Searches for ultra-high energy cosmic neutrinos with the IceCube neutrino detector

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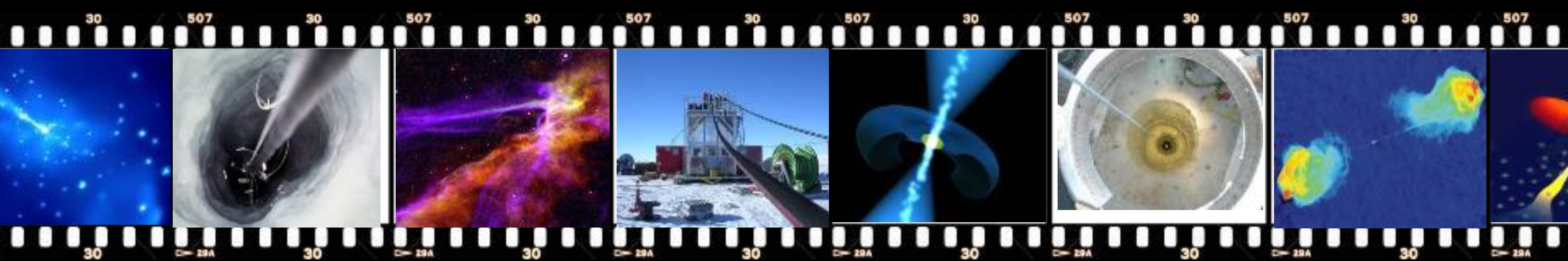


Aya Ishihara 2012/12/5 Kyoto University

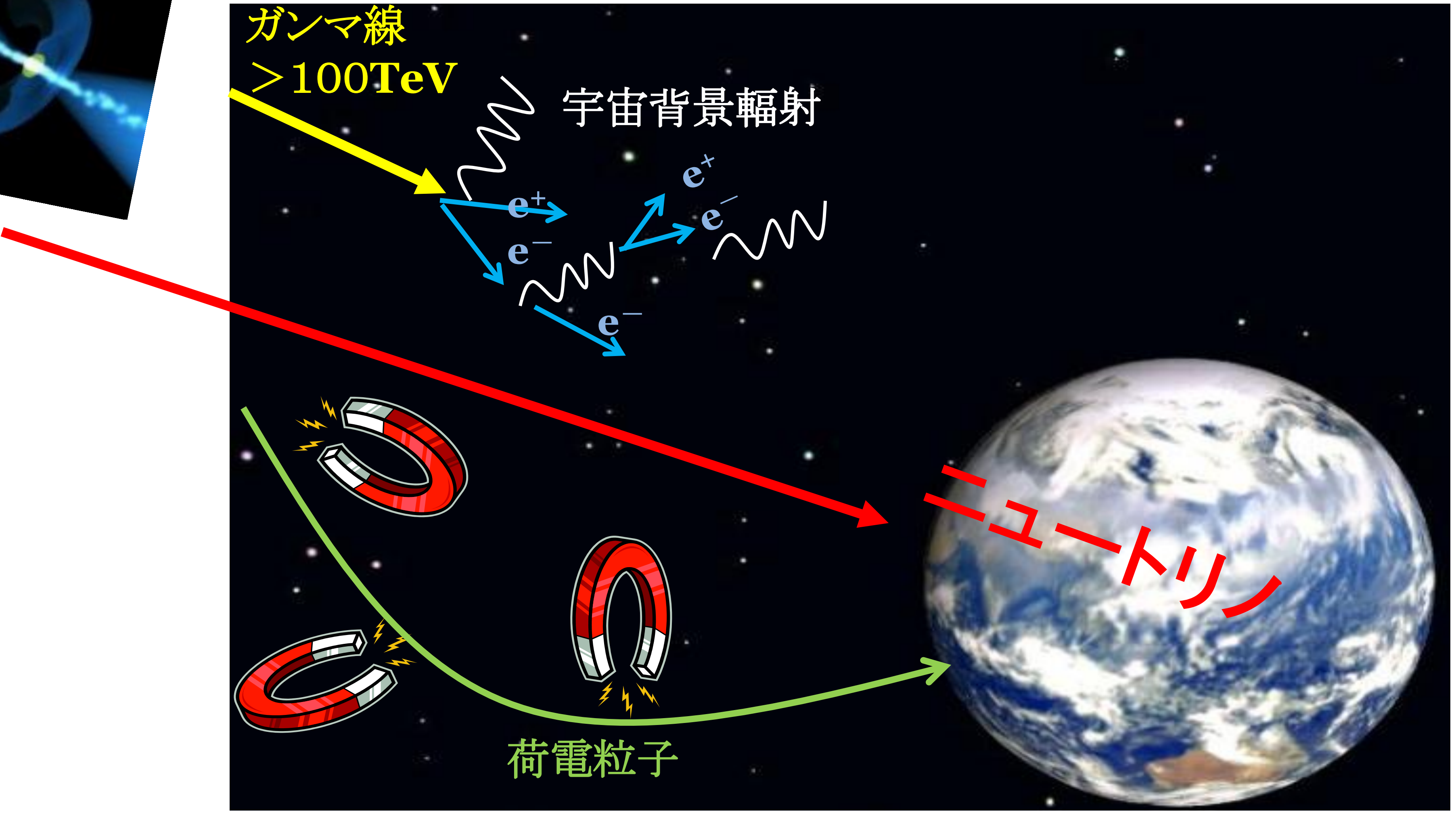
The High Energy Deep Universe Mystery

- 巨大ブラックホールである活動銀河核（AGN)や宇宙で最も激しい爆発現象であるガンマ線爆発（GRB)といった極限爆発現象は遠方（若い）宇宙に分布
  - Was young Universe more active, if so why/how?

- 起源のわからない高エネルギー粒子が宇宙から地球に飛来している。どこから？エネルギーはLHC加速器の1000万倍以上に達する（100EeV＝10keV(x-ray) x 10,000,000,000,000,000!)

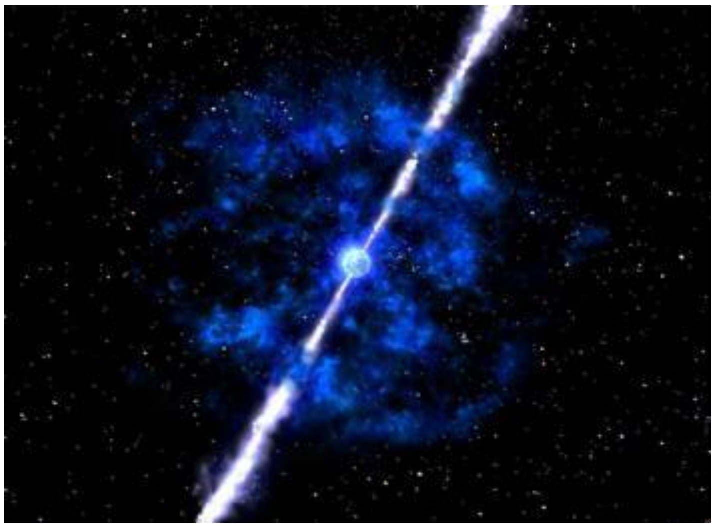
解明に向けた障壁

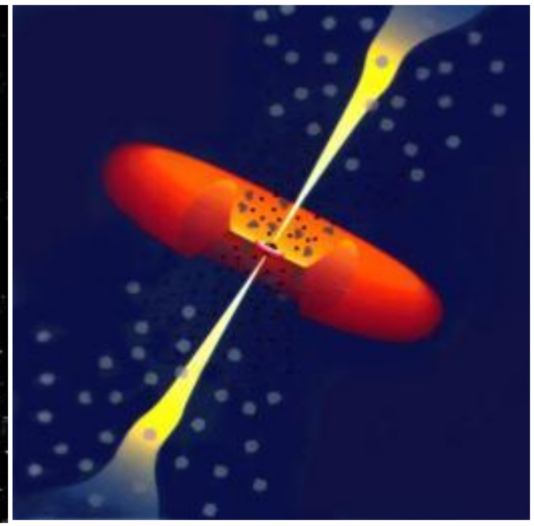
- 地球で観測される最高エネルギー粒子は電荷を持っているため宇宙磁場に曲げられてきており来た方向が分からない。
- 高エネルギー深宇宙を直接光で観測することが出来ない。
  - ガンマ線は3Kの宇宙背景輻射と反応してしまい、エネルギーを失ってしまう
  - 見られる範囲は10万光年(天の川銀河の直径)ほどで、現在の宇宙の大きさのわずか約1/47万

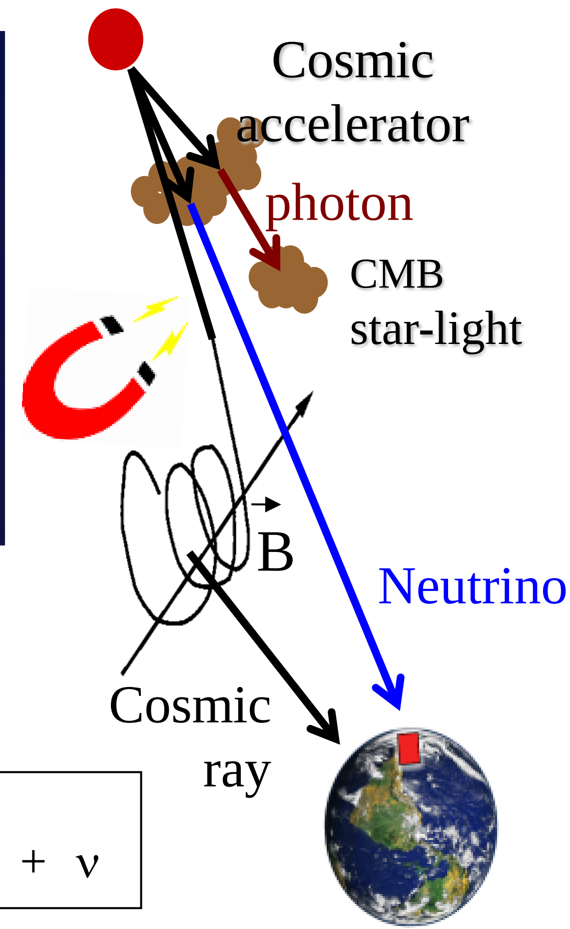


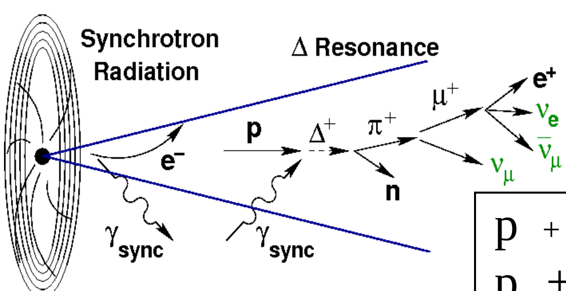
Neutrinos in the Astronomical Objects

high energy cosmic-ray sources, e.g. AGN, GRB…



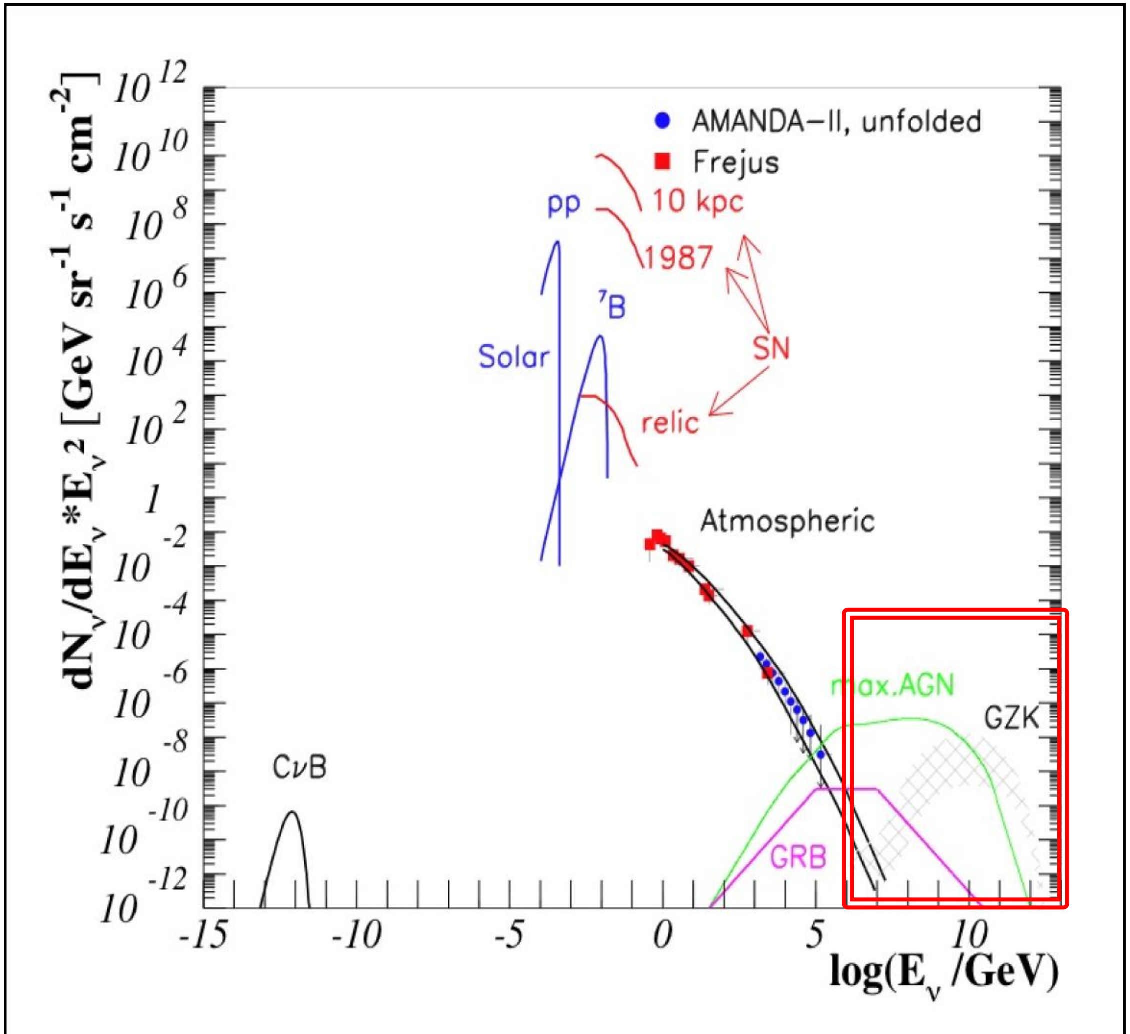






$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow p + \gamma\gamma$$
$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \rightarrow n + \mu + \nu$$

Why Ultra-high Energy Neutrinos?
PeV and above

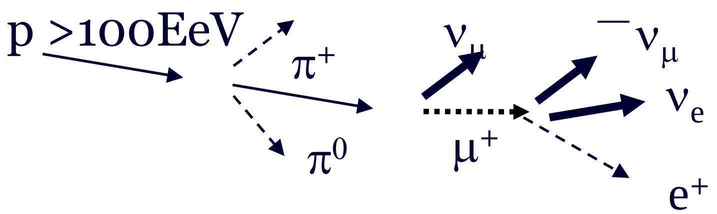


- **Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)**
- **Cosmogenic neutrino production is a 'guaranteed' ν source**
- **Energies above dominant atmospheric neutrinos**

The highest energy neutrinos

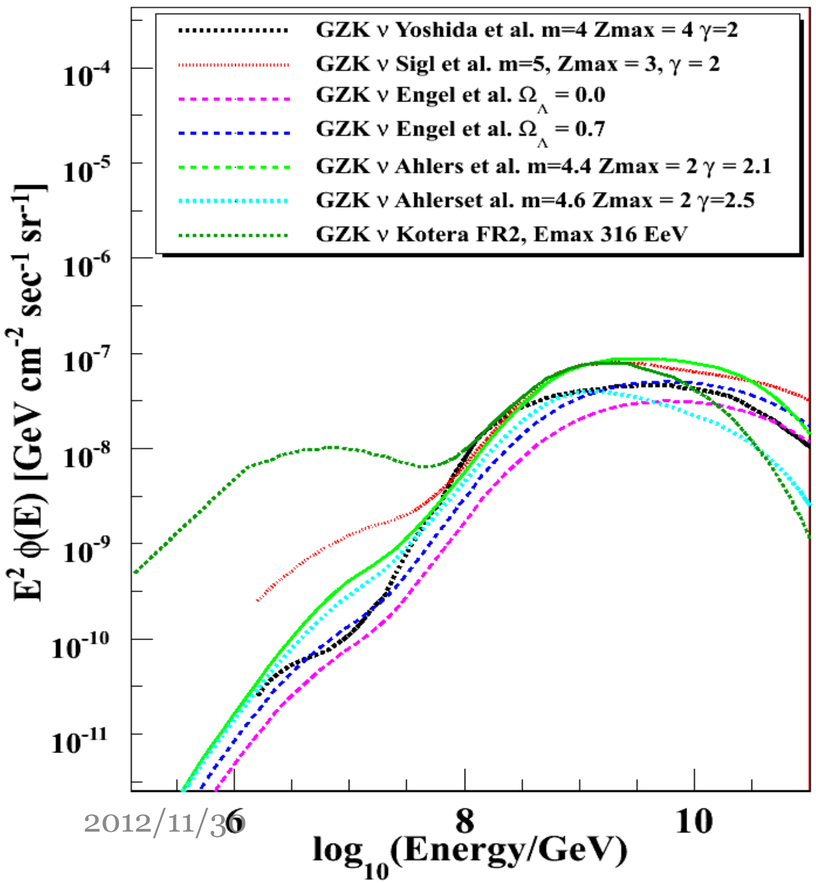
cosmogenic neutrinos induced by the interactions of cosmic-ray and CMB photons

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



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

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



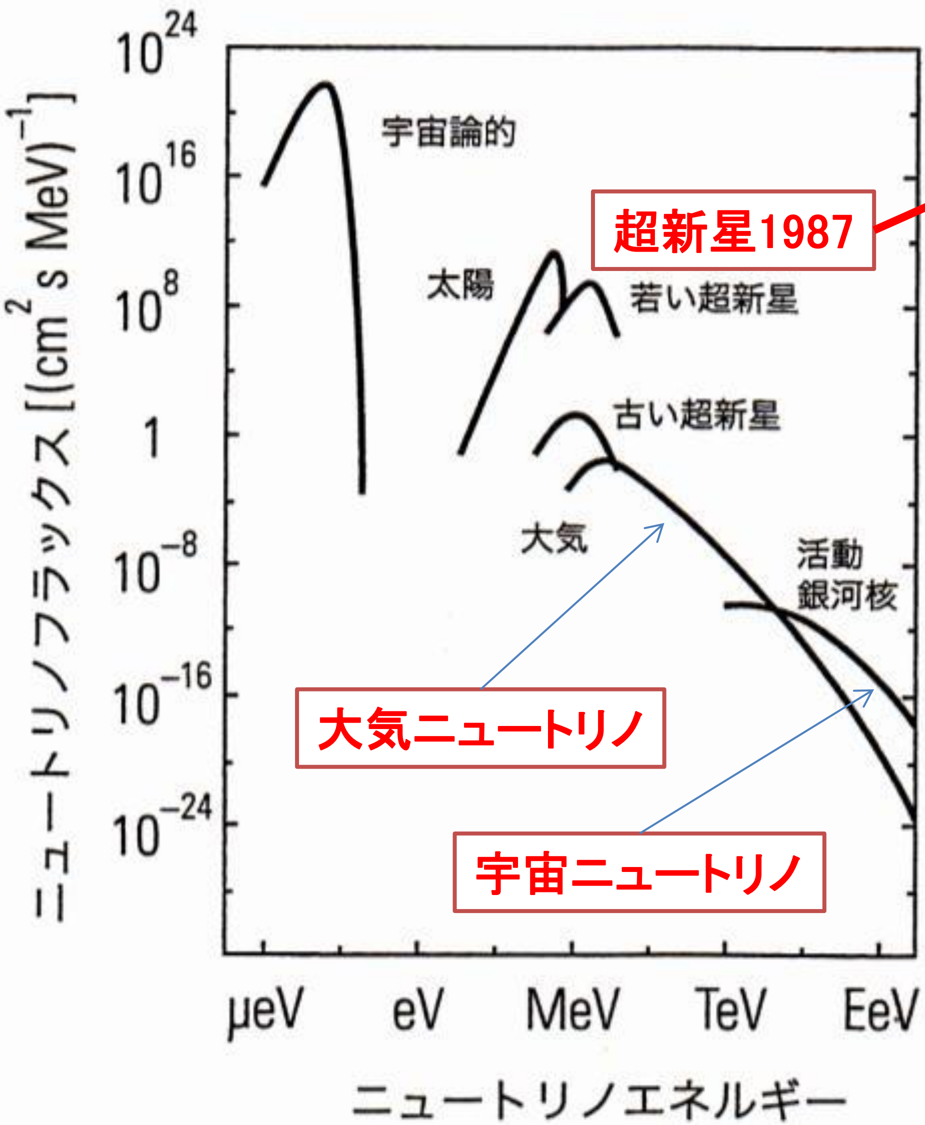
Various GZK ν models

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

どのような宇宙ニュートリノ検出器が必要か？

ニュートリノ流量のエネルギー分布



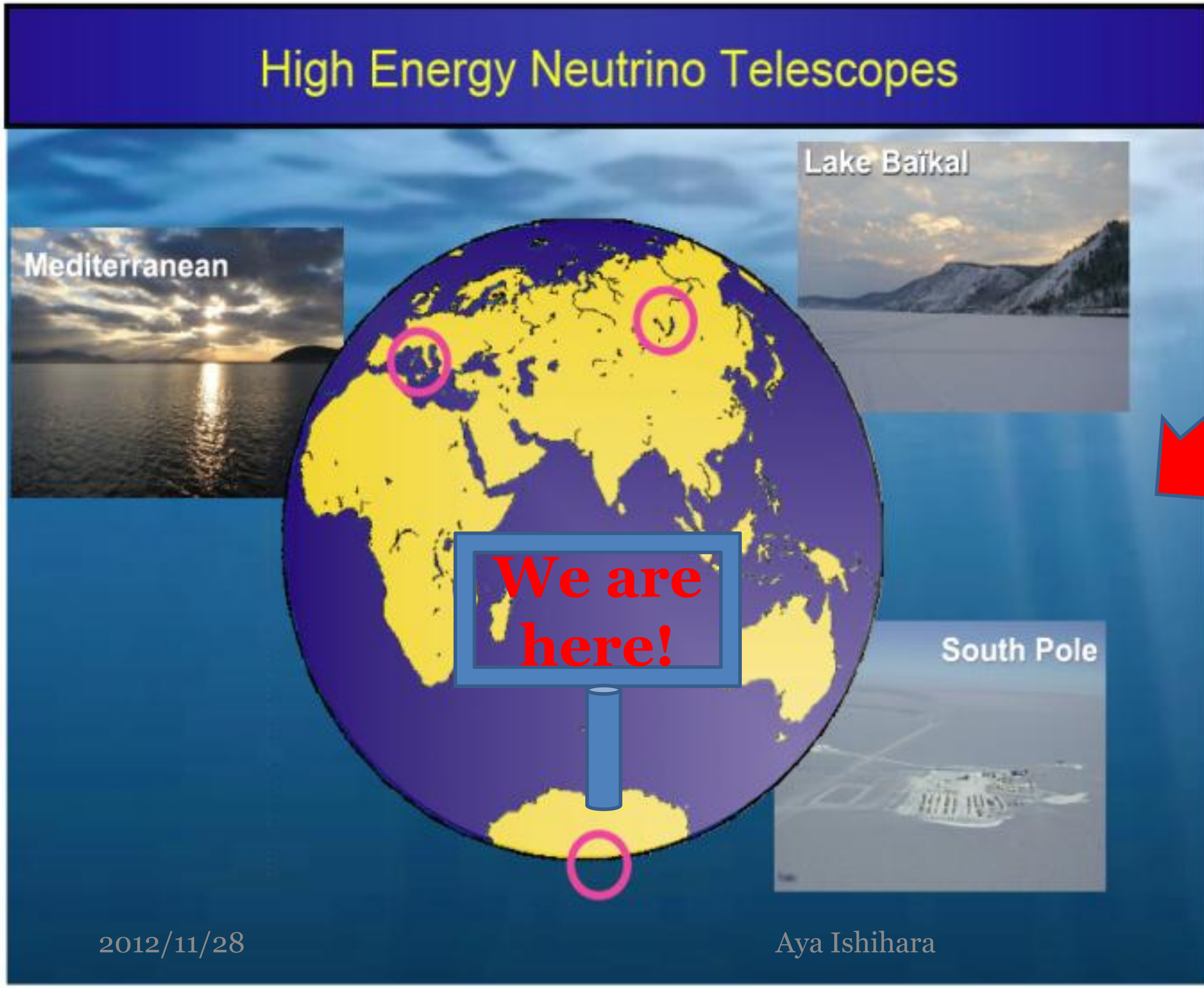
超新星爆発ニュートリノ
1987年2月23日にIMB実験とカミオカンデ実験により初めて観測（小柴昌俊氏が2002年にノーベル物理学賞）爆発的天体現象でニュートリノが出来ることがわかった

初の宇宙ニュートリノ発見以来、さまざまな実験によって超新星爆発ニュートリノエネルギーを超える,他の天体からの宇宙ニュートリノの検出研究が続けられているが、**25年間観測されていない**。

何故か？
9桁以上のエネルギー領域にわたって背景事象となる大気ニュートリノの量が宇宙ニュートリノ量より何桁も多く、宇宙ニュートリノを区別して観測することが出来ない！

High energy neutrino telescopes in the world

Since 1976 -
DUMAND, Lake Baikal. NESTOR, ANTARES, and NEMO…



ICECUBE at the South Pole
and
time to see

AMANDA/IceCube
The first test bed in 1991/1992

The IceCube Collaboration

http://icecube.wisc.edu

36 institutions, ~270 members

Canada
University of Alberta

US
Bartol Research Institute, Delaware
Pennsylvania State University
University of California - Berkeley
University of California - Irvine
Clark-Atlanta University
University of Maryland
University of Wisconsin - Madison
University of Wisconsin - River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University, Baton Rouge
University of Alaska, Anchorage
University of Alabama, Tuscaloosa
Georgia Tech
Ohio State University

Barbados
University of West Indies

Sweden
Uppsala Universitet
Stockholms Universitet

UK
Oxford University

Germany
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt-Universität zu Berlin
MPI Heidelberg
RWTH Aachen
Universität Bonn
Ruhr-Universität Bochum

Belgium
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Switzerland
EPFL, Lausanne

Japan
Chiba University

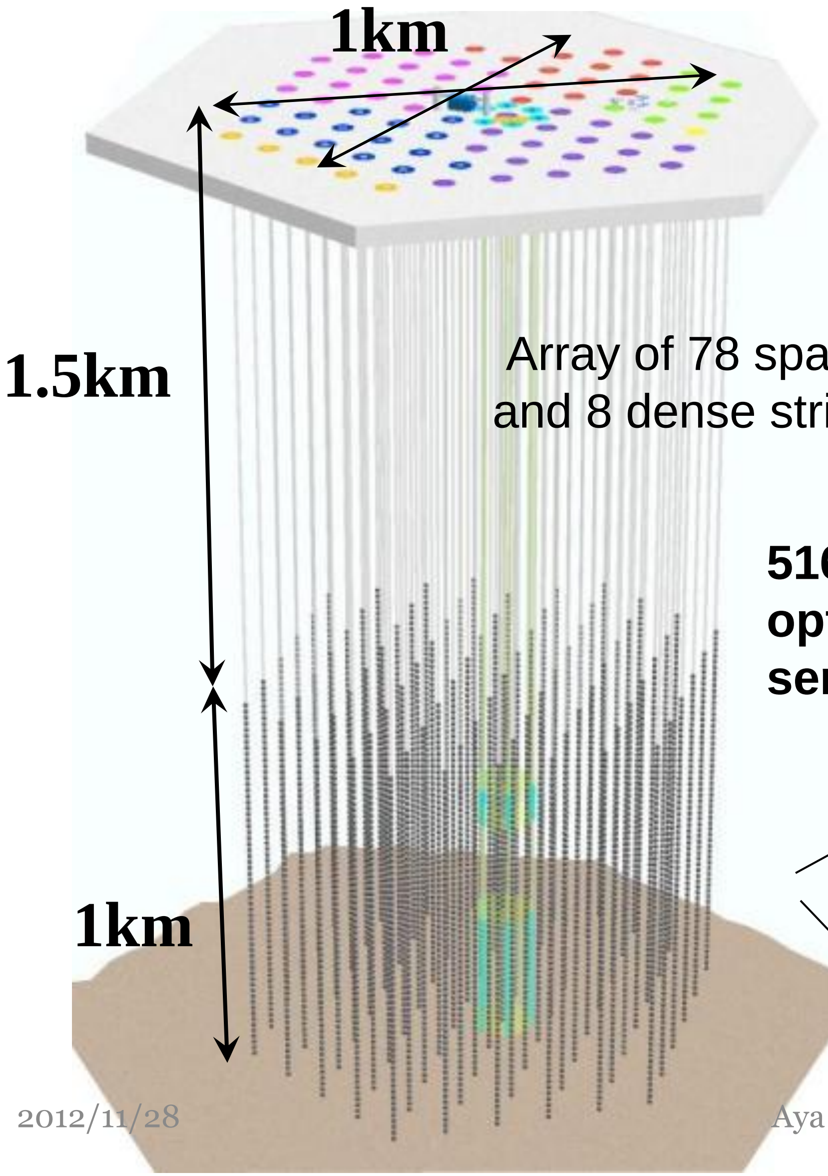
The first results from the full IceCube

ANTARCTICA
Amundsen-Scott Station

New Zealand
University of Canterbury

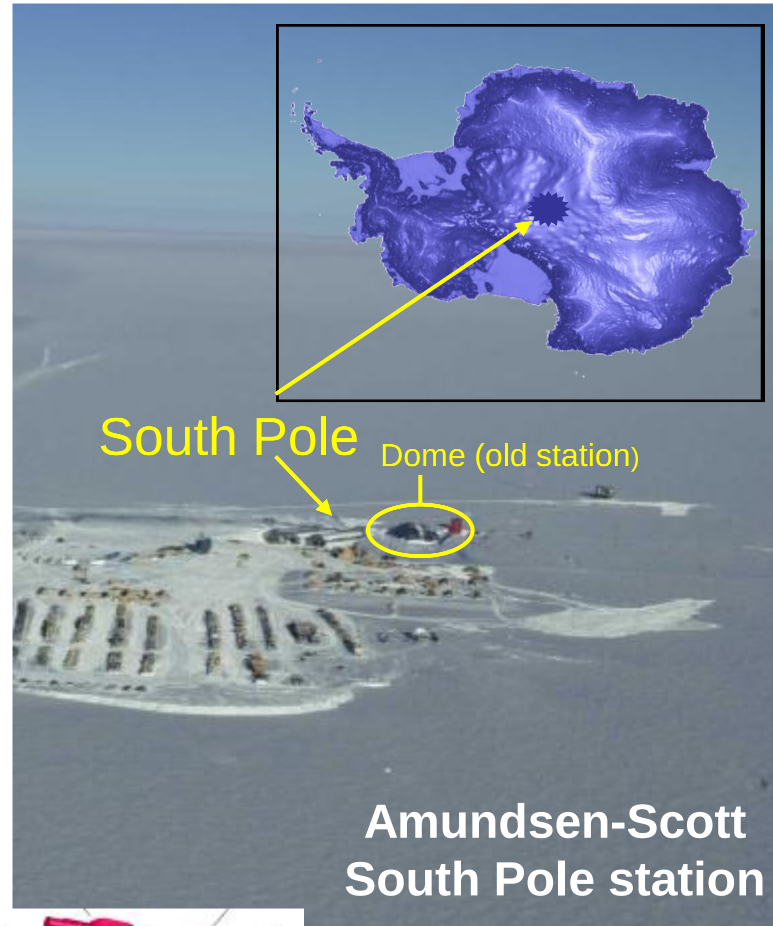
The Largest Neutrino Detector in the world:

