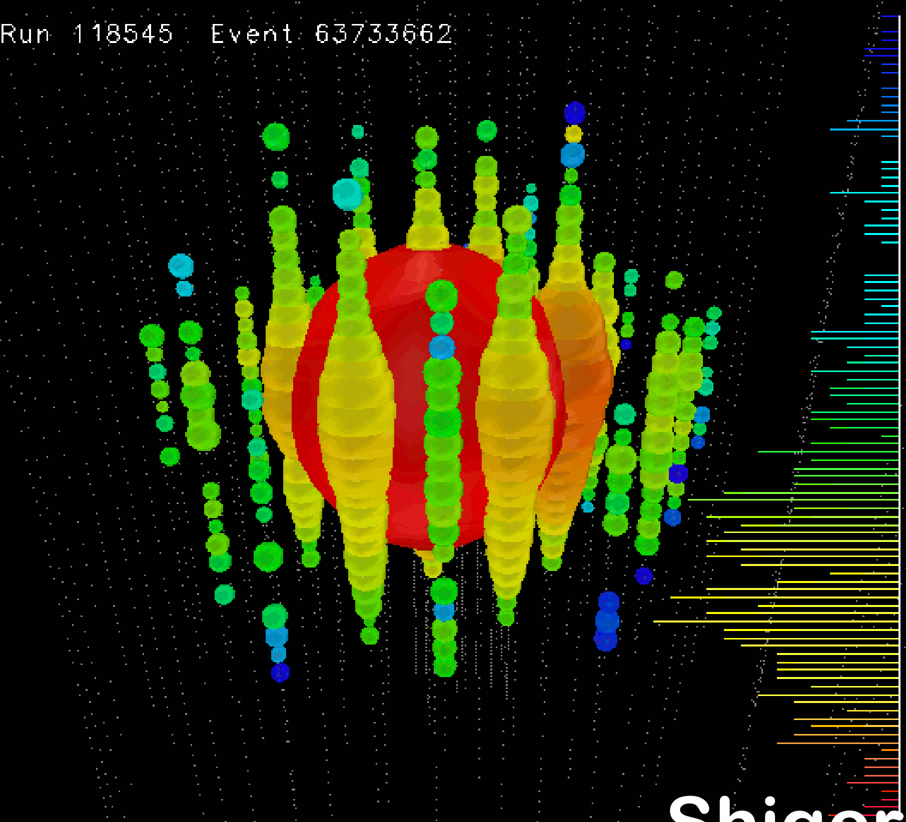
Detection of Ultra-high energy neutrinos

The ‘First Light’ of the high energy neutrino astronomy



Shigeru Yoshida

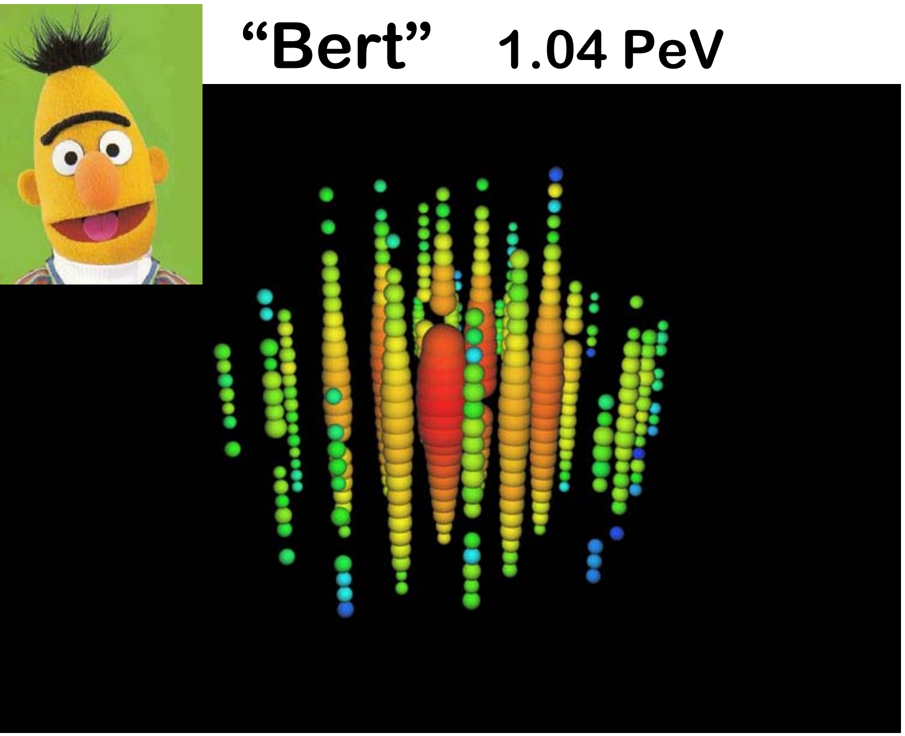
Department of Physics

Chiba University

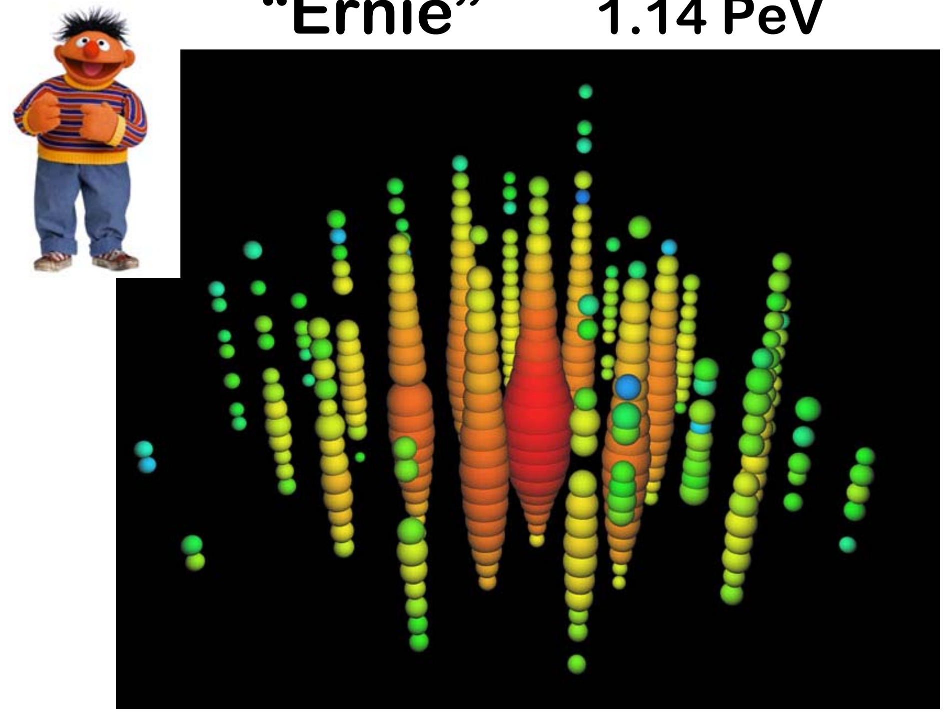
the 1st discovery of the PeV ν

Physical Review Letters 111, 021103 (2013)

“Bert” 1.04 PeV



“Ernie” 1.14 PeV



2.8 σ excess on the atmospheric background

very the 1st indication of astrophysical ν

"Cover-boy" of Physical Review Letters

NEWSPAPER

Observation of a high-energy particle shower event from August 2011, identified as a PeV-energy neutrino. Each sphere represents a digital optical module sensor in the IceCube detector. Sphere size is a measure of the recorded number of photoelectrons. Colors represent arrival times of photons (red, early; blue, late). Selected for a Synopsis in *Physics* and as an Editors' Suggestion. [M. G. Aartsen *et al.*, IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)]

PHYSICAL REVIEW LETTERS

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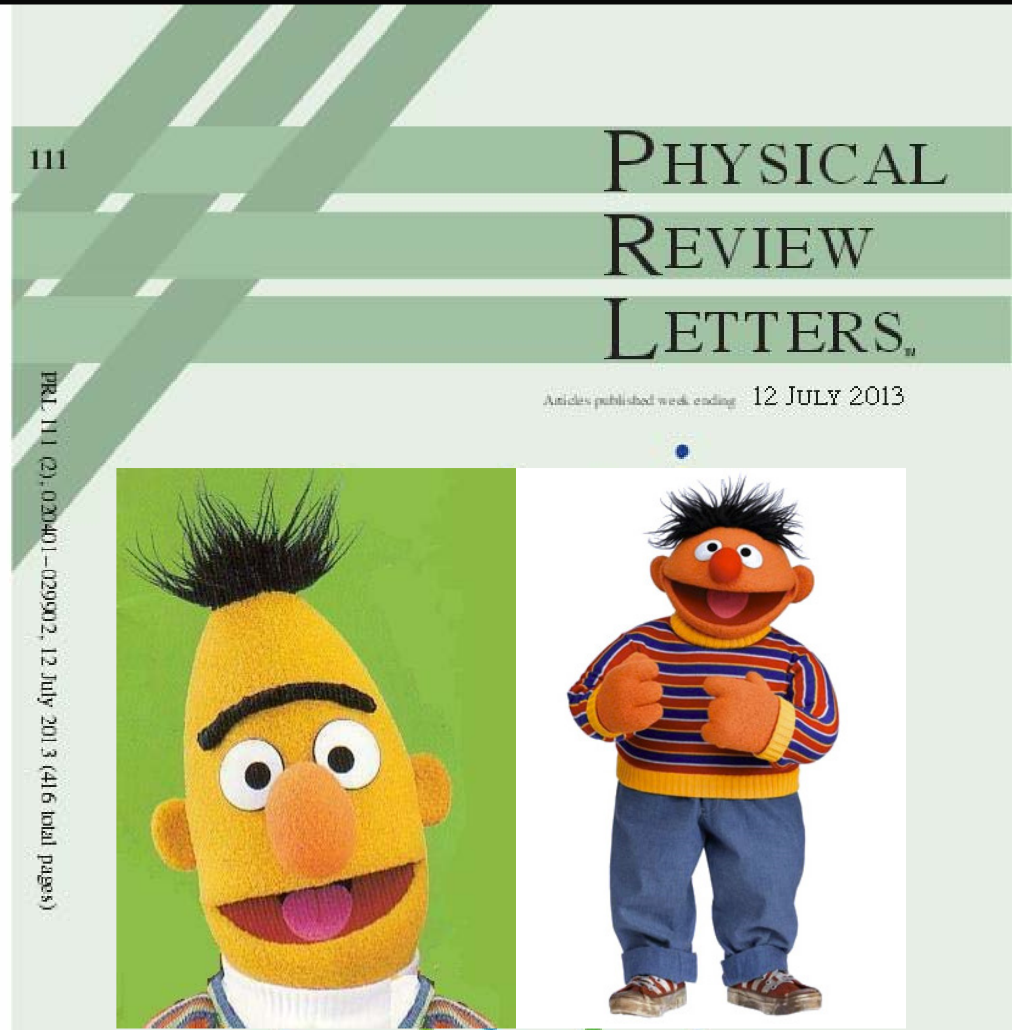
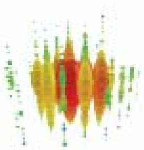
VOLUME 111, NUMBER 2 — 12 July 2013



"Cover-boy" of Physical Review Letters

NEWSPAPER



Observation of a high-energy particle shower event from August 2011, identified as a PeV-energy neutrino. Each sphere represents a digital optical module sensor in the IceCube detector. Sphere size is a measure of the recorded number of photoelectrons. Colors represent arrival times of photons (red, early; blue, late). Selected for a Synopsis in *Physics* and an Editors' Suggestion. [M. G. Aartsen *et al.*, IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)]

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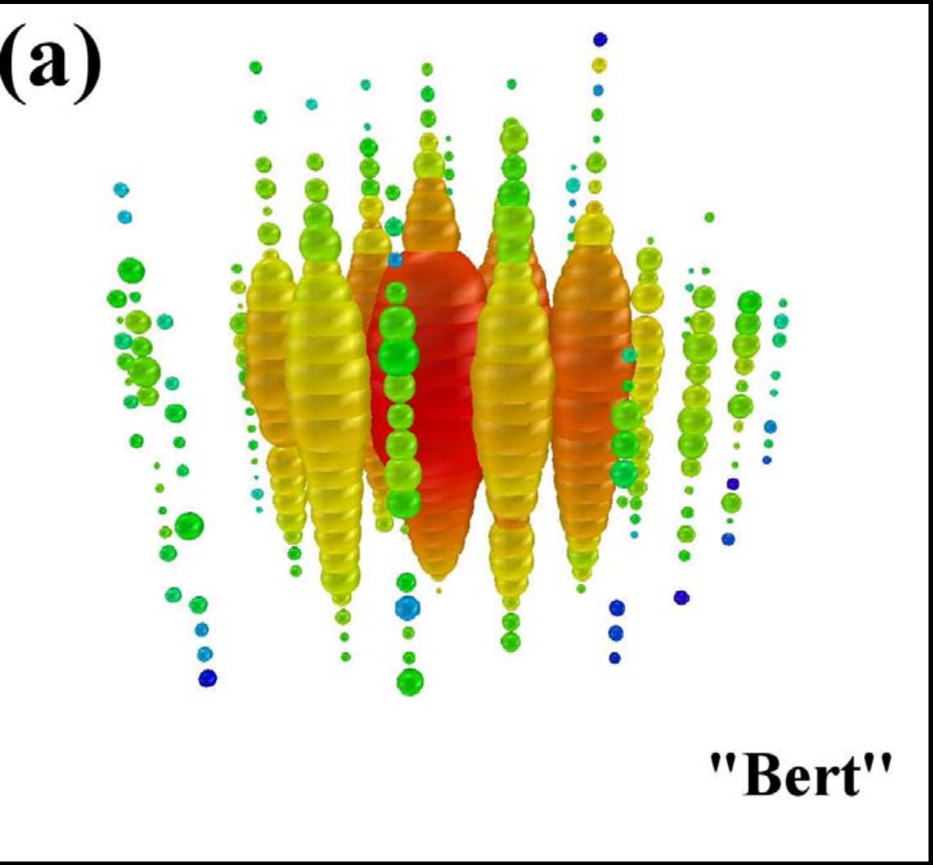
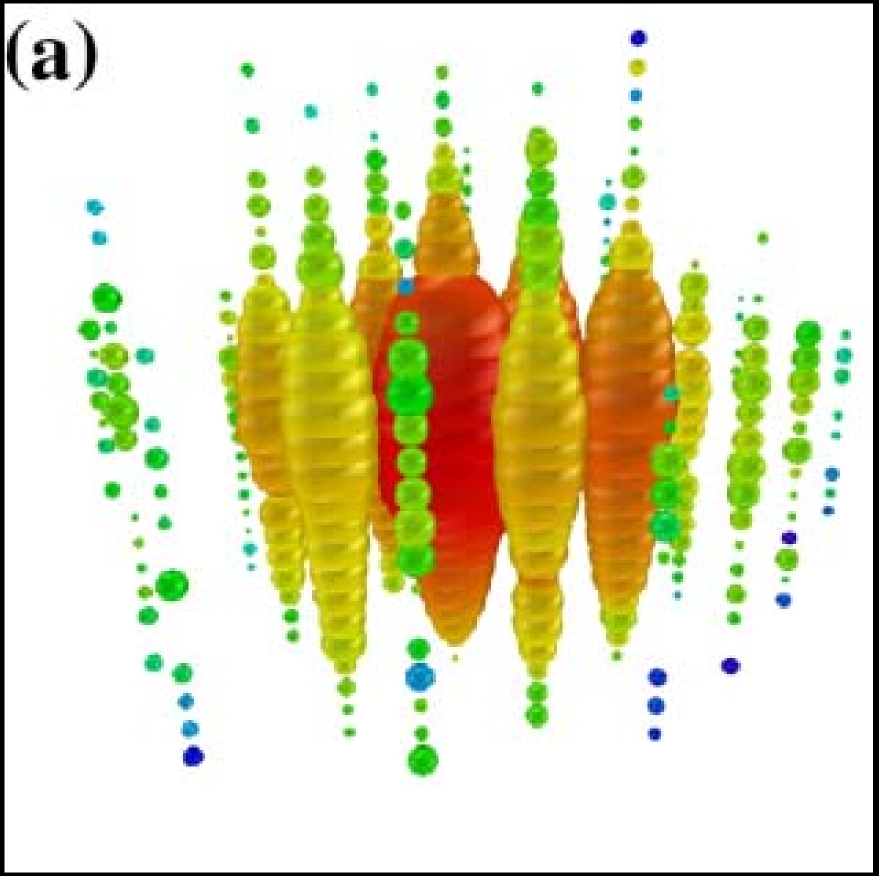
A proof of the PRL's high standard for publication

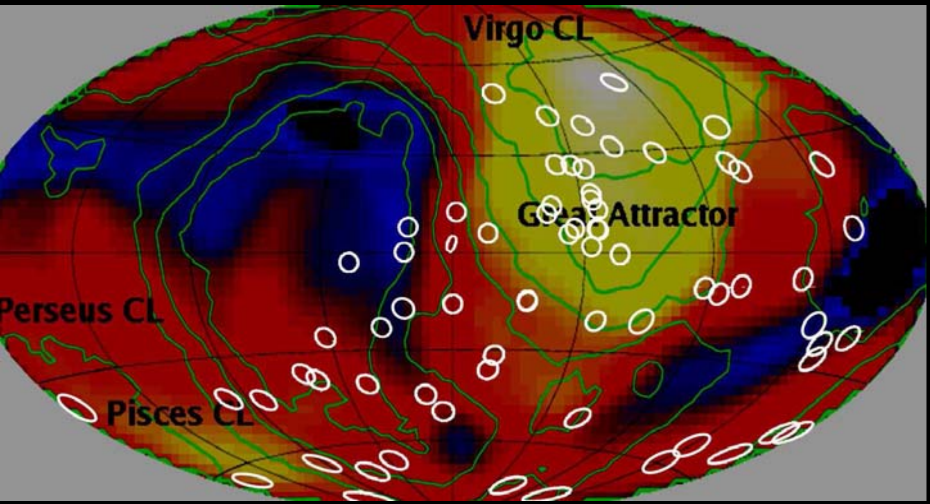
The version *submitted*



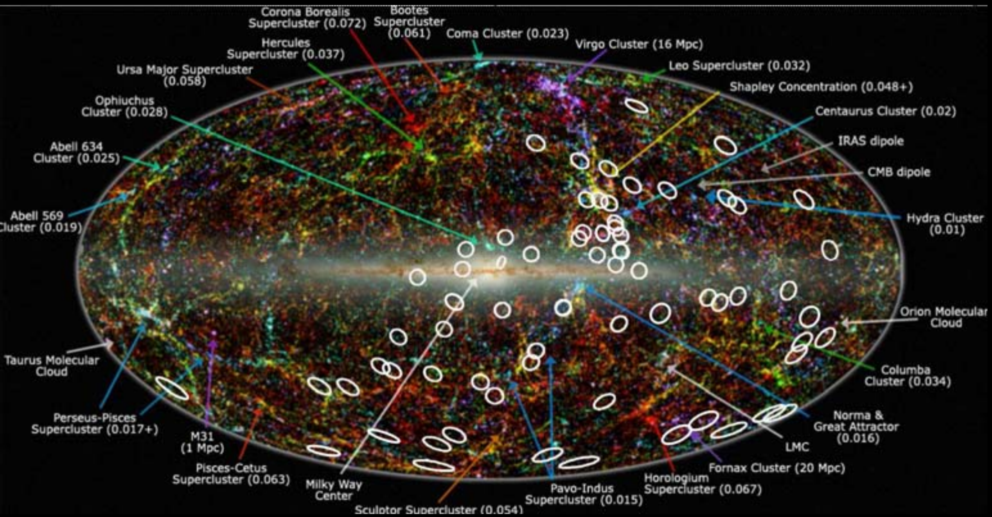
The version *accepted*



The challenge



Arrival directions of UHE cosmic-rays measured by Auger and the Integral X-ray map (above) or the nearby clusters (arxiv-1101.0273 D.Fargion et al)



No clear correlations…..

