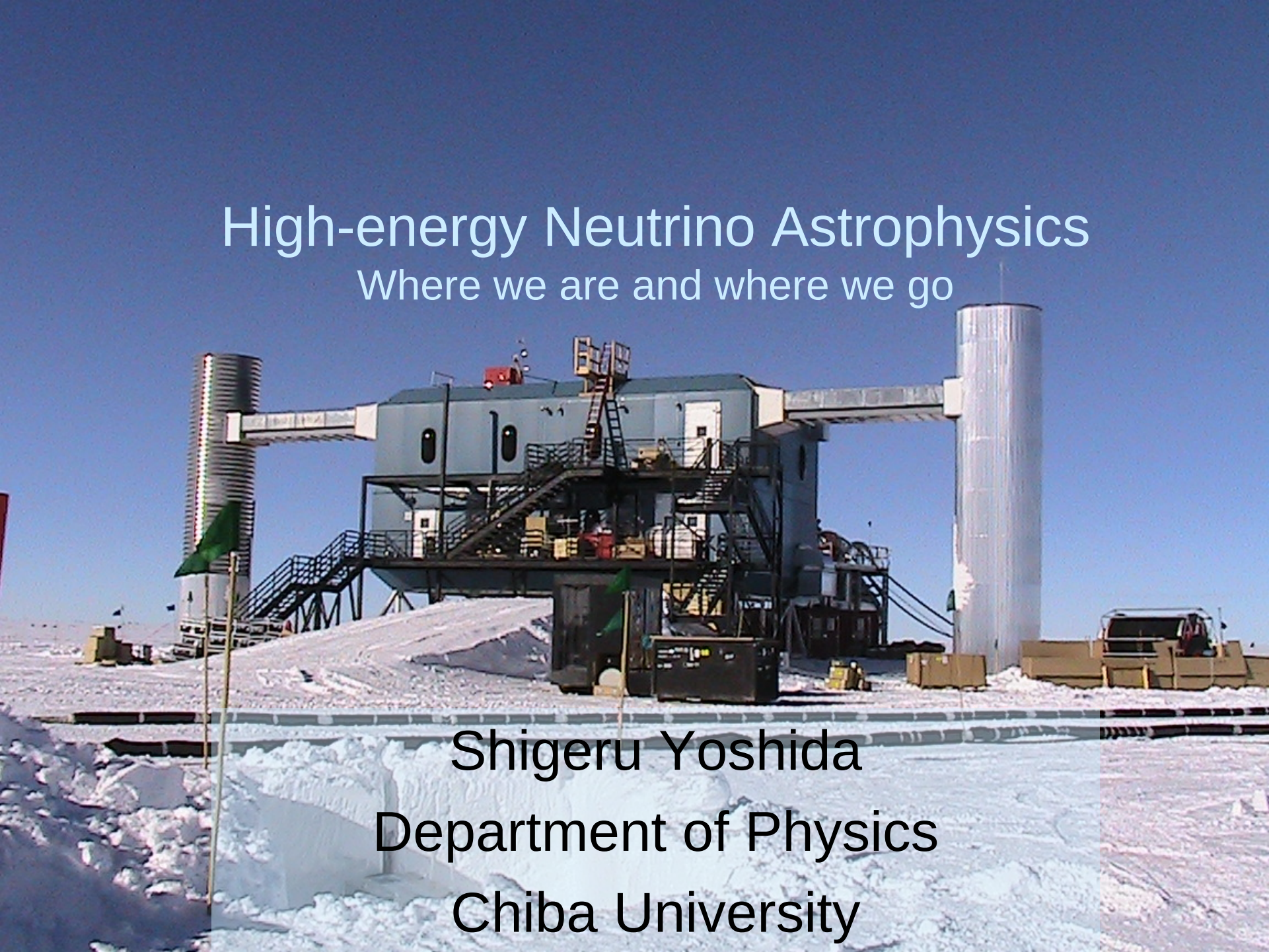
High-energy Neutrino Astrophysics

Where we are and where we go



Shigeru Yoshida

Department of Physics

Chiba University

The content

- The recent results from IceCube (UHECR-related)

  The project status
  Time-integrated ν point source search
  Search of ν from GRBs
  Correlation search with UHECRs (Auger/HiRes)
  Diffuse ν search (such as the GZK cosmogenic ν's)

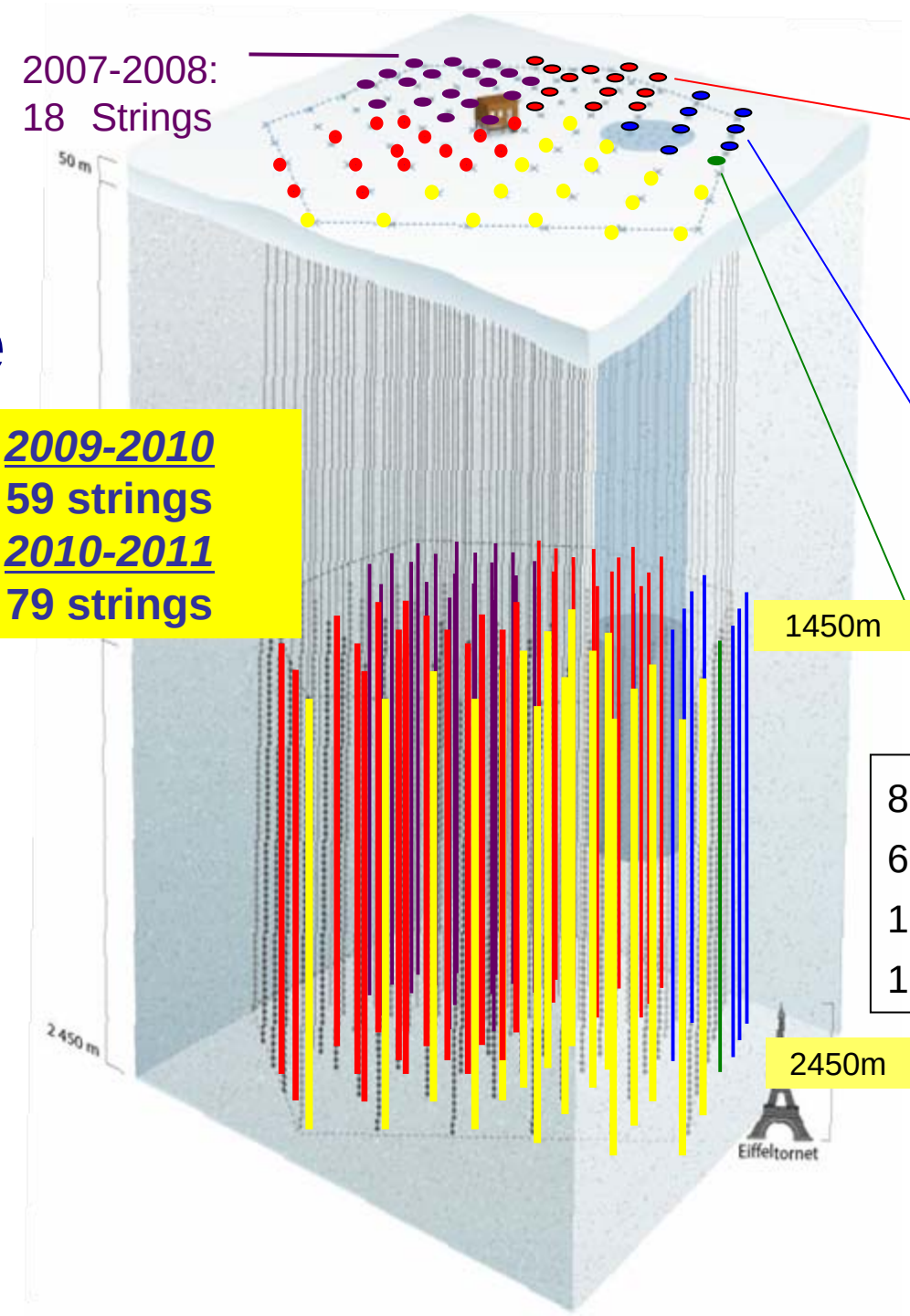
- Particle physics @ UHE region

  Constraints on $\sigma_{\nu N}$ @ $\sqrt{s} = O(10\,\mathrm{TeV})$

- Future prospective

  IceCube full-scale run
  ARA

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

2004-2005 : 1 String

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

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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
- Ruhr-Universität Bochum

Switzerland:
- EPFL

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

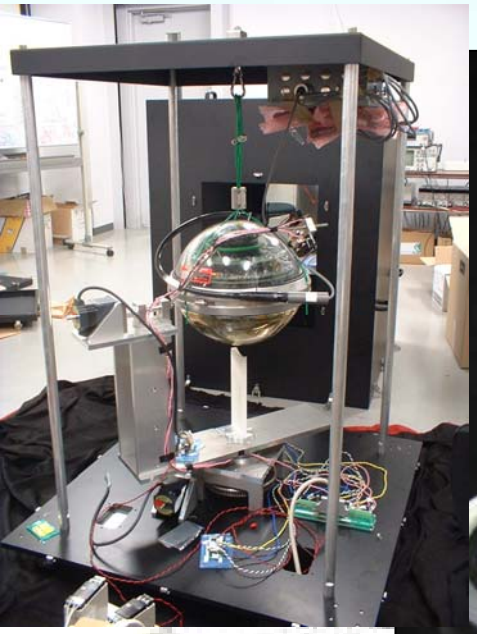
Japan:
- Chiba University

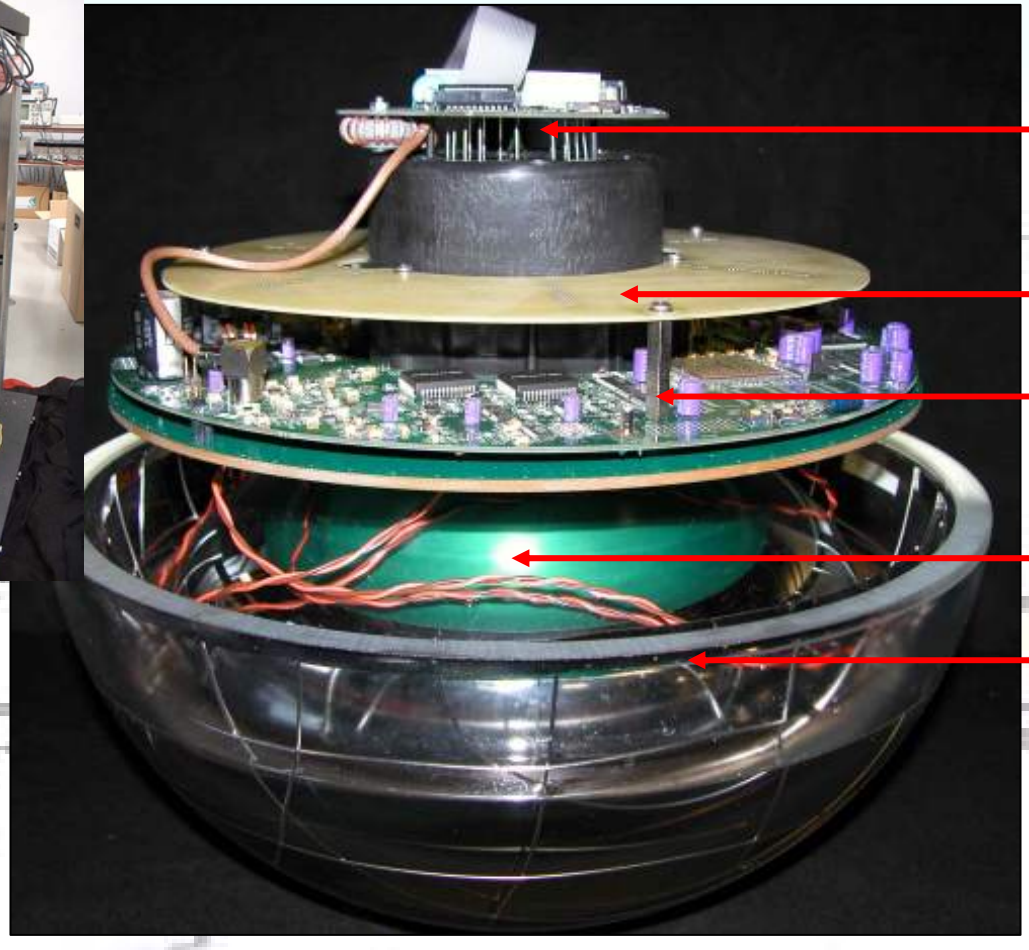
New Zealand:
- University of Canterbury

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

Cascade Filter
selects
"cascade"-like events

~17 Hz

Many others

Min Bias
Moon
IceTop
etc

NPE > 630 p.e.

