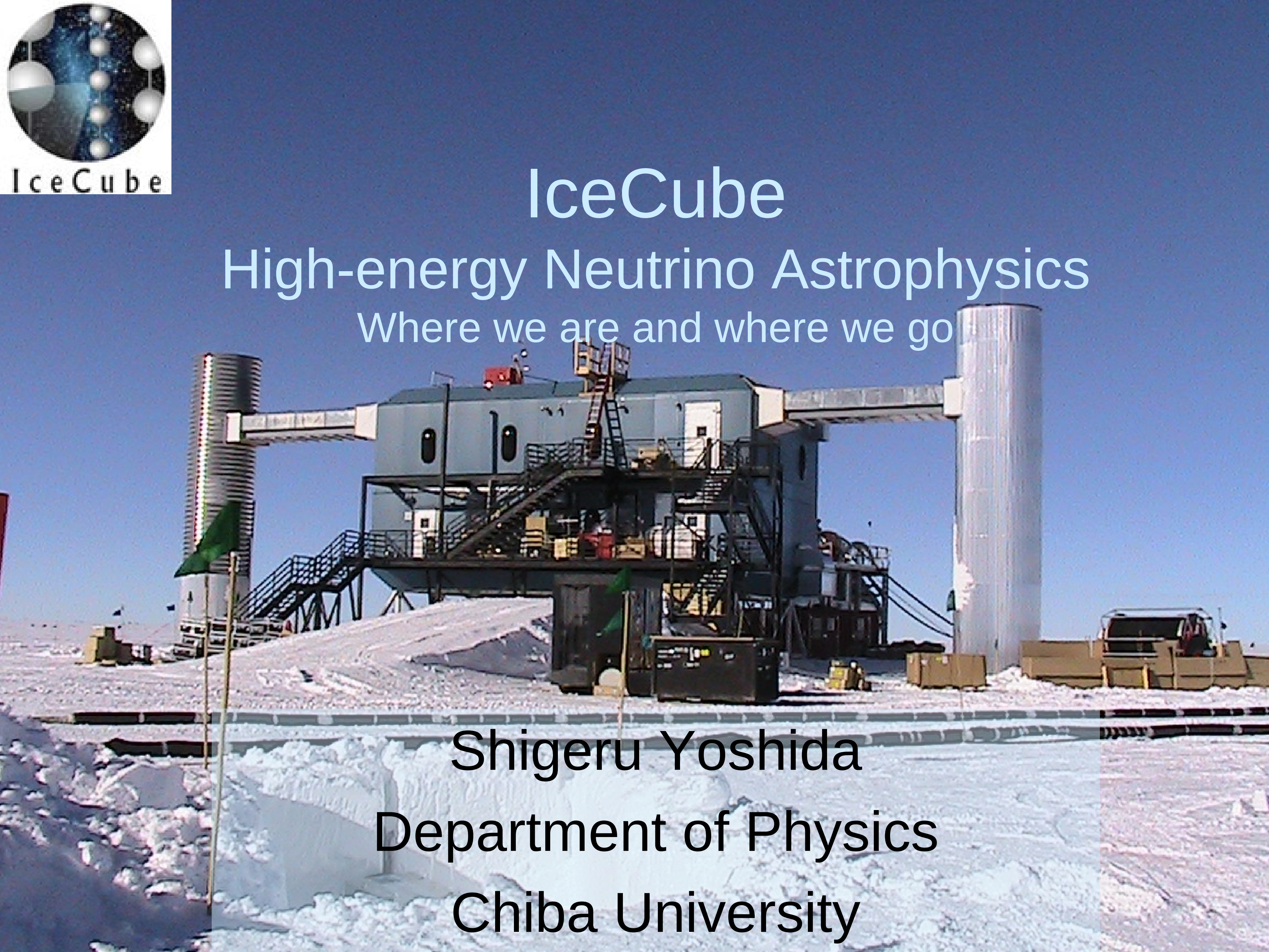
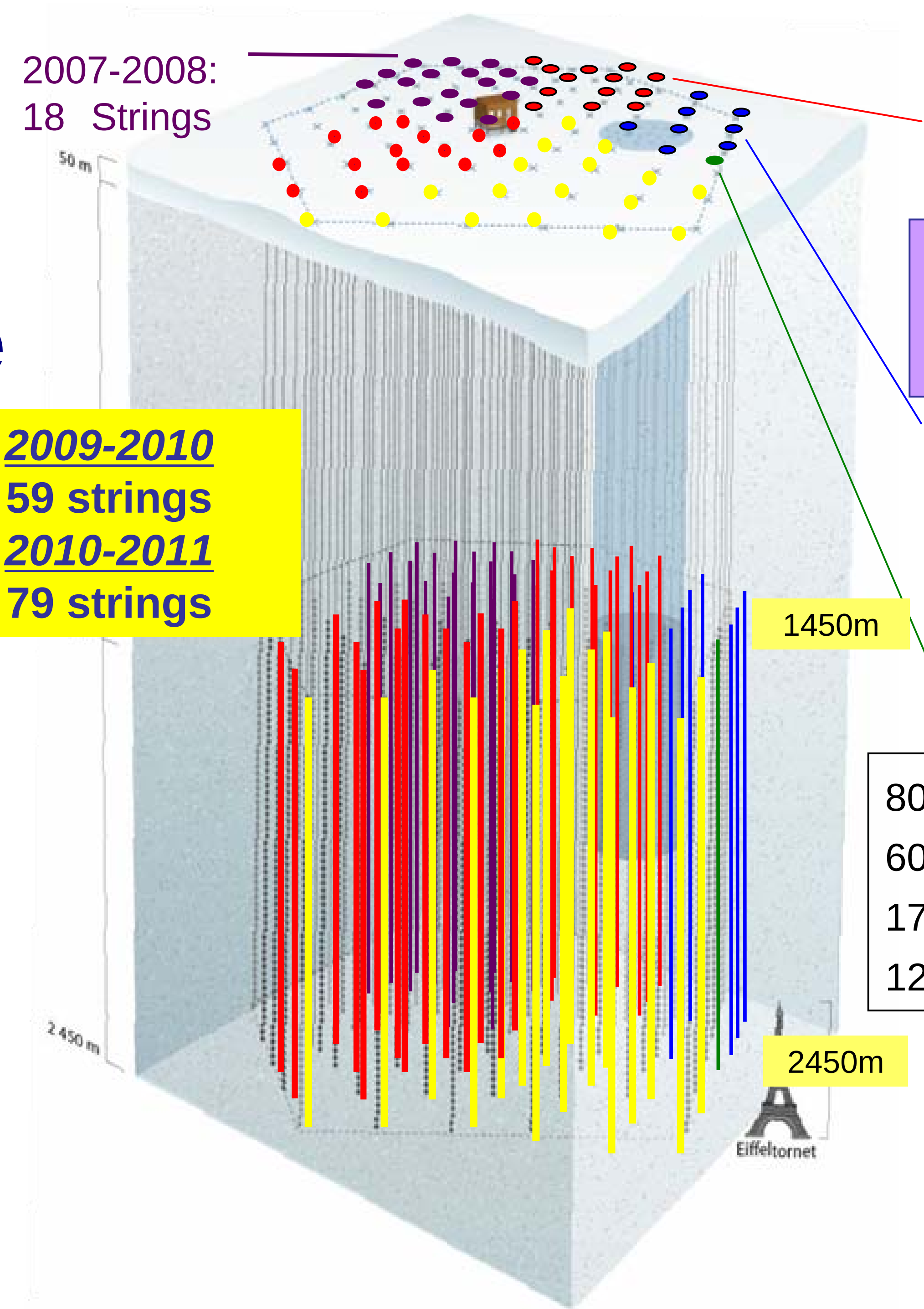


IceCube
High-energy Neutrino Astrophysics
Where we are and where we go

Shigeru Yoshida
Department of Physics
Chiba University

IceCube



2008 -2009 Data
40 strings
80 IceTop tank

2009-2010
59 strings
2010-2011
79 strings

80+6 Strings
60 Optical Modules
17 m between Modules
125 m between Strings

The IceCube Collaboration

IceCube

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

Sweden:
- Uppsala Universitet
- Stockholm Universitet

UK:
- Oxford University

Germany:
- DESY-Zeuthen
- Universität Mainz
- Universität Dortmund
- Universität Wuppertal
- Humboldt Universität
- MPI Heidelberg
- RWTH Aachen

