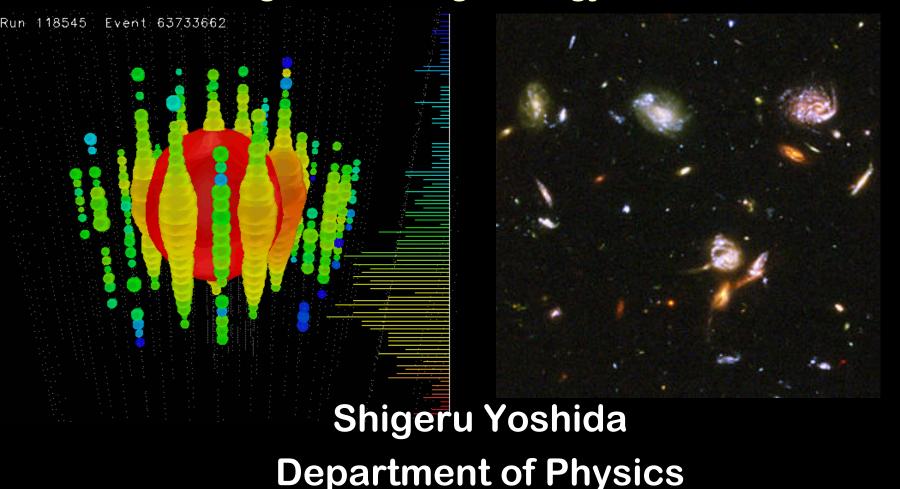
Detection of Ultra-high energy neutrinos

The 'First Light' of the high energy neutrino astronomy



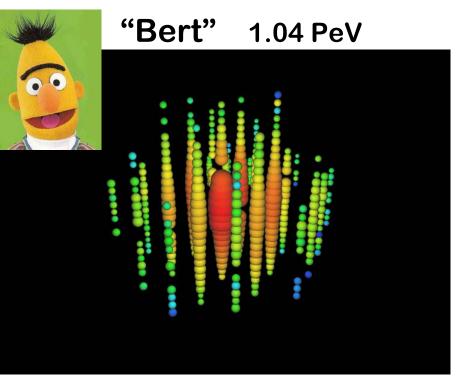
Department of Physics
Chiba University

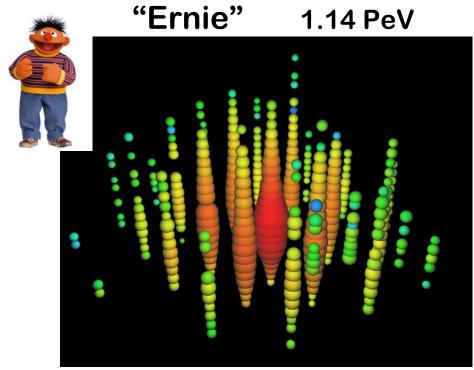




$^{ m UNIVERSÍTY}$ the 1st discovery of the PeV $^{ m V}$

Physical Review Letters 111, 021103 (2013)





2.8 σ excess on the atmospheric background

very the 1st indication of astrophysical V

"Cover-boy" of Physical Review Letters

NEWSPAPER

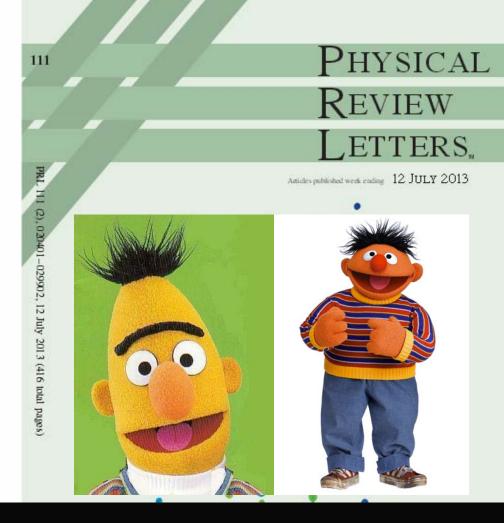
Chaevasi is of a high-energy particle drawer event from August 2011, itselfied as a BeV-energy sentries. Each other as no BeV-energy sentries. Each other exposers is digital optical smokine senter in the locable detector. Sphere size is a sensare of the recorded sucher of principal colorum. Cales represent servical times of photons ford, only, the local colorum of the colorum of

PHYSICAL REVIEW LETTERS ...

