IceCube: Ultra-high Energy Neutrinos

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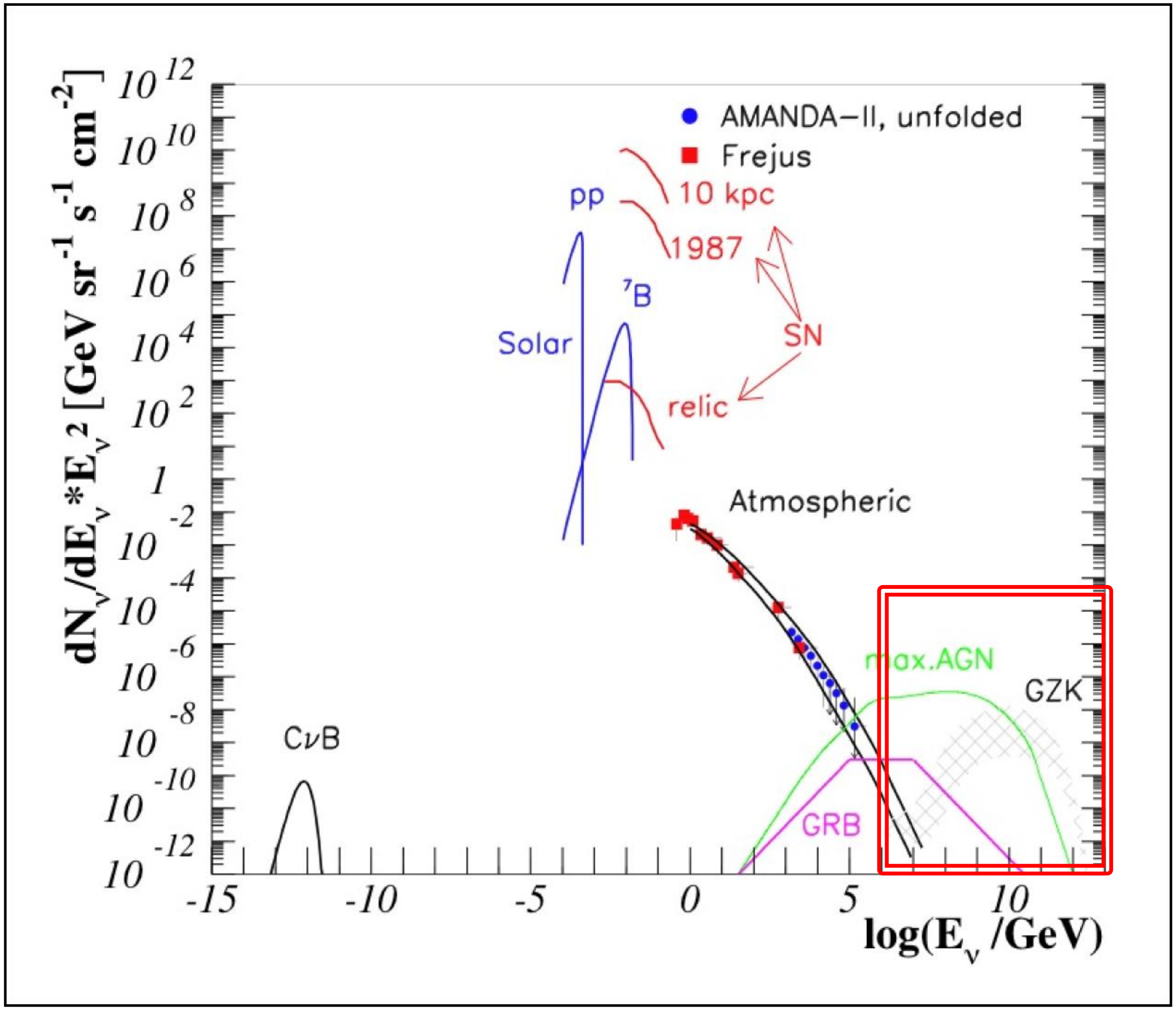
for the **IceCube** collaboration

Neutrino2012 at Kyoto June 8th 2012

Ultra-high Energy Neutrinos: *PeV and above*



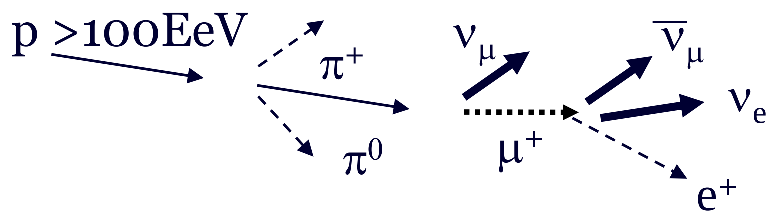
- Energies above dominant atmospheric neutrinos
- Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)
- Cosmogenic neutrino production is a ‘guaranteed’ ν source

The highest energy neutrinos

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

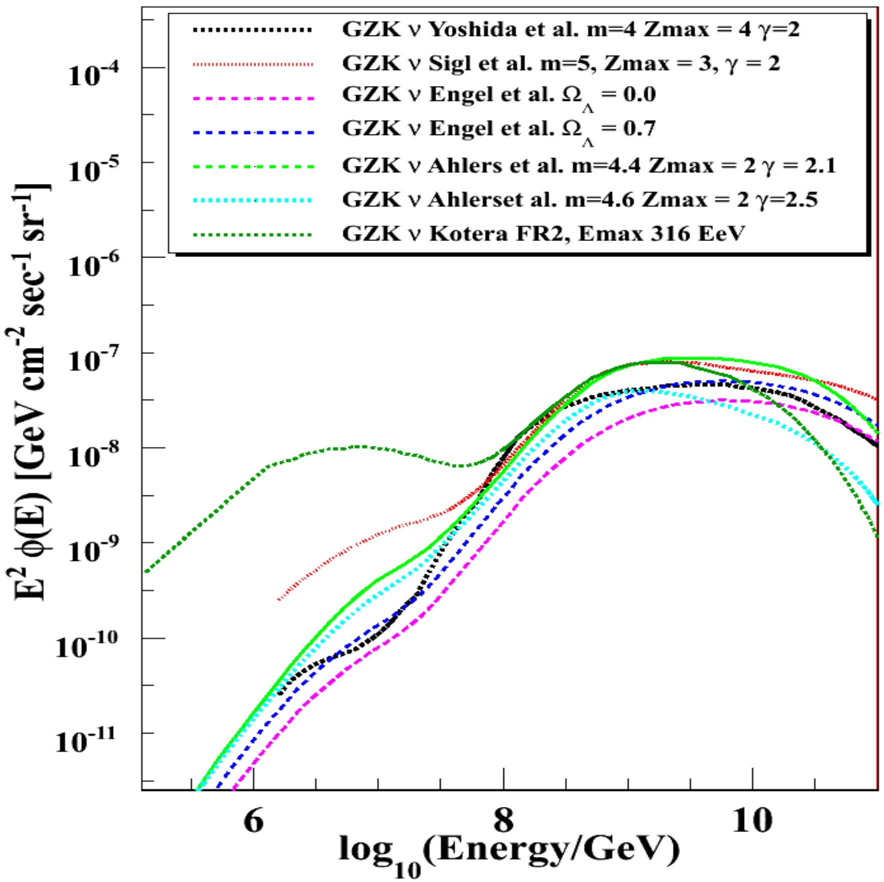
Off-Source (<50Mpc) astrophysical neutrino production via