Two possibilities

1. **Our hypotheses on the high energy cosmic ray emitters are totally wrong**

   We may not be so smart.

2. **Cannot handle pointing them back to their radiation points**

   Magnetic field?

   Particle charge?

   Proton or even iron?

Solutions

1. **Correct more and more events**

   A super high statistics may resolve B, charge, and source locations, all of which are uncertain at the moment

2. **Neutrinos!!**

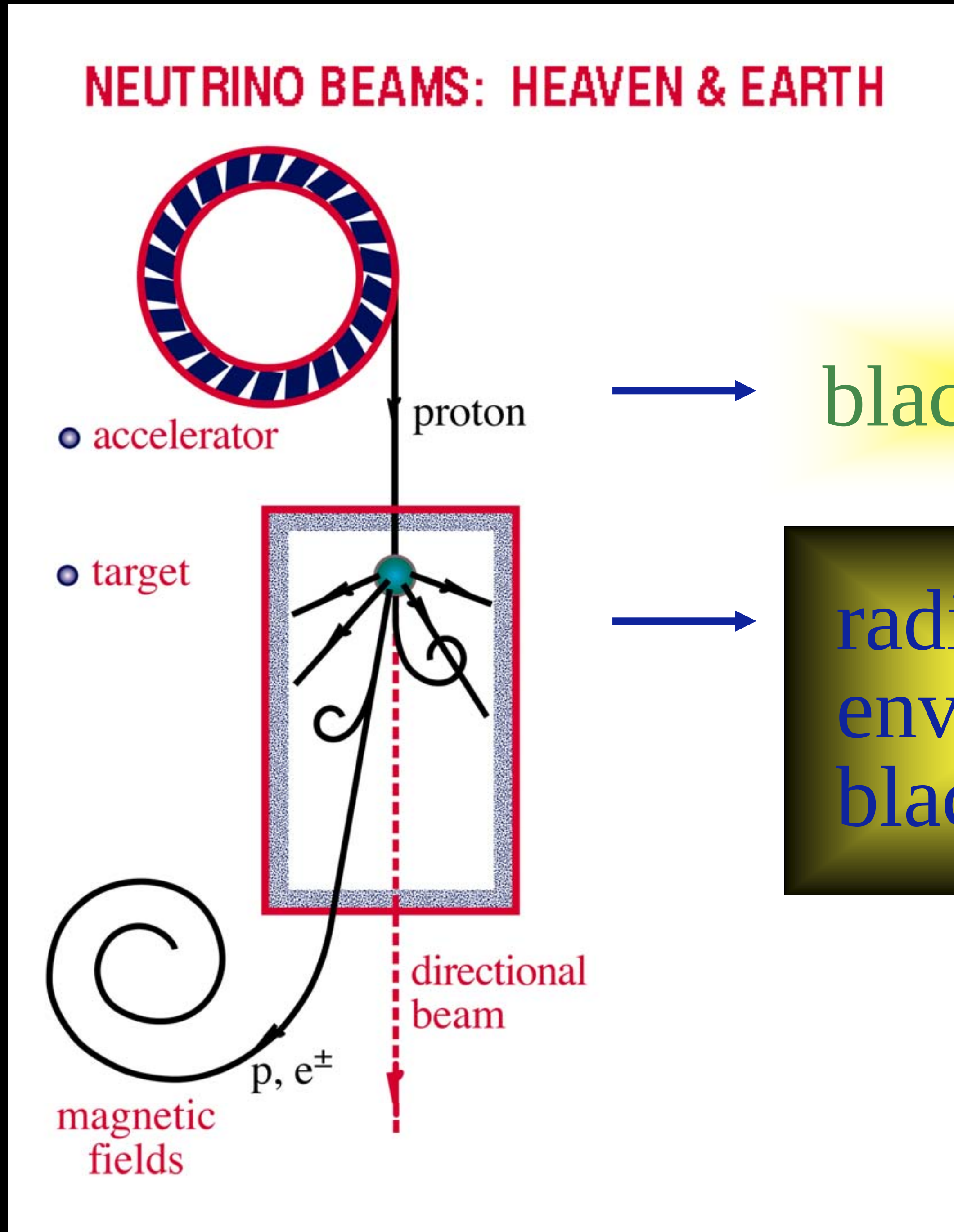
   No electric charge. Coming to us straight

   Highly complementary – ν can travel over a LONG distance

   The cons : measurement of ν's is really a tough business

They are weakly interacting particles → a huge detector
The atmospheric ν or μ backgrounds dominates
→ needs excellent filtering programs

