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

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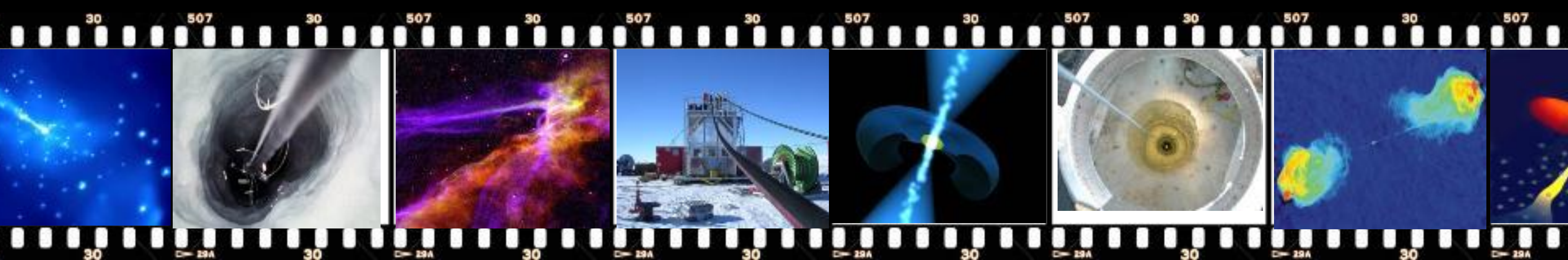

Aya Ishihara 2012/8/30 宇宙線研

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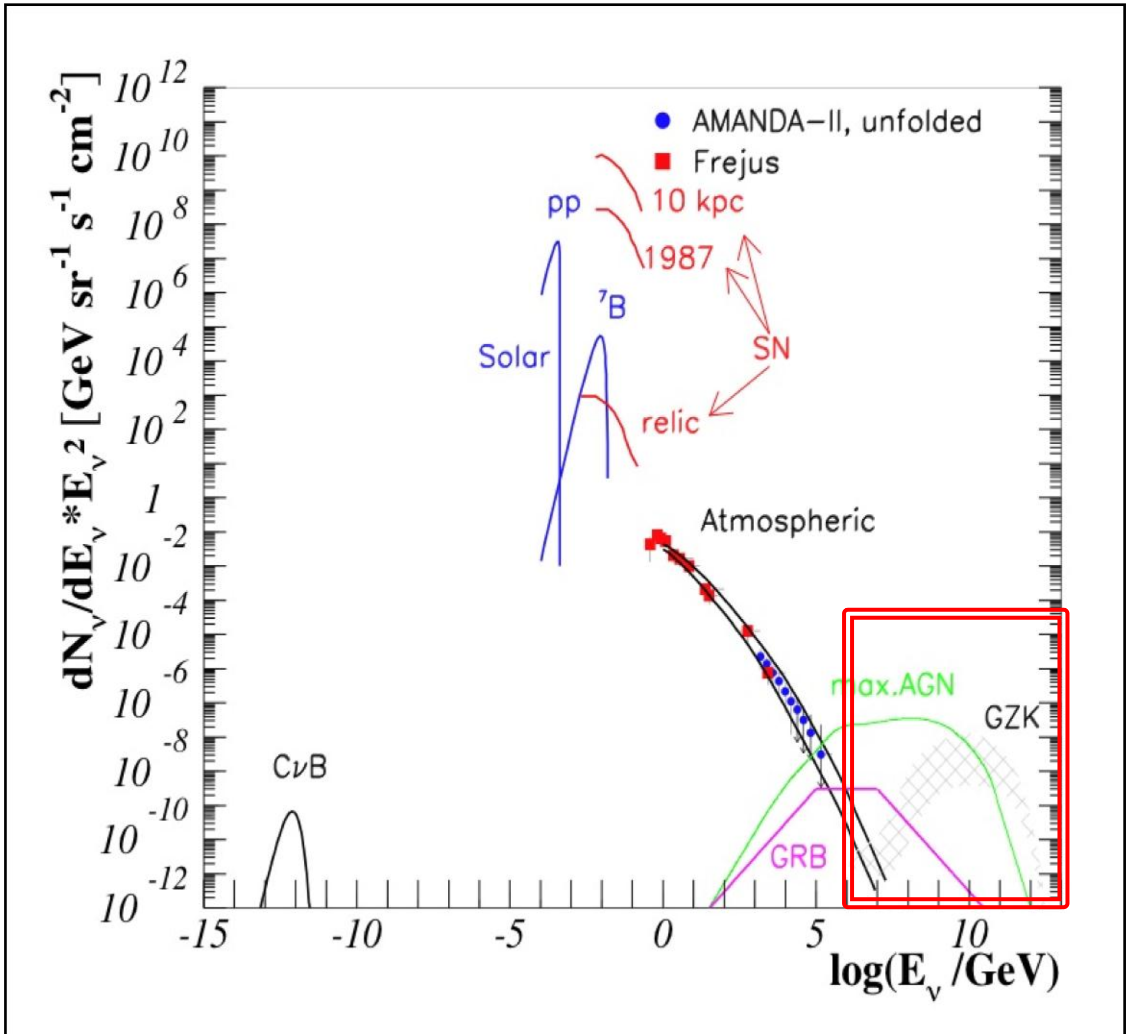
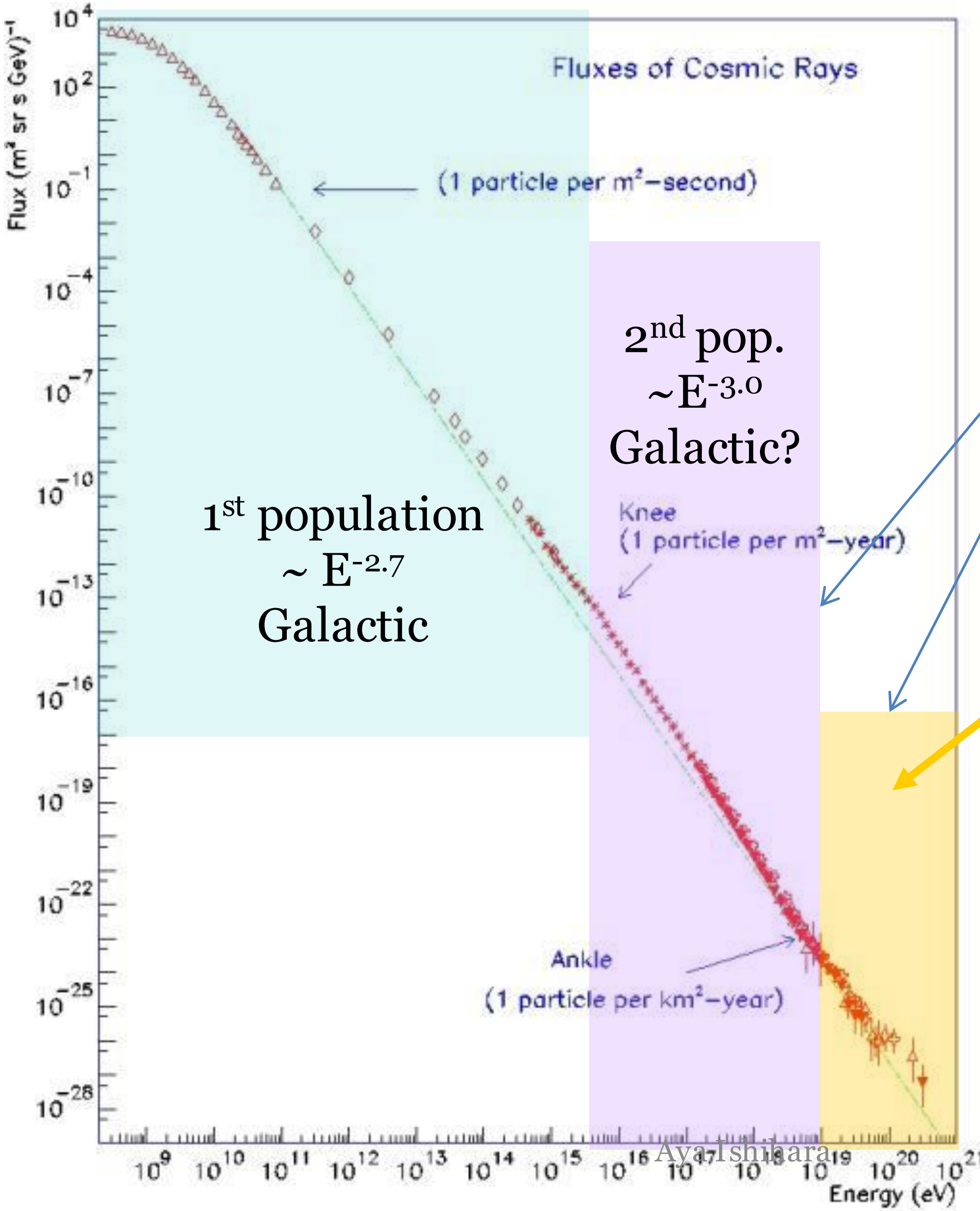
Ultra-high Energy Neutrinos: ***PeV and above***



- 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 First Piece of the Puzzle - Cosmic-rays

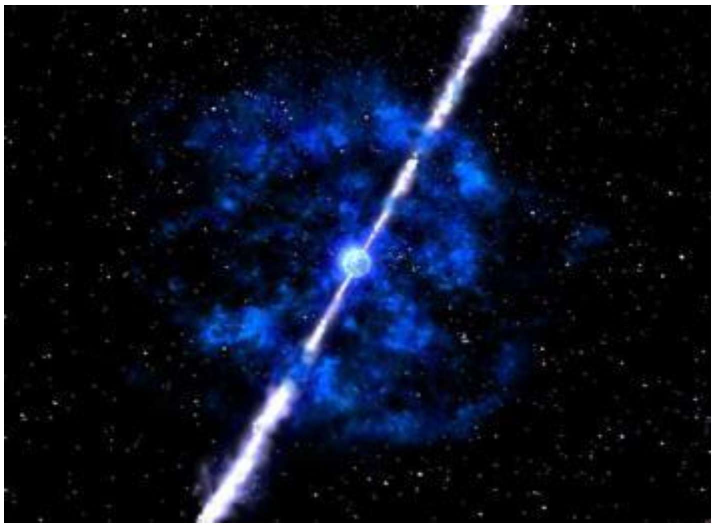


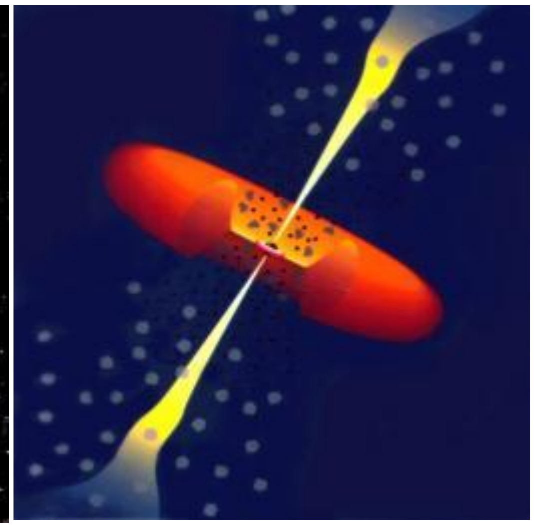
Possible clue to the origin!

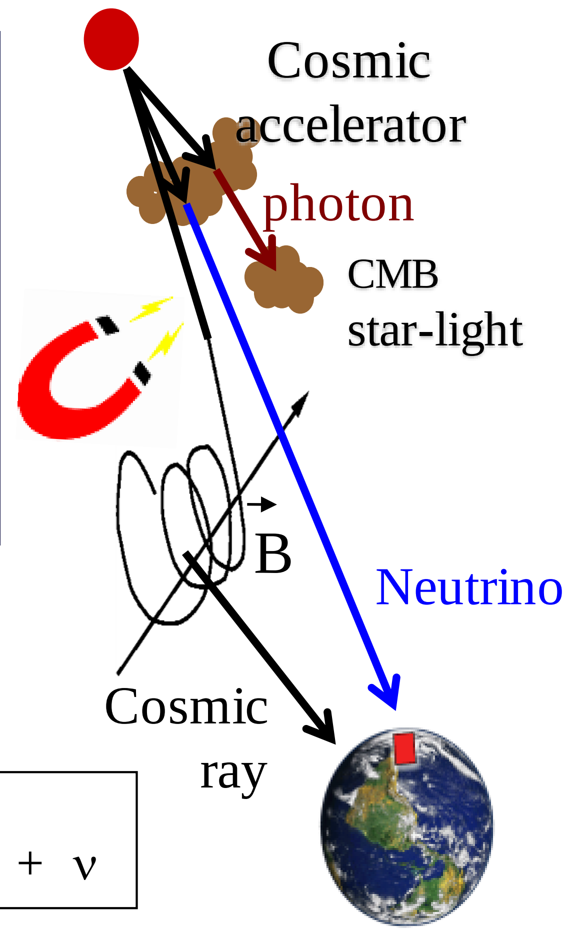
3rd population
The most energetic
E > O(J)

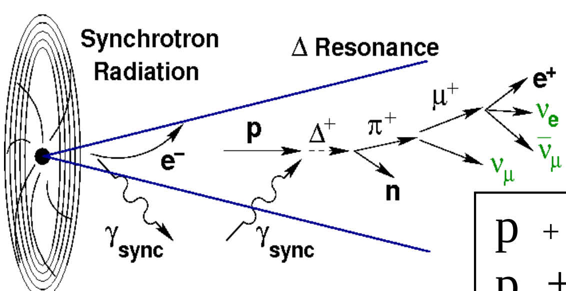
Neutrinos in the Astronomical Objects

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





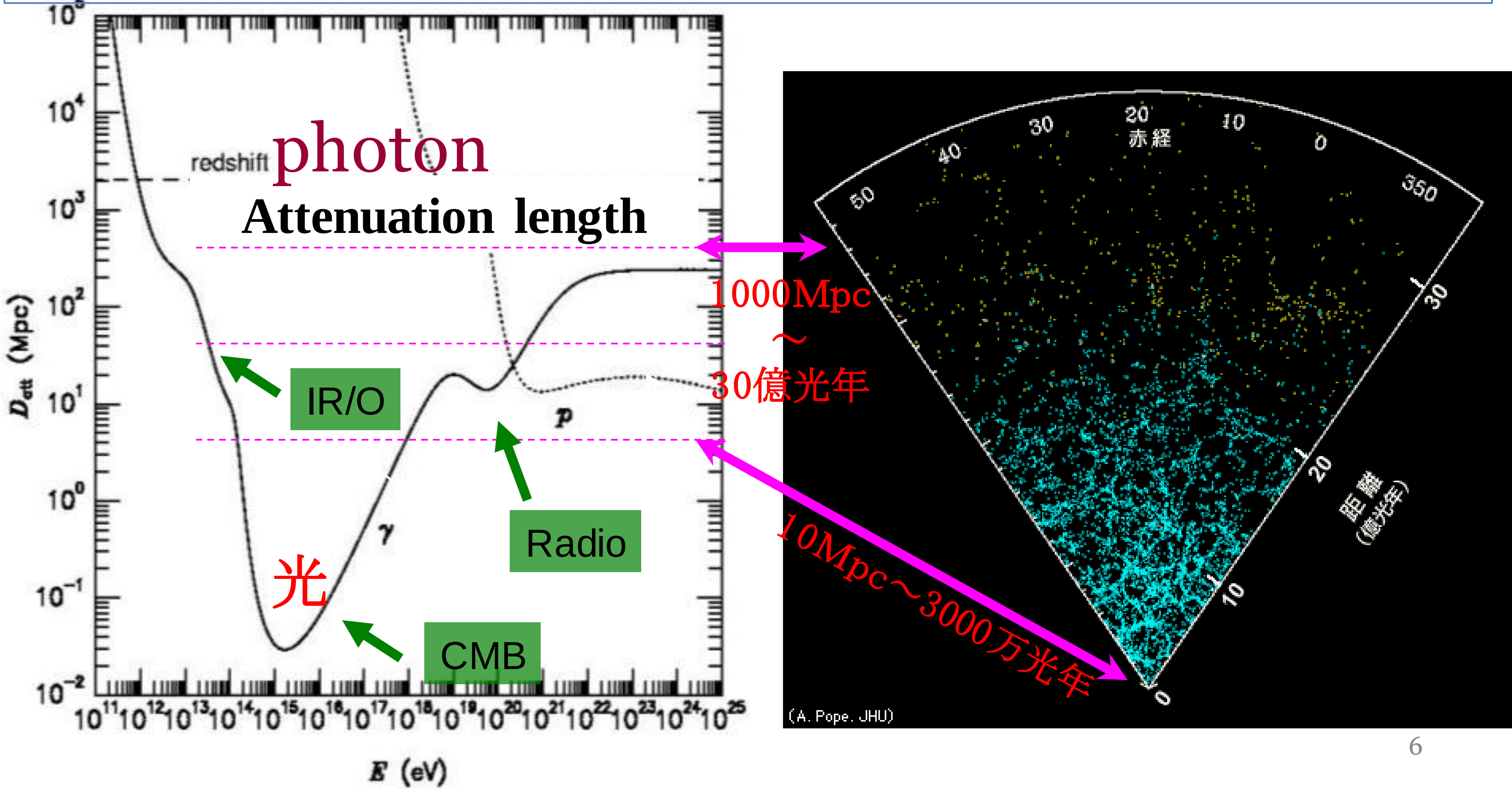




$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma$$
$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$$

Idea of the cosmic neutrino is simple and attractive

Investigate source candidates such as AGNs/GRBs distribute larger distance than attenuation length of photon with another undeflected and less absorbed particles!!

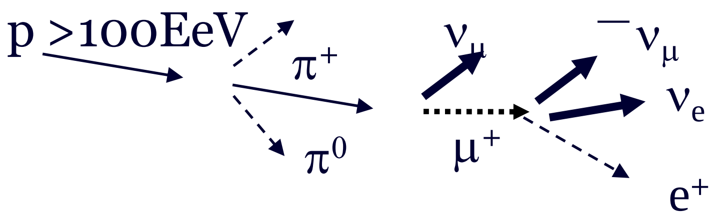


The highest energy neutrinos

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

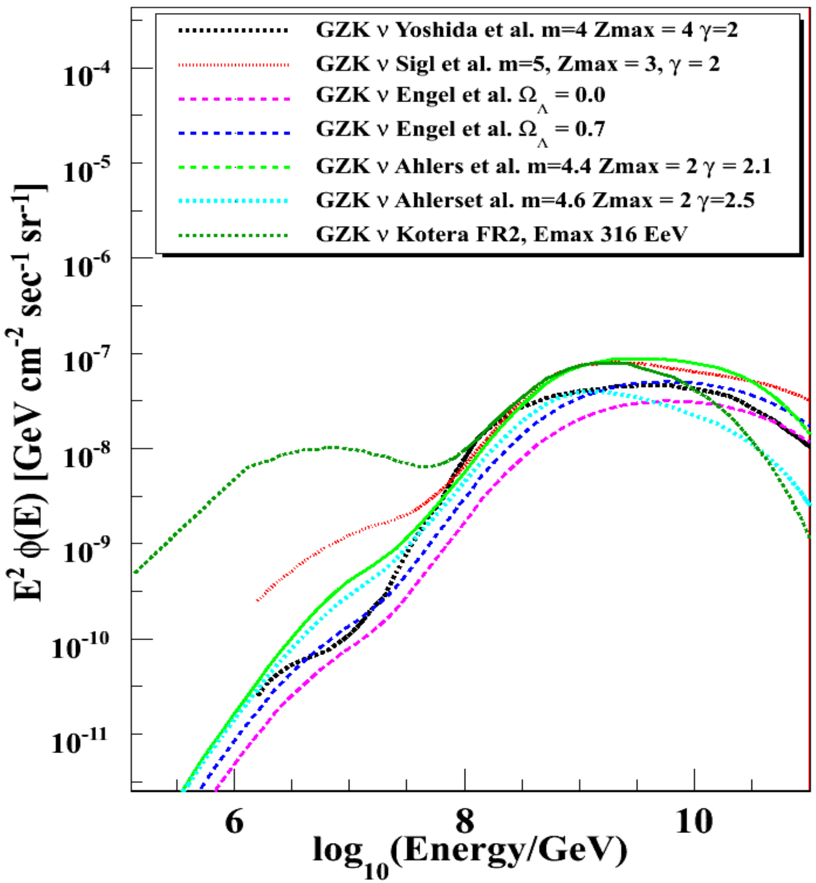
Off-Source (<50Mpc) astrophysical neutrino production via

GZK (Greisen-Zatsepin-Kuzmin) mechanism



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

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

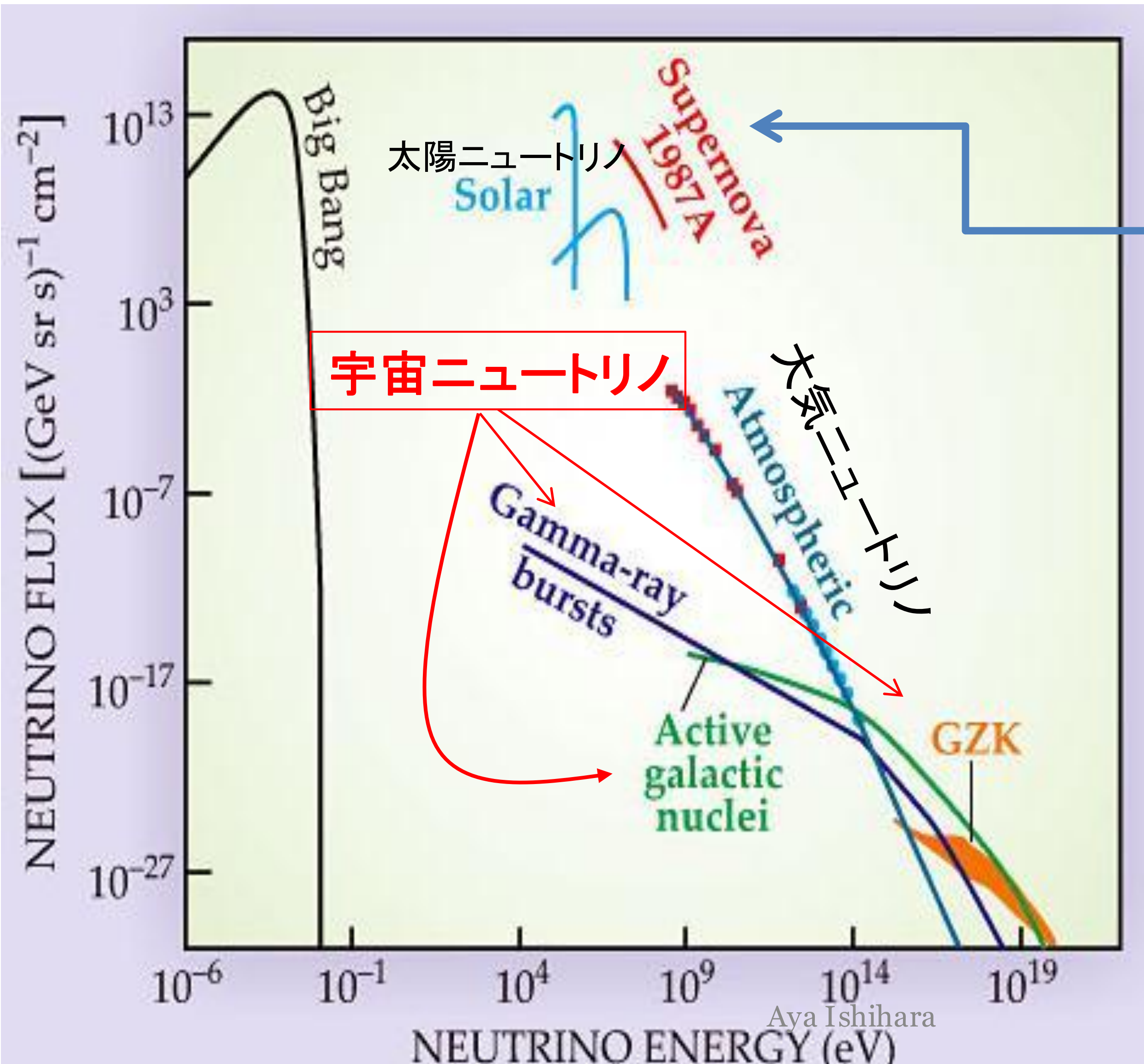


Various GZK ν models

Carries important physics

- Location of the cosmic-ray sources
- Cosmological evolution of the cosmic-ray sources
- Cosmic-ray spectra at sources
- The highest energy of the cosmc-rays
- Composition of the cosmic-rays
- Particle physics beyond the energies accelerators can reach

Question is why we have not seen them yet?

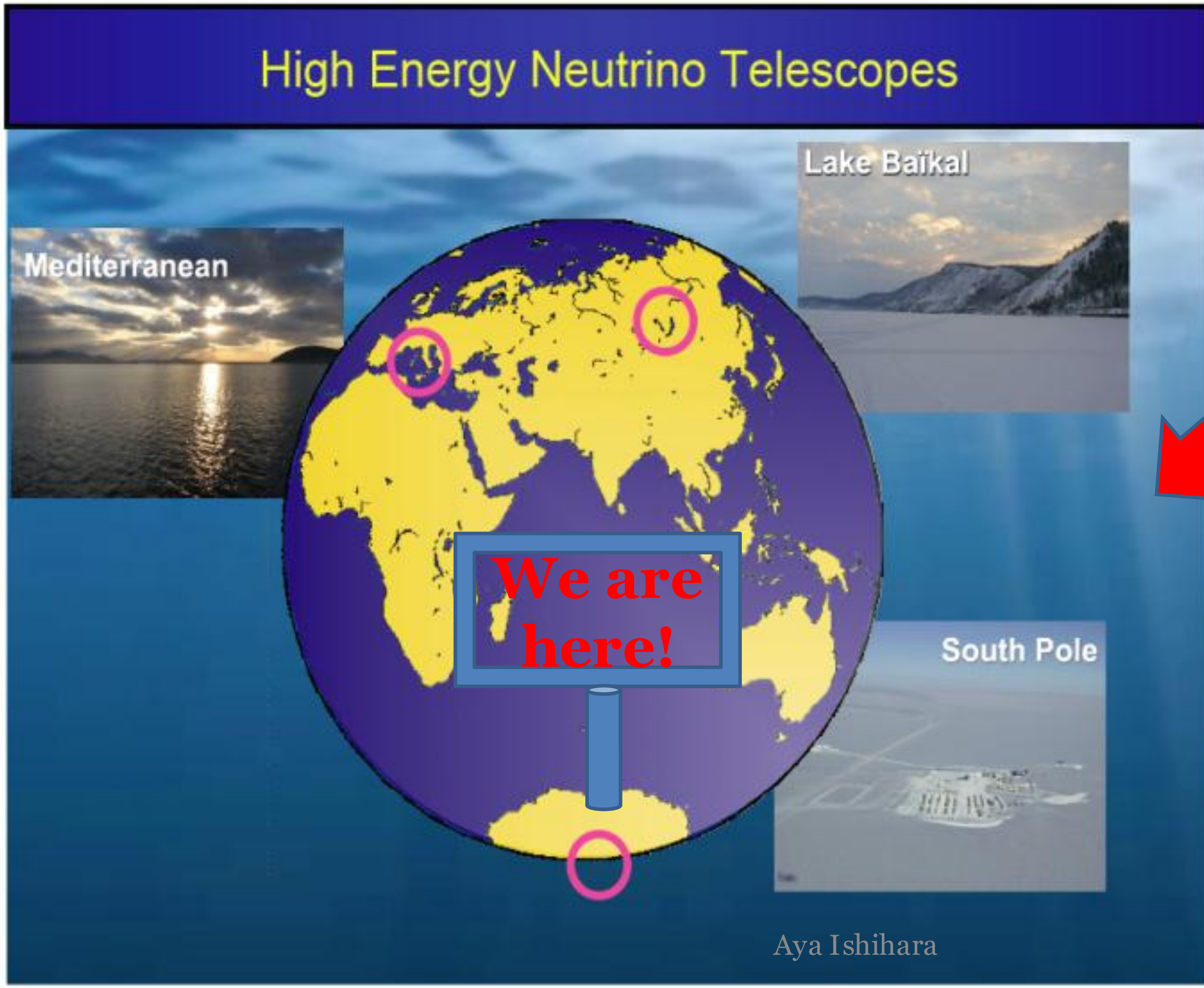


1987-2-23日
Supernova Neutrinos!
by Kamiokande/IMB

No cosmic neutrinos observed for last 25 years…

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

High energy neutrino telescopes in the world



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

ANTARCTICA
Amundsen-Scott Station

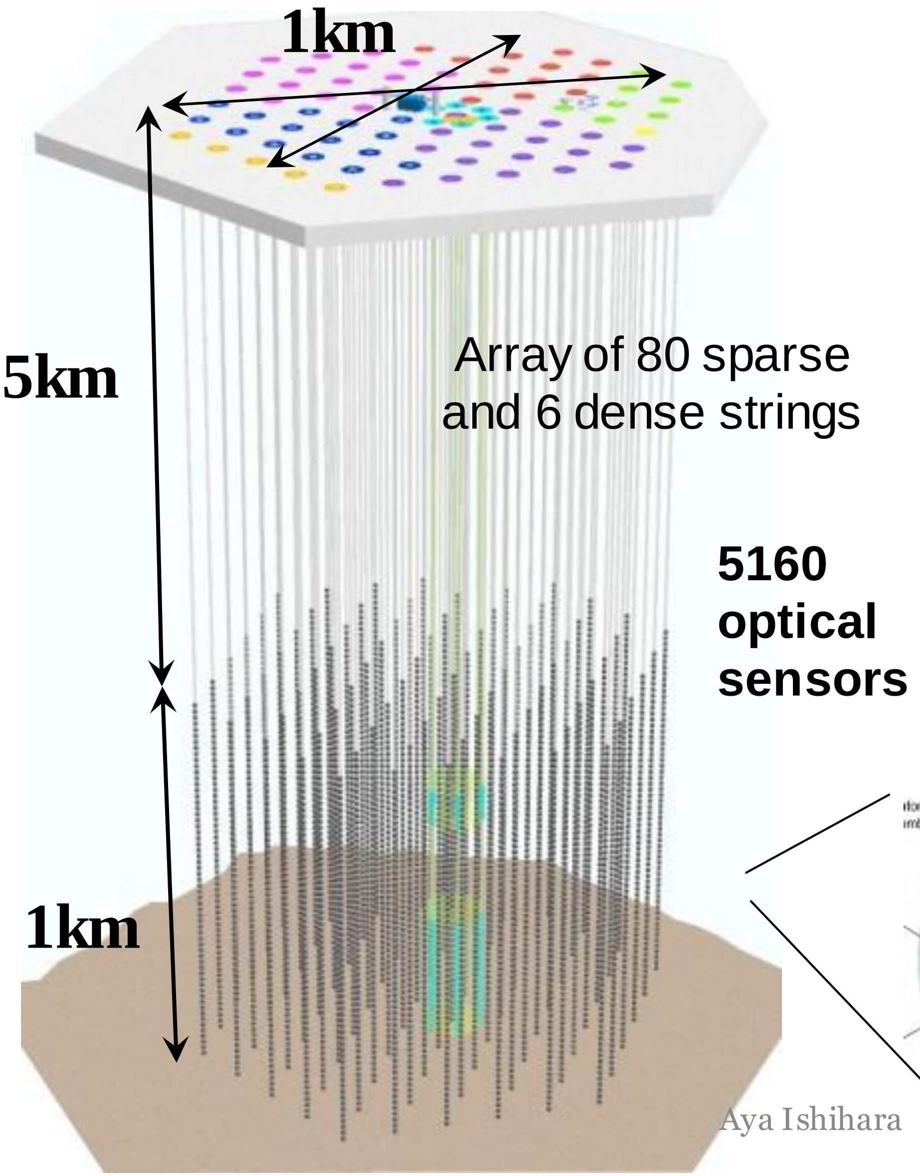
Japan
Chiba University

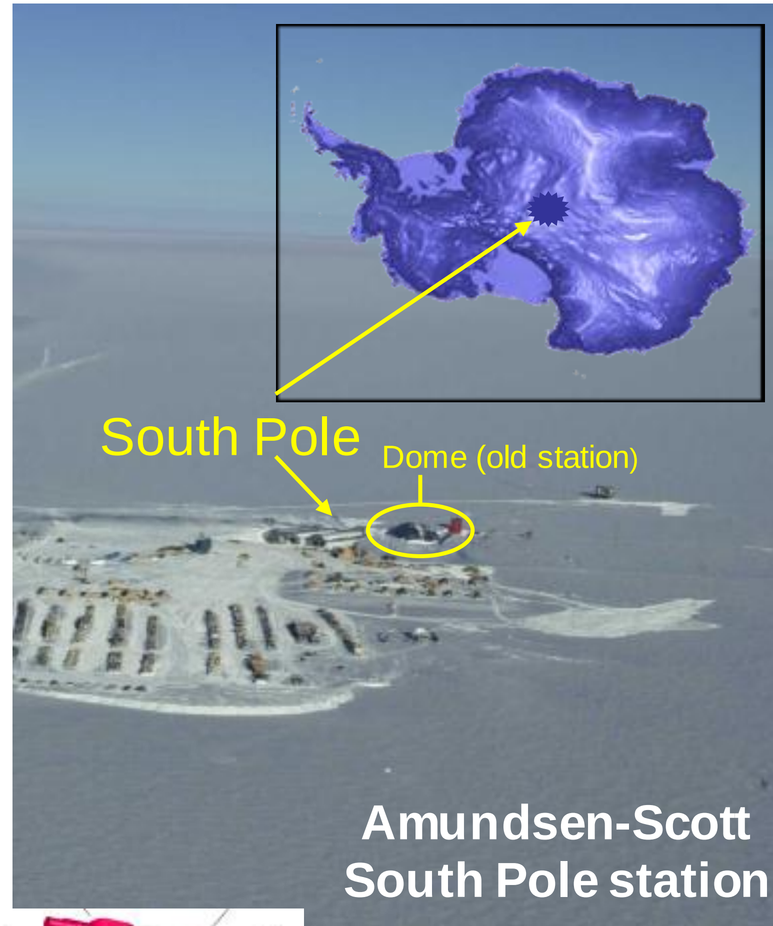
The first results from the full detector!