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Effective Field Theory Approach to Gravitationally Induced Decode esce M.P. Blencowe	021302



"Cover-boy" of Physical Review Letters

NEWSPAPER



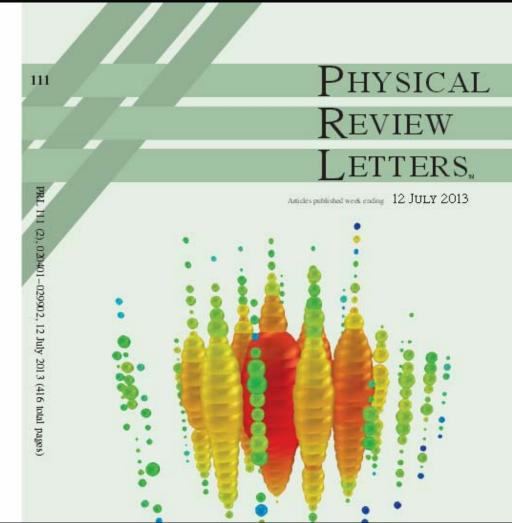
Charronins of a high-energy position denote reveal from August 2011, identified as a ReVenumy sentries. Each option represents a tighted option module sensor in the Incifude detector. Sphere size is a tensor of the recorded sentre represent served times of photons (red, core), blue, blue). Selected for a Systepsis in Physics at the Author Supposition (Incifude the August and Incifude Selected Selected Californius, Buye Rev. Lett. 111, 02(103) (2013).

PHYSICAL REVIEW LETTERS ,,

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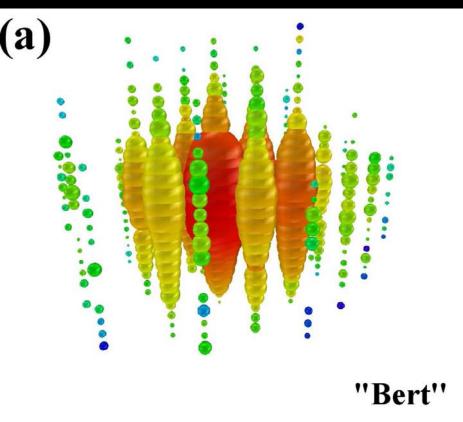
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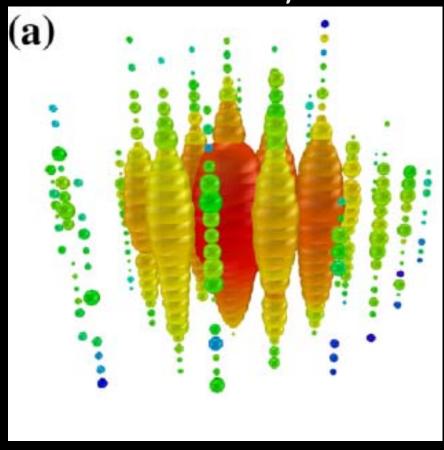


A proof of the PRL's high standard for publication

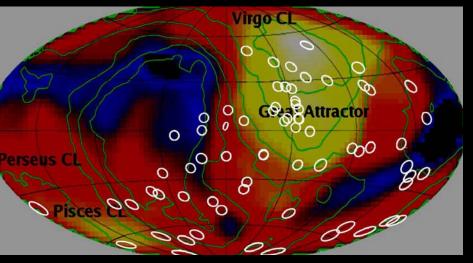
The version *submitted*

The version accepted



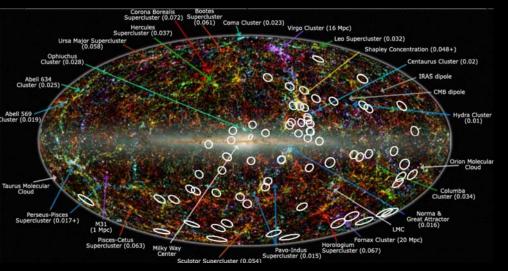


The challenge



Two possibilities

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)



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

No clear correlations.....