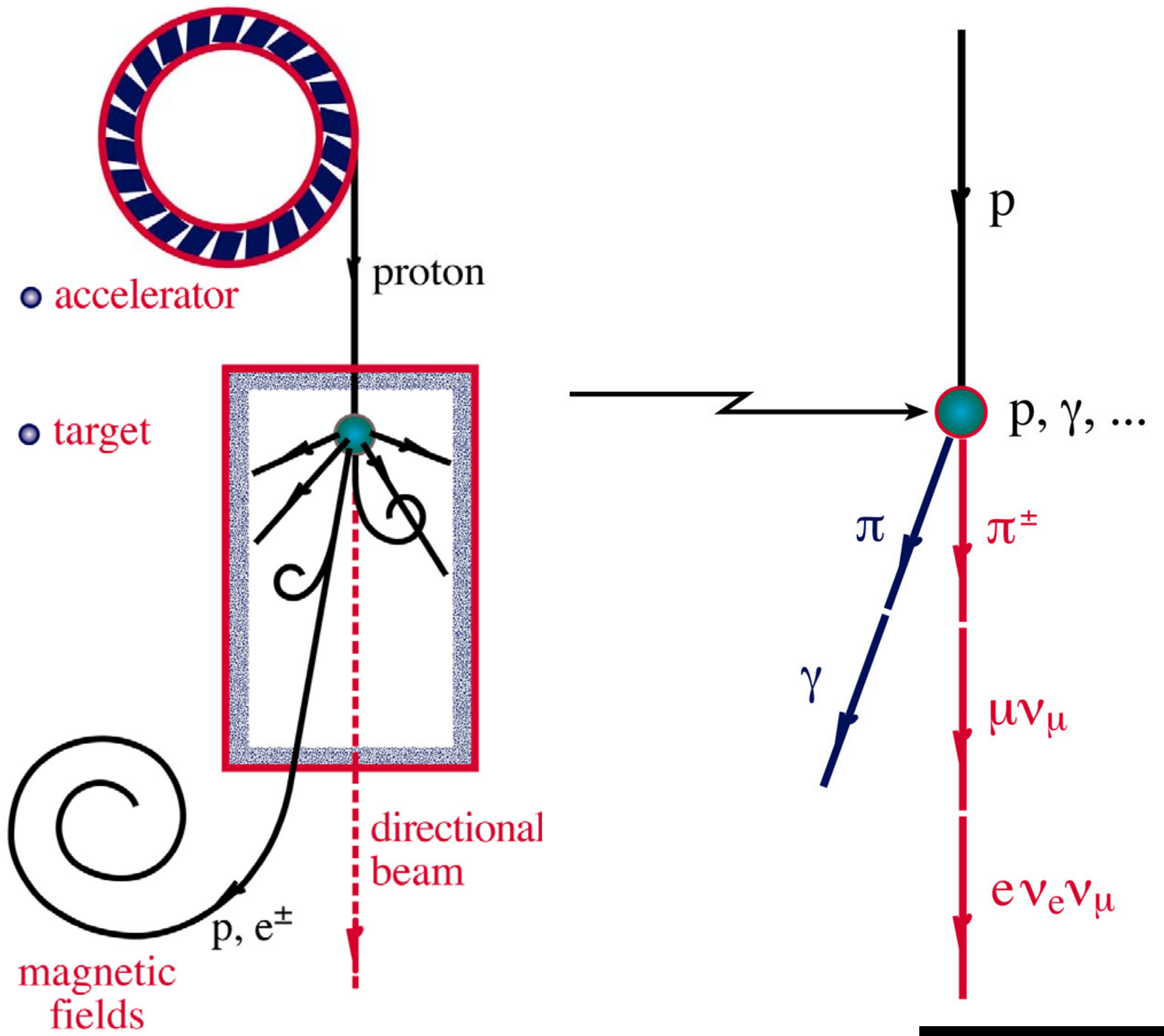
Main topic in this talk



black hole

radiation
enveloping
black hole

NEUTRINO BEAMS: HEAVEN & EARTH

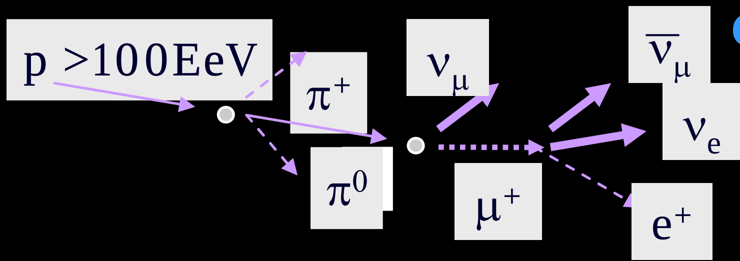


The highest energy neutrinos

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

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

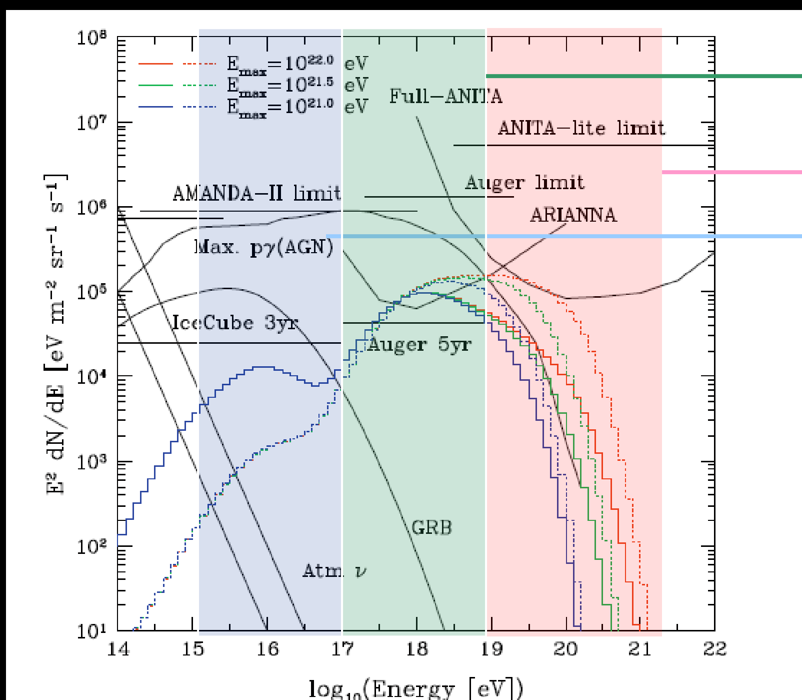
GZK (Greisen-Zatsepin-Kuzmin) mechanism



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

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

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



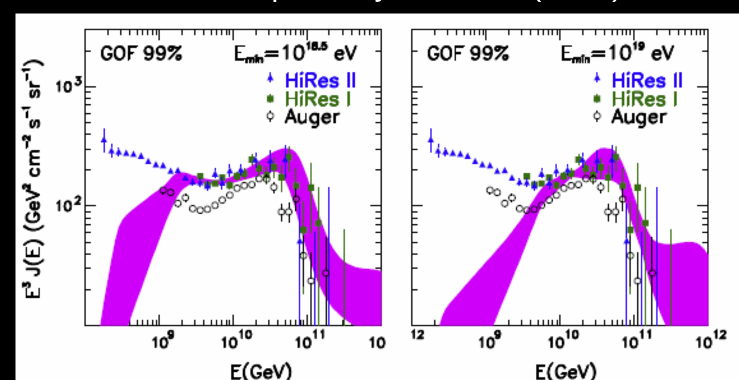
The region of the main GZK ν intensity

Trace the UHECR emission history

Probe maximal radiated energy

Probe transition from galactic to extra-galactic

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

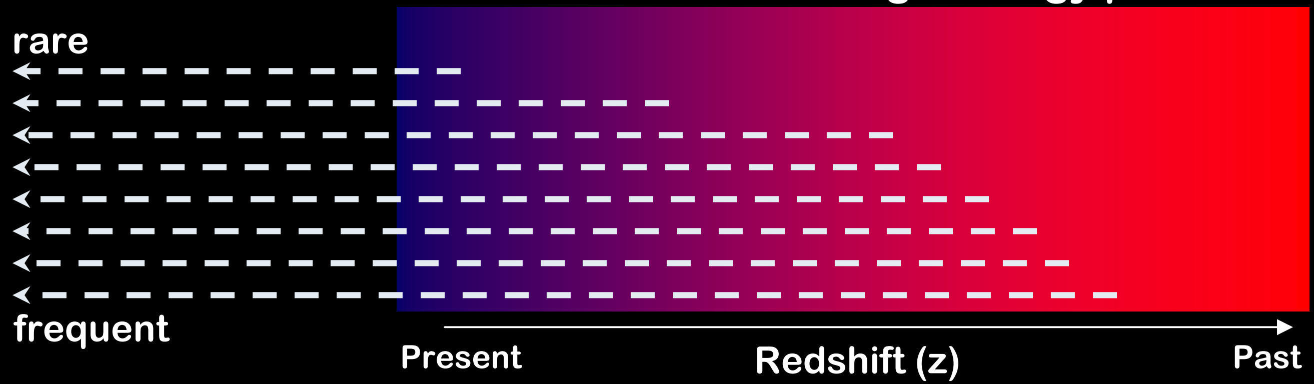


“Dip” model **“Ankle” model**

Tracing *history* of the particle emissions with ν flux

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

because ν beams are penetrating over cosmological distances

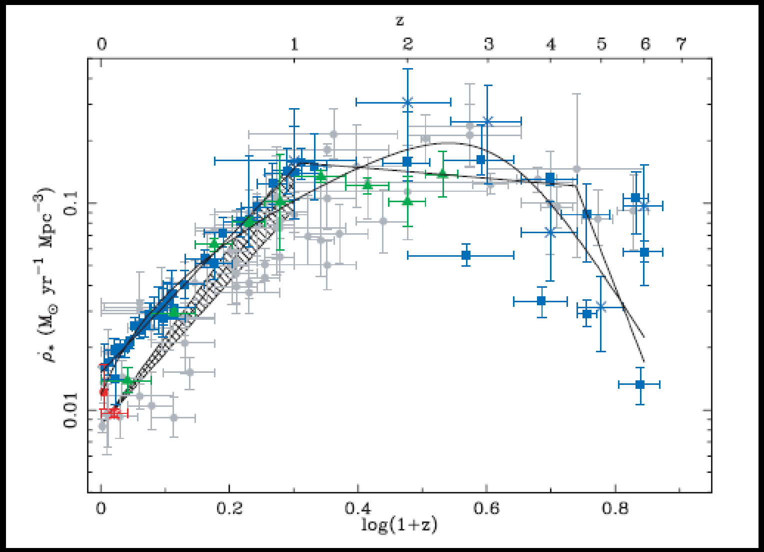


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→

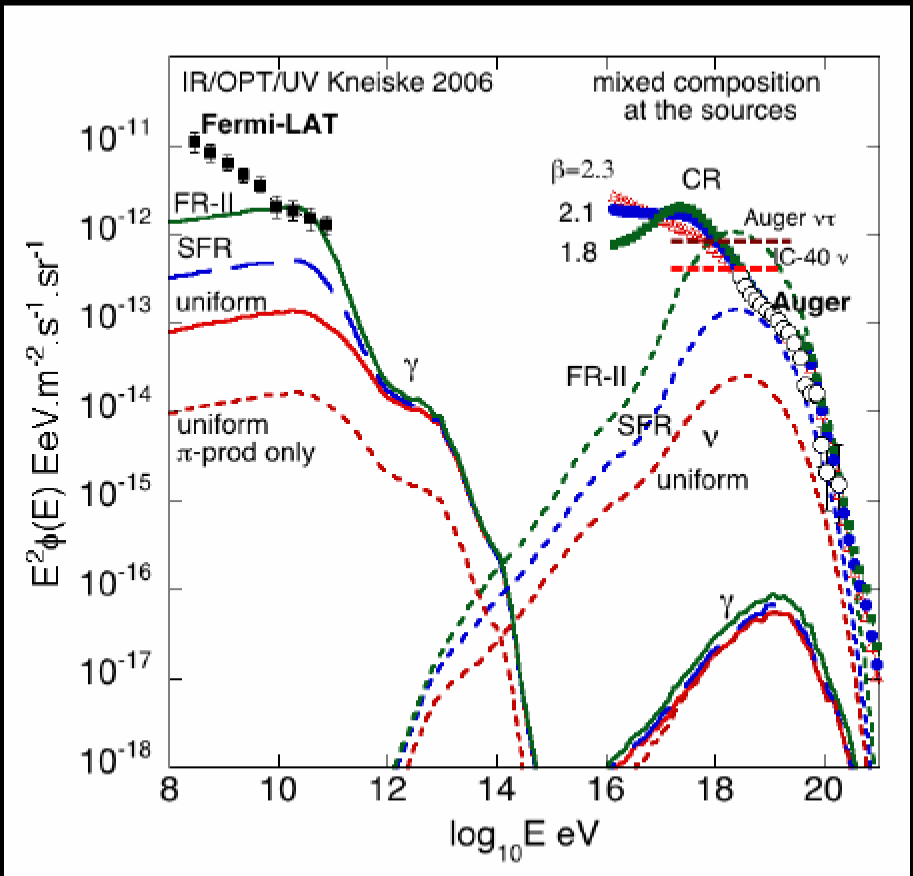


The spectral emission rate

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

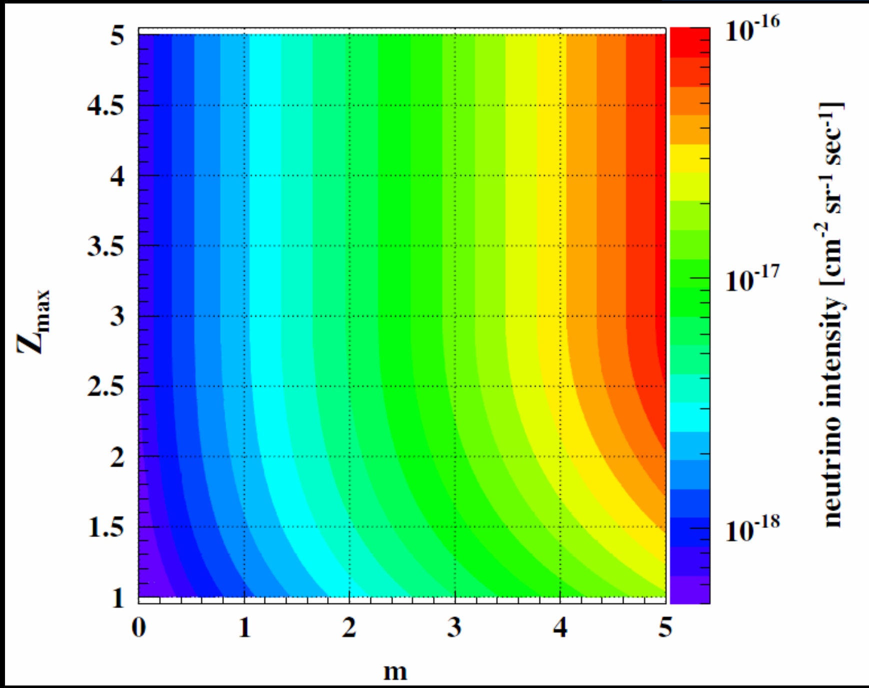
m= 0 : No evolution

Tracing *history* of the particle emissions with ν flux



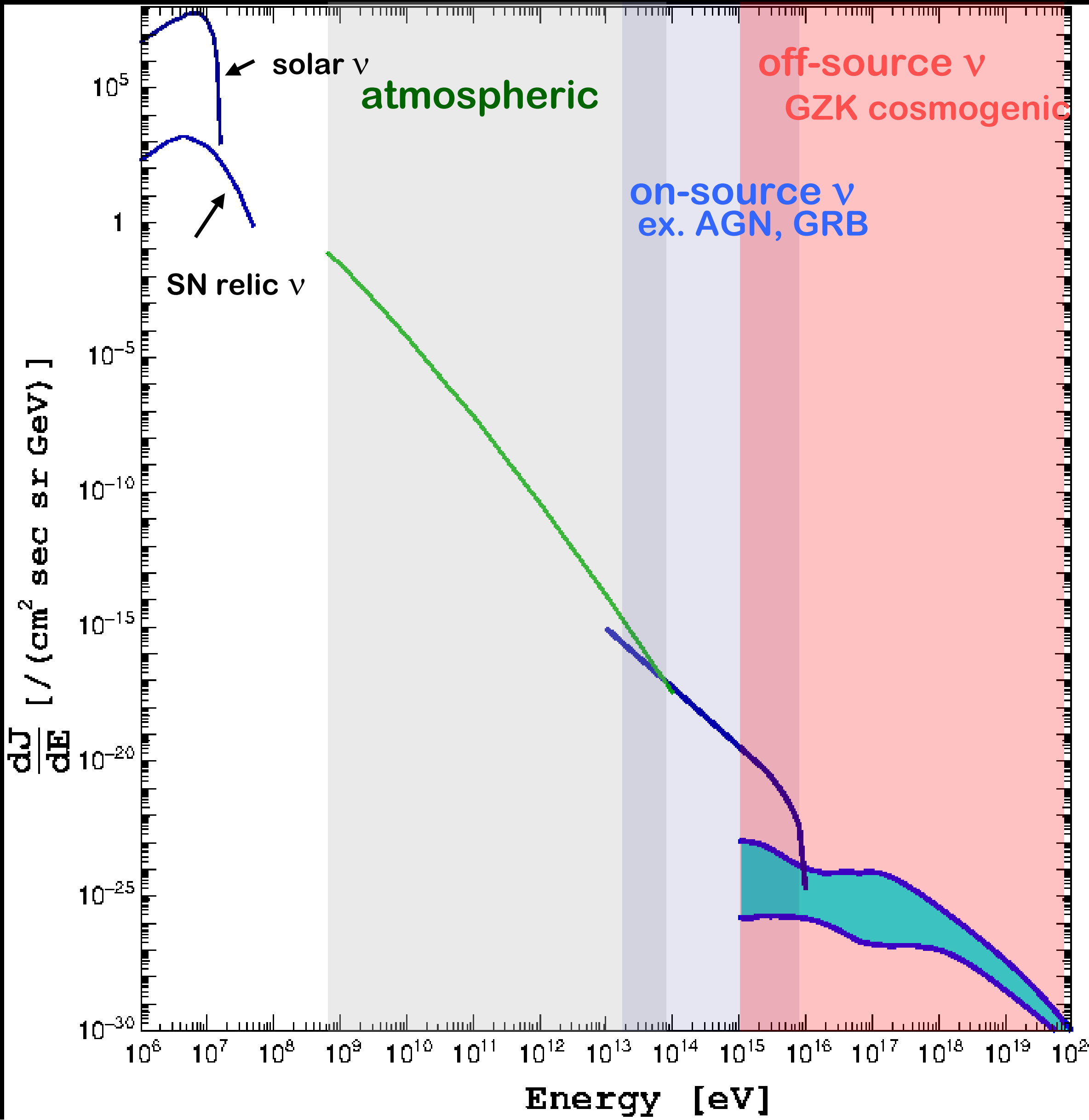
Decerprit and Allard, A&A (2012)

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



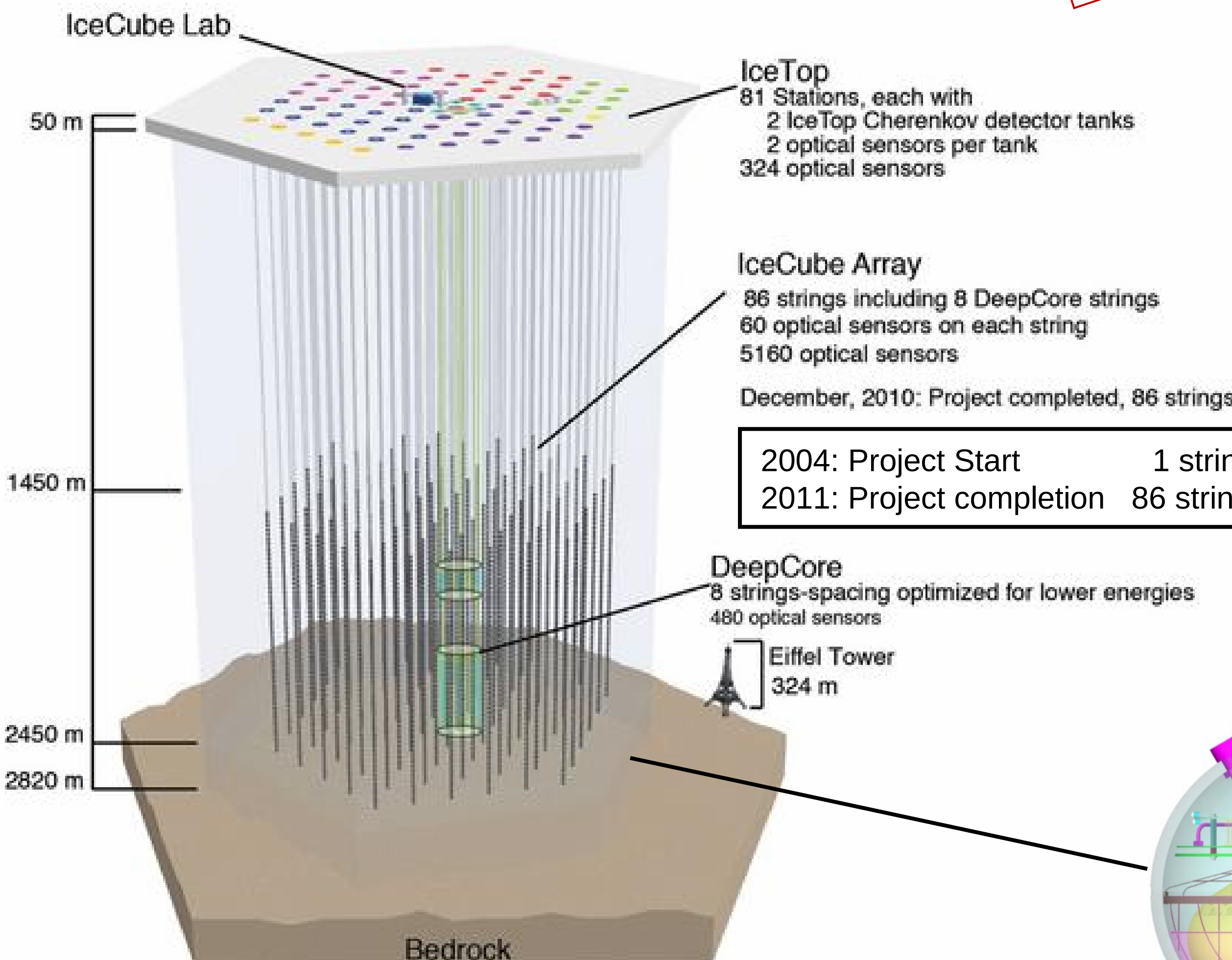
Yoshida and Ishihara, PRD 85, 063002 (2012)

The ν spectra from cosmos and atmosphere



The IceCube Neutrino Observatory

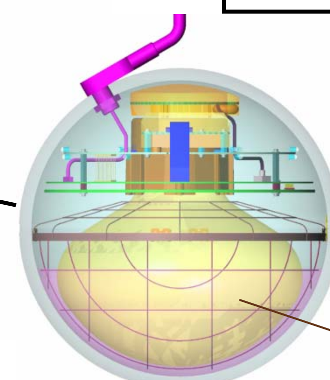
Completed: Dec 2010



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

Configuration chronology

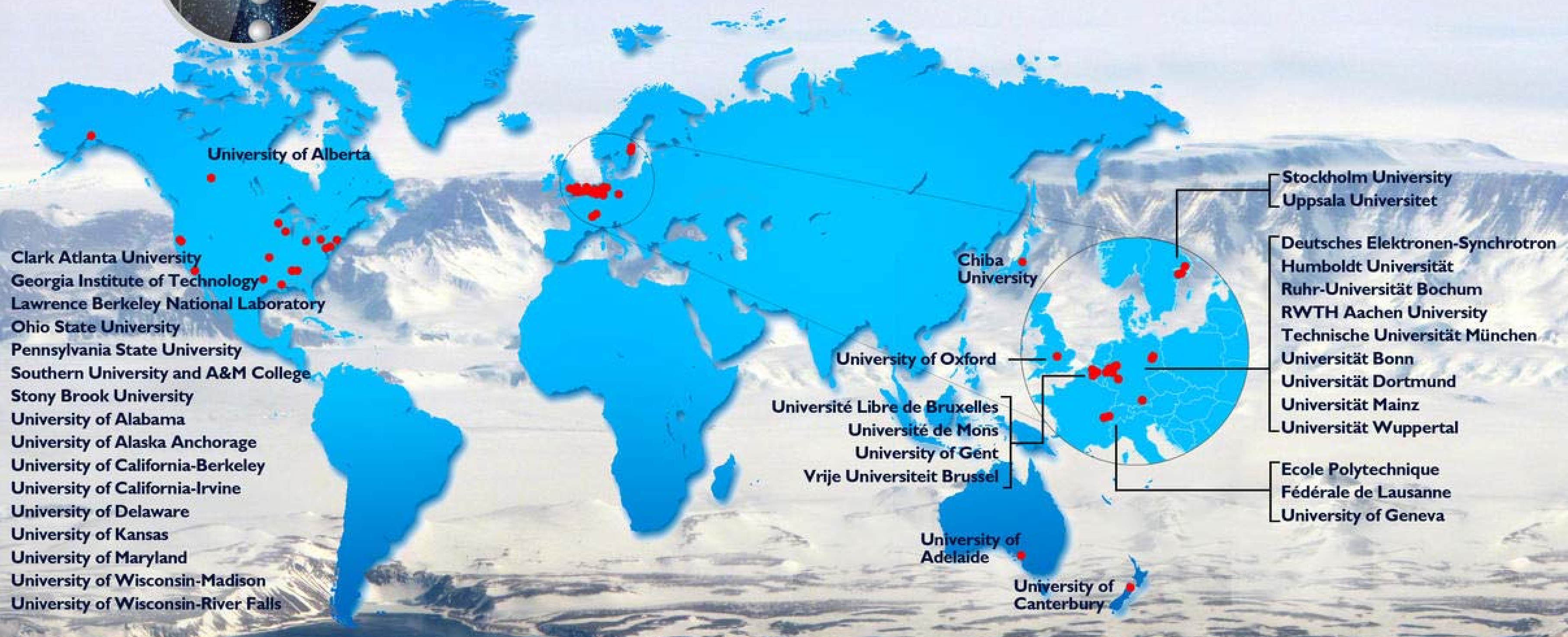
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Digital Optical Module (DOM)

Full operation with all strings since May 2011

The IceCube Collaboration



International Funding Agencies

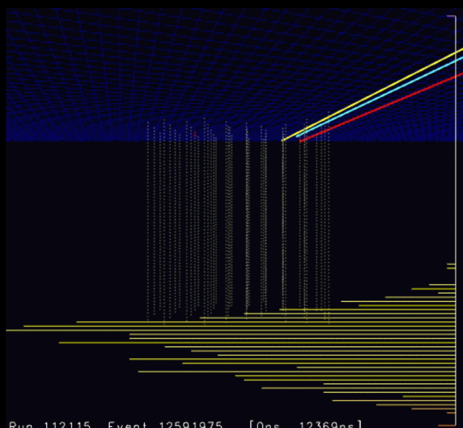
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

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)

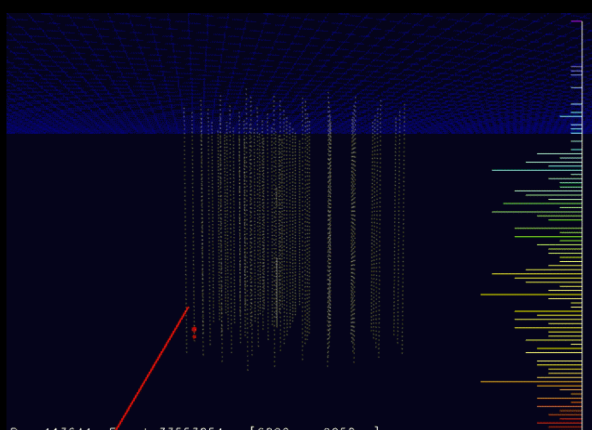
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Topological signatures of IceCube events



