IceCube and Physics Beyond the Standard Model

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IceCube Summer School, UW-Madison

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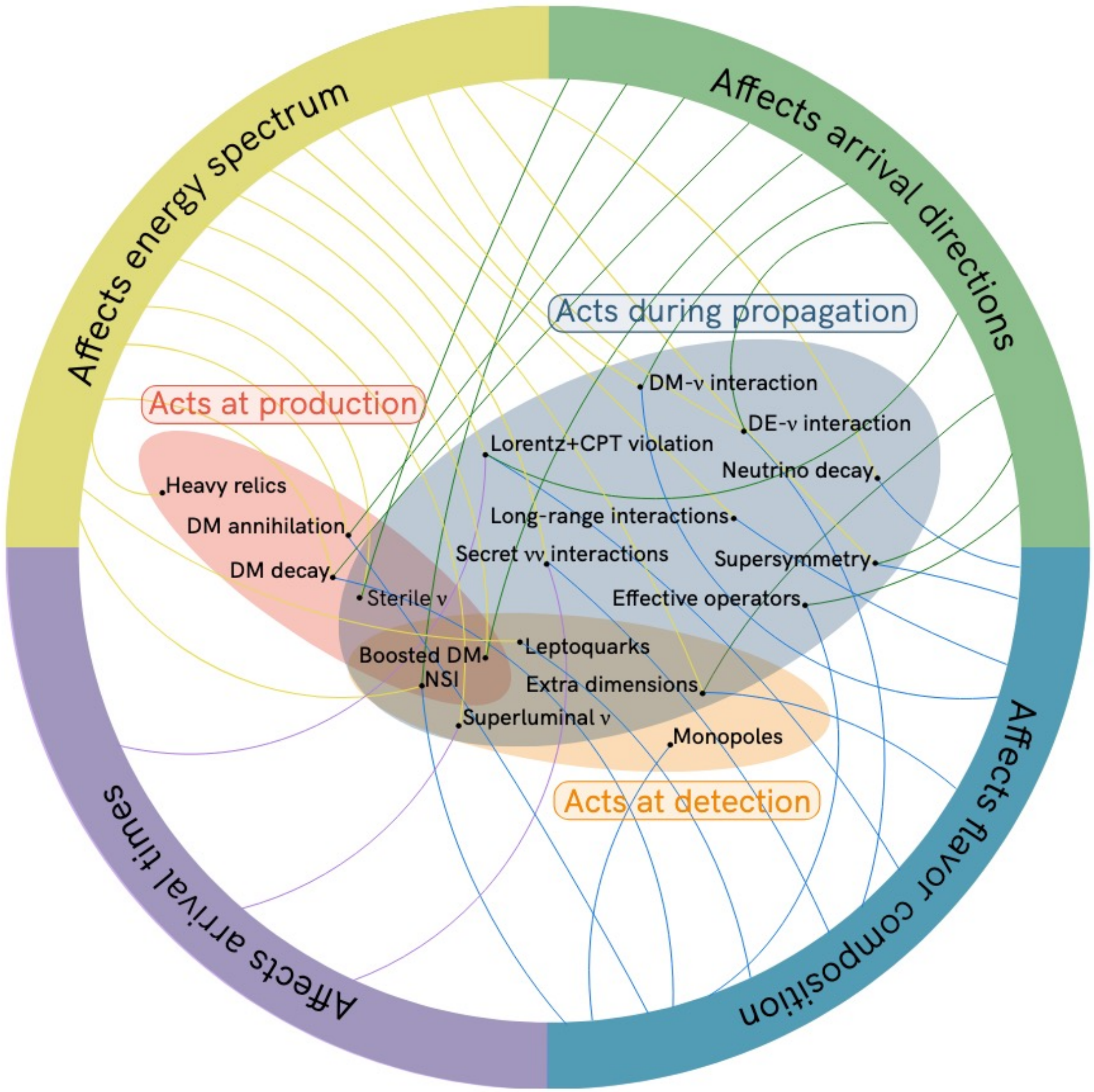
High-Energy Neutrinos Telescopes as a Probe of Fundamental Physics



Neutrino Oscillations

- In the Standard Model, the neutrinos are exactly massless and without masses, neutrinos do not oscillate → neutrino oscillations are BSM physics!
- The probability that a neutrino which starts out in the pure state, α, will be of flavor β after traveling a distance, L, is given by

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}) \sin^2\left(\frac{(m_i^2 - m_j^2)L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}) \sin\left(\frac{(m_i^2 - m_j^2)L}{2E}\right)$$

where U is the PMNS matrix:

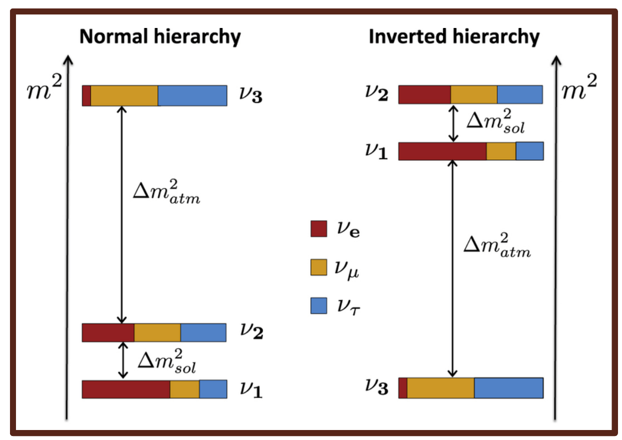
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23}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

- This boils down to a handful of free parameters:

  2 squared-mass splittings and the mass hierarchy

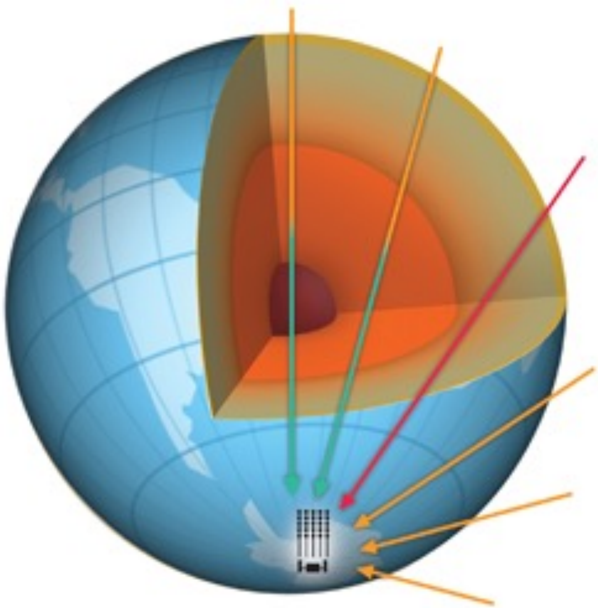
  3 mixing angles $(\theta_{13}, \theta_{23}, \theta_{12})$

