Latest results of the IceCube experiment

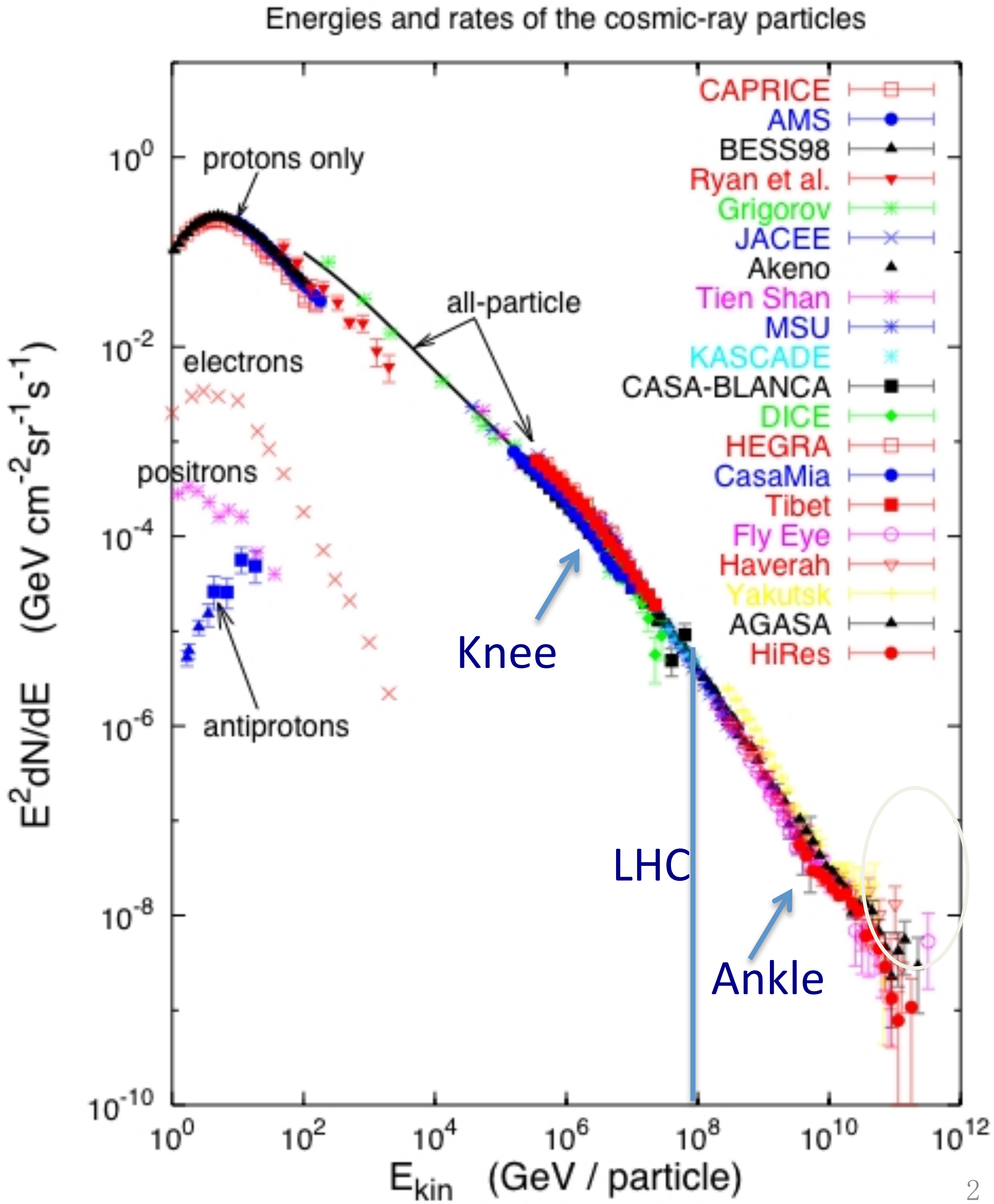
- Especially the extremely high energy cosmogenic neutrino search

K. Mase, Chiba Univ.

Cosmic rays

- Firstly detected by V. F. Hess in 1912
- Wide energy spectrum (10^{9-21} eV). (1eV: ~visible light)
- Believed to be accelerated in a shock of a source
- The origin not fully understood yet!

V. F. Hess



But, where?

Where are cosmic rays generated?

→ we don't know yet

(We know where electrons are accelerated)

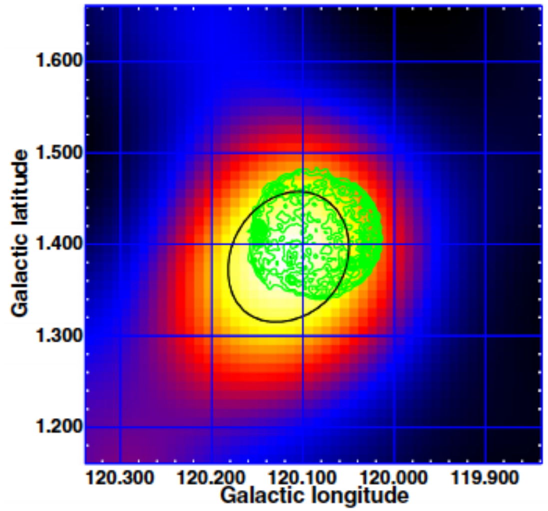
→ Neutrinos can tag it.

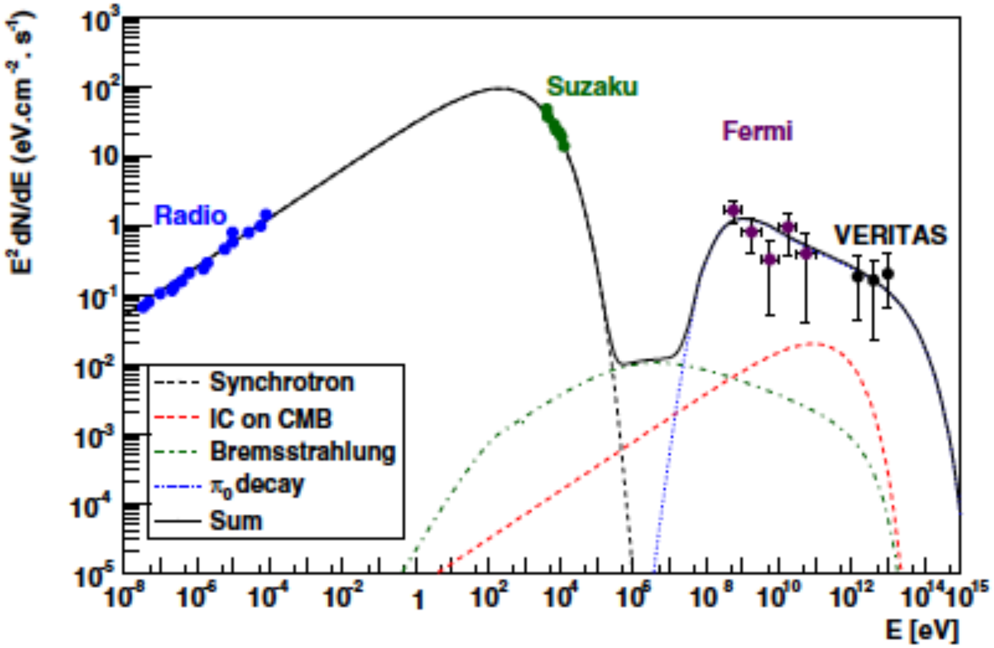
Note: in case of a photo-pion production, roughly same energy amount goes to neutrinos and gammas

$$p+\gamma \rightarrow n+\pi^{+} \rightarrow n+\mu+\nu_{\mu}$$
$$\rightarrow n+e+\nu_{e}+2\nu_{\mu}$$
$$p+\gamma \rightarrow p+\pi^{0}$$
$$\rightarrow p+2\gamma$$

Even more if we consider gamma-ray absorption.

Tycho





ApJ. Lett., 744 L2 (2012)

Neutrinos should be there

The source of cosmic rays are the neutrino source

$$p\gamma \rightarrow n\pi^{+} \rightarrow \mu\nu_{\mu}$$

Waxman-Bahcall limit

E. Waxman and J. Bahcall, PRD, 59, 023002 (1998)

Limit from observed CR
(optically thin assumed)

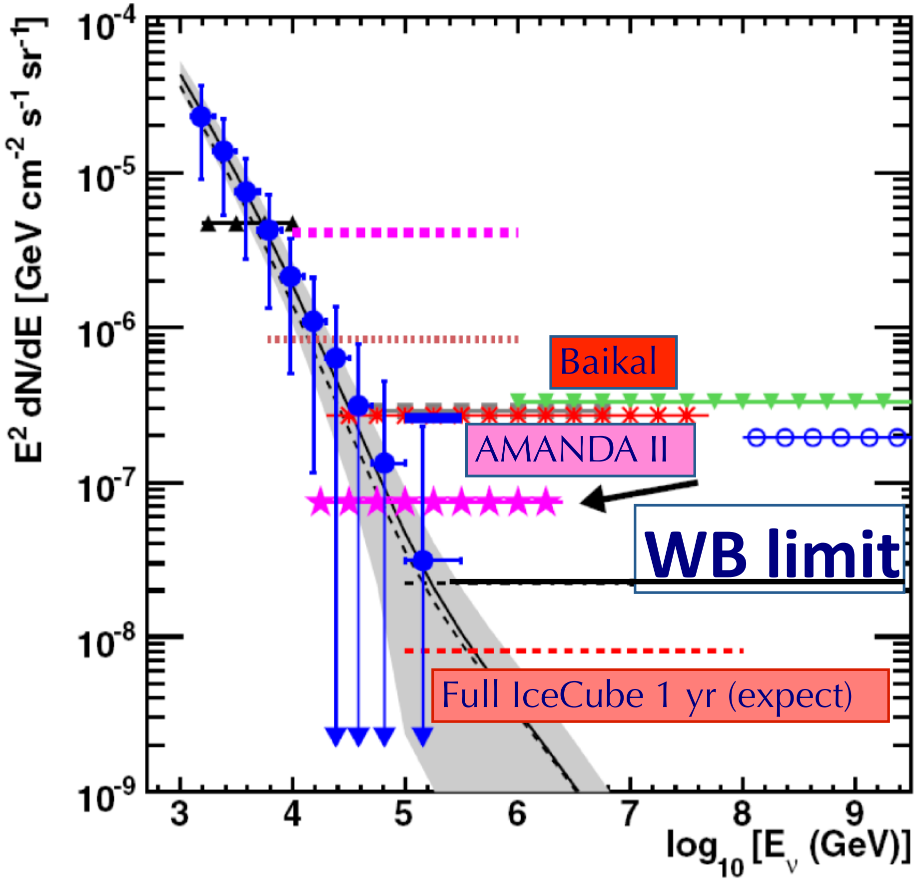
$$E_{\nu}^{2}\Phi_{\nu_{\mu}} = \frac{\varepsilon}{8}\xi_{Z}t_{H}\frac{c}{4\pi}E_{CR}^{2}\frac{d\dot{N}_{CR}}{dE_{CR}}$$

ε: fraction of energy going to neutrinos

ξ_z: cosmological evolution (order unity)

If ε=1, WB limit

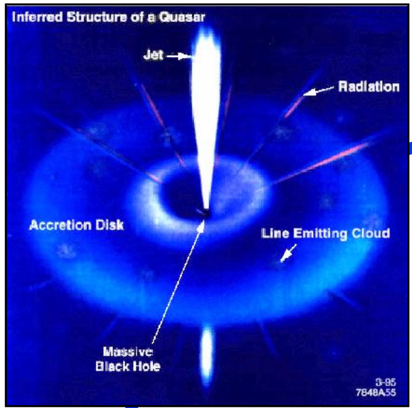
$$E_{\nu}^{2}\Phi_{\nu_{\mu}} \approx 2\times10^{-8}\ GeV\,cm^{-2}s^{-1}sr^{-1}$$



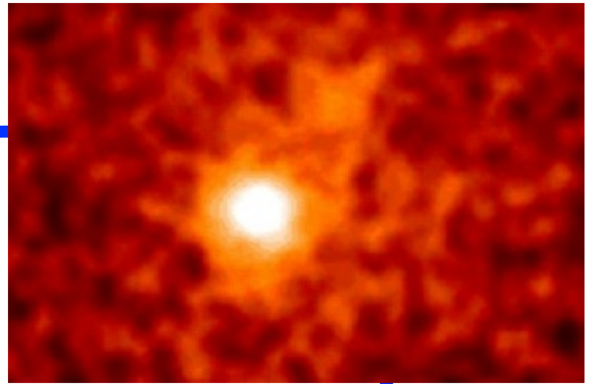
The sensitivity of 1 km^3 size detector is lower than WB limit.

The physics of IceCube

Want to open the neutrino astronomy

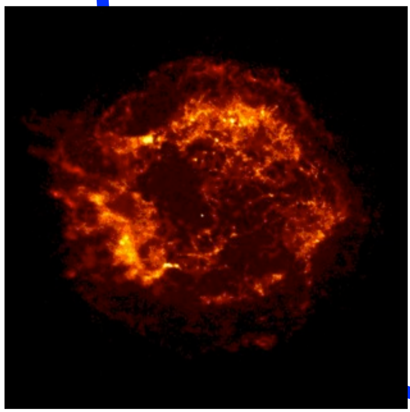


- AGNs

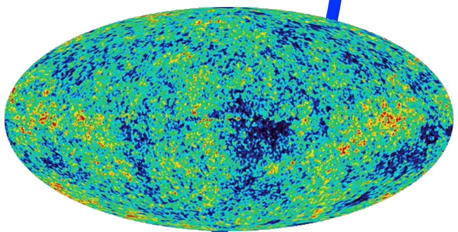


- GRBs

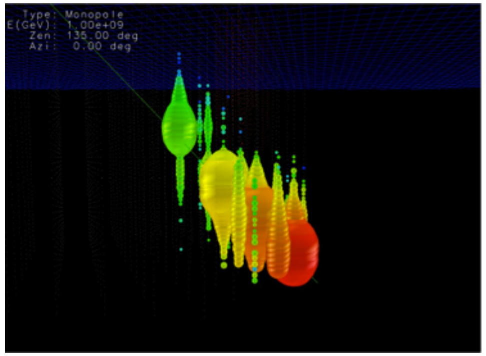
- Dark Matter
- **particle physics**
- **Cosmic ray origin**



- Supernova



- GZK neutrinos



- Exiotic

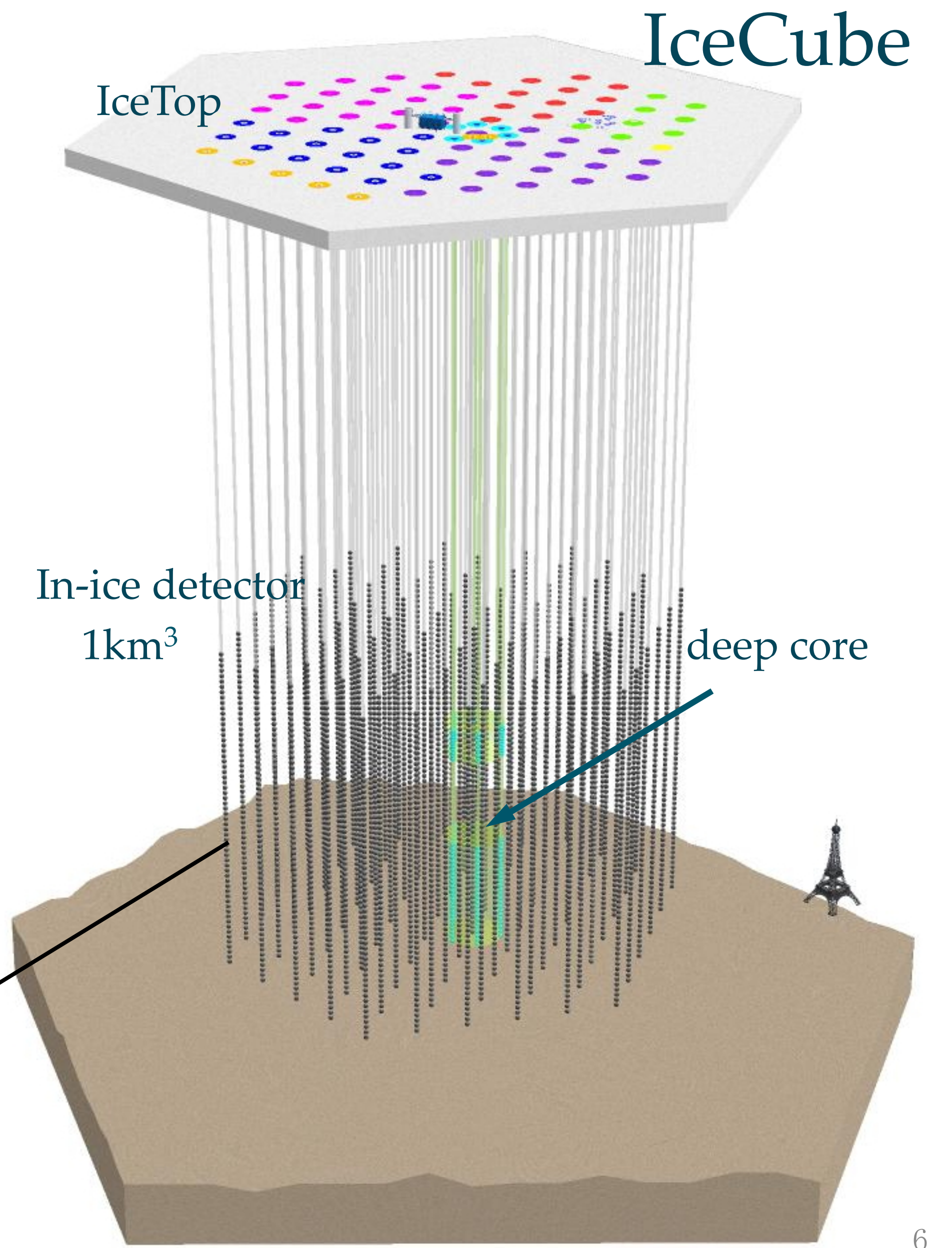
(monopole, Q-ball, etc…)

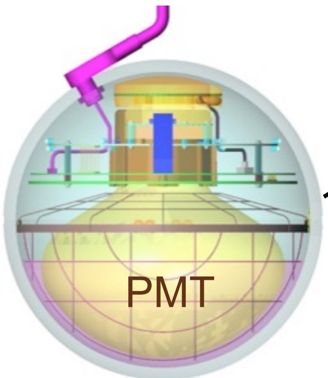
The IceCube experiment

- Deployed in the Antarctica glacier
- In-ice + IceTop + deep core
- 86 strings (completed 2010!)
- ~ 5,000 photo-multiplier tubes (PMTs)
- Detector volume: ~ 1 km^3
- ATWD 300MSPS

  3 different gains (x16, x2, x0.25)
- FADC for long duration pulse
- Targets for cosmic high energy neutrinos

  (>~ 100 GeV)





Digital Optical Module
(DOM)

The IceCube Collaboration

36 institutes and ~250 physists

Univ. of Alberata, Canada
Bartol Research Inst, Univ. of Delaware, USA
Pennsylvania State University, USA
Univ. of Wisconsin-Madison, USA
Univ. of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, USA
Univ. of Alaska Anchorage, USA
Georgia Tech, USA
Ohio State Univ., USA

Chiba Univ., Japan

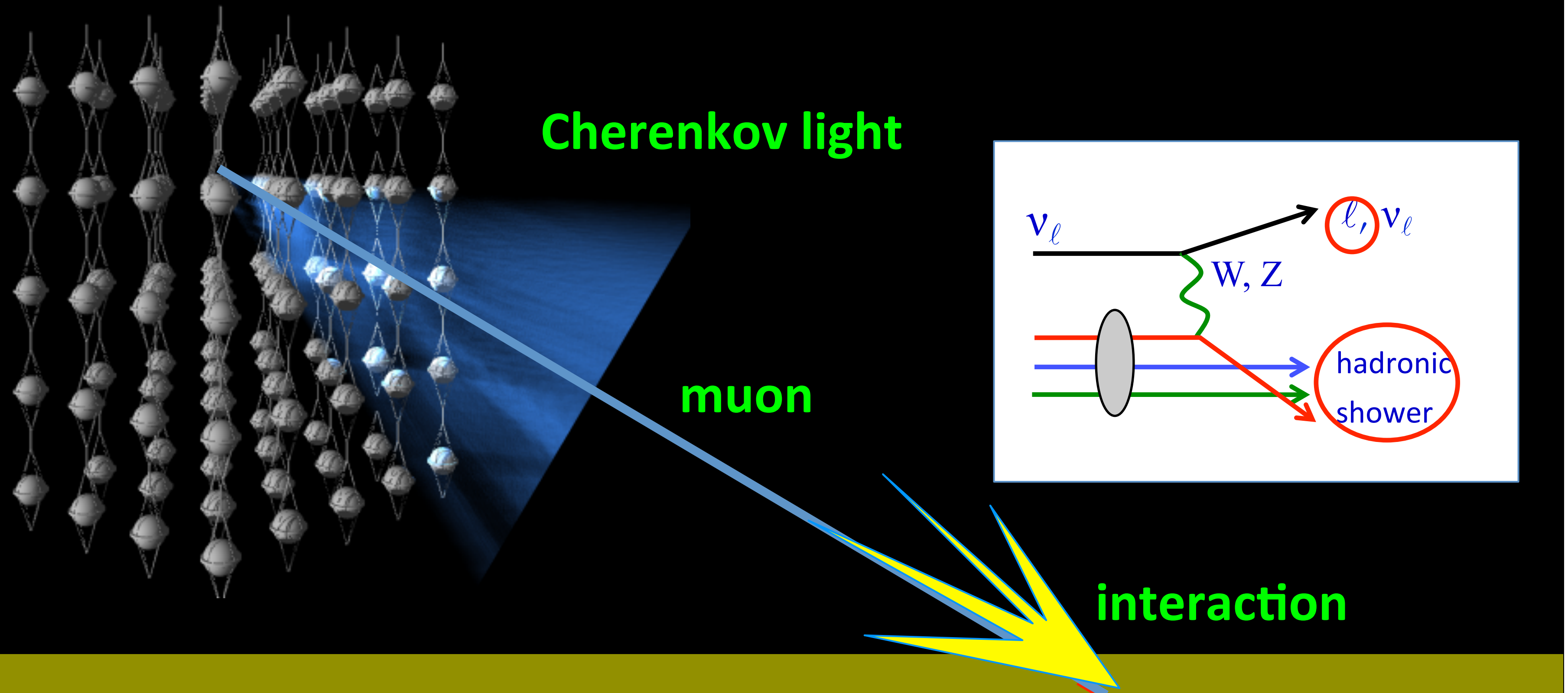
Univ. Of West Indies, Barbados

Univ. of Canterbury, New Zealand

Univ. Libre de Bruxelles, Belgium
Vrije Univ. Brussel, Belgium
Univ. de Mons-Hainaut, Belgium
Univ. of Gent, Belgium
Univ., Mainz, Germany
DESY-Zeuthen, Germany
Univ. Wuppertal, Germany
RWTH Aachen Univ., Germany
Humboldt Univ. zu Berlin, Germany