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

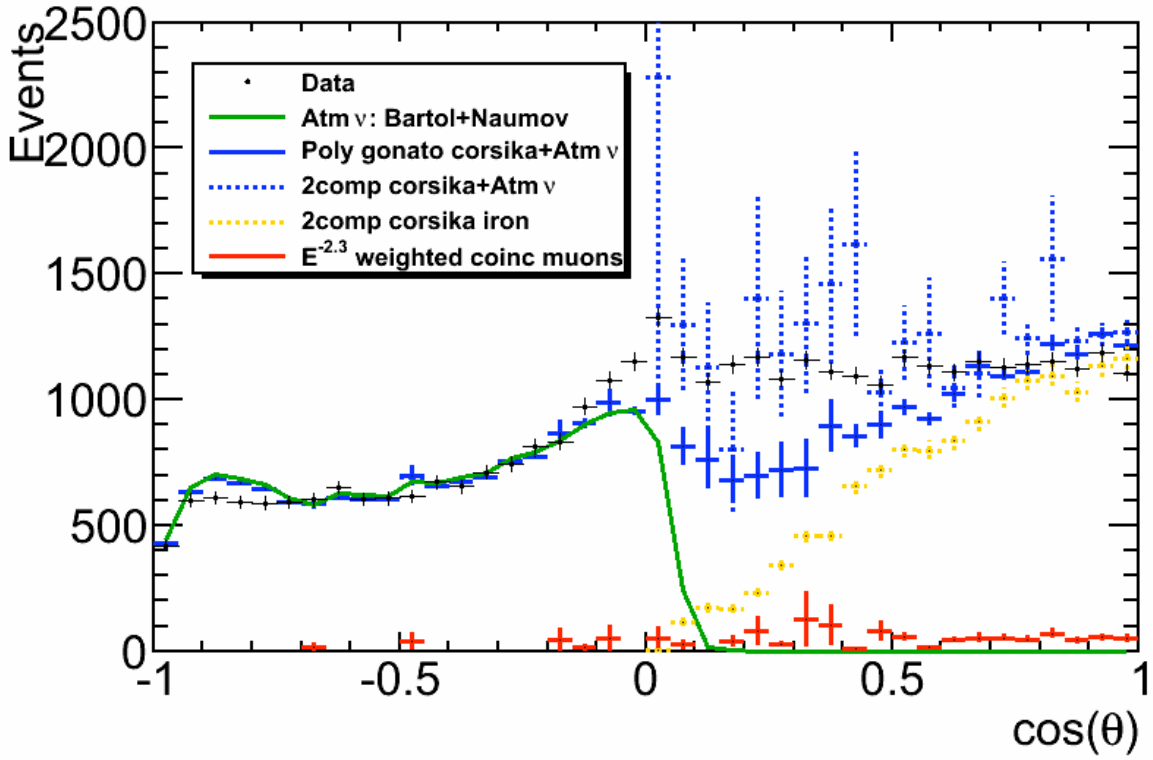
Common aspects
In many other analysis

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

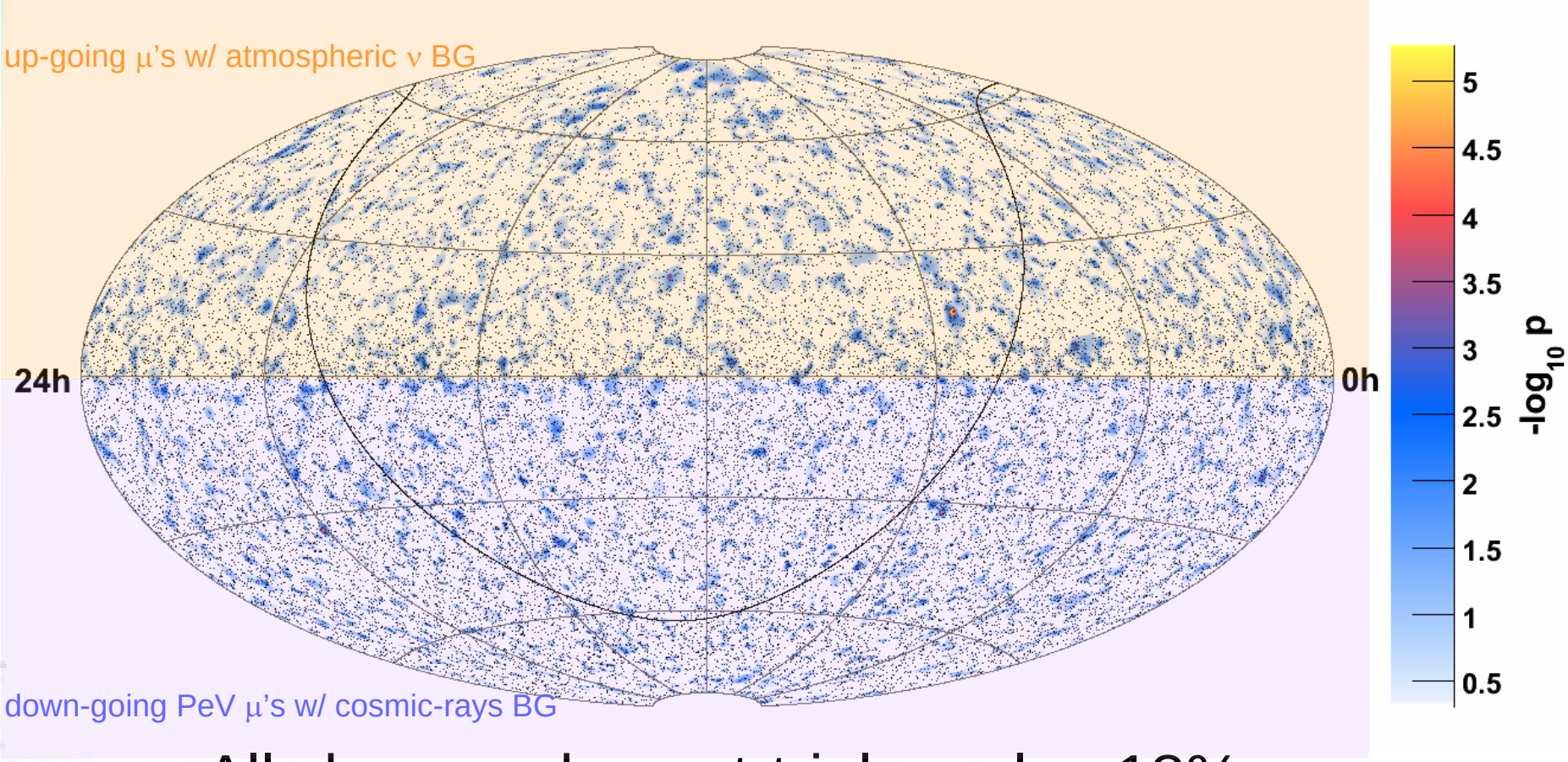
Zenith Angle Distribution in the final sample



* Introduced hard “down-going” cuts for extension to Northern sky

(retains only O(PeV) down-going events)

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)

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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

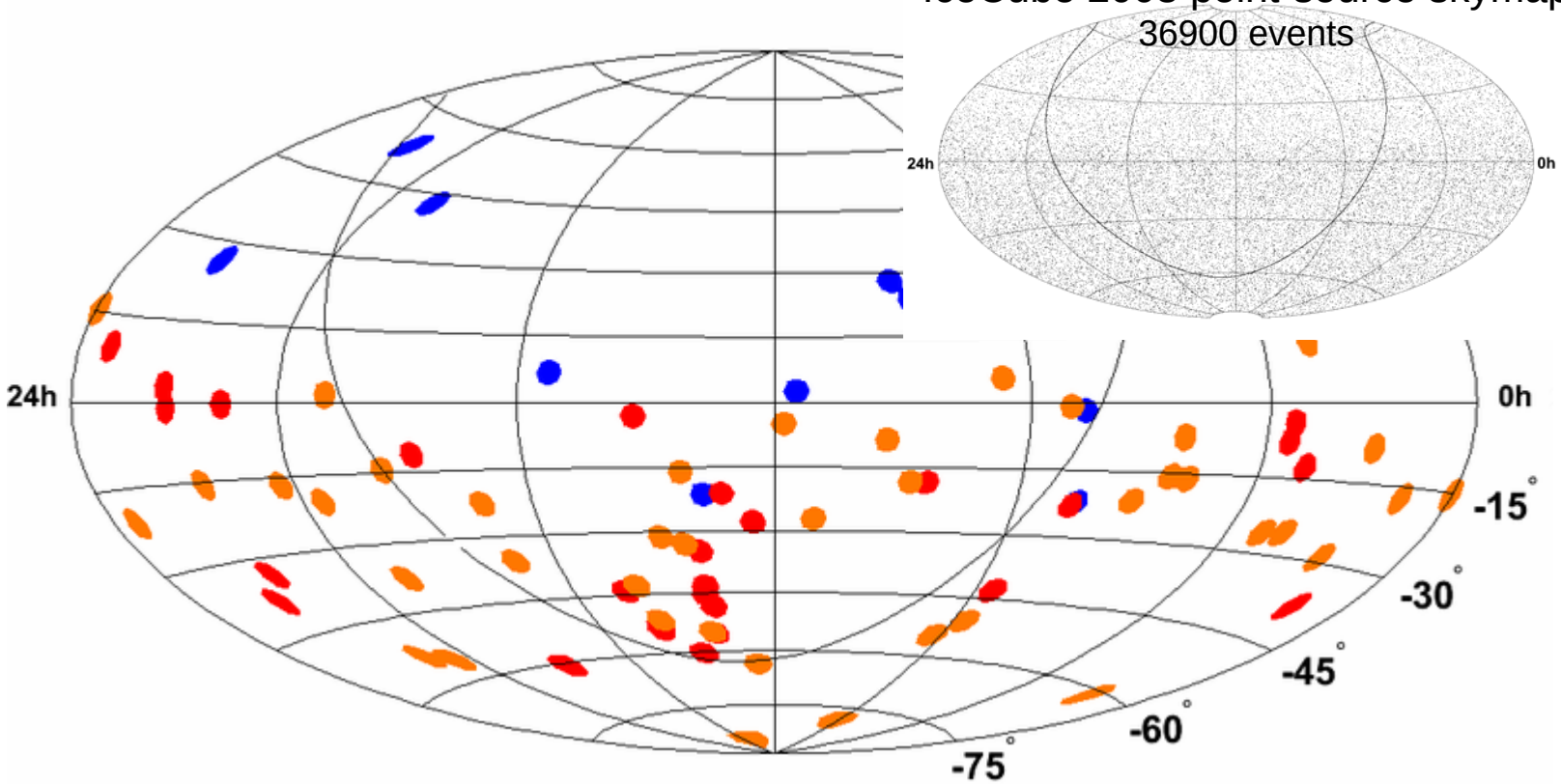
← The highest significance from list of the 39 IceCube sources

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

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

UHECR correlation analysis

IceCube 2008 point-source skymap
36900 events



- 27 events from PAO in the 2007 publication. Energy > 57 EeV
- 42 events released from PAO 2010. Energy > 57 EeV
- 13 stereo events from HiRes. Energy > 56 EeV

Robert Lauer (DESY)

UHECR correlation analysis

Correlation search optimized for
hypotheses of magnetic deflection of cosmic rays by 3 degree

J. Abraham et al (Pierre Auger collaboration) Astropart. Phys. **29** 188-204 (2008).

Unbinned Likelihood search with σ = 3 degree

IceCube Preliminary

-2(log L(signal) – log L(bg)) = 0 i.e., consistent with the background-only hypotheses

Binned search with 3 degree radius

298 IceCube events found in 82 bins of 3 deg radius

274 events expected from the background-only hypothesis

1.48 σ (p-value 0.069)

Note: ν emission is assumed here from O(TeV) extending to O(EeV)
(typically with E^{-2})
i.e., not like the GZK ν emission where main energy range is above PeV

Robert Lauer (DESY)

千葉大学
Chiba University

GRB model-dependent Search

Materials to cook

$\nu_\mu \rightarrow \mu$ base

μ filtered and EHE filtered

Require Quality cuts in multiple stages

Common aspects
In many other analysis

to filter out vastly dominated down-going muons

Zenith > 85 deg.

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

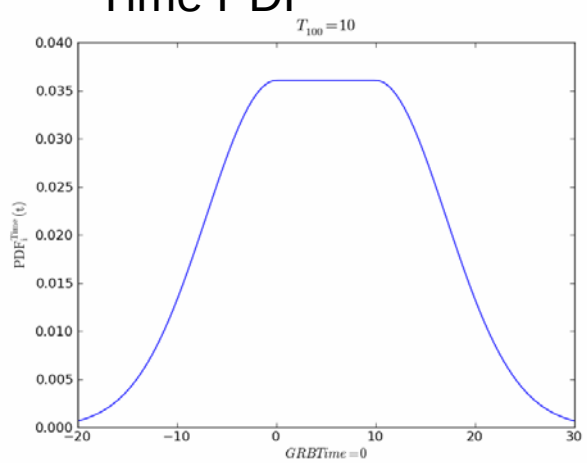
PDF

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

Total PDF

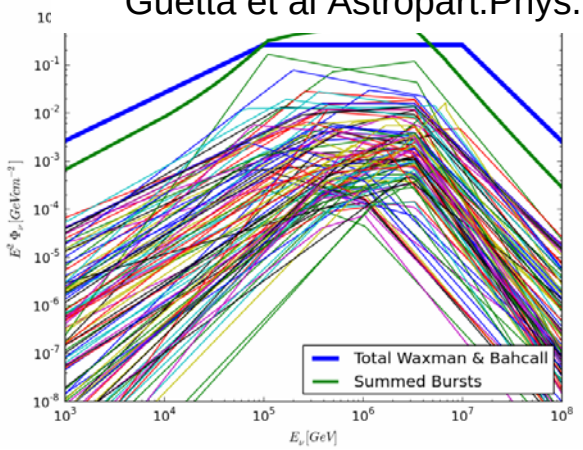
$$P_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma, n_s) = \frac{n_s}{n_{\text{tot}}} S_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma) + \left(1 - \frac{n_s}{n_{\text{tot}}}\right) B(\mathbf{x}_i, E_i)$$

Time PDF



Predicted ν spectra

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

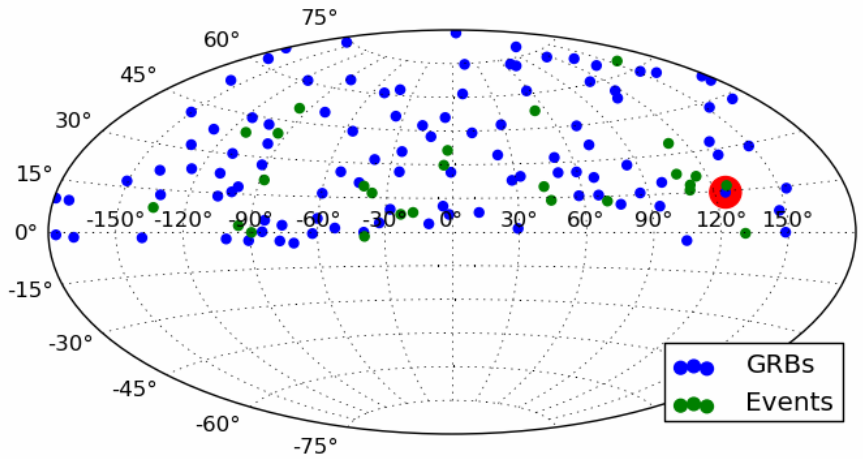


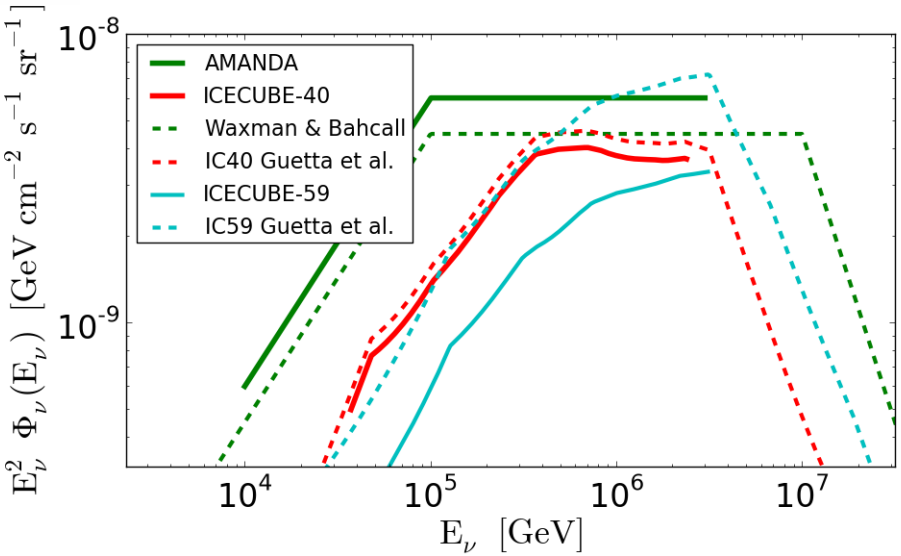
Optimize BTD score
to maximize the discovery
potential

No association of ν's with GRB..