Switzerland:
- EPFL

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

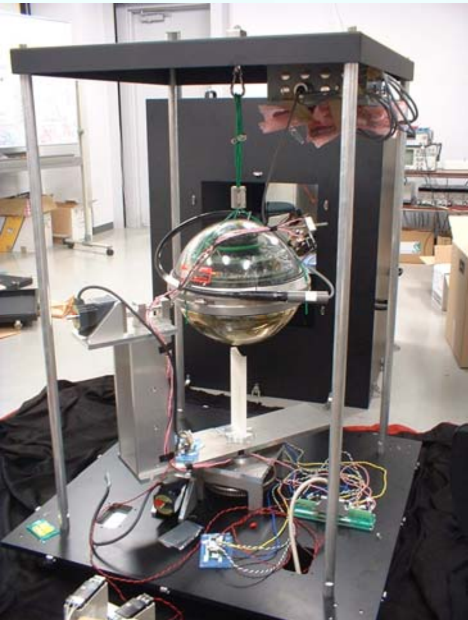
Japan:
- Chiba University

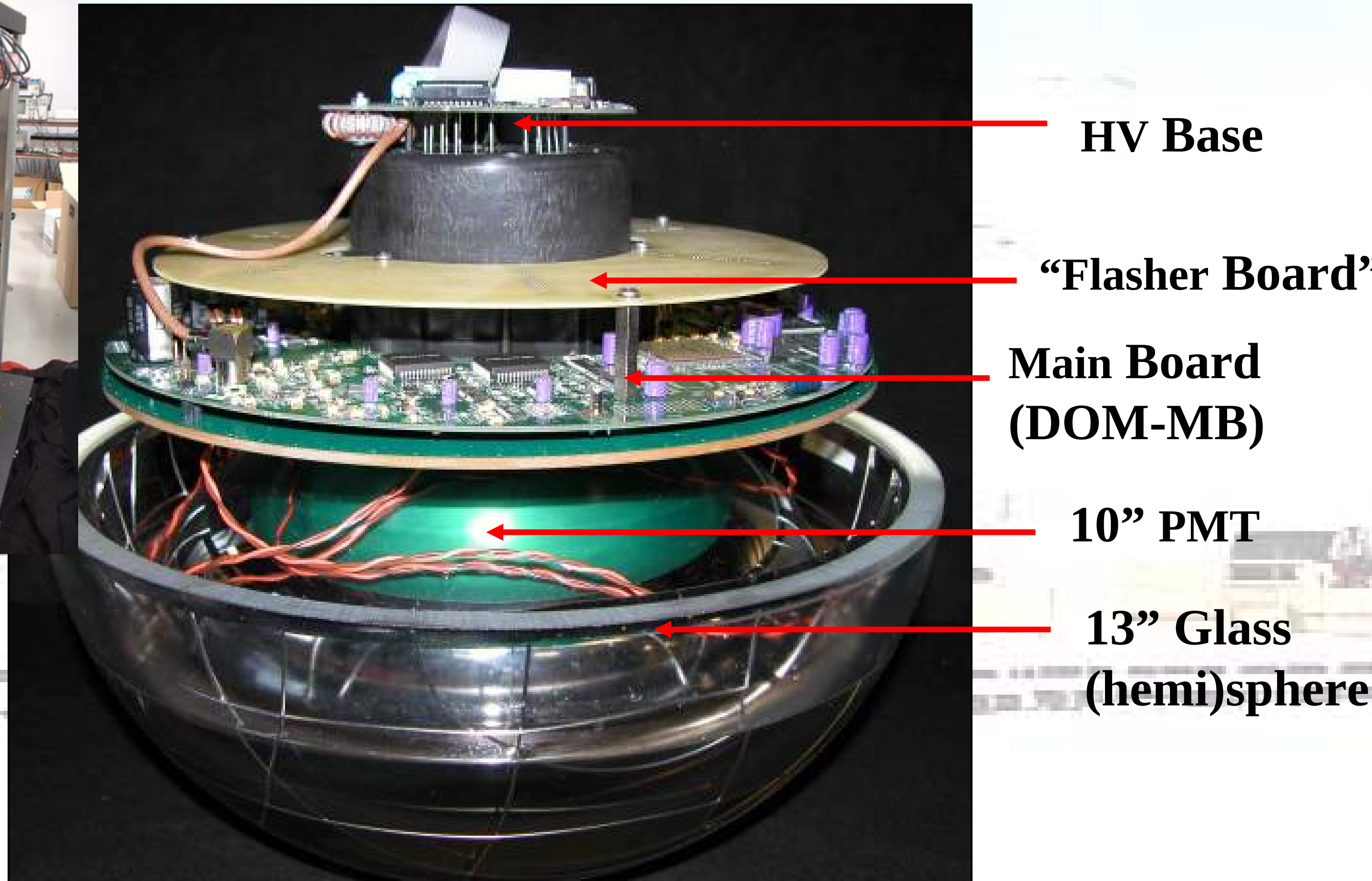
New Zealand:
- University of Canterbury

33 institutions, ~250 members

http://icecube.wisc.edu

DOM
Digital Optical Module





Data Filtering at South Pole

PY 2008 season

40 strings ~ a half of the completed IceCube

Simple Majority Trigger
8 folds with 5 μ sec

~ 950 Hz

Muon Filter
selects
"up-going" tracks

~20 Hz

EHE Filter
selects
"bright" events

~1.3 Hz

NPE > 630 p.e.

