

Searching for Quantum Gravity with AMANDA-II and IceCube

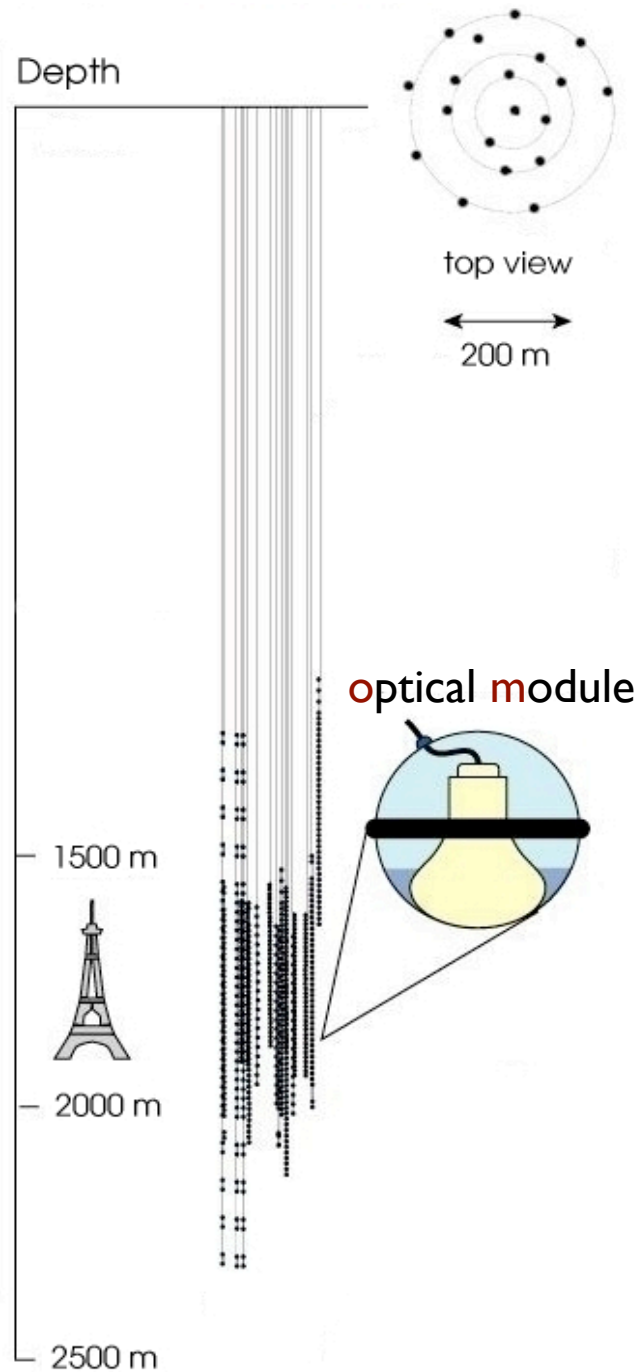
John Kelley for the IceCube Collaboration

Univ. of Wisconsin, Madison

November 11, 2008

PANIC'08, Eilat, Israel

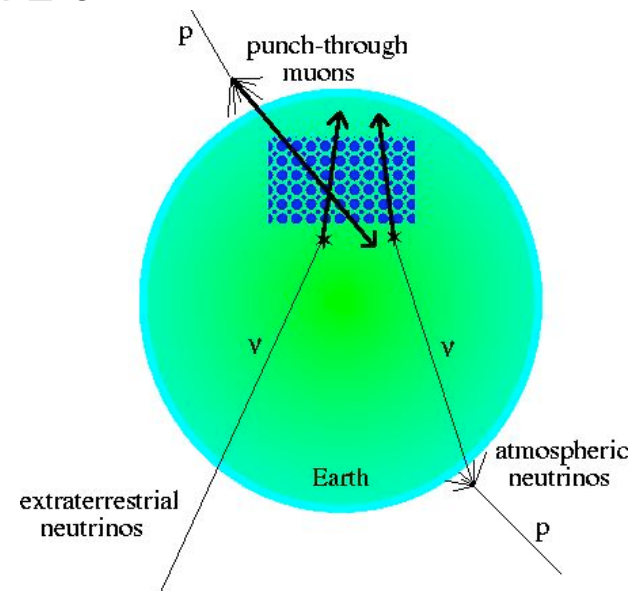
AMANDA-II



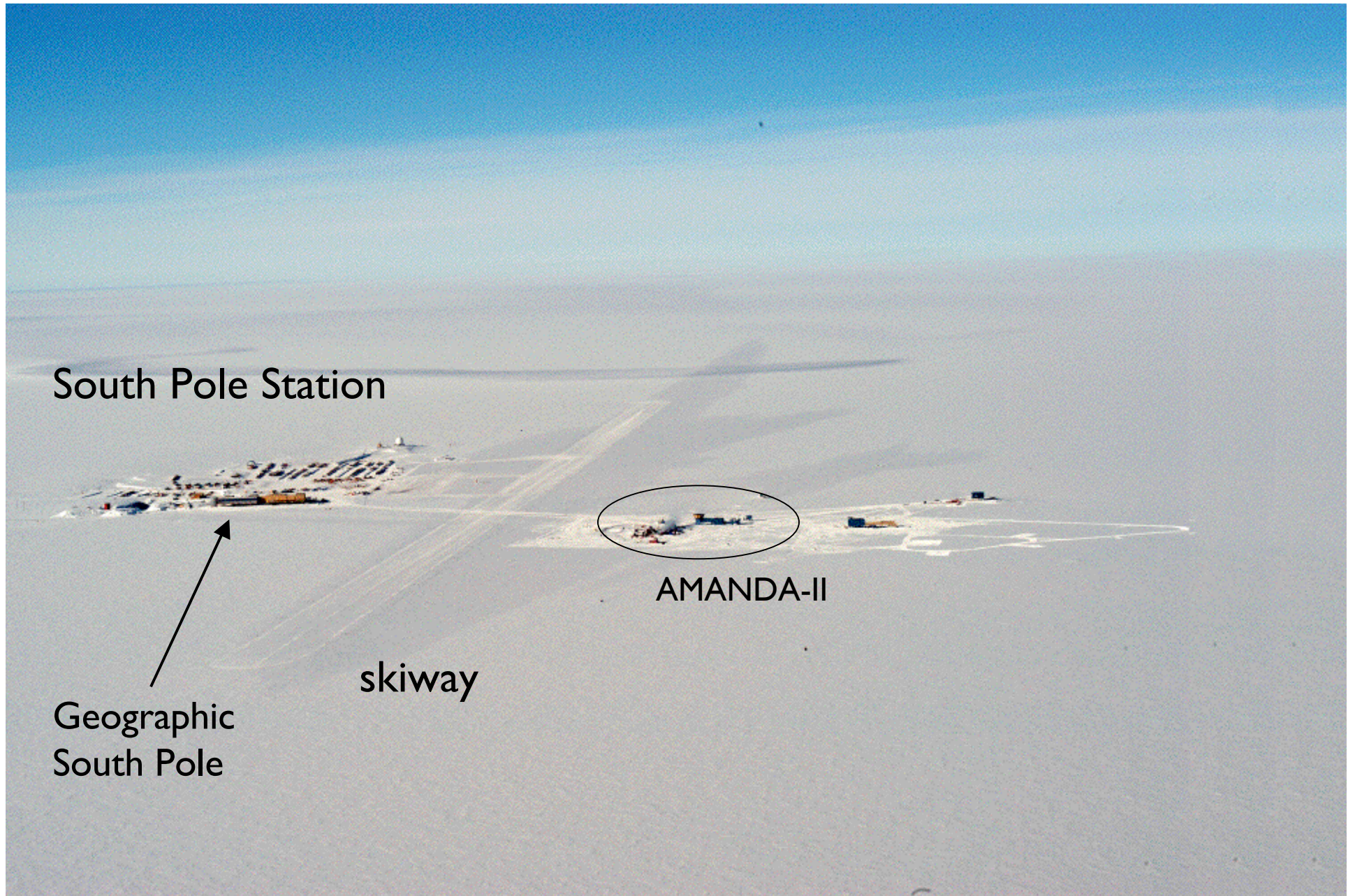
- The AMANDA-II neutrino telescope is buried in deep, clear ice, 1500m under the geographic South Pole