Univ. Bonn, Germany
Ruhr-Univ. Bochum, Germany
Univ. Dortmund, Germany
MPI Heidelberg, Germany
Uppsala Universitet, Sweden
Stockholm universitet, Sweden
University of Oxford, UK
Ècole Polytechnique Fèdèrale, Switzerland

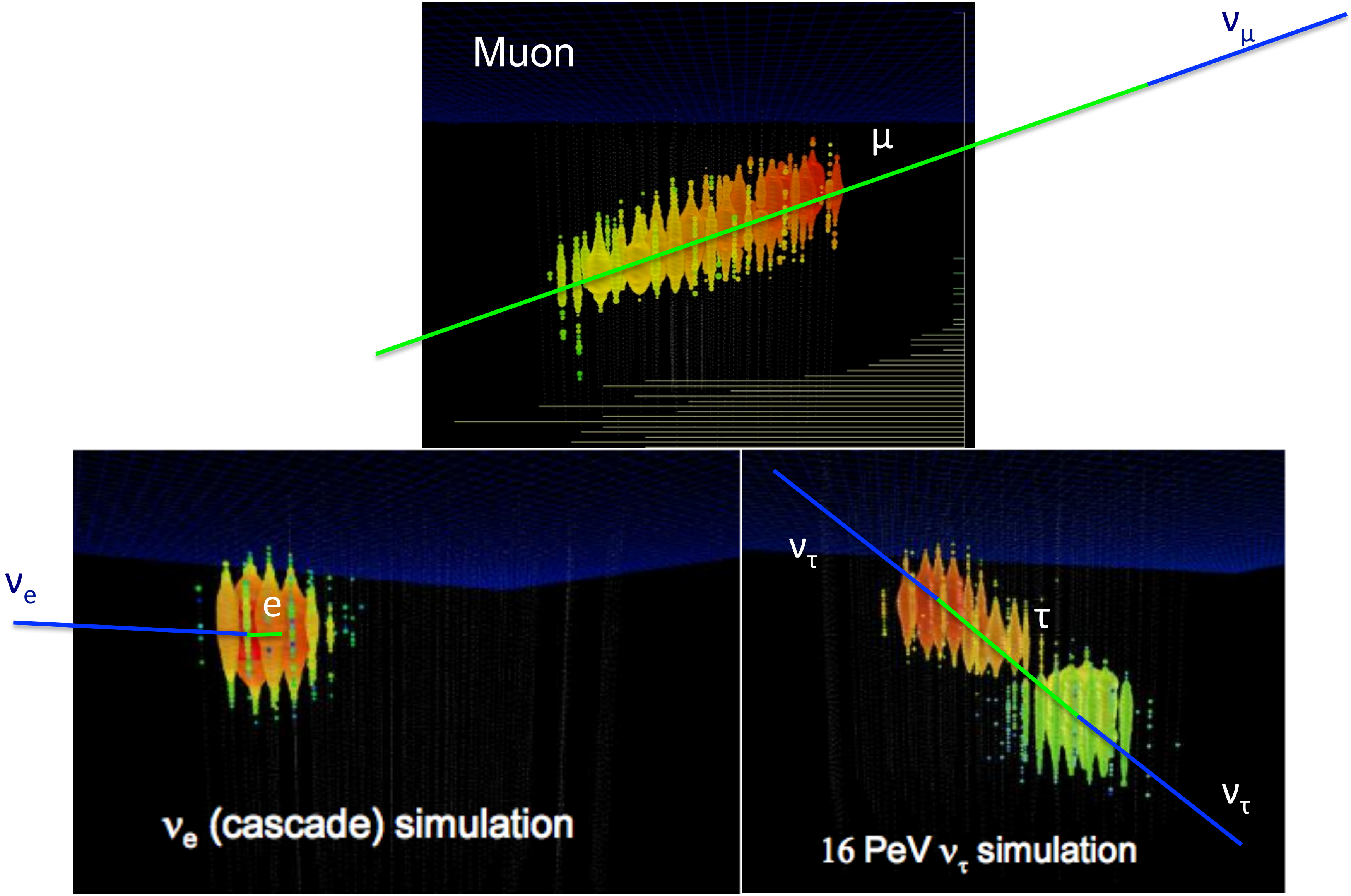
The detection principle



- A large volume
- transparent medium

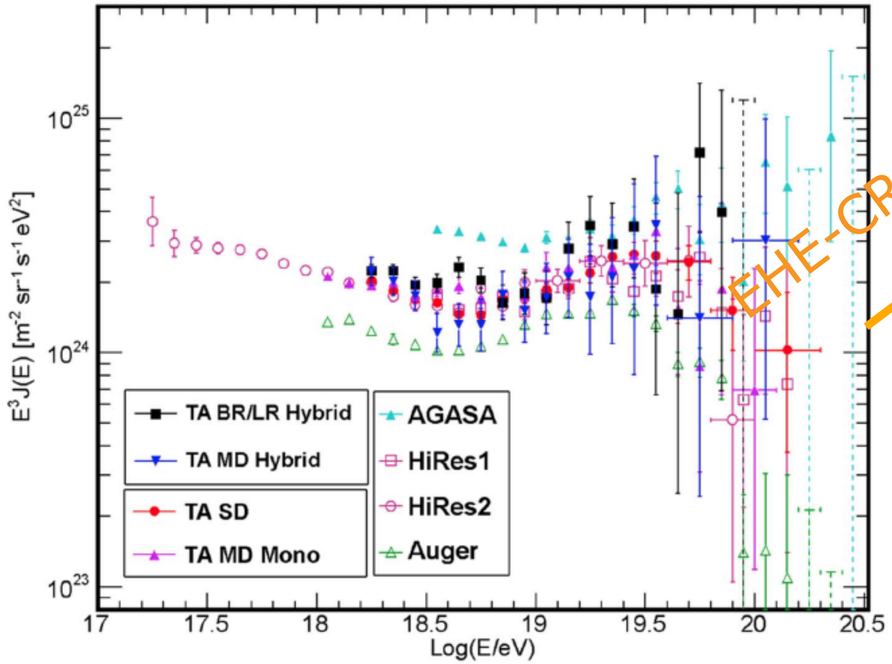
→ Antarctica glacier

Particle types

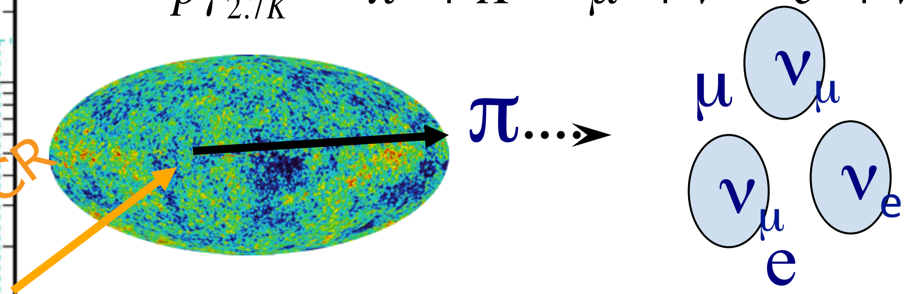


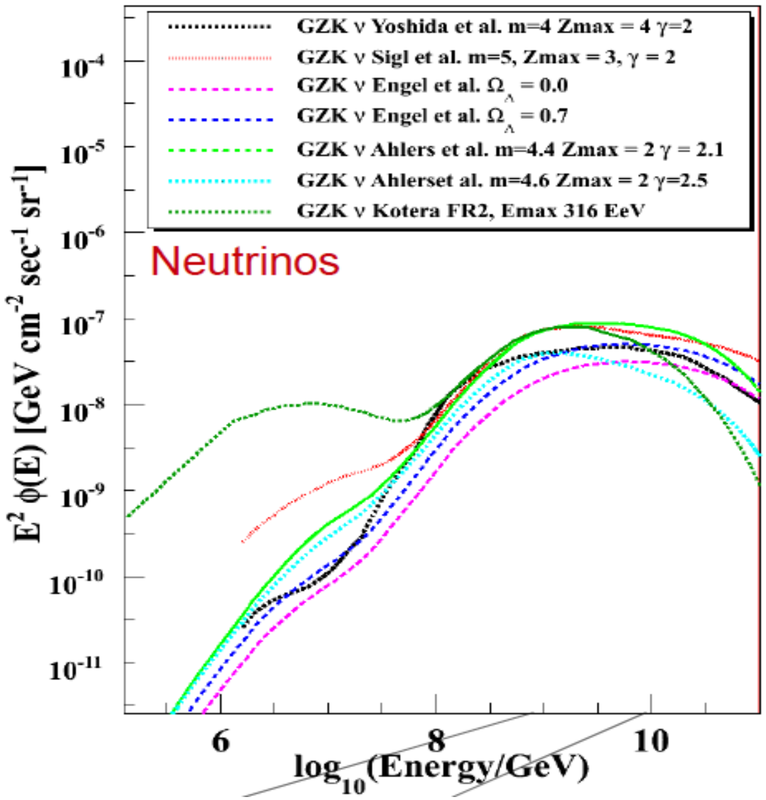
NC interactions also make cascades

The extremely high energy (EHE) cosmogenic neutrinos (> 10^8 GeV)



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





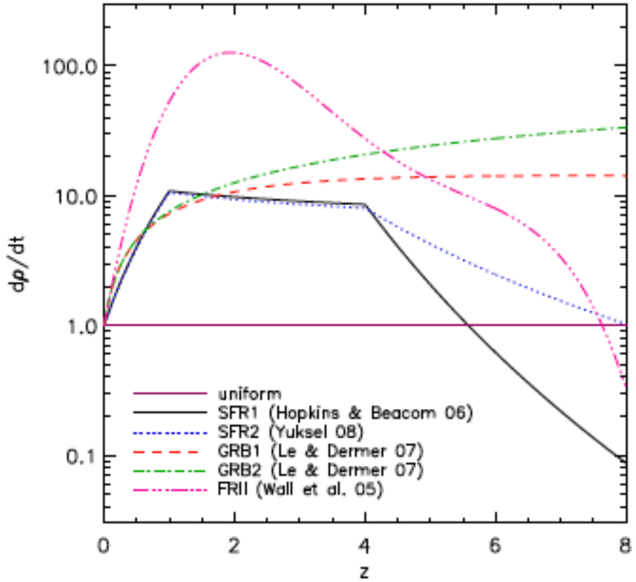
Shed light on the EHECR origin

- ✧ Source position
- ✧ Composition (proton/iron)?
- ✧ Source evolution / when the EHECR generation stars

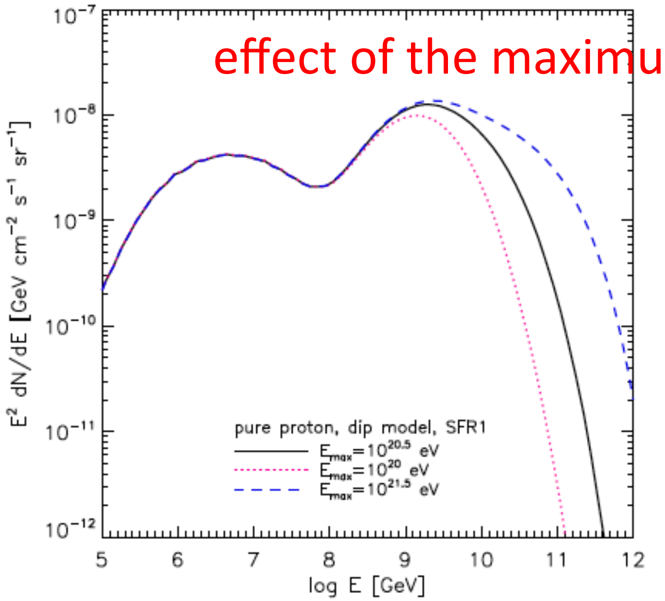
Predicted, but never detected

→ **detectable with IceCube**

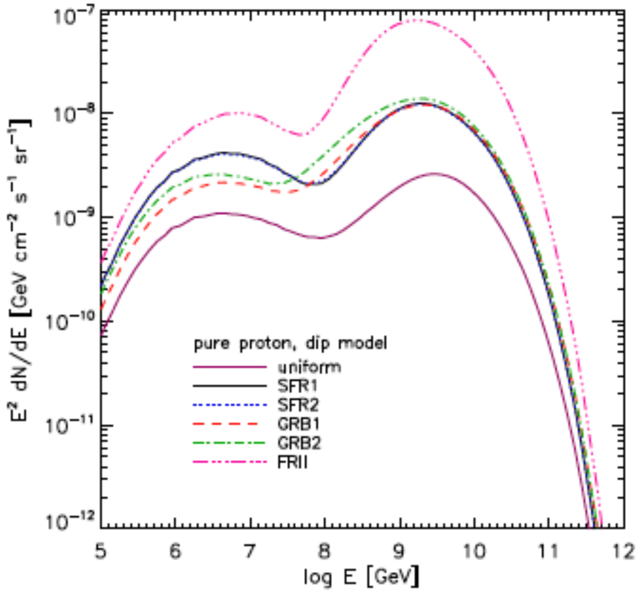
❑ Effect of source evolution and maximum energy on neutrino flux



effect of the maximum energy



effect of the source evolution

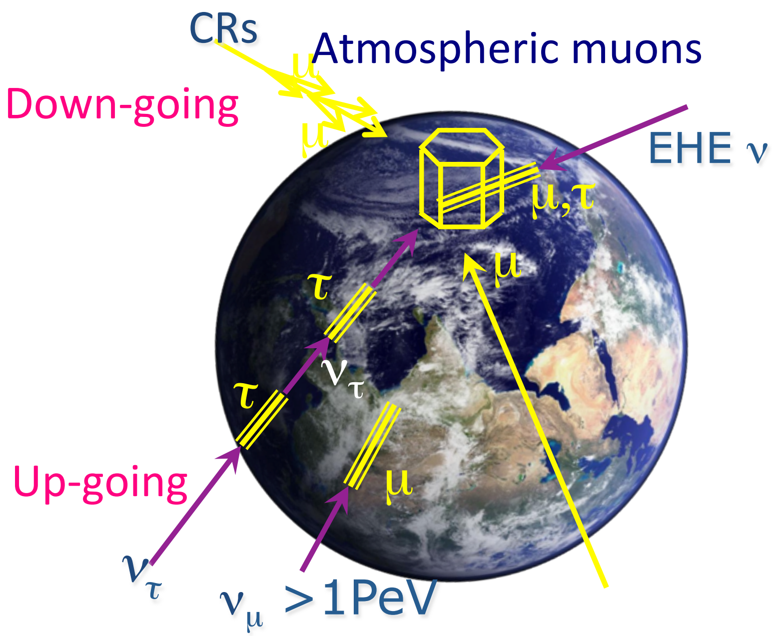


neutrino flux depend on the source evolution and maximum energy

-> constraint on the parameters

Kotera et al., JCAP 10 (2010) 013

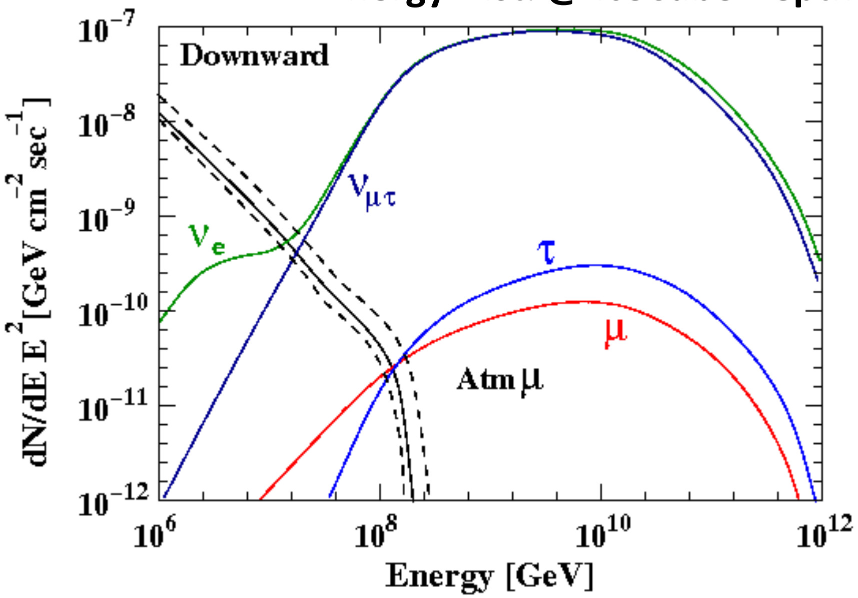
The detection principle



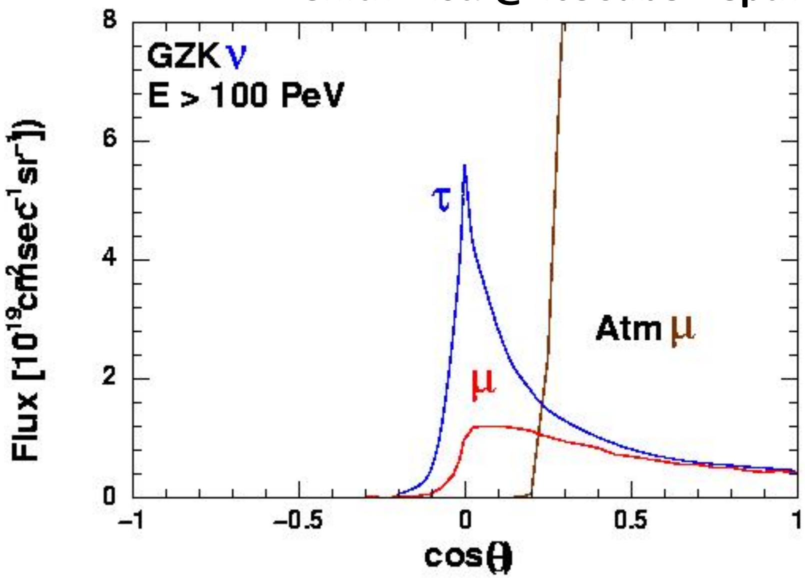
- EHE neutrino signal (all flavor)
  - horizontal (opaque to the earth)
  - high energy (> 10^8 GeV)
- Atmospheric muon background
  - down-going
  - low energy (the energy spectrum is steep (~$E^{-3.7}$))

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

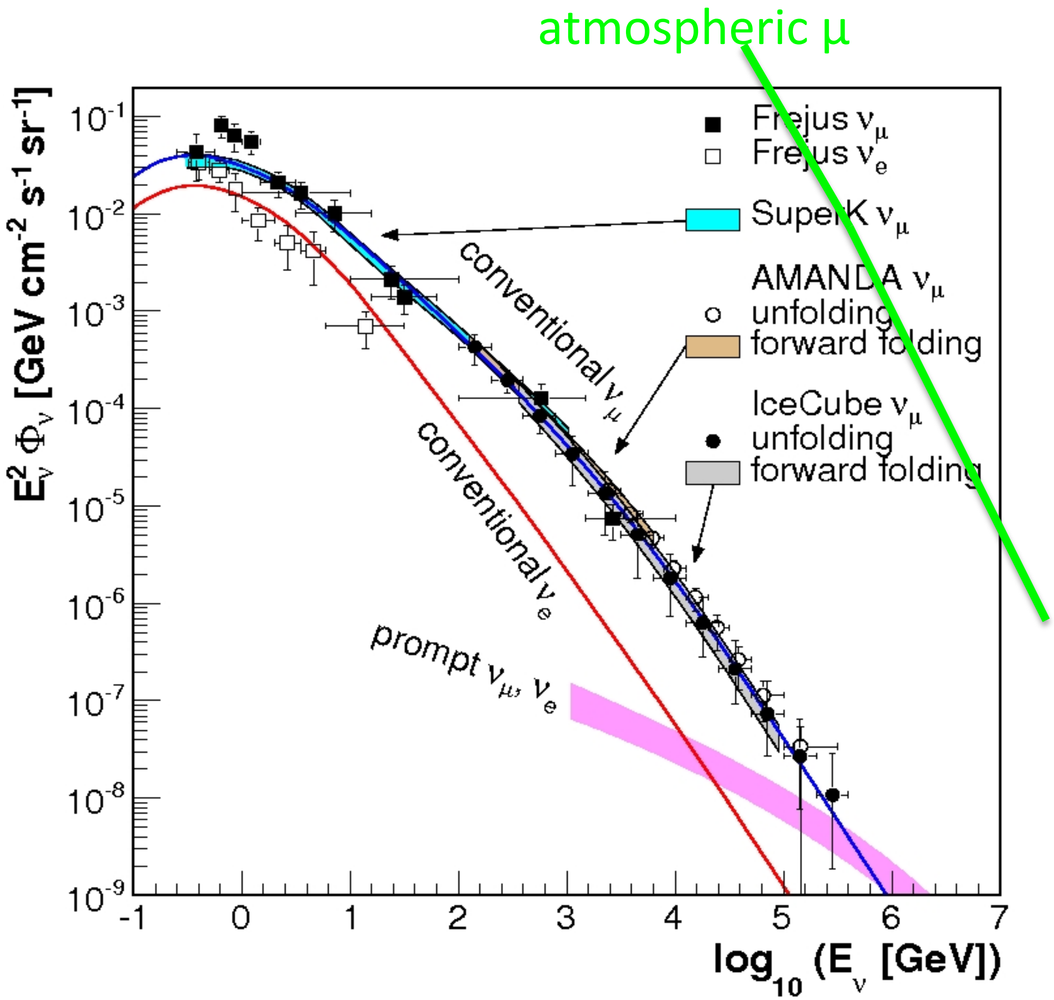
Energy Dist. @ IceCube Depth



Zenith Dist. @ IceCube Depth



The spectrum of backgrounds



$$\frac{dN}{dE} \propto \frac{dN_{CR}}{dE} \frac{A}{1 + B\cos\theta \frac{E}{\varepsilon}}$$

