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

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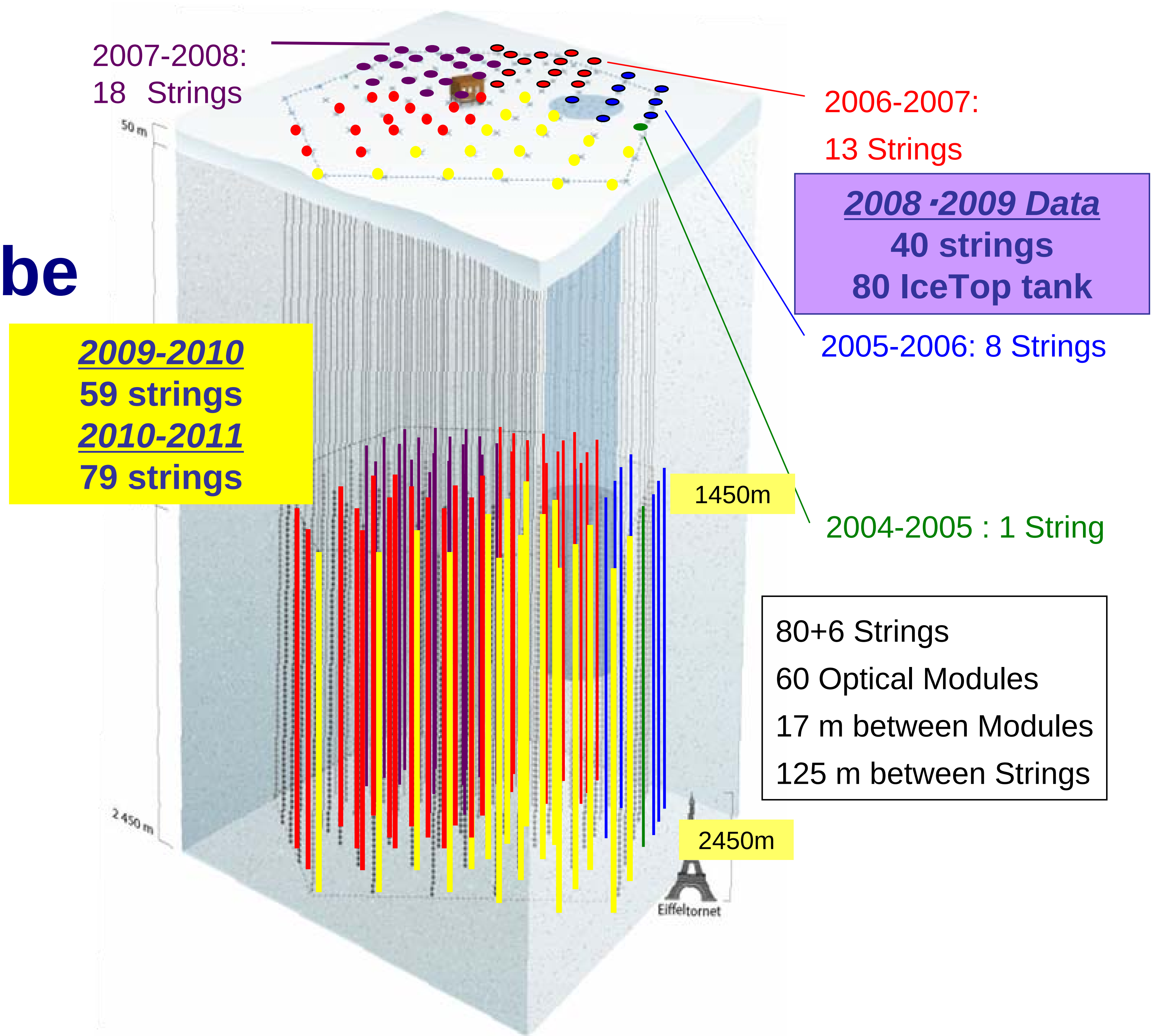
Chiba University

IceCube



2007-2008:
18 Strings
2006-2007:
13 Strings
2008 -2009 Data
40 strings
80 IceTop tank
2005-2006: 8 Strings
2009-2010
59 strings
2010-2011
79 strings
50 m
1450m
2004-2005 : 1 String
80+6 Strings
60 Optical Modules
17 m between Modules
125 m between Strings
2 450 m
2450m
Eiffeltornet