  1 CP-phase (δ_{CP})

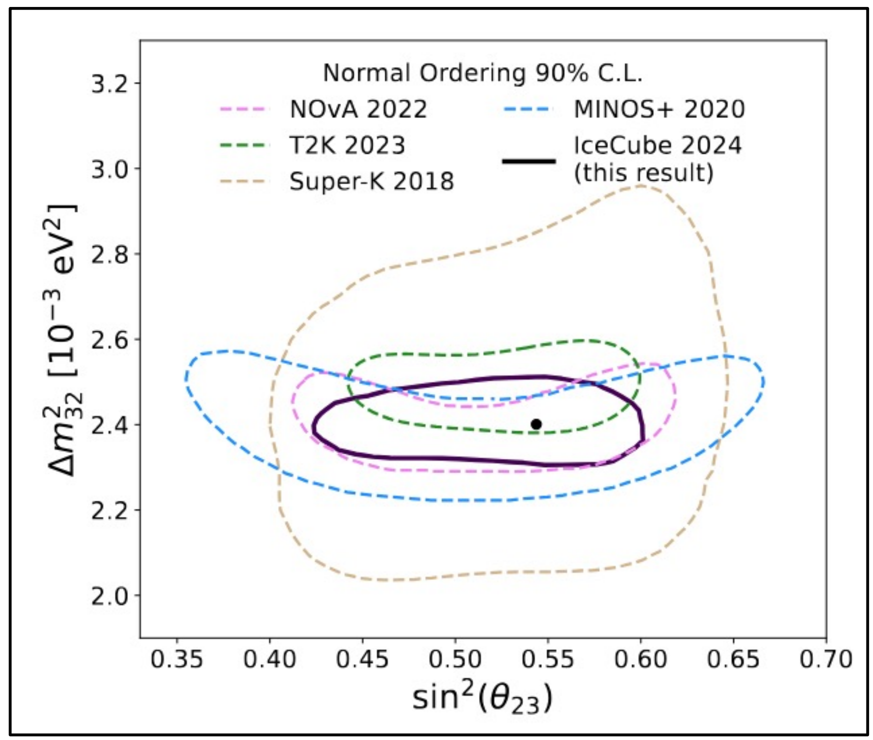


Measuring Neutrino Oscillation Parameters

- At ~5-100 GeV energies, earth-crossing ν_μ oscillate nearly maximally into ν_τ
- In other words, $\frac{\Delta m^2 L}{3E} \sim \frac{\pi}{2}$, maximizing $P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



- This enables IceCube/DeepCore to precisely measure both $\sin\theta_{23}$ and Δm^2_{32}

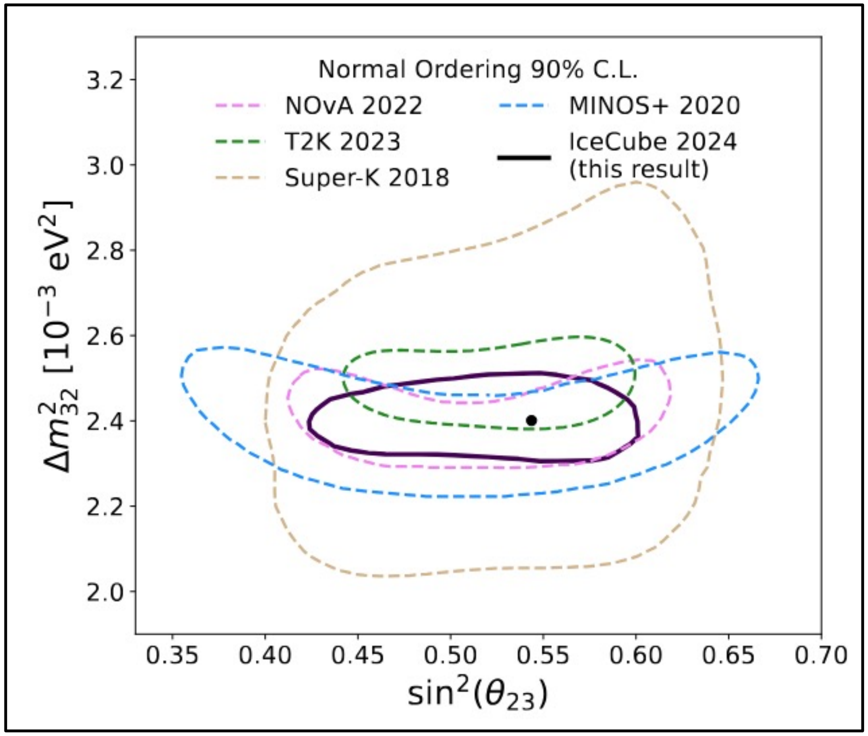


IceCube, arXiv:2405.02163, 2304.12236

Measuring Neutrino Oscillation Parameters

- In contrast to oscillation measurements that use MeV-GeV neutrinos, IceCube's results are largely insensitive to the value of δ_{CP} and are not subject to many of the uncertainties that impact accelerator-based measurements (ie. nuclear scattering cross sections)
- The IceCube Upgrade (to be deployed in 2025/26) will significantly enhance IceCube's ability to detect and measure GeV-TeV scale neutrinos – this will be critical for measuring oscillation parameters (including the neutrino mass hierarchy!)

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



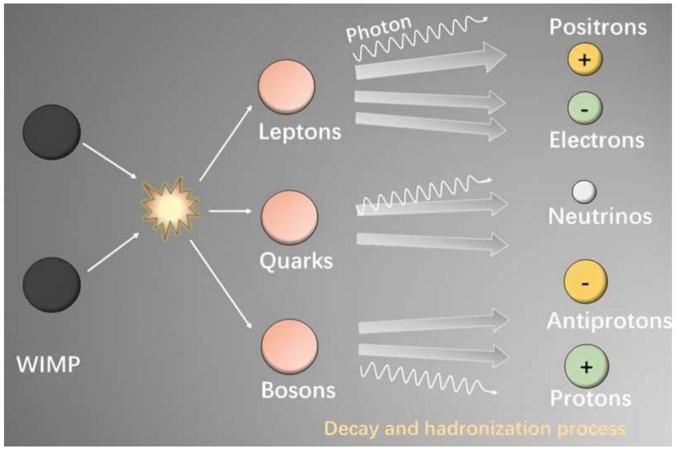
IceCube, arXiv:2405.02163, 2304.12236

Neutrinos From Dark Matter Annihilation

- Dark matter particles annihilate at a rate of, $\frac{d\Gamma_{XX}}{dV} = \frac{\langle \sigma v \rangle \rho_X^2}{2m_X^2}$
- This leads to the following flux of neutrinos:

$$\frac{dN_\nu}{dE_\nu} = \int \frac{\langle \sigma v \rangle \rho_X^2}{2m_X^2} \frac{dN_\nu}{dE_\nu}\bigg|_{\rm ann} \frac{dV}{4\pi d^2}$$

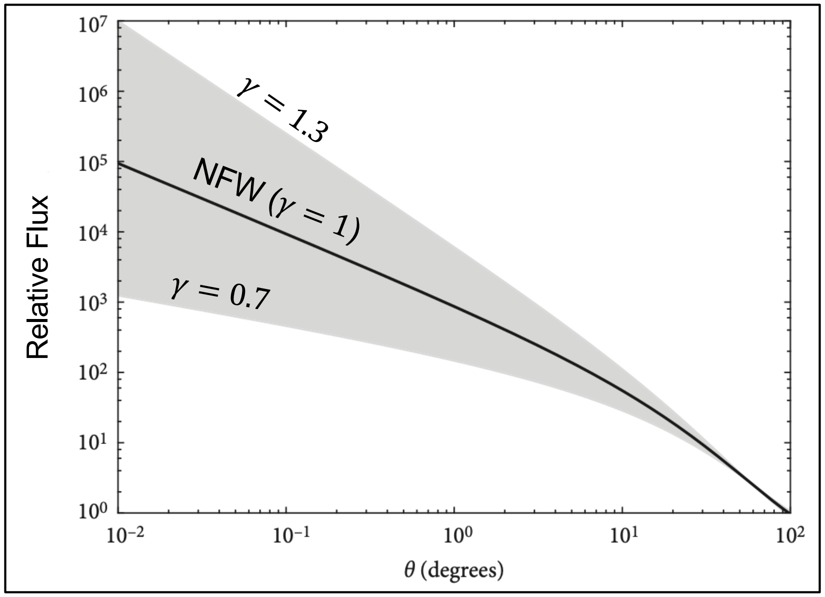
$$= \frac{\langle \sigma v \rangle}{8\pi m_X^2} \frac{dN_\nu}{dE_\nu}\bigg|_{\rm ann} \int_{\Delta\Omega} \int_{los} \rho_X^2(l,\Omega)\, dl\, d\Omega$$



- Parameterizing the distribution of dark matter in the Milky Way with a generalized-NFW profile:

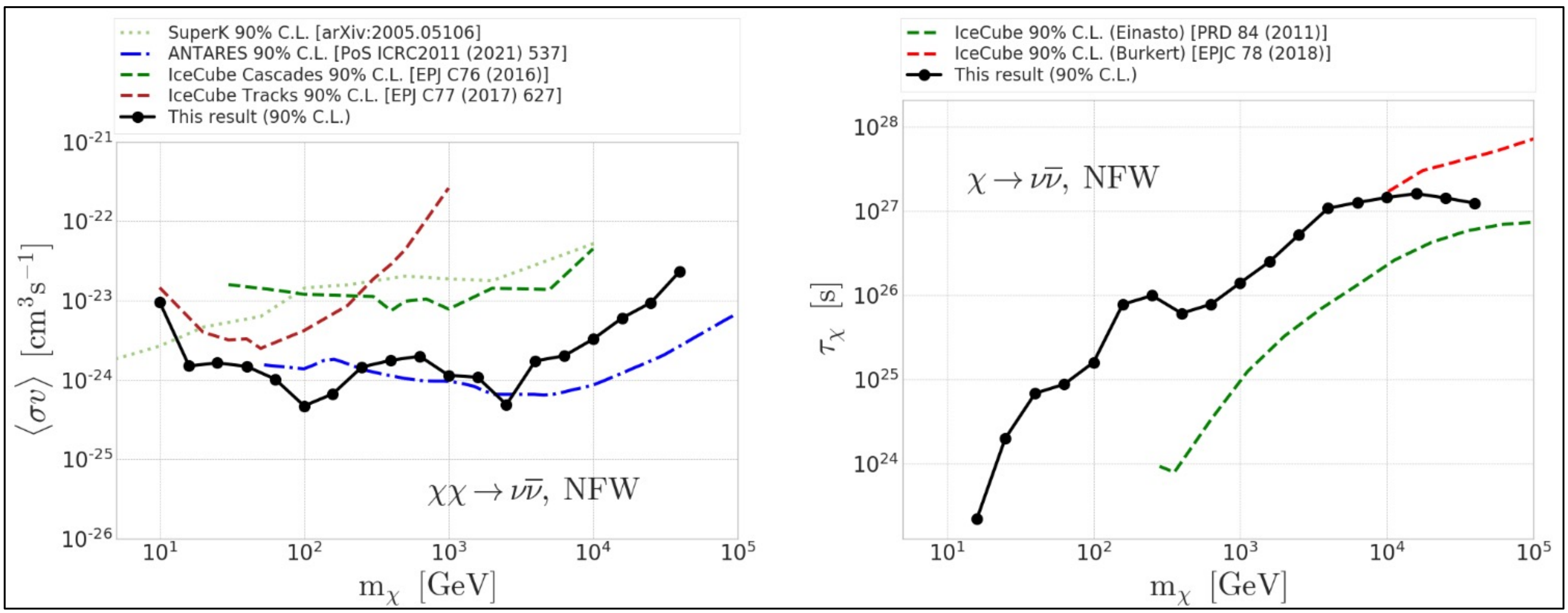
$$\rho(r) \propto \frac{(r/R_s)^{-\gamma}}{(1+r/R_s)^{3-\gamma}}$$

we arrive at



Dark Matter Searches

- For dark matter models that preferentially produce neutrinos (such as those in which $XX \rightarrow \nu\bar{\nu}$ or $XX \rightarrow \tau^+\tau^-$), neutrino telescopes can provide our most stringent constraints on dark matter annihilations/decays in the halo of the Milky Way
- Note that these cross sections are much larger than those typically expected of a thermal relic of the Big Bang



IceCube, arXiv:2303.13663

Dark Matter Annihilation in the Sun

- Alternatively, dark matter particles could scatter with nuclei in the Sun, causing them to become gravitationally captured, and accumulate in the core at the following rate:

$$\Gamma_{\rm cap} = 4\pi \int_0^{R_\odot} r^2 dr \int_0^\infty \frac{f(u)}{u}\, w\, \Omega_v(w)\, du$$

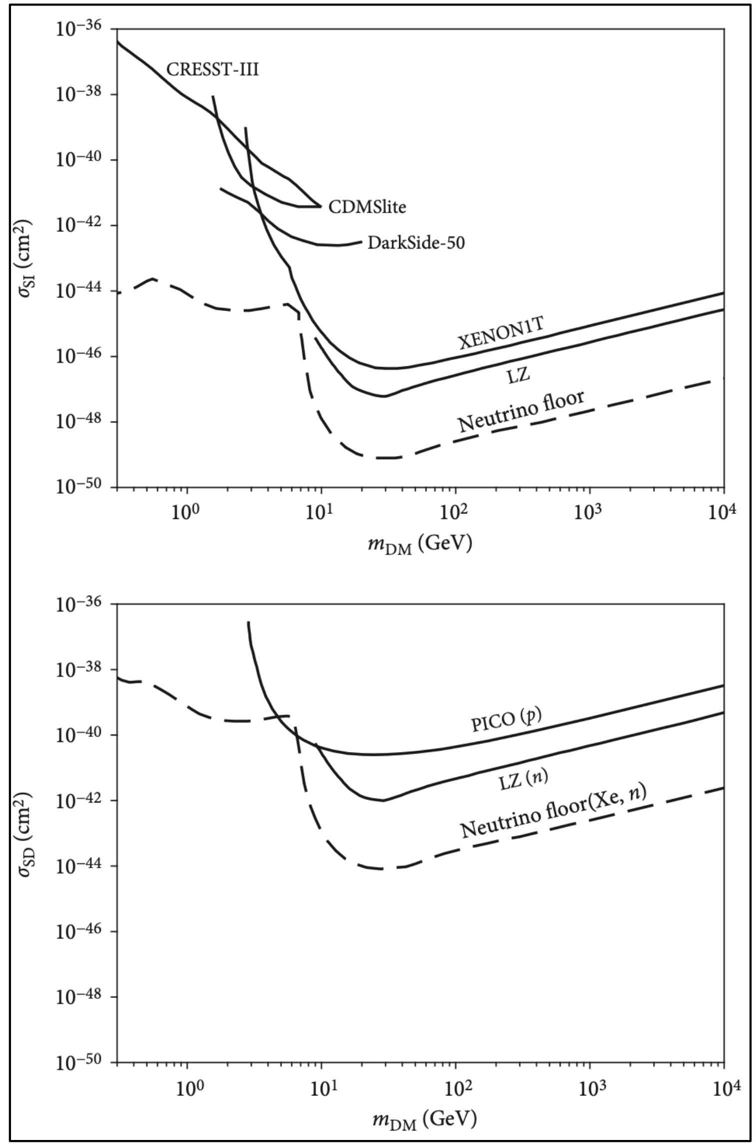
where Ω_v is the probability that a given dark matter particle will elastically scatter with a nucleus and be left with a velocity below the Sun's escape velocity:

$$\Omega_v(w) = \sum_i n_i\, w\, \Theta\left(\alpha_i - \frac{u^2}{w^2}\right) \int_{m_\chi u^2/2}^{\alpha_i m_\chi w^2/2} \frac{d\sigma_i}{dE}(w^2, q^2)\, dE$$

- This rate depends not on the dark matter's annihilation cross section, but on its elastic scattering cross section with nuclei
- When dark matter particles in the Sun's core annihilate, any photons, electrons, or nucleons that are produced are absorbed, but neutrinos can escape!

