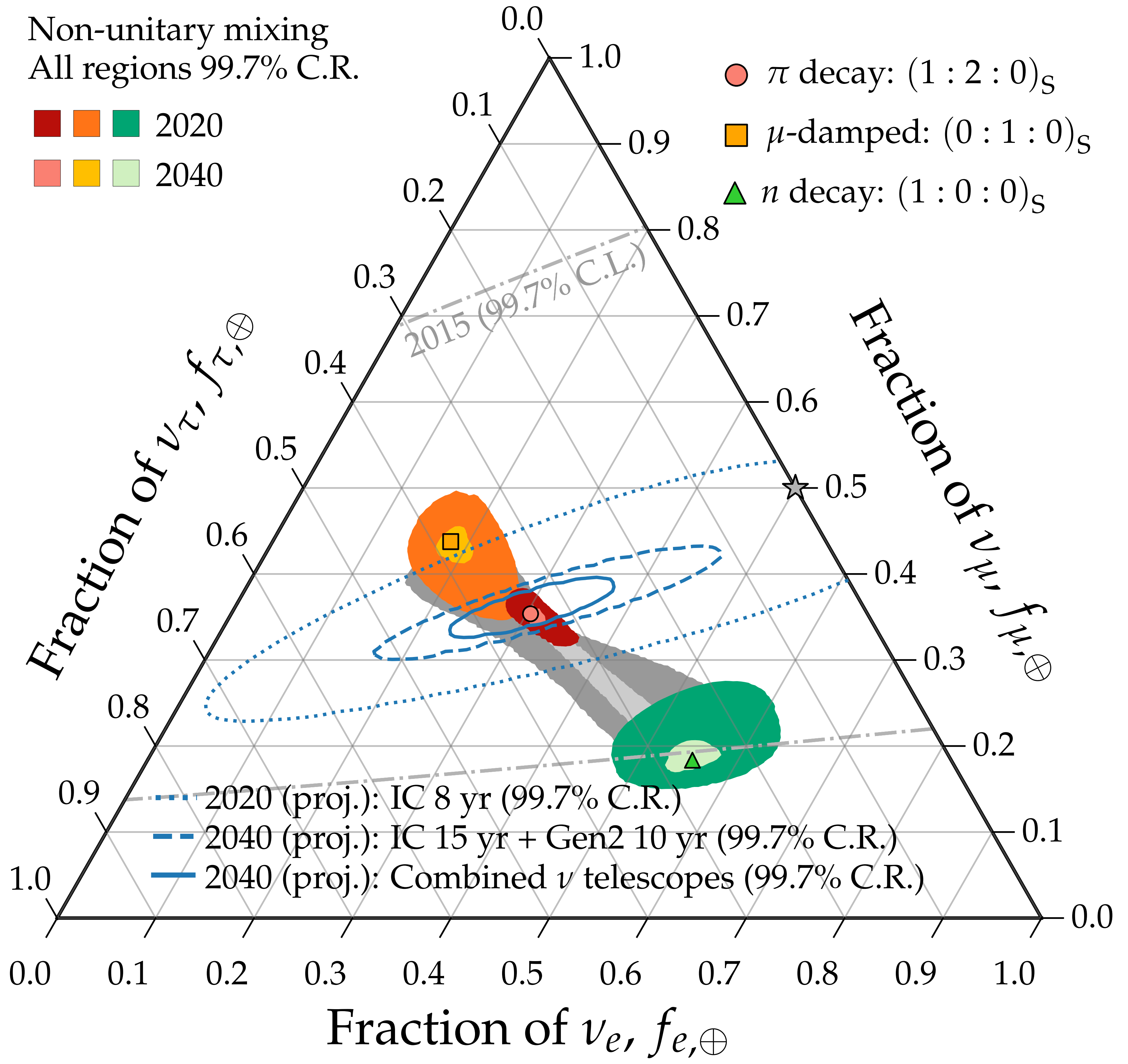


Grey: allowed region within the standard model
Colours: allowed region assuming a single source composition

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

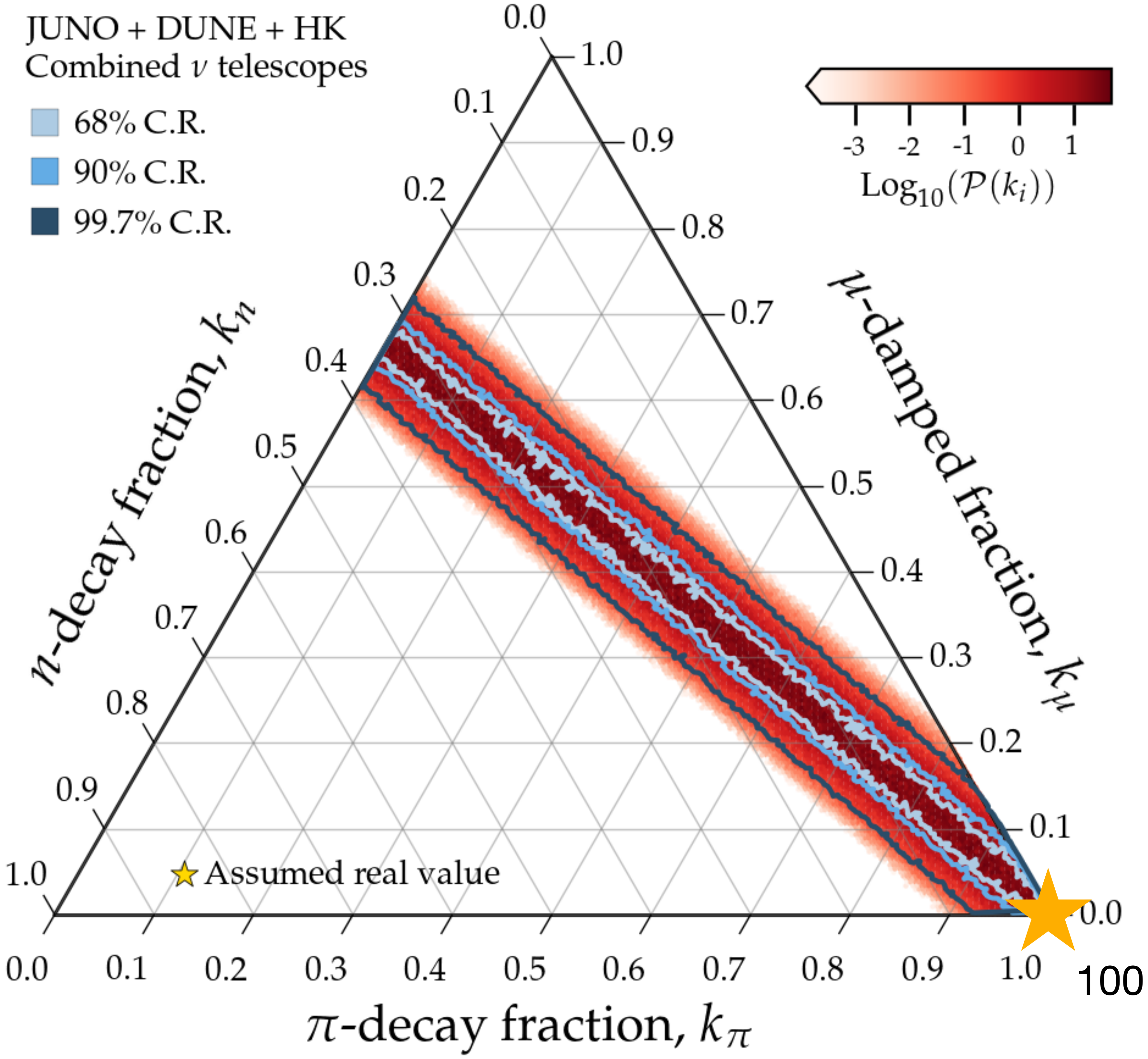
Without assuming unitary 3x3 PMNS matrix?





