ICECUBE実験による 超高エネルギーニュートリノ探査解析 における系統誤差の研究

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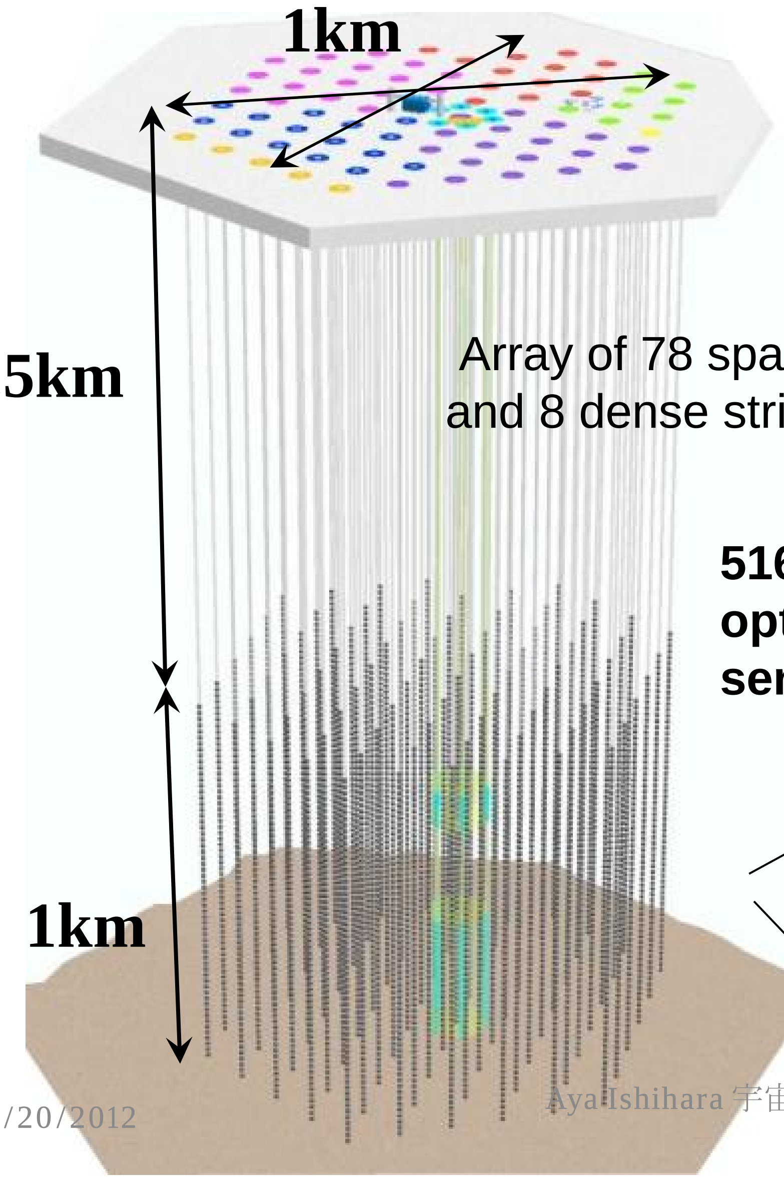
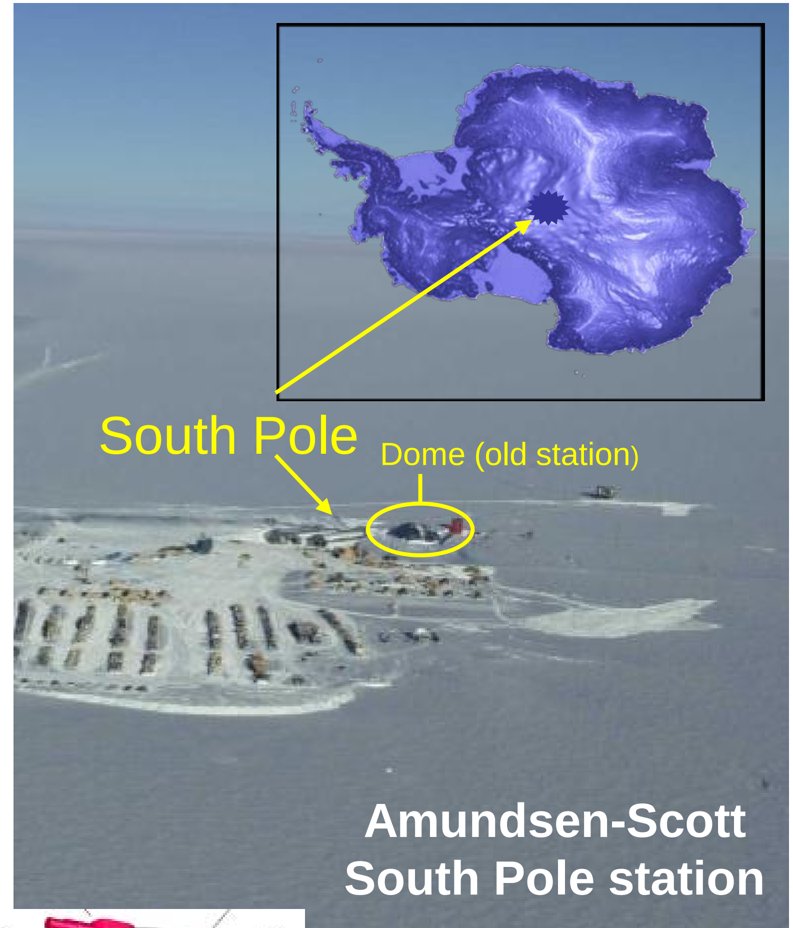
The Largest Neutrino Detector in the world:

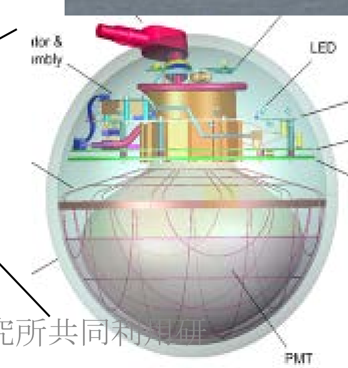
The IceCube Detector



Array of 78 sparse and 8 dense strings

5160 optical sensors

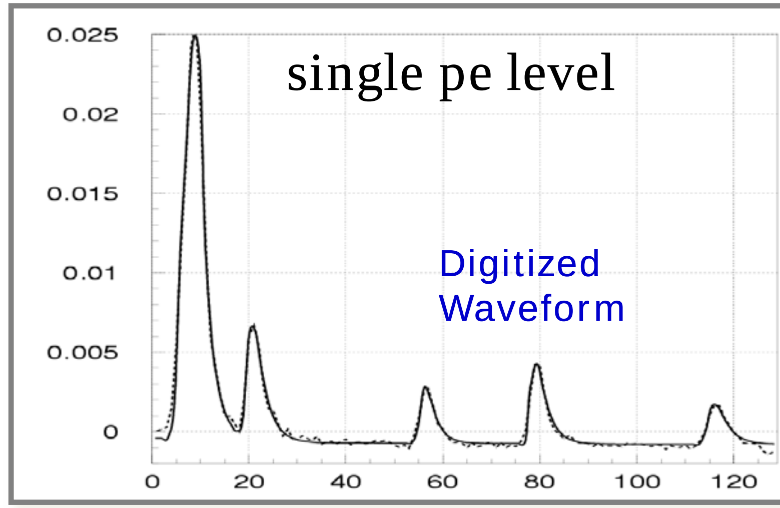


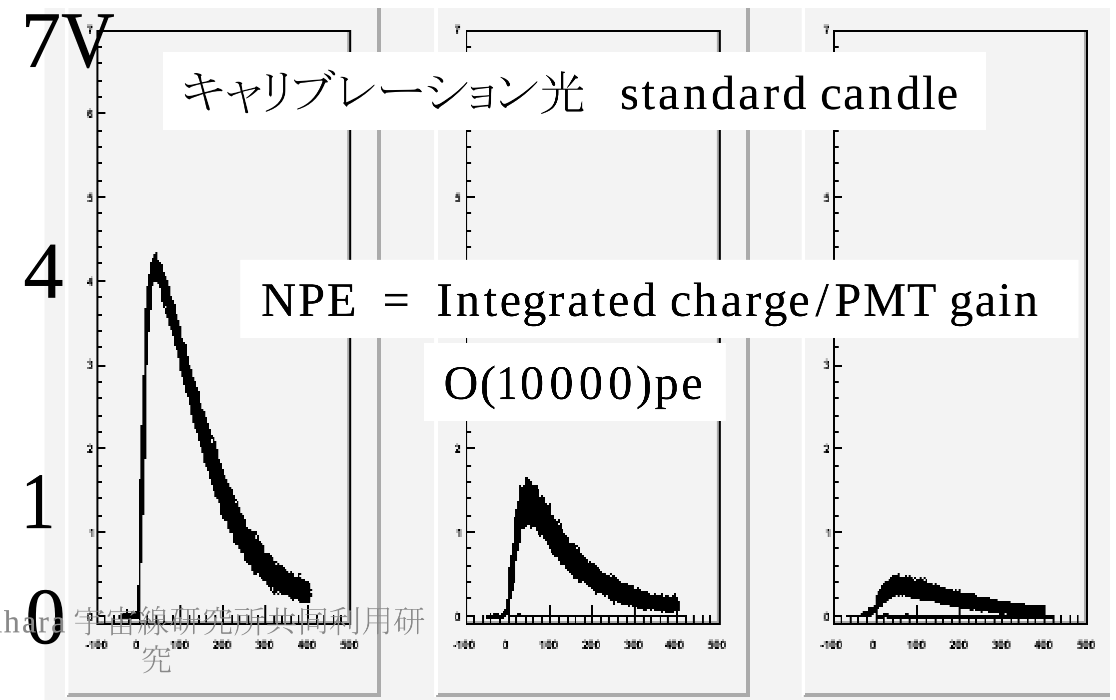


Waveforms from the IceCube optical sensors: From spe to 10000 pe

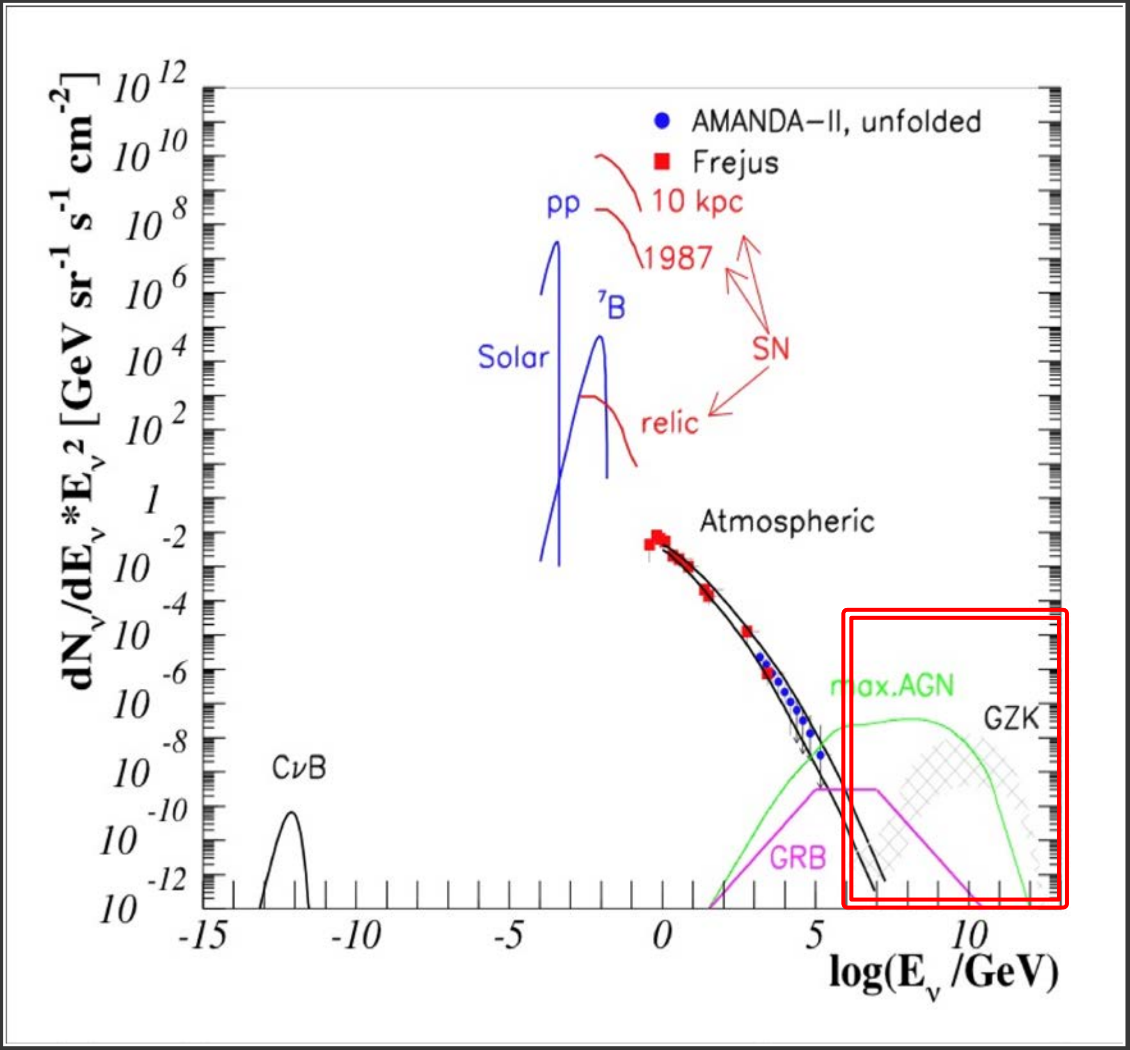
25 cm PMT

- **Digitize at 300 MHz for 400 ns with custom chip**
- **40 MHz for 6.4 µs with fast ADC**





WHY ULTRA-HIGH ENERGY NEUTRINOS?
PeV *AND ABOVE*

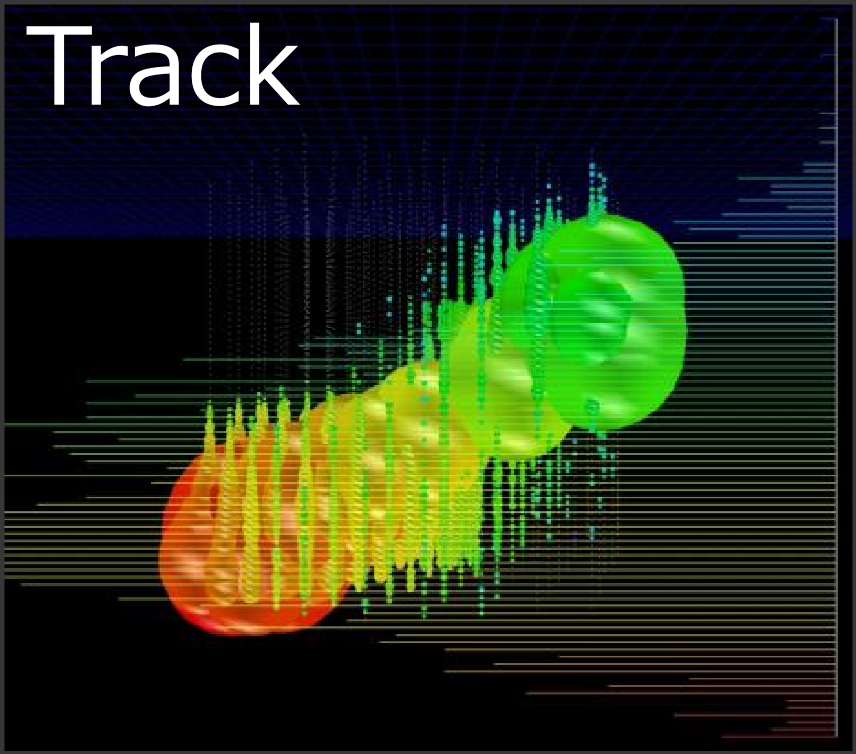


- **Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)**
- **Cosmogenic GZK neutrino production is a 'guaranteed' ν source**
- **Energies above dominant atmospheric neutrinos**

