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Searching for Quantum Gravity with Neutrino Telescopes

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Testing specific phenomenological predictions of quantum gravity in the neutrino sector is possible using existing detectors. In particular, flavor mixing in addition to conventional mass-induced oscillations can lead to distortions in the atmospheric neutrino spectrum as observed in high-energy neutrino telescopes such as AMANDA-II, ANTARES, and IceCube. Furthermore, discovery of galactic and/or extragalactic neutrino beams will open further avenues to search for violations of Lorentz invariance, quantum decoherence, and other quantum-gravitational effects.

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1. Introduction

While a comprehensive and predictive theory of quantum gravity (QG) still eludes us, recent advances in theory, phenomenology, and experimental techniques have made testing certain potential signatures of QG feasible. The neutrino sector is one promising place to search for such effects. In this overview, we first consider the detection principles for high-energy neutrinos and review the telescopes in operation or under construction. Second, we present two phenomenological signatures of QG that could be visible in existing neutrino telescopes: violation of Lorentz invariance (VLI) and quantum decoherence. Finally, we consider future prospects for QG constraint or detection using next-generation neutrino telescopes, once astrophysical sources of high-energy neutrinos are detected.

2. High-energy Neutrino Telescopes

The major obstacle to overcome in the detection of the neutrino is its small cross section – while the neutrino-nucleon cross section rises with energy, at 1 TeV the interaction length is still 2.5 *million* kilometers of water [1]. Thus, any potential detector must encompass an enormous volume to achieve a reasonable event rate. Once an interaction does occur in or near the detector, one can detect the resulting charged particles by means of their Čerenkov radiation. A (relatively) cost-effective approach is to use natural bodies of water or transparent ice sheets as the target material, and then instrument this volume with photomultiplier tubes. While originally proposed in 1960 by K. Greisen and F. Reines [2, 3], large-scale detectors of this sort have only been in operation for the past decade or so.

Water or ice Čerenkov neutrino detectors typically consist of vertical cables (called "strings" or "lines") lowered either into deep water or into holes drilled in the ice. Photomultiplier tubes (PMTs) in pressure housings are attached to the cables, which supply power and communications. A charged-current neutrino interaction with the surrounding matter produces a charged lepton via the process

$$\nu_l(\overline{\nu}_l) + d \rightarrow l^-(l^+) + u \; . \tag{2.1}$$

In the case of a muon neutrino, the resulting muon can travel a considerable distance within the medium. Precise (nanosecond-level) timing of photon hits in the PMTs allows reconstruction of the Čerenkov cone of the muon as it passes through the detector, resulting in directional reconstruction of the original neutrino to $O(1^\circ)$. An estimate of the energy of the muon is possible by measuring its energy loss, but this is complicated by stochastic losses, and in any case is only a lower bound for through-going muons. For charged-current ν_e and ν_τ interactions, or neutral-current interactions of any flavor, the event topology is less track-like than the muon case described above, and is instead more spherical or "cascade-like." Energy reconstruction is significantly better for this type of event, but angular resolution is much worse.

Cosmic rays, protons and nuclei with energies up to 10^{20} eV, produce muons and neutrinos in the atmosphere via charged pion and kaon decay (see figure 1). Even with kilometers of ice/water overburden, atmospheric muon events dominate over neutrino events by a factor of 10^6. For this reason, the ν_μ topology is especially useful: selecting only "up-going" track-like events allows

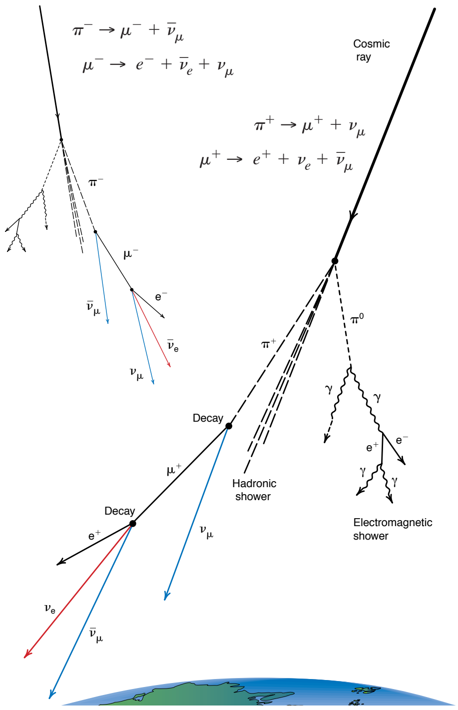

Figure 1: Atmospheric muon and neutrino production (from [4]).

one to reject the large background of atmospheric muons, using the Earth as a filter to screen out everything but neutrinos. In practice, one must also use other observables indicating the quality of the muon directional reconstruction, in order to eliminate mis-reconstructed events.