Dark Matter Annihilation in the Sun

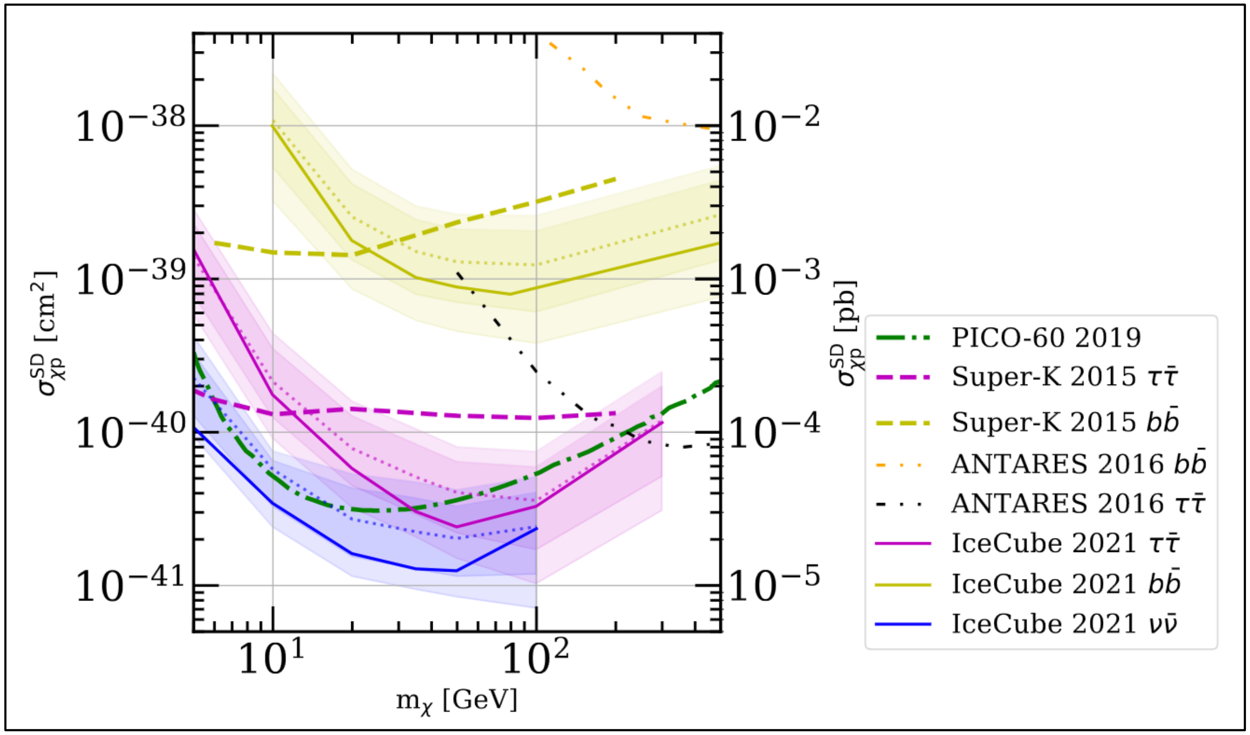
- At low velocities, the dark matter's elastic scattering cross section with nuclei reduces to a combination of the following:
  1) Spin-independent, $\sigma \propto A^2$
  2) Spin-dependent, $\sigma \propto J\,(J+1)$



- Direct detection experiments (which use targets of heavy nuclei) have already placed very stringent constraints on dark matter's spin-independent scattering cross section
- Alternatively, if the dark matter particles interact with nucleons through spin-dependent interactions, these particles could become captured in the core of the Sun and annihilate at a high rate, producing detectable fluxes of high-energy neutrinos

Dark Matter Annihilation in the Sun

- Neutrino telescopes provide the strongest constraints on dark matter candidates that annihilate to $\nu\bar{\nu}$ or $\tau^+\tau^-$



- The IceCube Upgrade will significantly increase our sensitivity to this variety of dark matter candidates

IceCube, arXiv:2111.09970; DH and F. Vassallo, arXiv:2505.06734

High-Energy Neutrinos as a Probe of Fundamental Physics

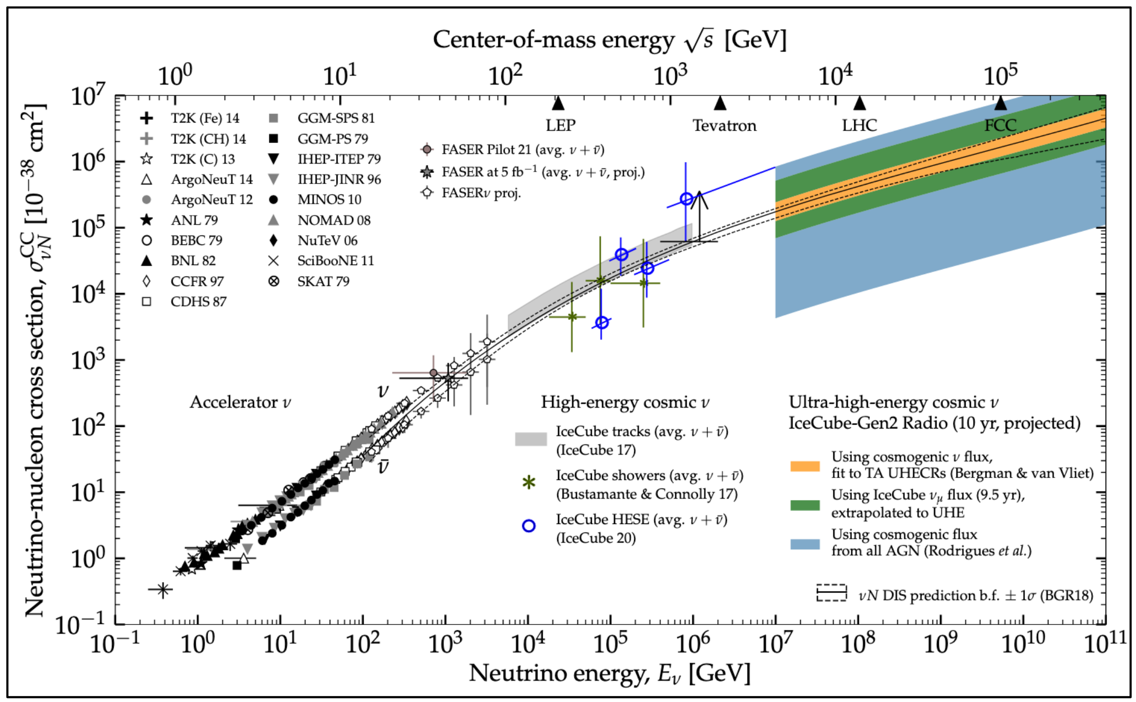
- Neutrino telescopes allow us to measure the interactions of neutrinos at much ***higher energies*** and over much ***longer baselines*** than is possible in any existing laboratory experiment
- Such measurements can serve as a probe of many scenarios featuring physics beyond the Standard Model

High-Energy Neutrino Interactions

- IceCube is a particle detector (analogous to CMS or ATLAS) that uses a naturally-occurring particle accelerator (sources of cosmic rays)
- In the center-of-momentum frame, the collision of a high-energy neutrino with a nucleon at rest has an energy of $E_{CM} \approx \sqrt{2m_p E_\nu}$

  -For $E_\nu > 500$ TeV, E_{CM} exceeds 1 TeV

  -For $E_\nu > 100$ PeV, E_{CM} exceeds 14 TeV
- Neutrino telescopes can be used to study particle collisions at energies beyond the reach of any existing accelerator



Ackermann, et al. (Snowmass)
arXiv:2203.08096

Studying Ultra-High-Energy Interactions

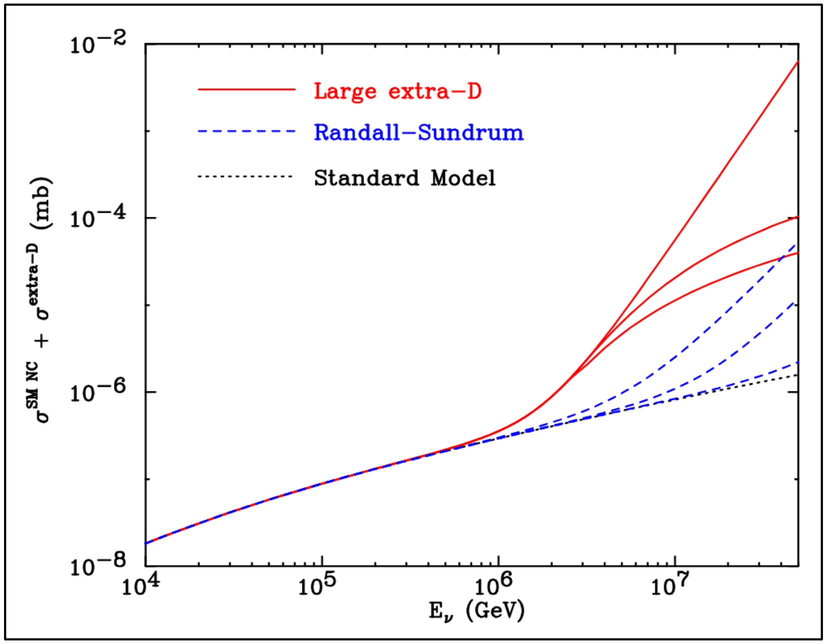
- What could cause the neutrino-nucleon cross section to be significantly different than that predicted by the SM at ultra-high energies?
- In general terms, neutrino telescopes are sensitive to new strong dynamics, involving new heavy particles with large couplings
- Such interactions are also sensitive to the structure of the nucleon, providing us with a novel probe of low-x and high-Q^2 QCD

