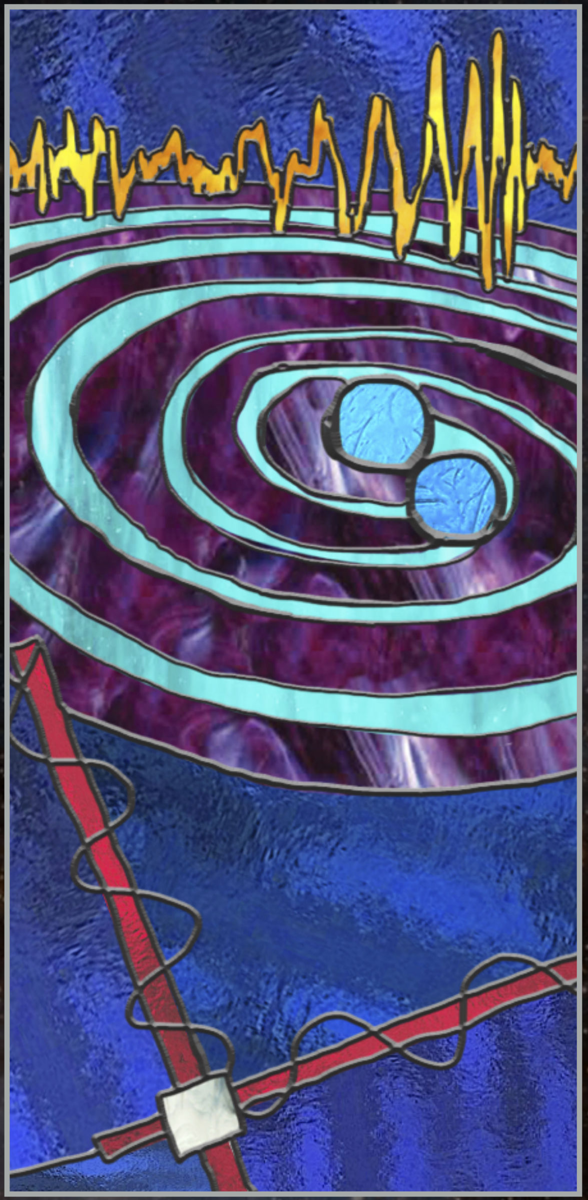
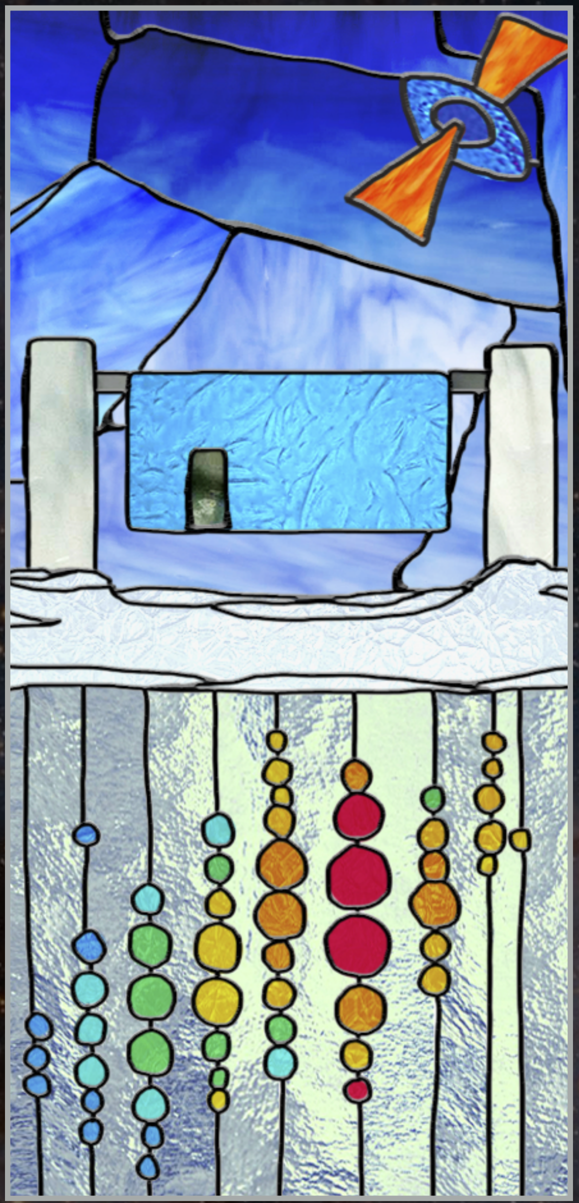
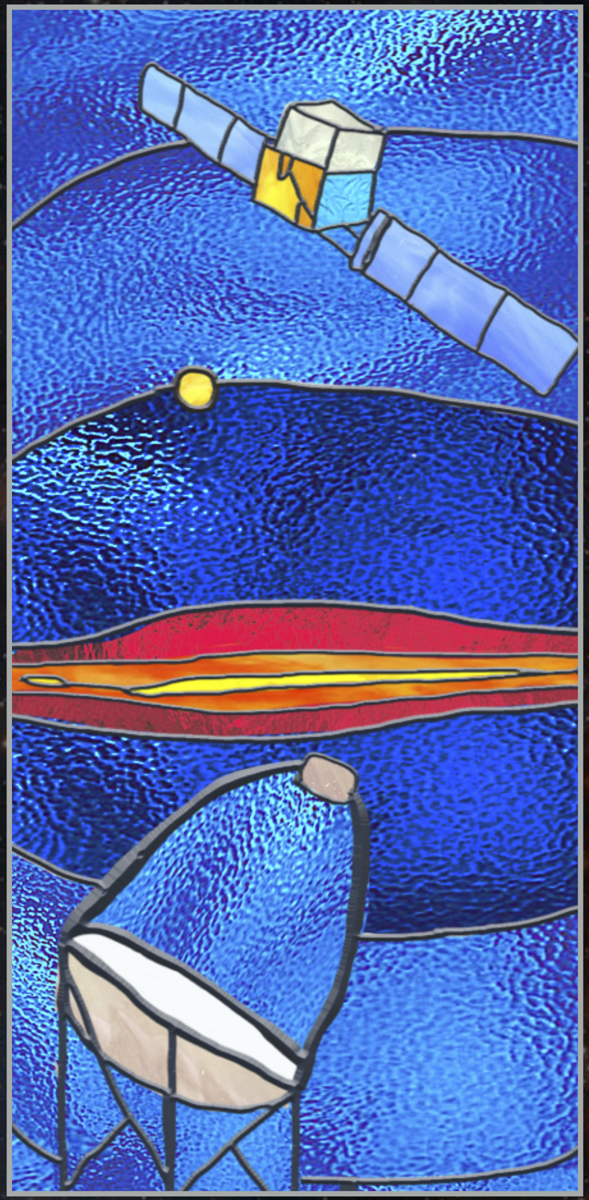
  

Cosmic ν's as a Probe of Fundamental Physics

Markus Ahlers

Niels Bohr Institute

Georges Lemaître Chair 2023

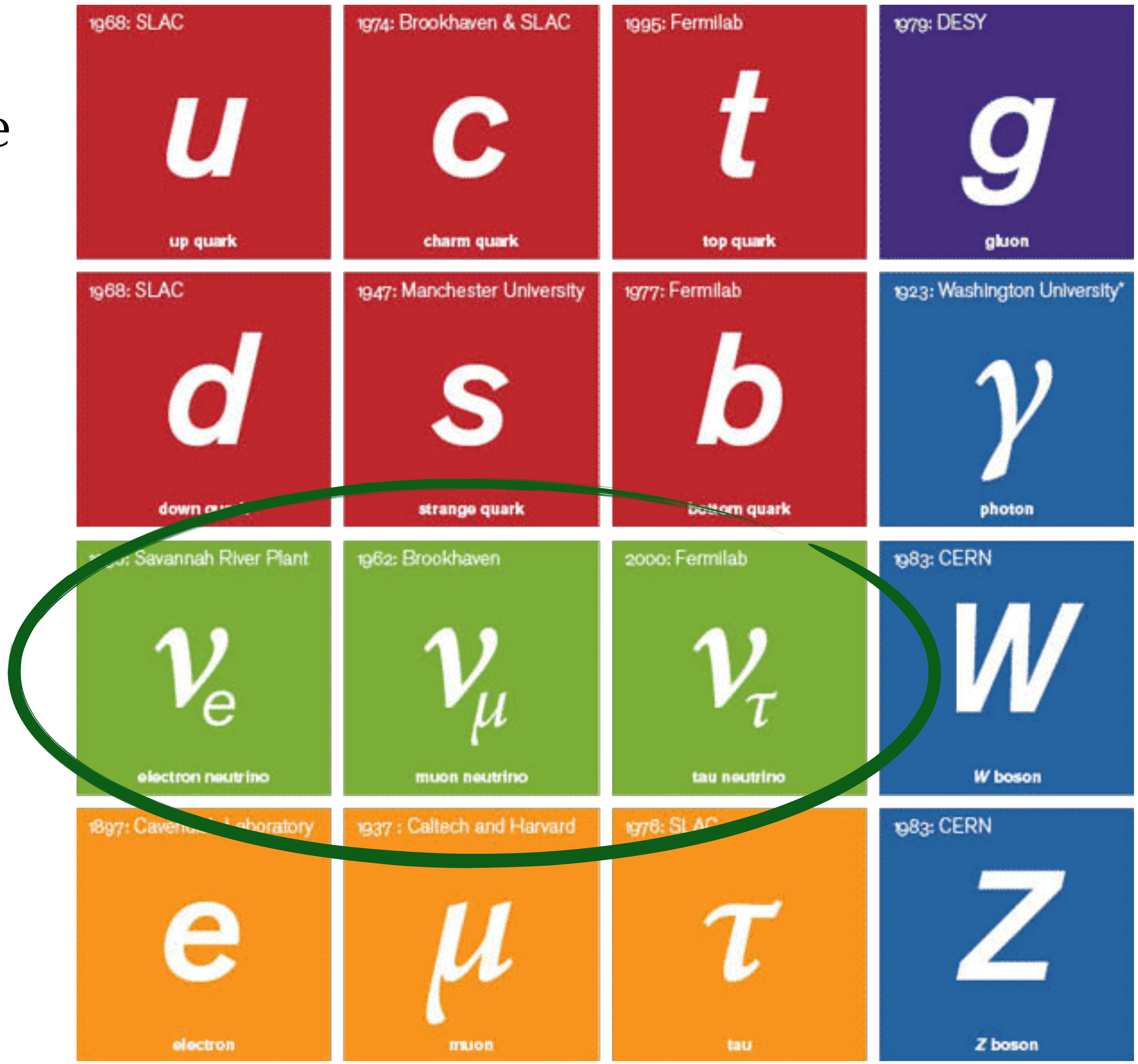
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

The Elusive Neutrino

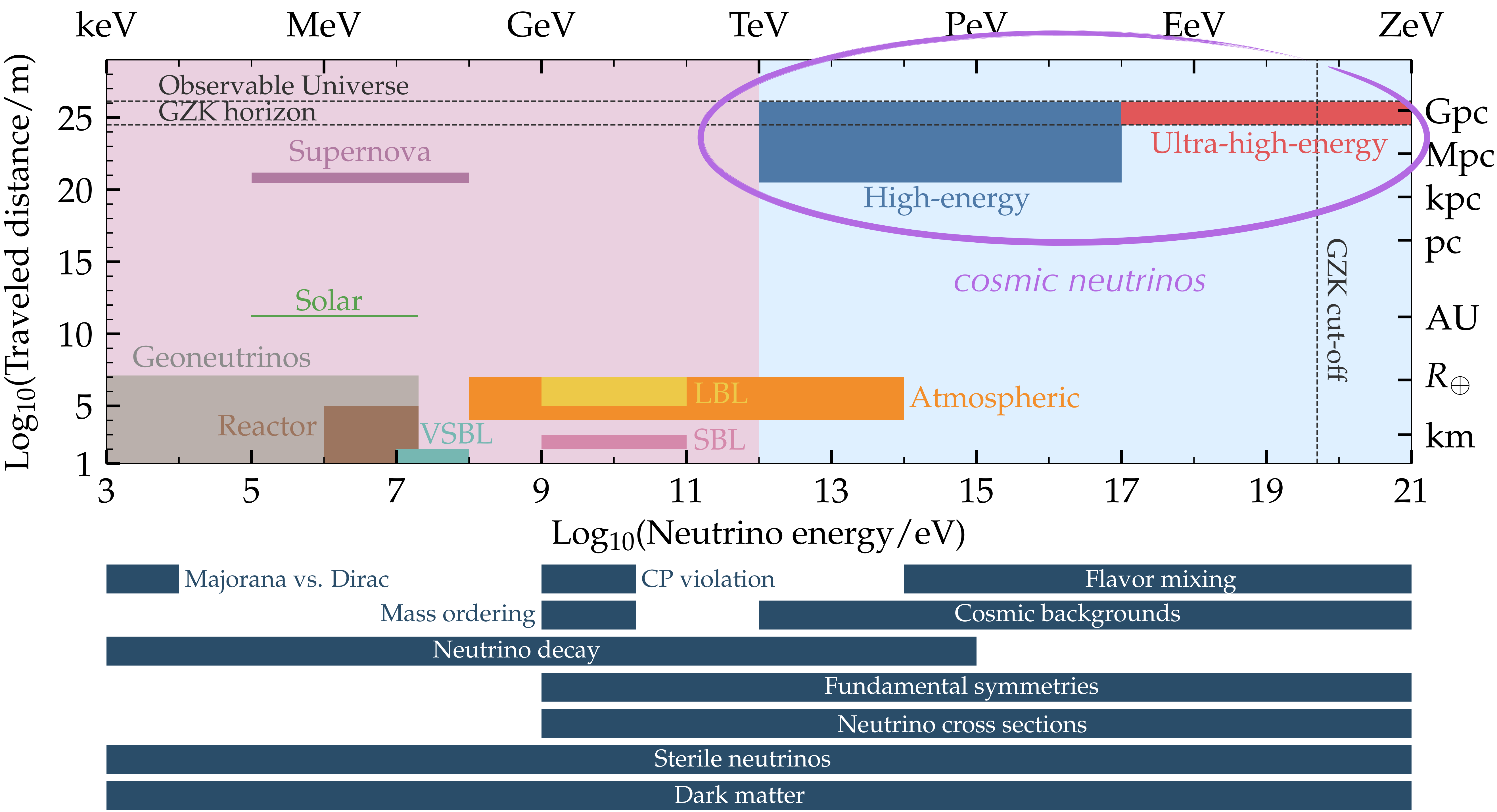
- **small masses** with uncertain origin and scale
- **large mixing** between flavour and mass states
- potential source of **CP violation** (*leptogenesis?*)
- **Dirac or Majorana** fermions
- susceptible to **beyond-the-SM** effects

Standard Model of Particle Physics



(+ Higgs boson)

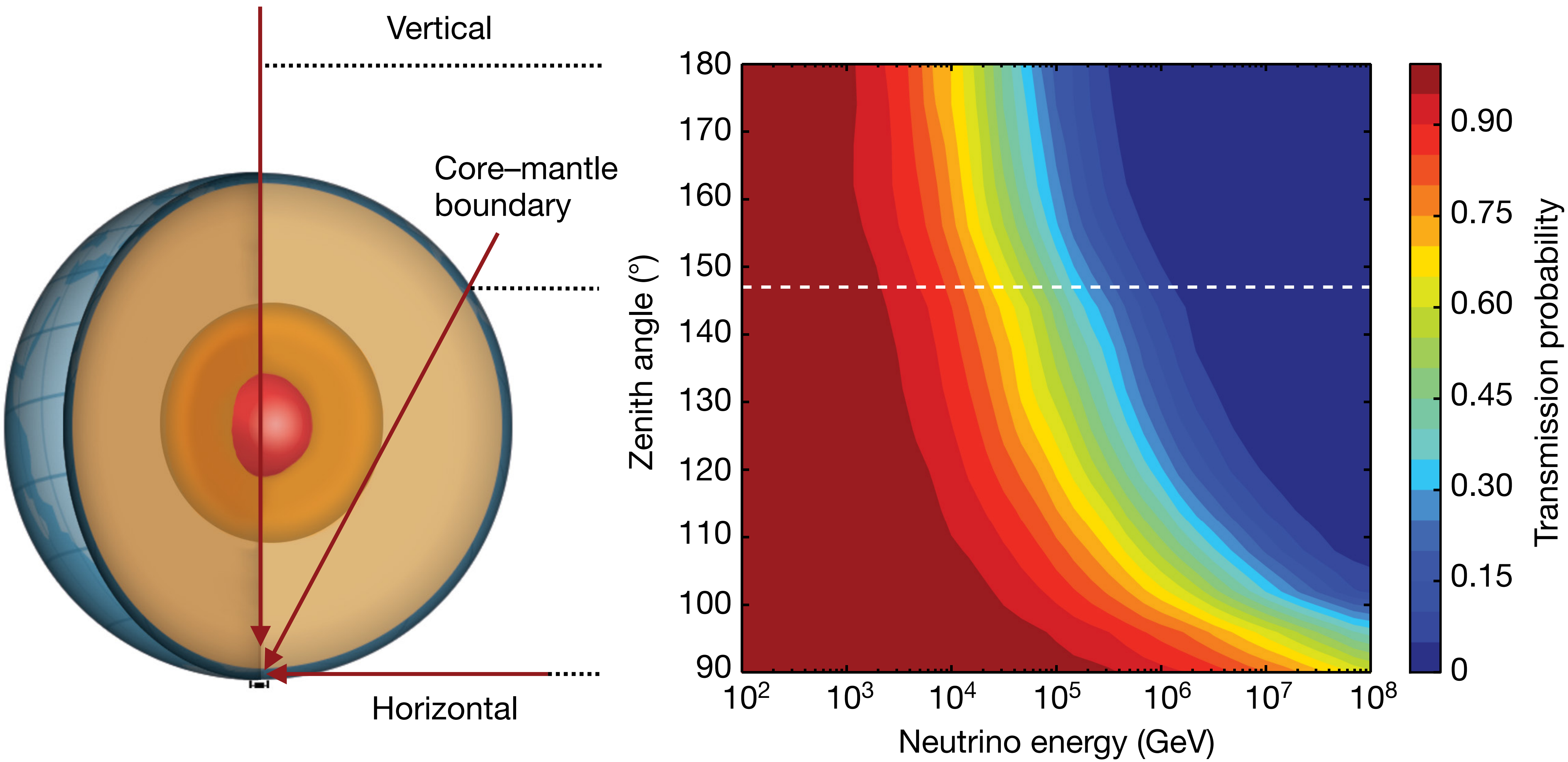
Probe of Fundamental Physics



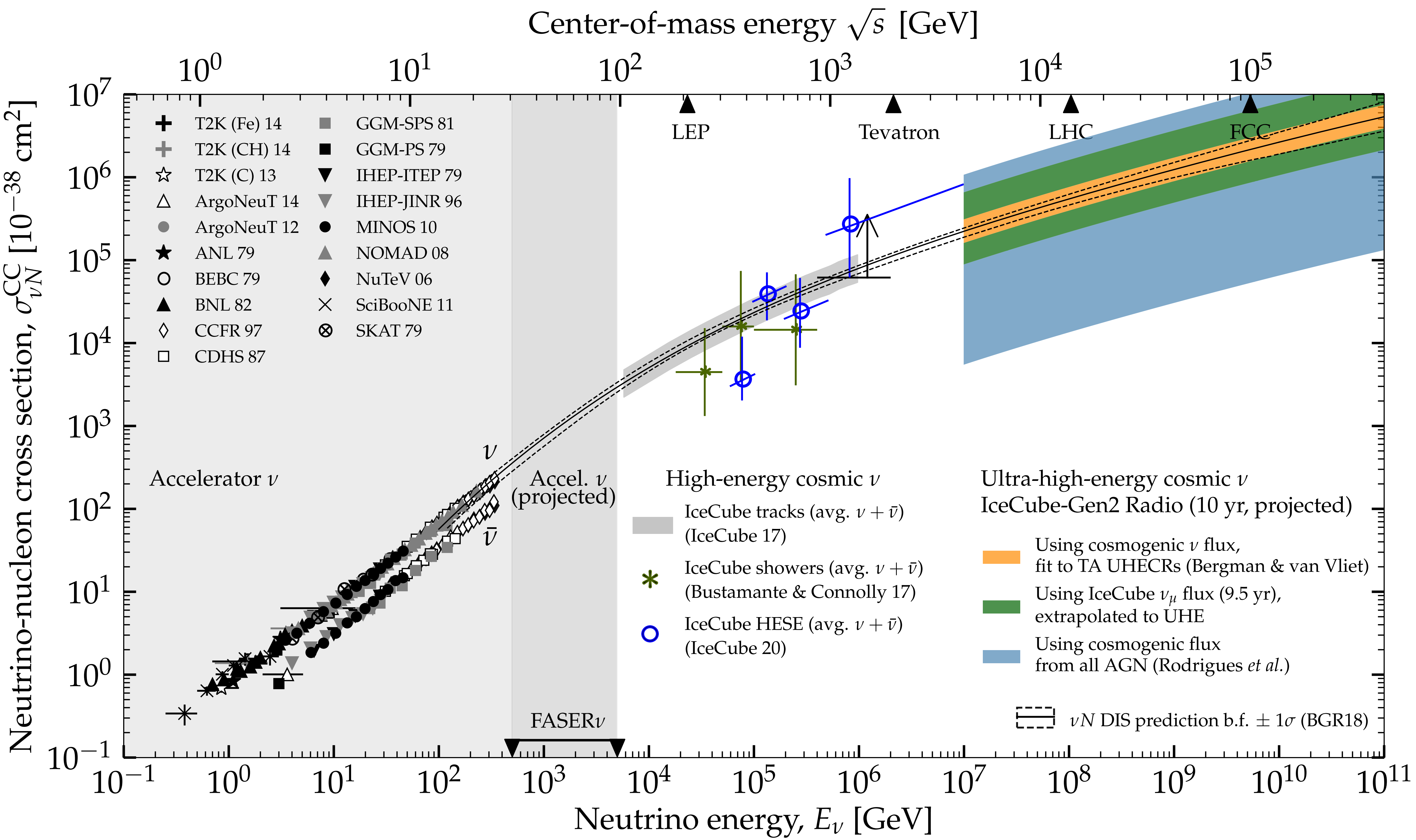
[Ackermann, MA, Anchordoqui, Bustamante+ **Bull.Am.Astron.Soc.** 51 (2019)]

Neutrino Cross Section

$$N_{\rm events}(\theta, E_\nu) \propto \sigma_{\nu N}(E_\nu) \exp\left(-\frac{\sigma_{\nu N}(E_\nu)}{m_p}\int d\ell\, \rho_\oplus(\mathbf{r}_{\rm IC} + \ell\,\hat{\mathbf{n}}(\theta))\right)$$



Neutrino Cross Section



[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Neutrino Mixing

1956: Savannah River Plant	1962: Brookhaven	2000: Fermilab
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Superpositions of mass eigenstates!

3 **flavour eigenstates** $|\nu_\alpha\rangle$ with greek index ($\alpha = e, \mu, \tau$)

3 **mass eigenstates** $|\nu_i\rangle$ with roman index ($i = 1,2,3$)

Mixing is parametrized by unitary mixing matrix U:

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

Two-Flavour Neutrino Oscillation

- Considering only two flavour oscillations (e.g. $\nu_\mu \leftrightarrow \nu_\tau$)

$$P_{\nu_\beta\to\nu_\alpha}(\ell) \simeq \sin^2(2\theta)\,\sin^2\left(\frac{(m_2^2 - m_1^2)\ell}{4E_\nu}\right)$$

- Similarly, the muon neutrino **survival probability** is given as:

$$P_{\nu_\beta\to\nu_\beta}(\ell) = 1 - P_{\nu_\beta\to\nu_\alpha}(\ell)$$

- Oscillation phase depends on **mass-squared difference**:

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

- Can be expressed as:

$$\frac{\Delta m_{ij}^2 \ell}{4E_\nu} \simeq 1.27\left(\frac{\Delta m_{ij}^2}{\mathrm{eV}^2}\right)\left(\frac{\ell}{\mathrm{km}}\right)\left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-1}$$

Oscillation Probes

Oscillation measurement are based on **reactor, solar, accelerator and atmospheric neutrinos** looking for the **appearance and disappearance.**

Source	Type of ν	$\overline{E}$[MeV]	L[km]	$\min(\Delta m^2)[\mathrm{eV}^2]$
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

(source: pdg.lbl.gov)

In practice, the destructive interference from the limited energy resolution of the detector or size of the neutrino source, require $L/\overline{E}$ to lie within the range of the first few oscillations.

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric" mixing | ~~CP~~ Dirac phase $\propto \sin\theta_{13}$ | "solar" mixing | ~~CP~~ Majorana phases

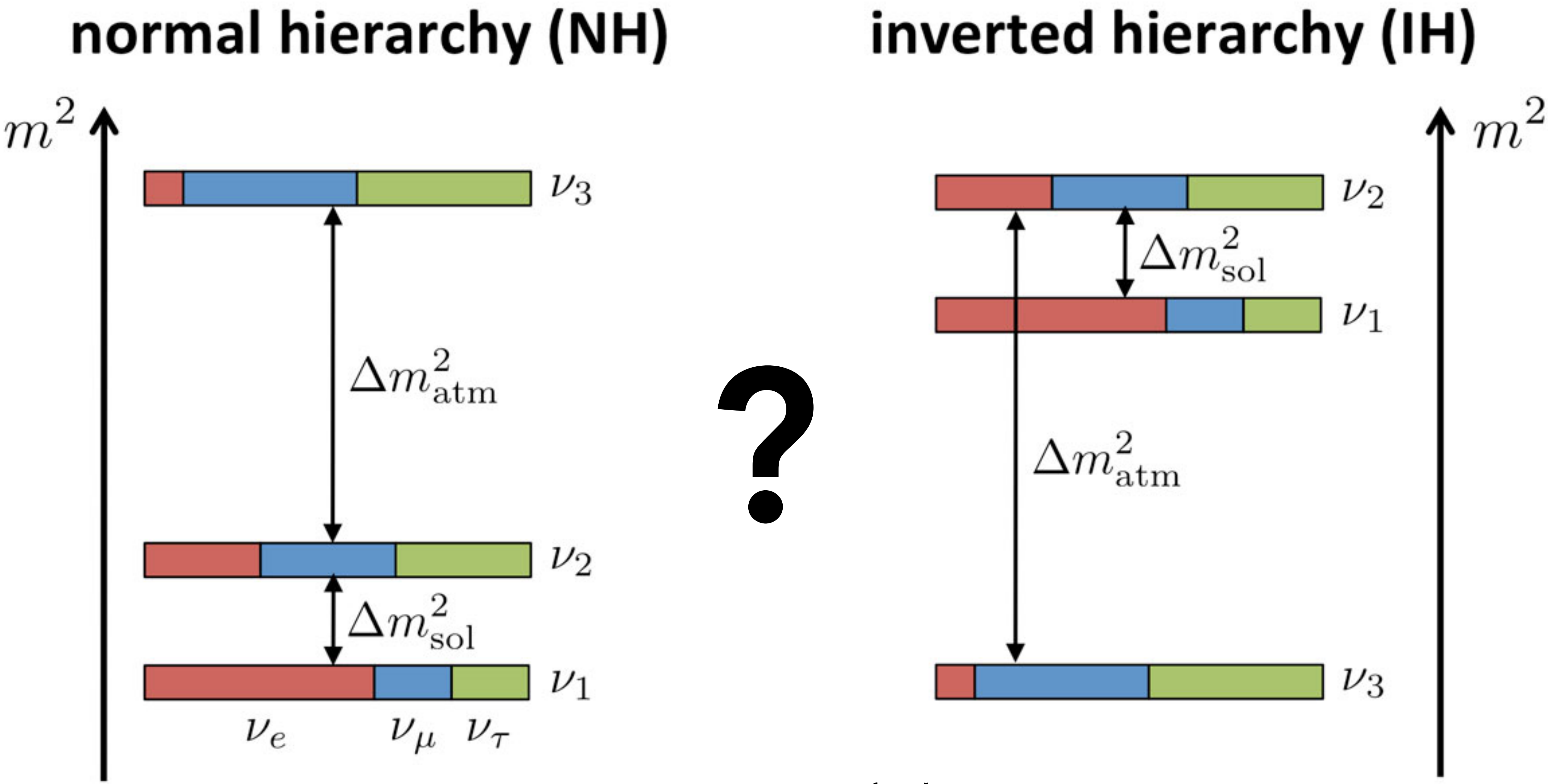
(notation: $c_{ij} \equiv \cos\theta_{ij}$ & $s_{ij} \equiv \sin\theta_{ij}$ & $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$)

best-fit values (NuFIT 5.2):

$$\sin^2\theta_{12} \simeq 0.303 \qquad \sin^2\theta_{13} \simeq 0.022 \qquad \sin^2\theta_{23} \simeq 0.57$$

$$\Delta m^2_{21} \simeq 7.41 \times 10^{-5}\mathrm{eV}^2 \qquad \Delta m^2_{32} \simeq \pm 2.5 \times 10^{-3}\mathrm{eV}^2$$