Currently completed and operational water/ice Čerenkov neutrino telescopes are:

- BAIKAL NT-200+, operating in water in Lake Baikal, Russia since 2005 (NT-200 since 1998) [5];
- and AMANDA-II, operating in deep ice under the geographic South Pole since 1998 [6].

A number of next-generation experiments are currently under construction in the Mediterranean and at the South Pole. These include:

- ANTARES, under construction in the Mediterranean [7], see fig. 2;
- NESTOR, under construction in the Mediterranean [8];
- NEMO, a cubic-kilometer-scale design for the Mediterranean [9];
- KM3NeT, a cubic-kilometer-scale design for the Mediterranean [10];
- and IceCube, cubic-kilometer detector under construction at the South Pole [11], see fig. 3.

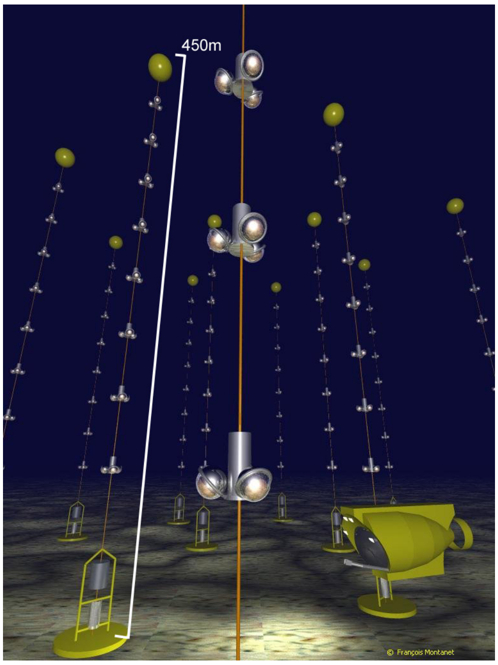

Figure 2: The ANTARES neutrino telescope [12].

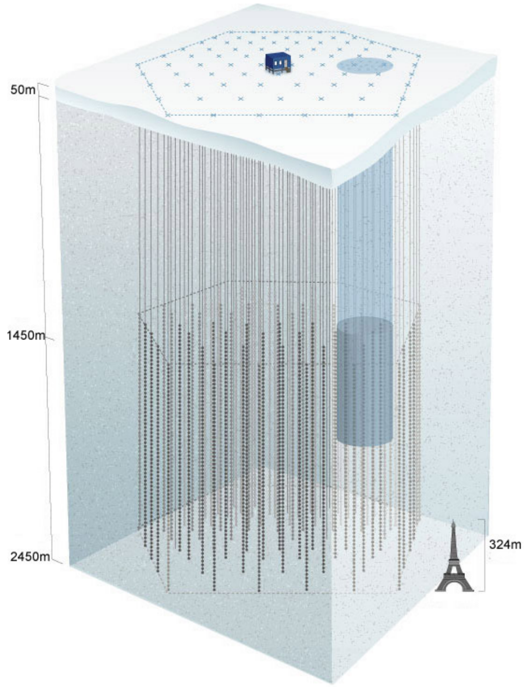

Figure 3: The IceCube neutrino telescope [13]. The smaller cylinder indicates the region occupied by AMANDA-II.

The first of these scheduled to complete is ANTARES, which is approximately the scale of AMANDA-II, but will have significantly better angular resolution [7]. As of 2007, the IceCube detector has deployed 22 of up to 80 strings and is currently taking physics data.

