IceCube: Ultra-high Energy Neutrinos

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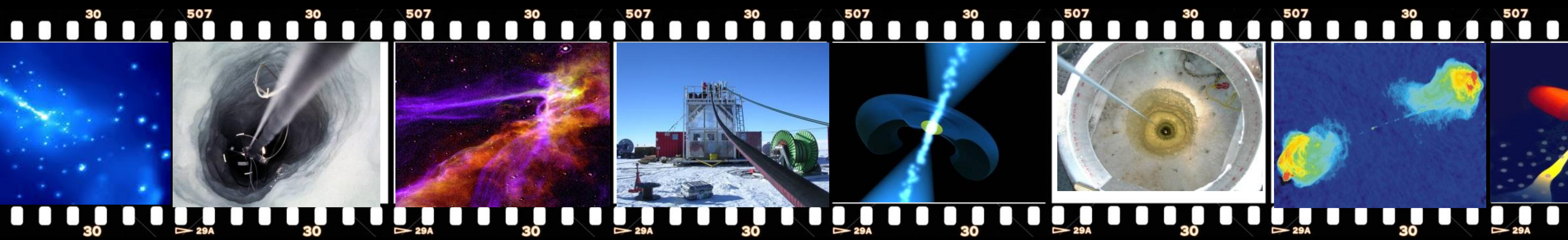
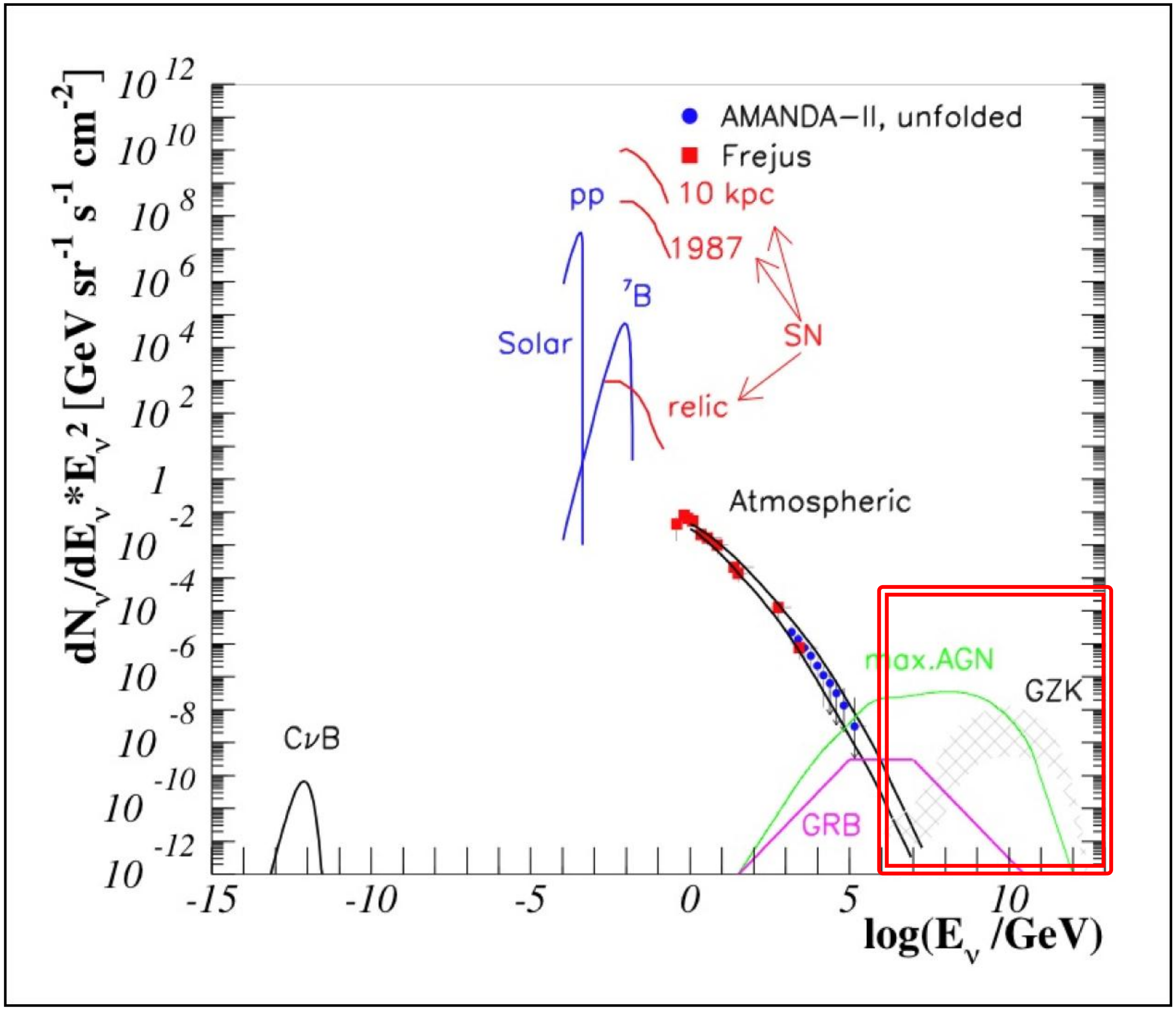
for the **IceCube** collaboration



Neutrino2012 at Kyoto June 8th 2012

Ultra-high Energy Neutrinos: *PeV and above*



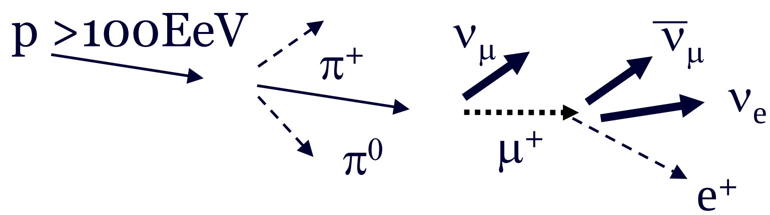
- Energies above dominant atmospheric neutrinos
- Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)
- Cosmogenic neutrino production is a ‘guaranteed’ ν source

The highest energy neutrinos

cosmogenic neutrinos induced by the interactions of cosmic-ray and CMB photons

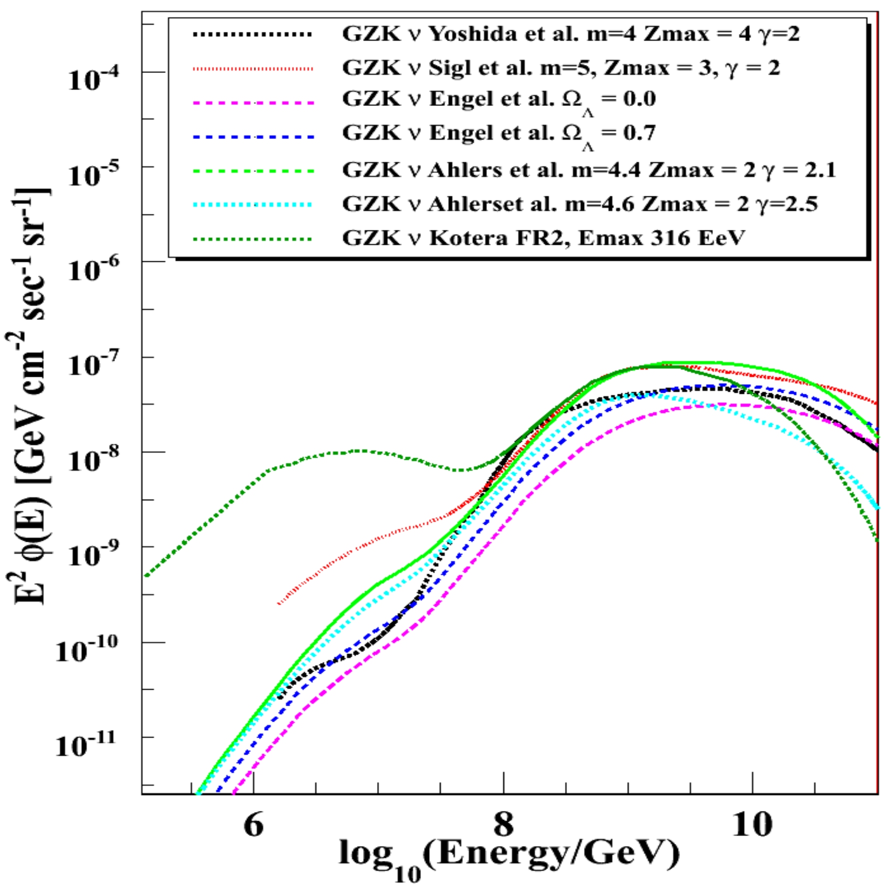
Off-Source (<50Mpc) astrophysical neutrino production via

GZK (Greisen-Zatsepin-Kuzmin) mechanism



The main energy range: **$E_\nu \sim 10^{8\text{-}10}$ GeV**

$$p\gamma_{2.7K} \rightarrow \pi^{+} + X \rightarrow \mu^{+} + \nu \rightarrow e^{+} + \nu's$$



