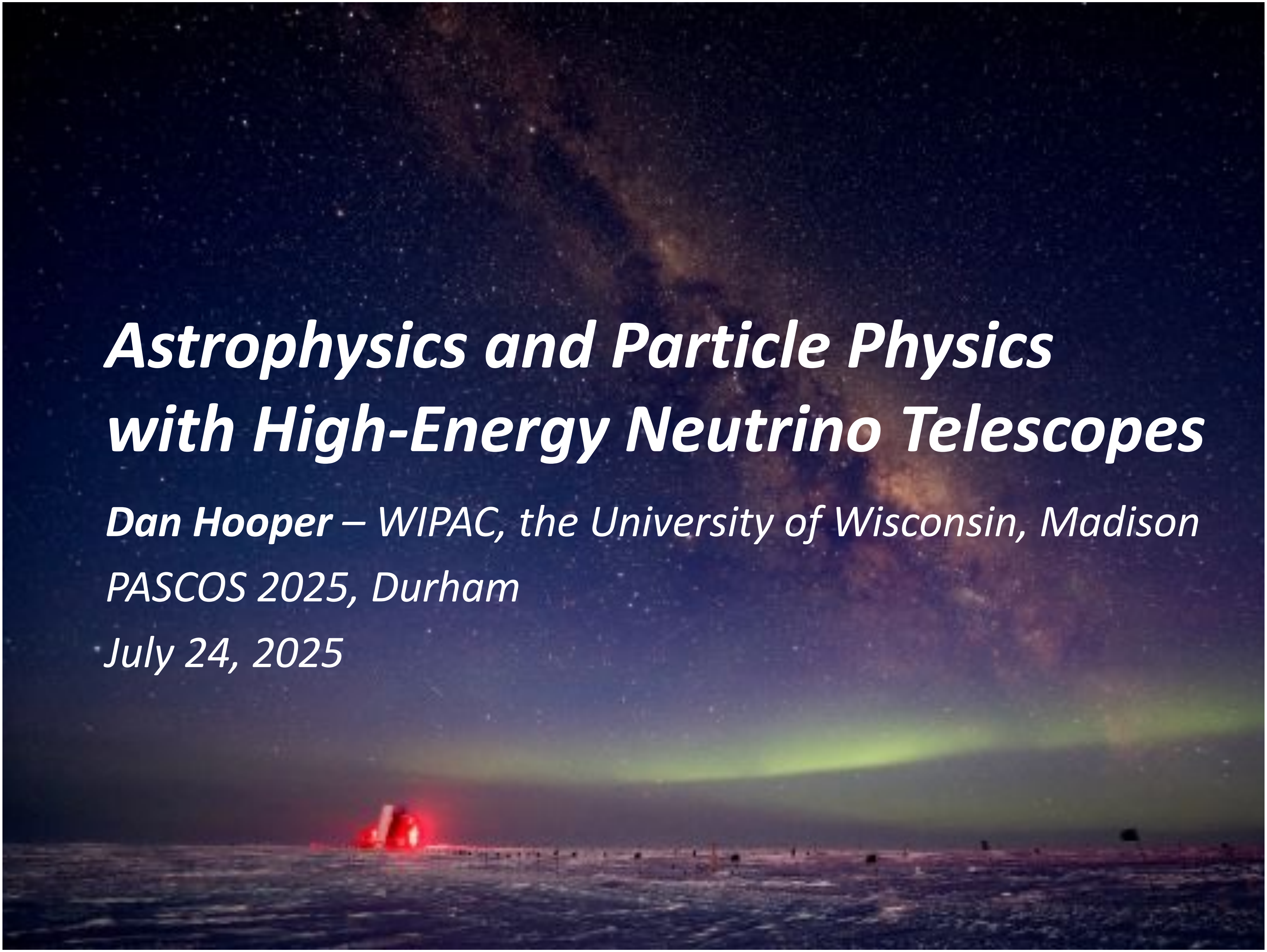

Astrophysics and Particle Physics with High-Energy Neutrino Telescopes

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PASCOS 2025, Durham

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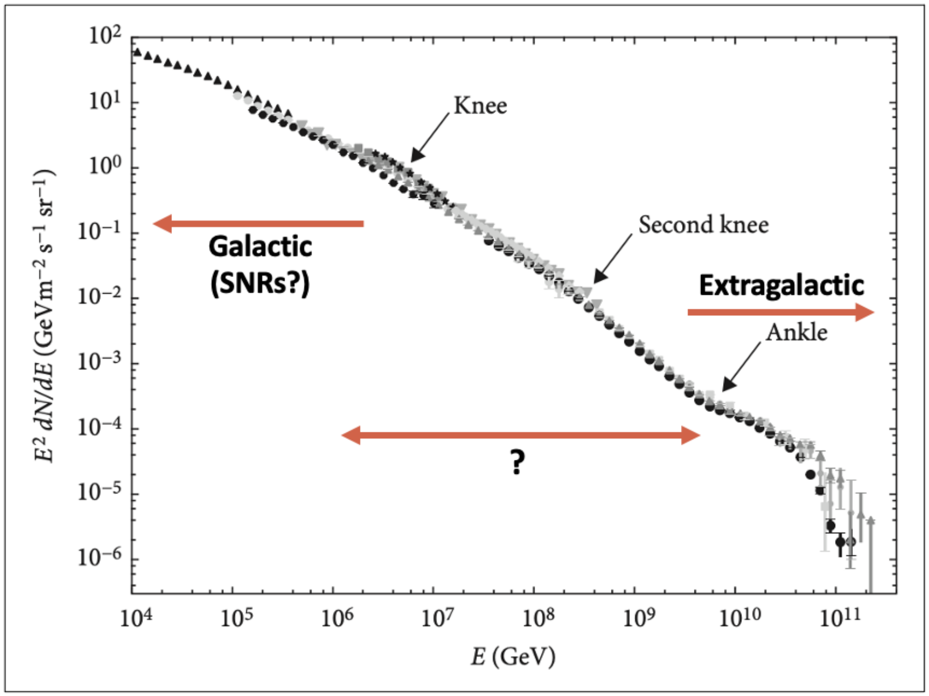
The Many Mysteries of Cosmic Rays

- Ever since they were discovered more than a century ago, cosmic rays have perplexed astronomers
- Today, we still lack answers to the most central of these questions:

-Where do cosmic rays come from?

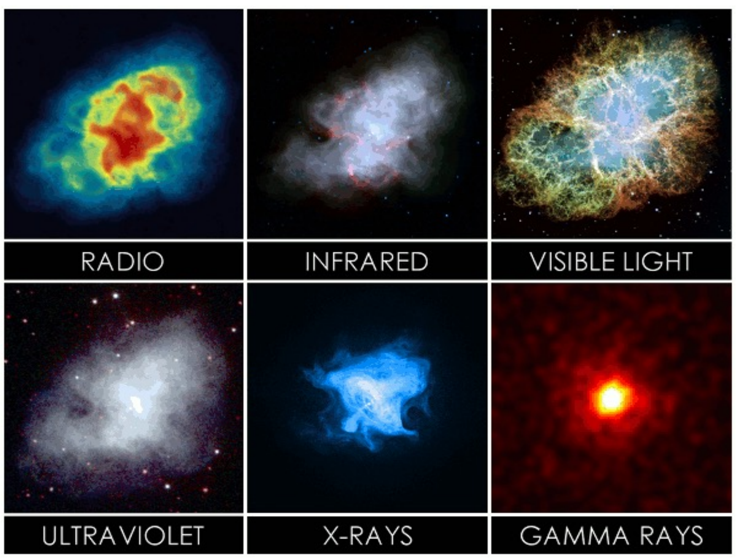
-How are these particles accelerated?

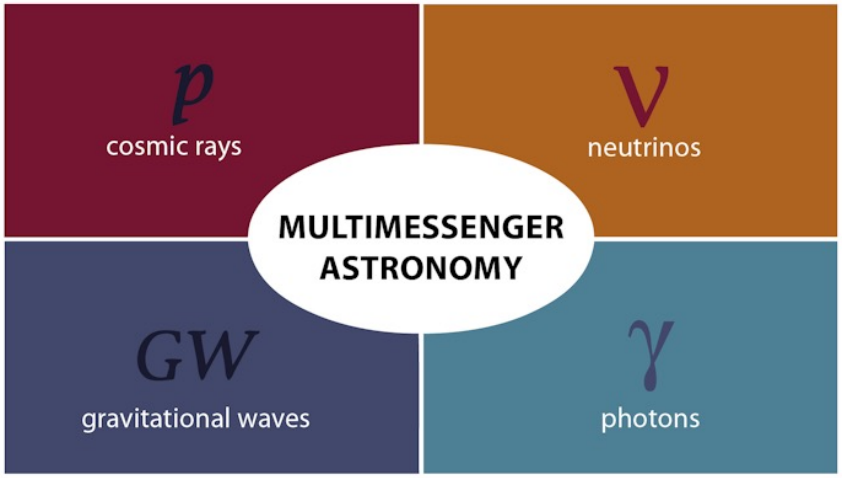


Victor Hess, preparing to measure cosmic rays from a balloon in 1911

Multi-Messenger Astrophysics

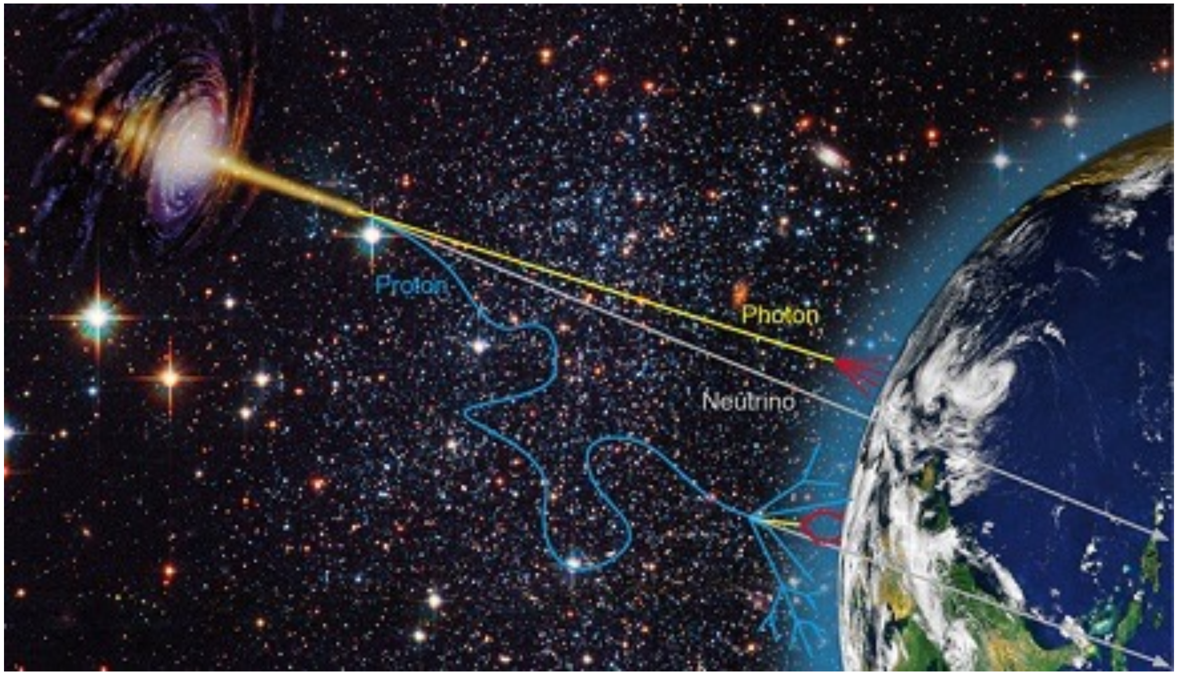
- Up until the middle of the 20th century, all of astronomy was conducted using visible light; these photons carry only a tiny fraction of the total information that reaches us from throughout the universe
- Astronomers have since developed ways of detecting and studying light at IR/UV/radio/X-ray/gamma-ray wavelengths
- Modern astronomy makes use not only of light, but other cosmic messengers, including cosmic rays, neutrinos, and gravitational waves, each of which provides us with different kinds of complementary information