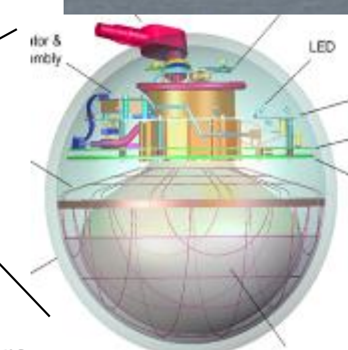
New Zealand
University of Canterbury

The Largest Neutrino Detector in the world:

The IceCube Detector





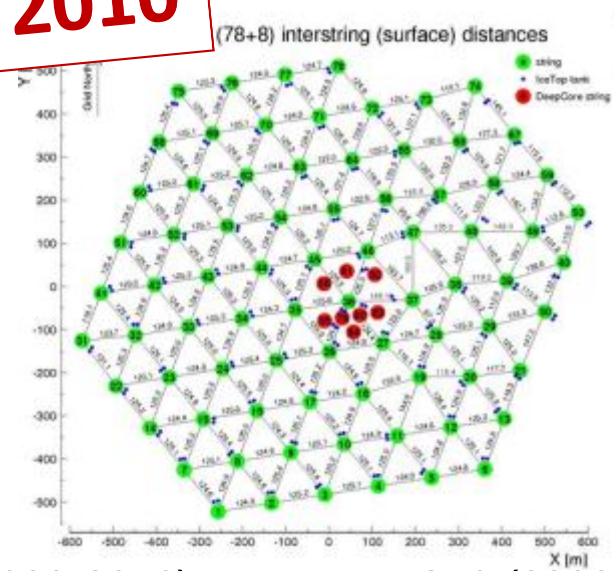


Detector history

Completed: Dec 2010

IC86 = full IceCube (2011~)

IceCube

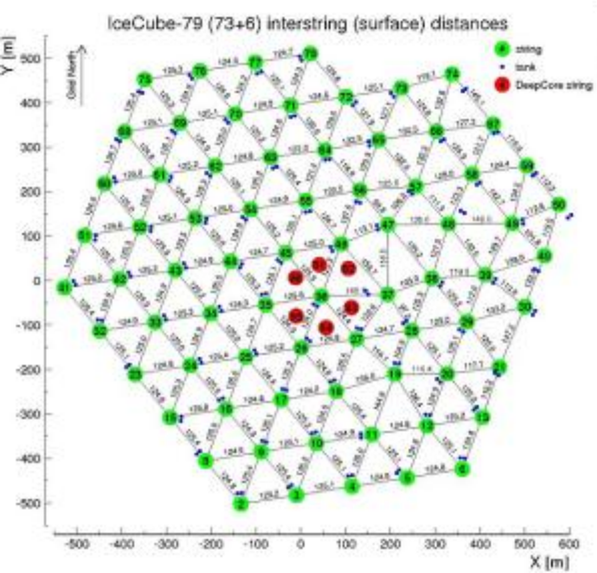


Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

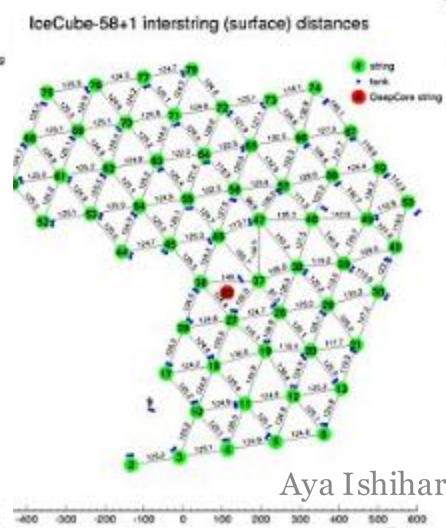
IC79 (2010-2011)

IceCube



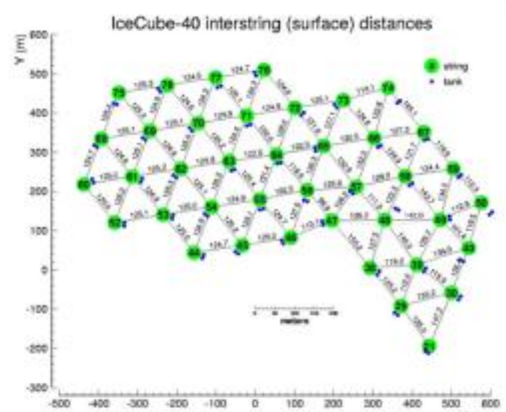
IC59 (2009-2010)

IceCube



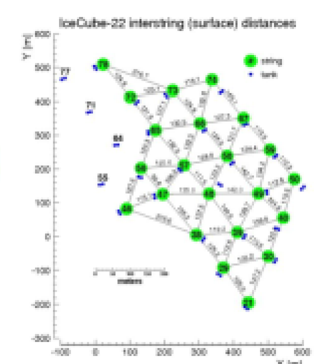
IC40 (2008-2009)

IceCube



IC22 (2007-2008)

IceCube

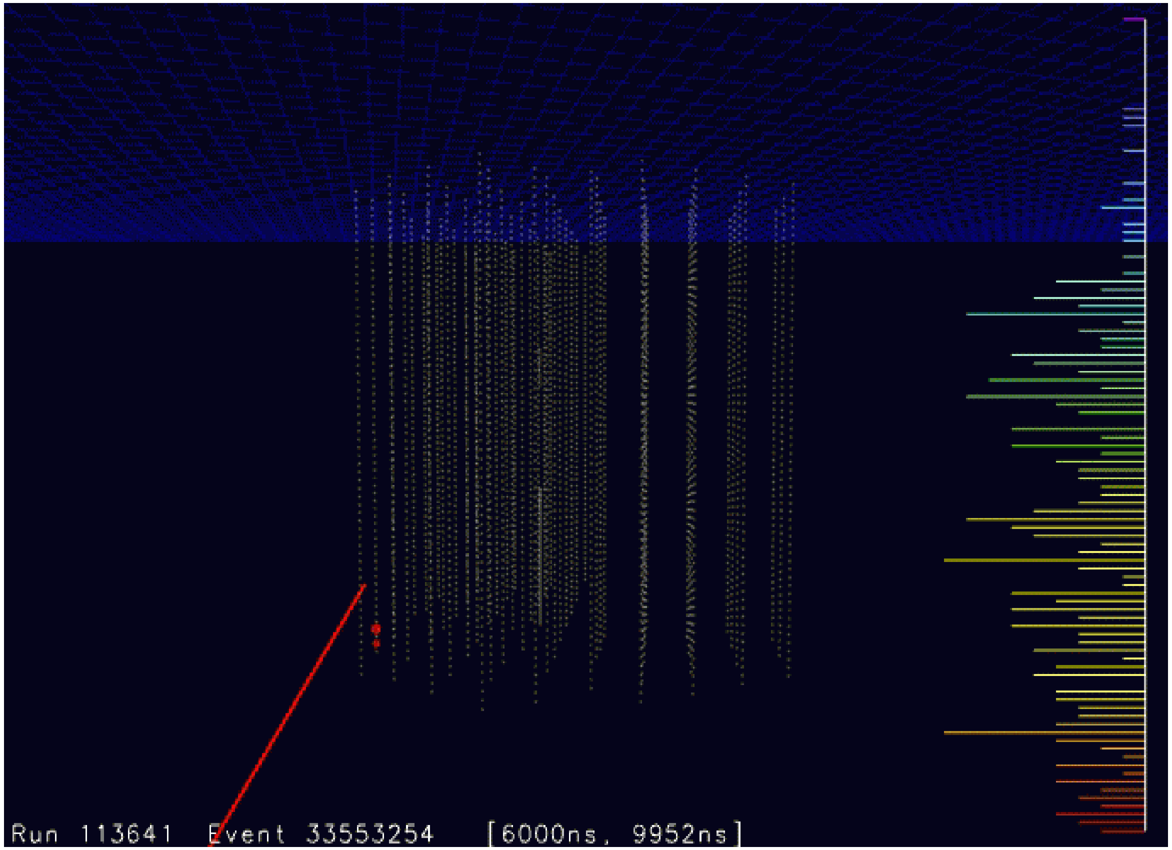


Event rates

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

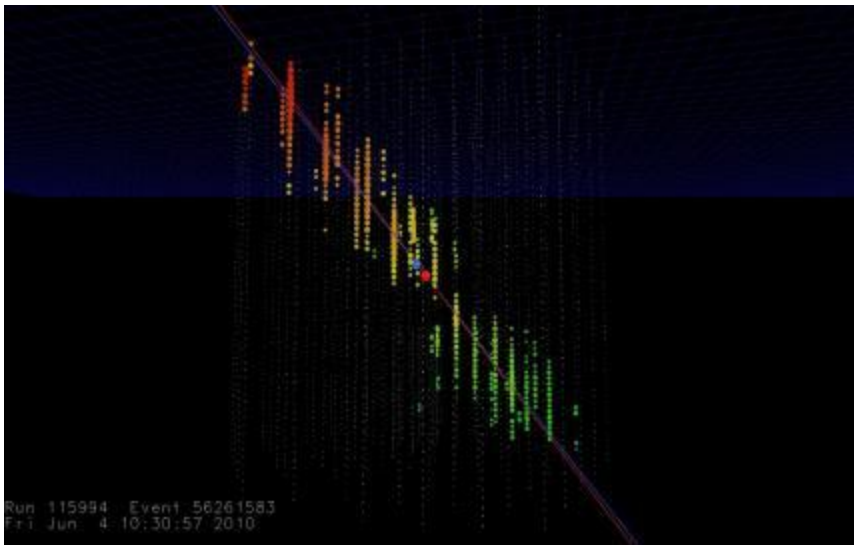
Neutrino Example



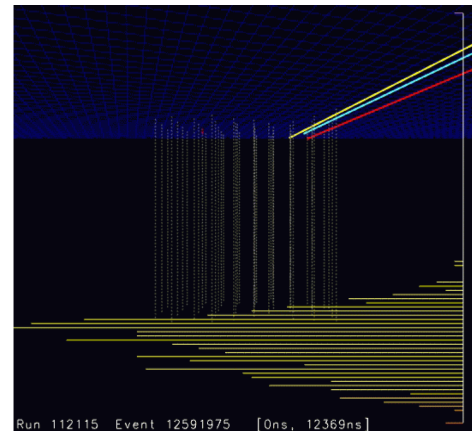
With 40 strings, 2009 May

IceCube Events

With 79 strings, 2010 June

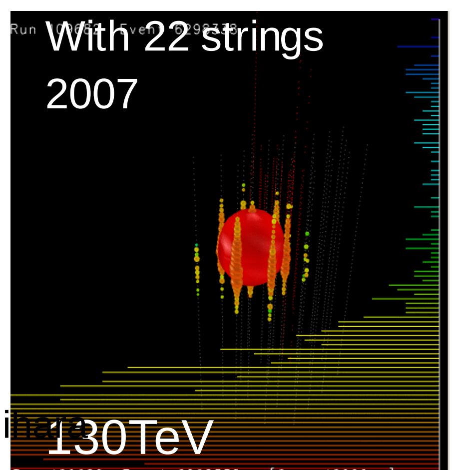


With 40 strings, 2008 Dec



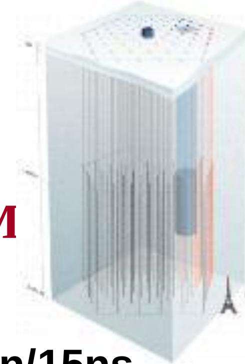
Energy threshold ~10 GeV
>10^8 muons/day
>100 neutrinos/day

With 22 strings
2007



130TeV

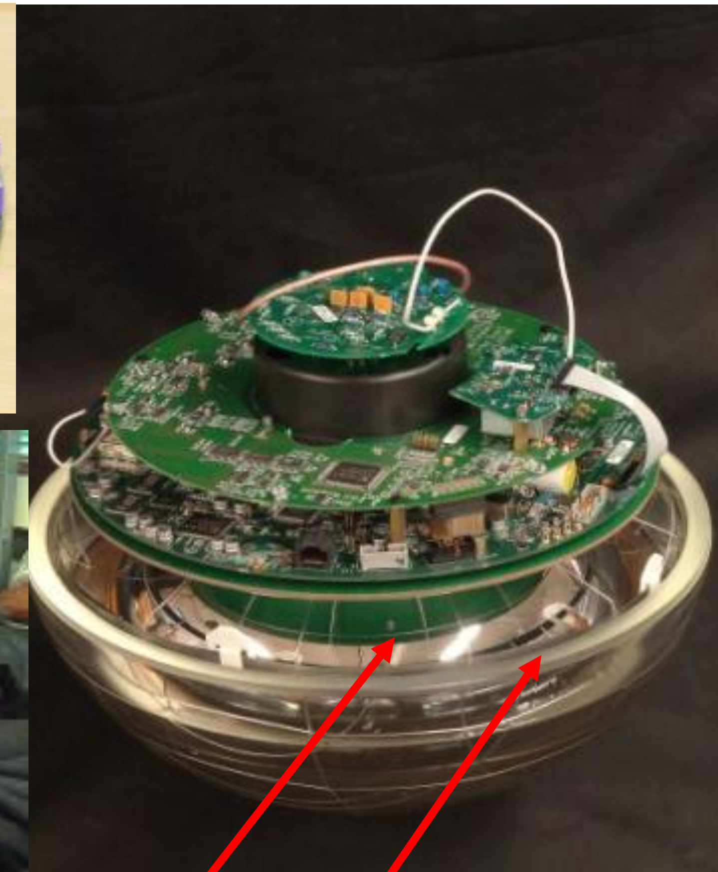
Digital Optical Module



- **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**

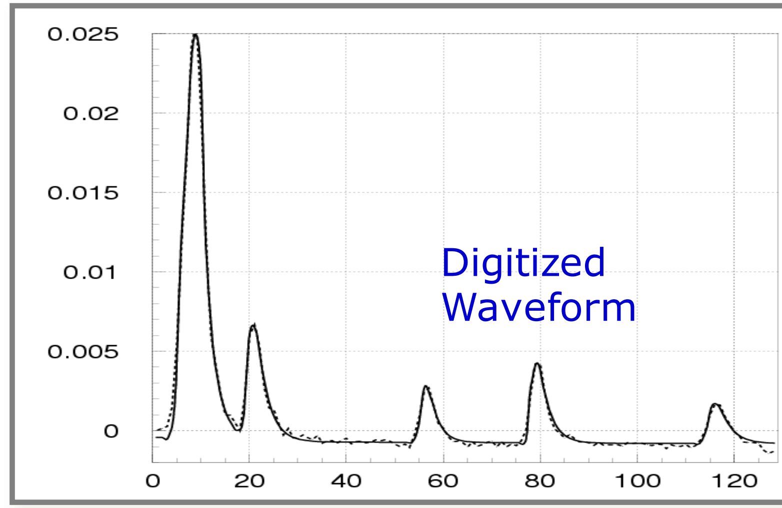


Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec

25 cm PMT
33 cm Benthosphere

Waveform examples from spe to 10000 pe

single pe level

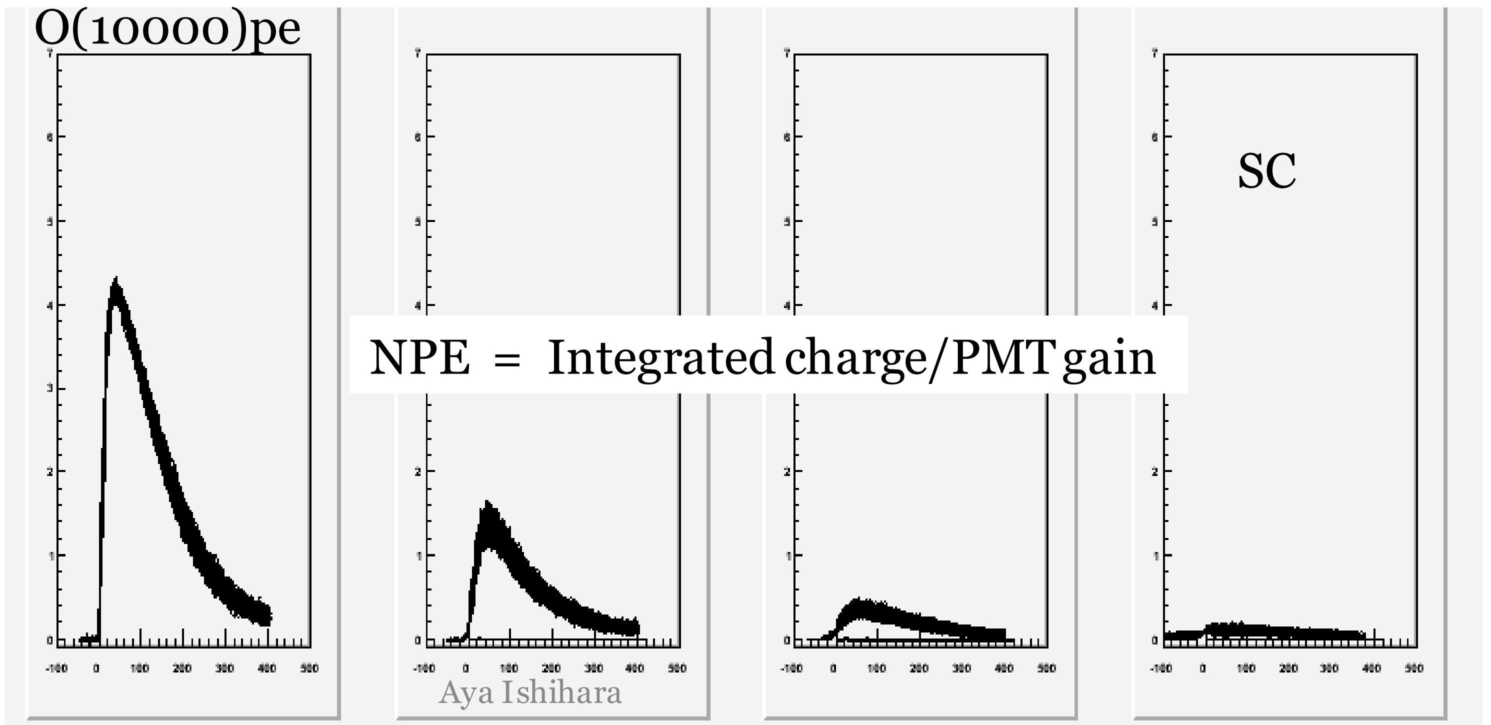


7V

4

1

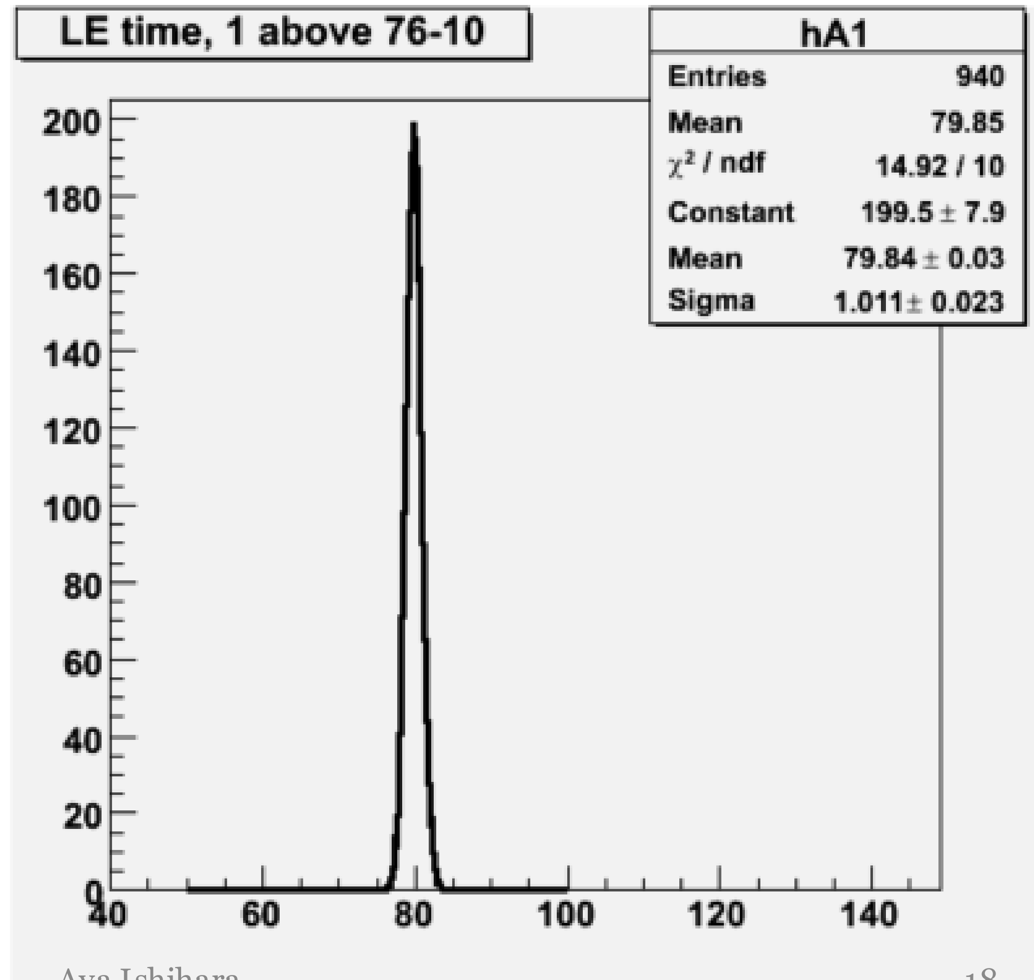
0



NPE = Integrated charge/PMT gain

Time resolution:
~1ns for bright pulses

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



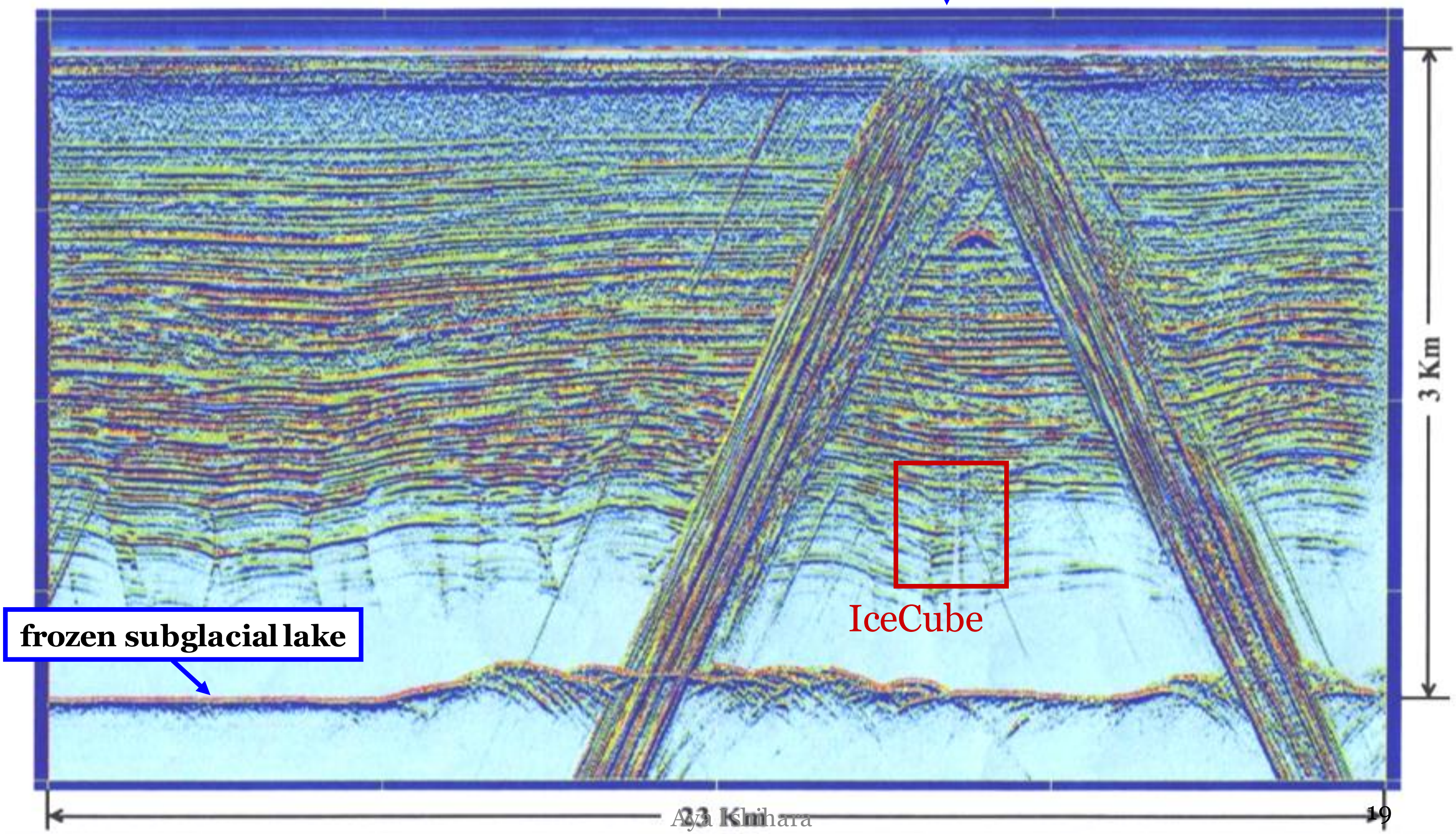
Ice Models

(One of the most important uncertainties)

South Pole station
and IceCube

airborne radar imaging

(Blankenship et al.)

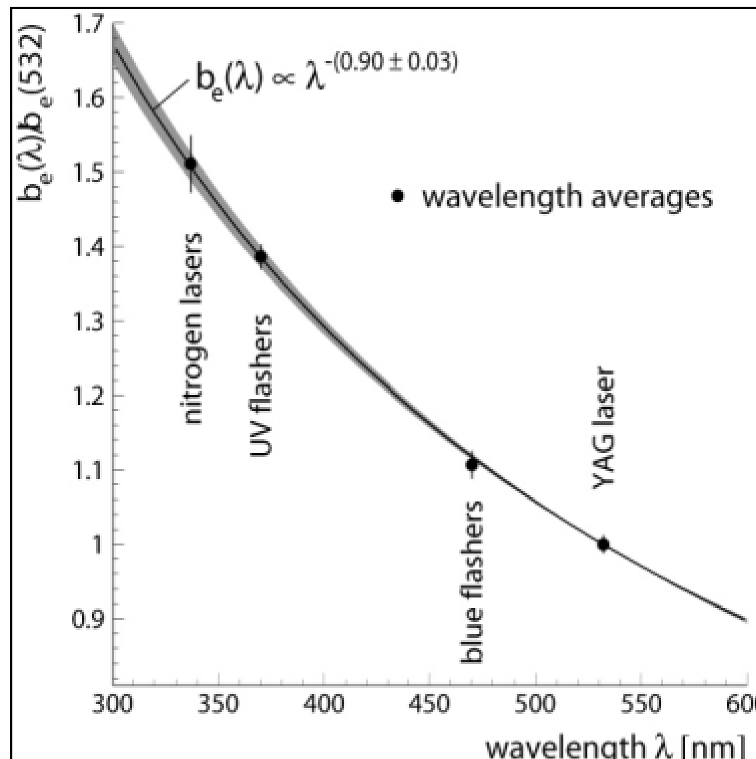


What causes scattering in the ice?

- In the ***shallow ice***, scattering is predominantly caused by air bubbles.
- In the deeper ice, ***below 1400 m***, the bubbles have converted to non-scattering air hydrate crystals, so-called clathrates, and scattering is caused by **dust**.
- This dust has four main components: mineral grains, salt, acids, and soot. Scattering is mainly caused by the mineral grain component.

The wavelength dependence of the scattering coefficient is described (in the wavelength range 300-600 nm) by a power law:

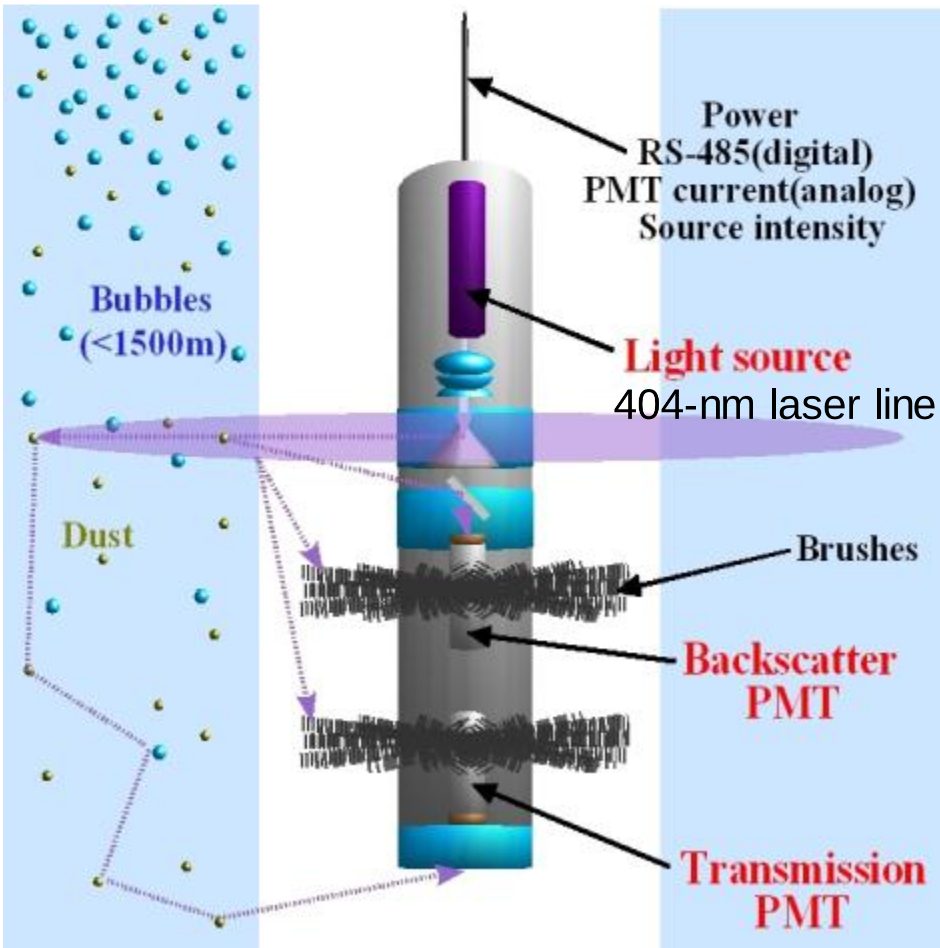
This power law was fitted to pulsed data at 4 wavelength for IceCube.



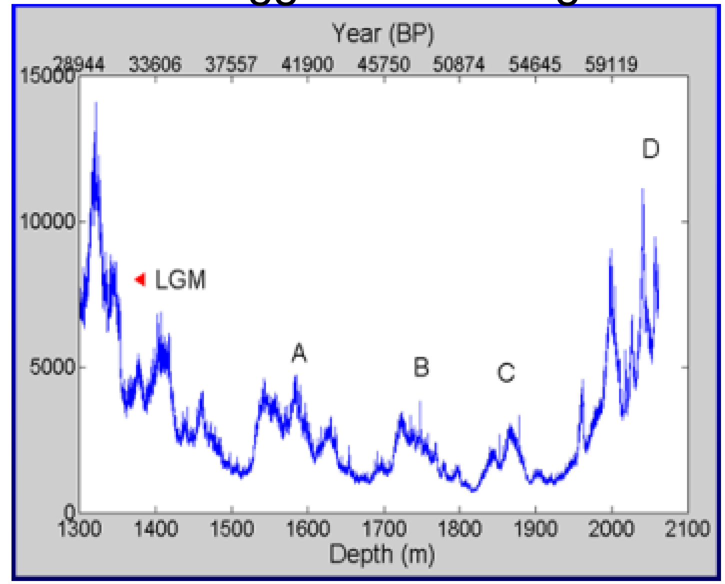
Absorption is caused by dust and the ice itself.

