Very-high-energy astrophysical neutrinos with IceCube

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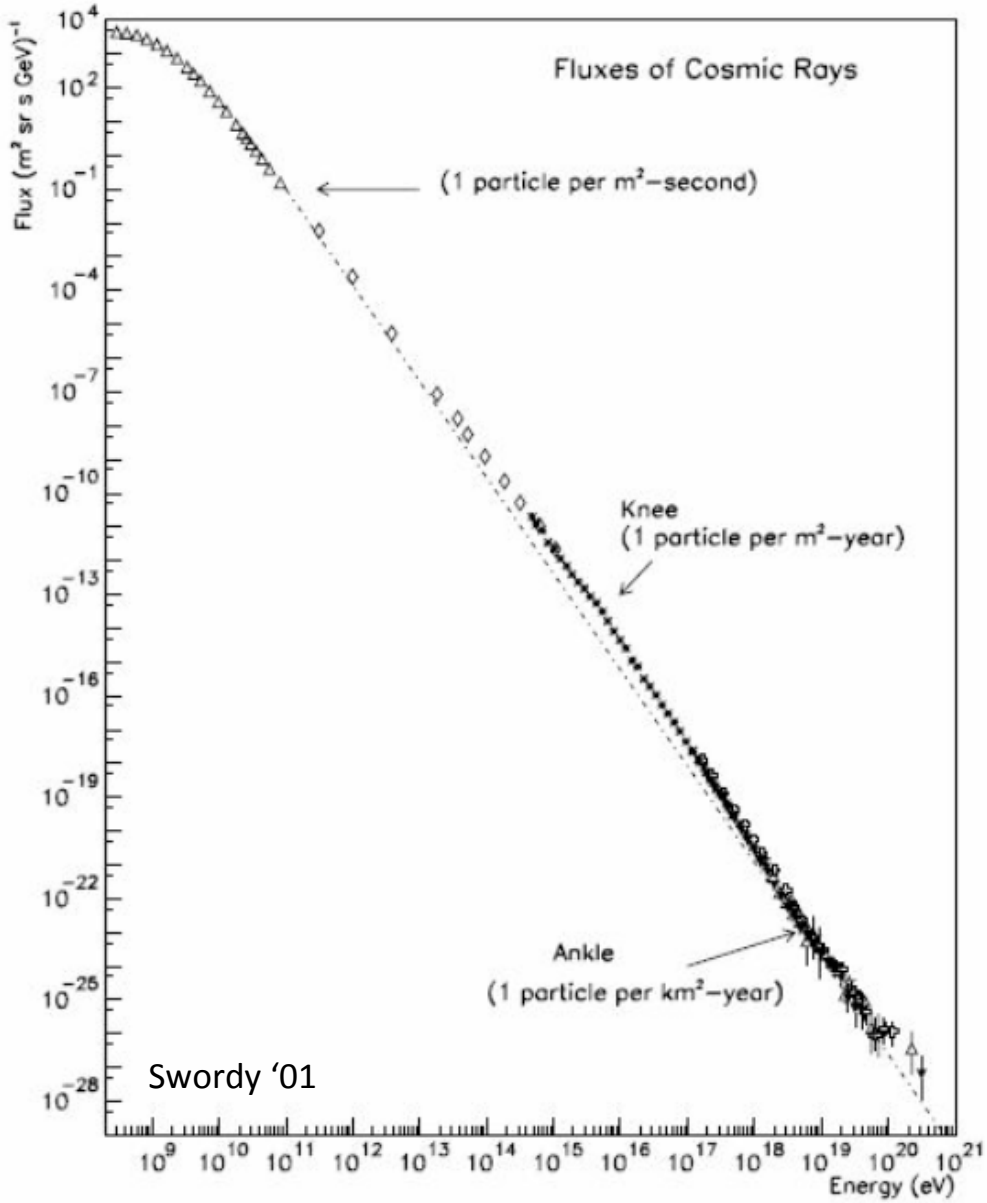
Cosmic Rays – Neutrinos – γ rays



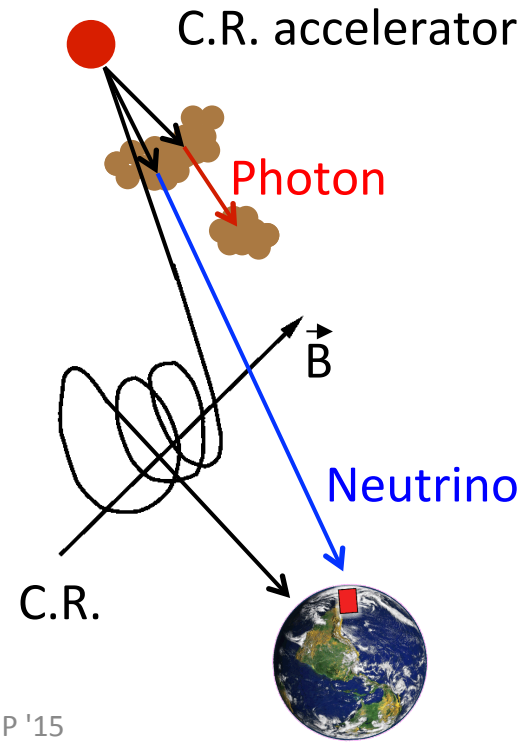
$$p + p \to \pi + \ldots$$

$$p + \gamma \to \Delta^+ \to \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

