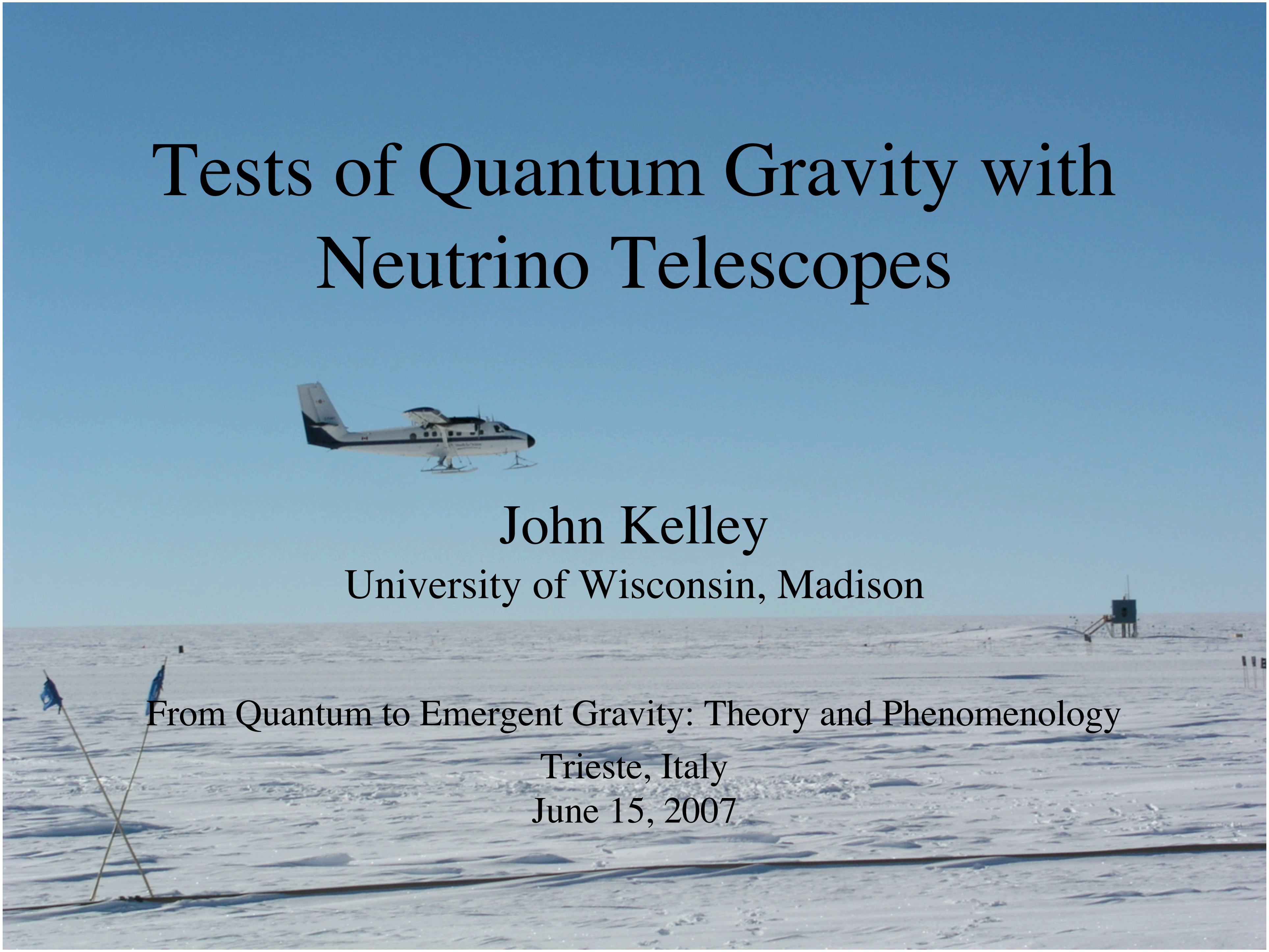


Tests of Quantum Gravity with Neutrino Telescopes

John Kelley
University of Wisconsin, Madison

From Quantum to Emergent Gravity: Theory and Phenomenology

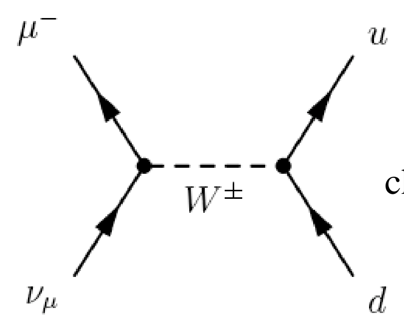
Trieste, Italy
June 15, 2007

Overview

- Detection principles of large-scale neutrino telescopes
  - Capabilities (and limitations)
  - Current status and future plans
- Tests of quantum gravity with existing data
  - violations of Lorentz invariance or equivalence principle
  - quantum decoherence
- Future prospects
  - decoherence of galactic (anti)neutrino source
  - time-of-flight tests, etc.

Neutrino Detection

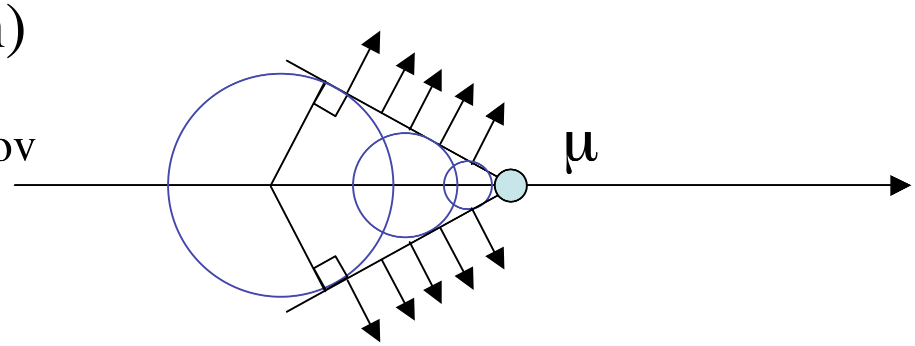
1. Need an interaction — small cross-section necessitates a big target!



