High-Energy Neutrino Astronomy

Opportunities For Particle Physics

Dan Hooper-University of Oxford

January 2004

Cracow, Poland

- Neutrino-Nucleon Interactions
  - -TeV Scale Extra Dimensions
  - -Microscopic Black Hole Production
  - -Electroweak Instanton Induced Interactions
- Particle Dark Matter
  - -Indirect Searches Using Neutrino Telescopes
  - -Neutrinos From Dark Matter In Top-Down Cosmic Ray Scenarios
- Neutrino Properties
  - -Neutrino Decay
  - -Pseudo-Dirac Mixing Scenarios
  - -Absolute Neutrino Masses

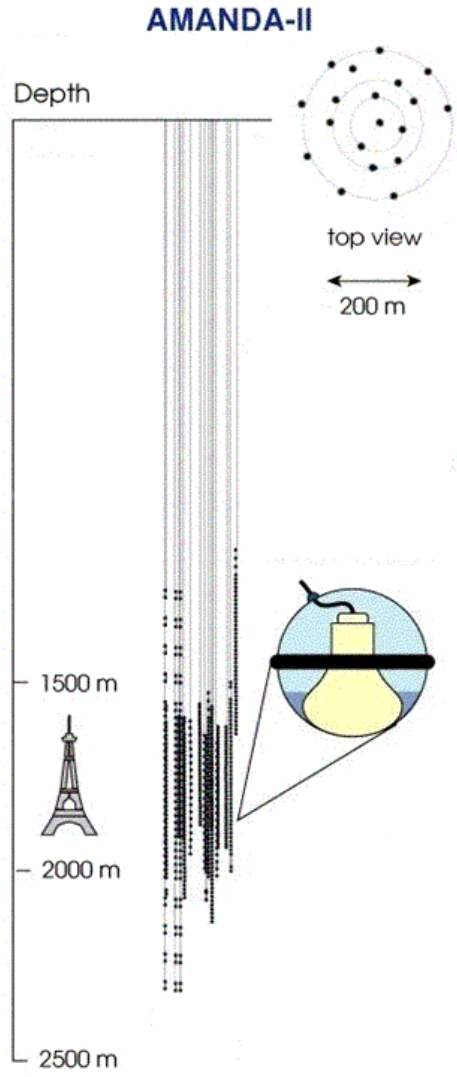
THE EXPERIMENTS

- AMANDA-II

  50,000 square meters effective area

  Antarctic ice Cerenkov medium

  Currently Taking Data



THE EXPERIMENTS

- ANTARES

  0.1 square kilometer scale

  Mediterranean Location

  Under Construction

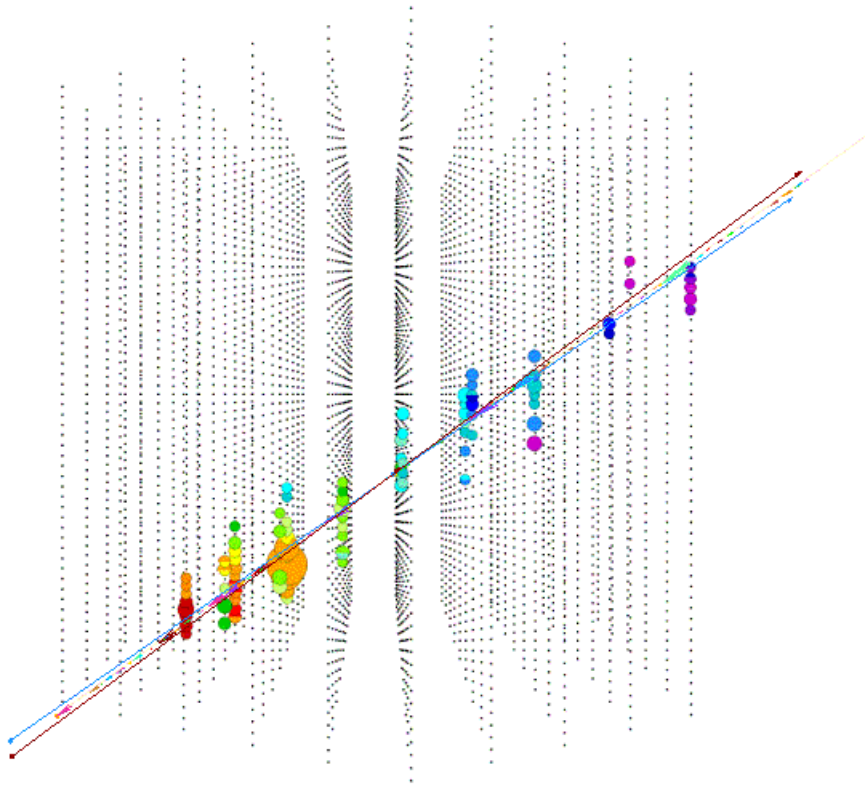
  Other Water Based Experiments: Baikal, Nestor

- Next Generation: ICECUBE!