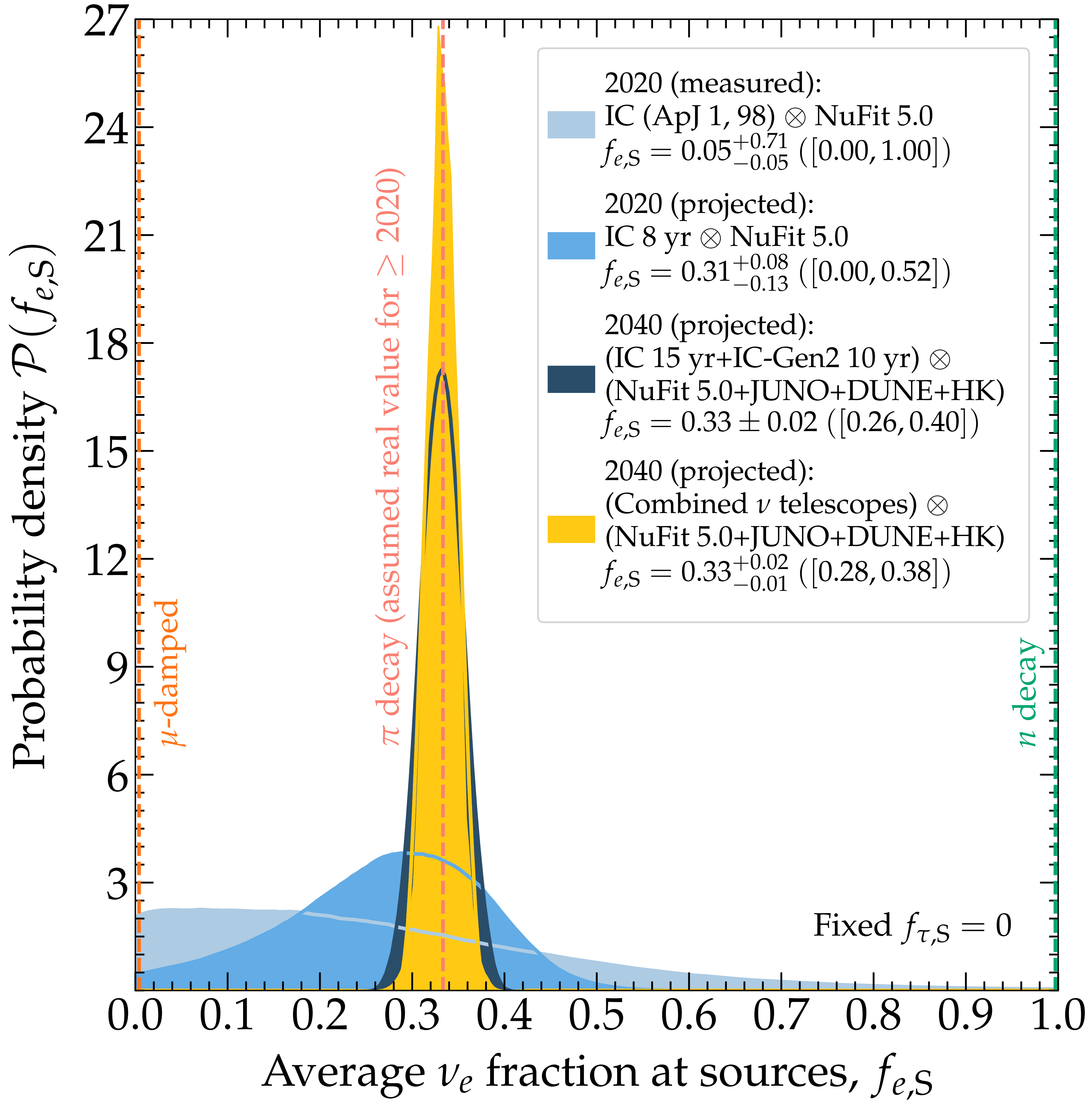
Flavour composition at the source?

100% μ
damped
(pions but no
muons)