GZK (Greisen-Zatsepin-Kuzmin) mechanism



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

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



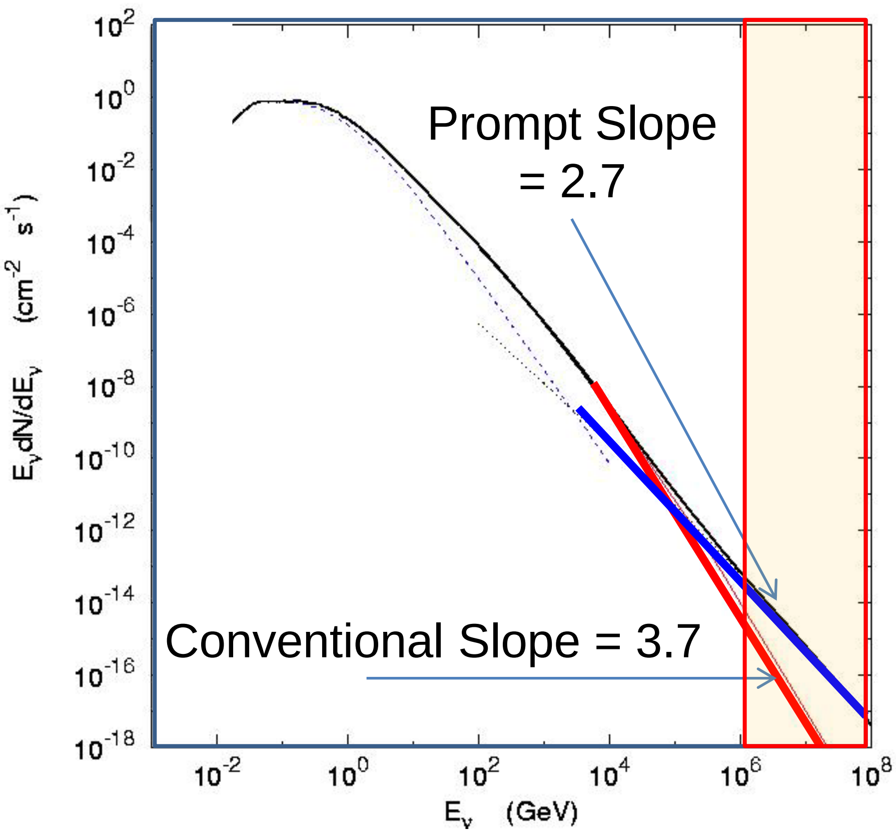
Various GZK ν models

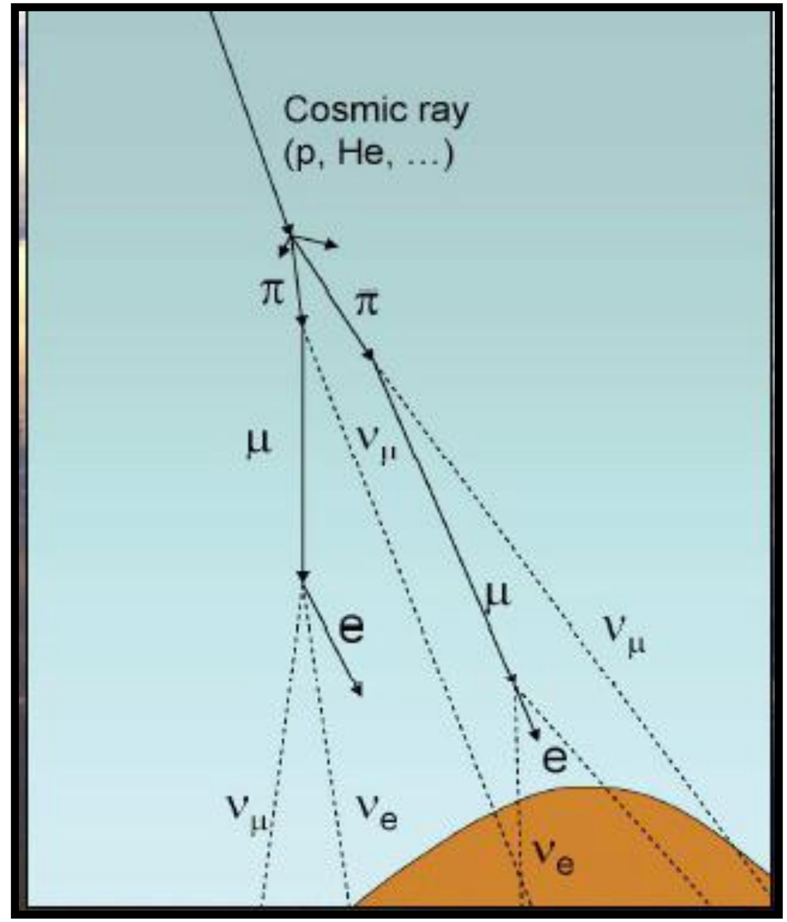
Carries important physics

- 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

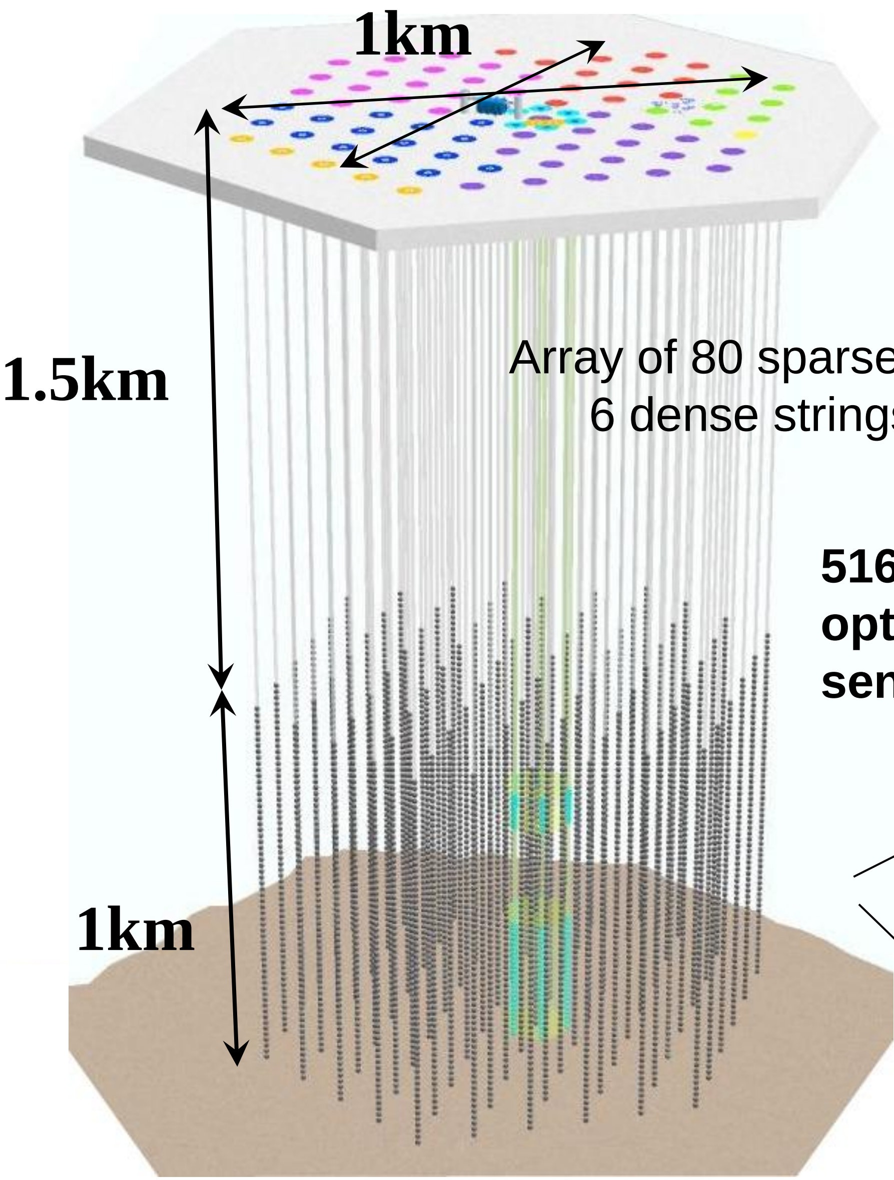




- No clear evidence of prompt atmospheric ν observed so far
- Conventional atmos. ν is considered to be background in this analysis
- Prompt atmos. ν as a signal model

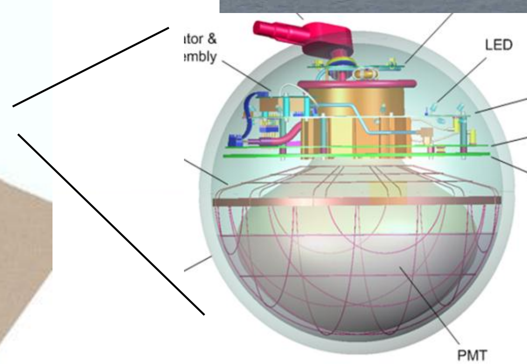
Physics of heavy flavor particle production