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

Switzerland:
- EPFL

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

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

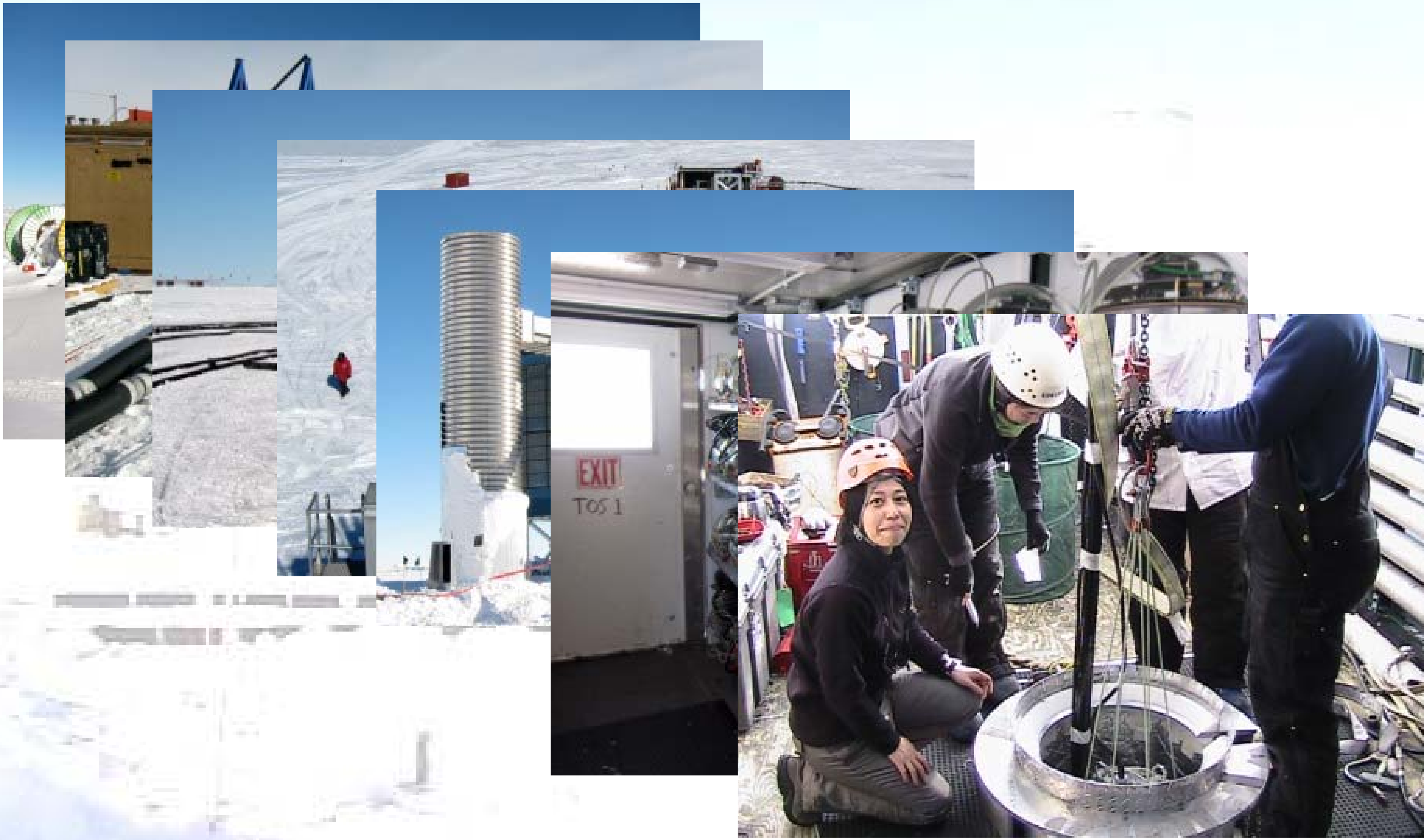
Japan:
- Chiba University

New Zealand:
- University of Canterbury

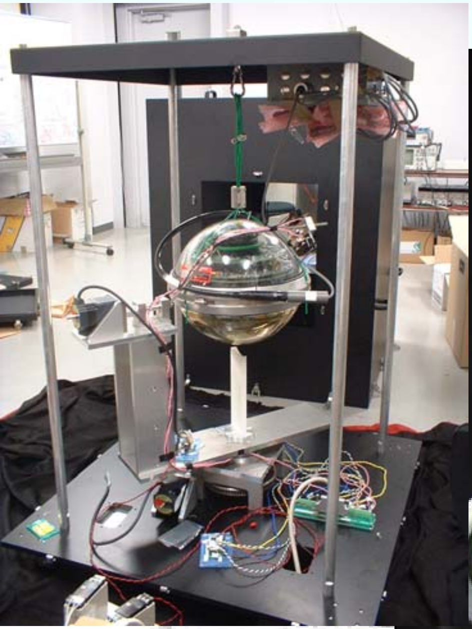
33 institutions, ~250 members

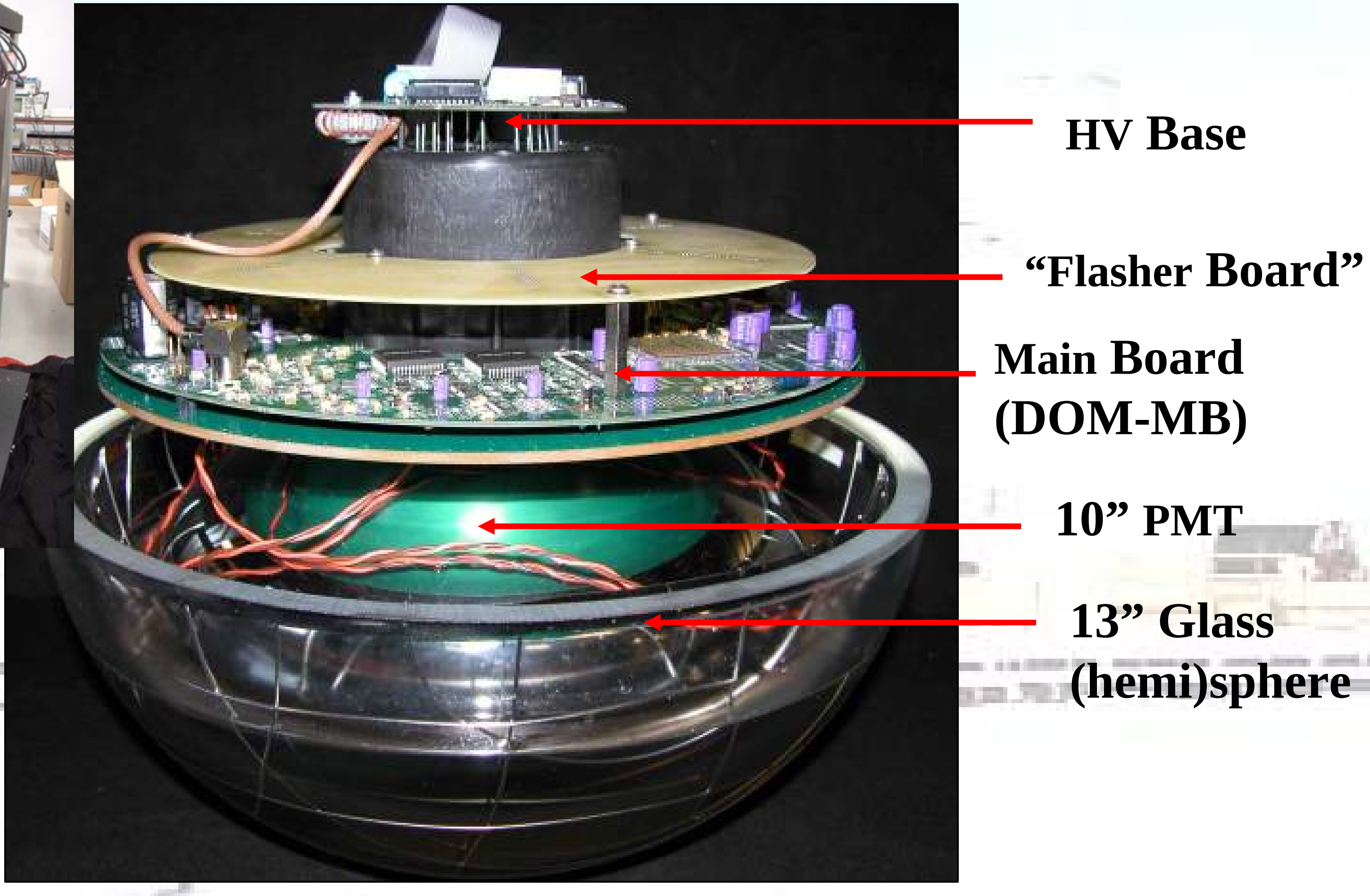
http://icecube.wisc.edu

Gigantic operations



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

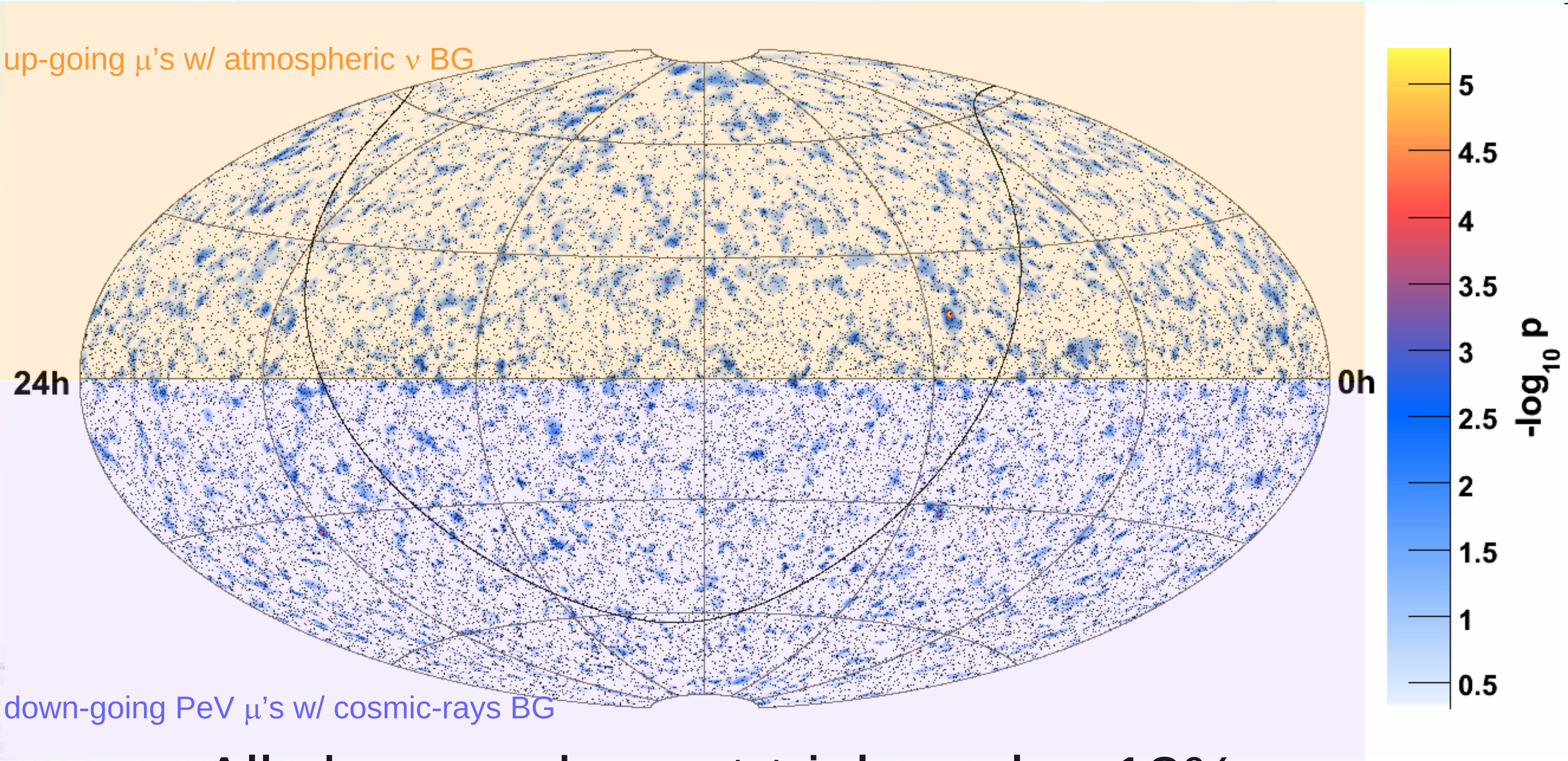
Common aspects
In many other analysis

- 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)

IceCube

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

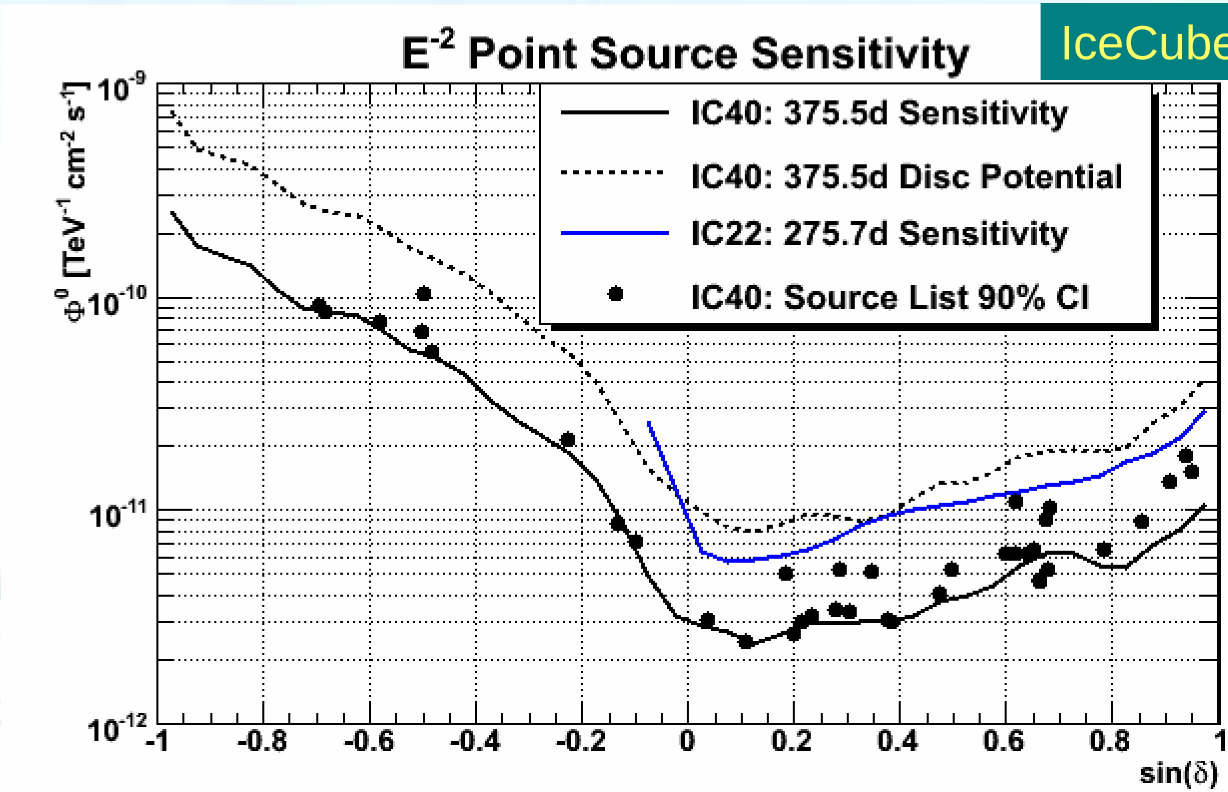
← The highest significance from list of the 39 IceCube sources

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

Diffuse ν Search

O(100 TeV) ~ 10 PeV

Materials to cook

μ filtered, EHE filtered events

$\nu_\mu \rightarrow \mu$ base

Require Quality cuts in multiple stages

Common aspects
In many other analysis

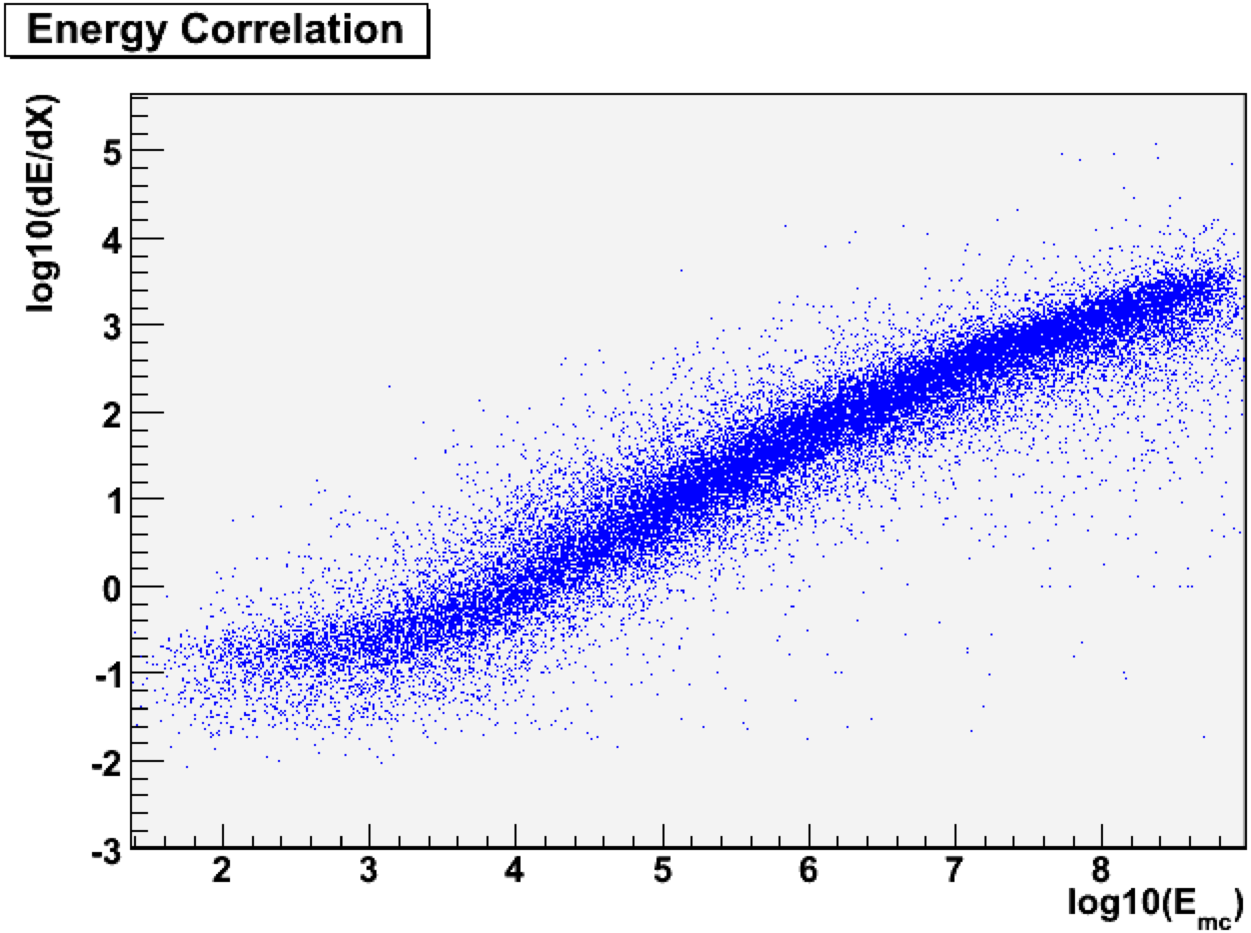
- to filter out vastly dominated down-going muons
- to realize reasonable agreement between MC and data

Diffuse analysis specific

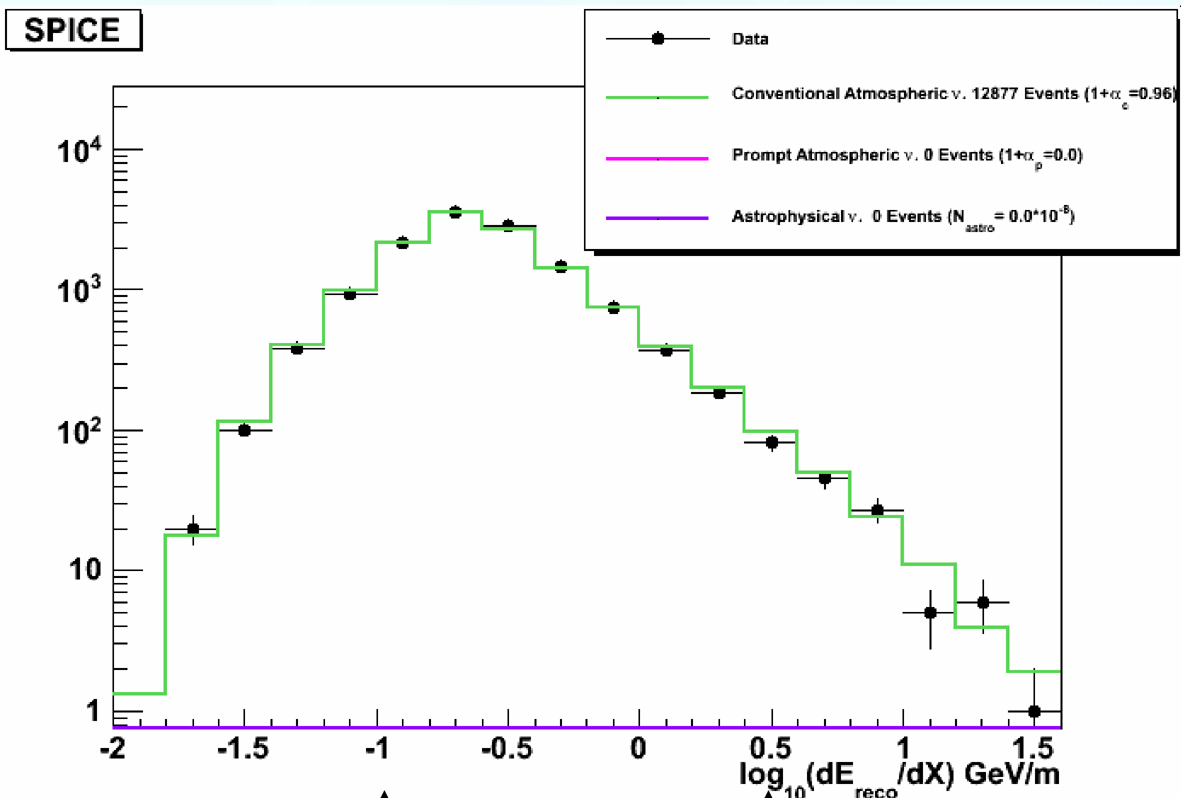
Stronger cuts (than PS search) required for enhancing purity of ν sample

