Testing Lorentz Invariance with Atmospheric Neutrinos and AMANDA-II

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CPT '07, Bloomington, Indiana
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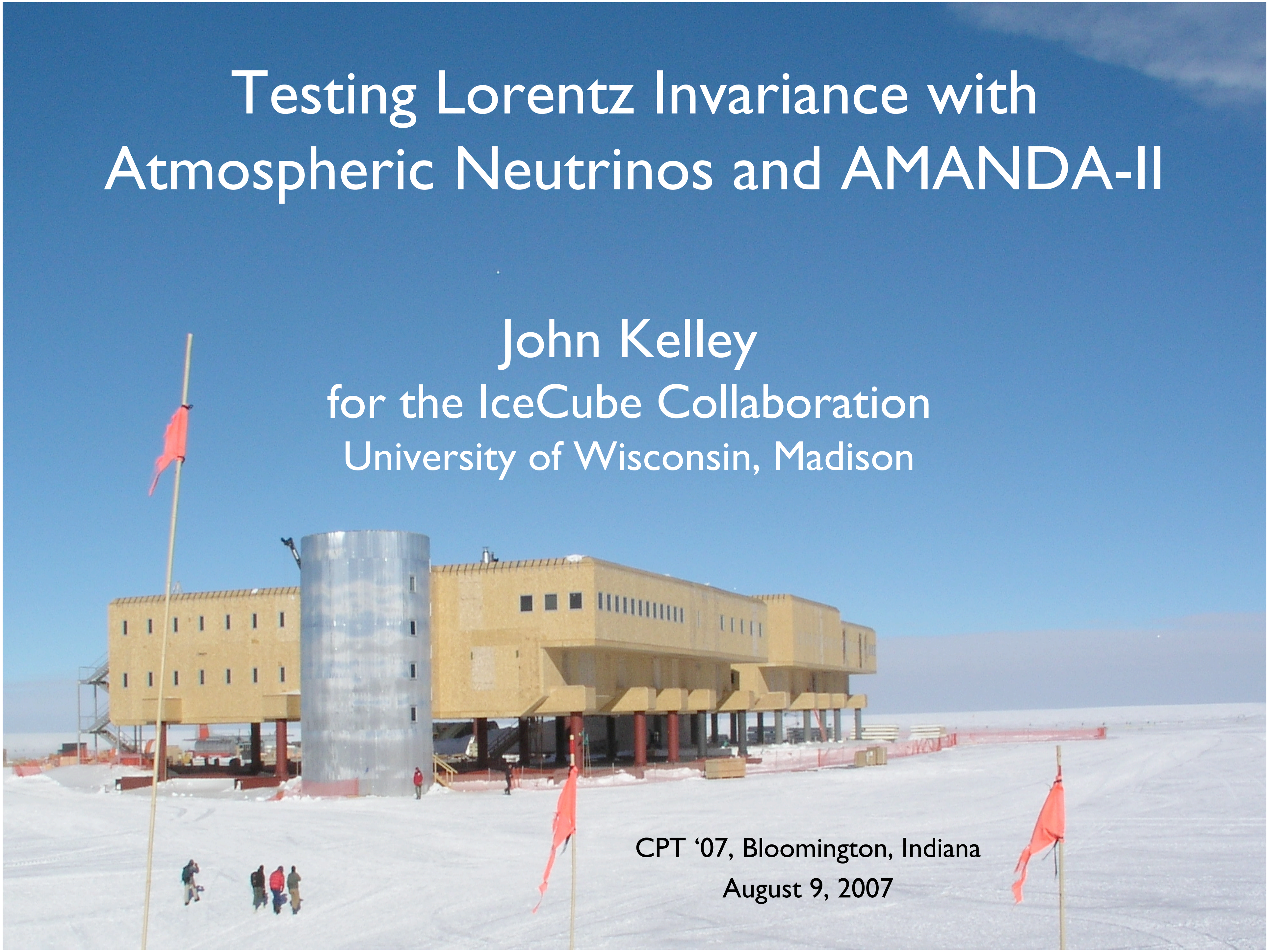


The IceCube Collaboration

USA:
- Bartol Research Institute, Delaware
- Pennsylvania State University
- UC Berkeley
- UC Irvine
- Clark-Atlanta University
- 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