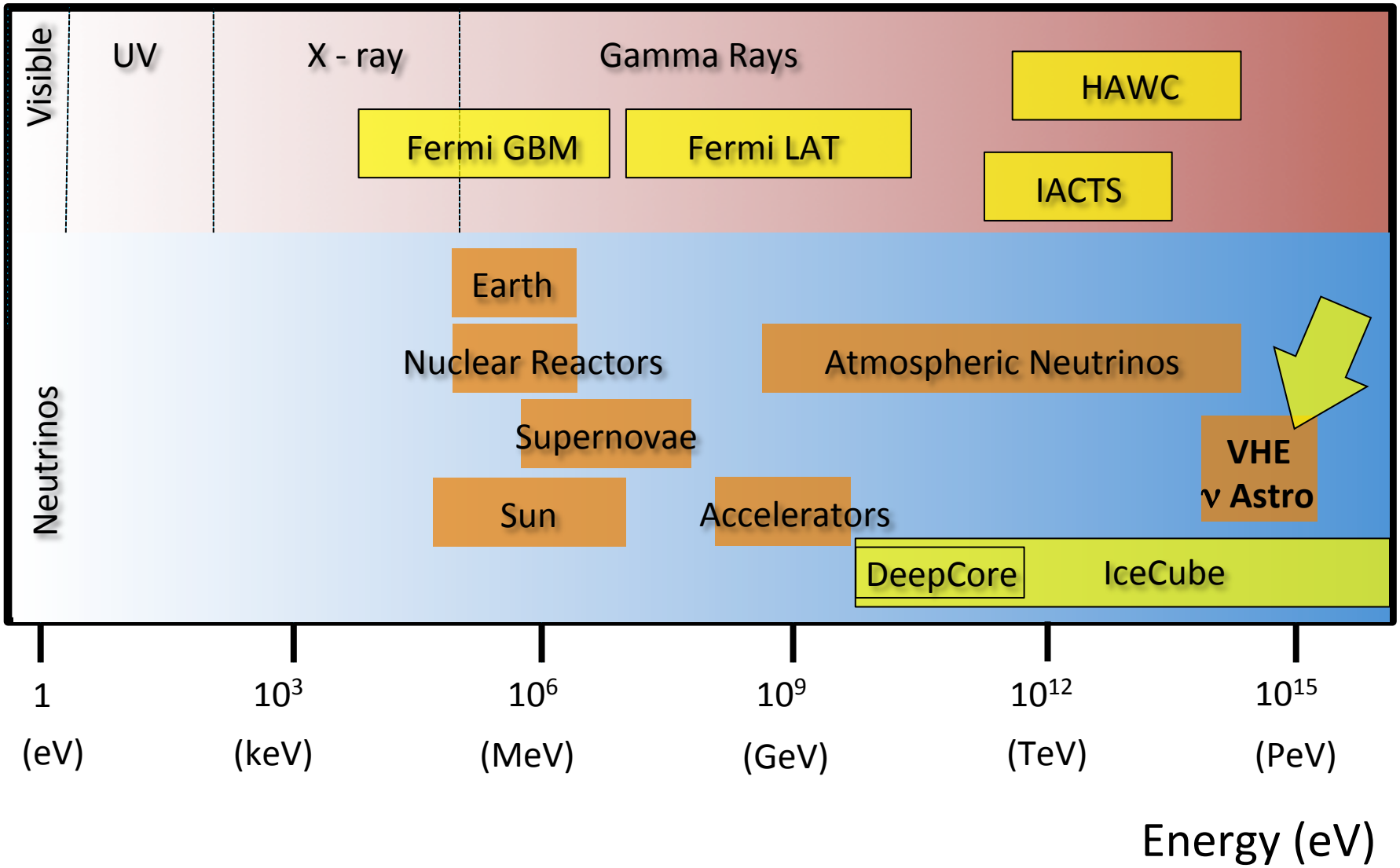
$$\pi^0 \to \gamma + \gamma$$

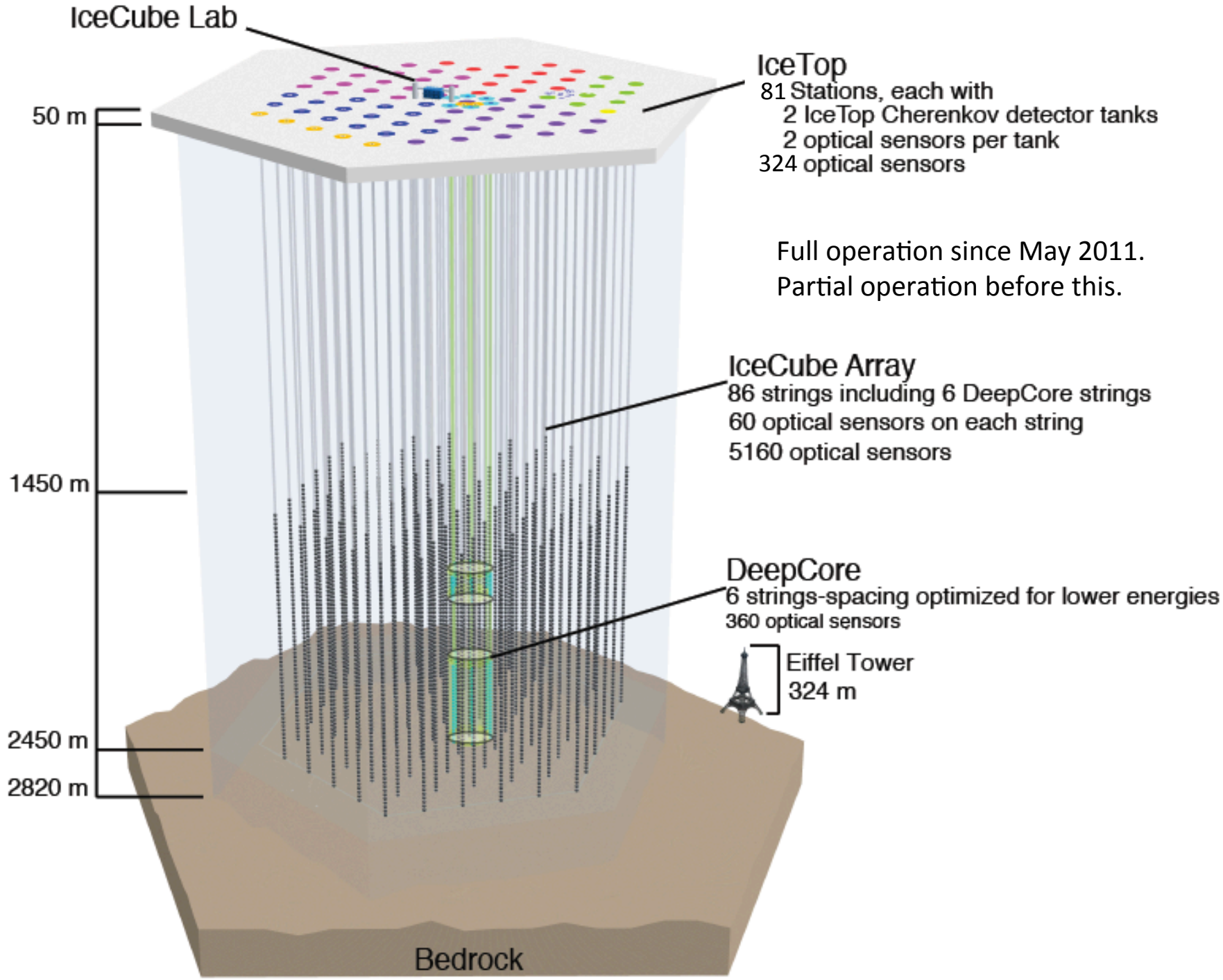
$$\pi^+ \to \mu^+ + \nu_\mu$$

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

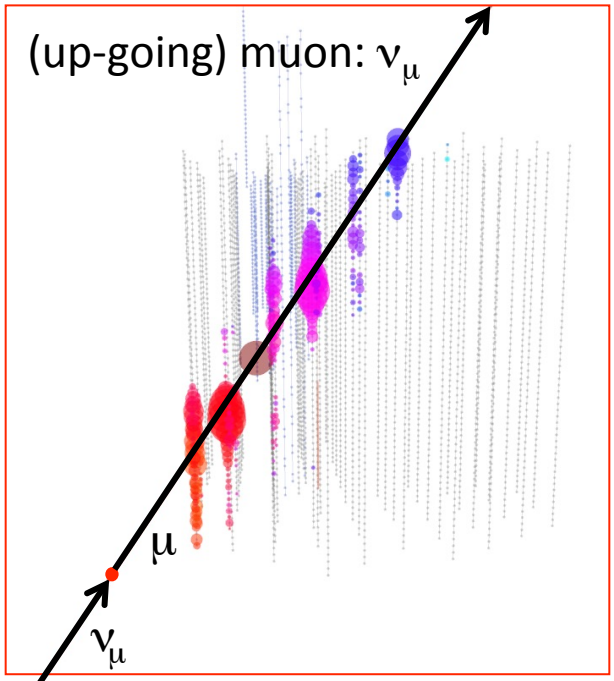


Neutrinos and γ rays

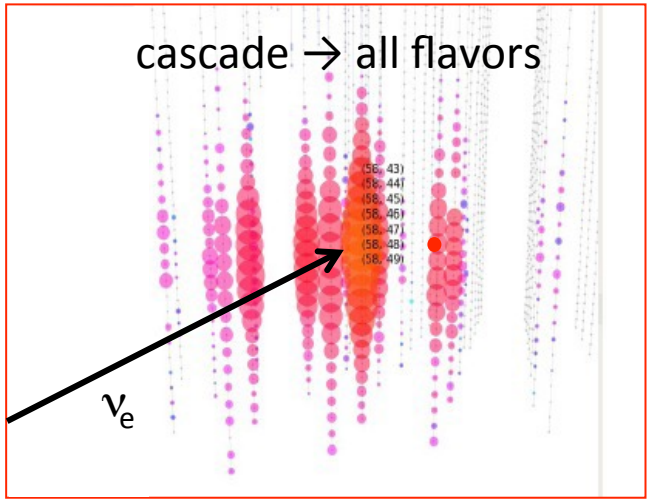



IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
50 m
Full operation since May 2011.
Partial operation before this.