Low-Scale Quantum Gravity

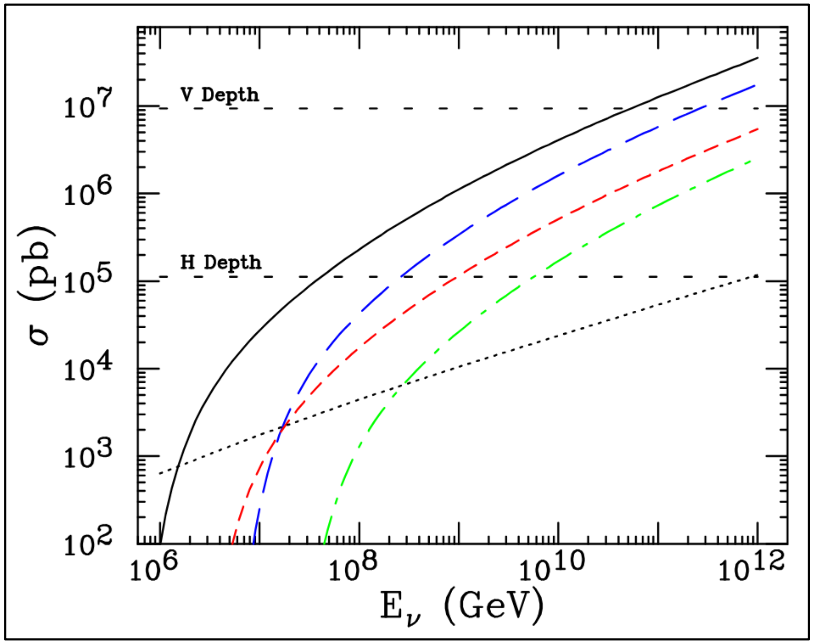
- In models with relatively large (~0.1 mm) or highly warped extra dimensions, the fundamental scale of quantum gravity can be far below the apparent Planck scale:

$$M_{PL}^2 \sim V_n M_D^{n+2}$$

- This can cause gravity to become strong at relatively modest energies (as low as the TeV-scale), leading to high rates for processes such as:



Kaluza-Klein Graviton Exchange
($\Lambda = 1 - 3$ TeV)

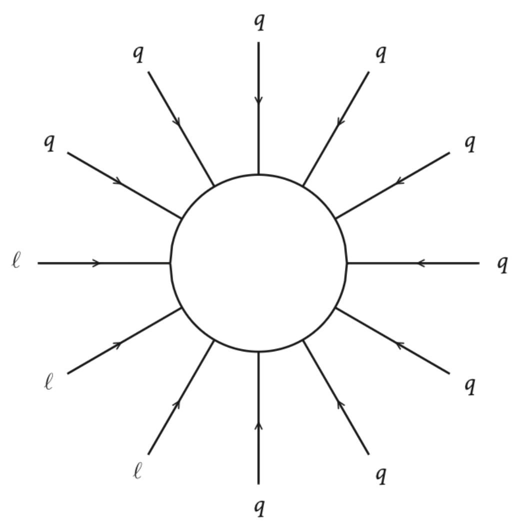


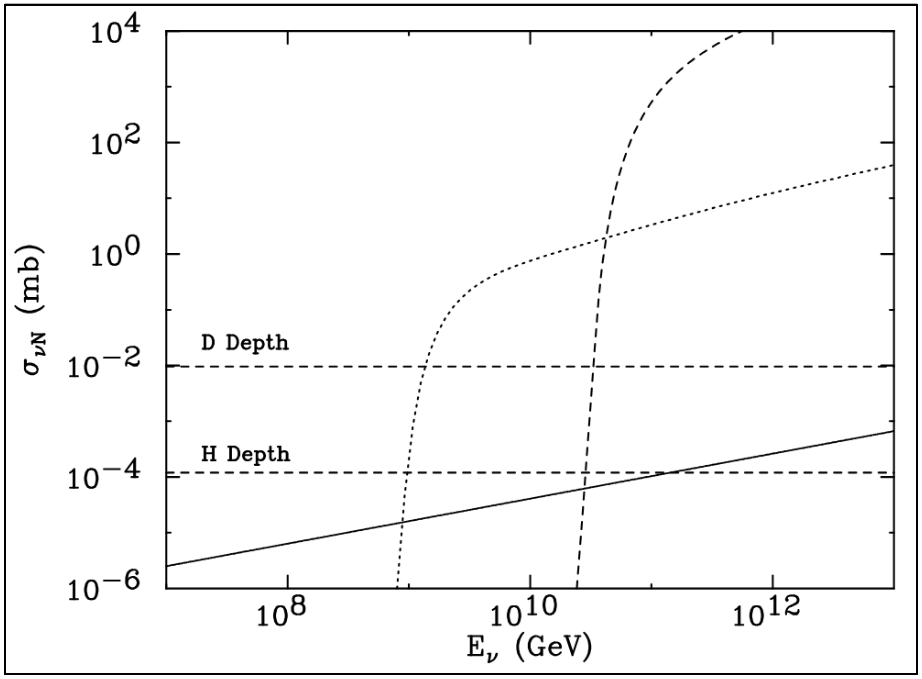
Microscopic Black Hole Production
($M_D = 1 - 2$ TeV)

Electroweak Instantons

- Standard Model electroweak instantons represent tunnelling transitions between topologically inequivalent vacua, allowing for processes that can change the total baryon-plus-lepton number (B + L)
- Such processes are exponentially suppressed at $\mathrm{E} < E_{\mathrm{sph}} \sim \frac{\pi M_W}{\alpha_W} \sim 10\ \mathrm{TeV}$
- Above this scale, the cross sections for such process could be quite large, potentially resulting in large rates of UHE neutrino-nucleon scattering
- Such events would also produce a high multiplicity of particles, leading to distinctive signatures

$$\nu_e u \to \bar{d}\bar{d} + \bar{c}\bar{c}\bar{s}\mu^+ + \bar{t}\bar{t}\bar{b}\tau^+ + nW + mH.$$





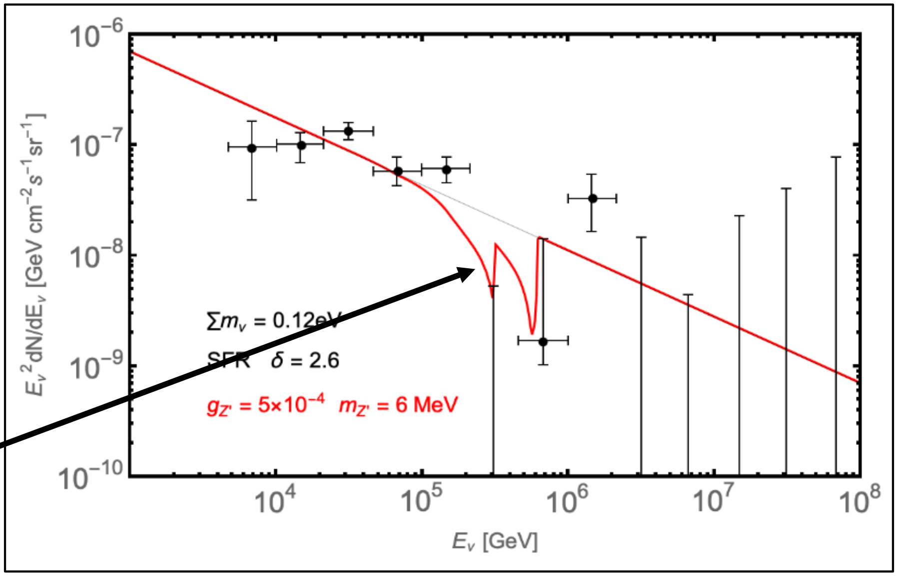
Probes of New Interactions?

