Observation of High-energy Astrophysical Neutrinos with IceCube

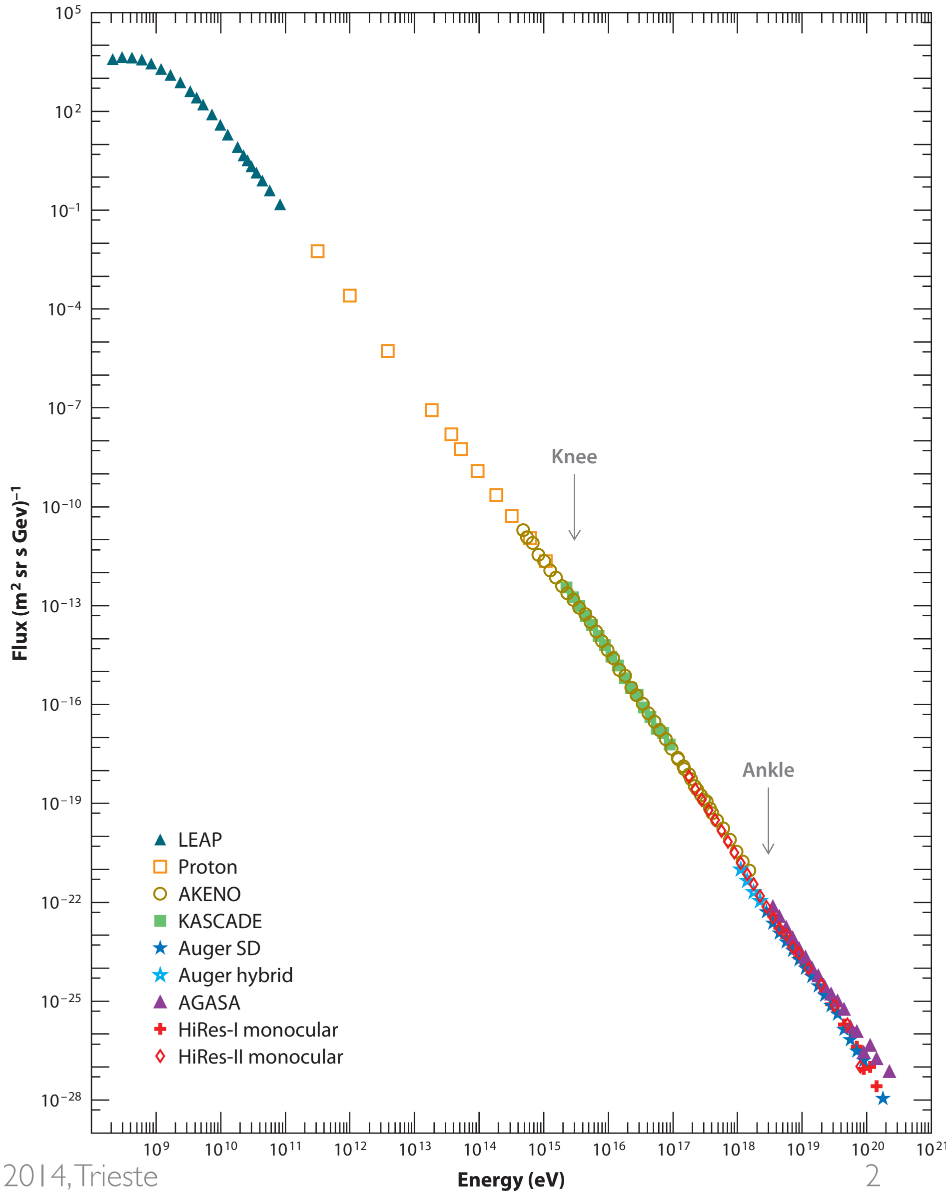
John Kelley for the IceCube Collaboration

Experimental Search for Quantum Gravity
SISSA, Trieste, Italy
September 5, 2014

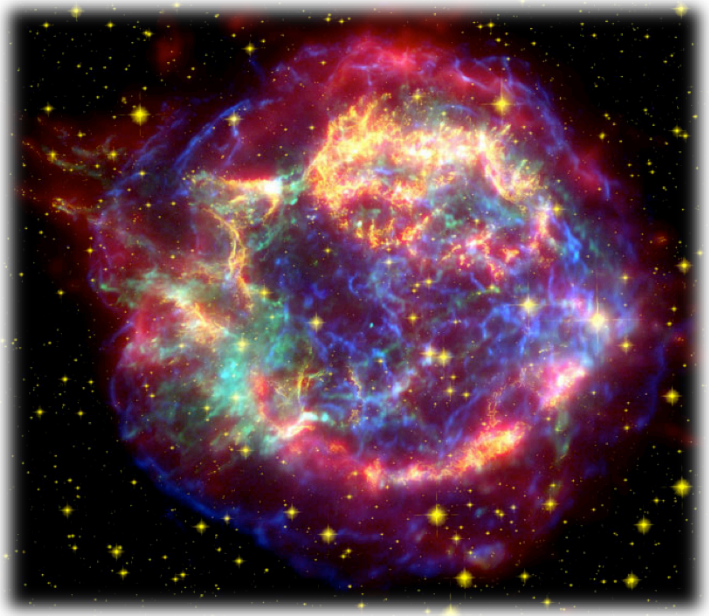
Motivation

- Cosmic ray sources: Nature's particle accelerators (up to 10^{20} eV!)
- Sources unknown
- Probes of both astrophysics and fundamental particle physics

J. Beatty and S. Westerhoff, Ann. Rev. Nucl. Par. Sci. 59 (2009)



Cosmic Ray Acceleration and Neutrino Production



Fermi shock acceleration: $dN/dE \sim E^{-2}$

$$p + \gamma \rightarrow p + \pi^0, n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

1:2:0 flavor ratio at source

Similar processes (incl. $p+p$) happening in:

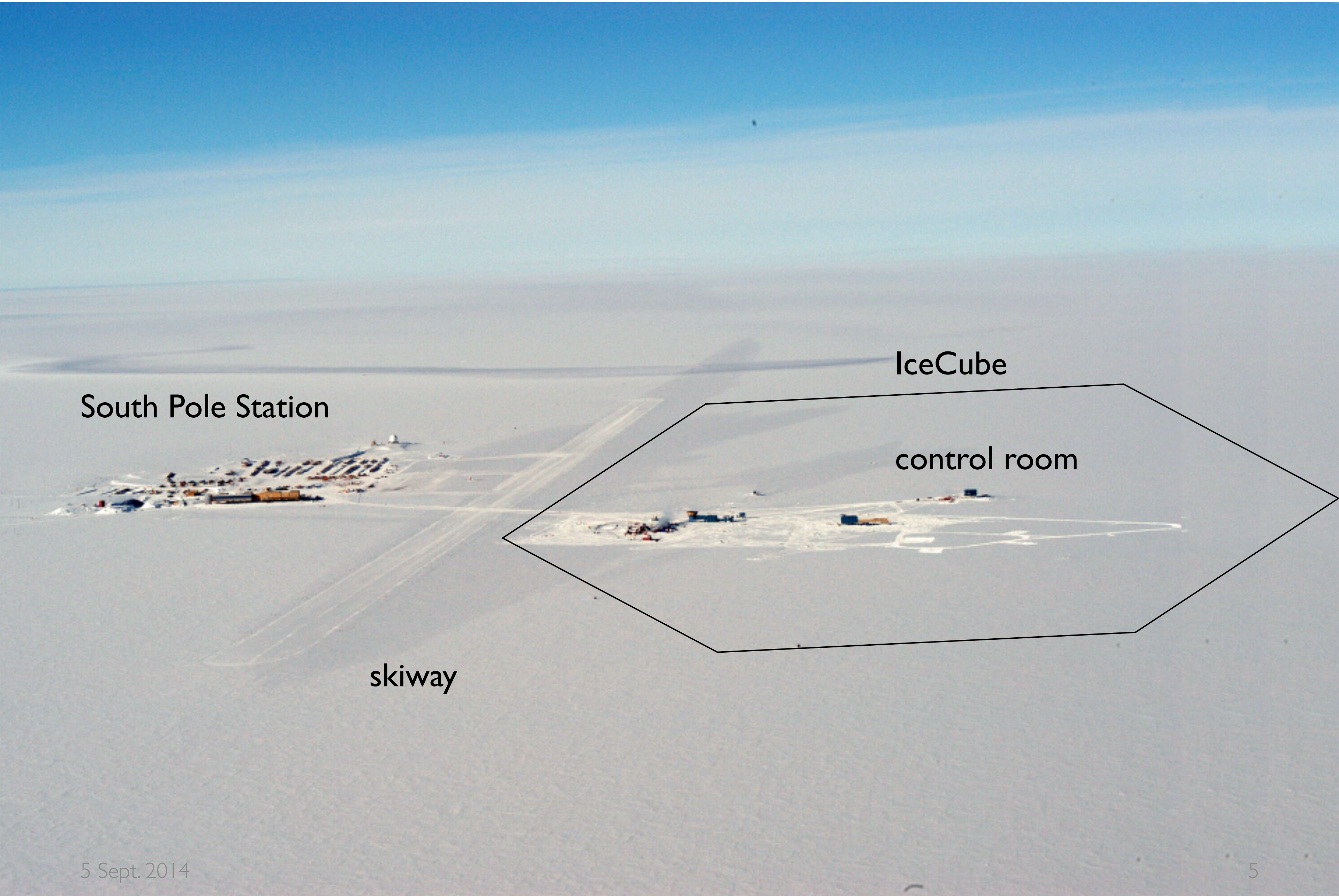
- cosmic ray sources (ambient light, gas) — astrophysical source neutrinos
- outer space (cosmic microwave background) — cosmogenic neutrinos
- Earth's atmosphere (N, O, etc. nucleus) — atmospheric neutrinos

Neutrinos as Quantum Gravity Probes

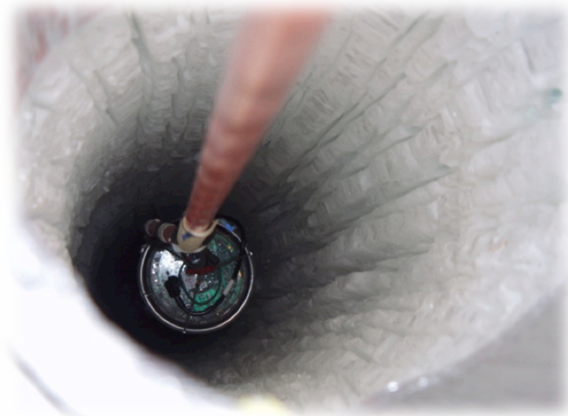
- Non-standard neutrino oscillations from Lorentz Invariance Violation
  - AMANDA-II and IceCube limits with atmospheric neutrinos*
- Propagation effects (more later)
  - dissipative effects in an emergent spacetime
  - superluminal vacuum e^+e^- pair production
  - quantum decoherence
- A distant, high-energy source of neutrinos is ideal
  - simpler than UHE cosmic rays (unknown nucleons)
  - complicated by astrophysics

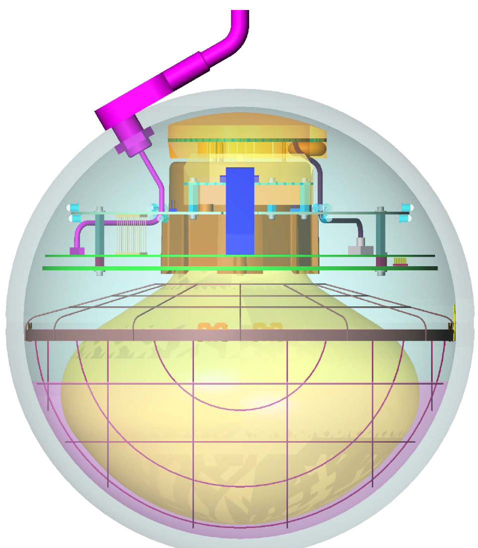
*PRD **79** 102005 (2009), PRD **82** 112003 (2010)