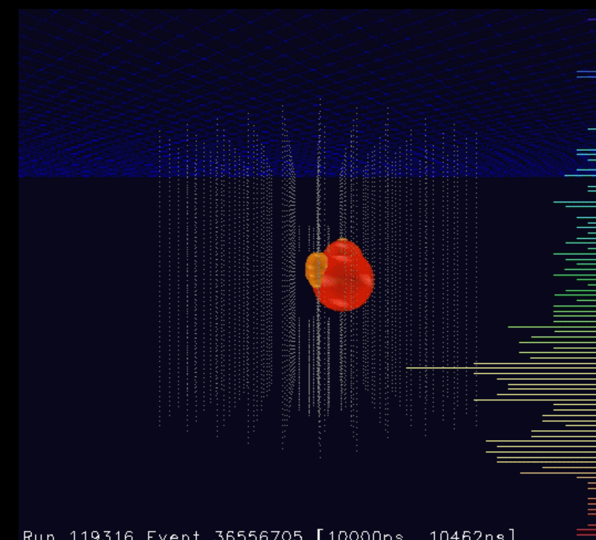
Down-going track

- 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

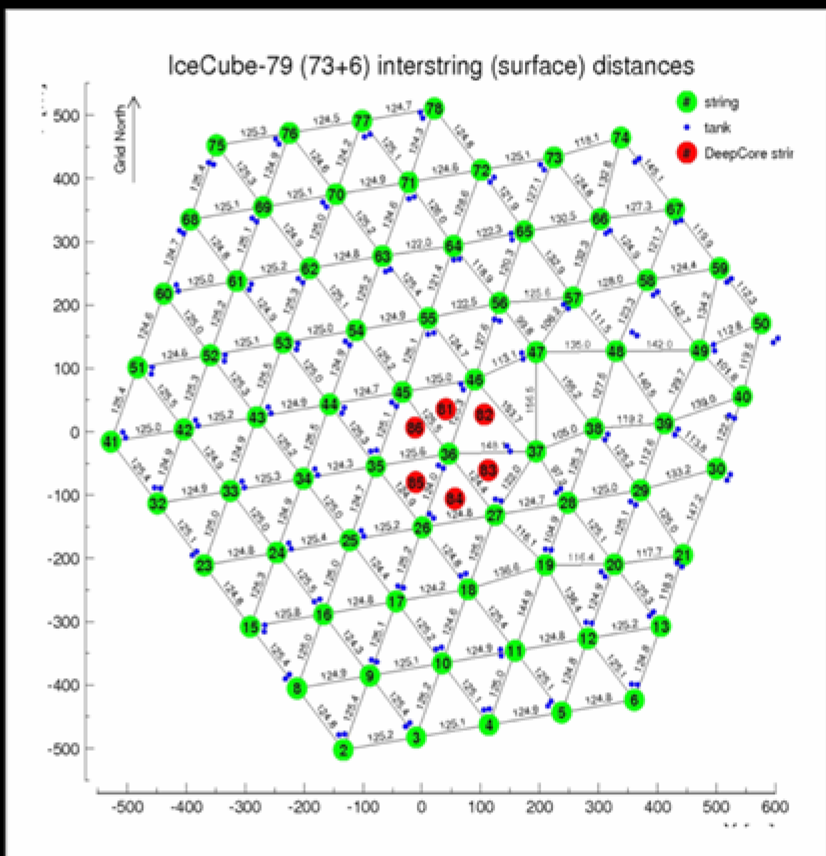
IceCube

published
PRD 83 092003 (2011)

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

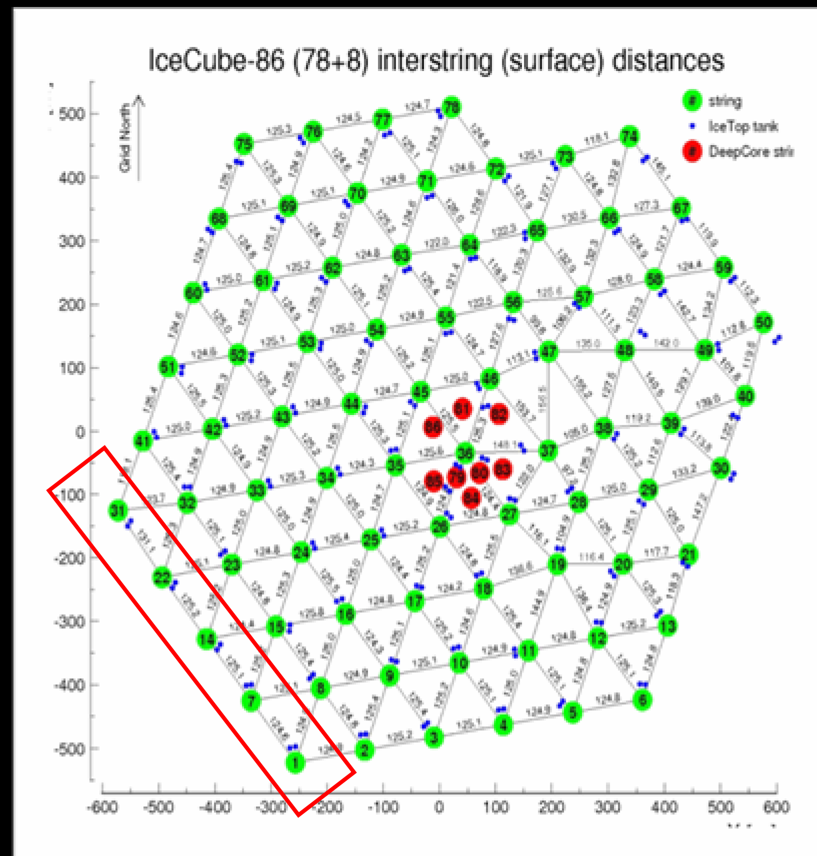
"IC79"

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

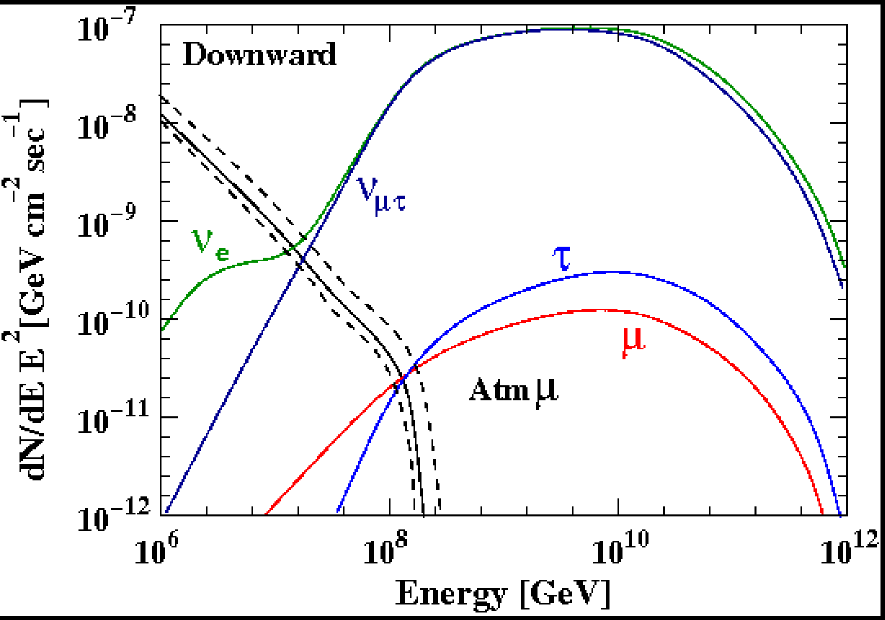
Many others
- Min Bias
- Moon
- IceTop
- etc

To Northern Hemisphere

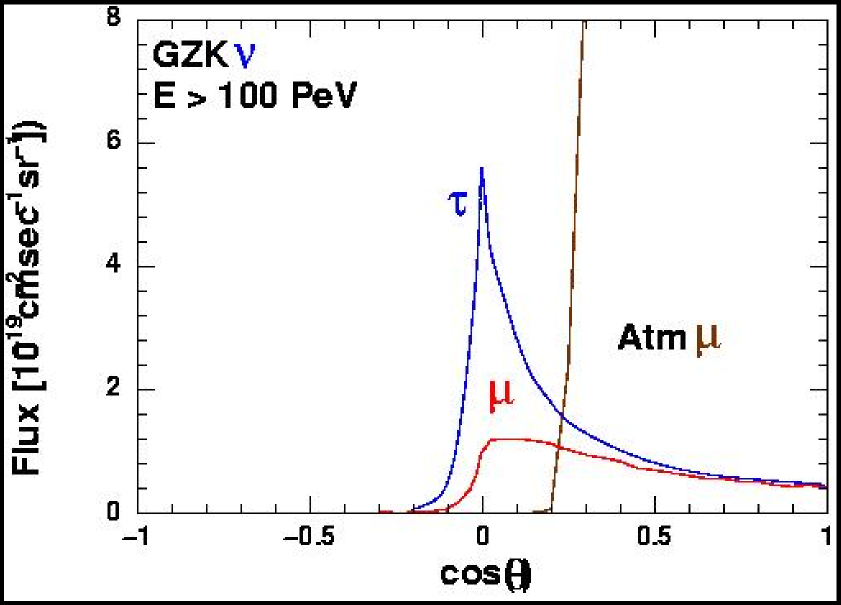
Ultra-high Energy ν search

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

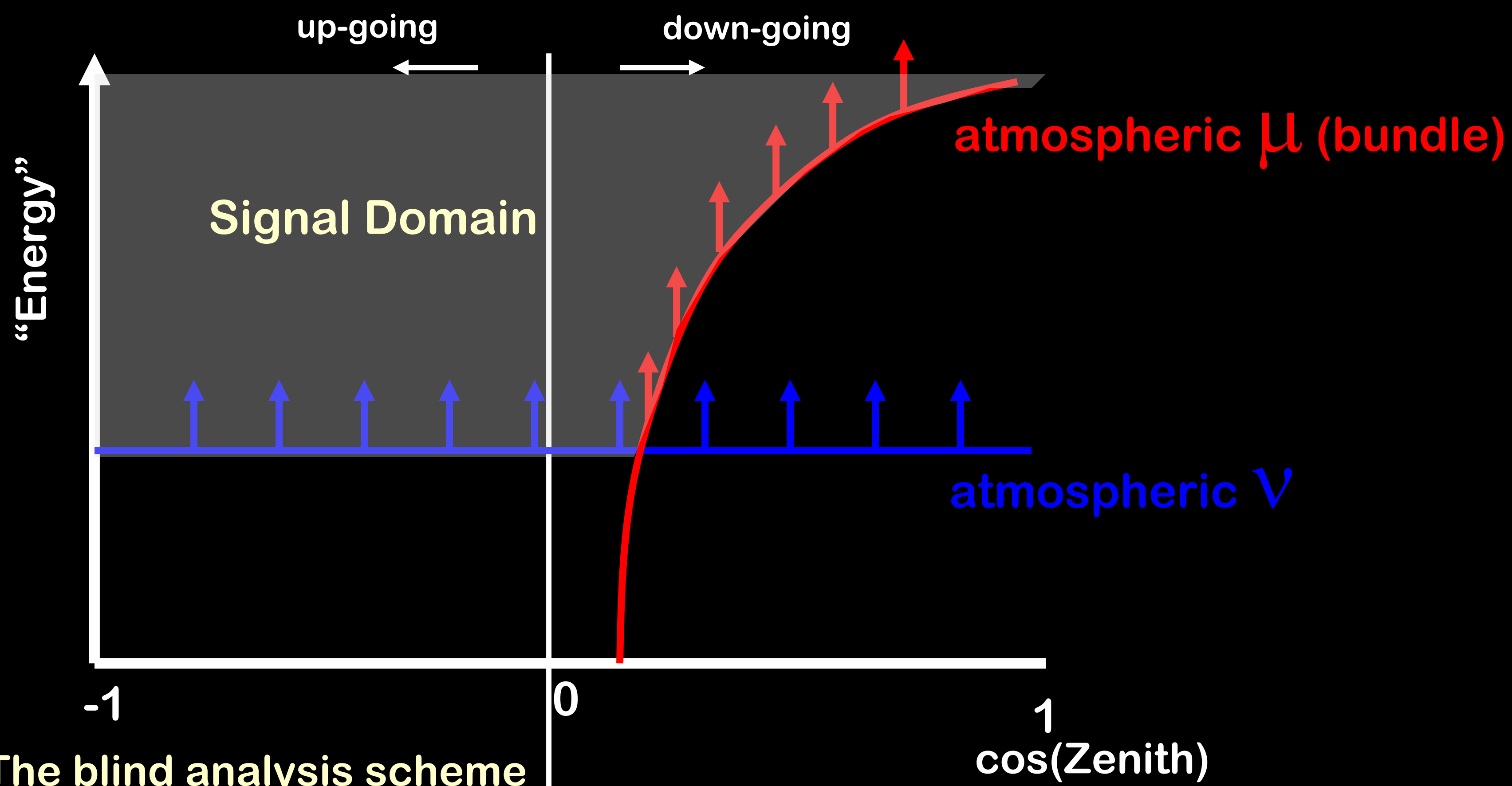
→ Sensitive to ν_e ν_μ ν_τ

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

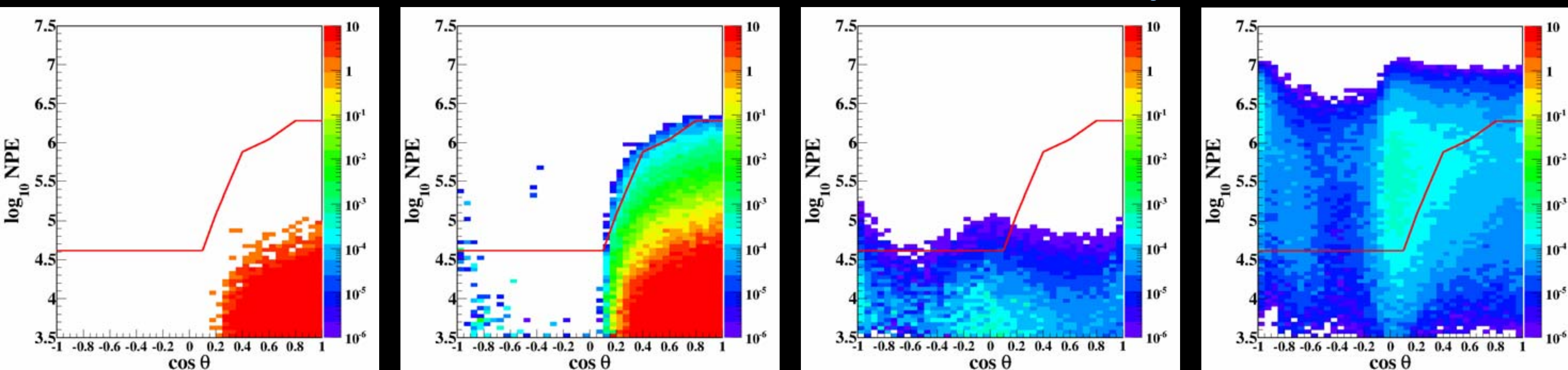
On the Analysis level

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

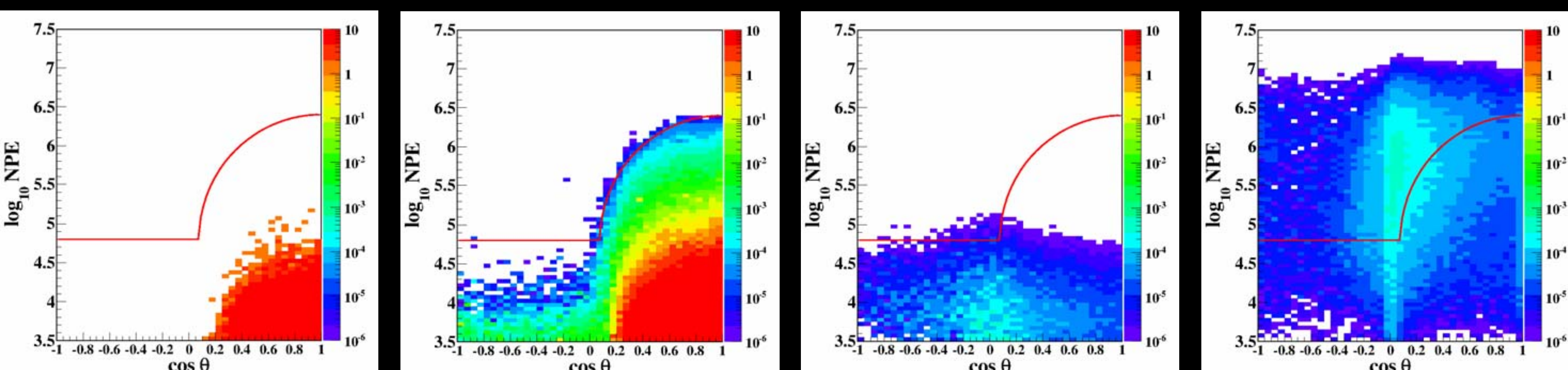
Number of events (z-axis) per the test-sample livetime

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

IC79



IC86



IceCube

Before reaching to this level

Introduced multi-staged filtering/quality cuts

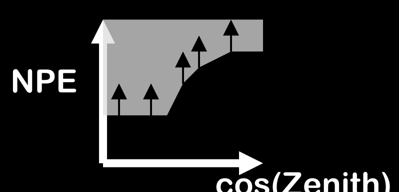
ensured the simulations reasonably describe
the test-sample data at each of the filter levels

of events

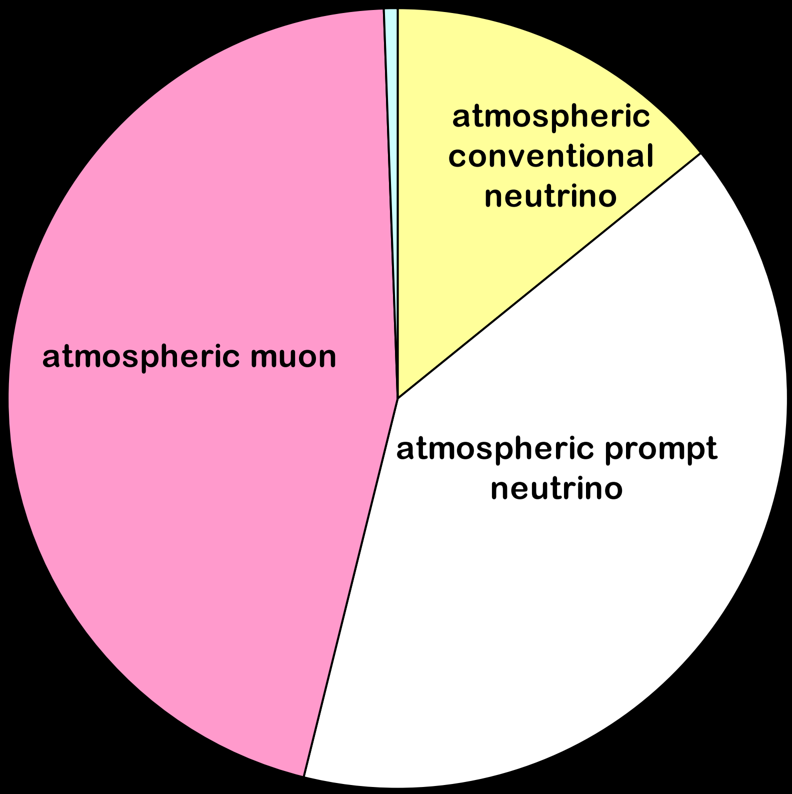
IC79(285.8days) + IC86 (330.1 days)