- As another example, consider a light Z' that couples to muons (and muon neutrinos), with a gauge coupling that could explain the FNAL and BNL measurements of g_μ-2
- Over cosmological distances, such a Z' would cause high-energy neutrinos to scatter with the cosmic neutrino background, leading to a resonant absorption features at:

$$E_\nu \approx \frac{m_{Z'}^2}{2m_{\nu,i}\,(1+z_{\rm abs})}$$

$$\approx 1\,{\rm PeV} \times \left(\frac{m_{Z'}}{10\,{\rm MeV}}\right)^2 \left(\frac{0.05\,{\rm eV}}{m_{\nu,i}}\right) \left(\frac{1}{1+z_{\rm abs}}\right)$$

- This could even provide an explanation for the dip-like feature hinted at in the IceCube data around $E_\nu \sim$ 200-1000 TeV



DH, Iguaz, Serpico, arXiv:2302.03571
DiFranzo, DH, arXiv:1507.03015
DH, arXiv:0701194

Neutrino Flavor Ratios

- Over very long baselines, standard oscillations lead to neutrino fluxes with predictable flavor ratios

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}) \, \sin^2\left(\frac{(m_i^2 - m_j^2)L}{4E}\right) + 2 \sum_{i>j} \mathrm{Im}(U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}) \, \sin\left(\frac{(m_i^2 - m_j^2)L}{2E}\right)$$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 2 \sum_{i>j} \mathrm{Re}(U_{\alpha i} U^\star_{\beta i} U^\star_{\alpha j} U_{\beta j}) + \sum_{i>j} \mathrm{Im}(U_{\alpha i} U^\star_{\beta i} U^\star_{\alpha j} U_{\beta j}).$$

- Making use of the fact that θ_{13} and δ_{CP} are small, this reduces to the following probabilities:

$$P_{\nu_e \to \nu_e} \approx 1 - 2 s_{12}^2 c_{12}^2 \approx 0.57,$$

$$P_{\nu_e \to \nu_\mu} = P_{\nu_\mu \to \nu_e} \approx 2 s_{12}^2 c_{23}^2 c_{12}^2 \approx 0.20,$$

$$P_{\nu_e \to \nu_\tau} = P_{\nu_\tau \to \nu_e} \approx 2 s_{12}^2 s_{23}^2 c_{12}^2 \approx 0.23,$$

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - 2(s_{12}^2 c_{12}^2 c_{23}^4 + s_{23}^2 c_{23}^2) \approx 0.41,$$

$$P_{\nu_\mu \to \nu_\tau} = P_{\nu_\tau \to \nu_\mu} \approx 2 s_{23}^2 c_{23}^2 (1 - s_{12}^2 c_{12}^2) \approx 0.39$$

$$P_{\nu_\tau \to \nu_\tau} \approx 1 - 2(s_{12}^2 c_{12}^2 s_{23}^4 + s_{23}^2 c_{23}^2) \approx 0.38,$$

Neutrino Flavor Ratios

- Astrophysical high-energy neutrinos are thought to be overwhelmingly produced through the production and decay of charged pions

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu \to e^- \nu_\mu \bar{\nu}_e \bar{\nu}_\mu.$$

- At the source, this yields a flavor ratio of $\nu_e{:}\,\nu_\mu{:}\,\nu_\tau = 1{:}\,2{:}\,0$, which after accounting for standard oscillations becomes

$$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = P_{\nu_e \to P_{\nu_e}} + 2P_{\nu_\mu \to P_{\nu_e}} : P_{\nu_e \to P_{\nu_\mu}} + 2P_{\nu_\mu \to P_{\nu_\mu}} : P_{\nu_e \to P_{\nu_\tau}} + 2P_{\nu_\mu \to P_{\nu_\tau}}$$

which, numerically, is approximately $\nu_e{:}\,\nu_\mu{:}\,\nu_\tau \approx 1{:}\,1{:}\,1$

Neutrino Flavor Ratios

- Astrophysical high-energy neutrinos are thought to be overwhelmingly produced through the production and decay of charged pions

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$
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- At the source, this yields a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$, which after accounting for standard oscillations becomes

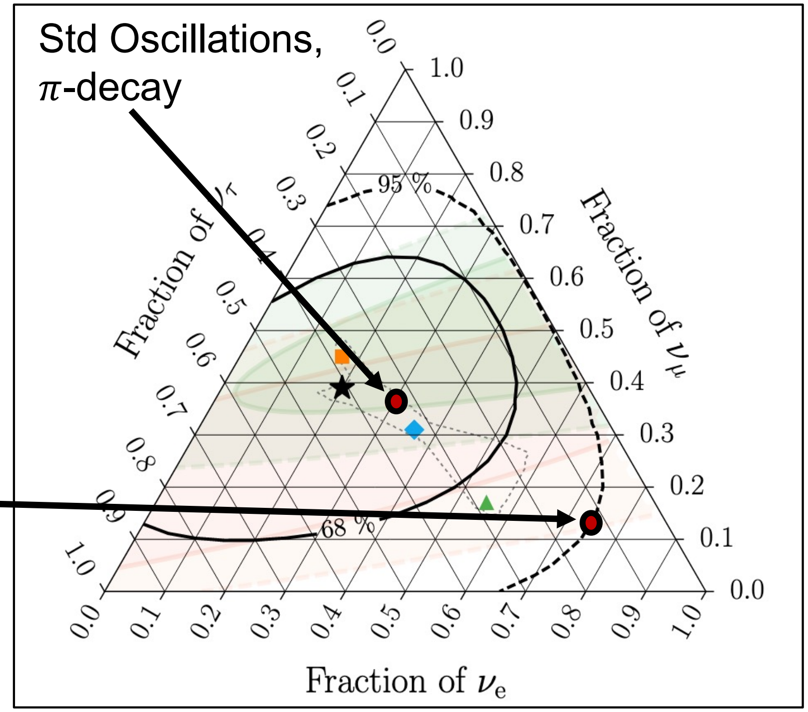
$$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = P_{\nu_e \rightarrow P_{\nu_e}} + 2P_{\nu_\mu \rightarrow P_{\nu_e}} : P_{\nu_e \rightarrow P_{\nu_\mu}} + 2P_{\nu_\mu \rightarrow P_{\nu_\mu}} : P_{\nu_e \rightarrow P_{\nu_\tau}} + 2P_{\nu_\mu \rightarrow P_{\nu_\tau}}$$

which, numerically, is approximately $\nu_e : \nu_\mu : \nu_\tau \approx 1:1:1$

- Other possible cases:
  - Neutrinos produced in neutron decay, $n \rightarrow p^+ \, e^- \, \nu_e$, leading to $\nu_e : \nu_\mu : \nu_\tau = 1:0:0 \rightarrow 0.6:0.2:0.2$
  - Neutrinos from $\pi^\pm$ decay in environments with very large magnetic fields, leading to $\nu_e : \nu_\mu : \nu_\tau = 0:1:0 \rightarrow 0.2:0.4:0.4$
  - Neutrinos from muon pair production and decay, leading to $\nu_e : \nu_\mu : \nu_\tau = 1:1:0 \rightarrow 0.4:0.3:0.3$
  - Physics beyond the Standard Model

Neutrino Decay

- It is possible that one or more neutrino species could be (slightly) unstable
- Such decays would be imperceptible in laboratory experiments, but would impact the flavor ratios of the astrophysical neutrinos that reach Earth
- Measurements by IceCube-Gen2 could plausibly enable us to improve constraints on the neutrino lifetime by several orders of magnitude, testing a variety of decay scenarios



IceCube, arXiv:2011.03561

TABLE I: Flavor ratios for various decay scenarios.

