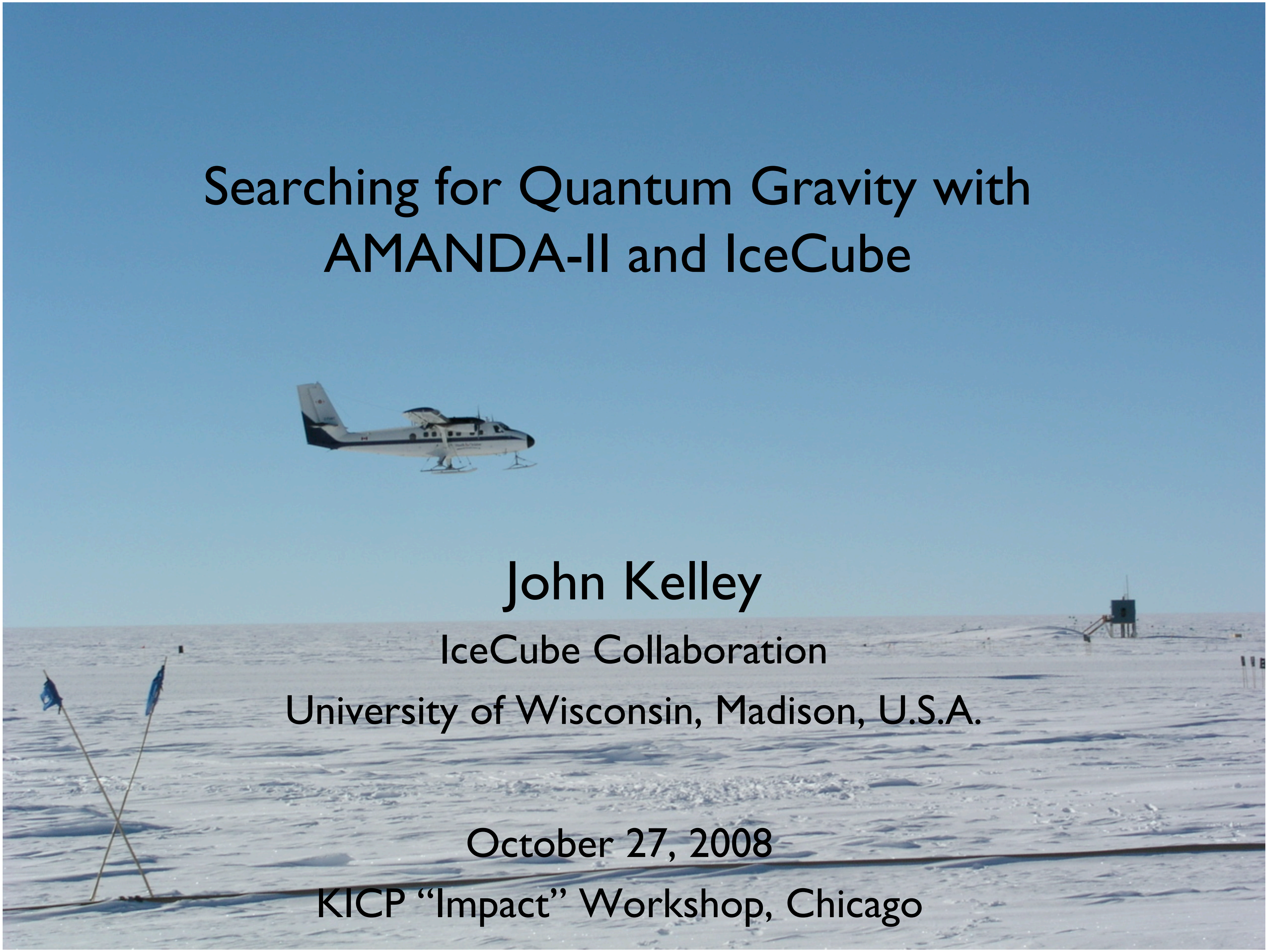


Searching for Quantum Gravity with AMANDA-II and IceCube

John Kelley

IceCube Collaboration

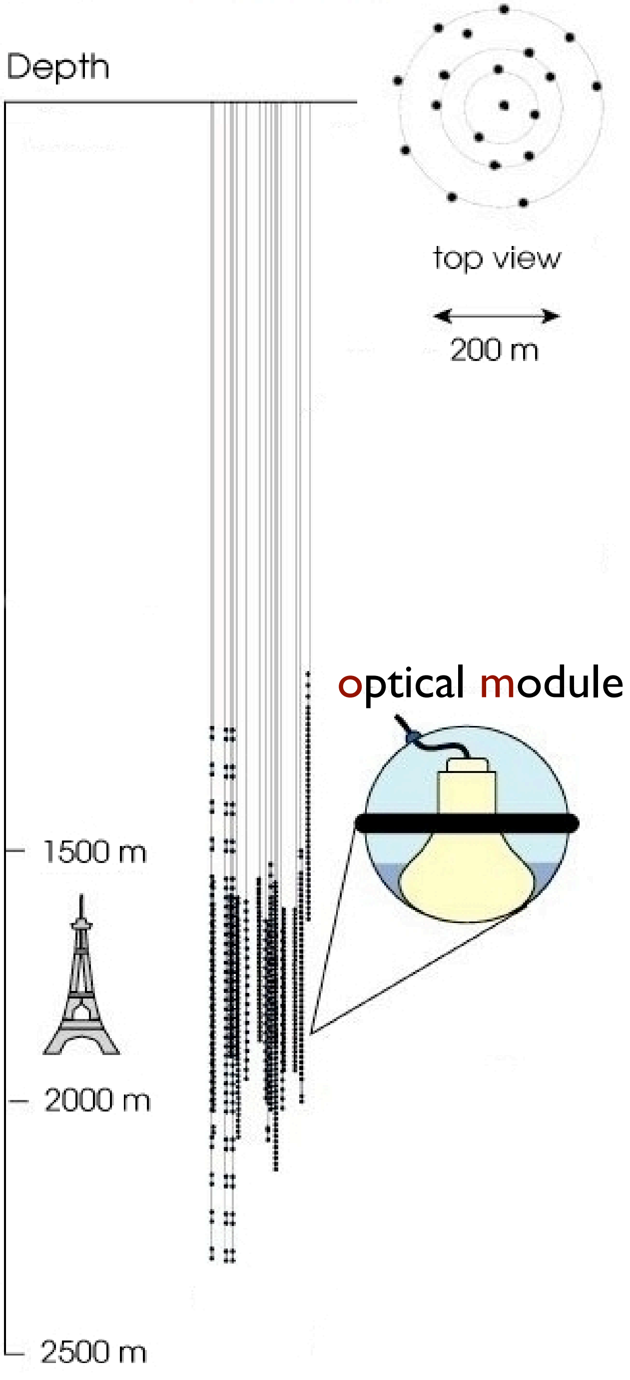
University of Wisconsin, Madison, U.S.A.