	Experimental data	Background MC atmospheric μ bundle atmospheric ν	Signal MC GZK ν Yoshida & Teshima (1993)
EHE filter level NPE>1000	1.00×10^8	1.33×10^8	4.49
Analysis level hit cleanings recalculation of NPEs NPE>3,200 NDOM>300 zenith angle reconstruction	1.04×10^6	2.11×10^6	3.26
Final level > $NPE^{threshold}(\cos(zenith))$	2	$0.050^{+56.7\%}_{-94.3\%}$ conventional only $0.082^{+49.3\%}_{+68.7\%}$ plus the atmospheric prompt ν	$1.92^{+13.6\%}_{-12.4\%}$

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



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

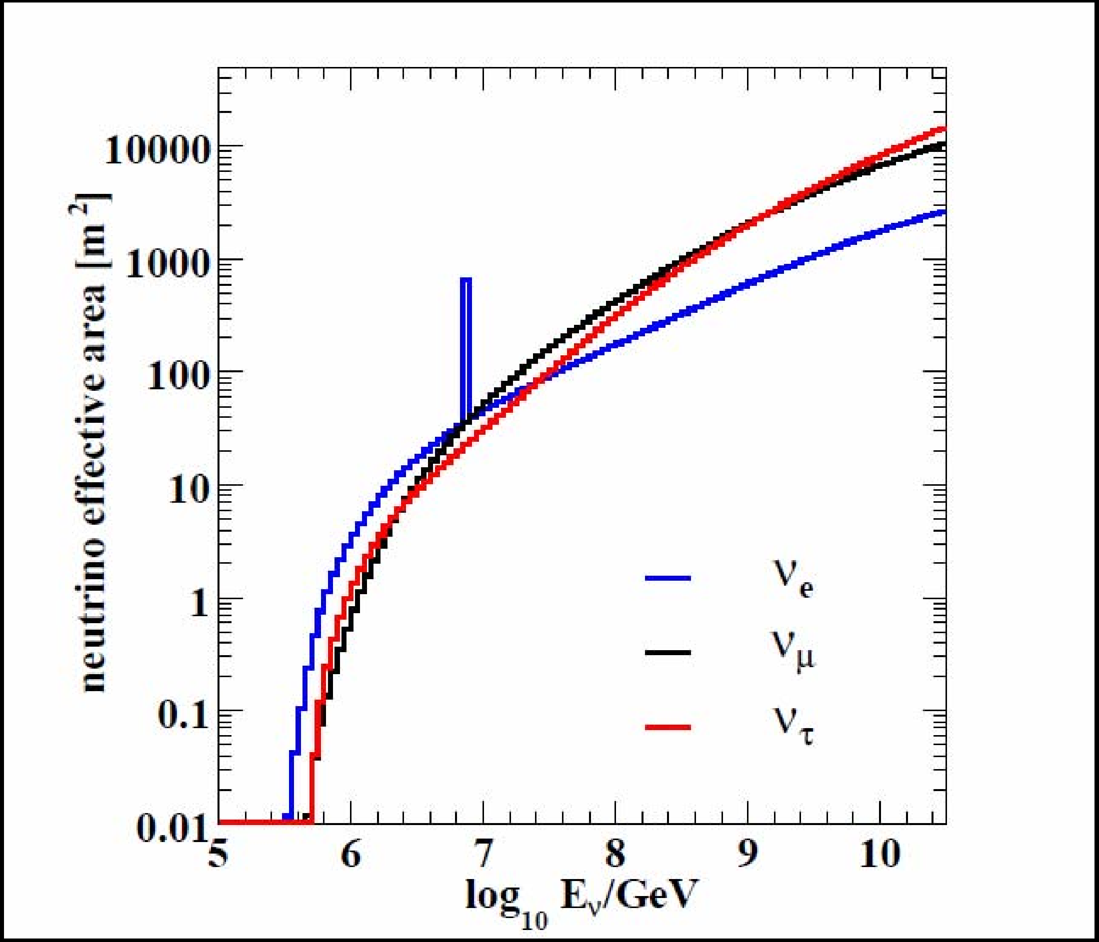
The systematic uncertainties on the BG rate

		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 615.9 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)

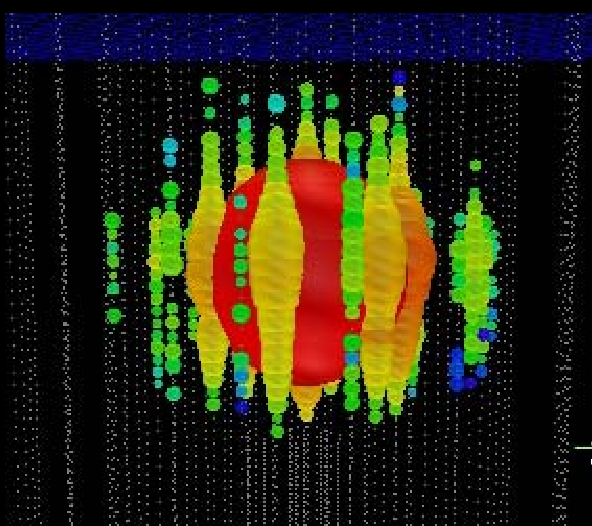
The Expected Backgrounds

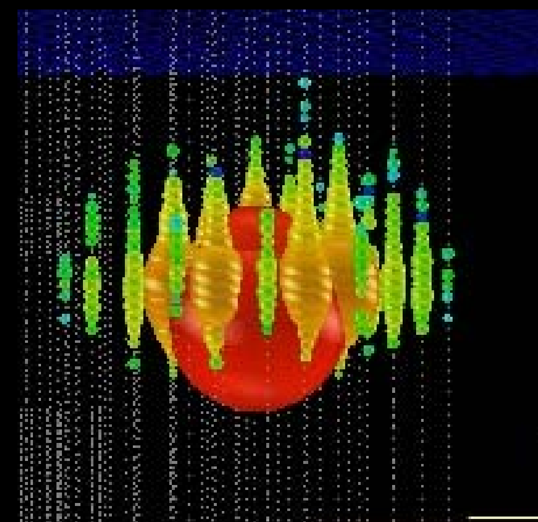
including prompt $0.082^{+0.041}_{-0.057}$

conventional only $0.050^{+0.028}_{-0.047}$

p-value 2.9×10^{-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

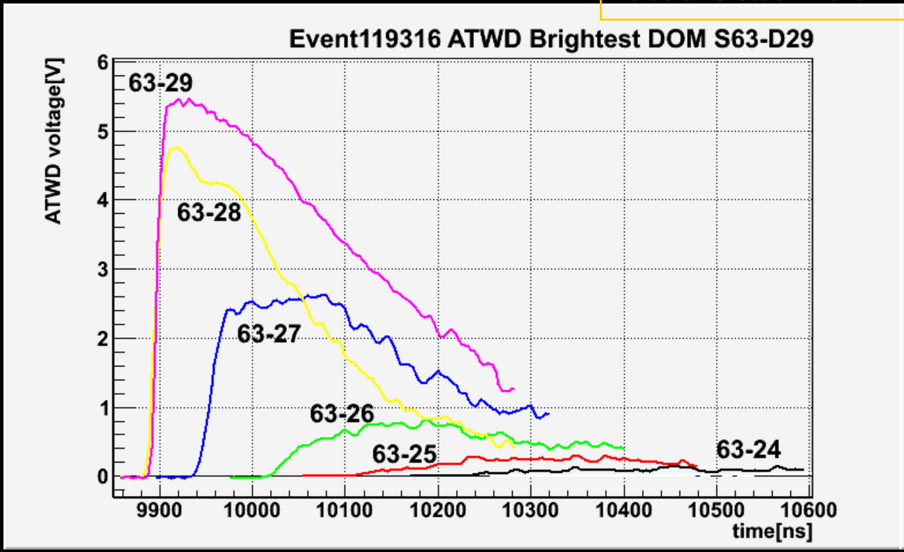
Run119316-Event36556705
Jan 3rd 2012 (“**Ernie**”)
NPE 9.628×10^4
Number of Optical Sensors 312

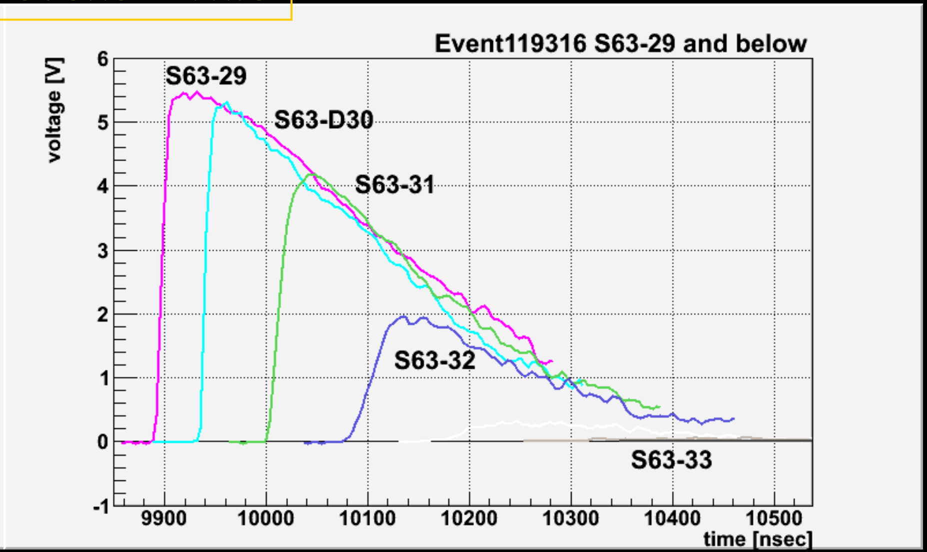
ICECUBE

Recorded pulses

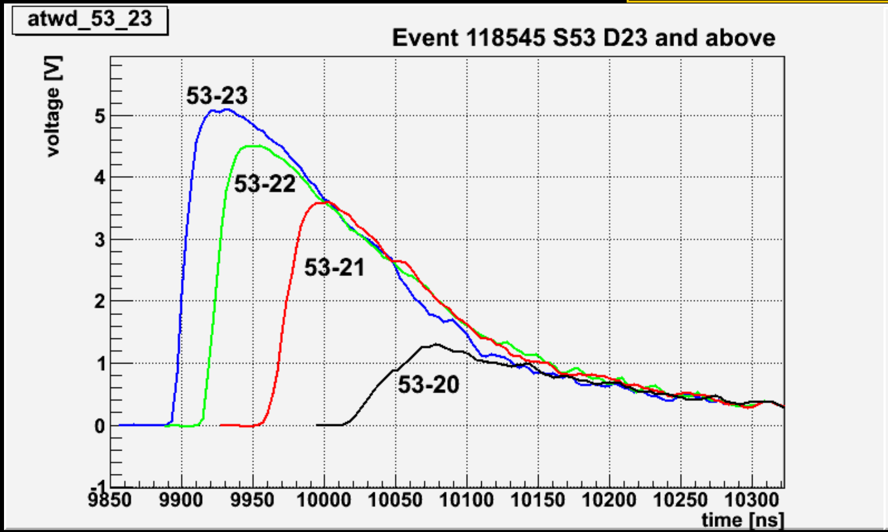
Clean and luminous bulk of photons !!

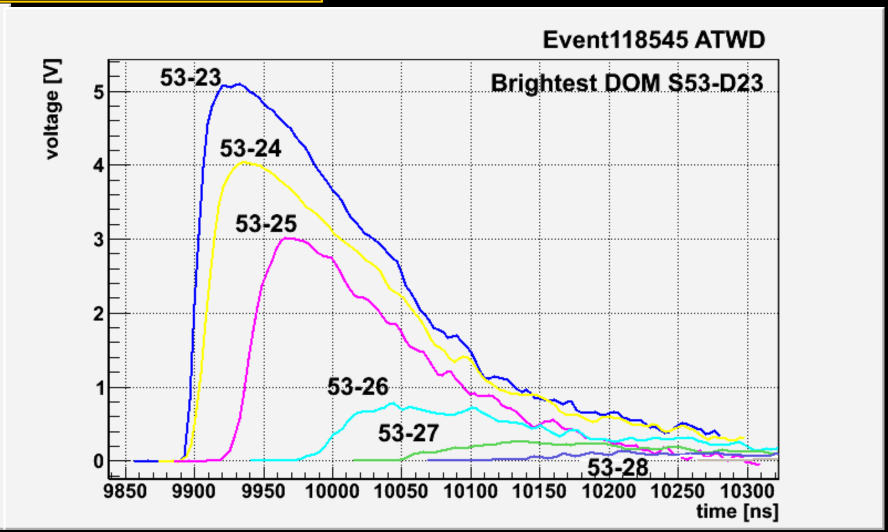
The Jan 2012 event - Ernie





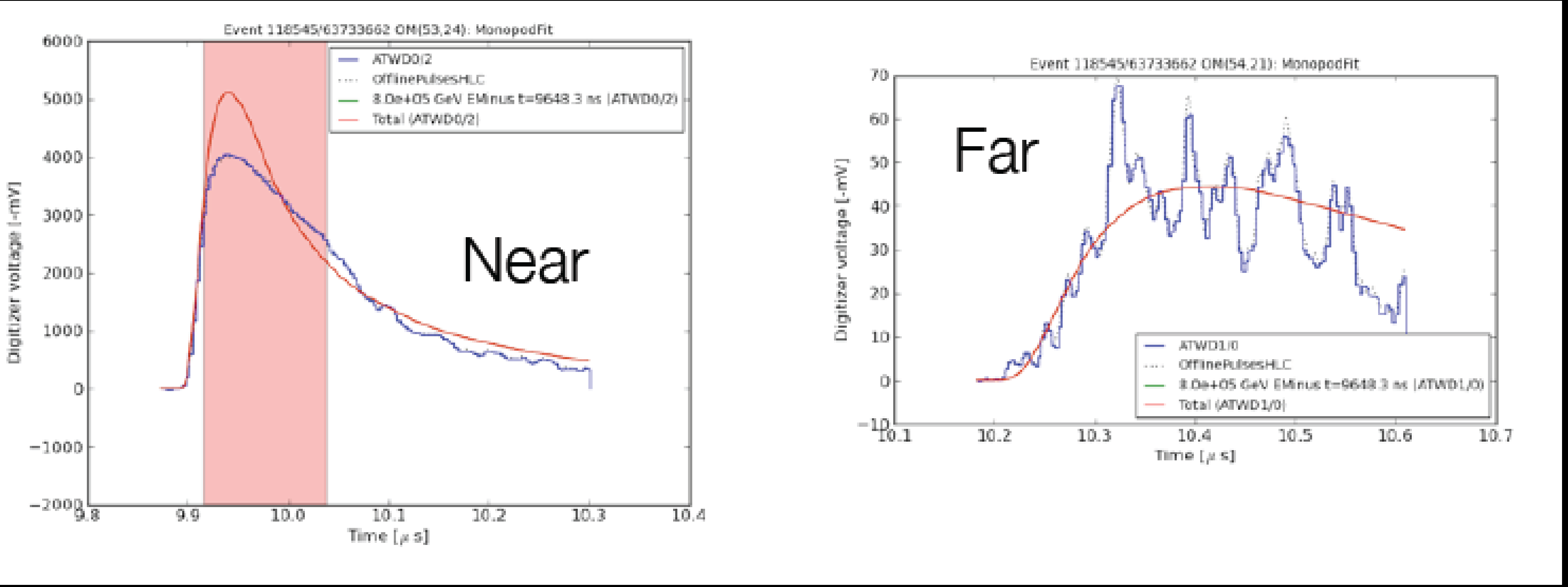
The Aug 2011 event - Bert





What are their energies?

- Maximizing the Poisson likelihood based on the recorded waveforms

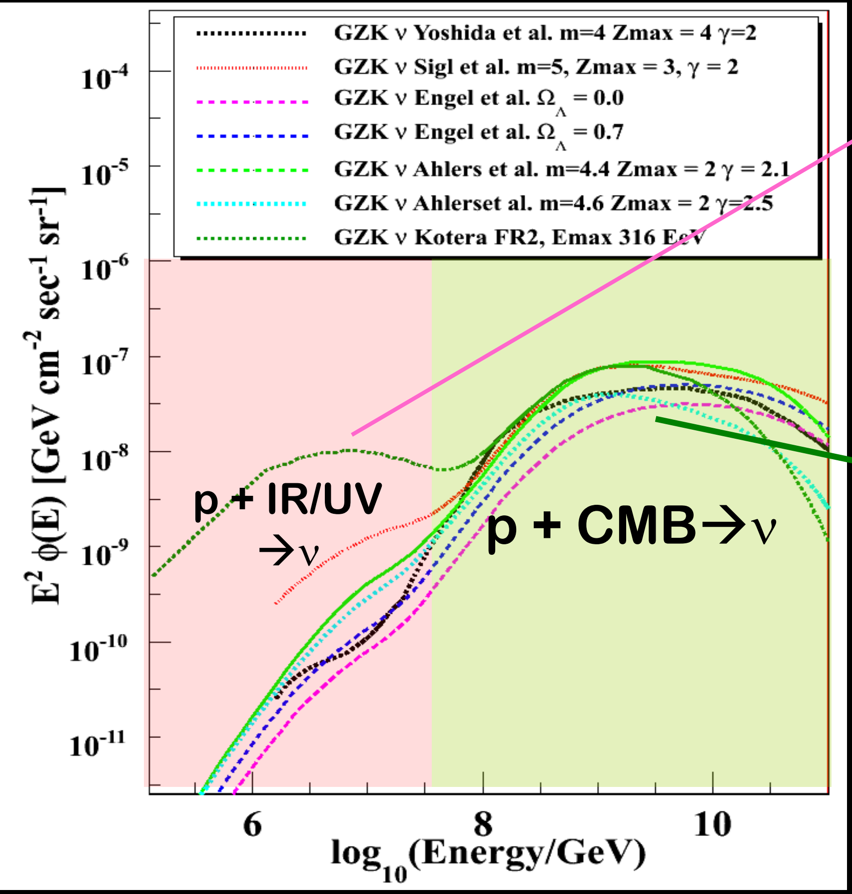


Estimated Energy Deposit +- 15% accuracy

- Jan 2012 event (Ernie) 1.04 PeV zenith 11deg
- Aug 2011 event (Bert) 1.14 PeV zenith 70deg

A PeV shower

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

Theme #1

The KS Test

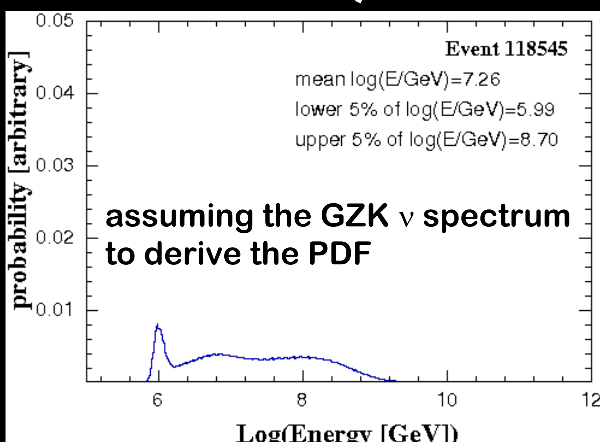
The energies of Bert & Ernie is consistent with the expectations from the GZK scenario?