Cascade Filter
selects
"cascade"-like events

~17 Hz

Many others

- Min Bias
- Moon
- IceTop
- etc

To Northern Hemisphere

Point Source Search

Materials to cook

$\nu_\mu \rightarrow \mu$ base

μ filtered, EHE filtered and min-bias events

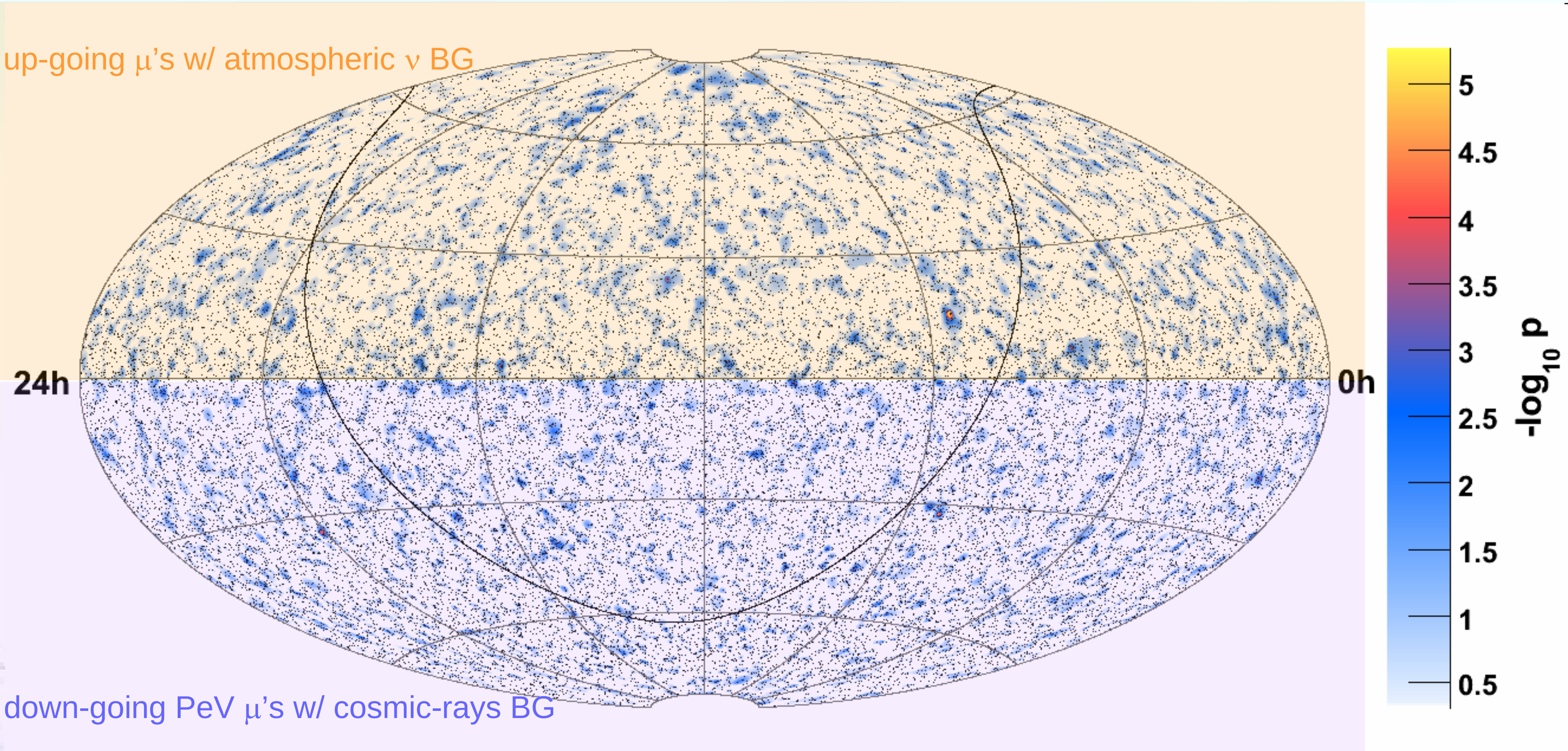
Require Quality cuts in multiple stages

Common aspects
In many other analysis

- to filter out vastly dominated down-going muons
- to realize reasonable agreement between MC and data

Point source specific → to create a sample of events with good angular resolution

ν skymap



All sky search: post-trial p-value 18%

Hottest spot: RA 113.75 Dec 15.15 -log(p)=5.28

Jon Dumm (UW-Madison)

Source List Results

IceCube Preliminary

	p-value
Crab	---
BL Lac	0.226
Mrk 501	0.421
Mrk 421	0.142
M87	---
CygA	0.439
PKS 1622-297	0.048

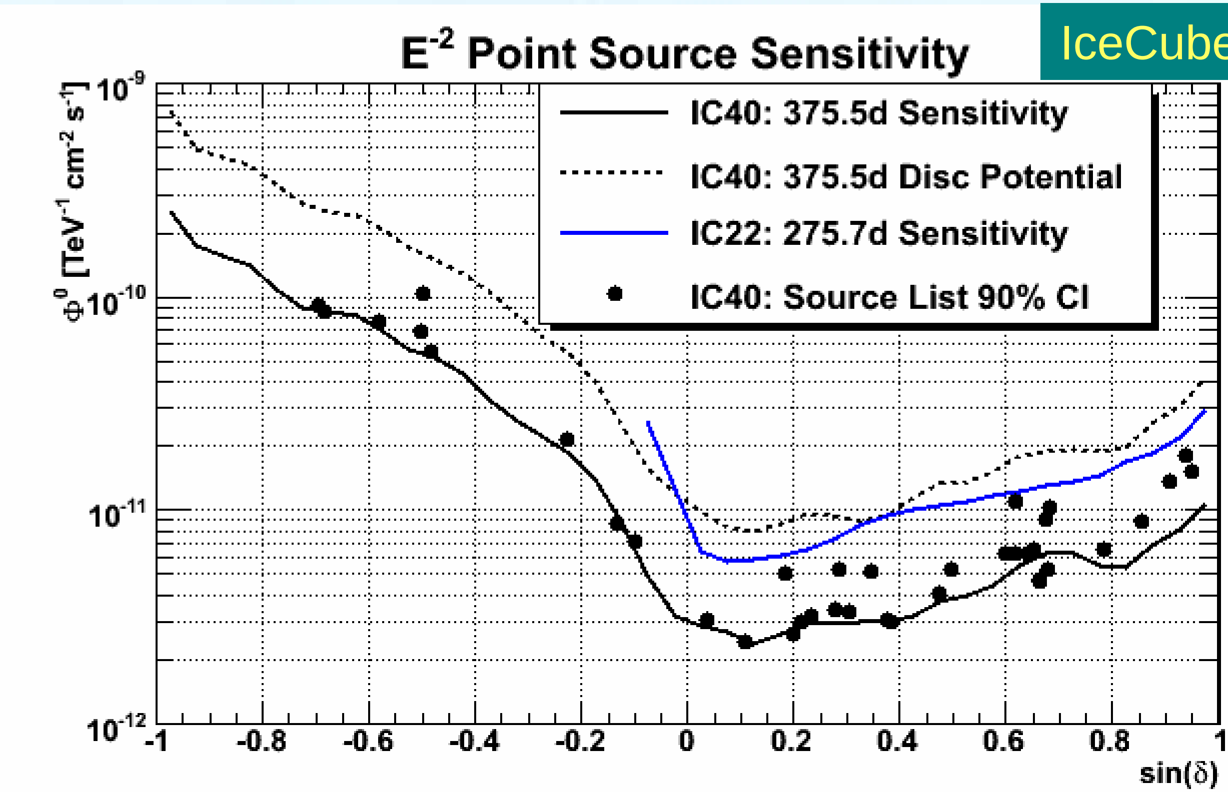
← The highest significance from list of the 39 IceCube sources

Pretrial 4.8 % →post-trial 62 % for the source list

* Shown here is only a part of the IceCube pre-determined source list

Point Source Sensitivity

IceCube Preliminary



Jon Dumm (UW-Madison)

Stacking Searches

	p-value	
Milagro Sources (17 sources)		
9 TeV SNRs + 8 new associated with Fermi	32 %	
(6 SNRs with Fermi association)	1%	(a *posteriori*)
Nearby starburst galaxies (127 sources)	33 %	
Clusters of glaxies (5 sources)	78 %	

Followed Murase, Inoue, Nagataki (2008)

Virgo, Perseus, Centaurus, Coma, Ophiuchus

GRB model-dependent Search

Materials to cook

$\nu_\mu \rightarrow \mu$ base

μ filtered and EHE filtered

Require Quality cuts in multiple stages

Zenith > 85 deg.

Common aspects
In many other analysis

- to filter out vastly dominated down-going muons
- to realize reasonable agreement between MC and data

GRB specific → use "off-time" data as the BG sample to train the BDT

Building of the PDFs

Unbinned Maximum Likelihood

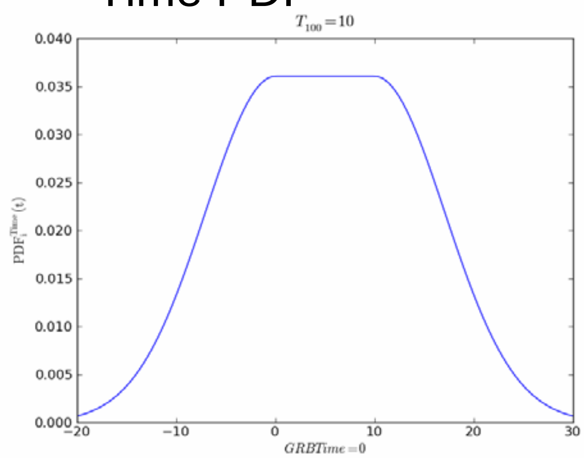
PDF

$$S_i^{tot}(\vec{x},t,E) = PDF_i^{space}(\vec{x}) * PDF_i^{time}(t) * PDF_i^{Energy}(E)$$

Total PDF

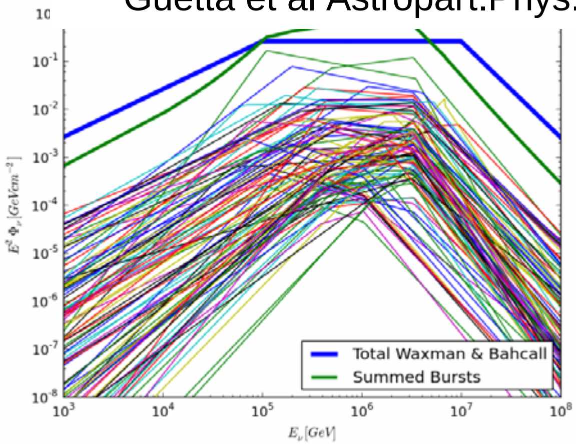
$$P_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma, n_s) = \frac{n_s}{n_{\mathrm{tot}}} S_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma) + \left(1 - \frac{n_s}{n_{\mathrm{tot}}}\right) B(\mathbf{x}_i, E_i)$$

