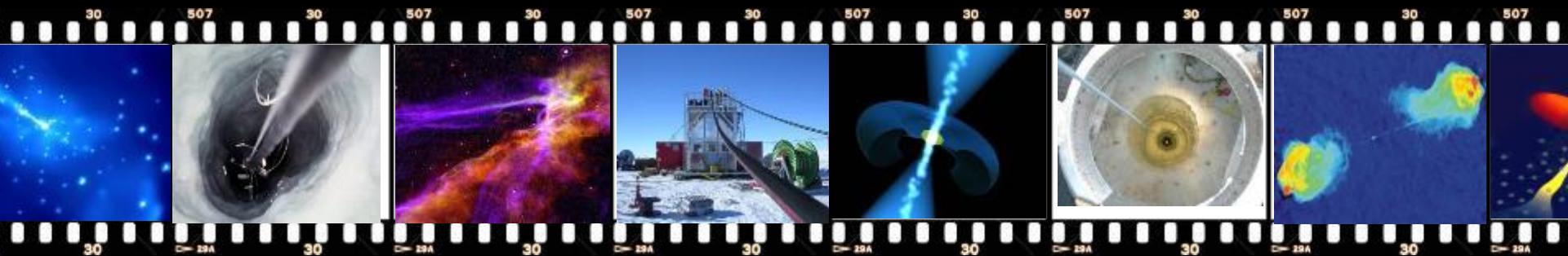


Beyond first observation of PeV-energy neutrinos with IceCube

石原安野 (Aya Ishihara)

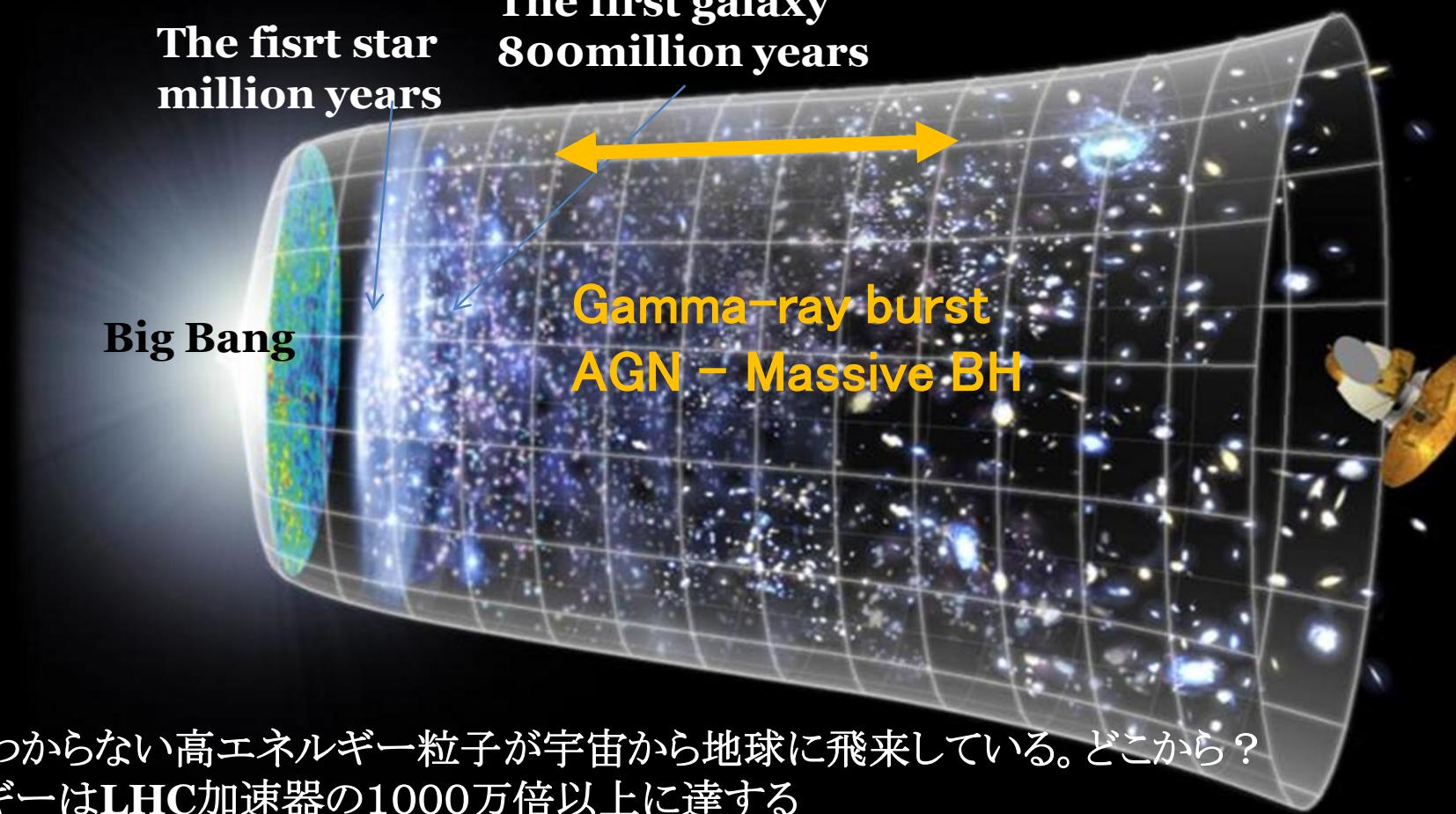
aya@hepburn.s.chiba-u.ac.jp

千葉大学



The High Energy Deep Universe Mystery

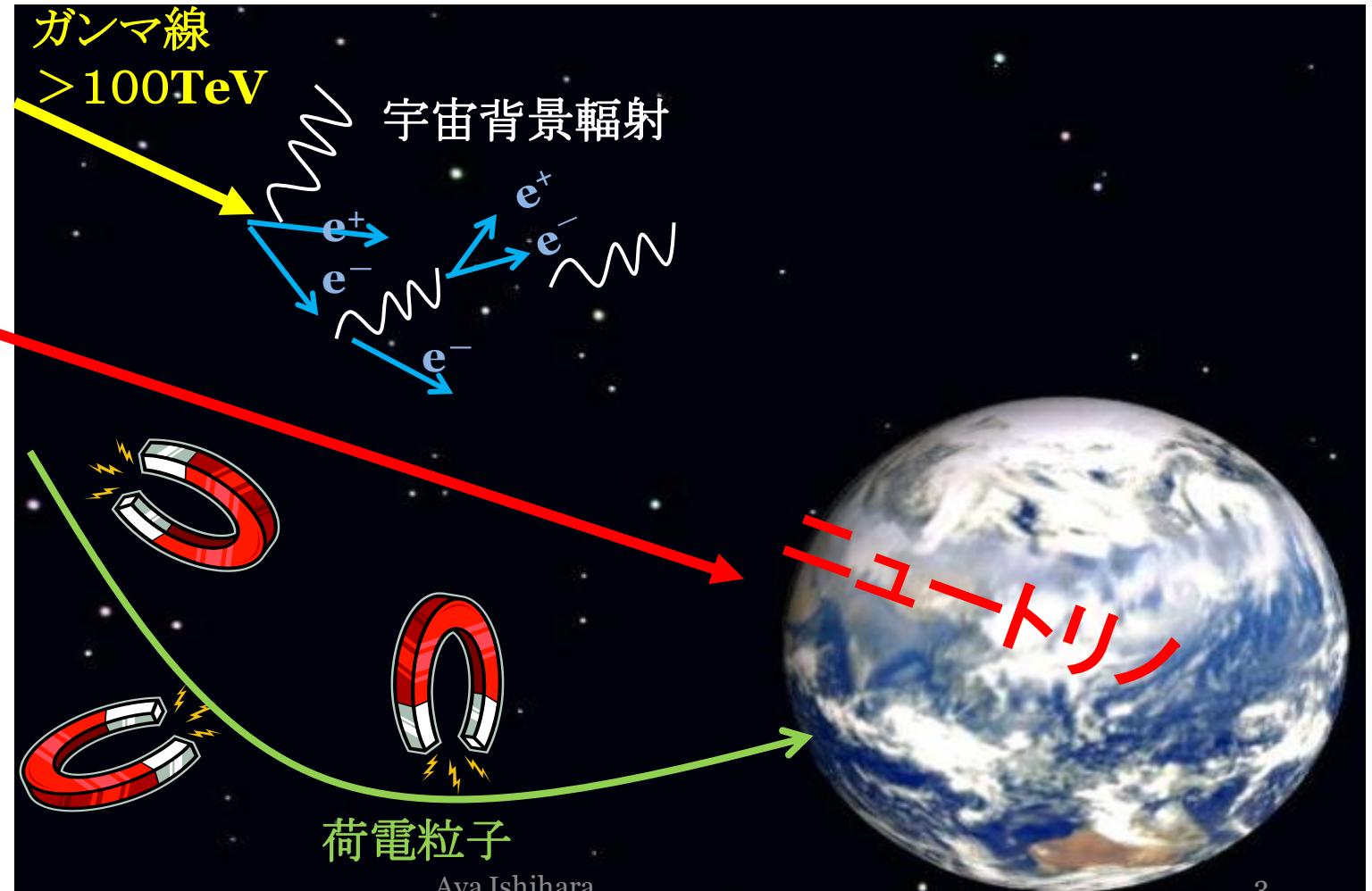
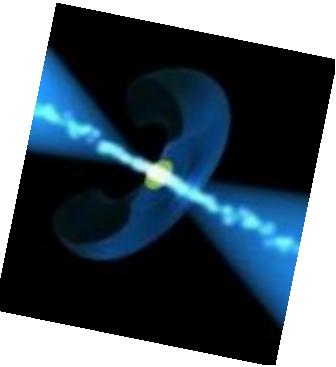
Present



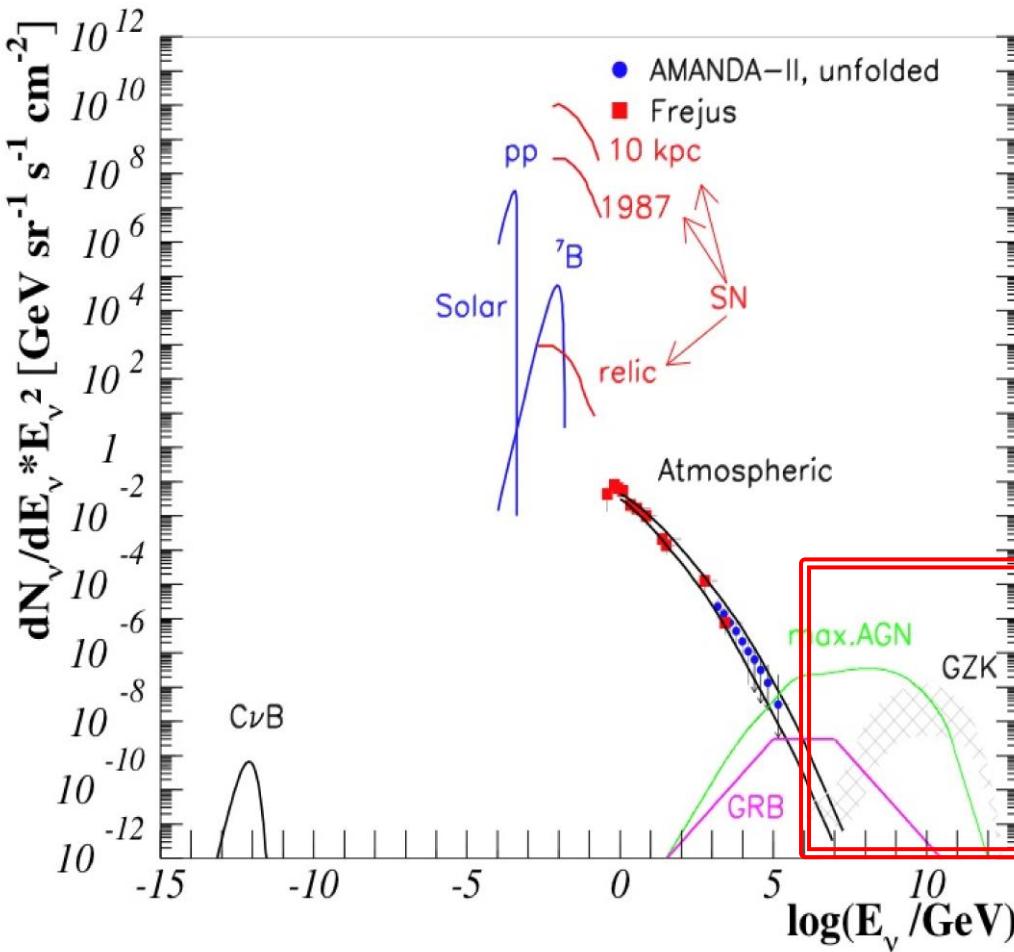
- 起源のわからない高エネルギー粒子が宇宙から地球に飛来している。どこから？ エネルギーはLHC加速器の1000万倍以上に達する
($100\text{EeV} = 10\text{keV(x-ray)} \times 10,000,000,000,000,000!$)
- 巨大ブラックホールである活動銀河核(AGN)や宇宙で最も激しい爆発現象であるガンマ線爆発(GRB)といった極限爆発現象は遠方(若い)宇宙に分布
 - Was young Universe more active? why? how high energy they can produce?

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事が出来ない。
 - 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
 - PeV宇宙を見られる範囲は10万光年(天の川銀河の直径)ほど
 - ハドロン・レプトン起源に対するambiguity



Ultra-high Energy - IceCube's sweet spot *PeV and above*



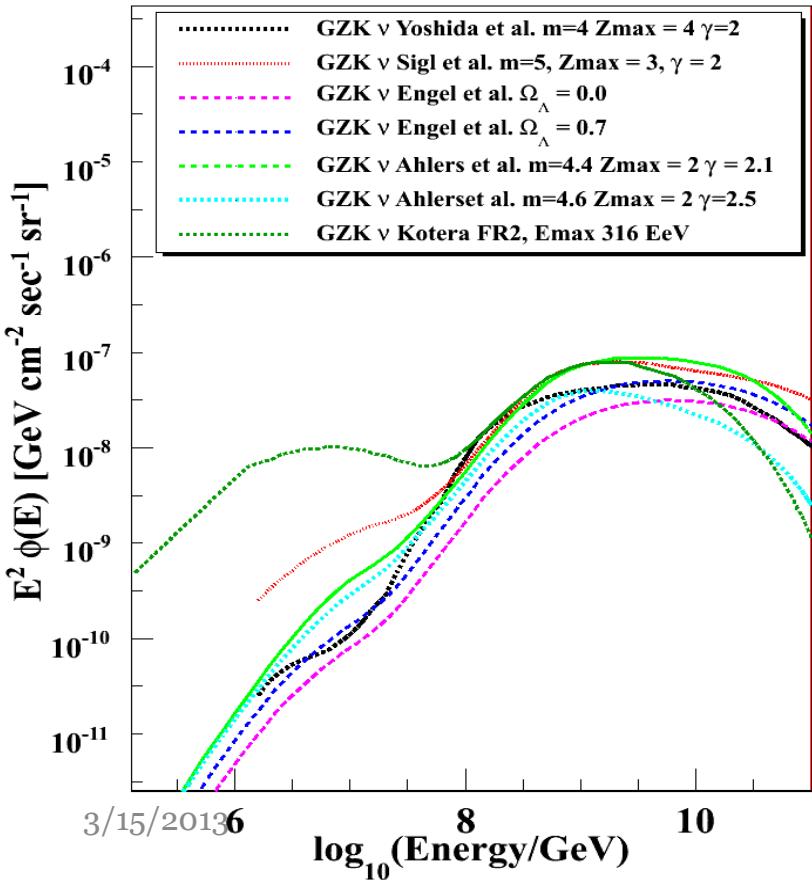
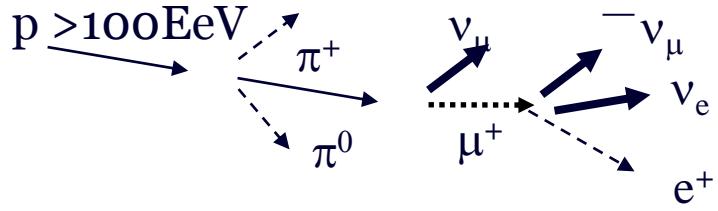
- **Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)**
- **Energies above dominant atmospheric neutrinos**
- **Cosmogenic neutrino production is a ‘guaranteed’ ν source**

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



Various
GZK ν
models

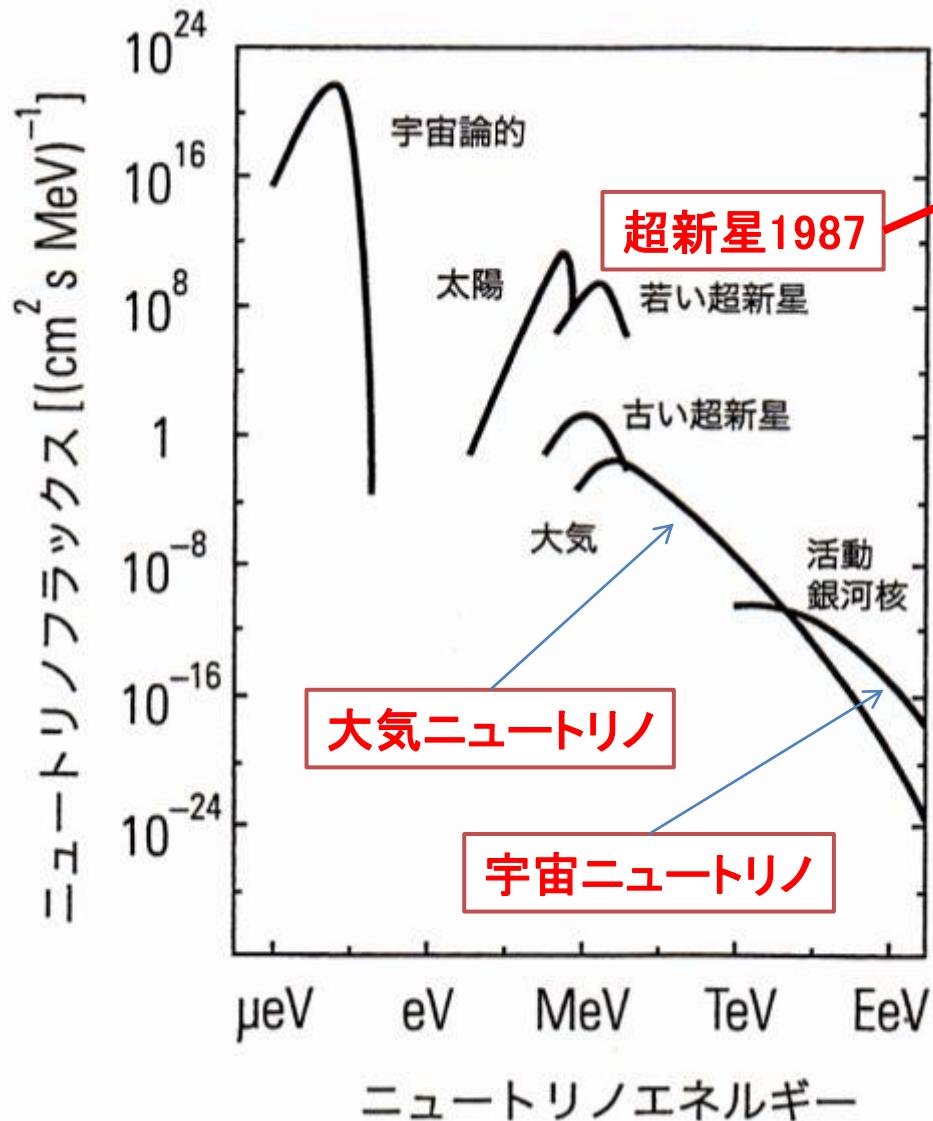
The main energy range: $E_\nu \sim 10^{8-10} \text{ GeV}$
 $p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu \rightarrow e^+ + \nu' s$

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 cosmic-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）爆発的天体现象でニュートリノが出来ることがわかつた

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...