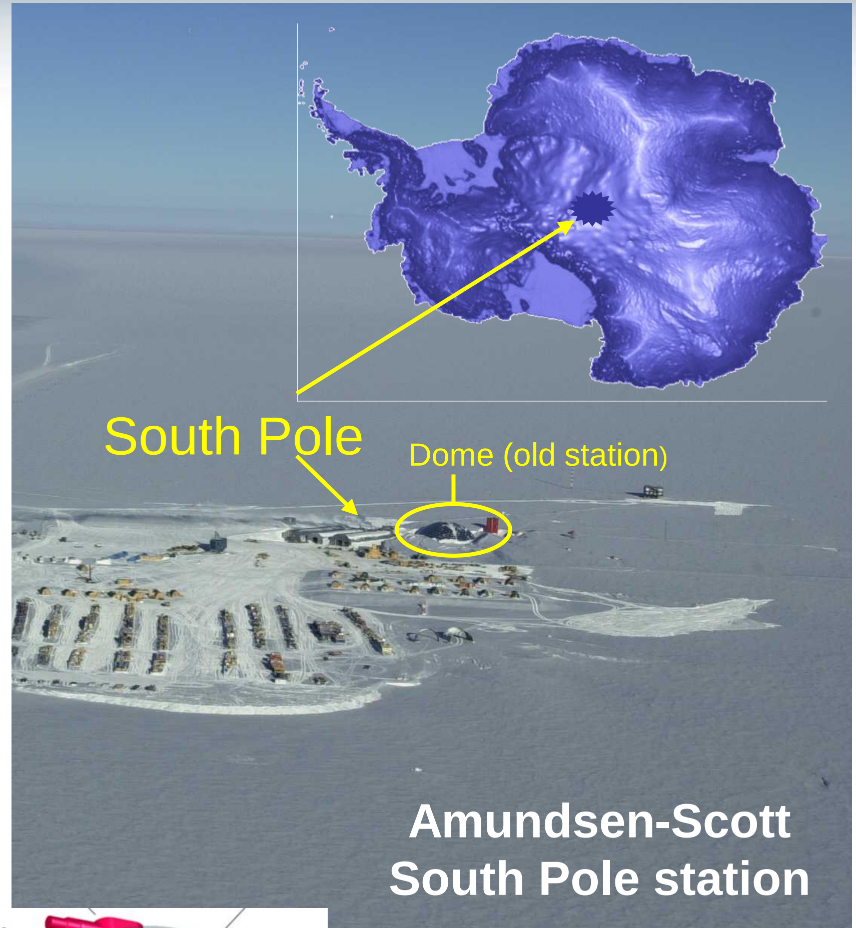
The IceCube Detector



Array of 80 sparse and 6 dense strings

5160 optical sensors



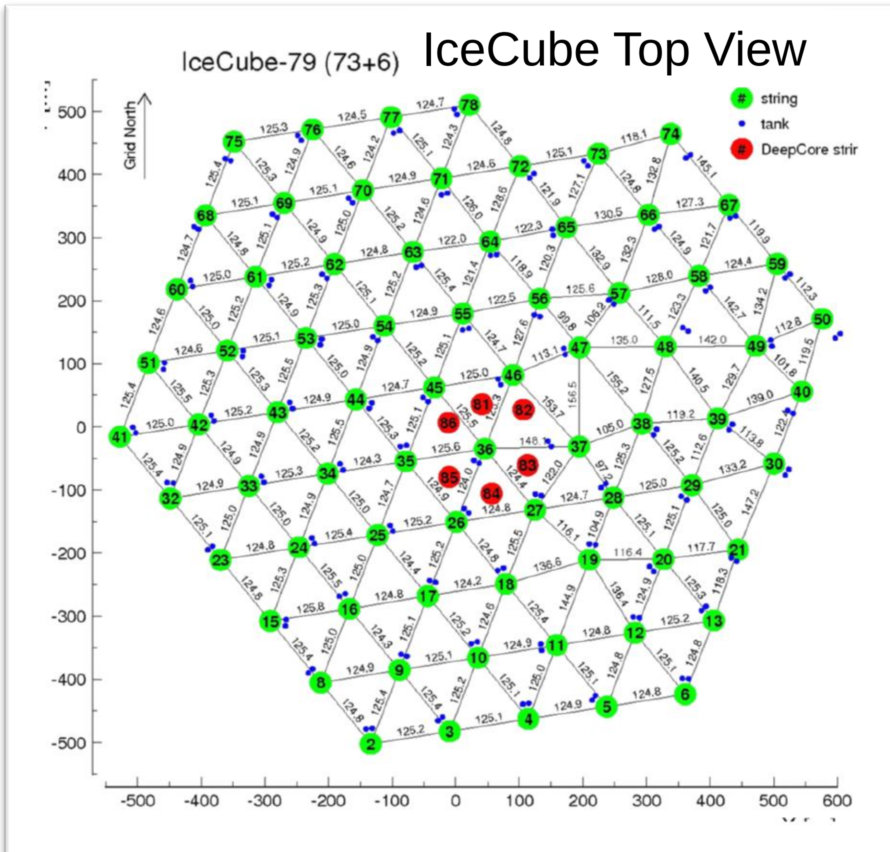


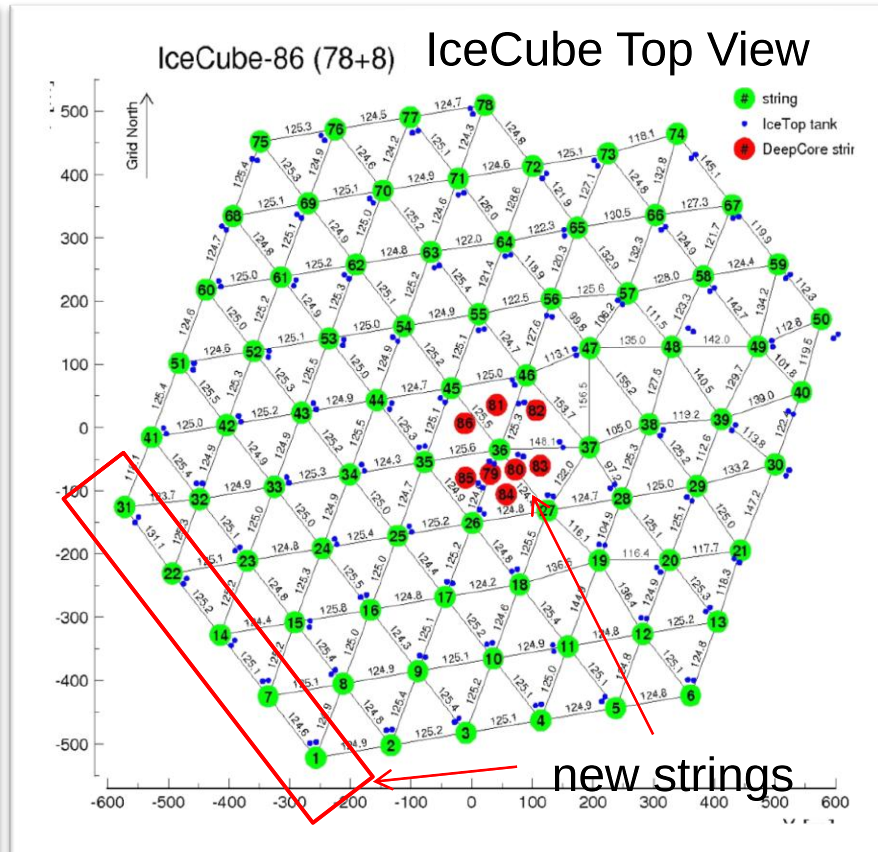
Data samples

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

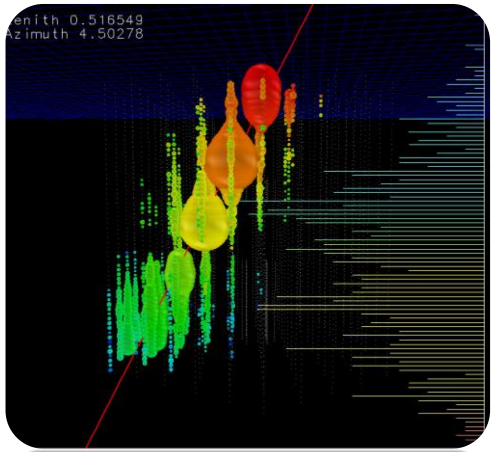
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

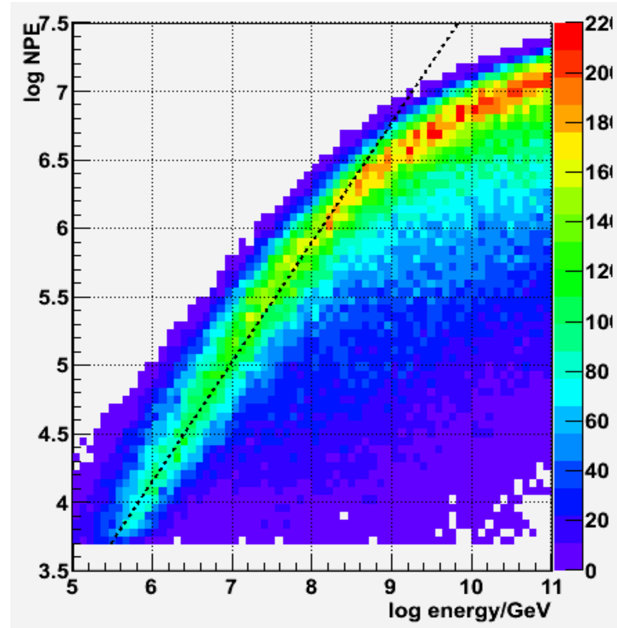




IceCube has been in a stable operation for more than 5 years

The Event Selection

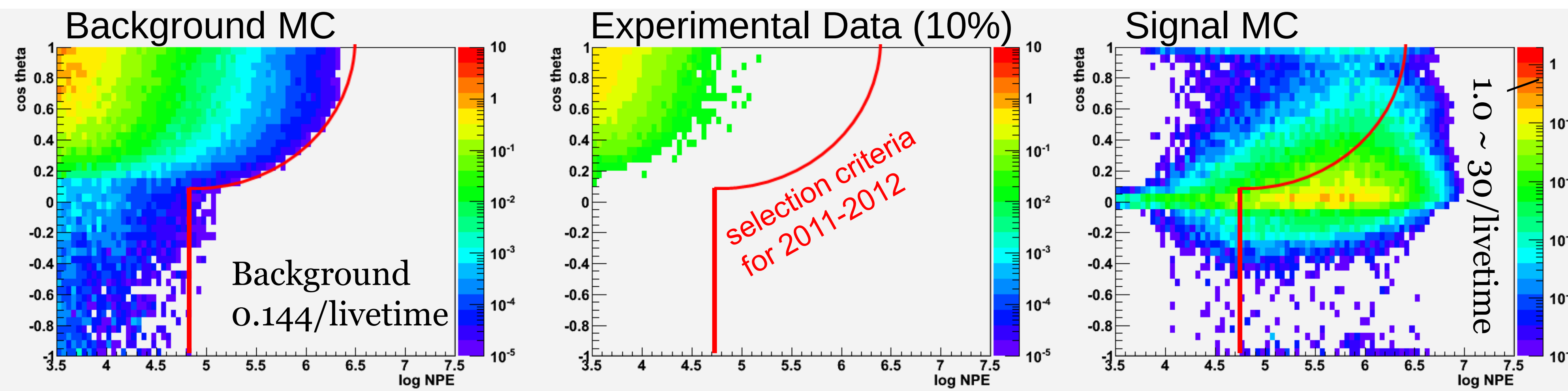




channel # > 300

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

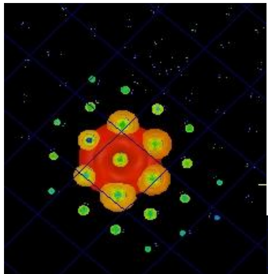
- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample



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

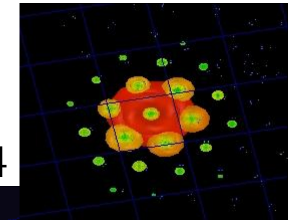
Two events passed the selection criteria

2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events
preliminary p-value: 0.0094 (2.36σ)

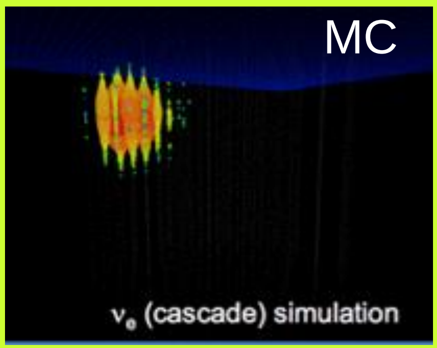


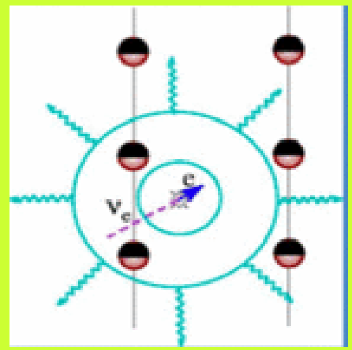
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10^4
Number of Optical Sensors 312

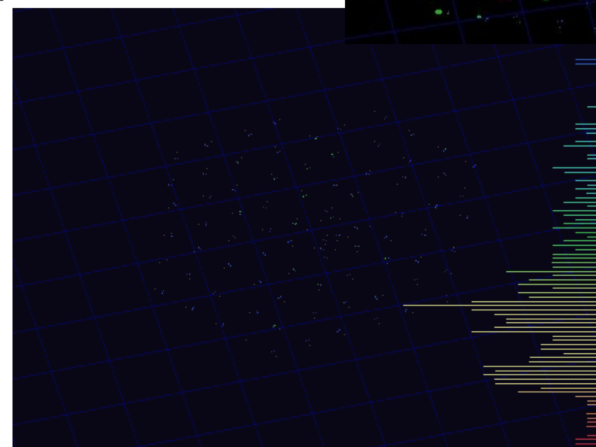
Run118545-Event63733662
August 9th 2012
NPE 6.9928x10^4
Number of Optical Sensors 354

