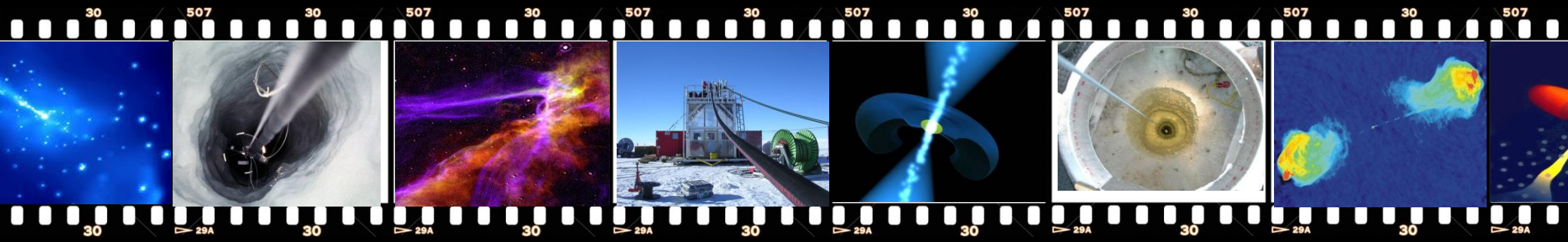
IceCubeによる超高エネルギー宇宙ニュートリノ探索
Status and Future Prospects



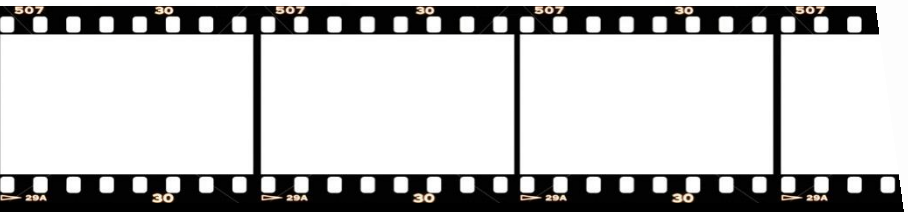
Aya Ishihara for the IceCube collaboration

JSPS Research Fellow at **Chiba University**

第24回宇宙ニュートリノ研究会

Outline

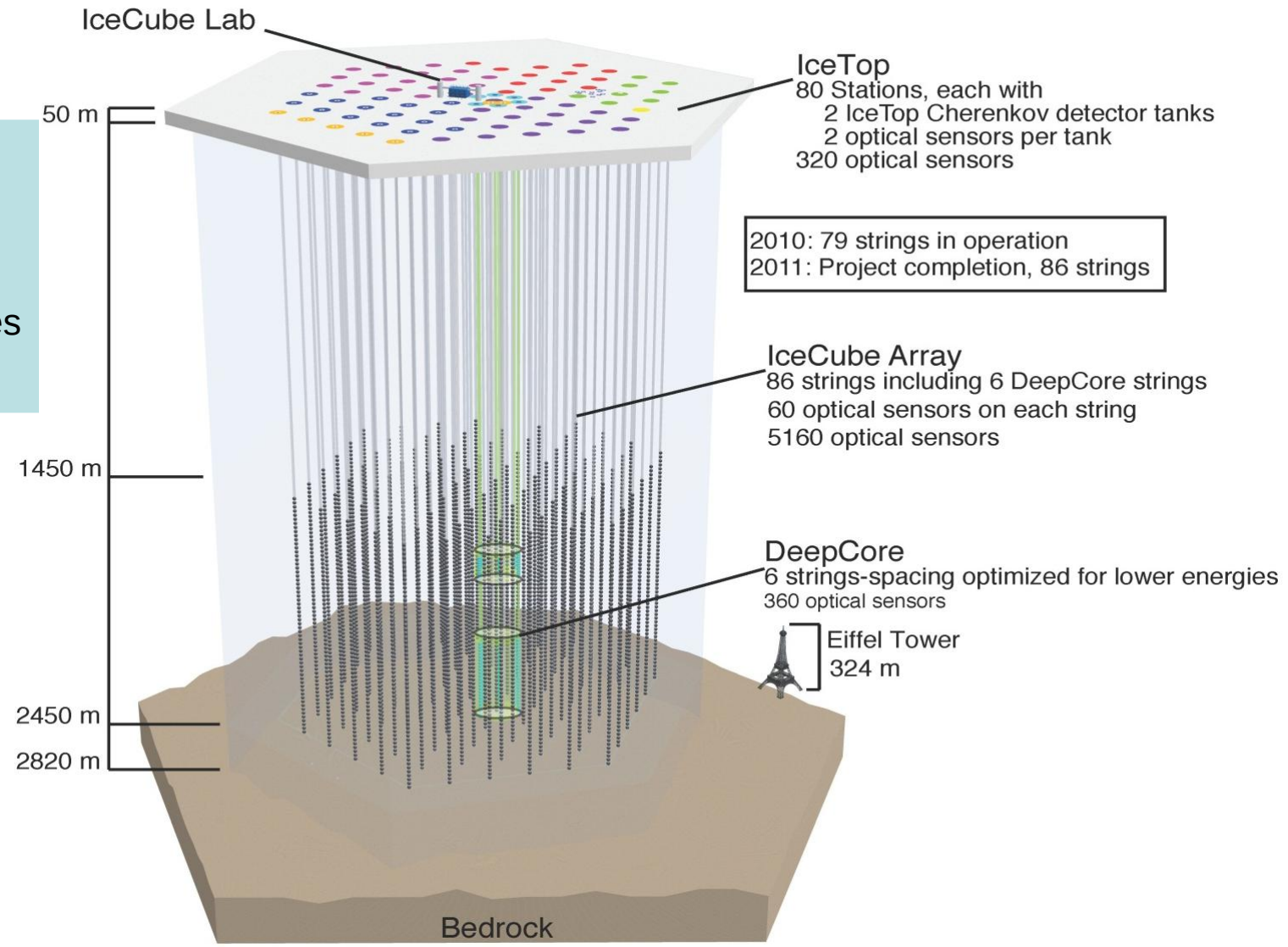
- IceCubeにおける超高エネルギーニュートリノ探索
- 超高エネルギーニュートリノ探索解析手法の現状と結果
- 現在、進められている最新データ解析に向けた新しい手法の開発・今後の展開



IceCube at South Pole

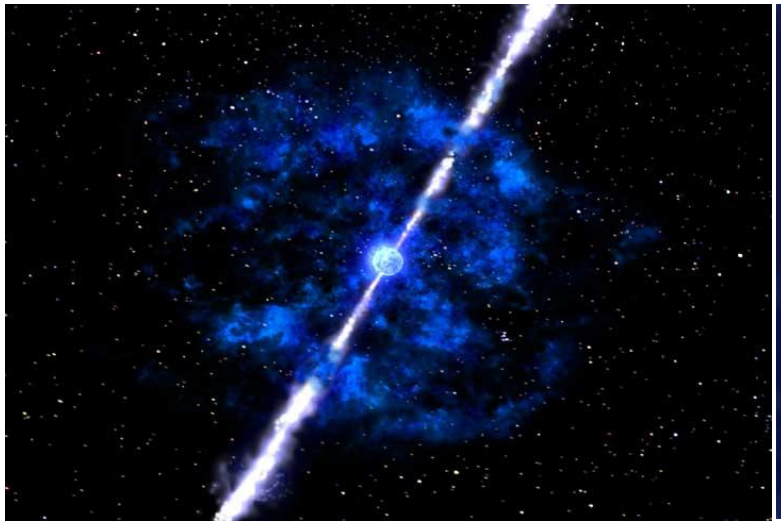
- 1km^3 volume
- 80+6 Holes
- 60 Optical Modules
- 17 m between modules
- 125 m between holes

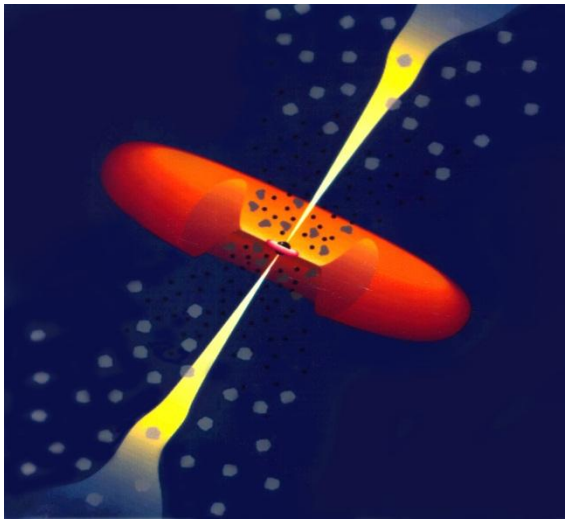
Construction Finished!!

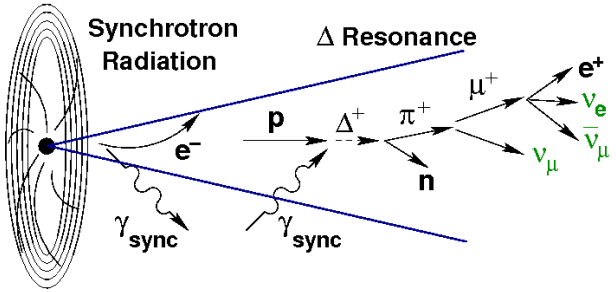


Astronomical Neutrino Sources

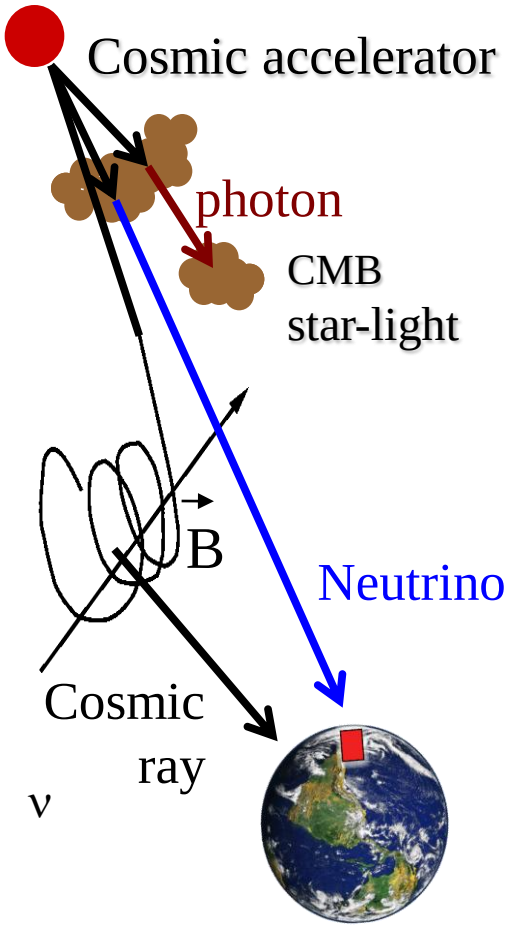
high energy cosmic-ray sources, e.g. AGN, GRB…