charged current

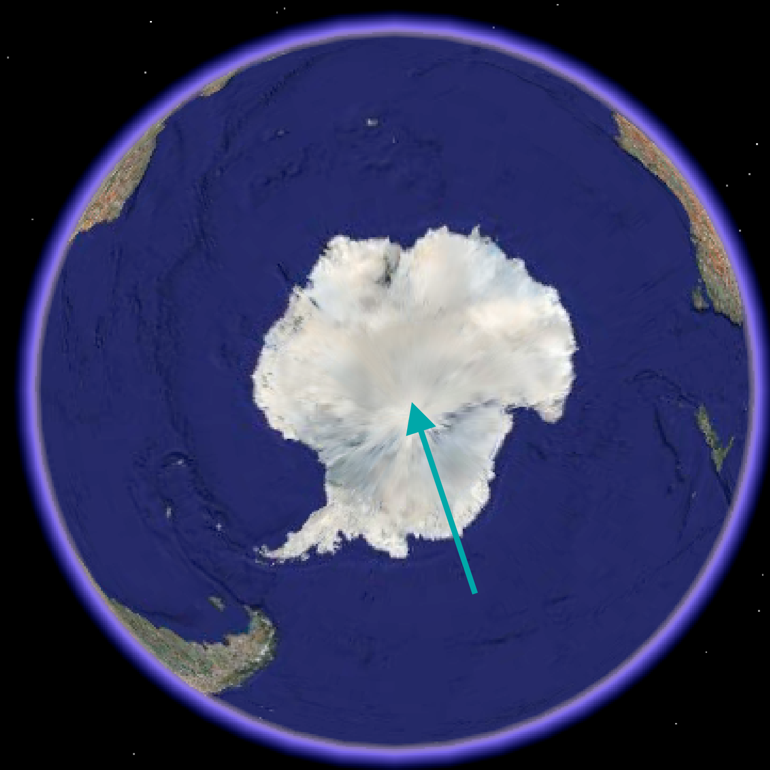
2. Then detect the interaction products (say, by their radiation)