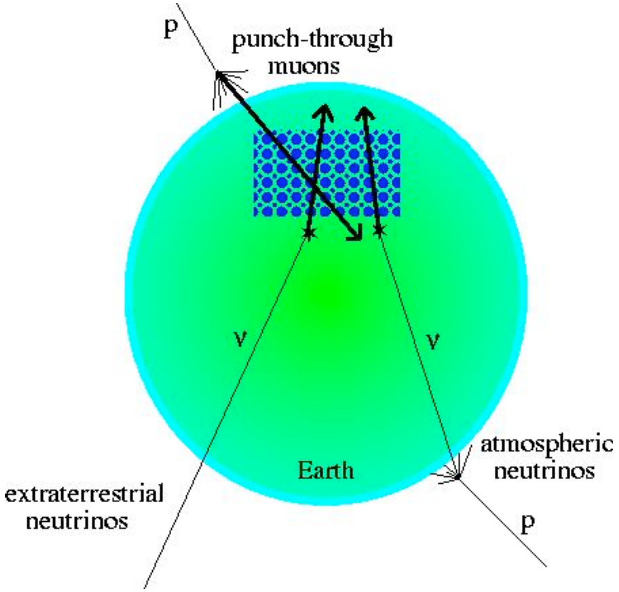
October 27, 2008

KICP “Impact” Workshop, Chicago

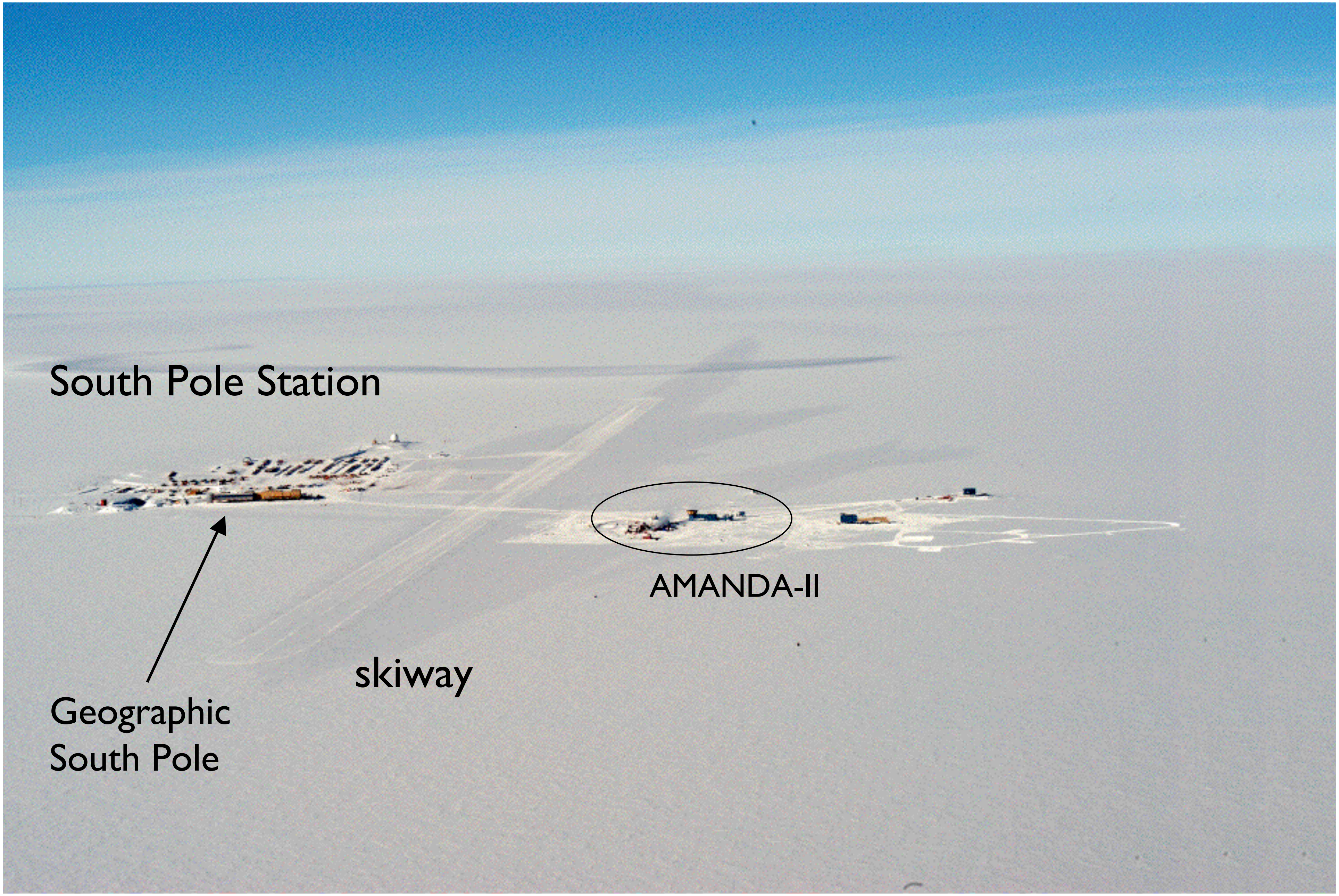
AMANDA-II

- 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°

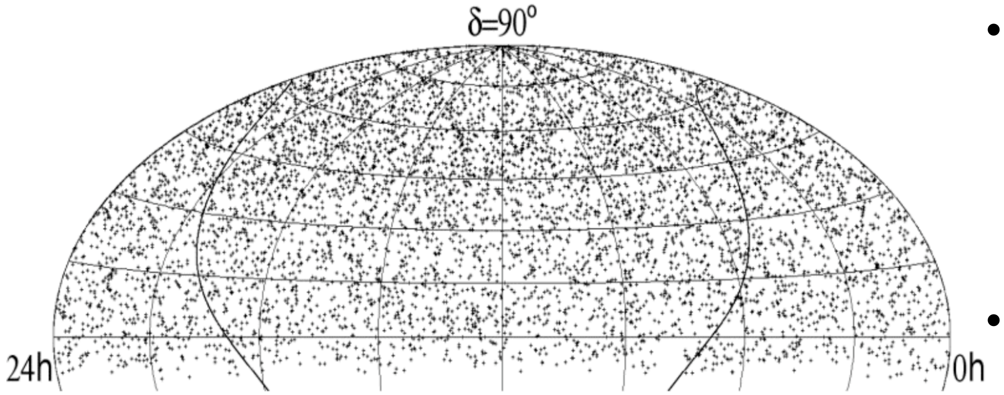




Amundsen-Scott
South Pole Research Station



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

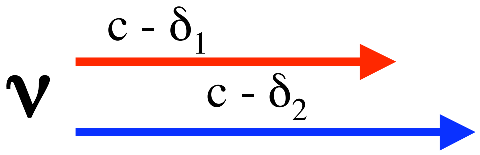
New Physics with Neutrinos?