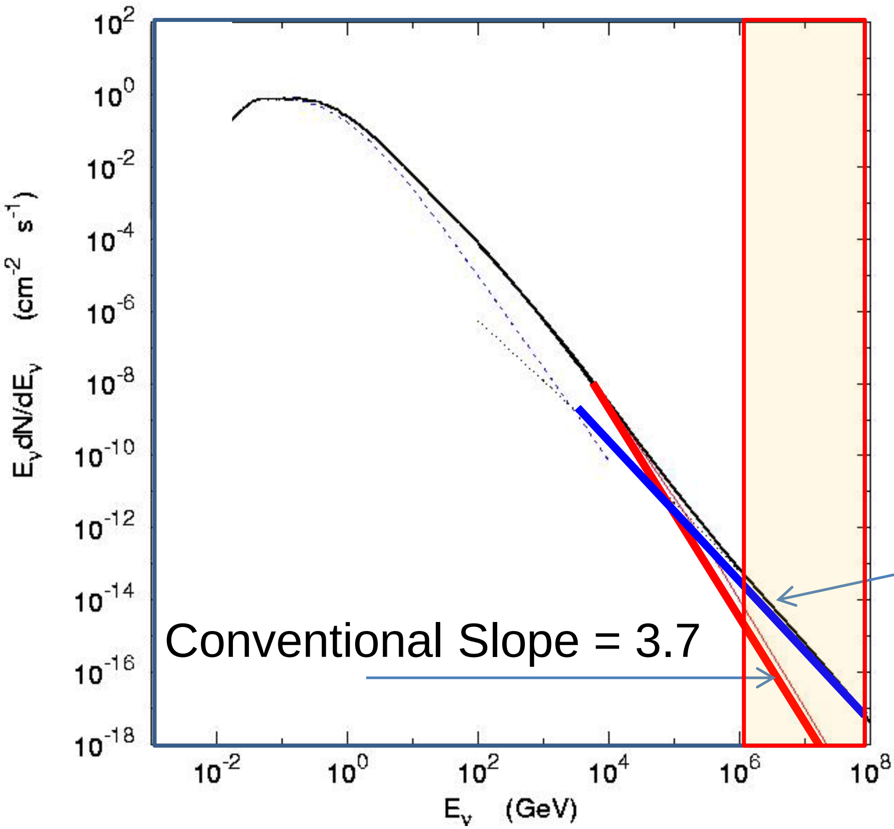
Various GZK ν models

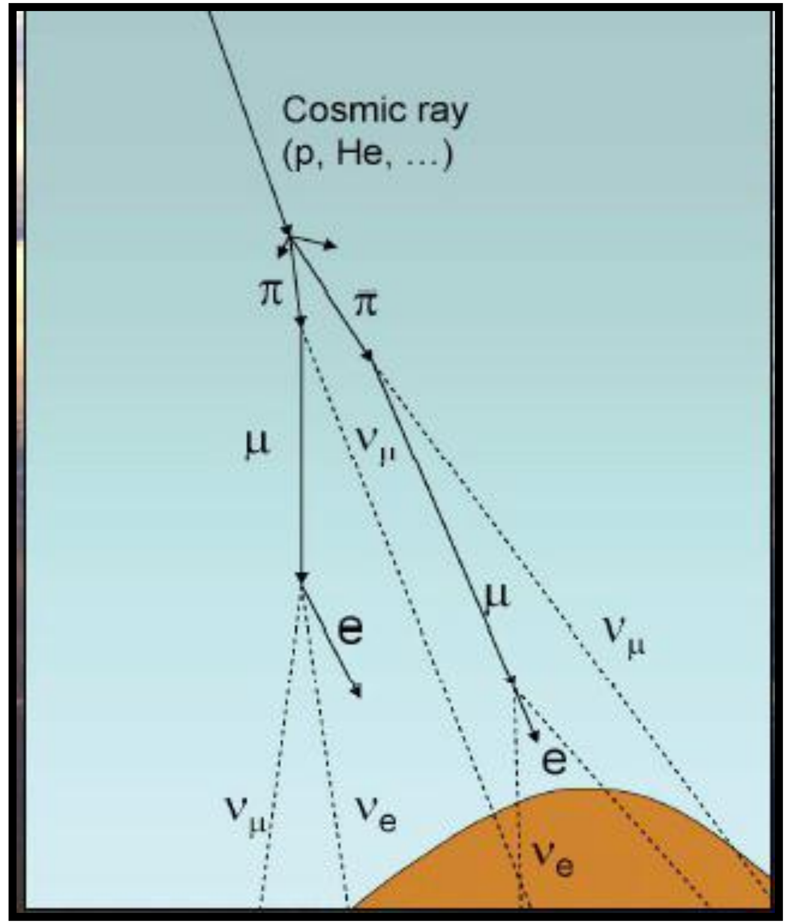
Carries important physics

- Location of the cosmic-ray sources
- Cosmological evolution of the cosmic-ray sources
- Cosmic-ray spectra at sources
- The highest energy of the cosmc-rays
- Composition of the cosmic-rays
- Particle physics beyond the energies accelerators can reach

Atmospheric neutrinos in PeV

- Conventional atmospheric neutrinos from decays of pion and kaons
- Prompt atmospheric neutrinos form decays of heavy flavor short lived mesons (charm, bottom)
- Prompt harder than conventional still steeper than astronomical spectra
- Transition around 3 x 10^5 GeV depending on the models

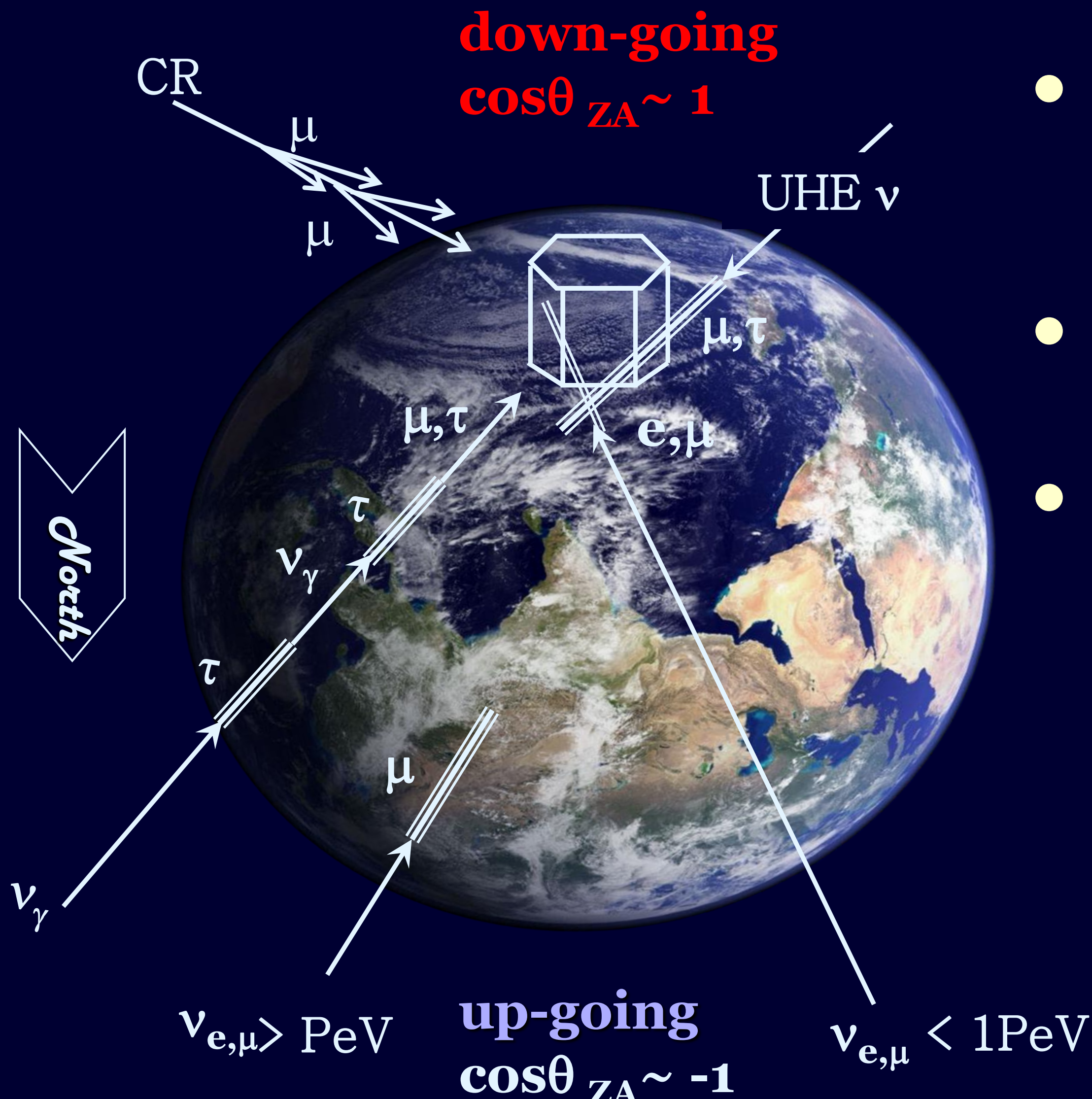




Prompt Slope = 2.7

Physics of heavy flavor particle production

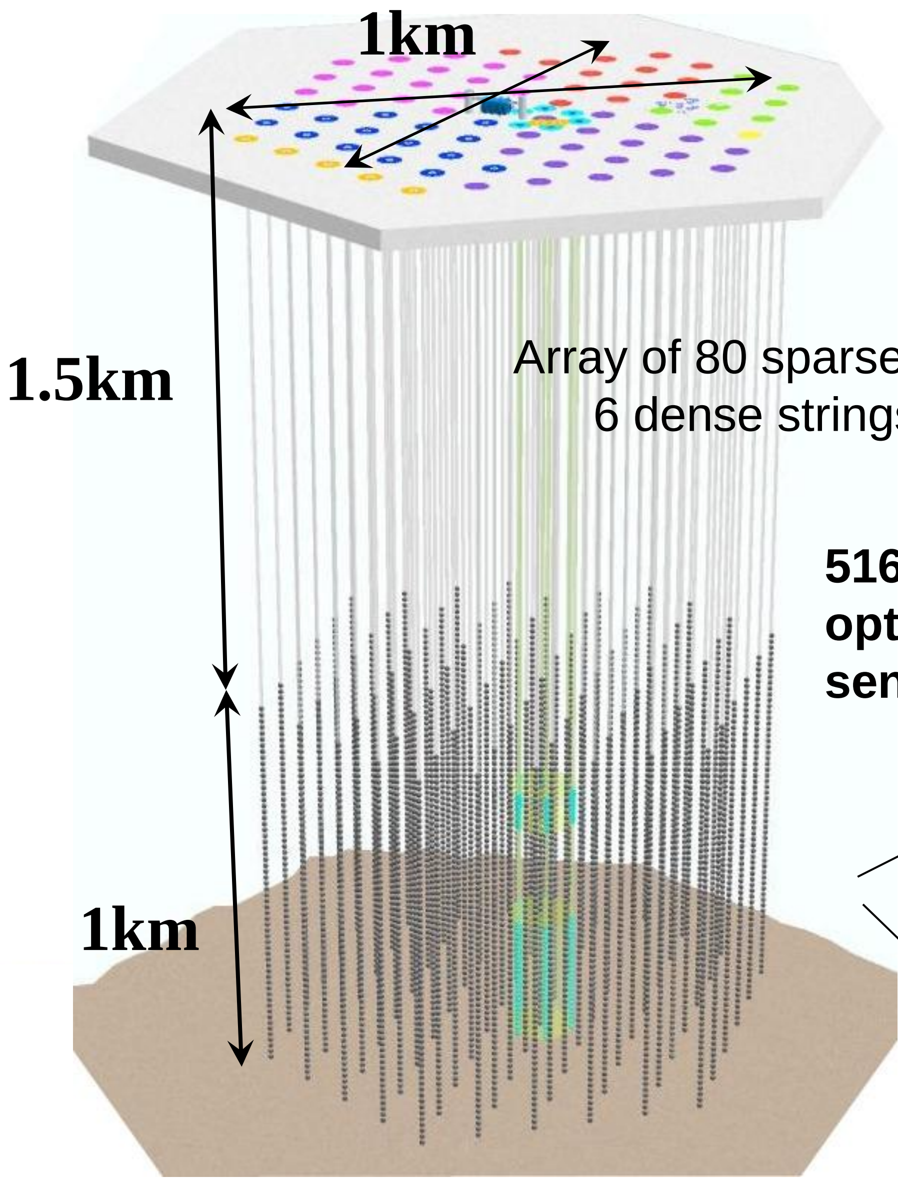
UHE Neutrinos In the Earth…



- Generally neutrinos identified as "through the Earth" up-going events
- Earth is opaque for UHE neutrinos
- UHE neutrino-induced events are coming from above and near horizontal direction