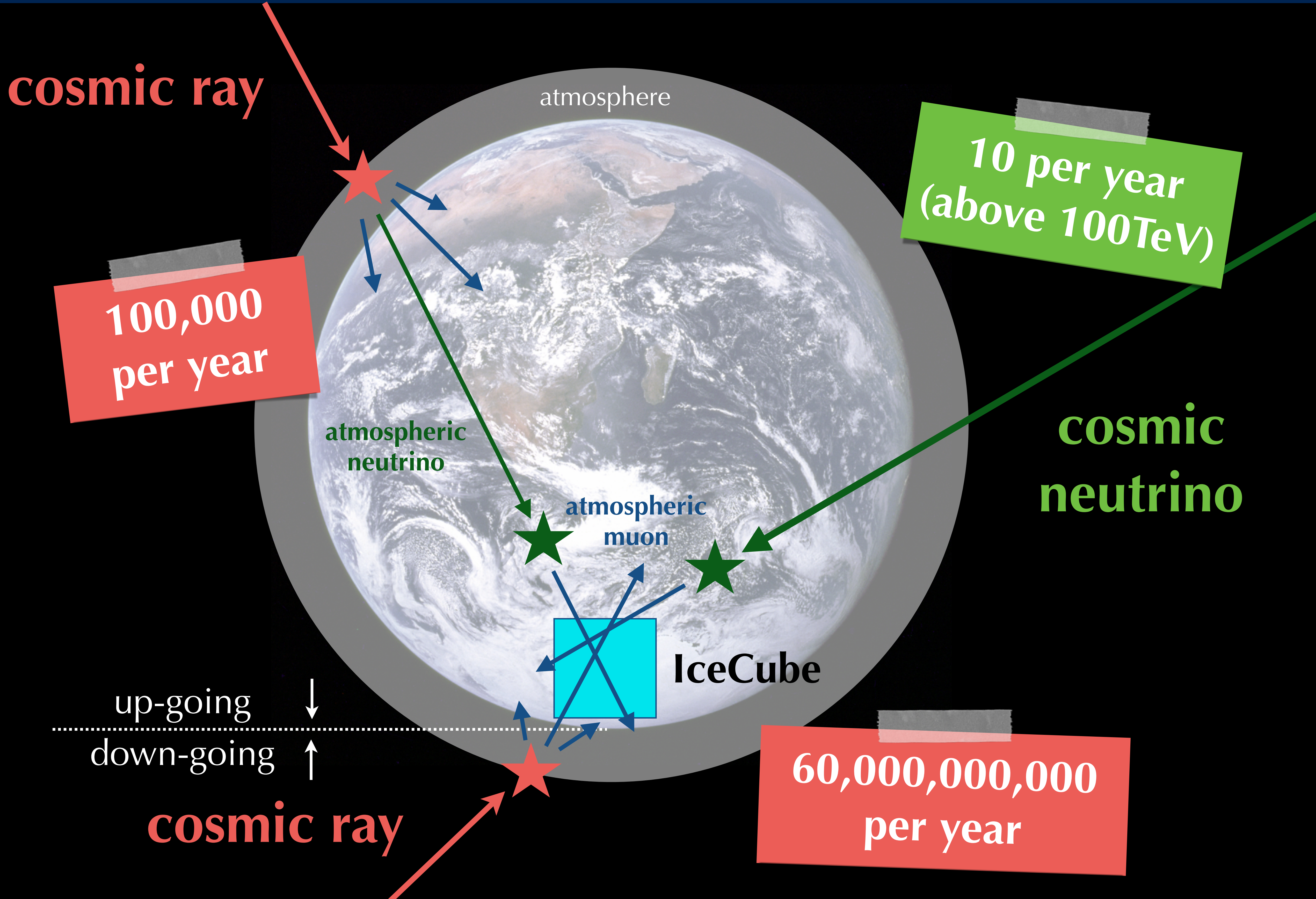
Neutrino Mass Ordering



(source: neutrinos.fnal.gov)

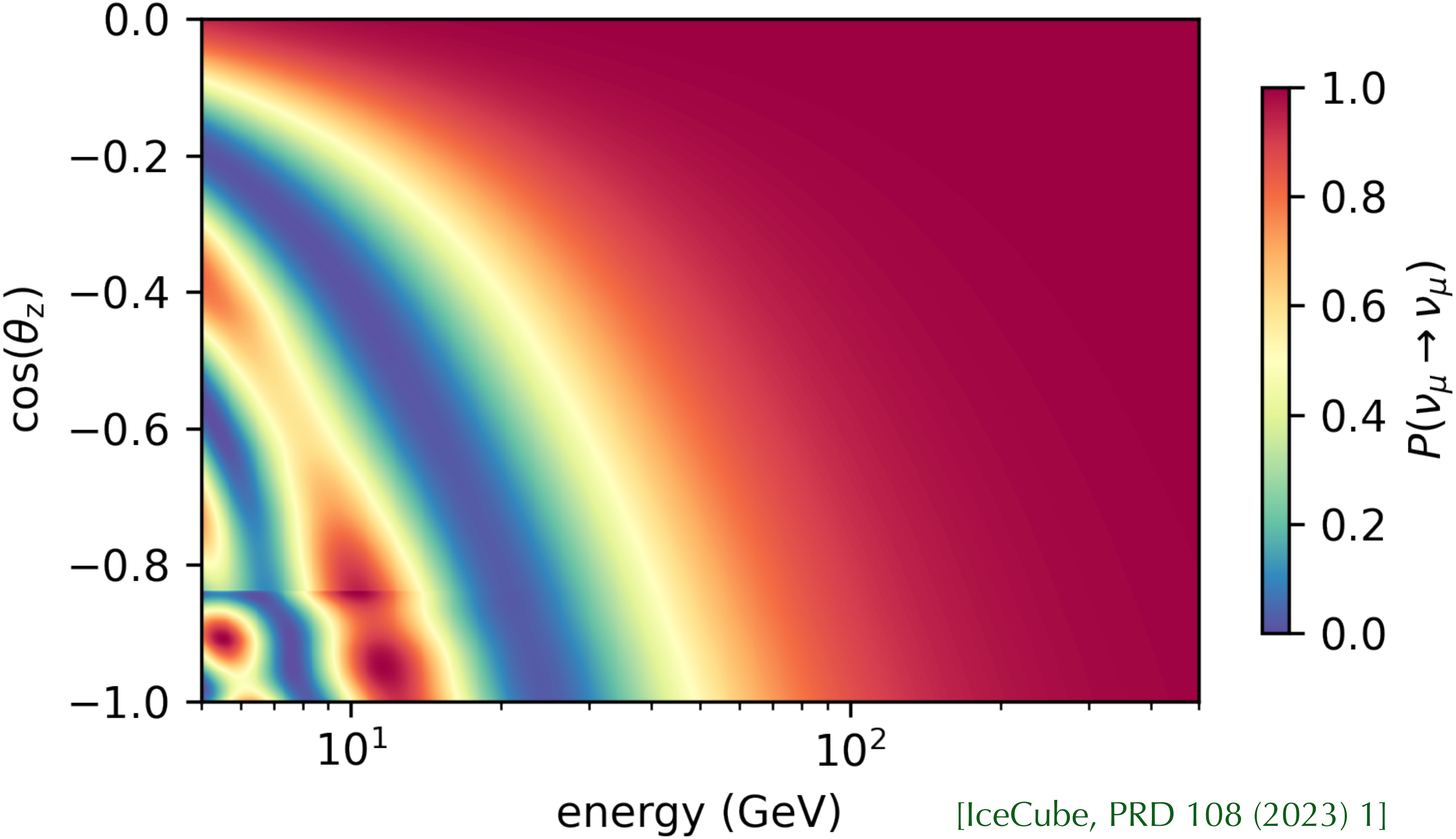
colours show relative contribution of ν_e, ν_μ and ν_τ

Neutrino Selection



Atmospheric Neutrino Oscillation

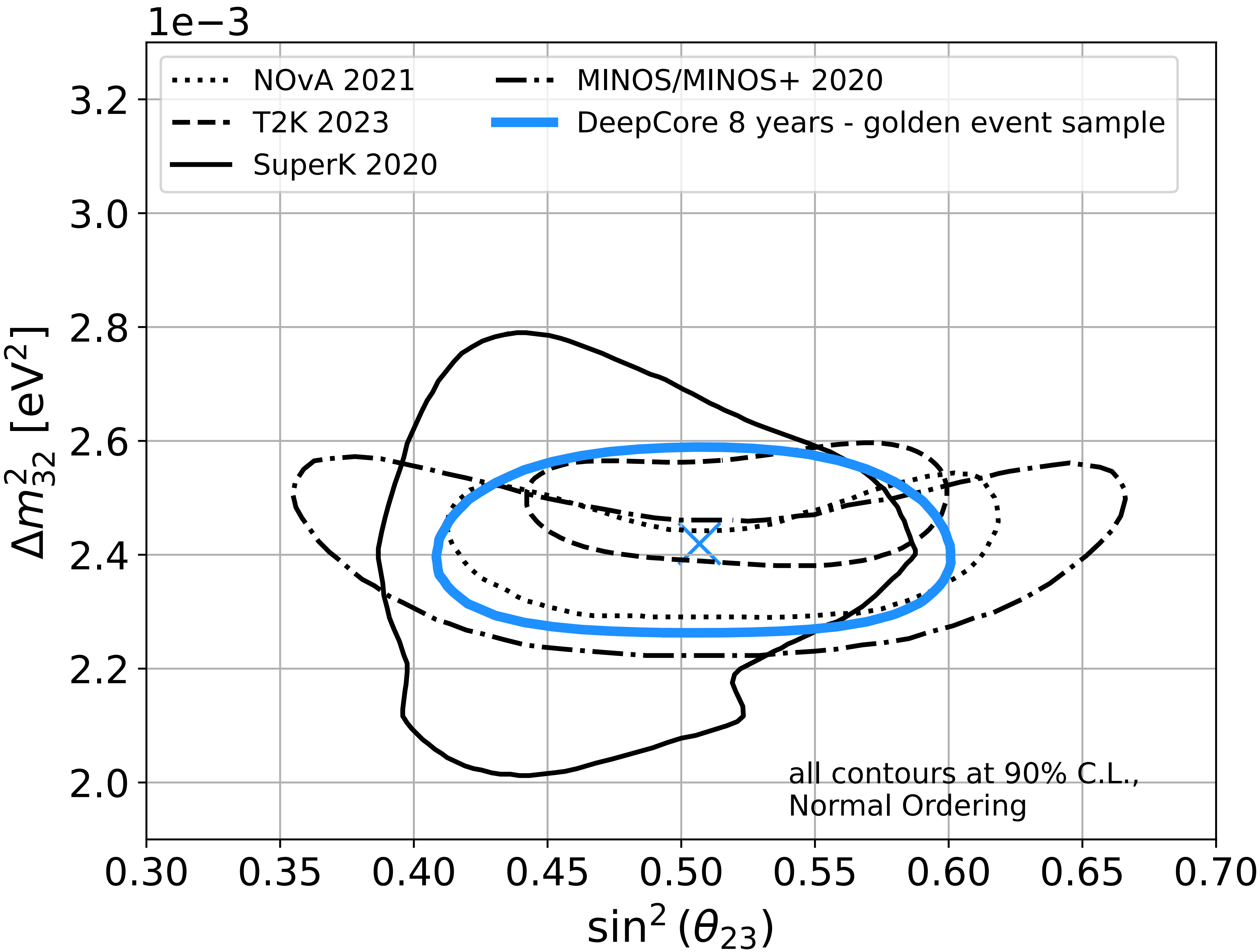
Atmospheric **muon neutrino survival probability**
as a function of energy and zenith angle θ_Z



[IceCube, PRD 108 (2023) 1]

Atmospheric Neutrino Oscillation

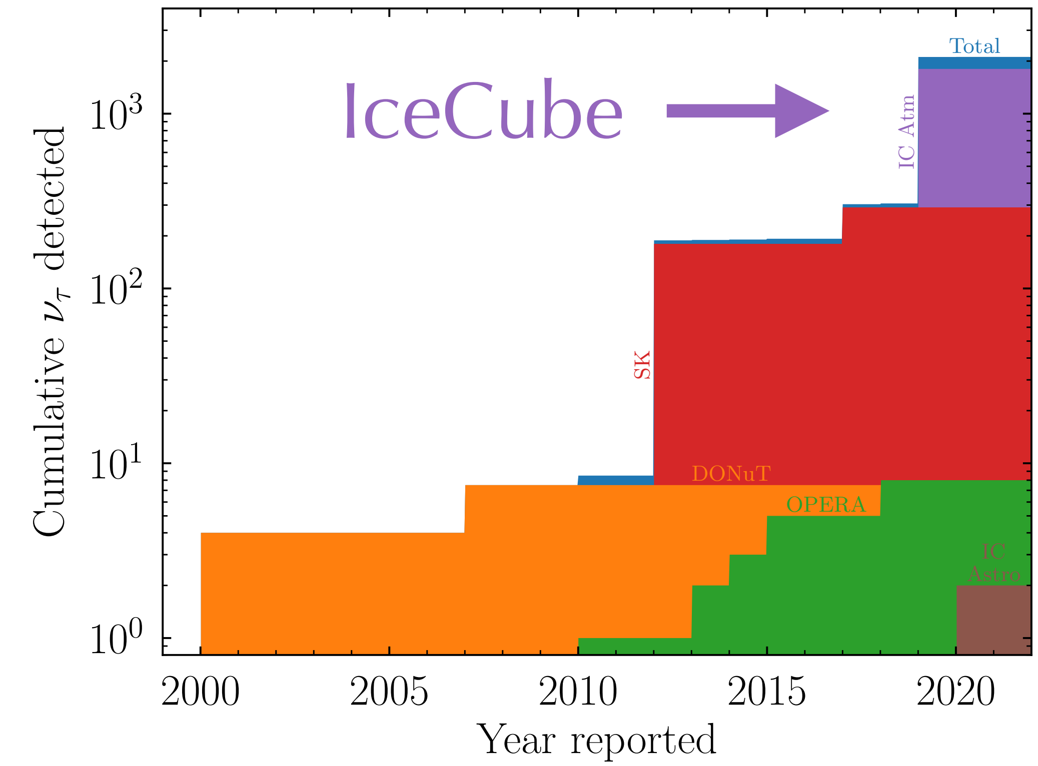
90% C.L. allowed region for atmospheric neutrino oscillation parameters



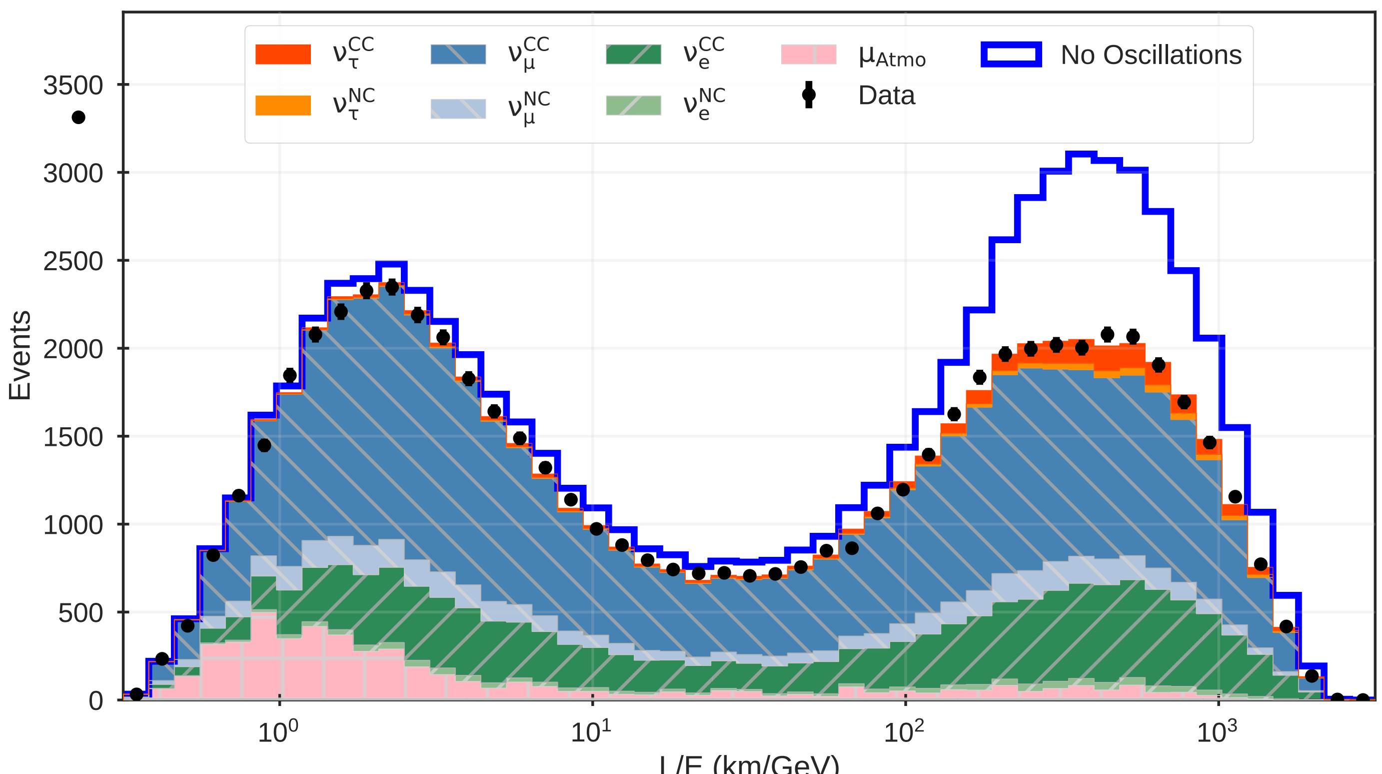
[IceCube, PRD 108 (2023) 1]

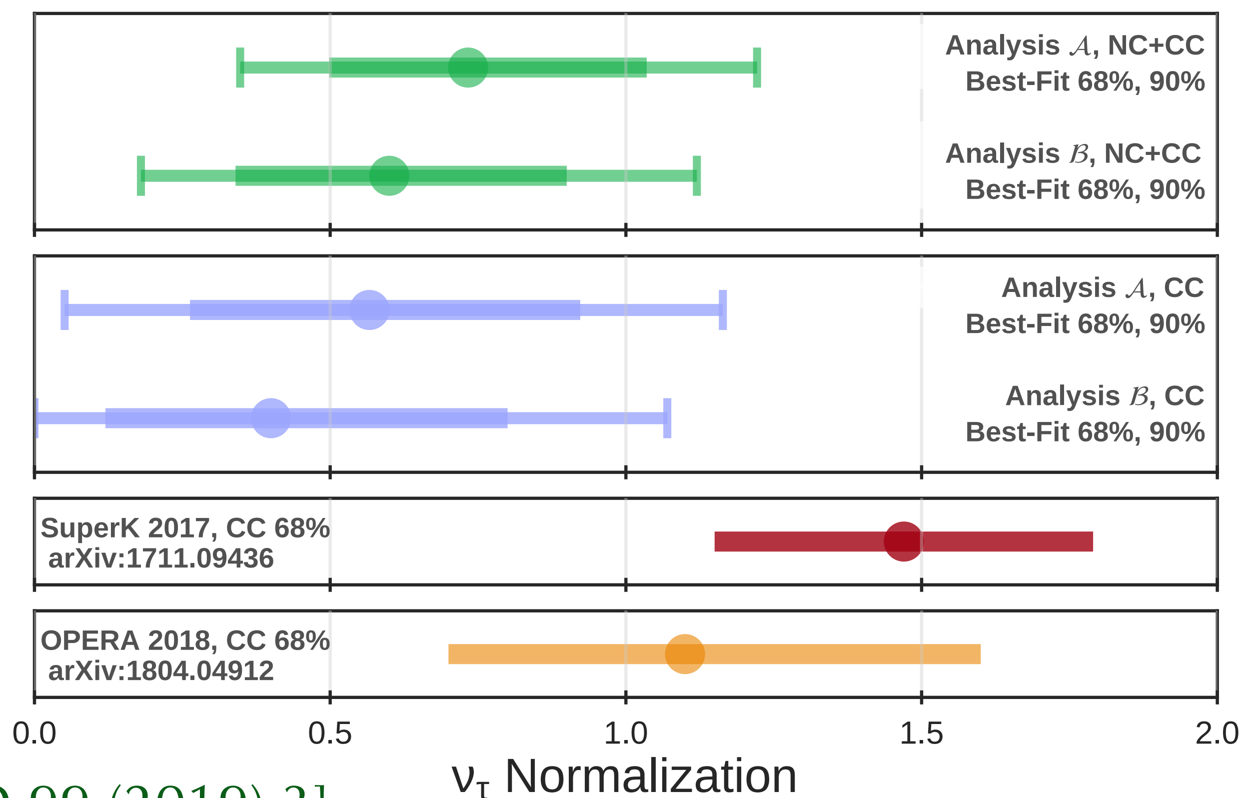
Tau Neutrino Appearance

- 86% of ν_τ global data from IceCube
- High statistics of ν_τ allow to make **precision tests** of the 3-flavour oscillation paradigm.
- Tau neutrino appearance at 3σ level with normalization $0.49 - 1.03$.



[arXiv:2203.05591]

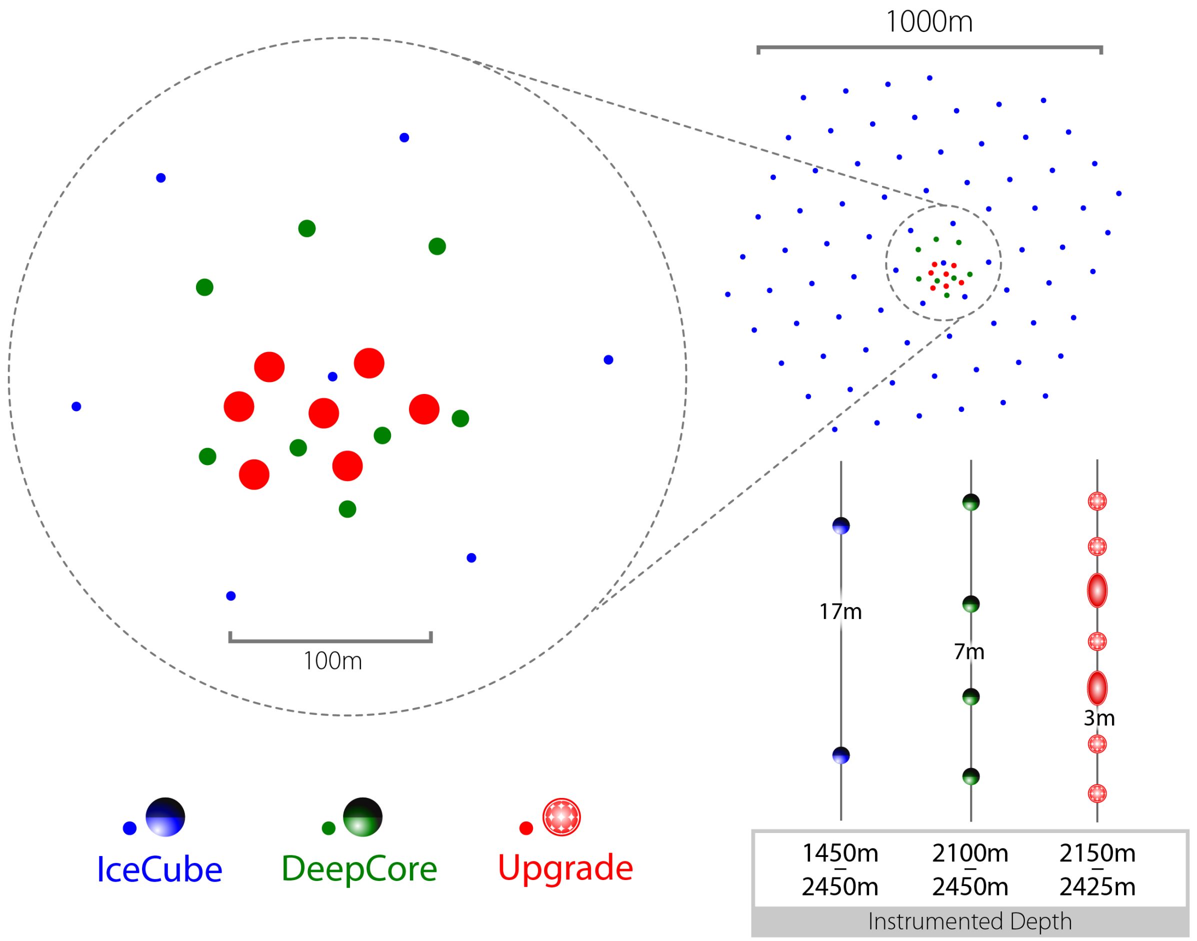


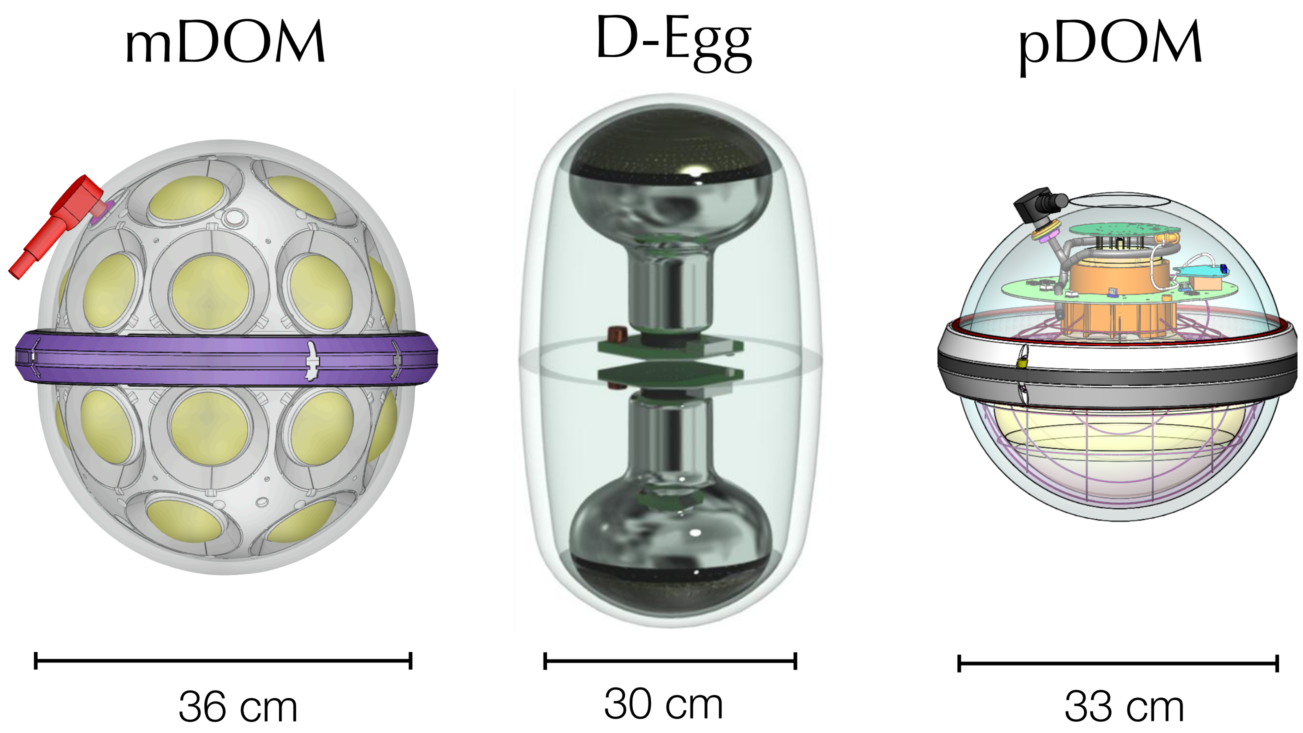


[IceCube, PRD 99 (2019) 3]

Outlook: IceCube Upgrade

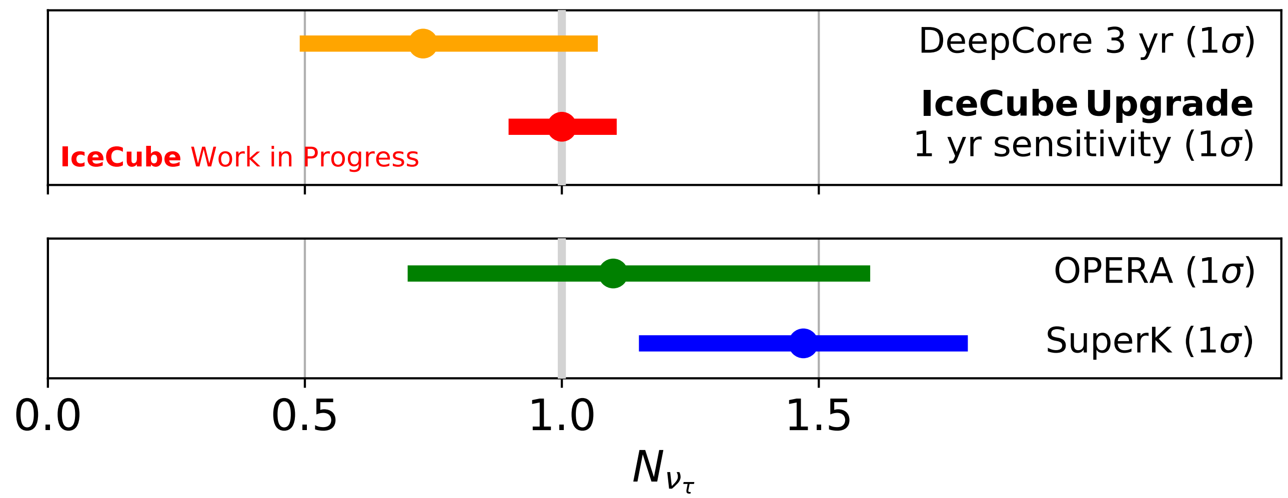
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Aim: deployment in 2025/26**