IceCube from the Air

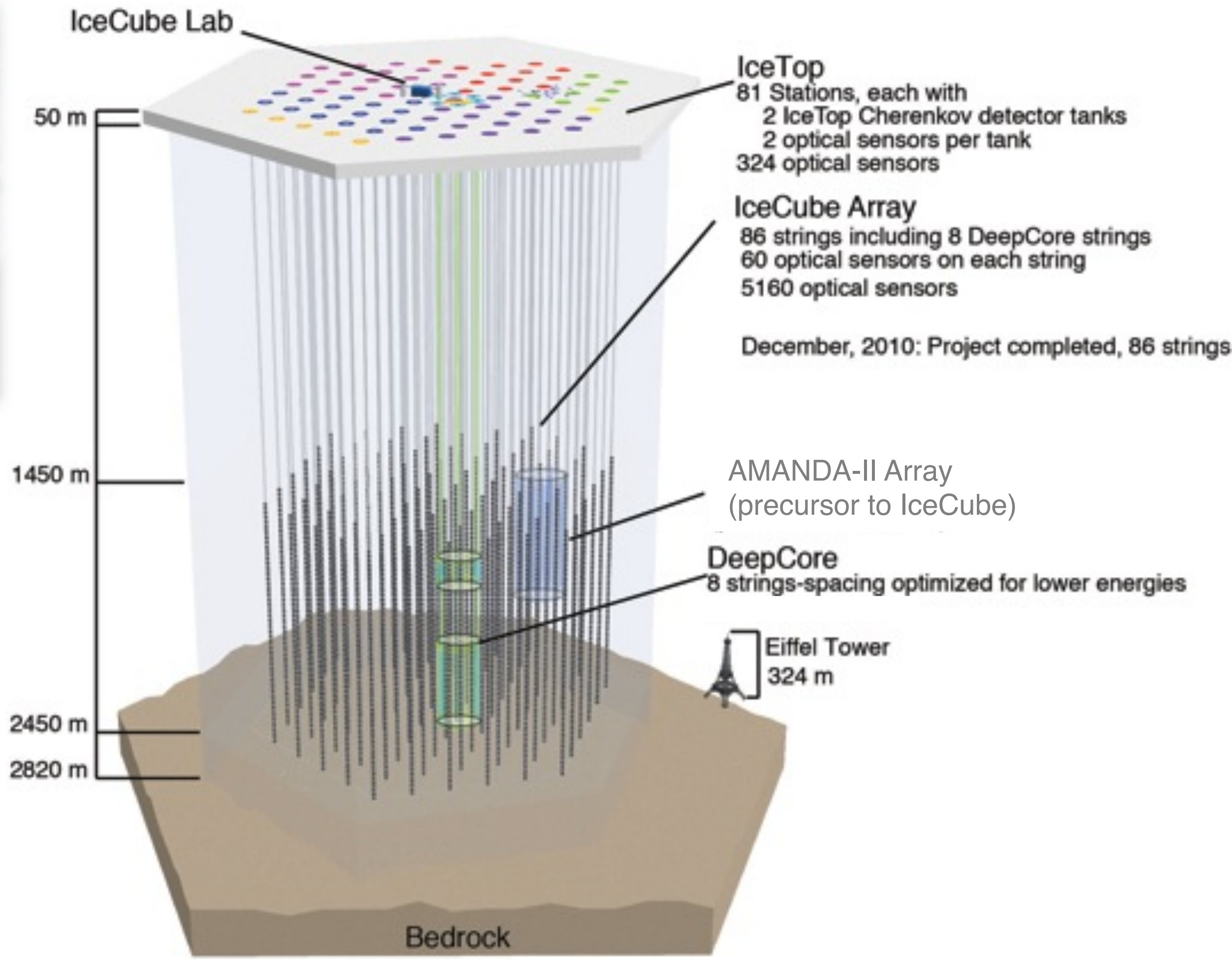


The IceCube Detector

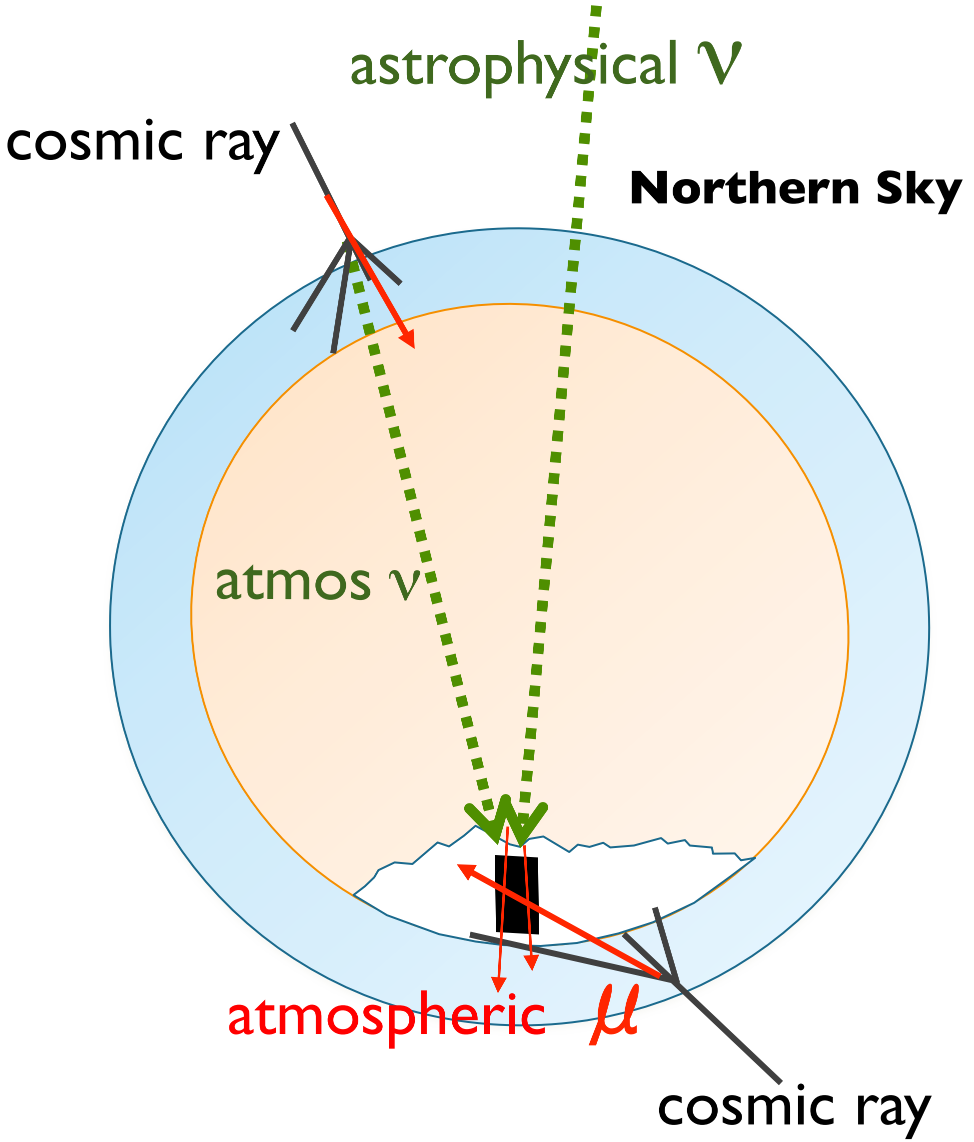


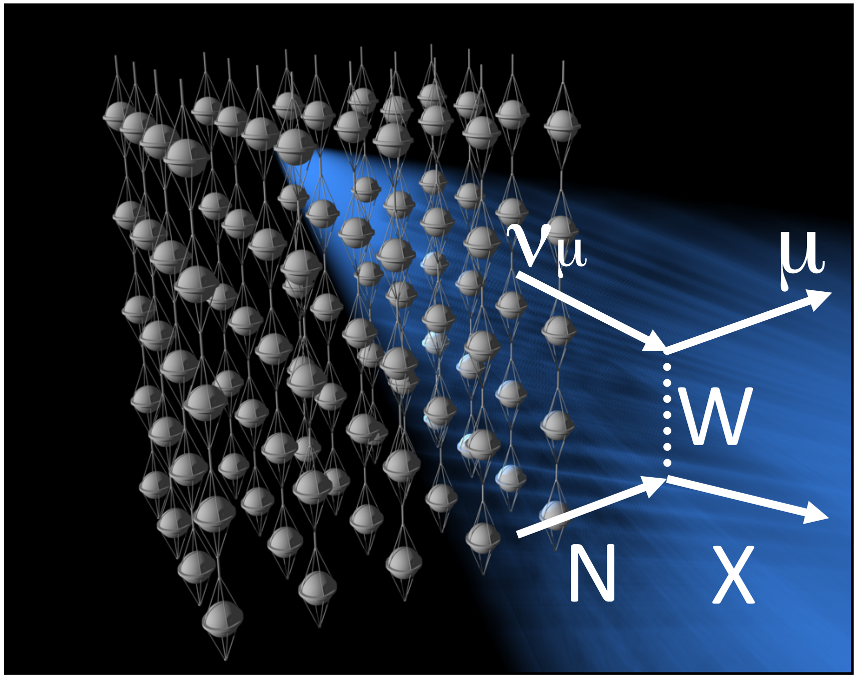


digital optical module (DOM)



Detection Principle

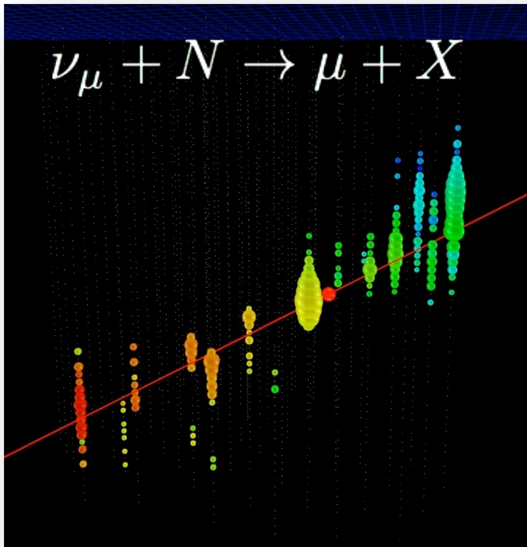




Cosmic-ray muons: ~3000 / second!
Atmospheric neutrinos: ~1 / 10 minutes
Astrophysical neutrinos: ???

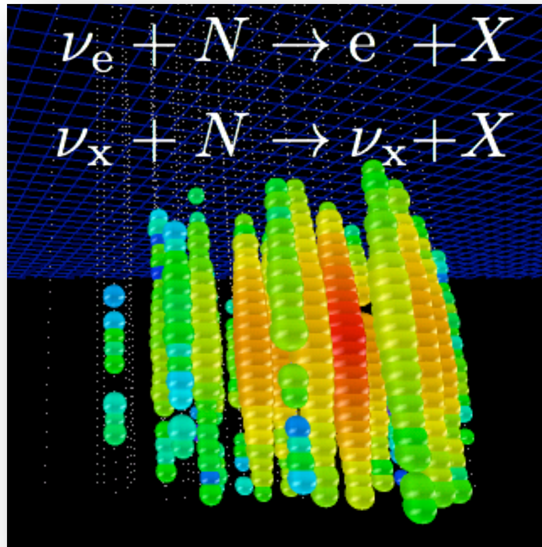
Event Topologies

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



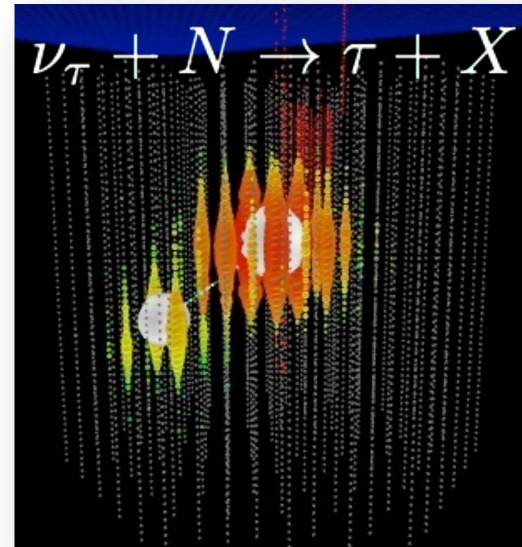
track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies



cascade / shower (data)

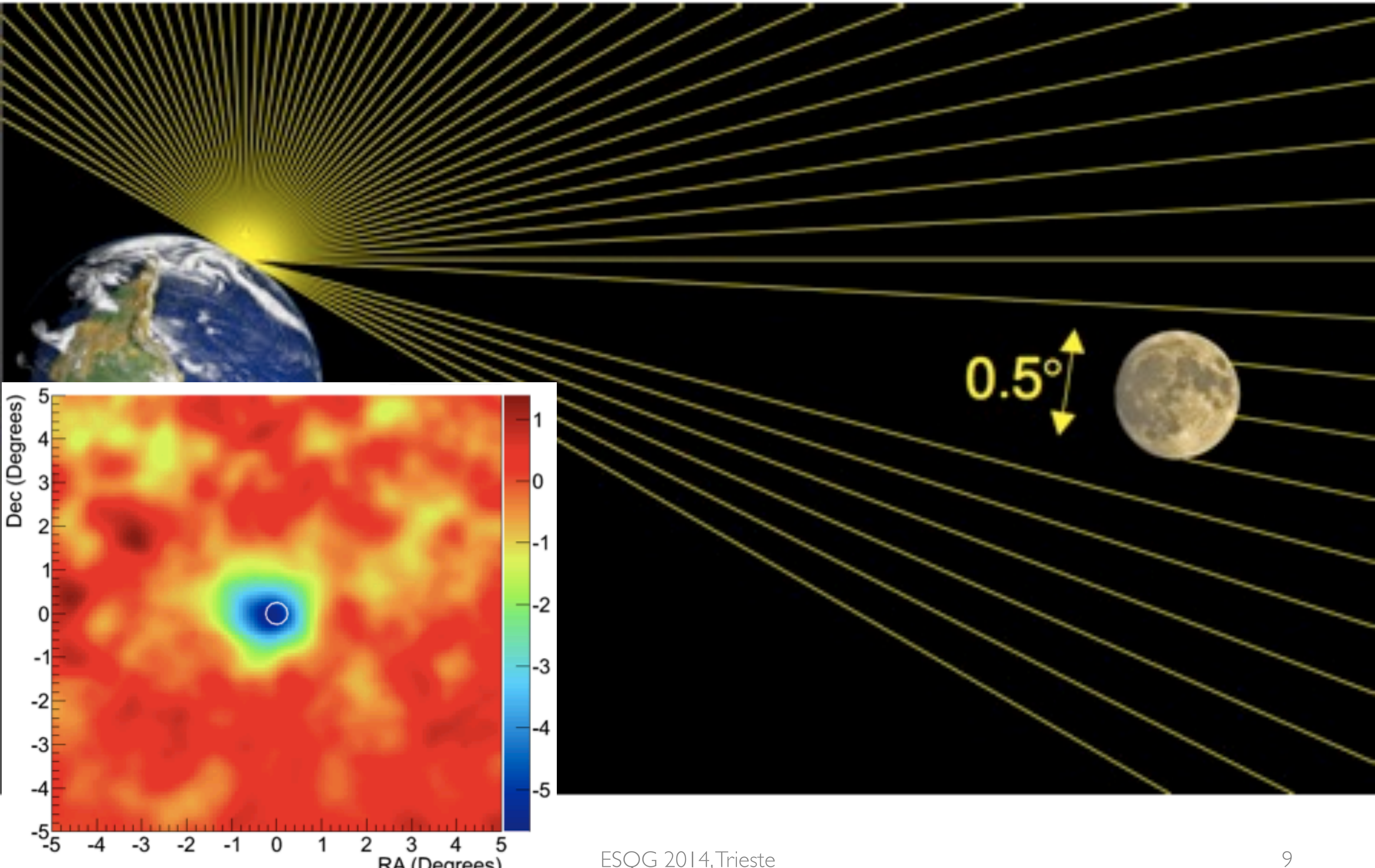
≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)



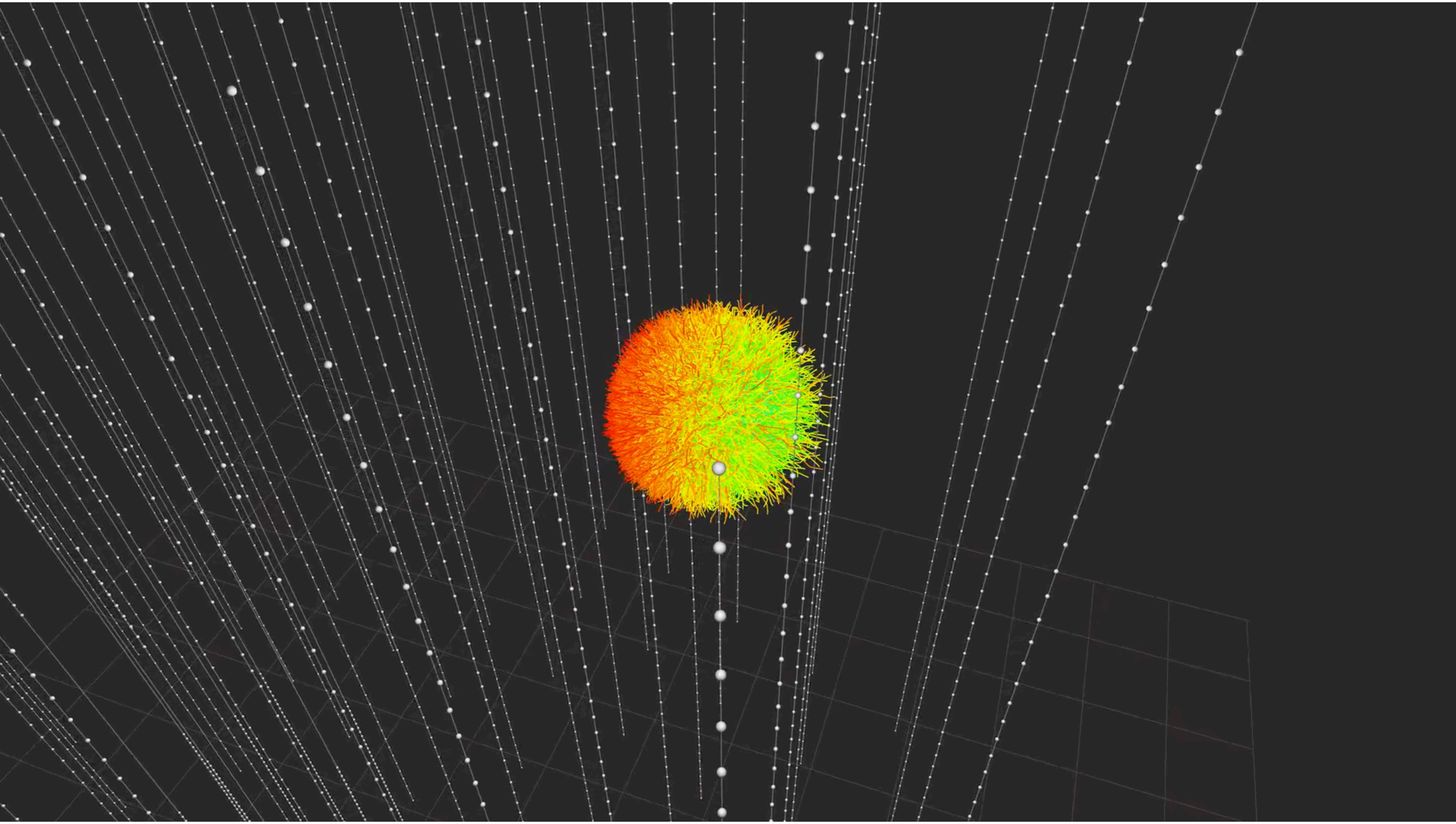
"double-bang" (≳10 PeV) and other signatures (simulation)

(not observed yet)