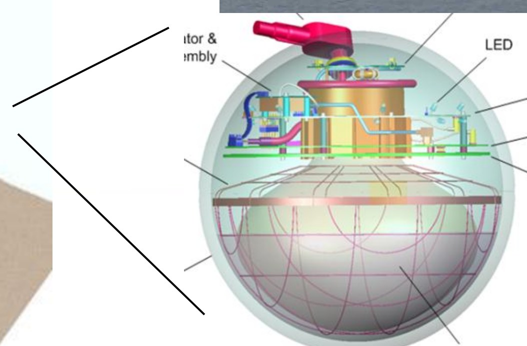
UHE neutrino mean free path
$\lambda_n \sim 100$ km << R_{Earth}
$\sigma^{cc}_{nN} \sim 10^{-6\sim-4}$ mb

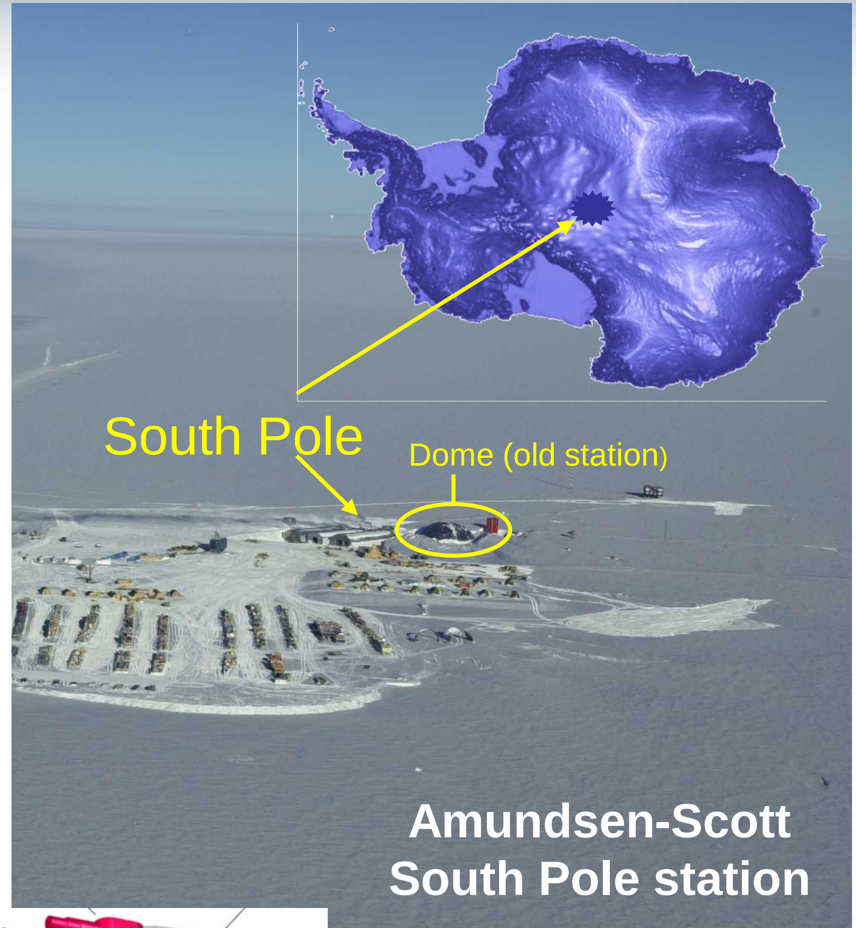
The IceCube Detector



Array of 80 sparse and 6 dense strings

5160 optical sensors





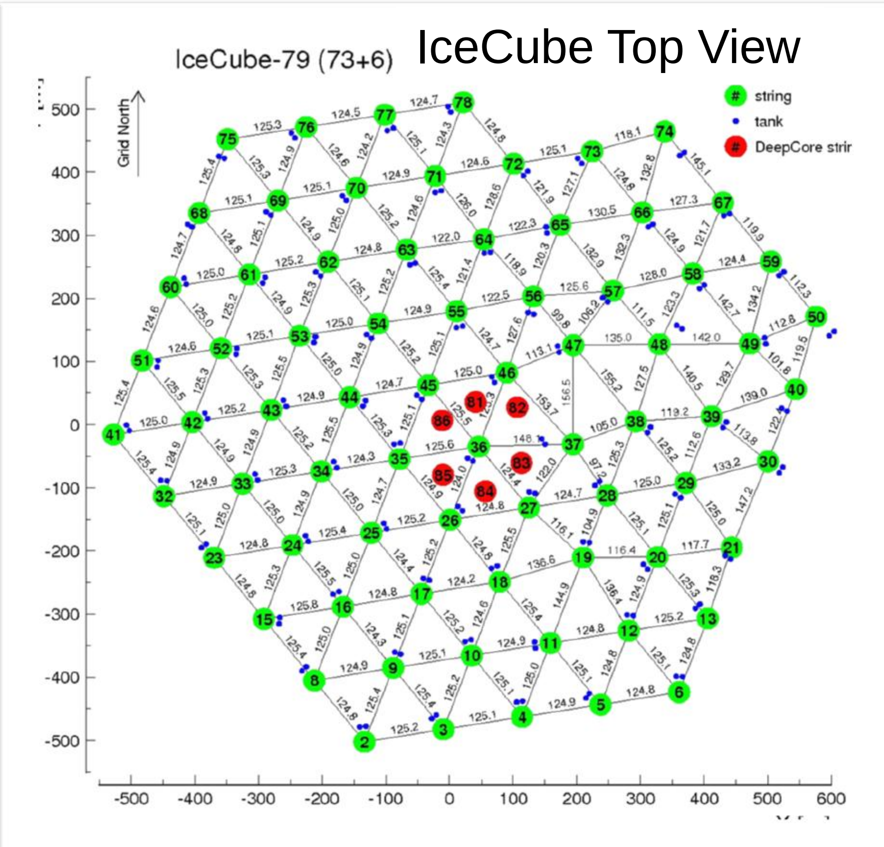
Data samples

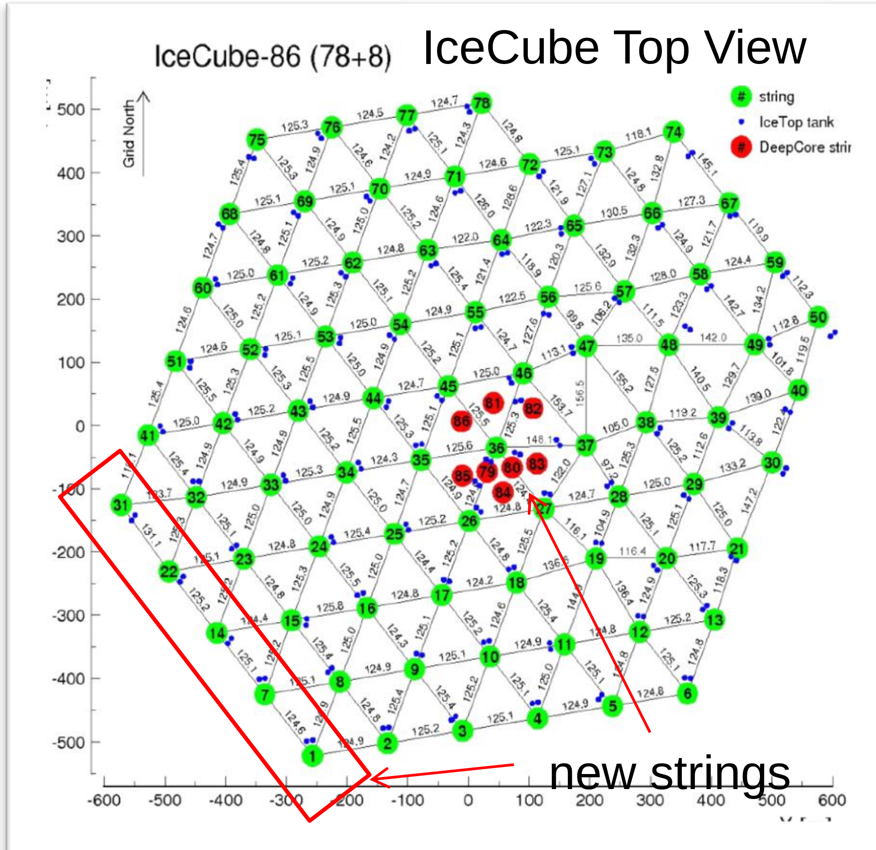
Effective livetime of 672.7days

2010-2011 - 79 strings config.
May/31/2010-May/12/2011
Effective livetime 319.07days

2011-2012 – 86 strings config
May/13/2011-May14/2012
Effective livetime 353.67 days

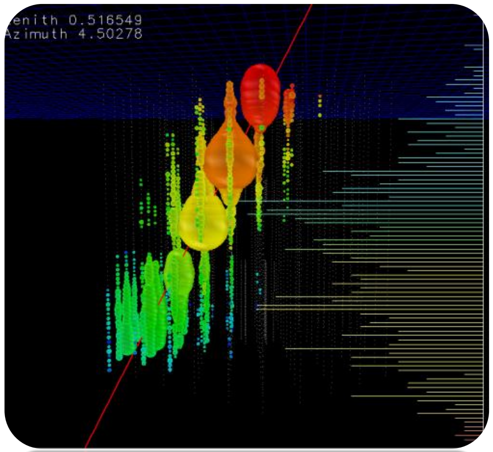
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