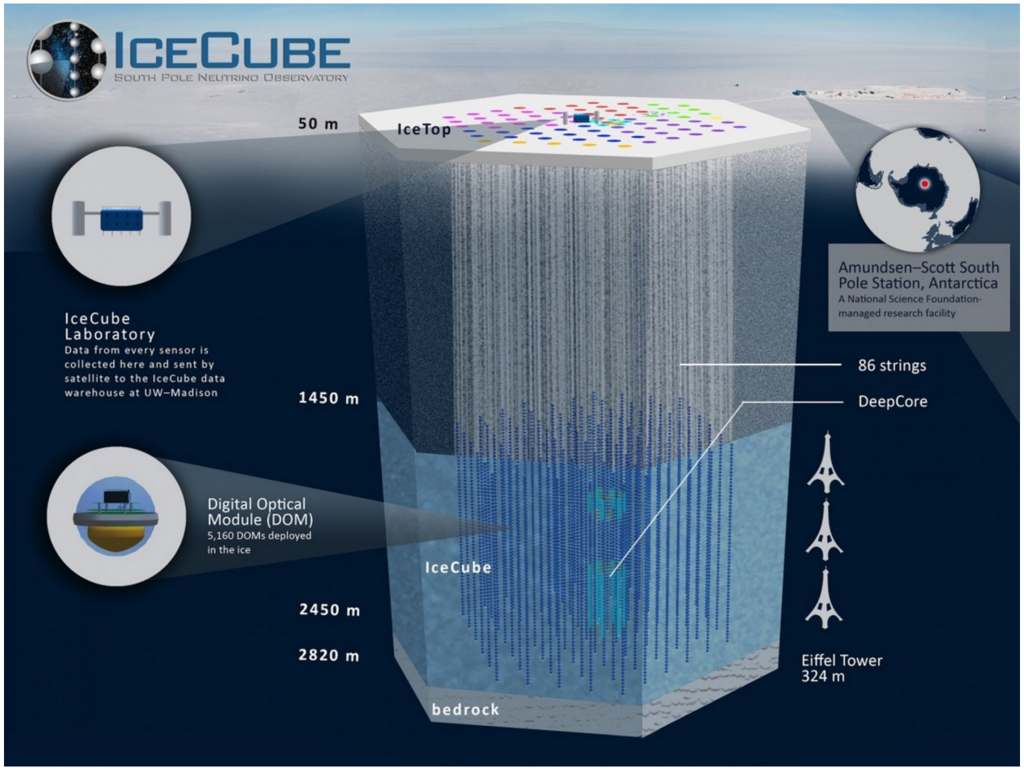
The Neutrino/Gamma Ray/Cosmic Ray Connection

- Cosmic rays are deflected by magnetic fields, concealing their origin
- Cosmic rays scatter with gas and radiation, however, photons and neutrinos which point in the direction of their sources
- High-energy gamma rays are produced through both hadronic and leptonic mechanisms, and are efficiently attenuated over cosmological distances
- In contrast, high-energy neutrinos are only produced through hadronic interactions, and are not significantly attenuated → for these reasons, neutrinos are the essential to identifying the origin of the cosmic ray spectrum

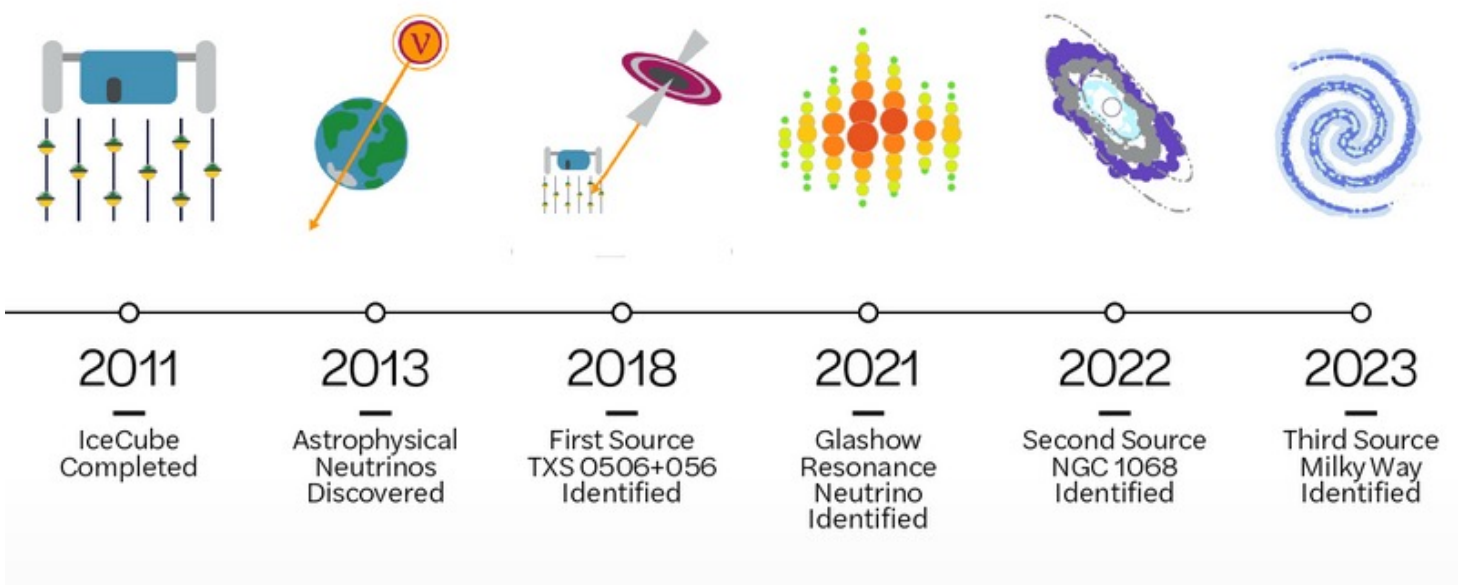


Neutrino Telescopes

- The flagship telescope in the field of high-energy neutrino astronomy is IceCube, located at the South Pole (KM3NeT is also under construction in the Mediterranean)
- IceCube consists of ~5000 optical modules connected to vertical strings distributed throughout ~1 km^3 of Antarctic ice
- IceCube detects muon tracks from charged current ν_μ events, showers from both charged and neutral current neutrino events, and events that are unique to PeV-scale ν_τ's (double bangs, lollipops)
- IceCube is sensitive to neutrinos with energies between the GeV- and EeV-scale
- At even higher energies, radio-based techniques (including ARA, RNO-G) are promising, but so far have not detected any neutrinos

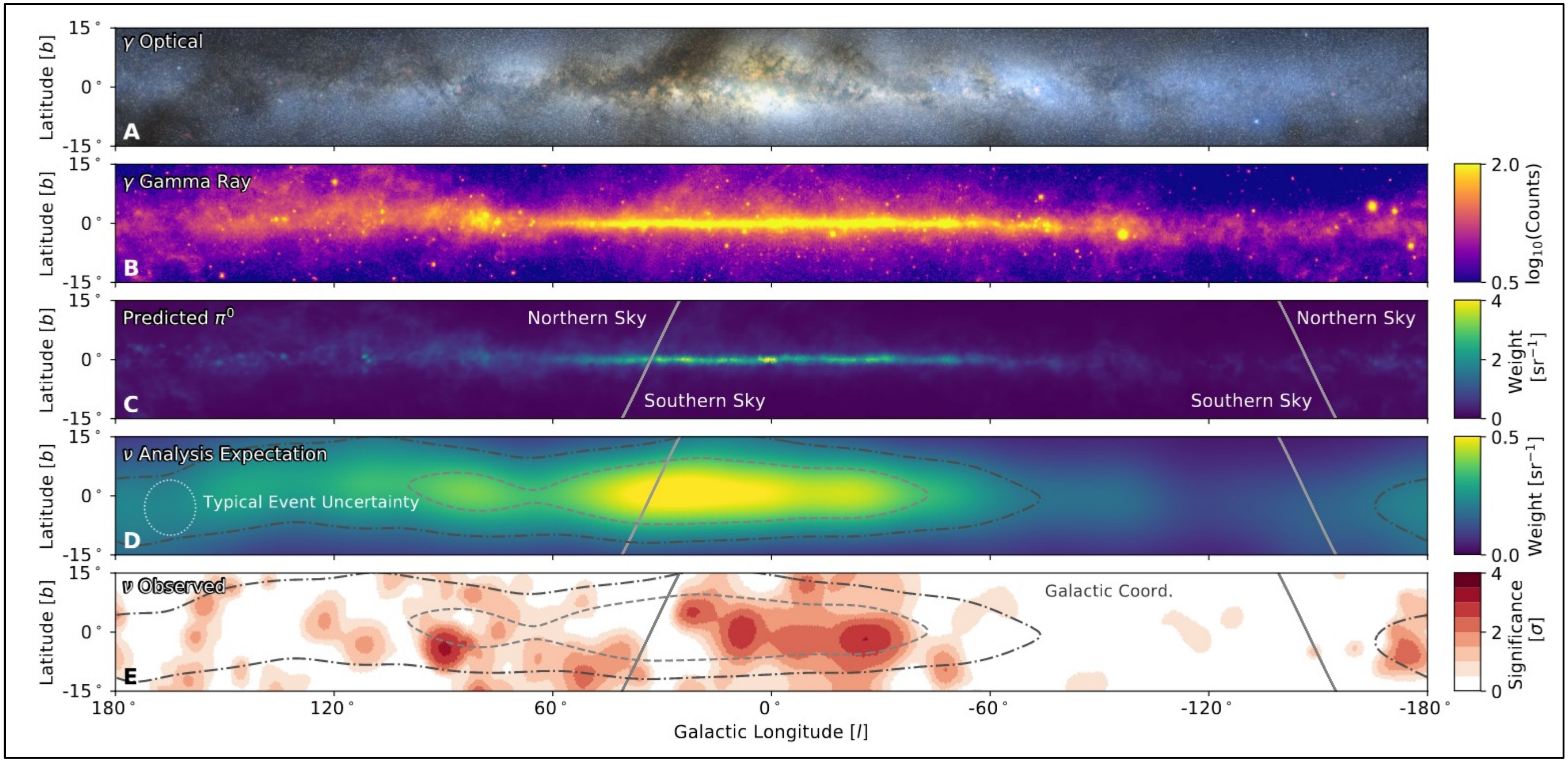


Some Highlights From IceCube



High-Energy Neutrinos From the Galactic Plane

- IceCube has detected a flux of ~1-100 TeV neutrinos from the Galactic Plane, with a significance of 4.5σ



IceCube, *Science*, 2307.04427

High-Energy Neutrinos From the Galactic Plane

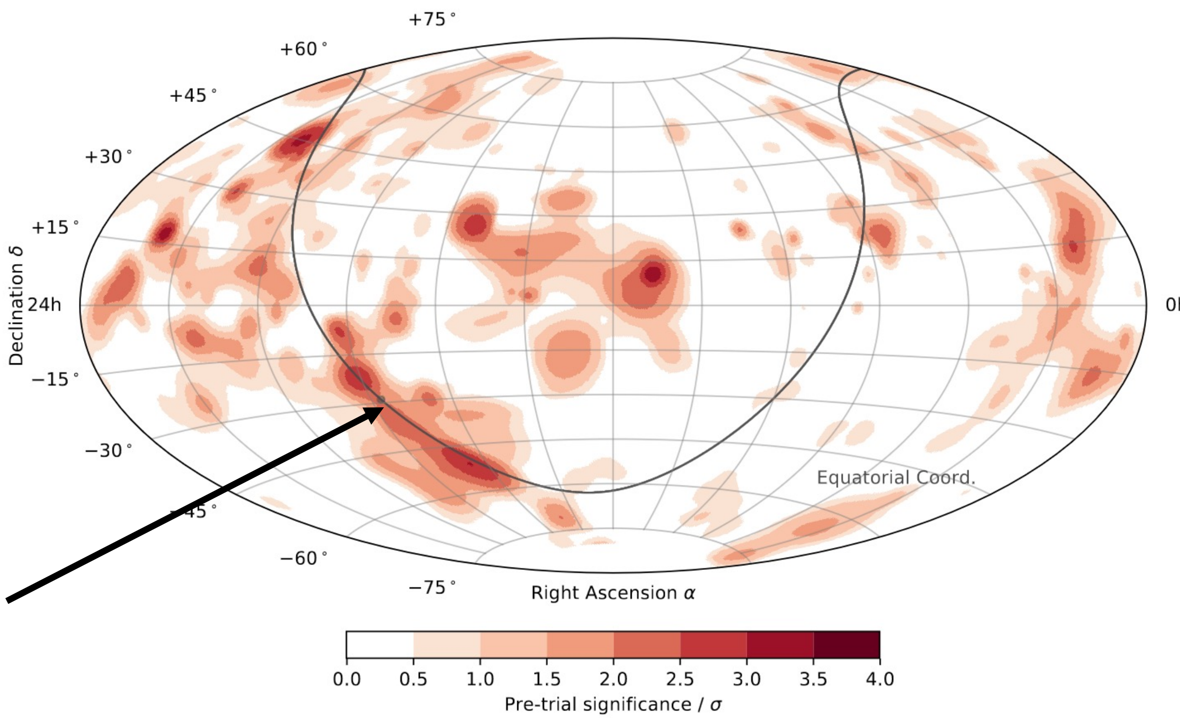
- What is the origin (or more likely, origins) of these neutrinos?