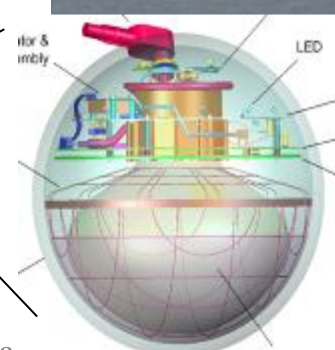
The IceCube Detector

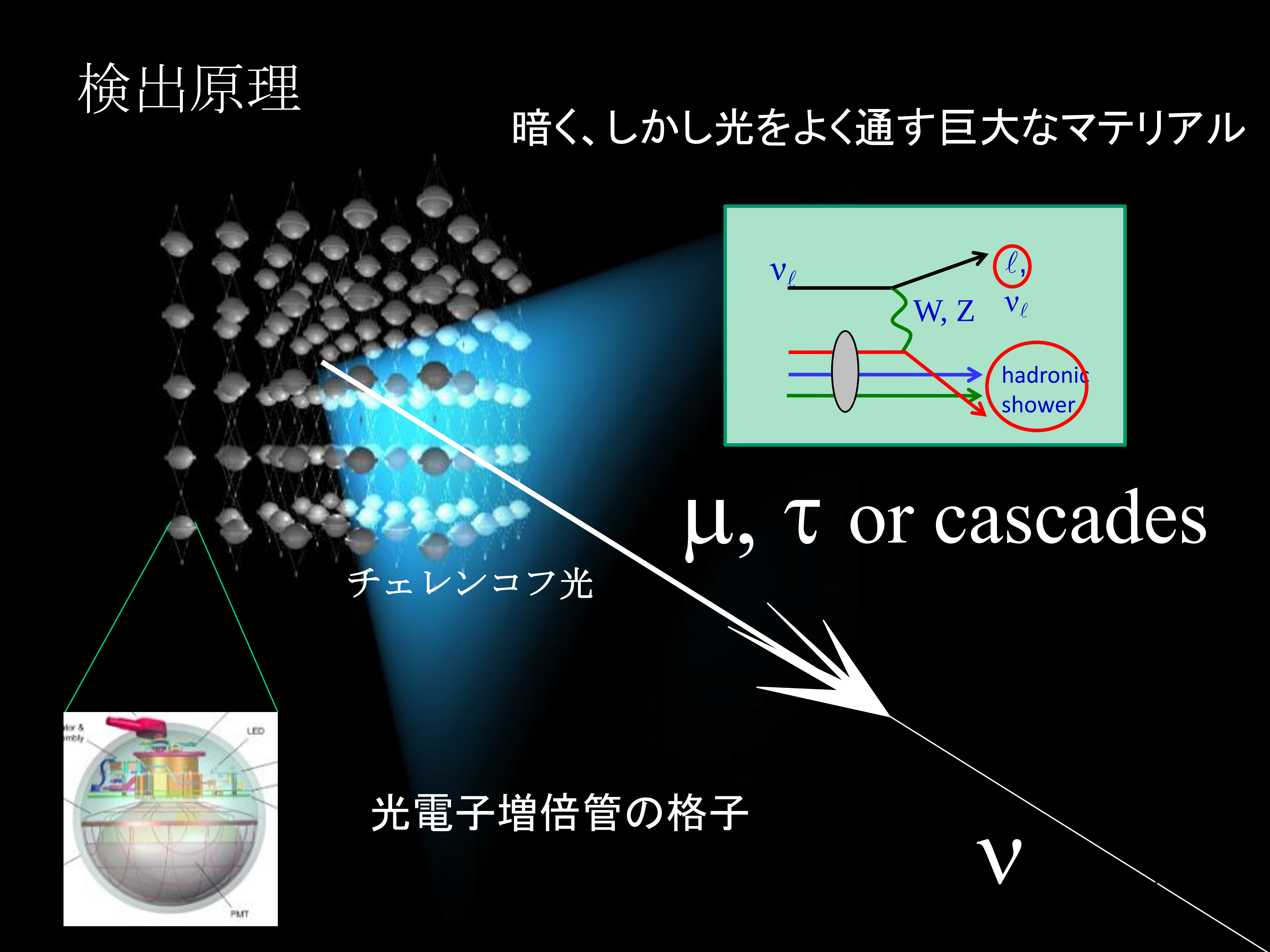


Array of 78 sparse and 8 dense strings

5160 optical sensors



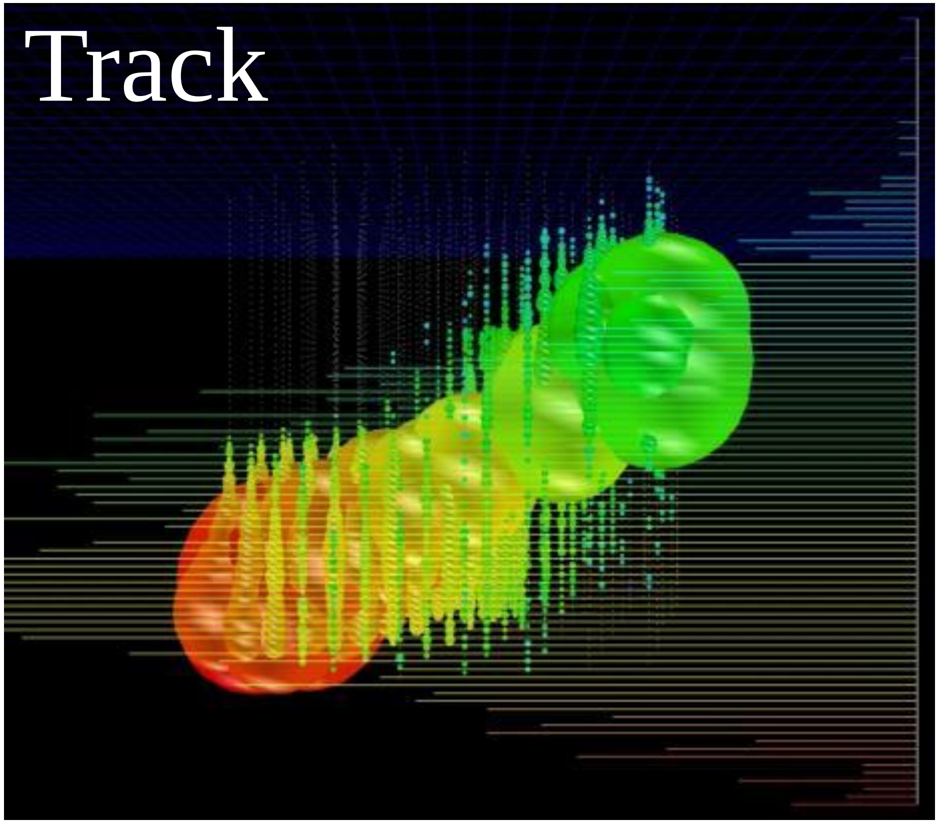



検出原理
暗く、しかし光をよく通す巨大なマテリアル
ν_ℓ
W, Z
ℓ,
ν_ℓ
hadronic
shower
μ, τ or cascades
チェレンコフ光
LED
PMT
光電子増倍管の格子
ν

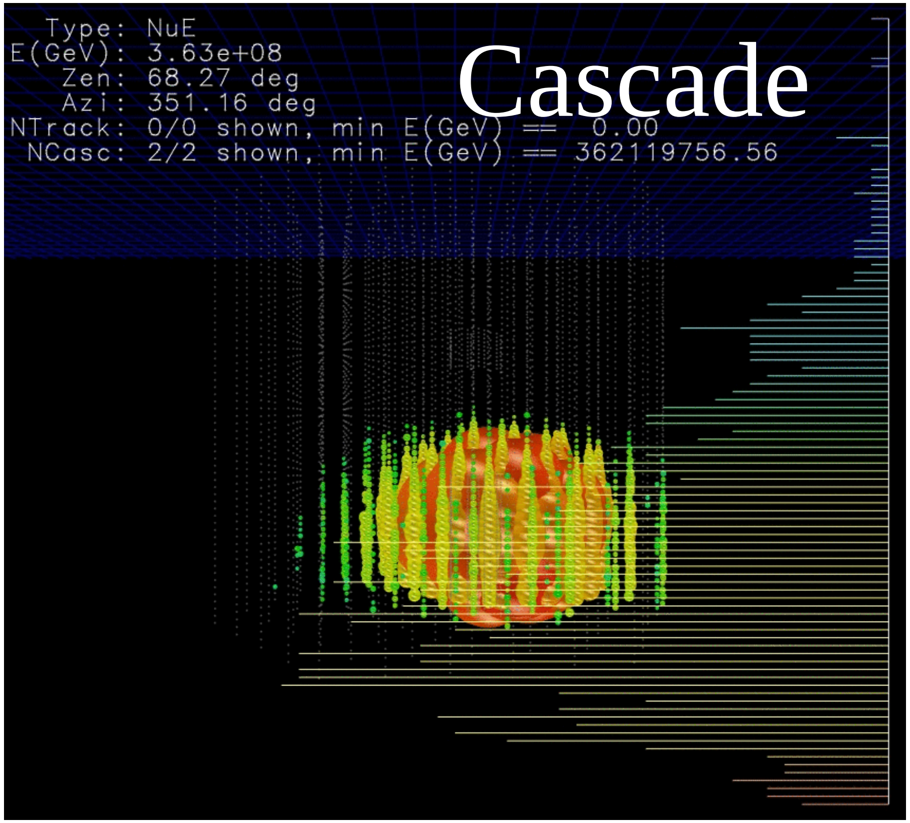
from MC simulation

Ultra-high Energy Signal Events

20PeV muon



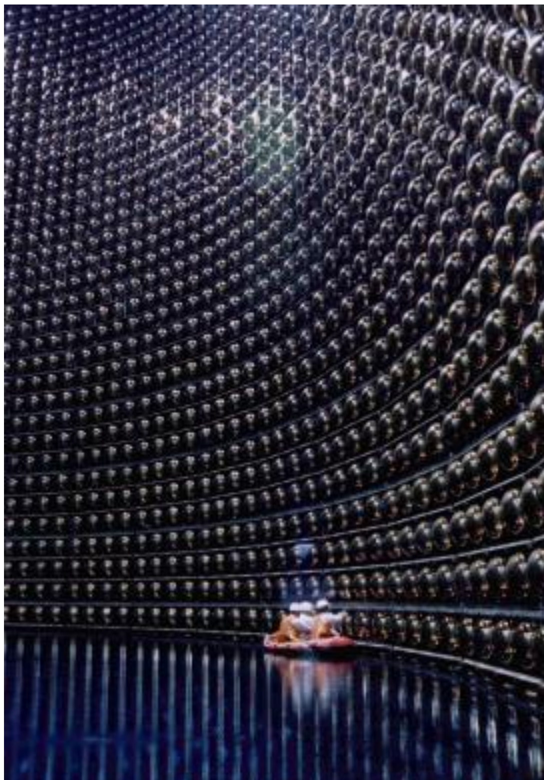
300PeV nu induced cascade



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

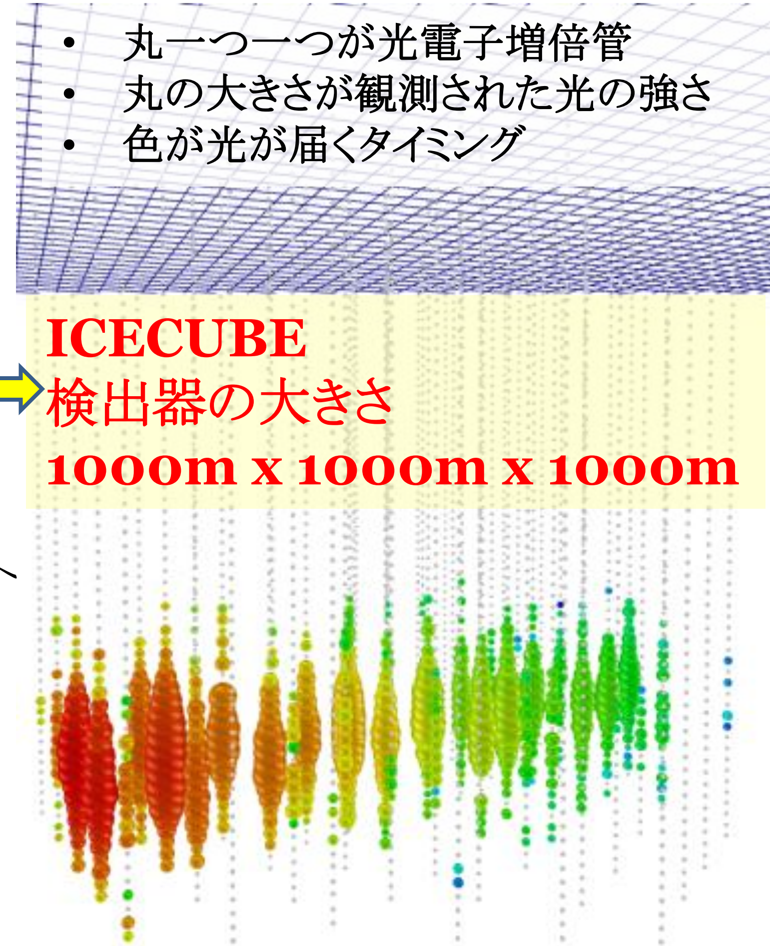
Comparison between IceCube's 3D events and SK 2D events

super-KAMIOKANDE
検出器の大きさ
40m x 40mx40m



>15,000倍

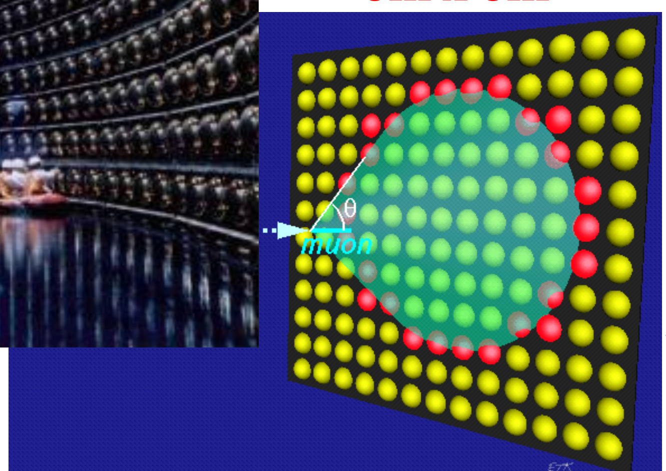
- 丸一つ一つが光電子増倍管
- 丸の大きさが観測された光の強さ
- 色が光が届くタイミング



ICECUBE
検出器の大きさ
1000m x 1000m x 1000m

2Dから3Dへ

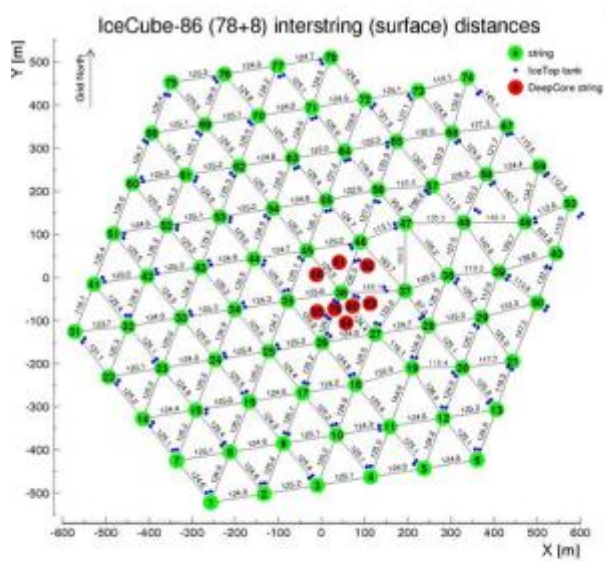
事象の大きさ
6m x 6m



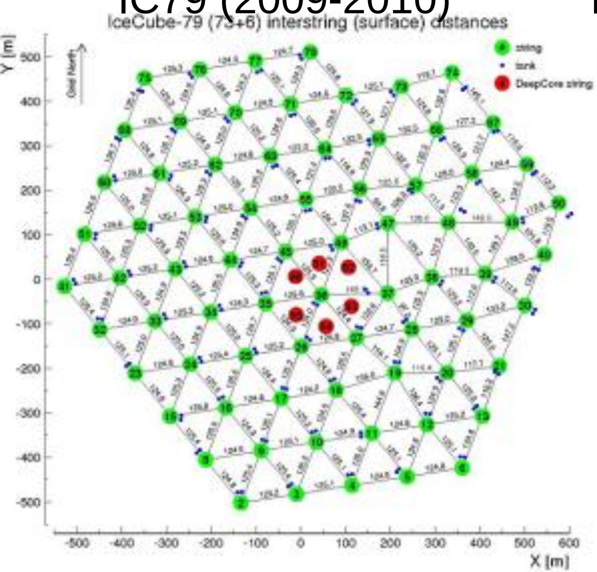
ICECUBE
事象の大きさ
800m x 300m x 300m

A big challenge: IceCube検出器の建設

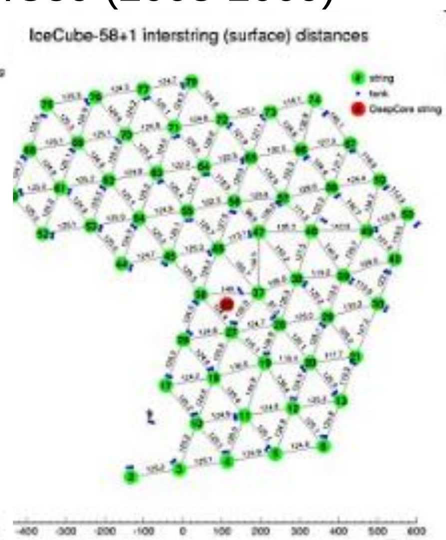
2006年に建設開始2010年末に建設終了 IC86 = full IceCube (2011~)



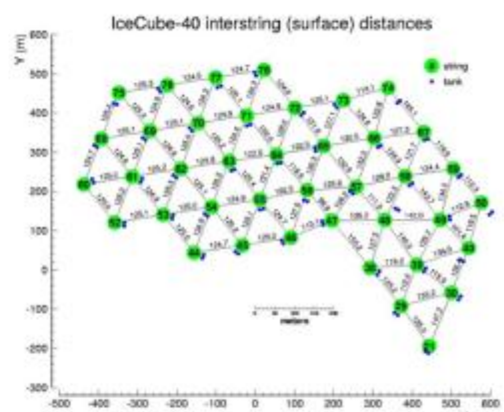
IC79 (2009-2010)



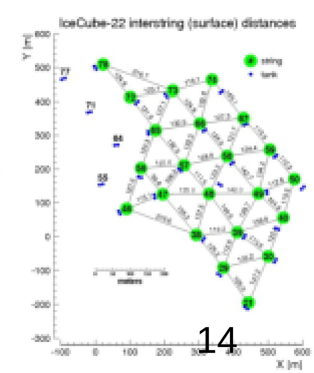
IC59 (2008-2009)



IC40 (2007-2008)



IC22 (2006-2007)

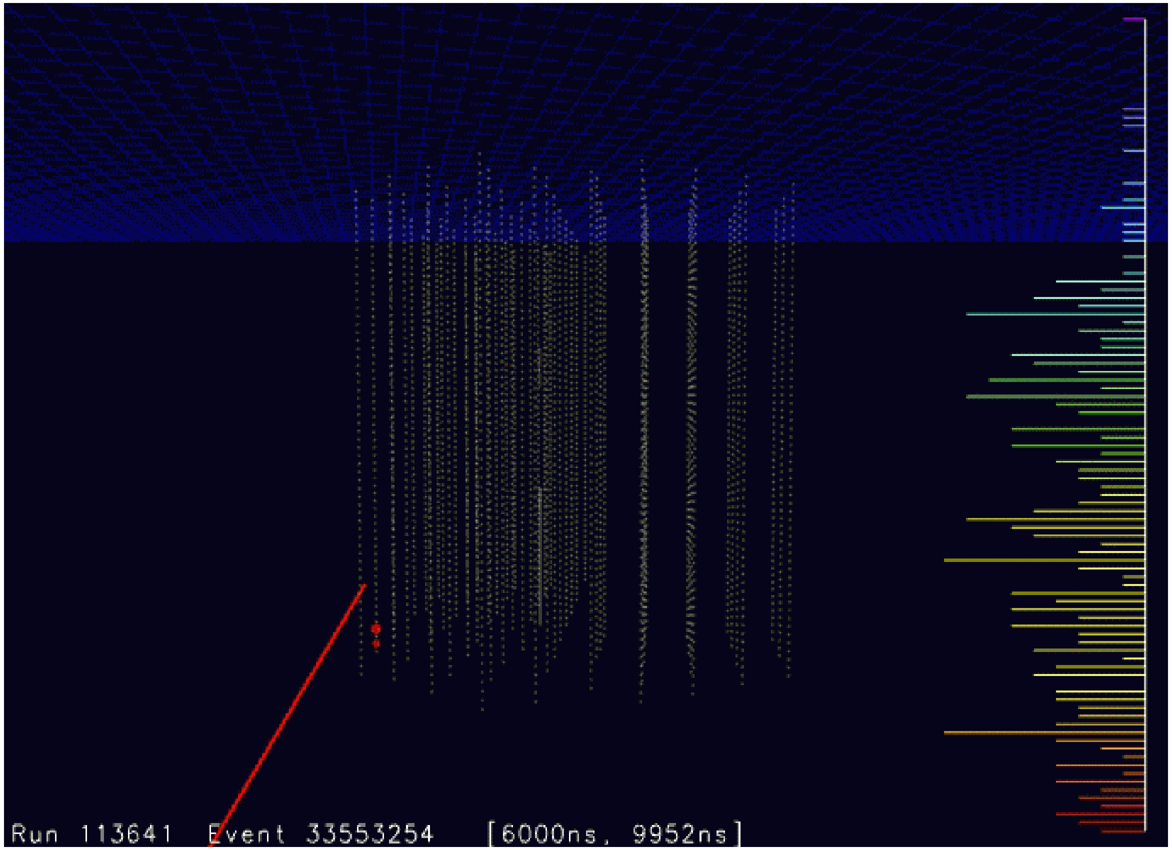


Event rates

Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	~5 / day
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	~100/day
IC86-I	2011- 2012	~ year	2700	processing
IC86-II	current		2700	running

IC86 achieving ~ 99% uptime

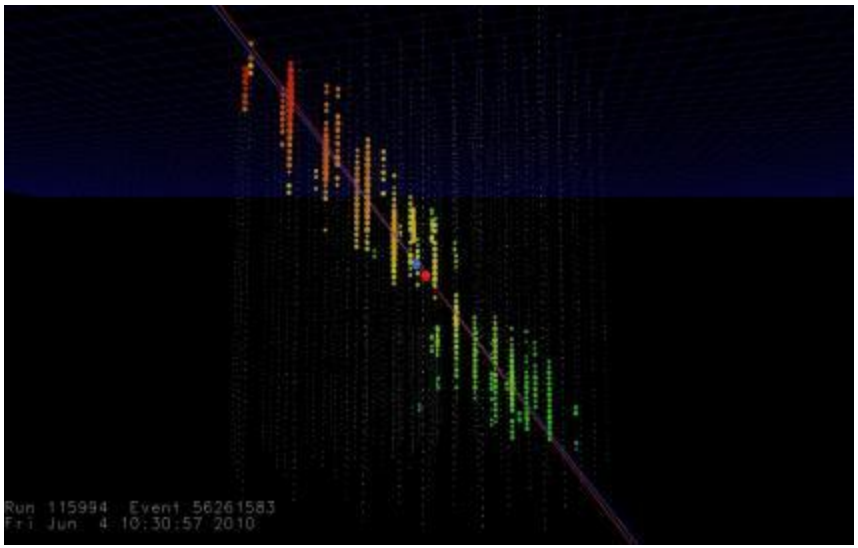
Neutrino Example



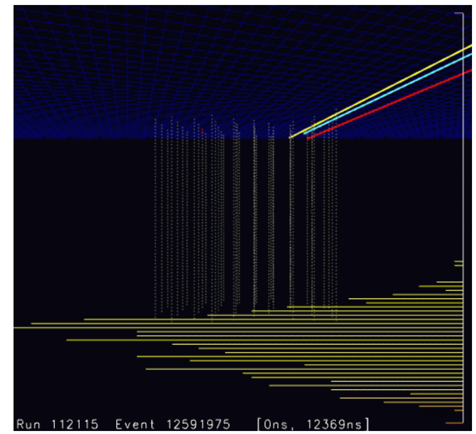
With 40 strings, 2009 May

IceCube Events

With 79 strings, 2010 June

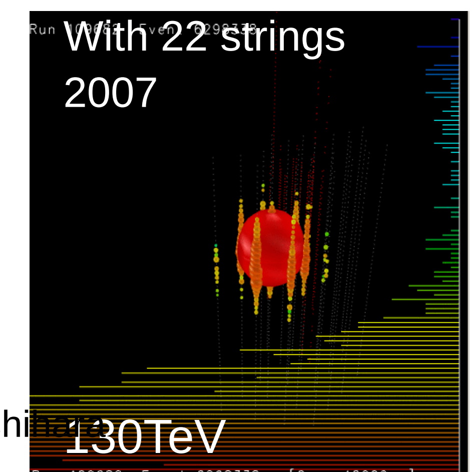


With 40 strings, 2008 Dec



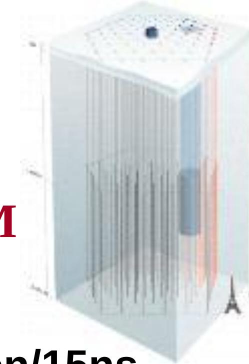
Energy threshold ~10 GeV
$>10^8$ muons/day
>100 neutrinos/day

With 22 strings
2007



130TeV

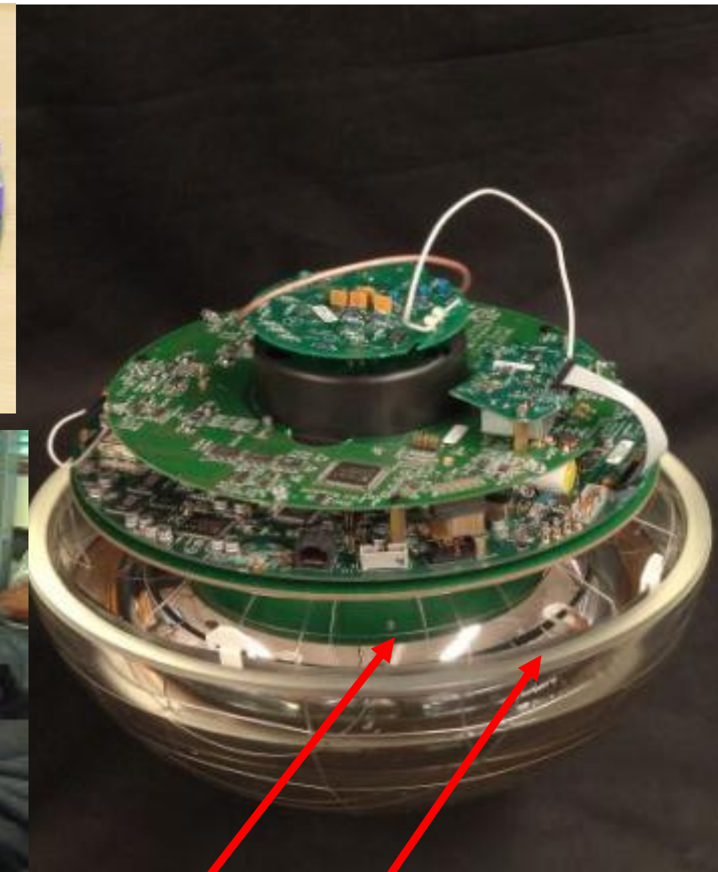
Digital Optical Module



- **PMT: 10 inch Hamamatsu**
- **Power consumption: 3 W**
- **Digitize at 300 MHz for 400 ns with custom chip**
- **40 MHz for 6.4 μs with fast ADC**
- **Flasherboard with 12 LEDs**
- **Local HV**

