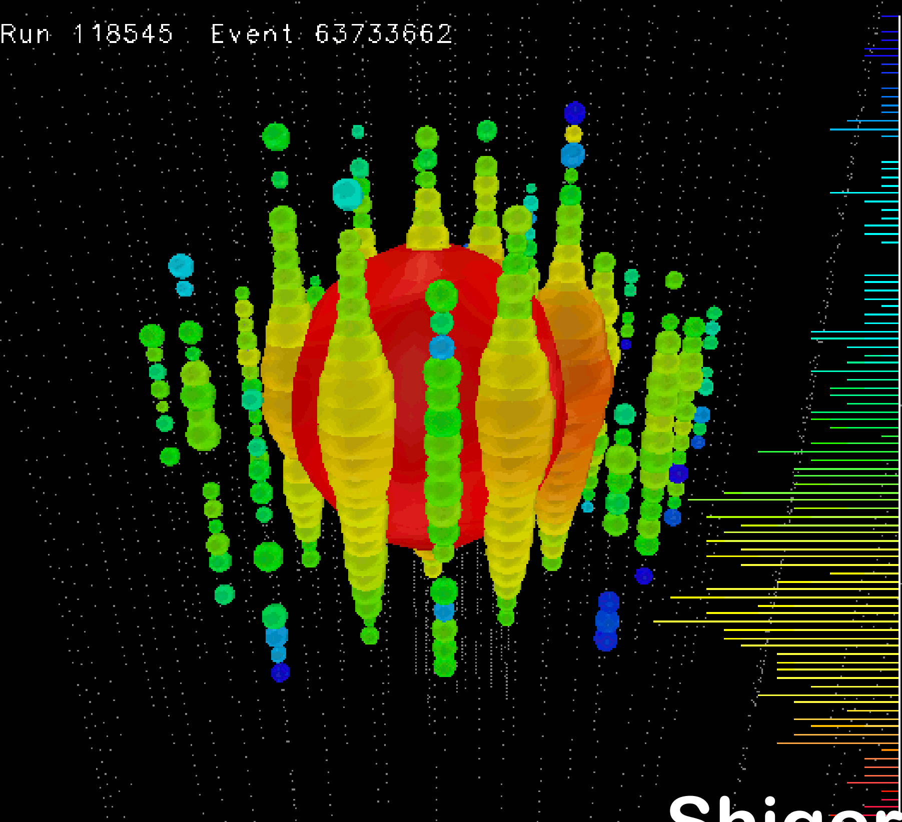
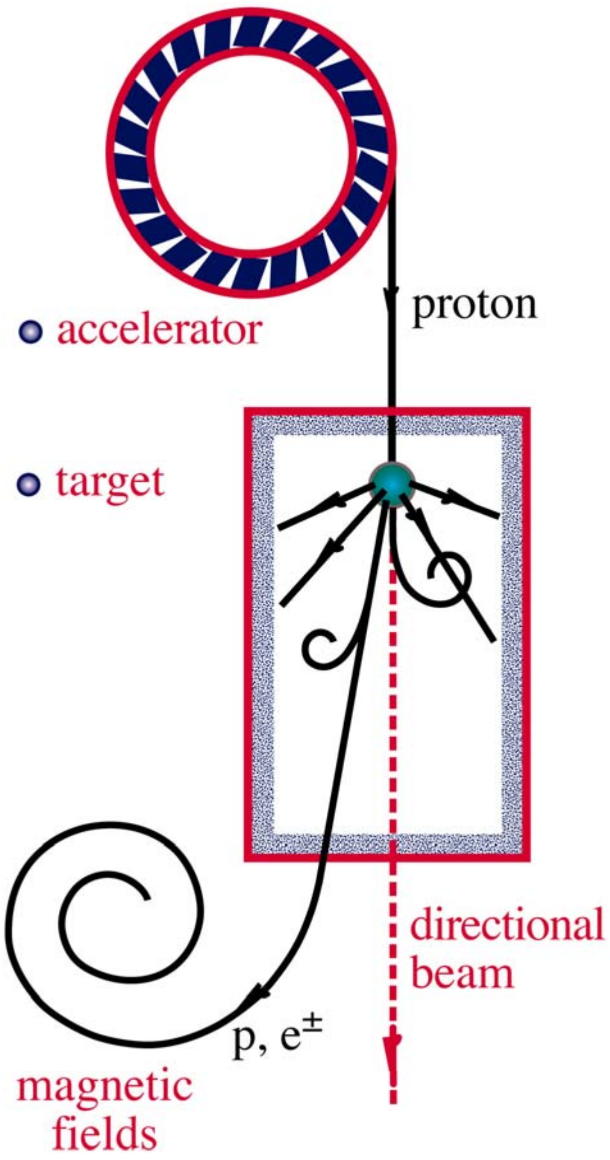
Detection of Ultra-high energy neutrinos

The 'First Light' of the high energy neutrino astronomy



Shigeru Yoshida
Department of Physics
Chiba University

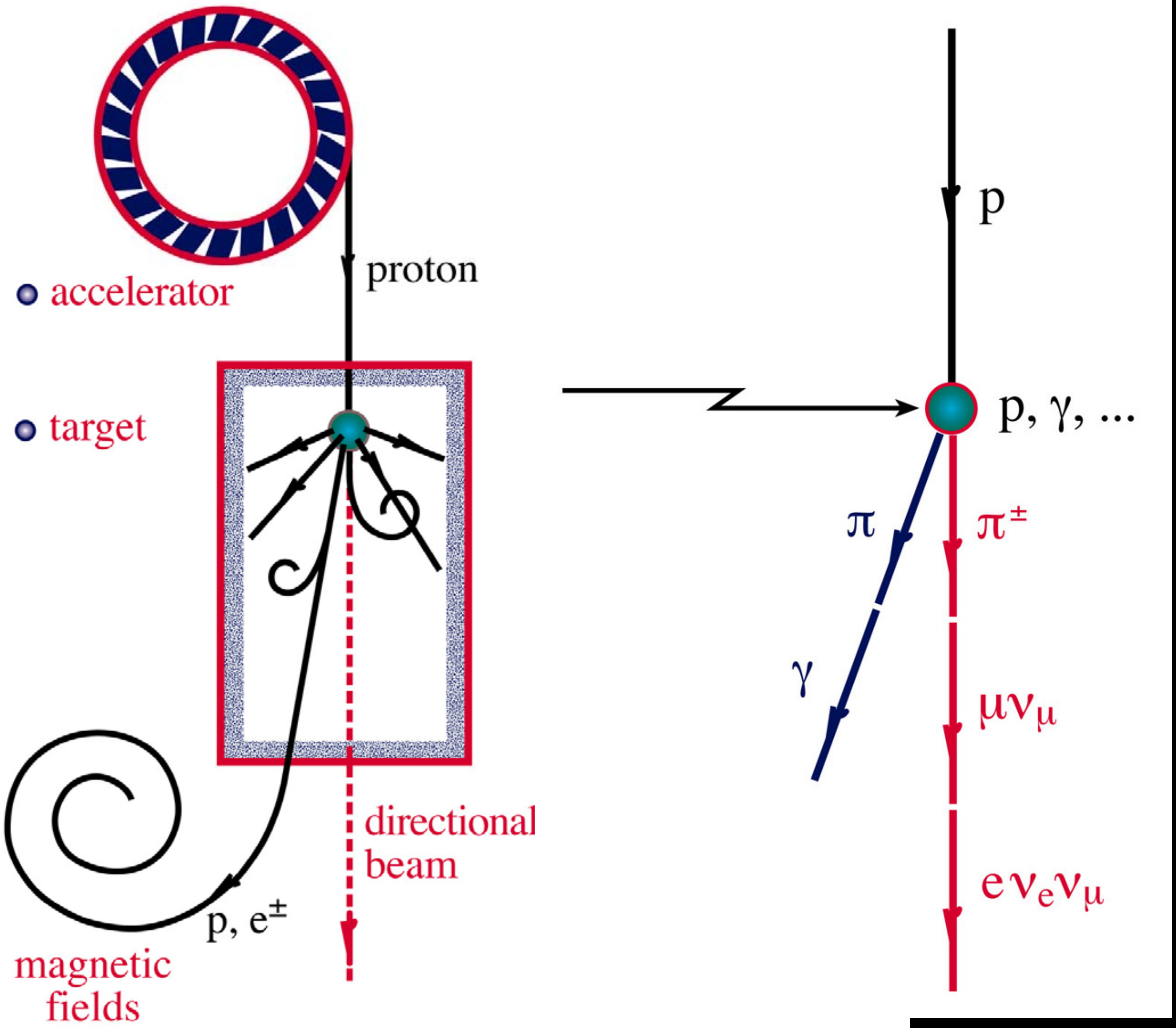
NEUTRINO BEAMS: HEAVEN & EARTH



black hole

radiation
enveloping
black hole

NEUTRINO BEAMS: HEAVEN & EARTH

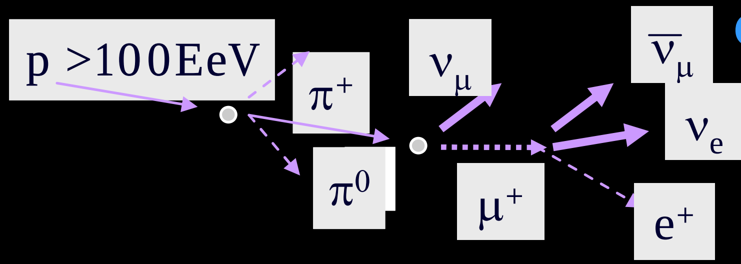


The highest energy neutrinos

cosmogenic **(GZK)** *neutrinos* induced by the interactions of cosmic-ray and CMBs

Off-Source (<50Mpc) astrophysical neutrino production via

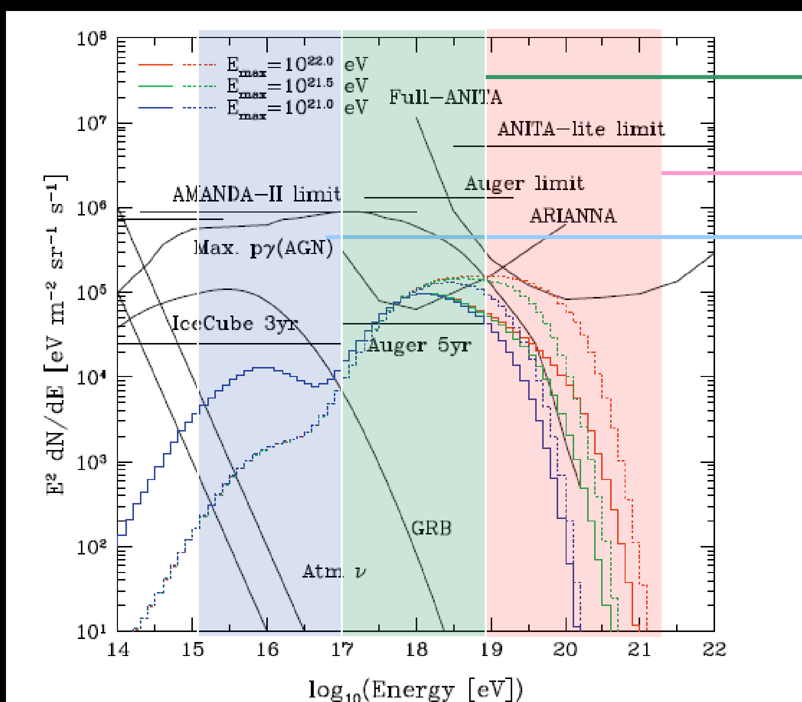
GZK (Greisen-Zatsepin-Kuzmin) mechanism



The main energy range: $\mathbf{E_\nu \sim 10^{8\text{-}10}}$ **GeV**

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

Takami et al Astropart.Phys. **31,** 201 (2009)



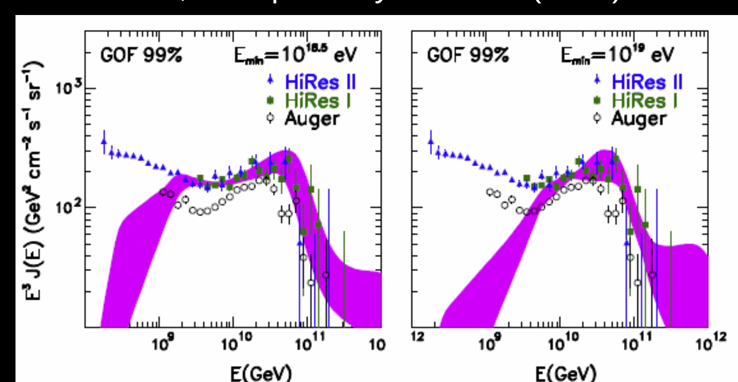
The region of the main GZK ν intensity

Trace the UHECR emission history

Probe maximal radiated energy

Probe transition from galactic to extra-galactic

Ahlers et al, Astropart.Phys. **34** 106 (2010)