- Neutrinos are already post-Standard Model (massive)
- For E > 100 GeV and $m_\nu < 1$ 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…”

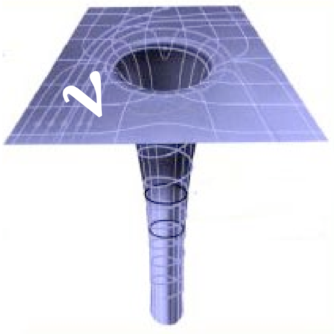
New Physics Effects

- 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 ⇒ quantum decoherence of flavor states‡



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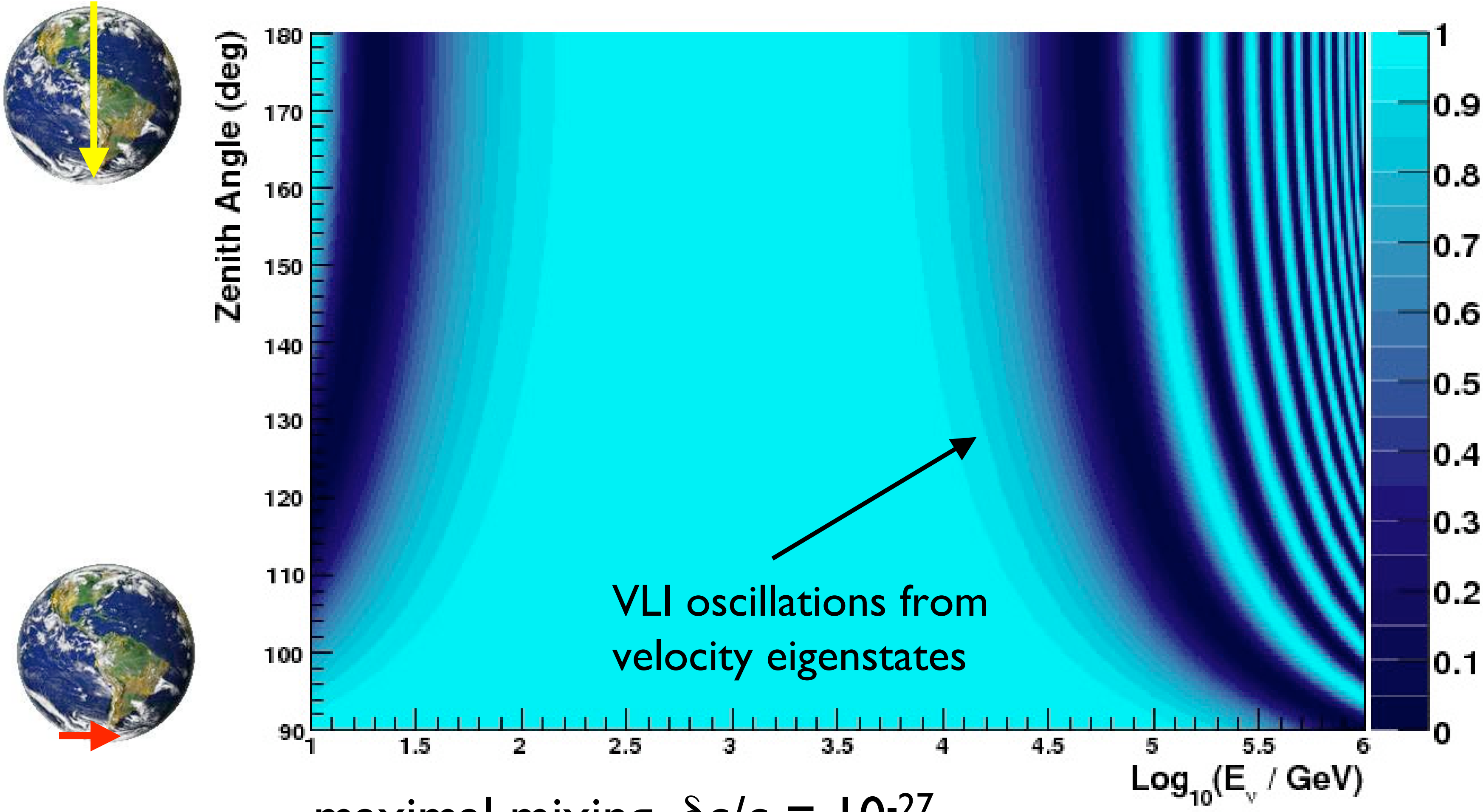
* see e.g. Carroll *et al.*, PRL **87** 14 (2001), Colladay and Kostelecký, PRD **58** 116002 (1998)

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

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

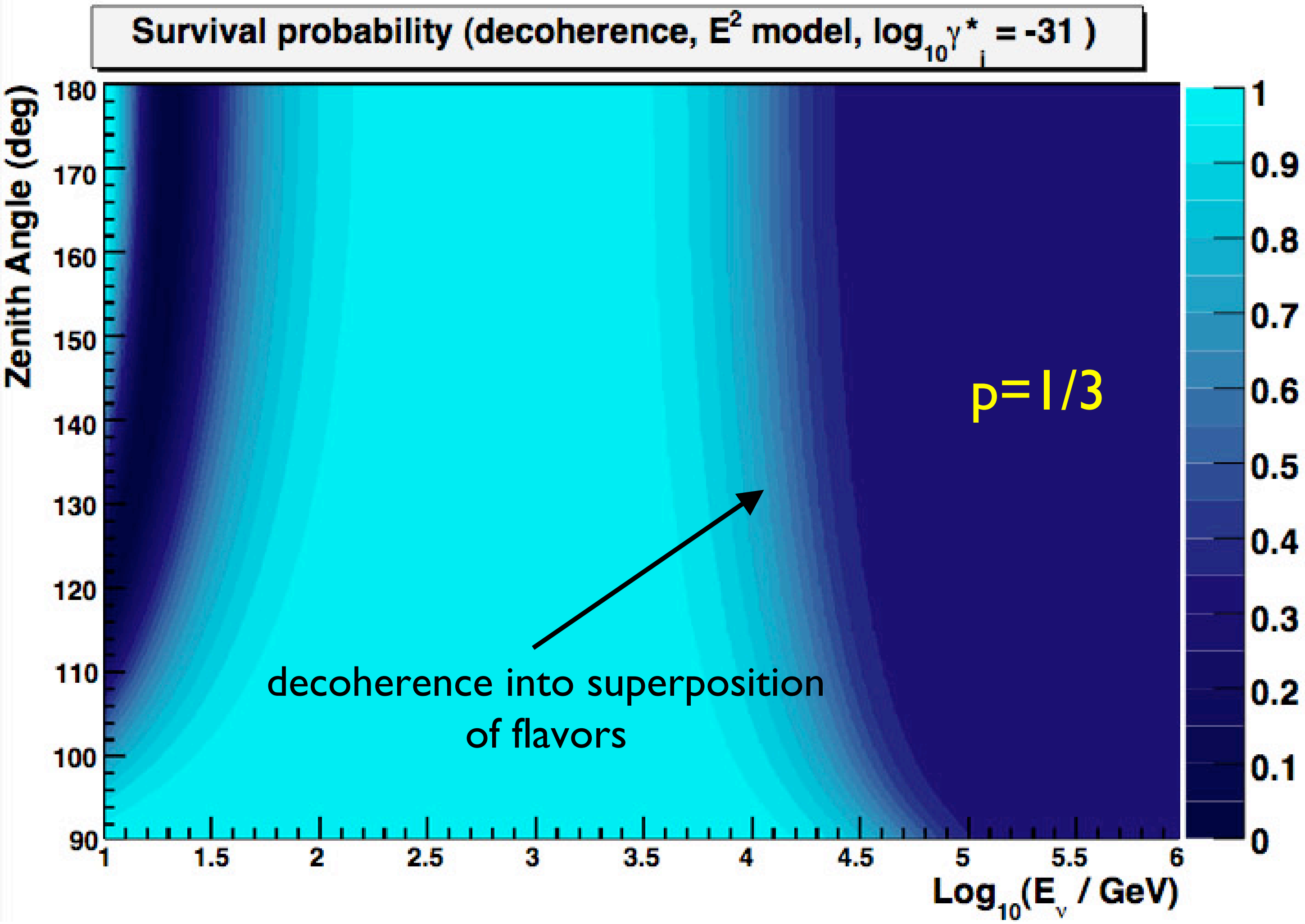
VLI Atmospheric ν_μ Survival Probability



