# IceCube: Ultra-high Energy Neutrinos

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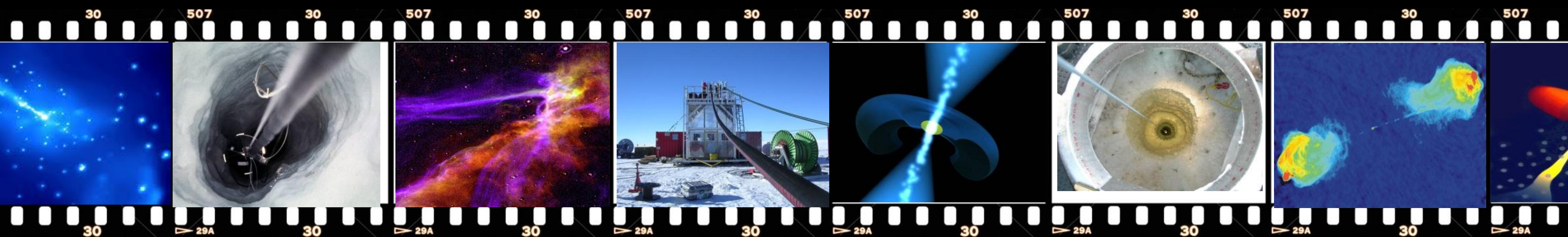
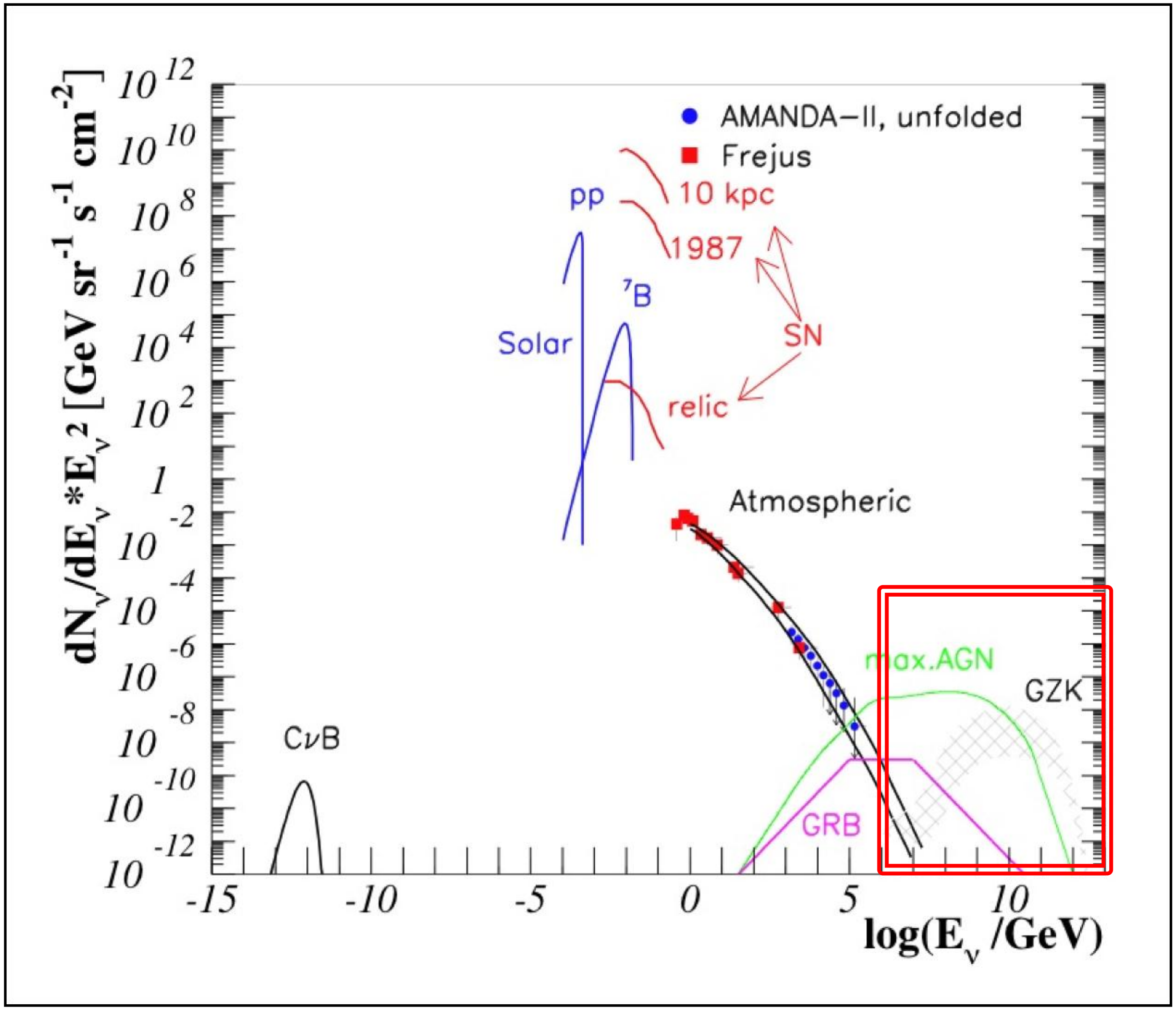
for the **IceCube** collaboration





Neutrino2012 at Kyoto June 8th 2012

# Ultra-high Energy Neutrinos: ***PeV and above***

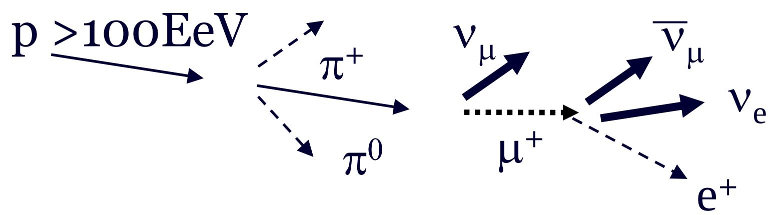



- Energies above dominant atmospheric neutrinos
- Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)
- Cosmogenic neutrino production is a 'guaranteed' ν source

# The highest energy neutrinos

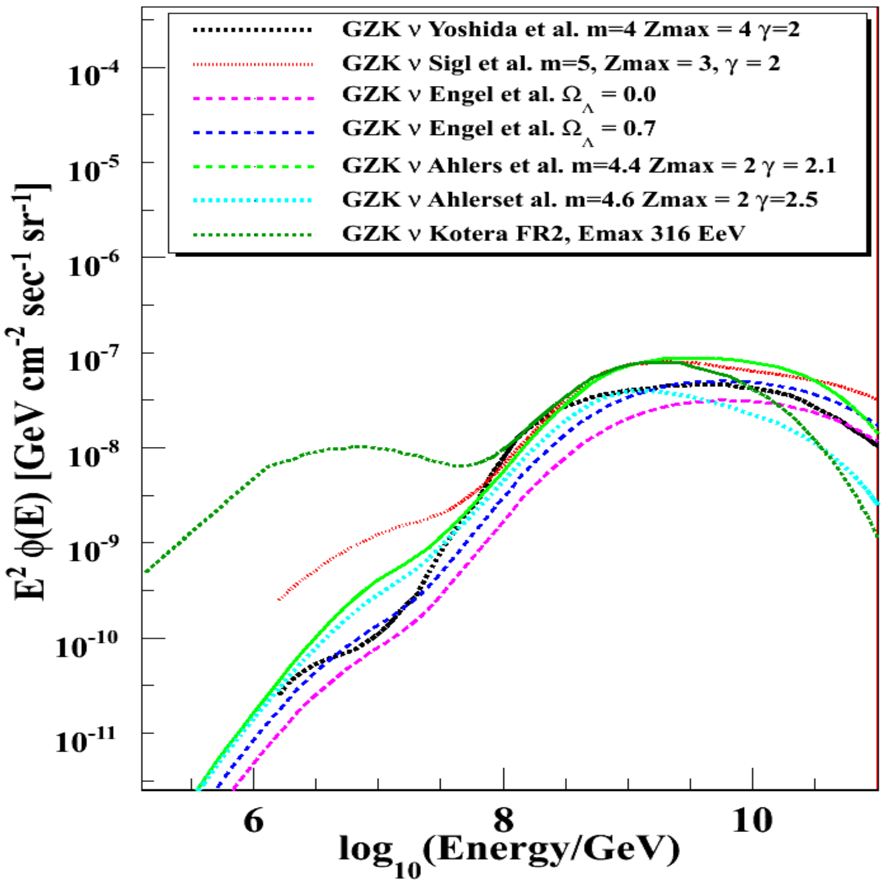
*cosmogenic neutrinos* induced by the interactions of cosmic-ray and CMB photons

Off-Source (<50Mpc) astrophysical neutrino production via GZK (Greisen-Zatsepin-Kuzmin) mechanism