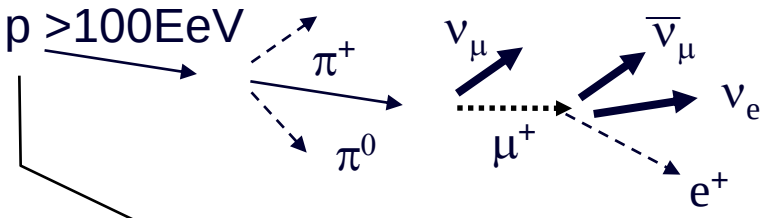


$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma$$
$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$$



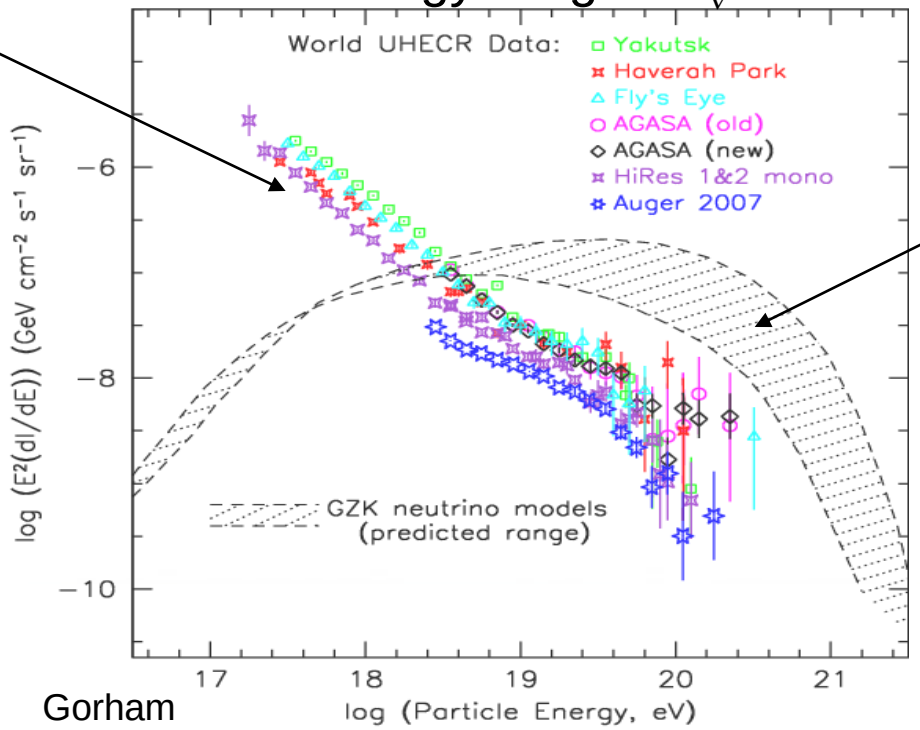
The sources of the highest energy neutrinos

EHE cosmic-ray and CMB induced neutrinos



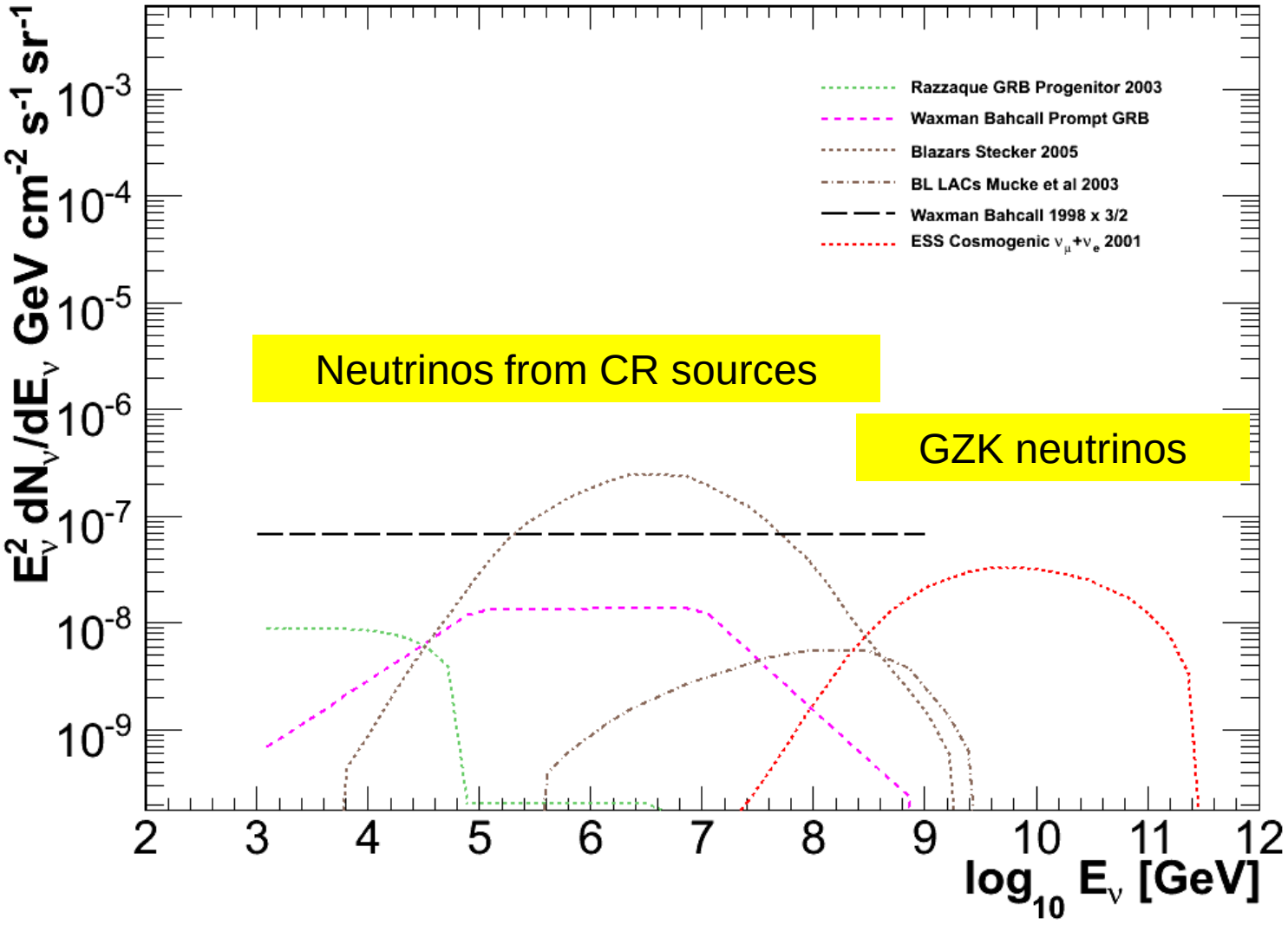
$$p\gamma_{2.7K} \rightarrow \pi^{\pm} + X \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu' s$$

The main energy range: $E_\nu \sim 10^{9\text{-}10}$ GeV



Gorham

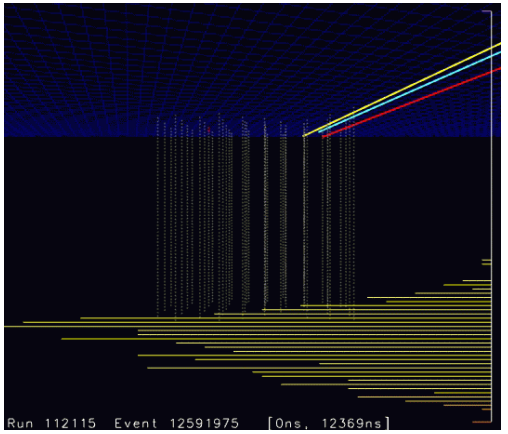
モデルエネルギー領域


Razzaque GRB Progenitor 2003
Waxman Bahcall Prompt GRB
Blazars Stecker 2005
BL LACs Mucke et al 2003
Waxman Bahcall 1998 x 3/2
ESS Cosmogenic $\nu_\mu+\nu_e$ 2001
Neutrinos from CR sources
GZK neutrinos
$E_\nu^2\, dN_\nu/dE_\nu$ GeV cm^{-2} s^{-1} sr^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
3
4
5
6
7
8
9
10
11
12
$\log_{10} E_\nu$ [GeV]