We may not be so smart.

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!!

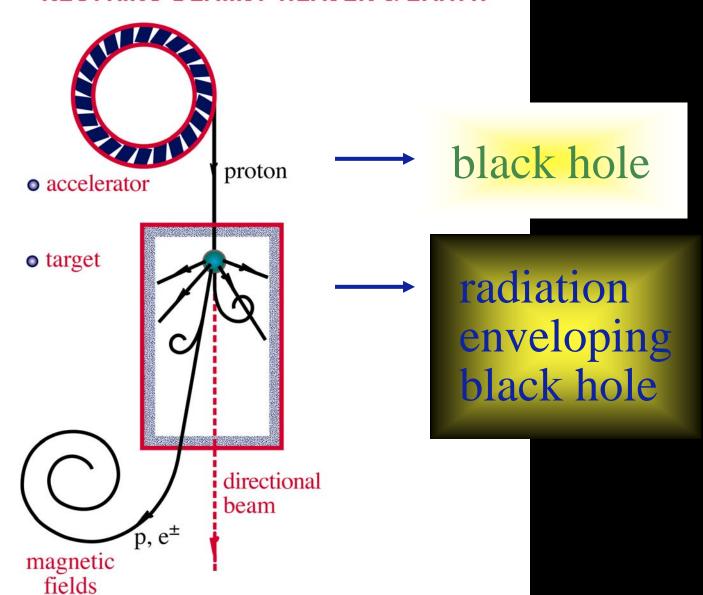
No electric charge. Coming to us straight

Highly complementary – v can travel over a LONG distance

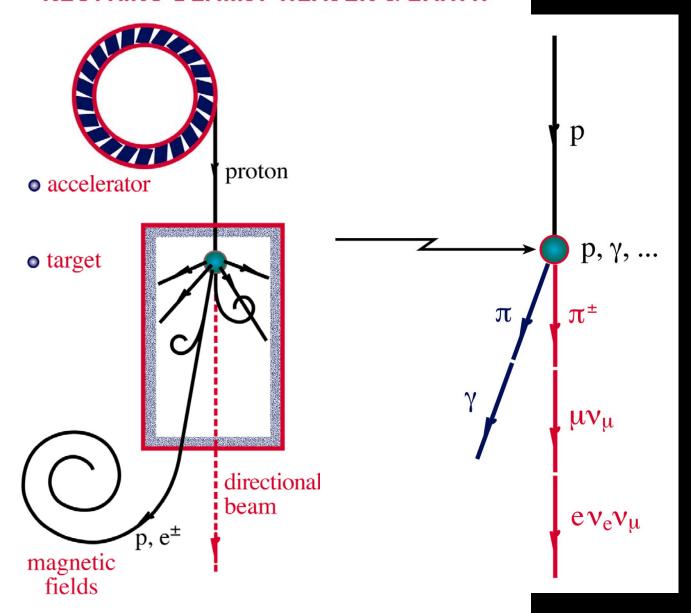
The cons : measurement of v's is really a tough business