Čerenkov effect



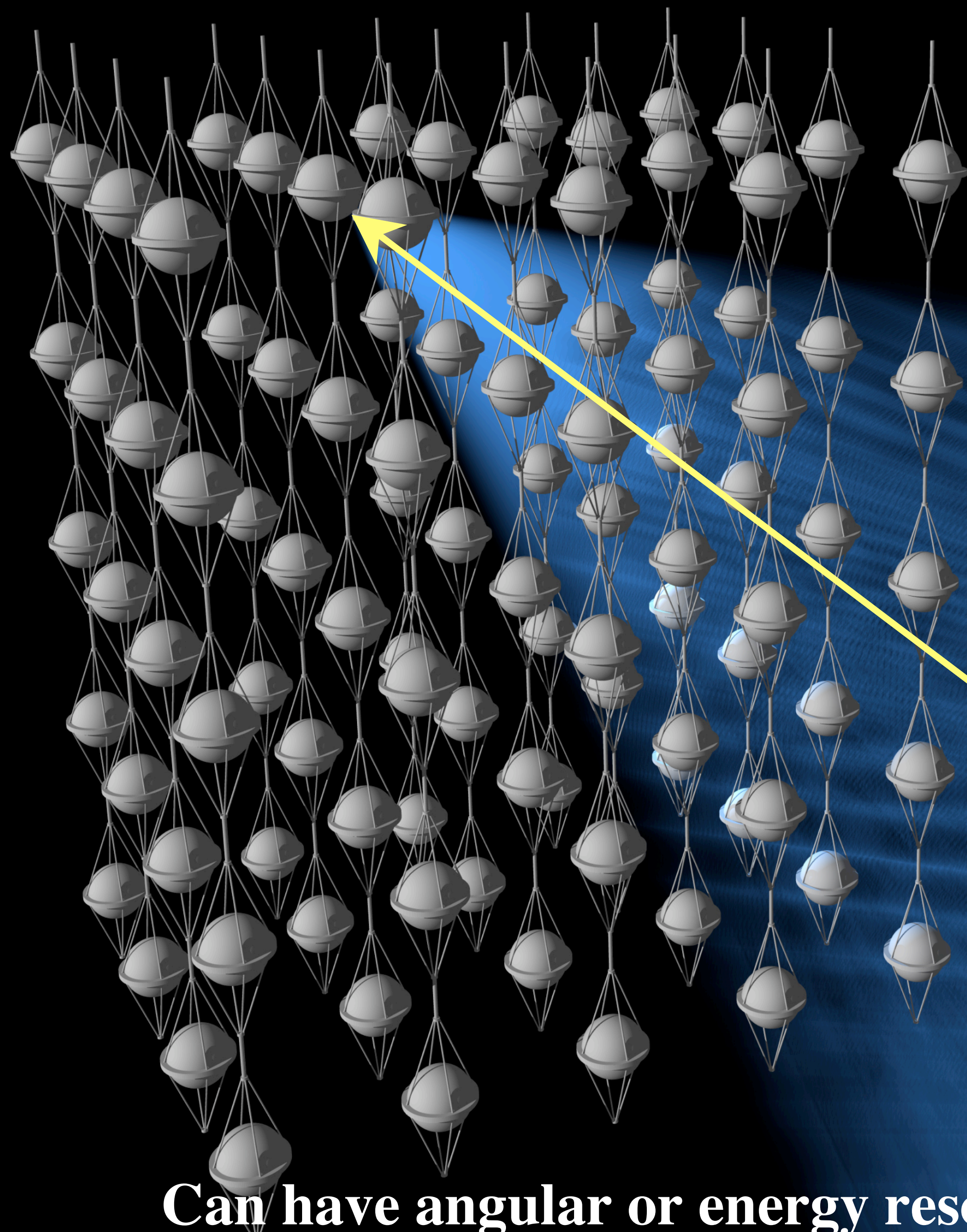
Earth's Transparent Medium: H_2O*

Mediterranean,
Lake Baikal



Antarctic ice sheet

*not the only possibility — *e.g.* NaCl domes

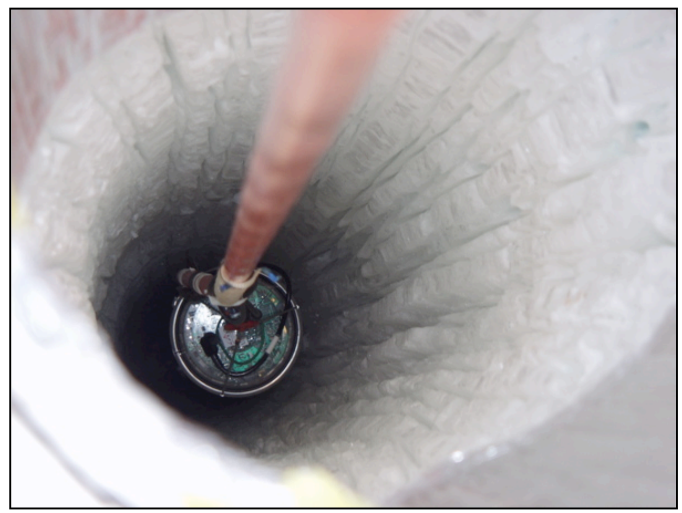


- Array of optical modules on cables (“strings” or “lines”)
- High energy muon (~TeV) from charged current ν_μ interaction
- Good angular reconstruction from timing (O(1°))
- Rough ν energy estimate from muon energy loss
- OR, look for cascades (ν_e, ν_τ, NC ν_μ)

Can have angular or energy resolution, but not both!

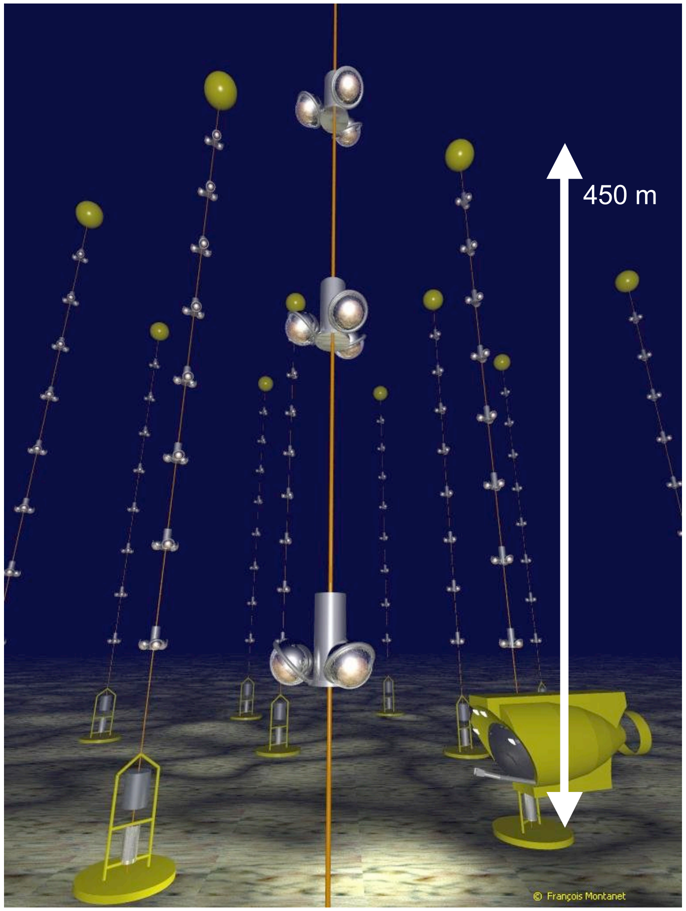
Water/Ice Čerenkov Detectors

- Completed:
  - BAIKAL NT-200 (Lake Baikal, since 1998)
  - AMANDA-II (South Pole, since 2000)
- Under construction / R&D:
  - ANTARES (Mediterranean)
  - NESTOR (Mediterranean)
  - NEMO (Mediterranean)
  - km3net (Mediterannean)
  - IceCube (South Pole)

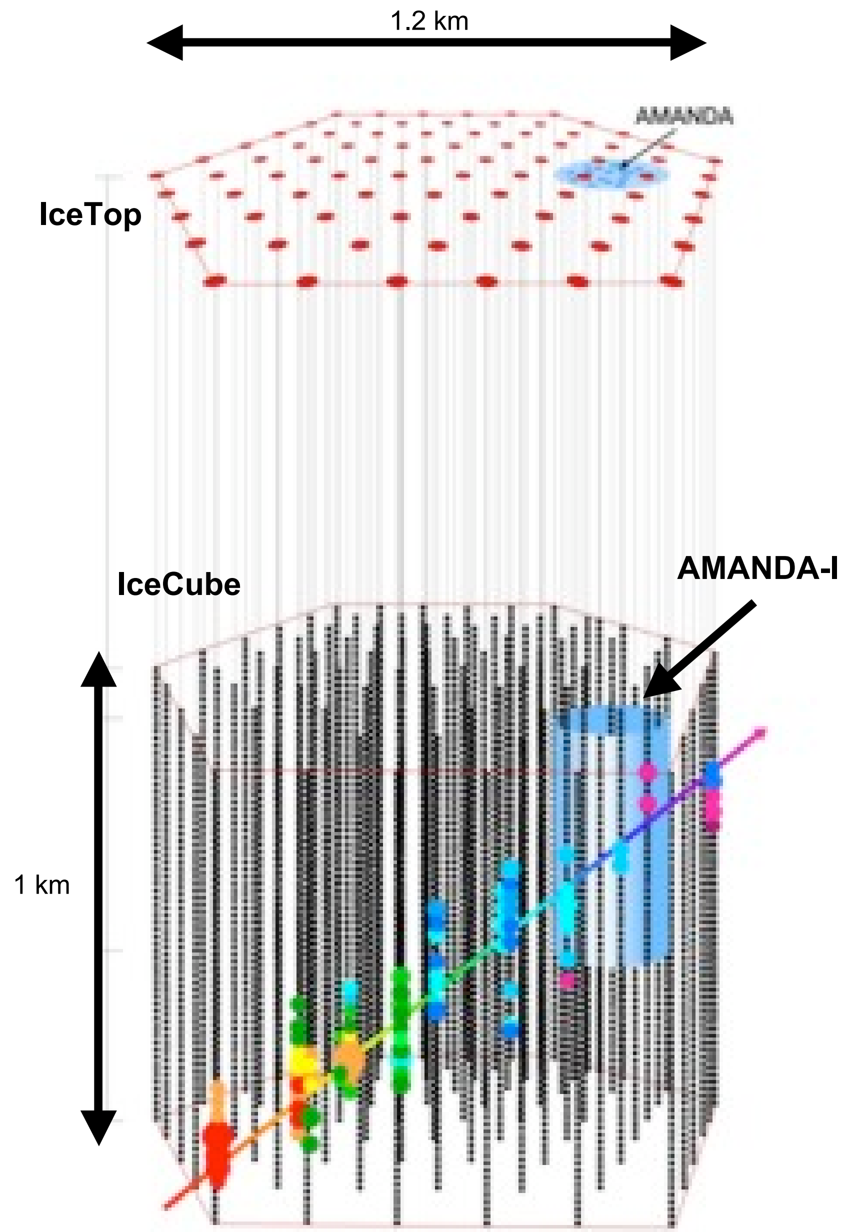


2500m deep hole!

