Queen's UNIVERSITY
Centre Canadien de Recherche en Physique des Astroparticules
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

High energy neutrinos and physics opportunities

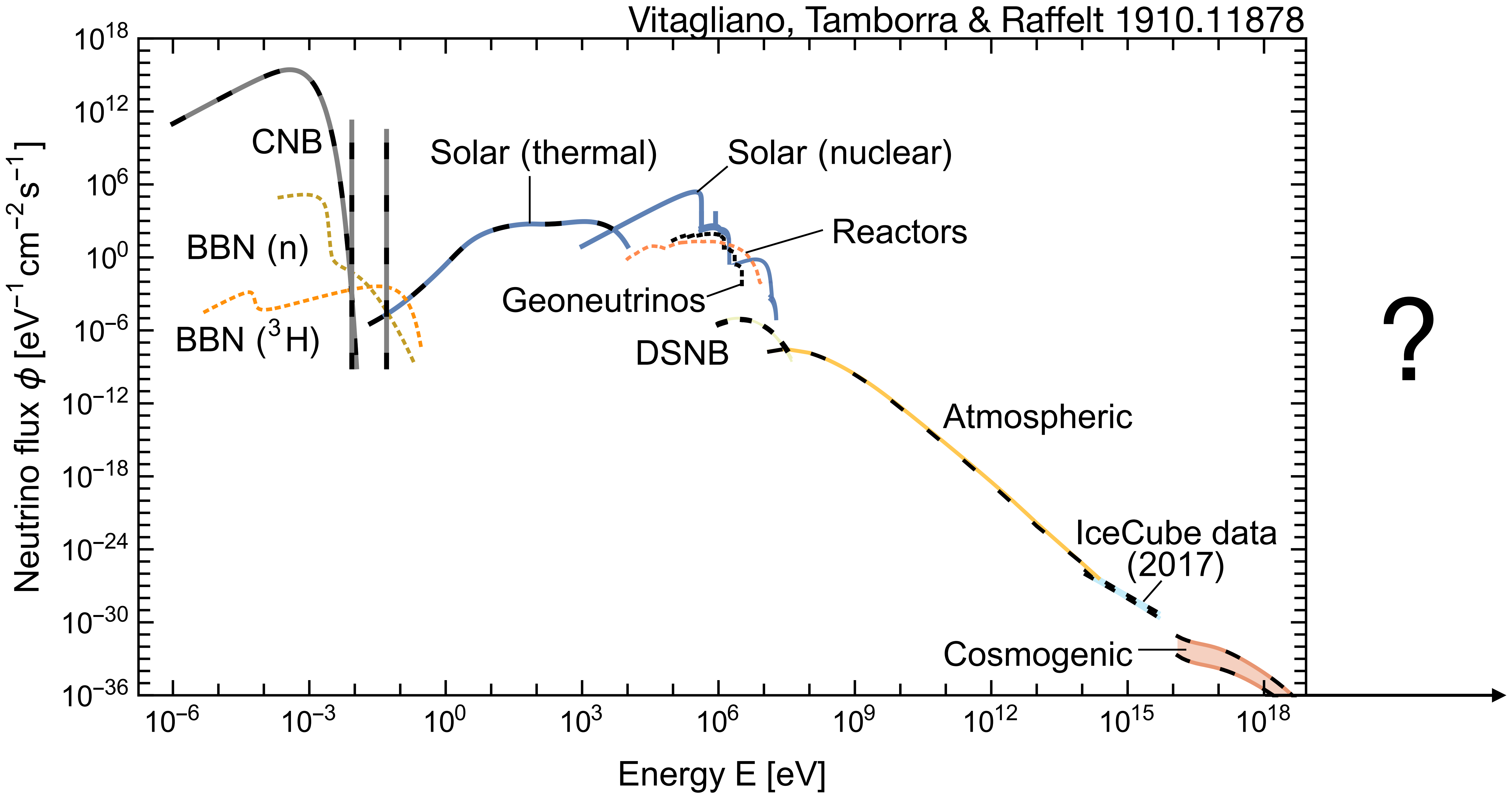
Aaron C. Vincent

NuTs 18/05/2022

Overview

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

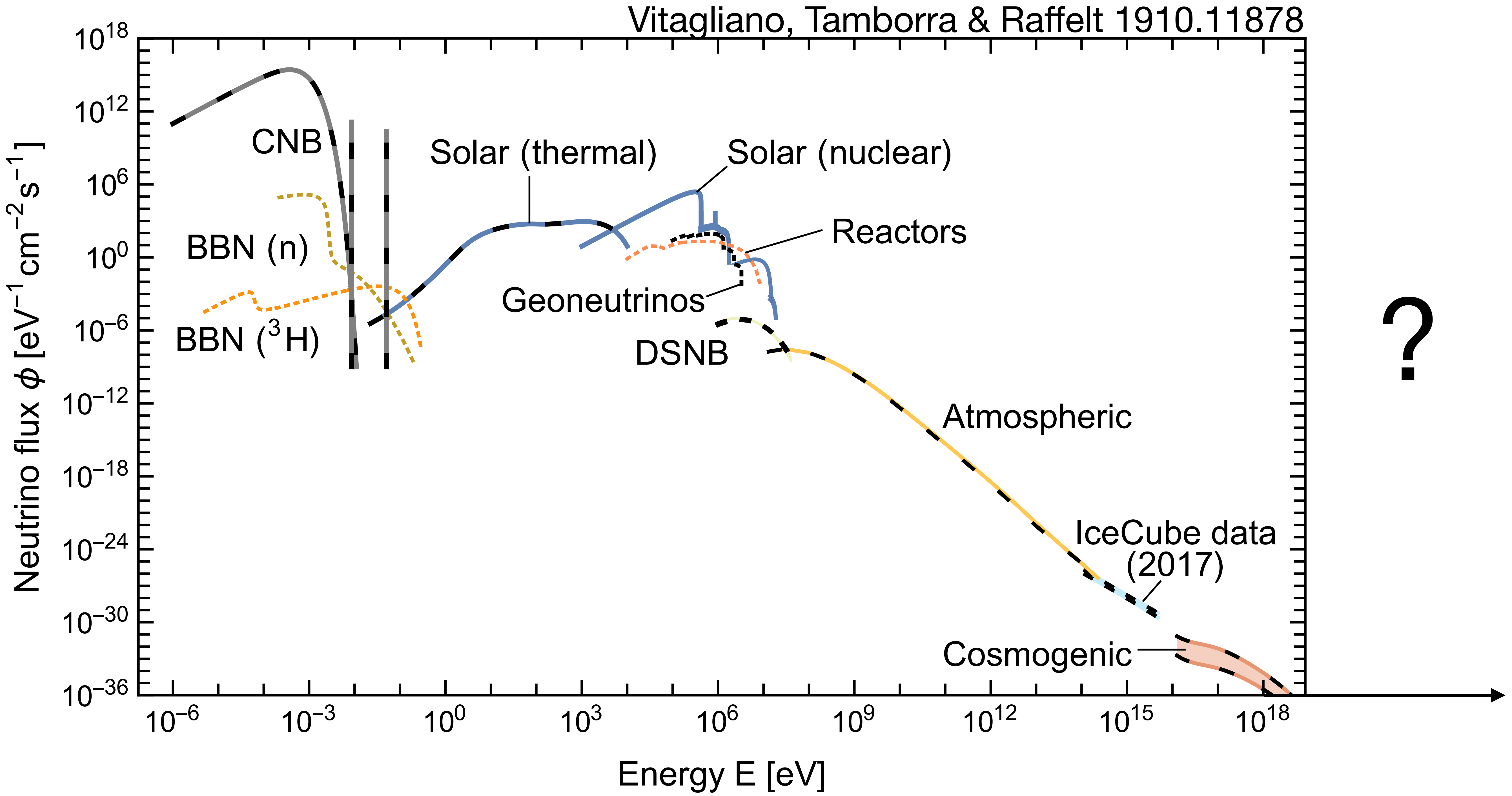
The neutrino sky


Vitagliano, Tamborra & Raffelt 1910.11878

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

The neutrino sky

Neutrinos from space carry:



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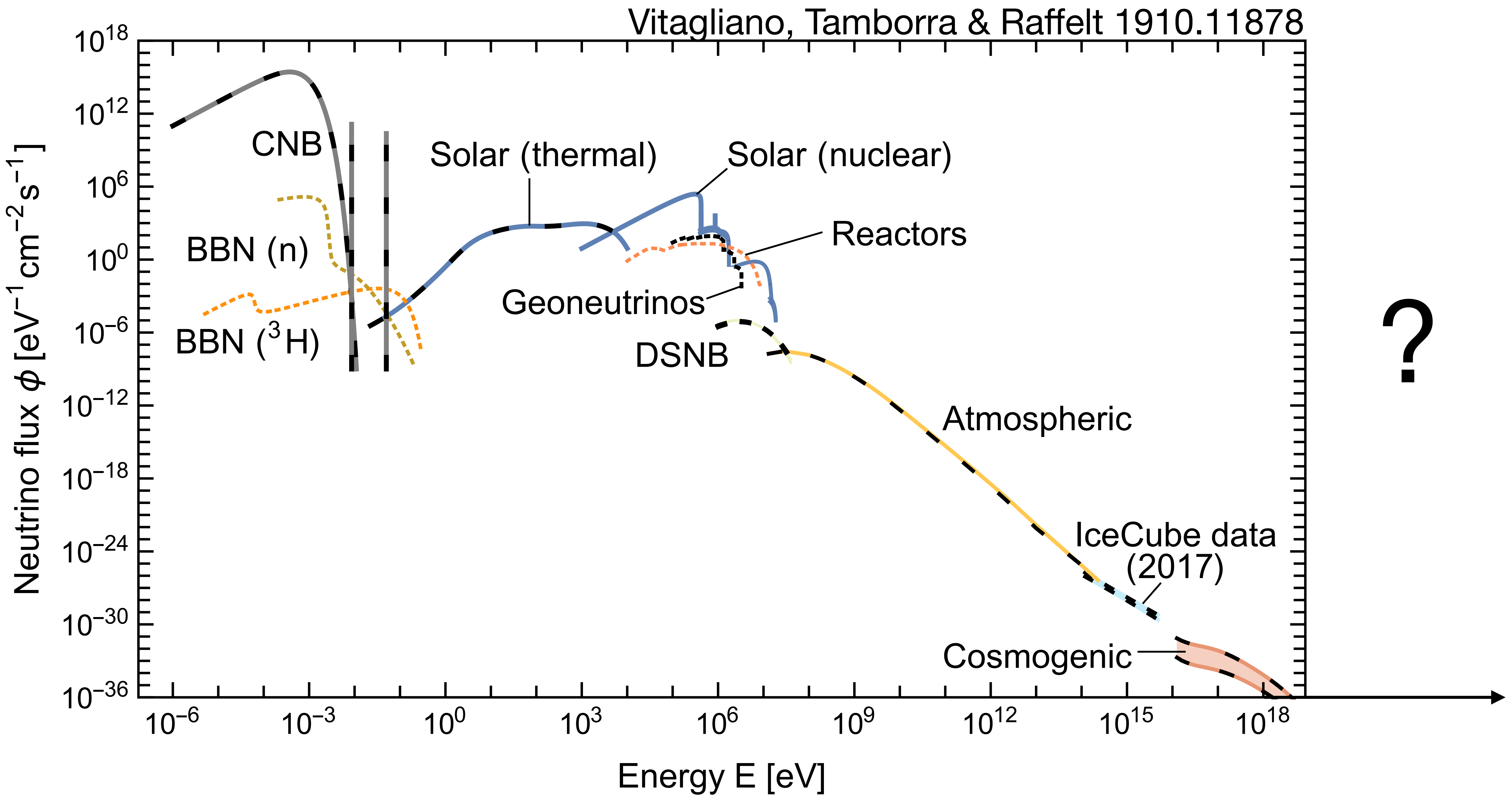
Neutrinos from space carry:

- Directional information



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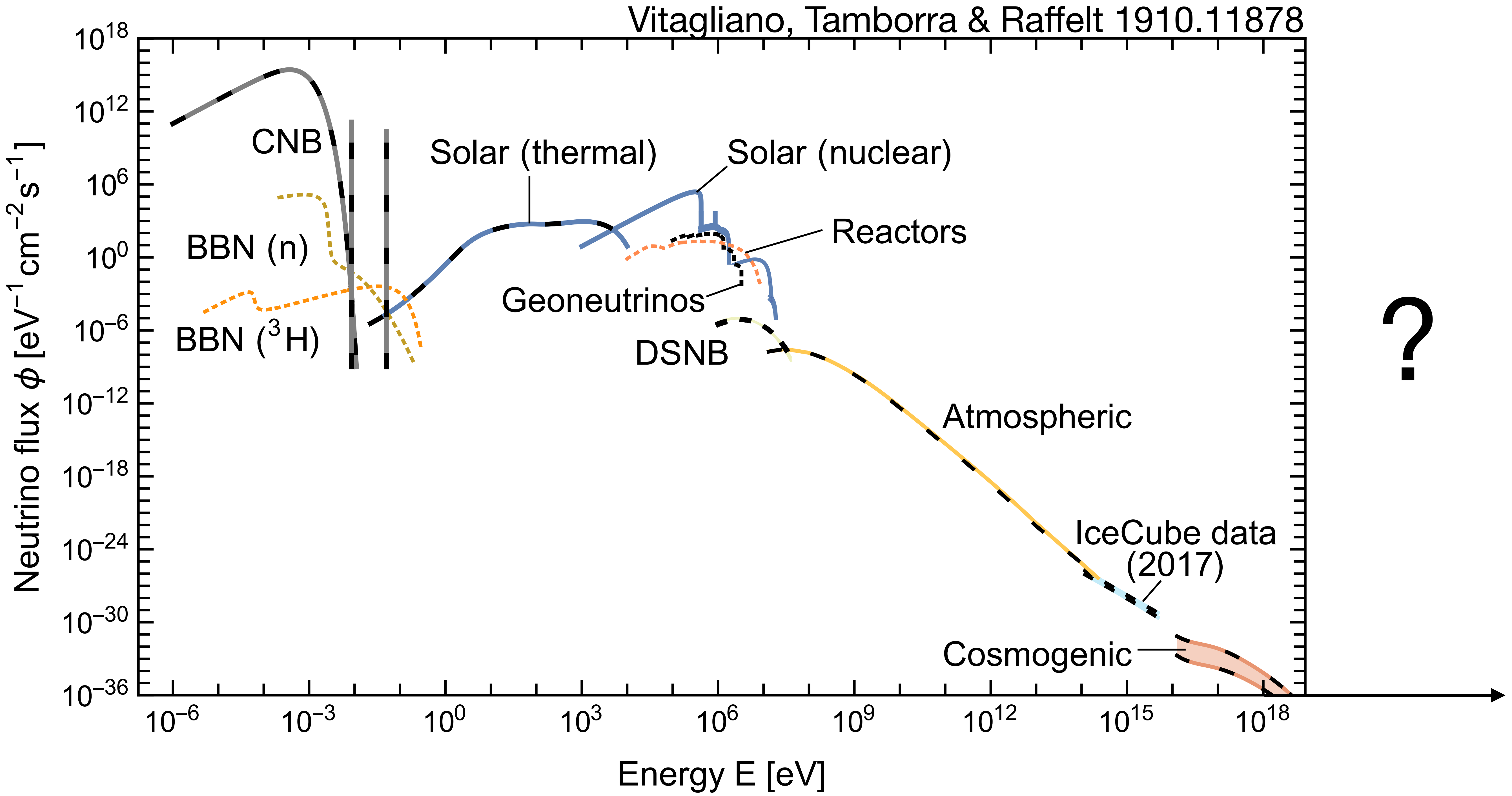
Neutrinos from space carry:

- Directional information
- Timing information



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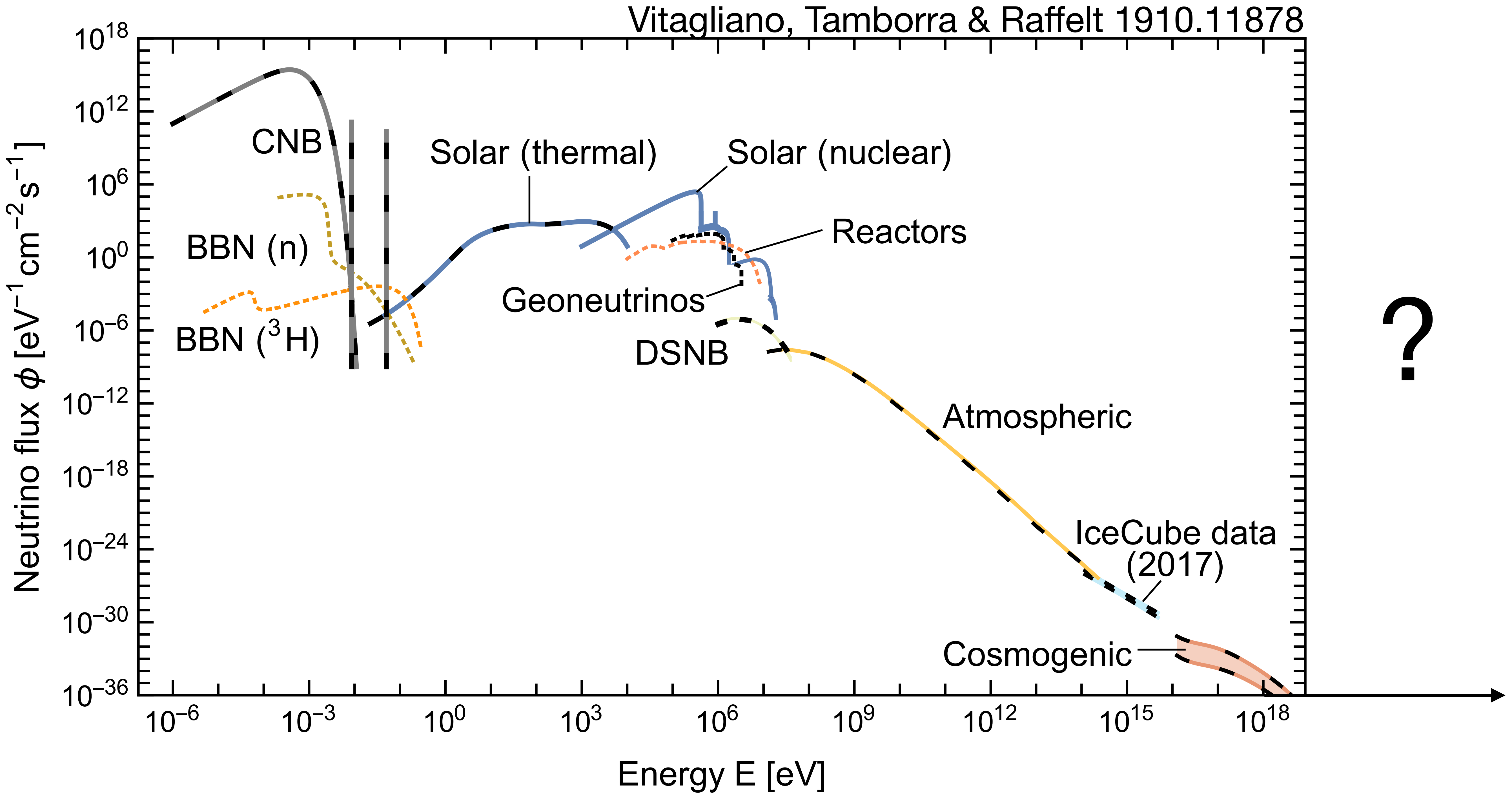
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- Timing information
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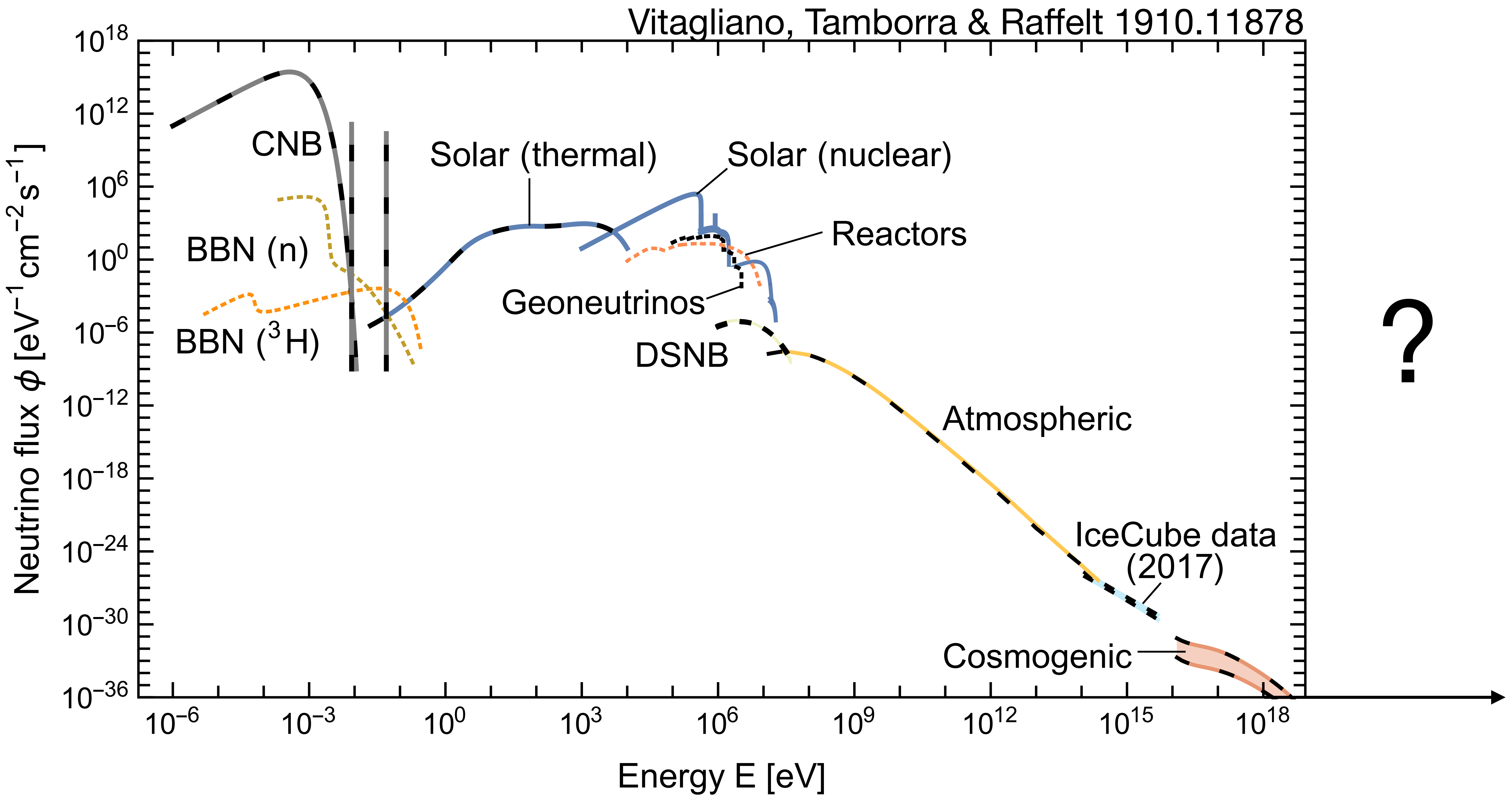
- **Flavour:** ν_e, ν_μ, ν_τ



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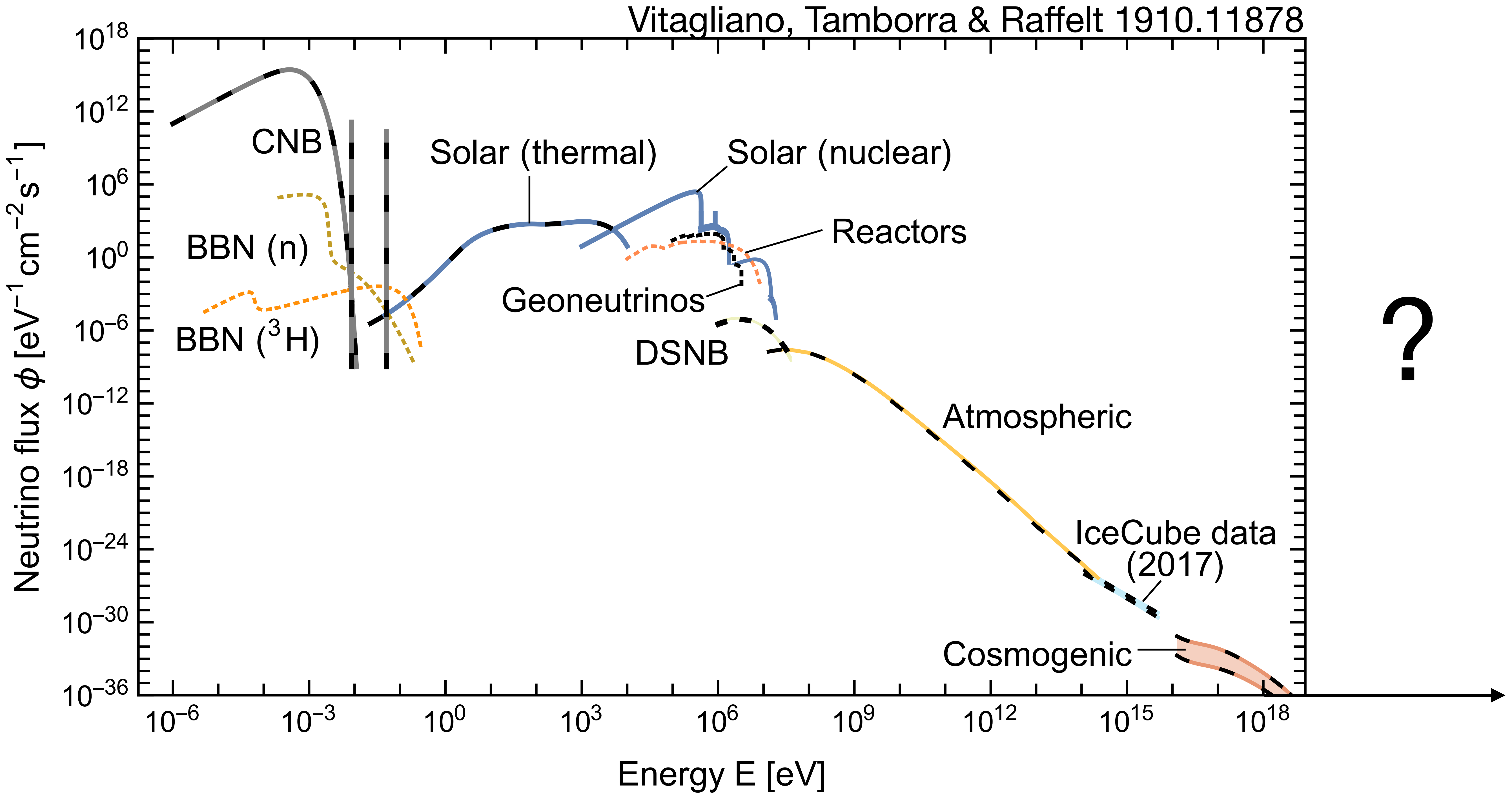
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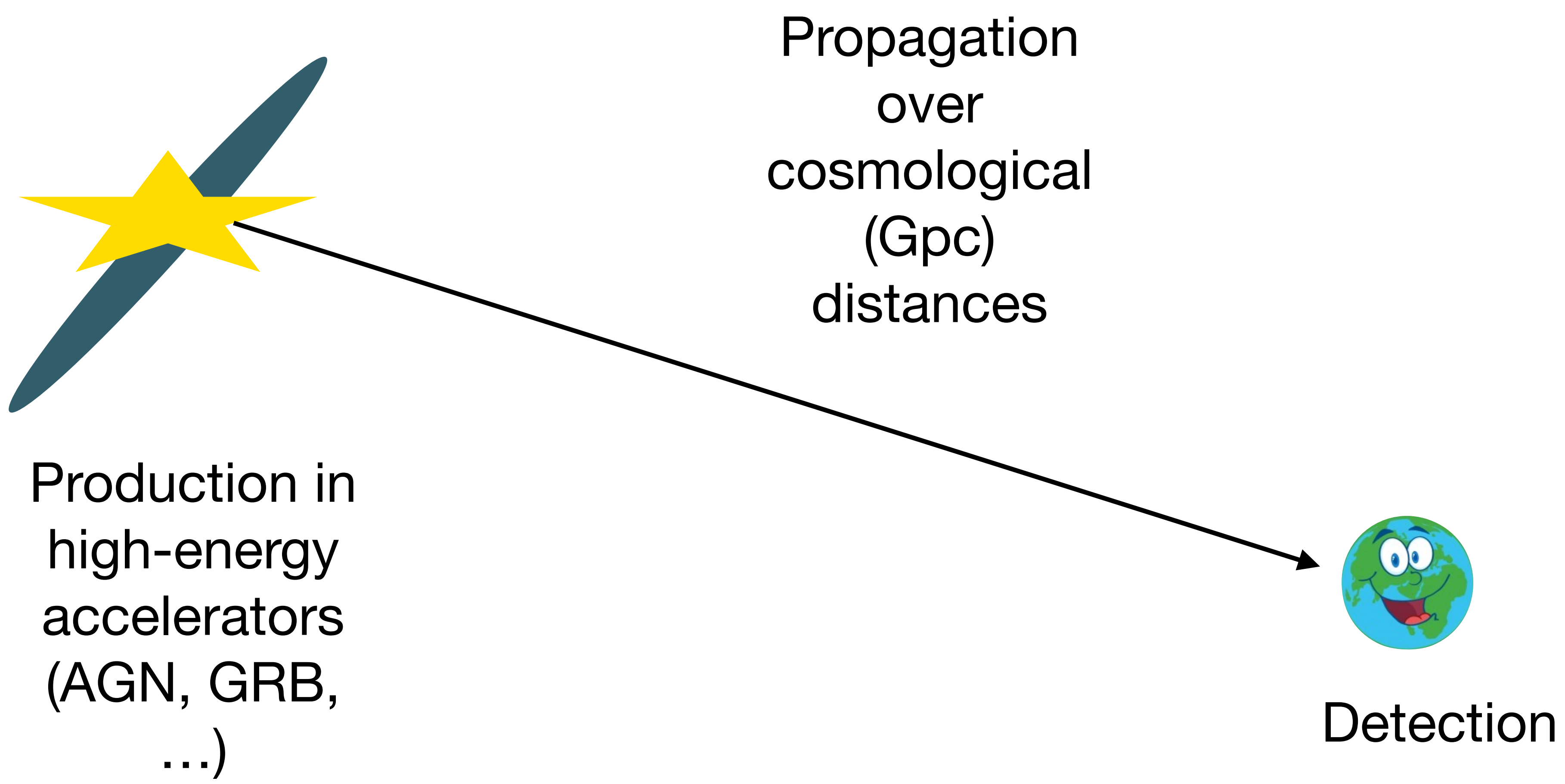
High energies & Flavour

The Future of High-Energy Astrophysical Neutrino Flavor Measurements

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

[Accepted/JCAP] https://arxiv.org/abs/2012.12893

High-energy neutrinos



Propagation
over
cosmological
(Gpc)
distances

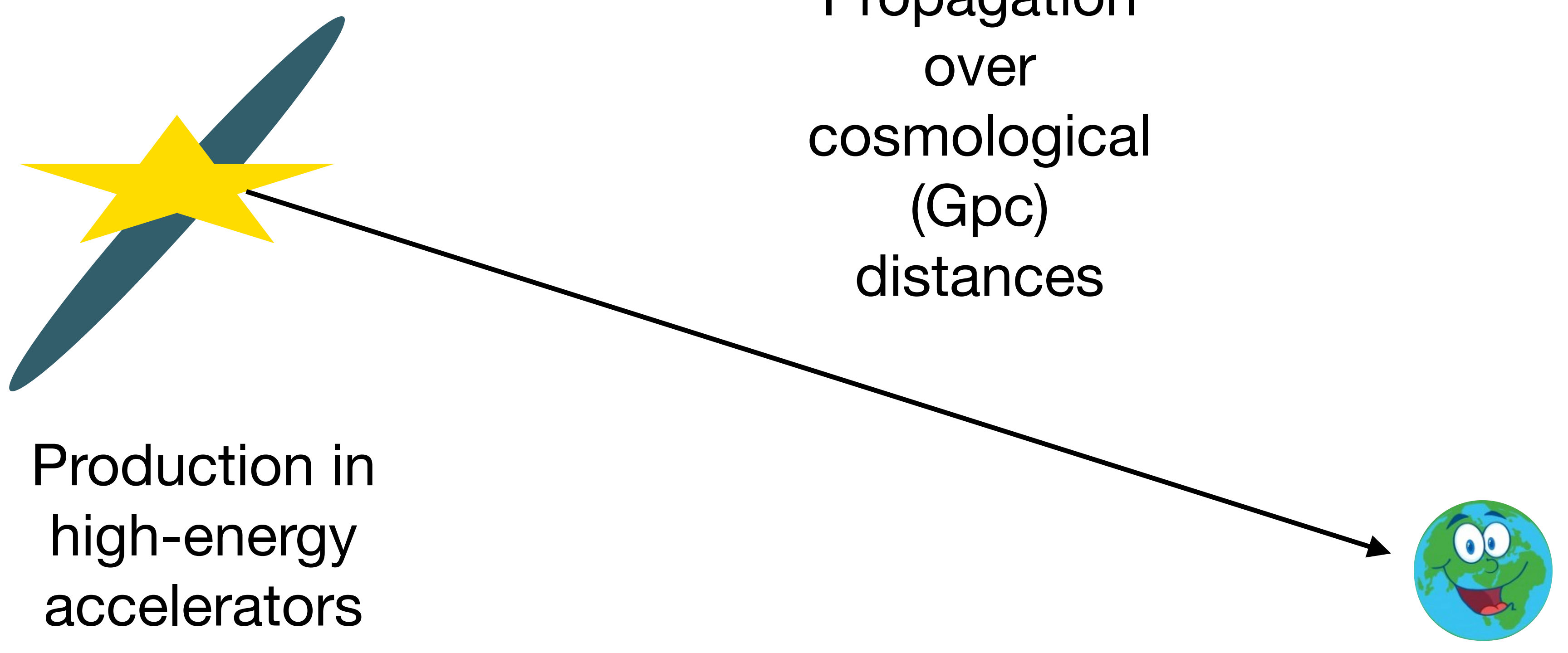
Production in
high-energy
accelerators
(AGN, GRB,
…)

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

High-energy neutrinos



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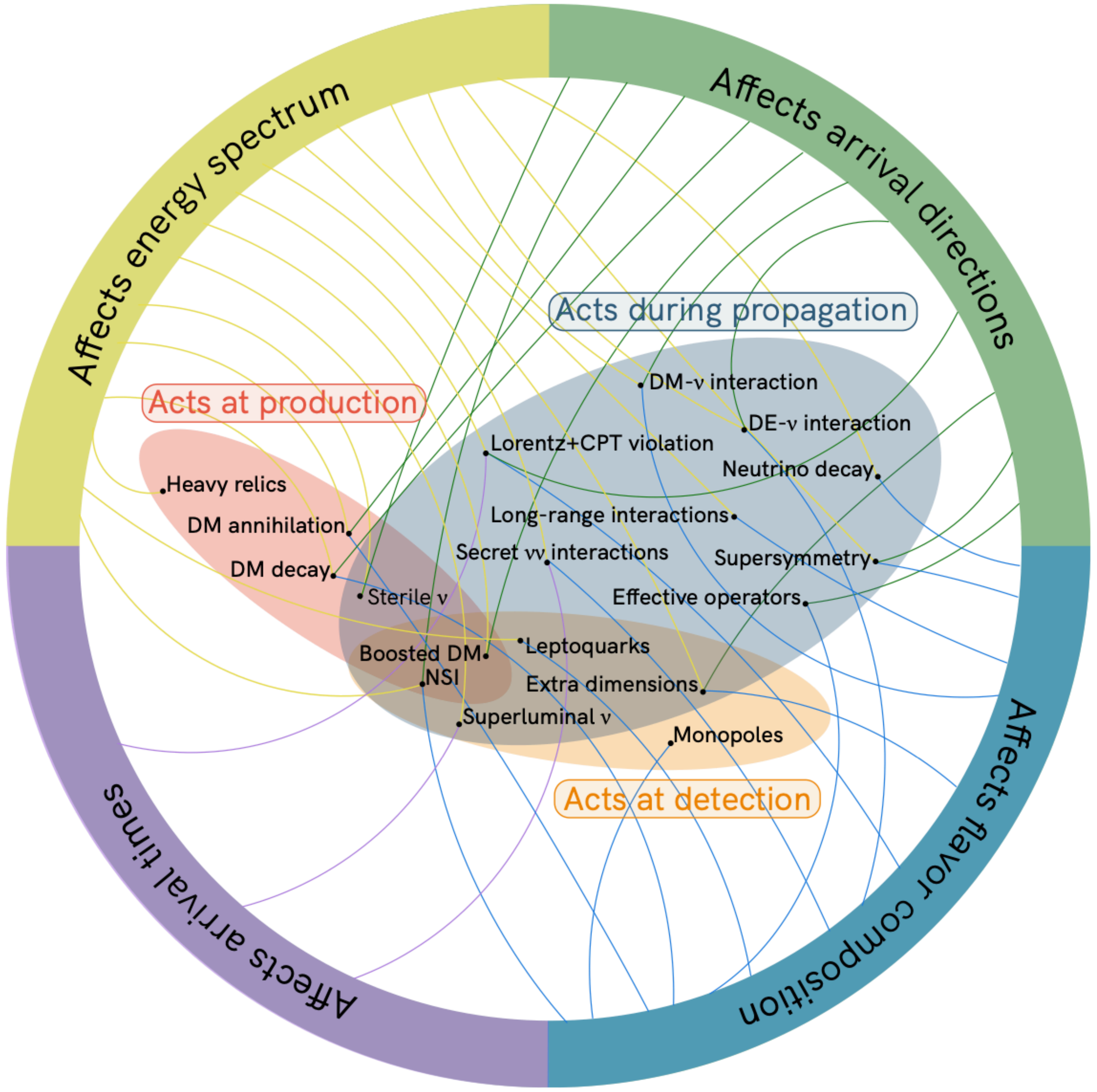

