Probing Exotic Physics With Cosmic Neutrinos

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Based in part on:

- Anchordoqui, Han, Hooper and Sarkar, (Sub. to Astropart. Phys.) hep-ph/0508312
- Han and Hooper, New J. Phys, hep-ph/0408348
- Beacom, Bell, Hooper, Pakvasa and Weiler, PRL, hep-ph/0211305; PRD hep-ph/0307025
- Hooper, Morgan and Winstanley, PLB, hep-ph/0410094; PRD, hep-ph/0506091

Colliders and Cosmic Rays - Energetics

- Current Generation Hadron Colliders Reach Energies of ~2 TeV (Tevatron), ~14 TeV (LHC)
- EeV Neutrino and Nucleon At Rest

  $\Rightarrow$ 43 TeV Center of Mass
- 100 EeV Neutrino

  $\Rightarrow$ 430 TeV Center of Mass!

Colliders and Cosmic Rays - Baselines

- Colliders test only processes which occur over very short distances, propagation lengths
- “Long baseline”, atmospheric and solar neutrino experiments are less limited
- High energy cosmic neutrinos provide opportunity to probe neutrino properties over 100’s or 1000’s of Mpc

Colliders and Cosmic Rays - Luminosity

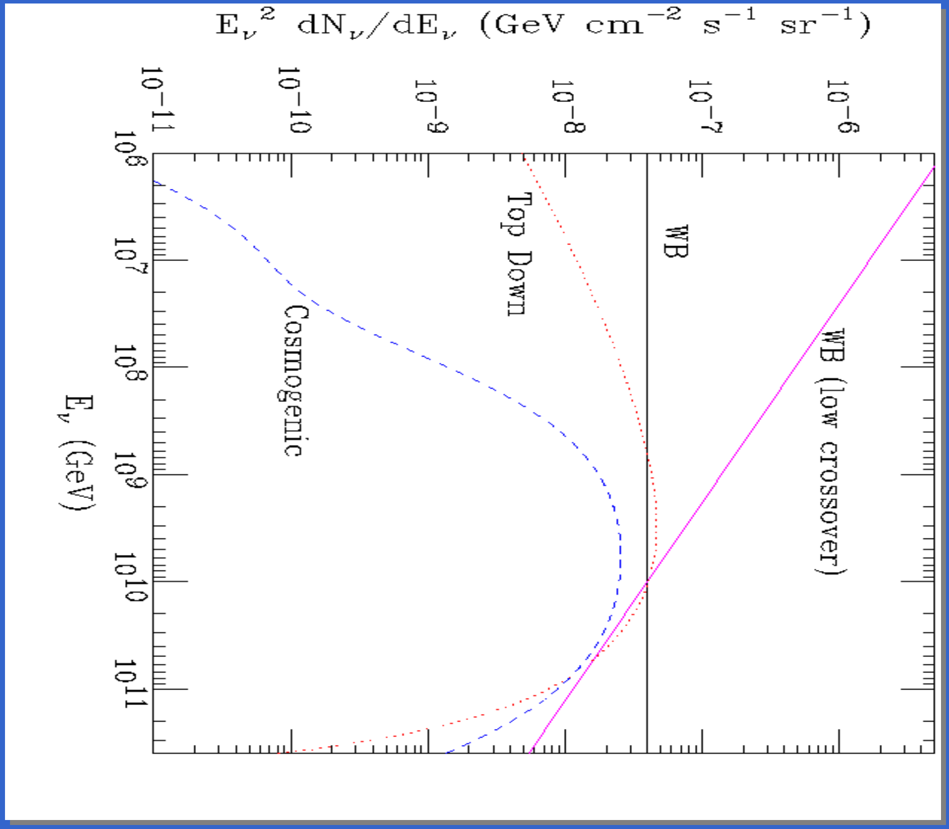
- Cosmic ray luminosity tiny compared to accelerator beams
- Cosmic neutrino luminosity unknown/uncontrolled
- Wide range of theoretical models of high energy and ultra-high energy cosmic neutrino spectrum

Plausible Sources of High Energy Cosmic Neutrinos

- Cosmic ray accelerators (gamma-ray bursts, active galactic nuclei, microquasars, etc.)
- Products of cosmic ray propagation (cosmogenic neutrino flux)
- Dark matter annihilations/decays
- Top-down models of cosmic ray origin

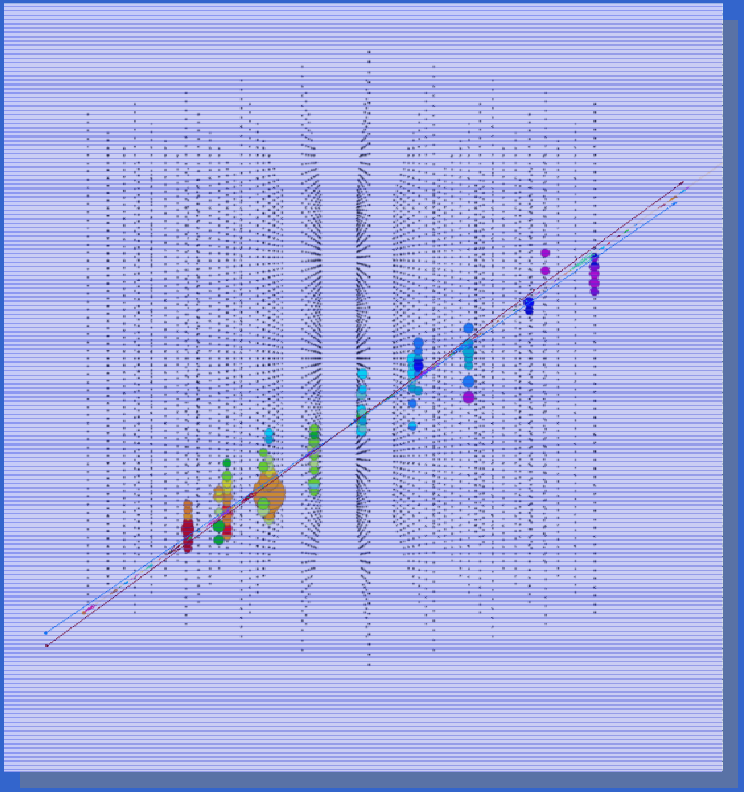
Sources of High Energy Cosmic Neutrinos

- Wide range of models
- Still, some predictions can be made with confidence
- Cosmogenic flux often called “guaranteed”
- Cosmic neutrinos associated with cosmic rays is required given hadronic acceleration



High-Energy Neutrino Telescopes

- AMANDA
  -Several Years of Data
- ANTARES
  -Under Deployment
- ICECUBE
  -Under Deployment
  -Full KM^3 Volume
  -Higher Energy Threshold