Waveforms, times digitized in each DOM

- **Dynamic range 500 photoelectron/15ns**

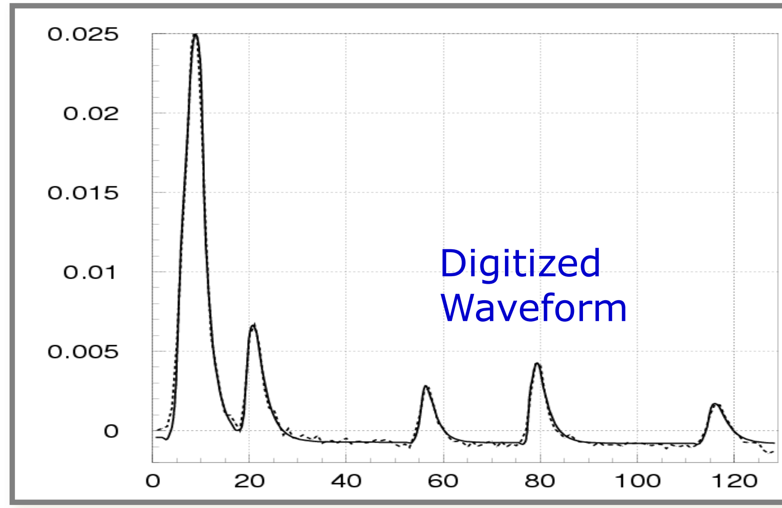


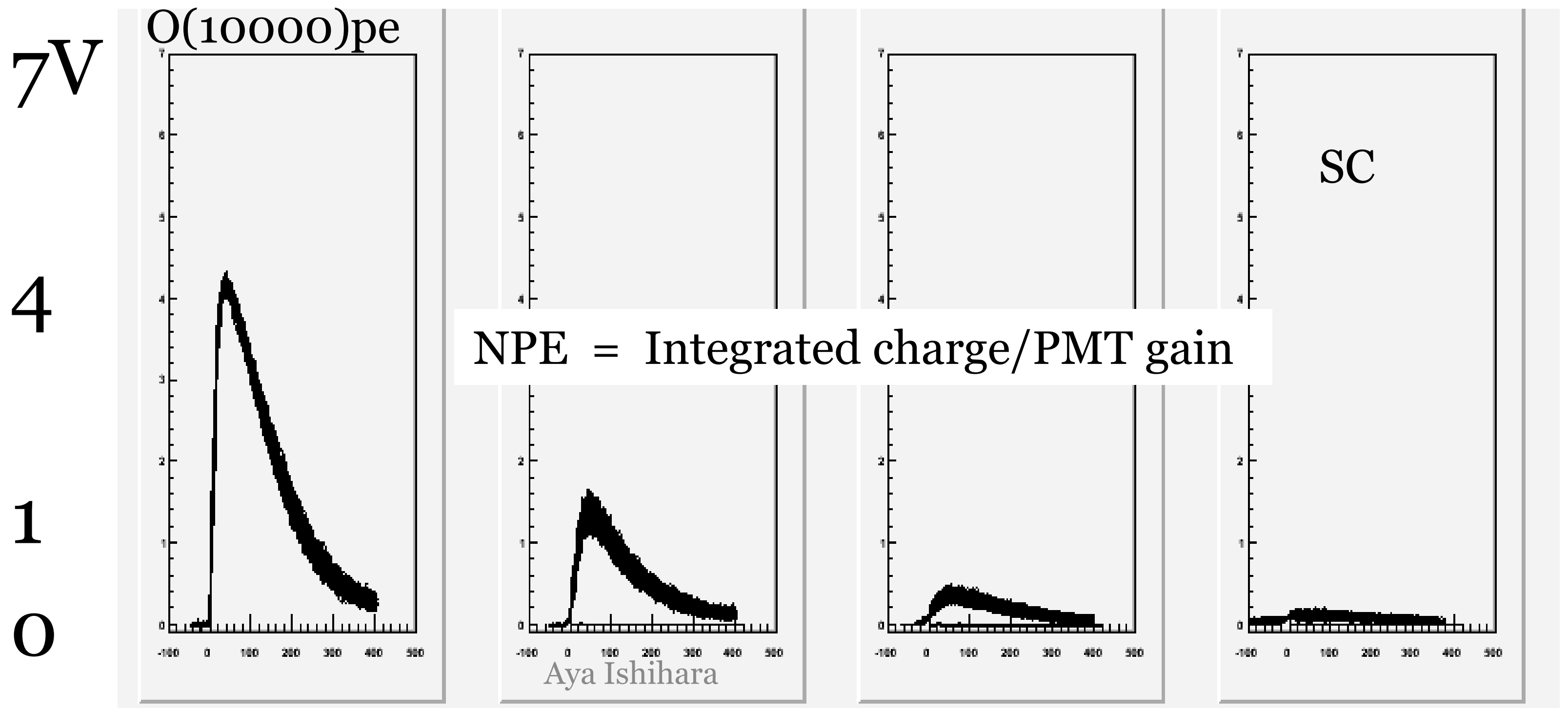
Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec

25 cm PMT
33 cm Benthosphere

Waveform examples from spe to 10000 pe

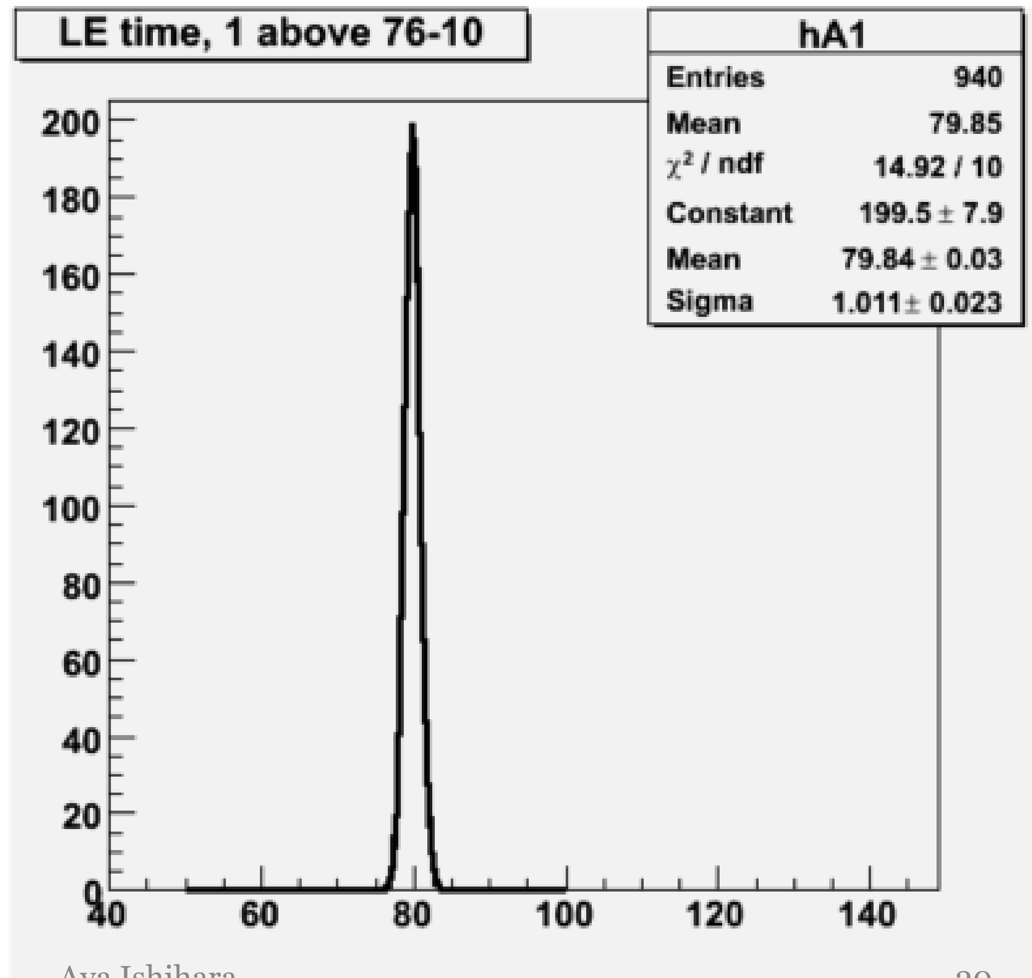
single pe level





Time resolution: ~1ns for bright pulses

- Time difference between neighboring DOMs fired with (bright) flasher pulses: 1 ns.



UHE neutrino analysis 2010-2012

Total 75 GBytes/day from the South Pole to the North

Name in Filter	Actual BW used (MB/day)	Rate of selected events (Hz)
MuonFilter_11	18400	30.25
SlopFilterTime_11	480	0.45
EHEFilter_11	3500	2.33
SlopFilterTrig_11	2850	0.81
DeepCoreFilter_11	9040	26.86
CascadeFilter_11	8750	27.12
IceTopSTA3_InIceSMT_11	2100	3.17
IceTopSTA3_11	2460	6.40
SDST_LowUp_11	600	31.36
SDST_VEF_11	160	7.96
GCLEStarting_11	2070	6.62
SDST_GCMinBias_11	7900	270.16
SDST_GCHE_11	3040	104.38
SDST_GCNWStarting_11	4700	190.94
FilterMinBias_11	860	2.69
PhysicsMinBiasTrigger_11	290	1.28

NPE > 1000

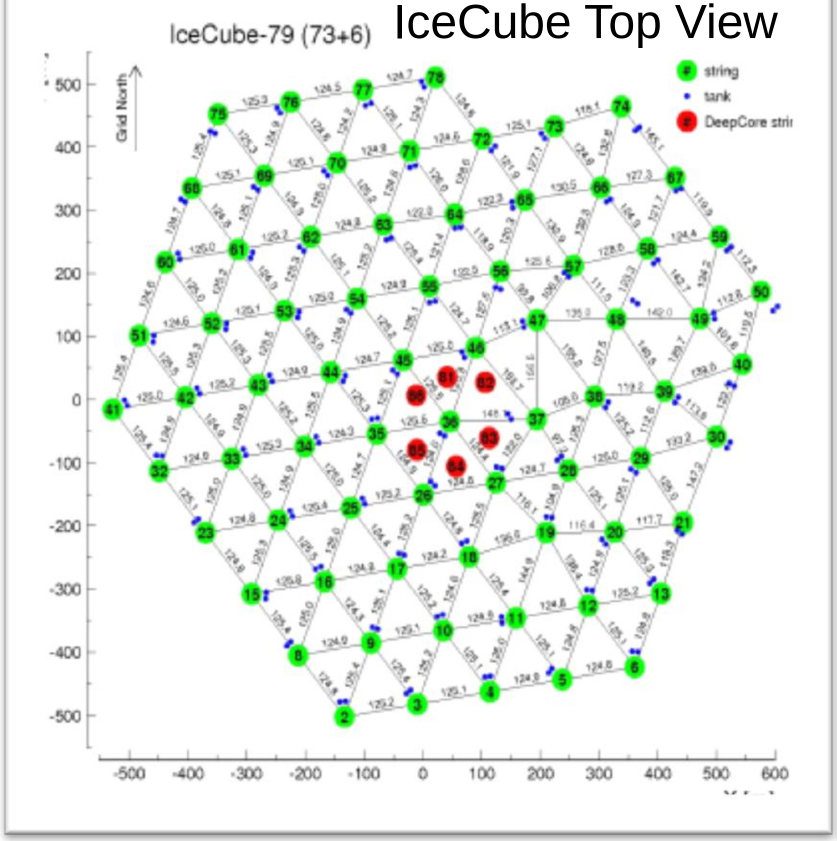
Data samples

Effective livetime of 670.1days

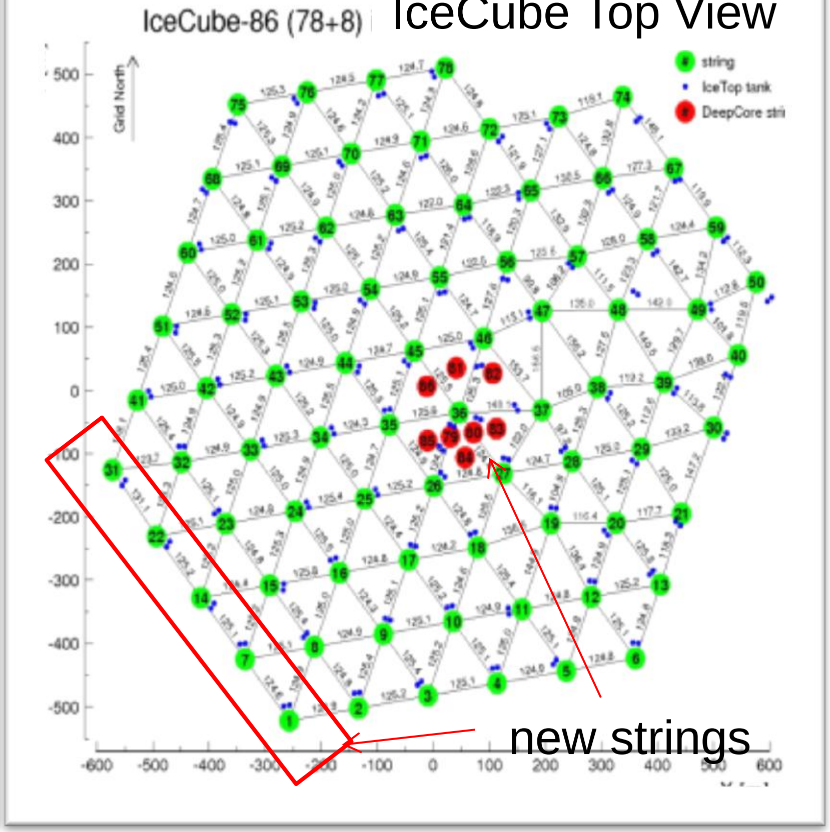
2010-2011 - 79 strings config. **May/31/2010-May/12/2011** Effective livetime 319.9days	2011-2012 – 86 strings config **May/13/2011-May14/2012** Effective livetime 350.1 days

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

IceCube Top View



IceCube Top View



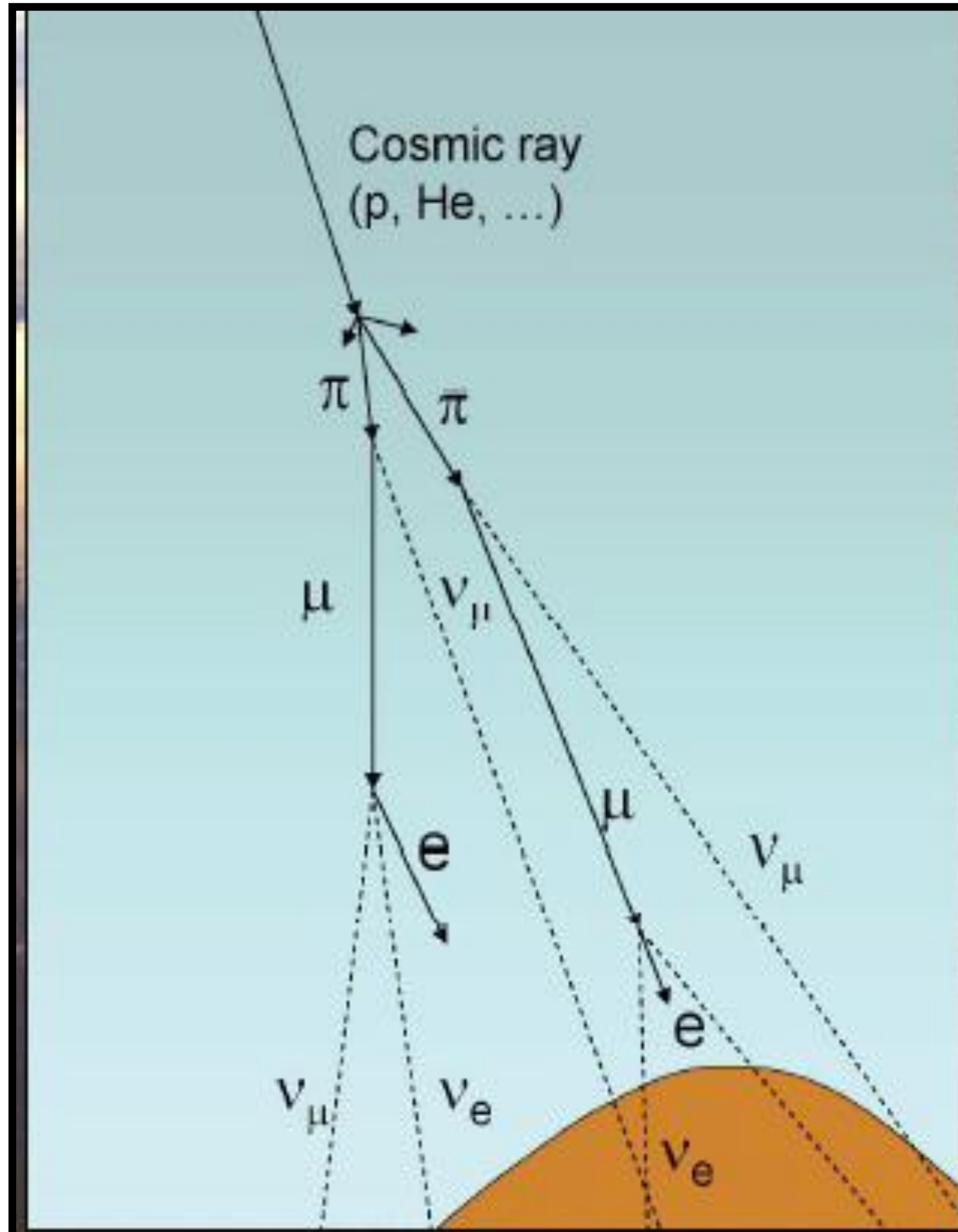
IceCube has been in a stable operation for more than 5 years

Background

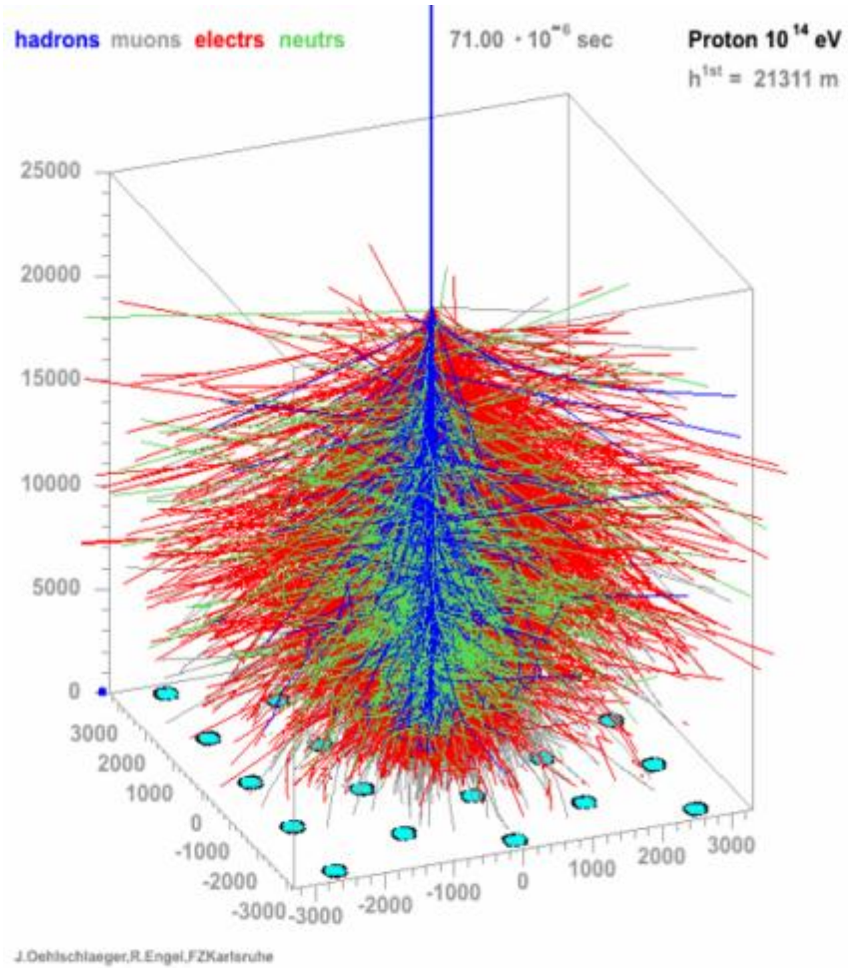
Atmospheric muons

and

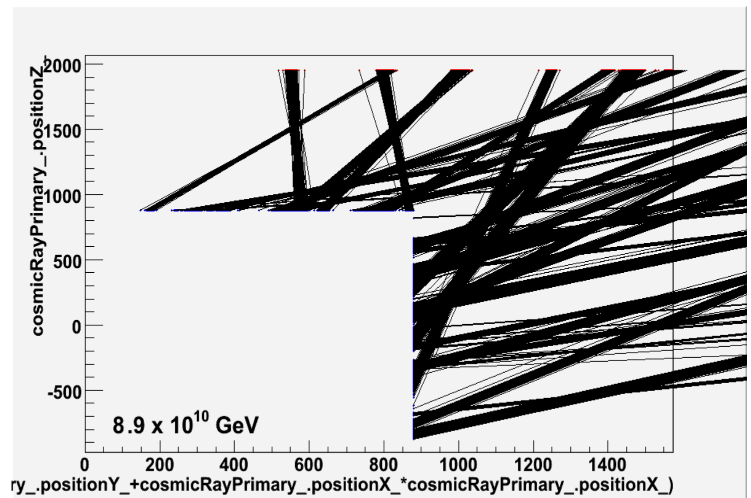
Atmospheric neutrinos



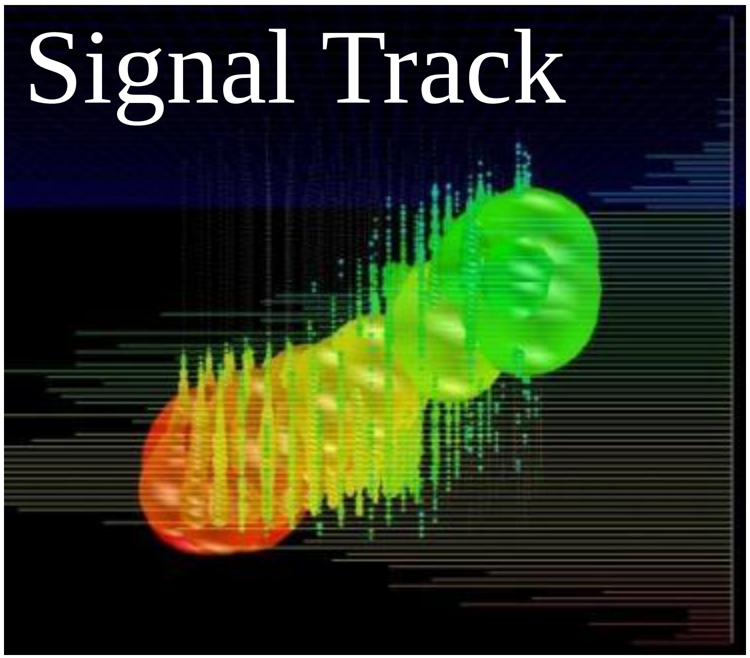
Major background is cosmic-ray muons (muon bundles) in rates

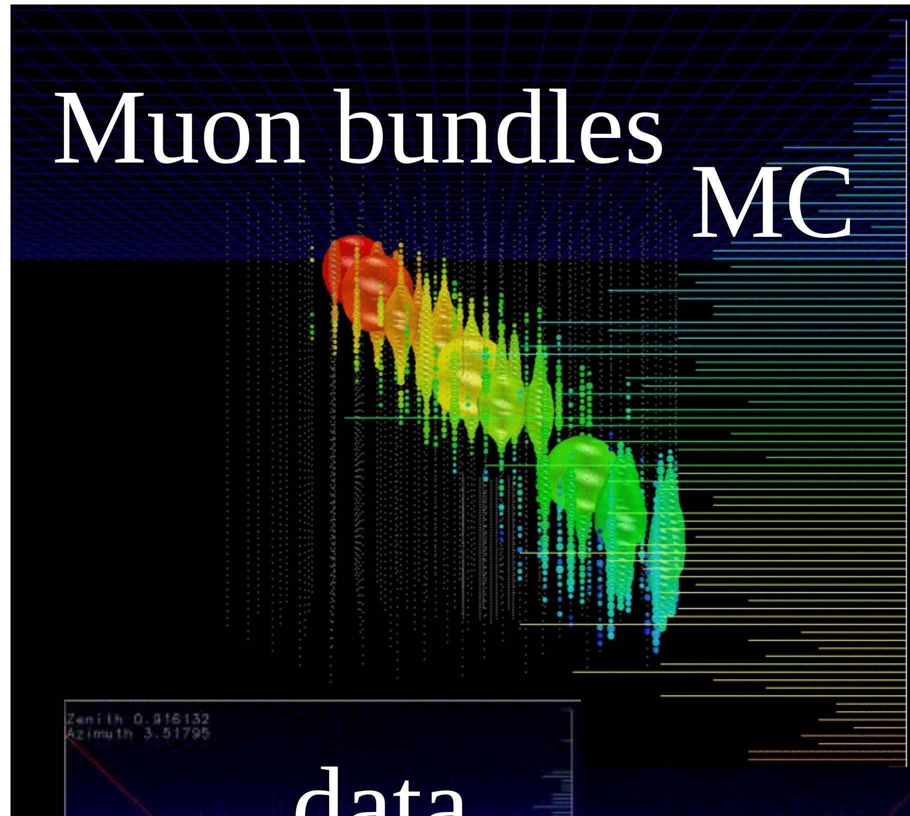


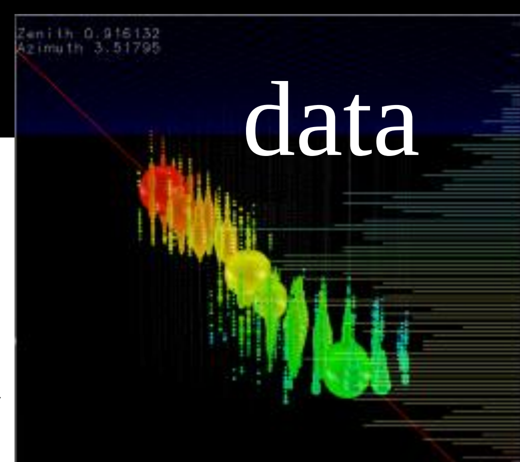
O(100-1000) muon multiplicity

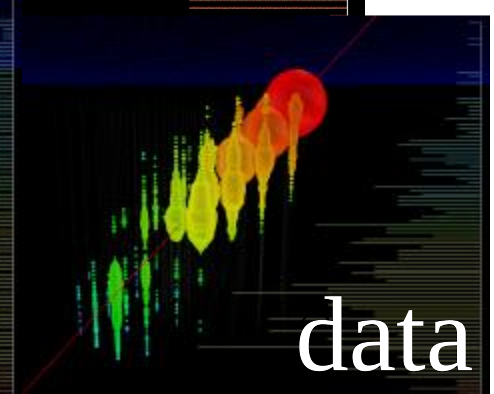


Signal and Background events



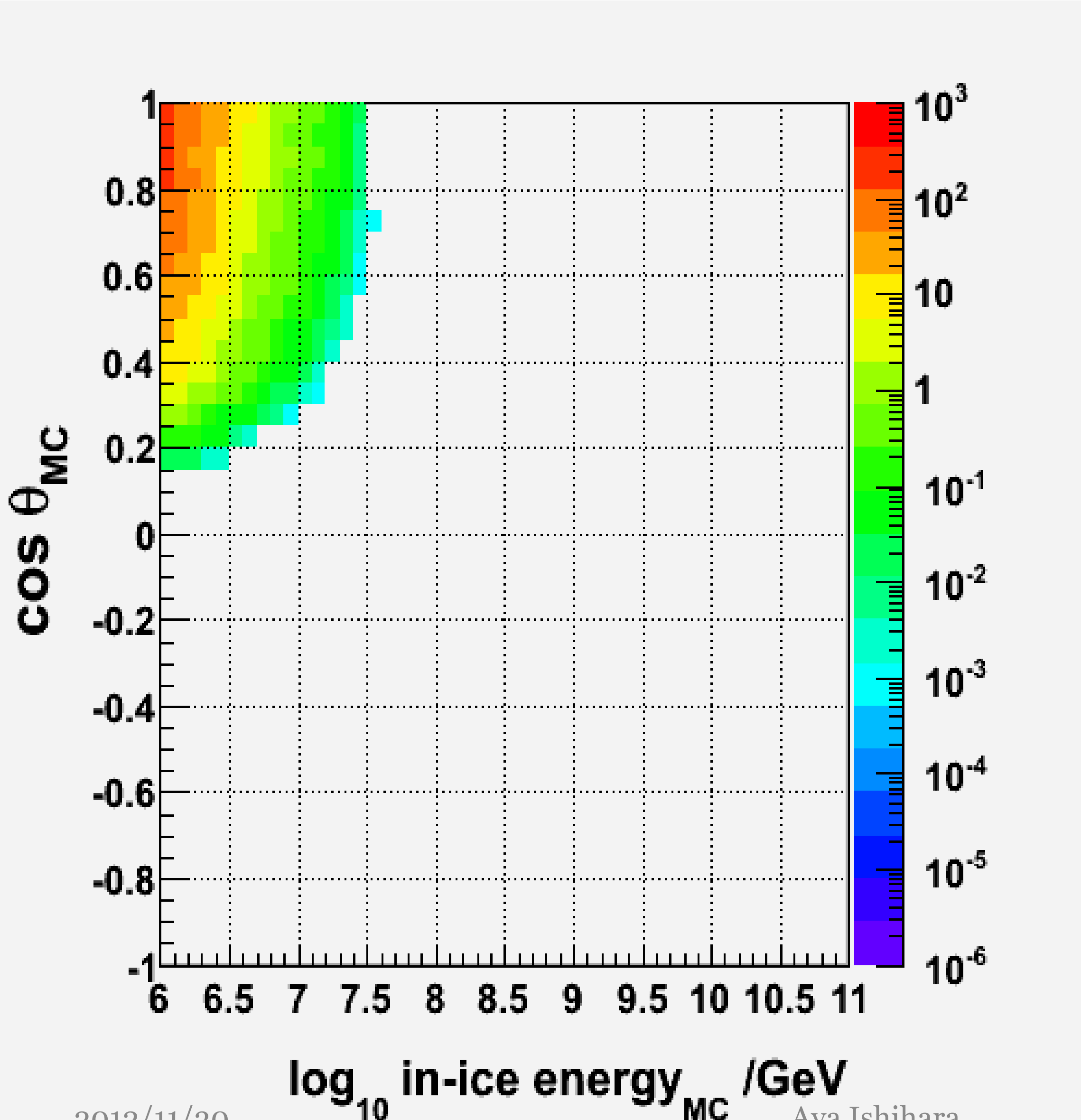






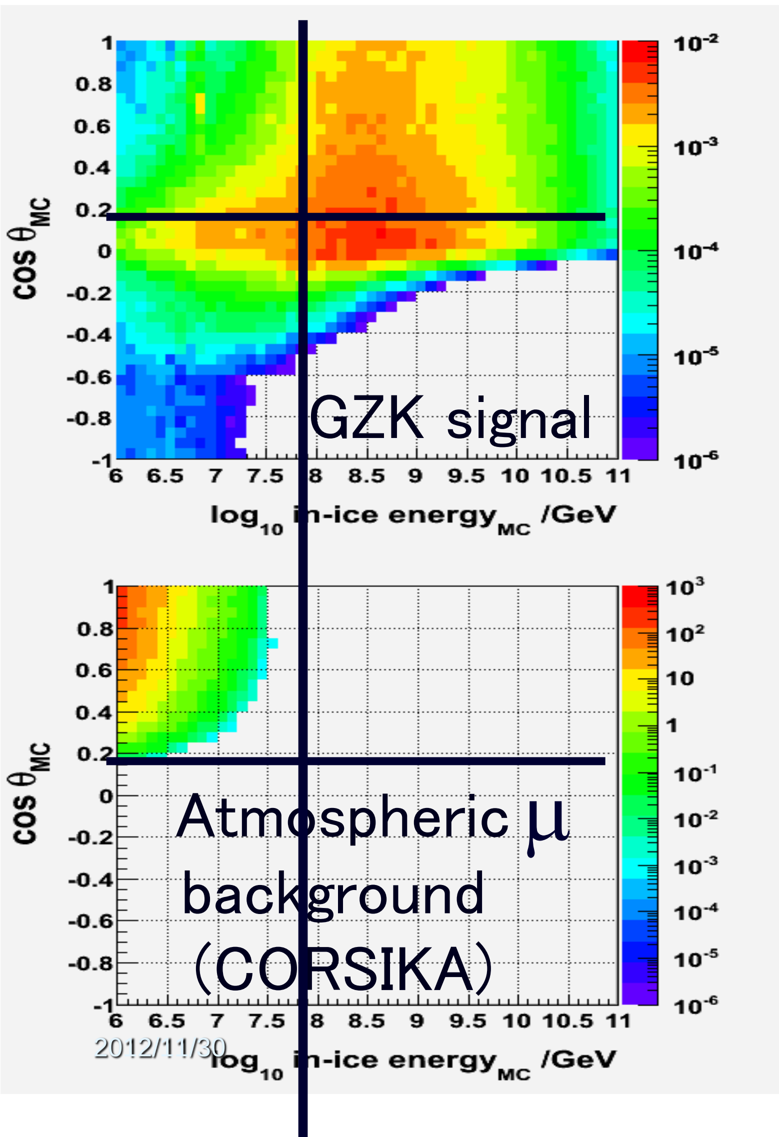
Burn sample
NPE~ $1x10^5$
μ bundle with ~ 3PeV