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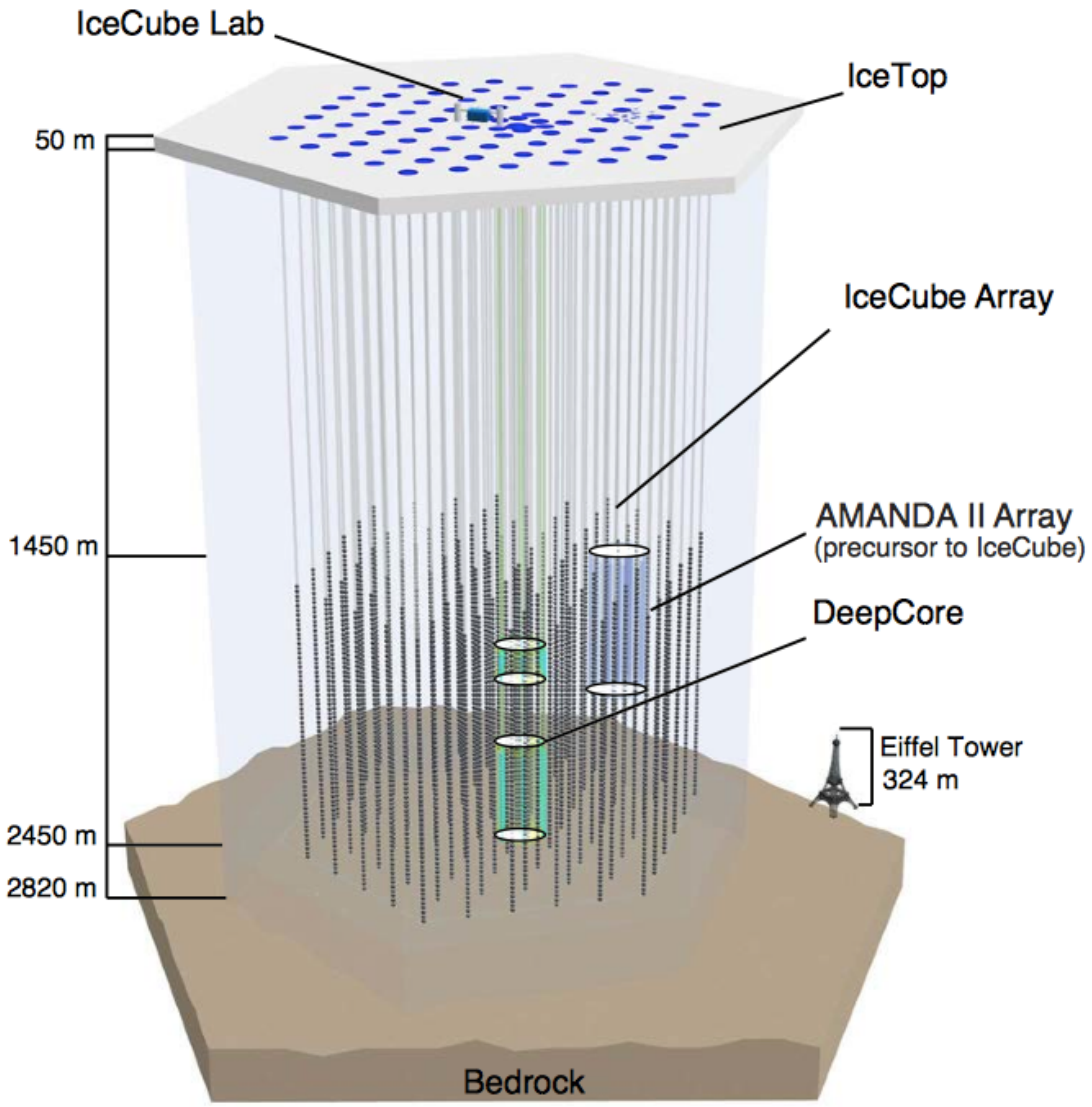
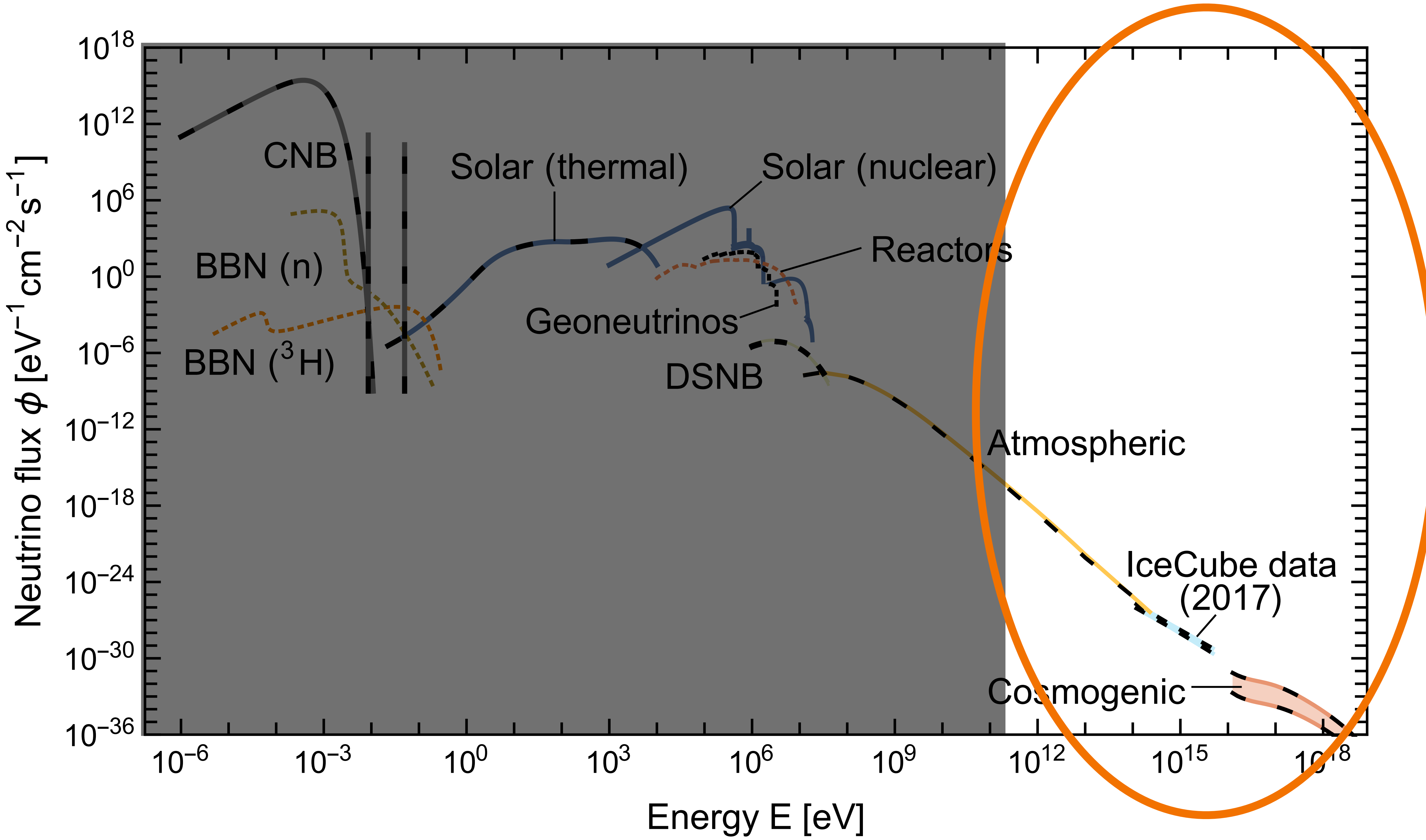
New Physics?

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

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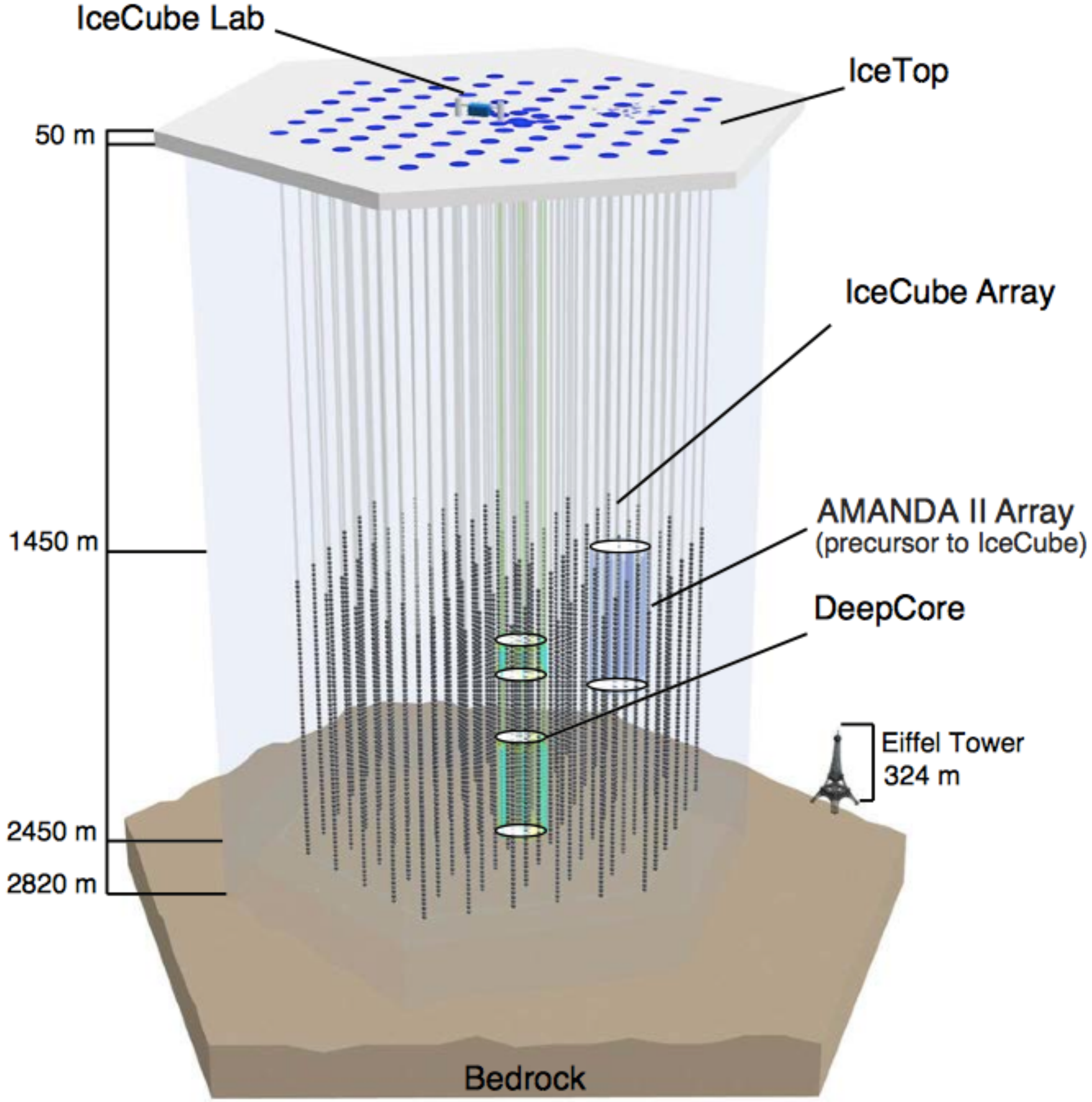
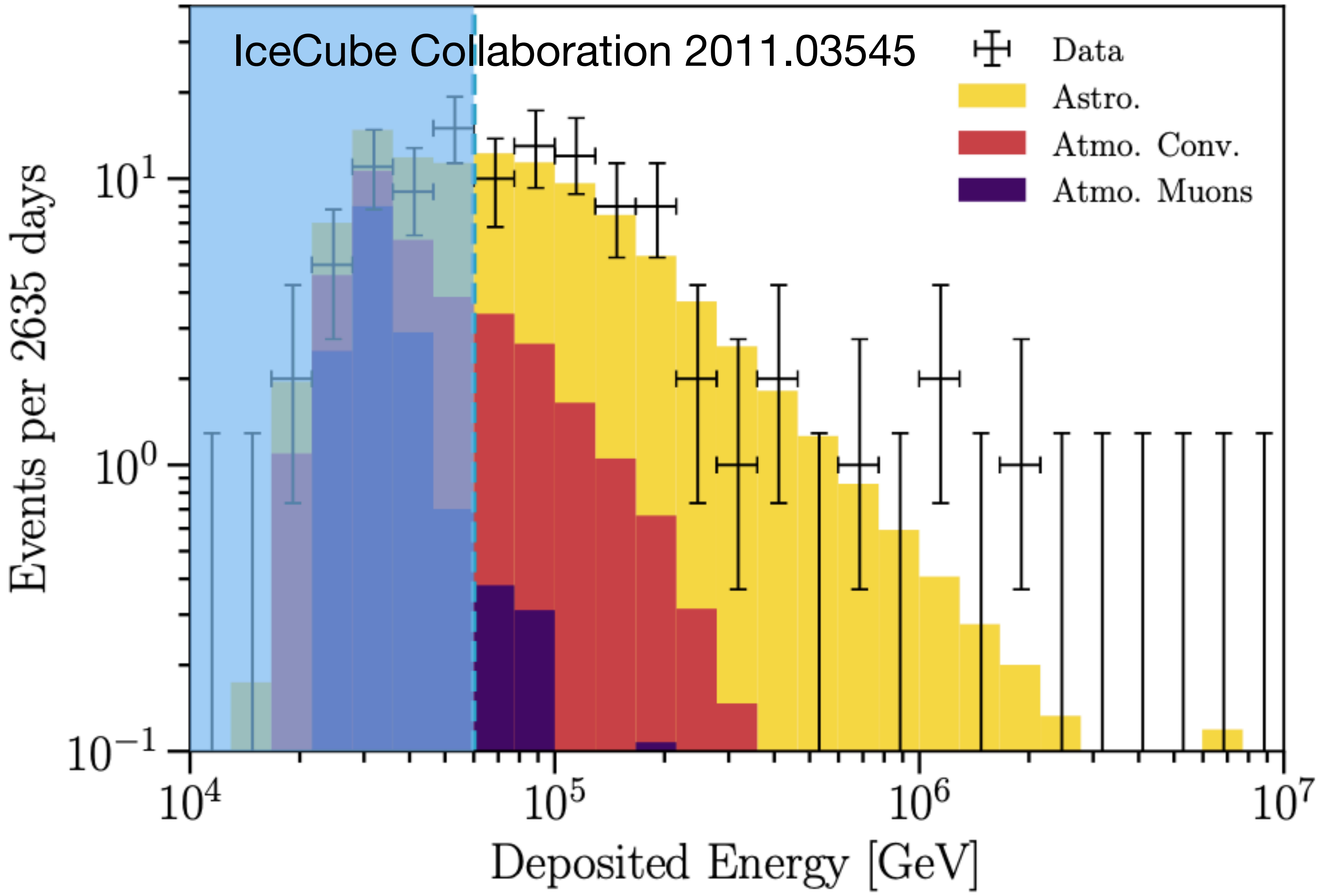
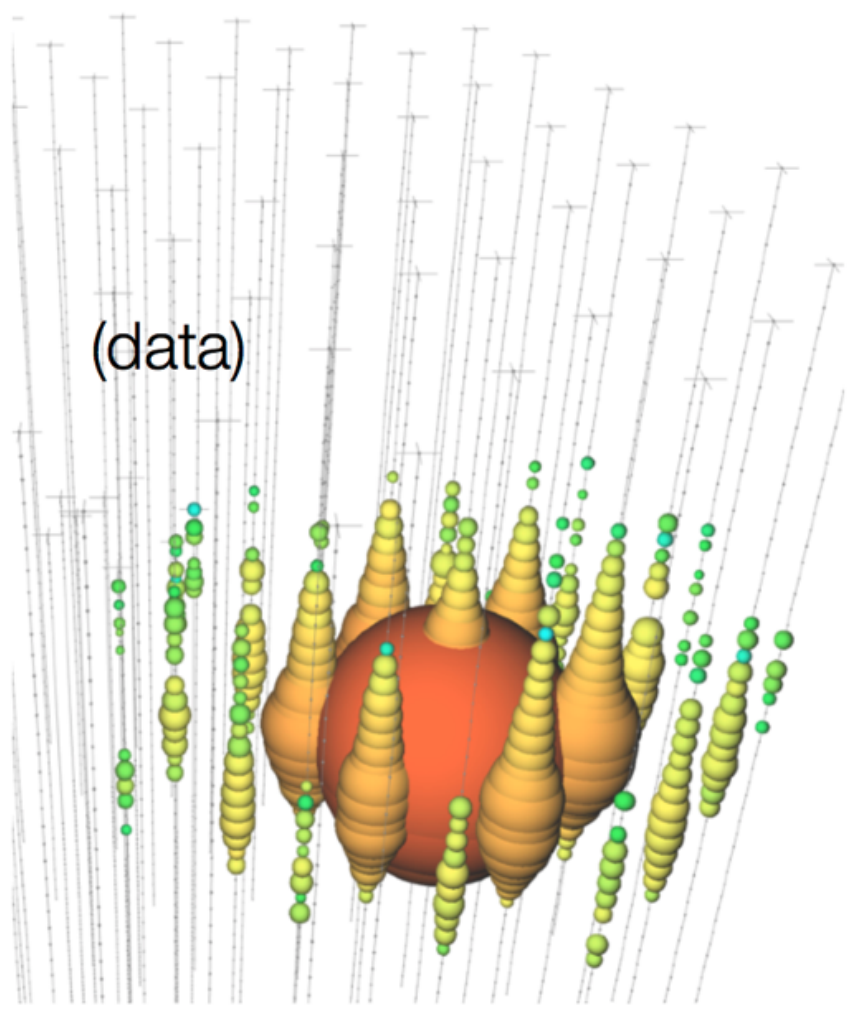




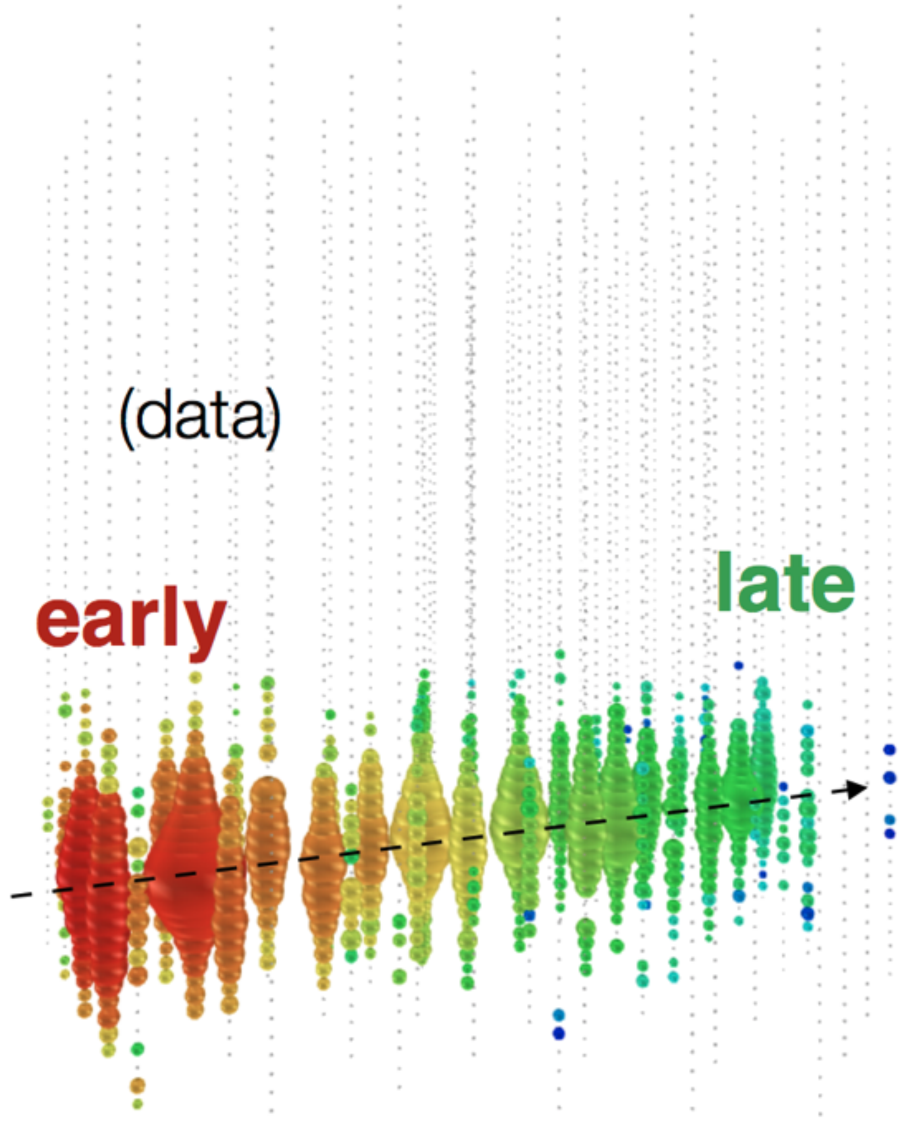
Flavour: event morphology

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

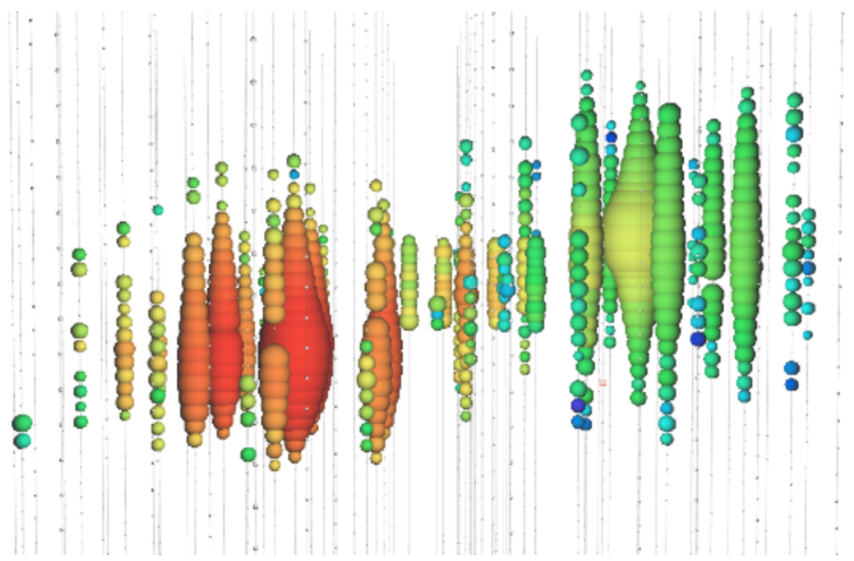
Charged-current ν_μ



Up-going track

Charged-current ν_τ

(simulation)



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^-)

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

(1 : 2 : 0)

■ **“muon-damped”**

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

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

Oscillation

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

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

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

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

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

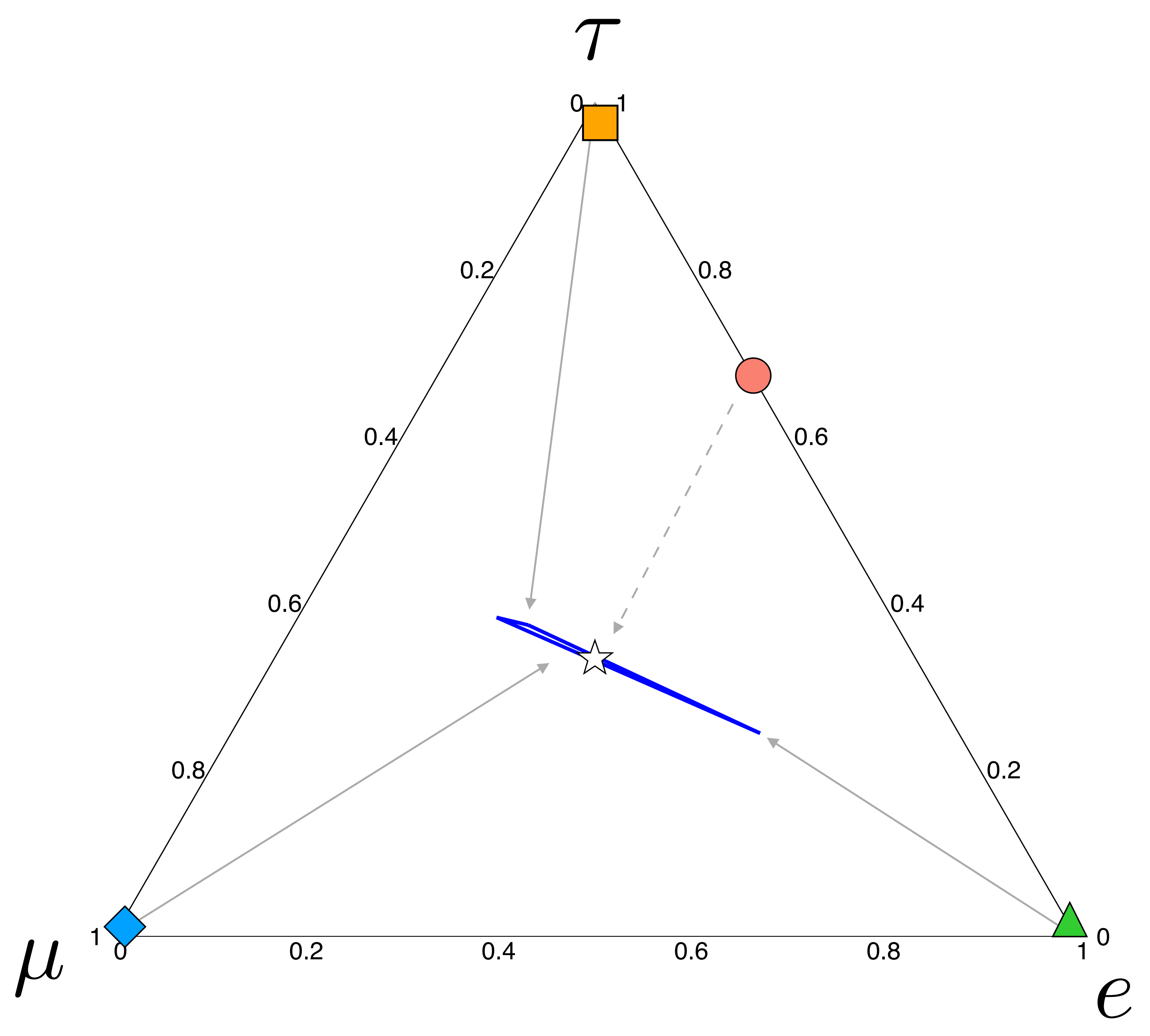
Flavour basis

PMNS mixing matrix

mass basis

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

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



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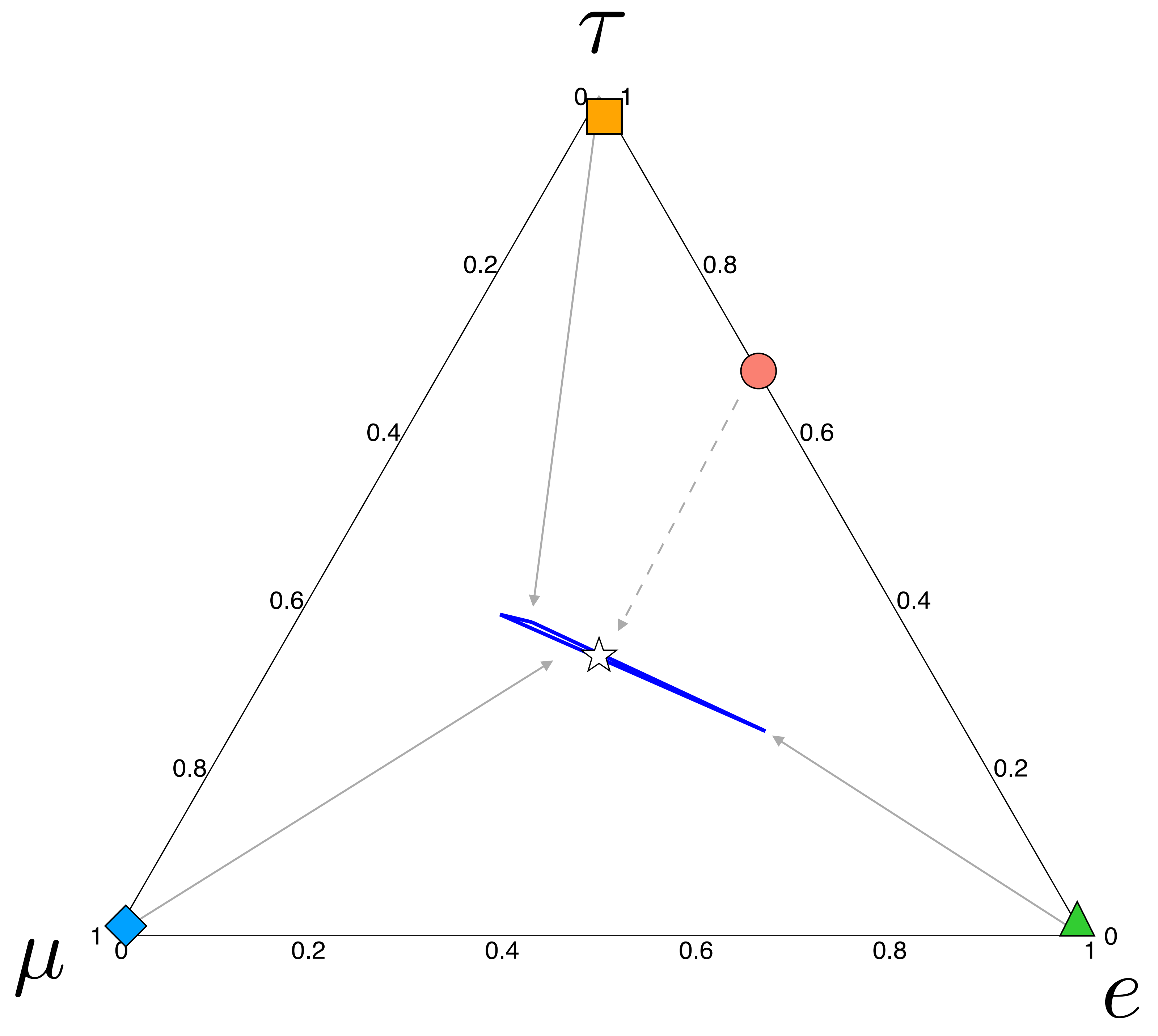
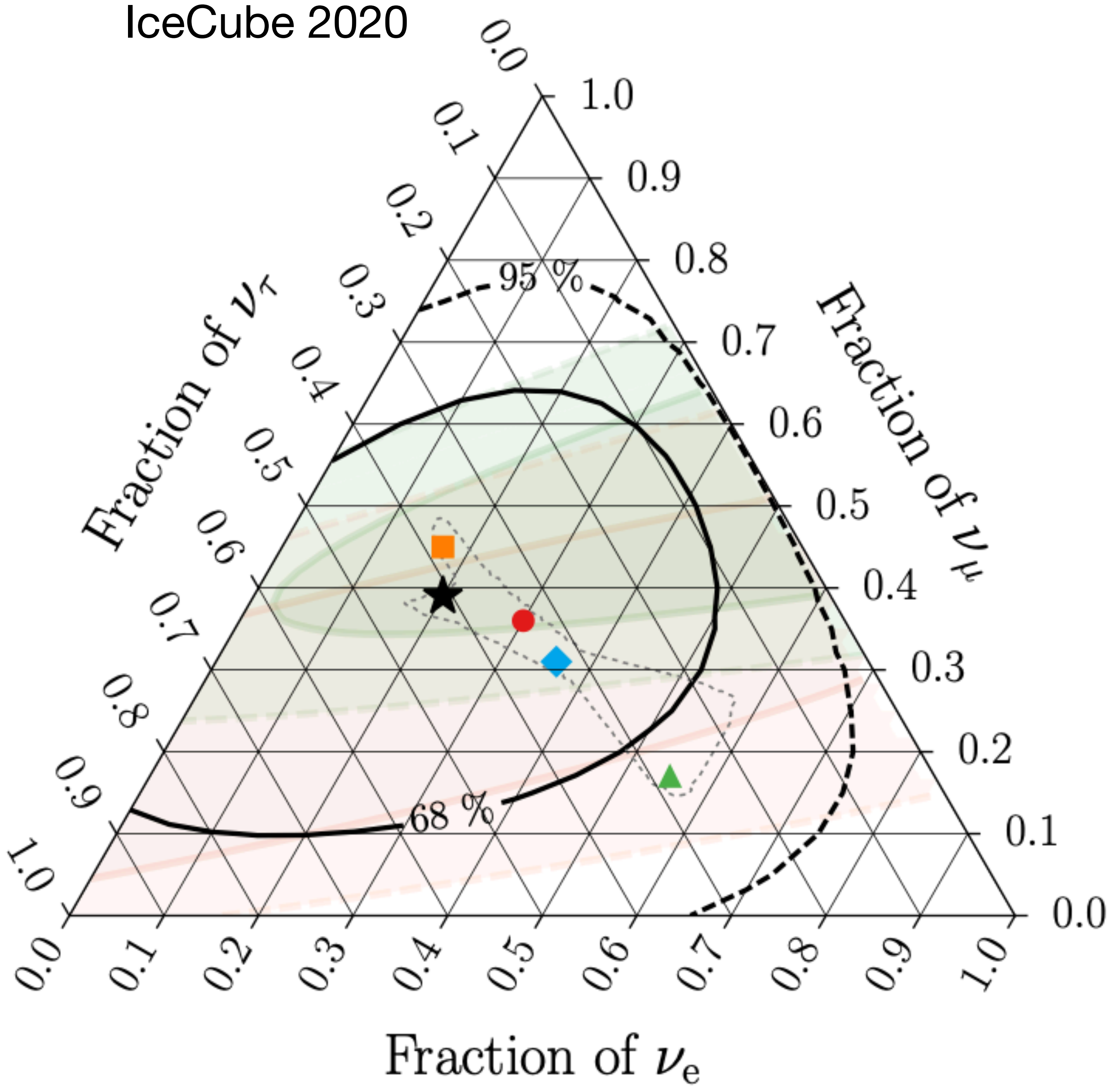
flavour composition at Earth

flavour composition at source



Flavour composition at Earth

IceCube 2020



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Two limits:

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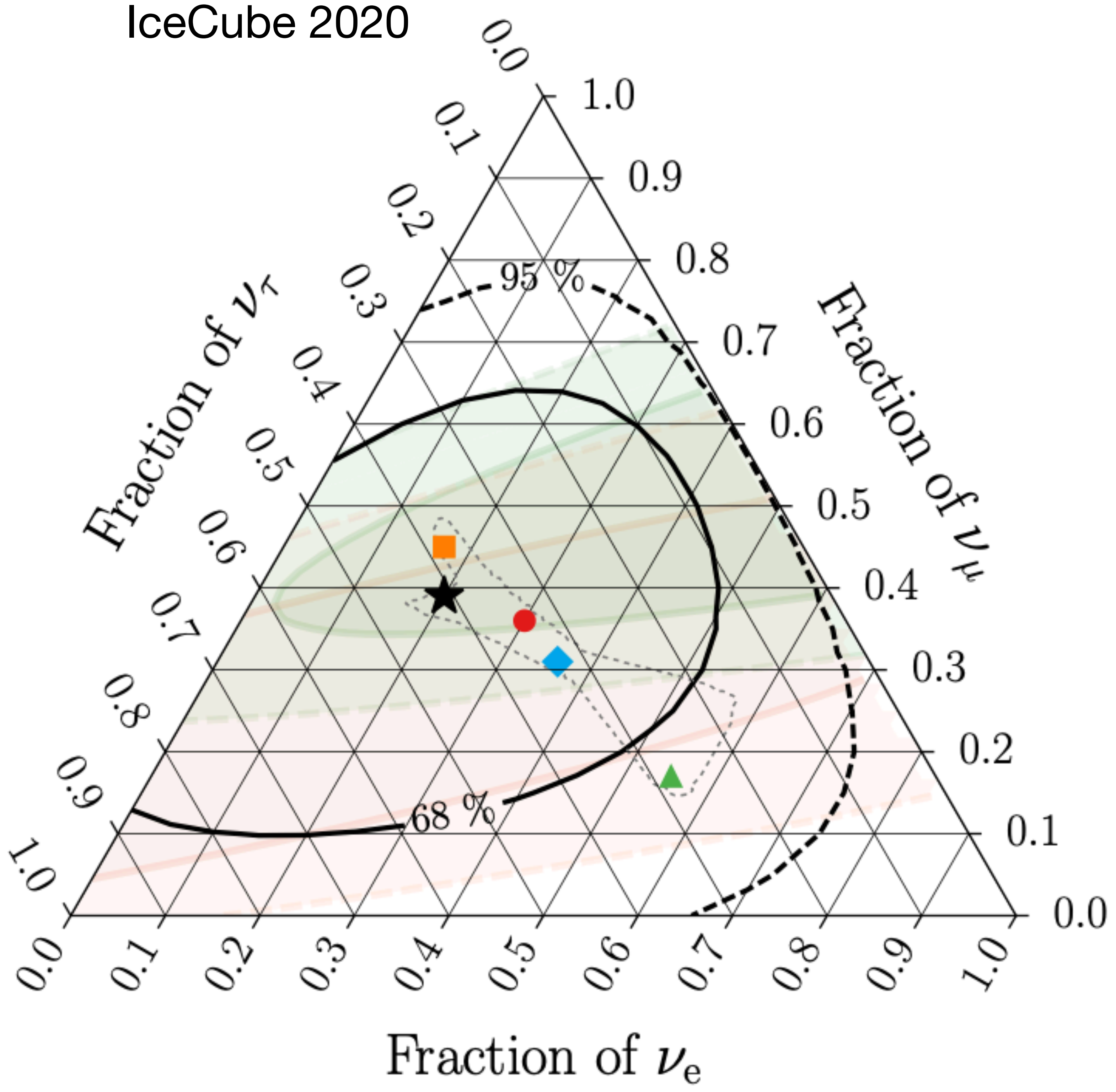