θ: zenith angle, ε: critical energy

- atmospheric μ

$$\frac{dN_\mu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\,GeV)$$

$$\frac{dN_\mu}{dE} \approx 10^6 \frac{dN_\nu}{dE}$$

- atmospheric ν

$$\frac{dN_\nu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\,GeV)$$

- prompt ν
  - decay from charmed particles

$$\frac{dN}{dE} \propto E^{-2.7} \; (< \varepsilon_{charm} = 10\,PeV)$$

❑ Datasets

Five datasets are used in this analysis:

1. Observational data
   - taken in 2010-2011 (319.2 days)
   - taken in 2011-2012 (350.9 days)

   EHE level2a data (NPE > 1000)
   ~3.0 M events, ~ 0.9-1.3 Hz (2010-2011)

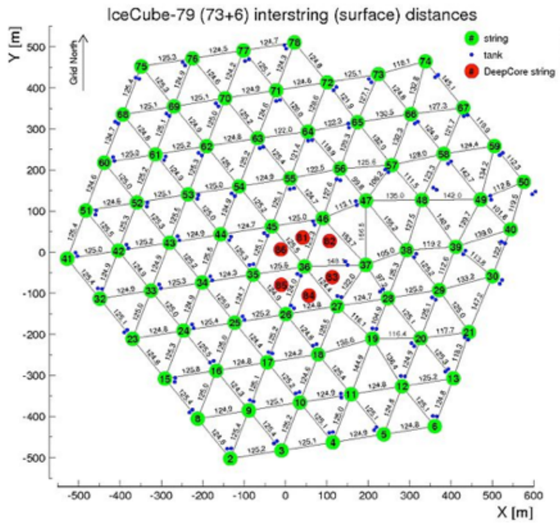
2. Signal MC data (JULIeT)
   10^5-10^{11} GeV, E^{-1}
   20k events for μ, τ, ν_e, ν_μ, ν_τ

3. Atmospheric muon background MC data (CORSIKA data)
   10^5-10^{11} GeV, E^{-1}, takes long time…
   15k events for proton and iron
   SIBYLL HE interaction model

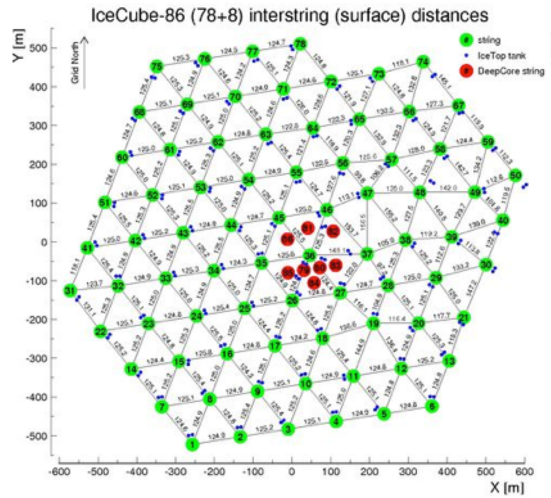
4. Coincidence muon MC data (CORSIKA data)
   600-10^{11} GeV, $E^{-1.7}$, polygonate model (J. R. Hoerandel, 2003)
   10G events (10000 files)
   SIBYLL HE interaction model

5. Atmospheric neutrino background MC data
   10^3-10^9 GeV, E^{-1}, ν_μ, ν_e
   10M events (2000 files)
   Honda flux (2007) + knee correction (Gaisser)

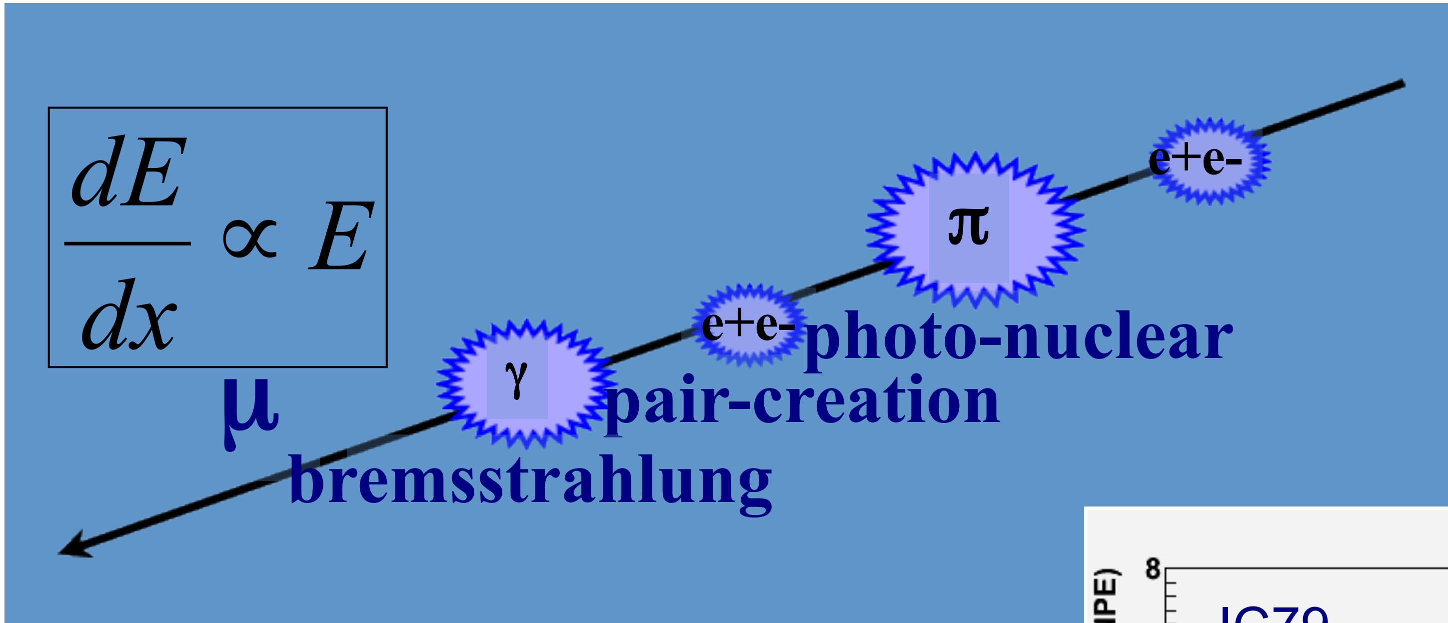
IC79 (2010-2011)

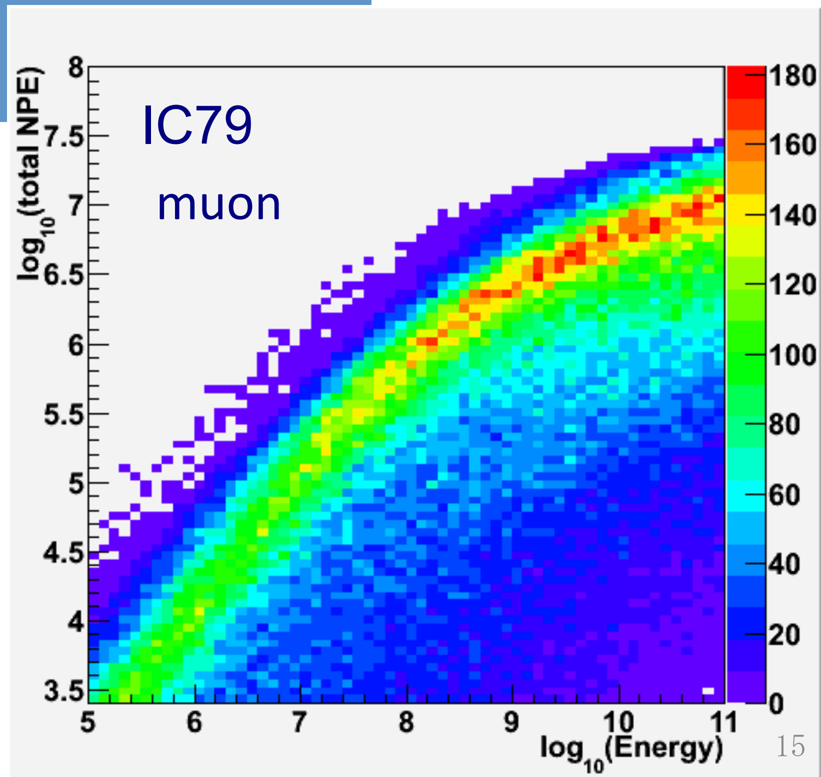


IC86 = full IceCube (2011~)



How to determine the energy





Detected total number of photo-electrons (NPE) ∝ Energy

NPE is a good energy estimator!

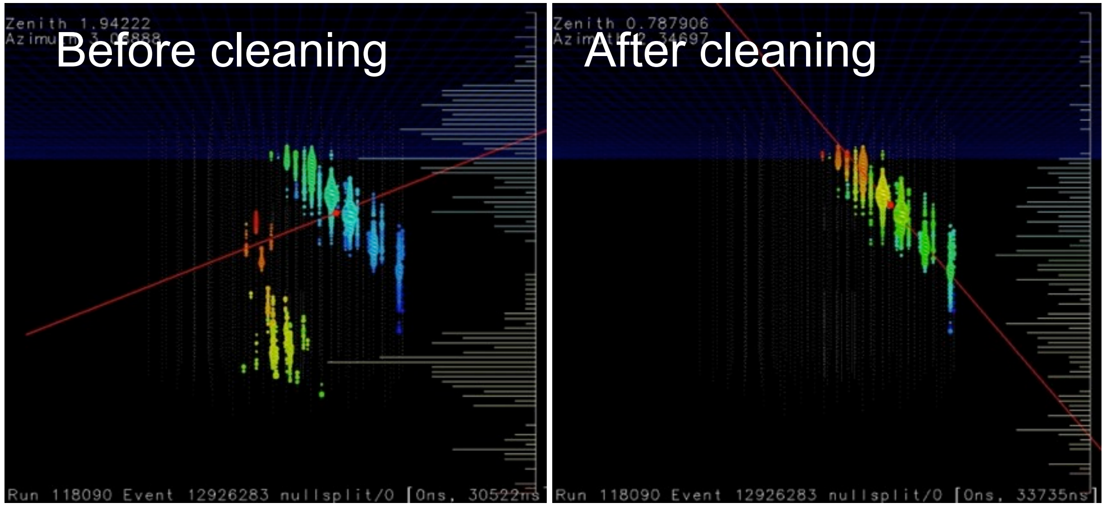
❑ Analysis scheme

- **Offline filter**: select high energy events and fundamental cleaning

  NPE > $10^{3.5}$

  NDOM > 300

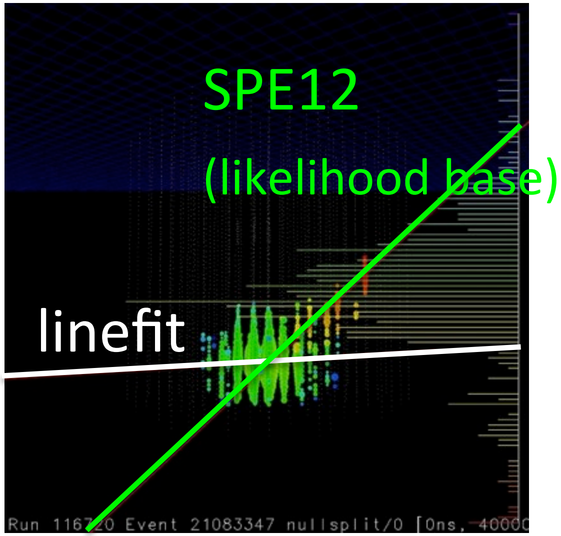
  coincidence cleaning



- **Final filter**:

  precise geometry reconstruction

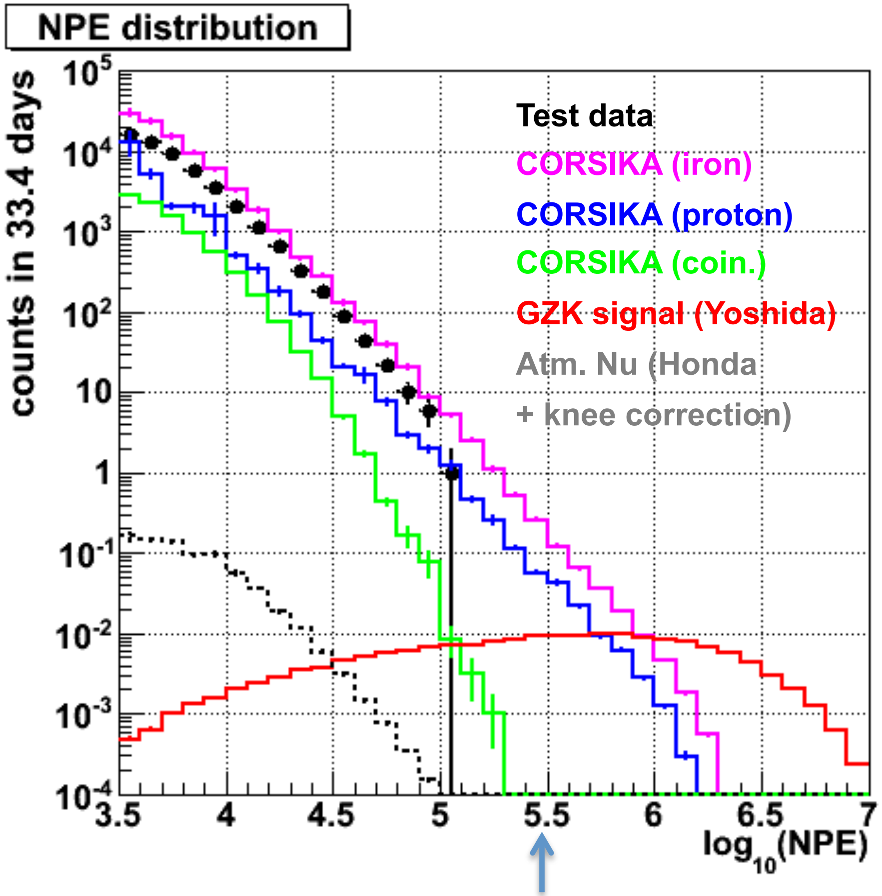
  remove remained coincidence events



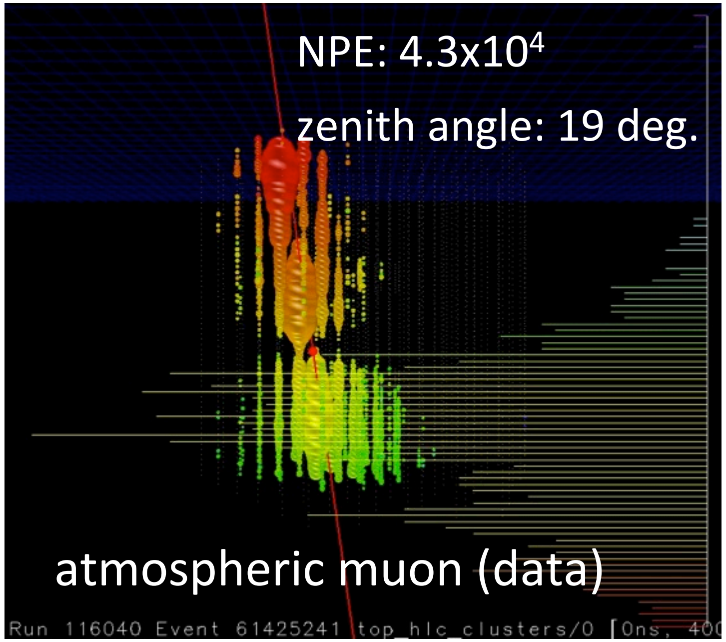
Offline filter level

NPE > $10^{3.5}$ && NDOM > 300 && Coincidence cleaning

33.4 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	$(5.23\pm0.02)\times10^4$	0.174 ± 0.001	$(2.53\pm0.51)\times10^4$	$(9.10\pm0.52)\times10^4$	$(8.74\pm0.08)\times10^3$	0.769 ± 0.032



10^8 GeV (at surface, GZK spectrum)
10^{10} GeV (CR primary)



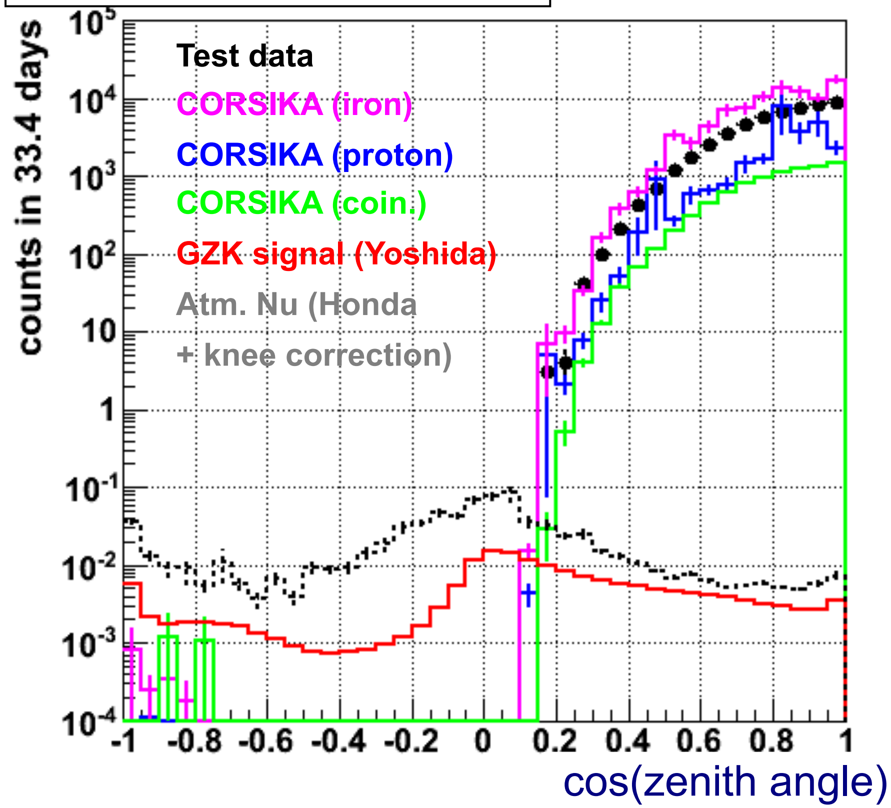
reasonable MC/data agreement
Dominated by atmospheric muons

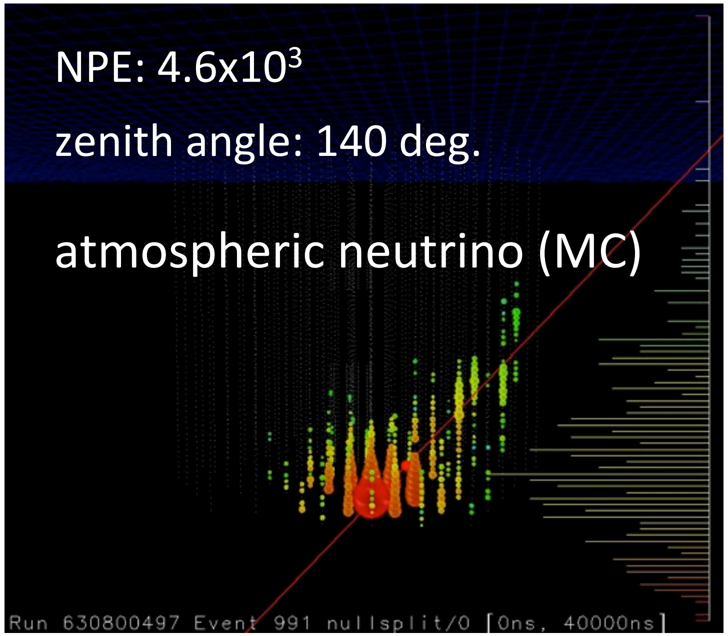
Final filter level

with precise reconstruction algorithms && further coincidence cleaning

33.4 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	$(5.22\pm0.02)\times10^4$	0.170±0.001	$(2.53\pm0.51)\times10^4$	$(9.10\pm0.52)\times10^4$	$(8.72\pm0.08)\times10^3$	0.769±0.032
Below horizon	0±0	0.0459±0.0004	$(2.25\pm0.94)\times10^{-4}$	$(1.61\pm0.80)\times10^{-3}$	$(2.35\pm1.63)\times10^{-3}$	0.383±0.017

Zenith angle distribution



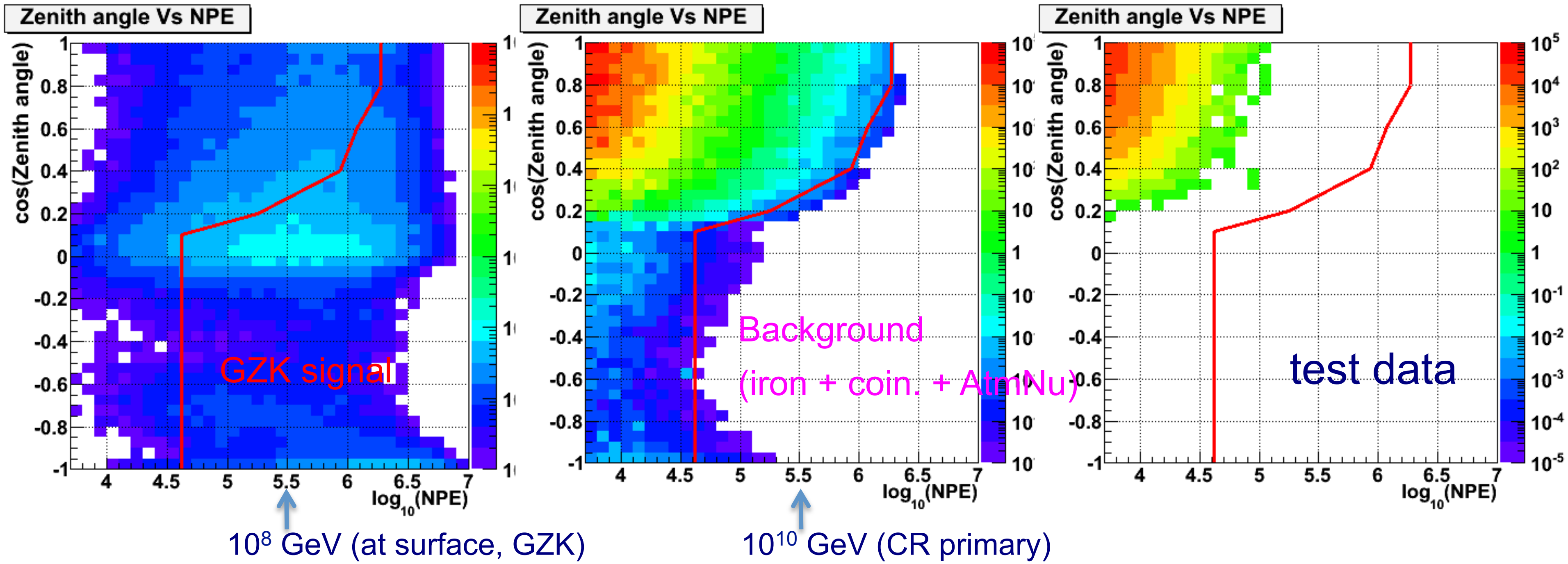


- mis-reconstructd events are cleaned
- atmospheric neutrinos also come from horizon, but low energy