Now look at "energy" distribution

Calculates μ's energy loss (dE/dX) from the Cherenkov γ profile

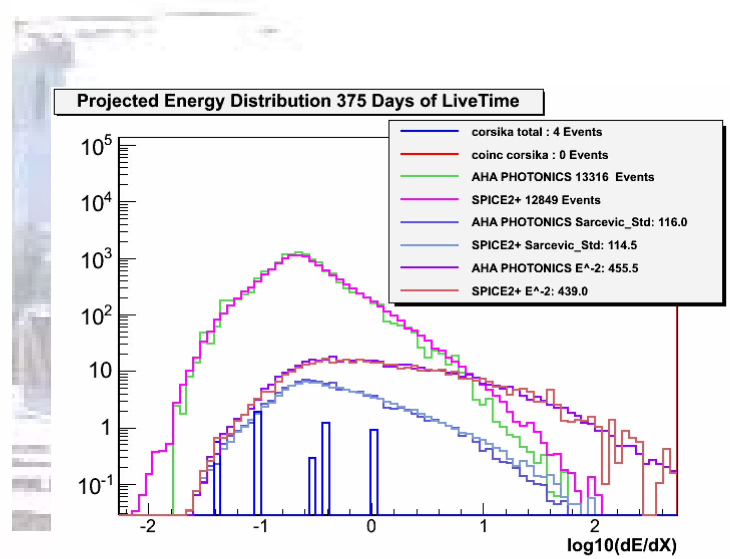


Final “Energy” distribution



O(100GeV~TeV)

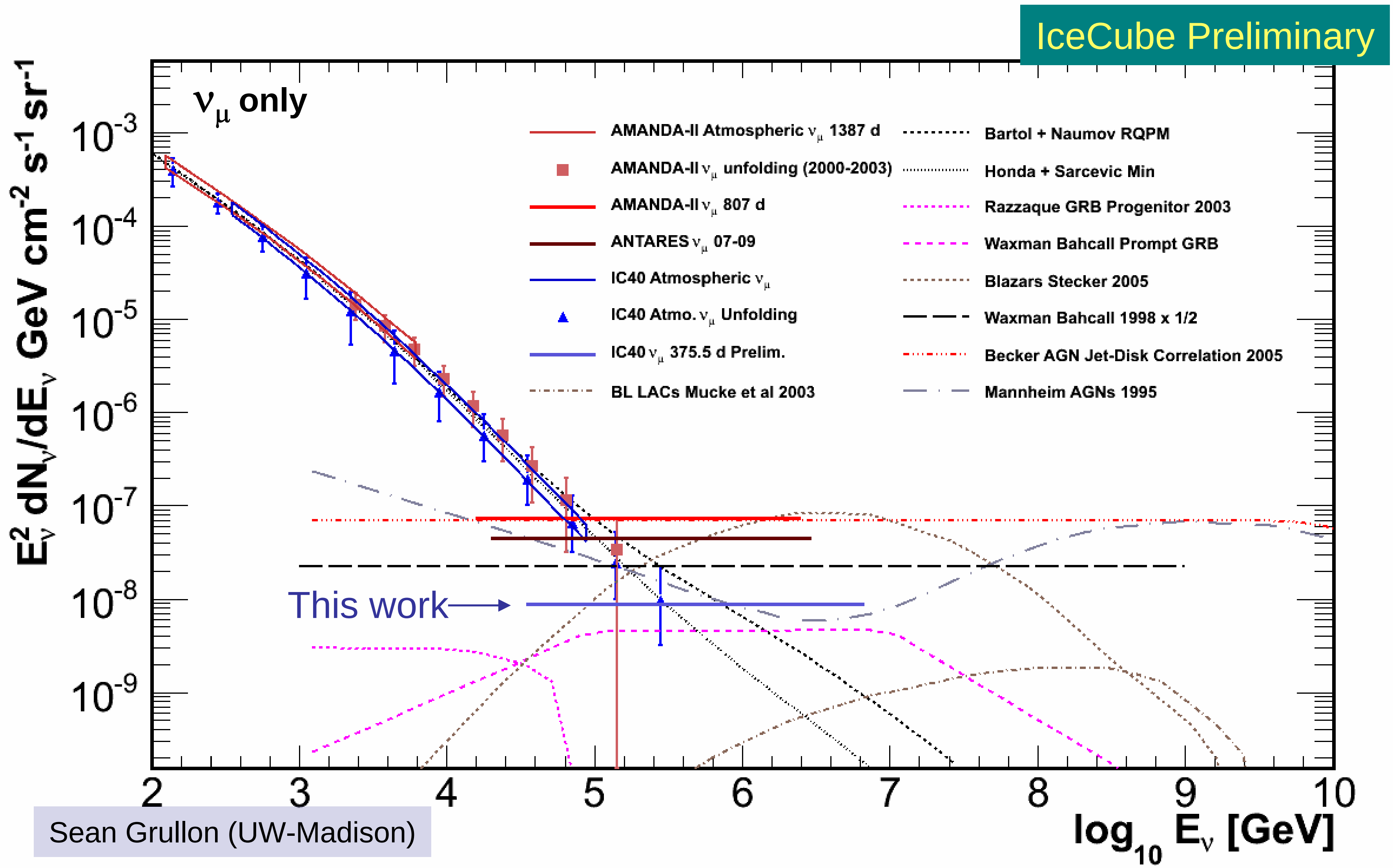
O(10TeV~100TeV)



Sean Grullon (UW-Madison)

Diffuse ν limit

Now below the Waxman-Bahcall limit



Sean Grullon (UW-Madison)

Atmospheric ν spectrum

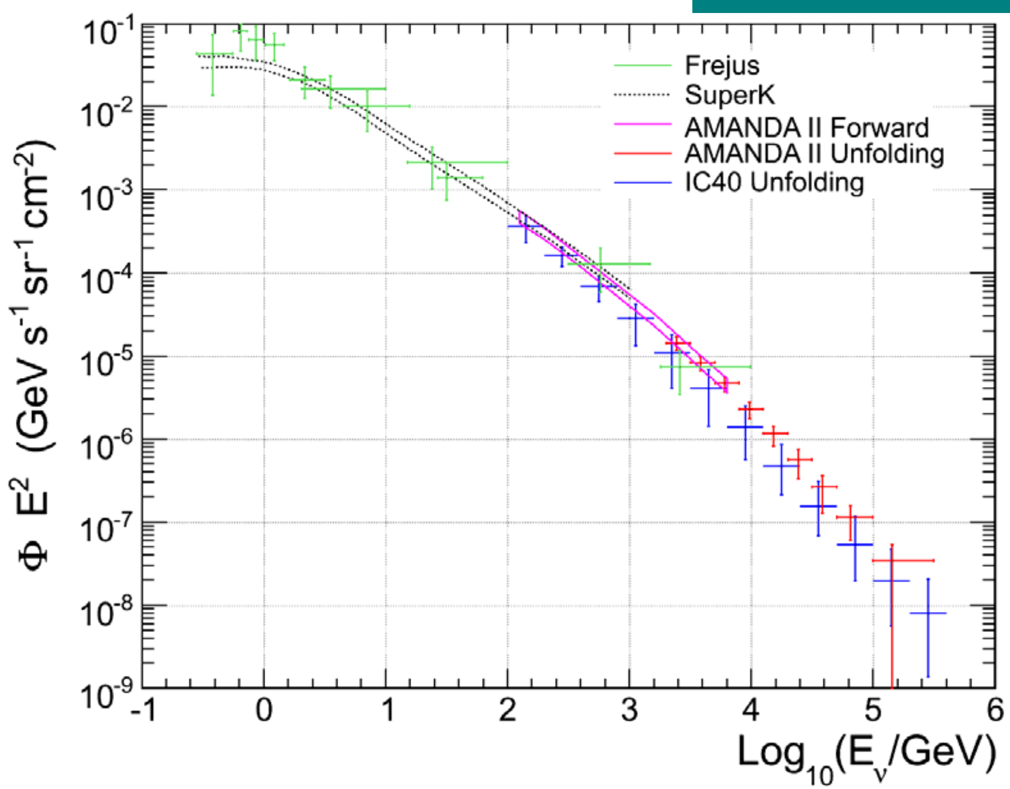
The quality cuts by the similar philosophy
but with **<u>the BDT training method</u>**

An independent analysis with slightly different event selections

IceCube Preliminary

dE/dX → Eν

Spectrum Unfolding
by SVD method
[NIM A 372 (1996) 469]



Warren Whuelsnitz (UMD)

No indication of prompt ν and new physics (e.g. quantum gravity)

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

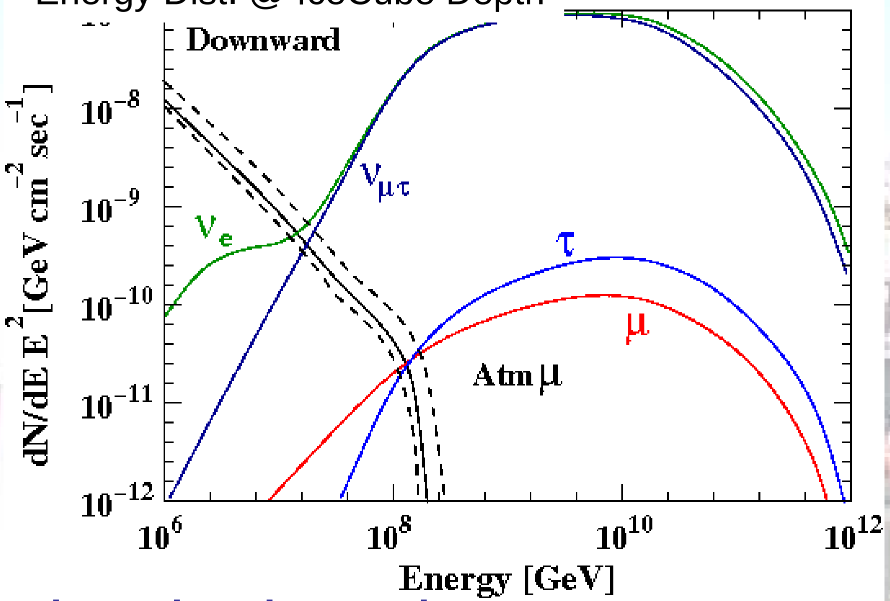
GZK analysis specific issues

- Earth filters out signal ν as well

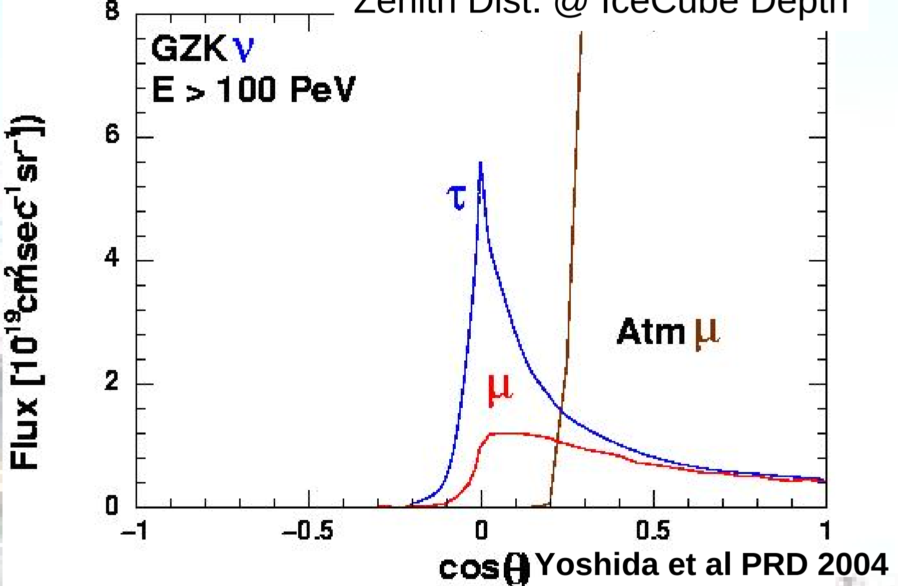
GZK ν search

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

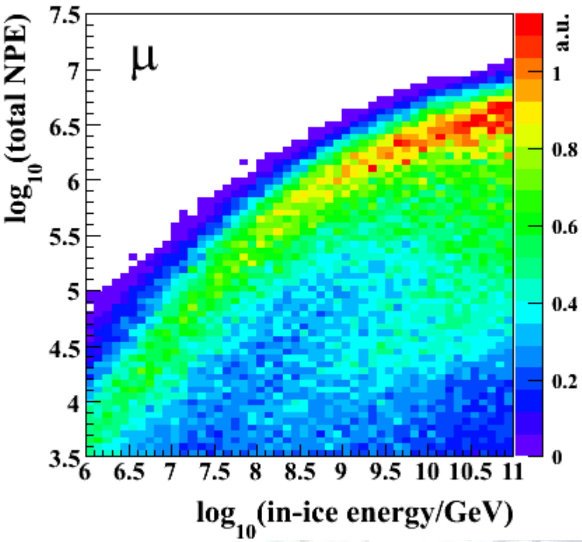
→ Sensitive to ν_e ν_μ ν_τ

And tracks arrive **horizontally**

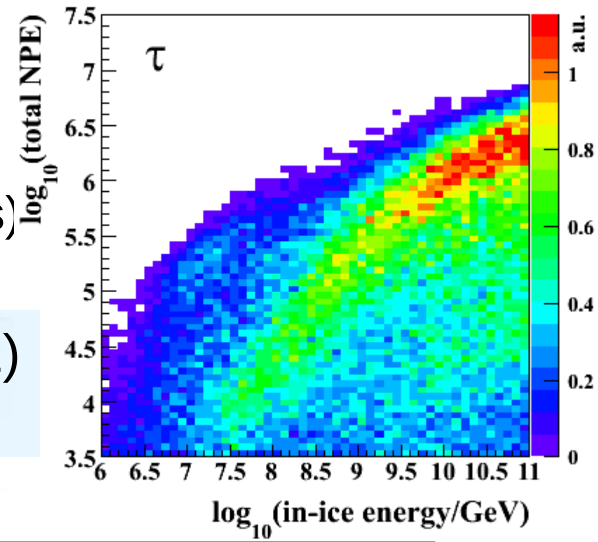
The detailed description available in PRD (2010)