  Full Square Kilometer Effective Area

  First Strings In 2004, Completed in 2009

IceCube



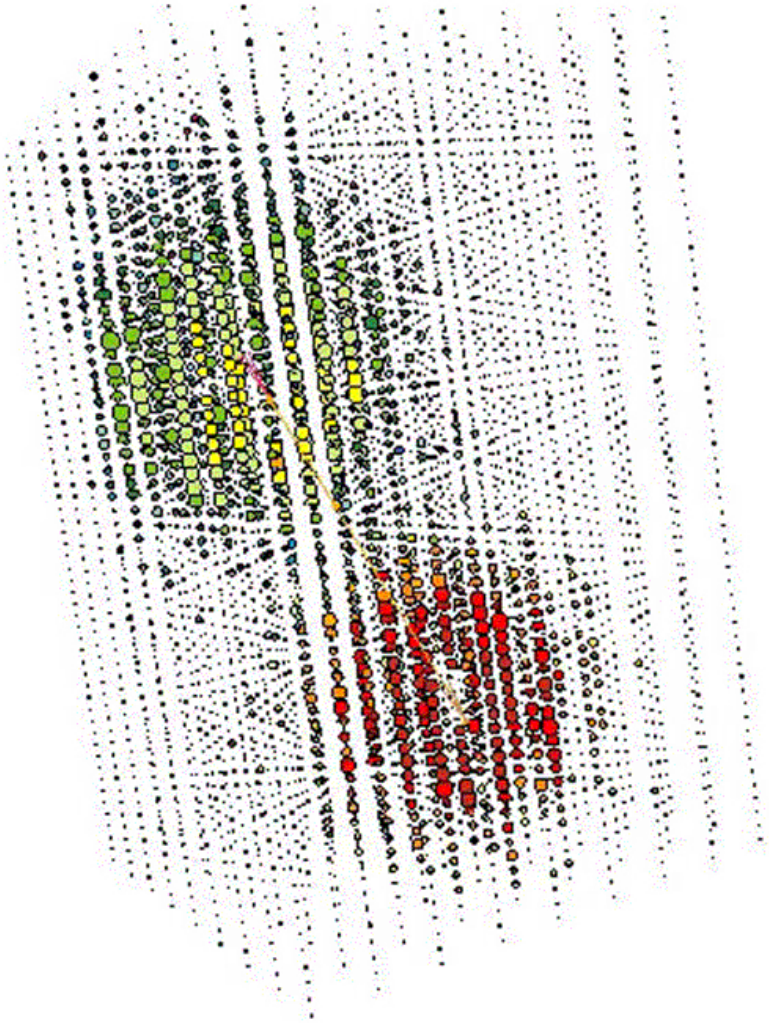
Performance

-Subdegree Angular Resolution

-Energy Resolution via Shower Radii

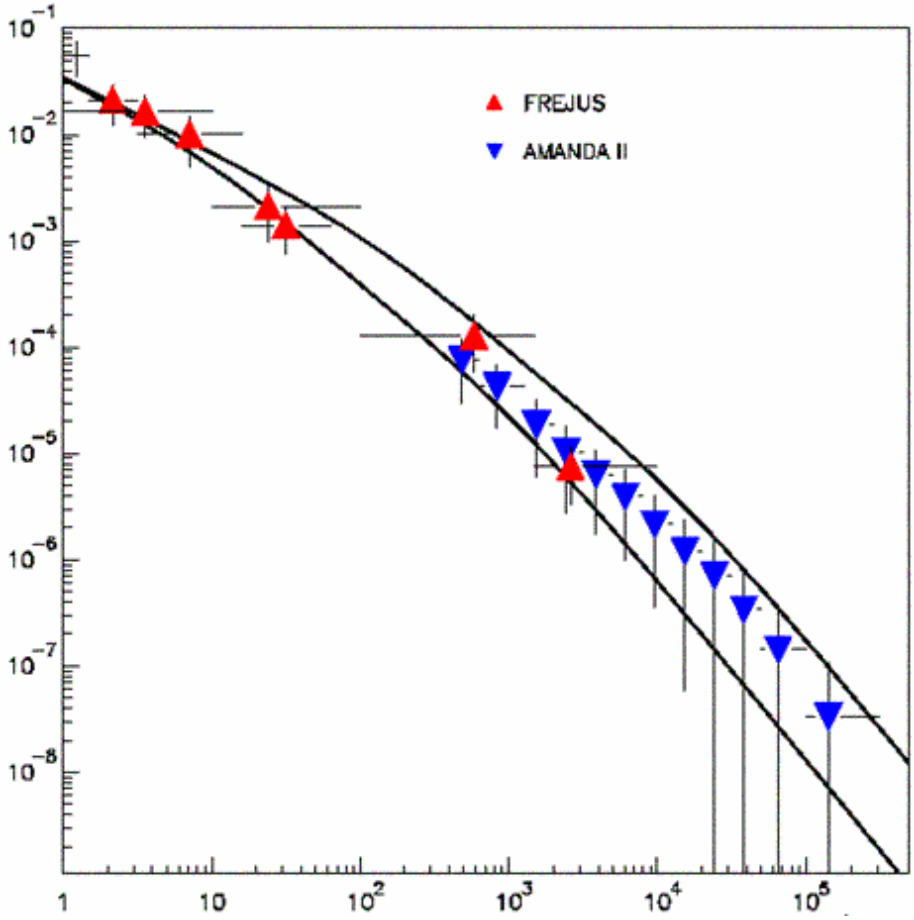
-Effective Volume Enhanced By Muon Range

IceCube



Flavor Discrimination
-Muon Tracks
-Hadronic/Electromagnetic Showers
-Double Bang Events

IceCube/AMANDA



Calibration

-New Experimental Methods Require Rigorous Calibration
-AMANDA Calibrated Using Atmospheric Neutrinos
-Difficult to Accomplish With UHE Experiments

Ultra-High Energy Experiments

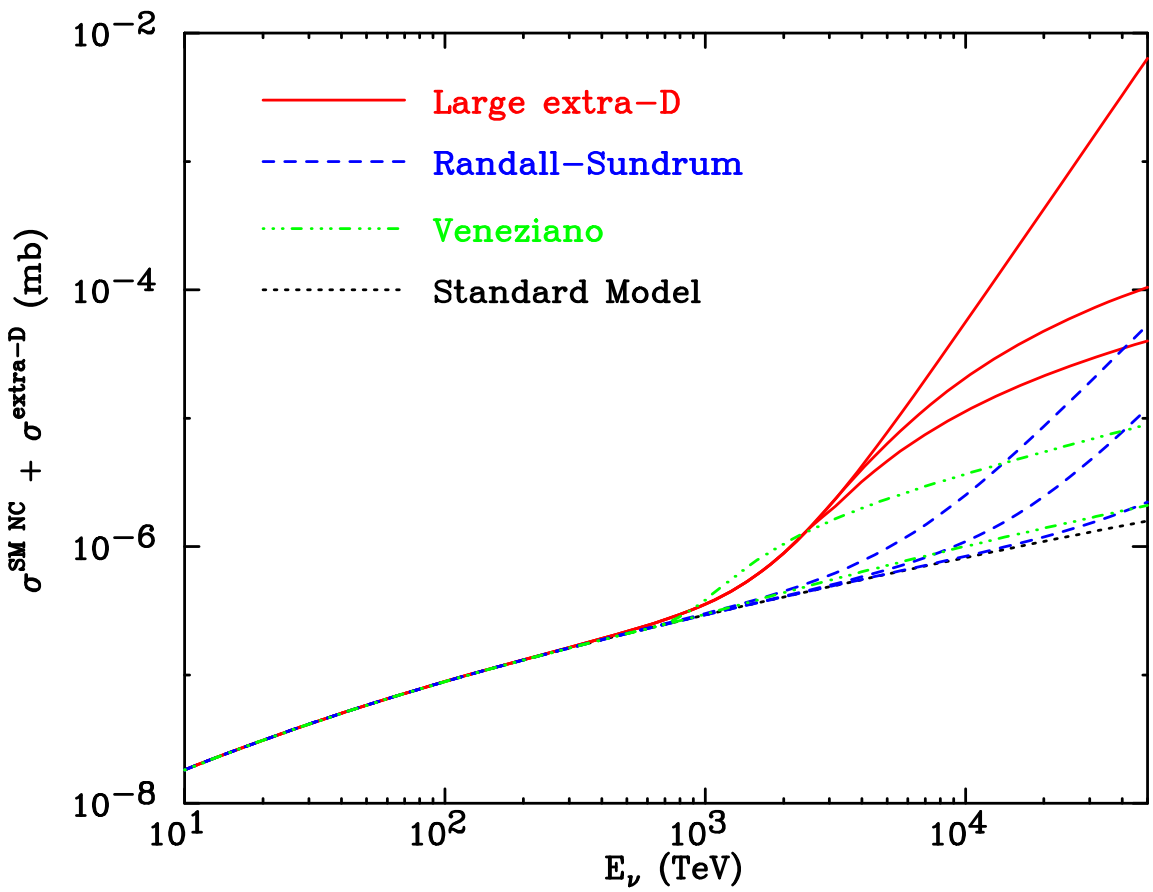
- Radio Cerenkov
  Rice (Ice)
  Anita (Baloon Flight)
- Air Shower Experiments
  AUGER (Ground Array)
  EUSO (ISS)
- Beyond Anita/EUSO
  Salsa (Salt Domes)
  IceCube-Plus/HyperCube

HIGH-ENERGY NEUTRINO INTERACTIONS

- Neutrino Interactions Via Gravity

  -Kaluza-Klein Resonances

  -String Excitations



See (for example):

Jain, McKay, Panda, Ralston, PLB (hep-ph/0001031);

Jain, Jain, McKay, Ralston, IJMP (2002 and hep-ph/0011310);

Freiss, Han and Hooper, PLB (hep-ph/0204112);