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
1450 m
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

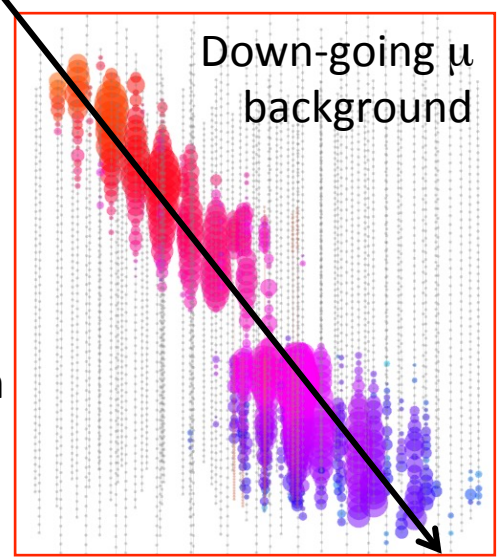
Event signatures



Good angular resolution <1°
<u>Visible</u> energy resolution ~20%
Poor ν-μ energy correlation



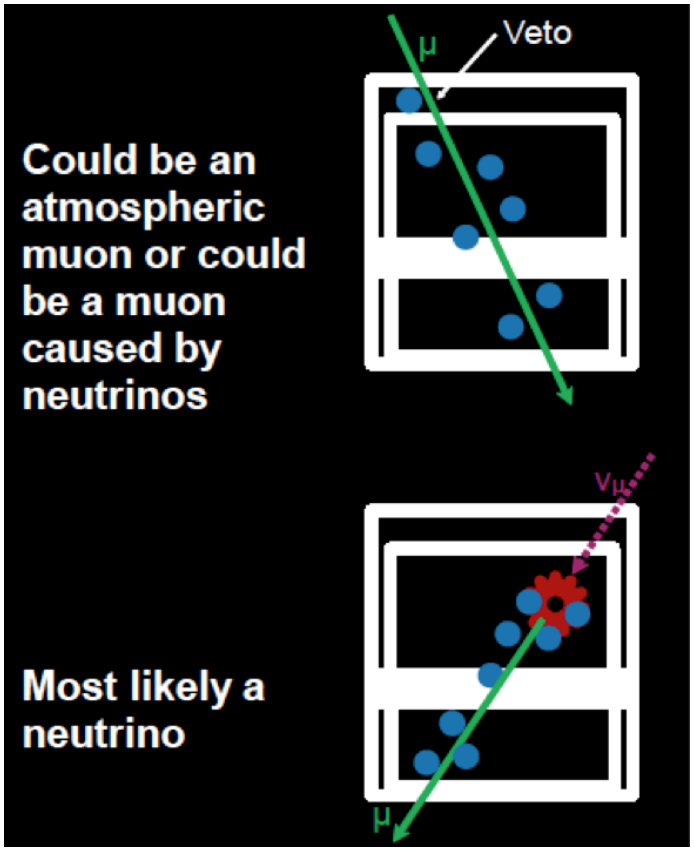
Poor angular resolution 10° – 40°
<u>Visible</u> energy resolution ~20%
Good(*) ν-cascade energy correlation

