

What Can Tao and I Do With High-Energy Neutrinos ?

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My First Recollections of Tao

- Tao arrived at UW-Madison in 1997, about two years before I started there as a grad student
- During my prospective student visit in 1999, I convinced Francis Halzen (or did he convince me?) to work with me and fund me on an RA during the summer before classes started, and we started working on a research project involving high-energy neutrino production in gamma-ray bursts
- Deep down, however, I wanted to do theoretical particle physics, which struck me as more fundamental and foundational than astrophysics (my views on this have become somewhat more nuanced over time)
- I was introduced to Tao through his student Bob McElrath, and he was very approachable; I started taking some of my questions about particle physics to Tao, and he seemed happy to interact with me

Tao the Sounding Board

- Sometime during the year 2000 (I think), I attended a colloquium at UW-Madison (I'm not sure by who) about the reach of the future Large Hadron Collider to new physics, including supersymmetry, technicolor, and models with extra dimensions
- After that colloquium, I went to Tao with a list of (very naïve) questions. One I recall asking was:
 - If the Higgs boson is supposed to be lighter than 120 GeV (as was often stated at the time), why hadn't we discovered it already at the Tevatron or LEP?
- At some point, Tao mentioned to me that in models with large or highly warped extra dimensions (such as ADD or RS), physics would change dramatically at very high energies, so a machine like the LHC would be able to test these models quite thoroughly
- To this I asked, what about IceCube? After all, it might be able to observe collisions with even more energy than the LHC?

Extra Dimensions Circa 2000

- The phenomenology of models with extra dimensions was an *incredibly* hot topic when I was in grad school
- Models with large (~mm-scale) dimensions in which the Standard Model was confined to a brane were proposed by Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali in 1998
- In 1999, Lisa Randall and Raman Sundrum introduced analogous models with warped extra dimensions
- In these models, the fundamental scale of quantum gravity can be far below the apparent Planck scale:

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

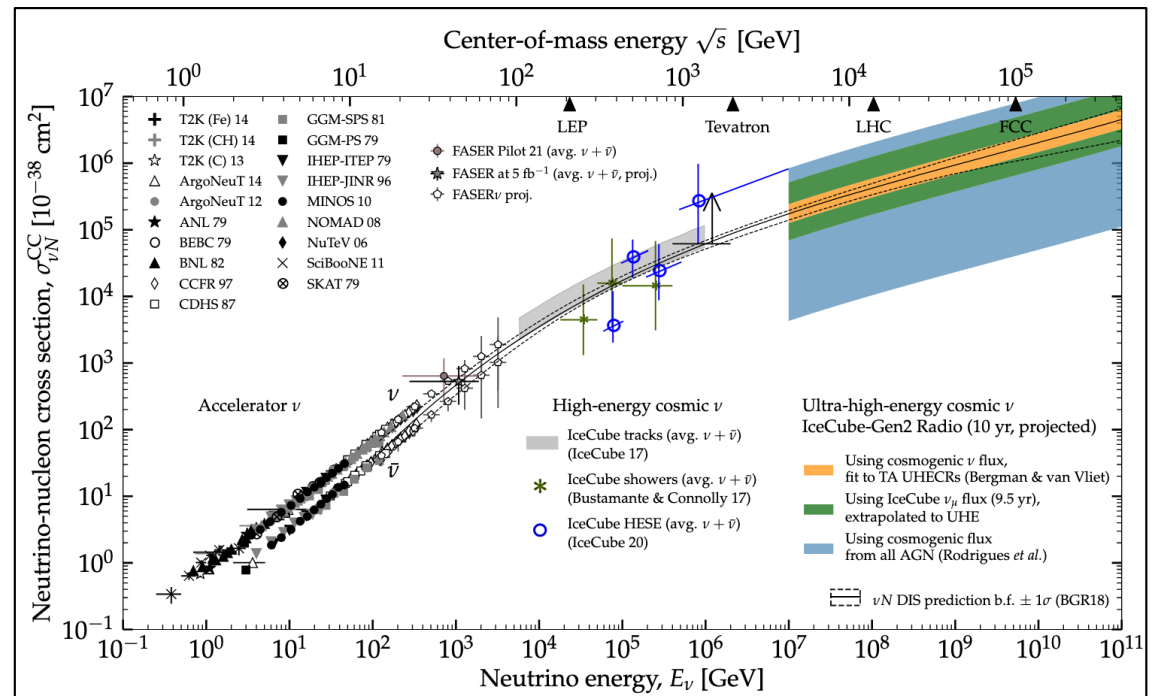
- Could these models connect TeV-scale physics to string theory? Could they solve the electroweak hierarchy problem?