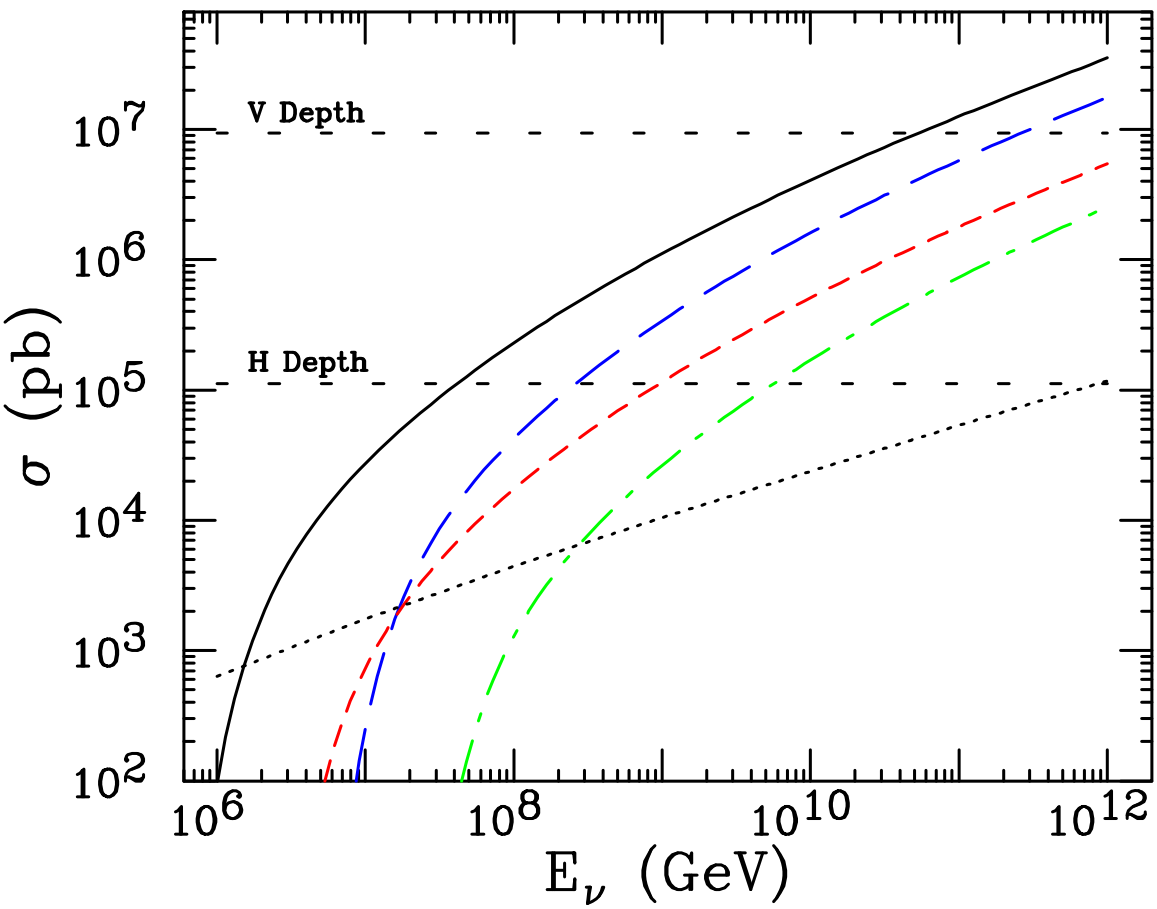
Alvarez, et al. PRL (hep-ph/0107057),PRD (hep-ph/0202081);

Anchordoqui, *et al*, (hep-ph/0112247, hep-ph/0311365, hep-ph/0112247);

Kowalski, Ringwald and Tu, PLB (hep-ph/0201139)

High-Energy Neutrino Interactions

- Microscopic Black Hole Production



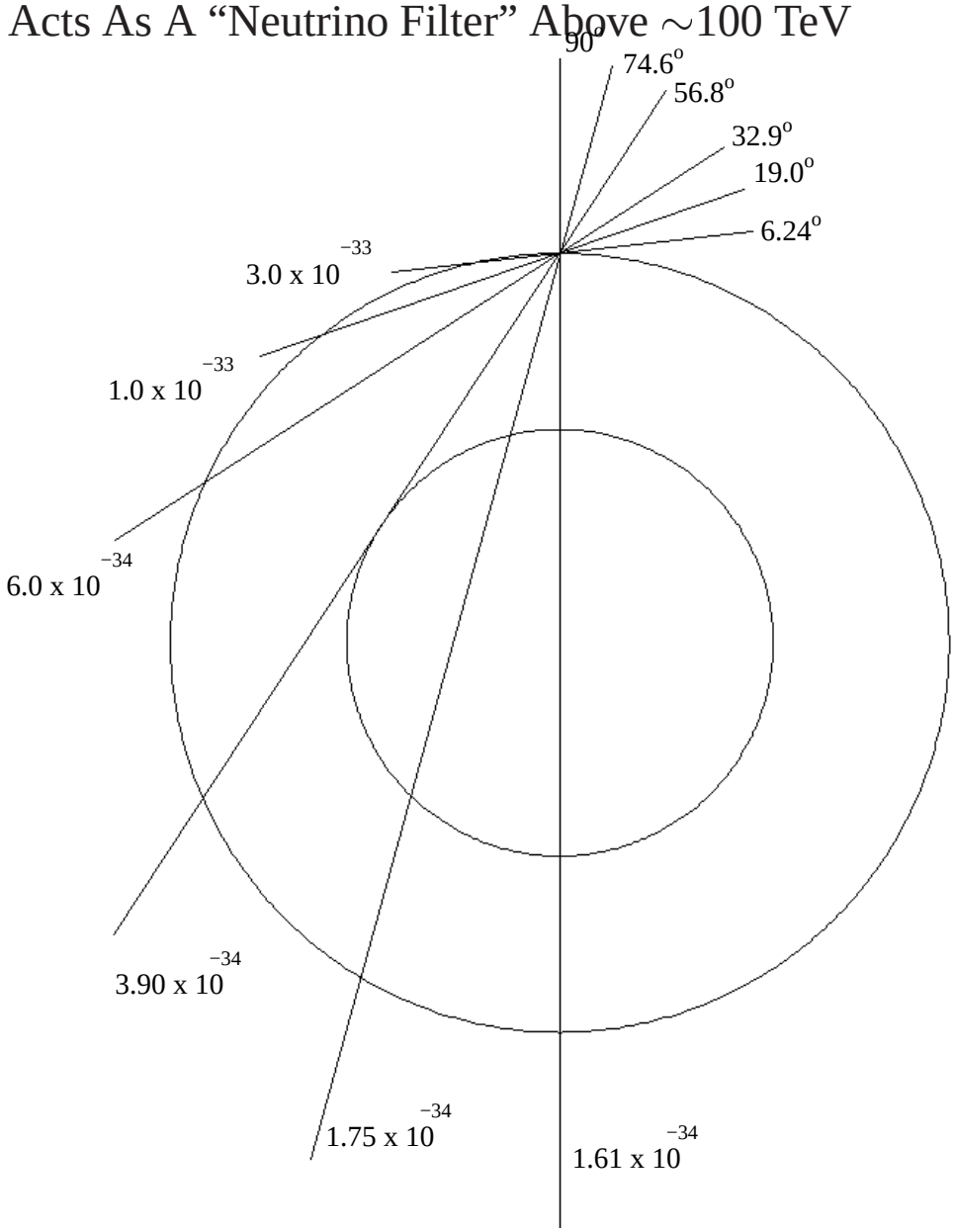
See (for example):
Giddings, Thomas, PRD (hep-ph/0106219);
Feng, Shapere, PRL (hep-ph/0109106);
Anchordoqui, Feng, Goldberg, Shapere, PRD (hep-ph/0112247);
Kowalski, Ringwald, Tu, PLB (hep-ph/0201139);
Alvarez, Feng, Halzen, Han, Hooper, PRD (hep-ph/0202081)

