Polar Particle Physics:
Measuring Fundamental Neutrino Properties with Antarctic Neutrino Detectors

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University of Hawai'i at Manoa
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Outline

1. Motivation and available neutrino sources
2. Atmospheric neutrinos
3. AMANDA and IceCube
   - violation of Lorentz invariance
   - sterile neutrinos
   - mass hierarchy
4. Cosmogenic neutrinos

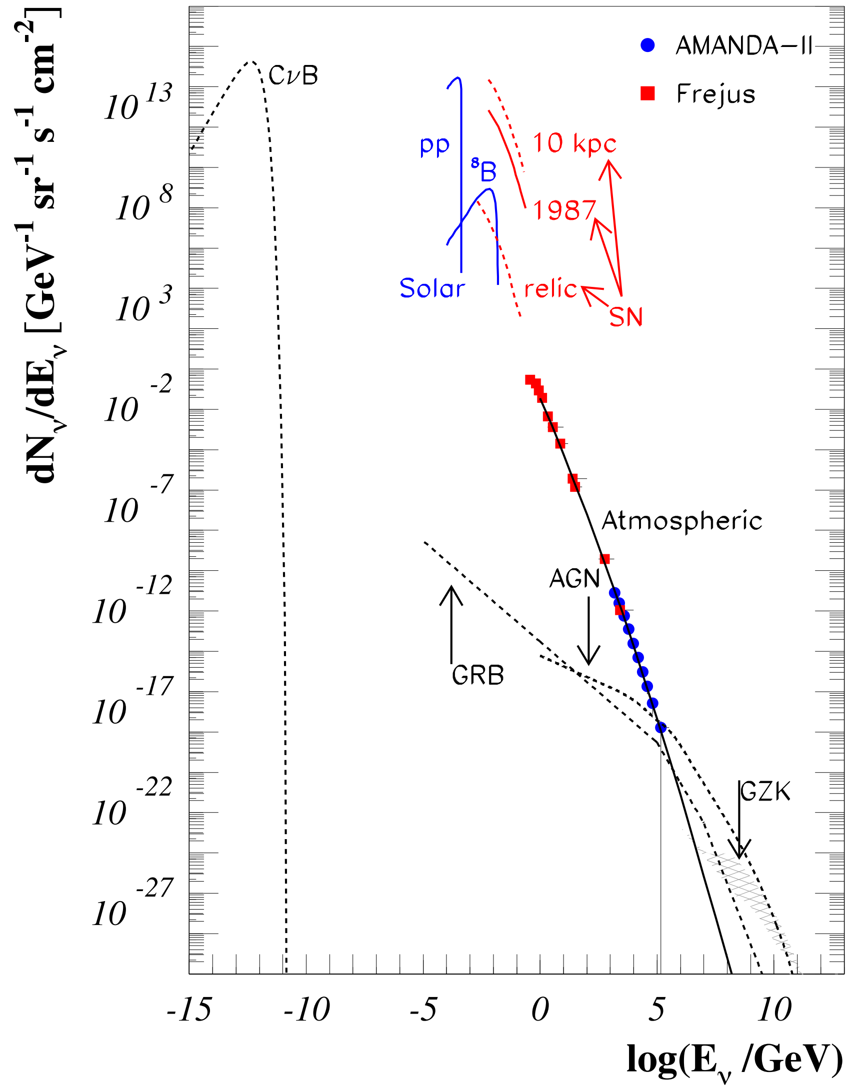
Neutrino Sources

- Neutrinos as new physics probes?
  - only known physics beyond SM
  - high energy
  - long baselines
  - high Lorentz boost (> 10^{11})

- All high-energy fluxes connected with cosmic rays

- Challenges:
  - low cross section and/or low fluxes
  - absolute fluxes often uncertain
  - "test beam" is astrophysical

Becker, Phys. Rep. **458**, 173 (2008)



Atmospheric Neutrinos

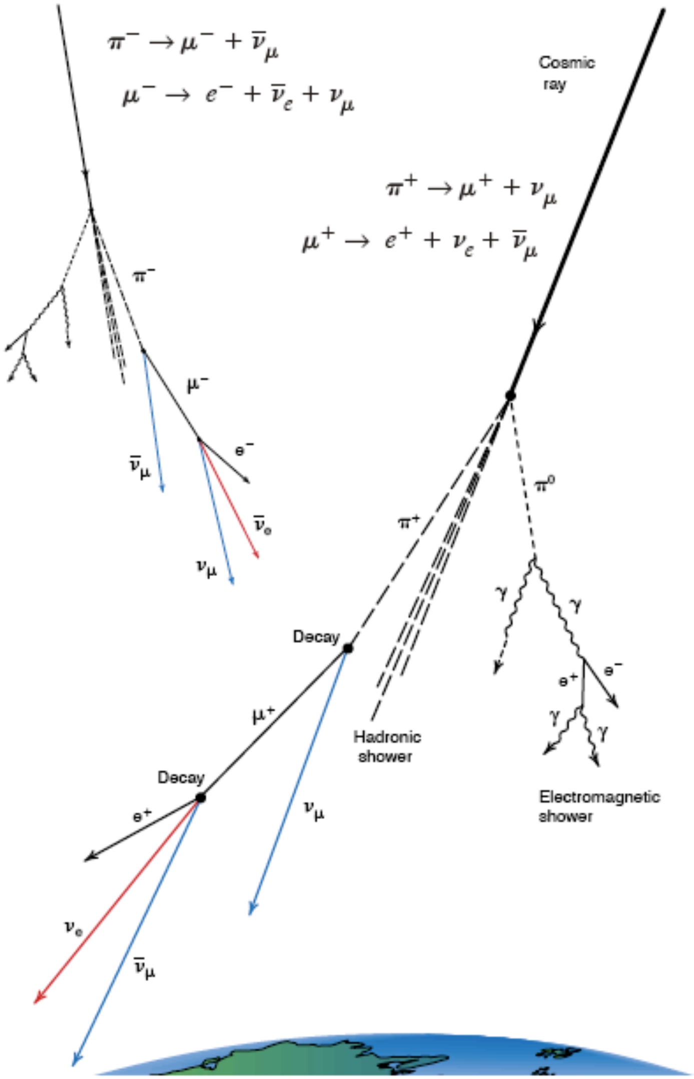


Figure from Los Alamos Science **25** (1997)

- Produced in cosmic ray interactions, charged pion/ kaon decay
- Below ~50 GeV: mass-induced oscillations!

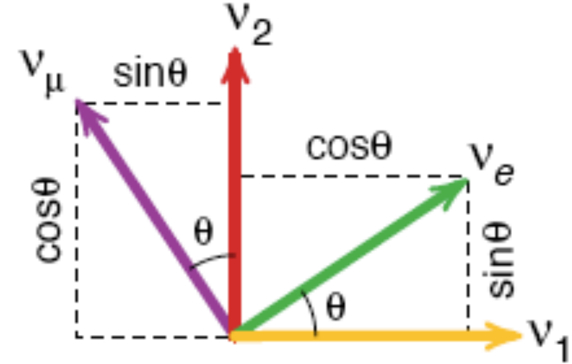
$$\nu_\mu \leftrightarrow \nu_\tau$$

Neutrino Oscillations

- Evidence (SuperK, SNO) that neutrinos oscillate flavors
  (see e.g. hep-ex/9807003)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Mass and weak eigenstates not the same (mixing angle(s))

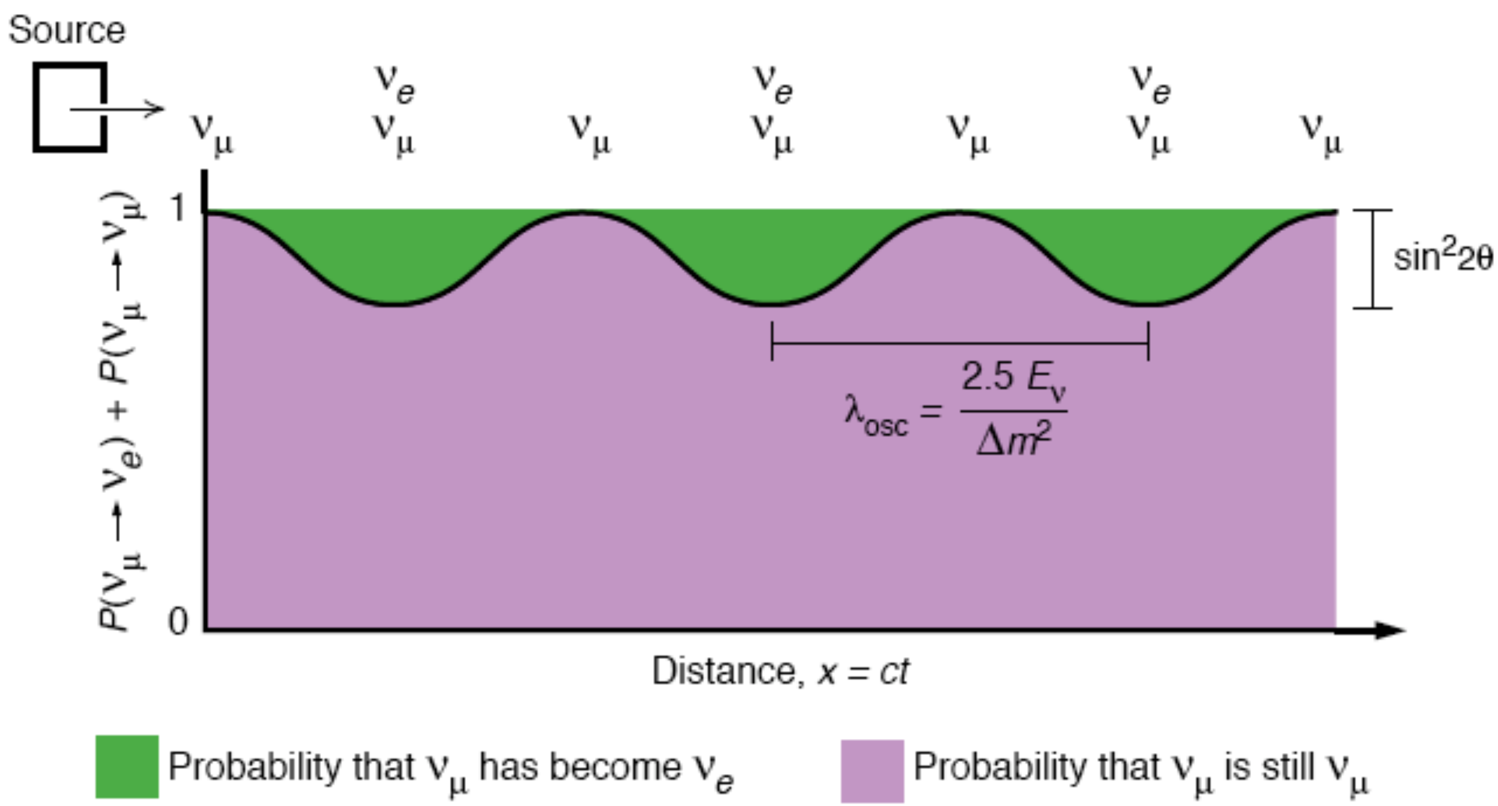


- Implies weak (flavor) states oscillate as they propagate (governed by energy differences)

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

Oscillation Probability

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) = \sin^2 2\theta \, \sin^2[1.27\, \Delta m^2 (L/E)]$$



Example 1: Violation of Lorentz Invariance

- Lorentz symmetry violation possible in various quantum gravity formulations

- "Fried chicken" VLI = 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 Glashow and Coleman, PRD **59** 116008 (1999)

