Searching for Quantum Gravity with AMANDA-II and IceCube

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The AMANDA-II neutrino telescope is buried in deep, clear ice, 1500m under the geographic South Pole.

- 677 optical modules: photomultiplier tubes in glass pressure housings (~540 used in analysis)

- Muon direction can be reconstructed to within 2-3°
Amundsen-Scott
South Pole Research Station

South Pole Station

Geographic South Pole

skiway

AMANDA-II
Current Experimental Status

• No detection (yet) of
  – point sources or other anisotropies
  – diffuse astrophysical flux
  – transients (e.g. GRBs, AGN flares, SN)

• Astrophysically interesting limits set

• Large sample of atmospheric neutrinos
  – AMANDA-II: >5K events, 0.1-10 TeV

Opportunity for particle physics with high-energy atmospheric $\nu$
New Physics with Neutrinos?

- Neutrinos are already post-Standard Model (massive)

- For $E > 100$ GeV and $m_\nu < 1$ eV, $\text{Lorentz } \gamma > 10^{11}$

- Oscillations are a sensitive quantum-mechanical interferometer — small shifts in energy can lead to large changes in flavor content

Eidelman et al.: “It would be surprising if further surprises were not in store…”
New Physics Effects

• Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*

• Violations of the equivalence principle (different gravitational coupling)†

• Interaction of particles with space-time foam $\Rightarrow$ quantum decoherence of flavor states‡

* see e.g. Carroll et al., PRL 87 14 (2001), Colladay and Kostelecký, PRD 58 116002 (1998)
† see e.g. Gasperini, PRD 39 3606 (1989)
‡ see e.g. Anchordoqui et al., hep-ph/0506168
VLI Atmospheric $\nu_\mu$ Survival Probability

maximal mixing, $\delta c/c = 10^{-27}$
QD Atmospheric $\nu_\mu$ Survival Probability

Survival probability (decoherence, $E^2$ model, $\log_{10} \gamma^* = -31$)

Decoherence into superposition of flavors

$p = 1/3$
Results: Observables

Data consistent with atmospheric neutrinos + O(1%) background
Confidence intervals constructed with F+C plus systematics
Results: Preliminary VLI limit

maximal mixing

- SuperK+K2K limit*: \( \delta c/c < 1.9 \times 10^{-27} \) (90%CL)
- This analysis: \( \delta c/c < 2.8 \times 10^{-27} \) (90%CL)

Results: Preliminary QD limit

- **SuperK limit**\(^{\ddagger}\) (2-flavor):
  \[ \gamma_i < 0.9 \times 10^{-27} \text{ GeV}^{-1} \] (90\% CL)

- **ANTARES sensitivity**\(^*\) (2-flavor):
  \[ \gamma_i \approx 10^{-30} \text{ GeV}^{-1} \] (3 years, 90\% CL)

- **This analysis:**
  \[ \gamma_i < 1.3 \times 10^{-31} \text{ GeV}^{-1} \] (90\% CL)

\(\ddagger\) Lisi, Marrone, and Montanino, PRL 85 6 (2000)

\(*\) Morgan et al., astro-ph/0412618
Conventional Analysis

- Parameters of interest: normalization, spectral slope change $\Delta \gamma$ relative to Barr et al.

- Result: determine atmospheric muon neutrino flux ("forward-folding" approach)

90%, 95%, 99% allowed
Update on IceCube
Installation Status & Plans

AMANDA

IceCube string deployed 12/05 – 01/06

IceCube string deployed 01/05

IceCube string deployed 12/05 – 01/06

IceCube string and IceTop station deployed 12/06 – 01/07

IceCube string deployed 12/07 – 01/08

IceCube Lab commissioned

2500m deep hole!

40 strings taking physics data

Planning for at least 16 strings in 2008/09
IceCube VLI Sensitivity

- IceCube: sensitivity of $\delta c/c \sim 10^{-28}$
  Up to 700K atmospheric $\nu_\mu$ in 10 years

(González-García, Halzen, and Maltoni, hep-ph/0502223)
Other Possibilities

• Extraterrestrial neutrino sources would provide even more powerful probes of QG
  – GRB neutrino time delay
    (see, e.g. Amelino-Camelia, gr-qc/0305057)
  – Electron antineutrino decoherence from, say, Cygnus OB2 (see Anchordoqui et al., hep-ph/0506168)

• Hybrid techniques (radio, acoustic) will extend energy reach — GZK neutrinos
THE ICECUBE COLLABORATION

USA:
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Pennsylvania State University
UC Berkeley
UC Irvine
Clark-Atlanta University
University of Alabama
Ohio State University
Georgia Institute of Technology
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M College, Baton Rouge
University of Alaska, Anchorage

UK:
Oxford University

Sweden:
Uppsala Universitet
Stockholm Universitet

Netherlands:
Utrecht University

Belgium:
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Germany:
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

Japan:
Chiba University

New Zealand:
University of Canterbury

Switzerland:
EPFL

Thank you!
Backup Slides
Violation of Lorentz Invariance (VLI)