While BAIKAL and AMANDA-II have set astrophysically interesting limits, high-energy neutrino point sources or diffuse fluxes have yet to be detected. These analyses do result, however, in relatively pure samples of high-energy atmospheric muon neutrinos in the 100 GeV to 10 TeV energy range (see fig. 4). Certain QG effects could distort the expected energy spectrum and zenith angle distribution of the atmospheric neutrinos and result in a detectable deviation.

3. Phenomenology of Neutrinos and Quantum Gravity

Neutrino oscillations provide an interferometer sensitive to very small shifts in energy and are thus a natural platform with which to search for QG effects. While conventional oscillations are well-explained by mass splittings [15, 16, 17], QG oscillations or other flavor changes which emerge at higher energies (above 50 GeV for atmospheric baselines) could remain compatible with existing results and yet signal a departure from the Standard Model. Several phenomenological models provide examples of such effects, and we review two specific ones here.

3.1 Violation of Lorentz Invariance

Many models of quantum gravity suggest that Lorentz symmetry may not be exact [18]. Even if a "final" QG theory is Lorentz symmetric, the symmetry may still be spontaneously broken in

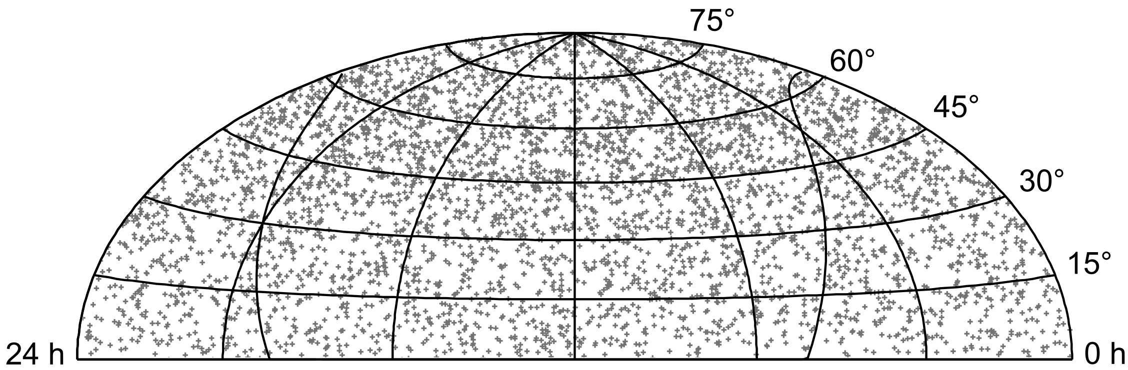

Figure 4: 4282 candidate muon neutrino events from five years of AMANDA-II data, in equatorial coordinates (from [14]). The data are consistent with the expected flux from atmospheric neutrinos.

our universe. Atmospheric neutrinos, with energies above 100 GeV and mass less than 1 eV, have Lorentz gamma factors exceeding 10^{11} and provide a sensitive test of Lorentz symmetry in this regime.

The Standard Model Extension (SME) provides an effective field-theoretic approach to violation of Lorentz invariance (VLI) [19]. The SME adds all coordinate-independent renormalizable Lorentz- and CPT-violating terms to the Standard Model Lagrangian. Even when restricted to first order effects in the neutrino sector, the SME results in numerous potentially observable effects [20, 21, 24]. To specify one particular model which leads to alternative oscillations at high energy, we consider only the the Lorentz-violating Lagrangian term

$$\frac{1}{2} i (c_L)_{\mu\nu ab} \overline{L}_a \gamma^\mu \overleftrightarrow{D}^\nu L_b \tag{3.1}$$

with the VLI parametrized by the dimensionless coefficient c_L [21]. Furthermore, we restrict ourselves to rotationally invariant scenarios (so-called "fried chicken" or FC models) with only nonzero time components in c_L, and we consider only a two-flavor system. The eigenstates of the resulting 2×2 matrix c_L^{TT} correspond to differing maximal attainable velocity (MAV) eigenstates. These may be distinct from either the flavor or mass eigenstates. Any difference $\delta c/c$ in the eigenvalues will result in neutrino oscillations. This is most easily seen by noting the equivalence of the above construction with a modified dispersion relationship of the form

$$E^2 = p^2 c_a^2 + m^2 c_a^4 \tag{3.2}$$

where c_a is the MAV for a particular eigenstate, and in general $c_a \neq c$ [22, 23].