Atmospheric muon distribution



Relatively easy to cut them away

Basic strategies for search for GZK neutrinos



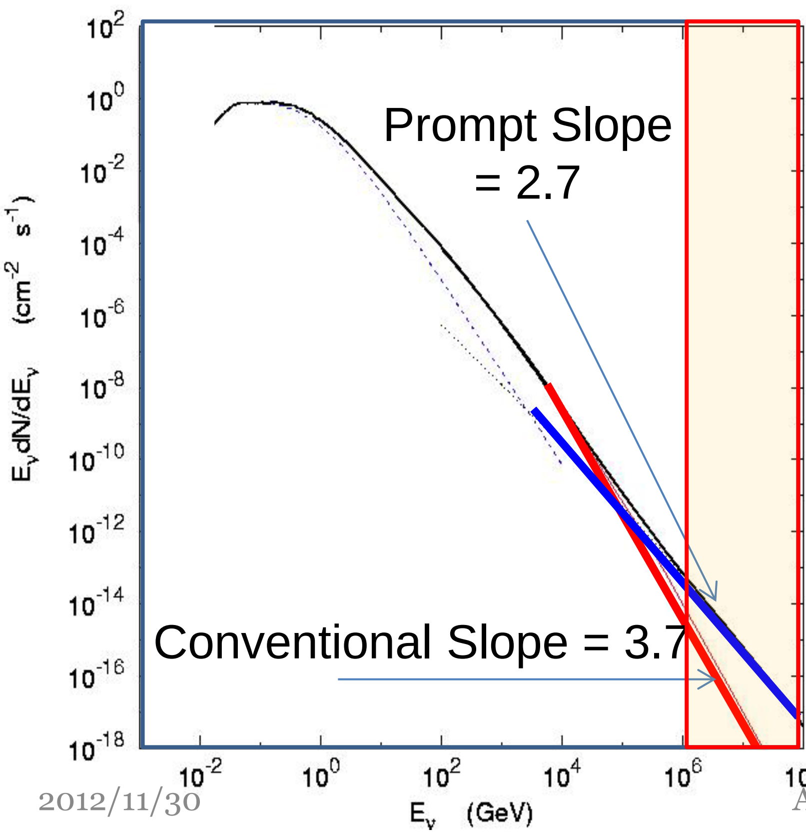
Background energy smaller than signal

Background is vertical downward-going while signal comes near horizon

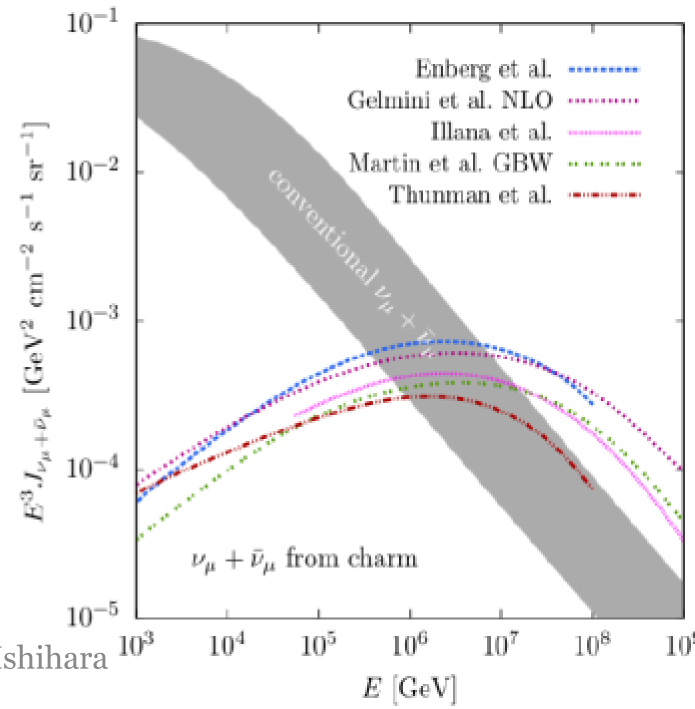
Atmospheric neutrinos in PeV

- 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**

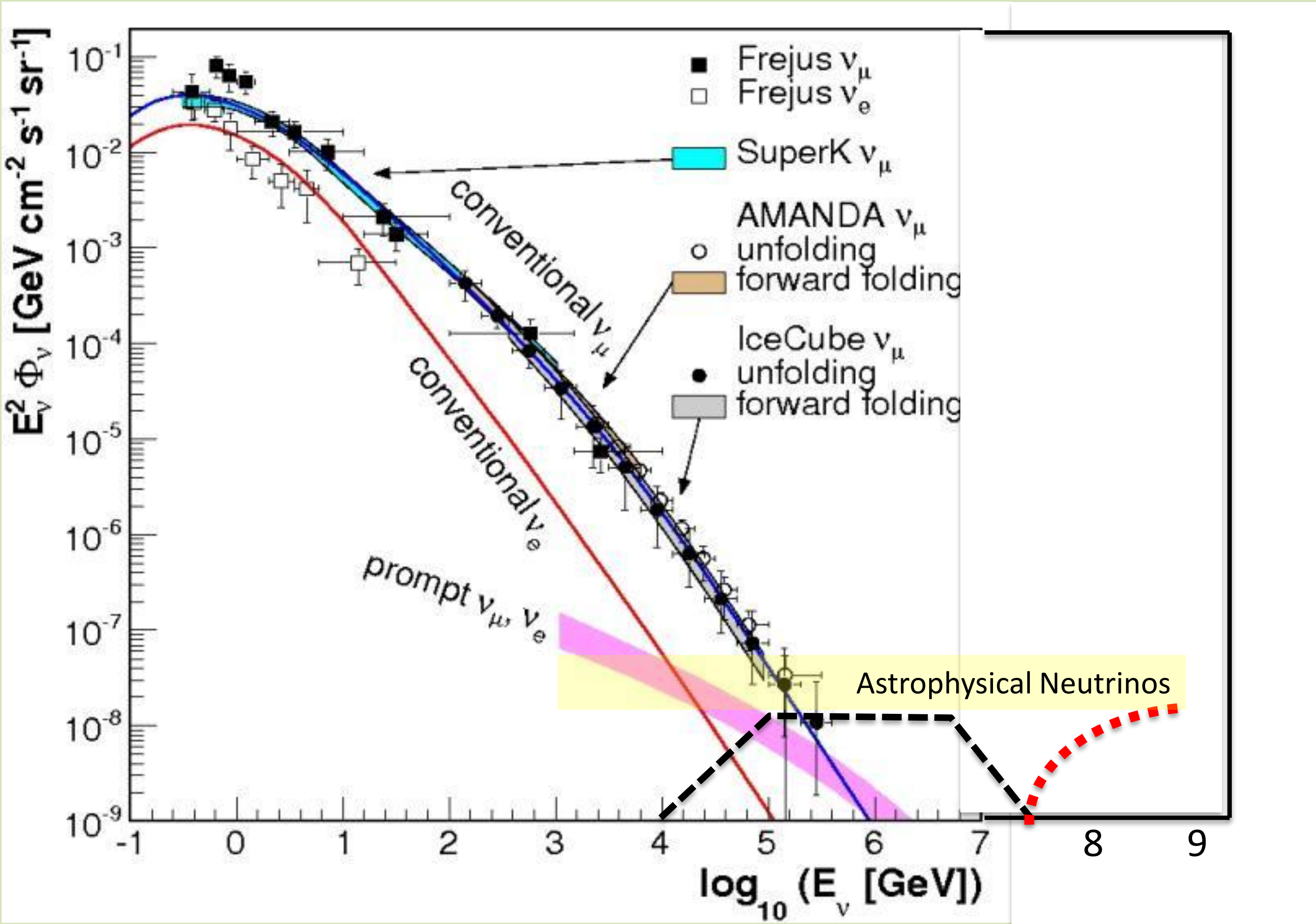


Physics of heavy flavor particle production

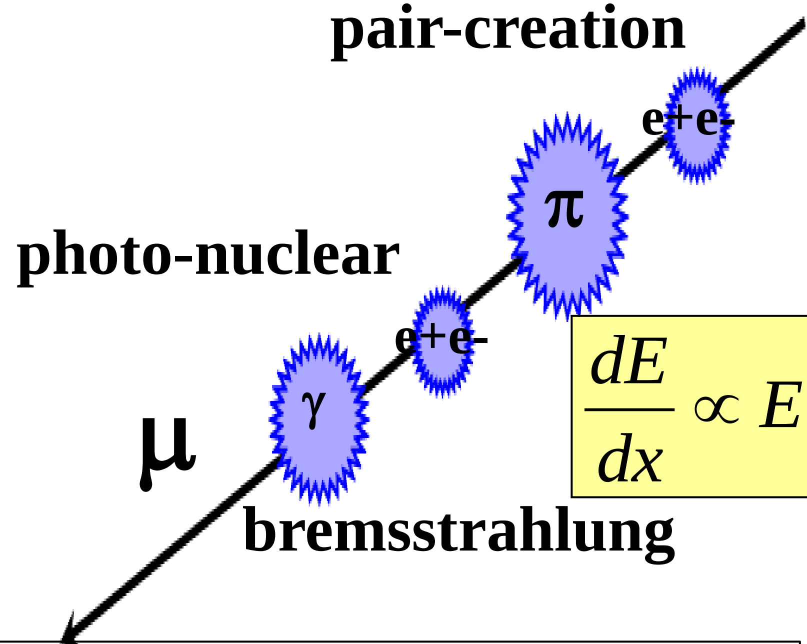


our default relatively high but not excluded

Atmospheric neutrinos in a wide energy range



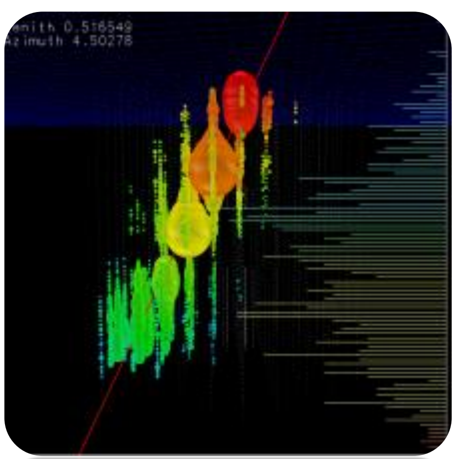
The Energy estimation

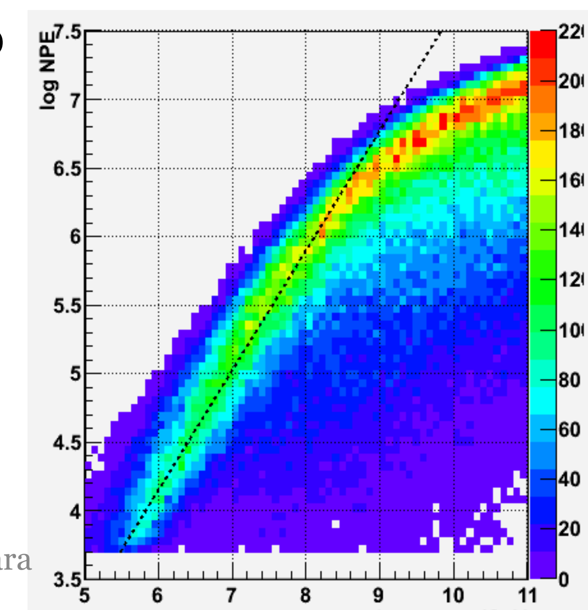


μ and τ tracks lose their energy by
radiative processes

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

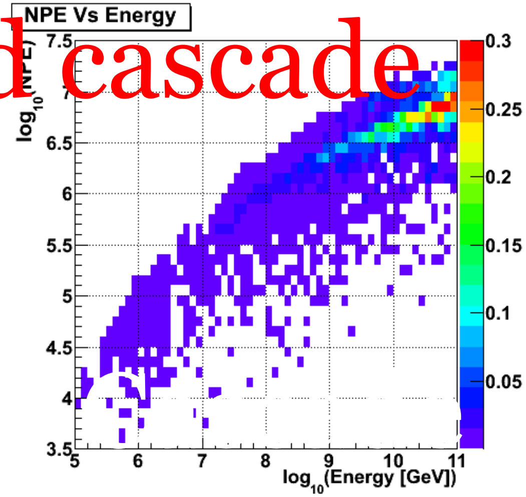
channel # > 300

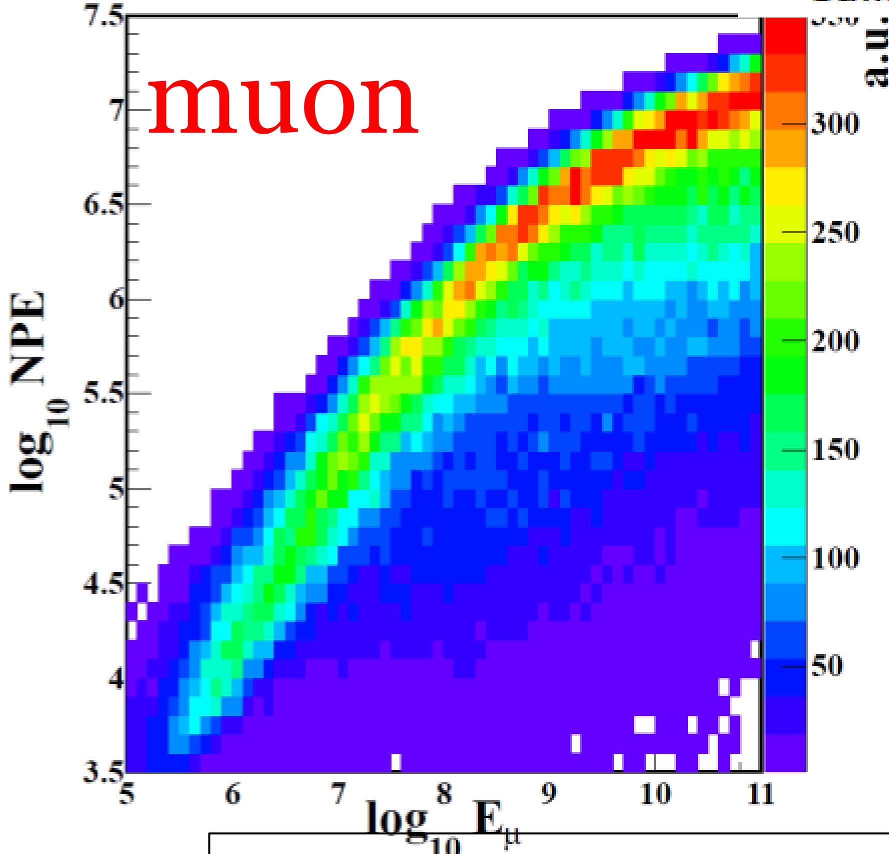


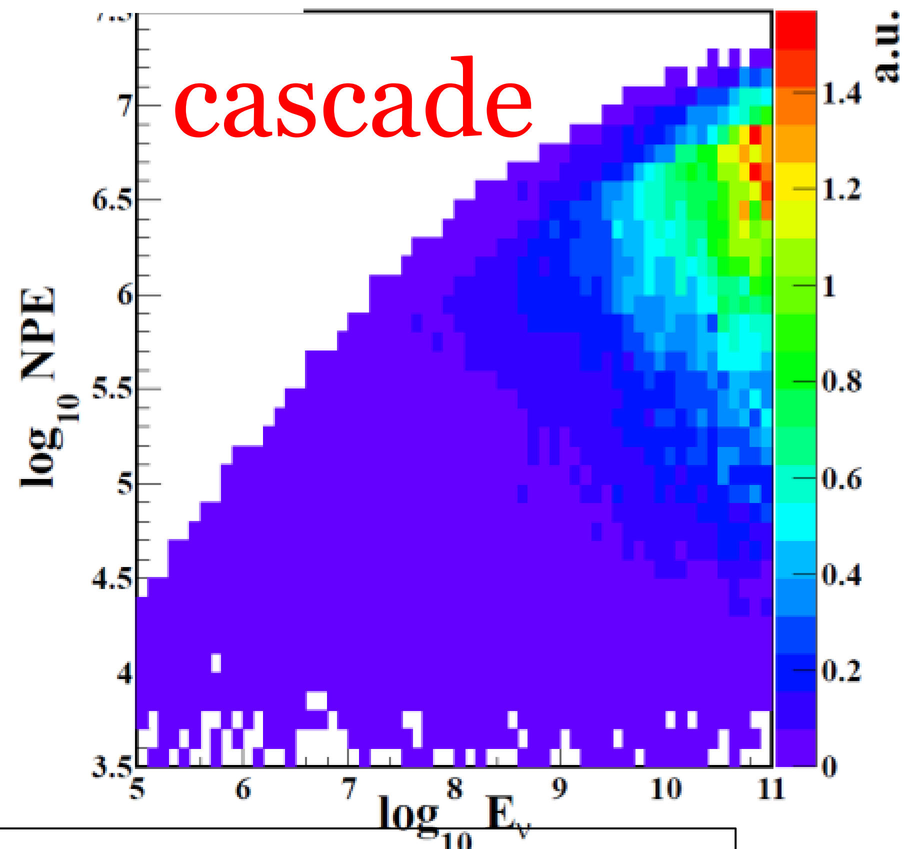


Energy NPE relations

Systematics
- Optical Properties of Ice
- Absolute Calibration



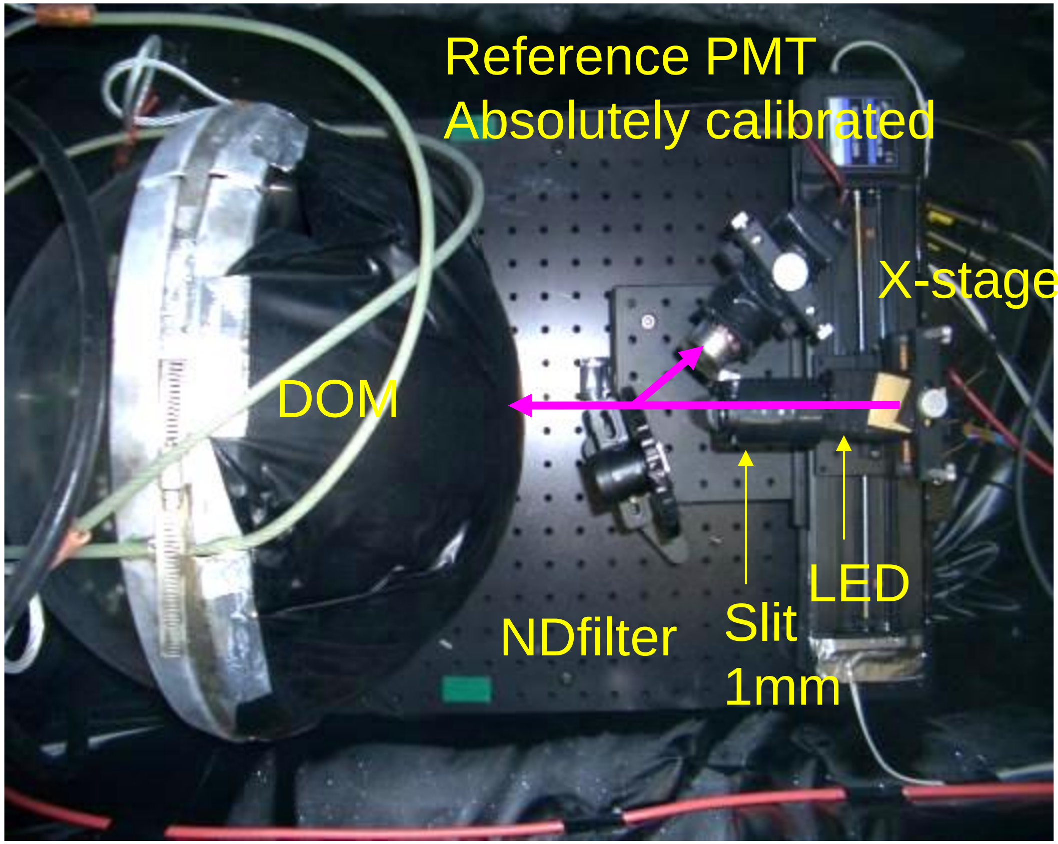


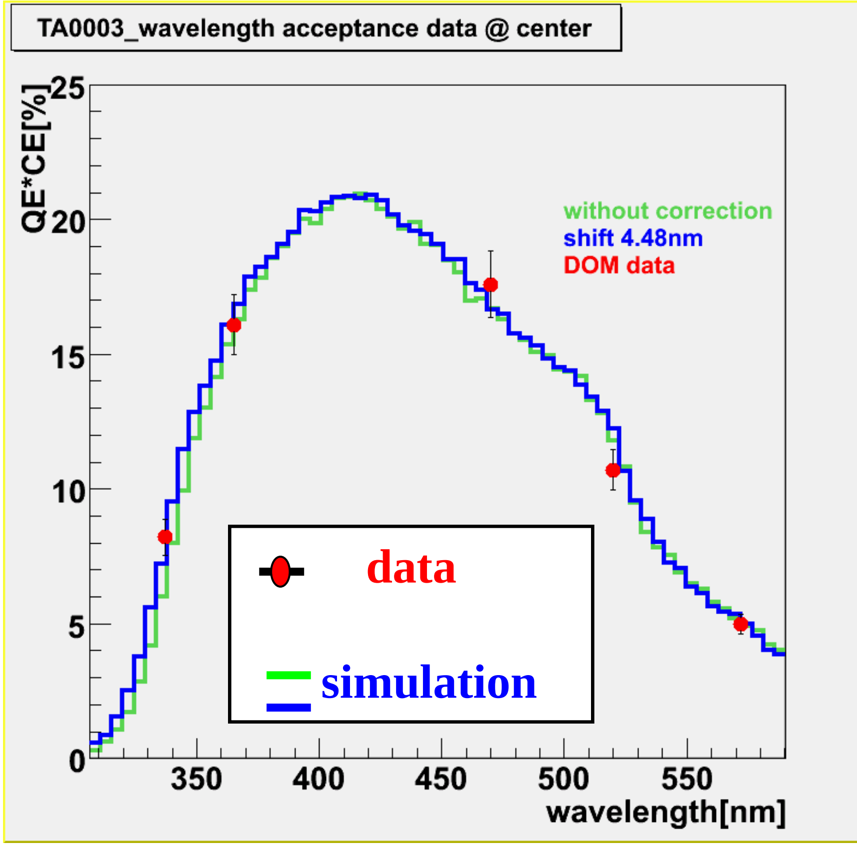


NPE and #of channels serve as a containment cut

Absolute Calibration of DOMs

QE×CE Absolute calibration





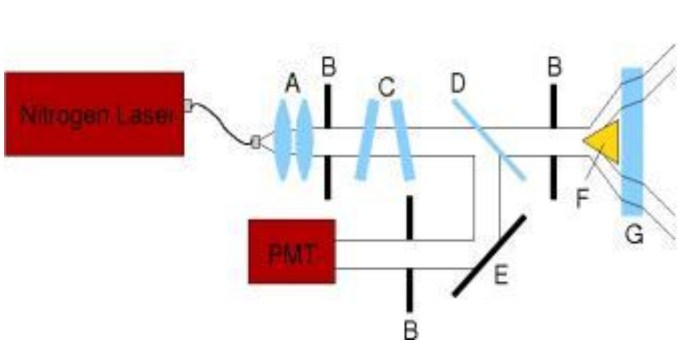
Reflectivity : 14.5%±0.73
Transmission : 50.7%±2.54

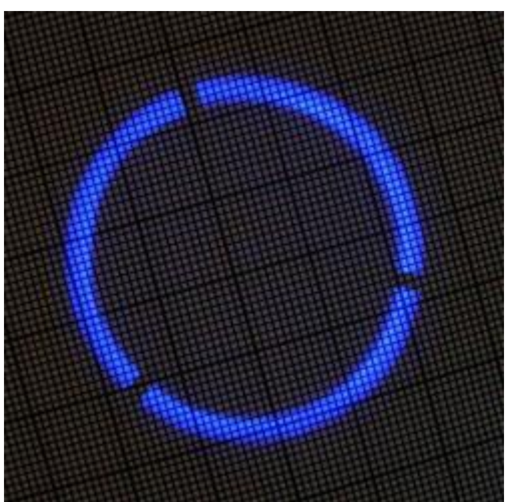
Nuclear Instruments and Methods A, 618 (2010)

In-*situ* Absolute Calibration

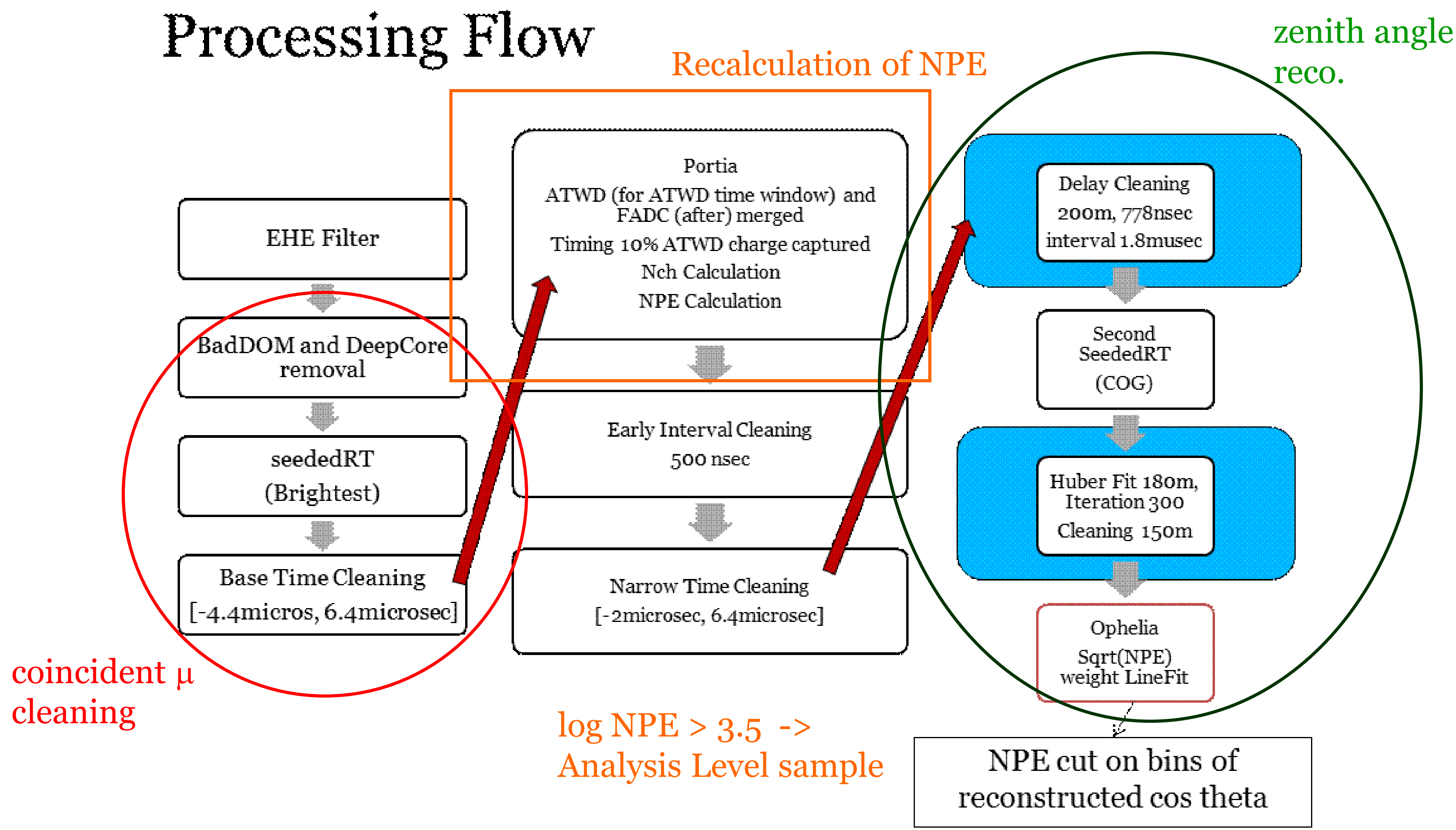
Calibrated light source: Standard Candle (w. UC Berkeley)

- **in-situ calibrated N_2 pulsed laser**
- **light wavelength 337 nm**
- **at 100% intensity generates 4×10^{12} photons per pulse emitted at 41^{o}**
- **output adjustable between 0.5% ~ 100%**





