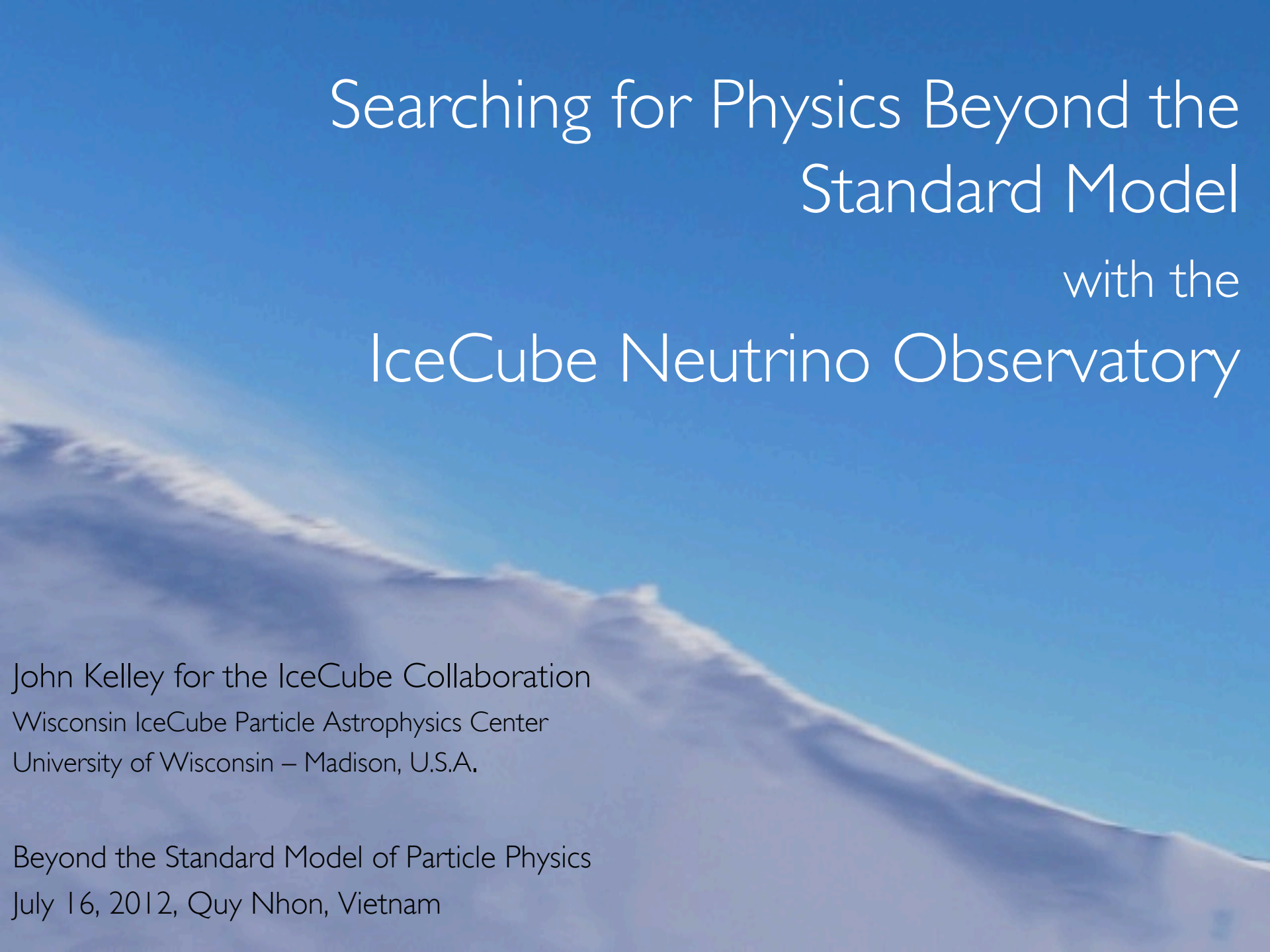
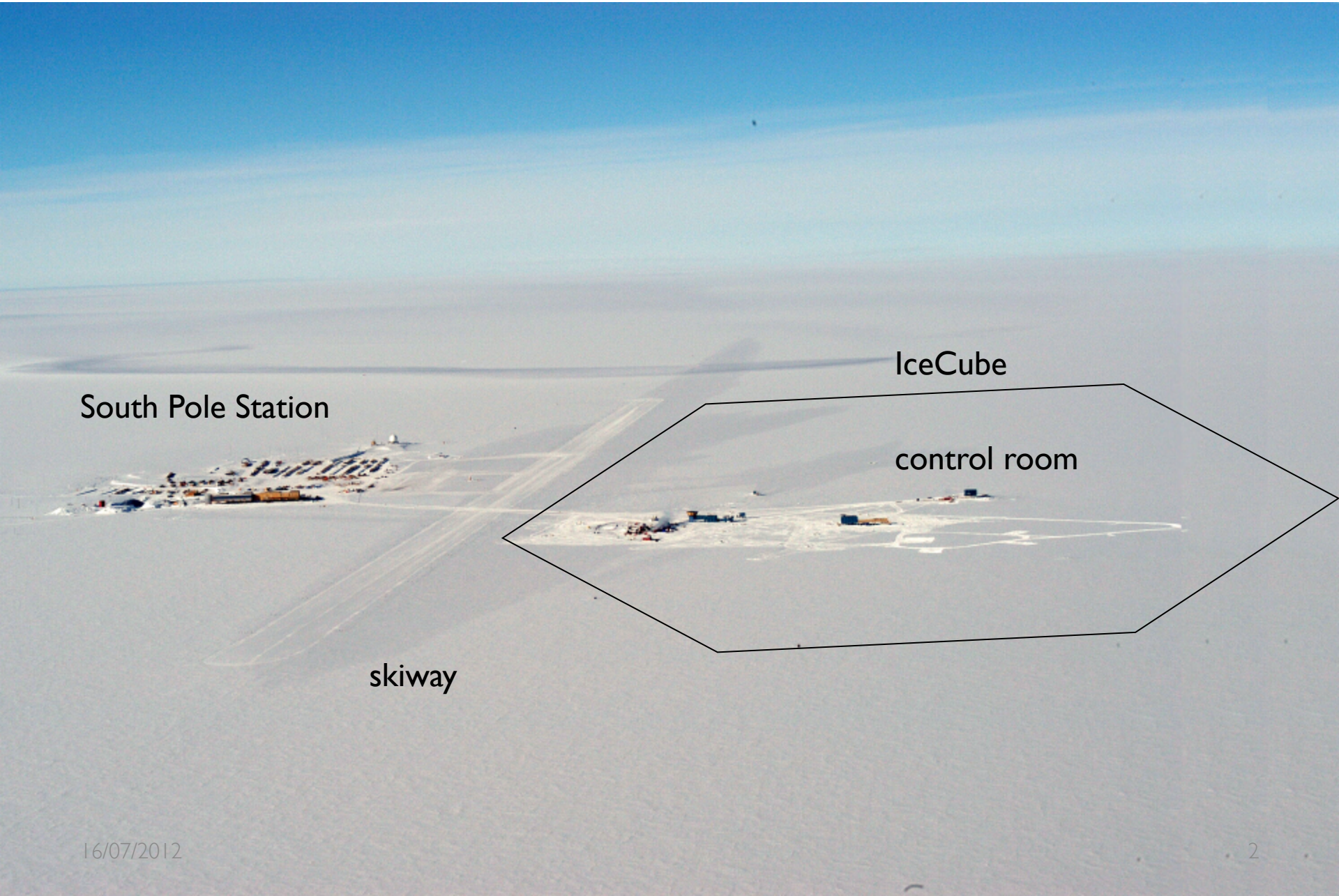


Searching for Physics Beyond the Standard Model with the IceCube Neutrino Observatory

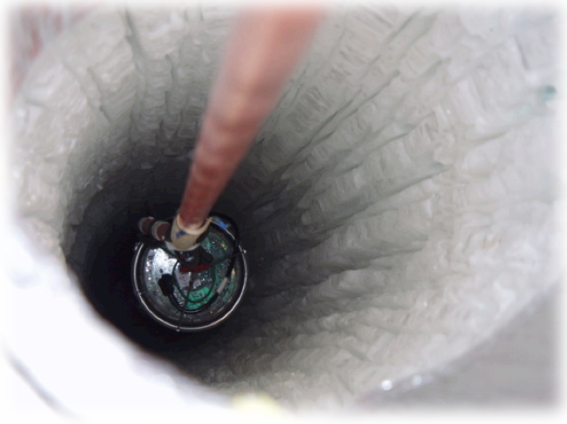
John Kelley for the IceCube Collaboration
Wisconsin IceCube Particle Astrophysics Center
University of Wisconsin – Madison, U.S.A.

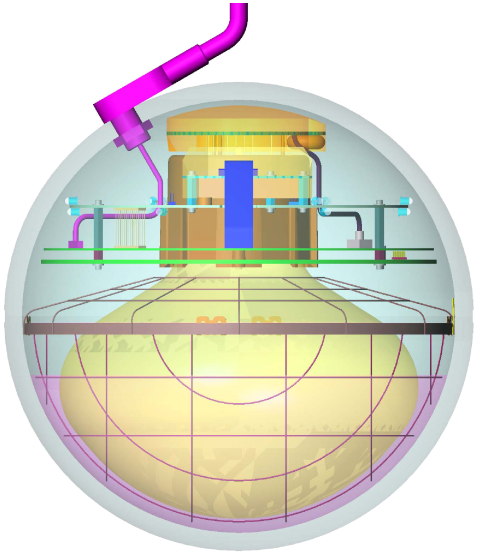
Beyond the Standard Model of Particle Physics
July 16, 2012, Quy Nhon, Vietnam