High Energy Neutrino Telescopes



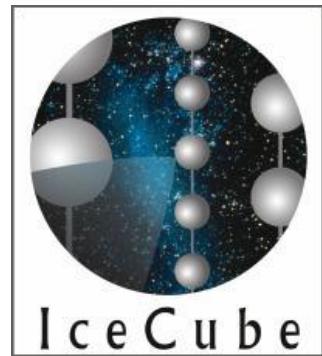
ICECUBE at
the South Pole
and
time to see
cosmic v !

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
3/15/2013

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

ANTARCTICA

Amundsen-Scott Station

Japan

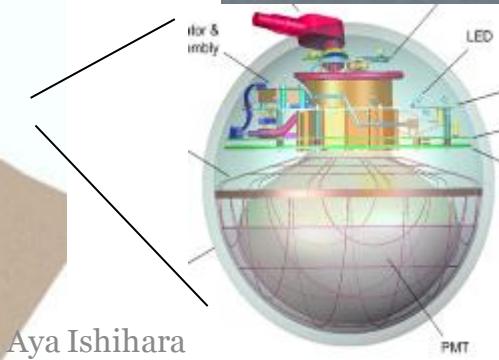
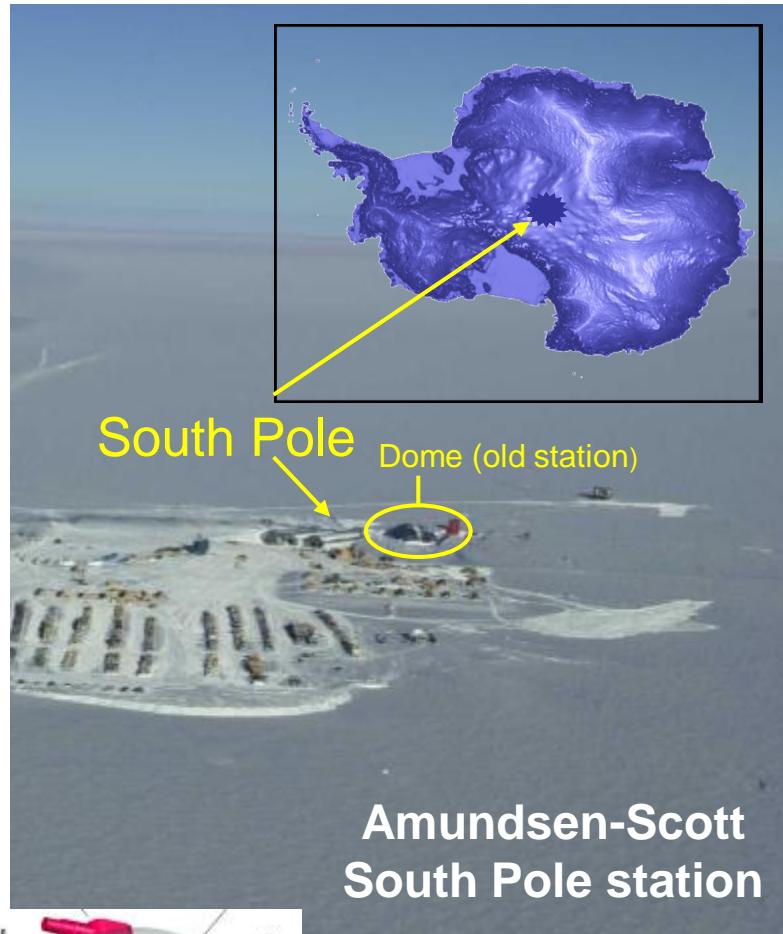
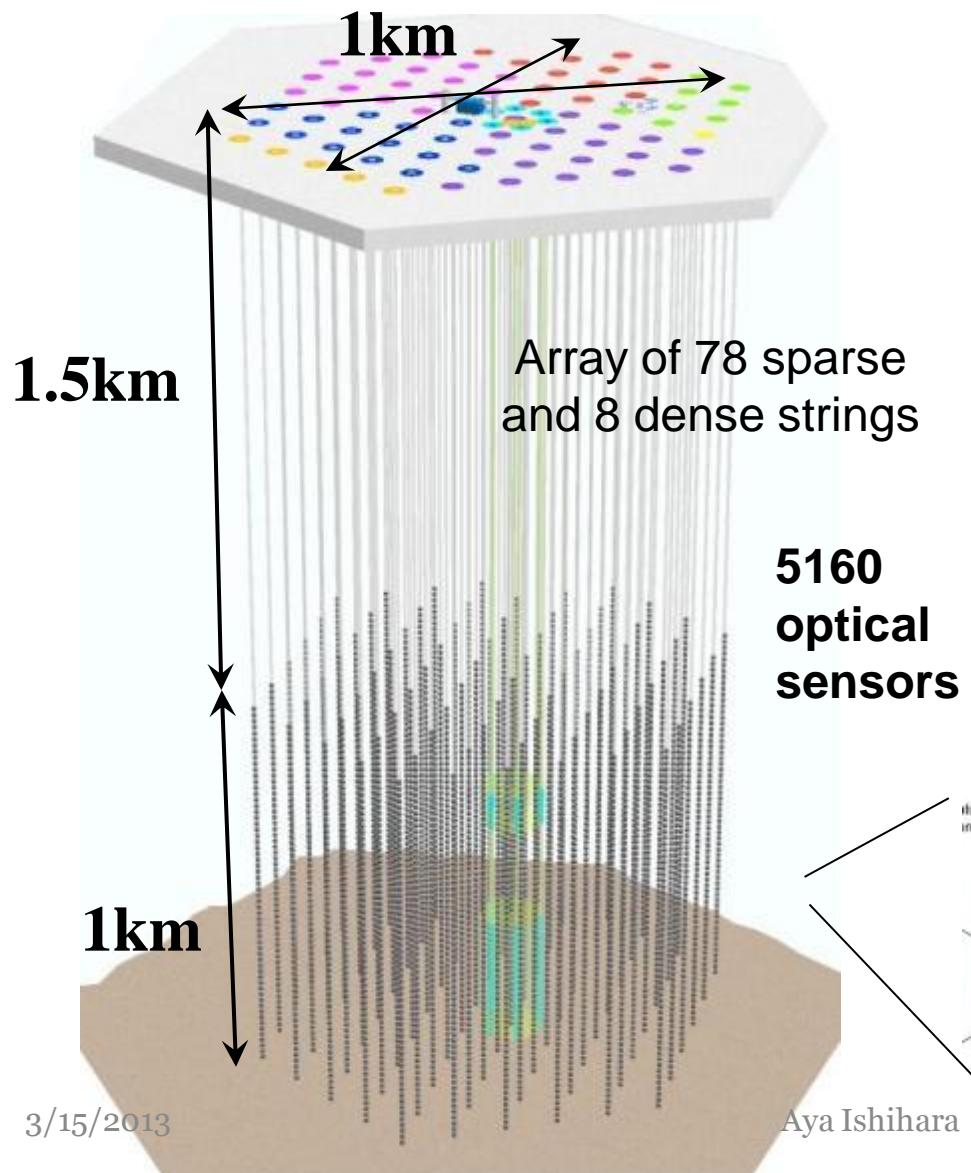
Chiba University

The first results from the full IceCube

New Zealand

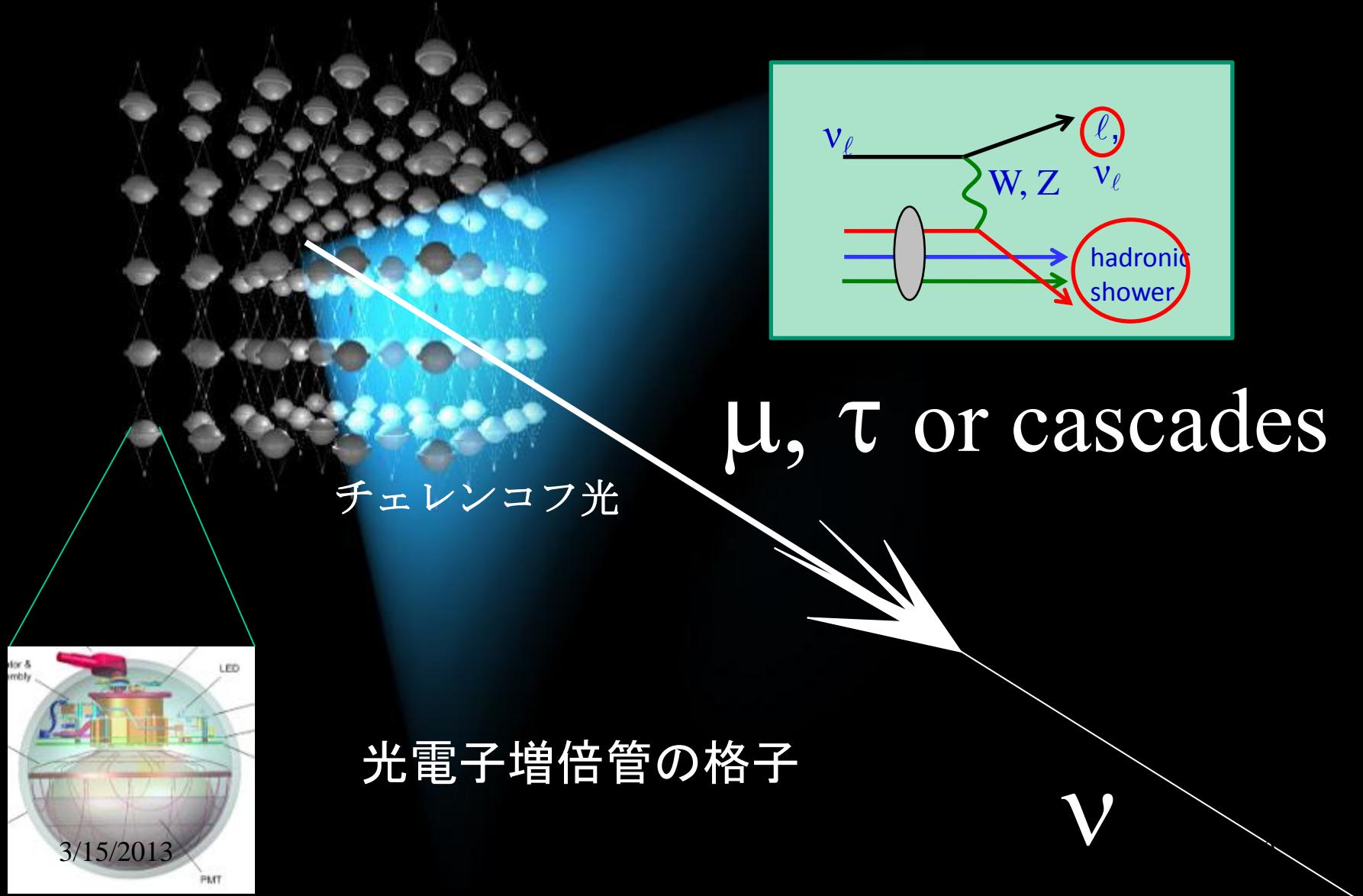
University of Canterbury
Aya Ishihara

The Largest Neutrino Detector in the world: The IceCube Detector



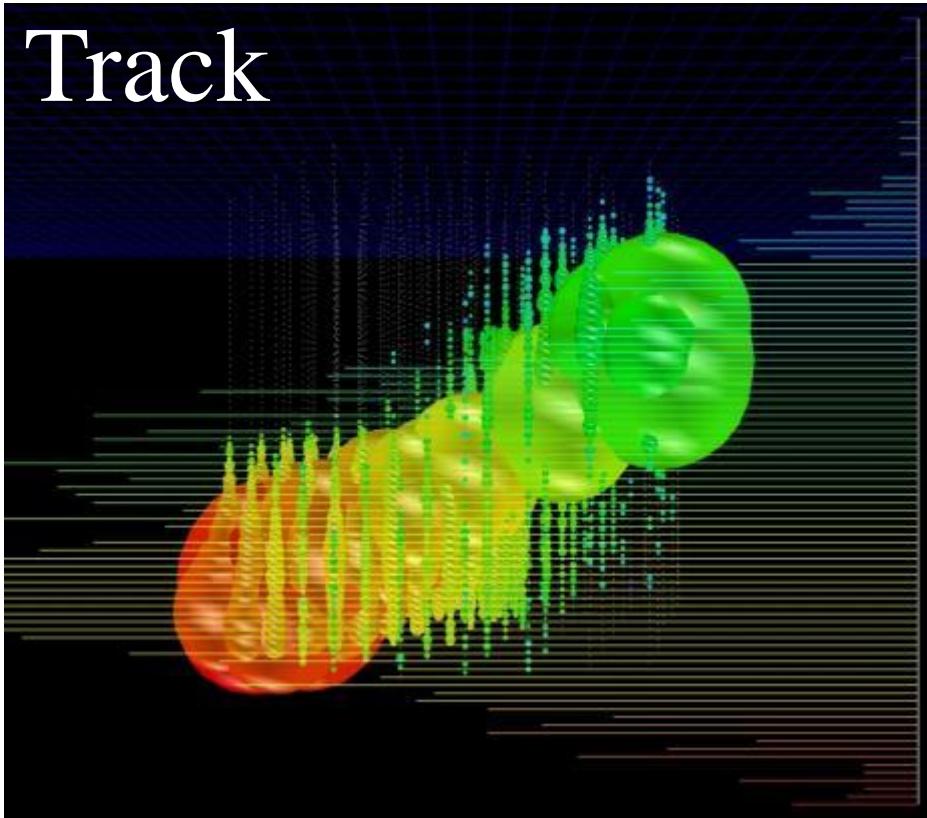
検出原理

暗く、しかし光をよく通す巨大なマテリアル

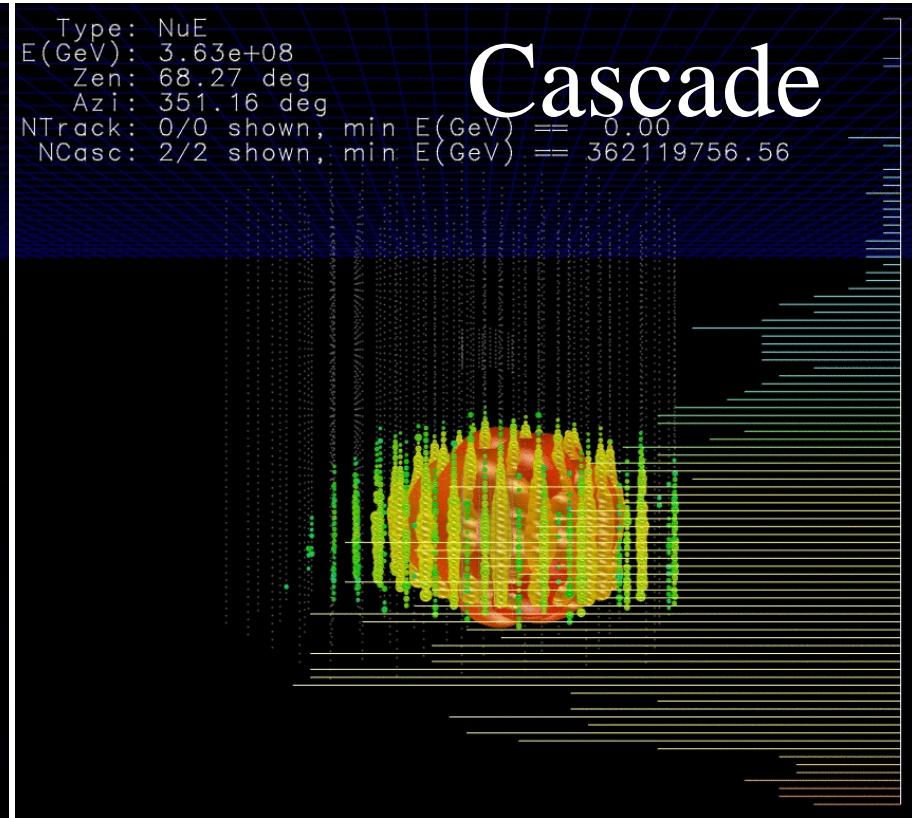


Ultra-high Energy Signal Events

20PeV muon



300PeV nu induced cascade

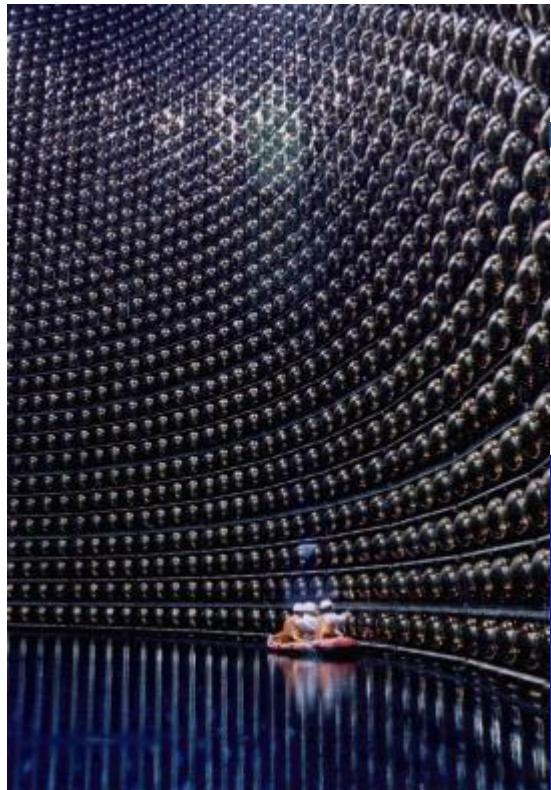


Not flavor sensitive except some special cases, however, we distinguish muon/tau tracks induced by nu mu, nutau CC and cascades induced by nu e CC and NC by 3 flavors of neutrinos

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

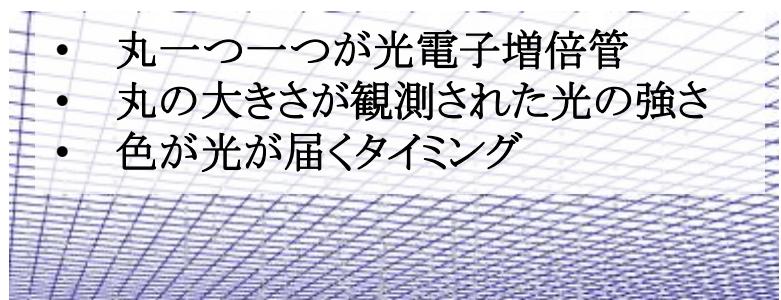
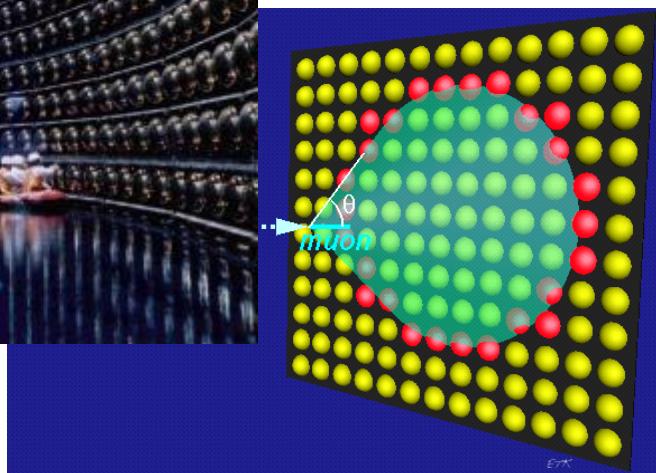
super-KAMIOKANDE
検出器の大きさ