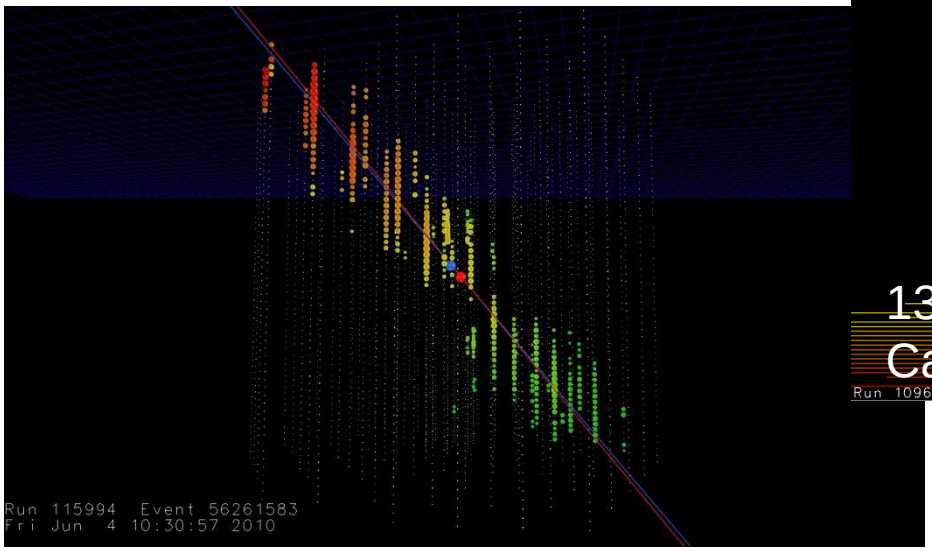
IceCube Event Gallery

Cherenkov light illuminations from particles

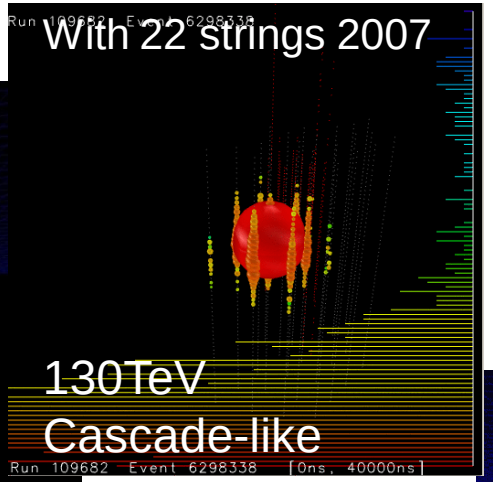
With 40 strings, 2008 Dec



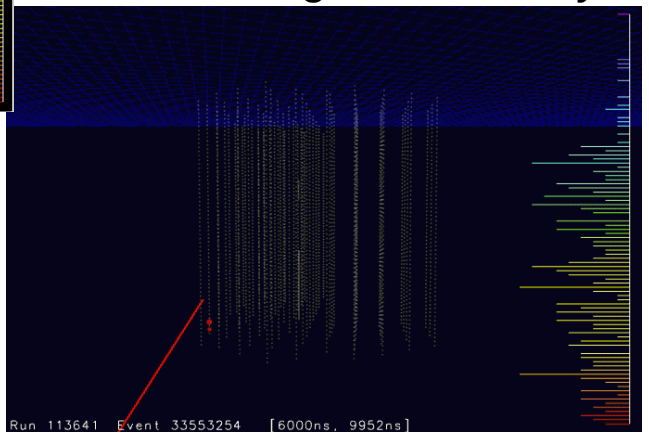
With 79 strings, 2010 June



With 22 strings 2007



With 40 strings, 2009 May

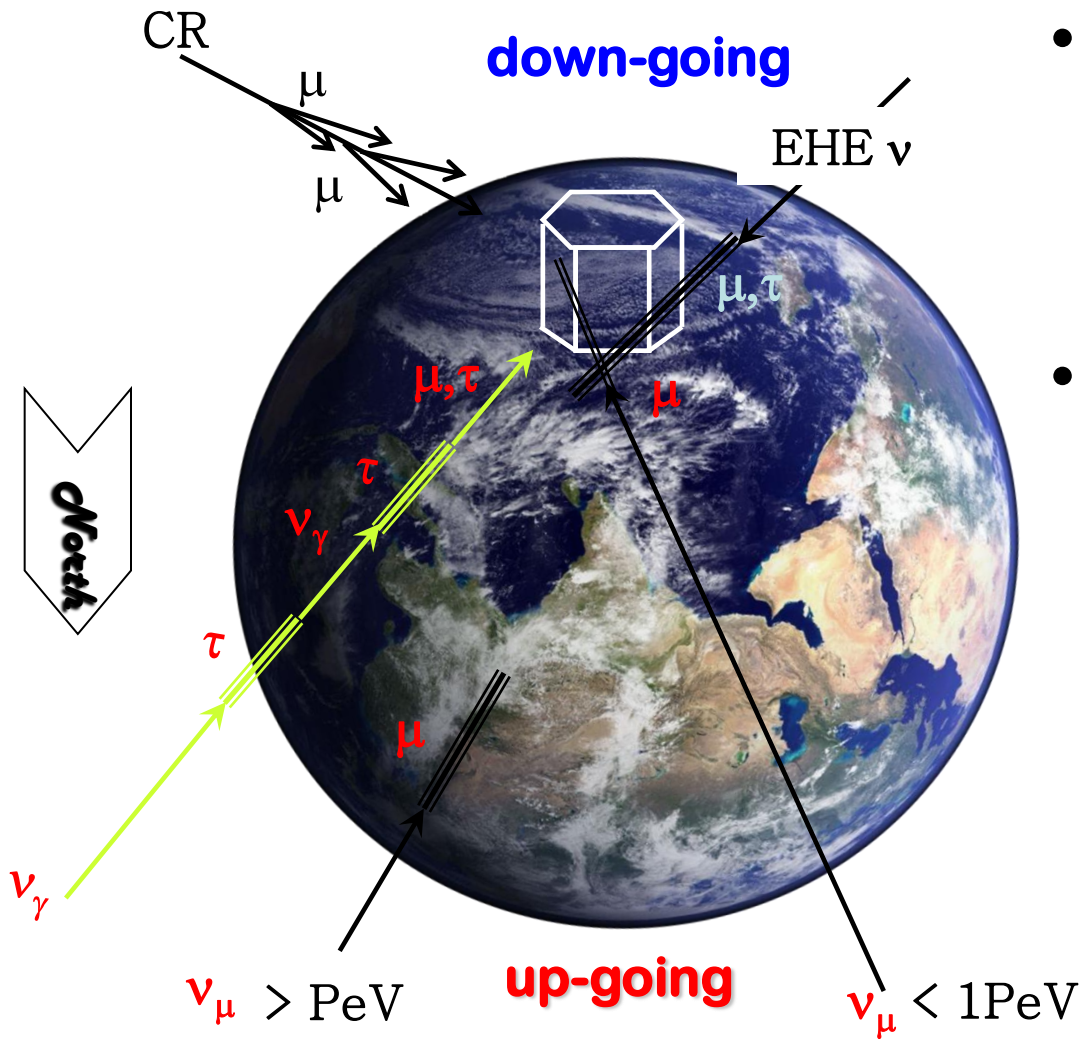


Energy threshold ~10 GeV

>10^8 muons/day

>200 neutrinos/day

Directions in IceCube: particle screening and the energy upper bound



- **Neutrinos identified as "through the Earth" up-going events but only upto < PeV**
- **EHE neutrino-induced events are coming from above and near horizontal direction**

EHE neutrino mean free path

$l_n \sim 100$ km $<< R_{Earth}$

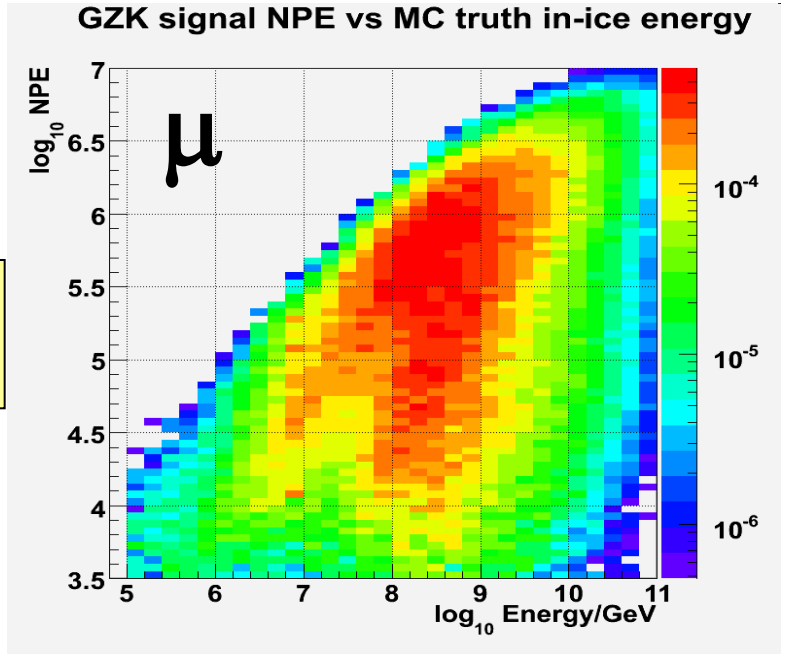
$s^{cc}_{nN} \sim 10^{-6\sim-4}$ mb

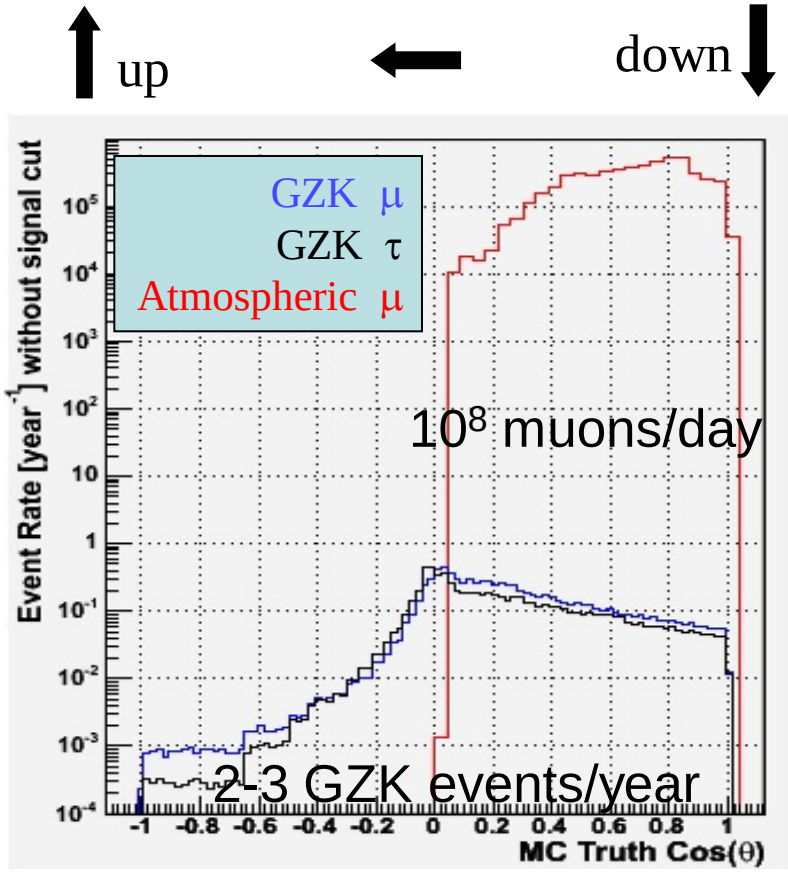
IceCube事象分類

- 事象の方向
  - Upward-going neutrinos
    - Conventional atmospheric neutrino background
    - Prompt neutrinos + astrophysical neutrinos
    - Directional reconstruction is important – initiated by only neutrino induced muon sensitive analysis
- 事象のエネルギー
  - All direction
  - High energy
  - All Flavor
- 事象のトポロジー
  - All direction
  - Flavor sensitive