VLI + Atmospheric Oscillations

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

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

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

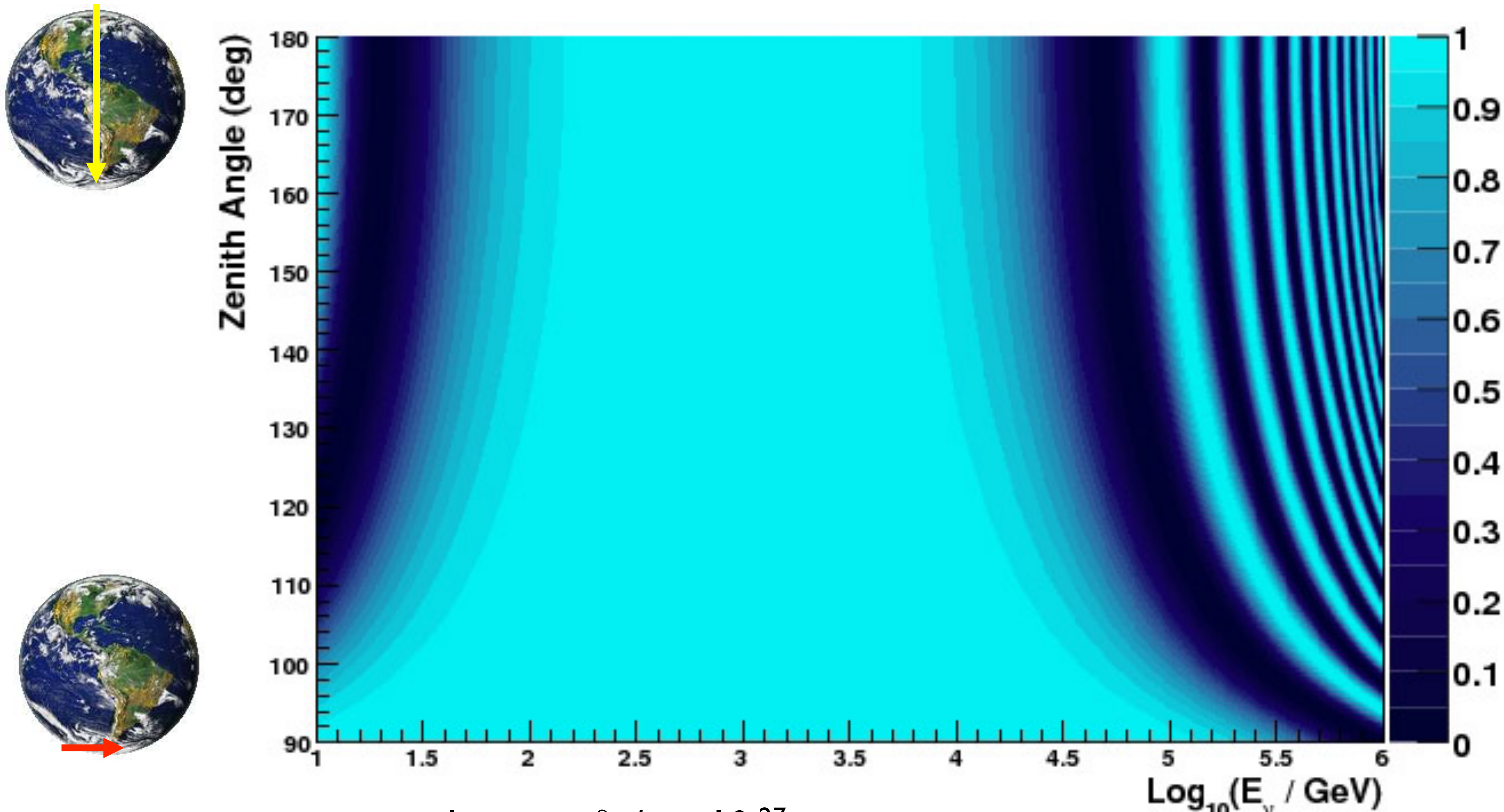
$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m^2_{23}}$$

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

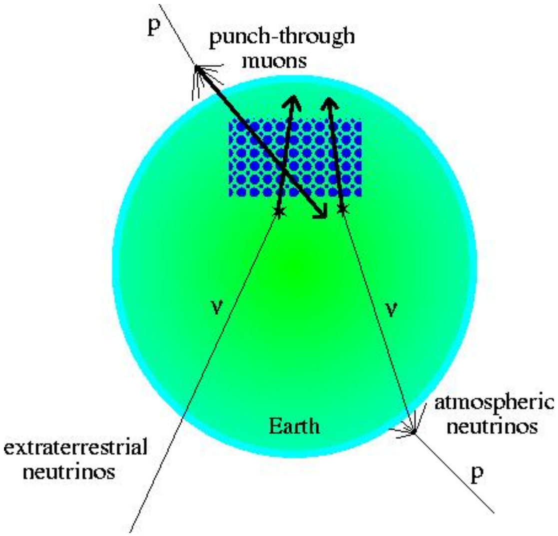
González-García, Halzen, and Maltoni, hep-ph/0502223

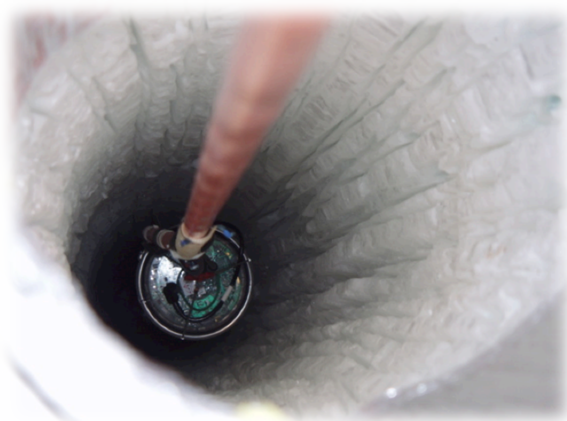
VLI Atmospheric ν_μ Survival Probability

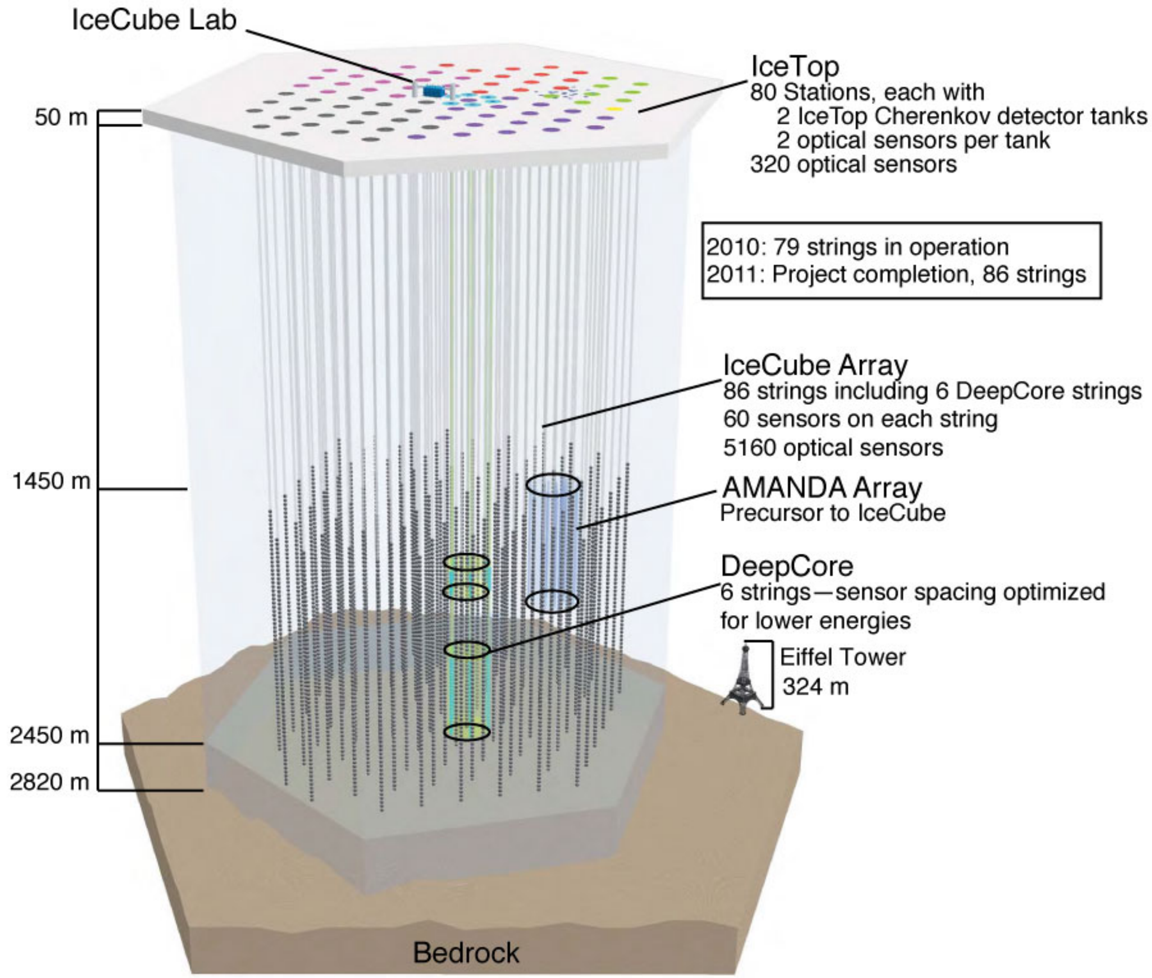


maximal mixing, $\delta c/c = 10^{-27}$

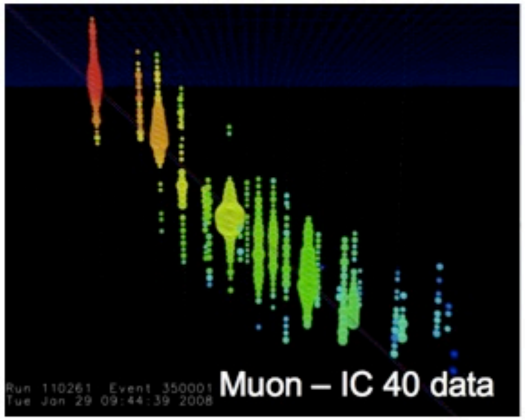
AMANDA and IceCube







Detection Principle

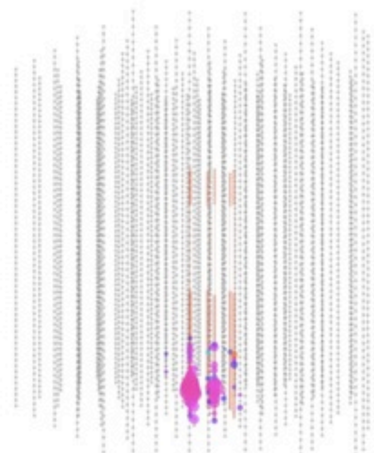


Tracks:

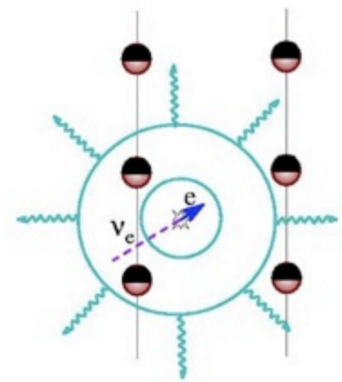
- through-going muons
- pointing resolution ~1°

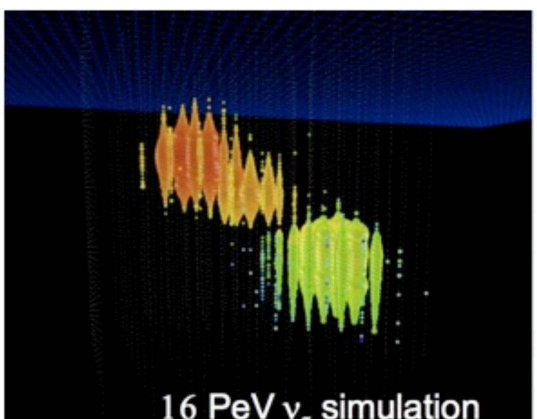
Cascades:

- Neutral current for all flavors
- Charged current for ν_e and low-E ν_τ
- Energy resolution ~10% in log(E)