  -Cosmic rays scattering with gas in the ISM?

  -Cosmic ray accelerators? (supernova remnants, pulsar wind nebulae,…)

High-Energy Neutrinos From the Galactic Plane

- What is the origin (or more likely, origins) of these neutrinos?
  - -Cosmic rays scattering with gas in the ISM?
  - -Cosmic ray accelerators? (supernova remnants, pulsar wind nebulae,…)
- There are some hints of individual neutrino point sources along the Galactic Plane, but with a statistical significance that does not overcome the trials factor
- Catalog stacking analyses (SNR, PWN) yield ~3.2σ, but the data is also consistent with arising entirely from diffuse processes in the Galactic Plane

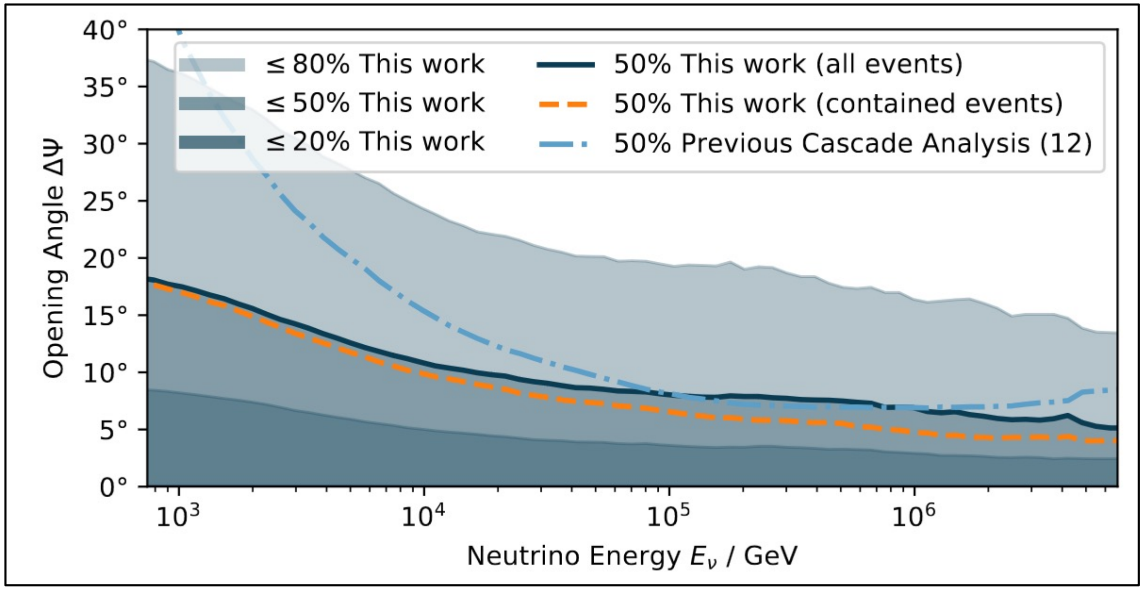


Galactic Plane

IceCube, 2307.04427

The Challenge of Resolving Galactic Neutrino Sources

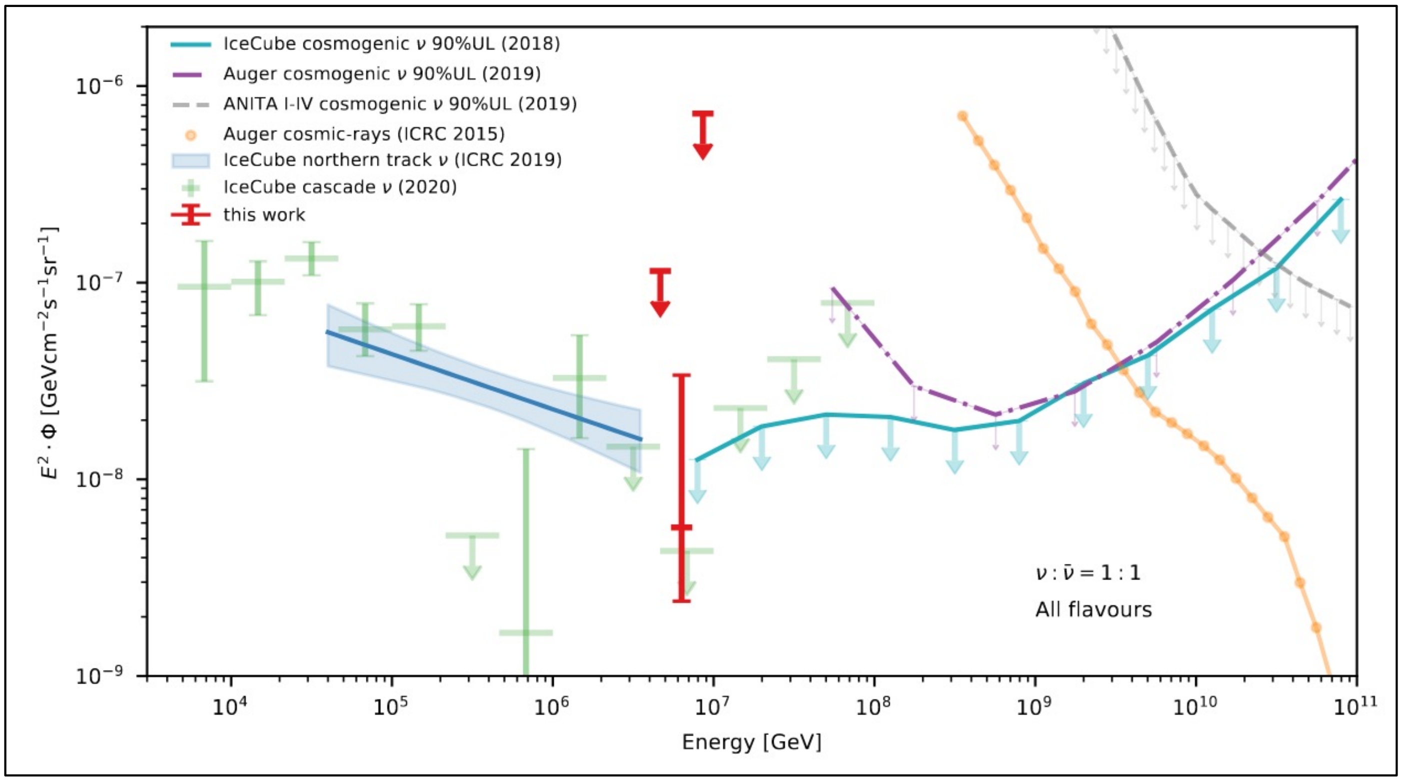
- The Galactic Plane (especially the Inner Galaxy) resides largely within the Southern sky, where cosmic-ray muon backgrounds are large for IceCube; this forces IceCube to rely on cascades and contained muon tracks
- At ~TeV-scale energies, the background from atmospheric neutrinos is large, limiting the utility of contained muons
- Compared to tracks, cascades have poor angular resolution (although this has been mitigated by machine learning techniques); this makes it challenging to resolve individual sources that might produce the neutrino emission observed from the Galactic Plane



IceCube, 2307.04427

High-Energy Extragalactic Neutrinos

- IceCube has measured a diffuse and approximately isotropic spectrum of astrophysical neutrinos, extending between ~10 TeV and (at least) ~10 PeV
- The origins of these particles remain unknown, but they are almost certainly produced by sources of high-energy cosmic rays



IceCube, arXiv:2110.15051

From the Cosmic Ray Spectrum to the High-Energy Neutrino Spectrum

- Back in the late 1990s, Waxman and Bahcall presented an argument that allowed them to use the observed cosmic-ray spectrum to estimate the flux of high-energy neutrinos that would be produced by the same sources
- For optically-thin sources (those with little absorption), this estimate is given as follows:

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = \int E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}(z)\, \epsilon\, f_{\pi^\pm} f_\nu \frac{c}{4\pi} \frac{dt}{dz} \frac{dz}{(1+z)}$$

The fraction of energy in CRs that goes into π's

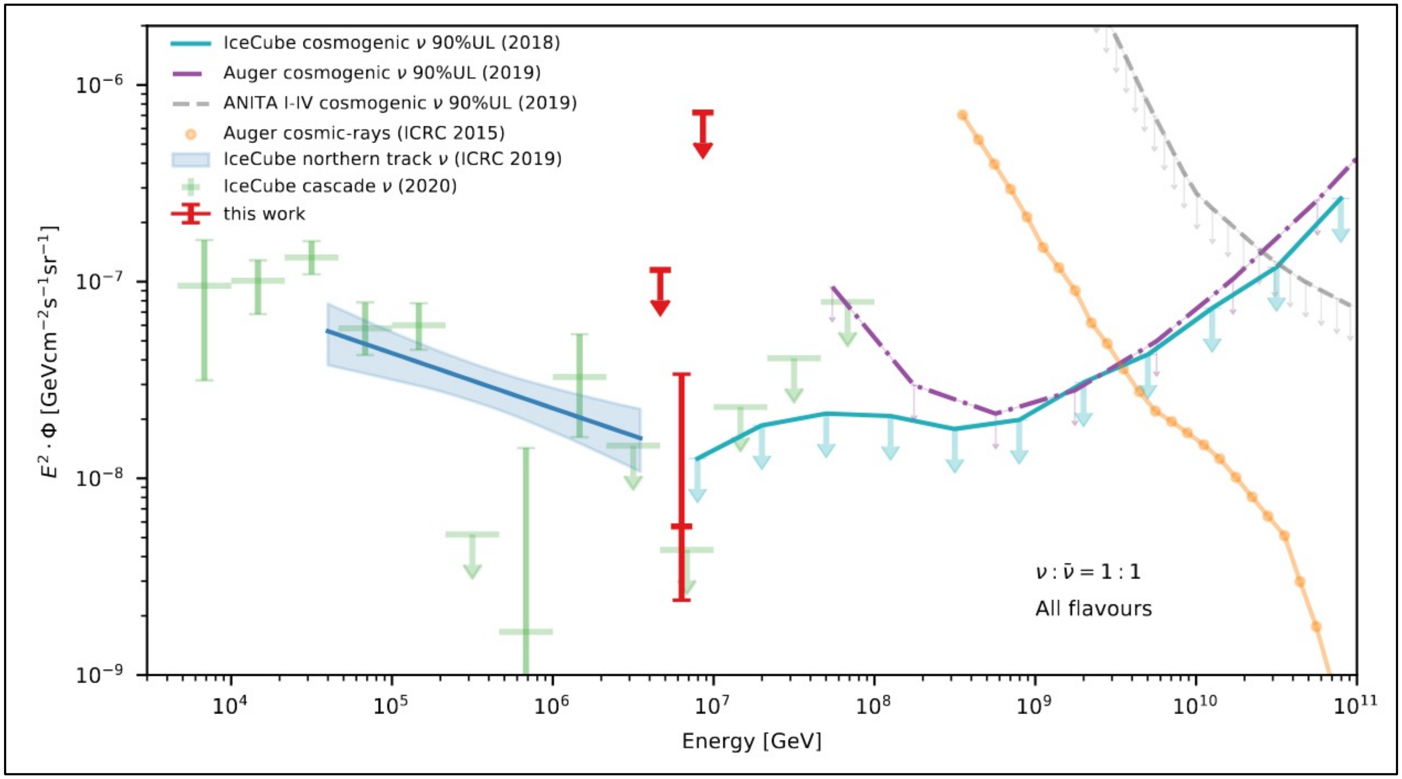
$f_{\pi^\pm} \sim \frac{1}{2}, \frac{2}{3}$