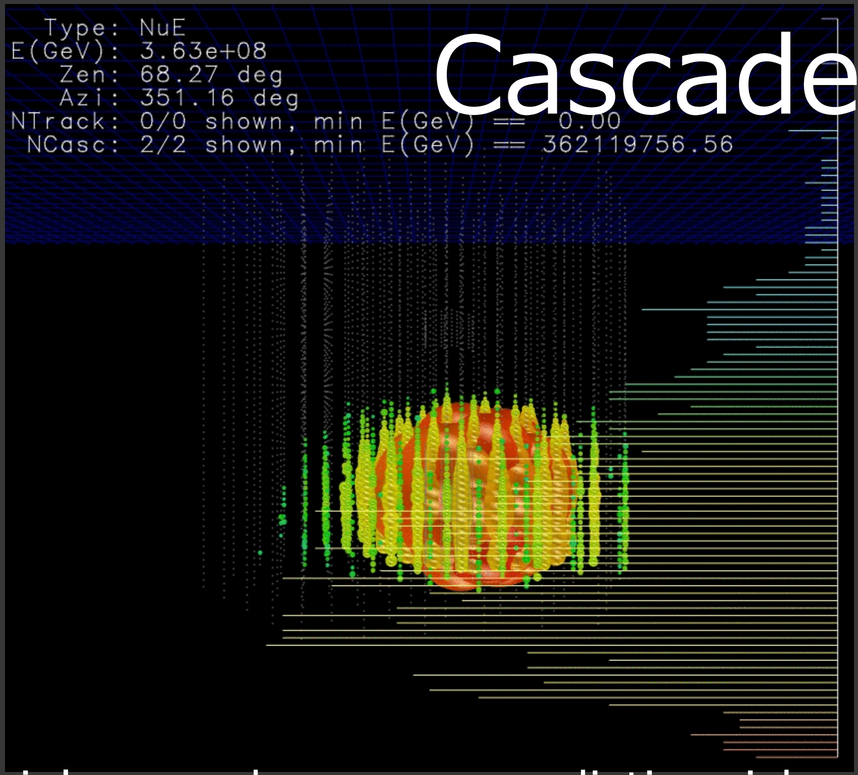
ULTRA-HIGH ENERGY SIGNAL EVENTS

from MC simulation

20PeV muon

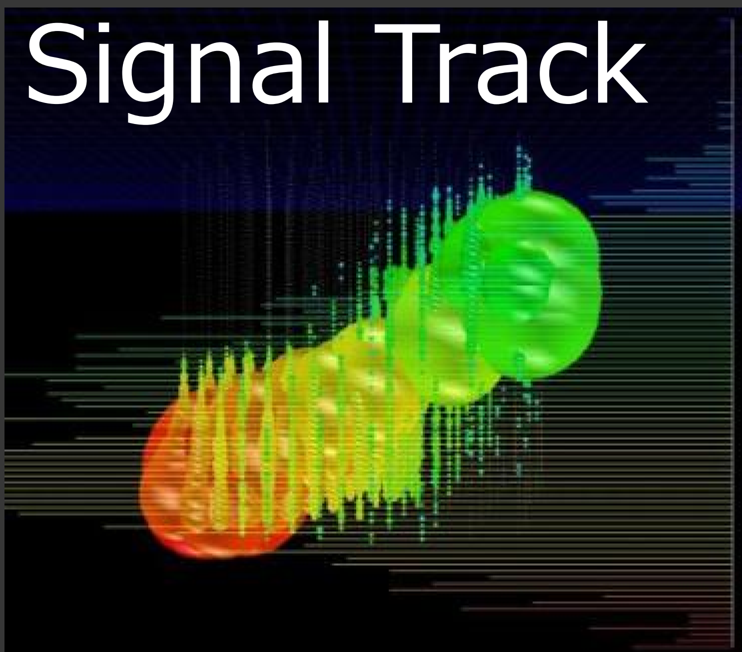


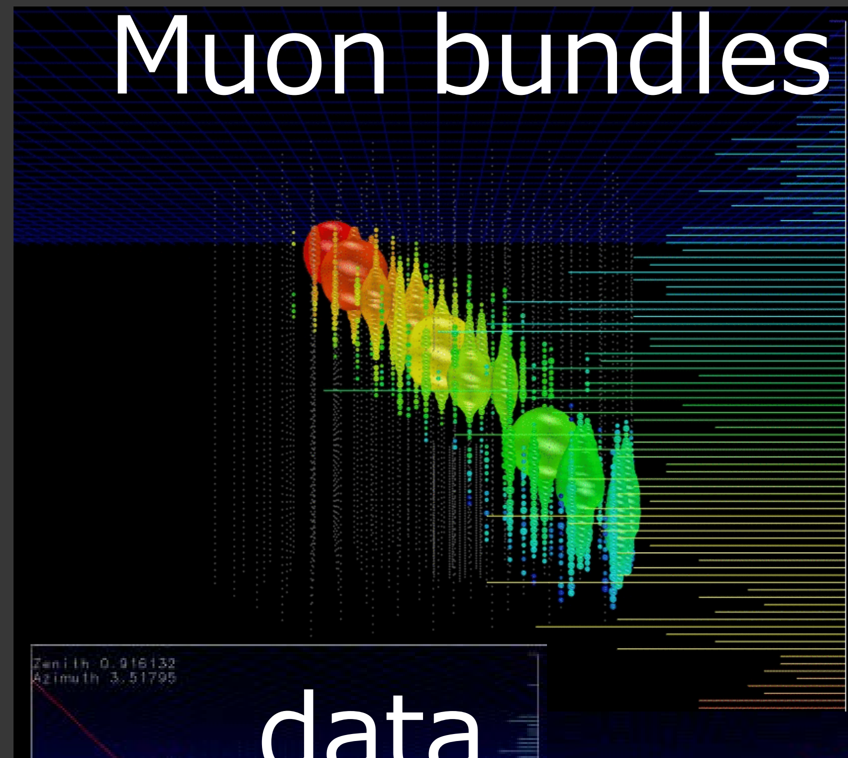
300PeV nu induced cascade

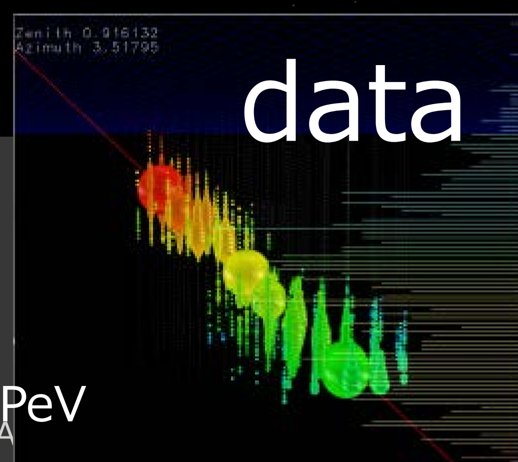


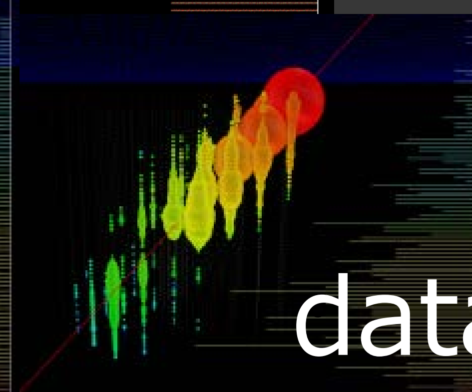
Not flavor sensitive except some special cases, however, we distinguish muon/tau tracks induced by nu mu, nutau CC and cascades induced by nu e CC and NC by 3 flavors of neutrinos