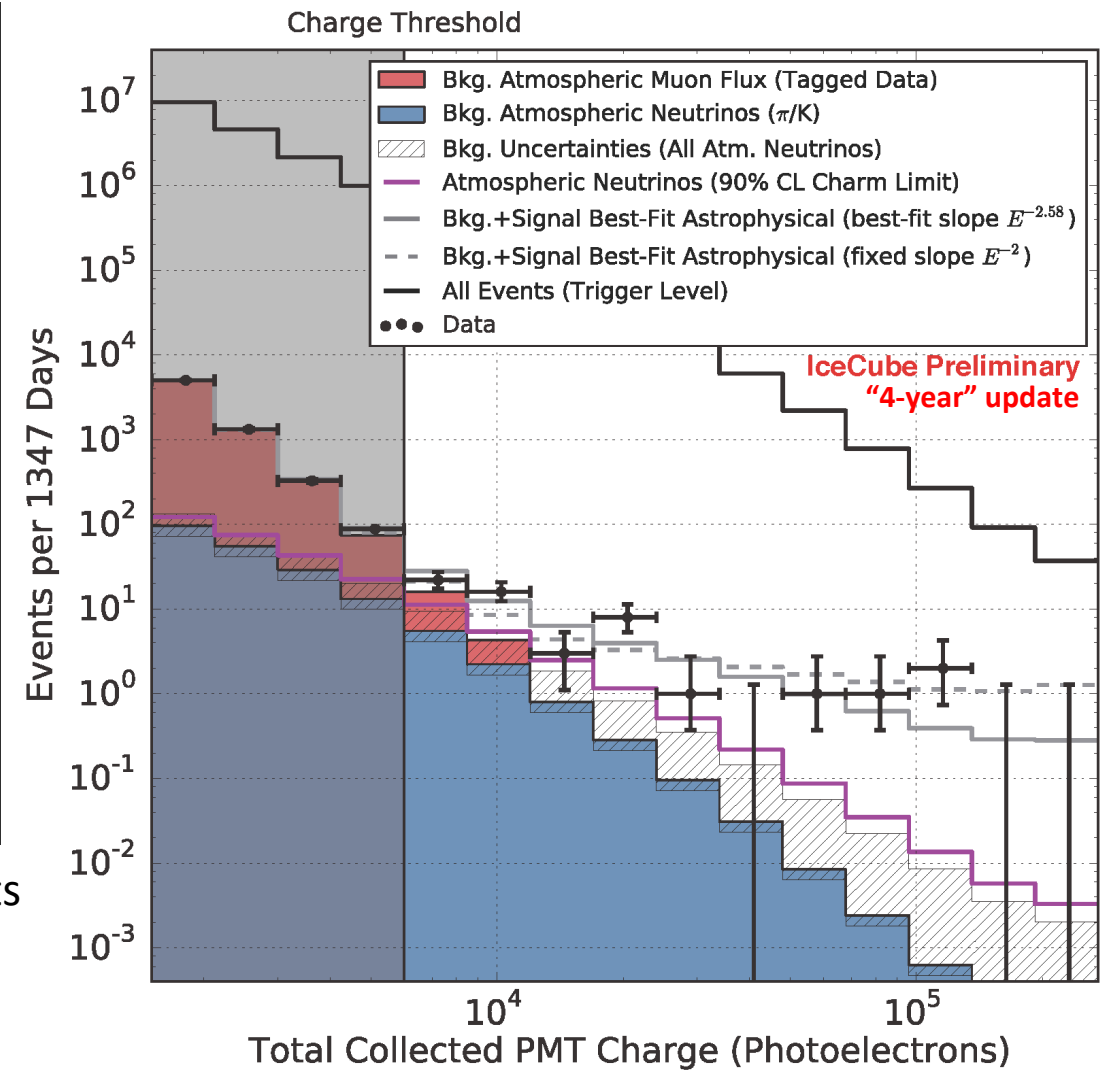


Main background
to ν studies

Other ν event topologies are possible
(* not true for sub-dominant neutral current interactions)