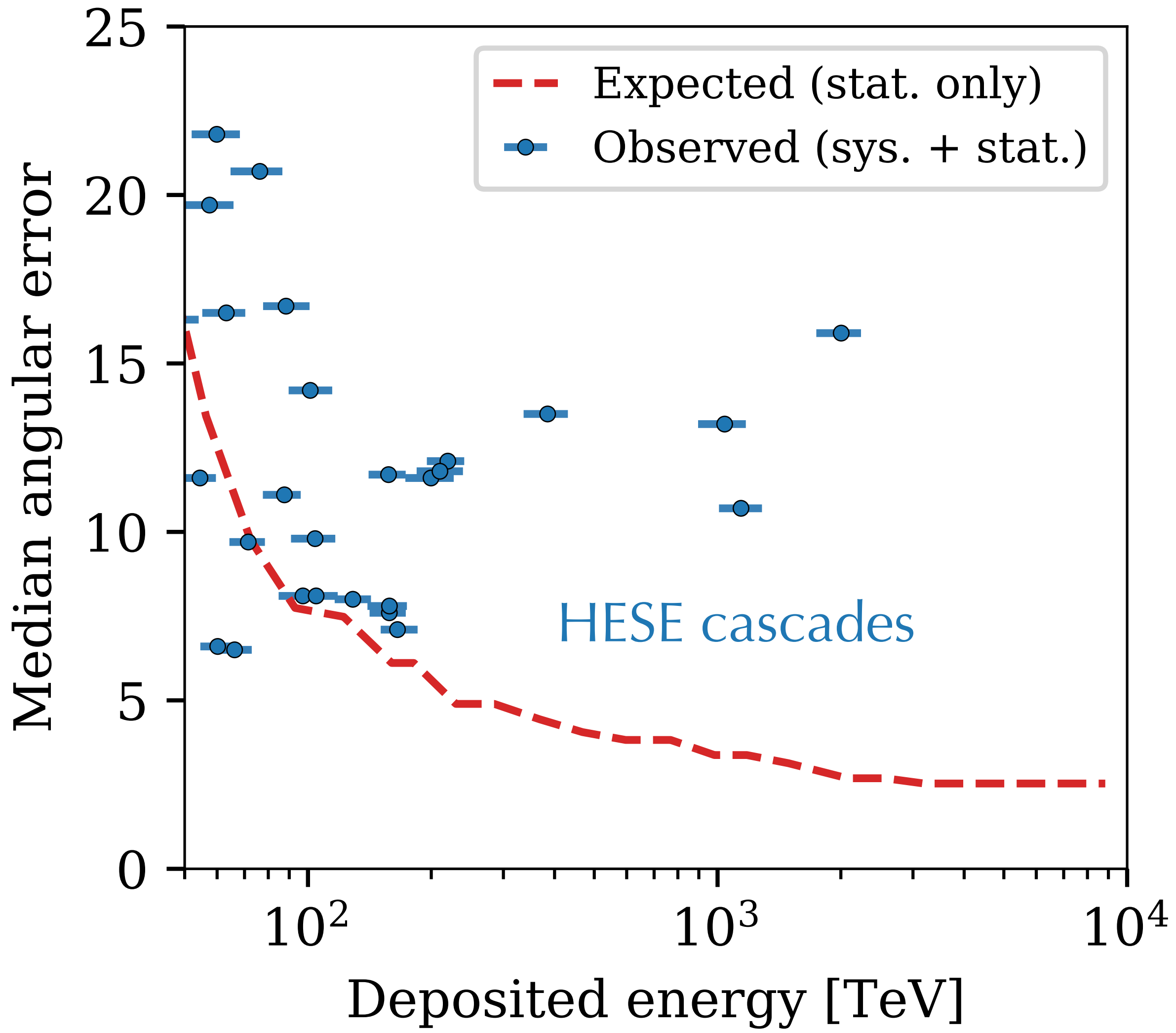


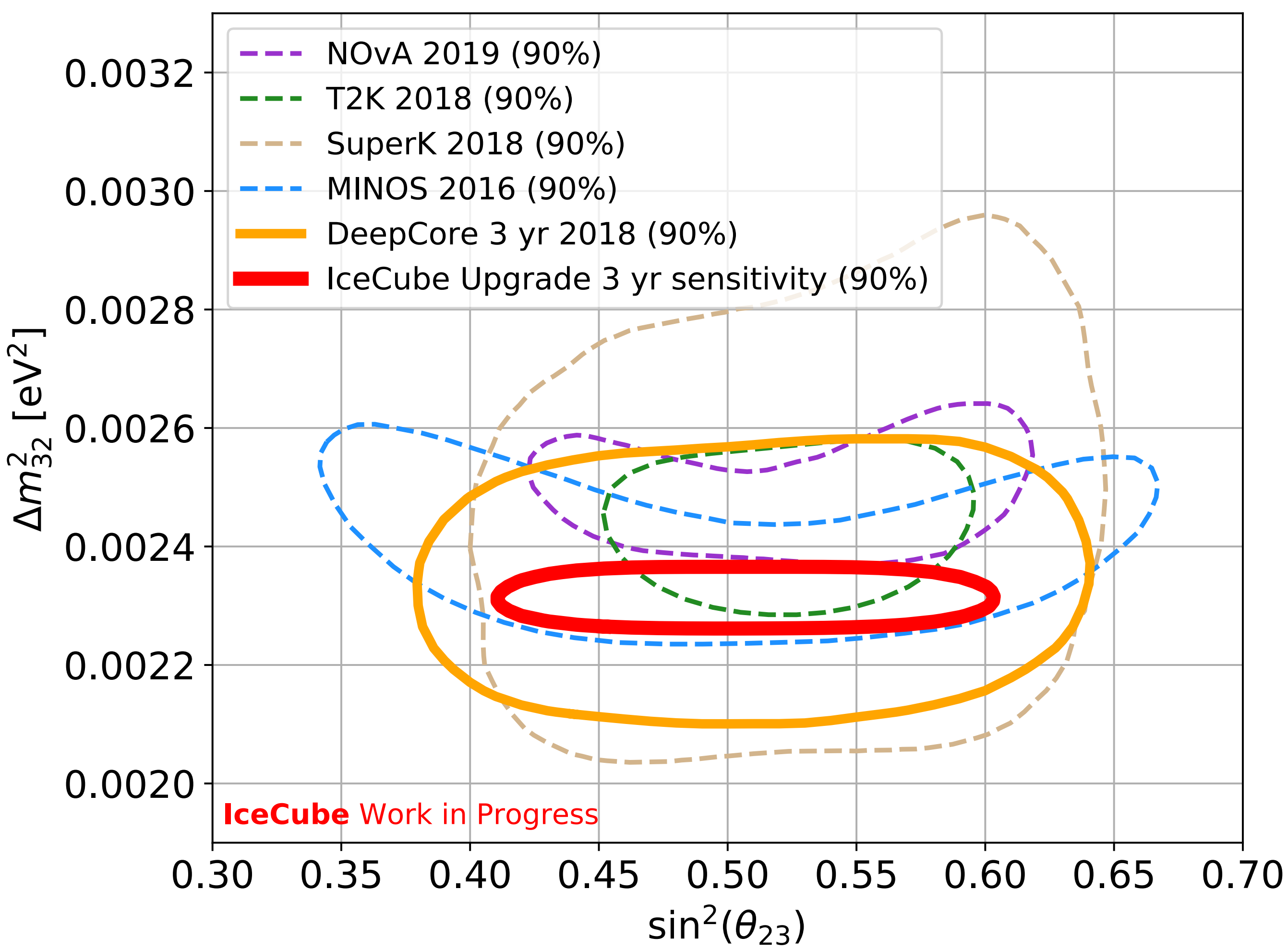


Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance
- **Improved energy and angular reconstructions** of IceCube data



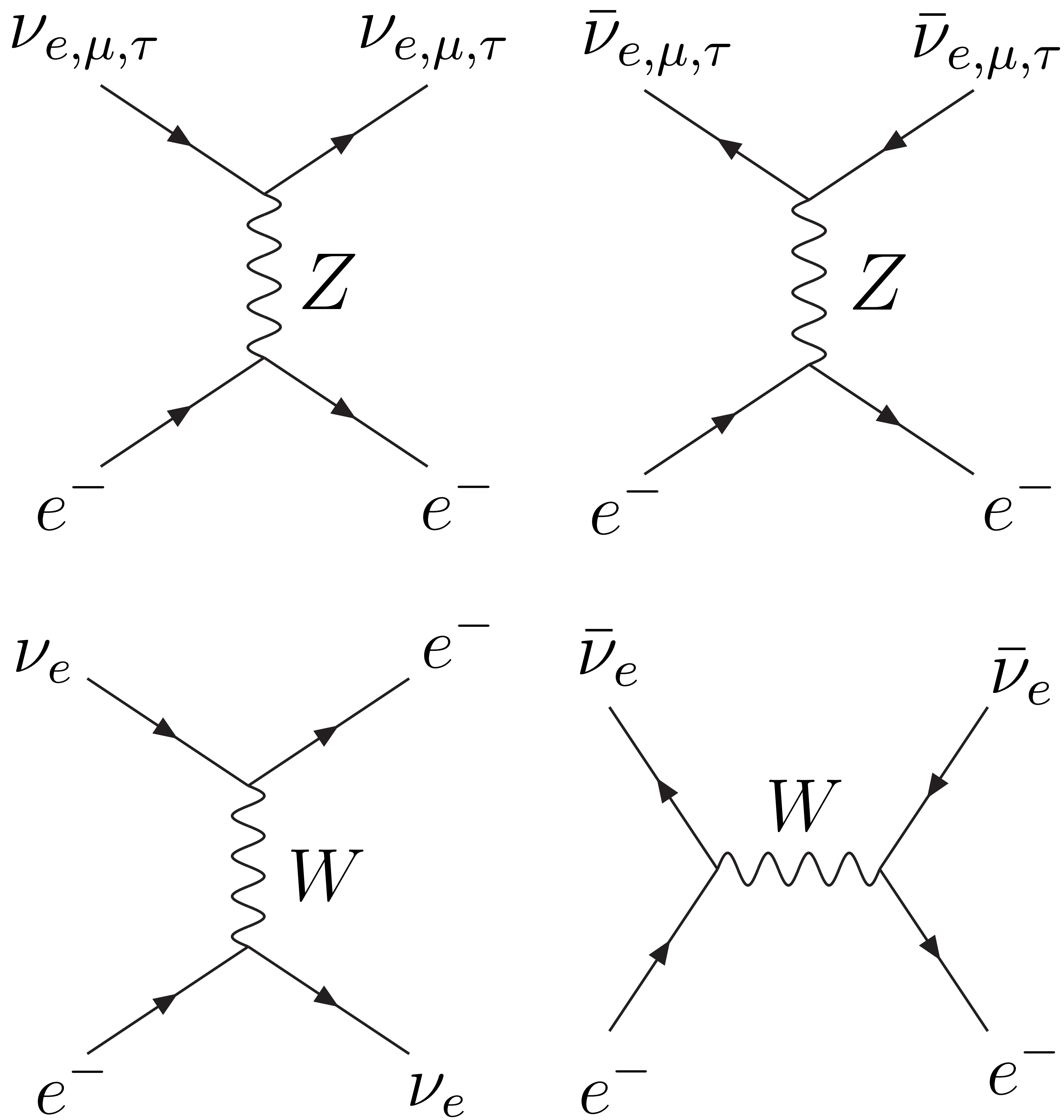




[IceCube, PoS (ICRC2019) 1031]

Matter Effects

Neutrino interactions with matter single out ν_e & $\bar{\nu}_e$ and introduce **non-universal effective potential**.



$$V_{\rm CC}(\mathbf{r}) = \begin{pmatrix} A(\mathbf{r}) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A(\mathbf{r}) = \begin{cases} +\sqrt{2}G_F n_e(\mathbf{r}) & \nu_e \\ -\sqrt{2}G_F n_e(\mathbf{r}) & \bar{\nu}_e \end{cases}$$

[Wolfenstein'78; Mikheyev & Smirnov'85]

Matter Effects

Matter effects in atmospheric ν oscillations are **sensitive to mass ordering**:

[Choubey & Roy'06]

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\mathbf{\Theta}_{13} \sin^2 \frac{\Delta\mathbf{M}^2_{31}\ell}{4E_\nu}$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \cos^2\mathbf{\Theta}_{13} \sin^2\left(\frac{(\Delta m^2_{31} + \Delta\mathbf{M}^2_{31})\ell}{8E_\nu} + \frac{\mathbf{A}\ell}{4}\right)$$

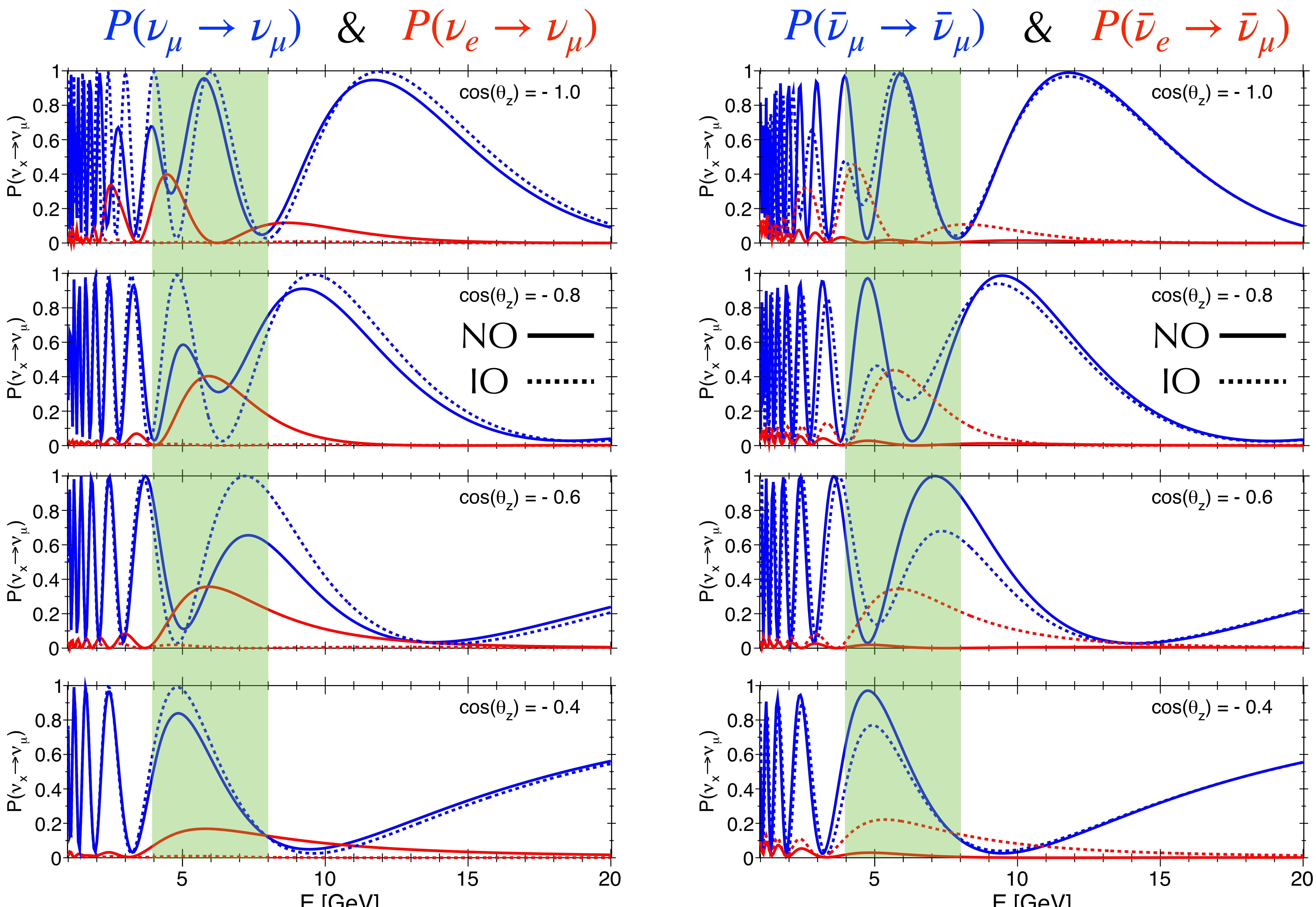
$$- \sin^2 2\theta_{23} \sin^2\mathbf{\Theta}_{13} \sin^2\left(\frac{(\Delta m^2_{31} - \Delta\mathbf{M}^2_{31})\ell}{8E_\nu} + \frac{\mathbf{A}\ell}{4}\right)$$

$$- \sin^4\theta_{23} \sin^2 2\mathbf{\Theta}_{13} \sin^2 \frac{\Delta\mathbf{M}^2_{31}\ell}{4E_\nu}$$

$$\sin^2 2\mathbf{\Theta}_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta\mathbf{M}^2_{31}}\right)^2 \qquad \Delta\mathbf{M}^2_{31} \equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - 2E_\nu A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})}$$

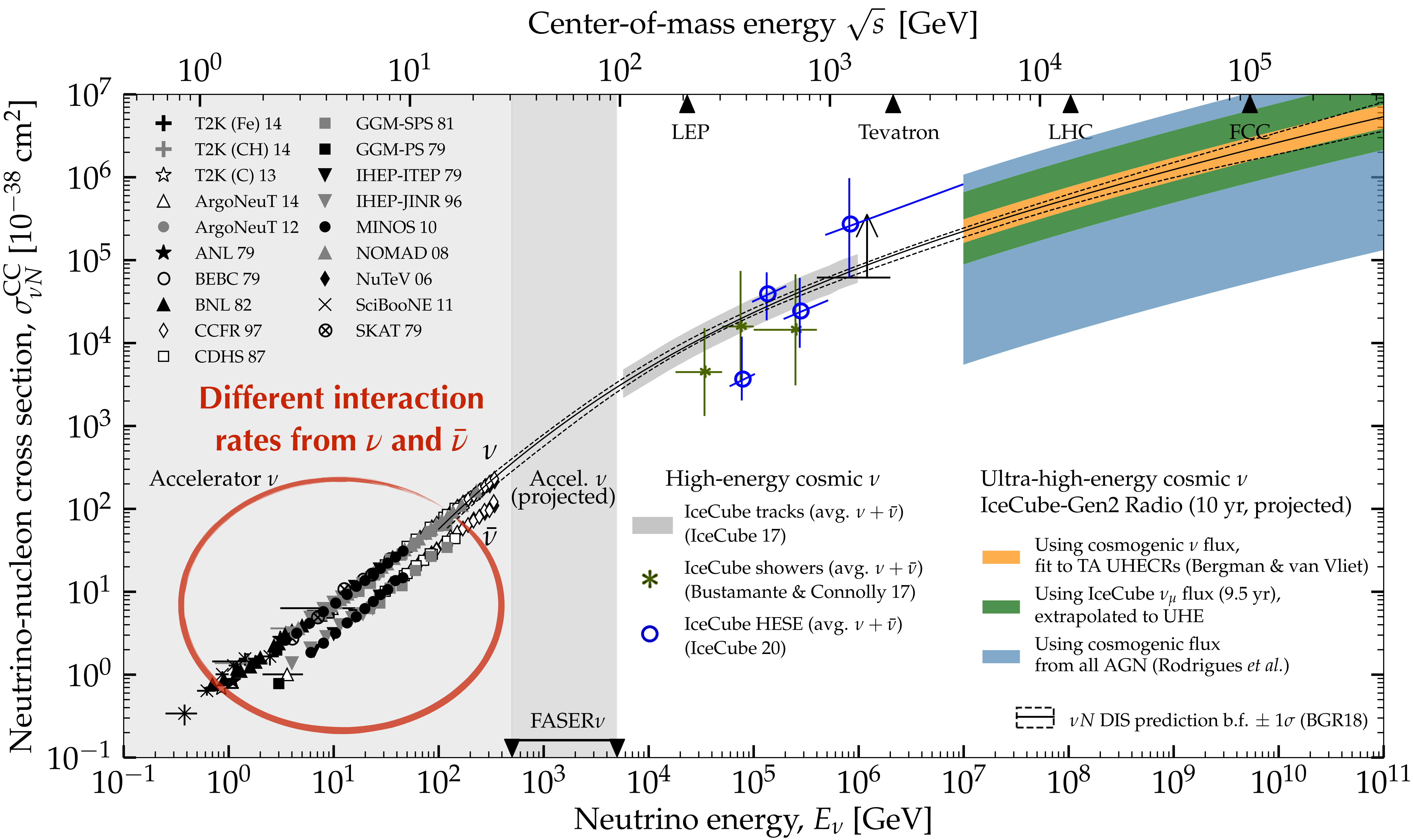
Maximal mixing $\sin^2 2\mathbf{\Theta}_{13} \to 1$ at energies $E_{\mathrm{res}} \simeq (4-8)\,\mathrm{GeV}$.

Sensitivity to Mass Ordering



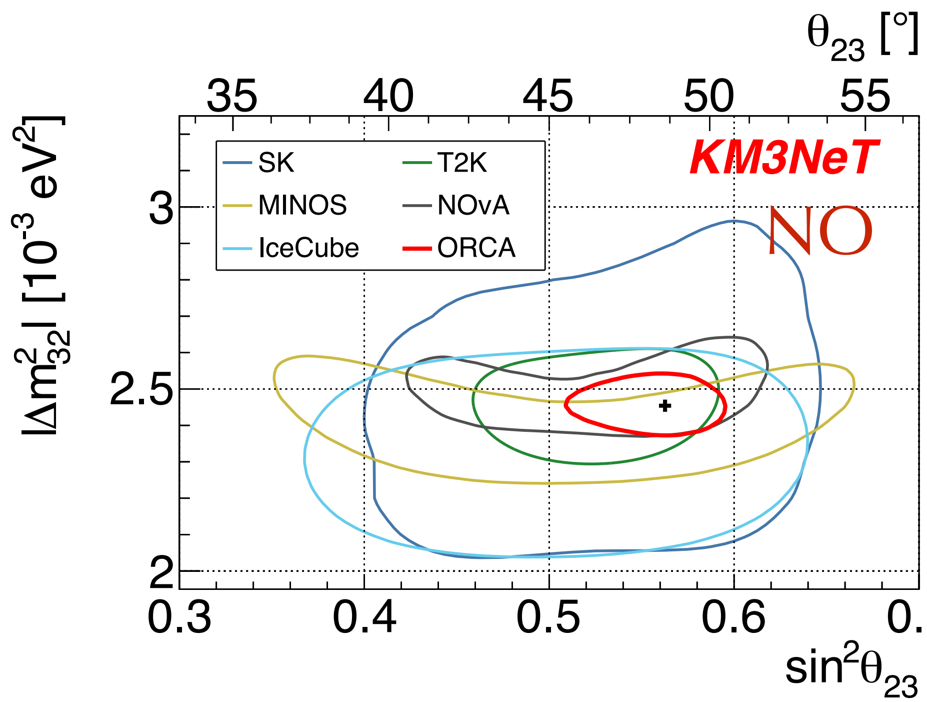
[KM3NeT/ORCA, J.Phys.G 43 (2016) 8]

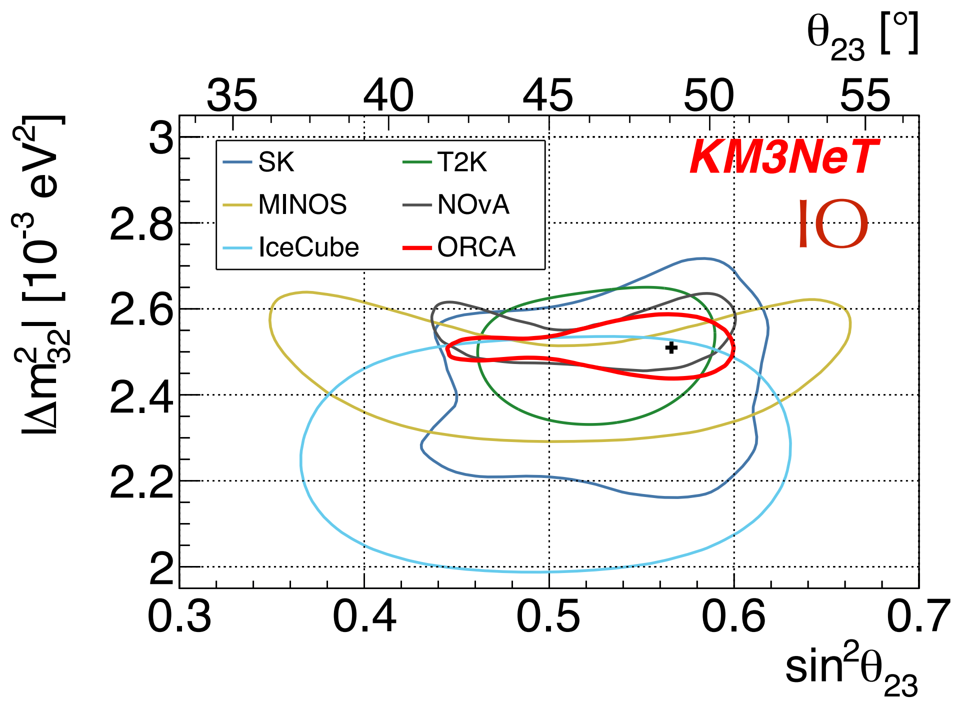
Neutrino Cross Section

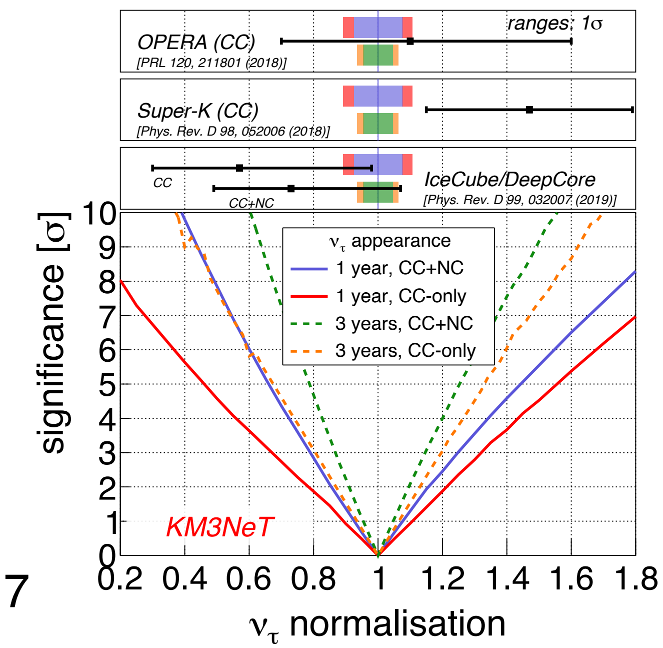


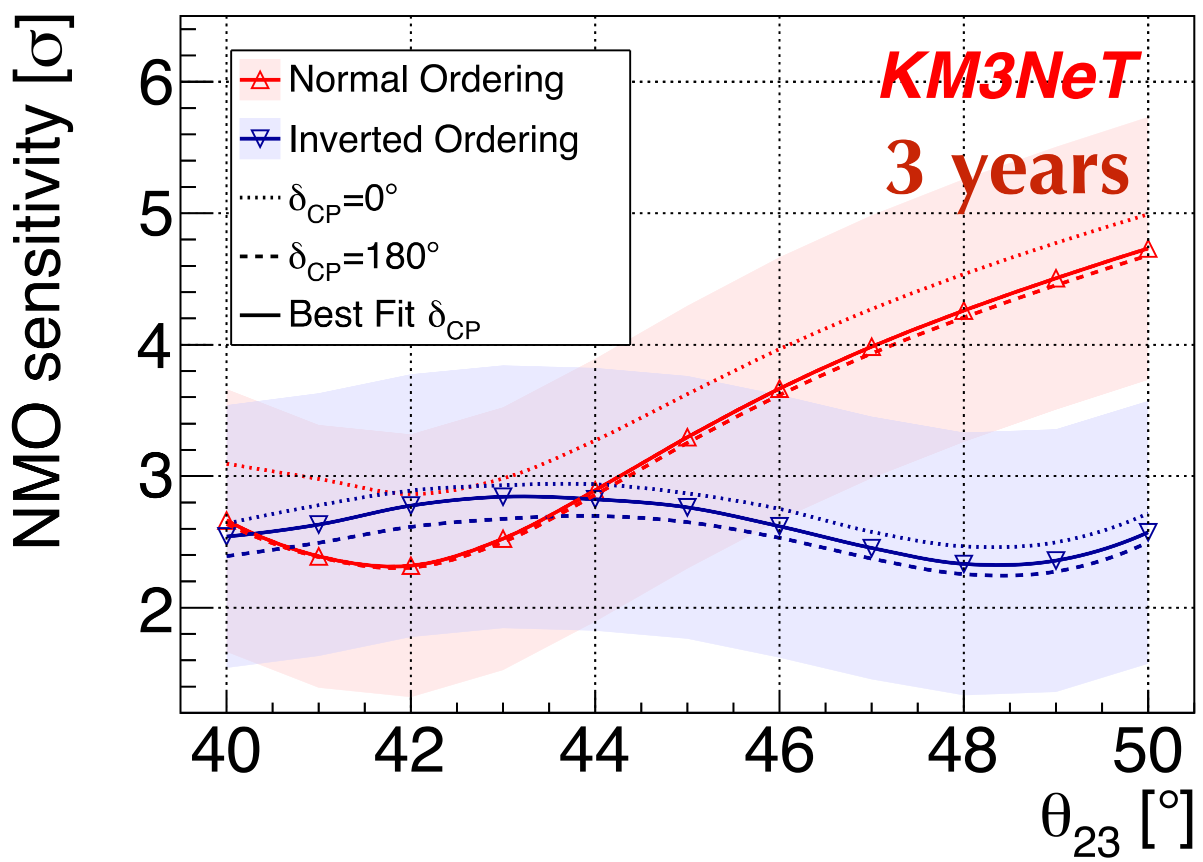
[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

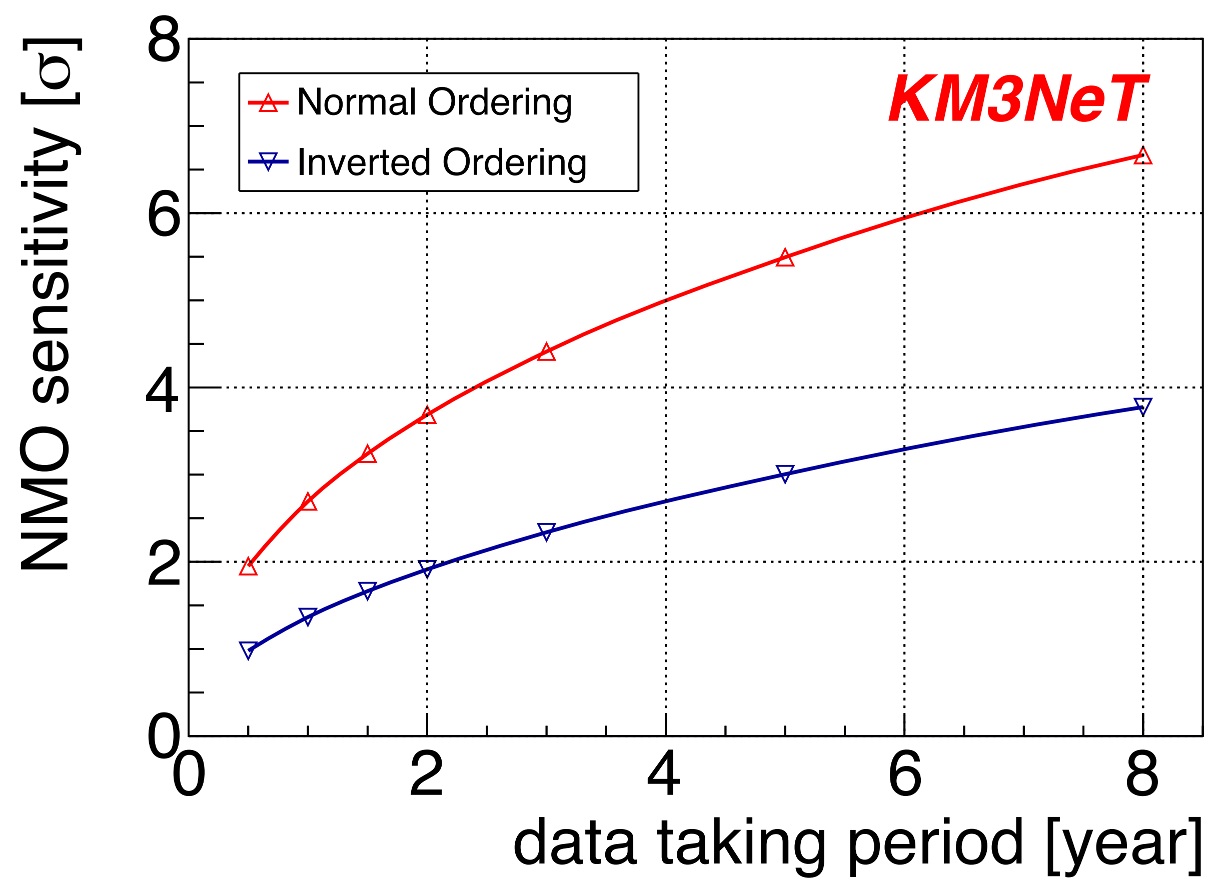
Sensitivity to Mass Ordering







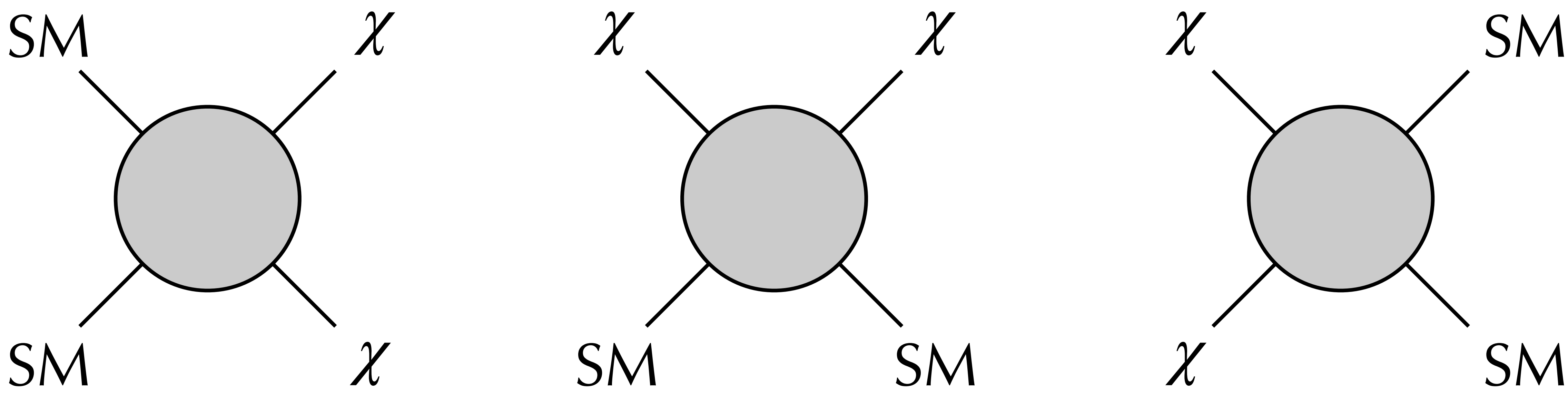




[KM3NeT/ORCA, EPJC 82 (2022) 1]

WIMP Dark Matter

Weakly Interacting Massive Particles (WIMPs) are well-motivated DM candidates that appear in extensions of the Standard Model, e.g., by supersymmetry.