SIGNAL AND BACKGROUND EVENTS



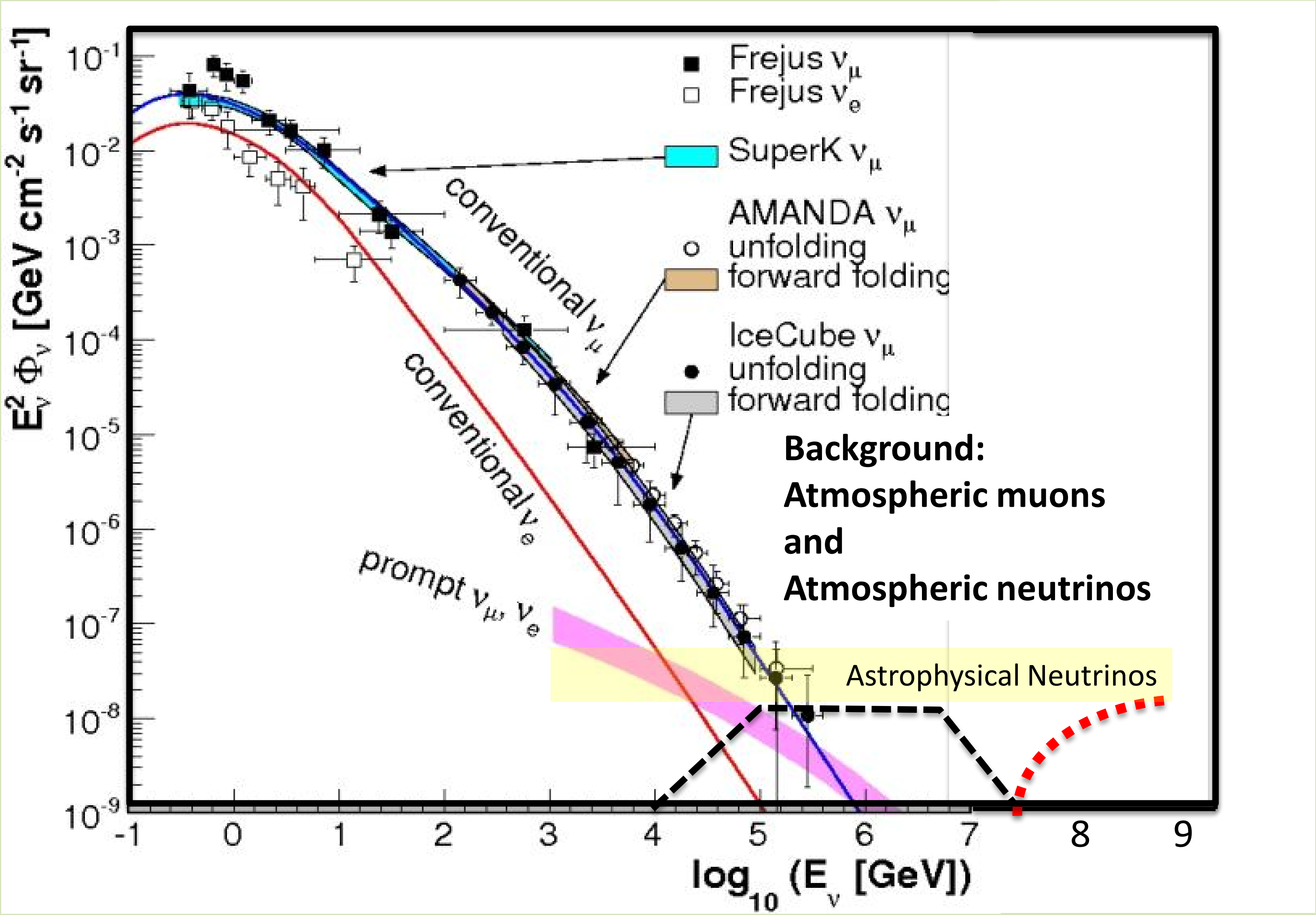






Burn sample
NPE~ 1×10^5
μ bundle with ~ 3PeV

Neutrinos in a wide energy range

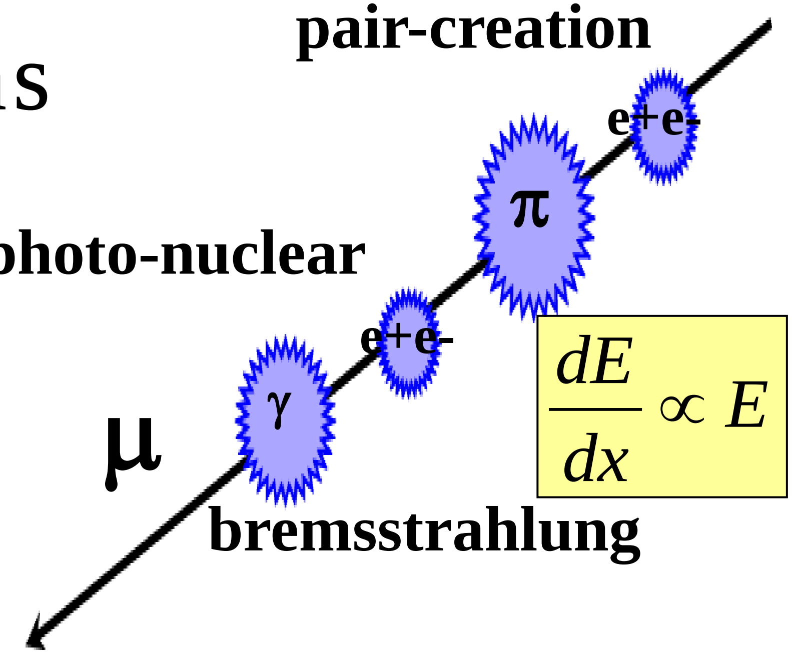


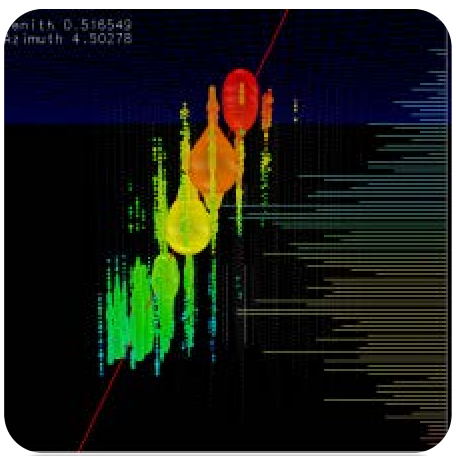
The Energy-NPE relations

μ and **τ** tracks lose their energy by
radiative processes

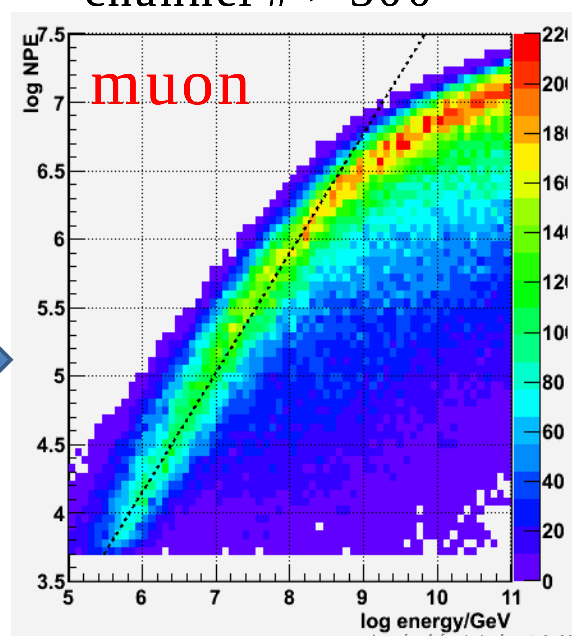
Energy of incoming particle
∝ Energy-losses in detector
∝ number of photo electrons (NPE)

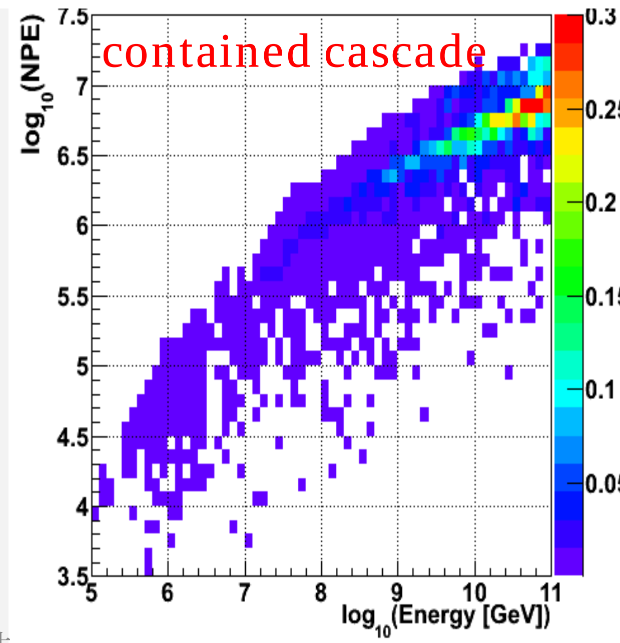
Systematics
- Optical Properties of Ice
- Absolute Calibration





channel # > 300





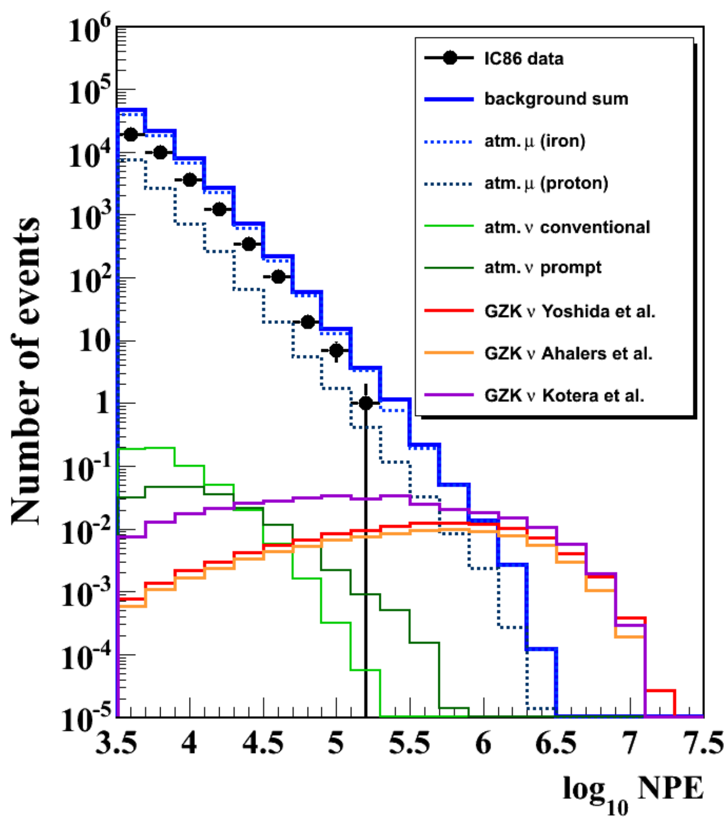
Data Distributions

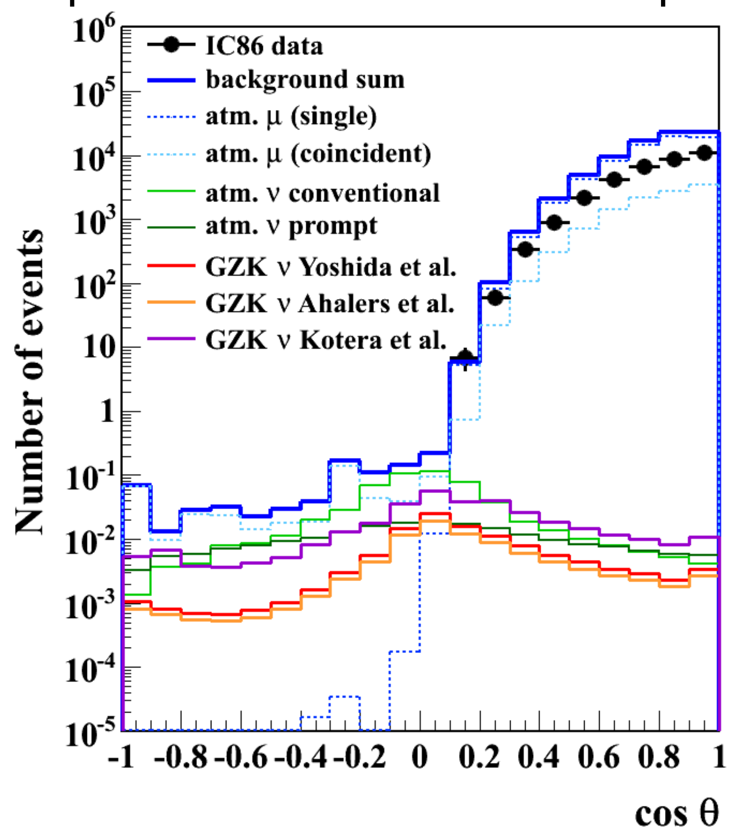
Effective livetime of 670.1days

2010-2011 - 79 strings config. **May/31/2010-May/12/2011** Effective livetime 319.9days	2011-2012 – 86 strings config **May/13/2011-May14/2012** Effective livetime 350.1 days