IceCube from the Air

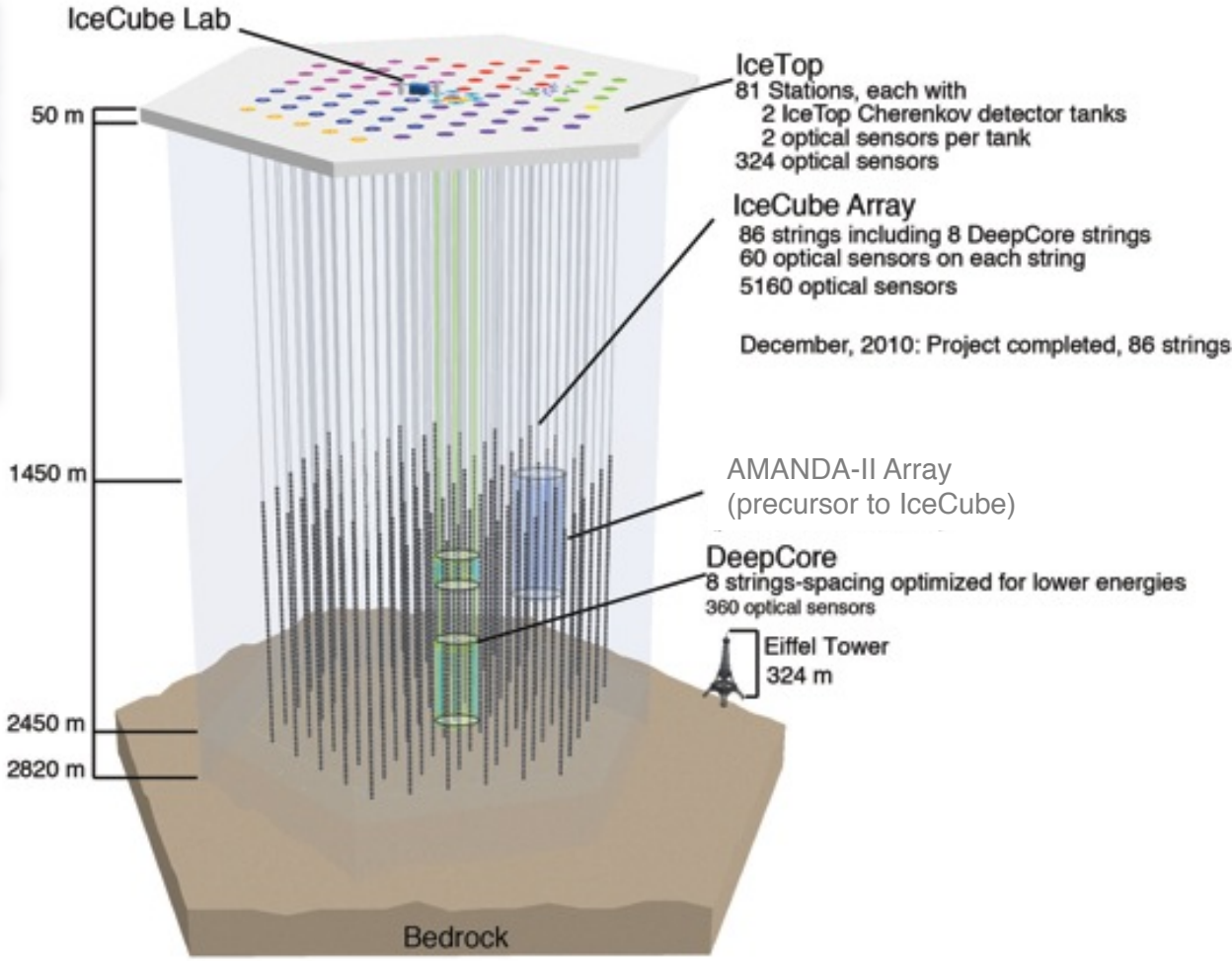


The IceCube Detector



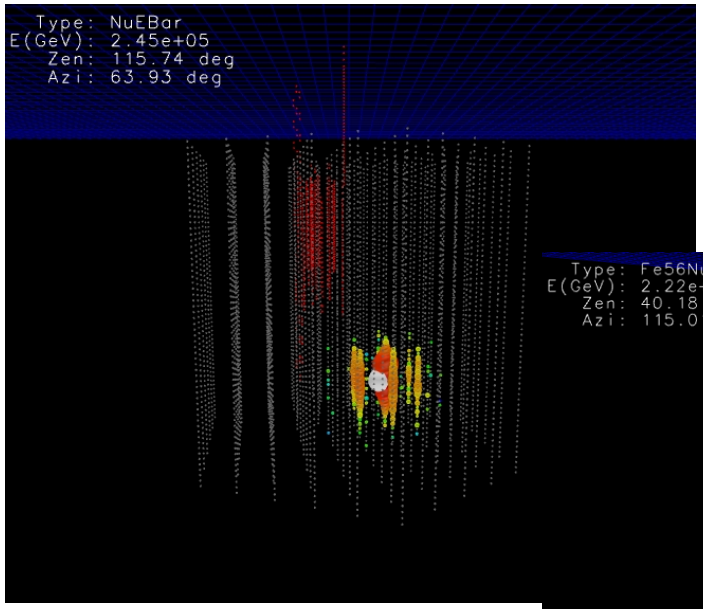


digital optical module (DOM)

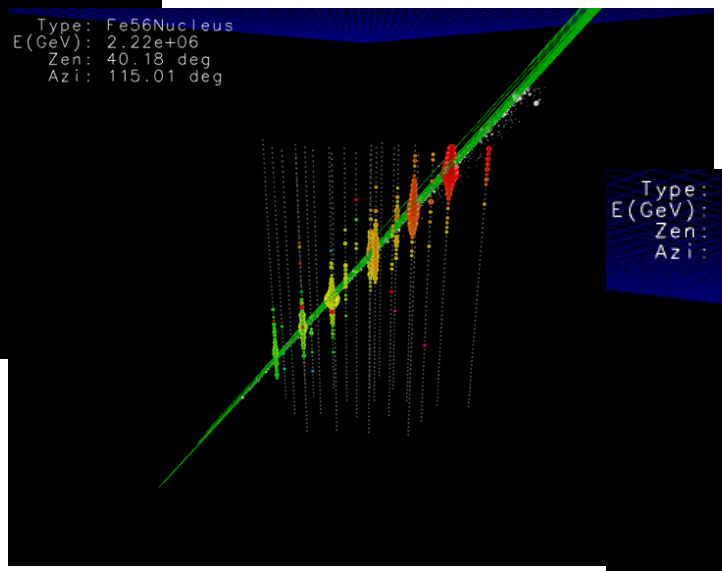


Event Signatures

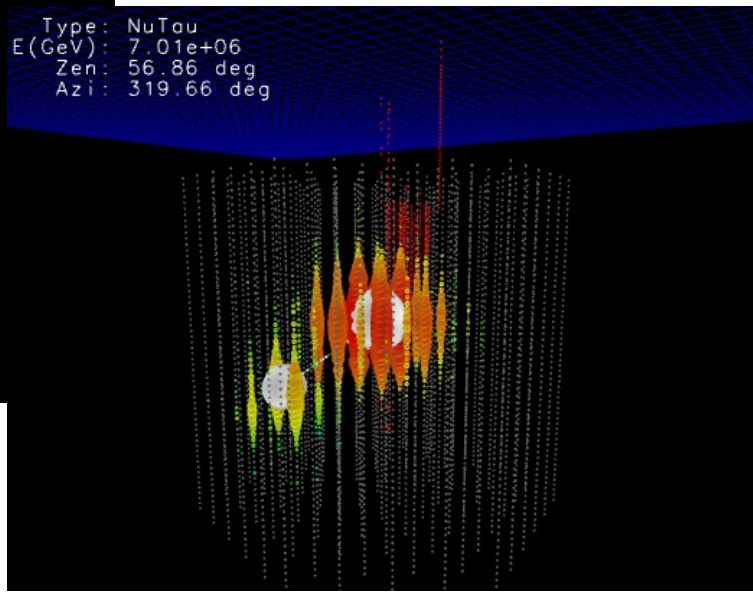
Positions, times, and amplitudes of Cherenkov light deposition: neutrino direction + energy



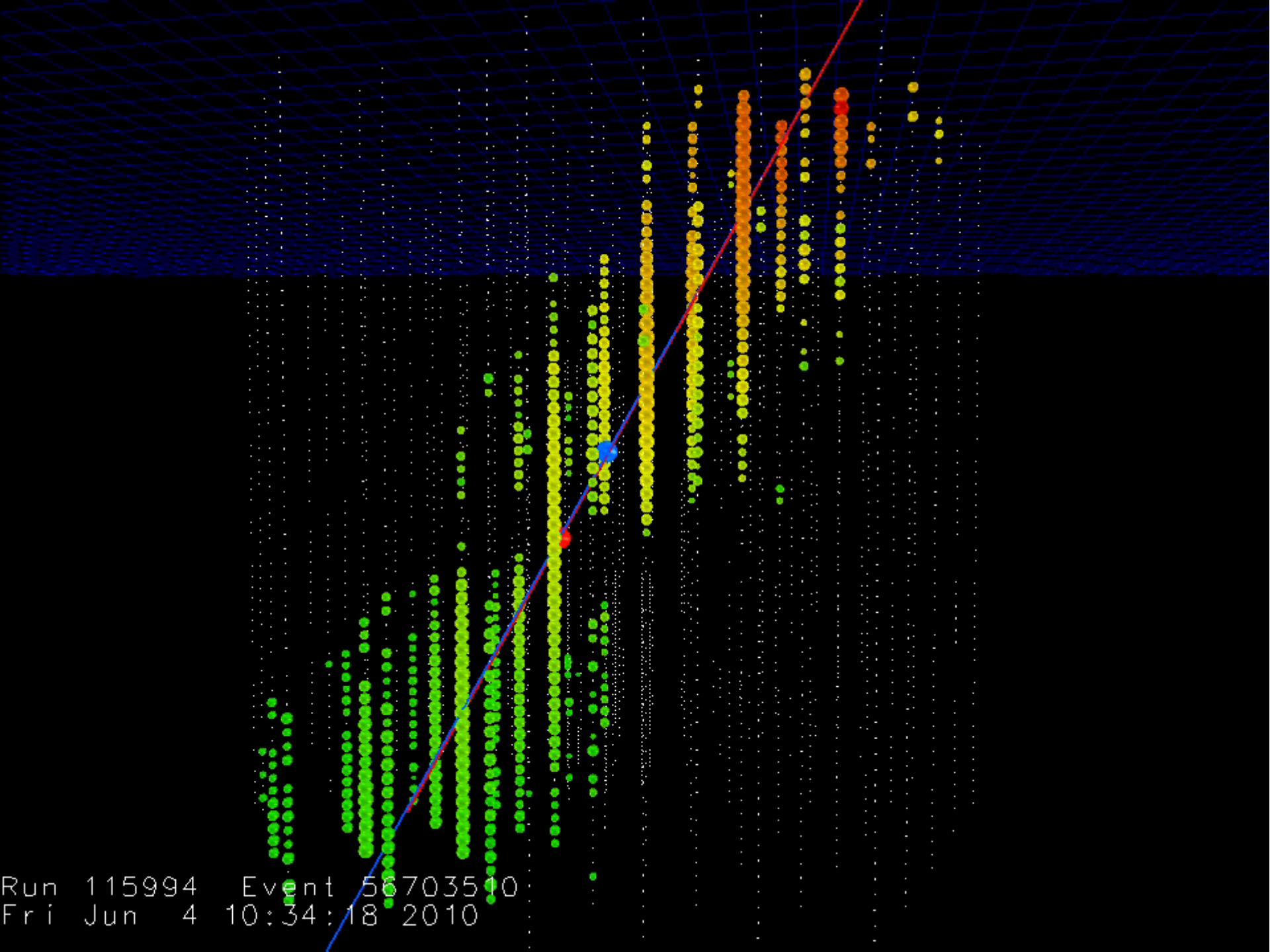
ν_e CC + all flavor NC



ν_μ CC (+CR muons!)