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

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



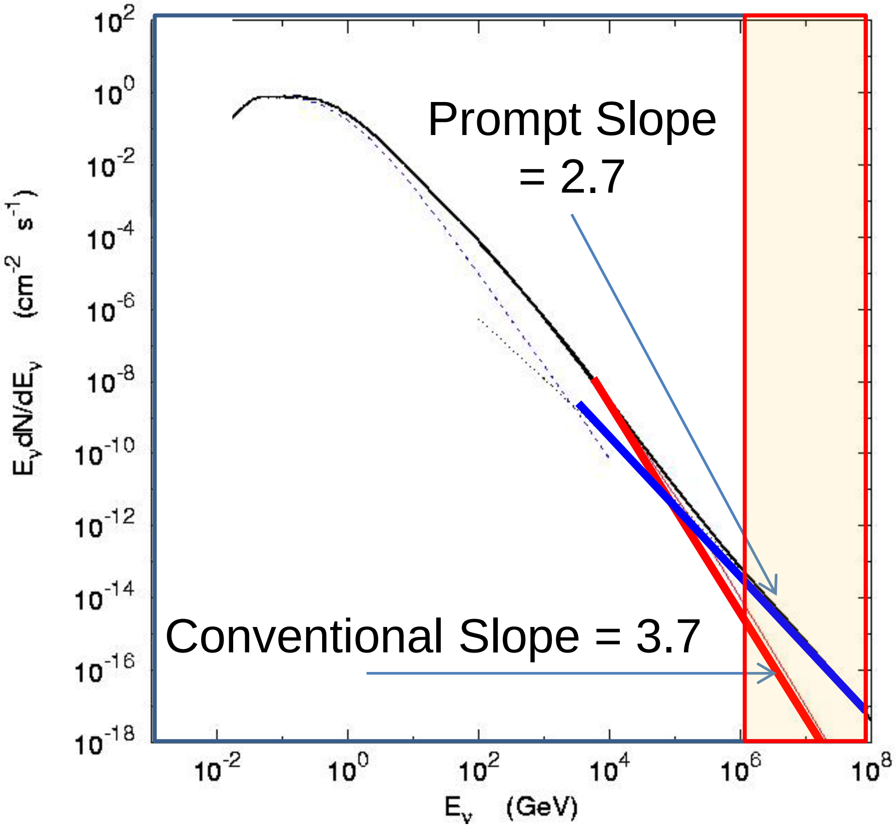

**Various GZK ν models**

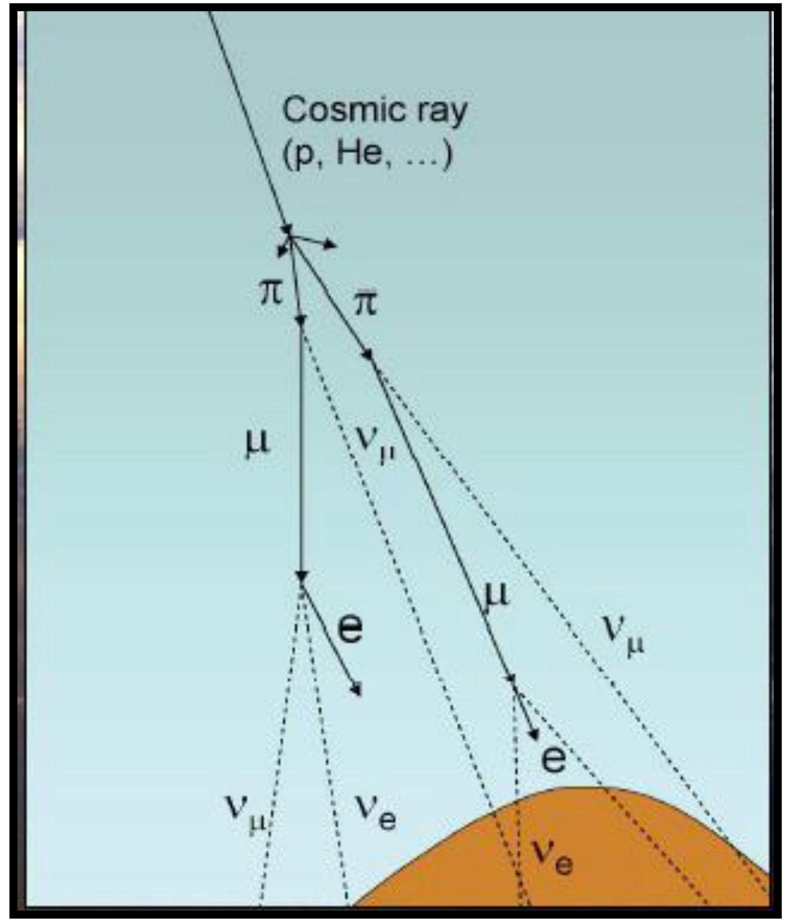
**Carries important physics**

- 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

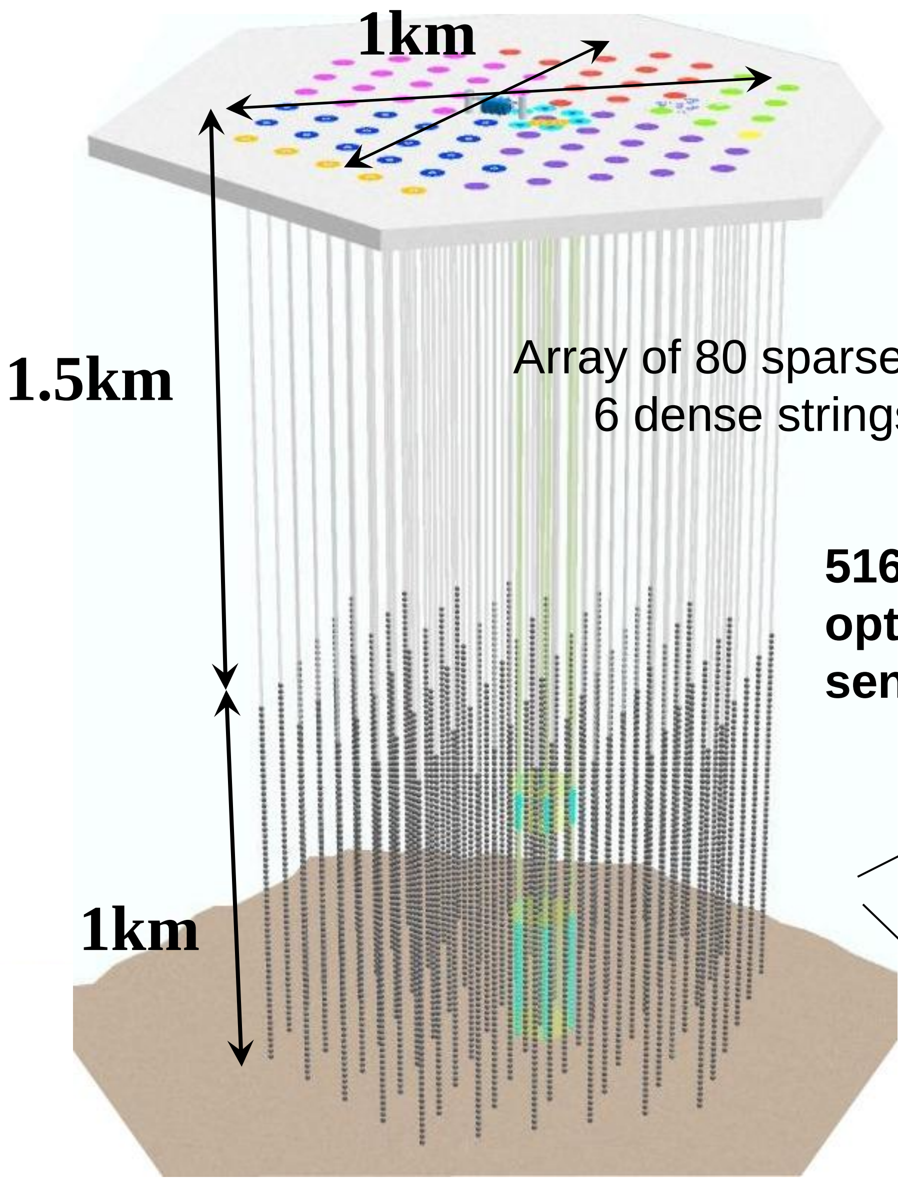



- No clear evidence of prompt atmospheric ν observed so far
- Conventional atmos. ν is considered to be background in this analysis
- Prompt atmos. ν as a signal model

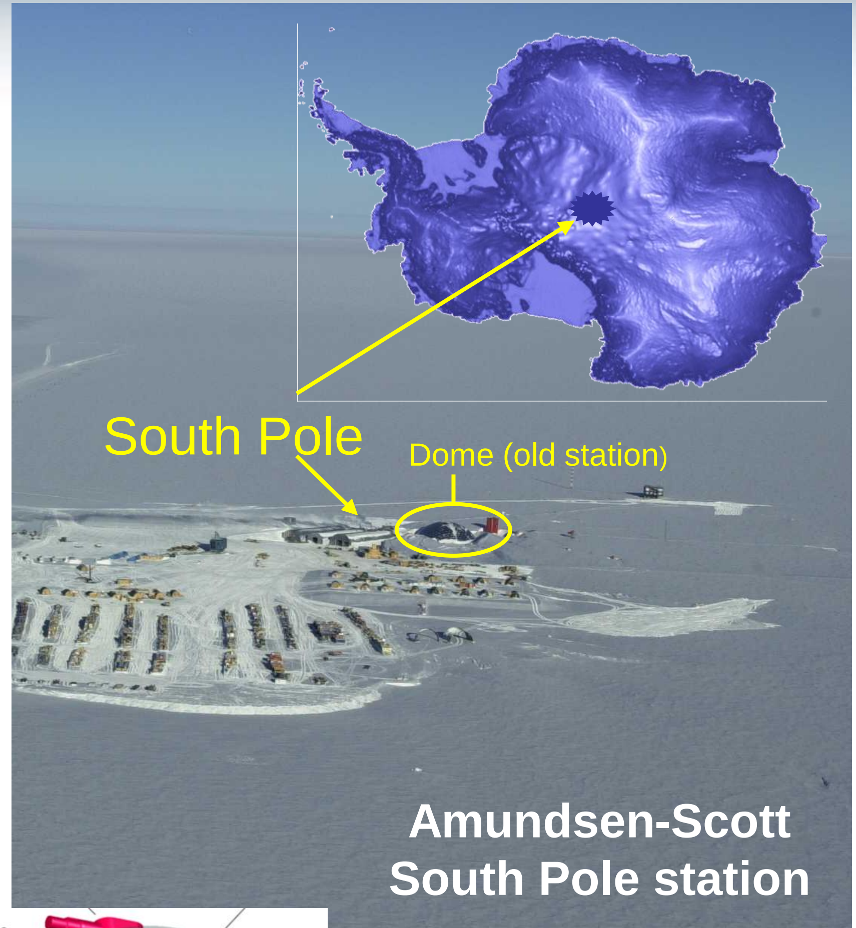
Physics of heavy flavor particle production