The analysis flow in 2011-2012

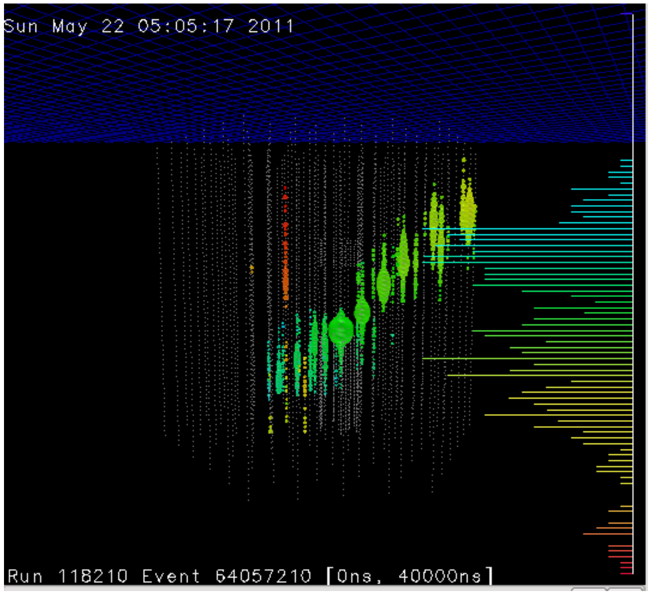


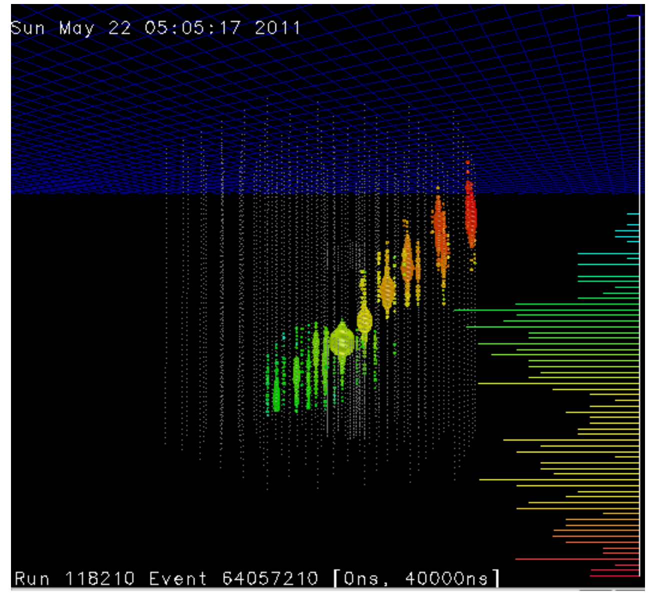
Coincident μ track cleaning

The "burn-sample" data

Example #1

Before

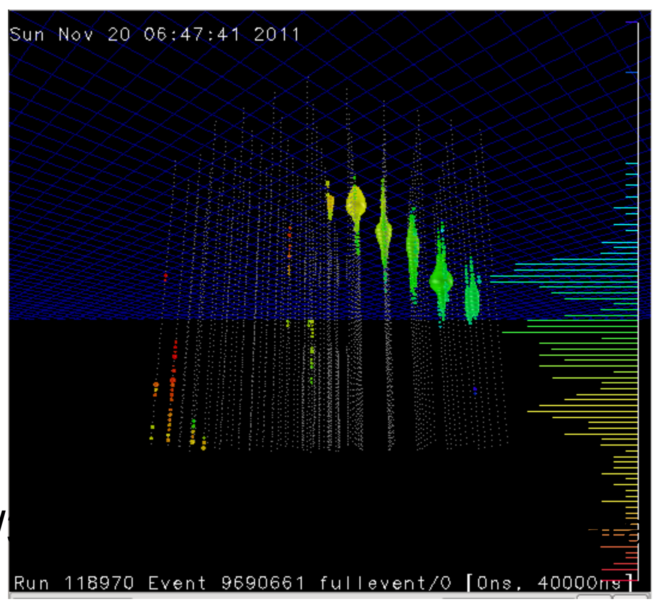


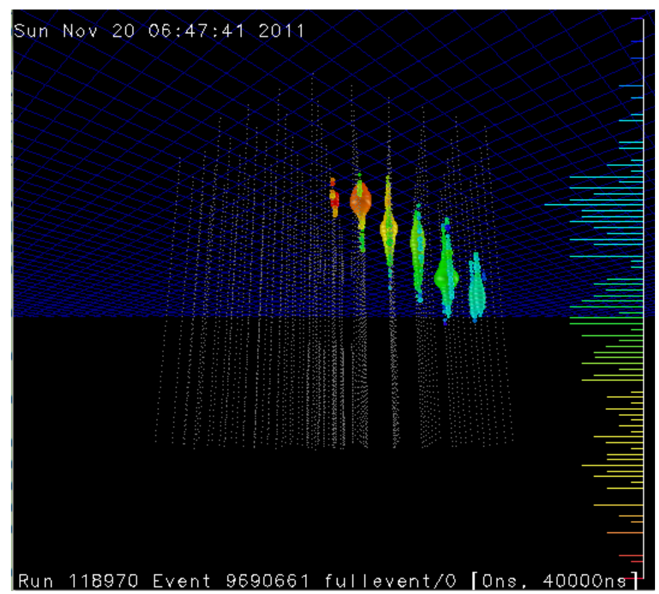


After

Example #2

Before

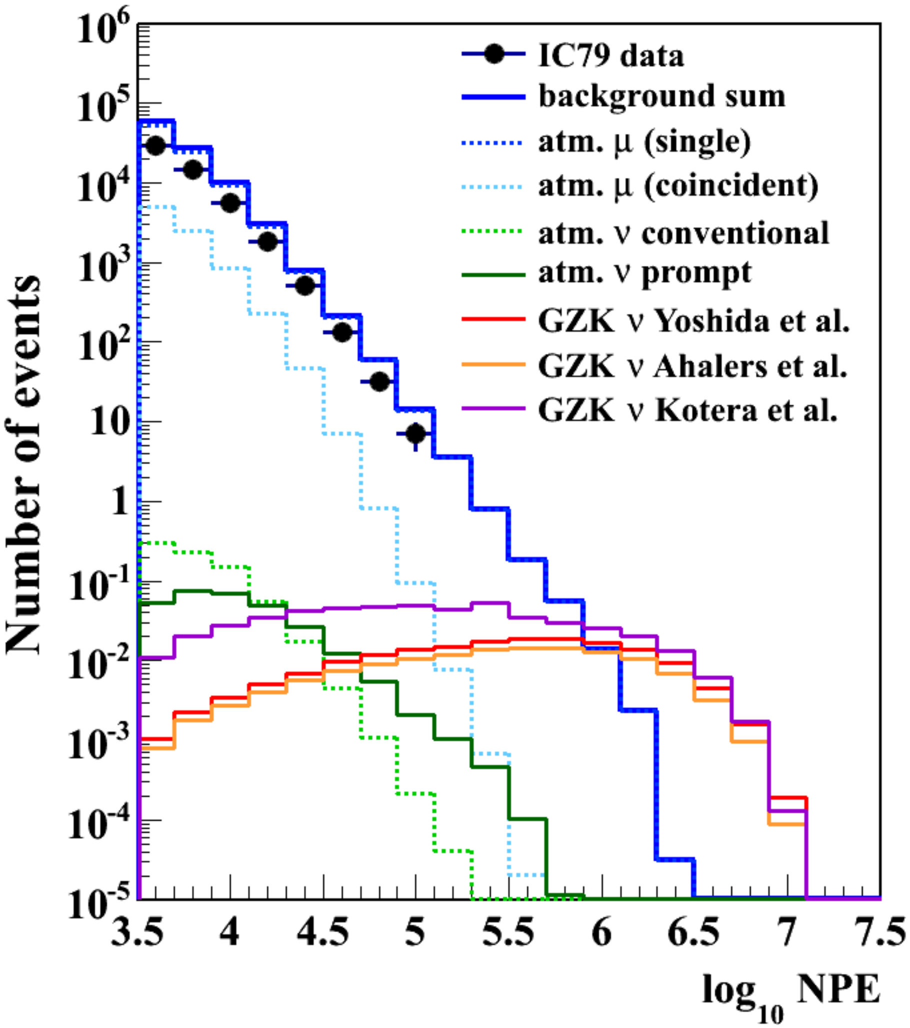


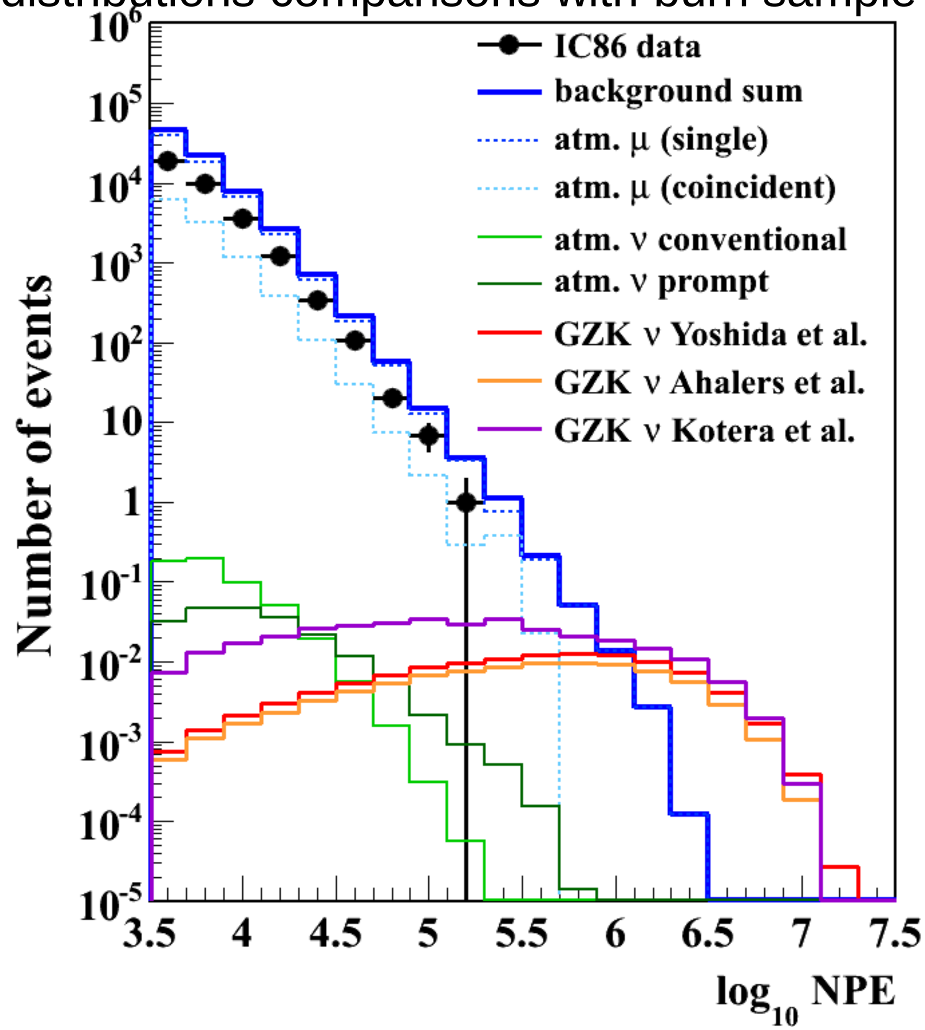


After

Analysis Level NPE Distributions

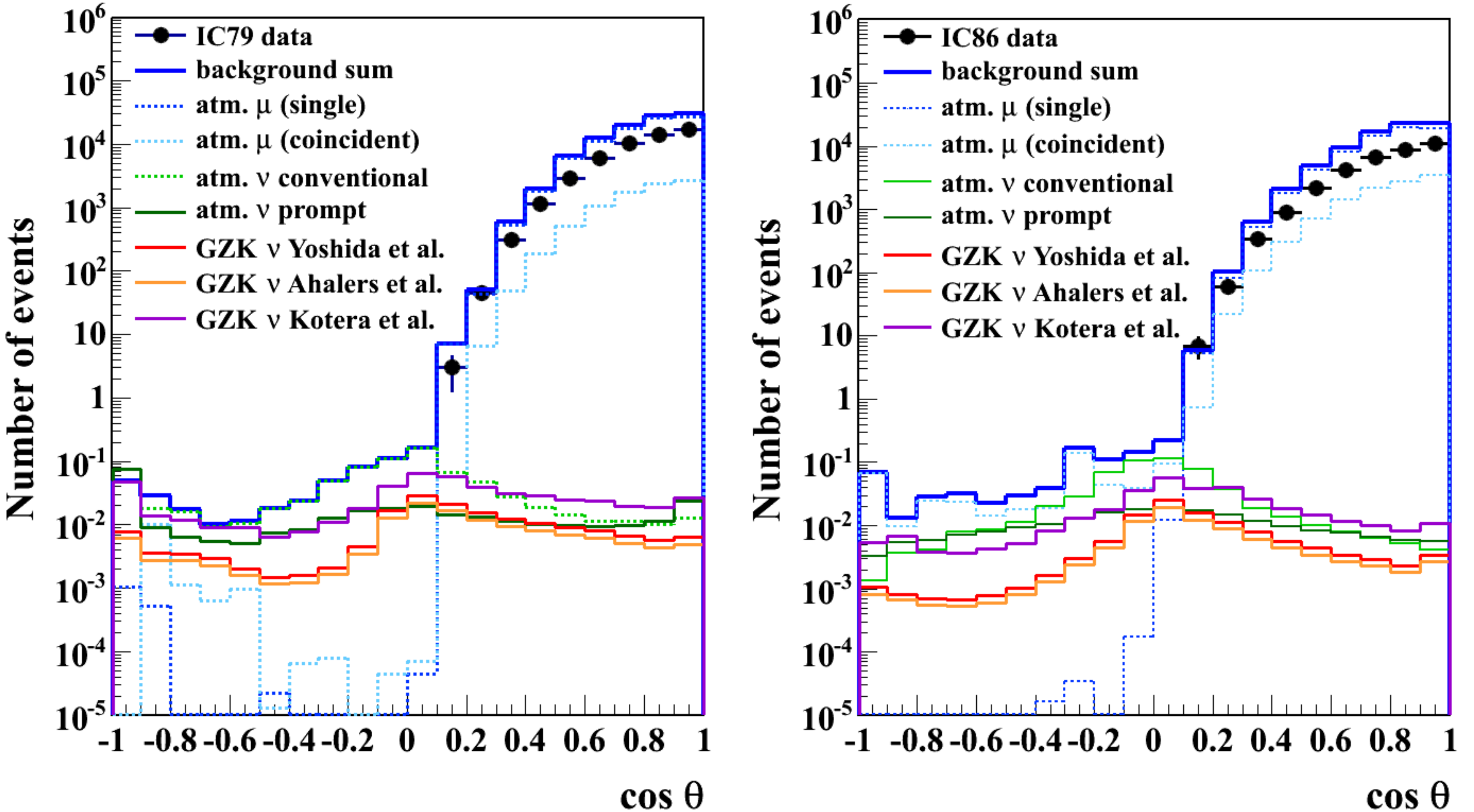
NPE distributions comparisons with burn sample



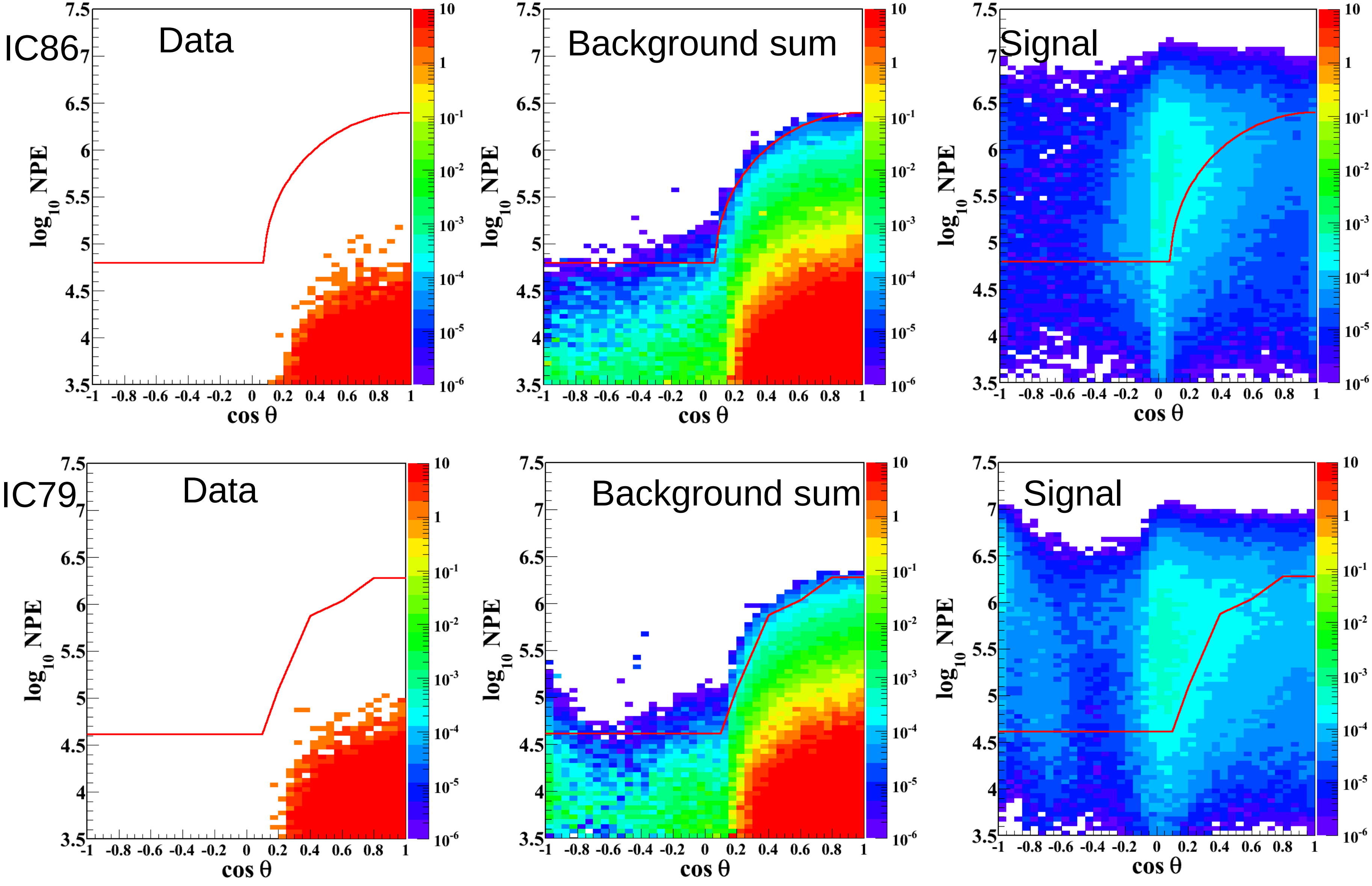


Analysis Level ZA Distributions

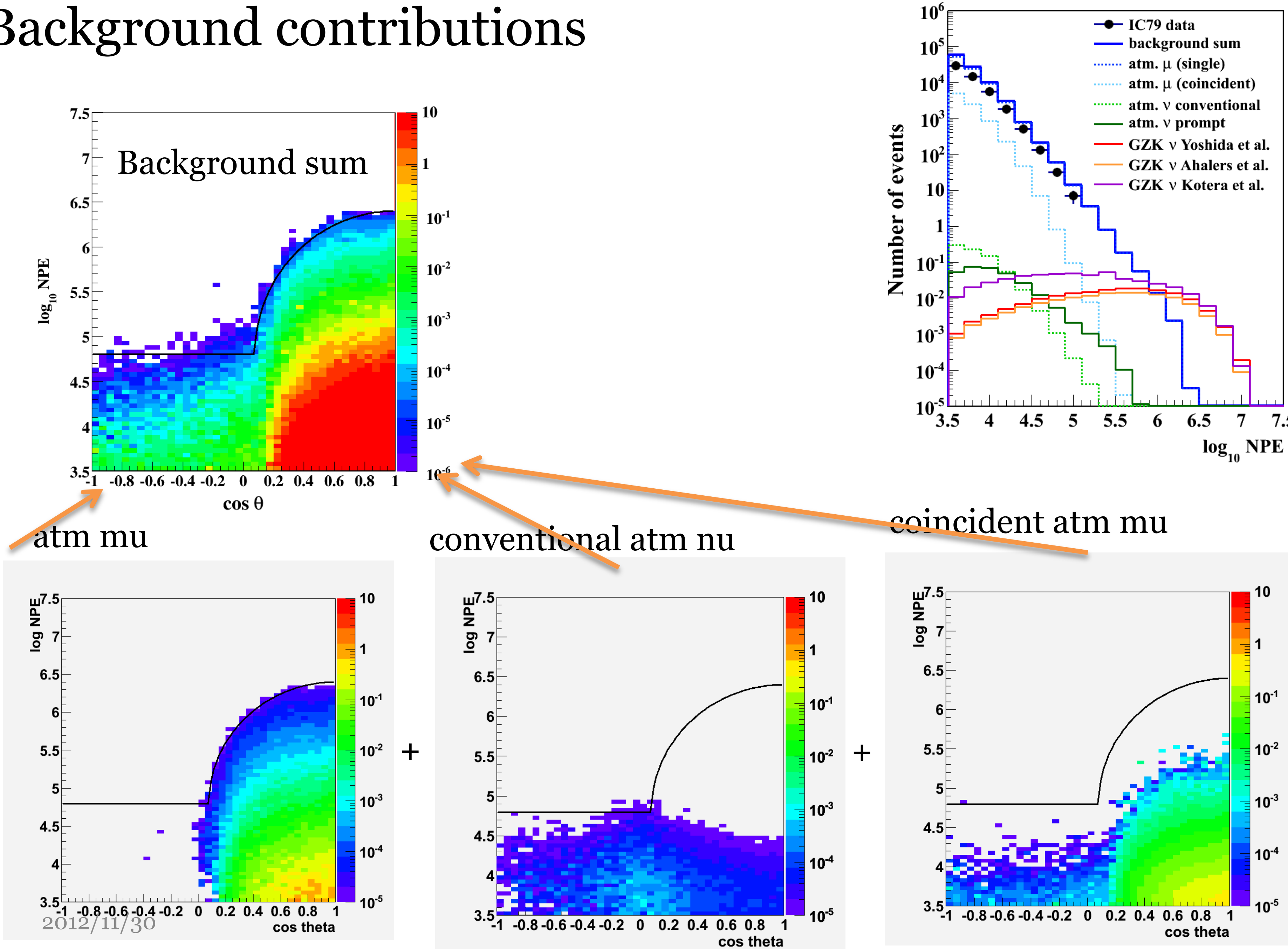
cos zenith angle distributions comparisons with burn sample



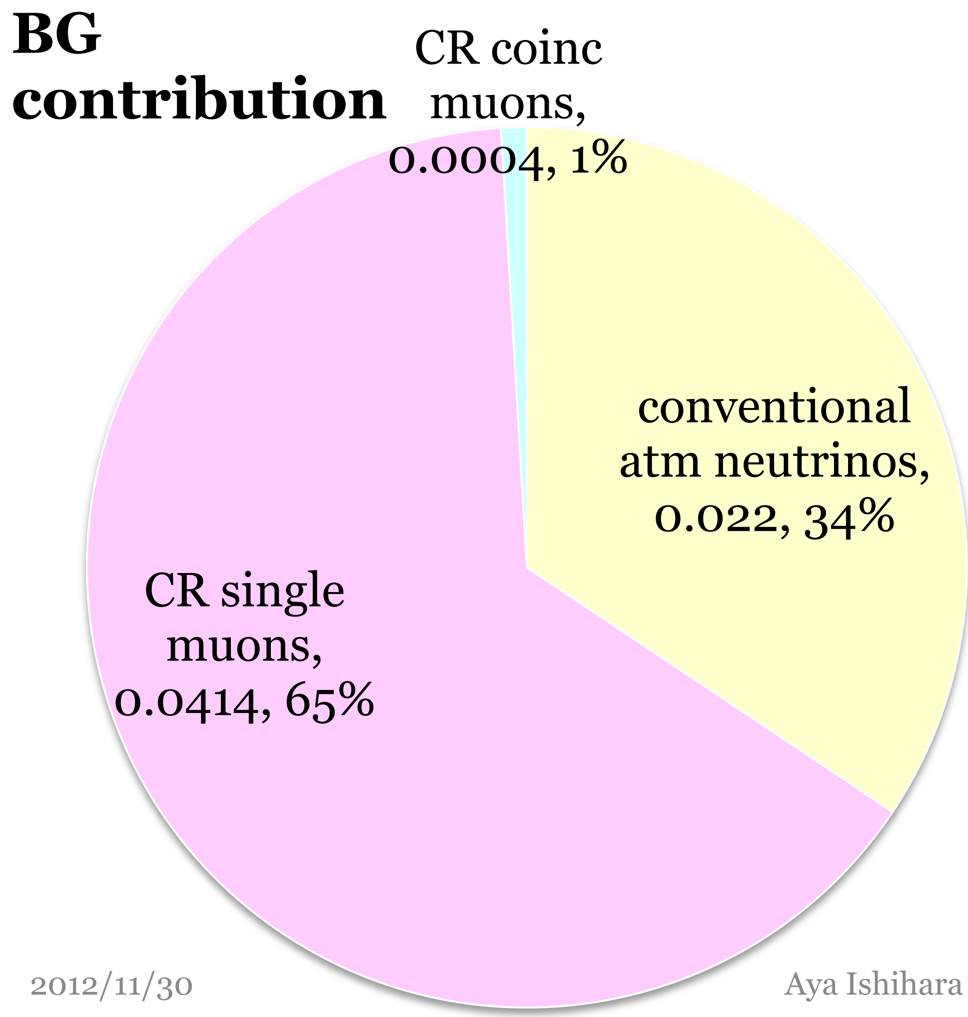
Analysis Level NPE vs ZA



Background contributions

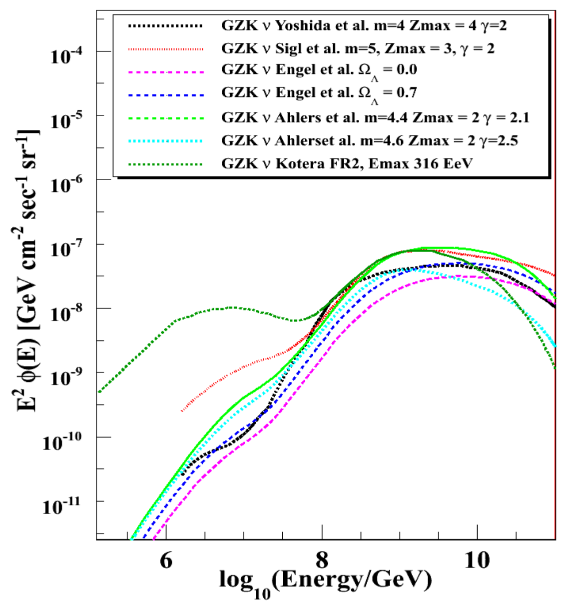


Background event rates



	Total background (IC79+ IC86)
Atmospheric μ	0.0414
Atmospheric conventional ν	0.0220
Coincidence μ	0.0004
Total	**0.064**
prompt ν	0.13 3+/- 0.0007
Total with prompt	**0.1972**

Signal Event Rates

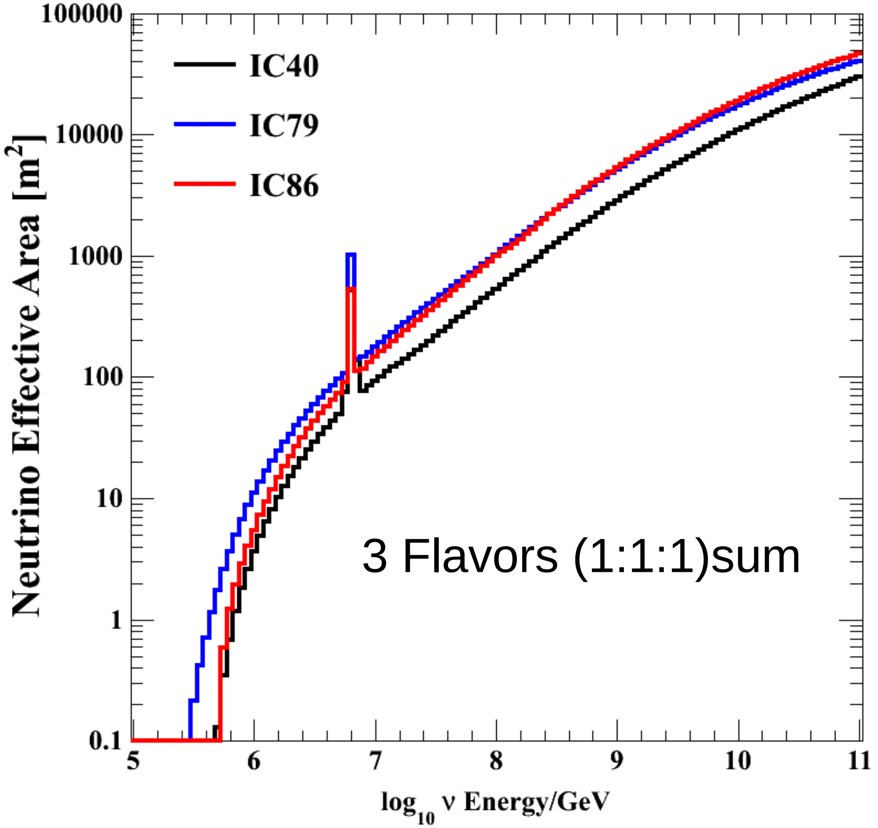
	IceCube 2008-2009 Phys. Rev D83 092003 (2011) 333days	**IceCube 2010-2012 per 615.9days**	
		All contributions (B)	**Contribution > 100 PeV**
GZK (Yoshida m=4)*	**0.57**	**2.0**	**1.9**
GZK (Ahlers max) **	**0.89**	**3.0**	**2.9**
GZK (Ahlers best fit) **	**0.43**	**1.5**	**1.4**
GZK (Kotera, dip FRII) ***		**4.2**	**2.7**
GZK (Kotera, dip SFR1)***		**0.9**	**0.6**