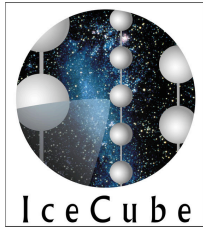
- 677 optical modules: photomultiplier tubes in glass pressure housings (~540 used in analysis)

- Muon direction can be reconstructed to within $2-3^\circ$

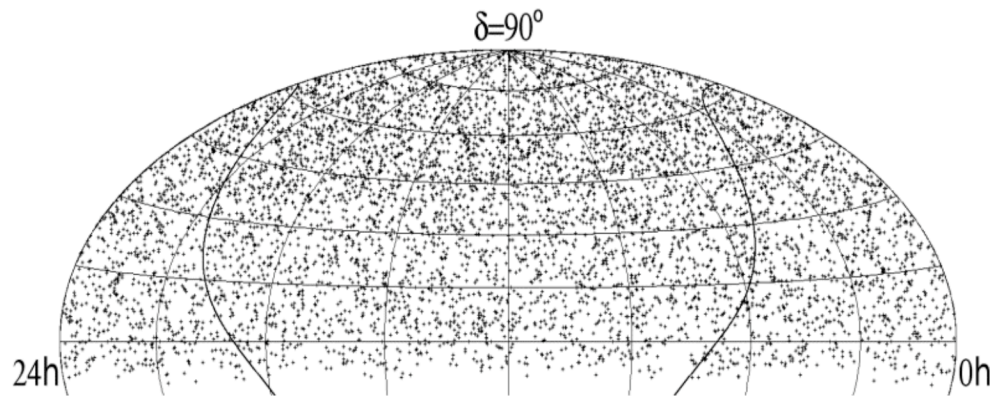


Amundsen-Scott South Pole Research Station





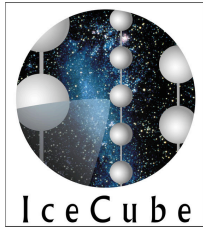
Current Experimental Status



2000-2006 neutrino skymap, courtesy of J. Braun
(publication in preparation; see his talk)

- 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

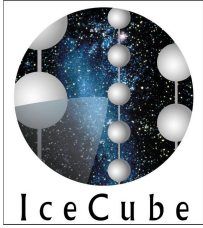
Opportunity for particle physics with high-energy atmospheric ν



New Physics with Neutrinos?

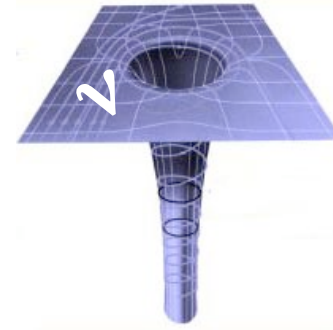
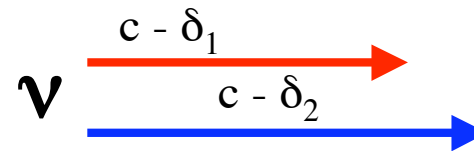
- Neutrinos are already post-Standard Model (massive)
- For $E > 100 \text{ GeV}$ and $m_\nu < 1 \text{ eV}$, Lorentz $\gamma > 10^{11}$
- Oscillations are a sensitive quantum-mechanical interferometer — small shifts in energy can lead to large changes in flavor content

Eidelman *et al.*: “It would be surprising if further surprises were not in store...”



New Physics Effects

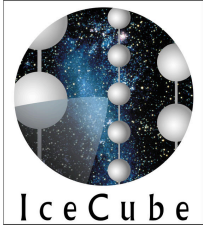
- Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*
- Violations of the equivalence principle (different gravitational coupling)[†]
- Interaction of particles with space-time foam \Rightarrow quantum decoherence of flavor states[‡]