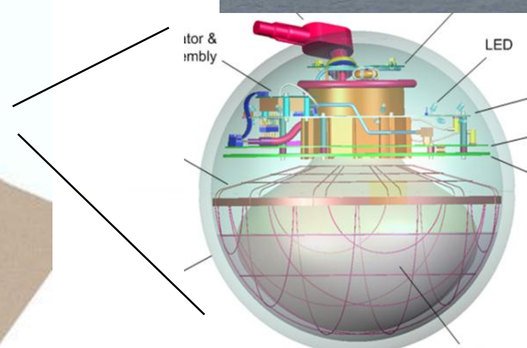
# The IceCube Detector




Array of 80 sparse and
6 dense strings

**5160
optical
sensors**



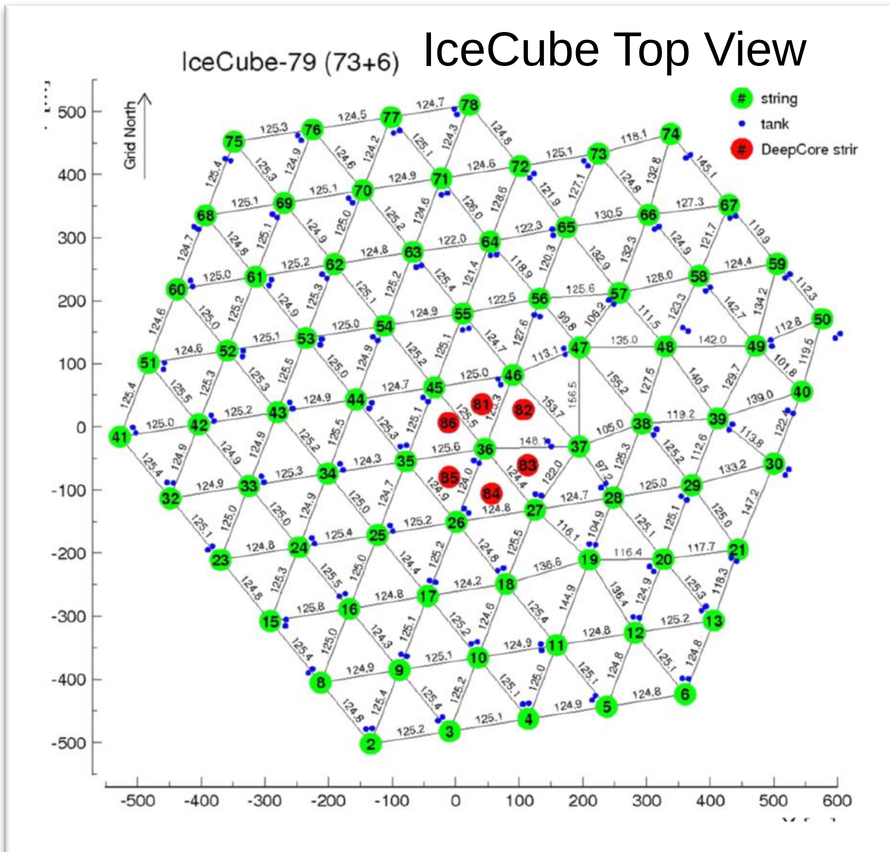
# Data samples

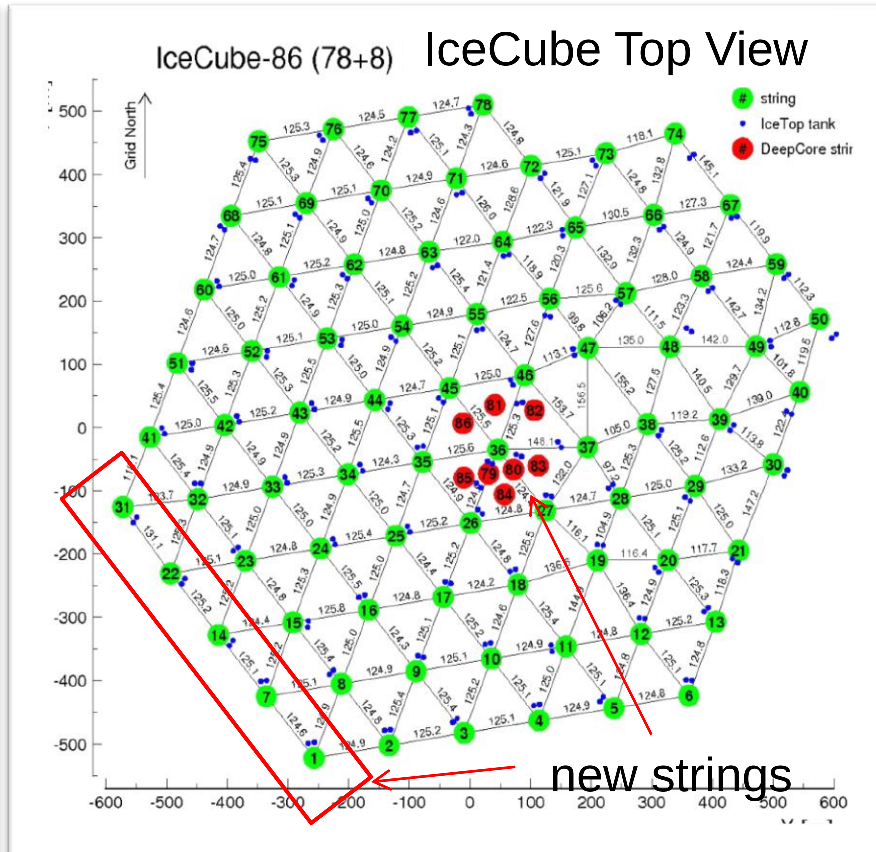
Effective livetime of 672.7days

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

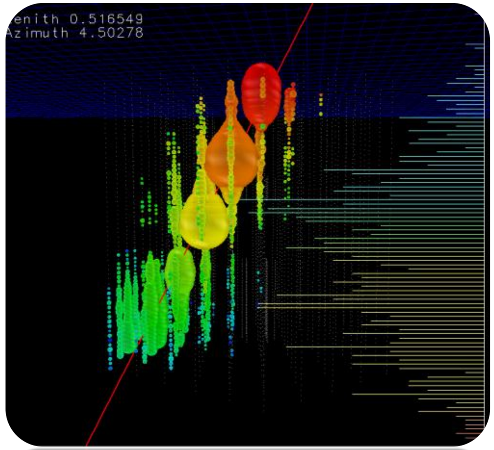
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

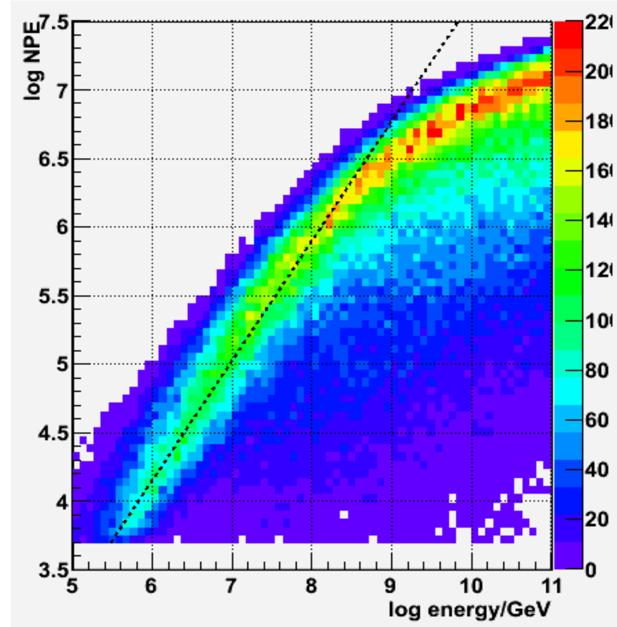



IceCube has been in a stable operation for more than 5 years

# The Event Selection

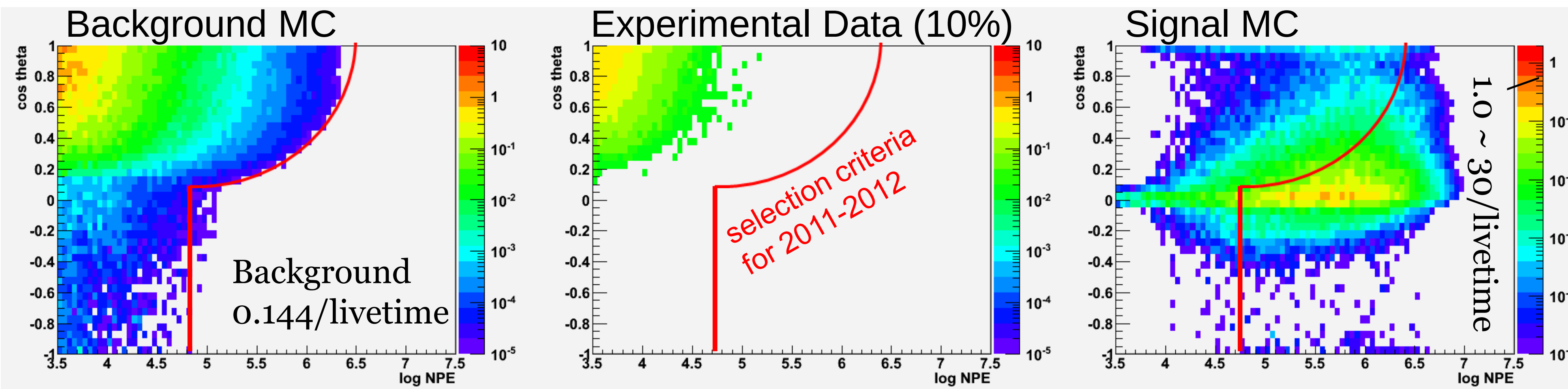



channel # > 300

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

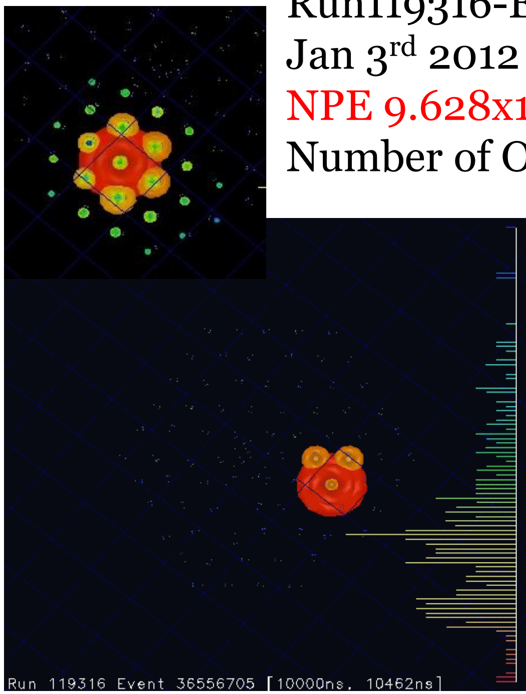



See the details of 2010-2011 data analysis: Poster #12-3 (Keiichi Mase)

# Two events passed the selection criteria

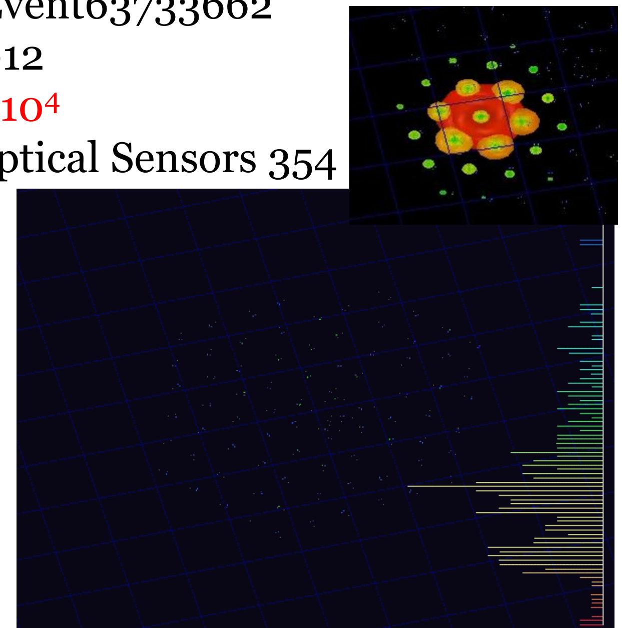
2 events / 672.7 days - background (atm. $\mu$ + conventional atm. $\nu$) expectation 0.14 events

preliminary p-value: 0.0094 (2.36$\sigma$)

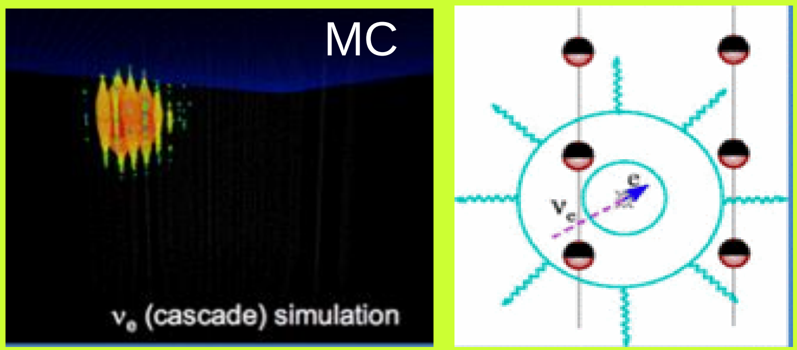


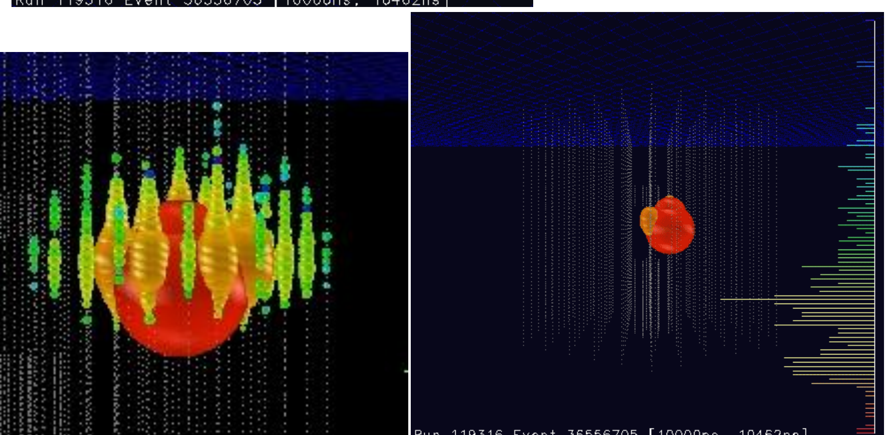

Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10$^{4}$
Number of Optical Sensors 312