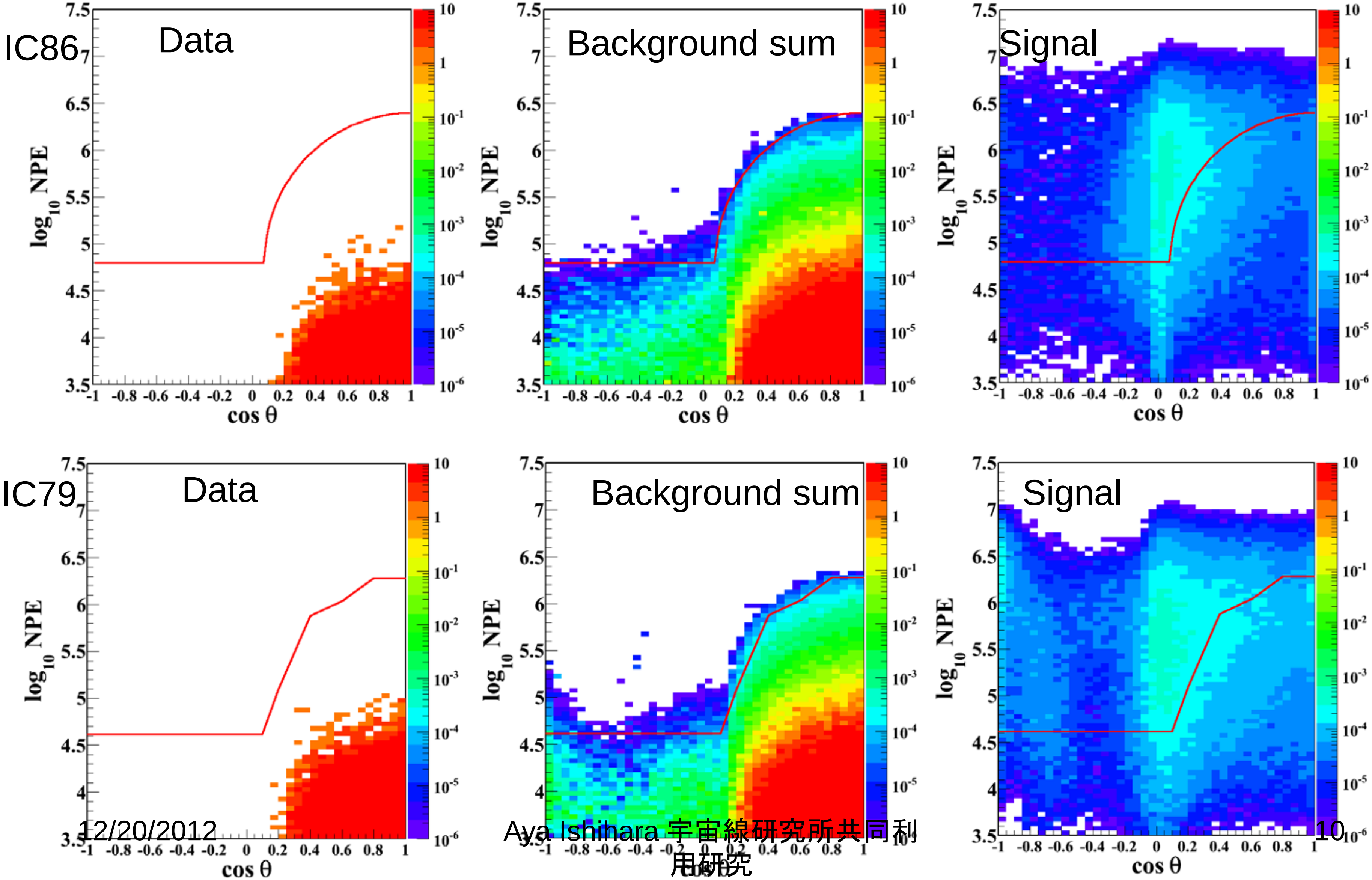
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

NPE and cos theta distributions comparisons with 2011 test sample





Analysis Level NPE vs ZA



FINAL LEVEL EVENT RATES

	Total background (IC79+IC86)
Atmospheric μ	0.038
Atmospheric conventional ν	0.023
BG total	**0.060**
prompt ν	0.13 1
BG total with prompt	**0.191**

GZK neutrino models	IceCube 2010-2012 per 615.9days	
	All	Contribution > 100 PeV
GZK (Yoshida m=4)	2.0	1.9
GZK (Ahlers max)	3.0	2.9
GZK (Ahlers best fit)	1.5	1.4
GZK (Kotera, dip FRII)	4.2	2.7
GZK (Kotera, dip SFR1)	0.9	0.6

SYSTEMATIC ERRORS ON SIGNAL AND BG

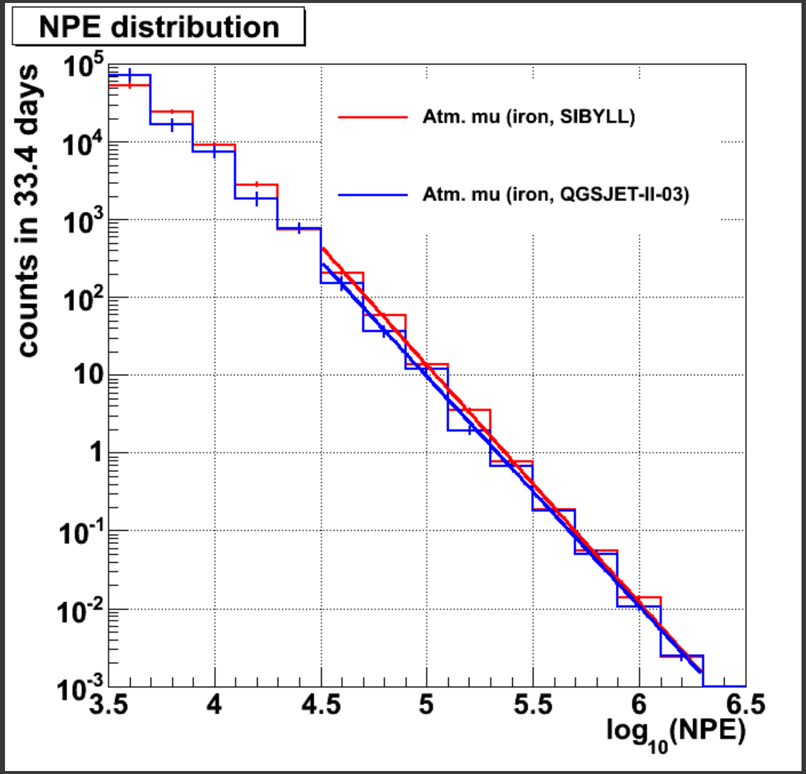
Signal

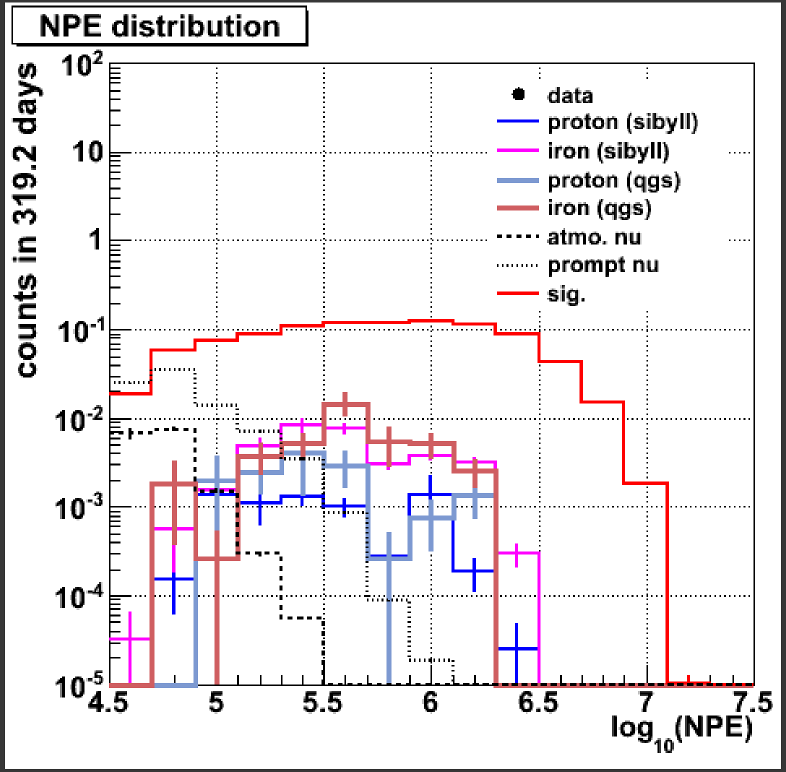
Sources	Errors on signal rate (%)
Statistical error	± 0.6
NPE (ice model, absolute sensitivity)	$+3.1, -7.4$
Neutrino cross section	± 9.0
Photo-nuclear interaction	$+10.0$
LPM effect	± 1.0
Total	± 0.6(stat) $+13.8 - 11.7$(sys)