Some Context

- Its worth appreciating that, at the time, very few people were thinking about using high-energy neutrinos to test physics beyond the Standard Model
- There had been quite a few papers written about searching for neutrinos from the Sun or Earth produced through the process of dark matter annihilation, but very little had been written about other tests of new physics
- My question to Tao was just one very naïve question among many I asked him that day – most of those questions were obviously uninformed, and they would have led only to dead ends
- Despite that, Tao took my questions seriously, and when I (eventually) asked a good one, he recognized it for its possibilities
- I'd like to think that I'd be as openminded and patient with my students as Tao was with me, but that's a very high bar to meet

Interactions of High-Energy Neutrinos

- IceCube is a particle detector that uses naturally-occurring particle accelerators (the 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 well beyond the reach of existing accelerators

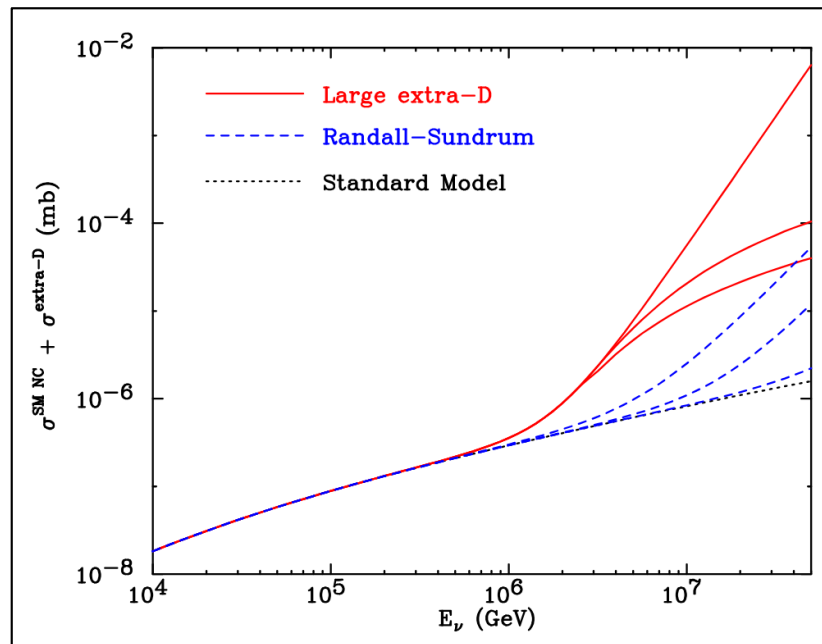


Interactions of High-Energy Neutrinos

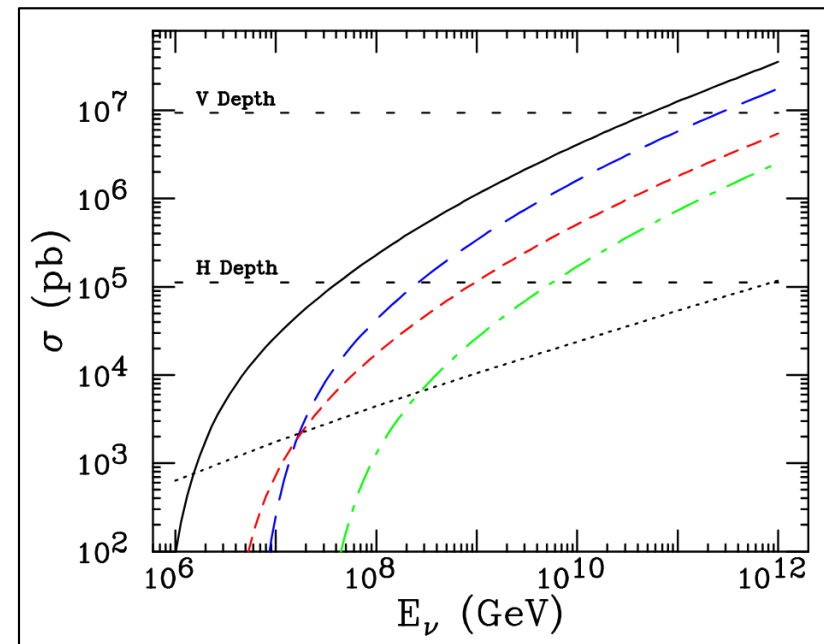
- What could cause the neutrino-nucleon cross section to be significantly different than that predicted by the SM at ultra-high energies?
- In general terms, neutrino telescopes are sensitive to new strong dynamics, involving new heavy particles with large couplings
- Such interactions are also sensitive 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, gravity can 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)