Time PDF



Predicted ν spectra

Guetta et al Astropart.Phys. 20 (2004) 429

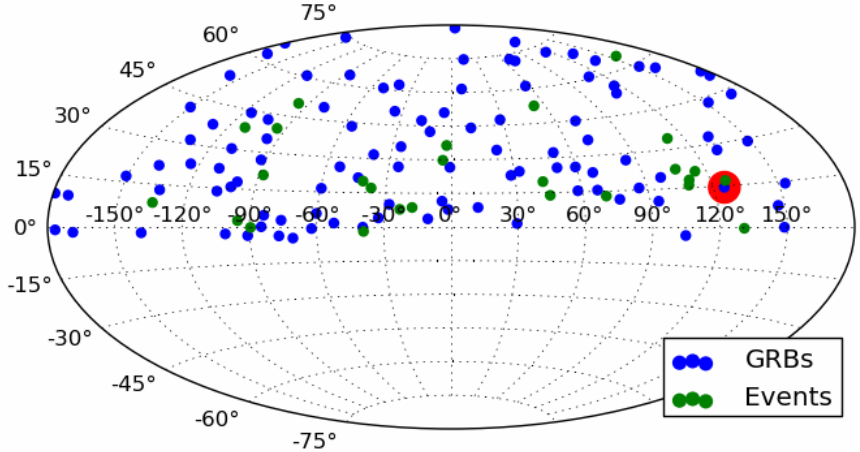


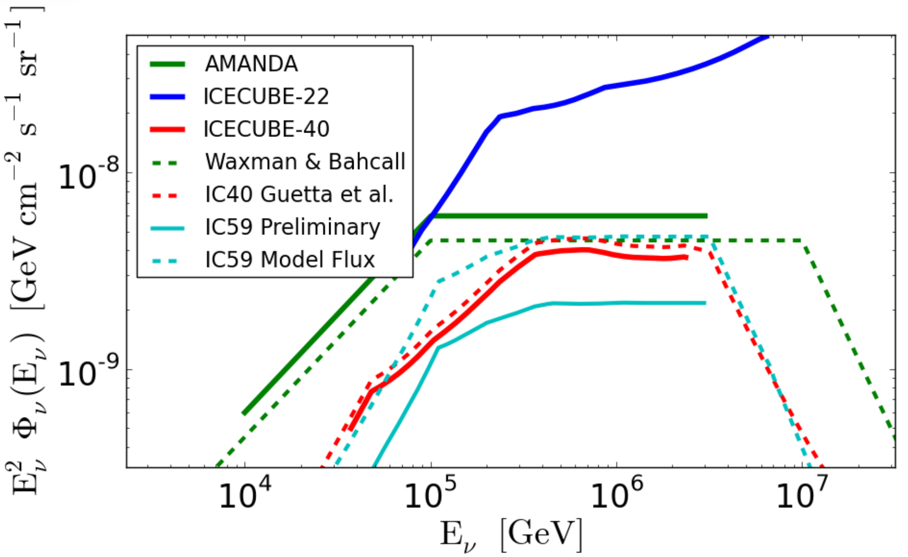
Optimize BDT score
to maximize the discovery
potential

No association of ν's with GRB..

109 GRBs detected by Fermi, Swift, Konus, and WAM in the IceCube FOV (2009 June – 2010 May)

Peter Redl (UMD)





We are on the way to indicate GRBs are unlikely to be a major UHECR origin.

GZK ν Search

O(PeV) ~ 10 EeV

Materials to cook

EHE filtered events

All ν flavor base

No strong quality cuts necessary because..

Unique features
in this particular analysis

these ν's are more energetic than atmospheric μ BG

Just increase energy threshold in analysis leads to better S/N

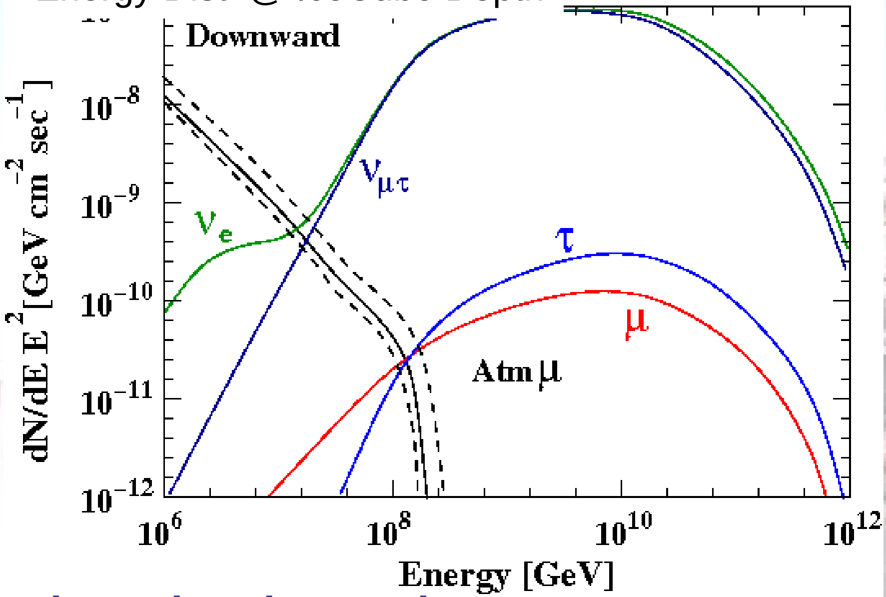
GZK analysis specific issues

- Earth filters out signal ν as well

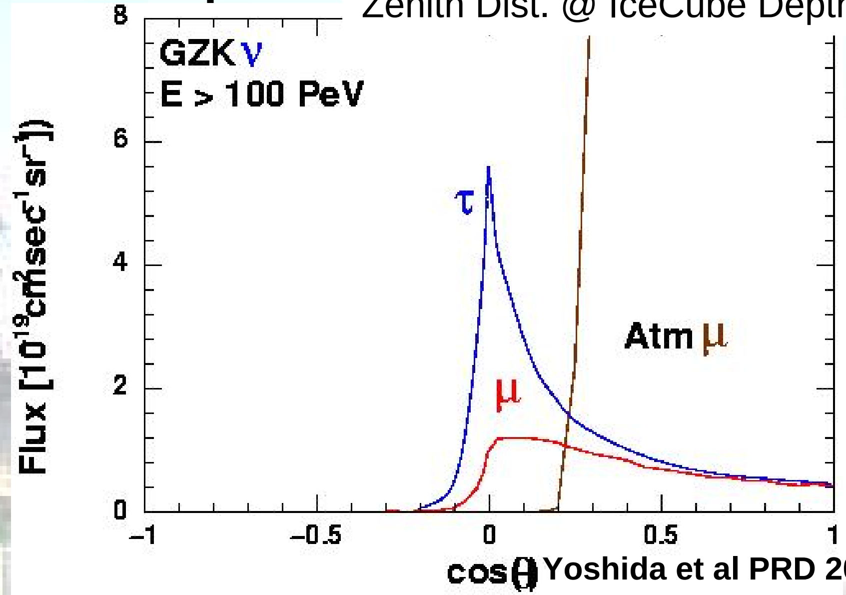
GZK ν search

Detection Principle

Energy Dist. @ IceCube Depth



Zenith Dist. @ IceCube Depth



Yoshida et al PRD 2004

through-going track

Secondary μ and τ from ν

→ Sensitive to ν_μ ν_τ

starting track/ cascade

Directly induced events from ν

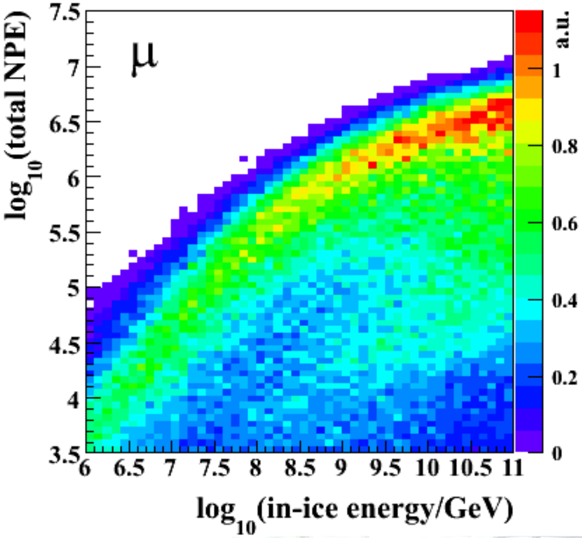
→ Sensitive to ν_e ν_μ ν_τ

And tracks arrive **horizontally**

The detailed description available in
Abbasi et al PRD **82** 072003 (2010)