Use the Kolmogorov-Smirnov statistics

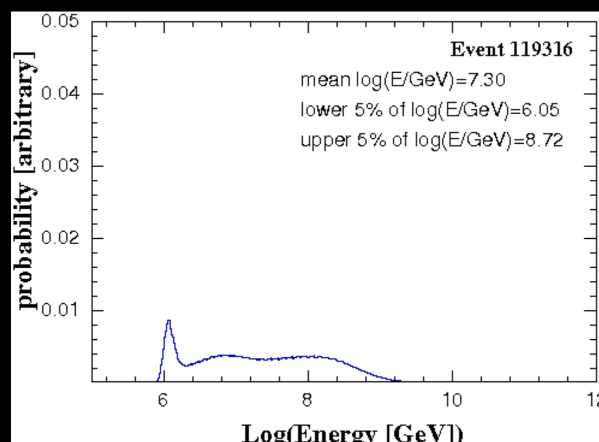
Take the energy uncertainty of Bert&Ernie into account

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

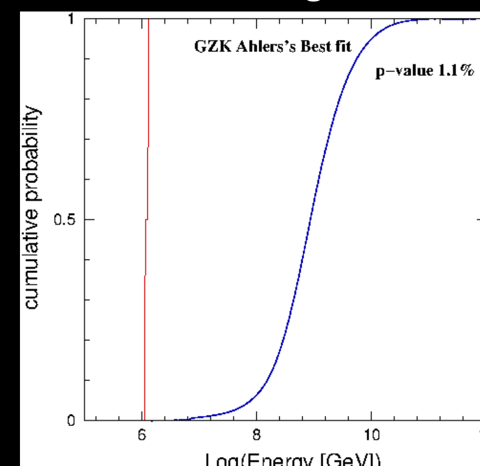
Energy PDF of Bert



Energy PDF of Ernie



KS statistical significance



The standard GZK	p-value 7.5×10^{-2}
The low energy GZK	p-value 3.9×10^{-2}

inconsistent at >90% C.L.
(not 99% CL)

Summarized statements on the origin of the 2 events

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

They are unlikely to be GZK cosmogenic

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

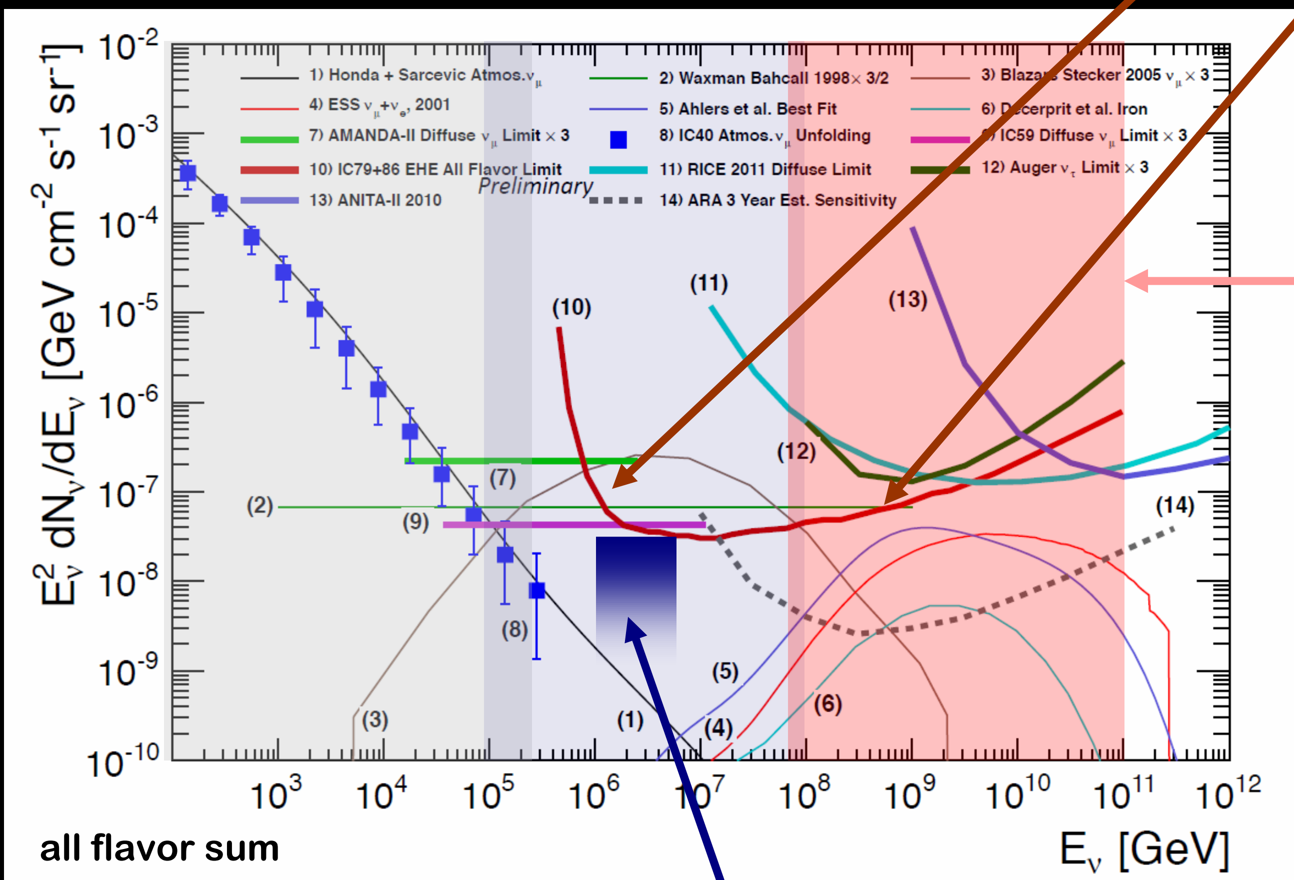
we would have detected events with greater energies, otherwise

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

Needs more data/follow-up analyses for further interpretation

The executive summary

The model-independent upper limit on flux in UHE



null observation in this regime

nearly exclude

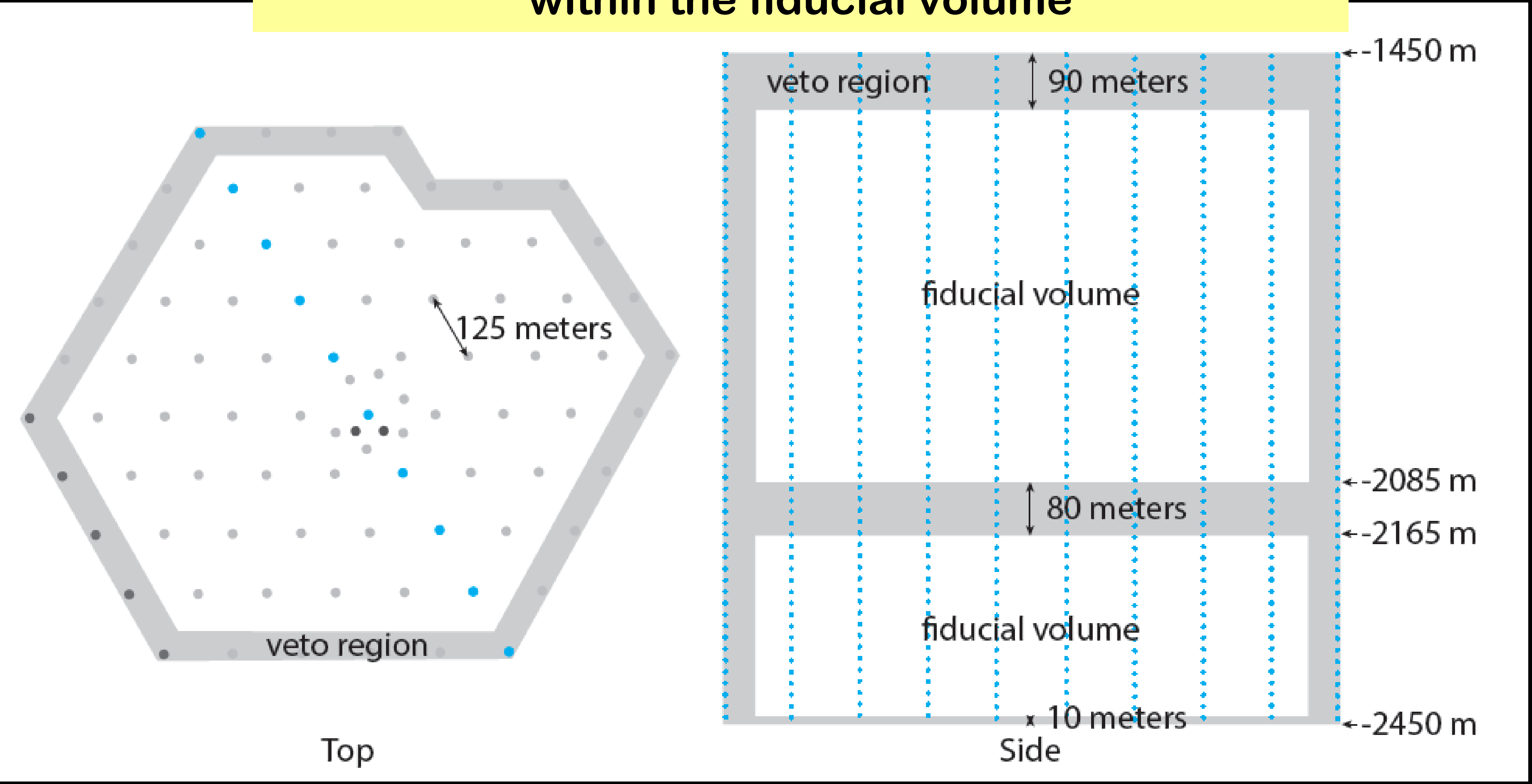
- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

Bert & Ernie

2.8 σ excess over atmospheric

A search for events originated within the detector interior

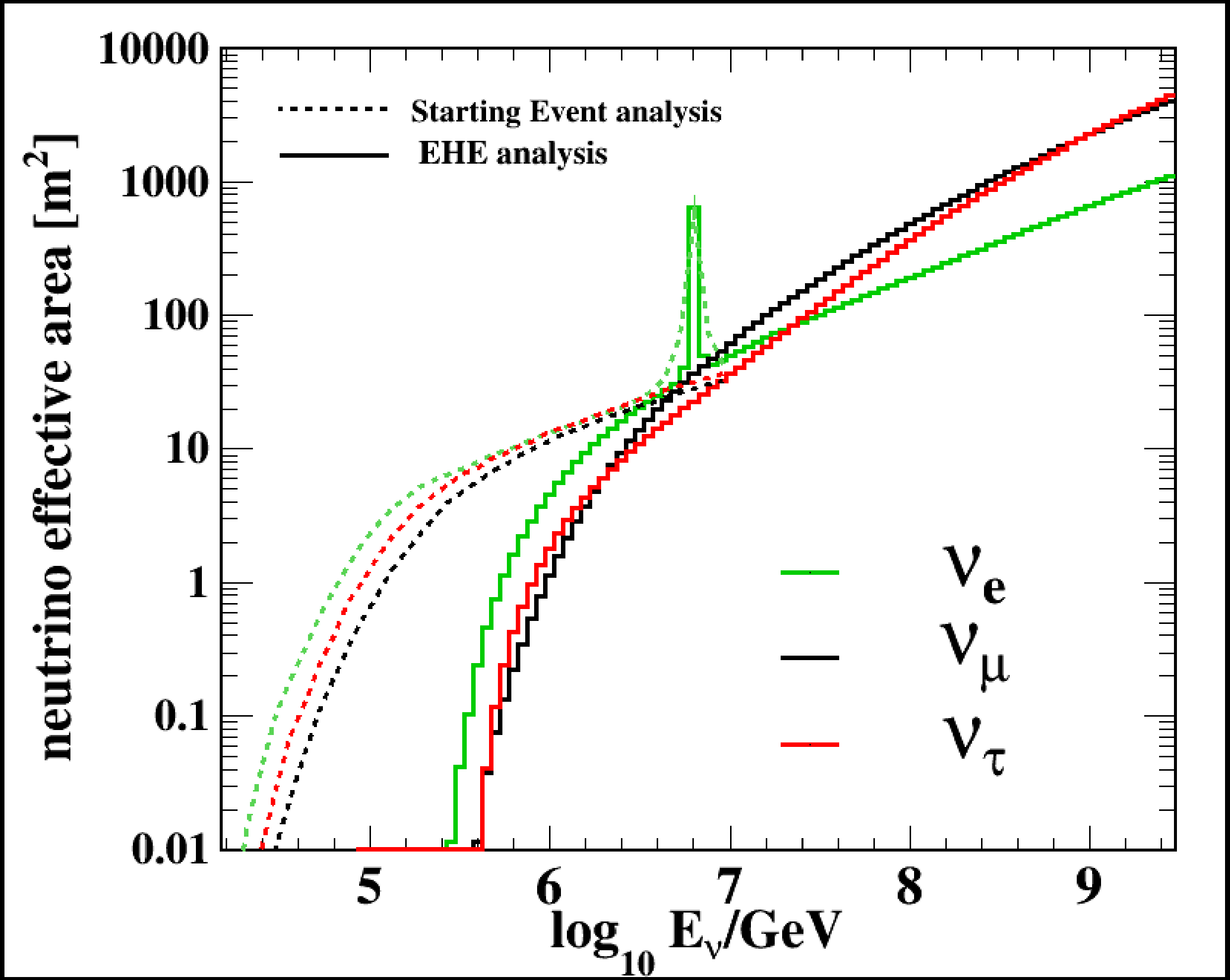
look for only events with their interaction vertices within the fiducial volume



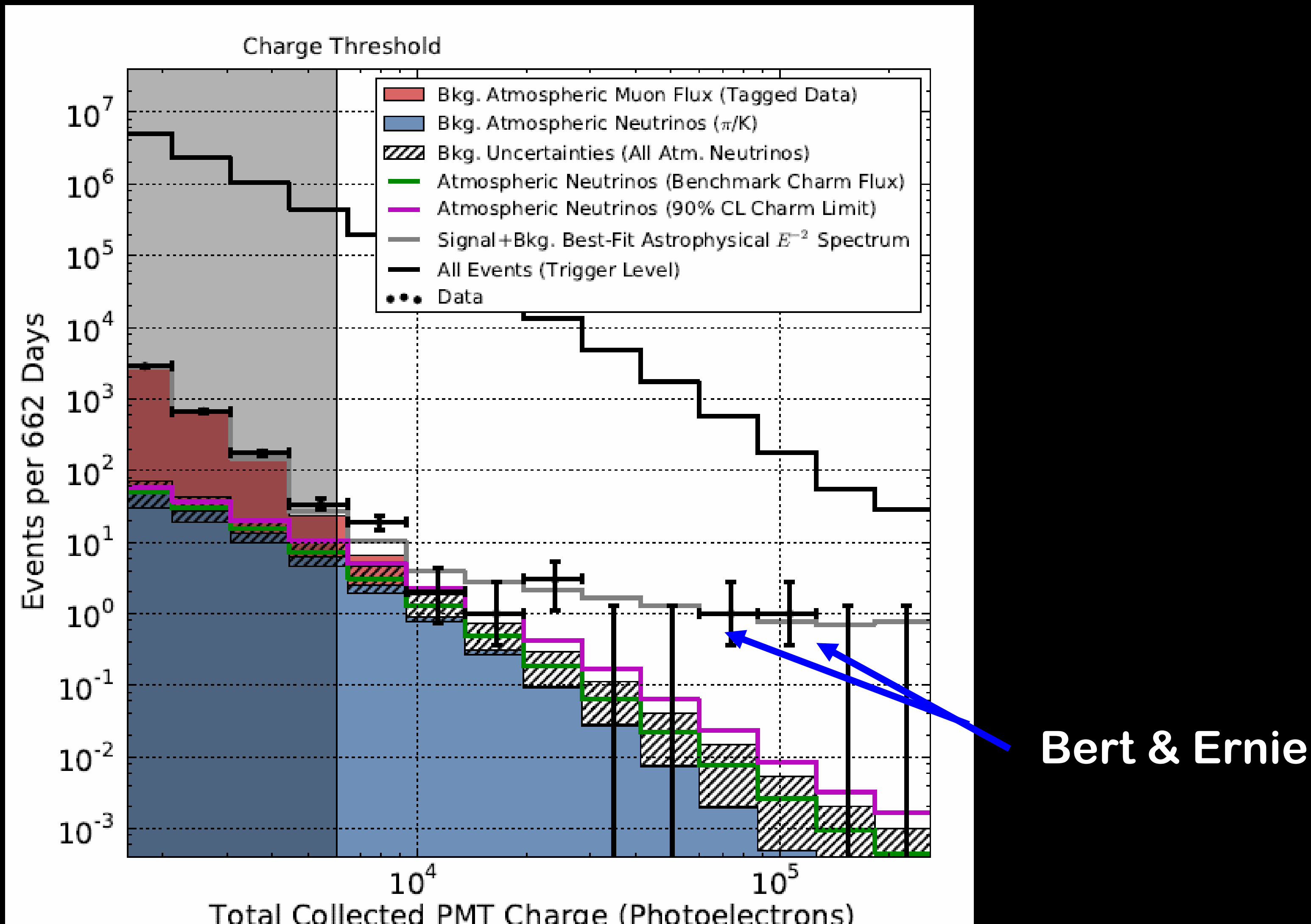
Effective Areas expanding down to 100 TeV's