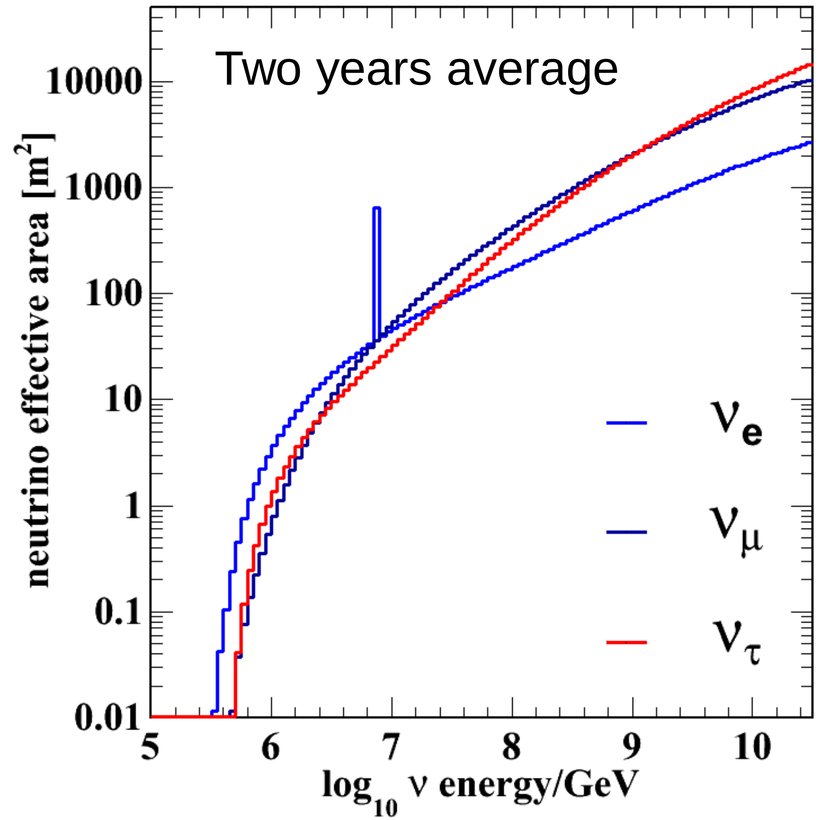
Systematic Errors on Signal and BG

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)

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)

Effective Area

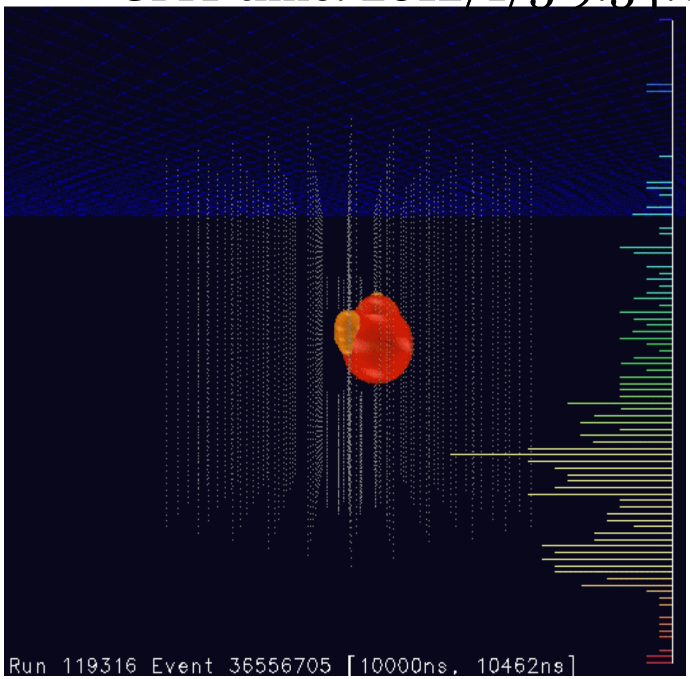




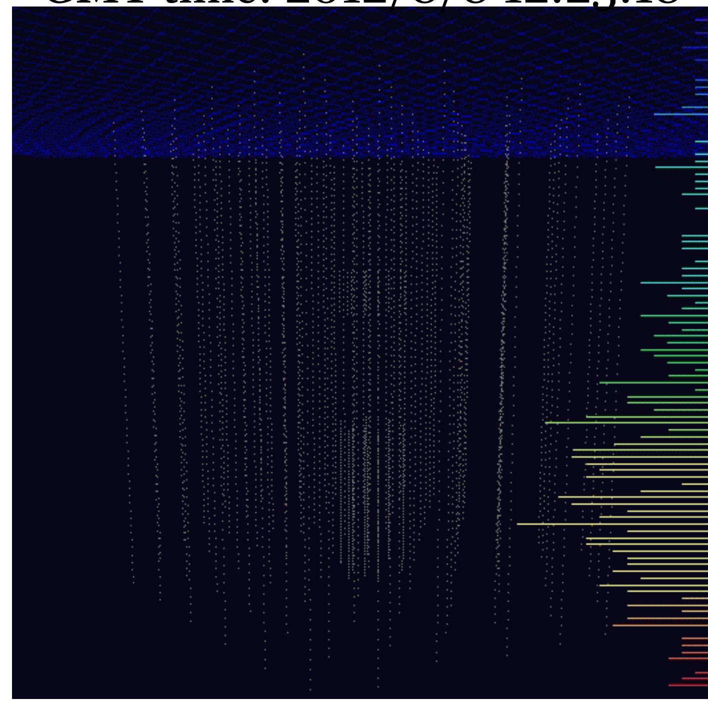
- A factor of 2 increase from IC40
- NPE threshold difference changes the response below PeV
- Larger for cascades than for track below 10PeV

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



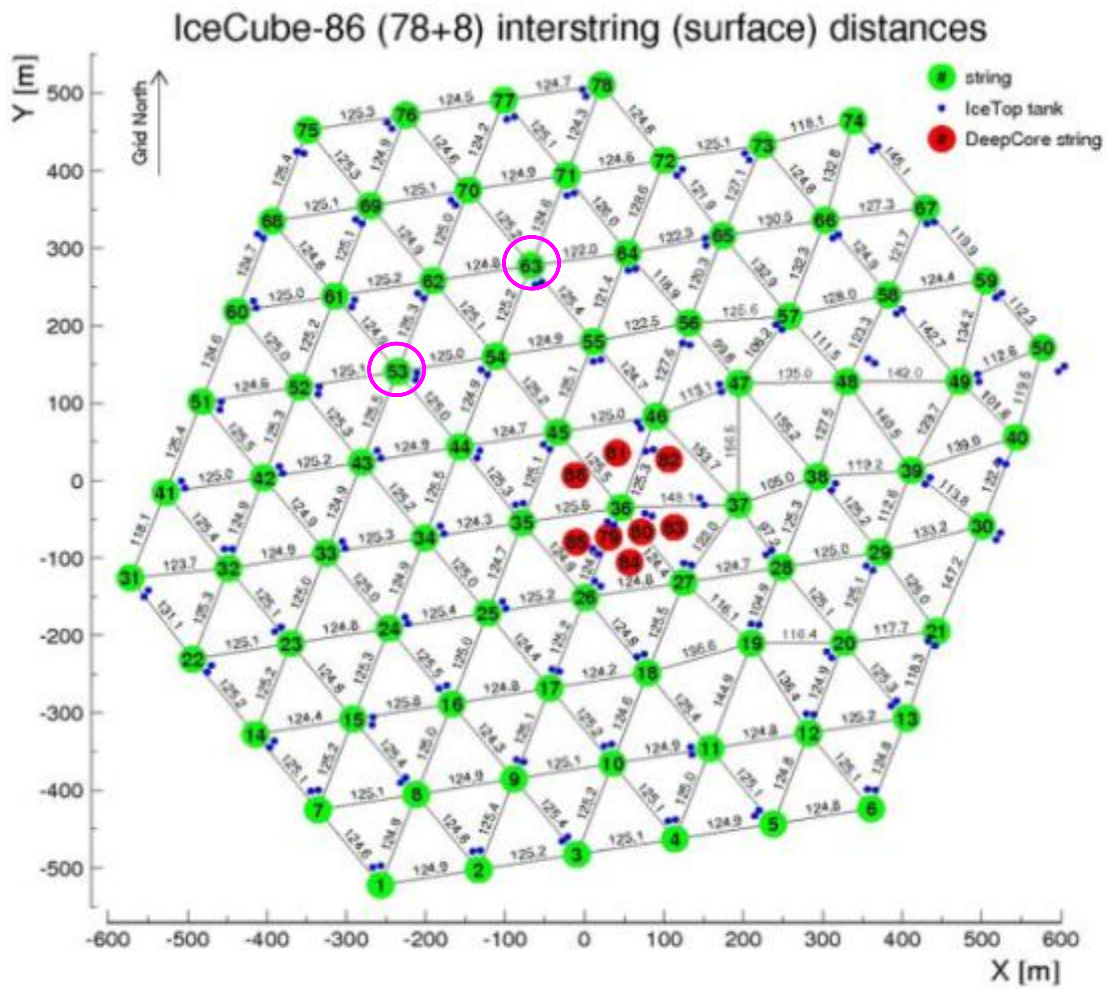
2 events / 615.9 days background (atm. μ + conventional atm. ν) expectation 0.060 events

Preliminary

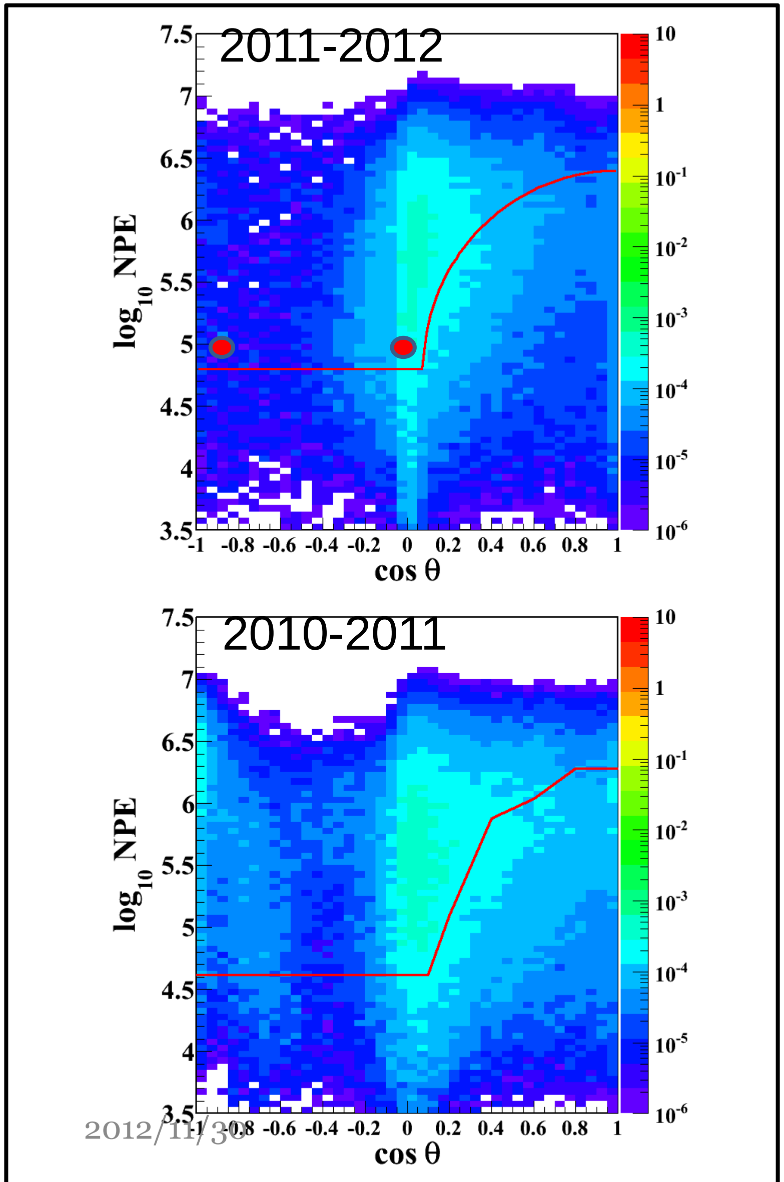
p-value 1.8×10^{-3} (2.9σ excess beyond conventional atmospheric neutrinos)
(2.2σ excess beyond bg with default prompt atmospheric neutrinos)

The highest Charged String Positions

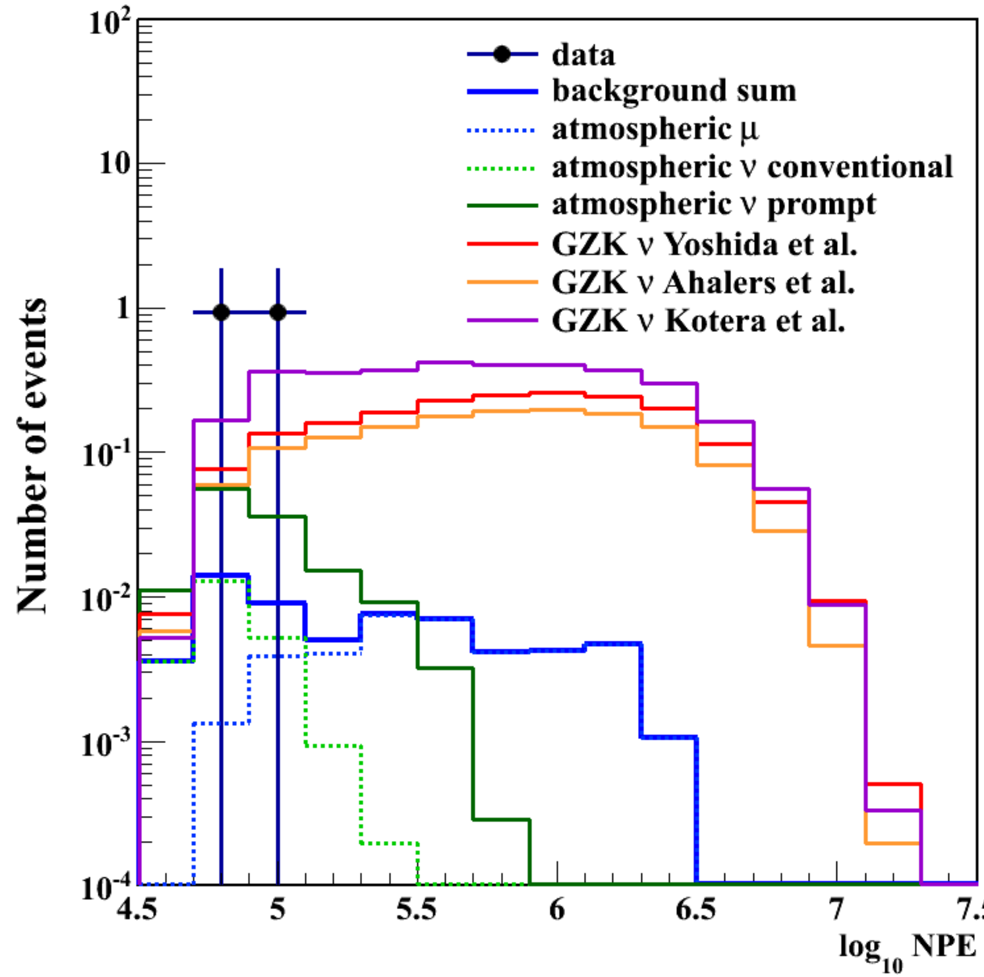
Well contained events



Two events observed in log NPE ~ 4.8-5.0



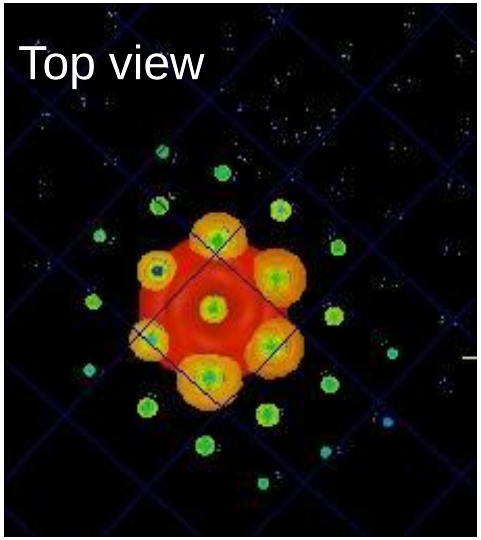
Final results are combined



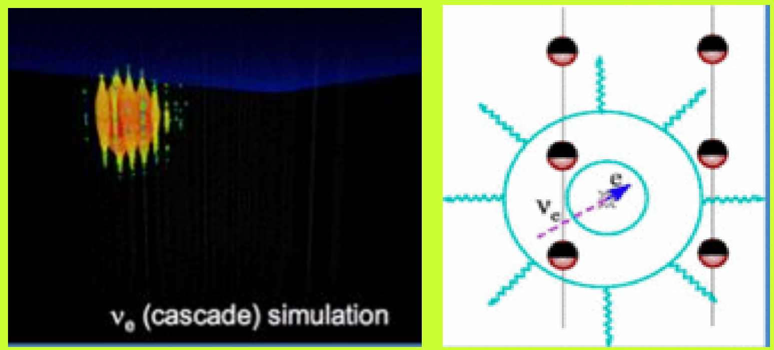
Reconstruction of the two cascade events

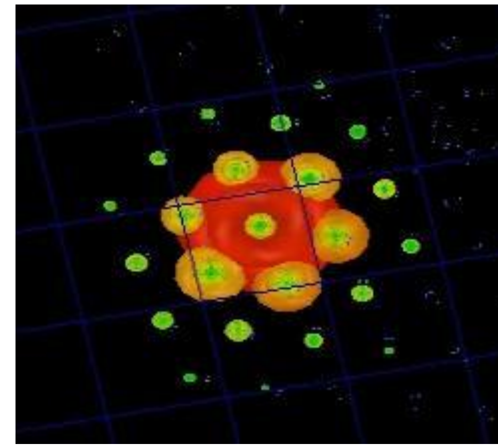
Direction and Energy

Consistent with cascade events in detector



CC/NC interactions in the detector

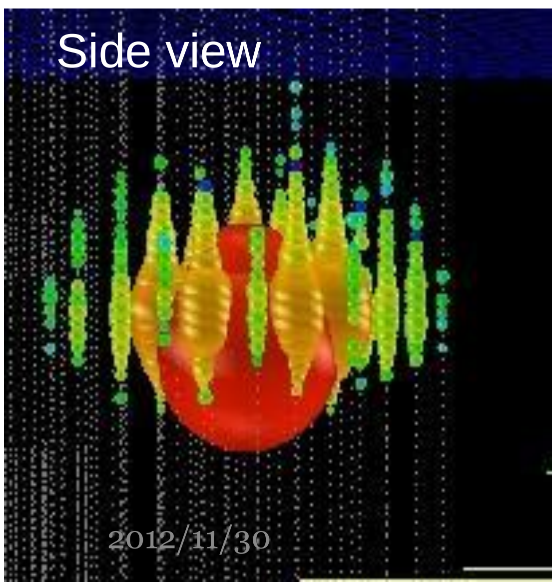


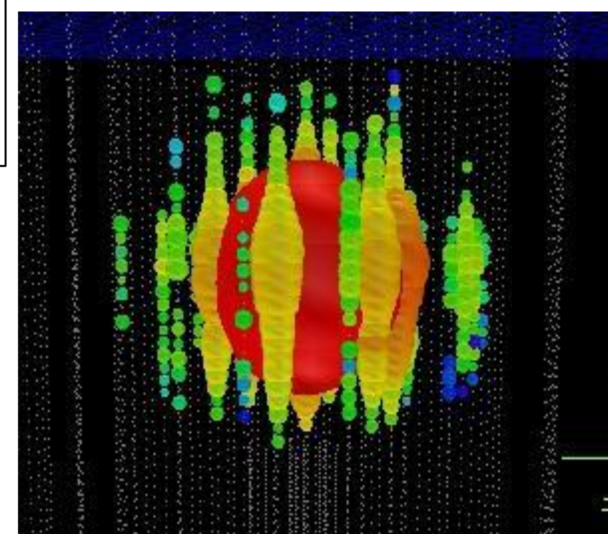


No indication

- that they are instrumental artifacts
- that they are cosmic-ray muon induced

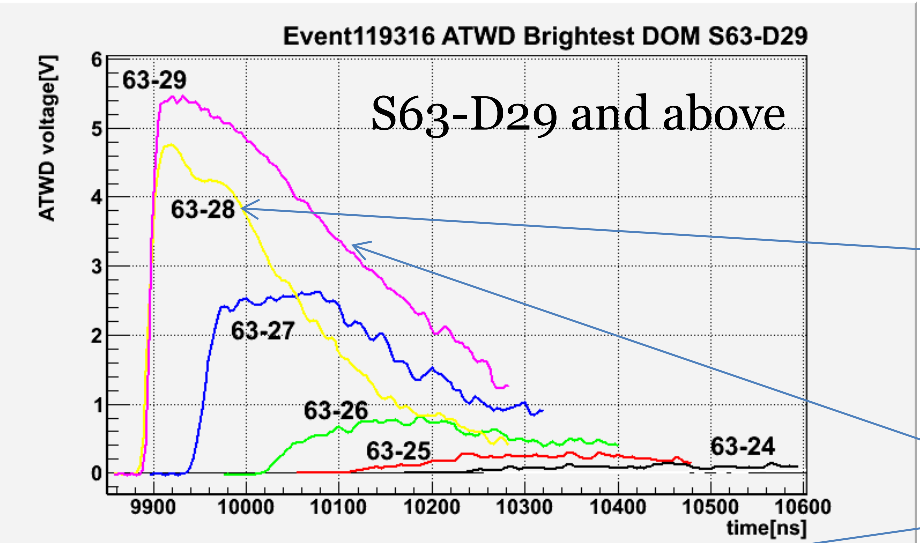
we can use **dedicated cascade hypothesis** to the reconstructions of these special events

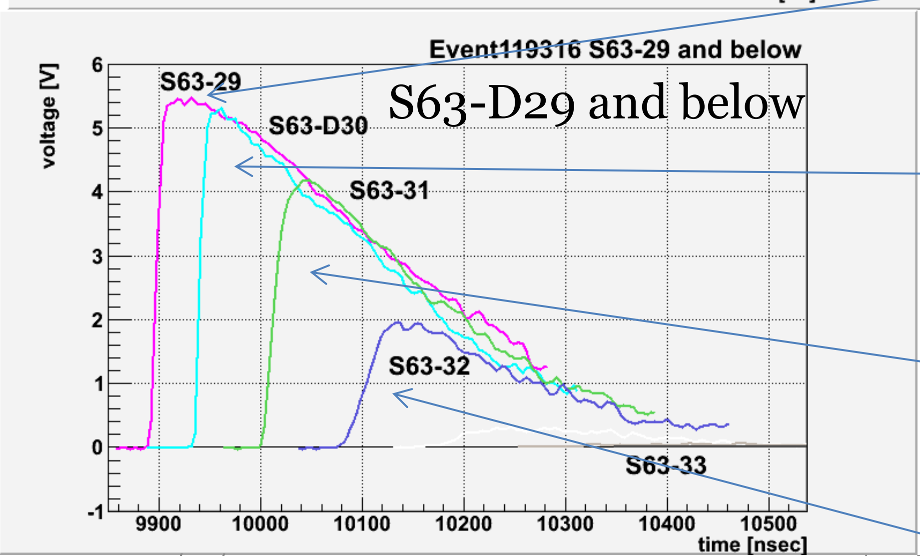


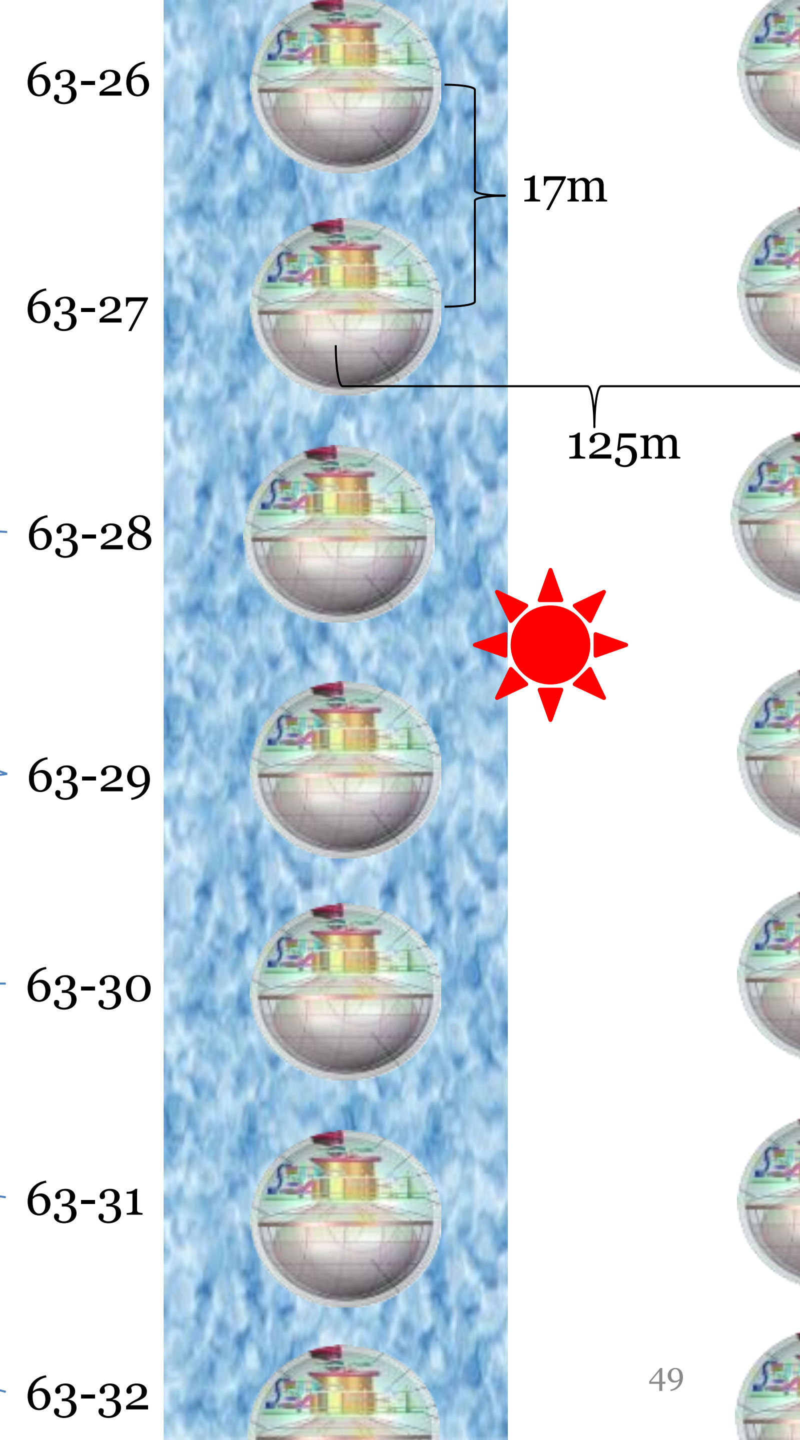


EHE-Jan-2012 **Recorded pulses**

Calibrated ATWD waveform above and below the highest charged DOM (S63-29)