Antares



(c) F.Montanet, CNRS/IN2P3 and UJF for Antares



Atmospheric Production

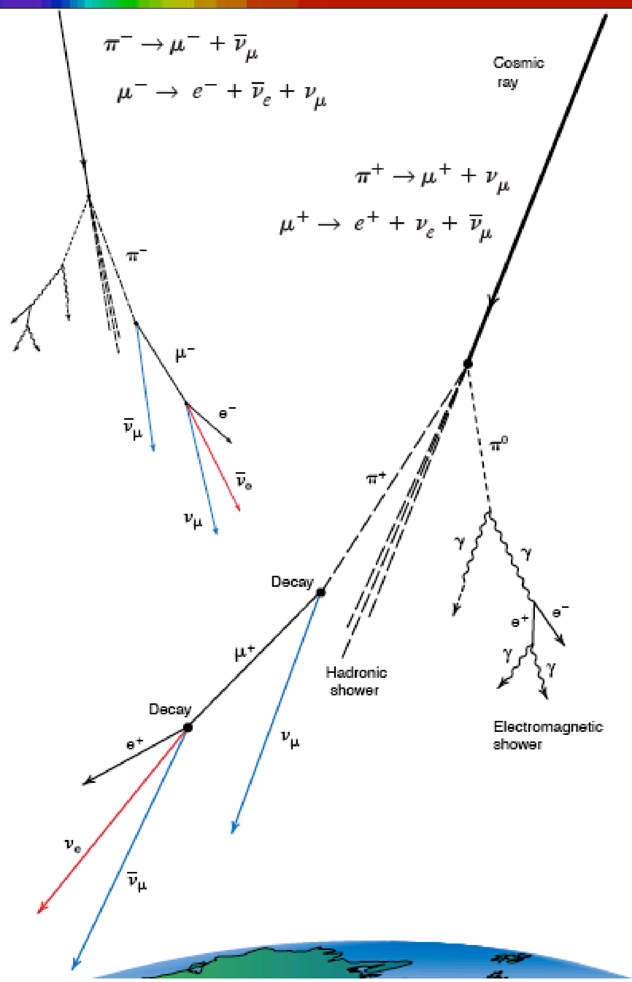


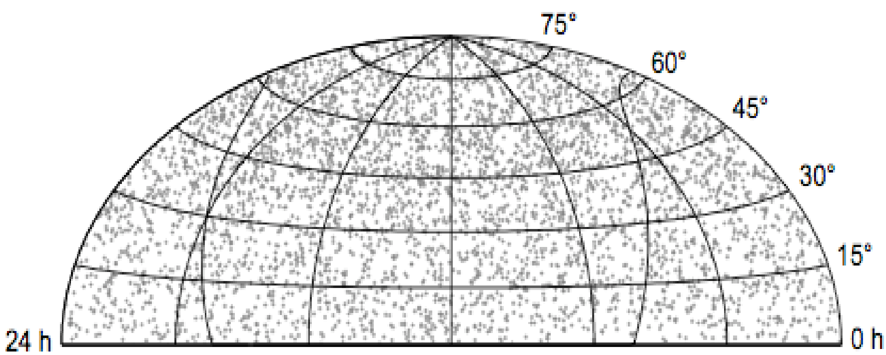
Figure from Los Alamos Science **25** (1997)

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

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

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
- ANTARES (7 of 12 lines) and IceCube (22 of 70-80 strings) under construction, taking data

Current QG searches: use high-energy atmospheric ν

Why Use Neutrinos?

- Neutrinos are already post-SM (massive)
- For $E > 100$ GeV and $m_\nu < 1$ eV*, Lorentz $\gamma > 10^{11}$
- Oscillations are a sensitive quantum-mechanical probe (an interferometer of sorts)

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

* From cosmological data, $\Sigma m_i < 0.5$ eV, Goobar *et*. *al*, astro-ph/0602155

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…)

“Fried Chicken” VLI

- Leads 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 Glashow and Coleman, PRD **59** 116008 (1999)