GZK ν search

Detection Principle

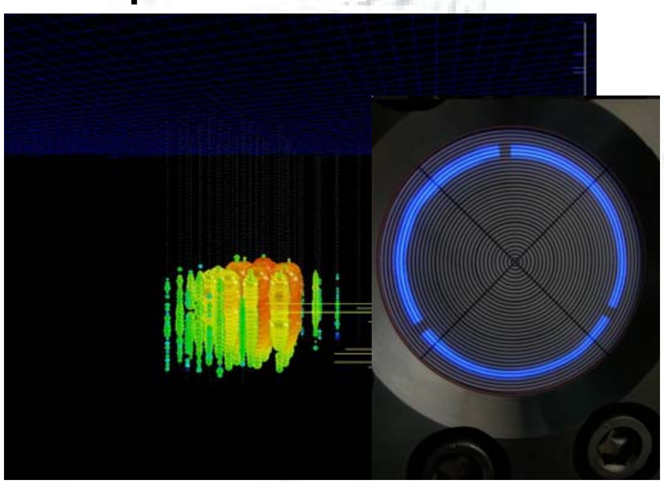


Energy
→ NPE (total # of photoelectrons)



Look for luminous (high NPE) horizontal events

Experimental verification



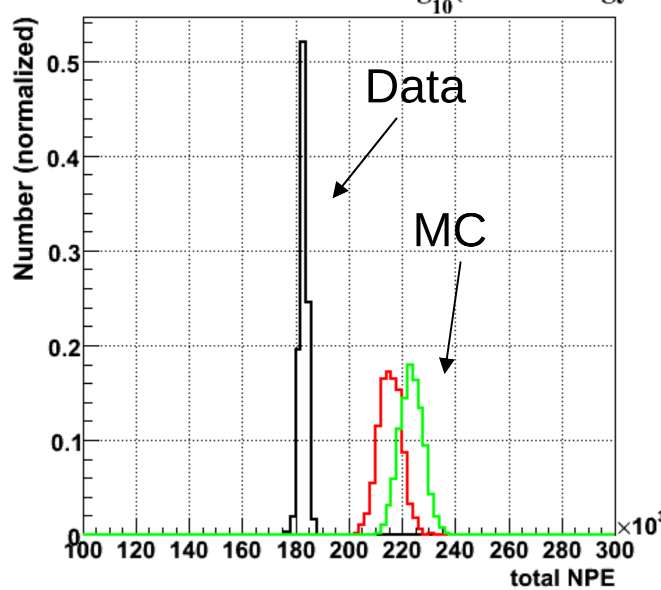
MC overestimates NPE by ~18%

↓

Sys. error

~ 7% in SIG rate

~ 50% in BG rate



GZK ν search

Aya Ishihara (Chiba)

Signal Selection Criteria for 2008 data (0.5xIceCube)

Level 1

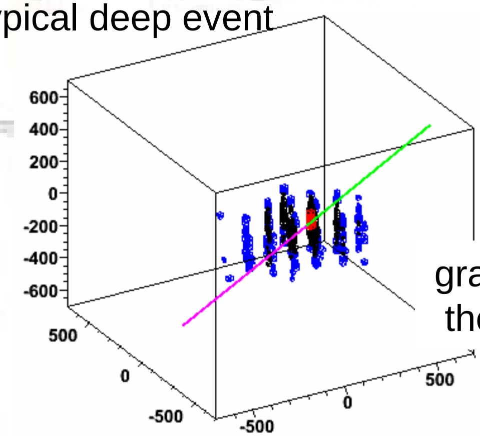
- Pulse Cleaning – using only detectors with pulses within [-4.4us 6.4us] from timing of the largest NPE
- Nch > 200 and NPE > $10^{3.5}$

Level 2

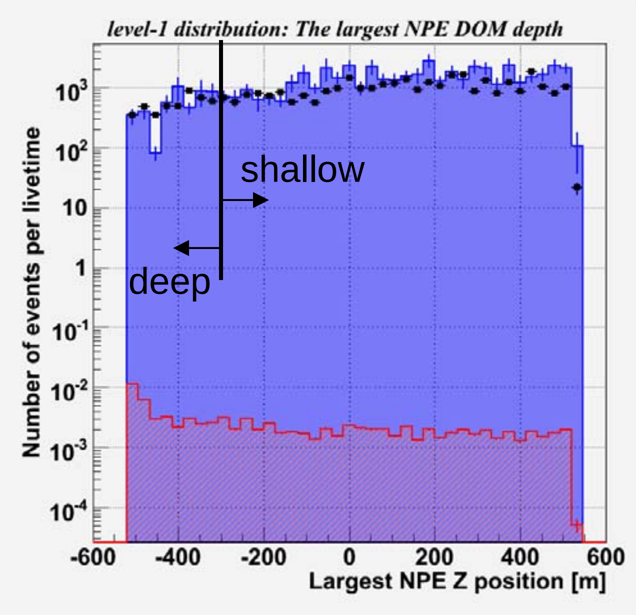
Shallow events   removal of wrongly reconstructed events by looking at pulse hit profile on time - z-depth plane

Deep events   NPE>10^4

A typical deep event



grazing at the bottom of the detector volume

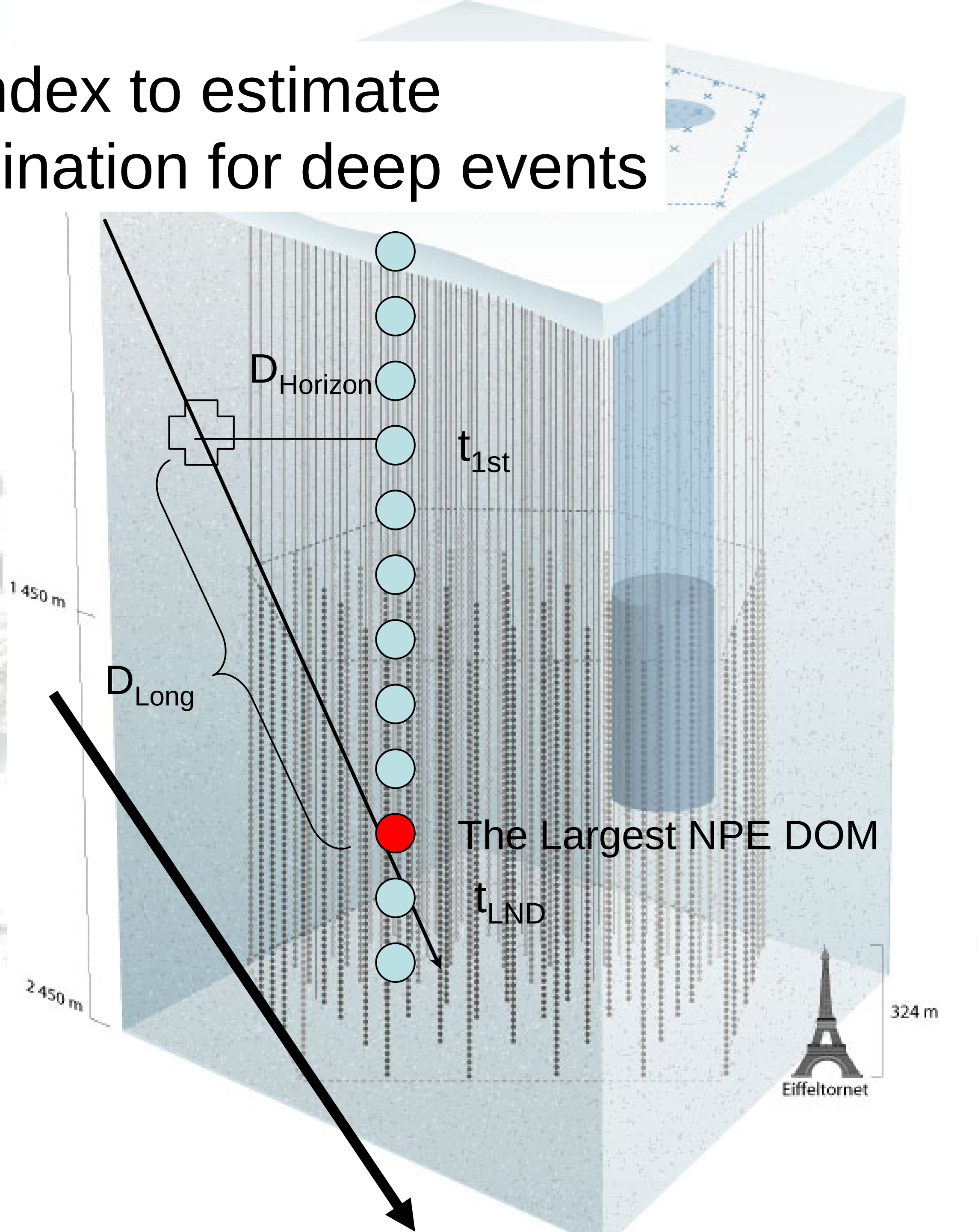


Index to estimate track inclination for deep events

$$\text{eventLength} \equiv t_{LND} - t_{1st}$$

Horizontal→ short length
Vertical → long length

Exhibited good agreement between MC and data



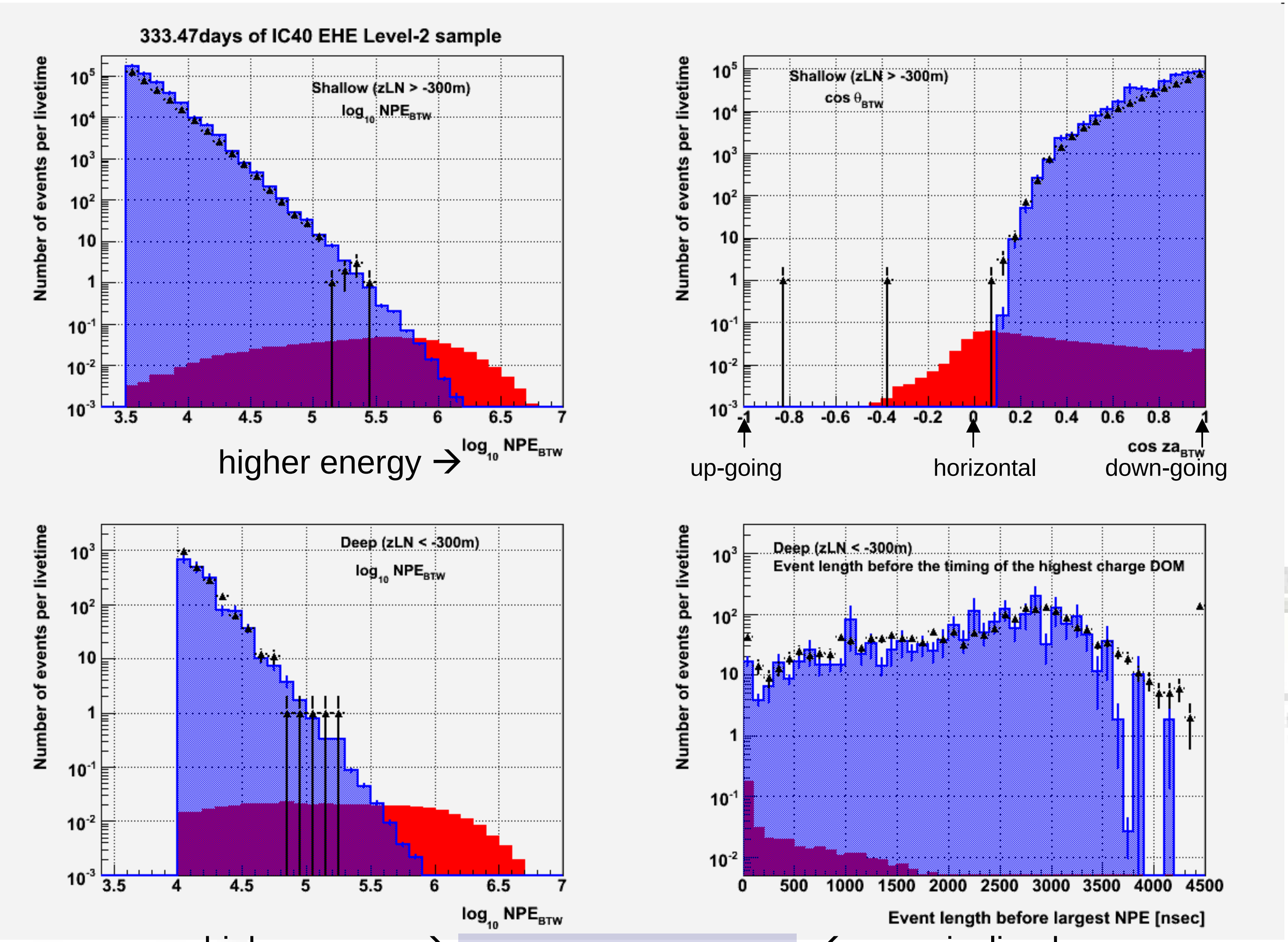
Aya Ishihara (Chiba)