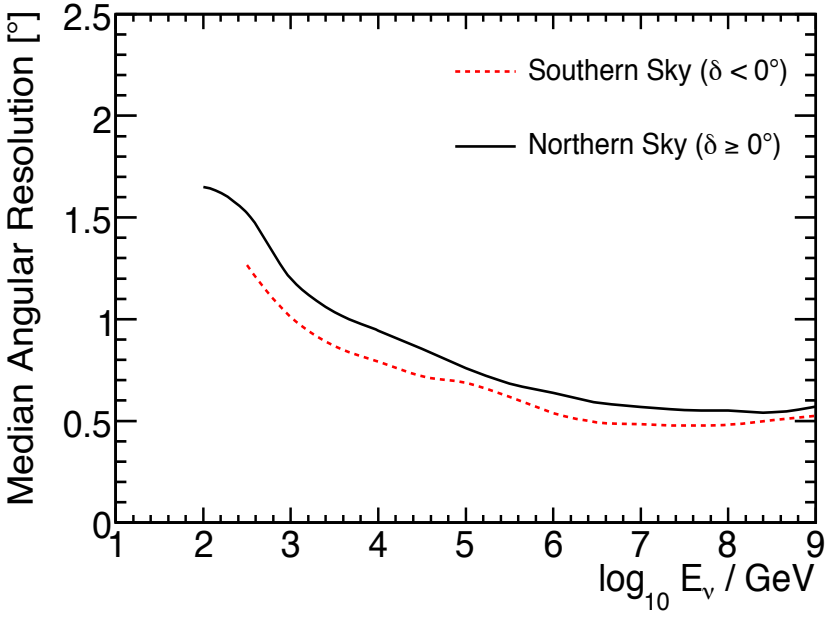


ν_τ CC ("double-bang")


Run 115994 Event 56703510
Fri Jun 4 10:34:18 2010

Detector Performance

Simulated tracks

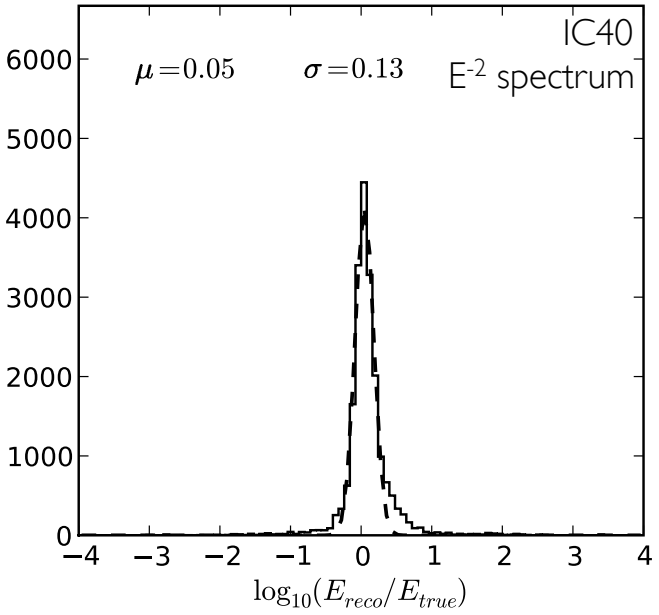


angular resolution: ~1°

(verified with CR Moon shadow)

μ energy estimation via dE/dx

Simulated cascades



energy resolution: ~35%

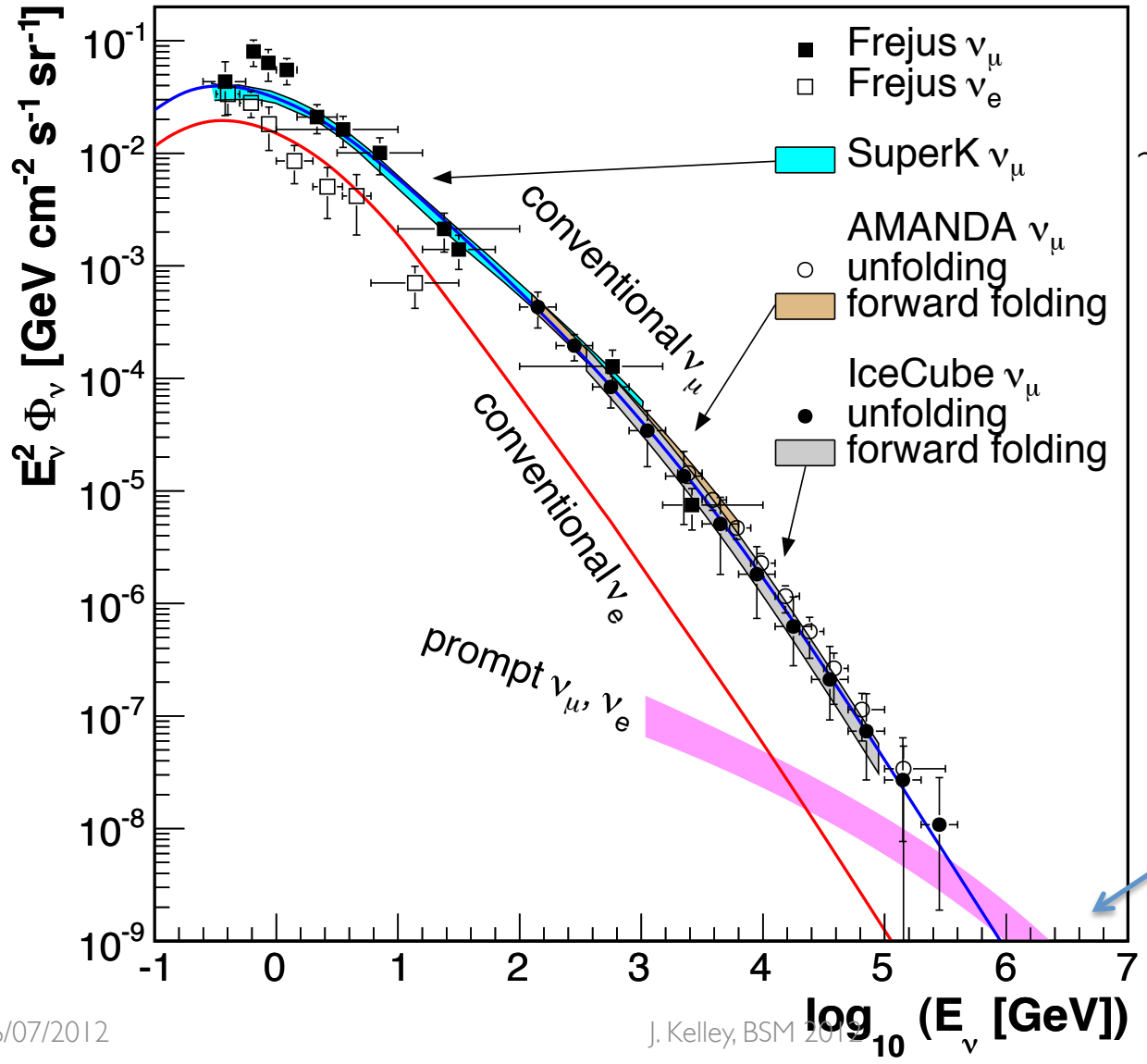
angular resolution: ~30°

Continual time synchronization to ~2 ns; ice calibration with in-situ flashers

Searches for New Physics with IceCube

- Need a neutrino source!
- Atmospheric neutrinos (CR+Earth's atmosphere)
  - violation of Lorentz invariance?
  - eV-scale sterile neutrinos?
- Neutrinos from dark matter annihilation
  - WIMP signal from the Sun, Earth, or Galactic Center?
- Neutrinos from cosmic ray accelerators or CR+CMB
  - may eventually be useful for new physics searches, but...
  - first step is detection!

Atmospheric Neutrino Spectra



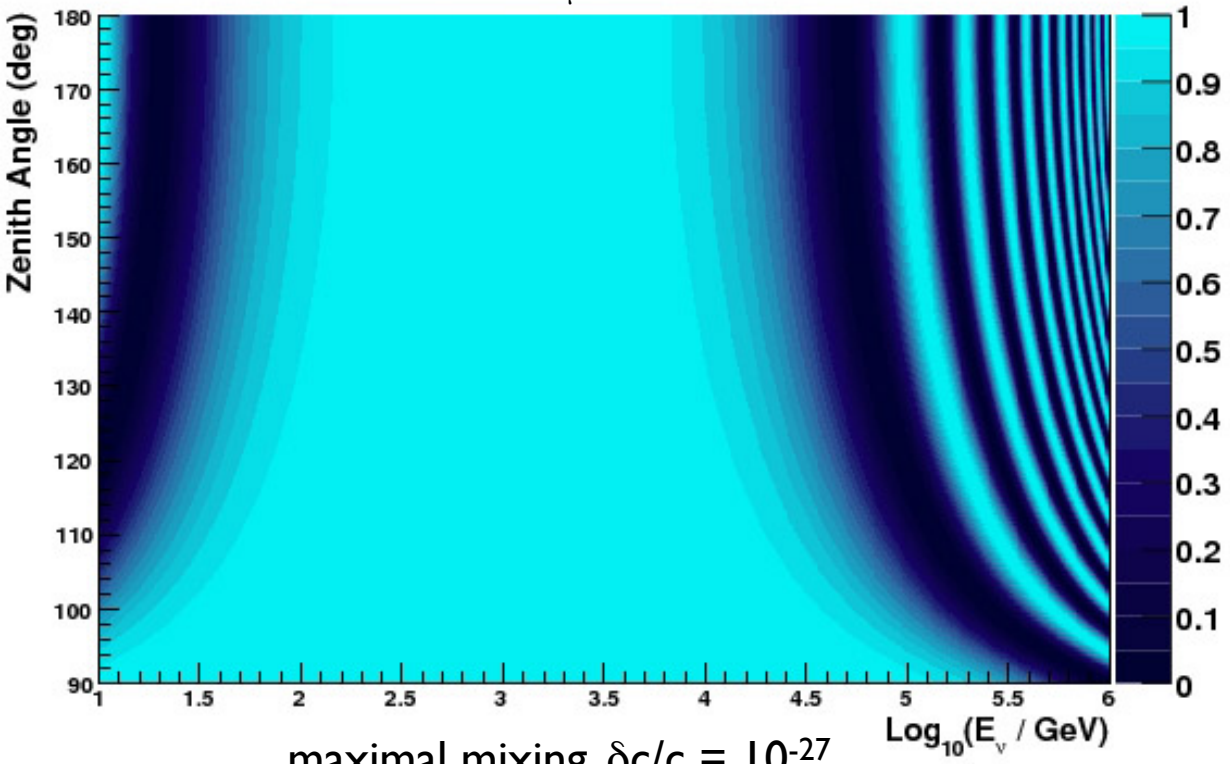
~200 atm. neutrinos / day in IceCube

neutrino point sources?
diffuse HE flux?
cosmogenic neutrinos?