Peter Redl (UMD)

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





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

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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

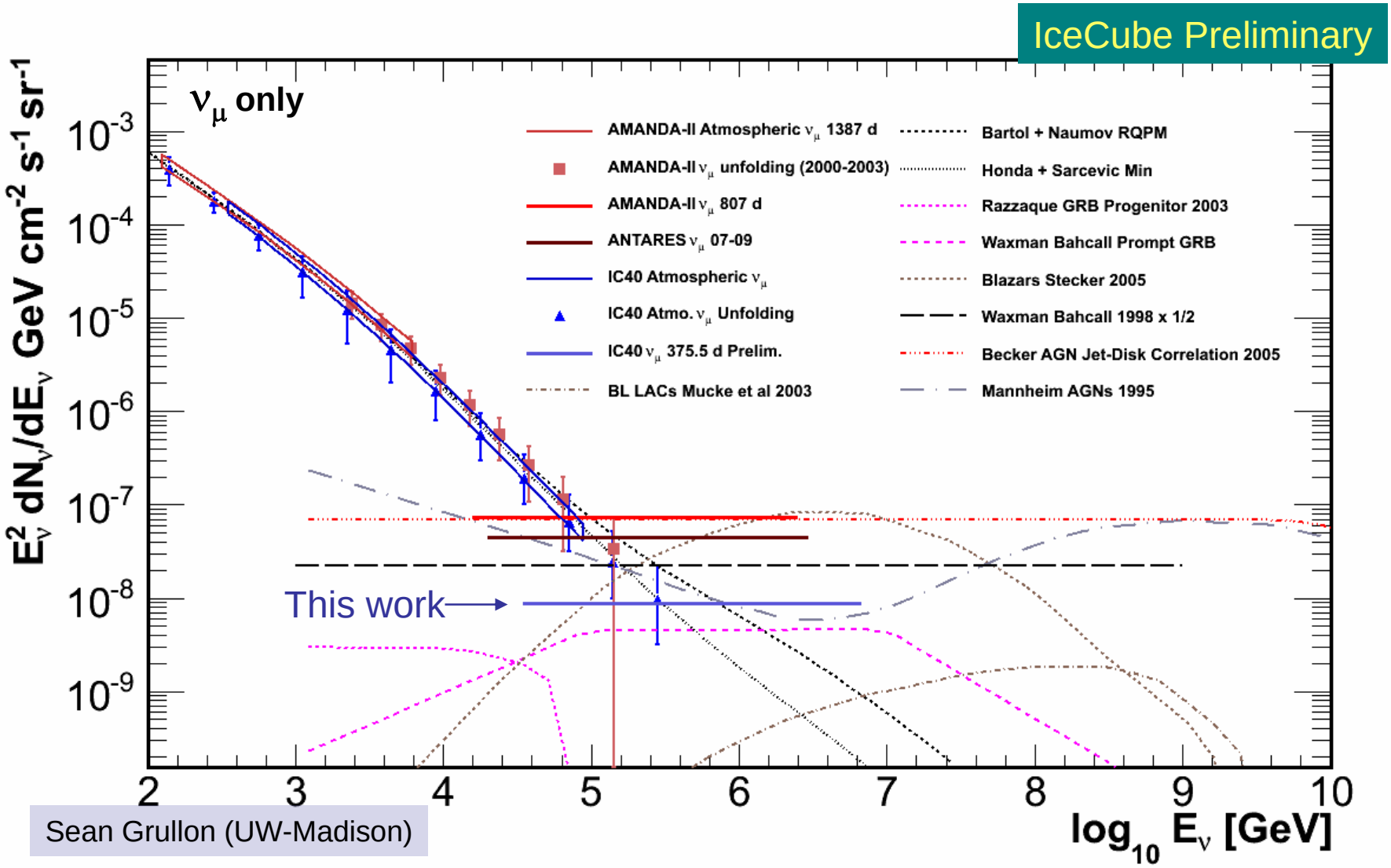
to realize reasonable agreement between MC and data

Diffuse analysis specific

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

Diffuse ν limit

Now below the Waxman-Bahcall limit



Sean Grullon (UW-Madison)

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

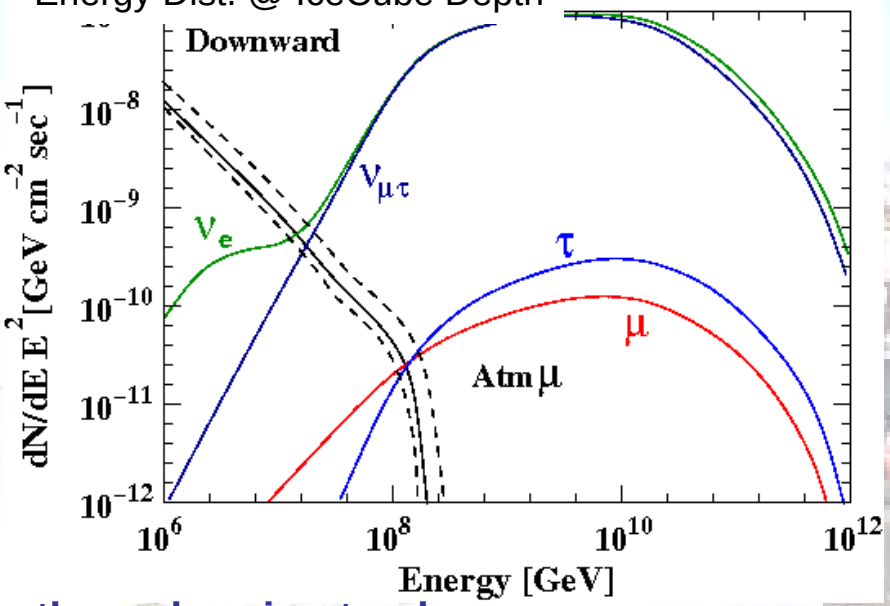
GZK analysis specific issues

- Earth filters out signal ν as well

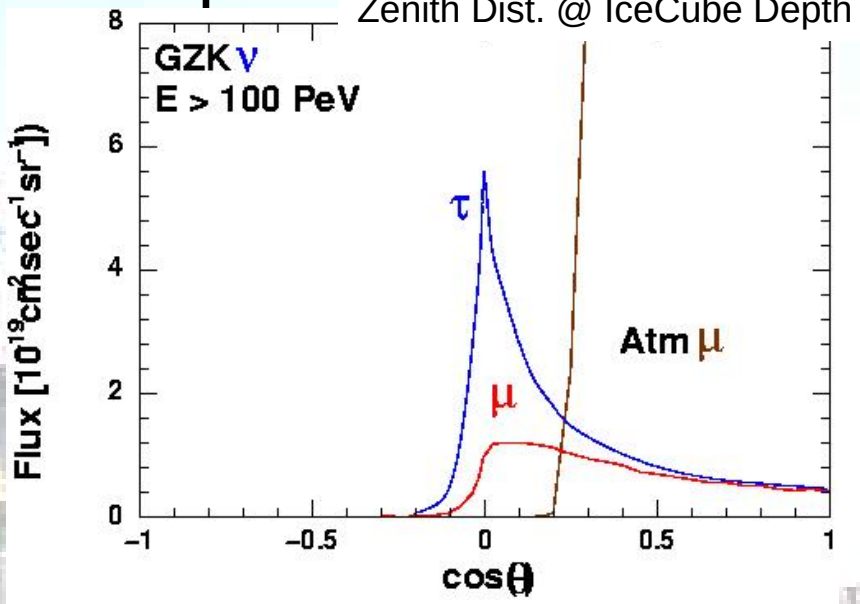
GZK ν search

Detection Principle

Energy Dist. @ IceCube Depth



Zenith Dist. @ IceCube Depth



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**

Yoshida et al PRD **69** 103004 (2004)

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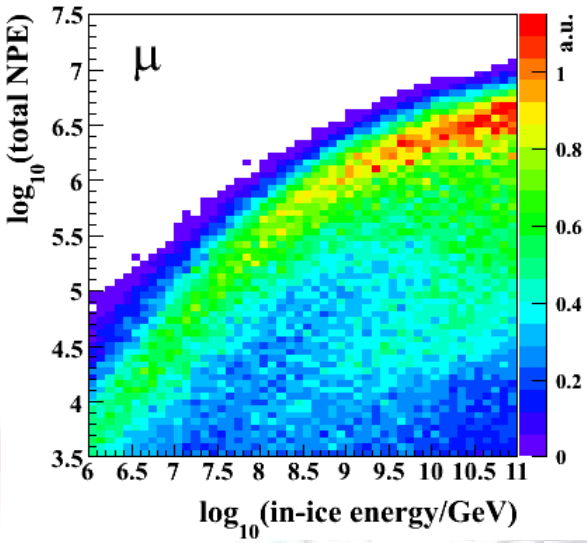
The detailed description available in
Abbasi et al PRD **82** 072003 (2010)

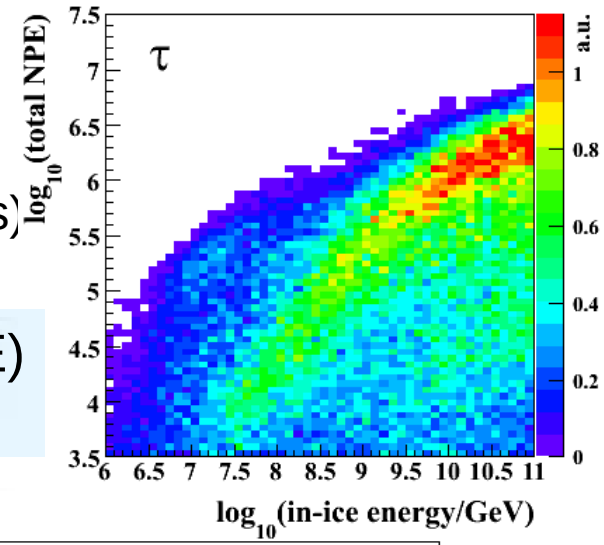
GZK ν search

Detection Principle

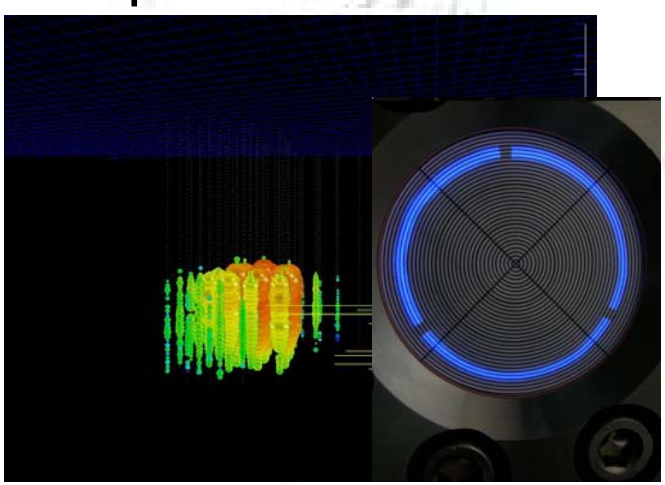


Energy
→ NPE (total # of photoelectrons)

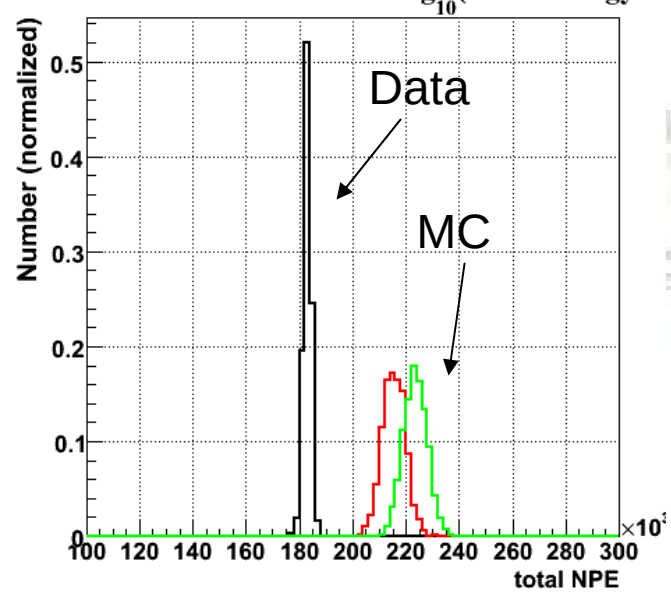
Look for luminous (high NPE) horizontal events



Experimental verification



MC overestimates NPE by ~18%
↓
Sys. error
~ 7% in SIG rate
~ 50% in BG rate



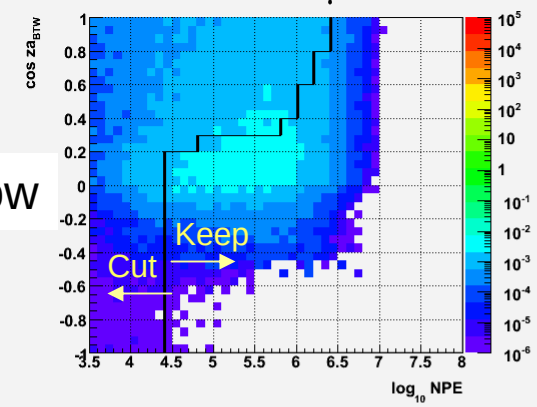
GZK ν search

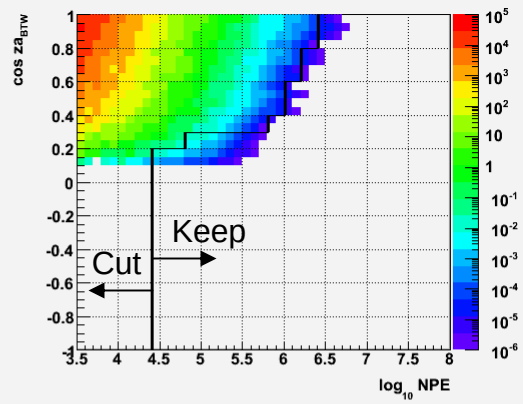
Final level 3 cut

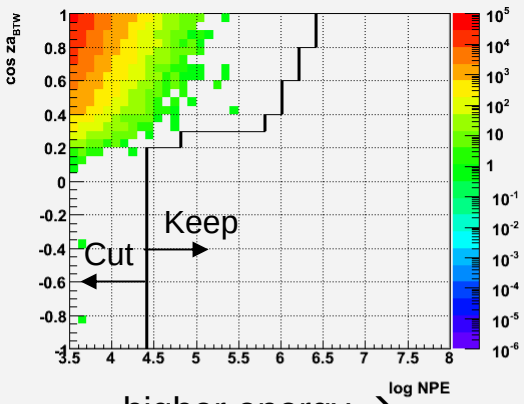
Selects bright(=high NPE) events penetrating long path from the earth surface

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

Shallow

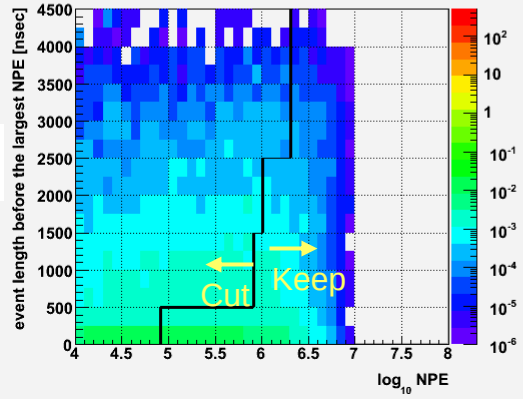


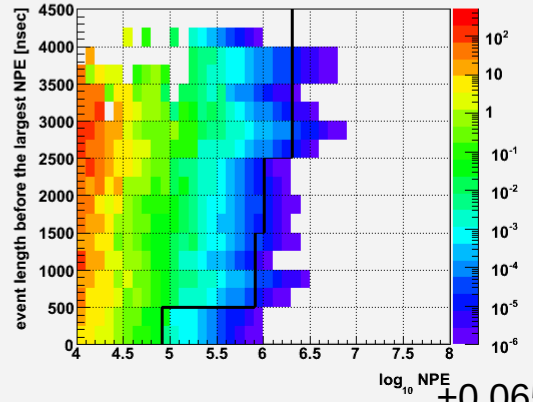


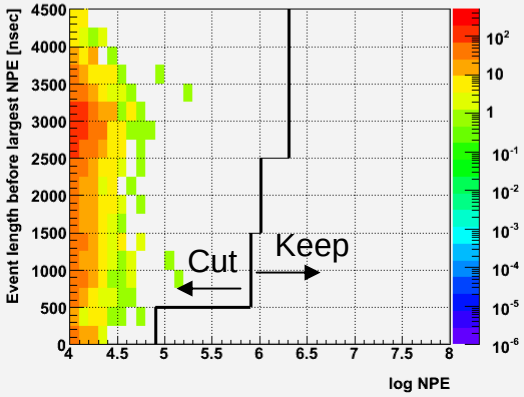


higher energy → | higher energy → | higher energy →

Deep







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)