- Lorentz and/or CPT violation is appealing as a (relatively) low-energy probe of QG


\[ (i\Gamma_{AB}^\nu \partial_\nu - M_{AB})\nu_B = 0 \]

\[ \Gamma_{AB}^\nu \equiv \gamma^\nu \delta_{AB} + c_{AB}^\mu \gamma_\mu + d_{AB}^\mu \gamma_5 \gamma_\mu + e_{AB}^\nu + i f_{AB}^\nu \gamma_5 + \frac{1}{2} g_{AB}^\lambda \gamma^\mu \sigma_{\lambda \mu}, \]

\[ M_{AB} \equiv m_{AB} + i m_{5AB} \gamma_5 + a_{AB}^\mu \gamma_\mu + b_{AB}^\mu \gamma_5 \gamma_\mu + \frac{1}{2} H_{AB}^{\mu \nu} \sigma_{\mu \nu}. \]

Addition of renormalizable VLI and CPTV+VLI terms; encompasses a number of interesting specific scenarios
Rotationally Invariant VLI

- Only $c_{AB}^{00} \neq 0$; equivalent to modified dispersion relation*:

$$E_2^2 = \vec{p}_a^2 c_a^2 + m_a^2 c_a^4.$$ 

- Different maximum attainable velocities $c_a$ (MAVs) for different particles: $\Delta E \sim (\delta c/c)E$

- For neutrinos: MAV eigenstates not necessarily flavor or mass eigenstates $\Rightarrow$ mixing $\Rightarrow$ VLI oscillations

$$H_\pm \equiv \frac{\Delta m^2}{4E} U_\theta \begin{pmatrix} -1 & 0 & 1 \end{pmatrix} U_\theta^\dagger + \frac{\Delta \delta_n}{2} E_{n} U_{\xi_n, \pm \eta_n} \begin{pmatrix} -1 & 0 & 1 \end{pmatrix} U_{\xi_n, \pm \eta_n}^\dagger$$

* see Glashow and Coleman, PRD 59 116008 (1999)
VLI Phenomenology

- Effective Hamiltonian
  (seesaw + leading order VLI+CPTV):

\[
(h_{\text{eff}})_{ab} = |\vec{p}| \delta_{ab} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2|\vec{p}|} \begin{pmatrix} (\bar{m}^2)_{ab} & 0 \\ 0 & (\bar{m}^2)_{ab}^* \end{pmatrix} + \frac{1}{|\vec{p}|} \left( [(a_L)^{\mu} p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]_{ab} - i \sqrt{2} p_\mu (\epsilon_+)_{\nu} [(g^{\mu\nu\sigma} p_\sigma - H^{\mu\nu}) C]_{ab}^* \right) \\
+ \frac{1}{|\vec{p}|} \left( i \sqrt{2} p_\mu (\epsilon_+)_{\nu}^* [(g^{\mu\nu\sigma} p_\sigma + H^{\mu\nu}) C]_{ab} \right)
\]

- To narrow possibilities we consider:
  - rotationally invariant terms (only time component)
  - only $c_{AB}^{00} \neq 0$ (leads to interesting energy dependence…)}
VLI + Atmospheric Oscillations

\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\Theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \mathcal{R} \right) \]

\[ \sin^2 2\Theta = \frac{1}{\mathcal{R}^2} \left( \sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta \right), \]

\[ \mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta)}, \]

\[ R = \frac{\delta c E}{c} \frac{4E}{\Delta m^2_{23}} \]

- For atmospheric \( \nu \), conventional oscillations turn off above \( \sim 50 \text{ GeV} \) (\( L/E \) dependence)

- VLI oscillations turn on at high energy (\( L E \) dependence), depending on size of \( \delta c/c \), and distort the zenith angle / energy spectrum (other parameters: mixing angle \( \xi \), phase \( \eta \))

González-García, Halzen, and Maltoni, hep-ph/0502223
Decoherence + Atmospheric Oscillations

Energy dependence depends on phenomenology: \( \gamma_i = \gamma_i^* E^n, \quad n \in \{-1, 0, 2, 3\} \)

- **\( n = -1 \)** preserves Lorentz invariance
- **\( n = 0 \)** simplest
- **\( n = 2 \)** recoiling D-branes\(^*\)
- **\( n = 3 \)** Planck-suppressed operators\(^\ddagger\)

\[ P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2} \left( e^{-\gamma_3 L} \cos^4 \theta_{23} + \frac{1}{12} e^{-\gamma_8 L} (1 - 3 \cos 2\theta_{23})^2 \right) \]

\[ + 4e^{-\gamma_6^* \gamma_7^* \frac{L}{2}} \cos^2 \theta_{23} \sin^2 \theta_{23} \left( \cos \left[ \frac{L}{2} \sqrt{(\gamma_6 - \gamma_7)^2 - \left( \frac{\Delta m_{23}^2}{E} \right)^2} \right] \right) \]

\[ + \sin \left[ \frac{L}{2} \sqrt{(\gamma_6 - \gamma_7)^2 - \left( \frac{\Delta m_{23}^2}{E} \right)^2} \right] \]

- \*Ellis et al., hep-th/9704169
- \^Anchordoqui et al., hep-ph/0506168