Violation of Lorentz Invariance (VLI)

Different limiting velocity eigenstates: VLI oscilations* $E_a^2 = \vec{p}_a^2 c_a^2 + m_a^2 c_a^4.$

VLI atmospheric ν_μ survival probability

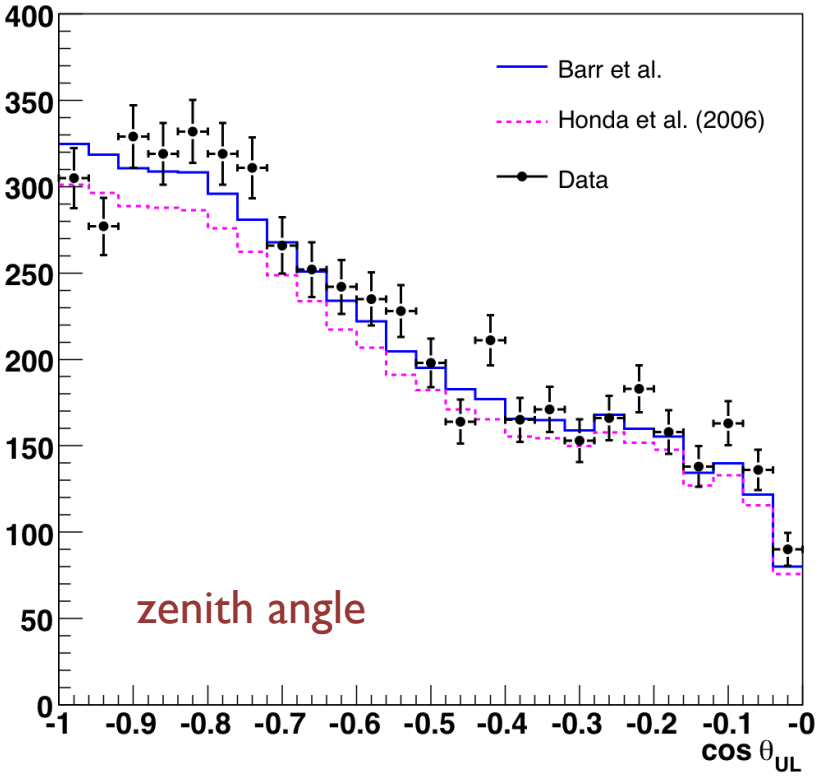


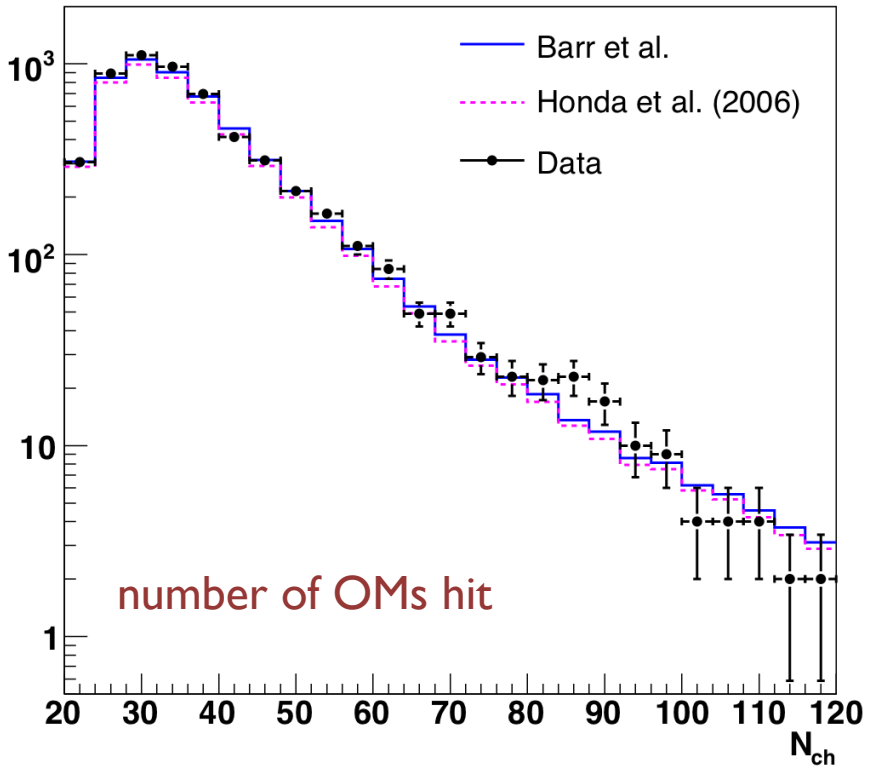
maximal mixing, $\delta c/c = 10^{-27}$

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

AMANDA 2000-2006 VLI limits

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





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

$\delta c/c < 2.8 \times 10^{-27}$ (90%CL) — IceCube will improve by an order of magnitude

Direction-dependent VLI Oscillations

Standard Model Extension includes interaction coefficients that violate rotational invariance

"Vector Model":

energy-independent directional VLI, a_L

\+ energy-dependent directional VLI, c_L

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2\left(L\left[\left(A_s\right)_{\mu\tau}\sin\left(RA+\phi_0\right)+\left(A_c\right)_{\mu\tau}\cos\left(RA+\phi_0\right)\right]\right.,$$

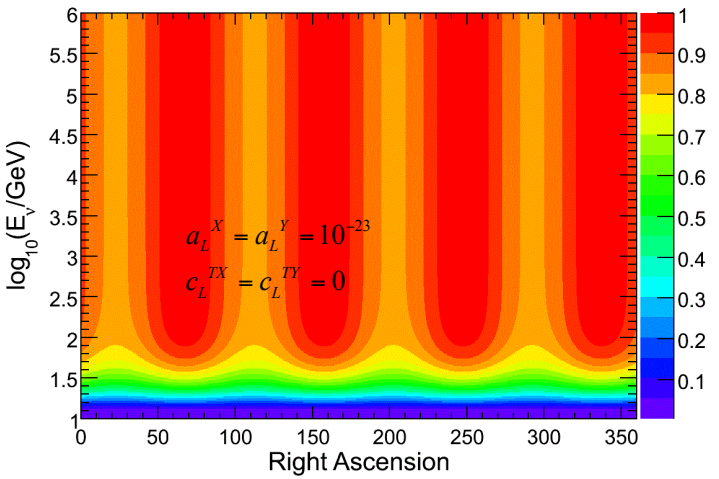
$$A_s^{\mu\tau} = \hat{N}^Y\left(a_L{}^X - 2Ec_L{}^{TX}\right) - \hat{N}^X\left(a_L{}^Y - 2Ec_L{}^{TY}\right)$$

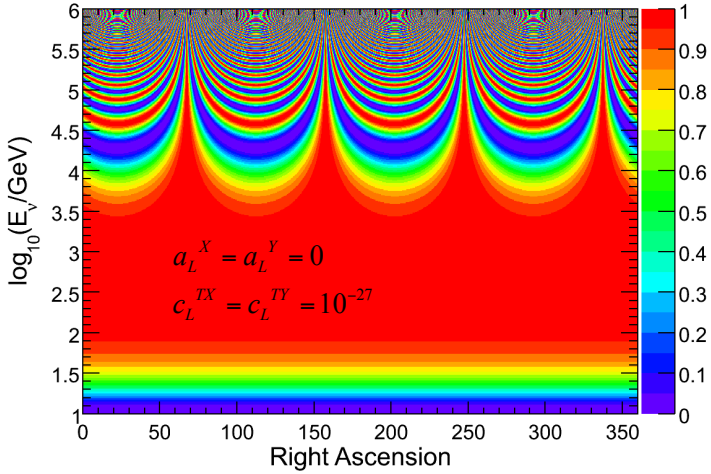
$$A_c^{\mu\tau} = -\hat{N}^X\left(a_L{}^X - 2Ec_L{}^{TX}\right) - \hat{N}^Y\left(a_L{}^Y - 2Ec_L{}^{TY}\right)$$

$\hat{N}^{X,Y}$ are unit vectors for the neutrino's direction, and depend on RA

Kostelecky and Mewes, PRD **70**, 076002

Survival probability





IceCube Direction-dependent VLI limits

- Right ascension distribution consistent with atmospheric neutrino expectation
- Set upper limits on VLI coefficients based on power in Fourier modes

$$a_L{}^X, a_L{}^Y < 1.8\times10^{-23}\ \text{GeV}$$
$$c_L{}^{TX}, c_L{}^{TY} < 3.7\times10^{-27}\ \ (3.3 + 0.4\ \text{syst.})$$

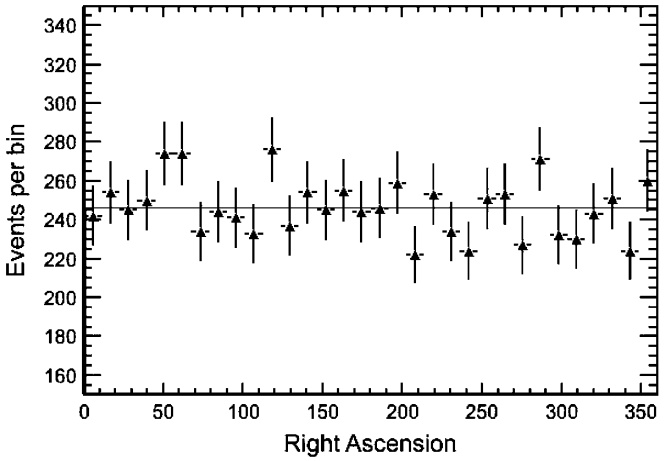
- For energy-dependent effects: results 3-4 orders of magnitude improved over MINOS

MINOS: $a < 3\times10^{-20}$ and $c < 9\times10^{-23}$

Adamson, et. al, Phys. Rev. Lett.101, 151601 (2008)

IC40 atmospheric muon neutrino RA

Phys. Rev. D 82, 112003 (2010)