← 40m x 40m x 40m →



>15,000倍

2Dから3Dへ
事象の大きさ
6m x 6m

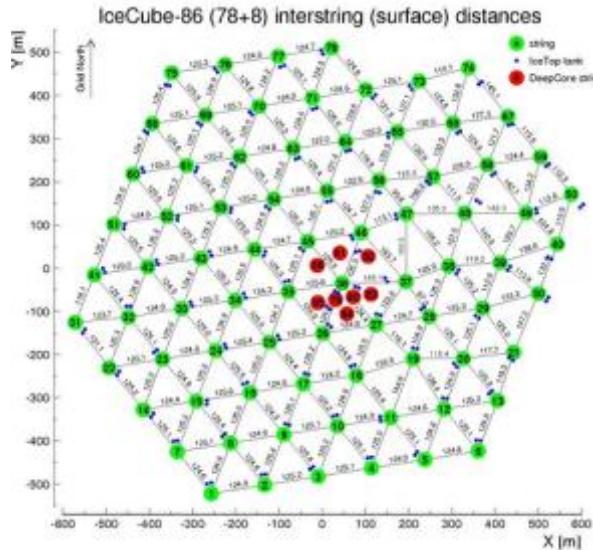


ICECUBE
検出器の大きさ
1000m x 1000m x 1000m

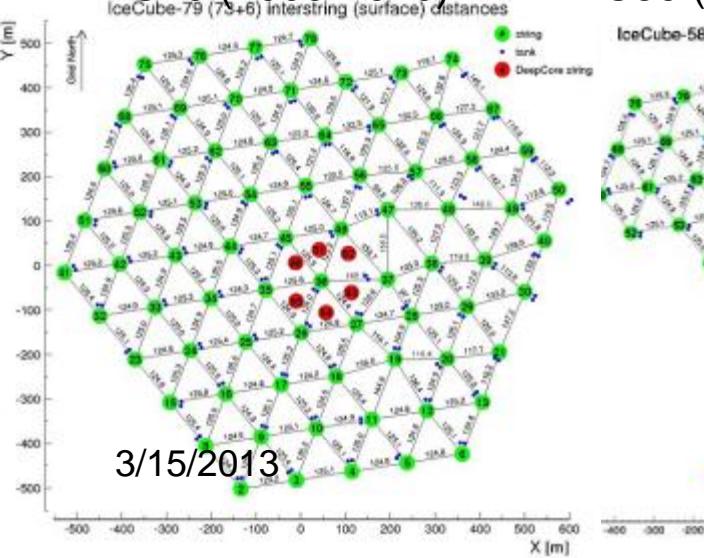
ICECUBE
事象の大きさ
800m x 300m x 300m

A big challenge: IceCube検出器の建設

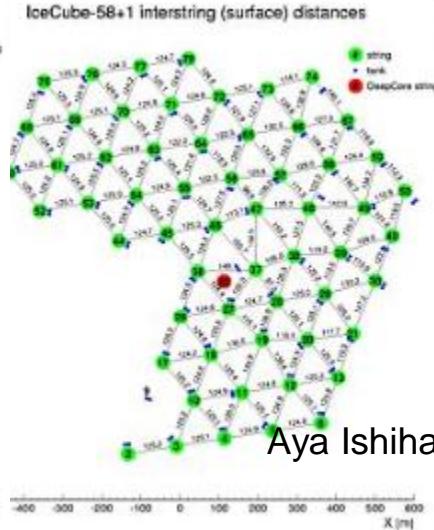
2006年に建設開始2010年末に建設終了 IC86 = full IceCube (2011~)



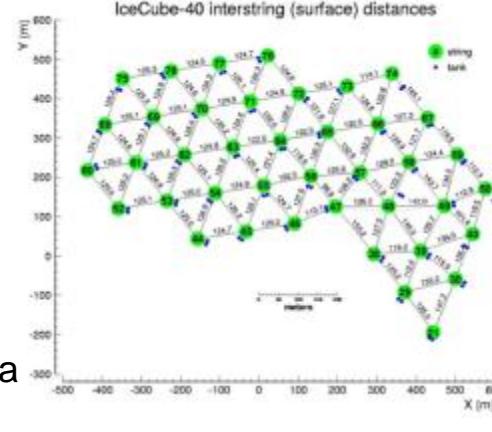
IC79 (2009-2010)



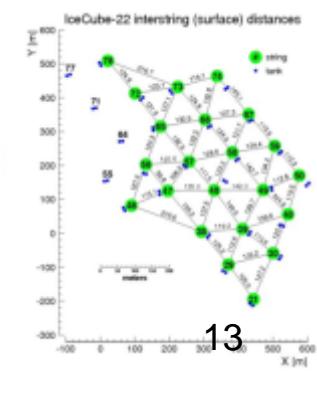
IC59 (2008-2009)



IC40 (2007-2008)



IC22 (2006-2007)

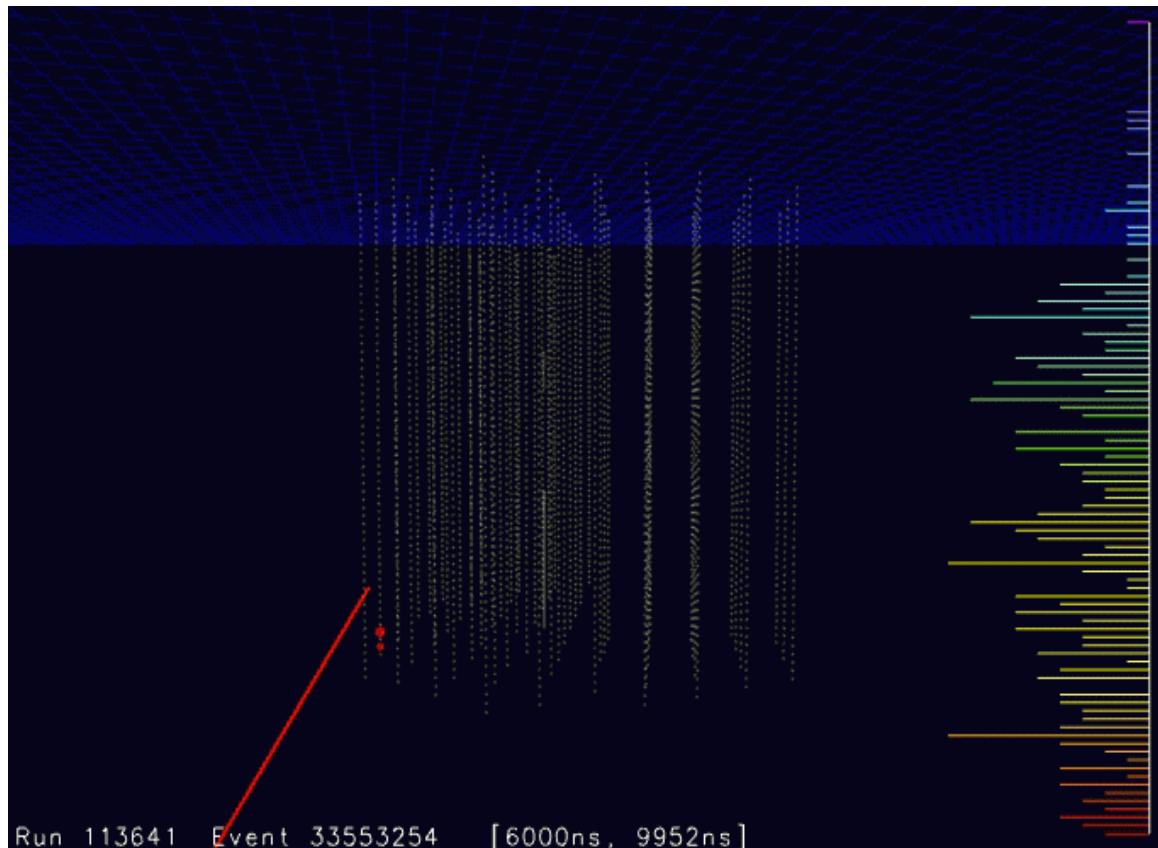


Event rates

Strings	Data (year)	Livetime	trigger rate (Hz)	HE v 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	360 days	2700	~120/day
IC86-II	current		2700	running

IC86 achieving ~ 99% uptime

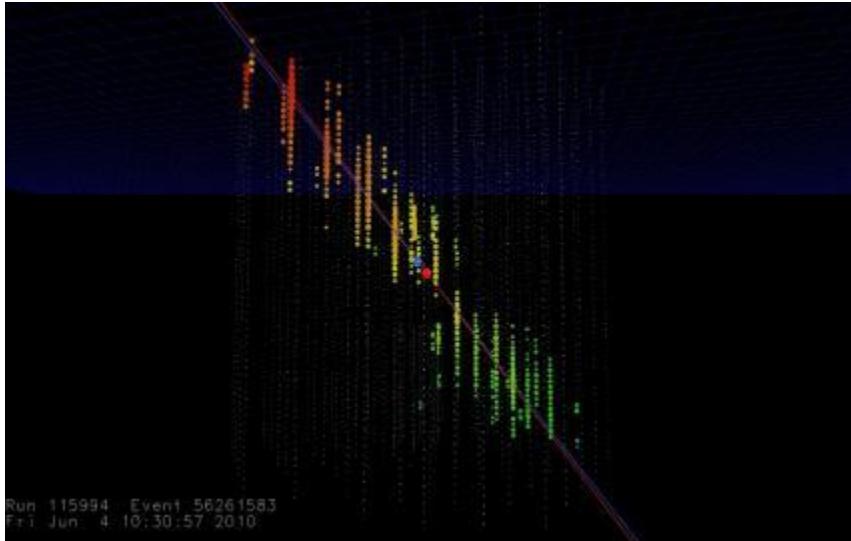
Neutrino Example



With 40 strings, 2009 May

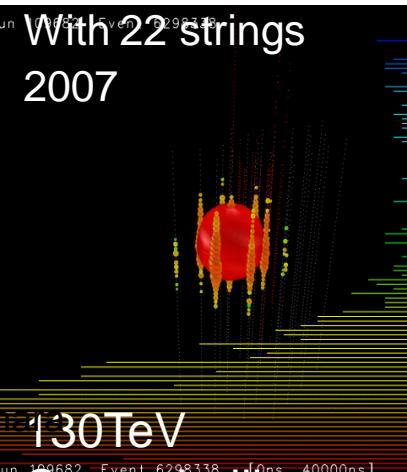
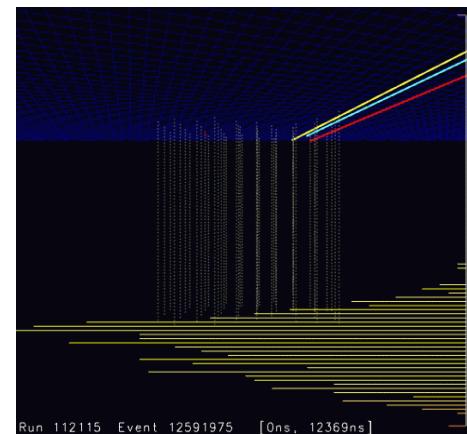
IceCube Events

With 79 strings, 2010 June



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

With 40 strings, 2008 Dec

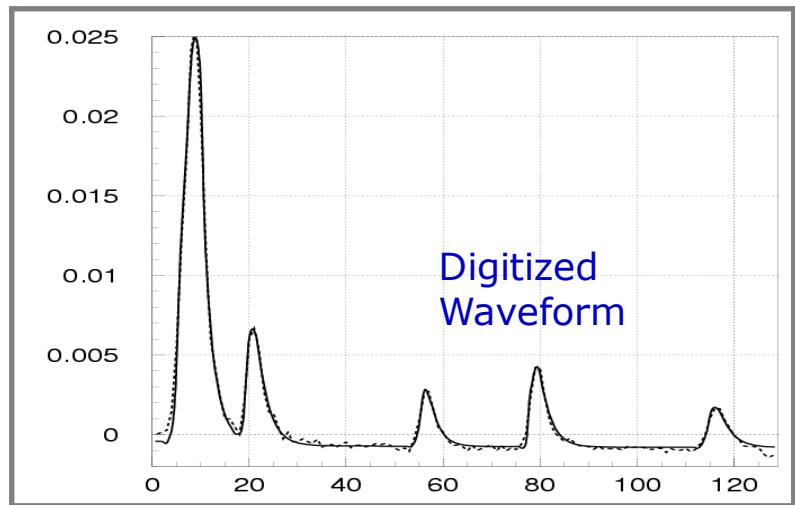


Waveform examples from spe to 10000 pe

25 cm PMT



single pe level



7V

O(10000)pe

4

1

0

2012/11/30

NPE = Integrated charge/PMT gain

Aya Ishihara

SC

UHE neutrino analysis 2010-2012

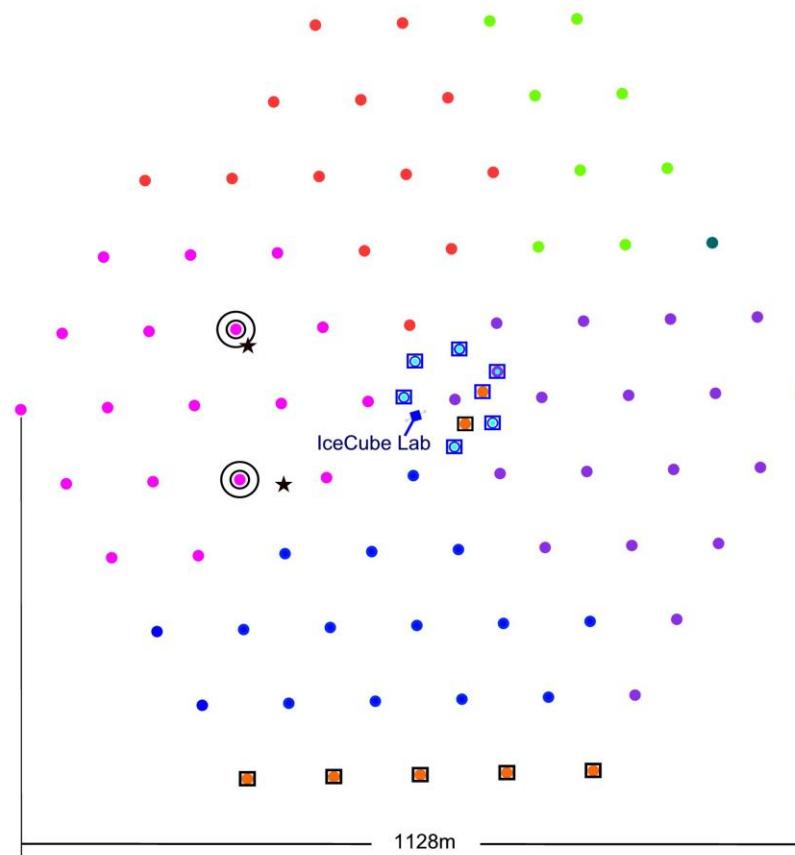
Data samples

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)



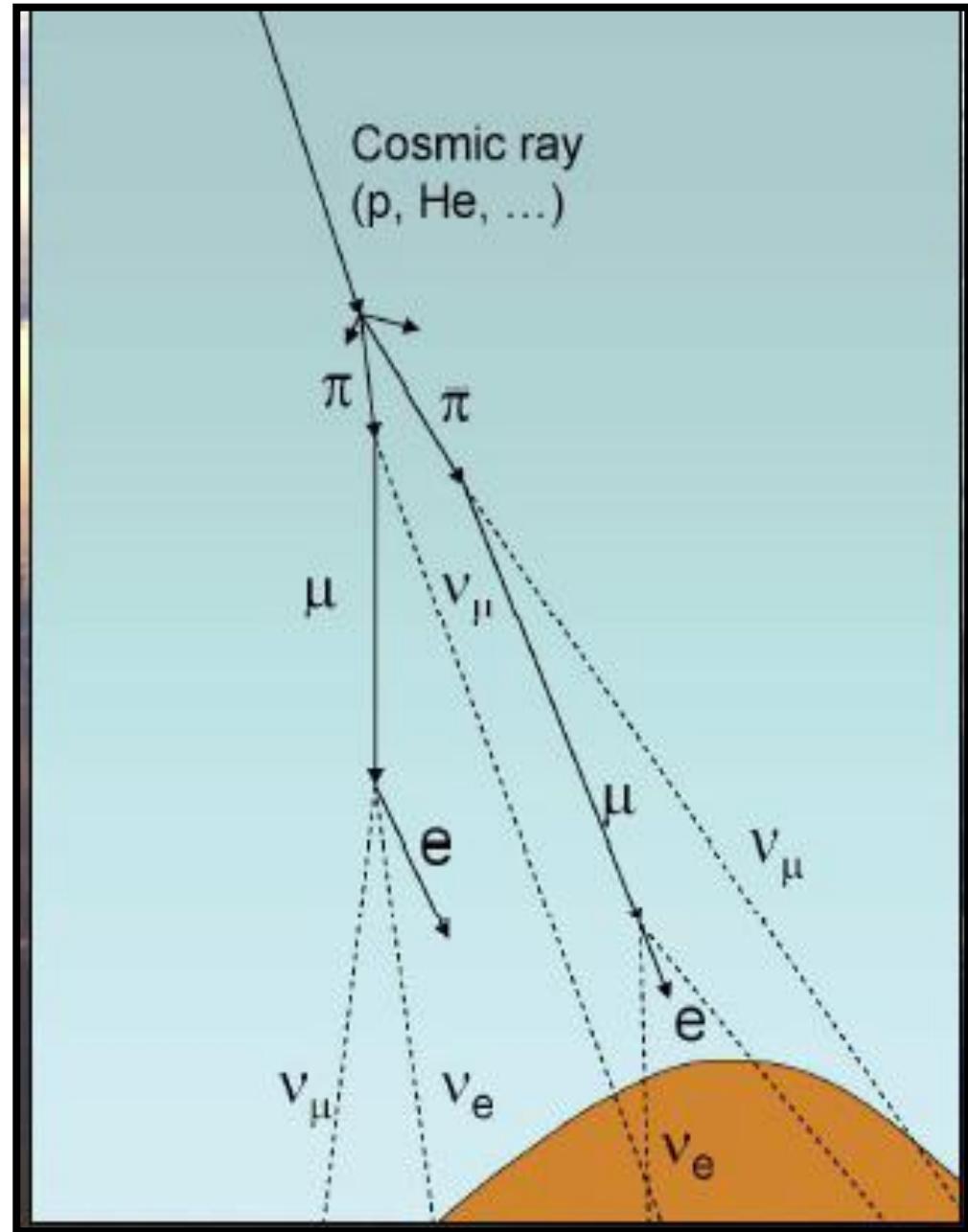
IceCube has been in a
stable operation for more
than 5 years