100%
Neutron
decay

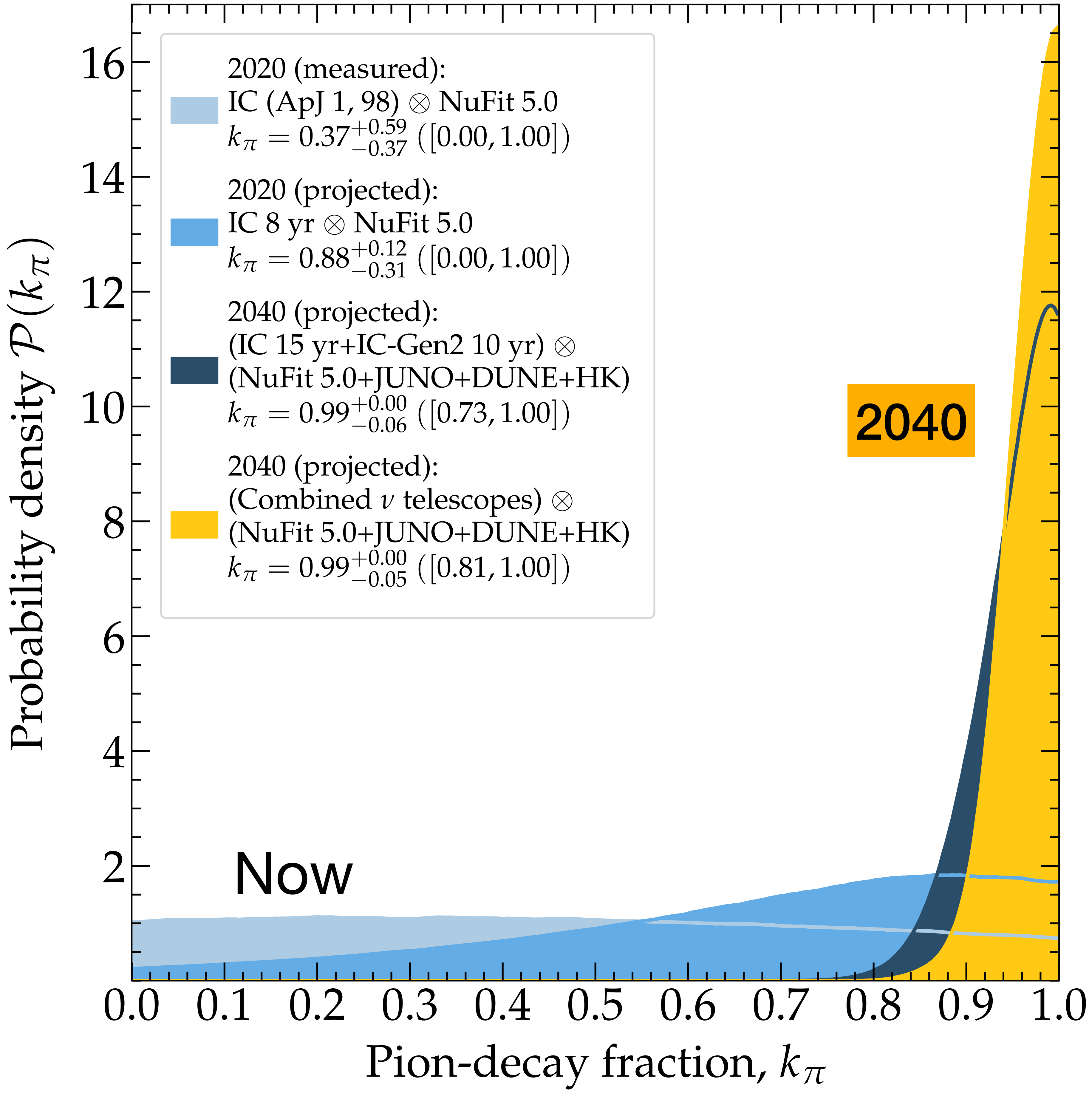
100% Pions



Flavour composition at the source

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

Assuming no neutron decay



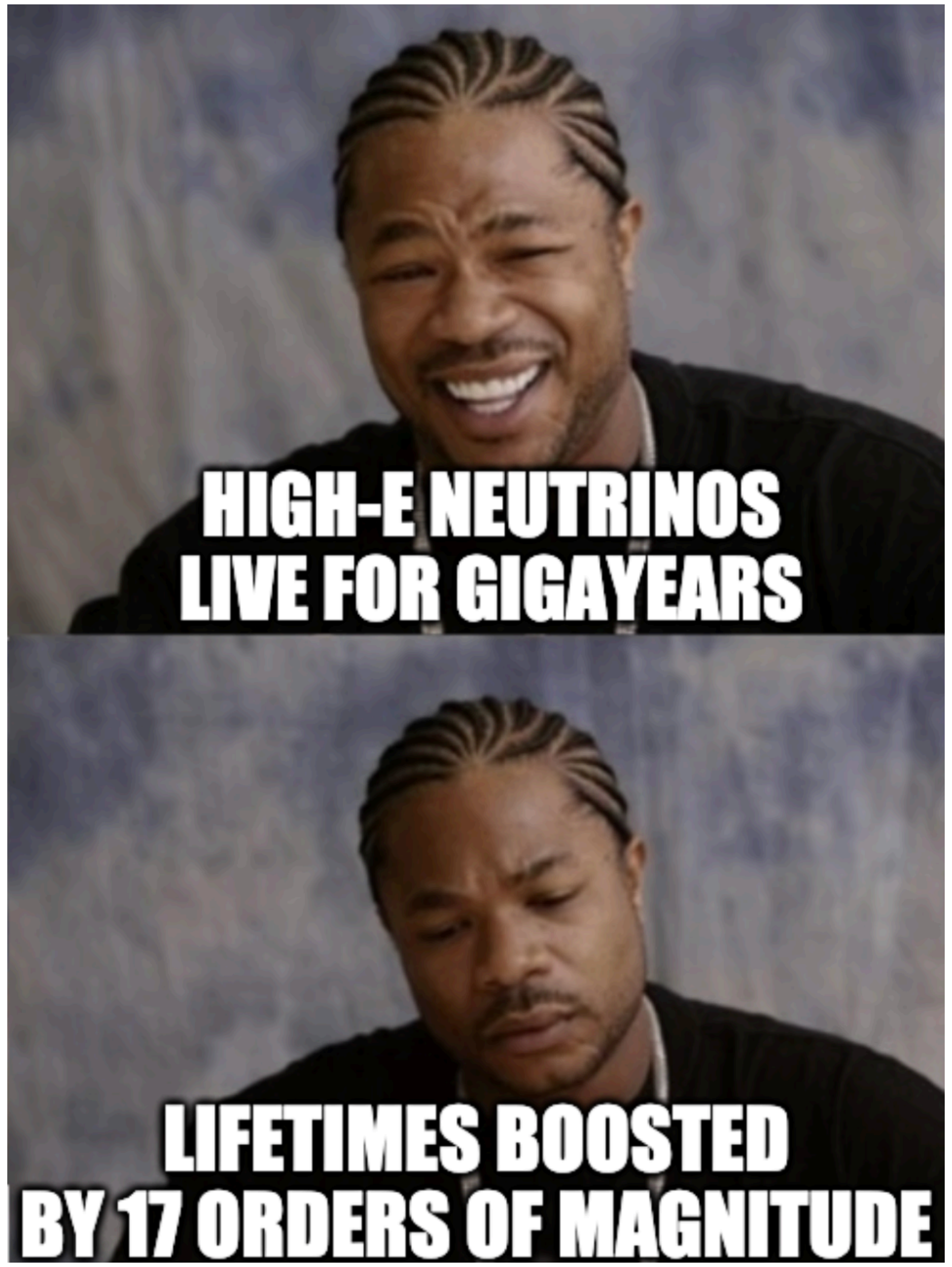
New physics: neutrino decay

Neutrino decay

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

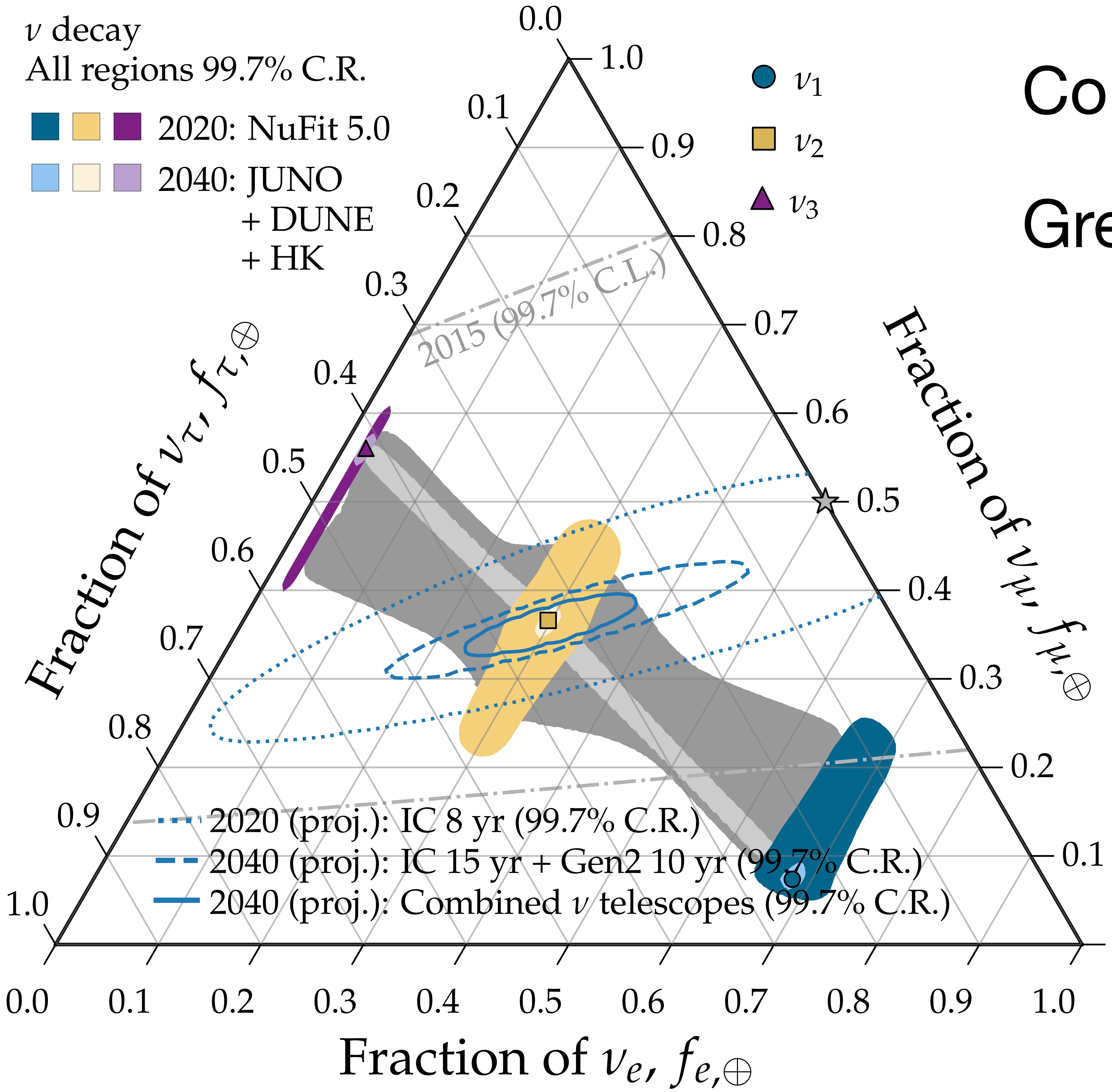
$$N_\nu = N(z_0)\exp\left\{ -\underbrace{\frac{m_\nu}{\tau E_\nu}}_{} \int_0^{z_0} \frac{dz}{(1+z)^2 H_0 \sqrt{\Omega(z)}} \right\}$$