VLI oscillations from velocity eigenstates

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

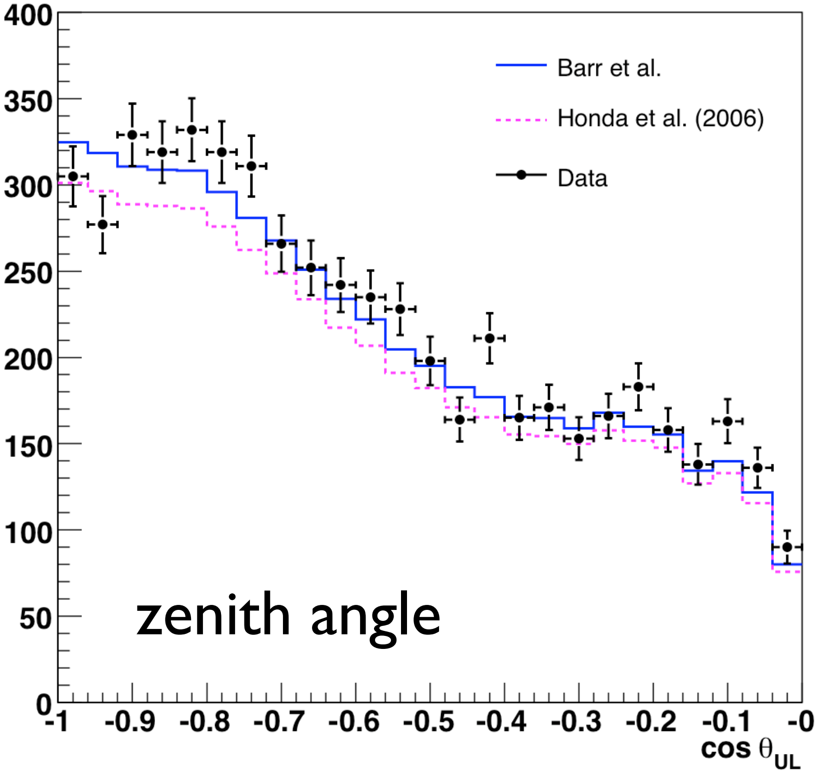
QD Atmospheric ν_μ Survival Probability

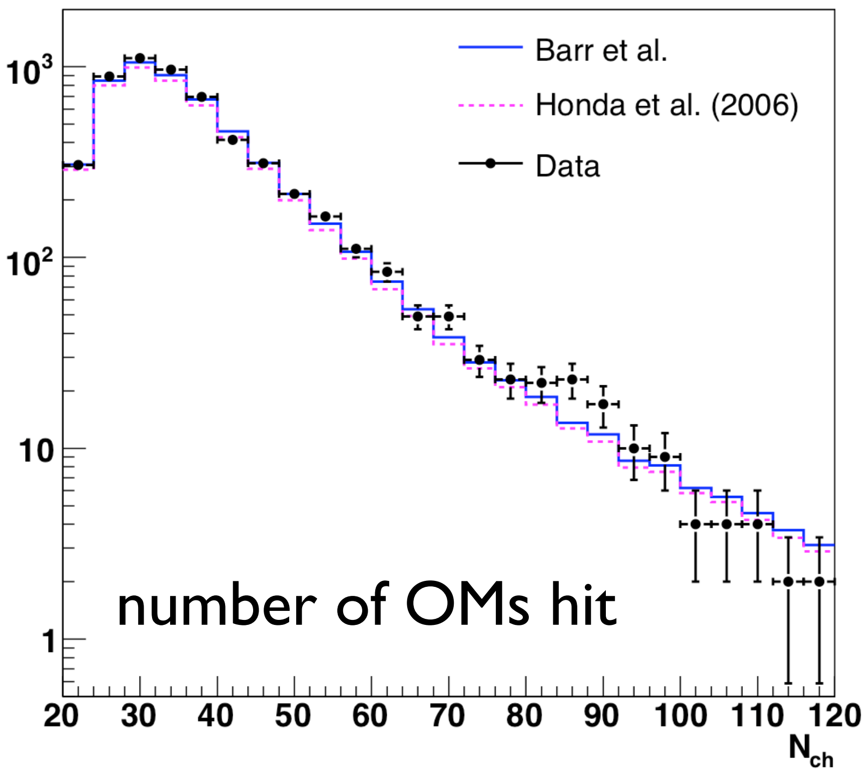


p=1/3

decoherence into superposition of flavors

Results: Observables

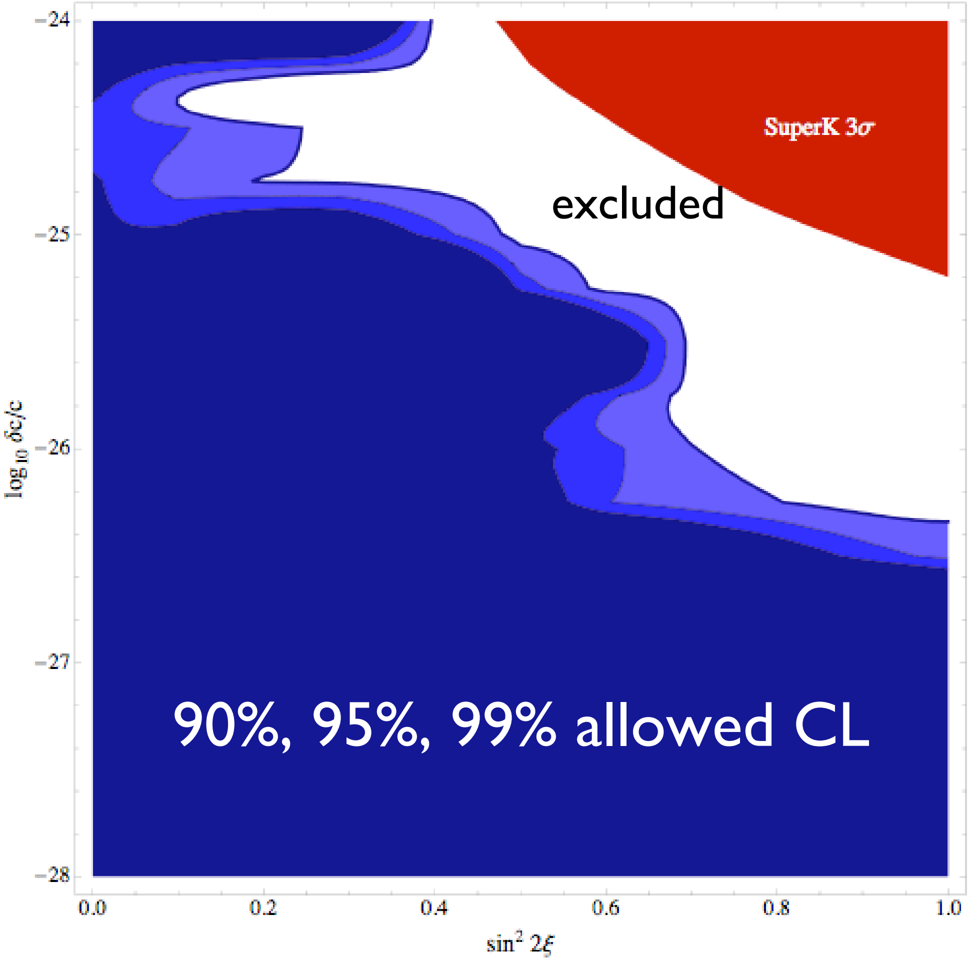




Data consistent with atmospheric neutrinos + O(1%) background

Confidence intervals constructed with F+C plus systematics

Results: Preliminary VLI limit



maximal mixing