Extremly-high Energy Neutrino Signal

$$\frac{dE}{dx} \propto E$$





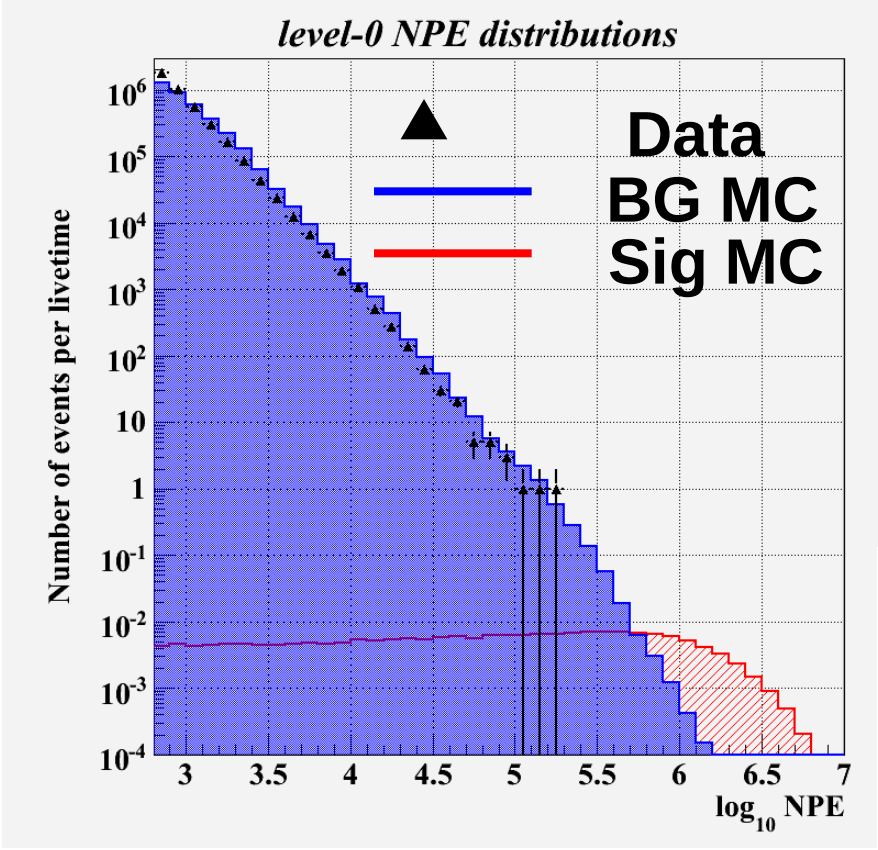
Analysis Flow
for 2008-2009 data with the half IceCube

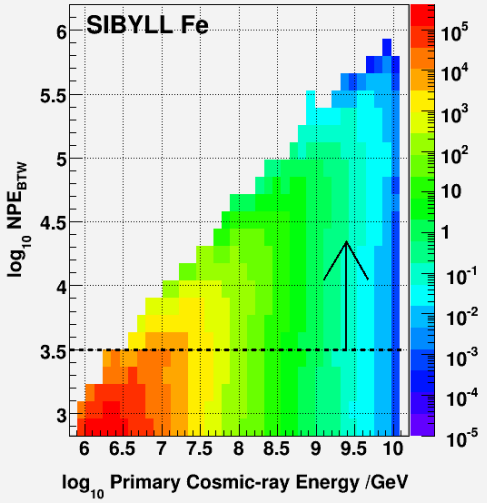
- Level-0 Online filter data reduction
- Level-1 appropriate sets of MCs/Data samples
  - MCs are high energy optimized
- Level-2 Quality cut
  - Less systematics
  - Detailed MC/Data comparisons
- Level-3 Final selection

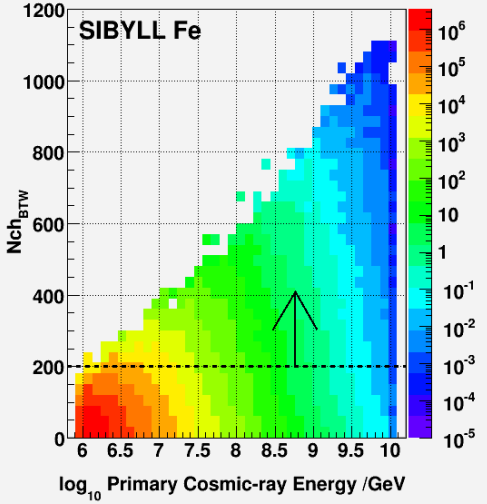
Level-1: Samples

Total livetime 370days

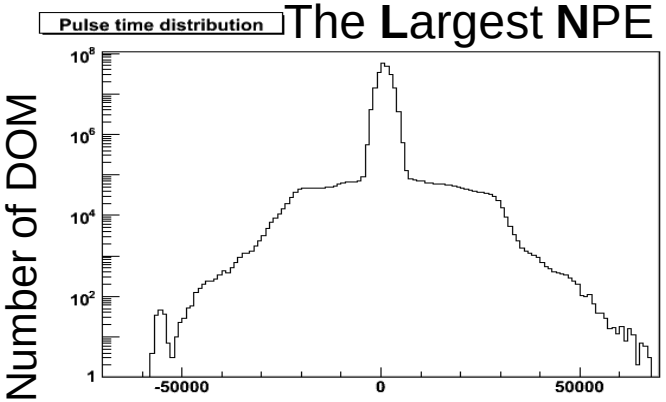
promising GZK neutrinos = high NPE horizontal events







The **L**argest **N**PE **D**OM (LND)

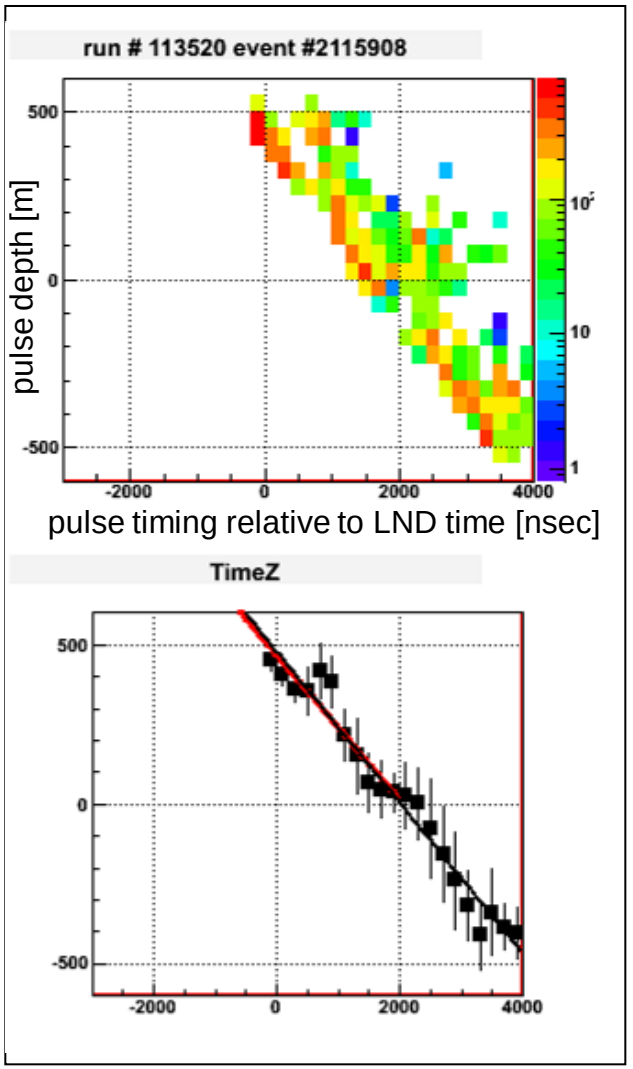


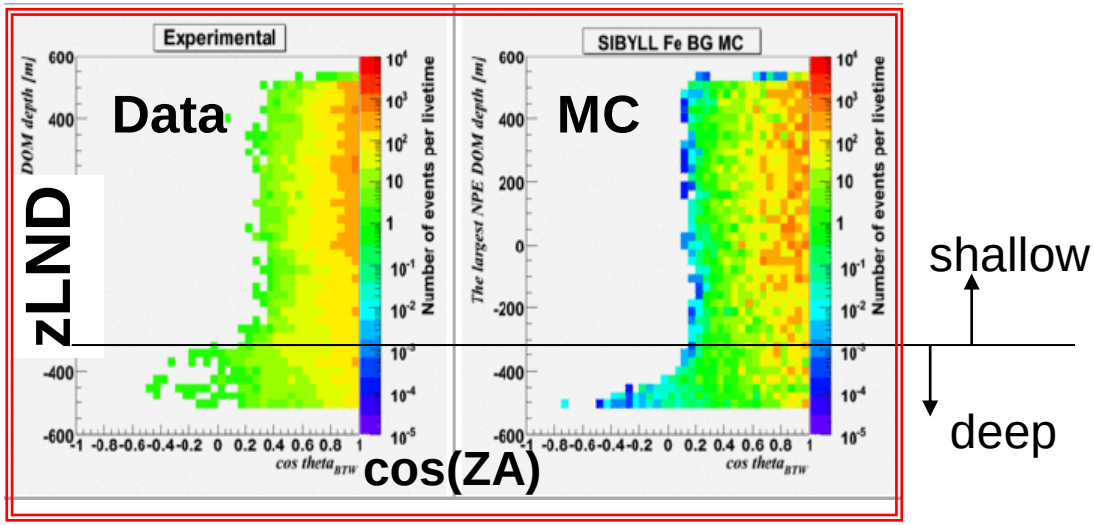
pulse timing relative to LND time[nsec]