Update on Discovery of a quasi-diffuse ν flux





"4 year" update: 54 events after cuts

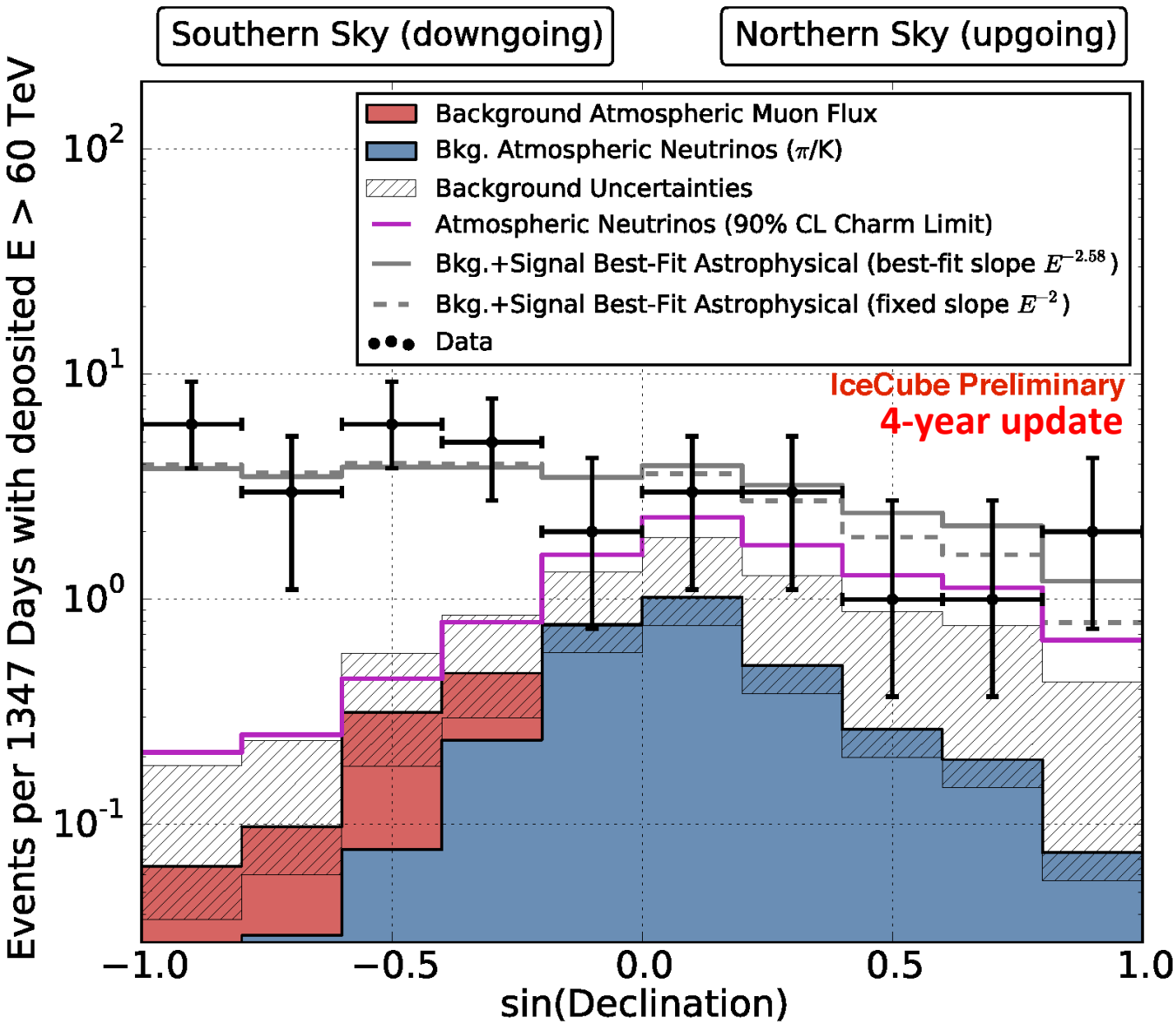
Background:

12.6 ± 5.1 down-going muons (tag)

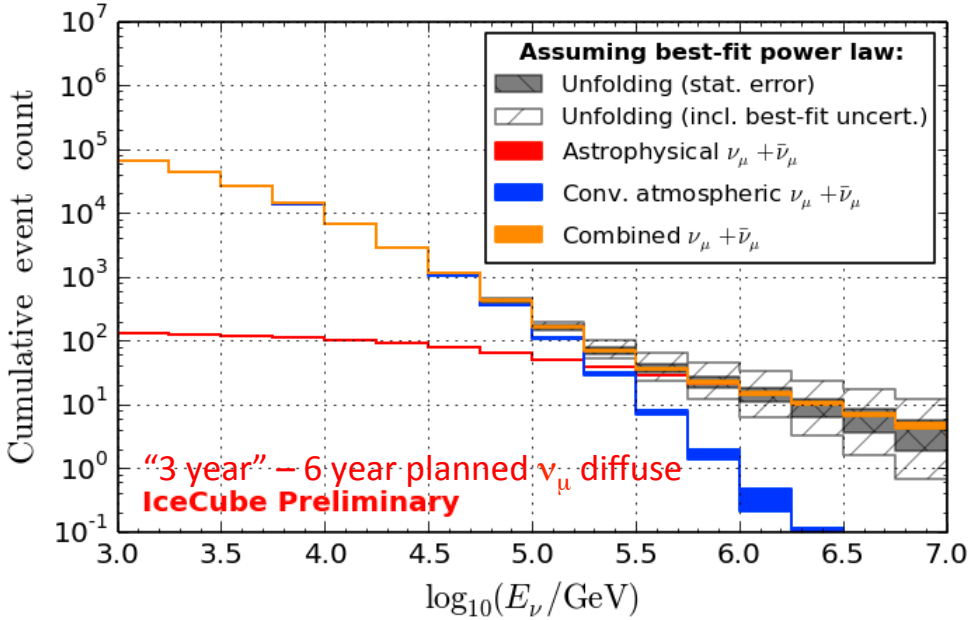
"3-year" study: Aarsten et al. PRL **113** 101101

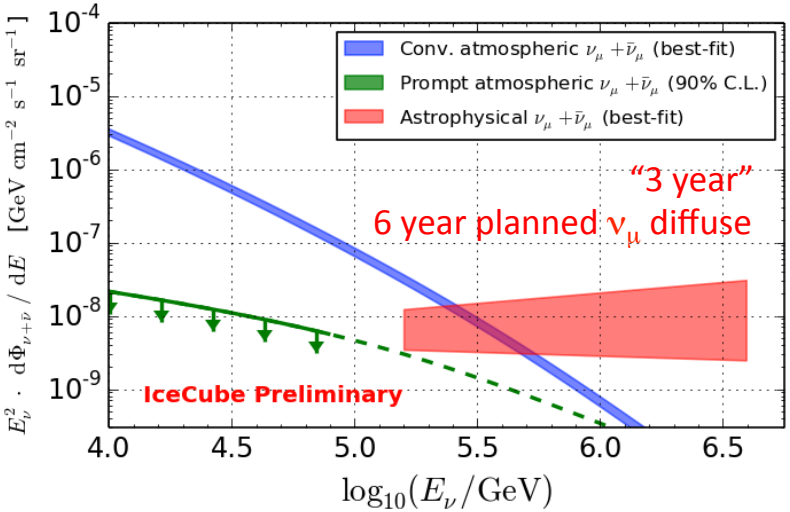
"2-year" study: Aarsten et al. Science **342** 6161