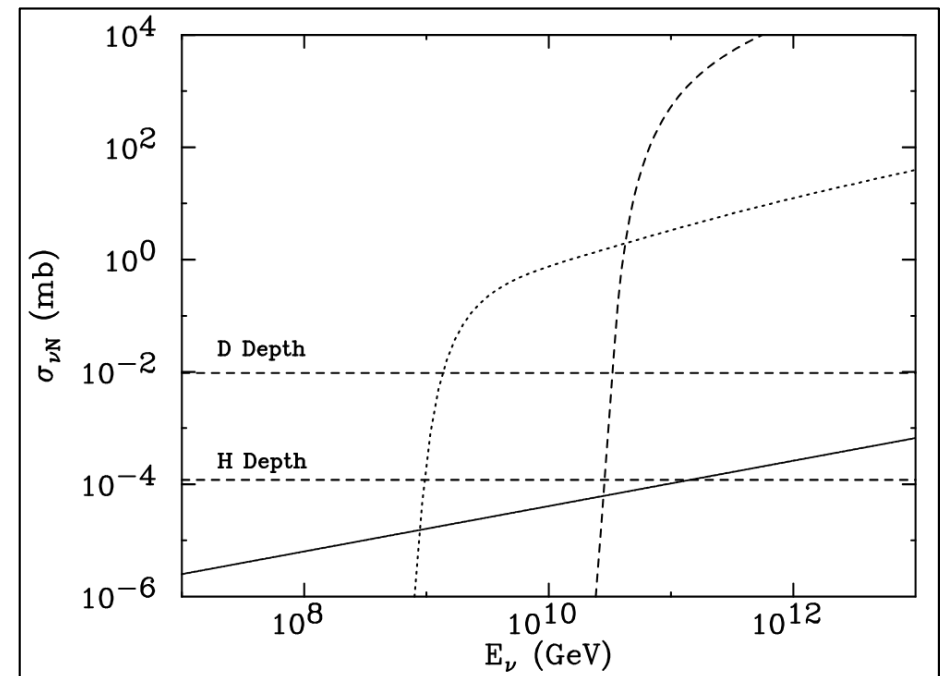
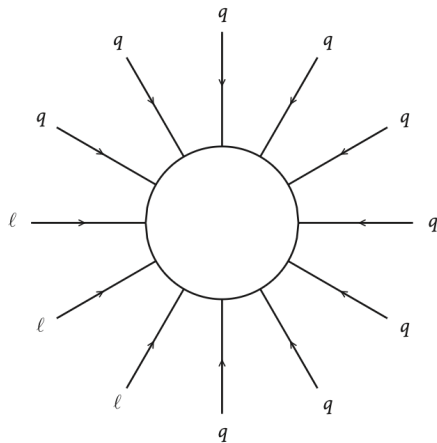
Alvarez-Muniz, Halzen, Han, DH, PRL, hep-ph/0107057

Alvarez-Muniz, Feng, Halzen, Han, DH, PRD, hep-ph/0202081

Electroweak Instantons

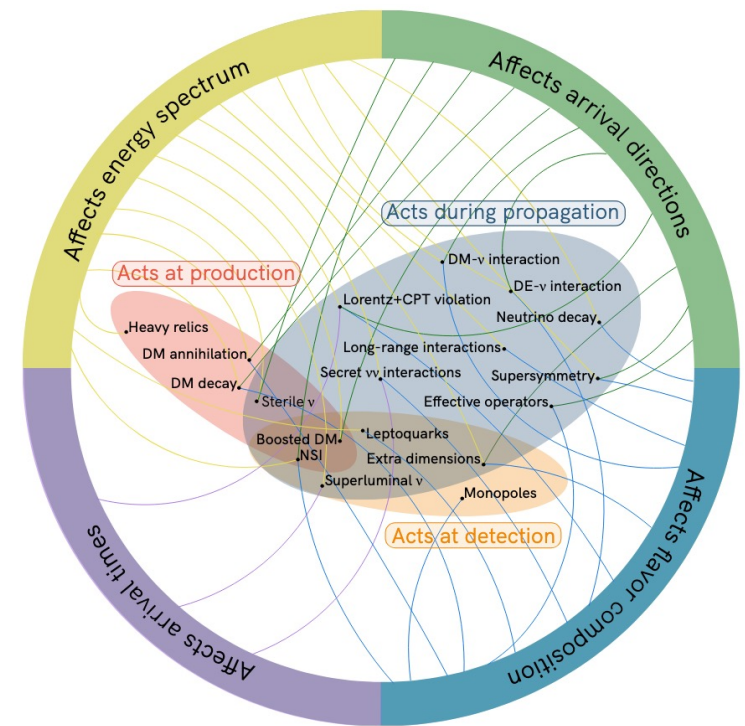
- Standard Model electroweak instantons represent tunnelling between topologically inequivalent vacua, allowing for processes that can change the total baryon-plus-lepton number
- Such processes are exponentially suppressed at $E < E_{\text{sph}} \sim \frac{\pi M_W}{\alpha_W} \sim 10 \text{ TeV}$, but above this scale, the cross sections for such process could be 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