Unstable	Daughters	Branchings	$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	$6 : 1 : 1$
ν_3	sterile	irrelevant	$2 : 1 : 1$
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 2} = 1$	$1.4 : 1 : 1$ $1.6 : 1 : 1$
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 1} = 1$	$2.8 : 1 : 1$ $2.4 : 1 : 1$
ν_3	anything	$B_{3\to 1} = 0.5$ $B_{3\to 2} = 0.5$	$2 : 1 : 1$

Beacom, Bell, DH, Pakvasa, Weiler, arXiv:0211305

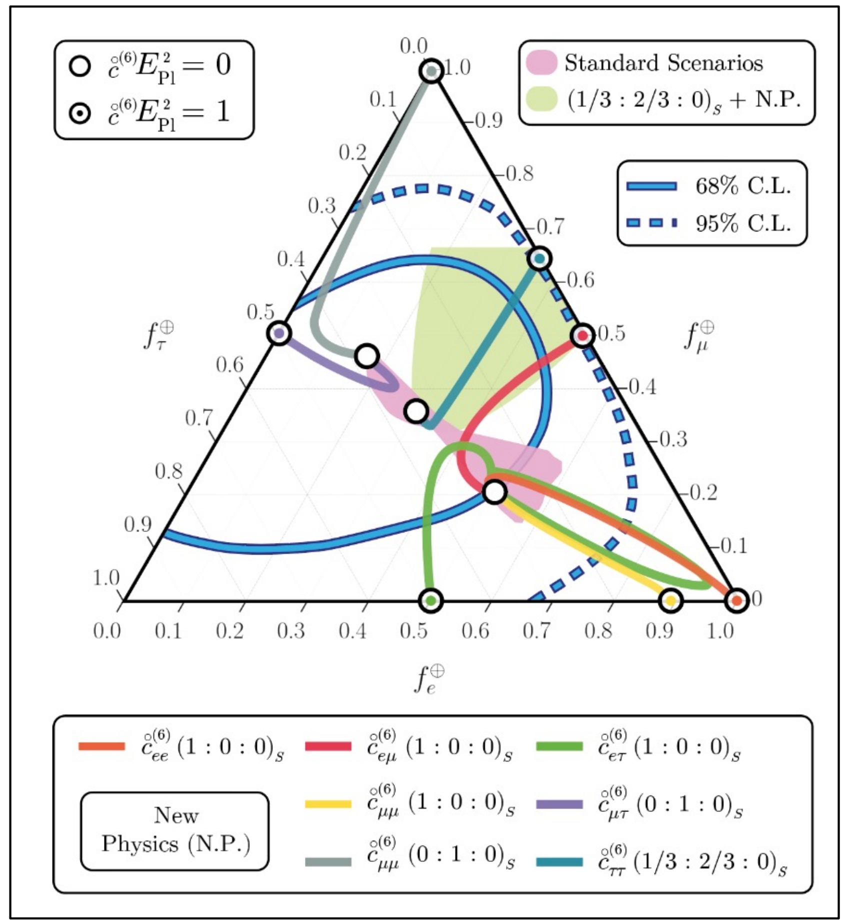
Probing Quantum Gravity

- Over cosmological baselines, the effects of quantum gravity (potentially including quantum decoherence, Lorentz violation, or even CPT violation) could lead to observable changes in the flavor ratios of the neutrinos that reach Earth
- In some models of quantum gravity, the universe is filled with a fluctuating quantum background – "spacetime foam" (one can think of this in terms of the formation of virtual black holes)
- If propagating neutrinos can exchange quantum information about their flavor or mass with this fluctuating environment, this would lead to the loss of their quantum coherence
- Quantum decoherence can erase neutrino flavor information over large distances
- The effects of quantum decoherence are expected to be greatest at high energies

DH, Morgan, Winstanley, arXiv:0506091, 0410094

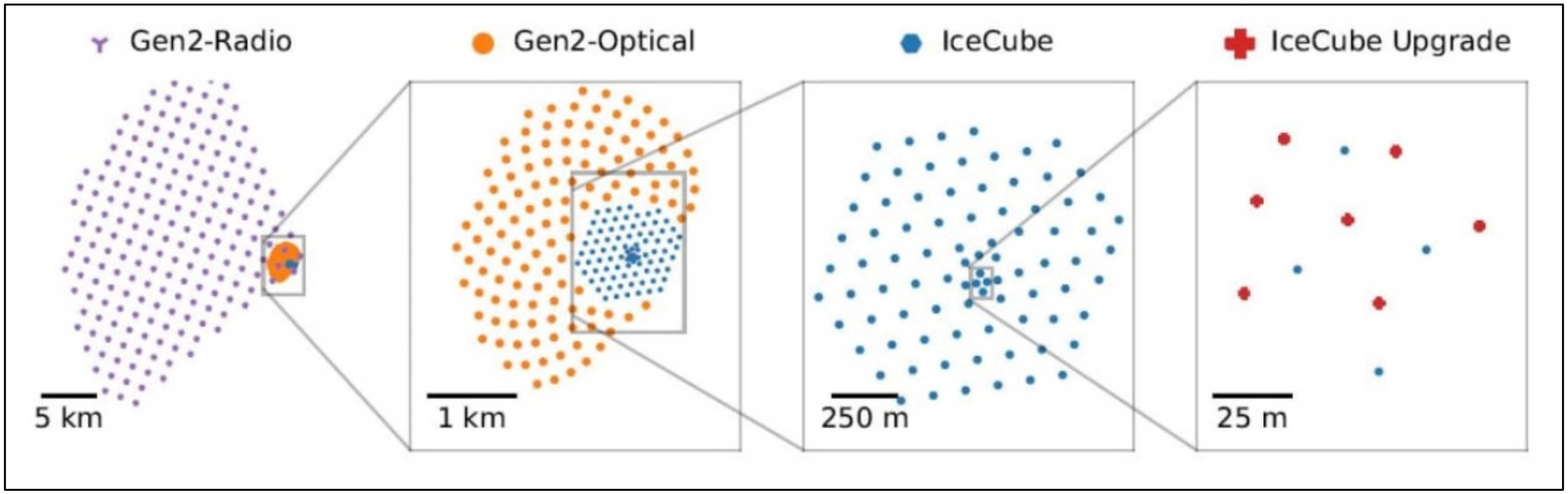
Probing Quantum Gravity

- When people first started to think about probing quantum gravity with neutrino telescopes (~2004/05), this seemed like an almost inconceivably difficult measurement
- Amazingly, IceCube published their first constraints on this class of models in 2021
- These measurements can be sensitive to well motivated quantum gravity scenarios, even for effective operators that are suppressed by the Planck scale
- For example, these measurements rule out dimension-6 operators with coefficients as small as $\sim 10^{-4}\, M_{Pl}^2$