$f_\nu \sim \frac{3}{4}$

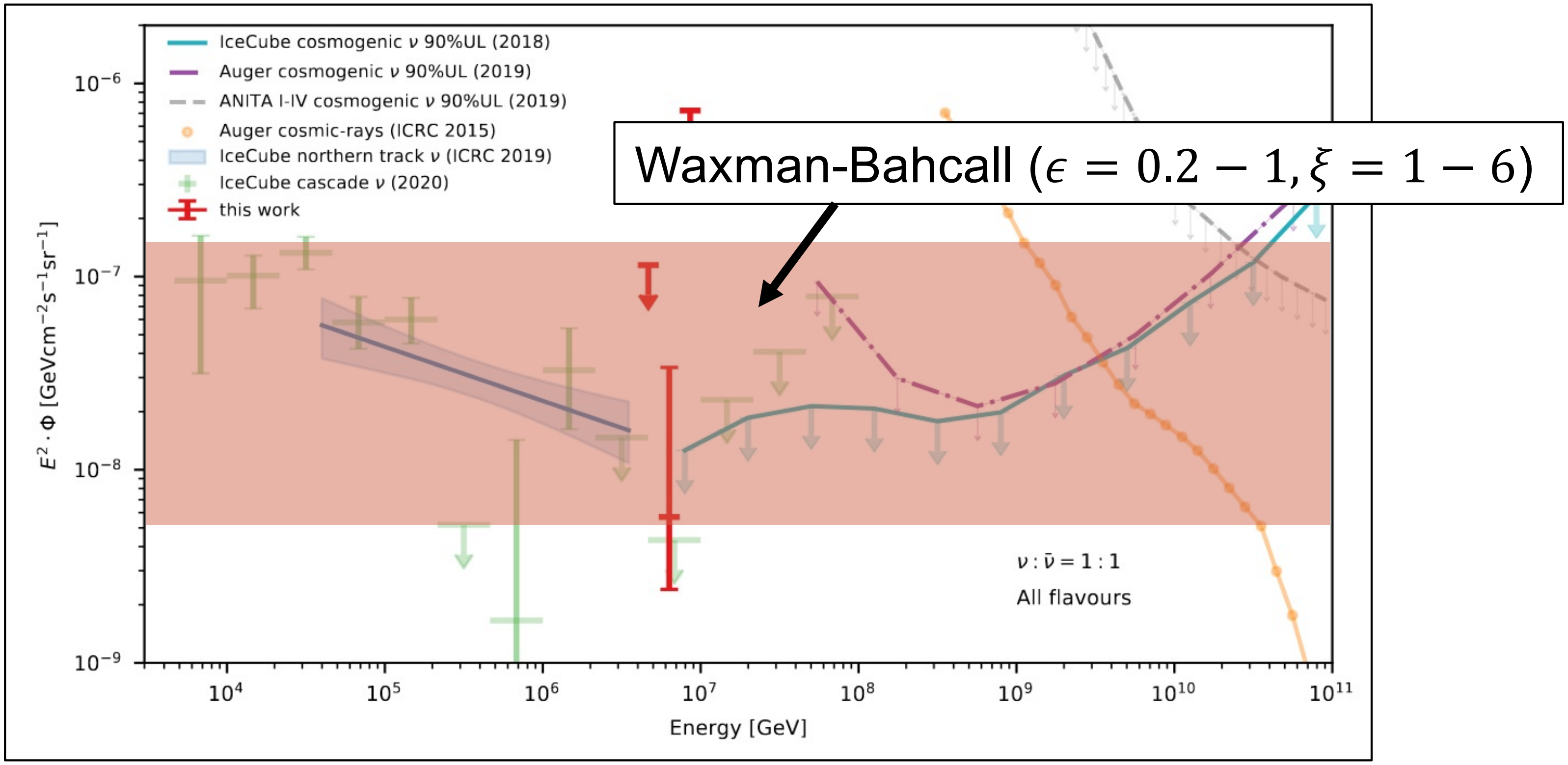
$\xi \sim 1-6$ (for realistic z distributions)

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx 2.5 \times 10^{-8}\, {\rm GeV/cm^2/s/sr} \times \left(\frac{\epsilon}{1}\right)\left(\frac{f_{\pi^\pm}}{0.5}\right)\left(\frac{\xi}{1}\right)$$

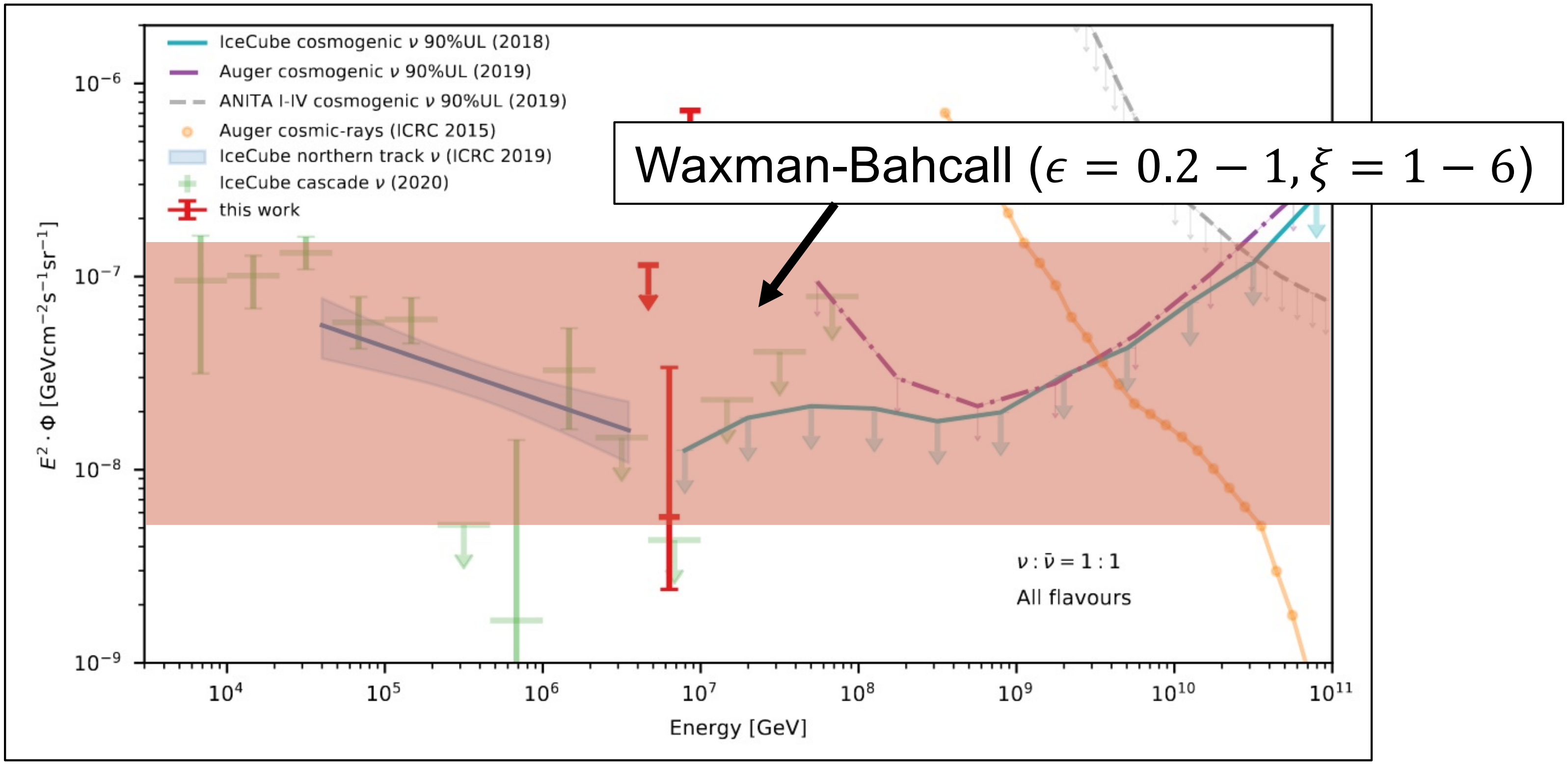
IceCube's High-Energy Neutrinos



IceCube's High-Energy Neutrinos



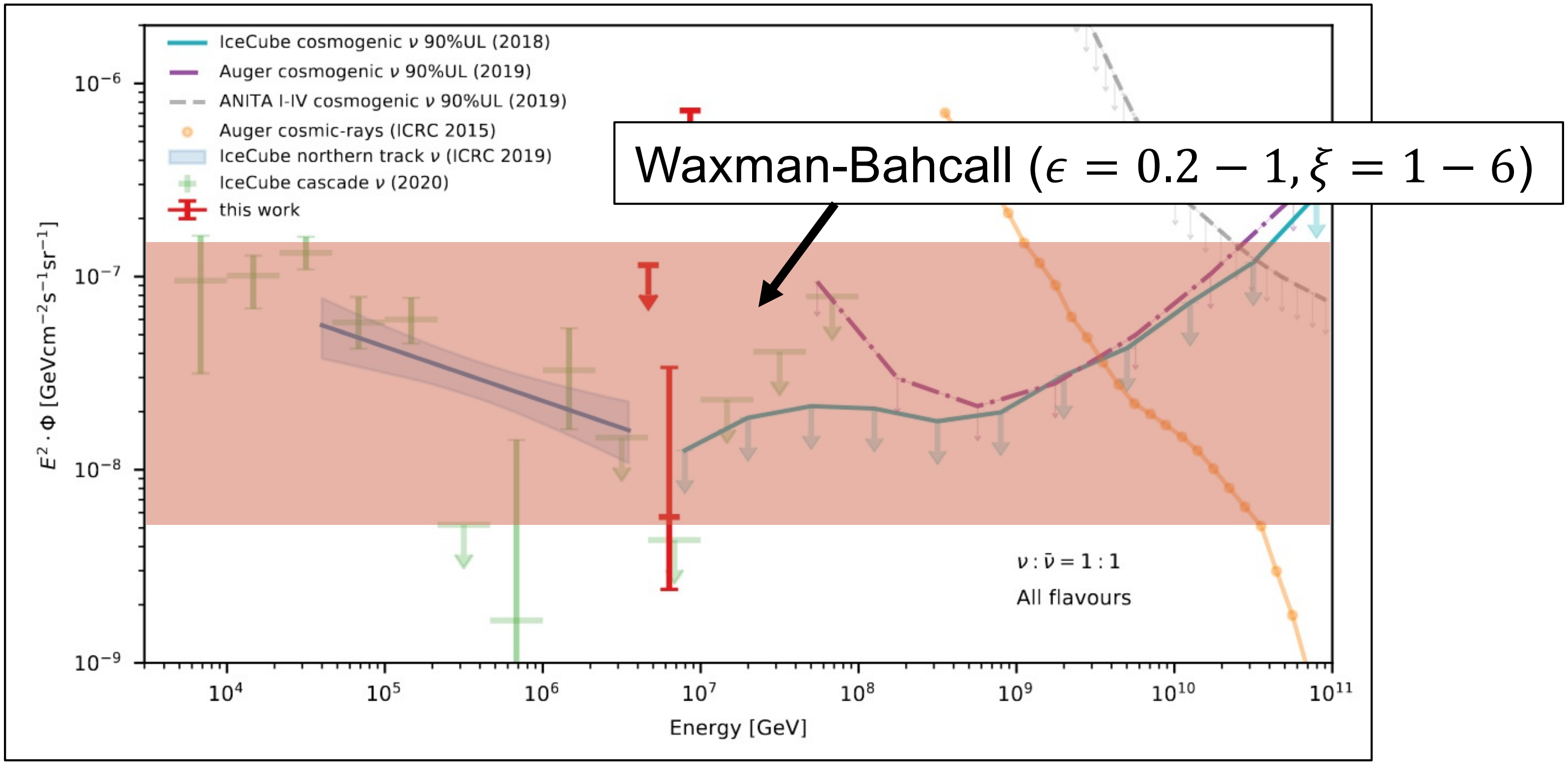
IceCube's High-Energy Neutrinos



This result leaves us with two possible interpretations:

1) IceCube's neutrinos might come from the sources of the high-energy cosmic rays (those sources must then have an average optical depth of $\epsilon \sim 0.2 - 1$)

IceCube's High-Energy Neutrinos



This result leaves us with two possible interpretations:

1) IceCube's neutrinos might come from the sources of the high-energy cosmic rays (those sources must then have an average optical depth of $\epsilon \sim 0.2 - 1$)

2) IceCube's neutrinos might come from optically thick "hidden" sources, which absorb most of the cosmic rays and gamma rays that they produce