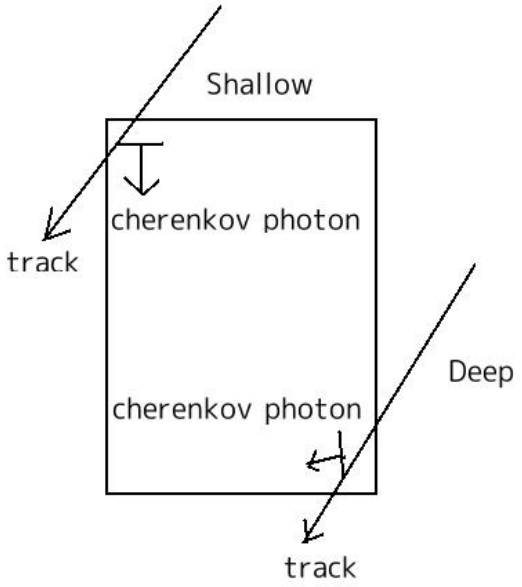
-4400nsec < time relative to the largest NPE time < +6400nsec

Level-2 Quality cut

promising GZK neutrinos = high NPE horizontal events



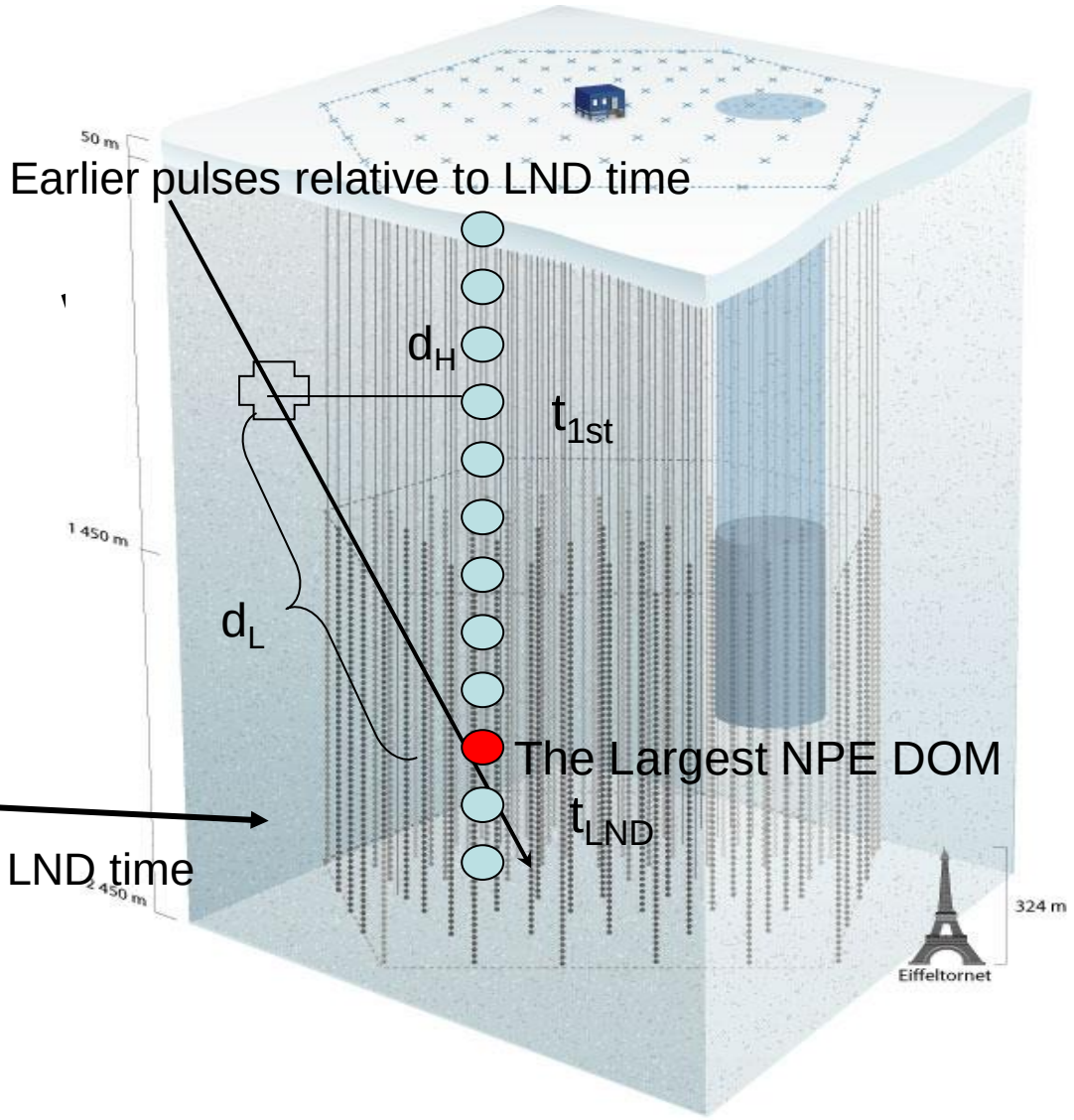




Pulse timing indicates the signal-like-ness

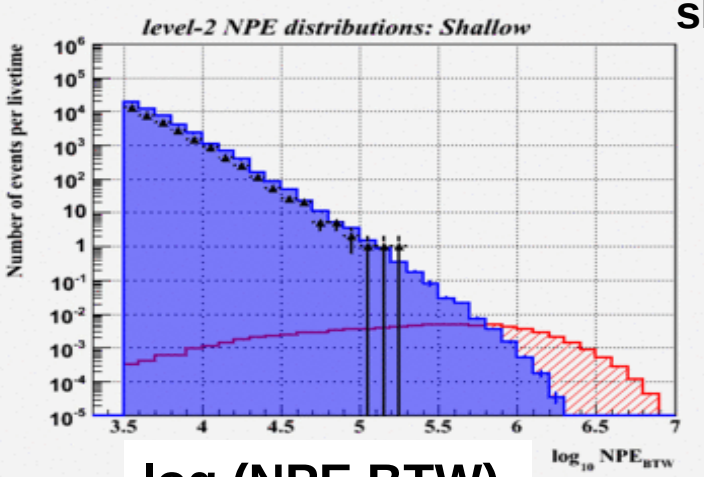
$$eventLength \equiv t_{LND} - t_{1st}$$

Horizontal→ short length
Vertical → long length

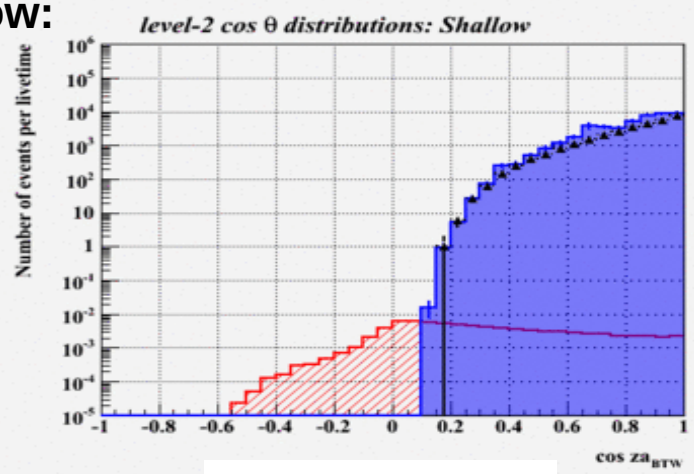


Data and Mcs at Level-2

shallow:

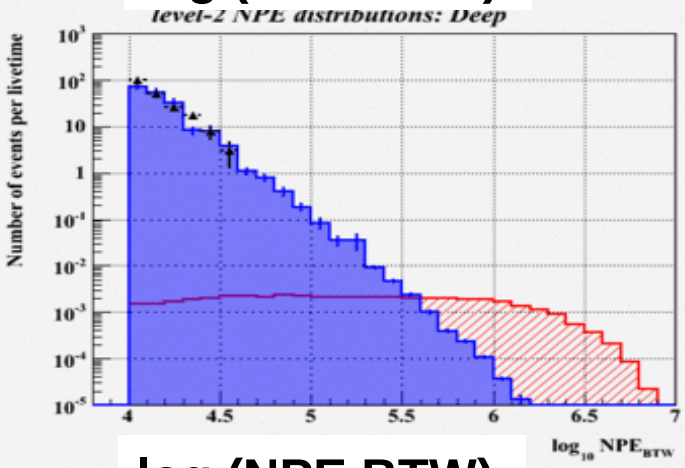


log (NPE BTW)



cos(za BTW)

deep:



log (NPE BTW)

E-LND time [nsec]