"Dip" model

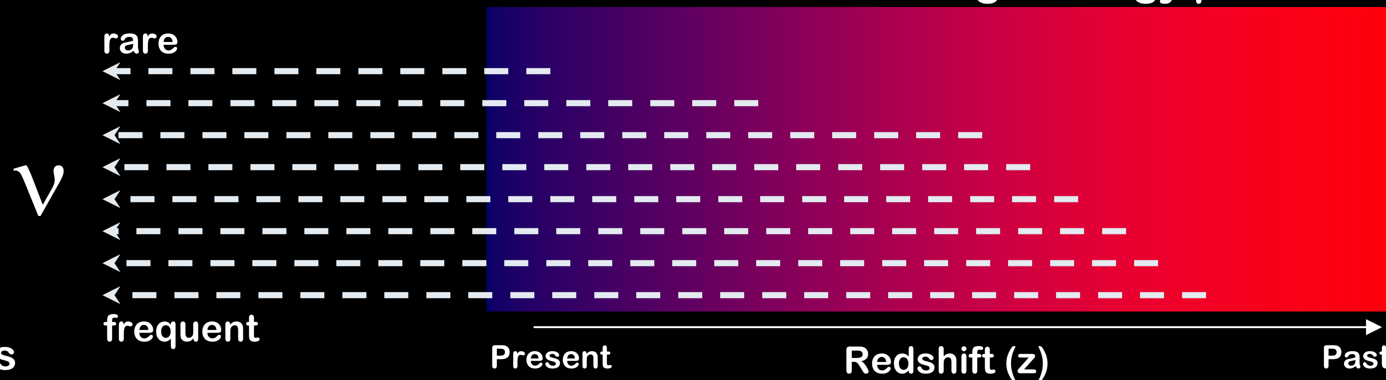
"Ankle" model

Tracing *history* of the particle emissions with ν flux

color : emission rate of ultra-high energy particles

Intensity gets higher if the emission is more <u>active</u> in the past

because ν beams are penetrating over cosmological distances

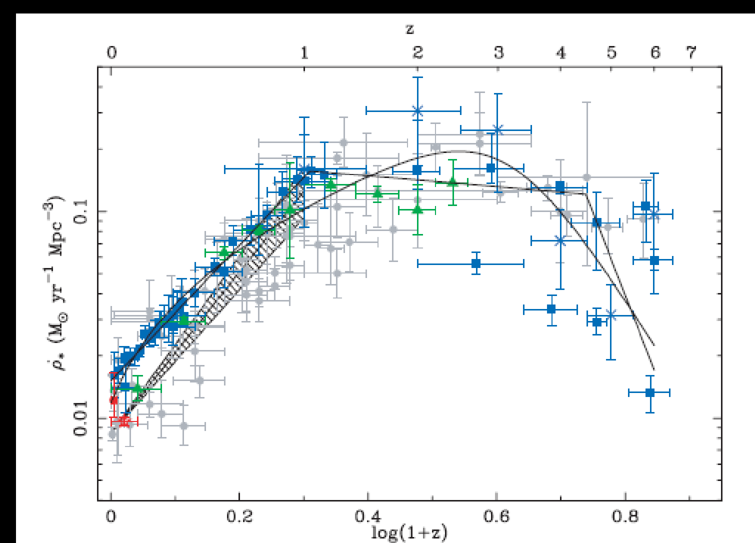


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→

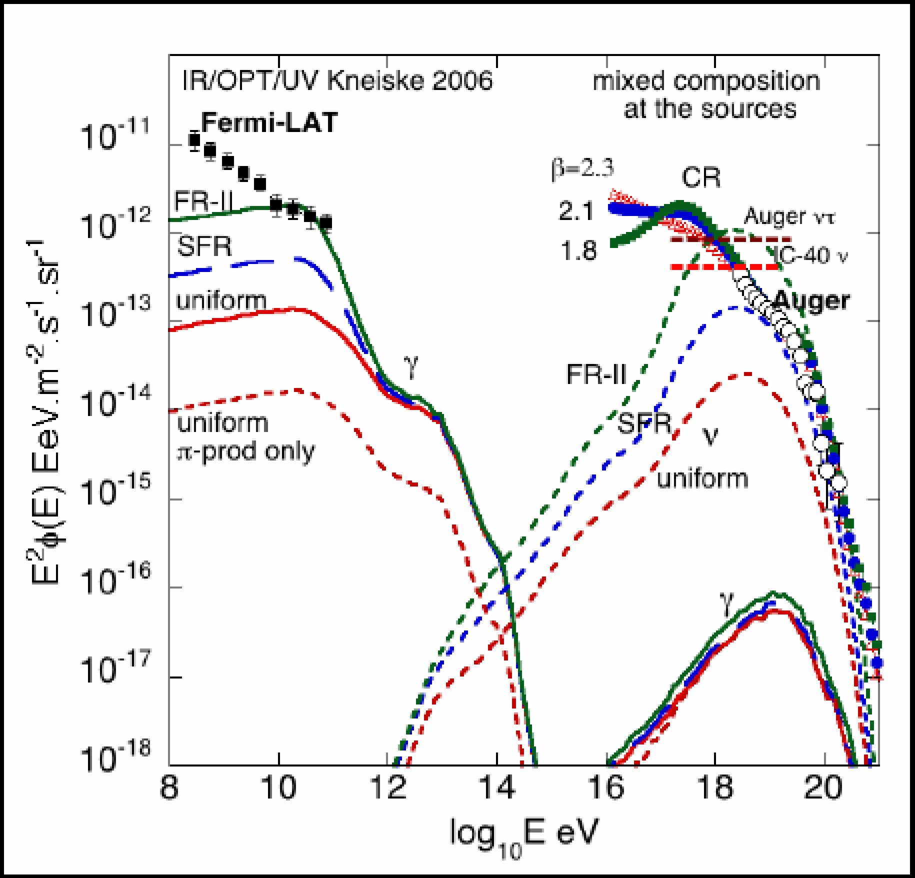


The spectral emission rate

$$\rho(z) \sim (1+z)^m$$

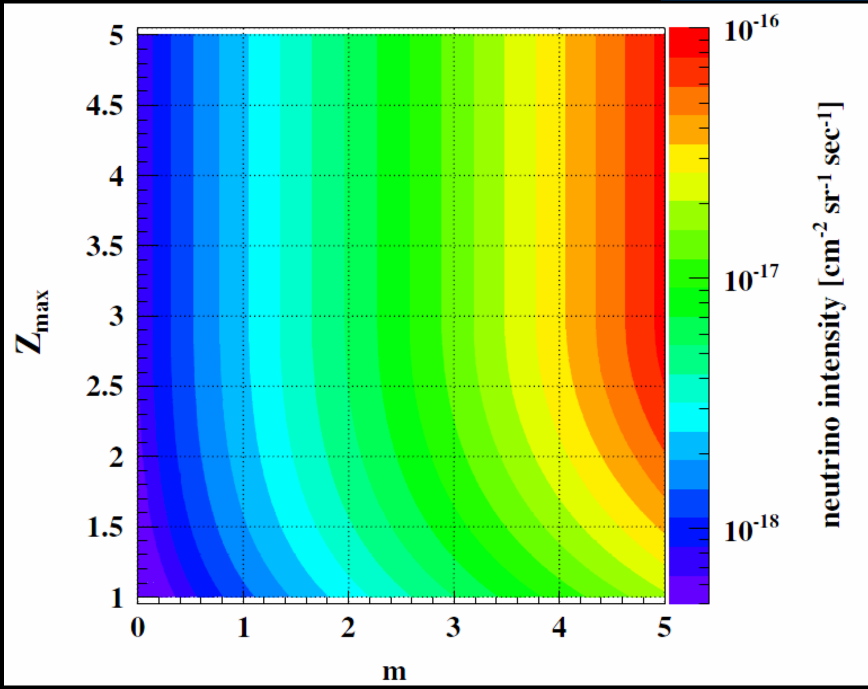
m= 0 : No evolution

Tracing *history* of the particle emissions with ν flux



Decerprit and Allard, A&A (2012)

$\rho \sim (1+z)^m$
$0<z<z_{max}$



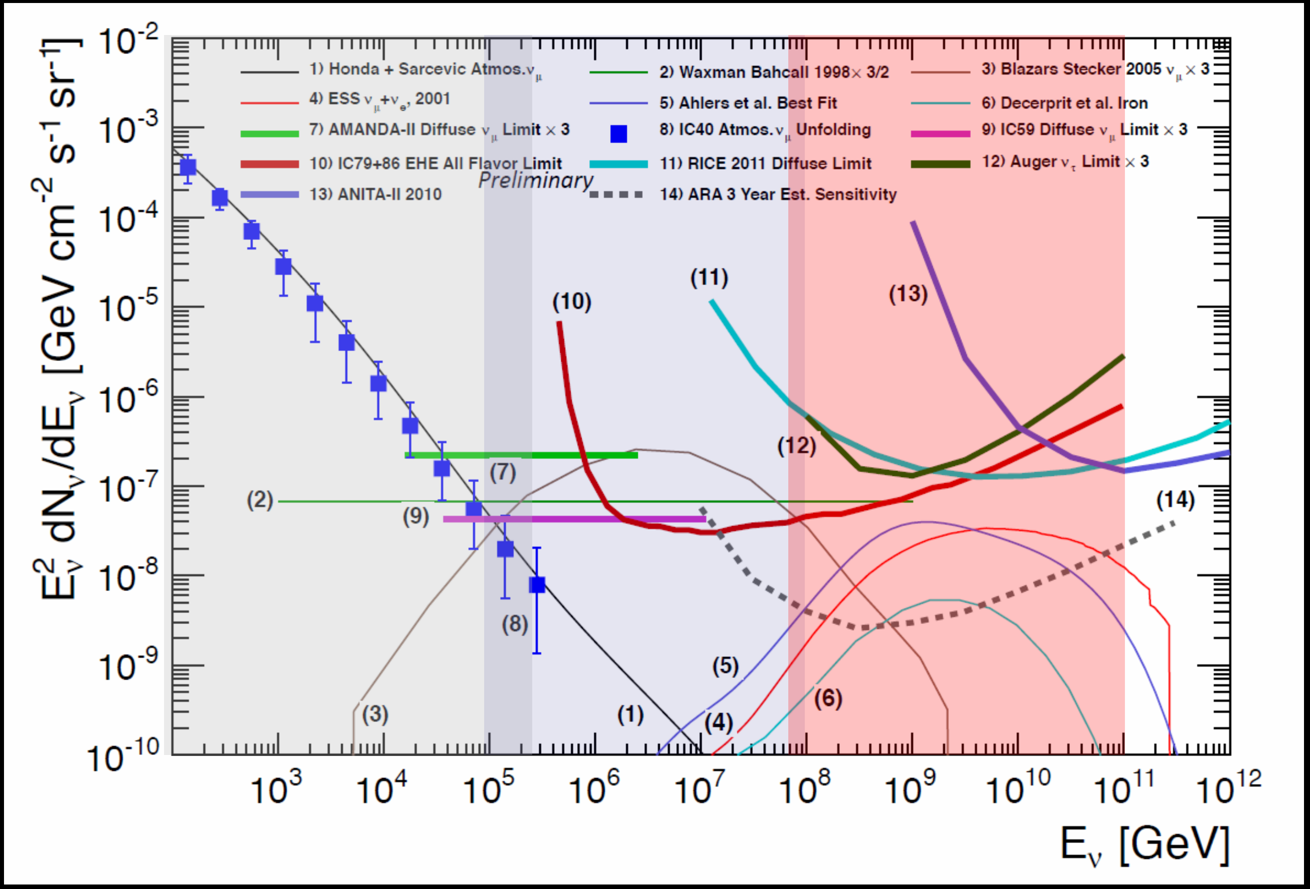
Yoshida and Ishihara, PRD 85, 063002 (2012)

The high energy ν involves..

atmospheric

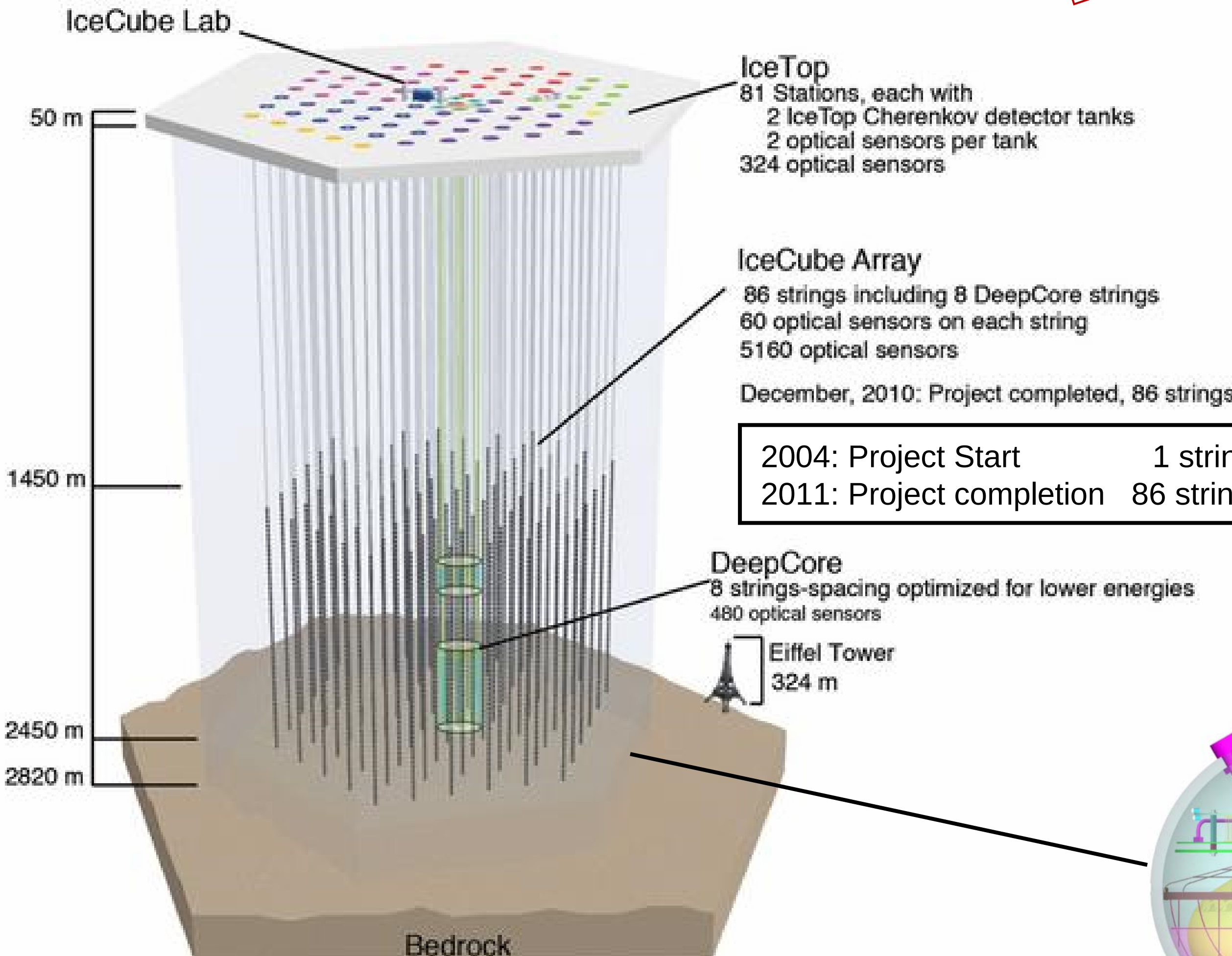
on-source ν
ex. AGN, GRB

off-source ν
GZK cosmogenic



The IceCube Neutrino Observatory

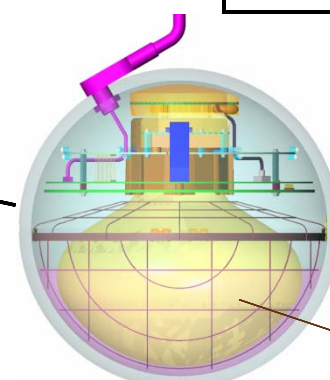
Completed: Dec 2010



2004: Project Start	1 string
2011: Project completion	86 strings

Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



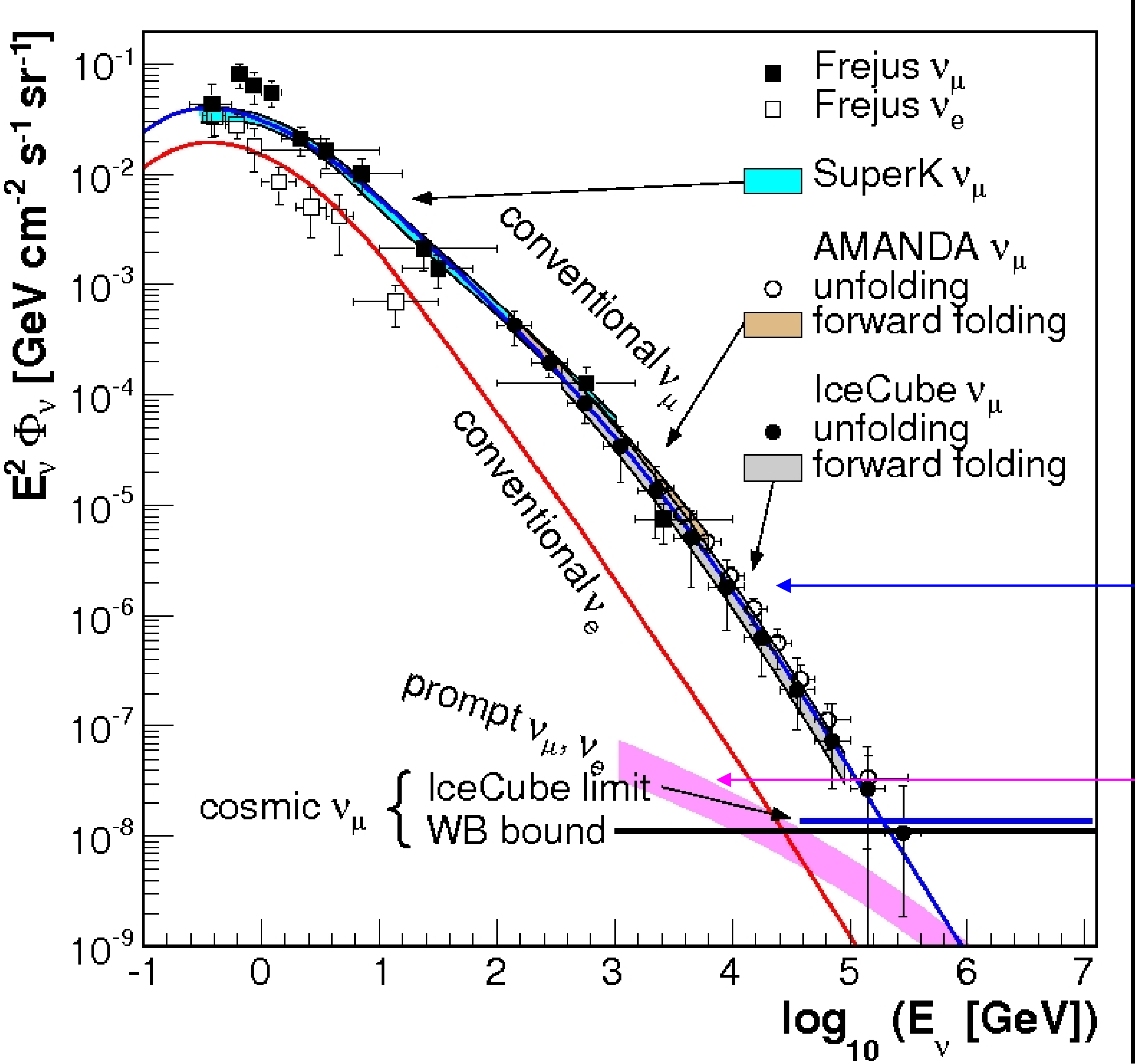
Full operation with all strings since May 2011

The IceCube Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The backgrounds for UHE ν search -Upward-going region-



Atmospheric ν

rapidly falling power-law

increasing energy threshold effectively filters them out

"conventional"

from π/K mesons

"prompt"

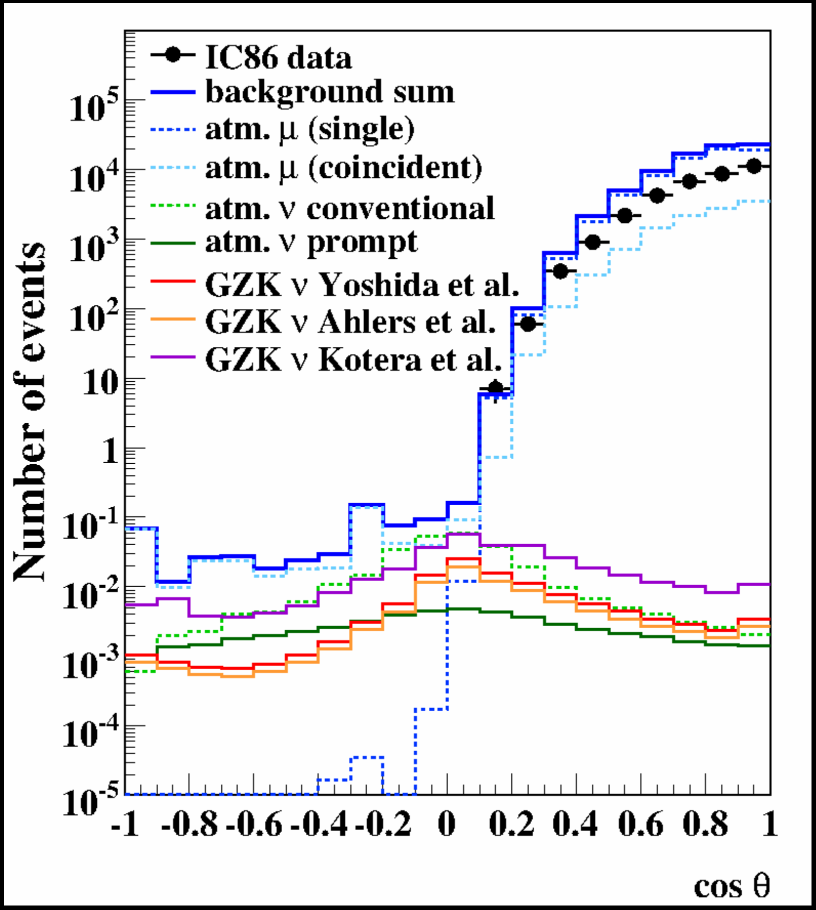
from charmed mesons

- never measured yet -

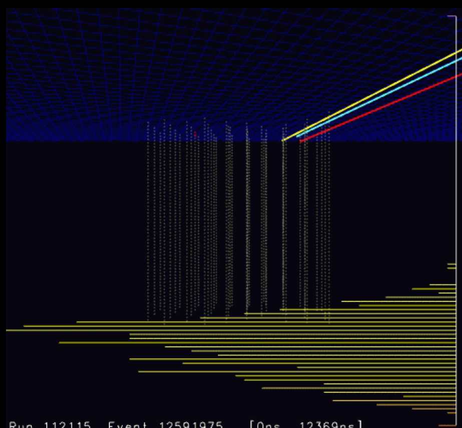
The backgrounds for UHE ν search -Downward-going region-