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



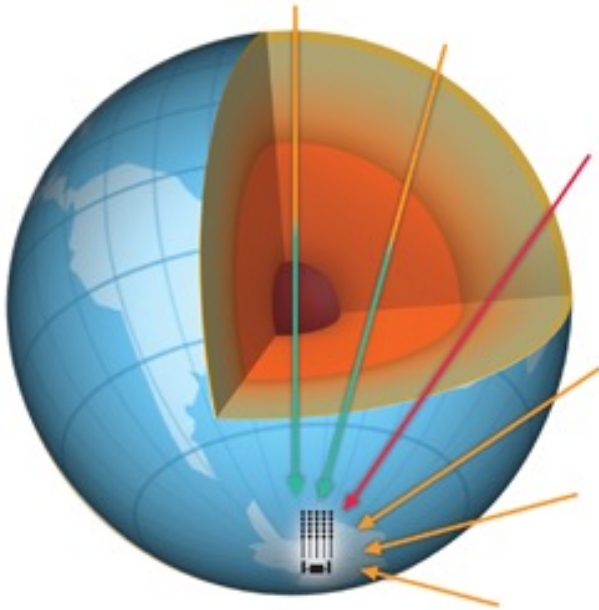
High-Energy Neutrinos as a Probe of Fundamental Physics

- Neutrino telescopes allow us to measure the interactions of particles 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

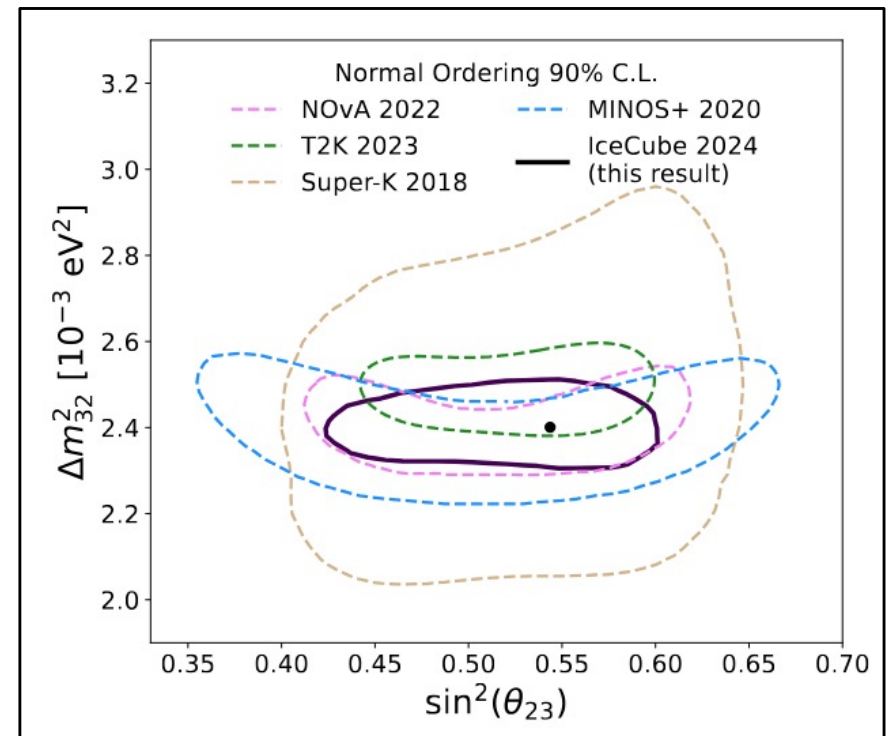


Neutrino Oscillations

- At $\sim 5\text{-}100$ 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 $P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