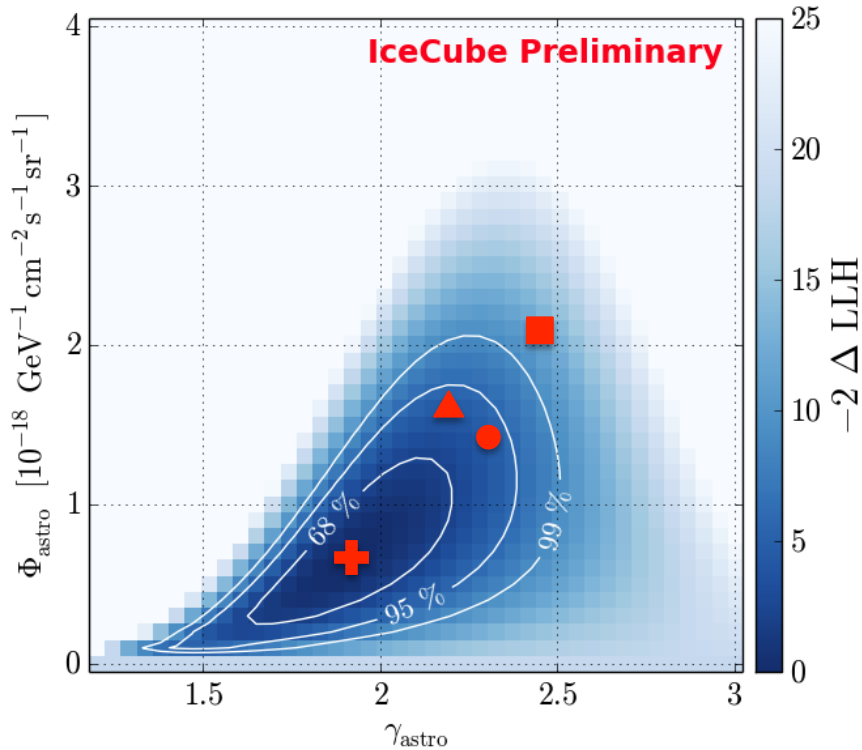
Deposited energy vs. declination



Other ways to study this flux

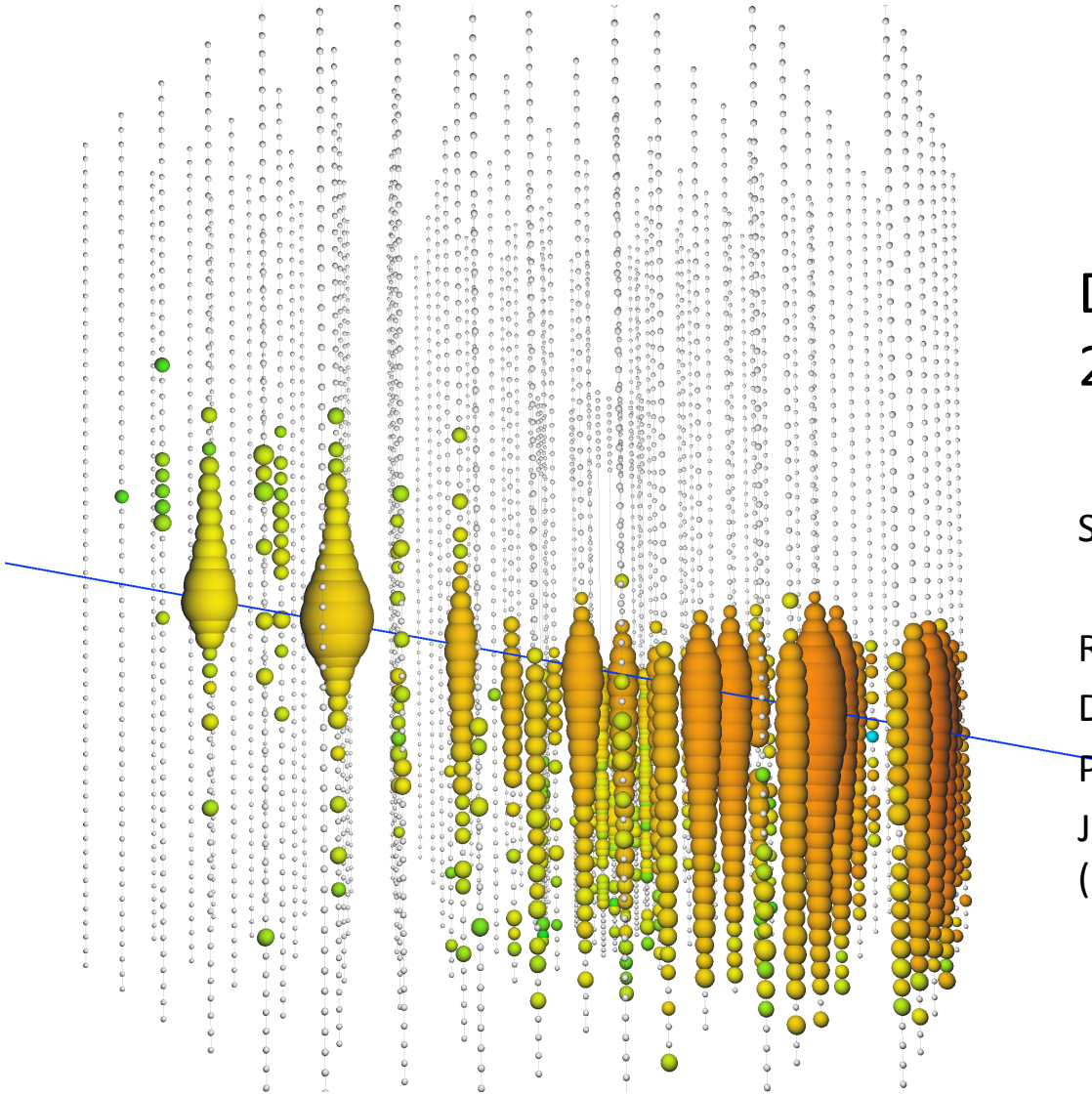






- ■ Phys. Rev. D 91, 022001
- ▲ Submitted to PRL arXiv:1507.04005
- ● Phys. Rev. Lett. 113, 101101
- ✚ 3 year ν_μ – preparation for 6 year