Background

**Atmospheric muons
(downward going and
very energetic,
dominated in number)**

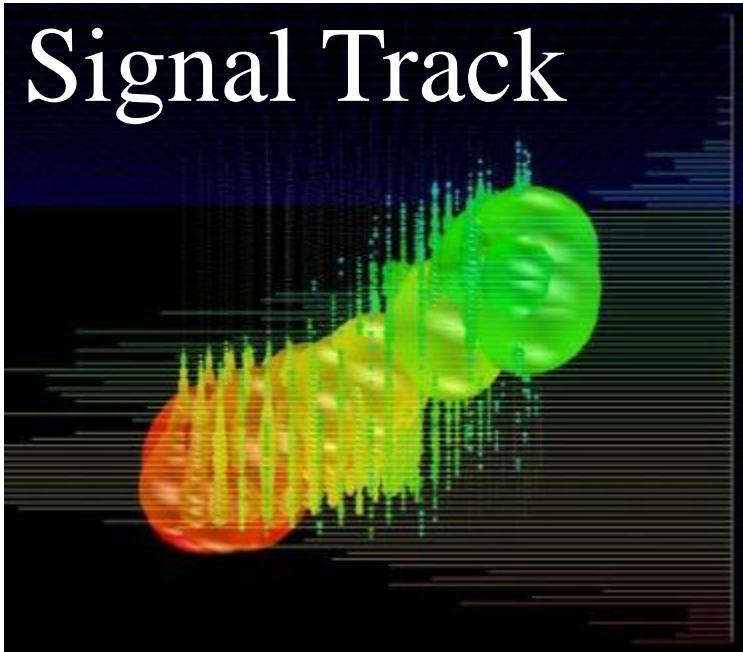
and

**Atmospheric neutrinos
(full angle, less
energetic, smaller in
rate)**



Signal and Background events

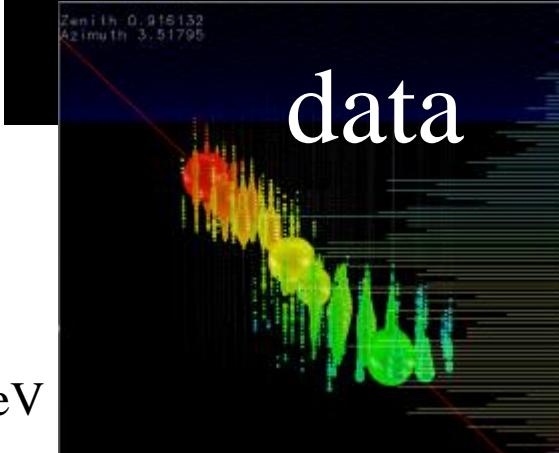
Signal Track



Muon bundles MC



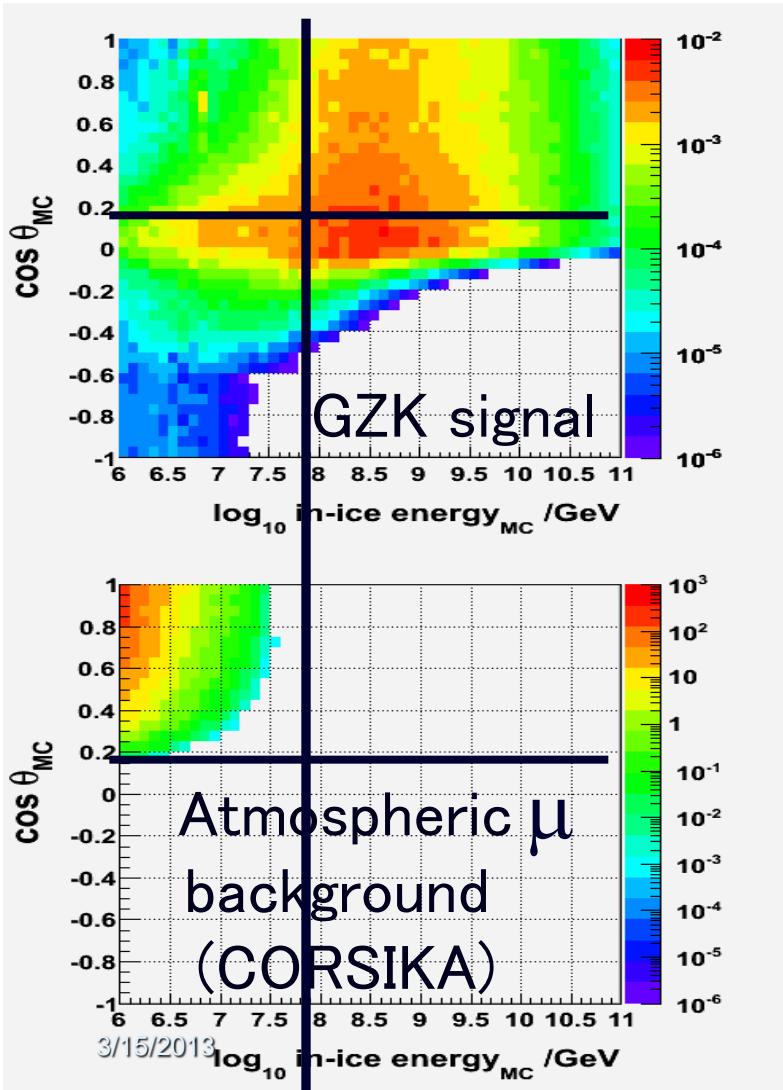
data



data

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

A Strategy for search for ultra-high energy neutrinos



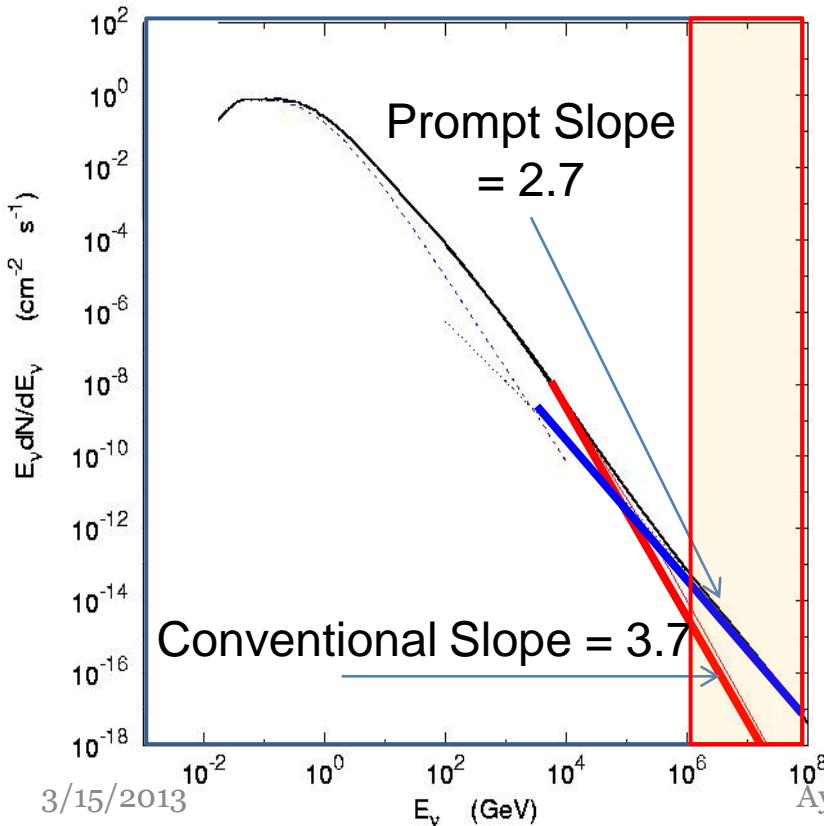
Background energy smaller than signal

Background is vertical downward-going while signal comes near horizon

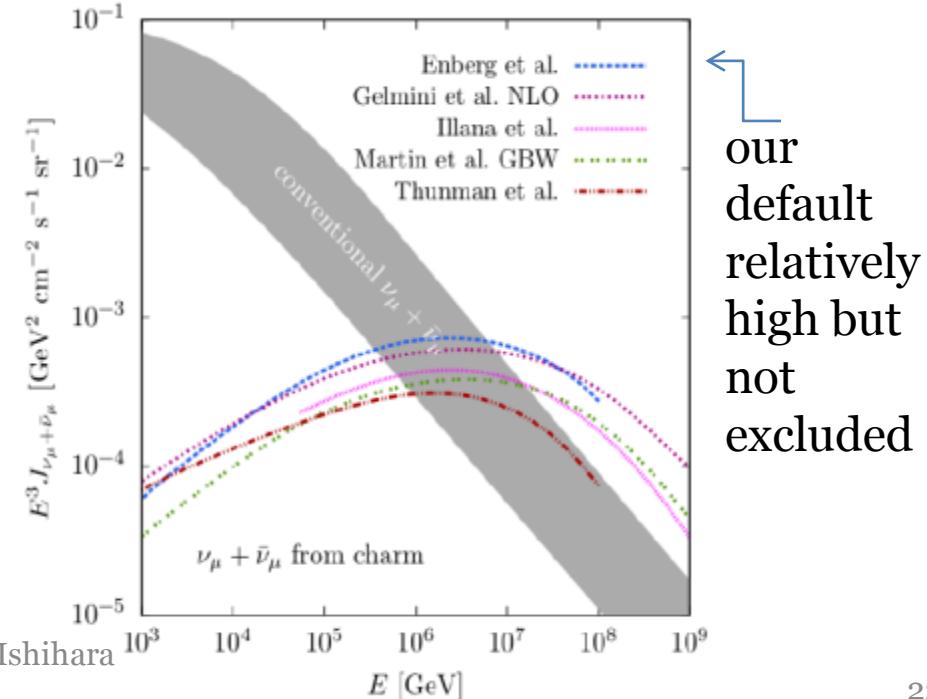
Atmospheric neutrinos in PeV

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

No clear evidence of prompt atmospheric ν observed so far

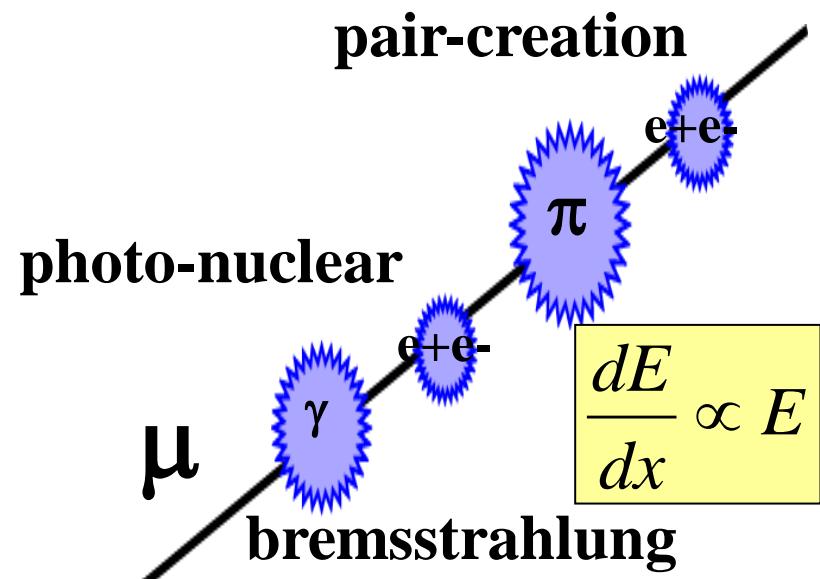


Physics of heavy flavor particle production



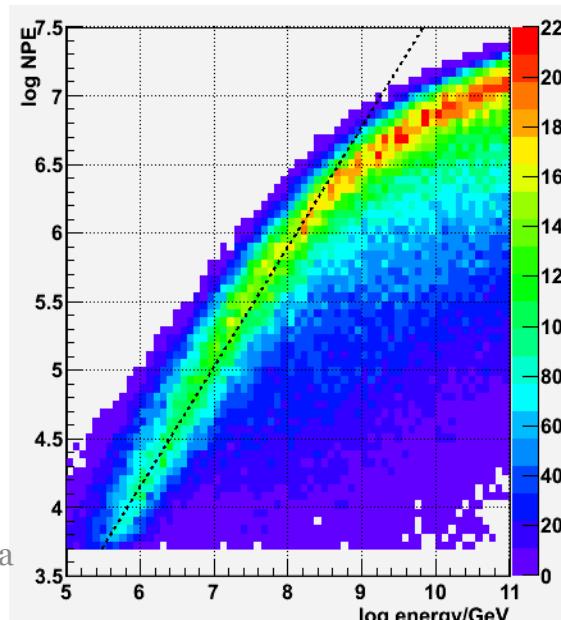
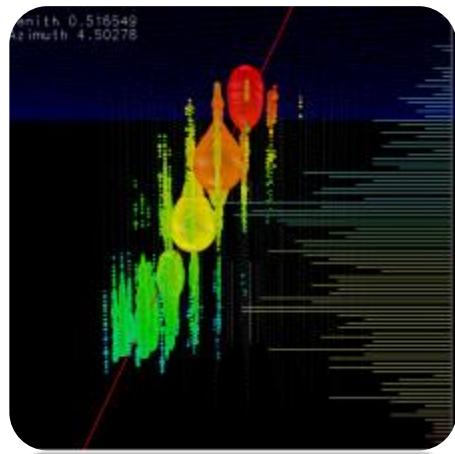
The Energy estimation

μ and τ tracks lose their energy by radiative processes



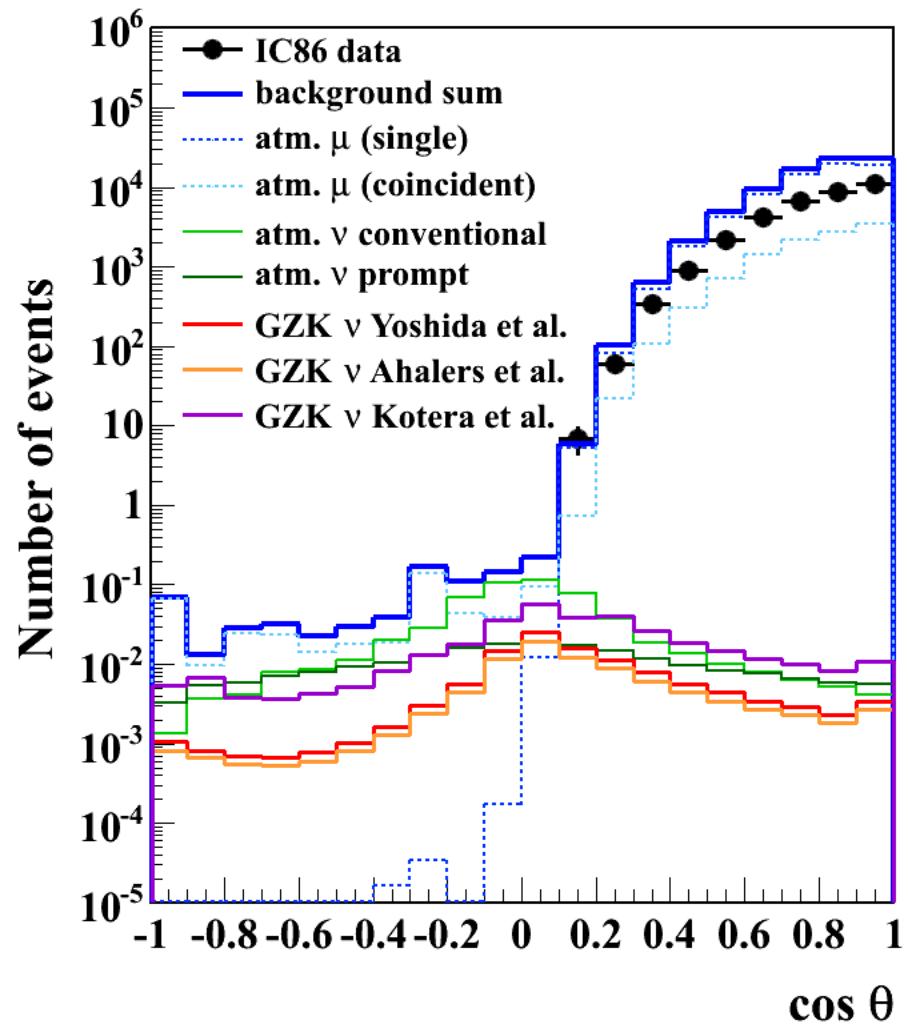
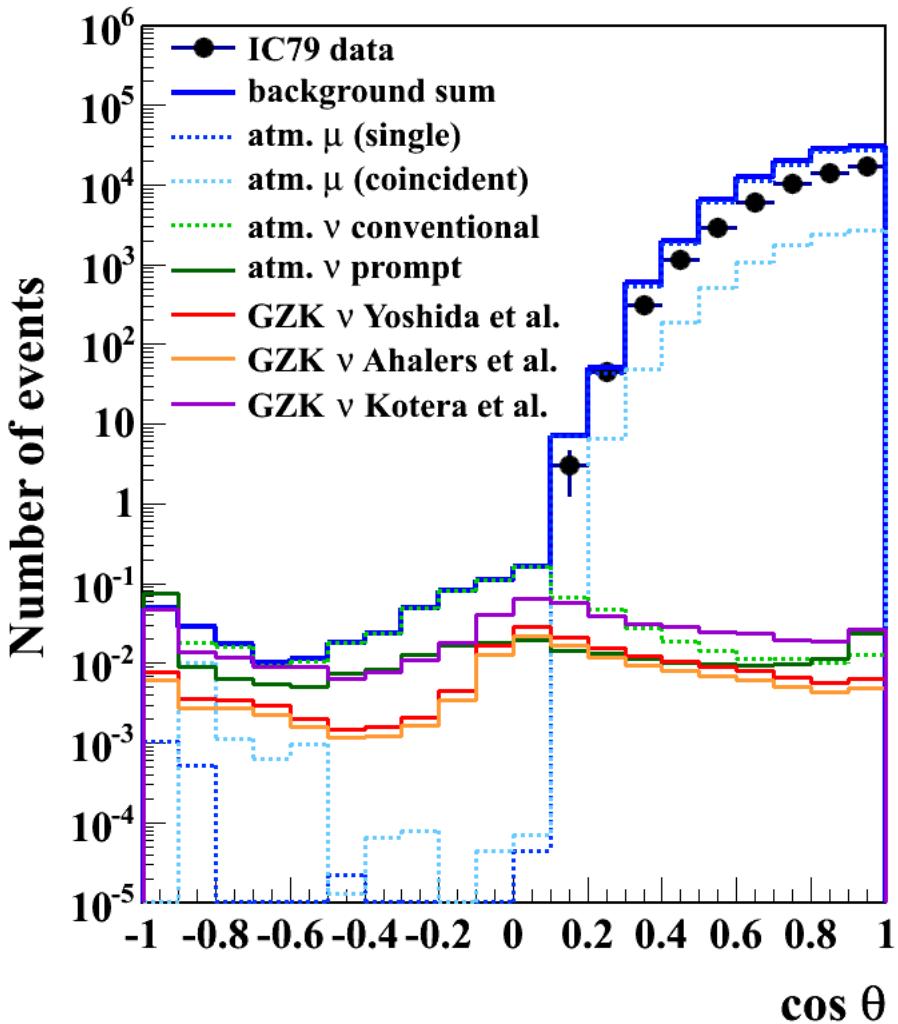
Energy of incoming particle \propto Energy-losses in detector \propto number of photo electrons (NPE)