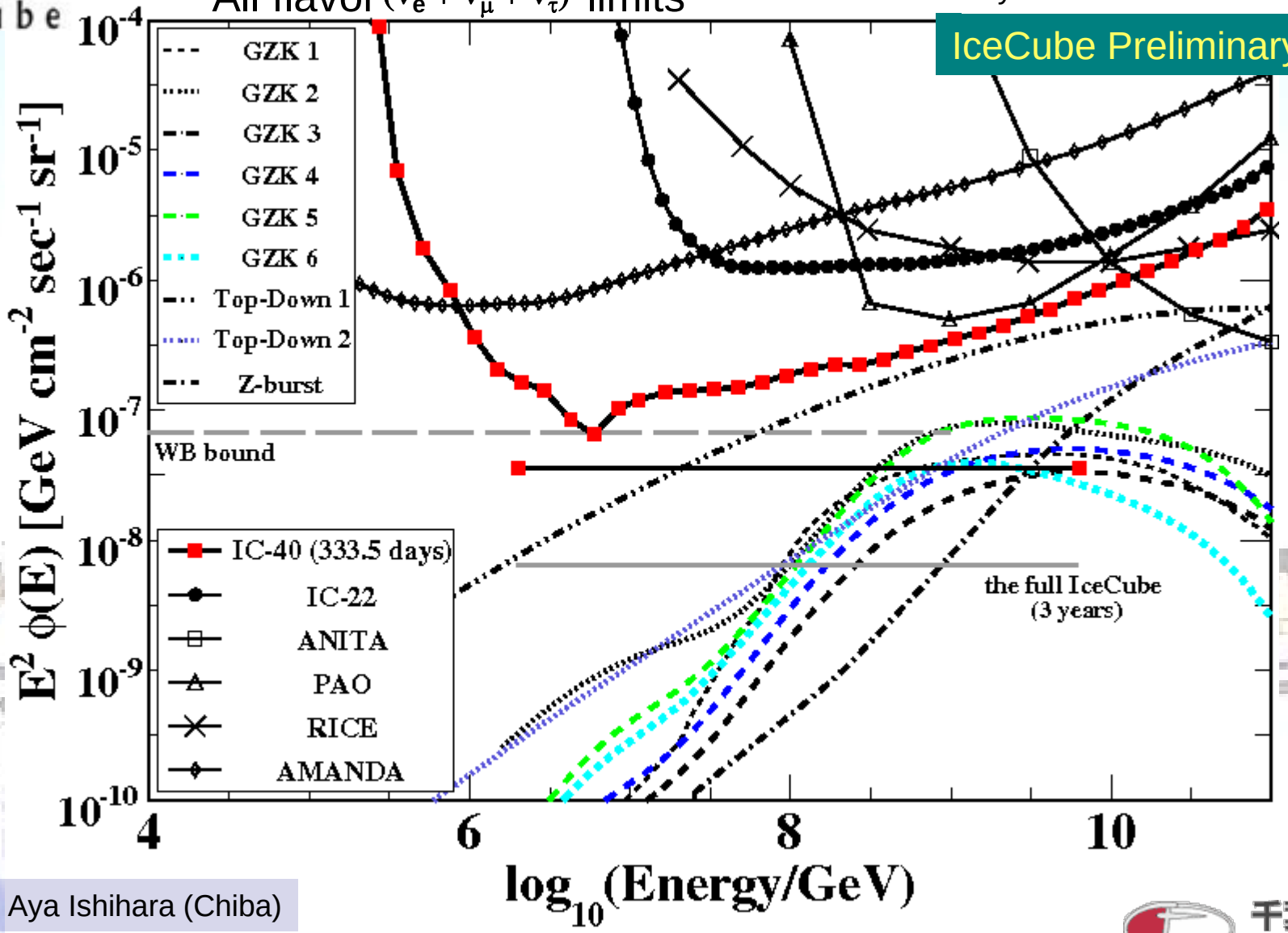
千葉大学 Chiba University

GZK ν search

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

Systematic errors included

IceCube Preliminary



Aya Ishihara (Chiba)

千葉大学
Chiba University

EHE ν Model Constraint

The 2008 half-IceCube observation
335.5 days sample

IceCube Preliminary

		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.

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Chiba University

Relative Systematic Errors

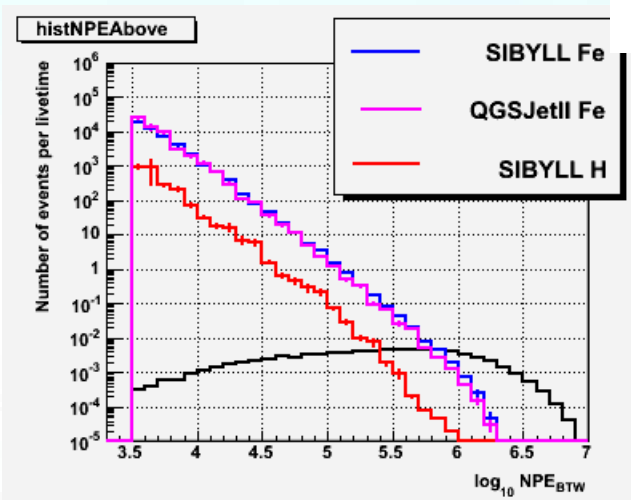
Aya Ishihara (Chiba)

Contributions to signal error	ratio in signal event rate (for the case the model GZK2 below)
statistical error	±0.8 %
Uncertainty (+10.1/-21.1%) in NPE measurements (in-situ calibration: -18.5% and in-lab calibration: ±10.1%)	+3.89 / -7.22 %
neutrino cross section	±9.0 %
photo-nuclear interaction	+10.0 %
LPM effect	±1.0 %
total	± 0.8 % (stat.) + 14.0 - 11.6 % (sys.)

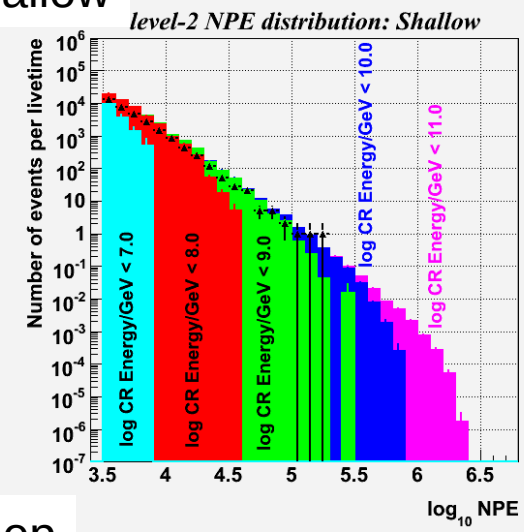
Contributions to background error	ratio in default background event rate (SIBYLL, IRON, AHA)
statistical error	±17.0 %
model uncertainty: composition = (N event H - N event Fe)/N event Fe	-83.86%
model uncertainty: interaction model = (N event QGSJETII - N event SIBYLL)/N event SIBYLL	+36.1%
coincidence simulation (cos theta>0.2) (N event coinc MC - N event bare mu MC)/N event bare mu MC	+29.4%
coincident data (cos theta<0.2) (N event coinc data - N event single mu data)/N event single mu data	+10.5%
ice property = (N event SPICE-I - N event AHA)/N event AHA	+30.2% / - 22.2%
Uncertainty (+10.1/-21.1%) in NPE measurements (in-situ calibration: -18.5% and in-lab calibration: ±10.1%)	+37.1% / -46.7%
total (assuming ice property error is included in NPE calculation)	± 17.0% (stat.) + 60.4 % - 96.0 % (sys.)

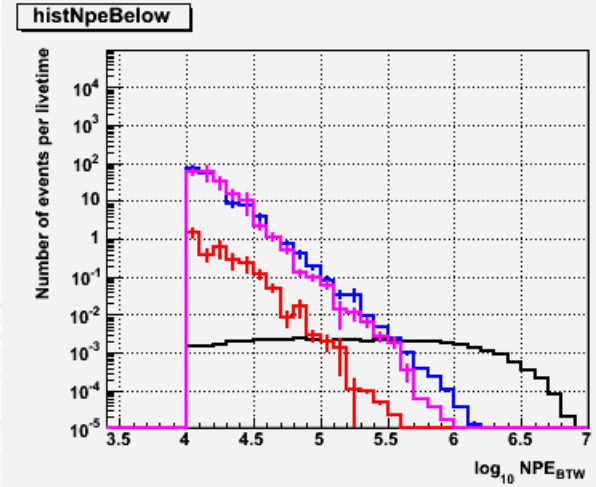
A little side trip

indication of UHECR composition?

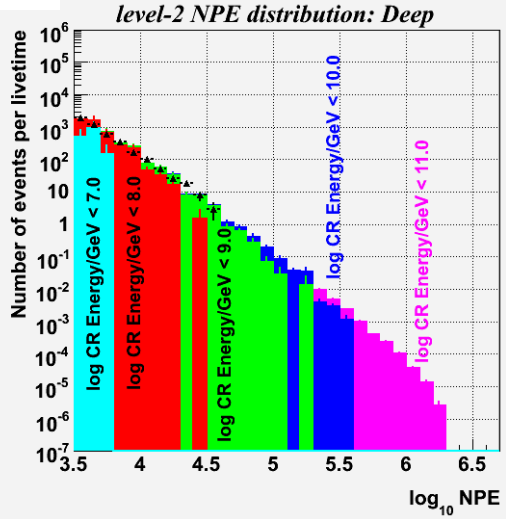


Shallow





Deep

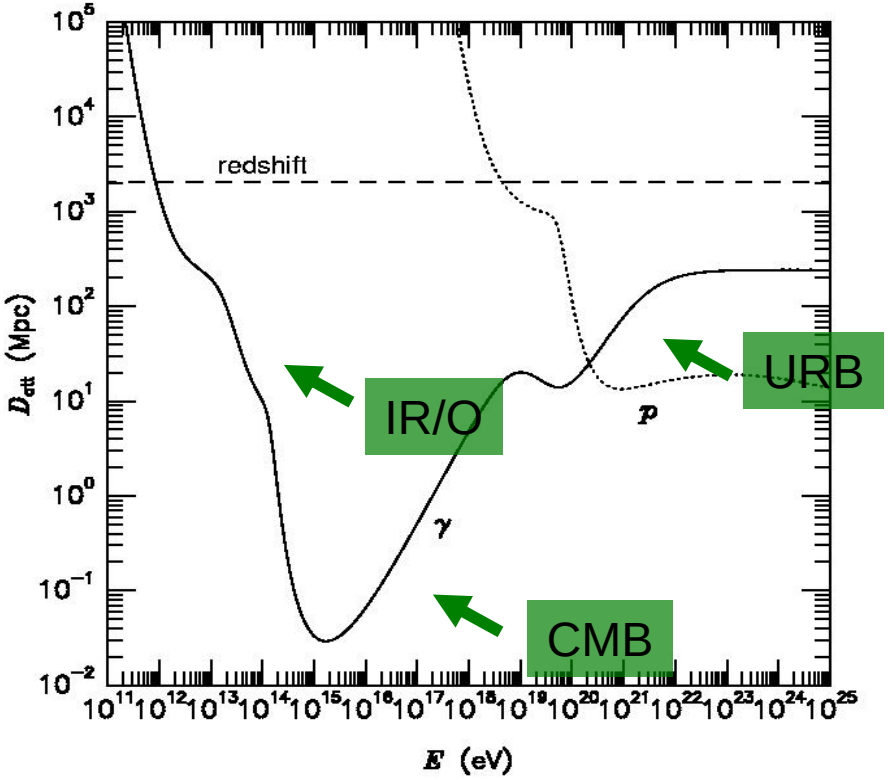


Protons are ***unlikely*** a major component of CRs @10PeV-1EeV

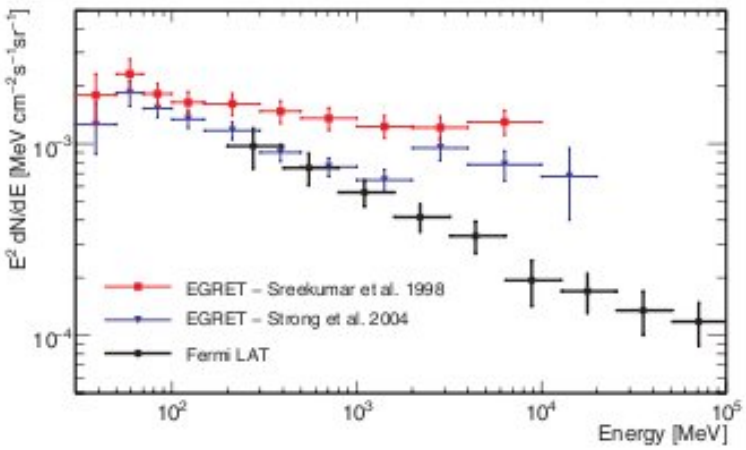
Confirmed the 2007 analysis

Constraints on Ultra-high energy cosmic ray emission

Fermi limits UHECR luminosity at cosmological distances



Fermi-LAT collaboration PRL 2010



Energy Conservation

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

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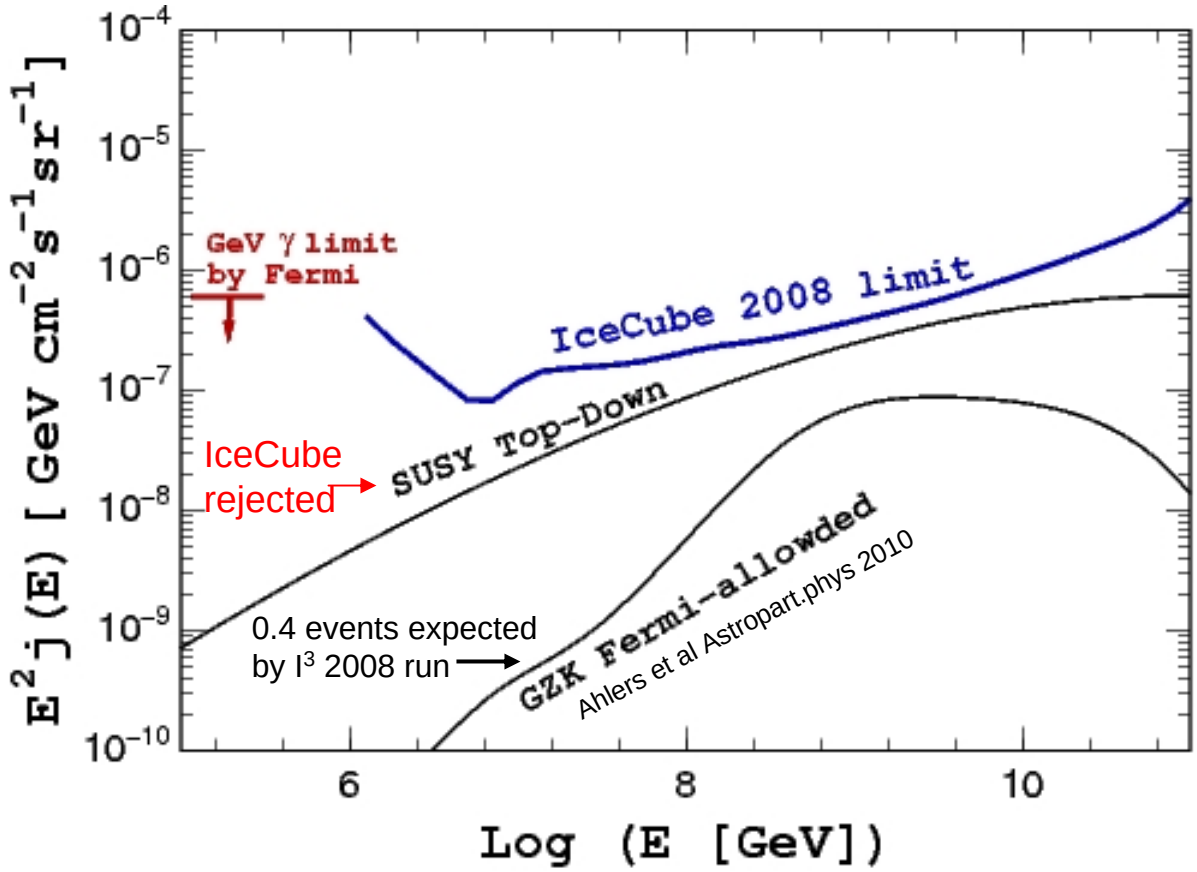
Constraints on Ultra-high energy cosmic ray emission