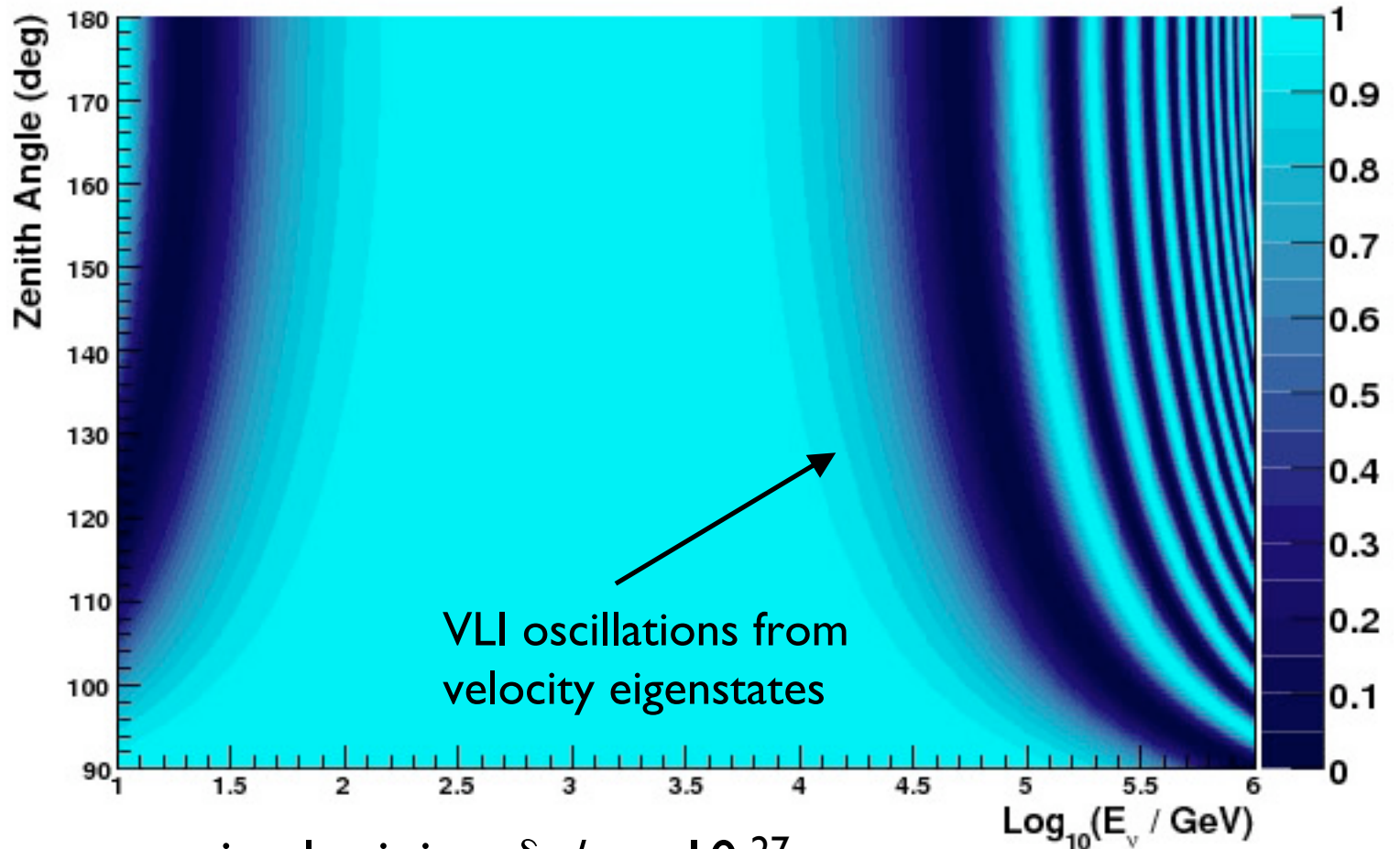
* see e.g. Carroll *et al.*, PRL **87** 14 (2001), Colladay and Kostelecký, PRD **58** 116002 (1998)

[†] see e.g. Gasperini, PRD **39** 3606 (1989)

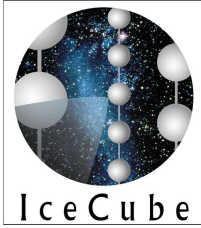
[‡] see e.g. Anchordoqui *et al.*, hep-ph/0506168



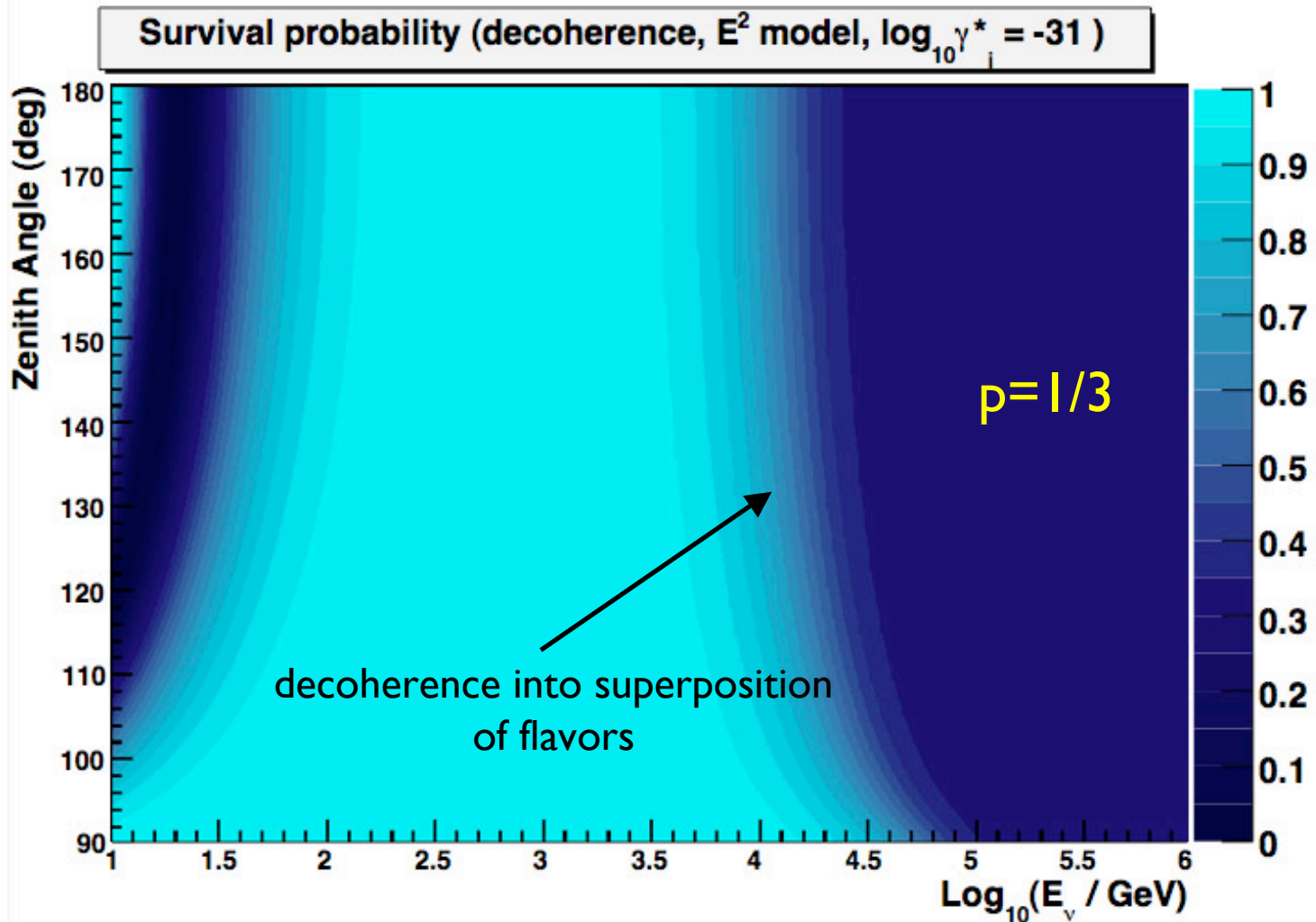
VLI Atmospheric ν_μ Survival Probability