channel # > 300



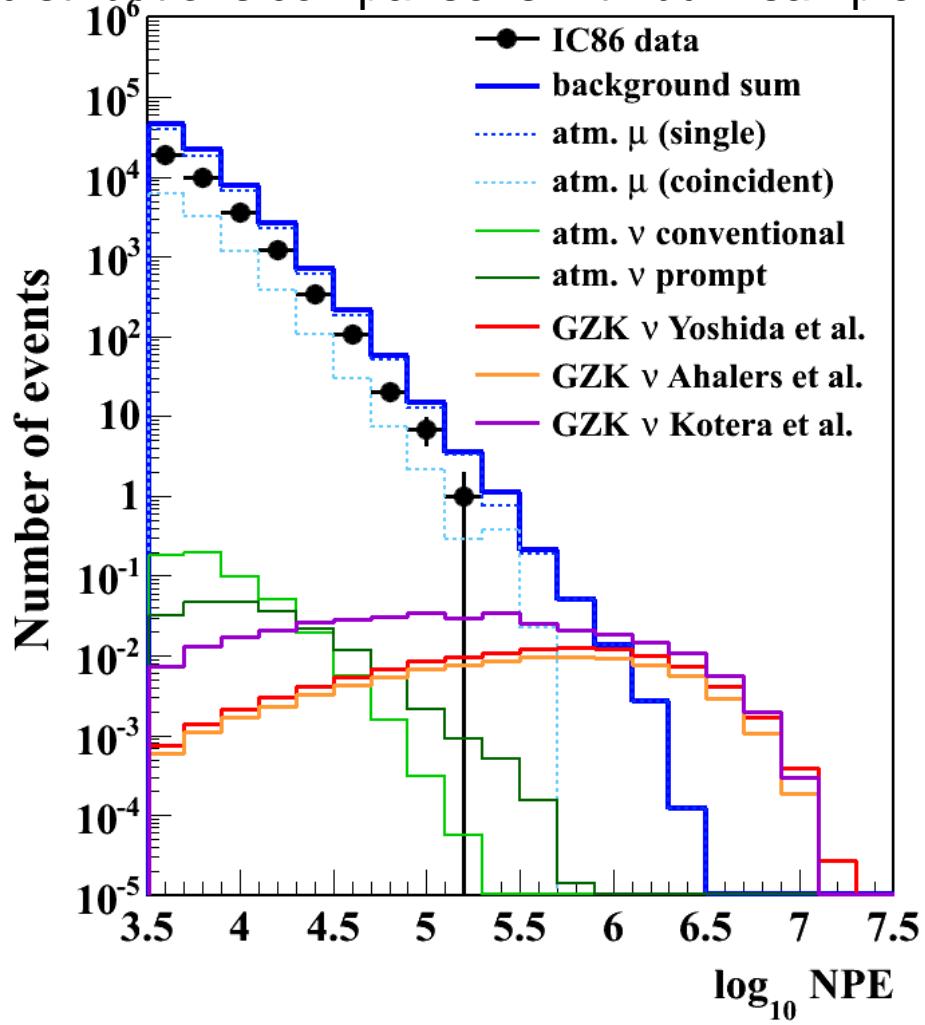
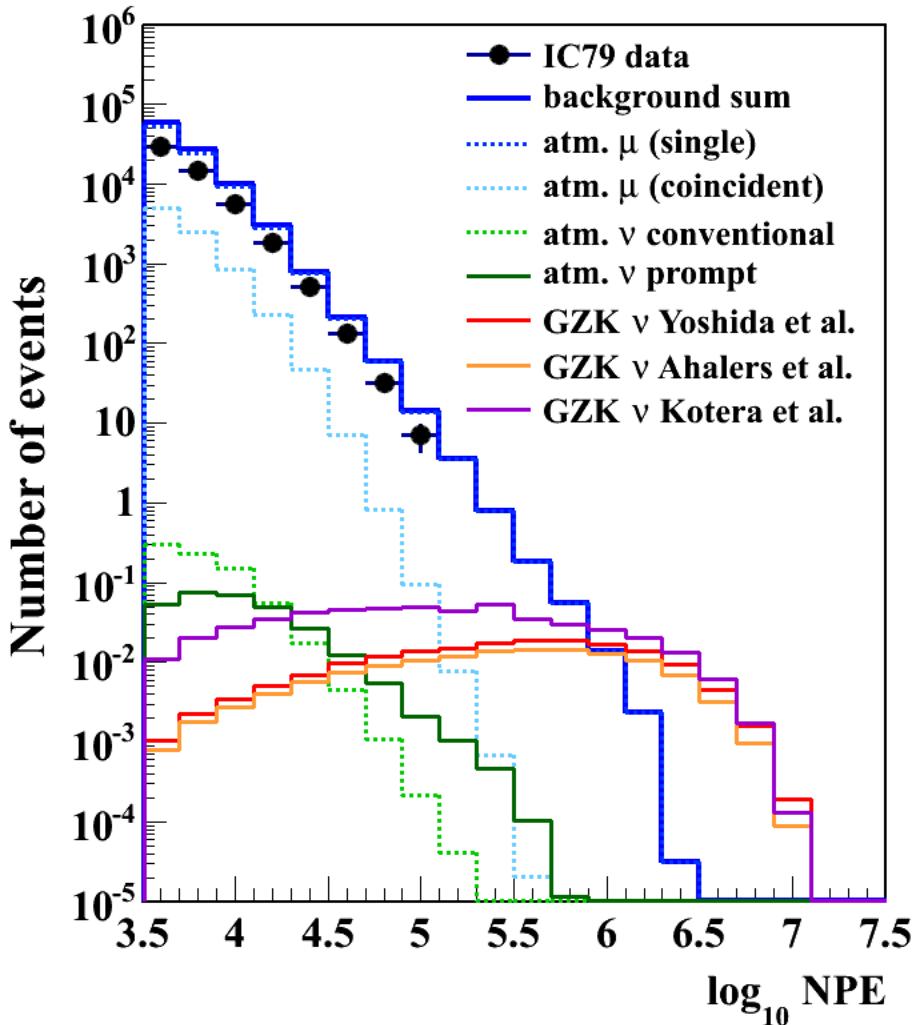
Analysis Level ZA Distributions

cos zenith angle distributions comparisons with burn sample

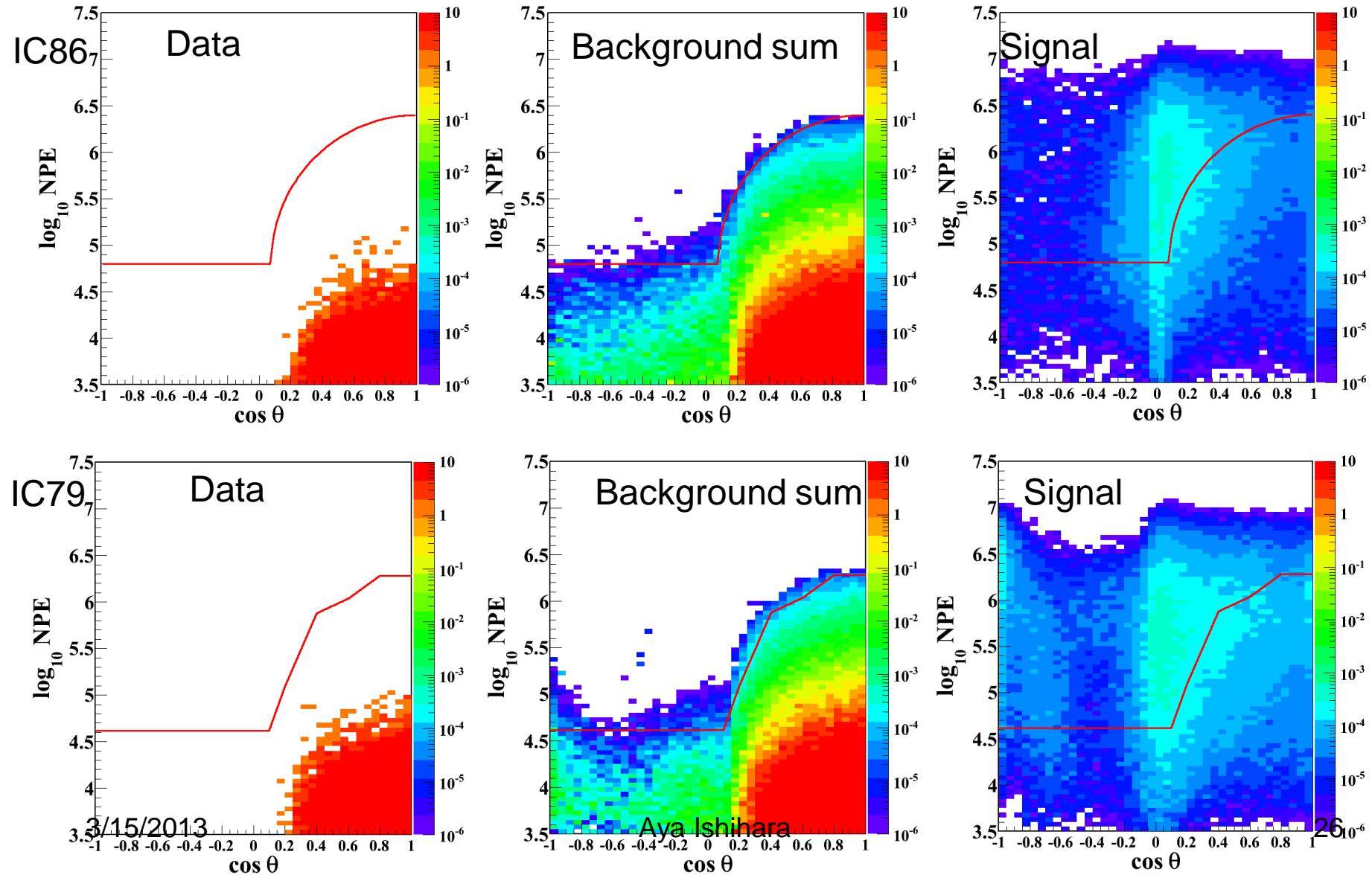


Analysis Level NPE Distributions

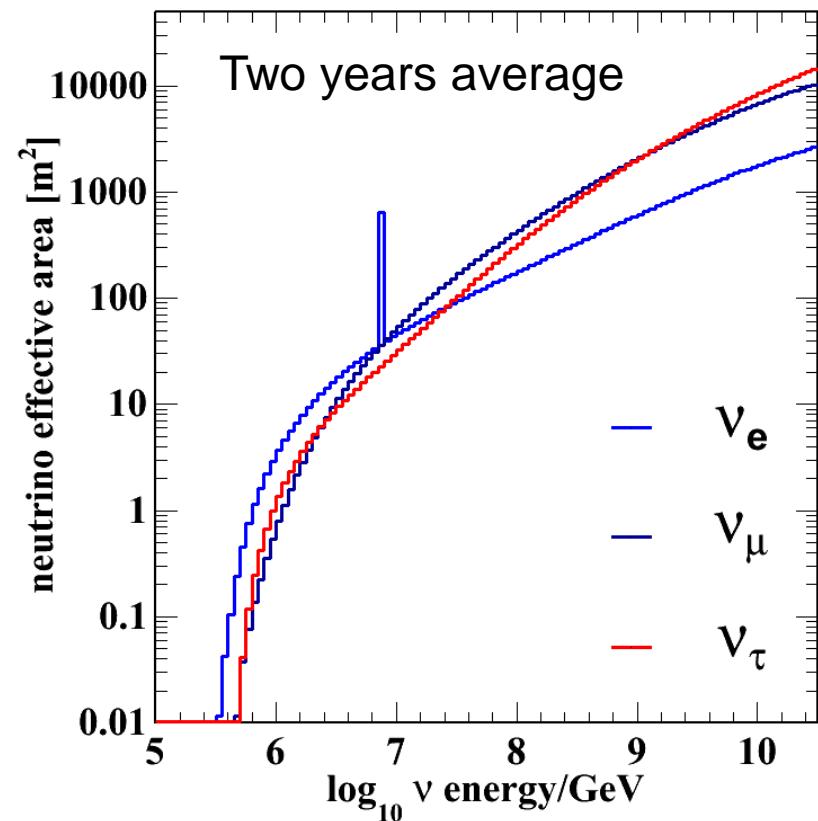
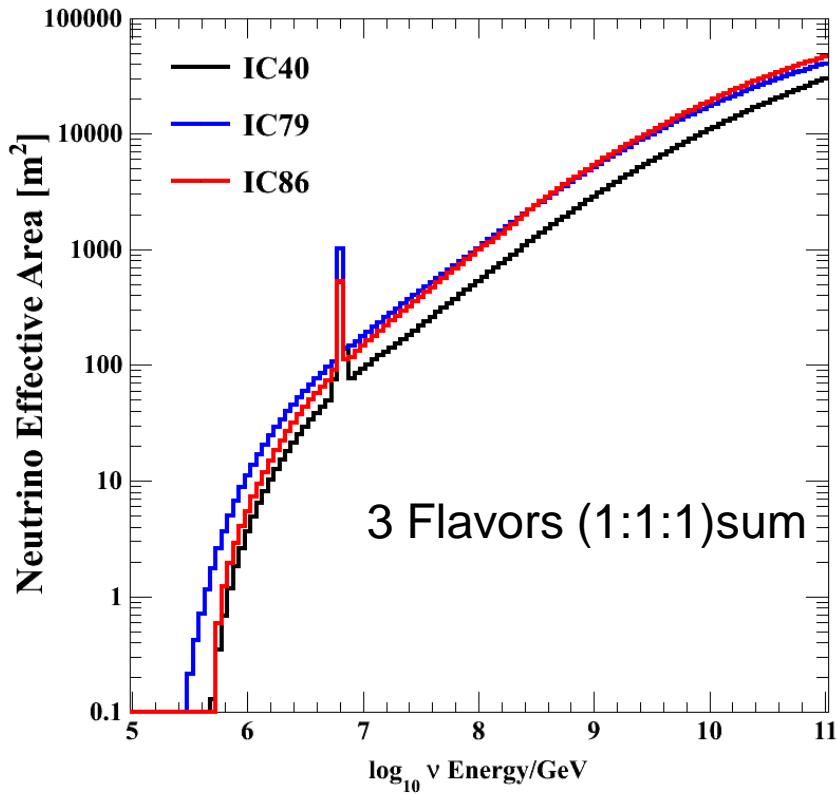
NPE distributions comparisons with burn sample



Analysis Level NPE vs ZA



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

Background event rates per effective livetime

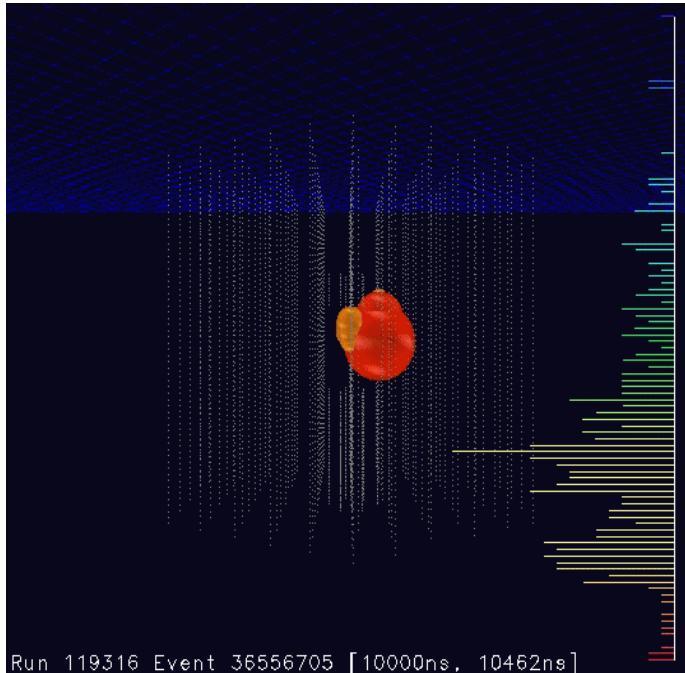
Contribution	IC79	IC86	Total (615.9days)
Atm mu	0.0296	0.0081	0.0377
conv Atm nu	0.0074	0.0044	0.0118
Atm mu and conv Atm nu	0.0370	0.0125	0.0495
prompt	0.0191	0.0137	0.0328
Atm mu, conv Atm nu and prompt	0.0561	0.0262	0.0823

GZK v Signal Event Rates

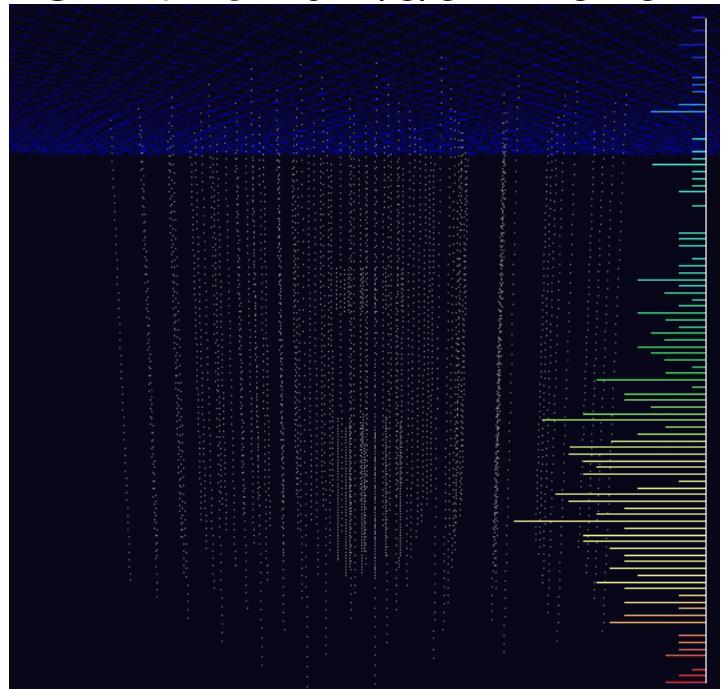
		IceCube 2010-2012 per 615.9days	
		All contributions (B)	Contribution > 100 PeV
	IceCube 2008-2009 Phys. Rev D83 092003 (2011) 333days		
GZK (Yoshida m=4)*	0.57	2.0	1.9
GZK (Ahlers max) **	0.89	3.0	2.9
GZK (Ahlers best fit) **	0.43	1.5	1.4
GZK (Kotera, dip FRII) ***		4.2	2.7
GZK (Kotera, dip SFR1)***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

After unblind - Observation of 2 events

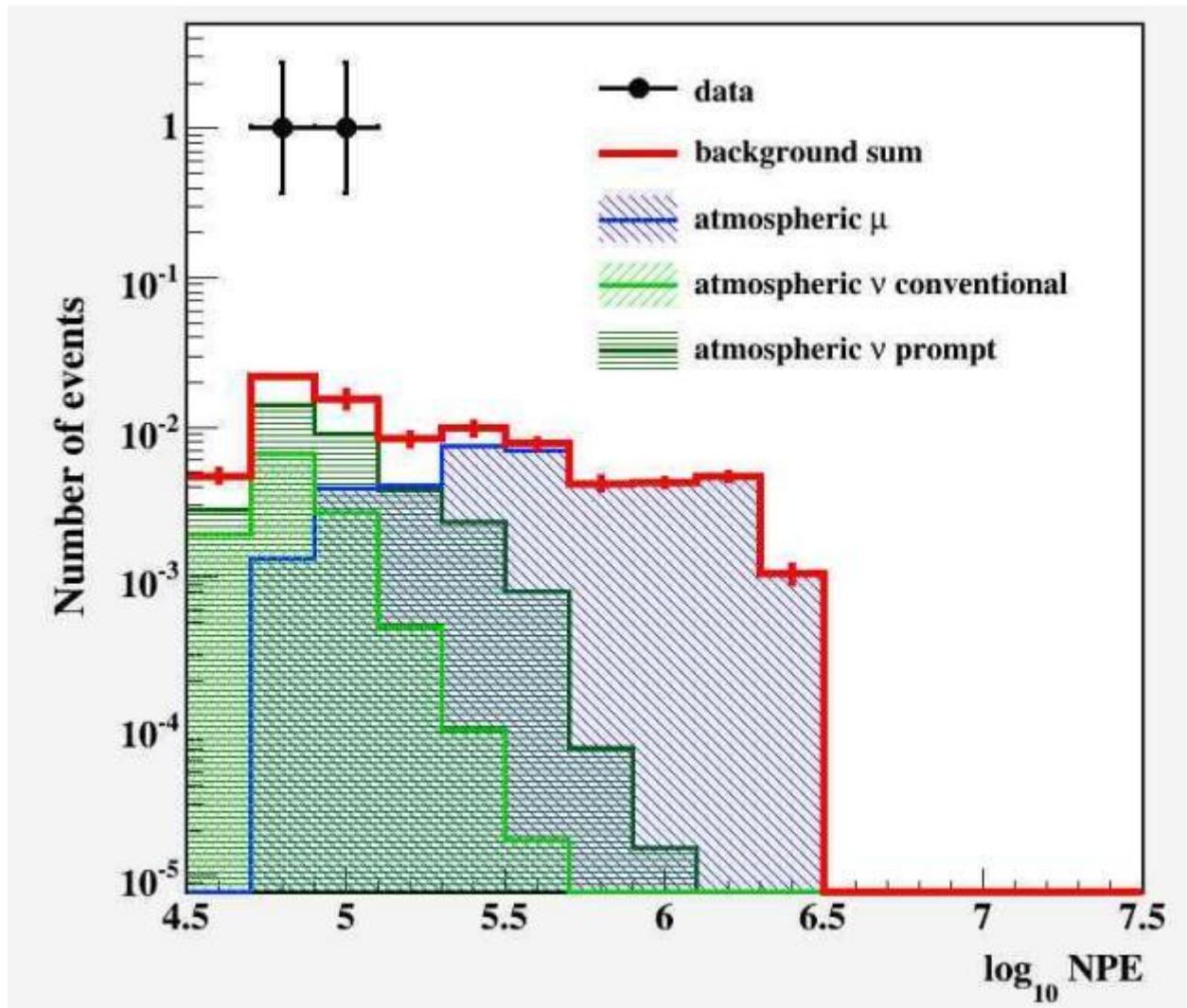
Run119316-Event36556705
NPE 9.628×10^4
GMT time: 2012/1/3 9:34:01