Background

Sources	Errors on conv. bg rate (%)
Statistical error	± 6.0
NPE (ice model, absolute sensitivity)	$+60.8, -56.1$
CR composition	-50.0
Hadronic interaction model	$+11.1$
CR flux variation	$+21.8, -33.2$
ν yield from CR nucleon	± 5.5
Total	± 6.0(stat) $+65.8$ -82.3(sys)

COSMIC-RAY COMPOSITION AND HADRONIC INTERACTION MODEL DEPENDENCE



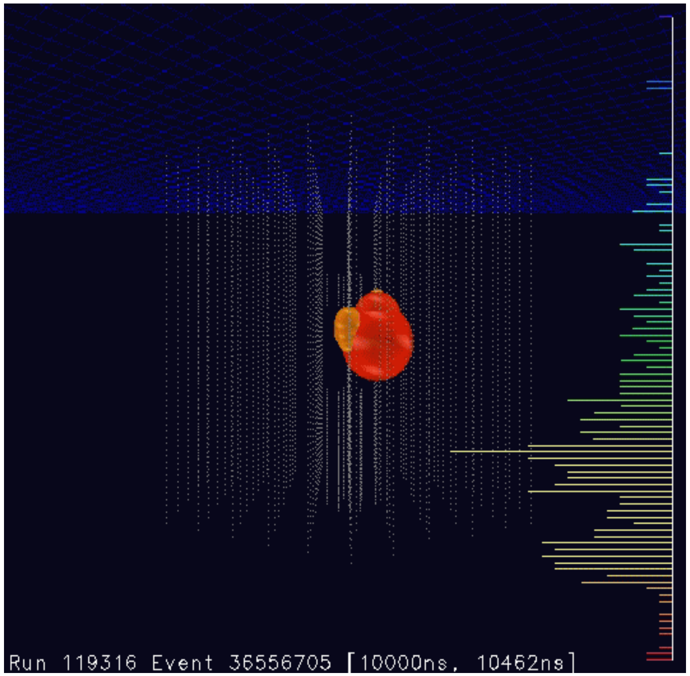


After unblind - Observation of 2 events

Run119316-Event36556705

NPE 9.628×10^4

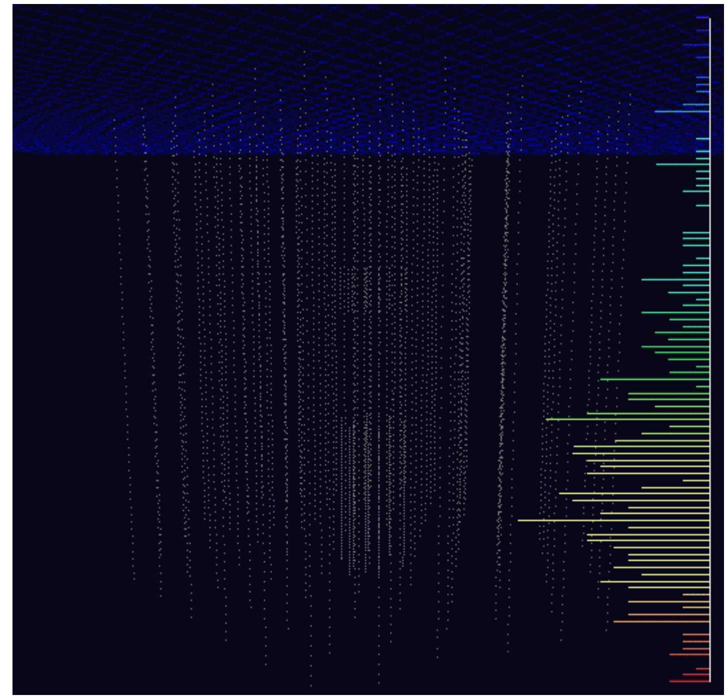
GMT time: 2012/1/3 9:34:01



Run118545-Event6373366

NPE 6.9928×10^4

GMT time: 2012/8/8 12:23:18



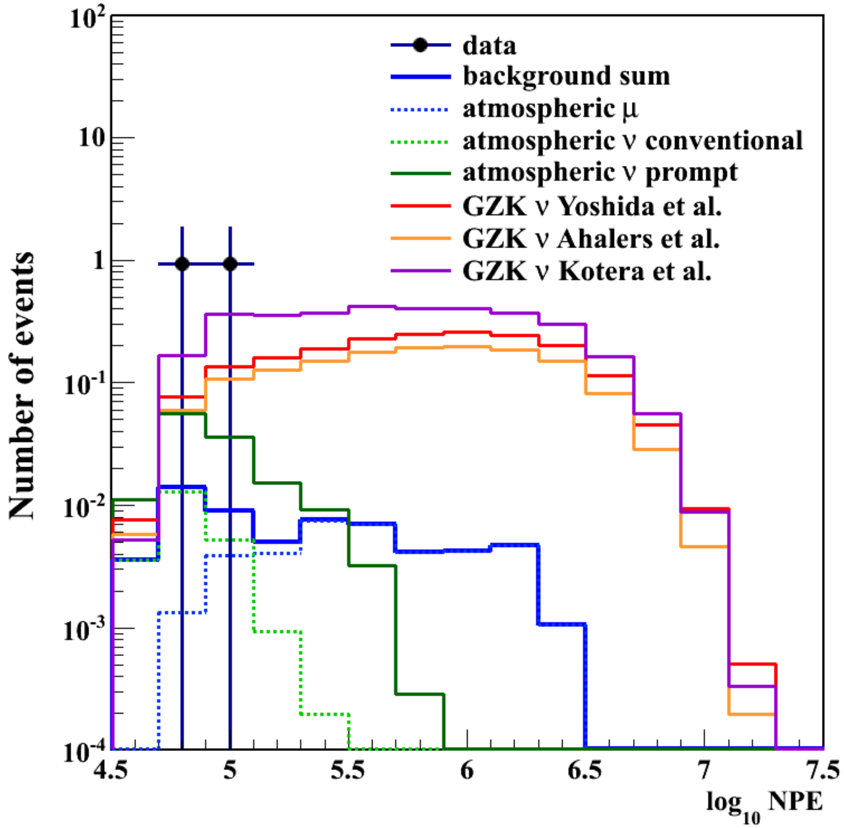
2 events / 615.9 days background (atm. μ + conventional atm. ν) expectation 0.060 events

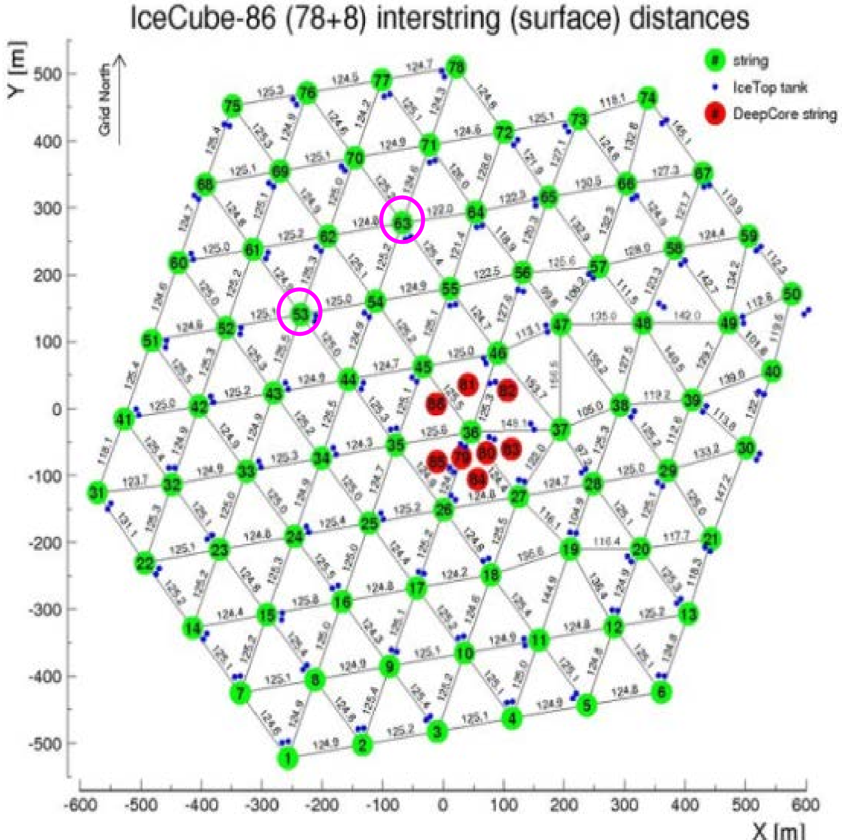
Preliminary

p-value 1.8×10^{-3} (2.9σ excess beyond conventional atmospheric neutrinos)