Atmospheric μ (bundle)

vastly dominates in vertically down-going region

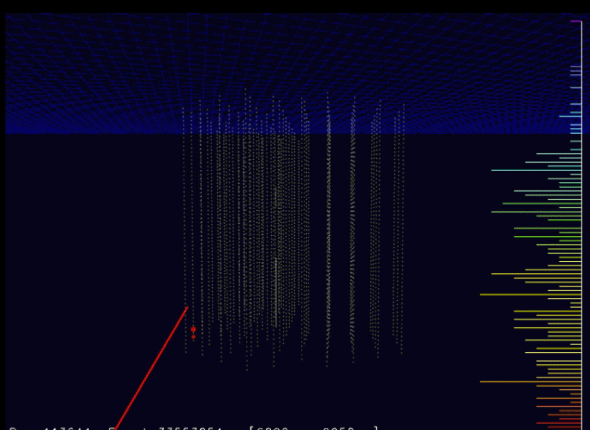


Topological signatures of IceCube events



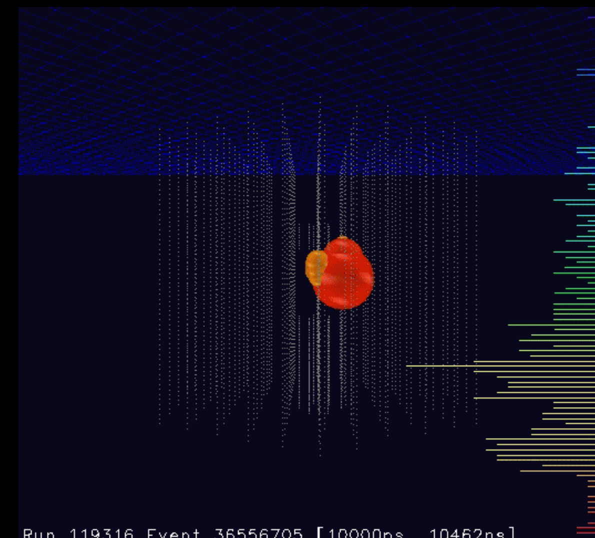
Down-going track

- atmospheric μ
- secondary produced
  μ from ν_μ
  τ from ν_τ @ >> PeV



Up-going track

- atmospheric ν_μ



Cascade (Shower)

directly induced by ν
inside the detector volume

- via CC from ν_e
- via NC from ν_e, ν_μ, ν_τ

all 3 flavor sensitive

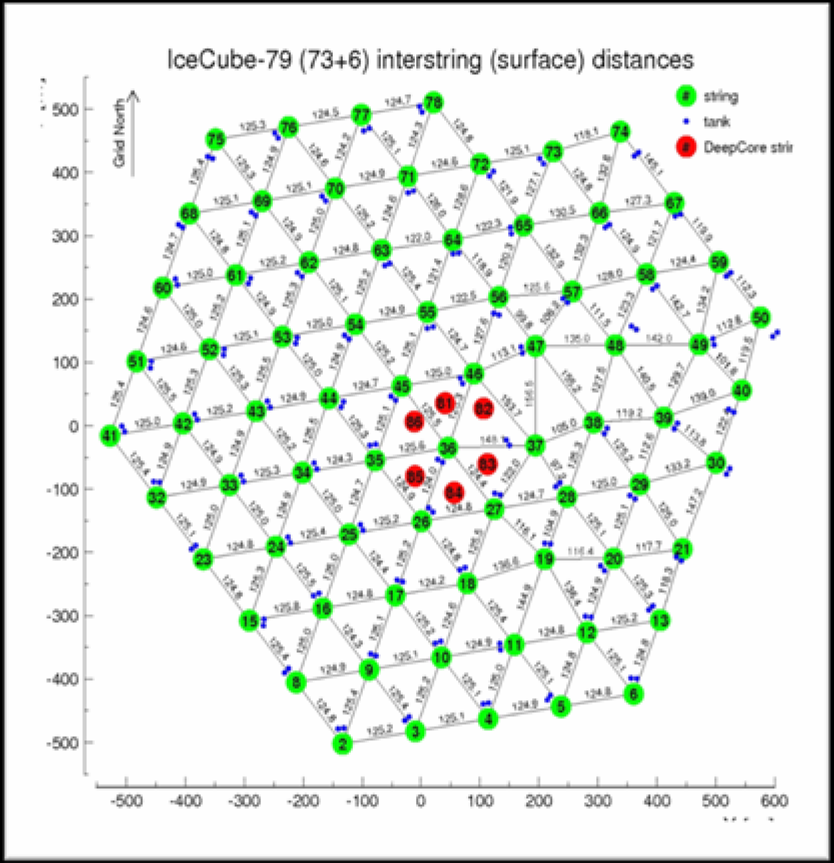
The dataset

9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

published
PRD 83 092003 (2011)

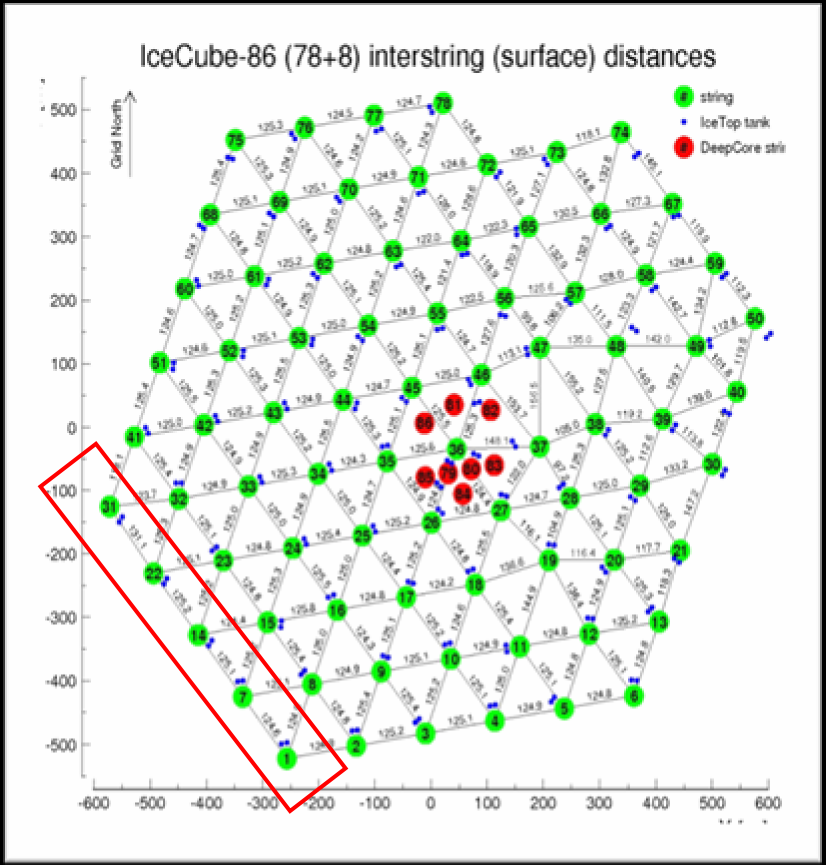
“IC79”

2010-2011 - 79 strings
May/31/2010-May/12/2011
Effective livetime 319.18days



“IC86”

2011-2012 – 86 strings
May/13/2011-May14/2012
Effective livetime 350.91 days



Data Filtering at South Pole

PY 2012 season

86 strings ~ the completed IceCube

Simple Majority Trigger
8 folds with 5 μ sec

~ 2.8 kHz

“2nd level” trigger

Muon Filter
selects
“up-going” tracks
~40 Hz

EHE Filter
selects
“bright” events
~1 Hz

NPE > 1000 p.e.

Cascade Filter
selects
“cascade”-like events
~34 Hz

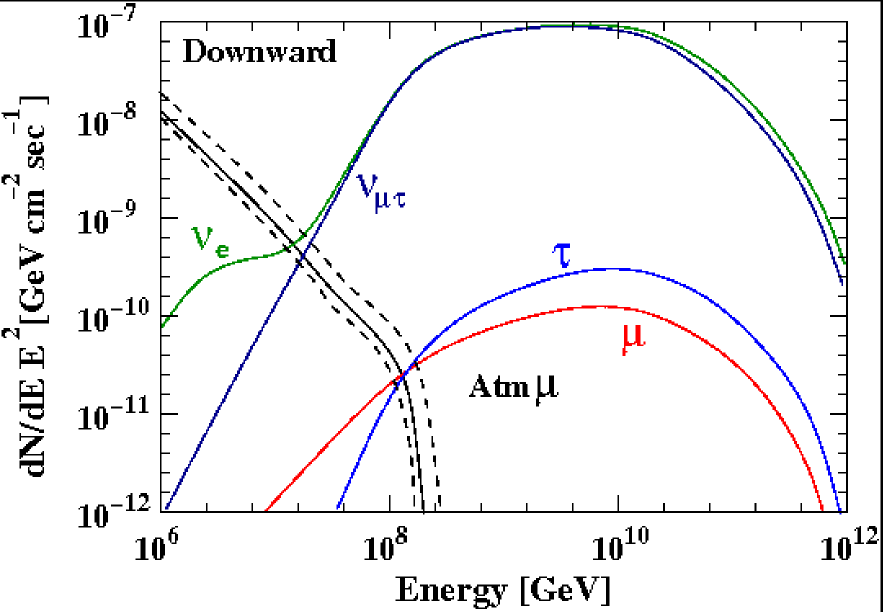
Many others
- Min Bias
- Moon
- IceTop
- etc

To Northern Hemisphere

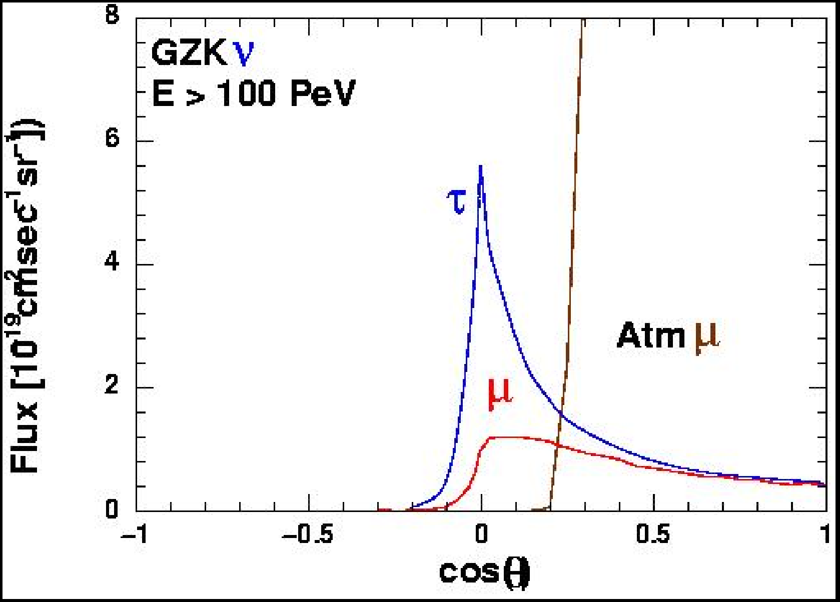
Ultra-high Energy ν search

Detection Principle

Energy Dist. @ IceCube Depth



Zenith Dist. @ IceCube Depth



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

through-going track

Secondary μ and τ from ν

→ Sensitive to ν_μ ν_τ

starting track/ cascade

Directly induced events from ν

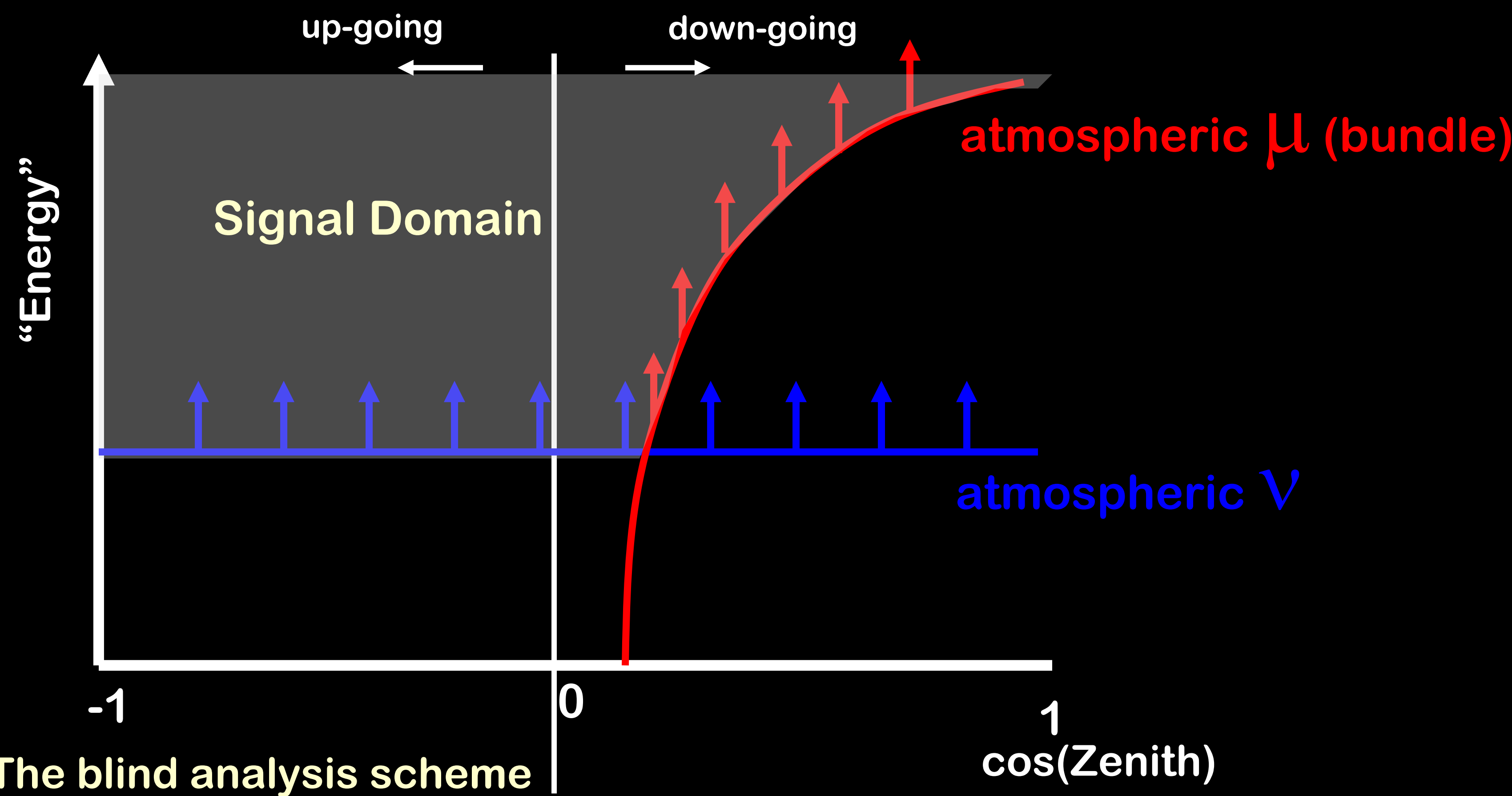
→ Sensitive to ν_e ν_μ ν_τ

And tracks arrive **horizontally**

千葉大学 Chiba University

Ultra-high Energy ν search

Detection Principle

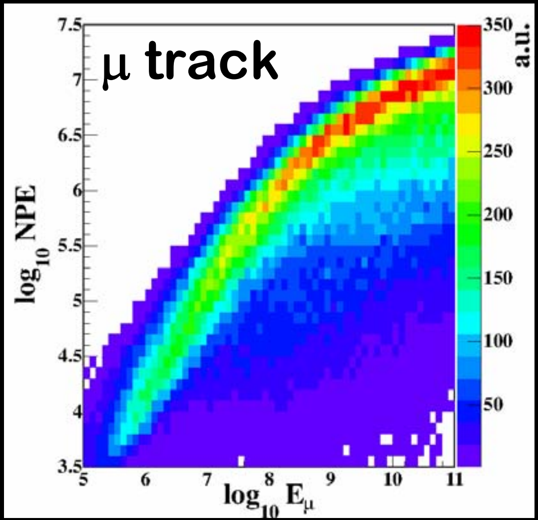


The blind analysis scheme

Use 10% of the data (test-sample) with masking the rest of them in optimizing the search algorithm with MC simulation

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

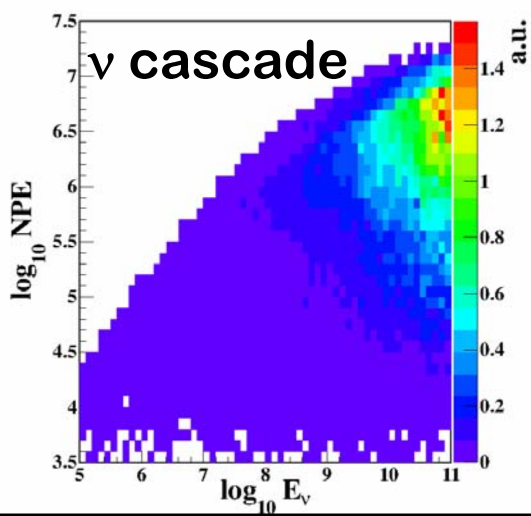
Ultra-high Energy ν search



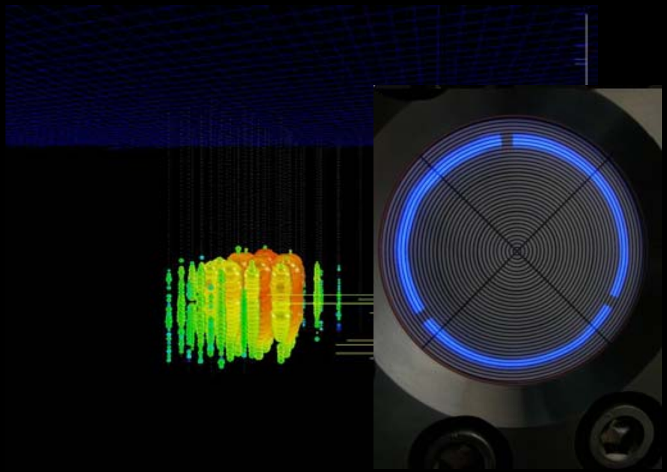
Detection Principle

Energy proxy
→ NPE (total # of photoelectrons)