Run118545-Event6373366
NPE 6.9928×10^4
GMT time: 2012/8/8 12:23:18

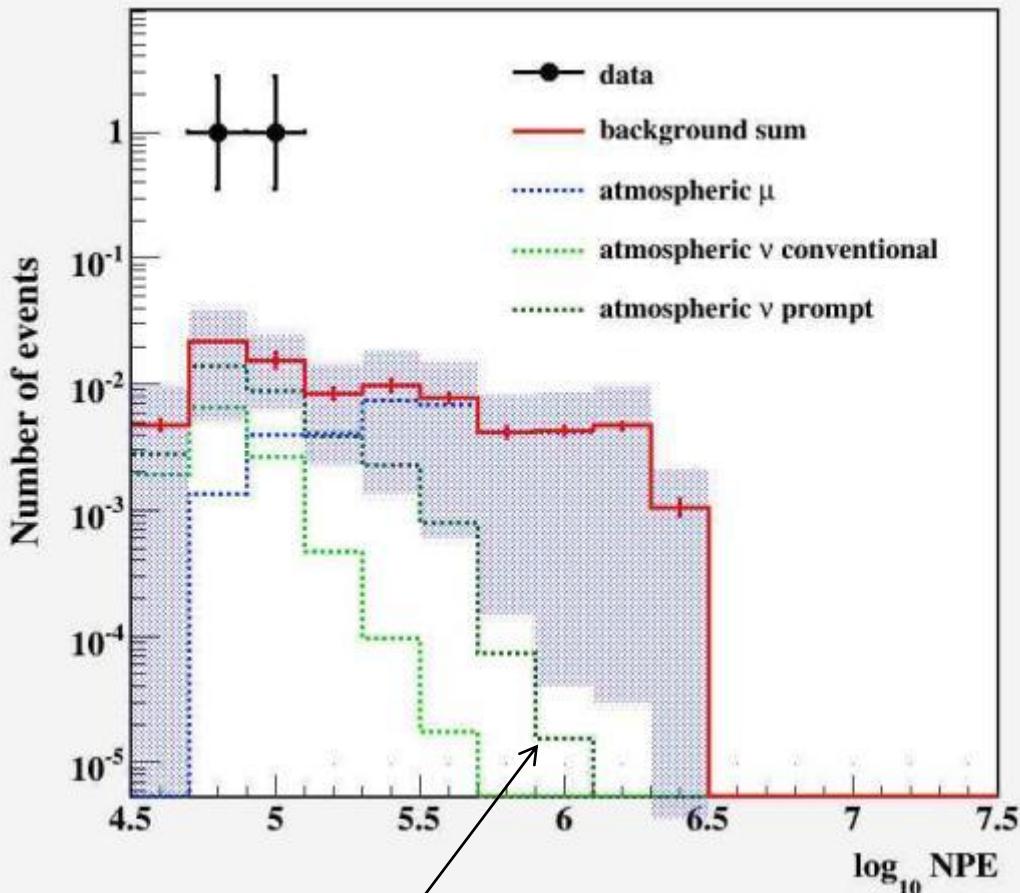


Background NPE distributions



Two events observed over an atmospheric background of 0.0823 events/livetime

Background Errors



The largest uncertainty is on the prompt (charm) ν model (a factor of 2 in pQCD model, up to a factor of 5 in nonpQCD)

a Ishihara

Sources	conventional Atm. μ , ν (%)	prompt (%)
Statistical error	± 7.3	± 1.1
DOM efficiency	+63.7, -30.8	+21.3, -18.9
Ice property and detector responses	-48.0	-29.8
Cosmic-ray flux variation	+24.0, -39.0	± 30.0
Cosmic-ray composition	-61.0	
Hadronic interaction	+13.5	
ν yield from cosmic-ray nucleon	± 3.5	
Total	$\pm 7.3(\text{stat})$ +69.5–92.5(sys)	$\pm 1.1(\text{stat})$ +36.8–46.4(sys)

P-values as a counting experiment

conventional atm nu and atm mu

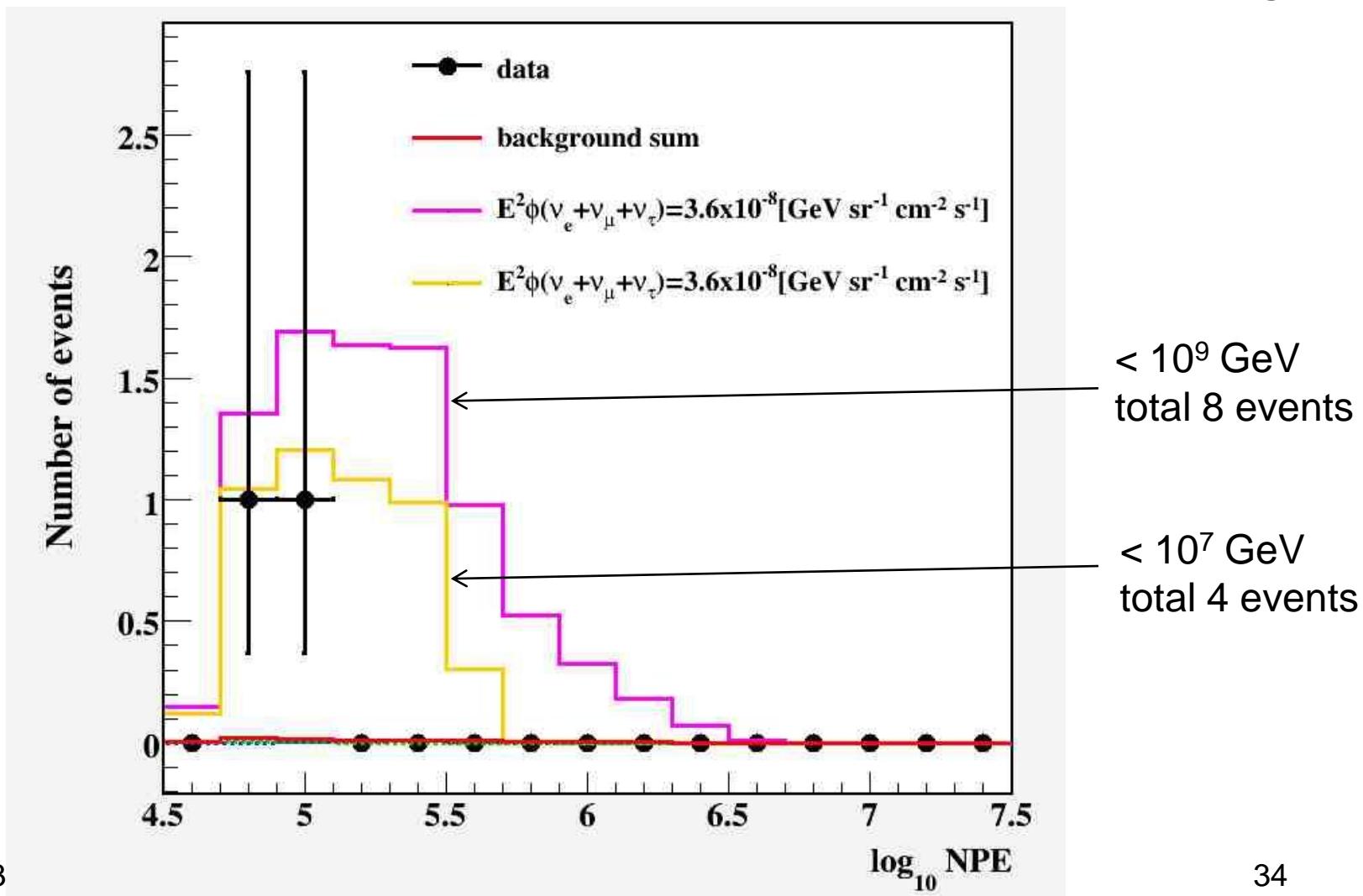
- BG 0.00495, observed 2
- BG errors assumes a flat distribution between +0.028 and -0.047
- **p-value with sys FC (BG=0.049500 observed=2)= 9.0x10⁻⁴**
- **3.13 sigma equivalent**

conventional and prompt atm nu and atm mu

- BG 0.00823, observed 2
- BG errors assumes a flat distribution between +0.039 and -0.055
- **p-value with sys FC (BG=0.082300 observed=2)=2.8x10⁻³**
- **2.77 sigma equivalent**

E^{-2} signal flux NPE distribution

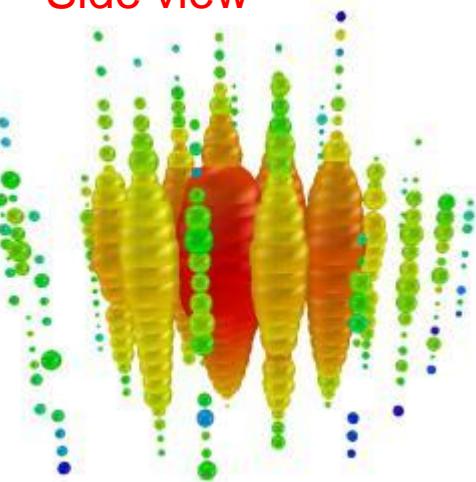
With different cut off energies



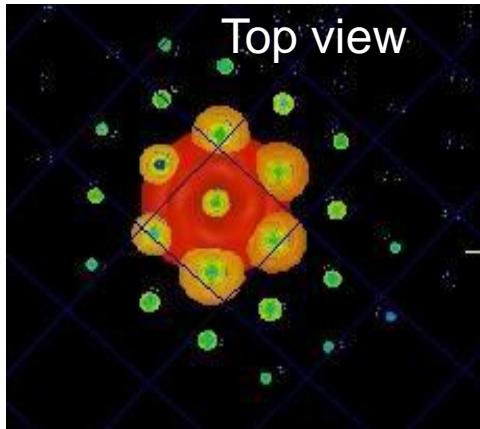


The two event properties

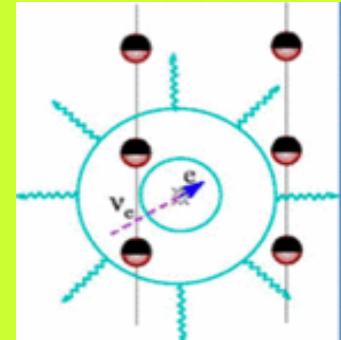
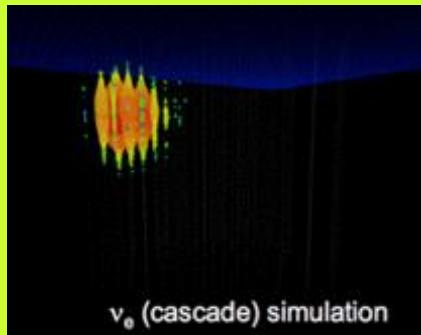
Side view



Top view



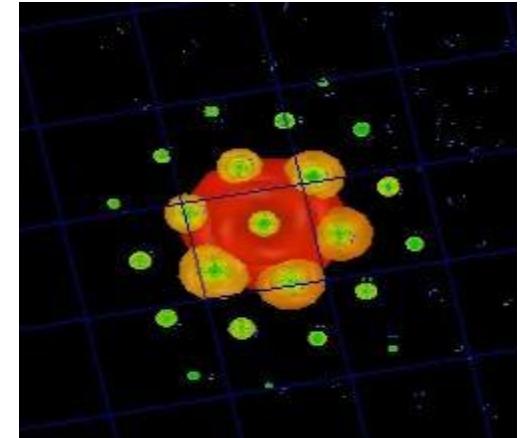
CC/NC interactions in the detector



No indication
that they are instrumental
artifacts
that they are cosmic-ray
muon induced

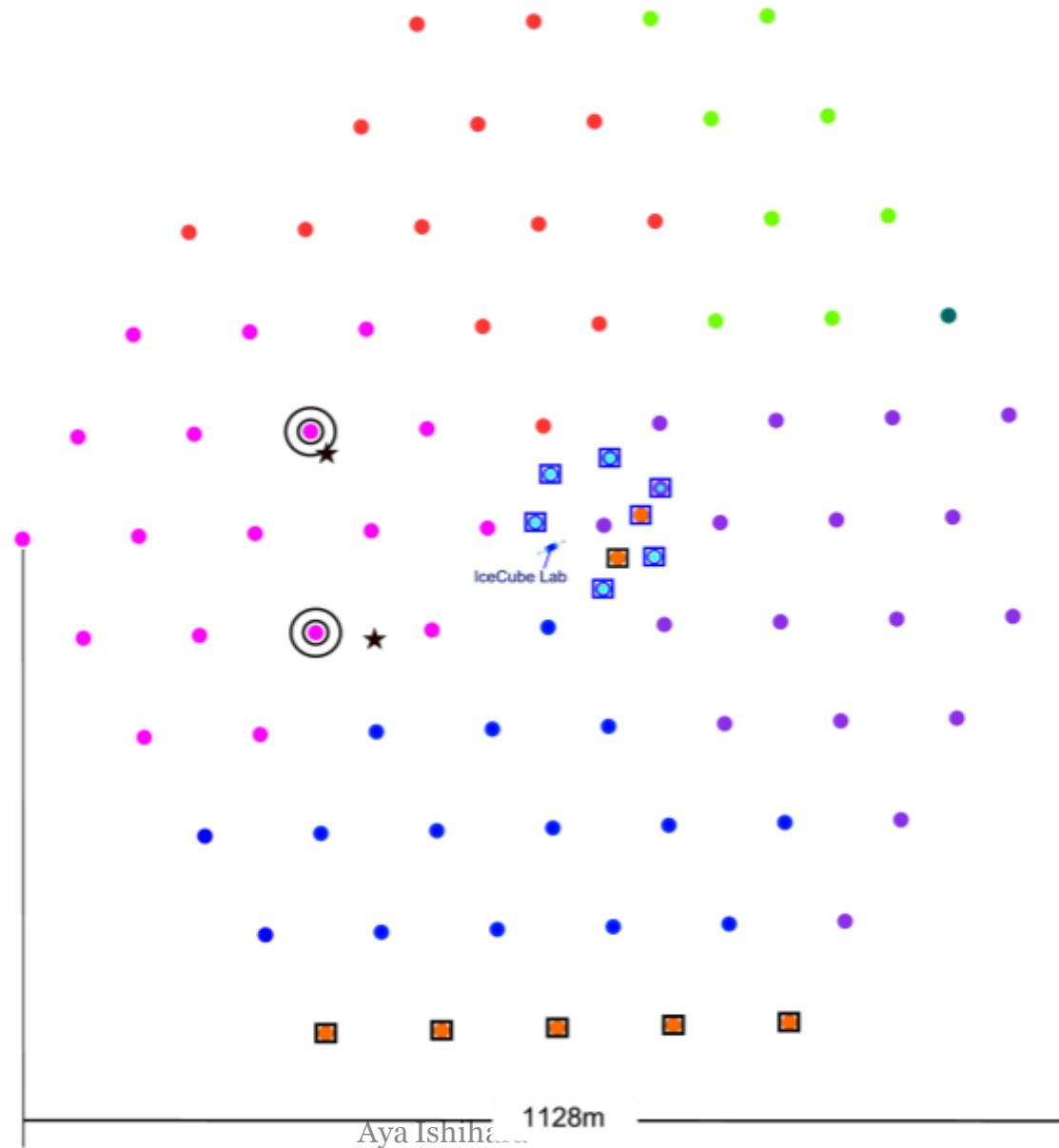


we can use **dedicated
cascade hypothesis** to the
reconstructions of these special
events



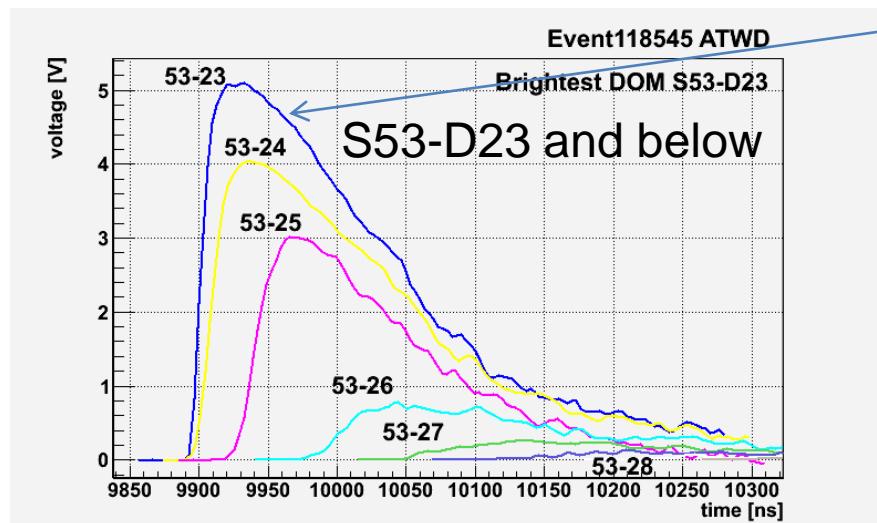
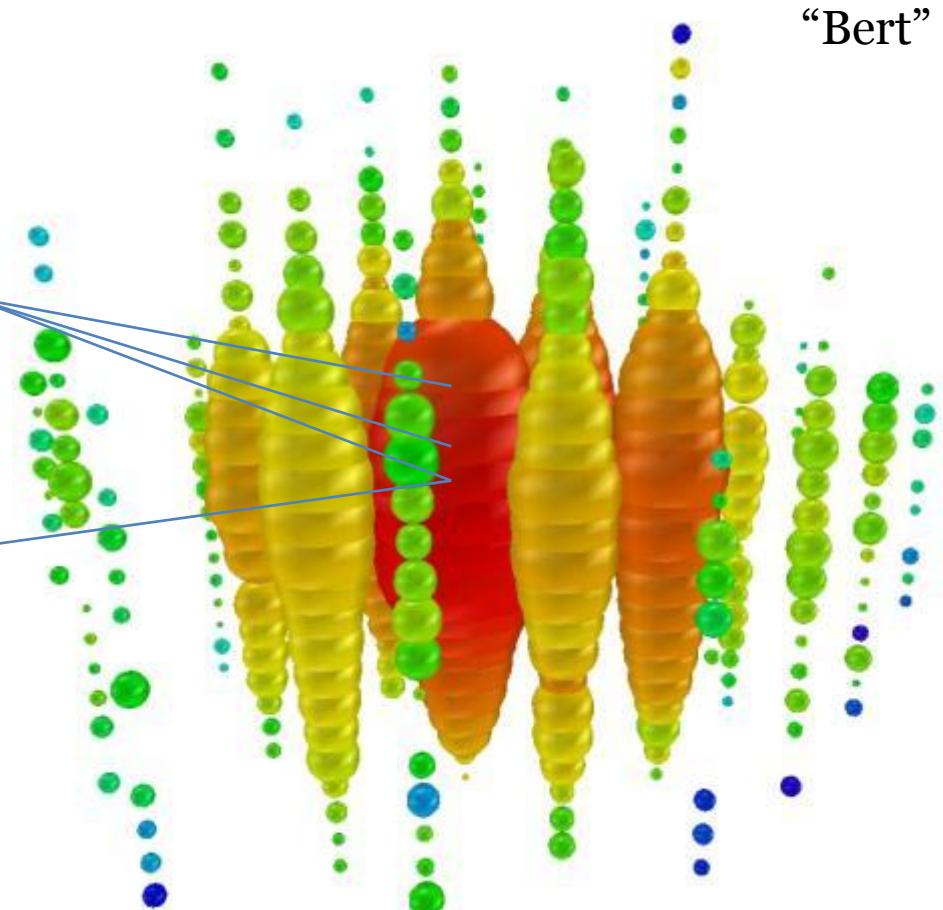
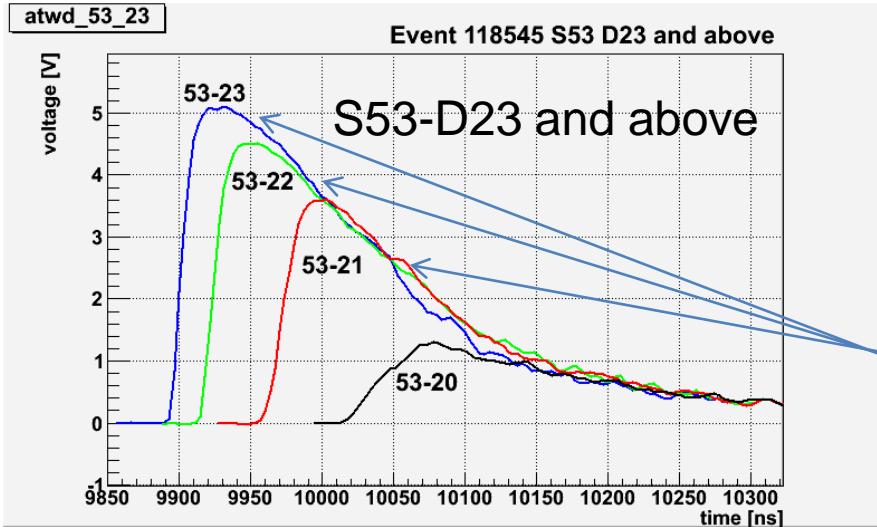
The highest Charged String Positions

