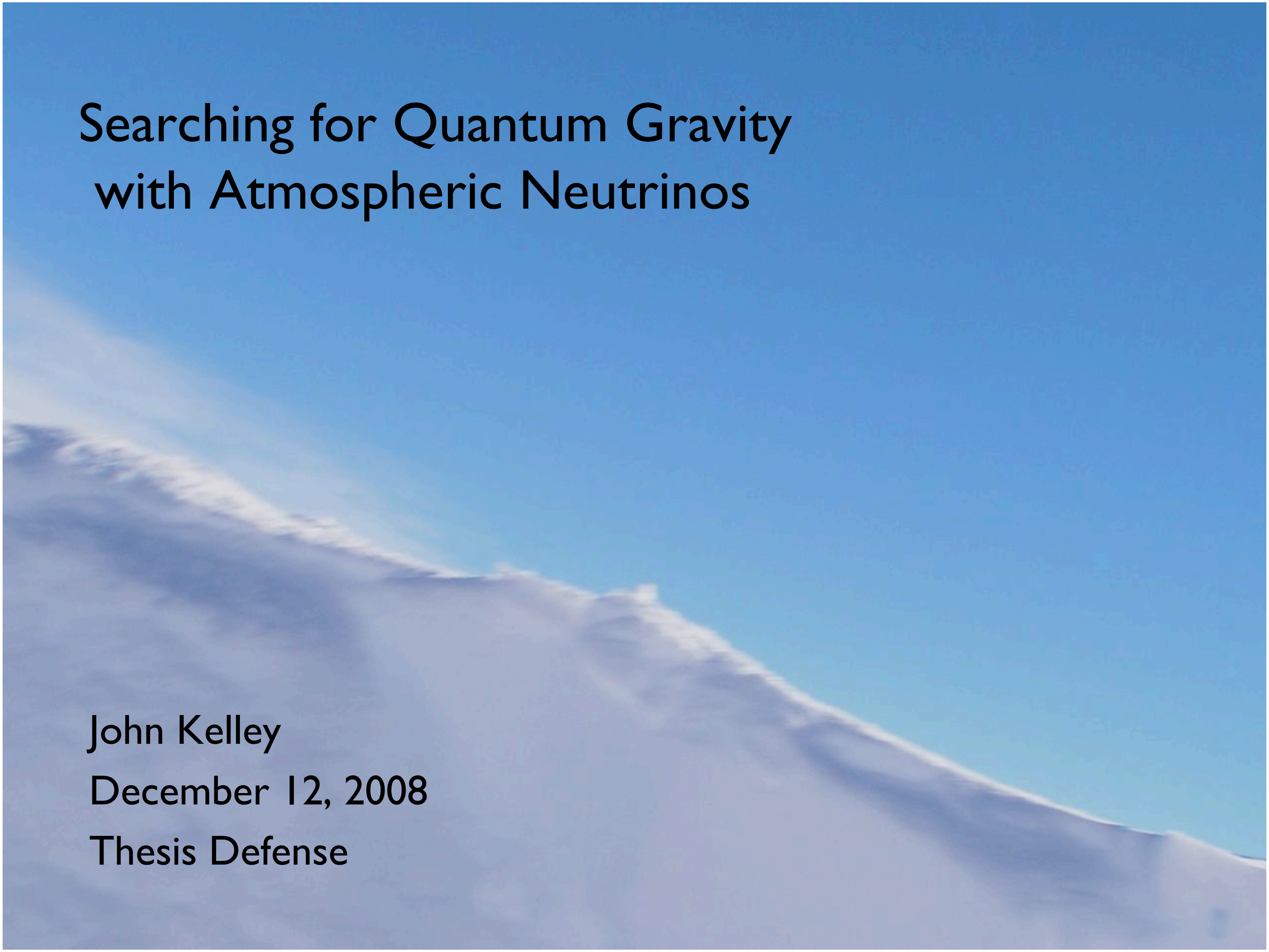


Searching for Quantum Gravity with Atmospheric Neutrinos

John Kelley

December 12, 2008

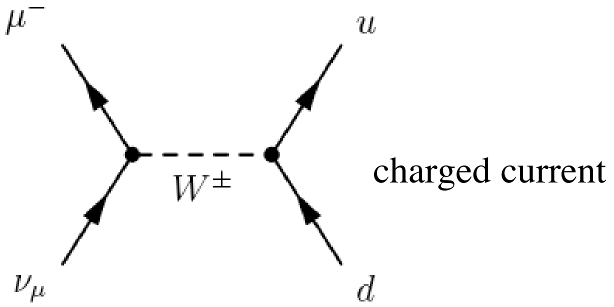
Thesis Defense

Outline

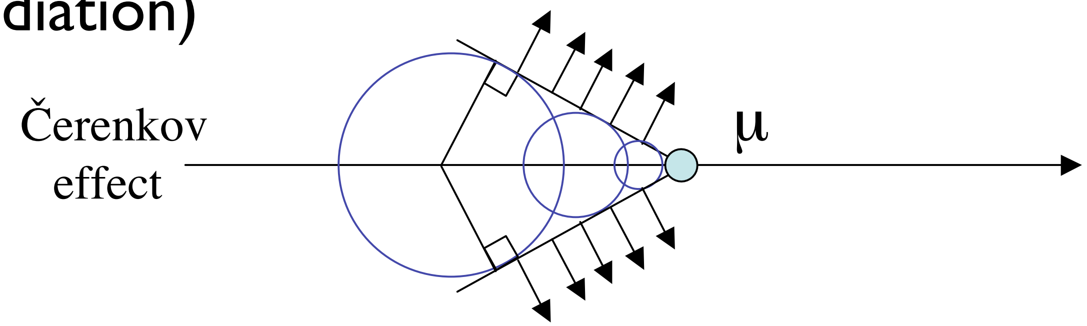
- Neutrino detection
- New physics signatures
- Data selection
- Analysis methodology
- Results
- Outlook