IC79 Cascade Event

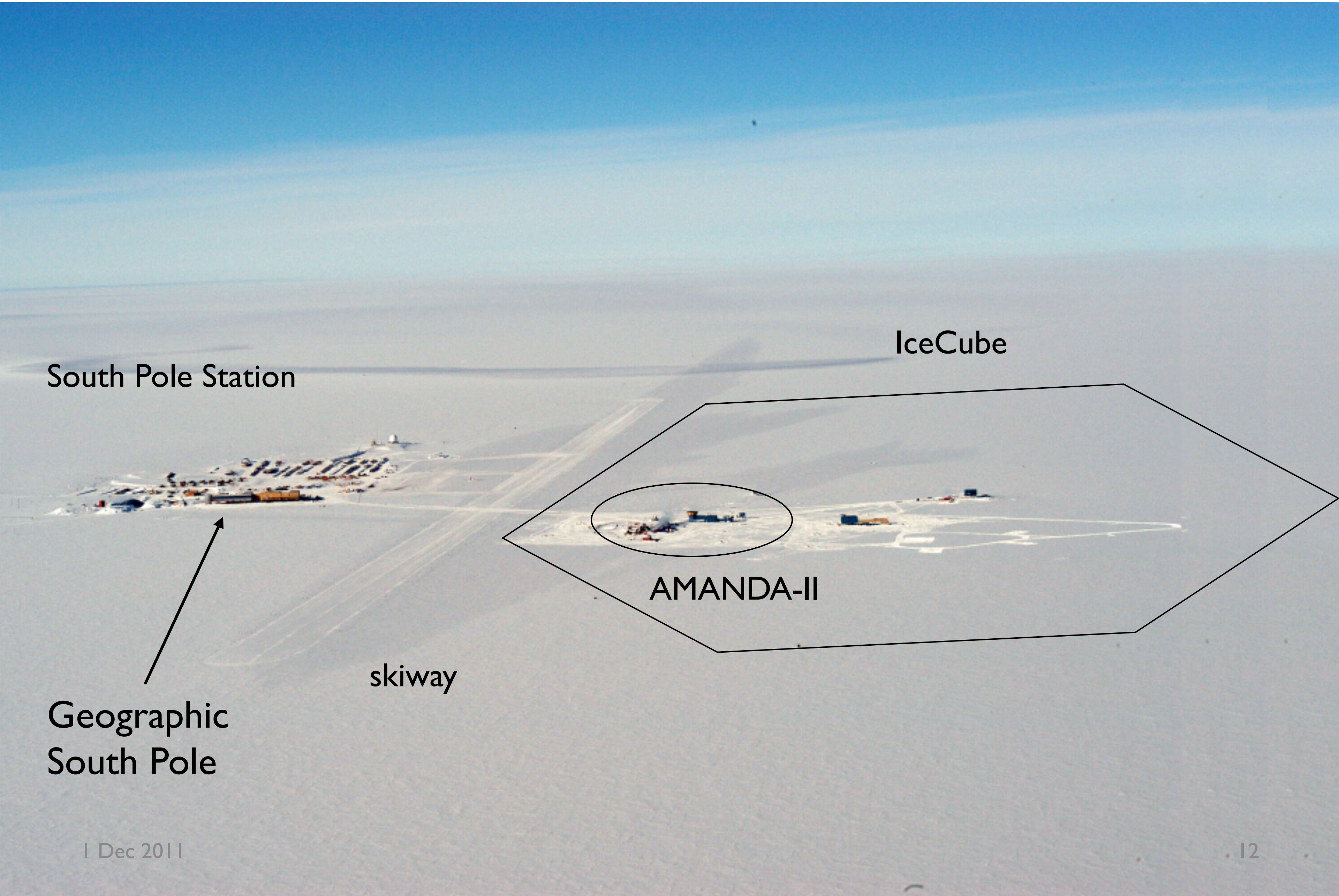


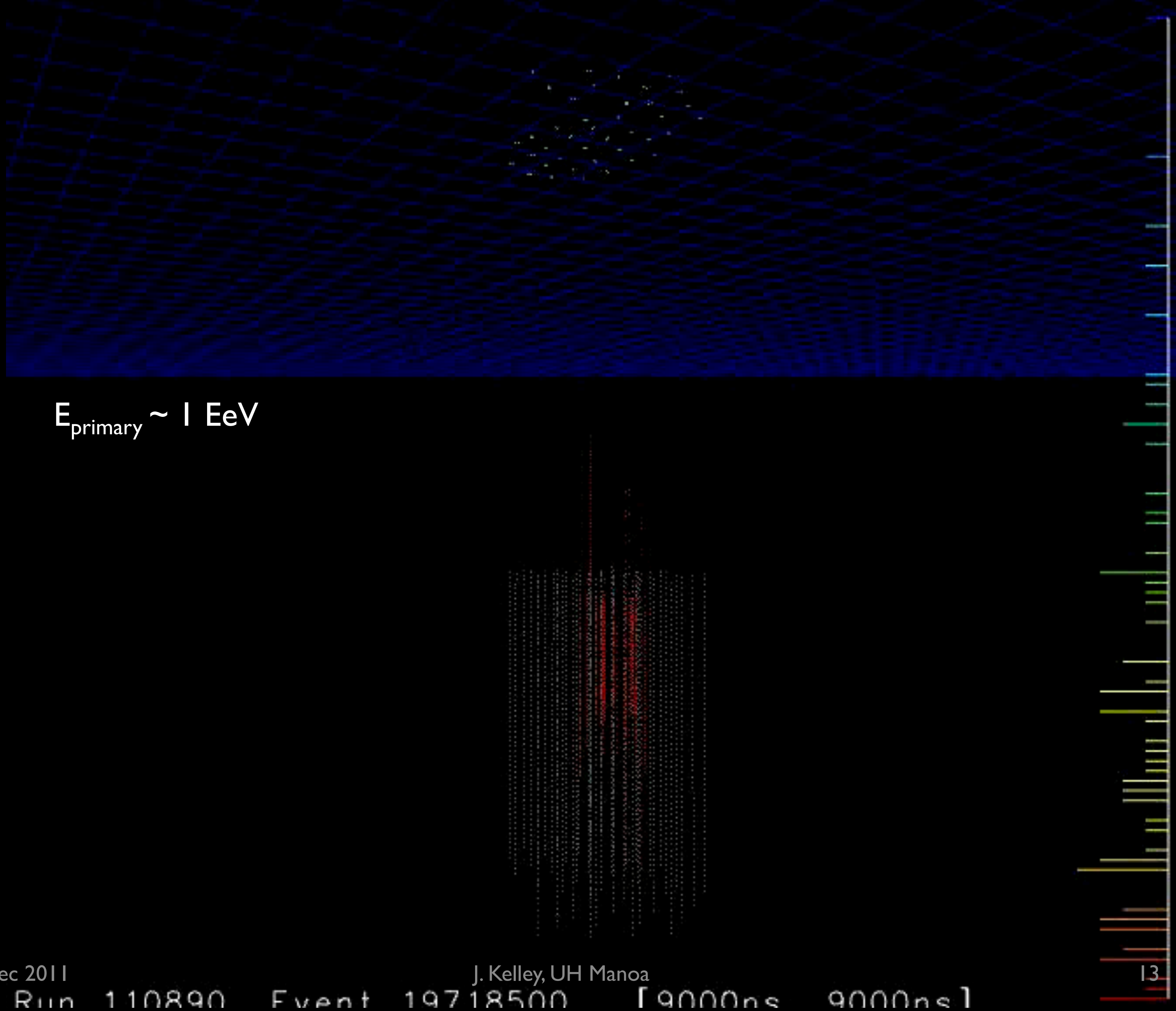


Composites:

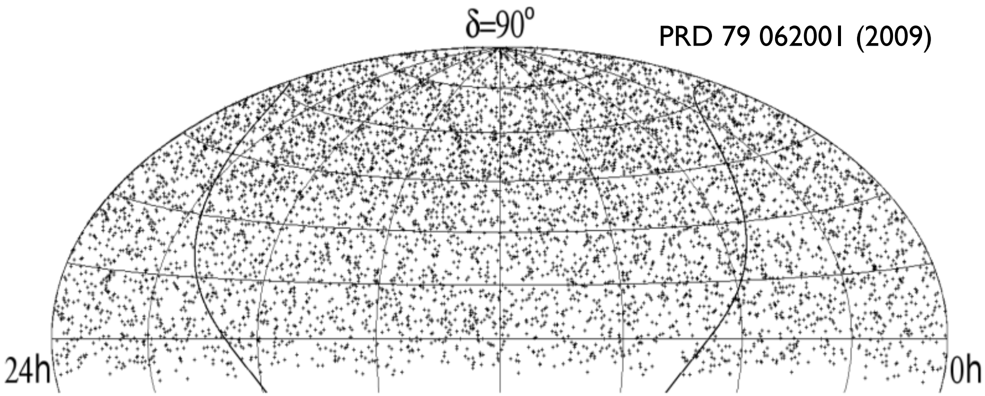
- Starting tracks
- high-E ν_τ (Double Bangs)
- Good directional and energy resolution

Amundsen-Scott
South Pole Research Station

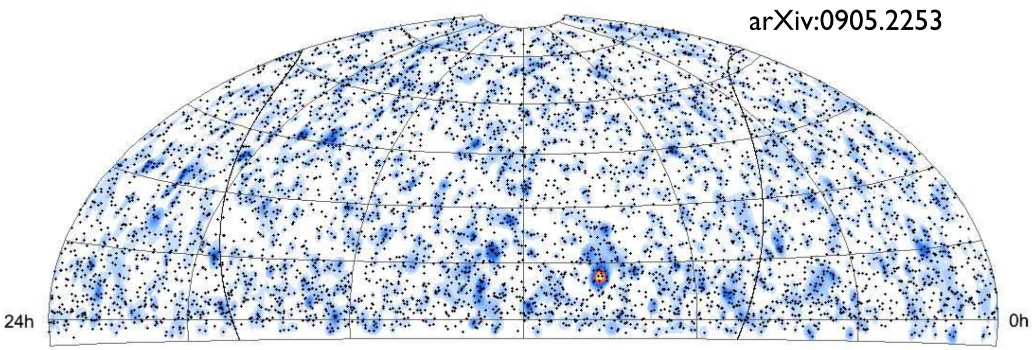



$E_{primary}$ ~ 1 EeV
Run 110890 Event 19718500 [9000ns 9000ns]

Current Experimental Status



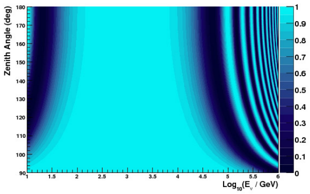
2000-2006 AMANDA neutrino skymap



22-string IceCube neutrino skymap (2007)

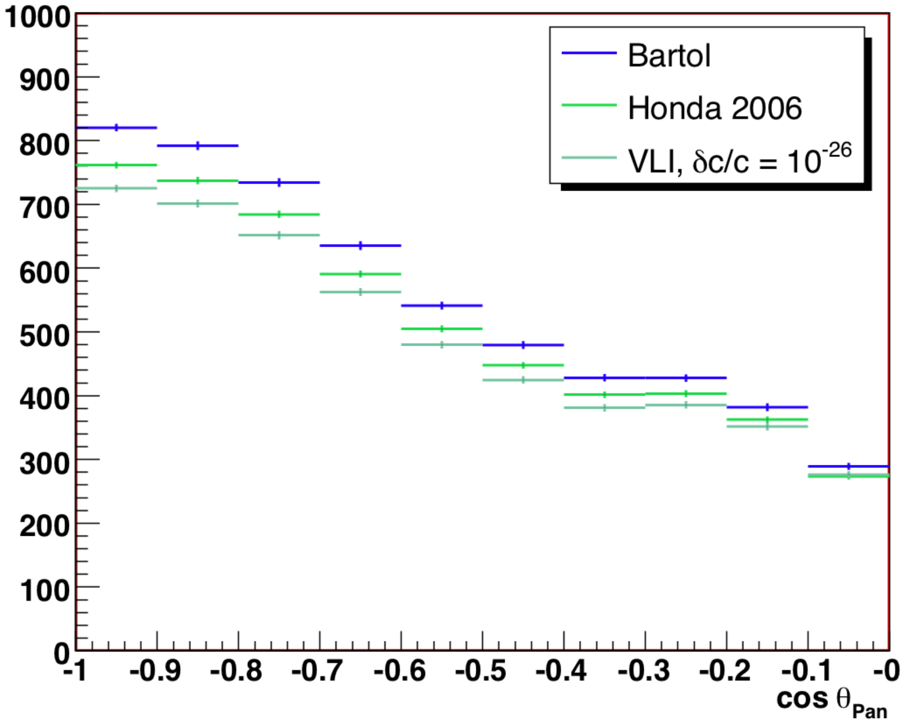
- No point sources (yet)
- Large sample of atmospheric muon neutrinos
  - AMANDA-II: 6500 events in 7 years, energy range: 0.1-10 TeV
  - One year of IceCube 22-string data: ~5700 neutrino candidates
  - One year of IceCube 40-string data: ~14000 neutrino candidates

Simulated Observables (AMANDA 2000-2006)