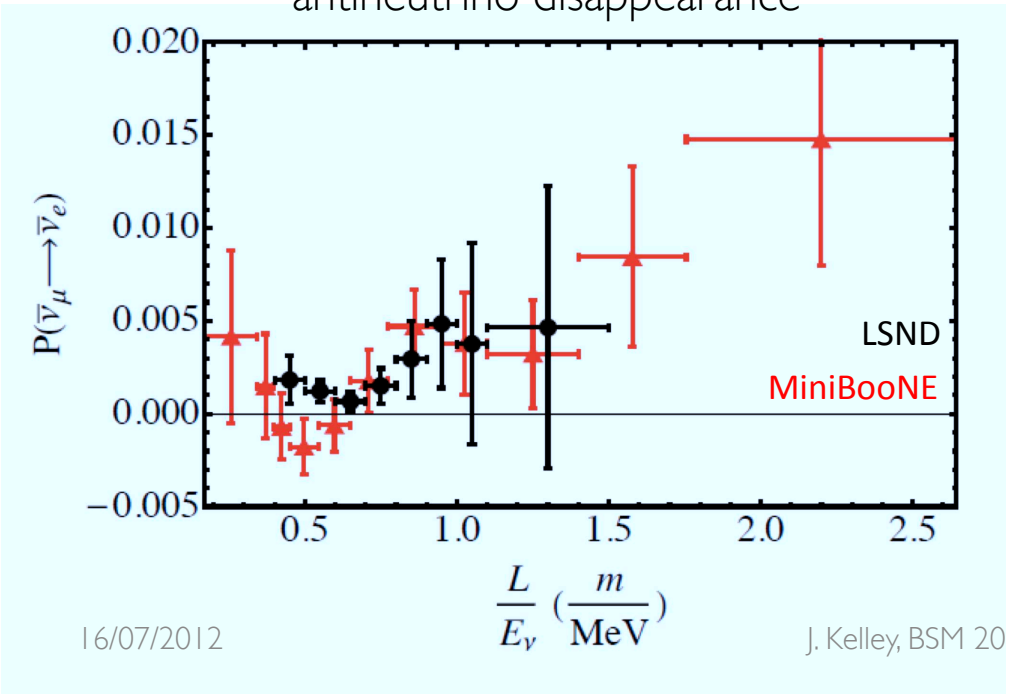
32 bins in RA (using zenith 97 to 120 degrees)

Sterile Neutrinos

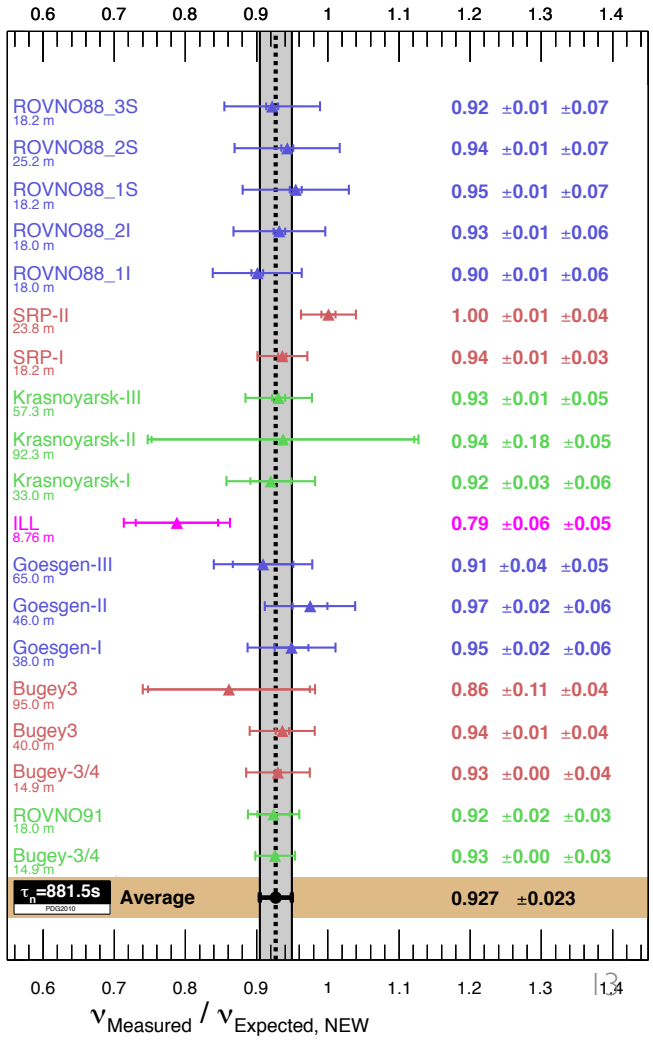
- No direct weak interactions
- Can mix with 3 active states
- Recent hints of an eV-scale sterile neutrino