Dust Logger

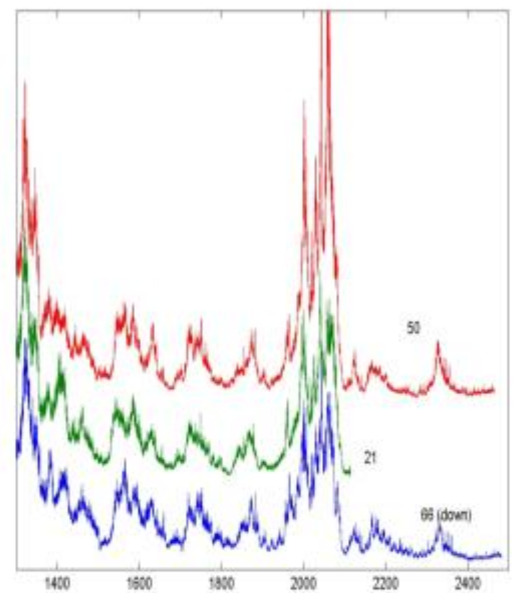
Since scattering is caused by **dust**.
It is important to understand



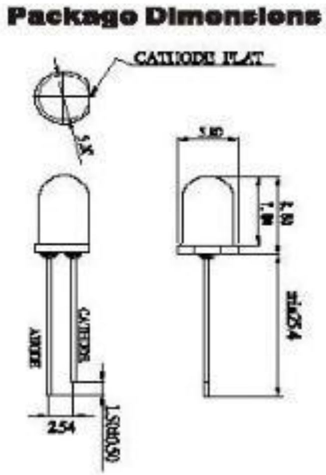
dust logger data string 21

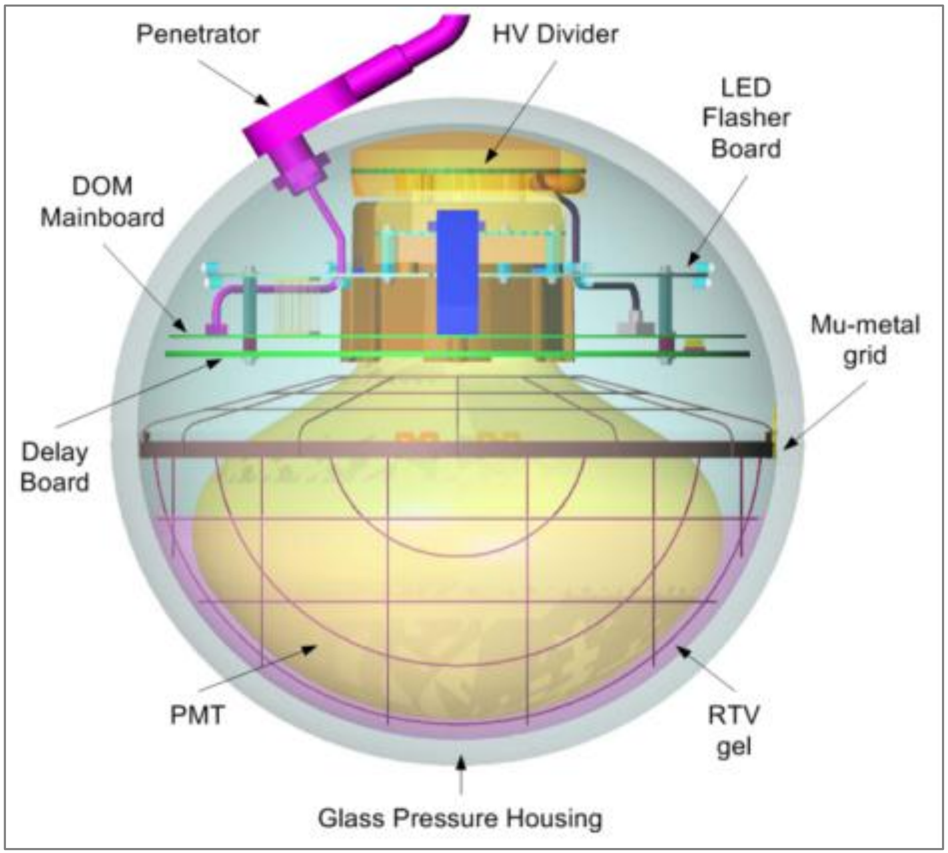


dust logger data of multiple location

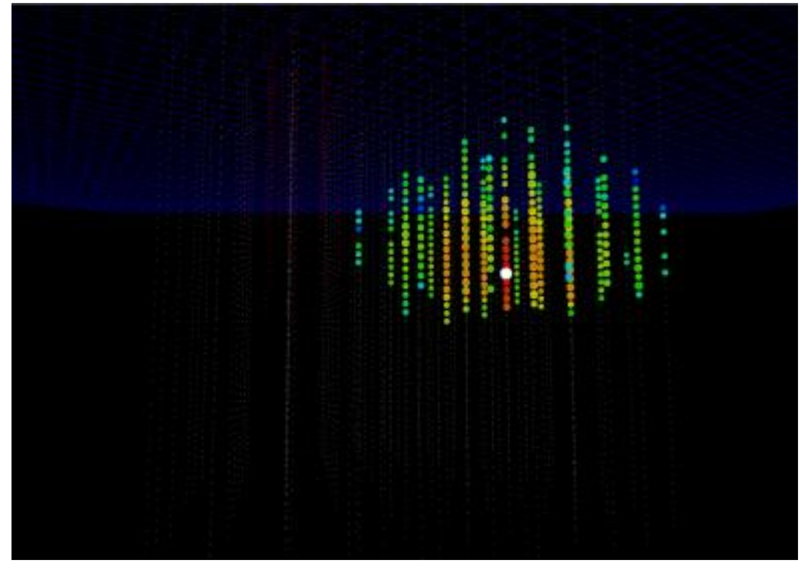


Flasher on the every DOM

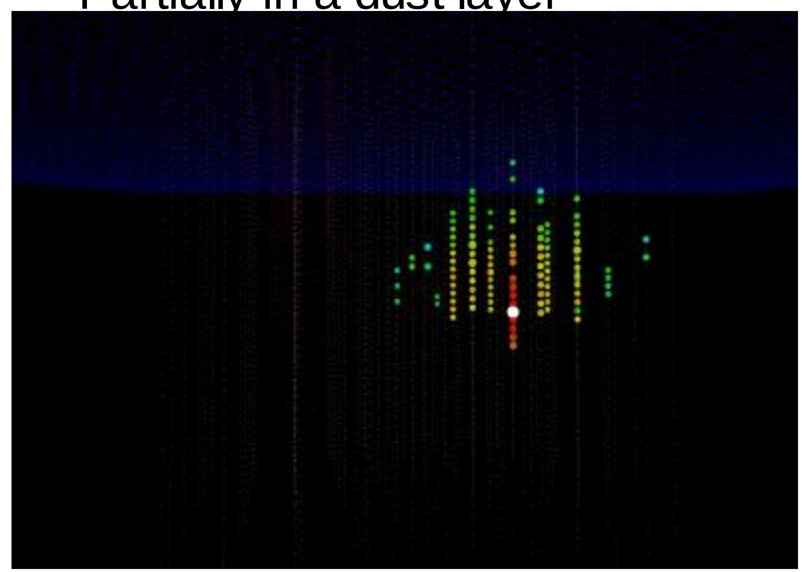




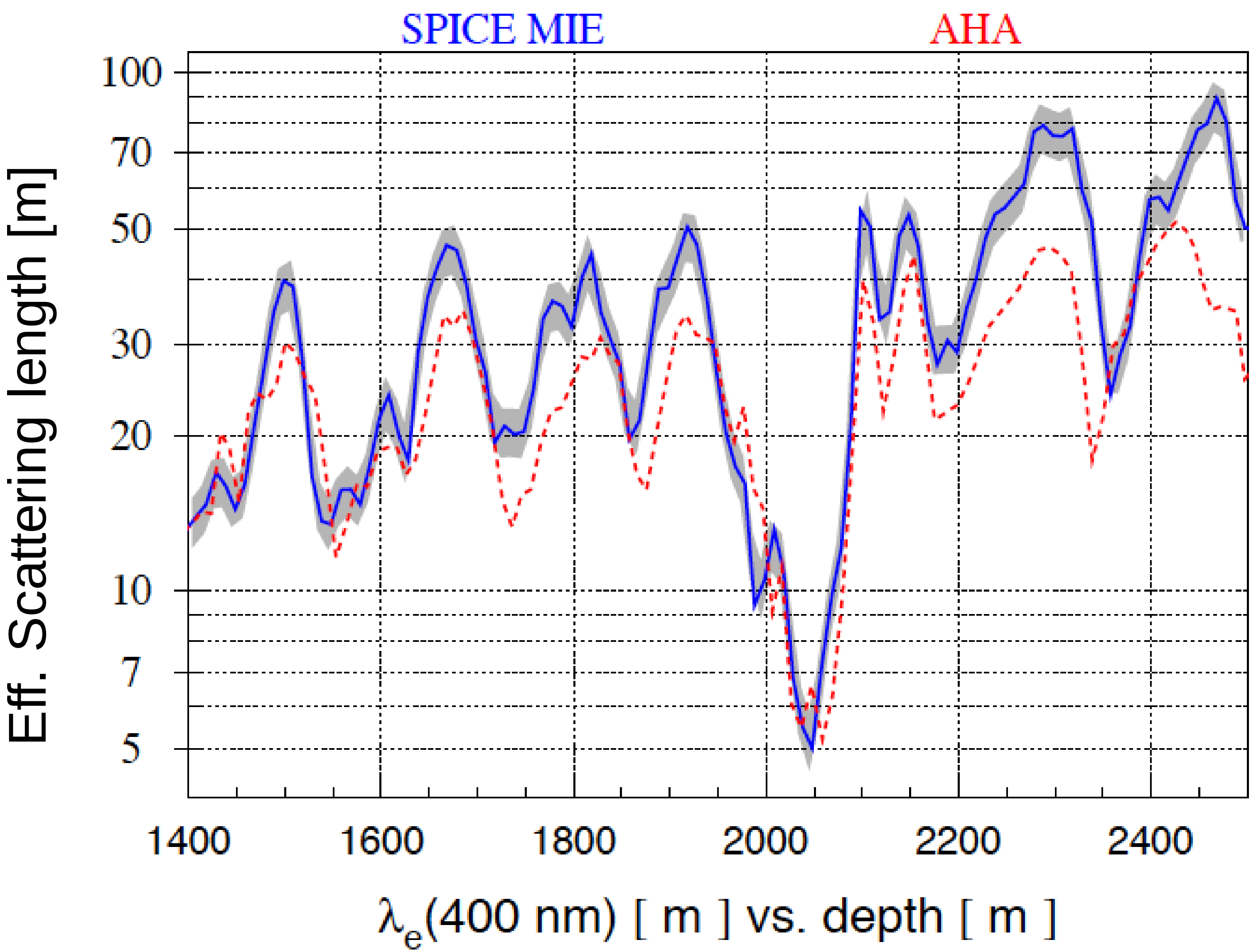
Above a dust layer



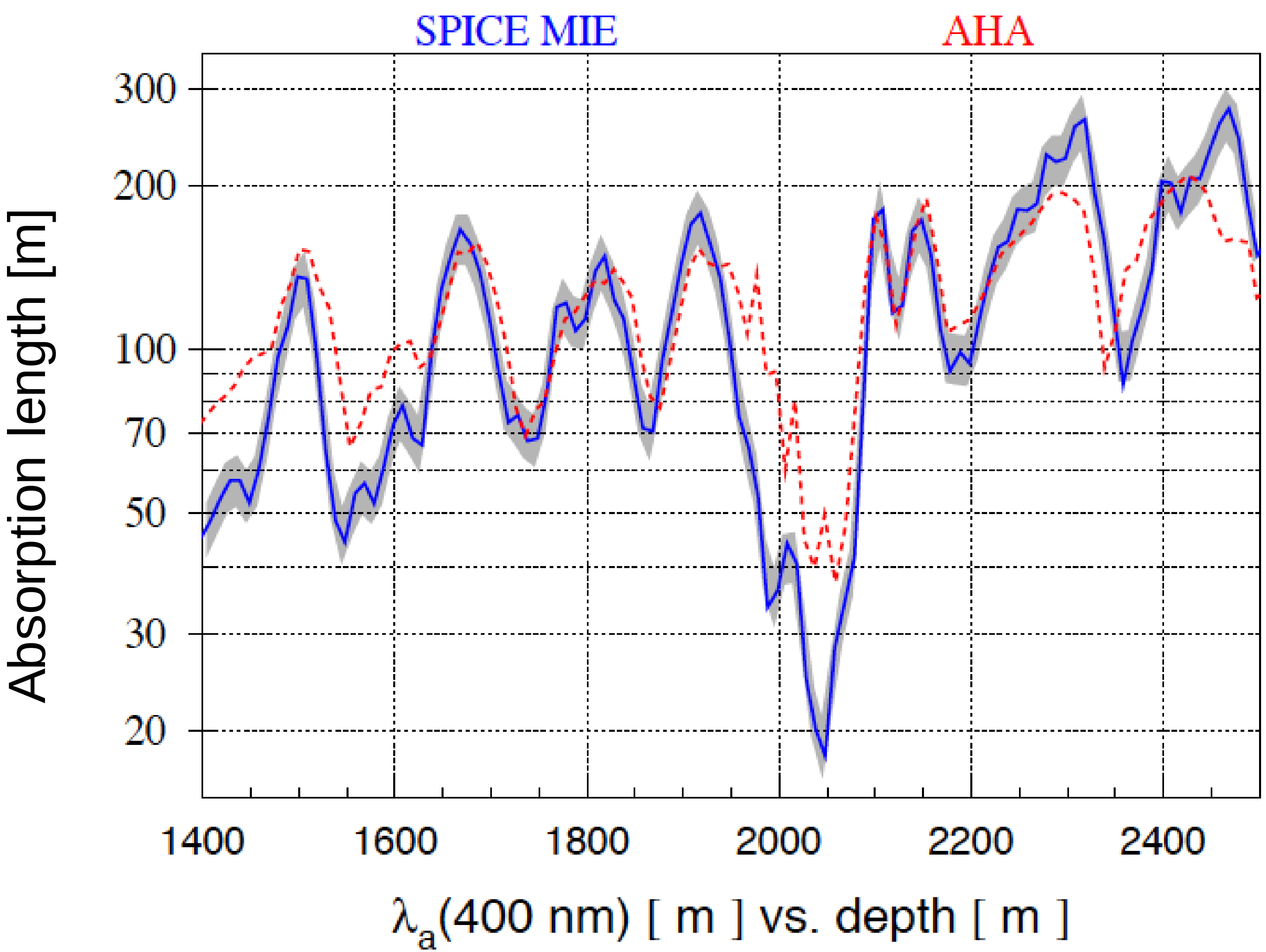
Partially in a dust layer



The Ice is very clear
Effective scattering length vs Depth



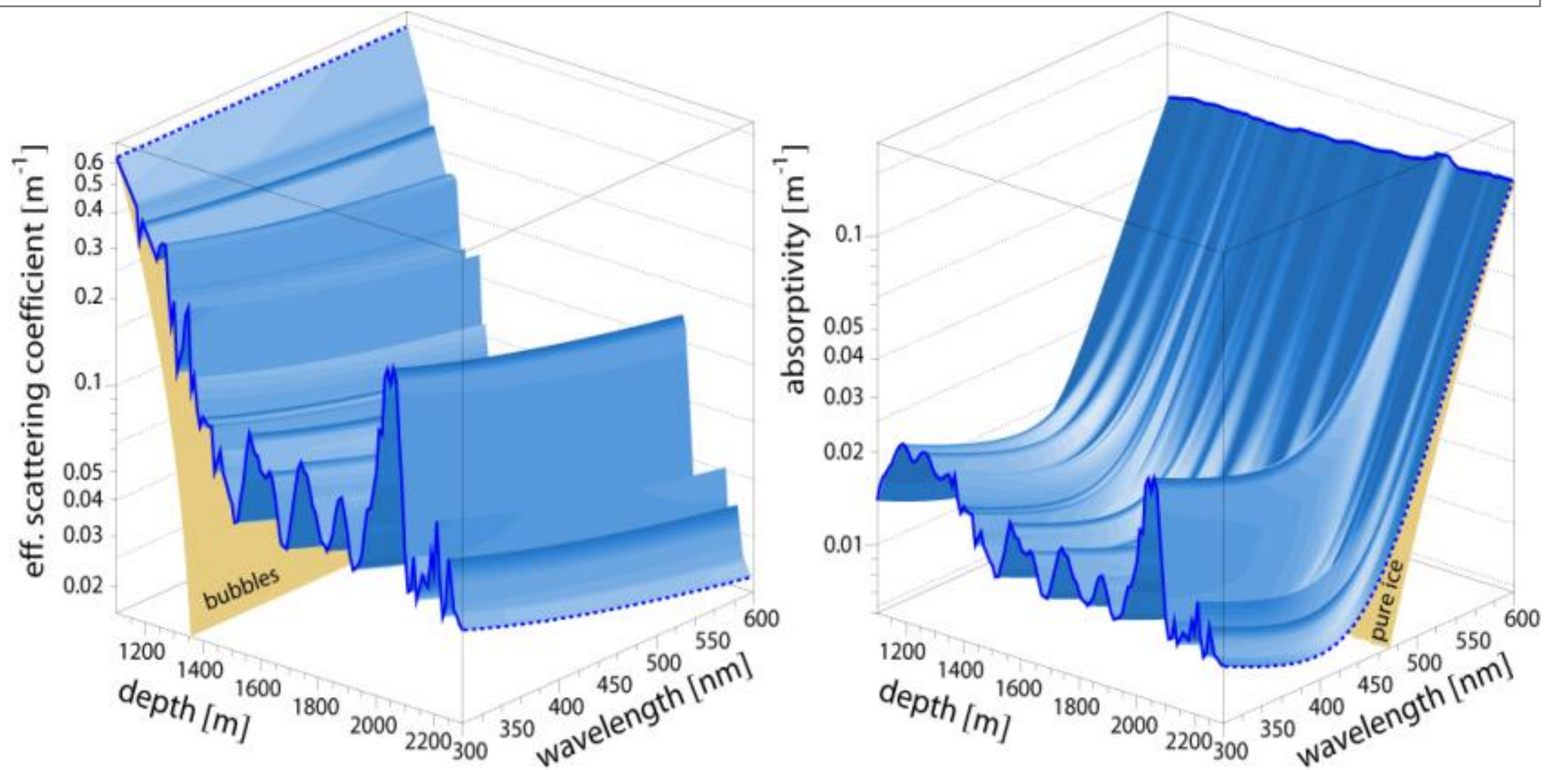
Absorption length vs Depth



Optical Properties

- Combining all the possible information
- These features are included in simulation
- We're always be developing them

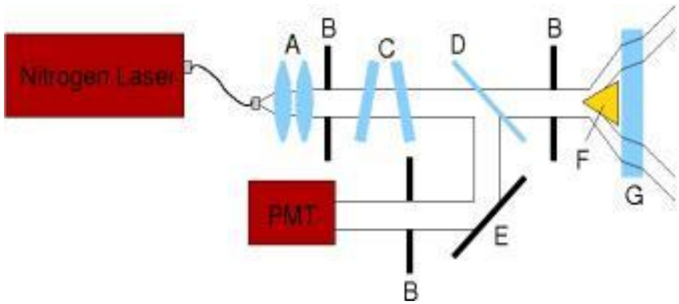
Nature never tell us a perfect answer but obtained a satisfactory agreement with data!

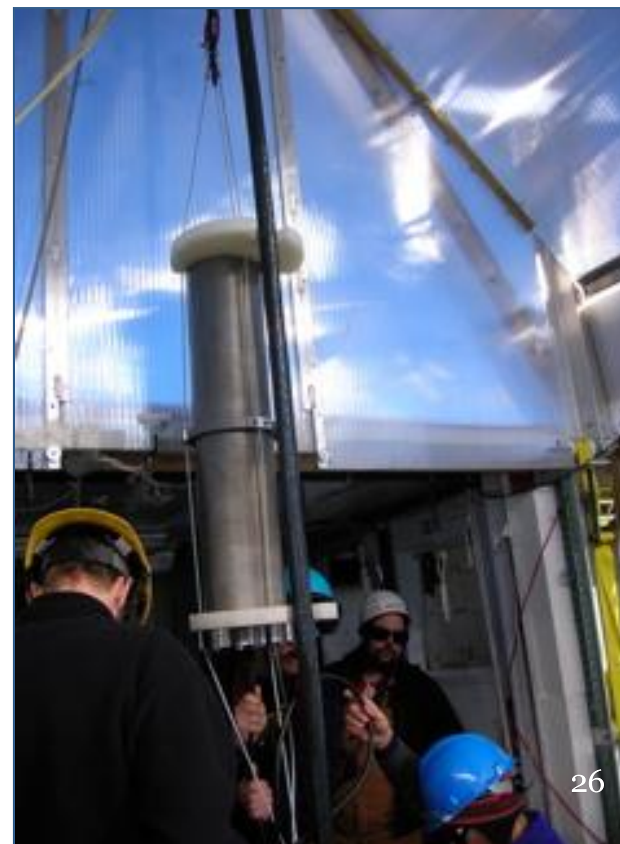


In-*situ* Absolute Calibration

Calibrated light source: Standard Candle

- **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%**

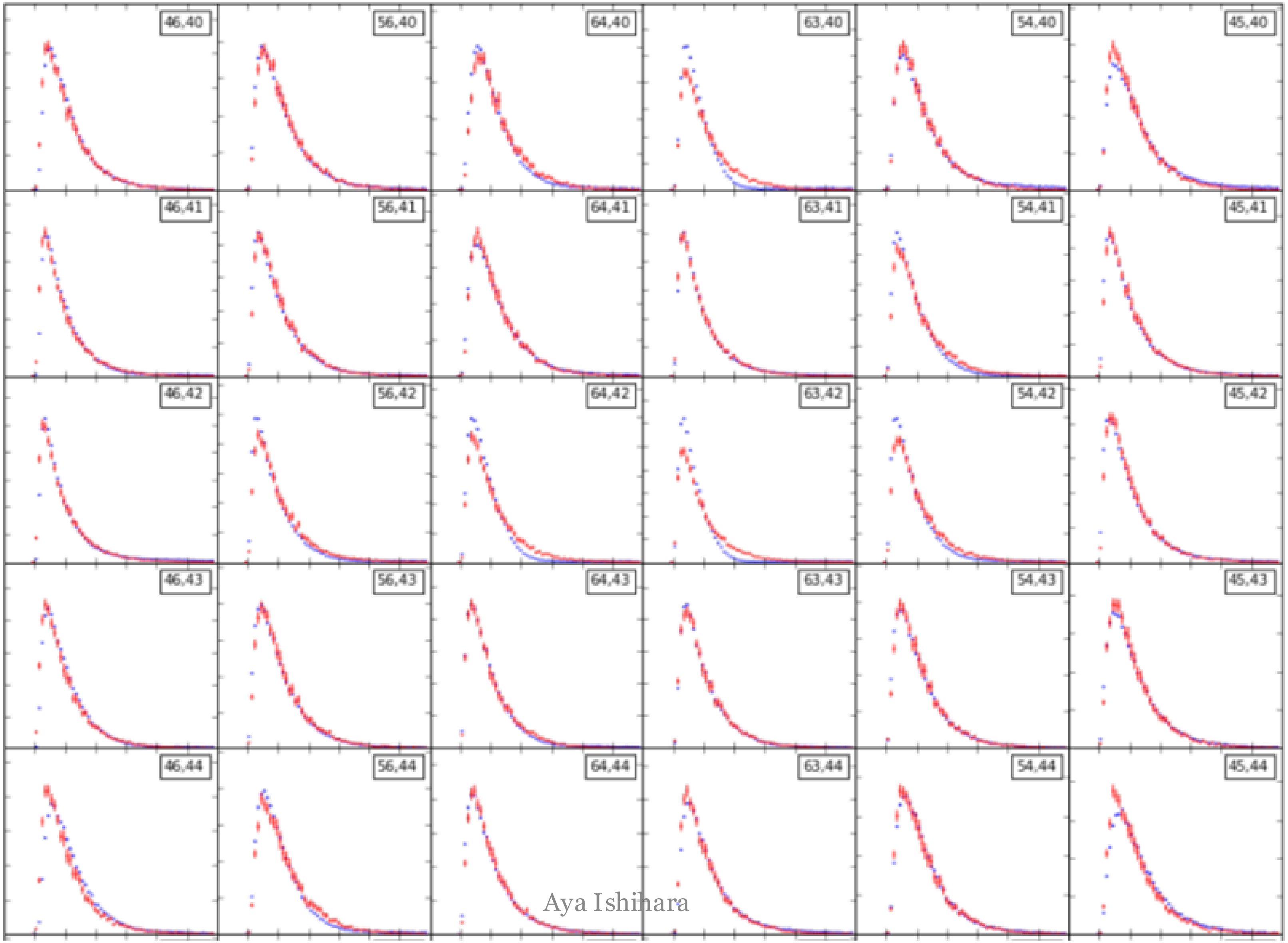




Checks of non saturated region

Red:data
Blue:MC

Comparisons of normalized waveforms in non saturated region (shape = photon timing)



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

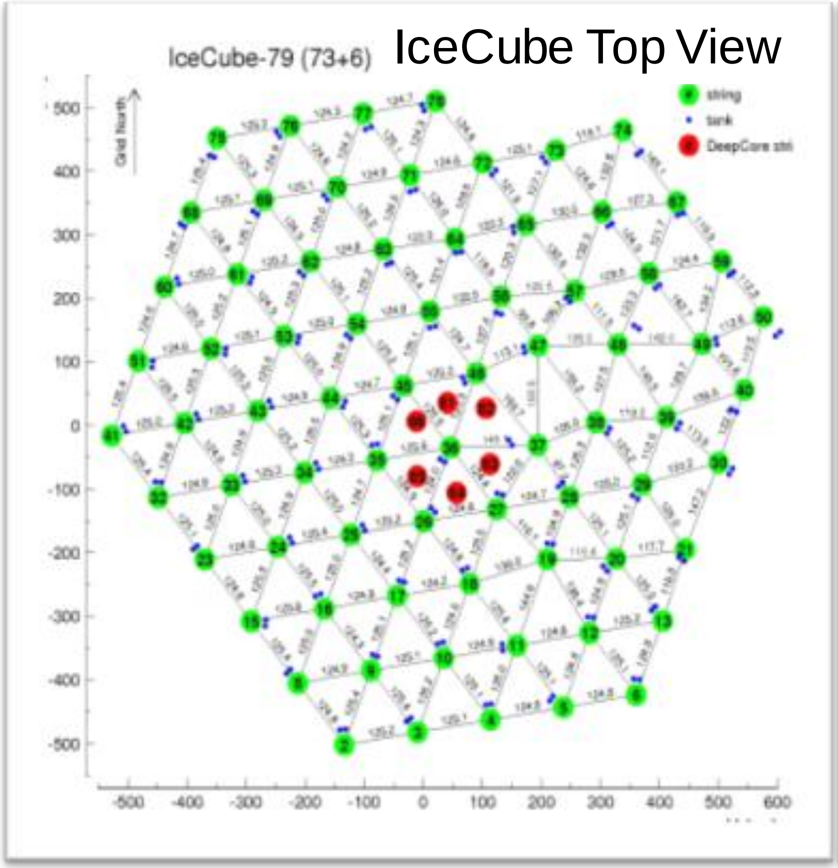
Data samples

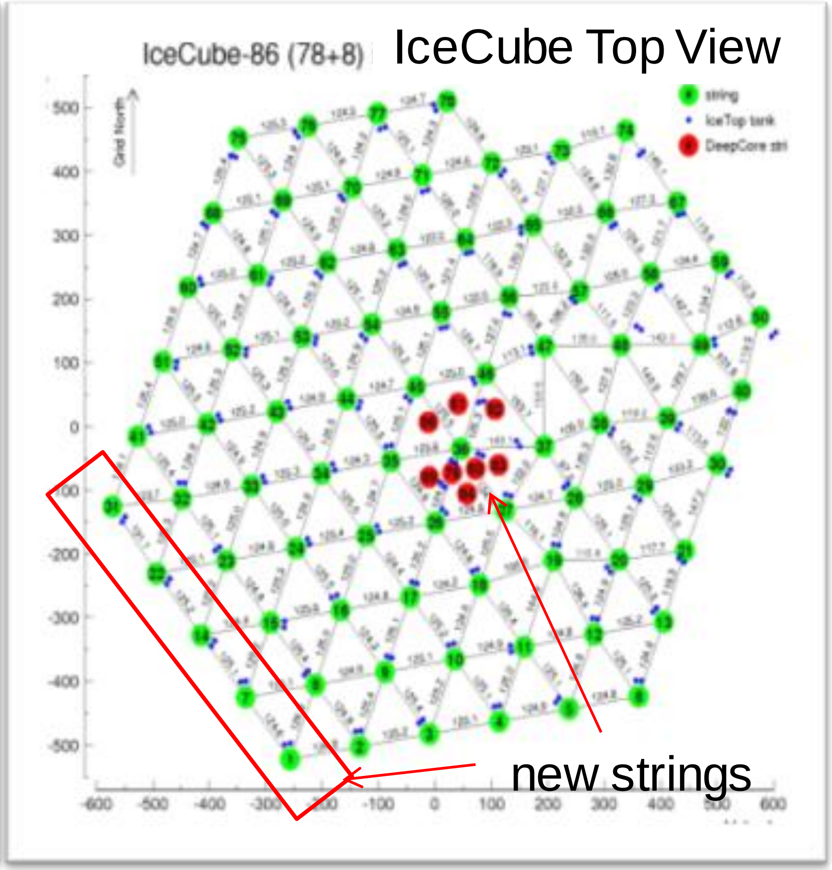
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

Effective livetime of 670.1days

2010-2011 - 79 strings config.
May/31/2010-May/12/2011
Effective livetime 319.9days

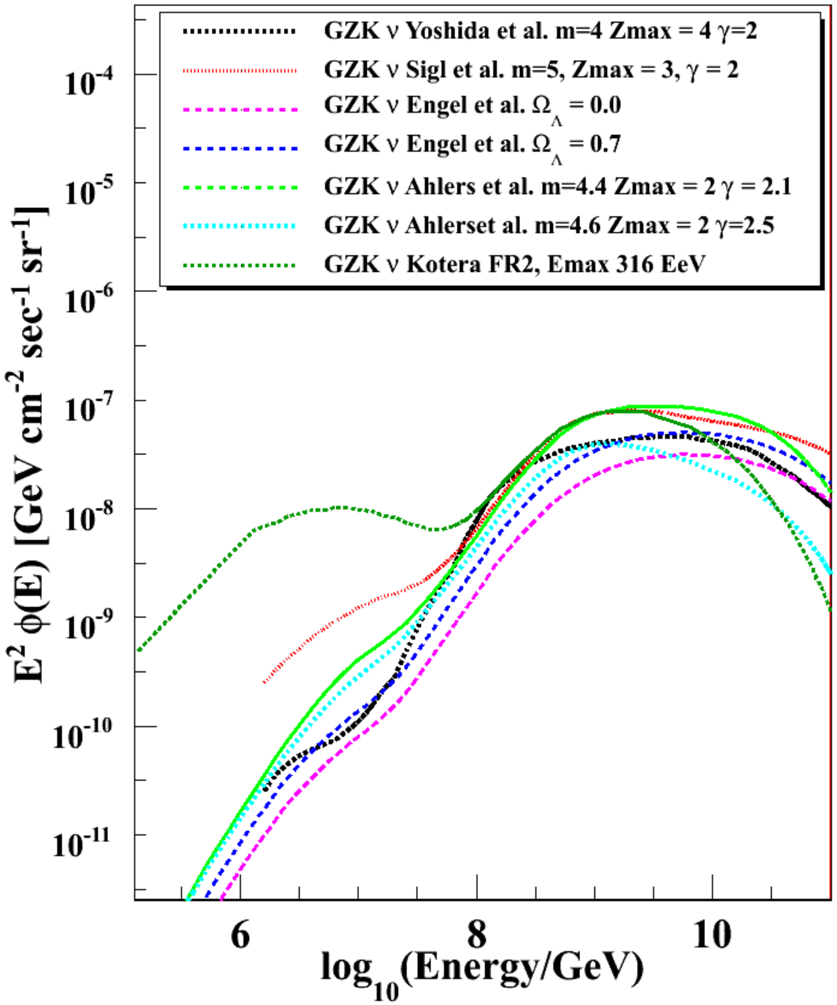
2011-2012 – 86 strings config
May/13/2011-May14/2012
Effective livetime 350.1 days