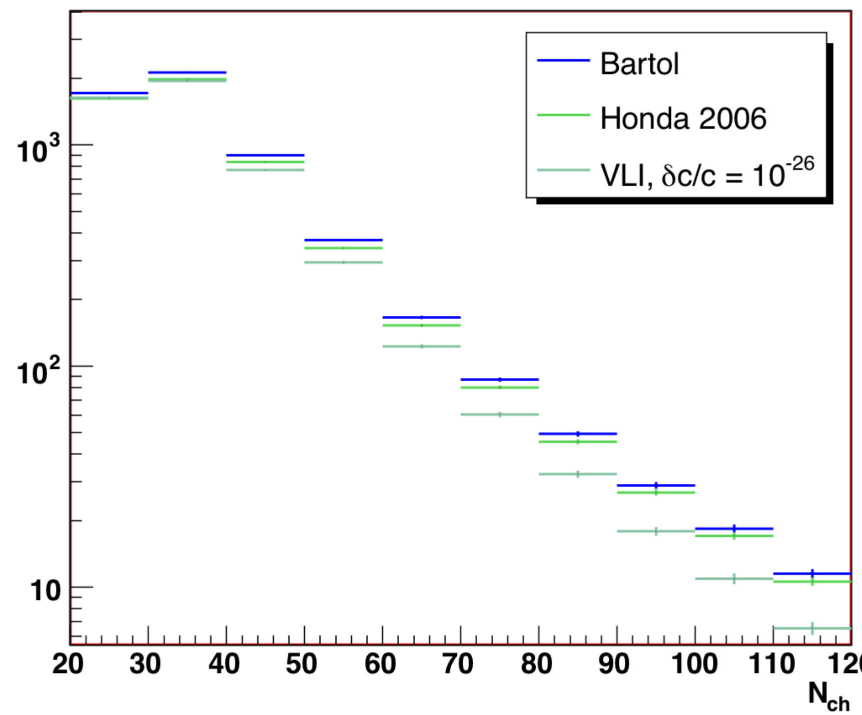


VLI signature: deficit of muon neutrinos at high energy, near vertical

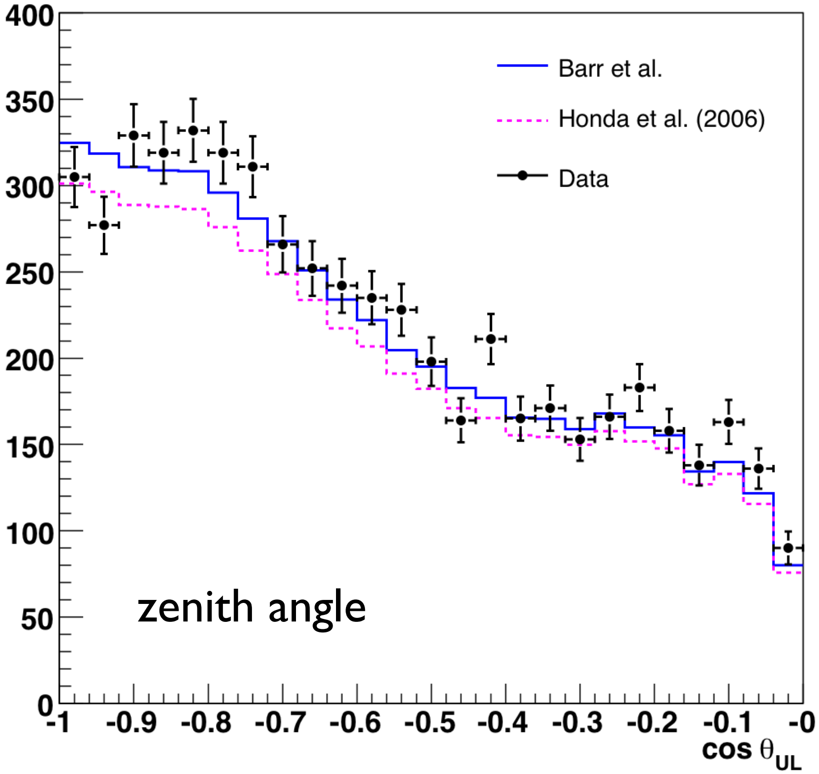
reconstructed zenith angle

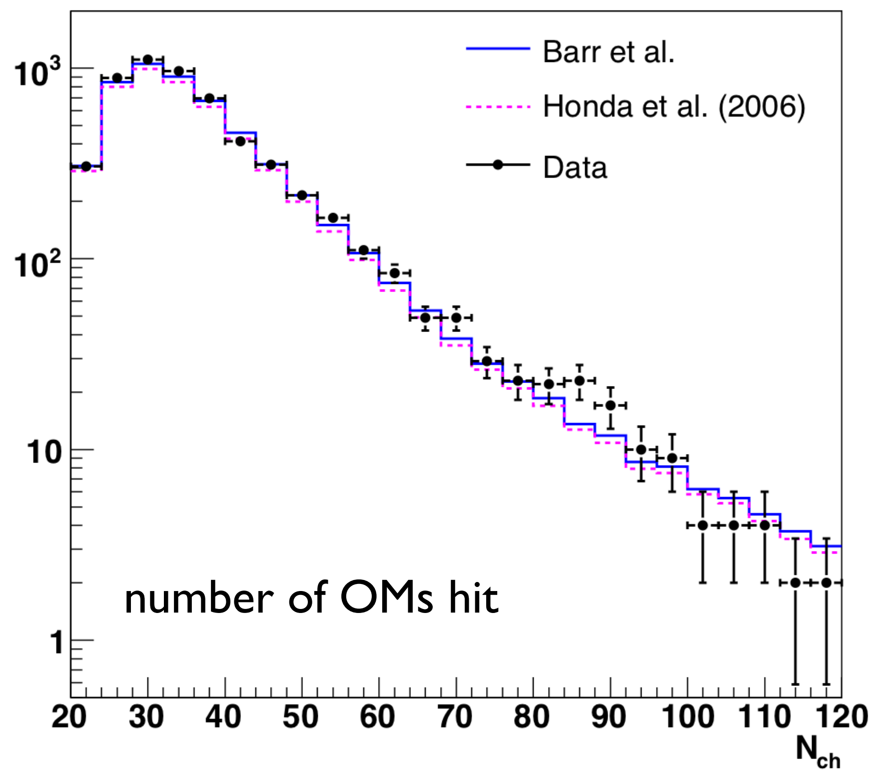


$N_{channel}$ (energy proxy)



Results: Observables (AMANDA 2000-2006)

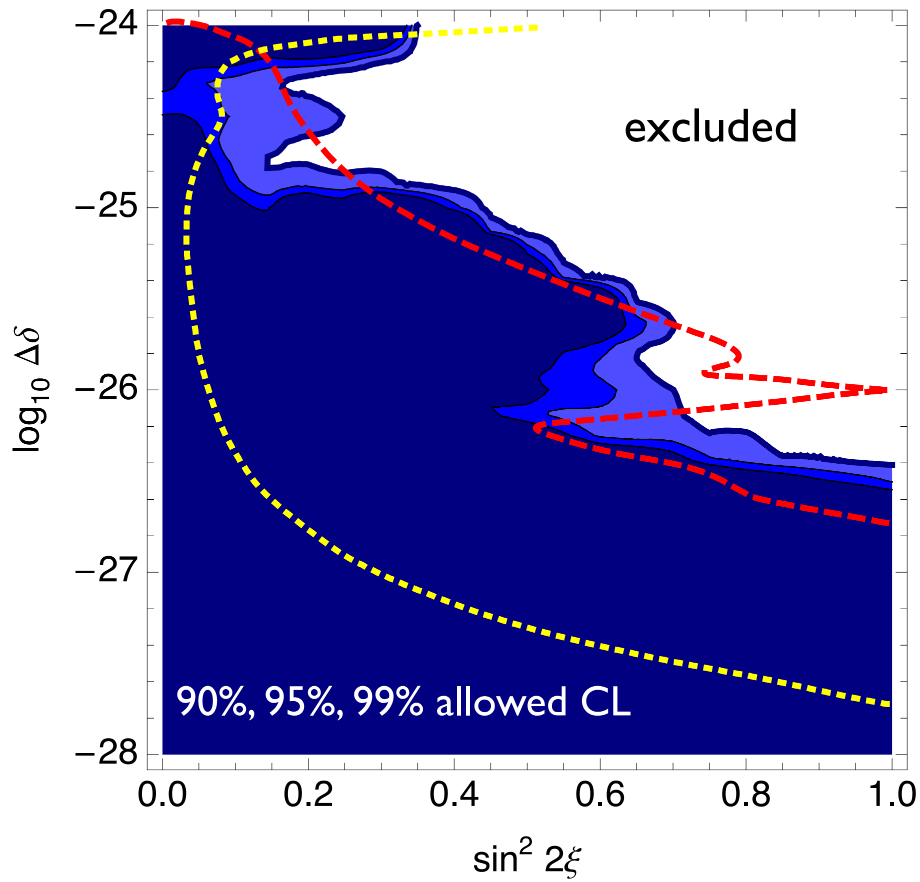




Data consistent with SM atmospheric neutrinos + O(1%) background

Results: VLI upper limit

Abbasi *et al.*, PRD **79**, 102005 (2009)



maximal mixing

- SuperK+K2K limit* (red dotted):

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

- AMANDA 2000-2006 data:

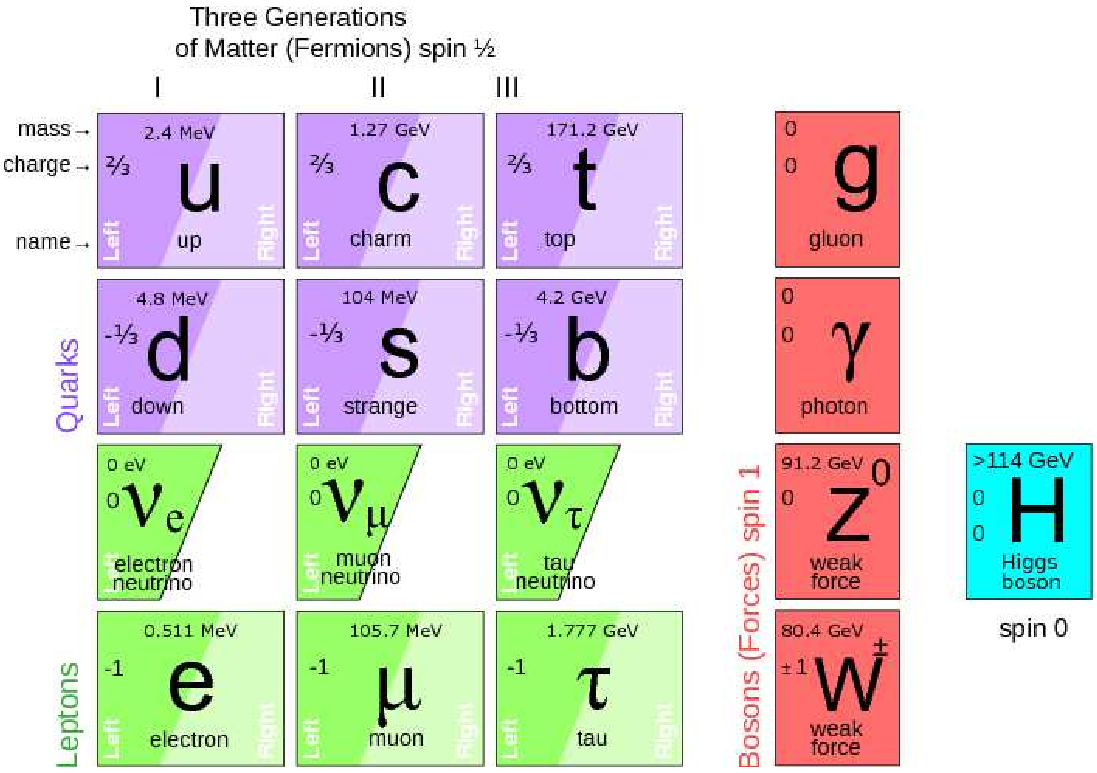
  $\delta c/c < 2.8 \times 10^{-27}$ (90%CL)

- Constrains interpretations of OPERA result (see e.g. arXiv:1109.5917)

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

Example 2: Sterile Neutrinos

- Missing ingredient in SM: neutrino mass



Example 2: Sterile Neutrinos

- Missing ingredient in SM: neutrino mass
- Extend with right-handed ν
- No SM interactions (“sterile”), but can participate in oscillations

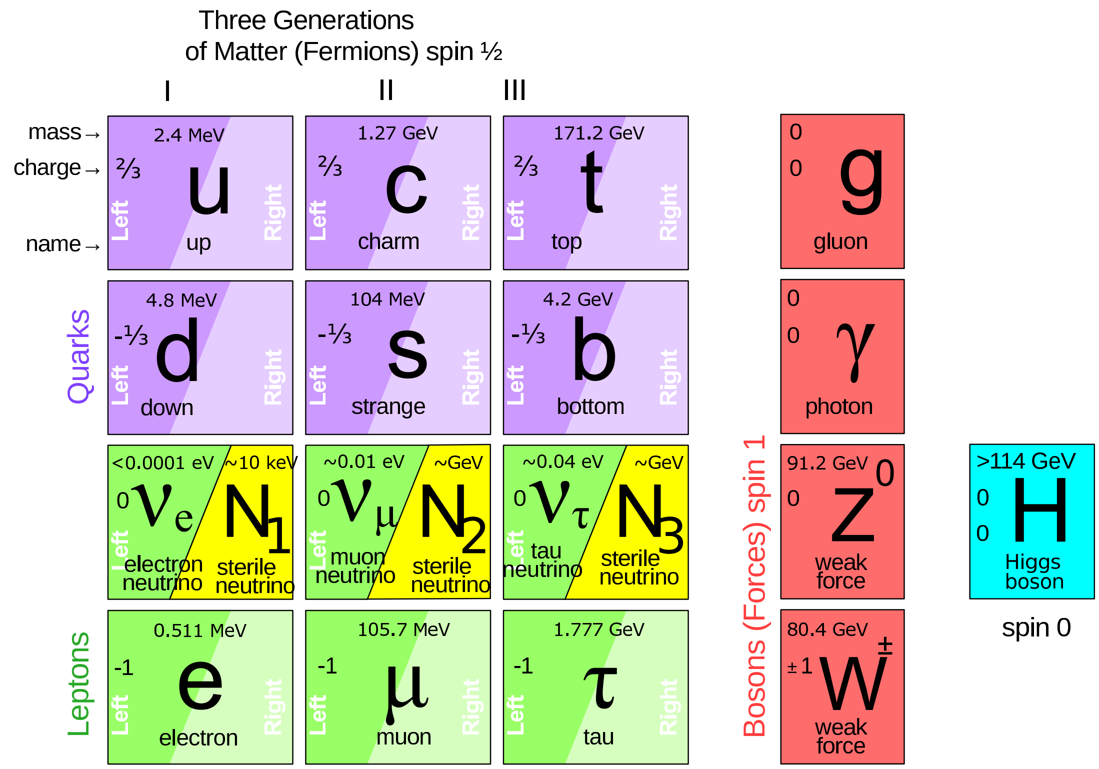
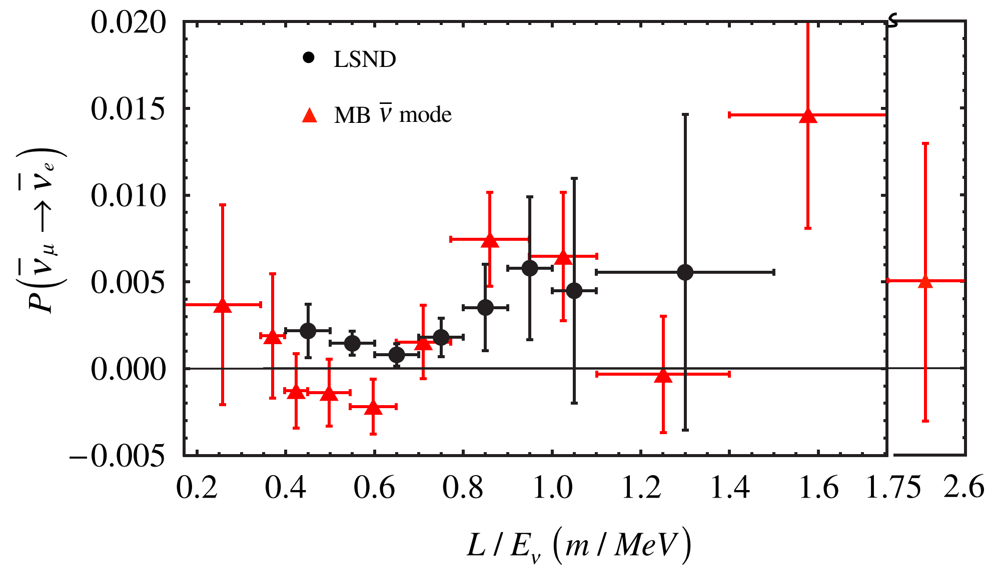


figure: O. Ruchayskiy

Hints of Sterile Neutrino(s)?