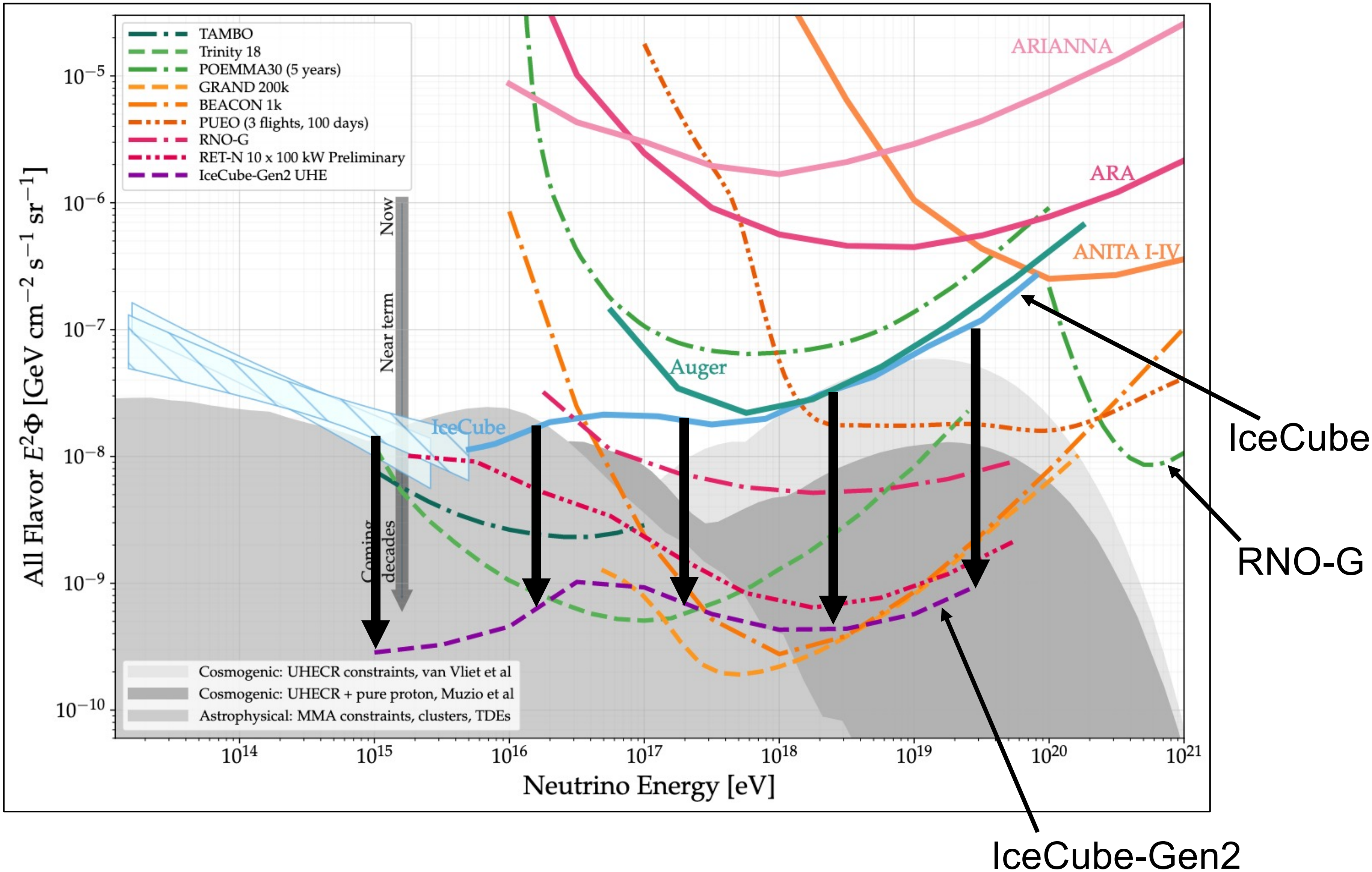
DH, Morgan, Winstanley, arXiv:0506091, 0410094
IceCube, arXiv:2111.04654, 2308.00105

The IceCube Upgrade and IceCube-Gen2



- The IceCube Upgrade (to be deployed in 2025/26) will significantly increase the resolution of IceCube, as well as its sensitivity to GeV-TeV neutrinos (important for many reasons, including oscillation parameters)
- IceCube-Gen2 will increase the effective volume of IceCube by an order of magnitude (and even more at UHEs)
- Along with optical detectors, Gen2 will include a large volume array of radio detectors, which will dramatically enhance this telescope’s sensitivity to ultra-high energy neutrinos

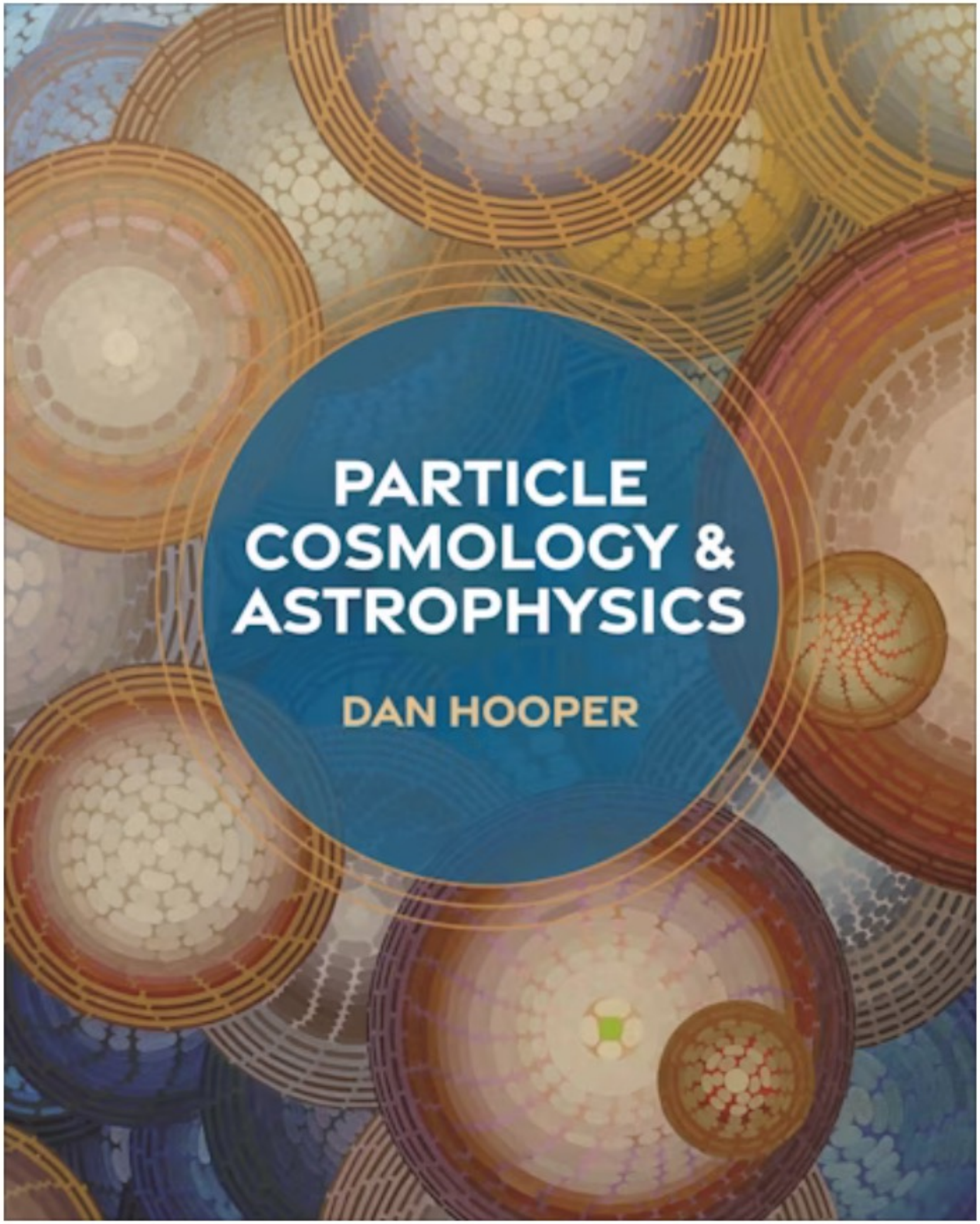
The Reach of IceCube-Gen2



Ackermann et al., Snowmass White Paper, 2203.08096

Summary

- High-energy neutrino telescopes provide several unique opportunities to study physics beyond the Standard Model
  - -Neutrino oscillation parameter determinations
  - -Interactions at energies beyond the reach of Earth-based accelerators
  - -Propagation of particles over cosmological baselines
  - -Neutrinos from dark matter annihilation/decay or other exotic origins
- In many ways, neutrino telescopes and other particle-astrophysics experiments are highly complementary to accelerator-based approaches to studying fundamental physics
- IceCube-Gen2 will improve upon the current sensitivity of IceCube in many respects by roughly ~2 orders of magnitude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