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

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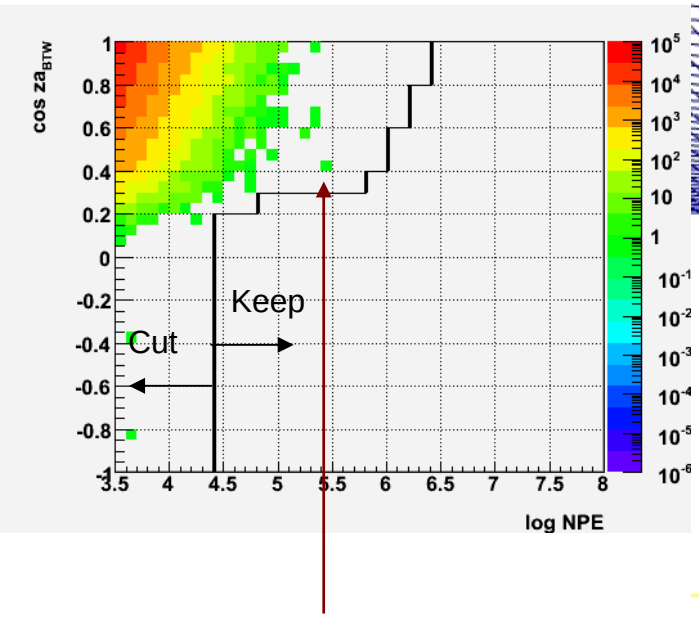
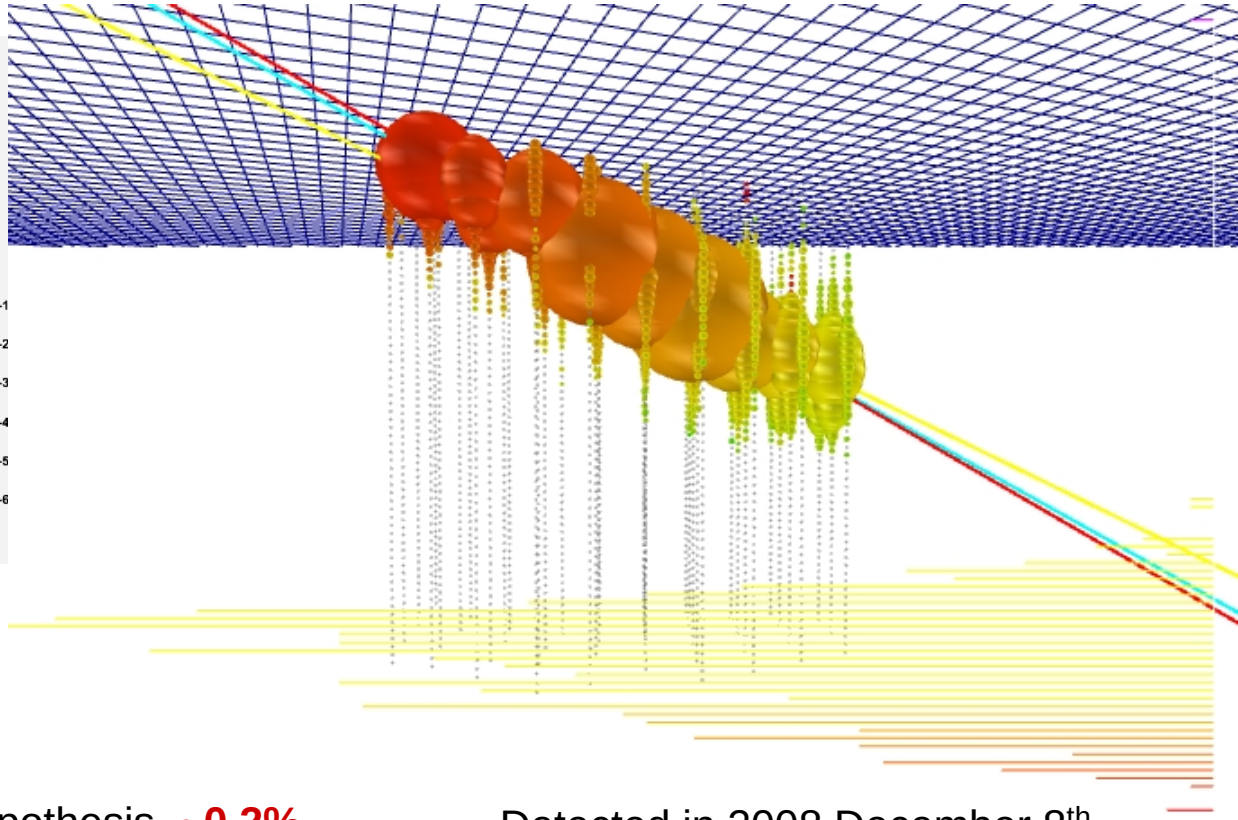
The Highest NPE event



This event



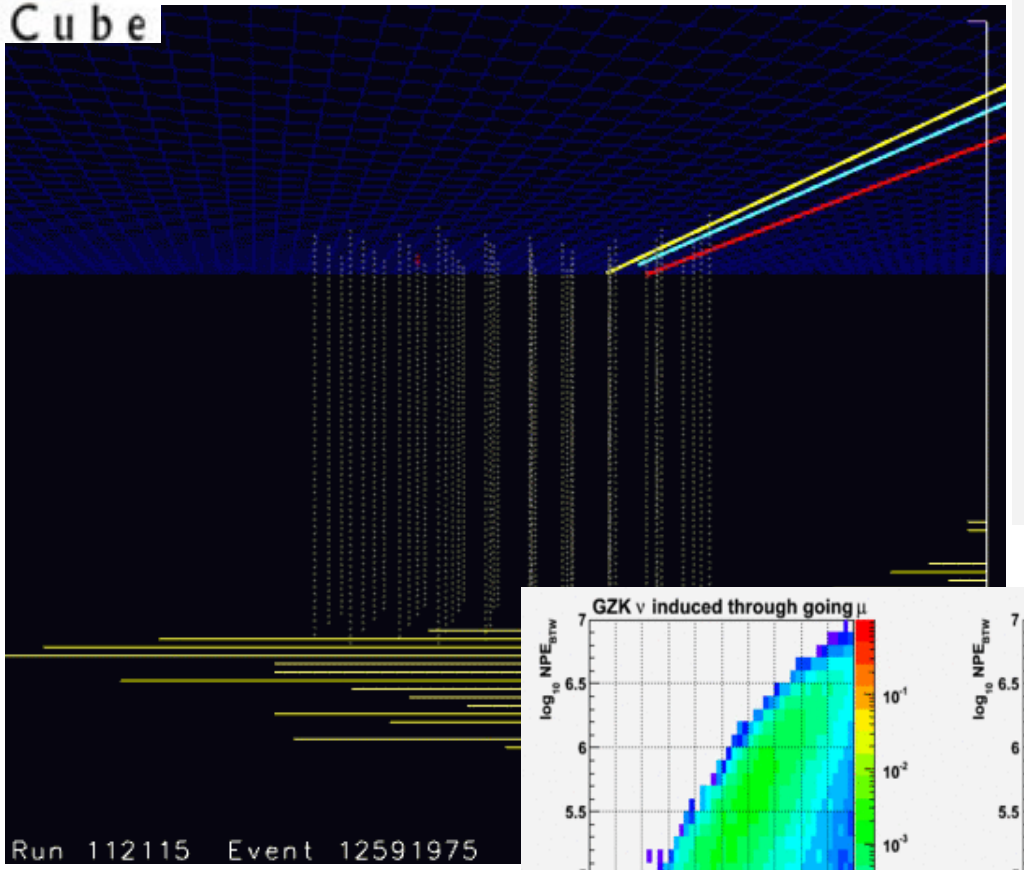
p-value for the background hypothesis **~0.2%**
(posteriori)

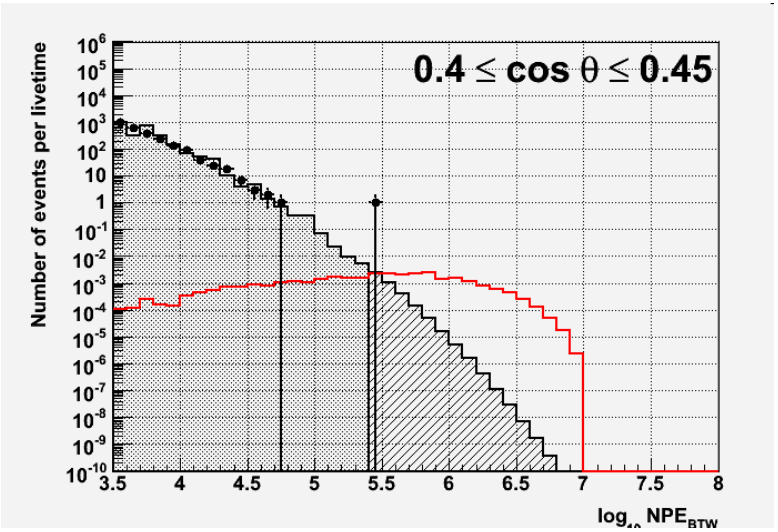
- Detected in 2008 December 8th
- NPE 2.55x10^5 photo-electrons
- Zenith 64.7 deg

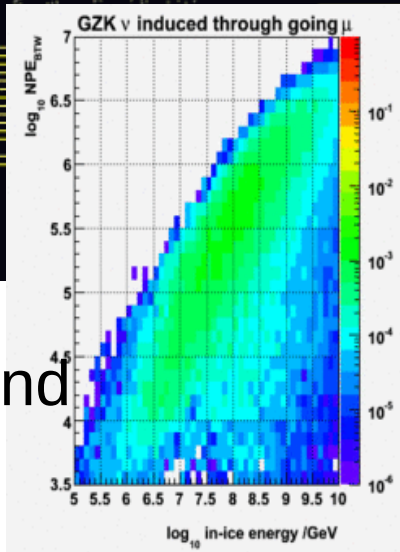
Aya Ishihara (Chiba)

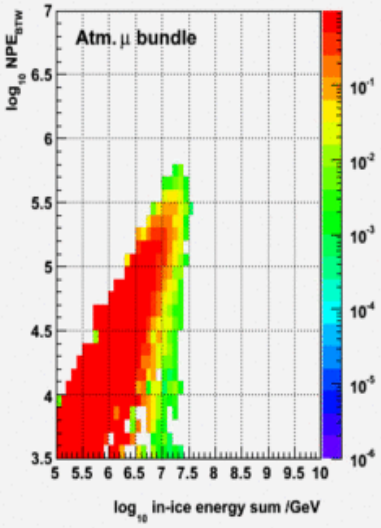
千葉大学 Chiba University

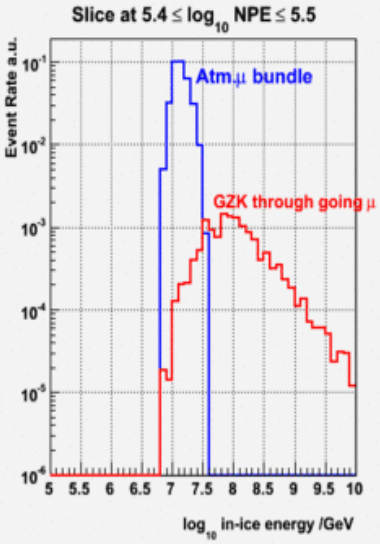
The Highest NPE event











~ 10 PeV if background

~ 100 PeV if (GZK) ν

Constraints on neutrino-nucleon interactions

ν Flux measurement

$$\mathrm{Rate} = \mathrm{V}\,\Omega\,\mathrm{T} \otimes N_A \sigma \otimes \phi(\mathrm{E}_\nu) \exp(-N_A \sigma\, \mathrm{X})$$

Detector+ Geometry

Interaction

Unknown FLUX

Absorption

Constraints on neutrino-nucleon interactions

ν cross section is constrained !!

$$\mathrm{Rate} = \mathrm{V}\,\Omega\,\mathrm{T} \otimes N_A \sigma \otimes \phi(\mathrm{E}_\nu)\exp(-N_A \sigma\, \mathrm{X})$$