MEASURING ν CROSS SECTIONS

- Angular and Energy Distributions

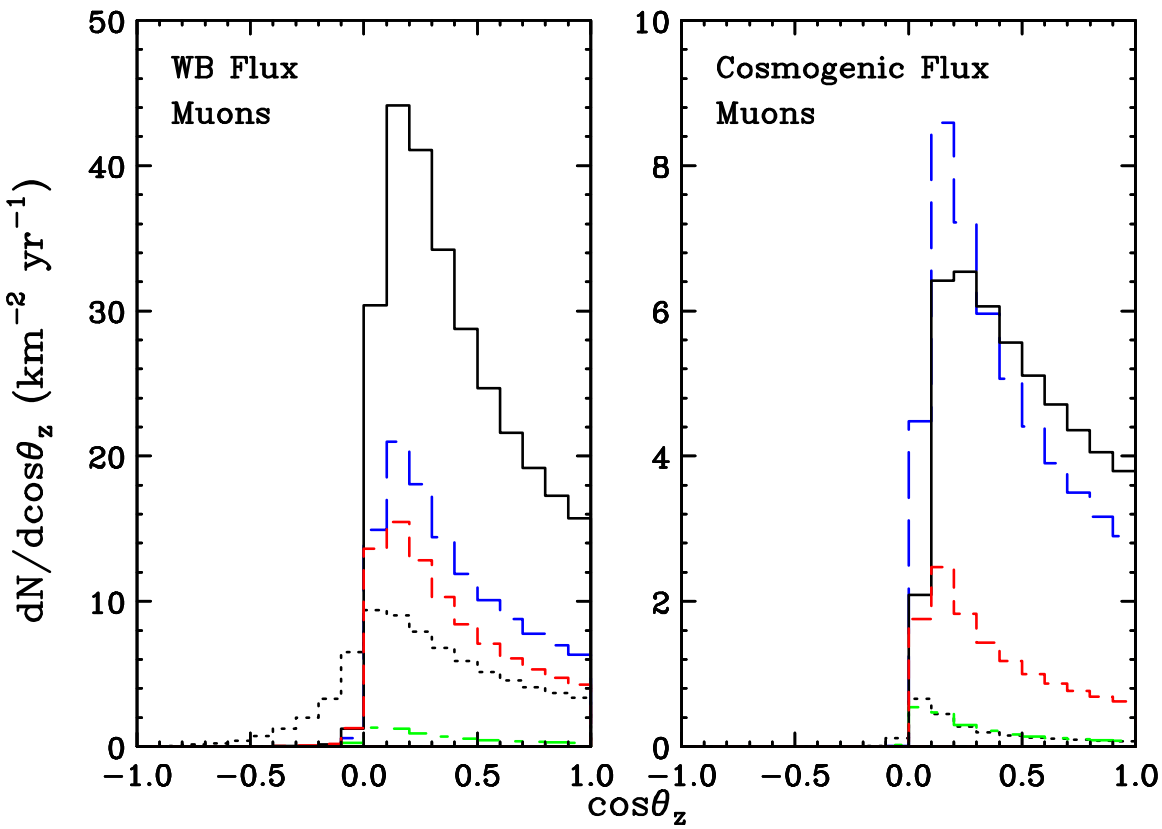
  -Fluxes Unknown $\rightarrow$ Rates Useless Alone

  -Earth Acts As A "Neutrino Filter" Above $\sim$100 TeV



Measuring ν Cross Sections

- Use Angular and Energy Distributions



Measuring ν Cross Sections

- Low-Scale Quantum Gravity

  -ADD $\rightarrow$ Up To 1-2 TeV with IceCube

  -Randall-Sundrum $\rightarrow$ Only Sensitive to ~ 500 GeV Resonances

  -Stringy Resonances Via Veneziano Amplitudes

  $\rightarrow$ Up To 1-2 TeV Via Gluon Interactions

- Black Hole Production

  -Current Cosmic Ray Data Excludes Below $\sim$1-1.5 TeV

  -AUGER Will Reach $\sim$2-4 TeV

  -IceCube Will Reach Sensitivity For $\sim$1-2 TeV

  -3 Channel Measurement

- Electroweak Instantons

  -Similar Techniques

  -Prospects Depend On Details of Cross Section Calculation

  (Ringwald, JHEP, hep-ph/0307034;

  Han and Hooper, PLB, hep-ph/0307120)

Particle Dark Matter

- Neutrinos From Sun

  WIMP Capture In Sun/Earth Via Elastic Scattering

  Annihilation In Sun/Earth Enhanced

  Observe Neutrinos Produced In Annihilations

- Dark Matter Candidates

  Supersymmetry $\rightarrow$ Neutralino Dark Matter

  Universal Extra Dimensions $\rightarrow$ Kaluza-Klein Dark Matter

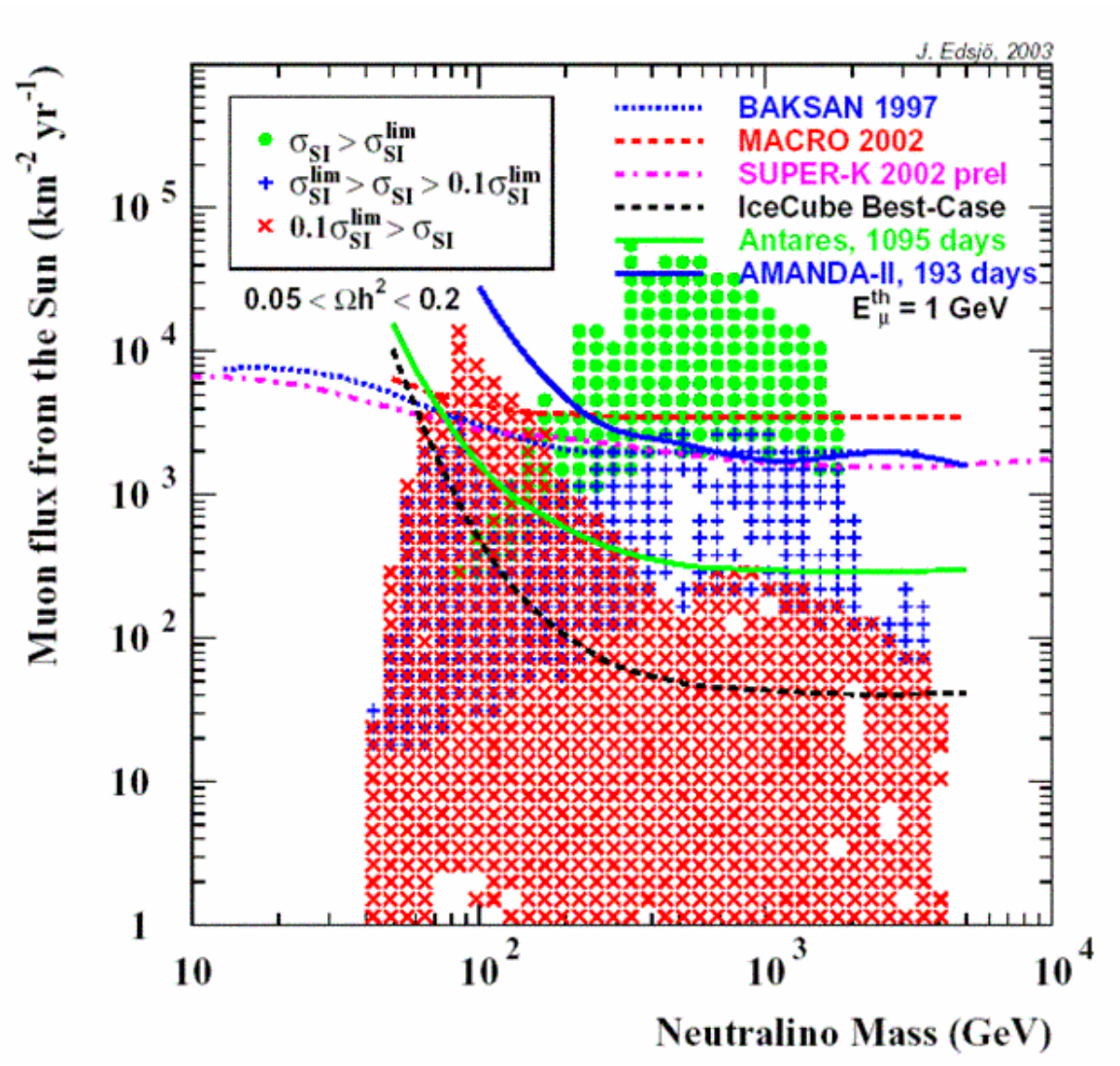
NEUTRALINO DARK MATTER

- Neutralino Properties

  -Gaugino-Like: Annihilation to $b\bar{b}$ or $t\bar{t}$ (85-100%)