neutrino lifetime at rest



Must be integrated over distribution of cosmic sources

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

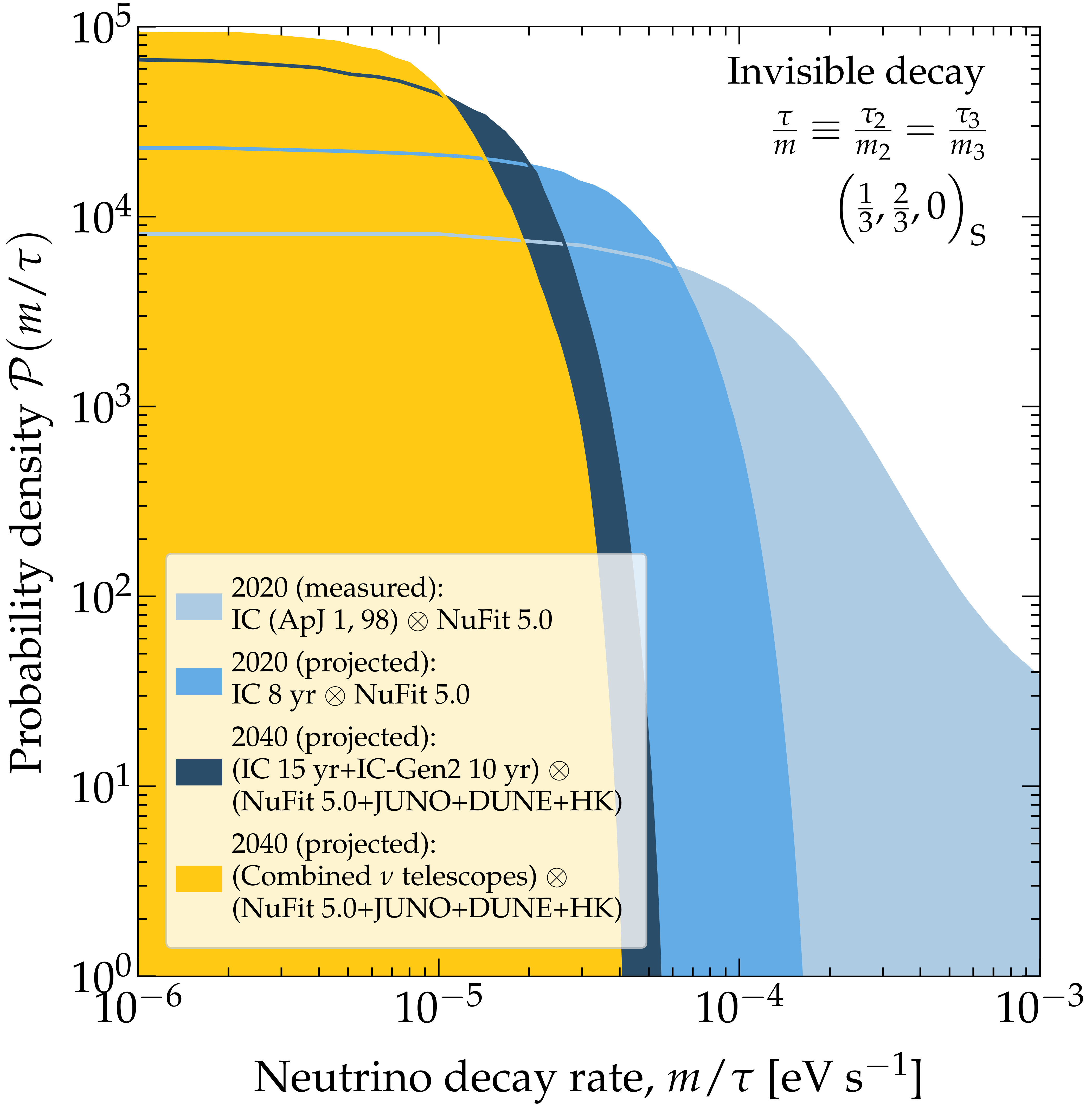


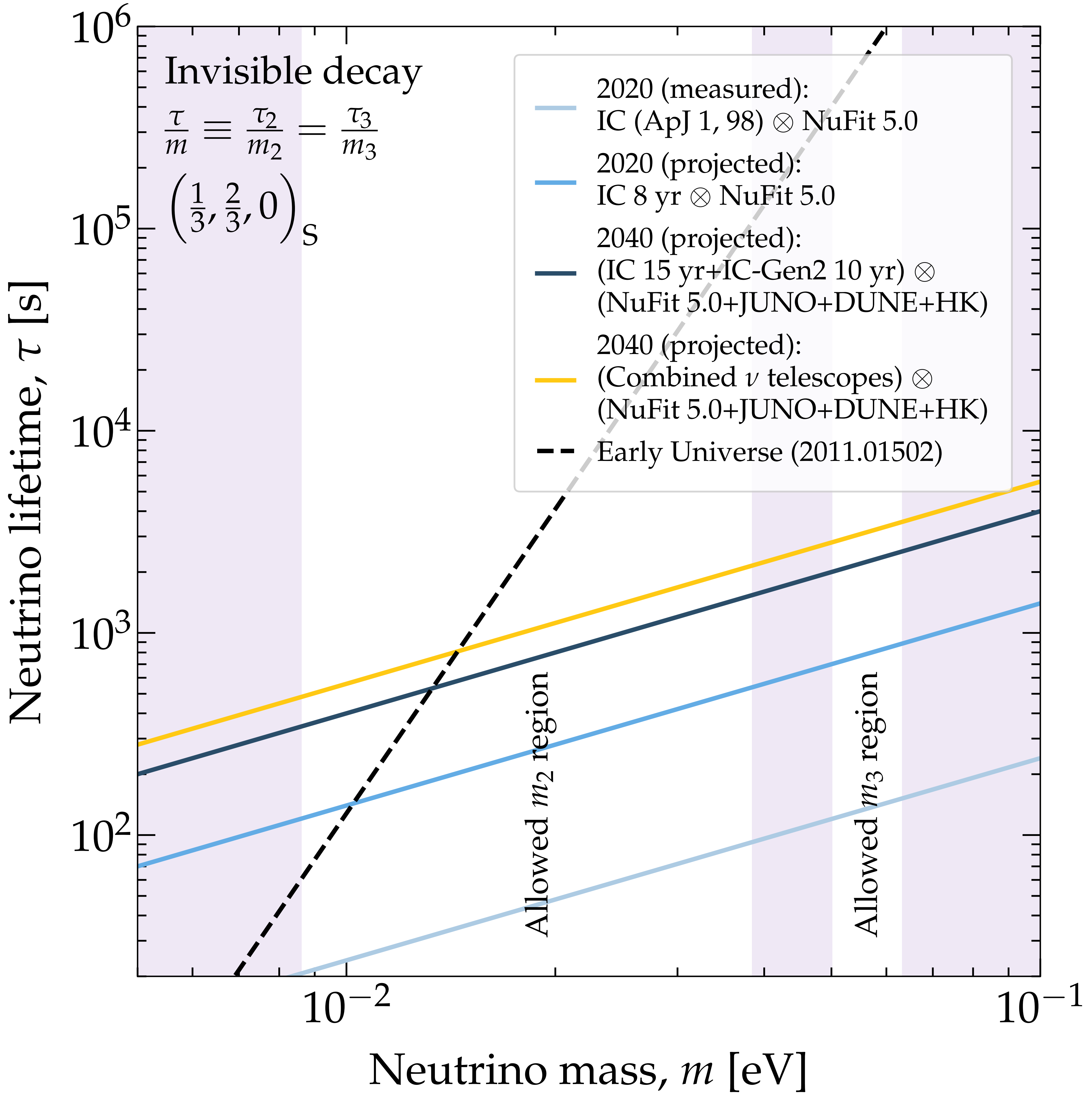
Colour: full decay

Grey: partial decay

Full decay of m_2 and m_3 almost excluded now

Sensitivity to single mass eigenstates


Invisible decay
$\frac{\tau}{m} \equiv \frac{\tau_2}{m_2} = \frac{\tau_3}{m_3}$
$\left(\frac{1}{3}, \frac{2}{3}, 0\right)_S$
2020 (measured): IC (ApJ 1, 98) ⊗ NuFit 5.0
2020 (projected): IC 8 yr ⊗ NuFit 5.0
2040 (projected): (IC 15 yr+IC-Gen2 10 yr) ⊗ (NuFit 5.0+JUNO+DUNE+HK)
2040 (projected): (Combined ν telescopes) ⊗ (NuFit 5.0+JUNO+DUNE+HK)
Probability density $\mathcal{P}(m/\tau)$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Neutrino decay rate, m/τ [eV s^{-1}]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2040 (projected): (Combined ν telescopes) ⊗ (NuFit 5.0+JUNO+DUNE+HK)
Early Universe (2011.01502)
Allowed m_2 region
Allowed m_3 region
Neutrino lifetime, τ [s]
10^6
10^5
10^4
10^3
10^2
10^{-2}
10^{-1}
Neutrino mass, m [eV]

Dark matter

Dark Matter Annihilation to Neutrinos

Carlos A. Argüelles, Alejandro Diaz, Ali Kheirandish, Andrés Olivares-Del-Campo, Ibrahim Safa, Aaron C. Vincent

[Accepted/Reviews in Modern Physics] https://arxiv.org/abs/1912.09486

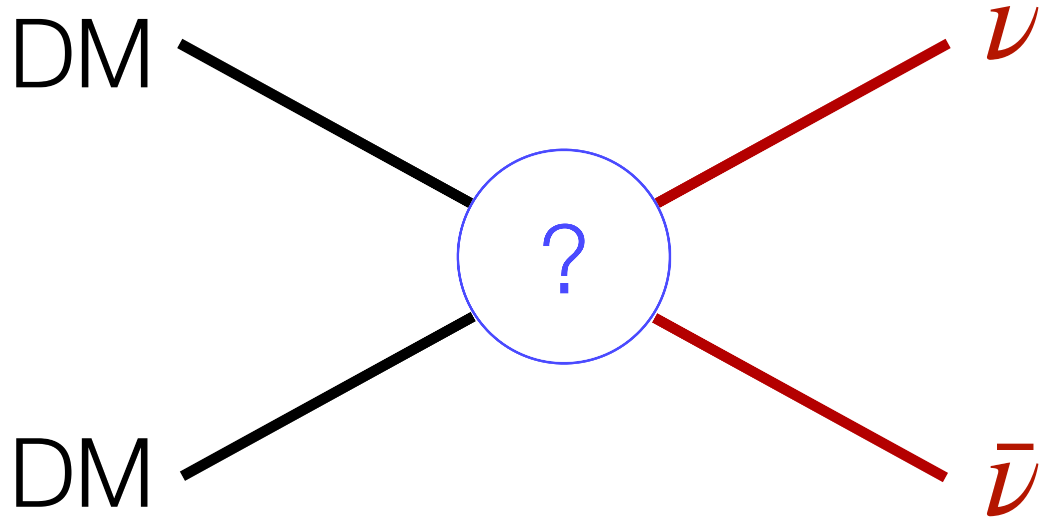
What is the sensitivity of neutrino detectors to new physics?