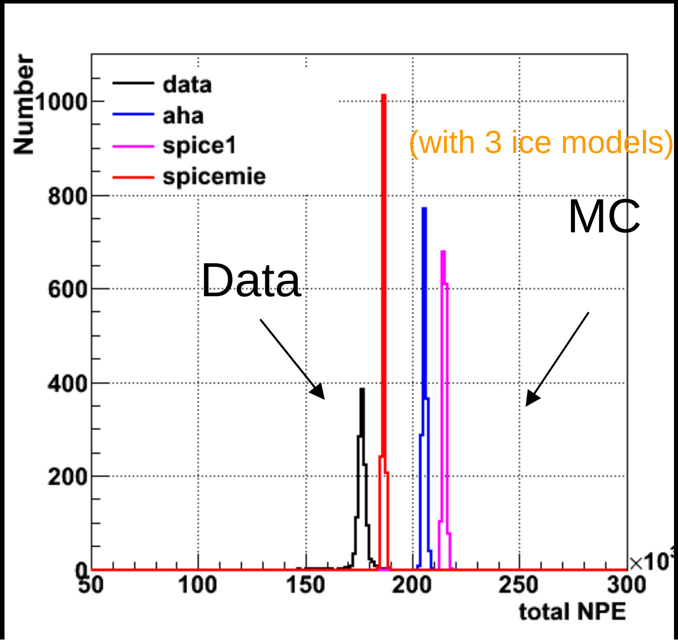
Look for luminous (high NPE) events



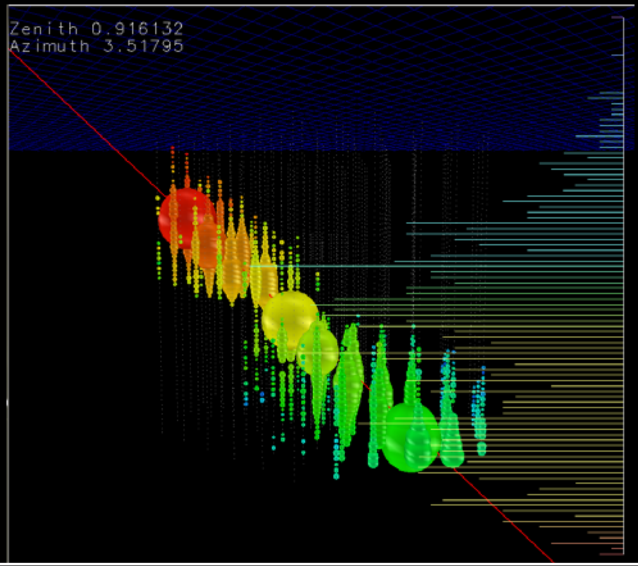
Experimental verification



Agreement within ~17%



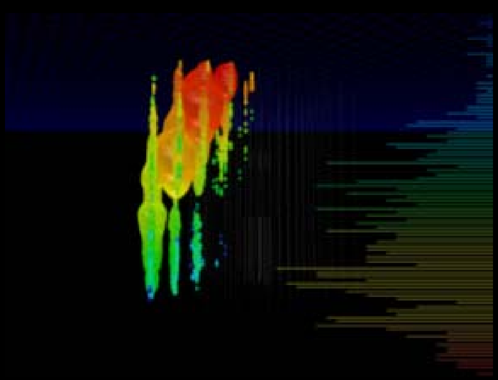
Reconstruction of zenith angle



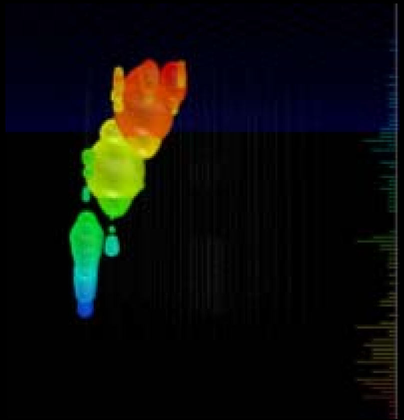
μ bundle with ~ 3PeV

Fit the photon hit timing with a track hypothesis

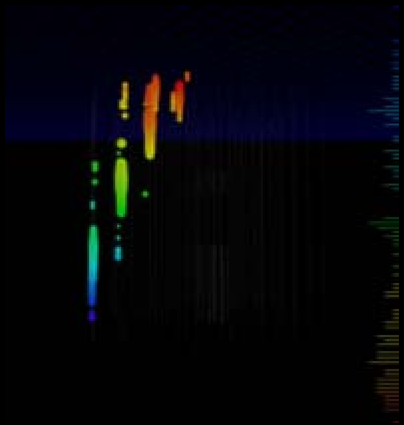
The filtering tech. used for IC86



"Delay-Clean"

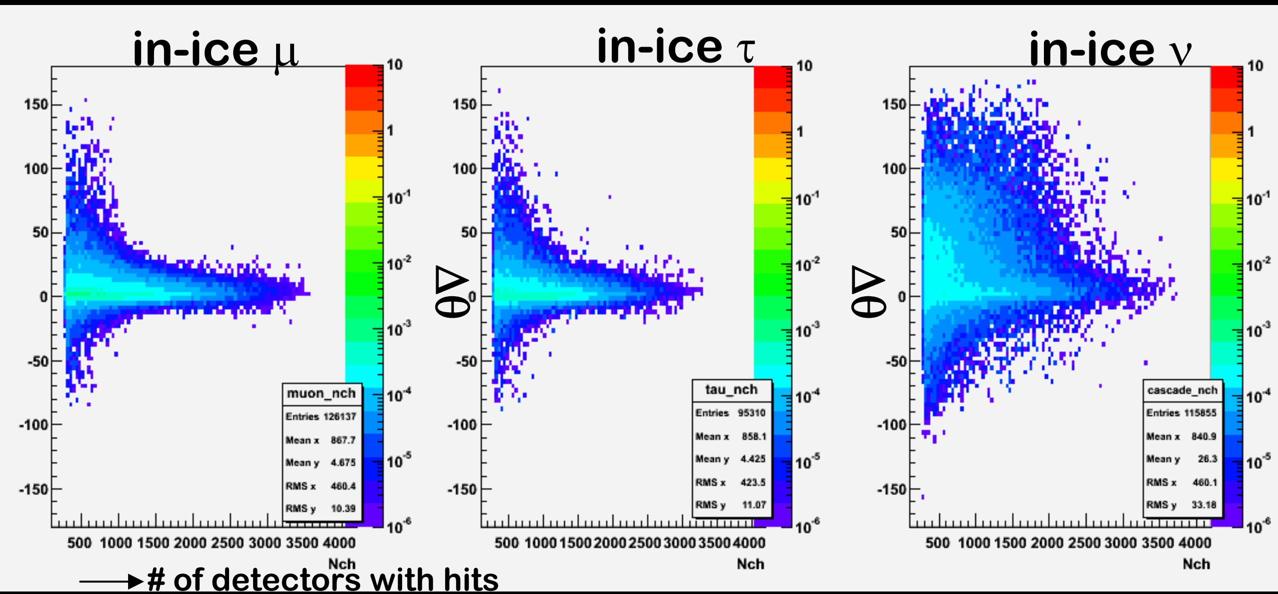


"de-biased"



Reconstruction of zenith angle

track events | **cascade events**



the algorithms used in the search tend to reconstruct cascades as horizontal/upward-going, leading to retaining them in the final sample even if they would be rejected by their true direction

The performance is good enough to reject down-going atmospheric μ bundles

The dedicated CPU-extensive reconstruction algorithms
will apply to a signal candidate event(s) (= that passes the final selection cuts)

The event distribution

in the plane of NPE (energy) and cos(zenith)

The final criteria

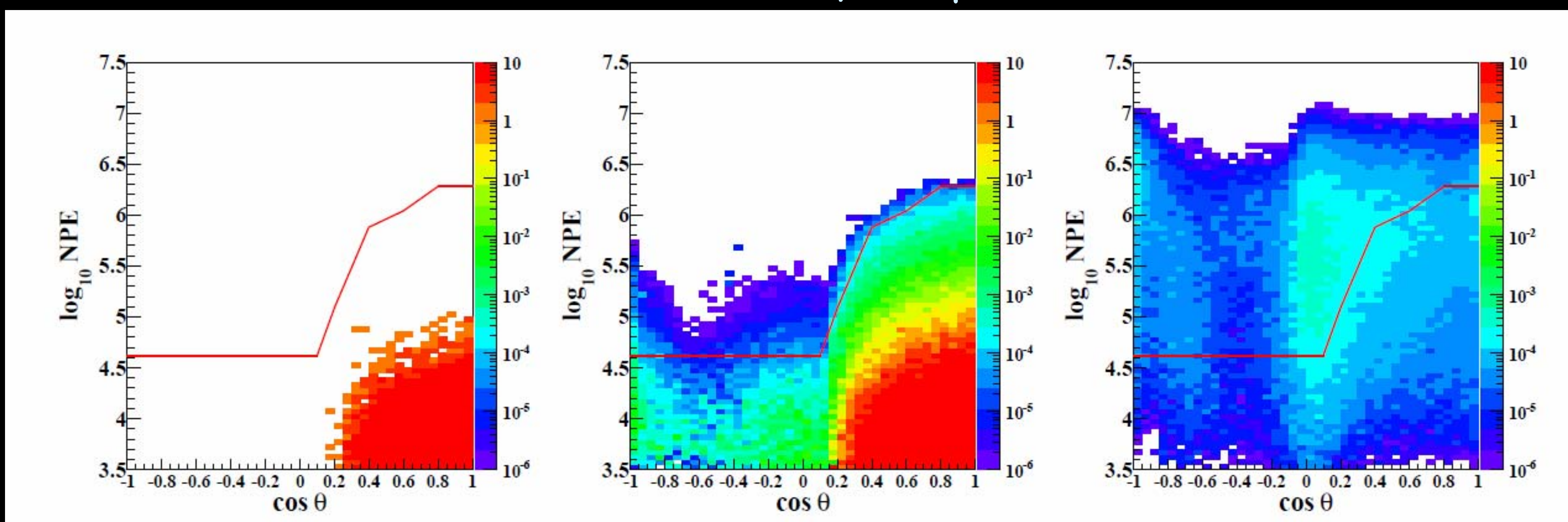
optimized and determined fully
by simulations (without looking at data)
to maximize the "discovery potential"

IC79 (2010-2011)

test-sample data

background MC
atmospheric ν
atmospheric μ

signal MC
cosmogenic ν



Before reaching to this level

Introduced multi-staged filtering/quality cuts

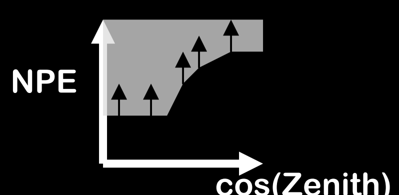
ensured the simulations reasonably describe the test-sample data at each of the filter levels

of events

IC79(319.2days) + IC86 (350.9 days)

	Experimental data	Background MC atmospheric μ bundle atmospheric ν	Signal MC GZK ν Yoshida & Teshima (1993)
EHE filter level NPE>1000	1.08×10^{8}	1.44×10^{8}	4.93
Analysis level hit cleanings recalculation of NPEs NPE>3,200 NDOM>300 zenith angle reconstruction	1.13×10^{6}	2.29×10^{6}	3.54
Final level $> NPE^{threshold}(\cos(zenith))$	2	$0.055^{+56.7\%}_{-94.3\%}$ conventional only $0.091^{+49.3\%}_{+68.7\%}$ plus the atmospheric prompt ν	$2.09^{+13.6\%}_{-12.4\%}$

Note: assuming the pure Fe UHECR yielding the higher rate – See the following slides