Neutrino Detection

1. Need an interaction — small cross-section necessitates a big target!

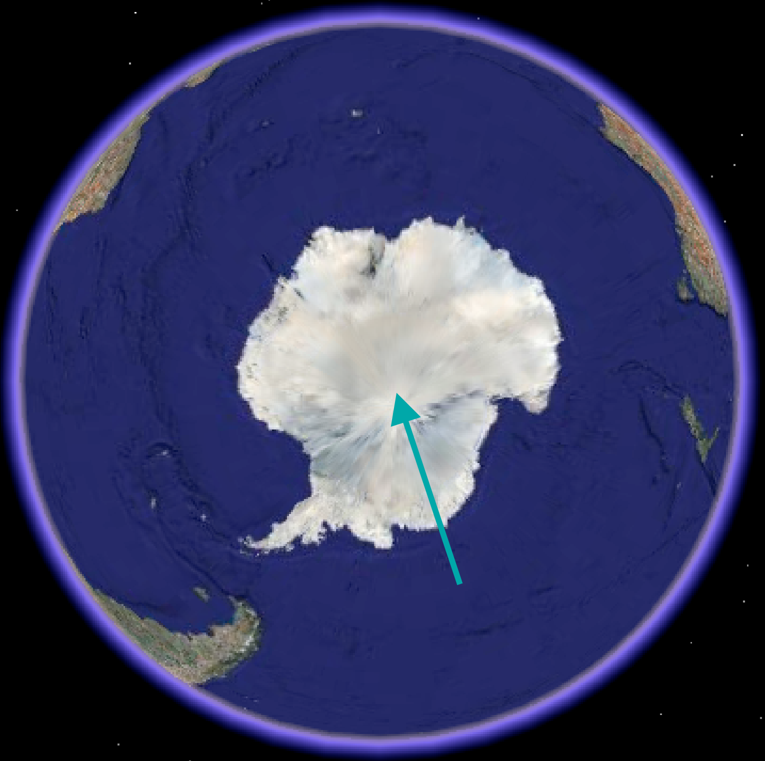


2. Then detect the interaction products (say, by their radiation)

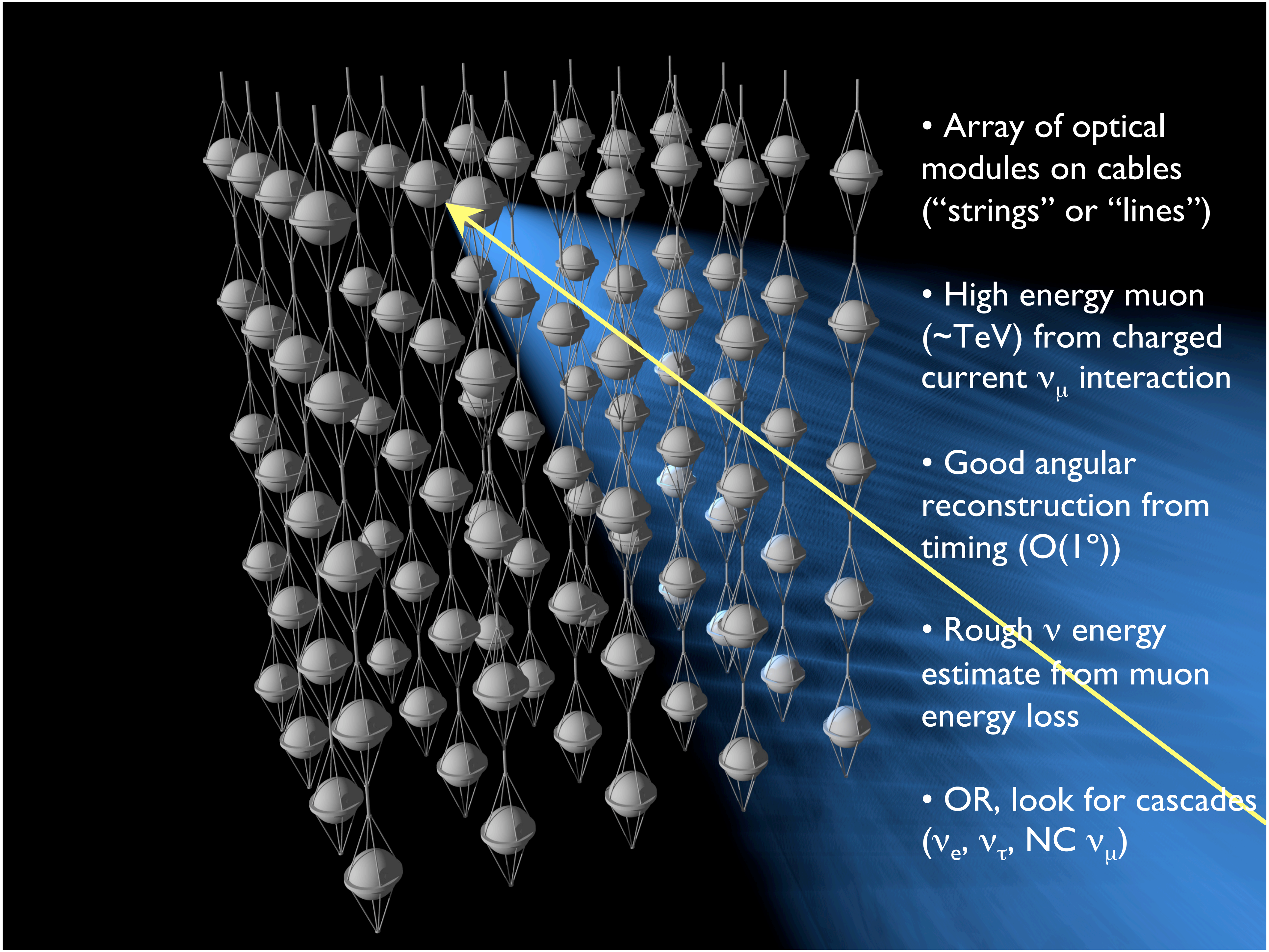


Earth's Transparent Medium: H_2O

Mediterranean,
Lake Baikal

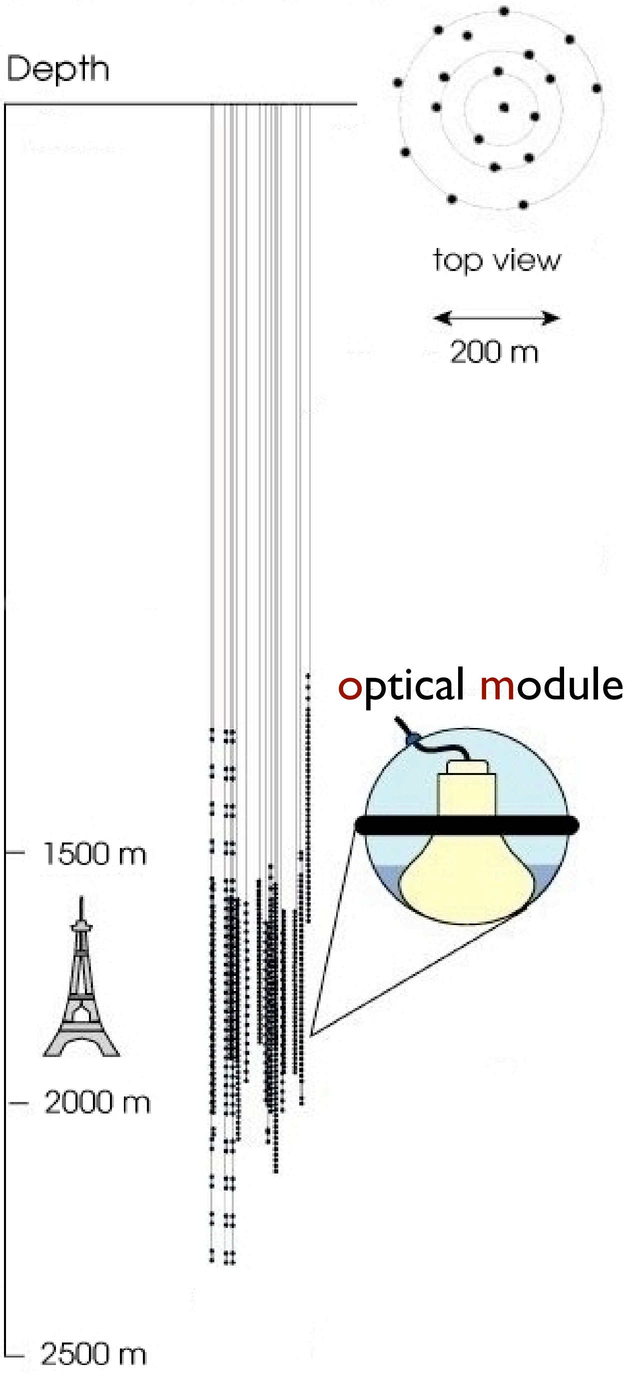


Antarctic ice sheet



- 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)

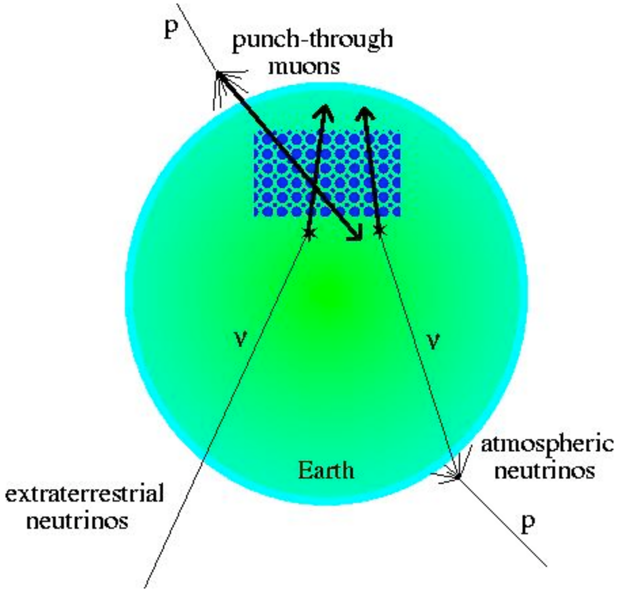
AMANDA-II



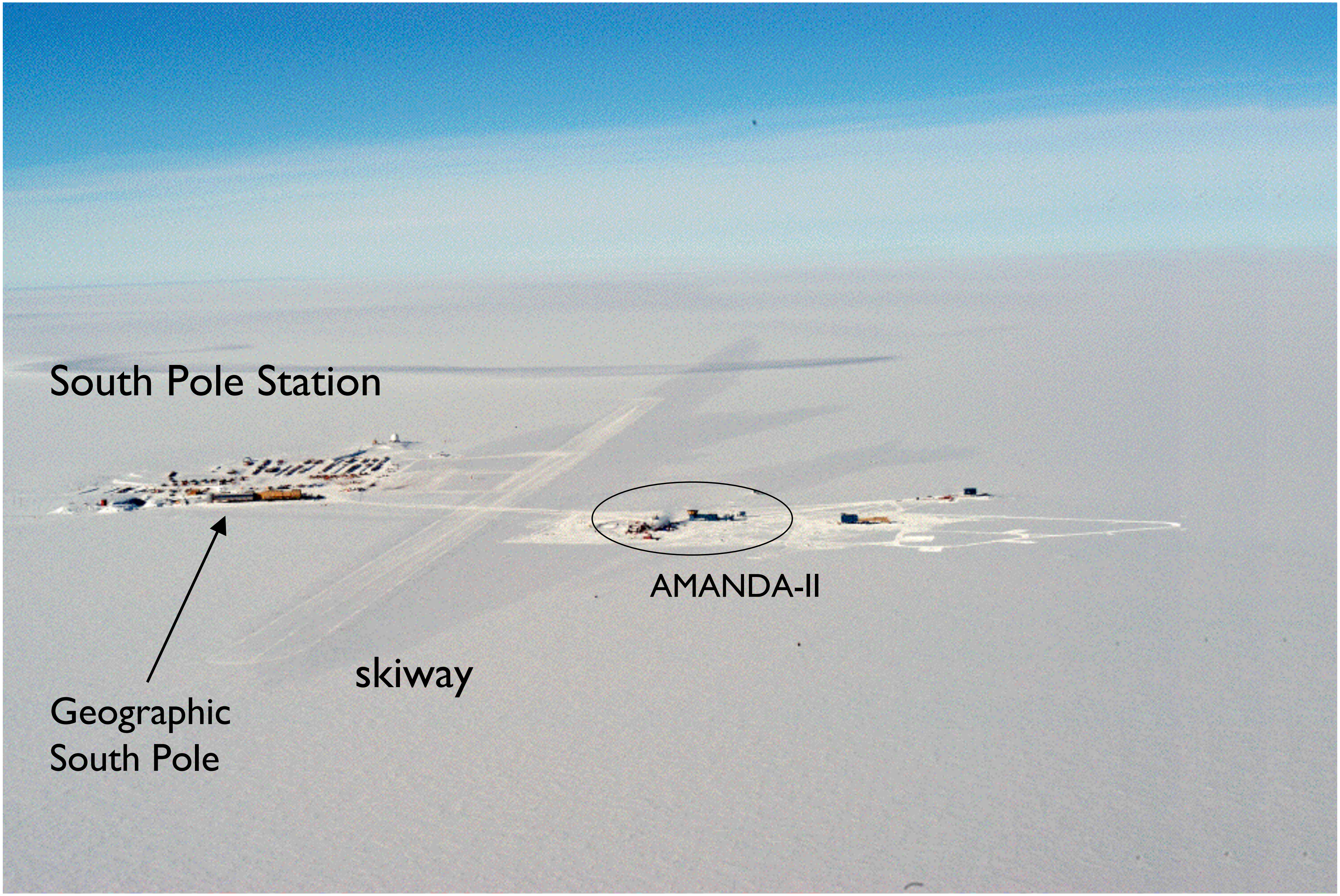
- The AMANDA-II neutrino telescope is buried in deep, clear ice, 1500m under the geographic South Pole

- 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 Neutrino Production

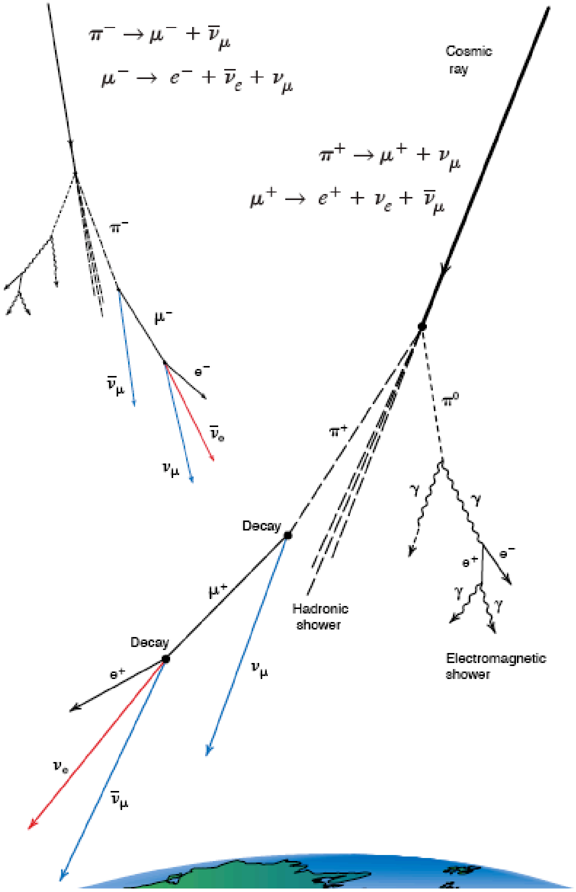


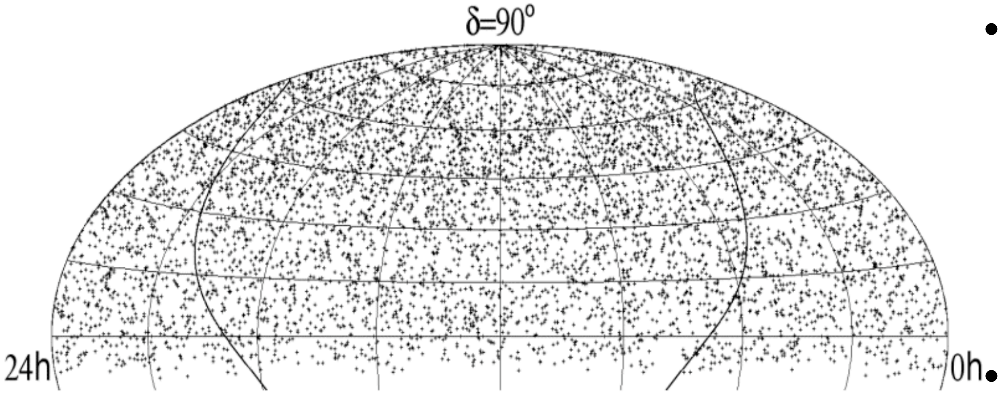
Figure from Los Alamos Science **25** (1997)

Cosmic rays produce muons, neutrinos through charged 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



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

- No detection (yet) of
  - point sources or other anisotropies
  - diffuse astrophysical flux
  - transients (*e.g.* GRBs, AGN flares, SN)
  - DM annihilation (Earth or Sun)
- 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

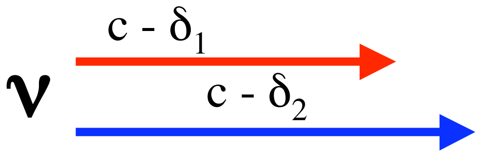
New Physics with Neutrinos?