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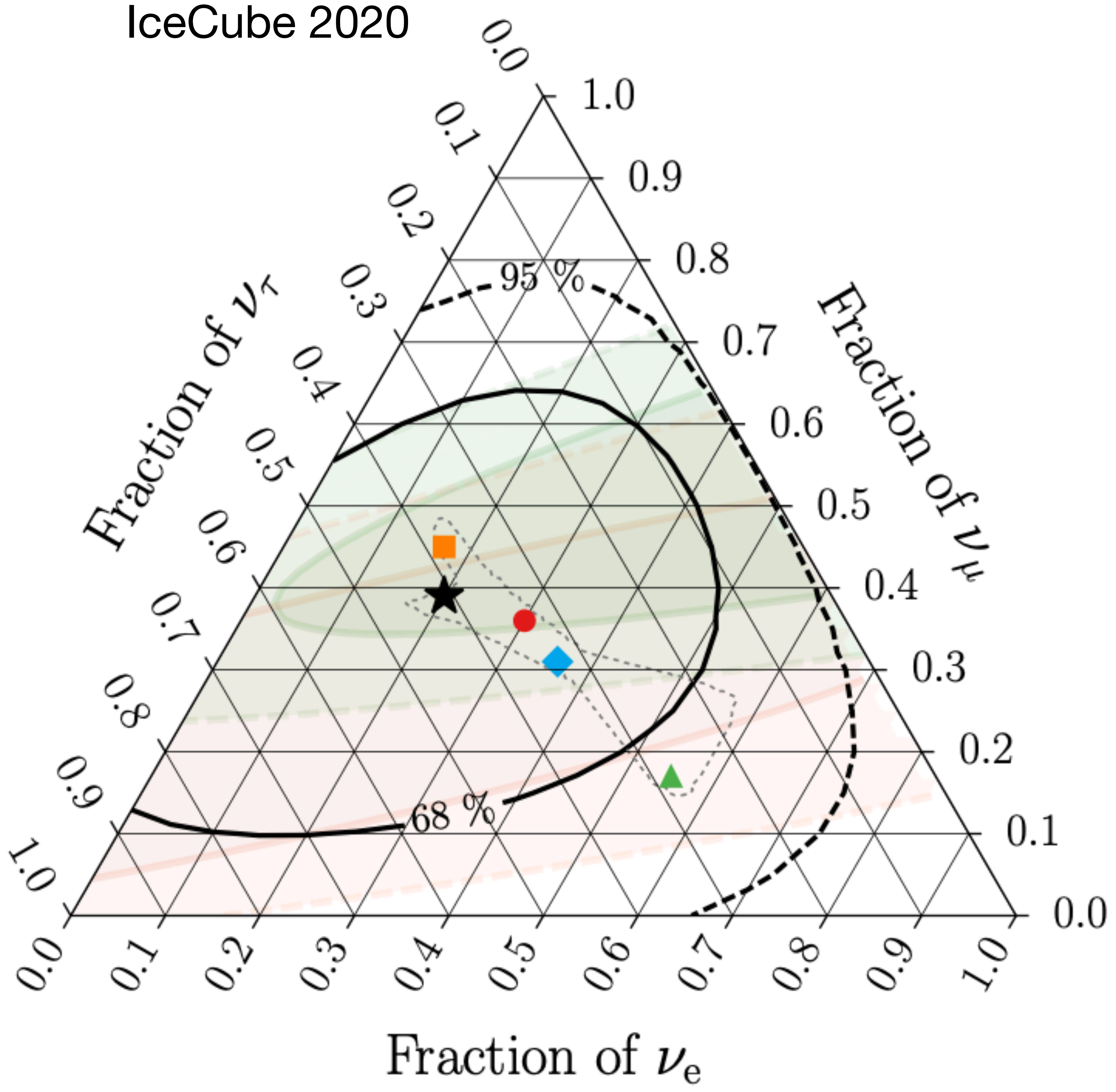

Two limits:

- Statistics (astrophysical neutrinos)

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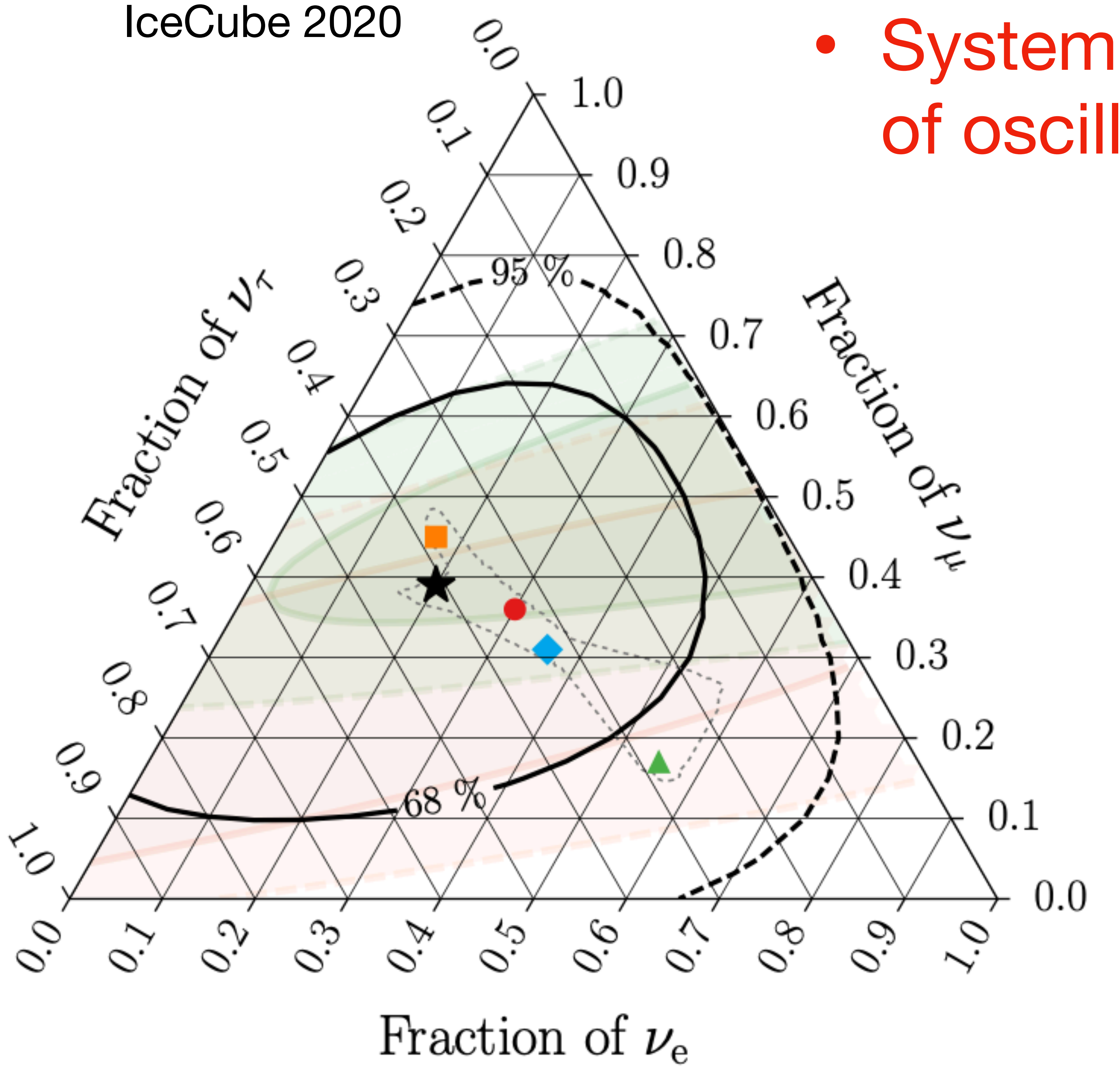

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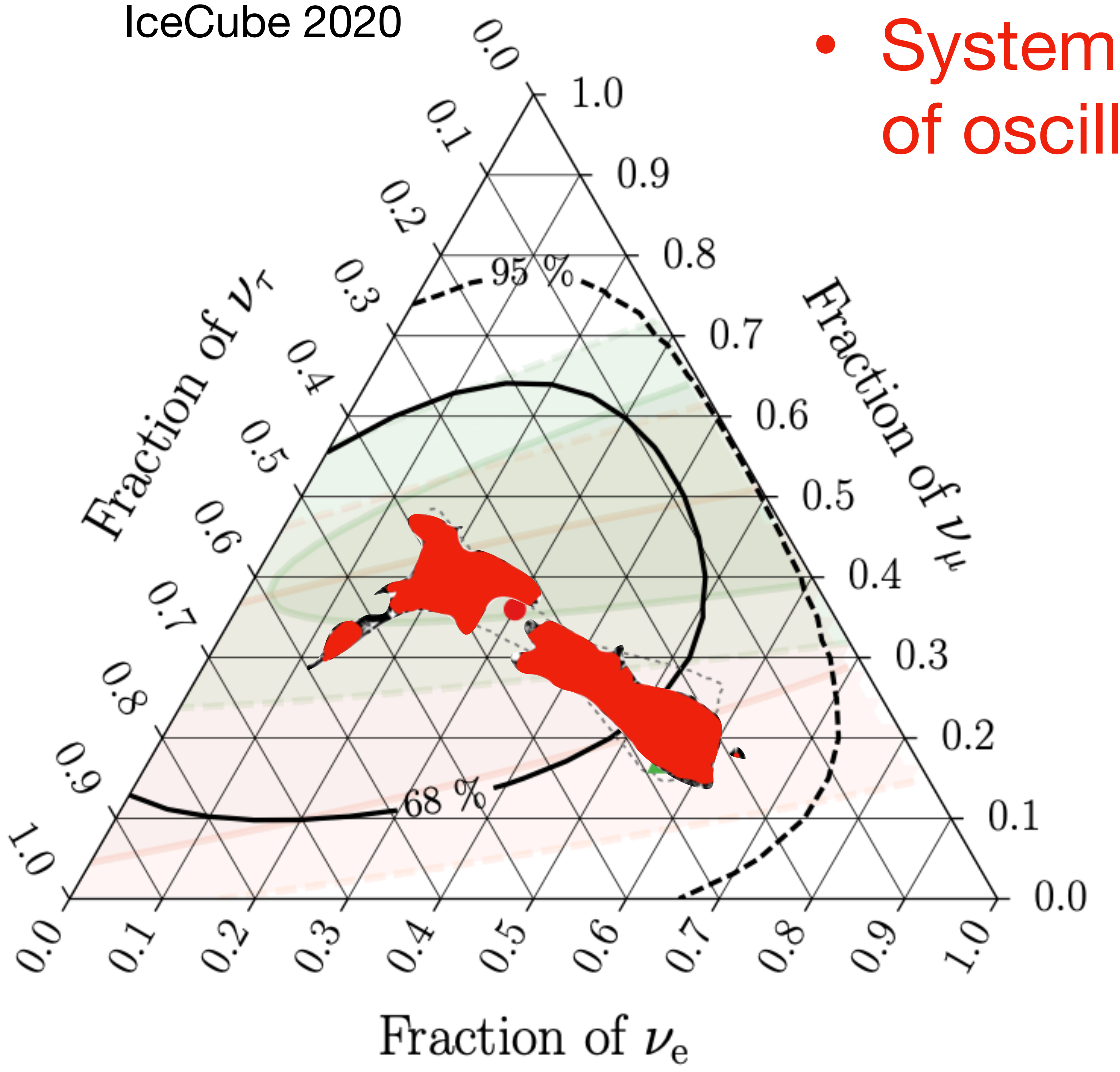

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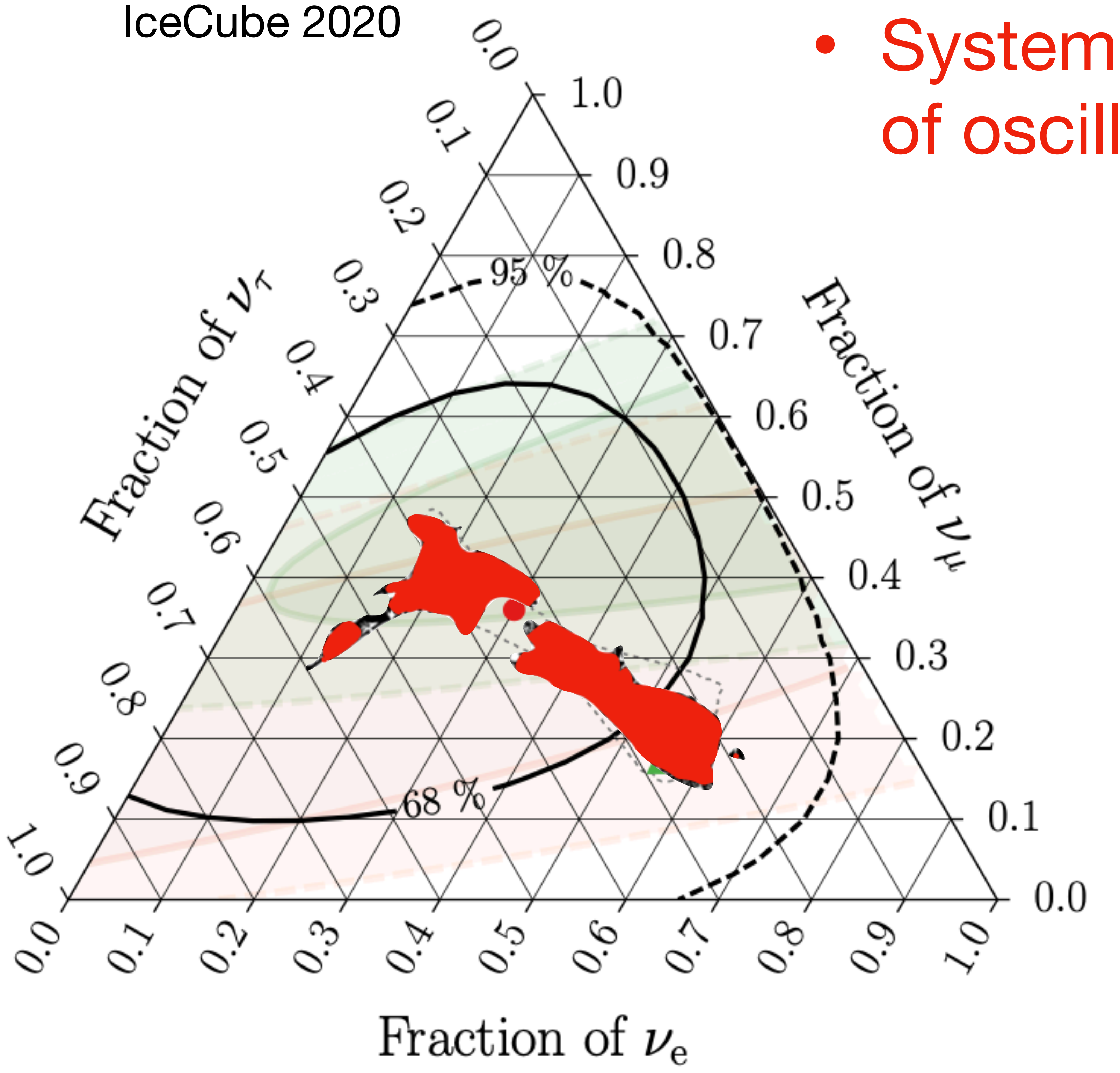

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NuFit 5.0 global fit

Parameter	Normal ordering	Inverted ordering
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.575^{+0.016}_{-0.019}$
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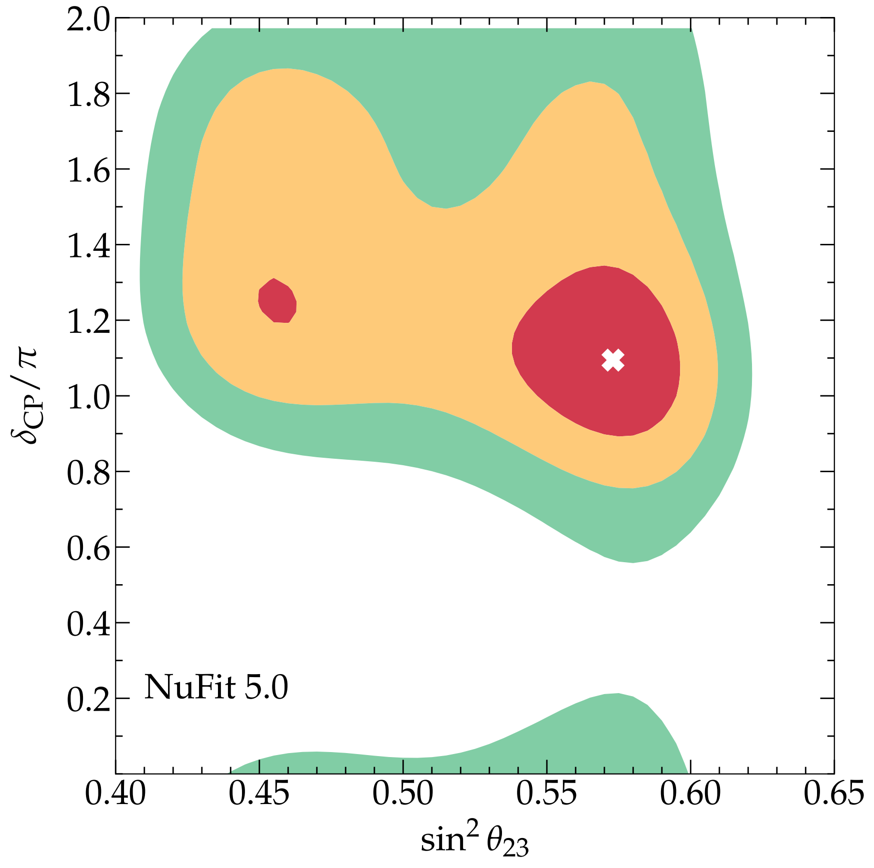
θ_{12} (solar angle): Solar, reactor experiments

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

θ_{13} Reactor experiments

δ_{CP} Long-baseline experiments

Mostly uncorrelated except:



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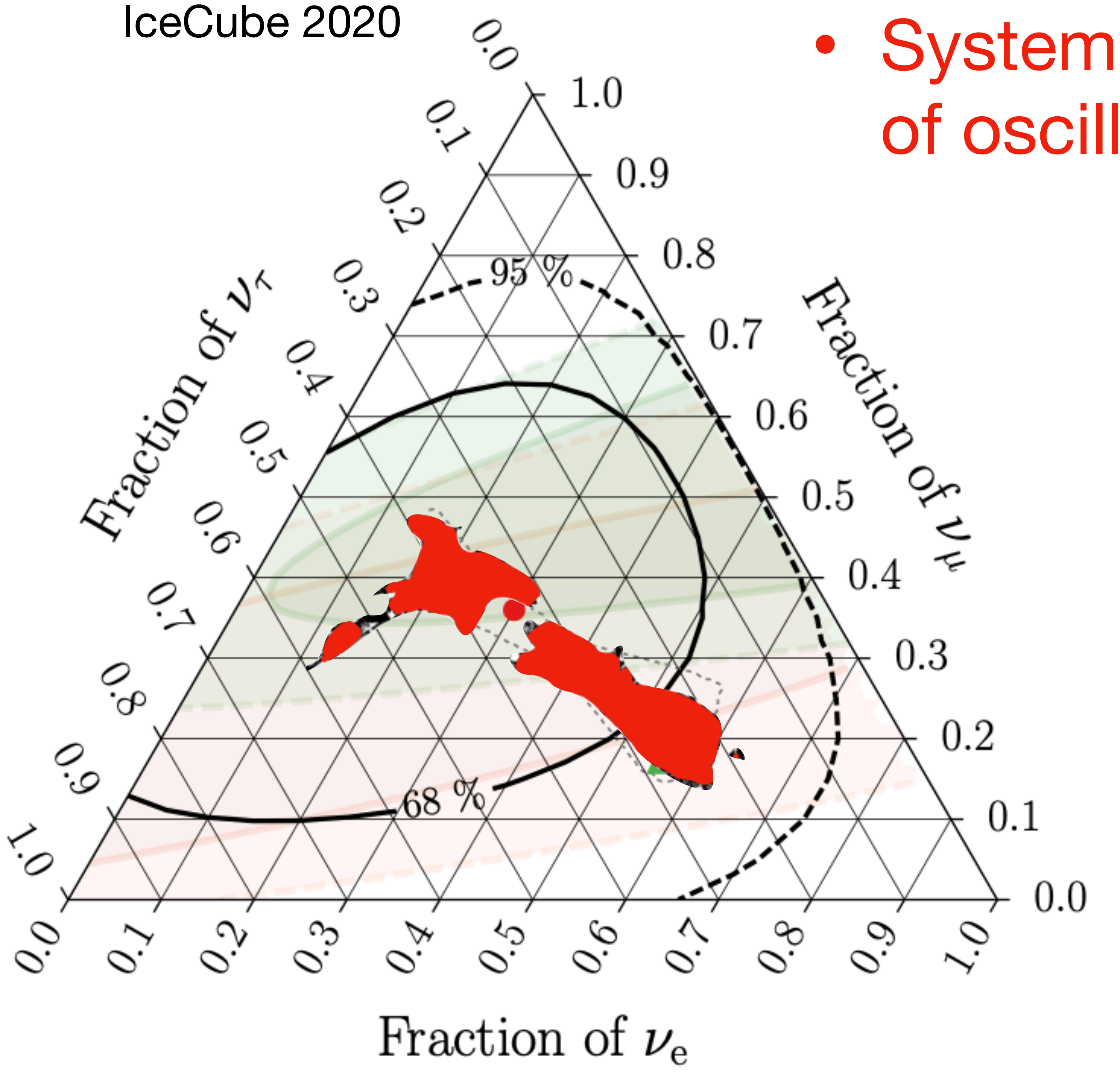

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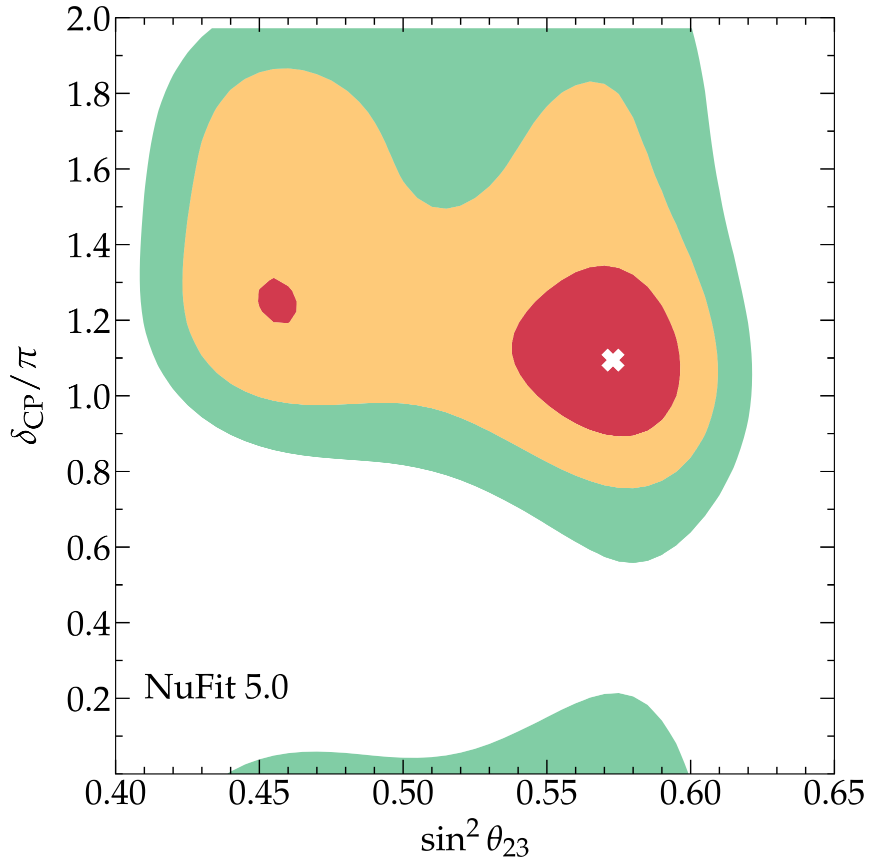
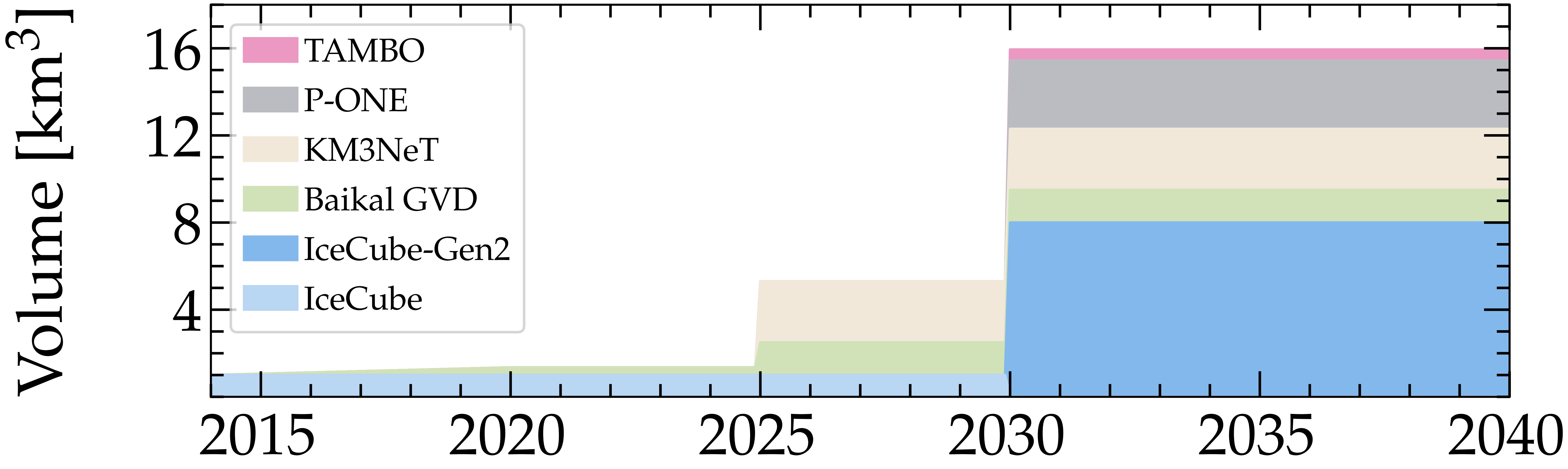


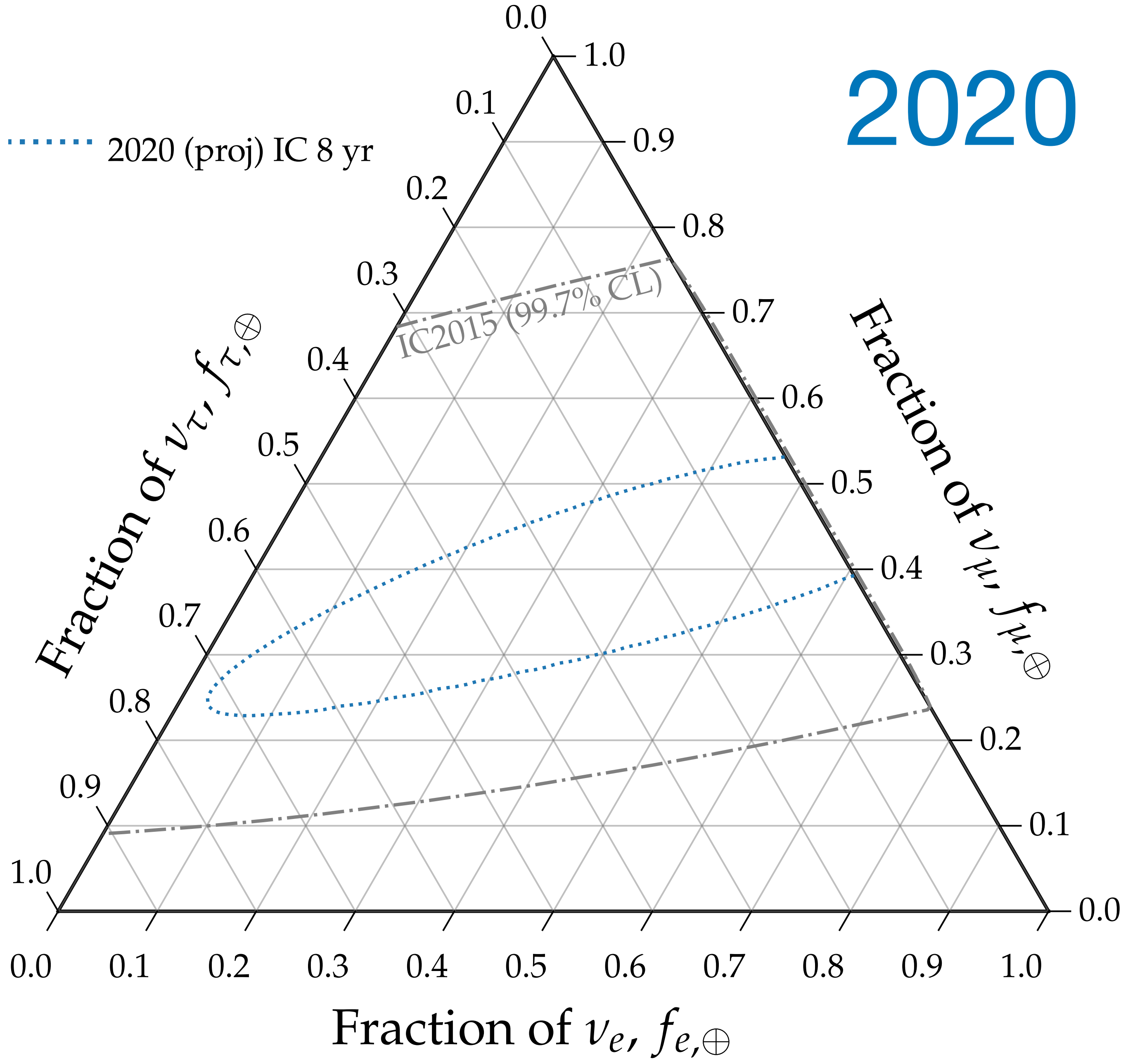
What does the future say about this?

Statistics: need more Cherenkov telescopes!



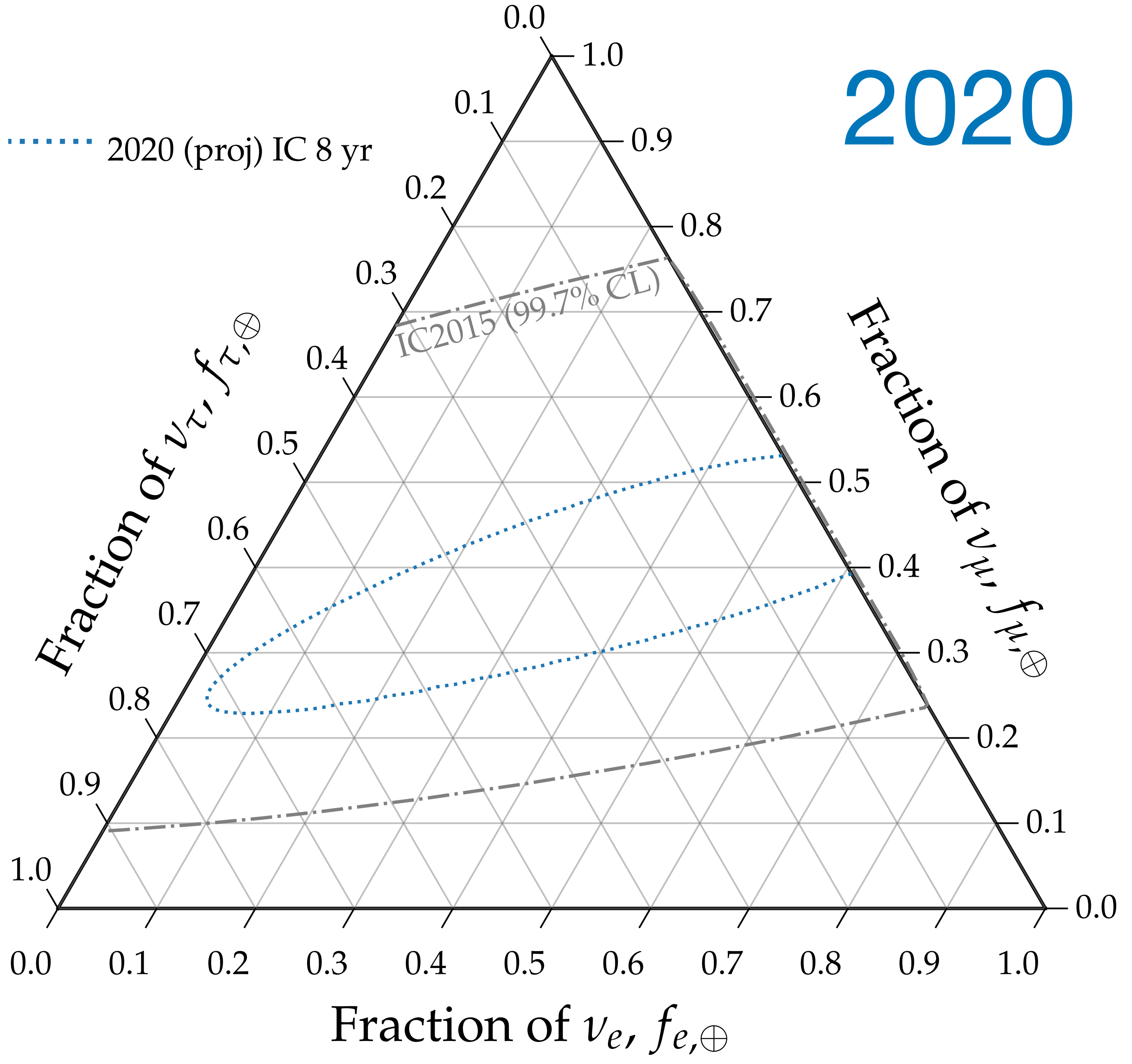
Telescope	Medium	Location	Exposure (km^3)
IceCube-Gen2	Ice	South pole (HE upgrade of IceCube)	~6-9
KM3NeT	Seawater	Mediterranean Sea (successor to ANTARES)	~2-3
GVD	Freshwater	Lake Baikal	1.5
P-ONE	Seawater	Cascadia Basin (Pacific Ocean)	π
TAMBO	Rock/air/water Cherenkov	Peru	~10 (very high E, tau only)

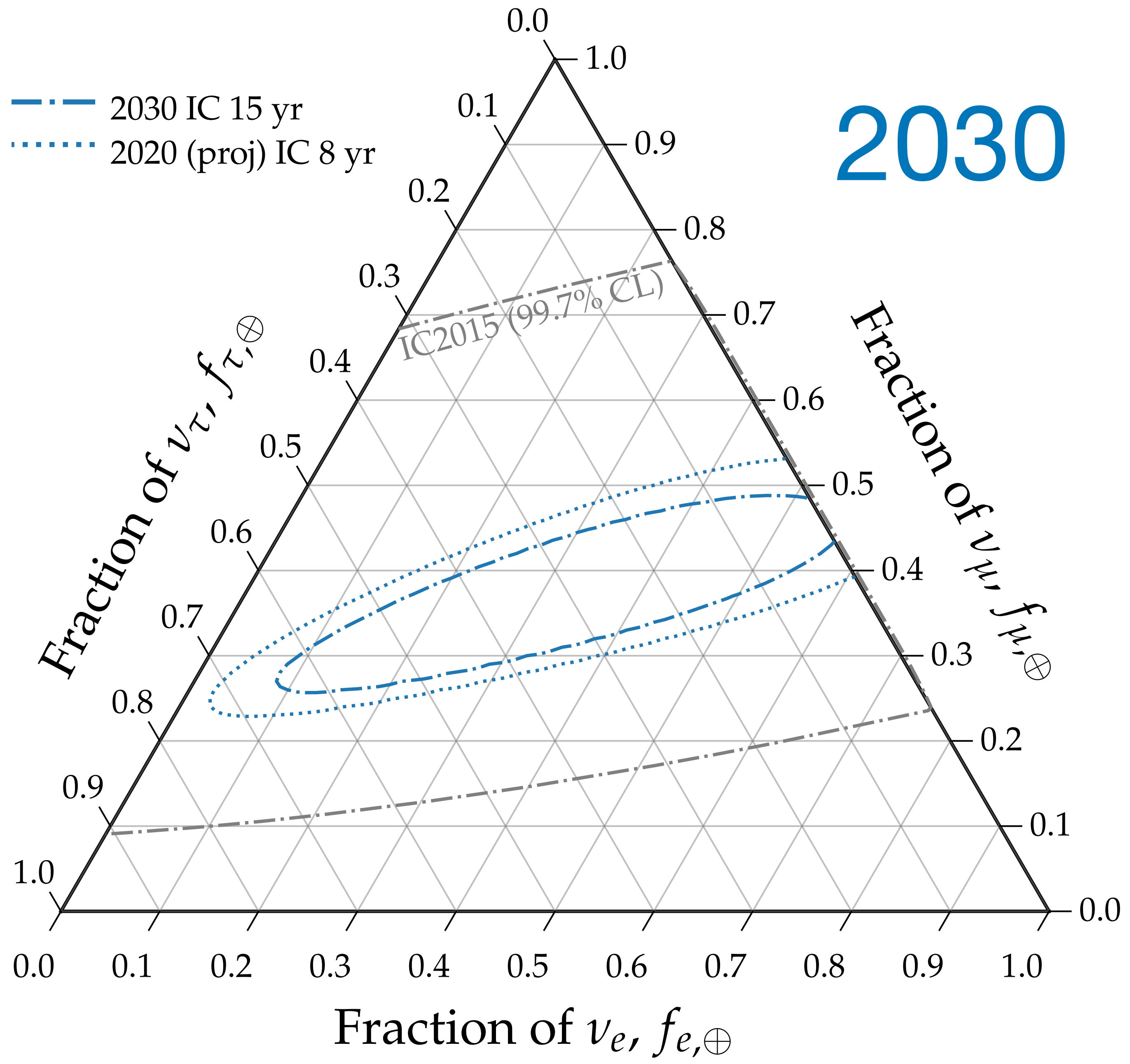
Statistics



2020

Statistics


2020
2020 (proj) IC 8 yr
IC2015 (99.7% CL)
Fraction of ν_e, $f_{e,\oplus}$
Fraction of ν_μ, $f_{\mu,\oplus}$
Fraction of ν_τ, $f_{\tau,\oplus}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