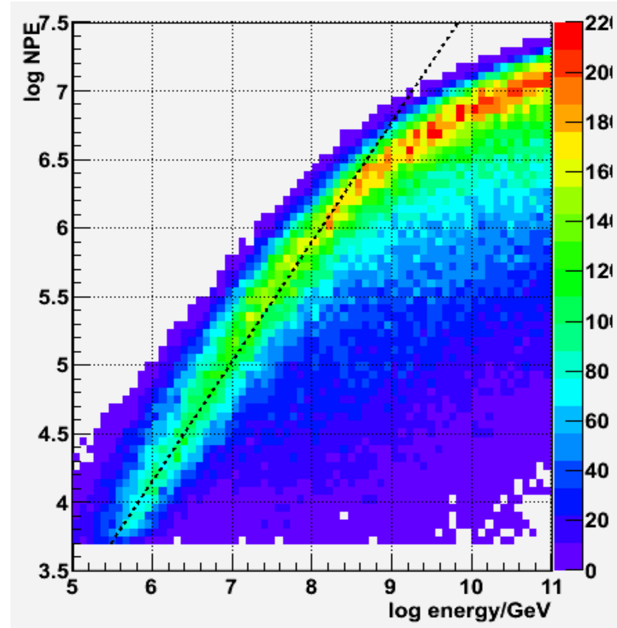




IceCube has been in a stable operation for more than 5 years

The Event Selection

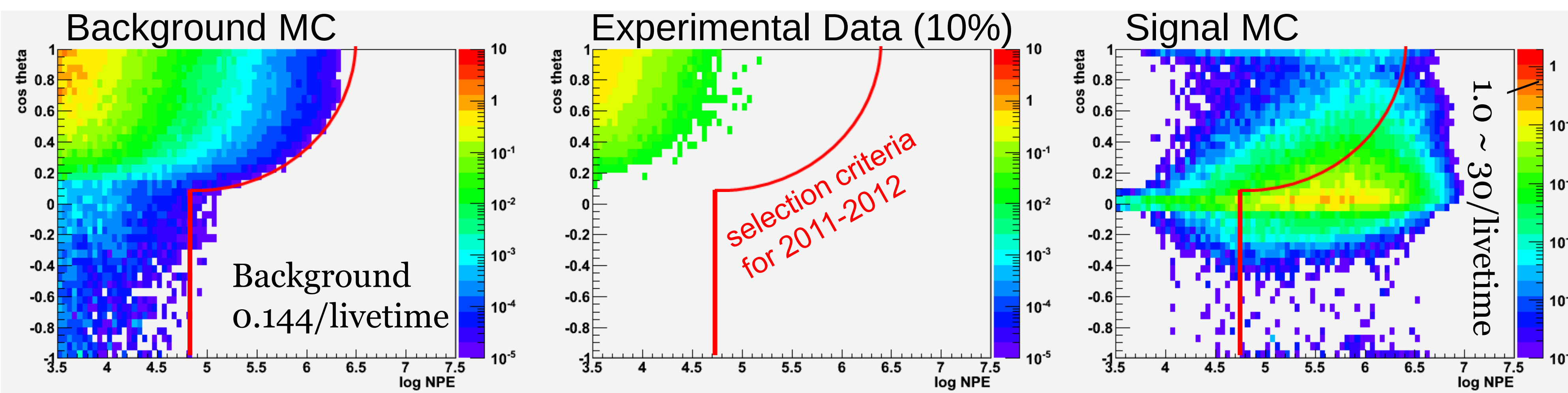




channel # > 300

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample



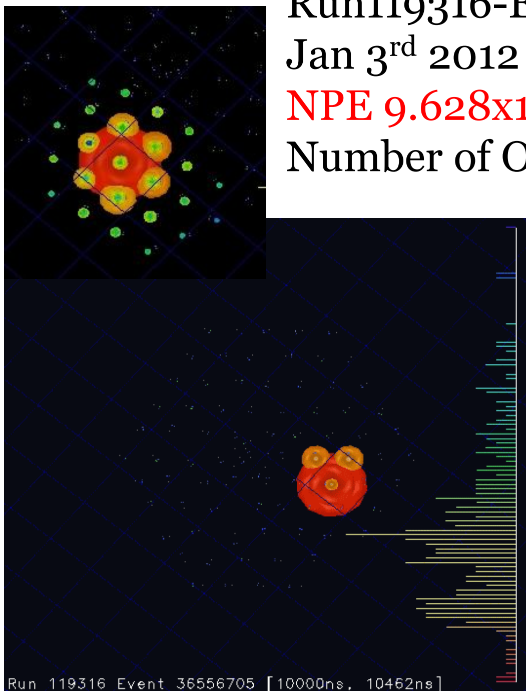
See the details of 2010-2011 data analysis: Poster #12-3 (Keiichi Mase)

Two events passed the selection criteria

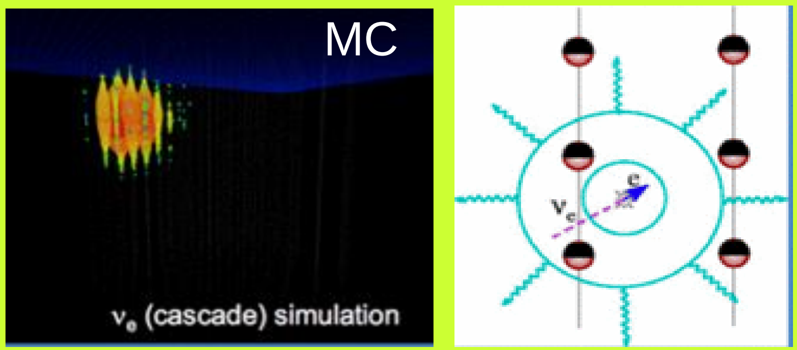
2 events / 672.7 days (background expectation 0.14 events)
preliminary p-value: 0.0094 (2.36σ)

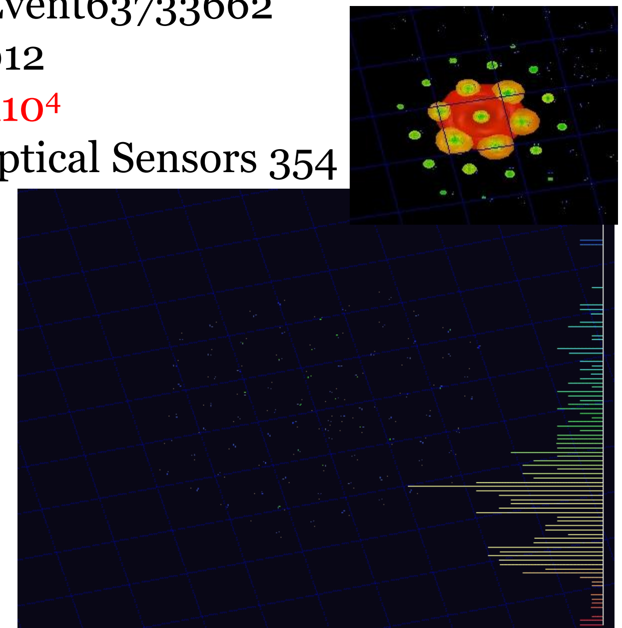
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10^4
Number of Optical Sensors 312

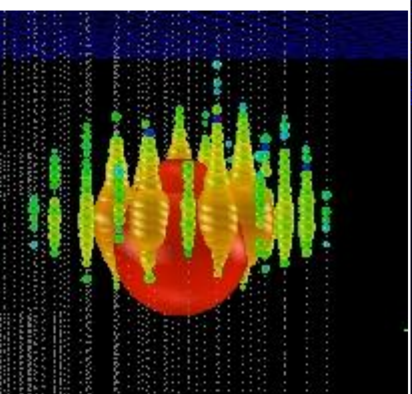
Run118545-Event63733662
August 9th 2012
NPE 6.9928x10^4
Number of Optical Sensors 354