❑ Final selection criteria

Model discovery potential method used (4 sigma)

Iron + coin. + atm. nu is used for the background to be conservative

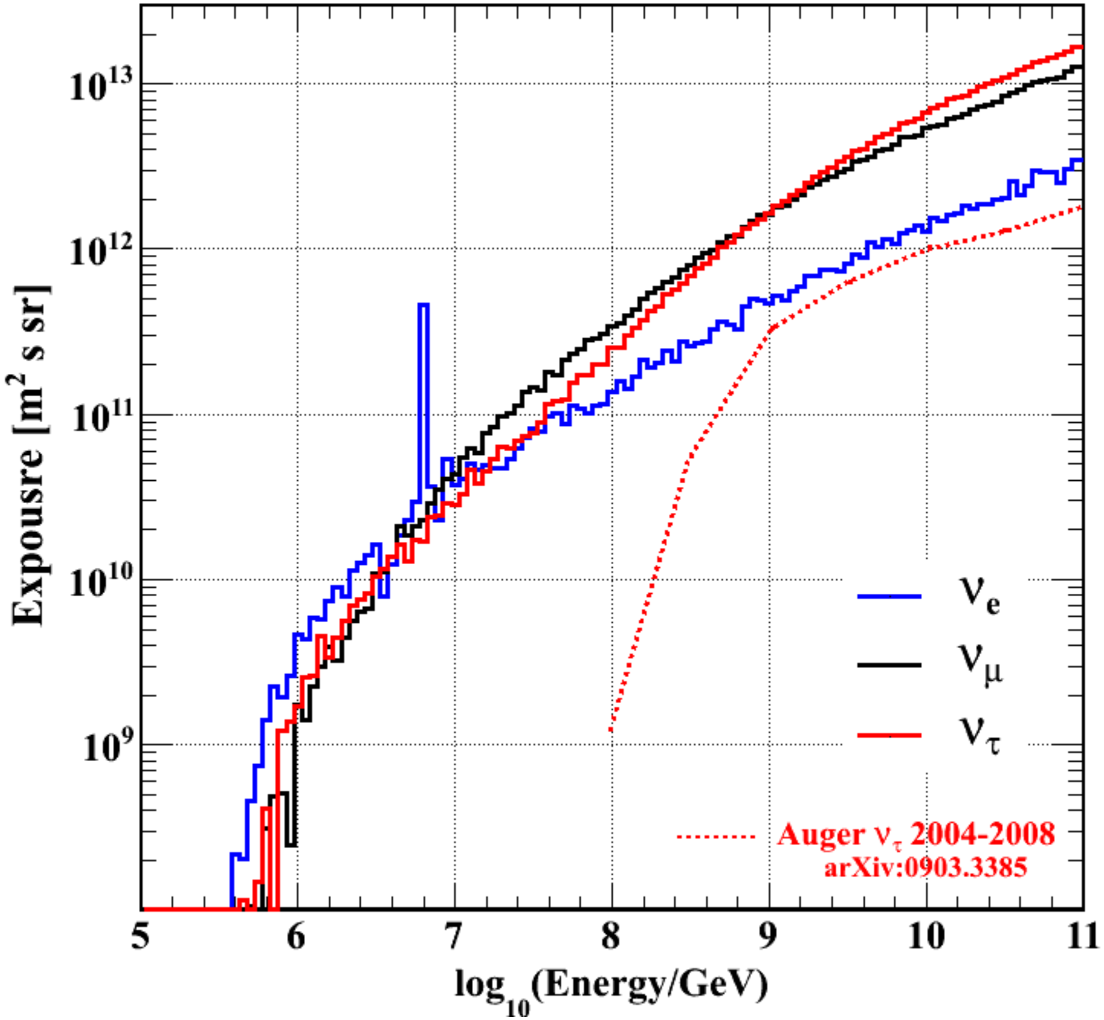


319.2 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	0±0	**0.978±0.005**	$(6.77\pm1.29)\times10^{-3}$	$(3.31\pm0.25)\times10^{-2}$	0±0	$(1.59\pm0.10)\times10^{-2}$
Below horizon	0±0	0.0363±0.003	$(7.88\pm6.08)\times10^{-4}$	$(1.92\pm1.09)\times10^{-3}$	0±0	$(1.29\pm0.09)\times10^{-2}$

* 0.57 per 333 days for IC40

❑ The total exposure (IC79 + IC86)

2010-2011 (319.2 days)
2011-2012 (350.9 days)
both effective areas are similar

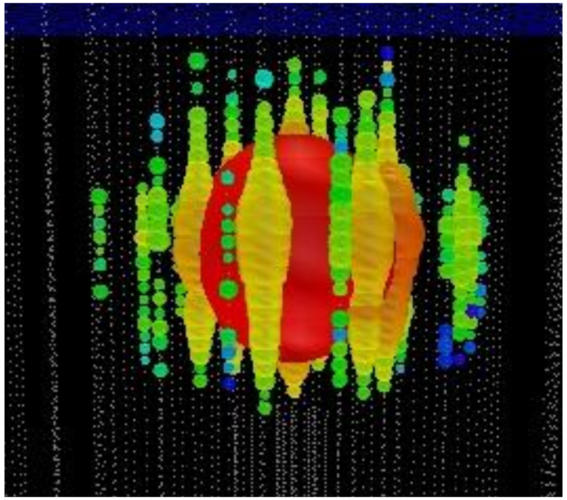


Two cascade like events found in 2011-2012 data

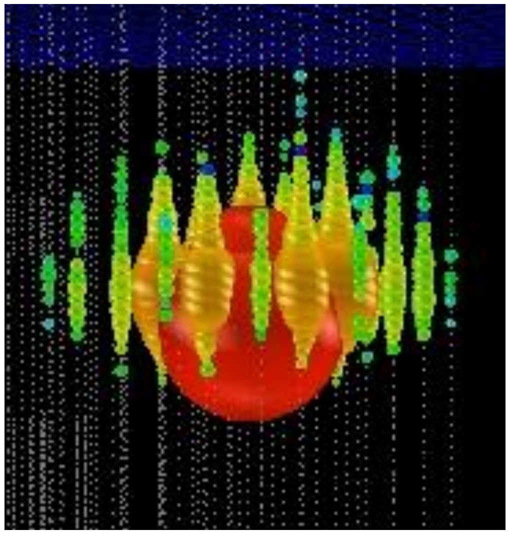
May, 2011 - May, 2012 (350.9 days), IC86 configuration

Either CC interaction of ν_e or NC interaction of any flavor ν

Aug., 9th, 2011
Run118545
-Event63733662
NPE: 7.0×10^4
NDOM: 354



Jan, 3rd, 2012
Run119316
-Event36556705
NPE: 9.6×10^4
NDOM: 312



by A. Ishihara

	event rate in 670.1 days
Atmospheric muons	0.036 ± 0.0062
conventional atmospheric neutrinos	0.021 ± 0.001
total background	0.0573 ± 0.0063
total background with prompt neutrinos [1]	0.190 ± 0.0063

significance:

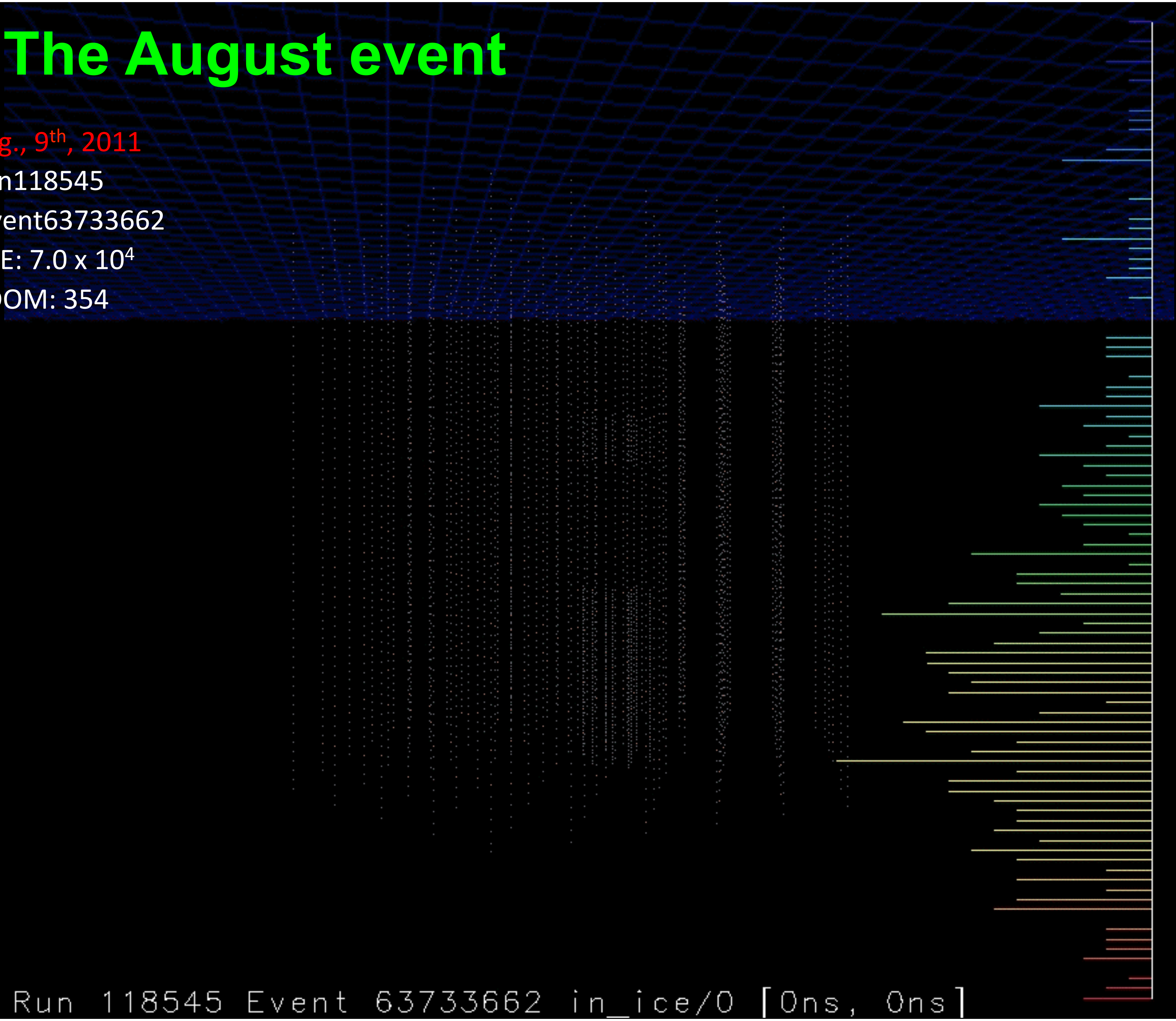
2.95 sigma without prompt [1]

2.18 sigma with prompt [1]

[1] R. Enberg, M.H. Reno, and I. Sarcevic. PRD78, 043005 (2008).

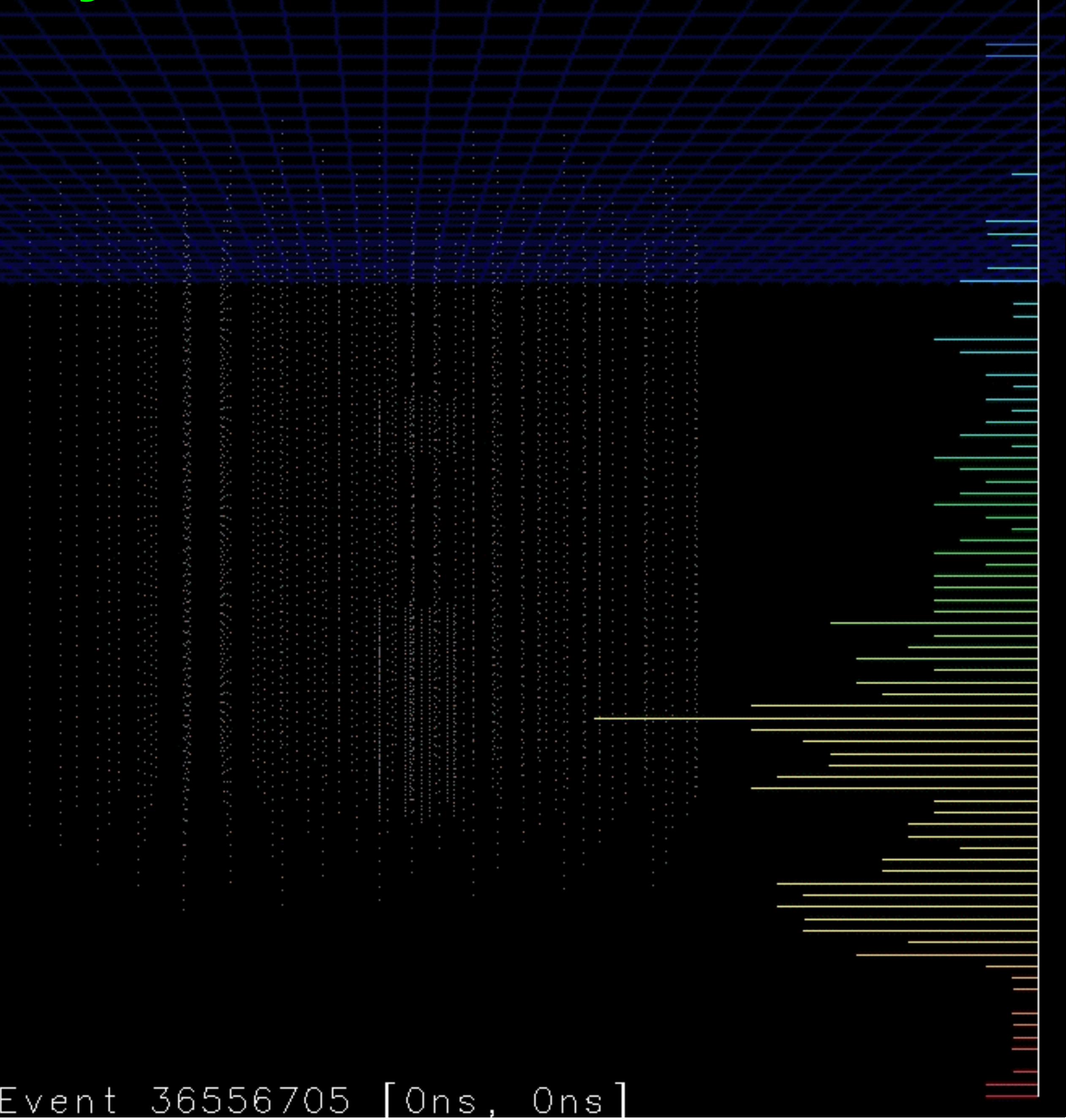
The August event

Aug., 9th, 2011
Run118545
-Event63733662
NPE: 7.0×10^4
NDOM: 354



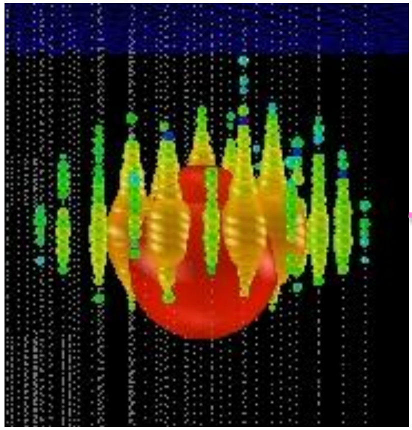
The January event

Jan, 3rd, 2012
Run119316
-Event36556705
NPE: 9.6×10^4
NDOM: 312

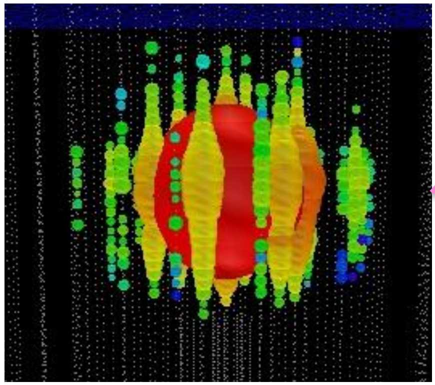


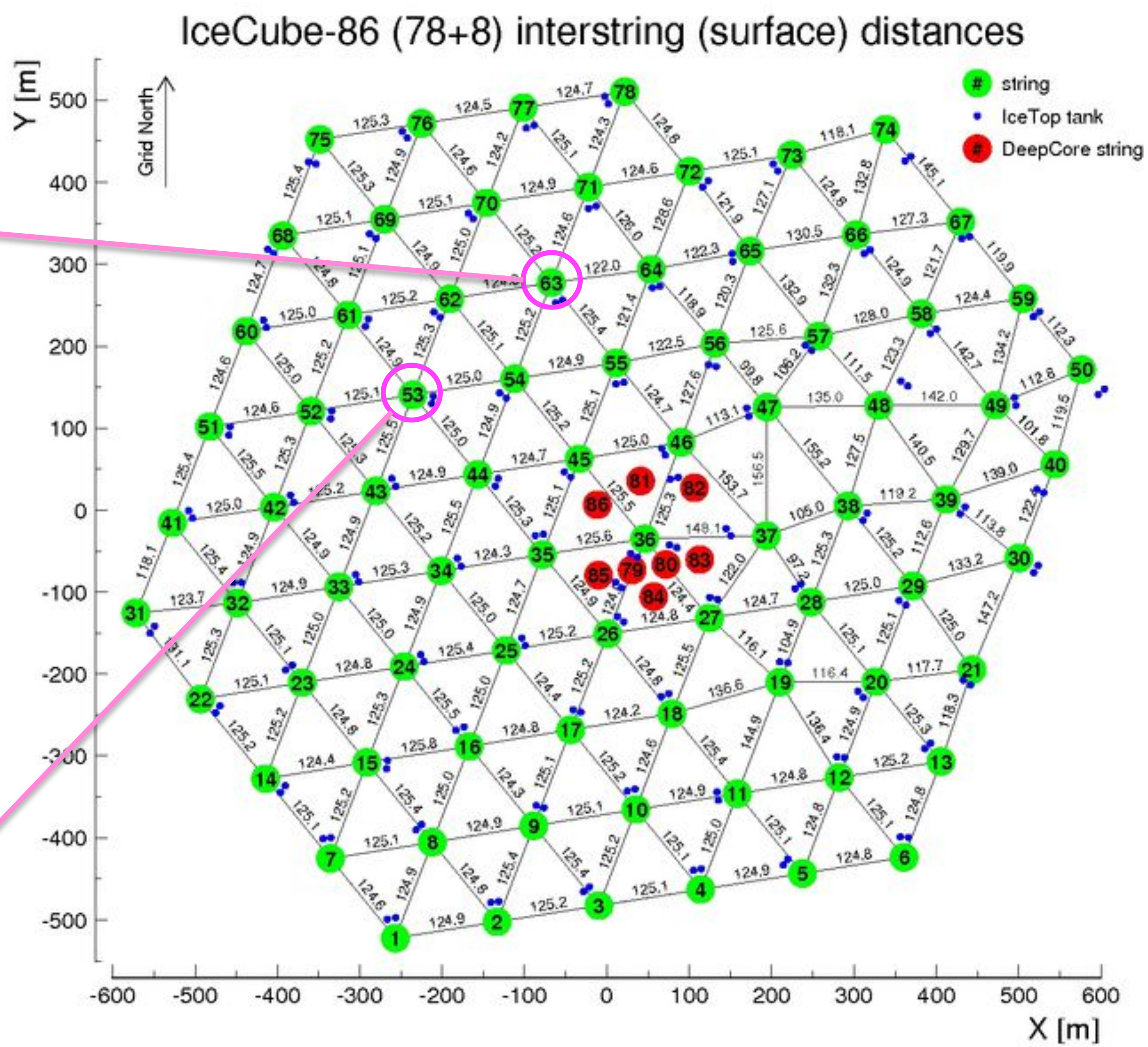
❑ The brightest string positions

Jan.



Aug.