"make it" — thermal production in the early Universe

"shake it" — direct observation in scattering experiments

"break it" — indirect observation by final stable SM particles

Annihilation and Decay

- Neutrino emission from DM annihilation ($\rho_\chi = m_\chi n_\chi$) at a rate:

$$Q^{\rm ann}_{\nu_\alpha}(\mathbf{r}) = \frac{1}{2}\rho^2_\chi(\mathbf{r})\frac{\langle\sigma_A v\rangle}{m^2_\chi}\frac{{\rm d}N_{\nu_\alpha}}{{\rm d}E_\nu} \qquad Q^{\rm dec}_{\nu_\alpha}(\mathbf{r}) = \rho_\chi(\mathbf{r})\frac{\Gamma_\chi}{m_\chi}\frac{{\rm d}N_{\nu_\alpha}}{{\rm d}E_\nu}$$

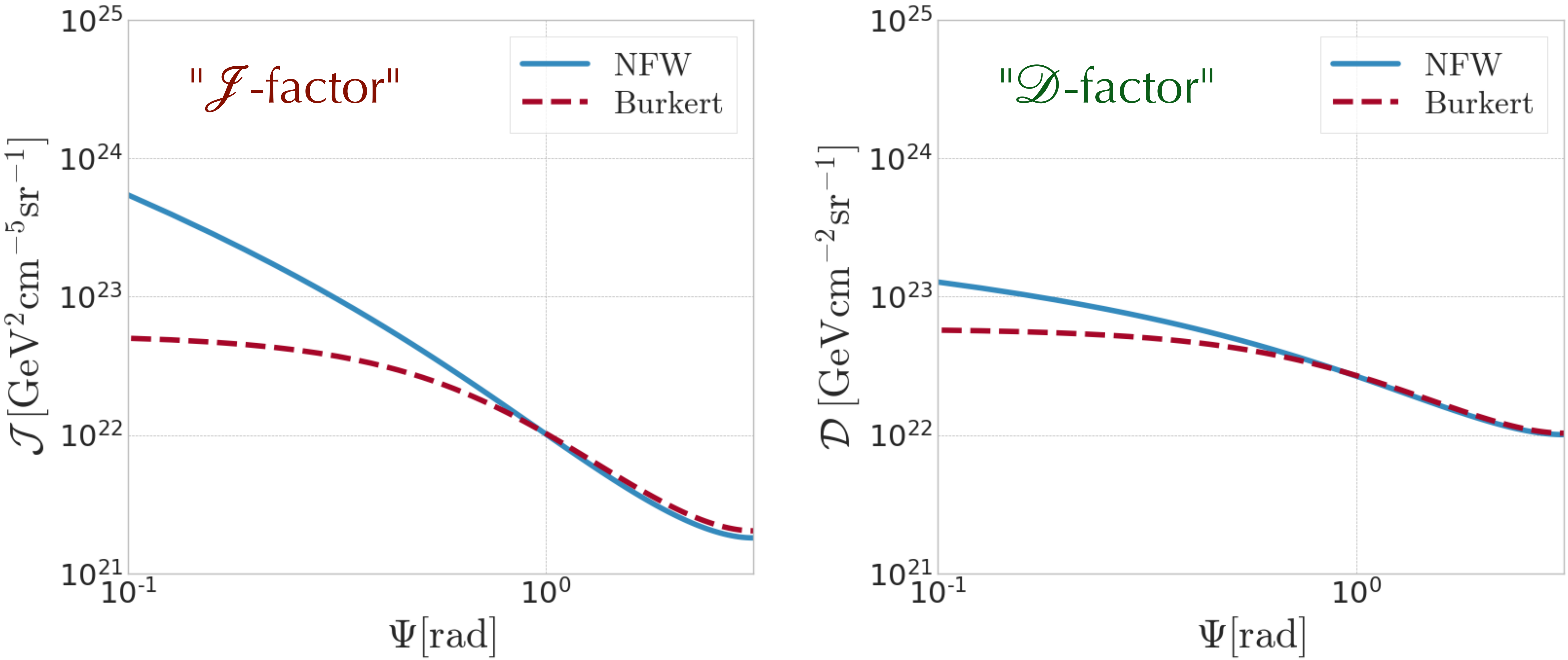
- Neutrino flux observed per solid angle from Earth's location $\mathbf{r}_\oplus$:

$$\phi_{\nu_\beta}(E_\nu) = \sum_{\nu_\alpha} P_{\nu_\alpha\to\nu_\beta}\underbrace{\left[\int_0^\infty d\ell\,\rho^2_\chi(\mathbf{r}_\oplus + \ell\,\hat{\mathbf{n}})\right]}_{\text{"}\mathcal{J}\text{-factor"}}\frac{\langle\sigma_A v\rangle}{8\pi m^2_\chi}\frac{dN_{\nu_\alpha}}{dE_\nu}$$

$$\phi_{\nu_\beta}(E_\nu) = \sum_{\nu_\alpha} P_{\nu_\alpha\to\nu_\beta}\underbrace{\left[\int_0^\infty d\ell\,\rho_\chi(\mathbf{r}_\oplus + \ell\,\hat{\mathbf{n}})\right]}_{\text{"}\mathcal{D}\text{-factor"}}\frac{\Gamma_\chi}{4\pi m_\chi}\frac{dN_{\nu_\alpha}}{dE_\nu}$$

Galactic DM Distribution

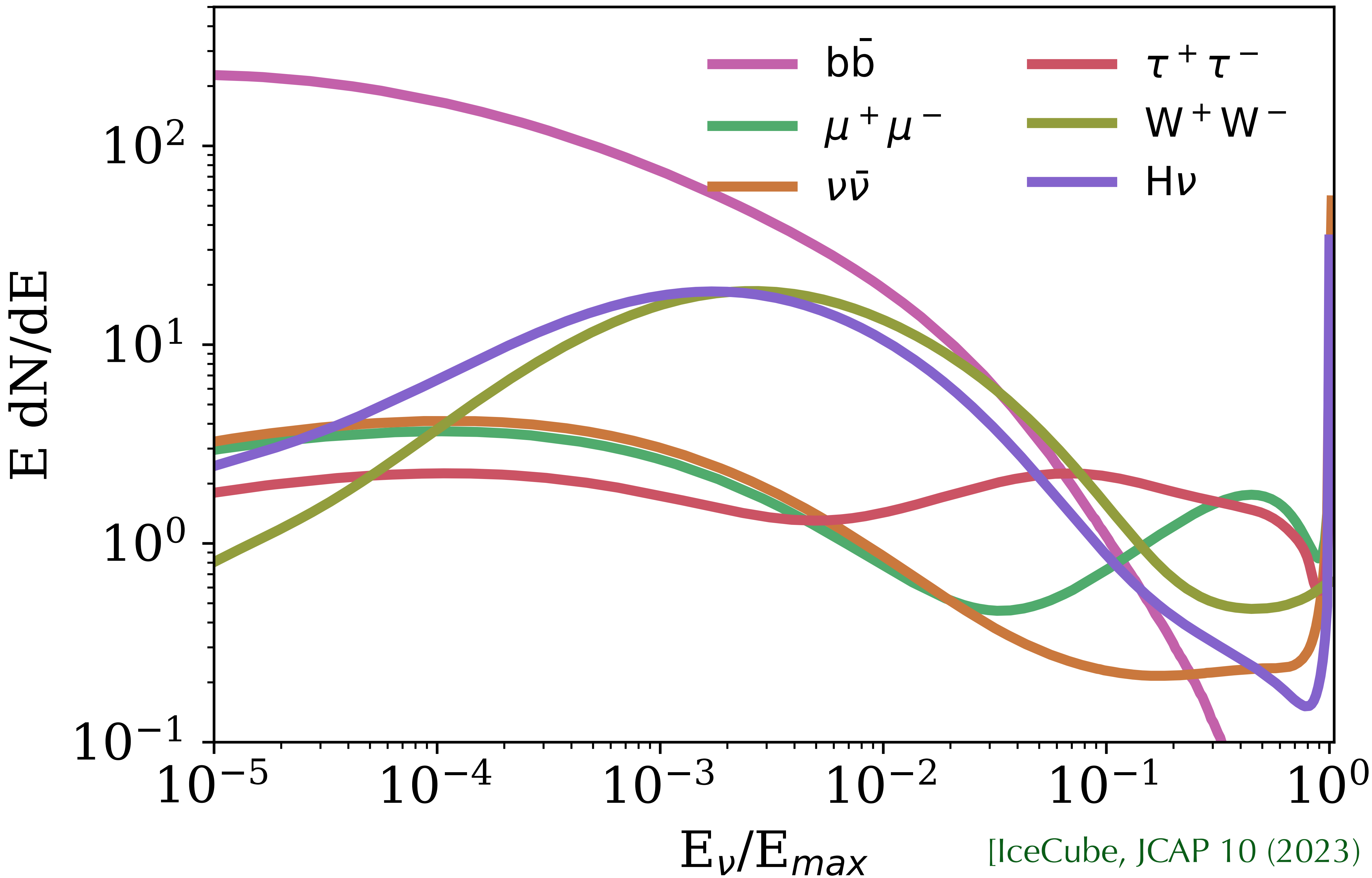
Distribution of neutrino flux depends on the "cuspiness" of the Milky Way dark matter distribution, in particular for the annihilation signal ($\mathcal{J}$-factor).



[IceCube, PRD 108 (2023) 10]

Neutrino Spectra from DM

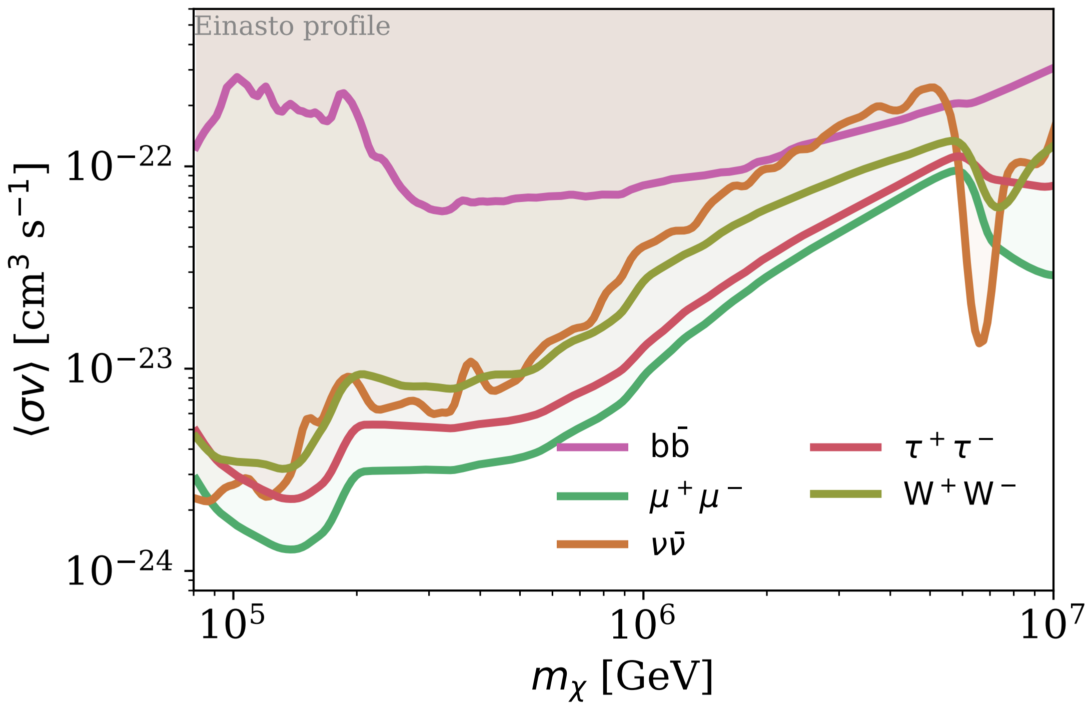
Neutrino energy distribution from dark matter decay or annihilation.

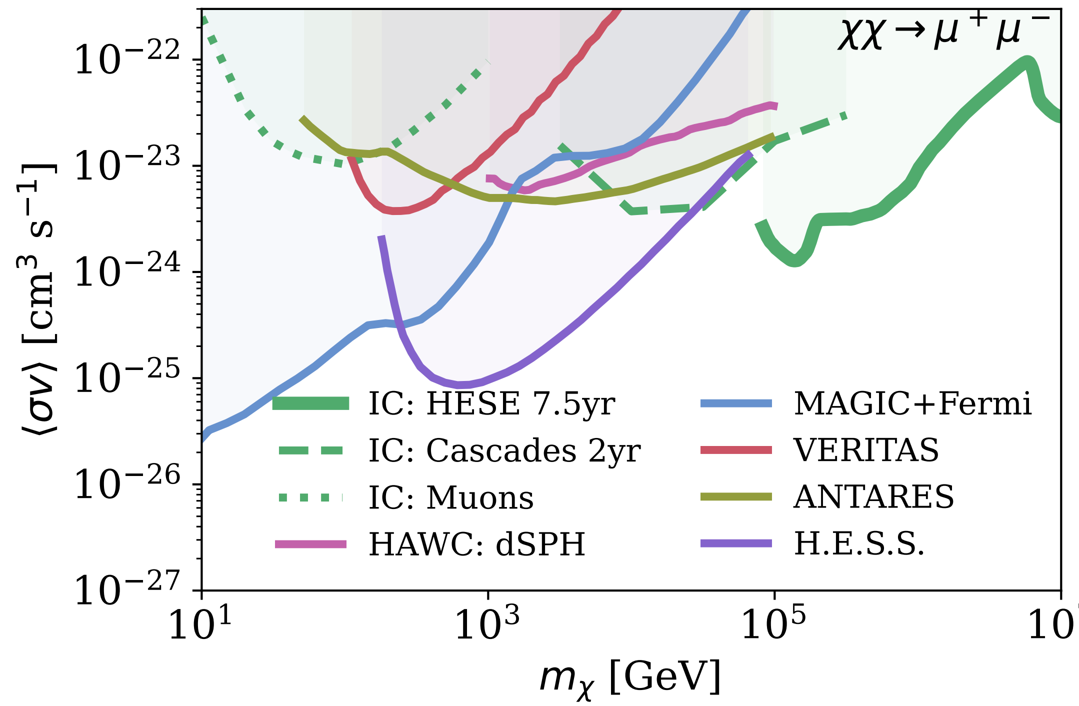


[IceCube, JCAP 10 (2023) 003]

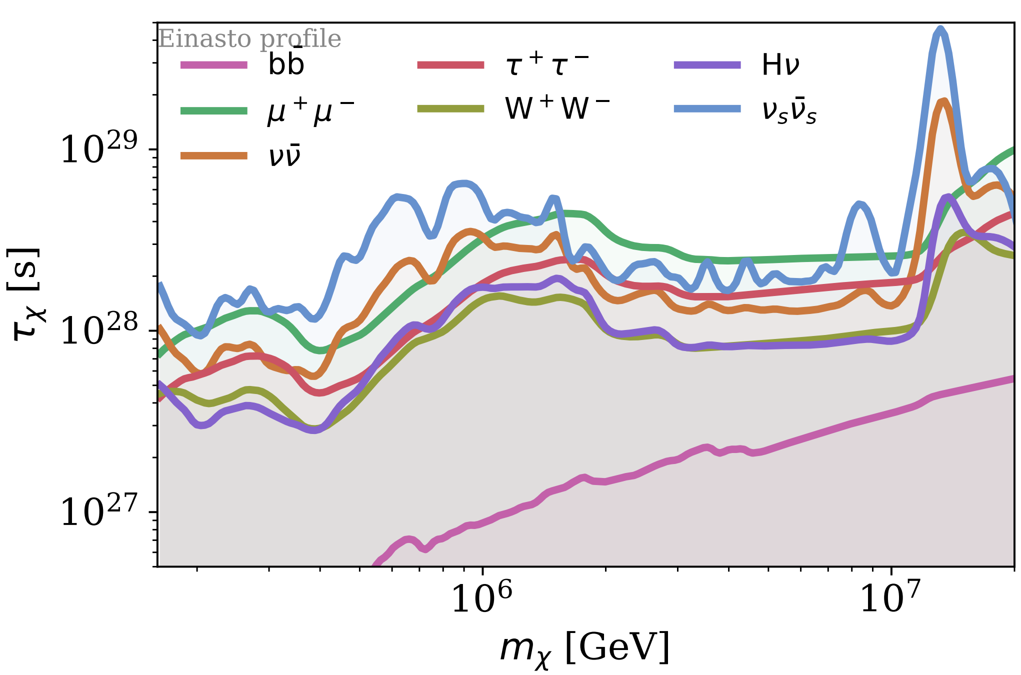
Indirect DM Limits

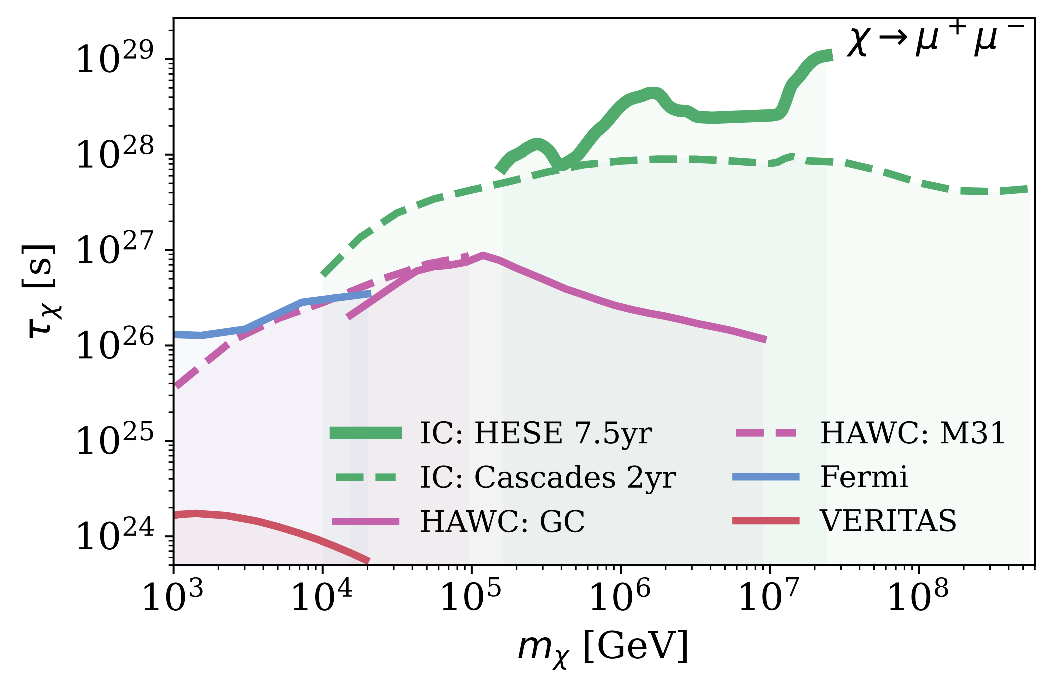
Upper limits on **velocity-averaged self-annihilation cross-section**.





Lower limits on the **dark matter lifetime**.

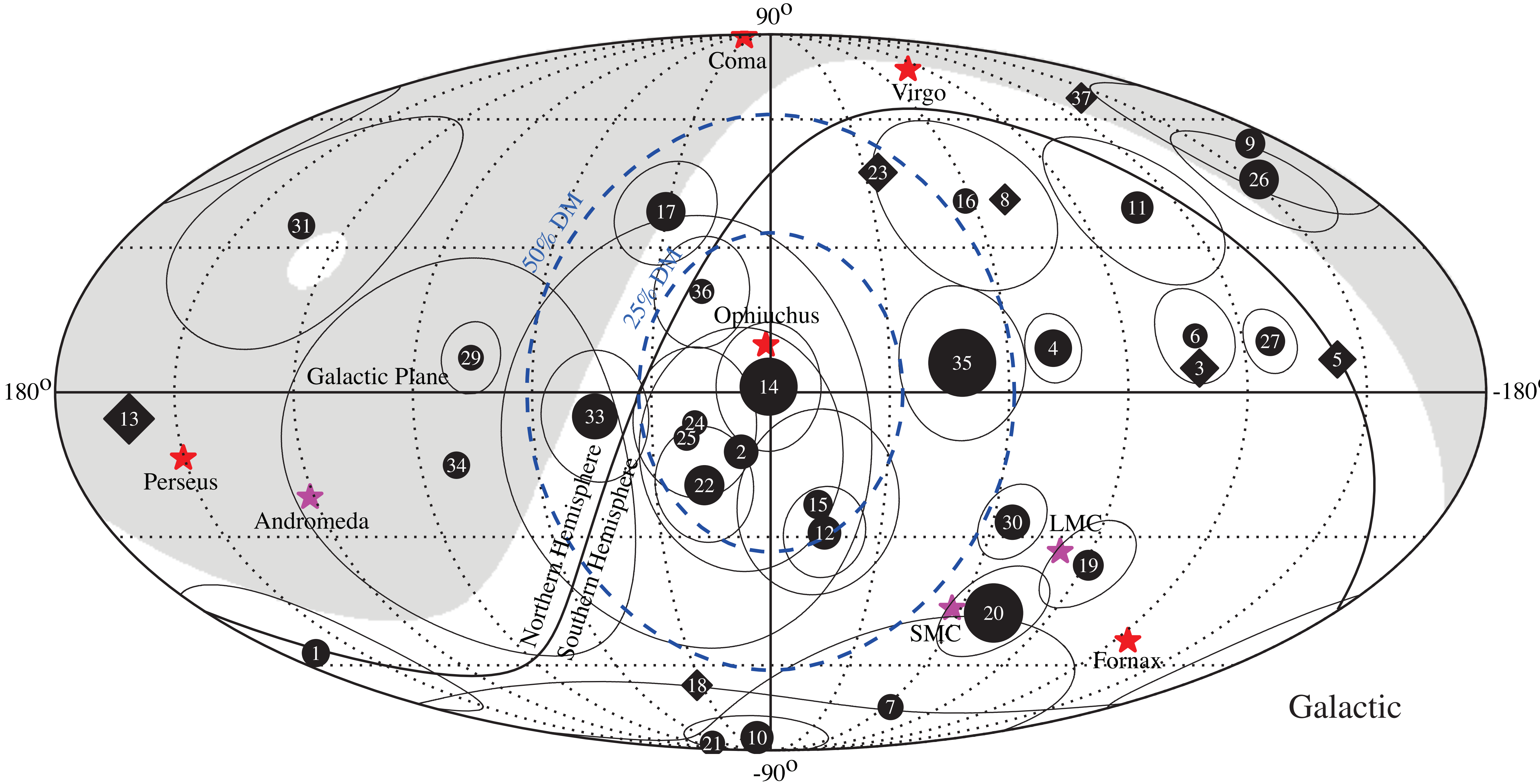




[IceCube, JCAP 10 (2023) 003]

Cosmic Neutrinos & PeV DM

Distribution of cosmic neutrinos from 2013 HESE analysis.