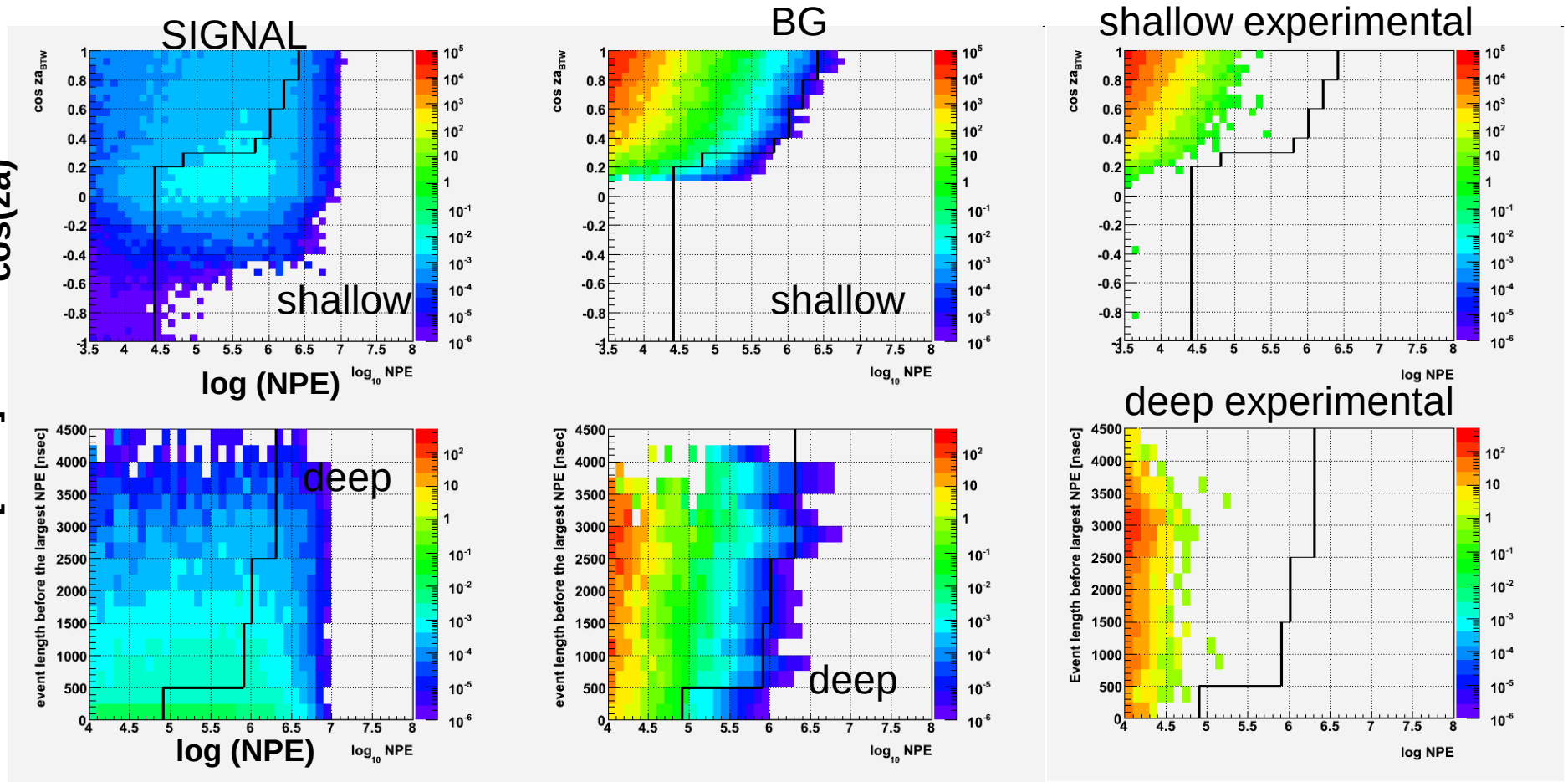
▲ Data (BTW)

BG MC

Sig MC

Level-3 Final Selection

promising GZK neutrinos = high NPE horizontal events



Summary of analysis

Level-0	**Online filtering level – log NPE > 2.8**
Level-1	**Coincidence pulse cleaning,** **MC applicability: Nch > 200 && log NPE > 3.5**
Level-2	**Horizontally mis-reco event cleaning for shallow and timing distributions for deep events**
Level-3	**Final Candidate Selection Criteria**

Error Budget

Signal (GZK1)
± 0.8 %(stat.)
+14.0 -11.6 %(sys.)

Err. Sources	Signal (GZK model)
statistical error	± 0.8 %
NPE measurement in-situ calib. -18.5% in-lab calib. 10.1%)	+3.89 / -7.22 %
neutrino cross section	± 9.0 %
photo-nuclear interaction	+10.0 %
LPM effect	± 1.0 %

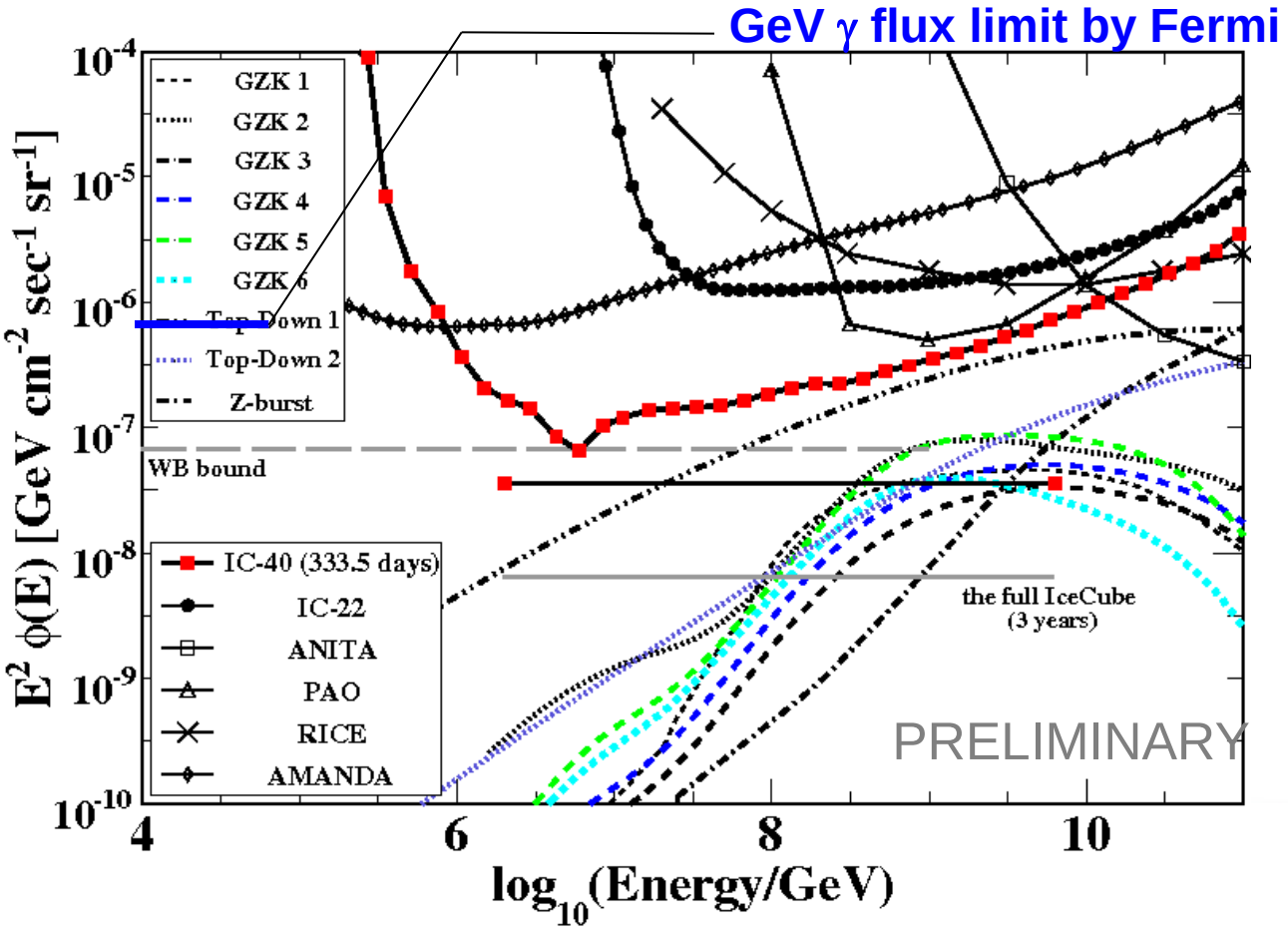
Background
± 17.0% (stat.)
+60.4 % -96.0%(sys.)

Err. Sources	Background
statistical error	±17.0 %
Composition	-83.86%
interaction model	+36.1%
Coincident event (cos theta>0.2)	+29.4%
Coincident event (cos theta<0.2)	+10.5%
ice property	+30.2% / - 22.2%
NPE measurements	+37.1% / -46.7%

Diffuse neutrinos with extremely-high energies

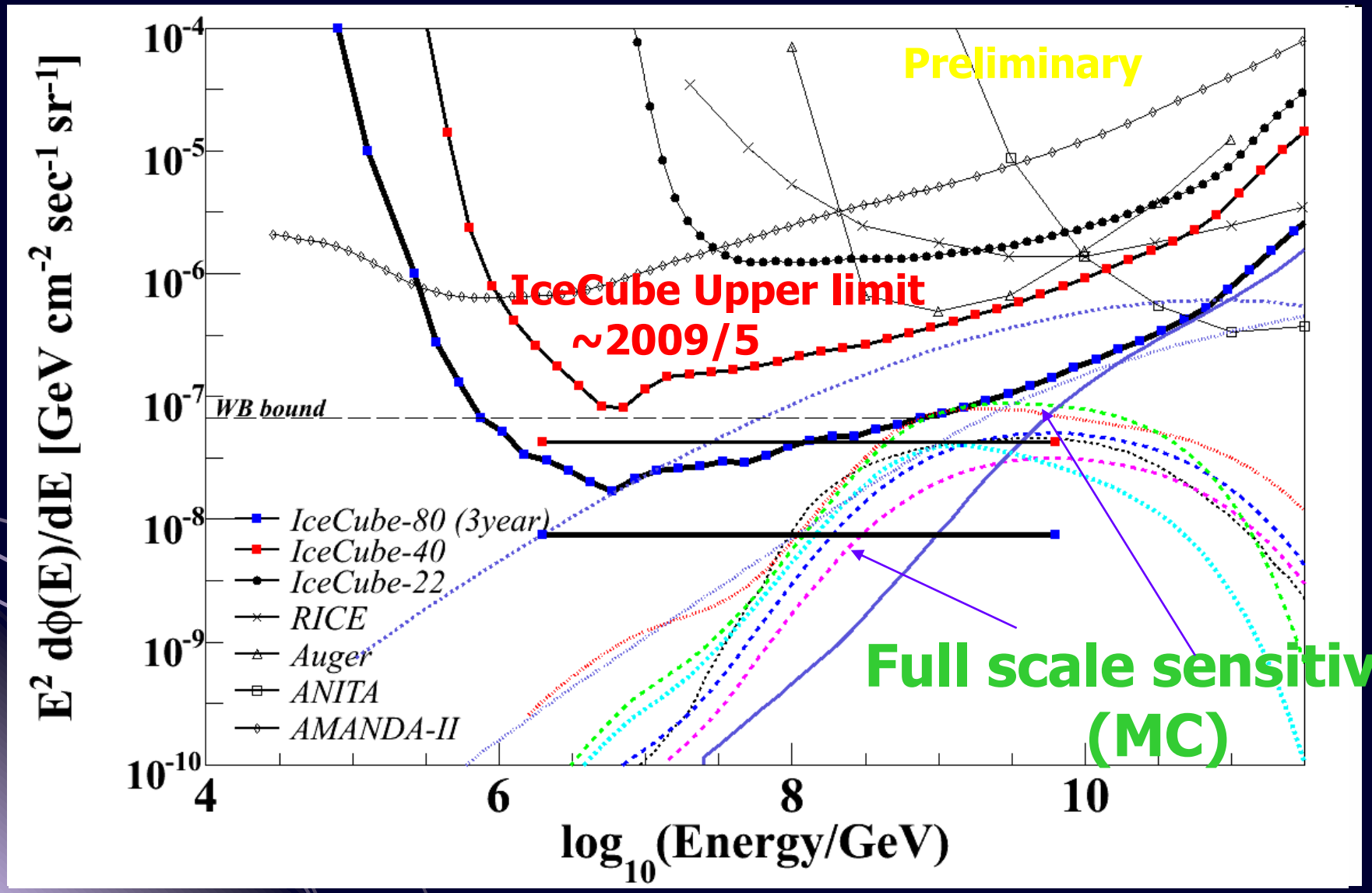
E^{-2} flux upper limit in $10^{6.3}$ < Energy/GeV < $10^{9.8}$