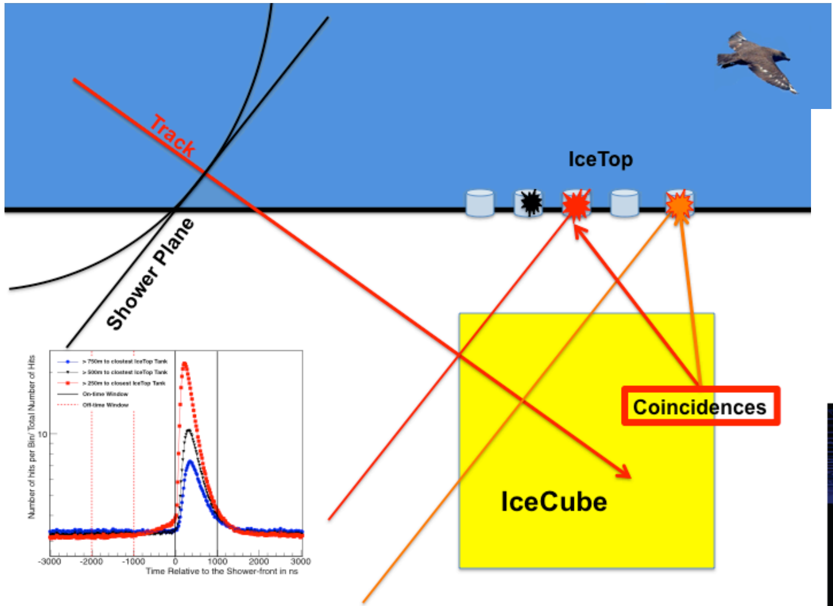




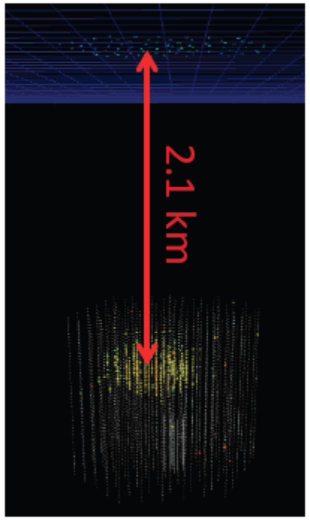
by A. Ishihara

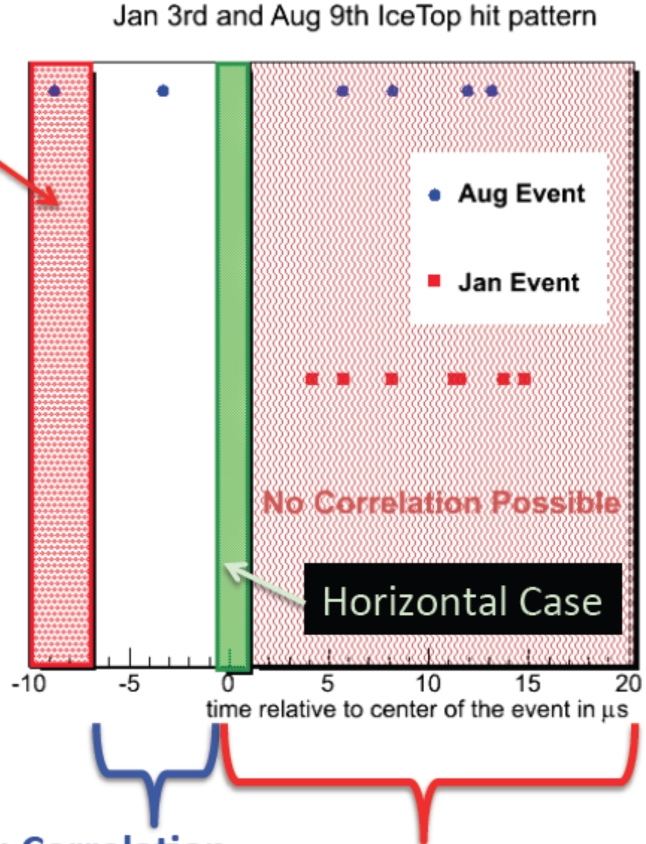
Well contained

❑ IceTop (surface array) veto information



Geometrical not possible as Cascades 2 .1km deep





Before first Hit: Correlation possible

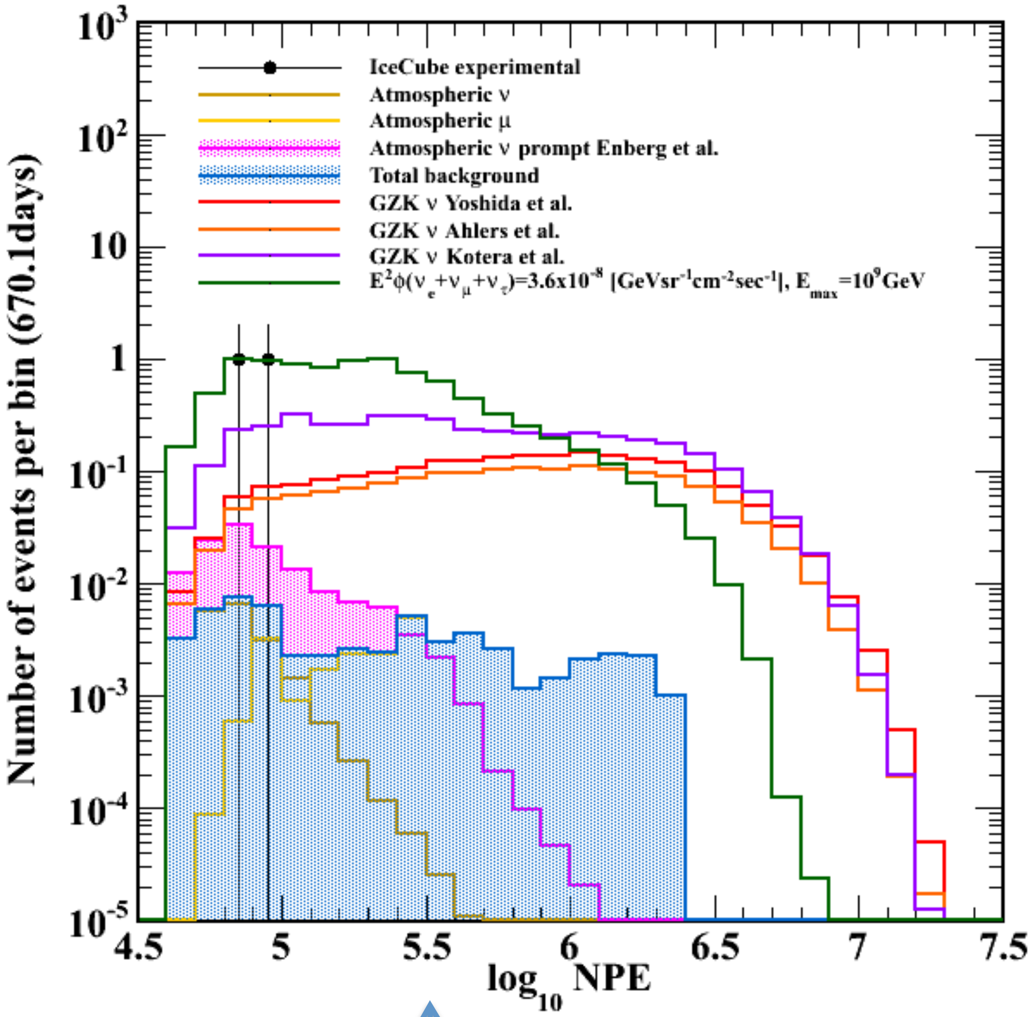
After the Event no Down-going correlation possible

- IceTop veto information was checked
- hits search in allowed 8µs time window
- 0 and 1 hit observed again 2.1 hits expected

-> No CR shower

by J. Auffenberg

The NPE distribution

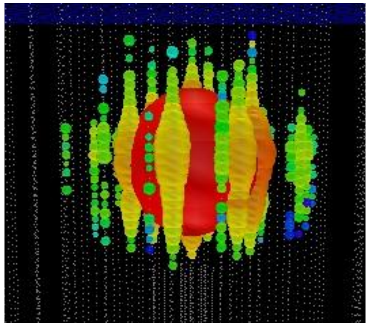


10^8 GeV (at surface, GZK)

model	event rate in 670.1 days
GZK Yoshida and Teshima	2.1
GZK Kotera et al. (FRII)	4.1
GZK Ahlers et al. (maximal)	3.2
GZK Ahlers et al. (best fit with Fermi)	1.6
$E^2\phi$	11.7
prompt	0.13
total BG	0.057
observed	2

by A. Ishihara

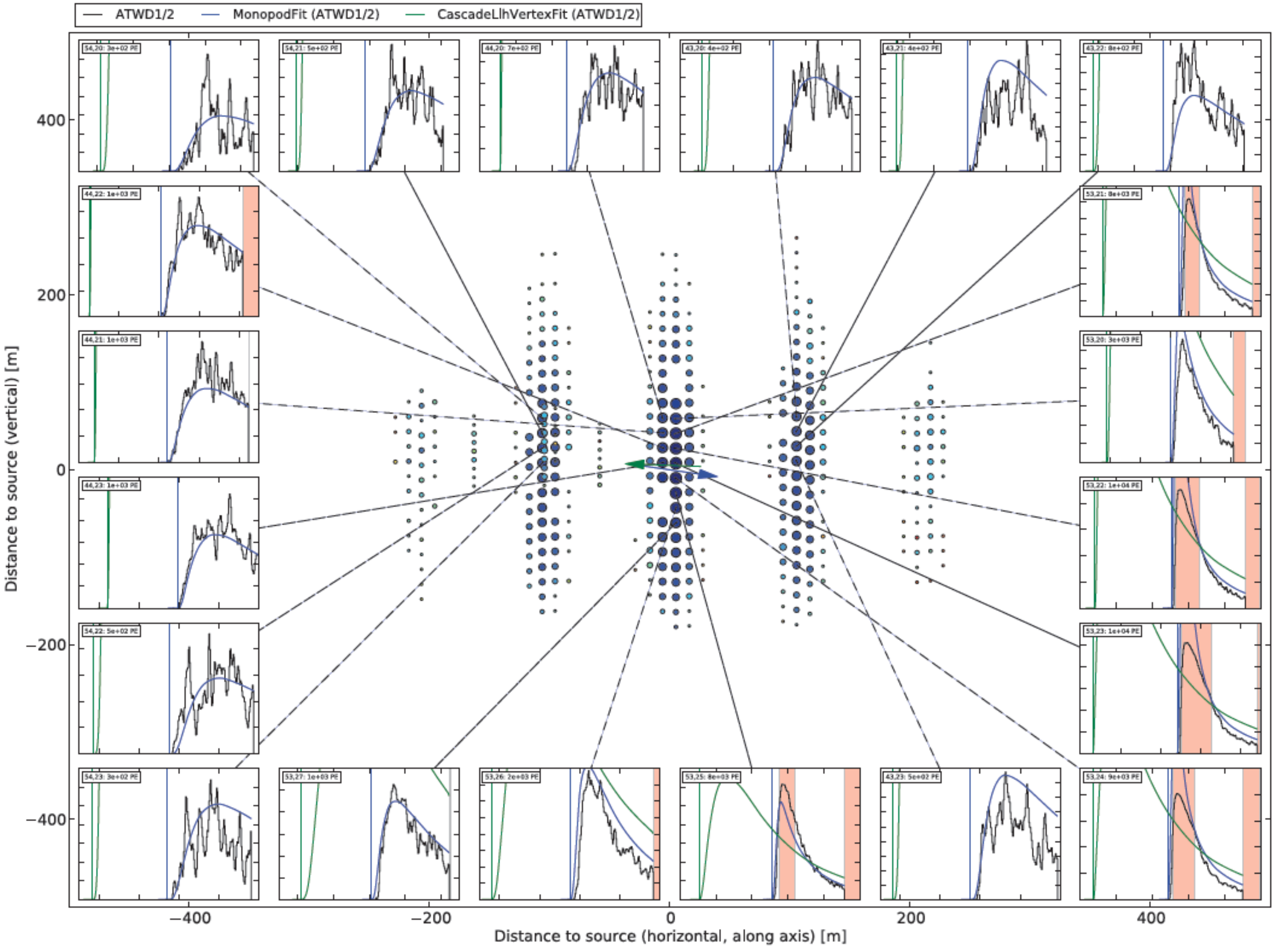
❑ The energy deposit reconstruction

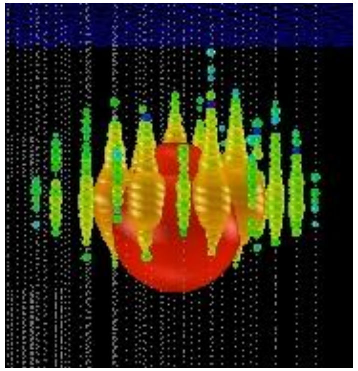


Aug.

1.1±0.4 PeV

red shaded region not used for the fit due to saturation





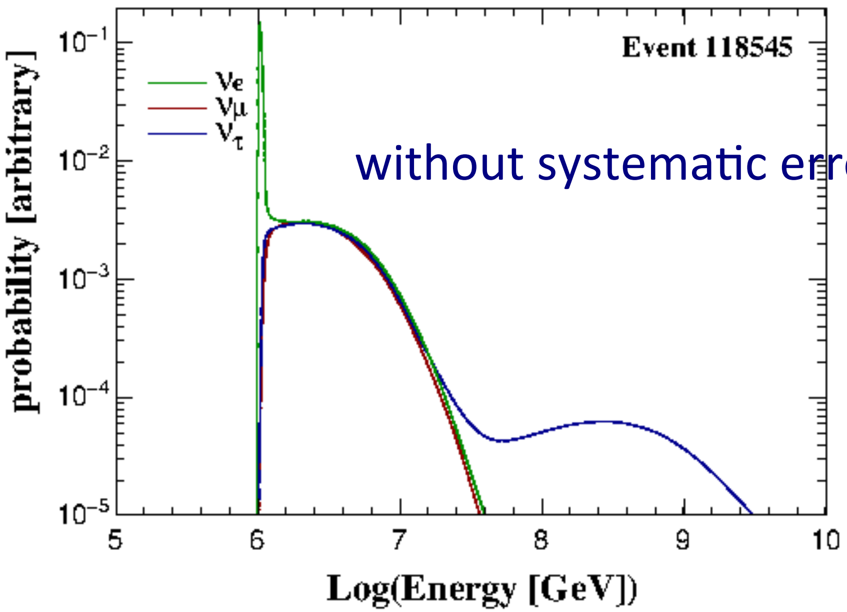
Jan.

1.3±0.5 PeV

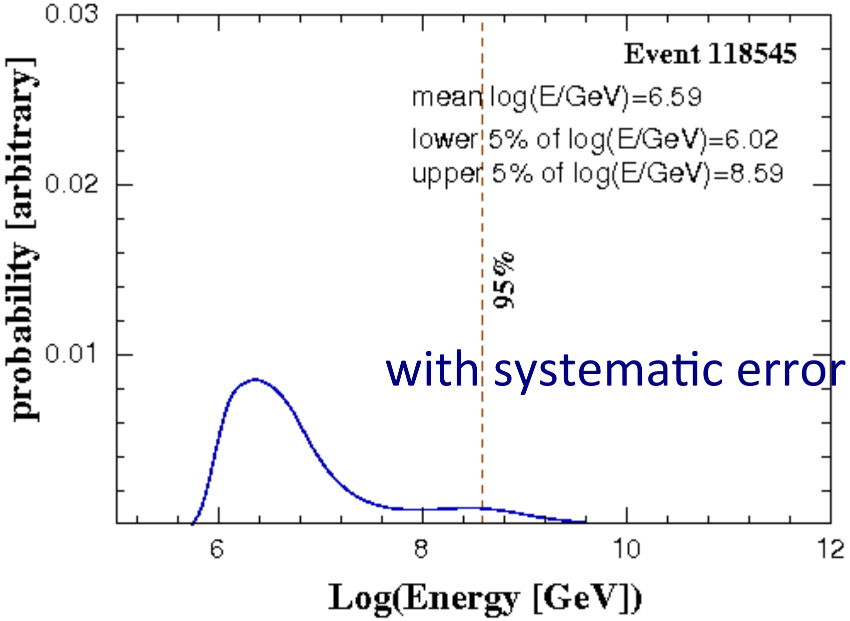
including systematics (reconstruction + ice + DOM eff.)

by J. Santen

❑ Reconstructed energy at surface



without systematic error



with systematic error

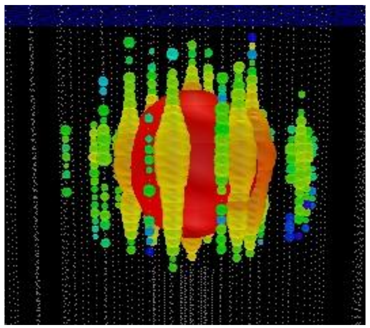
GZK flux assumed

Top-down approach (in-ice) + propagation to surface

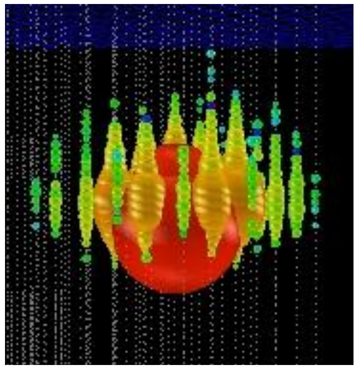
In case of ν_e CC, full energy deposit

Other case of NC, partial energy deposit by Bjorken y

by S. Yoshida



Aug.
6.01 < log(E/GeV) < 8.03
(90%)



Jan.
6.09 < log(E/GeV) < 8.65
(90%)

Model test for two events

How models are compatible with the two events

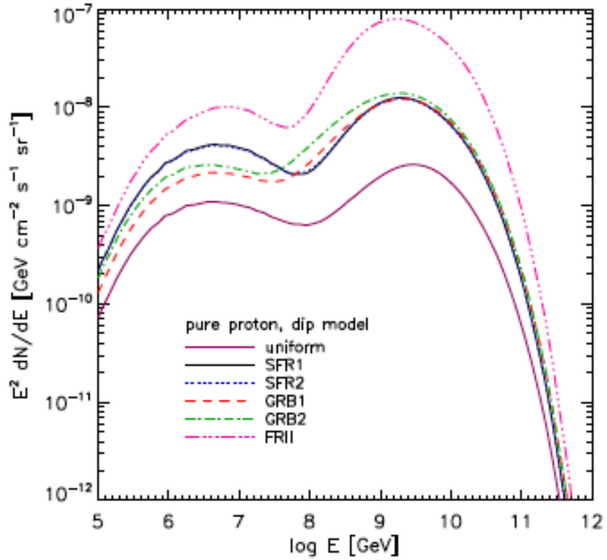
Fisher's method

$$\chi^2 = -2\ln(P_E) - 2\ln(P_{pois}(2;\mu))$$

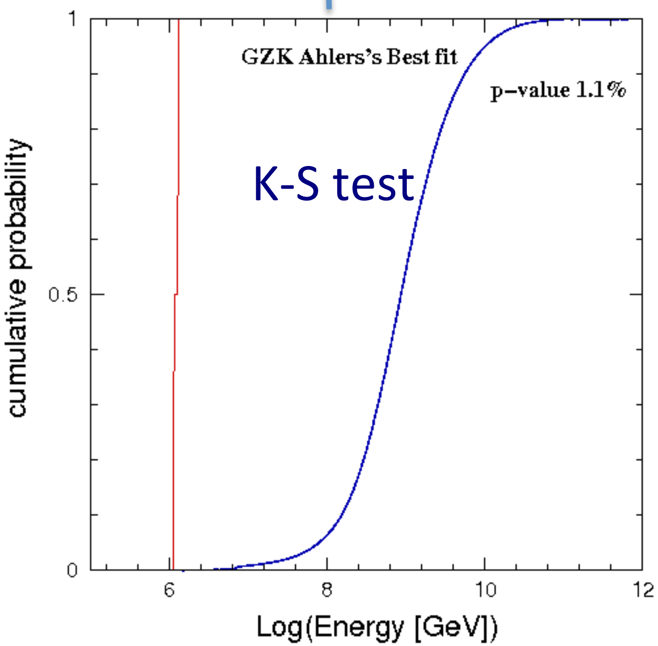
follows 4 degrees of freedom

Energy distribution

rate (Poisson)



Kotera et al., JCAP 10 (2010) 013



Preliminary

IC40+IC79+IC86

neutrino model	P_E	expected rate	P_{pos}	x^2	p-value
GZK Yoshida and Teshima	6.0×10^{-1}	2.8	5.5×10^{-1}	6.82	1.5×10^{-1}
GZK Kotera FR-II	1.8×10^{-1}	5.9	3.8×10^{-2}	9.91	4.2×10^{-2}
GZK Kotera GRB-1	2.5×10^{-1}	1.12	4.2×10^{-1}	4.56	3.4×10^{-1}
GZK Ahlers Fermi best	6.0×10^{-2}	2.1	7.3×10^{-1}	6.25	1.8×10^{-1}

GZK Kotera FR-II is rejected with 2 sigma

-> high flux model is not preferable

power-law spectrum is more preferable

by S. Yoshida

❑ The model test with null hypothesis

assumes two events are from other sources

estimated the effect of the two events by the energy PDF

IC40+IC79+IC86

model	expected rate (>100 PeV)	p-value
GZK Yoshida Teshima, m=4, Zmax=4	2.6	9.6×10^{-2}
GZK Sigl, m=5, Zmax =3	4.0	2.4×10^{-2}
GZK Yoshida Ishihara, m=5, Zmax=2	2.8	7.4×10^{-2}
GZK Ahrlers, Fermi best	2.0	16.2×10^{-2}
GZK Ahrlers, Fermi max	4.1	2.3×10^{-2}
GZK Kotera, SFR	0.60	67×10^{-2}
GZK, Kotera, GRB	0.63	66×10^{-2}
GZK, Kotera, FRII	3.8	3.1×10^{-2}
Top-down SUSY	21	$<0.1 \times 10^{-2}$
Top-down GUT	5.0	$<0.1 \times 10^{-2}$