- Oscillation data
  - LSND
    Aguilar *et al.*, PRD **64** 112007 (2001)
  - MiniBooNe

Aguilar-Arevalo *et al.*, PRL **105**, 181801 (2010)

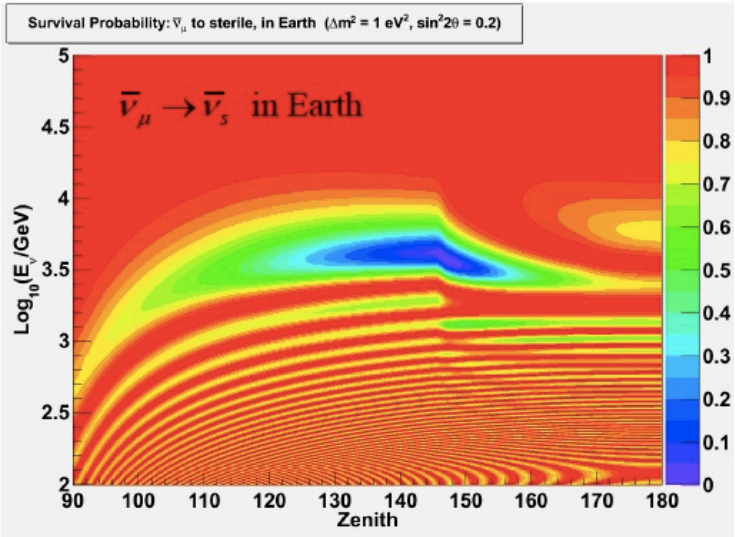


- Reactor "antineutrino anomaly"
  Mention *et al.*, PRD **83** 073006 (2011)

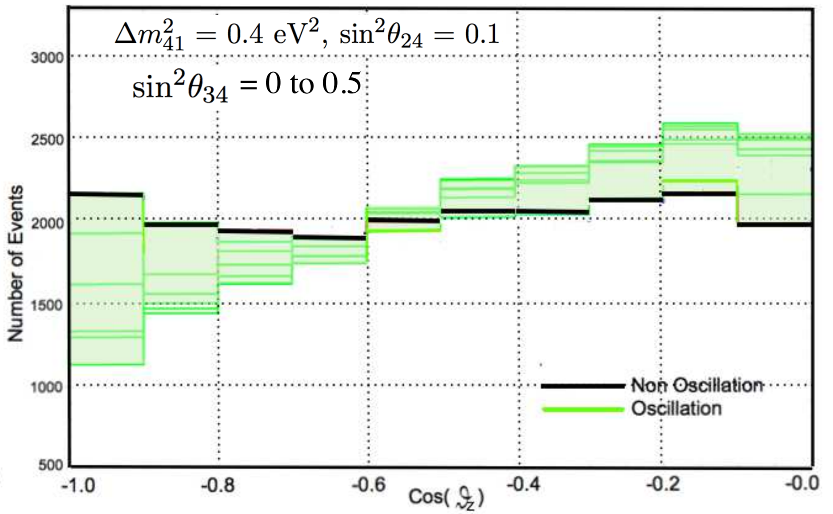
- Dark matter? Pulsar kicks? Cosmology (SPT)?

- Not a magic bullet
  - see e.g. Hamann *et al.* (arXiv:1108.4136)

Sterile MSW Resonance



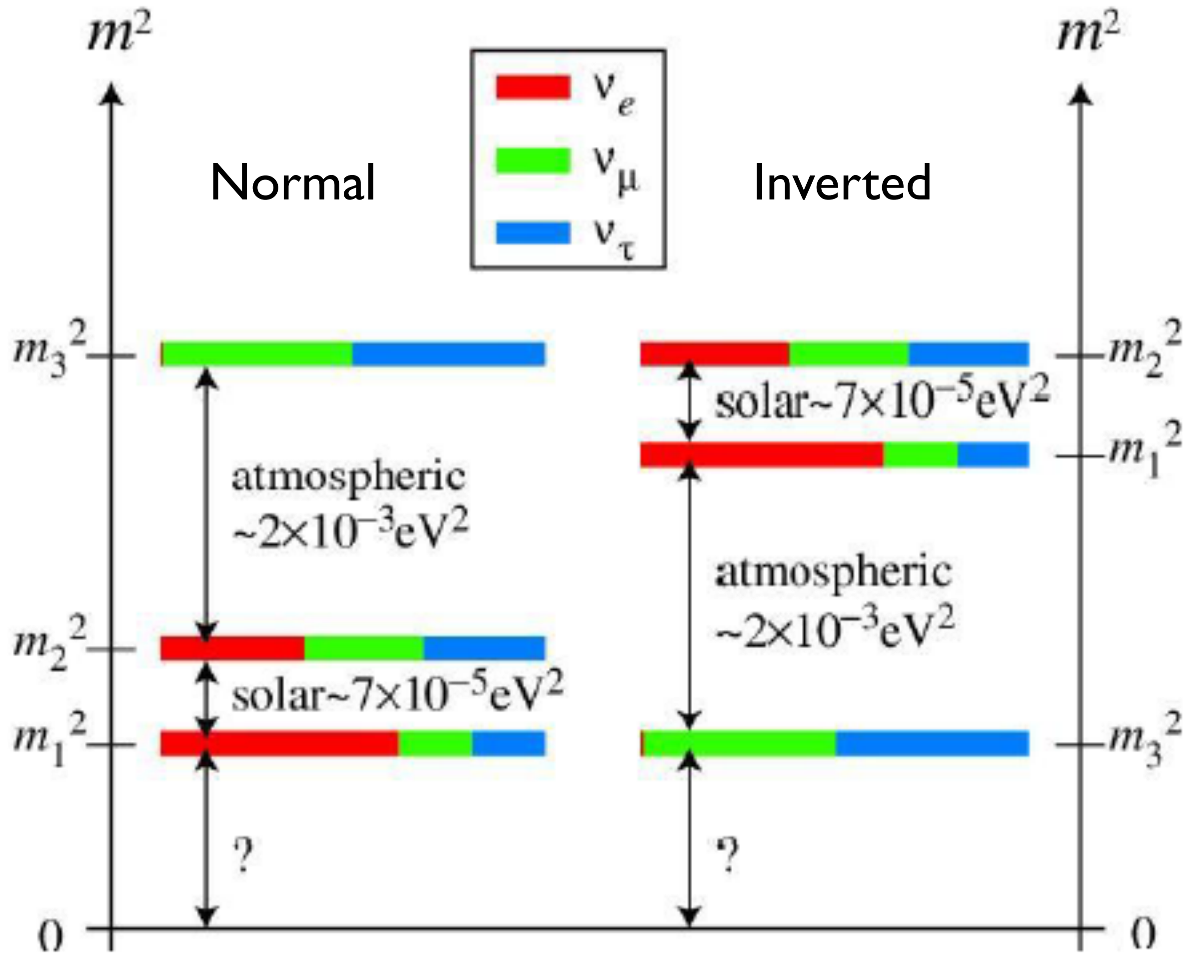
courtesy W. Huelsnitz



courtesy A. Esmaili and F. Halzen

- Matter effects can enhance oscillations (MSW effect)
- Resonant O(1 eV) sterile neutrino oscillation in atmospheric neutrinos
  - see e.g. Choubey JHEP 0712, 014 (2007)
- Observable in IceCube! (with control of systematics)