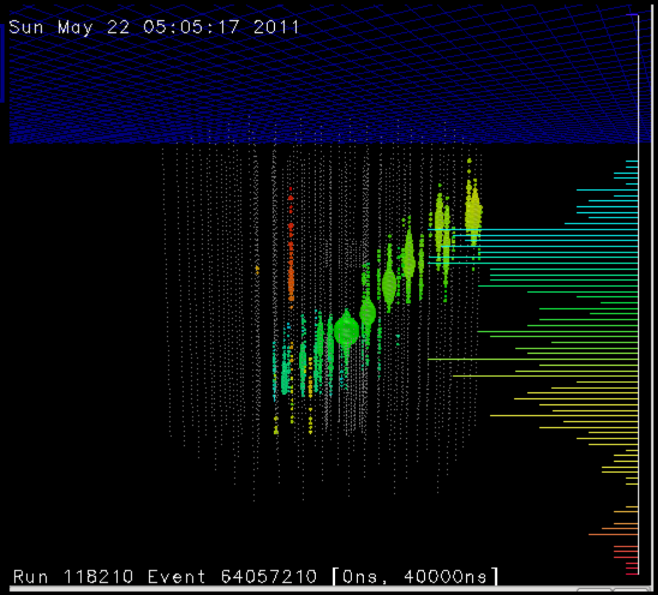


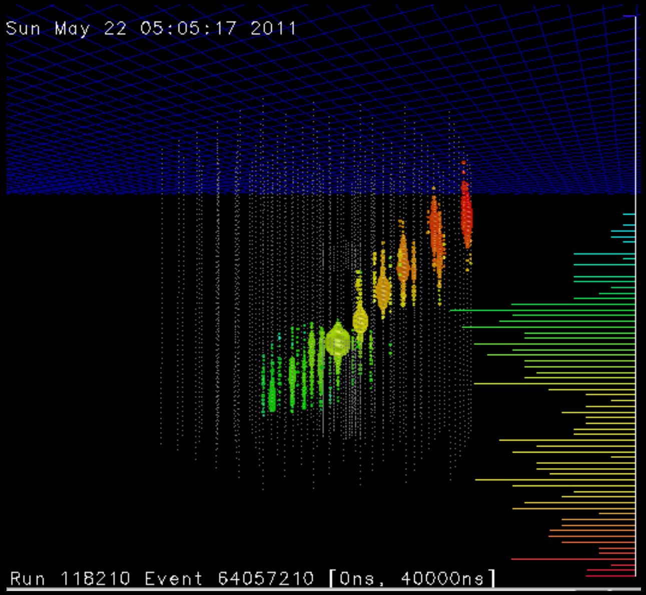
On the Analysis level

Coincident μ track cleaning

Example #1

Before

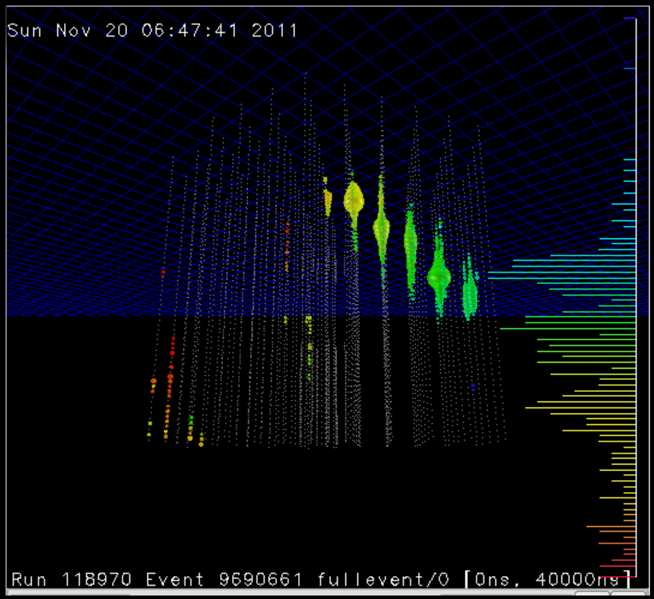


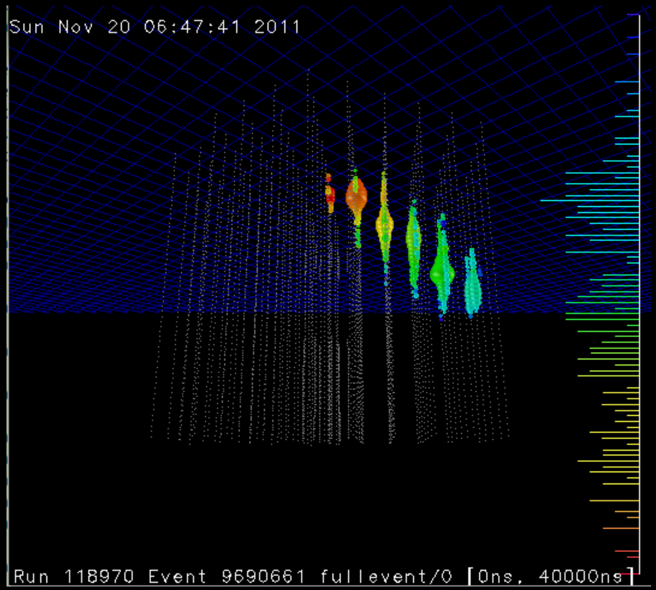


After

Example #2

Before

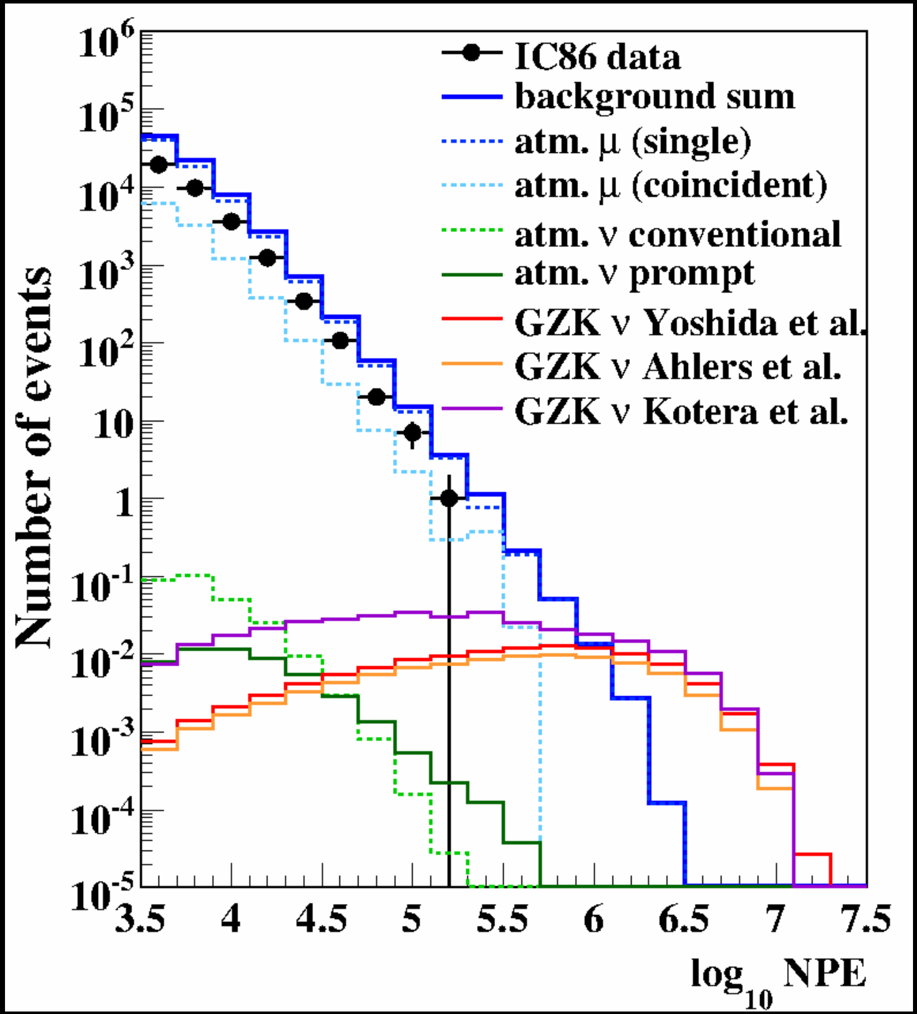


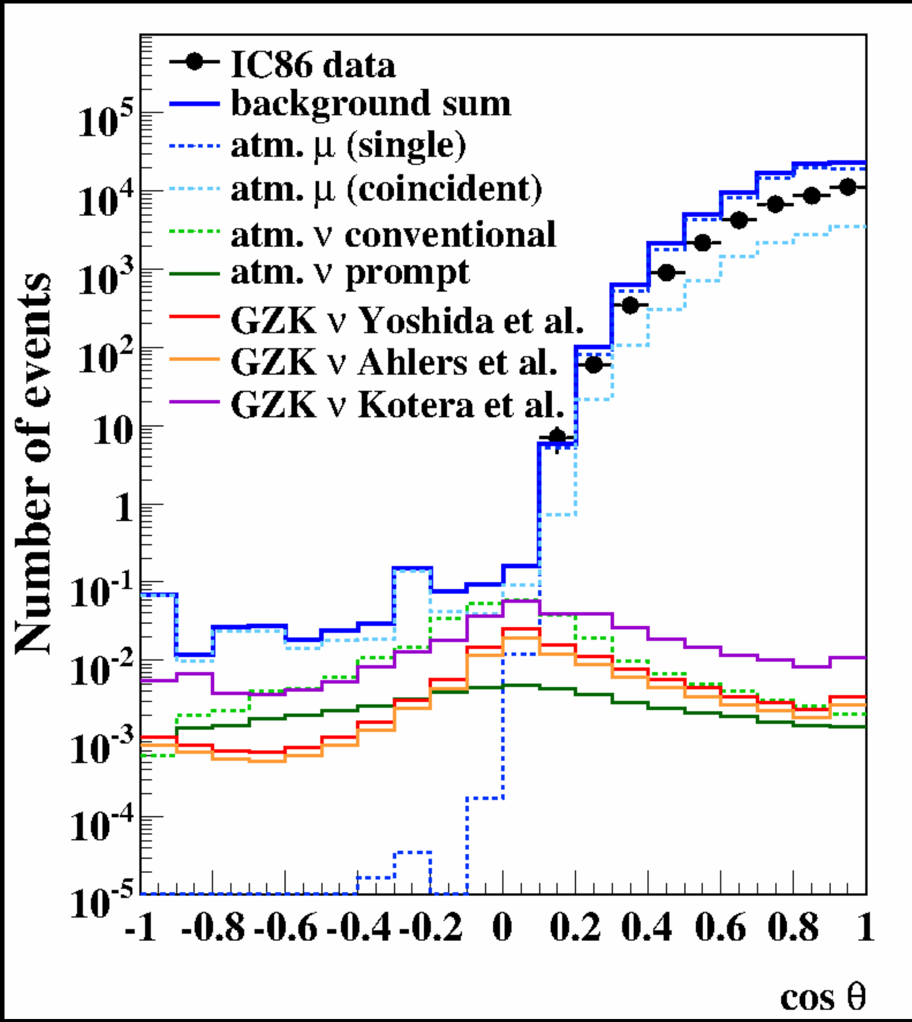


After

On the Analysis level

The event distributions as functions of NPE and zenith





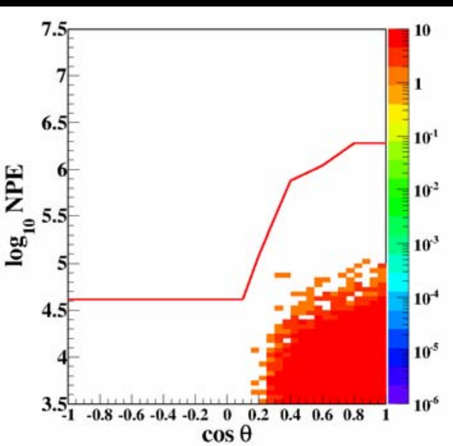
On the Analysis level

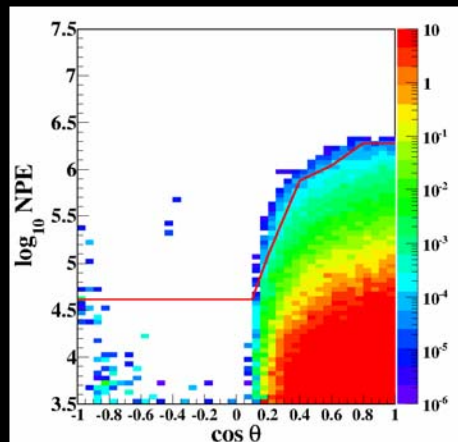
The final-level selection criteria in the plain of NPE-cos(zenith)

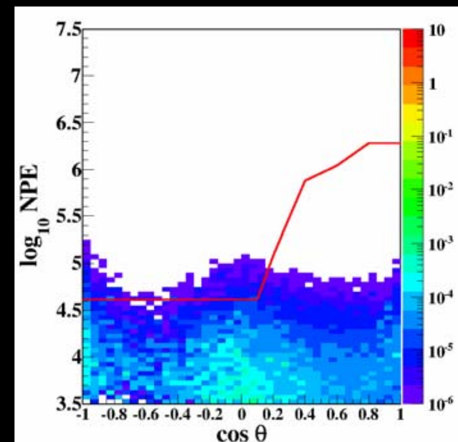
Number of events (z-axis) per the test-sample livetime

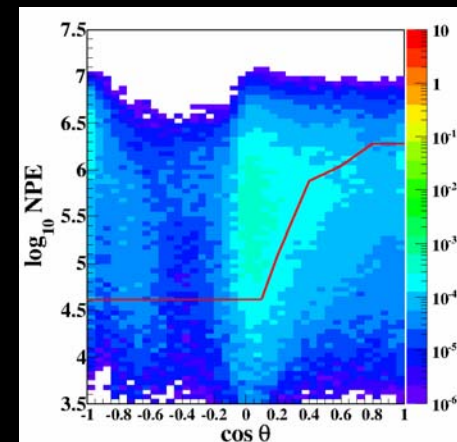
test-sample data | atmospheric μ | atmospheric ν (conventional only) | signal GZK ν

IC79

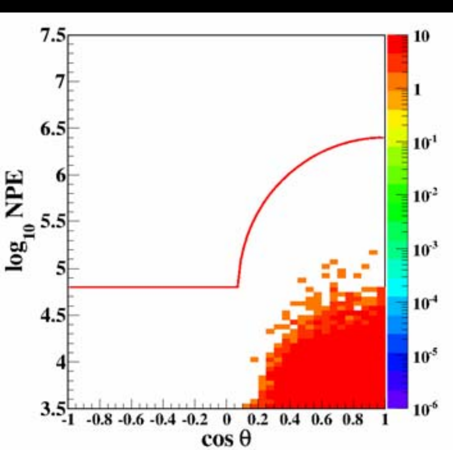


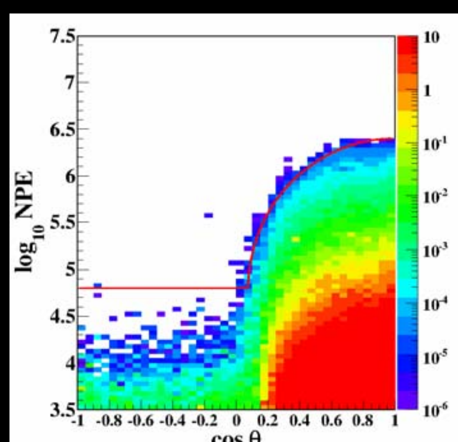


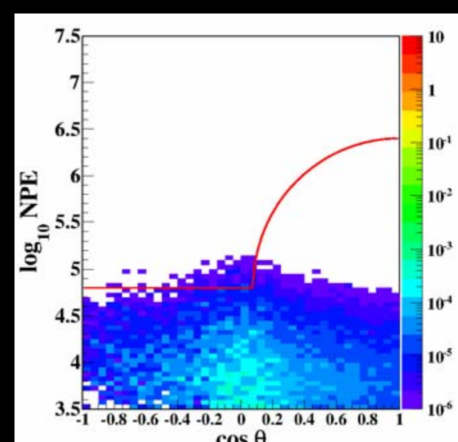


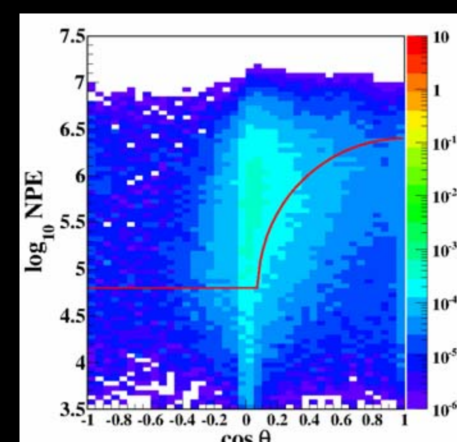


IC86









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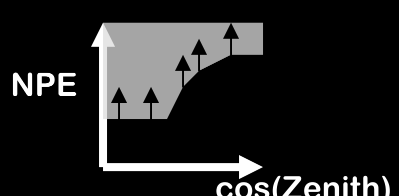
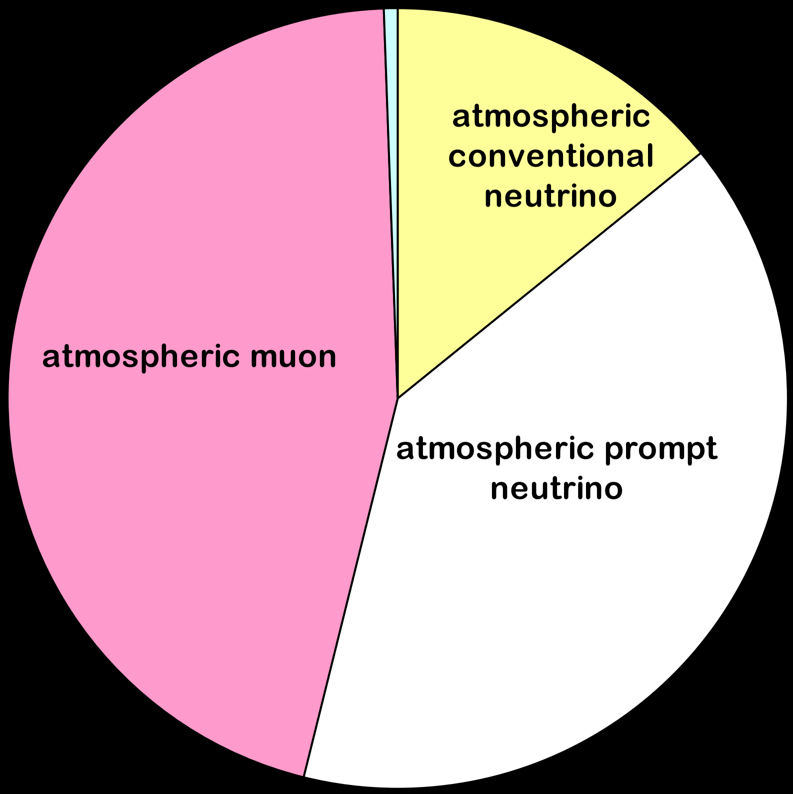


Background Breakdown



	Total background (IC79＋IC86)
Atmospheric μ	0.0414
Atmospheric ν (Conventional)	0.0129
Coincidence μ	0.0004
Total	**0.055**
prompt ν	0.0359
Total with prompt	**0.0905** **(0.0823)** **excluding the test-sample livetime**

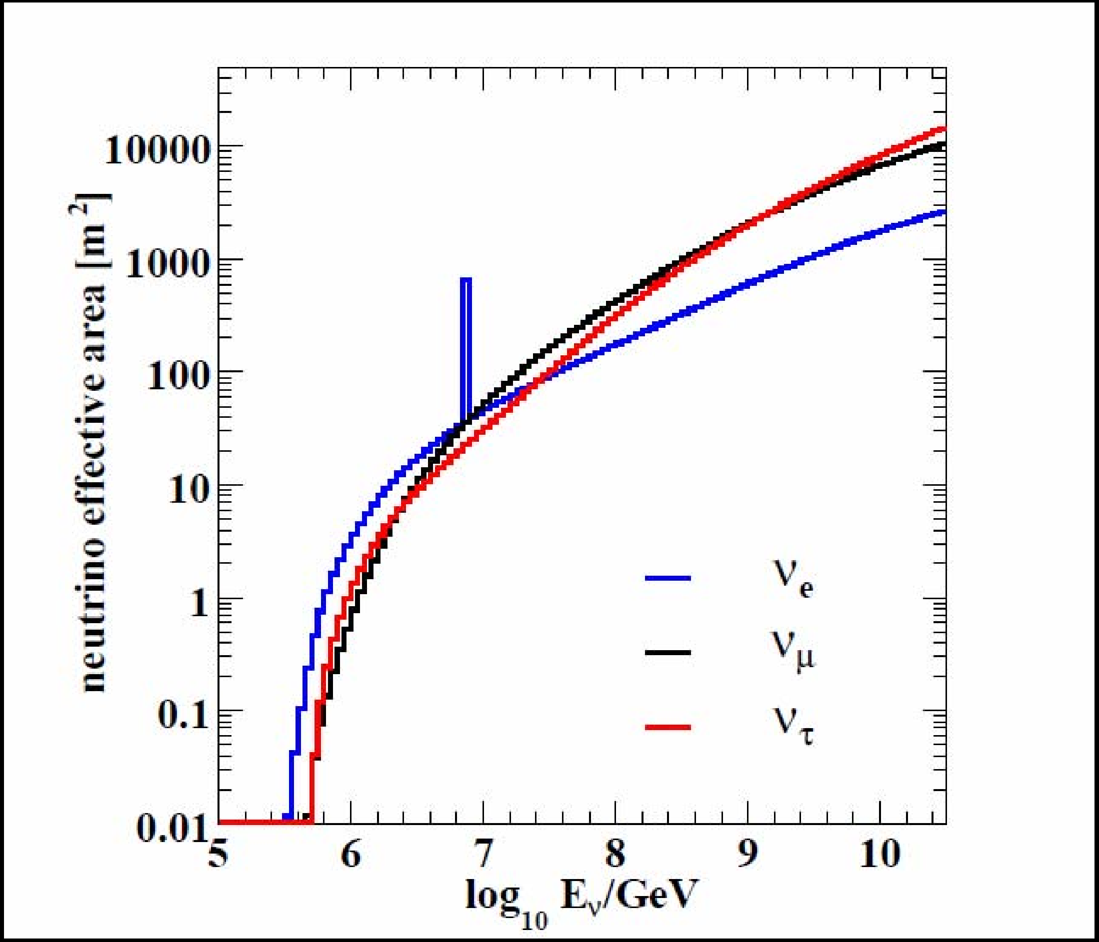
The systematic uncertainties on the BG rate

		remarks
Detector efficiency	+43.1% - 26.1%	absolute PMT/DOM calibration
Ice properties/Detector response	- 41.7%	in-situ calibration by laser
Cosmic-ray flux variation	+18.7% - 26.3%	UHECRs : HiRes – Auger Uncertainties on The Knee spectrum
Cosmic-ray composition	- 36.7%	The baseline to calculate atm μ: 100% Fe Compared against the pure proton case
Hadronic interaction model	+8.1%	The baseline : Sibyll 2.1 Compared to QGSJET –II - 03
ν yield from cosmic-ray nucleon	+2.2% - 2.2%	The Elbert model
prompt ν model	+12.6% - 16.1%	The Enberg model perturbative-QCD