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

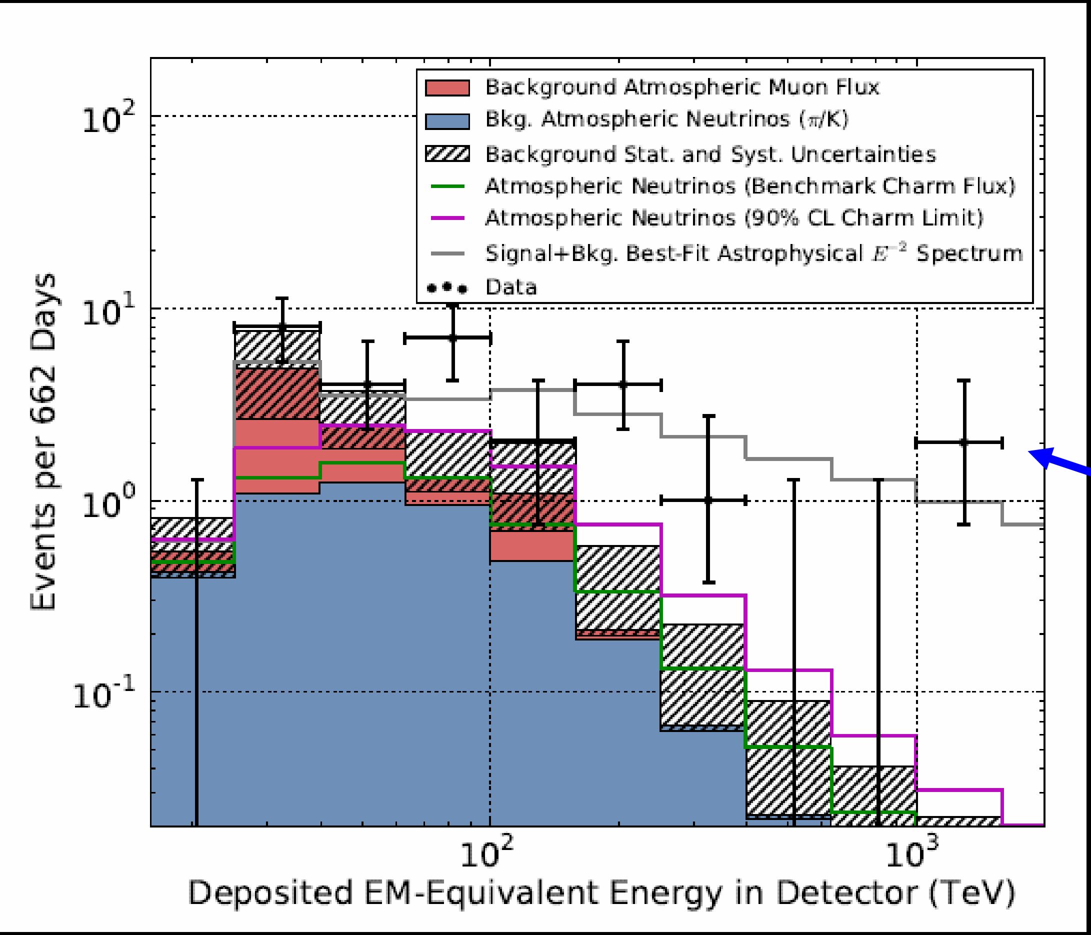
IC79+IC86 livetime 670.1 days



sub-PeV ν samples



sub-PeV ν samples



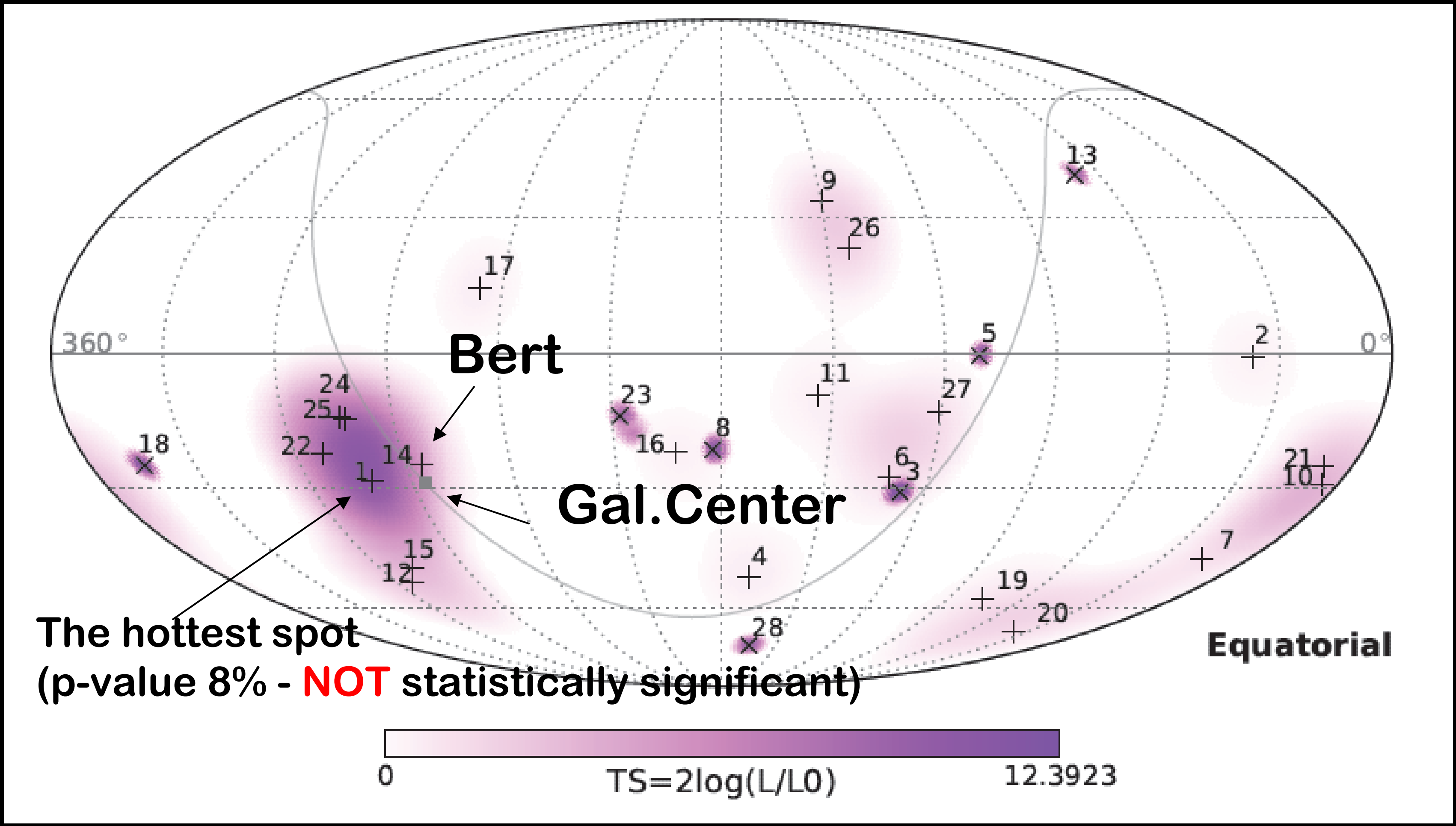
28 events observed against bg of $10.6^{+5.0}_{-3.6}$ (4.1σ excess)

Bert & Ernie

$$E^2 \phi_{\nu_{e+\mu+\tau}}(E) \sim (3.6 \pm 1.2) \times 10^{-8}$$

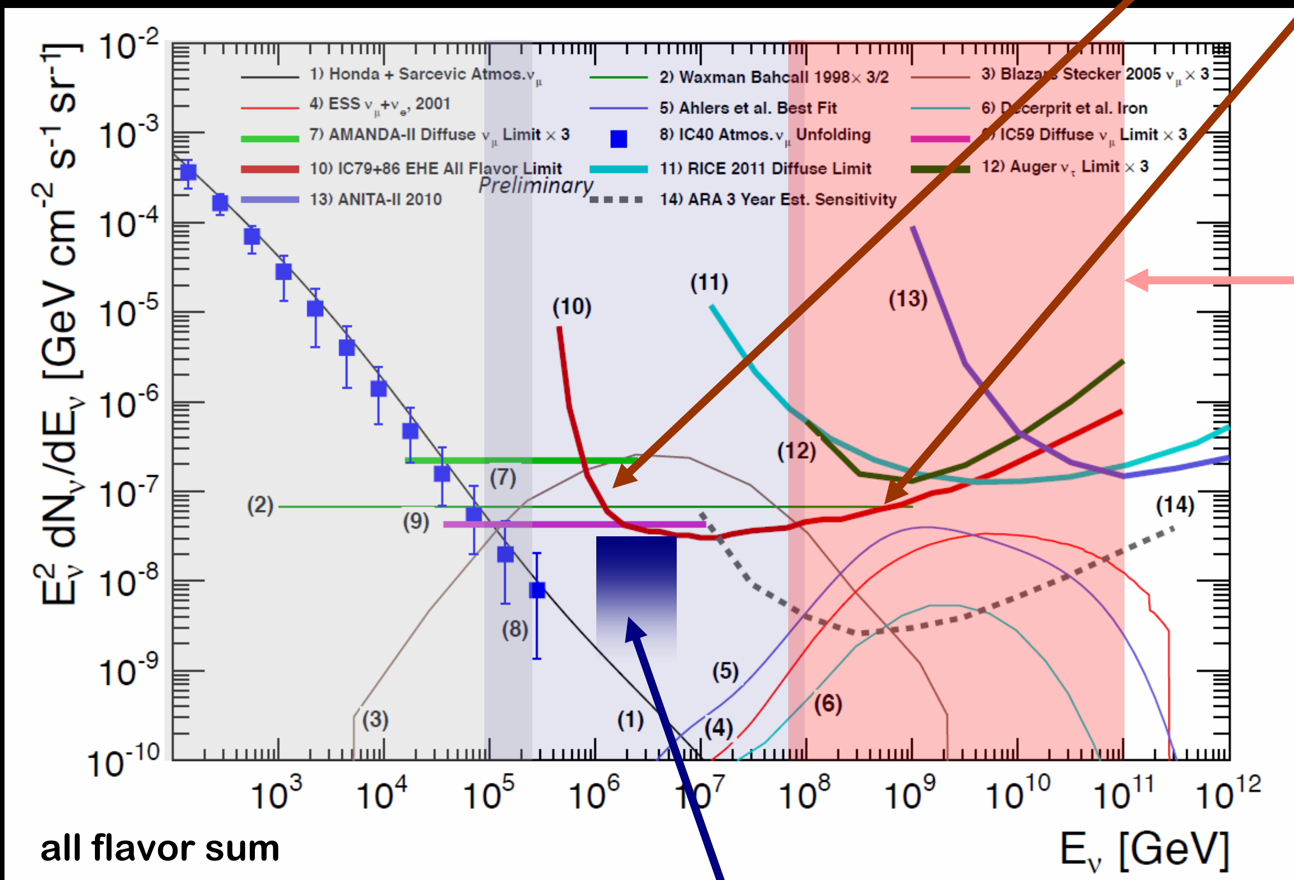
[GeV/cm^2 sec sr]

sub-PeV ν samples



The executive summary

The model-independent upper limit on flux in UHE



null observation in this regime

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- emission maximally allowed by the Fermi γ

Bert & Ernie + O(10) sub-PeV events

4.1 σ excess over atmospheric

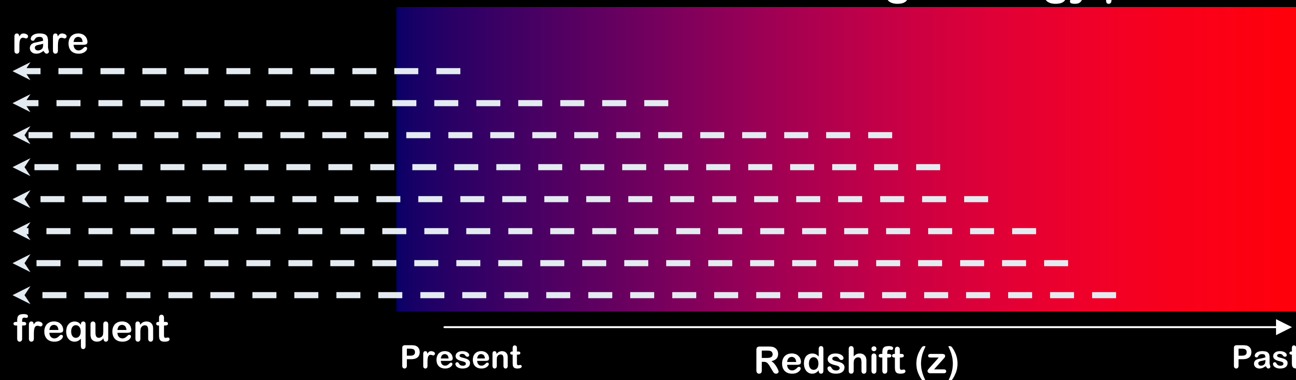
Tracing *history* of the particle emissions with ν flux

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

ν

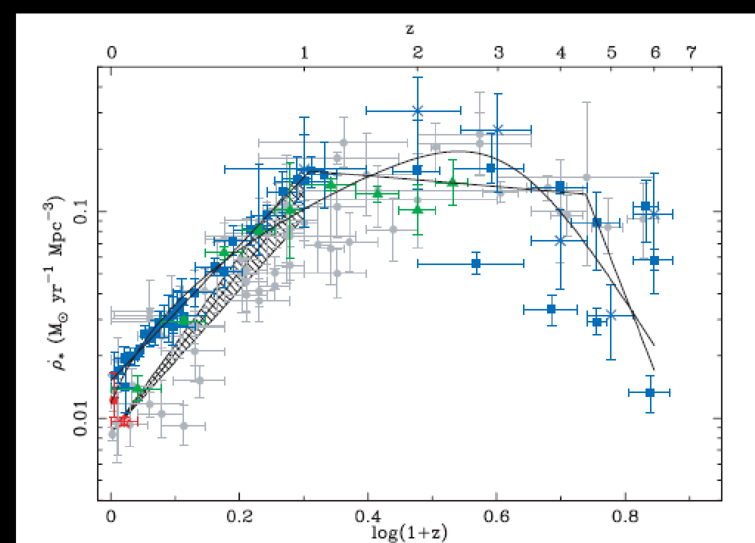


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→



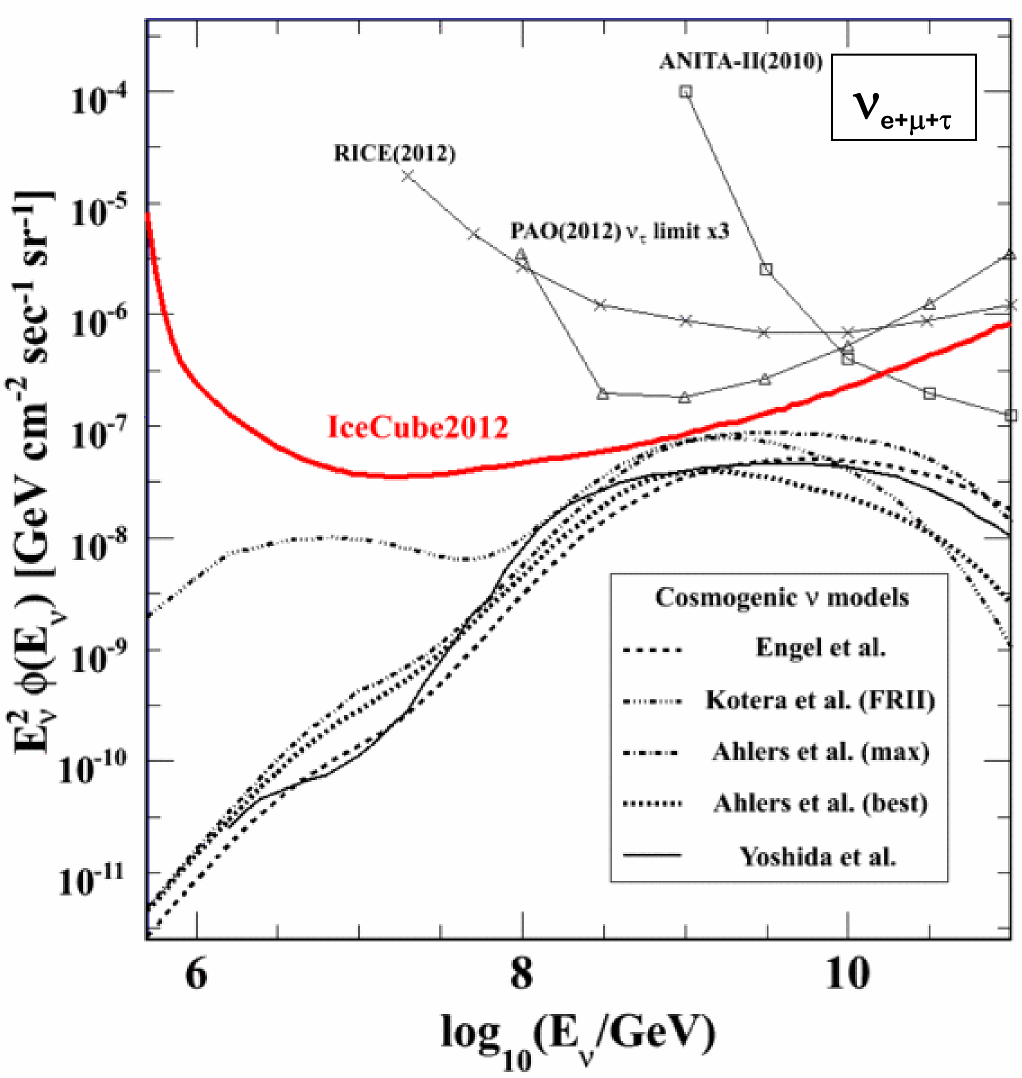
The spectral emission rate

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

m= 0 : No evolution

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

ICECUBE

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	2.0	3.1	1.5	3.1	2.9	0.5	3.9
Model Rejection Factor	1.13	0.74	1.50	0.72	0.79	4.95	0.59
p-value	1.4×10^{-1}	4.6×10^{-2}	2.2×10^{-1}	4.4×10^{-2}	5.2×10^{-2}	6.7×10^{-1}	2.1×10^{-2}