Ultra-High Energy Cosmic Neutrino Experiments

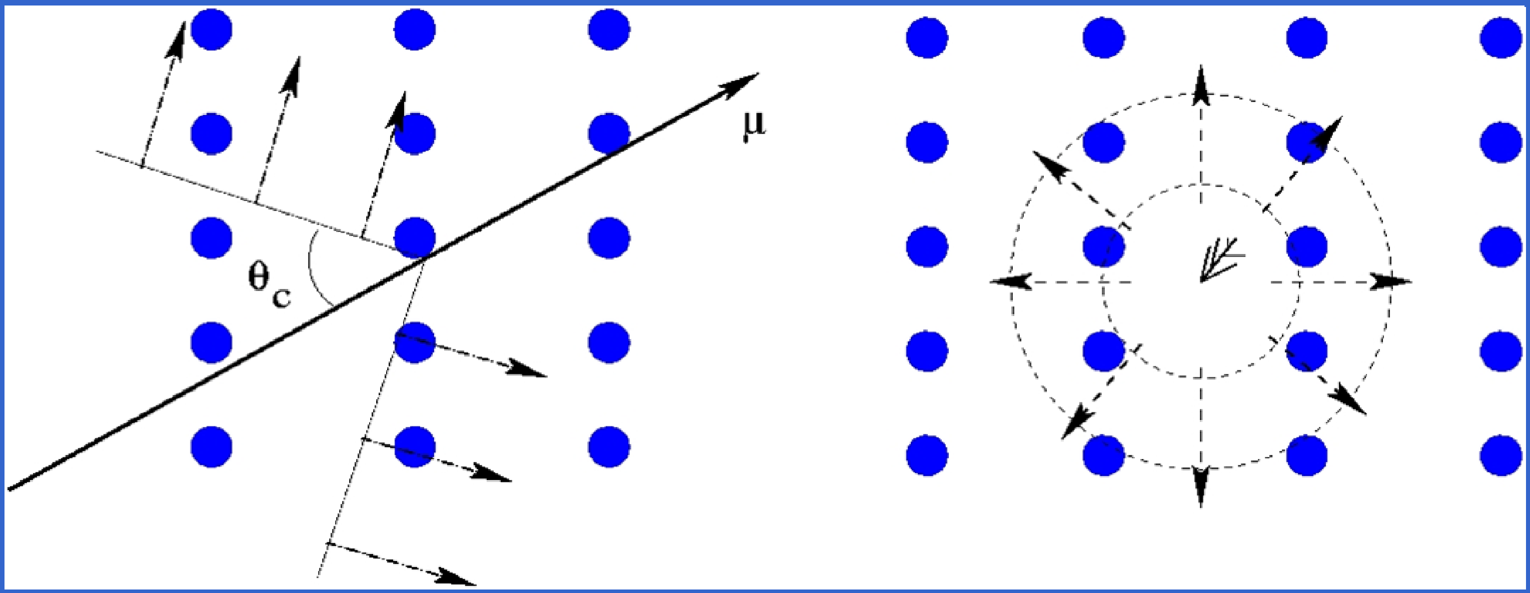
- PIERRE AUGER OBSERVATORY
  -Recently Released First Data
  (no neutrino data yet)

- ANITA
  -Radio Antenna Balloon Flight
  -First Flight Scheduled For Dec 2006

- EUSO/OWL
  -Satellite/Space Station Based
  -Enormous Aperture
  -Future Uncertain

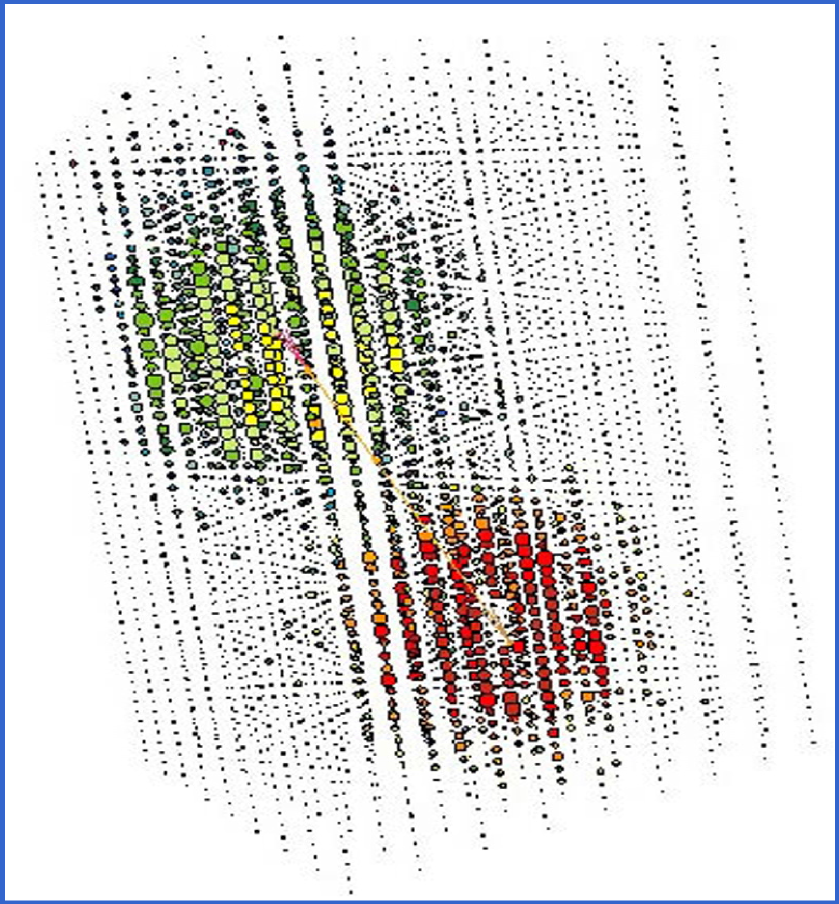
IceCube

- ~100 GeV Threshold (few TeV for showers)
- Full Kilometer Instrumented Volume
- Muon Tracks, EM/Hadronic Showers



IceCube

- Tau Neutrino Unique Events
  - -Double Bangs
  - -Lollipops
- PeV Thresholds
- Rare, But Interesting



Pierre Auger Observatory:
Deeply Penetrating, Quasi-Horizontal Airshowers

- Most neutrino induced airshowers cannot be distinguished from hadronic/photonic primaries
- Hadronic/Photonic UHECRs interact at top of Earth's atmosphere; Neutrinos interact at all column depths (nearly) equally
- Nearly horizontal airshowers, generated deep inside of the atmosphere, can be identified as neutrino initiated events

Pierre Auger Observatory:
Earth Skimming Tau Neutrinos

- UHE ν_e, ν_μ's are efficiently absorbed through charged current interactions in the Earth
- ν_τ's produce a τ which can decay before losing its energy (regeneration)
- Earth-skimming ν_τ's can decay in the atmosphere, and be detected by Auger

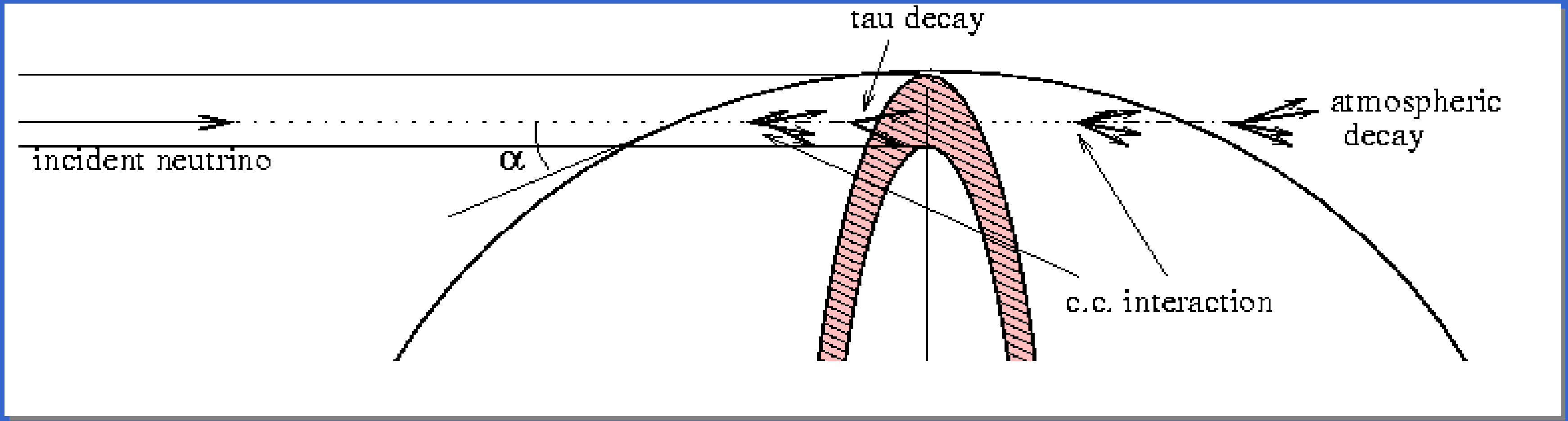


Figure from Bertou et al., astro-ph/0104452

IceCube and Auger

- ICECUBE

  -Sensitive above ~100 GeV

  -km^3 instrumented volume

  -Observes:

  muon tracks

  CC/NC showers

  tau unique events

- PIERRE AUGER

  -Sensitive above ~10^7 GeV

  -3000 km^2 surface area

  -Observes:

  horizontal showers

  upgoing tau neutrinos

The Role of Neutrino Astronomy in Exploring Exotic Physics

- Focus on scenarios which benefit from the strengths of neutrino astronomy in contrast to collider programs:

  -Models with substantial deviations from SM at energies beyond reach of colliders

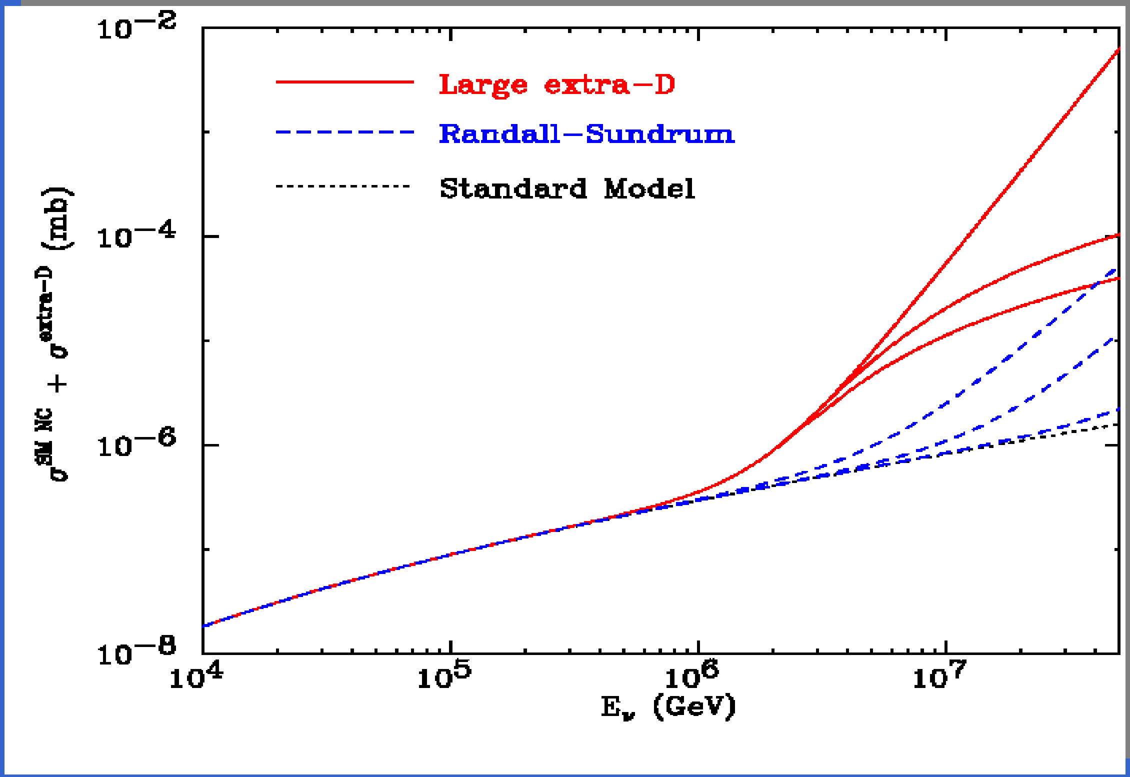
  -Models with substantial deviations from SM over timescales and/or propagation lengths beyond the range observable at colliders

TeV Scale Gravity

- $E_{CM} \sim M_{PL}$, KK Graviton Exchange
- $E_{CM} > M_{PL}$, String Resonances
- $E_{CM} >> M_{PL}$, Black Hole Production

Kaluza-Klein Gravitons

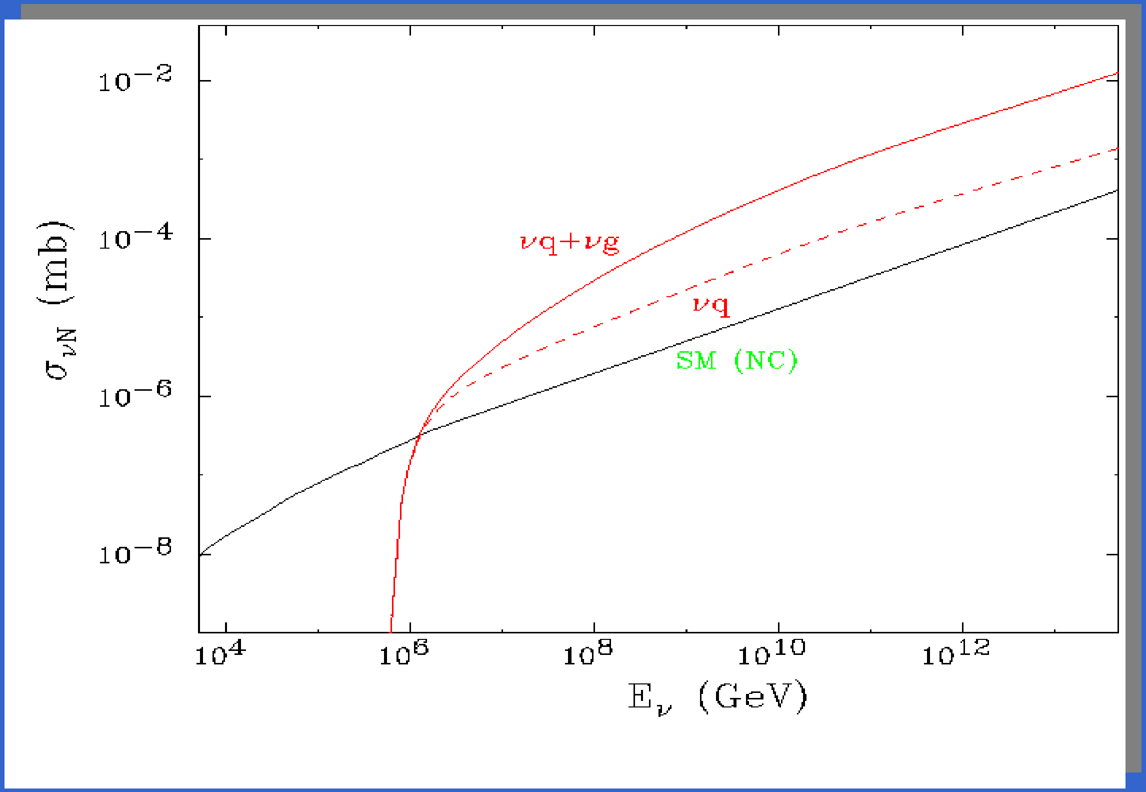
- Model Dependent Cross Sections
- Not Valid Very Far Above $E_\nu \sim TeV^2/2m_p \sim PeV$



Alvarez, Halzen, Han, Hooper, PRL hep-ph/0107057

TeV String Resonances

- Valid At All Energies
- Only Mild Model Dependence (Chan-Patton)