- This enables IceCube/DeepCore (and soon the IceCube Upgrade) to precisely measure $\sin \theta_{23}$ and Δm_{32}^2

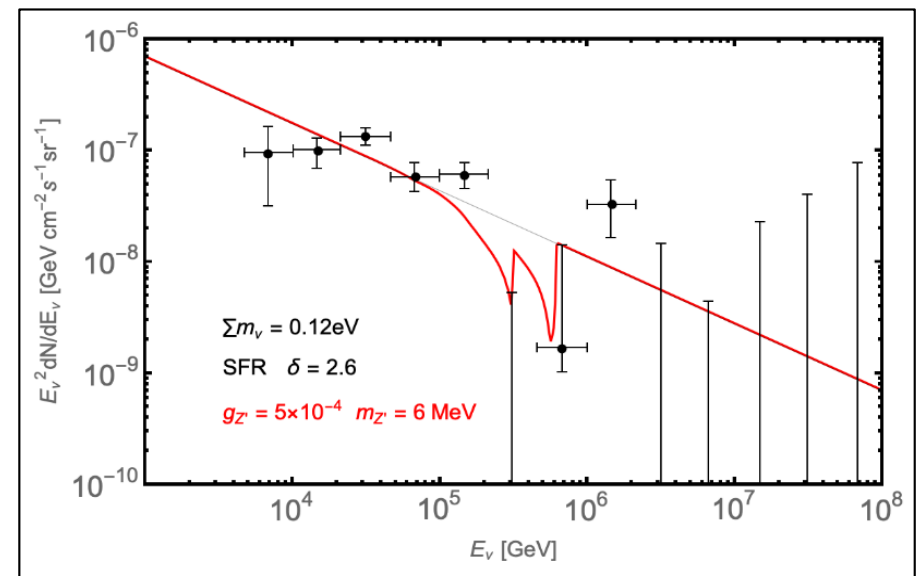


New Light Gauge Bosons

- Consider a light Z' with a small gauge coupling to muons (and muon neutrinos)
- 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:

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

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



DH, Iguaz, Serpico, arXiv:2302.03571

DiFranzo, DH, arXiv:1507.03015

DH, arXiv:0701194

Neutrino Flavor Ratios

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$

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

- 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

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

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

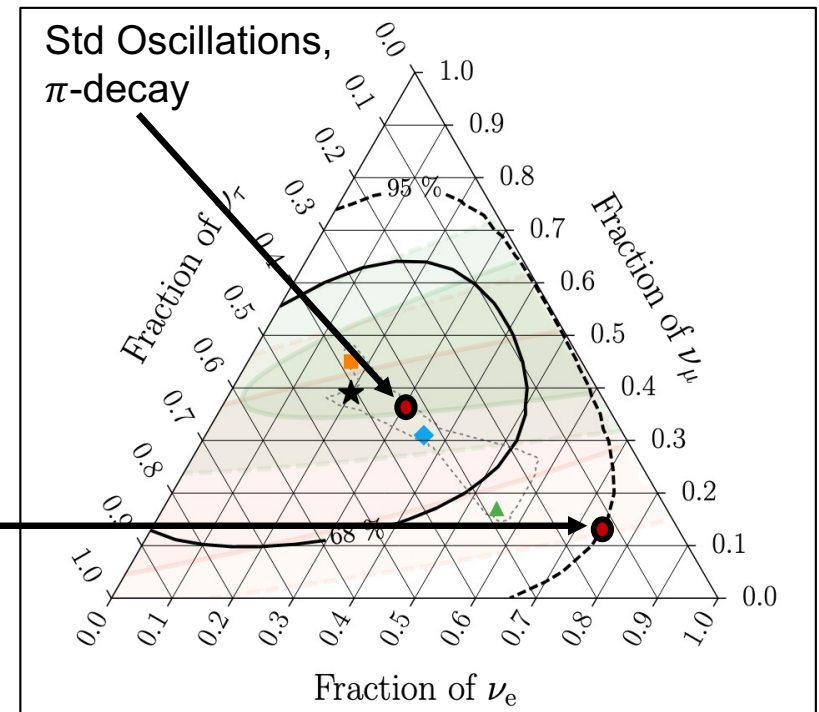
- Physics beyond the Standard Model could alter this prediction