GZK ν search

Distributions at level 2

Shallow

Deep



higher energy →

higher energy →

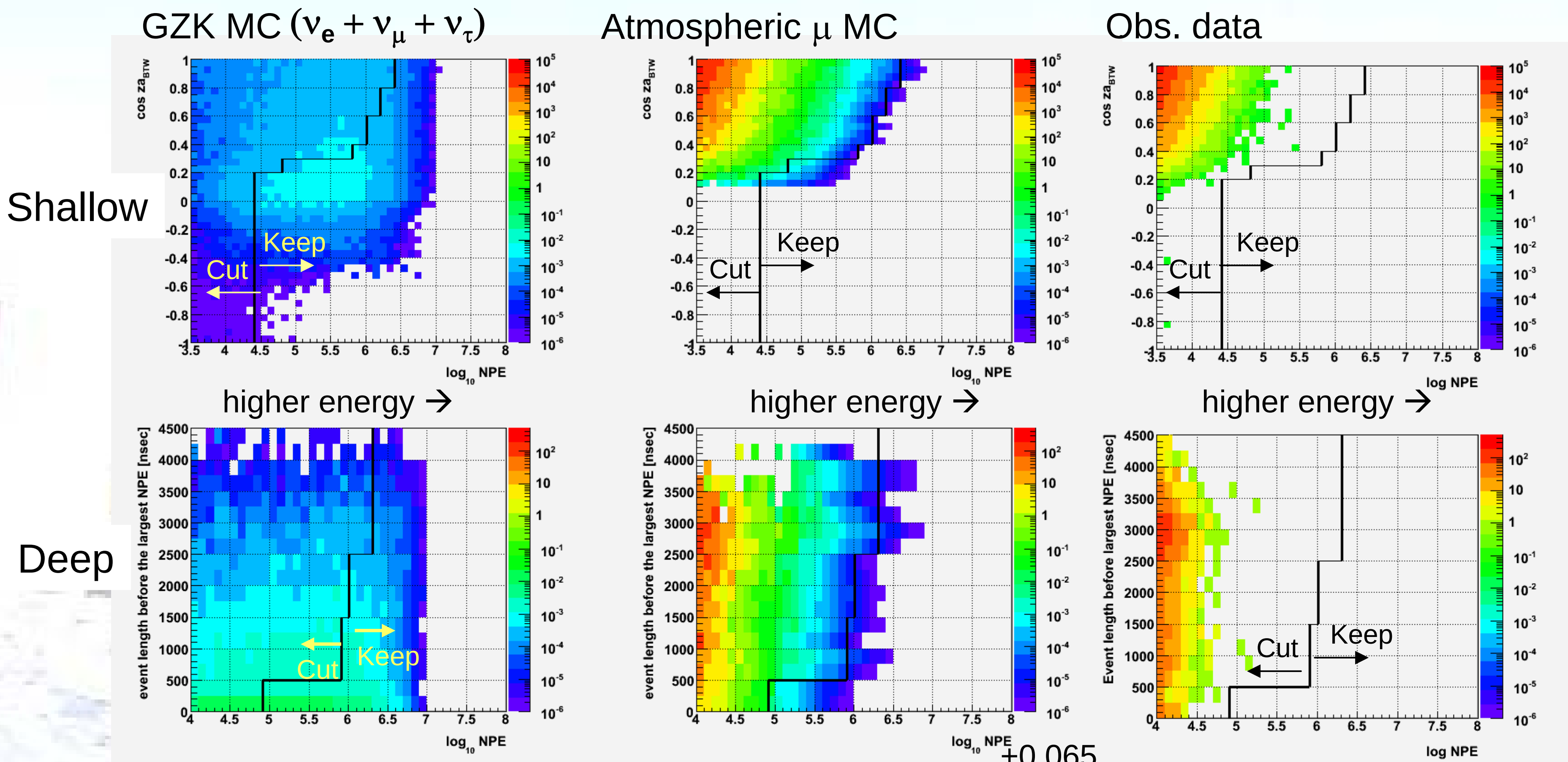
← more inclined

Aya Ishihara (Chiba)

GZK ν search

Final level 3 cut

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



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

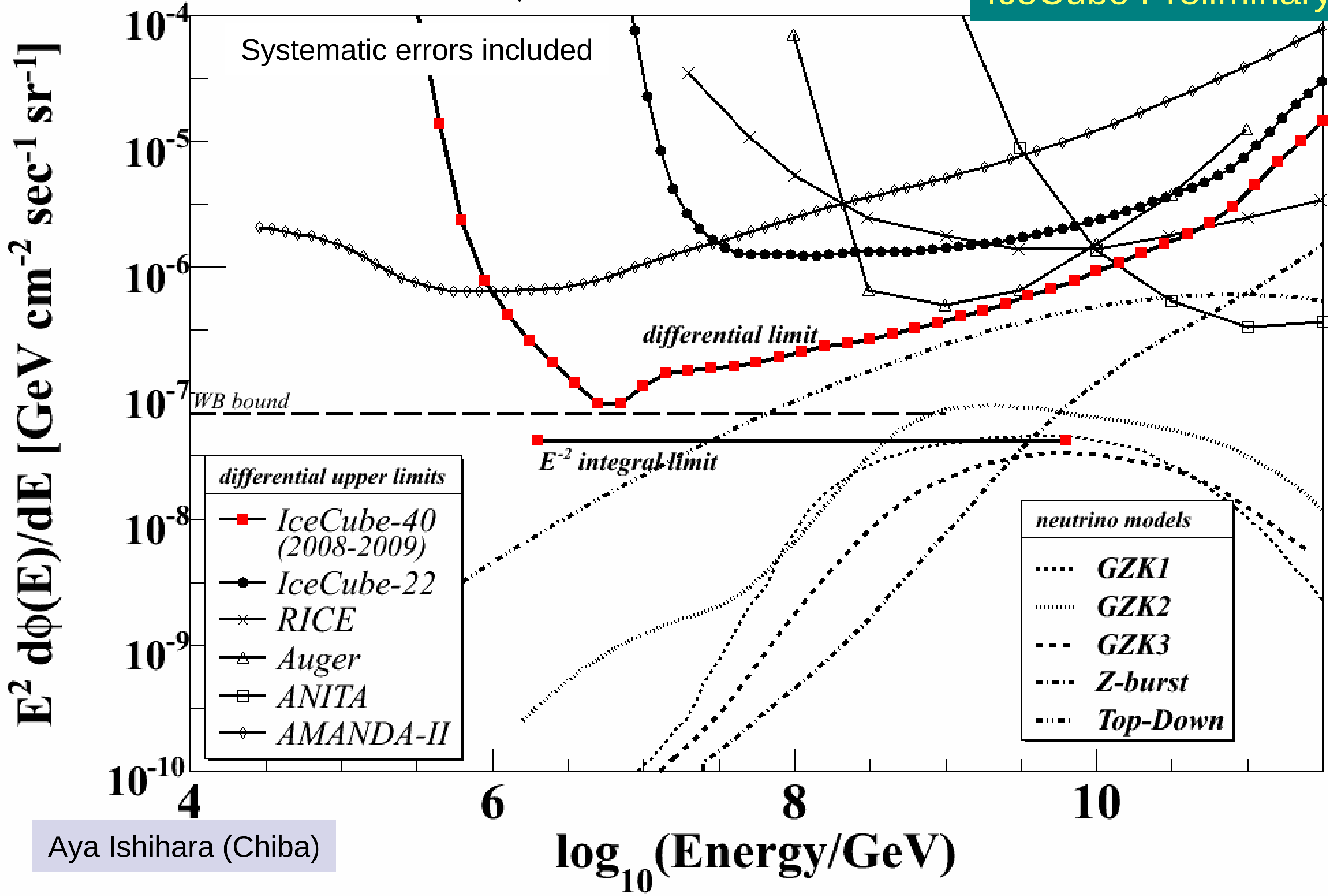
GZK 0.573 +/- 0.005 (stat.) $^{+0.080}_{-0.066}$ (sys)

Aya Ishihara (Chiba)

GZK ν search

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

IceCube Preliminary



Aya Ishihara (Chiba)

EHE ν Model Constraint

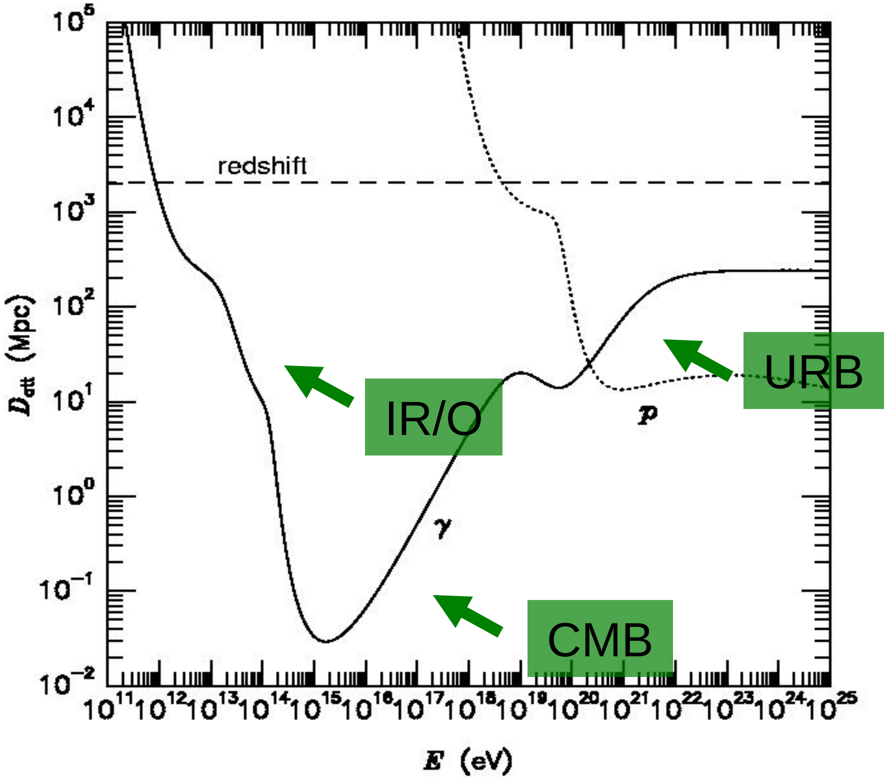
The 2008 half-IceCube observation
335.5 days sample

IceCube Preliminary

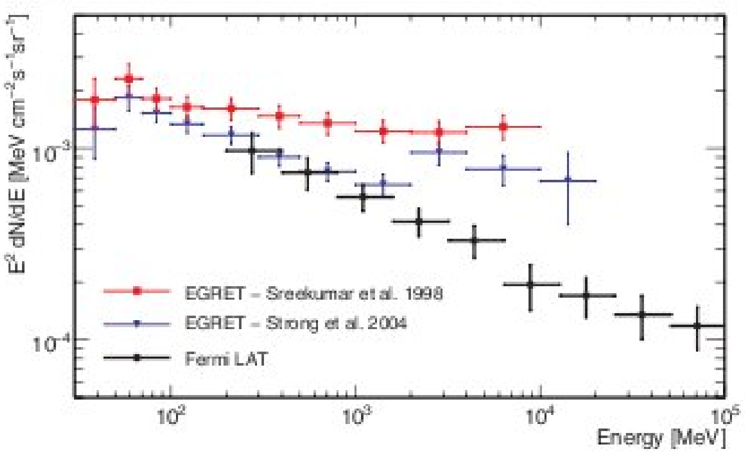
Model	Expected # of events
GZK m=4 Zmax=4 (Yoshida et al ApJ 1997)	**0.570**
GZK m=5 Zmax=2 (Kalahsev et al PRD 2002)	**0.910**
GZK Λ = 0.7 (Engel et al PRD 2001)	**0.470**
GZK Fermi constrained m=4.45 (Ahlers et al AstroP 2010)	**0.885**
GZK Fermi constrained γ=2.5 (Ahlers et al AstroP 2010)	**0.431**
Z-burst (Yoshida et al PRL 1998)	**1.027**
Top-down SUSY (Sigl et al PRD 1998)	**5.677** ← excluded by 99.6 % C.L.