The effective Hamiltonian $H_\pm$ representing the energy shifts from both mass-induced and VLI oscillations can be written

$$H_\pm = \frac{\Delta m^2}{4E} \mathbf{U}_{\theta_m} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}^\dagger_{\theta_m} + \frac{\delta c}{c}\frac{E}{2} \mathbf{U}_{\theta_c} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}^\dagger_{\theta_c} \tag{3.3}$$

with two mixing angles θ_m and θ_c [25]. This results in a ν_μ survival probability of

$$P_{\nu_\mu \to \nu_\mu} = 1 \; - \; \sin^2 2\Theta \, \sin^2 \left(\frac{\Delta m^2 L}{4E} \, \mathscr{R} \right) \; , \tag{3.4}$$

where

$$\sin^2 2\Theta = \frac{1}{\mathscr{R}^2} (\sin^2 2\theta_m + R^2 \sin^2 2\theta_c + 2R \sin 2\theta_m \sin 2\theta_c \cos\eta) \; , \tag{3.5}$$

$$\mathscr{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_m \cos 2\theta_c + \sin 2\theta_m \sin 2\theta_c \cos\eta)} \; , \tag{3.6}$$

and

$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m^2} \tag{3.7}$$

for a muon neutrino of energy E and traveling over baseline L (in inverse energy units). Standard oscillations are characterized by the mass-squared difference Δm^2 and mixing angle θ_m, while VLI oscillation parameters include the velocity difference $\delta c/c$, the mixing angle θ_c, and the phase η. The phase η can be complex but is often simply set to 0 or 1. If we take both conventional and VLI mixing to be maximal ($\theta_c = \theta_m = \pi/4$) and set $\cos\eta = 1$, this reduces to the following:

$$P_{\nu_\mu \to \nu_\mu}(\text{maximal}) = 1 \; - \; \sin^2 \left(\frac{\Delta m^2 L}{4E} + \frac{\delta c}{c} \frac{LE}{2} \right) \; . \tag{3.8}$$

Note the different energy dependence of the two effects. For atmospheric neutrinos, the zenith angle functions as a surrogate for the baseline L, allowing path lengths up to the diameter of the Earth. Figure 5 shows the survival probability as a function of neutrino energy and zenith angle for the maximal case, as in equation 3.8.

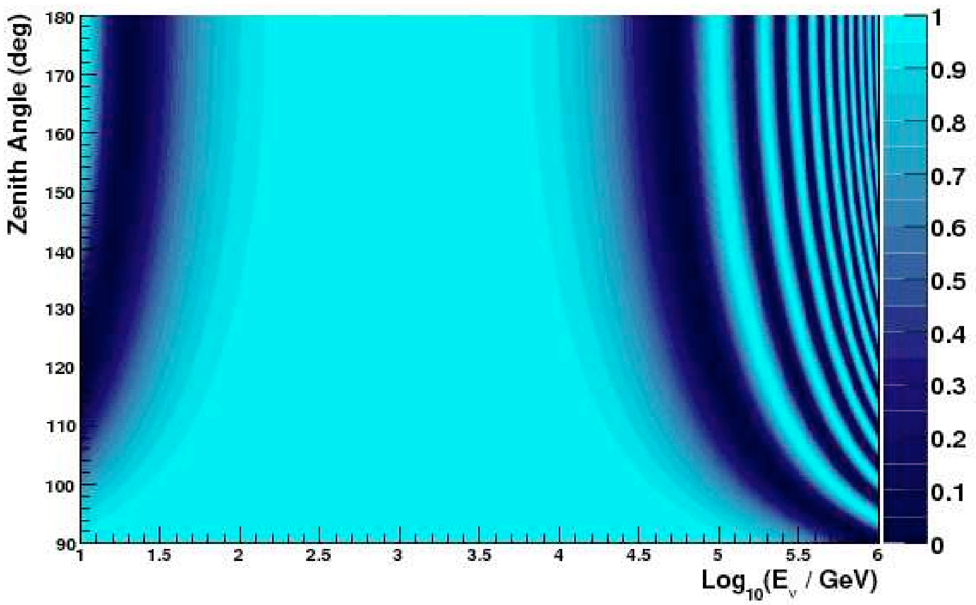

Figure 5: Atmospheric ν_μ survival probability as function of neutrino energy and zenith angle. Conventional oscillations are present at low energies, while high-energy oscillations are due to VLI (maximal mixing, $\delta c/c = 10^{-27}$).