Highest energy neutrino in 6 years (ν_μ search)



Deposited energy:
2.6 ± 0.3 PeV

Schoenen & Raedel et al. ATel # 7856

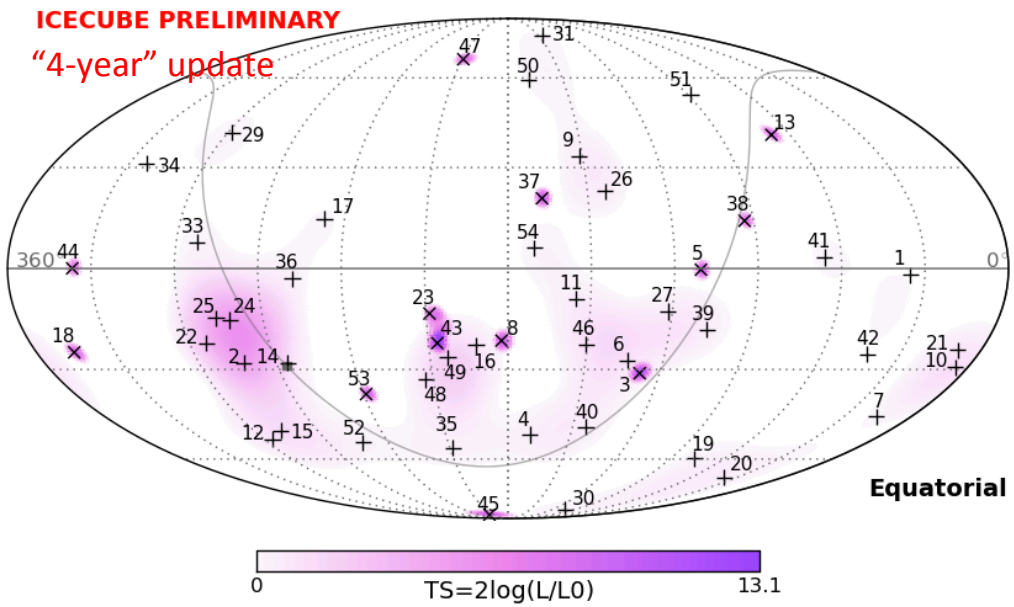
RA: 110.34°

Dec: 11.48°

PSF 99%: 1°

June 11, 2014
(56819.20444852863 MJD)

What are the sources?



Event distribution is consistent with a diffuse flux

Event flavor consistent with oscillations over astrophysical scale

Point source: No (p-value 0.44 cascades / 0.58 all)

Less than ~100 sources explaining the astro-ν flux would have been detected in "traditional" IceCube ν_μ point source search.

Follow up by multiple instruments (e.g γ ray): No obvious counterpart

GRBs (prompt < 1-3%, ±20h <12%): No

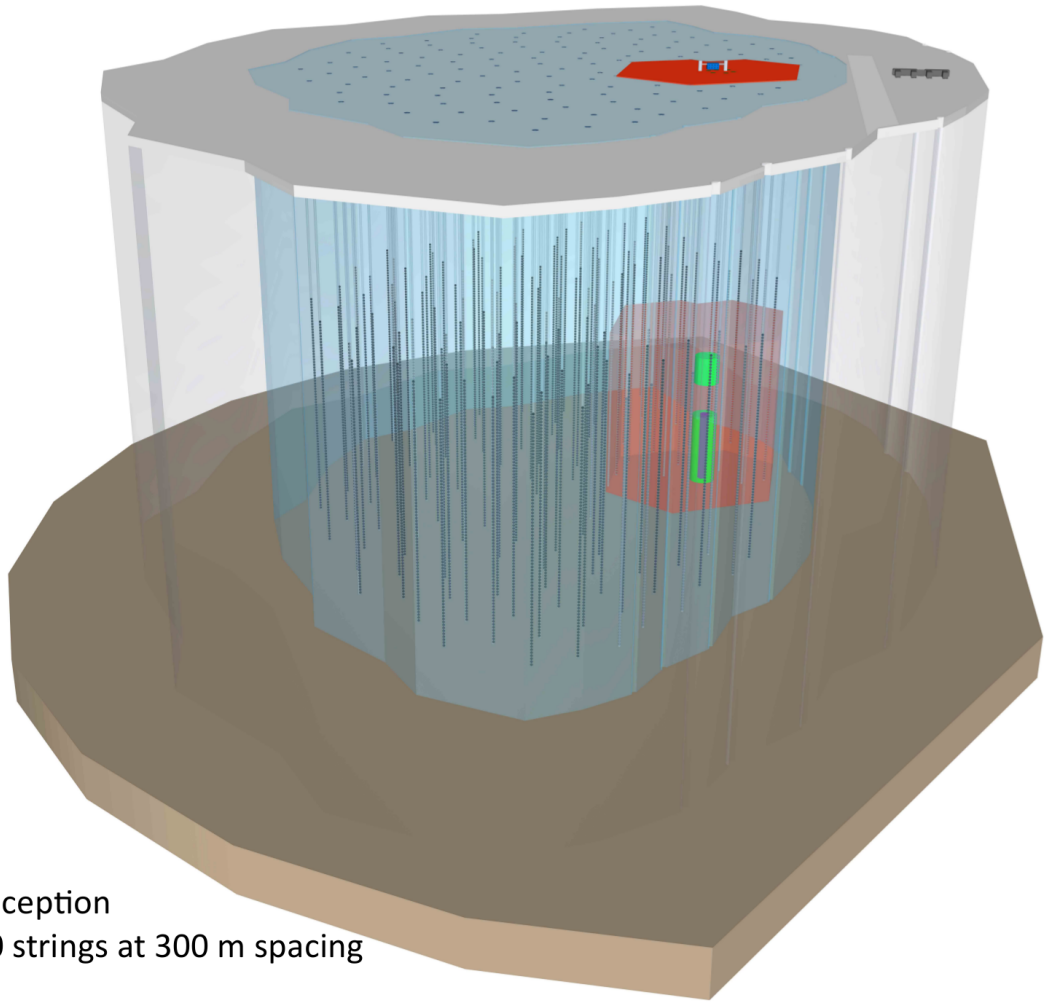
Short (<100 s) transients: Probably not.