- 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

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

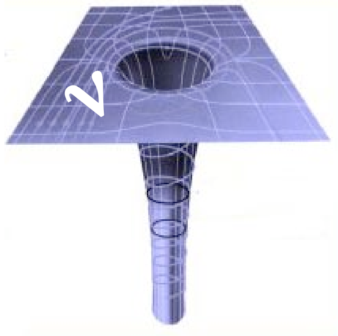
New Physics Effects

- 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

“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

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

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

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

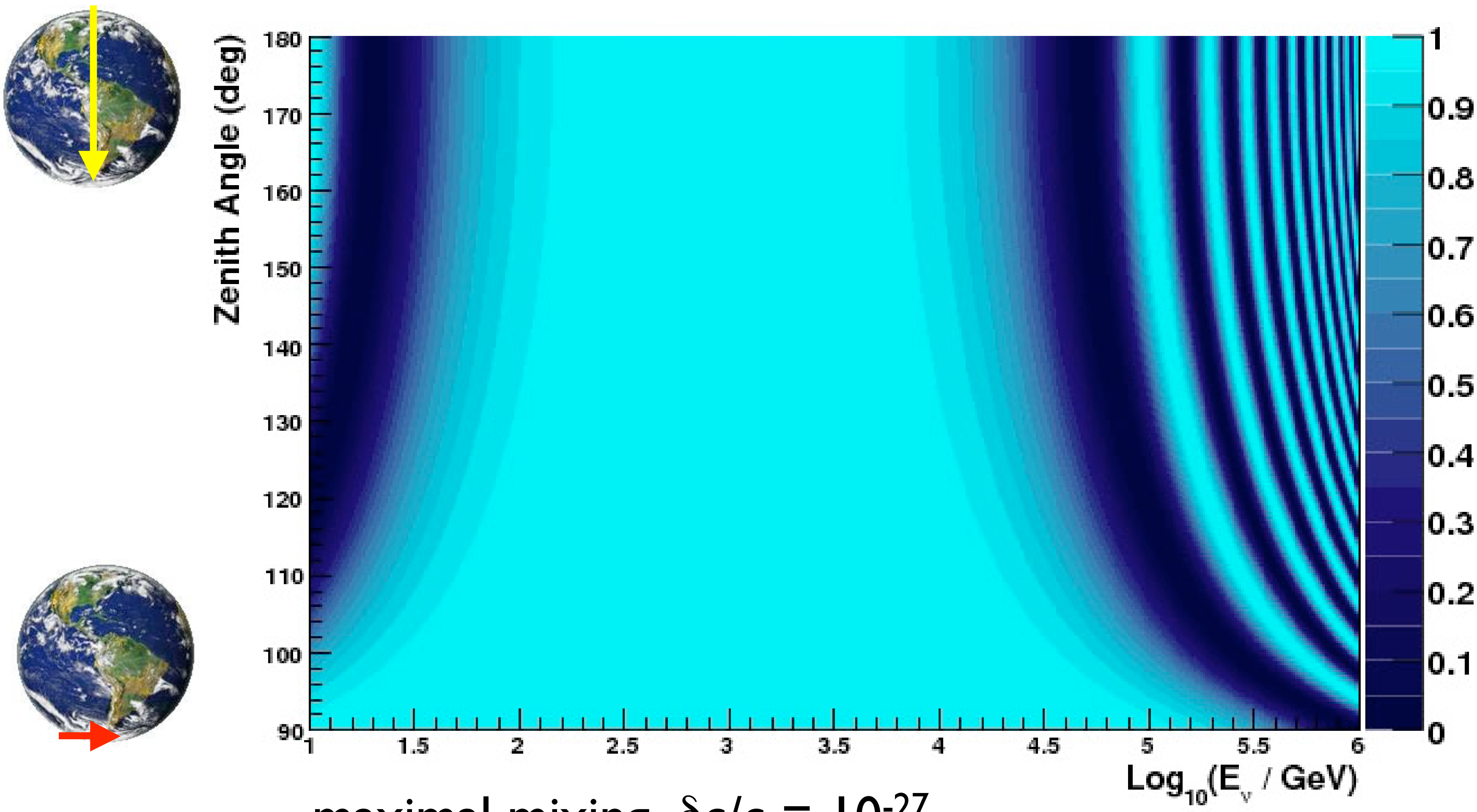
$$R = \frac{\delta c}{c}\frac{E}{2}\frac{4E}{\Delta m^2_{23}}$$

- 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 *δc*/*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



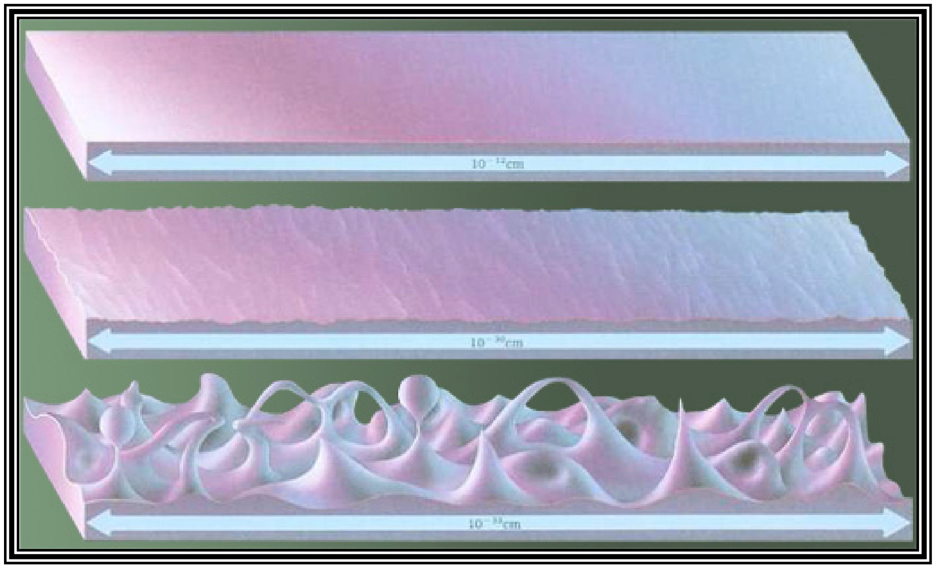
maximal mixing, $\delta c/c = 10^{-27}$

Quantum Decoherence (QD)

- Another possible low-energy signature of quantum gravity: quantum decoherence

- Heuristic picture: foamy structure of space-time (interactions with virtual black holes) may not preserve certain quantum numbers (like ν flavor)

- Pure states interact with environment and decohere to mixed states



Decoherence + Atmospheric Oscillations

characteristic exponential behavior

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

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

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

1:1:1 ratio after decoherence

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

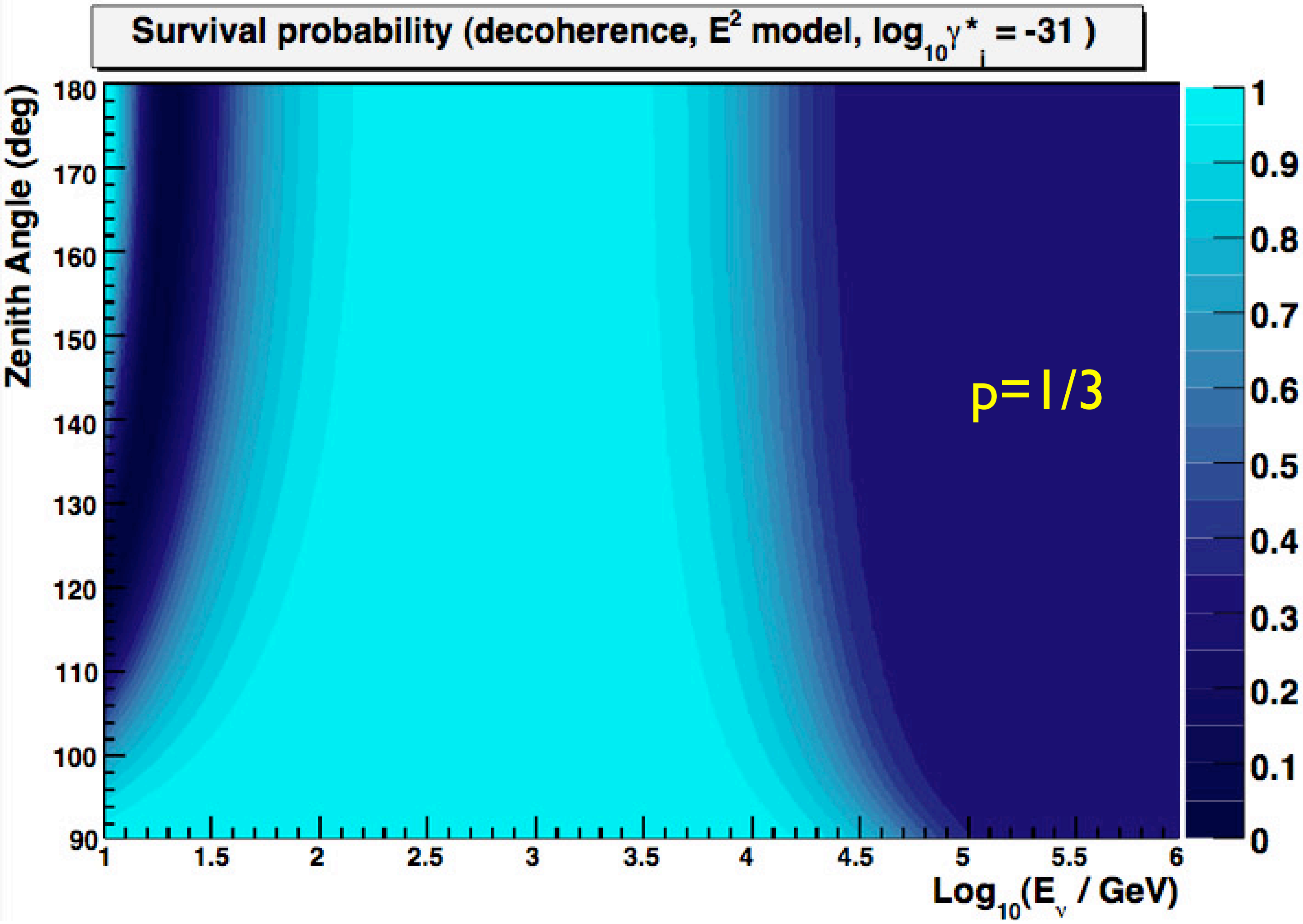
Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