- SuperK+K2K limit*:

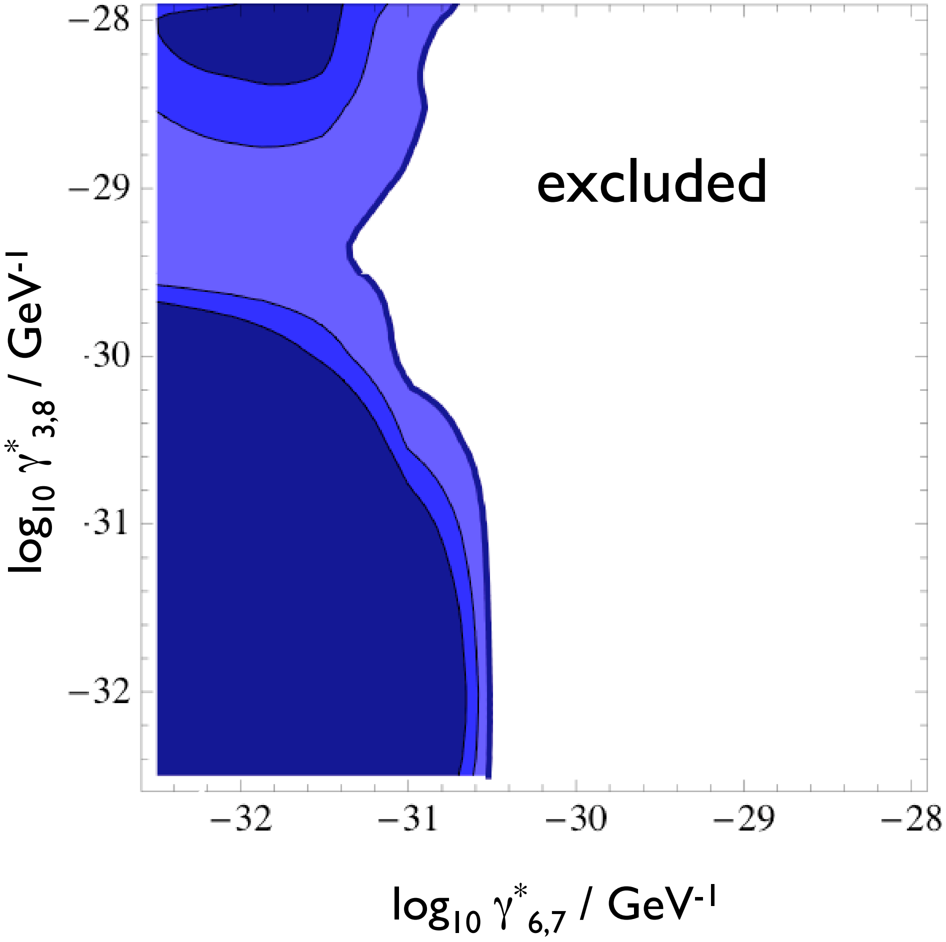
  $\delta c/c < 1.9 \times 10^{-27}$ (90%CL)

- This analysis:

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

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

Results: Preliminary QD limit



E^2 model

- SuperK limit[‡] (2-flavor):

  $\gamma_i < 0.9 \times 10^{-27}$ GeV^{-1} (90% CL)

- ANTARES sensitivity* (2-flavor):

  $\gamma_i \sim 10^{-30}$ GeV^{-1} (3 years, 90% CL)

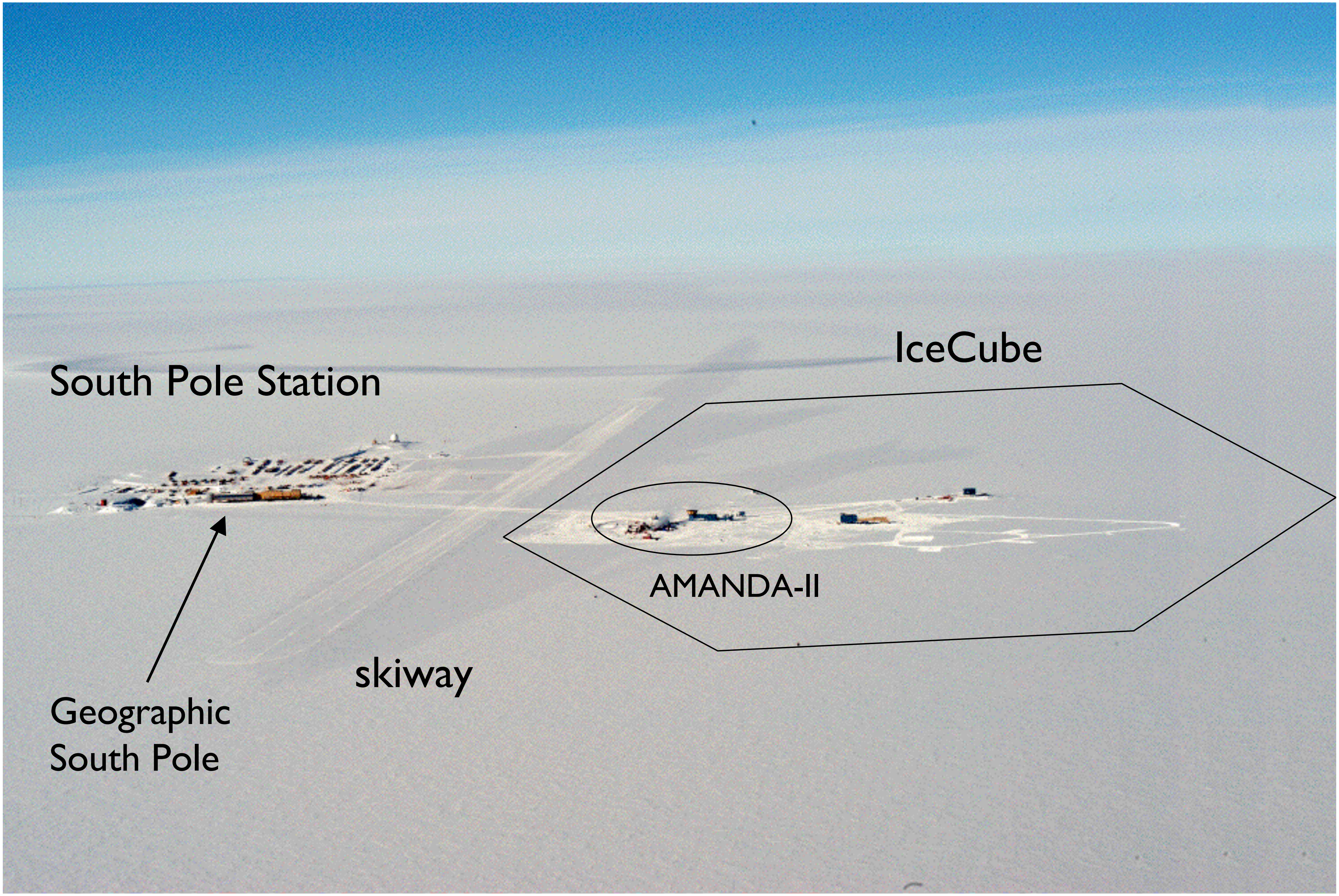
- This analysis:

  $\gamma_i < 1.3 \times 10^{-31}$ GeV^{-1} (90% CL)

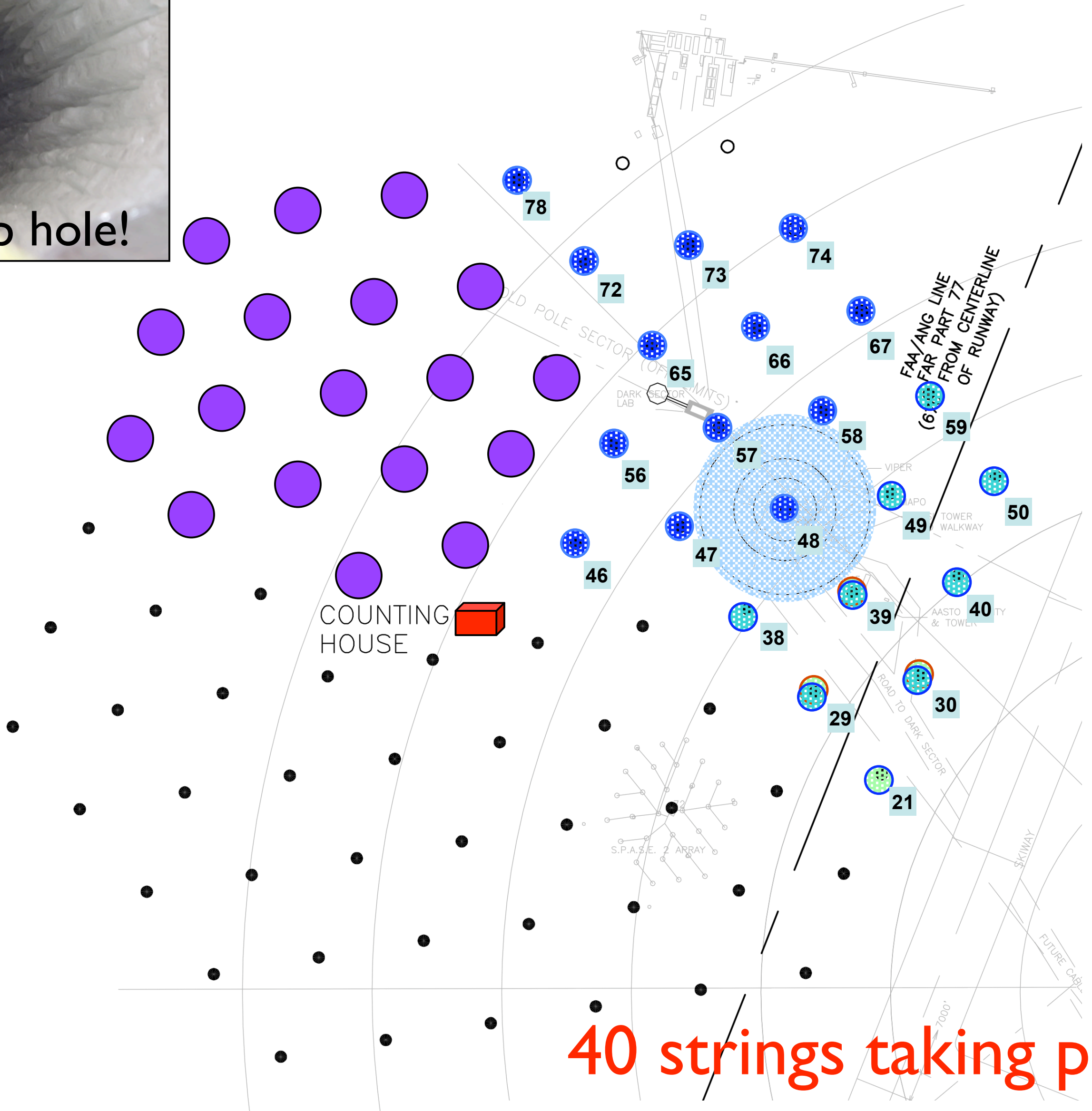
* Morgan *et al.*, astro-ph/0412618

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

Update on IceCube



Installation Status & Plans



▨ AMANDA

● IceCube string deployed 01/05

● IceCube string deployed 12/05 – 01/06

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

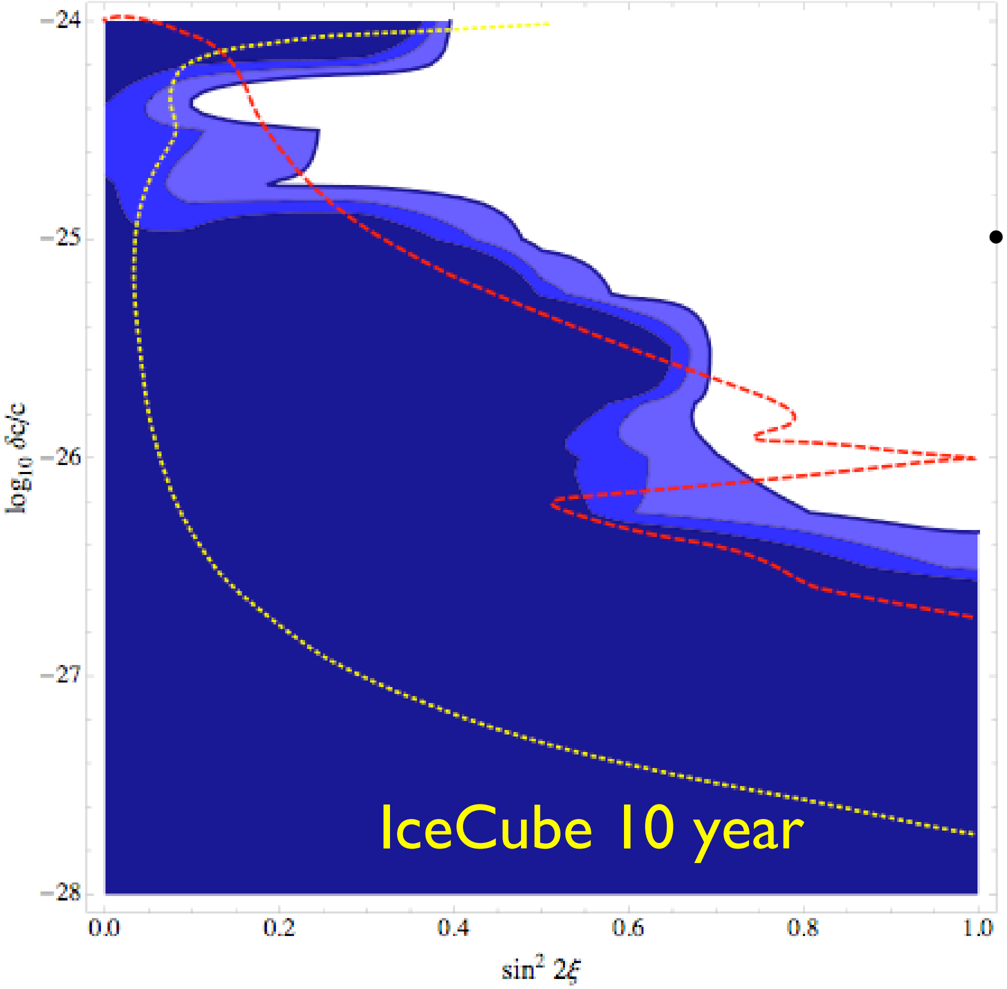
● IceCube string deployed 12/07 – 01/08

🟥 IceCube Lab commissioned

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

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:

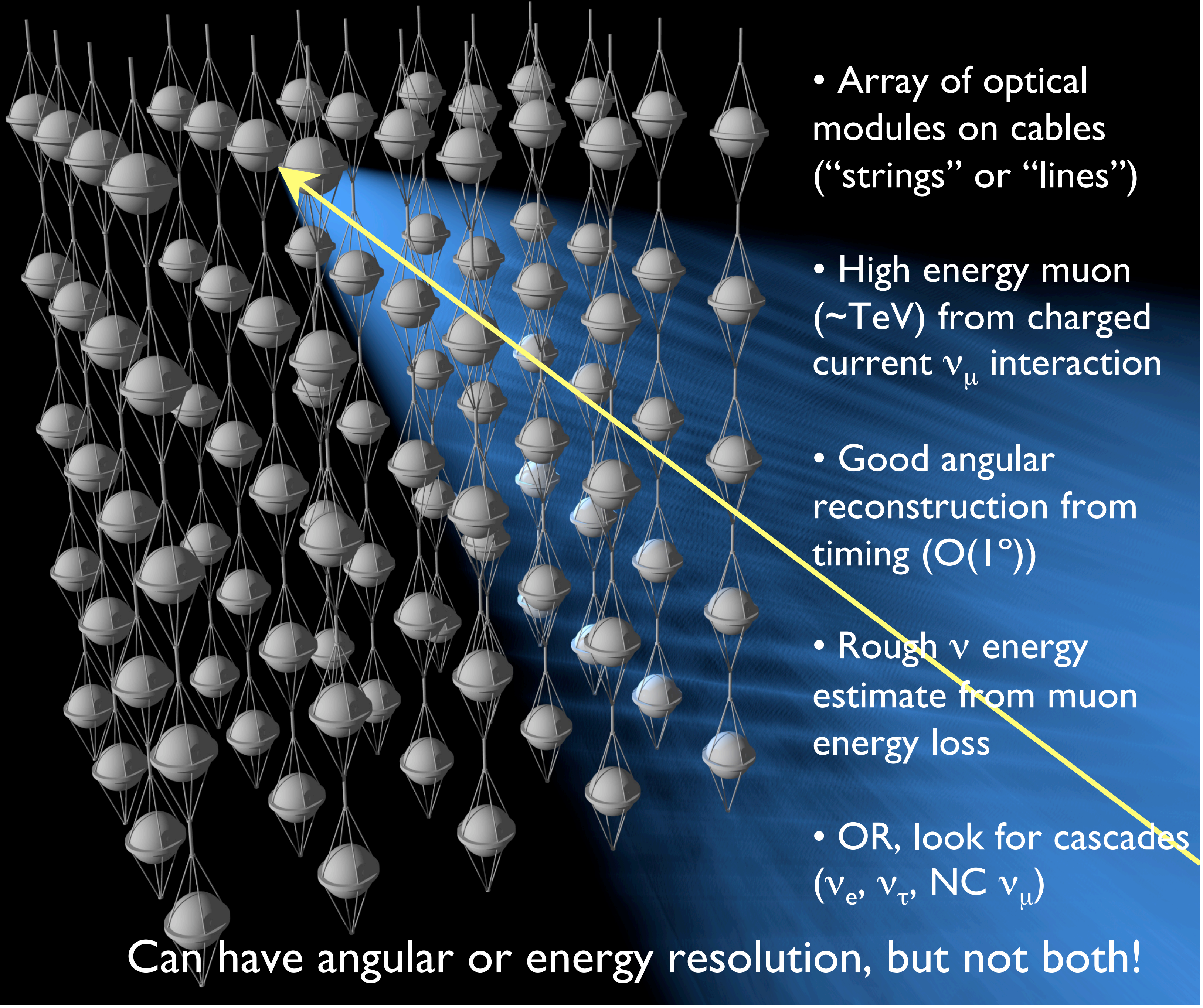
Chiba University

New Zealand:

University of Canterbury

Thank you!

Backup Slides



- Array of optical modules on cables ("strings" or "lines")
- High energy muon (~TeV) from charged current ν_μ interaction
- Good angular reconstruction from timing (O(1°))
- Rough ν energy estimate from muon energy loss
- OR, look for cascades (ν_e, ν_τ, NC ν_μ)

Can have angular or energy resolution, but not both!

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)

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

$$\Gamma^{\nu}_{AB} \equiv \gamma^{\nu}\delta_{AB} + \underline{c^{\mu\nu}_{AB}\gamma_{\mu}} + \underline{d^{\mu\nu}_{AB}\gamma_5\gamma_{\mu}} + \underline{e^{\nu}_{AB}} + \underline{if^{\nu}_{AB}\gamma_5} + \underline{\tfrac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu}},$$

$$M_{AB} \equiv m_{AB} + im_{5AB}\gamma_5 + \underline{a^{\mu}_{AB}\gamma_{\mu}} + \underline{b^{\mu}_{AB}\gamma_5\gamma_{\mu}} + \underline{\tfrac{1}{2}H^{\mu\nu}_{AB}\sigma_{\mu\nu}}.$$

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

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

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

VLI Phenomenology

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

$$(h_{\text{eff}})_{ab} = |\vec{p}|\delta_{ab}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{1}{2|\vec{p}|}\begin{pmatrix}(\widetilde{m}^2)_{ab} & 0\\ 0 & (\widetilde{m}^2)^*_{ab}\end{pmatrix}$$

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

- 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

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

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

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

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

- 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 δ*c*/*c*, and distort the zenith angle / energy spectrum (other parameters: mixing angle ξ, phase η)