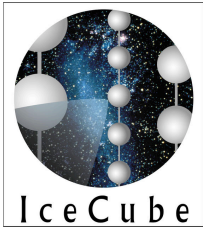


maximal mixing, $\delta c/c = 10^{-27}$

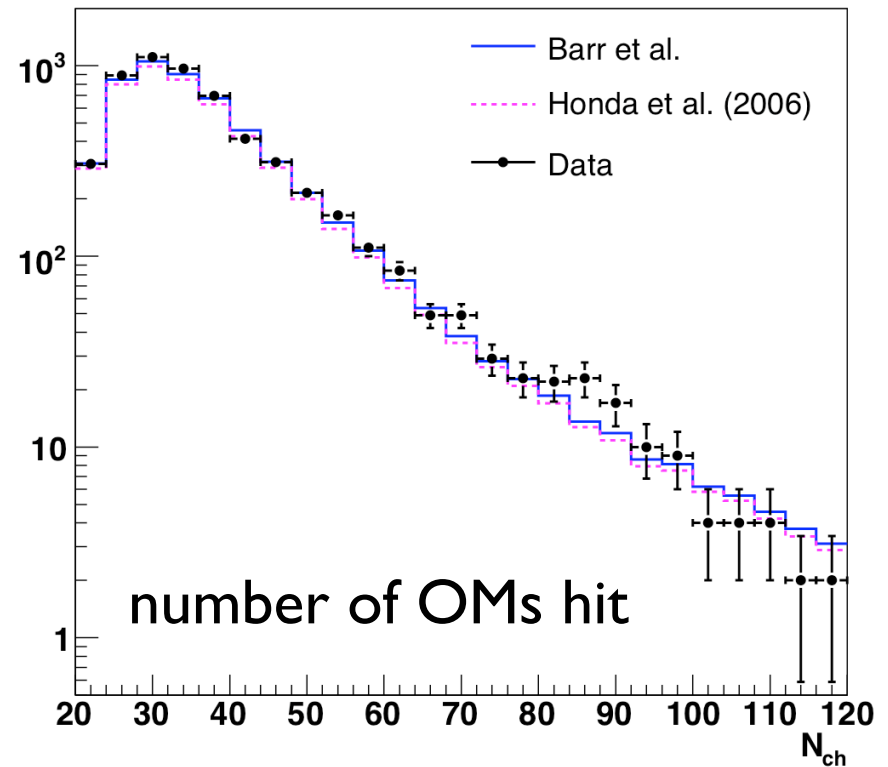
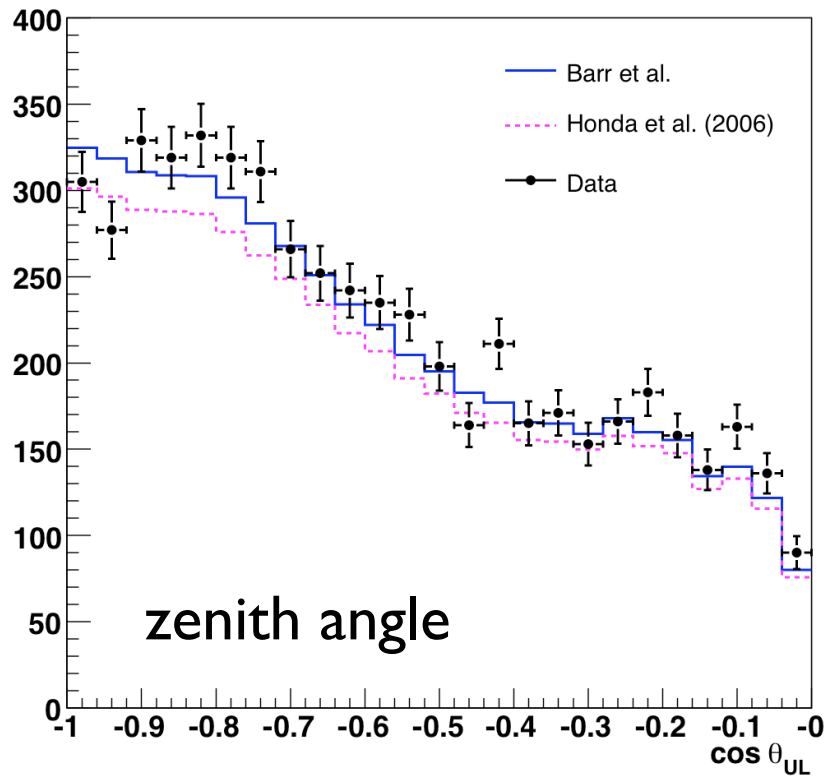


QD Atmospheric ν_μ Survival Probability

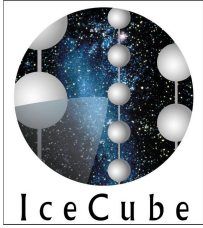




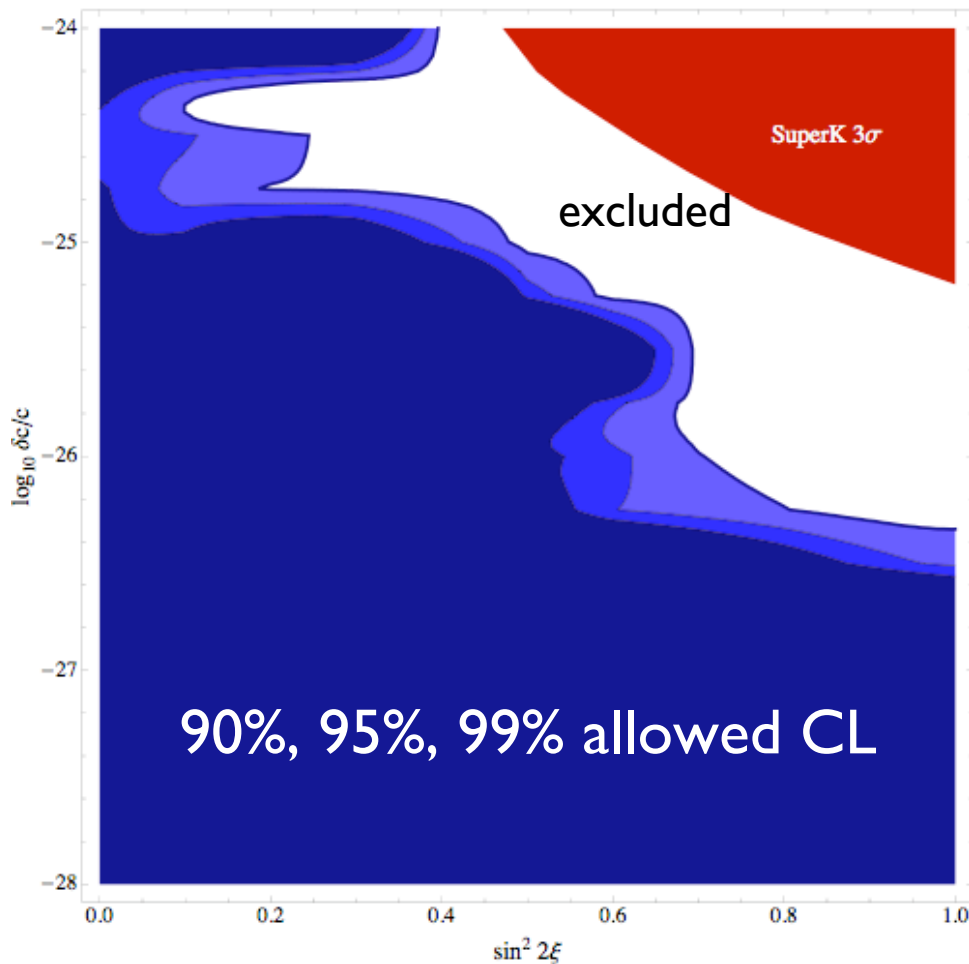
Results: Observables



Data consistent with atmospheric neutrinos + $O(1\%)$ background
Confidence intervals constructed with F+C plus systematics