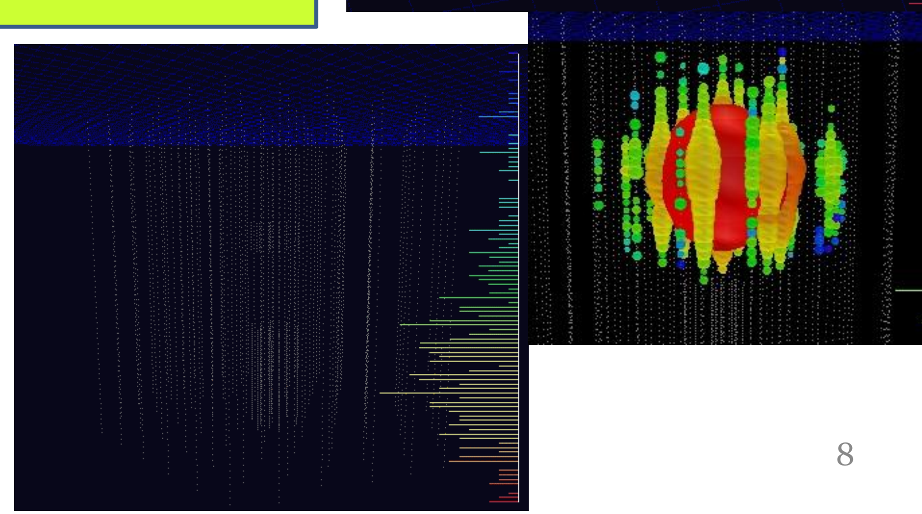
Run118545-Event63733662
August 9th 2012
NPE 6.9928x10$^{4}$
Number of Optical Sensors 354



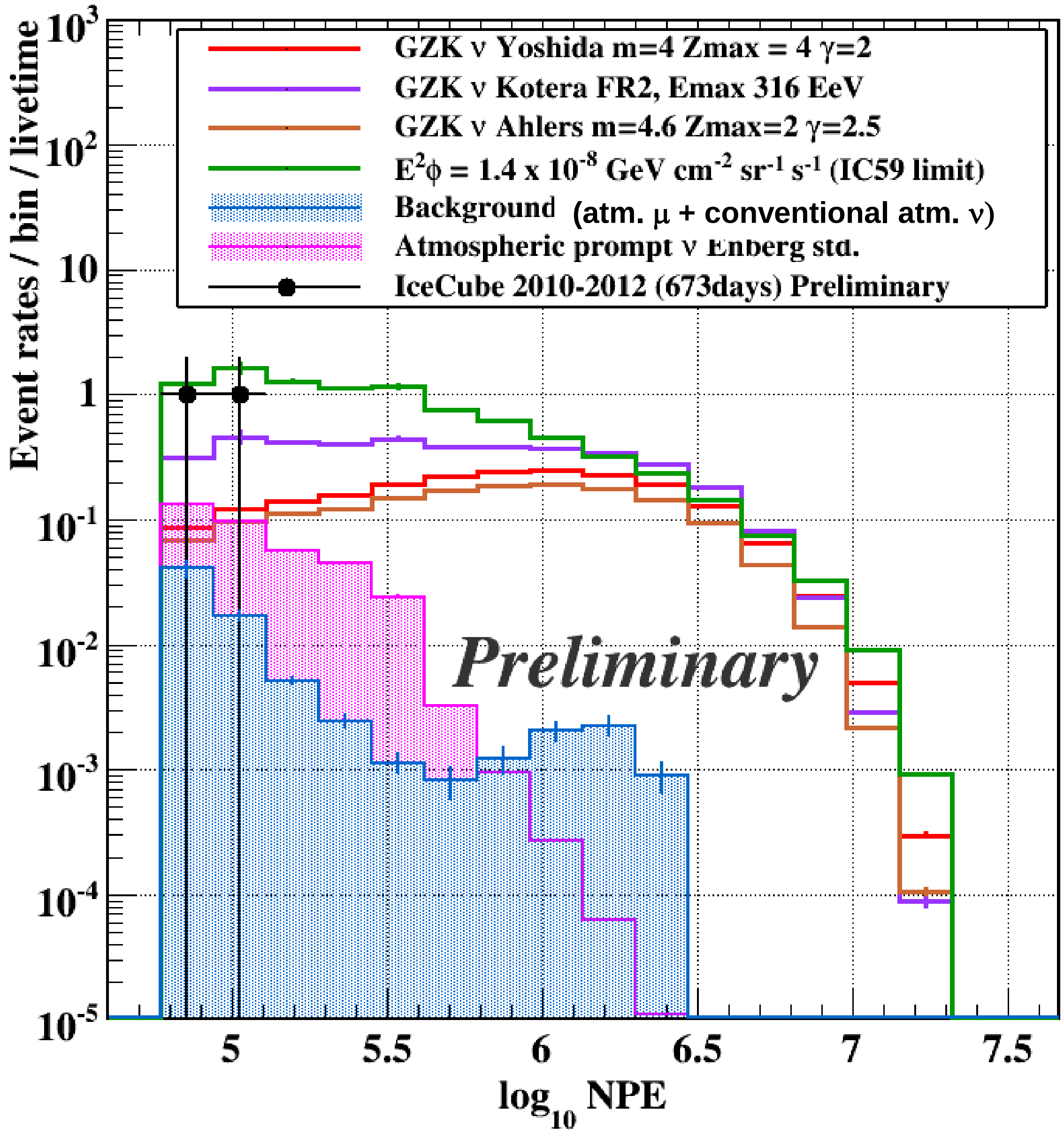
CC/NC interactions in the detector



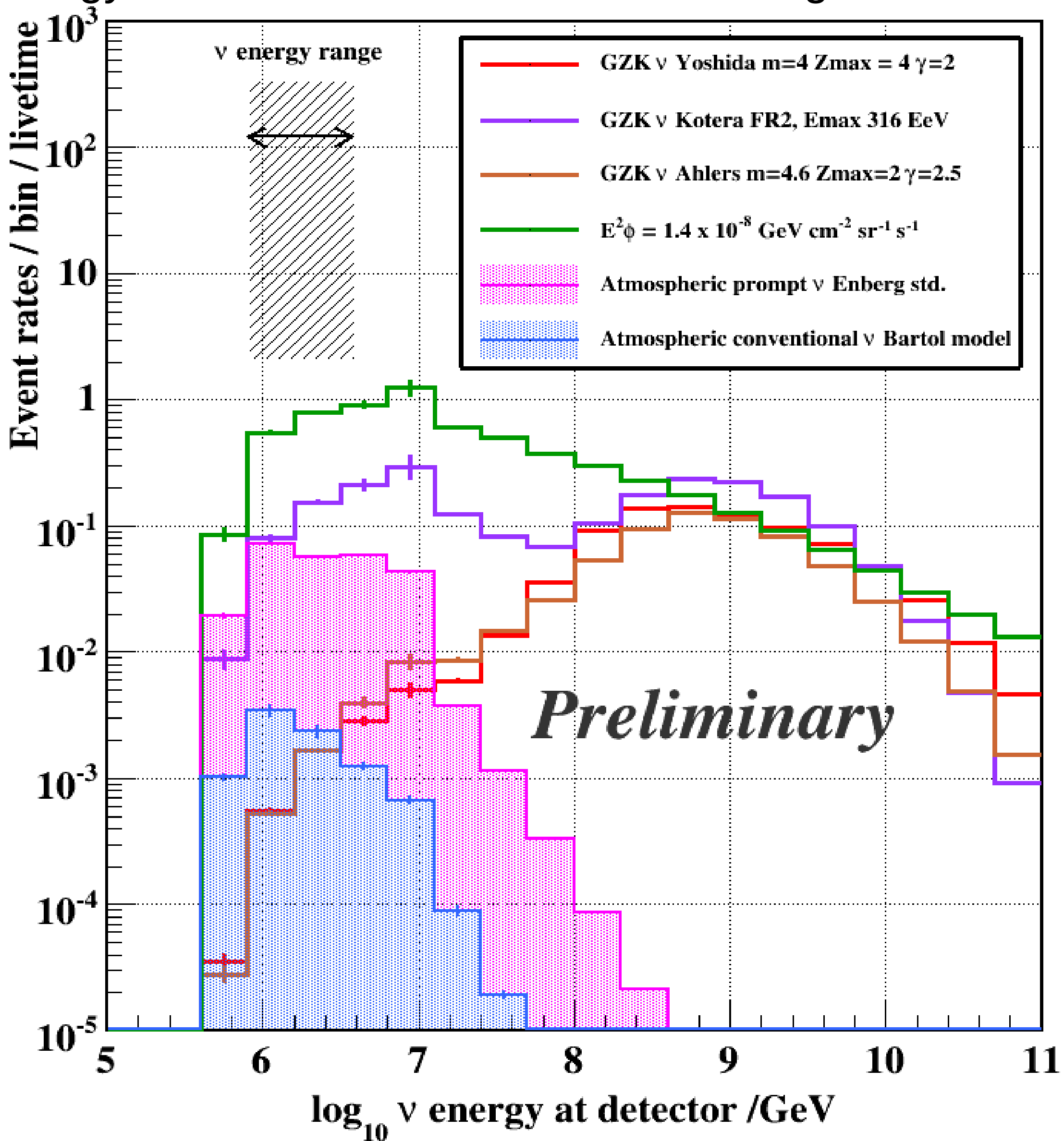
# Event Brightness (NPE) Distributions 2010-2012




- 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!

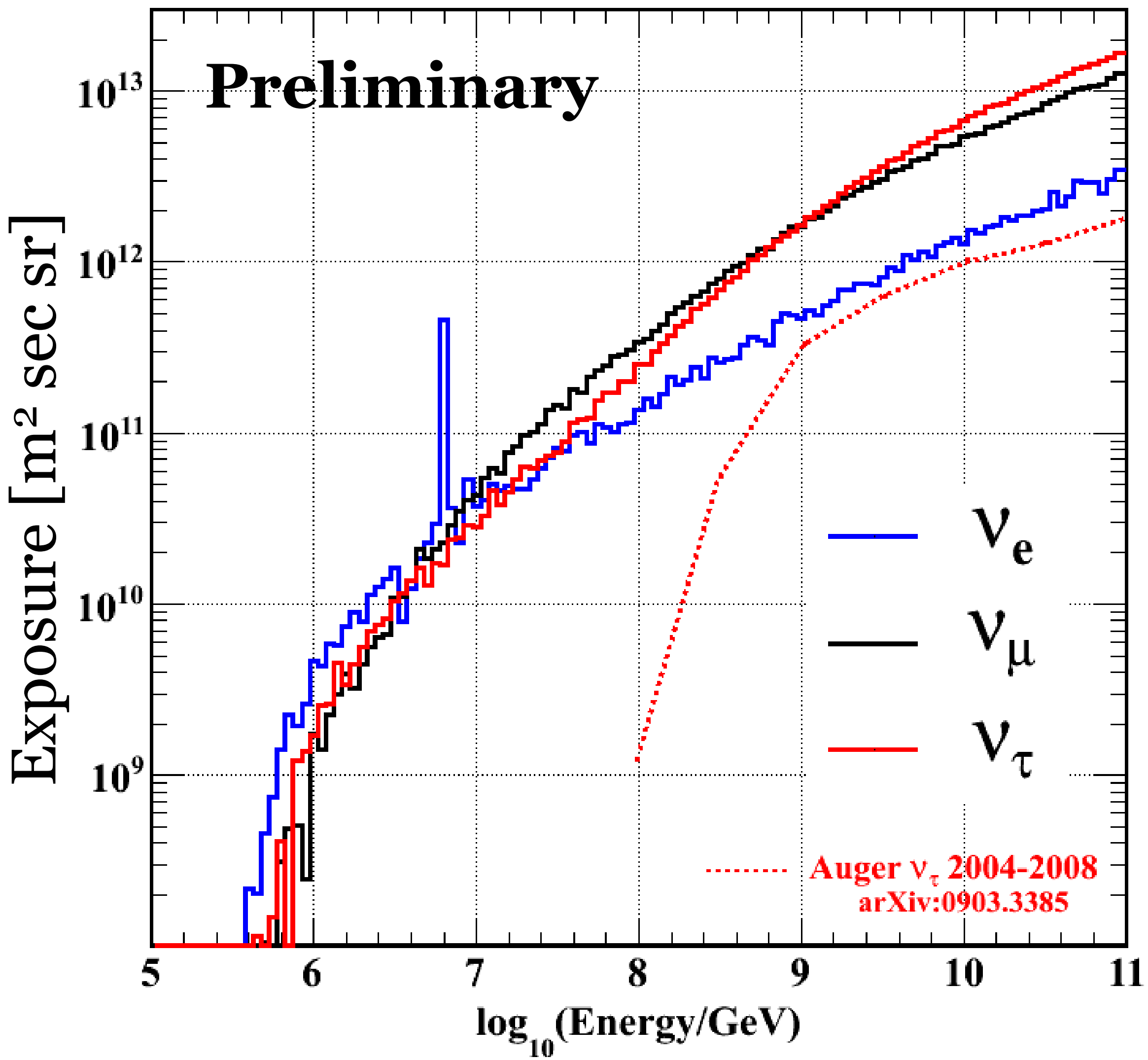
# Expected Numbers of UHE Events

| Preliminary<br><br>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 ^^<br>$E^2\phi = 1.4 \times 10^{-8}$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 |