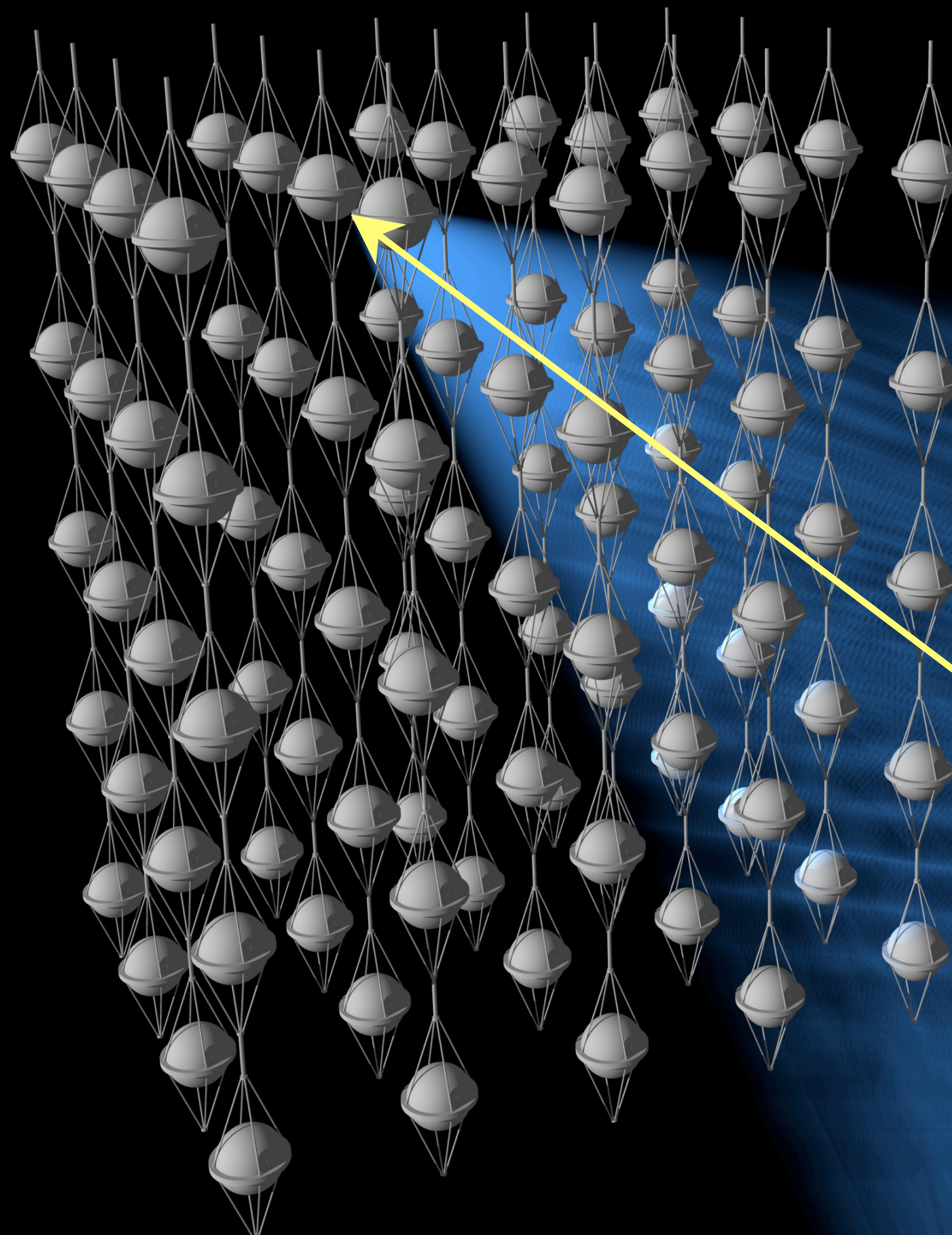
Germany:
- Universität Mainz
- DESY-Zeuthen
- Universität Dortmund
- Universität Wuppertal
- Humboldt Universität zu Berlin
- MPI Heidelberg
- RWTH Aachen