Shadow of the Moon



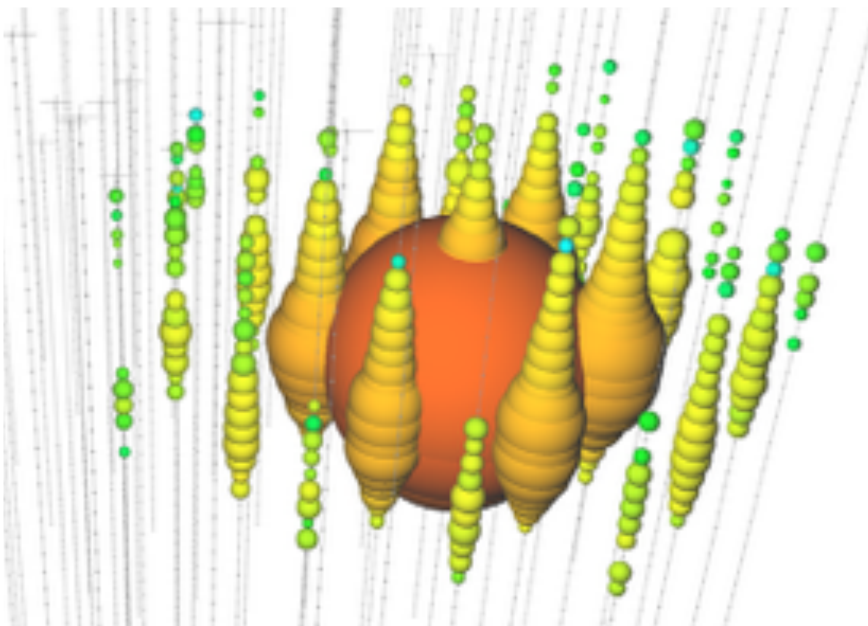
Cascade Directional Reconstruction



Energy Reconstruction

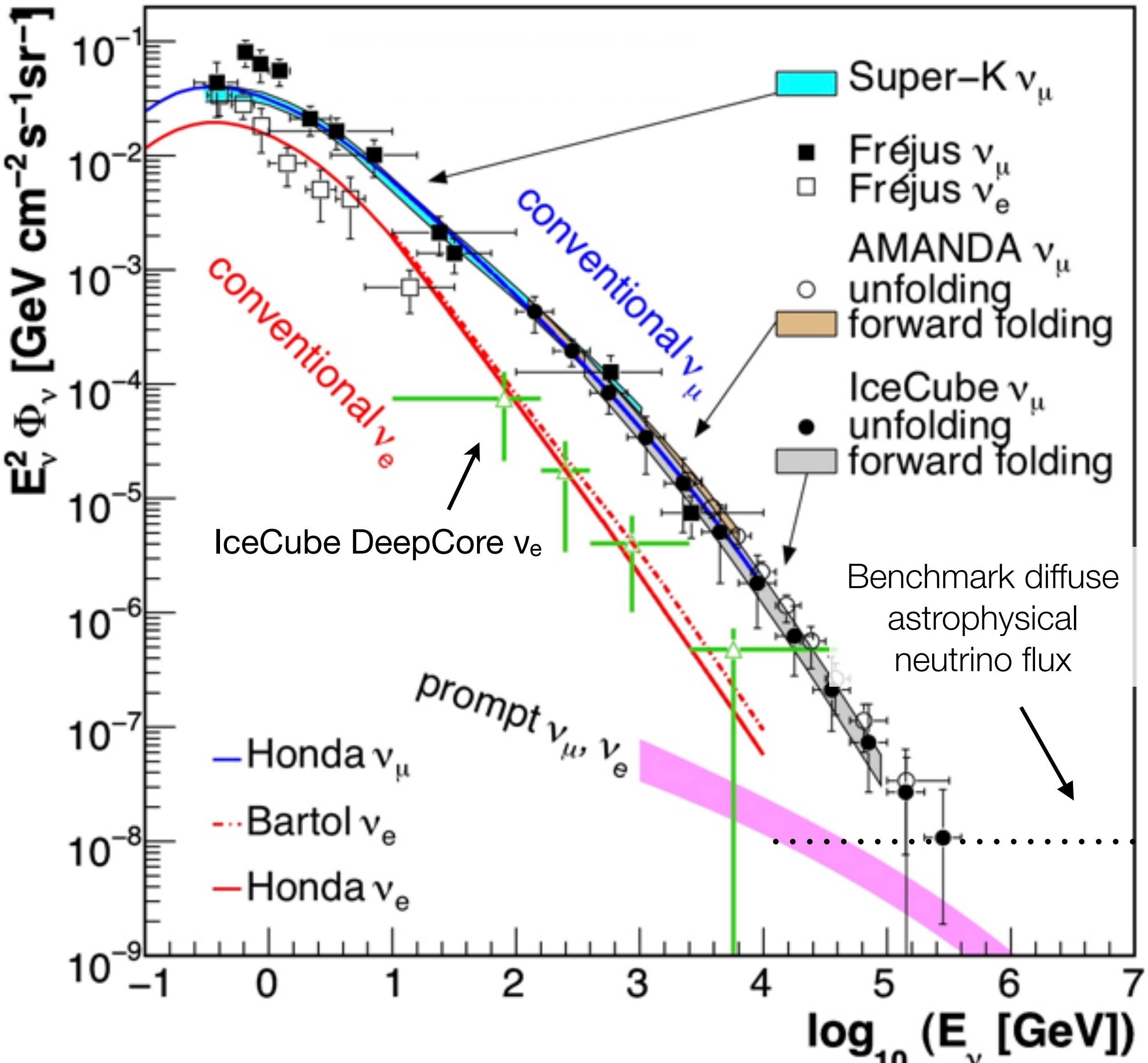
Aartsen *et al.*, JINST **9** (2014), P03009

Interaction	Signature	E_{vis}/E_{ν}; $E_{\nu} = 1$ TeV	$E_{\nu} = 10$ TeV	$E_{\nu} = 100$ TeV
$\nu_e + N \rightarrow e + had.$	Cascade	94%	95%	97%
$\nu_\mu + N \rightarrow \mu + had.$	Track (+ Cascade)	94%	95%	97%
$\nu_\tau + N \rightarrow \tau + had. \rightarrow had.$	Cascade/Double Bang	$< 94\%$	$< 95\%$	$< 97\%$
$\nu_\tau + N \rightarrow \tau + had. \rightarrow \mu + had.$	Cascade + Track	$< 94\%$	$< 95\%$	$< 97\%$
$\nu_l + N \rightarrow \nu_l + had.$	Cascade	33%	30%	23%



- ~15% resolution on deposited (visible) energy
- NC interactions have large fraction of invisible energy
- Visible energy may leave detector (muons, uncontained cascades)

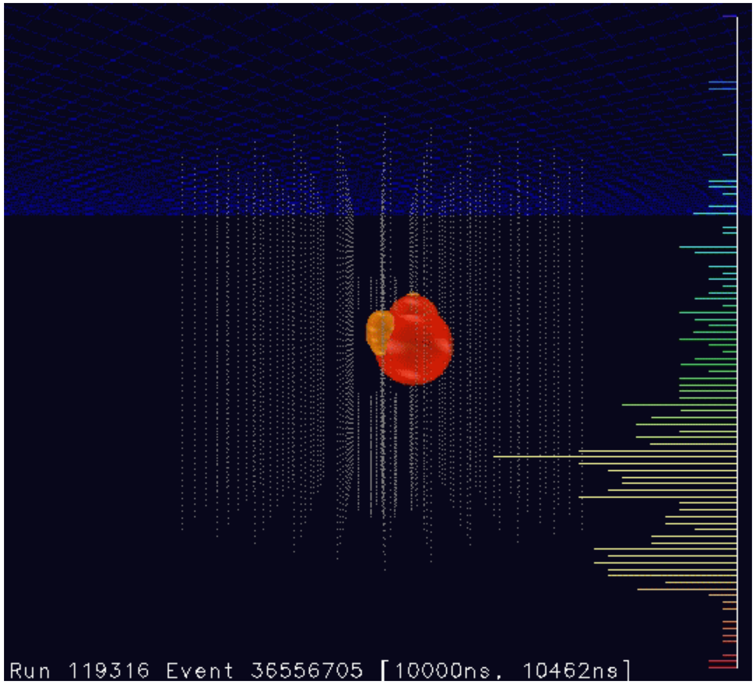
Neutrino Energy Spectra at Earth



First Two High-energy Neutrinos Observed

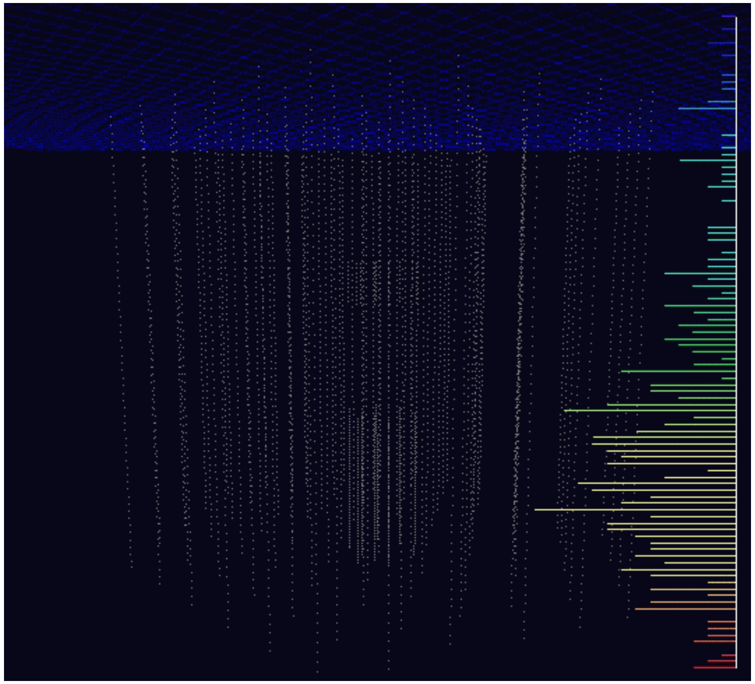
Two cascade events in extremely high-energy data sample
(background estimation: 0.14 events; 2.8 σ , P = 0.29%)

9 Aug. 2011: 70k PE, 354 DOMs



"Bert" ~1100 TeV

3 Jan 2012: 96k PE, 312 DOMs

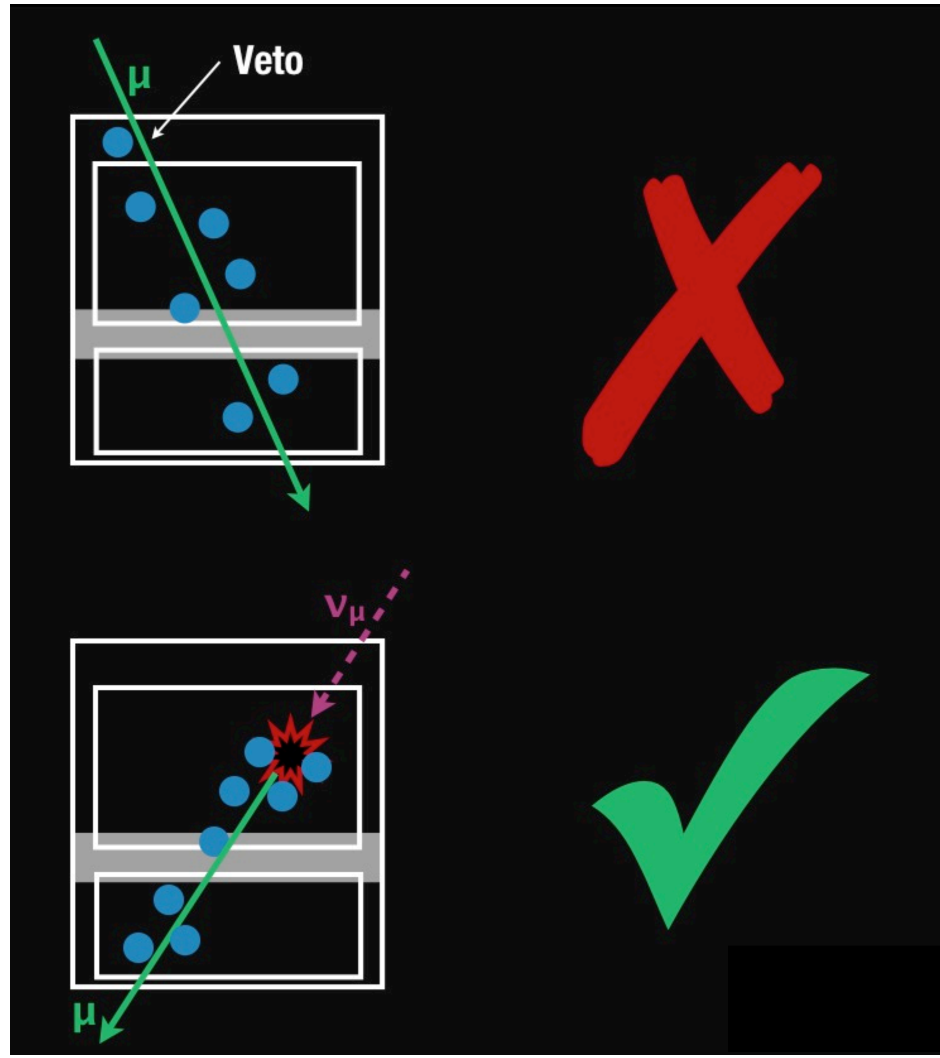


"Ernie" ~1300 TeV

Phys. Rev. Lett. 111, 021103 (2013)

How to find more?

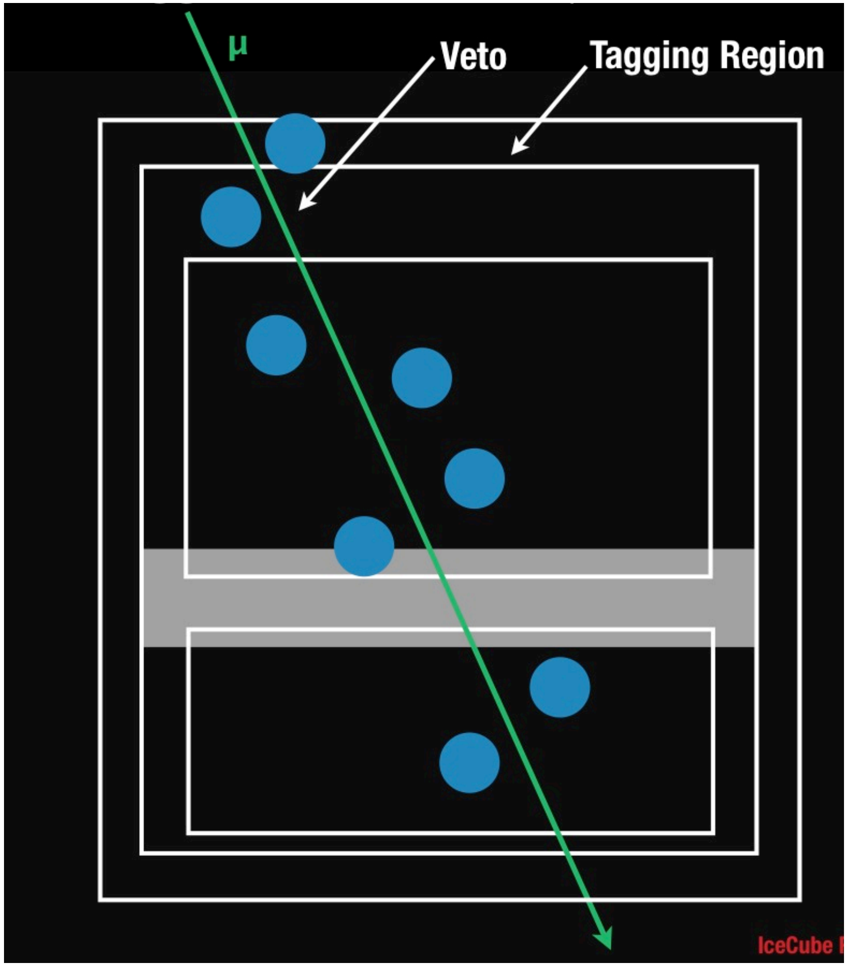
- High-energy starting event ("HESE") search
  - May 2010 to May 2013
- Veto layer excludes atmospheric muons and some atmospheric neutrinos
- Sensitive to all flavors, all directions



courtesy C. Kopper

Muon Background Estimation From Data

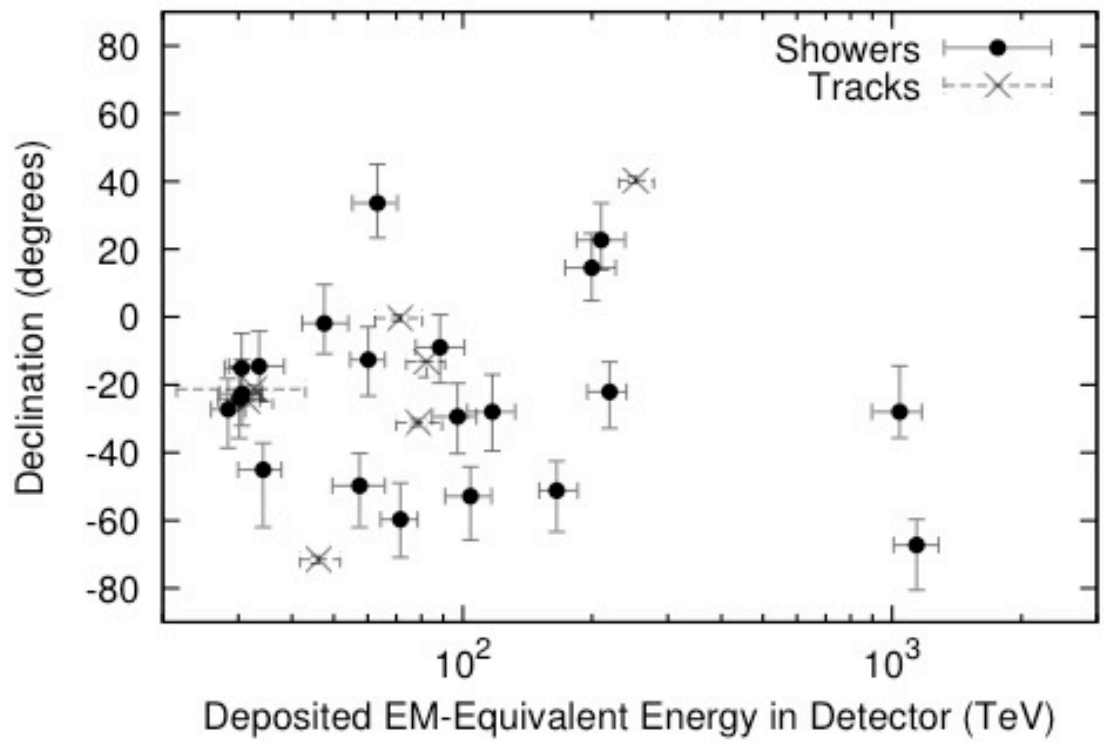
- Add one layer of DOMs to "tag" known background events
  - use these to evaluate veto efficiency
- Can be checked at lower energies where background dominates
- Estimated muon background:
  - 2.8 ± 1.4 events / year
- Remaining background is atmospheric neutrinos
  - $2.2^{+2.0}_{-0.5}$ events / year