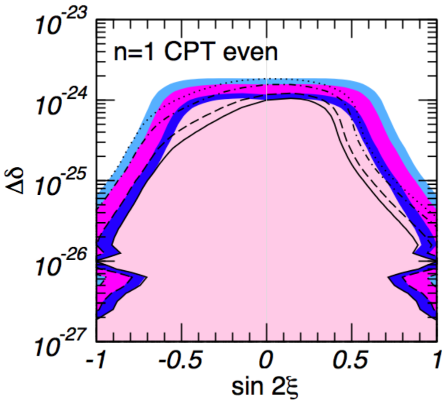

Figure 6: SuperK+K2K limits on VLI oscillations. Here $\Delta\delta \equiv \delta c/c$ and $\xi \equiv \theta_c$. Contours are 90%, 95%, 99%, and 3σ CL. Figure from [25].

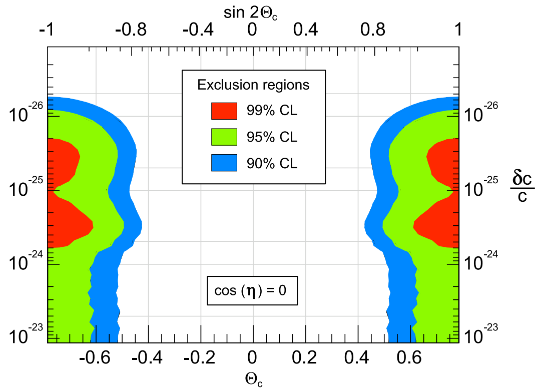

Figure 7: Preliminary AMANDA-II limits on VLI oscillations, for $\cos\eta = 0$. Exclusion regions for $\cos\eta = 1$ are similar. Figure from [28].

No evidence for this type of VLI oscillation has been observed, and several neutrino experiments have set limits on this phenomenon, including MACRO [26], Super-Kamiokande [27], and a combined analysis of K2K and Super-Kamiokande data [25]. The latter is the best current result, with a 90% CL limit of $\delta c/c < 2.0 \times 10^{-27}$ for maximal mixing (see fig. 6).

Using four years of data acquired from 2000 to 2003, AMANDA-II has set a preliminary 90% CL limit of $\delta c/c < 5.3 \times 10^{-27}$ for maximal mixing [28] (see fig. 7), and additional improvements in sensitivity are expected [29]. ANTARES has an expected sensitivity of up to $\delta c/c < 4.1 \times 10^{-25}$ for three years of data and maximal mixing [30].

Once completed, the IceCube detector will record upwards of 40,000 atmospheric neutrinos per year. With ten years of data, the expected sensitivity to maximal VLI oscillations is improved by an order of magnitude to 2×10^{-28} ([31]; see fig. 8).

We note again that while this particular example of FC VLI is quite well-studied, this model represents only a small fraction of the full SME neutrino-sector parameter space. We have chosen to focus on this model largely because of its simplicity and energy dependence (the $L\,E$ oscillation frequency). Lower-energy experiments like Super-Kamiokande have constrained FC models with energy-independent VLI, and we do not expect to improve on these bounds significantly with high-energy neutrino telescopes. However, non-FC models with directional asymmetries in the oscillation parameters remain largely unexplored.

3.2 Quantum Decoherence

Another possible low-energy signature of QG is the evolution of pure states to mixed states via interaction with the environment of space-time itself, or quantum decoherence. One heuristic picture of this phenomenon is the production of virtual black hole pairs in a "foamy" spacetime, created from the vacuum at scales near the Planck length[32, 33]. Interactions with the virtual black holes may not preserve certain quantum numbers like neutrino flavor, causing decoherence into a superposition of flavors.