[Murase, Laha, Ando & MA'15]

[Feldstein, Kusenko, Matsumoto & Yanagida'13; Esmaili & Serpico'13; Zavala'14]

DM Annihilation in the Sun

- Evolution of the DM density in compact celestial objects:

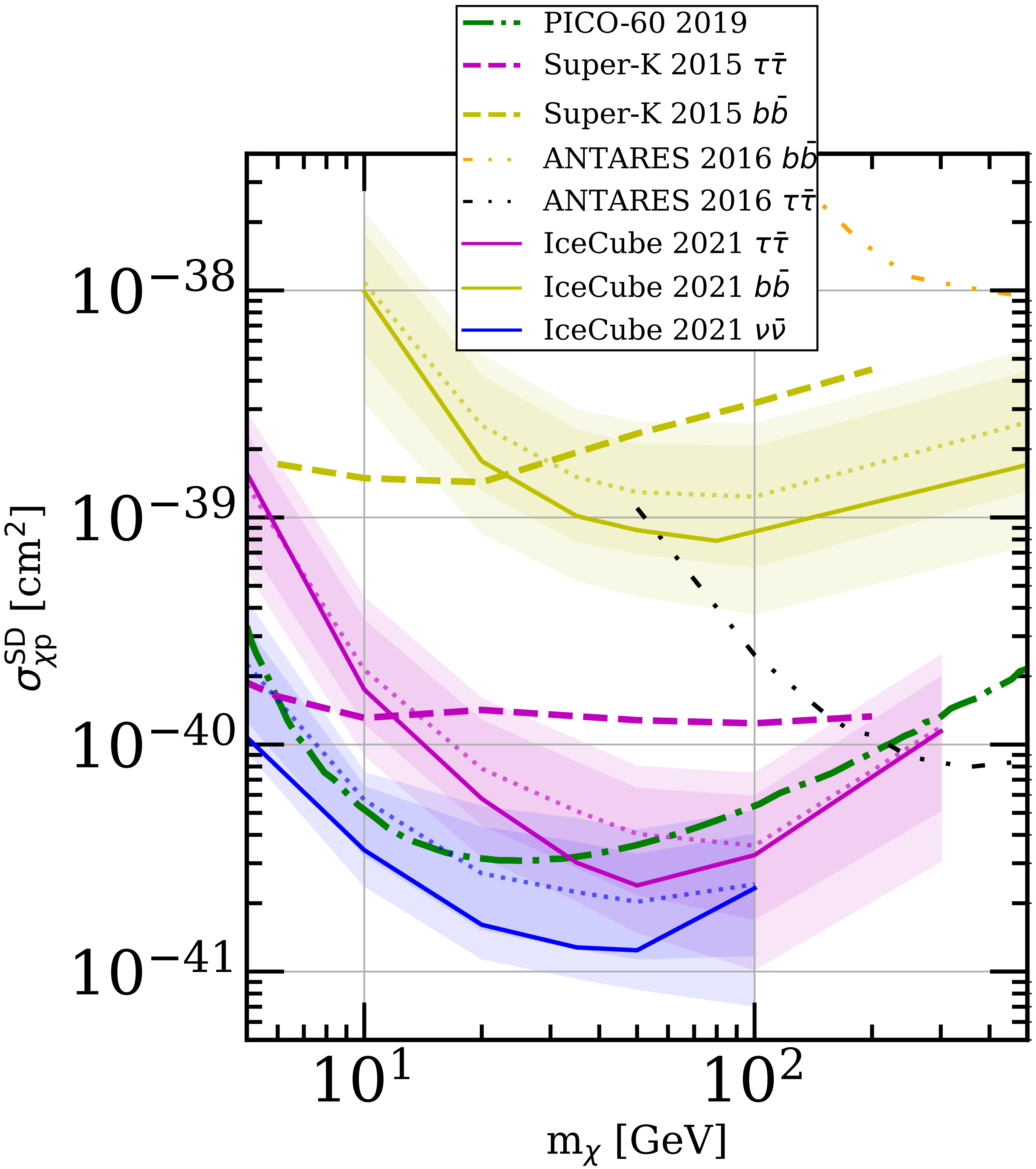
$$\dot{n}_\chi = Q_C - 2\langle\sigma_A v\rangle \frac{n_\chi^2}{2}$$

- DM **equilibrium density**:

$$n_{\chi,\mathrm{eq}} = \sqrt{\frac{Q_C}{\langle\sigma_A v\rangle}}$$

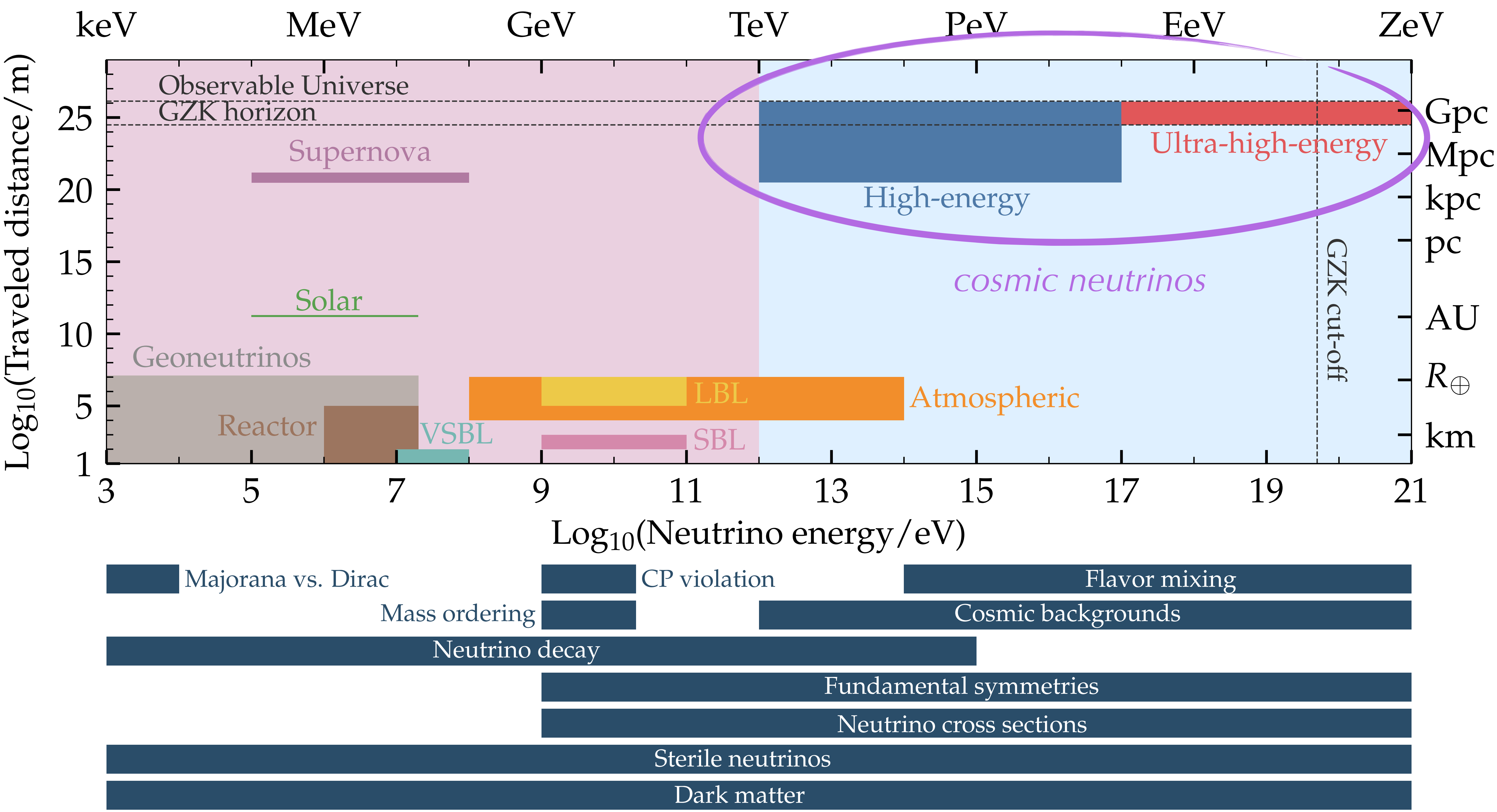
- The neutrino emission proportional to **capture rare**:

$$Q^{\mathrm{ann}}_{\nu_\alpha}(\mathbf{r}) = \frac{Q_C}{2}\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} \propto \sigma_{\chi N}$$



[IceCube, PRD 105 (2022) 6]

Probe of Fundamental Physics



[Ackermann, MA, Anchordoqui, Bustamante+ **Bull.Am.Astron.Soc.** 51 (2019)]

Sterile Neutrinos

- Sterile $\mathcal{O}(1)\,\mathrm{eV}$ neutrino motivated by **anomalous data** of accelerator, reactor, and radioactive source experiments:

$$\nu_\mu \rightarrow \nu_e \,\&\, \bar{\nu}_\mu \rightarrow \bar{\nu}_e \text{ appearance}$$

(LSND & MiniBooNE)

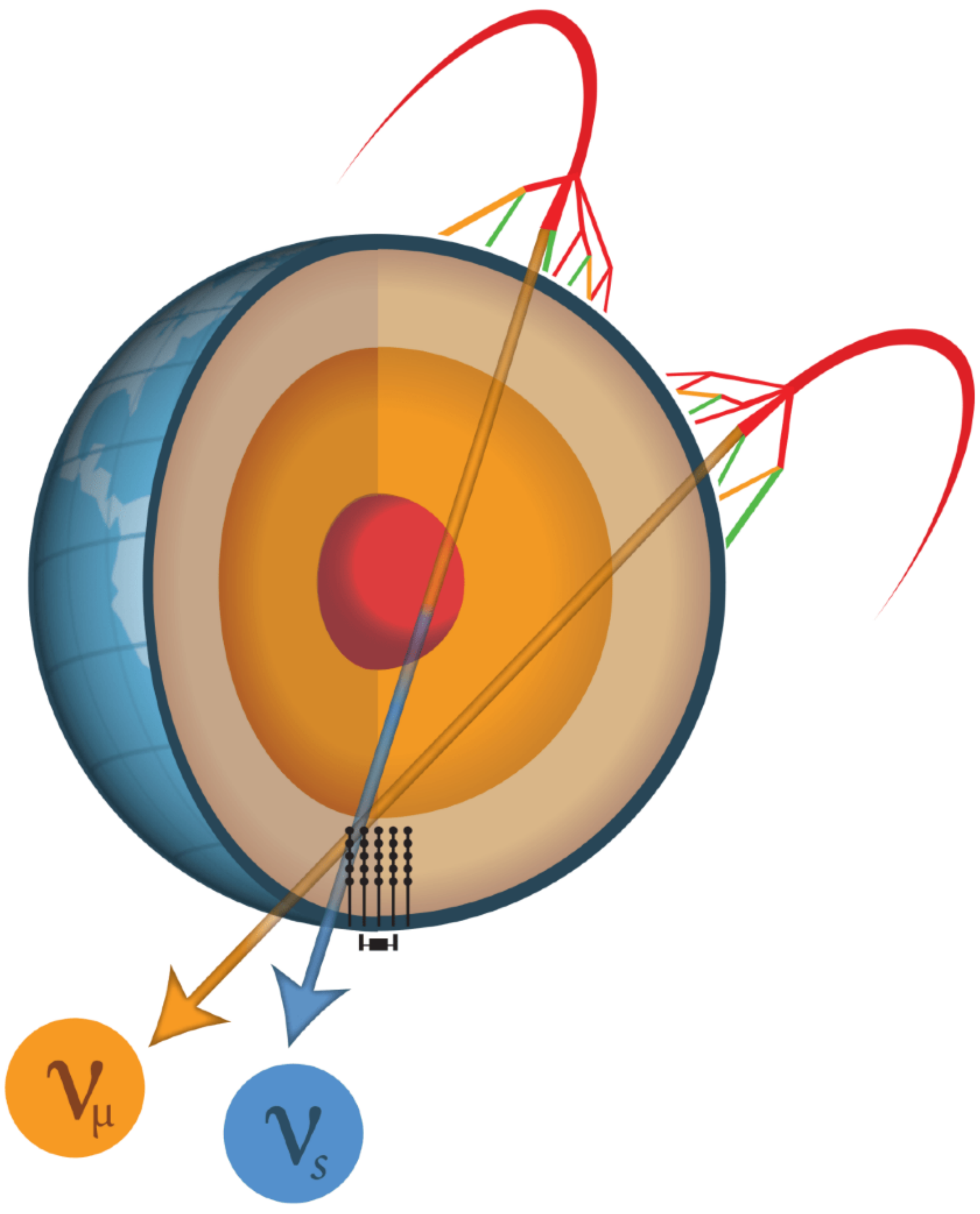
$$\nu_e \,\&\, \bar{\nu}_e \text{ disappearance}$$

(reactor, GALLEX & SAGE)

- IceCube is sensitive to the "3+1" sterile neutrino model:

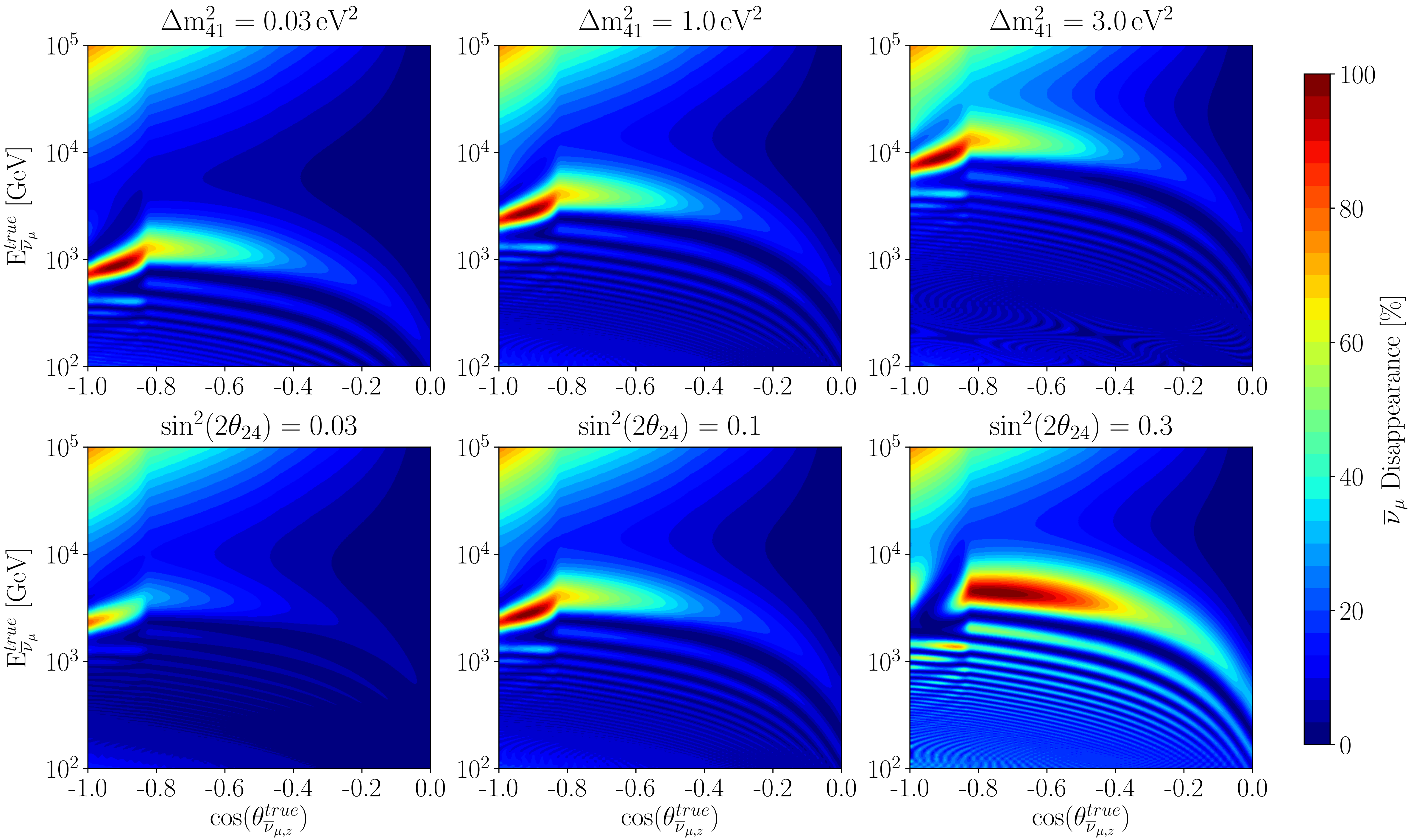
$$U_{4\times4} = R_{34}R_{24}R_{14}U_{\mathrm{PMNS}}$$

- Energy-dependent distortions of atmospheric $\nu_\mu \,\&\, \bar{\nu}_\mu$ **disappearance** in **matter-enhanced oscillations.**



Sterile Neutrinos

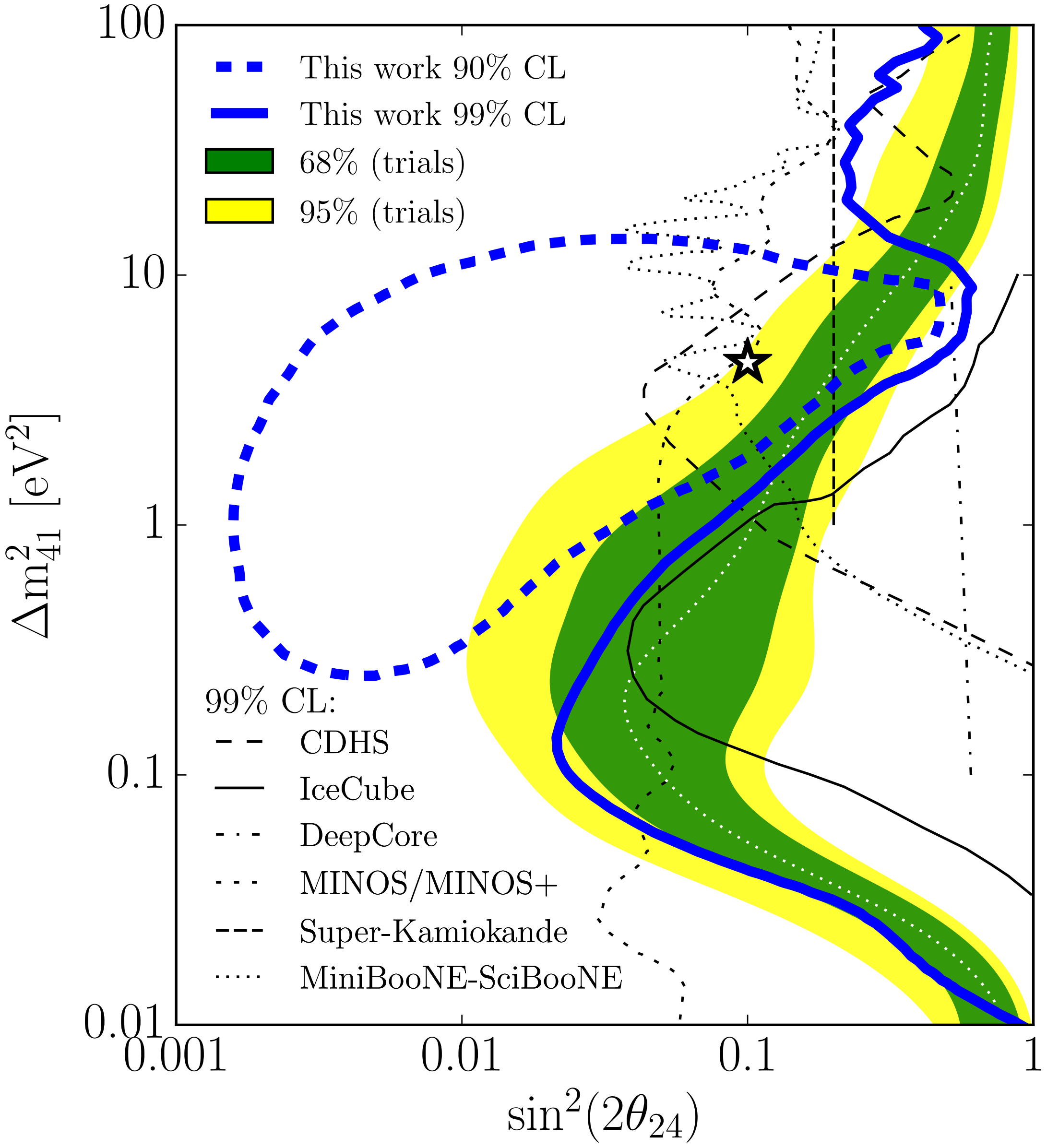
$$|U_{\mu 4}|^2 = \sin^2\theta_{24} \quad \& \quad |U_{e4}|^2 = |U_{\tau 4}|^2 = 0$$



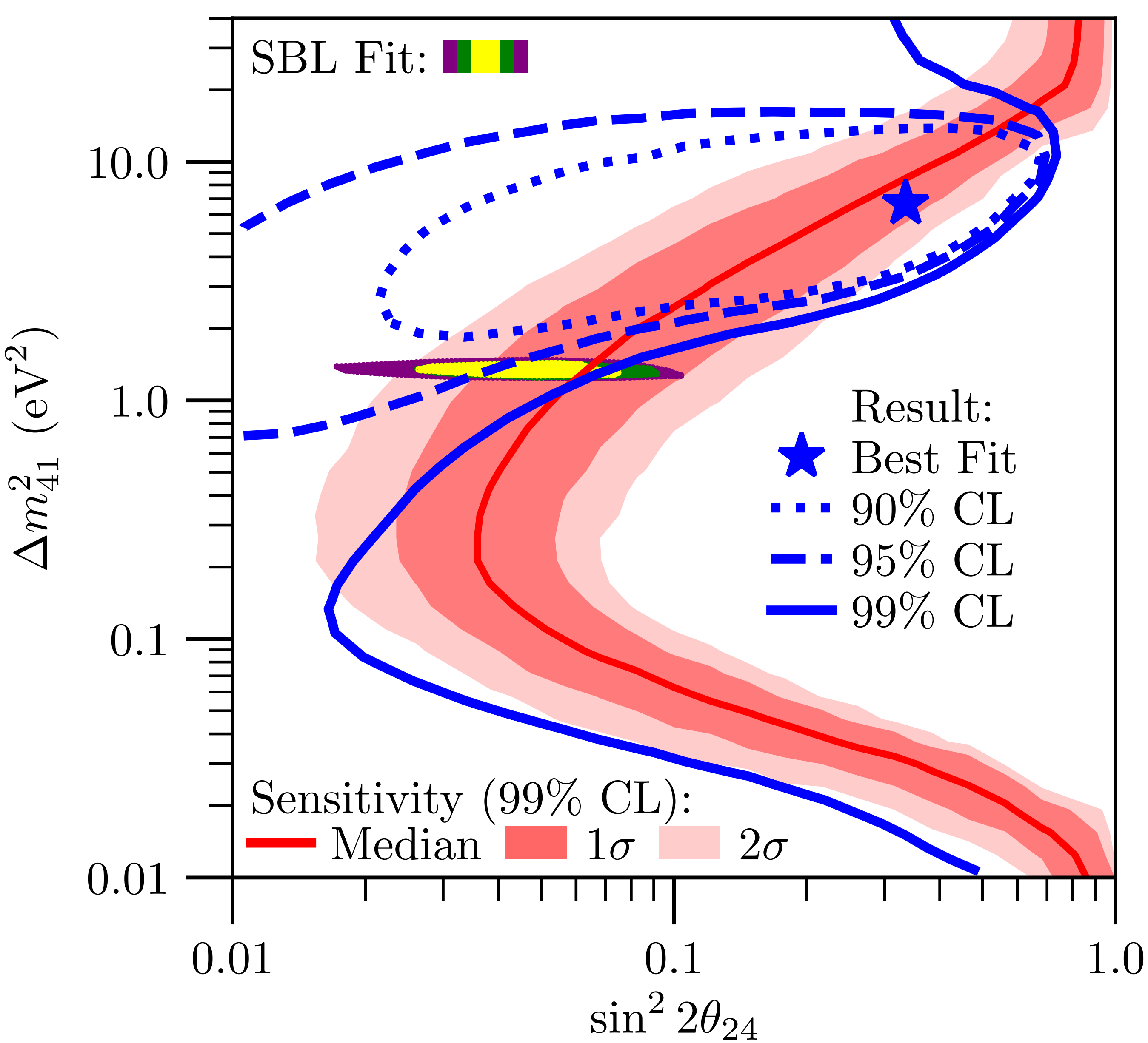
[IceCube, PRL 125 (2020) 14; PRD 102 (2020) 5]

Sterile Neutrino Searches

Best-fit contours in for **stable** (left) and **unstable** (right) sterile neutrinos.



[IceCube, PRL 125 (2020) 14; PRD 102 (2020) 5]

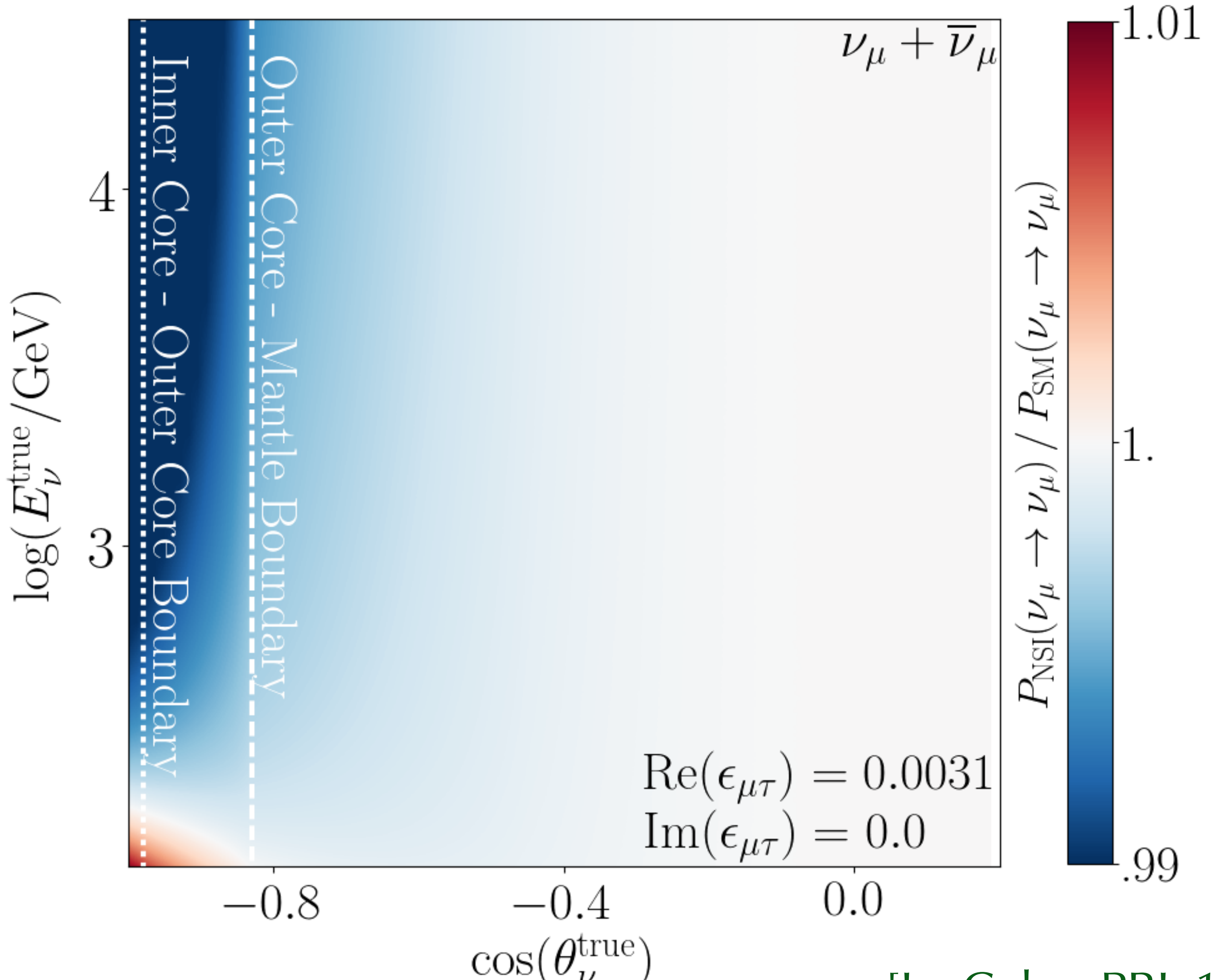


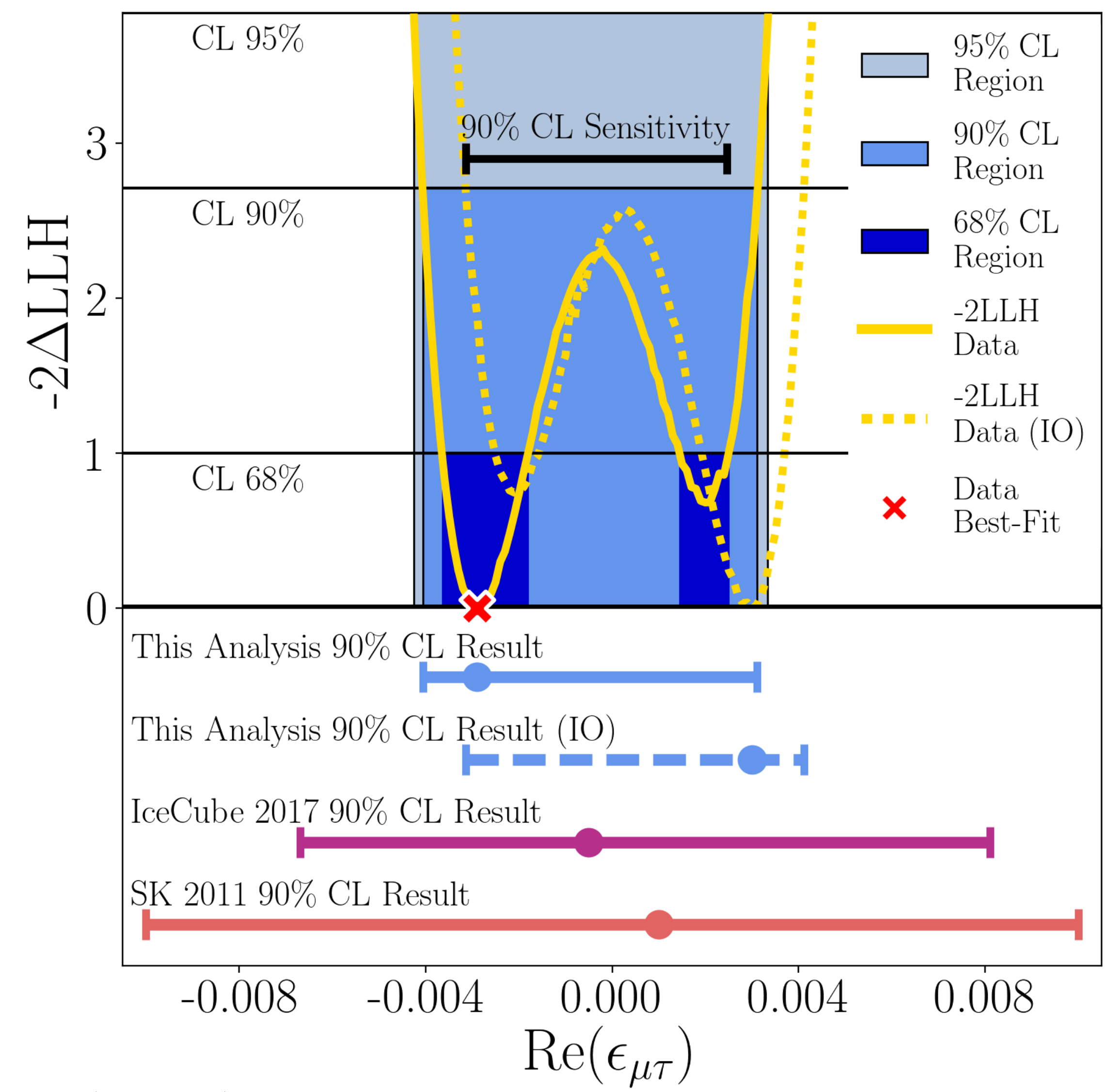
[IceCube, PRL 129 (2022) 1]

Nonstandard Neutrino Interactions

Hamiltonian including nonstandard interactions with matter:

$$H_{\rm mat}(x) = V_{\rm CC}(x)\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

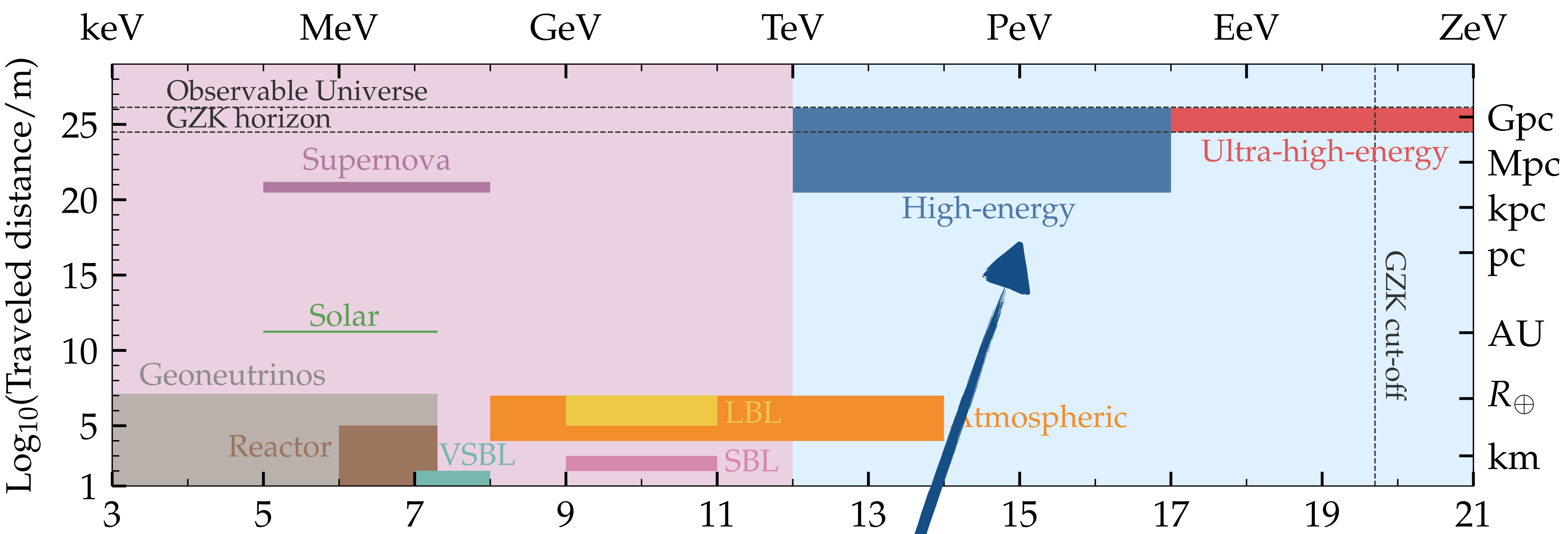




[IceCube, PRL 129 (2022) 1]

Probe of Fundamental Physics

IceCube neutrinos test new energy and distance regime.