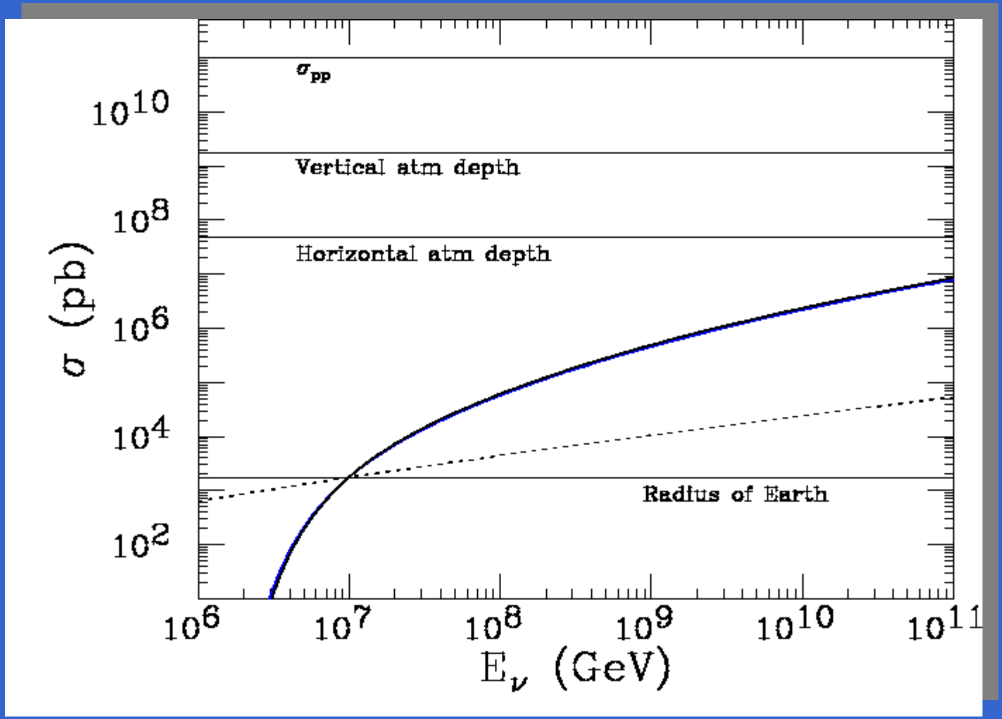
Friess, Han and Hooper, PLB, hep-ph/0204112

Microscopic Black Hole Production

- At center-of-mass energies above fundamental Planck scale, black holes can be formed
- Naïve picture suggests geometric cross section, $\sigma \sim \pi R^2_{sch}$
- TeV black holes rapidly Hawking radiate

Microscopic Black Hole Production

- Valid At All Energies
- Dominates at Very High Energies



See Anchordoqui, Feng, Goldberg and Shapere, PLB hep-ph/0311265; PRD hep-ph/0307228; PRD hep-ph/0112247

Microscopic Black Hole Production

- Likely the most easily observed signature of TeV gravity
- Open questions remain:

  -Energy loss to gravitational waves

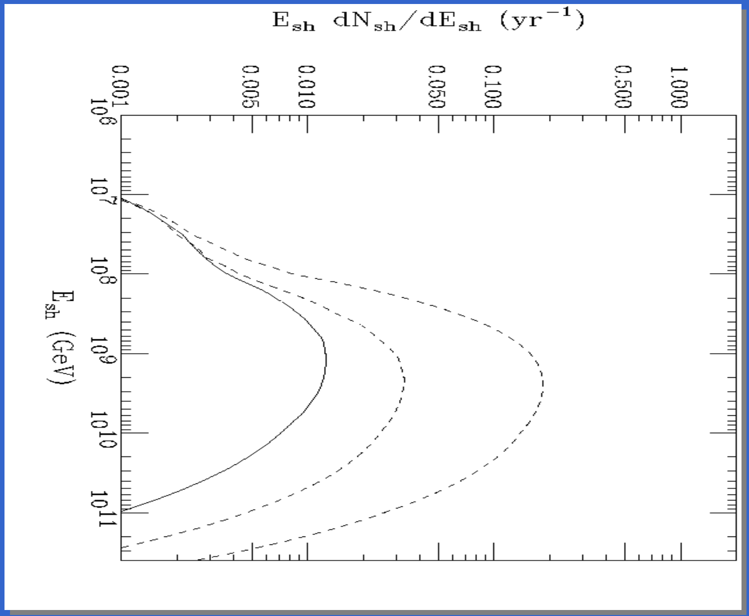
  -Many model dependent features

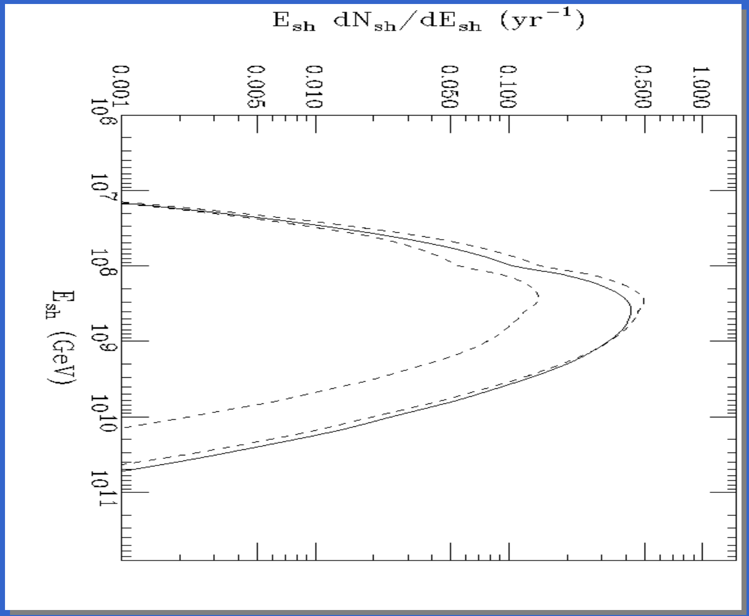
  -P brane production likely to dominate, but behavior of Hawking radiation unknown

TeV Scale Gravity At Auger

- Sensitive above 100 PeV
- Beyond range of KK Graviton exchange
- Very sensitive to string resonances, black hole production

TeV Scale Gravity At Auger



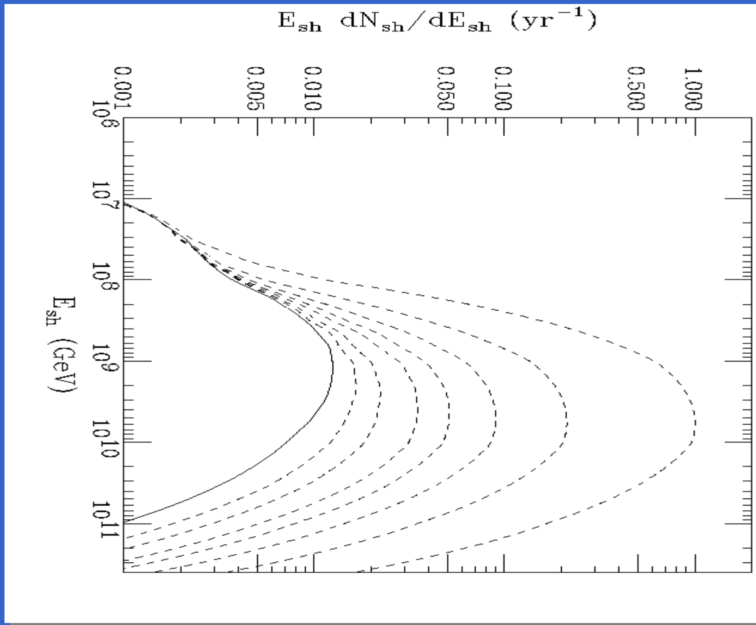


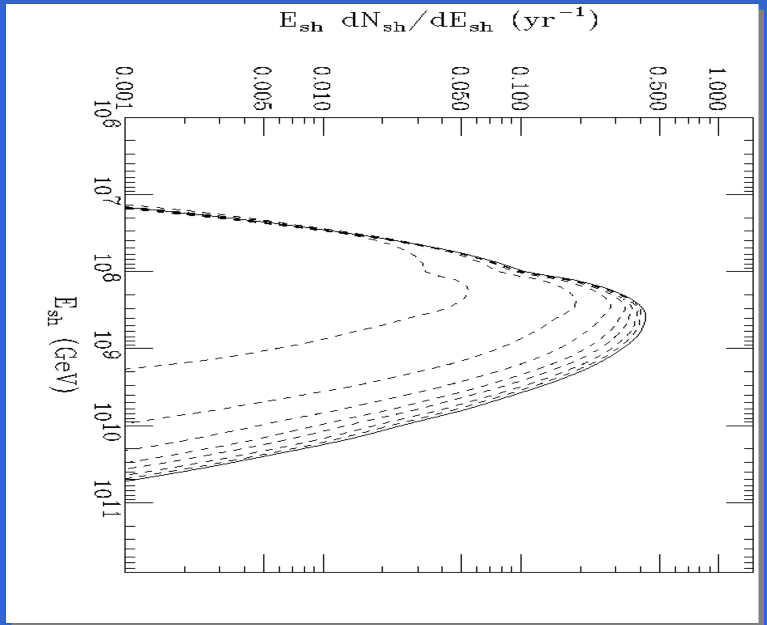
- Rate of quasi-horizontal showers grows, while Earth skimming showers are suppressed