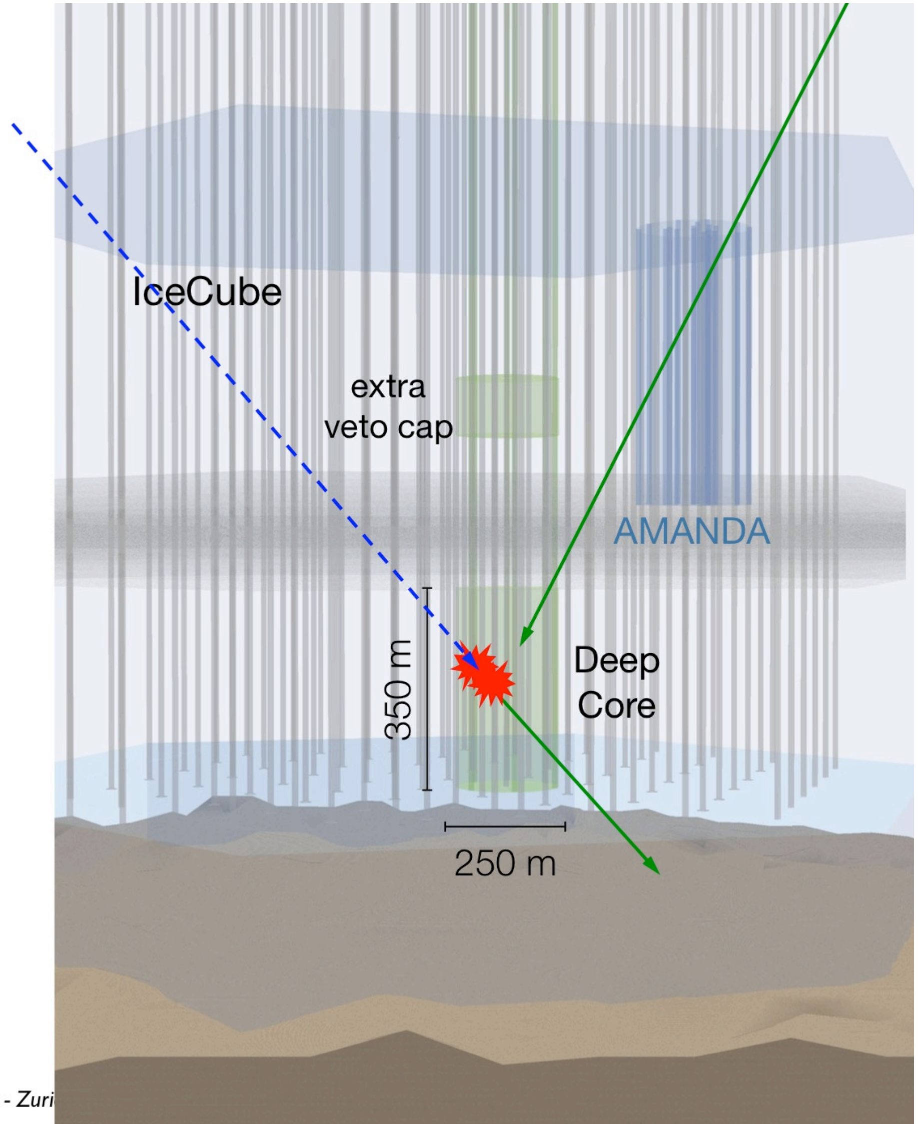
Example 3: Neutrino Mass Hierarchy



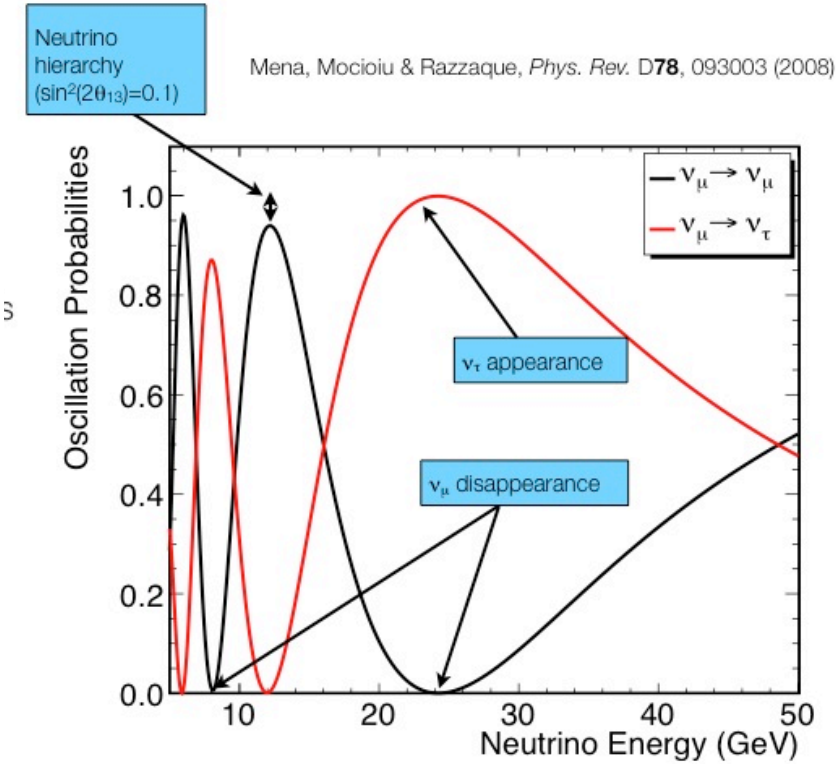
DeepCore and PINGU

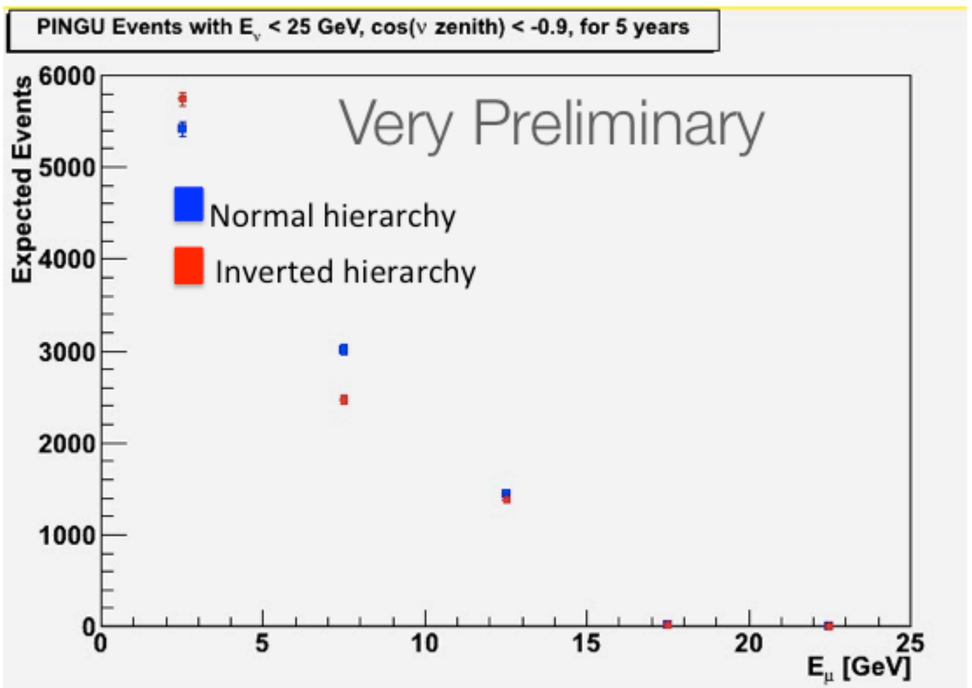
- DeepCore (completed)
  - 30 MTon sub-detector
  - ~10 GeV threshold
  - IceCube acts as a veto
  - O(100k) physics quality atmospheric ν/yr

- PINGU-I (proposal in progress)
  - 20 more strings
  - ~1 GeV threshold
  - access to more oscillation minima



Sensitivity to Hierarchy

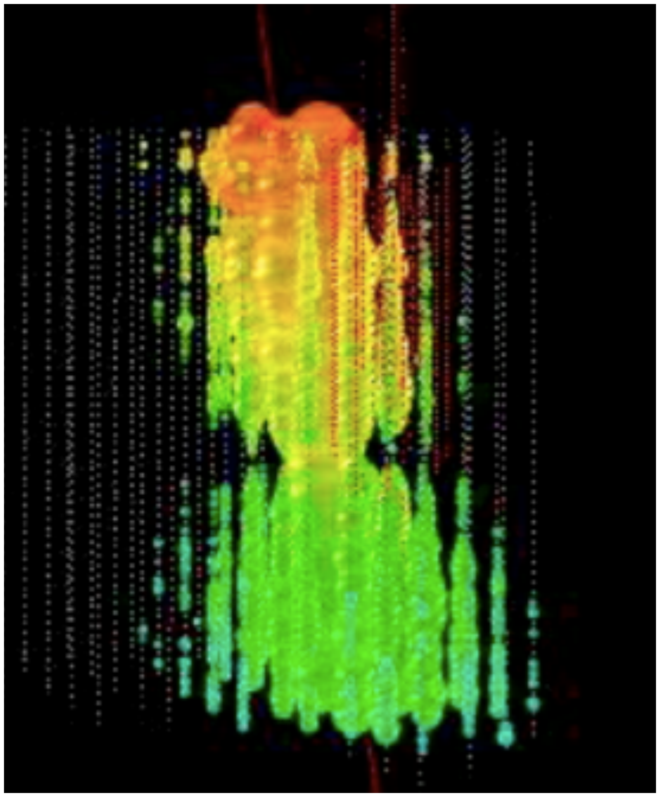


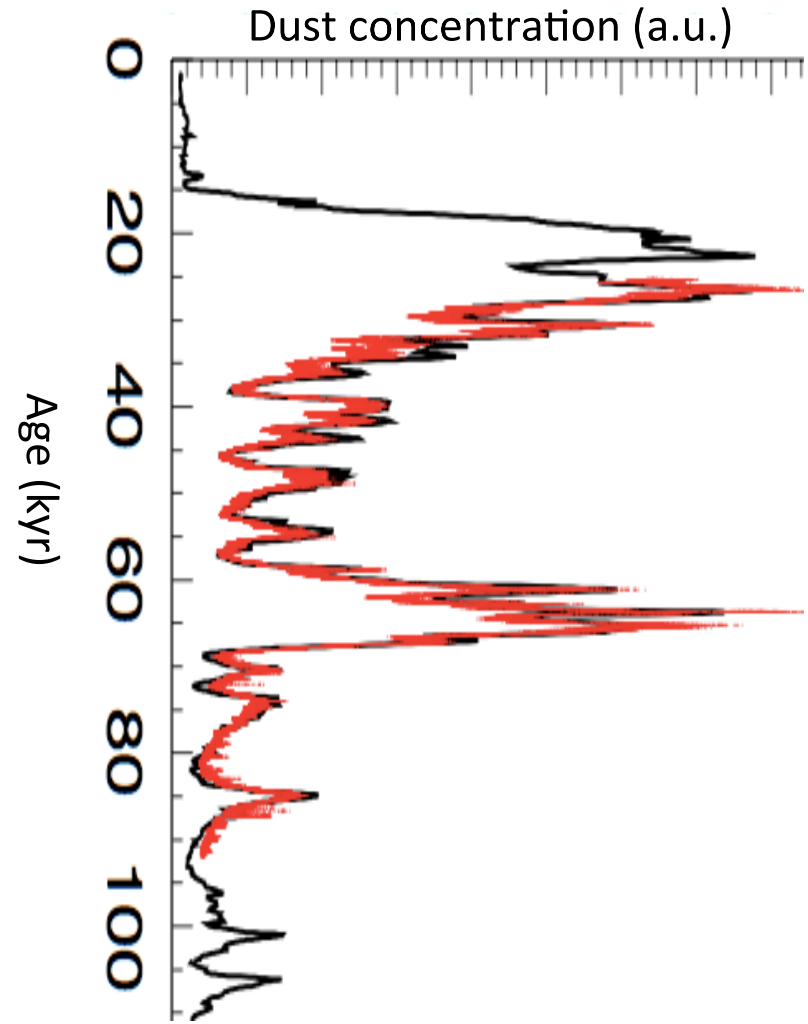


10 σ effect in several bins... but does not yet include analysis efficiencies!

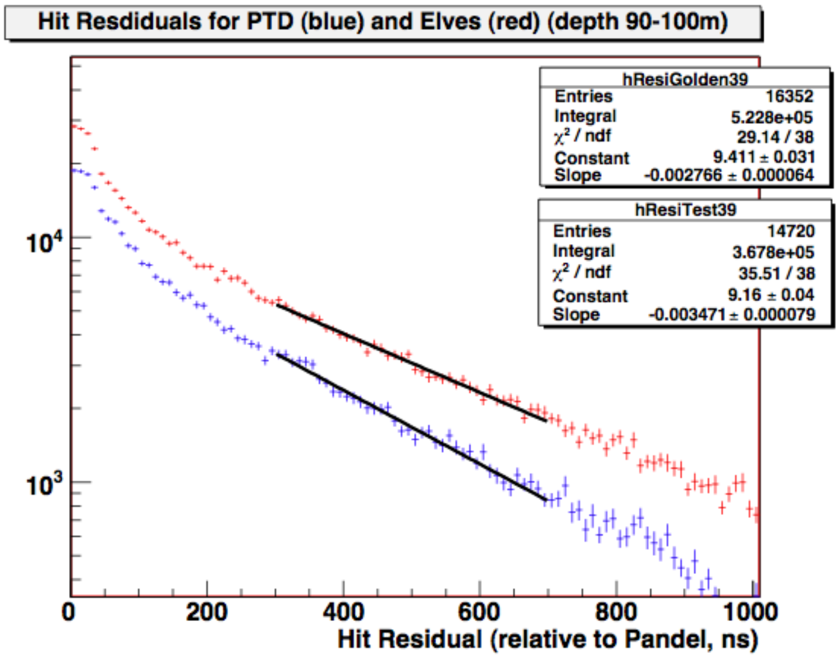
Depends strongly on size of θ_{13} (T2K results promising)

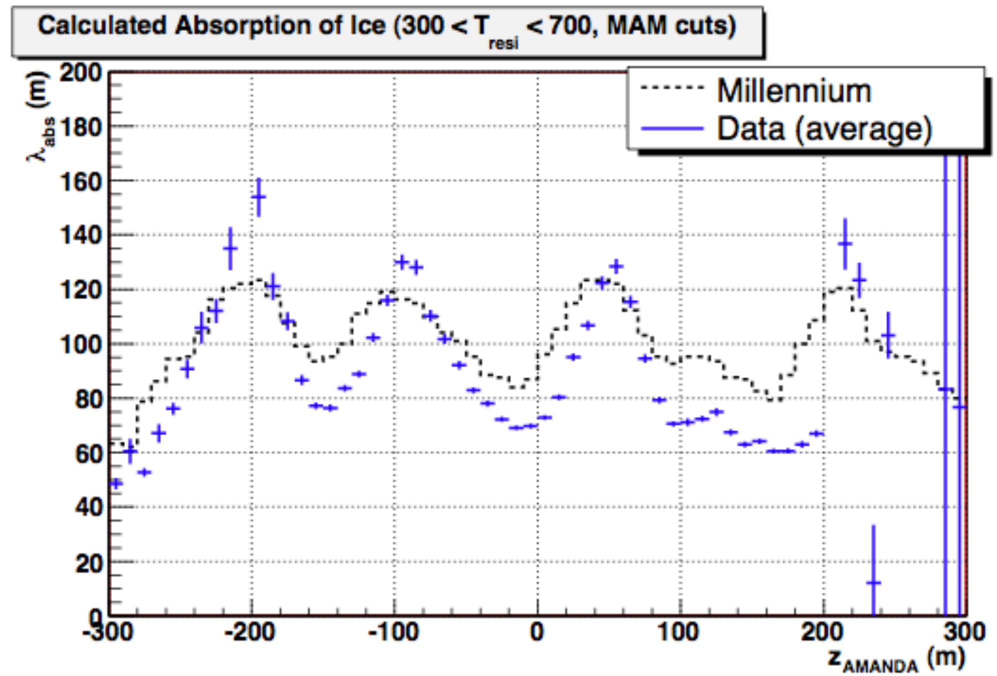
An Aside on Systematics: Ice





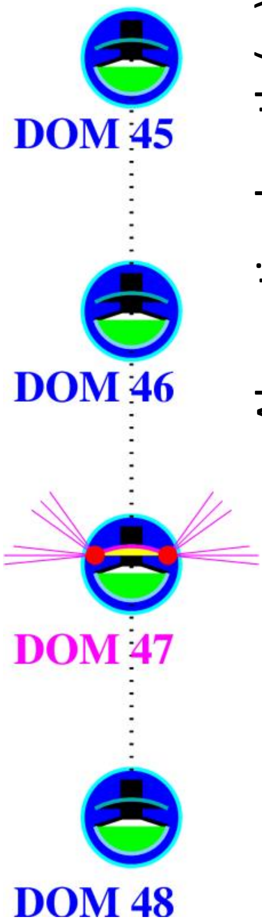
Dust Absorption via Muon Timing Residuals