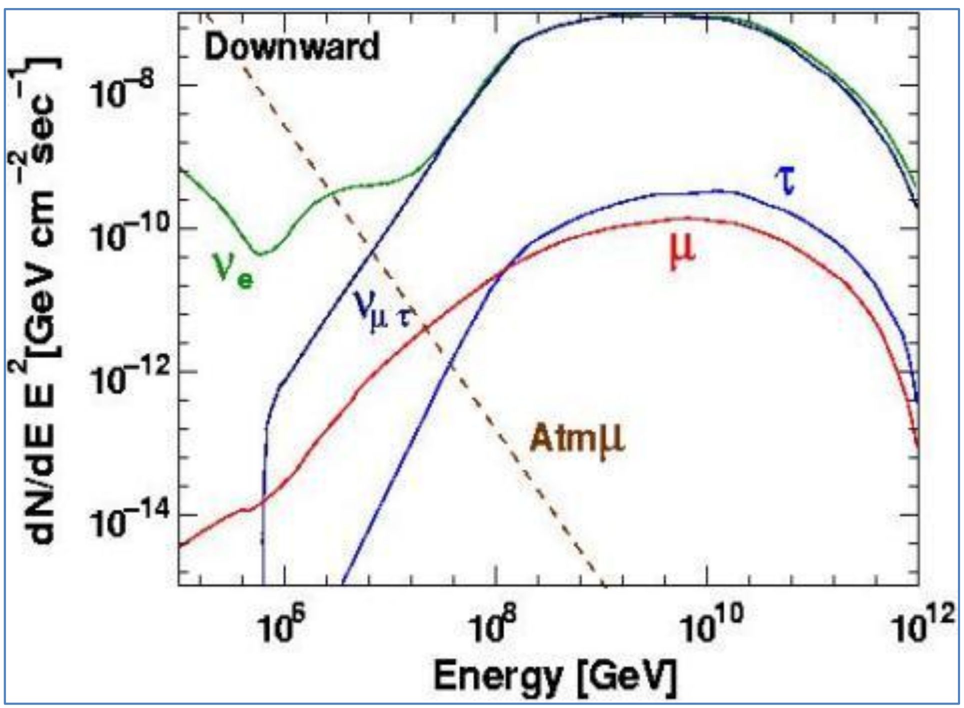


IceCube has been in a stable operation for more than 5 years

Signal models



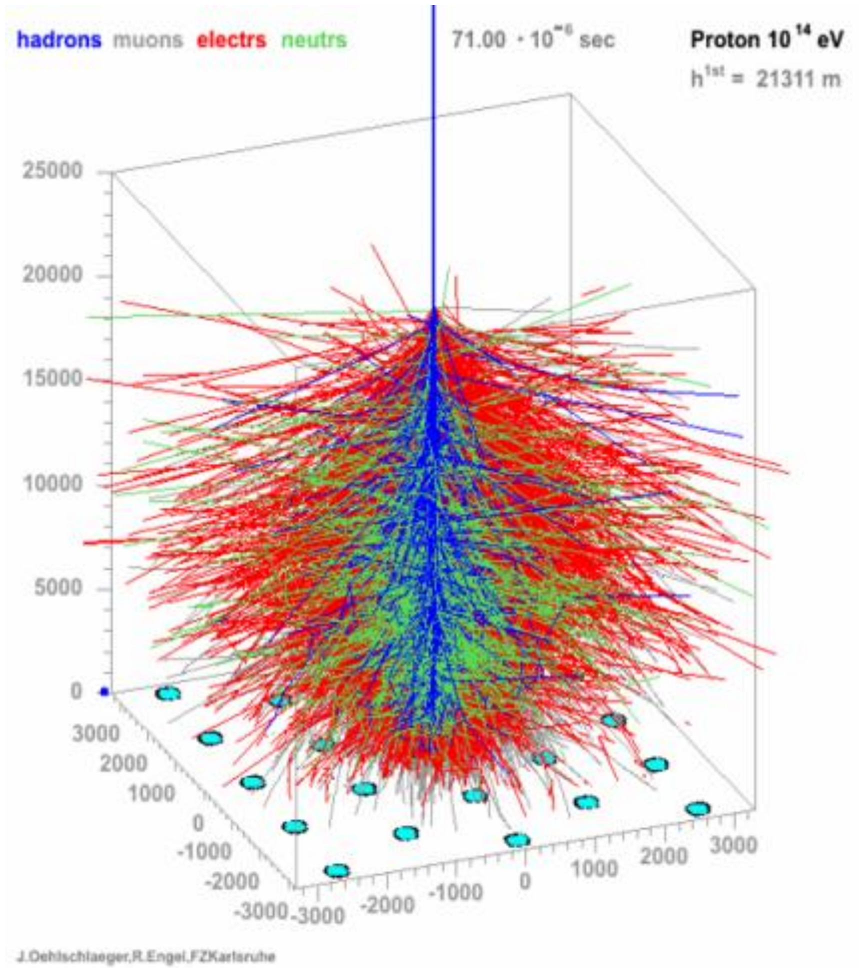
Various GZK ν models

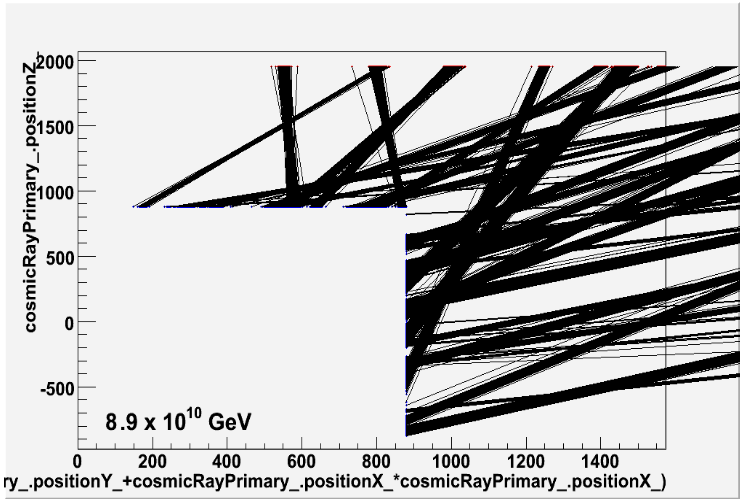


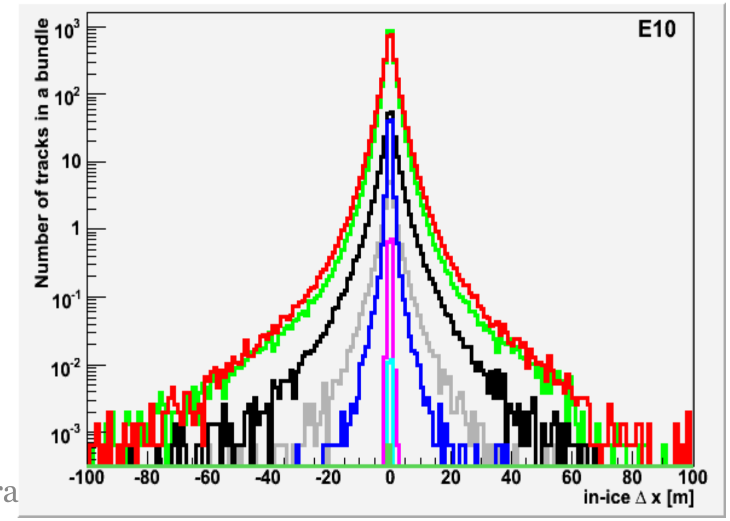
Background

- Atmospheric muons
- Atmospheric neutrinos

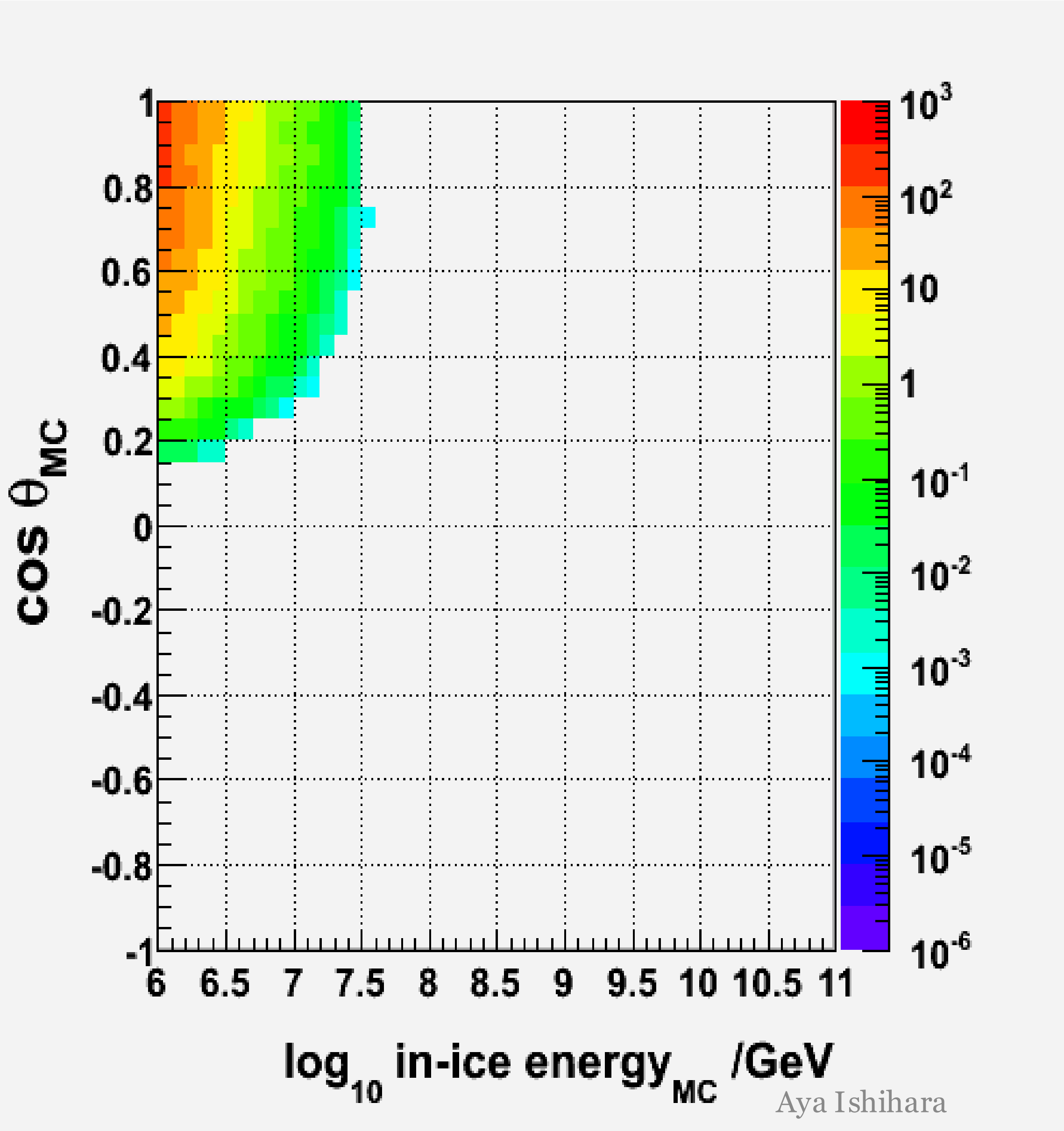
Major background is cosmic-ray muons (muon bundles)





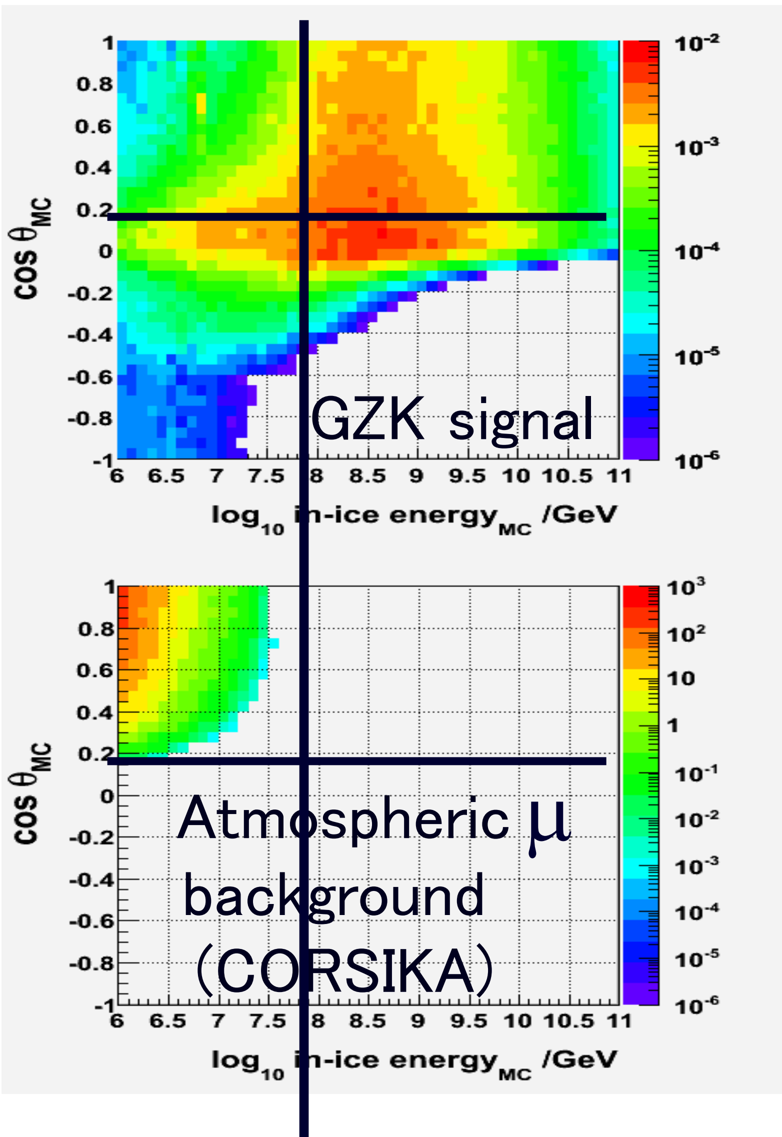


Atmos. muon distribution



Relatively easy to cut them away

Basic strategies for search for GZK neutrinos



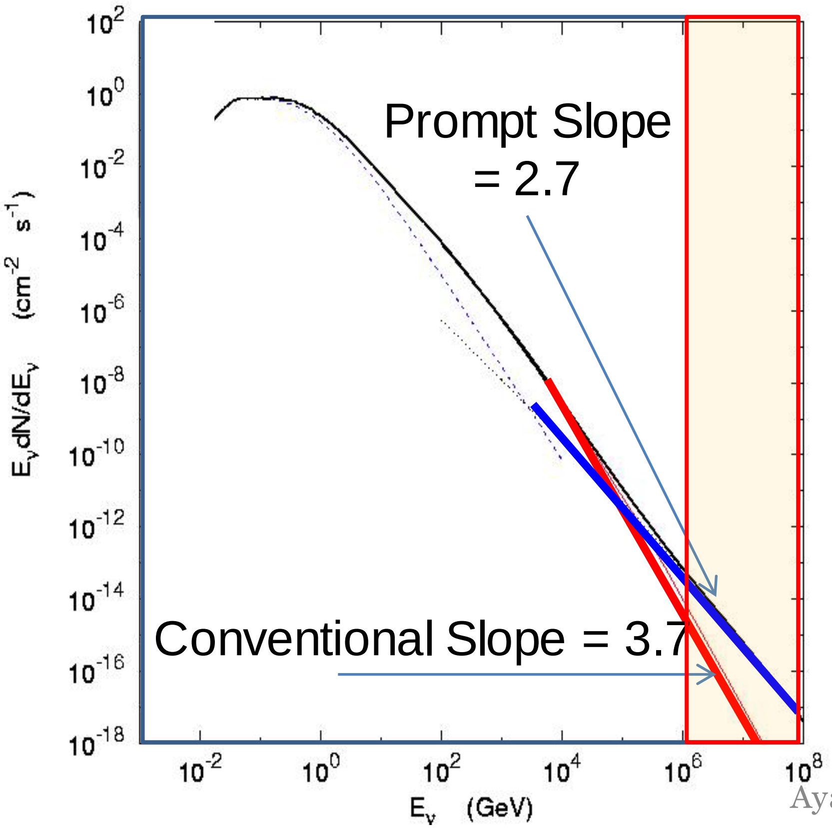
Background energy smaller than signal

Background is vertical downward-going while signal comes near horizon

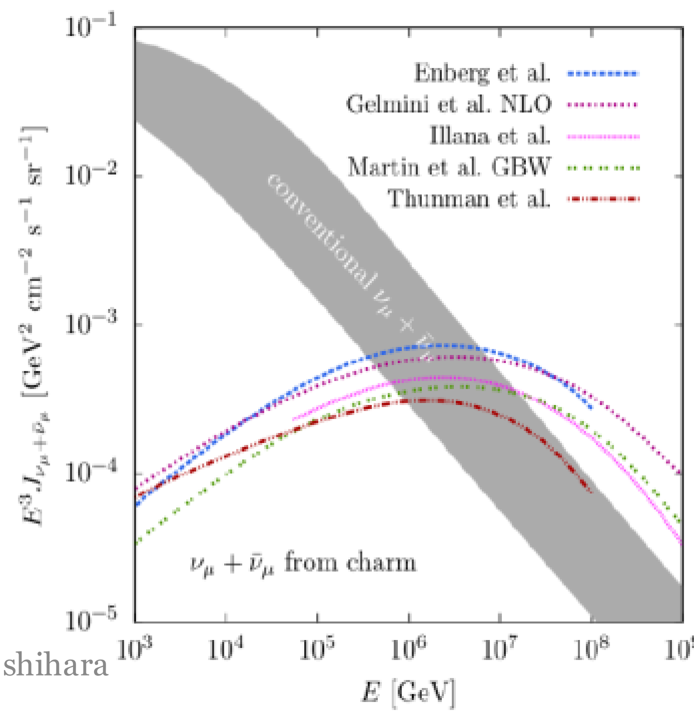
Atmospheric neutrinos in PeV

- 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**

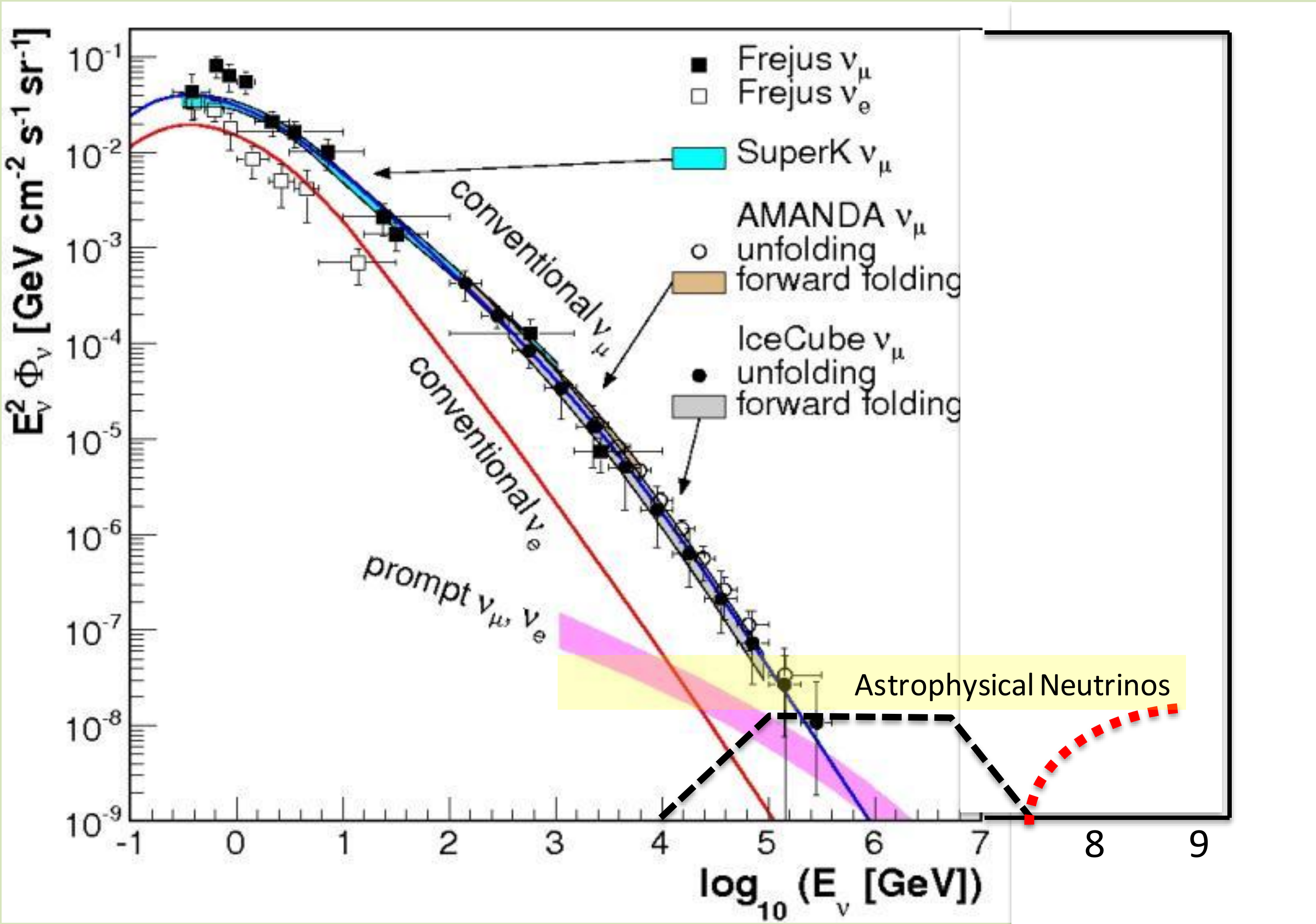


Physics of heavy flavor particle production

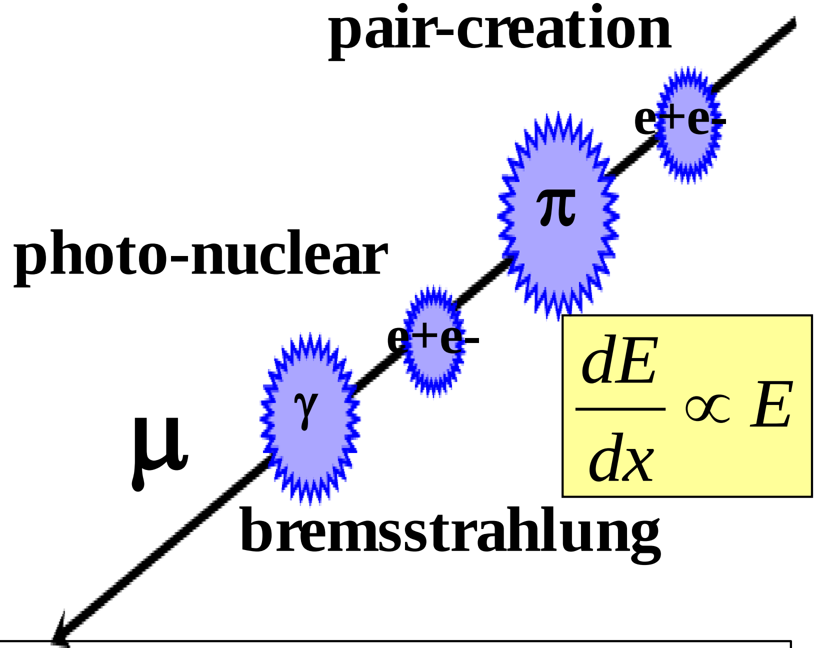


our default relatively high but not excluded

Atmospheric neutrinos in a wide energy range



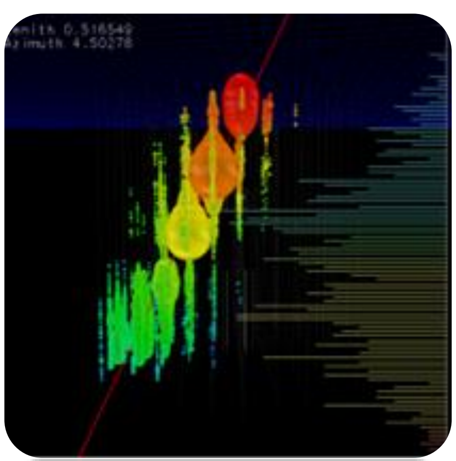
The Energy estimation

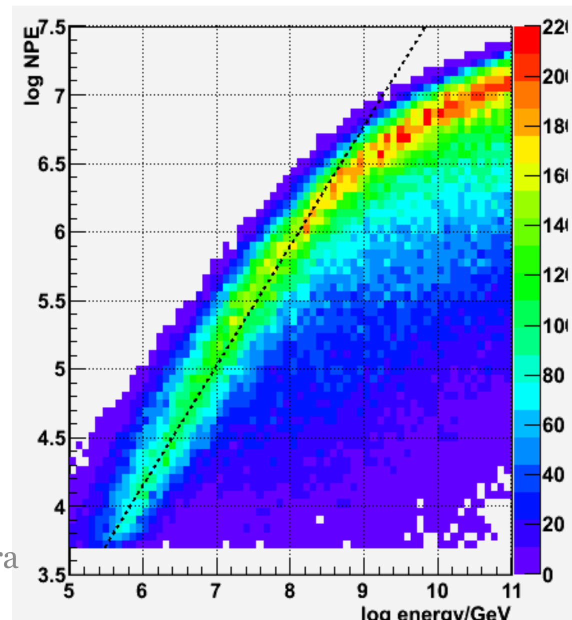


μ and τ tracks lose their energy by
radiative processes

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

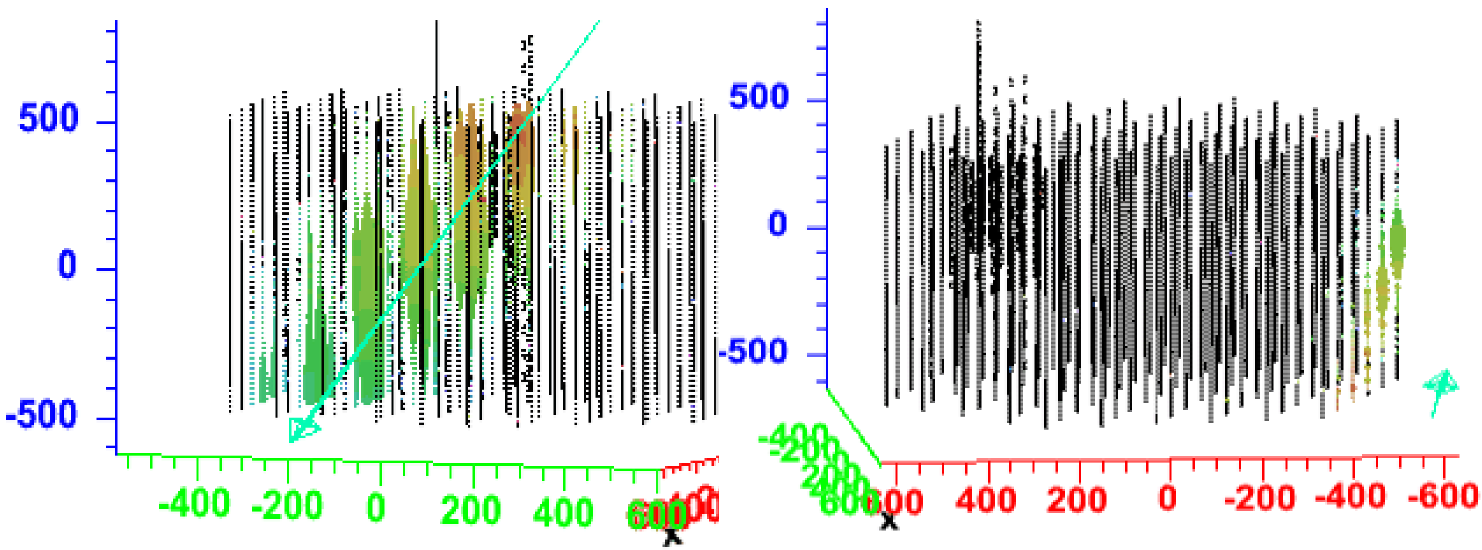
channel # > 300





Note that there is position dependence

Events with the same energy ~ 30PeV

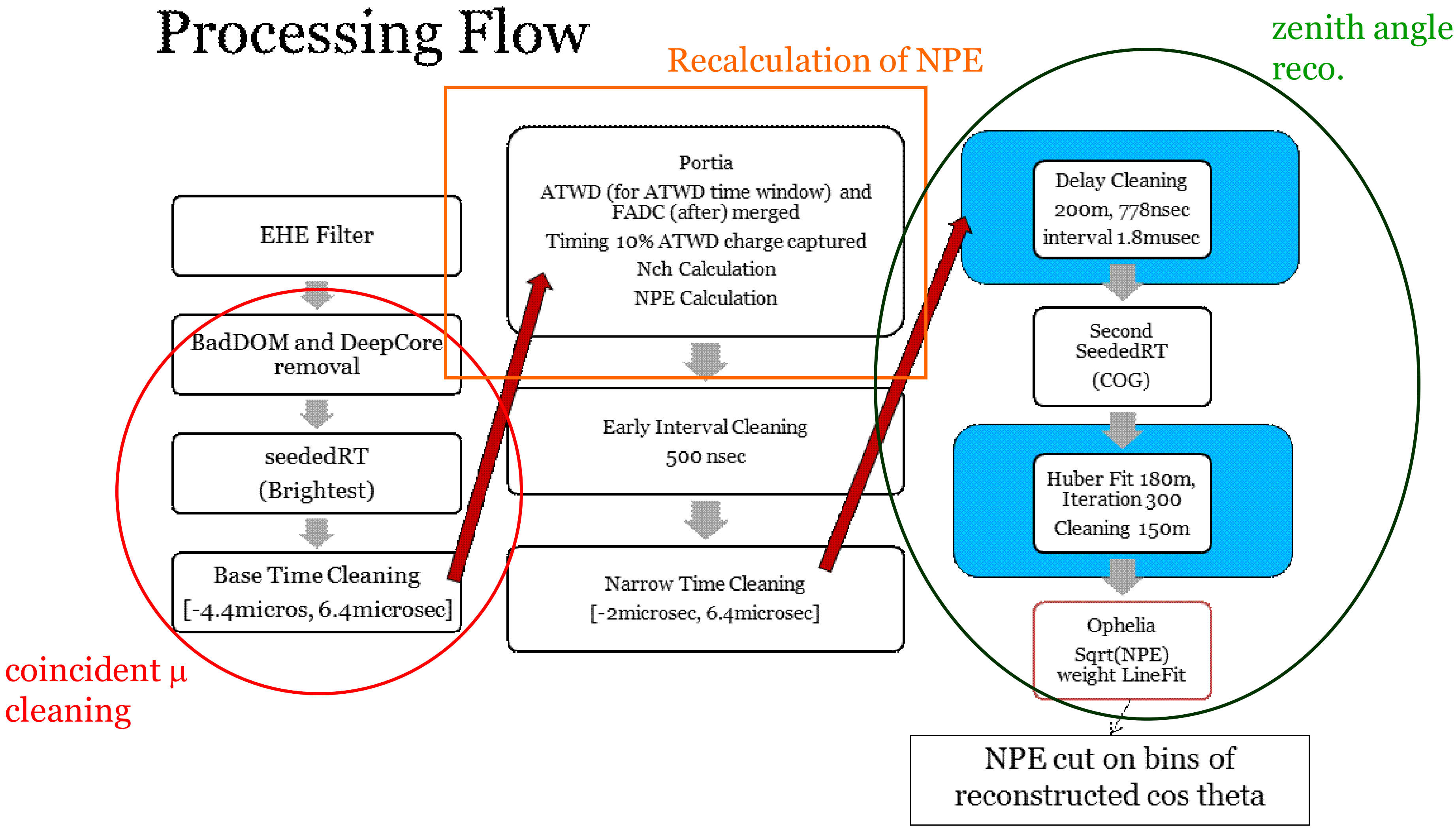


contained
High npe: 10^7 npe

uncontained
Low npe: 1000 npe

NPE and #of channels serve as a containment cut

The analysis flow in 2011-2012

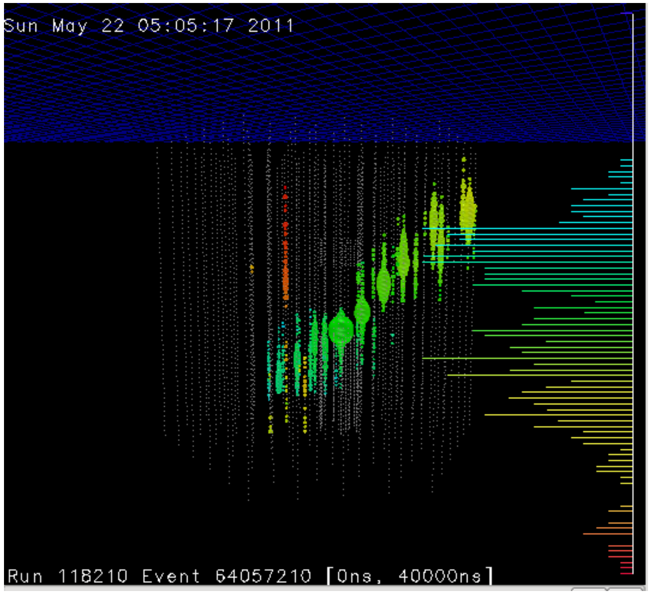


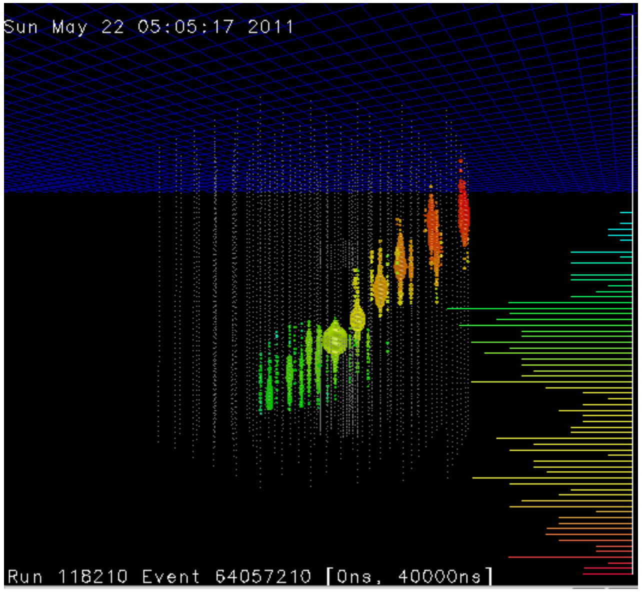
Coincident μ track cleaning

The “burn-sample” data

Example #1

Before

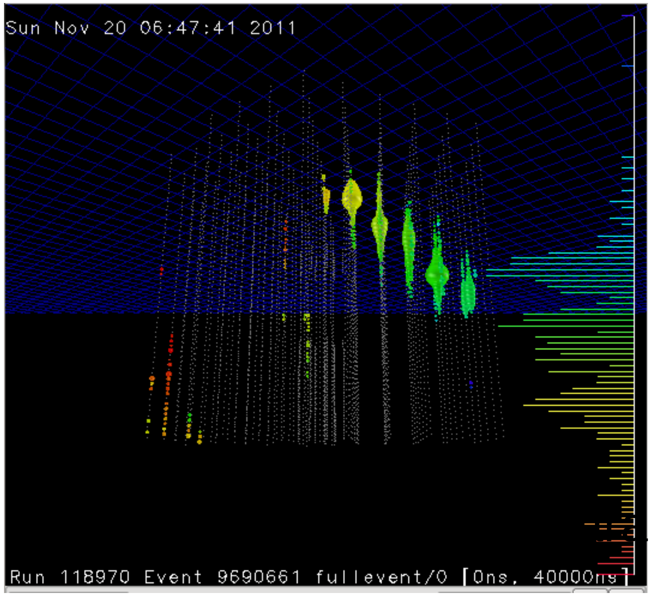


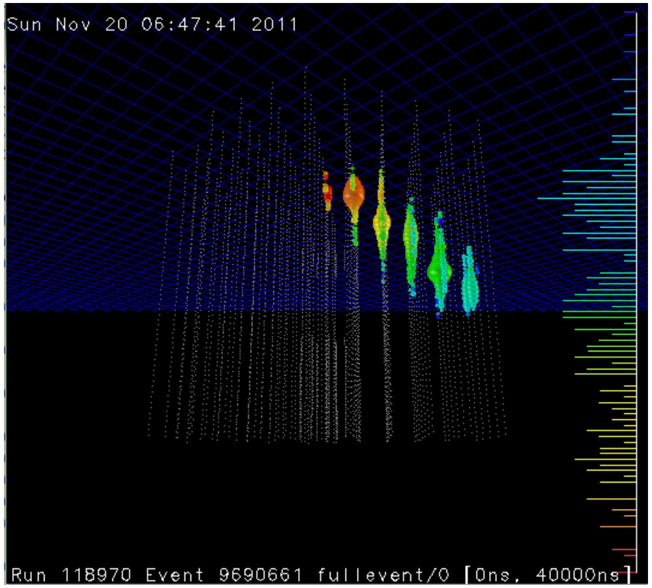


After

Example #2

Before





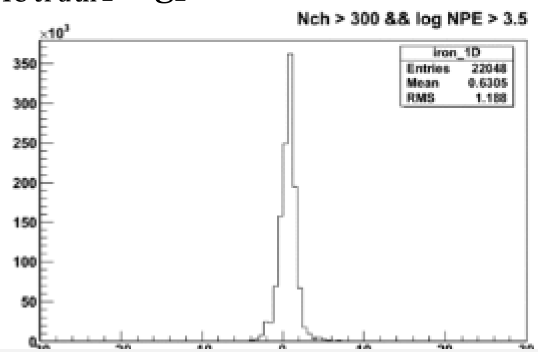
After

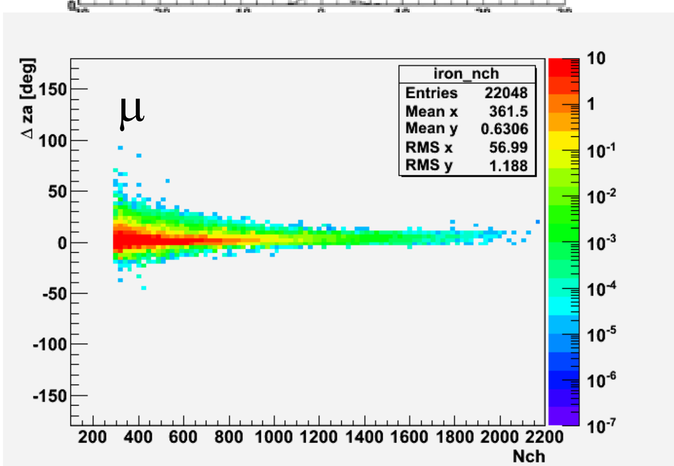
Zenith angle resolution in the UHE analysis