Model	QH/ES Ratio
SM	0.05
2 TeV	0.11
1 TeV	2.1

Anchordoqui, Han, Hooper and Sarkar, hep-ph/0508312

TeV Scale Gravity At Auger





- Auger is exceptionally well suited for probing microscopic black hole production

Model	QH/ES Ratio
SM	0.05
8 TeV	0.10
3 TeV	0.54
2 TeV	2.0
1 TeV	36.0

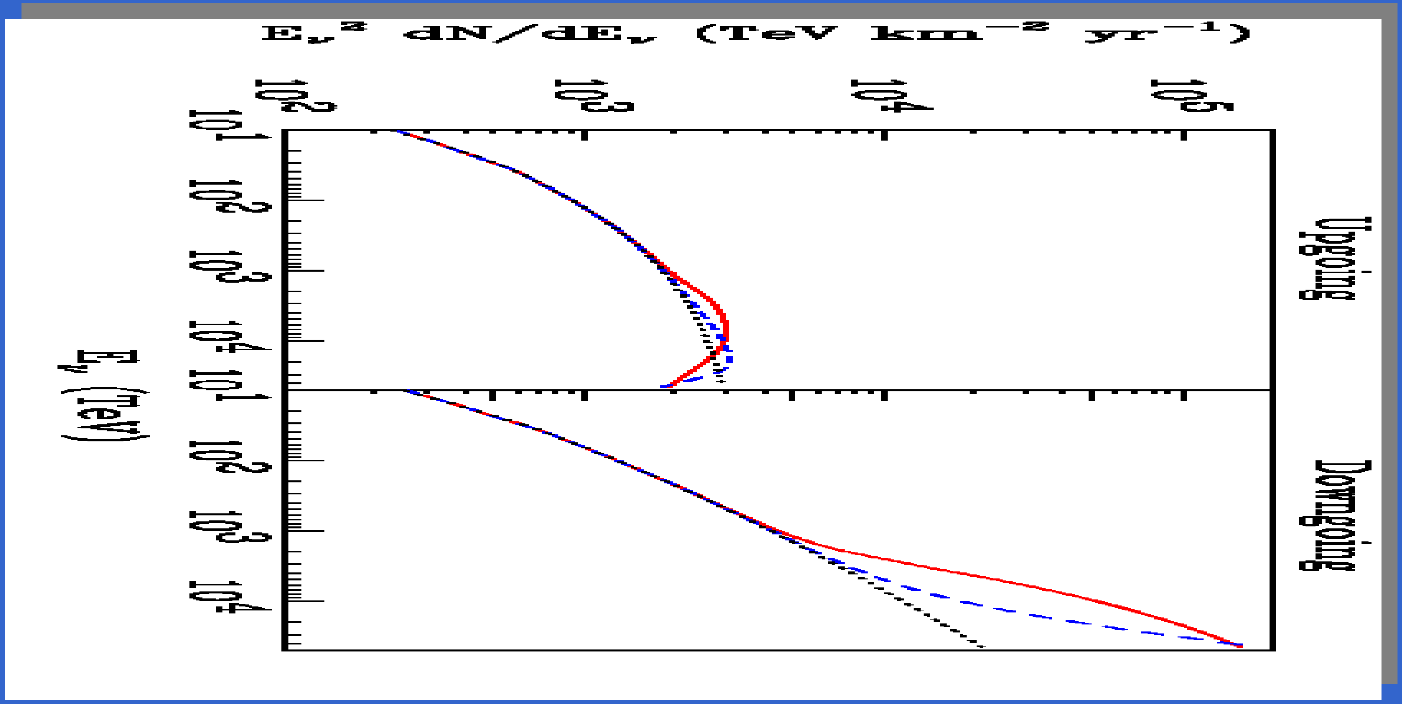
Anchordoqui, Han, Hooper and Sarkar, hep-ph/0508312

TeV Scale Gravity At IceCube

- Most Sensitive in TeV-PeV Range
- Well Suited To Probe KK Graviton Exchange
- Black Hole Production Generates Observable Muons, Taus and Showers