Conventional+VLI Oscillations

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

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

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

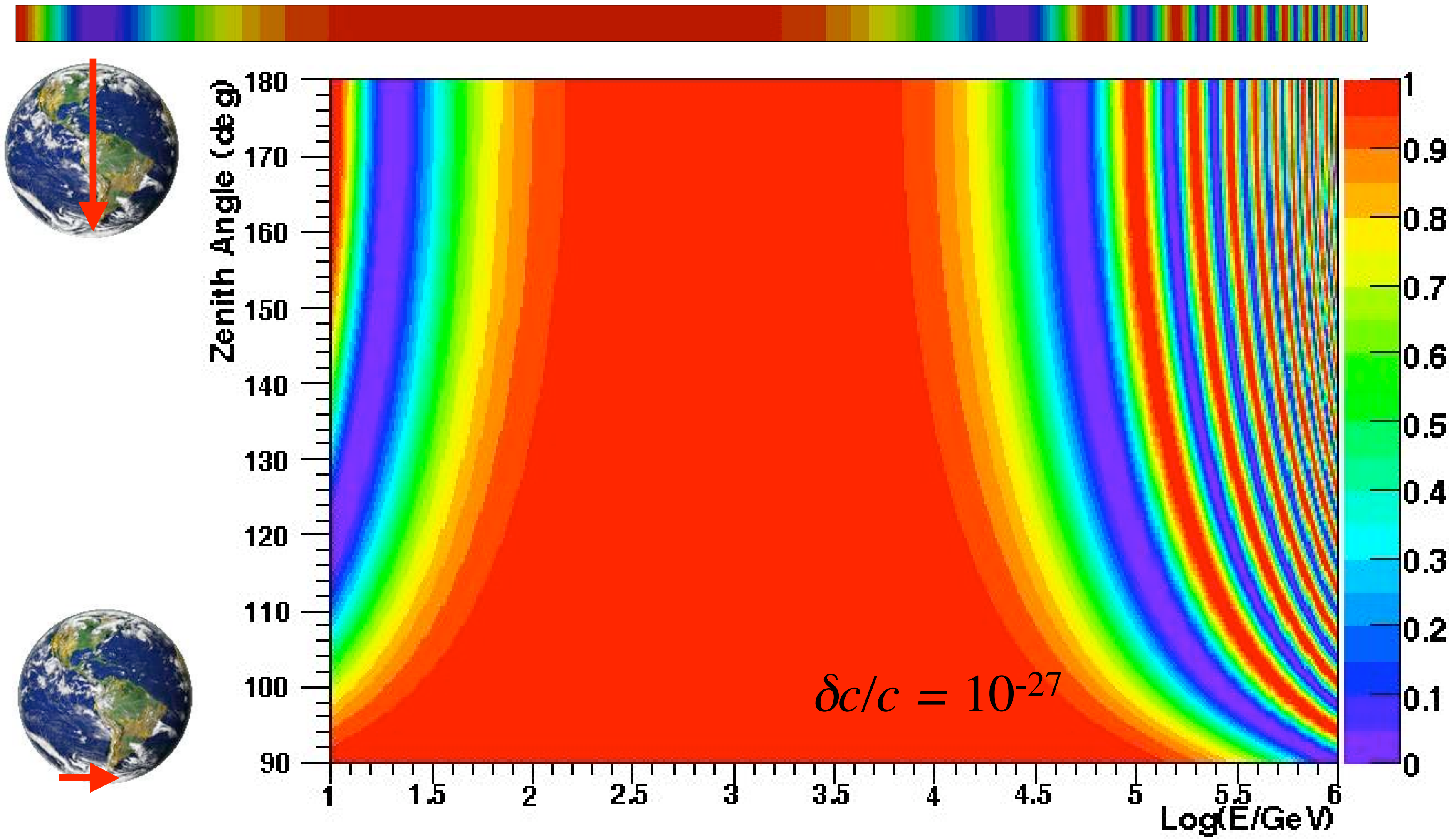
$$R_n = \sigma_n^+ \frac{\Delta\delta_n E^n}{2} \frac{4E}{\Delta m^2} ,$$

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 (Conventional + VLI oscillations)



Limits and Future Sensitivity (maximal mixing)

- Existing limits:
  - 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)

- AMANDA-II: sensitivity of $\delta c/c \sim 10^{-27}$ (7 years)

  (JK, astro-ph/0701333)

- IceCube: sensitivity of $\delta c/c \sim 10^{-28}$

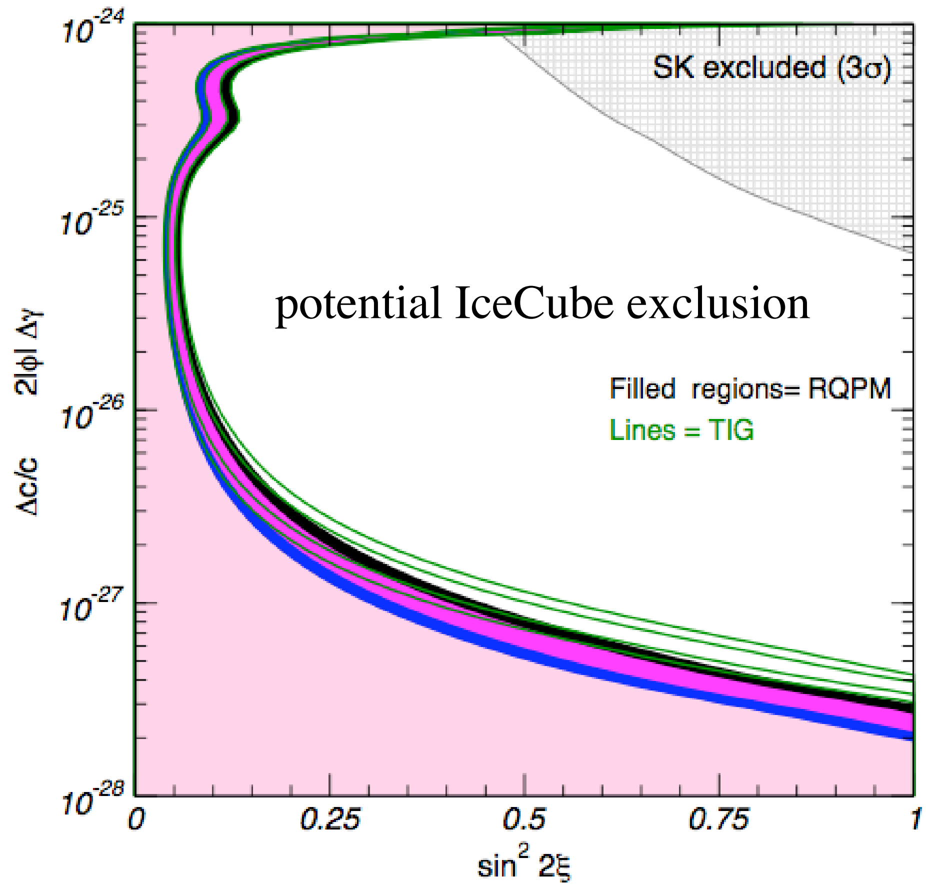
  700K atmospheric ν_μ in 10 years

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

IceCube Sensitivity

Bonus: VLI limits ⇔ limits violation of equivalence principle (VEP)

VLI / VEP parameter



VLI mixing angle

Quantum Decoherence

- Another possible low-energy signature of quantum gravity: 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

QD Phenomenology

- Modify propagation through density matrix formalism:

$$\dot{\rho} = -i[H, \rho] + \not{\delta} H \rho.$$

- Evolution via Lindblad form / dynamical semigroup approach, plus a couple of general constraints:
  - Energy conservation on the average
  - Monotonic increase of von-Neumann entropy

$$\not{\delta} H \rho = -\sum_n [D_n, [D_n, \rho]]$$

D_n :self-adjoint operators which commute with H

*for more details, please see Morgan *et al.*, astro-ph/0412628

QD in Neutrino System

- Choose basis, enforce unitarity on decoherence matrix *h'*:

$$\dot{\rho}_\mu = (h_{\mu\nu} + h'_{\mu\nu})\rho_\nu \qquad h' = -2 \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & b & d \\ 0 & b & \alpha & \beta \\ 0 & d & \beta & \delta \end{pmatrix}$$