[Ackermann et al., arXiv:1903.04333]

$$H \simeq \sum_i \frac{m_i^2}{2E_\nu}\left(|\nu_i\rangle\langle\nu_i| + |\overline{\nu}_i\rangle\langle\overline{\nu}_i|\right) \quad + \quad \frac{E_\nu^n}{\Lambda^n}\sum_\alpha\left(\epsilon_\alpha|\nu_\alpha\rangle\langle\nu_\alpha| + \overline{\epsilon}_\alpha|\overline{\nu}_\alpha\rangle\langle\overline{\nu}_\alpha|\right)$$

standard Hamiltonian

"exotic" contributions?

Lorentz Invariance Violation

- Quantum gravity could modify dispersion relations of neutrinos (or photons, CRs, *etc.*) inducing **Lorentz Invariance Violation (LIV)**:

[e.g. Alves Batista et al.'23]

$$E^2 = \mathbf{p}^2 \left[1 \pm \left(\frac{E}{\Lambda}\right)^n\right]$$

- Modification of the **neutrino velocity**:

$$v(E) = \frac{\partial E}{\partial p} \simeq 1 \pm \frac{n+1}{2}\left(\frac{E}{\Lambda}\right)^n$$

- This causes **energy-dependent time delays** of cosmic neutrinos:

$$\Delta t = \pm \frac{n+1}{2}\frac{E_0^n - E_1^n}{\Lambda^n}\int_0^z dz' \frac{(1+z')^n}{H(z')}$$

- TXS 0506+056 ν-γ coincidence constrains $\Lambda \gtrsim 3 \times 10^{16}\,\mathrm{GeV}$ ($n = 1$).

[Ellis, Mavromatos, Sakharov & Sarkisyan-Grinbaum'18; Laha'18]

Lorentz Invariance Violation

- LIV can also modify neutrino oscillations via an anomalous energy dependence of the effective Hamiltonian.

- For **isotropic LIV effects** we can make the ansatz for the effective Hamiltonian of flavour states: [Kostelecky & Mewes'12]

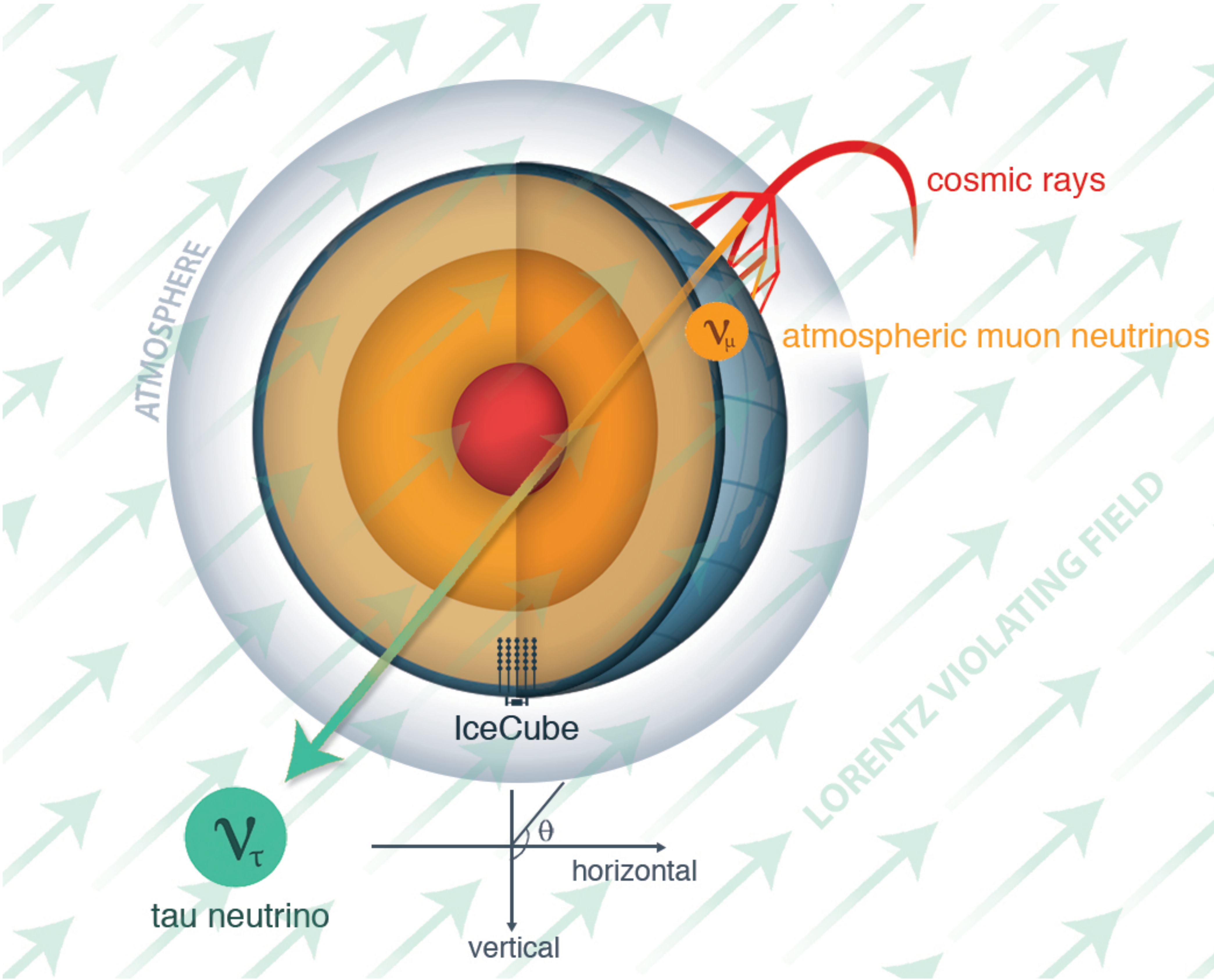
$$H \simeq \frac{m^2}{2E_\nu} + \mathring{a}^{(3)} - E\mathring{c}^{(4)} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} + \ldots$$

- The LIV 3×3 matrices $a^{(d)}$ are CPT odd and $c^{(d)}$ are CPT even with mass dimension $4 - d$.

- The flavour eigenstates can now be expressed as superpositions of LIV Hamiltonian eigenstates $|\nu_\mathfrak{a}\rangle$:

$$|\nu_\alpha\rangle = \sum_\mathfrak{a} U^*_{\alpha\mathfrak{a}}(E_\nu)\,|\nu_\mathfrak{a}\rangle$$

Atmospheric Neutrinos & LIV



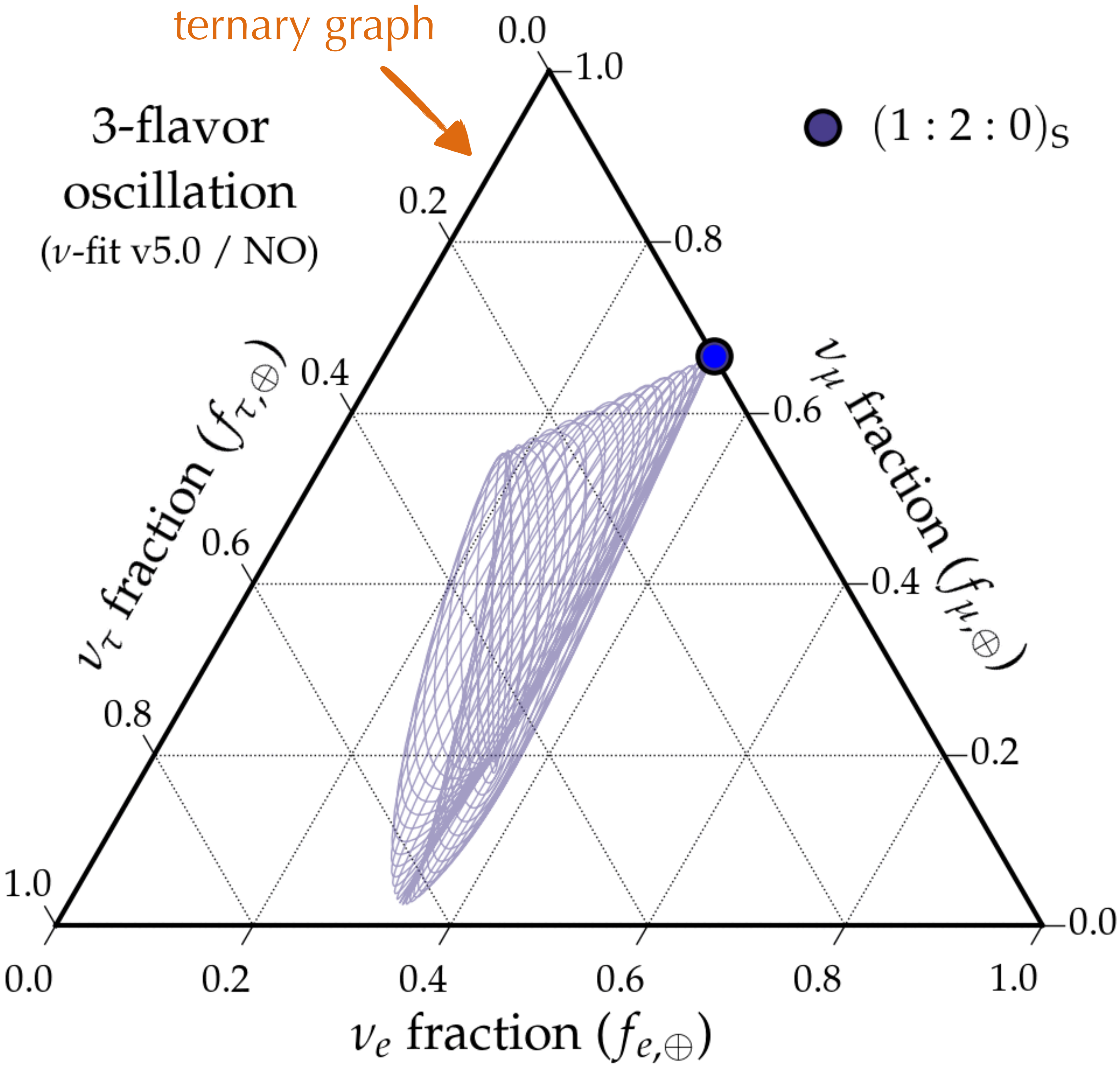
Atmospheric Neutrinos & LIV

Limits on LIV operators using atmospheric neutrinos

dim.	method	type	sector	limits		ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[5]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[6]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

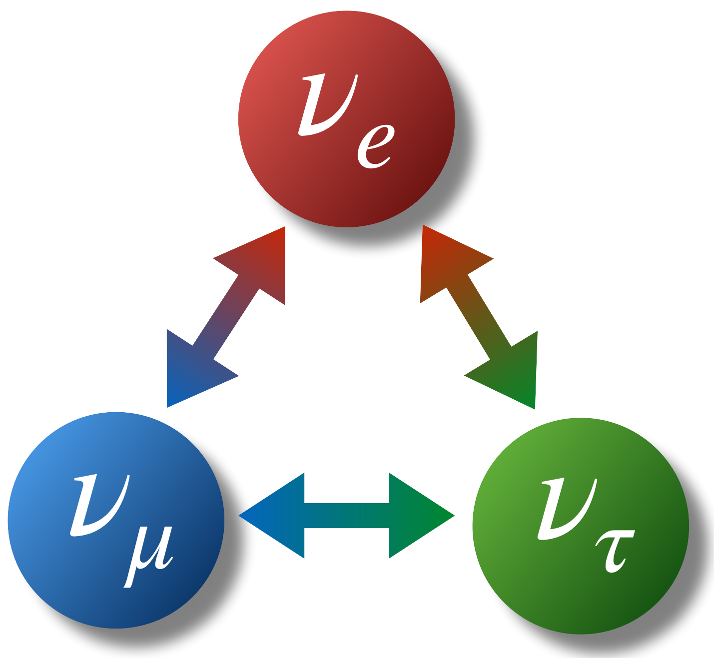
[IceCube, Nature Phys. 14 (2018) 9]

Cosmic Neutrinos & LIV



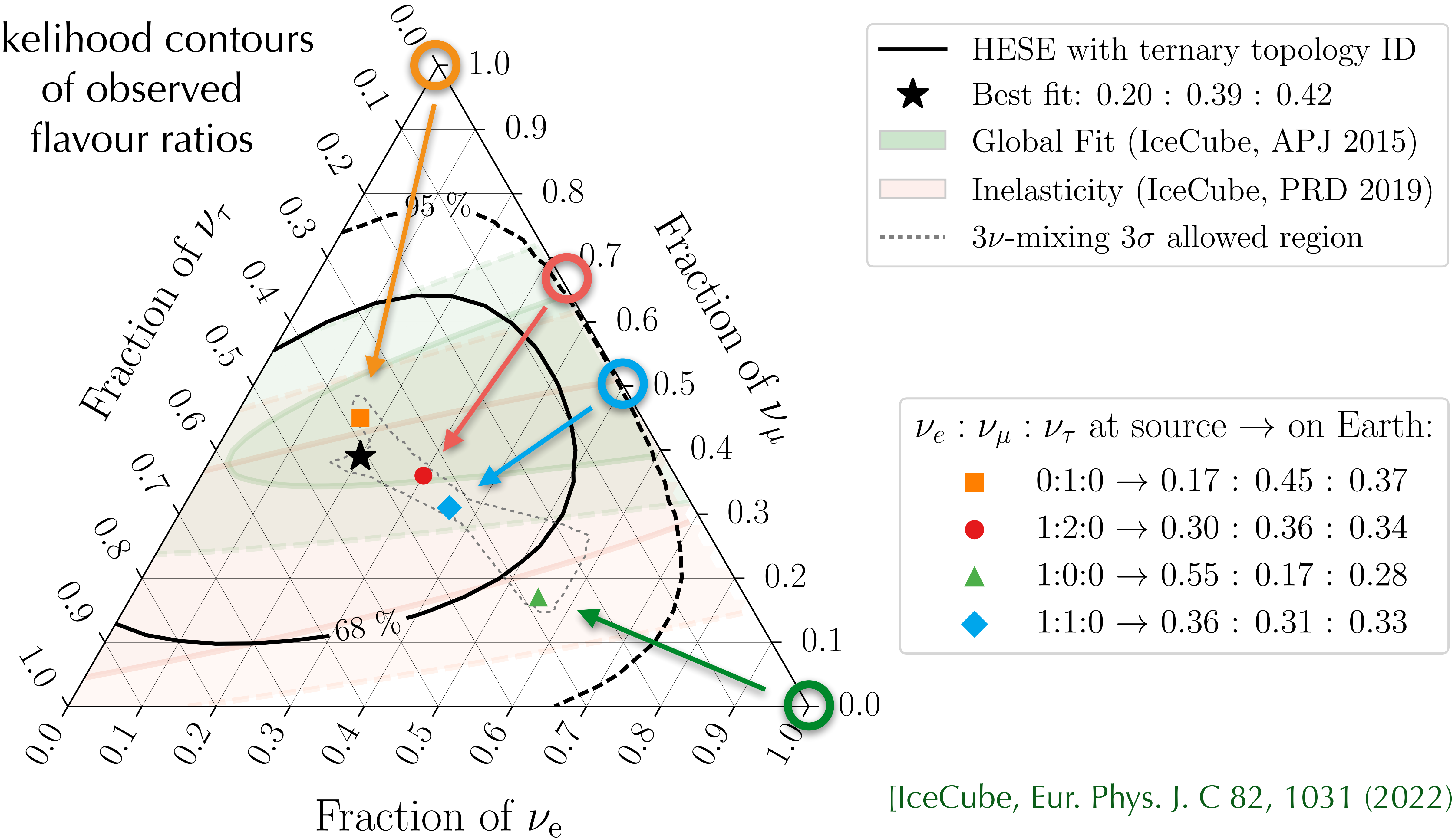
flavour ratios on production

Superposition of flavour and mass states induce oscillations.

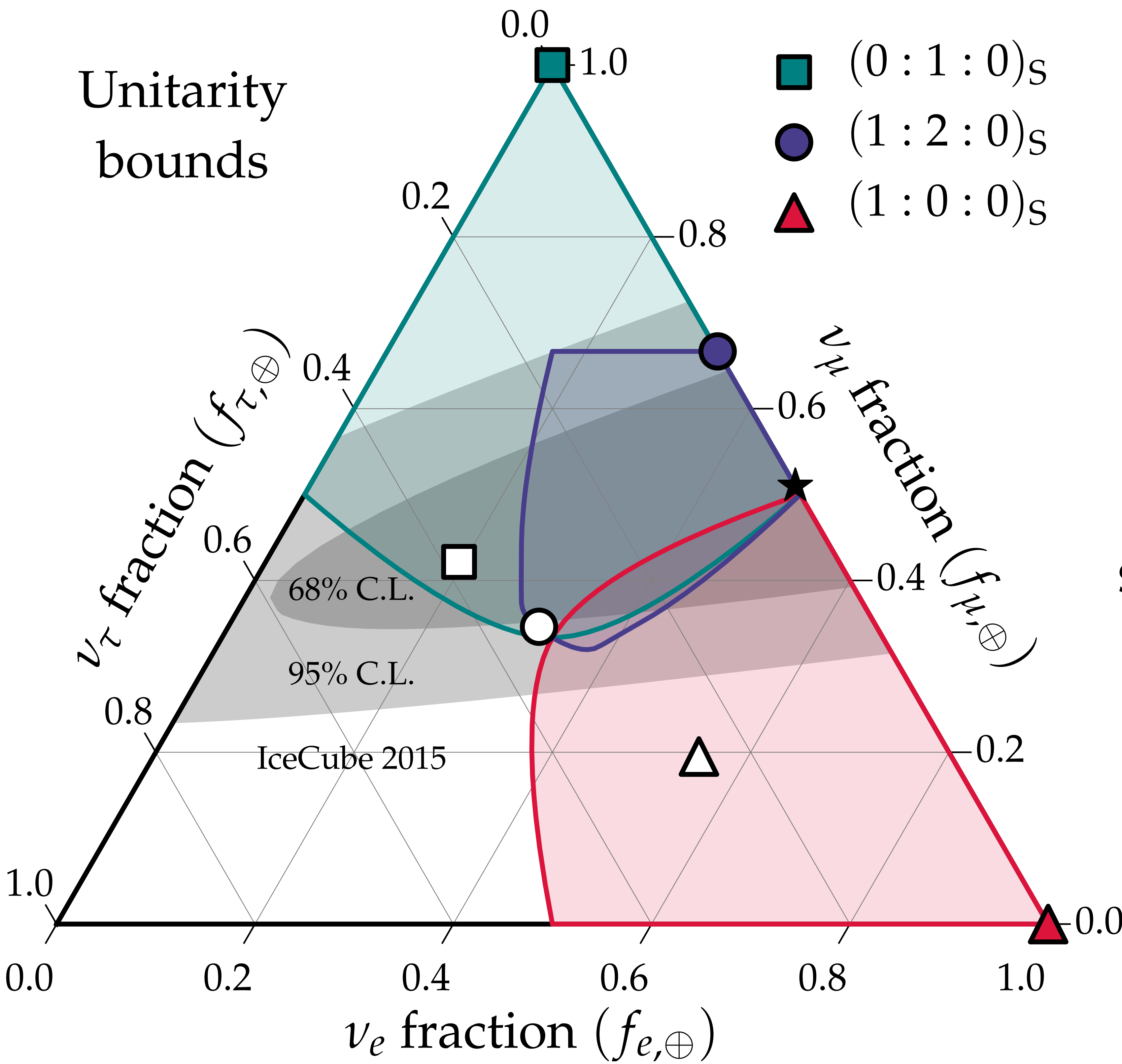


Cosmic neutrinos visible via their oscillation-averaged flavour.

Likelihood contours of observed flavour ratios



[IceCube, Eur. Phys. J. C 82, 1031 (2022)]



unitary mixing matrix

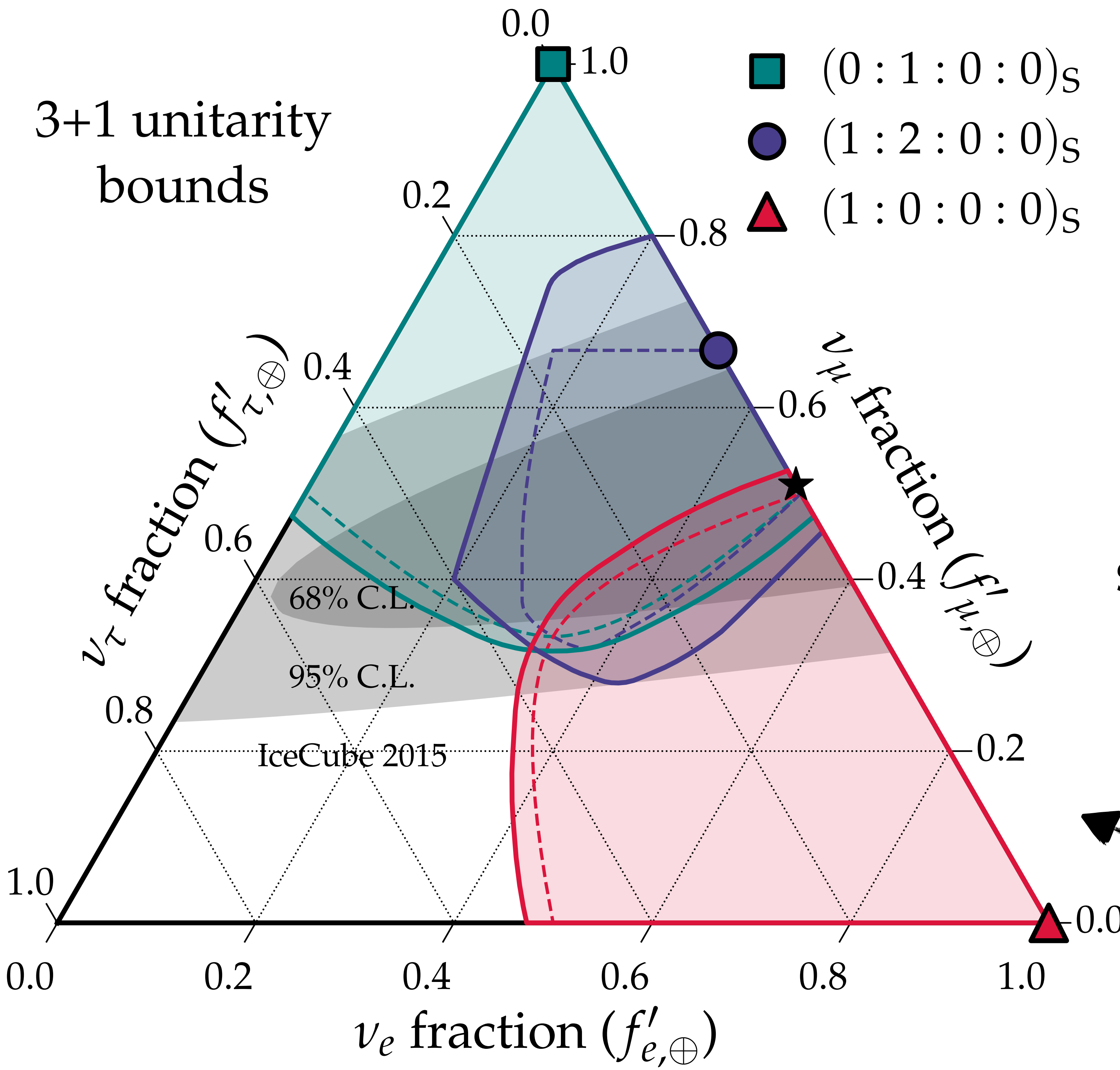
$$U^\dagger U = 1$$

$$|\nu_\alpha\rangle = \sum_{\mathfrak{a}} U^*_{\alpha\mathfrak{a}} |\nu_{\mathfrak{a}}\rangle$$

superposition of flavor and LIV eigenstates

[MA, Bustamante & Mu'18]

Cosmic Neutrinos & LIV



unitary mixing matrix

$$U^\dagger U = 1$$

$$|\nu_\alpha\rangle = \sum_{\mathfrak{a}} U^*_{\alpha\mathfrak{a}} |\nu_{\mathfrak{a}}\rangle$$

superposition of flavor and LIV eigenstates

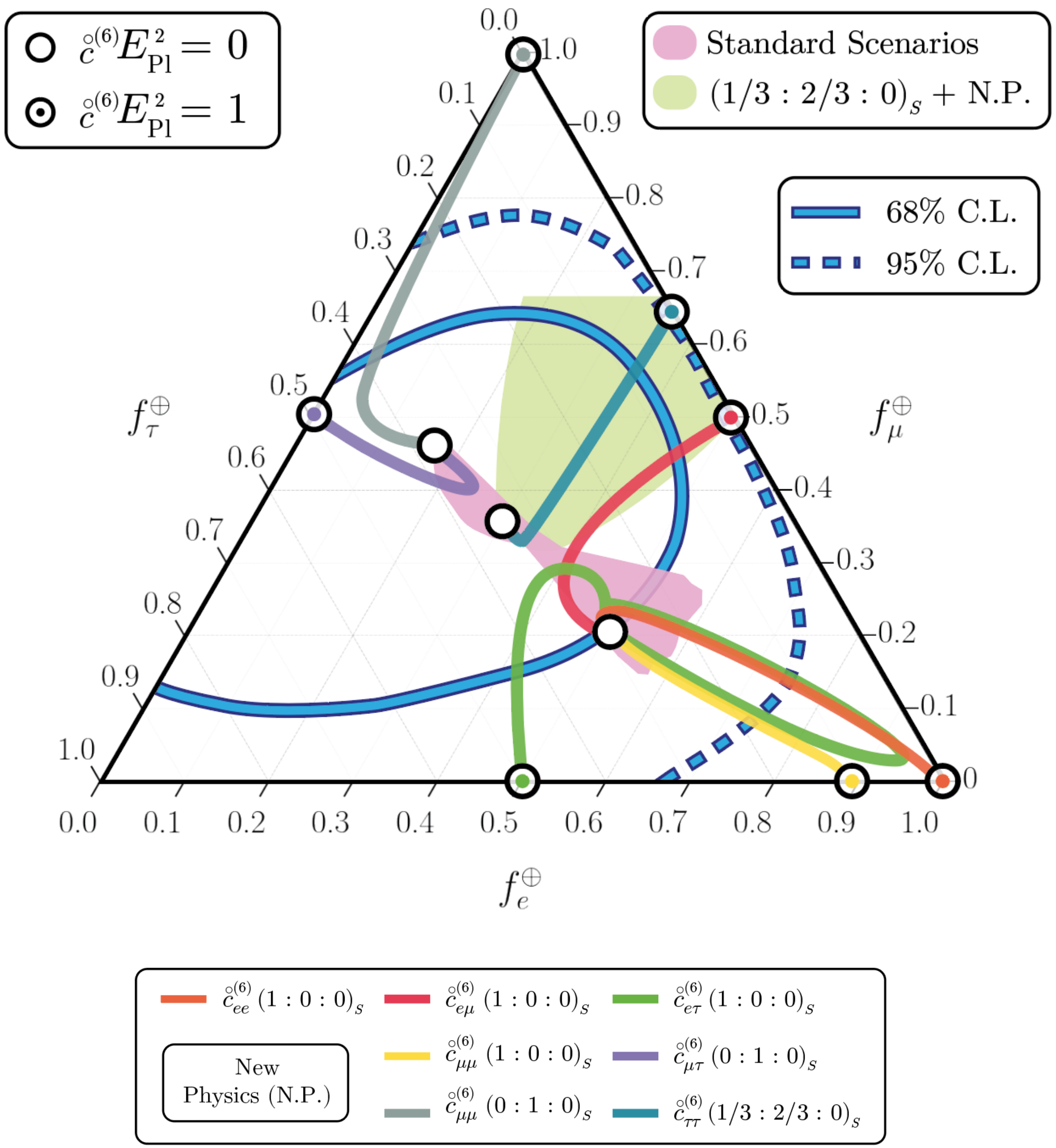
+ 1 sterile neutrino

$$f'_\alpha \equiv \frac{f_\alpha}{1 - f_s}$$

active flavor ratios

[MA, Bustamante & Willesen'21]