- 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

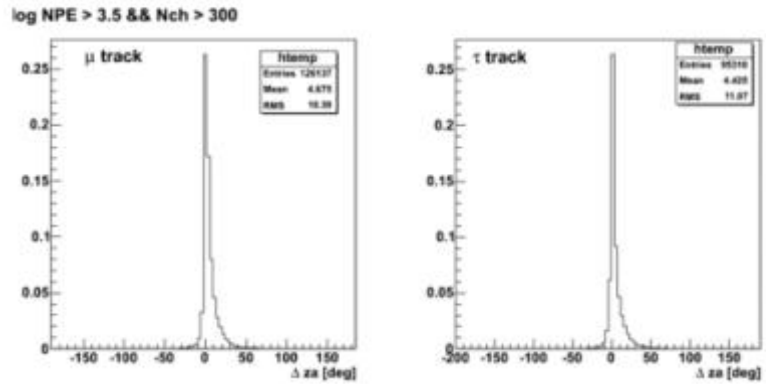
$\theta_{reco} - \theta_{MC\,truth}$ [deg]



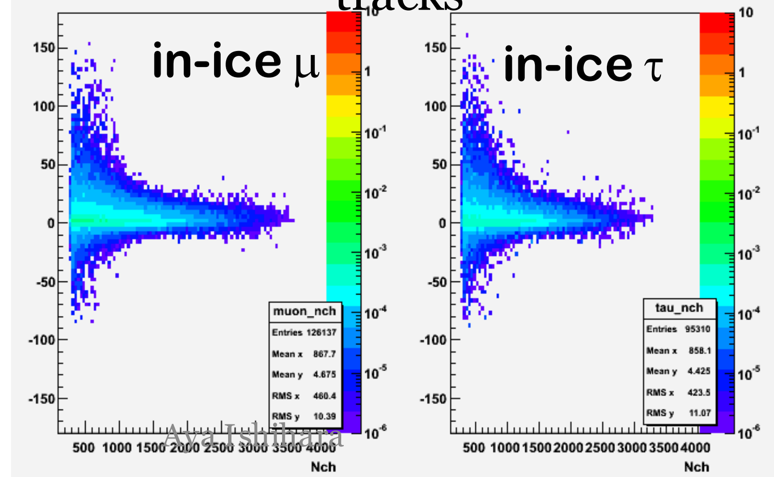


resolution for signal mu, tau tracks

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

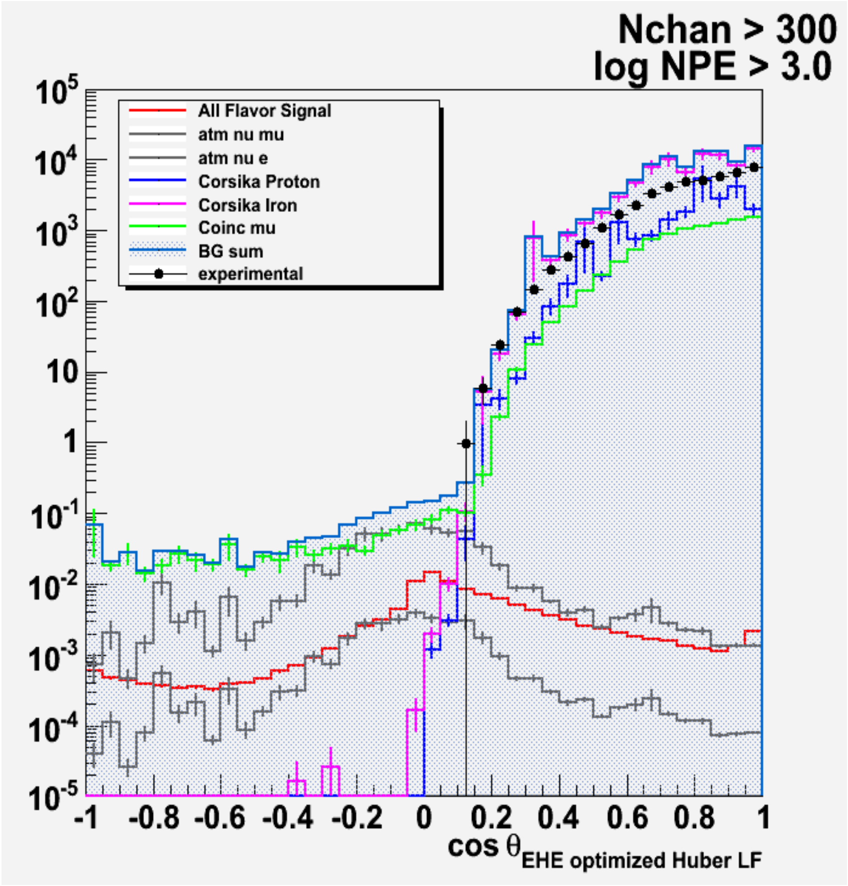


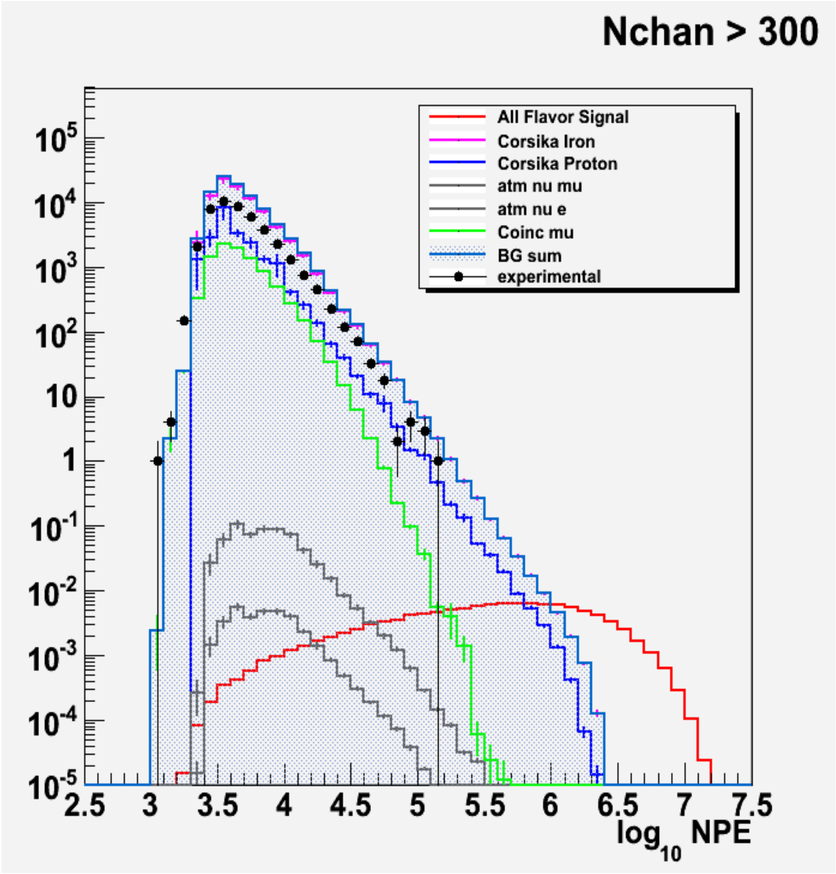
tracks



Filtering level NPE and cos theta distributions

NPE and cos zenigh angle distributions comparisons with burn sample





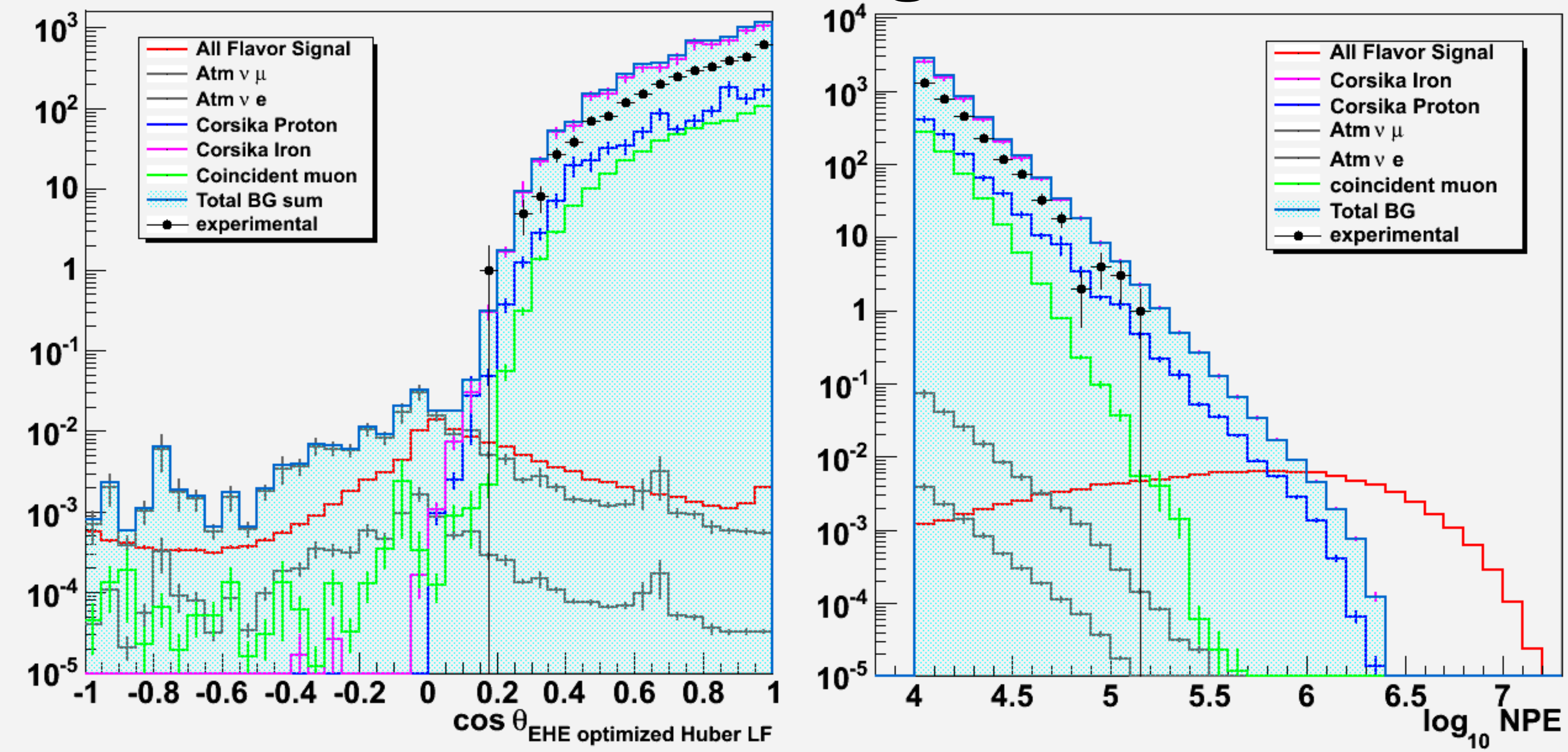
Reco Zenith and NPE distributions (Level-1: #OM > 300, log NPE > 3.5)

Year-1 IC86 data sample

Green – iron CORSICA
Blue – proton CORSIKA
Black – burn sample
Red - signal MC

2011-2012 dataset

level-1: reasonable agreements with MC

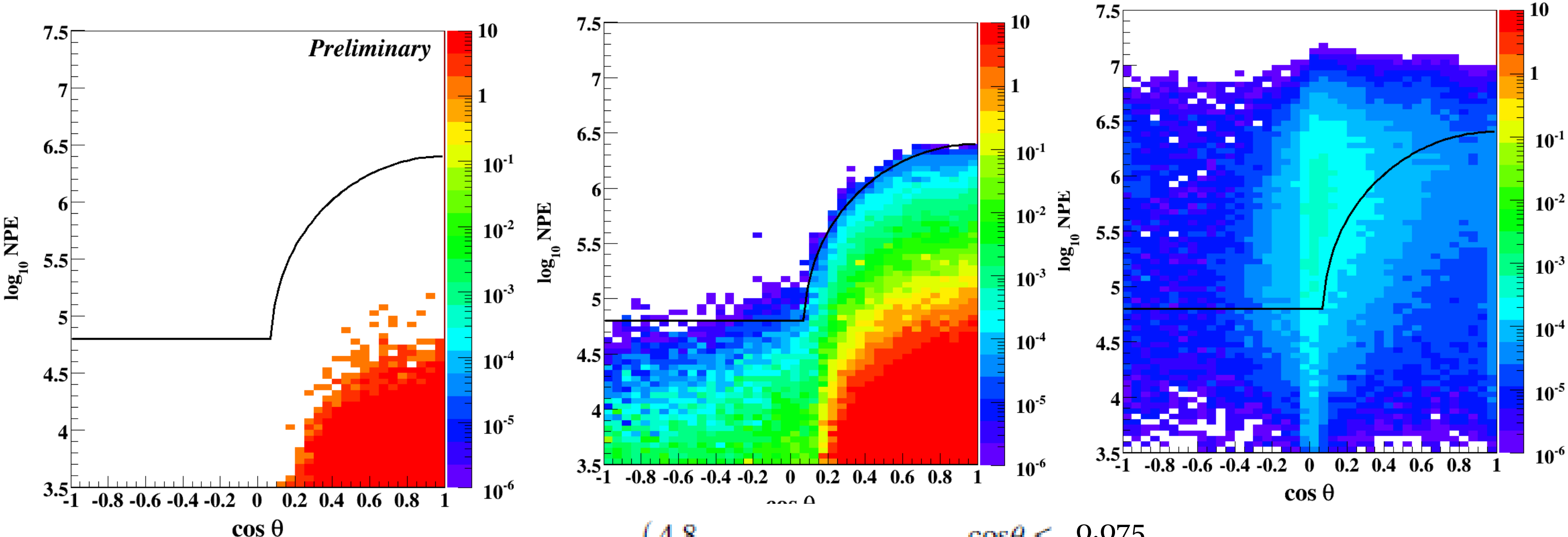


The Event Selection for 2011-2012

- Optimization fully based on MC (blind analysis)
- MC verification based on 10% experimental ‘burn’ sample
- Optimization for 2010-2011 data very similar slightly different in values

channel # > 300

Experimental Data (10%) Background MC Signal MC



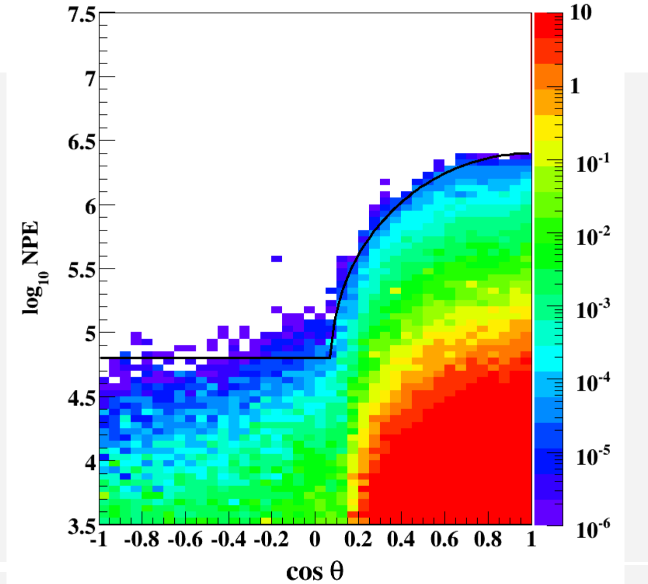
$$\log_{10}\mathrm{NPE} \geq \begin{cases} 4.8 & \cos\theta \leq 0.075 \\ 4.8 + 1.6\sqrt{1-\left(\frac{\cos\theta - 1.0}{0.925}\right)^2} & \text{otherwise.} \end{cases}$$

signal MC Yoshida（m=4, z=4） 1．0事象/年

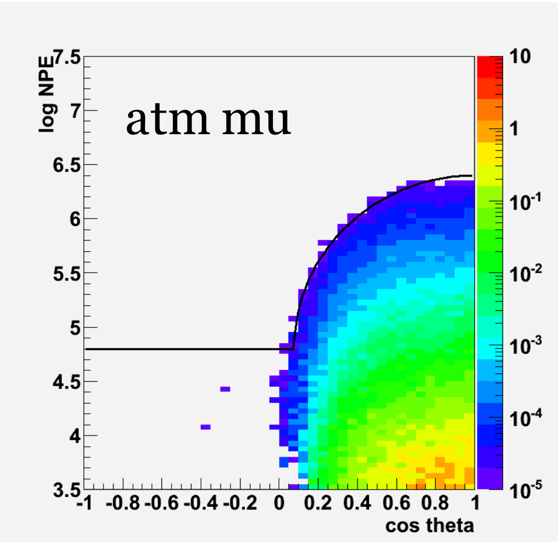
Background (atm nu + atm mu) 0．015事象/年

Background contributions

Background MC

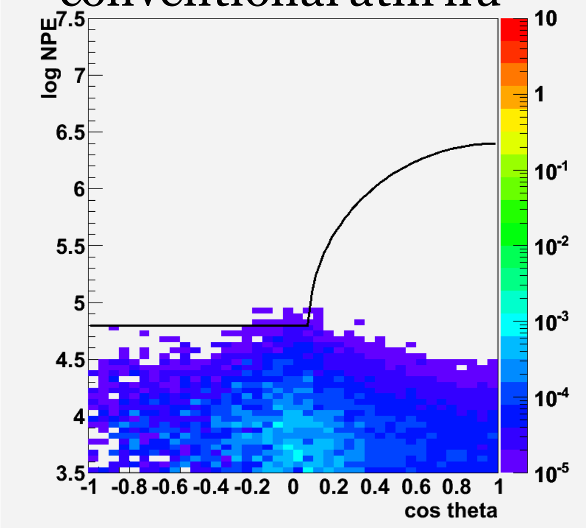


atm mu



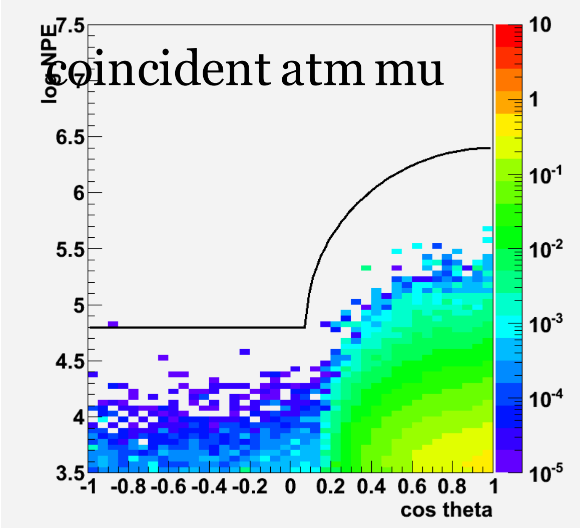
+

conventional atm nu



+

coincident atm mu



Total updated background per 670 days

	Total background (IC79+IC86)
Atmospheric μ	0.0363
Atmospheric conventional ν	0.0212
Total	**0.0573 (with prompt 0.190)**
prompt ν (Enberg et al.)	0.133+/- 0.0007

2011-2012

	rates per livetime
Atmospheric μ	0.0089 +/- 0.0030
Atmospheric conventional ν	0.0060 +/- 0.0004
Total	**0.0147 (*0.0628*)**
prompt ν	0.0481 +/- 0.0004

2010-2011

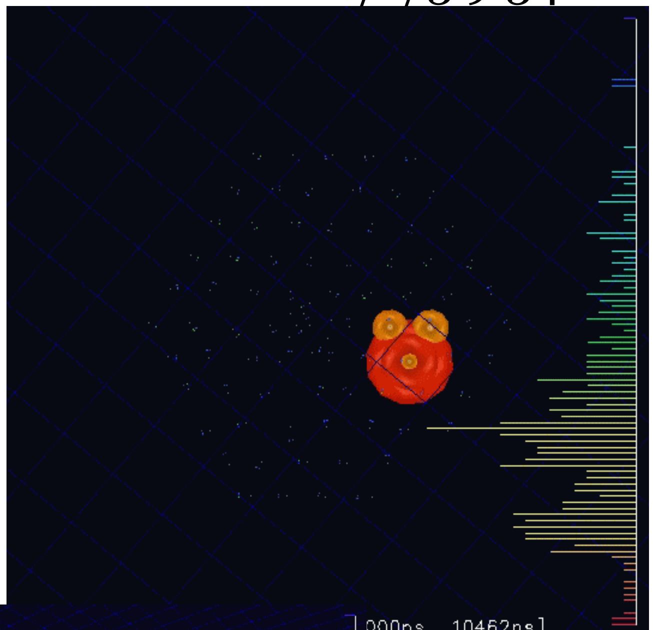
	rates per livetime
Atmospheric μ	0.02742 +/- 0.0054
Atmospheric conventional ν	0.01520 +/- 0.0007
Total	**0.0426 (0.127)**
prompt ν	0.0851 +/- 0.0007

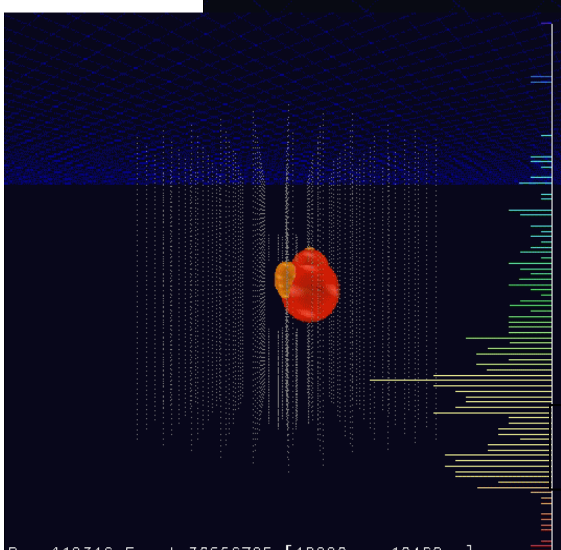
After unblind - Observation of 2 events

Run119316-Event36556705

NPE 9.628x10^4

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

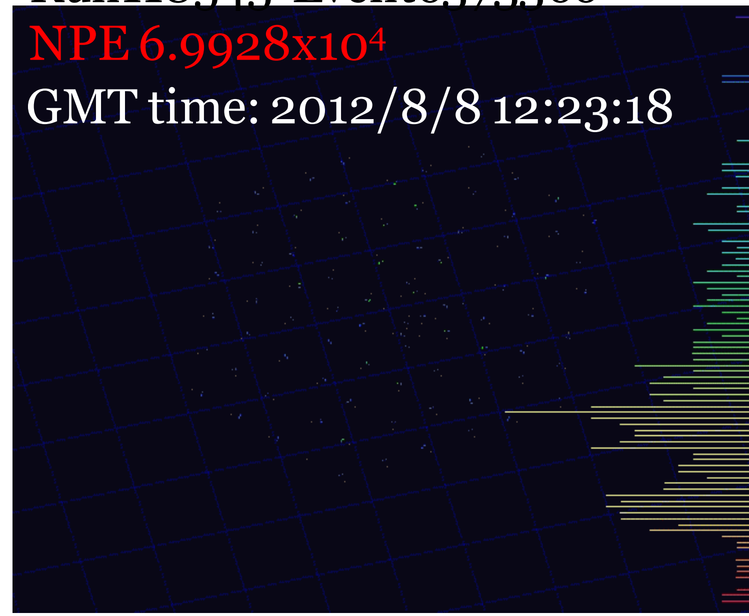


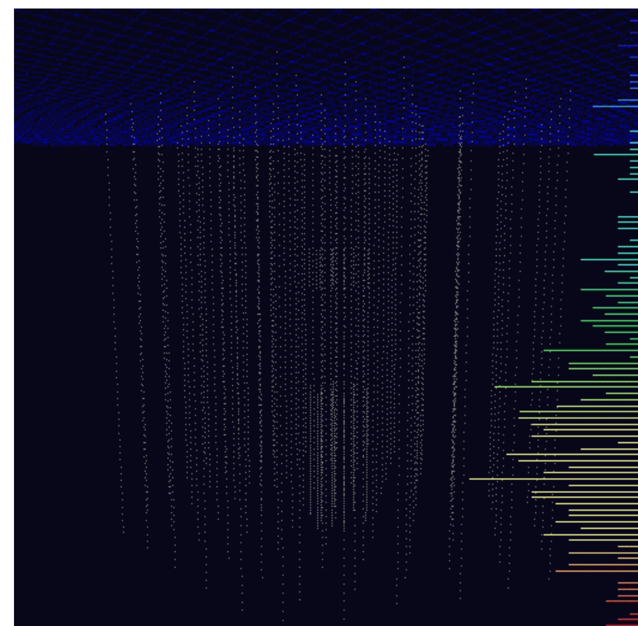


Run118545-Event6373366

NPE 6.9928x10^4

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





2 events / 670 days
background (atm. μ + conventional atm. ν) expectation 0.057 events

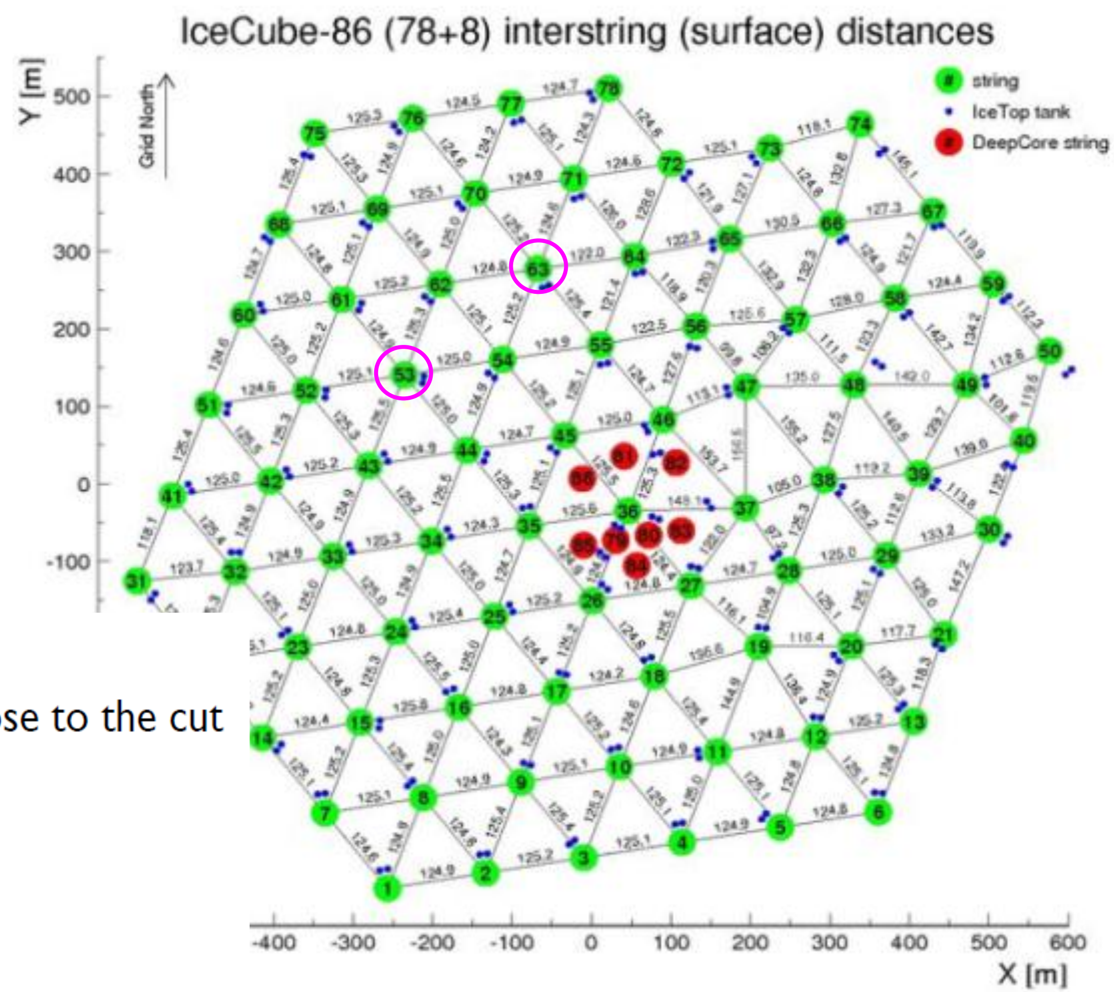
Preliminary

p-value 1.581x10^{-4} (2.95σ)

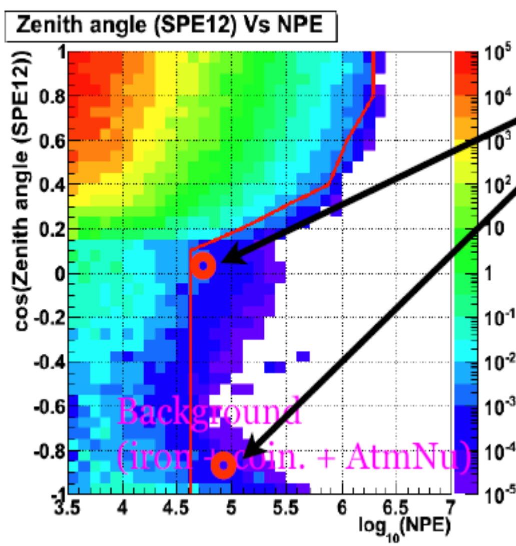
Aya Ishihara

The highest Charged String Positions

Well contained



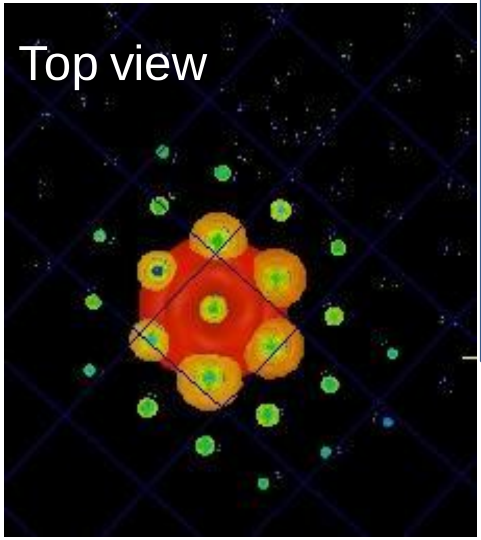
close to the cut

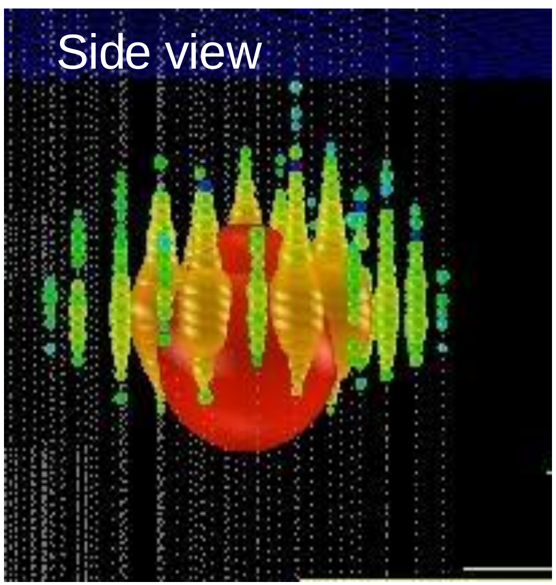


Reconstruction of the two cascade events

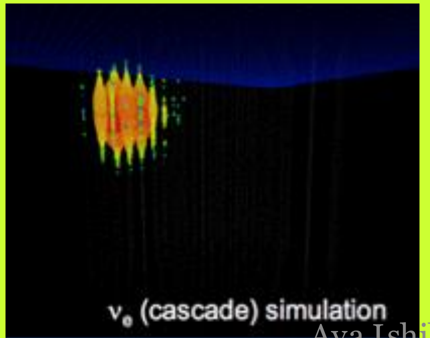
Direction and Energy

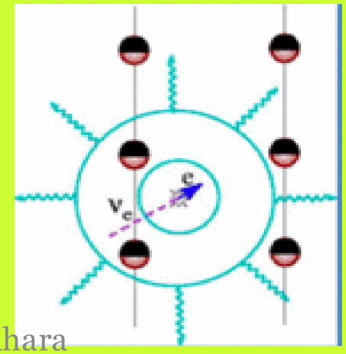
Consistent with cascade events in detector





CC/NC interactions in the detector

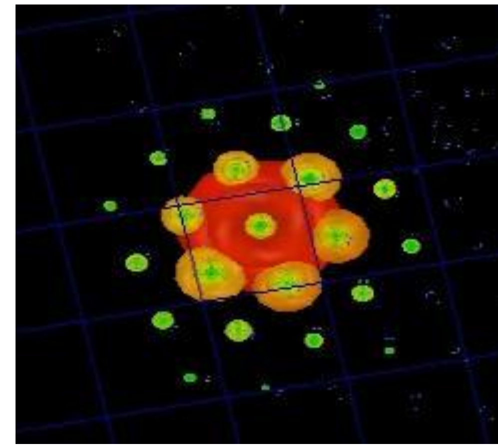


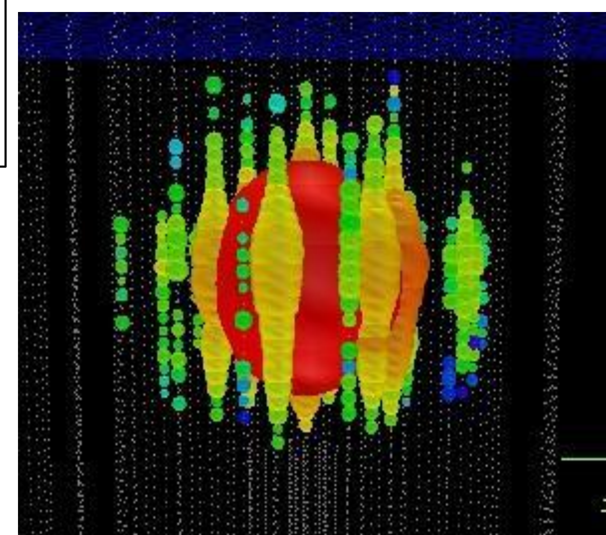


Aya Ishihara

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
Many students/posdocs contributed