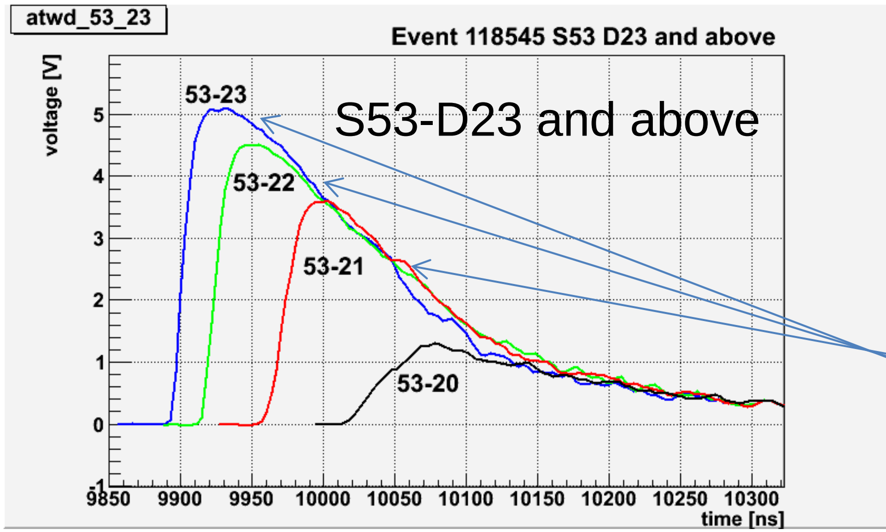


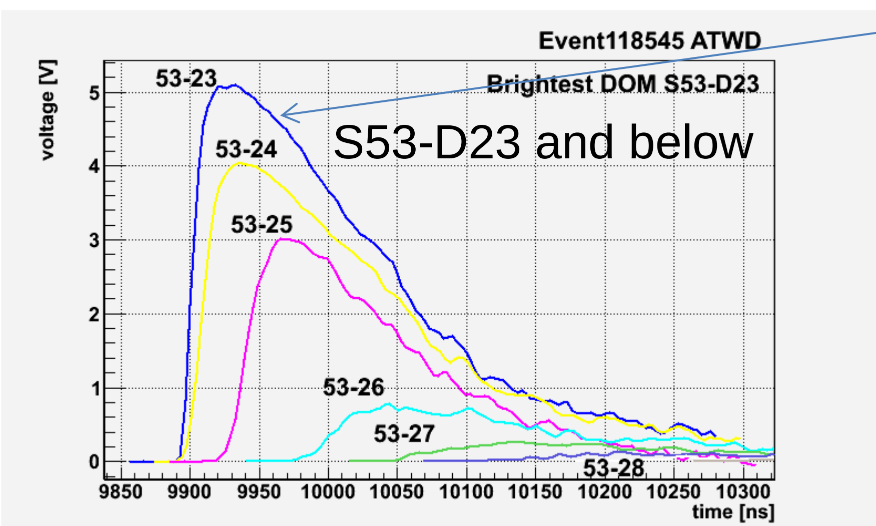




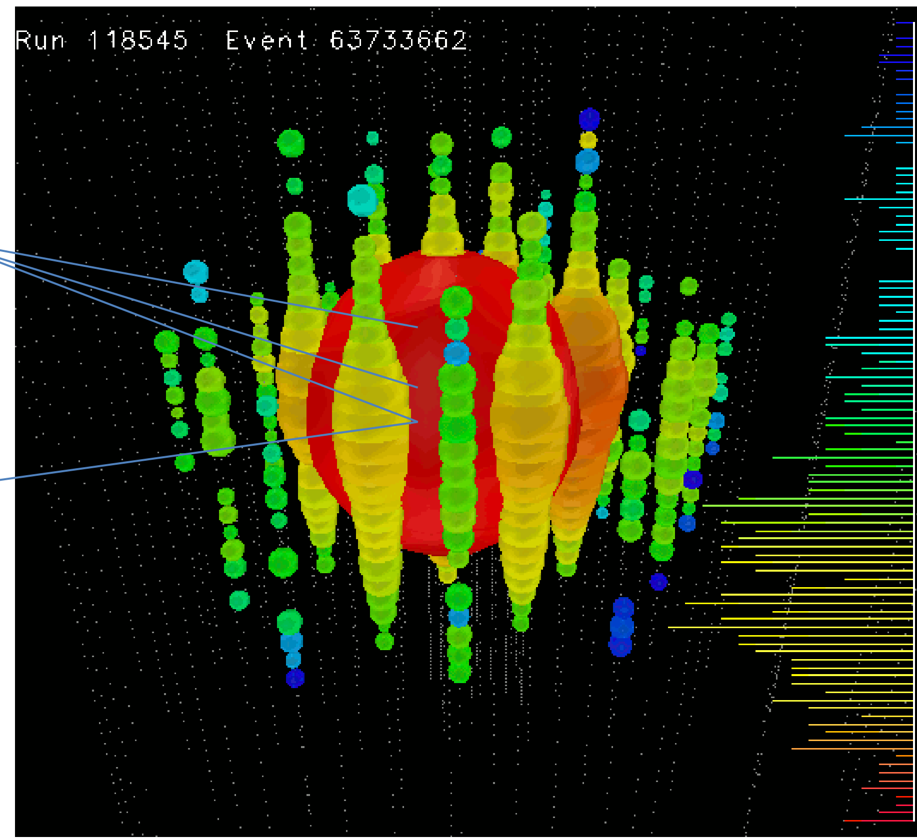
Event from Aug-2011

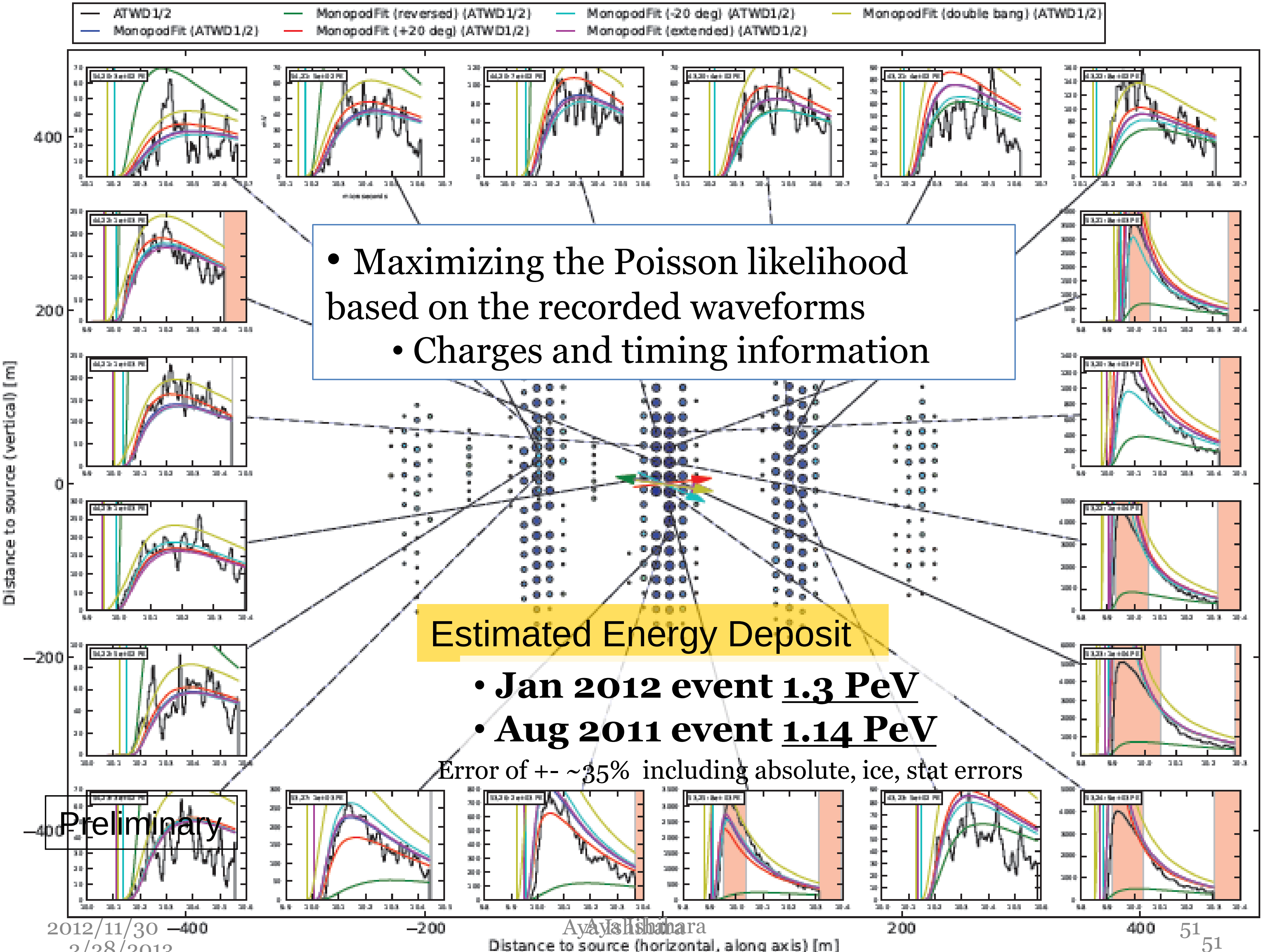
Calibrated ATWD waveform above and below the highest charged DOM (S53-23)





“Bert”





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

Estimated Energy Deposit

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

Error of +- ~35% including absolute, ice, stat errors

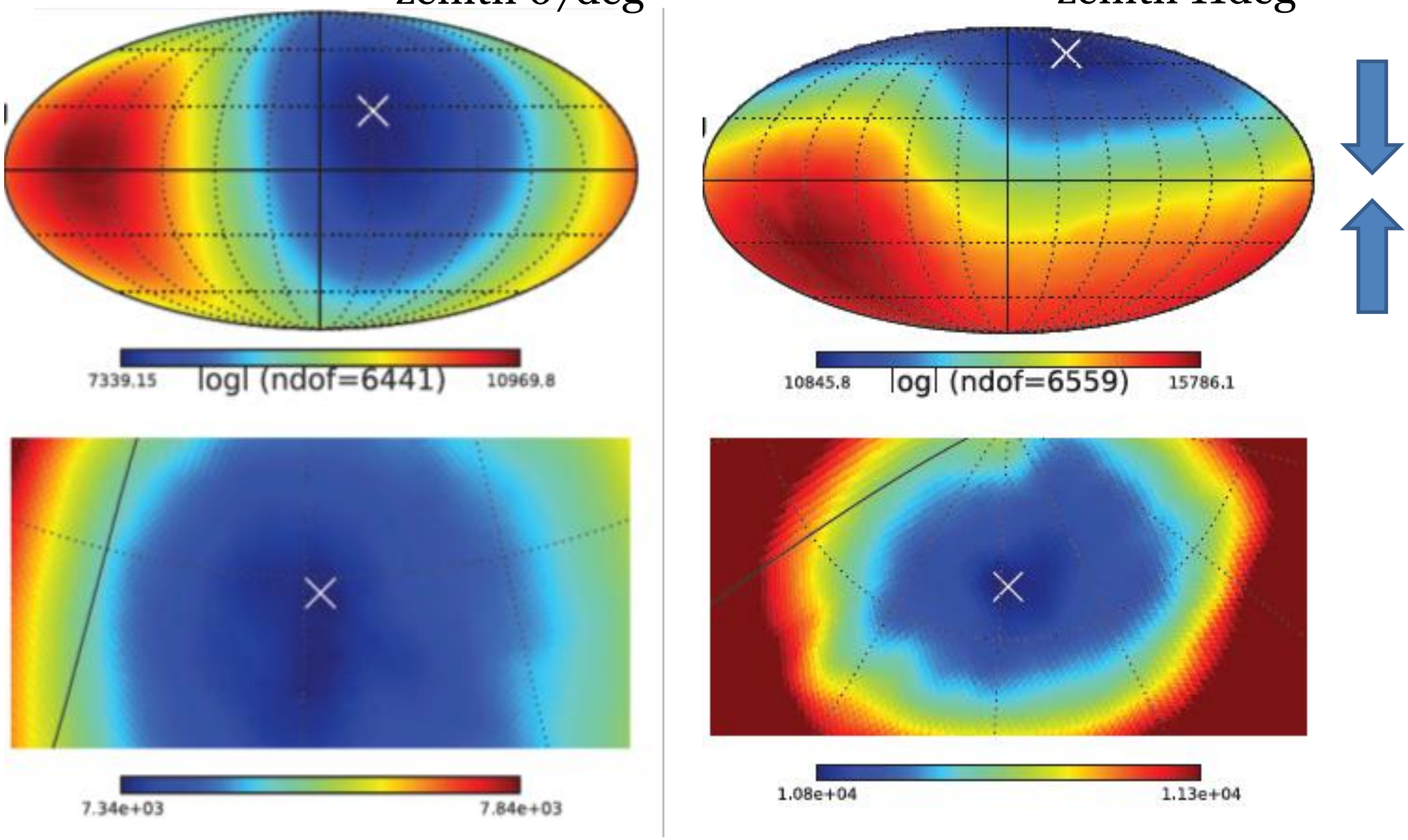
Aya Ishihara
51

log LLH distributions on directional plane

Downward-going PeV showers

zenith 67deg

zenith 11deg



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

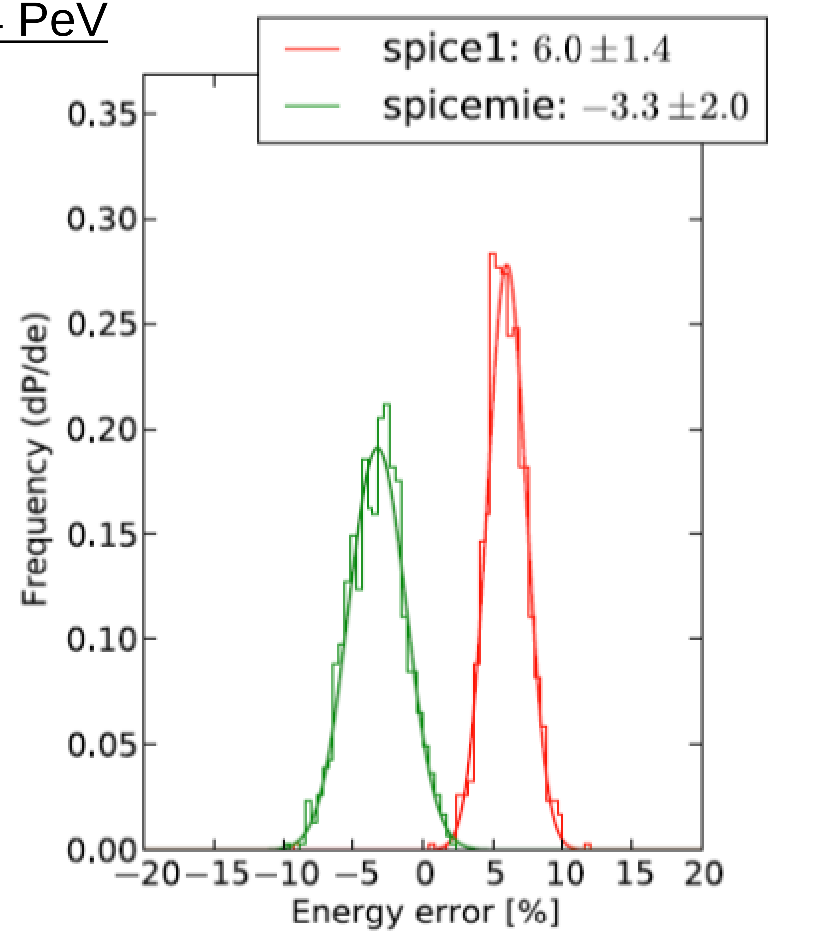
Preliminary

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

Jan 2012 event

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**

Deposited Energy → ν Energy

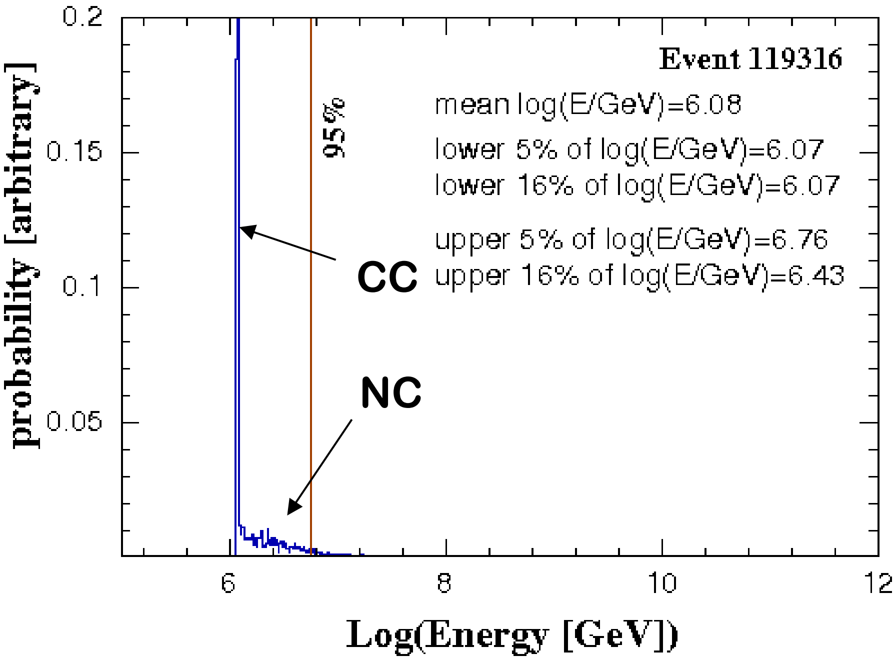
(At the IceCube depth = in-ice energy)

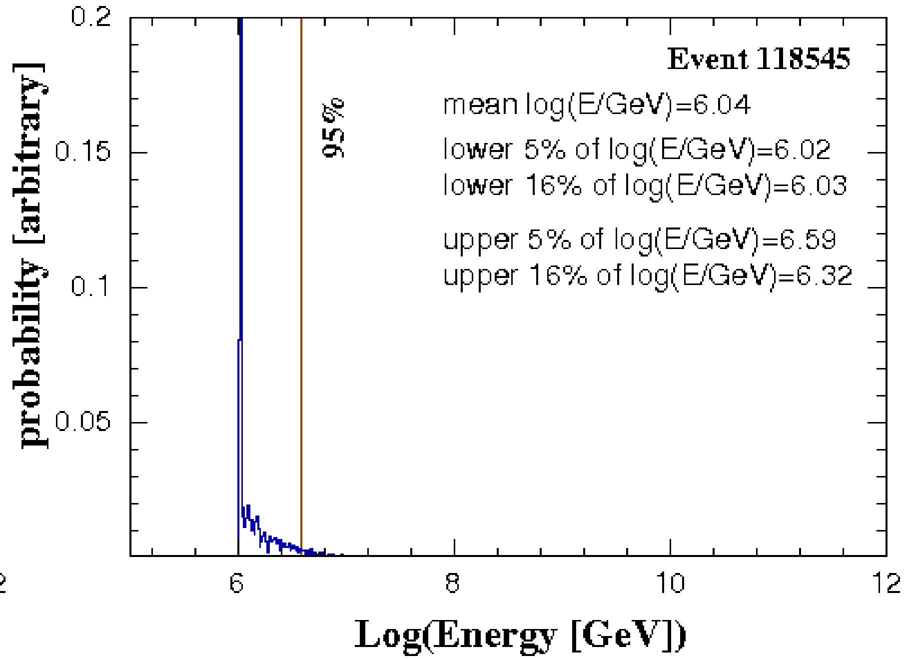
$\nu_e \rightarrow$ **e + X** (CC reaction) energy deposit = neutrino energy

$\nu_x \rightarrow \nu_x$ **+ X** (NC reaction) energy deposit = a partial neutrino energy

Jan 2012 event **Aug 2011 event**

Both events: ~1 PeV < Eν < ~4 PeV



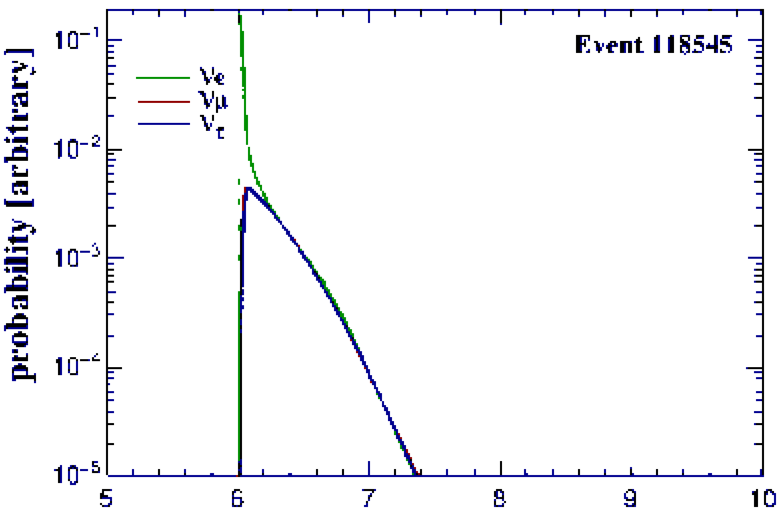


In-ice ν Energy → ν Energy at the Earth surface

The in-earth ν propagation effects

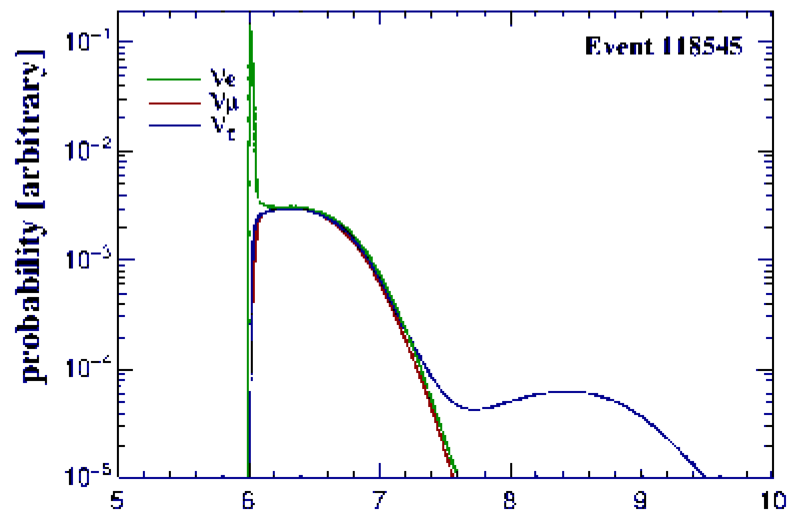
What is $E\nu^{surface}$ that could induce the PeV event ?

when the primary ν spectrum $\phi(E\nu) \sim E_\nu^{-2}$



Log10(ν energy at the Earth surface [GeV])

when the primary ν spectrum $\phi(E\nu) \sim$ *a la* GZK : harder spectrum



Log10(ν energy at the Earth surface [GeV])

Note: Systematic errors *NOT* included

Sharp fall-off of ν_e and ν_μ at 10^7 GeV

higher energy population should have converted to the charge leptons (e or μ) before reaching to the IceCube instrumentation volume

EeV (=10^9 GeV) tail of ν_τ

The regeneration: ν→τ→ν

Earth-surface Eν probability

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

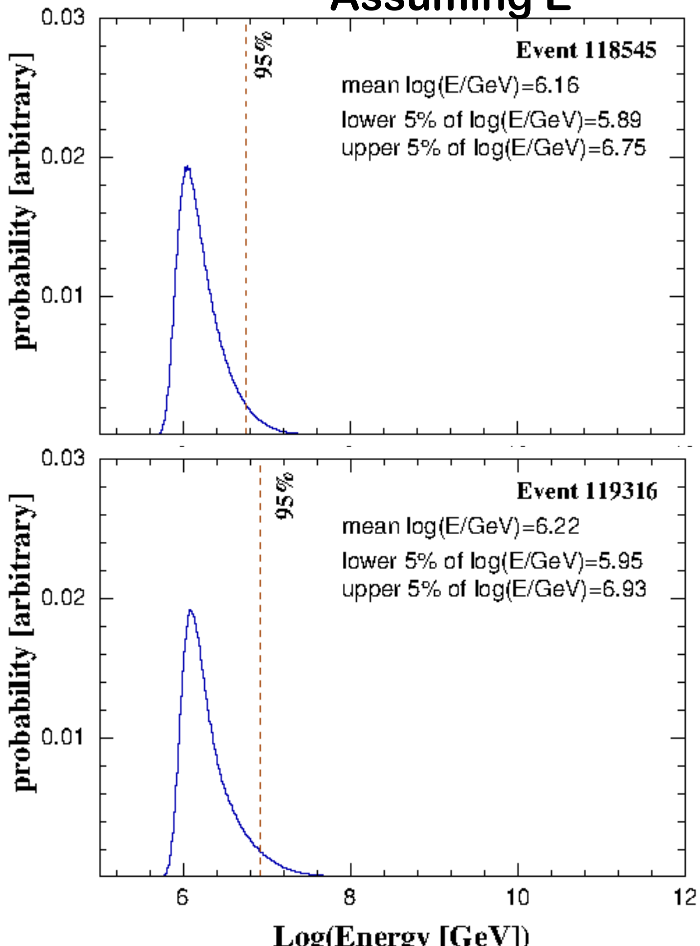
Jan 2012 event

Note: Systematic errors *included*

Assuming E^{-2}

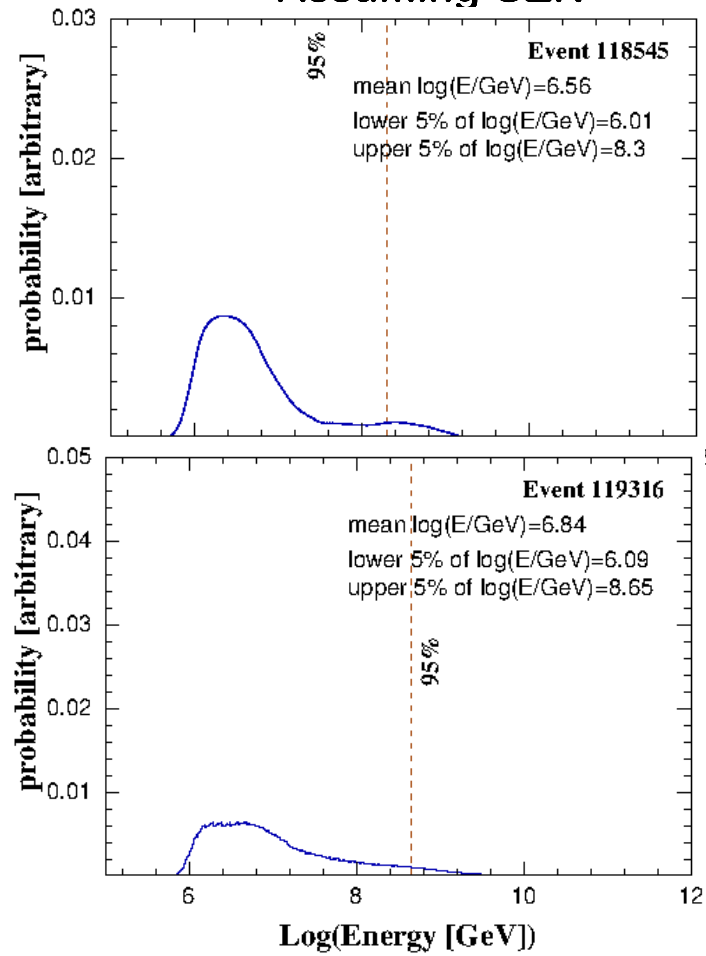
"Bert"

"Ernie"



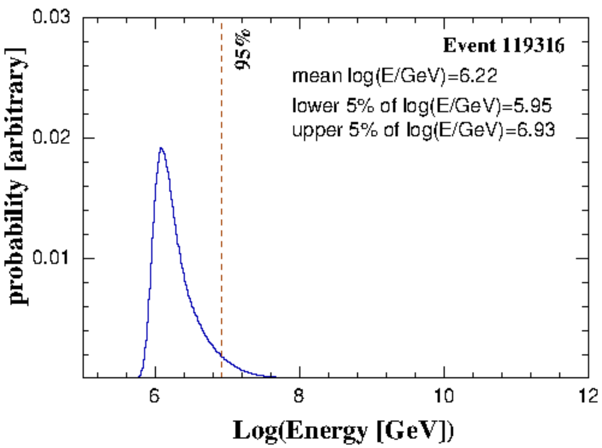
Aug 2011 event

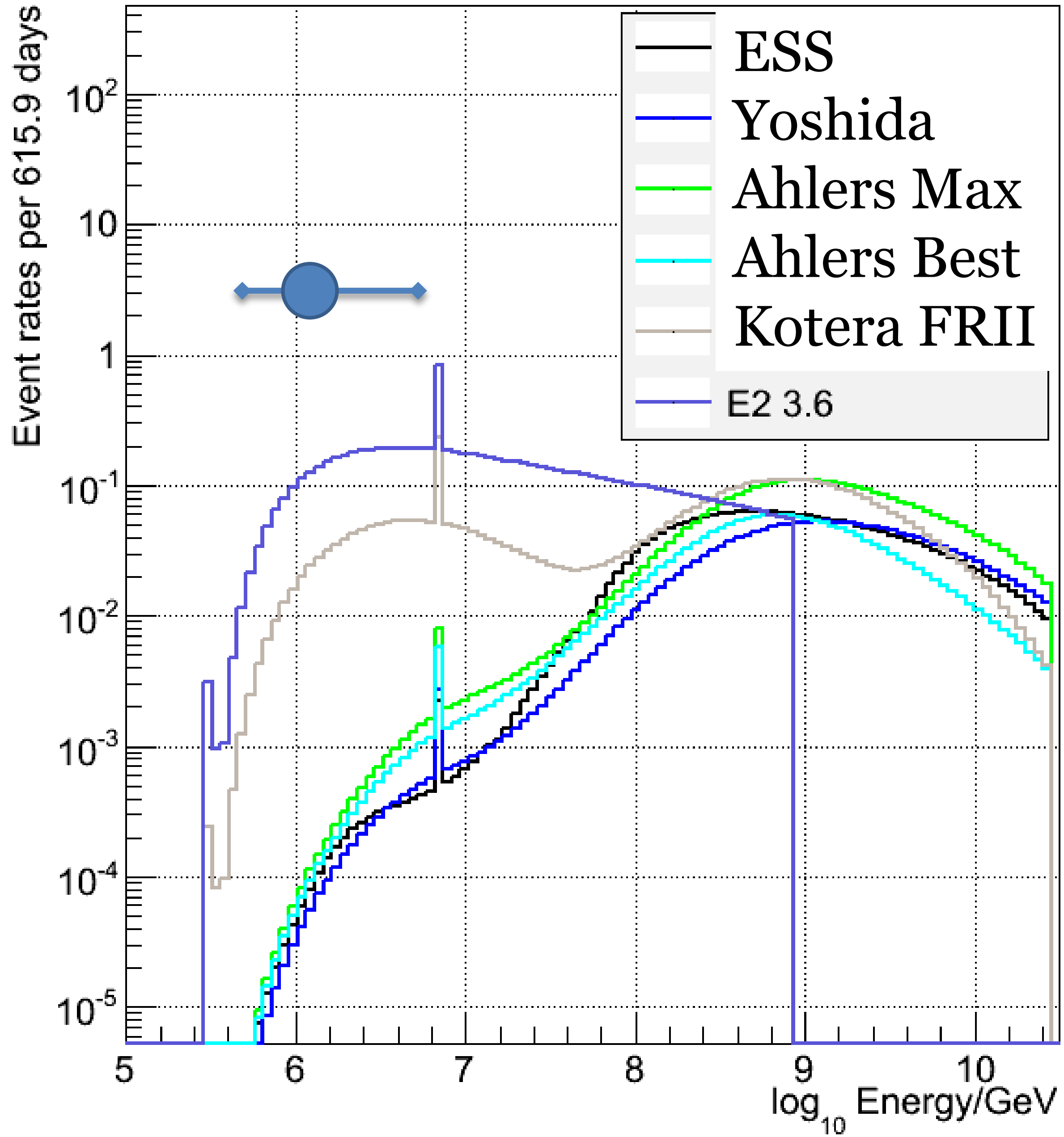
Assuming GZK



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

Model energy distributions





Two model tests

1. KS tests + full range event counting

$$\chi^2 = -2\ln(p_E) - 2\ln(\text{Poisson}(N=2,\mu))$$

The rate term

The energy term: p-value to the expected energy distribution predicted by each of the cosmic ν models

Use the Kolmogorov-Smirnov statistics

p-value =

$$\int d\log E_{Bert}\, \rho_{Bert}(\log E_{Bert}) \int d\log E_{Ernie}\, \rho_{Erine}(\log E_{Ernie})\, P_{KS}(\log E_{Bert}, \log E_{Ernie})$$

2. Counting events above 100 PeV

- Most of the EHE ν models predicts ν with energies >100PeV
- Probability of two events being >100PeV is small

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

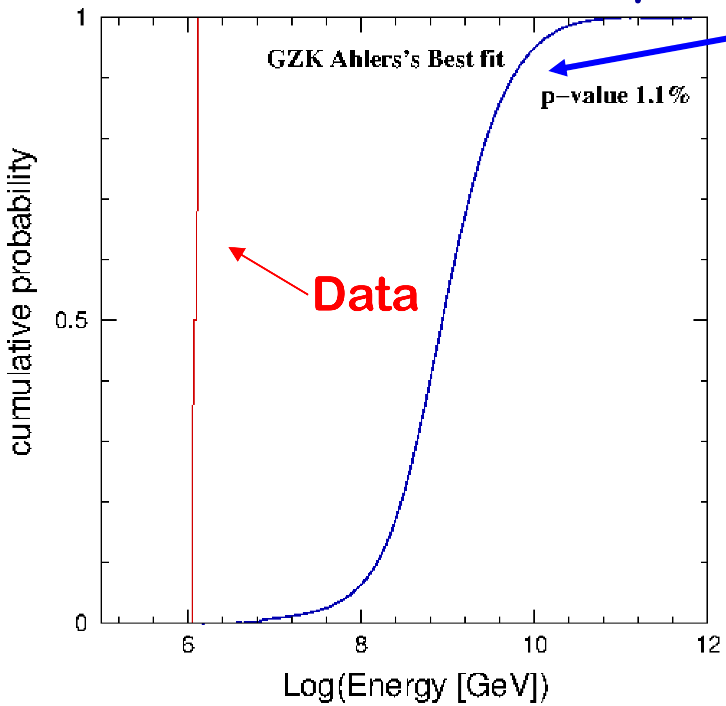
$$\frac{N_{100(1-\alpha)\%}}{\mu_\nu + \mu_{BG}} = 1$$

P_n probability of n events above 100 PeV
α p-value

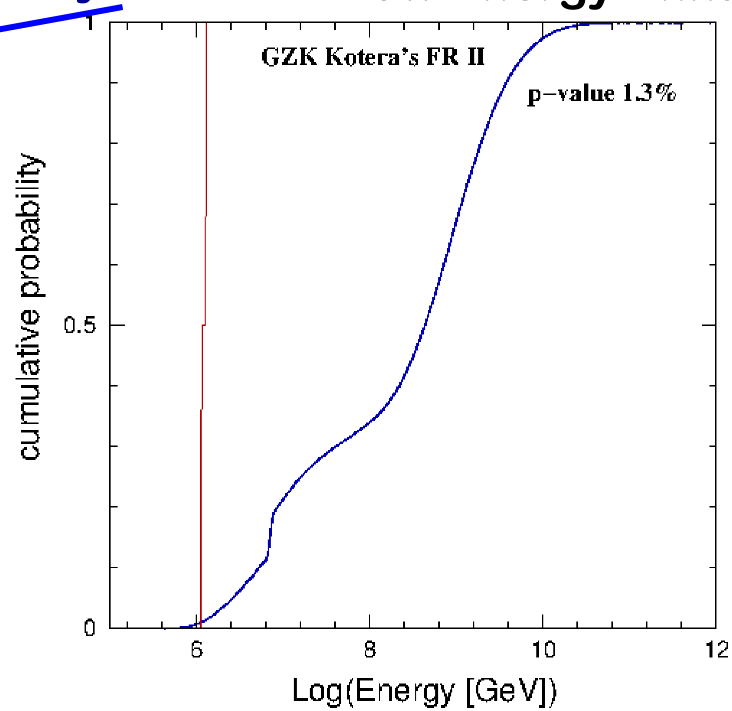
The KS test

The predicted Eν cumulative probability

“Standard” GZK



“Low Energy Enhanced” GZK



p-values O(1%)

Results from KS tests + full range event counting

Combined with IC40

Neutrino Model	KS Test P_E	Expected Event Rate	Poisson Significance	Final p-values
GZK Yoshida/Teshima m=4, Zmax=4	6.0×10^{-2}	2.8	5.5×10^{-1}	1.5×10^{-1} Marginally excluded
GZK Ahlers Fermi Best	6.0×10^{-2}	2.1	7.3×10^{-1}	1.8×10^{-1} Marginally excluded
GZK Kotera FR-II	3.4×10^{-2}	5.9	3.8×10^{-2}	1.0×10^{-2} Excluded by 95% C.L.
GZK Kotera GRB	4.4×10^{-2}	1.1	4.2×10^{-1}	9.2×10^{-2} Excluded by 90% C.L.