Results: 2 years of data (2010-2012)

- 28 events in 662 days
  - 7 tracks, 21 showers
- Estimated backgrounds:
  - $4.6^{+3.7}_{-1.2}$ atm. neutrinos
  - 6.0 ± 3.4 atm. muons
- Significance over background-only hypothesis: 4.1σ
- First evidence for a high-energy astrophysical neutrino flux

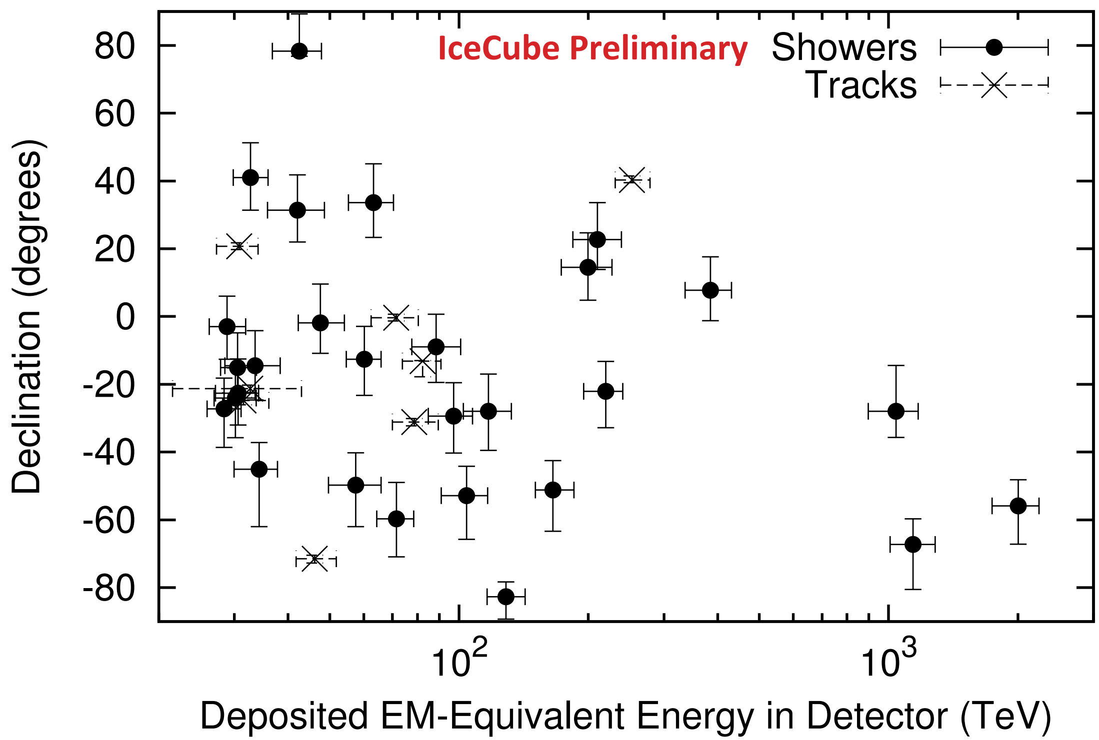
Science **342**, 1242856 (2013)



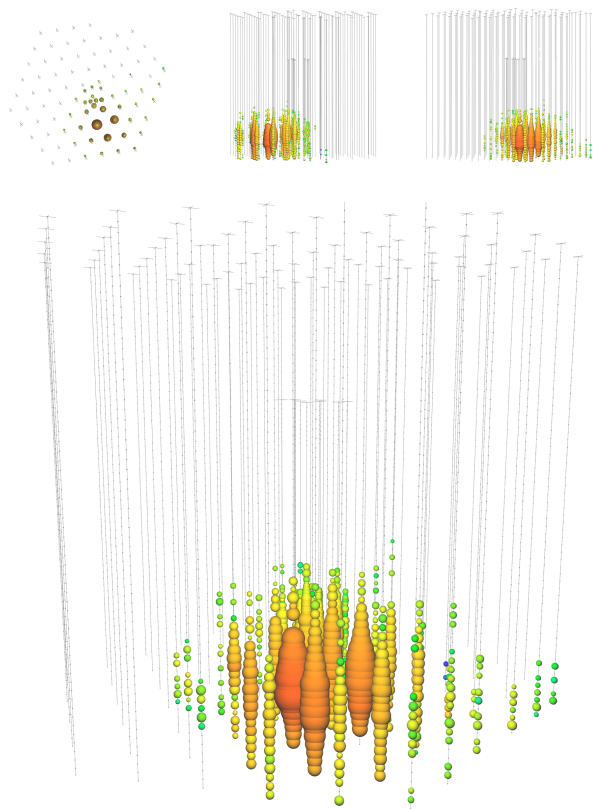
Results: 3 years of data (2010-2013)

- 37 events in 988 days
  - 8 tracks, 28 showers, 1 double track (two air showers)
- Estimated backgrounds:
  - $6.6^{+5.9}_{-1.6}$ atm. neutrinos
  - 8.4 ± 4.2 atm. muons
- Significance over background-only hypothesis: 4.8σ
- Full likelihood fit: 5.7σ

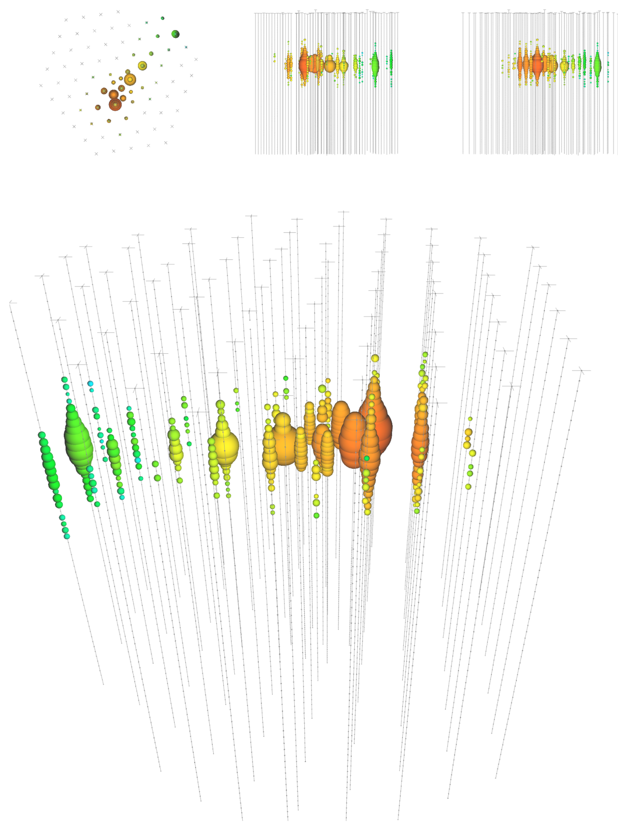
Phys. Rev. Lett. **113**, 101101 (2014)



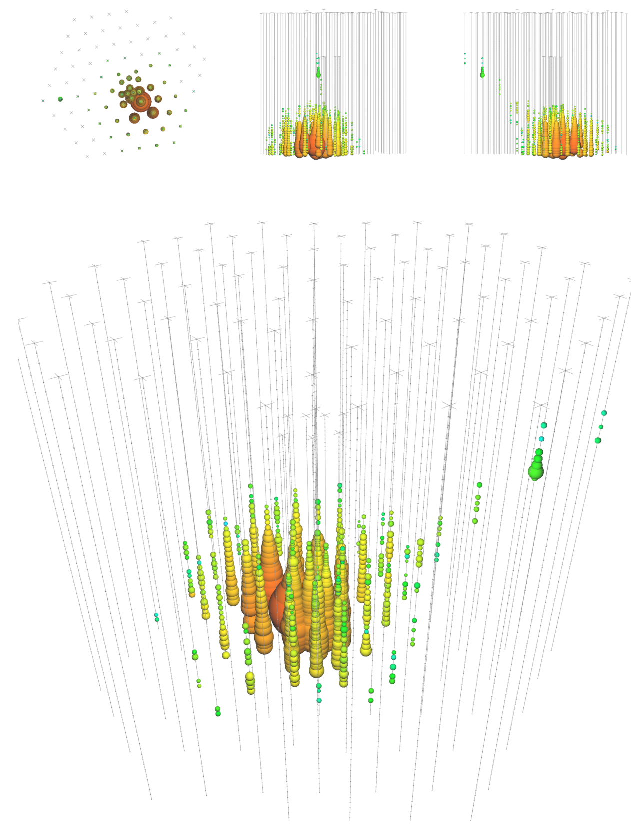
A Few Events



declination: -13.2°
deposited energy: 82TeV

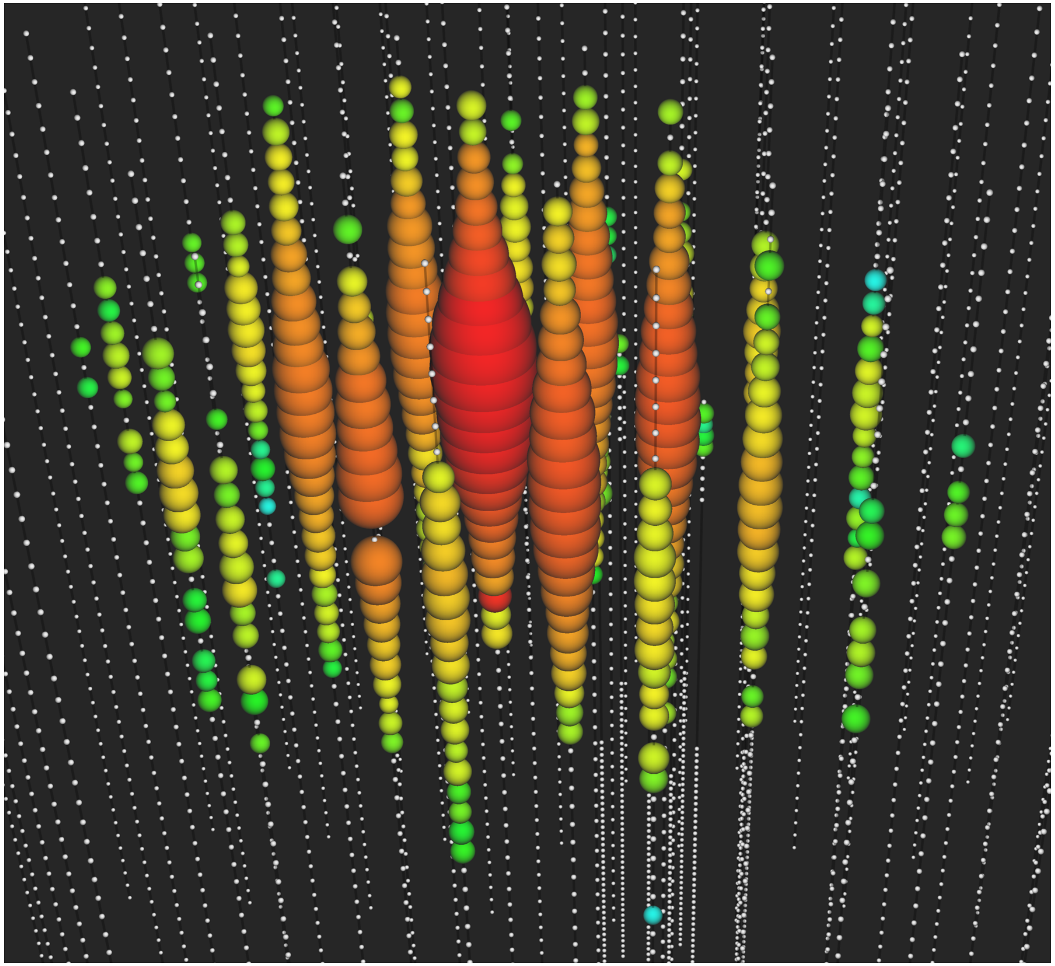


declination: -0.4°
deposited energy: 71TeV



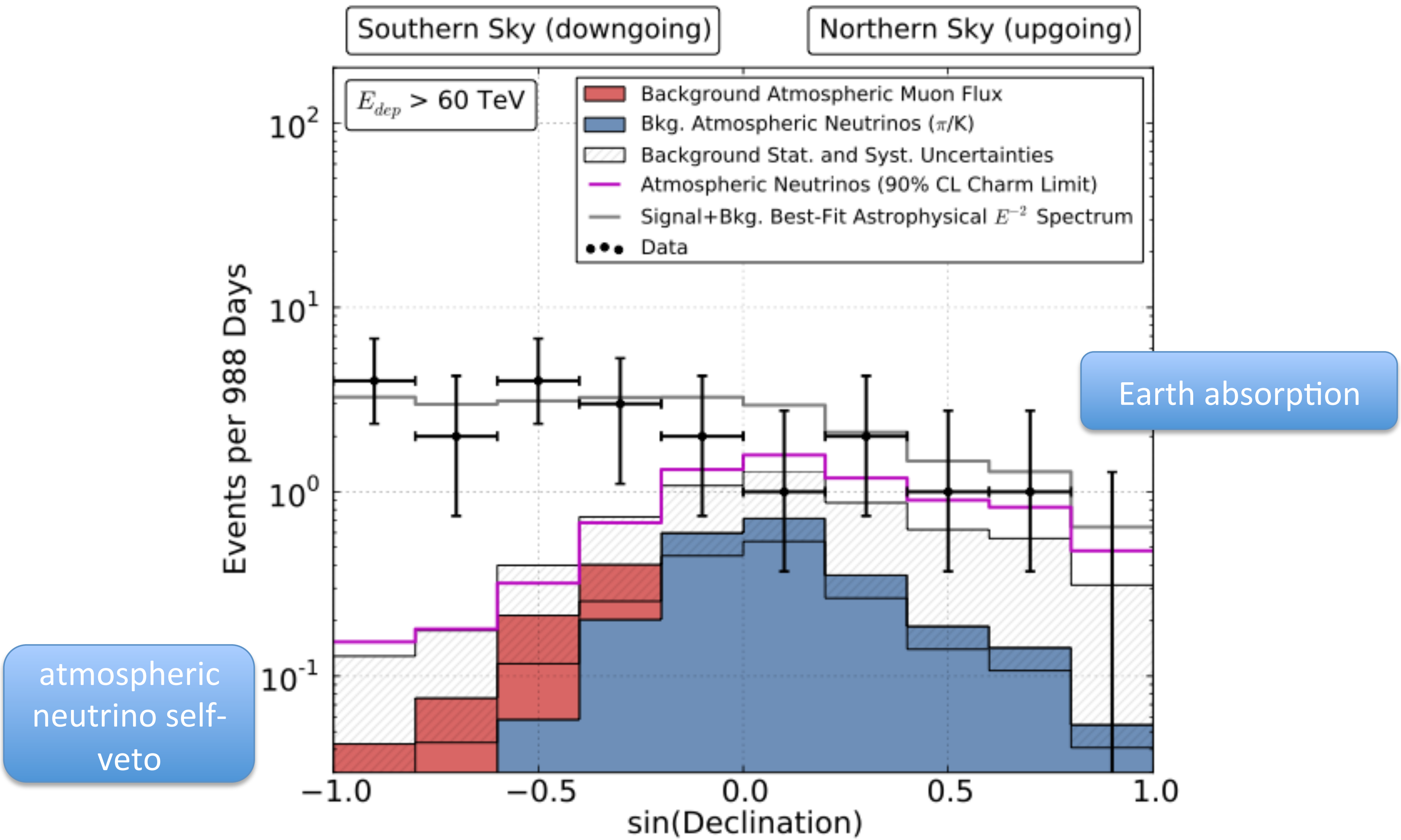
declination: 40.3°
deposited energy: 253TeV