Results: Preliminary VLI limit



maximal mixing

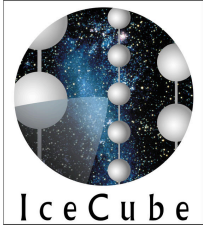
- SuperK+K2K limit*:

$$\delta c/c < 1.9 \times 10^{-27} \text{ (90\%CL)}$$

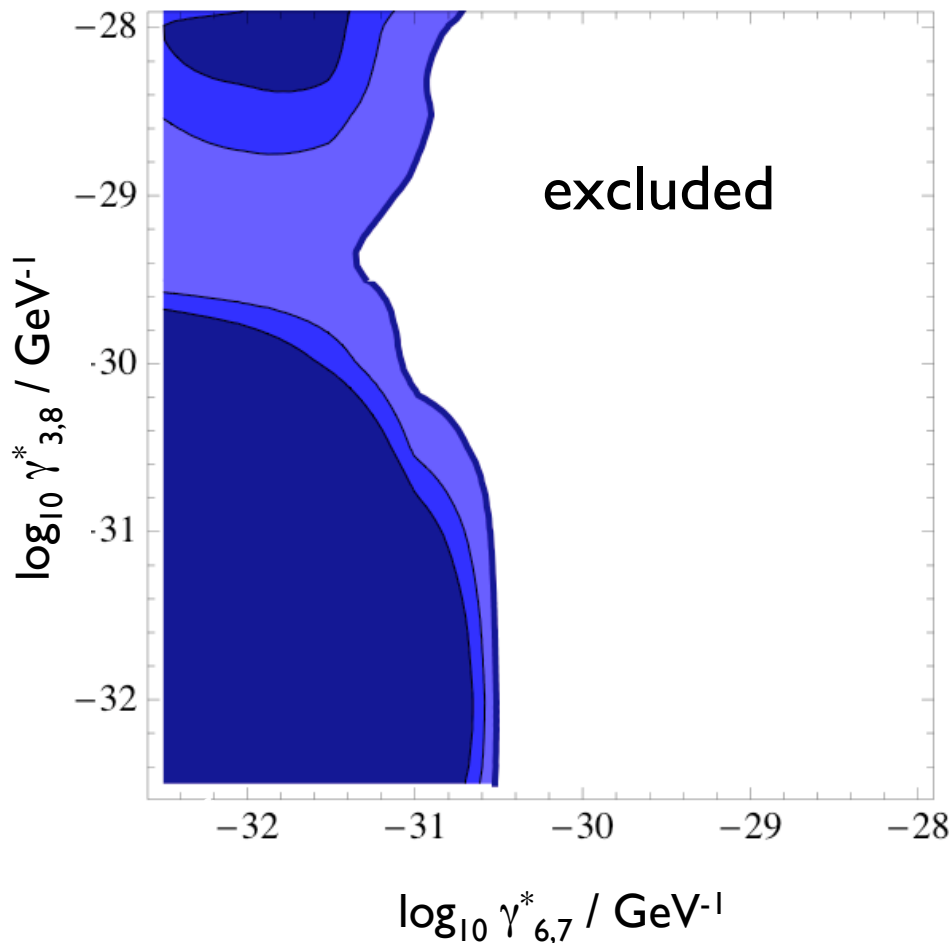
- This analysis:

$$\delta c/c < 2.8 \times 10^{-27} \text{ (90\%CL)}$$

*González-García & Maltoni, PRD **70** 033010 (2004)



Results: Preliminary QD limit

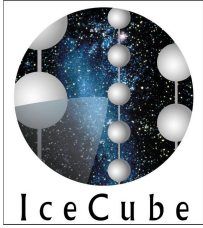


E^2 model

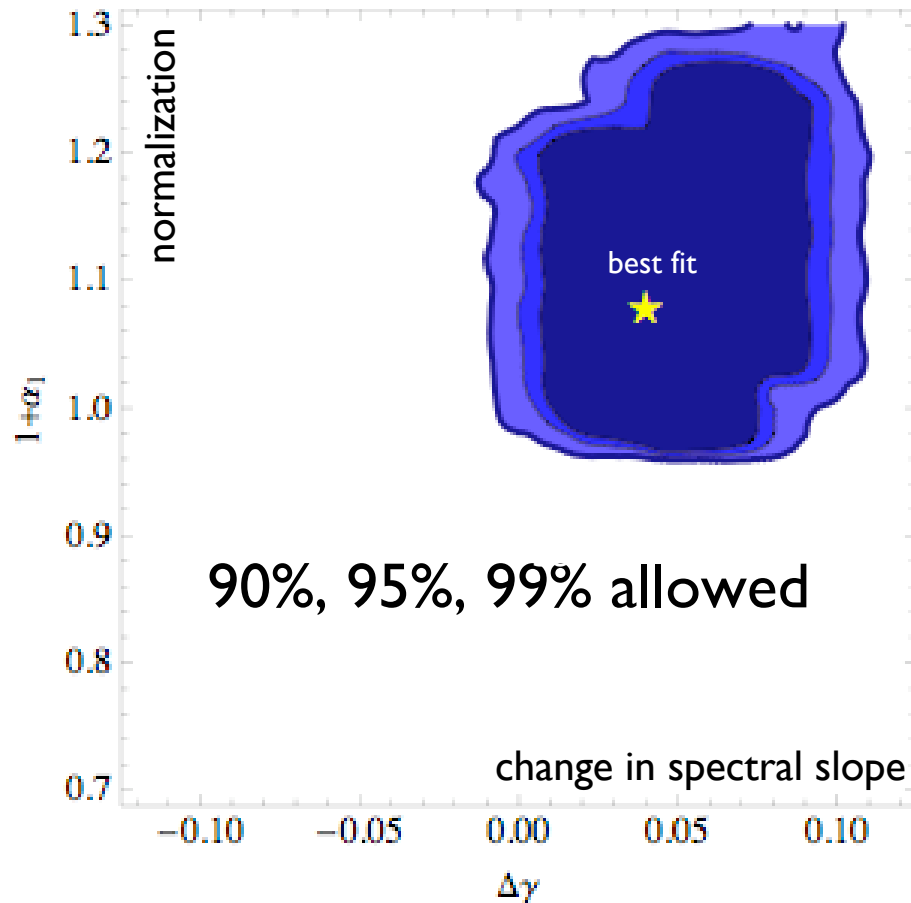
- SuperK limit[‡] (2-flavor):
 $\gamma_i < 0.9 \times 10^{-27} \text{ GeV}^{-1}$ (90% CL)
- ANTARES sensitivity* (2-flavor):
 $\gamma_i \sim 10^{-30} \text{ GeV}^{-1}$ (3 years, 90% CL)
- This analysis:
 $\gamma_i < 1.3 \times 10^{-31} \text{ GeV}^{-1}$ (90% CL)