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

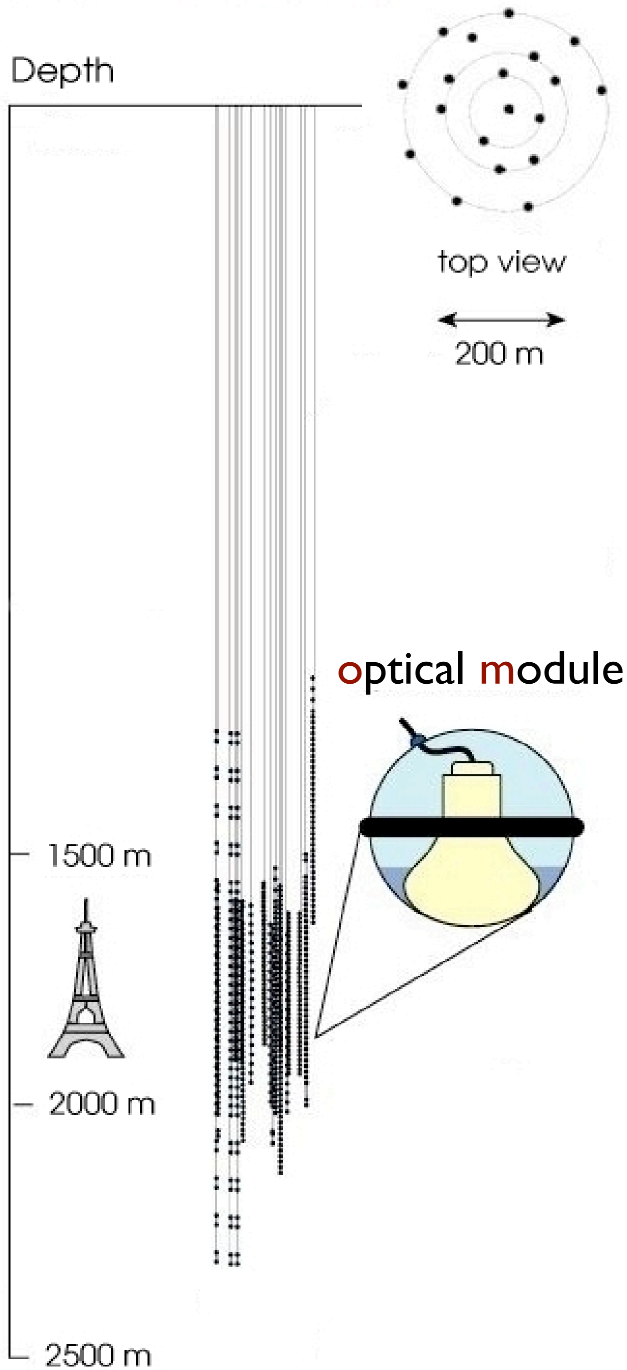
Japan:
- Chiba University

New Zealand:
- University of Canterbury

29 institutions, ~250 members
http://icecube.wisc.edu



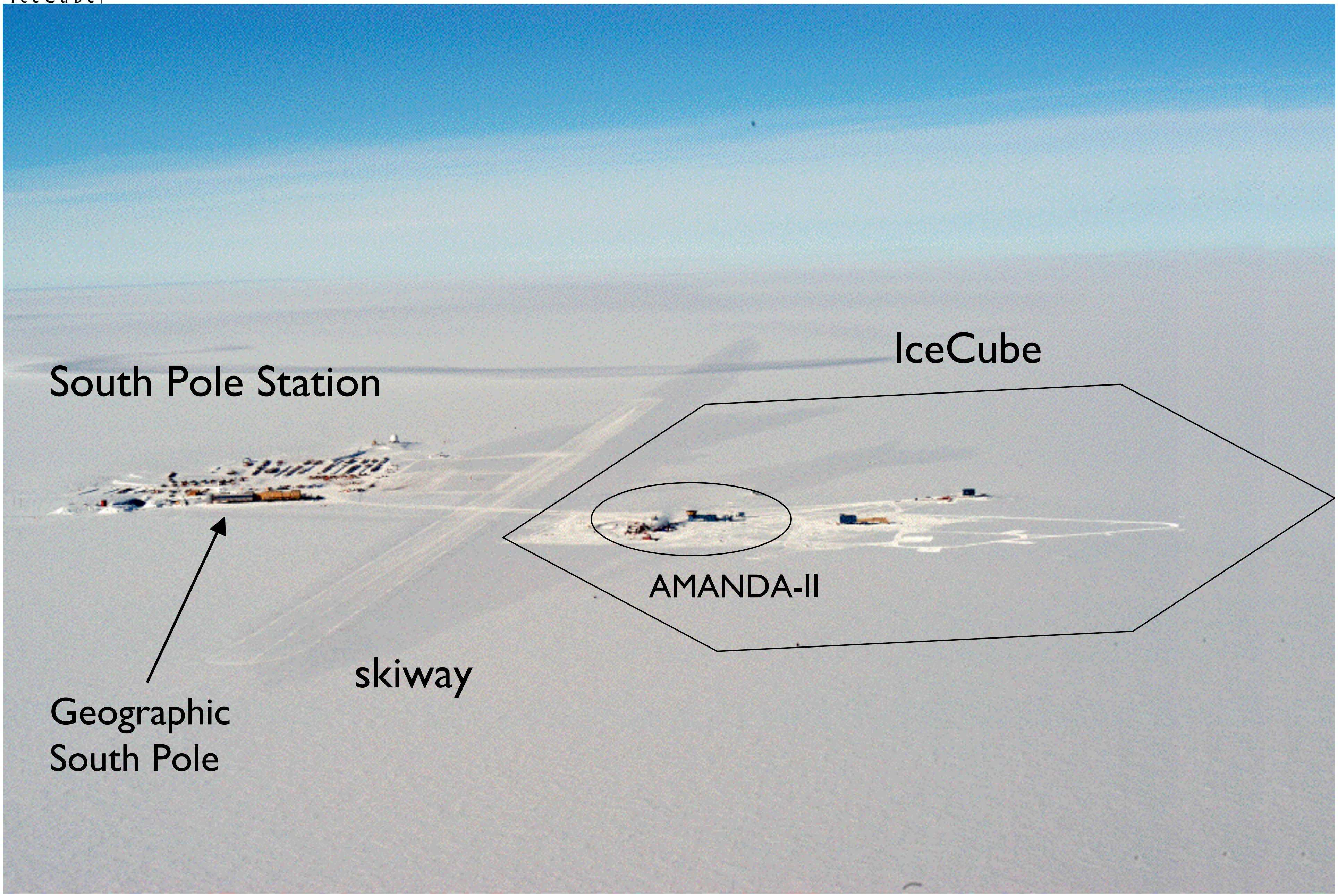
- Array of optical modules on cables in ice or water (“strings” or “lines”)
- High energy muon (~TeV) from charged current ν_μ interaction
- Good angular reconstruction from timing of Cherenkov cone
- Rough ν energy estimate from muon energy loss
- OR, look for cascades (ν_e, ν_τ, NC ν_μ)