González-García, Halzen, and Maltoni, hep-ph/0502223

Decoherence + Atmospheric Oscillations

characteristic exponential behavior

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

1:1:1 ratio after decoherence

$$+ 4e^{-\frac{\gamma_6+\gamma_7}{2}L}\cos^2\theta_{23}\sin^2\theta_{23}\left(\cos\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right]\right.$$

$$\left.\left. + \sin\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right]\frac{(\gamma_6-\gamma_7)}{\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}}\right)\right)$$

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

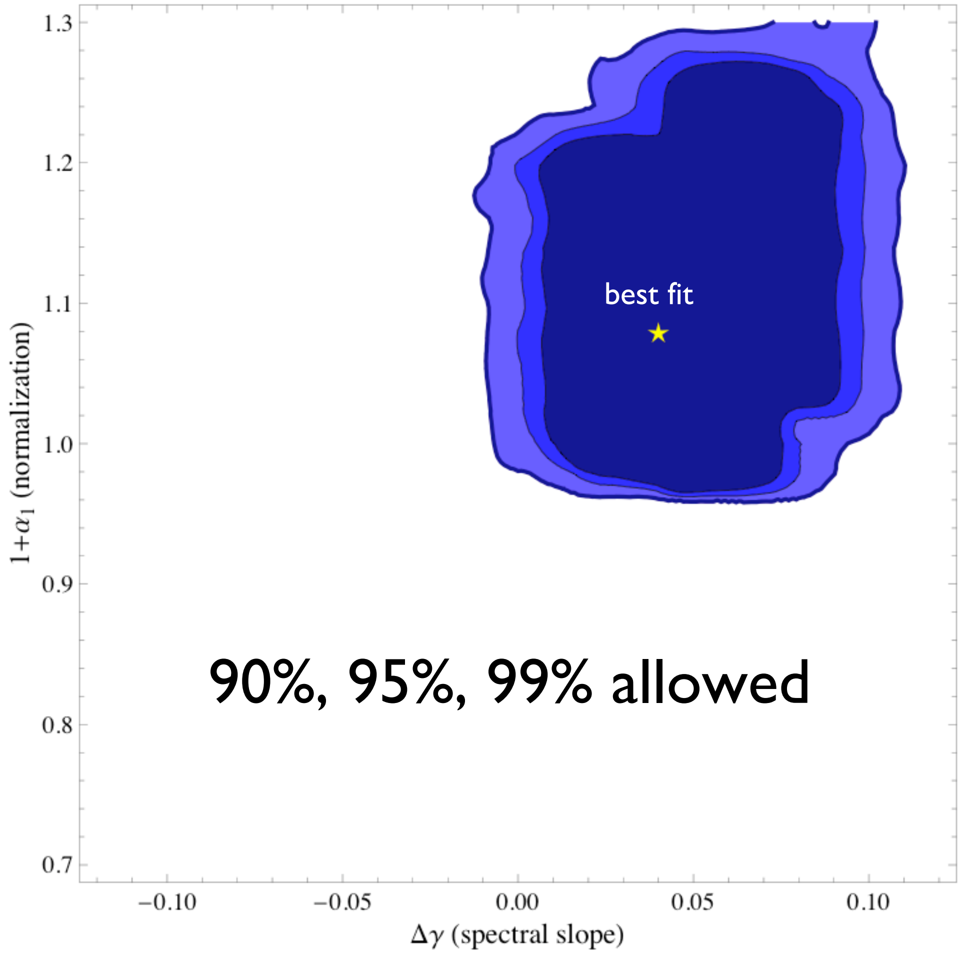
Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

n = -1	*n = 0*	*n = 2*	*n = 3*
preserves Lorentz invariance	simplest	recoiling D-branes*	Planck-suppressed operators‡

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

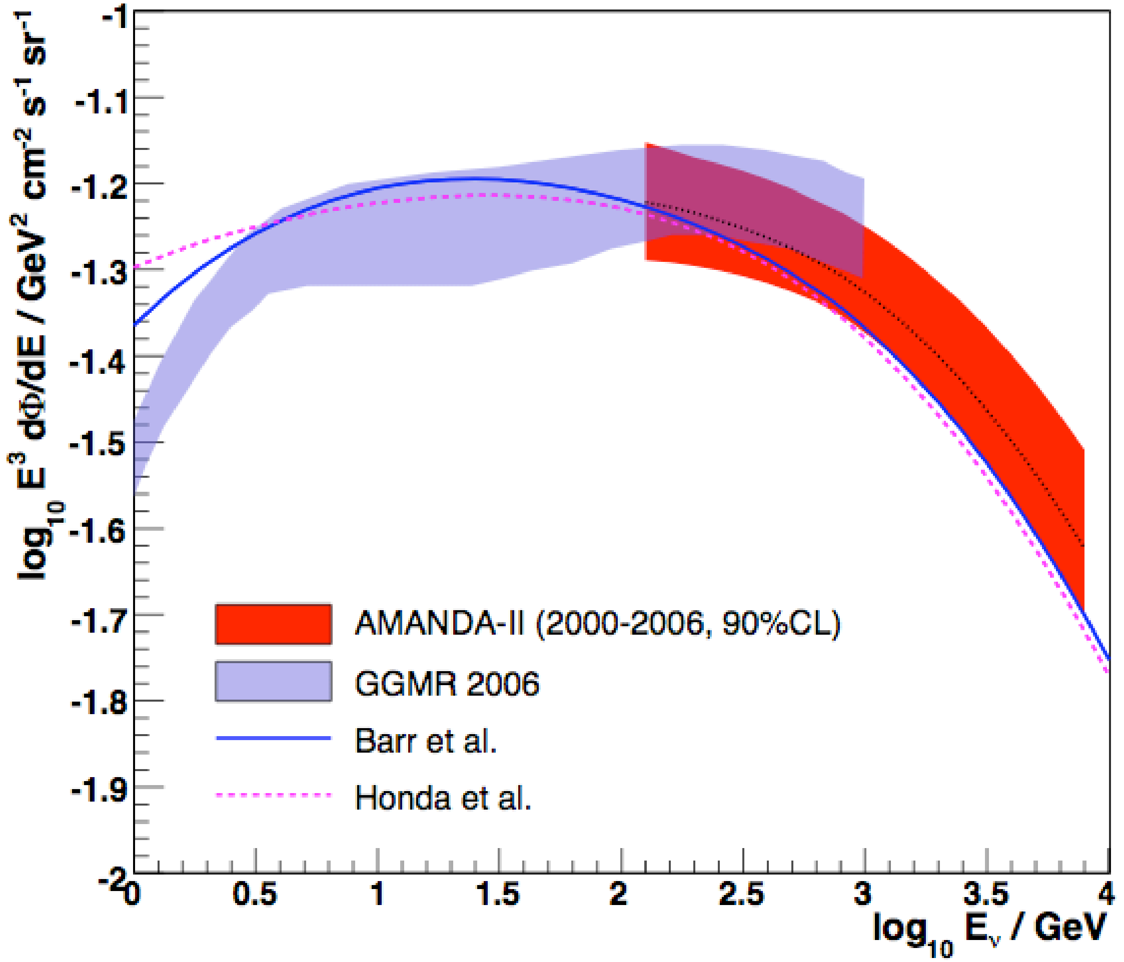
‡ Anchordoqui *et al.*, hep-ph/0506168

Conventional Analysis



- Parameters of interest: normalization, spectral slope change Δγ 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