Highest-energy Event

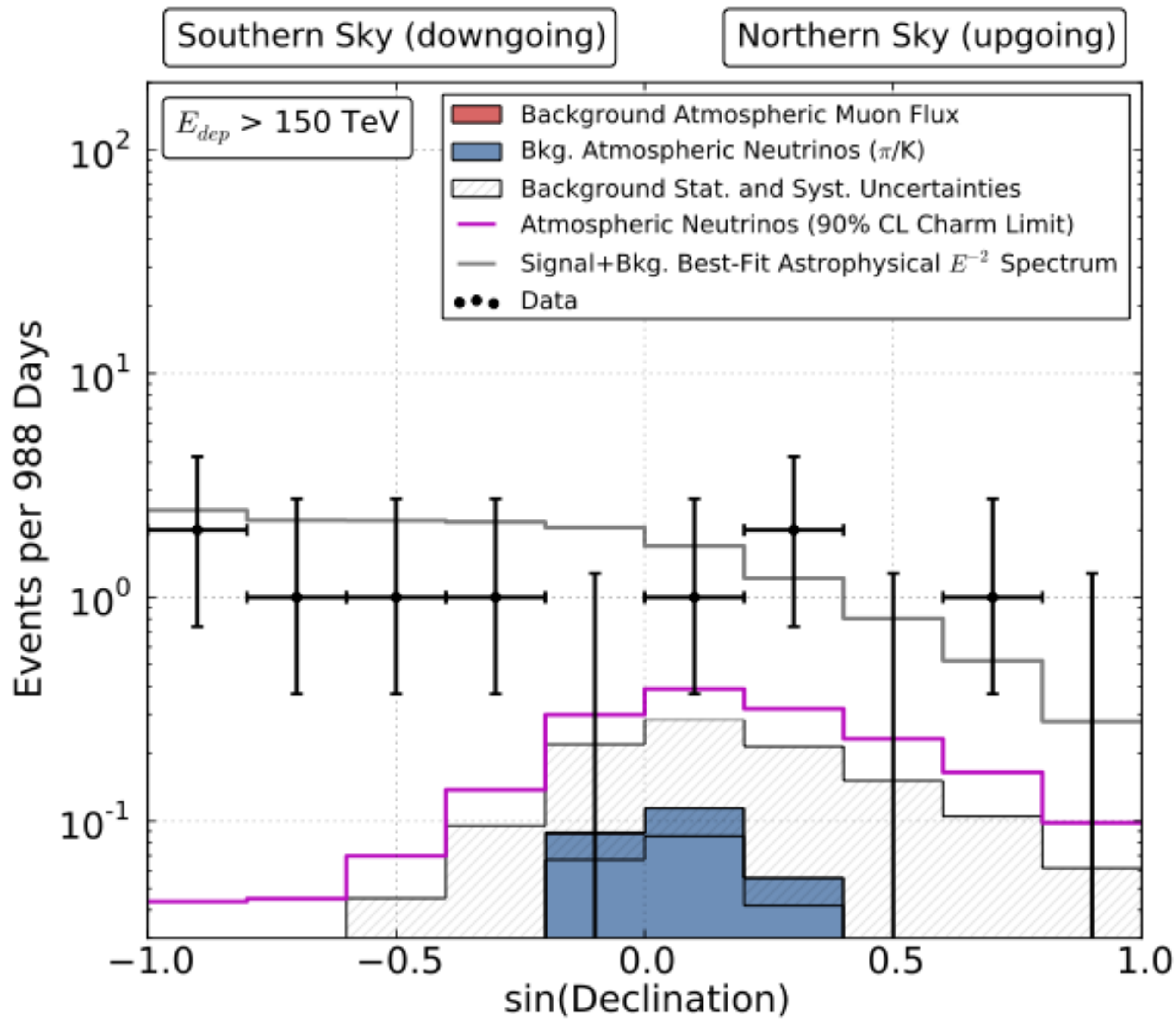


2 PeV event - “Big Bird”

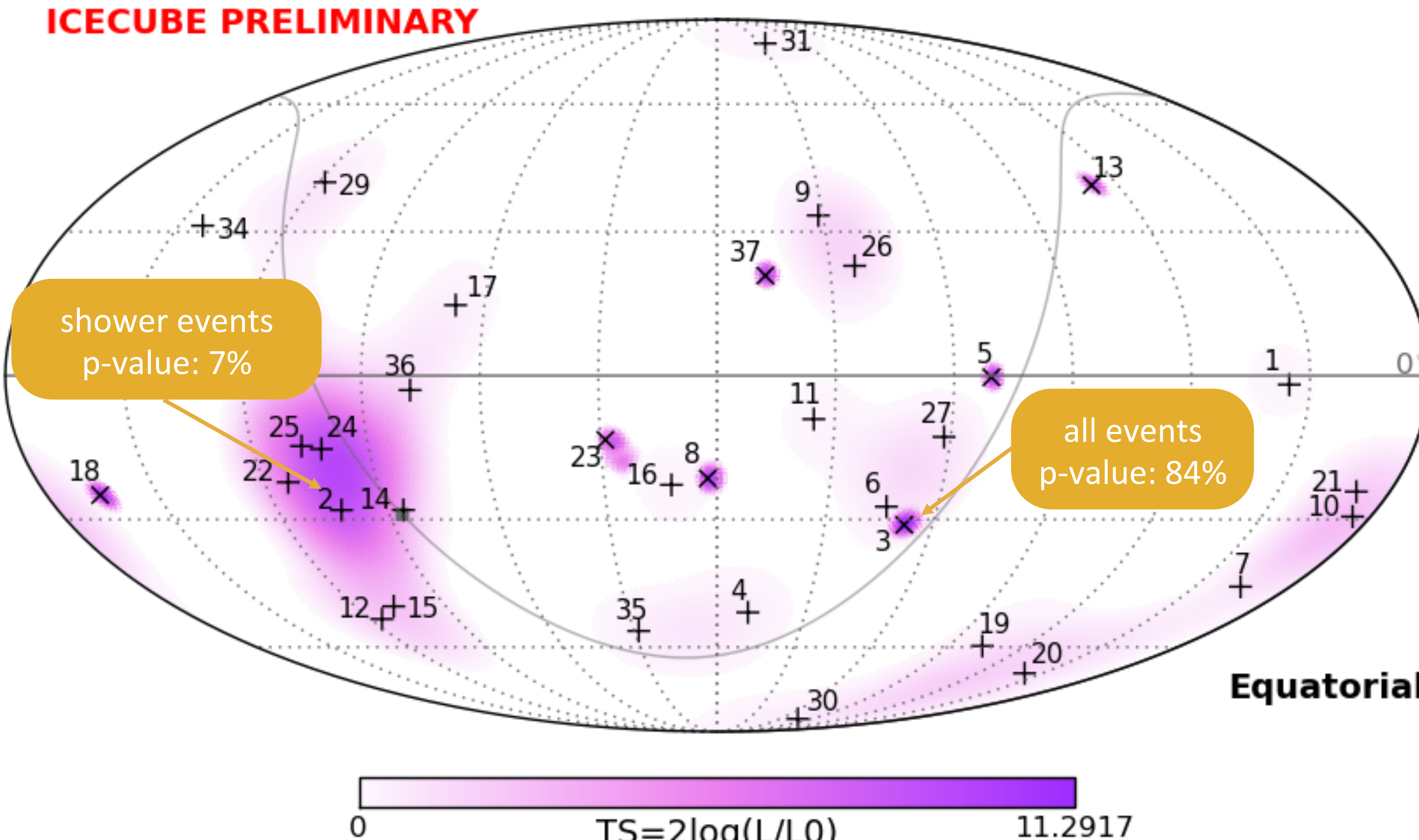
Angular Distribution



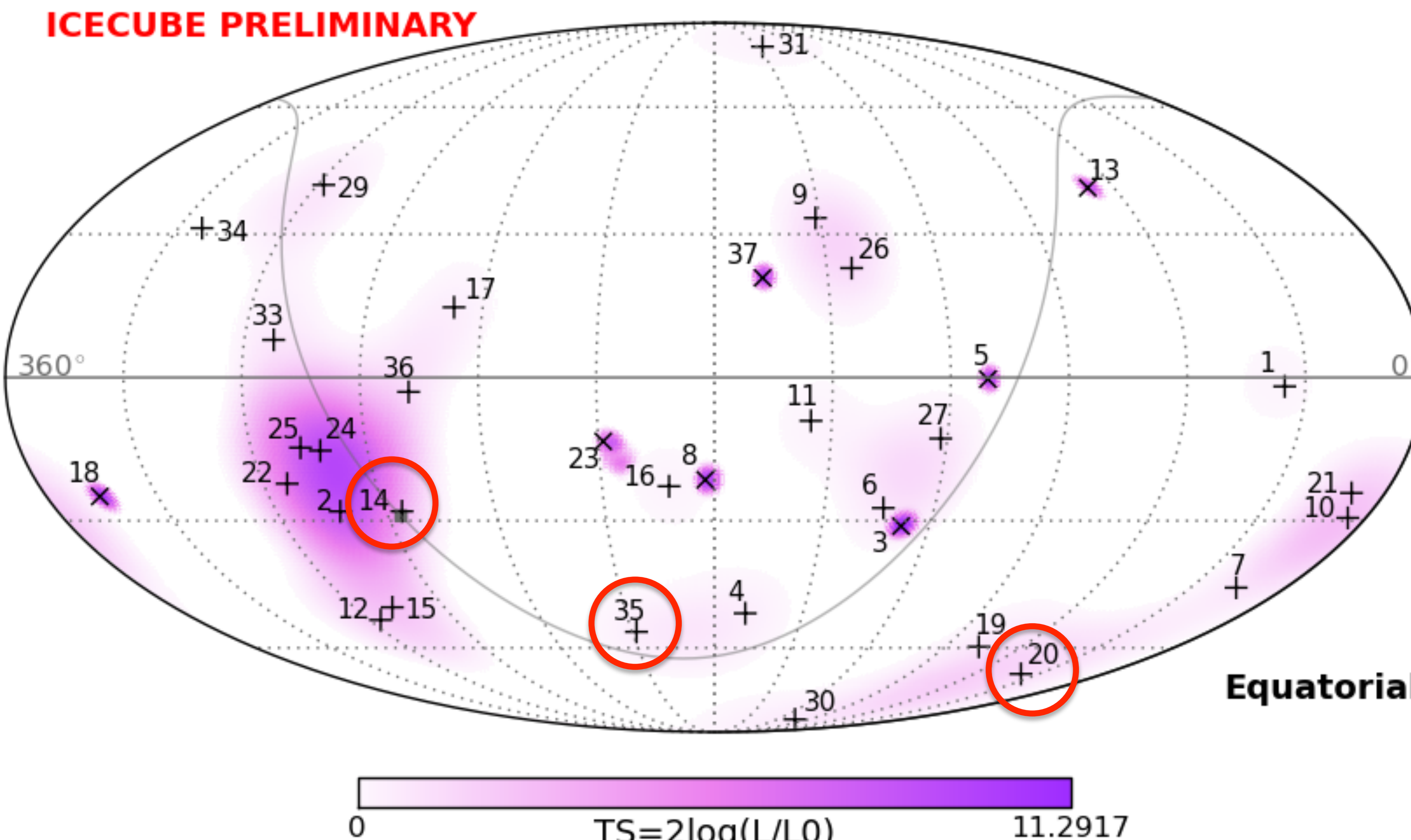
Angular Distribution (higher energy)



Skymap (3 years)

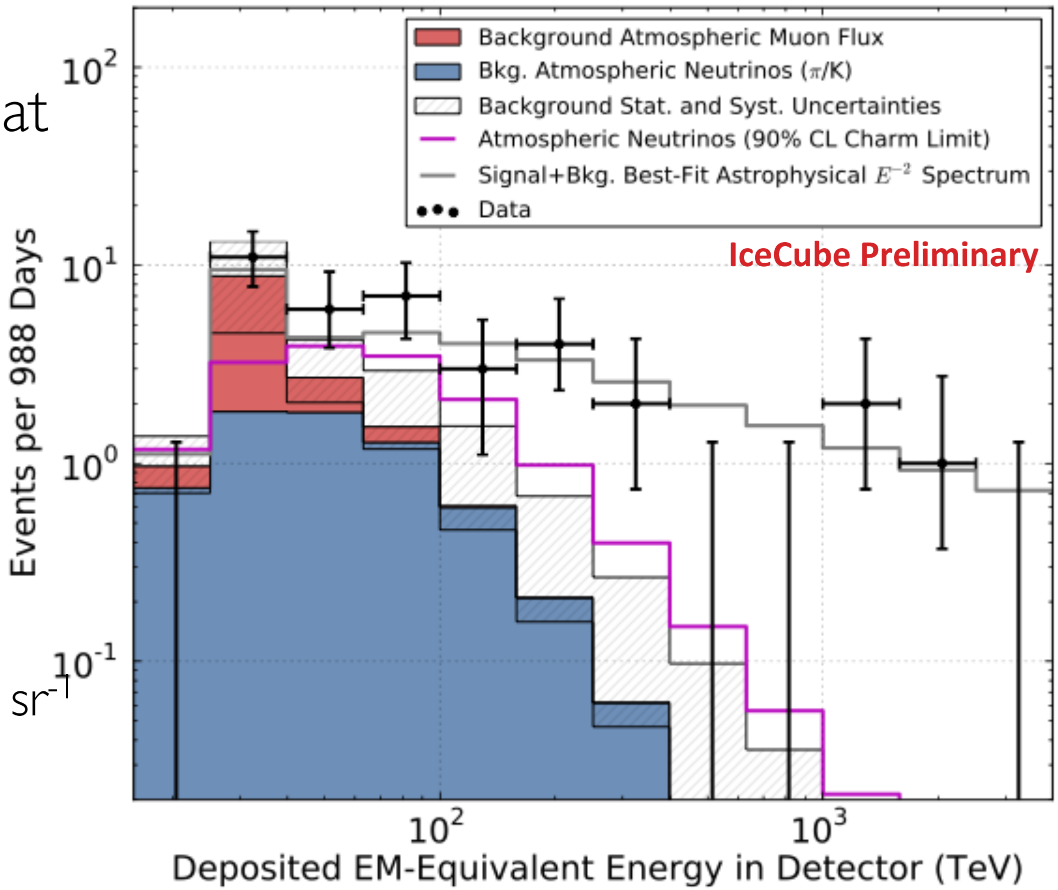


Events with $E_{deposited}$ > 1 PeV



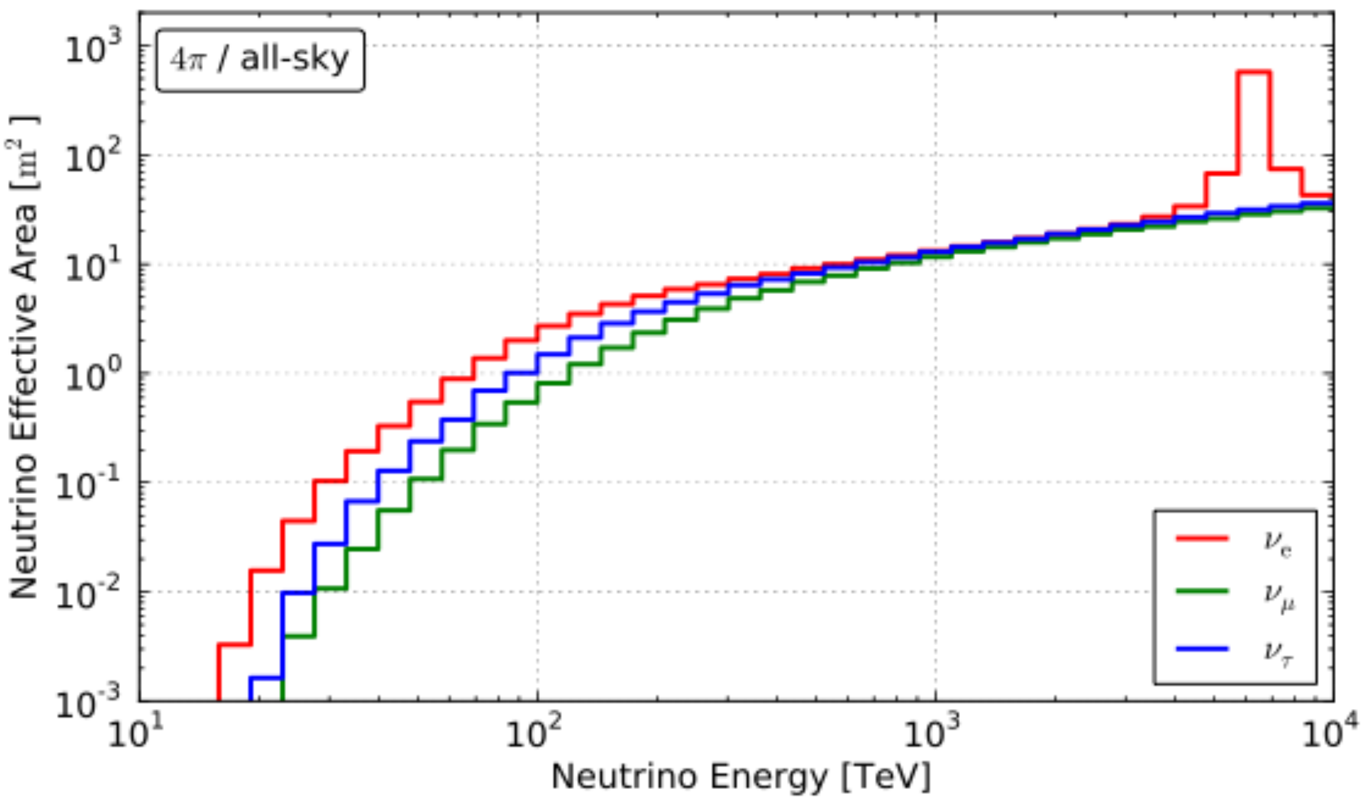
Deposited Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into background at low energies
- Potential cutoff at ~2-5 PeV?
  - 0 events / 3 expected
  - or simply a softer spectrum
- Best-fit per-flavor E^{-2} flux:
  $(0.95 \pm 0.3) \times 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$