2030
2030 IC 15 yr
2020 (proj) IC 8 yr
IC2015 (99.7% CL)
Fraction of ν_e, $f_{e,\oplus}$
Fraction of ν_μ, $f_{\mu,\oplus}$
Fraction of ν_τ, $f_{\tau,\oplus}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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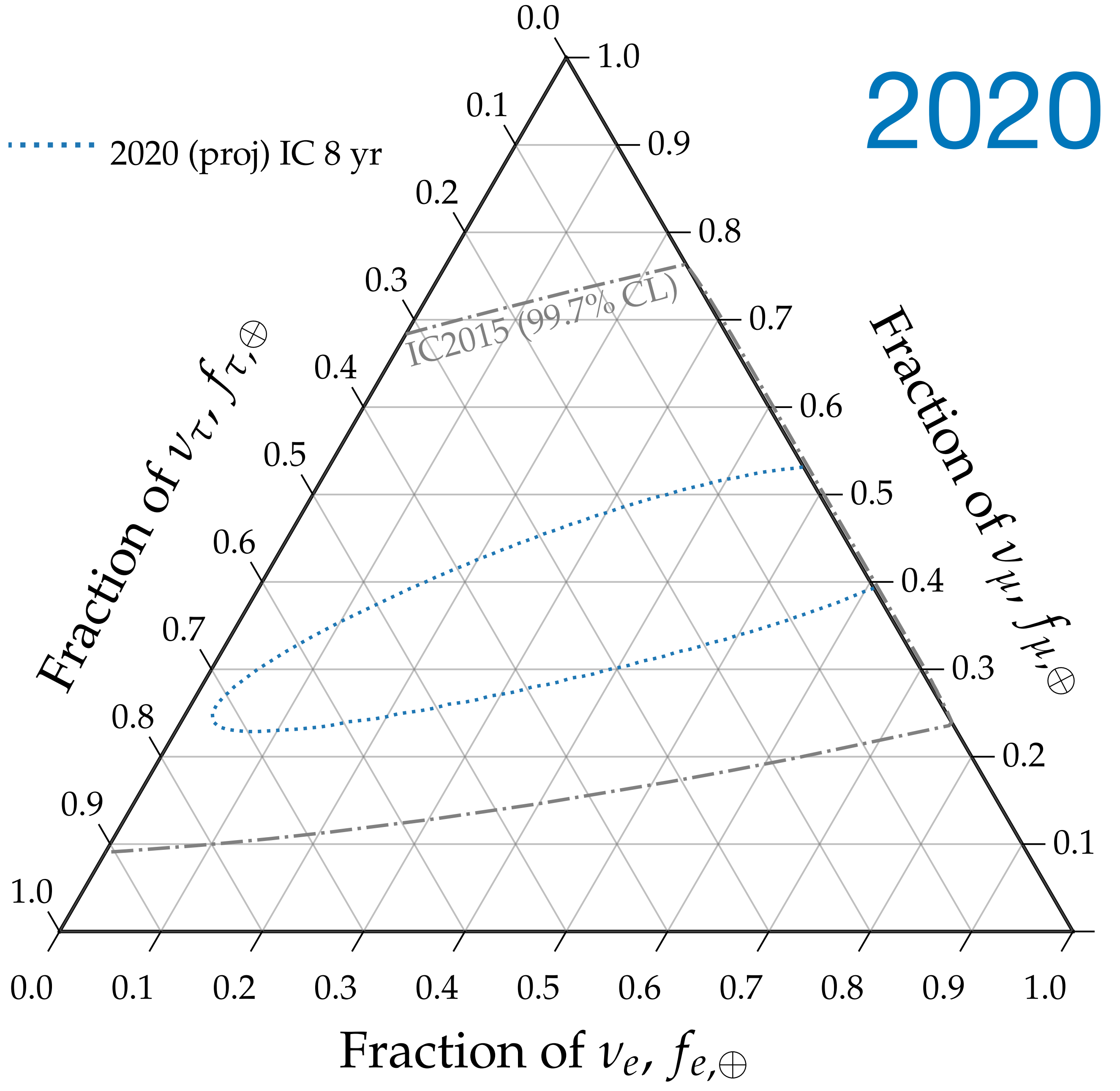
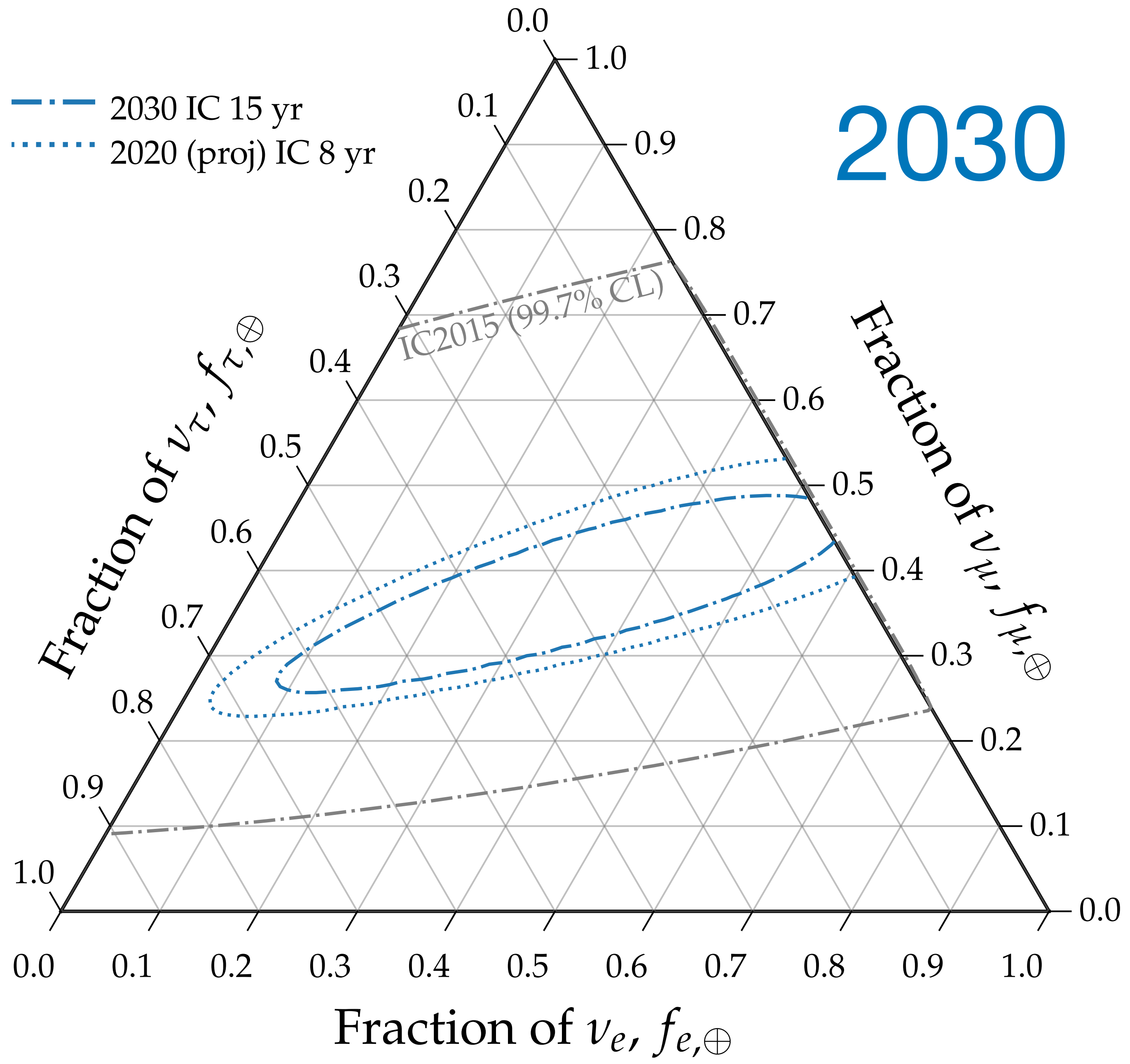
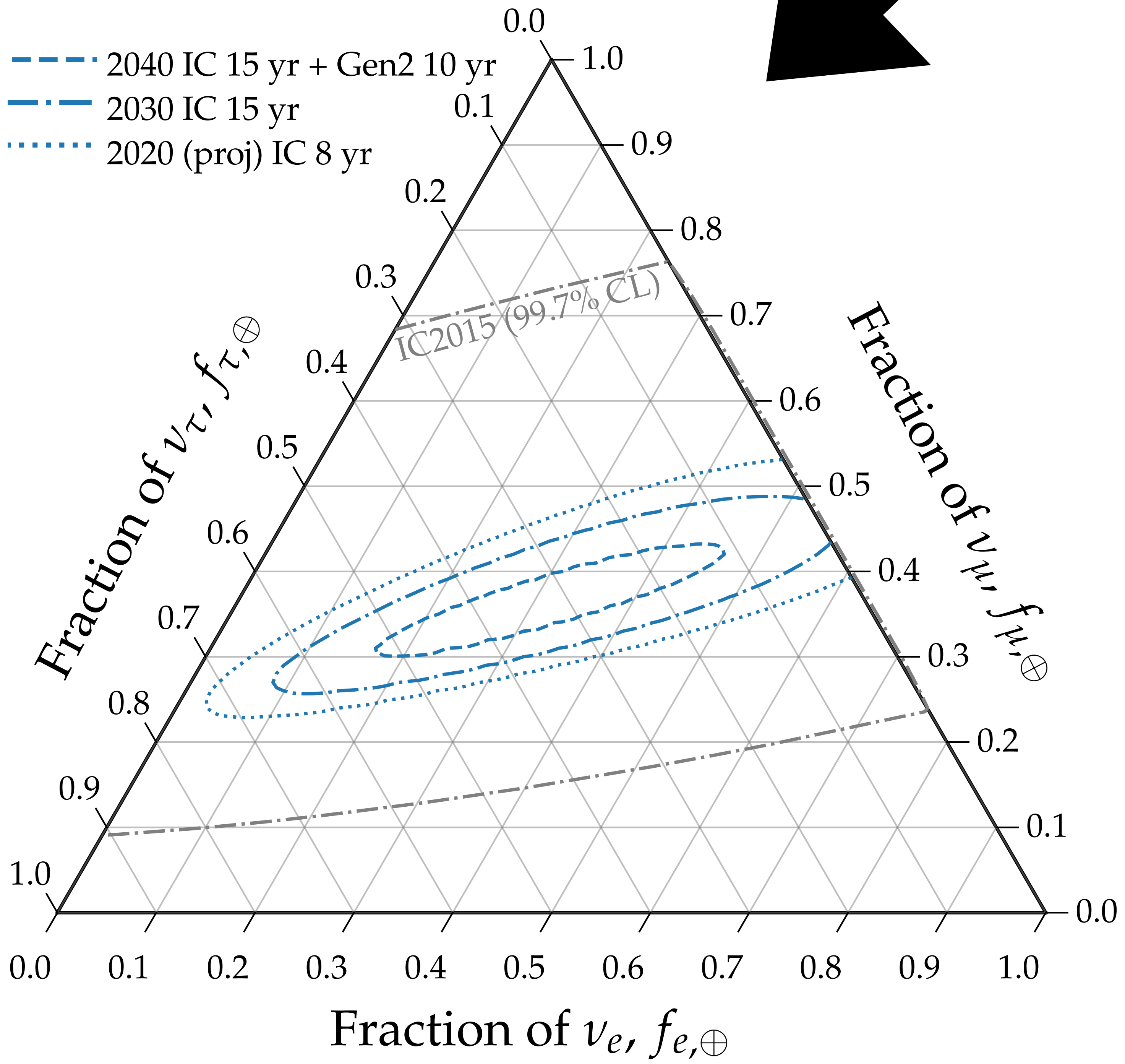


2020



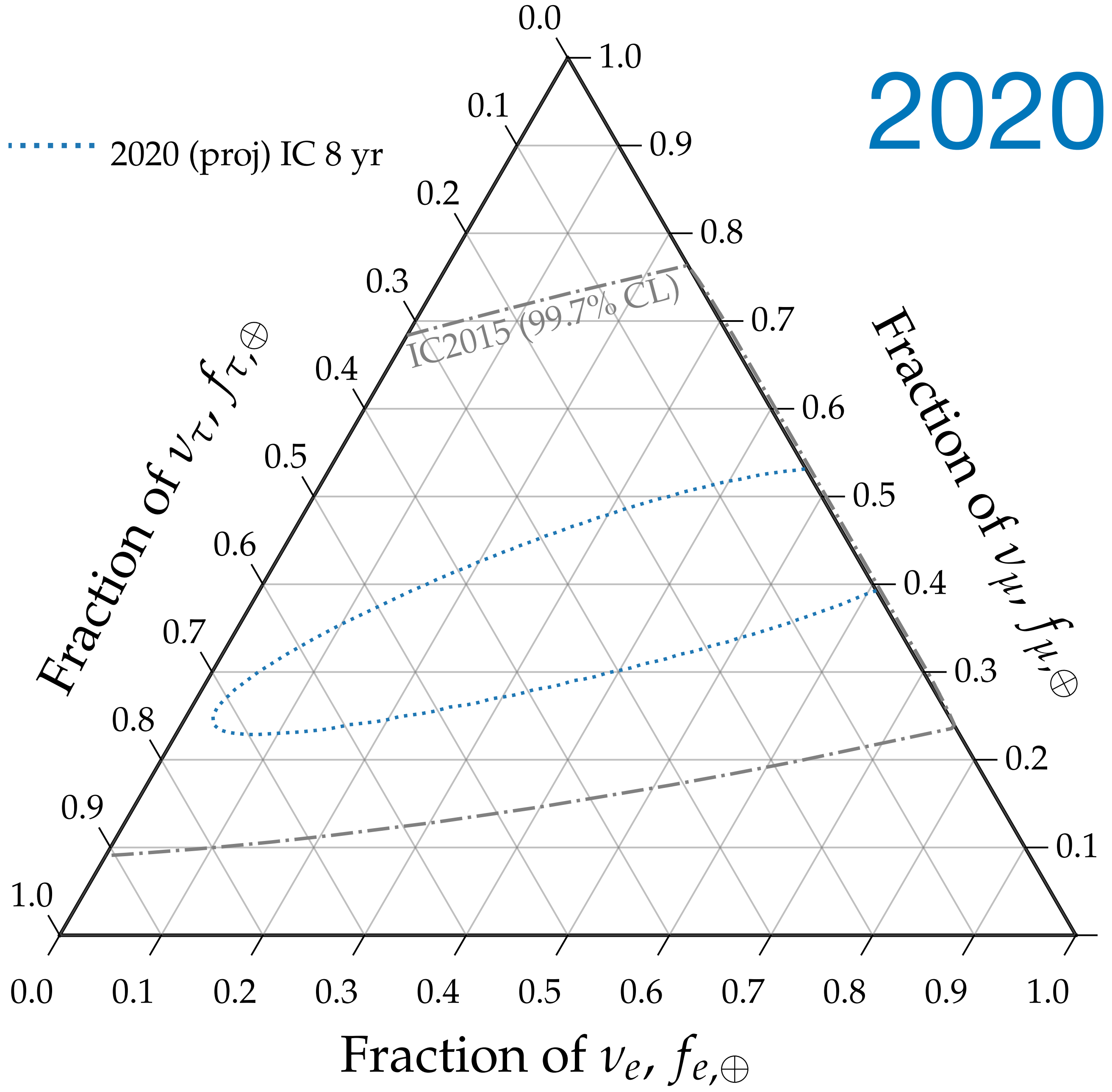
2030



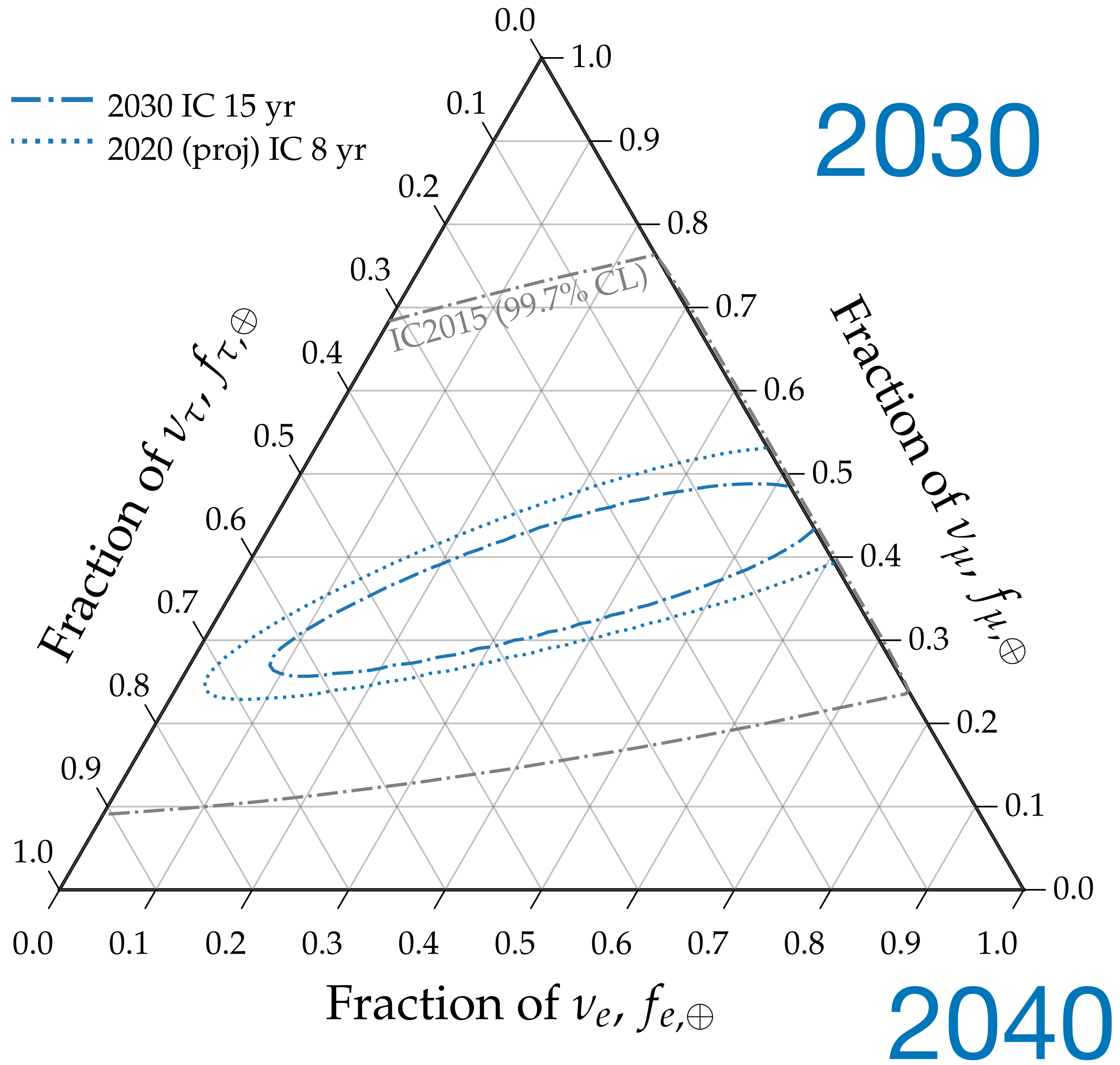
2040 (IceCube-Gen2)

Statistics

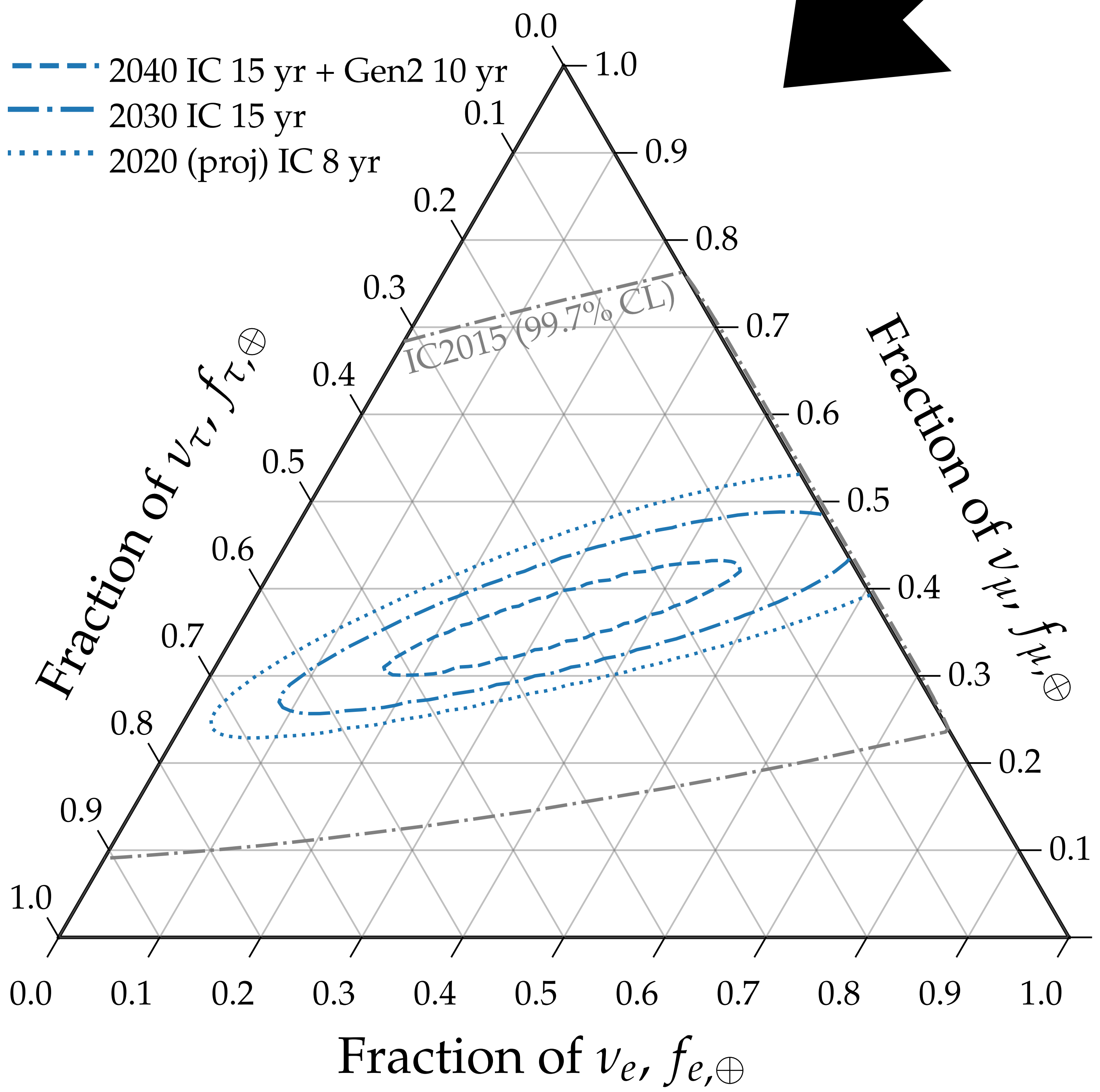
2020



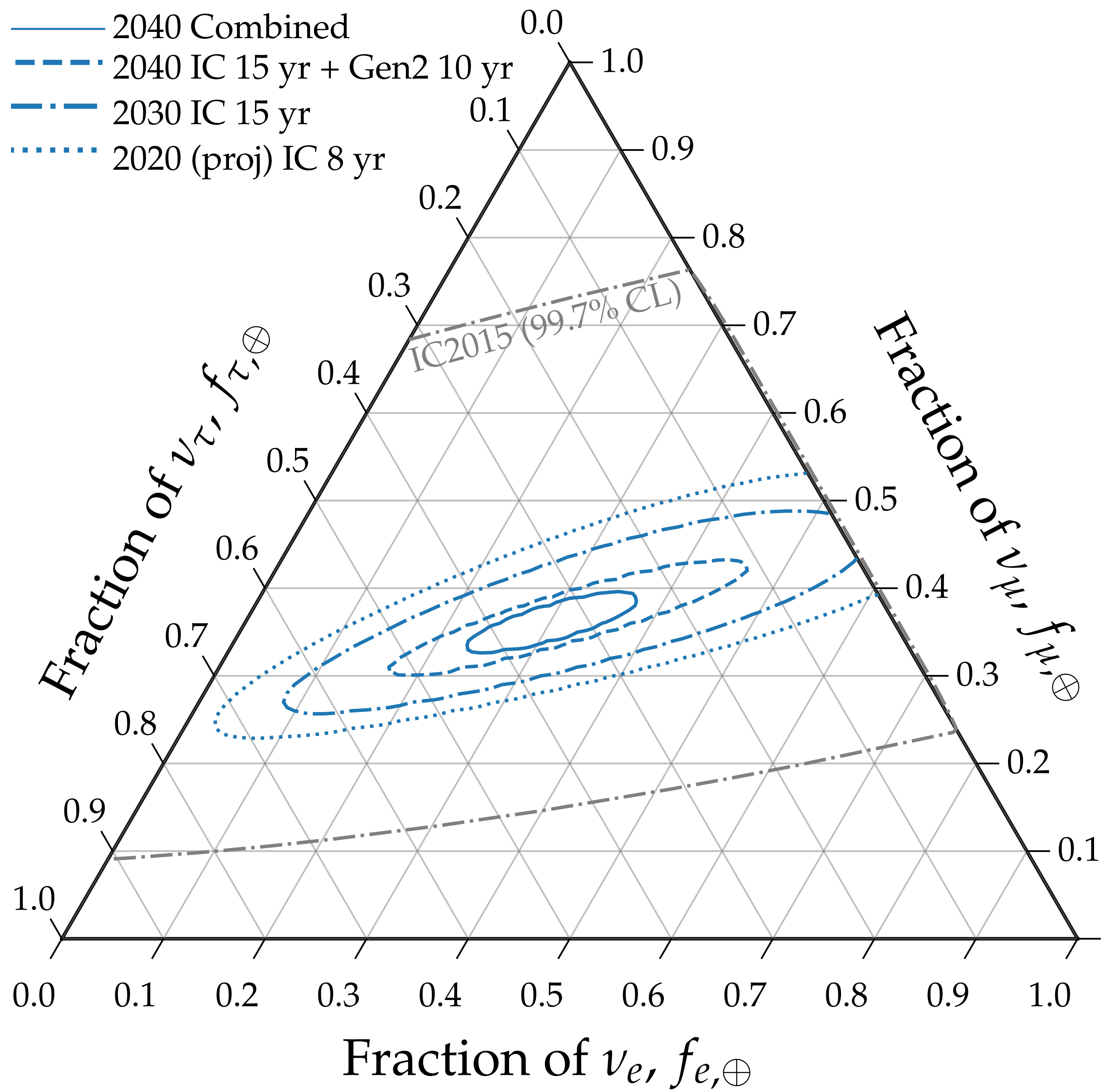
2030



2040 (IceCube-Gen2)



2040(all experiments)



Systematics: terrestrial experiments

- JUNO: 2022-2028: 20kt liquid scintillator reactor measurement.
  0.52% uncertainty on $\sin^2\theta_{12}$
- DUNE: ~2026-2033: 40kt liquid argon long baseline experiment.
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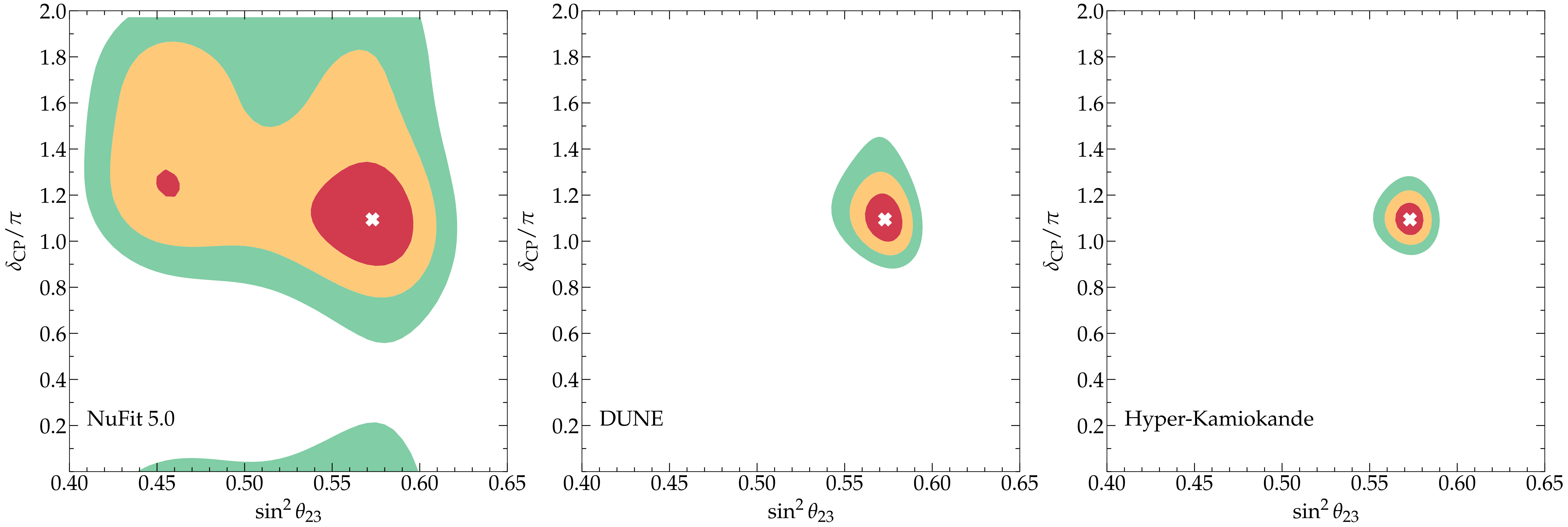

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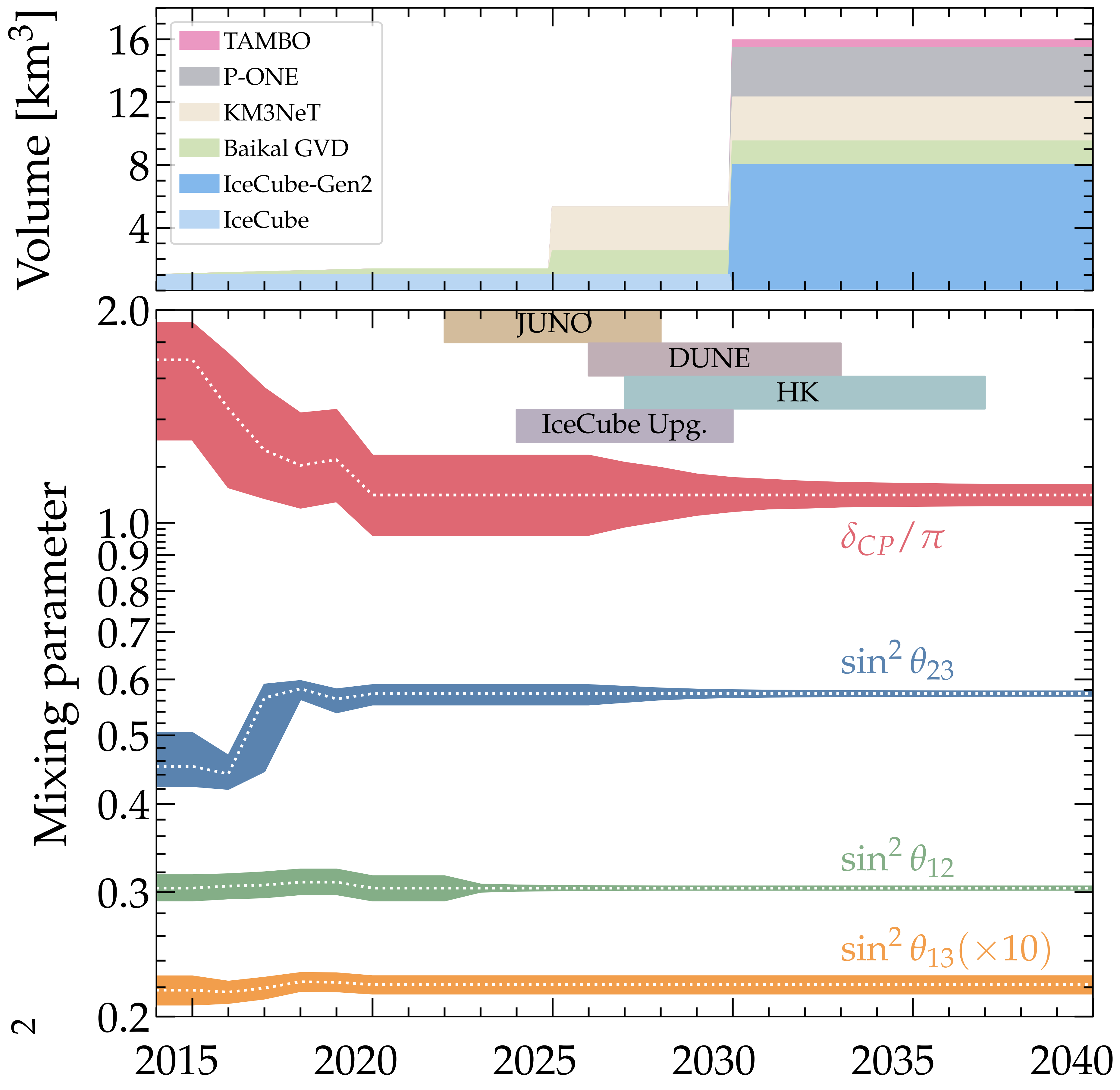
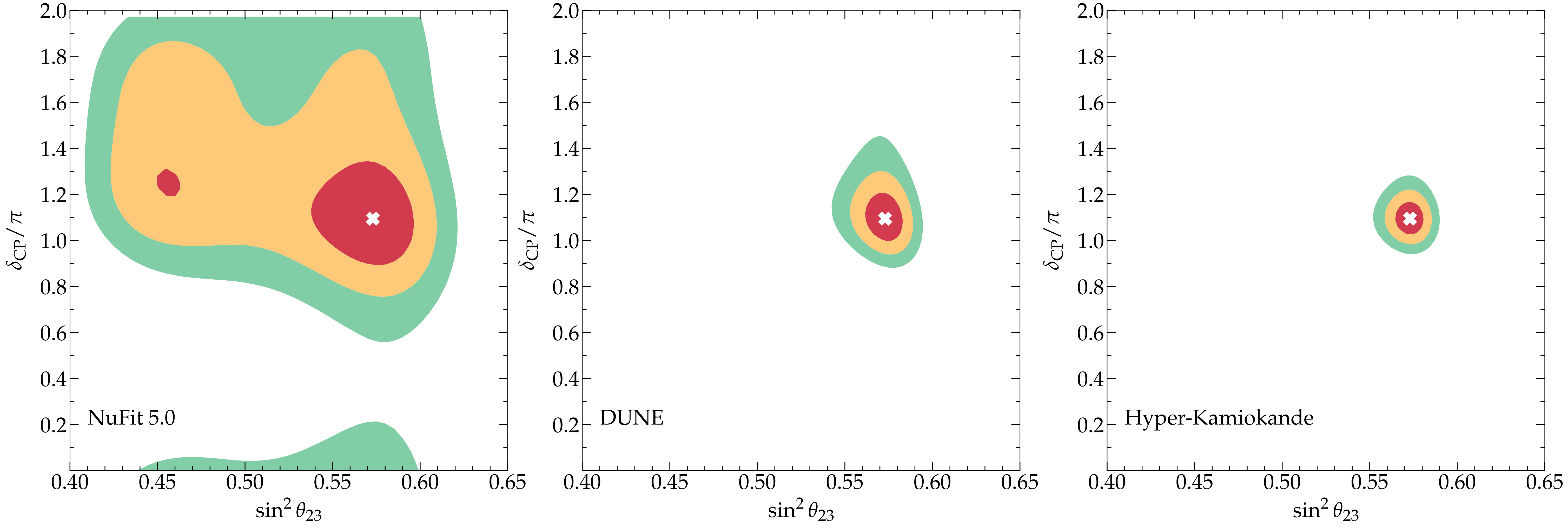
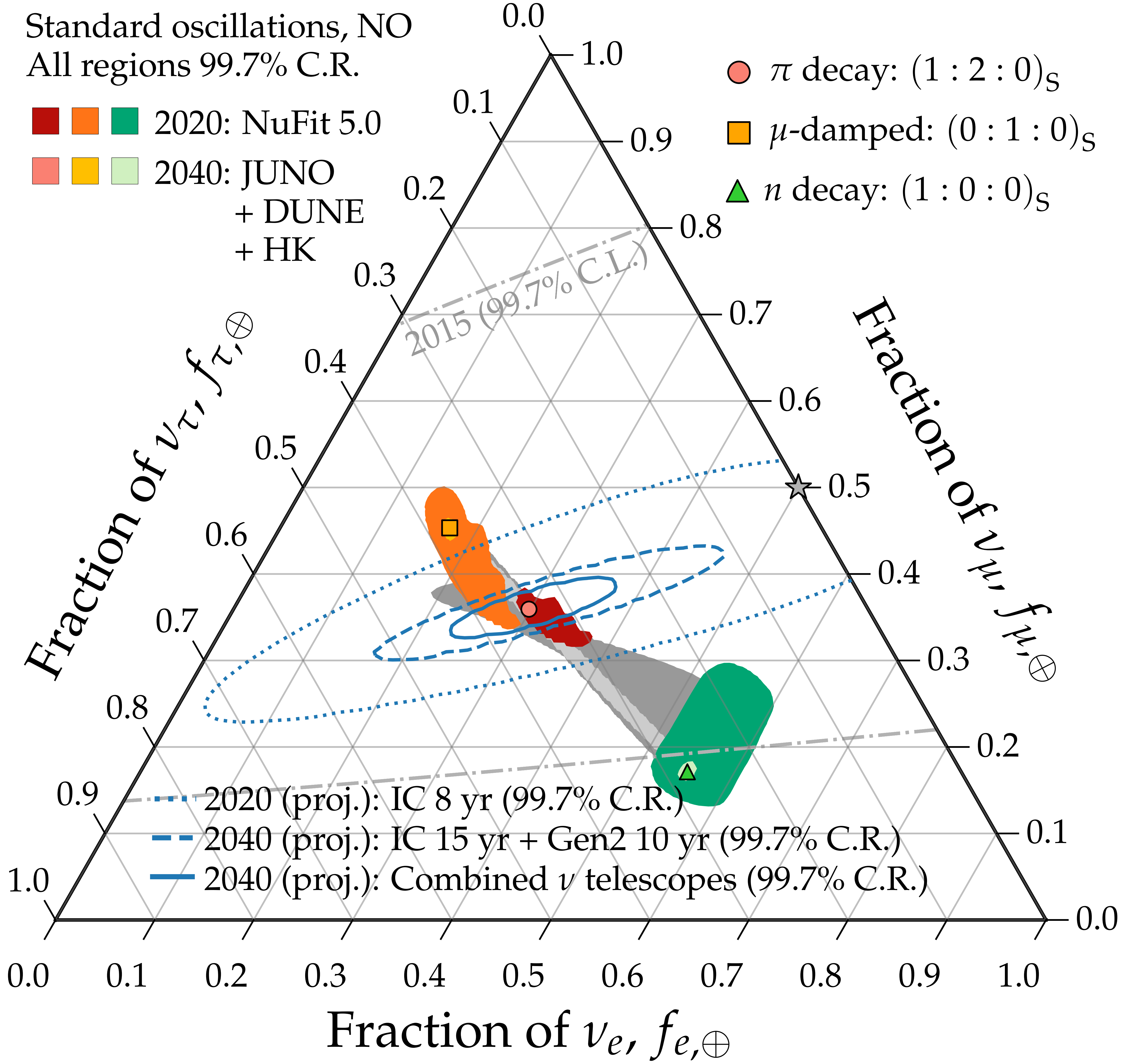