Effective Areas

Area x ν flux x 4π x livetime = event rate

IC79+IC86 livetime 670.1 days



ν_e larger below 10 PeV

due to effective energy deposition by showers

$\nu_{\mu\ \tau}$ dominant above 100 PeV

due to the secondary produced μ and τ tracks

τ's are no longer short-lived particles in EeV

Two events passed the final criteria

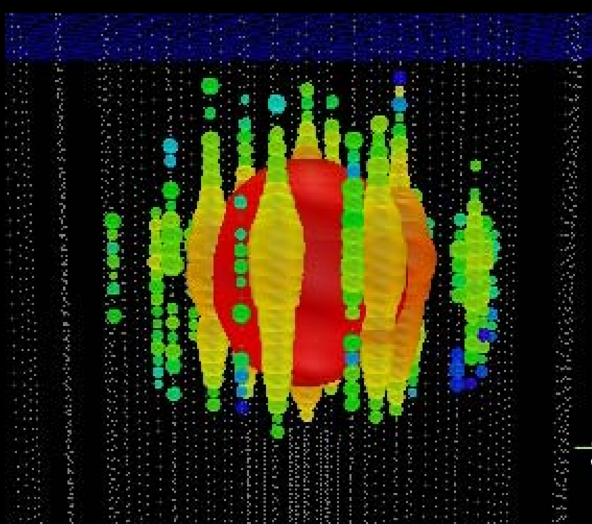
2 events / 615.9 days (excluding the test-sample livetime)

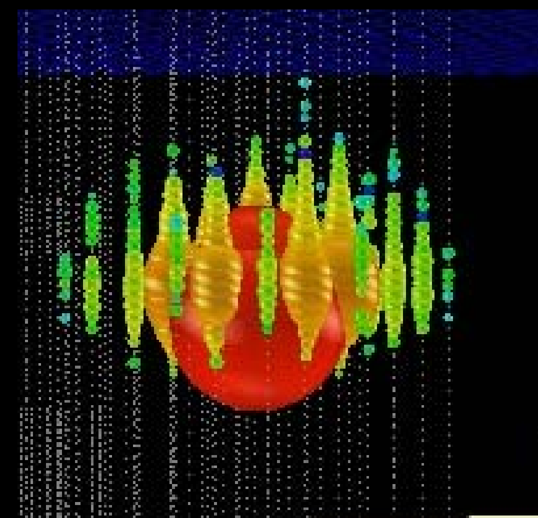
The Expected Backgrounds

including prompt	**0.082**	$^{+0.041}_{-0.057}$
conventional only	**0.050**	$^{+0.028}_{-0.047}$

p-value 2.8×10^{-3} (2.8σ)

p-value 9.0×10^{-4} (3.1σ)





Super-nicely contained cascades!

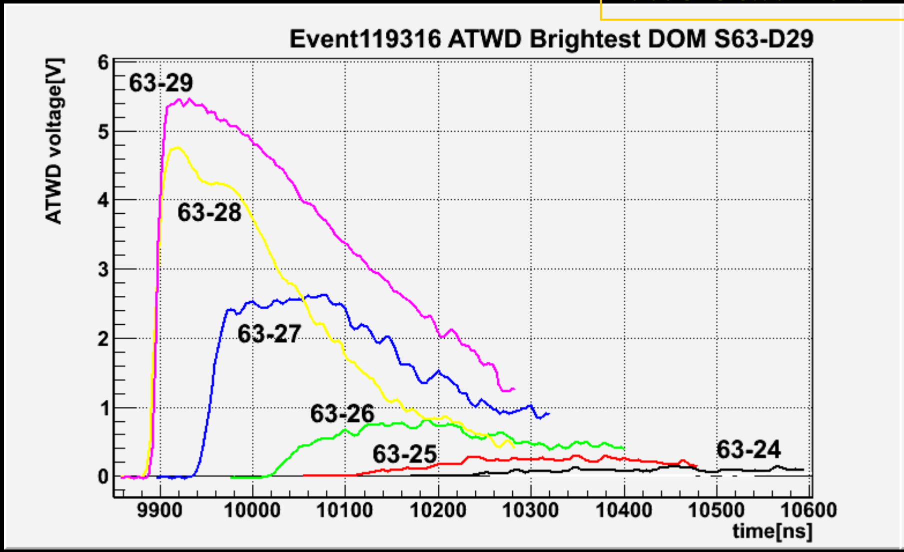
Run118545-Event63733662
August 9th 2011 ("**Bert**")
NPE 6.9928×10^4
Number of Optical Sensors 354

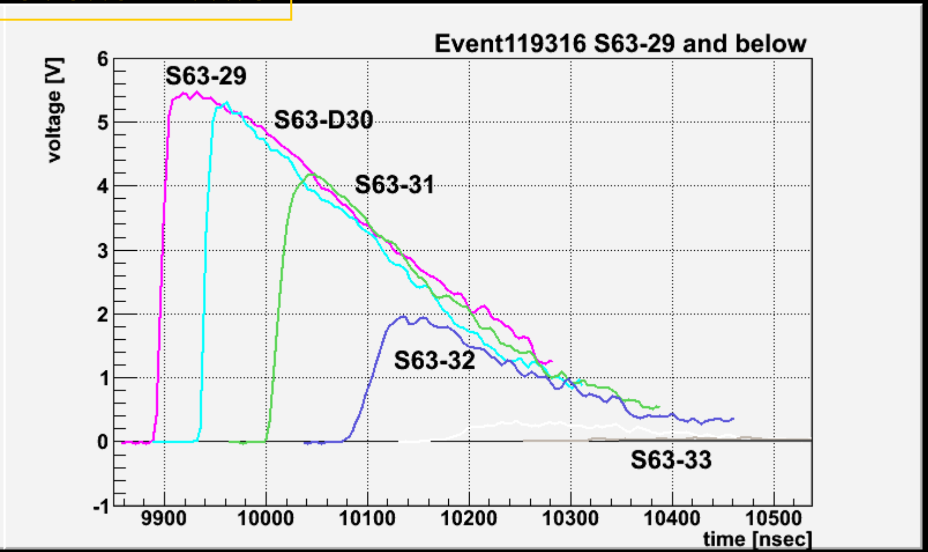
Run119316-Event36556705
Jan 3rd 2012 ("**Ernie**")
NPE 9.628×10^4
Number of Optical Sensors 312

Recorded pulses

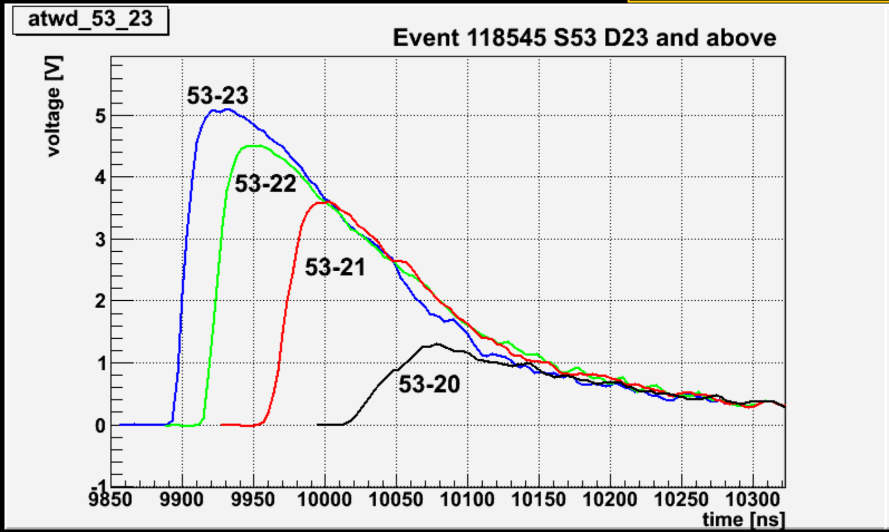
Clean and luminous bulk of photons !!

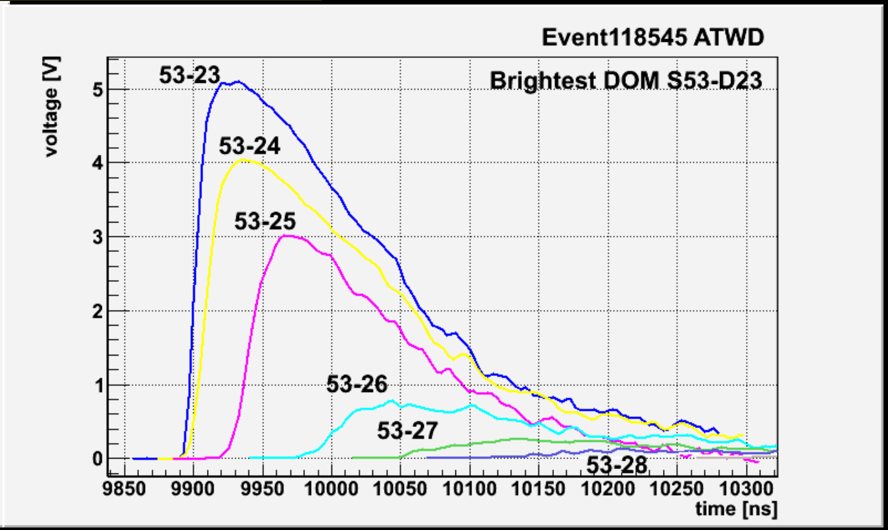
The Jan 2012 event - Ernie





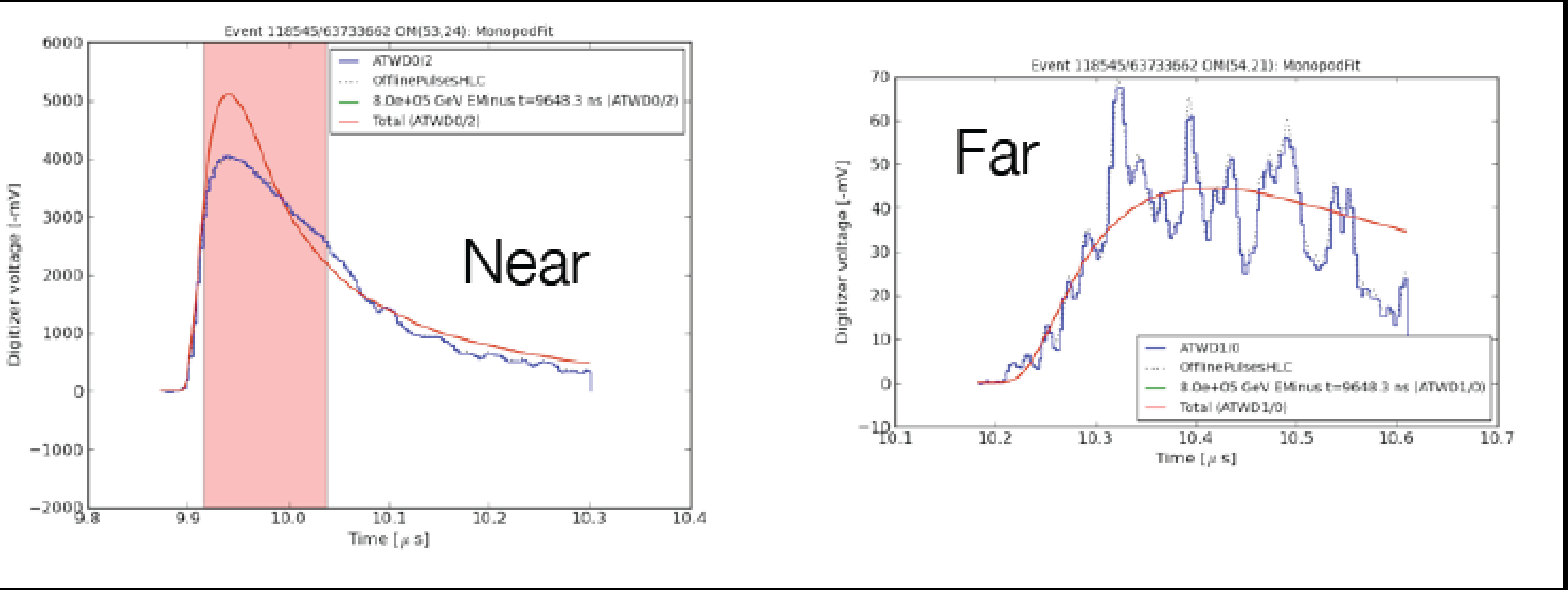
The Aug 2011 event - Bert





What are their energies?

- Maximizing the Poisson likelihood based on the recorded waveforms



Estimated Energy Deposit +- 15% accuracy

Preliminary

- Jan 2012 event (Ernie) 1.1 PeV zenith 11deg
- Aug 2011 event (Bert) 1.0 PeV zenith 70deg

A PeV shower

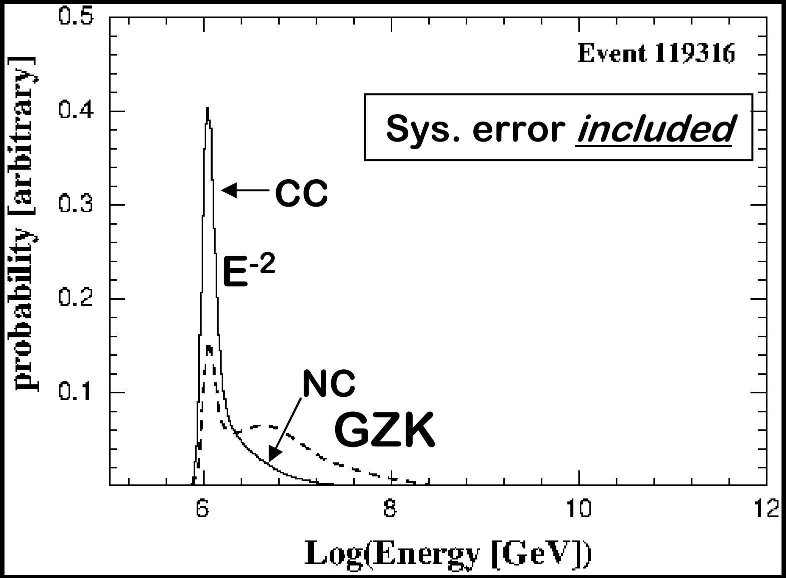
Earth-surface Eν probability

All flavor sum ($\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1)

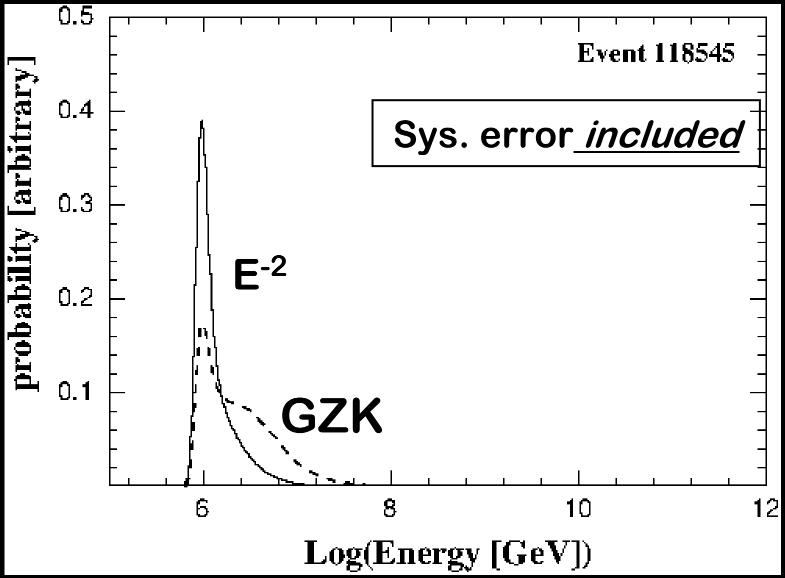
$\nu_e \rightarrow$ e + X (CC reaction) energy deposit = neutrino energy

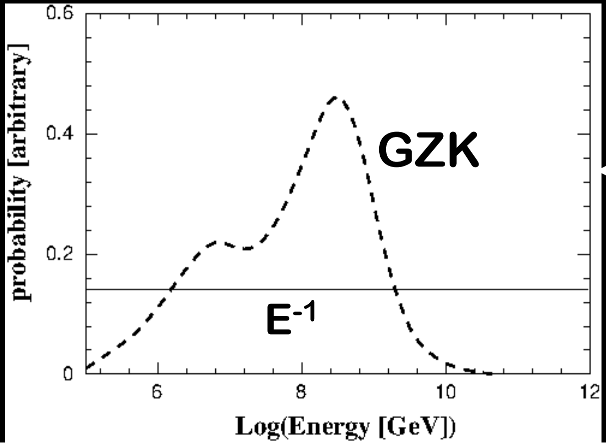
$\nu_x \rightarrow \nu_x$ + X (NC reaction) energy deposit = a partial neutrino energy