Illustrate with DM annihilation to neutrinos

Indirect searches $\chi\chi \to SM, SM$: gammas dominate, *except* if neutrinos are the only product

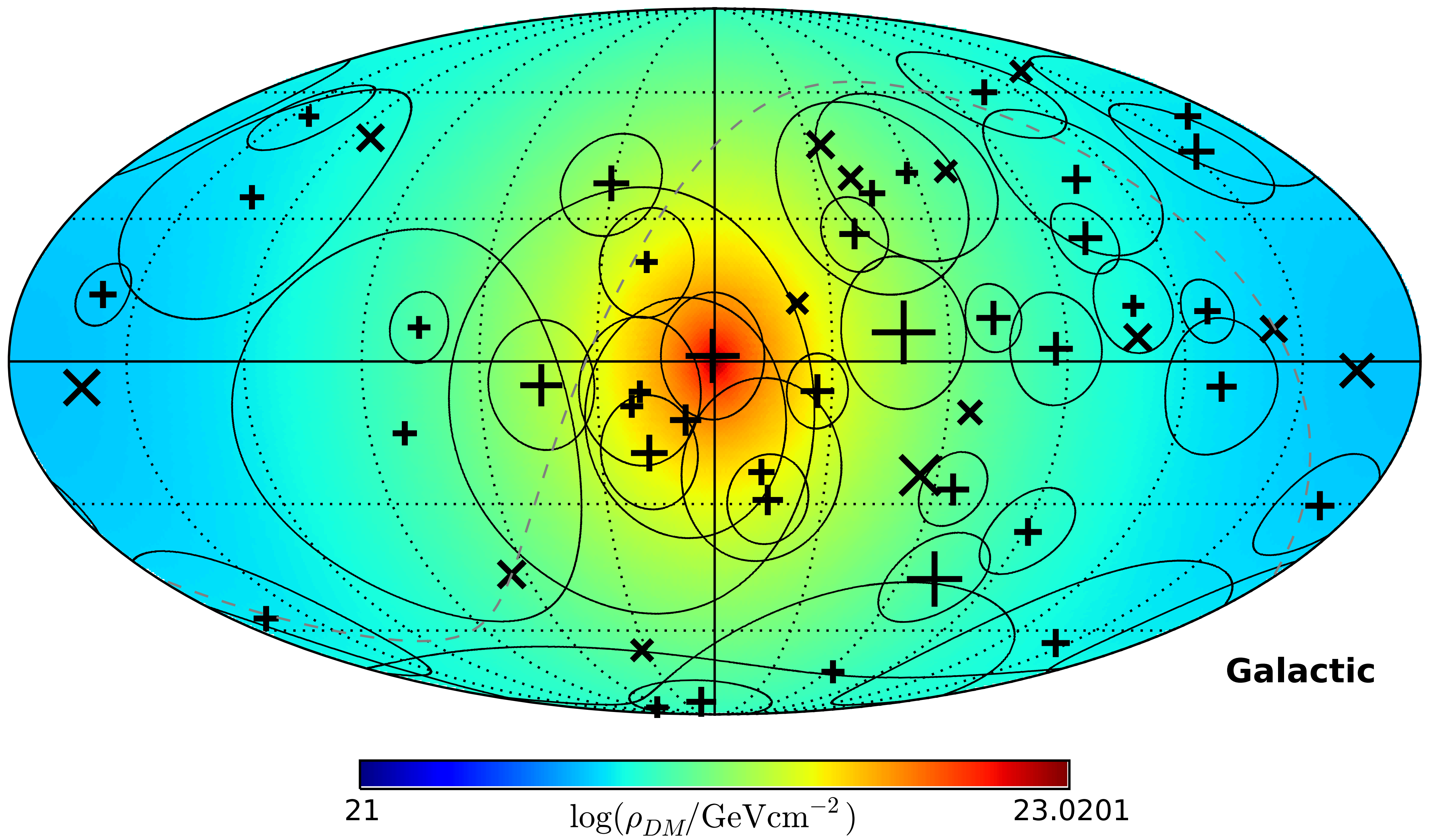
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\kappa m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE_\nu}J(\Omega)$$

$$J \equiv \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} \rho_\chi^2(x)dx$$



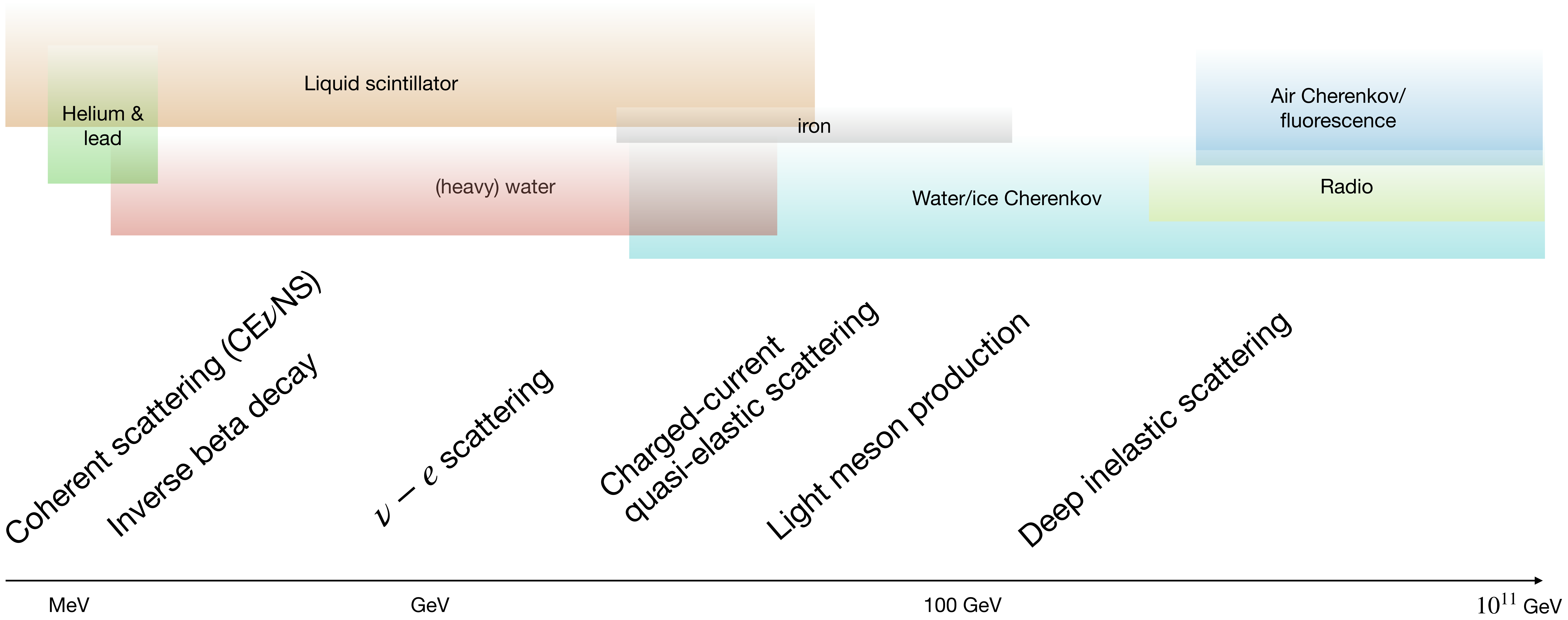
$$\frac{dN_\nu}{dE_\nu} = 2\delta(1 - E/m_\chi)m_\chi/E^2\,.$$