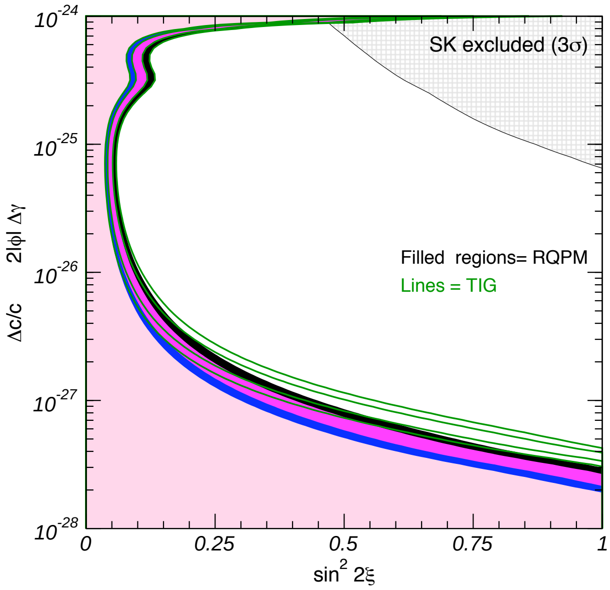

Figure 8: Sensitivity to VLI oscillations for ten years of IceCube data. Contours are 90%, 95%, 99%, and 3σ CL. Here $\xi \equiv \theta_c$. Figure from [31].

To construct a phenomenological framework in which to study these effects, we follow the approach in [34] of modifying the time-evolution of the density matrix ρ with a dissipative term $\not{\delta} H \rho$:

$$\dot{\rho} = -i[H,\rho] + \not{\delta} H \rho \; . \tag{3.9}$$

We adopt the Lindblad form for $\not{\delta} H \rho$, which has also been applied in the context of "normal" decoherence due to interaction with the environment. In this case we have a set of self-adjoint environmental operators D_j which commute with the Hamiltonian, in which case eq. 3.9 becomes

$$\dot{\rho} = -i[H,\rho] + \sum_j [D_j,[D_j,\rho]] \; . \tag{3.10}$$

This is by no means the only form for the decoherence term, and we refer the reader to [35] for a more general approach. Solving eq. 3.10 for a two-neutrino system results in the following for the ν_μ survival probability [36]:

$$P_{\nu_\mu \to \nu_\mu} = 1 \; - \; \frac{1}{2} \sin^2 2\theta_m \left[1 - e^{-2\alpha L} \cos\left(2\frac{\Delta m^2 L}{4E}\right)\right] \tag{3.11}$$

where α is the decoherence parameter, and L is the neutrino baseline in inverse energy units.

The decoherence parameter α may have an energy dependence, depending on the model. Three which have been considered are [35]:

- no energy dependence;
- an inverse energy dependence. This particular case preserves Lorentz invariance and has also been tested as an alternative explanation to mass-induced oscillations [37];

- or, an energy-squared dependence. This form is suggested by decoherence calculations involving recoiling D-brane geometries [39] as well as in loop quantum gravity [40]. In this case we write

$$\alpha = \frac{1}{2}\kappa_\alpha E^2 \,. \tag{3.12}$$

The E^2 or κ-model is particularly interesting for high-energy neutrino telescopes because of the strong energy dependence. The atmospheric ν_μ survival probability is shown in figure 9.

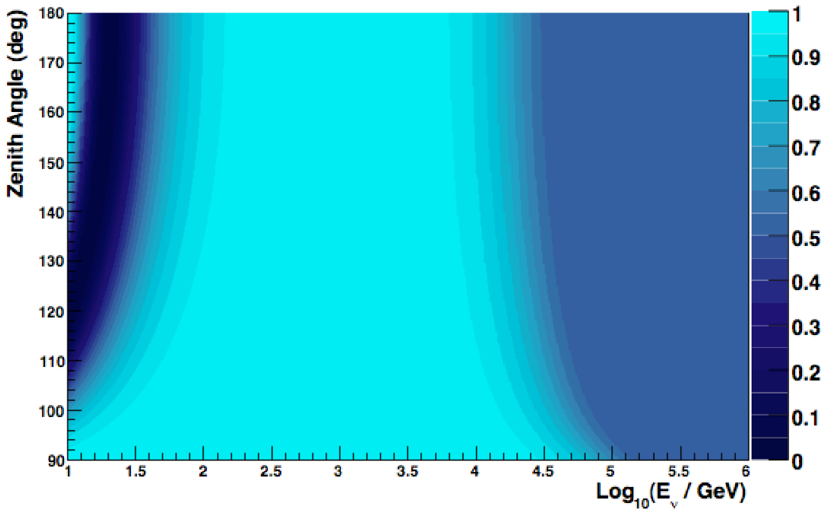

Figure 9: Atmospheric ν_μ survival probability as function of neutrino energy and zenith angle. The high-energy disappearance is due to two-family κ-model (E^2) quantum decoherence, with $\kappa_\alpha = 4\times10^{-32}$.