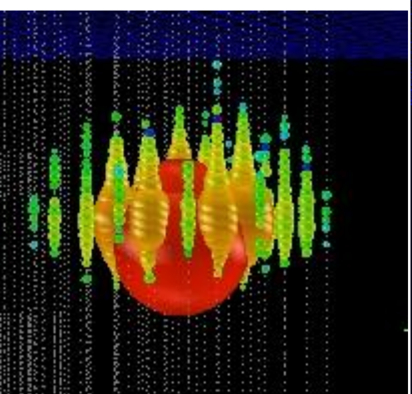


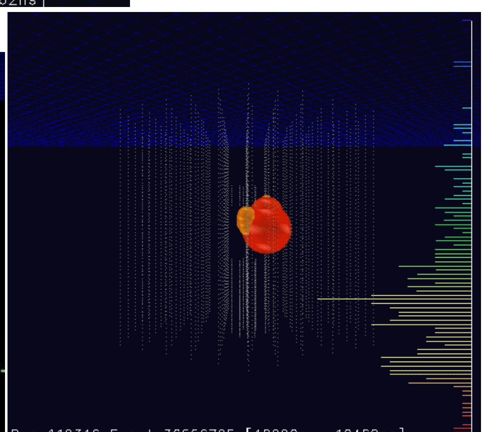
CC/NC interactions in the detector

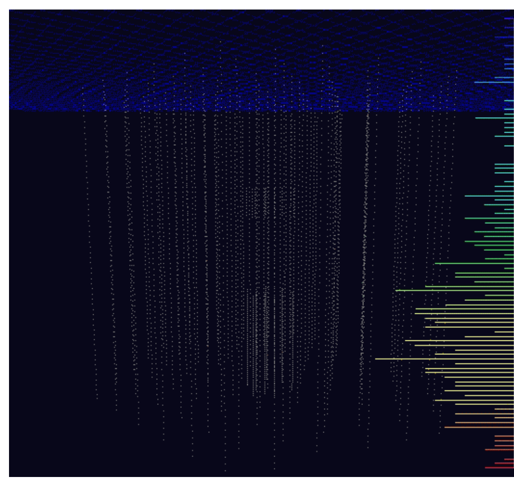


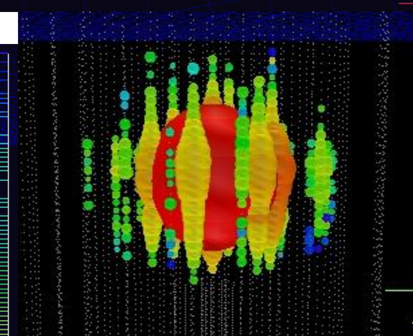




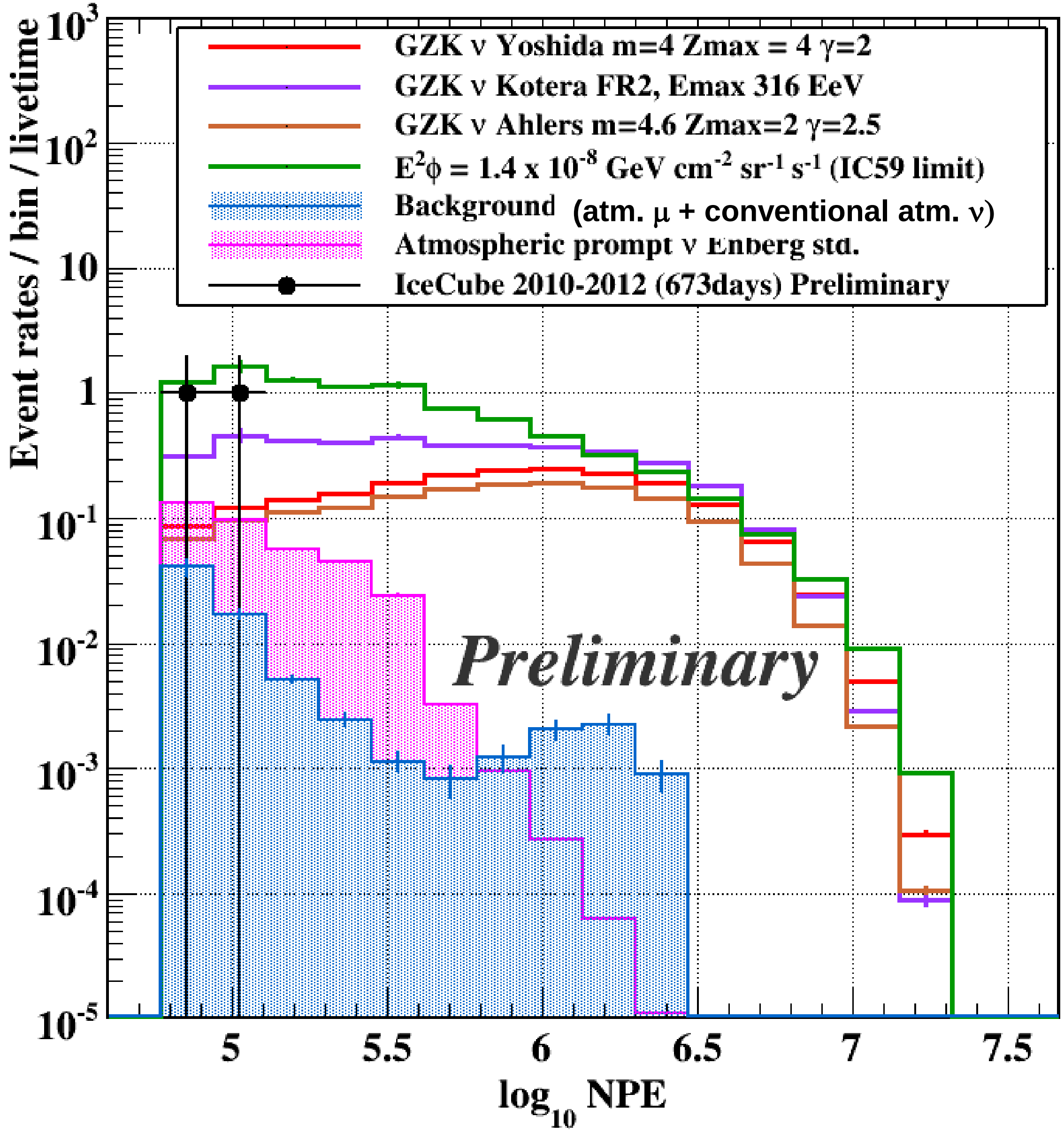








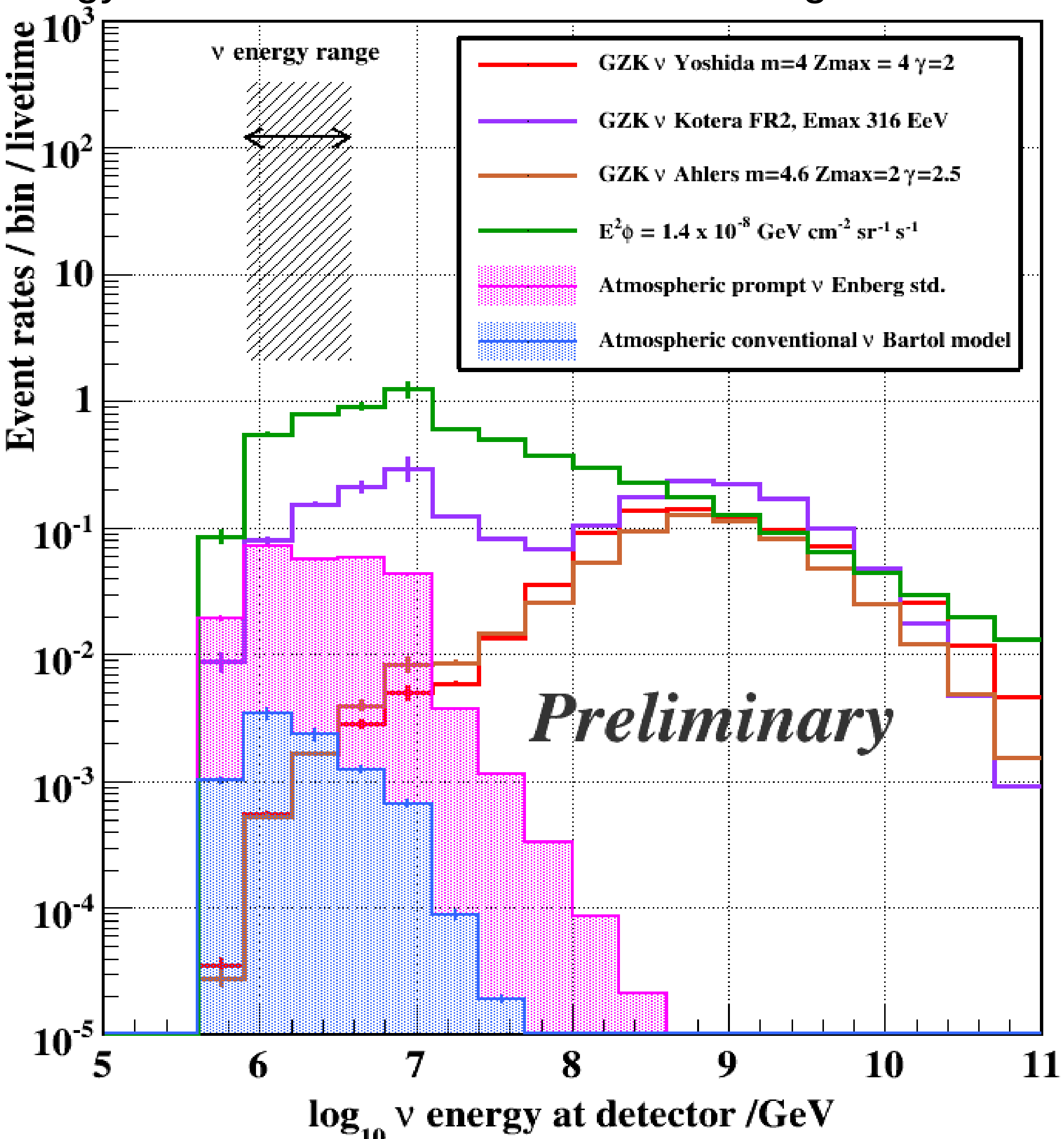
Event Brightness (NPE) Distributions 2010-2012



- 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+hadronic (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

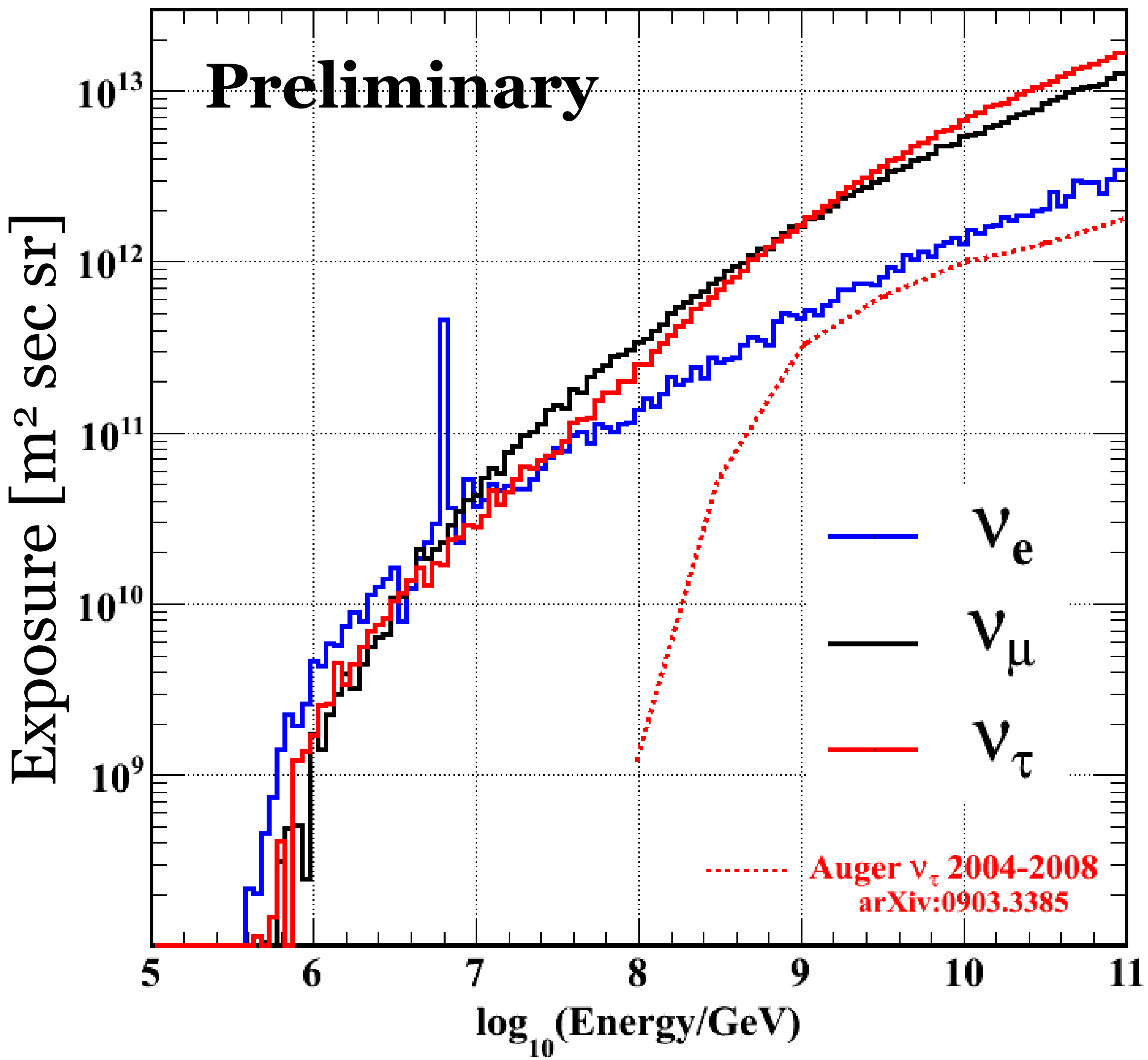
Preliminary

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**
Prompt atm. 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 (conv. 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**