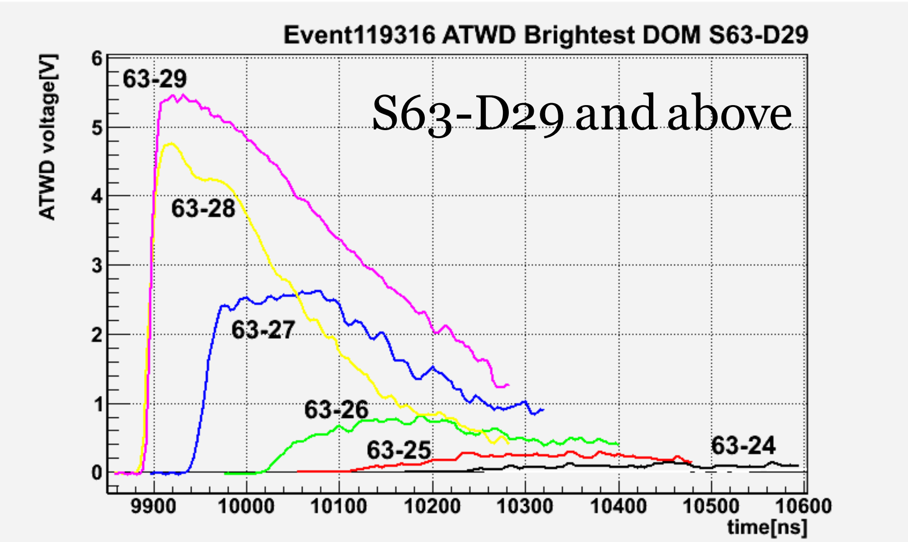


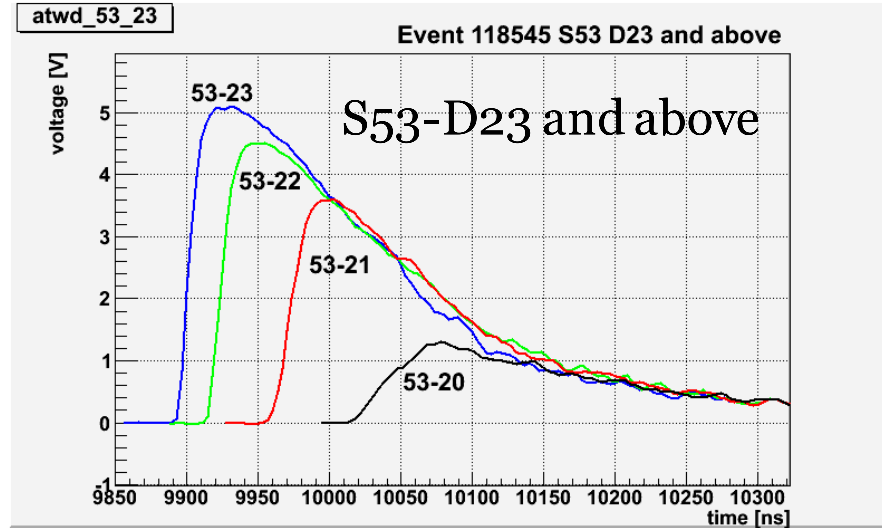


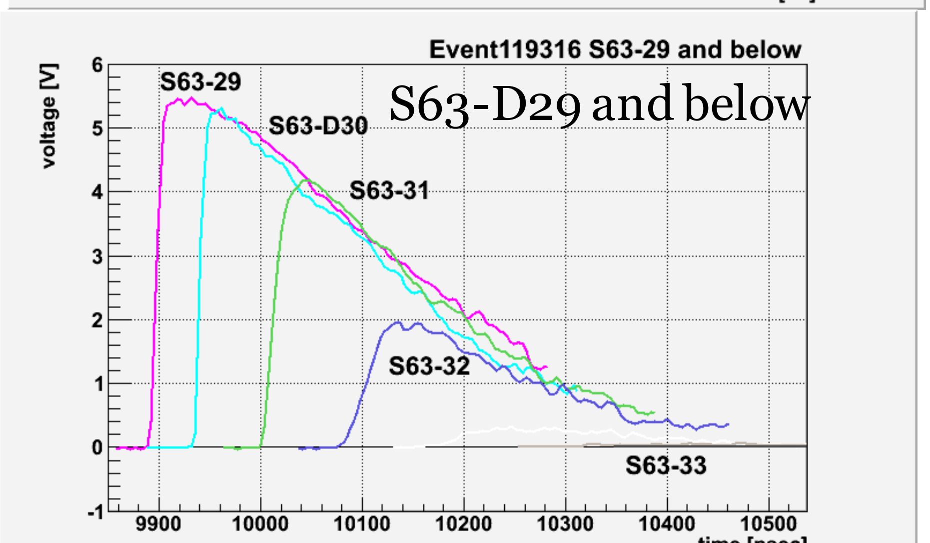
EHE-Jan-2012 **Recorded pulses** EHE-Aug-2011

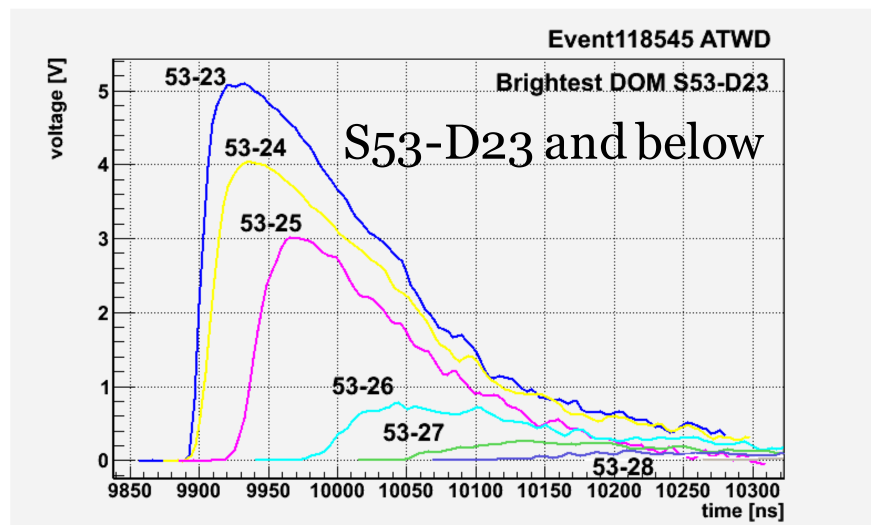
Calibrated ATWD waveform above and below the highest charged DOM (S63-29)

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

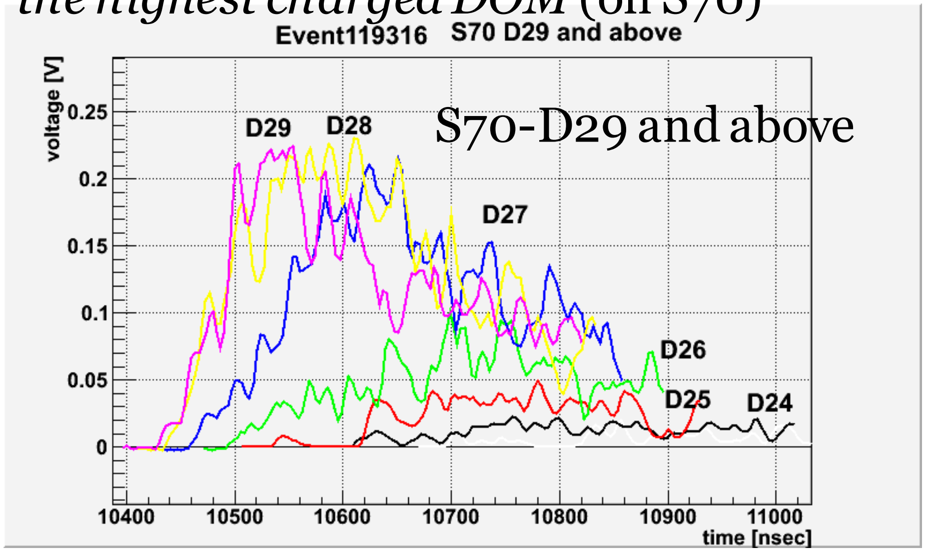


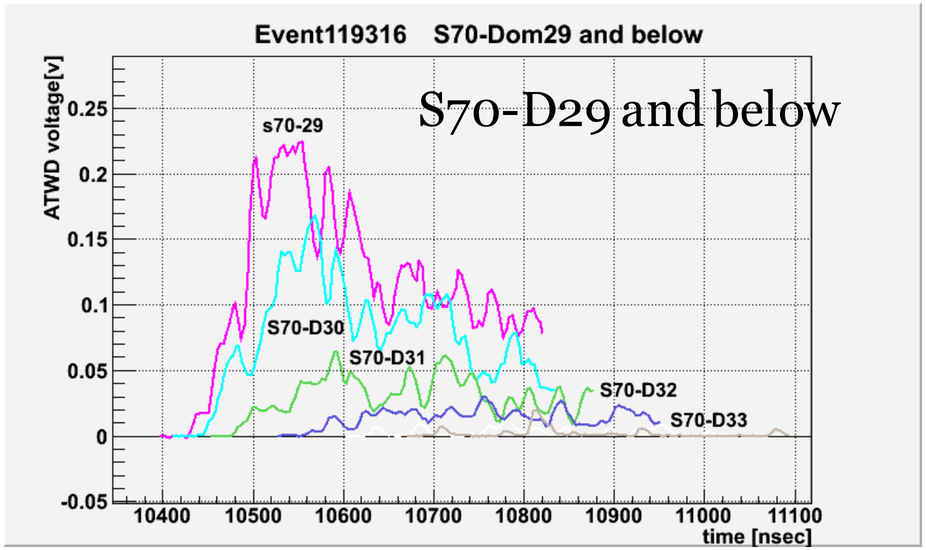






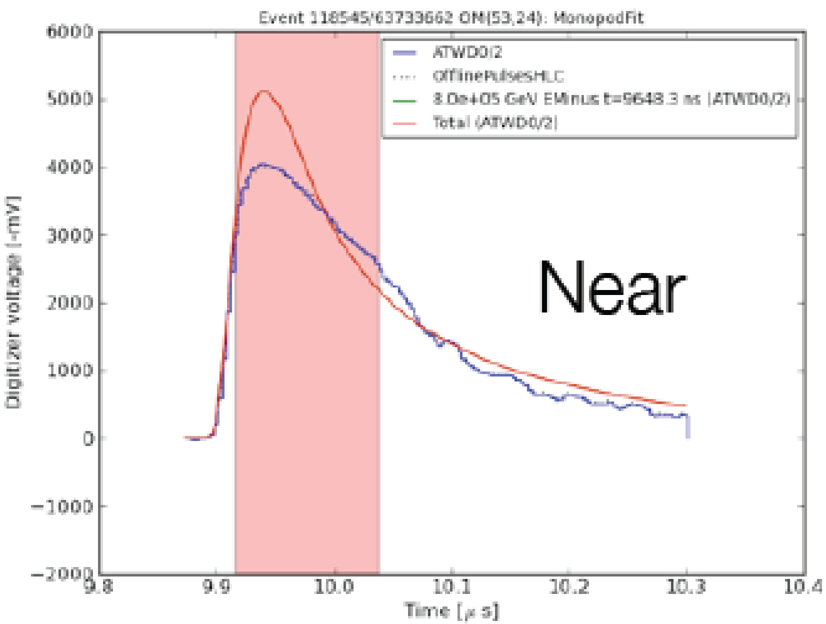
The next brightest string above and below *the highest charged DOM* (on S70)

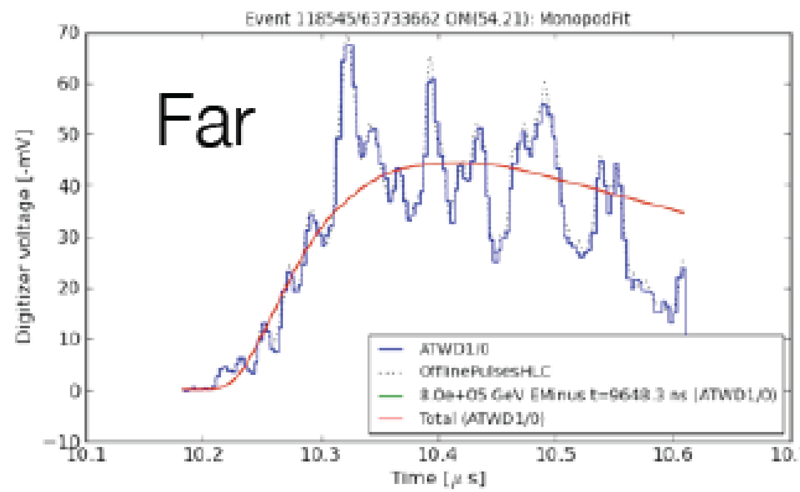




What are their energies and directions?

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



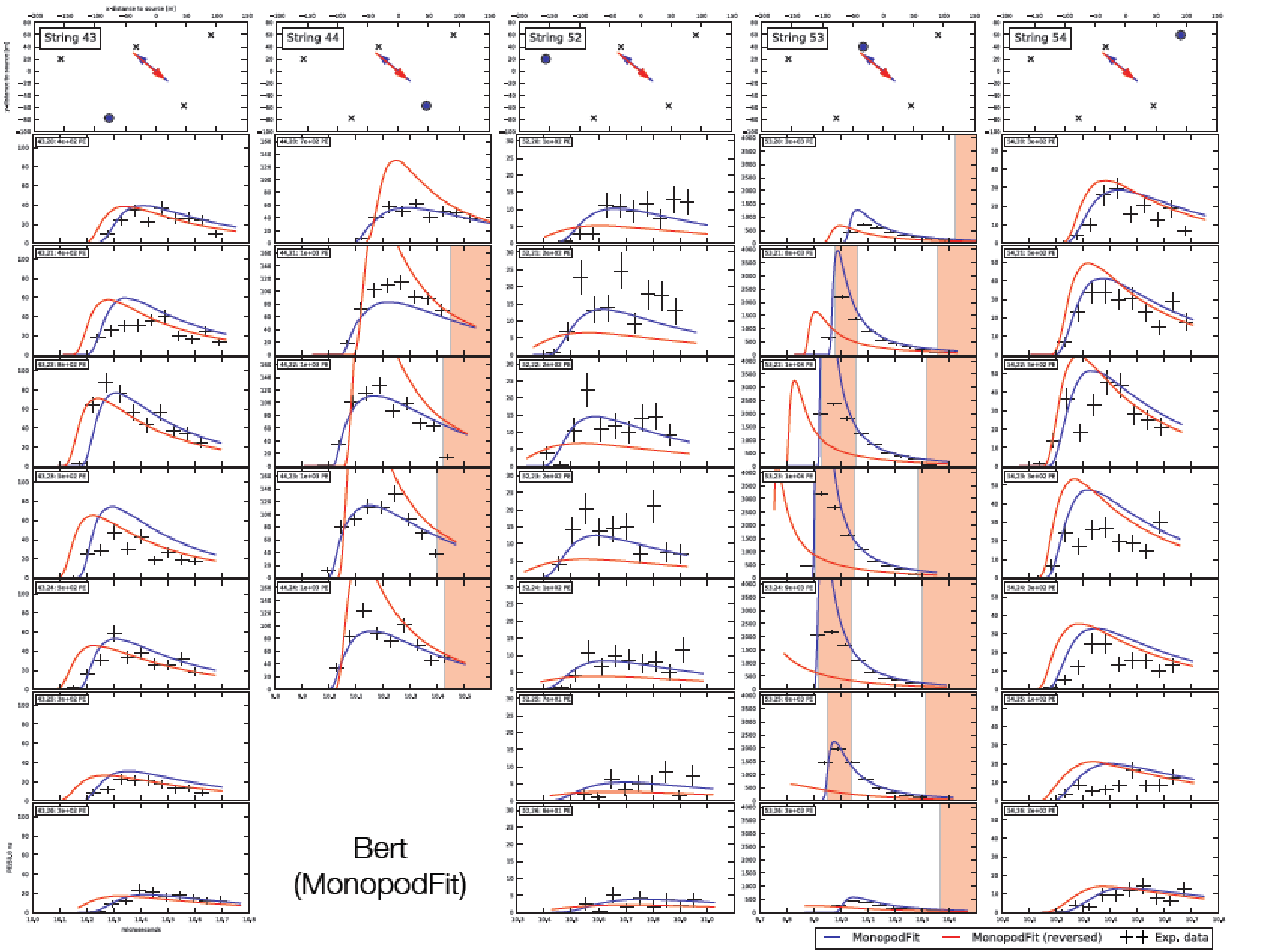


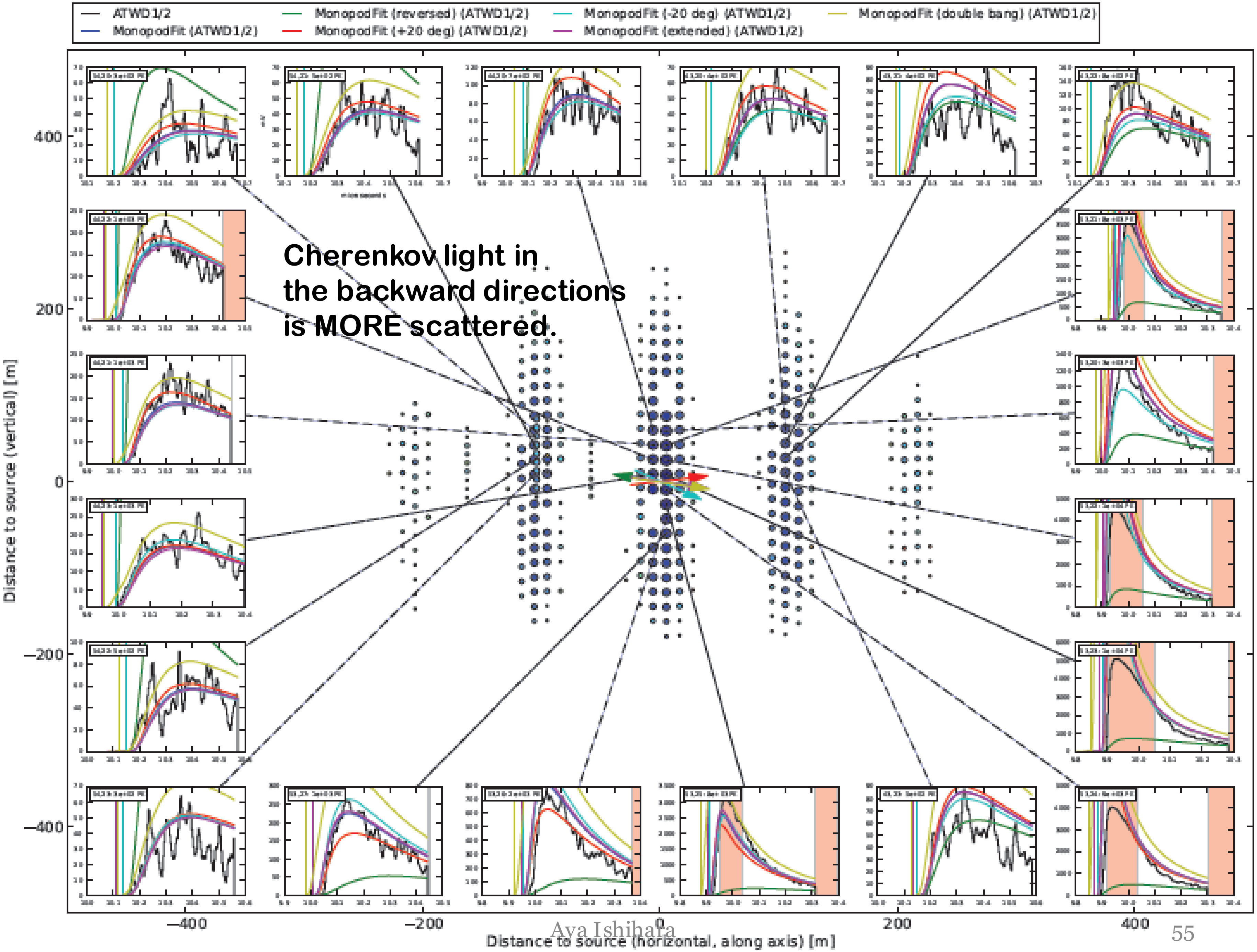
Estimated Energy Deposit

Preliminary

- Jan 2012 event <u>1.3 PeV</u> zenith 17deg
- Aug 2011 event <u>1.14 PeV</u> zenith 79deg

Downward-going PeV showers


String 43
String 44
String 52
String 53
String 54
Bert
(MonopodFit)
MonopodFit
MonopodFit (reversed)
Exp. data


ATWD1/2
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)
Cherenkov light in
the backward directions
is MORE scattered.
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400

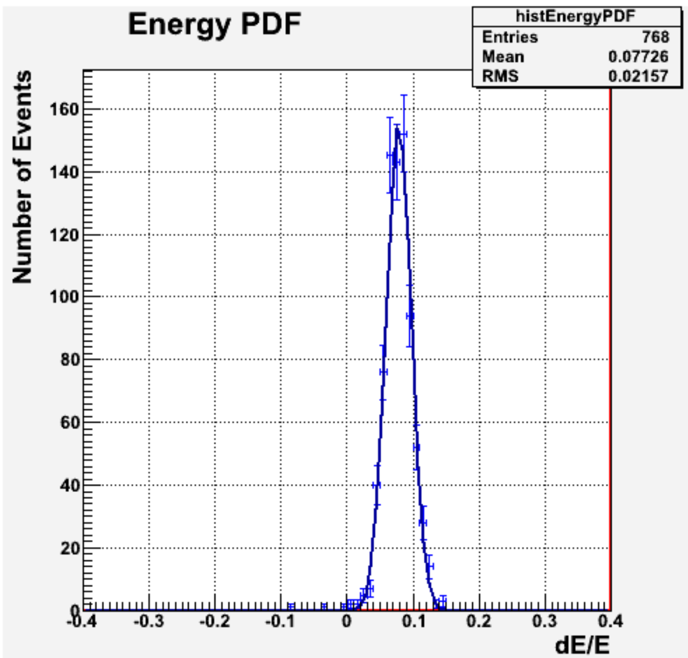
PDF of the deposited energy

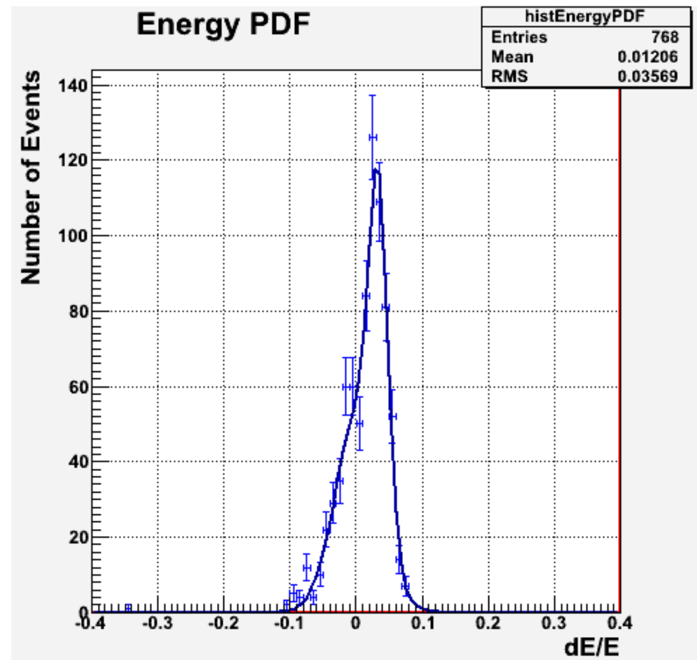
The “top-down” approach : Inject MC electrons with the event-relevant phase space and reconstruct them by the same method

Preliminary

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

Jan 2012 event





MC with the different ice models → systematic error

$$\frac{E_{\mathrm{reco}} - E_{\mathrm{MCtruth}}}{E_{\mathrm{MCtruth}}} \leq \pm 10$$

Deposited Energy → ν Energy

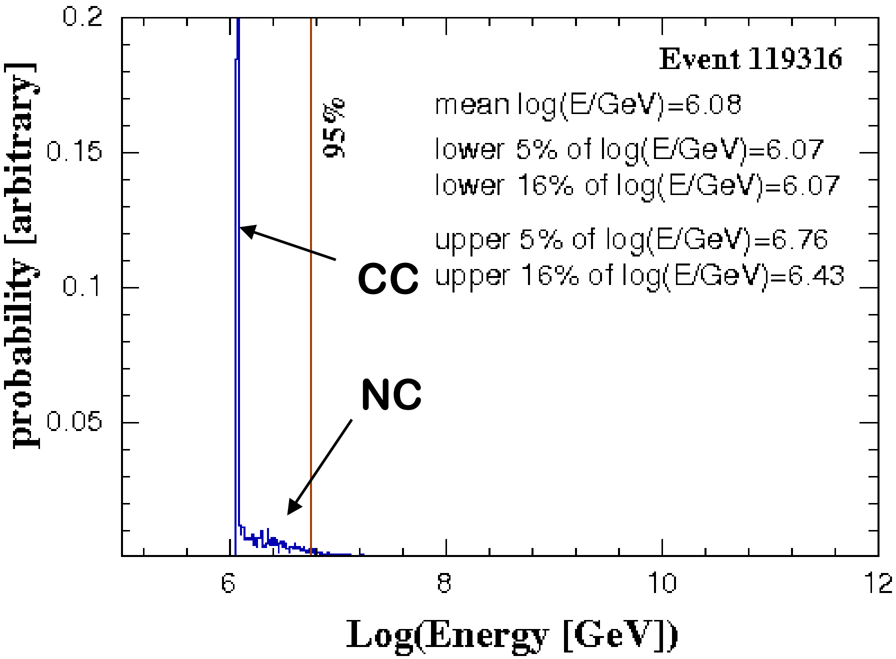
(At the IceCube depth = in-ice energy)

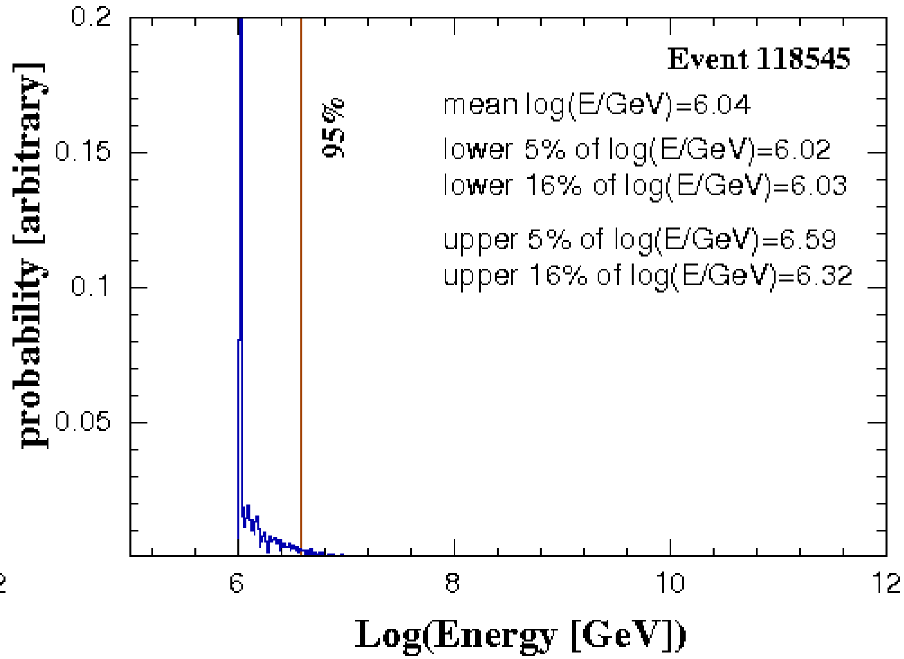
$\nu_e \rightarrow$ **e + X** (CC reaction) energy deposit = neutrino energy

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

Jan 2012 event **Aug 2011 event**

Both events: ~1 PeV < Eν < ~4 PeV



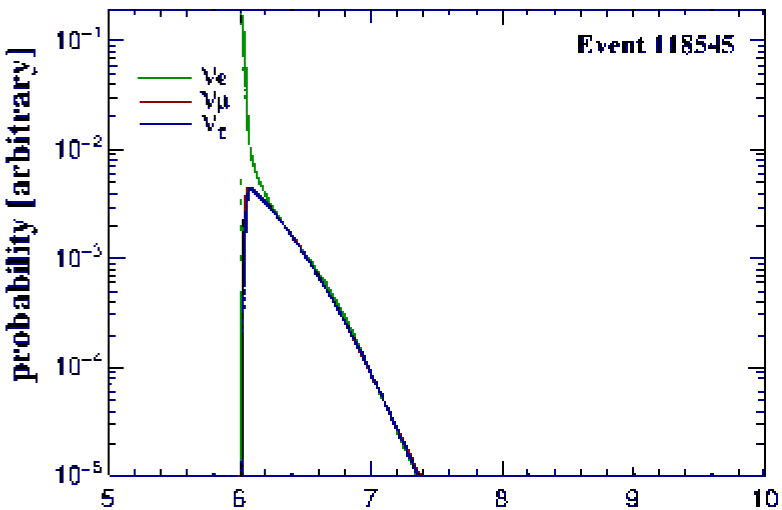


In-ice ν Energy → ν Energy at the Earth surface

The in-earth ν propagation effects

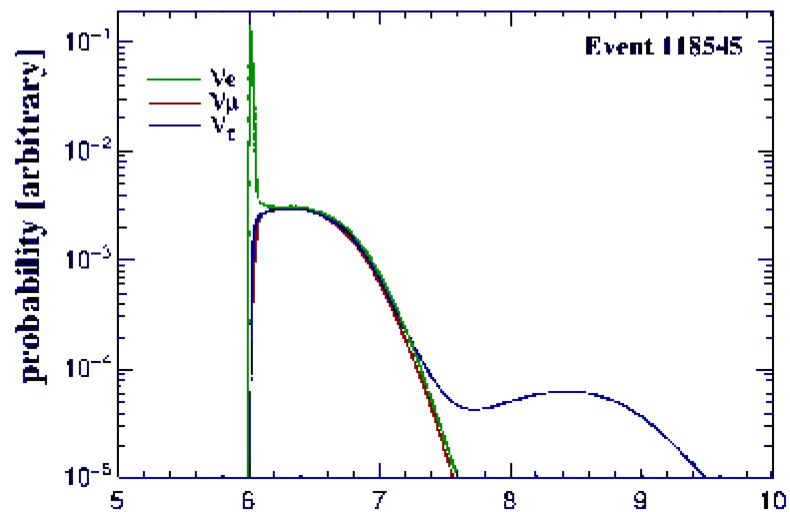
What is $E\nu^{surface}$ that could induce the PeV event?