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
- IceCube can already probe (at $\sim 2\sigma$) the most extreme of these scenarios
- IceCube-Gen2 is expected to improve these constraints by several orders of magnitude, to roughly $\tau_\nu > 10^4 s$

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	$B_{3 \rightarrow 2} = 1$	1.4 : 1 : 1
	degraded ($\alpha = 2$)		1.6 : 1 : 1
ν_3	full energy	$B_{3 \rightarrow 1} = 1$	2.8 : 1 : 1
	degraded ($\alpha = 2$)		2.4 : 1 : 1
ν_3	anything	$B_{3 \rightarrow 1} = 0.5$	2 : 1 : 1
		$B_{3 \rightarrow 2} = 0.5$	



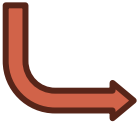
IceCube, arXiv:2011.03561

Tests of Quantum Gravity

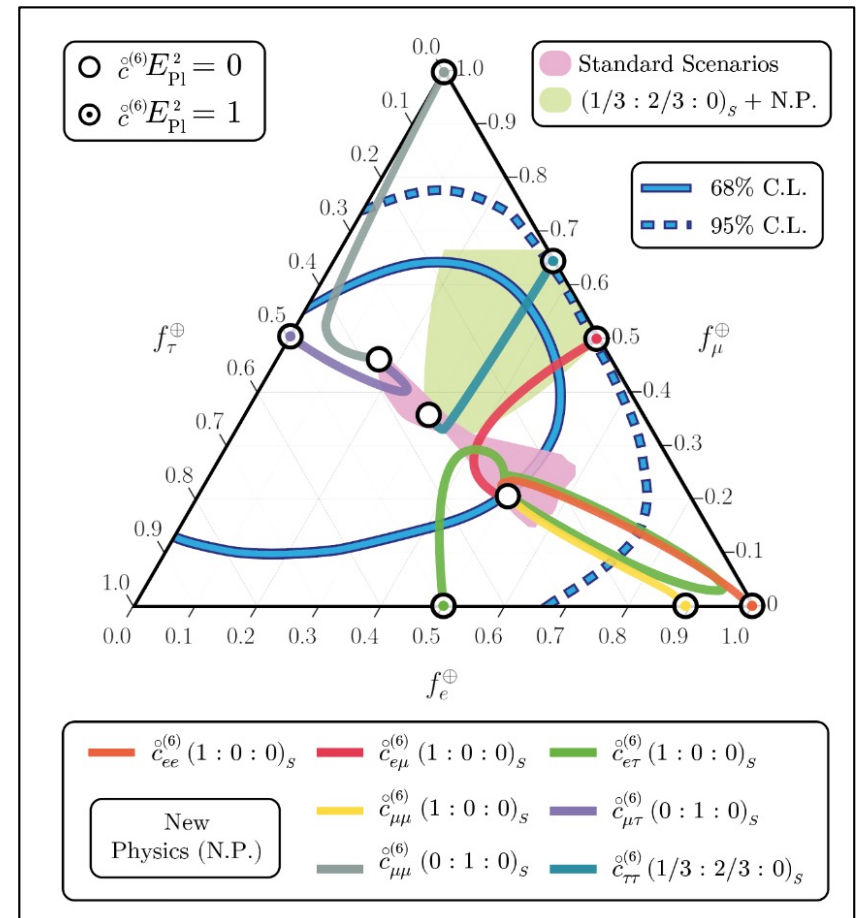
- Over cosmological baselines, the effects of quantum gravity (potentially including quantum decoherence, Lorentz violation, or even CPT violation) could lead to observable changes in the flavor ratios of the neutrinos that reach Earth
- In some models of quantum gravity, the universe is filled with 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

Tests of 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 are 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 $\sim 10^{-4} M_{Pl}^2$



$$H \sim \frac{m^2}{2E} - E^3 \cdot \dot{c}^{(6)}$$



DH, Morgan, Winstanley (2004, 2005)

IceCube, arXiv:2111.04654, 2308.00105

Summary

- As a graduate student, my interactions with Tao led me down a path of research that would shape much of my future career
- I would be a very different physicist today if it had not been for Tao
- Tao and I wrote six papers together (between 2001-2005), but what I learned from those interactions lead me to write many more papers in the years and decades that followed
- As a mentor and advisor to students and postdocs today, I strive to be as available, as openminded, and as patient as Tao was with me – *I do not always live up to this lofty goal!*

Thank you, Tao for what you have done for me, and what you have done for the entire particle physics community!