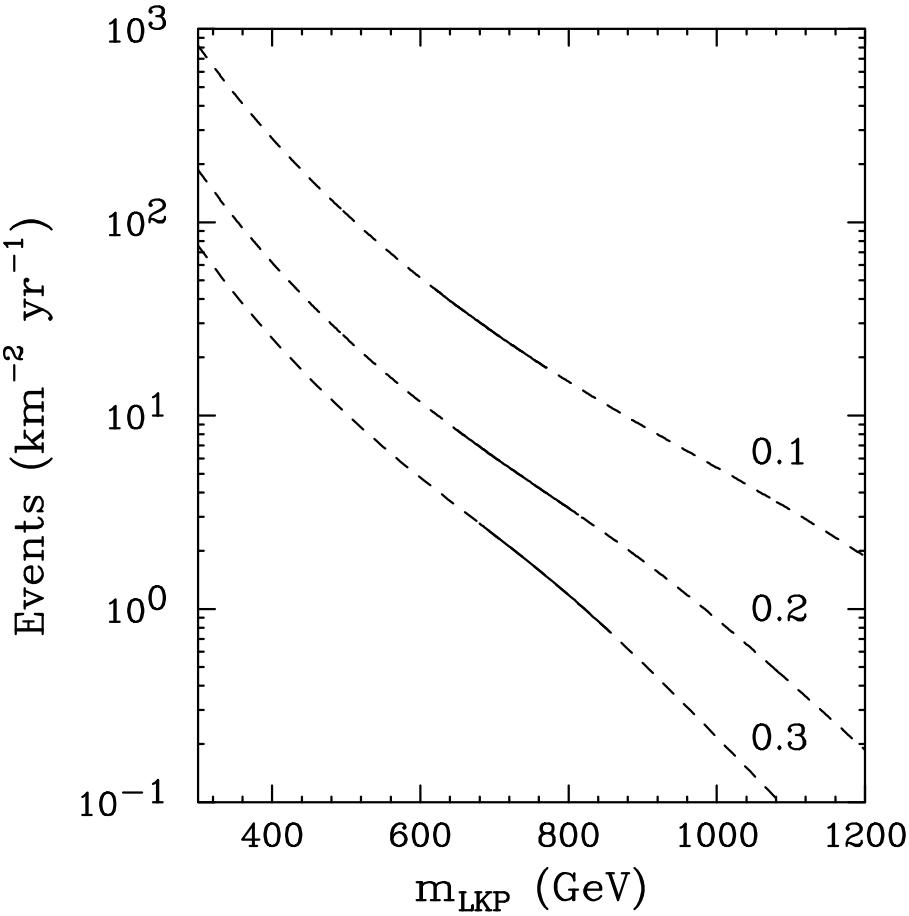
  -Higgsino-Like: Annihilation to ZZ, W^+W^-

  -No Direct Annihilation To Neutrinos



KALUZA-KLEIN DARK MATTER

- Universal Extra Dimensions
  - -All Particles Propagate In Bulk
  - -Kaluza-Klein (KK) Towers Appear
  - -KK Number Analogous to R-Parity $\rightarrow$ Lightest KK State Stable
- Lightest Kaluza-Klein Particle
  - -LKP Likely to be Excitation of B
  - -Annihilates to $\tau^+\tau^-$ (23%)
  - -Direct Annihilation to Neutrinos (4%)



D. Hooper, G. Kribs, PRD, hep-ph/0208261

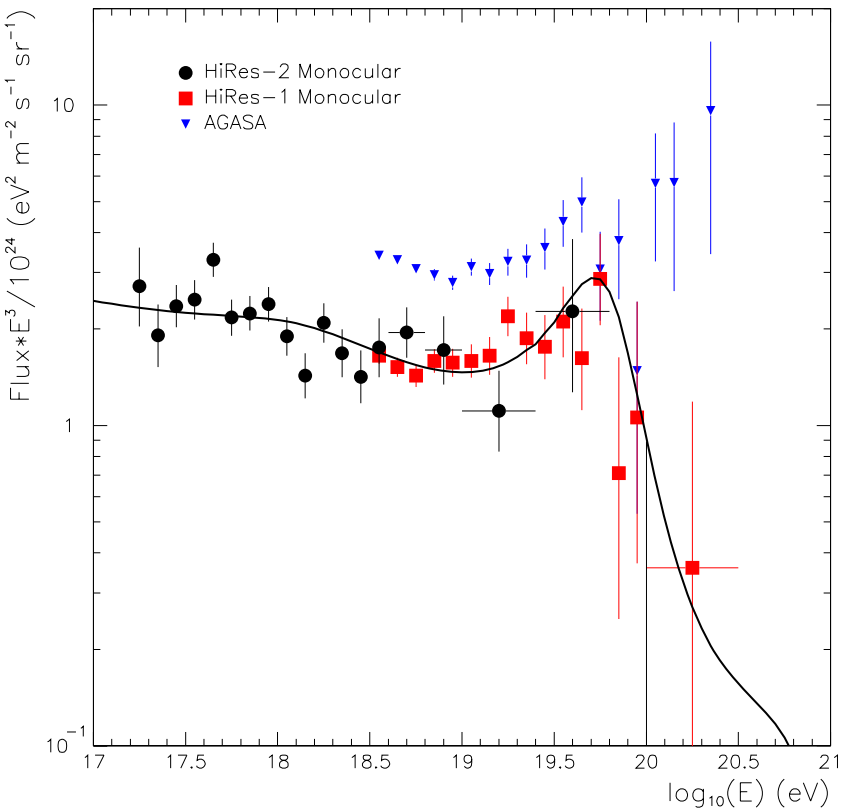
SUPERHEAVY DARK MATTER AND UHE COSMIC RAYS

- The UHE Cosmic Ray Problem

  Events Observed Beyond GZK Cutoff

  HiRes and AGASA in Disagreement?!

  Sources of High-Energy Cosmic-Rays Remain Unknown



Superheavy Dark Matter and UHE Cosmic Rays

- Possible Solutions

  -Astrophysical Sources Within 10-50 Mpc Discovered

  -Lorentz Violation

  -Exotic Particles (Strongly Interacting Neutrinos, etc.)

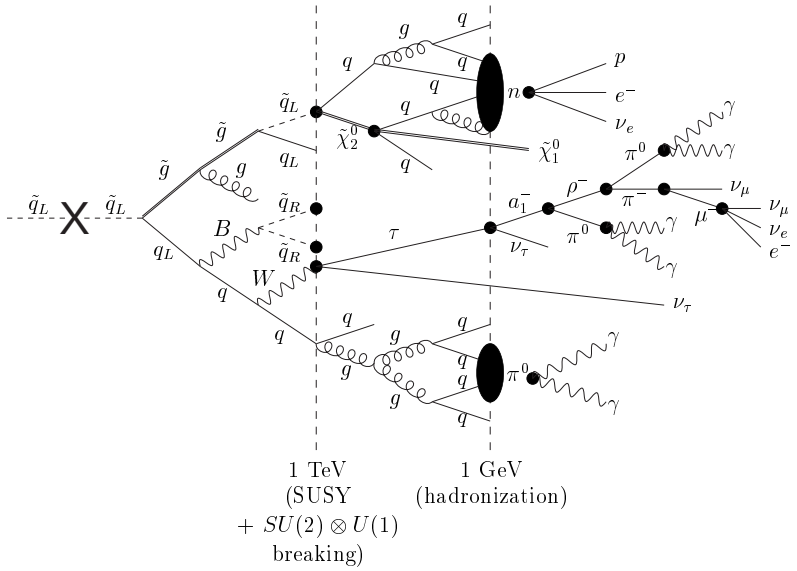
  -Decaying/Annihilating GUT-Scale Relics