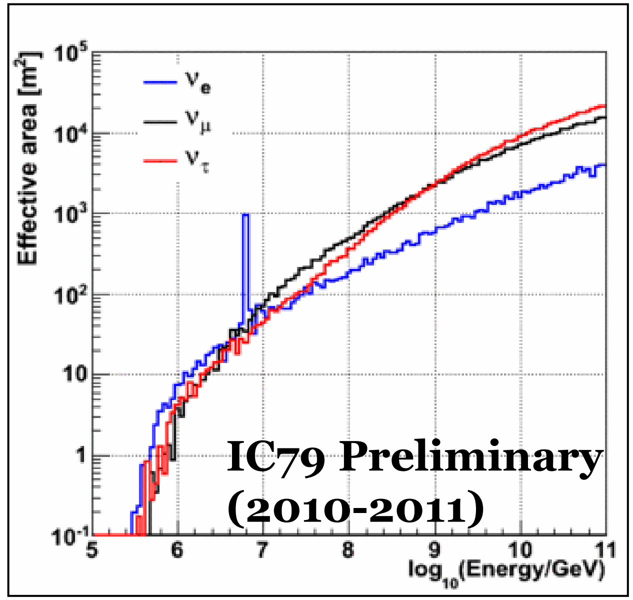
*Yoshida et al The ApJ 479 547-559 (1997), **Ahlers et al, Astropart. Phys. 34 106-115 (2010, ***Kotera et al, ^R. Enberg, M.H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008), ^^ Talk G. Sullivan This conference

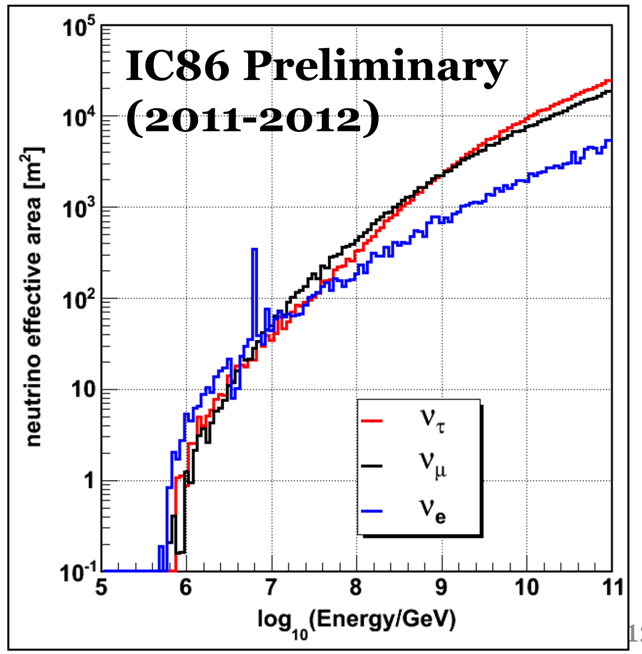
# The Exposure and Effective Area

IceCube UHE 2 Years Exposure (2010-2012)

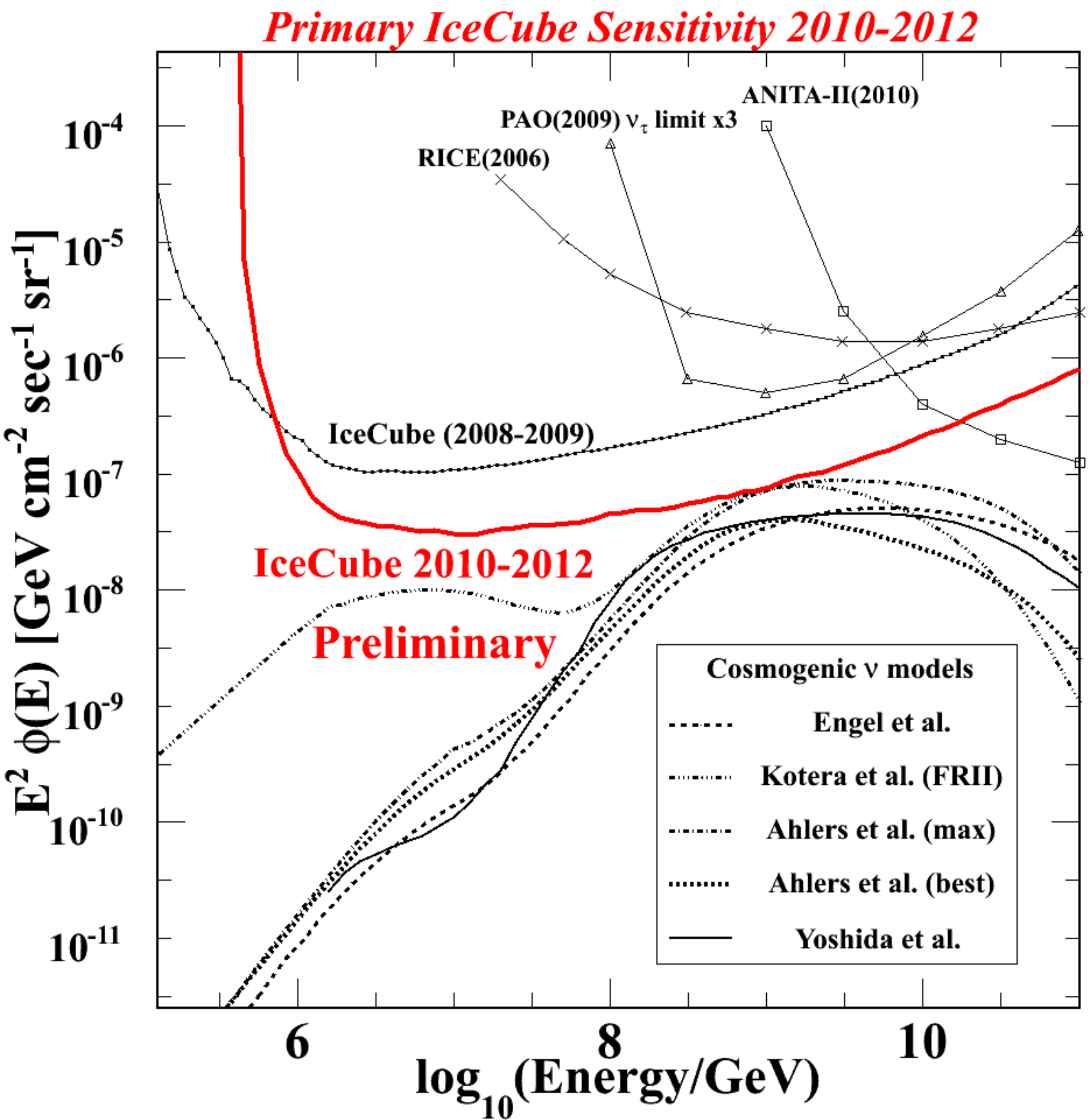



Effective Areas



# 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

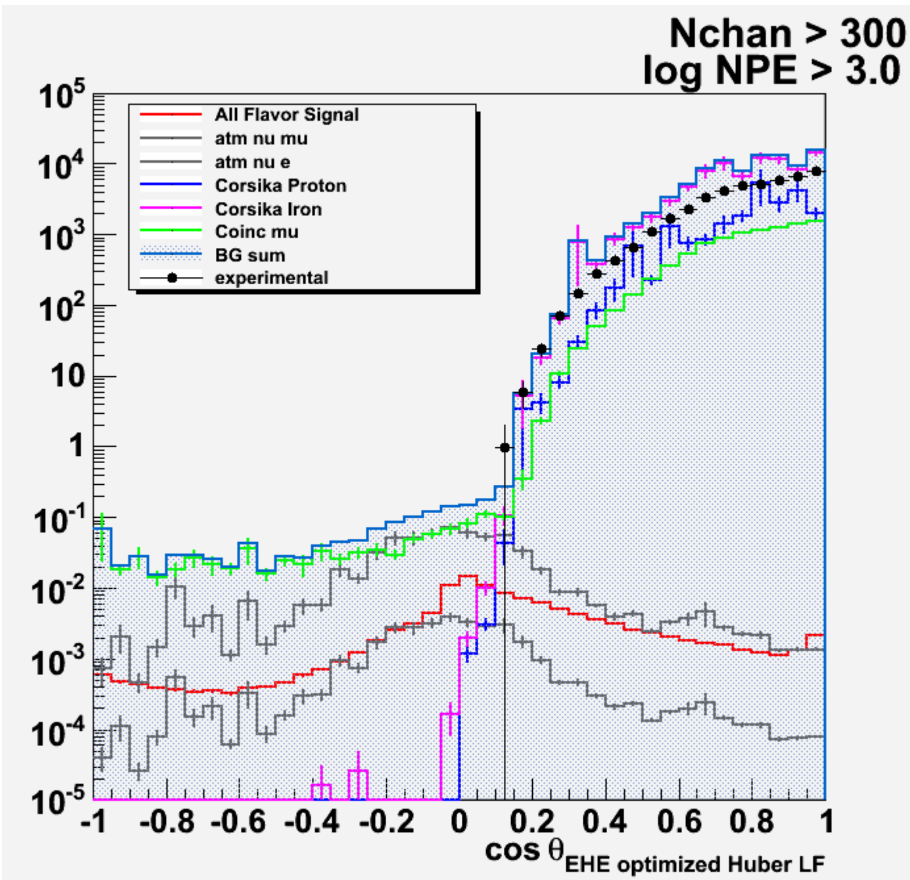
# Summary

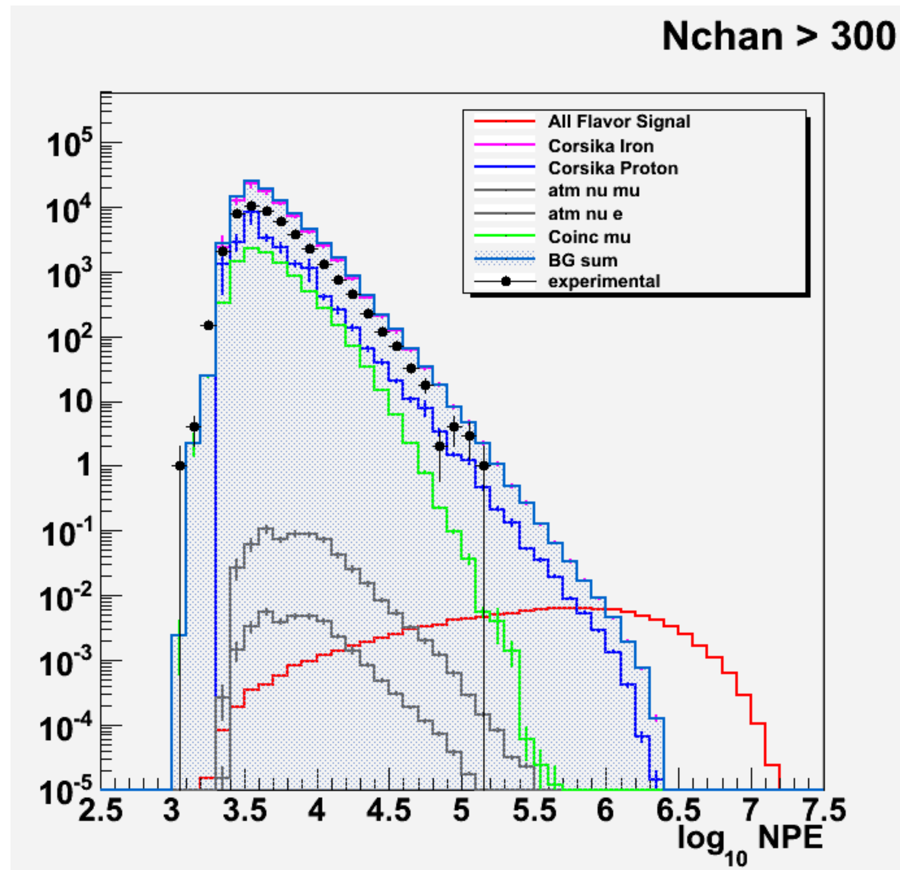
- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - The highest energy events observed ever!
- Likely to be beyond the conventional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