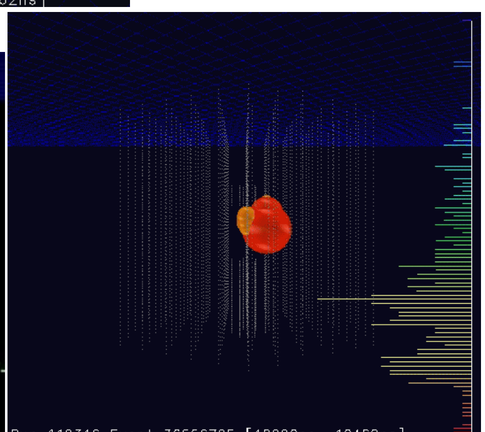


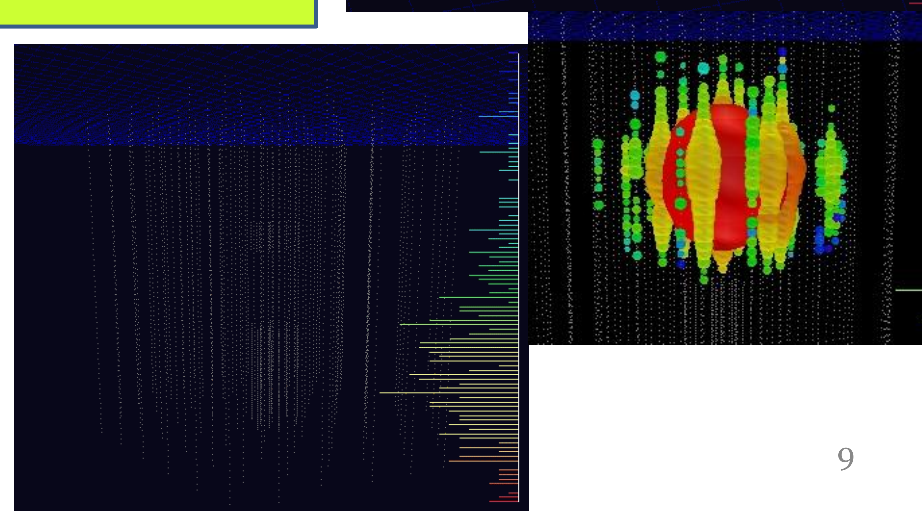
CC/NC interactions in the detector



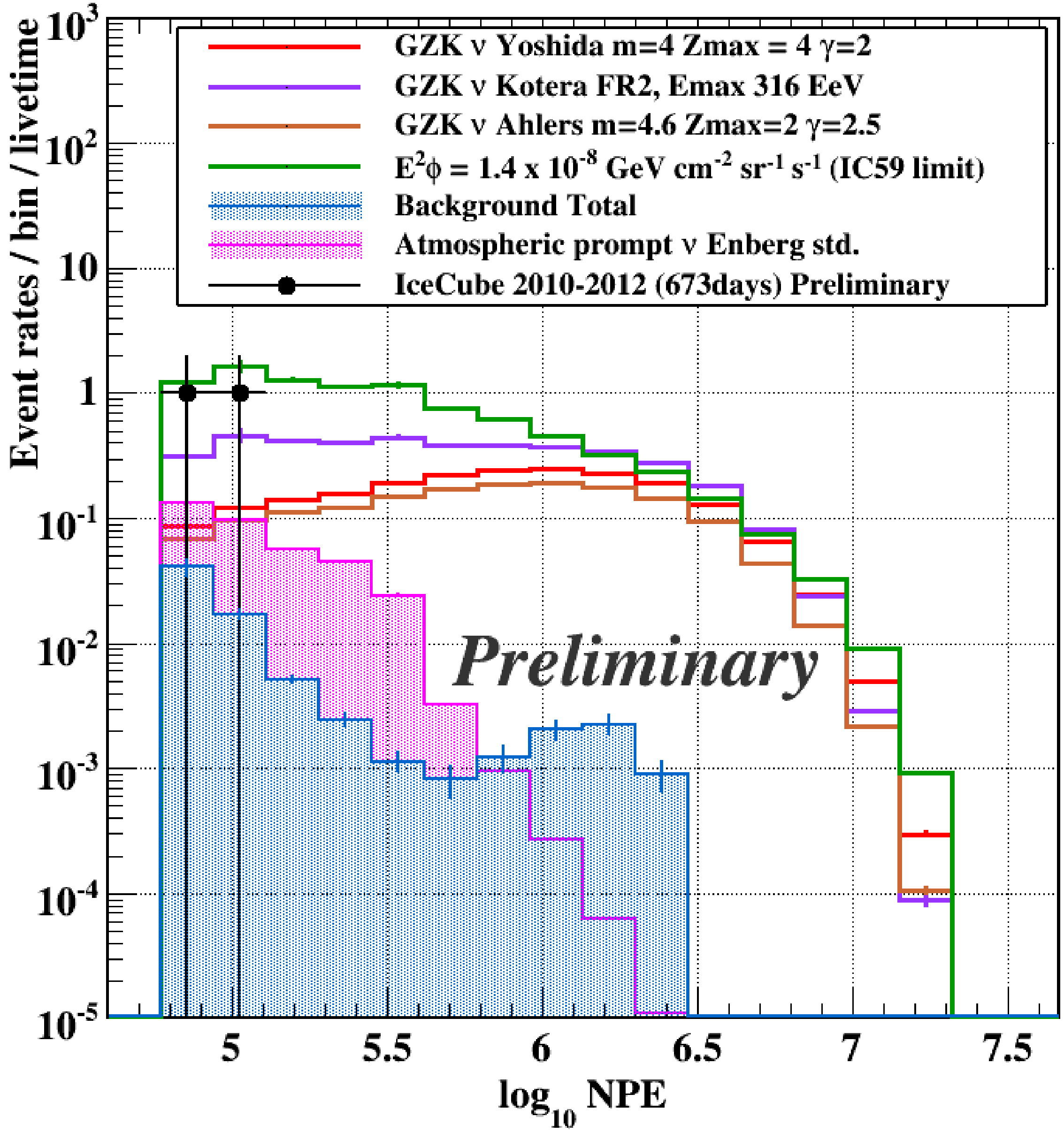








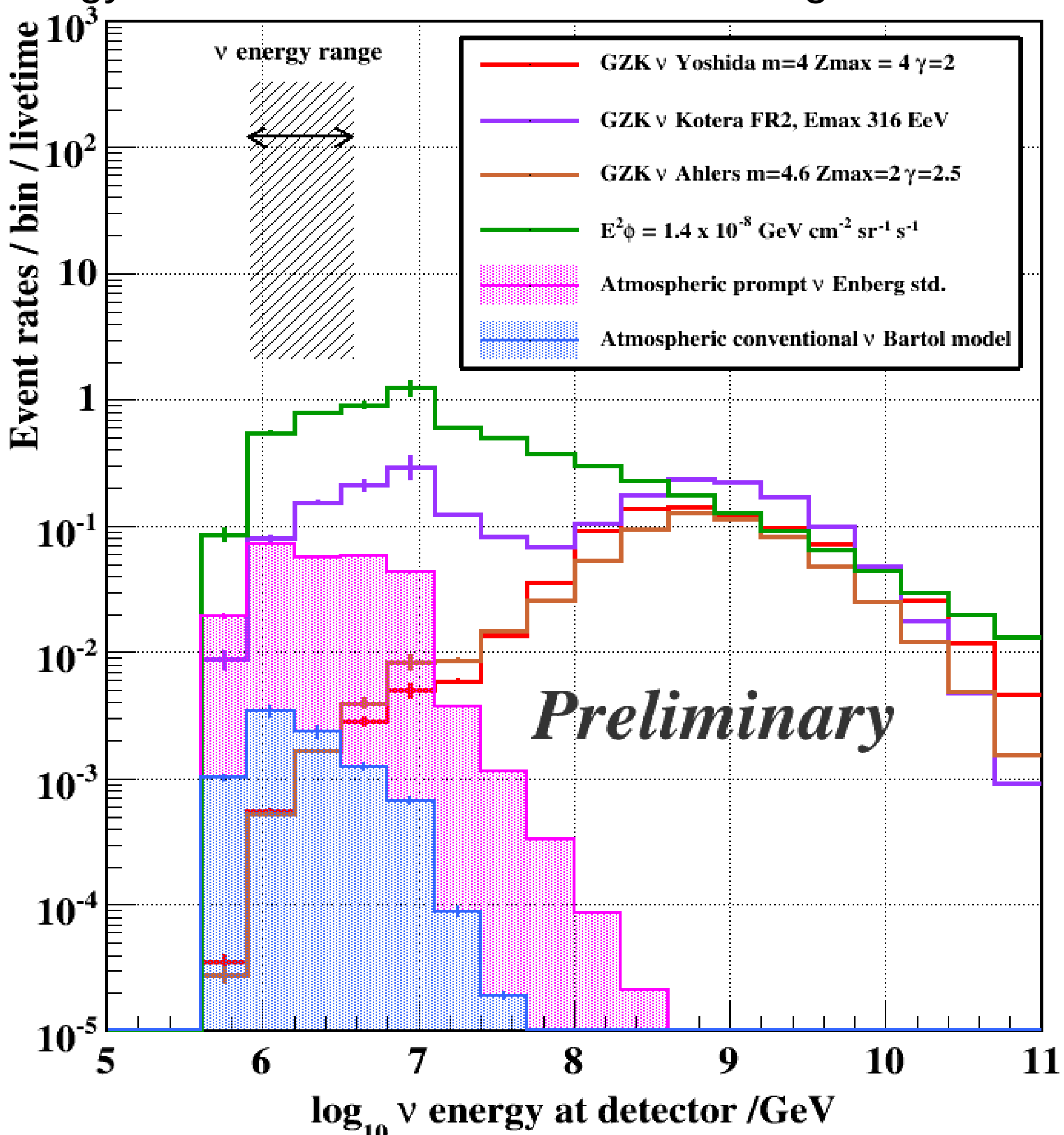
Event Brightness (NPE) Distributions 2010-2012



- Observed 2 high NPE events near the NPE threshold
- **No** indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced
- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accelerators
  - atmospheric prompt ν
  - atmospheric conventional ν

Neutrino Energy Distributions (2010-2012)

energy distributions of neutrinos reaching to the IceCube depth



- EM+hardronic (CC) or hadronic (NC) cascade energy ~ PeV
- Most likely to be PeV to 10 PeV neutrinos
- The highest energy neutrino events observed ever!

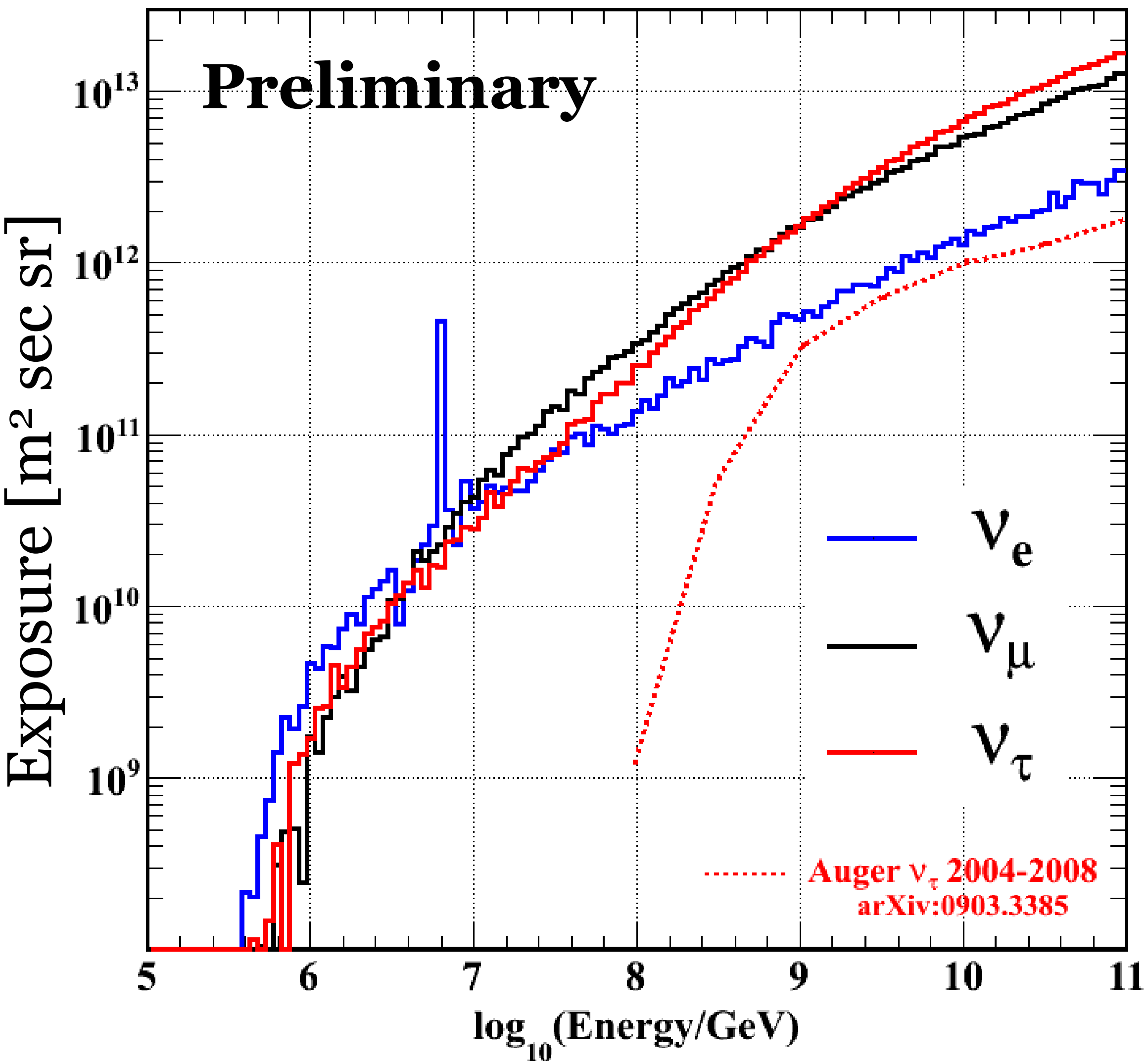
Expected Numbers of UHE Events

Preliminary Models	IceCube 2008-2009 Phys. Rev D83 092003 (2011) 333days	IceCube 2010-2012 per 672.7days	
		$E^{detector} < 10^8$ GeV and interaction in detector	All contributions
Atmos. prompt ν (Enberg std.)^		0.3	0.4
IC59 diffuse limit ^^ $E^2\phi = 1.4 \times 10^{-8}$GeV cm^{-2} sr^{-1} sec^{-1}		5.0	9.1
Background (atm. ν + atm. μ)	0.11	0.01	0.14
Experimental data	*0*	*2*	*2*
GZK (Yoshida m=4)*	0.57	0.4	2.1
GZK (Ahlers max) **	0.89	0.5	3.2
GZK (Ahlers best fit) **	0.43	0.3	1.6
GZK (Kotera, dip FRII) ***		1.7	4.1
GZK (Kotera, dip SFR1)***		0.6	1.0