Well
contained
events

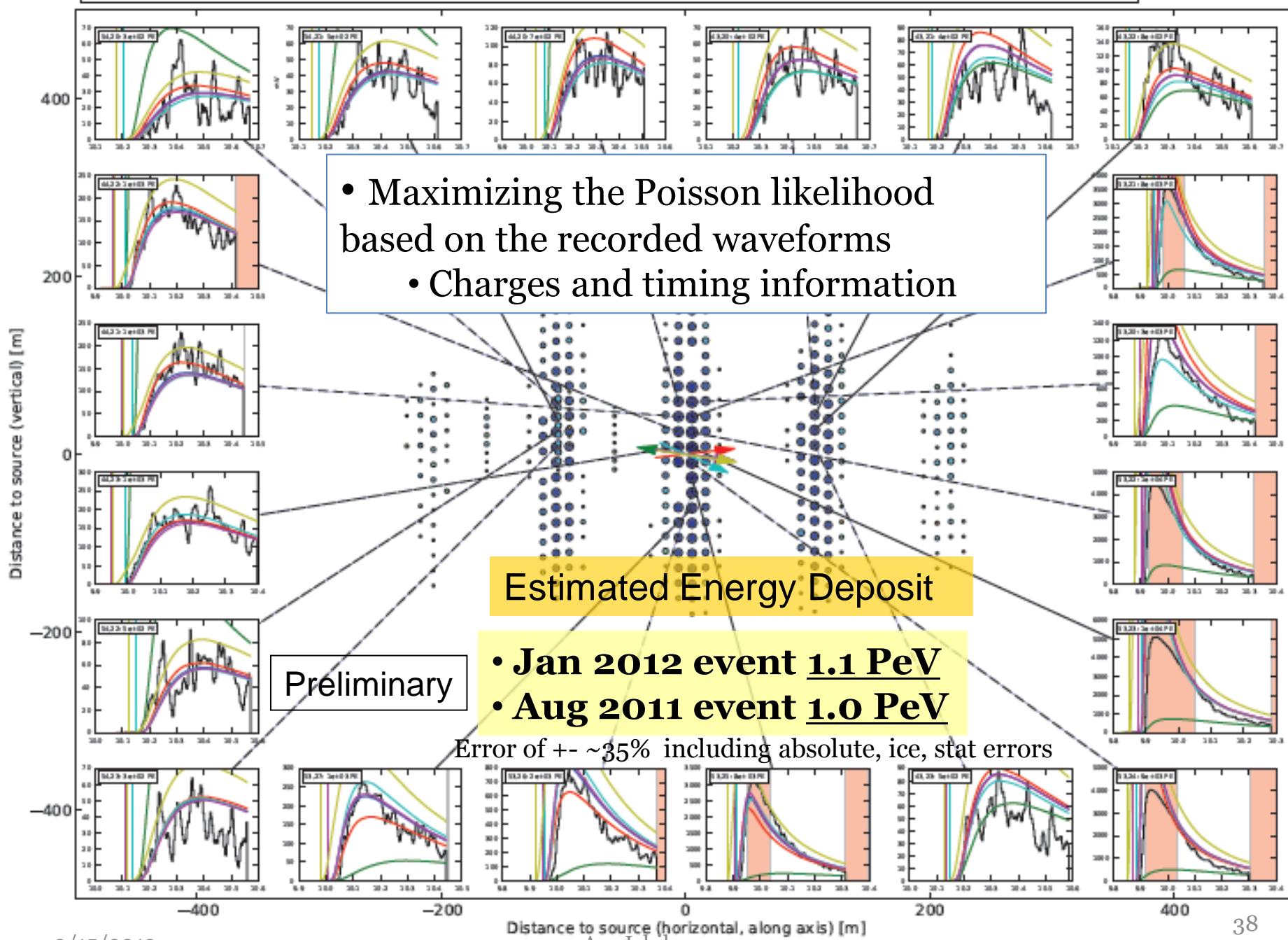


Event from Aug-2011

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



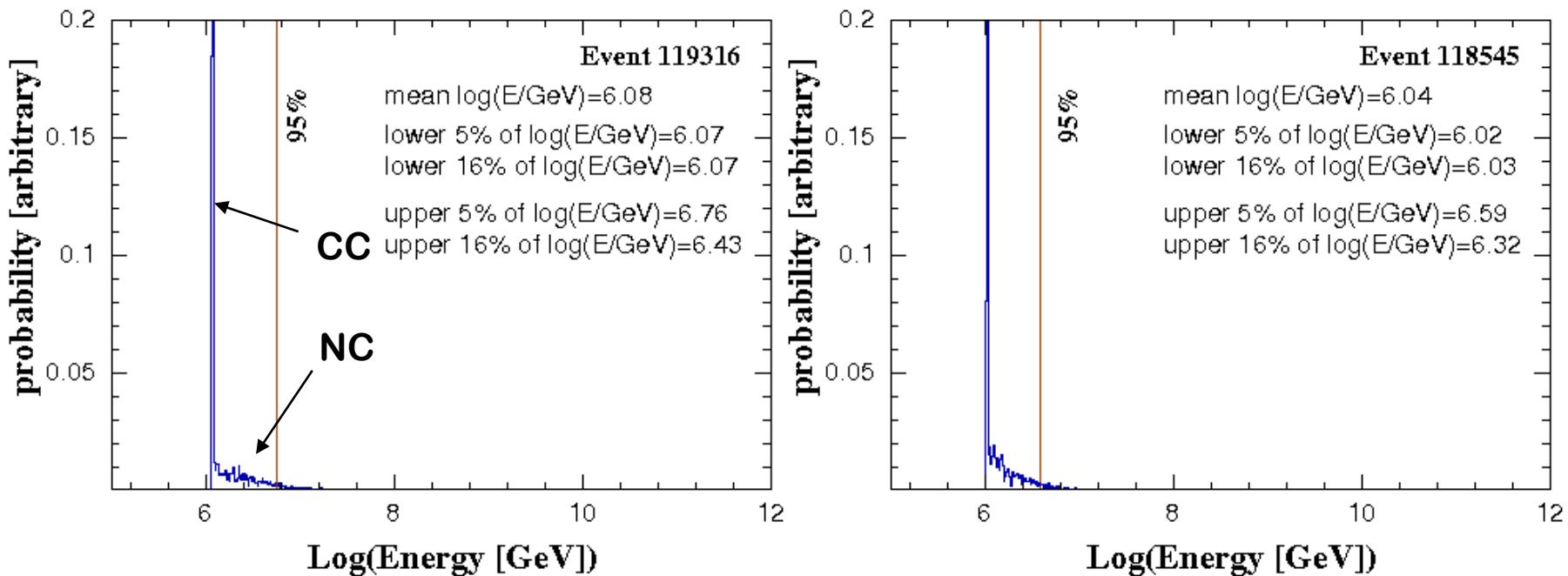
— ATWD 1/2
 — MonopodFit (ATWD1/2)
 — MonopodFit (reversed) (ATWD1/2)
 — MonopodFit (+20 deg) (ATWD1/2)
 — MonopodFit (-20 deg) (ATWD1/2)
 — MonopodFit (extended) (ATWD1/2)
 — MonopodFit (double bang) (ATWD1/2)



Neutrino Energy

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

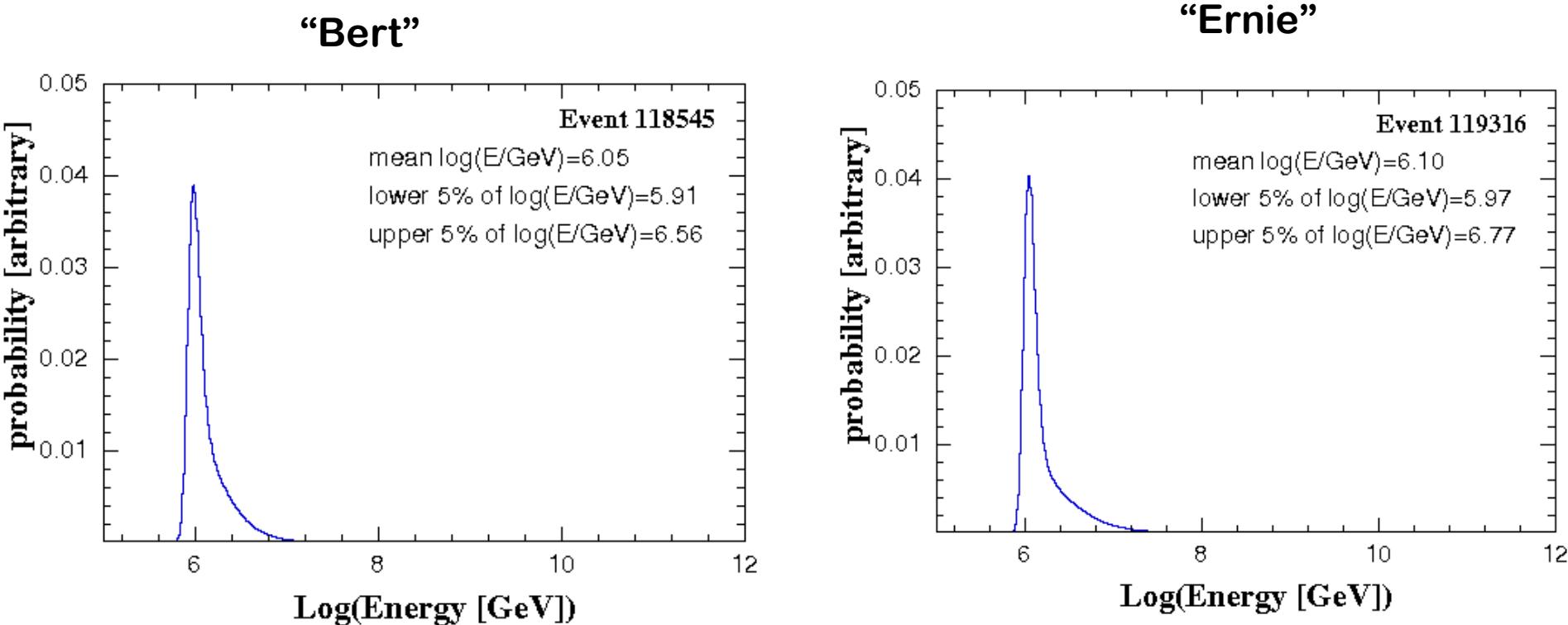
$\nu_x \rightarrow \nu_x + X$ (NC reaction) energy deposit = a partial neutrino energy



Both events: $\sim 1 \text{ PeV} < E_\nu < \sim 4 \text{ PeV}$ at the IceCube depth = in-ice energy

Neutrino Energy at the Earth surface

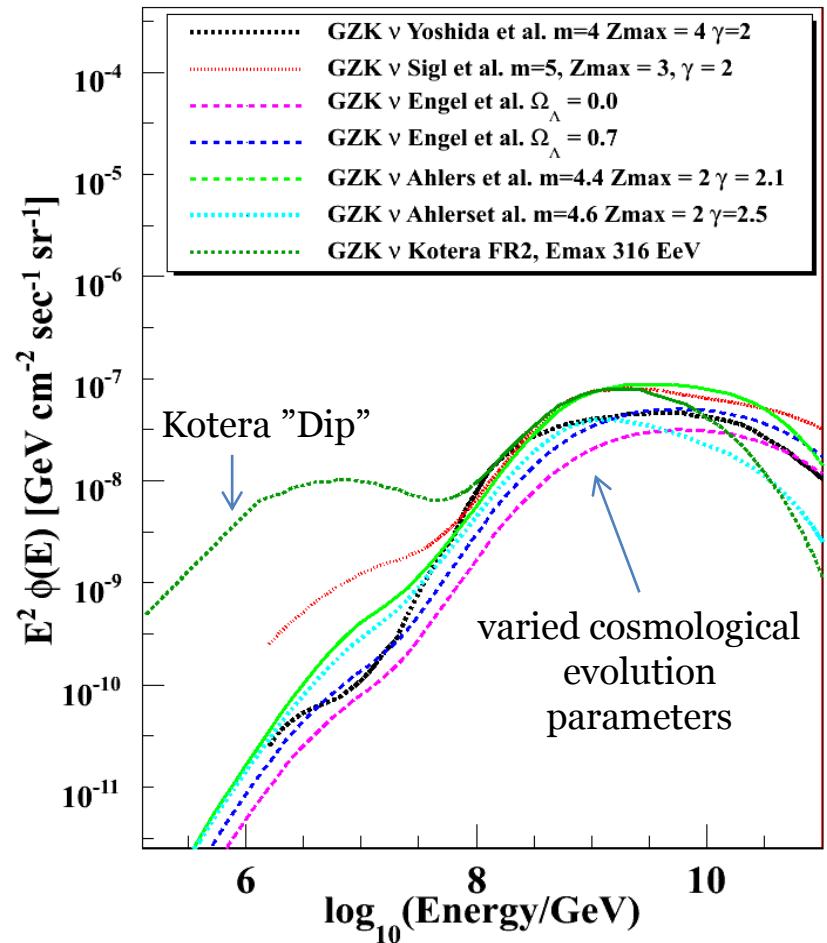
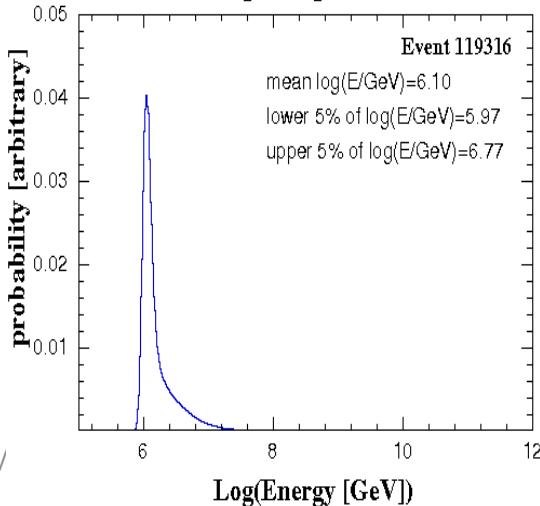
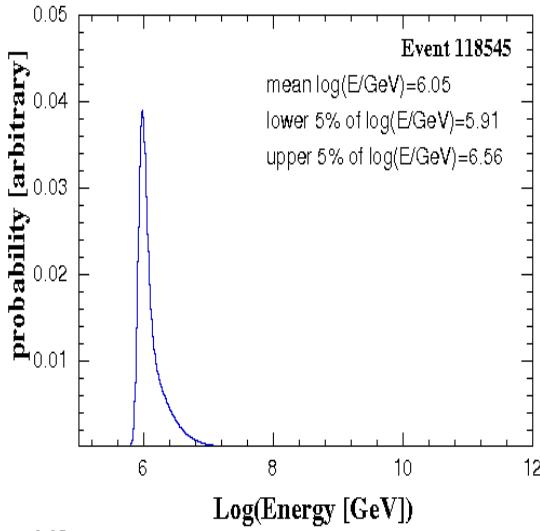
The in-earth neutrino propagation effects taken into account assuming the primary ν spectrum $\phi(E_\nu) \sim E_\nu^{-2}$



90% confidence interval of
810TeV-3.6PeV and 930TeV-5.9PeV

Implication to the highest energy cosmic-ray origin

observation \longleftrightarrow models the GZK neutrino



Two model tests

1. KS tests + full range event counting

Consistency check with the 2 event observation

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

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

The rate term

p-value =

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

Use the Kolmogorov-Smirnov statistics

2. Counting events above 100 PeV

Constraint on cosmological evolution parameters

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

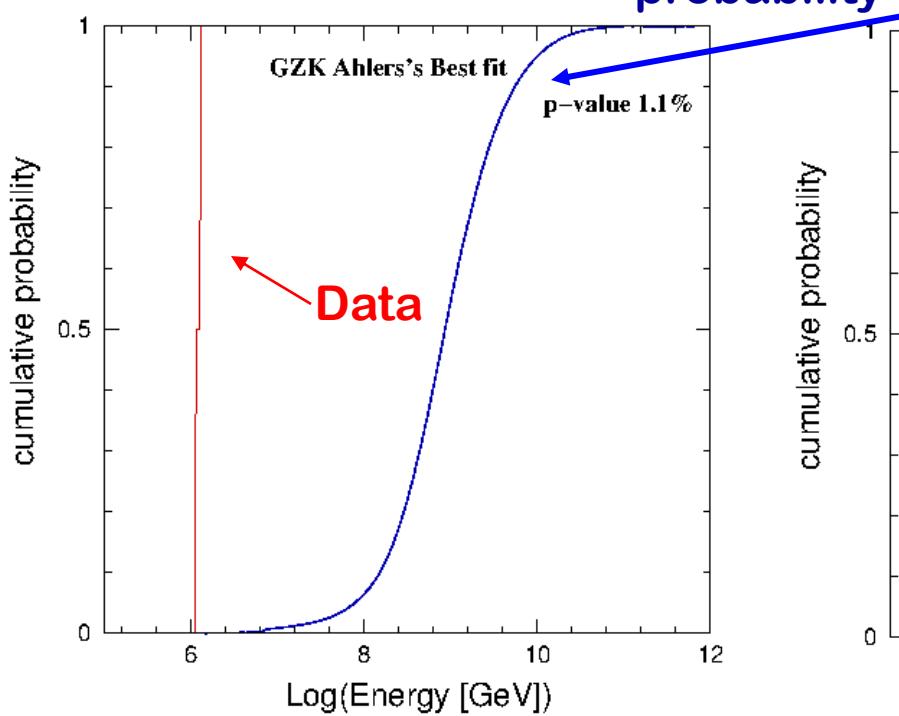
$$N_{100(1-\alpha)\%} = \sum_{n=0} P_n N_{n,(100-\alpha)\%}$$