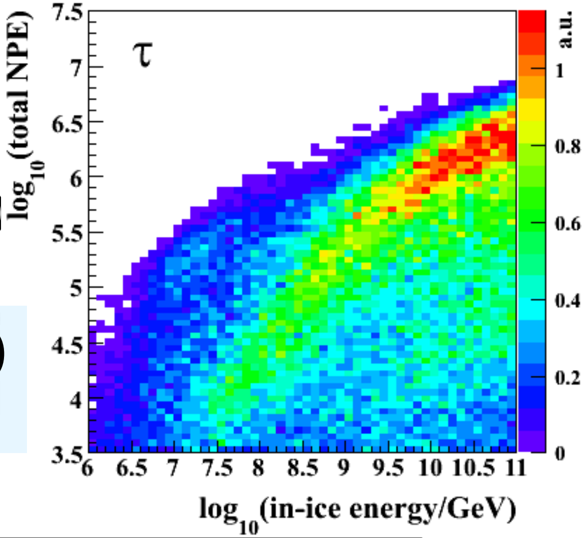
GZK ν search

Detection Principle

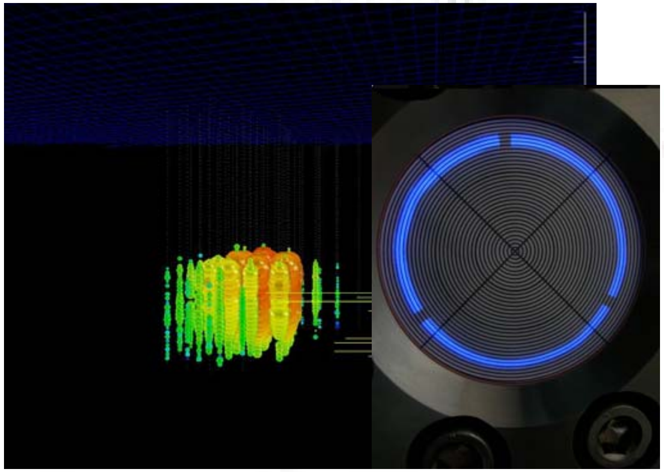


Energy
→ NPE (total # of photoelectrons)

Look for luminous (high NPE) horizontal events



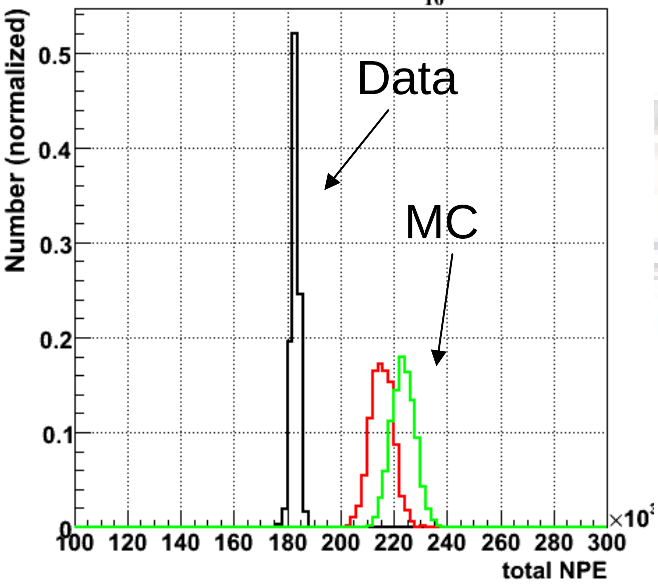
Experimental verification



MC overestimates NPE by ~18%

↓

Sys. error
~ 7% in SIG rate
~ 50% in BG rate

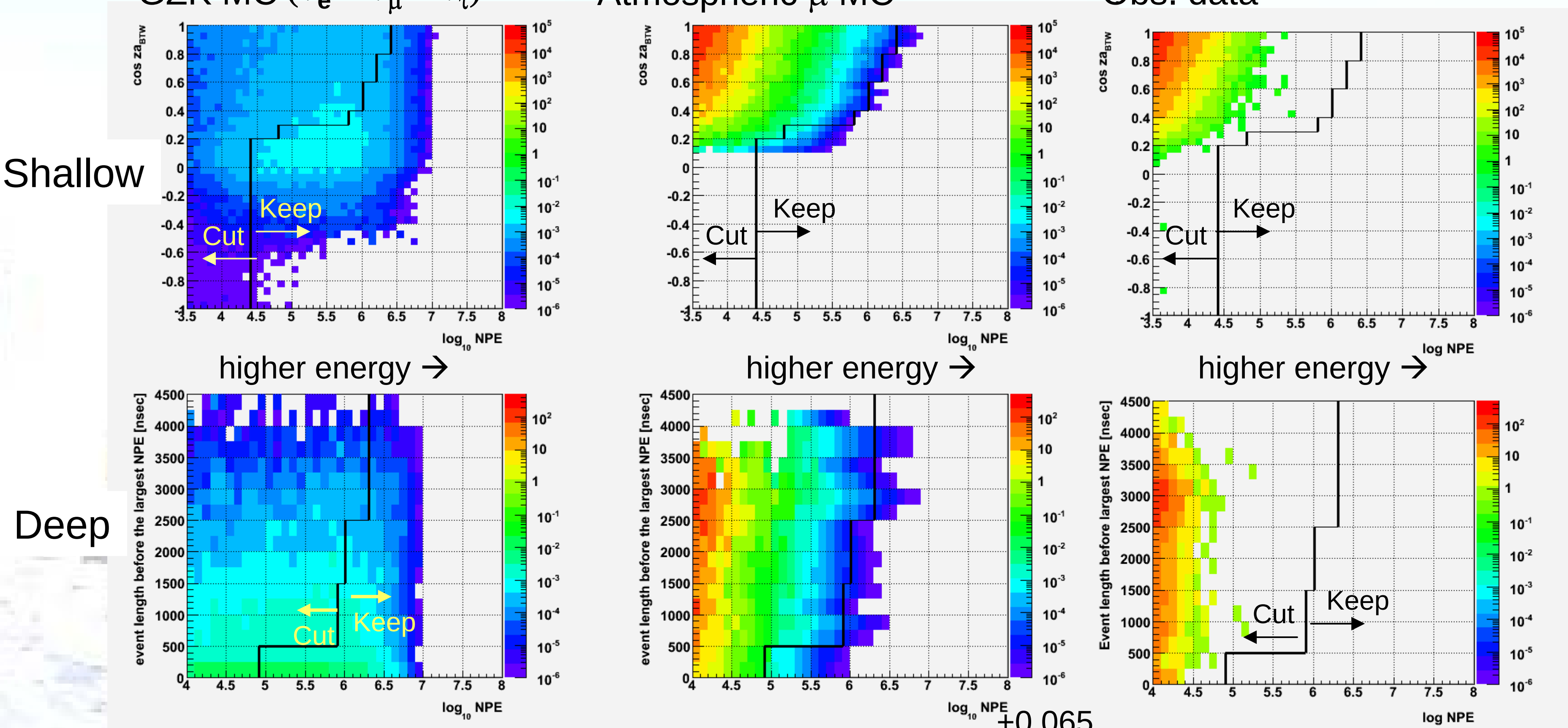


GZK ν search

Final level 3 cut

Selects bright(=high NPE) events penetrating long path from the earth surface

GZK MC ($\nu_e + \nu_\mu + \nu_\tau$) | Atmospheric μ MC | Obs. data



Final BG 0.107 +/- 0.015 (stat.) $^{+0.065}_{-0.103}$ (sys)