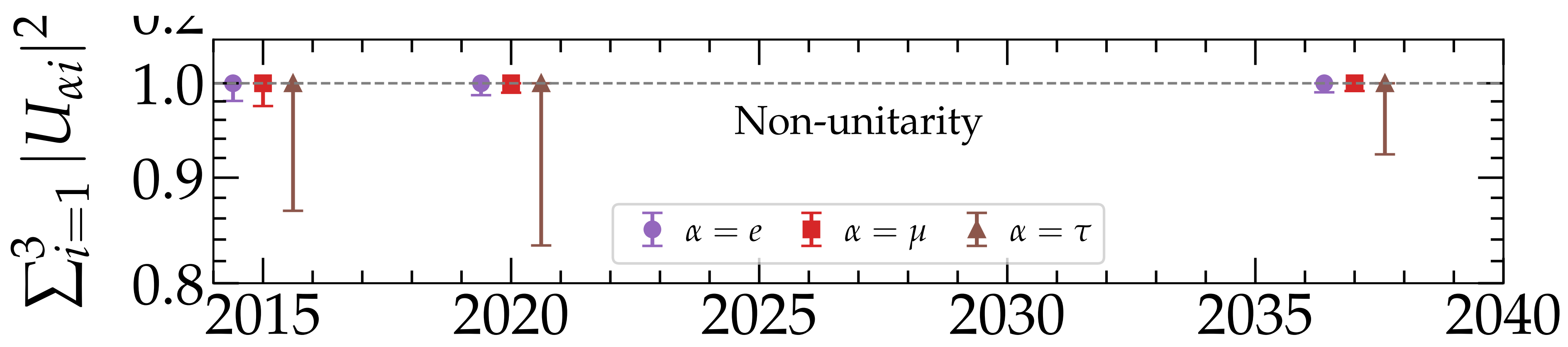


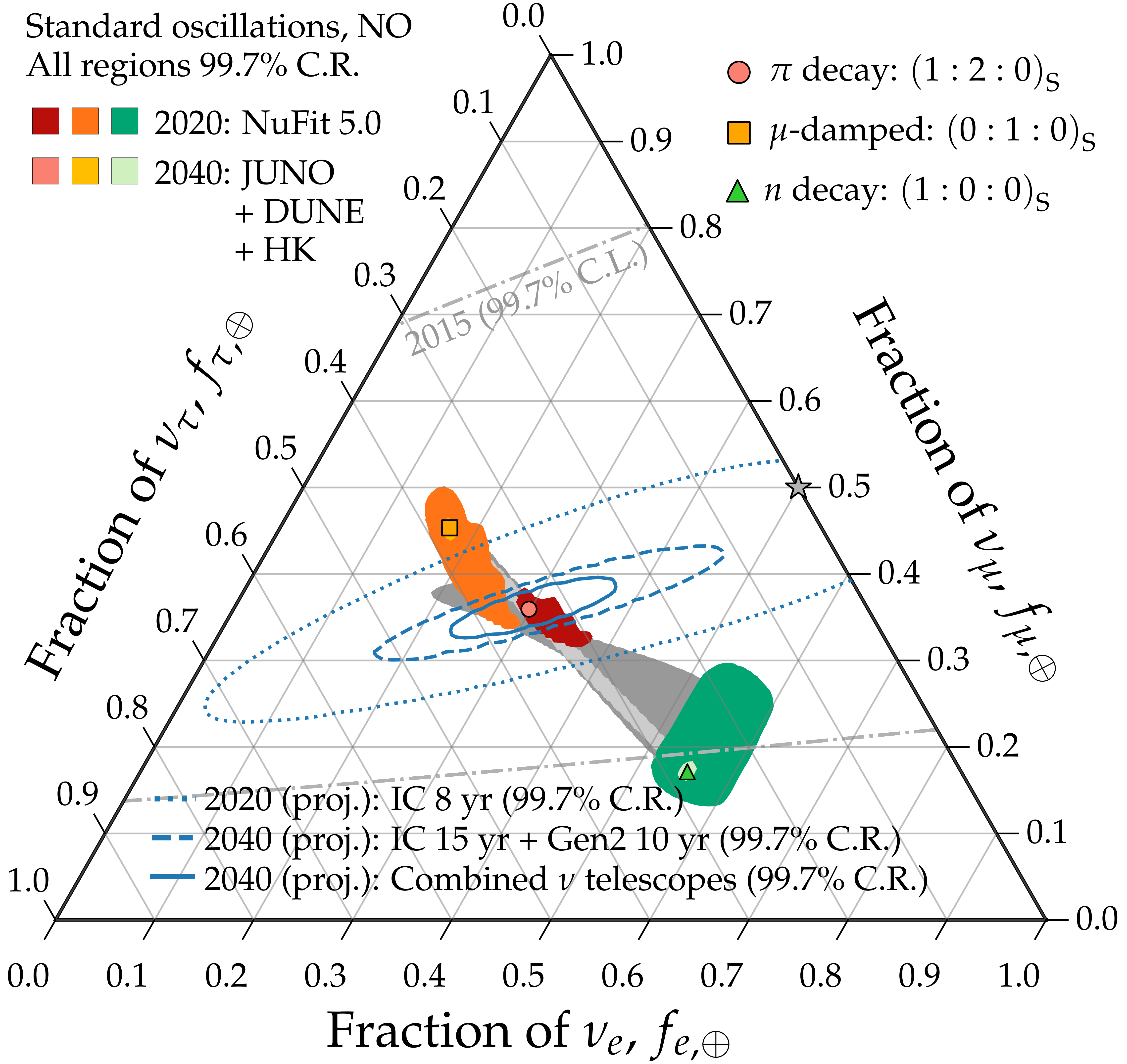


Grey: allowed region within the standard model
Colours: allowed region assuming a single source composition

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

Without assuming unitary 3x3 PMNS matrix?





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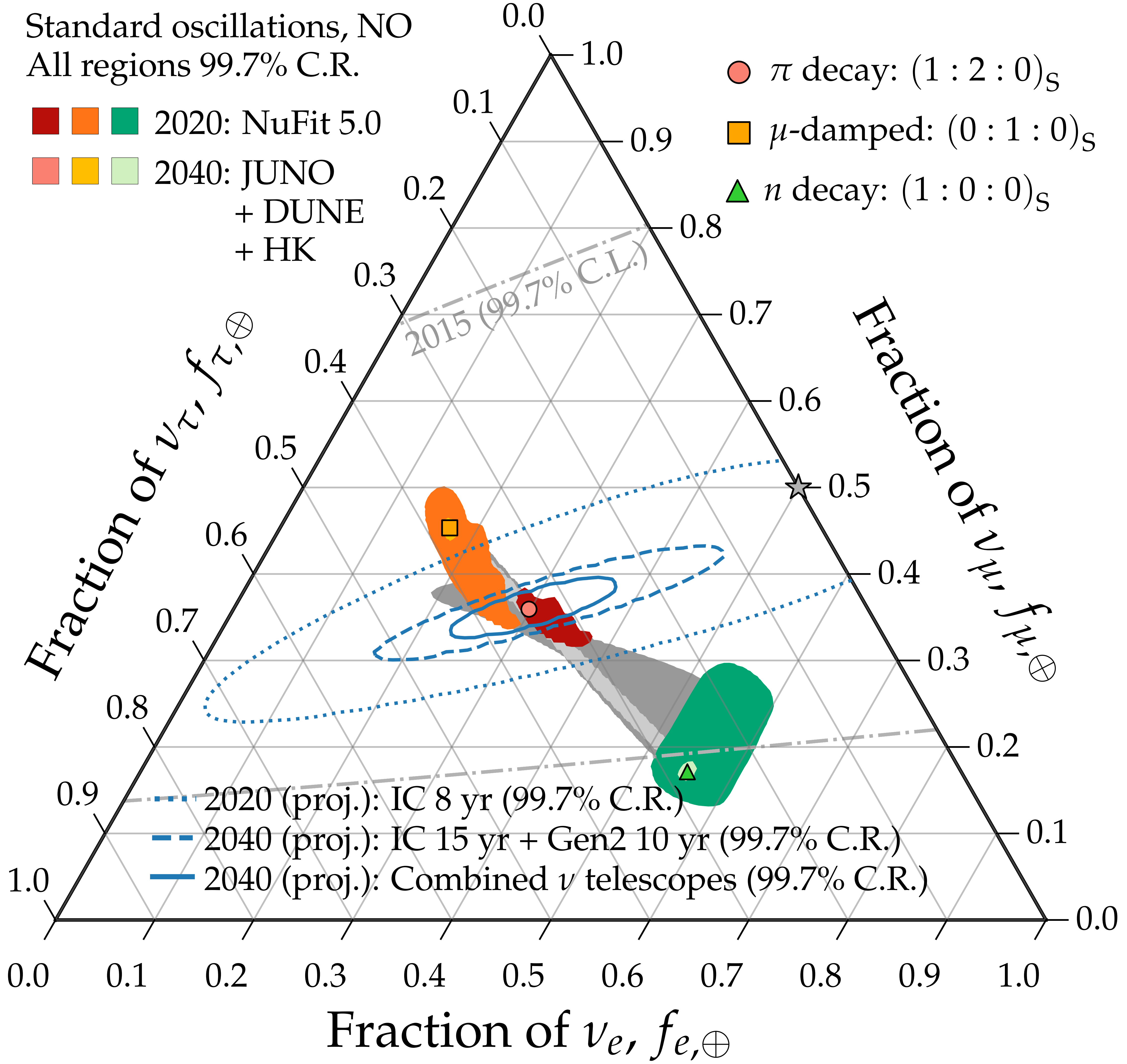

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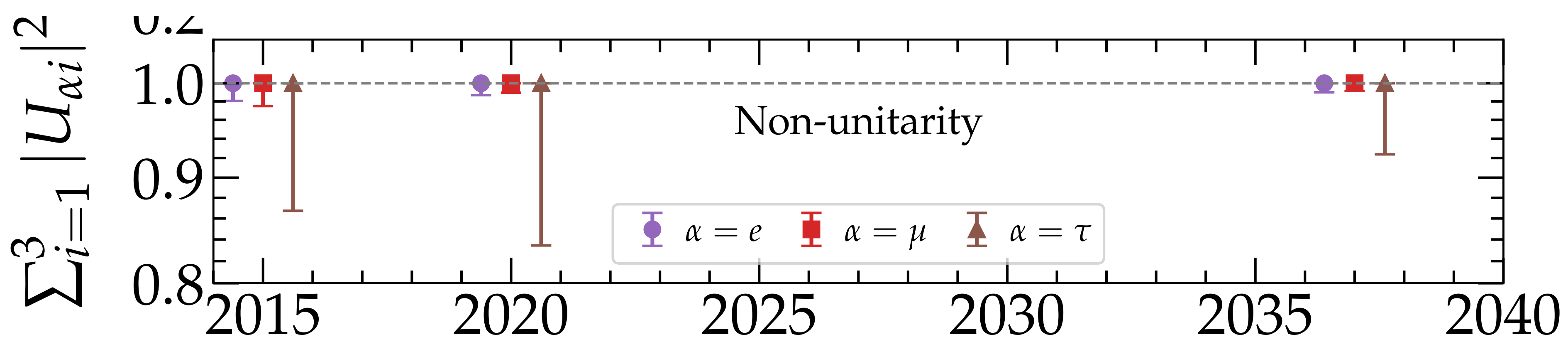
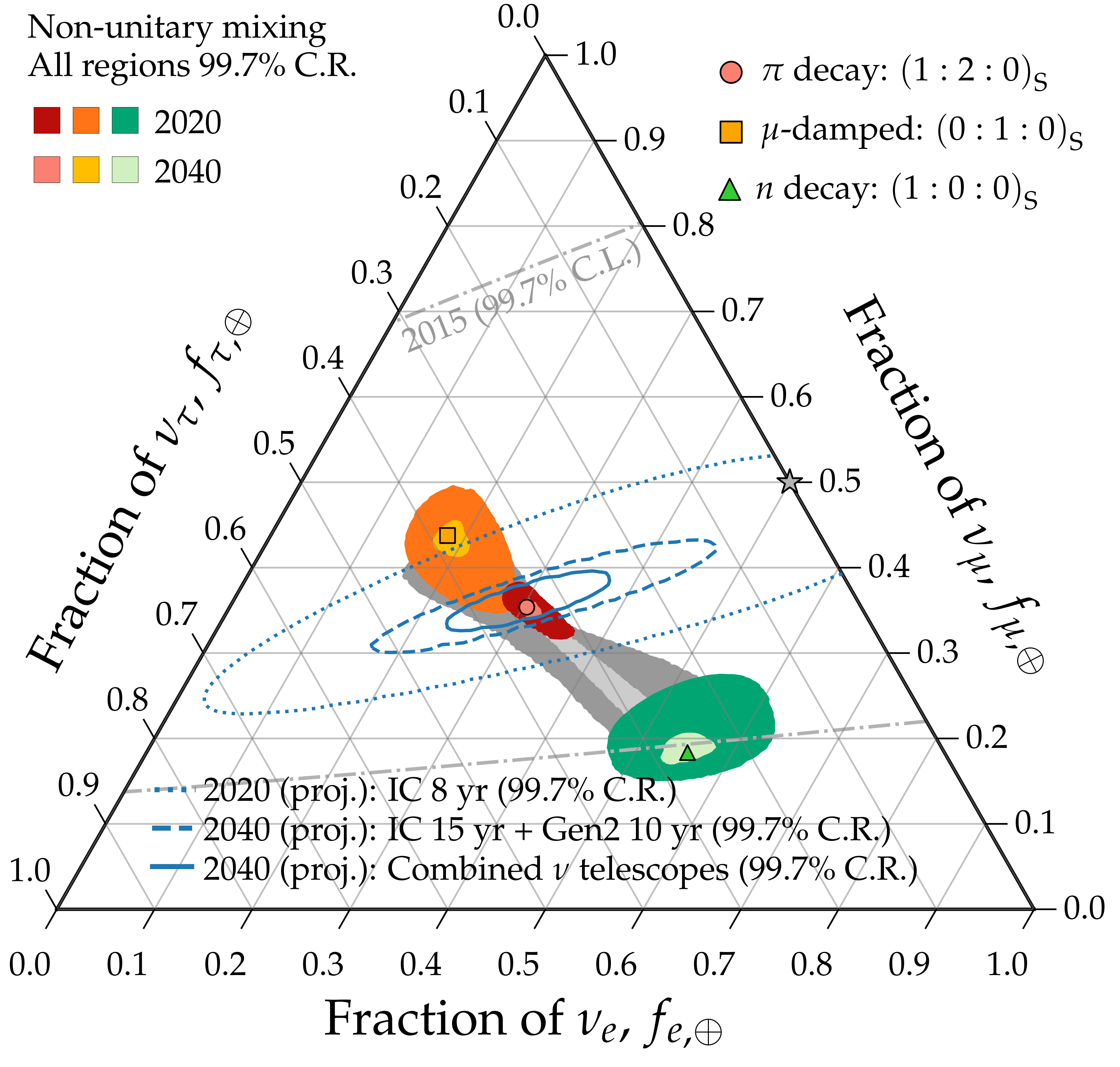
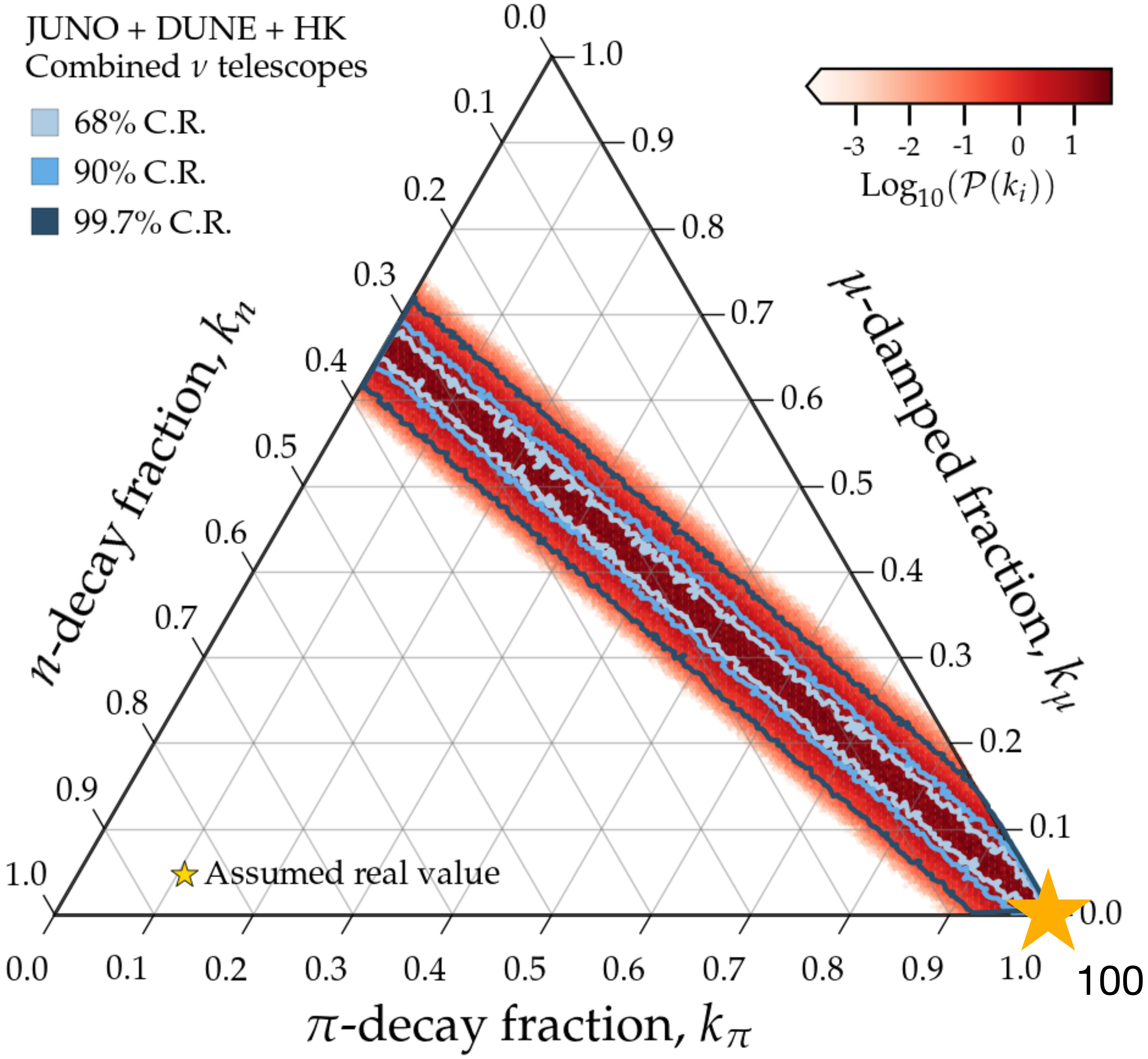




Flavour composition at the source?

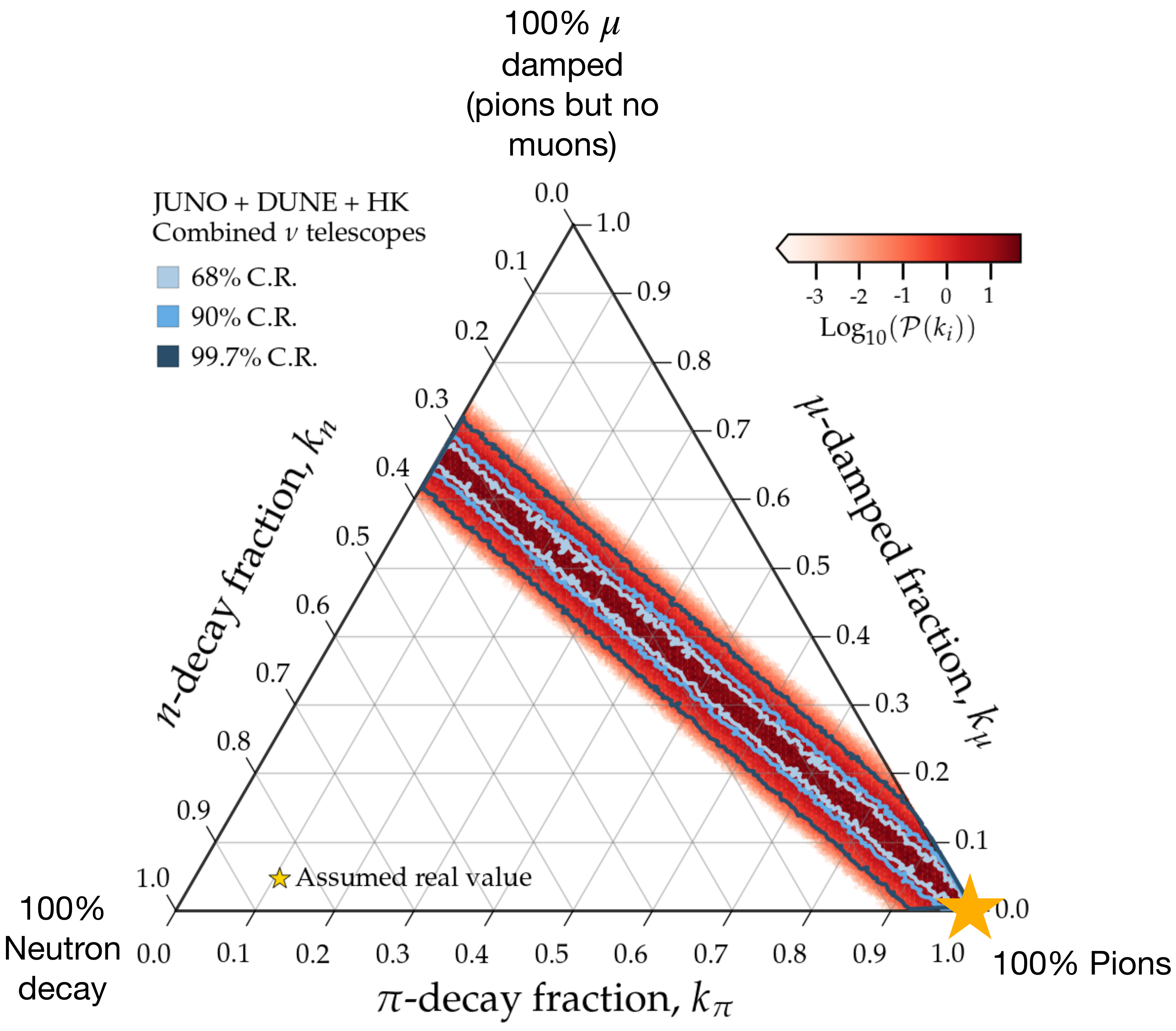


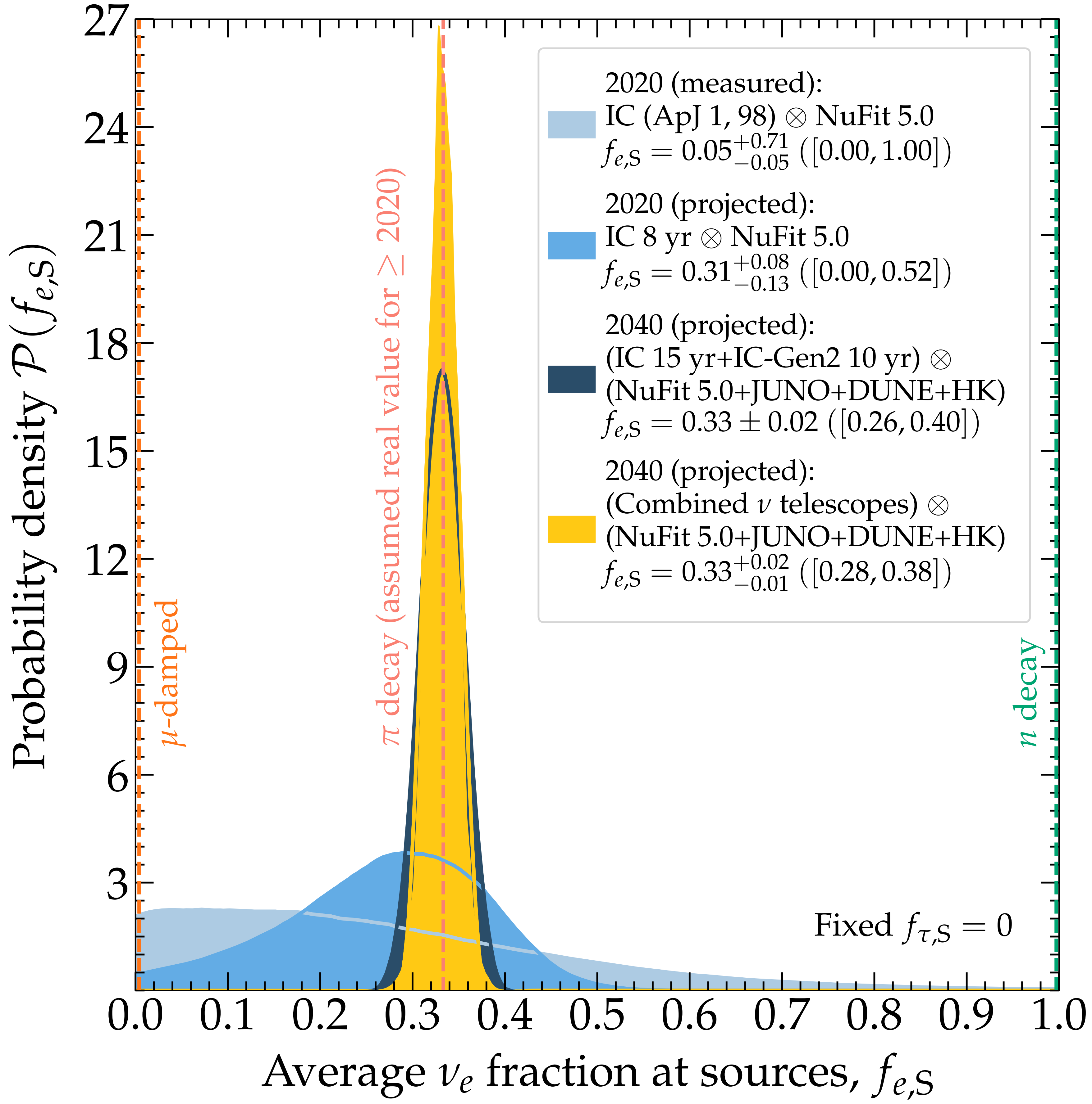
100% μ damped (pions but no muons)

100% Neutron decay

100% Pions

Flavour composition at the source?

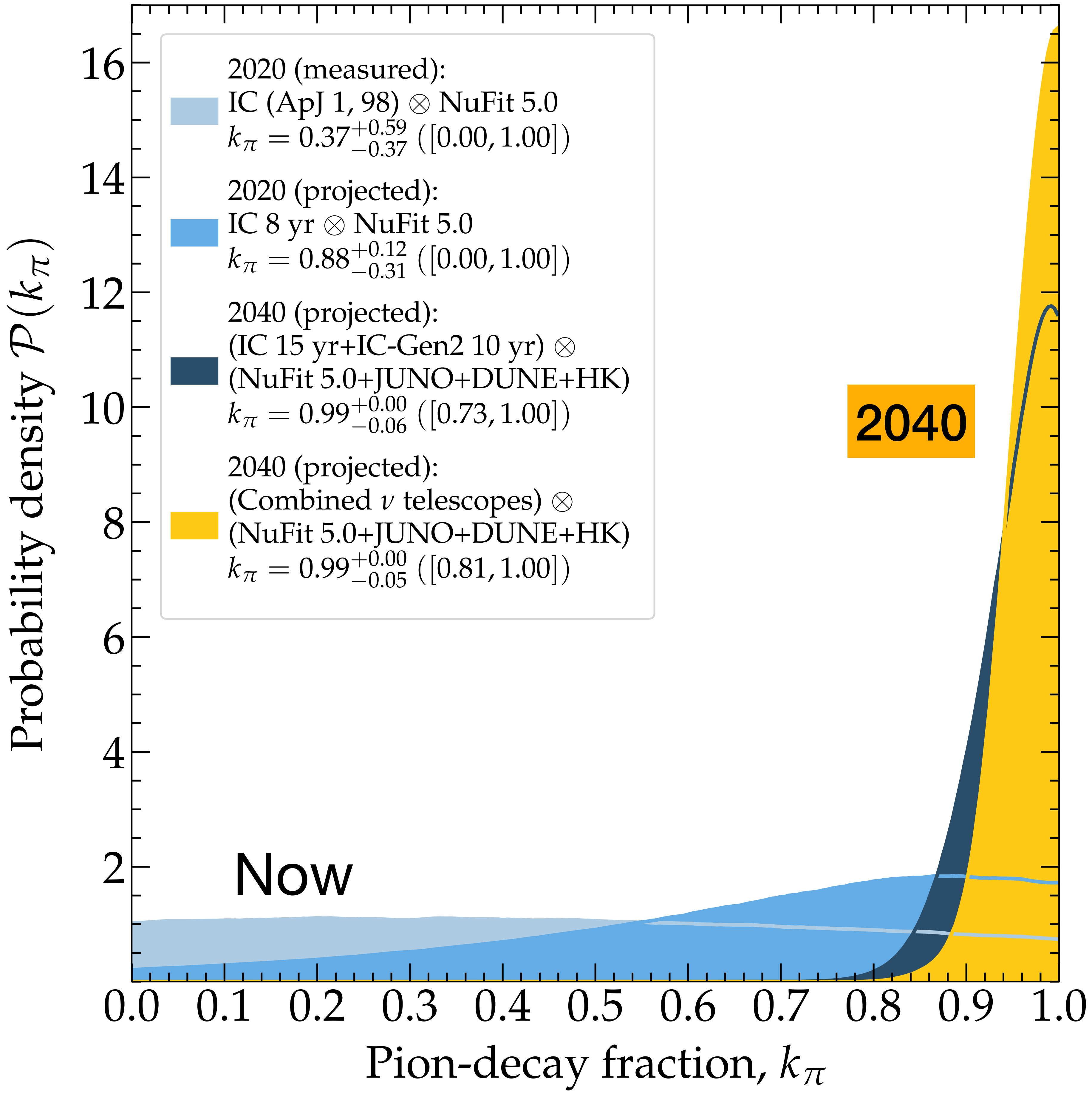




Flavour composition at the source

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.