Constraints on Ultra-high energy cosmic ray emission

Fermi limits UHECR luminosity at cosmological distances



Fermi-LAT collaboration PRL 2010

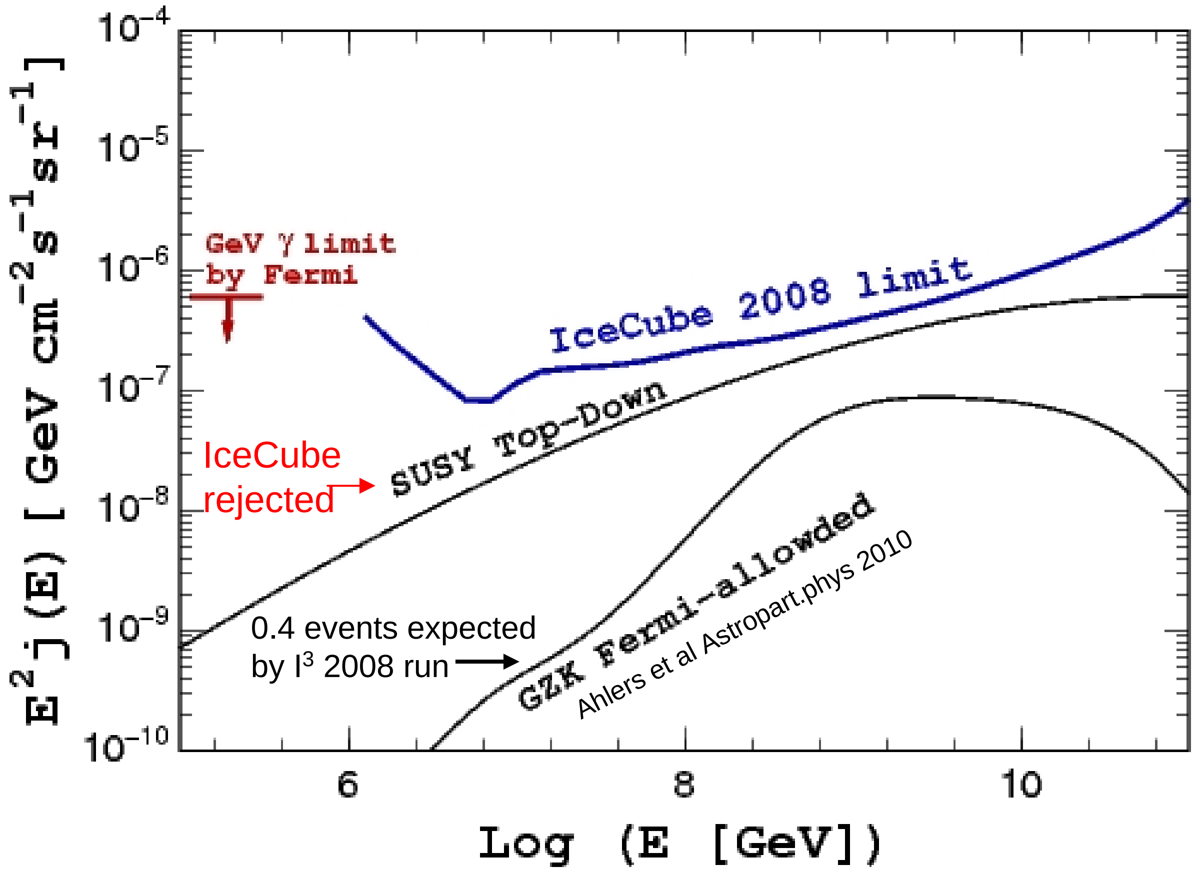


Energy Conservation

$$E^2 \frac{dN}{dE}\Big|_{EHE} \longmapsto E^2 \frac{dN}{dE}\Big|_{GeV}$$

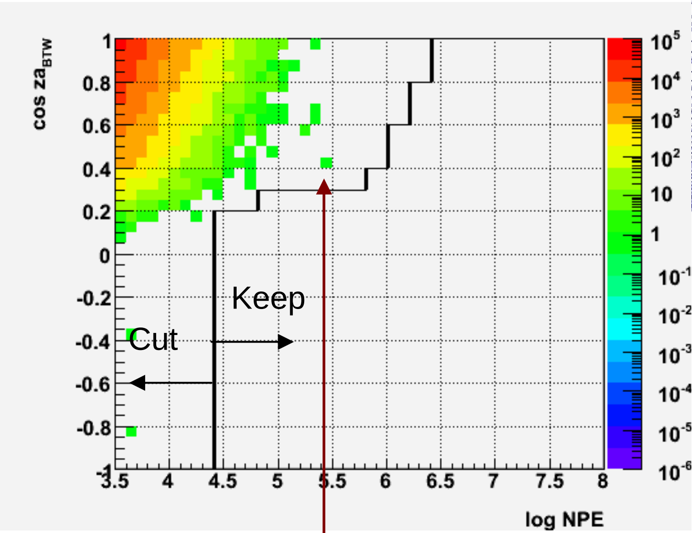
Constraints on Ultra-high energy cosmic ray emission

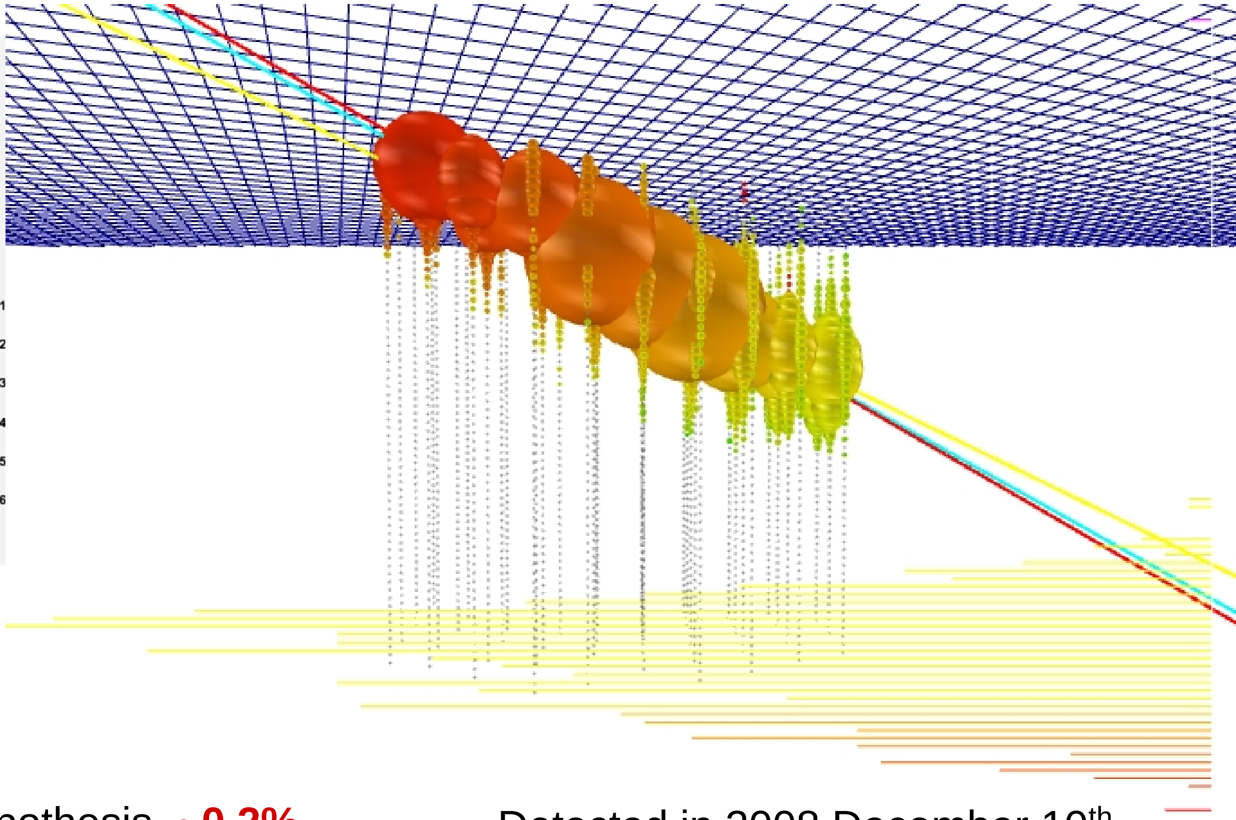
Now IceCube : constrained UHECR cosmological luminosity at the comparable level with Fermi, ***but more direct way***



A major fraction of the Fermi diffuse γ is <u>*NOT*</u> responsible for UHECR emissions

The Highest NPE event





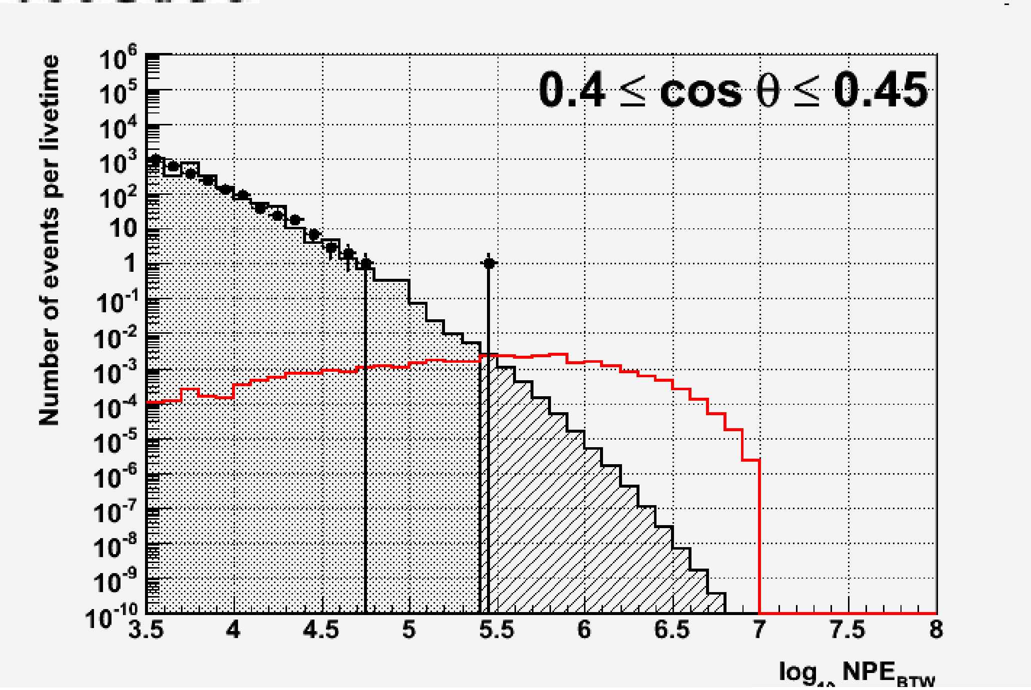
This event

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

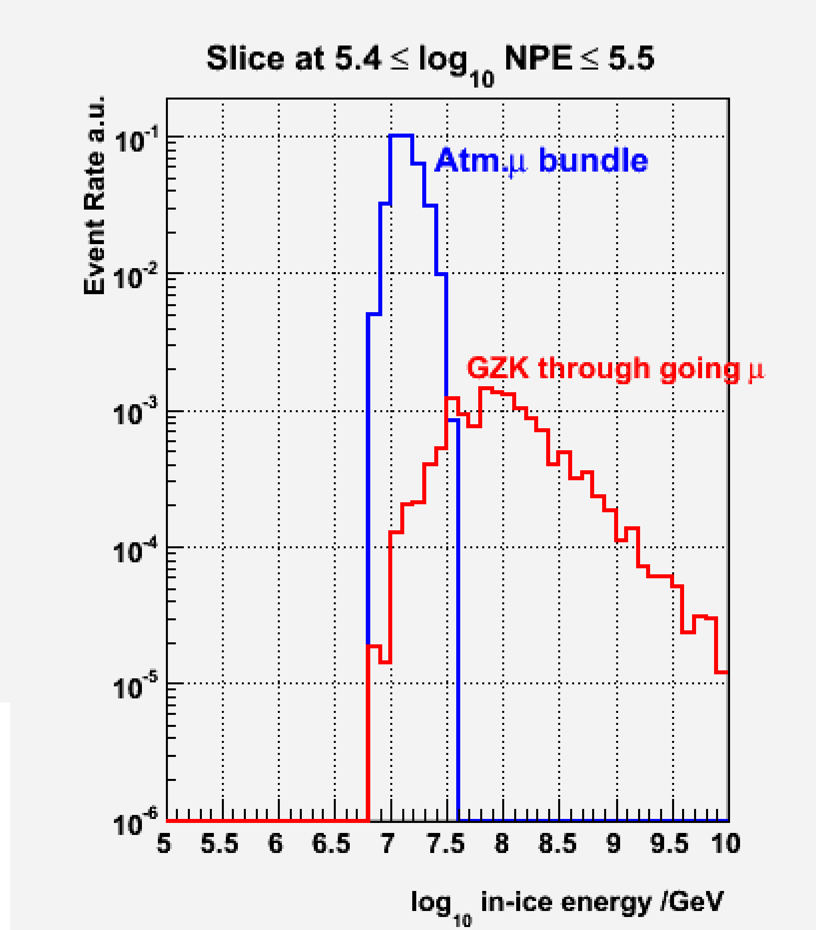
- Detected in 2008 December 10th
- NPE 2.55×10^5 photo-electrons
- Zenith 64.7 deg

Aya Ishihara (Chiba)