GZK 0.573 +/- 0.005 (stat.) $^{+0.080}_{-0.066}$ (sys)

Aya Ishihara (Chiba)

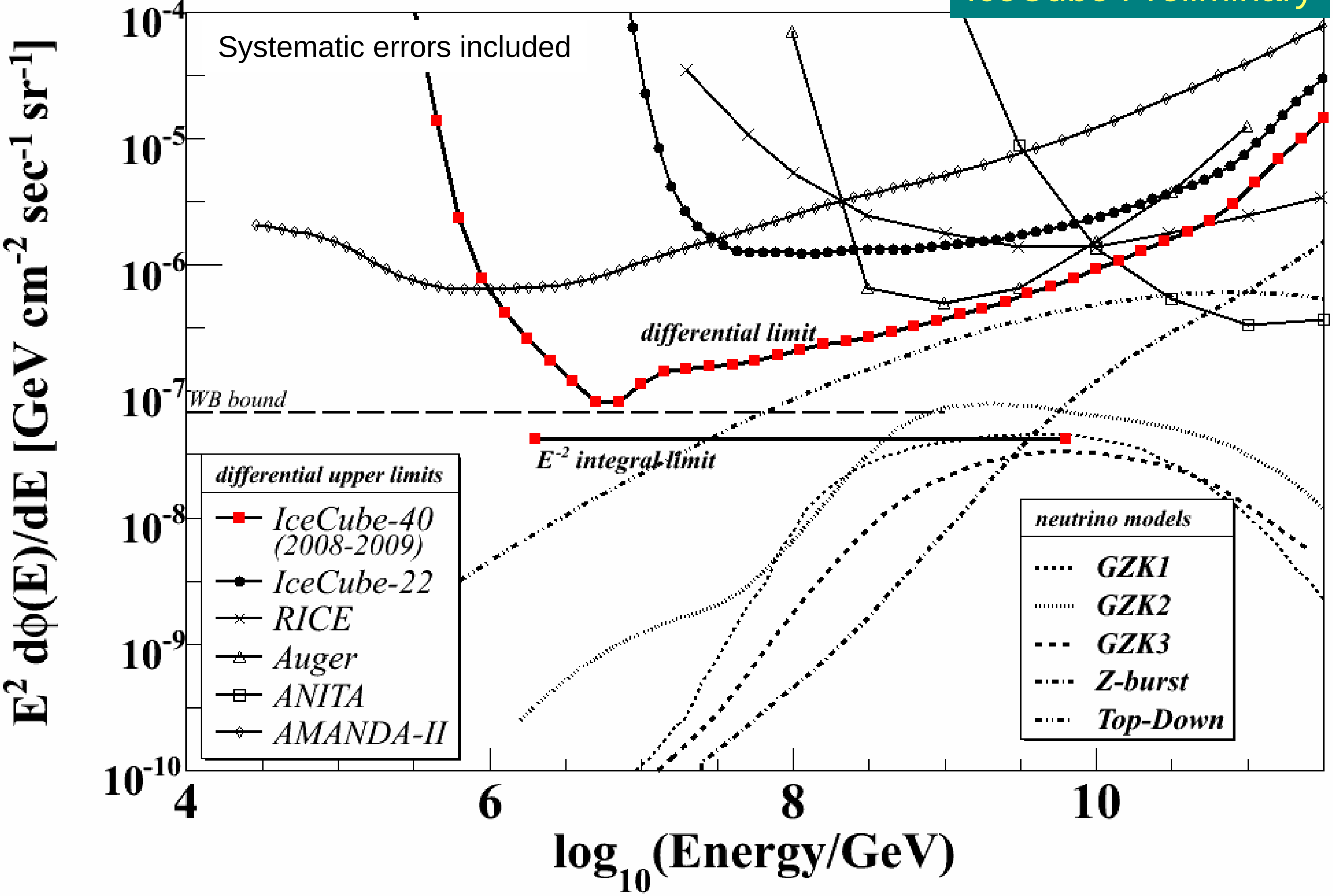
Upper limits in EHE

Aya Ishihara (Chiba)

$E^2\,\phi(E) < 4.2\times10^{-8}$ GeV/cm^2 sec sr (2PeV < E < 8 EeV)

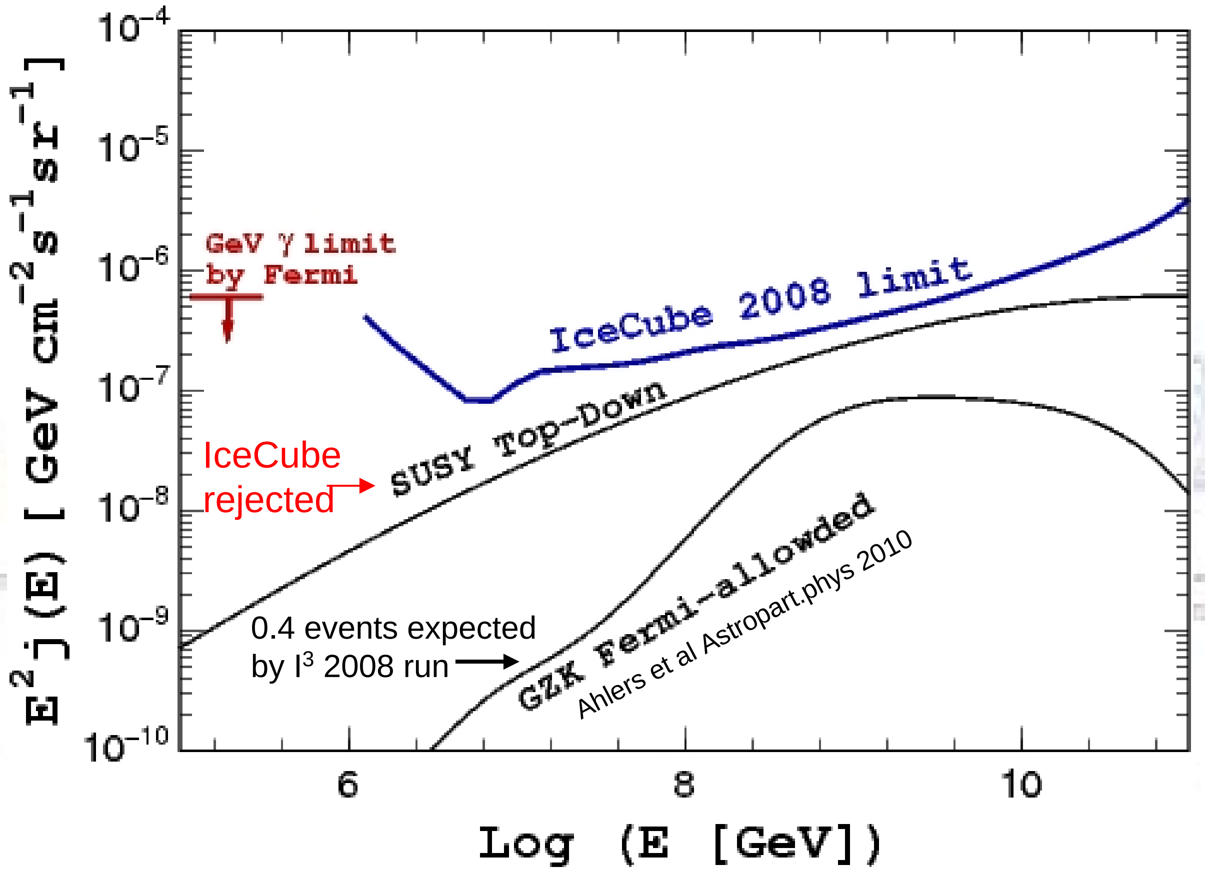
All flavor $(\nu_e + \nu_\mu + \nu_\tau)$ limits