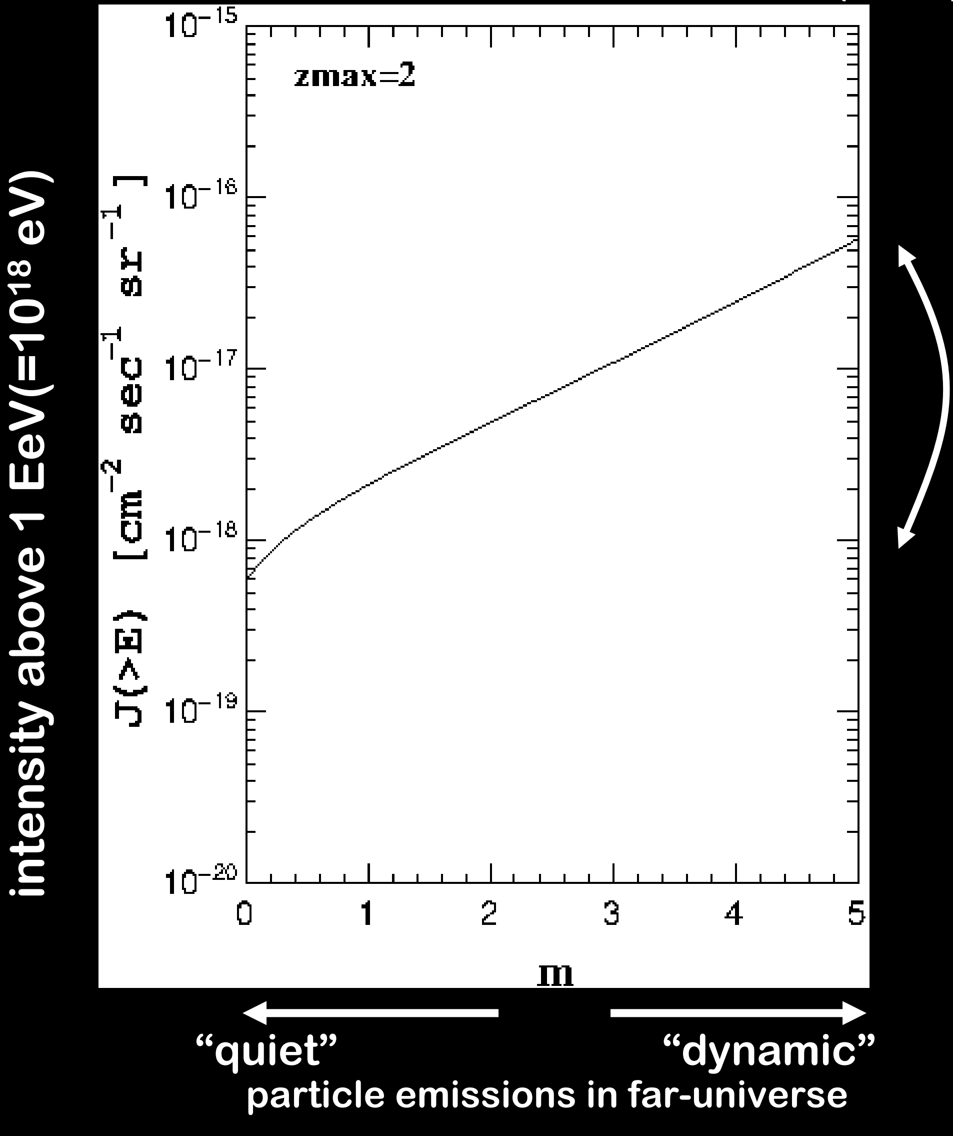
Maximal ν flux allowed by the Fermi γ-ray measurement

- Excluded (red)
- Mildly Excluded (orange)
- Consistent (blue)

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

Ultra-high energy ν intensity
depends on the emission rate in far-universe

Yoshida and Ishihara, PRD 85, 063002 (2012)



more than an order of magnitude difference

千葉大学
Chiba University

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

Yoshida and Ishihara, PRD 85, 063002 (2012)

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

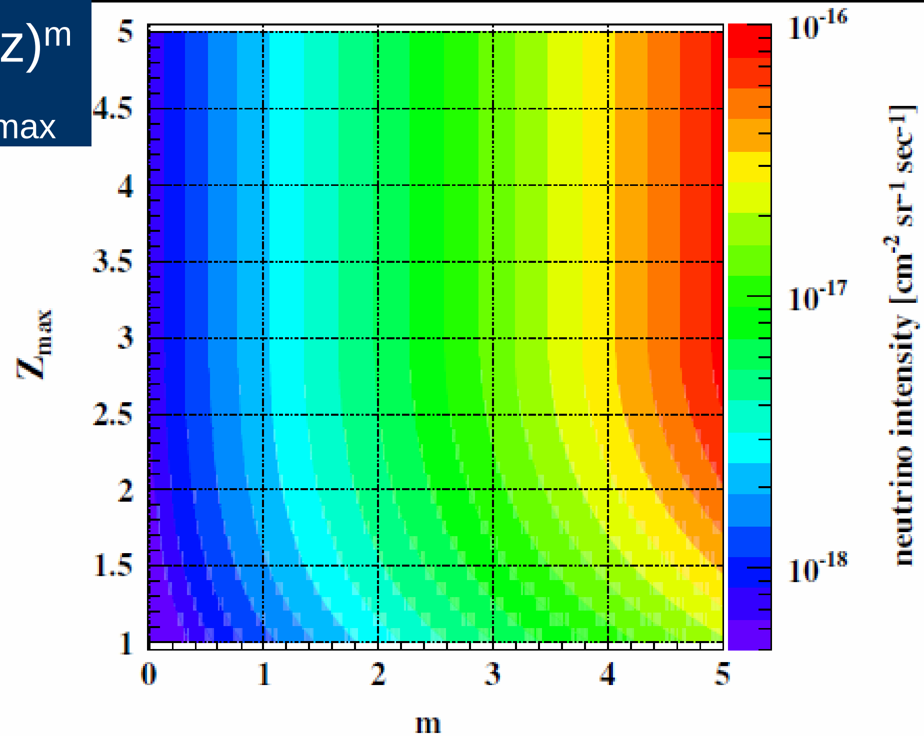


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

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

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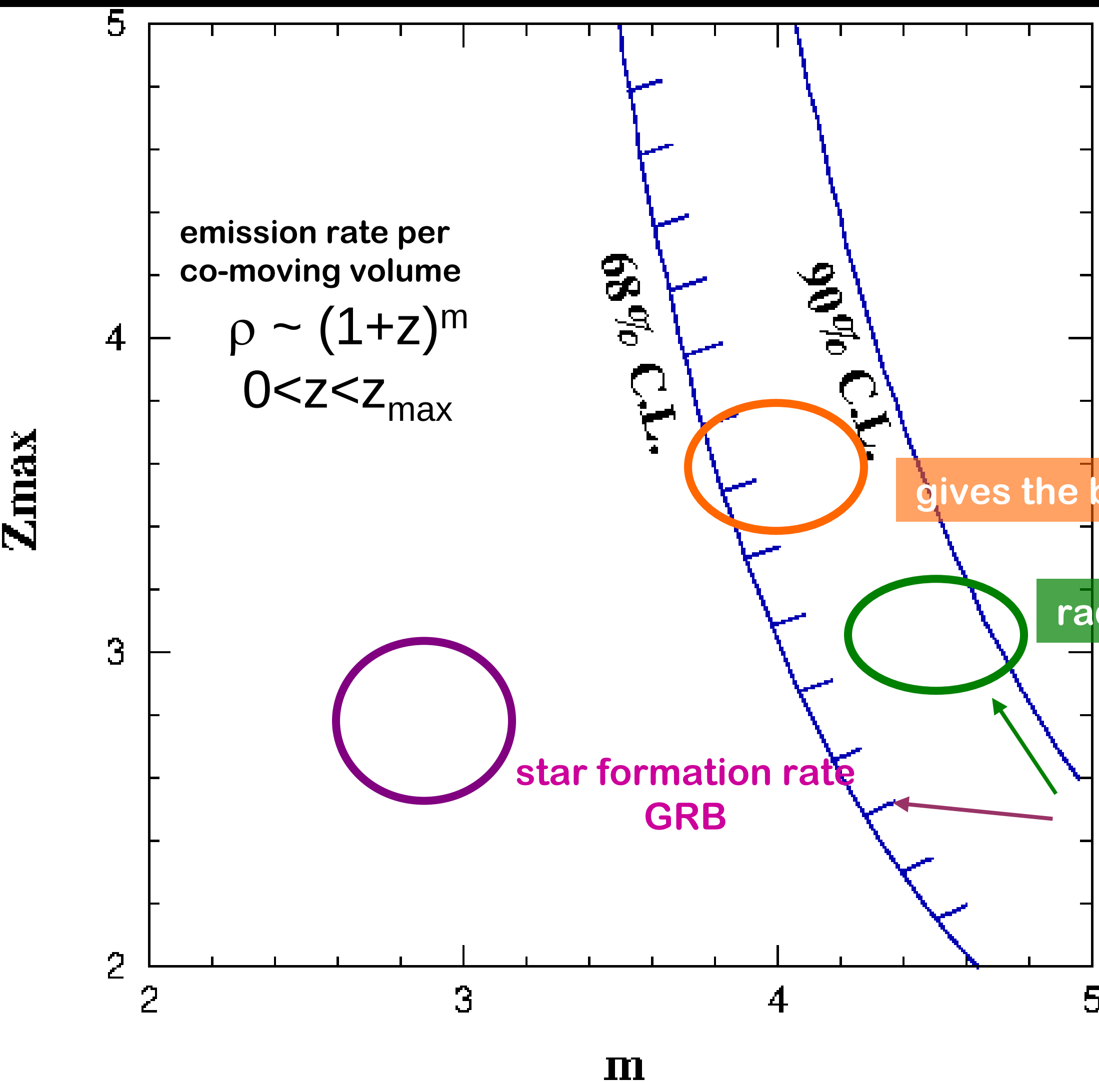
Constraints on the evolution

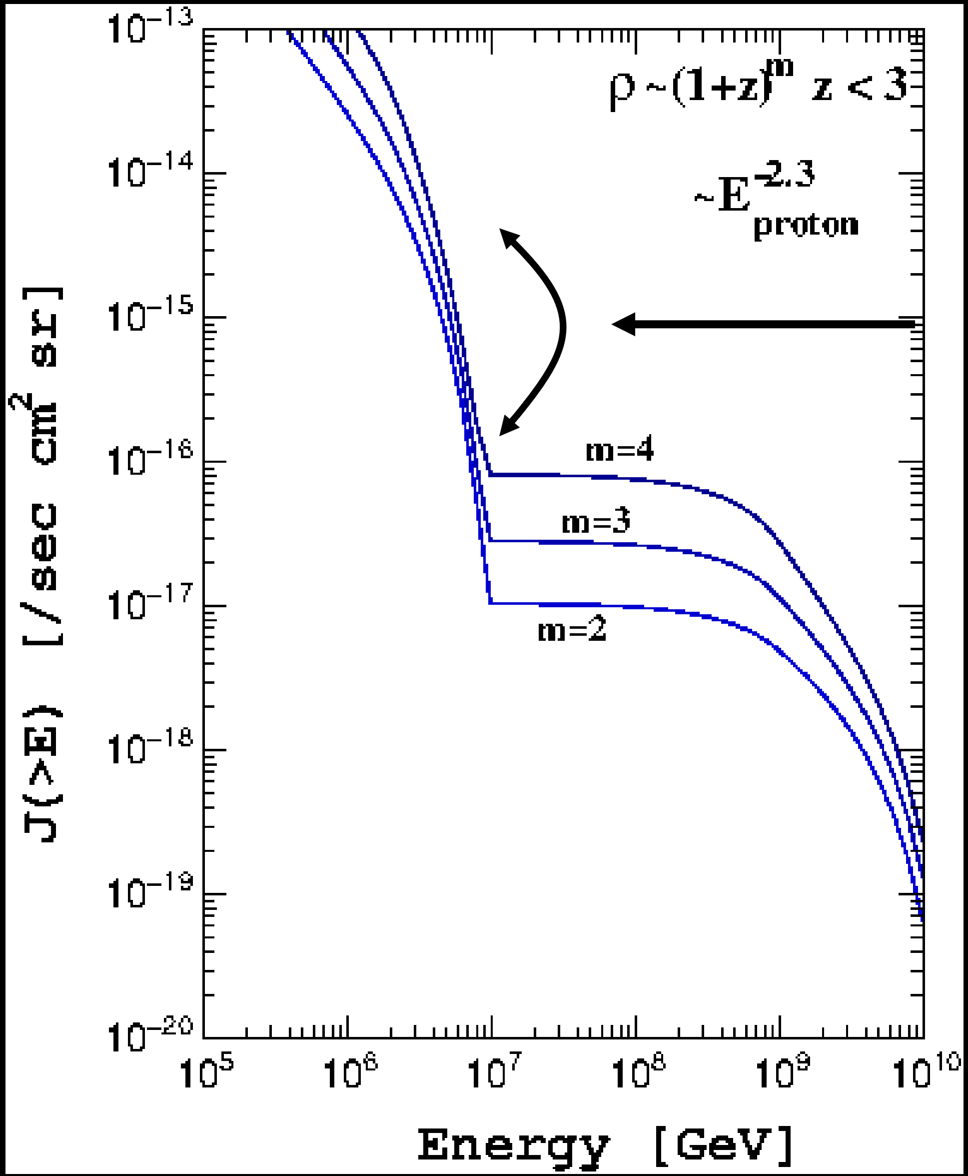
90% C.L. = 3.3 evens above 100PeV
68% C.L. = 1.9 evens above 100PeV



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

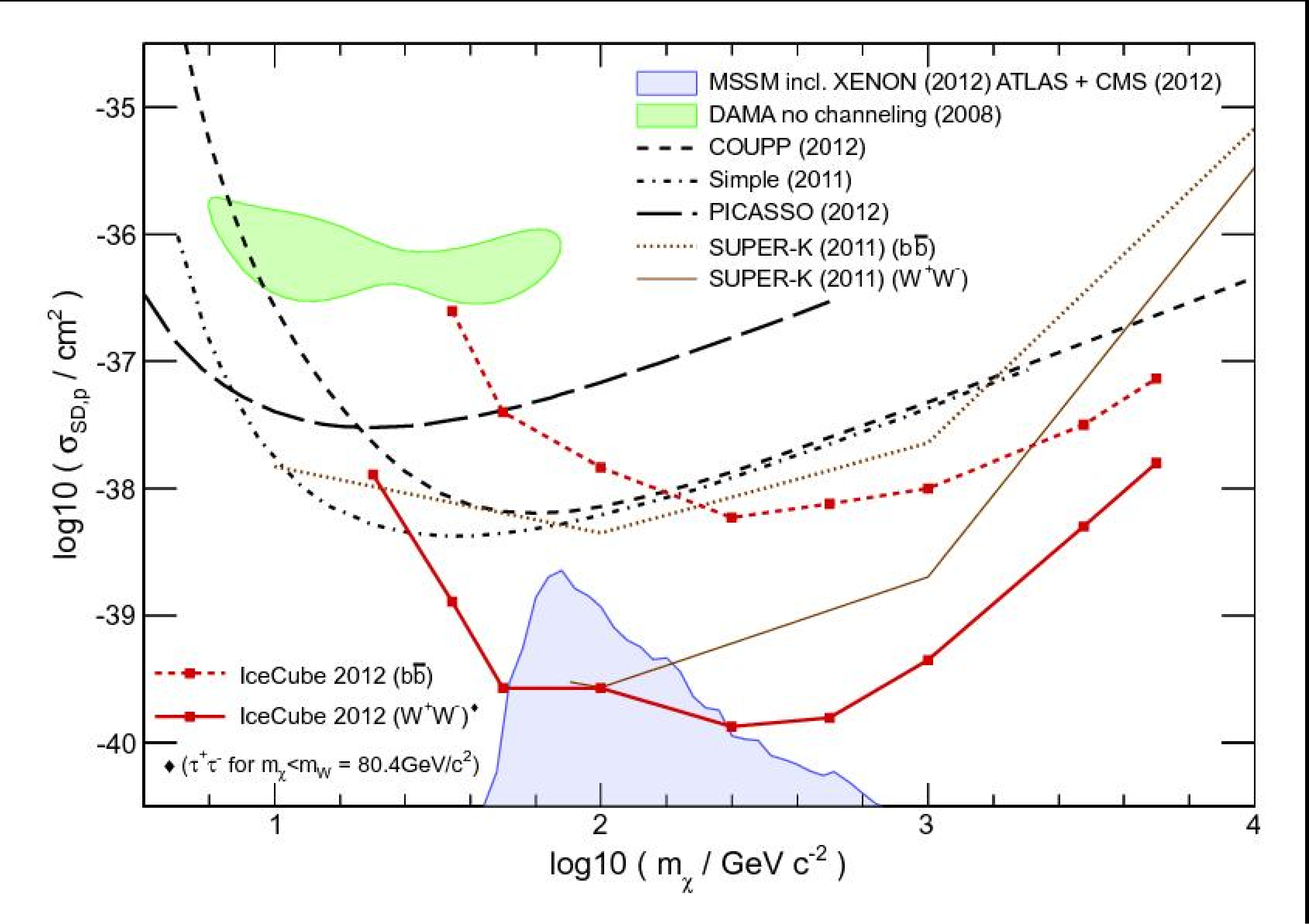
- any scenario involving sources evolved stronger than SFR will soon be ruled out by IceCube if we see no events in EeV rage.

Ultra-high energy ν intensity
depends on the emission rate in far-universe



more than an order of magnitude difference

WIMP from Sun



WIMP from Sun