Ernie



Bert





Energy spectrum in building the PDF

if E^{-2}

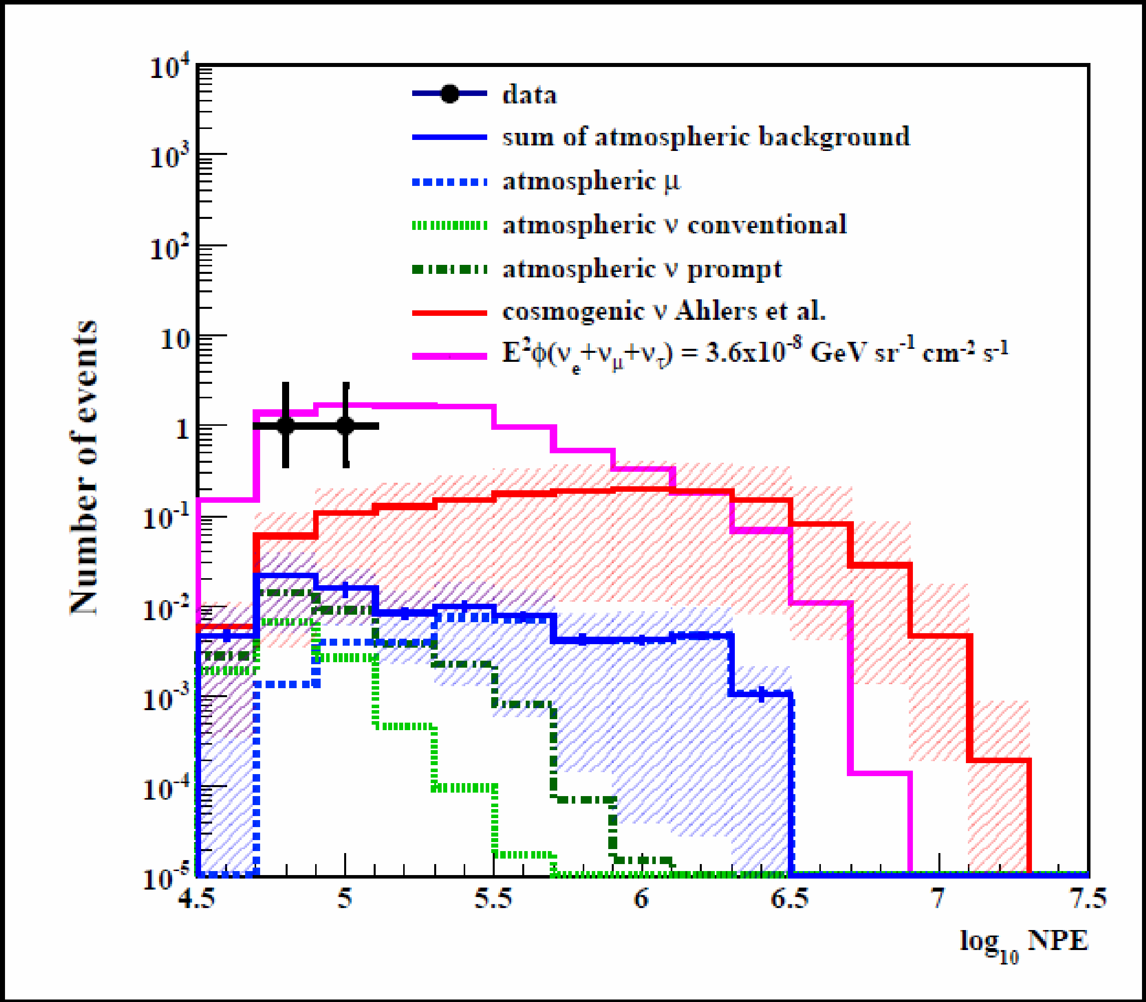
~1 PeV < E_ν < ~6PeV

if "GZK" like spectrum

~1 PeV < E_ν < ~50PeV

Event distribution on NPE

and comparisons to the model predictions

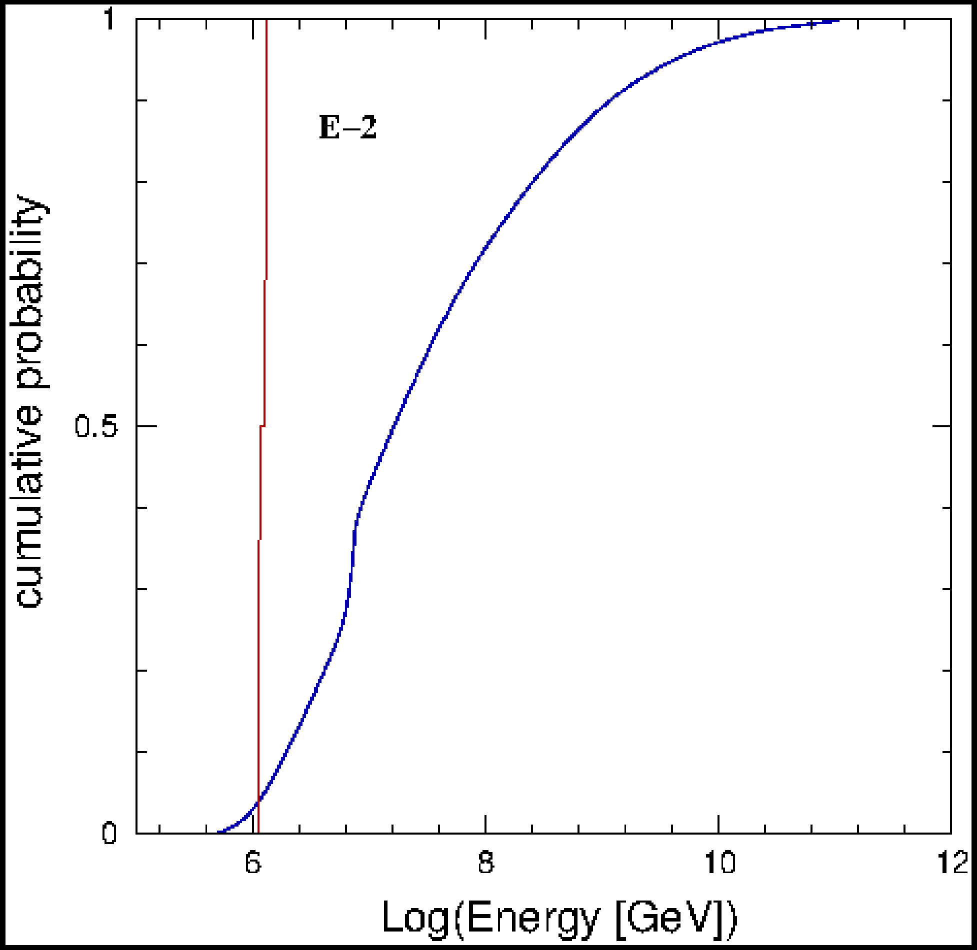


well above the Backgrounds

any signal models to predict
ν unbroken spectrum
appears *unlikely*

An unbroken E^{-2} flux explains?

KS test



rejected by 90% C.L.

E^{-2} up to 1 EeV

p-value 6.6×10^{-2}

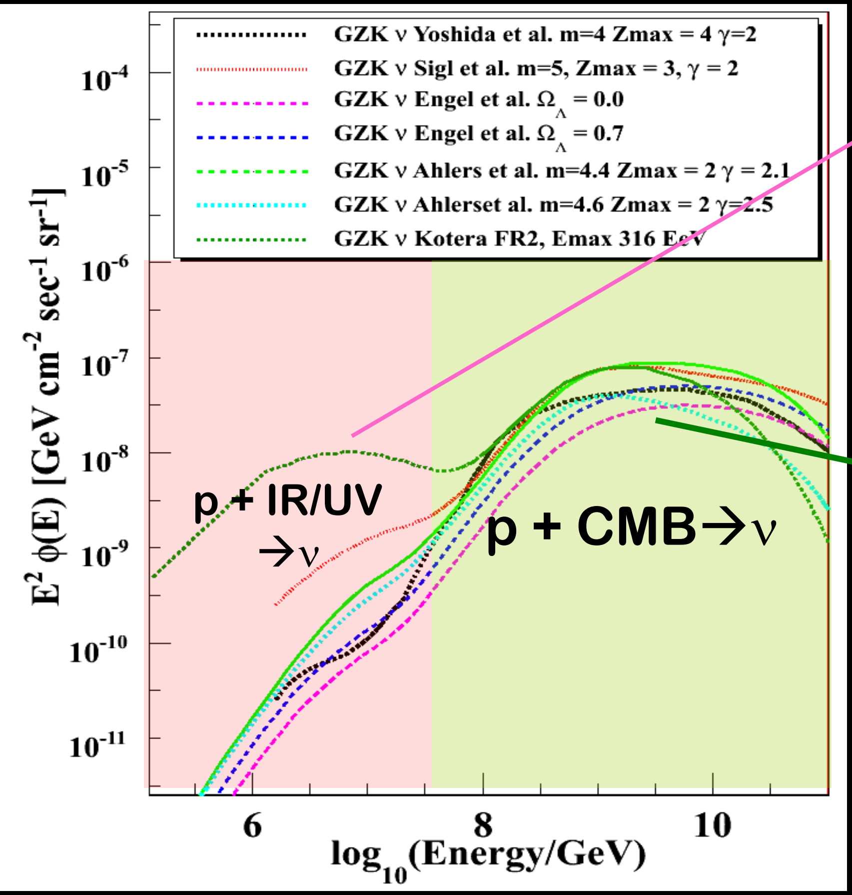
E^{-2} up to 100 PeV

p-value 8.6×10^{-2}

E^{-2} up to 10 PeV

p-value 1.4×10^{-1}

The GZK cosmogenic ν ?



The "low Energy enhanced" GZK scenarios

- Stronger IR/UV yield at high redshift
- Assume "dip" type transition of UHECRs from galactic to extragalactic

Ex. Kotera et al JCAP (2010)

The "Standard" GZK scenarios

- The CMB collisions dominates in streaming ν
- EeV (=10^9 GeV) is the key energy region

The Model Test

$$\chi^2 = -2 \ln (p_E) - 2 \ln (\mathrm{Poisson}(N=2,\mu))$$

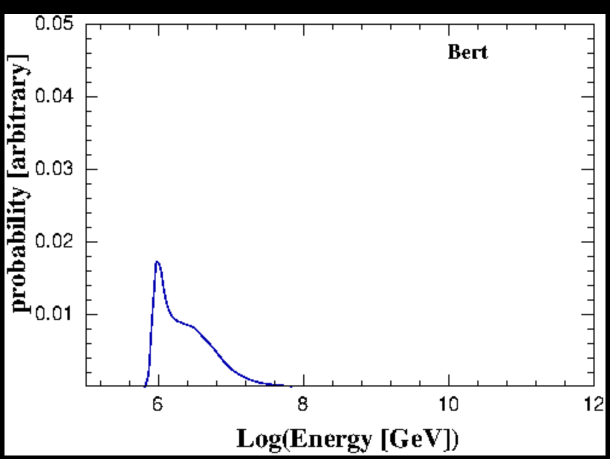
The rate term

The energy term: p-value to the expected energy distribution predicted by each of the cosmic ν models

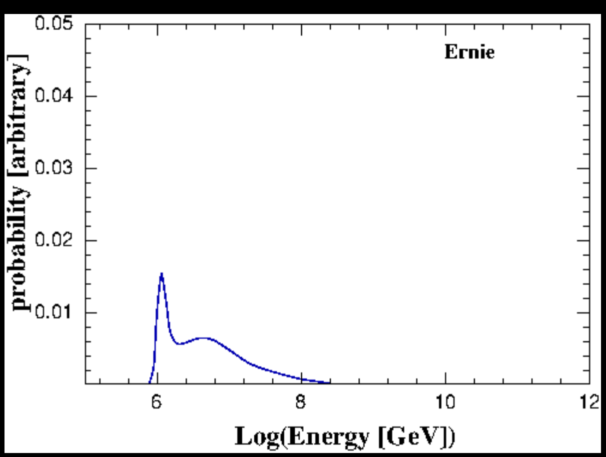
Use the Kolmogorov-Smirnov statistics

$$p_E = \int d\log E_{\mathrm{Bert}}\, \rho_{\mathrm{Bert}}(\log E_{\mathrm{Bert}}) \int d\log E_{\mathrm{Ernie}}\, \rho_{\mathrm{Erine}}(\log E_{\mathrm{Ernie}})\, P_{\mathrm{KS}}(\log E_{\mathrm{Bert}}, \log E_{\mathrm{Ernie}})$$

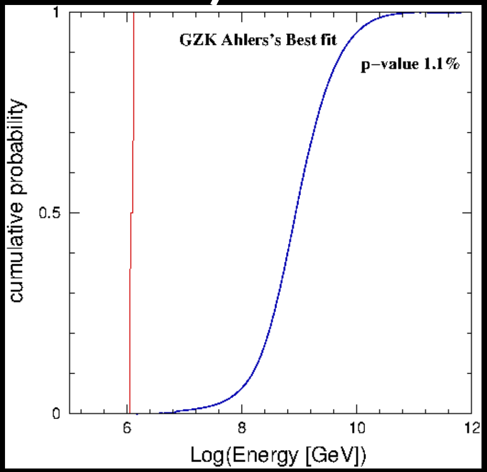
Energy PDF of Bert



Energy PDF of Ernie



KS statistic



The Score Board

	Neutrino Model	KS Test P_E	Expected Event Rate	Poisson Significance	Final p-values
standard GZK	GZK Yoshida/Teshima m=4, Zmax=4	1.4×10^{-2}	2.8	5.5×10^{-1}	4.5×10^{-2} Excluded by 95% C.L
	GZK Ahlers Fermi Best	6.0×10^{-2}	2.1	7.3×10^{-1}	5.8×10^{-2} Excluded by 90% C.L.
low energy enhanced GZK	GZK Kotera FR-II	2.4×10^{-2}	5.9	3.8×10^{-2}	7.3×10^{-3} Excluded by 99% C.L.
	GZK Kotera GRB	3.0×10^{-2}	1.1	4.2×10^{-1}	6.8×10^{-2} Excluded by 90% C.L.

Summarized statements on the origin of the 2 events

<u>if</u> astrophysical (very likely, but not conclusive)

They are NOT GZK cosmogenic

ν emission from cosmic-ray sources responsible for these two events are NOT extending above 100 PeV

we would have detected events with greater energies, otherwise

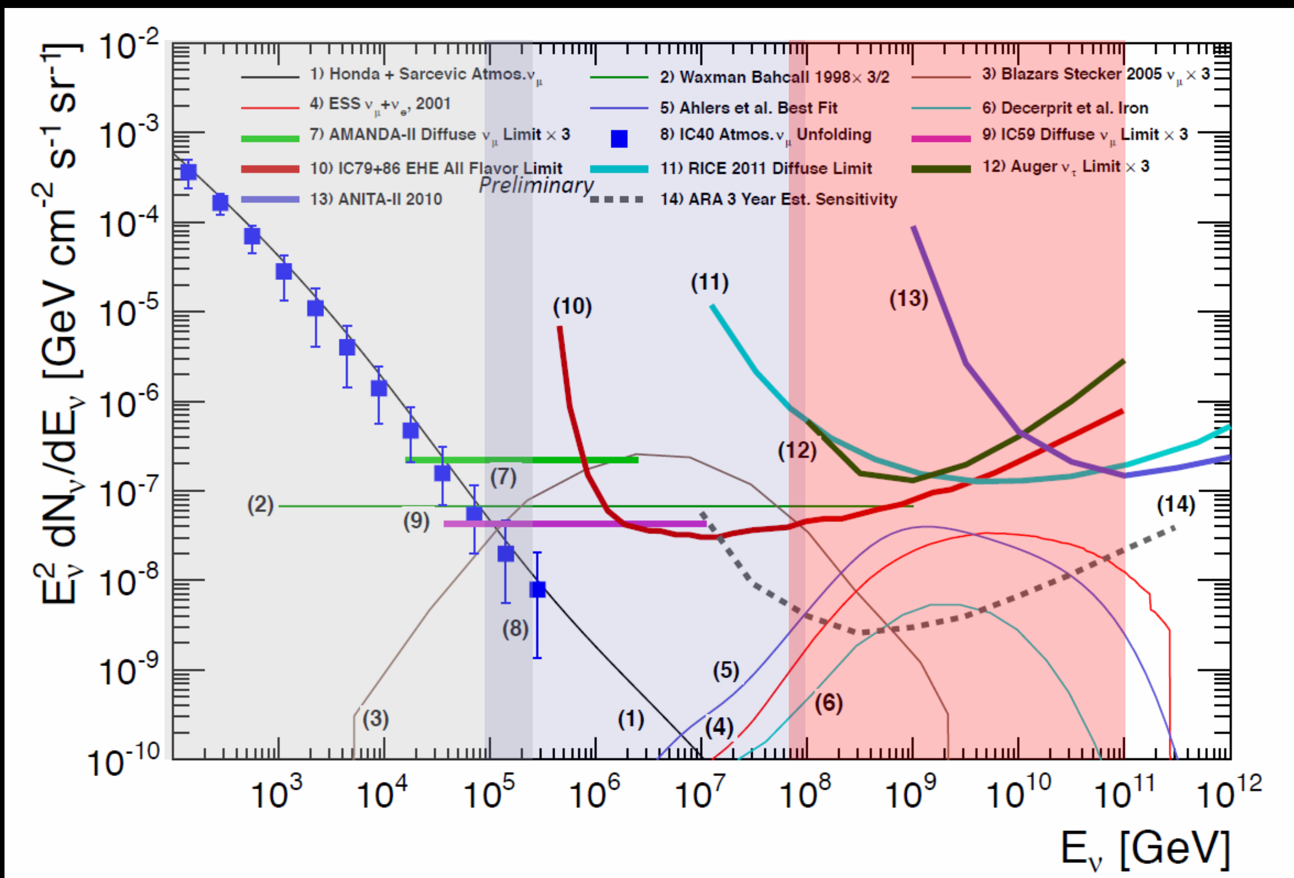
$\nu_{e+\mu+\tau}$ intensity of ~ 10^{-8} GeV/cm2 sec sr