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

QD Atmospheric ν_μ Survival Probability

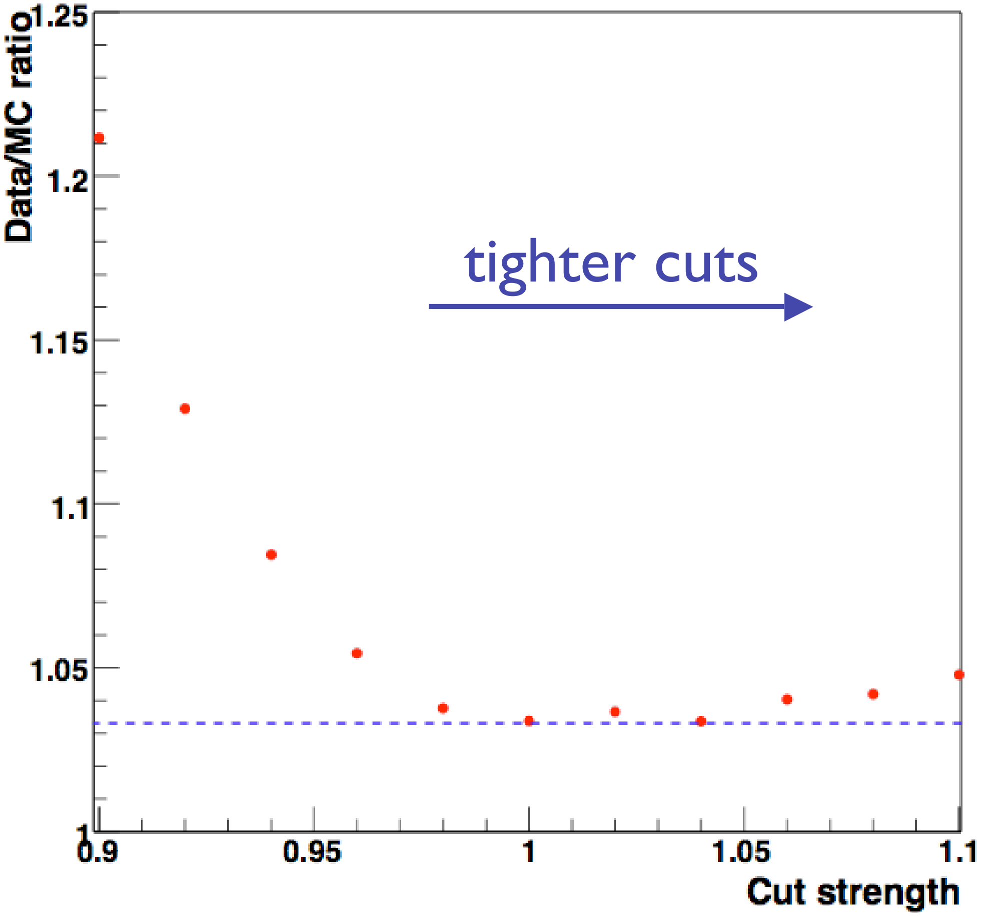


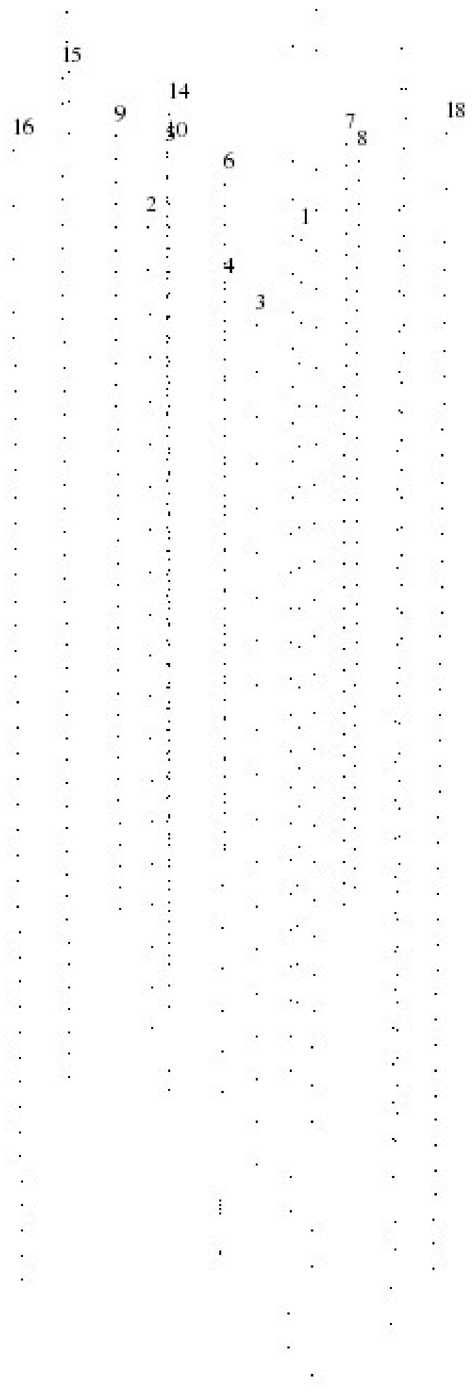
Event Selection (2000-2006 data)

- Initial data filtering
  - noise + crosstalk cleaning
  - bad optical module filtering
  - fast directional reconstruction, loose “up-going” cut
  - 80 Hz → 0.1 Hz
- Final quality cuts
  - iterative full likelihood reconstruction (timing of photon hits)
  - cuts on track quality variables
    - smoothness of hits, angular error estimate, likelihood ratio to downgoing muon fit, space angle between reconstructions, etc.
  - 0.1 Hz → 4 / day (for atm. ν: 24% eff., 99% purity)
- Final sample: 5544 events below horizon (1387 days livetime)

Purity Level

- Simulating final bit of background not feasible
- Estimate contamination by tightening cuts until data/MC ratio stabilizes
- Procedure shows essentially no contamination at final cut level (strength = 1)



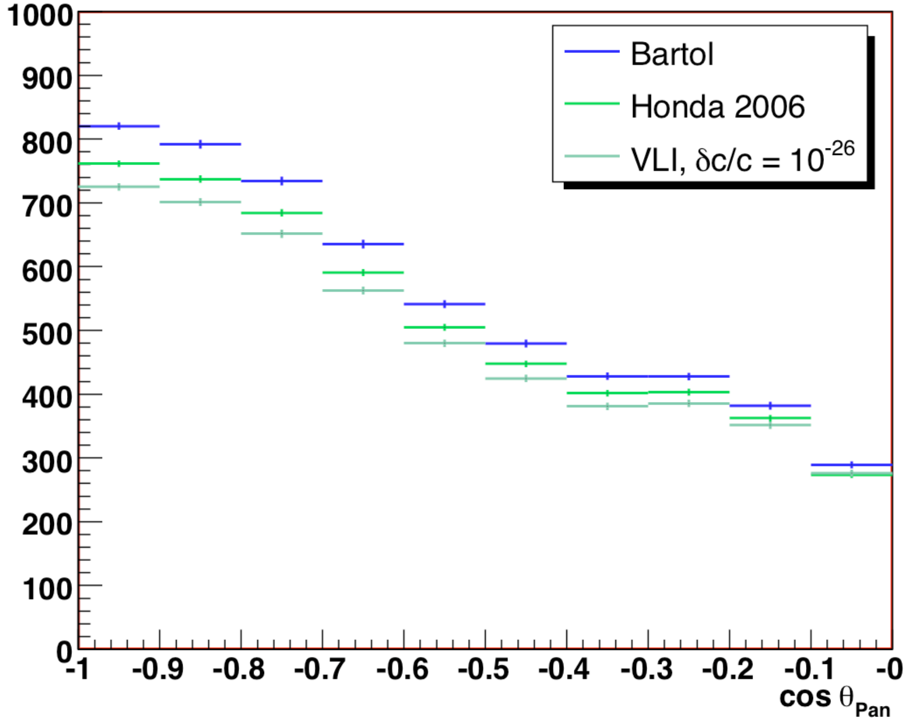


Event 5119326 (May 30, 2005)

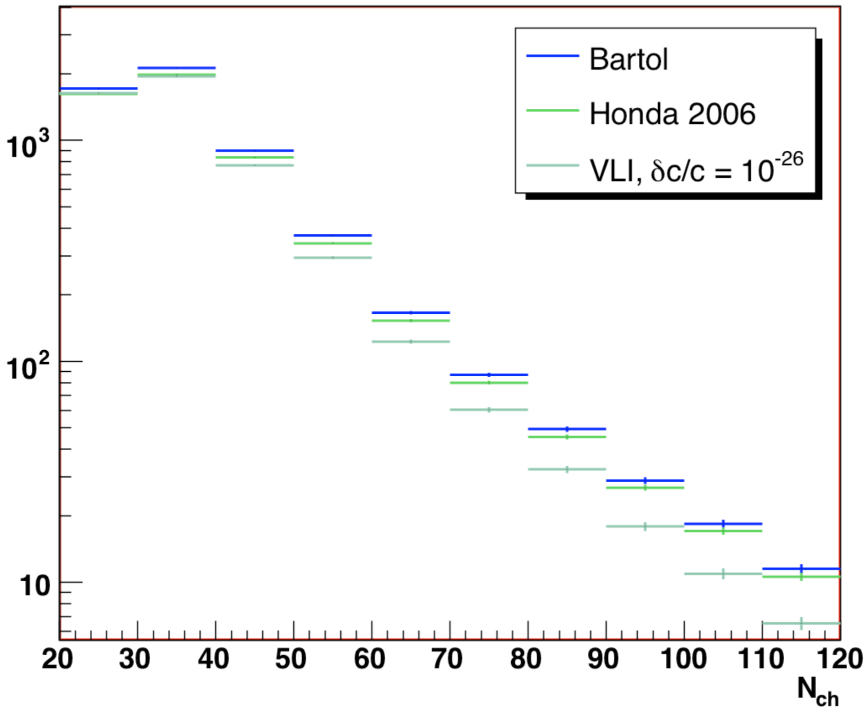
199 OMs hit
zenith angle 158°
angular error 0.7°
ν energy > ~20 TeV

Simulated Observables

reconstructed zenith angle

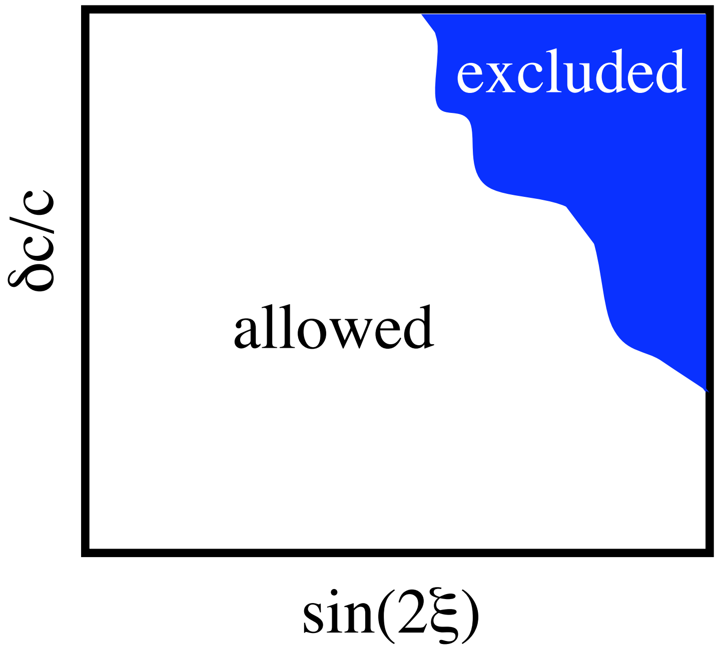


$N_{channel}$ (energy proxy)



QG signature: deficit at high energy, near vertical

Testing the Parameter Space



Given observables *x*, want to determine values of parameters $\{\theta_r\}$ that are allowed / excluded at some confidence level

Binned likelihood + Feldman-Cousins

Feldman-Cousins Recipe (frequentist construction)

- Test statistic is likelihood ratio:
  ΔL = LLH at parent $\{\theta_r\}$ - minimum LLH at some $\{\theta_{r,best}\}$
  (compare hypothesis at this point to best-fit hypothesis)

$$2\sum_{i=1}^{N}(\mu_i - n_i \ln \mu_i + \ln n_i!)$$

- For each point in parameter space $\{\theta_r\}$, perform many simulated MC "experiments" to see how test statistic varies (close to χ^2)

- For each point $\{\theta_r\}$, find ΔL_{crit} at which, say, 90% of the MC experiments have a lower ΔL

- Compare ΔL_{data} to ΔL_{crit} at each point to determine exclusion region

Feldman & Cousins, PRD **57** 7 (1998)

Nuisance Parameters / Systematic Errors

How to include nuisance parameters $\{\theta_s\}$:

- test statistic becomes *profile likelihood*

$$l = \frac{L(x|\theta_{r0}, \hat{\hat{\theta}}_s)}{L(x|\hat{\theta}_r, \hat{\theta}_s)}$$

Variable	Meaning
θ_r	physics parameters
θ_s	nuisance parameters
$\hat{\theta}_r, \hat{\theta}_s$	unconditionally maximize $L(x\|\hat{\theta}_r, \hat{\theta}_s)$
$\hat{\hat{\theta}}_s$	conditionally maximize $L(x\|\theta_{r0}, \hat{\hat{\theta}}_s)$