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
- Muon direction can be reconstructed to within 2-3°

Amundsen-Scott
South Pole Research Station



Atmospheric Production

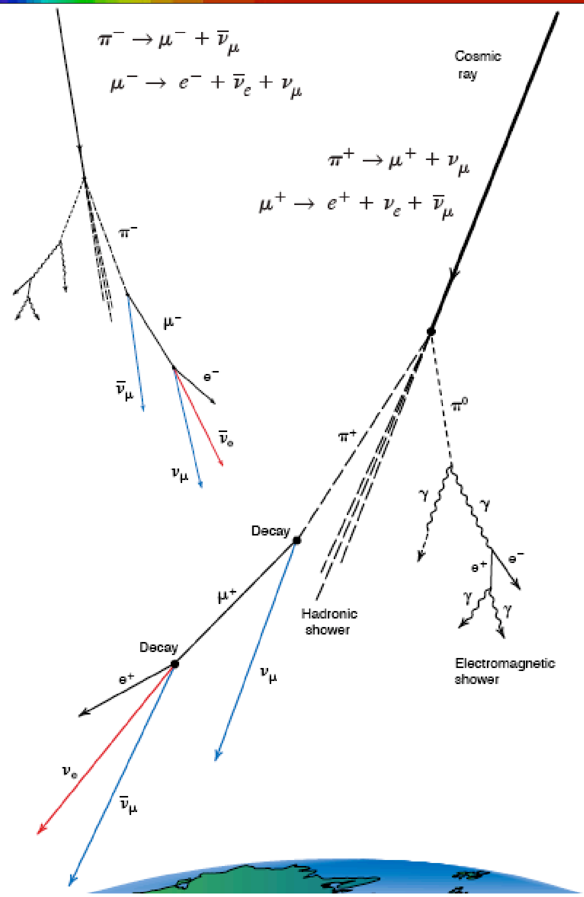


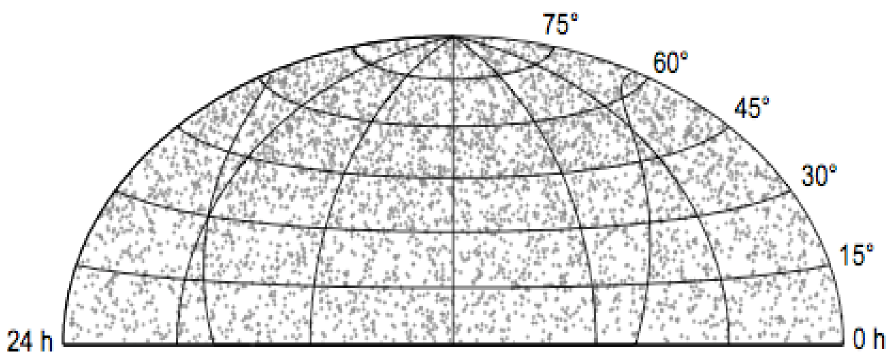
Figure from Los Alamos Science **25** (1997)

Cosmic rays (mostly p^+) produce muons, neutrinos through pion / kaon decay

Even with > km overburden, atm. muon events dominate over ν by ~10^6

Neutrino events: reconstruct direction + use Earth as filter, or look only for UHE events

Current Experimental Status



A. Achterberg *et al.*, astro-ph/0611063

- 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: >4K events, 0.1-10 TeV

Opportunity for particle physics with high-energy atmospheric ν

Violation of Lorentz Invariance (VLI)

- Effective field-theoretic approach by Kostelecký, Colladay, *et al.* (SME: hep-ph/9809521; +ν, 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

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…)

*see Kostelecký & Mewes, PRD **69** 016005 (2004)

VLI Oscillations

- 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 ⇒ mixing ⇒ VLI oscillations

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

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

VLI Oscillations (continued)

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

$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2}\left(\sin^2 2\theta + R_n^2 \sin^2 2\xi_n + 2R_n \sin 2\theta \sin 2\xi_n \cos\eta_n\right) ,$$

$$\mathcal{R} = \sqrt{1 + R_n^2 + 2R_n\left(\cos 2\theta \cos 2\xi_n + \sin 2\theta \sin 2\xi_n \cos\eta_n\right)} ,$$