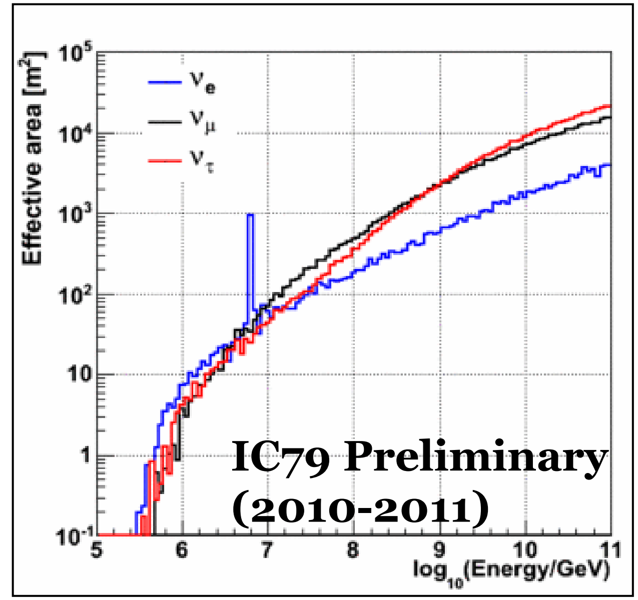
*Yoshida et al The ApJ 479 547-559 (1997), **Ahlers et al, Astropart. Phys. 34 106-115 (2010, ***Kotera et al, ^R. Enberg, M.H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008), ^^ Talk G. Sullivan This conference

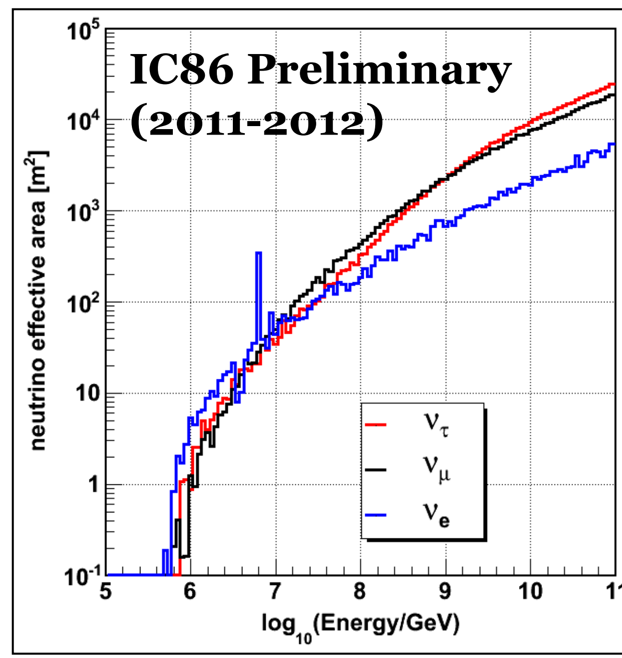
The Exposure and Effective Area

IceCube UHE 2 Years Exposure (2010-2012)

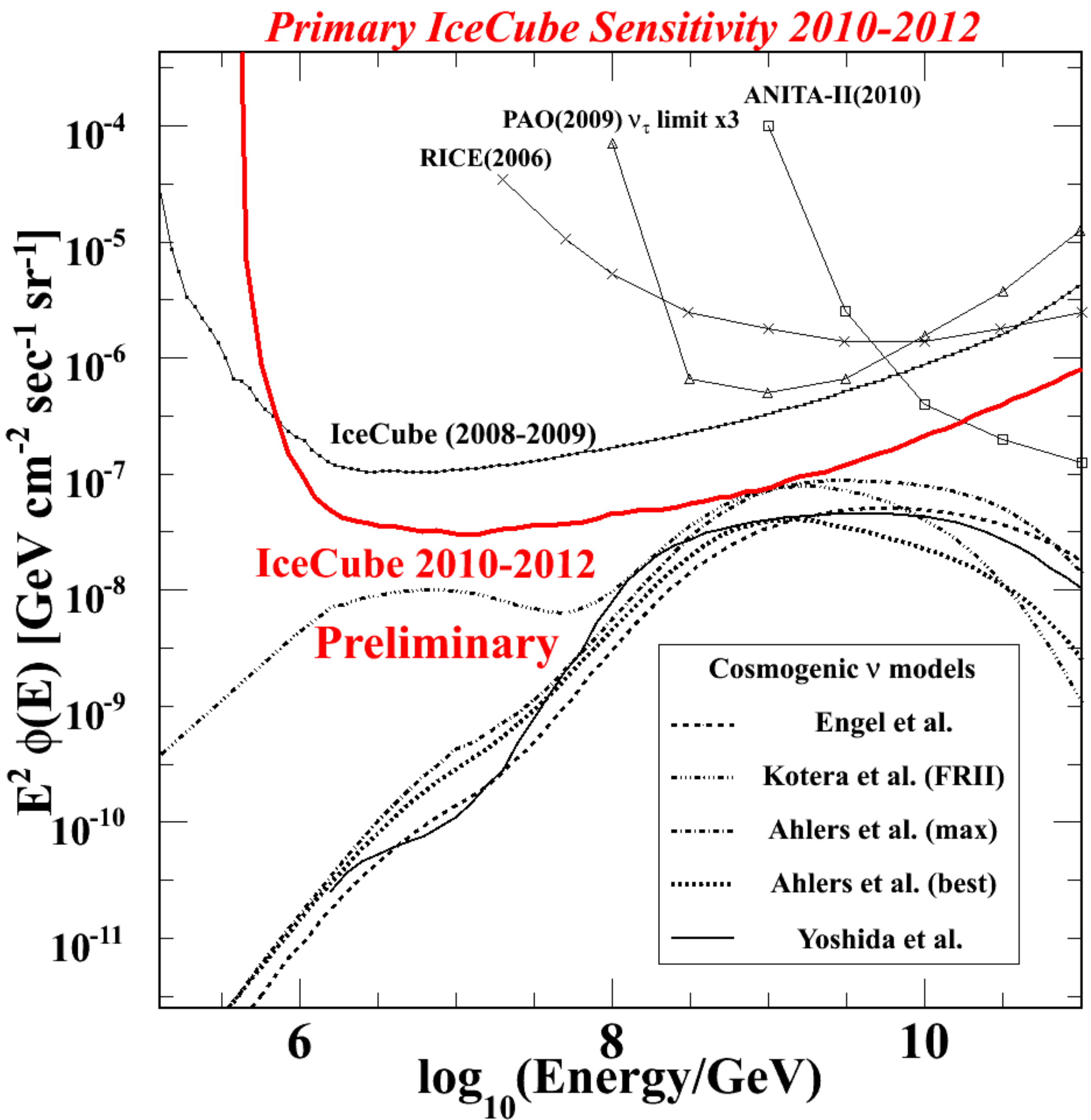


Effective Areas





IceCube UHE Sensitivity 2010-2012



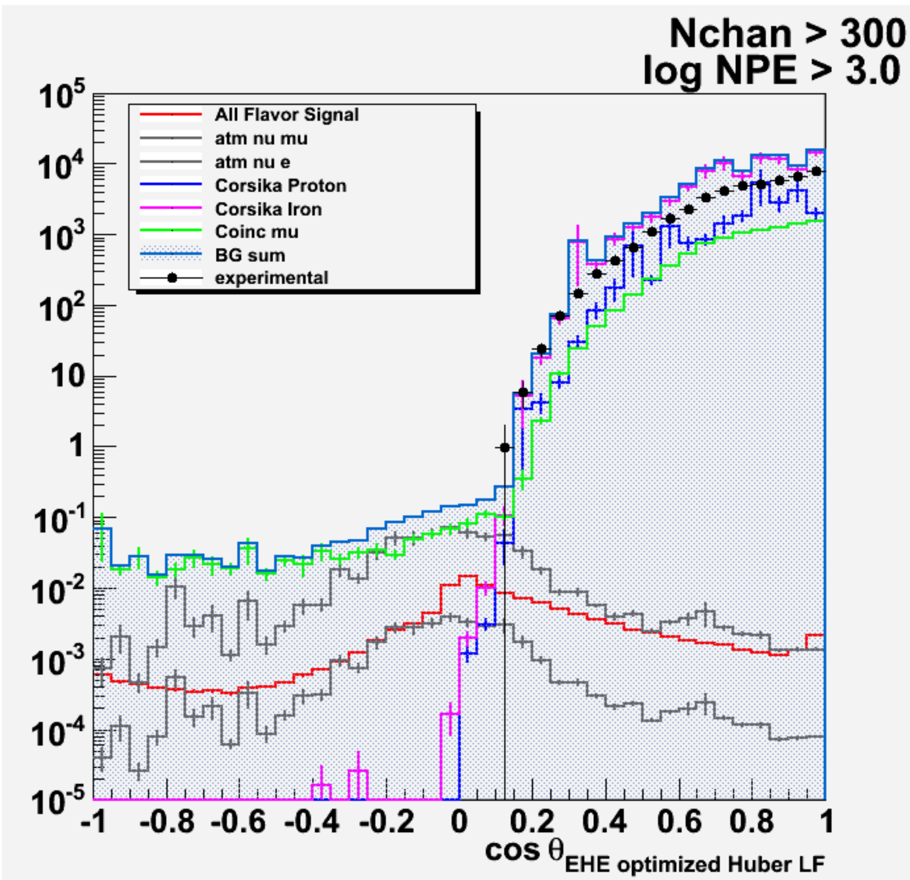
- Significantly improved from the previous IceCube results
- The world's best sensitivity!
- Will constrain (or detect) the neutrino fluxes down to mid-strong cosmological evolution models