- MC experiments use “worst-case” value of nuisance parameters (Feldman’s *profile construction* method)
  - specifically, for each θ_r, generate experiments fixing n.p. to data’s $\hat{\hat{\theta}}_s$, then re-calculate profile likelihood as above

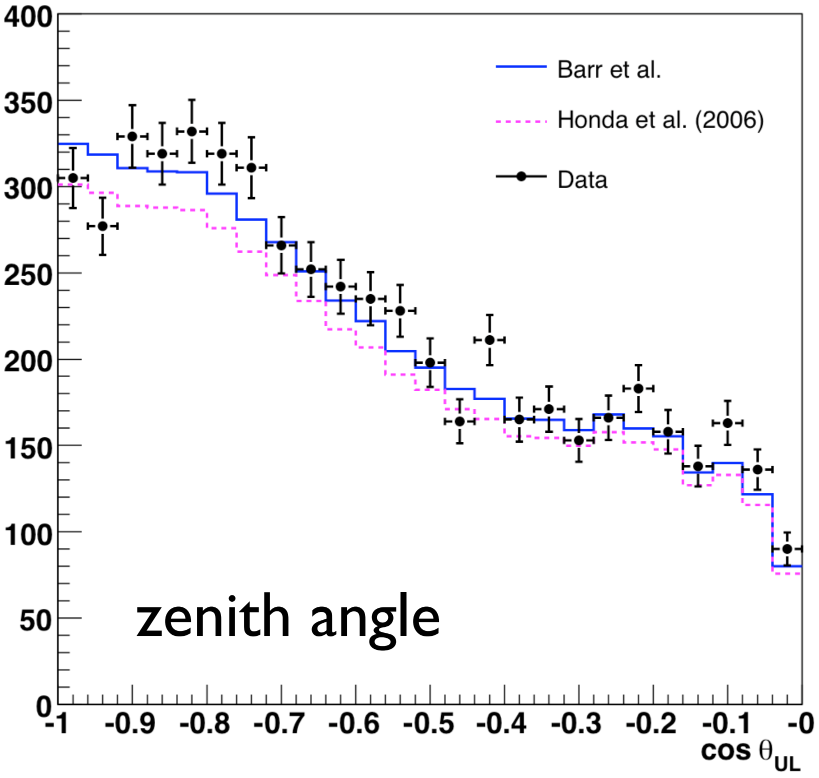
Atmospheric Systematics

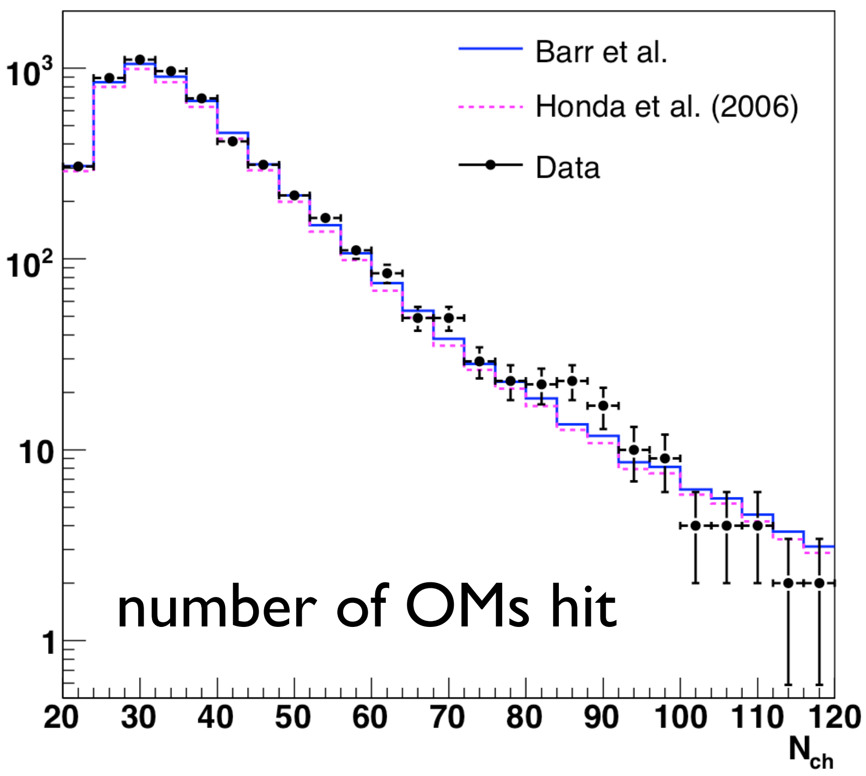
- Separate systematic errors into four classes, depending on effect on observables:
  - normalization
    - e.g. atm. flux normalization
  - slope: change in primary spectrum
    - e.g. primary CR slope
  - tilt: tilts zenith angle distribution
    - e.g. π/K ratio
  - OM sensitivity (large, complicated shape effects)
    - includes uncertainties in ice properties

Systematics Summary

error	type	size	method
atm. ν flux model	norm.	±18%	MC study
σ_ν, ν-μ scattering angle	norm.	±8%	MC study
reconstruction bias	norm.	-4%	MC study
ν_τ-induced muons	norm.	+2%	MC study
charm contribution	norm.	+1%	MC study
timing residuals	norm.	±2%	5-year paper
μ energy loss	norm.	±1%	5-year paper
rock density	norm.	<1%	MC study
primary CR slope (incl. He)	slope	$\Delta\gamma = \pm 0.03$	Gaisser *et al.*
charm (slope)	slope	$\Delta\gamma = +0.05$	MC study
π/K ratio	tilt	tilt +1/-3%	MC study
charm (tilt)	tilt	tilt -3%	MC study
OM sensitivity, ice	OM sens.	sens. ±10%	MC, downgoing μ

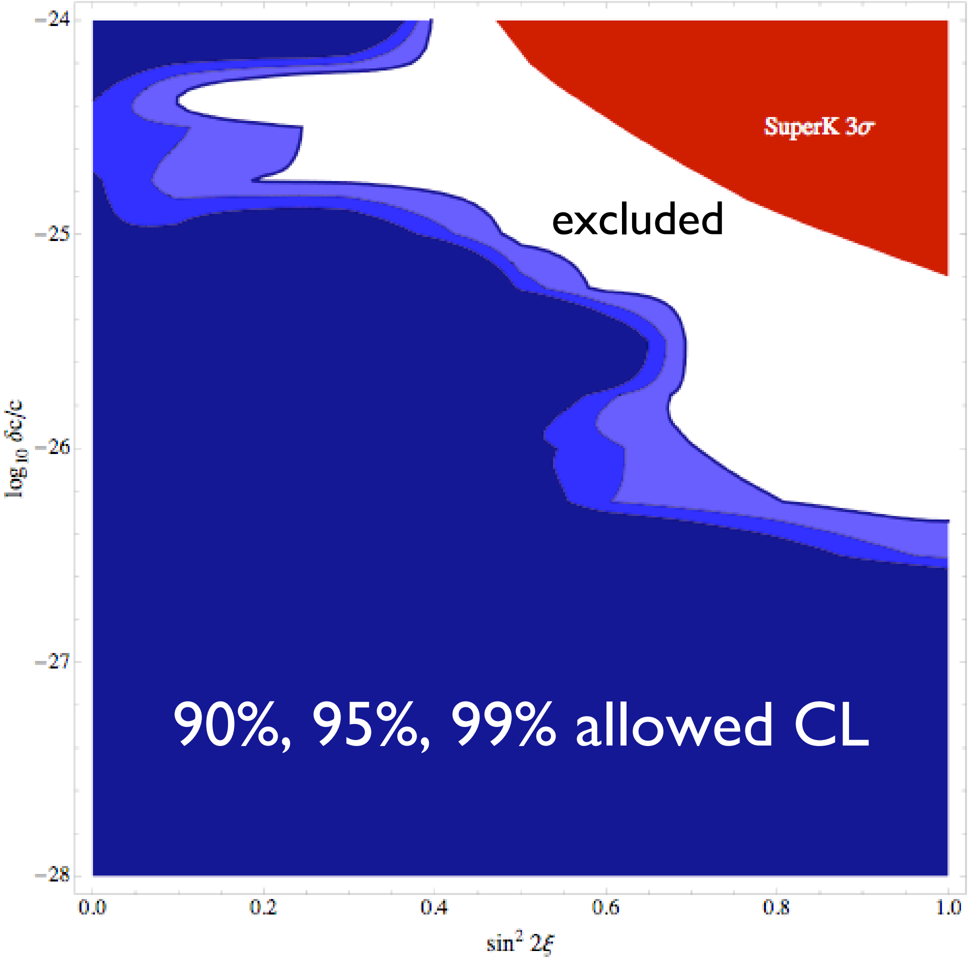
Results: Observables





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

Results: VLI upper limit



maximal mixing

- SuperK+K2K limit*:

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

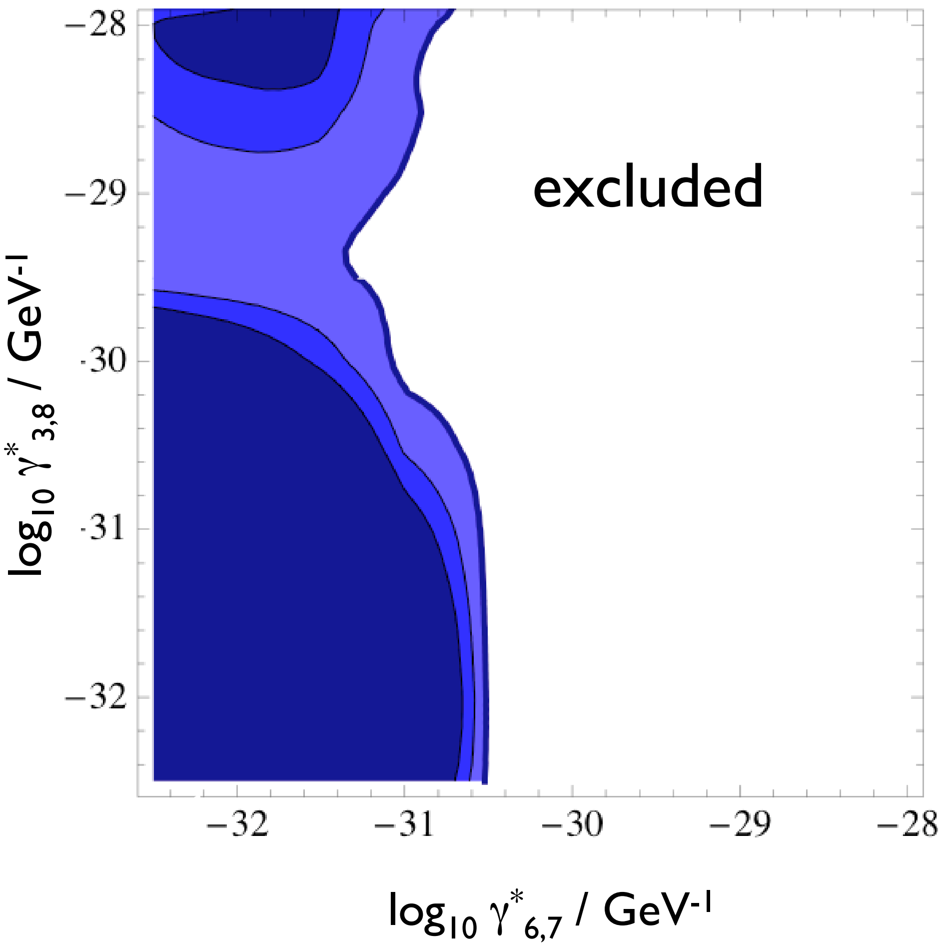
- This analysis:

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

- Limits also set on E^2, E^3 effects

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

Results: QD upper limit



E^2 model (E, E^3 limits also set)

- 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)

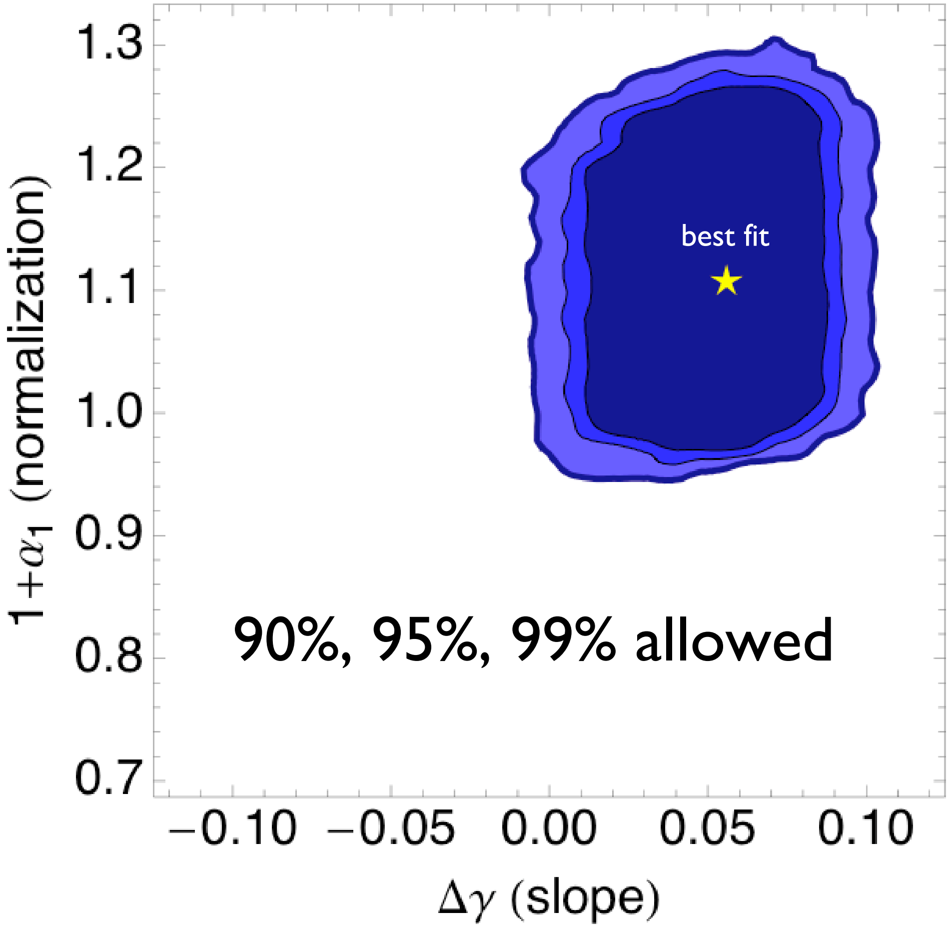
- This analysis:

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

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

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

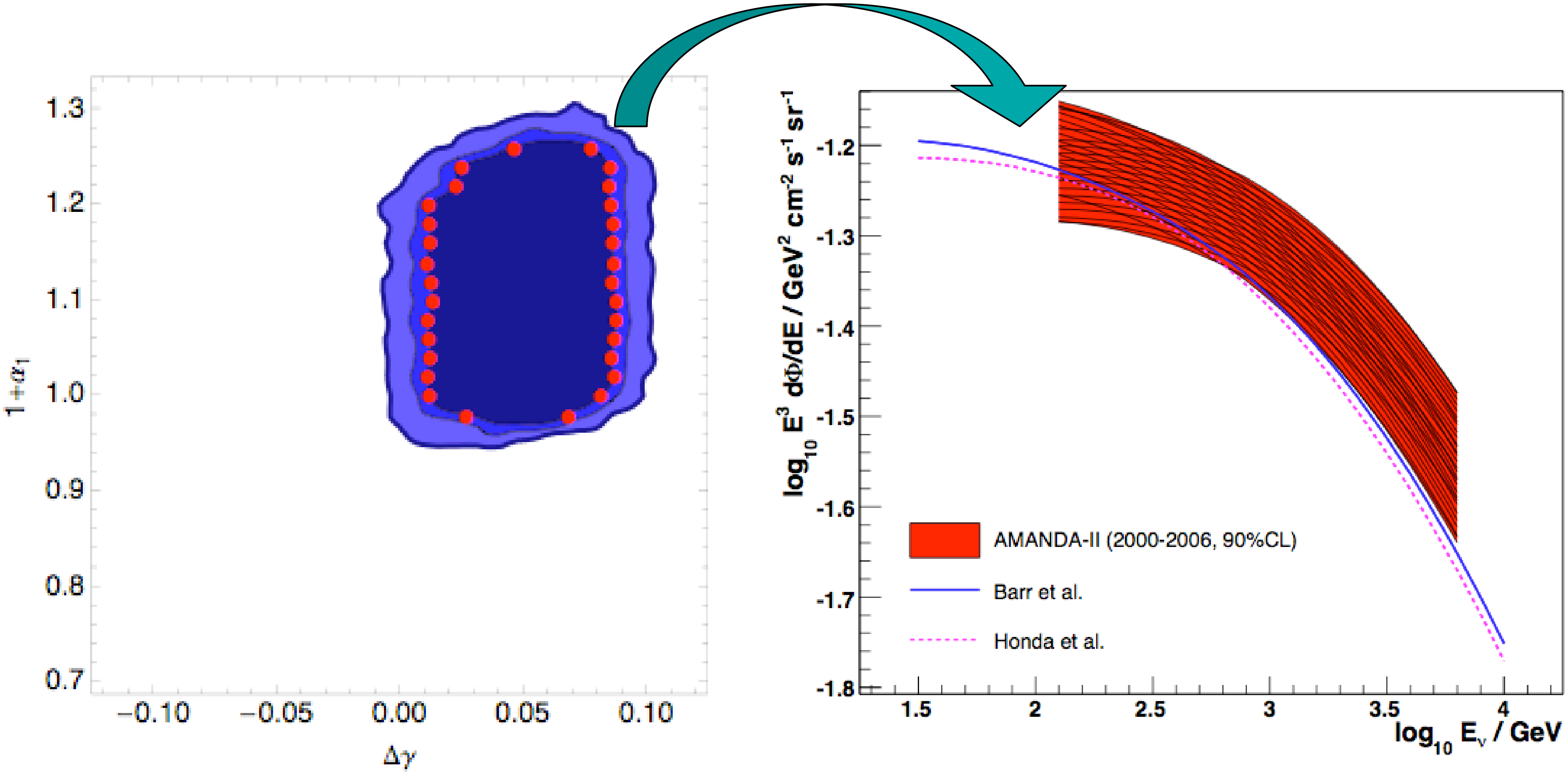
Conventional Analysis



- Parameters of interest: normalization, spectral slope change Δγ relative to Barr *et al.*

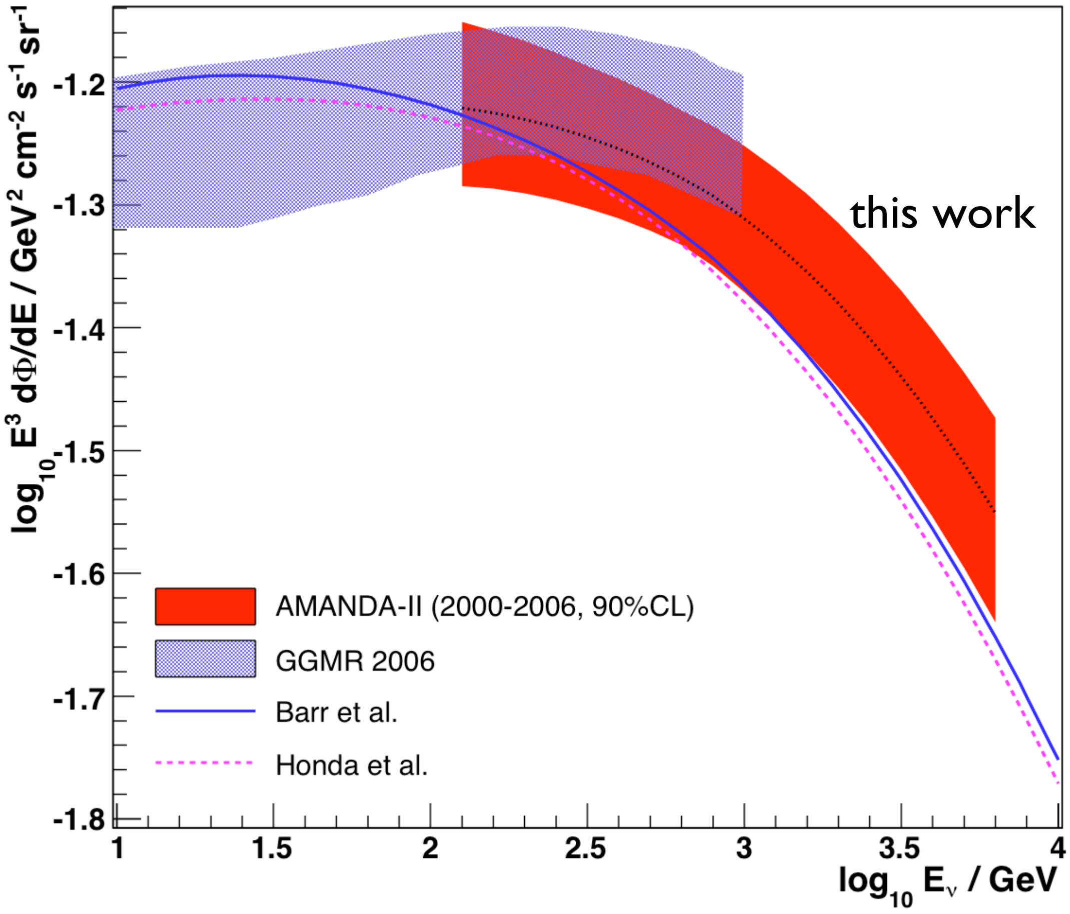
- Result: determine atmospheric muon neutrino flux ("forward-folding" approach)