* Morgan *et al.*, astro-ph/0412618

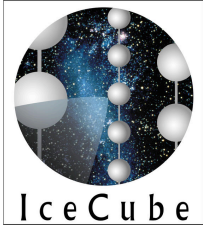
‡ Lisi, Marrone, and Montanino, PRL **85** 6 (2000)



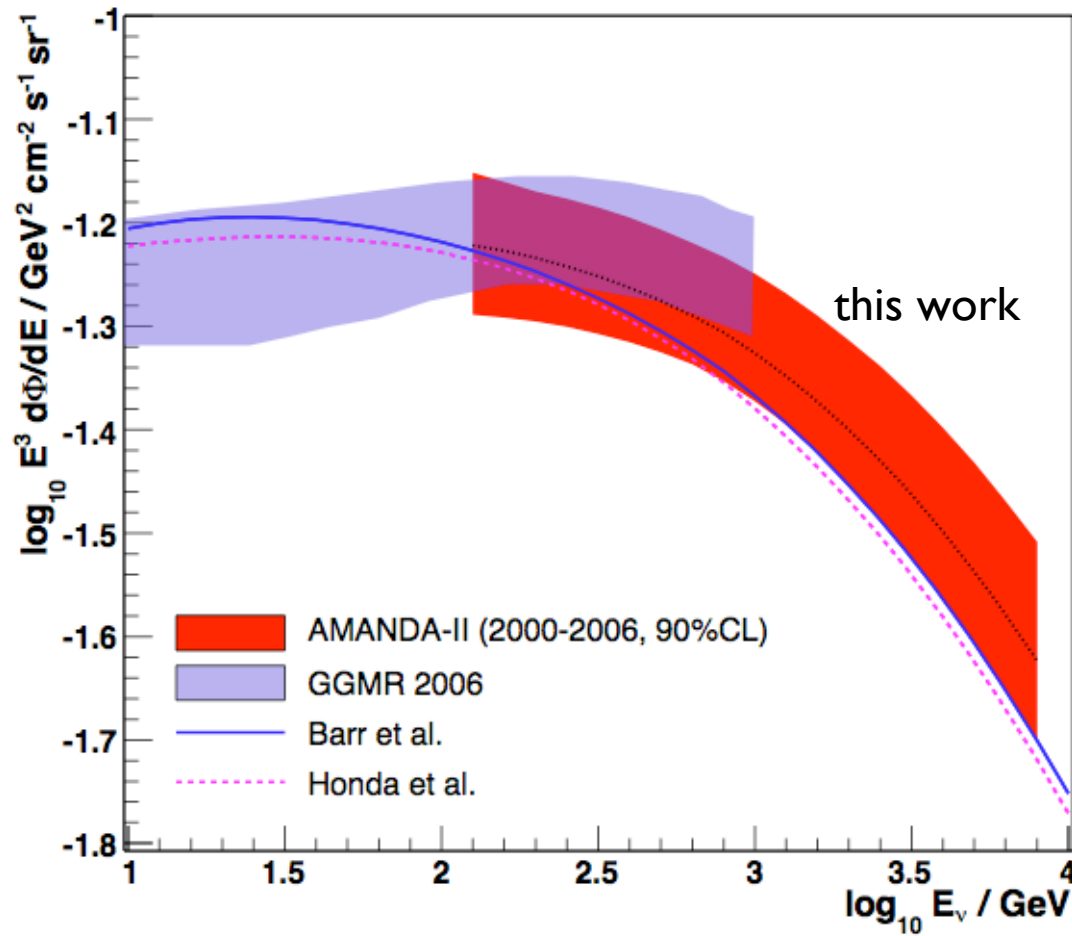
Conventional Analysis



- Parameters of interest: normalization, spectral slope change $\Delta\gamma$ relative to Barr *et al.*
- Result: determine atmospheric muon neutrino flux (“forward-folding” approach)