The Sources of IceCube's High-Energy Neutrinos

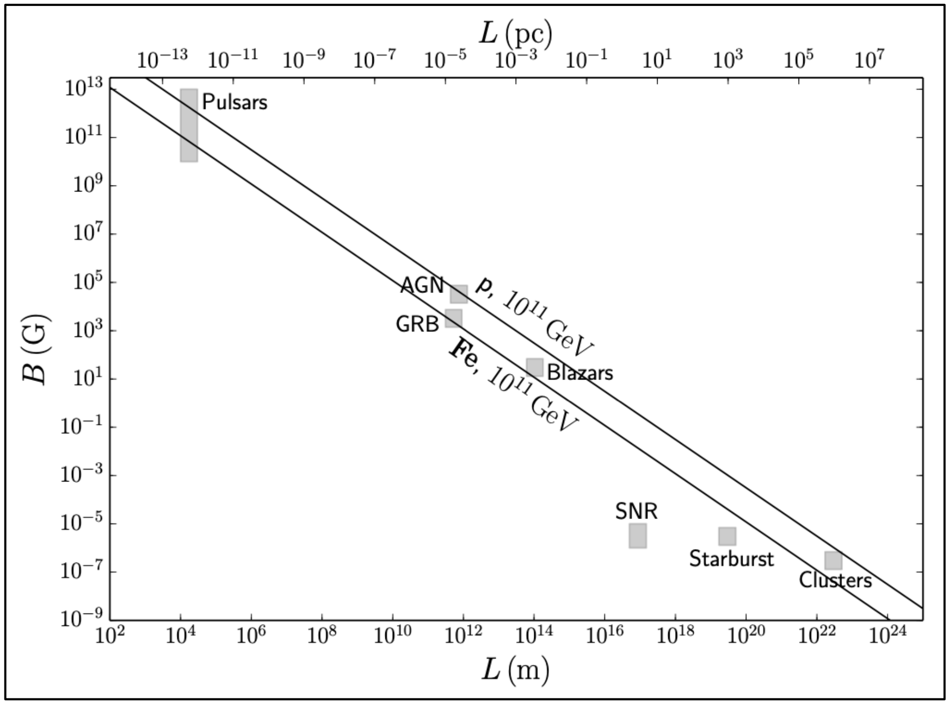
- The production of ~1-10 PeV neutrinos requires the acceleration of ~10^2 PeV protons
- There are not many astrophysical environments that are expected to be capable of accelerating particles to such high energies
- In light of this, there is a relatively short list of candidates for the sources of the highest-energy neutrinos detected by IceCube, including:

  -Gamma Ray Bursts

  -Blazars

  -Other Active Galactic Nuclei

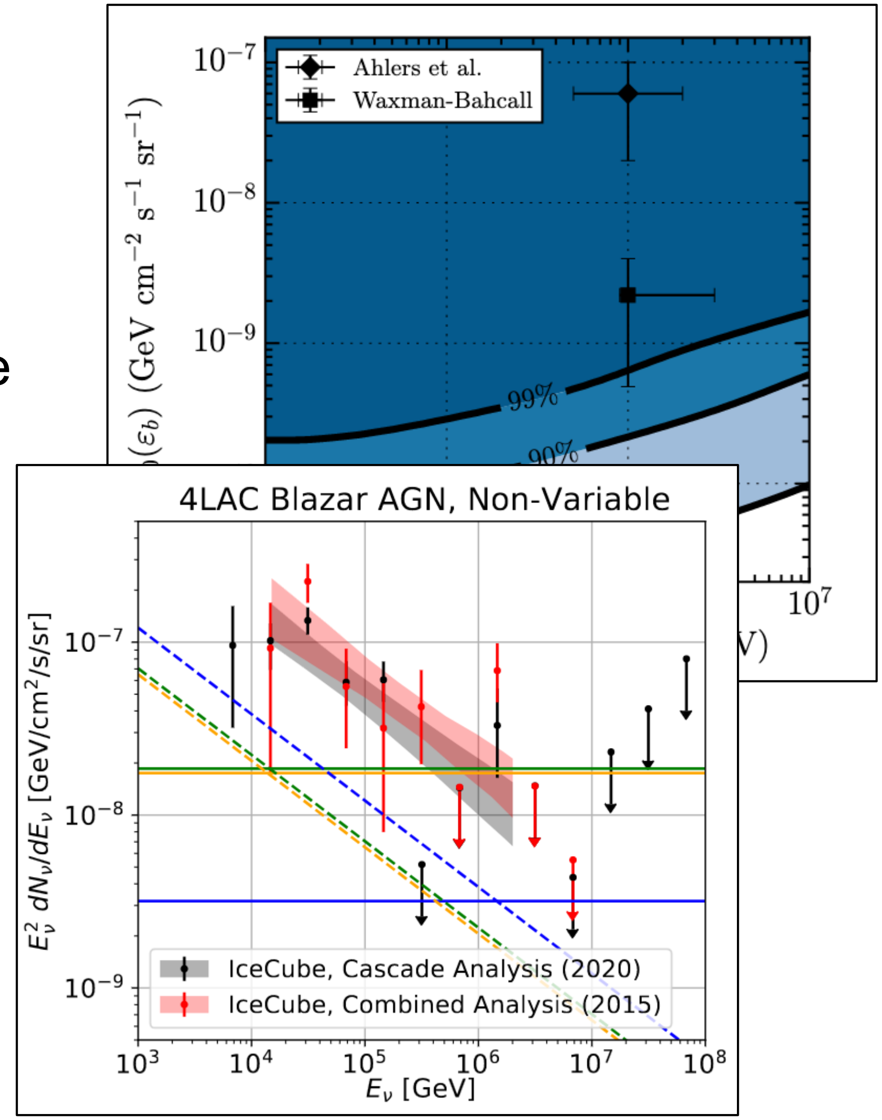
  -Star-Forming/Starburst Galaxies



Neutrinos From Gamma-Ray Bursts and Blazars

- Individual GRB are bright and brief, making it possible to search for neutrino events with very low backgrounds, yet no such events have been observed
- Blazars are relatively rare ($\sim 10^4$ in the observable universe), most of which have been detected in the gamma ray and/or radio bands; no correlations have been observed between blazar catalogs and the arrival directions of neutrinos

Conclusion: *GRB are blazars cannot produce most of IceCube's neutrino flux; whatever sources are responsible for these neutrinos must be less individually bright and more numerous*



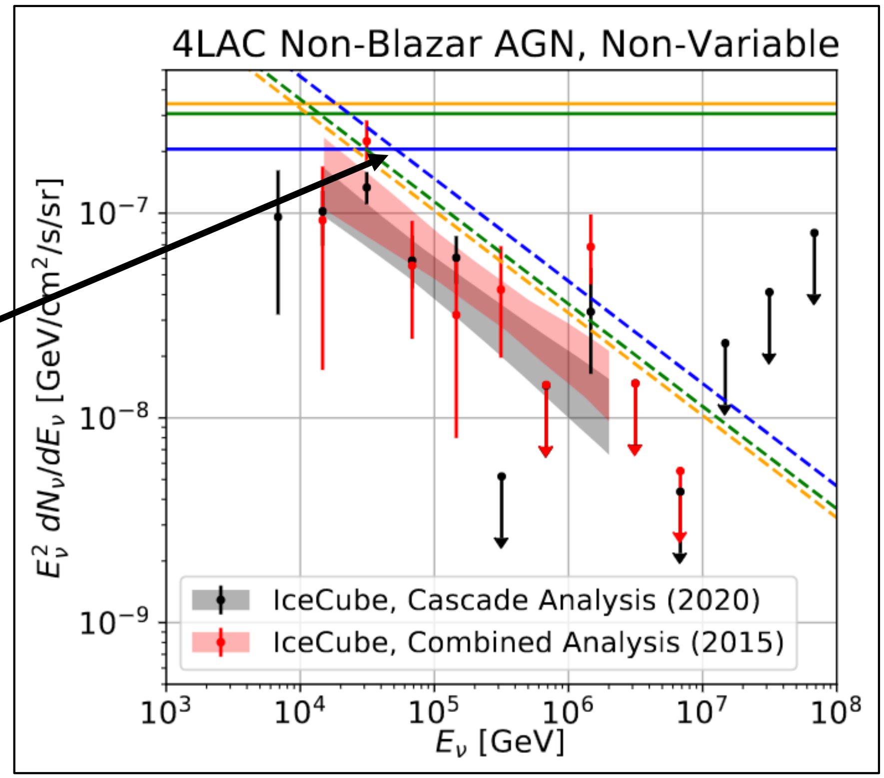
IceCube, 2205.11410, 1702.06868, 1601.06484, 1412.6510, 1204.4219
Smith, et al., 2007.12706, IceCube, 2304.12675, Kun et al., 2203.14780, Zhou et al., 2103.12813

Neutrinos from *Non-Blazar* AGN

- For every blazar, there are $\sim 10^4$ AGN, making it much more difficult to search for correlations between these objects and the arrival directions of individual neutrinos

Neutrinos from *Non-Blazar* AGN

- For every blazar, there are $\sim 10^4$ AGN, making it much more difficult to search for correlations between these objects and the arrival directions of individual neutrinos
- It remains plausible that AGN could generate the entire astrophysical neutrino flux observed by IceCube
- IceCube is currently approaching the level of sensitivity that would be needed to test this hypothesis

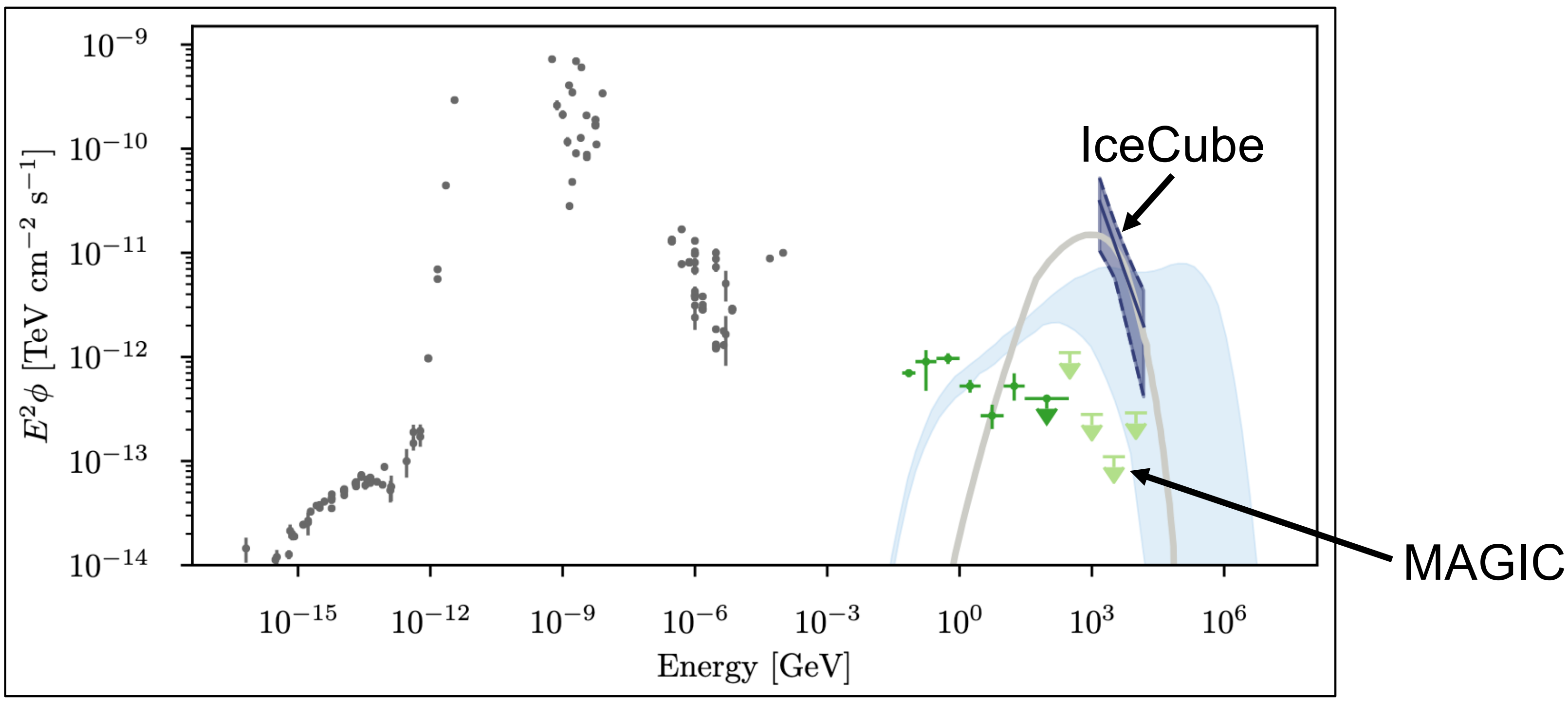


Smith, DH, Vieregg (2020)

IceCube, arXiv: 2304.12675, 1611.03874
Kun et al, 2203.14780
Zhou et al., 2103.12813