review: Abazajian *et al.*, arXiv1204.5379

LSND and MiniBooNE antineutrino disappearance

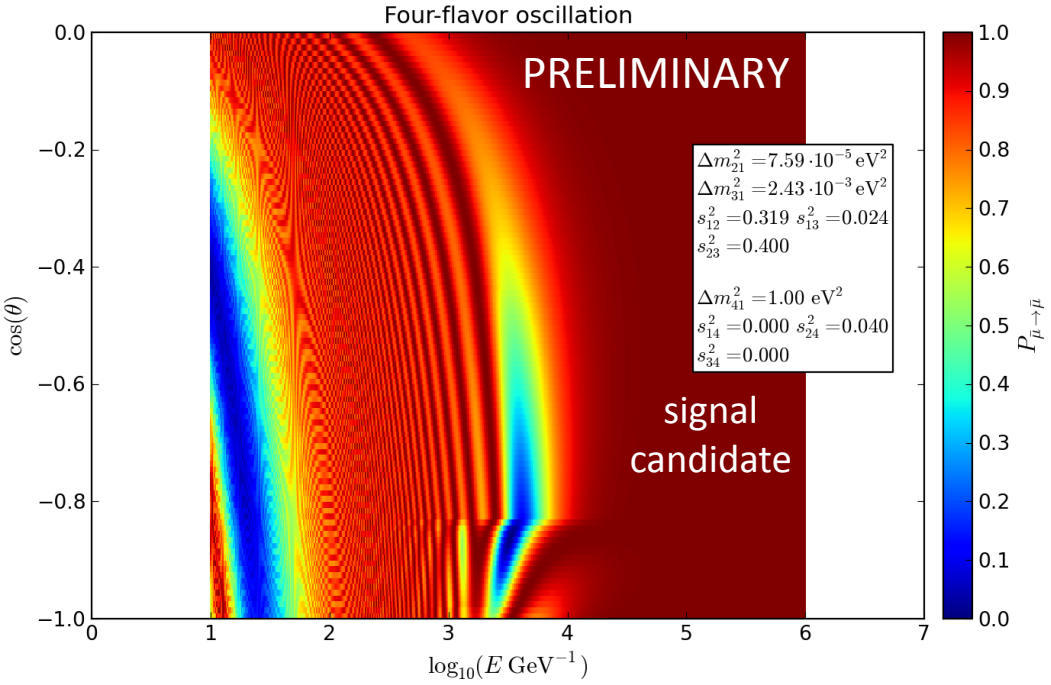


Reactor antineutrino anomaly



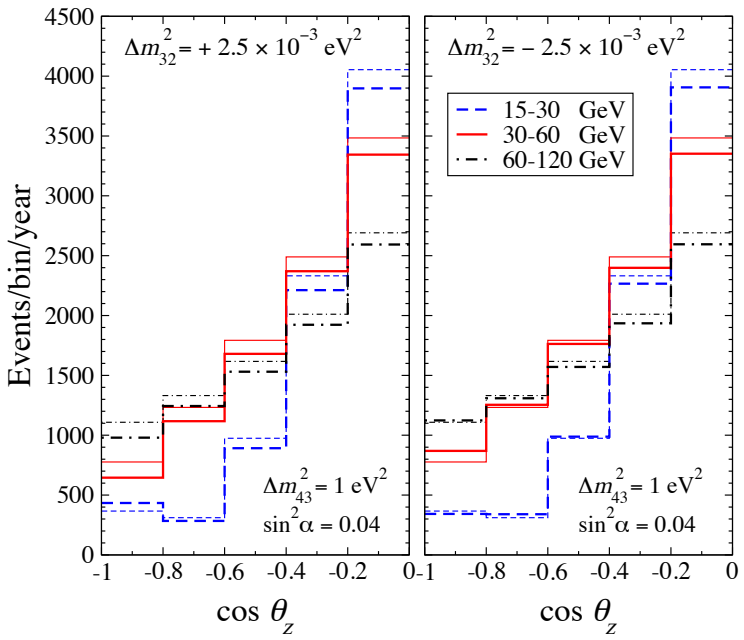
Sterile MSW Resonance

calculated muon antineutrino survival probability



predicted DeepCore rates

thick: with sterile; thin; without

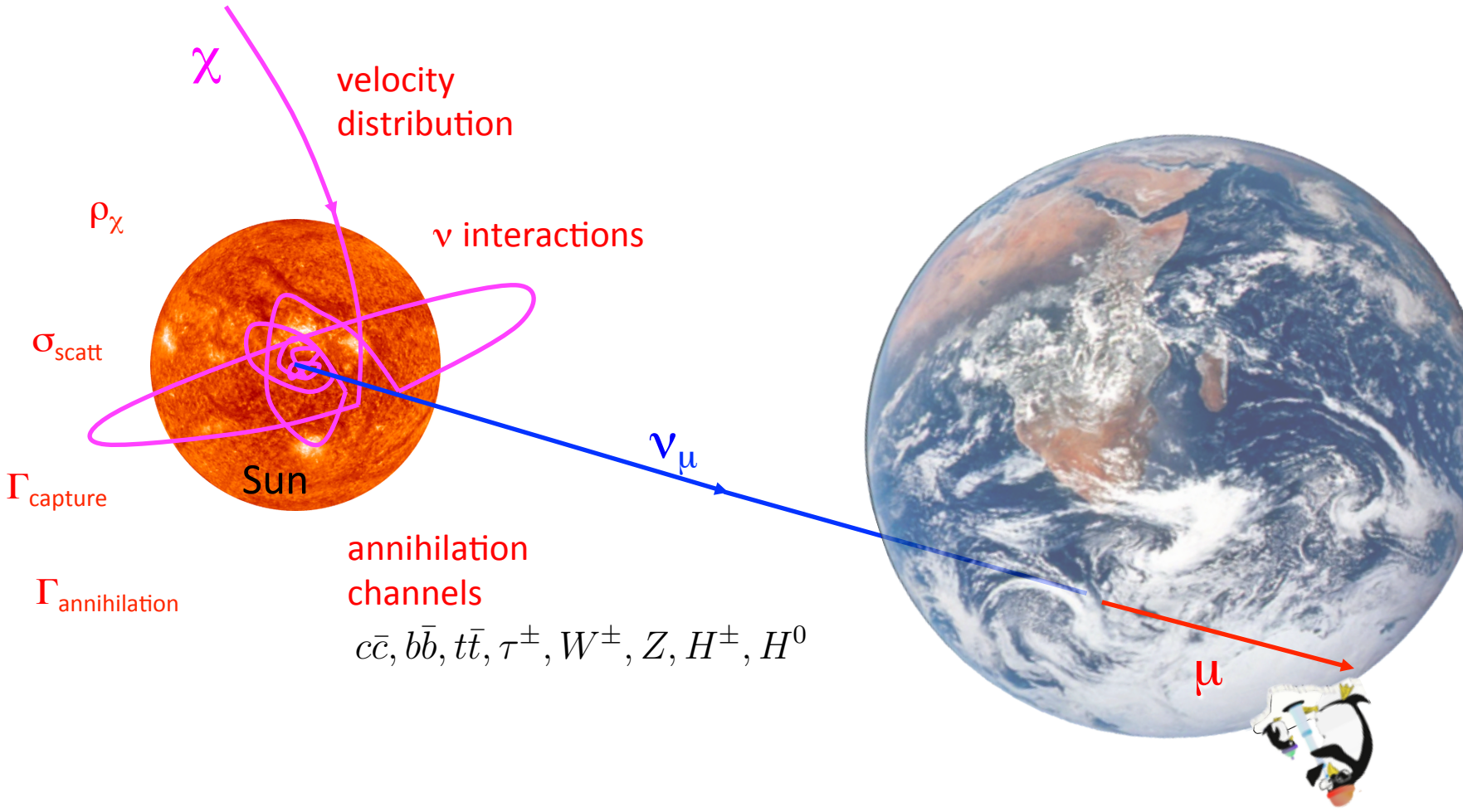


Effects on oscillations observable in both TeV and sub-TeV range

With control of systematics: IceCube will conclusively test this explanation of LSND/MiniBooNE!

Choubey, arXiv:0709.1937
Razzaque and Smirnov, arXiv:1203.5406
Esmaili, Halzen, and Peres, arXiv: 1206.6903

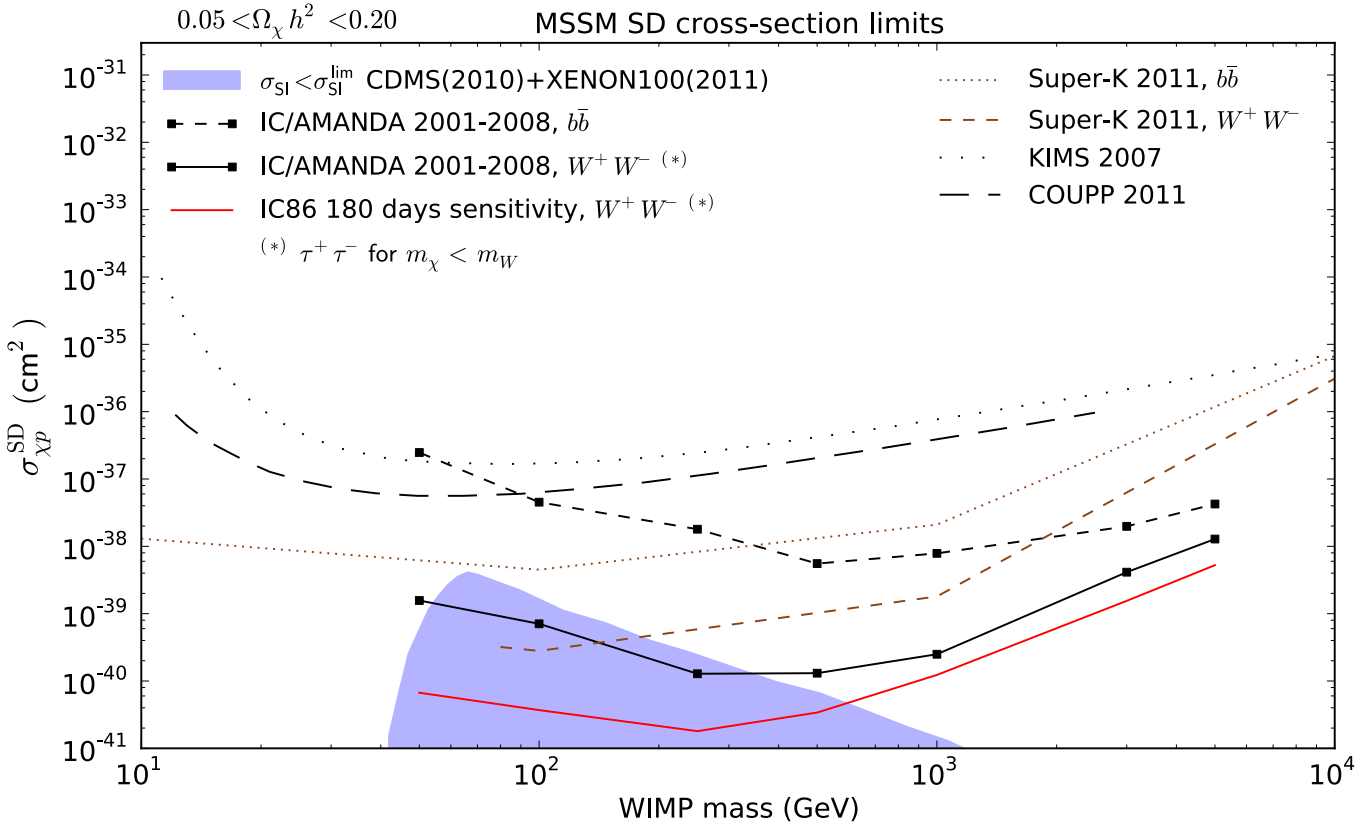
Indirect Detection of Dark Matter



Similar accumulation near Galactic Center, Earth core, and dwarf spheroidal galaxies

Limits on Scattering Cross Section

Phys. Rev. D 85, 042002 (2012)



no excess of high-energy neutrinos from Sun

↓ MSSM branching ratios

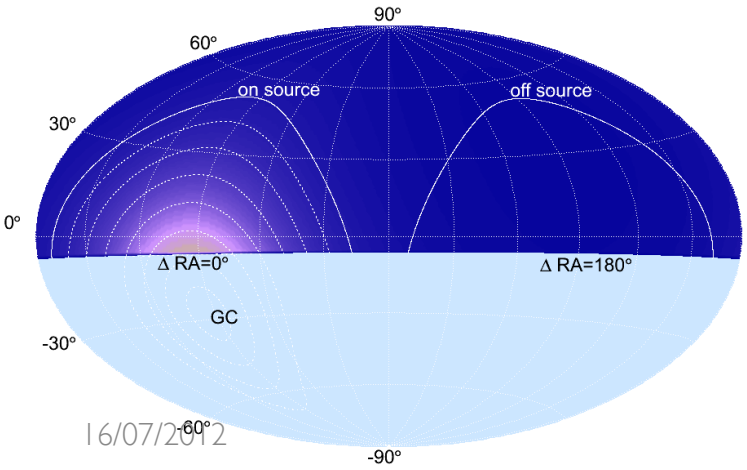
WIMP annihilation limit

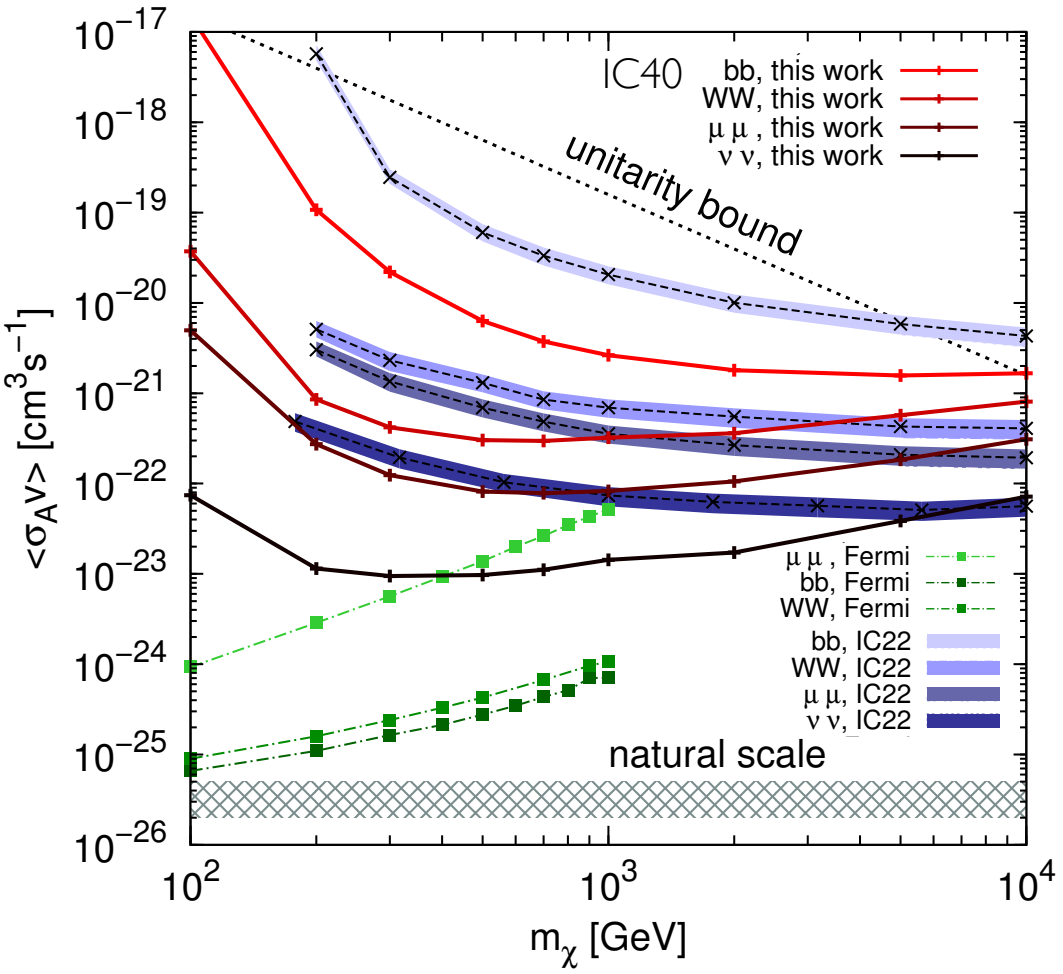
↓ DM density; capture rates; equilibrium