Important special case: $a = \alpha$, others 0 (complete positivity+energy conservation)

$$M(E,L) = \exp\left[-2\mathcal{H}(E)L\right], \qquad \mathcal{H}(E) = \begin{pmatrix} a & b - \frac{\Delta m^2}{4E} & d \\ b + \frac{\Delta m^2}{4E} & \alpha & \beta \\ d & \beta & \delta \end{pmatrix}.$$

QD Parameters

- Solve DEs for neutrino system, get oscillation probability:

$$P[\nu_\mu \to \nu_\tau] = \frac{1}{2}\Big\{1 - \cos^2(2\theta) M_{33}(E,L) - \sin^2(2\theta) M_{11}(E,L) - \frac{1}{2}\sin 4\theta \left[M_{13}(E,L) + M_{31}(E,L)\right]\Big\},$$

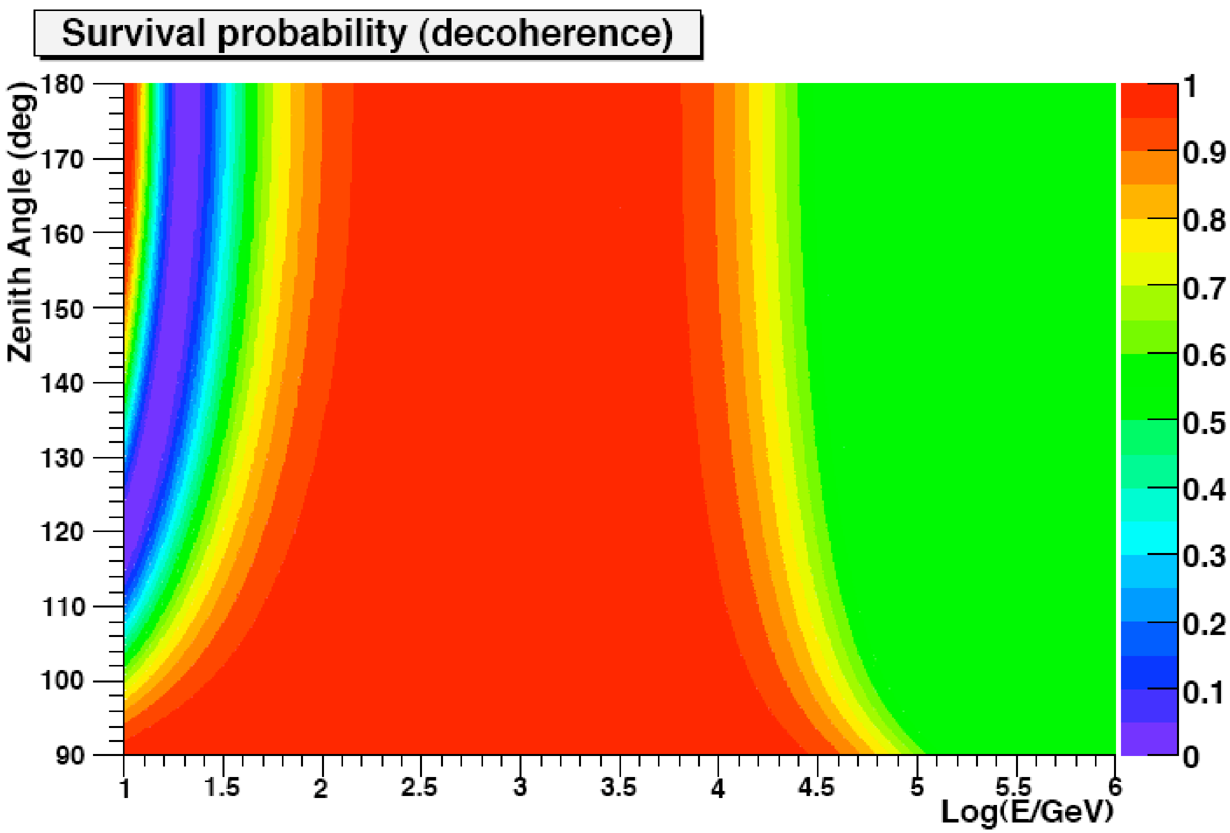
- Various proposals for how decoherence parameters depend on energy:

$\alpha = \frac{1}{2}\gamma_\alpha,$	$\alpha = \frac{\mu_\alpha^2}{4E}.$	$\alpha = \frac{1}{2}\kappa_\alpha E^2$	$\sim E^3$
simplest	preserves Lorentz invariance	recoiling D-branes*	???

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

Atmospheric ν_μ Survival Probability (κ model)

$$P[\nu_\mu \to \nu_\mu] = \frac{1}{2} \; + \; e^{-(\alpha+a)L} \cos\left(2\frac{\Delta m^2 L}{4E}\right) \qquad (\sin^2(2\theta) = 1,\; b = \beta = d = \delta = 0)$$



$a = \alpha =$
$4 \times 10^{-32} (E^2 / 2)$

Note: only 2-flavor system!

Existing Limits and Sensitivities (E^2 model)

- SuperK limit[‡]: $\kappa_{a,\alpha} < 0.9 \times 10^{-27}$ GeV^{-1}
- AMANDA-II sensitivity: $\kappa_{a,\alpha} \sim 10^{-31}$ GeV^{-1} (7 years)
- ANTARES sensitivity*: $\kappa_{a,\alpha} \sim 10^{-30}$ GeV^{-1} (3 years)

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

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

Model Improvements

- 2-flavor approximation is simple, but seems unjustified
- Certain regions of parameter space are unphysical
- Barenboim, Mavromatos *et al*. (hep-ph/0603028):