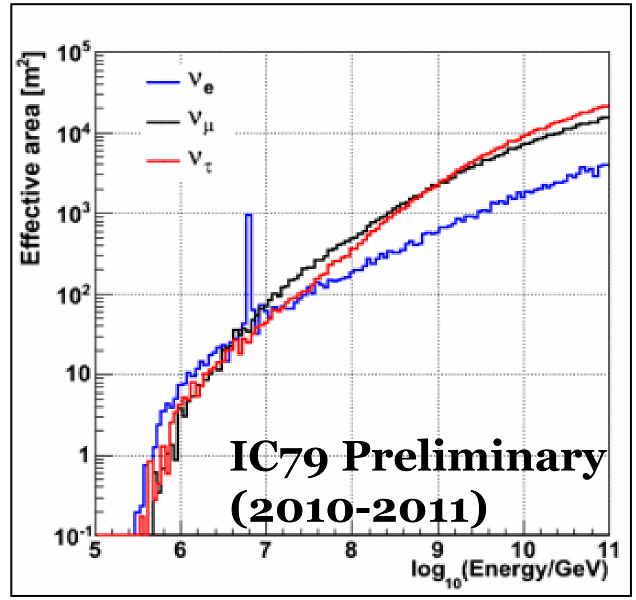
*Yoshida et al The ApJ 479 547-559 (1997), **Ahlers et al, Astropart. Phys. 34 106-115 (2010, ***Kotera et al, ^R. Enberg, M.H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008), ^^ Talk G. Sullivan This conference

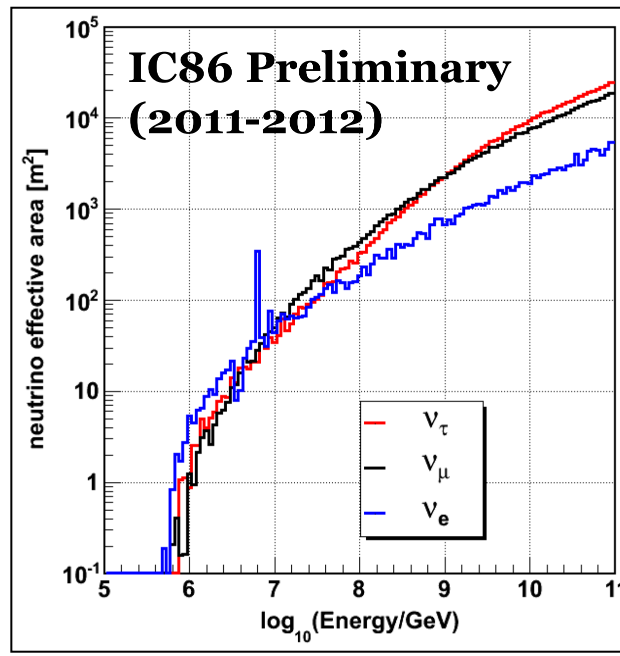
The Exposure and Effective Area

IceCube UHE 2 Years Exposure (2010-2012)

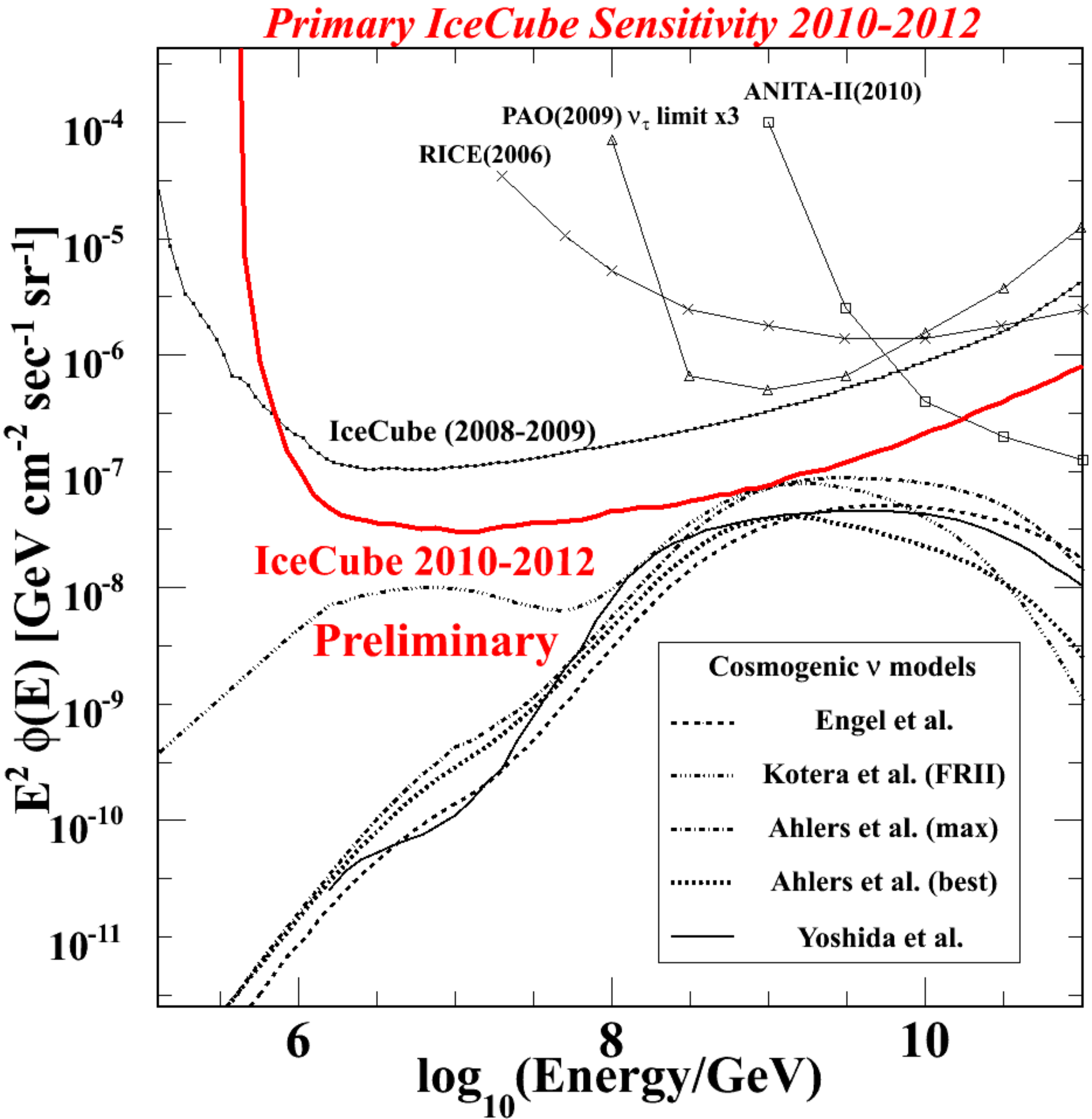


Effective Areas





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

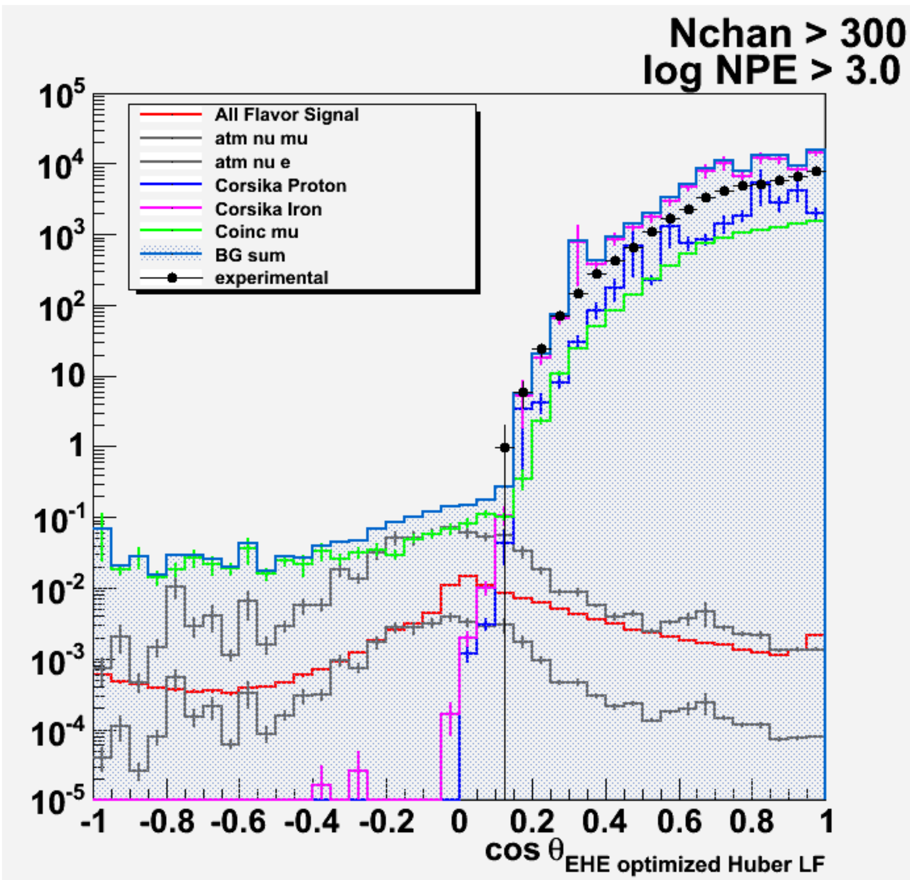
Summary

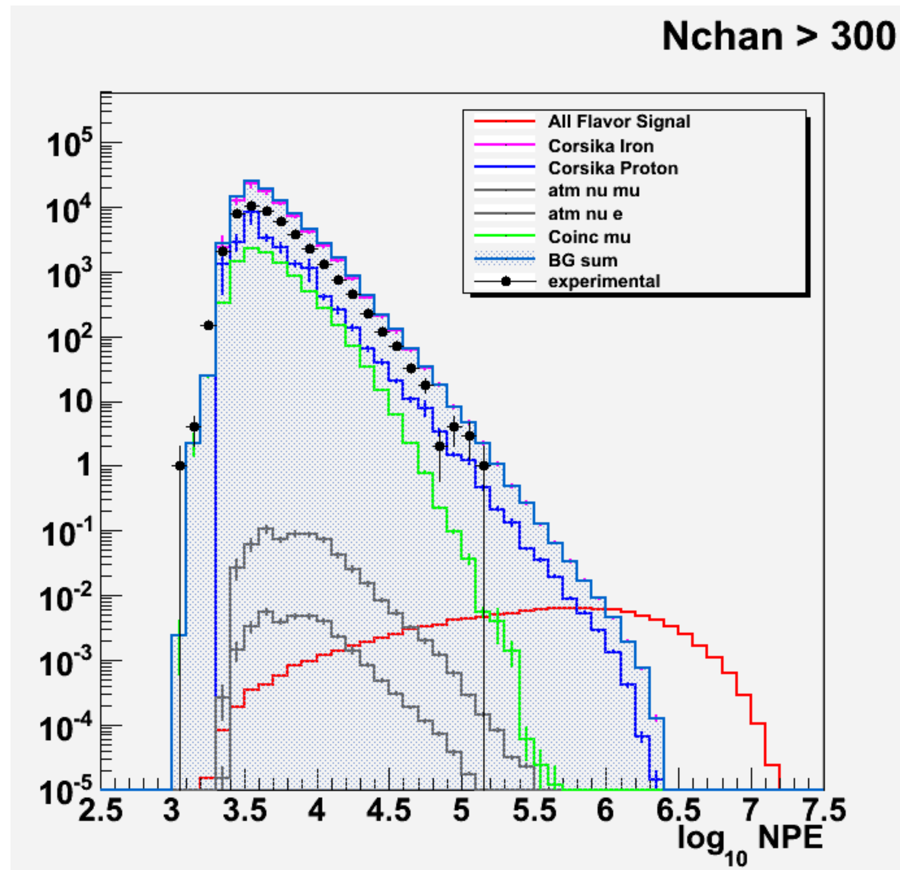
- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - The highest energy events observed ever!
- Likely to be beyond the conventional 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