The Highest NPE event



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



~ 10 PeV if background
~ 100 PeV if (GZK) ν

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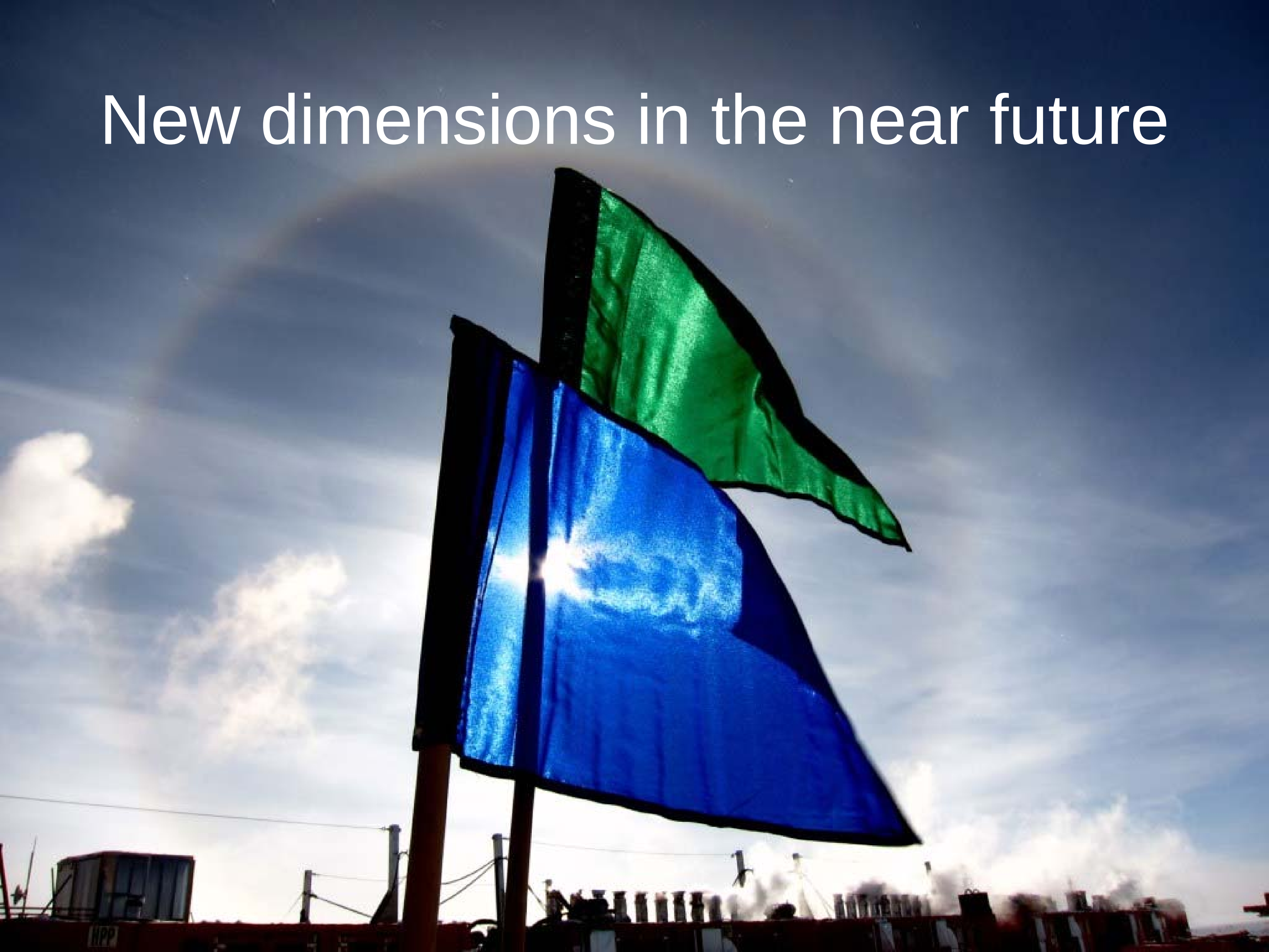
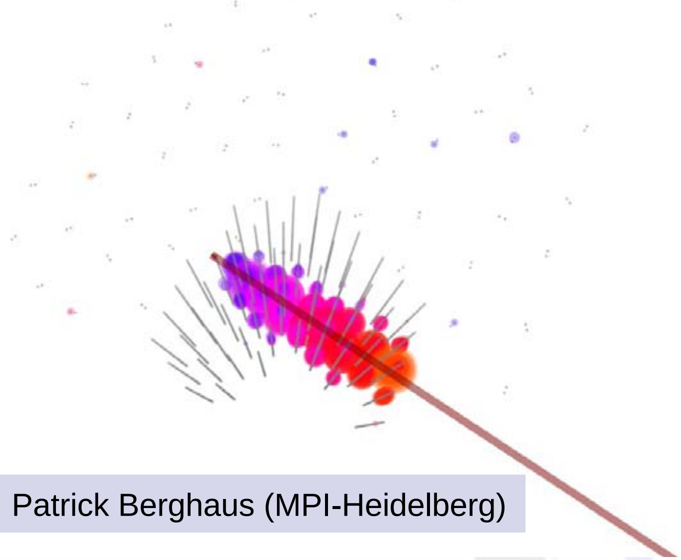
New dimensions in the near future



New dimensions in the near future

hybrid analysis with IceTop



Patrick Berghaus (MPI-Heidelberg)

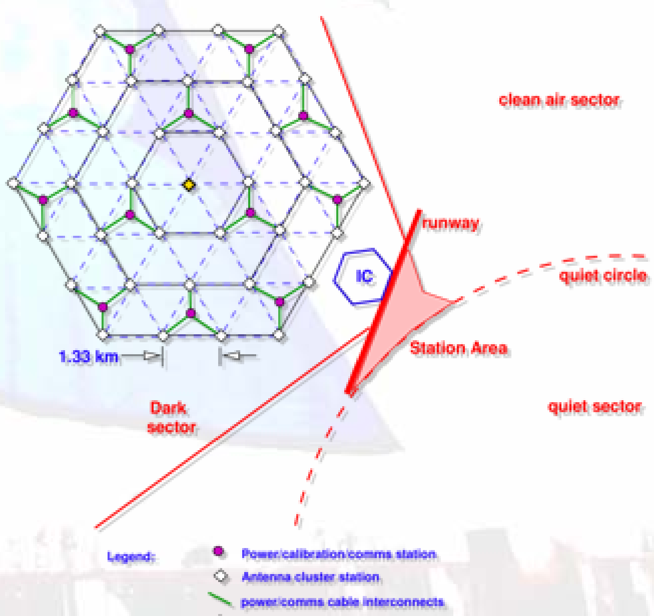
More multi-messenger analysis coming

- Gamma-ray follow-up
- Optical follow-up
- Correlations with UHECRs

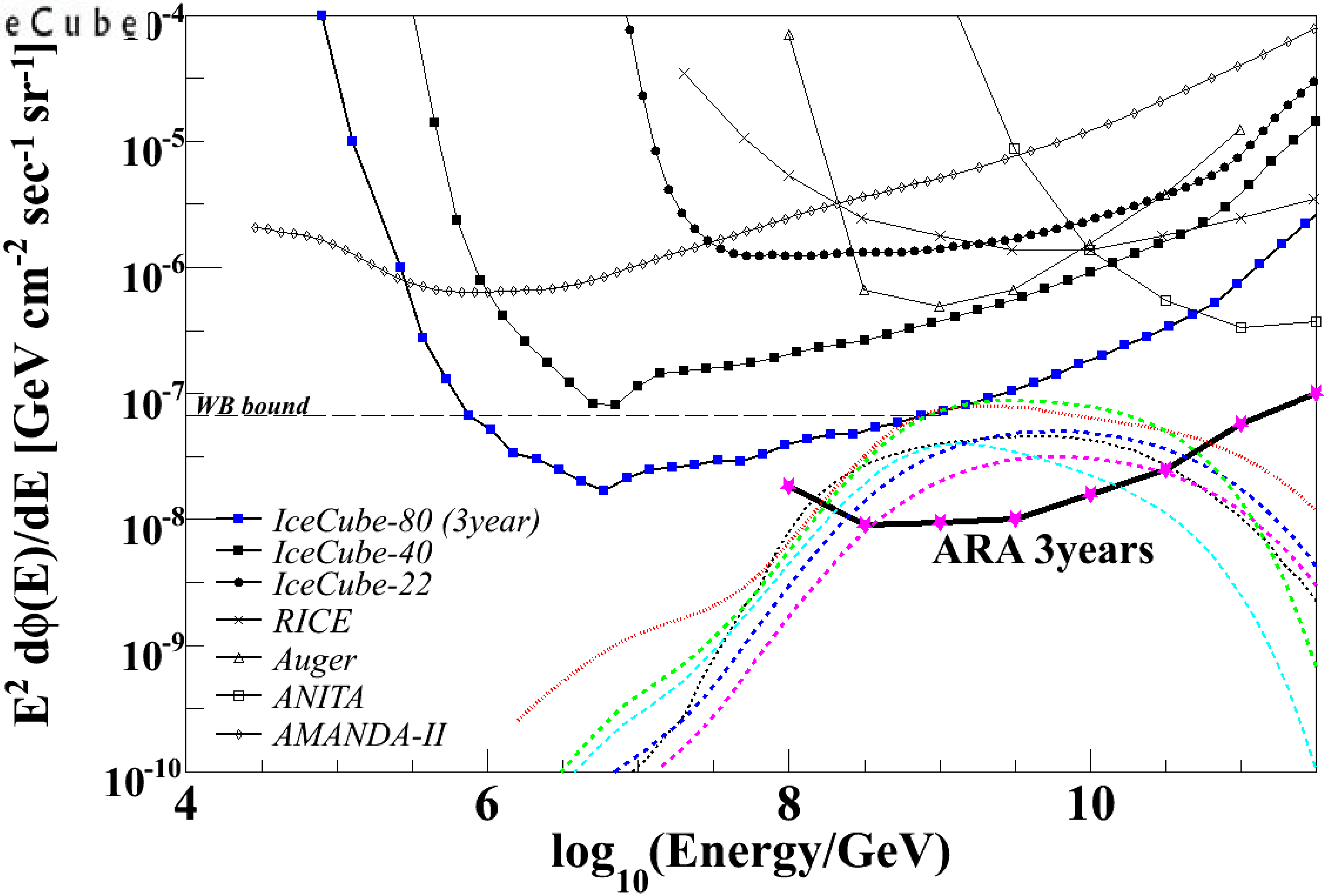
} On-going

- Extremely-high energy event alert

Askaryan Radio Array



We will reach this level



Conclusion

- A half of full IceCube with 1 year operation has already led to the world-best flux limit.

  The 2008-9 run has marked….

✓ the limit below the theoretical bound @ O(100 TeV)

✓ GZK rate O(0.5 events) → started to constrain UHECR sources

✓ rejection of the top-down scenarios

Obviously, *more expected* in the full operation starting soon

- Some interesting stuff observed; stay tuned.

✓ correlations with Milagro/Fermi SNRs

✓ The very high energy μ events

And we are getting even more bigger

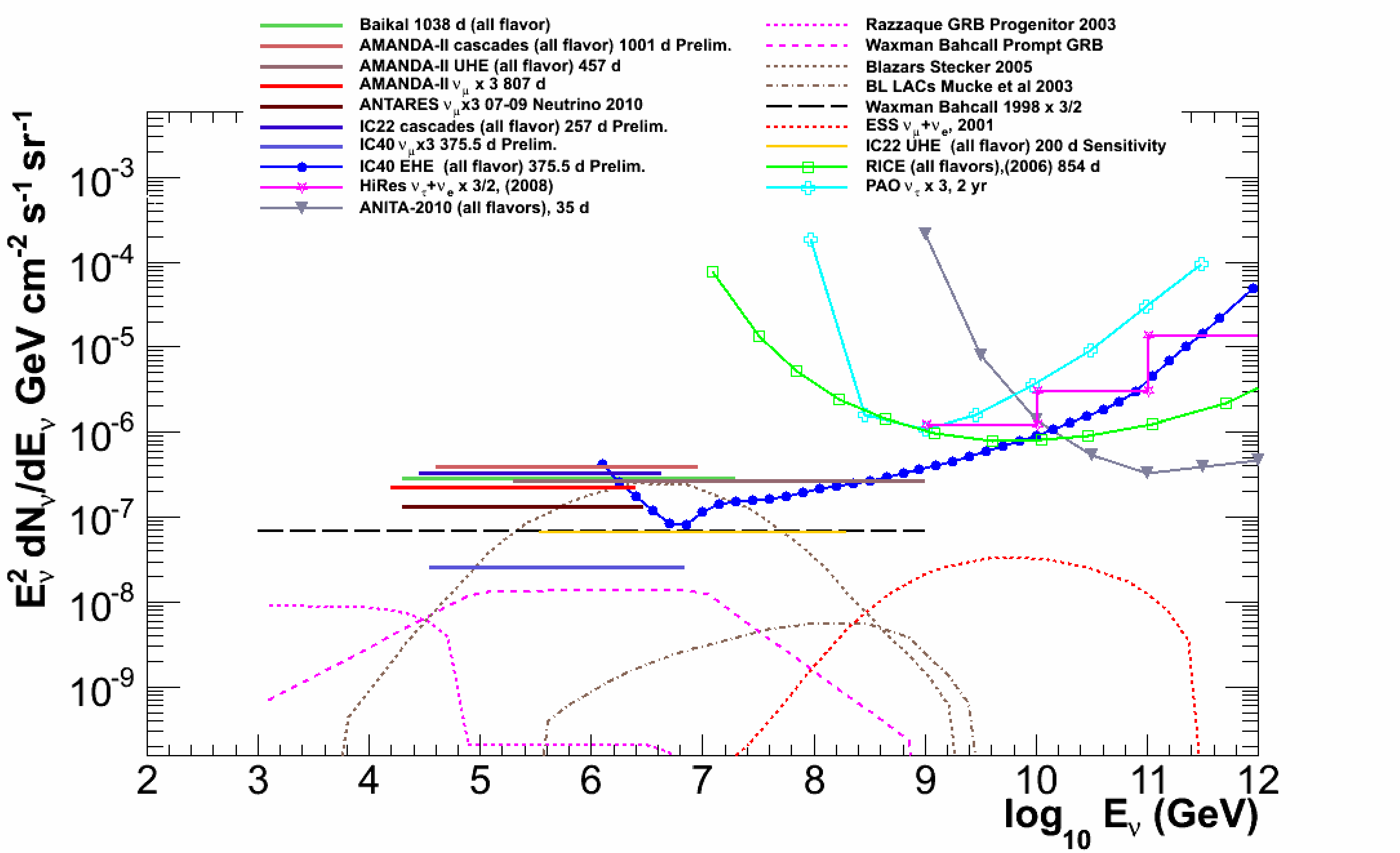
The main contributors

- (Time-independent) Pont Source
  Jon Dumm, Chad Finley, Teresa Montarulli
- Diffuse ν_μ search
  Sean Grullon, Dima Chirkin, Gary Hill
- Atmospheric ν
  Warren Whuelsnitz
- Extremely-high energy (GZK) ν search
  Aya Ishihara, Keiich Mase