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An analysis of Super-Kamiokande data has resulted in a limit at the 90% CL of $\kappa_\alpha < 0.9\times 10^{-27}$ GeV^{-1} [37]. High-energy neutrino telescopes should be able to improve this significantly: ANTARES will have a sensitivity using three years of data of $\kappa_\alpha < 10^{-30}$ GeV^{-1} [35], and AMANDA-II has a sensitivity using seven years of data of $\kappa_\alpha < 10^{-31}$ GeV^{-1}.

We note that the above analyses have all used a two-flavor neutrino system for simplicity; however, this seems particularly unjustified in the decoherence scenario, and recent work has generalized the phenomenology to a three-flavor system [41, 42]. At the simplest level, this will reduce the limiting value of the ν_μ survival probability to 1/3 instead of 1/2, allowing possible improvements in sensitivity.

4. Future Prospects

High-energy astrophysical sources of neutrinos could provide even better sensitivity to QG effects, both through higher neutrino energy as well as longer baselines. We expect detection of such sources with the upcoming generation of cubic-kilometer-scale telescopes such as IceCube and KM3NeT.

4.1 Decoherence of Antineutrinos

High-energy neutrinos propagating over astrophysical baselines can provide sensitive tests of quantum decoherence, given the right source characteristics. In the standard scenario of hadronic acceleration at the production sites of cosmic rays, neutrinos are produced via decays of charged pions and kaons:

$$\begin{aligned} pp, p\gamma &\rightarrow \pi^0 \rightarrow \ \gamma\gamma \\ &\rightarrow \pi^{\pm} \rightarrow \ \mu^{\pm}\nu_\mu(\overline{\nu}_\mu) \\ &\qquad\qquad \rightarrow e^{\pm}\nu_e\overline{\nu}_\mu\nu_\mu(\overline{\nu}_e\nu_\mu\overline{\nu}_\mu)\ . \end{aligned} \tag{4.1}$$

Mass-induced oscillations over long baselines convert this initial flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 2:1:0$ to $1:1:1$ at Earth. Three-flavor quantum decoherence over long baselines also results in a $1:1:1$ flavor ratio, regardless of the initial source content, so in order to distinguish between the effects, we need a non-standard flavor ratio at the source.

Such a scenario is provided by an electron antineutrino source from the decays of high-energy neutrons. One possible site is the Cygnus OB2 star association, in which clustered supernovae remnants may accelerate heavy nuclei which then photodisintegrate on the ambient photon fields to produce high-energy neutrons [43]. The highest-energy neutrons have a large enough boost to create a cosmic-ray anisotropy from the region, allowing verification of the neutron hypothesis. Lower-energy neutrons decay via $n \rightarrow p^+e^-\overline{\nu}_e$, and mass-induced oscillations alter the pure $\overline{\nu}_e$ to a flavor ratio of $\approx 5:2:2$ at Earth. Given enough statistics and proper flavor discrimination, this could be distinguished from the decoherence case of $1:1:1$, and deviation from the latter would set strong limits on decoherence phenomena.

Recall from section 2 that flavor discrimination in neutrino telescopes is accomplished primarily by event topology (track-like or shower-like classification). In 15 years of data-taking, IceCube is expected to accumulate as many as 62 track-like events and 72 shower-like events from Cygnus OB2, given the neutron hypothesis and no decoherence [43]. Backgrounds for such a search include the atmospheric neutrino flux and any other TeV neutrino sources in the angular search region, such as J2032+4130, that may produce a standard $1:1:1$ flavor ratio. Sensitivity to decoherence can be calculated for various background flux levels and energy dependencies (see fig. 10). For low background, IceCube has a sensitivity to E^2 quantum decoherence of $\kappa_2 \leq 2.0 \times 10^{-44}$ GeV^{-1} at the 90% CL. This would improve the current Super-Kamiokande limit by 17 orders of magnitude, and bests the AMANDA-II / ANTARES sensitivity using atmospheric neutrinos by 13 orders of magnitude. Important caveats here are that such an analysis requires the unusual $\overline{\nu}_e$ source in the first place, as well as improvements in the angular resolution for shower-like events.