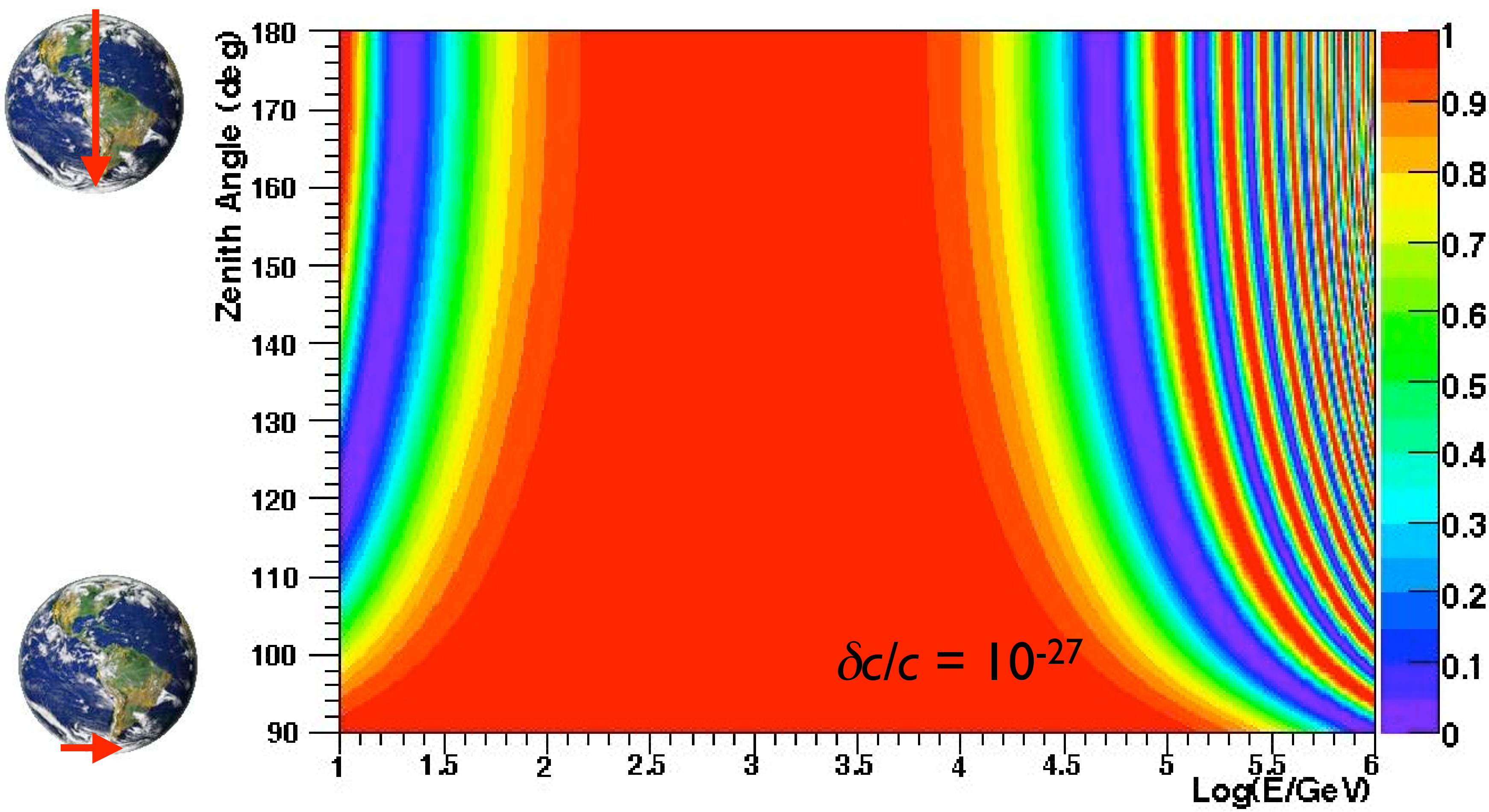
$$R_n = \sigma_n^+ \frac{\Delta\delta_n E^n}{2} \frac{4E}{\Delta m^2} ,$$

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

- For atmospheric ν, conventional oscillations turn off above ~50 GeV (*L/E* dependence)