TeV Scale Gravity At IceCube

- Cross Section Measurements
- Comparison of Upgoing to Downgoing Events



Alvarez, Han, Halzen and Hooper, PRL hep-ph/0107057

TeV Scale Gravity At IceCube

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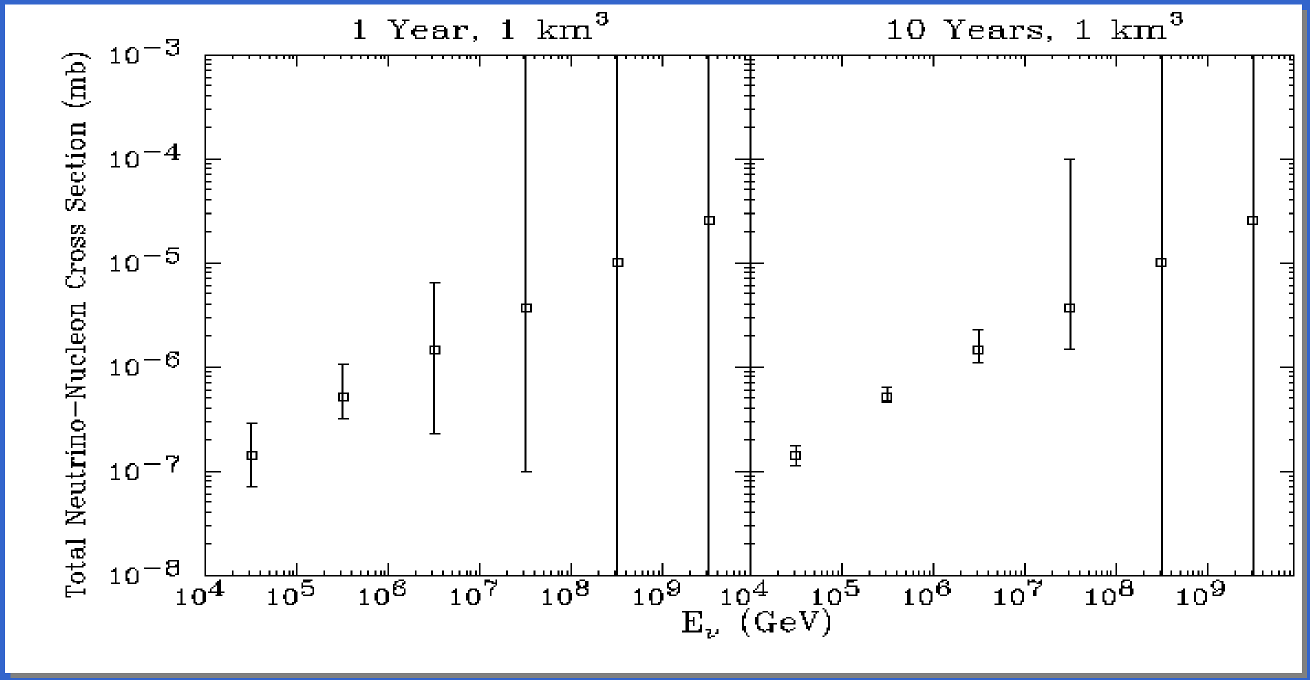
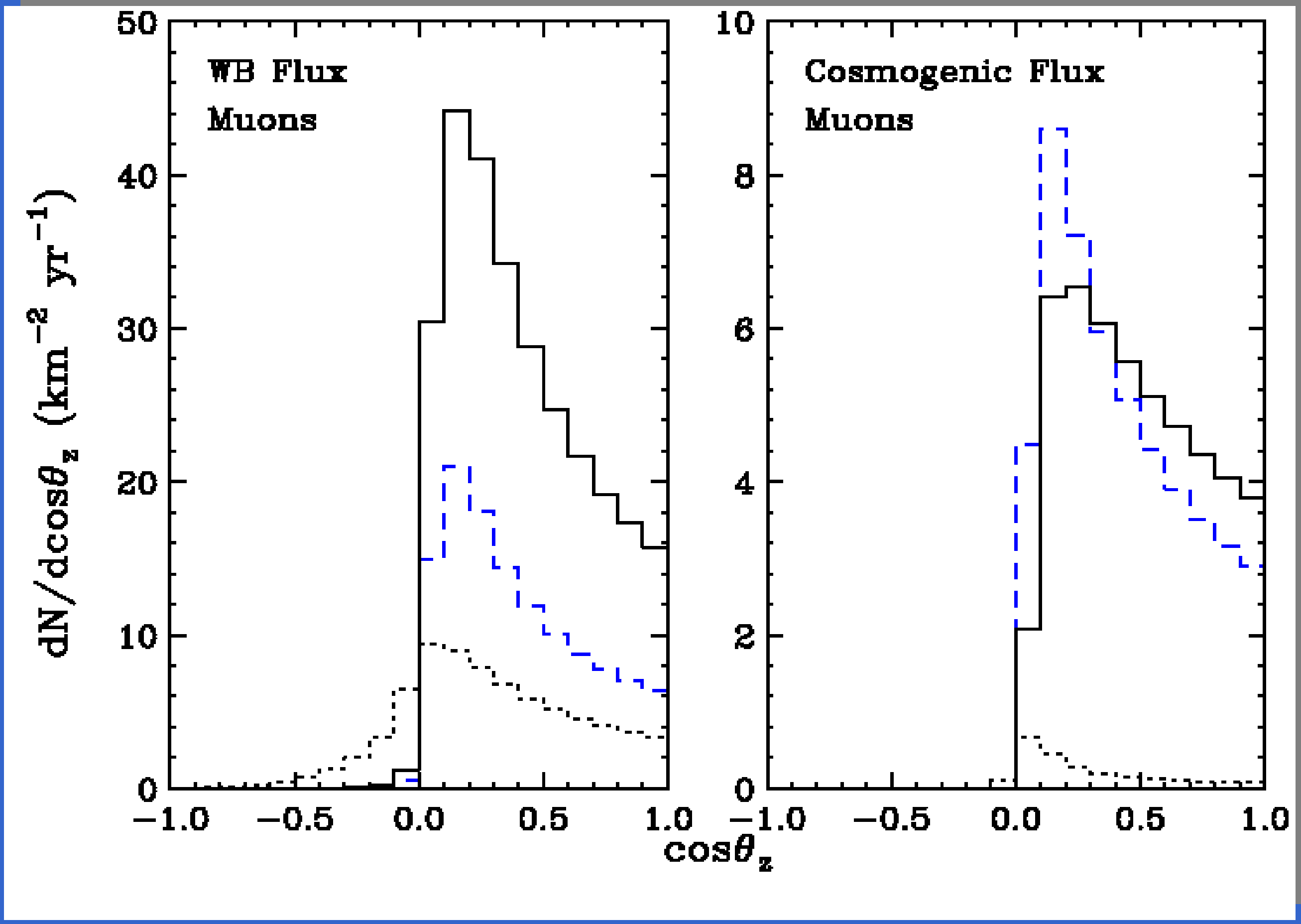


Hooper, PRD hep-ph/0203239

TeV Scale Gravity At IceCube

- Angular Distribution of Events



Alvarez, Han, Halzen and Hooper, PRD hep-ph/0202081

TeV Scale Gravity At IceCube:
Multi-Channel Measurements

- KK gravitons, string resonances contribute to shower rate only
- Use shower/muon ratio to test for deviations from SM prediction
- Hawking radiation from microscopic black holes generates taus, muons and showers

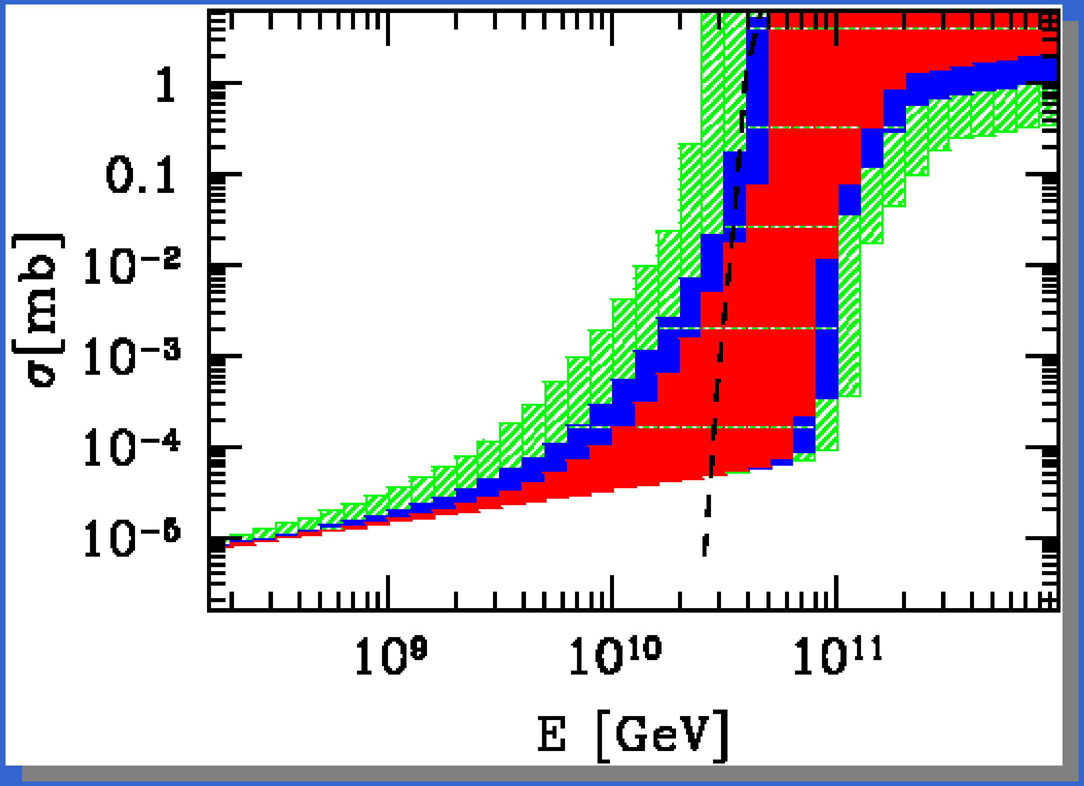
SM Electroweak Instanton Induced Interactions

- Transitions between degenerate vaccua (with different B+L) are possible within the context of the SM
- Below "Sphaleron" mass, $\pi M_W/\alpha_W \sim 8$ TeV, such transitions are exponentially suppressed
- Above this energy, enormous cross sections may be expected for such processes

See: Ringwald Nuc Phys B (1990), Aoyama and Goldberg PLB (1987)