High-Energy Neutrinos From NGC 1068

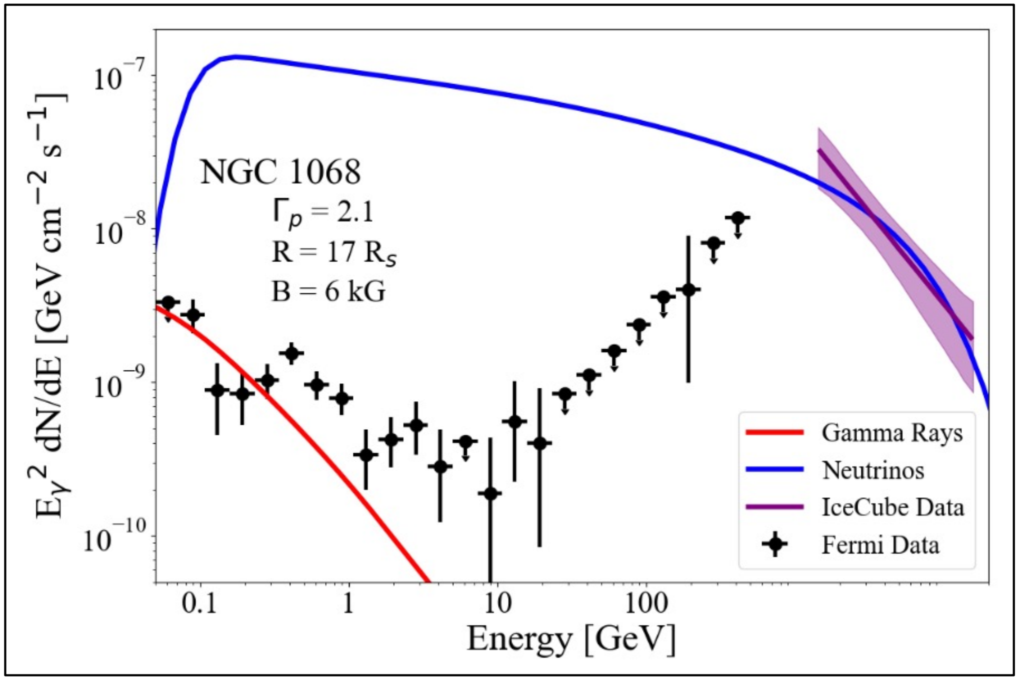
- In 2022, the IceCube Collaboration reported the detection of TeV-scale neutrinos from the direction of the nearby AGN, NGC 1068 (4.2σ, post-trials)
- Surprisingly, the flux of this neutrino emission is more than an order of magnitude greater than the gamma-ray flux
- This poses the question: If this source produces neutrinos through charged pions, where are the corresponding gamma rays from neutral pion decay?



IceCube, Science, 2211.09972

High-Energy Neutrinos From NGC 1068

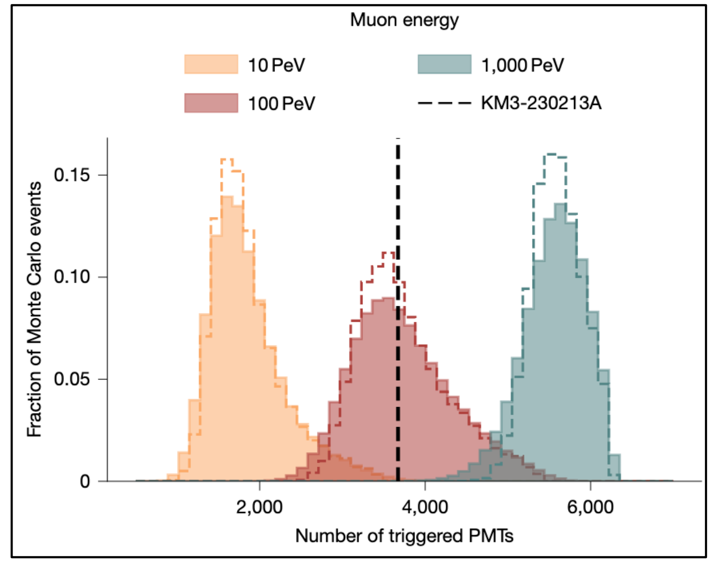
- For the TeV-scale gamma-rays to be absorbed enough to be consistent with the data, the protons that are responsible for these neutrinos must be accelerated within the dense and optically thick corona that surrounds NGC 1068's supermassive black hole → NGC 1068 is an example of a "hidden source"
- This requires rather large magnetic fields (B > 6 kG), and otherwise quite plausible physical conditions
- To normalize the observed neutrino flux requires there to be a similar luminosity in high-energy protons as in X-rays ($L_p \sim L_X$)
- This source will be a very exciting target for future MeV-scale gamma-ray telescopes (such as AMEGO-X, e-ASTROGAM)



Blanco, DH, Linden, Pinetti, arXiv:2307.03259

The Incredible KM3NeT Event

- Earlier this year, the KM3NeT Collaboration reported the detection of a muon track with an enormous energy of ~120 PeV; this the highest energy neutrino-induced event observed to date
- Given IceCube's much larger effective area and operating time, it should be able to see ~200 such events for each one detected by KM3NeT
- From this perspective, this event seems to be a lucky upward fluctuation
- That being said, this event demonstrates that the astrophysical neutrino spectrum extends up to at least ~100 PeV



KM3NeT, Nature (2025)
Li et al, 2502.04508

- This could be the first detection of a neutrino that was produced by a source of ultra-high-energy cosmic rays, or that was produced by an ultra-high-energy cosmic ray during propagation (ie. a cosmogenic neutrino)

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

High-Energy Neutrinos as a Probe of Fundamental Physics

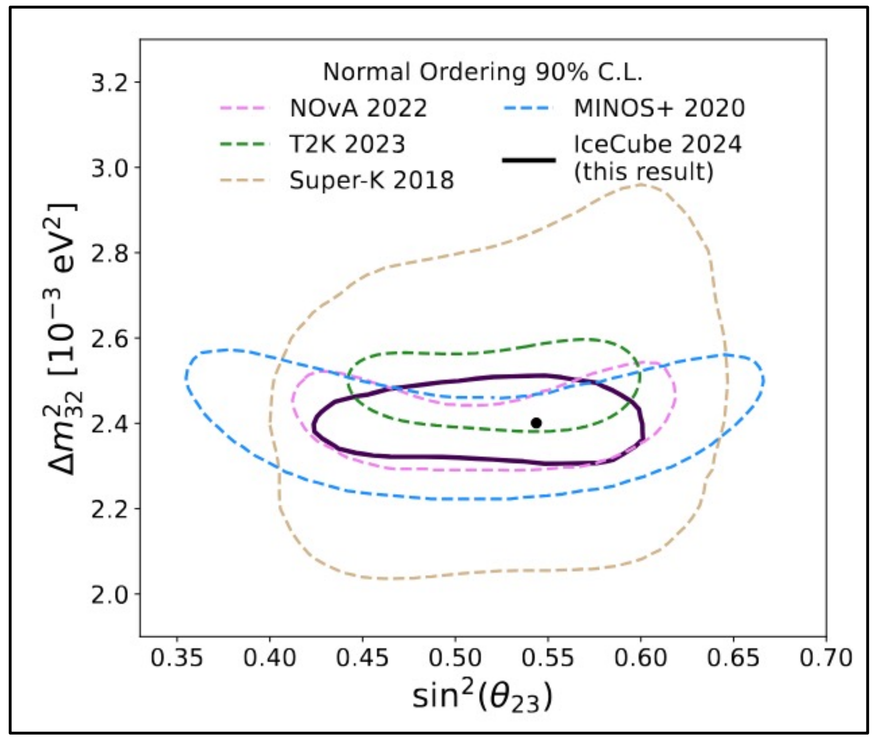
To astrophysicists, the importance of neutrino astronomy is obvious – neutrinos are the key to unraveling the puzzle of the origin of the cosmic rays, and they provide us with our clearest view of our universe's most violent and energetic environments

But when I give talks about neutrino astronomy at particle physics conferences, I sometimes find some people asking, "But this is all astrophysics! Why should I care?"

Measuring Neutrino Oscillation Parameters

- At ~5-100 GeV energies, earth-crossing ν_μ oscillate nearly maximally into ν_τ
- This enables IceCube to precisely measure both $\sin\theta_{23}$ and Δm^2_{32}
- In contrast to oscillation measurements that use lower-energy 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 will significantly enhance this program's ability to detect and measure GeV-TeV scale neutrinos – this will be critical for measuring oscillation parameters (including the neutrino mass hierarchy)

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



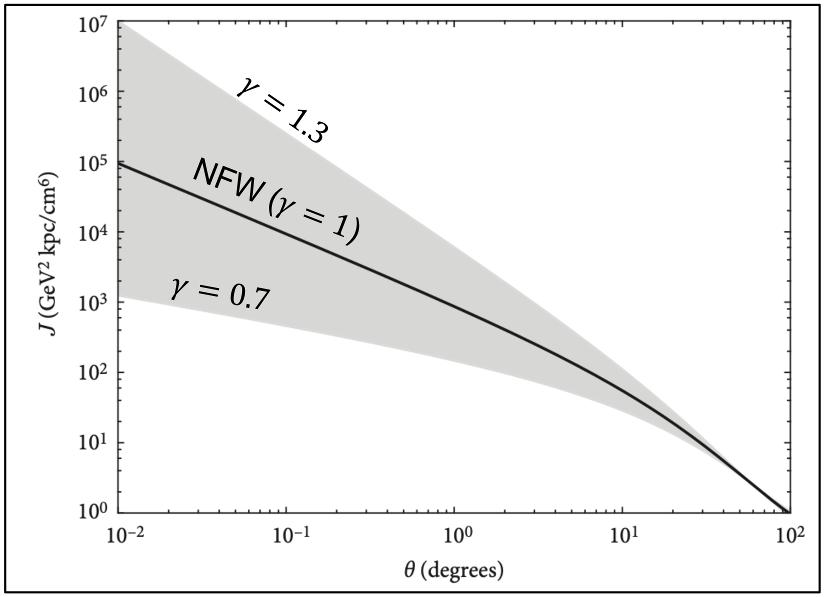
IceCube, arXiv:2405.02163, 2304.12236

Neutrinos From Dark Matter Annihilation

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

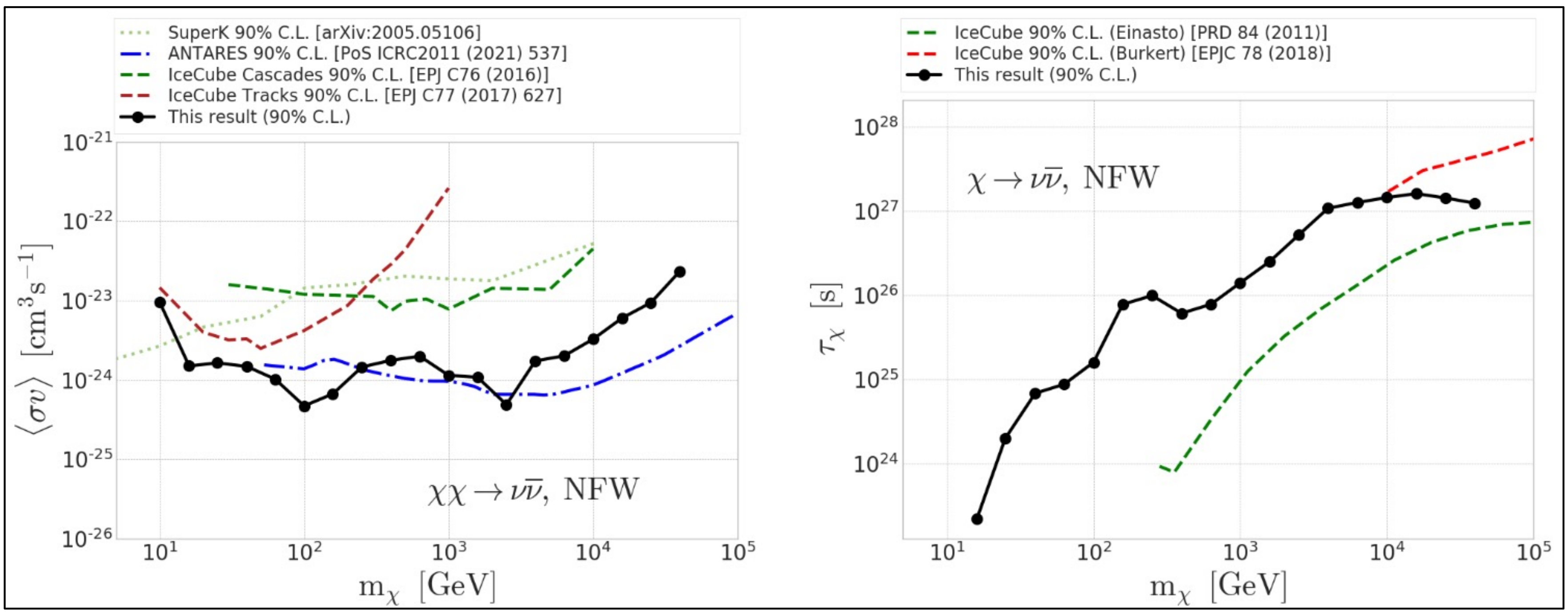
$$\frac{dN_\nu}{dE_\nu} = \int \frac{\langle \sigma v \rangle \, \rho_X^2}{2 m_X^2} \left. \frac{dN_\nu}{dE_\nu} \right|_{\rm ann} \frac{dV}{4\pi d^2} = \frac{\langle \sigma v \rangle}{8\pi m_X^2} \left. \frac{dN_\nu}{dE_\nu} \right|_{\rm ann} \int_{\Delta\Omega} \int_{los} \rho_X^2(l, \Omega) \, dl \, d\Omega$$