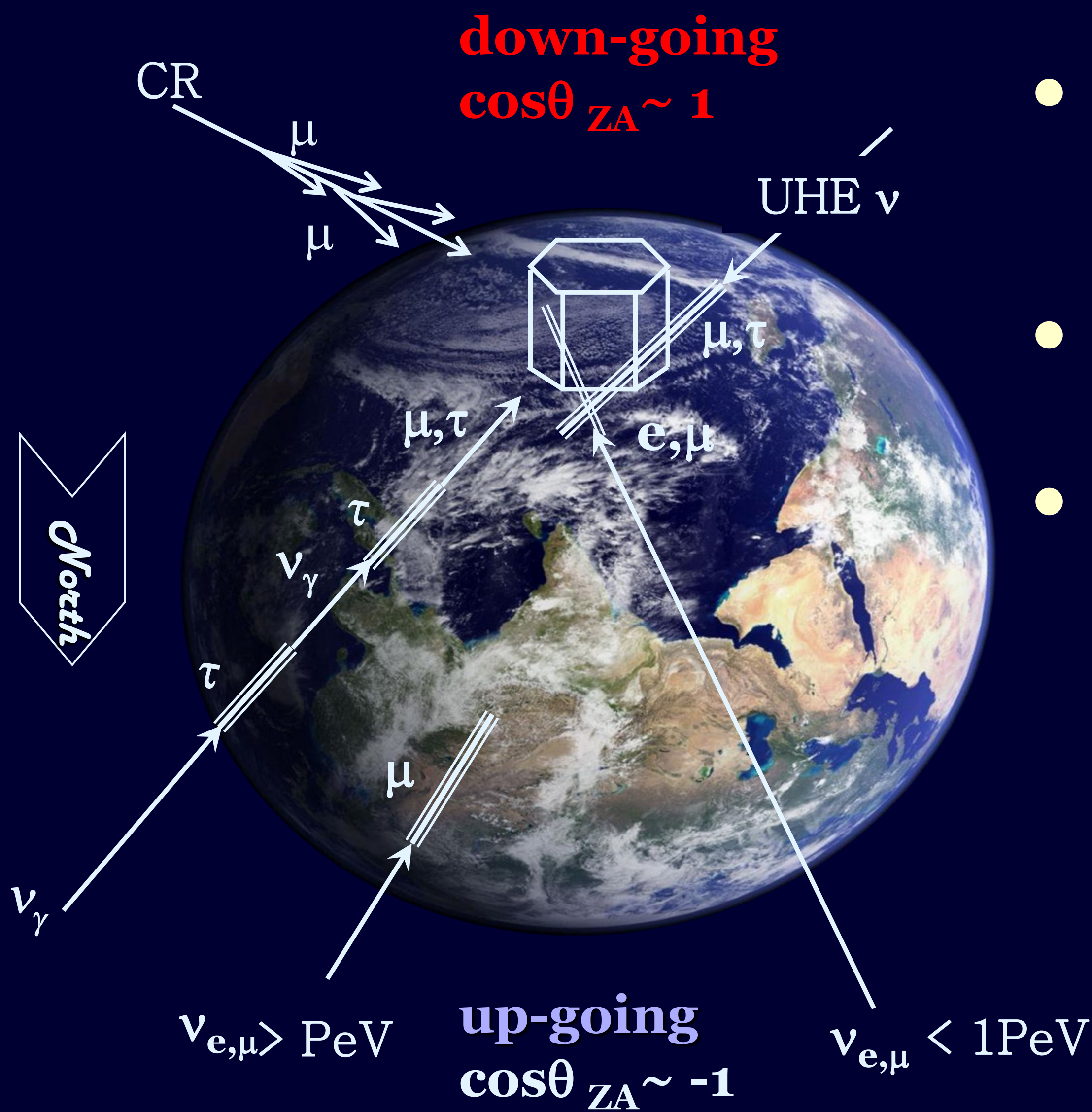
# Initial level NPE and cos theta distributions

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 $<< R_{Earth}$

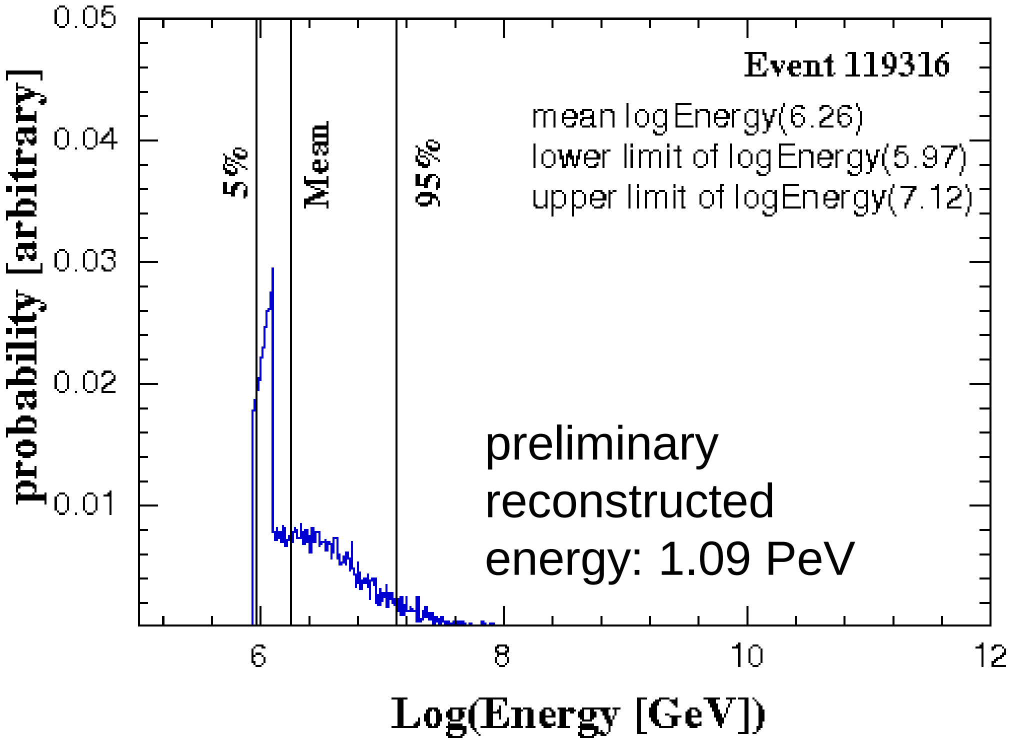
$\sigma^{cc}_{nN} \sim 10^{-6\sim-4}$ mb

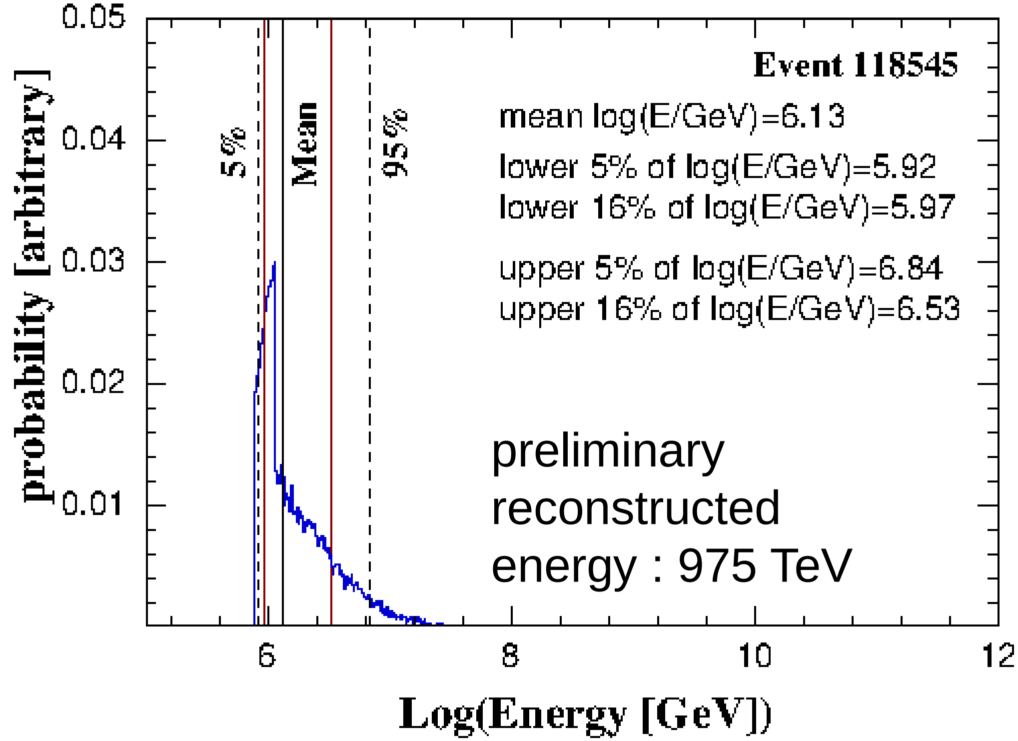
# Passing rates (stat. errors only)

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 $\times 10^6$ | 2.34+/-0.08 $\times 10^6$ | 2.881+/-0.005 $\times 10^5$ | 163.2+/-3.0 | 9.85+/-1.3 $\times 10^5$ | 0.1528+/-0.0006 |
| (NPE > 1000, Nch > 300) | 44458 | 8.37+/-0.49 $\times 10^4$ | 9.48+/-0.03 $\times 10^3$ | 0.648 +/- 0.032 | 2.16+/-0.34 $\times 10^4$ | 0.1136+/-0.0004 |
| (NPE > 10^3.5, Nch > 300) | 34411 | 6.85+/-0.40 $\times 10^4$ | 7655.0+/-23.0 | 0.625+/-0.031 | 1.75+/-0.32 $\times 10^4$ | 0.1133+/-0.0004 |
| (NPE > 10^4.0, Nch > 300) | 3019 | 5.65 +/- 0.271 $\times 10^3$ | 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