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])

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

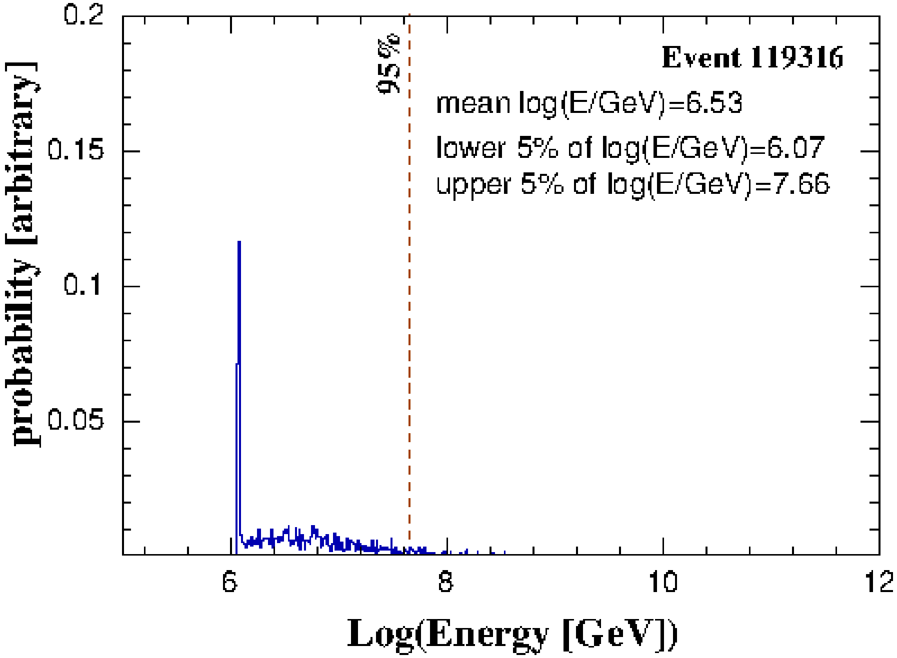
EeV (=10^9 GeV) tail of ν_τ

The regeneration: ν→τ→ν

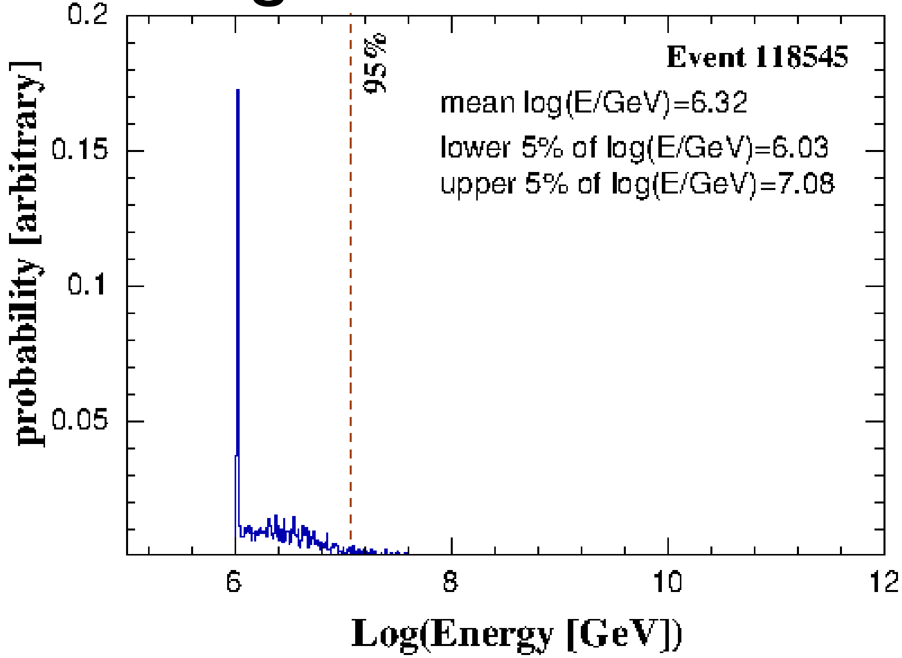
Earth-surface Eν probability

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

Jan 2012 event



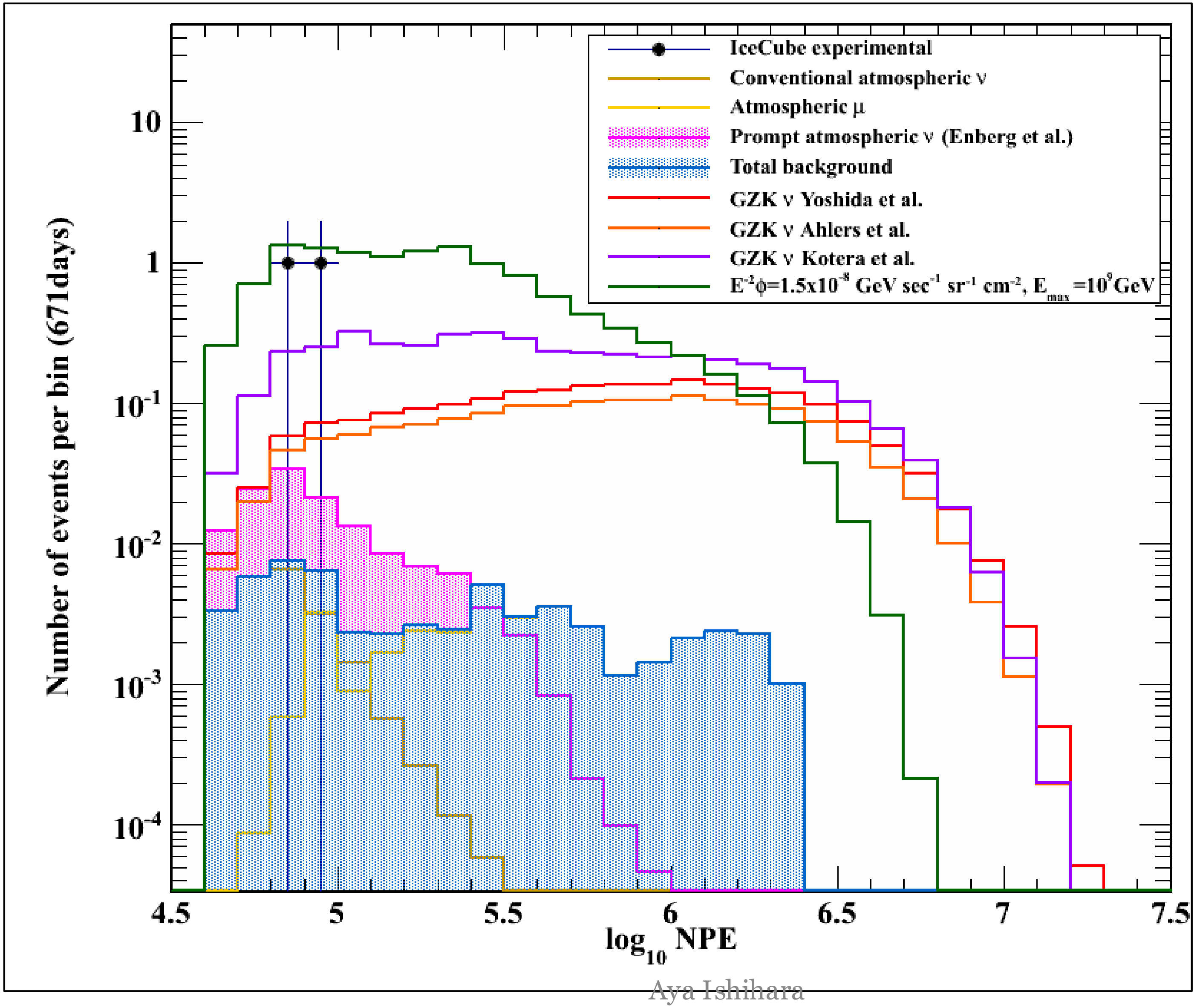
Aug 2011 event



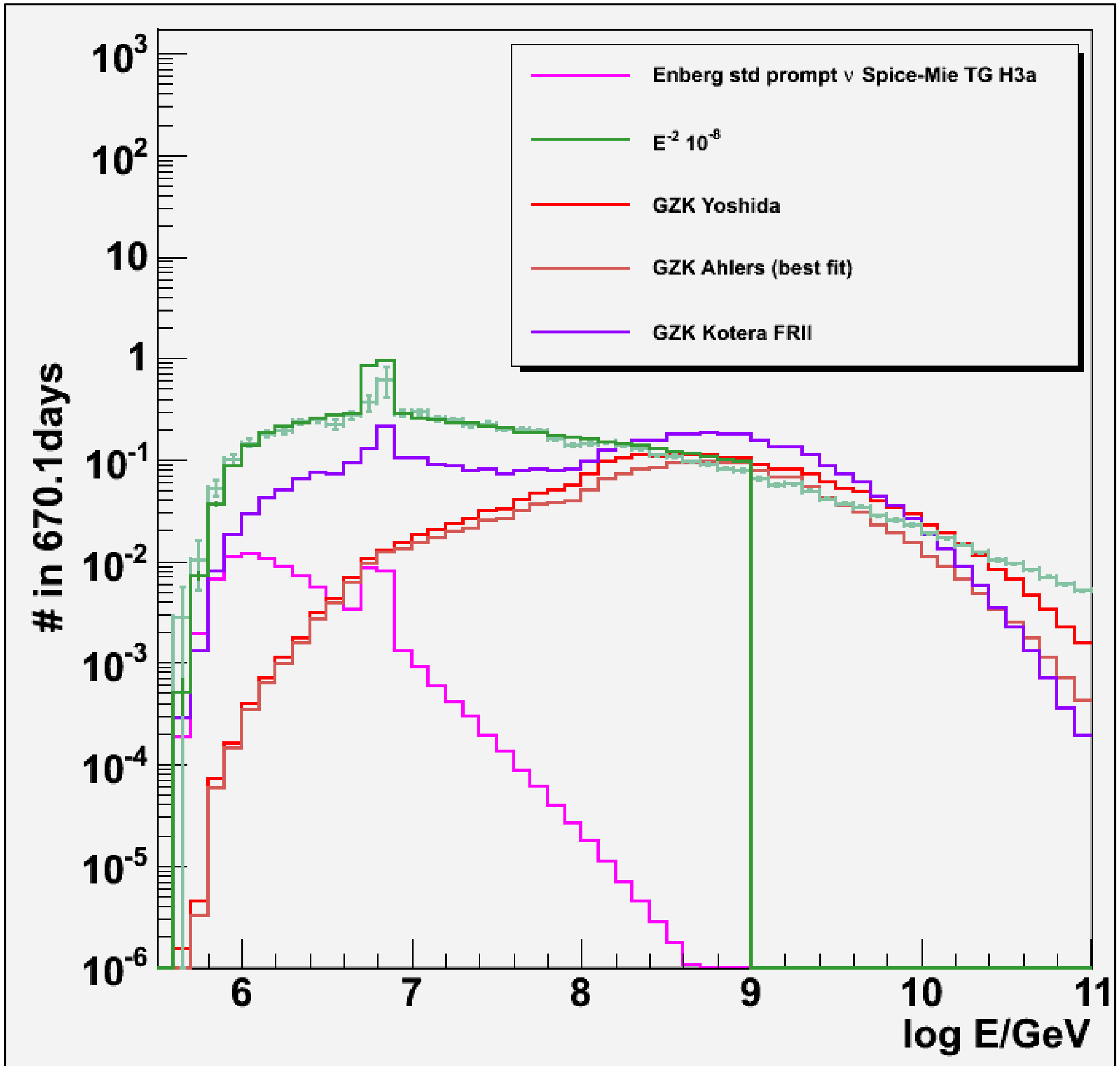
Even assuming the hard GZK-type spectrum and the in-earth propagation effects, the primary energy of these 2 events must be 1PeV < Eν < 50 PeV at 90% C.L.

This is very conservative statement on their energies

Final selection level - NPE distributions



Final selection level – Energy distribution

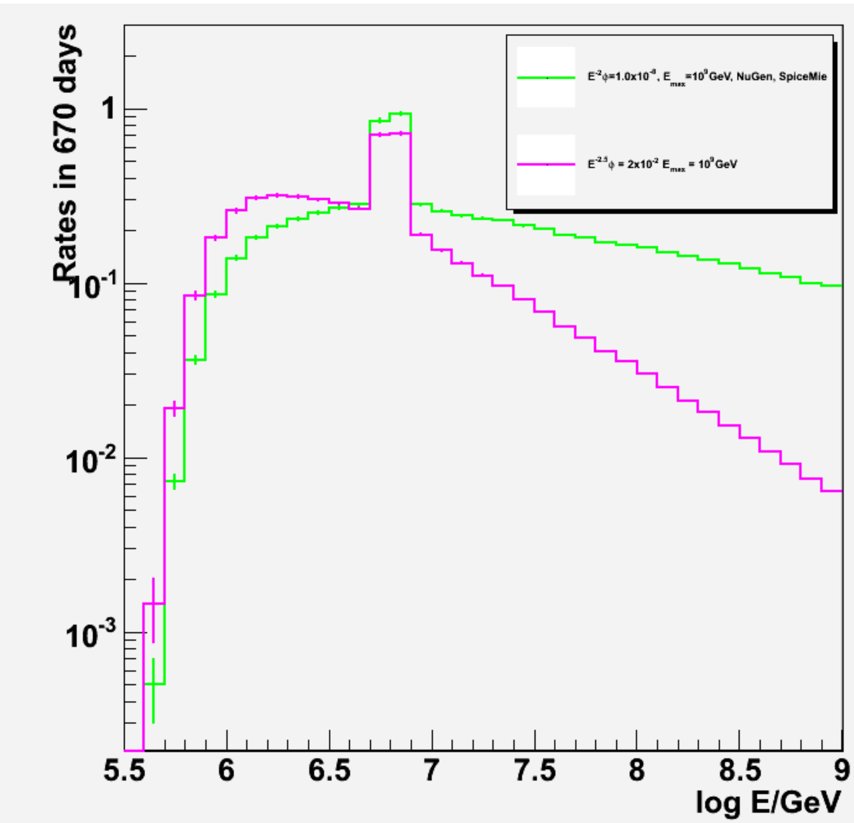


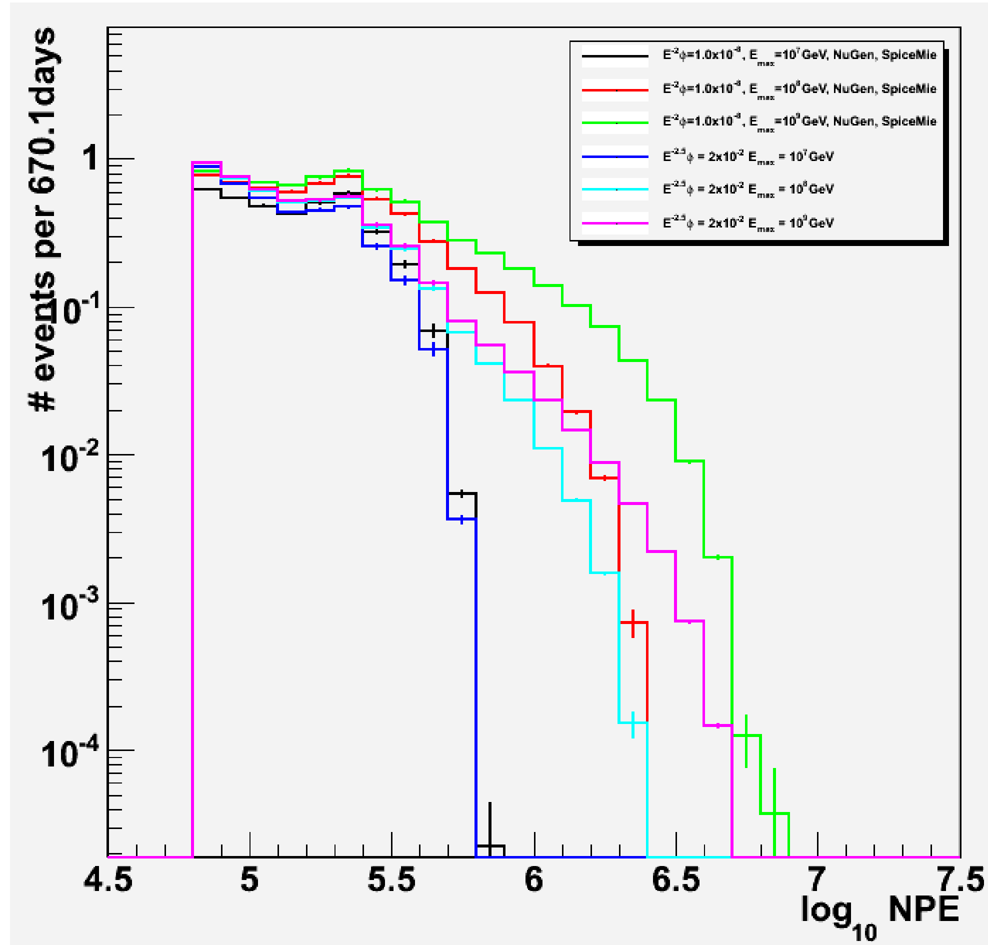
Numbers of UHE Events

Preliminary Models	IceCube 2008-2009 Phys. Rev D83 092003 (2011) 333days	IceCube 2010-2012 per 670days		
		$E^{detector}$ < 10^8 GeV and interaction in detector (A)	All contributions (B)	(B) - (A)
Background (conv. atm. ν + atm. μ)	0.11		0.14	
Experimental data	*0*	*2*	*2*	*0*
GZK (Yoshida m=4)*	0.57	0.4	2.1	1.7
GZK (Ahlers max) **	0.89	0.5	3.2	2.7
GZK (Ahlers best fit) **	0.43	0.3	1.6	1.3
GZK (Kotera, dip FRII) ***		1.7	4.1	2.4
GZK (Kotera, dip SFR1)***		0.6	1.0	0.4

*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

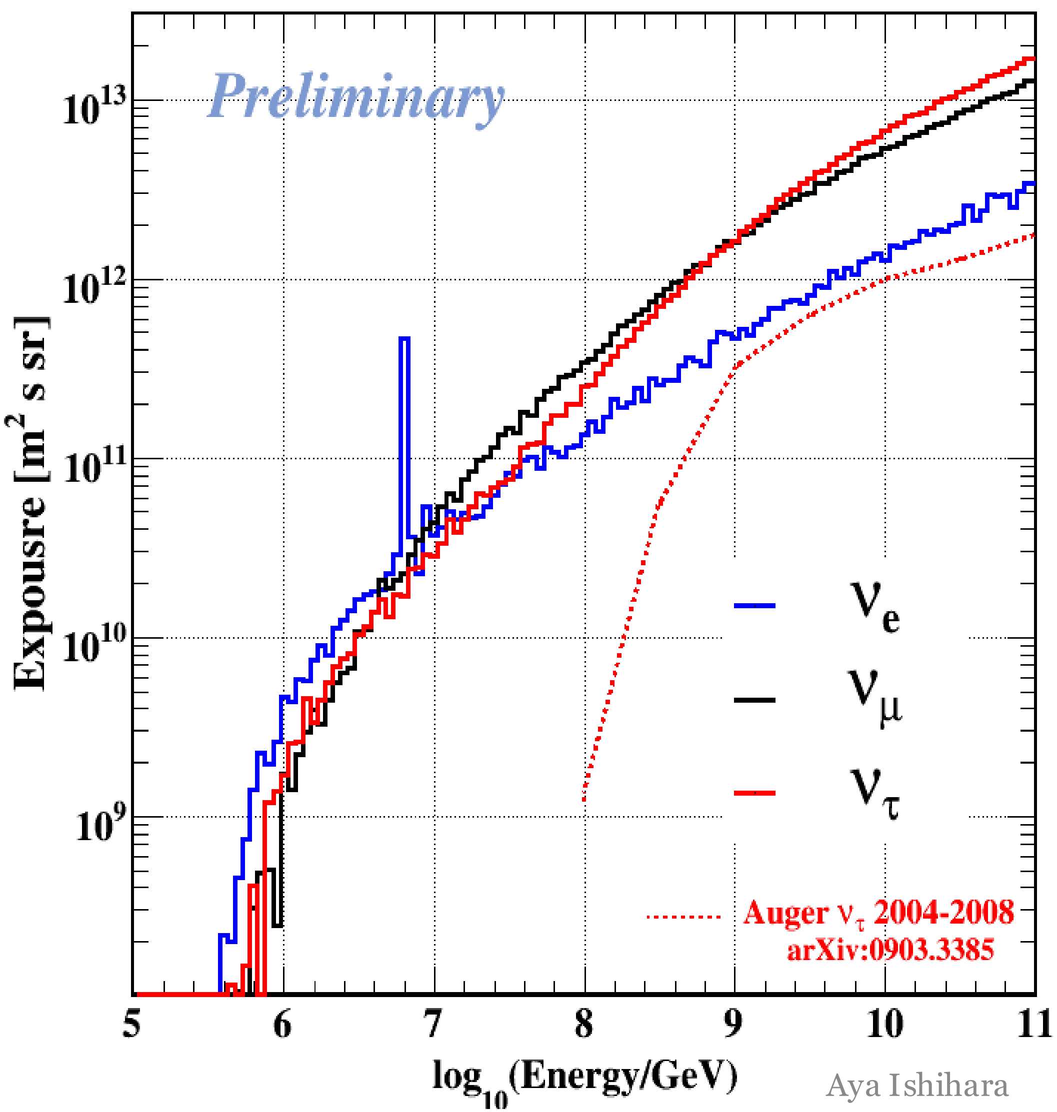
A note on the power law fluxes



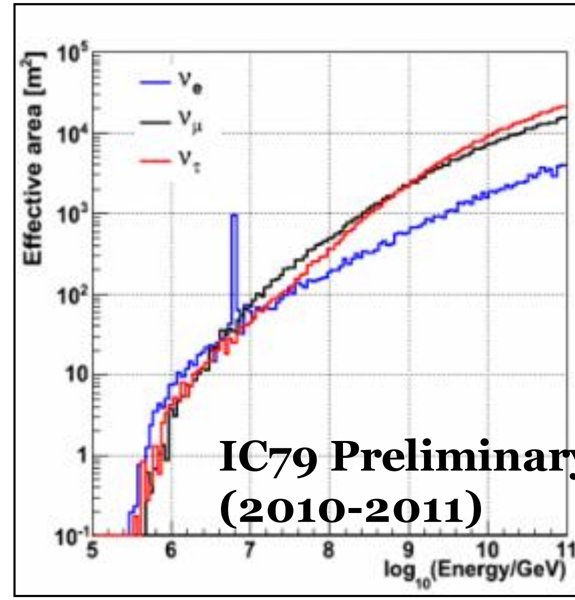


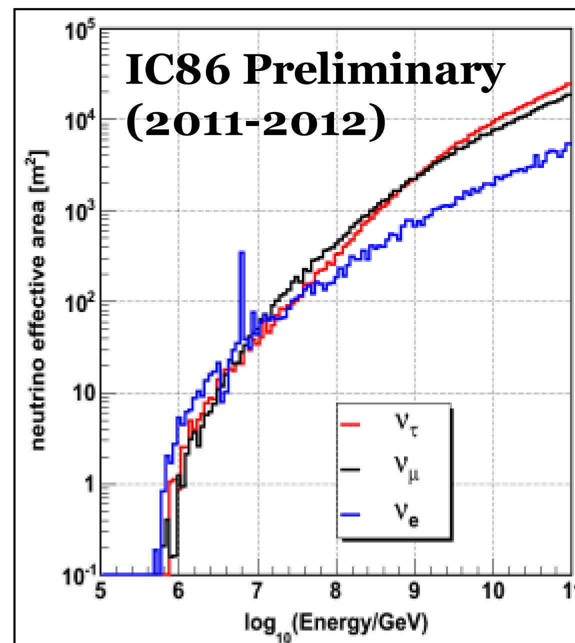
The Exposure and Effective Area

IceCube UHE 2 Years Exposure (2010-2012)

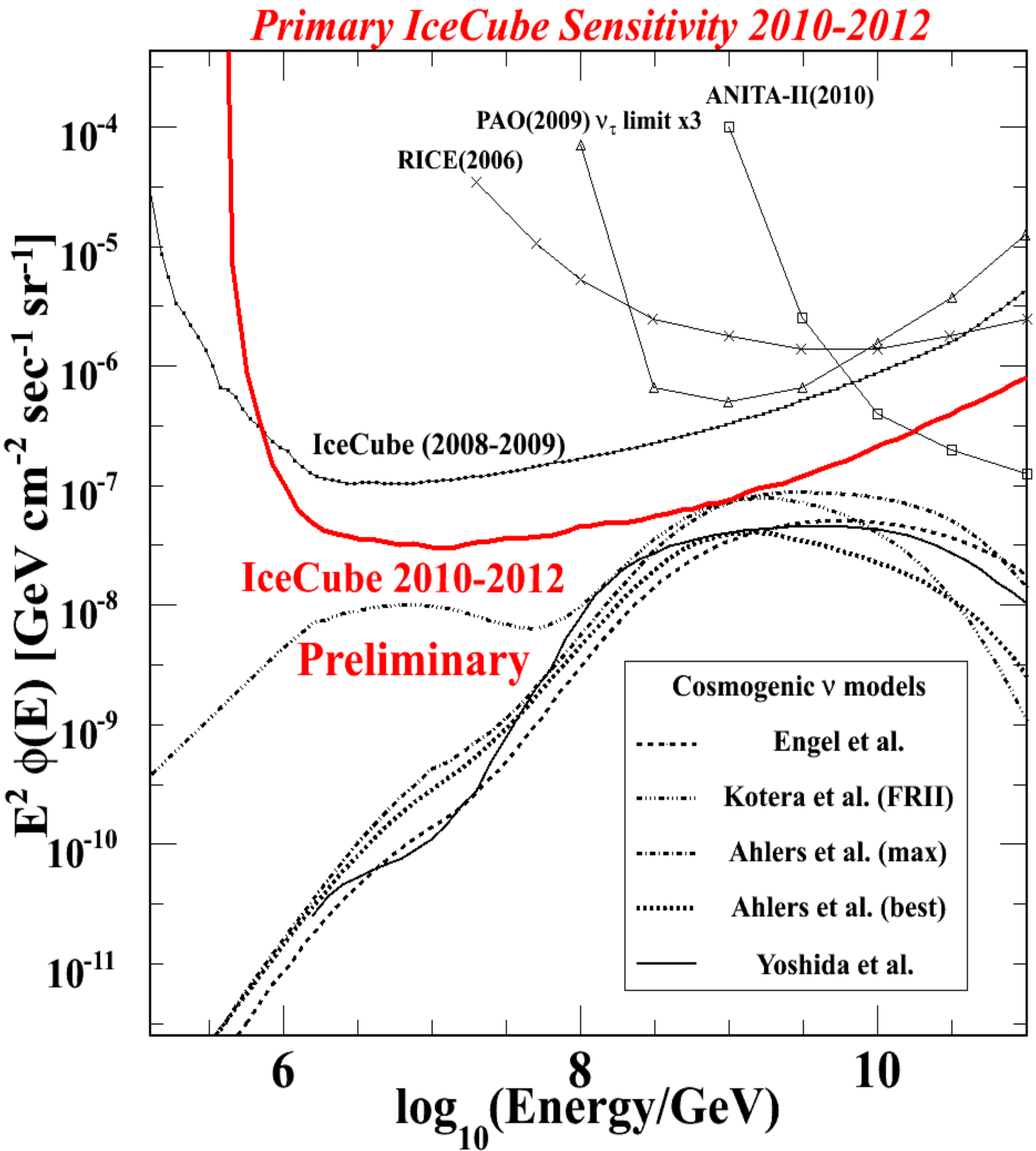


Effective Areas





IceCube UHE Sensitivity 2010-2012



- 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

On-going improvements

- IceTop VETO
- Starting event

Note that we also have seen positive fluctuation from 2008-2009 cascade analysis and 2009-2010 muon neutrino analysis

Summary

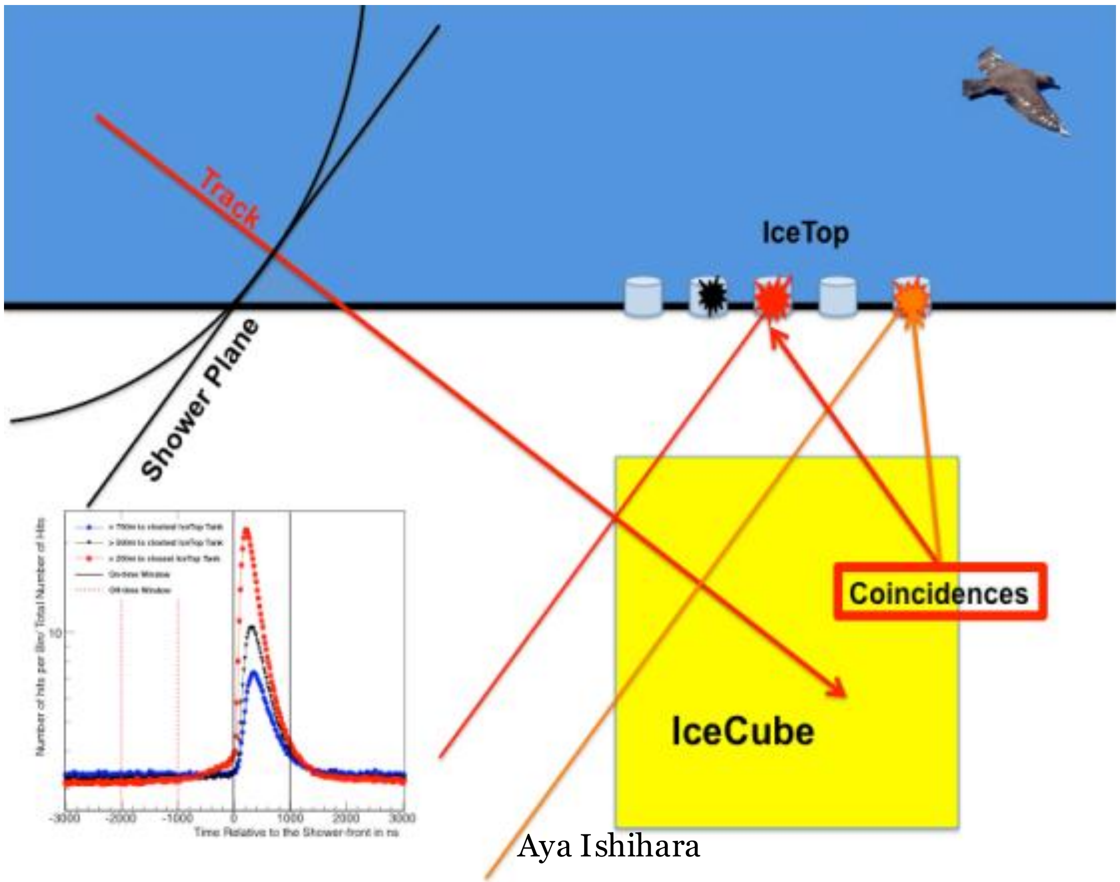
- Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data
- Two candidate events observed
  - PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  - The highest energy neutrino events observed ever!
- Beyond the conventional atmospheric neutrinos
- Any post-unblinding analysis indicates higher significance (but not official)
- Hints for the PeV events origin from different energy-region
  - More cascade event sensitive analysis
  - Lower energy regions for the spectral transition
  - more statistics

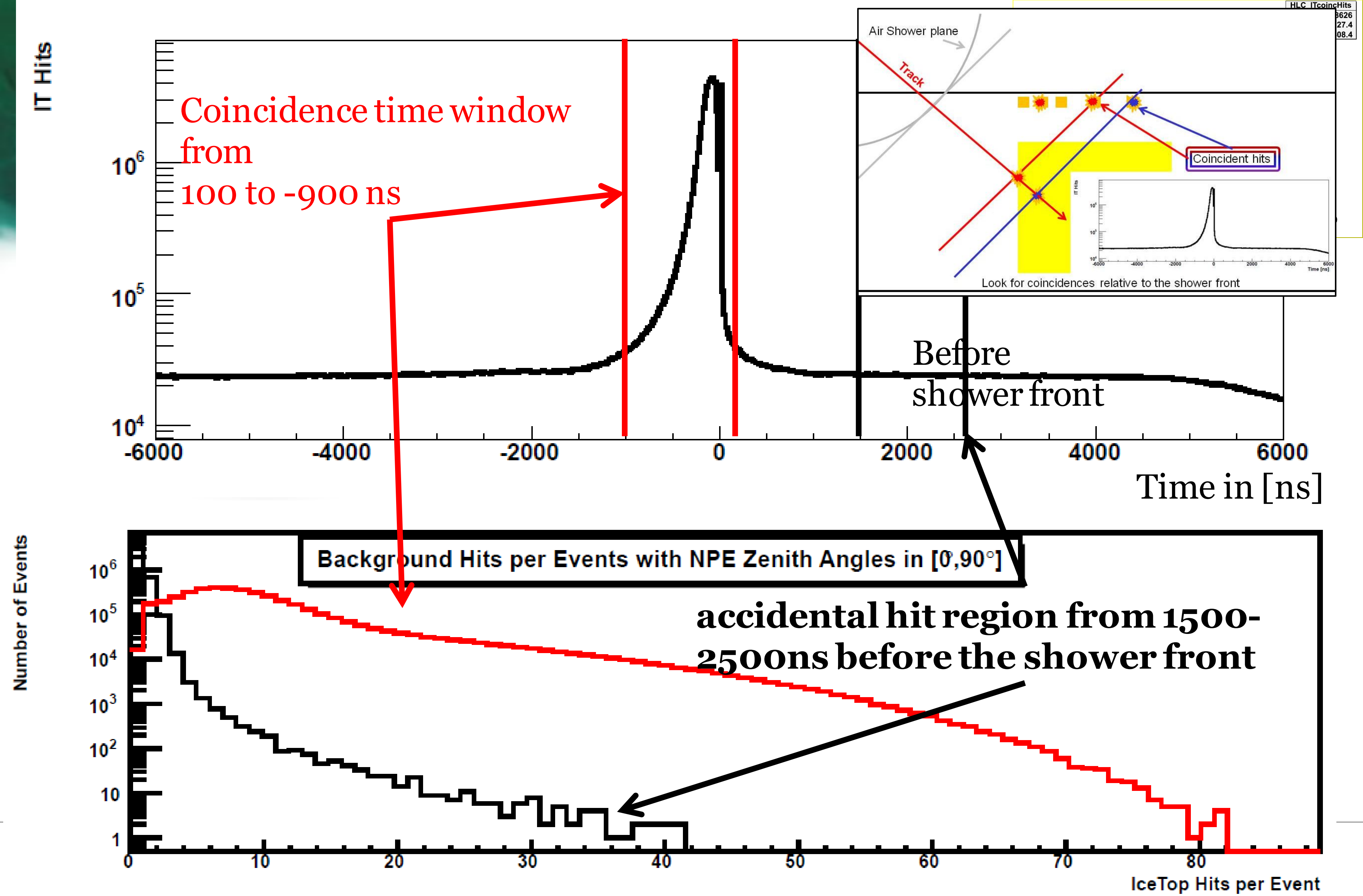
will answer some of questions in relatively short time

Backup

An improvement 1
Background Veto with IceTop

Downward-going region is airshower induced muon background dominated



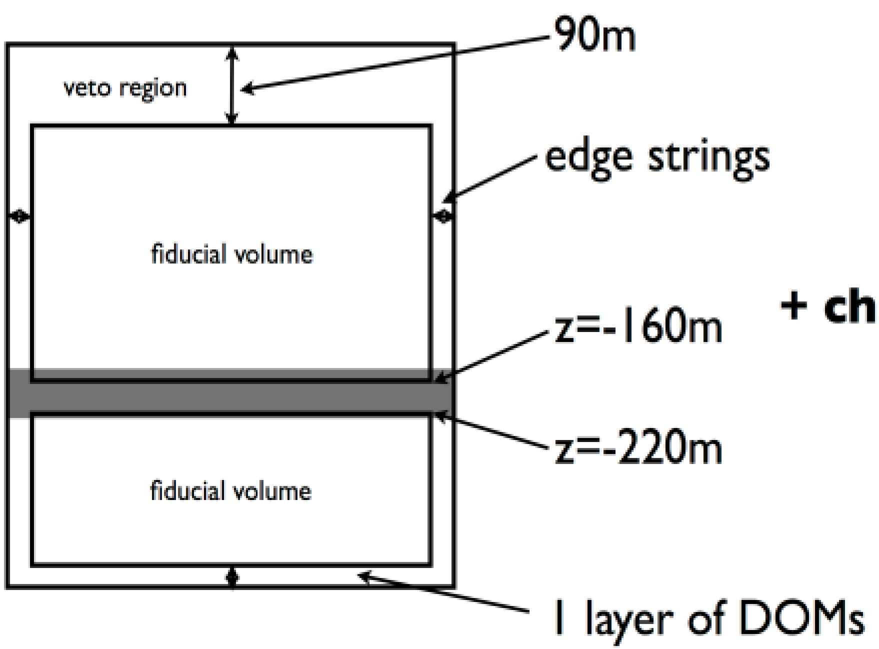


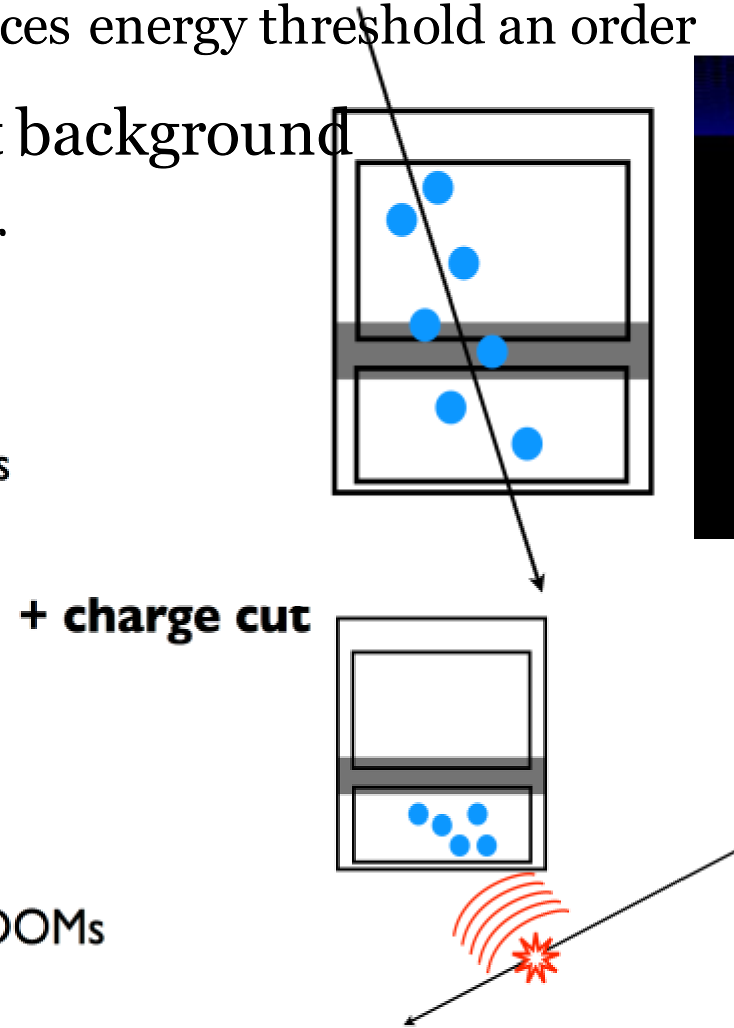
- Unblinded for 2010-2011 data, no event passed
- Eff area 10% improved in down going region