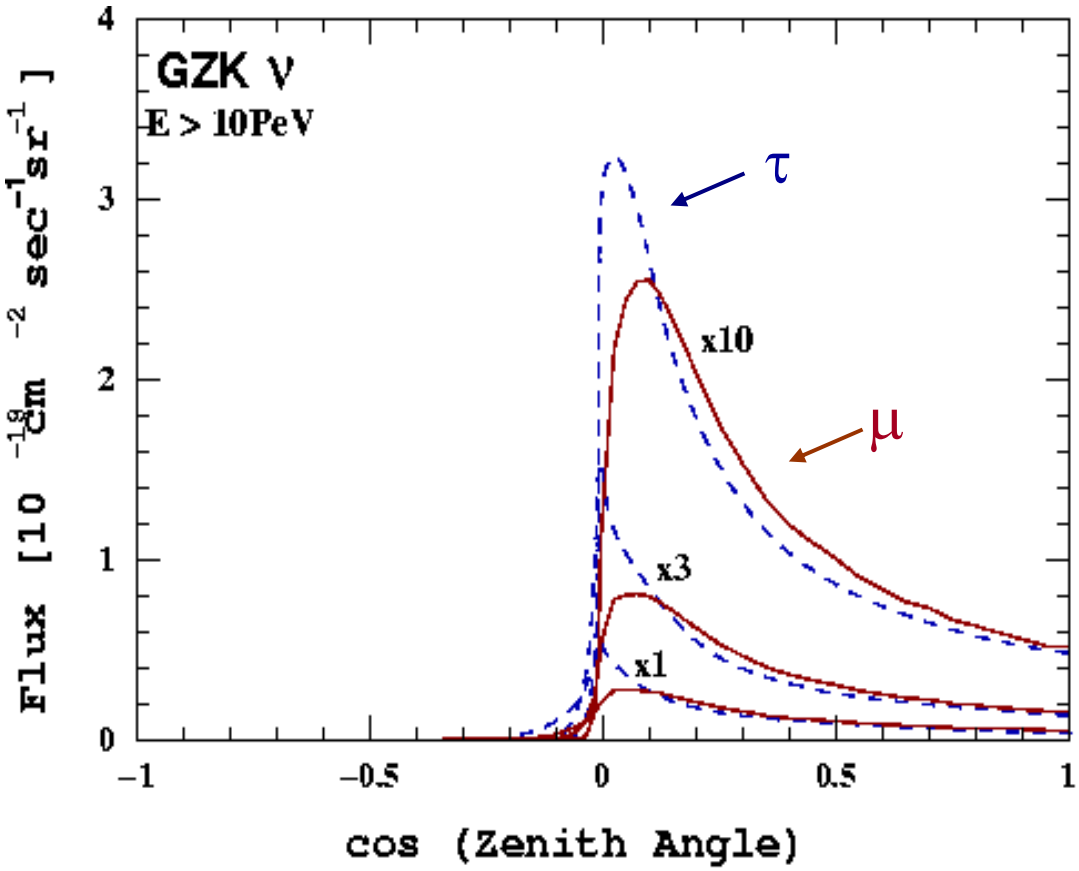
Detector+ Geometry

Interaction

UHE ν FLUX

Absorption

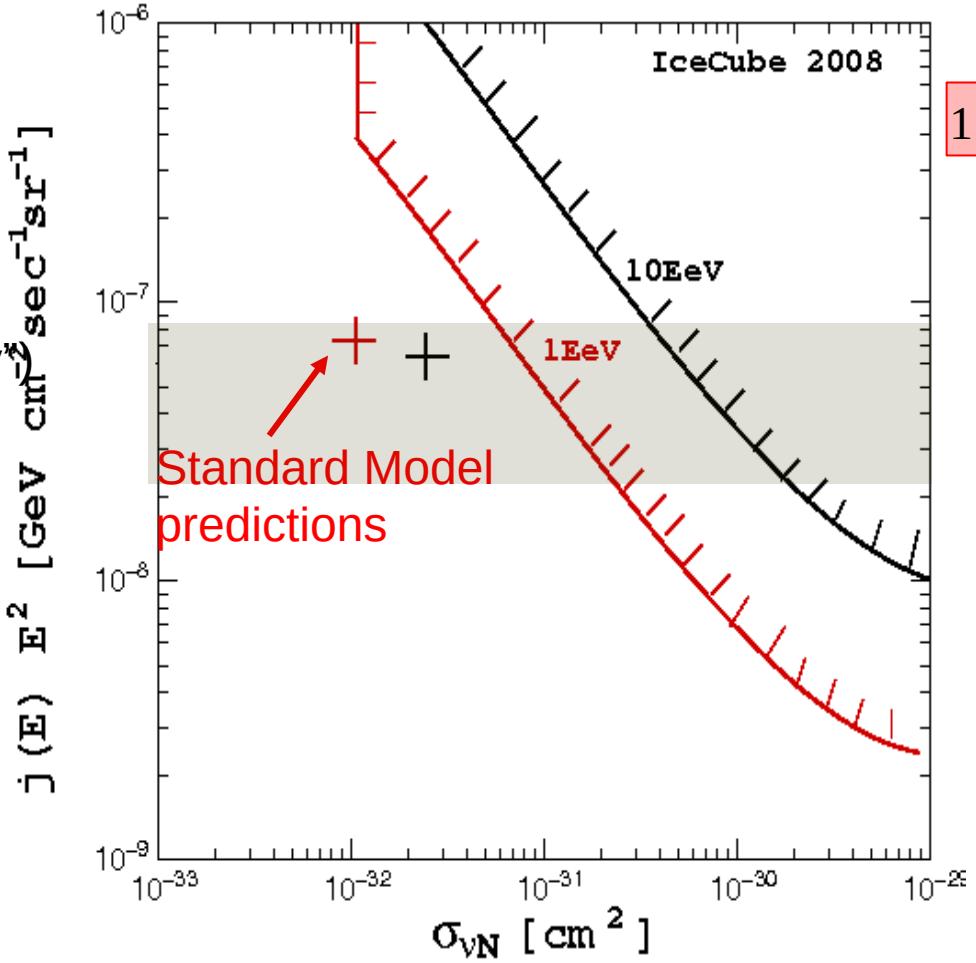
Secondary μ and τ Fluxes at IceCube depth
-- enhanced by N_{scale}--



S.Yoshida PRD **82** 103012 (2010)

νN CC cross section bound with the IceCube 2008 observation

Flux of cosmic ν
("Beam Intensity")



$1\,\mathrm{EeV} \sim \sqrt{s} = 40\,\mathrm{TeV}$

$\sigma_{\nu N}^{SM}$ calculated by Cooper-Sarkar & Sarkar JHEP01:075 (2010)

S.Yoshida PRD **82** 103012 (2010)

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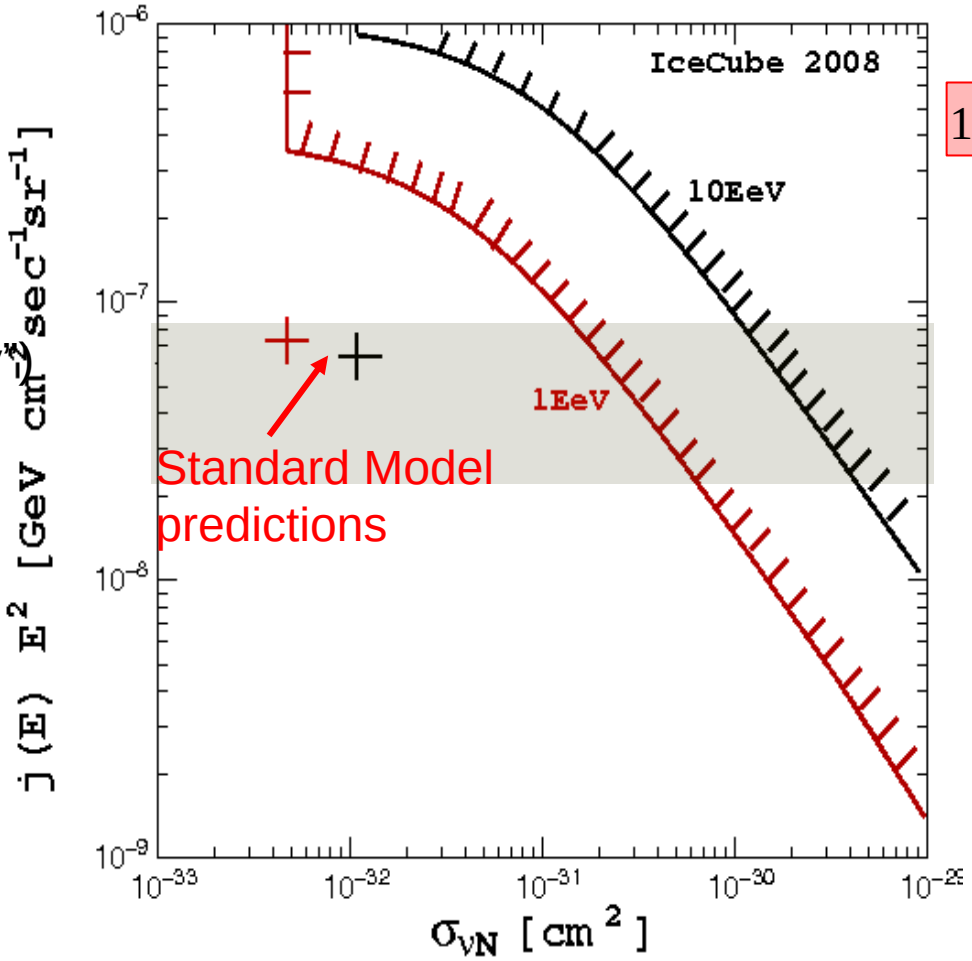
νN NC cross section bound with the IceCube 2008 observation

Flux of cosmic ν
("Beam Intensity")



$1\,\mathrm{EeV} \sim \sqrt{s} = 40\,\mathrm{TeV}$

$\sigma_{\nu N}^{SM}$ calculated by Cooper-Sarkar & Sarkar JHEP01:075 (2010)

S.Yoshida PRD **82** 103012 (2010)

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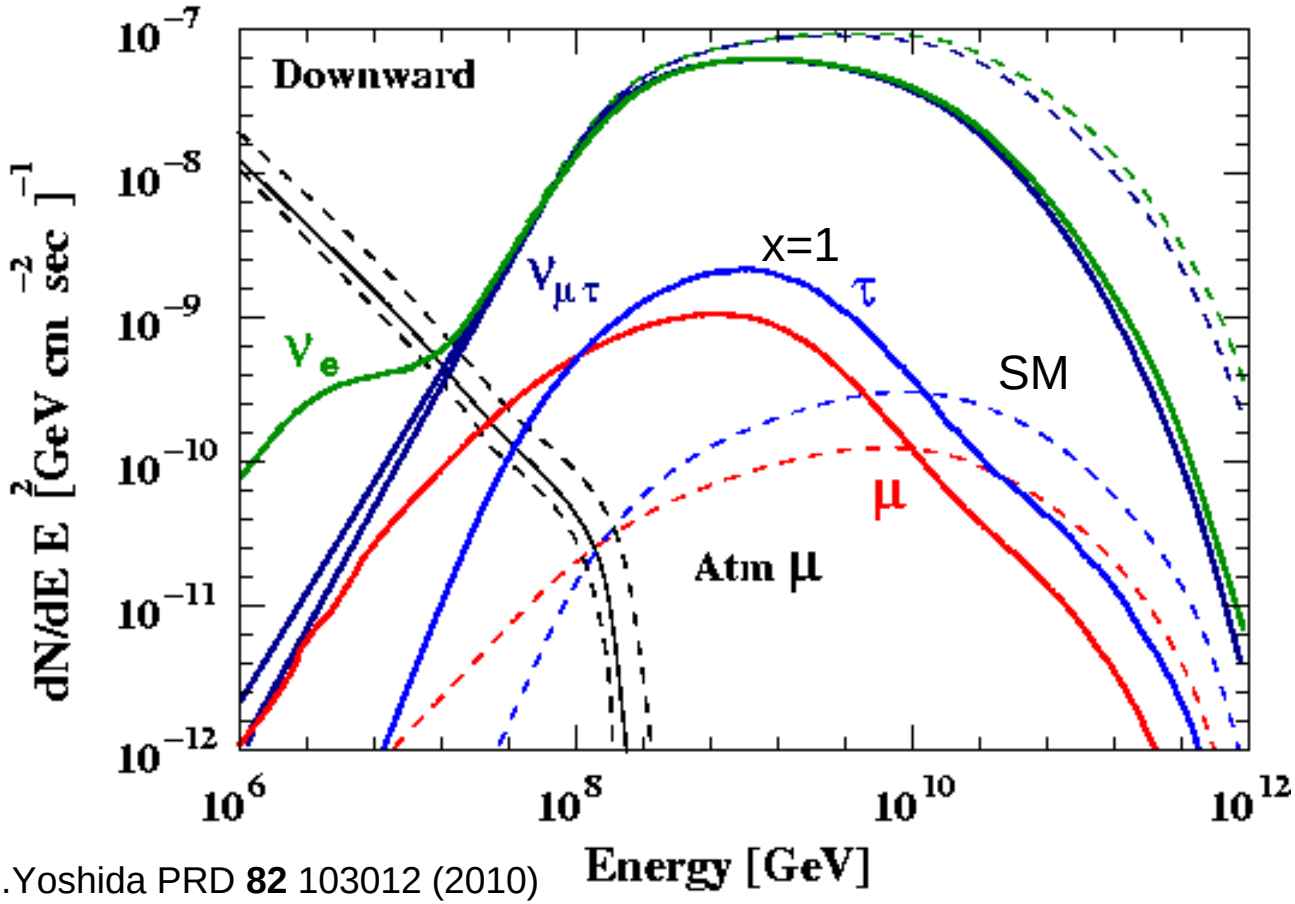
Fluxes at the IceCube depth

Black Hole evaporation scenario

J.Alvarez-Muniz et al PRD **65**, 103002 (2002)



S.Yoshida PRD **82** 103012 (2010)