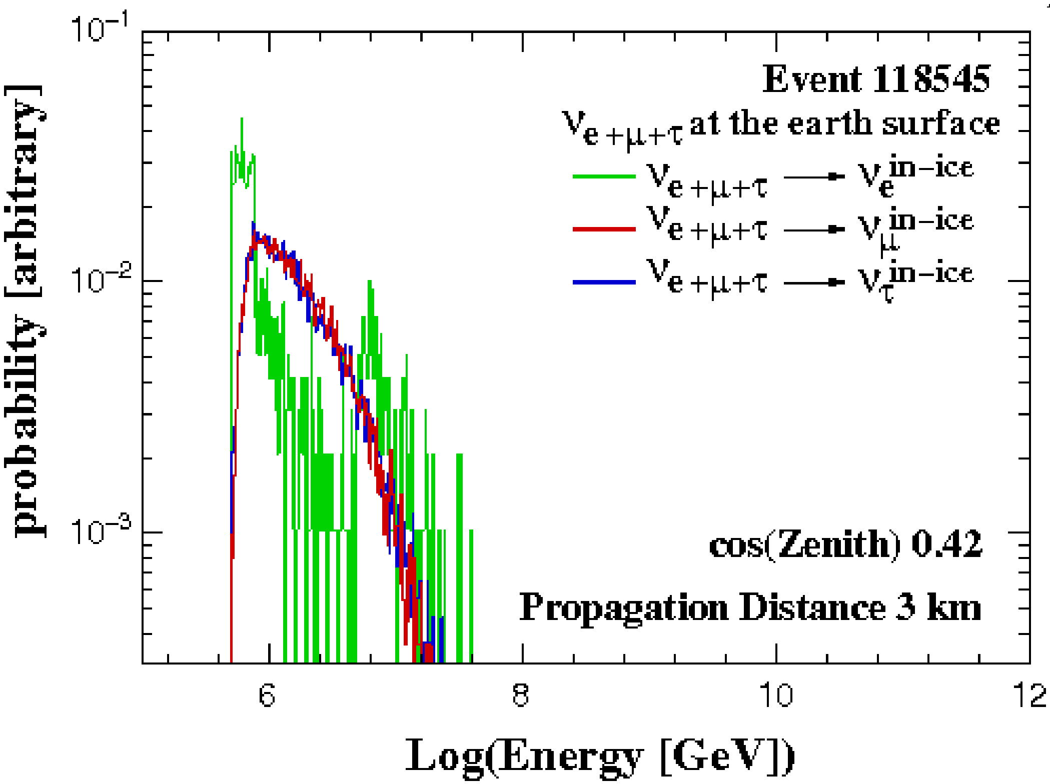


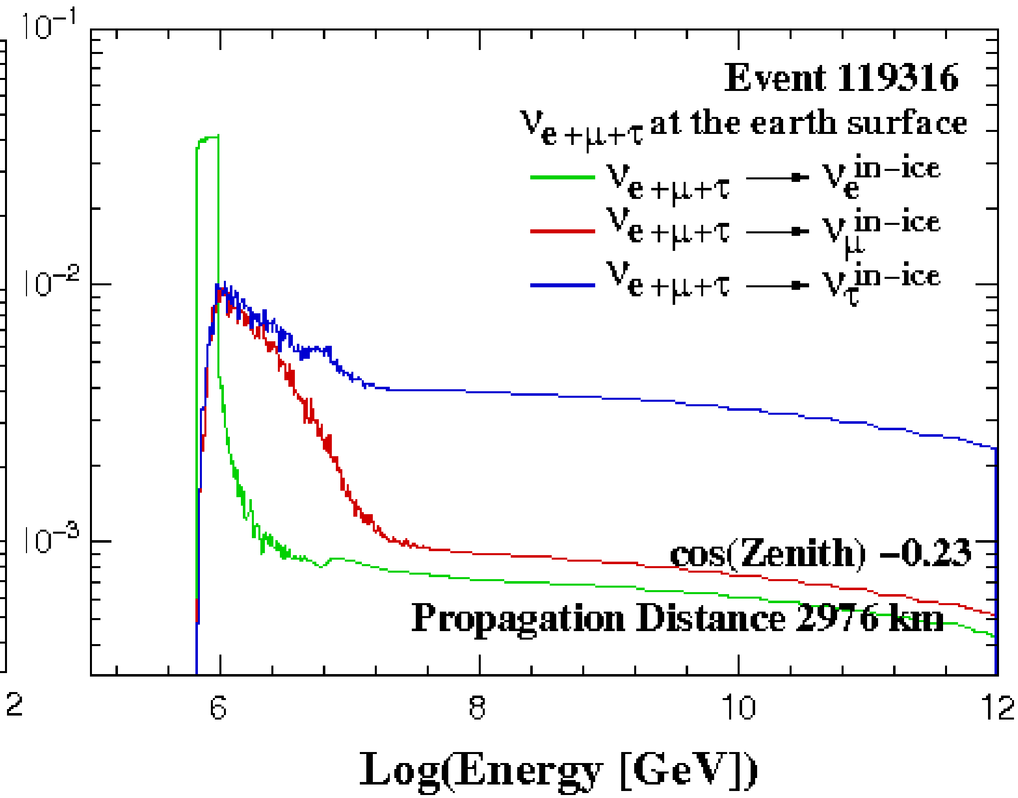




A method of the cascade energy reconstruction
- Poisson likelihood for all pulses
- Analytic likelihood maximization for energy
- Numerical minimization (Gulliver) in x, y, z, time, zenith, azimuth

# 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.

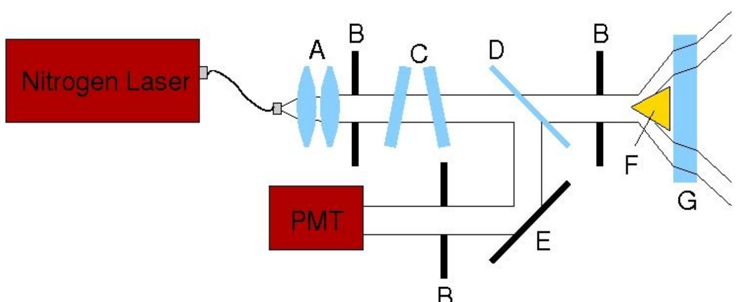


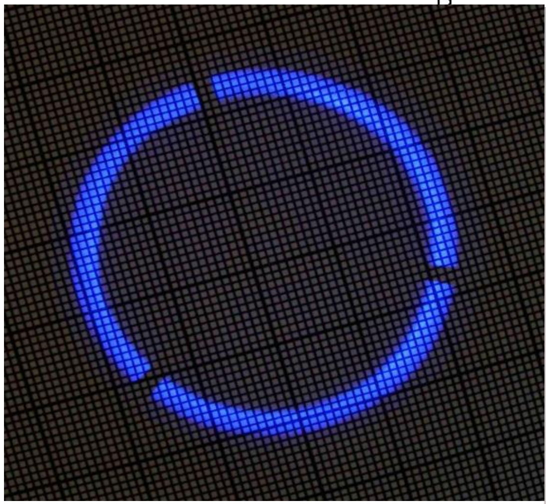



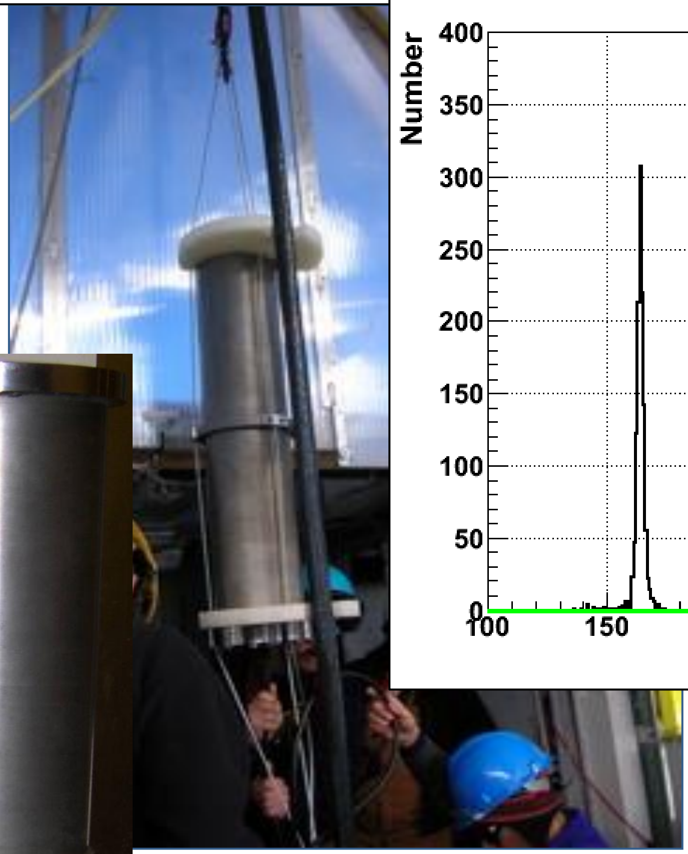
# In-*situ* energy scale calibration

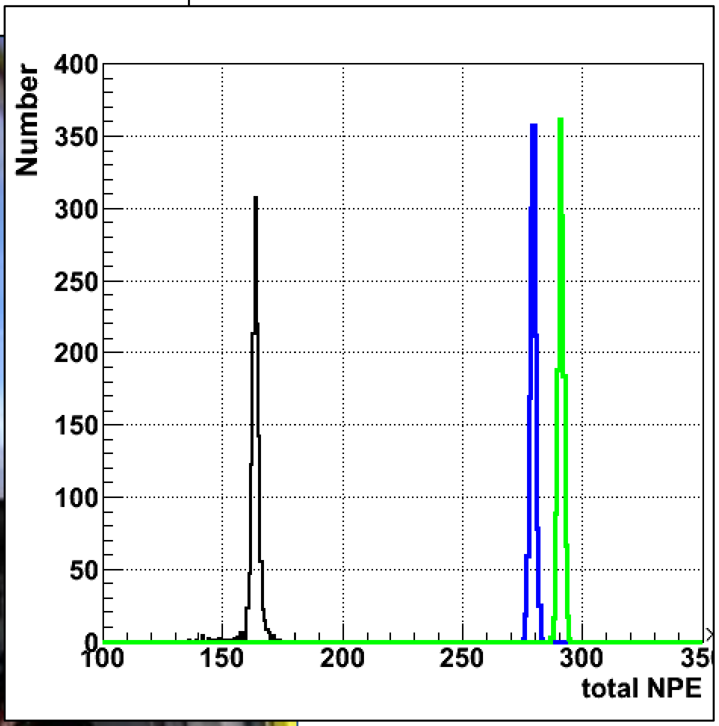
## Calibrated light source: Standard Candle