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

neutrino lifetime at rest

Must be integrated over distribution of cosmic sources

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

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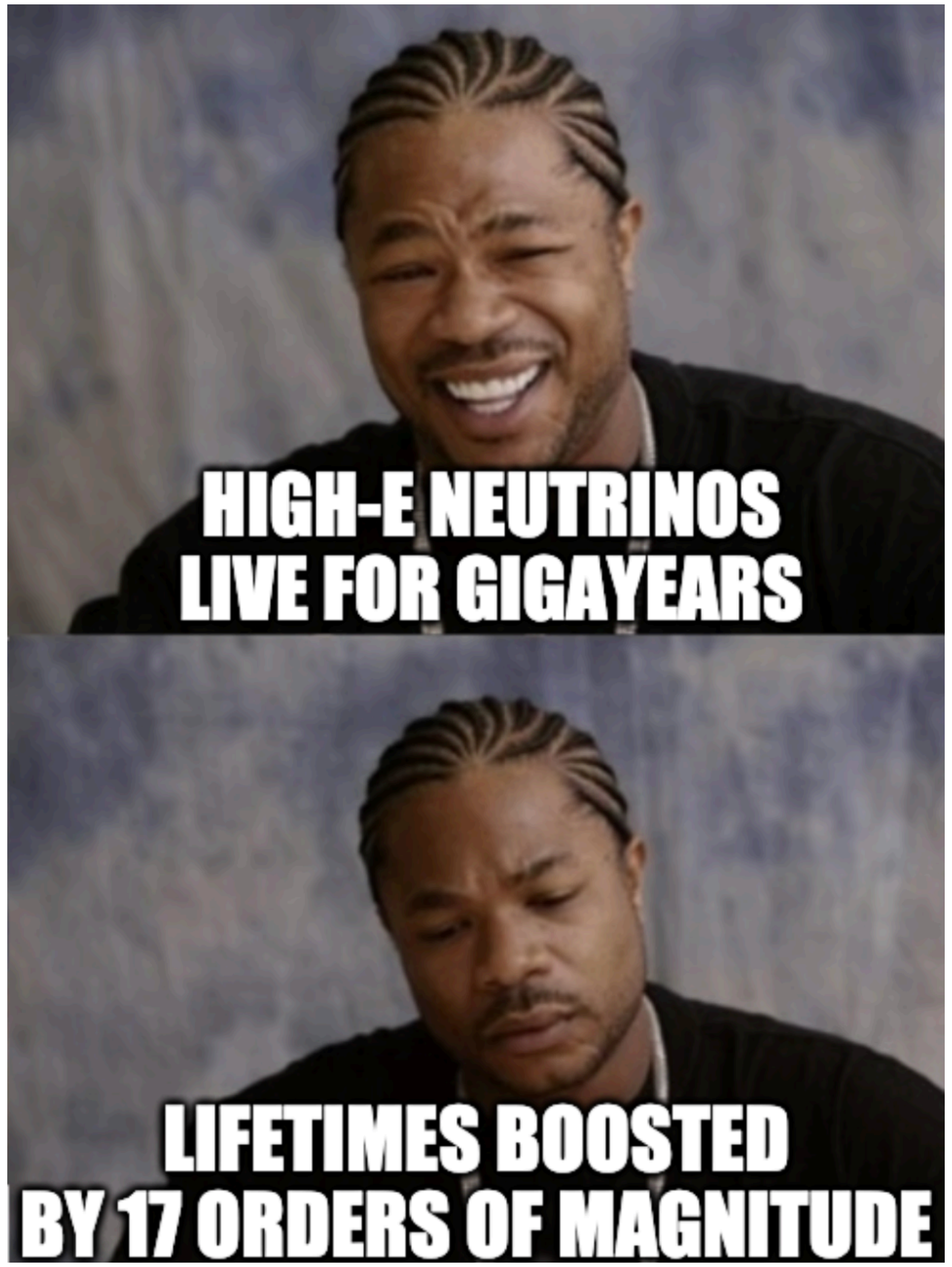

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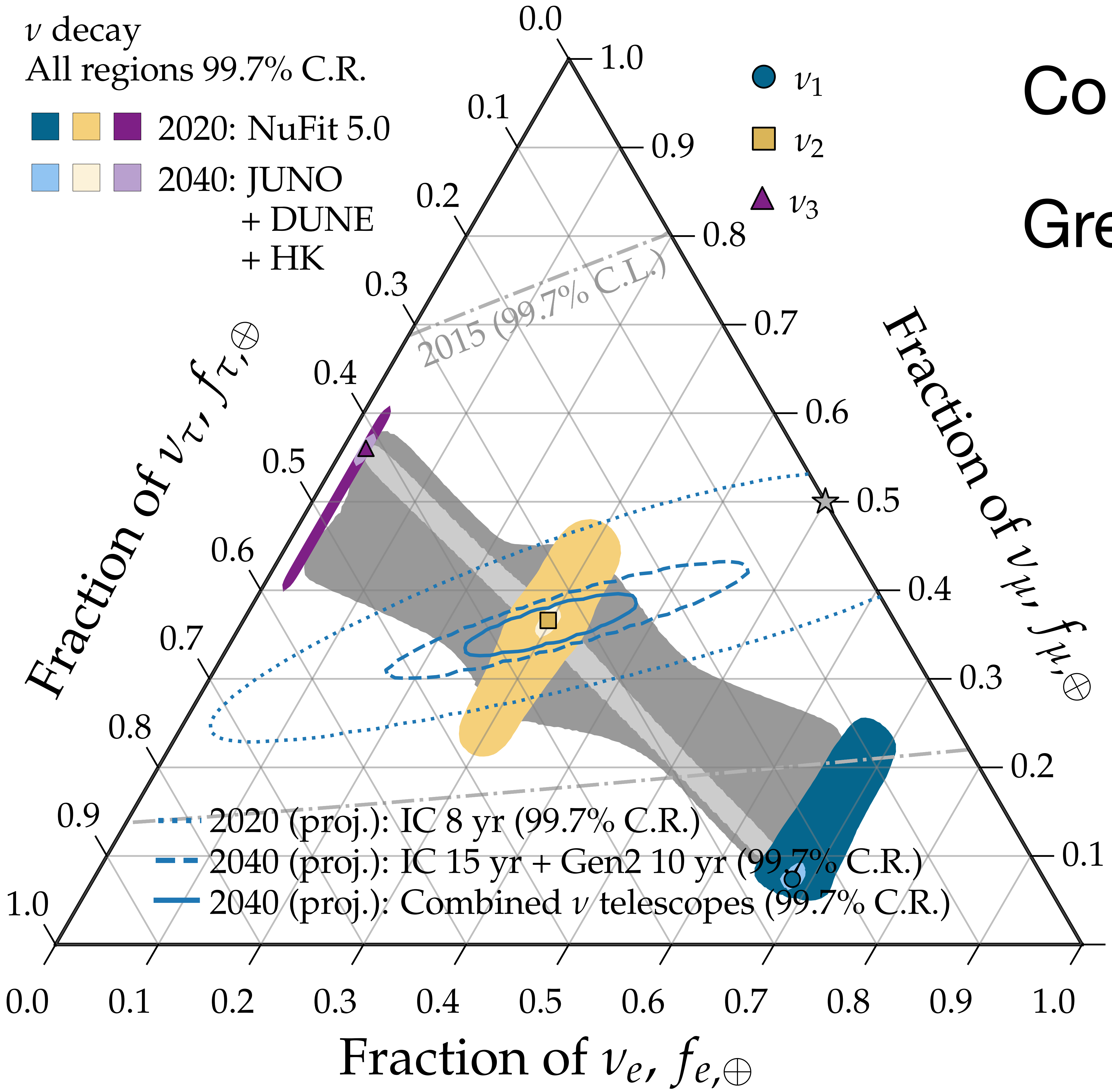
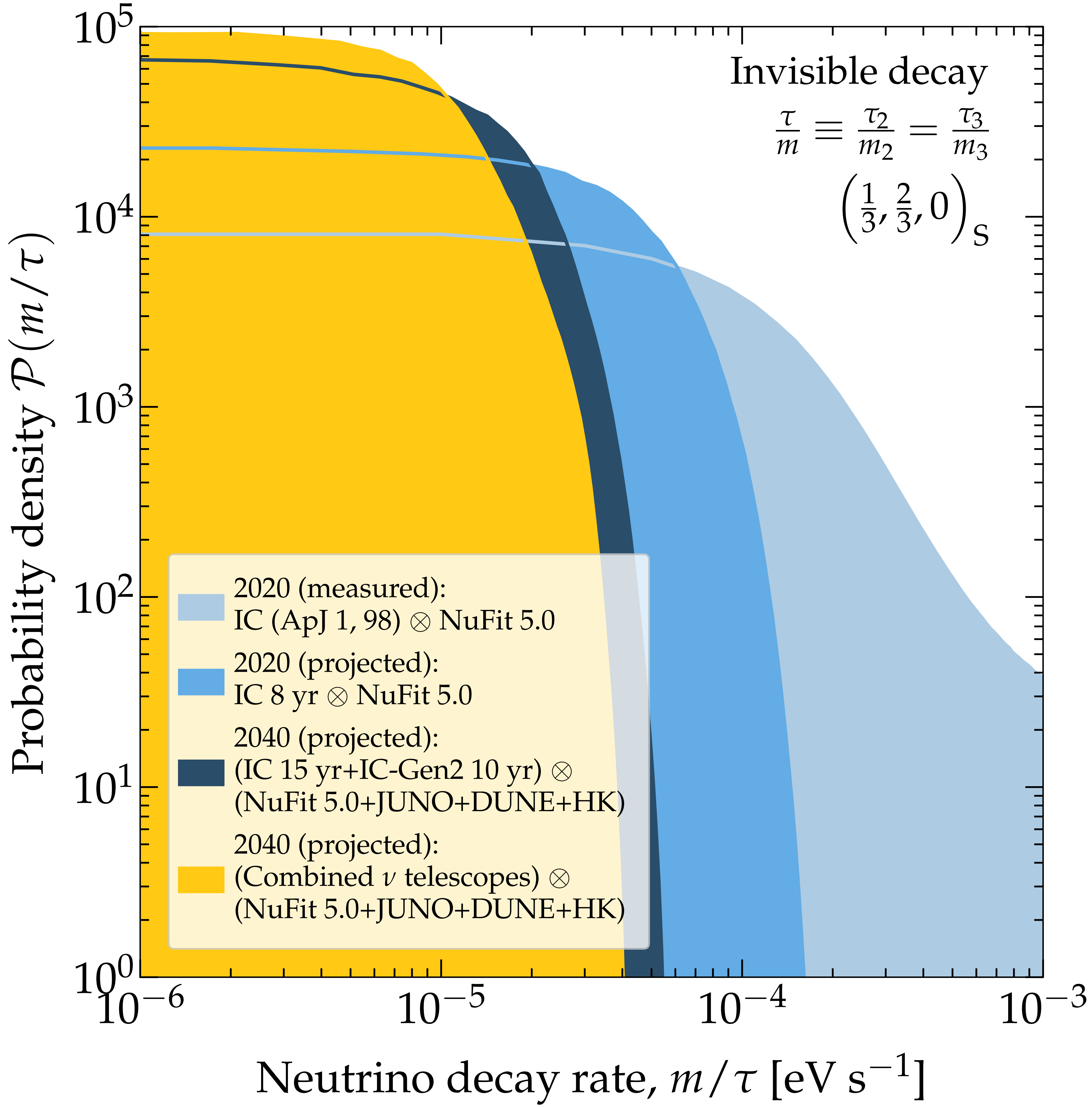
Sensitivity to single mass eigenstates

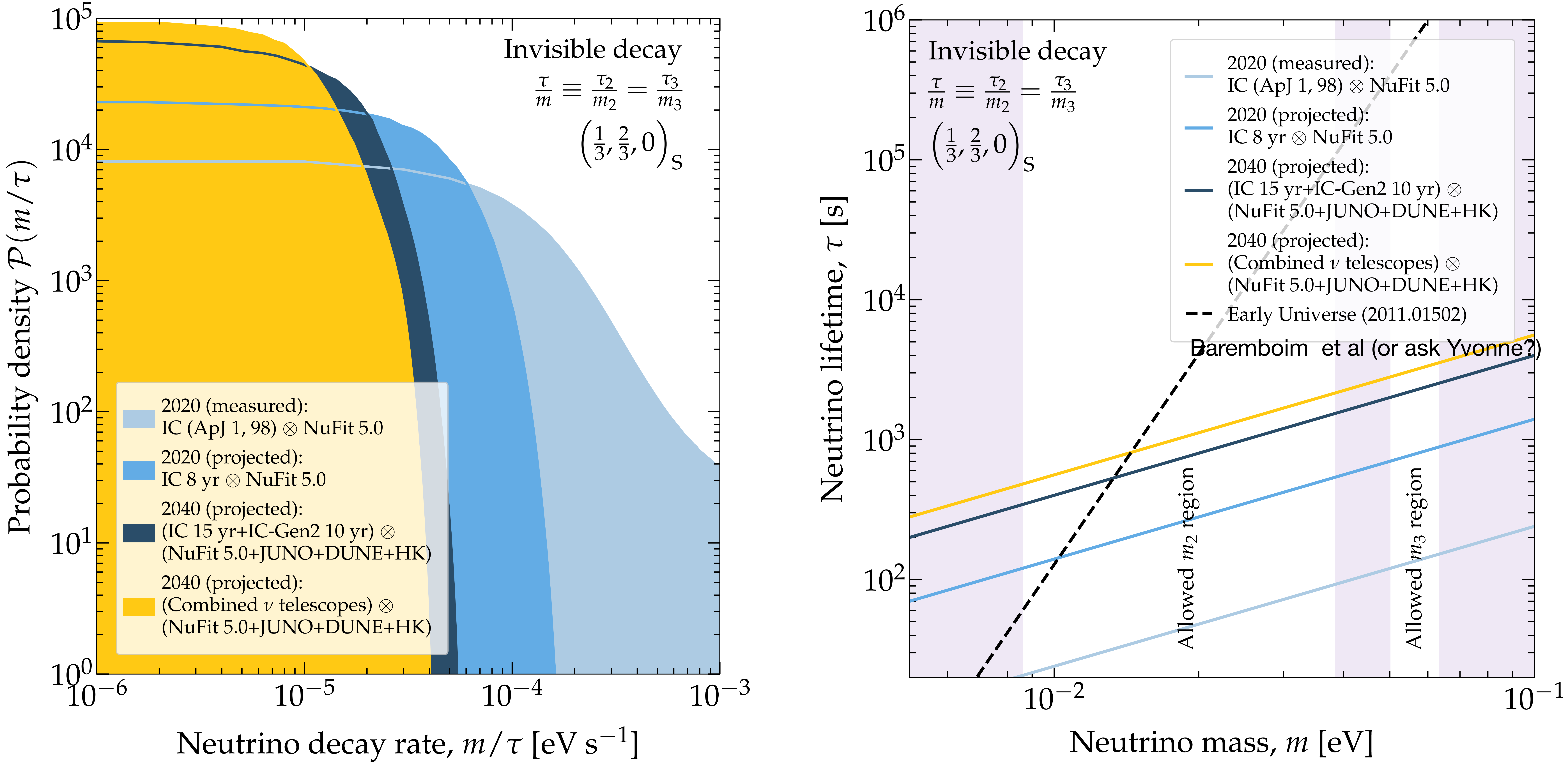


Colour: full decay

Grey: partial decay

Full decay of m_2 and m_3 almost excluded now


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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10^0
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Neutrino mass, m [eV]
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10^3
10^4
10^5
10^6
10^{-2}
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(Combined ν telescopes) ⊗
(NuFit 5.0+JUNO+DUNE+HK)
Early Universe (2011.01502)
Baremboim et al (or ask Yvonne?)
Allowed m_2 region
Allowed m_3 region

Dark matter

Dark Matter Annihilation to Neutrinos

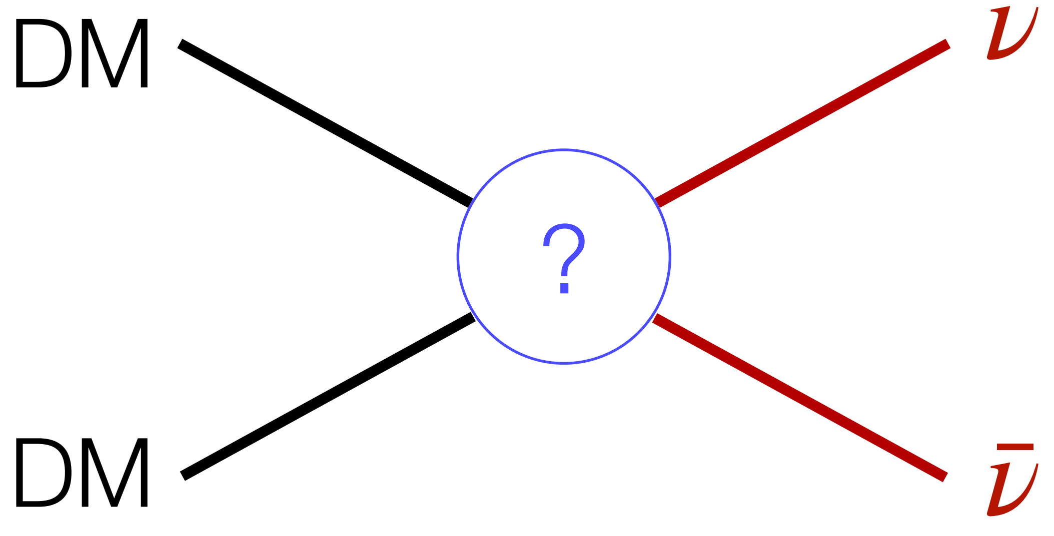
Carlos A. Argüelles, Alejandro Diaz, Ali Kheirandish, Andrés Olivares-Del-Campo, Ibrahim Safa, Aaron C. Vincent

[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



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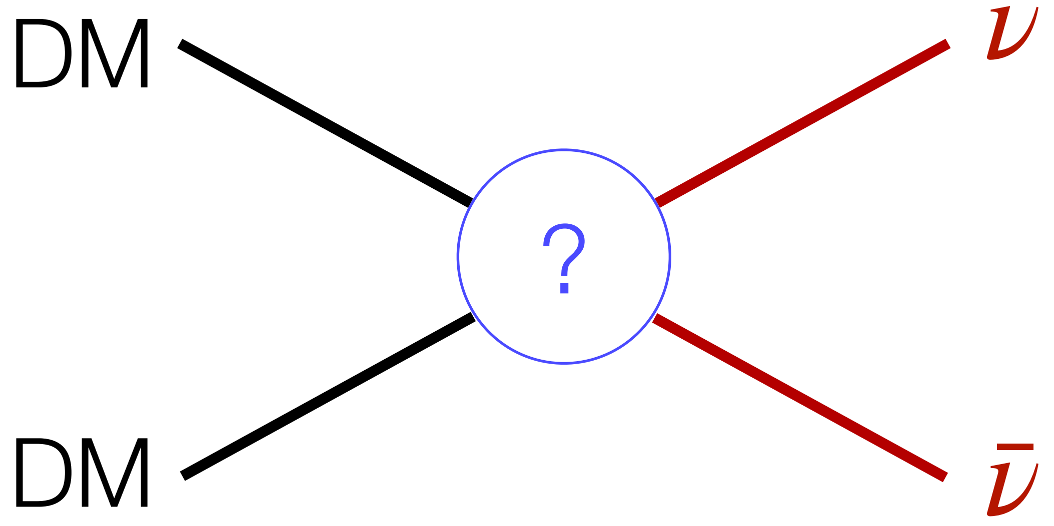
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\kappa m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE_\nu}J(\Omega)$$

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



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

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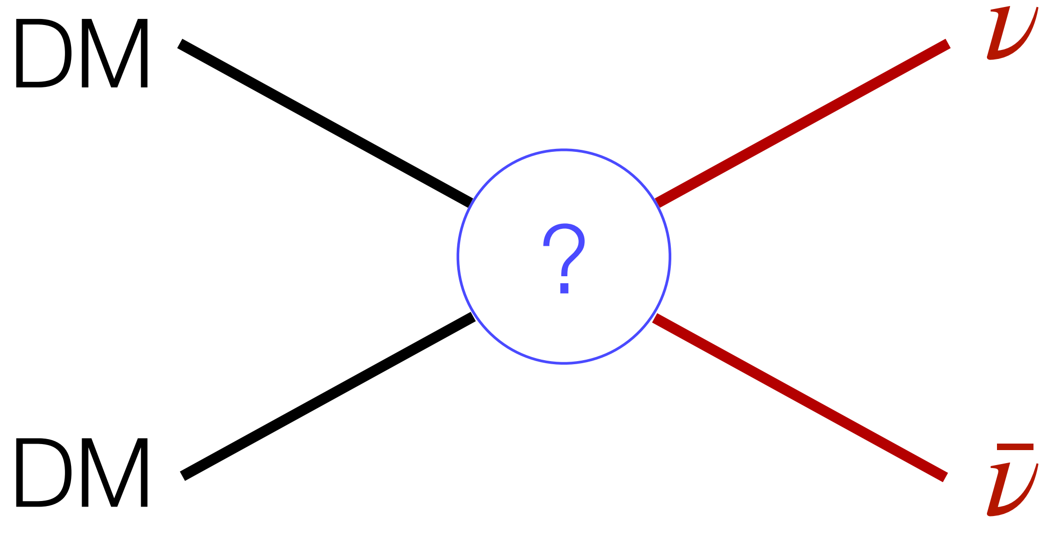

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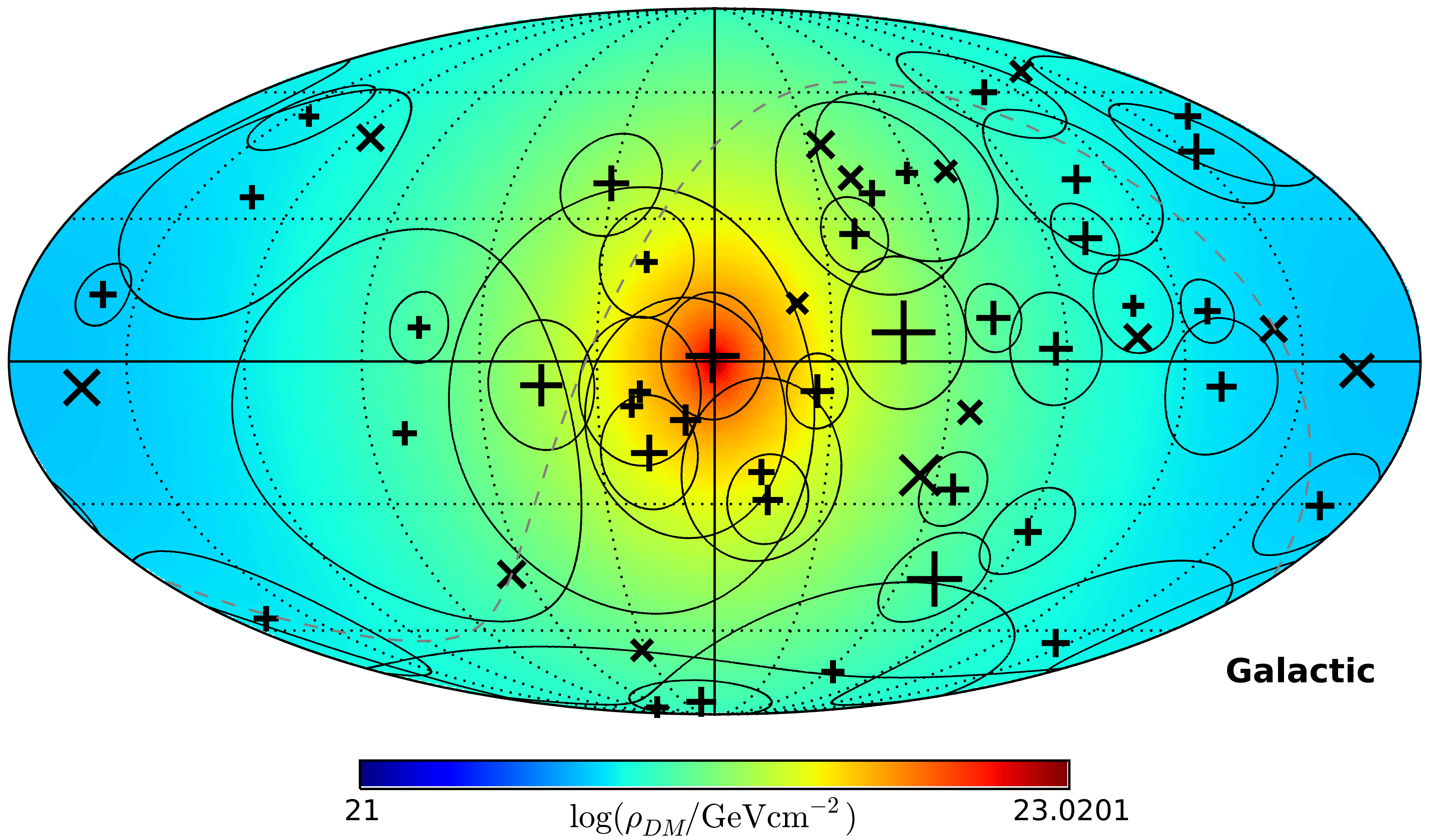
Dark matter column density



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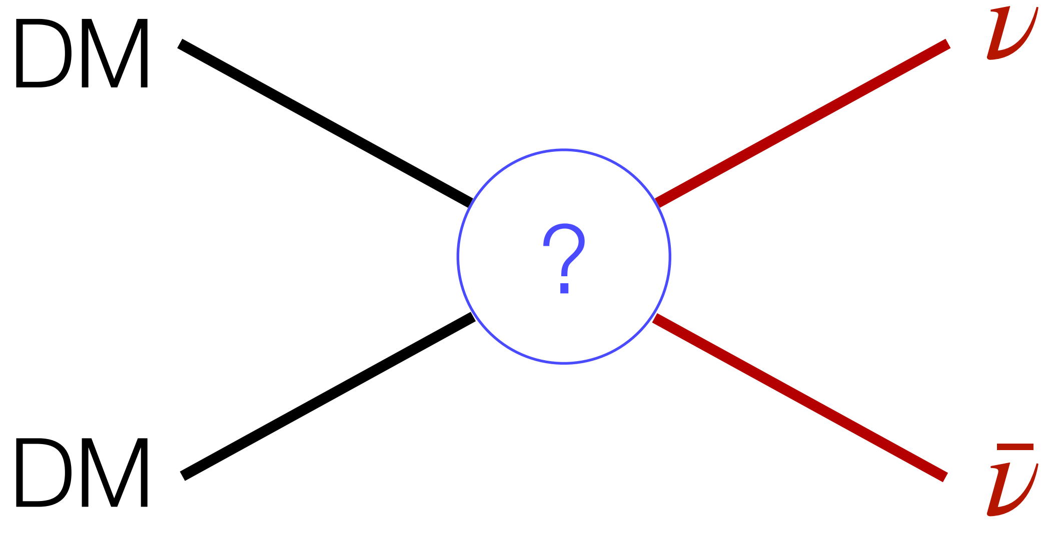

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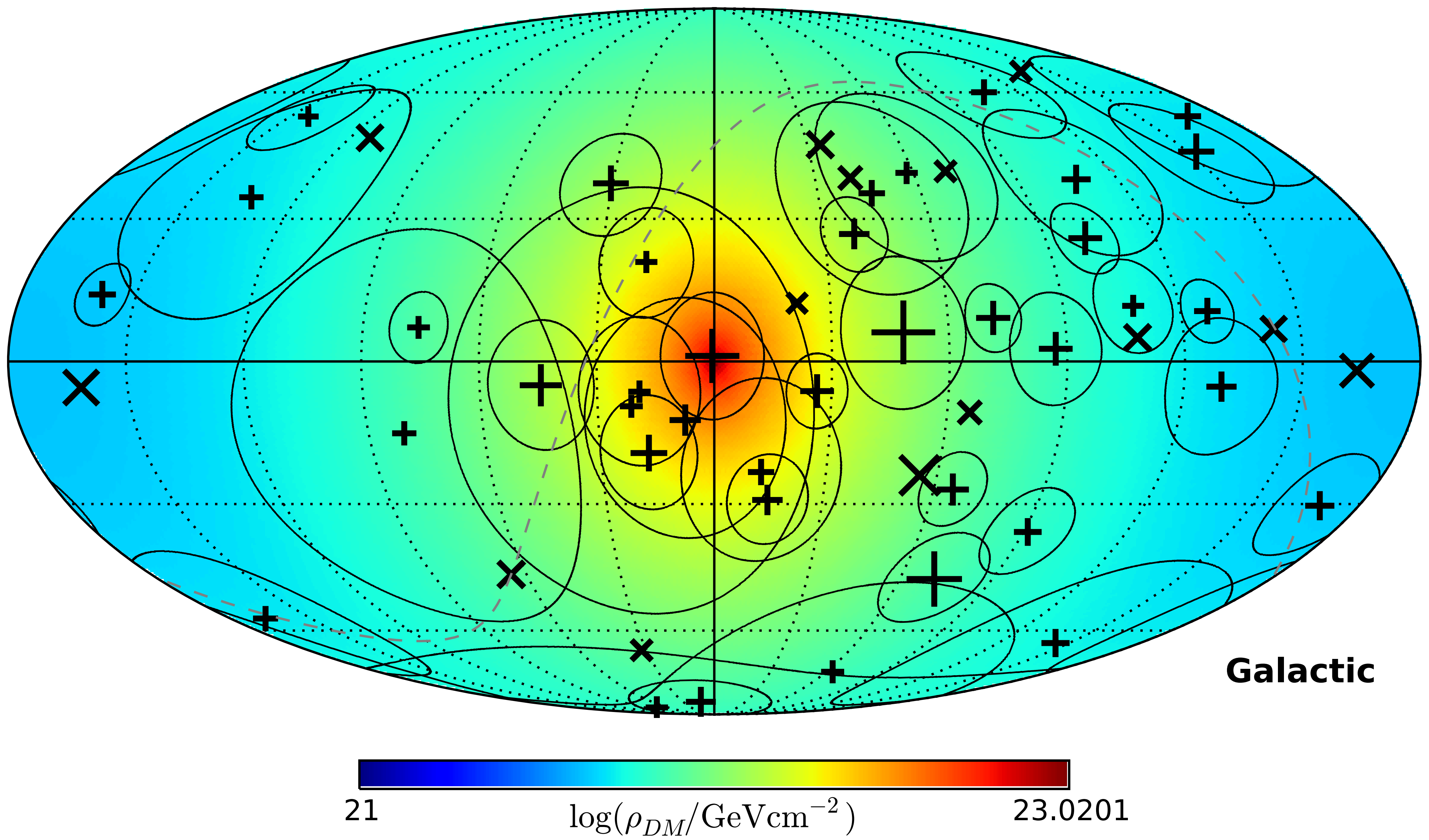
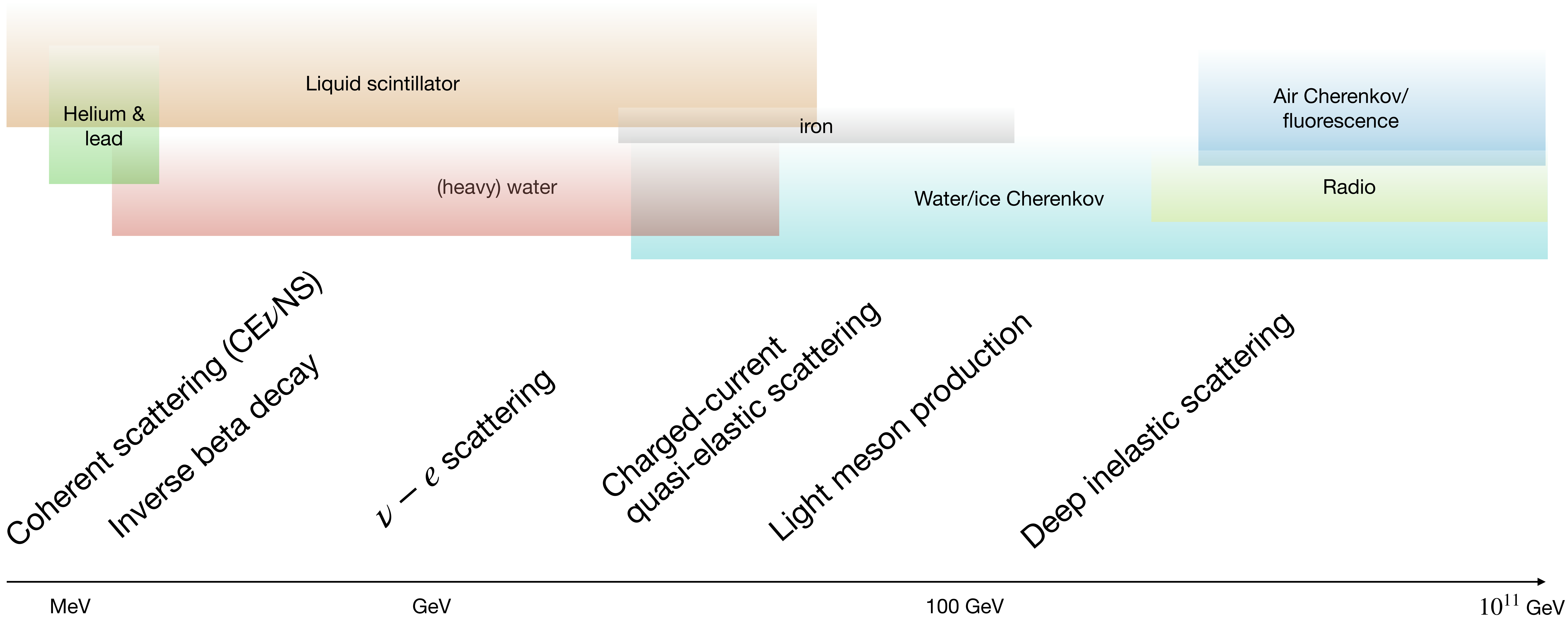
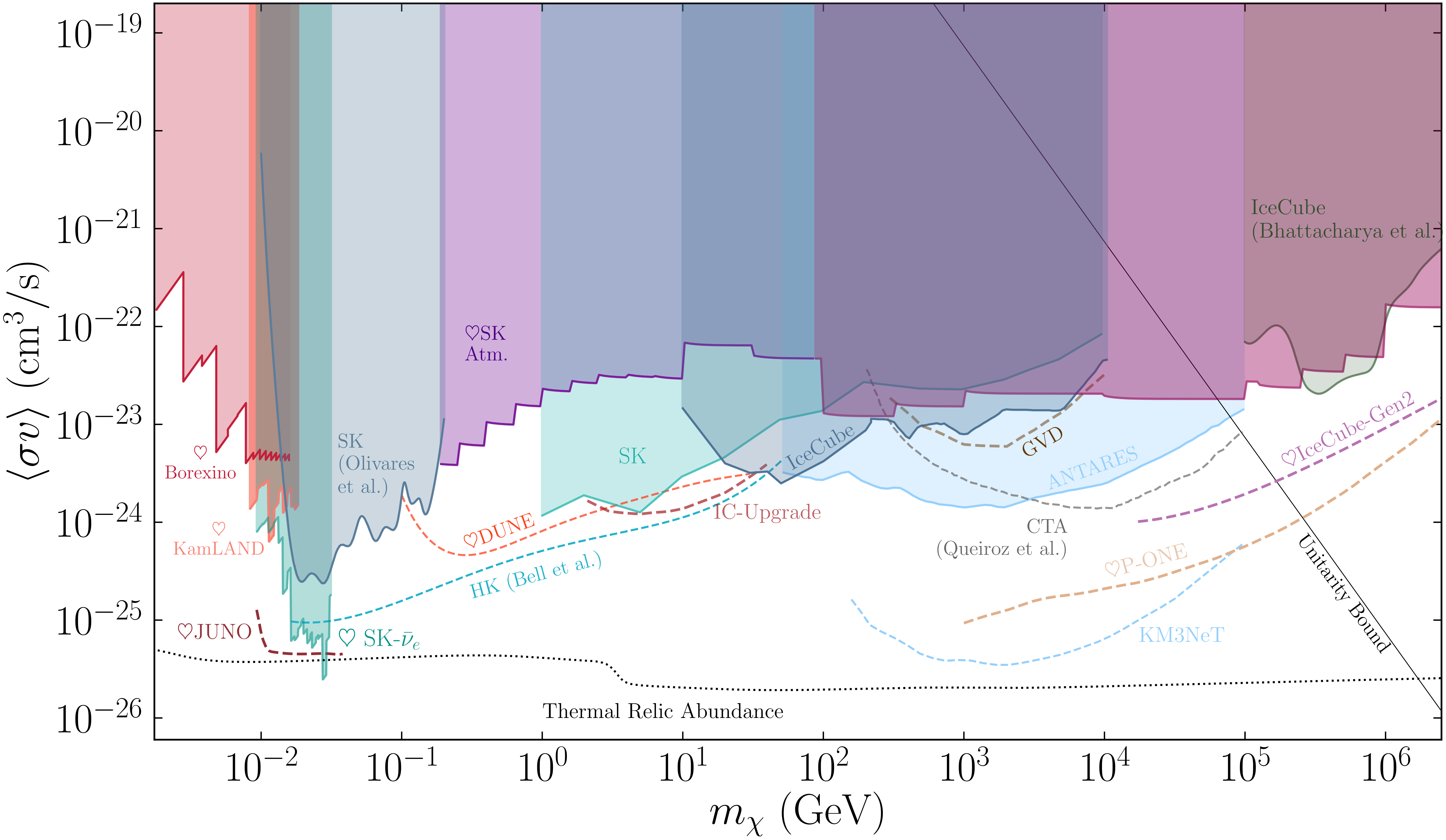
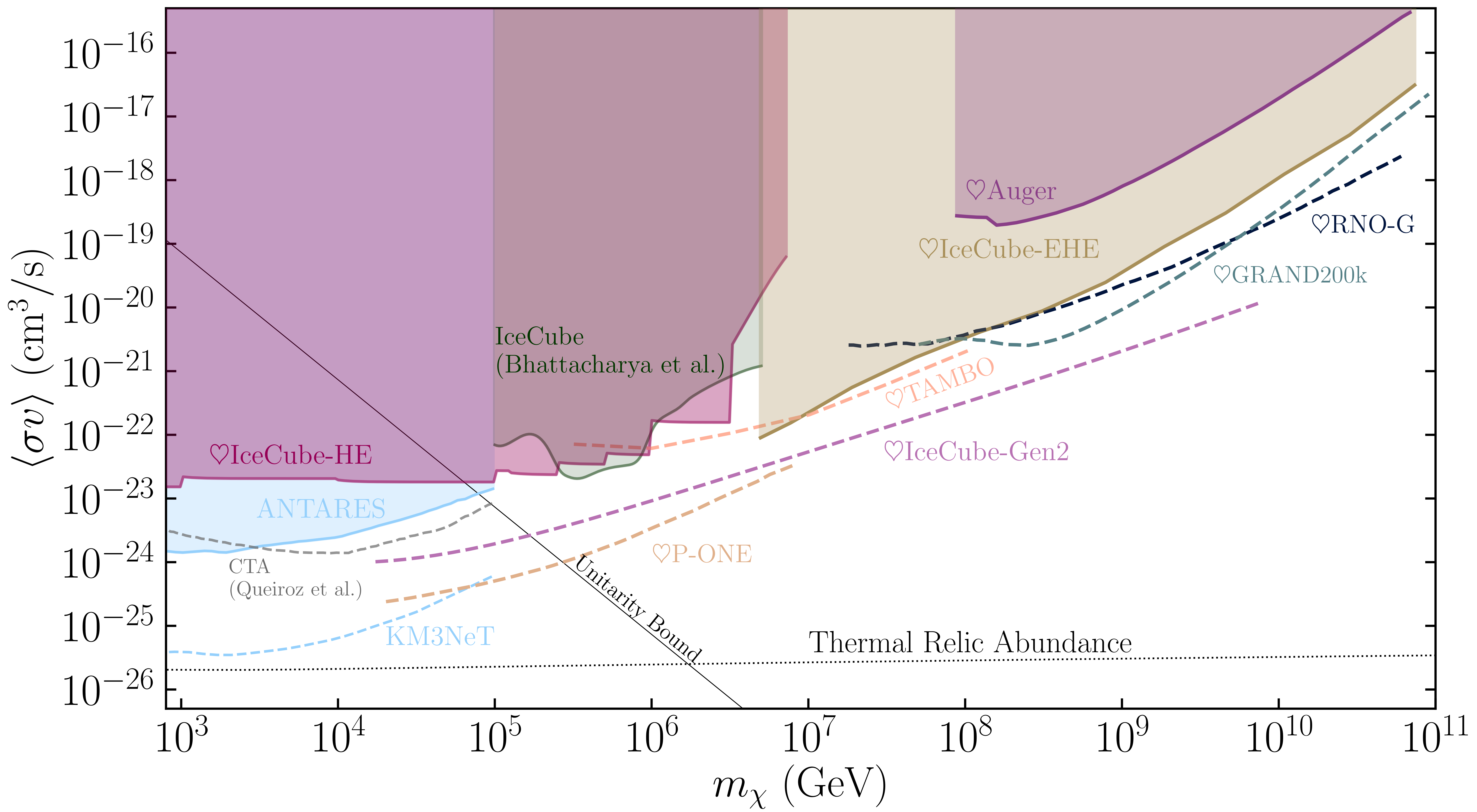


*We also spent a long time calculating extragalactic constraints. They are subdominant though