4.2 Other Possibilities

Several other possibilities exist for using astrophysical neutrino sources for QG searches. A detailed treatment is not possible here, but we will list a few other intriguing proposals.

First, we consider a search for time delays between photons and neutrinos from gamma-ray bursts (GRBs) which might be caused by violation of Lorentz invariance (and resulting modification of the dispersion relationship). Given the cosmological distances traversed, the time delay

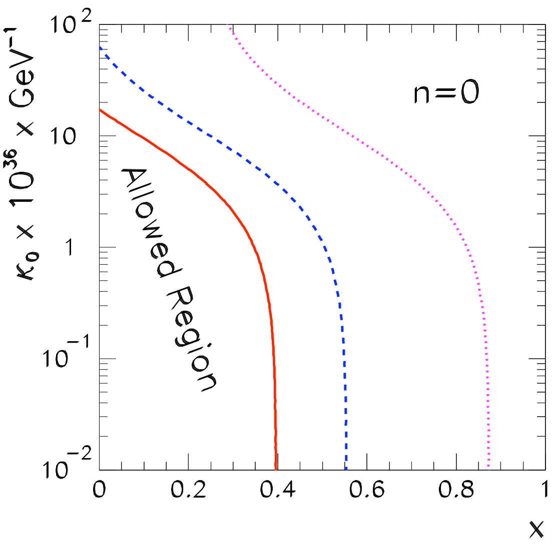

Figure 10: IceCube sensitivity to quantum decoherence using a $\overline{\nu}_e$ beam from Cygnus OB2. The x-axis parametrizes a background ν flux with 1 : 1 : 1 flavor ratio. The lines represent 90%, 95%, and 99% exclusion regions for an *energy-independent* decoherence parameter κ_0. Other energy dependencies are also examined (figure from [43]).

due to VLI could range from $1\,\mu$s to 1 yr, depending on the power of suppression by M_{Planck} [44]. Detection of high-energy neutrinos from multiple GRBs at different redshifts would allow either confirmation of the delay hypothesis or allow limits below current levels by several orders of magnitude [45]. Such a search is complicated by the low expected flux levels from individual GRBs, as well as uncertainty of any intrinsic $\gamma - \nu$ delay due to production mechanisms in the source.

Second, studies of the neutrino cross section at TeV-PeV energies can test models of quantum gravity that suggest enhancements at the TeV scale. Such models include large extra dimensions (ADD), Kaluza-Klein gravitons in a Randall-Sundrum scenario, or parametrization by Veneziano amplitudes [46]. A cubic-kilometer-scale detector such as IceCube or KM3NeT could be sensitive to such enhancements if the flux of high-energy neutrinos is substantial enough.

Finally, we consider detection of extremely high-energy (EHE) neutrinos (10^{19} eV or above). Such a detection from cosmological distances would imply the absence of vacuum Čerenkov radiation at those energies and thus set limits on any type of VLI that produces such an effect, although this also depends on the rate of the radiation [47]. EHE event rates in cubic-kilometer-scale detectors are likely too low for such an observation, requiring space-based detectors, such as the proposed EUSO, or a hybrid radio and/or acoustic high-energy IceCube extension [48].

5. Conclusions

Searches for quantum-gravitational signatures are currently possible with existing neutrino telescopes. Using high-energy atmospheric neutrinos, effects such as oscillations induced by violation of Lorentz invariance or ν_μ disappearance due to quantum decoherence can be detected or constrained at levels beyond current experimental limits. Furthermore, the construction of cubic-kilometer-scale detectors such as IceCube and KM3NeT should allow detection of galactic and extra-galactic neutrinos sources, enabling new avenues of exploration, such as decoherence of electron antineutrinos or time-delay measurements of GRB emission. Such tests may give us our first experimental glimpse into the world of quantum gravity.

6. Acknowledgments

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