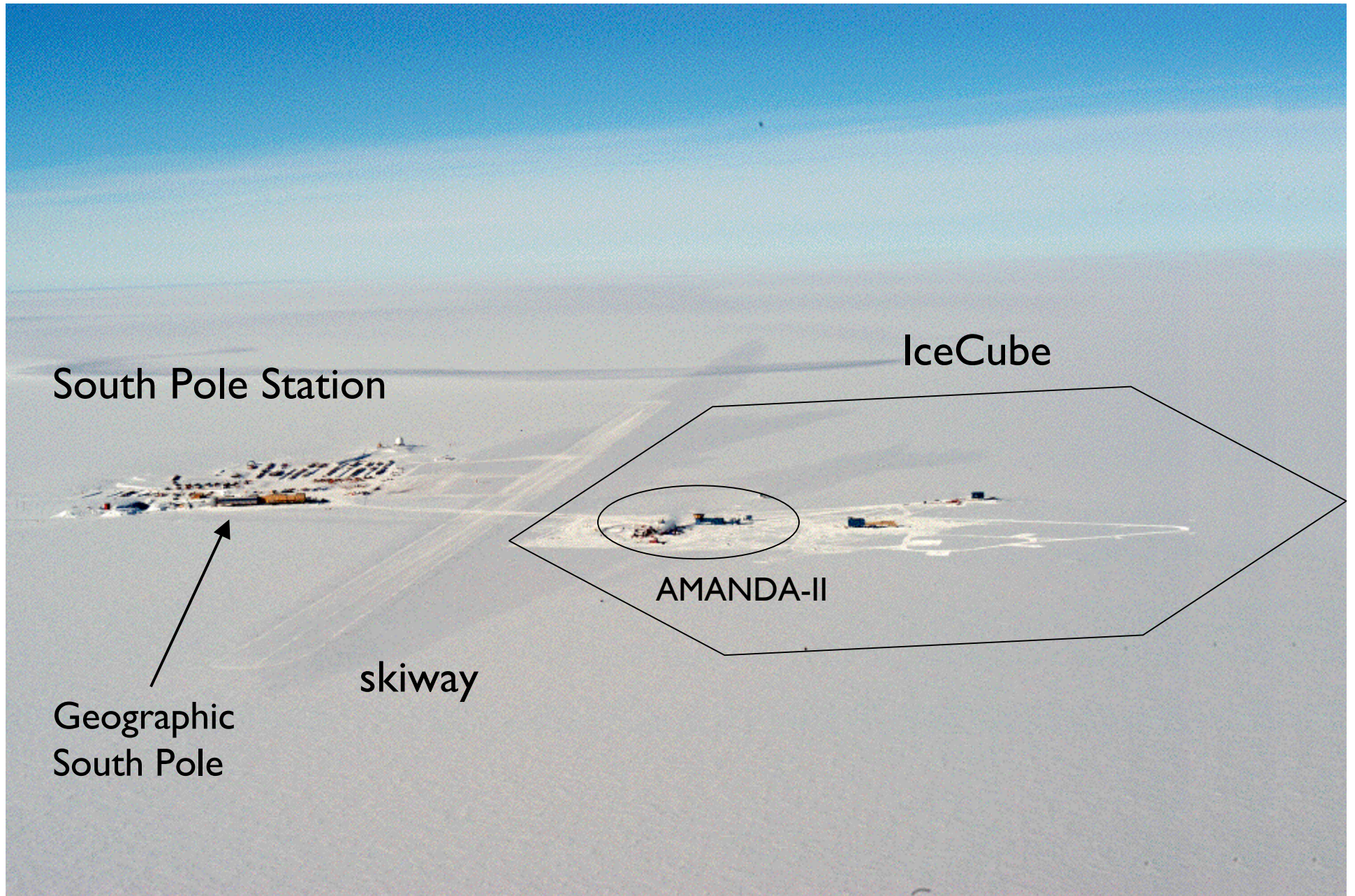


Result Spectrum



Blue band: SuperK data, González-García, Maltoni, & Rojo, JHEP 0610 (2006) 075

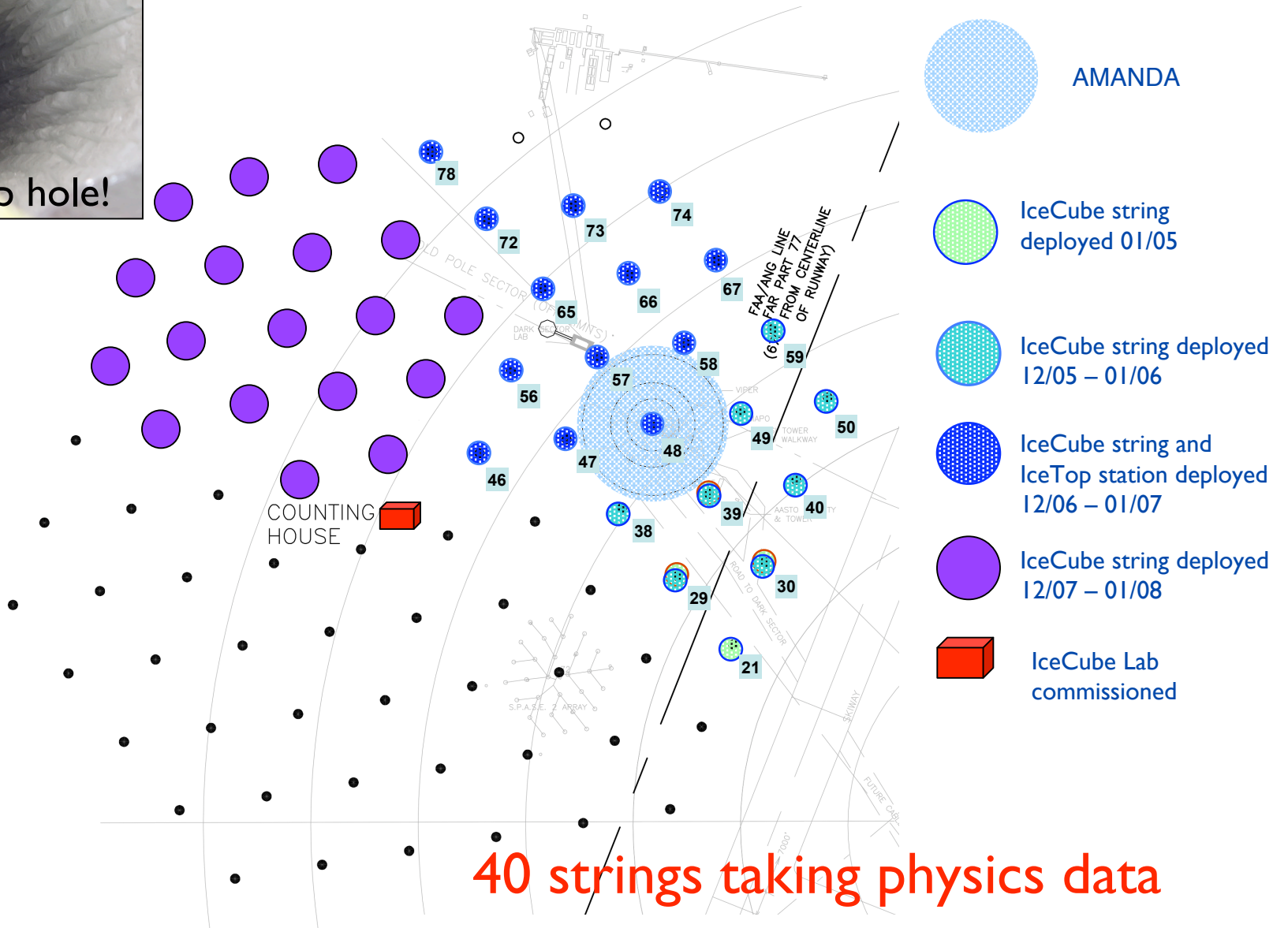
Update on IceCube





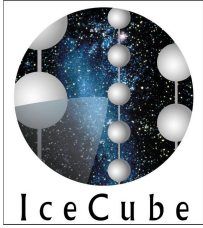
2500m deep hole!