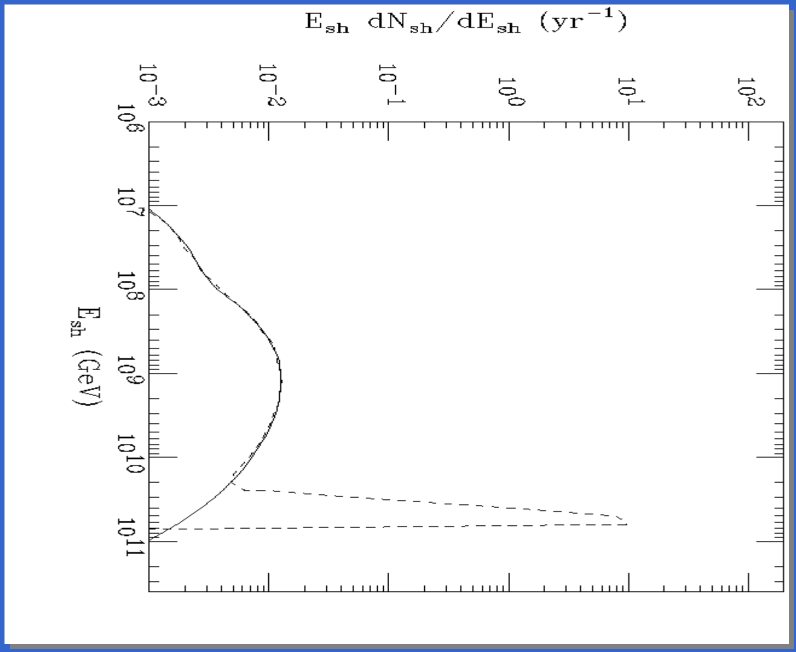
Instanton Induced Interactions

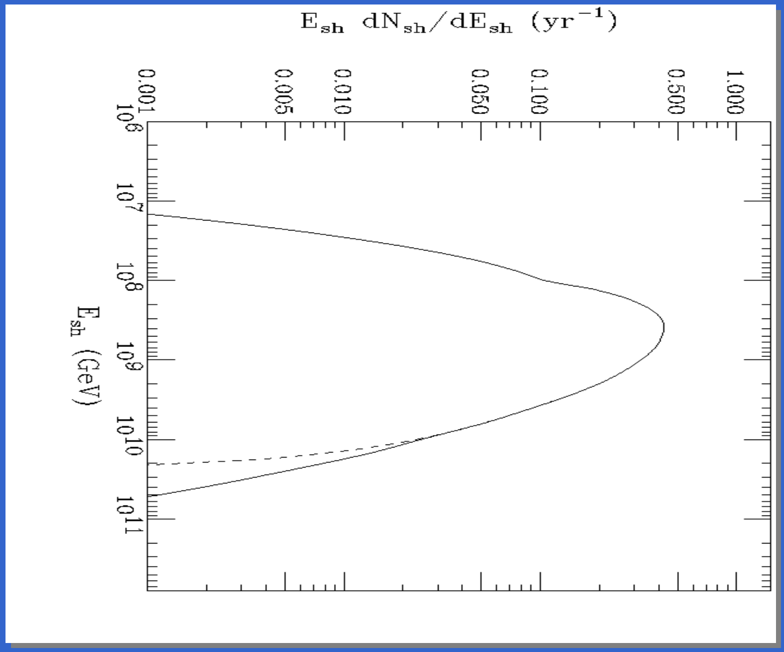
- Neutrino-nucleon cross section, based on QCD-like picture and data
- Ideally suited for Auger



Ahlers, Ringwald and Tu, astro-ph/0506698

Instantons At Auger





- Substantial deviations expected above 10^{10} GeV
- Roughly 4 QH showers/yr predicted, roughly 30 times more than CC/NC alone
- Very strong probe of Electroweak Instanton Induced Interactions

Anchordoqui, Han, Hooper and Sarkar, hep-ph/0508312

Long Baseline Measurements

- Colliders probe phenomena at (very) sub-second scales
- Low energy neutrino experiments probe scales of Γ / m ~ 10^{-4} sec / eV (sun)

  (supernovae may, in future, improve on this)
- High energy cosmic neutrinos may improve on this by a factor of:

  $\sim 10^7$ (L / 100 Mpc) (10 TeV / E_ν)
- Powerful test of neutrino decay, quantum decoherence, Lorentz violation, …

Cosmic Neutrino Flavors

- Astrophysical accelerators generate neutrinos through charged pion decay:

$$\pi^{+/-} \Rightarrow \mu\ \nu_\mu \Rightarrow e\ \nu_e\ \nu_\mu\ \nu_\mu$$

- Neutrinos produced in the ratio:

$$\nu_e:\nu_\mu:\nu_\tau = 1 : 2 : 0$$

- After oscillations, this leads to: $\nu_e:\nu_\mu:\nu_\tau \approx 1 : 1 : 1$
- Caveat: Energy losses in source might modify

(Kashti and Waxman, astro-ph/0507599)

Neutrino Decay

- Scenario 1: All mass eigenstates decay to lightest mass eigenstate (or invisible) with normal hierarchy; flavor ratios of:

  $$\nu_e:\nu_\mu:\nu_\tau = \cos^2\theta_S : (1/2)\sin^2\theta_S : (1/2)\sin^2\theta_S \approx 6 : 1 : 1$$

- Scenario 2: Same, but with inverted hierarchy:

  $$\nu_e:\nu_\mu:\nu_\tau = U^2{}_{e3} : U^2{}_{\mu 3} : U^2{}_{\tau 3} \approx 0 : 1 : 1$$

- Scenario 3: (only) ν_3 decays invisibly; with normal hierarchy, flavor ratios of:

  $$\nu_e:\nu_\mu:\nu_\tau \approx 2 : 1 : 1$$

- Many other scenarios possible

Measuring Cosmic Neutrino Flavor Ratios

- With IceCube:
  - Muons/showers roughly translates to ν_μ/ν_{tot}
  - Tau unique events provide confirmation

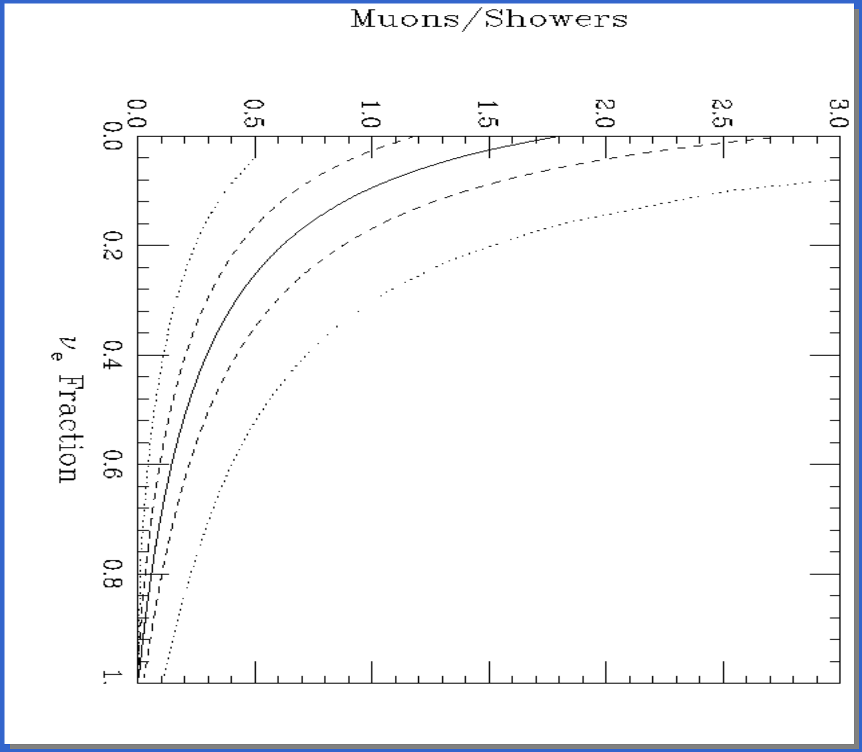
Beacom, Bell, Pakvasa, Hooper and Weiler, hep-ph/0307025

- With Auger:
  - ES/QH roughly translates to ν_τ/ν_{tot}
  - Low event rate yields less sensitivity