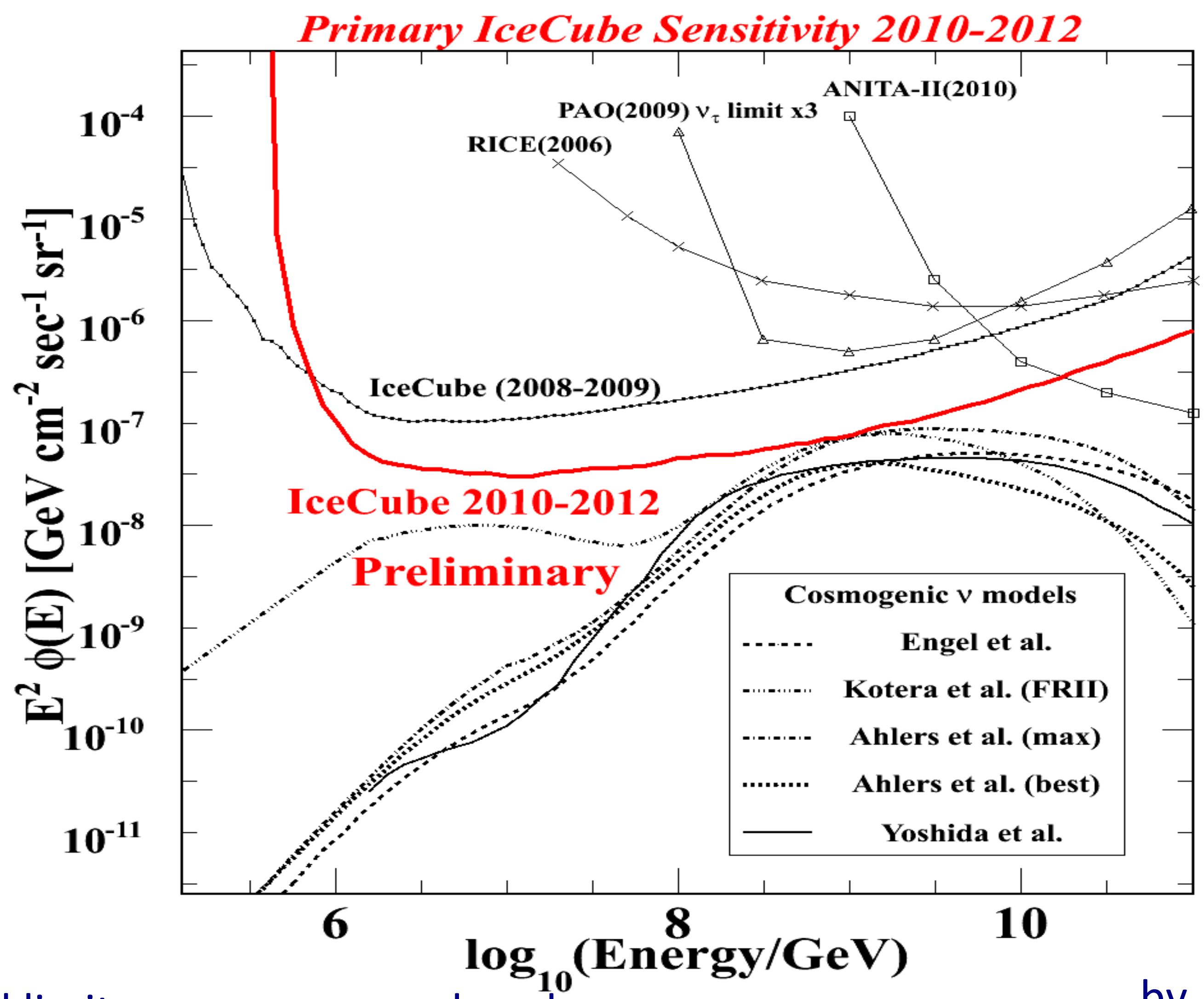
Preliminary

high evolution models (m>4) are ruled out

by S. Yoshida

❑ The model independent upper limit

similar as previous, but model independent



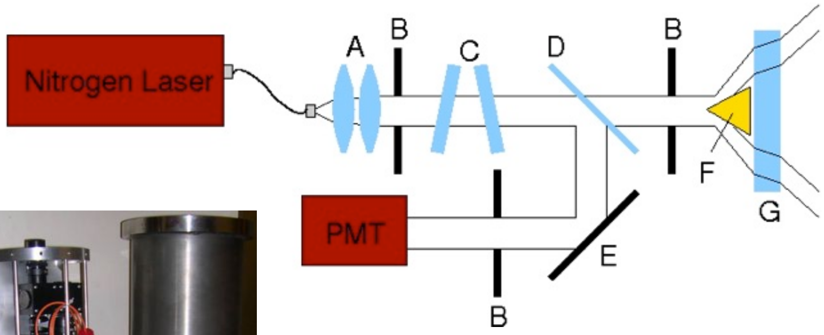
differential limit per one energy decade

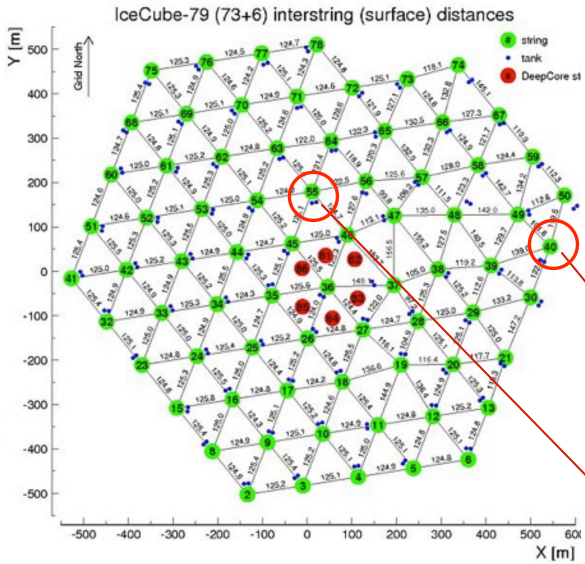
by A. Ishihara

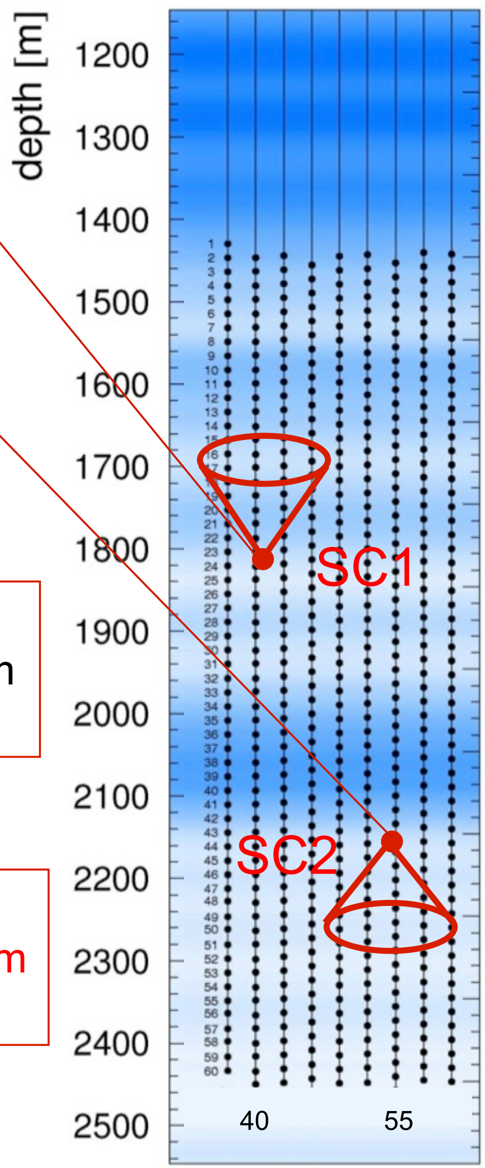
❑ Energy calibration by the standard candles (SCs)

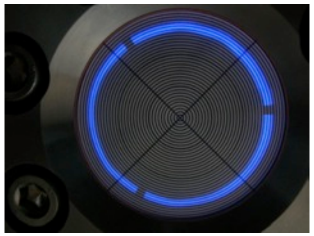
Absolutely calibrated source

337 nm (nitrogen laser)







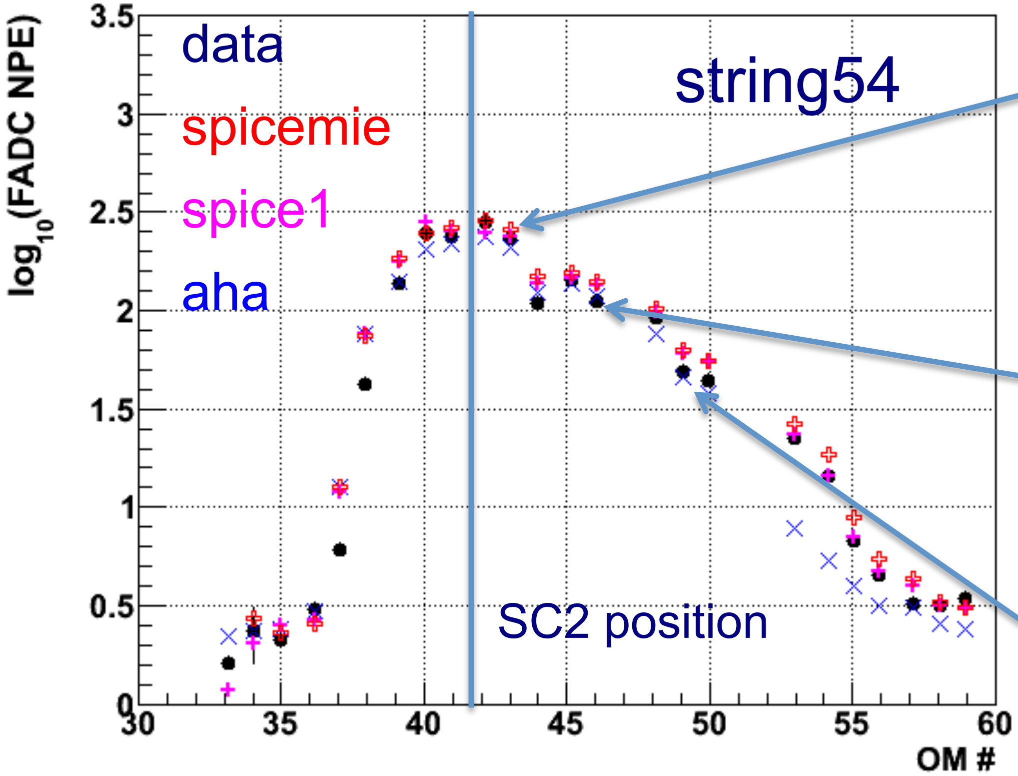


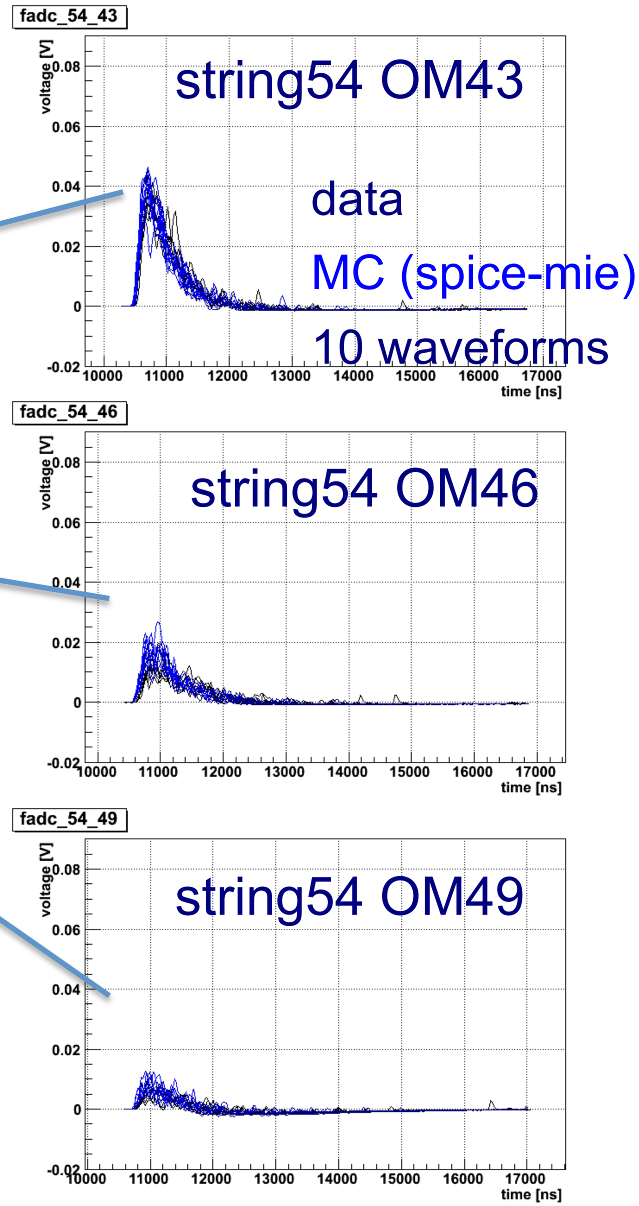
Standard Candle Ⅰ
- string 40, depth = 1810m
- pointing upward

Standard Candle II
- string 55, depth = 2153m
- pointing downward

❑ Agreement between data and MC

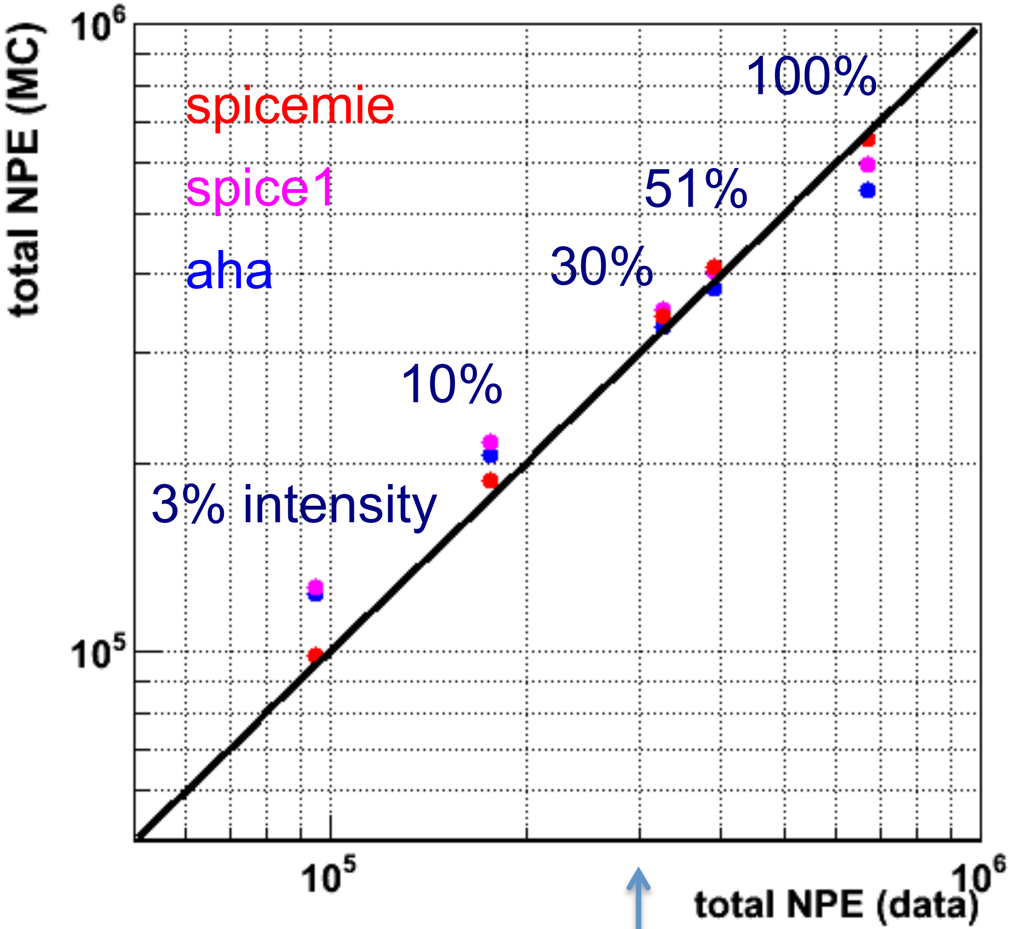
SC2 3 % intensity



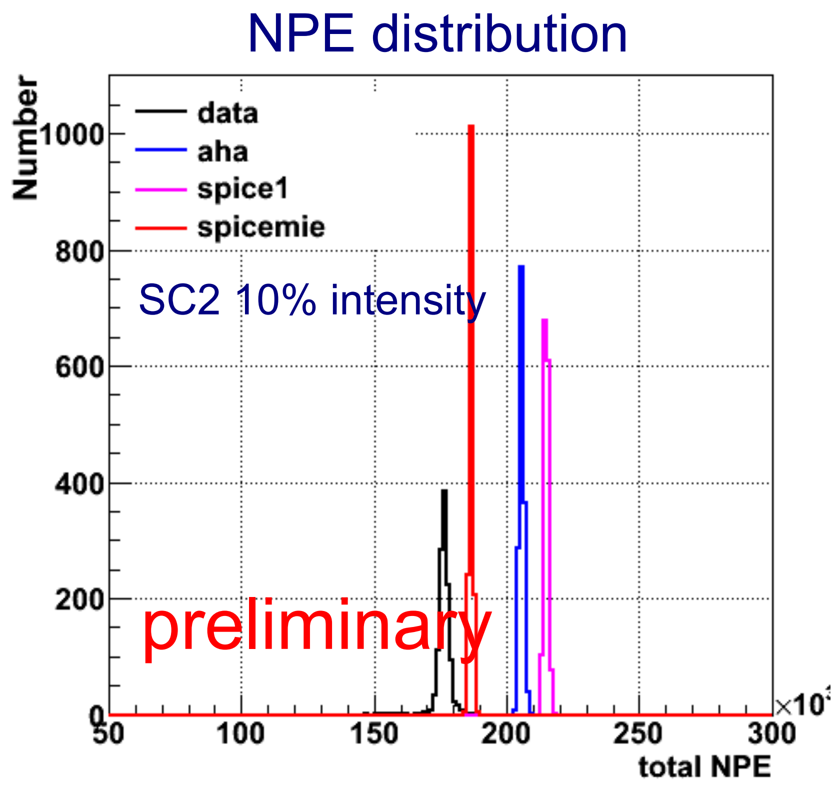


data and MC agree well

❑ MC vs Data comparison



10^8 GeV (at surface, GZK spectrum)



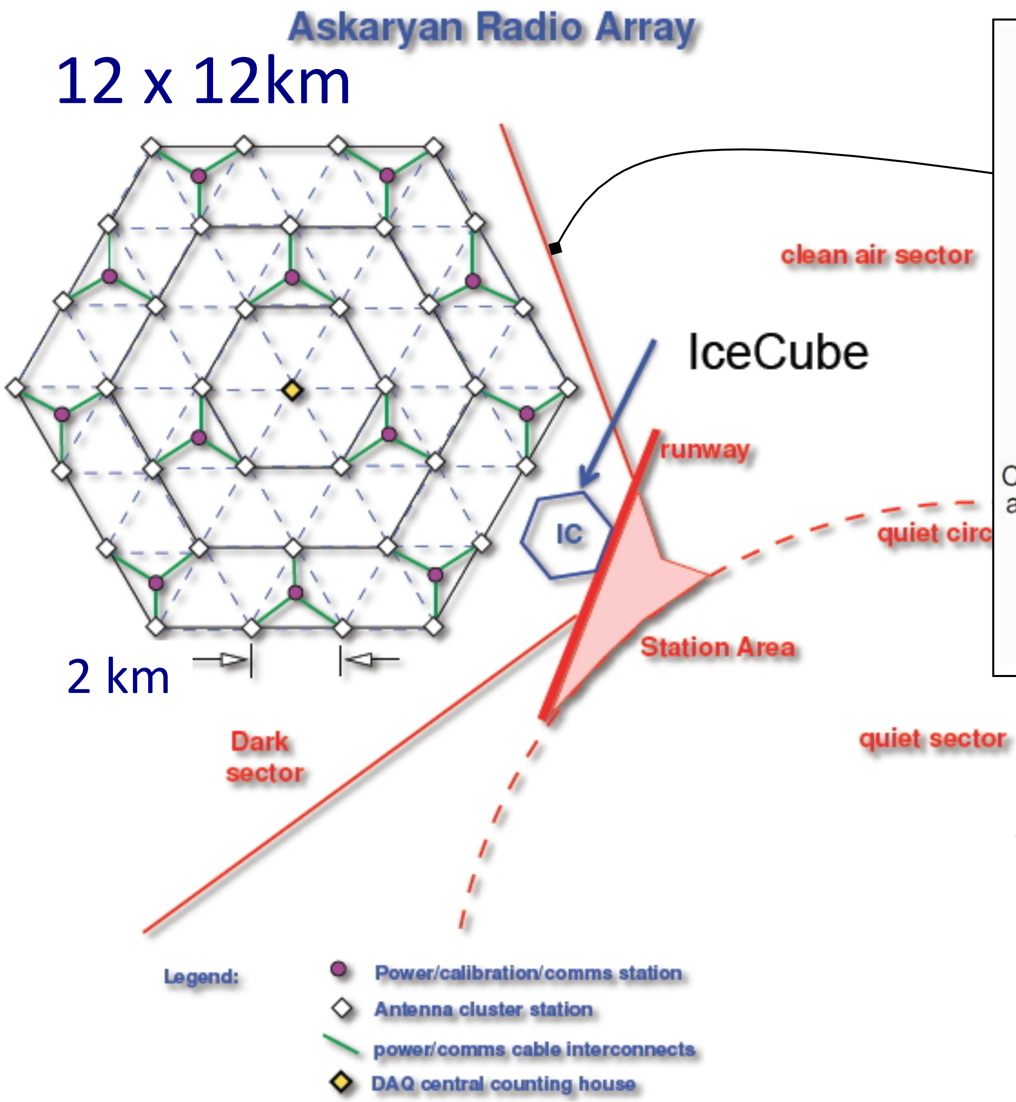
(data-MC)/MC = -17.8%

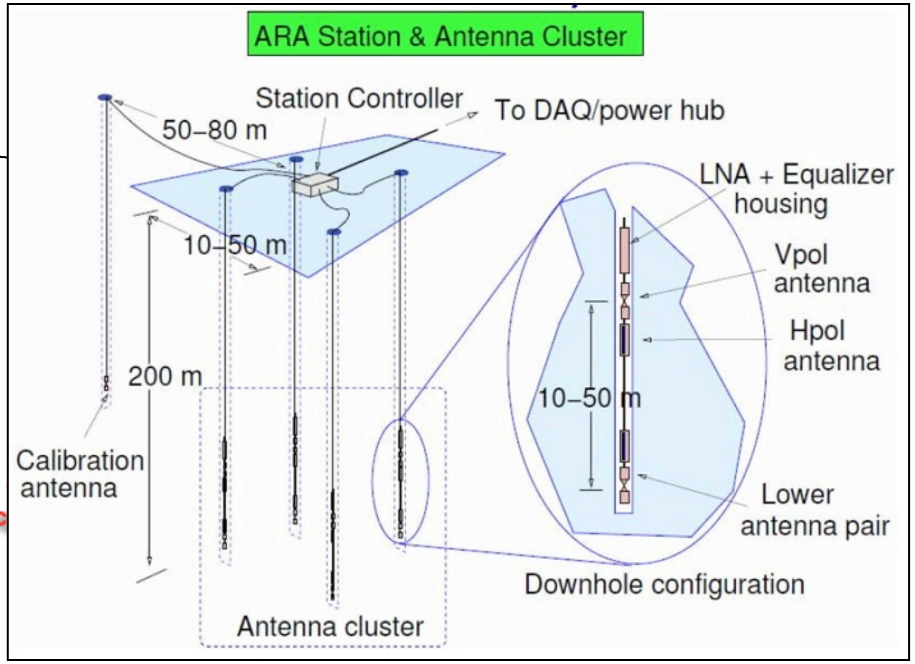
*spice1

❑ Error budget

	BG	signal
Stat. error	± 9.3%	± 0.6%
NPE shift	-	+2.9 -6.8 %
Yearly variation	± 17 %	-
Neutrino cross section	-	± 9%
Photo-nuclear int.	-	+ 10%
LPM effect	-	± 1%
Hadronic int. model	+36.9%	-
total	± 9.3(stat.) ± 40.7(sys.) %	± 0.6 (stat.) +13.8 -11.3 (sys.) %