Installation Status & Plans

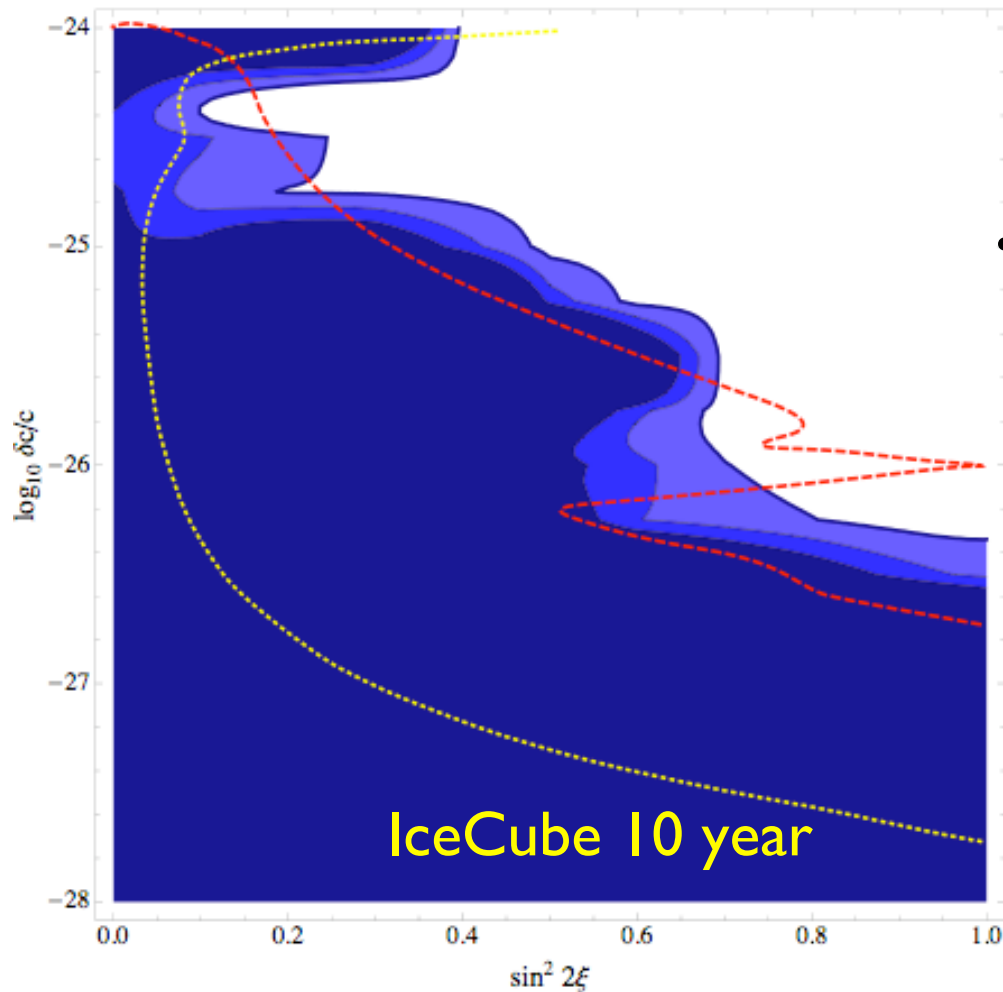


40 strings taking physics data

Planning for at least 16 strings in 2008/09

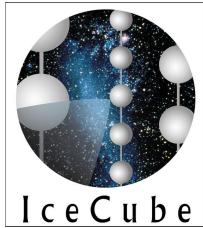


IceCube VLI Sensitivity



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

Bartol Research Institute, Delaware
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

Sweden:

Uppsala Universitet
Stockholm Universitet

UK:

Oxford University

Netherlands:

Utrecht University

Switzerland:

EPFL

Germany:

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

Belgium:

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

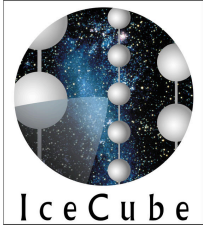
Japan:

Chiba University

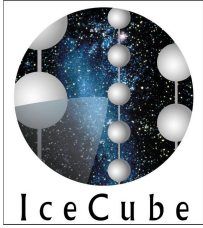
New Zealand:

University of Canterbury

Thank you!



Backup Slides



Violation of Lorentz Invariance (VLI)

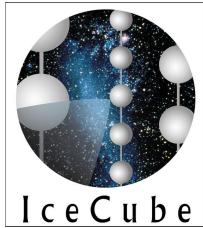
- Lorentz and/or CPT violation is appealing as a (relatively) low-energy probe of QG
- Effective field-theoretic approach by Kostelecký *et al.* (SME: hep-ph/9809521, hep-ph/0403088)

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

$$\Gamma_{AB}^\nu \equiv \gamma^\nu \delta_{AB} + \underline{c_{AB}^{\mu\nu}} \gamma_\mu + \underline{d_{AB}^{\mu\nu}} \gamma_5 \gamma_\mu + \underline{e_{AB}^\nu} + \underline{if_{AB}^\nu} \gamma_5 + \underline{\frac{1}{2} g_{AB}^{\lambda\mu\nu}} \sigma_{\lambda\mu},$$

$$M_{AB} \equiv m_{AB} + im_{5AB} \gamma_5 + \underline{a_{AB}^\mu} \gamma_\mu + \underline{b_{AB}^\mu} \gamma_5 \gamma_\mu + \underline{\frac{1}{2} H_{AB}^{\mu\nu}} \sigma_{\mu\nu}.$$

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



Rotationally Invariant VLI

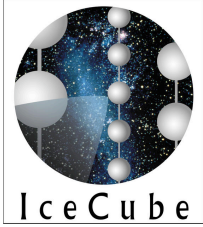
- Only $c_{AB}^{00} \neq 0$; equivalent to modified dispersion relation*:

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

- 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

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

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

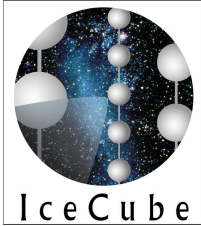


VLI Phenomenology

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

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

- 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

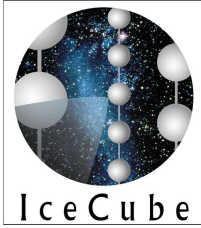
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\Theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \mathcal{R} \right)$$

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

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

$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m_{23}^2}$$

- For atmospheric ν , conventional oscillations turn off above ~ 50 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 ξ , phase η)



Decoherence + Atmospheric Oscillations

characteristic exponential behavior

$$P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2} \left(e^{-\gamma_3 L} \cos^4 \theta_{23} + \frac{1}{12} e^{-\gamma_8 L} (1 - 3 \cos 2\theta_{23})^2 \right. \\ \left. + 4e^{-\frac{\gamma_6 + \gamma_7}{2} L} \cos^2 \theta_{23} \sin^2 \theta_{23} \left(\cos \left[\frac{L}{2} \sqrt{\left| (\gamma_6 - \gamma_7)^2 - \left(\frac{\Delta m_{23}^2}{E} \right)^2} \right|} \right] \right. \right. \\ \left. \left. + \sin \left[\frac{L}{2} \sqrt{\left| (\gamma_6 - \gamma_7)^2 - \left(\frac{\Delta m_{23}^2}{E} \right)^2} \right|} \right] \frac{(\gamma_6 - \gamma_7)}{\sqrt{\left| (\gamma_6 - \gamma_7)^2 - \left(\frac{\Delta m_{23}^2}{E} \right)^2} \right|}} \right) \right)$$

1:1:1 ratio after decoherence

derived from Barenboim, Mavromatos *et al.* (hep-ph/0603028)

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

$n = -1$
preserves
Lorentz invariance

$n = 0$
simplest

$n = 2$
recoiling
D-branes*

$n = 3$
Planck-suppressed
operators‡

*Ellis *et al.*, hep-th/9704169

‡ Anchordoqui *et al.*, hep-ph/0506168