- Top-Down Cosmic Ray Sources

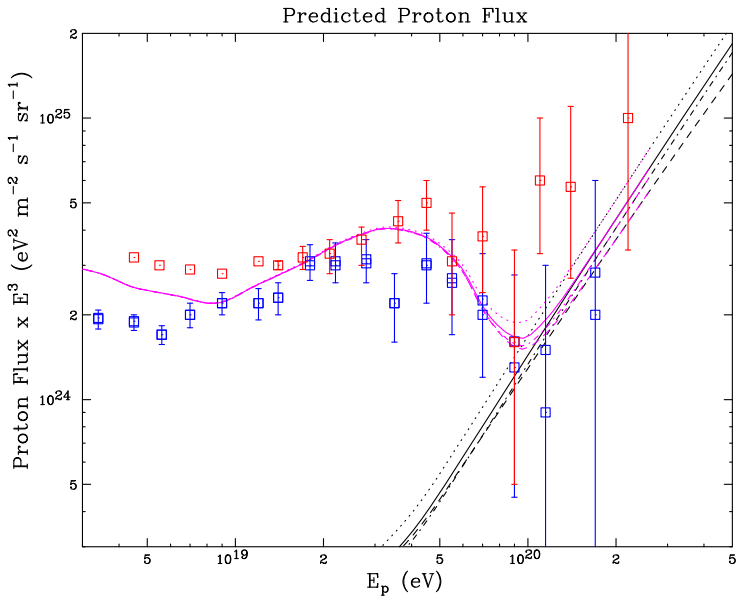
  -Particles or Topological Defects of $\sim 10^{12} - 10^{16}\,\mathrm{GeV}$ mass

  -Decay/Annihilation Channels Unknown

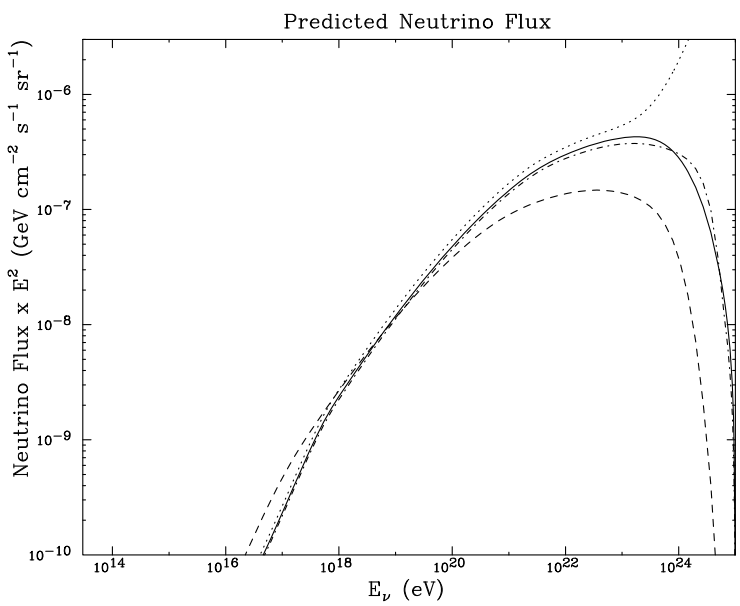
C. Barbot and M. Drees, Astro. Part. Phys., hep-ph/0211406


1 TeV
(SUSY
+ $SU(2) \otimes U(1)$
breaking)
1 GeV
(hadronization)

Decaying GUT-Scale Relic



UHE Neutrino Spectrum



Neutrino Rates

AMANDA: 0.05-10/yr, AUGER: 0.5-35/yr,
$\rightarrow$ IceCube: 1-200/yr

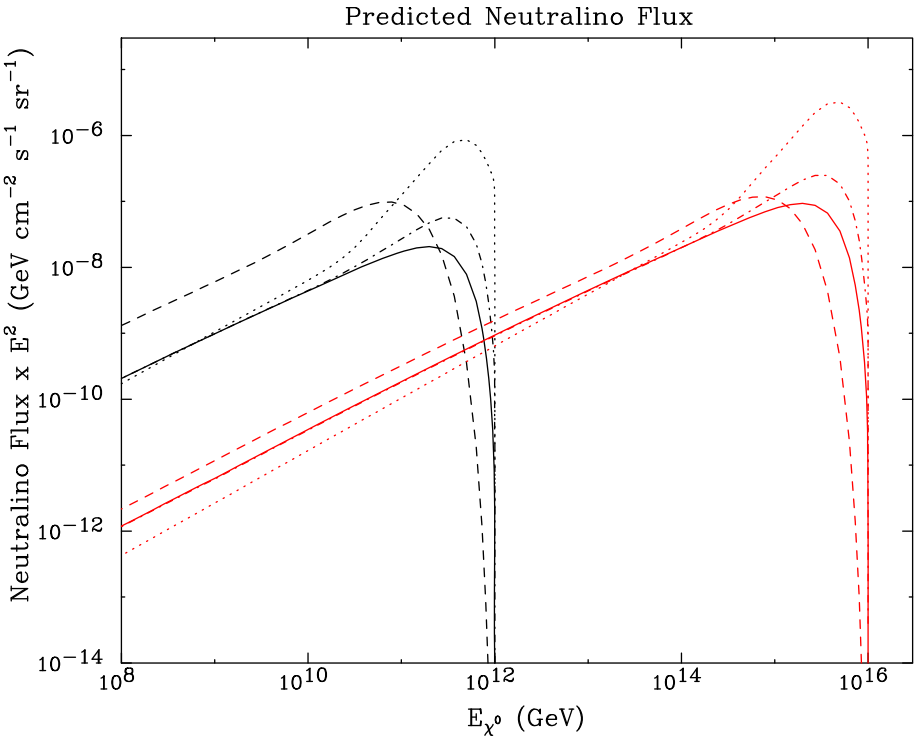
C. Barbot, M. Drees, F. Halzen, D. Hooper, PLB, hep-ph/0205230