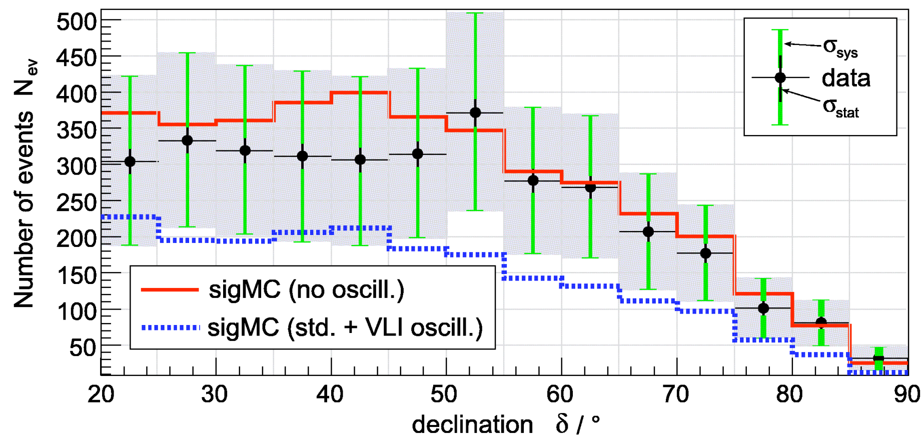
- VLI oscillations turn on at high energy (n=1 above; *L E* dependence), depending on size of *δc/c*, and distort the zenith angle / energy spectrum

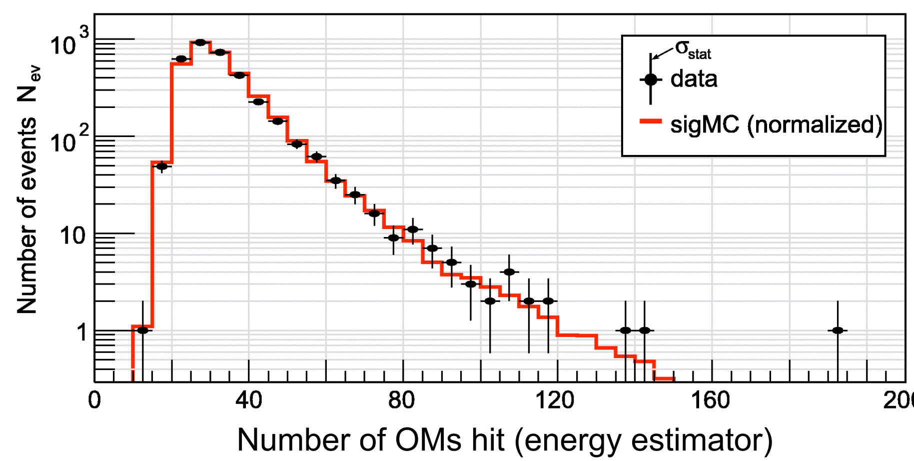
Atmospheric ν_μ Survival Probability



2000-2003 AMANDA-II Data

- Quality selection criteria used to separate neutrinos from background atmospheric muons
- Bad OMs, electrical crosstalk, and mis-reconstructed muons eliminated
- Total livetime is 807.2 days
- 3401 neutrino candidate events survive the selection criteria





J. Ahrens, Ph.D. thesis, Univ. of Mainz

Analysis Method

4 bins: 2 zenith × 2 N_{ch}

function parametrizing sys. errors

$$\chi^2\left(\delta c/c, \Theta_c, \cos\eta\right) = \sum_{i=1}^{N_{\mathrm{Bins}}} \frac{\left(N_i^{\mathrm{D}} - N_i^{\mathrm{BG}} - F \cdot N_i^{\mathrm{MC}}\left(\delta c/c, \Theta_c, \cos\eta\right)\right)^2}{N_i^{\mathrm{D}} + N_i^{\mathrm{BG}} + \left(\sigma_i^{\mathrm{MC}}\right)^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\kappa}{\sigma_\kappa}\right)^2 + \left(\frac{\epsilon}{\sigma_\epsilon}\right)^2$$

VLI parameter space

systematic errors: σ_α = flux normalization (30%)

σ_κ = OM sensitivity (11.5%)

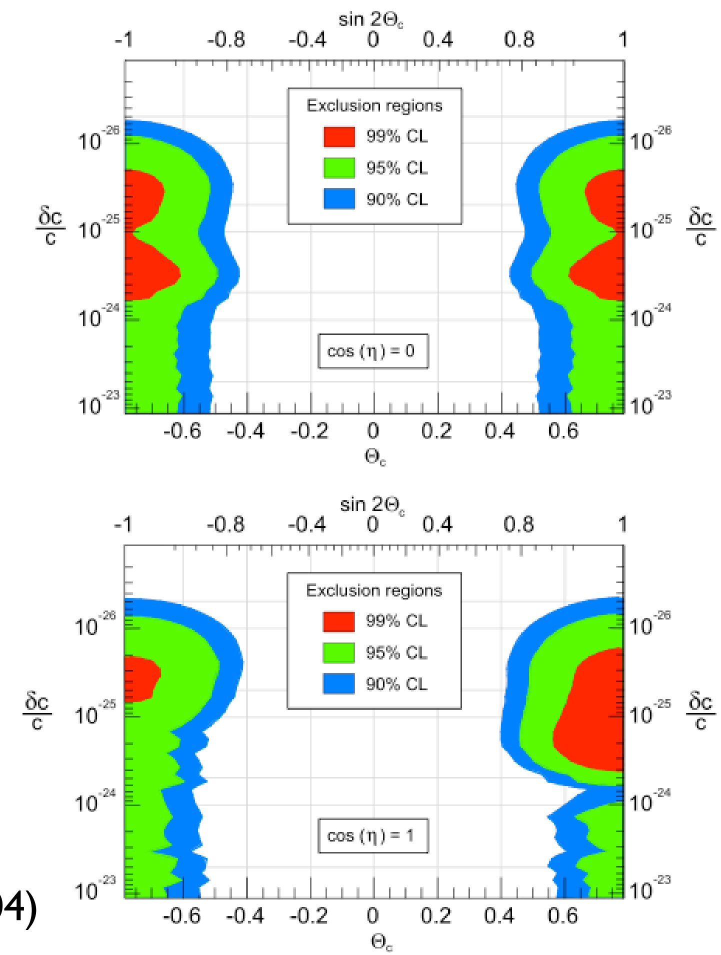
σ_ε = $K^\pm / \pi^\pm$ ratio (6%)