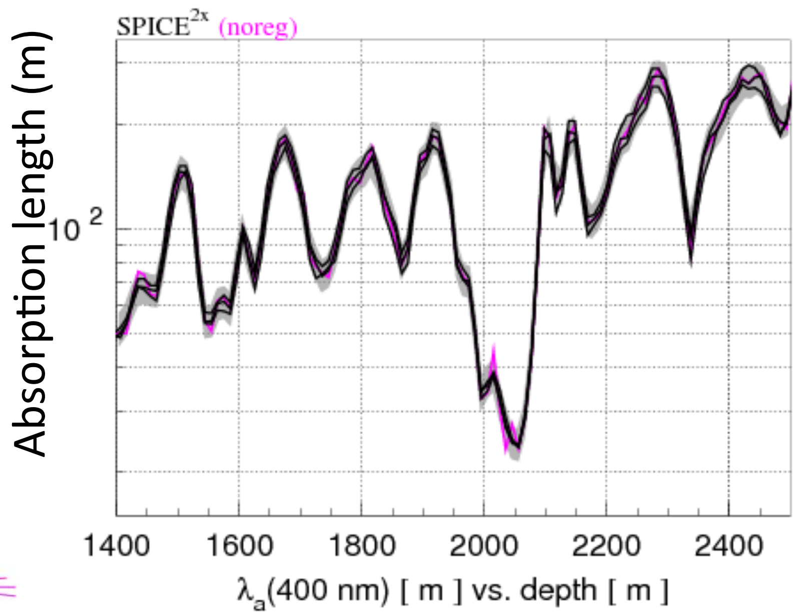


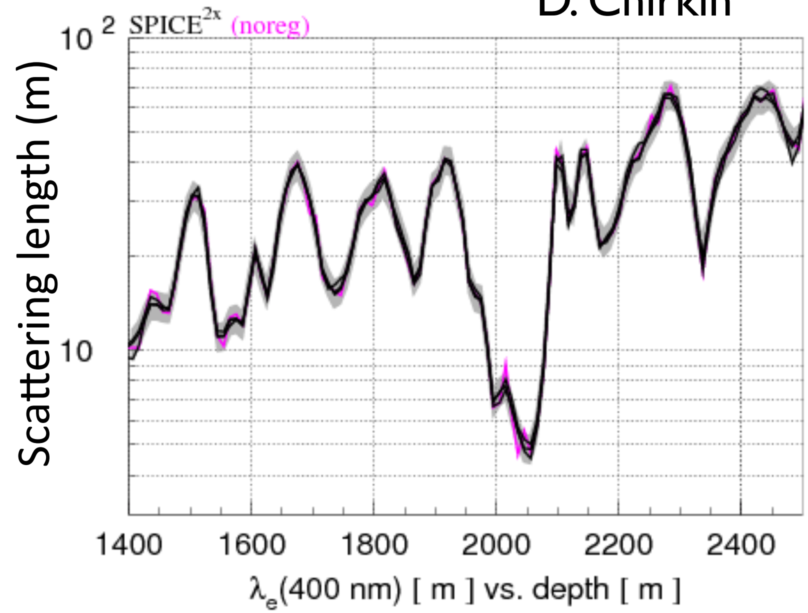
Dust layers "washed out" in old ice model!

Present: Global Fit to Flasher Data



D. Chirkin



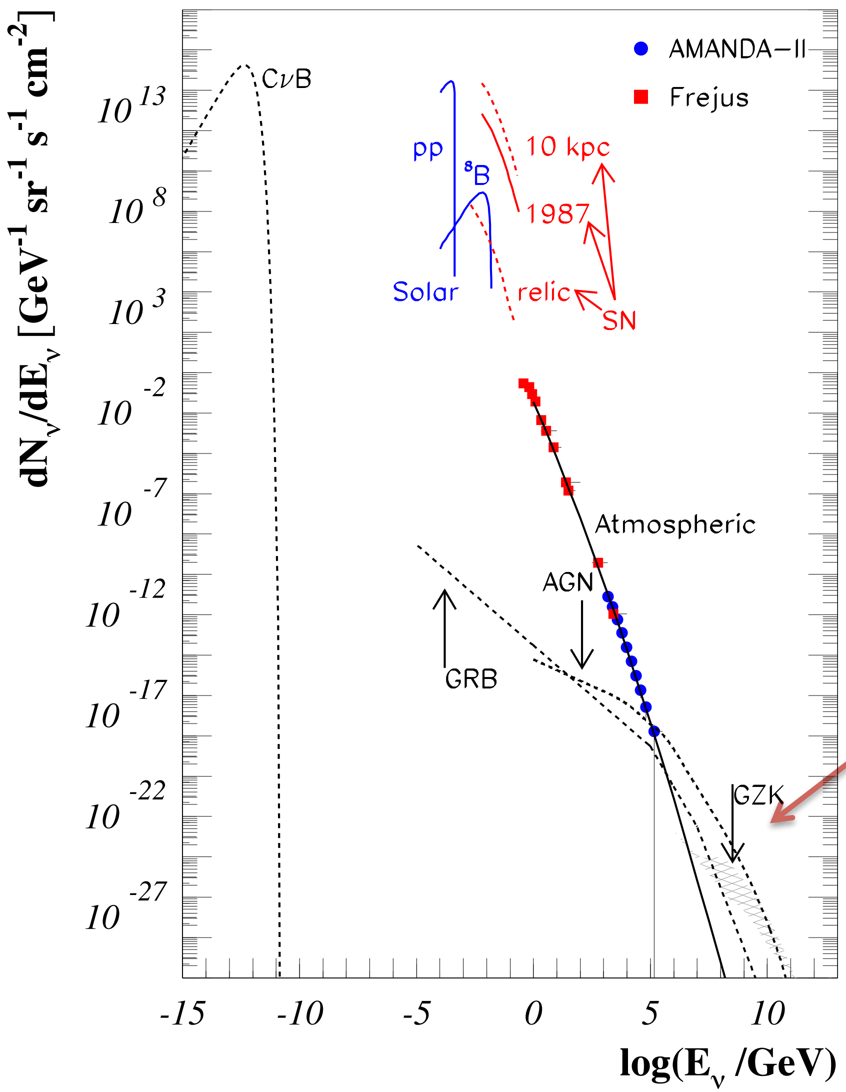


Two generations of ice model later:

much better agreement with data, fine structures resolved

Simulation includes photon propagation through ice using GPU cluster

Neutrino Spectra



New "test beam": cosmogenic neutrinos!

GZK Effect

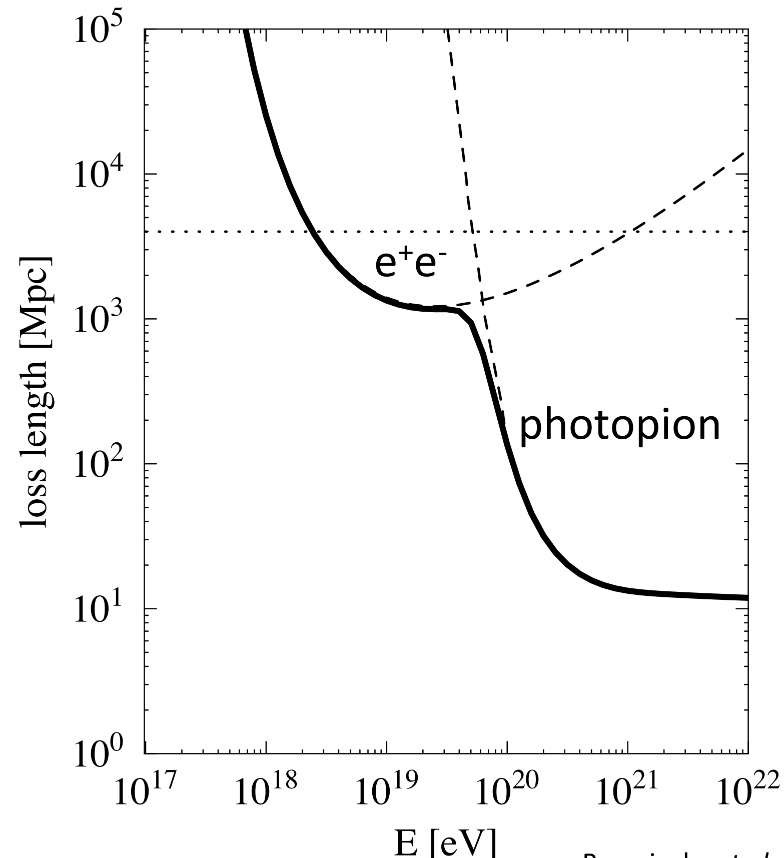
- Suppression ("cutoff") of high-energy cosmic rays due to interaction with CMB photons (Greisen-Zatsepin-Kuzmin)

$$p + \gamma \rightarrow \Delta(1232 \text{ MeV}) \begin{array}{ll} \rightarrow & p + \pi^0 \\ \rightarrow & n + \pi^+ \end{array}$$

- Threshold ~ 6×10^{19} eV

- Pion decay results in neutrinos

proton loss length



Berezinsky *et al.* 2007

The Neutrino Connection

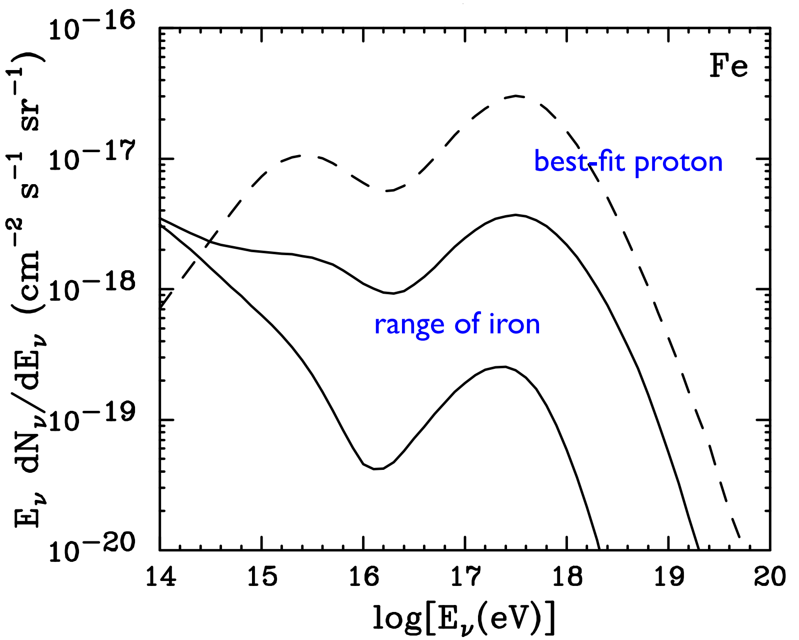
- GZK process also produces UHE neutrinos!

$$p\gamma \rightarrow n\pi^+ \rightarrow n\mu + \nu_\mu.$$

- Nuclei will tend to photodisintegrate first (reduced flux)

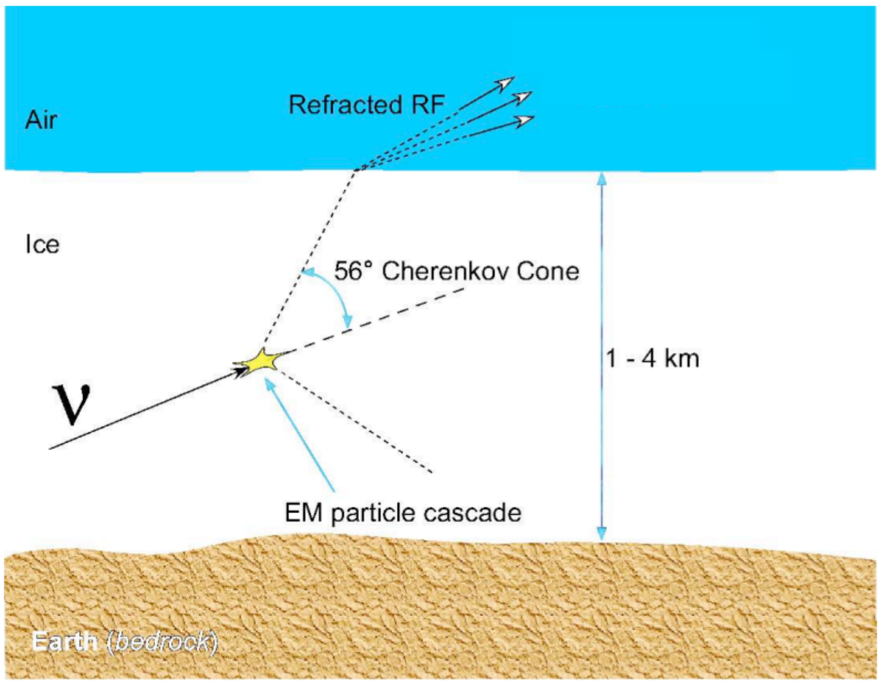
- UHE "test beam" for new physics tests
  - cosmological baselines probed
  - energies ~ 10^{18}-10^{19} eV

GZK neutrino flux models



Anchordoqui *et al.*, PRD **76** 123008 (2007)