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

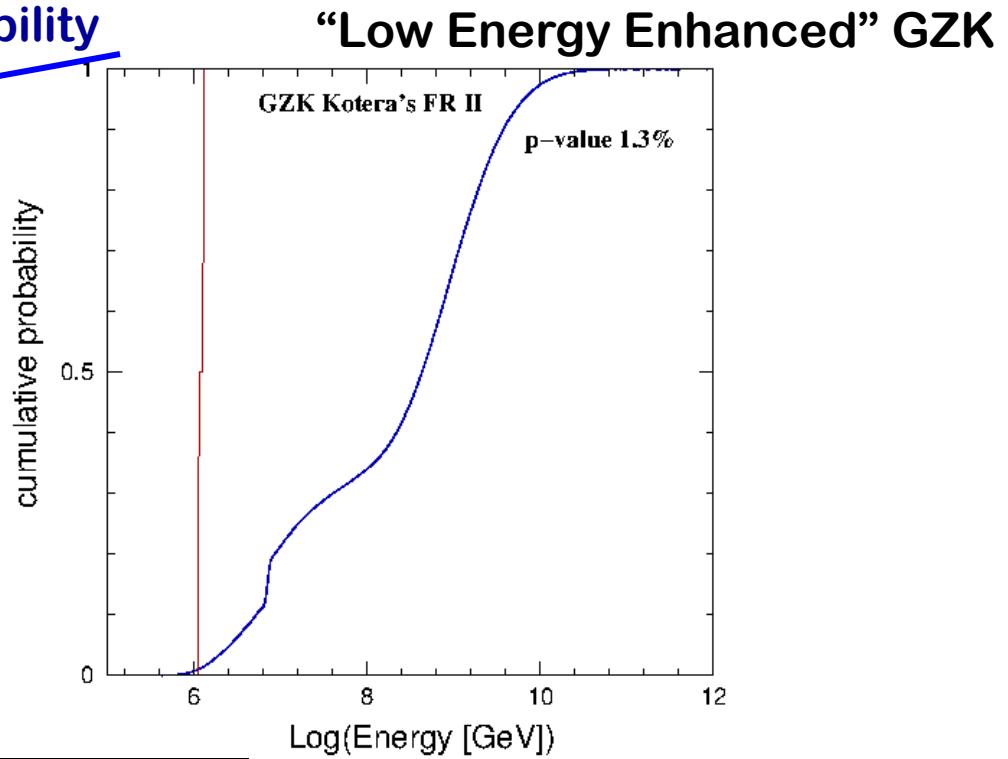
P_n probability of n events above 100 PeV
 α p-value

The KS test

“Standard” GZK



The predicted E_V cumulative probability



“Low Energy Enhanced” GZK

p-values O(1%)

Results from KS tests + full range event counting

2事象の観測はどのGZKモデルともconsistentではない

Combined with IC40

Neutrino Model	KS Test P_E	Expected Event Rate	Poisson Significance	Final p-values
GZK Yoshida/Teshima $m=4$, $Z_{max}=4$	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 <small>m=4, zmax=4</small>	GZK Sigl <small>m=5, zmax=3</small>	GZK Ahler <small>Fermi Best</small>	GZK Ahler <small>Fermi Max</small>	GZK Kotera <small>FR-II</small>	GZK Kotera <small>SFR/GRB</small>	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

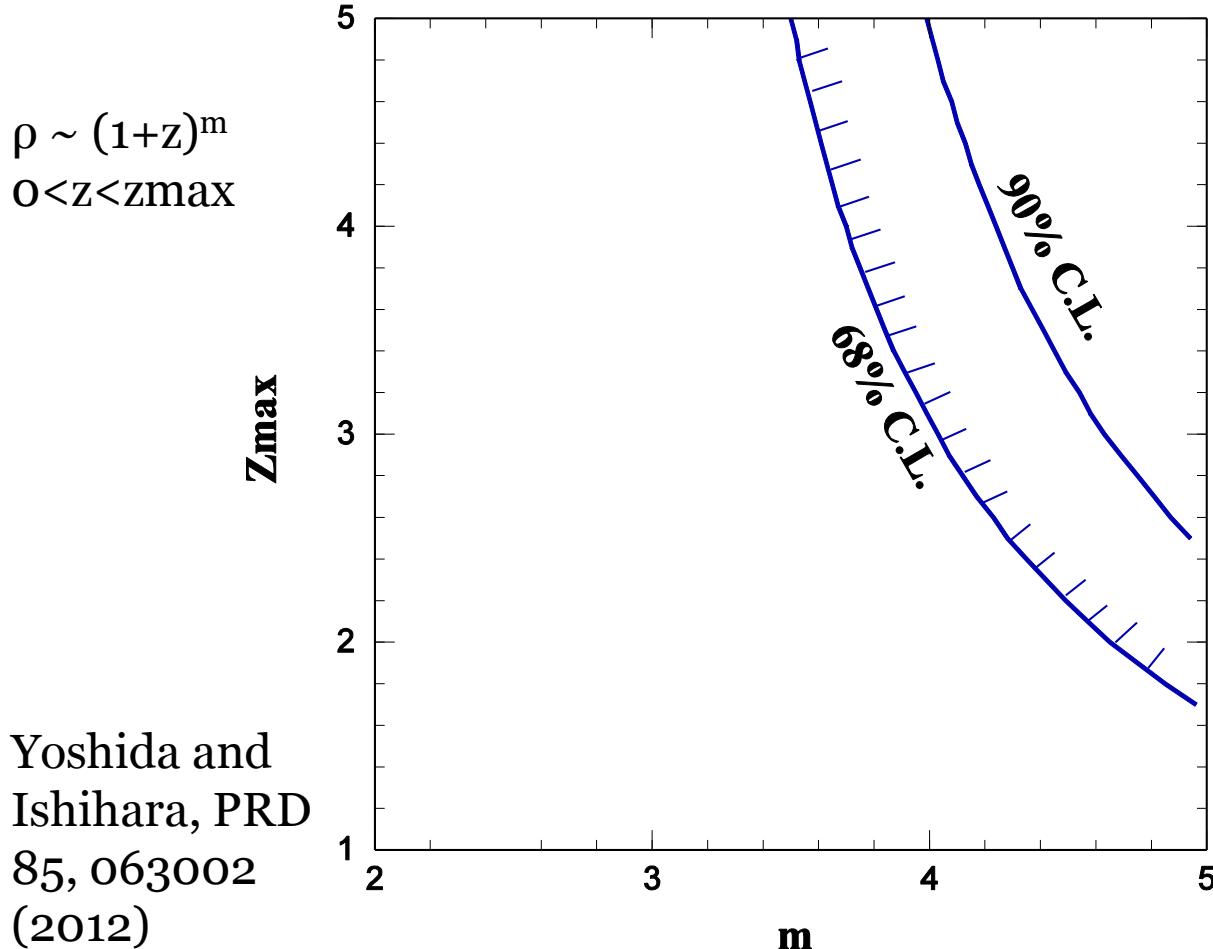


Mildly Excluded



Consistent

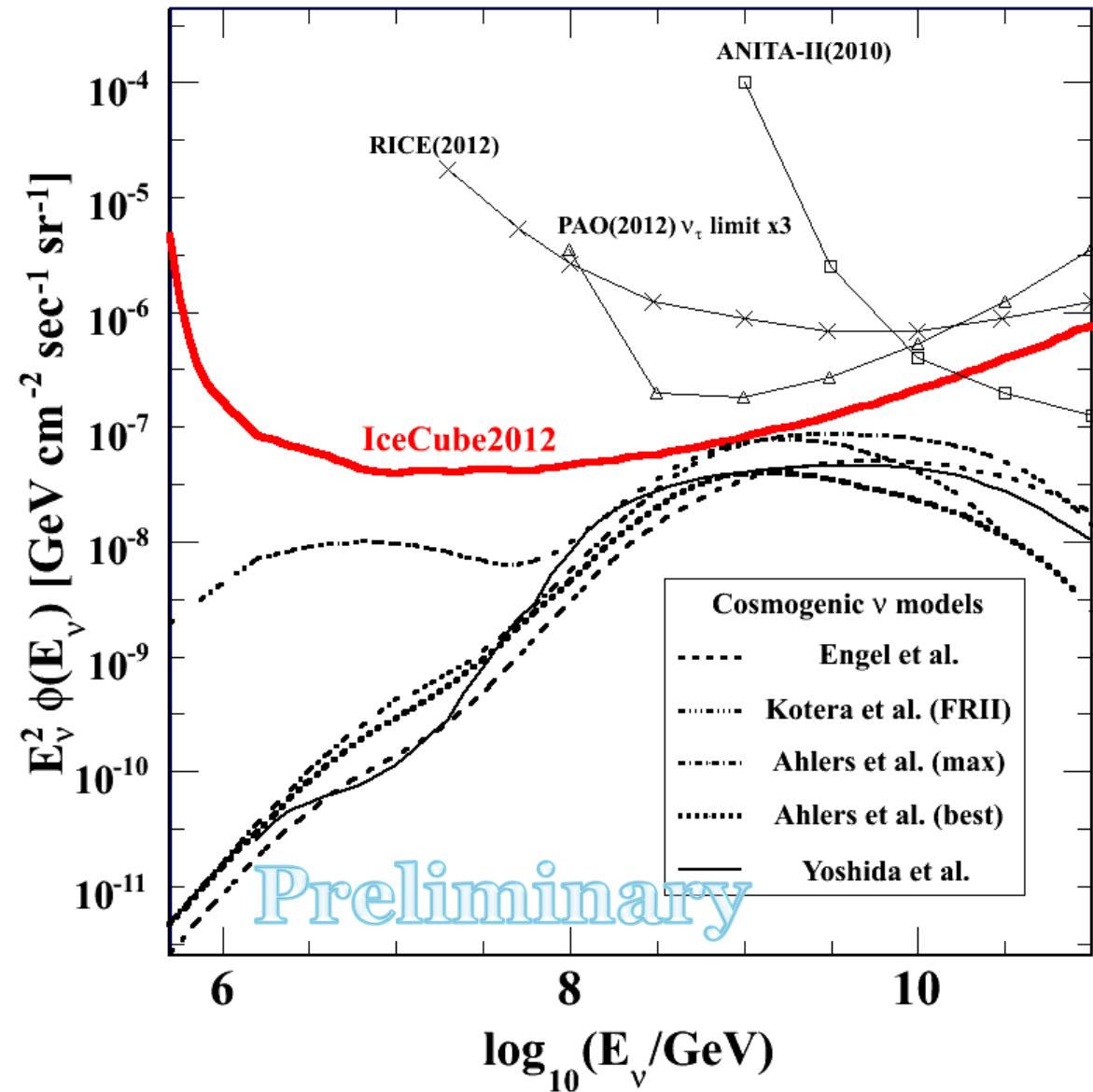
最高エネルギー宇宙線源のEvolution parameterに対する制限



A strongly evolved astronomical object (like FR-II radio galaxy) is disfavored

Any sources evolved stronger than SFR will soon be ruled out by IceCube or to be observed!

Model Independent Upper limit



(Systematics included)

— 90% C.L. upperlimit

F-C Upper fluctuation

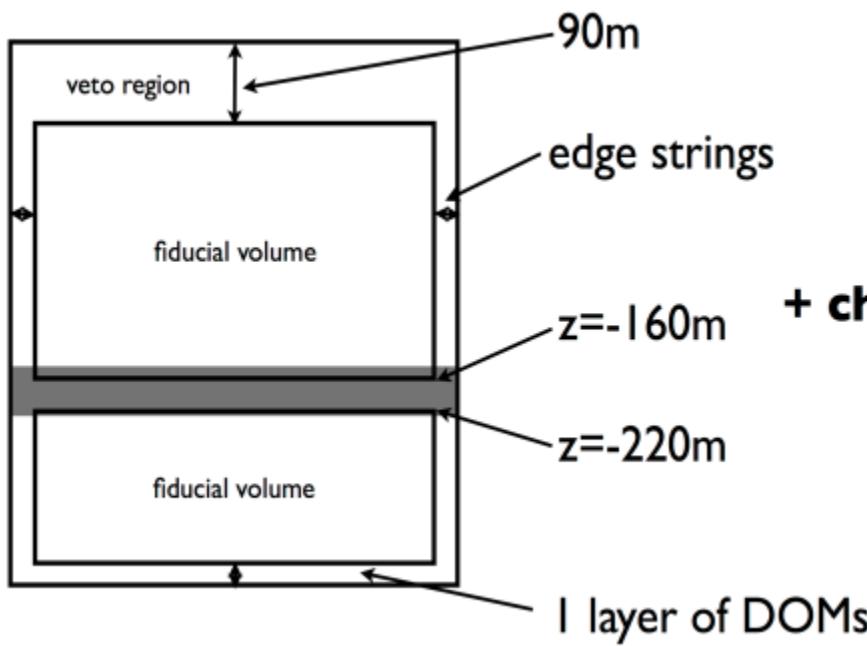
- A factor of ~ 4 improved from the previous IceCube results
- The world's best sensitivity!
- Will constrain the neutrino fluxes down to mid-strong cosmological evolution models

Still at least a factor of two improvement to come in 1-2 years

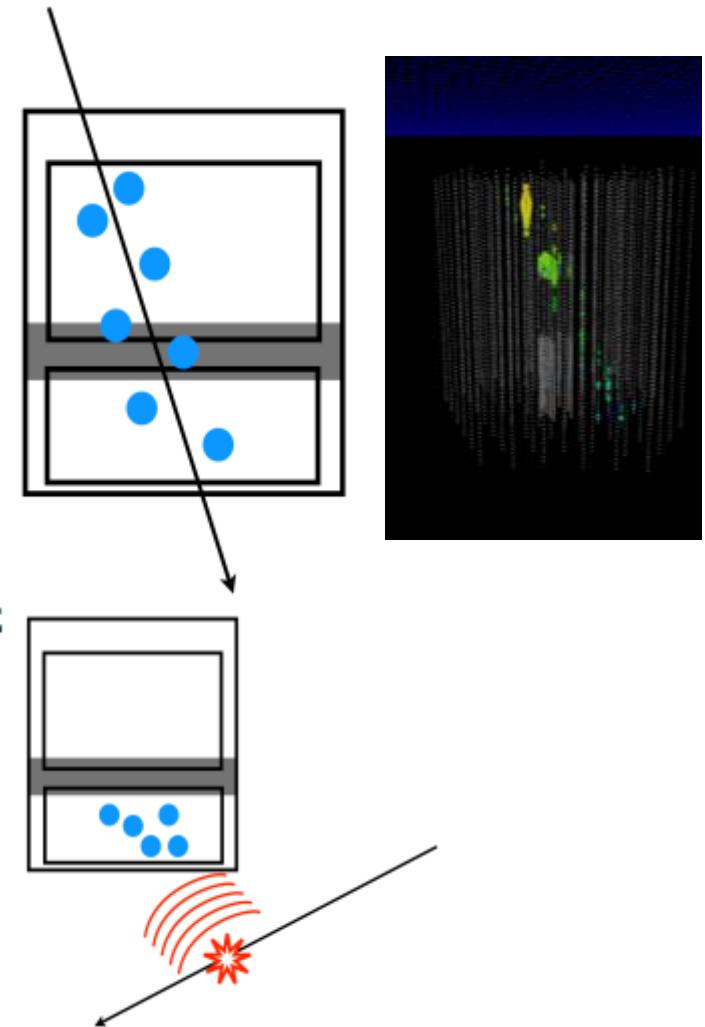
PeV事象のFollow up analysis

Starting Event Analysis

- Bright ($>6000\text{ope}$)
- Outer veto cut to reject background
 - Events started in detector

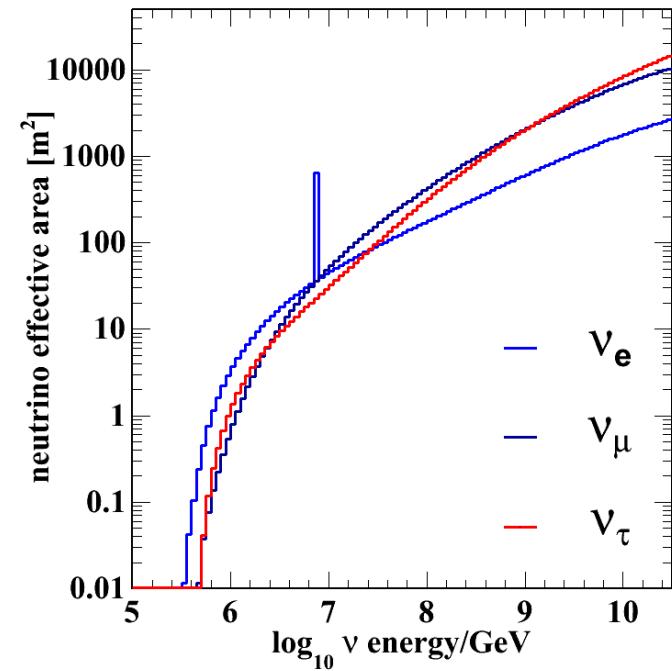
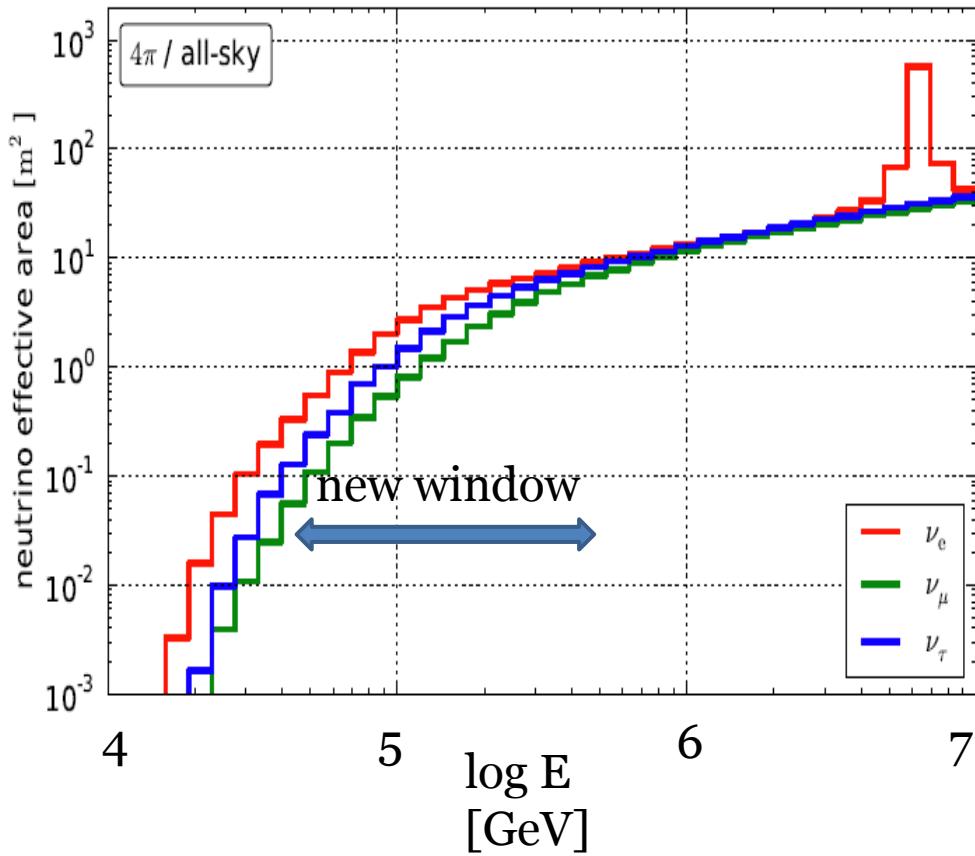


+ charge cut



より低いエネルギー領域からのスキャン

Improvements in 100TeV region from the starting event analysis



Summary from recent 2012 results

- IceCubeが完成し、初のデータ解析を行った
- 特に2つのDiffuse ν解析、PeV以上のニュートリノ解析とそこから検出された2事象の研究、その事象にOPTIMIZEした100TeV以上の事象を調べる FOLLOWUP解析による進展
- それぞれ 3σ レベルの大気背景事象を超えるニュートリノ事象が観測。2つの解析からの結果を統合すると約 4σ レベルの*EVIDENCE*
- 詳細な2+26事象の研究を行っている
- 今のところ、この28事象の特徴を全て説明できるシグナル・バックグラウンドモデルは存在していない
- 1論文はほぼ完成3月中にSUBMIT, 2論文は4月中にSUBMITを予定

近い今後について – 2013

- 初めの解析のラウンドとしては、**1)**どのようなシグナルが出てくるかわからないため、**2)**出来る限り不定性などに影響を受けないよう、**3)**早く解析を行うため、比較的ロバストな、詳細な事象再構築等によらないシンプルな解析を行ってきた
- **2013**は事象トポジーでオプティマイズしたミューオンやカスケードの特徴による解析結果が期待。これらの解析は違ったチャンネルのエネルギー領域を観測することが可能
- オンライン解析の充実 – **Collaboration with photons**
- 宇宙ニュートリノがほぼ見つかった。 統計量には限界があるがそこにチャレンジしてその特性を調べていく - その先は、**unpredictable**