Results

- No evidence for alternative oscillations found
- 90% CL limit set on VLI and VEP parameter for maximal mixing angle:

$$\delta c/c,\ 2|\phi|\delta\gamma \leq 5.3 \times 10^{-27}$$

- Result comparable to other experiments
  - –MACRO: $\delta c/c < 2.5 \times 10^{-26}$ (90% CL)
    Battistoni *et al.*, hep-ex/0503015
  - –SuperK + K2K: $\delta c/c < 2.0 \times 10^{-27}$
    González-García & Maltoni, PRD **70** 033010 (2004)

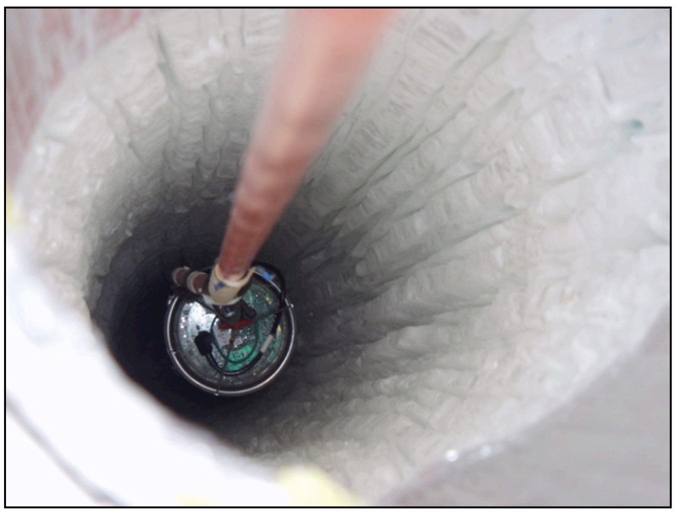


Future Sensitivity (maximal mixing)

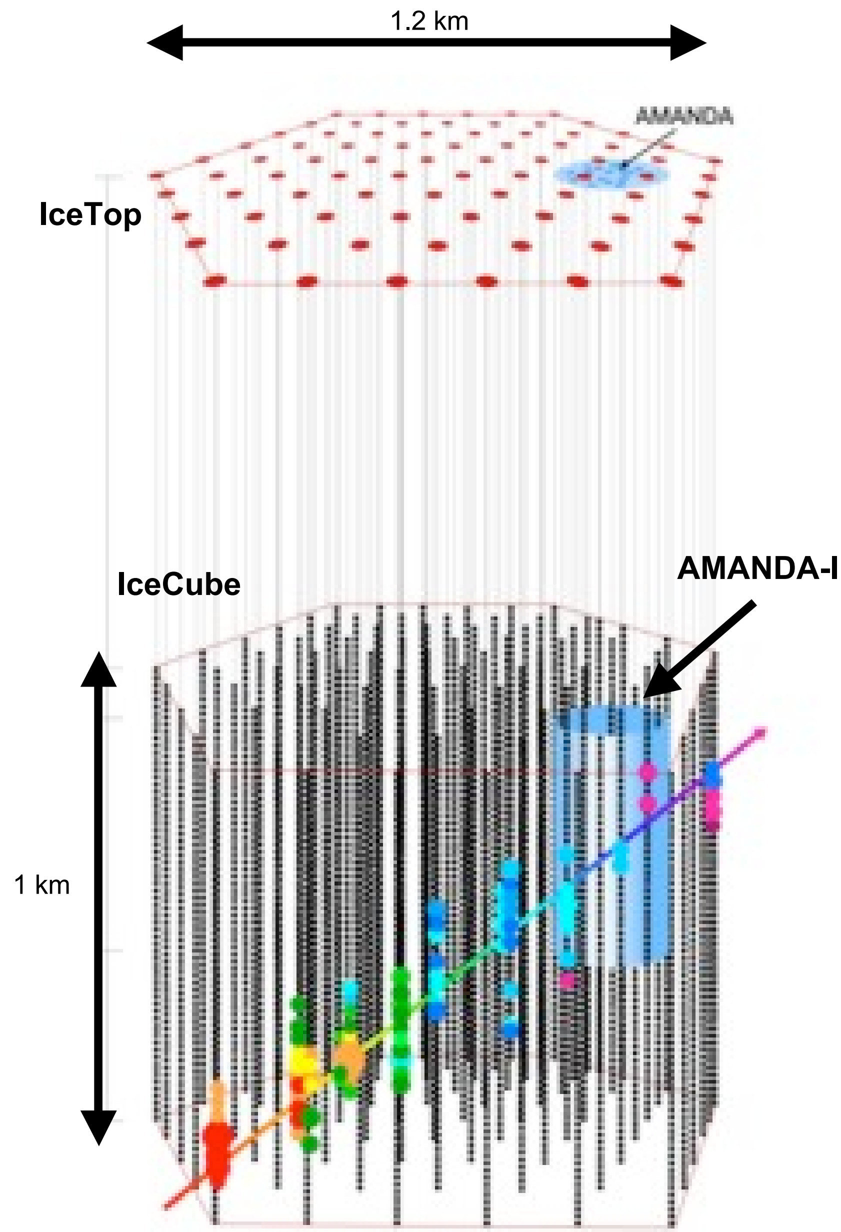
- AMANDA-II: sensitivity of $\delta c/c \sim 10^{-27}$ (7 years) with full likelihood analysis technique (JK, astro-ph/0701333)
  - Analysis will also test for quantum decoherence, LE^2, LE^3, rotation?