Cosmic Neutrinos & LIV

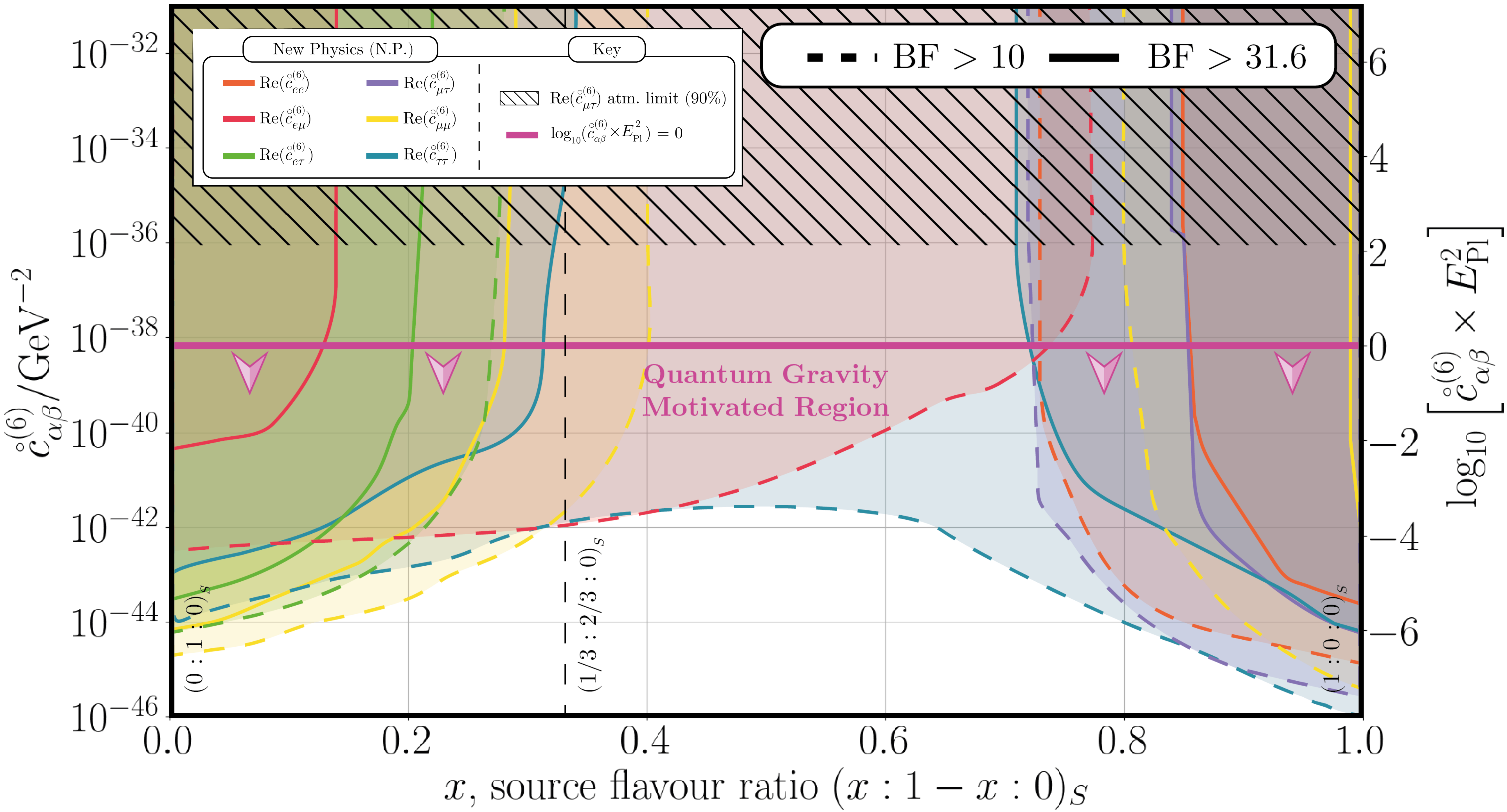


Limits on LIV operators using cosmic neutrinos

dim	coefficient	limit	dim	coefficient	limit	$(\phi_e^i : \phi_\mu^i : \phi_\tau^i)_S$
3	$\mathrm{Re}\,(\mathring{a}_{e\mu}^{(5)})$	6×10^{-26} GeV	4	$\mathrm{Re}\,(\mathring{c}_{e\mu}^{(6)})$	2×10^{-31}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{e\tau}^{(5)})$	3×10^{-27} GeV		$\mathrm{Re}\,(\mathring{c}_{e\tau}^{(6)})$	7×10^{-33}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\mu}^{(5)})$	3×10^{-27} GeV		$\mathrm{Re}\,(\mathring{c}_{\mu\mu}^{(6)})$	4×10^{-33}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(5)})$	5×10^{-27} GeV		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(6)})$	1×10^{-32}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{ee}^{(3)})$	4×10^{-28} GeV		$\mathrm{Re}\,(\mathring{c}_{ee}^{(4)})$	6×10^{-33}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\tau}^{(3)})$	6×10^{-27} GeV		$\mathrm{Re}\,(\mathring{c}_{\mu\tau}^{(4)})$	7×10^{-34}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(3)})$	2×10^{-27} GeV		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(4)})$	8×10^{-34}	$(1:0:0)_S$
5	$\mathrm{Re}\,(\mathring{a}_{e\mu}^{(5)})$	3×10^{-36} GeV^{-1}	6	$\mathrm{Re}\,(\mathring{c}_{e\mu}^{(6)})$	4×10^{-41} GeV^{-2}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{e\tau}^{(5)})$	9×10^{-39} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{e\tau}^{(6)})$	3×10^{-44} GeV^{-2}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\mu}^{(5)})$	8×10^{-39} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{\mu\mu}^{(6)})$	7×10^{-45} GeV^{-2}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(5)})$	3×10^{-38} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(6)})$	1×10^{-43} GeV^{-2}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(5)})$	2×10^{-35} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(6)})$	3×10^{-36} GeV^{-2}	$(1/3:2/3:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{ee}^{(5)})$	7×10^{-40} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{ee}^{(6)})$	2×10^{-44} GeV^{-2}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\tau}^{(5)})$	4×10^{-39} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{\mu\tau}^{(6)})$	6×10^{-45} GeV^{-2}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(5)})$	2×10^{-38} GeV^{-1}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(6)})$	6×10^{-45} GeV^{-2}	$(1:0:0)_S$
7	$\mathrm{Re}\,(\mathring{a}_{e\mu}^{(7)})$	5×10^{-46} GeV^{-3}	8	$\mathrm{Re}\,(\mathring{c}_{e\mu}^{(8)})$	1×10^{-50} GeV^{-4}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{e\tau}^{(7)})$	4×10^{-50} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{e\tau}^{(8)})$	6×10^{-56} GeV^{-4}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\mu}^{(7)})$	4×10^{-50} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{\mu\mu}^{(8)})$	5×10^{-56} GeV^{-4}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(7)})$	2×10^{-49} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(8)})$	6×10^{-55} GeV^{-4}	$(0:1:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(7)})$	3×10^{-45} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(8)})$	3×10^{-49} GeV^{-4}	$(1/3:2/3:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{ee}^{(7)})$	8×10^{-51} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{ee}^{(8)})$	3×10^{-55} GeV^{-4}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\mu\tau}^{(7)})$	2×10^{-49} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{\mu\tau}^{(8)})$	5×10^{-55} GeV^{-4}	$(1:0:0)_S$
	$\mathrm{Re}\,(\mathring{a}_{\tau\tau}^{(7)})$	3×10^{-49} GeV^{-3}		$\mathrm{Re}\,(\mathring{c}_{\tau\tau}^{(8)})$	8×10^{-56} GeV^{-4}	$(1:0:0)_S$

[IceCube, Nature 18 (2022) 11]

Limits on the **dimension-six operator**.



[IceCube, Nature 18 (2022) 11]

Neutrino Decoherence

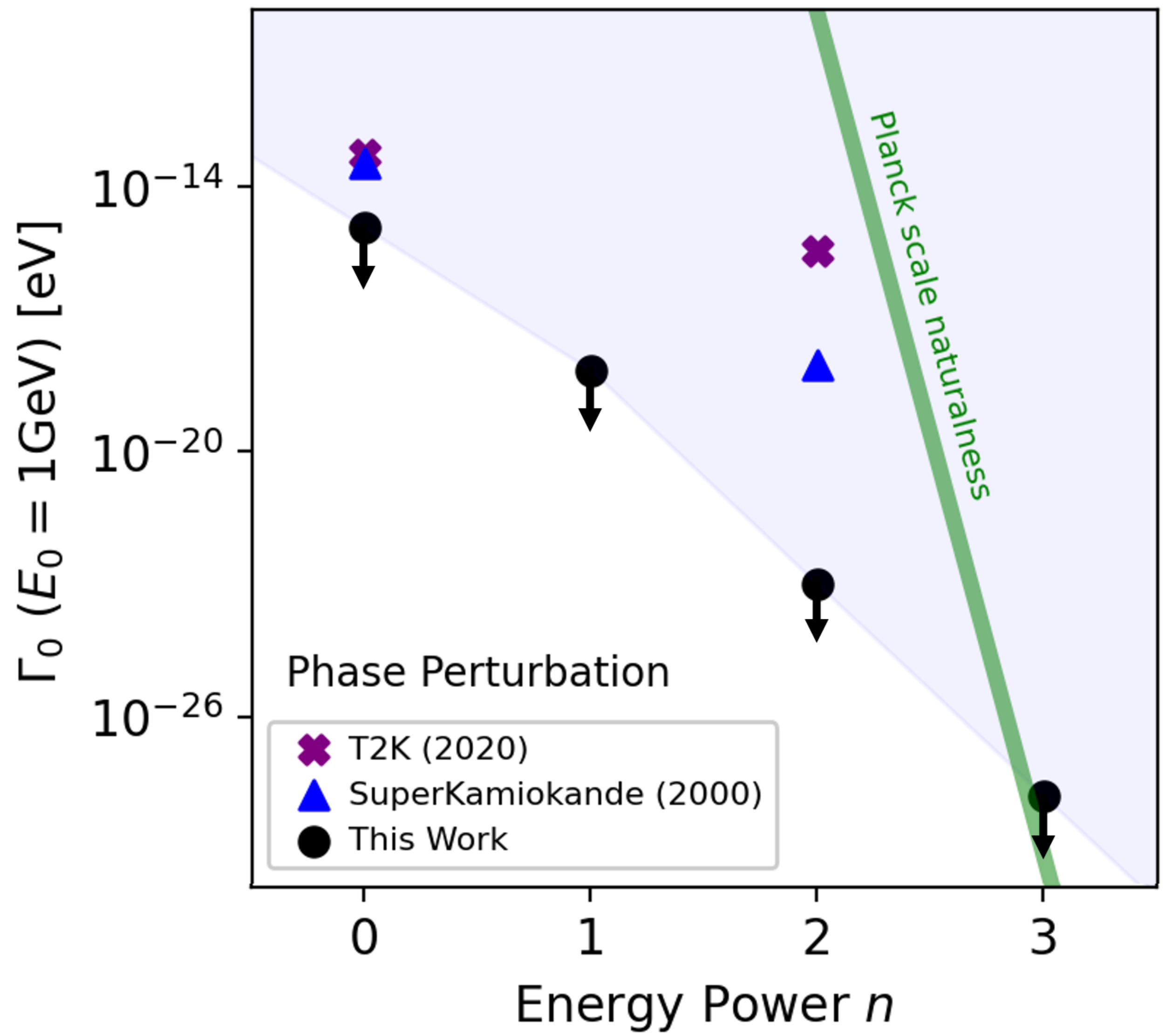
- Quantum gravity could also induce decoherence in the evolution of the neutrino density operator:

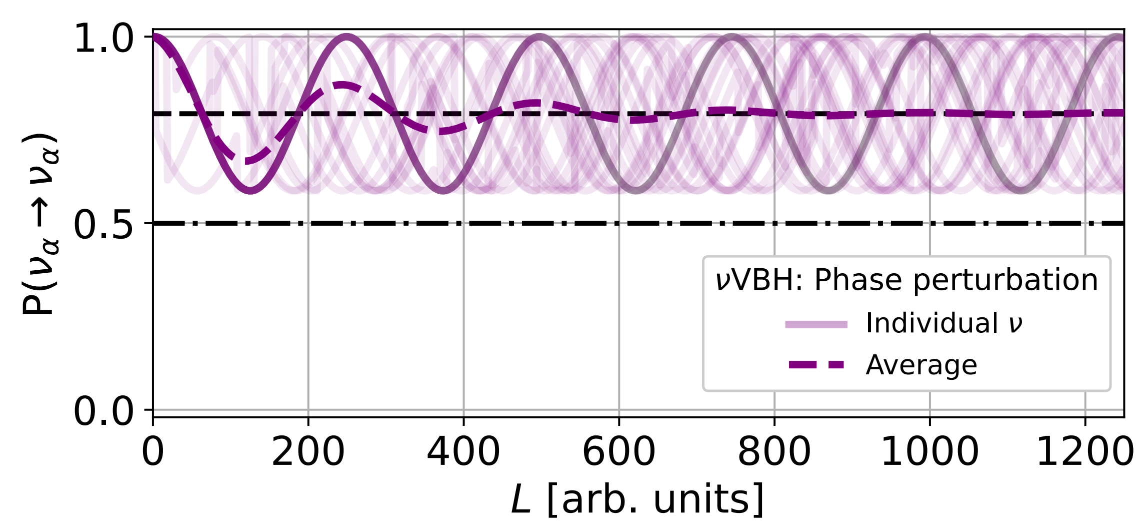
$$\dot{\rho} = -i[H,\rho] - \mathscr{D}[\rho]$$

- The non-unitary **decoherence term** $\mathscr{D}[\rho]$ can be parametrized via **Lindblad operators**.
- For instance, uniform decoherence in the basis of mass eigenstates:

$$\mathscr{D}(\rho) = \Gamma_0 \left(\frac{E_\nu}{E_0}\right)^n \begin{pmatrix} 0 & \rho_{12} & \rho_{13} \\ \rho_{21} & 0 & \rho_{23} \\ \rho_{31} & \rho_{32} & 0 \end{pmatrix}$$

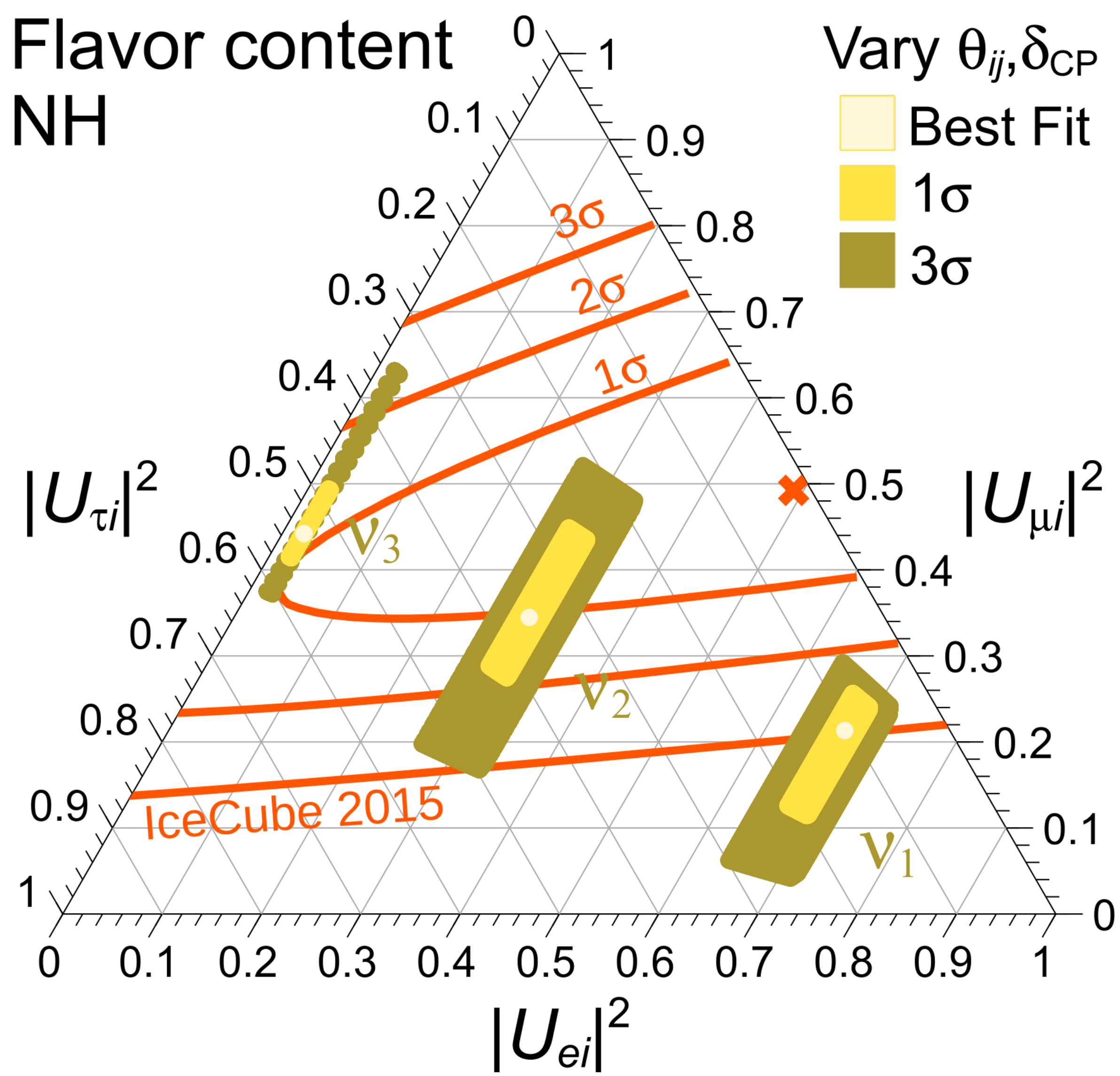
[IceCube, arXiv:2308.00105]

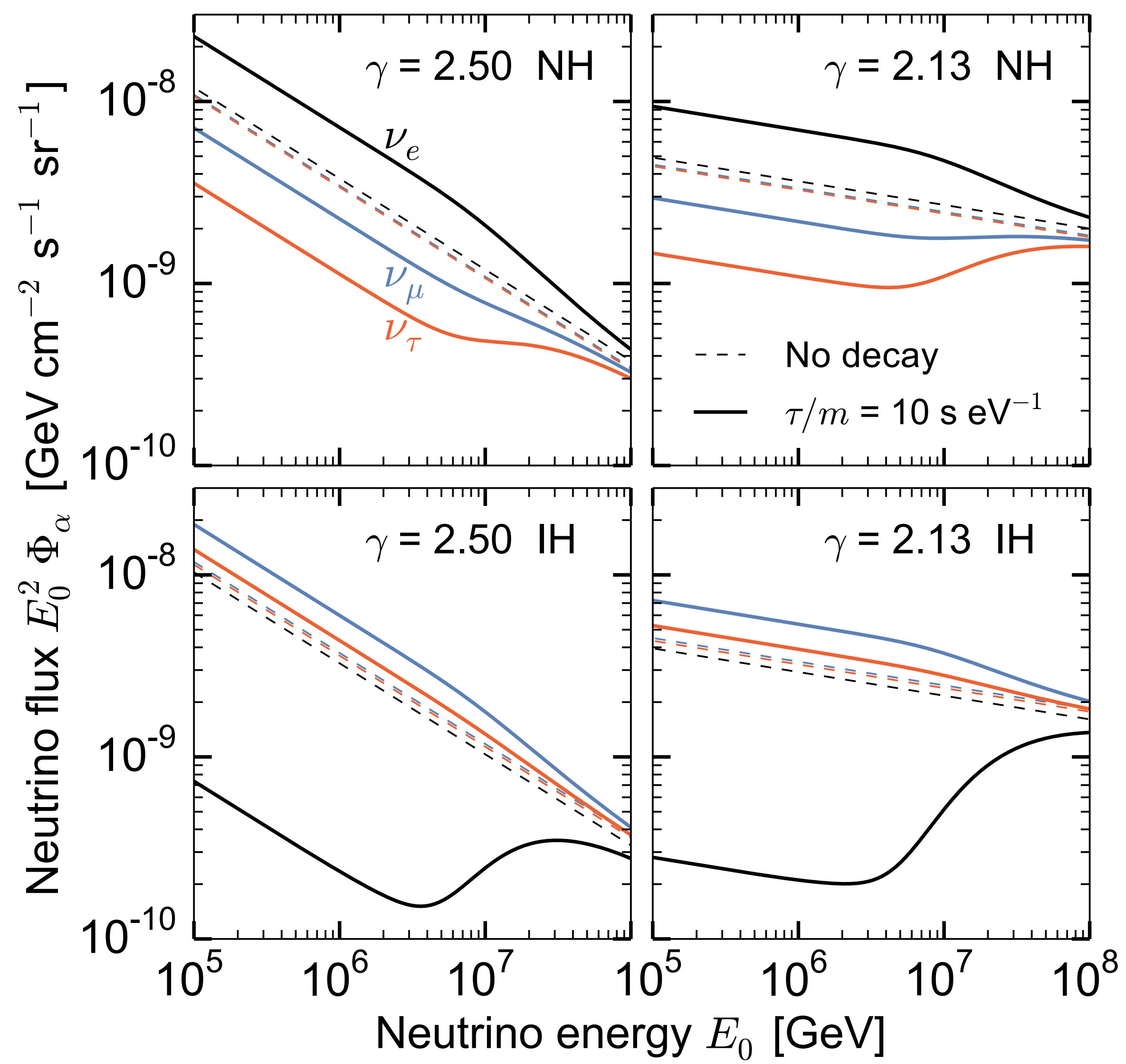




Visible Neutrino Decay

Slow decay of neutrino mass states $\nu_i \to \nu_j + X$ over cosmological time scales impacts neutrino **flavour fractions** (left) and **spectra** (right).

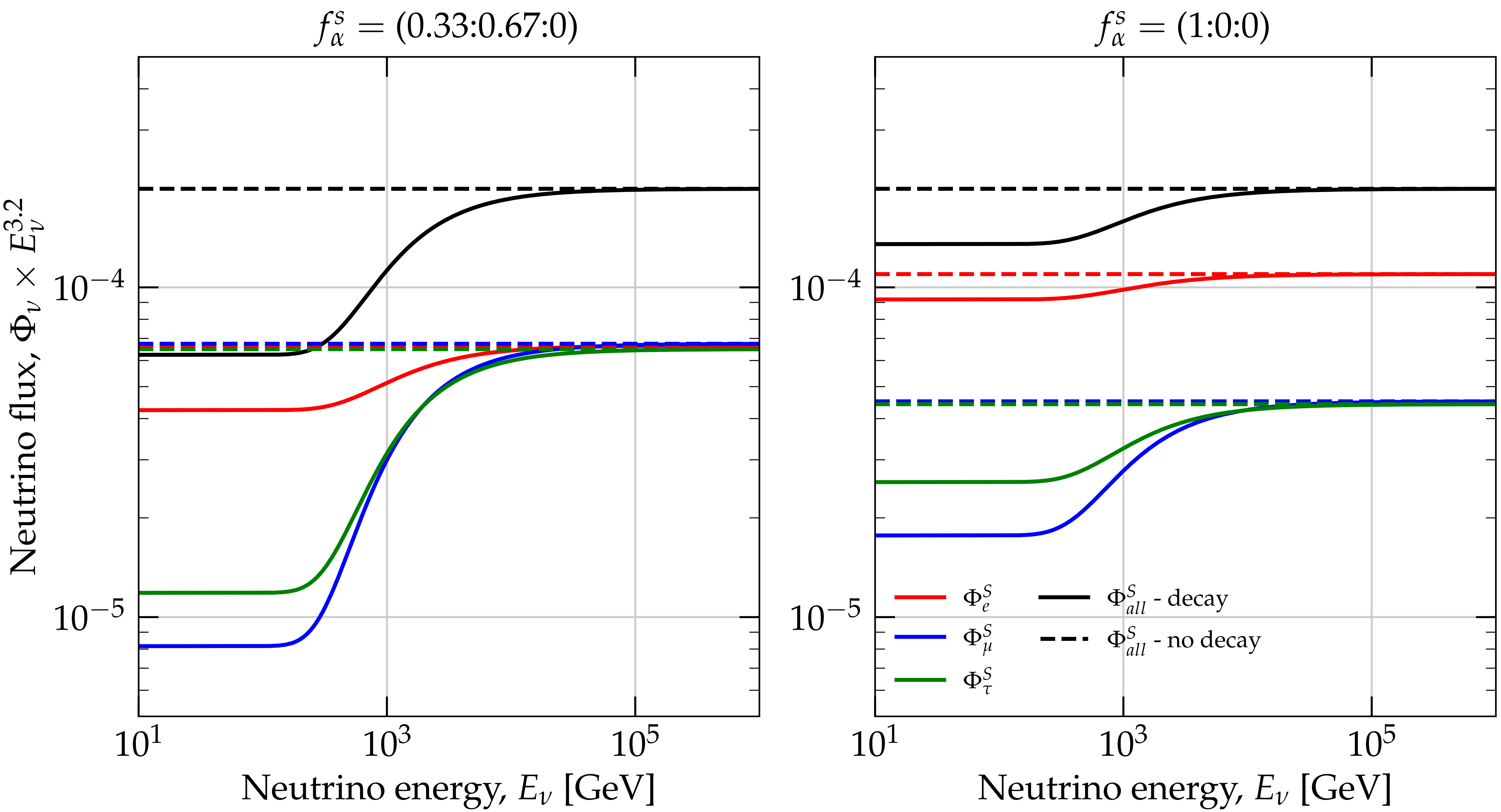




[Bustamante, Beacom & Murase'17]

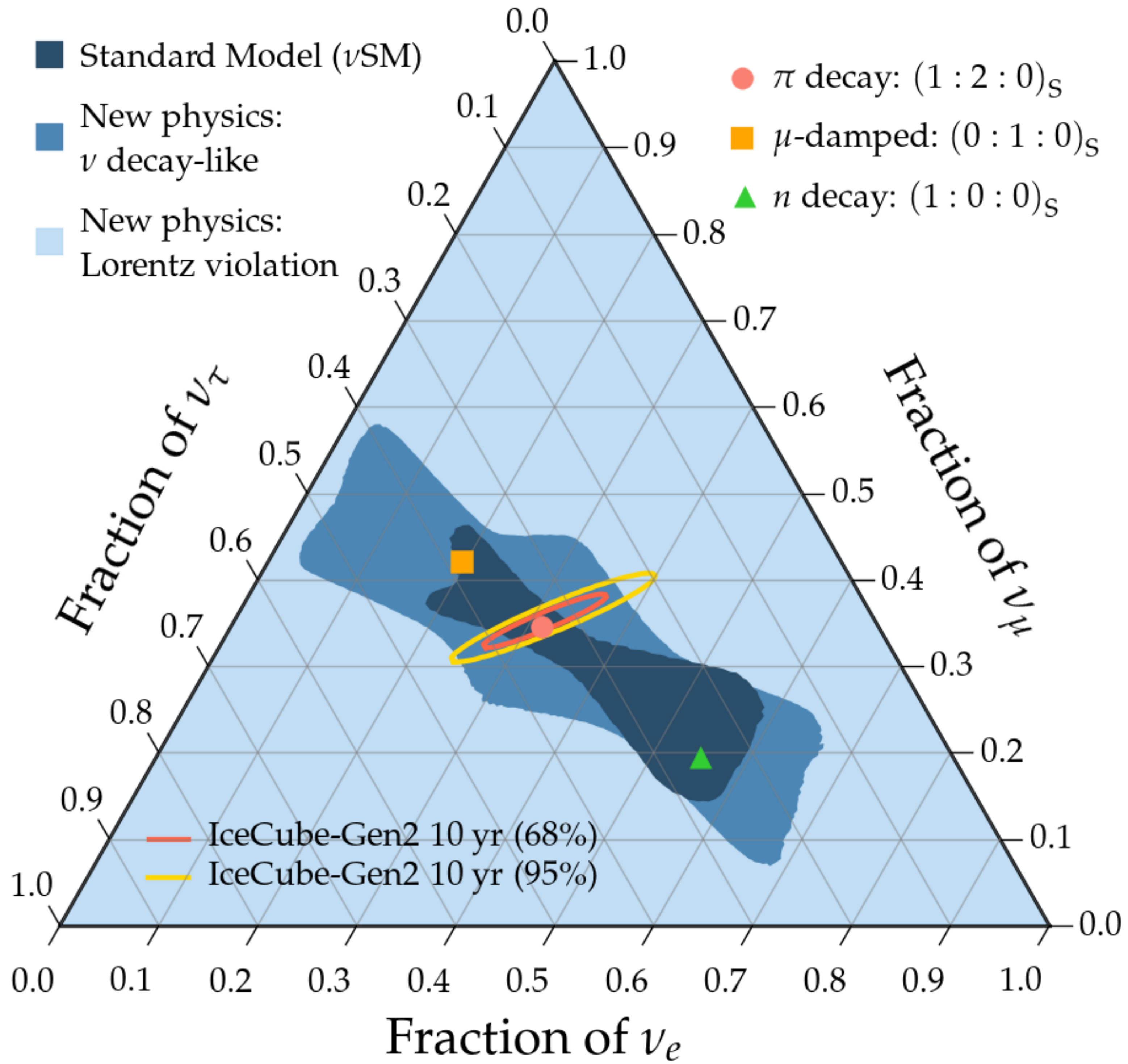
Visible Neutrino Decay

Energy-dependent flavour ratios testable with IceCube-Gen2.