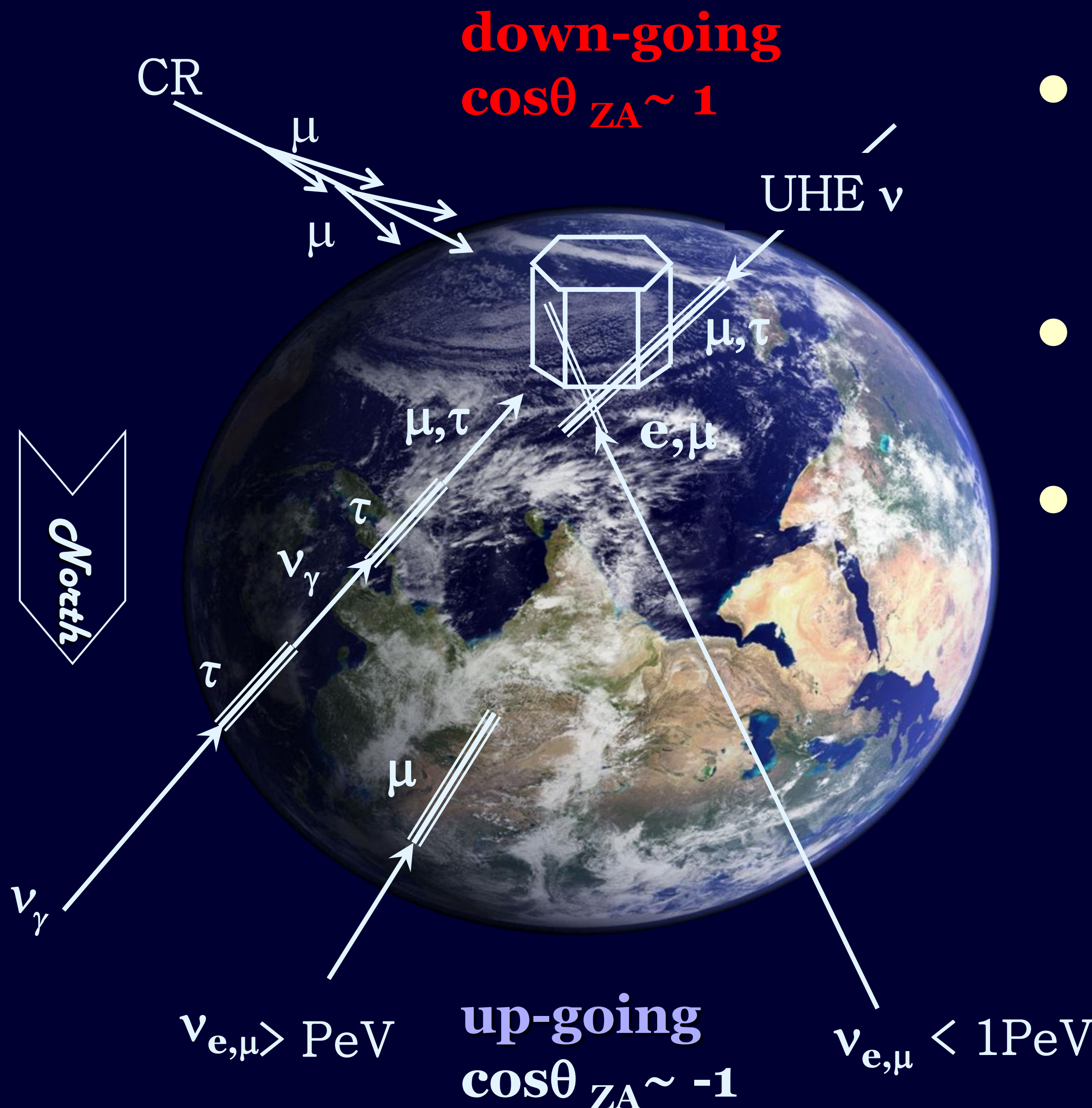
Initial level NPE and cos theta distributions

NPE and cos zenigh angle distributions comparisons with burn sample





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

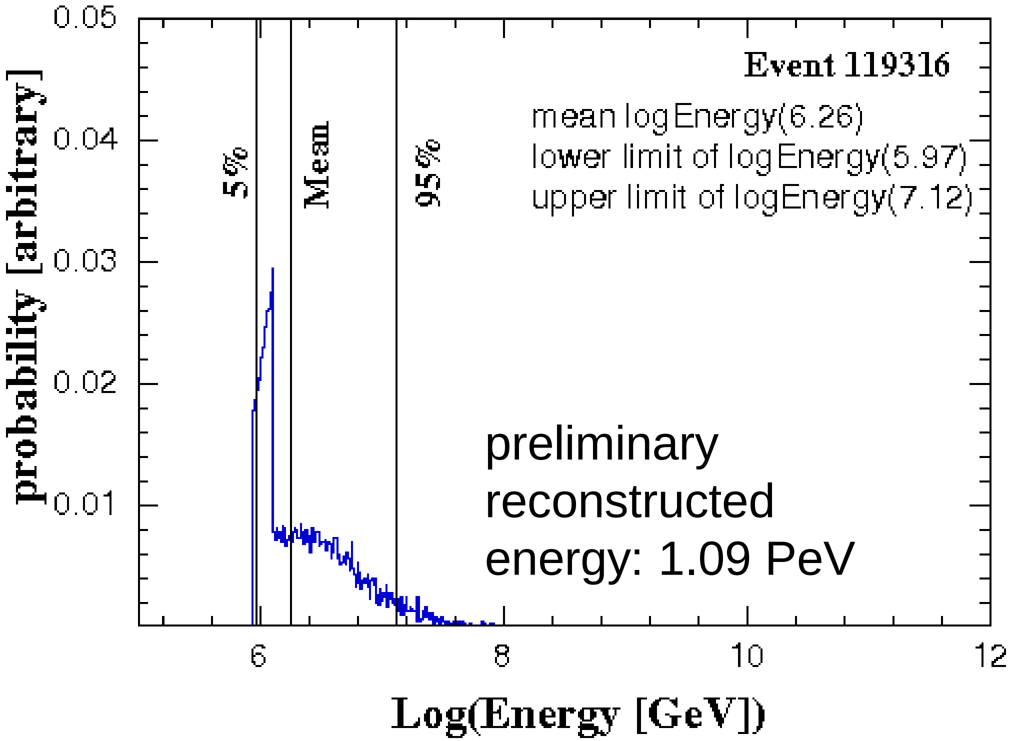
UHE neutrino mean free path
$\lambda_n \sim 100$ km << R_{Earth}
$\sigma^{cc}_{nN} \sim 10^{-6\sim-4}$ mb

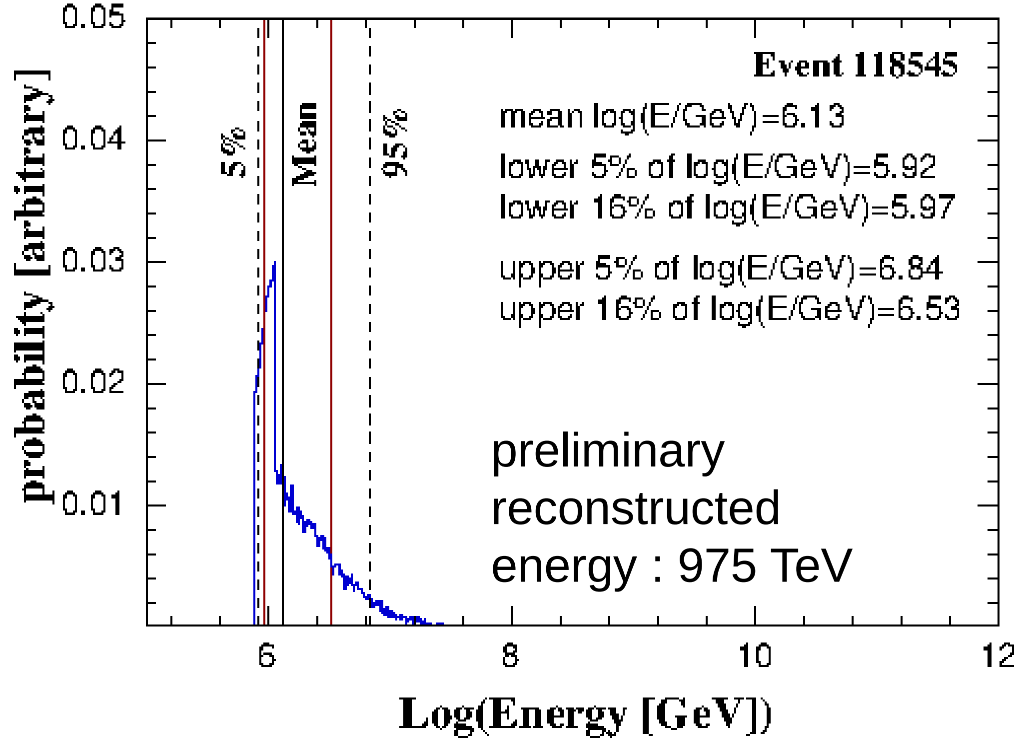
Passing rates (stat. errors only)