$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(t) = & \frac{1}{3} + \frac{1}{2}\Bigg\{\left[\rho_1^\alpha \rho_1^\beta \cos\left(\frac{|\Omega_{12}|t}{2}\right) + \left(\frac{\Delta\mathcal{D}_{21}\rho_1^\alpha \rho_1^\beta}{|\Omega_{12}|}\right)\sin\left(\frac{|\Omega_{12}|t}{2}\right)\right] e^{(\mathcal{D}_{11}+\mathcal{D}_{22})\frac{t}{2}} \\
& + \left[\rho_4^\alpha \rho_4^\beta \cos\left(\frac{|\Omega_{13}|t}{2}\right) + \left(\frac{\Delta\mathcal{D}_{54}\rho_4^\alpha \rho_4^\beta}{|\Omega_{13}|}\right)\sin\left(\frac{|\Omega_{13}|t}{2}\right)\right] e^{(\mathcal{D}_{44}+\mathcal{D}_{55})\frac{t}{2}} \\
& + \left[\rho_6^\alpha \rho_6^\beta \cos\left(\frac{|\Omega_{23}|t}{2}\right) + \left(\frac{\Delta\mathcal{D}_{76}\rho_6^\alpha \rho_6^\beta}{|\Omega_{23}|}\right)\sin\left(\frac{|\Omega_{23}|t}{2}\right)\right] e^{(\mathcal{D}_{66}+\mathcal{D}_{77})\frac{t}{2}} \\
& + \Bigg[\left(\rho_3^\alpha \rho_3^\beta + \rho_8^\alpha \rho_8^\beta\right)\cosh\left(\frac{\Omega_{38}t}{2}\right) \\
& + \left(\frac{2\mathcal{D}_{38}(\rho_3^\alpha \rho_8^\beta - \rho_8^\alpha \rho_3^\beta) + \Delta\mathcal{D}_{83}\left(\rho_3^\alpha \rho_3^\beta - \rho_8^\alpha \rho_8^\beta\right)}{\Omega_{38}}\right)\sinh\left(\frac{\Omega_{38}t}{2}\right)\Bigg] e^{(\mathcal{D}_{33}+\mathcal{D}_{88})\frac{t}{2}}
\end{aligned}
$$

Future Prospects

Cygnus OB2 region, IPHAS H-α

High-energy Astrophysical ν

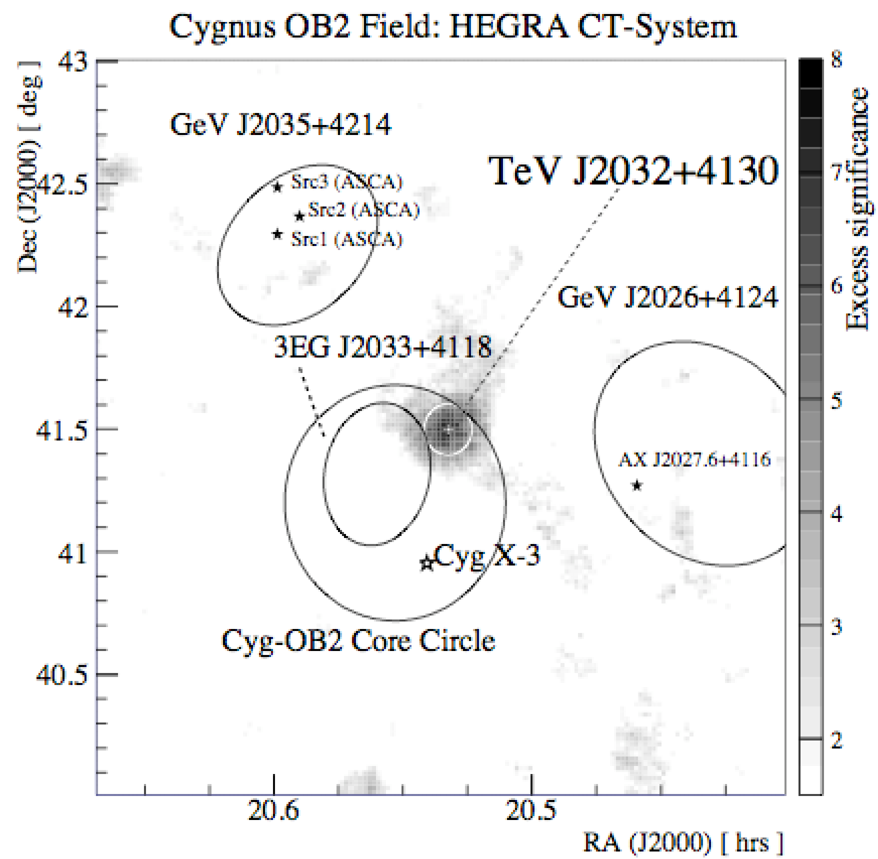
- Hadronic acceleration at sources of cosmic rays
  - Suspects: SNR, GRBs, AGN, etc.

- Standard production chain:
  - $pp,\ p\gamma \rightarrow \pi^0 \rightarrow \gamma\,\gamma$
    $\rightarrow \pi^{\pm} \rightarrow \mu^{\pm}\,\nu_\mu(\overline{\nu_\mu}) \rightarrow e^{\pm}\,\nu_e(\overline{\nu_e})\ \overline{\nu_\mu}(\nu_\mu)\ \nu_\mu(\overline{\nu_\mu})$

- Flavor ratio at source $\nu_\tau : \nu_\mu : \nu_e = 0:2:1$
  - Mass-induced oscillations $\Rightarrow$ 1:1:1 at Earth
  - Same for quantum decoherence

Antineutrino Sources

- Cygnus OB2: massive star-forming region
  - Clustered supernova remnants
  - Photodisintegration of heavy nuclei
    $N\gamma \rightarrow X + n \rightarrow X + p^{+}e^{-}\overline{\nu}_{e}$
  - Can create HE neutrons (CR anisotropies!) and electron antineutrino source
  - Flavor ratio ν_τ: ν_μ: ν_e at Earth:
    - 2:2:5 for conventional oscillations
    - 1:1:1 for decoherence