- For well-motivated models of the dark matter distribution, one predicts a flux of dark matter annihilation products that peaks in the direction of the Galactic Center



Dark Matter Searches

- For dark matter candidates that preferentially produce neutrinos (such as $XX \rightarrow \nu\bar{\nu}$ or $XX \rightarrow \tau^{+}\tau^{-}$), searches for high-energy neutrinos from the Galactic Halo can provide some of our most stringent constraints on the dark matter's annihilation cross section (or lifetime in the case of decays)
- Note, however, that these cross sections are much larger than those typically expected for dark matter in the form of a thermal relic



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:

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

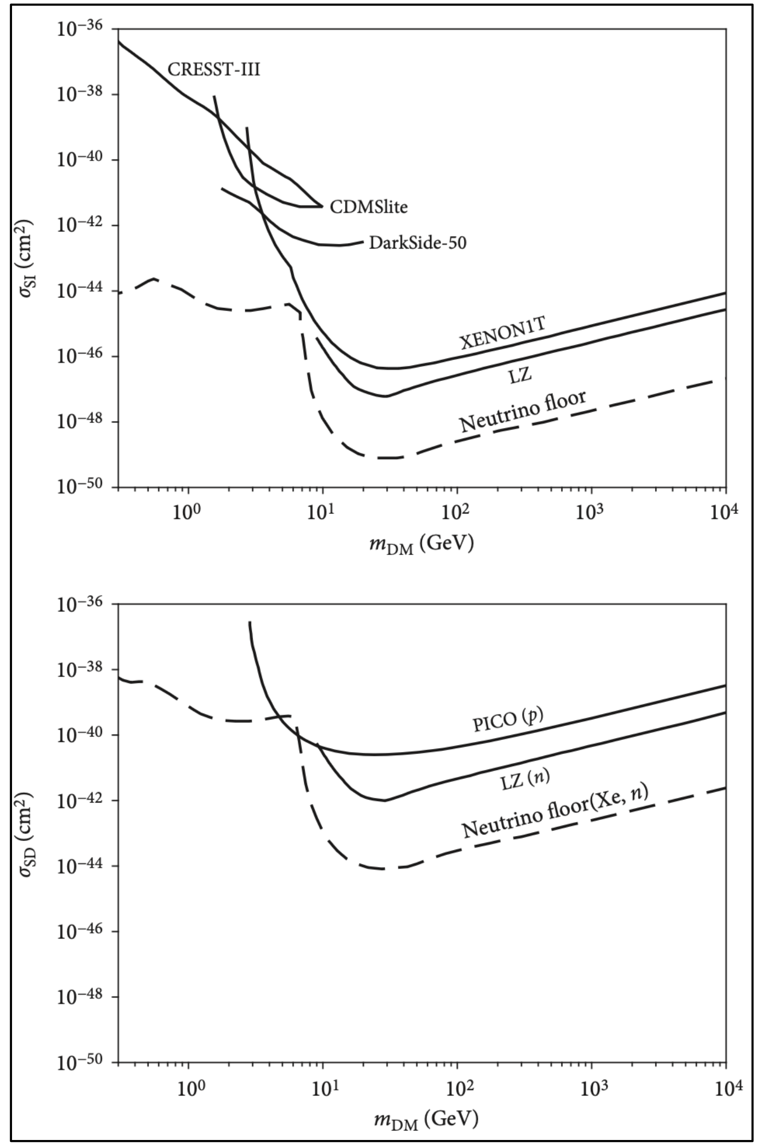
where Ω_v is the probability that a given dark matter particle will elastically scatter with a nucleus and be left with a velocity below the Sun's escape velocity,

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

- This rate doesn't depend on the dark matter's annihilation cross section, but instead on its elastic scattering cross section with nuclei
- As the number of dark matter particles in the Sun's core increases, so does the annihilation rate, potentially reaching equilibrium with the capture rate
- 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

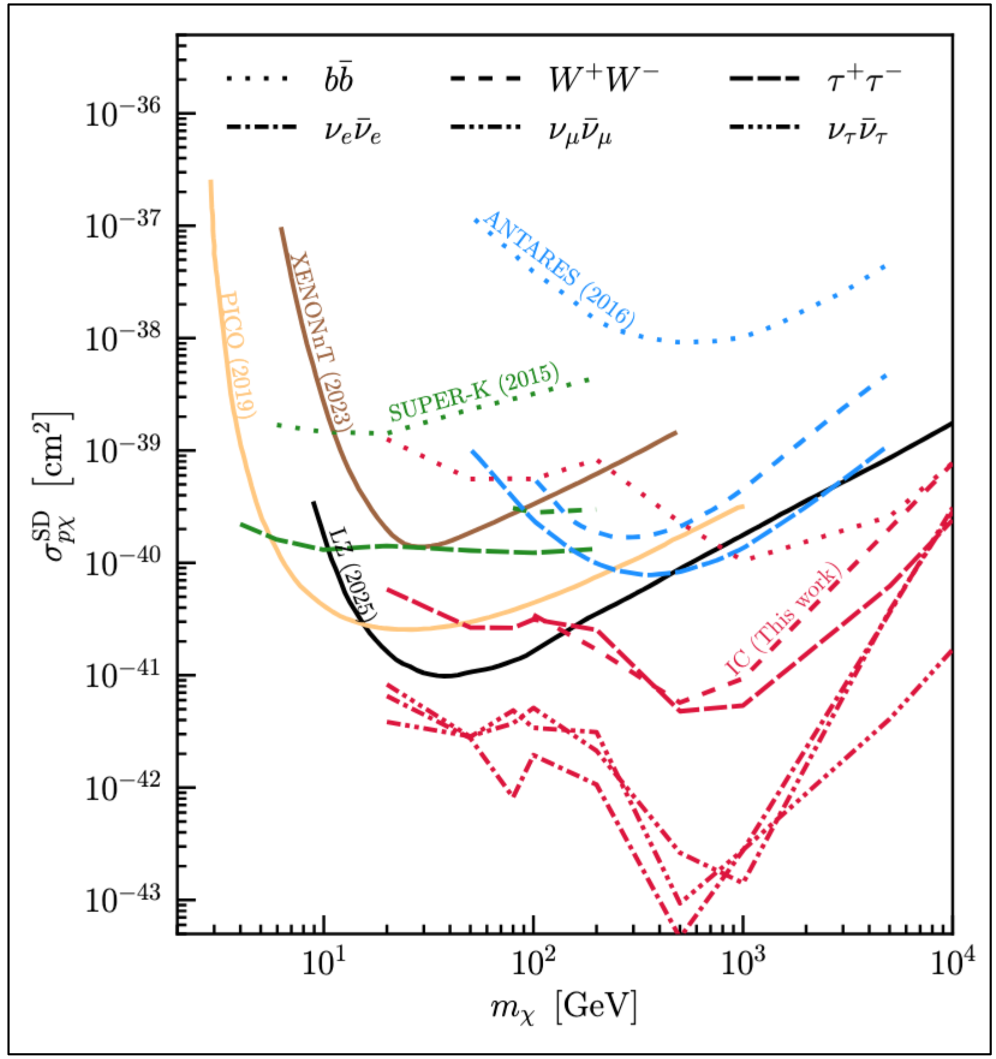
- At low velocities, the dark matter's elastic scattering cross section with nuclei can be reduced to a combination of
  1) Spin-independent, $\sigma \propto A^2$
  2) Spin-dependent, $\sigma \propto J\,(J+1)$



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

Dark Matter Annihilation in the Sun

- Neutrino telescopes currently provide the strongest constraints on dark matter candidates with spin-dependent interactions, and that annihilate to $\nu\bar{\nu}$ or $\tau^+\tau^-$
- The upcoming Upgrade will significantly increase IceCube's sensitivity to dark matter annihilation in the Sun

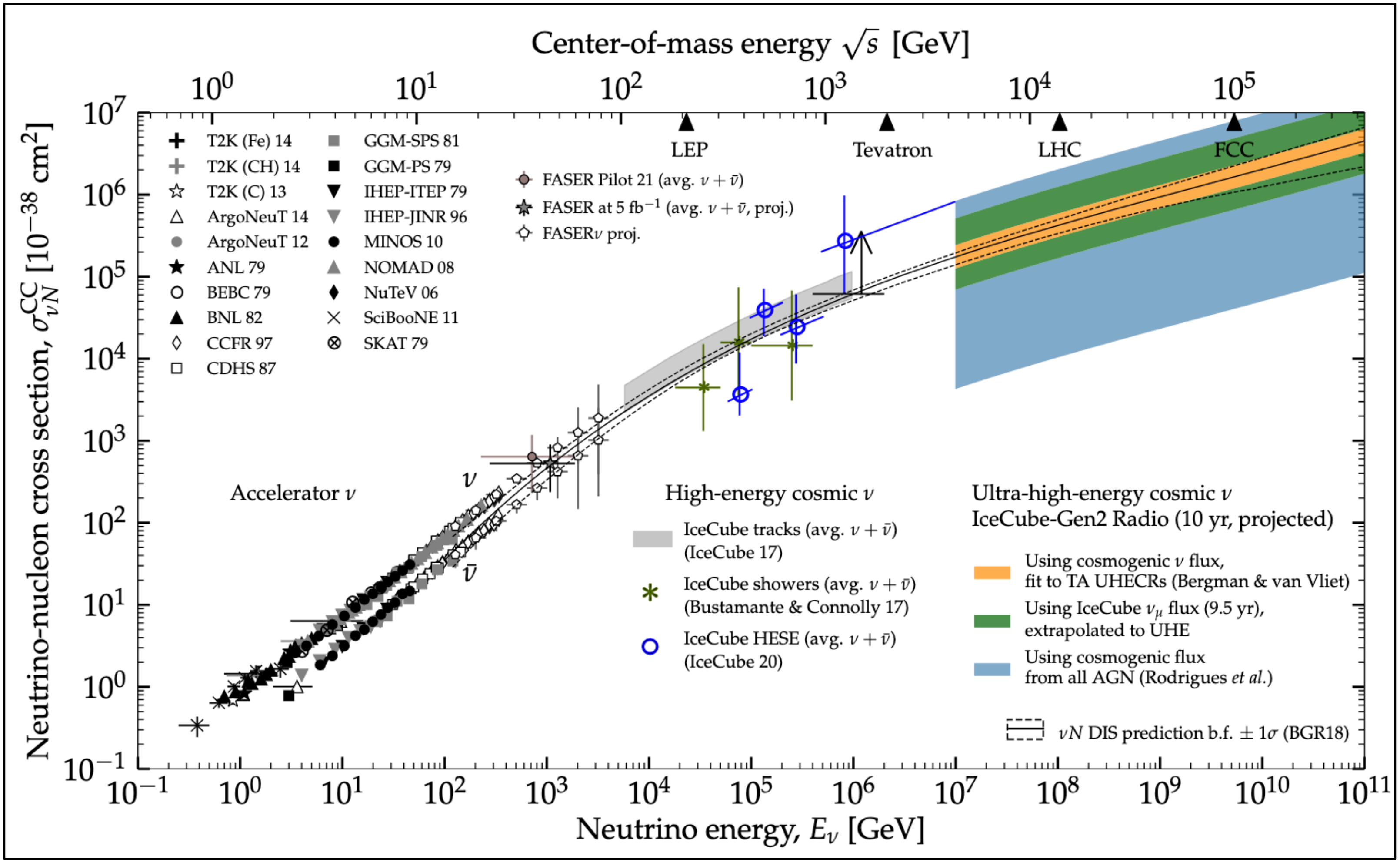


IceCube, arXiv:2507.08457, 2111.09970; DH and F. Vassallo, arXiv:2505.06734

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 in any existing laboratory experiment
- Such measurements can serve as a probe of many scenarios featuring physics beyond the Standard Model