(2.2σ excess beyond bg with default prompt atmospheric neutrinos)

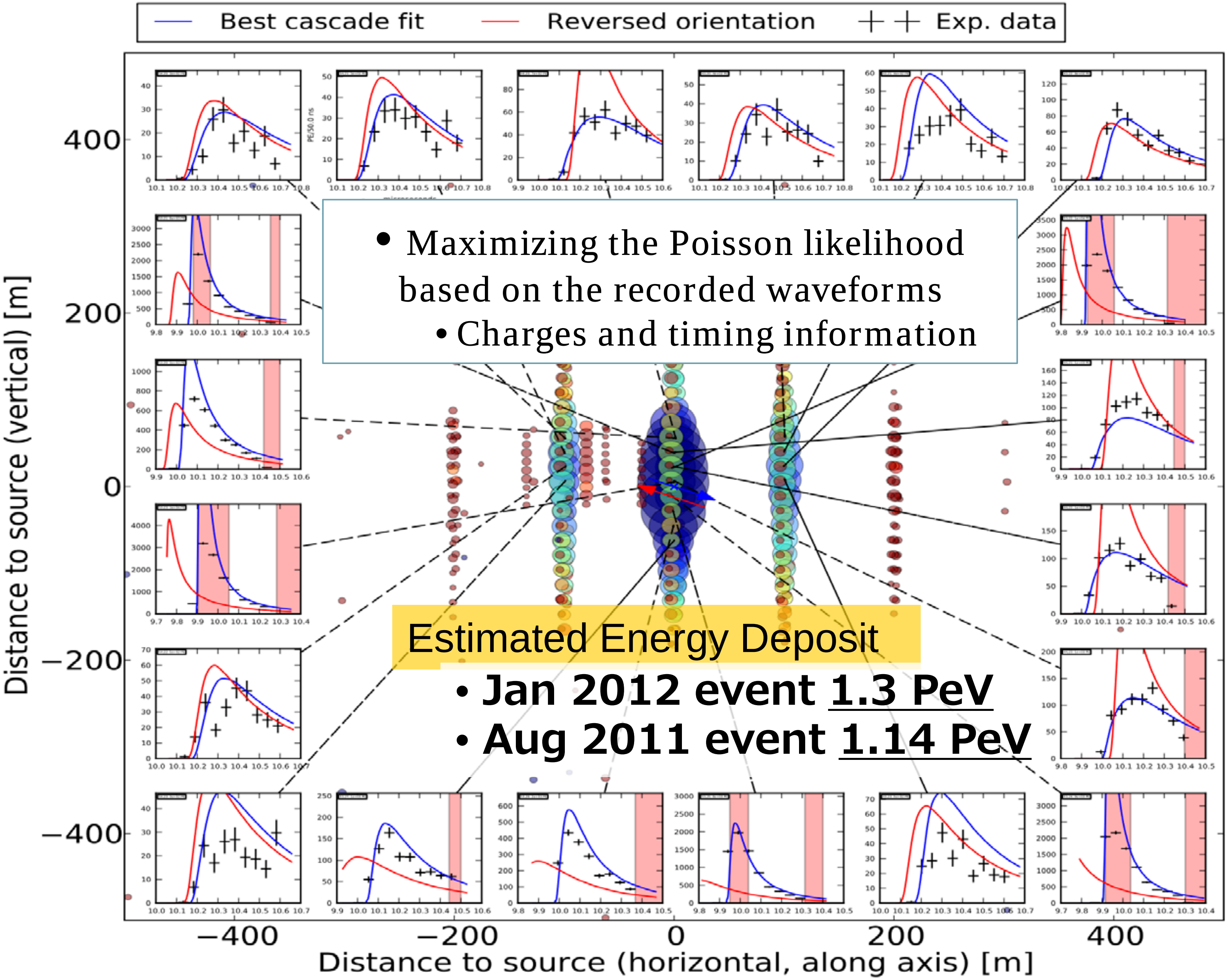
Vertex positions and the final NPE dist.





Well contained events

EVENT RECONSTRUCTION



- Maximizing the Poisson likelihood based on the recorded waveforms
  - Charges and timing information

Estimated Energy Deposit

- Jan 2012 event 1.3 PeV
- Aug 2011 event 1.14 PeV

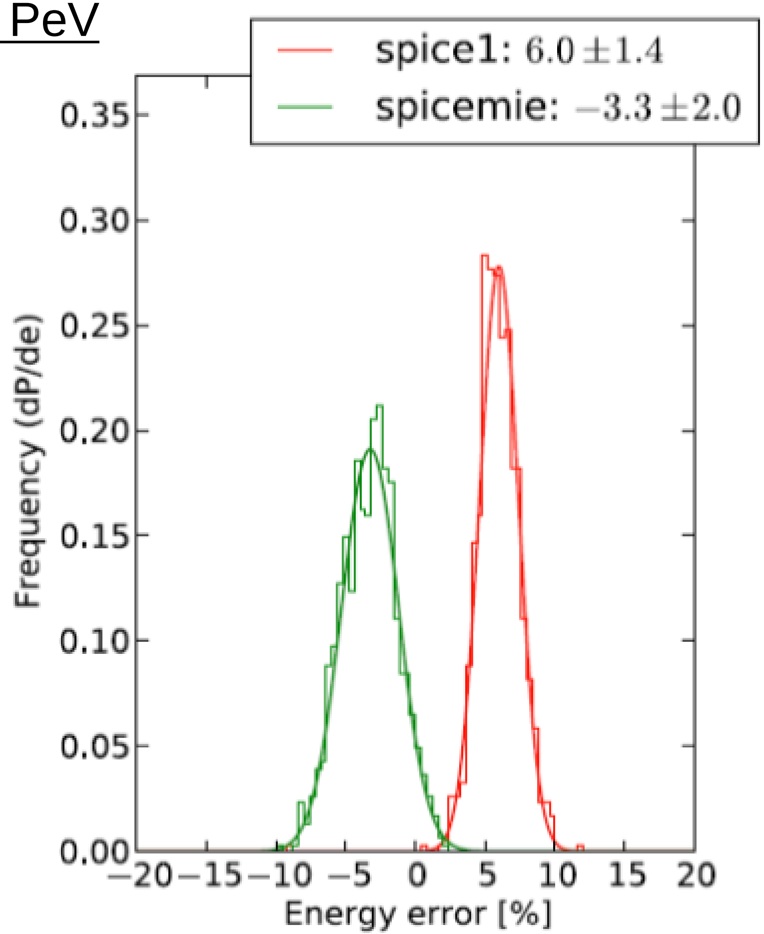
PDF of the deposited energy

The “top-down” approach : Inject MC electrons with the event-relevant phase space and reconstruct them by the same method

- Jan 2012 event <u>1.3 PeV</u>
- Aug 2011 event <u>1.14 PeV</u>

Stat error
~2%
+
MC with the different ice models
~15% (*)
+
absolute sensitivity
~10%
+
Different reconstruction methods
~10% (*)

→ systematic error ~ 20-25%
but publically currently 35% is used
since (*) not concluded



Reconstruction assuming Spice 1

Earth-surface Eν probability

All flavor sum ($\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1)