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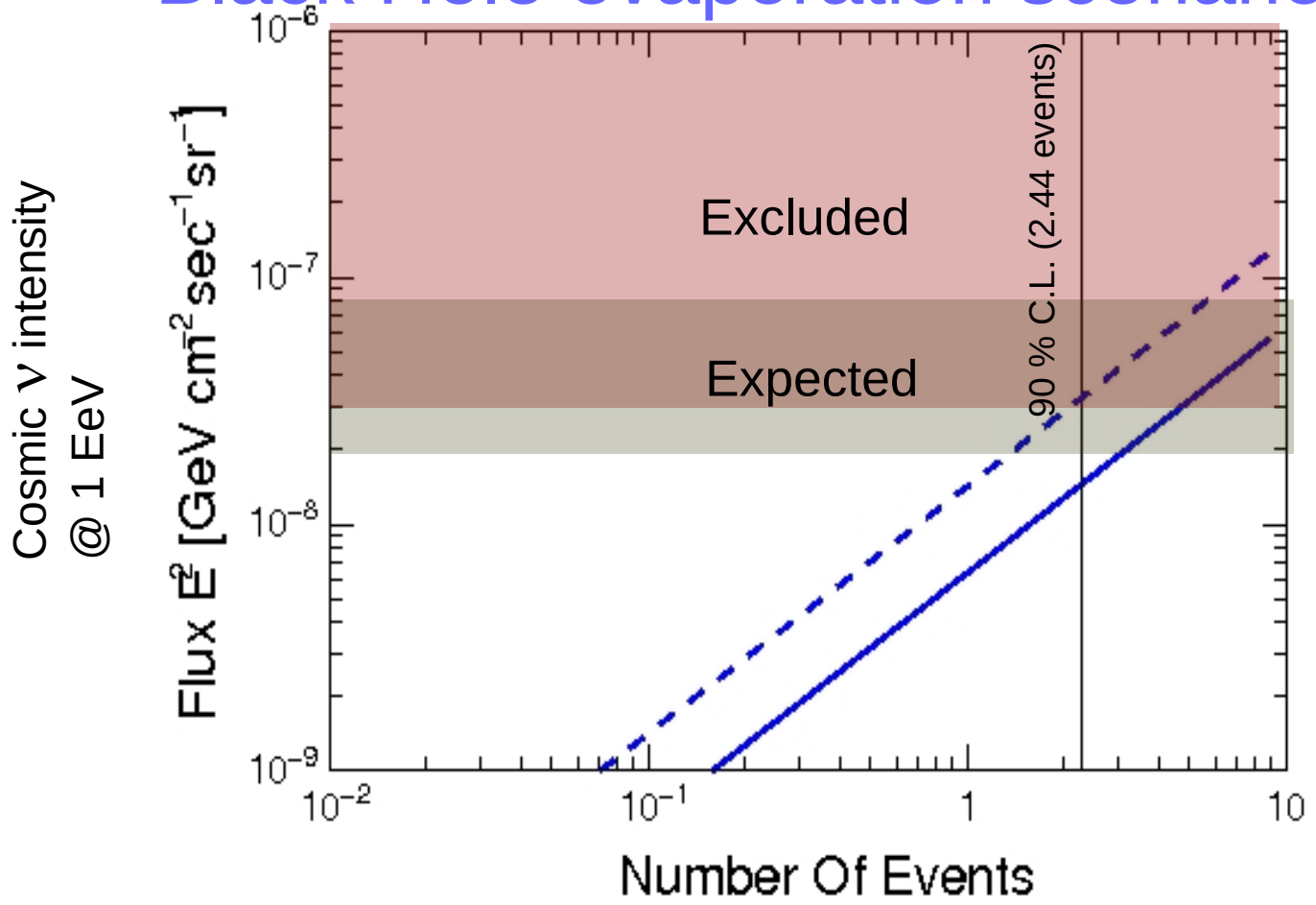
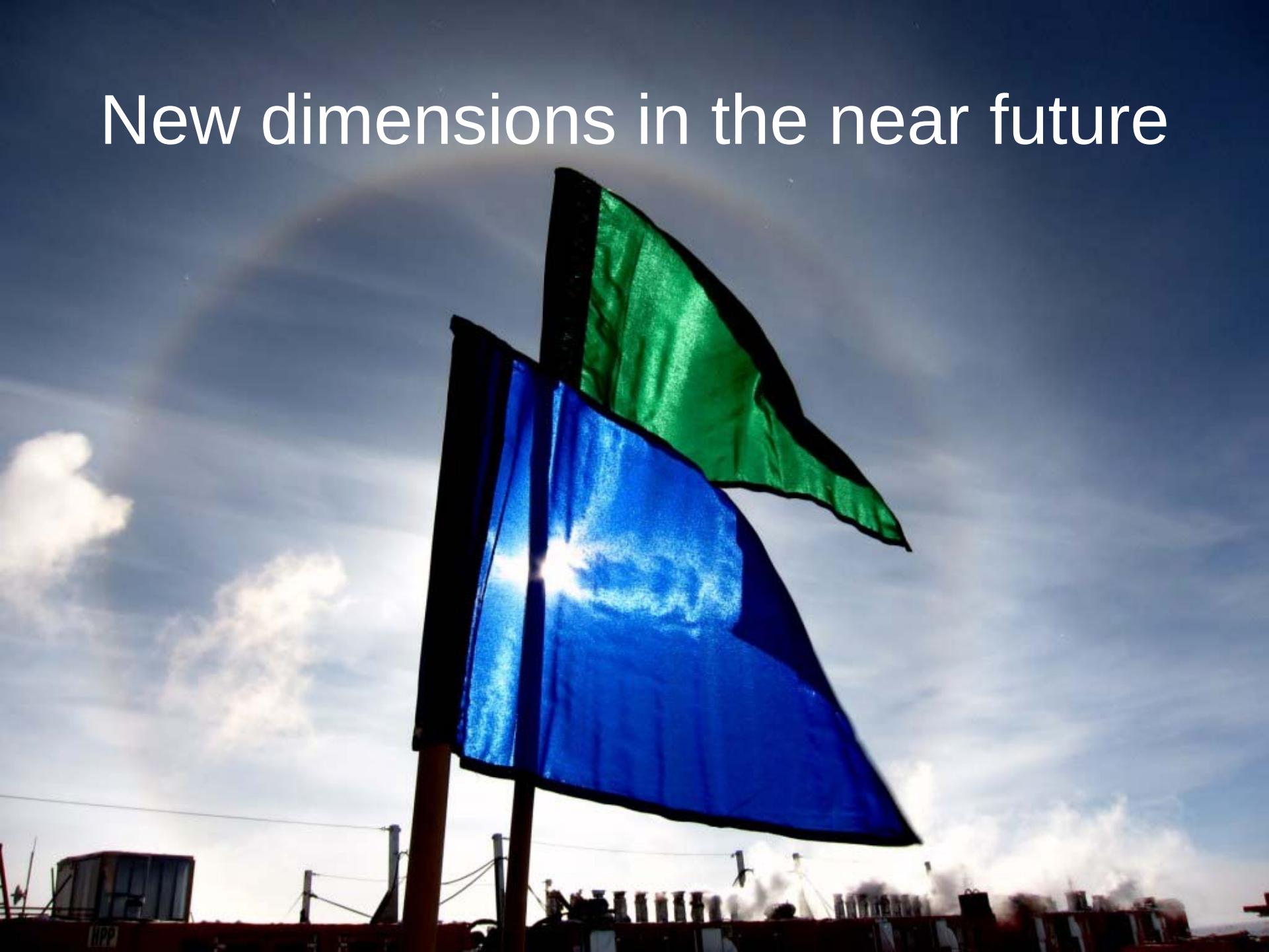
Number of events in the IceCube 2008 run

Black Hole evaporation scenario



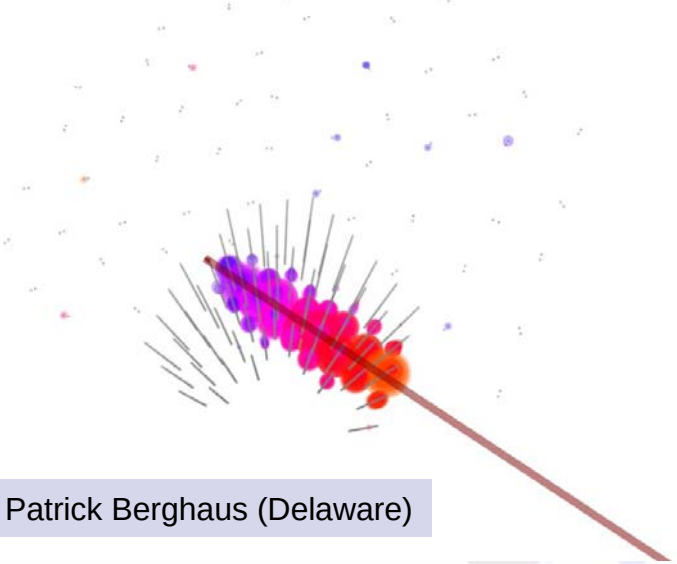
S.Yoshida PRD **82** 103012 (2010)

New dimensions in the near future



New dimensions in the near future

hybrid analysis with IceTop



Patrick Berghaus (Delaware)

More multi-messenger analysis coming

Gamma-ray follow-up

Optical follow-up

Correlations with UHECRs

On-going

Extremely-high energy event alert

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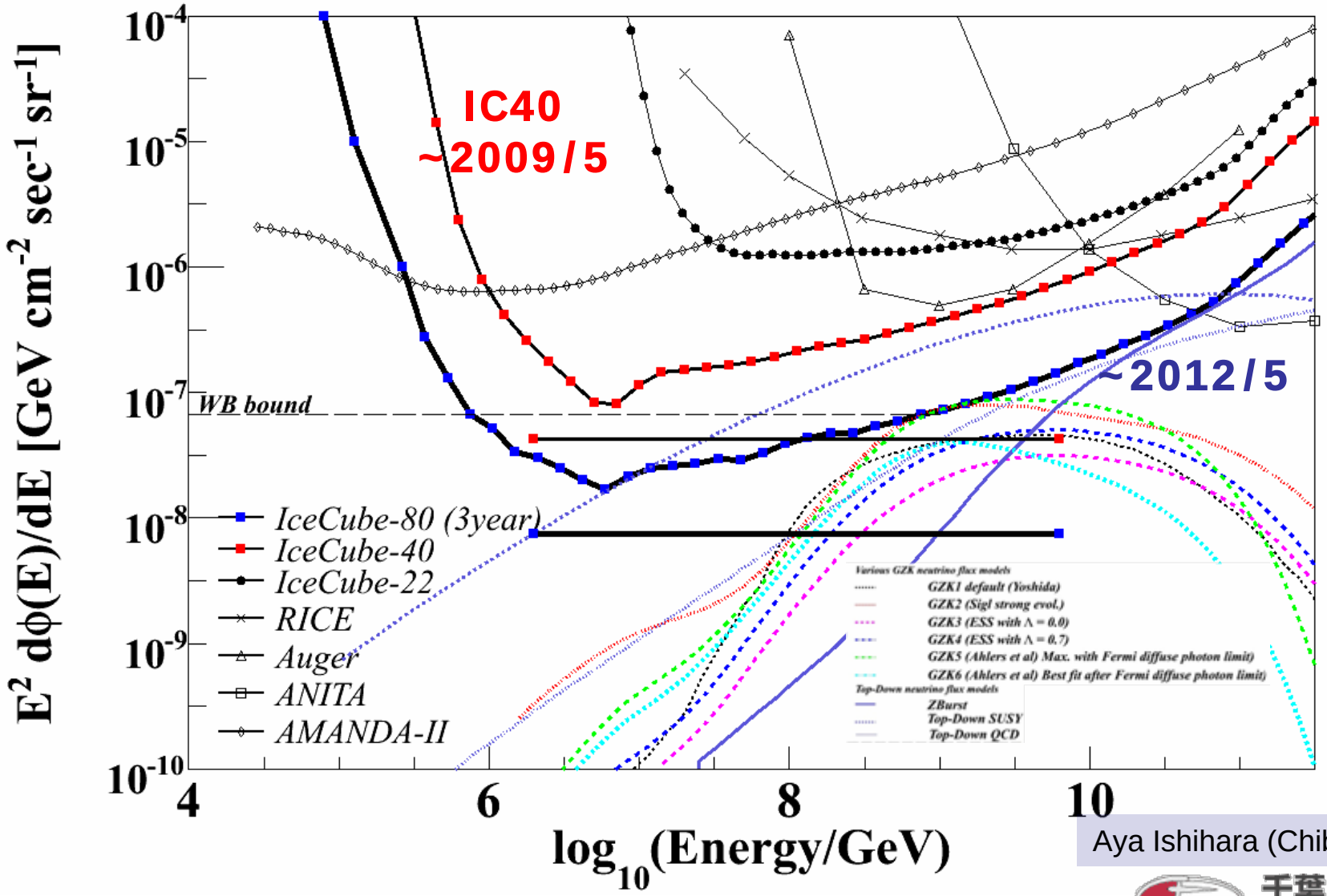
IceCube baseline Sensitivity

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



Aya Ishihara (Chiba)

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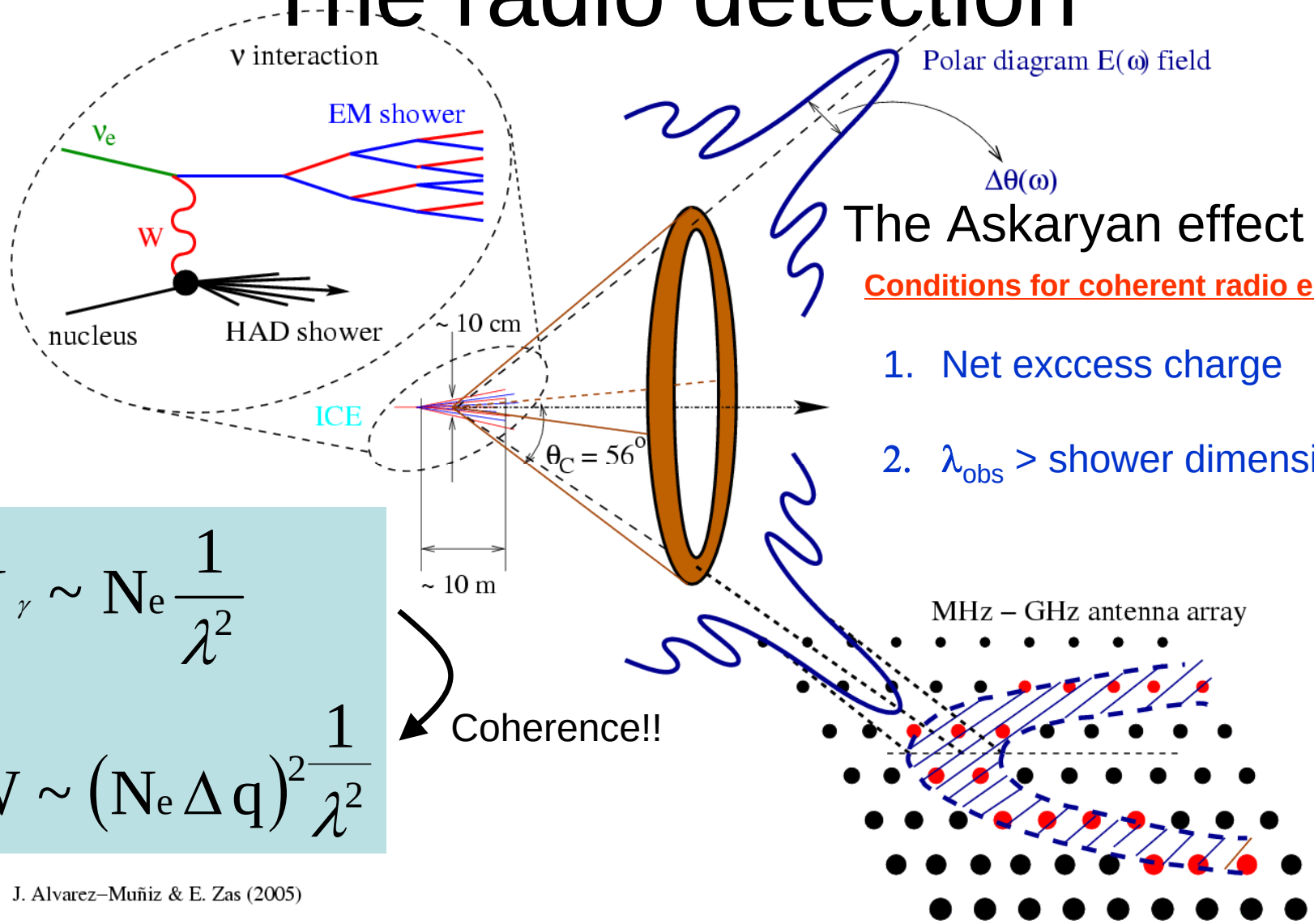
Expected # of EHE signal events

Models	IC40 (2008 config.) # 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

The radio detection



The Askaryan effect

Conditions for coherent radio emission

1. Net exccess charge
2. λ_{obs} > shower dimensions

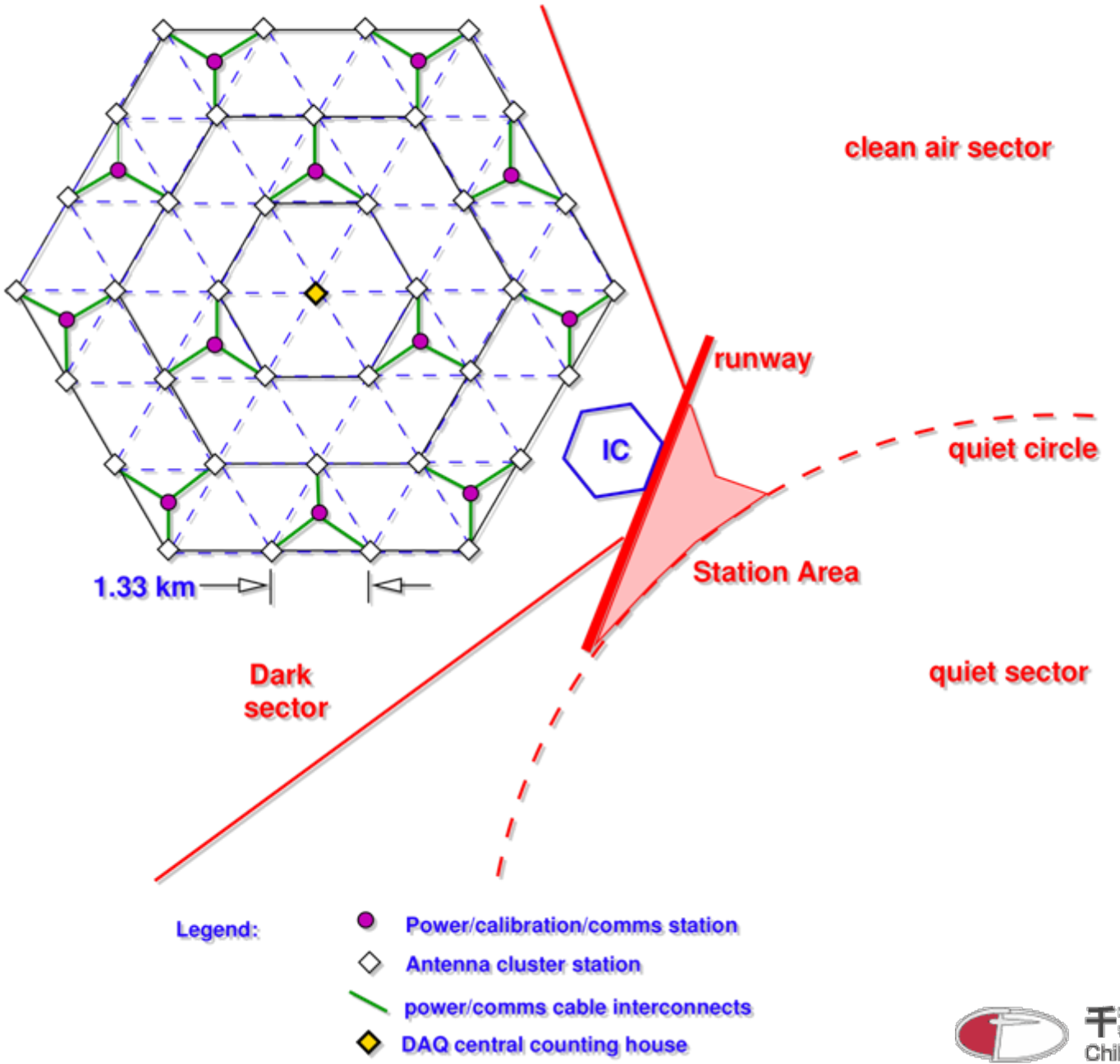
$$N_\gamma \sim N_e \frac{1}{\lambda^2}$$

$$W \sim (N_e \Delta q)^2 \frac{1}{\lambda^2}$$

Coherence!!