- 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)

IceCube: 22 strings deployed

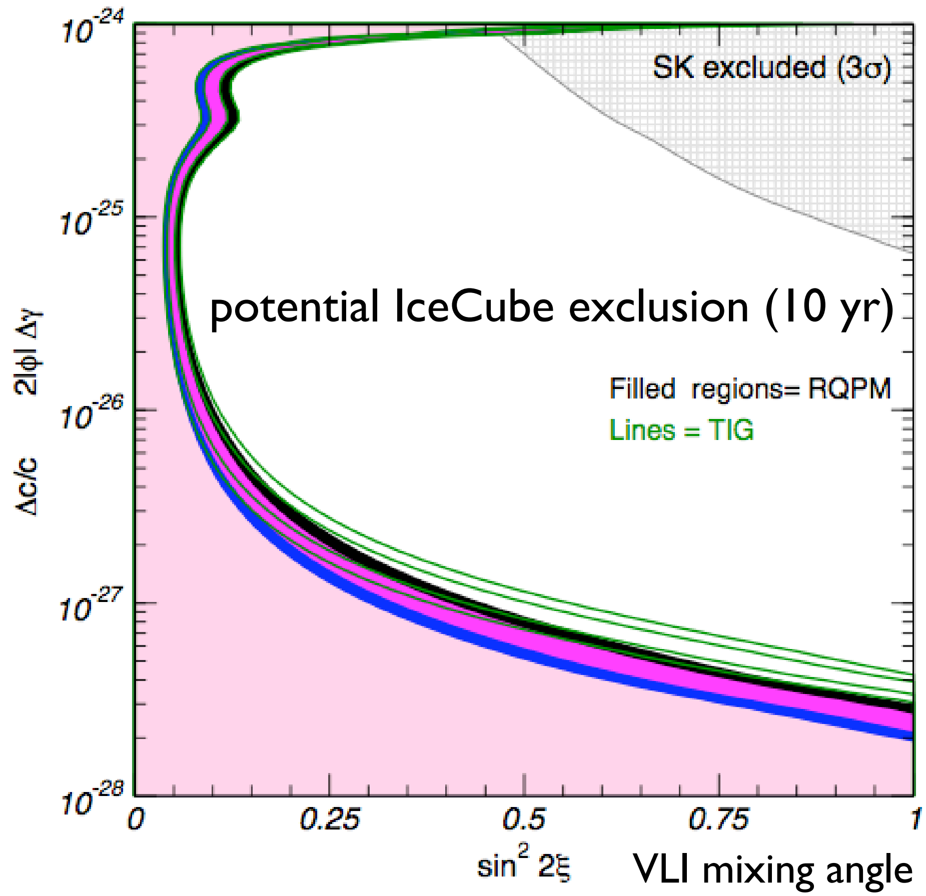


2500m deep hole!



IceCube Sensitivity

VLI / VEP parameter



VLI mixing angle

Summary

- Neutrino telescopes provide a large sample of HE atmospheric ν — probe of new physics

- AMANDA-II 2000-03 VLI limit in neutrino sector:
  $\delta c/c \leq 5.3 \times 10^{-27}$ (maximal mixing)

- Improvements on the way with more AMANDA-II data, IceCube