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**

Neutrino energy estimation

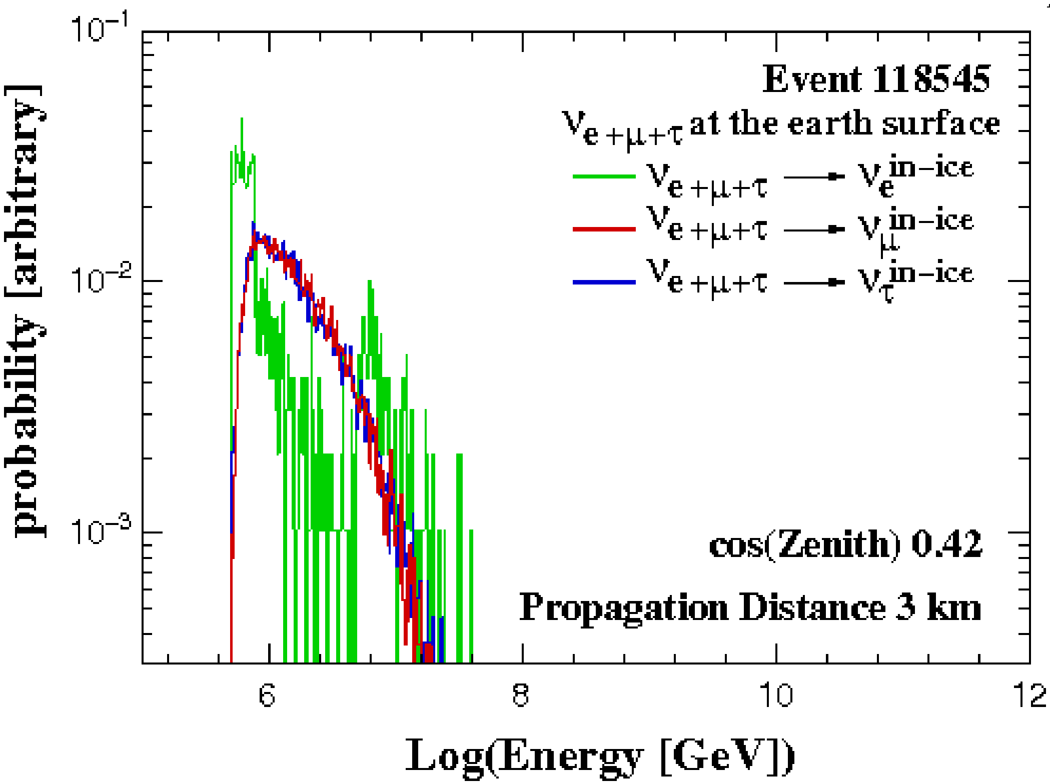


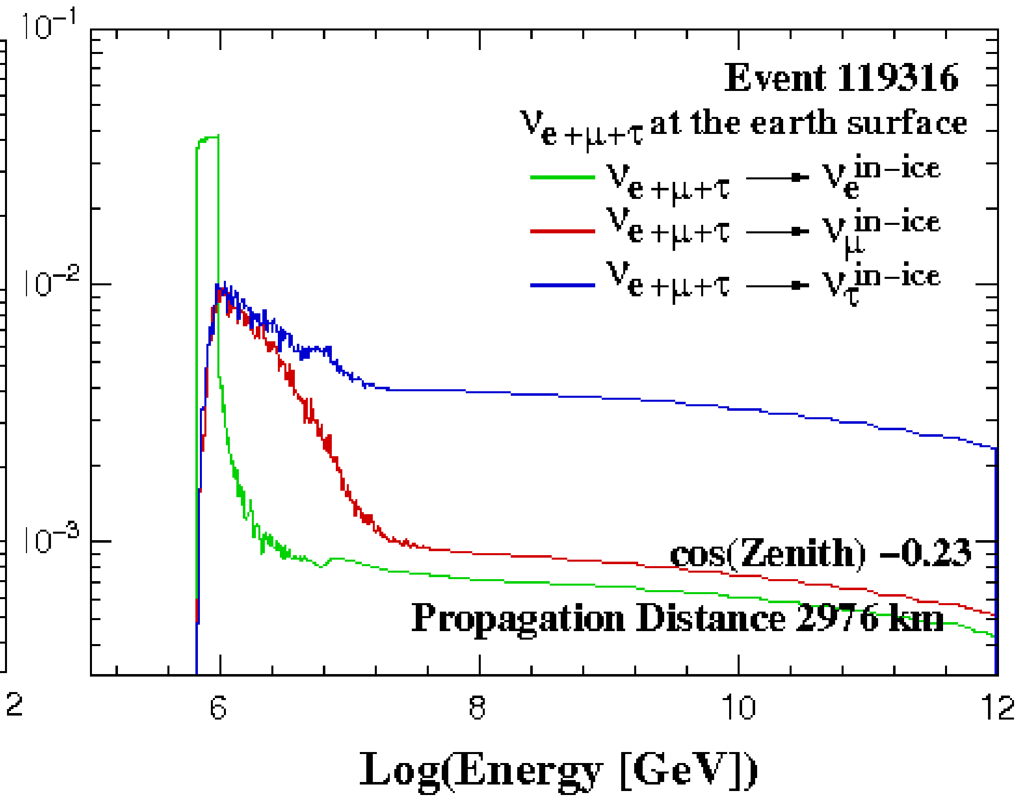


A method of the cascade energy reconstruction
- Poisson likelihood for all pulses
- Analytic likelihood maximization for energy
- Numerical minimization (Gulliver) in x, y, z, time, zenith, azimuth

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.

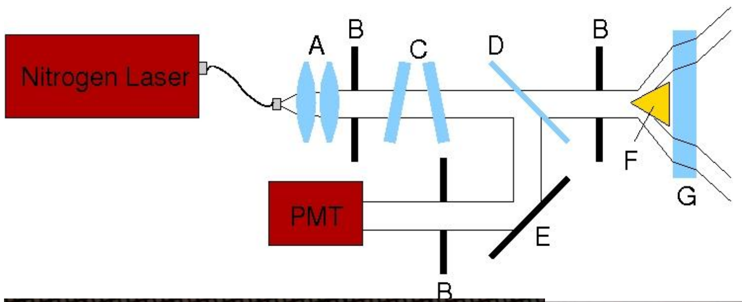


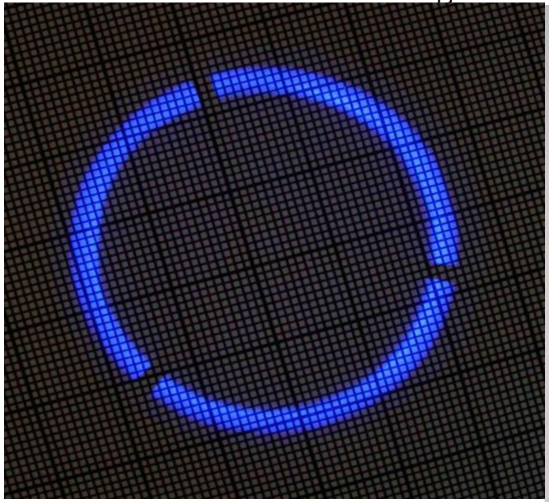


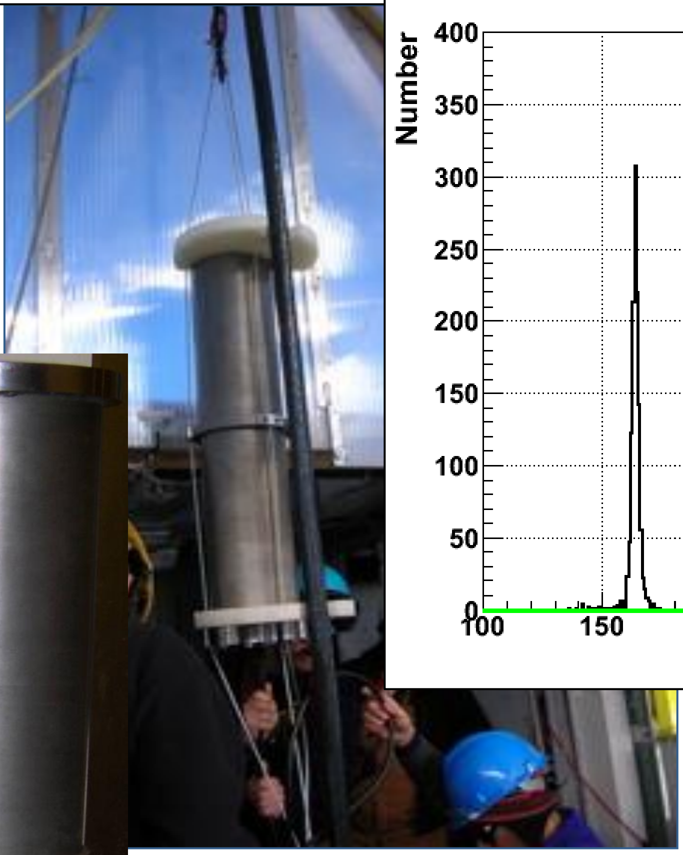
In-*situ* energy scale calibration

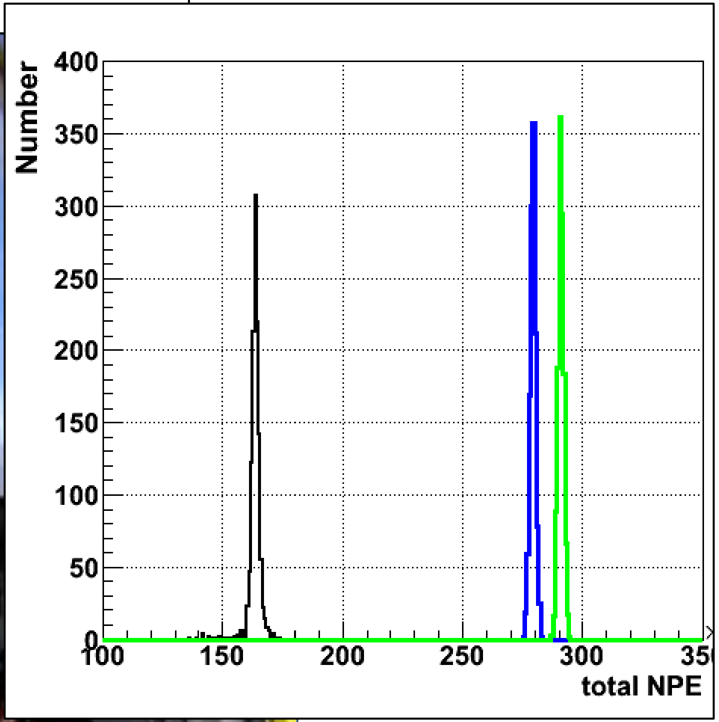
Calibrated light source: Standard Candle