Next plan - Askaryan Radio Array (ARA)



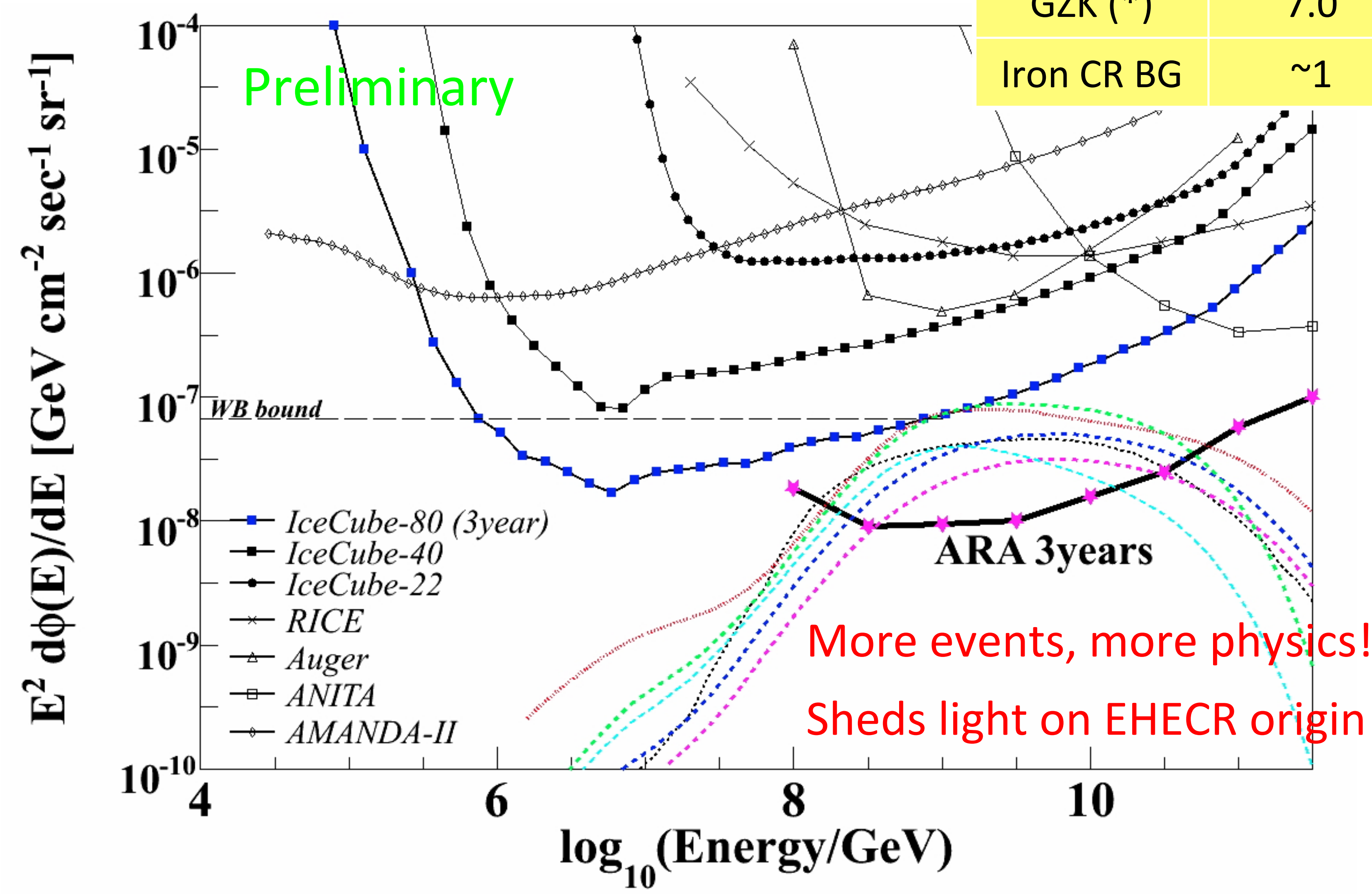


37 string clusters

- Each cluster has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (200 MHz - 1 GHz)
- Total surface area ~180 km^2

The ARA sensitivity

Model	#/year
GZK (*)	7.0
Iron CR BG	~1



(*) Yoshida et al., ApJ, 1997, m=4, Z_{max}=4

Summary

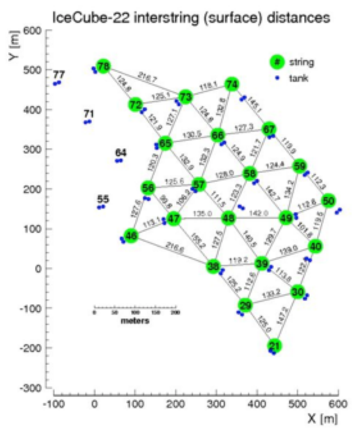
- IceCube is aim for detecting neutrinos from astronomical origins to shed light on the cosmic ray origin
- The IceCube detector completed in 2010
- The sensitivity is below Waxman-Bahcall limit
- Two cascade like events found
- Significance of cosmogenic neutrino hypothesis is 2.95 sigma without taking prompt contribution into account
- High evolution GZK models are ruled out
- Larger detector (ARA) is coming

backups

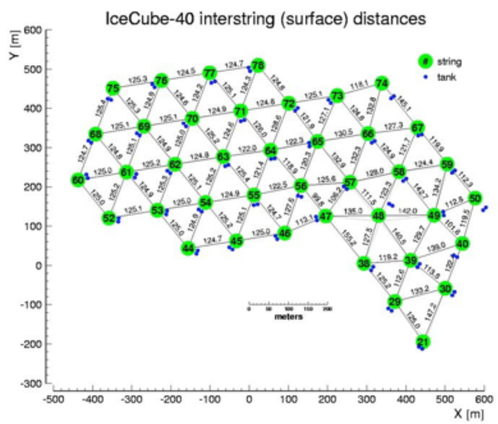
The history

2004: project started
2006-2007: IC9
2007-2008: IC22
2008-2009: IC40
2009-2010: IC59
2010-2011: IC79
2011: IceCube completed!
2011~: IC86

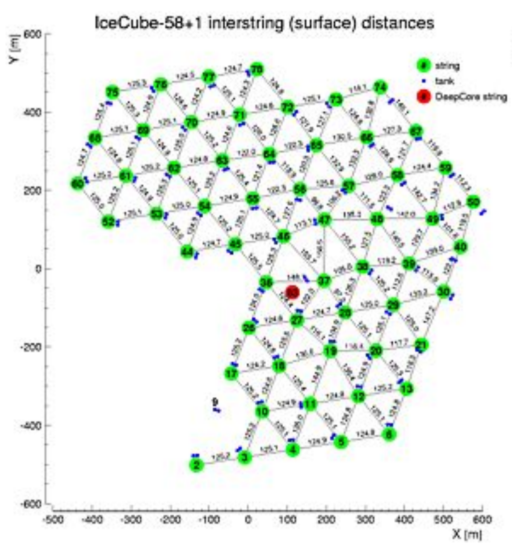
IC22 (2007-2008)



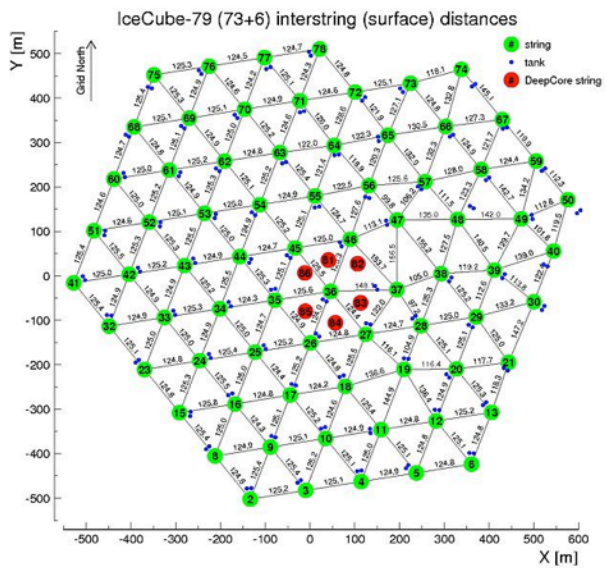
IC40 (2008-2009)



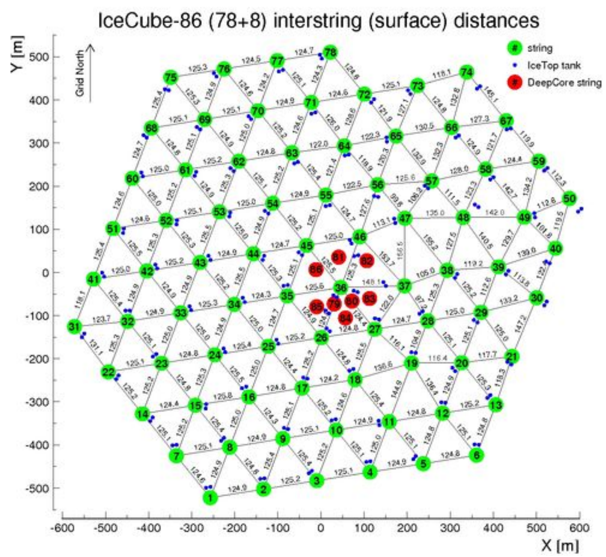
IC59 (2009-2010)



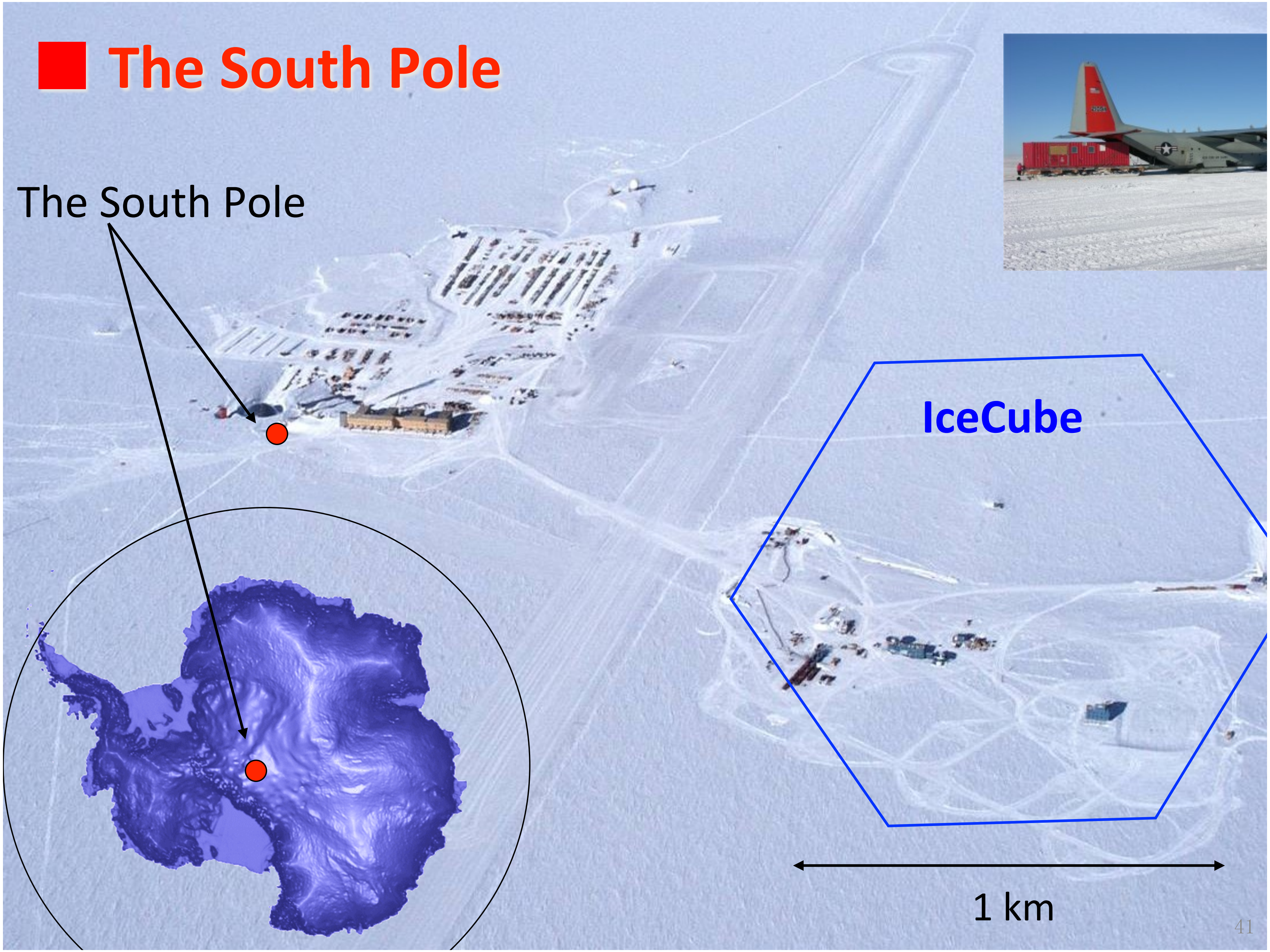
IC79 (2010-2011)



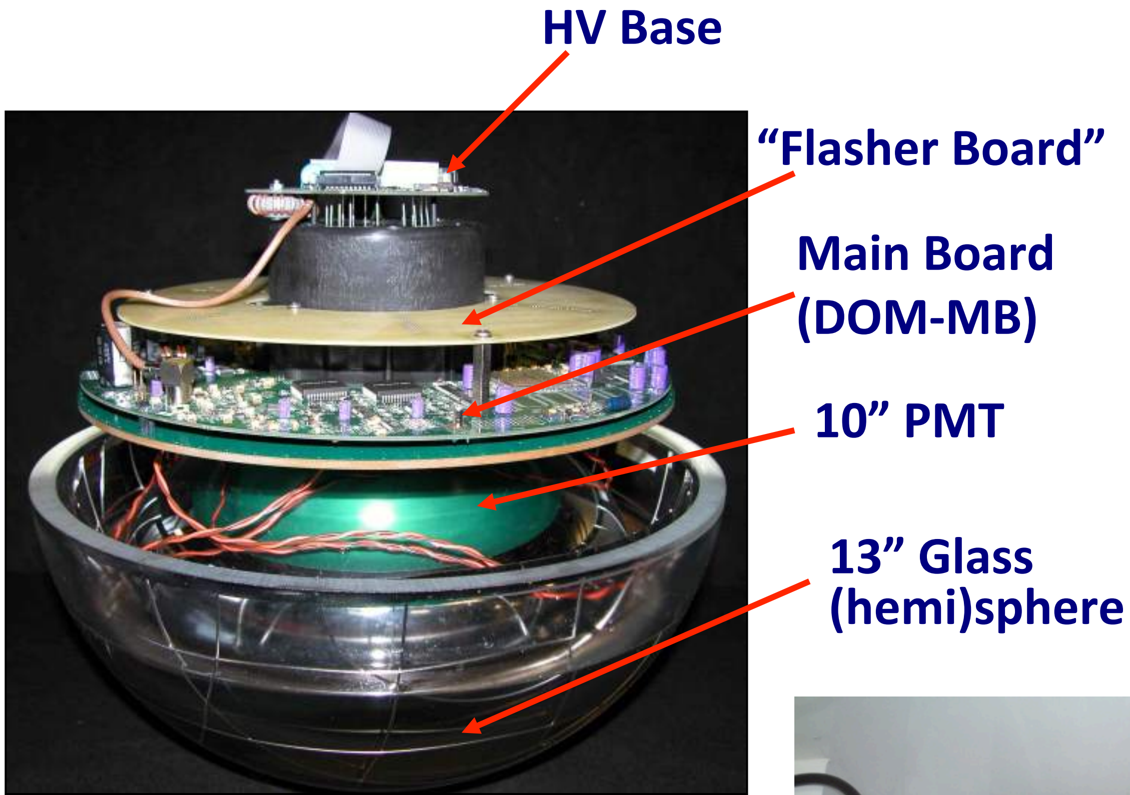
IC86 = full IceCube (2011~)

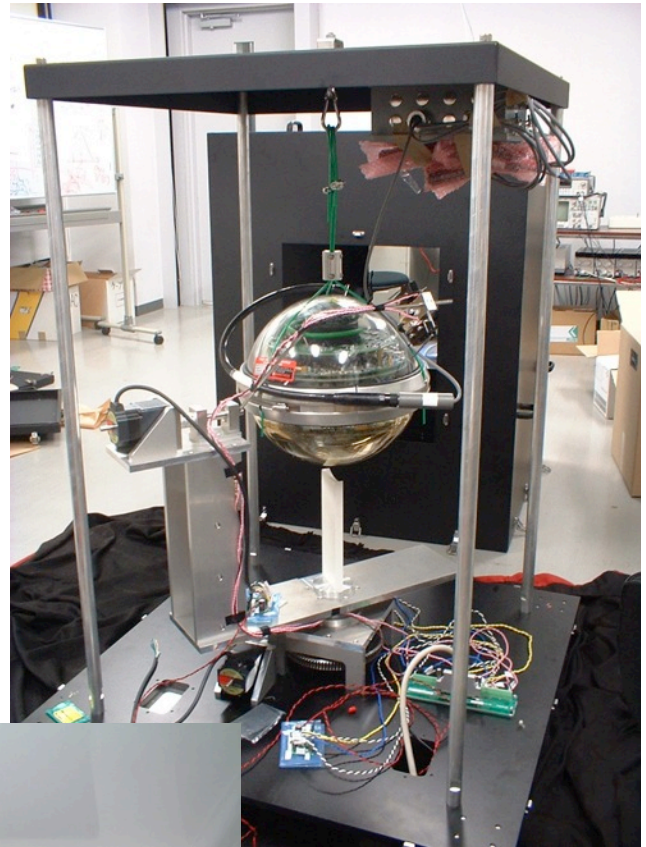


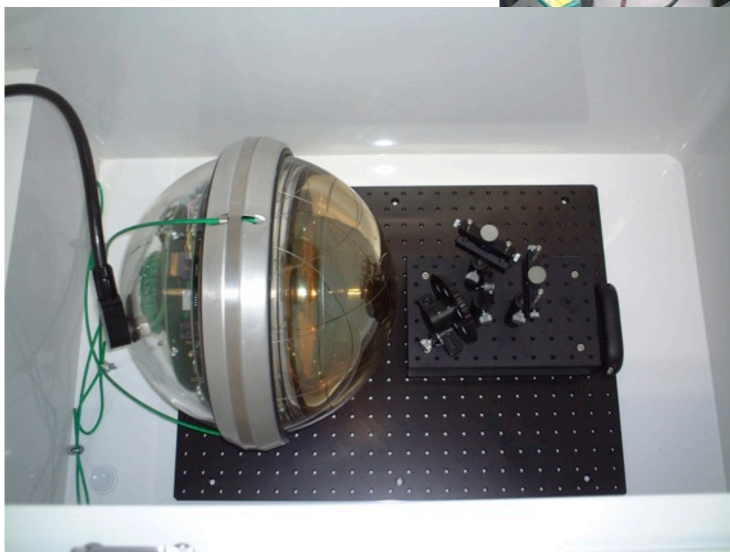
The South Pole



The Digital Optical Module (DOM)