IceCube Preliminary



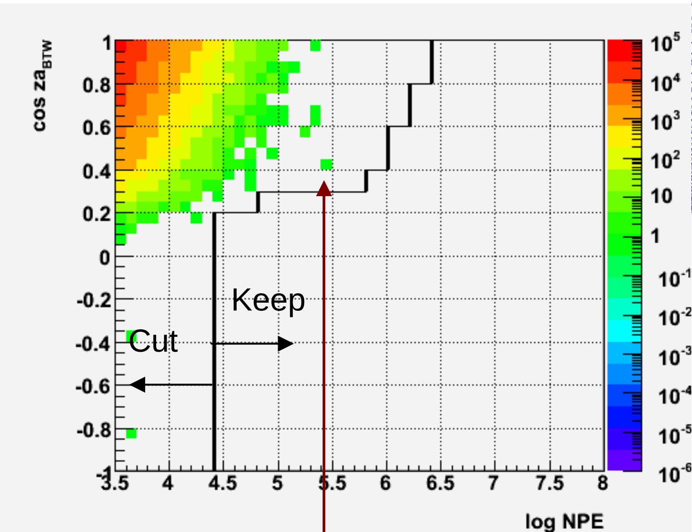
Constraints on Ultra-high energy cosmic ray emission

Now IceCube : constrained UHECR cosmological luminosity at the comparable level with Fermi, ***but more direct way***

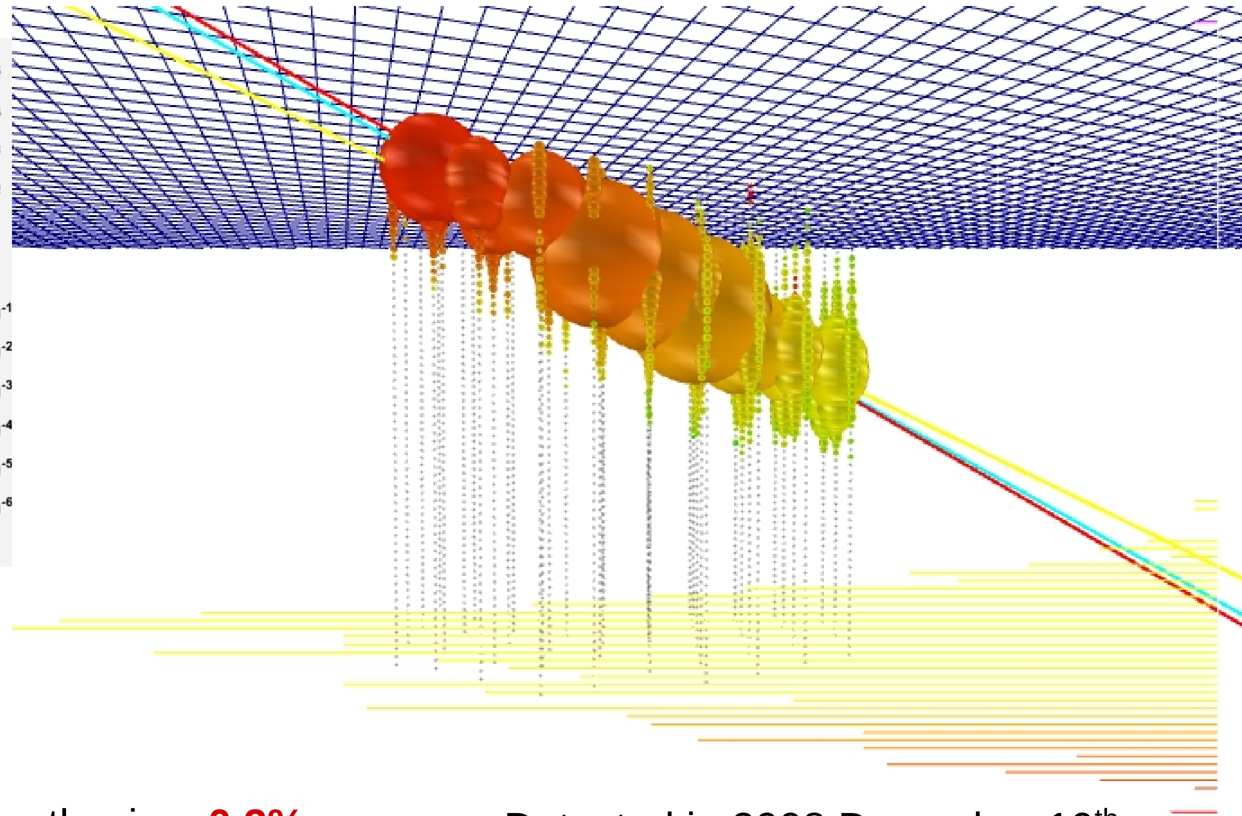


A major fraction of the Fermi diffuse γ is *NOT* responsible for UHECR emissions

The Highest NPE event



This event

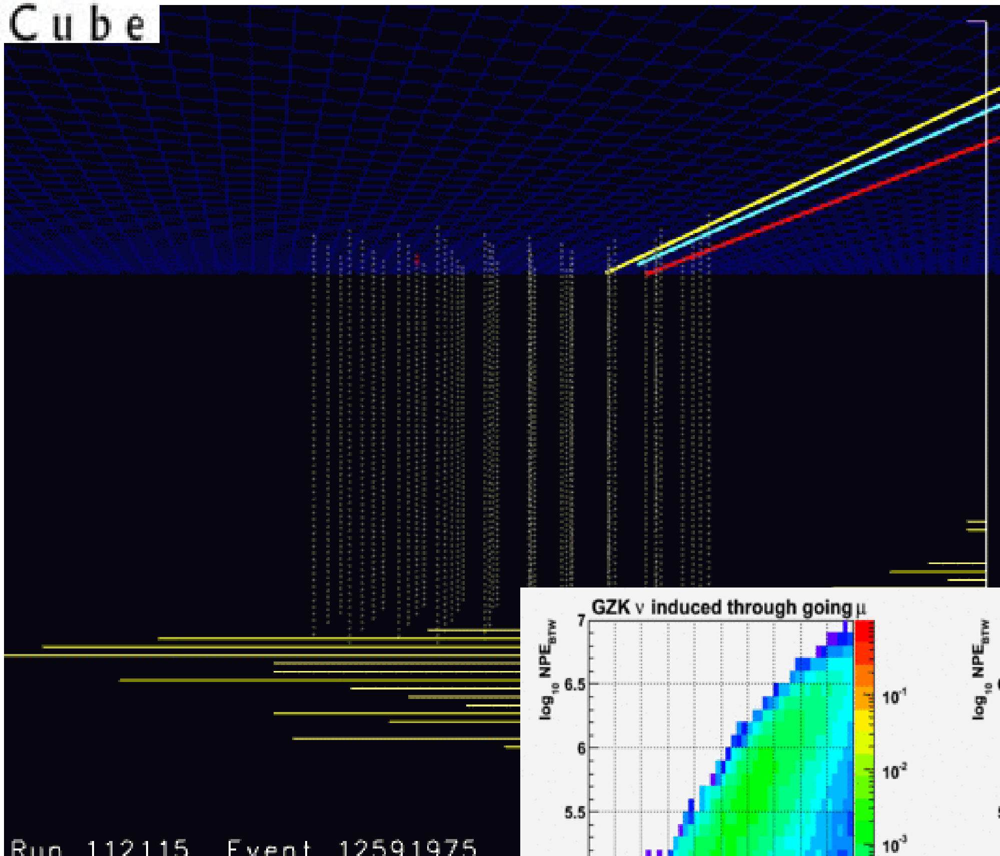


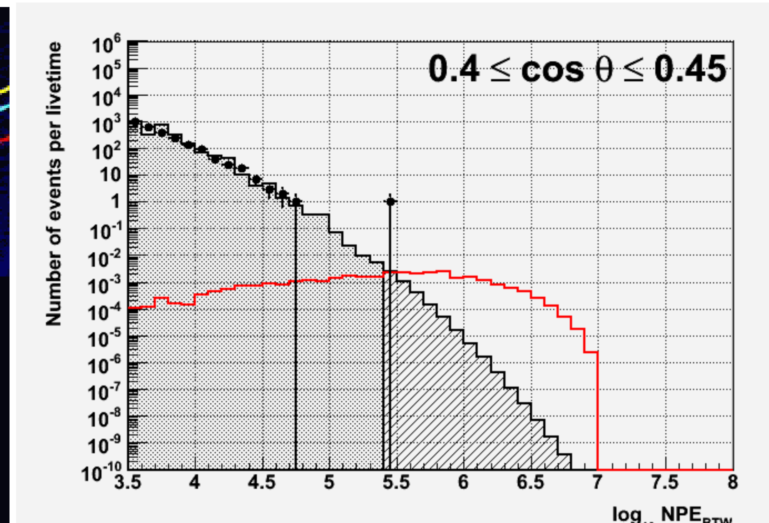
p-value for the background hypothesis **~0.2%** (posteriori)