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



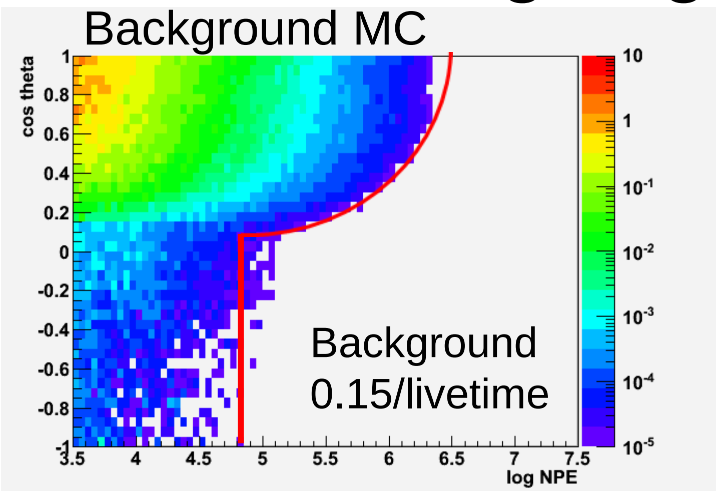



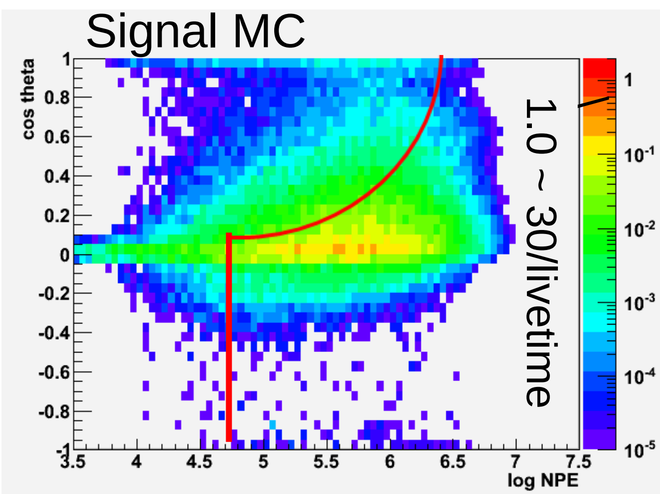


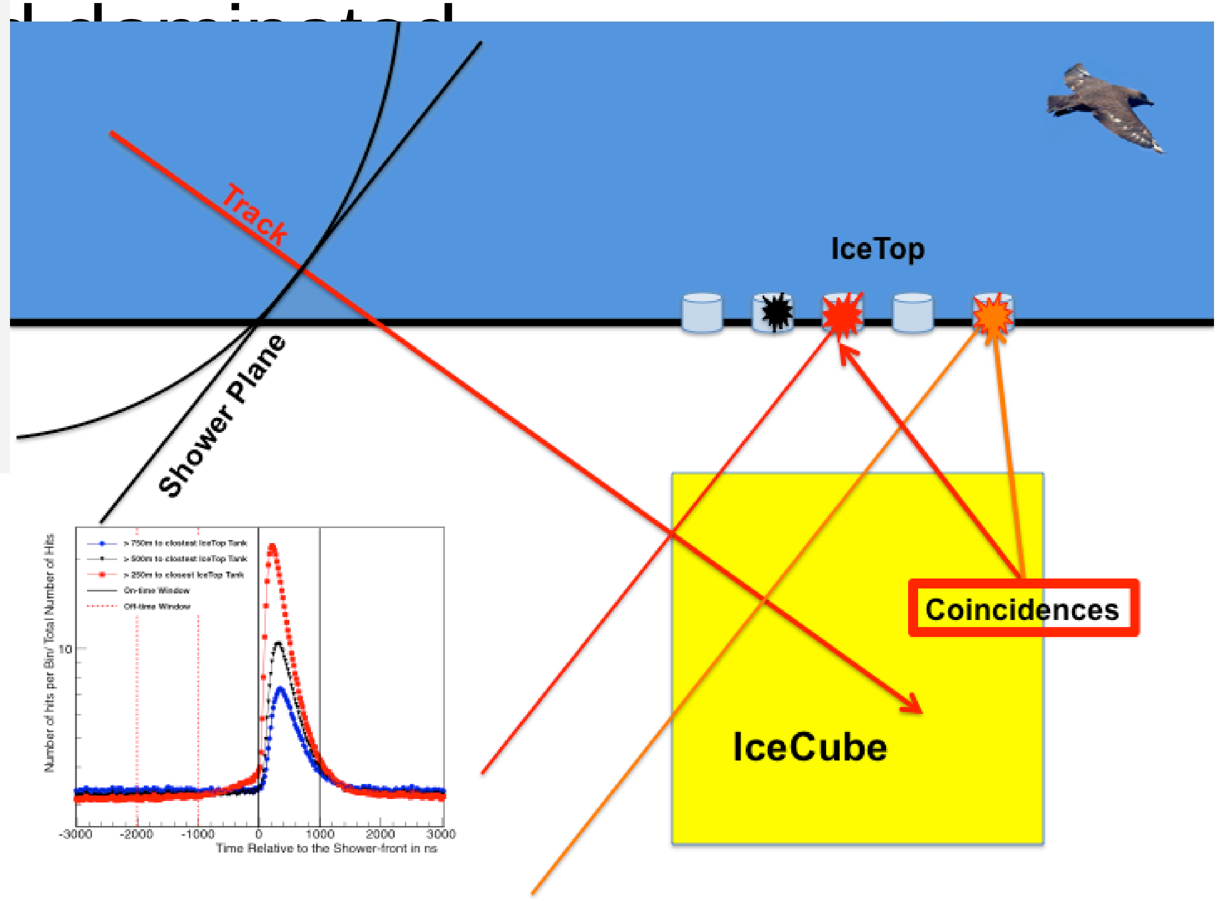


# Near future improvement
# Background Veto with IceTop

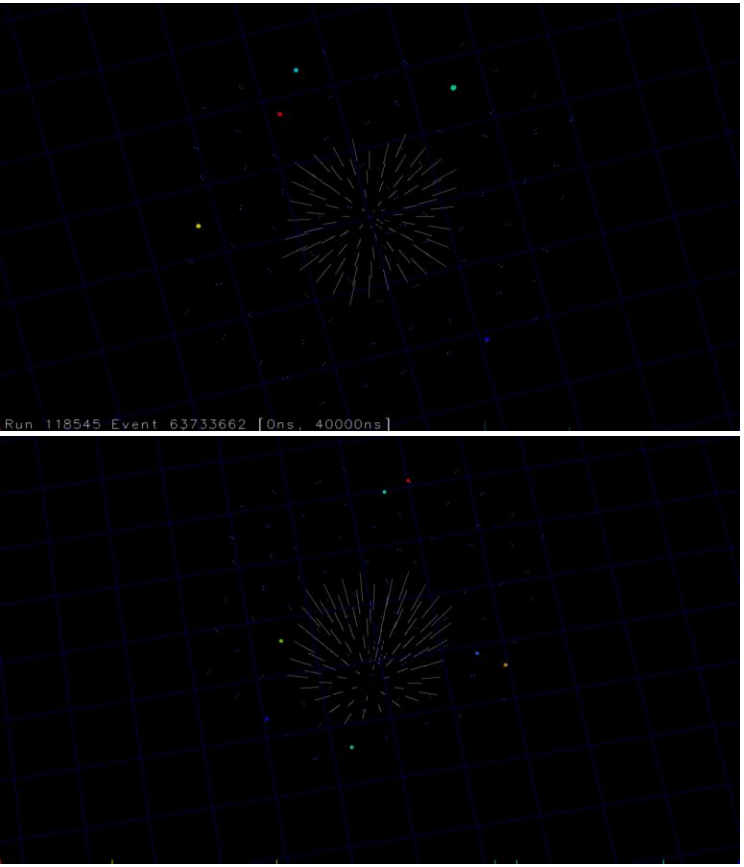
## Downward-going region is airshower induced



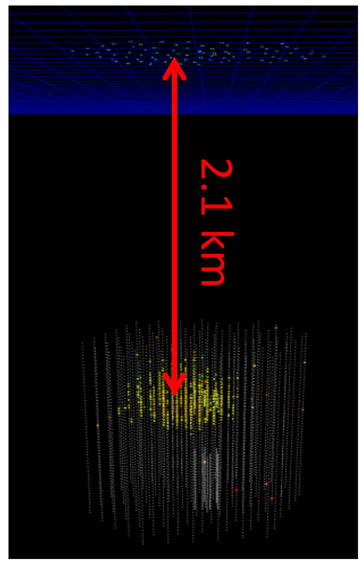



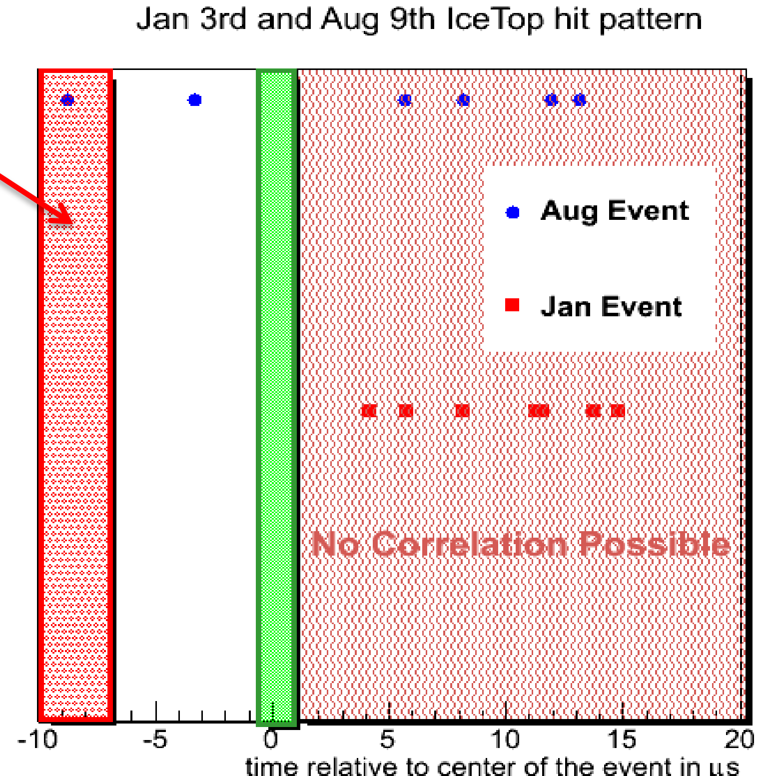



# Do The Jan and Aug events have correlated hits in IceTop?




**Geometrical not possible as Cascades 2 .1km deep**



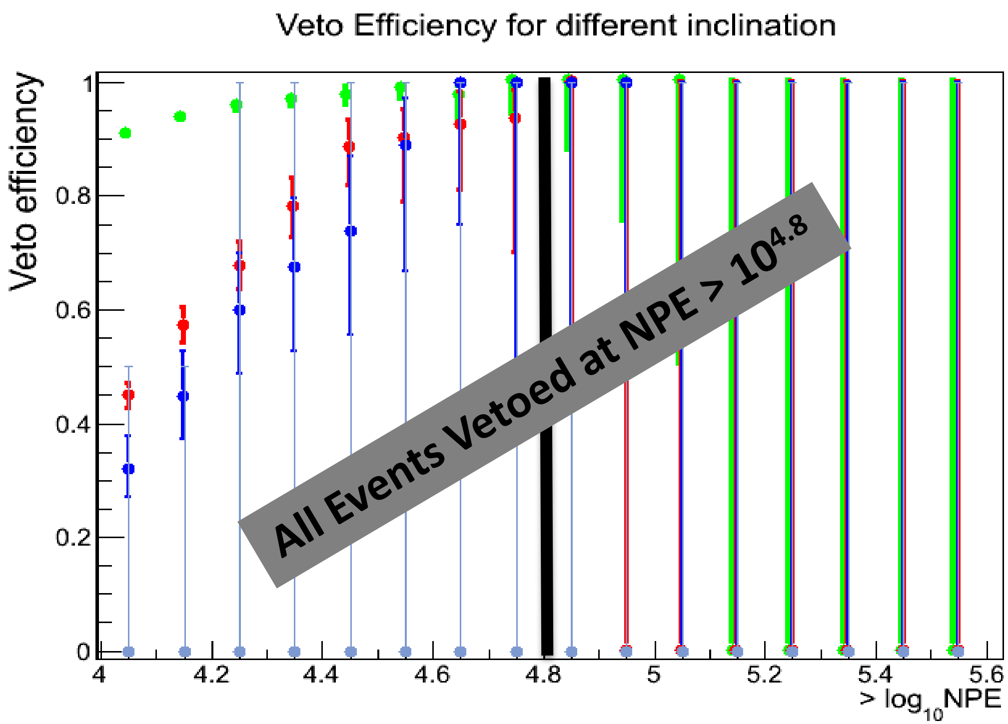

**Before first Hit: Correlation possible**

**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