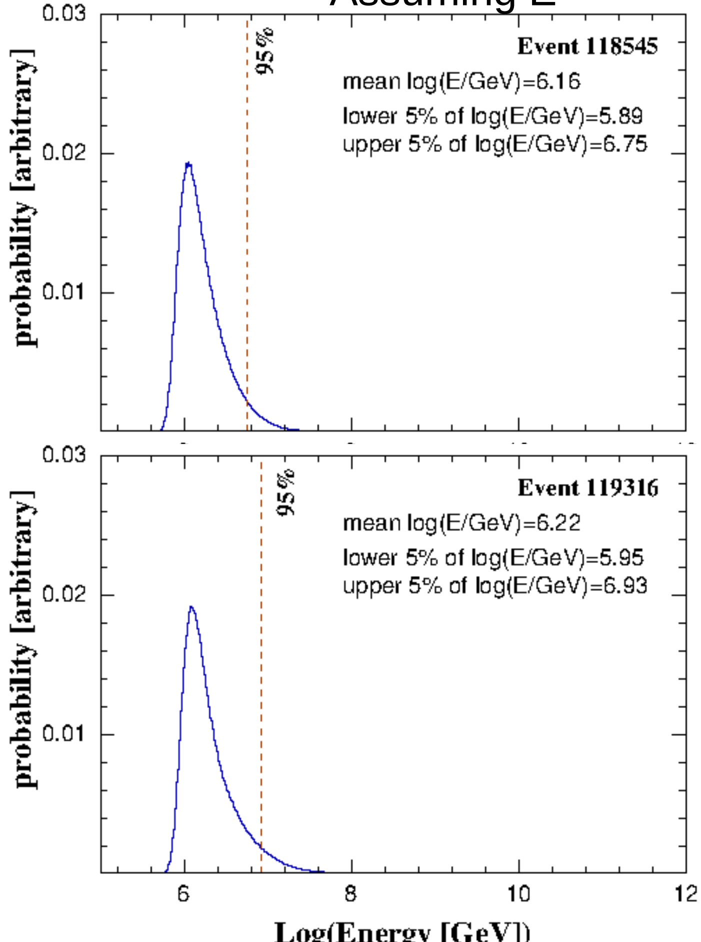
Jan 2012 event

Note: Systematic errors _included_

Assuming E^{-2}

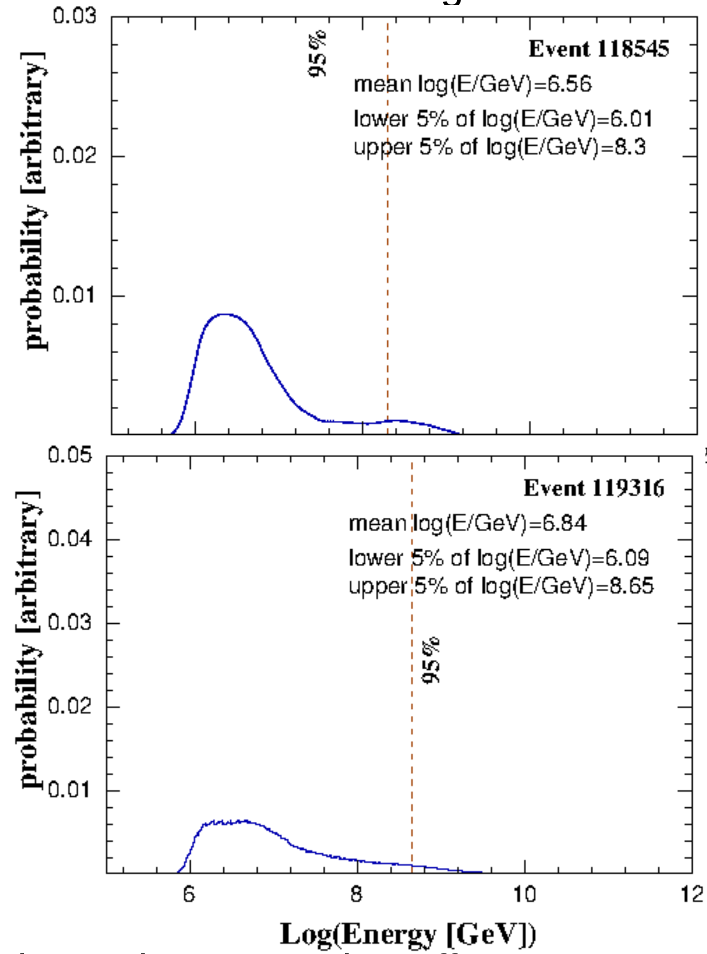
“Bert”

“Ernie”



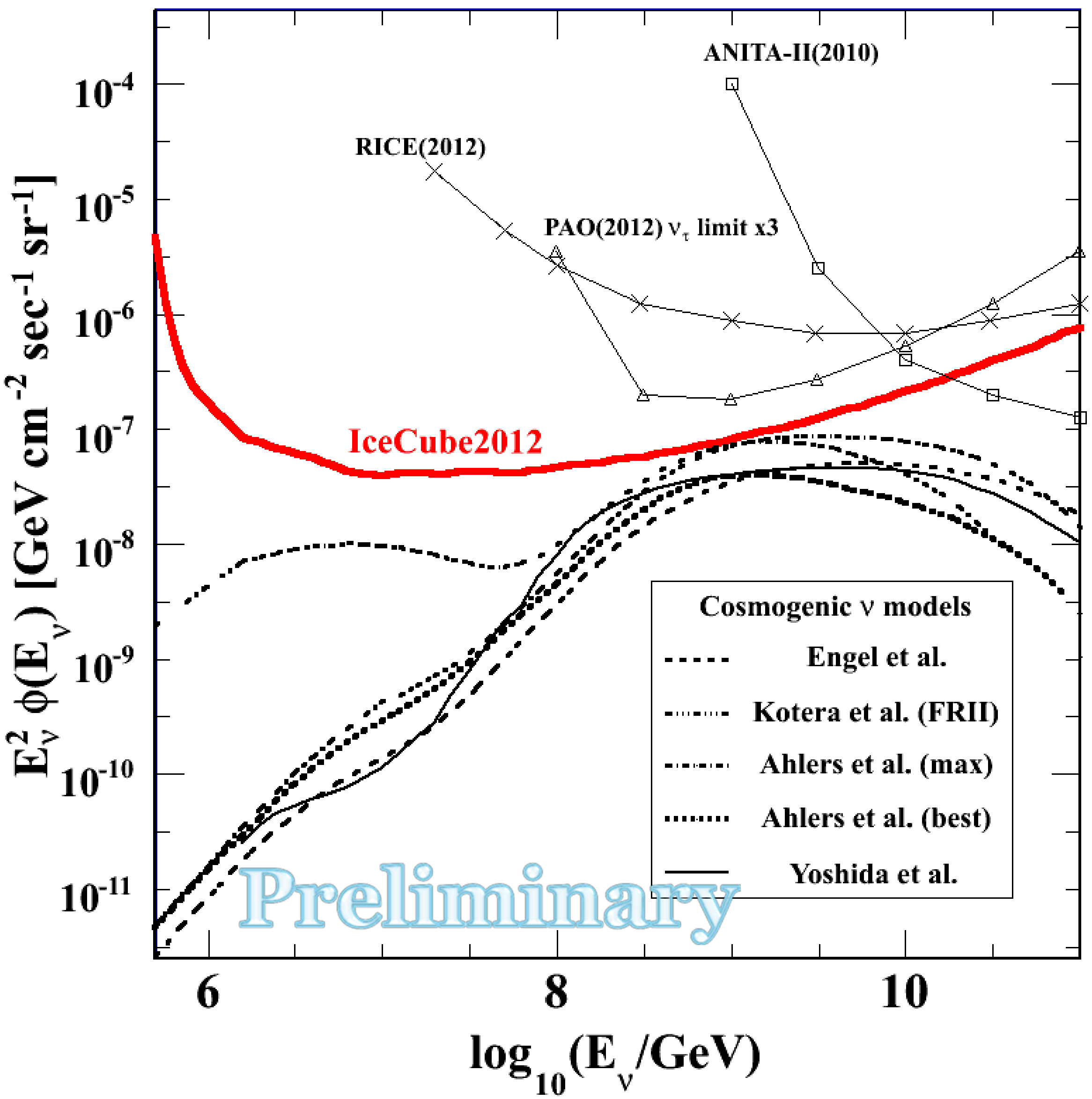
Aug 2011 event

Assuming GZK



Even assuming the hard GZK-type spectrum and the in-earth propagation effects, probability above 100PeV is

Differential Upper limits (Systematics included)



90% C.L. upperlimit

F-C Upper fluctuation

- **A factor of ~4 improved from the previous IceCube results**
- **The world's best sensitivity!**
- **Will constrain the neutrino fluxes down to mid-strong cosmological evolution models**

Model検定例

Event rates(>100 PeV) and p-values

ν Model	GZK Y&T m=4,zmax=4	GZK Sigl m=5, zmax=3	GZK Ahler Fermi Best	GZK Ahler Fermi Max	GZK Kotera FR-II	GZK Kotera SFR/GRB	Topdown GUT
Rate >100PeV	2.6	4.0	2.0	4.1	3.8	0.6	5.0
Model Rejection Factor	0.98	0.65	1.27	0.64	0.69	3.6	0.53
p-value	9.6×10^{-2}	2.4×10^{-2}	1.6×10^{-1}	2.3×10^{-2}	3.1×10^{-2}	6.7×10^{-1}	$<10^{-2}$

Preliminary

- Excluded
- Mildly Excluded
- Consistent

$$N_{100(1-\alpha)\%} = \sum_{n=0}^{2} P_n N_{n,(100-\alpha)\%}$$

P_n probability of n events above 100 PeV

α p-value

Summary

- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- IceCube is the largest neutrino detector and rejection of the atmospheric neutrinos was achieved by setting energy threshold
- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - <u>The highest energy neutrino events</u> observed ever!
- Performed systematic studies, paper drafts under collaboration review
- Very likely beyond the conventional atmospheric neutrinos
- Unlikely GZK neutrinos (energies too low)
- The strongest constraints on the GZK neutrino models to date