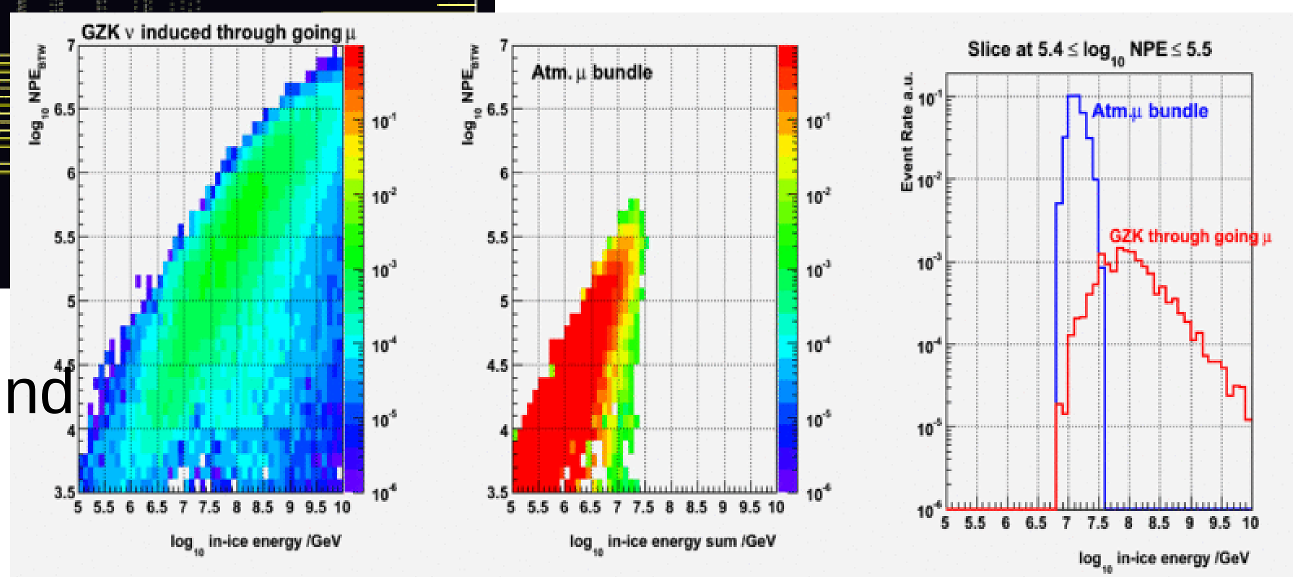
- Detected in 2008 December 10th
- NPE 2.55×10^5 photo-electrons
- Zenith 64.7 deg

Aya Ishihara (Chiba)

The Highest NPE event





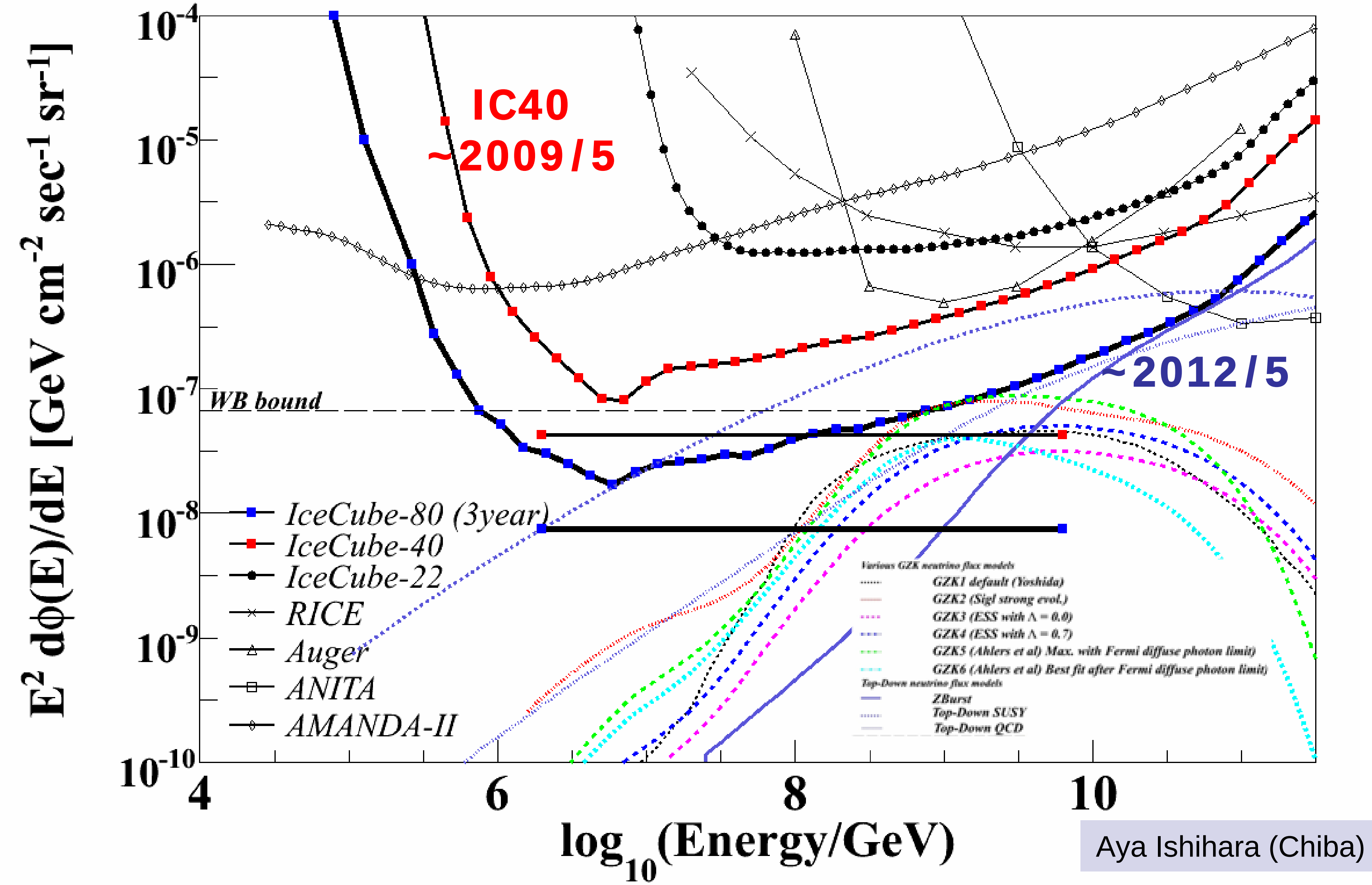


~ 10 PeV if background

~ 100 PeV if (GZK) ν

IceCube baseline Sensitivity

The same analysis method/systematics applied on the full IceCube MC



Aya Ishihara (Chiba)

Expected # of EHE signal events

Models	IC40 # of events (333days)	IC80(full) # of events (3 years, by 2012/5)
GZK1 (Yoshida et al)	0.57	**3.1**
GZK2 Strong Evol. (Sigl)	0.91	**4.9**
GZK3 (ESS with W_L=0.0)	0.29	**1.5**
GZK4 (ESS with W_L=0.7)	0.47	**2.5**
GZK5 (Ahlers max)	0.89	**4.8**
GZK6 (Ahlers best fit)	0.43	**2.3**
Z-Burst	1.03	**5.1**
Top Down(SUSY)	**5.68**	**31.6**
Top Down(QCD)	1.19	**6.3**
W&B(evol)	3.7	**24.5**
W&B(no evol)	1.1	**5.5**