SUPERHEAVY DARK MATTER AND UHE COSMIC RAYS

- SUSY In The Sky

  GUT-Scale Fragmentation Includes Stable Neutralinos

  UHE Supersymmetric Particles Smoking Gun For Top-Down Models



C. Barbot, M. Drees, F. Halzen and D. Hooper, PLB, hep-ph/0207133

Superheavy Dark Matter and UHE Cosmic Rays

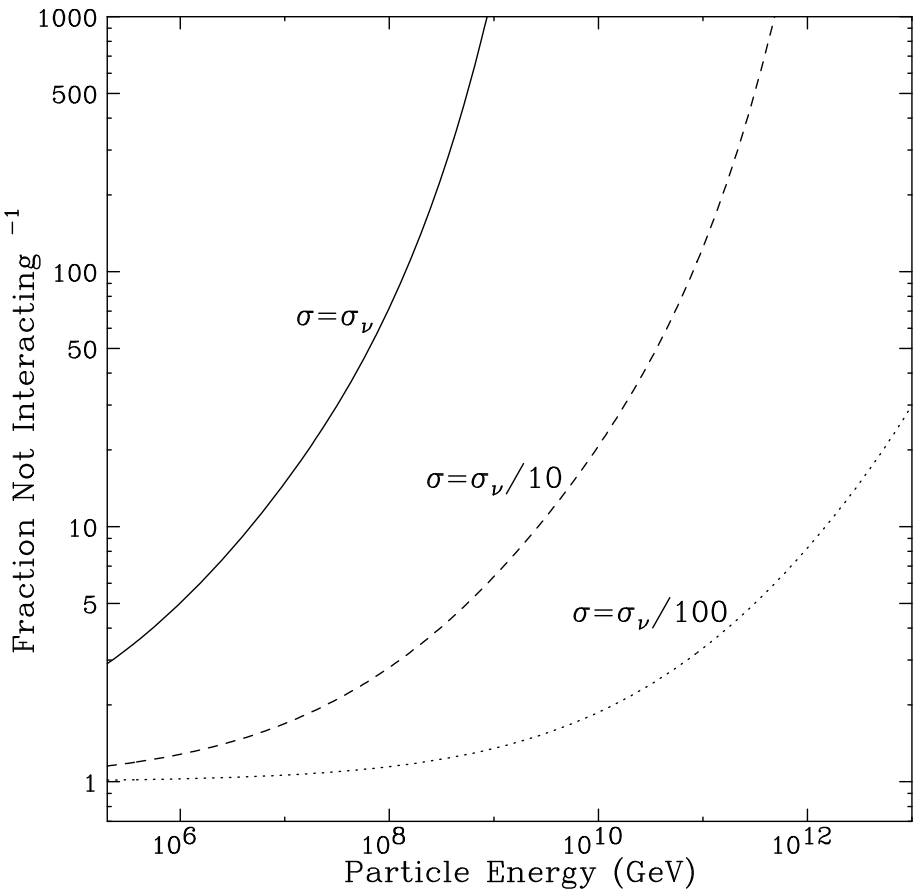
- Detecting UHE Neutralinos

  Cascade Signatures Similar To Neutrinos

  Neutralinos Typically Have Smaller Cross Sections

  $\rightarrow$ Use Earth As A Filter

  Potentially Observable With EUSO/OWL



C. Barbot, M. Drees, F. Halzen and D. Hooper, PLB, hep-ph/0207133

Neutrino Properties

- Neutrino Lifetimes
- Absolute Neutrino Masses
- Neutrino Mixing Parameters

NEUTRINO DECAY?

- Cosmic Neutrino Flavors

  At Source $\rightarrow \phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} \simeq 1 : 2 : 0$

  After Oscillations $\rightarrow \phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} \simeq 1 : 1 : 1$

- Decay Modifies Flavor Ratios

  $\nu_i \rightarrow \nu_j + X$ or $\nu_i \rightarrow \bar{\nu_j} + X$

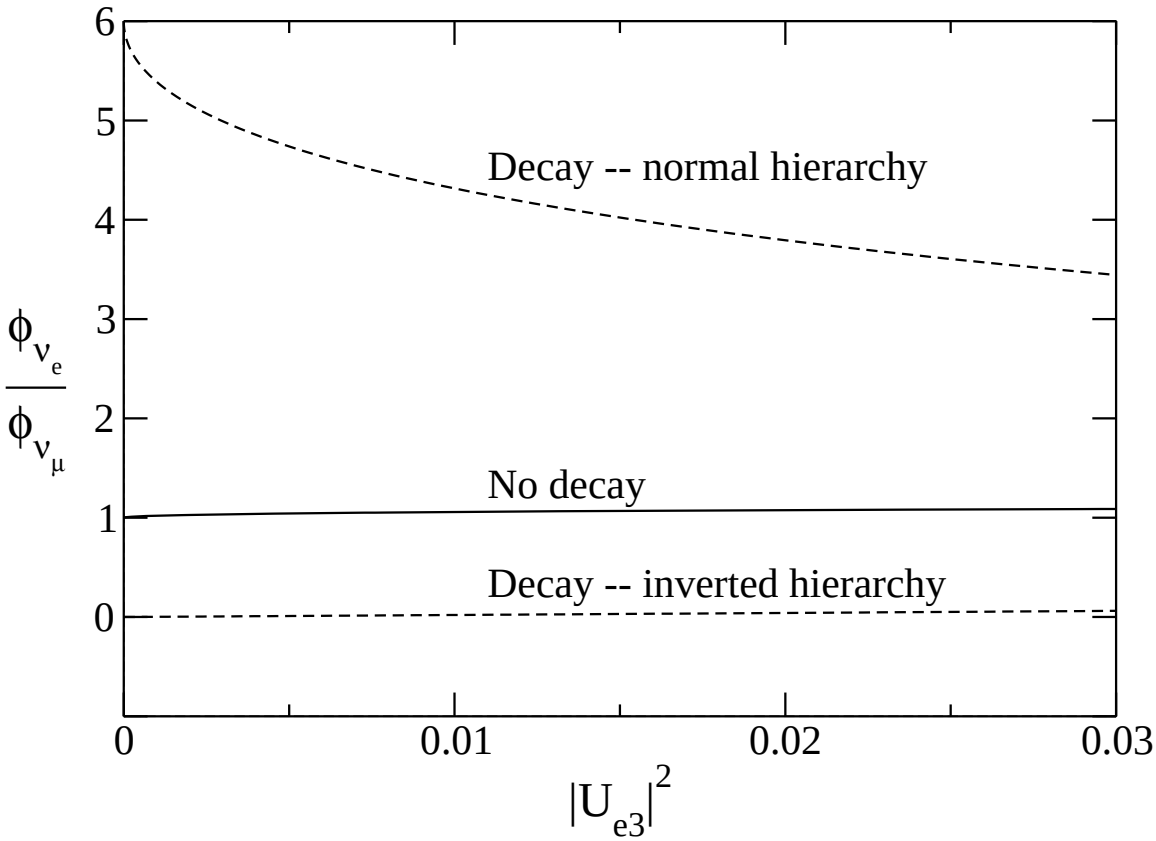
Table 1: Flavor ratios for various decay scenarios.

Unstable	Daughters	Branchings	$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	$6 : 1 : 1$
ν_3	sterile	irrelevant	$2 : 1 : 1$
ν_3	full energy	$B_{3\rightarrow 2} = 1$	$1.4 : 1 : 1$
	degraded ($\alpha = 2$)		$1.6 : 1 : 1$
ν_3	full energy	$B_{3\rightarrow 1} = 1$	$2.8 : 1 : 1$
	degraded ($\alpha = 2$)		$2.4 : 1 : 1$
ν_3	anything	$B_{3\rightarrow 1} = 0.5$	$2 : 1 : 1$
		$B_{3\rightarrow 2} = 0.5$	

J. Beacom, N. Bell, D. Hooper, S. Pakvasa, T. Weiler, PRL, hep-ph/0211305

NEUTRINO DECAY?

- Effect of Neutrino Mixing Parameters



J. Beacom, N. Bell, D. Hooper, S. Pakvasa, T. Weiler, PRL, hep-ph/0211305

Measuring Neutrino Flavor Ratios

- Experimental Observables

  -Muon Tracks

  -Showers (Hadronic+Electromagnetic)

  -Tau-Unique Events (Double Bang+Lollipop Events)

- Reconstruct Flavor Ratios

  $\nu_\mu - \nu_\tau$ Symmetry

  Muons/Showers$\rightarrow \phi_{\nu_\mu}/\phi_{\nu_e}$

  Tau-Unique Events Used As Confirmation

- Sensitivity to Decay

  IceCube $\sim 10^7$ Times More Sensitive Than Solar Experiments!