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

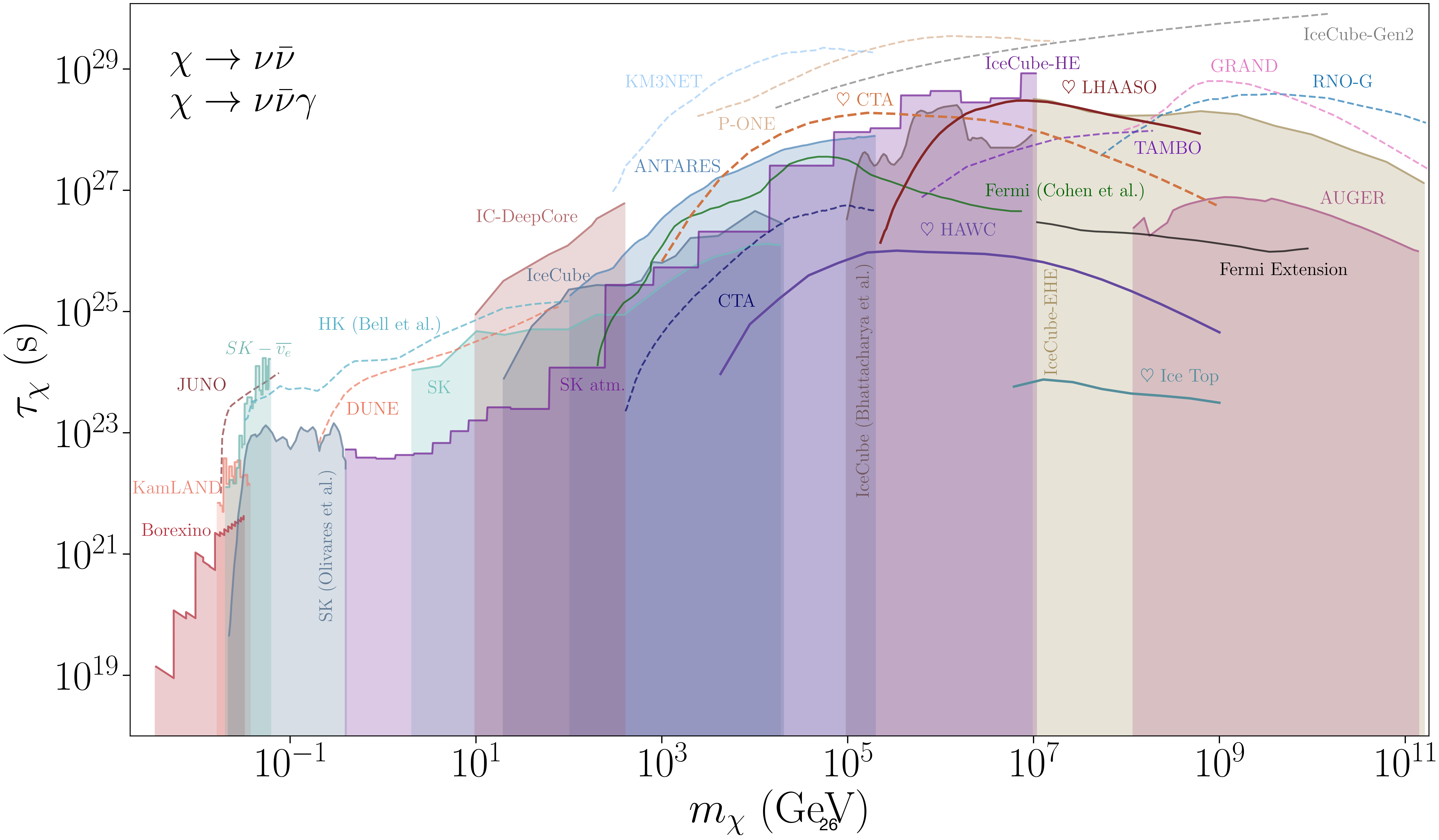



10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$\langle \sigma v \rangle$ (cm^3/s)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
m_χ (GeV)
♡ Borexino
♡ KamLAND
♡JUNO
SK (Olivares et al.)
♡ SK-$\bar{\nu}_e$
♡SK Atm.
♡DUNE
HK (Bell et al.)
SK
IC-Upgrade
IceCube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


10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$\langle \sigma v \rangle$ (cm^3/s)
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
m_χ (GeV)
♡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

Decay to $\chi \to \bar{\nu}\nu$

(Argüelles, Delgado, Friedlander, Kheirandish, Safa, ACV, White, preliminary)



Large extra dimensions

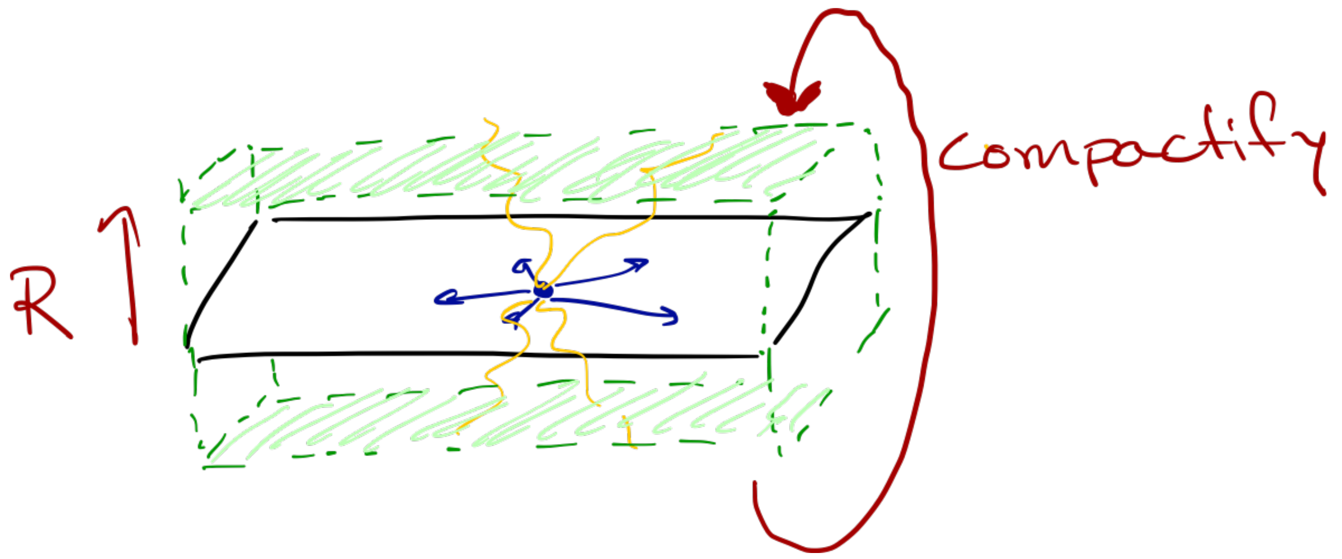
Signatures of microscopic black holes and extra dimensions at future neutrino telescopes

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

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

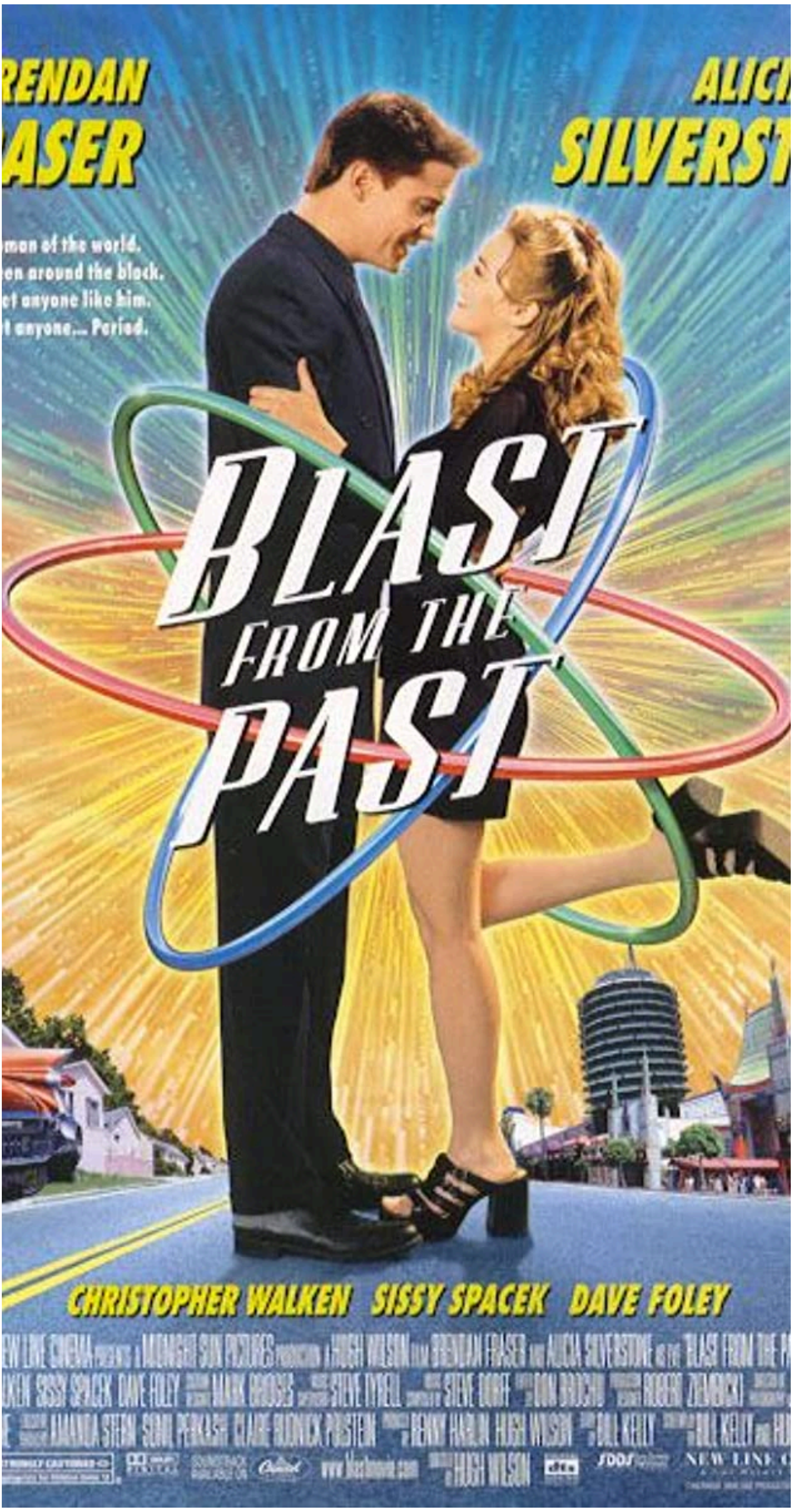
High energies: Black holes from large extra dimensions (ADD)

If the scale of gravity is set by extra dimensions,



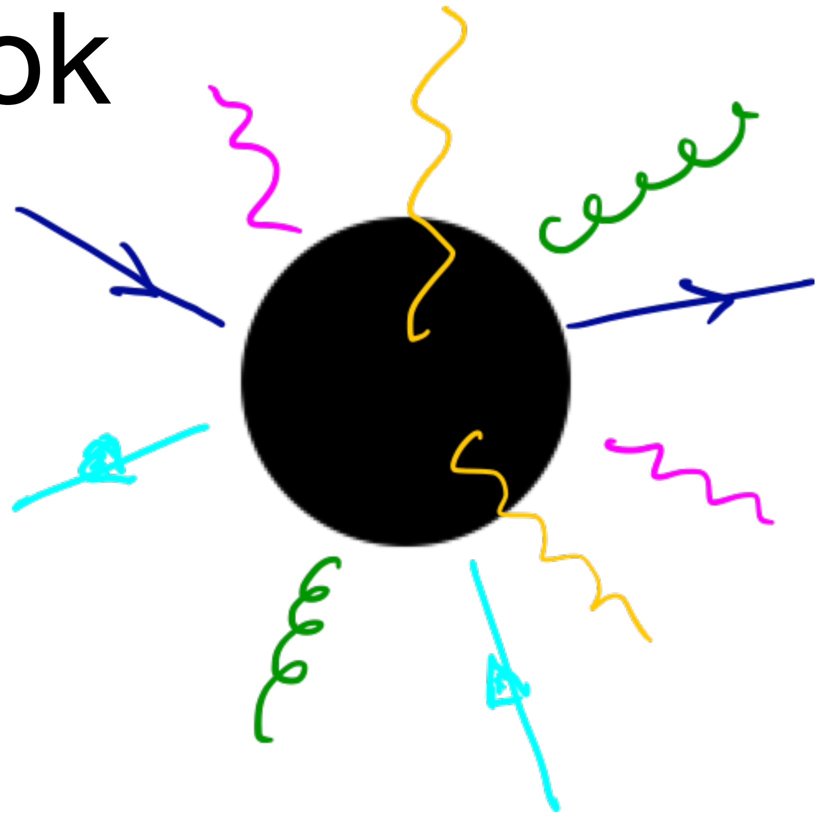
$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \ (r \ll R).$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r}, \ (r \gg R)$$



If true Planck scale $M_\star$~10 TeV: can produce microscopic black holes in high-energy collisions.

These evaporate immediately to high-energy products. Since these **anything coupled to gravity**, and most of the standard model is **hadronic**, these showers will look hadronic (as opposed to electroweak).

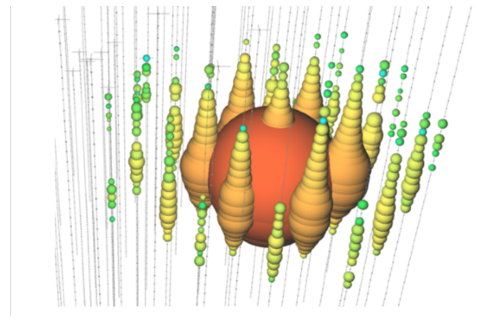


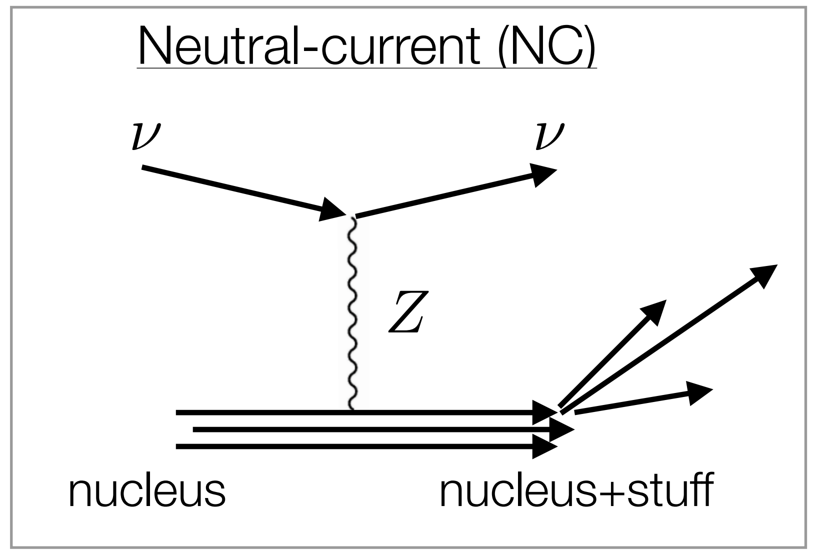
Neutrinos with E > PeV can produce CM collisions at higher energies than LHC

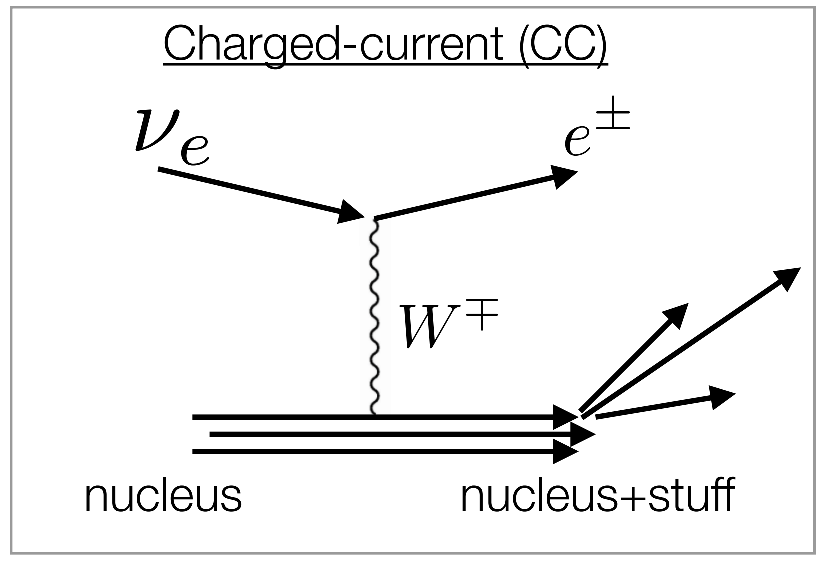
SM

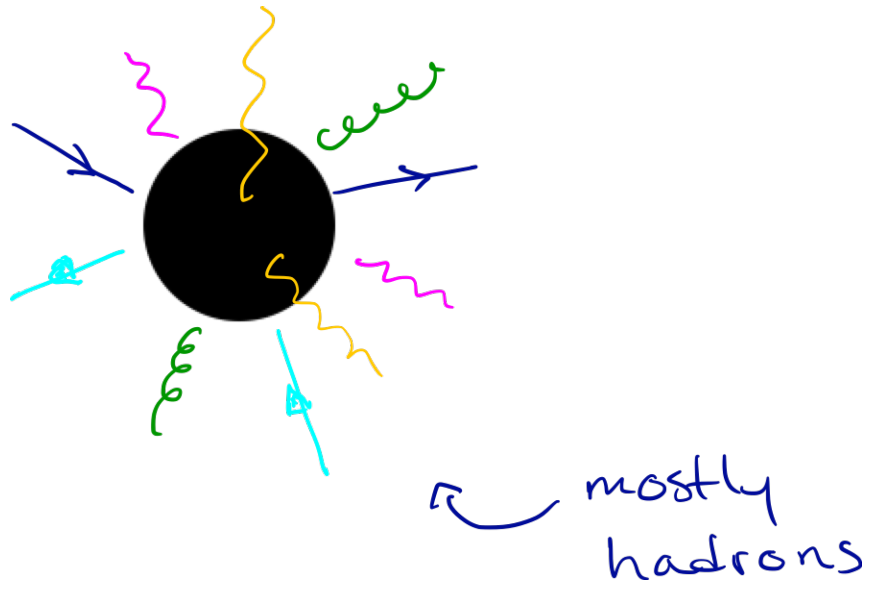
Black hole from $\nu-$nucleus collision

Showers



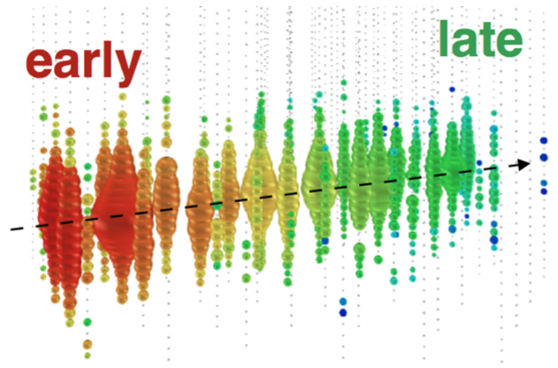


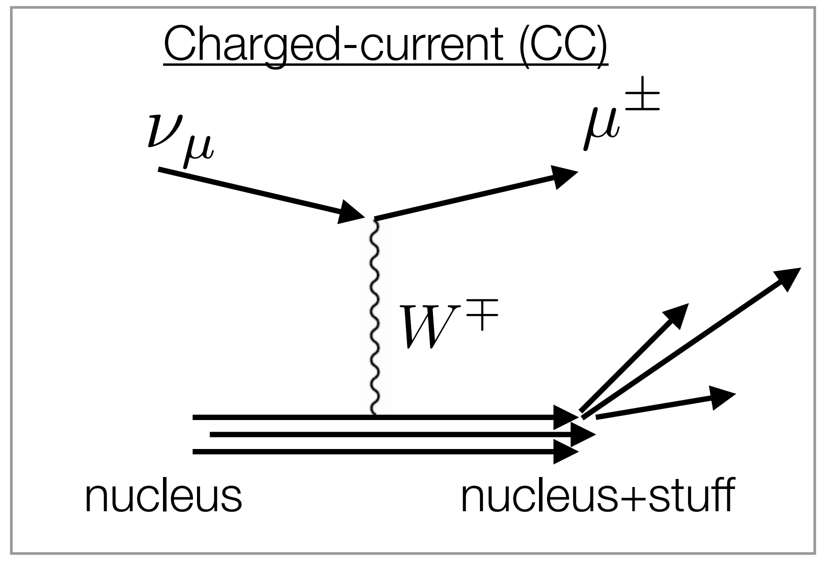


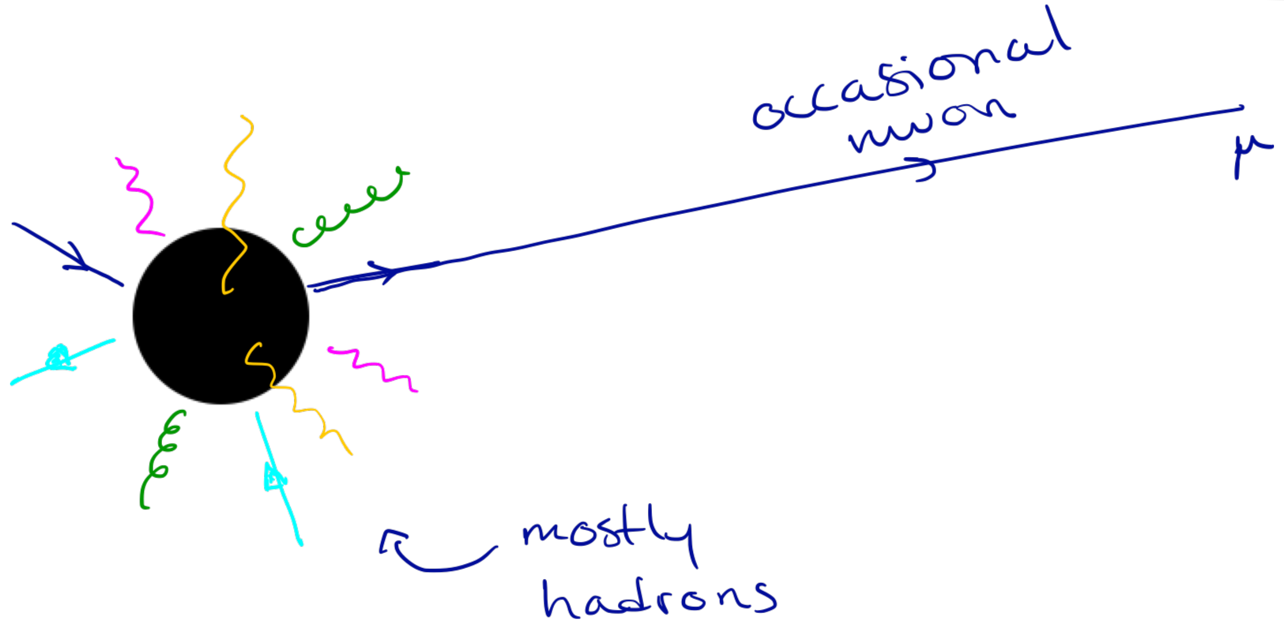


some electrons

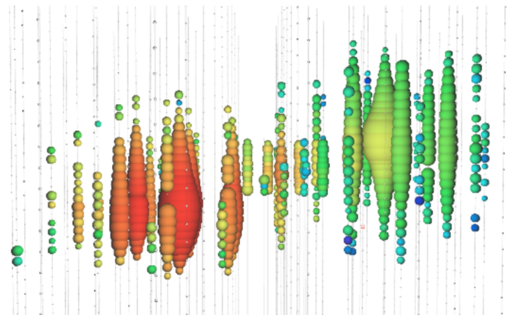
Tracks

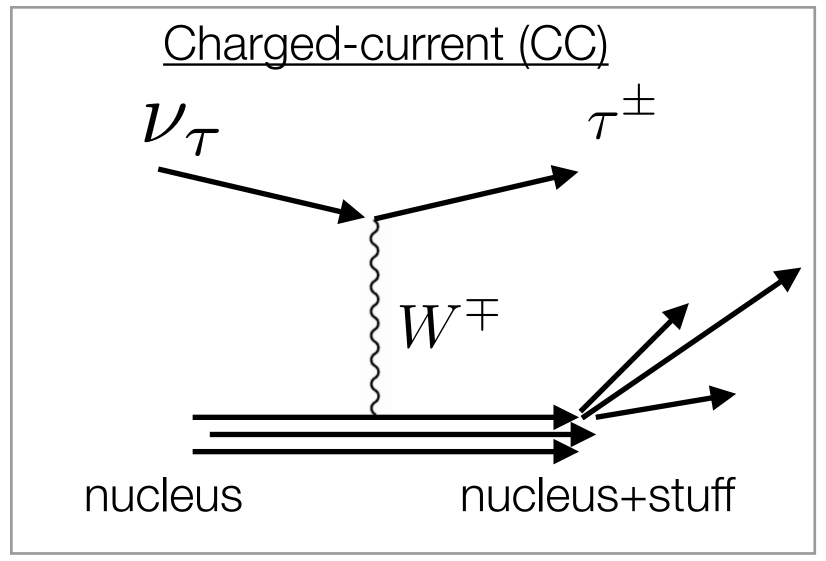


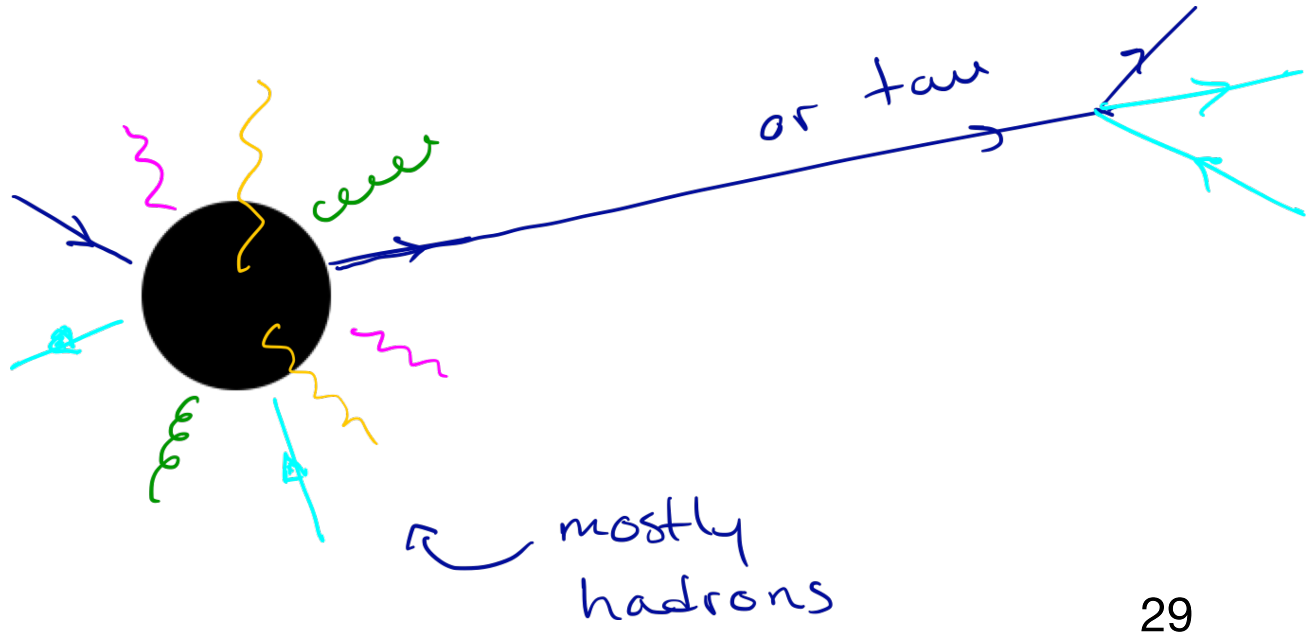




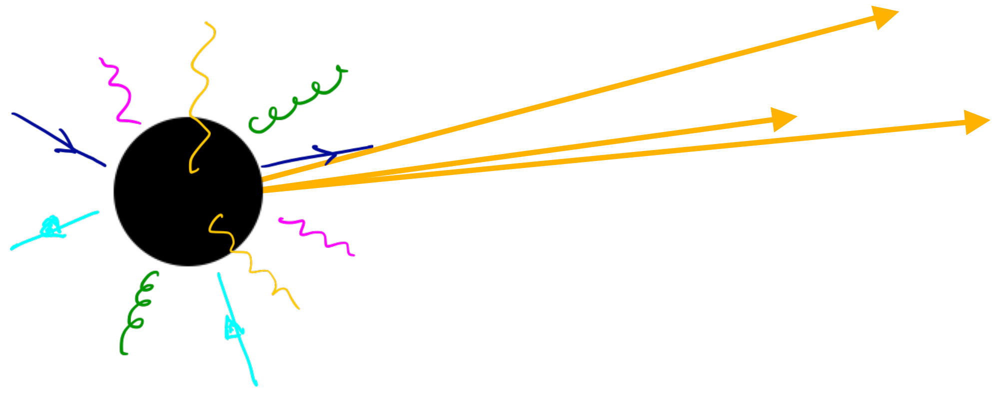
double-bangs







Other crazy morphologies that don't occur in the SM



Multitrack (hard to see)

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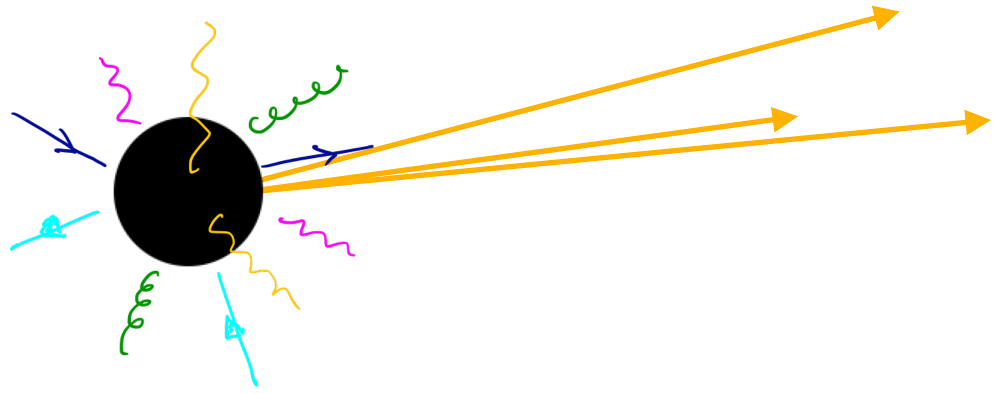

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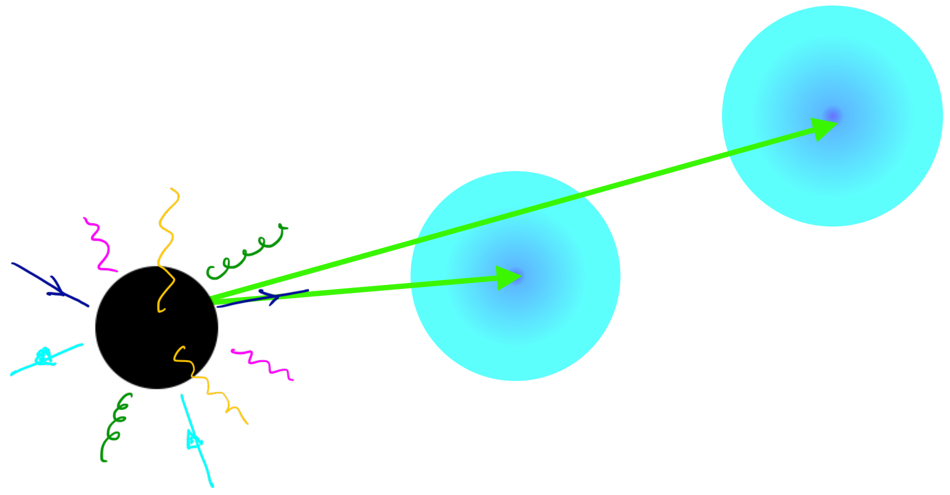

n-bang (*only* 0.2% of black hole events)

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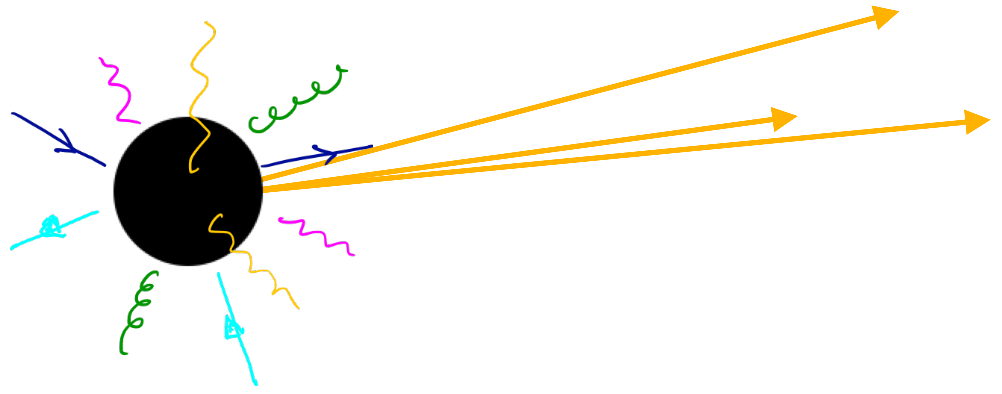

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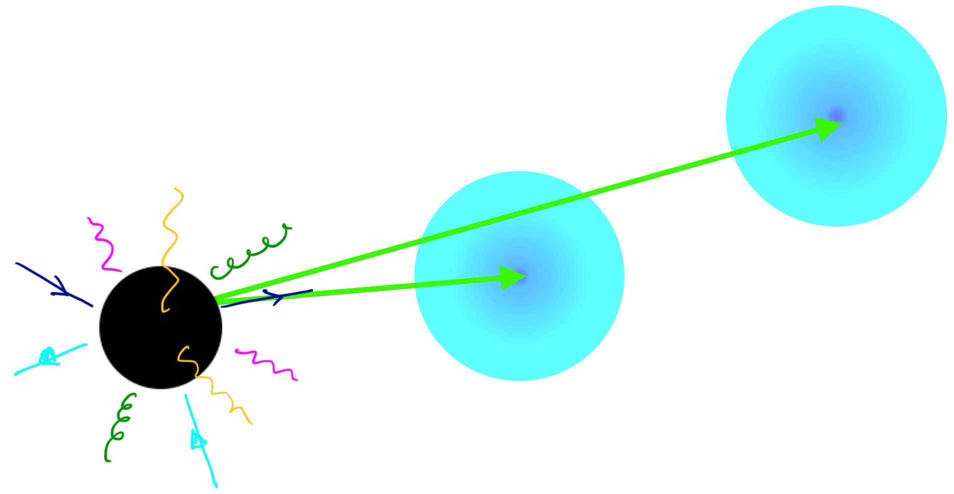

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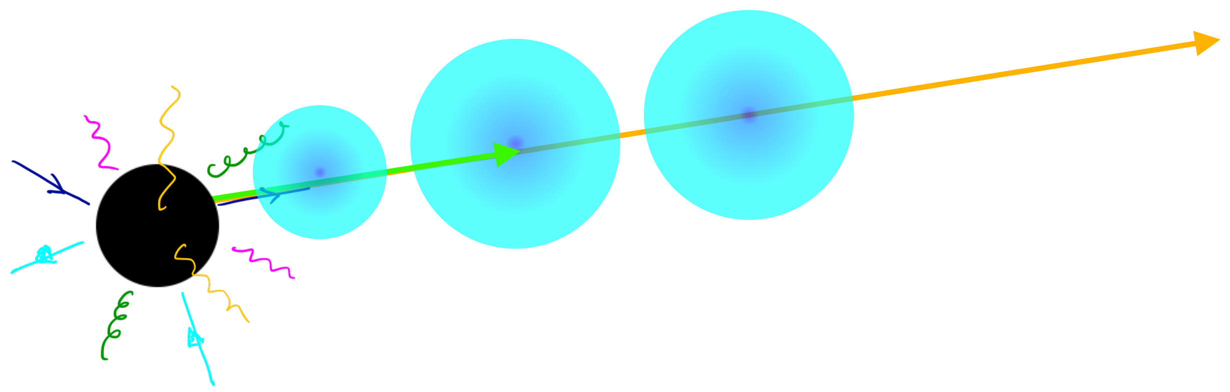

***Kebab*:** (About 3% of cases)

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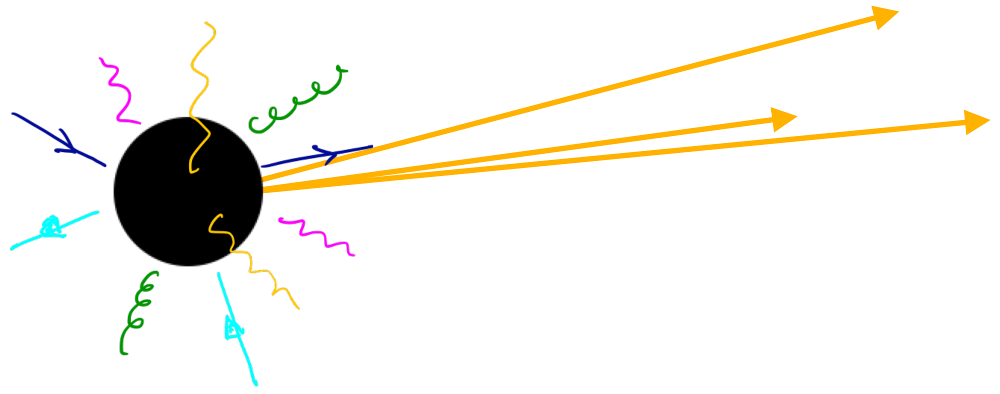