333.4 days upper limit with only the half detector



*Yoshida et al The ApJ 479 547-559 (1997), **Kalahsev et al , Phys.Rev.Rev. D 66 063004 (2002), ***Engel et al, Phys. Rev. D, 64(9):093010, 2001, ****Ahlers et al, Astropart. Phys. 34 106-115 (2010) #Yoshida et al, Phys.Rev.Lett. 81 5505 (1998),##Sigl et al , Phys.Rev.Rev. D 59 043504 (1998), ^Razzaque et al(2003)

Near Future Sensitivity



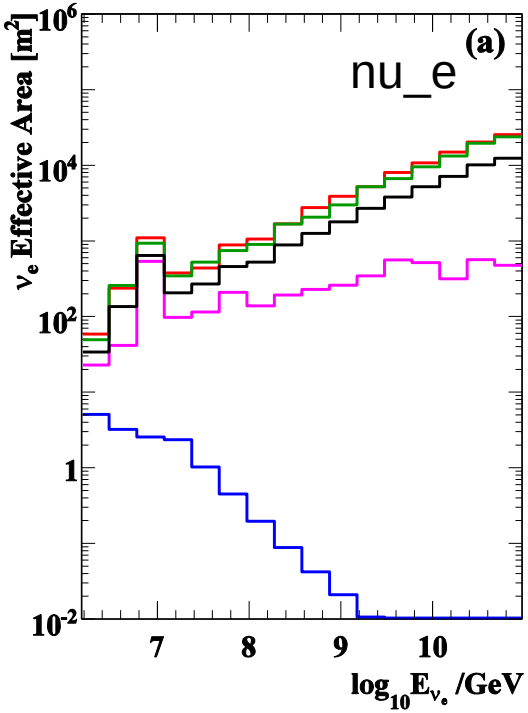
Expected EHE signal event rates

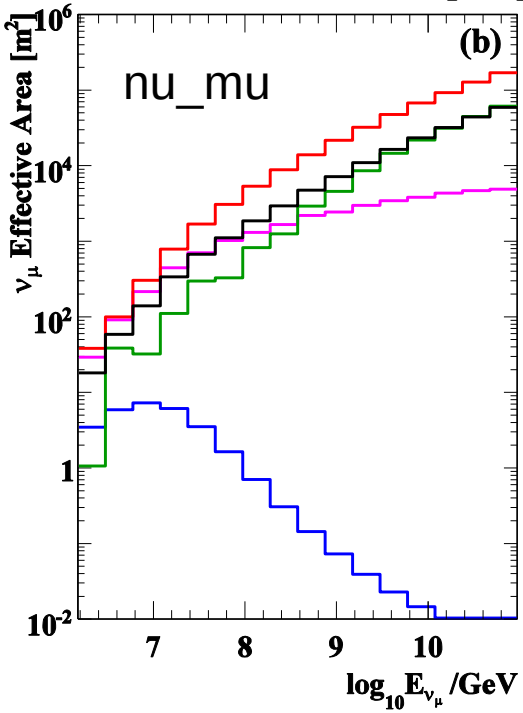
Models	The half IceCube # of events	The full IceCube # of events (3 years)
GZK1 (Yoshida et al) *	0.57	3.1
GZK2 Strong Evol. (Sigl) **	0.91 (C.L 53.4%)	4.9
GZK3 (ESS with W_L=0.0) ***	0.29	1.5
GZK4 (ESS with W_L=0.7) ***	0.47	2.5
GZK5 (Ahlers max) ****	0.89 (C.L 52.8%)	4.8
GZK6 (Ahlers best fit) ****	0.43	2.3
Z-Burst #	1.03 (C.L 55.7%)	5.1
Top Down(SUSY) ##	5.68 (C.L 99.6%)	31.6
Top Down(QCD) ###	1.19 (C.L 66.4%)	6.3
W&B(evol) ^	3.7	24.5
W&B(no evol) ^	1.1	5.5

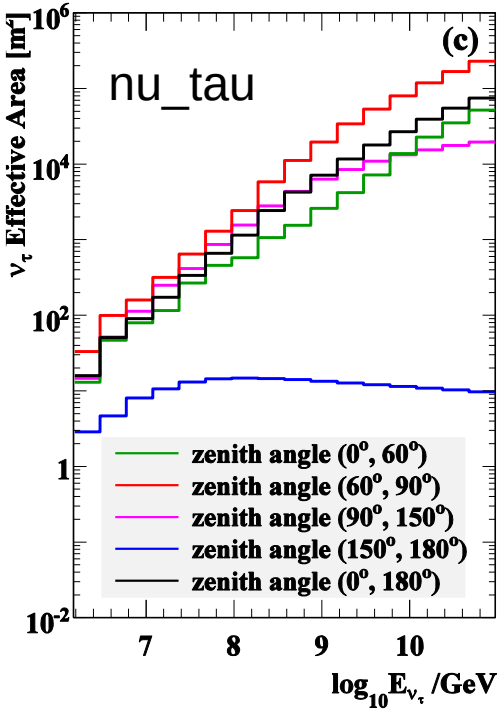
*Yoshida et al The ApJ 479 547-559 (1997), **Kalahsev et al , Phys.Rev.Rev. D 66 063004 (2002), ***Engel et al, Phys. Rev. D, 64(9):093010, 2001, ****Ahlers et al, Astropart. Phys. 34 106-115 (2010) #Yoshida et al, Phys.Rev.Lett. 81 5505 (1998),##Sigl et al , Phys.Rev.Rev. D 59 043504 (1998), ^Razzaque et al(2003)

Flavor and Angle Dependence

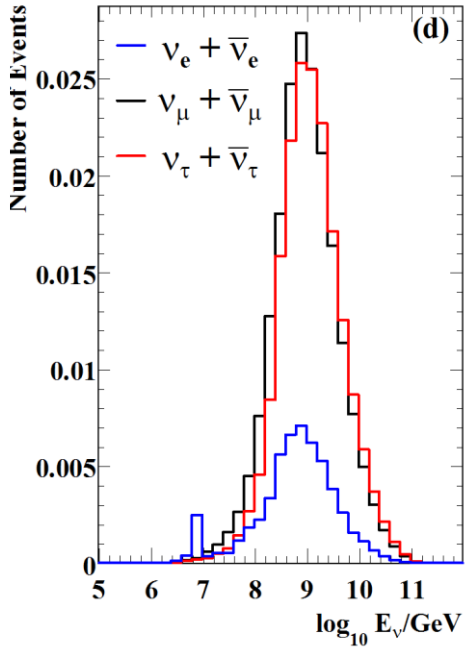
Effective Area [m^2]