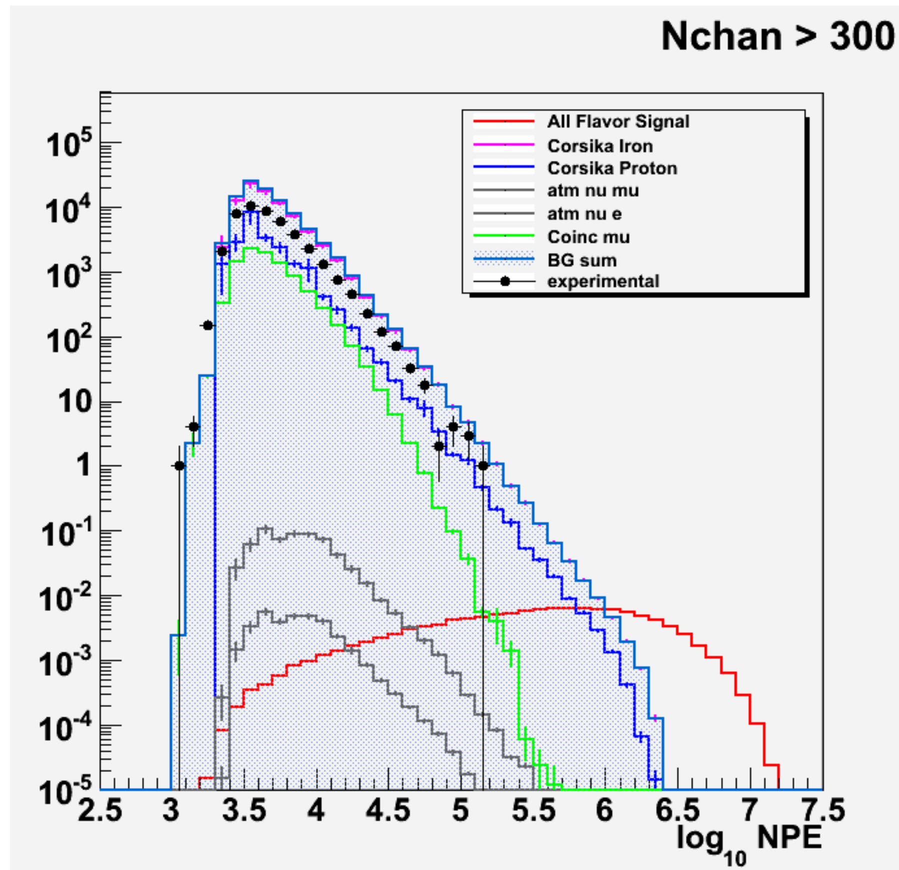
Summary

- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - The highest energy events observed ever!
- Likely to be beyond the conventional atmospheric neutrinos
- Hints for the PeV events origin from different energy-region / channels are also coming soon!
  - More cascade event sensitive analysis
  - Lower energy regions for the spectral transition
- Statistical confirmation foreseen with an independent sample
- **We are into a very interesting era of neutrino astrophysics!**

Backup

NPE and cos zenigh angle distributions comparisons with burn sample





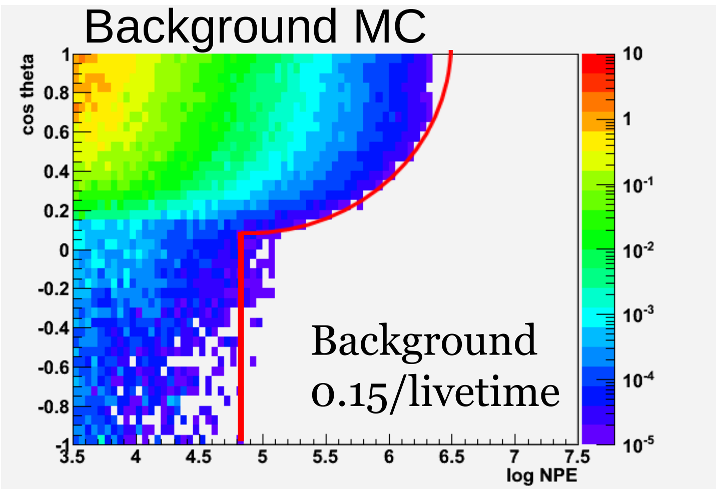
Passing rates (stat. errors only)

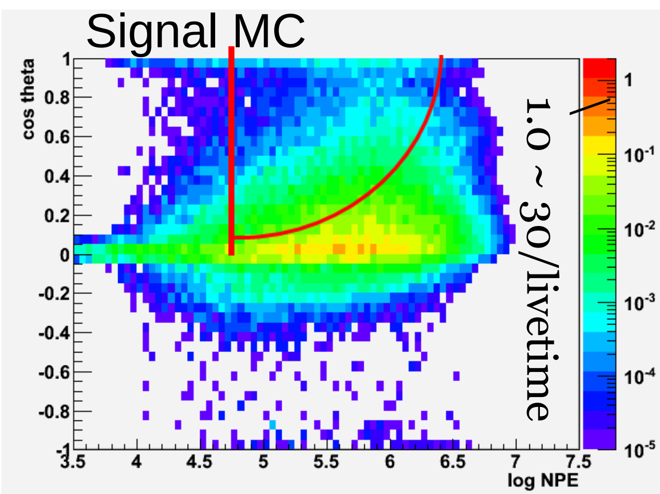
Passing rates (per burn sample live time of 498.350 hours) table

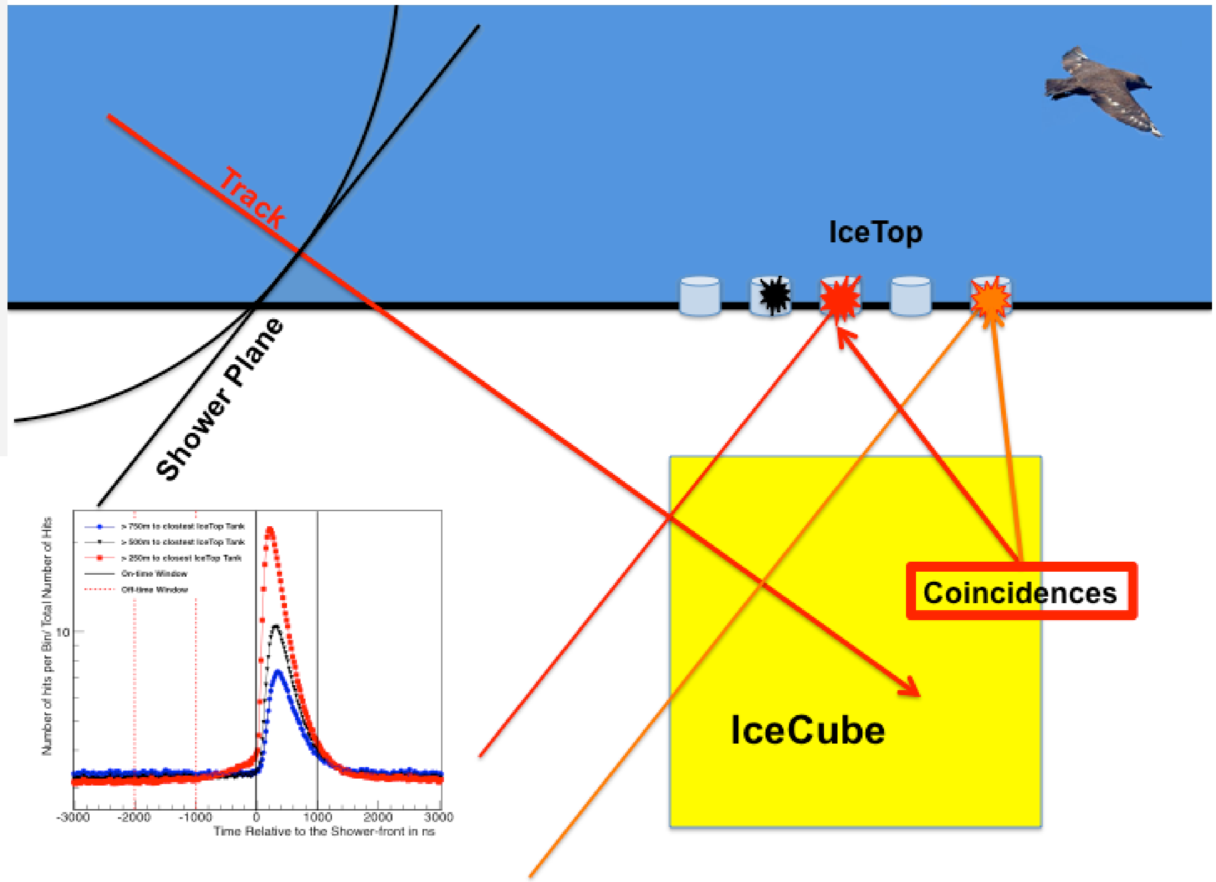
	Experimental	Atm mu SIBYLL Fe	Coincident muon	atmospheric neutrinos	Atm mu SIBYLL H	Signal
Filter Online	**3539908 (1.973Hz)**					
Filter Offline (NPE > 1000, Nch > 50)	**$1.615\ x10^6$**	**$2.34+/-0.08\ x10^6$**	**$2.881+/-0.005\ x10^5$**	**163.2+/-3.0**	**$9.85+/-1.3\ x10^5$**	**0.1528+/-0.0006**
(NPE > 1000, Nch > 300)	**44458**	**$8.37+/-0.49\ x10^4$**	**$9.48+/-0.03\ x10^3$**	**0.648 +/- 0.032**	**$2.16+/-0.34\ x10^4$**	**0.1136+/-0.0004**
(NPE > 10^3.5, Nch > 300)	**34411**	**$6.85+/-0.40\ x10^4$**	**7655.0+/-23.0**	**0.625+/-0.031**	**$1.75+/-0.32\ x10^4$**	**0.1133+/-0.0004**
(NPE > 10^4.0, Nch > 300)	**3019**	**$5.65\ +/-\ 0.271\ x10^3$**	**558.7+/-3.4**	**0.185+/-0.011**	**631.72+/-59.61**	**0.1102+/-0.0004**
(NPE > 10^4.5, Nch > 300)	**134**	**253.4 +/- 13.9**	**9.53 +/- 0.20**	**0.0232 +/-0.0013**	**27.7 +/- 2.2**	**0.1019+/-0.0004**
Final criteria	**0.0**	**0.00059 +/-0.00024**	**6.37e-07 +/-4.50e-07**	**0.0028 +/-0.0002**	**8.2e-05 +/- 5.7e-05**	**0.0645 +/-0.0003**