Askaryan Emission

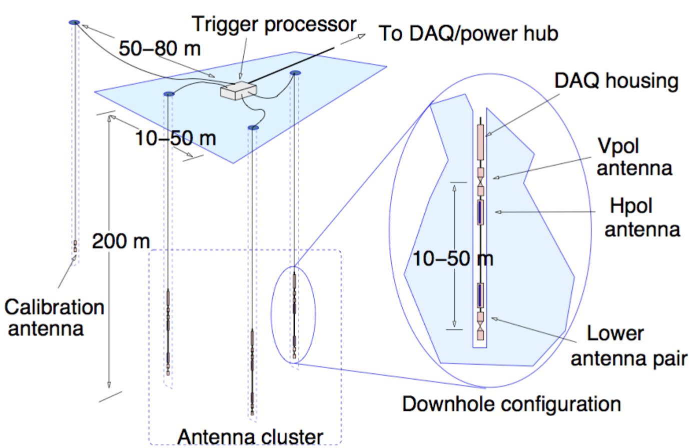


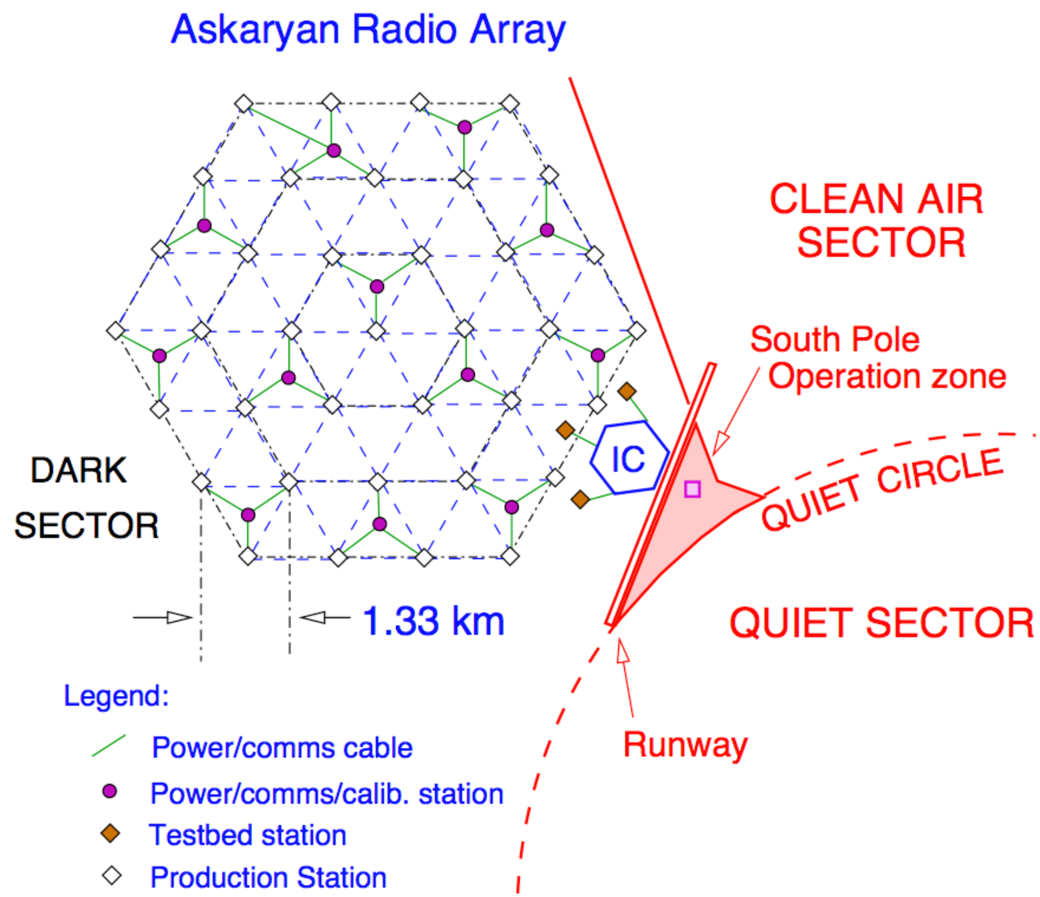
Kowalski *et al.* 2007

- Coherent radio pulse from charge excess (60-1000 MHz) in neutrino-induced showers
- Radiation characteristics confirmed in sand, salt, and ice
  (see e.g. Gorham *et* al., PRL 99:171101,2007)
- Cold ice is exceptionally RF-transparent
- Radio is scalable to very large arrays

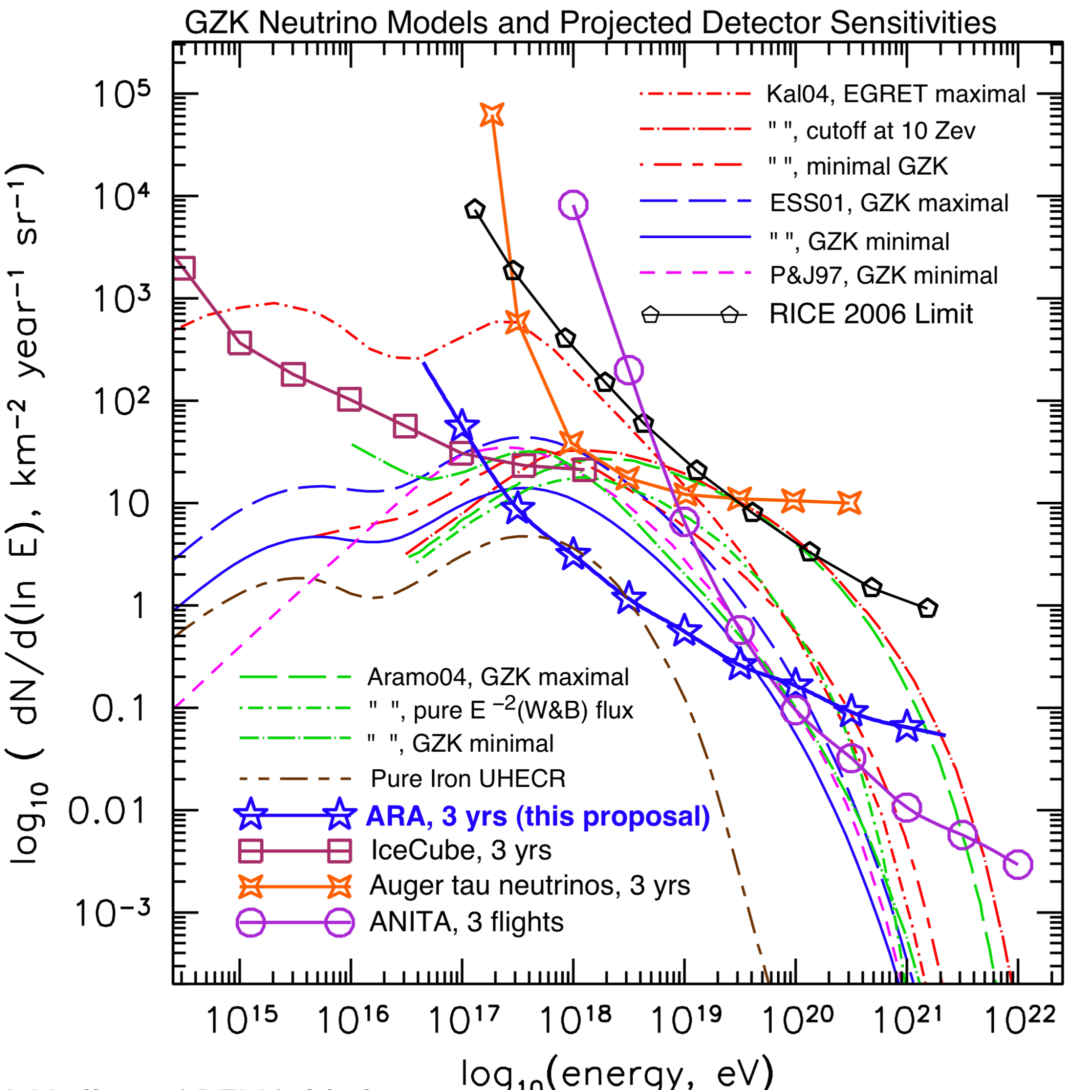
ARA: Askaryan Radio Array

- 80 km^2 radio-frequency UHE neutrino detector
- Cosmogenic neutrino rates up to 25 events / year
- Iron UHECR: ~1 ev/yr





ARA Sensitivity



K. Hoffman, ARENA 2010

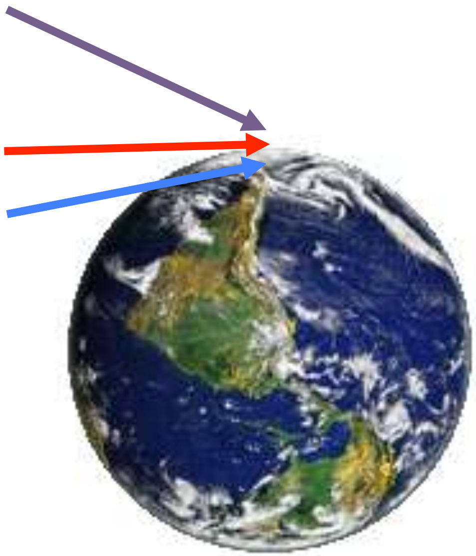
- ARA primary scientific goal: determine absolute flux level
- Combine with cosmic ray experiments to pin down astrophysical unknowns
- A larger-scale experiment necessary to:
  - measure spectrum
  - flavor identification

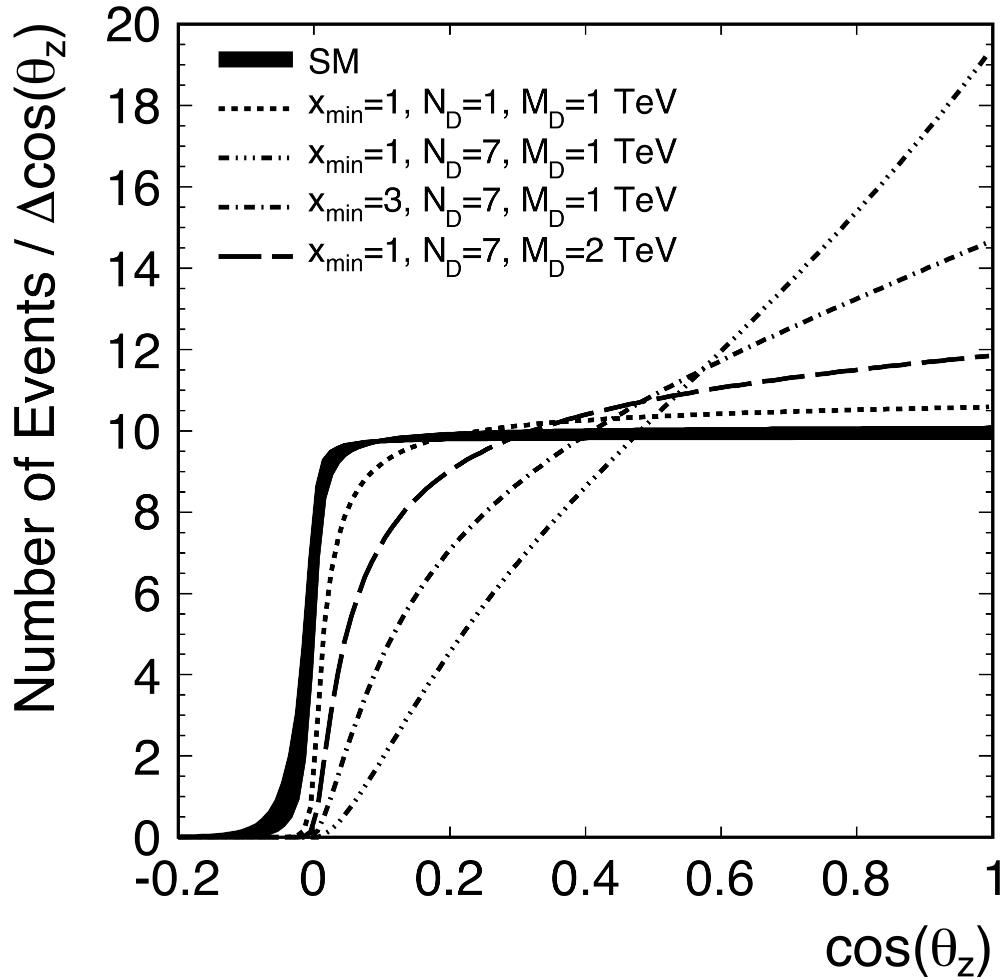
Physics with Cosmogenic Neutrinos

- VLI-induced neutrino splitting $\nu \rightarrow \nu\nu\bar{\nu}$
  - modification of spectral shape
  - see e.g. Mattingly, Liberati *et al.*, arXiv: 0911.0521
- Neutrino / dark energy coupling leading to VLI / CPTV
  - flavor ratio via angular dependence
  - see e.g. Ando *et al.*, arXiv:0910.4391
- Cross section measurement
  - large extra dimensions / black hole production

Neutrino Cross Section with ARA

Connolly, Thorne, & Waters, PhysRevD.83.113009 (2011)





Summary

- IceCube (+extensions): neutrino physics using the atmospheric neutrino spectrum
  - searches for Lorentz violation
  - searches for sterile neutrinos
  - neutrino mass hierarchy
- ARA will extend the search using cosmogenic neutrinos
  - neutrino splitting, dark energy coupling
  - cross section measurement
- Not just "exotic" physics
  - neutrino energy spectra, oscillation parameters
- Astrophysical neutrino sources mean even more opportunities

Thank you!