Needs more data/follow-up analyses for further interpretation

Constraints on UHECR origin

The two event domain

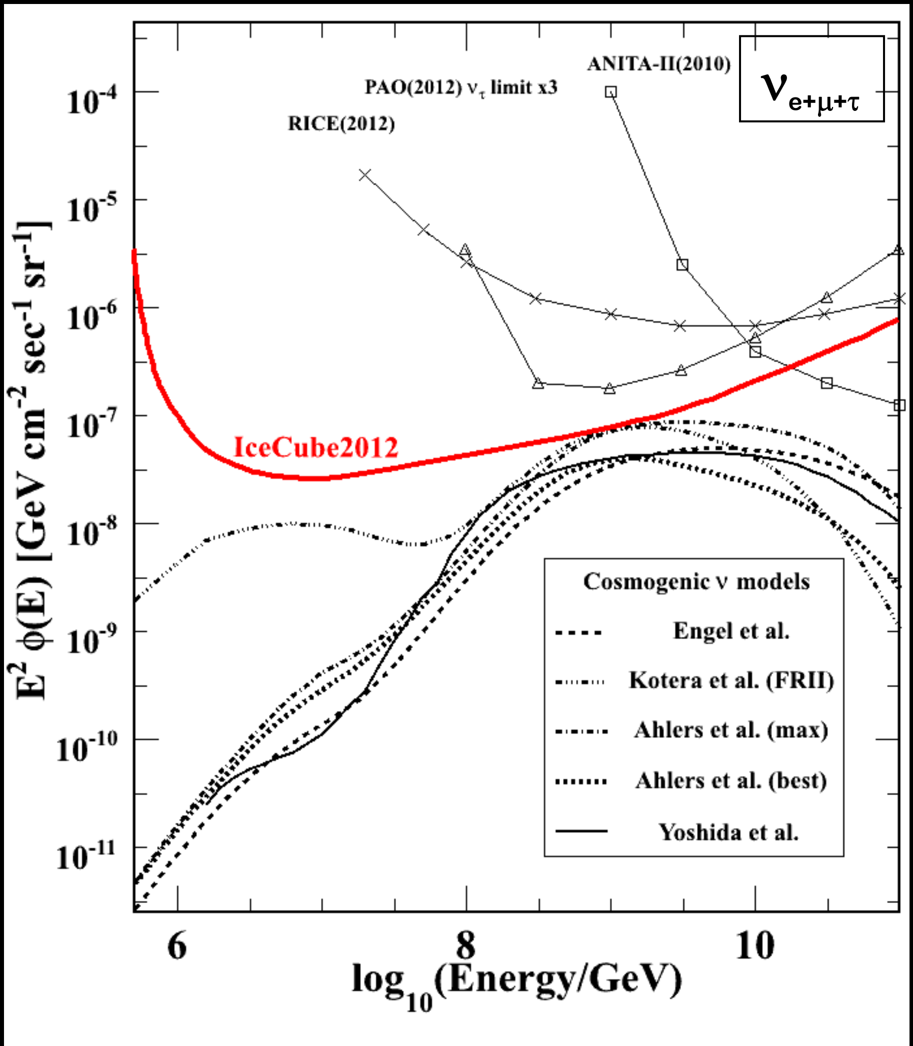
The GZK domain



The GZK ν yield and its limit constrain the ultra-high energy cosmic-ray origin

Constraints on UHECR origin

The model-independent upper limit on flux



any model adjacent to the limit is disfavored by the observation

Effective $\nu_{e+\mu+\tau}$ detection exposure

6×10^7 m^2 days sr @ 1EeV
= 0.2 km^2 sr year

(6 x Auger ν_τ exposure)

Note: ϕ_{CR}(>1EeV) ~ 20/km^2 sr year

ν with CR comparable flux should have been detected

Constraints on UHECR origin

model-dependent limit based on the rate >100 PeV

comparison to the nearly ~0 events in the present data

ν Model	GZK Y&T m=4,zmax=4	GZK Sigl m=5, zmax=3	GZK Ahler Fermi Best	GZK Ahler Fermi Max	GZK Kotera FR-II	GZK Kotera SFR/GRB	Topdown GUT
Rate >100PeV	2.6	4.0	2.0	4.1	3.8	0.6	5.0
Model Rejection Factor	0.89	0.58	1.18	0.57	0.60	3.6	0.47
p-value	7.3×10^{-2}	1.8×10^{-2}	1.5×10^{-1}	1.7×10^{-2}	2.3×10^{-2}	6.4×10^{-1}	8.0×10^{-3}

Excluded

Mildly Excluded

Consistent

Maximal ν flux allowed by the Fermi γ-ray measurement

Ruled out
relatively strong evolved sources
if UHECRs are proton-dominated

GZK-CMB ν intensity @ 1EeV
Measurements of the evolution

Yoshida and Ishihara, PRD 85, 063002 (2012)

$\rho \sim (1+z)^m$
$0<z<z_{max}$

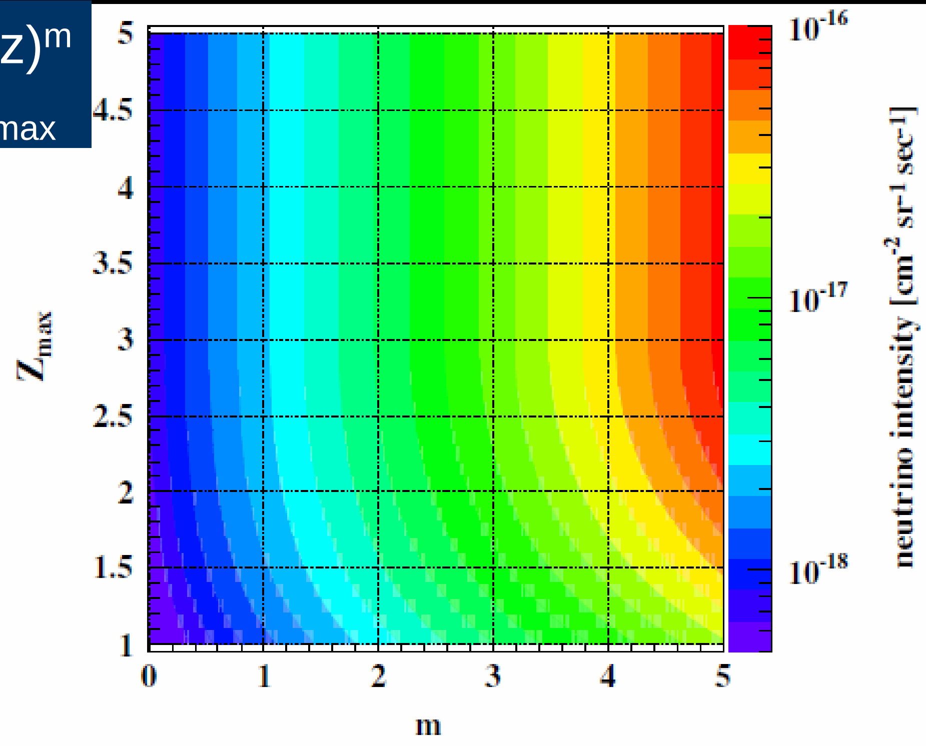


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and $z_{\max}$.

GZK(-CMB) ν flux

x IceCube Exposure

↓

Number of events we should have detected

↓

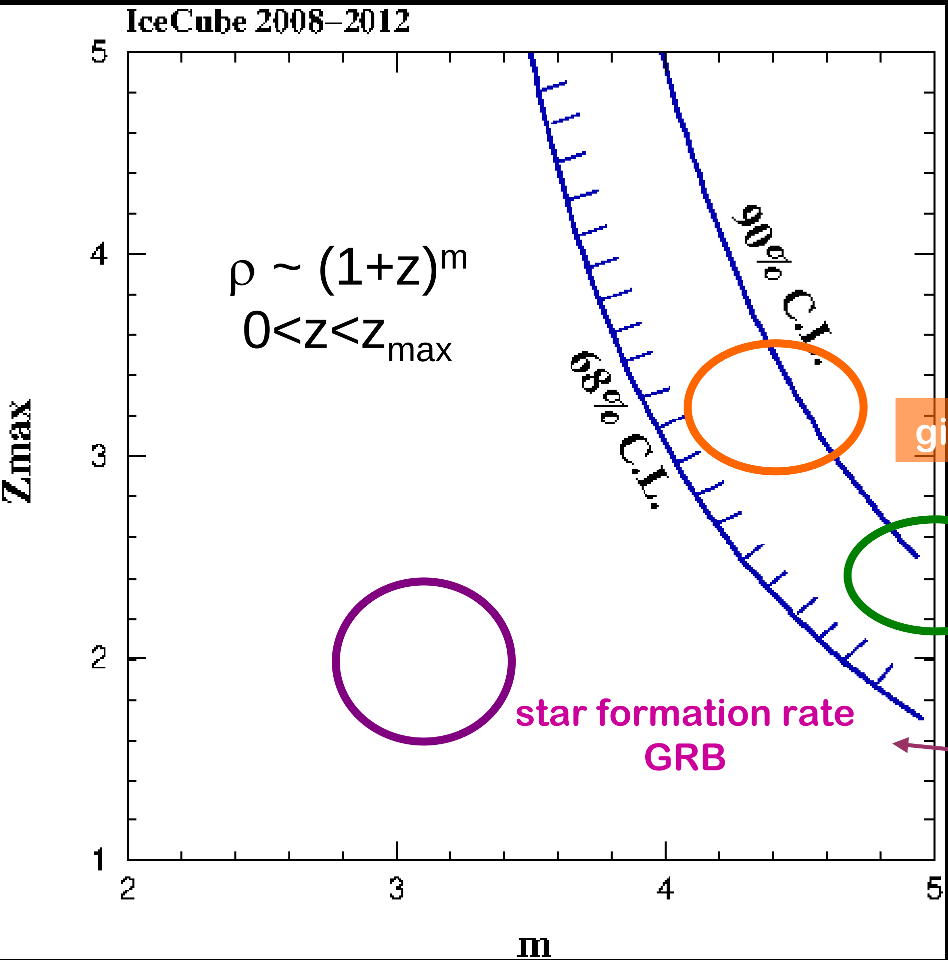
Evolution of UHECR sources

↓

Identify classes of astronomical objects responsible for UHECRs

Constraints on the evolution

90% C.L. = 2.7 evens above 100PeV
68% C.L. = 1.6 evens above 100PeV



- A strongly evolved astronomical object (like FR-II radio galaxy) has already been disfavored

- any scenario involving sources evolved stronger than SFR will soon be ruled out by IceCube if we see no events in EeV rage.

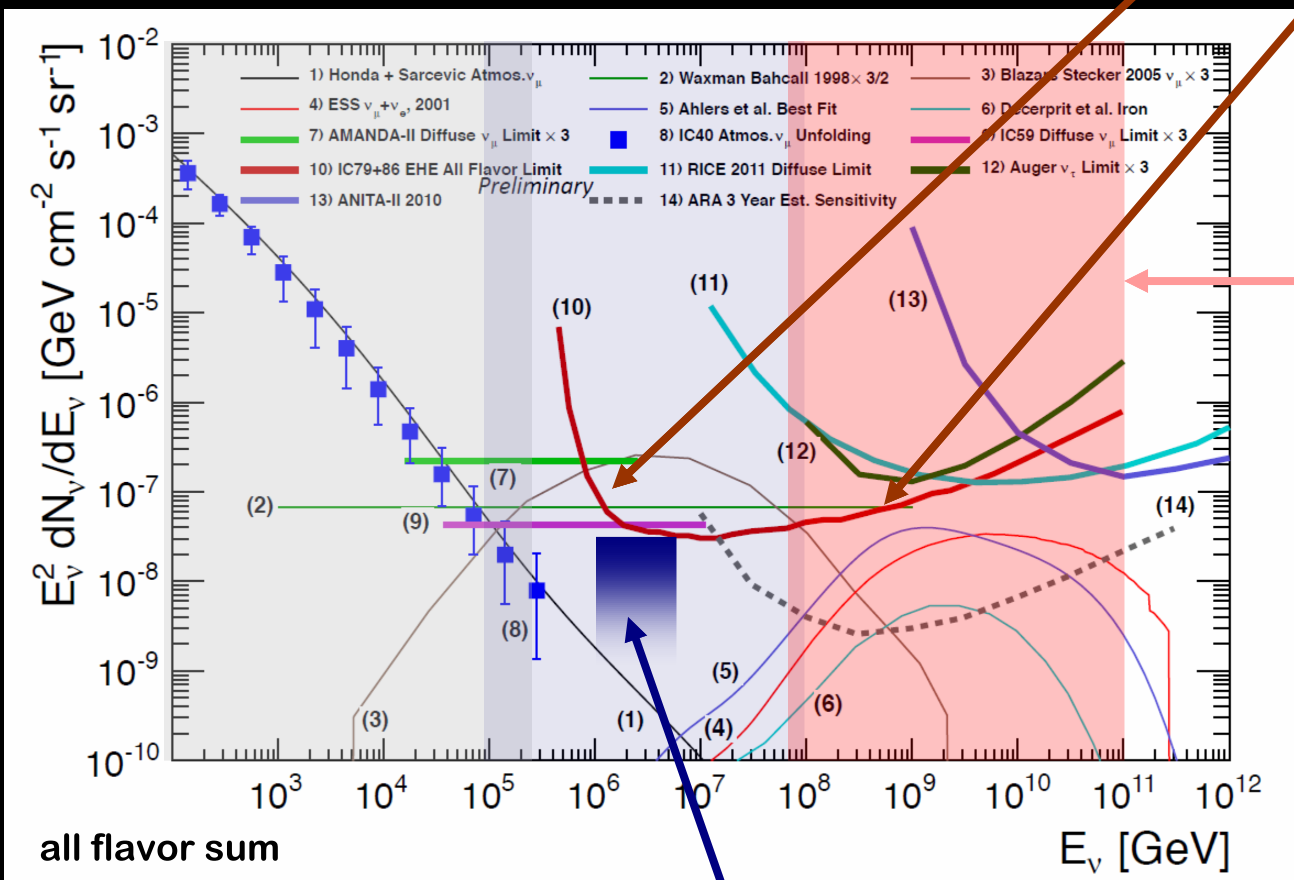
gives the best fit with UHECR spectrum

radio laud AGN

Note: Not precisely known

The executive summary

The model-independent upper limit on flux in UHE



null observation in this regime

nearly exclude

- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

Bert & Ernie

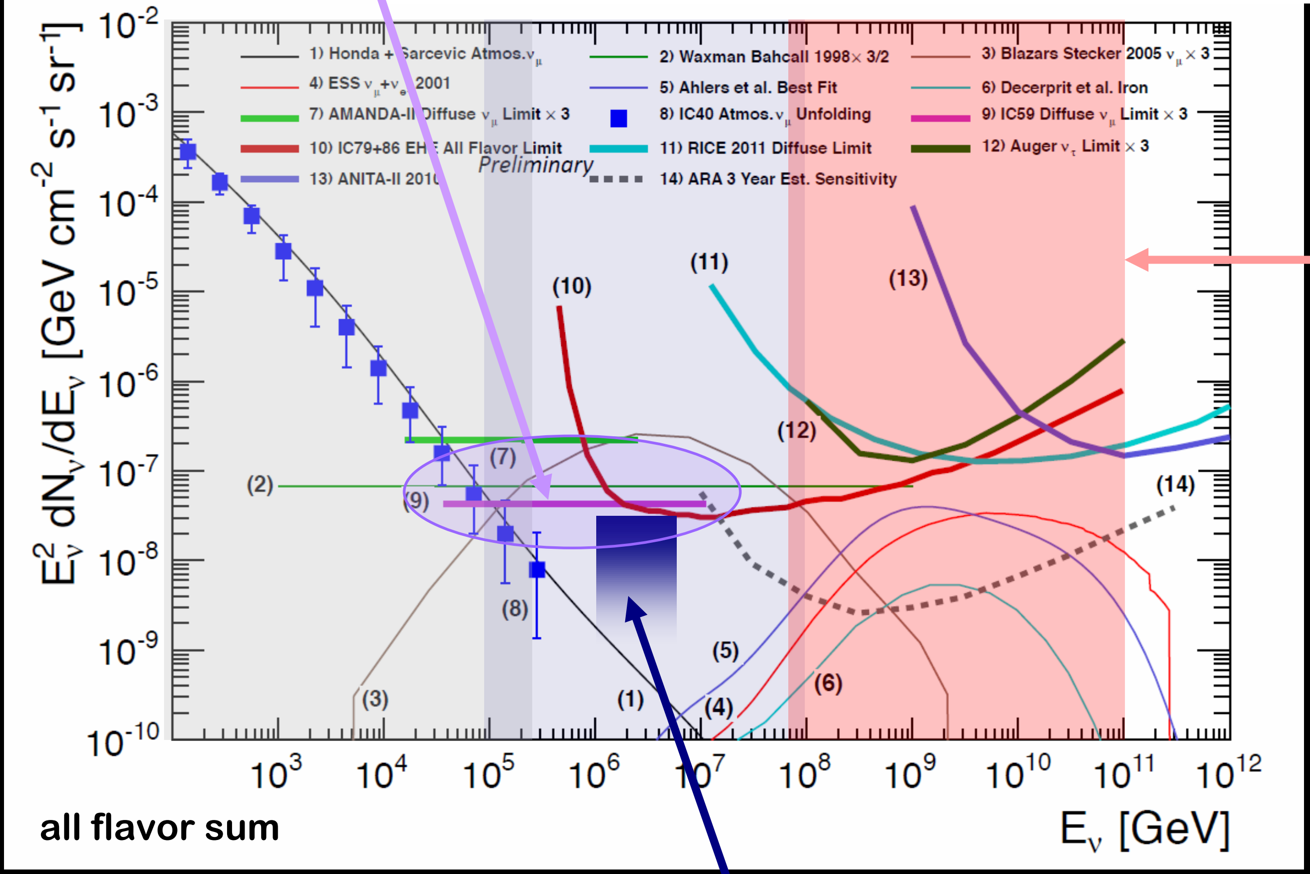
2.8 σ excess over atmospheric

ICECUBE

The coming analyses

The diffuse ν_μ limit (x3) by IC59

- rapidly improved by IC79,IC86
- independent searches by looking cascades or vertices-contained events



null observation in this regime

nearly exclude

- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

The background veto by the EAS array

Bert & Ernie

2.8 σ excess over atmospheric