J. Alvarez–Muñiz & E. Zas (2005)

Askaryan Radio Array



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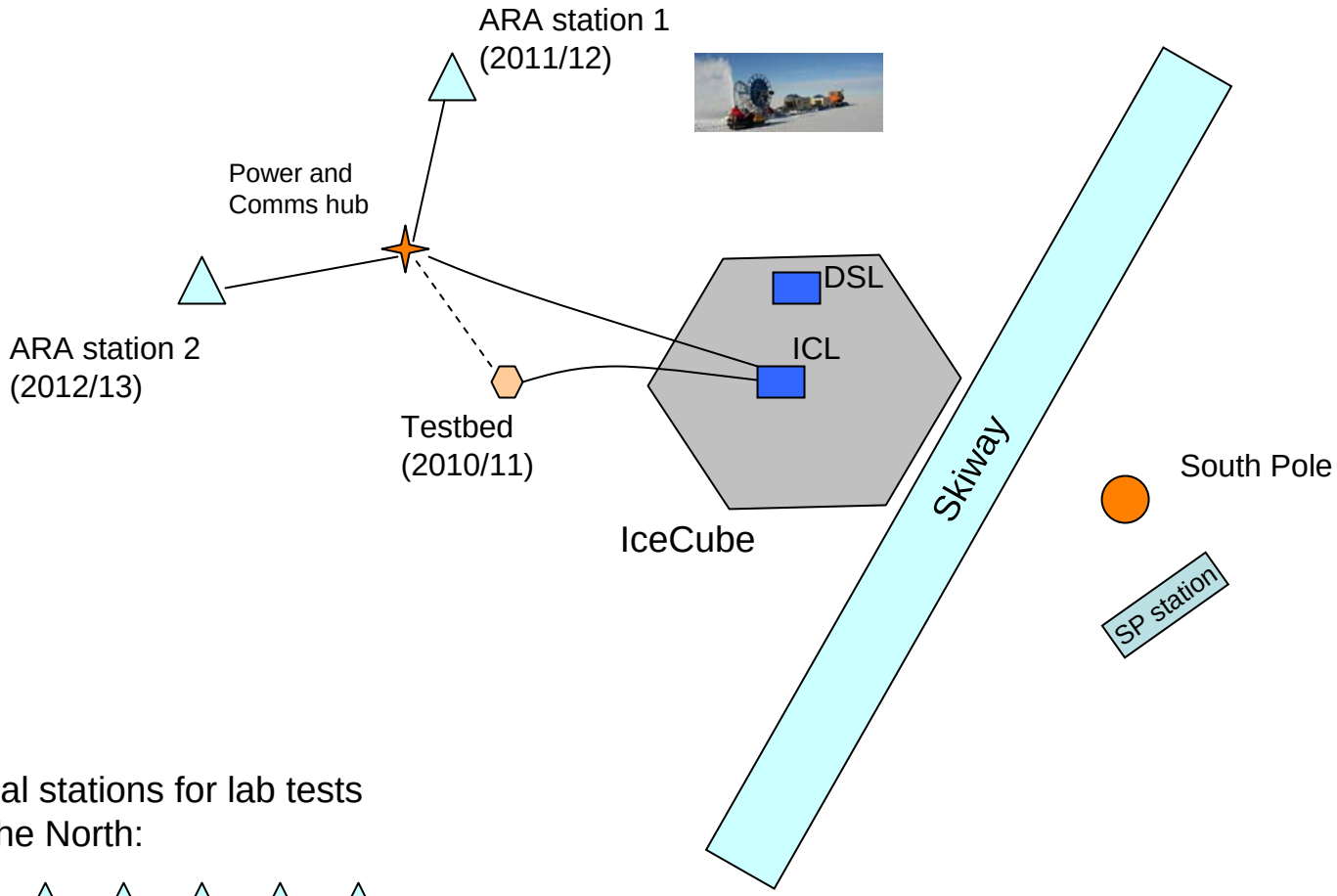
Start-up phase
funded by NSF-MRI



Additional stations for lab tests
stay in the North:

The ARA collaboration

Vrije Universiteit Brussel

University Coll. London

Nat' l Taiwan Univ.

DESY, Zeuthen

Universität Wuppertal

Chiba University

University of Kansas

University of Maryland

University of Wisconsin-Madison

University of Hawaii

U Delaware

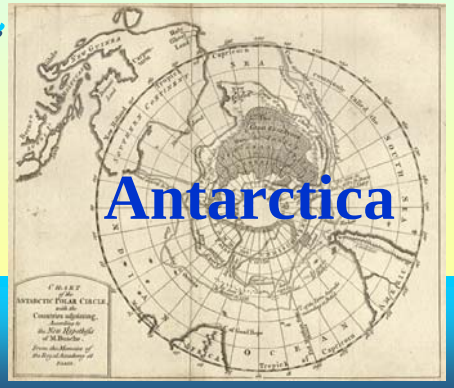
Ohio State Univ.

Univ. Alabama

Colorado St. Univ.

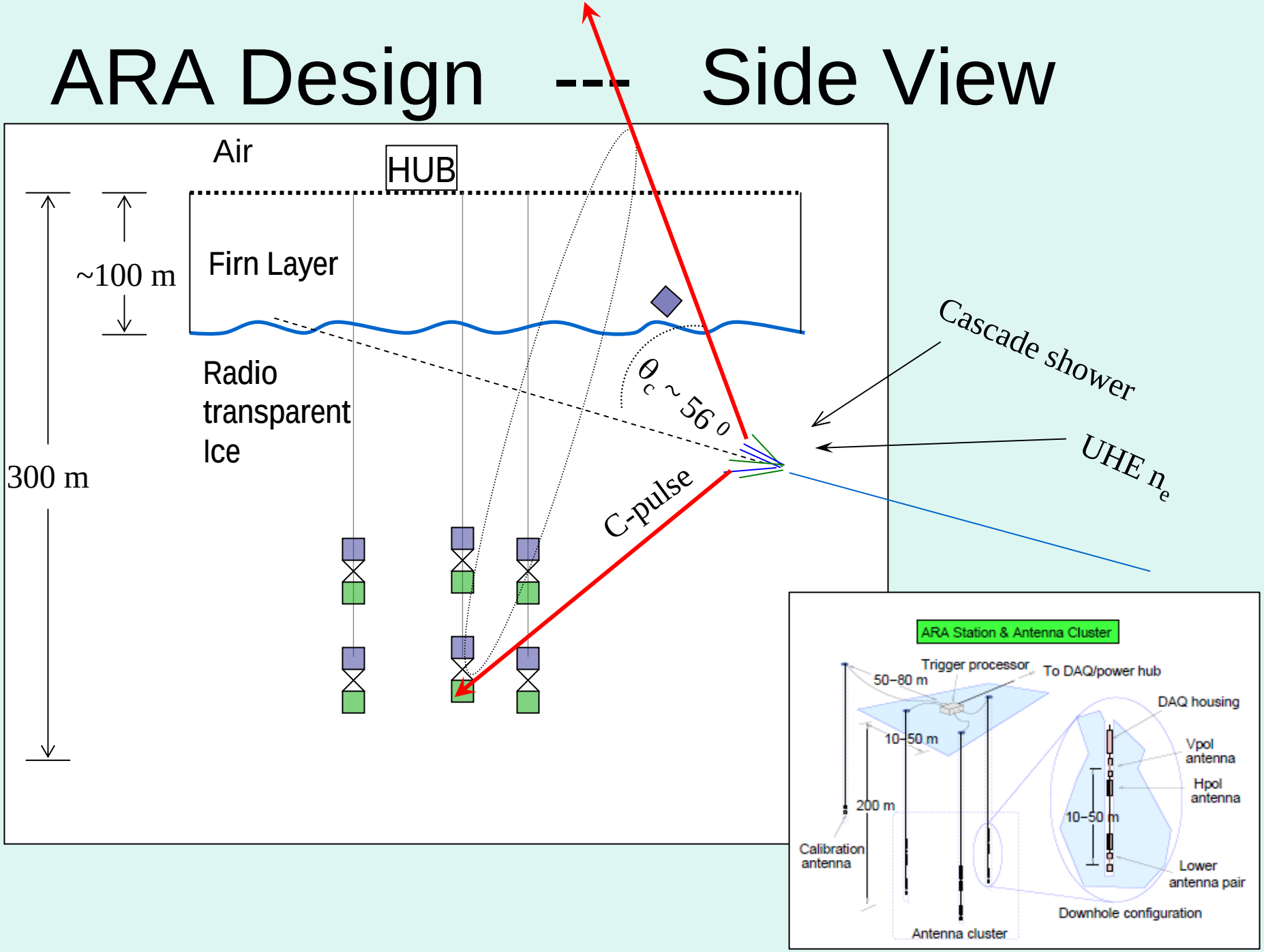
Penn St. Univ.

University of Nebraska

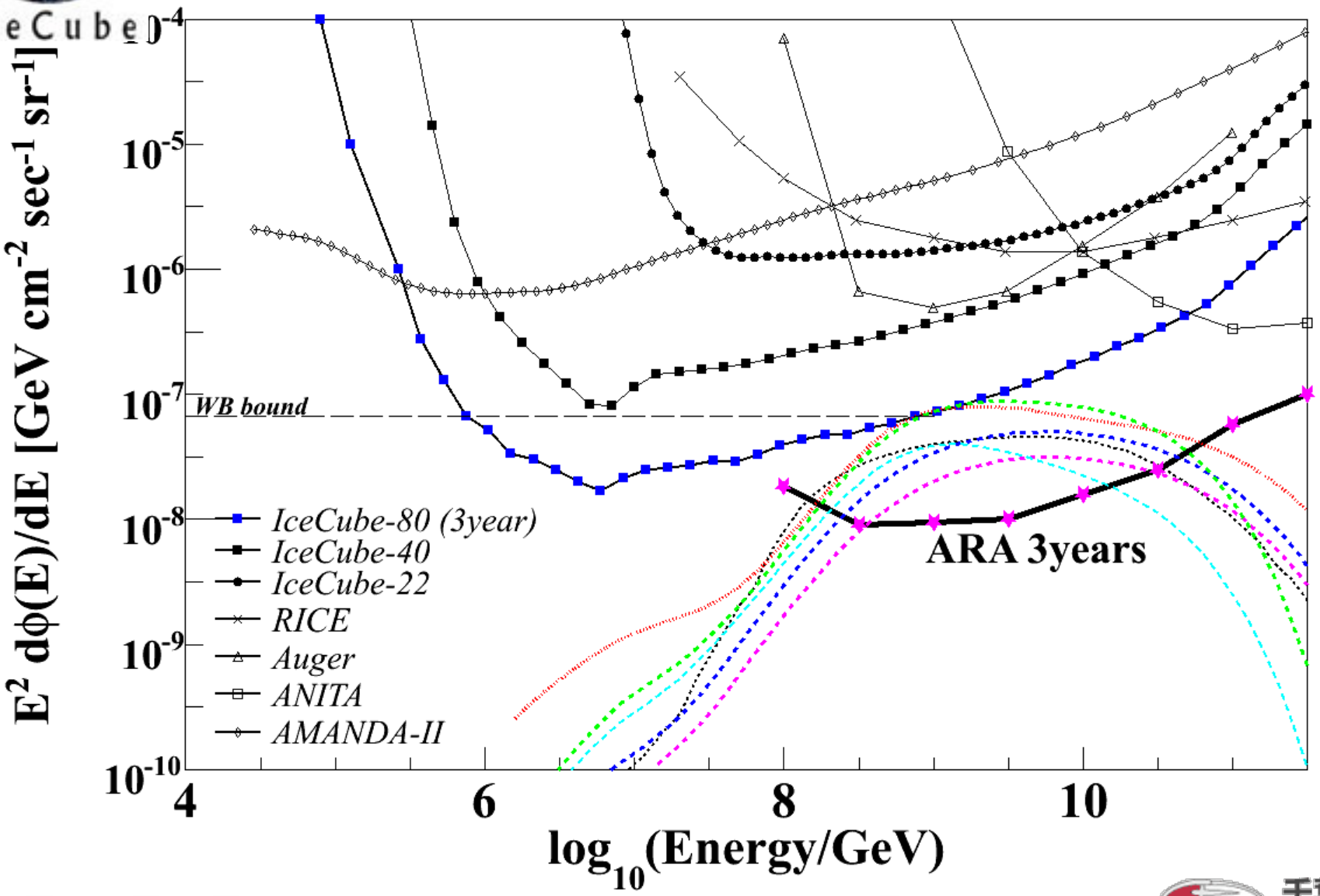


Antarctica

ARA Design --- Side View



We will reach this level



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Summary

- The IceCube starts full operation next year
- The half-IceCube science run 2008-2009 has already started to constrain astrophysical ν generation

  Diffuse ν flux limits at high energies (O(TeV) – O(PeV)) and
  even UHEs (O(10PeV)-O(10EeV) below the Waxman-Bahcall bound
- The present ν observation tells a few things about UHECR origin

  GRBs now in question. TopDown models very unlikely.
- Yet the GZK ν detection and the multi messenger approach (include. with Auger/TA) very feasible to shed lights into UHECR origin

  unless UHECRs are heavy nuclei dominated

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Backup