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



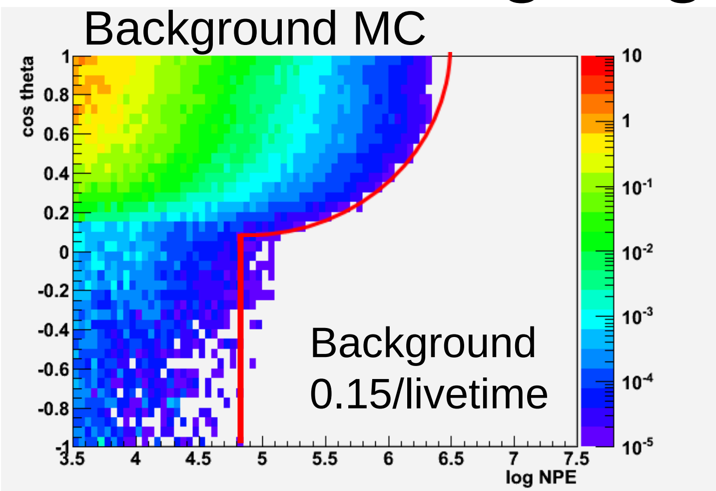


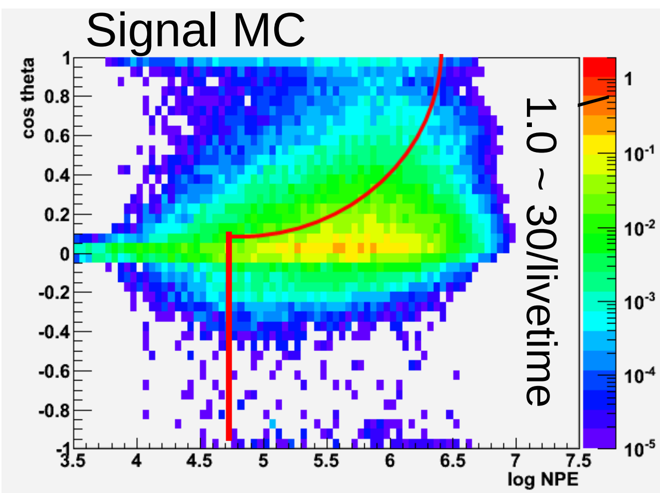


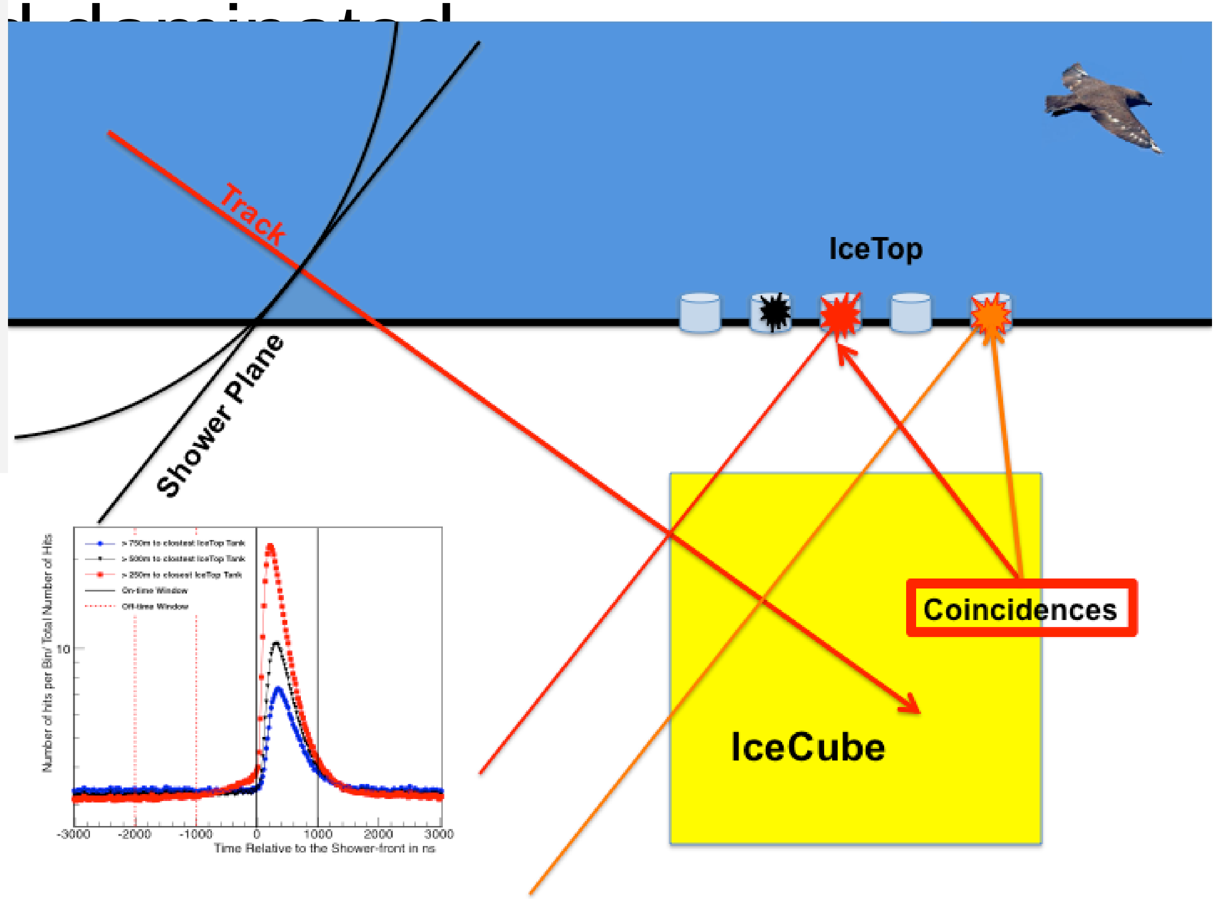


Near future improvement
Background Veto with IceTop

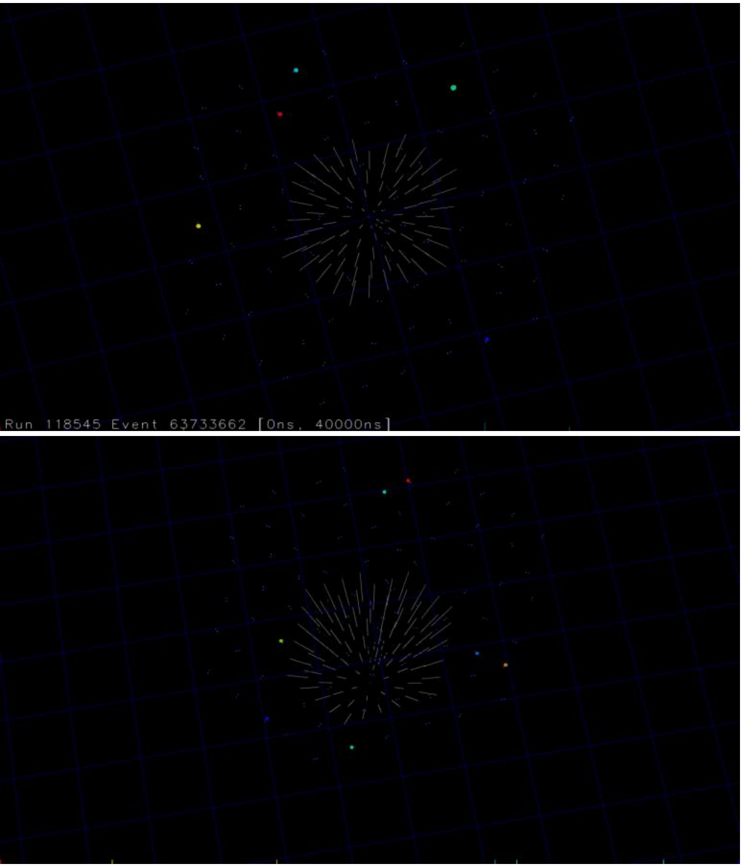
Downward-going region is airshower induced



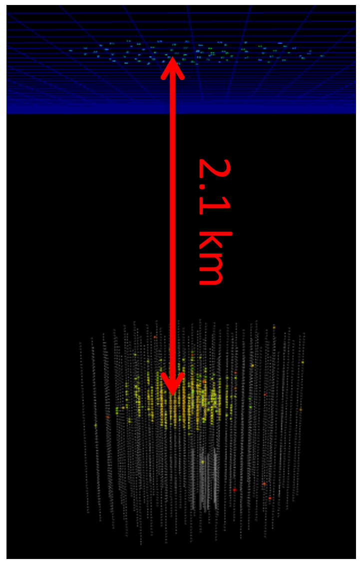


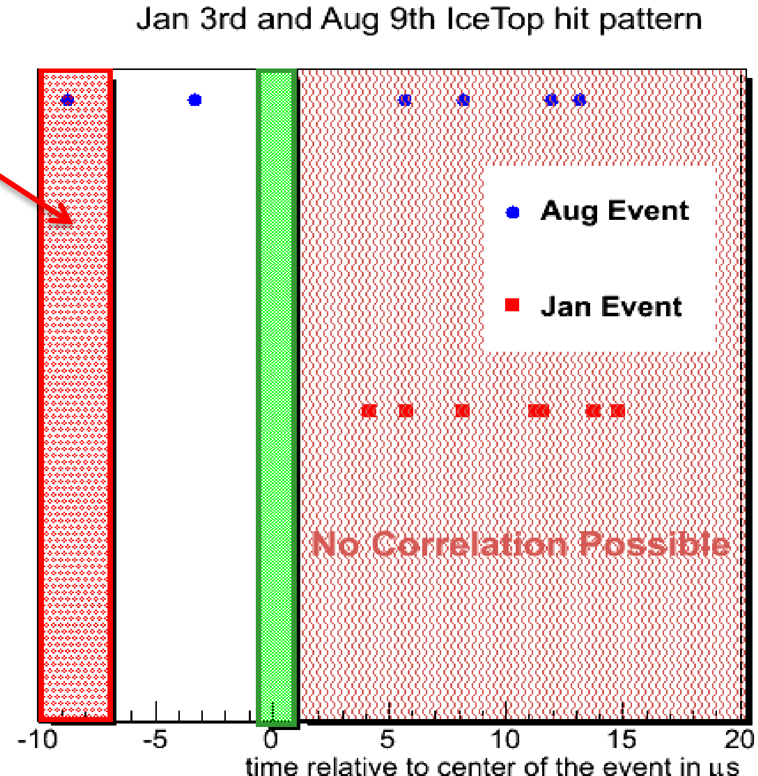


Do The Jan and Aug events have correlated hits in IceTop?



Geometrical not possible as Cascades 2 .1km deep





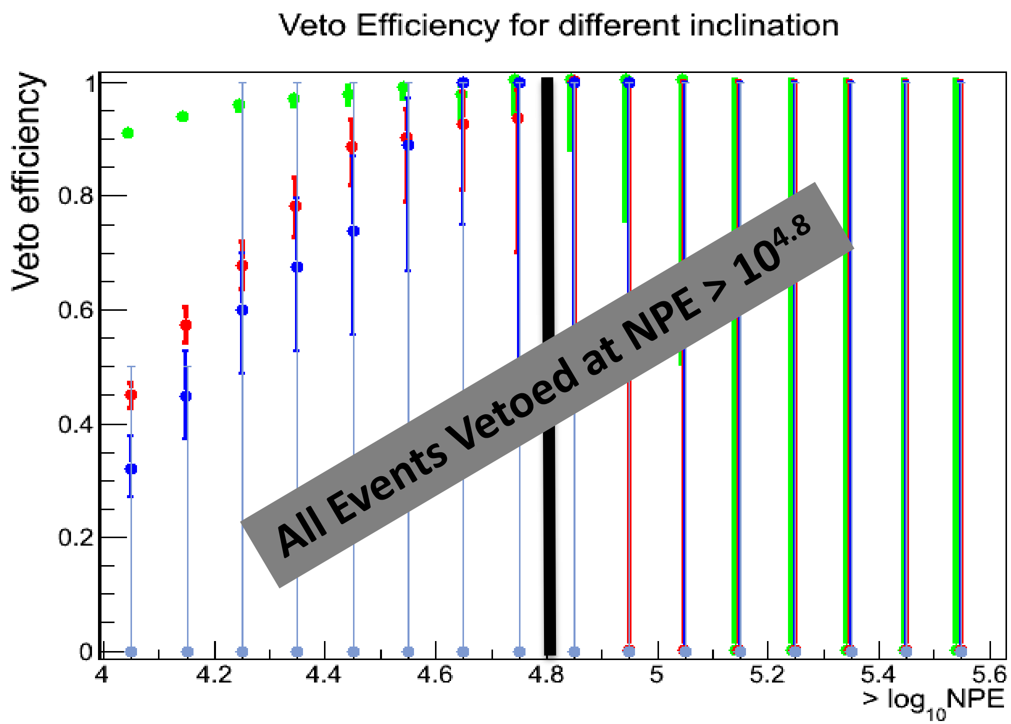
Before first Hit: Correlation possible

After the Event no Down-going correlation possible

Jan Auffenberg May 26th 2012

Conclusions

- We saw 0 Hits and 1 Hit in the possible time window of ~8µs. This is a slide under- fluctuation compared with the measured background rate of (0.26/µs = 2.08/8µs).
- There is no evidence for an Air Shower in the two events.
- Veto efficiency is uncertain for prompt neutrino events



No cascades in
un-vetoed Events:

http://wiki.icecube.wisc.edu/index.php/EHE_IT_Veto_Analysis_unblinding_request#Events_we_don.27t_Veto