Glashow Resonance

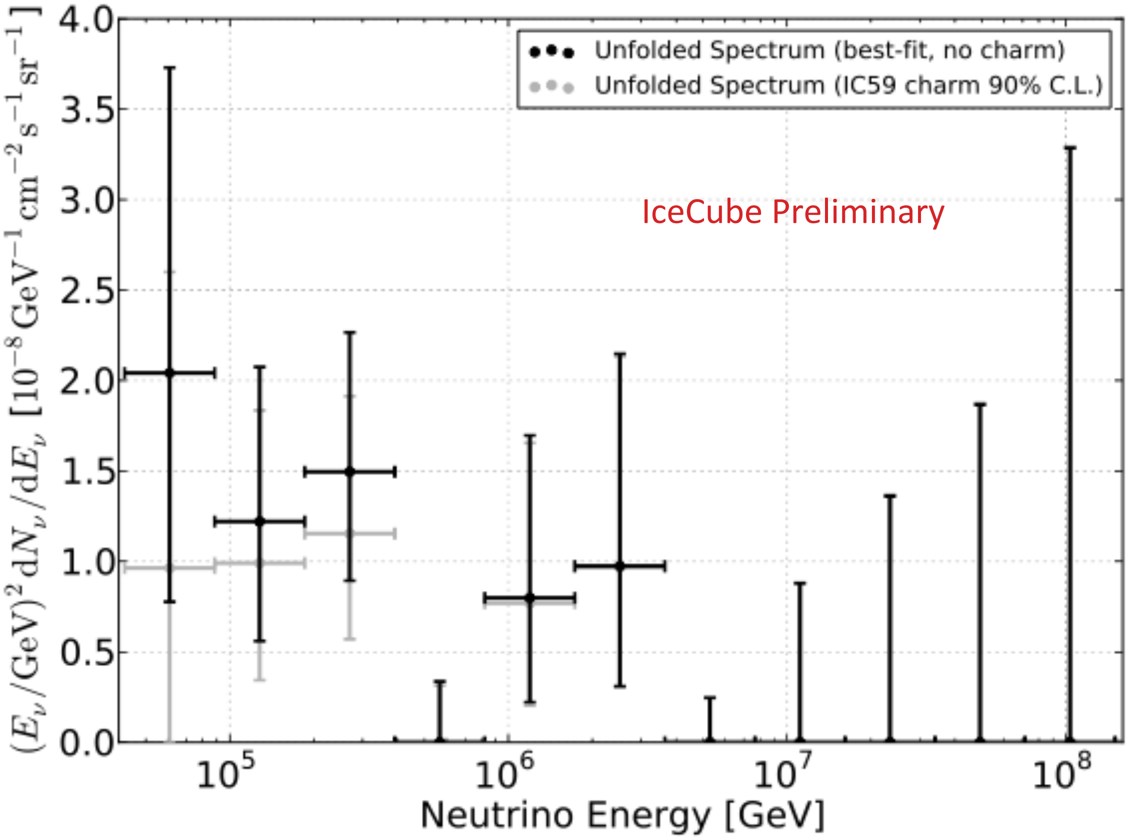
HESE Analysis Effective Area



$$\bar{\nu}_e + e^- \rightarrow W^-$$

Enhancement in cross section at 6.3 PeV
can eventually constrain cutoff / spectral slope

Unfolded Neutrino Energy Spectrum



- Unfold deposited energy to true neutrino energy, fitting for backgrounds
- Assumes 1:1:1 flavor ratio, 1:1 nu/anti-nu

Best-fit power law: $E^2 \phi(E) = 1.5 \times 10^{-8} (E/100\mathrm{TeV})^{-0.3}$ GeV cm^{-2} s^{-1} sr^{-1}

Spectral determination depends on unknown charm atmospheric neutrino flux

Lorentz-violating Particle Interactions

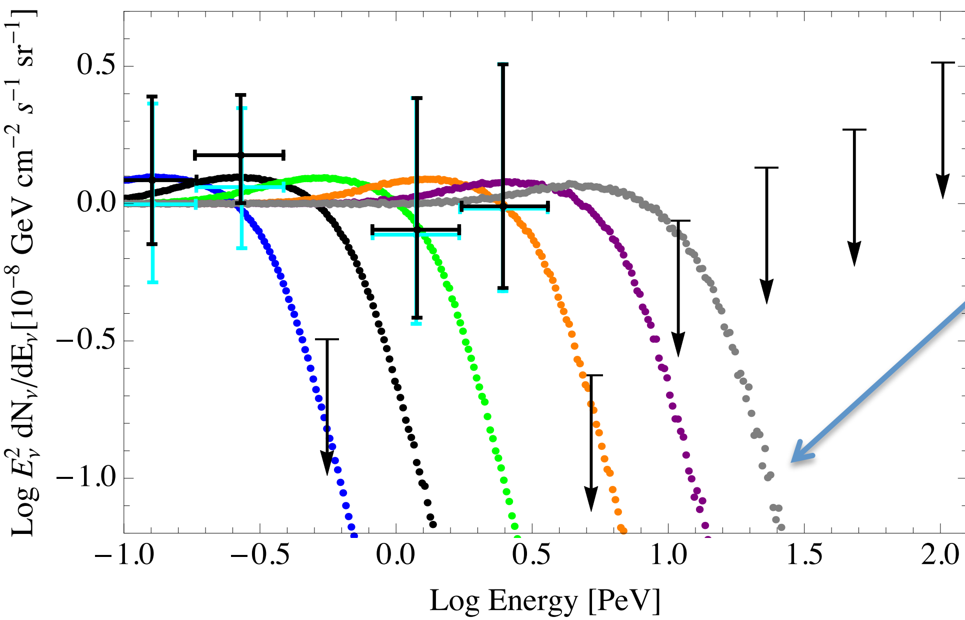
Energy-loss mechanisms during propagation:

vacuum pair emission	$\nu \rightarrow \nu e^+ e^-$	Cohen and Glashow, PRL **107**, 181803 (2011)
vacuum Cherenkov	$\nu \rightarrow \nu\gamma$	Coleman and Glashow, Phys. Lett. B **405**, 249 (1997)
neutrino splitting	$\nu \rightarrow \nu\nu\bar{\nu}$	Mattingly *et al.*, JCAP 2010 (02), 007

Constraints from IceCube Events

Existence of HE neutrinos leads to limits on superluminal velocity

F. Stecker & S. Scully, arXiv:1404.7025



Pair-production thresholds of 1 to 40 PeV
10 PeV required for consistency with IceCube

Maximum velocity difference upper limit:

$$\delta_{\nu e} = \delta_\nu - \delta_e \leq \ 5.2 \times 10^{-21}$$

Cutoff can be modeled as vacuum pair emission (or astrophysics!)

Constraints on Planck-Scale Dissipative Effects

S. Liberati and L. Maccione, PRL **112**, 151301 (2014)

- Modified dispersion relationship in generic LV scenario also induces dissipative effects
- Use Analogue Gravity formalism to model spacetime "fluid"

$$\omega^2 = c^2 k^2 - i\sigma_2 c^2 \frac{k^3}{M_{\rm Pl}}$$

dissipative term

$$\sigma_2 c^2 \frac{k^3}{M_{\rm Pl}} \equiv 2\omega\Gamma$$

LV parameter

energy-loss rate

Limits on Dissipation

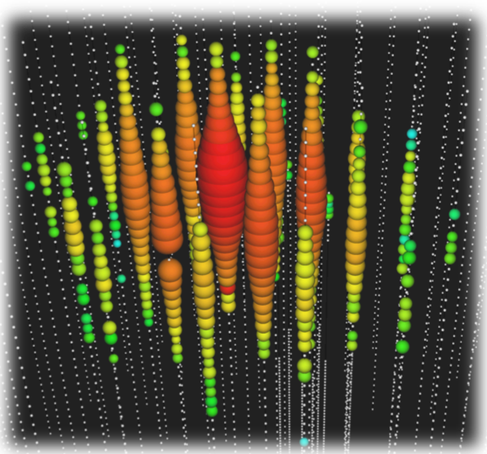
S. Liberati and L. Maccione, PRL **112**, 151301 (2014)

For IceCube (conservatively):

E_ν ~ 100 TeV, D ~ 8 kpc (if galactic)

upper limit on dissipative LV parameter: $$\sigma_2 \lesssim 2 \times 10^{-27}$$

factor of ~6 better than limit using gamma rays from Crab nebula



Limits can be dramatically improved if we can demonstrate extragalactic nature!
(D ~ 10 to 100 Mpc)

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

see e.g. Morgan *et al.*, astro-ph/0412628

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

- Observable effect on neutrino oscillations with characteristic exponential behavior:

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

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

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

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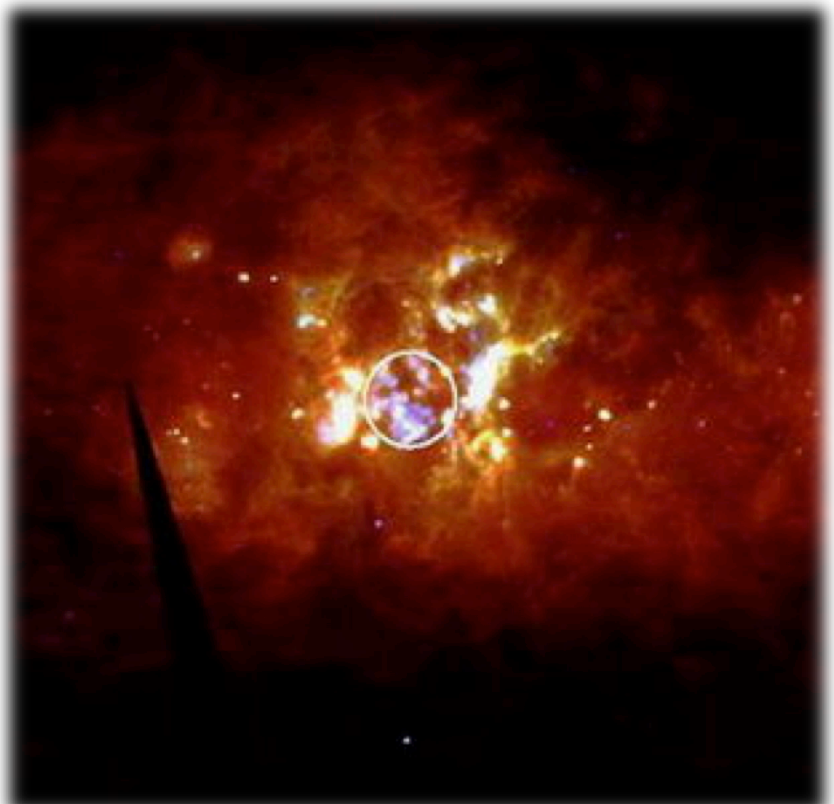
- Limits using atmospheric neutrinos with AMANDA-II (PRD **79** 102005 (2009))

QD from Galactic Neutron Source

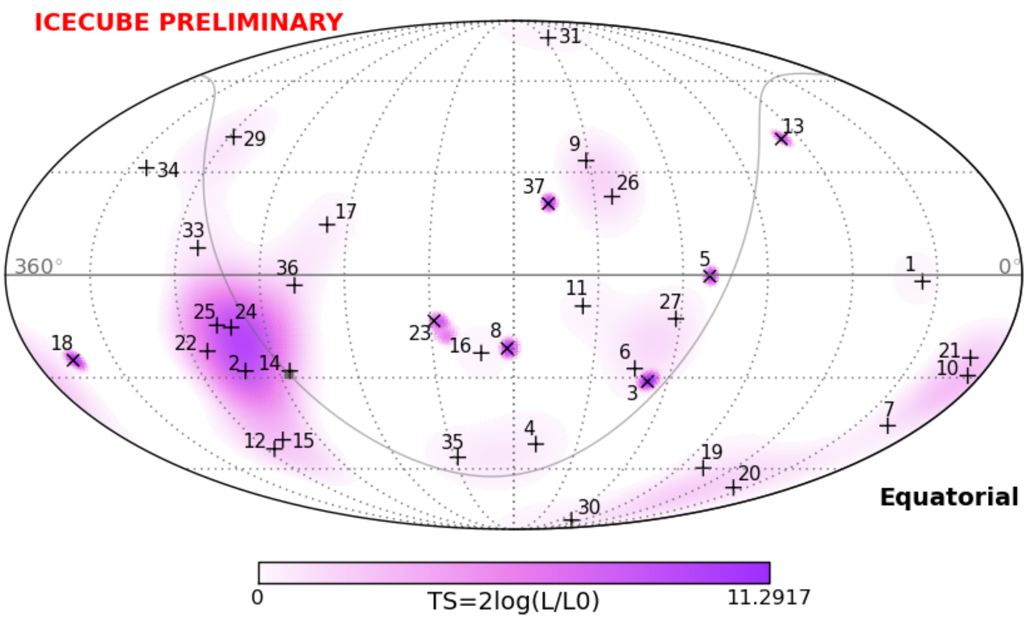


Cygnus OB2 region
courtesy of J. Knoedlseder

- Standard hadronic source: 1:2:0 oscillates to 1:1:1 regardless of QD
- But a source of anti-electron neutrinos could provide strong limits
  - 0.56:0.24:0.20 expected
  - 1:1:1 after QD

Anchordoqui *et al.*, Phys. Rev. D **72** 065019 (2005)

Some Open Questions

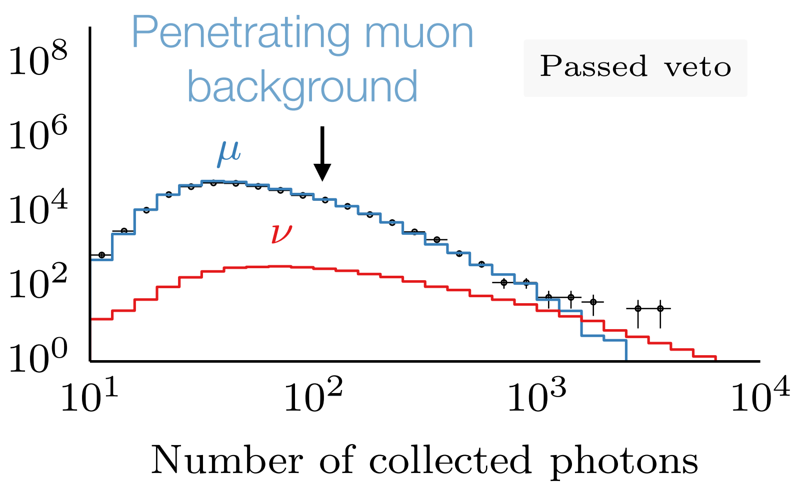


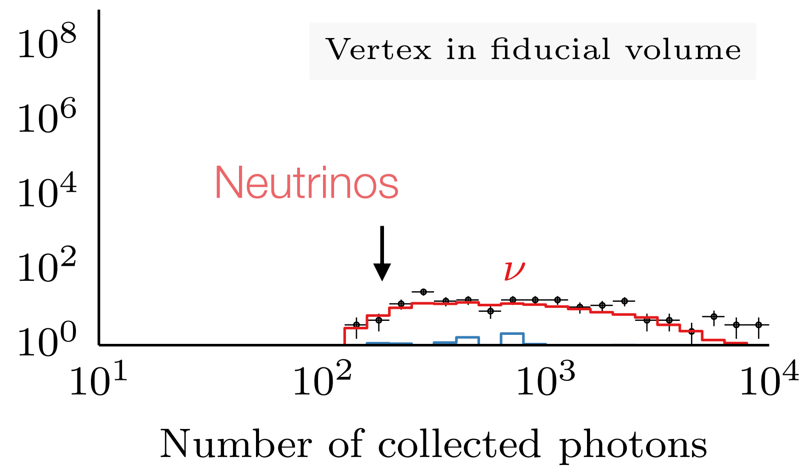
- Is there a "cutoff"?
- What is the flavor ratio?
- Are the events isotropic, i.e. likely extragalactic?
- What are the sources?