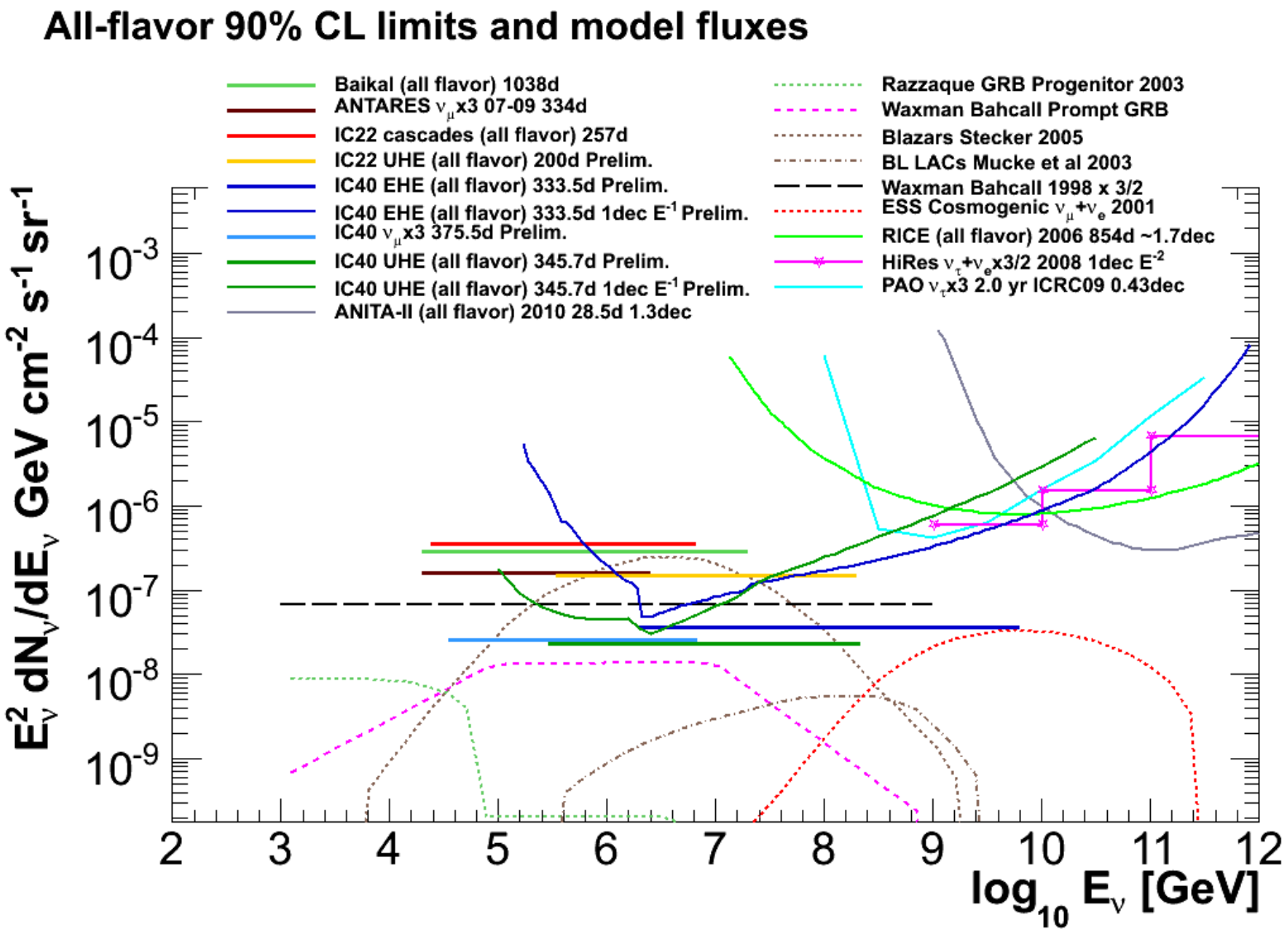




Event rates

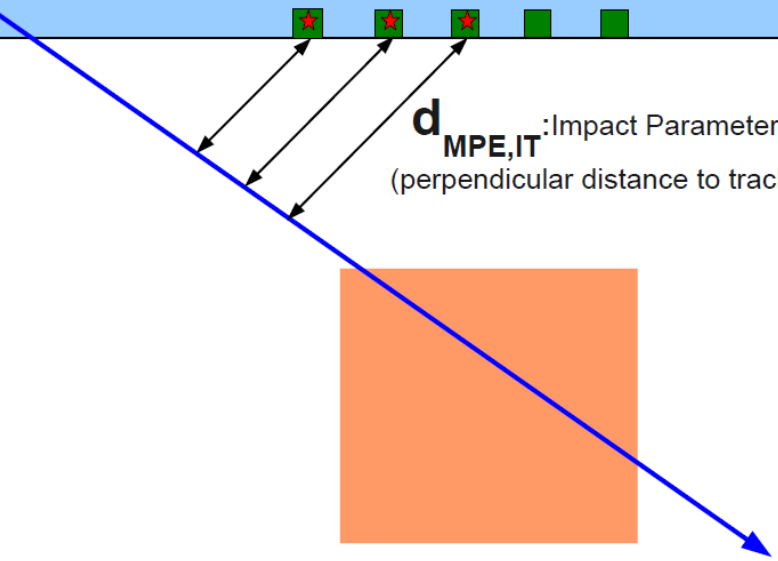


IceCube Sees Wide Energy Range



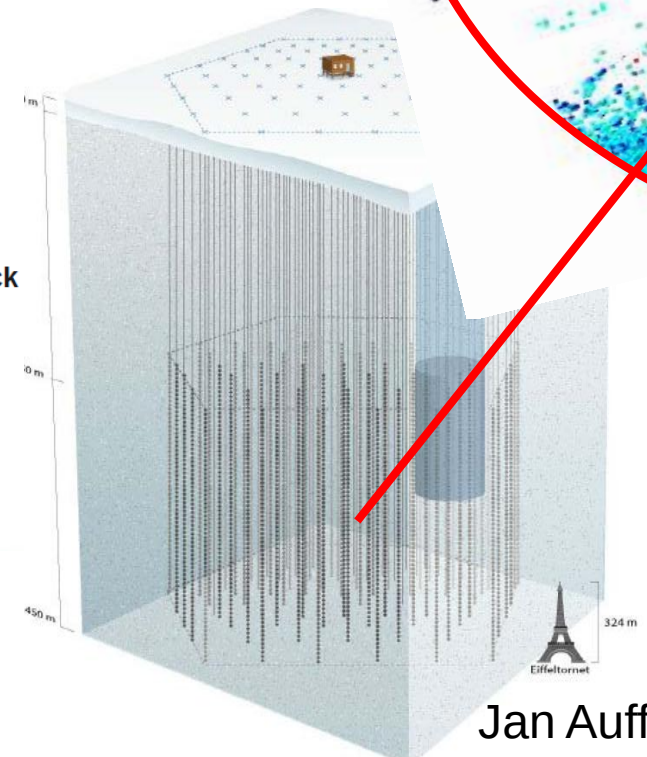
Future implementation 1: IceTop SLC Veto

Δt: Time difference between intersection of shower plane with IT tank and IT hit time stamp (raw!)



$d_{MPE,IT}$:Impact Parameter
(perpendicular distance to track)

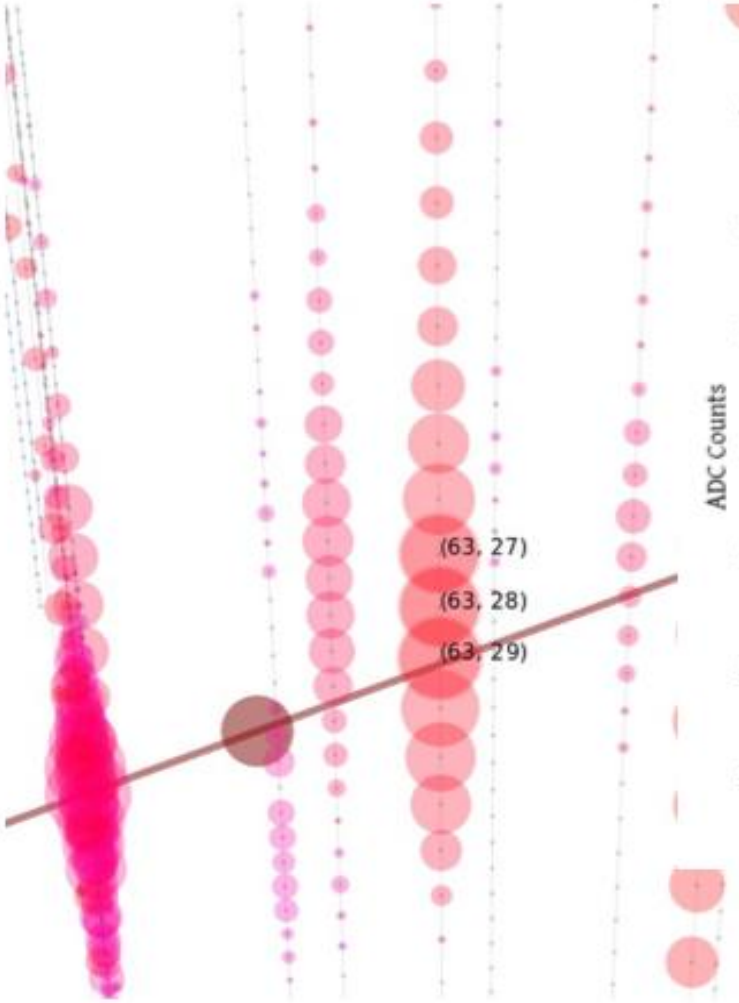
InIce Track

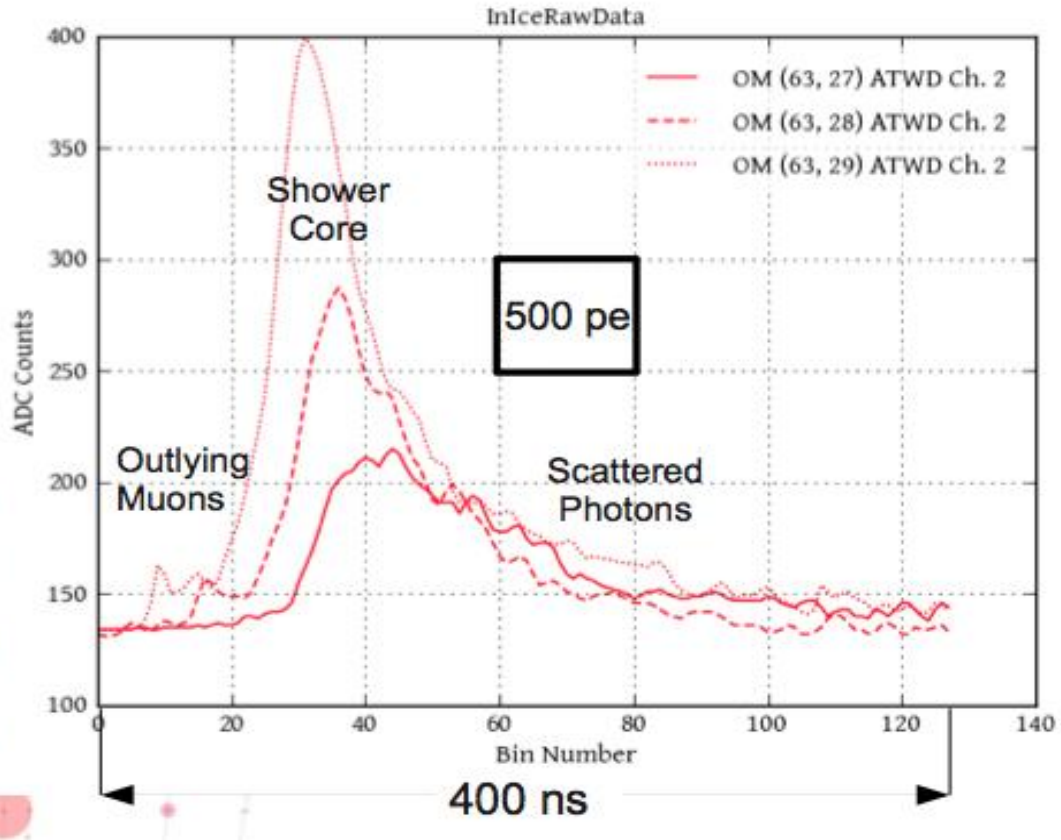


Jan Auffenberg and Shirit Cohen

Future implementation2: Bundles, outlying muons & more

DOM Waveforms and Event Topology





Patric Berghaus and Shirit Cohen

Outlook

- 2008-2009データによる、EHE ニュートリノ解析によってIceCubeにおけるGZKニュートリノ探索のベースラインは確立。（DraftはFinal Collaboration review中、来週中にはペーパーSubmitします）
- 2009-2010年度データ解析中（ICRC2011）
  - 2008-2010　Combinedデータで現在のリミットの1/2
- 2010-2011年度データ解析にむけた新しいBG vetoの手法の開発中（ICRC2011）
- 2008年4月から2012年5月までのCombinedデータ解析（Full IceCube 3年分相当）でGZKモデルの議論が可能！

The IceCube Collaboration

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