Translation to Flux



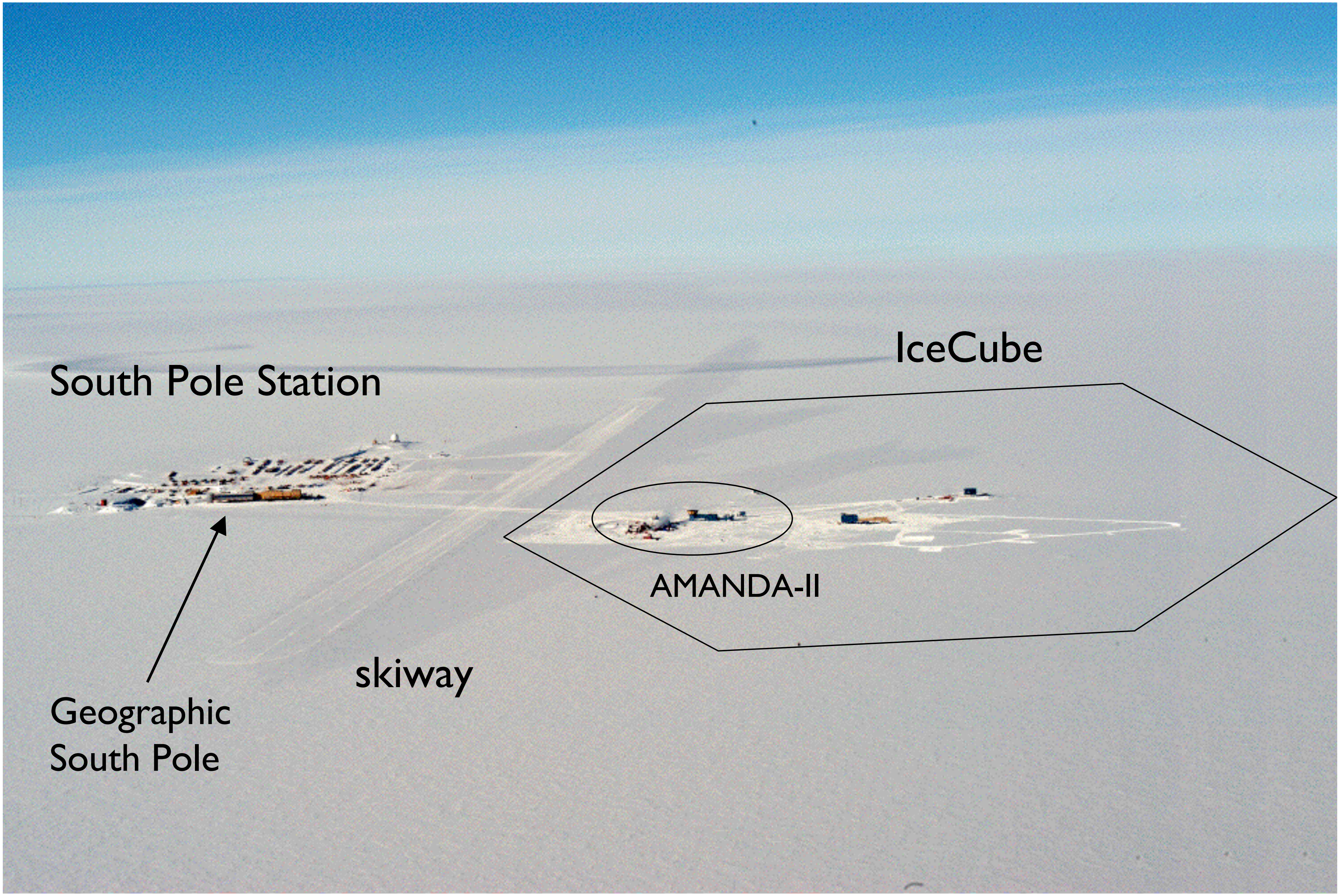
Range of allowed flux determined by envelope of curves

Result Spectrum



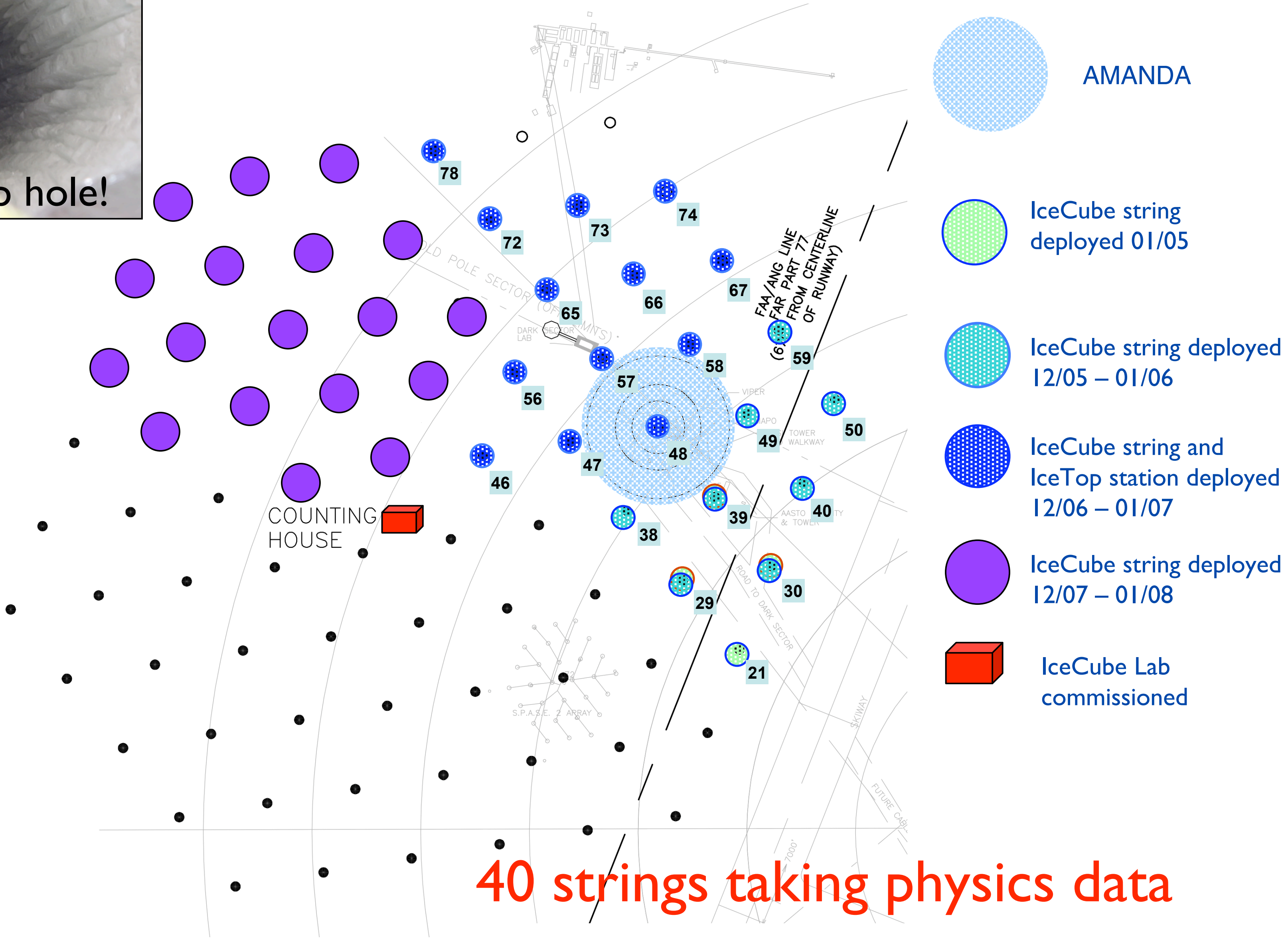
Blue band: SuperK data, González-García, Maltoni, & Rojo, JHEP 0610 (2006) 075

IceCube


IceCube
South Pole Station
AMANDA-II
skiway
Geographic
South Pole

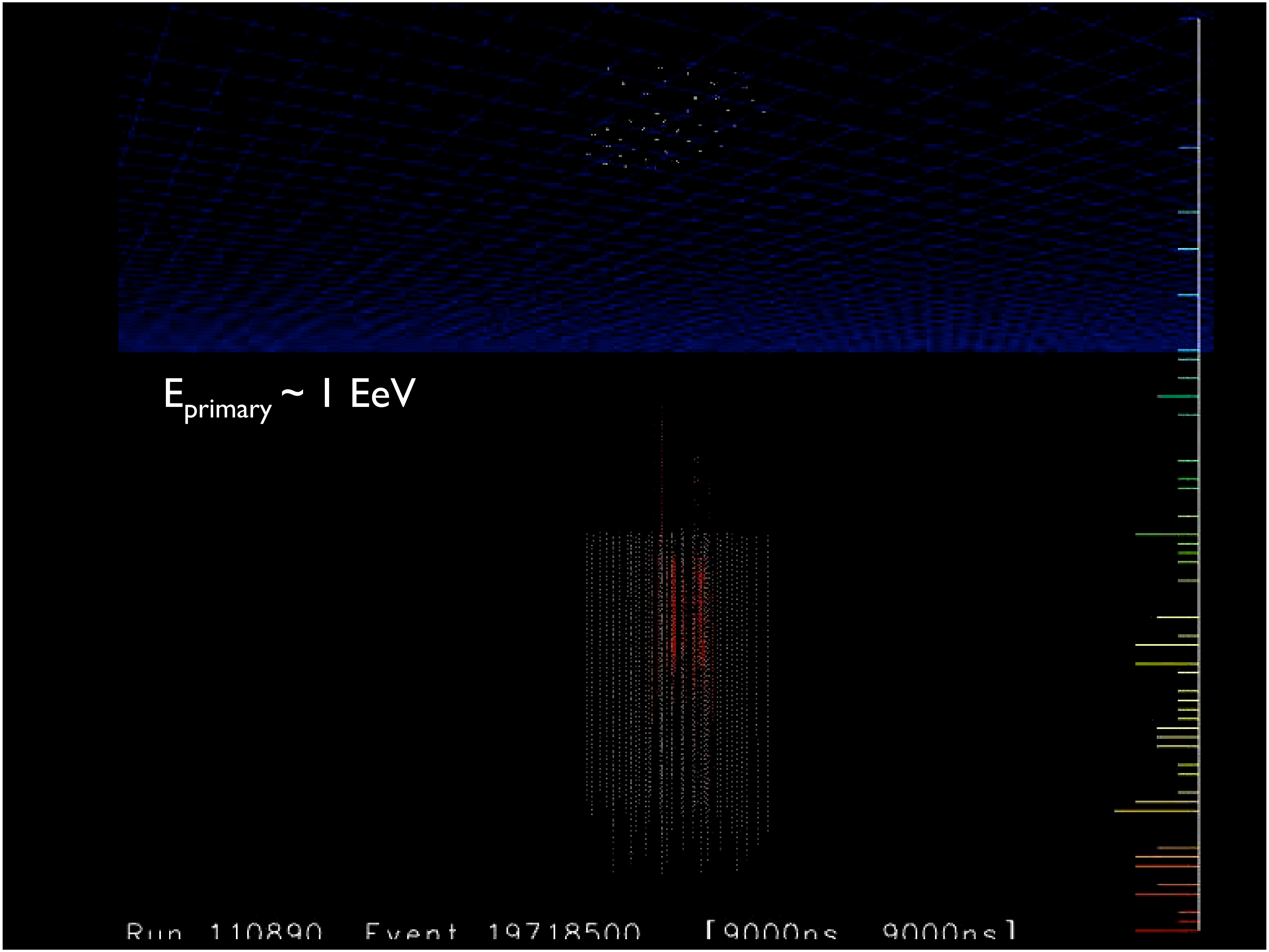
Installation Status & Plans

2500m deep hole!