Near future improvement
Background Veto with IceTop

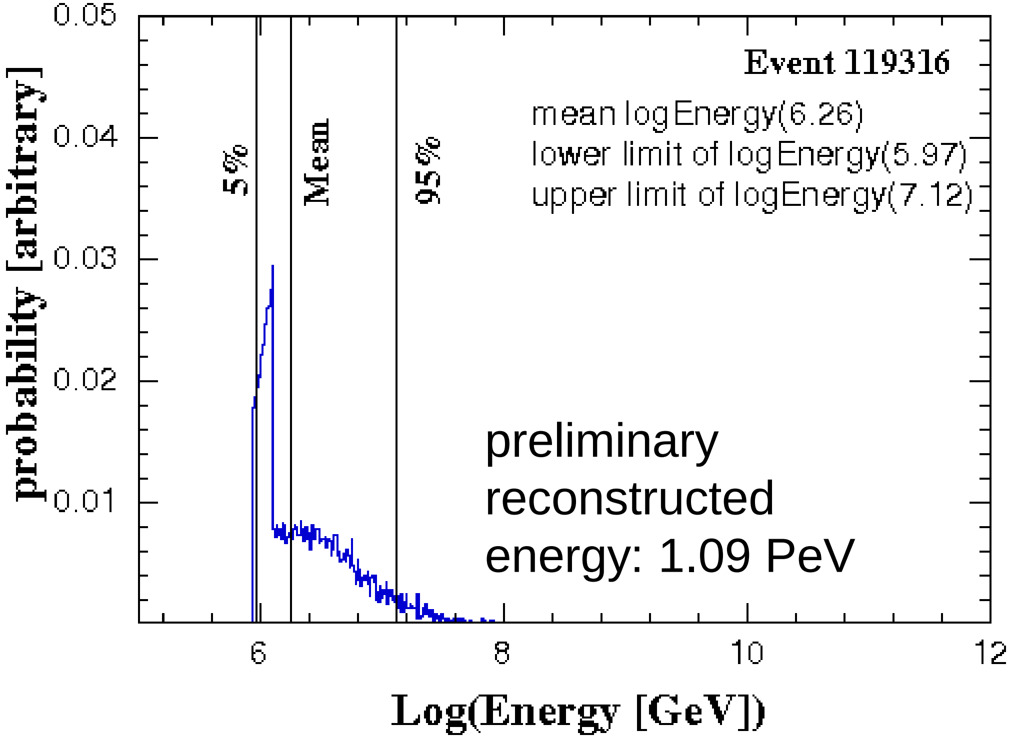
Downward-going region is airshower induced muon background dominated

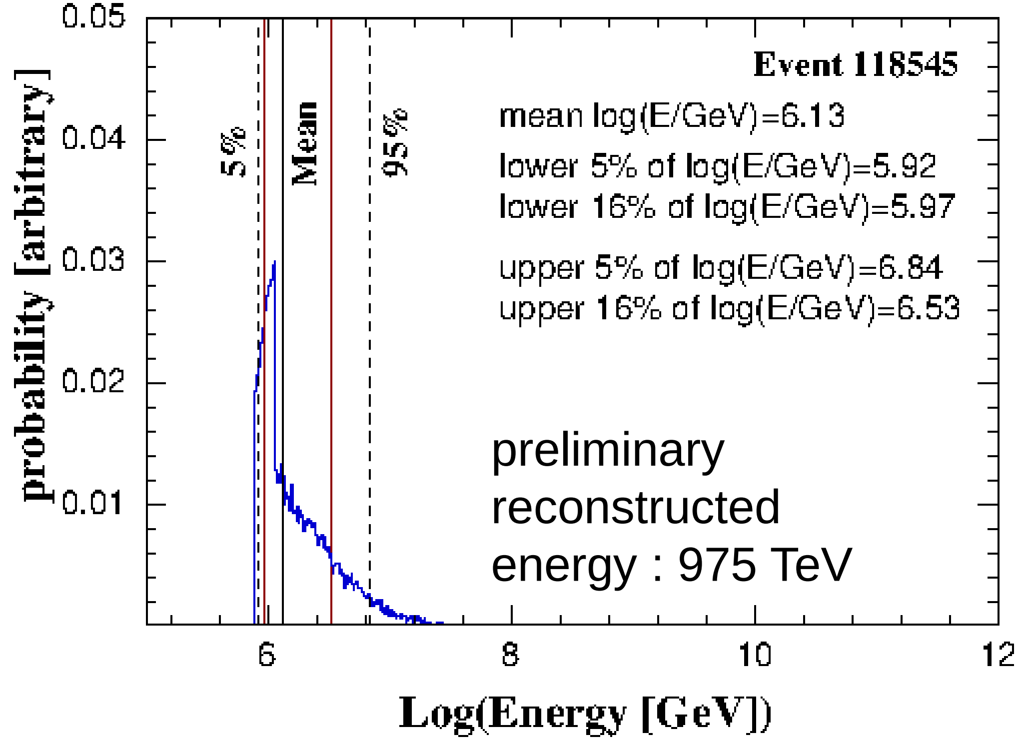






Neutrino energy estimation

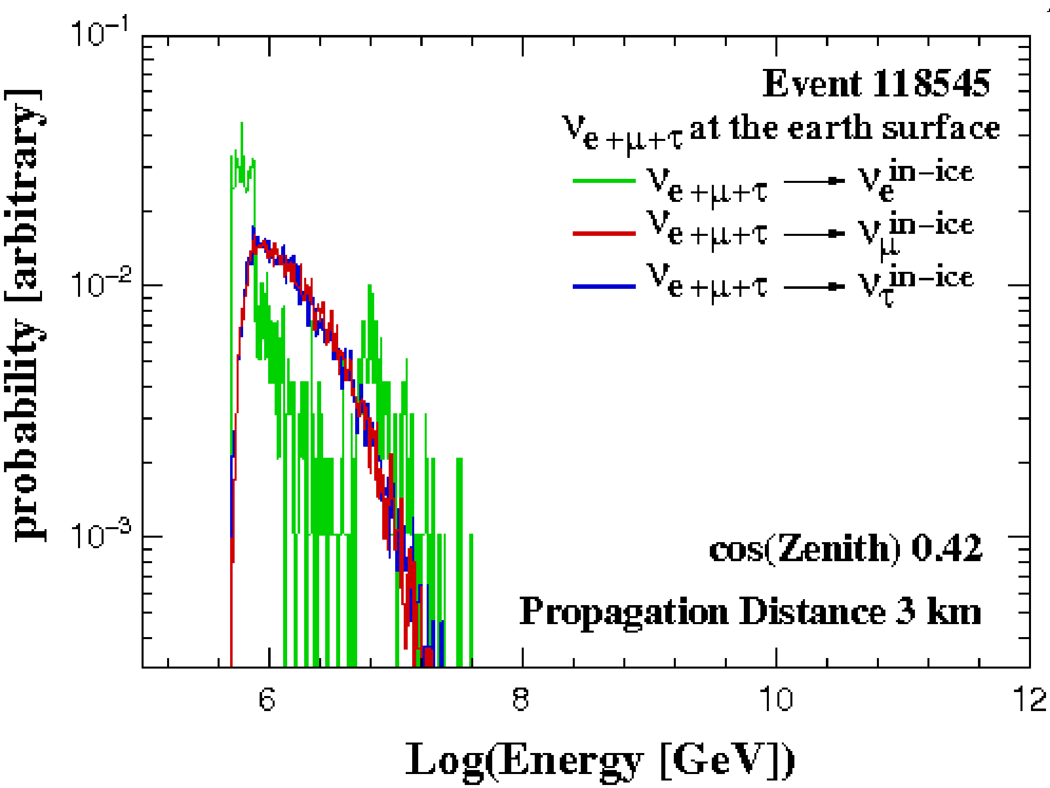


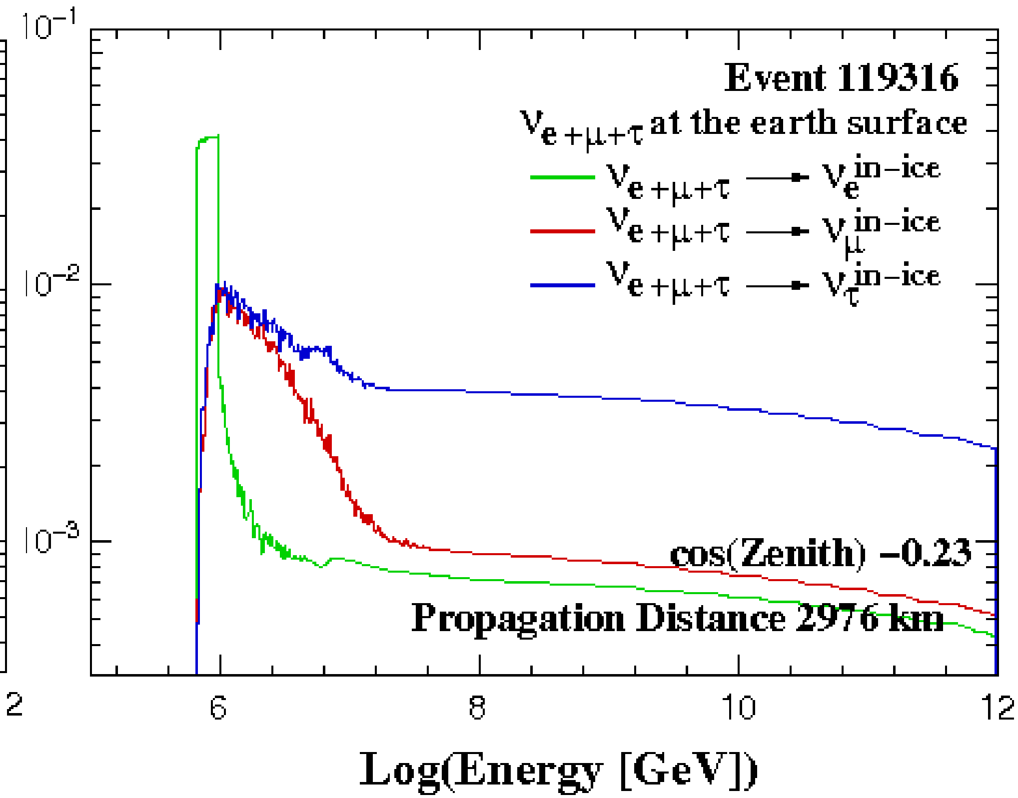


A method of the cascade energy reconstruction
- Poisson likelihood for all pulses
- Analytic likelihood maximization for energy
- Numerical minimization (Gulliver) in x, y, z, time, zenith, azimuth

Surface Energy Distribution of Flavor Dependence

For the downward-going geometry difference due to different parent neutrino flavors on surface is small. For the upward-going geometry it is more relevant, still uncertainty extend not more than 1 energy decades.





In-*situ* energy scale calibration

Calibrated light source: Standard Candle

- **in-situ calibrated N_2 pulsed laser**
- **light wavelength 337 nm**
- **at 100% intensity generates $4x10^{12}$ photons per pulse emitted at 41^o**
- **output adjustable between 0.5% ~ 100%**