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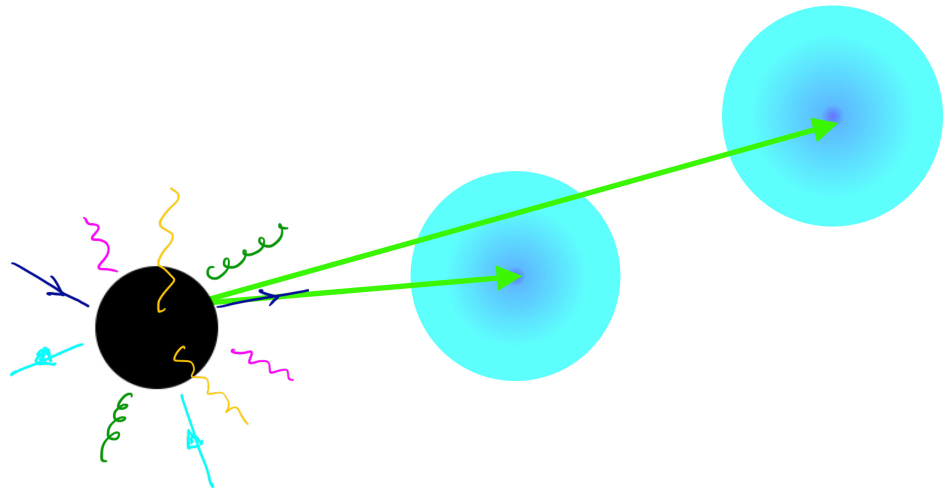

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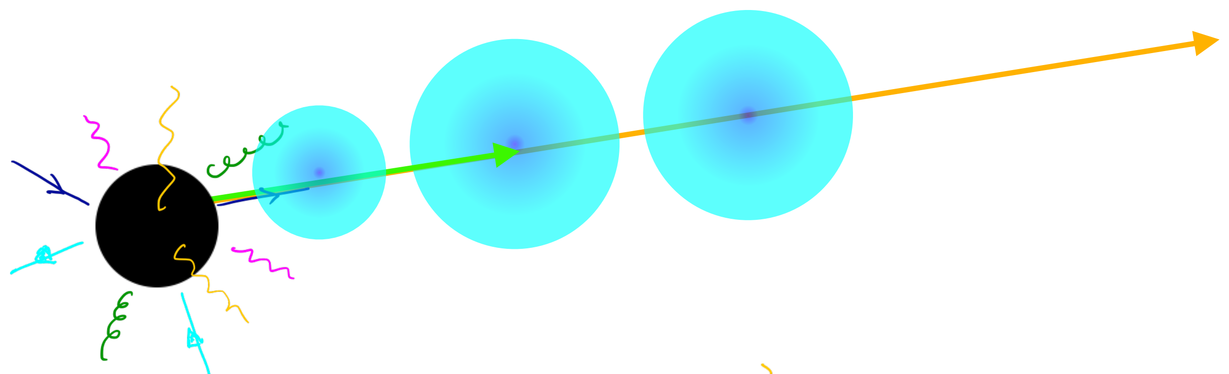

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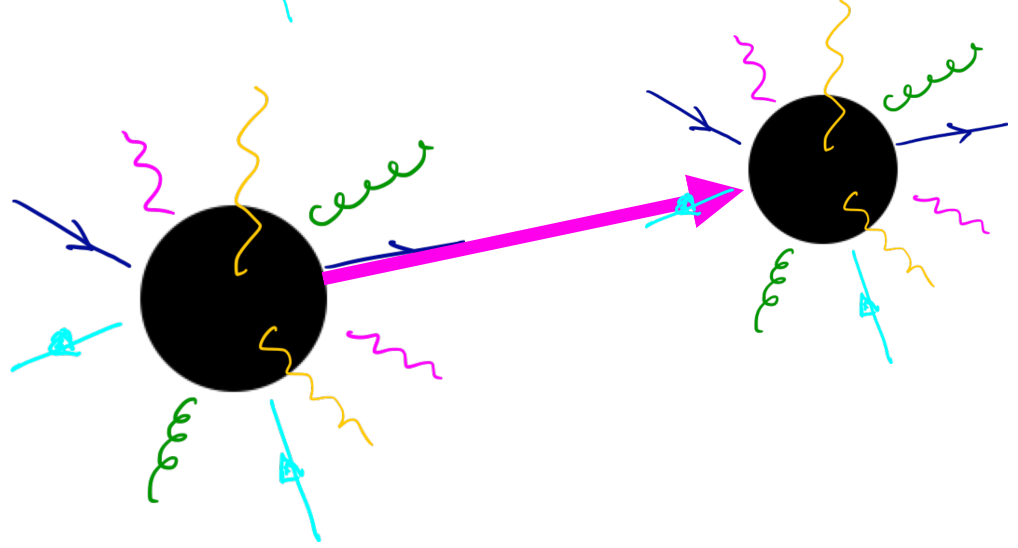

***Double black hole bang*:** (very rare!!)

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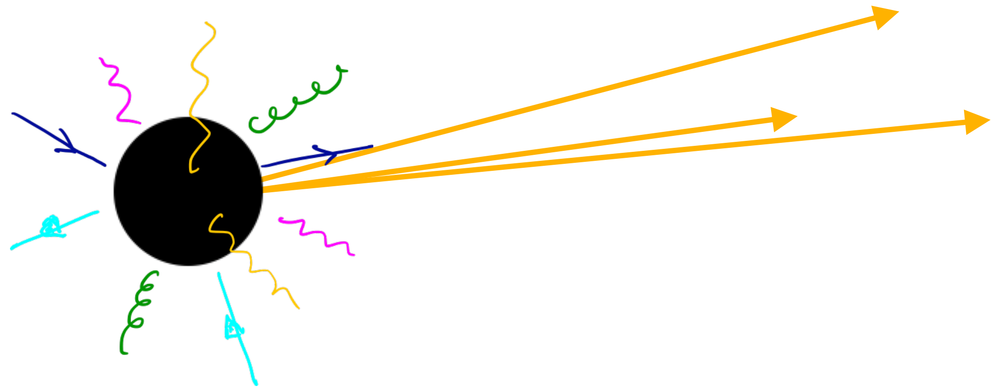

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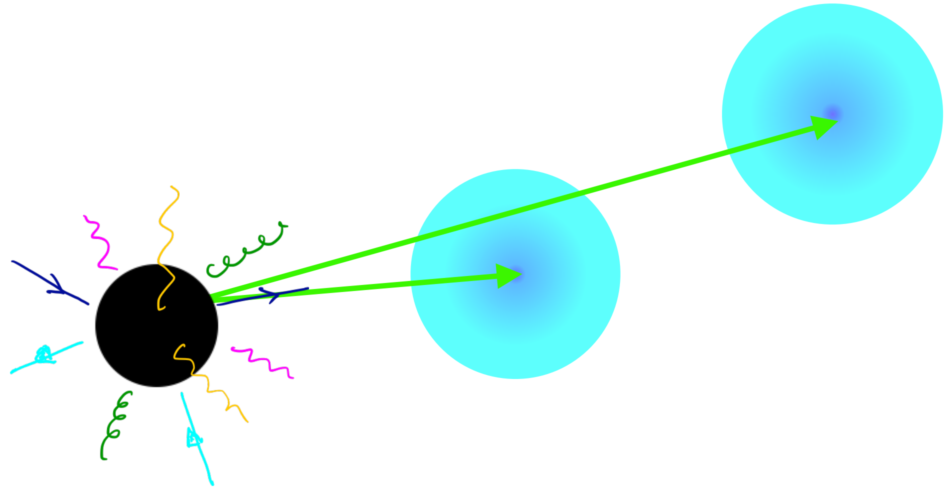

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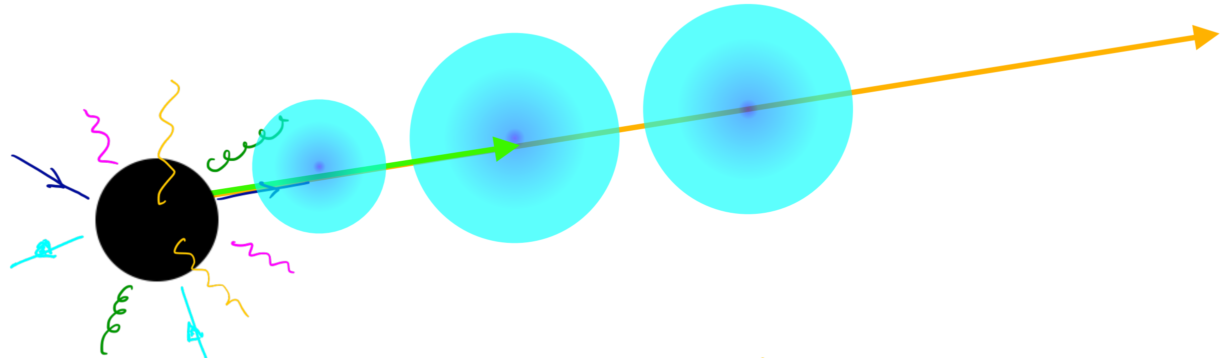

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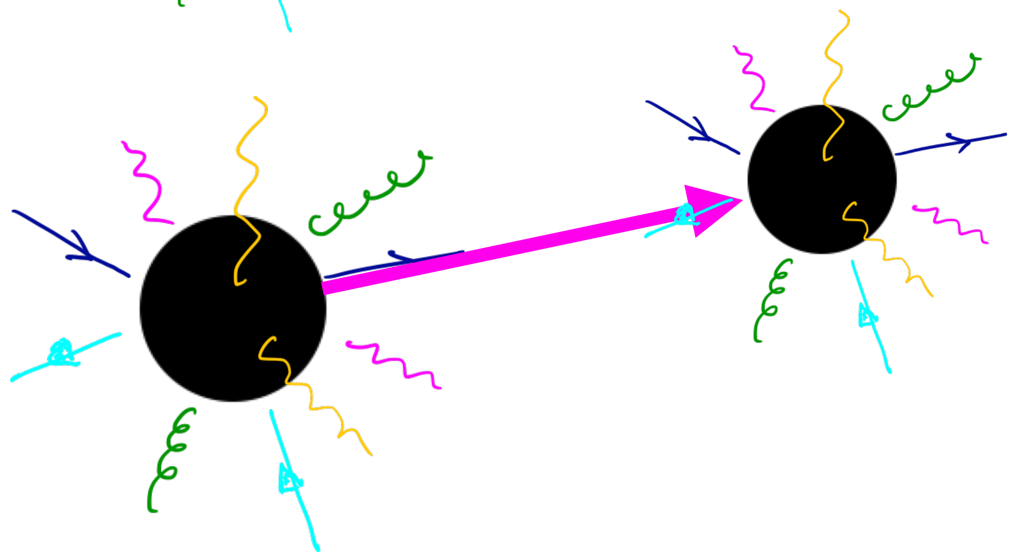
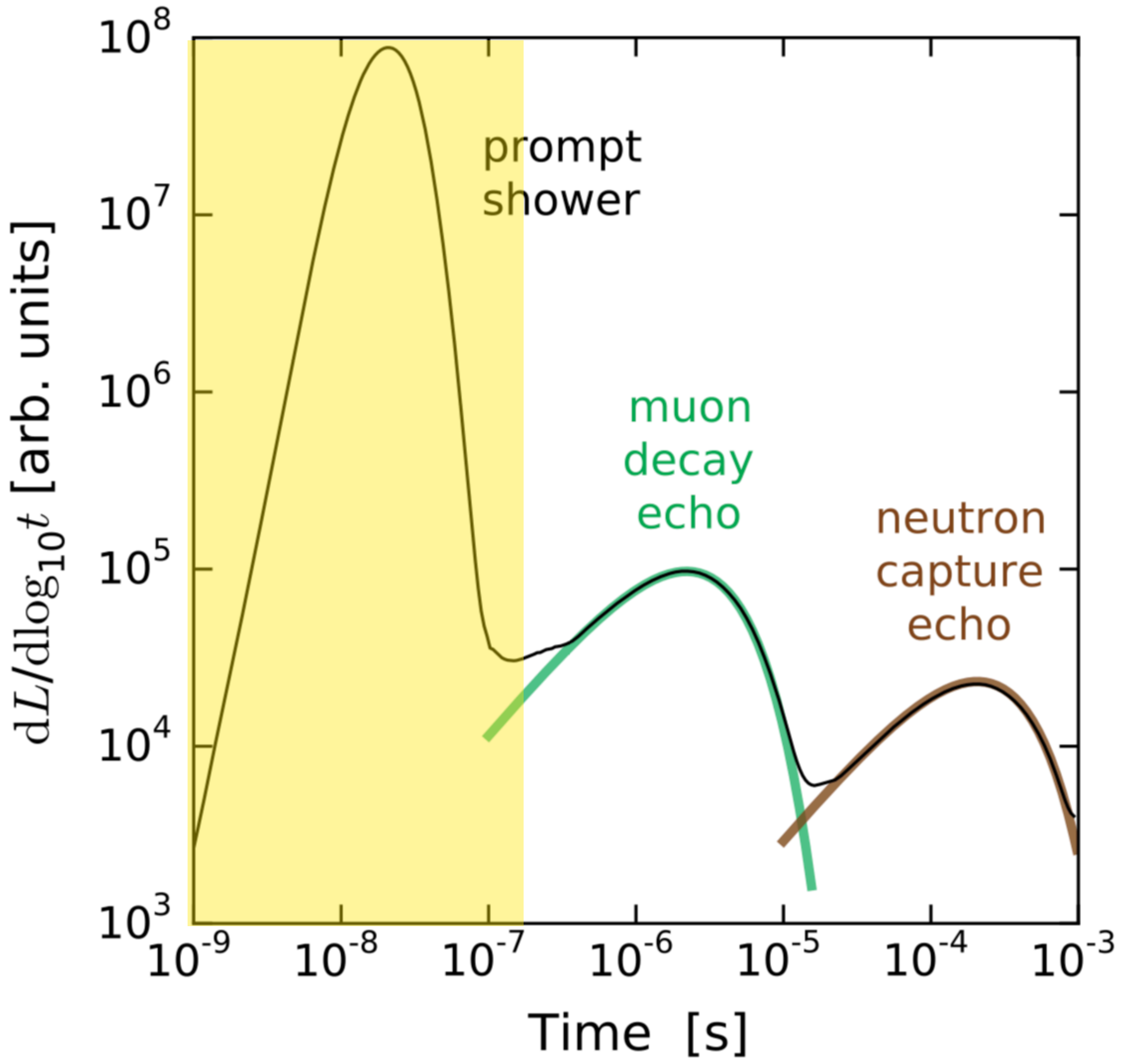


***Double black hole bang*:** (very rare!!)

These are rare, but if we see even one
we can suspect LEDs are involved!!

Hadronic vs electromagnetic energy deposition: **Cherenkov light echoes**

First interaction of neutrinos in ice produces a large **prompt** Cherenkov burst that lasts $\sim 10^{-7}$ s, proportional to the total event energy.



Li, Bustamante, Beacom
1606.06290

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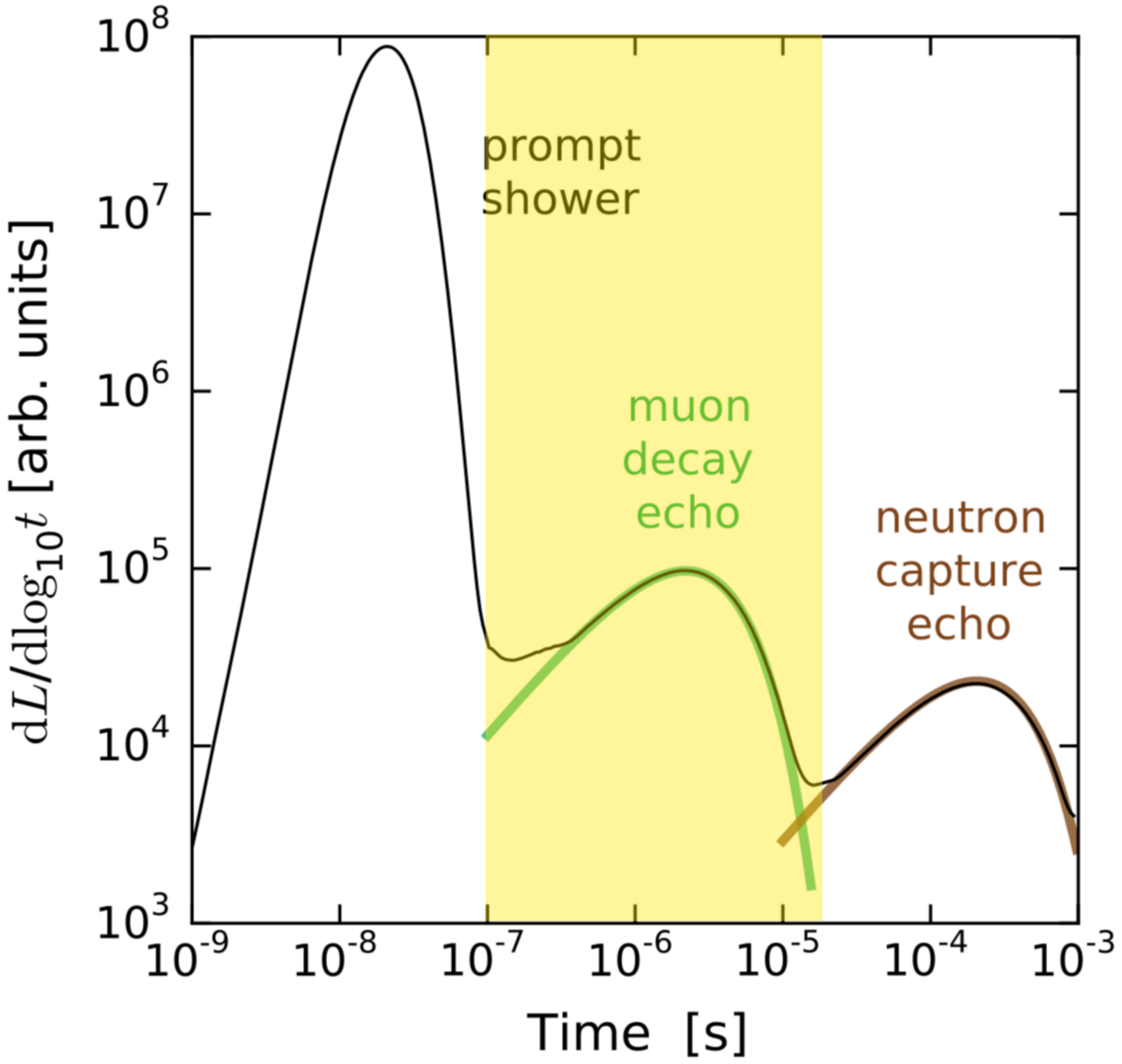

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Muons can be copiously produced at low energies, and live $\sim 10^{-6}$s, leading to a second **muon echo** as they decay

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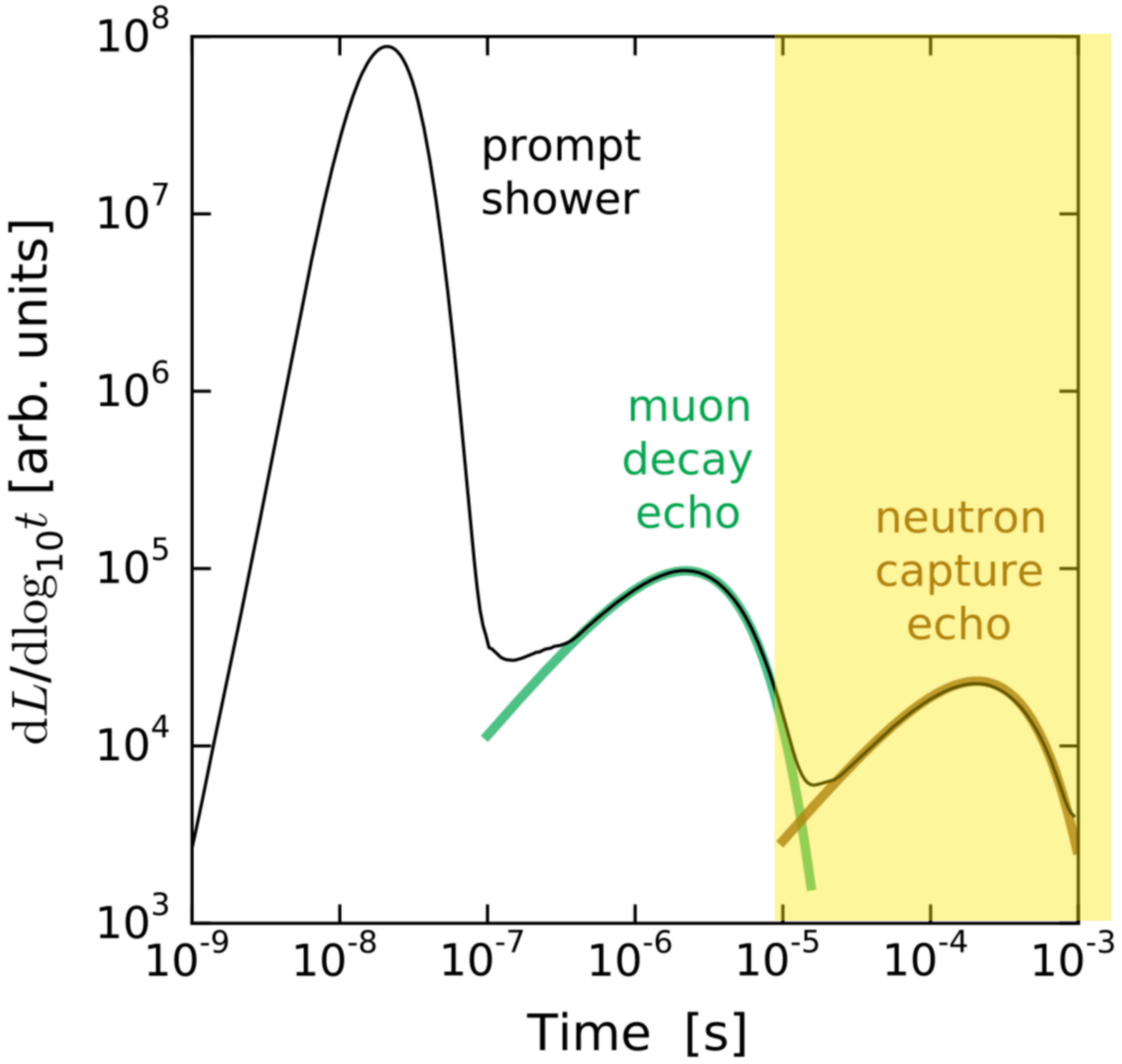


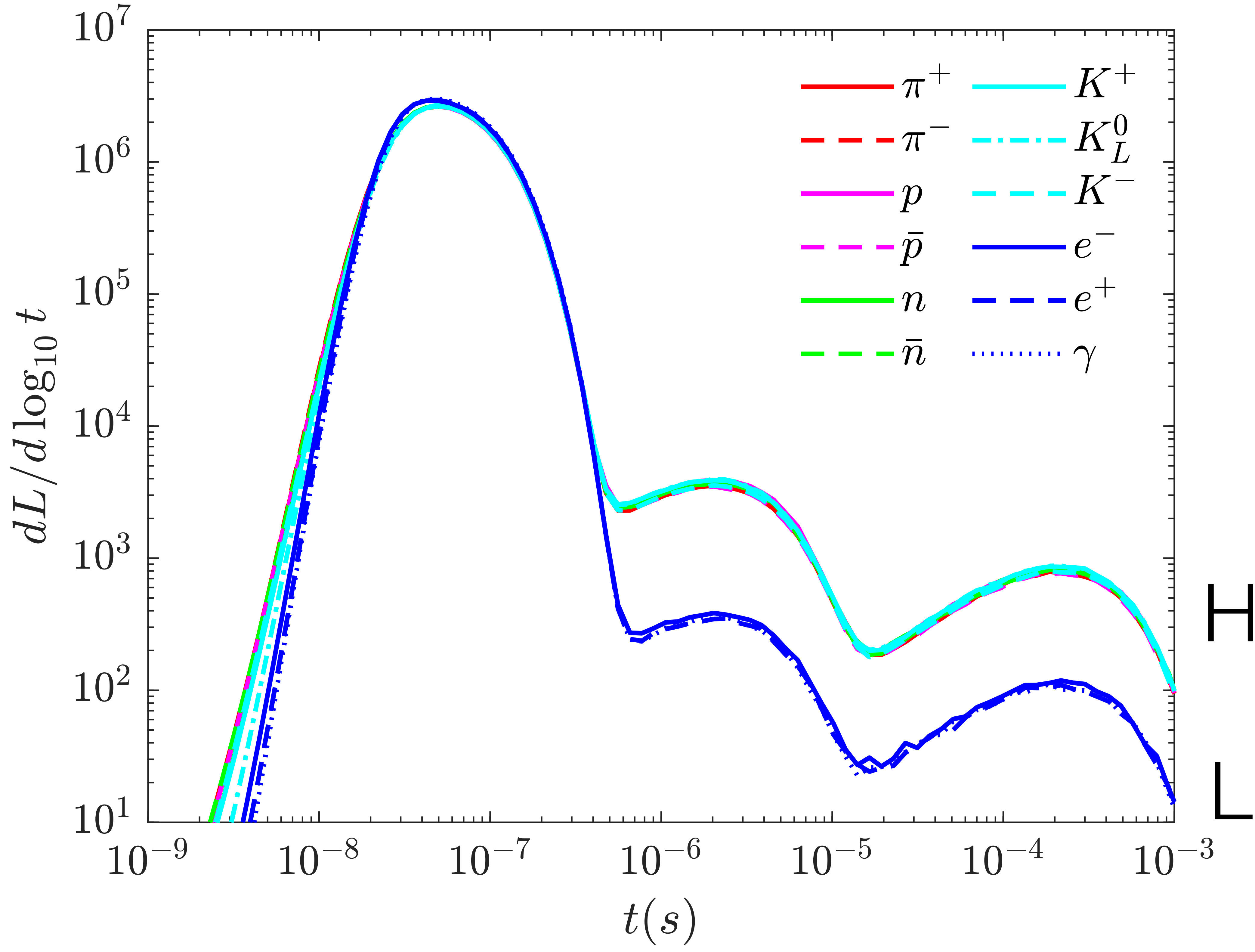
Li, Bustamante, Beacom
1606.06290

Muons can be copiously produced at low energies, and live $\sim 10^{-6}$s, leading to a second **muon echo** as they decay

Neutrons can live for up to .1 ms before being captured, leading to a third **neutron capture echo**

Cherenkov light echoes

Cherenkov light generation for specific particles injected in the ice

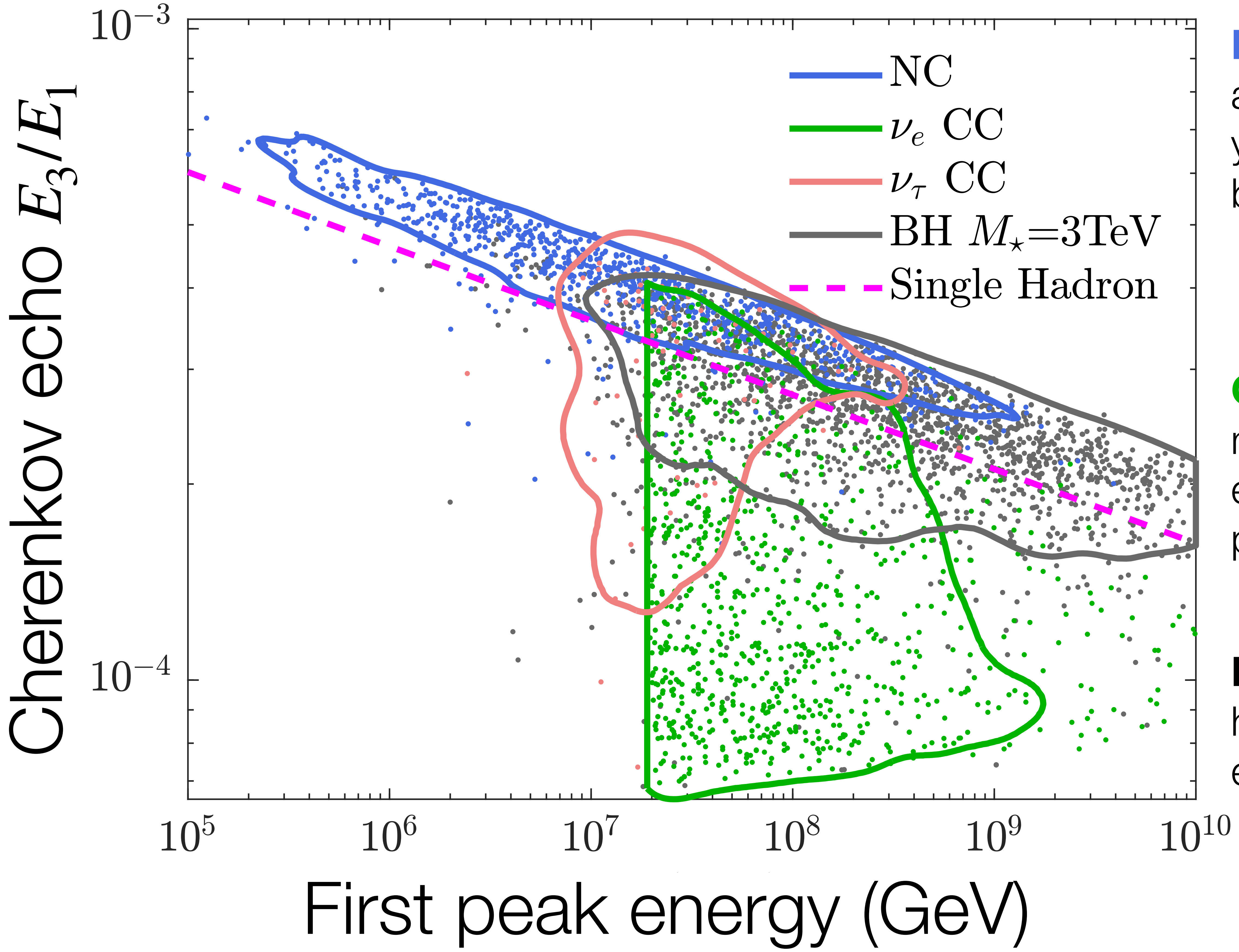


Hadrons

Leptons

Does not seem to be possible at IceCube due to PMT afterpulses, but future telescopes could observe this

Messy in reality (statistics to the rescue!)



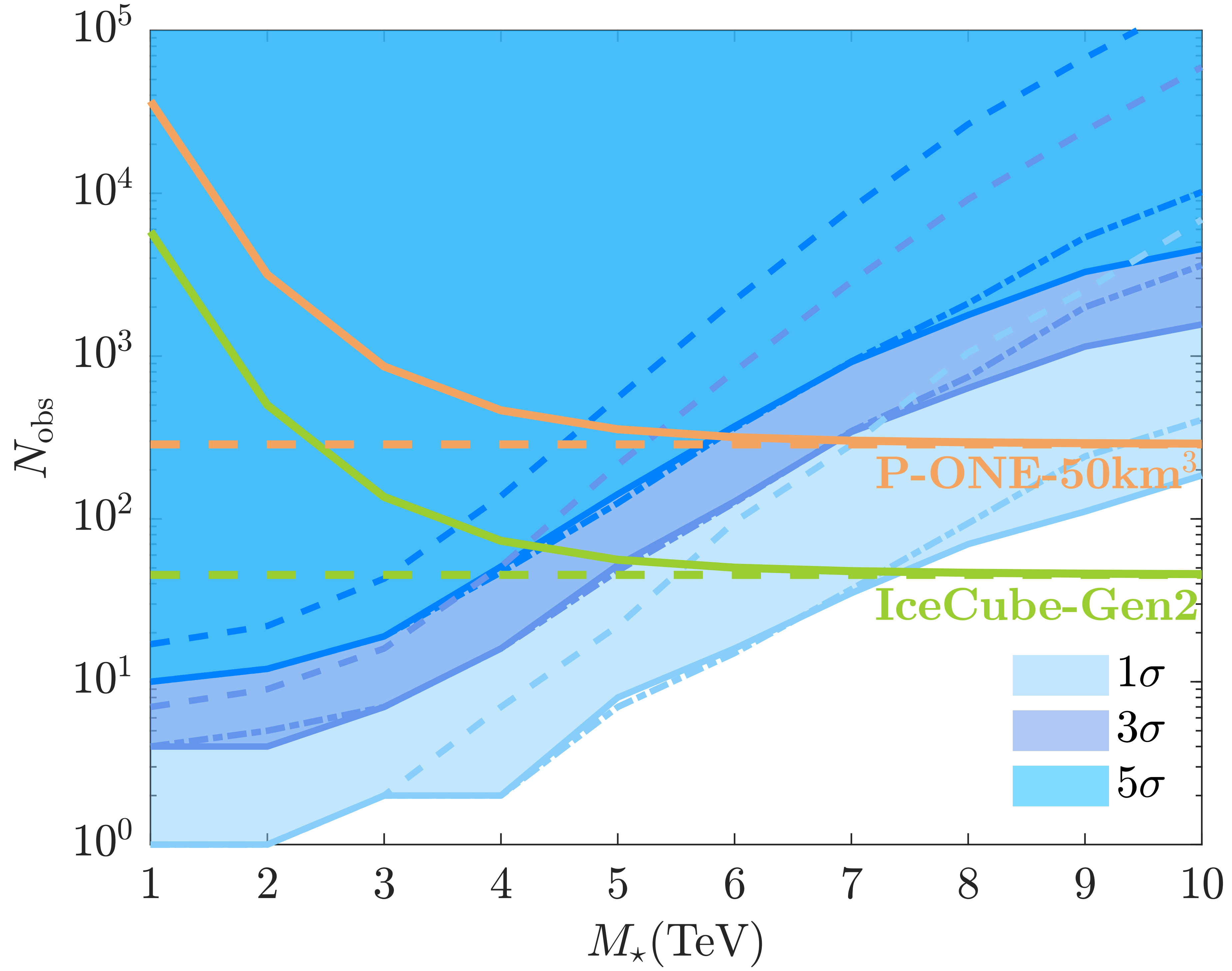
Neutral current events: above the hadron line since hadronization yields mostly hadrons + a few γ. Low energy because neutrino takes away most of the E.

Charged current events: much lower muon/neutron light echo, because most energy injection is from an electron or positron

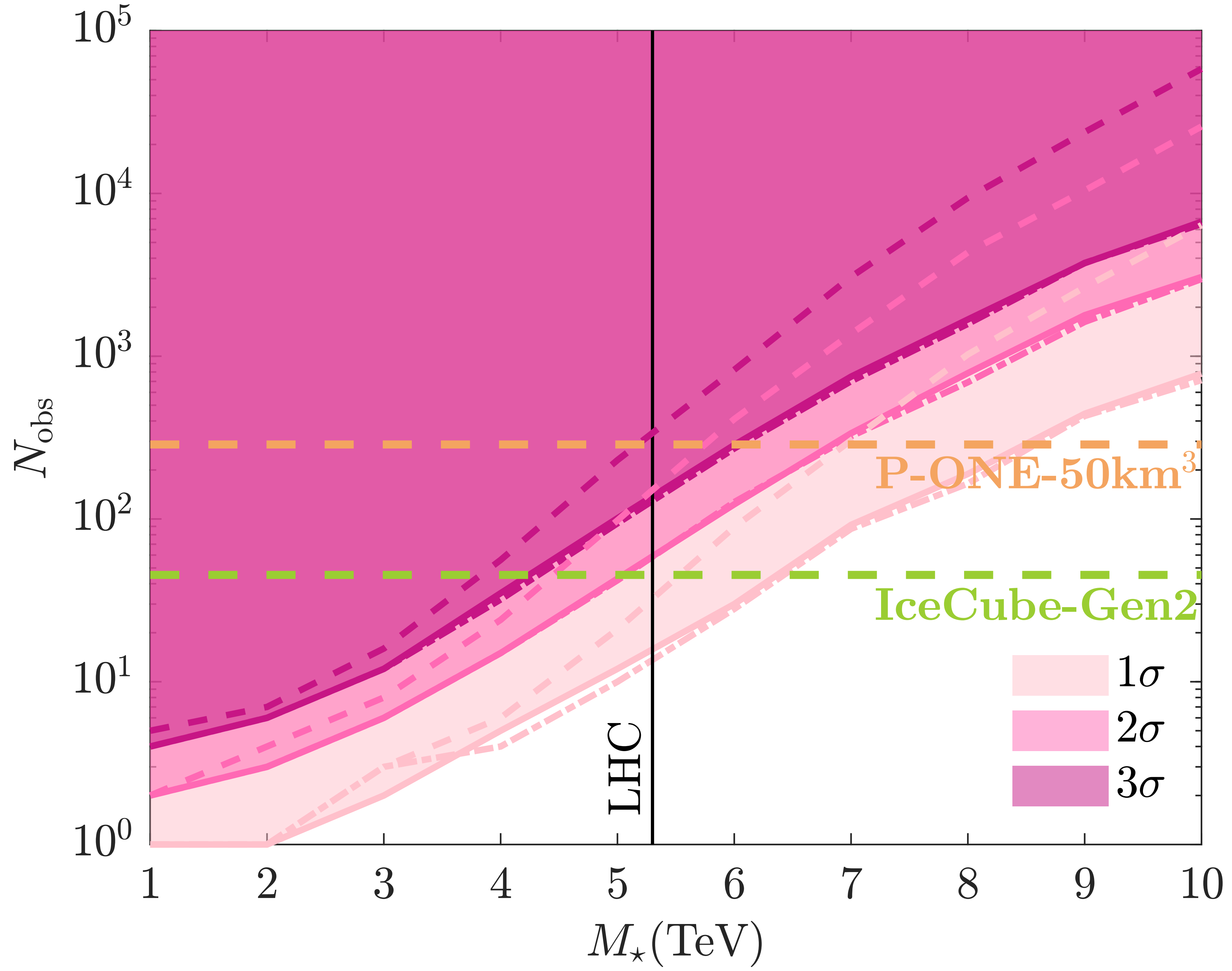
Black Holes: Most of the energy is hadronic: high energy and large Cherenkov echo.

Detecting large extra dimensions with neutrino telescopes

Detection prospects



Exclusion prospects



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
  - large extra dimensions

Thank you