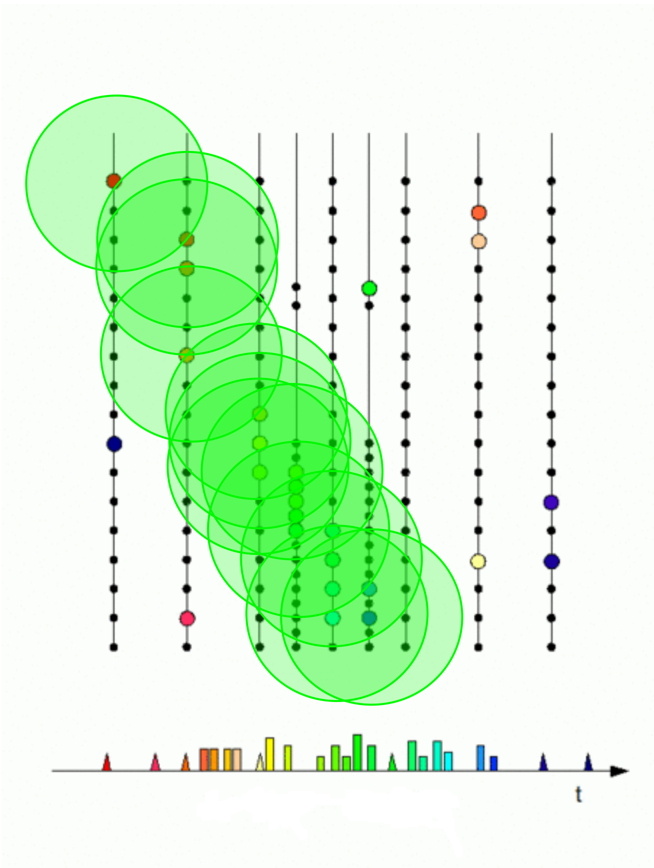


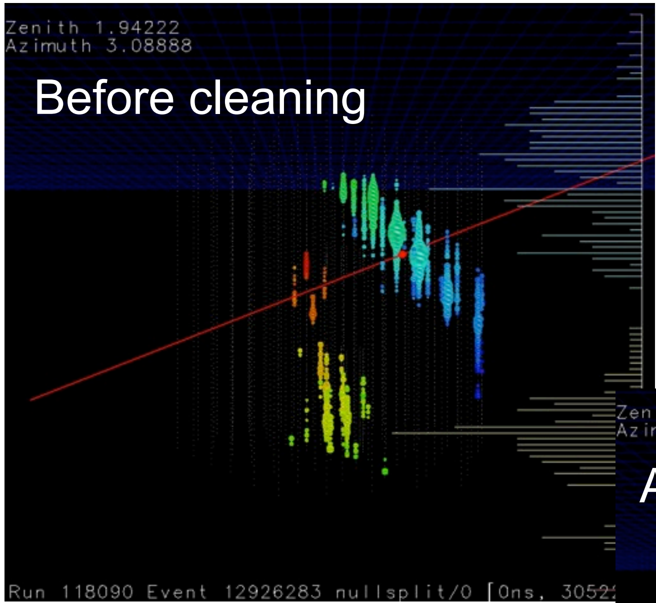


Calibrated at Chiba University

千葉大学
Chiba University

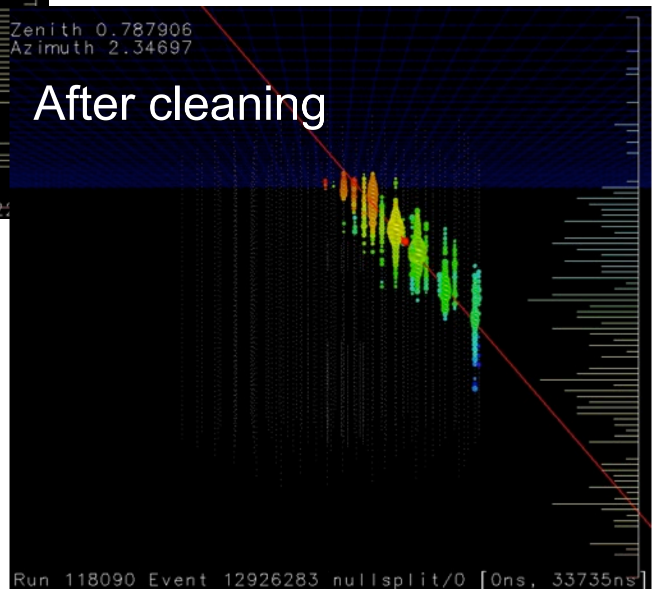
❑ Coincident event cleaning





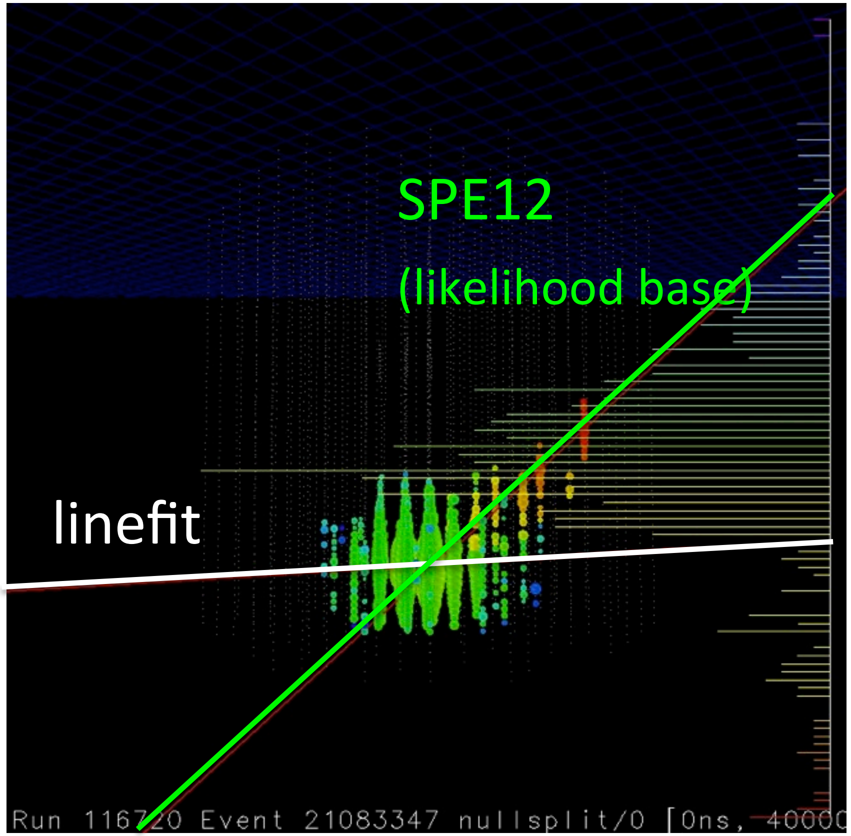
R: 150m

t: 1000 ns

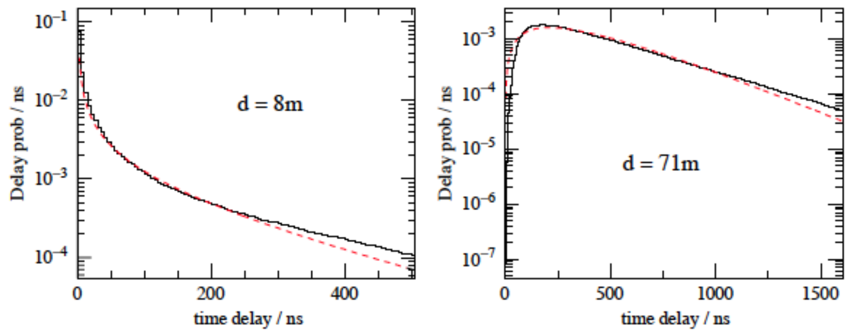


- ✓ Geometrical and time constraint is used to separate coincident events
- ✓ Useful to clean coincident events

❑ Better reconstruction for corner clippers



SPE12: uses only the arrival time of the first photon in optical modules to construct likelihood



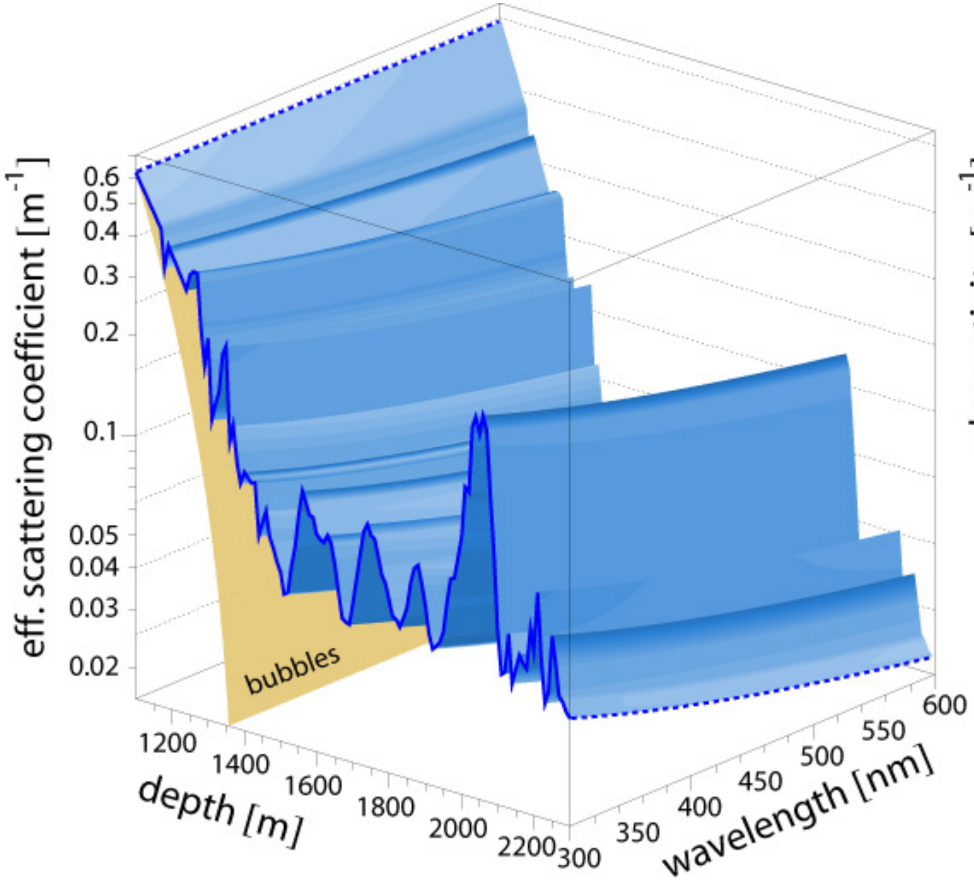
J. Ahrens et al., NIM A 524 (2004)

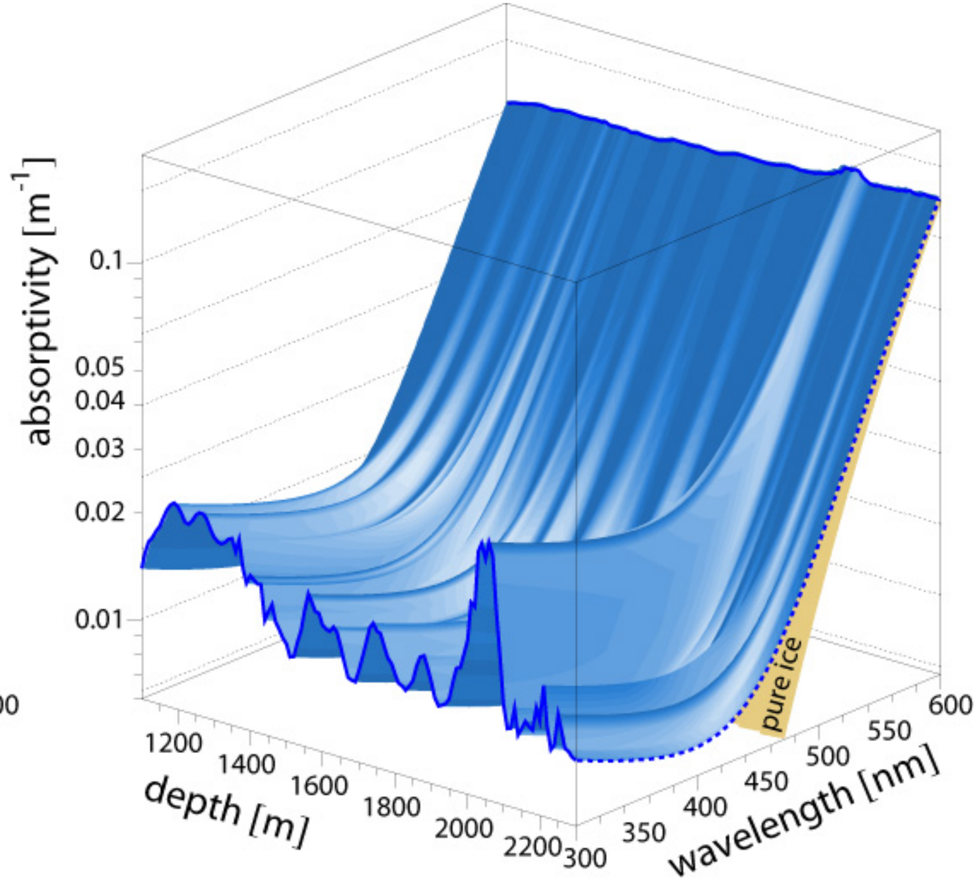
red: Pandel function (model),

black: simulation data

- ✓ Linefit mis-reconstructs corner clippers
- ✓ Likelihood-base reconstruction reconstructs corner clippers better

The ice property





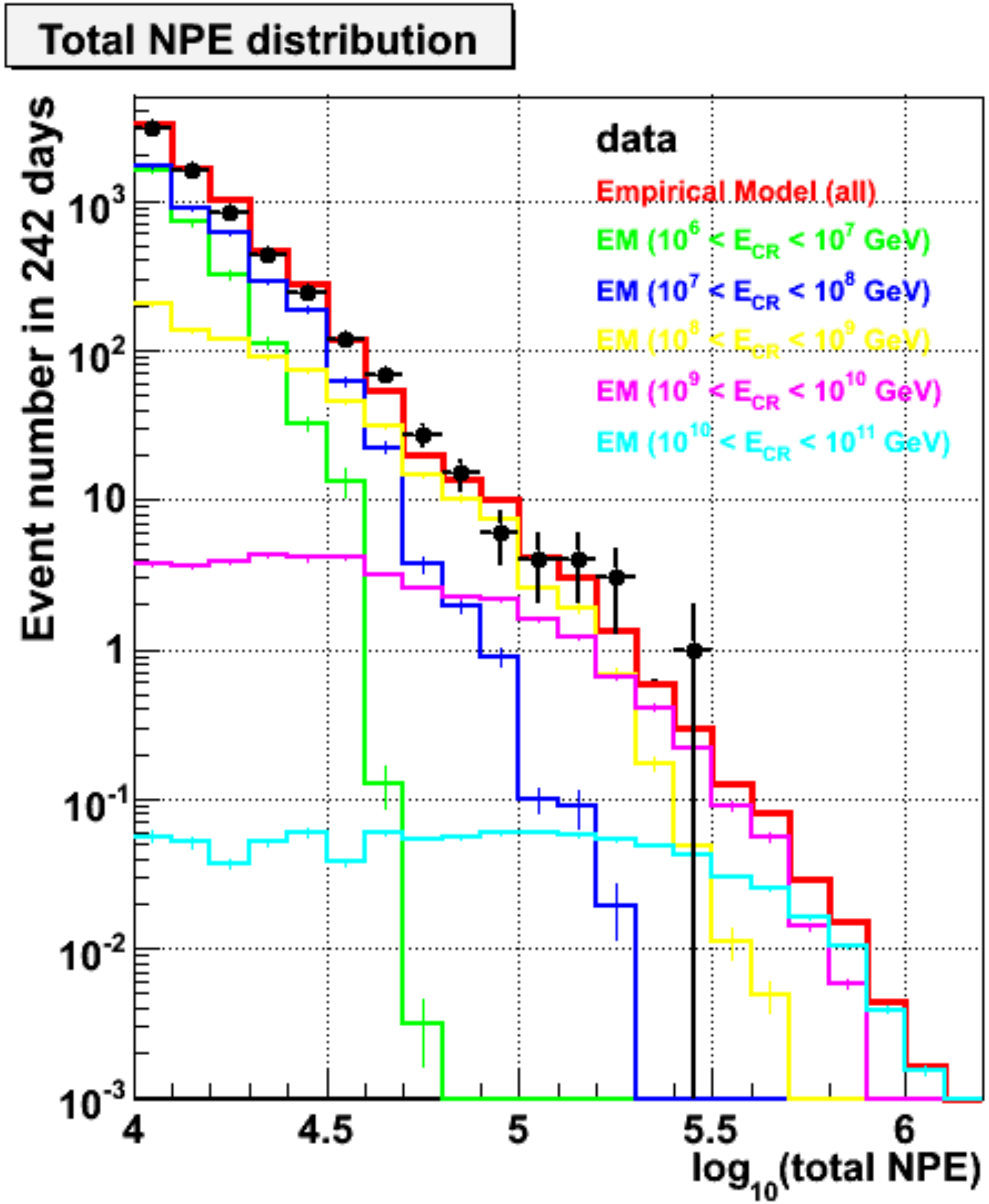
Average optical parameters:

λ_{abs} ~ 110 m @ 400 nm

λ_{scat} ~ 20 m @ 400 nm

Clear depth dependence

→ taken into account in simulation

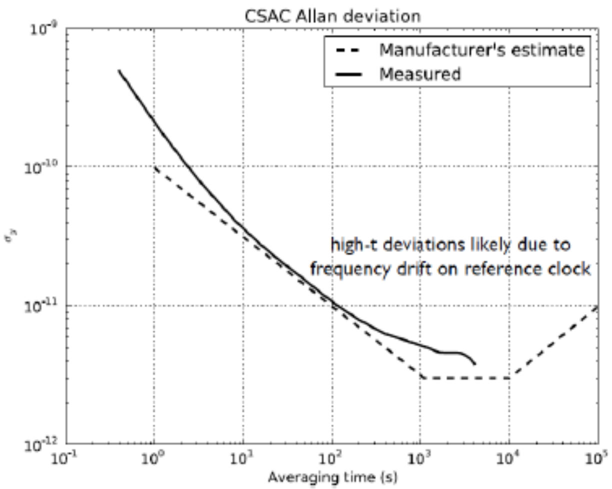

Total NPE distribution
data
Empirical Model (all)
EM (10^6 < E_{CR} < 10^7 GeV)
EM (10^7 < E_{CR} < 10^8 GeV)
EM (10^8 < E_{CR} < 10^9 GeV)
EM (10^9 < E_{CR} < 10^{10} GeV)
EM (10^{10} < E_{CR} < 10^{11} GeV)
Event number in 242 days
$\log_{10}$(total NPE)
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
4
4.5
5
5.5
6

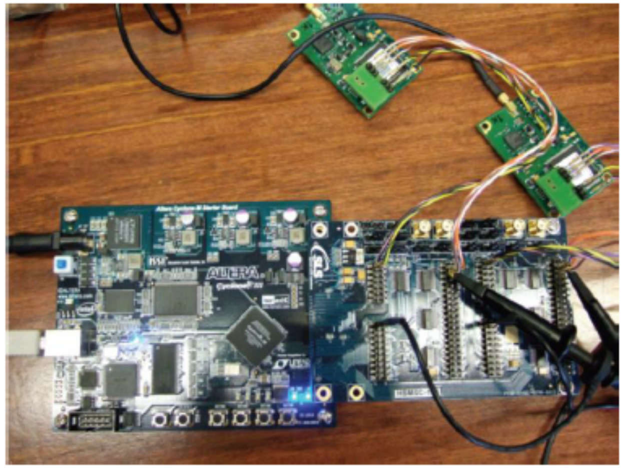
Chiba-IIHE collaboration

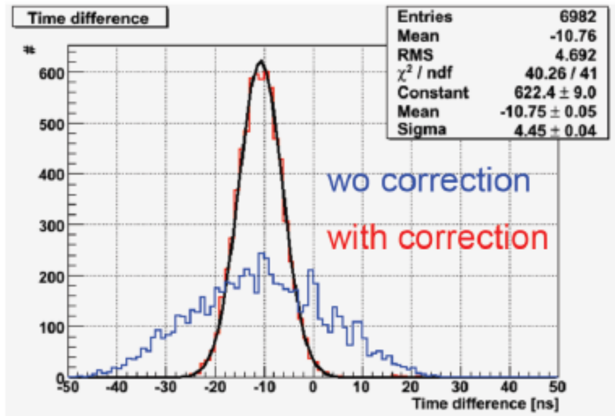
GPS/Rubidium Clock

- **Timing precision for ARA stations using GPS and Rubidium clocks**
  - **GPS for synchronization between stations: aim for 2ns precision**
  - **Rubidium clock for station internal timing stability: aim for ~100ps precision**
- **Challenge: Find devices with adequate performance but lowest power consumption**

Symmetricom SA.45s CSAC



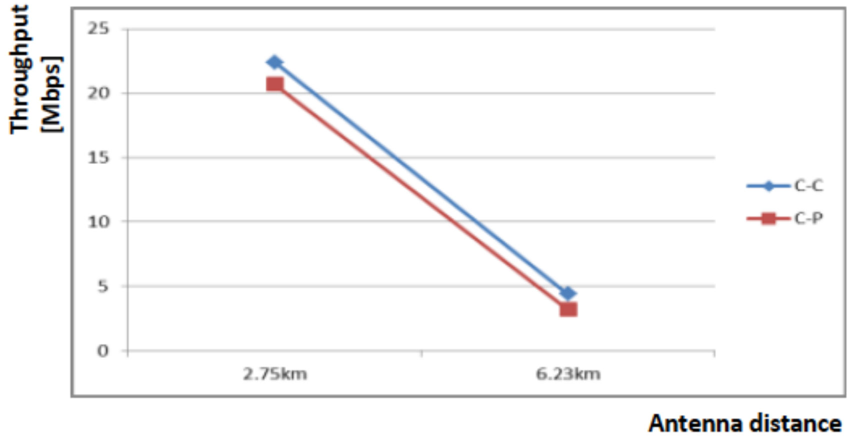


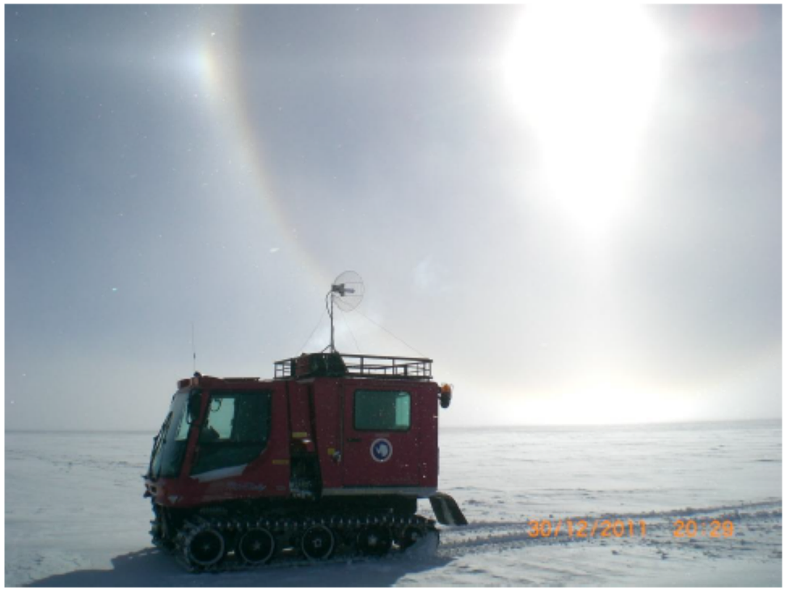


Chiba-IIHE collaboration

Wireless data transmission

- Array spread with an radius of ~6 km
- Try to avoid cables → Wireless data transmission over 6km
- Main test-sites: Kujukurihama, South Pole





GZK1 and 2: S. Yoshida et al. (1997) [1], m=4, Z_{max}=4, γ=2, E_{max}=10 ZeV and m=4, Zmax=5, γ=1.5, E_{max}=10 ZeV,

GZK3 and GZK4: Kotera et al. (2010), SFRI and FRII with γ=2.5, E_{max}=316 EeV,

GZK 5 and 6: M. Ahlers et al. (2010), E_{min}=10 EeV, E_{max}=1 ZeV best fit with Fermi, m=4.6, Z_{max}=2, γ=2.5 and m=4.4, Z_{max}=2, γ=2.1 (max)