Long-distance Decoherence Phenomenology

Large distance ⇒ only diagonal decoherence terms; eventually 1:1:1

note: does assume CPT

$$P_{\overline{\nu}_e\to\overline{\nu}_\mu} = P_{\overline{\nu}_\mu\to\overline{\nu}_e} = P_{\nu_e\to\nu_\mu} = P_{\nu_\mu\to\nu_e} = \frac{1}{3} + f_{\nu_e\to\nu_\mu}\mathrm{e}^{-\overline{\gamma}\,d} \,,$$

$$P_{\overline{\nu}_e\to\overline{\nu}_\tau} = P_{\overline{\nu}_\tau\to\overline{\nu}_e} = P_{\nu_e\to\nu_\tau} = P_{\nu_\tau\to\nu_e} = \frac{1}{3} + f_{\nu_e\to\nu_\tau}\mathrm{e}^{-\overline{\gamma}\,d} \,,$$

$$P_{\overline{\nu}_\mu\to\overline{\nu}_\tau} = P_{\overline{\nu}_\tau\to\overline{\nu}_\mu} = P_{\nu_\mu\to\nu_\tau} = P_{\nu_\tau\to\nu_\mu} = \frac{1}{3} + f_{\nu_\mu\to\nu_\tau}\mathrm{e}^{-\overline{\gamma}\,d} \,,$$

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = P_{\nu_e\to\nu_e} = \frac{1}{3} - (f_{\nu_e\to\nu_\mu} + f_{\nu_e\to\nu_\tau})\,\mathrm{e}^{-\overline{\gamma}\,d} \,,$$

$$P_{\overline{\nu}_\mu\to\overline{\nu}_\mu} = P_{\nu_\mu\to\nu_\mu} = \frac{1}{3} - (f_{\nu_e\to\nu_\mu} + f_{\nu_\mu\to\nu_\tau})\,\mathrm{e}^{-\overline{\gamma}\,d} \,,$$

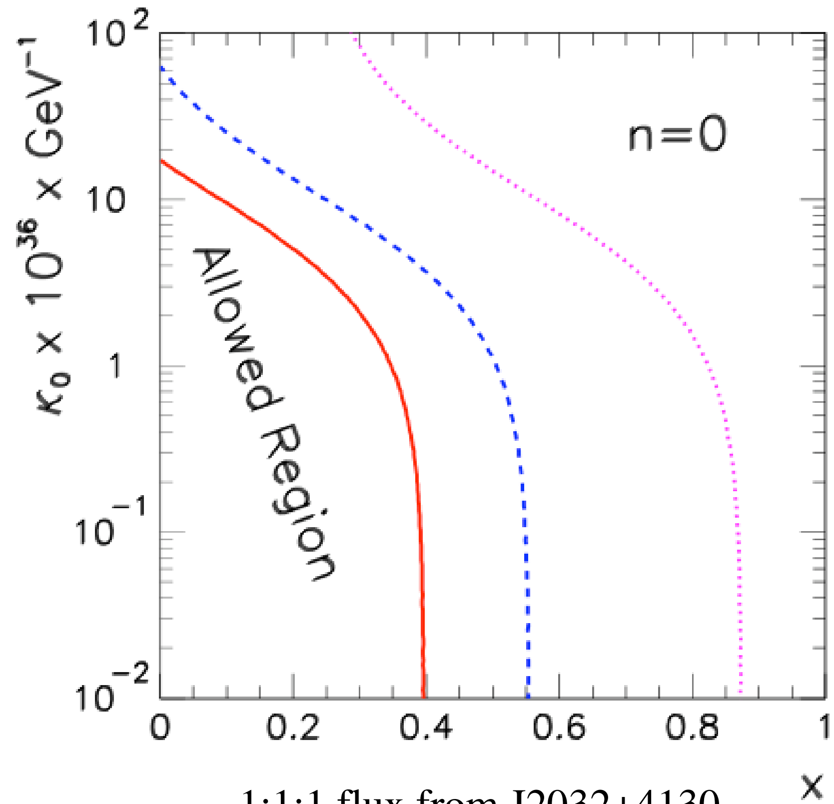
$$P_{\overline{\nu}_\tau\to\overline{\nu}_\tau} = P_{\nu_\tau\to\nu_\tau} = \frac{1}{3} - (f_{\nu_e\to\nu_\tau} + f_{\nu_\mu\to\nu_\tau})\,\mathrm{e}^{-\overline{\gamma}\,d} \,.$$

$$\overline{\gamma} = \kappa_n\ (E_\nu/\mathrm{GeV})^n$$

Generic energy dependence
$n \in [-1, 3]$

IceCube Sensitivity

- 15 years: signal of ~50 tracks, 15 showers (after angular + quality cuts)
- Backgrounds: atmospheric, other nearby ν sources!



1:1:1 flux from J2032+4130

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

IceCube Sensitivity, Cont.

$$\kappa_{-1} \leq 1.0 \times 10^{-34} \; (2.3 \times 10^{-31}) \text{ GeV}$$
$$\kappa_{0} \leq 3.2 \times 10^{-36} \; (3.1 \times 10^{-34}) \text{ GeV}$$
$$\kappa_{1} \leq 1.6 \times 10^{-40} \; (7.2 \times 10^{-39}) \text{ GeV}$$
$$\kappa_{2} \leq 2.0 \times 10^{-44} \; (5.5 \times 10^{-42}) \text{ GeV}$$
$$\kappa_{3} \leq 3.0 \times 10^{-47} \; (2.9 \times 10^{-45}) \text{ GeV}$$

} many orders of magnitude improvement over existing limits

Caveats:
- requires a source!
- flavor ratio analysis is non-trivial
- will need decent angular resolution for showers

Other VLI Possibilities

- Time-of-flight difference between ν and γ (or gravitational waves!) from GRBs* (talk by Piran)

$$energy\ scale \cong \frac{L}{c}\frac{\Delta E}{\Delta t} \cong M_{Planck}$$

  - cosmological distances traversed
  - $\Delta t \sim 1\ \mu s$ to 1 yr (!), depending on M_P suppression power
  - requires sufficient statistics + understanding of time evolution of GRB

- Cross-section enhancements at E > TeV (talk by Sigl)

- Observation of EHE ν ($\sim 10^{20}$ eV) could set limits via absence of vacuum Čerenkov radiation†
  - might require space-based detectors?

* see, *e.g*. Amelino-Camelia, gr-qc/0305057

† see discussion in Jacobson, Mattingly *et al*., hep-ph/0407370

Summary

- Searches for QG effects are ongoing
  - Atmospheric neutrino samples
  - Violations of Lorentz invariance (esp. HE subdominant oscillations)
  - Quantum decoherence (larger energy dependences better)

- Other tests are possible once ν point sources are detected
  - Electron antineutrino decoherence
  - Time-of-flight comparisons
  - Absence of vacuum Čerenkov

- Theory-pheno-experiment feedback crucial!