Galactic plane: No (p-value 0.025; 7.5^o band)

Interpretation (incomplete list)

Title	Author(s)	Journal reference	ArXiv	Category
IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance	Barger, Learned, Pakvasa	PRD 87, 037302 (2013)	1207.4571	Glashow resonance
Neutrino decays over cosmological distances and the implications for neutrino telescopes	Baerwald, Bustamante, Winter	JCAP10(2012)020	1208.4600	Neutrino decay
On the interpretation of IceCube cascade events in terms of the Glashow resonance	Bhattacharya, Gandhi, Rodejohann, Watanabe	---	1209.2422	Glashow resonance
PeV neutrinos from the propagation of ultra-high energy cosmic rays	Roulet, Sigl, van Vliet, Mollerach	JCAP01(2013)028	1209.4033	GZK
Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos	Pakvasa, Joshipura, Mohanty	PRL 110, 171802 (2013)	1209.5630	Neutrino decay
On the origin of IceCube's PeV neutrinos	Cholis, Hooper	JCAP06(2013)030	1211.1974	Extragalactic (GRB)
Diffuse PeV Neutrinos from Gamma-ray Bursts	Liu, Wang	ApJ 766, 73 (2013)	1212.1260	Extragalactic (GRB)
Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons	Kistler, Stanev, Yuksel	---	1301.1703	Extragalactic
PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei	Kalashev, Kusenko, Essey	PRL 111, 041103 (2013)	1303.0300	Extragalactic (AGN)
Diffuse PeV neutrino emission from ultraluminous infrared galaxies	He, Wang, Fan, Liu, Wei	PRD 87, 063011 (2013)	1303.1253	Extragalactic (Infrared galaxies)
Stringent constraint on neutrino Lorentz invariance violation from the two IceCube PeV neutrinos	Borriello, Chakraborty, Mirizzi, Serpico	PRD 87, 116009 (2013)	1303.5843	Lorentz invariance
Neutrinos at IceCube from heavy decaying dark matter	Feldstein, Kusenko, Matsumoto, Yanagida	PRD 88, 015004 (2013)	1303.7320	Exotic (dark matter decay)
Galactic PeV Neutrinos	Gupta	---	1305.4123	Galactic
Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy	Fox, Kashiyama, Meszaros	ApJ 774, 74 (2013)	1305.6606	Galactic
Superheavy Particle Origin of IceCube PeV Neutrino Events	Barger, Keung	---	1305.6907	Exotic (Leptoquark)
PeV neutrinos observed by IceCube from cores of active galactic nuclei	Stecker	PRD 88, 047301 (2013)	1305.7404	Extragalactic (AGN)
TeV–PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars	Murase, Ioka	PRL 111, 121102 (2013)	1306.2274	Extragalactic (GRB)
Demystifying the PeV cascades in IceCube: Less (energy) is more (events)	Laha, Beacom, Dasgupta, Horiuchi, Murase	PRD 88, 043009 (2013)	1306.2309	
Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube	Murase, Ahlers, Lacki	---	1306.3417	Extragalactic
Pinning down the cosmic ray source mechanism with new IceCube data	Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weiler	---	1306.5021	Galactic
Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events	Stecker	---	1306.6095	Lorentz invariance
TeV-PeV neutrinos over the atmospheric background: originating from two groups of sources?	He, Yang, Fan, Wei	---	1307.1450	Two source populations
The Galactic Pevatron	Neronov, Semikoz, Tchernin	---	1307.2158	Galactic
Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube	Winter	---	1307.2793	Extragalactic
Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos	Joshipura, Mohanty, Pakvasa	---	1307.5712	
Are IceCube neutrinos unveiling PeV-scale decaying dark matter?	Esmaili, Sercipo	---	1308.1105	Exotic (dark matter decay)
Establishing the astrophysical origin of a signal in a neutrino telescope	Lipari	---	1308.2086	
Testing Relativity with High-Energy Astrophysical Neutrinos	Diaz, Kostelecky, Mewes	---	1308.6344	Lorentz invariance
A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube	Chen, Bhupal Dev, Soni	---	1309.1764	
The Galactic Center Origin of a Subset of IceCube Neutrino Events	Razzaque	---	1309.2756	Galactic
Probing the Galactic Origin of the IceCube Excess with Gamma-Rays	Ahlers, Murase	---	1309.4077	Galactic

Outlook: IceCube-Gen2



Artist conception
Here: 120 strings at 300 m spacing

See highlight presentation by J. Koskinen – Sat. Aug. 29

Thank you!


The IceCube Collaboration
Canada
University of Alberta–Edmonton
University of Toronto
USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University
Niels Bohr Institutet, Denmark
Sweden
Stockholms universitet
Uppsala universitet
Germany
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Technische Universität Dortmund
Universität Mainz
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Université de Mons
Universiteit Gent
Vrije Universiteit Brussel
Université de Genève, Switzerland
University of Adelaide, Australia
University of Canterbury, New Zealand
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The Swedish Research Council (VR)
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US National Science Foundation (NSF)

Energy spectrum