  $\rightarrow \tau_\nu/m_\nu \gtrsim 10^3 \ \mathrm{sec/eV}$

J. Beacom, N. Bell, D. Hooper, S. Pakvasa, T. Weiler, PRL, hep-ph/0307025

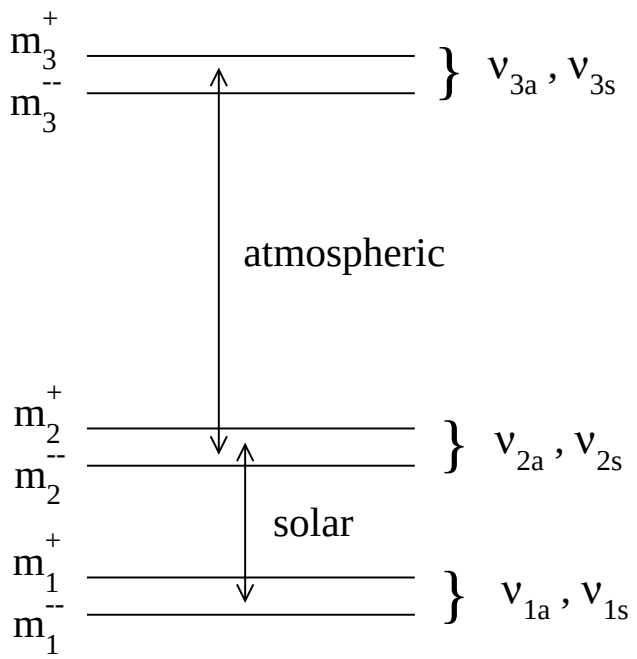
NEUTRINO MIXING

- Psueo-Dirac States

  -Standard Neutrino Oscillations for $\delta m^2 \lesssim 10^{-12}\,\mathrm{eV}^2$

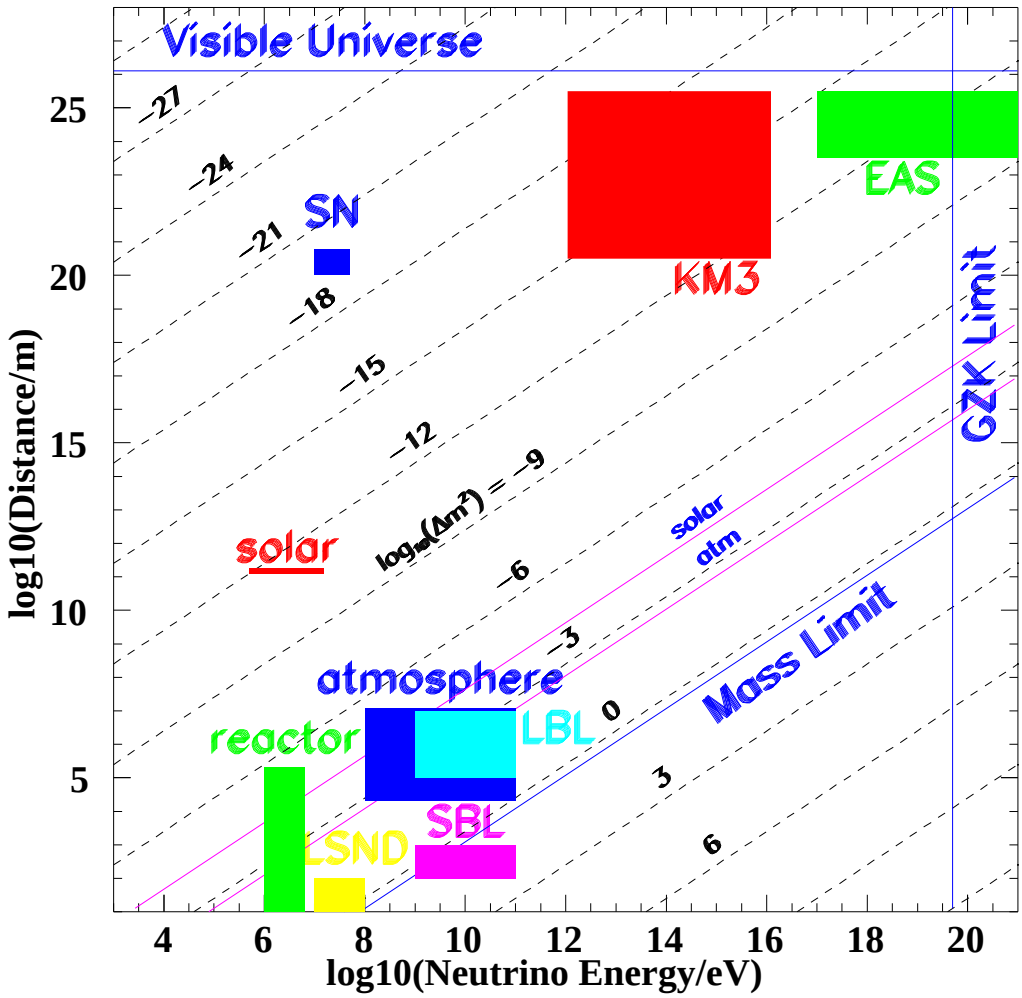
  -Neutrinoless Double Beta Decay Highly Suppressed

  -New Oscillation Phenomenology Over 100 Mpc Baselines



J. Beacom, N. Bell, D. Hooper, J. Learned, S. Pakvasa, T. Weiler, PRL, hep-ph/0307151

Sensitivity to Psuedo-Dirac Masses



Performance

Reach To $\sim 10^{-20}$ eV^2 Mass Splittings
Far Beyond Conventional Experiments

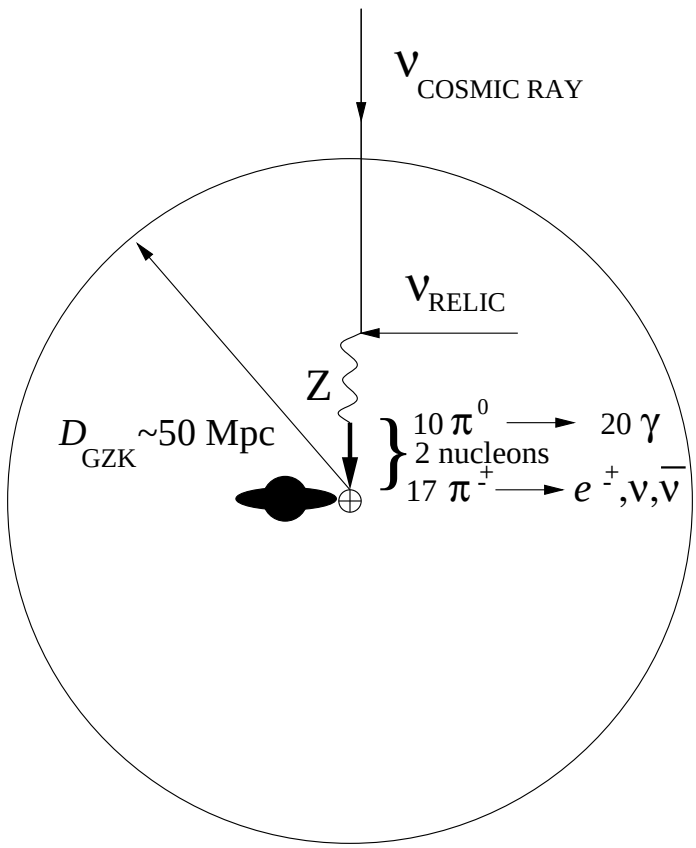
Absolute Neutrino Masses

- Z-Burst (Weiler) Mechanism

  $\nu_{\mathrm{UHE}} + \nu_{\mathrm{BG}} \rightarrow Z$ (at Resonance)

  For eV Neutrino Masses, $E_\nu \sim 10^{21}\,\mathrm{eV}$

  Proposed as Solution to the UHECR Problem



The Future: Ultra-High Energy Neutrino Spectroscopy???

T. Weiler, A. Ringwald, *et al.*, in preparation

Conclusions

- Next Generation Experiments
  - -AMANDA, RICE Have Seen First Light
  - -IceCube, ANTARES, AUGER, ANITA, etc. Soon To Follow
  - -Rapid Progress Being Made Experimentally
- Particle Physics Laboratory
  - -Neutrino Cross Section Measurements
  - -Neutrino Properties: Decays, Absolute Masses, Mixings
  - -Particle Dark Matter Searches
  - -Probe GUT Scale (Top Down Cosmic Ray Models)
- Complementary To Colliders
  - -Take Advantage of Natural Particle Accelerators
  - -Collider Energies Limited