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

NEUTRINO BEAMS: HEAVEN & EARTH



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

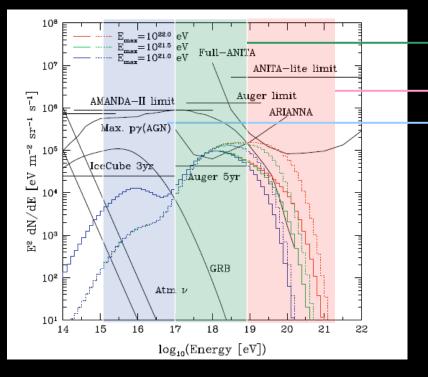
p > 100 EeV π^+ ν_{μ} ν_{e} ν_{e}

GZK (Greisen-Zatsepin-Kuzmin) mechanism

The main energy range: $E_v \sim 10^{8-10} \text{ GeV}$

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

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



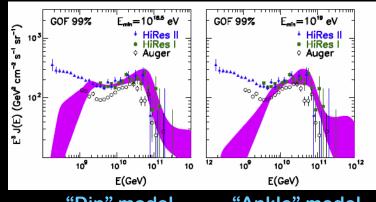
The region of the main GZK ν intensity

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

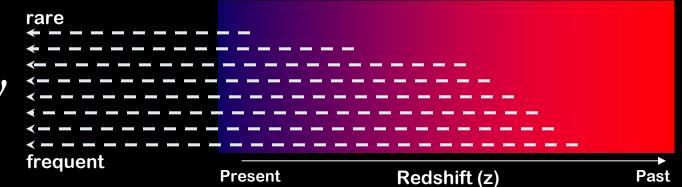
"Ankle" model

Tracing *history* of the particle emissions with v flux

color: emission rate of ultra-high energy particles

Intensity gets higher if the emission is more active in the past

because v beams are penetrating over cosmological distances



The cosmological evolution

Many indications that the past was more active.