[Valera, Fiorillo, Esteban & Bustamante'23]

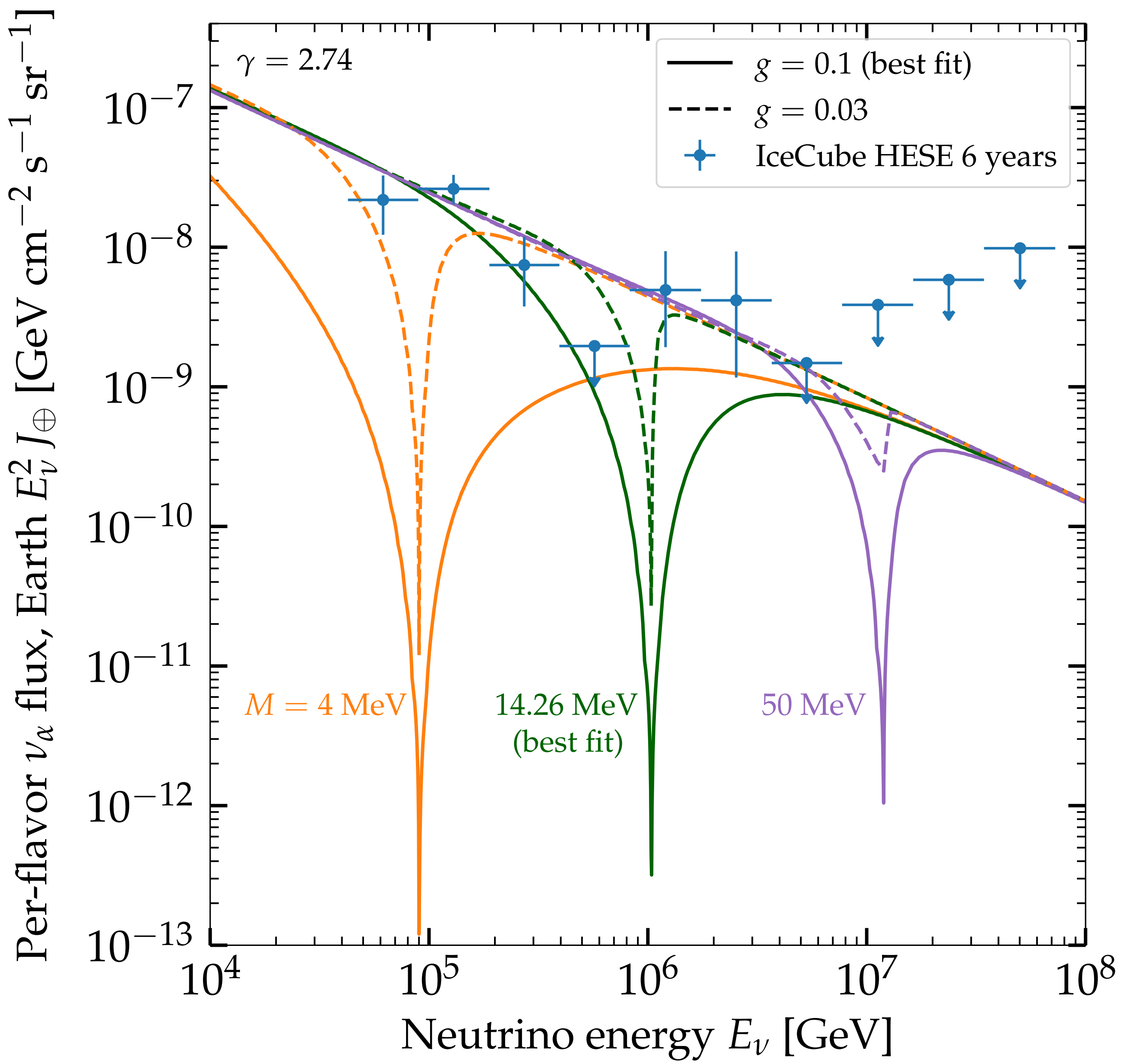
IceCube-Gen2 Flavour Sensitivity



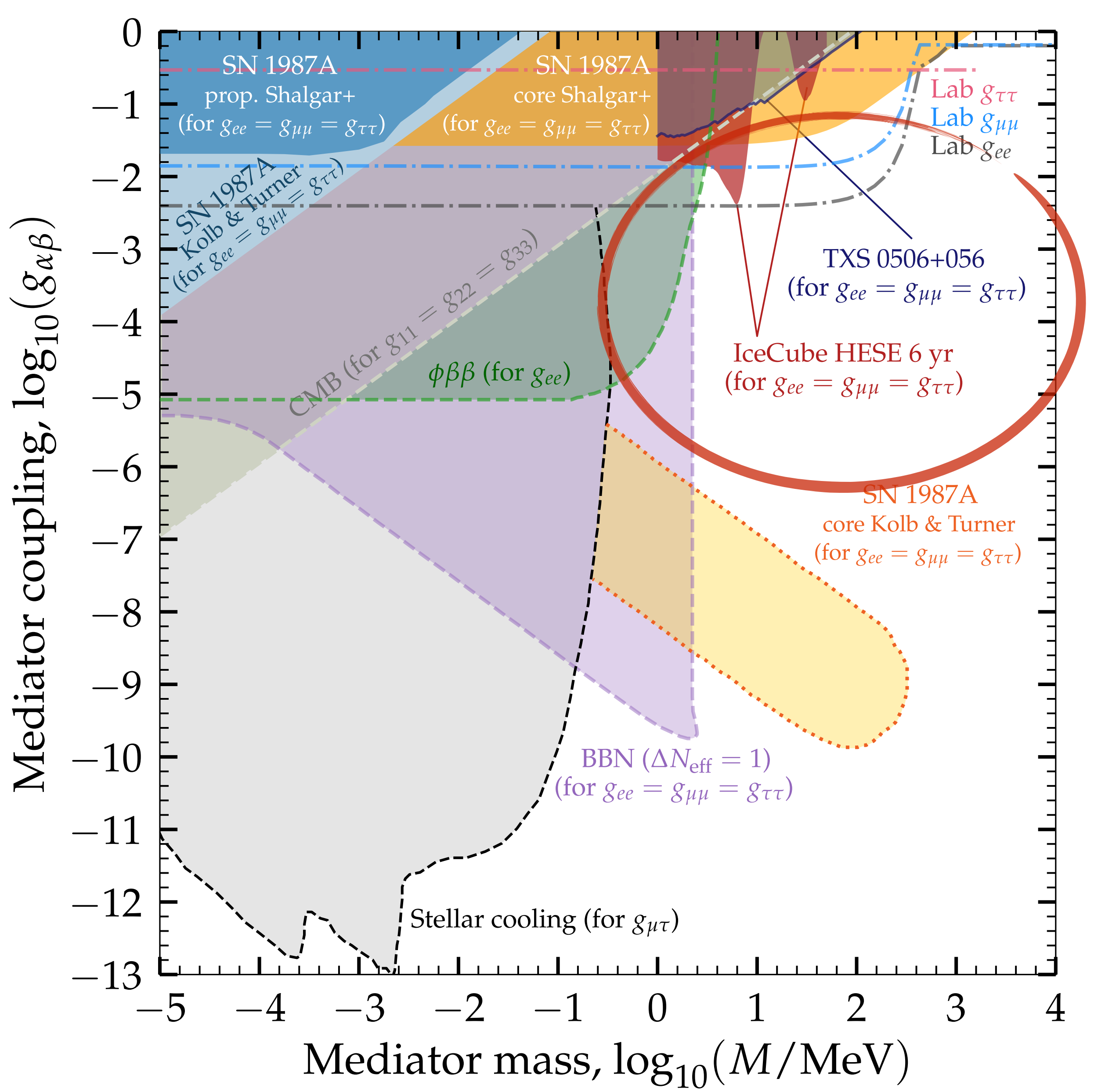
[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Neutrino Self Interactions

Neutrino self interactions can modify cosmic neutrino emission, for instance, by resonant scattering on the CνB.

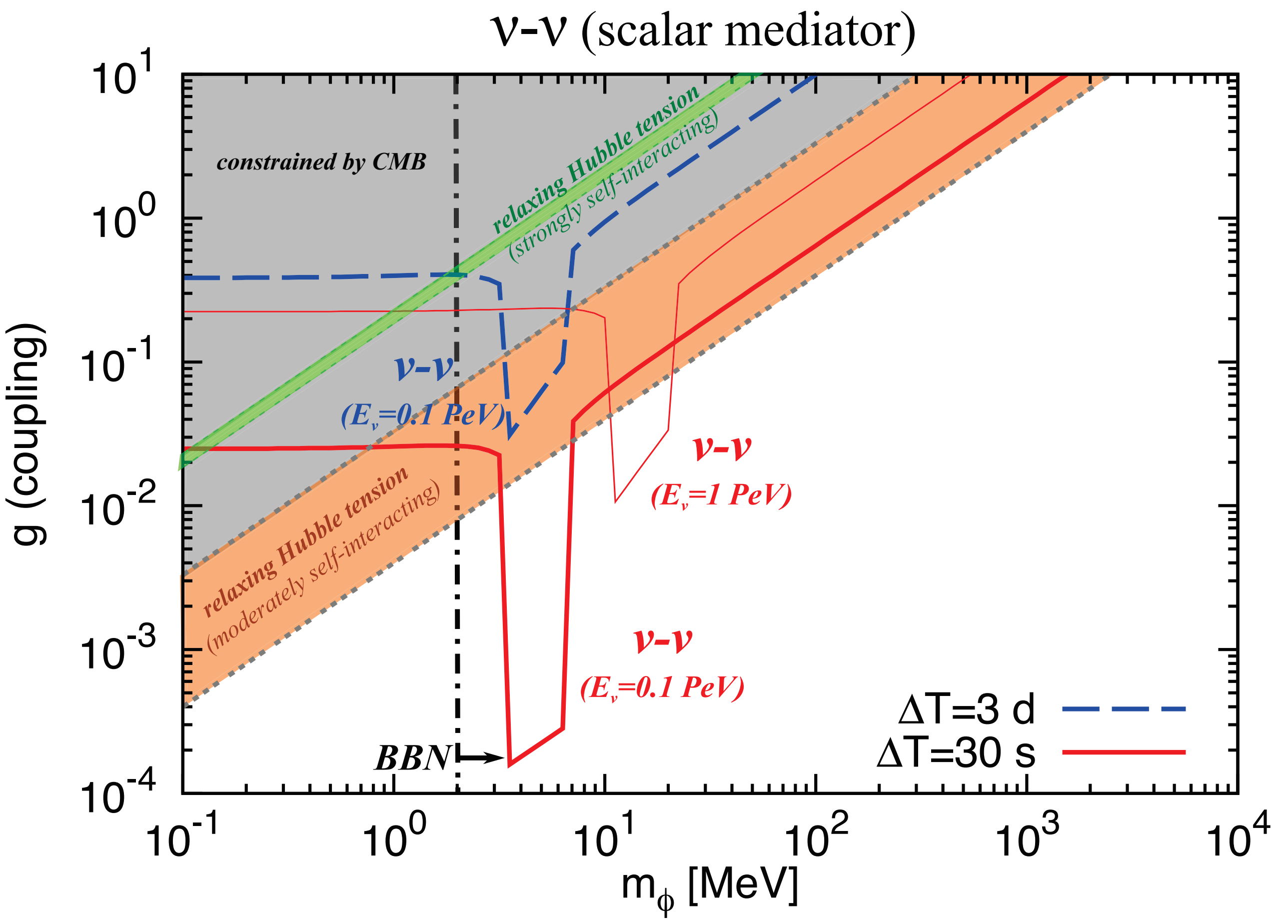


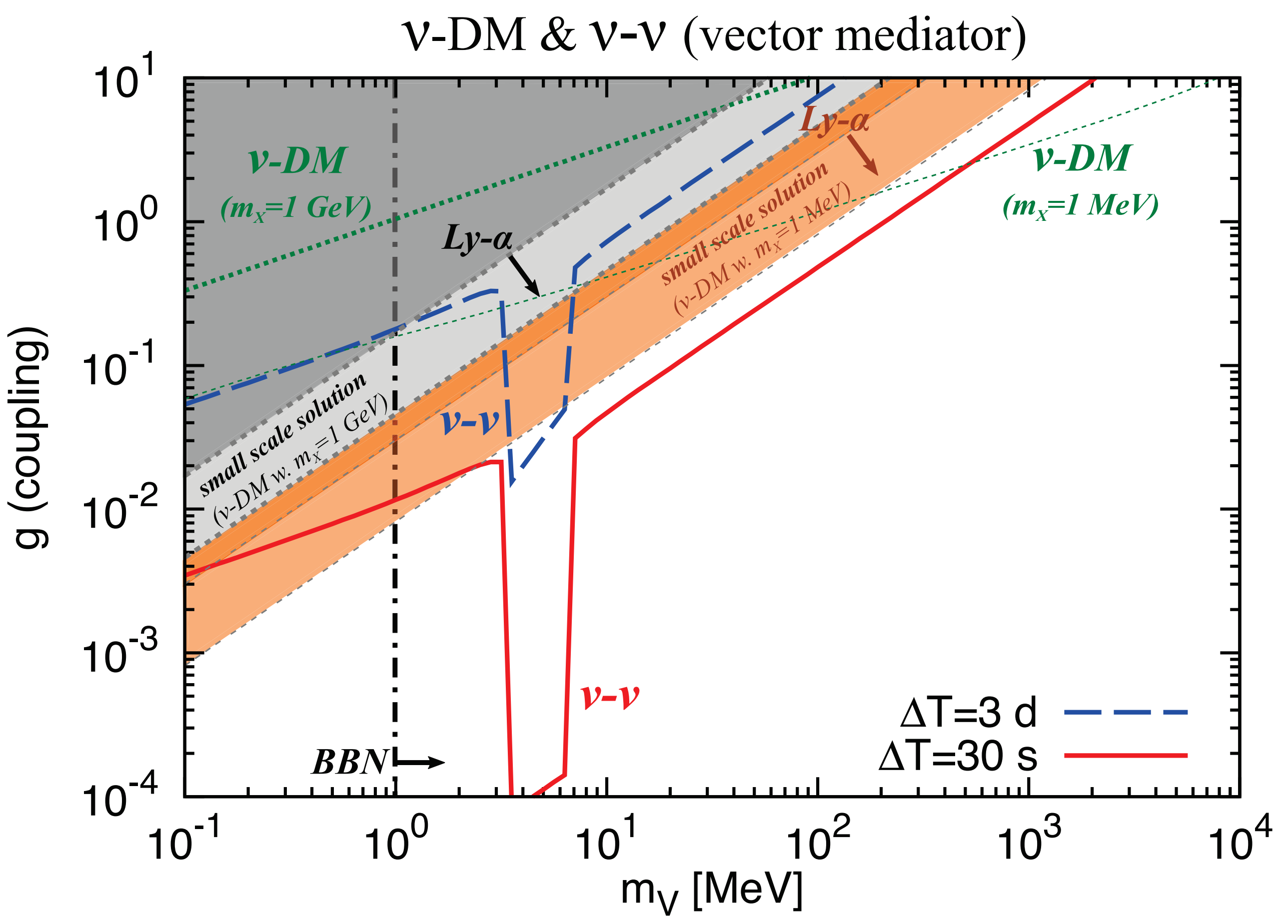
[Bustamante, Rosenstroem, Shalgar & Tamborra'20]



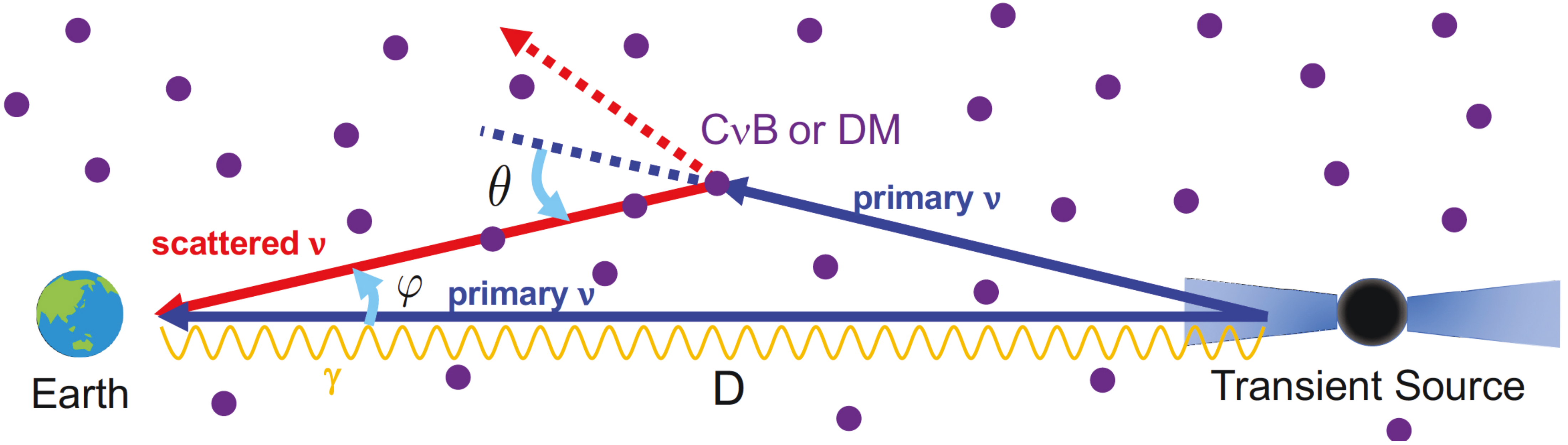
[Blinov, Bustamante, Kell & Zhang'22]

Neutrino "Echos" in TXS 0506+056



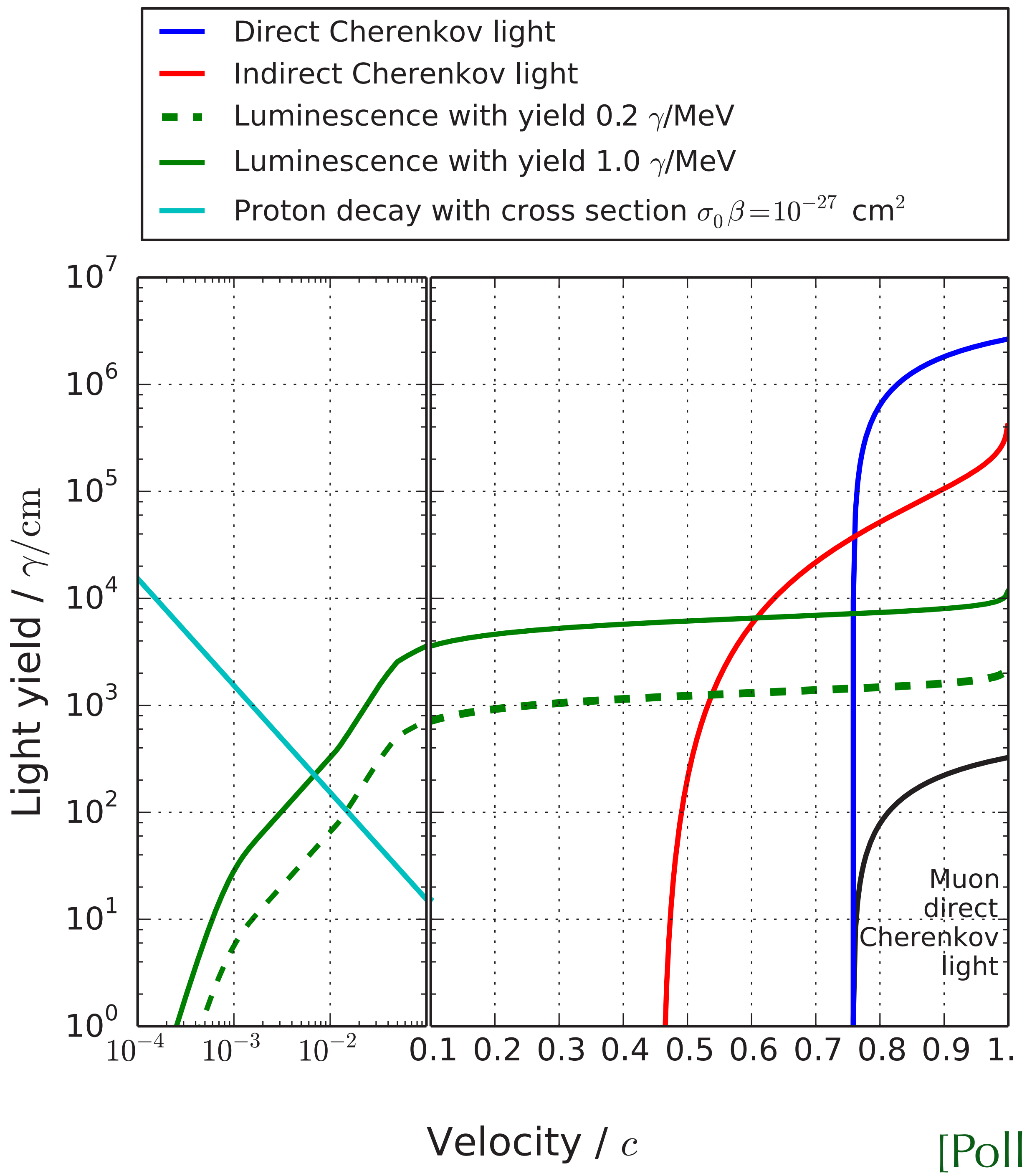


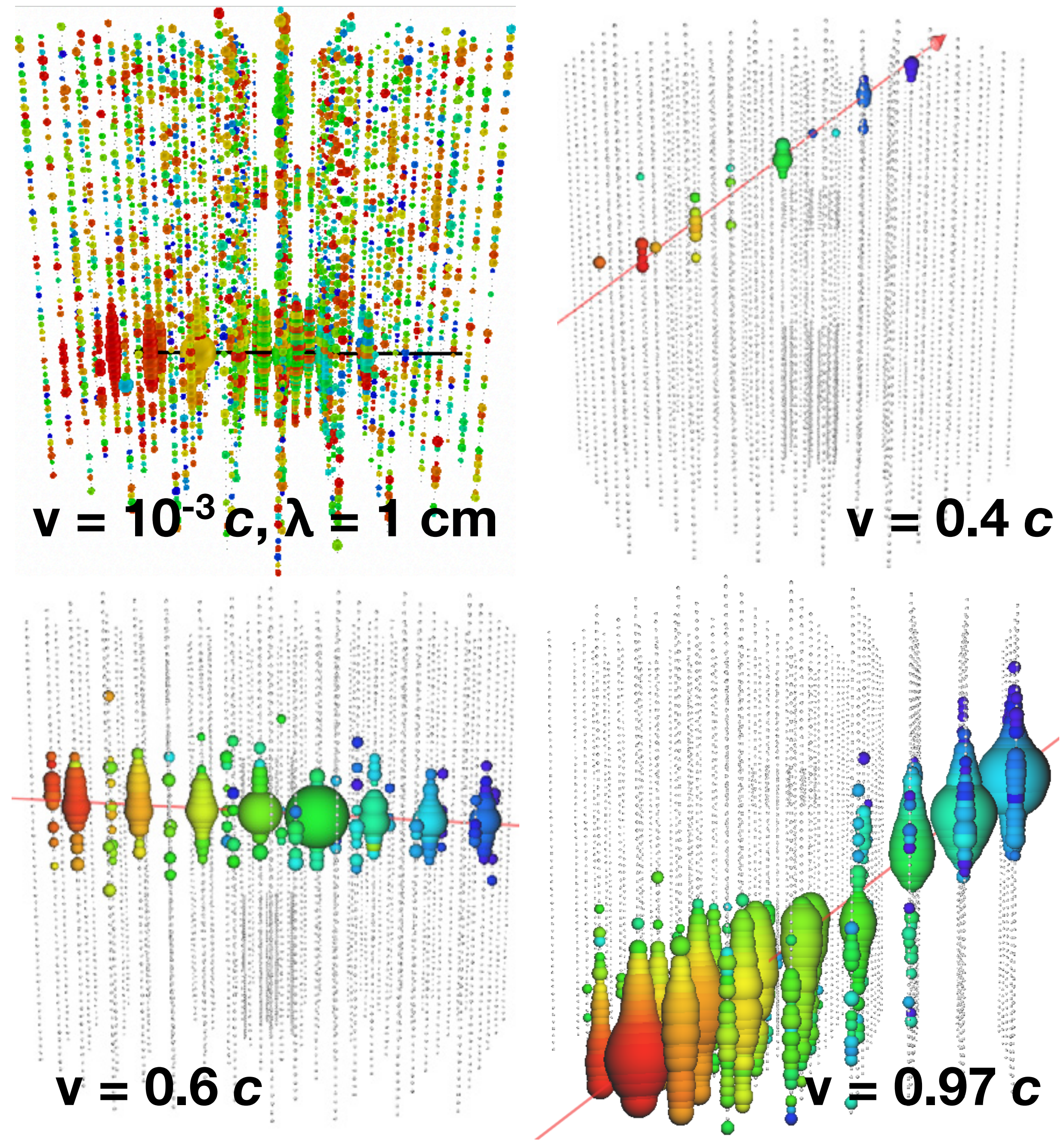
[Murase & Shoemaker '19]



Exotic Signatures: Monopoles

Magnetic monopoles visible via characteristic electromagnetic interactions or via monopole-catalyzed baryon decays in GUTs.

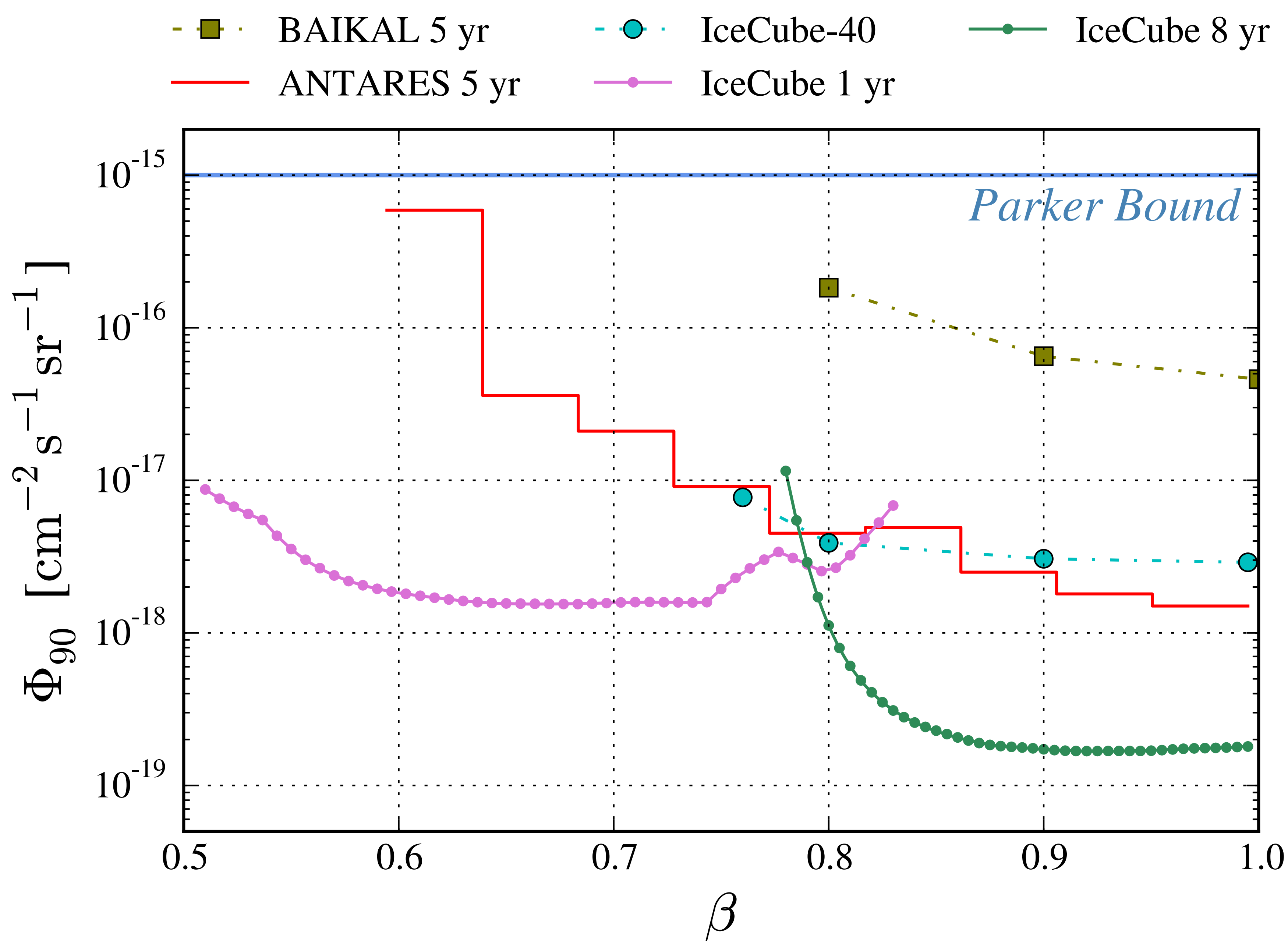




[Pollmann'18]

Limits on Primordial Monopoles

Neutrino telescopes sets meaningful limits on primordial monopoles below the *Parker bound* (short-circuit of Galactic magnetic fields).



[IceCube PRL 128 (2022) 5]

Summary

- High-energy cosmic radiation has been a powerful probe of particle physics in the 20th century (discovery of *positron, muon, pion, …*).
- **Neutrino astronomy** offers complementary and unique probes of fundamental physics.
- *Long propagation baselines and large neutrino energies beyond the reach of accelerator facilities.*
- This allows us to study:
    - atmospheric **neutrino oscillations** and **neutrino interactions** in SM
    - **dark matter** in Milky Way, Sun, Earth, nearby galaxies, etc.
    - **neutrino decay, feeble interactions, non-standard oscillations**
    - *etc.*
- *We only highlighted a few selected topics and probes!*