Anchordoqui, Han, Hooper and Sarkar, hep-ph/0508312

Flavor Ratios At IceCube

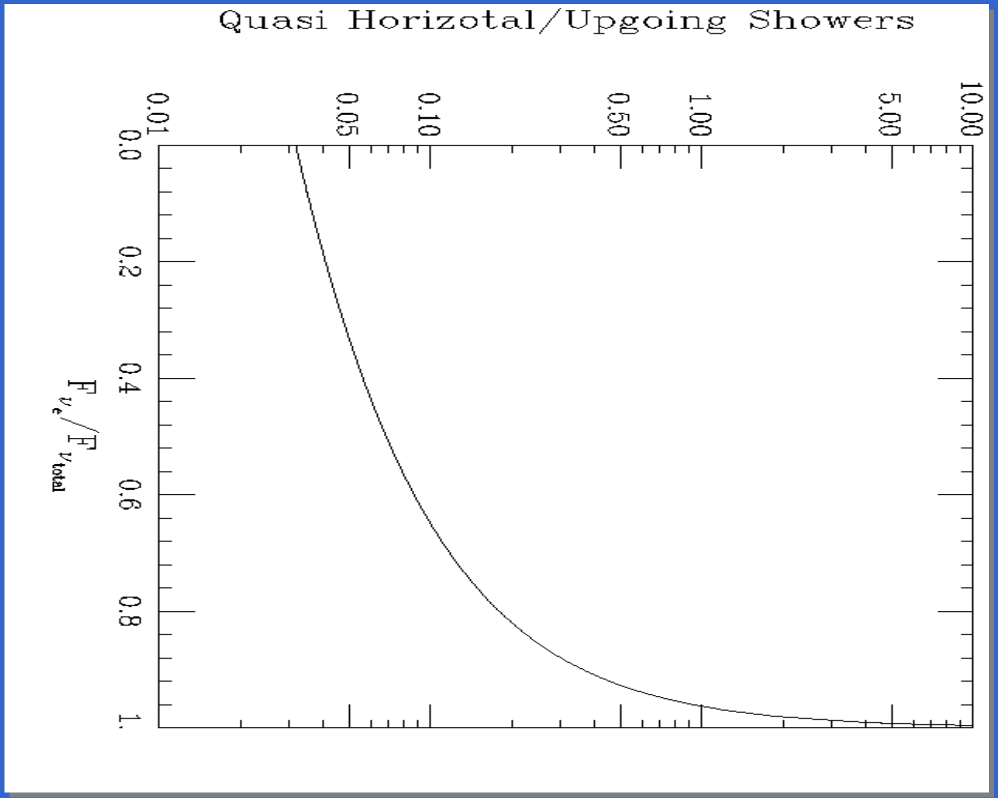
- Ratio of muons to showers translates to flavor ratio
- Example: TeV threshold,
  $E^2\, dN/dE = 10^{-7}$ GeV cm^{-2} s^{-1}, 2 x 10^{-8} GeV cm^{-2} s^{-1}



Beacom, Bell, Pakvasa, Hooper and Weiler, hep-ph/0307025

Flavor Ratios At Auger

- Deviations in QH/ES translate to deviations in flavor ratios
- Limited potential



Anchordoqui, Han, Hooper and Sarkar, hep-ph/0508312

Quantum Decoherence

- In many pictures of quantum gravity, information loss may be expected during propagation (black hole formation/radiation, quantum foam)

- Regardless of initial flavors, cosmic neutrinos gradually evolve toward:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

- This is the similar to the prediction from pion decay (after oscillations), and thus is impossible to distinguish

Quantum Decoherence

- To probe effects of quantum decoherence, another (non-pion) source of neutrinos is needed
- Photodisintegration of UHE nuclei generates neutrons which decay producing *uniquely* electron anti-neutrinos
- After oscillations, such a source yields:

$$\nu_e : \nu_\mu : \nu_\tau \approx 3 : 1 : 1$$

- Potentially distinguishable from quantum decoherence effects

Hooper, Morgan and Winstanley, PLB, hep-ph/0410094

UHE Neutron Sources and Quantum Decohence

- UHE neutrons can travel multi-kpc scales without decaying
- Neutral UHECRs can reveal point sources
- Can be used to infer the presence of lower energy neutrons which decay generating (anti-)neutrinos
- Cygnus region point source detected by AGASA in EeV range at 4-4.5σ significance (4% of flux)
- Supporting data from Sugar, as well as galactic plane excess seen by Fly's Eye

Anchordoqui, Goldberg, Gonzalez-Garcia, Halzen, Hooper, Sarkar and Weiler, PRD hep-ph/0506168

Summary and Conclusions

- High energy neutrino astronomy provides a new window into possible exotic physics scenarios which are beyond the reach of planned collider experiments
- Very high energies, very long baselines are in many cases *uniquely* assessable with neutrino astronomy

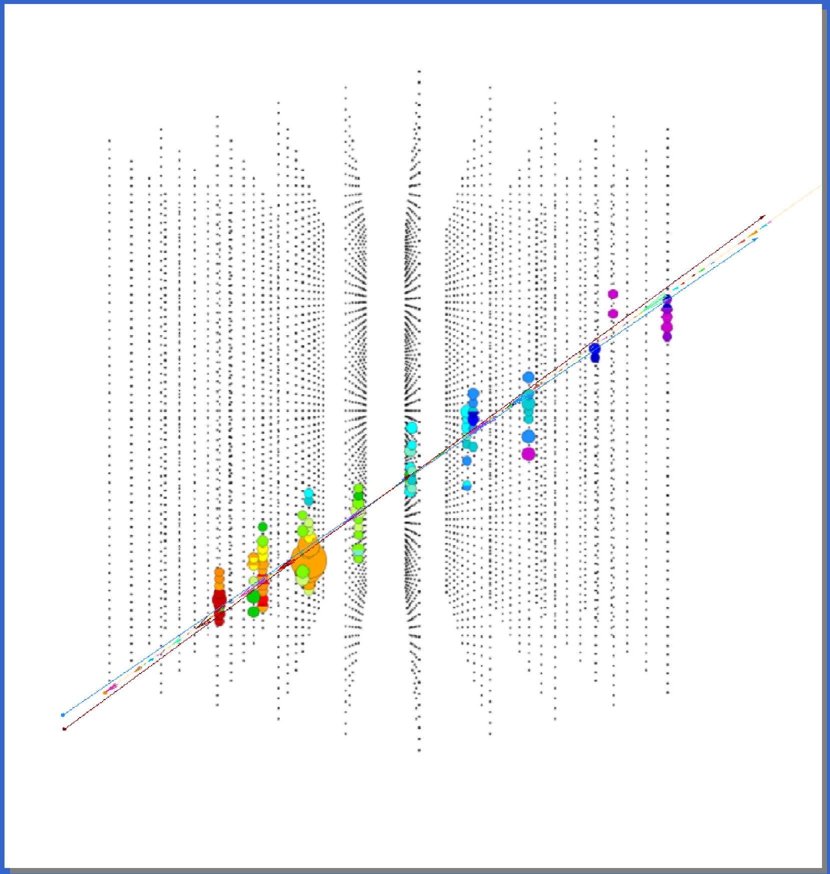
Summary and Conclusions

- Such scenarios include (but are not limited to):
  - -Low scale quantum gravity
  - -Electroweak instanton induced interactions
  - -Neutrino decay
  - -Quantum Decoherence

The Future of Particle Physics

- Greater energies scales continue to be explored with colliders (Tevatron, LHC, ILC, VLHC,…)
- Greater energies prove to be increasingly expensive and technically challenging
- Future of collider-based particle physics is uncertain
- To overcome these challenges, a broad vision of experimental particle physics is needed
- Cosmic ray physics, neutrino astronomy, gamma-ray astronomy and early Universe cosmology each contribute to our understanding of particle properties and interactions under conditions inaccessible to colliders
- Complementary should be taken fully advantage of

The End



Long Lived Staus

- In Gauge Mediated SUSY Breaking (GMSB) models, NLSP stau can be long lived, eventually decaying to gravitino LSP
- Stau pairs generated in HE neutrino interactions are potentially observable at IceCube

(Albuquerque, Burdman and Chacko hep-ph/0312197)