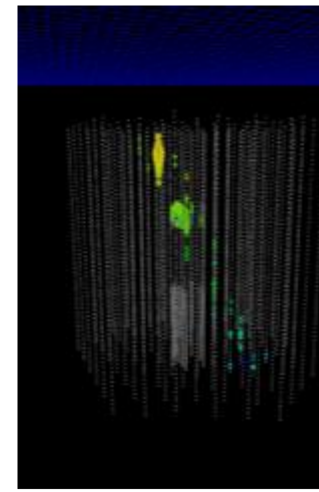
Starting event analysis

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

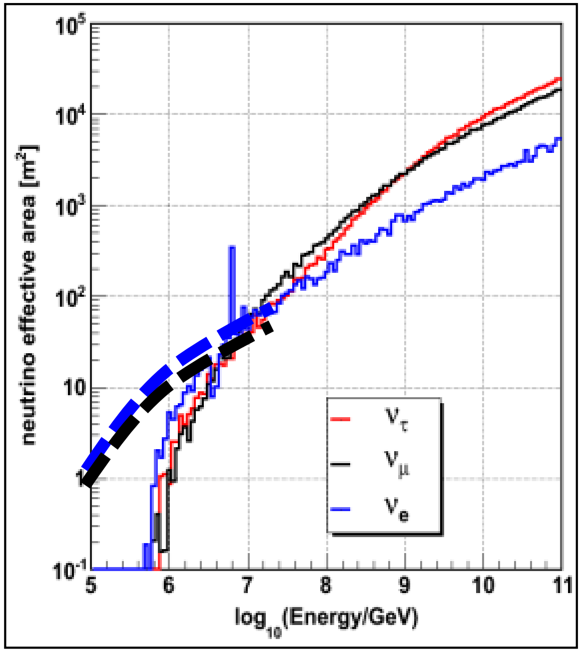


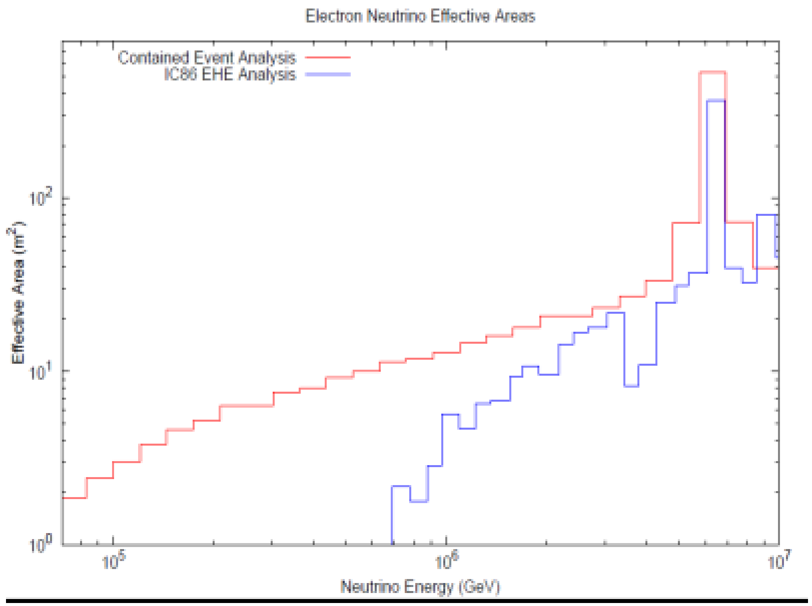


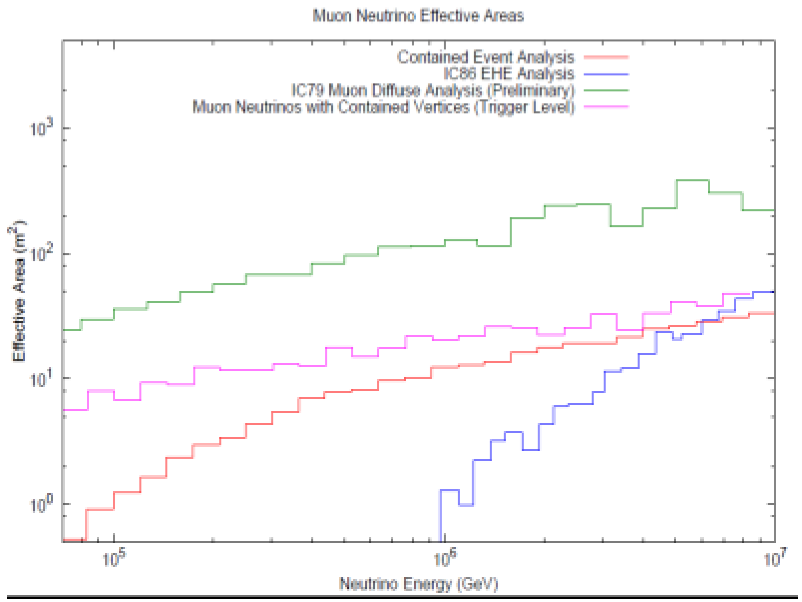


New effective area

Improvements in 100TeV region

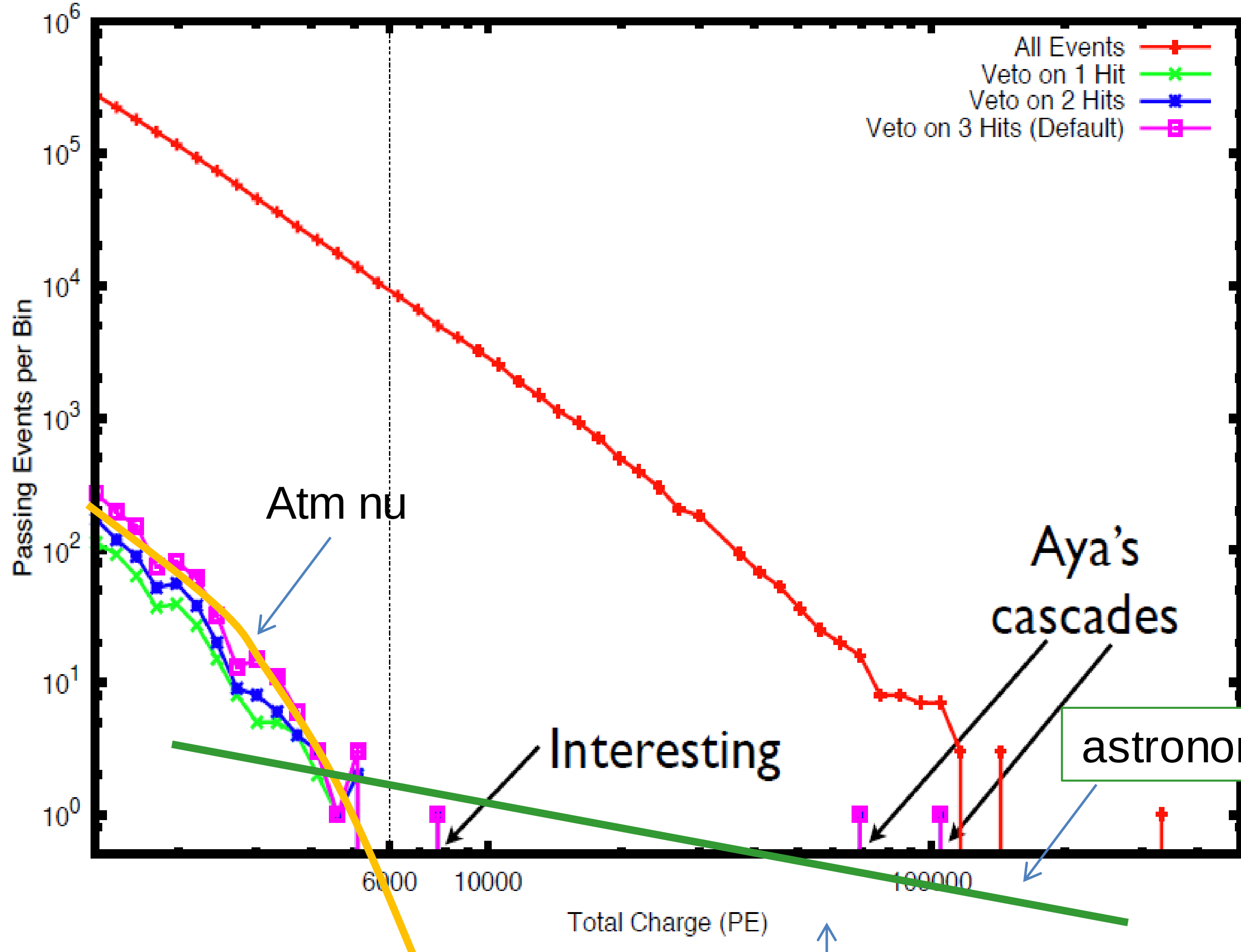






Nathan Whitehorn and Claudio Kopper

Burn sample （10%）

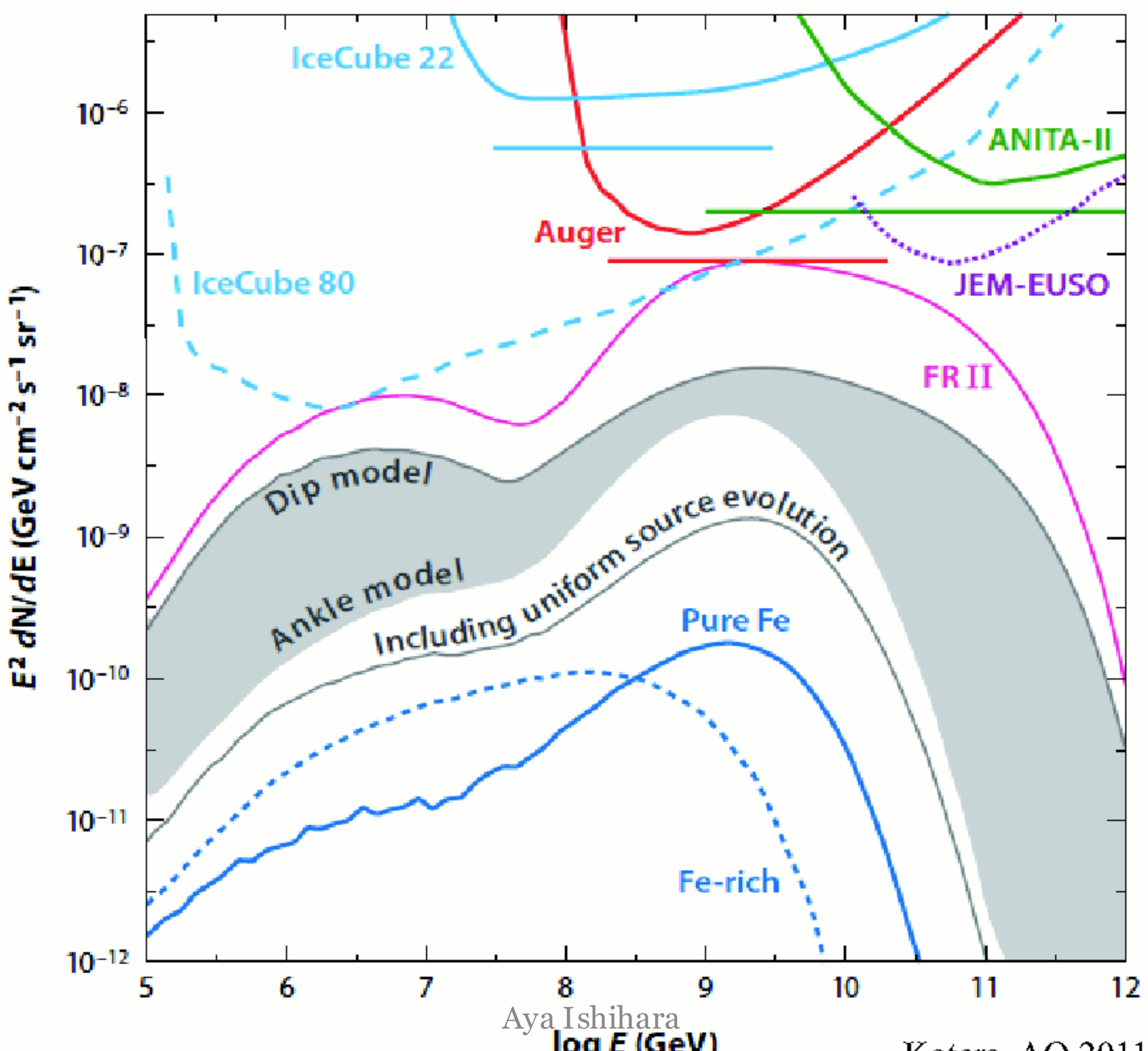


according to them the 2 events are much larger than 3 sigma

astronomical neutrino!

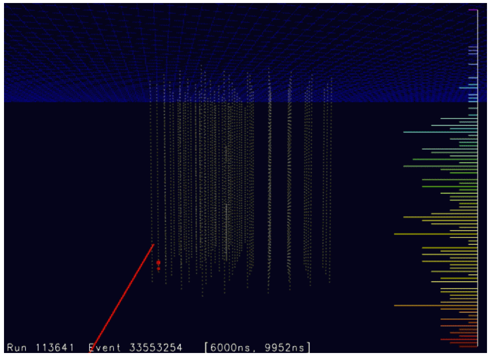
We will check how special the observed events are

We'll expect another 10 events from the fluxes consistent with the 2 events

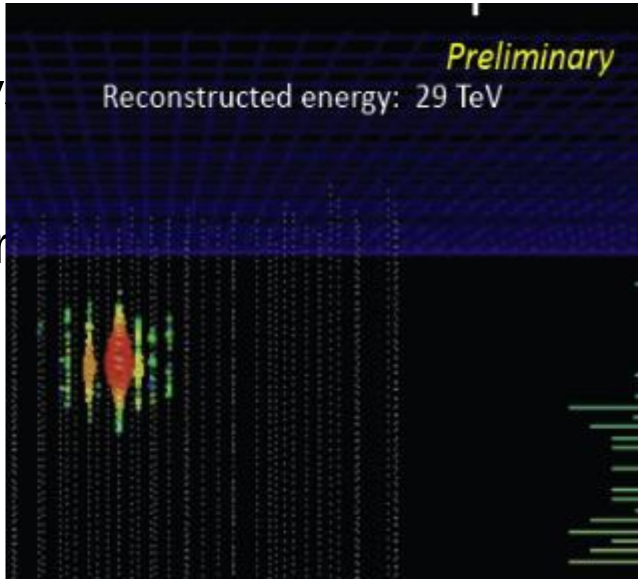


Kotera, AO 2011

IceCube Event Classifications



- Event Topology
  - All direction
  - Flavor sensitive
- Event Direction
  - Upward-going neutrinos
    - neutrino induced muon sensitive analy
    - Conventional atmospheric neutrinos
    - Prompt neutrinos + astrophysical neutr



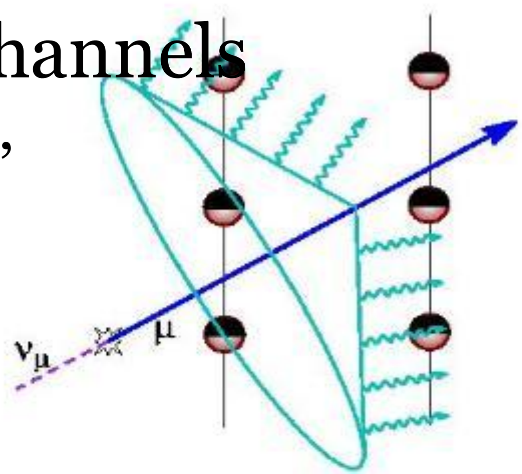
- Event Energy
  - All direction
  - Higher energy than background
  - All Flavor

Or the combination of these features

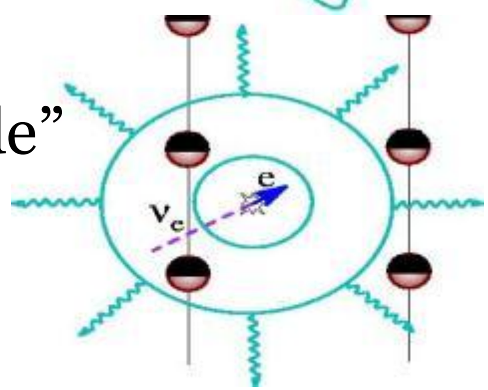
IceCube Event Topology

Main channels

"Track"

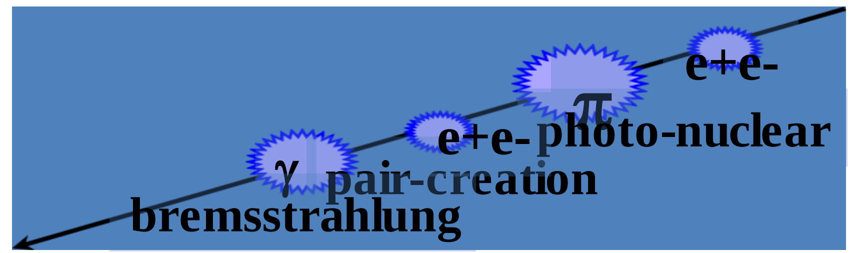


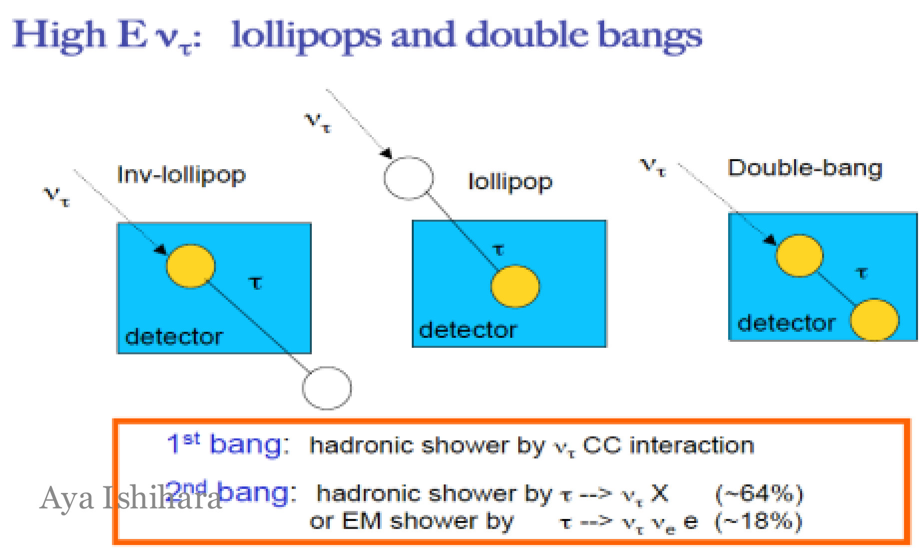
"Cascade"



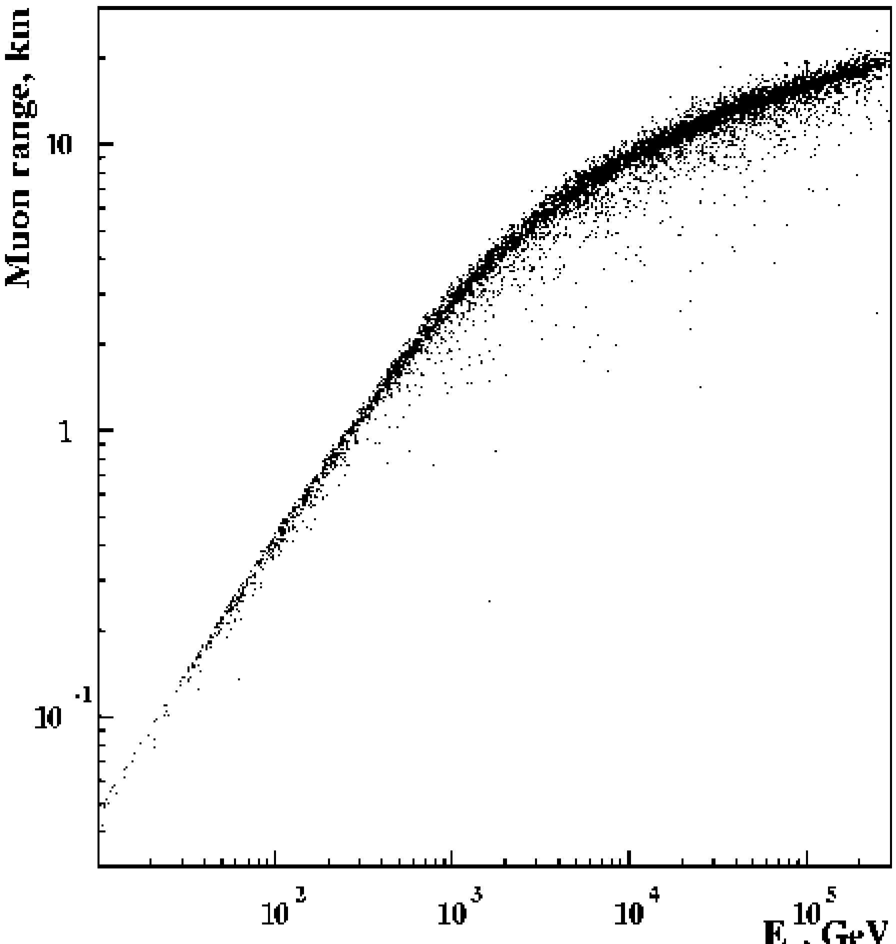
sub-channels

"Composite Bright Track"





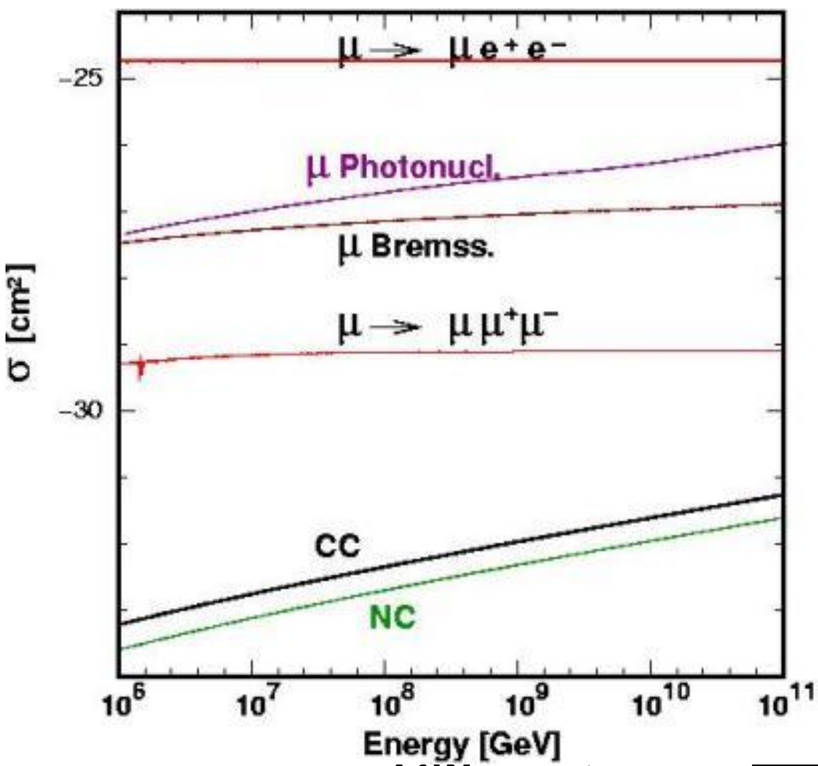
ミューオンの走る距離

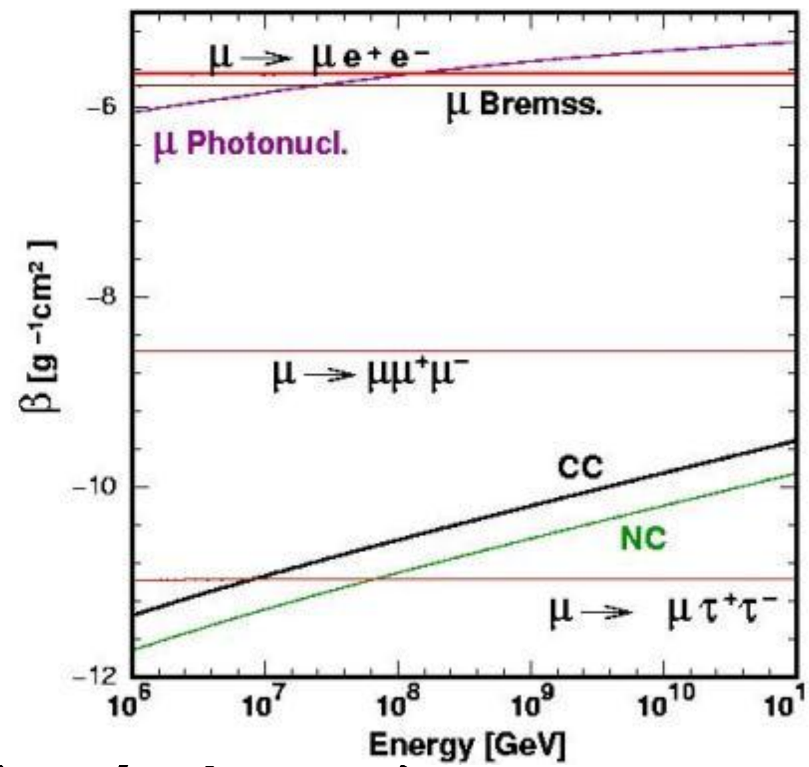


Muon propagator: MMC , Chirkin, D. 27th ICRC, HE 220, Hamburg 2001

Muon range in ice
＞＞1Km

ミューオンのエネルギーロス



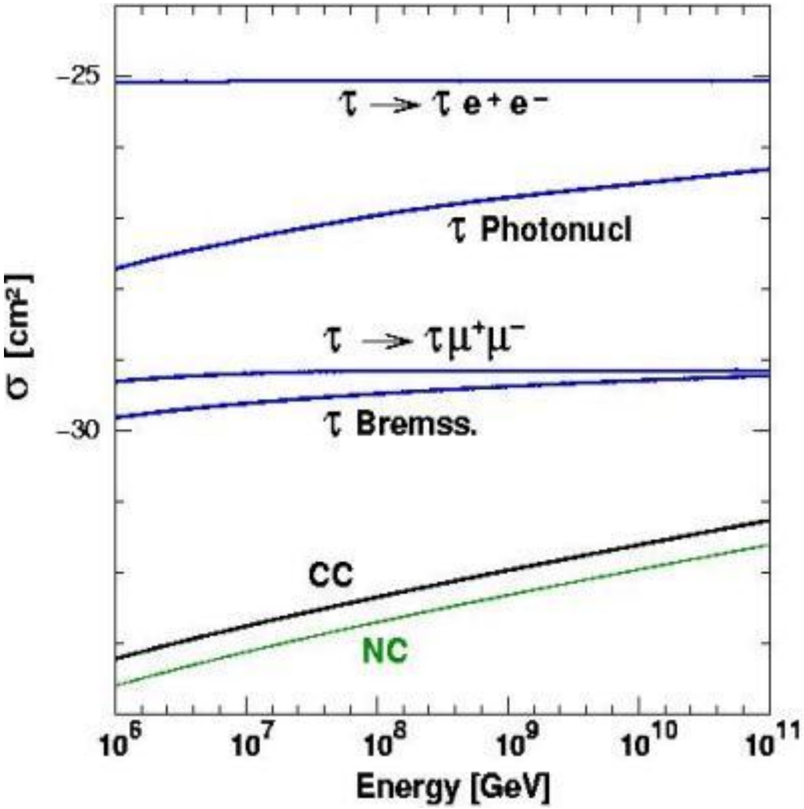


μ→μe+e-（数mに一回）ペアクリエーション

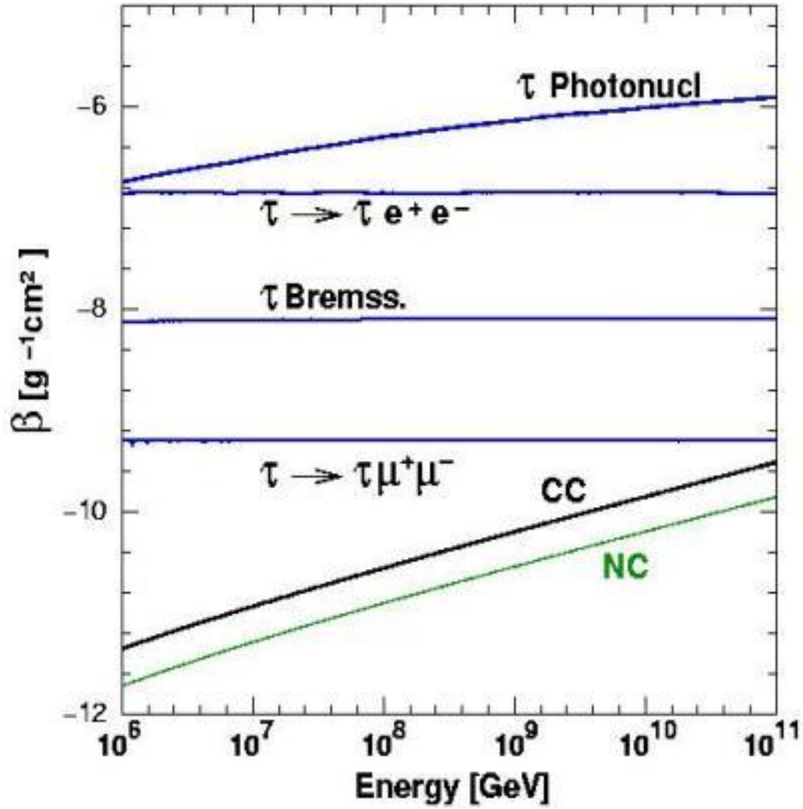
μ→μγ（数10～100mに一回）Bremsstrahlung

μ→μπ （数10～100mに一回）Photonuclear

Case of tau



σ [cm²]
−25
−30
τ → τ e⁺ e⁻
τ Photonucl
τ → τμ⁺μ⁻
τ Bremss.
CC
NC
10^6
10^7
10^8
10^9
10^10
10^11
Energy [GeV]



β [g⁻¹cm²]
−6
−8
−10
−12
τ Photonucl
τ → τ e⁺ e⁻
τ Bremss.
τ → τμ⁺μ⁻
CC
NC
10^6
10^7
10^8
10^9
10^10
10^11
Energy [GeV]

• *Neutrino cross-section*

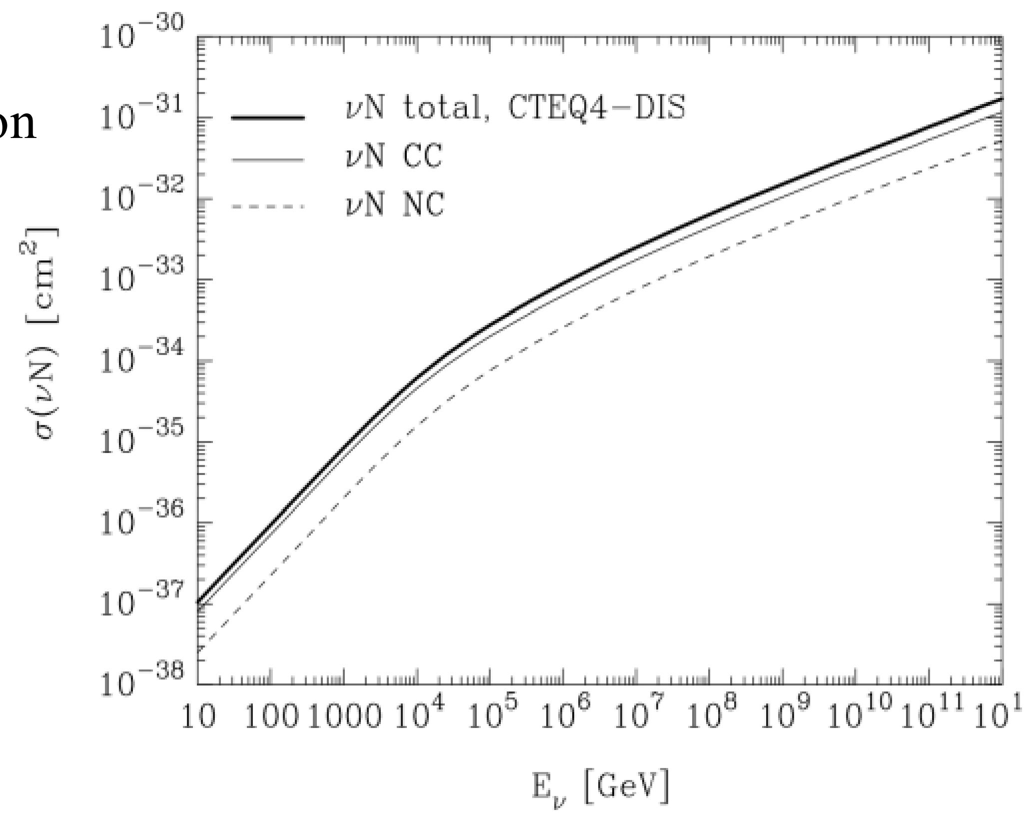
For $E_\nu < 10^4$ GeV the x-section rises linearly with the energy

W-bosonが止まっていると考えられる領域（ゲージボソンの自由度）

For $E_\nu > 10^4$ GeV (due to the W-boson propagation)

$$\sigma_{tot}(\nu N) = 7.84 \times 10^{-36} cm^2 \left(\frac{E_\nu}{1GeV}\right)^{0.363}$$

2.3(NC), 5.5(CC)



NA*rho = 5.5g/cm3 / 1.67×10^{-24}g
= 3×10^{24}/cm3
at PeV $\lambda = 1/(1.5 \times 10^{-32} \times 3 \times 10^{24})$cm $< R_{EARTH}$

Cross-section measured up to 300 GeV. Up to about 10 TeV based on structure functions from HERA. Above different extrapolations.