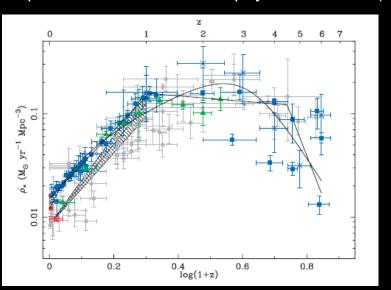
Star formation rate →

The spectral emission rate

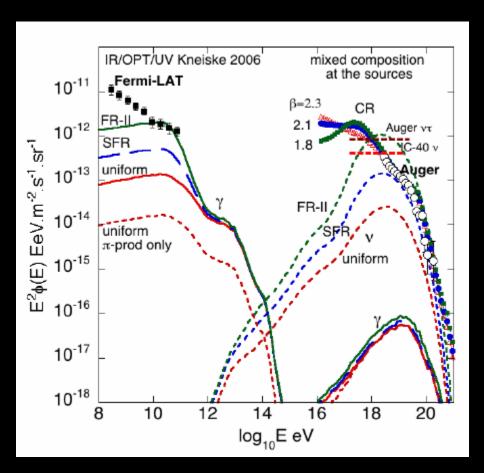
$$\rho(z) \sim (1+z)^{m}$$

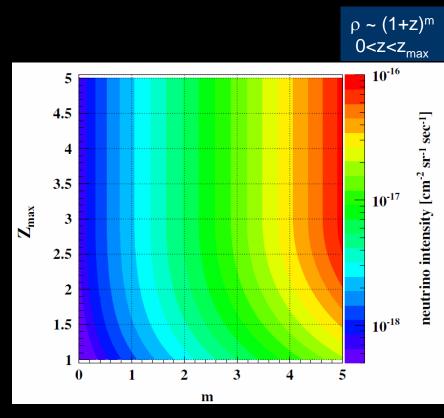
m= 0: No evolution

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

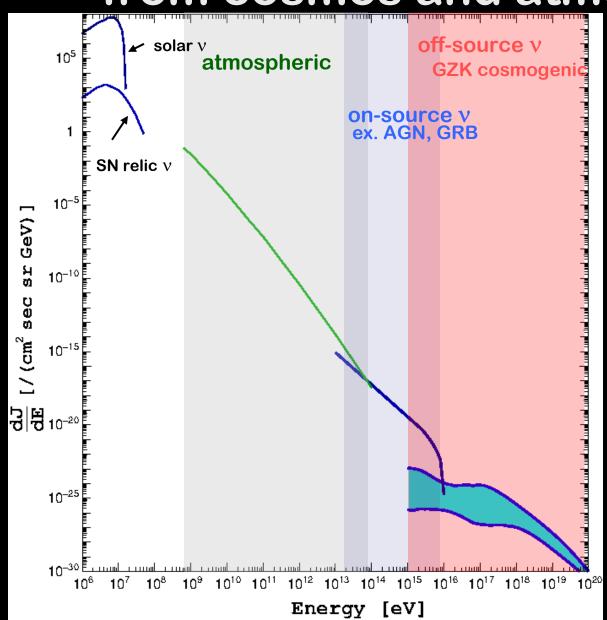


Tracing *history* of the particle emissions with v flux

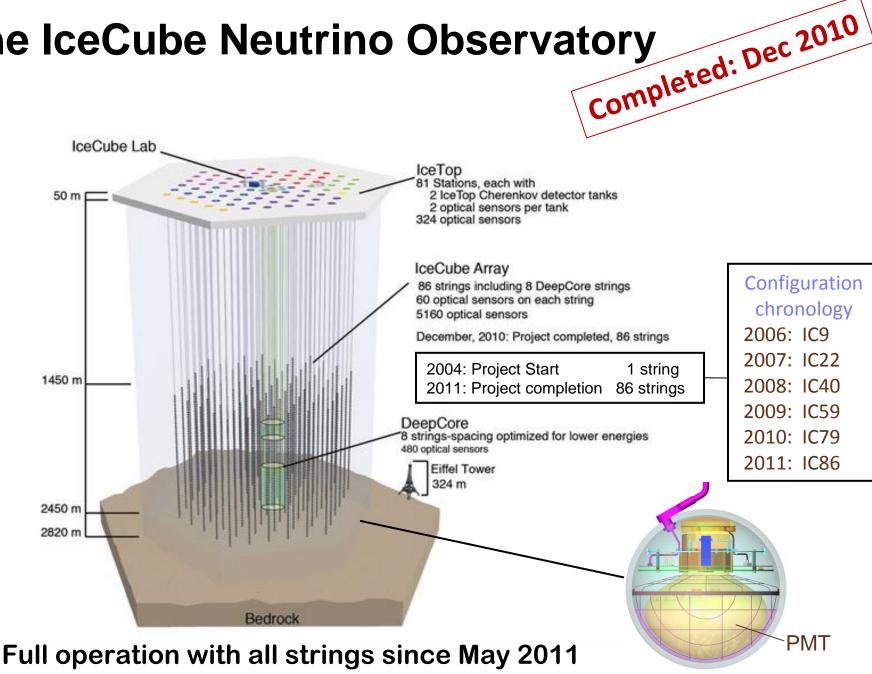




The v spectra from cosmos and atmosphere



The IceCube Neutrino Observatory



Digital Optical Module (DOM)

The IceCube Collaboration



Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alabama
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison

Stockholm University Uppsala Universitet **Deutsches Elektronen-Synchrotron** Humboldt Universität University Ruhr-Universität Bochum **RWTH Aachen University** Technische Universität München University of Oxford Universität Bonn Universität Dortmund Universität Mainz Université Libre de Bruxelles LUniversität Wuppertal Université de Mons University of Gent **Ecole Polytechnique** Vrije Universiteit Brussel Fédérale de Lausanne University of Geneva University of University of Canterbury

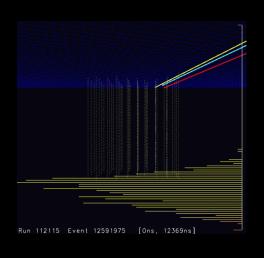
International Funding Agencies

University of Wisconsin-River Falls

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)

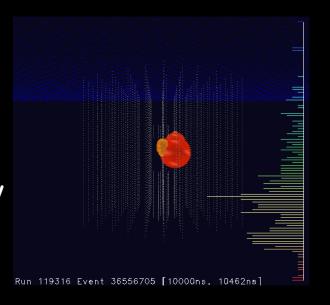


Topological signatures of lceCube events



Down-going track

- atmospheric μ
- secondary produced $\mu \text{ from } \nu_{\mu}$ $\tau \text{ from } \nu_{\tau} \text{ @ >> PeV}$