Backup

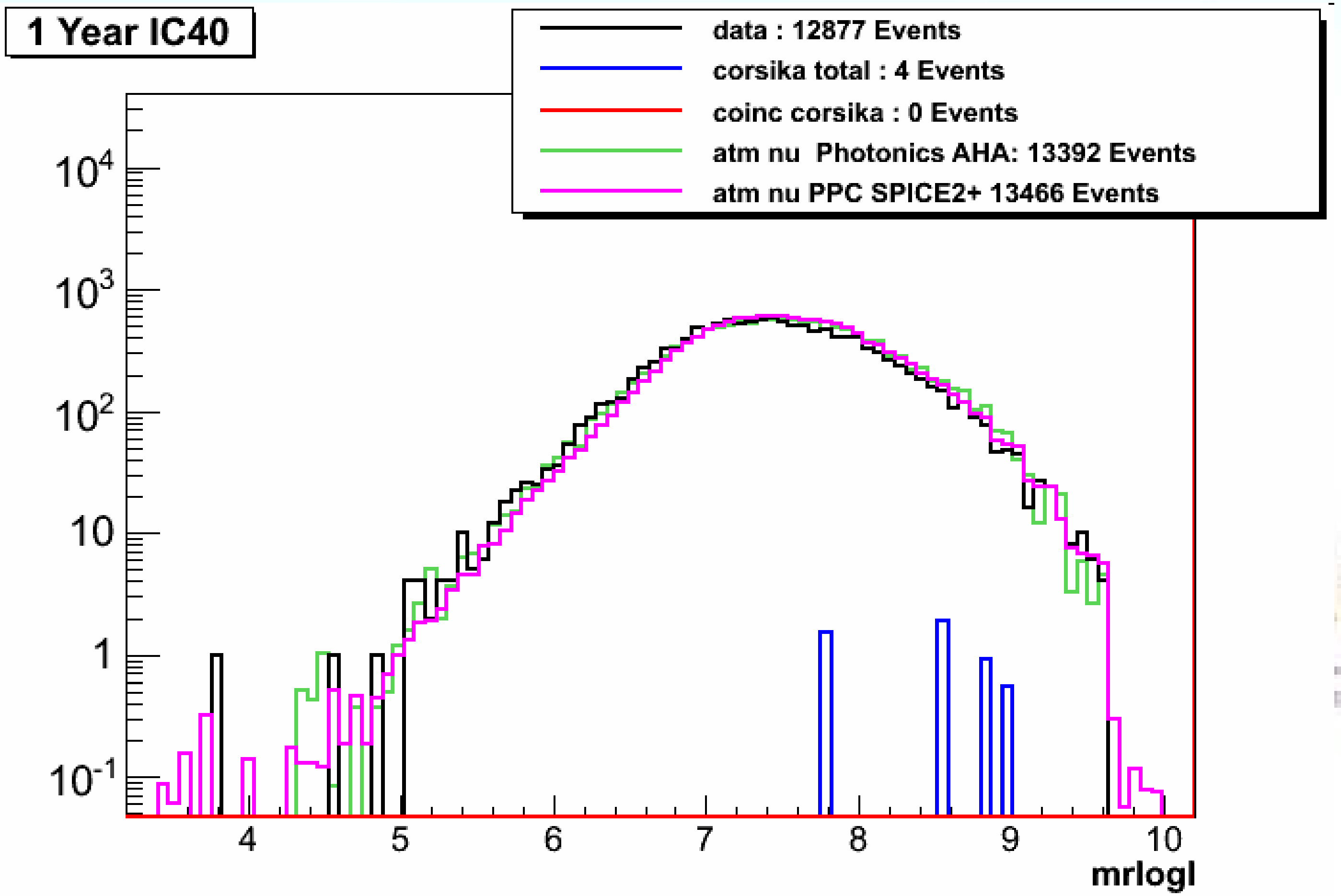
IceCube

Flux Summary



Diffuse ν search

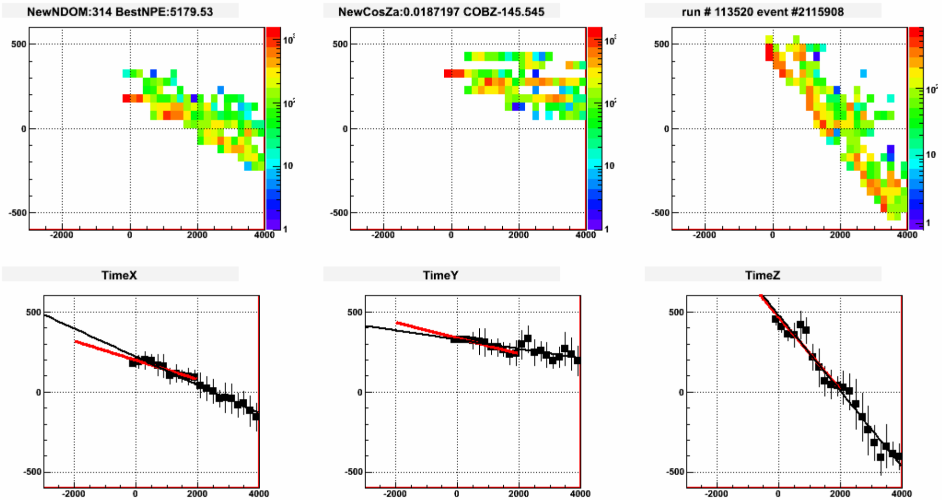
μ track likelihood distribution after the final cut

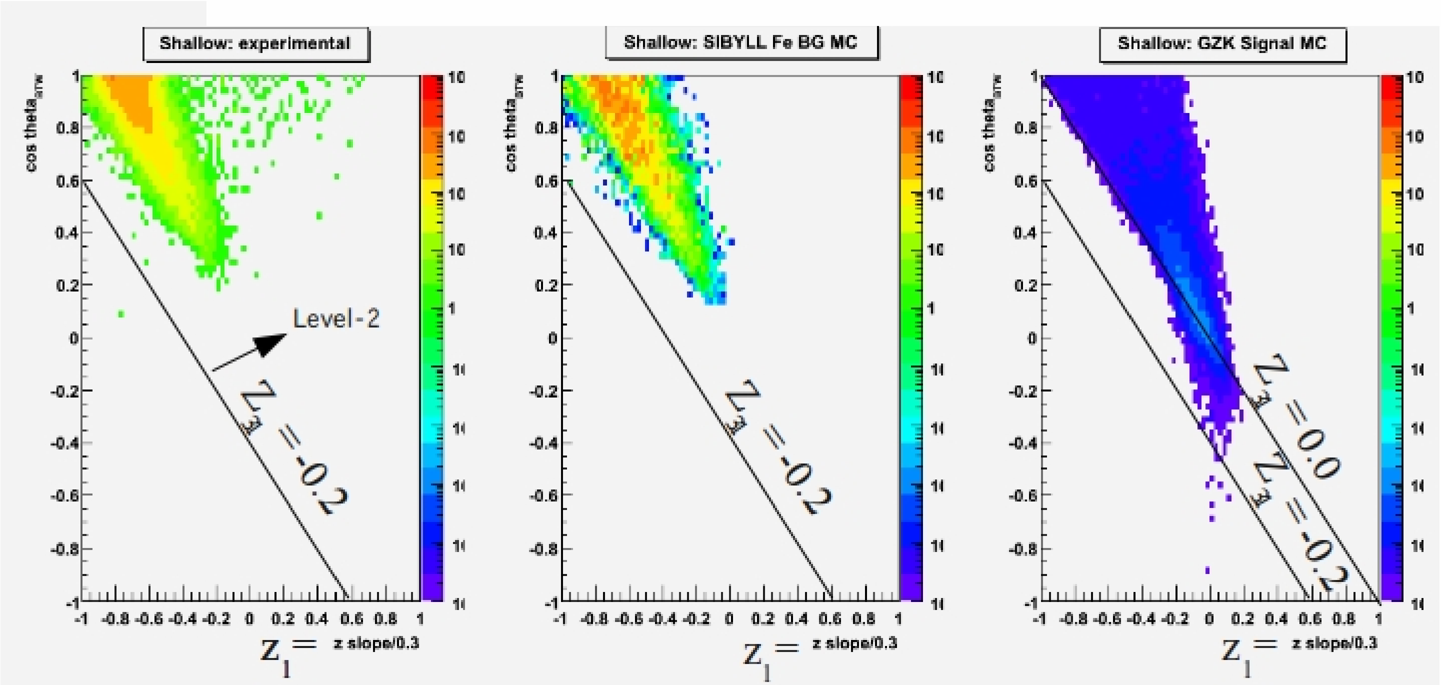


Systematic errors in the diffuse ν search

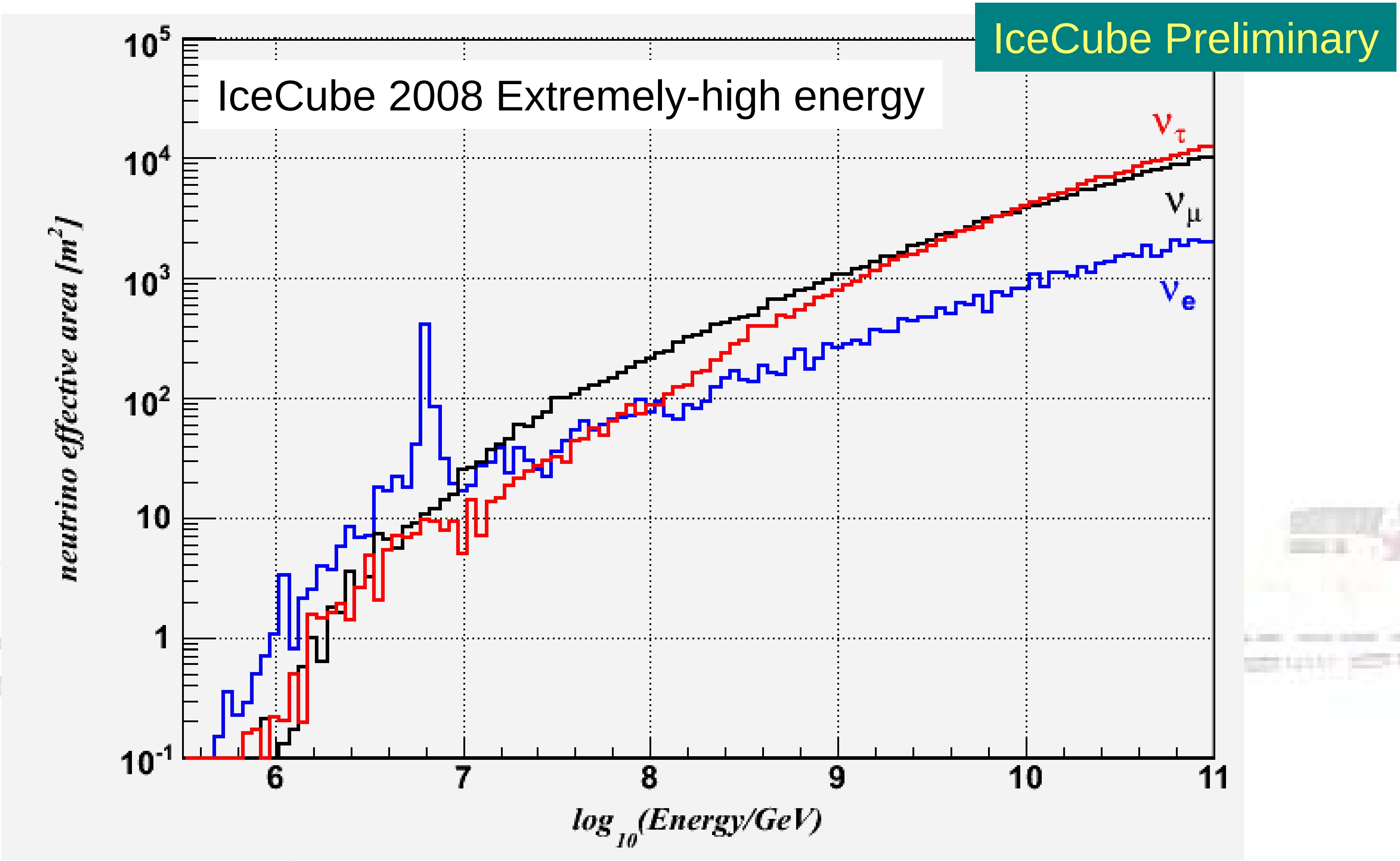
α_c	± 0.25	Honda et al, PRD 75, 043006 (2007)
$\Delta\gamma$	± 0.03	Gaisser, et al
α_p	$0.56 - 1.25$	Enberg, et al, hep-ph 0806
ϵ	$-30.87 - -2.16$	Kotoyo Dom Efficiency Study
$a(405)/b_e(405)$	$\pm 10\%$	Error in SPICE2+ fit
ν cross section	$\pm 3\%$	
μ energy loss	$\pm 1\%$	

Level 2 cut for shallow events





Neutrino Effective Area EHE (GZK) regime



Relative Systematic Errors in GZK (EHE) ν search

	BG rate	Signal rate
Cosmic-ray composition	-83.9 %	——
Hadronic Interaction model	+36.1%	——
Coincidence μ rate	+29.4% +10.5%	——
NPE yield	+37.1% - 46.7%	+3.9% - 7.2%
Neutrino-nucleon cross section	——	+/- 9.0%
Photo-nuclear interaction	——	+10.0%
LPM	——	+/- 1.00%
TOTAL	**+60.4% -96.0%**	**+14.0% -11.6%**