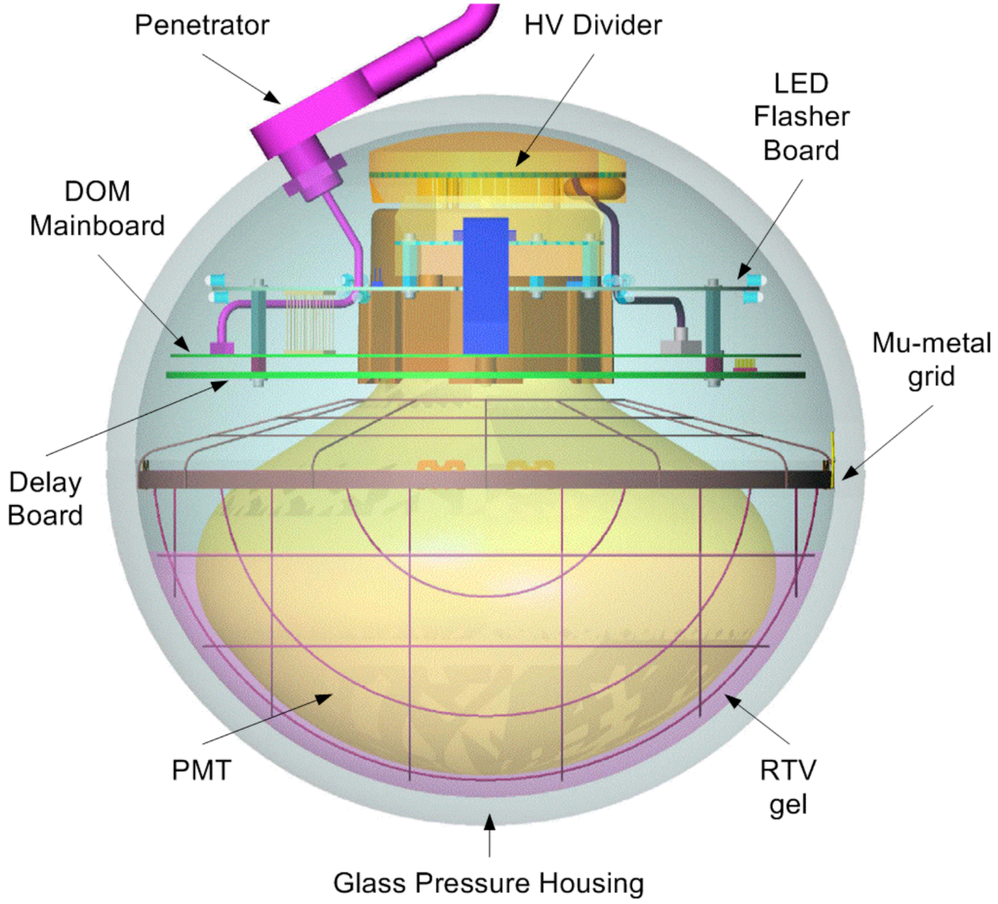
40 strings taking physics data

Update: 3 of ~16 strings this season



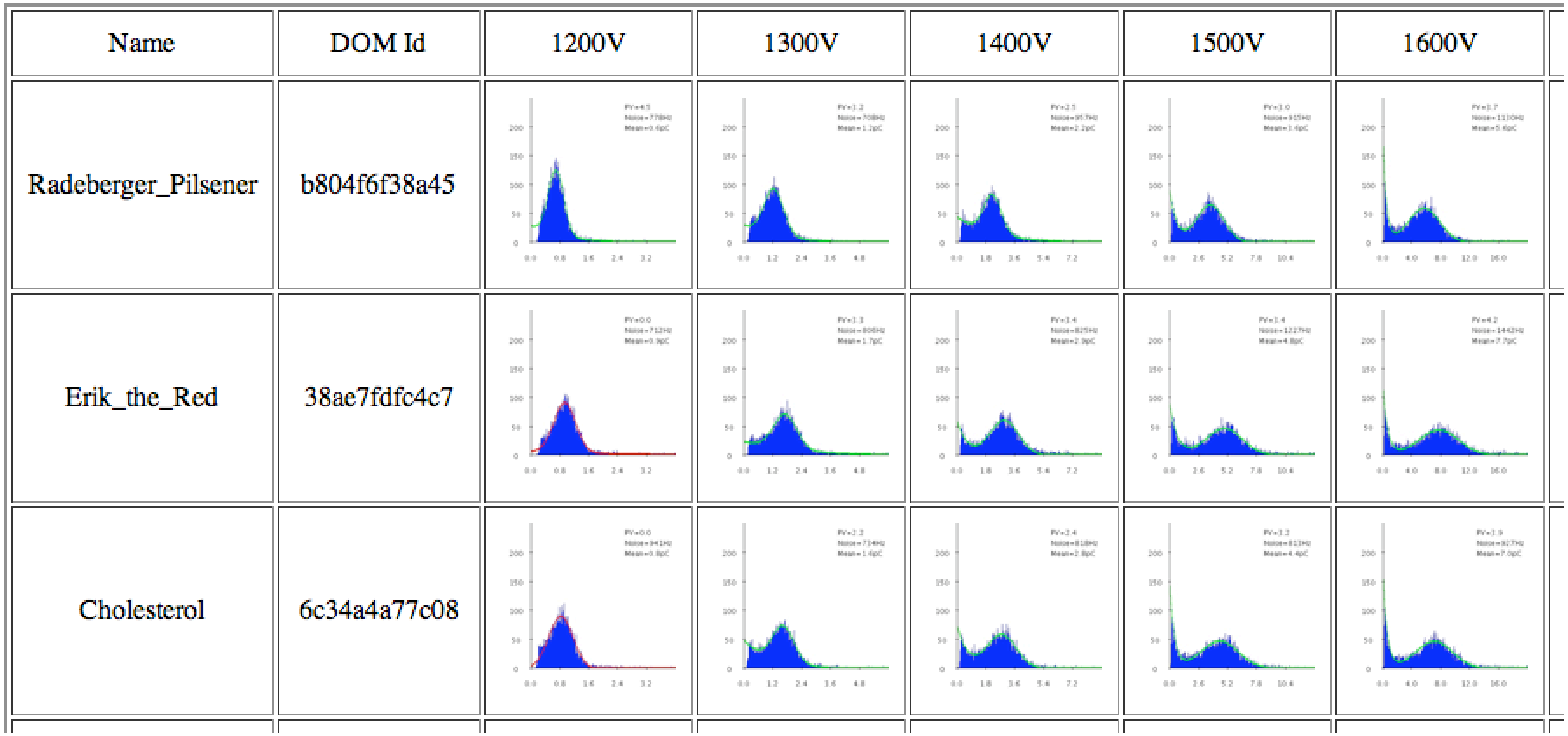
$E_{\text{primary}} \sim 1$ EeV

DOM Calibration



- With J. Braun, developed primary DOM calibration software (“DOM-Cal”)
- Bootstrap approach calibrates:
  - front-end amplifier gain
  - waveform charge vs. time
  - PMT gain vs. high voltage
  - PMT transit time vs. high voltage
- Entire detector (2500+ DOMs) calibrates itself in parallel in ~1 hour

Gain Calibration



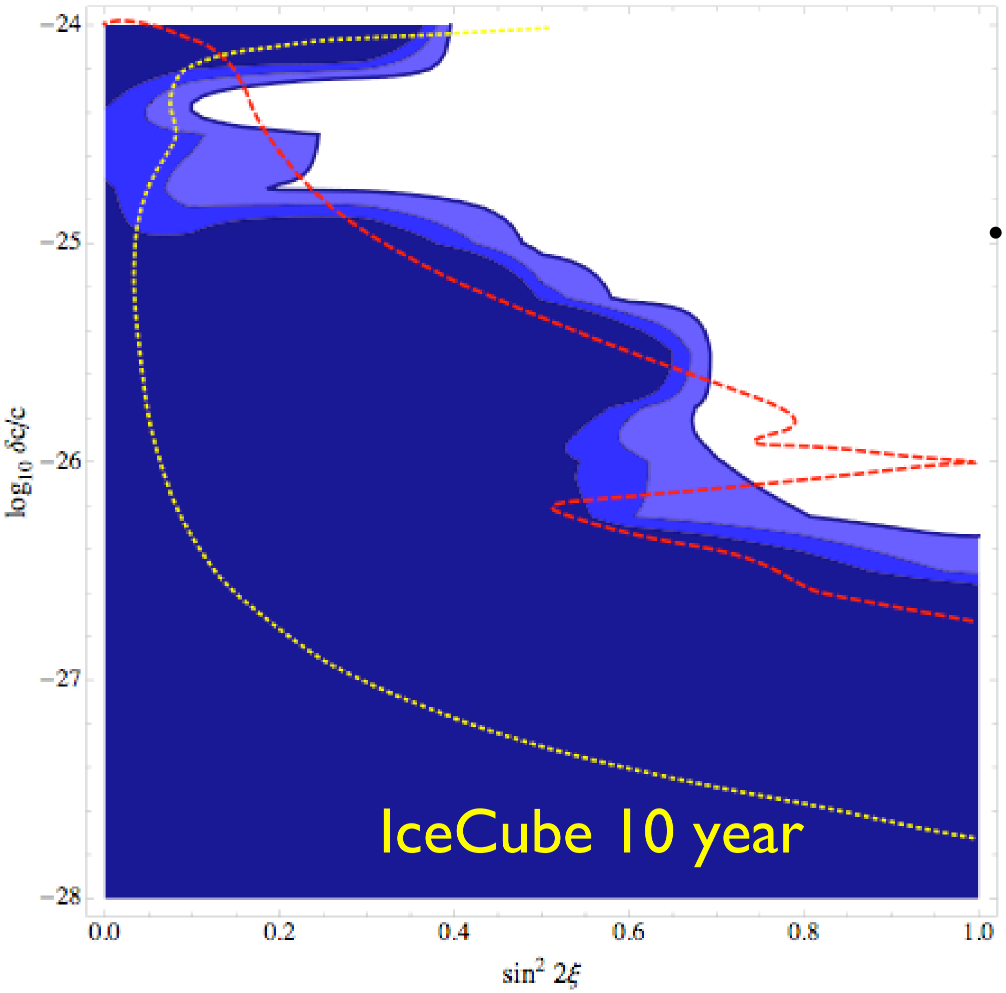
Name	DOM Id	1200V	1300V	1400V	1500V	1600V
Radeberger_Pilsener	b804f6f38a45					
Erik_the_Red	38ae7fdfc4c7					
Cholesterol	6c34a4a77c08					

. . .

⋮

DOMs fit their own single PE charge spectra!

IceCube VLI Sensitivity



- IceCube: sensitivity of $\delta c/c$ ~ 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) + Deep Core will extend energy reach in both directions

Thank you!

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

VLI Phenomenology

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

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

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

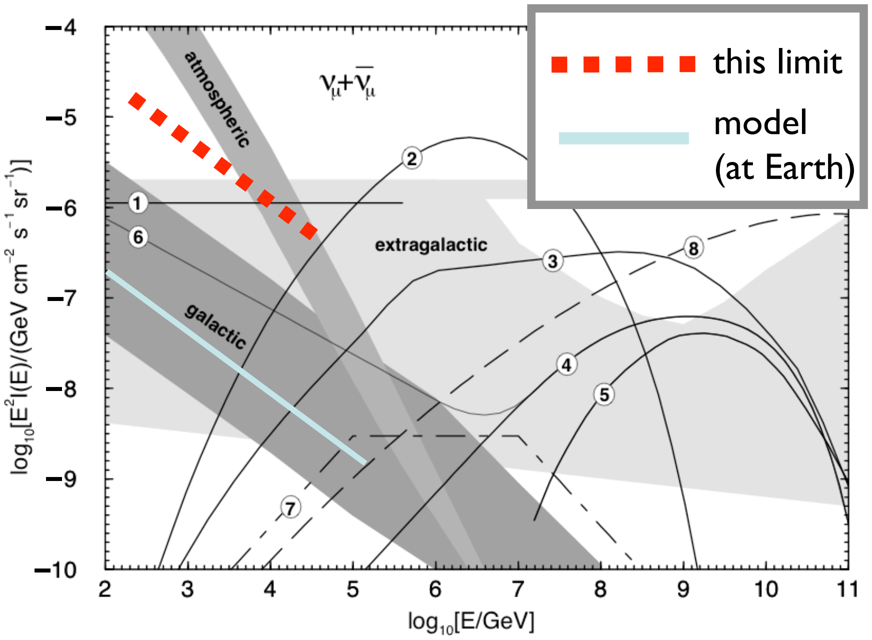
- To narrow possibilities we consider:
  - rotationally invariant terms (only time component)
  - only $c_{AB}^{00} \neq 0$ (leads to interesting energy dependence…)

Galactic Plane Limits

On-source region	On-source events	Expected background	90% event upper limit	Line source limit	Diffuse limit	Gaussian limit
±2.0°	**128**	129.4	19.8	6.3×10^{-5}	6.6×10^{-4}	—
±4.4°	**272**	283.3	20.0	—	—	4.8×10^{-4}

$\mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ rad^{-1}}$

$\mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$



Data used: AMANDA 2000-03

Limits include systematic uncertainty of 30% on atm. ν flux

Energy range: 0.2 to 40 TeV