Run 113641 Event 33553254 [6000ns, 9952ns]

Up-going track

• atmospheric v_{μ}

Cascade (Shower) directly induced by v inside the detector volume

- via CC from ν_e
- via NC from v_e, v_μ, v_τ

all 3 flavor sensitive



The dataset

"IC86"

9 strings (2006)

22 strings (2007)

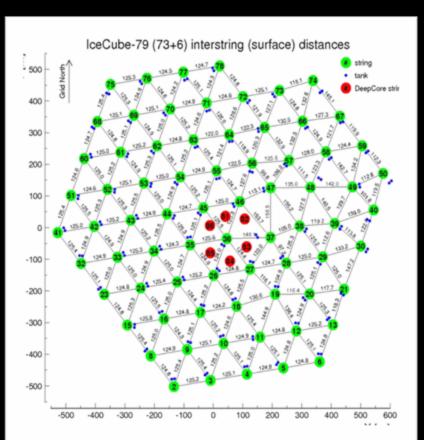
published \rightarrow 40 strings (2008) PRD 83 092003 (2011) 59 strings (2009)

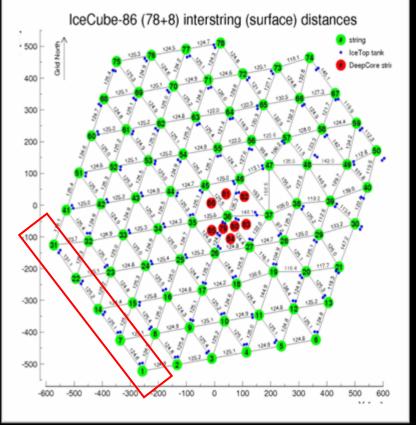
79 strings (2010)

86 strings (2011)

"IC79"

2010-2011 - 79 strings May/31/2010-May/12/2011 Effective livetime 319.18days 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 <u>IceCube</u>

Simple Majority Trigger 8 folds with 5 μ sec

"2nd level" trigger

~ 2.8 kHz

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

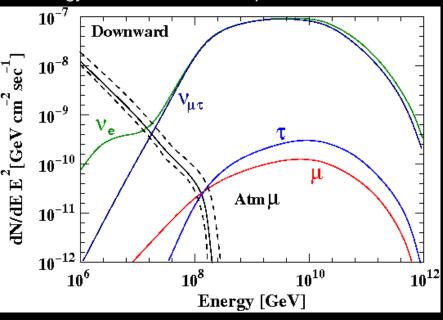
To Northern Hemisphere

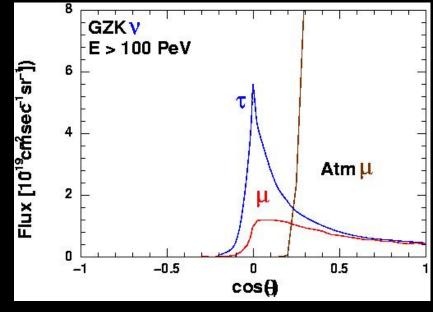




Ultra-high Energy v search

Energy Dist. @ IceCube Depth Detection Principle Zenith Dist. @ IceCube Depth





through-going track Secondary μ and τ from ν

ightarrow Sensitive to $ightarrow_{\mu}$ $ightarrow_{\mu}$ starting track/ cascade