Extending to Lower Energies

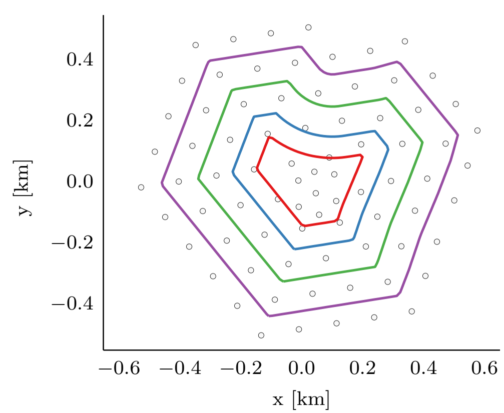
Outer-layer veto → Energy-dependent veto

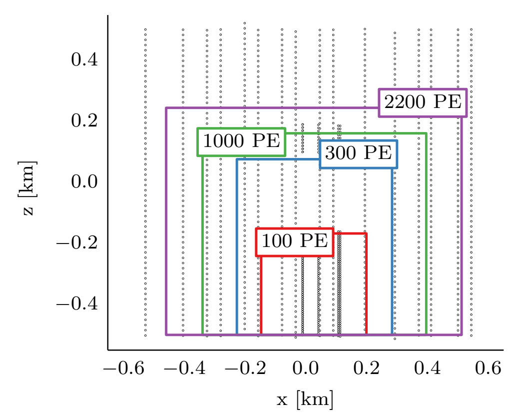
Neutrino-dominated for E_{dep} > 60 TeV — **Neutrino-dominated for E_{dep} > 1 TeV**





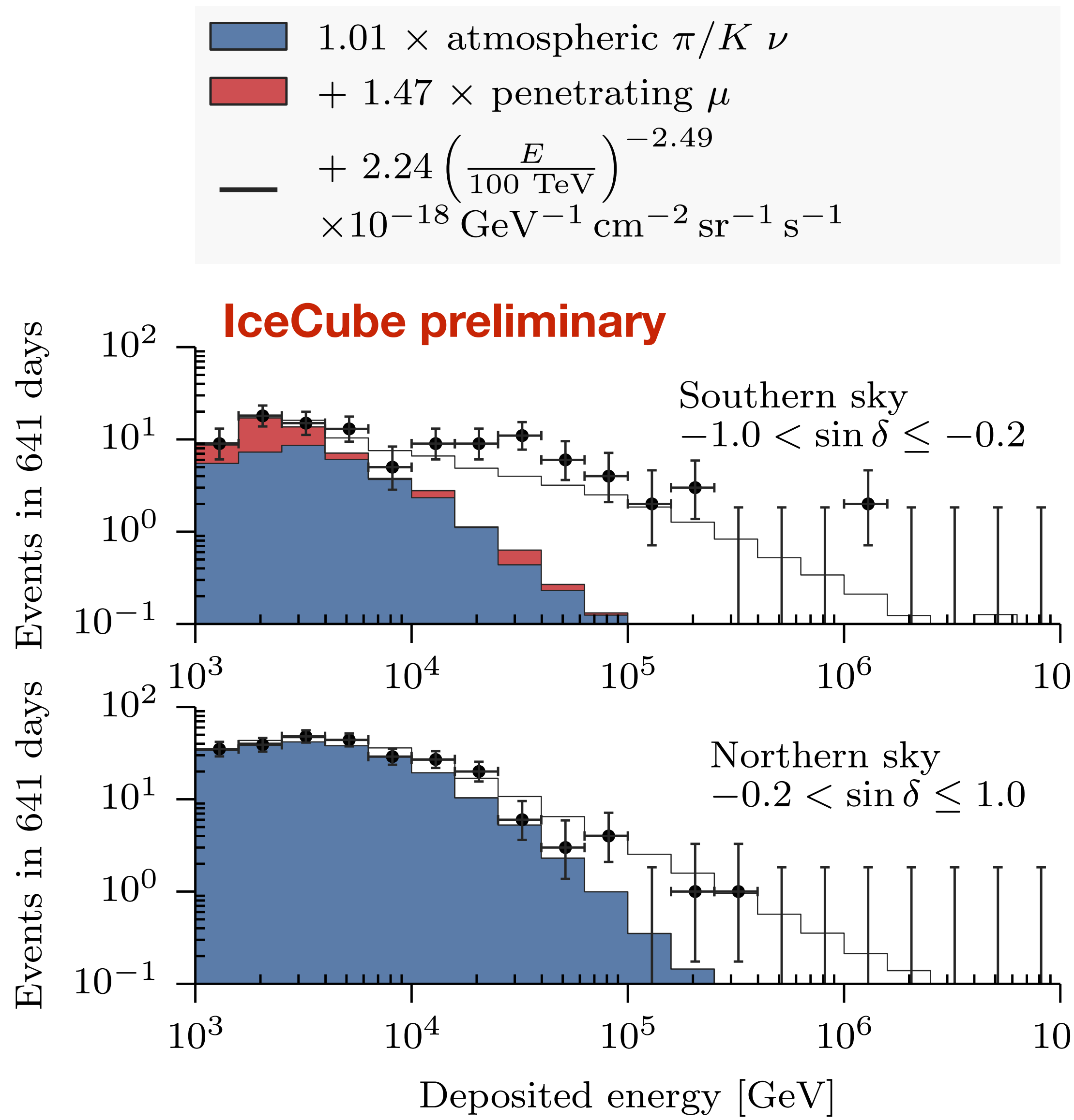
Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance



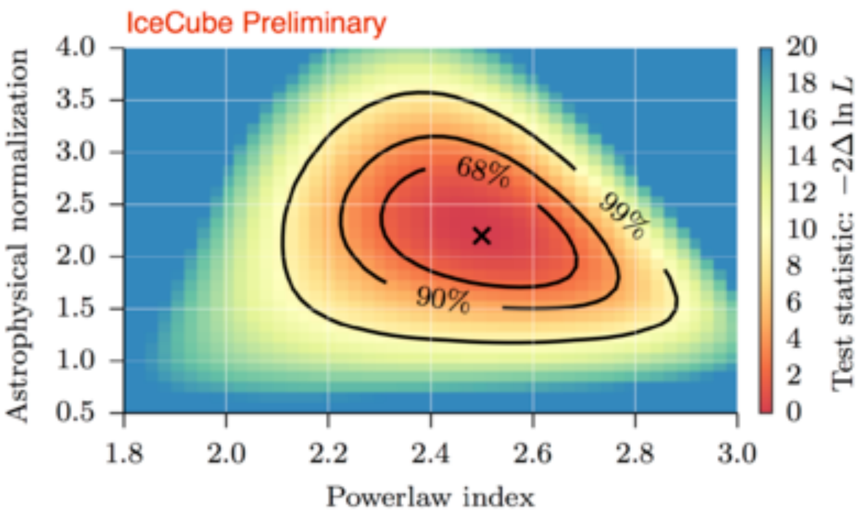


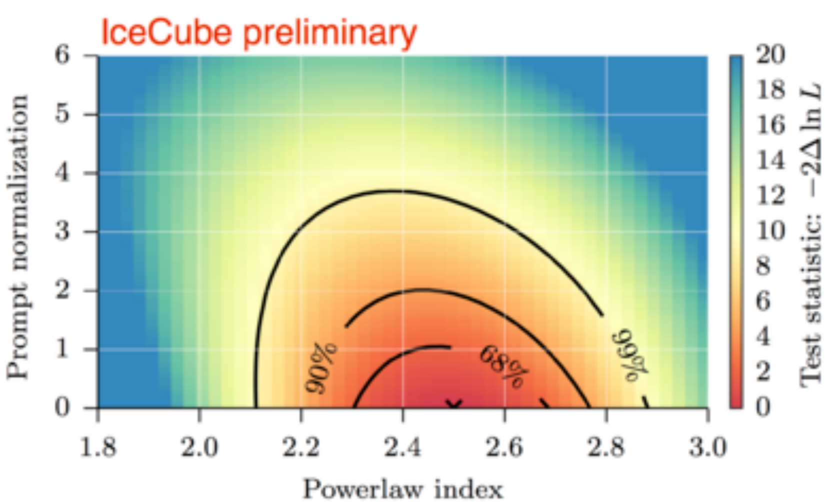
Deposited Energy Spectrum

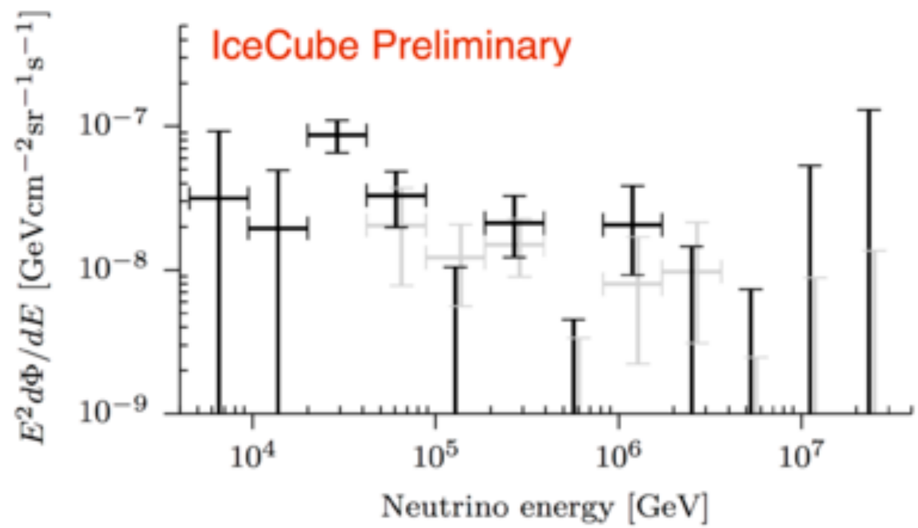
- 283 showers, 105 tracks observed in 2 years of data
- Astrophysical excess continues to lower energies (~10 TeV)
- No atmospheric charm component observed, upper limit set
- Best-fit spectrum is $E^{-2.49}$



Unfolded Energy Spectrum





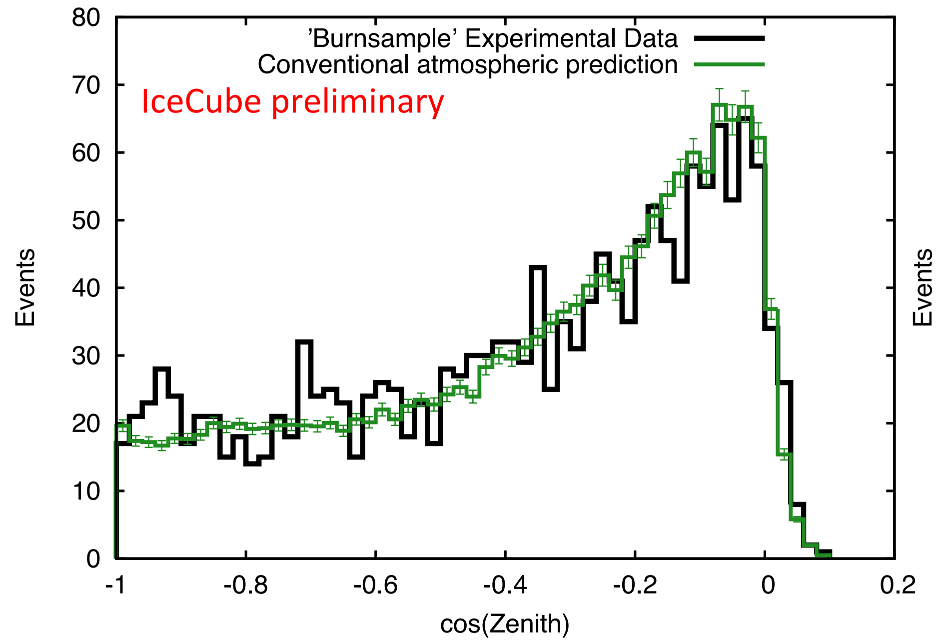


Unfolded neutrino spectrum from 2-year energy-dependent veto analysis

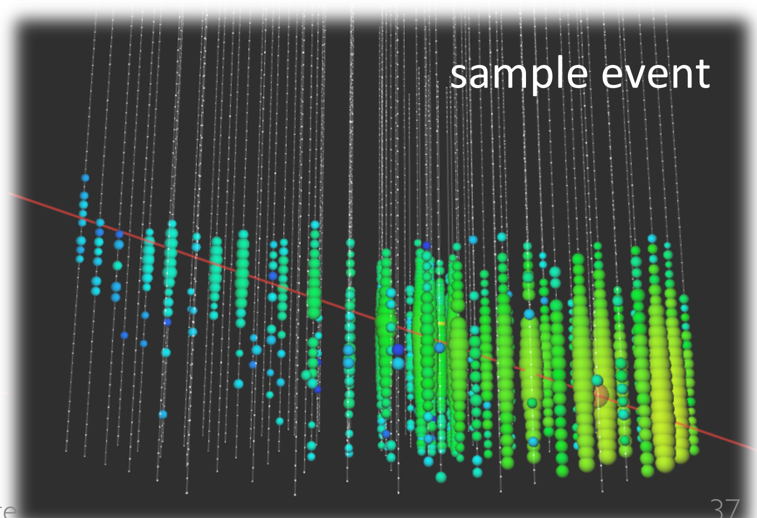
Grey points: HESE 3-year spectrum

Northern Hemisphere Muon Neutrinos

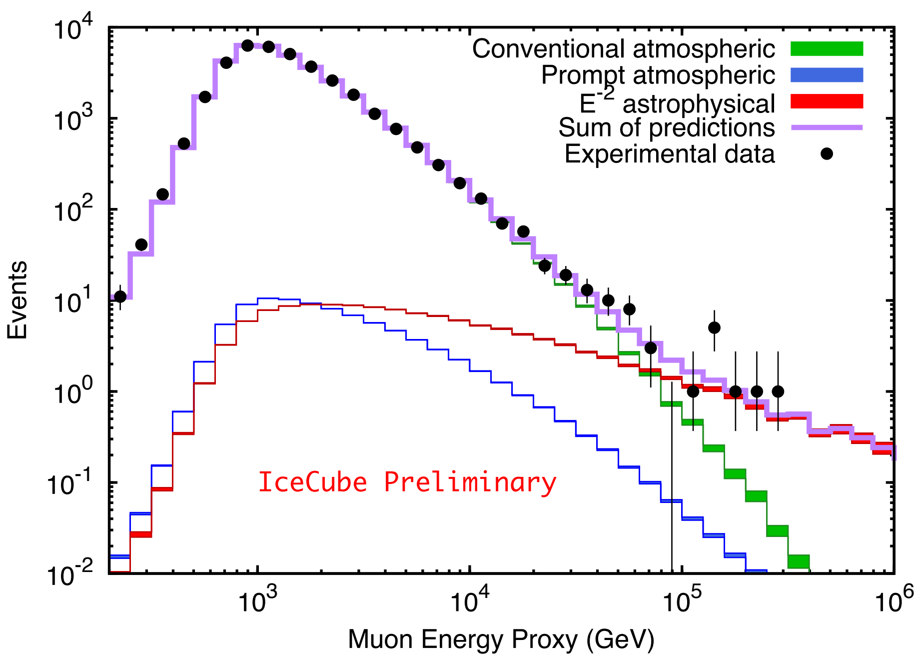
- Conventional analysis of up-going track-like events
  - Earth as a filter for cosmic-ray muons
  - sensitive to muon neutrinos only



- ~35000 neutrinos in two years of data (mostly atmospheric)