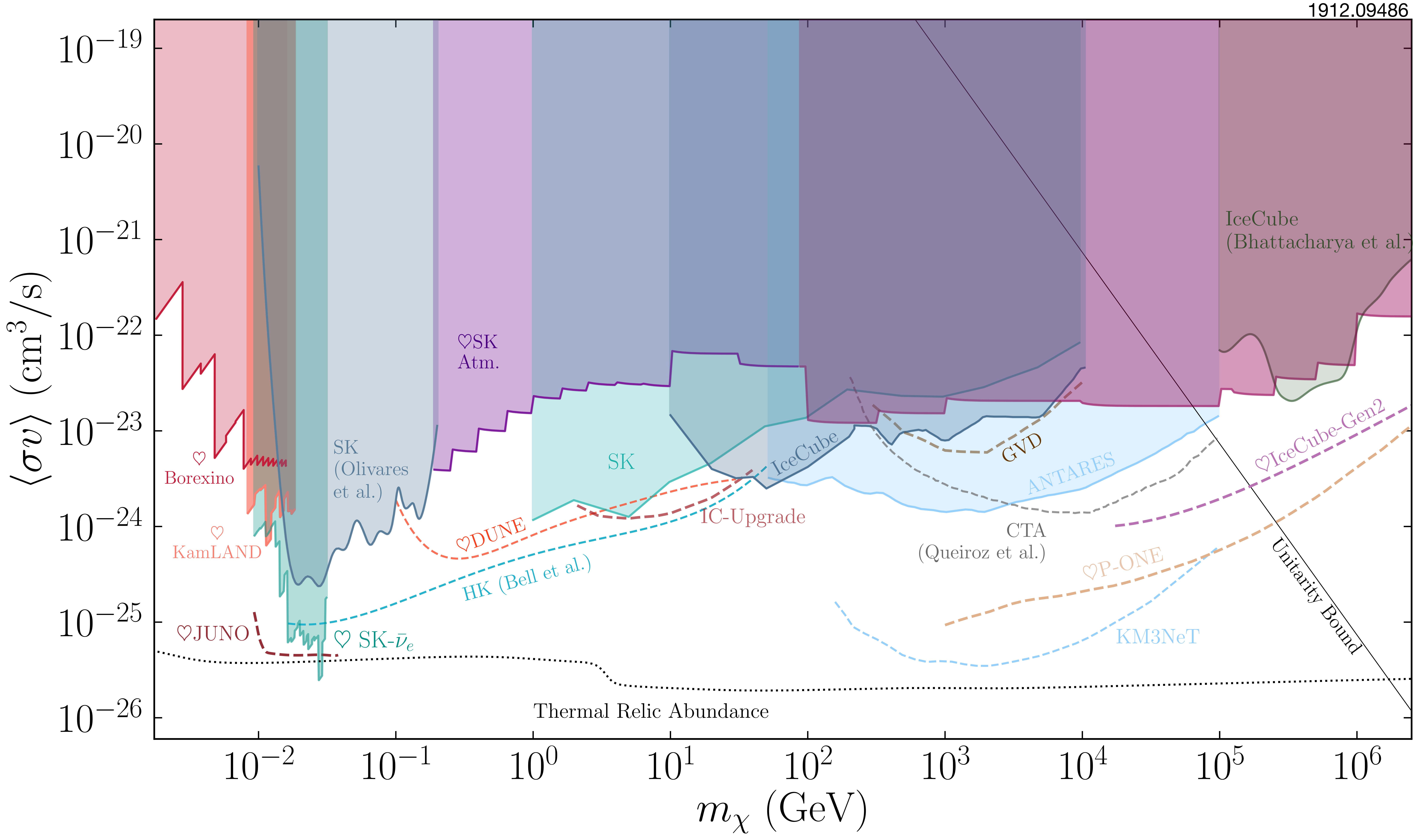
Dark matter column density

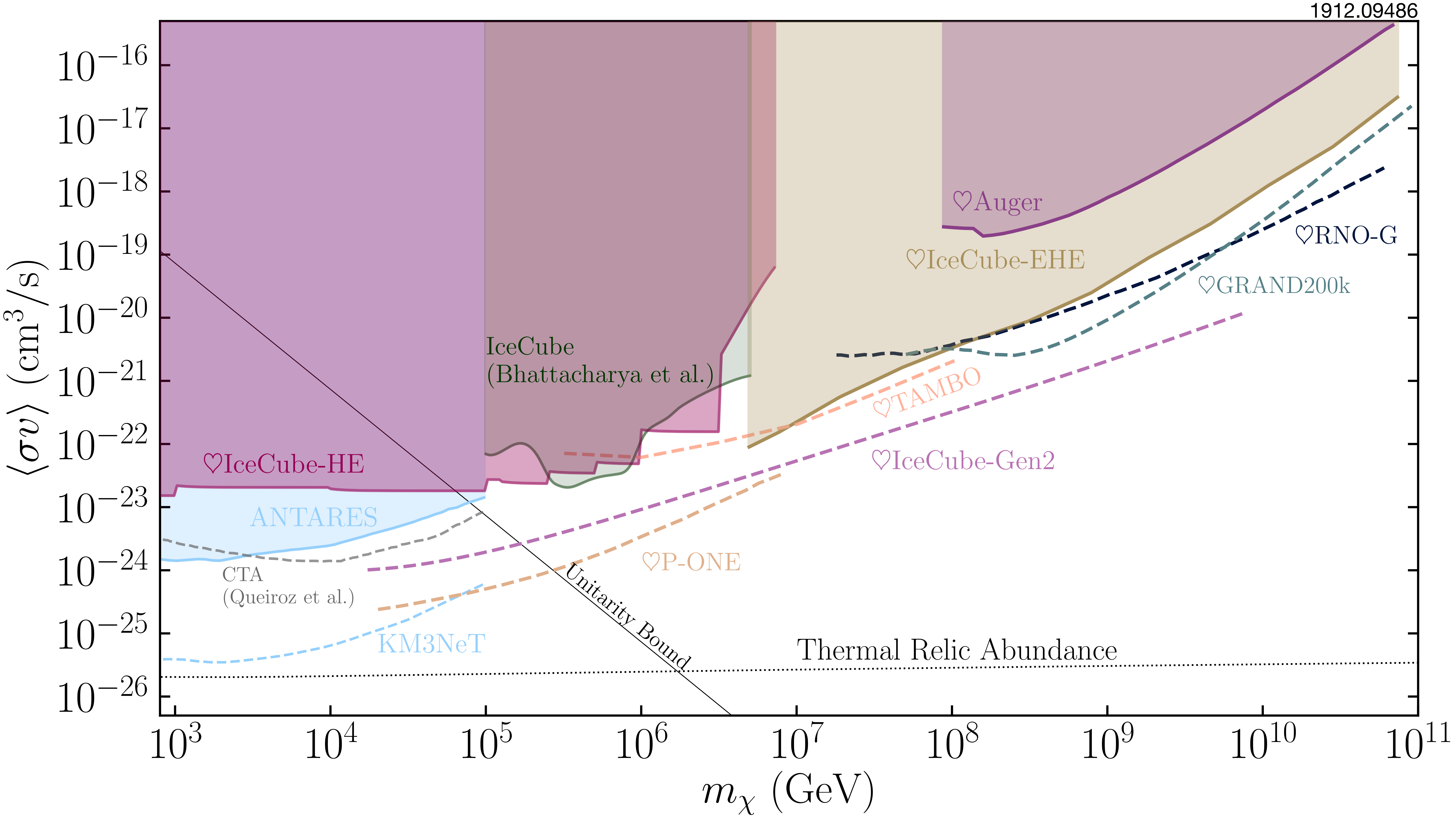


*We also spent a long time calculating extragalactic constraints. They are subdominant though

What if we looked at *every neutrino telescope in the world?*




1912.09486
$\langle \sigma v \rangle$ (cm^3/s)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
m_χ (GeV)
IceCube
(Bhattacharya et al.)
♡SK
Atm.
SK
(Olivares
et al.)
♡
Borexino
♡
KamLAND
SK
IceCube
GVD
ANTARES
♡IceCube-Gen2
♡DUNE
IC-Upgrade
CTA
(Queiroz et al.)
HK (Bell et al.)
♡P-ONE
♡JUNO
♡ SK-$\bar{\nu}_e$
KM3NeT
Unitarity Bound
Thermal Relic Abundance

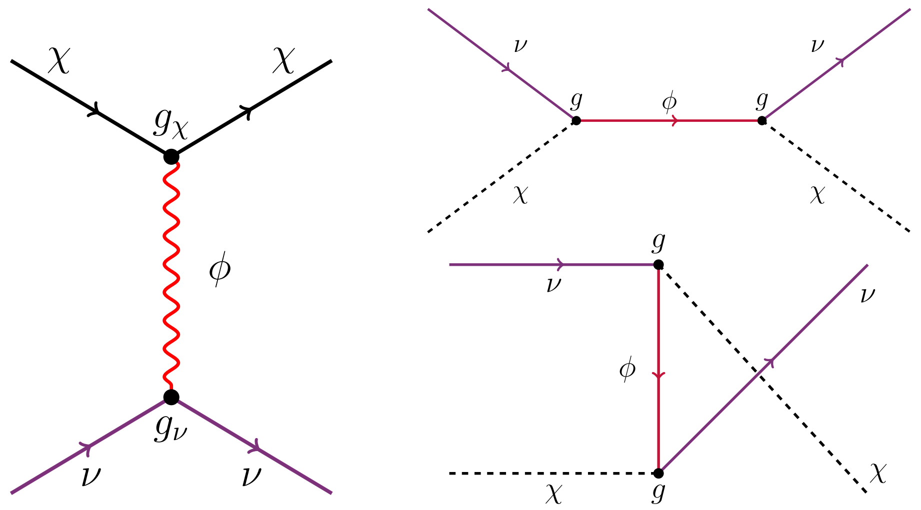

1912.09486
$\langle \sigma v \rangle$ (cm^3/s)
m_χ (GeV)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
♡Auger
♡IceCube-EHE
♡RNO-G
♡GRAND200k
IceCube
(Bhattacharya et al.)
♡TAMBO
♡IceCube-HE
♡IceCube-Gen2
ANTARES
♡P-ONE
CTA
(Queiroz et al.)
Unitarity Bound
KM3NeT
Thermal Relic Abundance