Preliminary

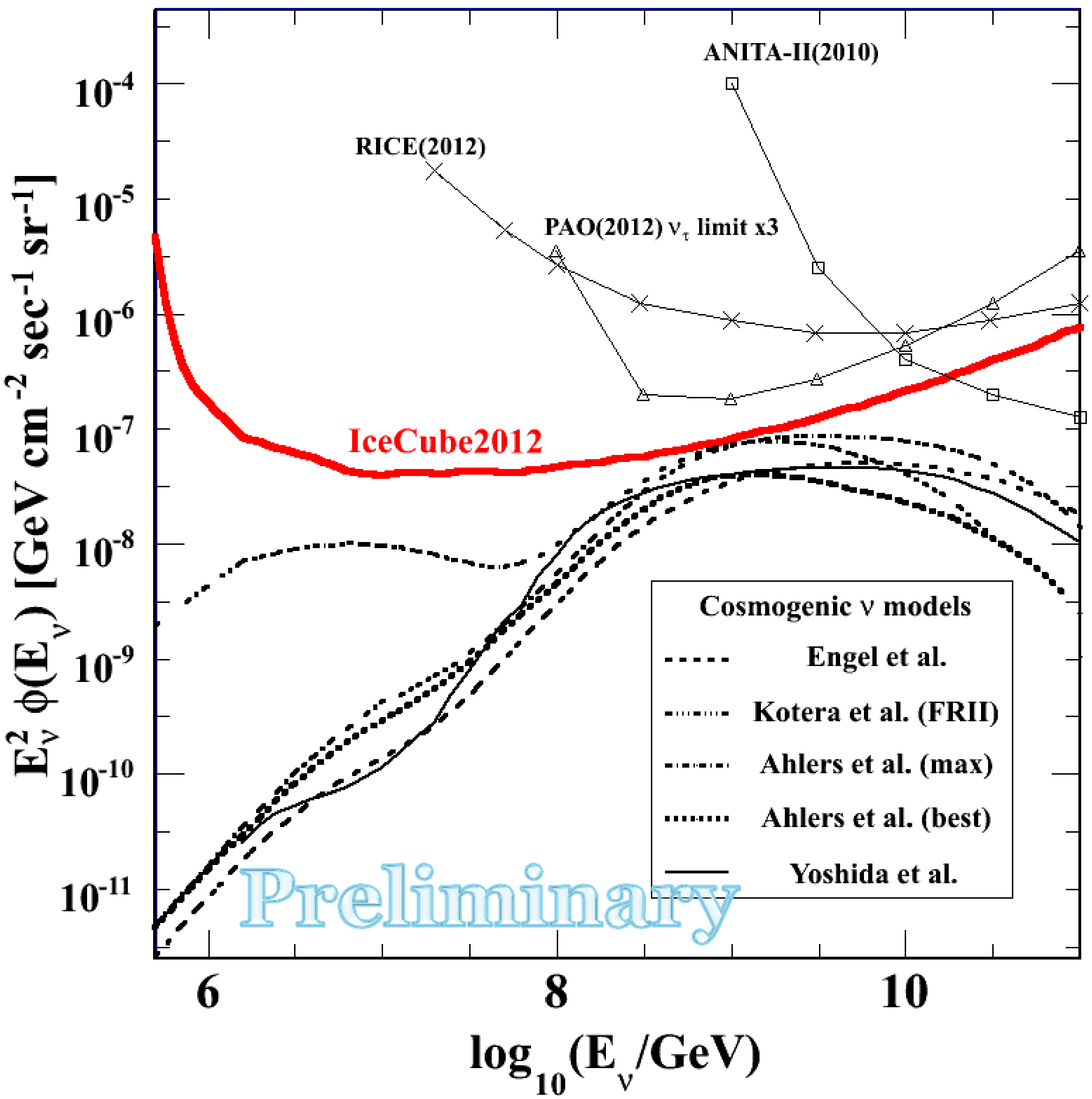
Event rates(>100 PeV) and p-values

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 (red)
- Mildly Excluded (orange)
- Consistent (blue)

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**

Still at least a factor of 2 improvement to come in 2 years

A short summary on the present constraints

- None of the GZK cosmogenic ν scenarios appears consistent with the present observation.

  Energies of the two events are too low

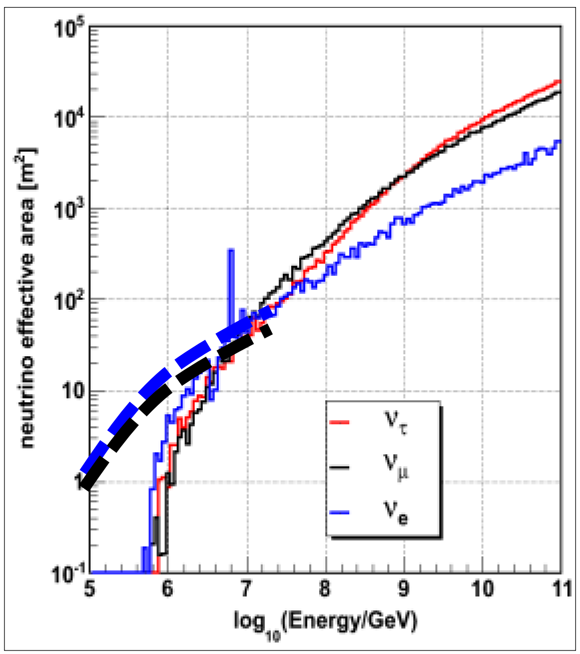
- A model predicting ν spectrum extending beyond ~100 PeV would not account the observation.

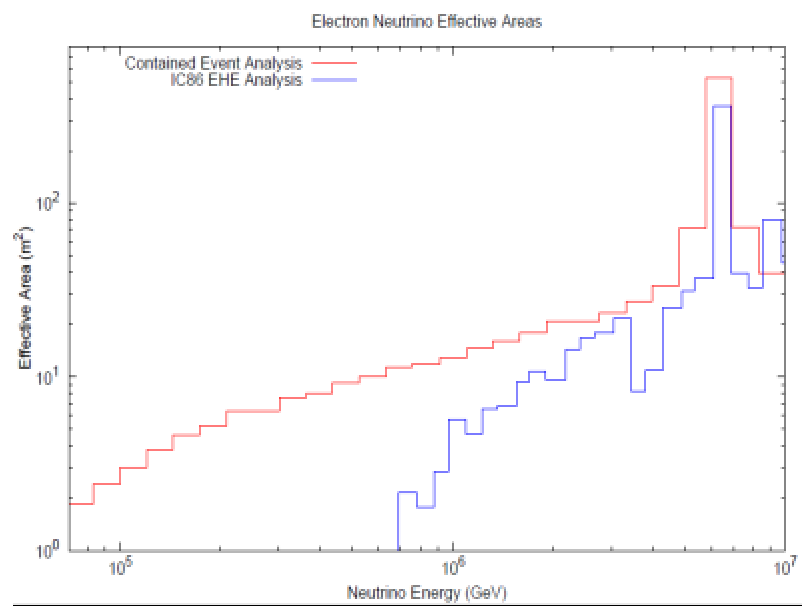
  IceCube have a greater exposure at EeV

Additional note: no sensitivity if UHECRs are heavy nuclei dominated

Then what are they?
Reducing the energy threshold

Improvements in 100TeV region from the starting event analysis

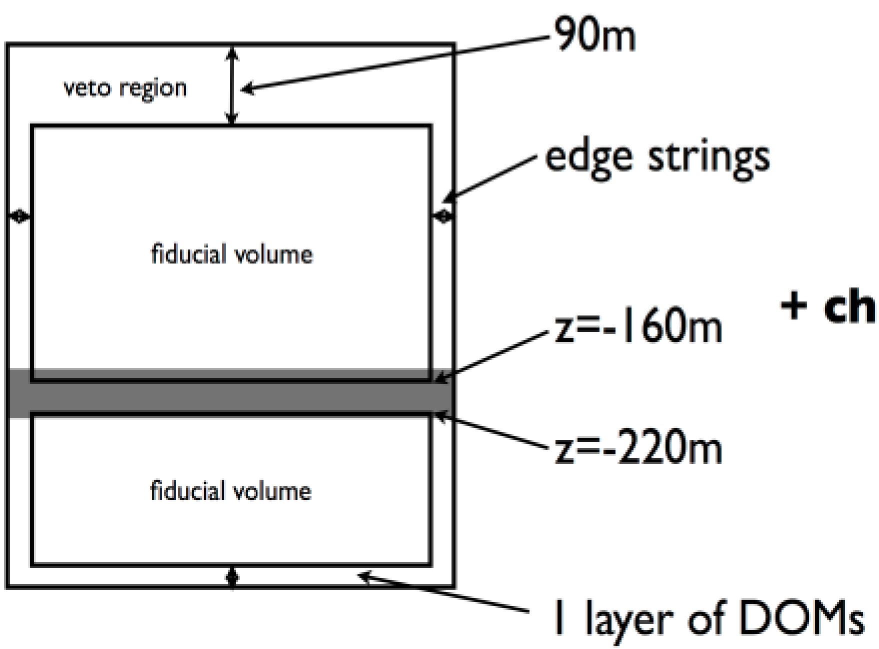


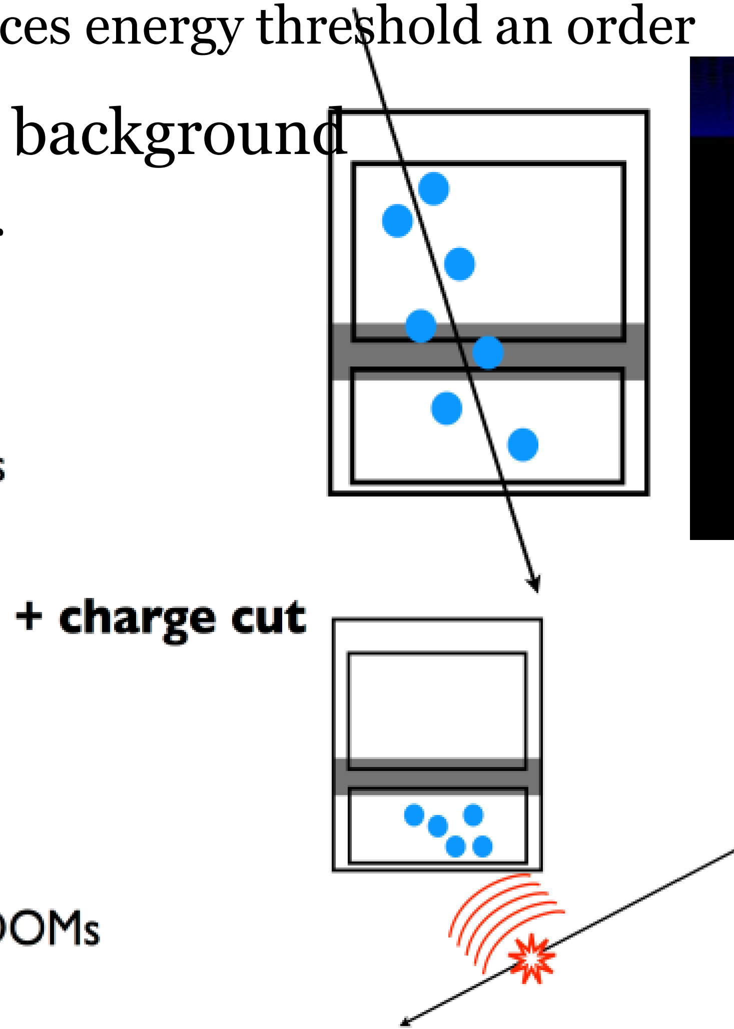


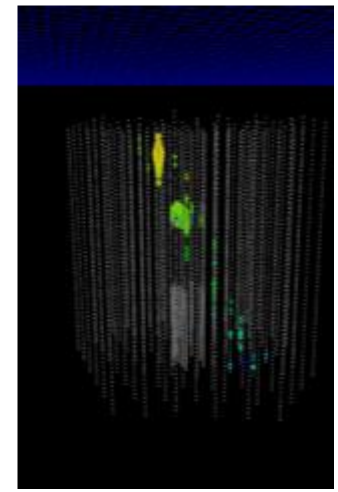
Starting event analysis

Nathan Whitehorn and Claudio Kopper (UW)

- Bright (>6000pe)
  - was > 63000pe, this reduces energy threshold an order
- Outer veto cut to reject background
  - Events started in detector





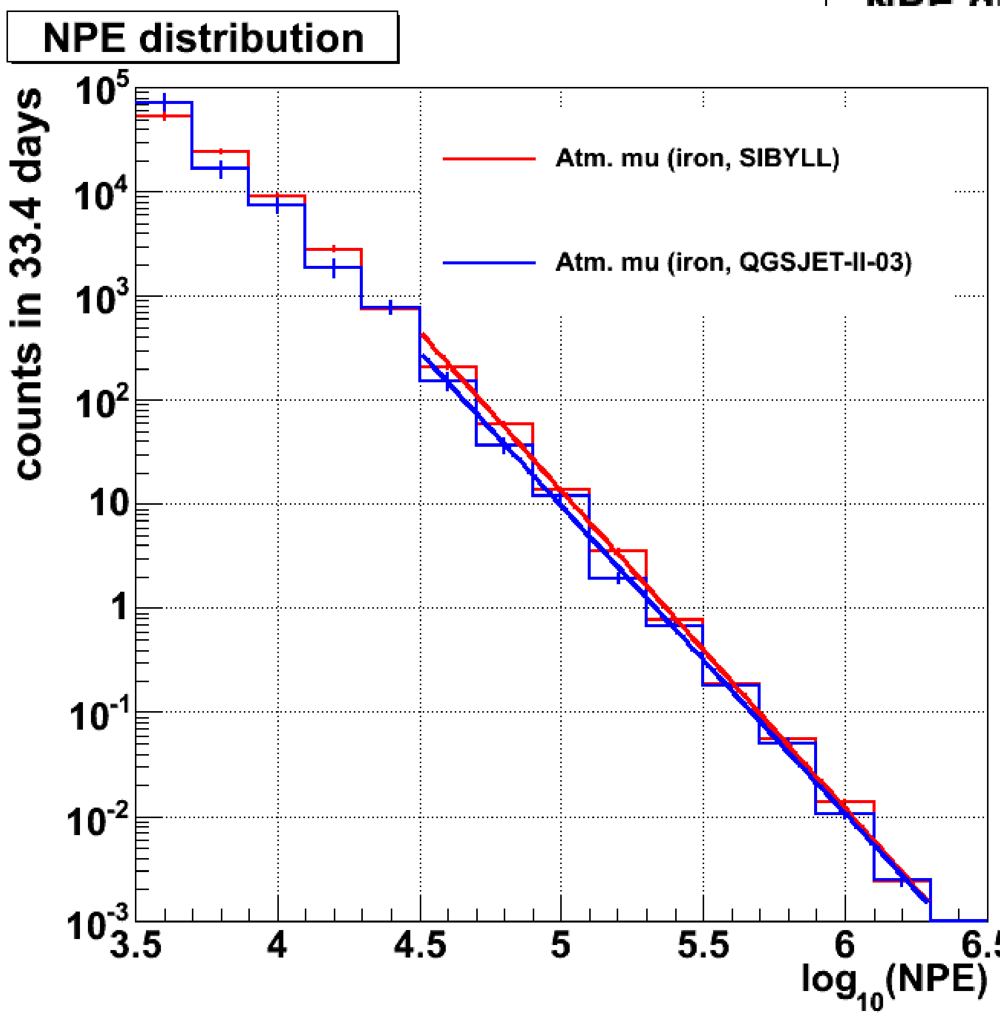


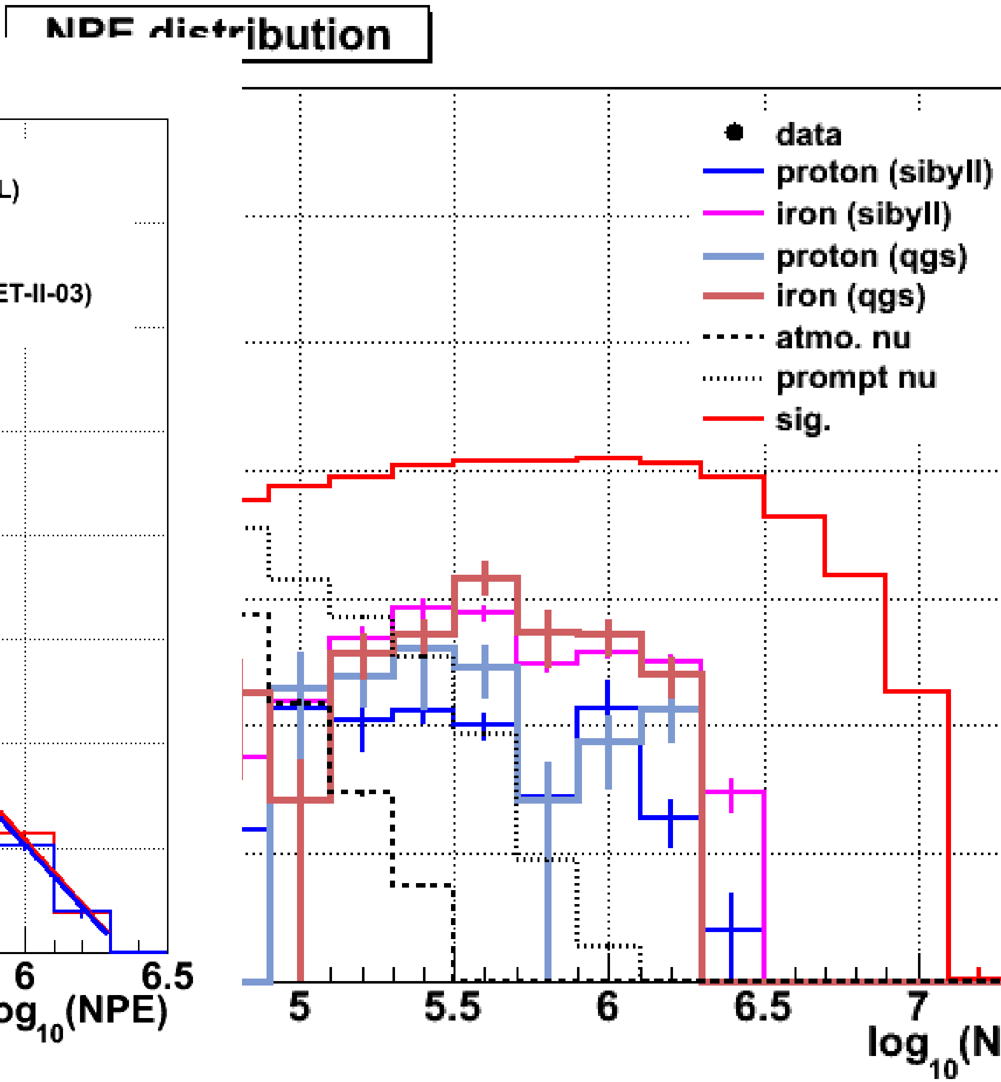
Summary

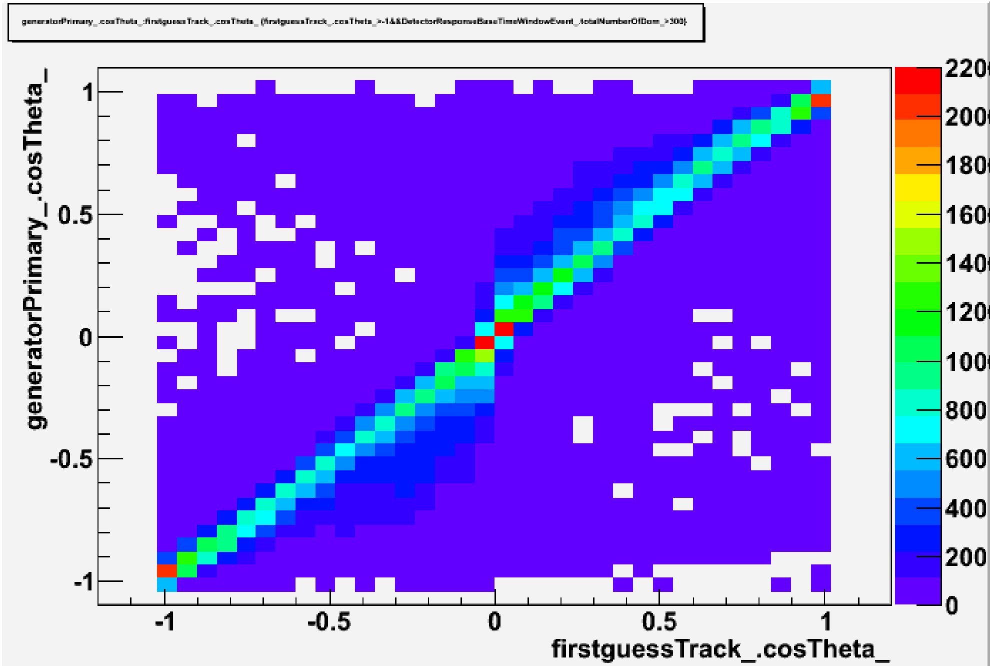
- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- IceCube is the largest neutrino detector and rejection of the atmospheric neutrinos was achieved by setting energy threshold

- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - The highest energy neutrino events observed ever!
- Very likely beyond the conventional atmospheric neutrinos

- Hints for the PeV events origin from different energy-region coming!?
  - 26 additional starting events found
  - p-values to be calculated – initial expectation ~3sigma beyond prompt taking zenith angle information into account
  - No events near PeV energies… The PeV 2 events population is a bit away from E-2 flux expected from lower energy region
- New information coming next years from IceCube would be very interesting


NPE distribution
counts in 33.4 days
Atm. mu (iron, SIBYLL)
Atm. mu (iron, QGSJET-II-03)
log10(NPE)


NPE distribution
data
proton (sibyll)
iron (sibyll)
proton (qgs)
iron (qgs)
atmo. nu
prompt nu
sig.



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firstguessTrack_.cosTheta_
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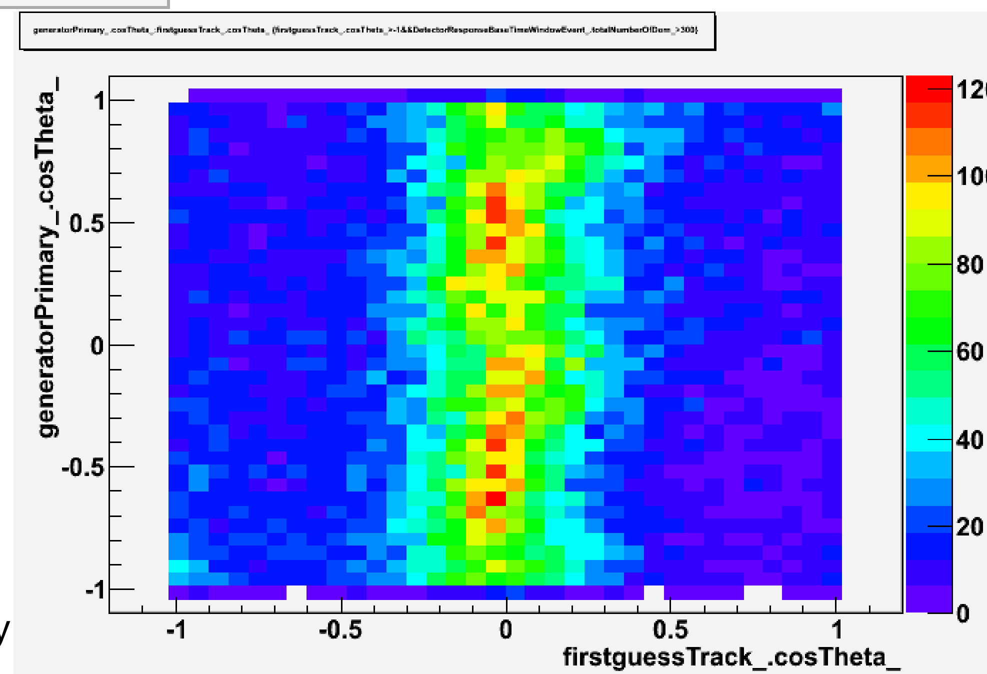
0.5
0
-0.5
-1



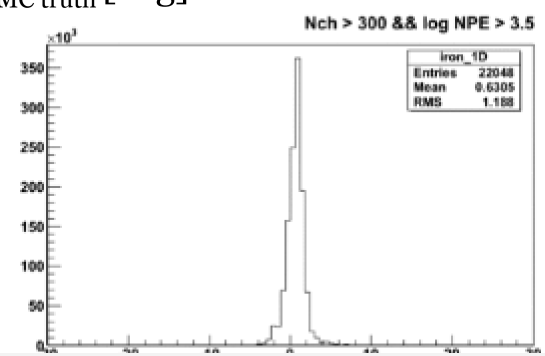
generatorPrimary_.cosTheta_:firstguessTrack_.cosTheta_ {firstguessTrack_.cosTheta_>-1&&DetectorResponseBaseTimeWindowEvent_.totalNumberOfDom_>300}
generatorPrimary_.cosTheta_
firstguessTrack_.cosTheta_
120
100
80
60
40
20
0

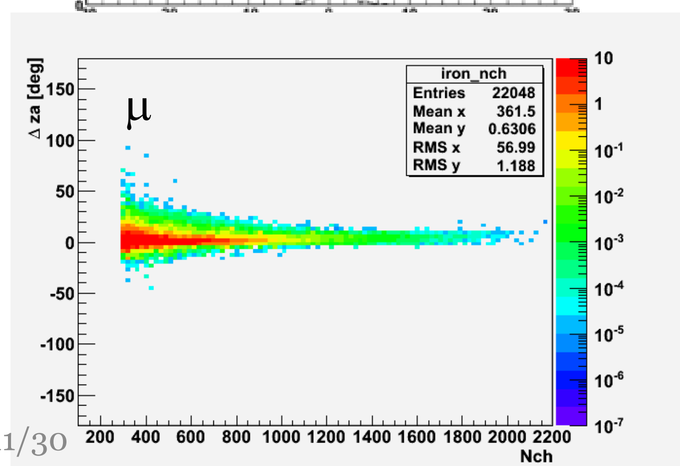
Zenith angle resolutions

- resolution (RMS) for background is ~1.2 deg
- resolution (RMS) for signal is ~10 deg due to its stochastic nature
  - resolution improves with increasing Nch
  - No strong dependence with NPE

resolution for Corsika cr muons

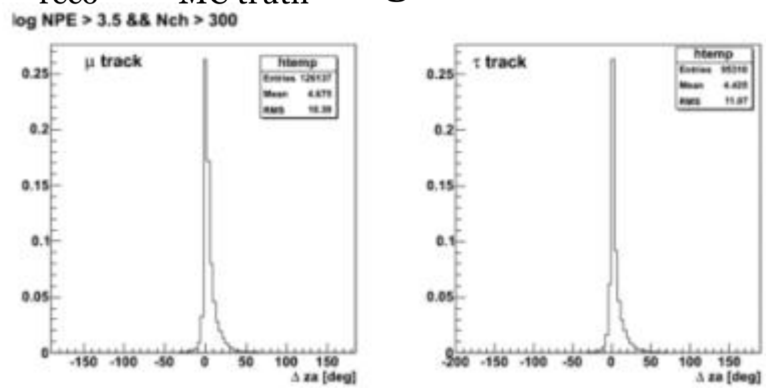
$\theta_{reco} - \theta_{MC\ truth}$ [deg]





resolution for signal mu, tau tracks

$\theta_{reco} - \theta_{MC\ truth}$ [deg]



tracks