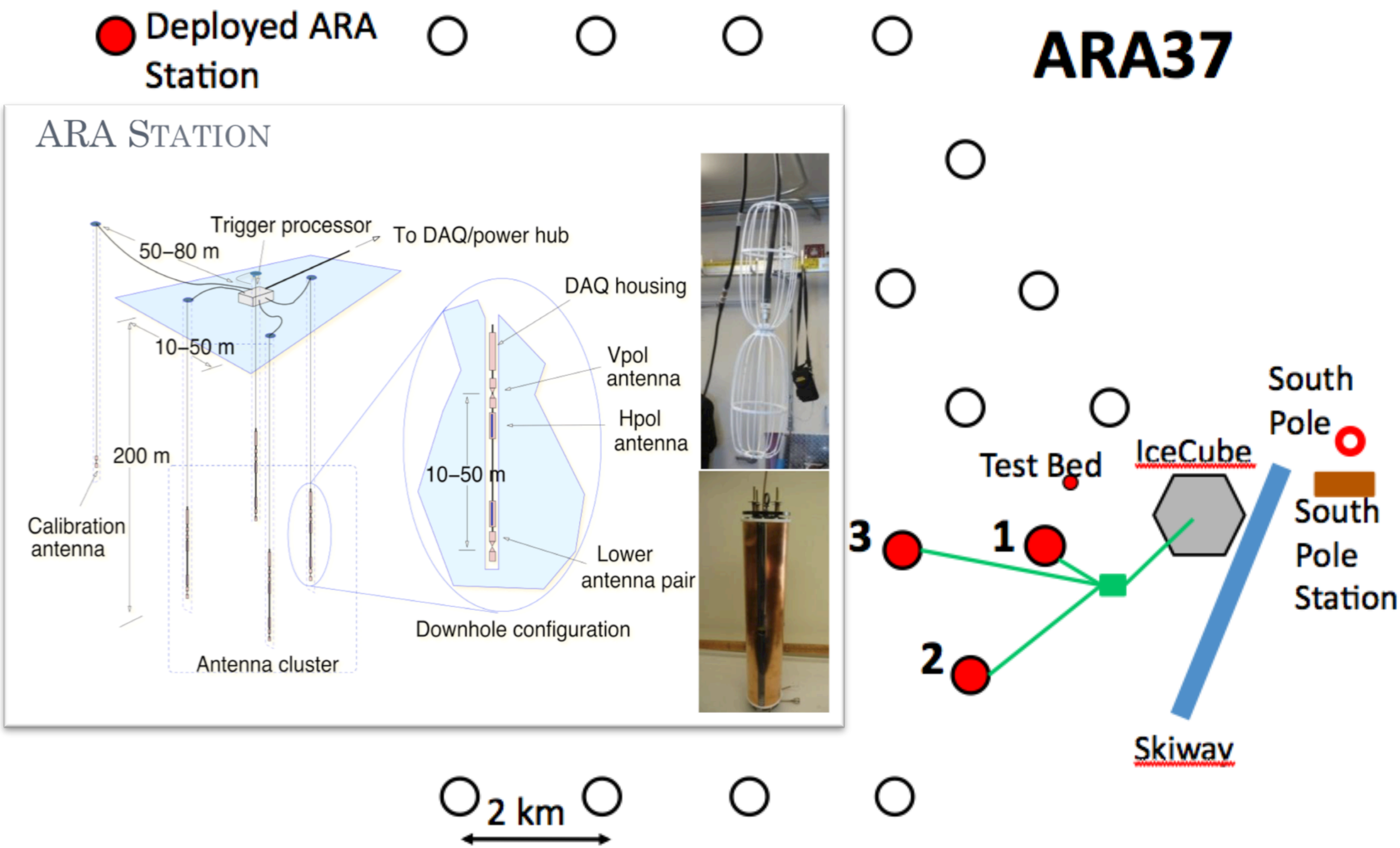


ν_μ Diffuse Flux



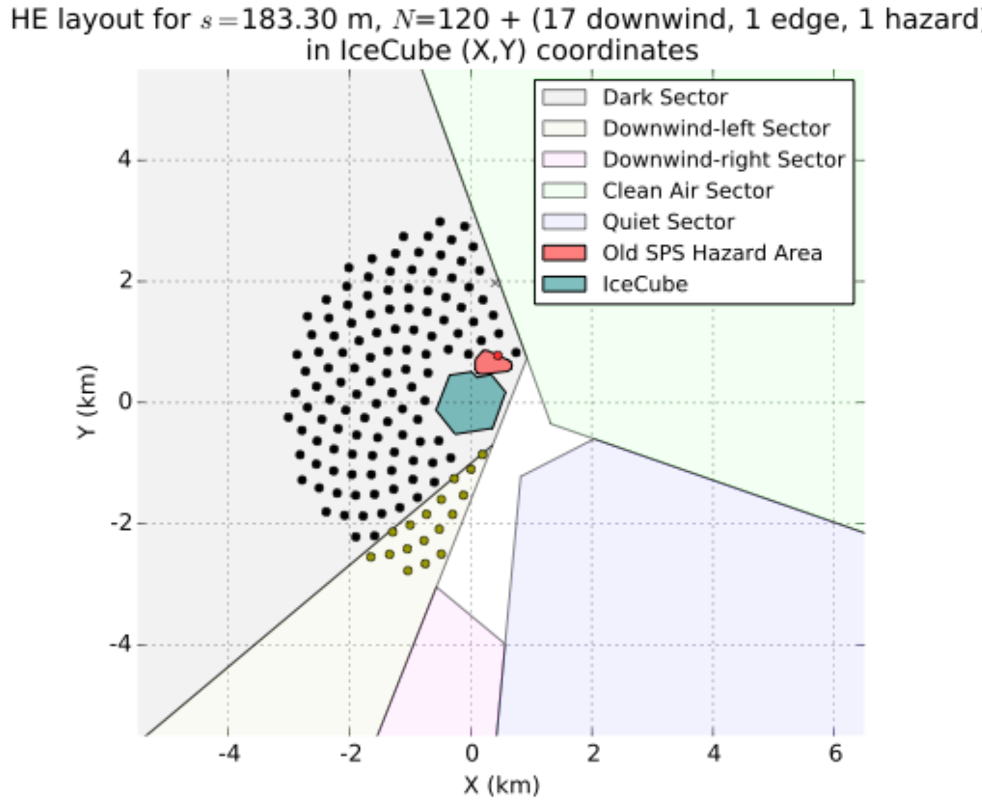
- Best-fit E^{-2} flux: 0.96×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- Atmospheric-only hypothesis disfavored at 3.9σ
- Supporting evidence for isotropy and 1:1:1 flavor ratio
- With free spectral index: best-fit power law is $E^{-2.2}$

Looking Forward: ARA

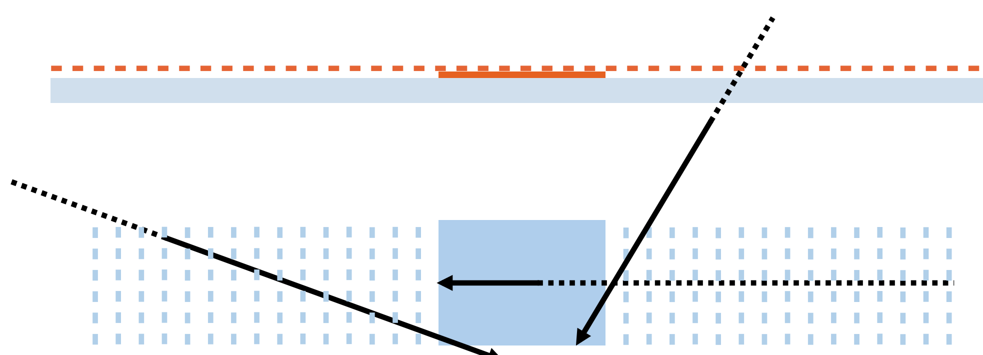


Looking Forward: IceCube HEX

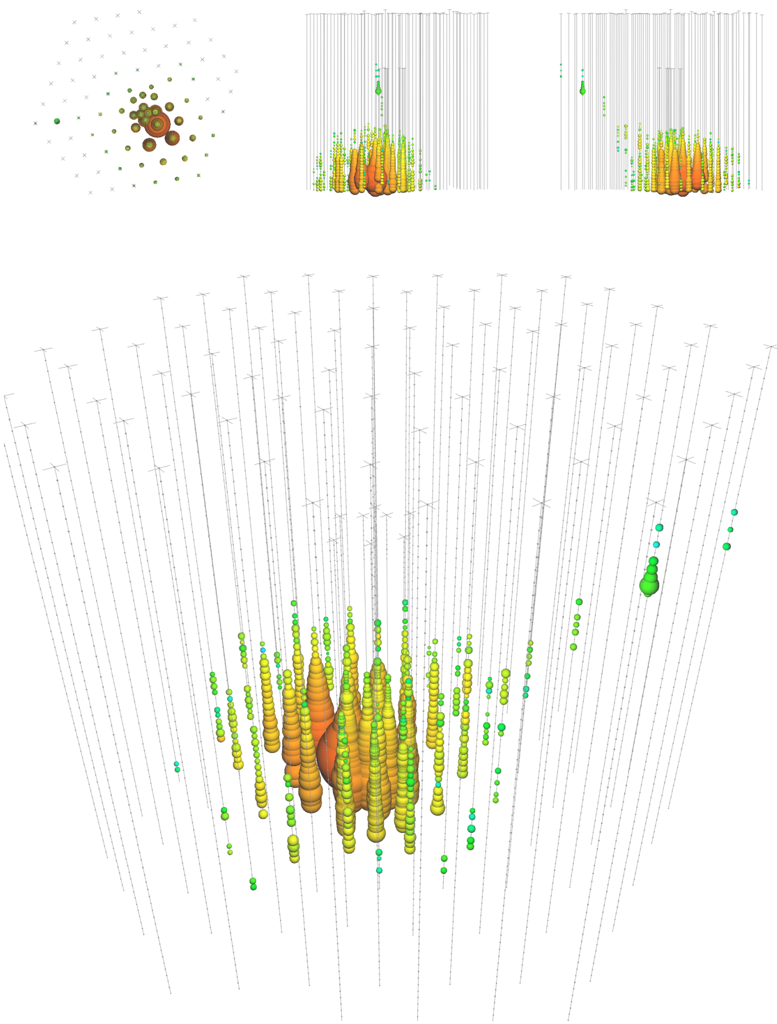
- IceCube High-energy extension
  - high-statistics energy spectrum
  - high-energy track events to pinpoint sources



- Extended surface veto



What We've Seen



- IceCube has observed a diffuse flux of high-energy astrophysical neutrinos
- Flavor ratio consistent with 1:1:1
  - quantitative analysis underway
- No evidence of anisotropy
  - at least partially extragalactic?
- Astrophysical component measured at lower energies, and in muon neutrino sample
  - some tension in energy spectrum
  - reality more complicated than simple hypothesis?

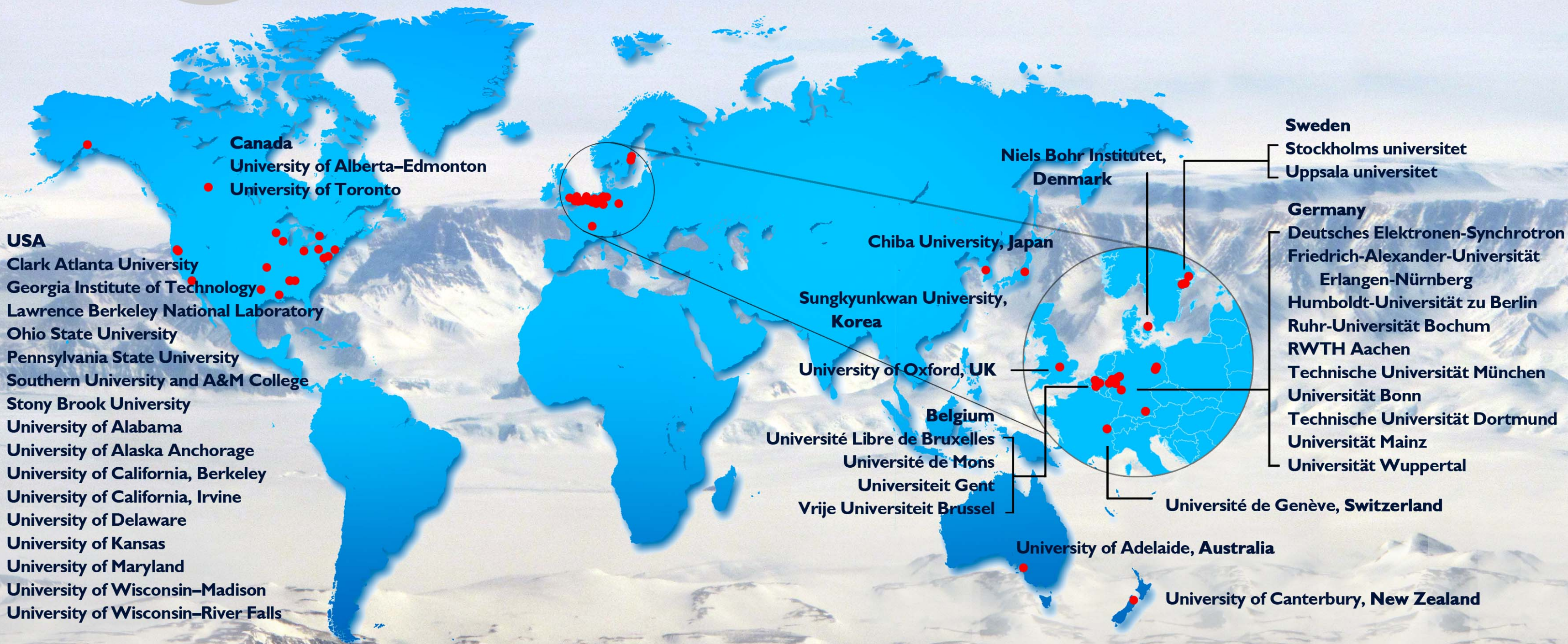
Implications for QG Phenomenology

- Observation of *O*(PeV) neutrinos can constrain:
  - superluminal propagation
  - dissipative effects from underlying spacetime structure

- Expect limits to improve...
  - as we observe higher-energy events
  - if events are extragalactic

- Ongoing analyses will help us understand the astrophysics

The IceCube Collaboration



Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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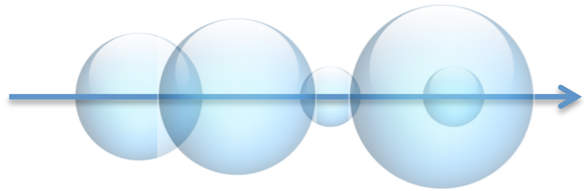
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Thank you!

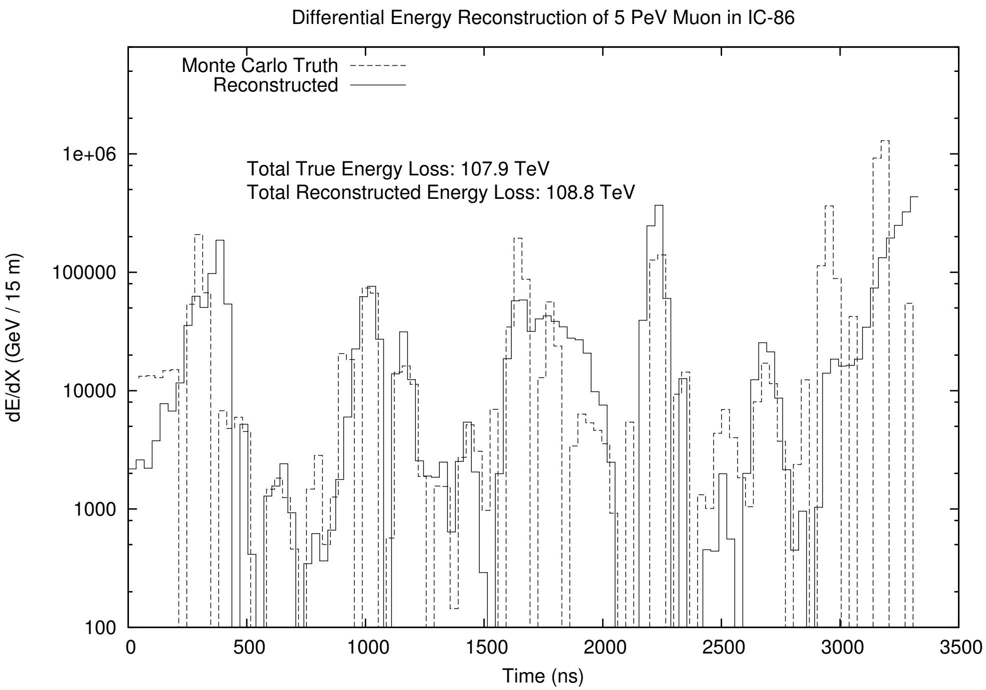
Backup

Deposited vs. Neutrino Energy

Aartsen *et al.*, JINST **9** (2014), P03009



Unfolding of *dE/dx* along muon track



Muon *dE/dx* vs. neutrino energy