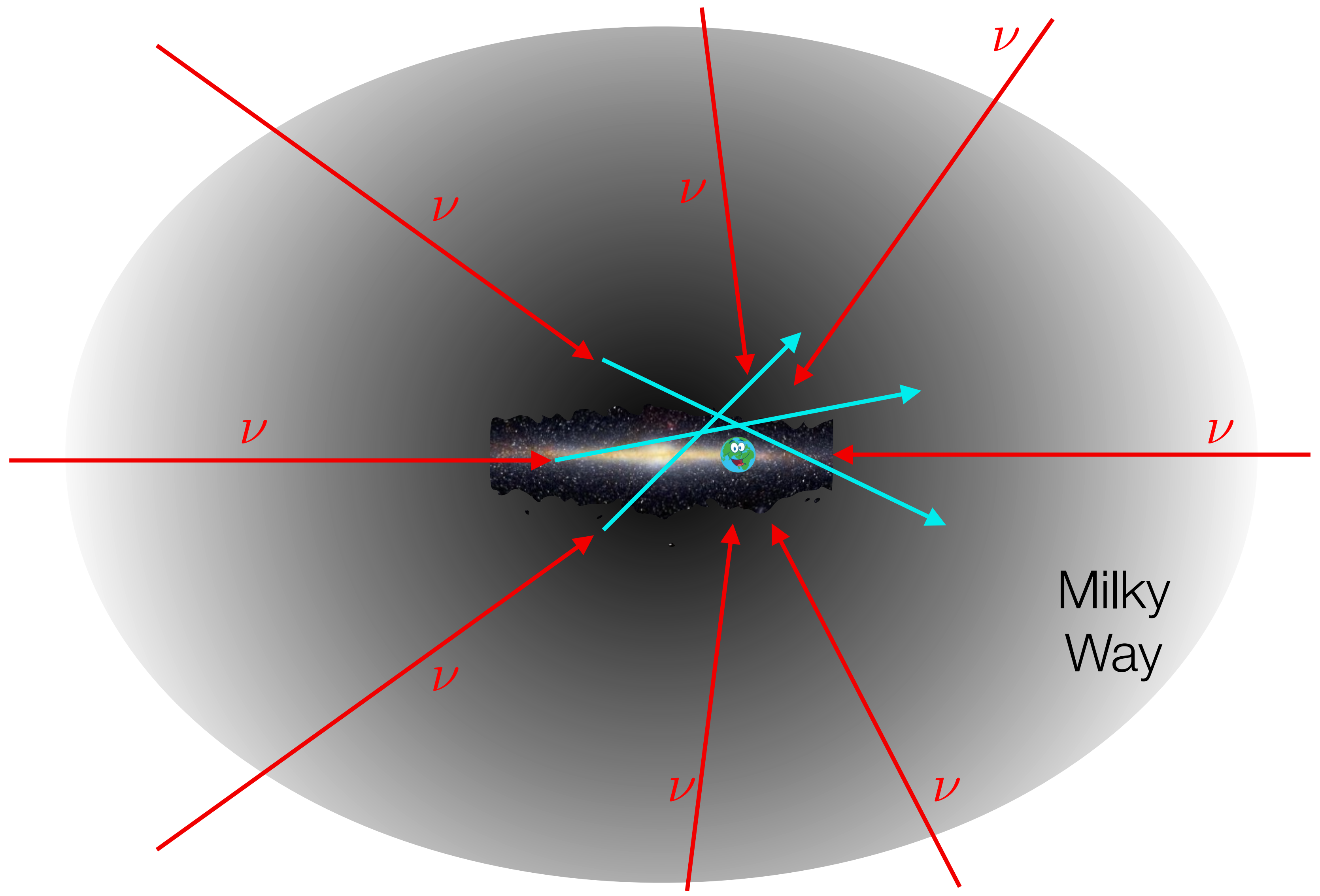
Neutrino-dark matter *elastic scattering*

Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos

Carlos A. Argüelles, Ali Kheirandish, Aaron C. Vincent

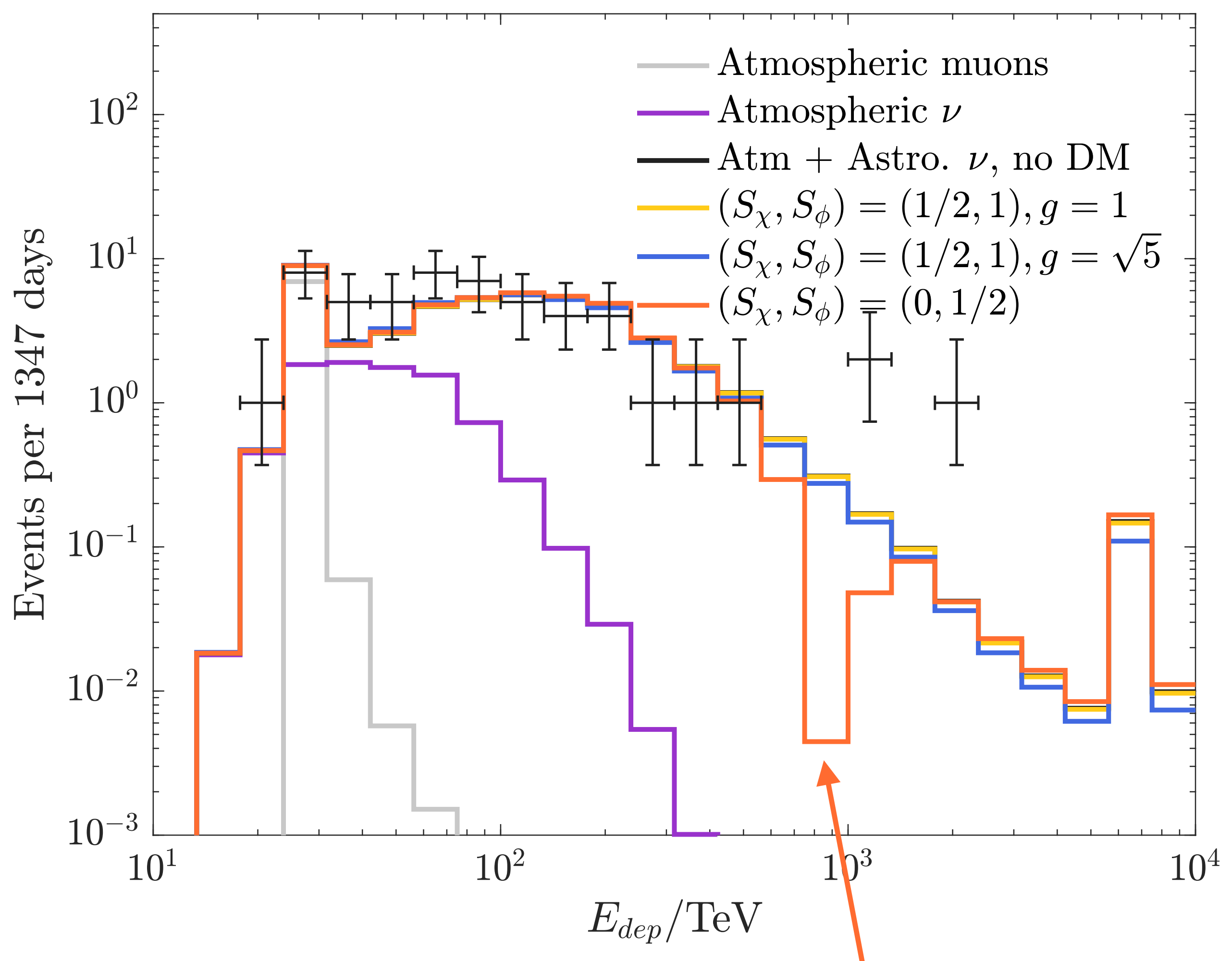
PRL https://arxiv.org/abs/1703.00451





Anisotropic deflection/ energy loss

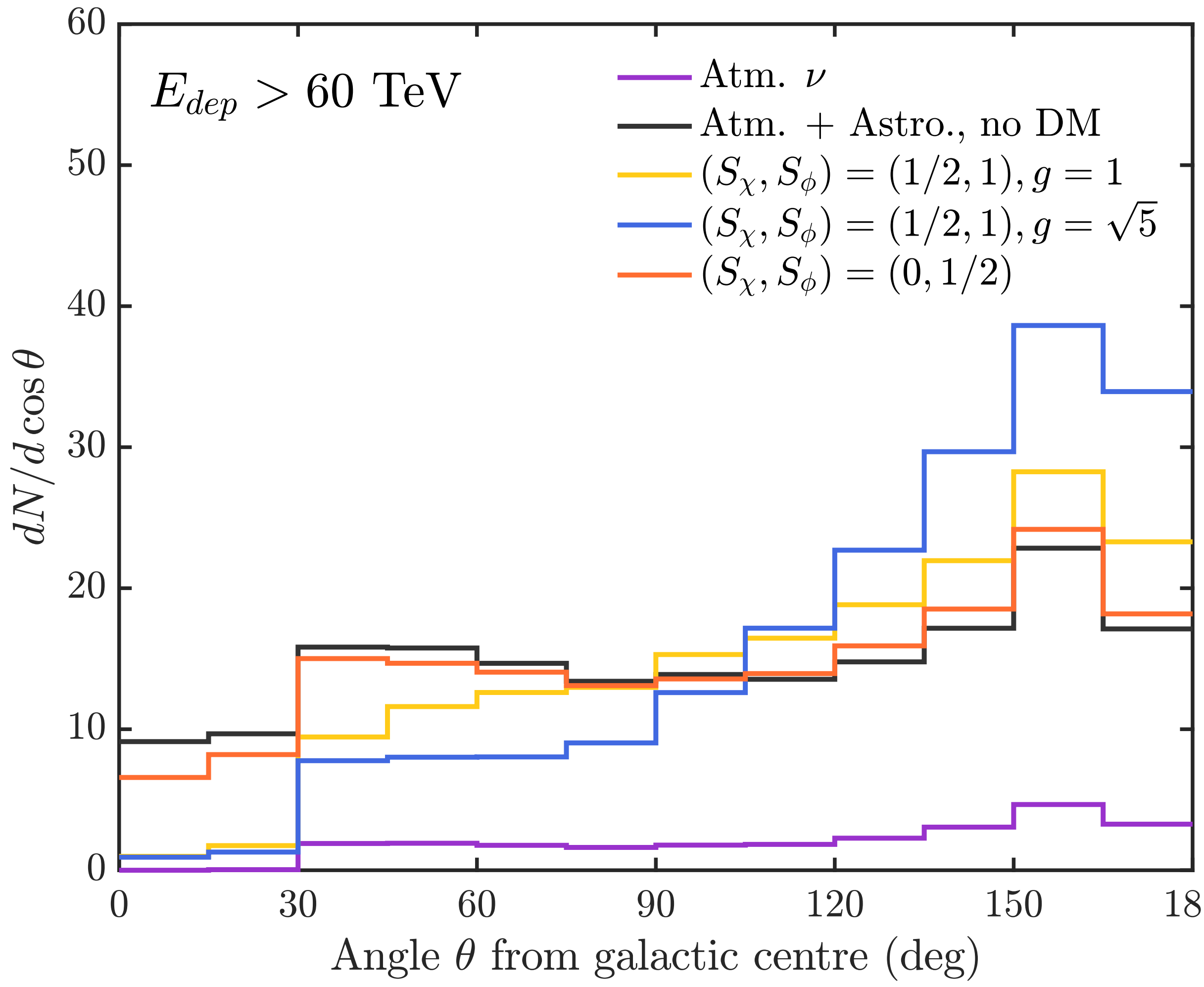
Energy



Resonance @ 810 TeV

IceCube HESE events

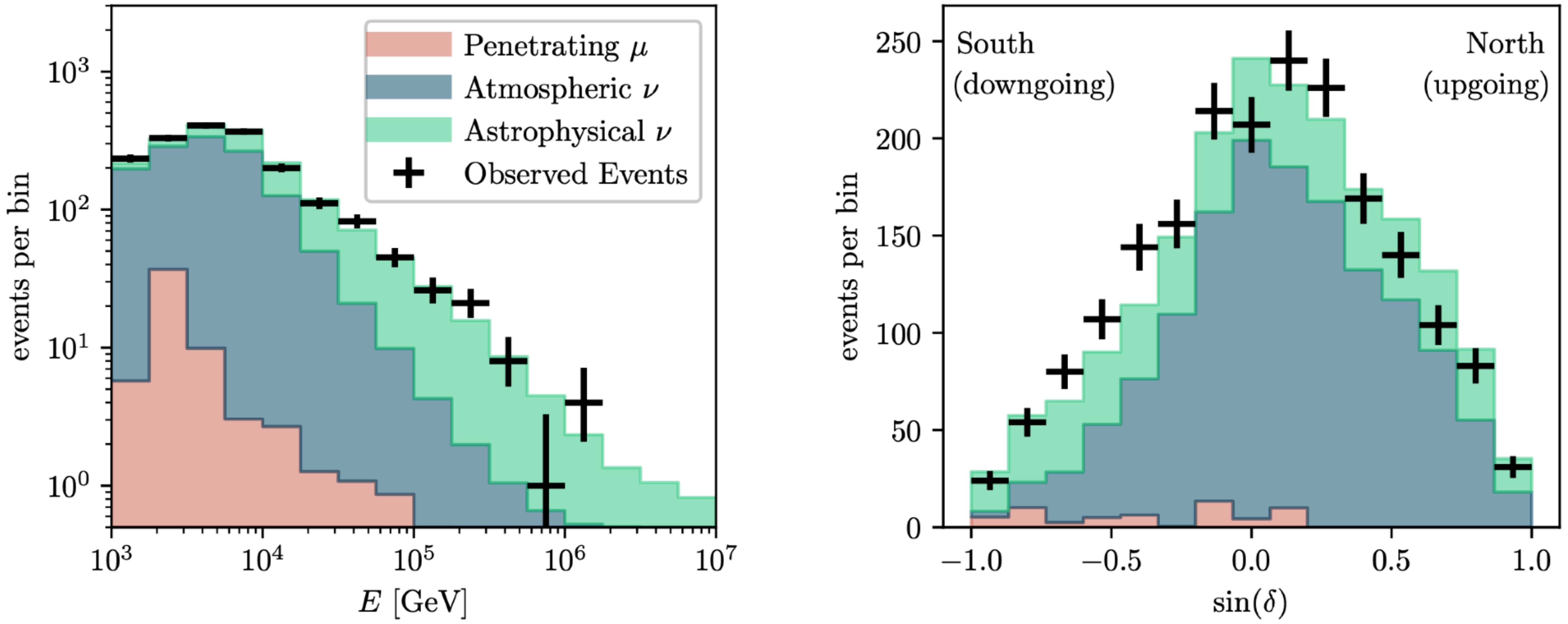
Angle from galactic centre



DM-neutrino elastic scattering: all energies?

Currently working on official IceCube analysis with O(1000) events.
DarkFATE code, adapted from nuFATE (neutrino fast attenuation through Earth https://github.com/aaronvincent/nuFATE)

IceCube https://arxiv.org/abs/1907.06714



(official IceCube Analysis by Adam McMullen - preliminary results not public)

Large extra dimensions

No time - happy to answer questions!

Signatures of microscopic black holes and extra dimensions at future neutrino telescopes

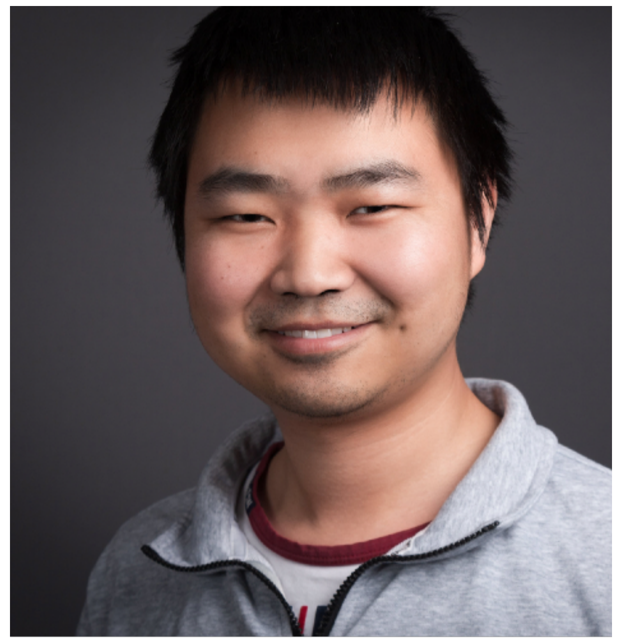
Katherine J. Mack, Ningqiang Song, Aaron C. Vincent

JHEP https://arxiv.org/abs/1912.06656

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!

Please check out



Ningqiang Song

Closing the window for WIMPy inelastic dark matter with heavy nuclei

Particle physics session 17:15 Jun 9

Avi Friedlander

Signatures of Primordial Black Holes in theories of Large Extra Dimensions (← link to video)

Neal Avis Kozar

Exploring dark matter detection using Solar capture and the Non-Relativistic Effective Operator formalism (←link to poster)

GatherTown Room 5, poster J83

Merci!