SD cross section limit

Galactic Center and halo limits

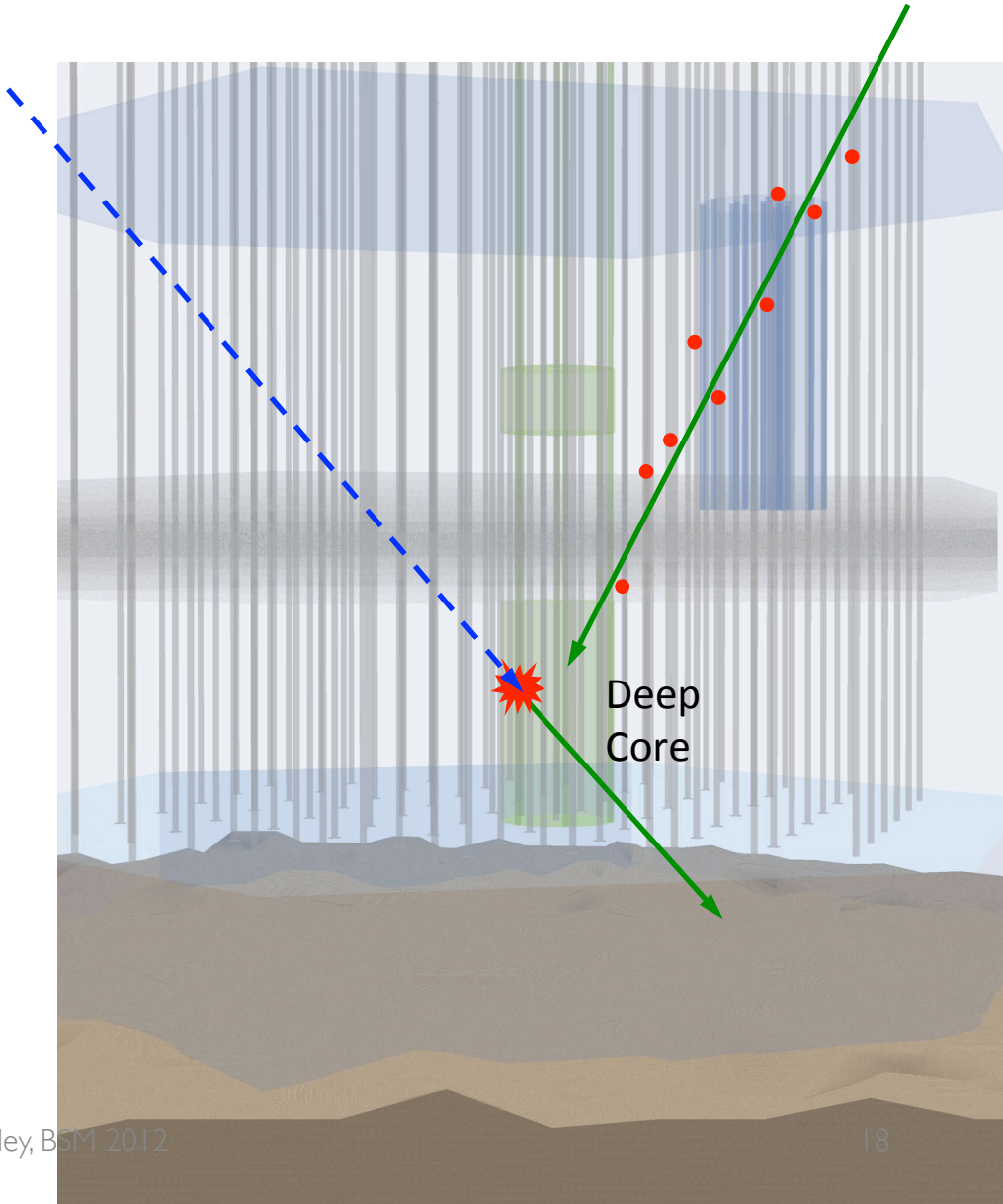
- Probes velocity-averaged self annihilation cross-section
- Galactic halo analysis:
  - IC22 up-going tracks
    Phys.Rev. D84 (2011) 022004
- Galactic Center analysis:
  - IC40 downgoing tracks
  - compare with off-source region





WIMP Searches with DeepCore

- Densely instrumented core of IceCube (30 MTon)
- Can use surrounding detector as a veto
- Allows efficient searches above the horizon (Galactic Center)
- Lower energy threshold (to ~10 GeV): can probe lower WIMP masses



GZK Effect

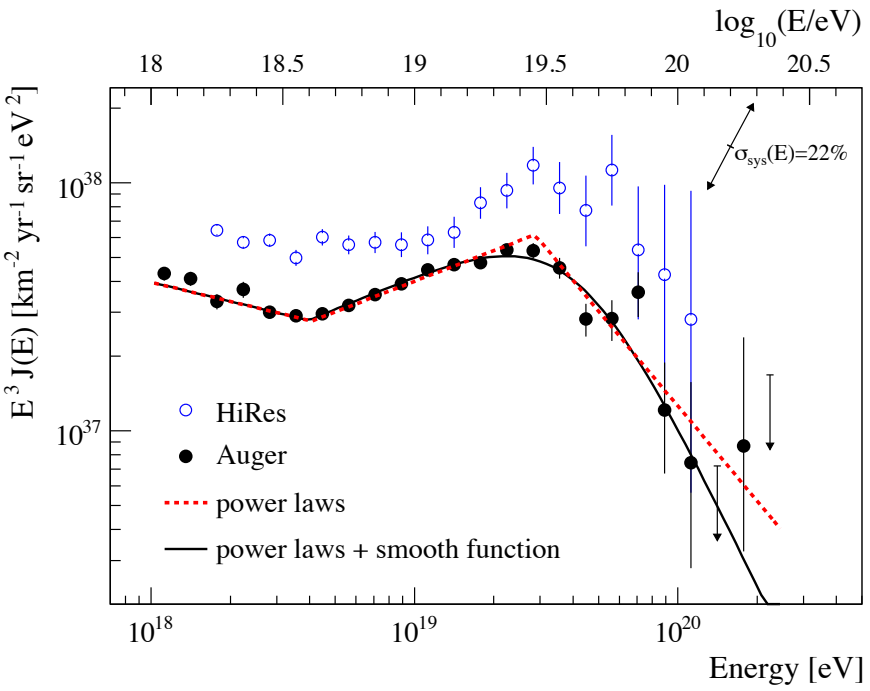
- Suppression ("cutoff") of high-energy cosmic rays due to interaction with CMB photons (Greisen-Zatsepin-Kuzmin)

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

- Threshold ~ 6 × 10^{19} eV

- Suppression observed in cosmic-ray flux consistent with GZK explanation

Cosmic ray energy spectrum



Auger Collaboration,
Phys. Lett. **B685** (2010) 239

The Neutrino Connection

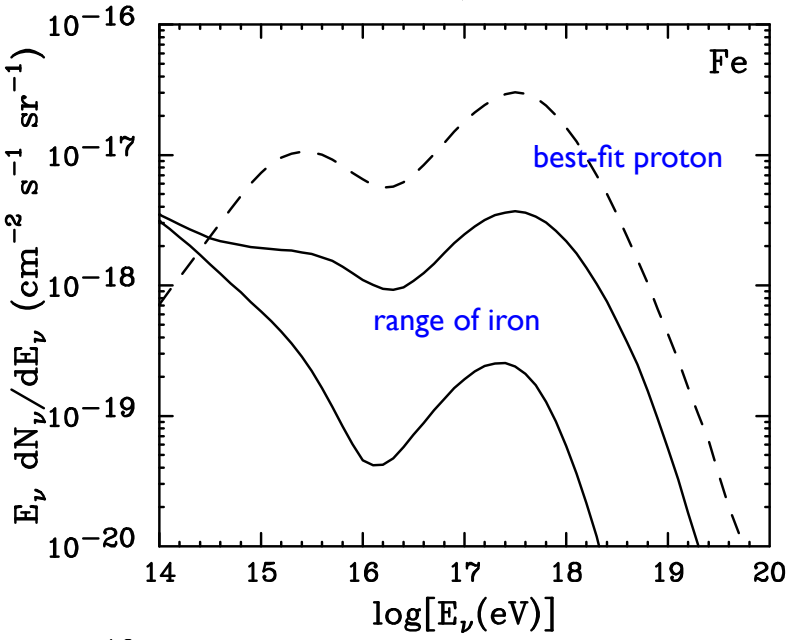
- GZK process also produces UHE neutrinos!

$$p\gamma \rightarrow n\pi^{+} \rightarrow n\mu + \nu_{\mu}$$

- Nuclei will tend to photodisintegrate first (reduced flux)

- New source for SM tests
  - cosmological baselines probed
  - energies ~ 10^{18}-10^{19} eV

GZK neutrino flux models



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

Possible New Physics with GZK neutrinos

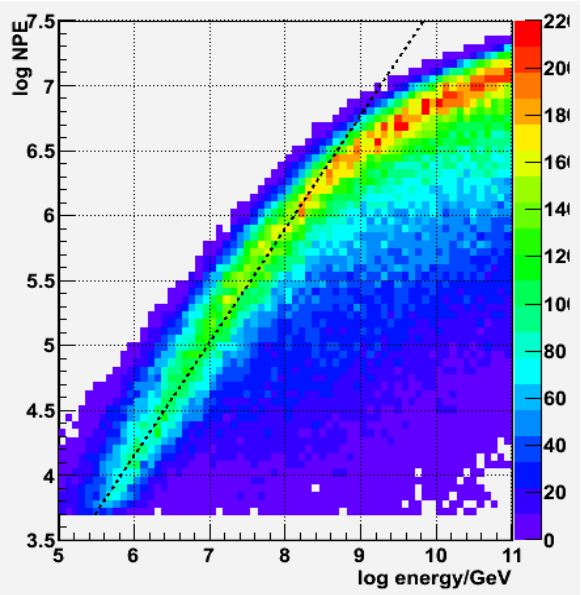
- VLI-induced neutrino splitting
  - modification of spectral shape
  - see e.g. Mattingly, Liberati *et al.*, arXiv: 0911.0521

$$\nu \rightarrow \nu\nu\bar{\nu}$$

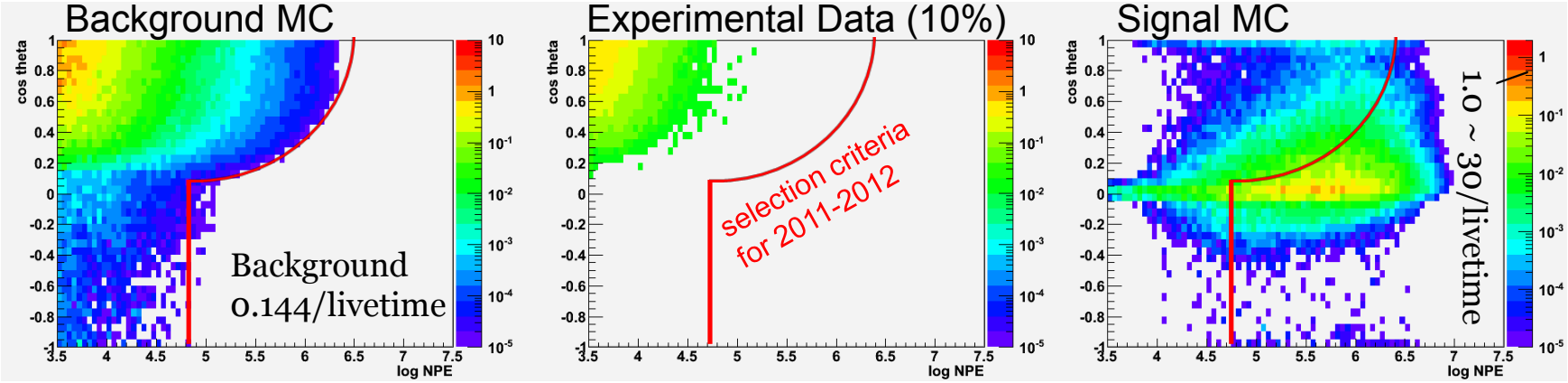
- Neutrino / dark energy coupling leading to VLI / CPTV
  - flavor ratio via angular dependence
  - see e.g. Ando *et al.*, arXiv:0910.4391