Studying Ultra-High-Energy Interactions



Ackermann, et al. (Snowmass White Paper), arXiv:2203.08096

Studying Ultra-High-Energy Interactions

- In general terms, neutrino telescopes are sensitive to new strong dynamics, involving new heavy particles with large couplings
  - -Models with low-scale quantum gravity (ADD, Randall-Sundrum, etc.)
  - -Electroweak instanton mediated interactions
  - -Leptoquark mediated interactions
  - -etc.
- High-energy neutrino interactions are also sensitive to the structure of the nucleon, providing us with a novel probe of low-x and high-Q^2 QCD
- Resonant scattering of high-energy neutrinos with the CνB

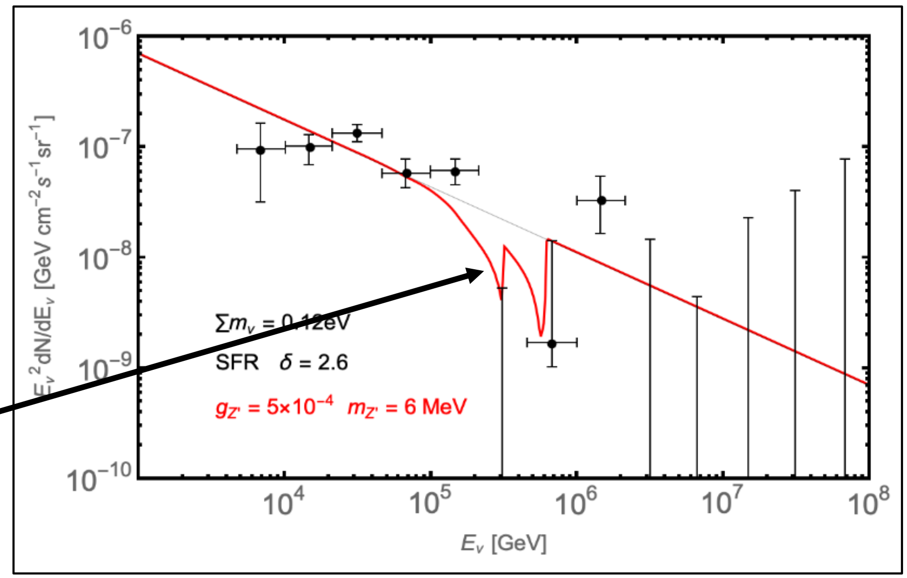
New Forces?

- Consider a light Z' that couples to neutrinos with a coupling that is small enough to evade laboratory constraints
- Over cosmological distances, such a Z' would cause high-energy neutrinos to scatter with the cosmic neutrino background, leading to resonant absorption features at:

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

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

- This could even provide an explanation for the dip-like feature that is hinted at around ~200-1000 TeV



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

Neutrino Flavor Ratios

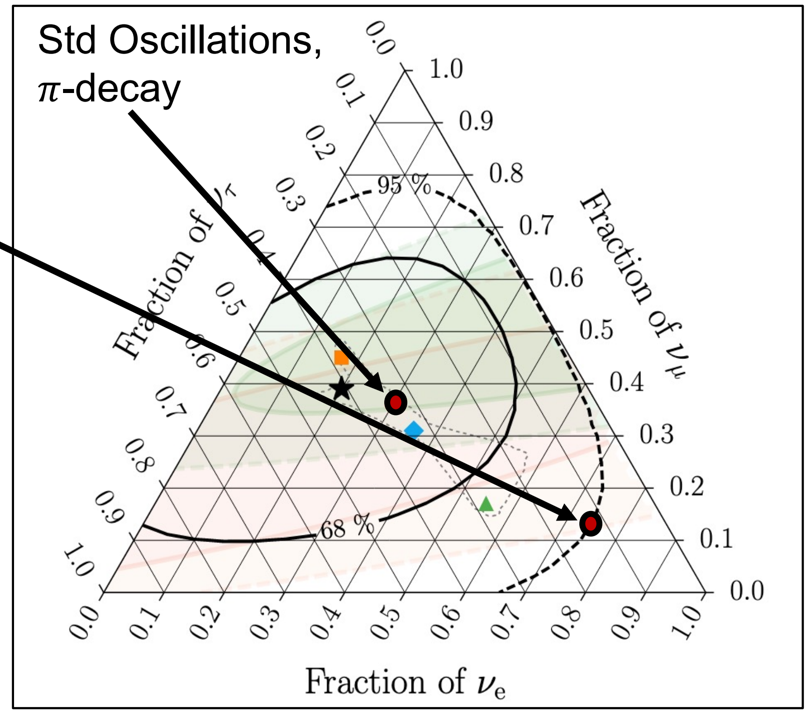
- Over very long baselines, standard oscillations lead to neutrino fluxes with predictable flavor ratios
- Astrophysical high-energy neutrinos are primarily produced through the production and decay of charged pions
- At the source, this yields a flavor ratio of $\nu_e\!:\!\nu_\mu\!:\!\nu_\tau = 1\!:\!2\!:\!0$, which after standard oscillations becomes $\nu_e\!:\!\nu_\mu\!:\!\nu_\tau \approx 1\!:\!1\!:\!1$
- Physics beyond the Standard Model could alter this prediction

Neutrino Decay

- Consider, for example, a scenario in which one or more of the neutrino species is unstable, and can decay into lighter neutrinos
- Such decays would be imperceptible in laboratory experiments, but still impact the flavor ratios of the astrophysical neutrinos that reach Earth

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



IceCube, arXiv:2011.03561

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

Beacom, Bell, DH, Pakvasa, Weiler (2002)

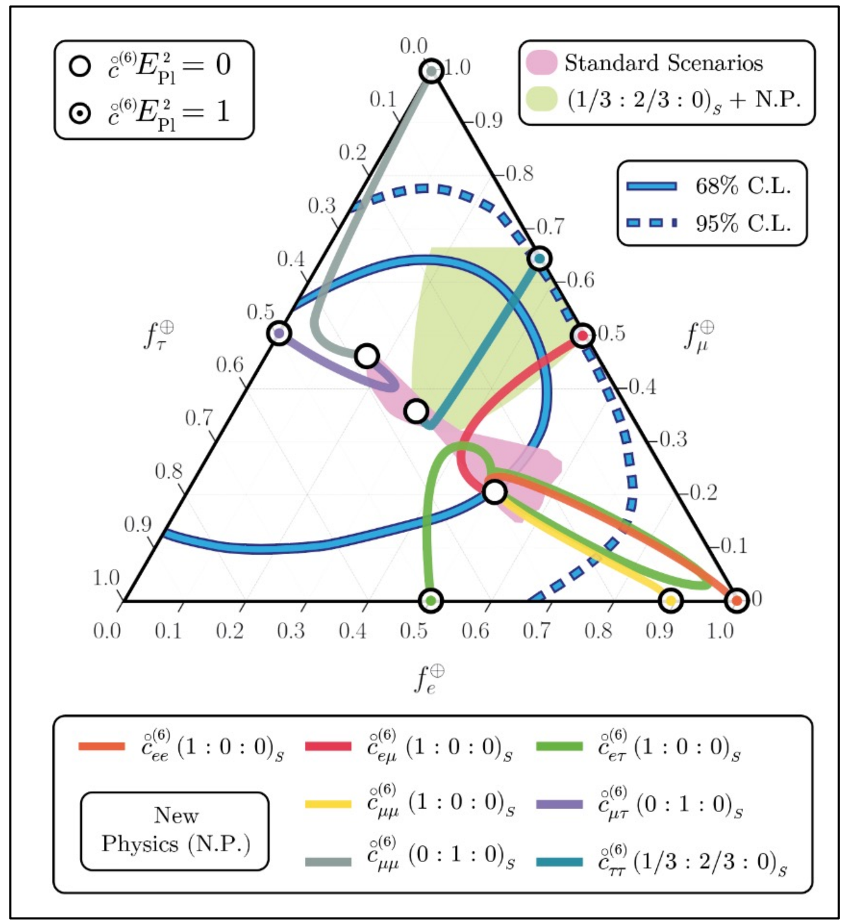
Probing Quantum Gravity

- Over cosmological baselines, the effects of quantum gravity (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 – the "spacetime foam"
- 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 the highest energies

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 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 $\sim 10^{-4}\, M_{Pl}^2$

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



DH, Morgan, Winstanley (2004, 2005)
IceCube, arXiv:2111.04654, 2308.00105

Summary

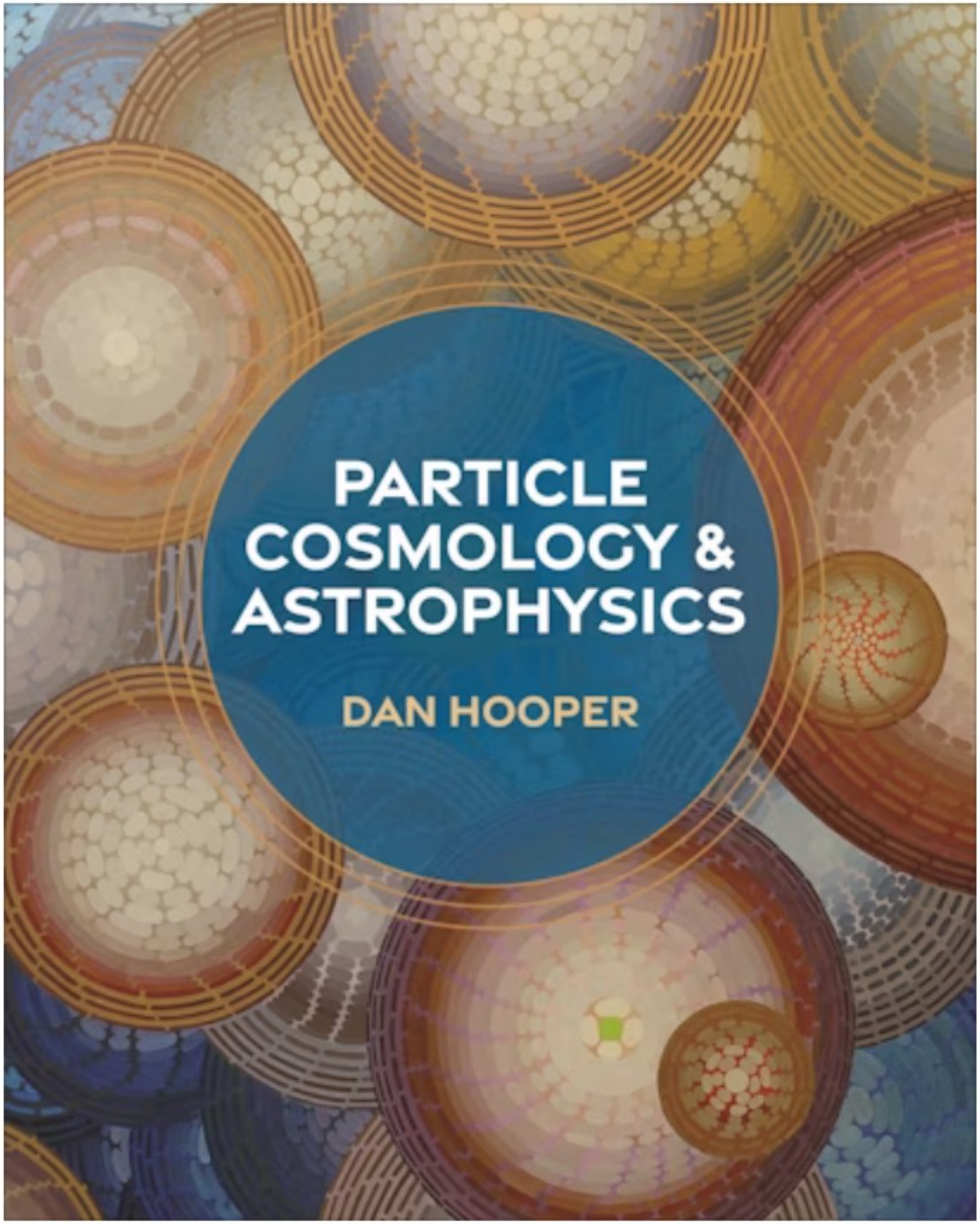
- After more than a century, we are finally closing in on the sources of the cosmic ray spectrum
- This is fundamentally a question for multi-messenger astrophysics, with important roles to be played by high-energy neutrino telescopes, gamma-ray telescopes, and cosmic-ray detectors
- IceCube-Gen2 will be capable of identifying many of the individual sources that produce the observed diffuse neutrino flux, and with it the sources of the high- and ultra-high-energy cosmic rays
- High-energy neutrino telescopes can provide us with unique opportunities to probe physics beyond the Standard Model:

  -Neutrino oscillation parameter determinations

  -Interactions at energies beyond the reach of Earth-based accelerators

  -Propagation of neutrinos over cosmological baselines

  -Neutrinos from dark matter annihilation/decay or other exotic origins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