- Cross section enhancement from large extra dimensions
  - detection via angular dependence of event rate
  - see e.g. Connolly, Thorne, and Waters, arXiv:1102.0691

IceCube EHE Neutrino Search



- May 2010 – May 2012 (672.7 days livetime)
- Primary selection criterion: high NPE
- Track reconstruction quality removes corner-clippers, coincident CR events

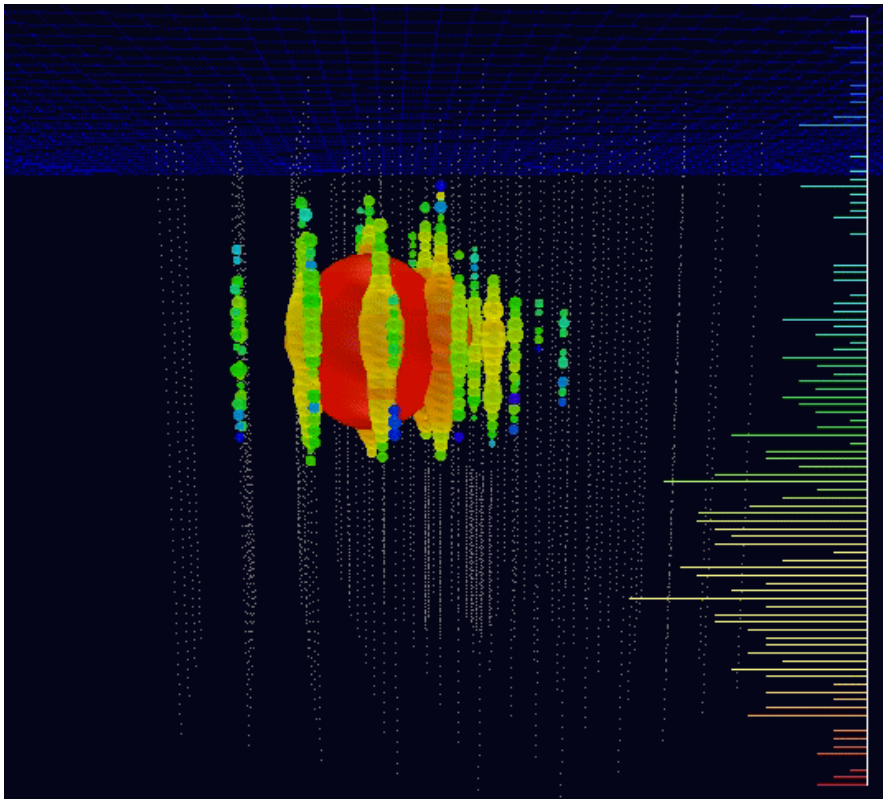


see also first IceCube upper limits: Phys. Rev. D 82, 072003 (2010)

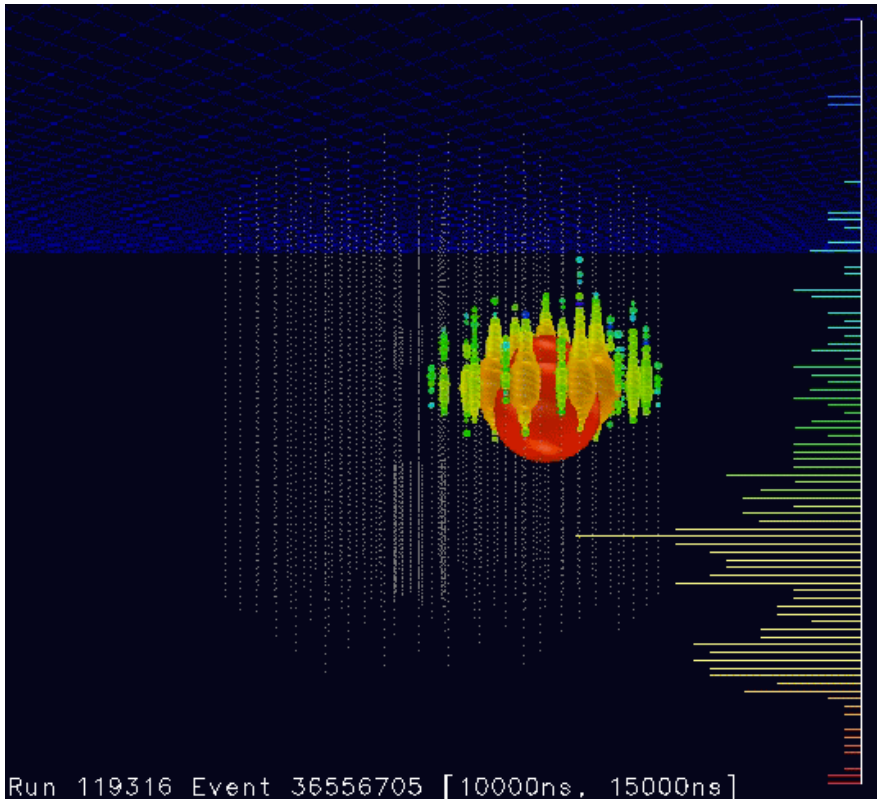
Neutrino Candidates

Two events in unblinded data sample (background estimation: 0.14 events; 2.36 σ)

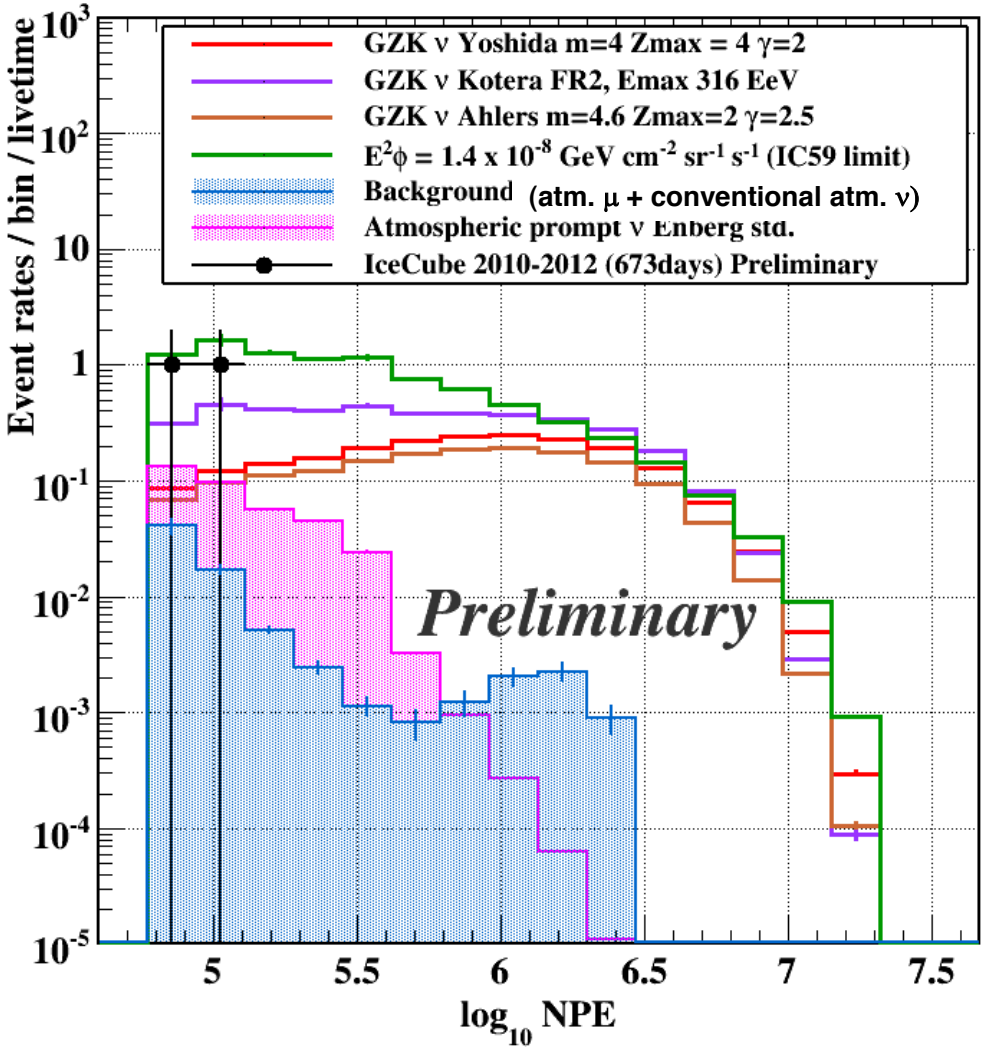
3 Jan 2012: 96k PE, 312 DOMs



9 Aug. 2011: 70k PE, 354 DOMs



Event Brightness



- No indication that they are cosmic-ray muons
- ~PeV energy deposit in detector (would imply 1-10 PeV neutrinos)
- Analysis of energy, directions ongoing

Conclusions and Outlook

- IceCube is completed and is operating well

- Atmospheric neutrinos: our high-statistics source
  - limits on violation of Lorentz invariance
  - searches for eV-scale sterile neutrino in progress

- WIMP searches
  - MSSM-constraining limits on spin-dependent scattering cross section (via Sun)
  - competitive limits on self-annihilation cross section (via GC, halo)
  - extending to dwarf spheroidal galaxies

- EHE searches for the cosmogenic neutrinos
  - no significant excess so far
  - may eventually provide the next "test beam"