Directly induced events from $\boldsymbol{\nu}$

 \rightarrow Sensitive to $v_e v_\mu v_\tau$

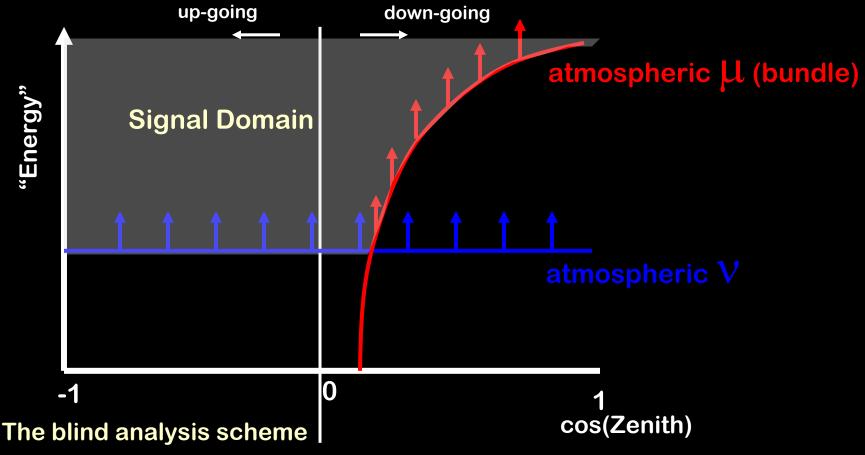
Yoshida et al PRD 69 103004 (2004)

And tracks arrive horizontally





Ultra-high Energy v search Detection Principle



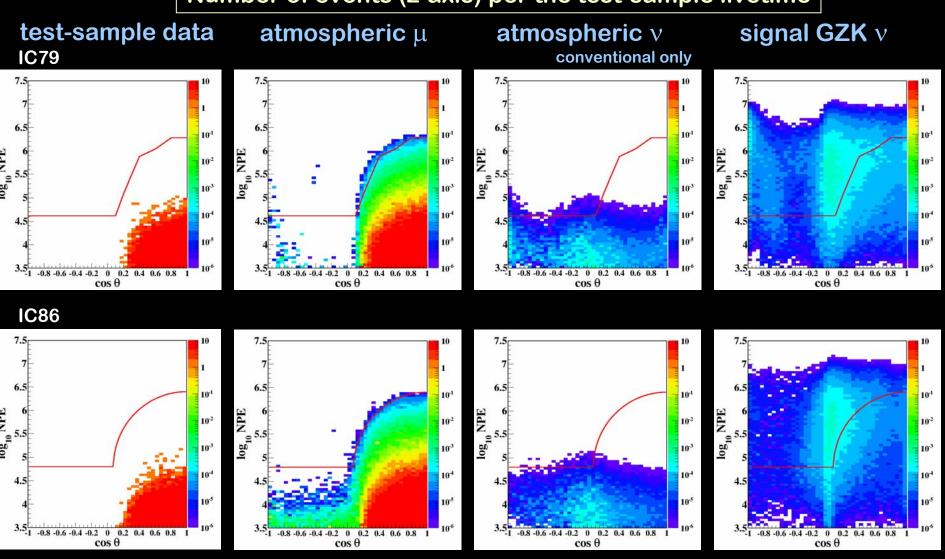
Use 10% of the data (test-sample) with masking the rest of them in optimizing the search algorithm with MC simulation



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





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 v

Signal MC

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 1.04 x 10⁶

 2.11×10^6

3.26

NPE>3,200 NDOM>300

zenith angle reconstruction

Note: assuming the pure Fe UHECR

yielding the higher rate - See the following slides

Final level

+56.7% 0.050- 94.3%

1.92 +13.6%

> NPE^{threshold}(cos(zenith))

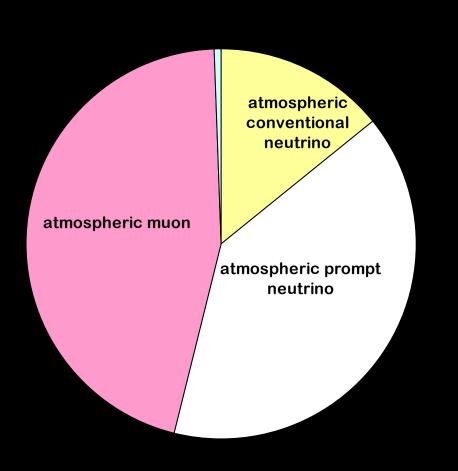
NPE cos(Zenith) conventional only

0.082

plus the atmospheric prompt V



Background Breakdown



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



The systematic uncertainties on the BG rate

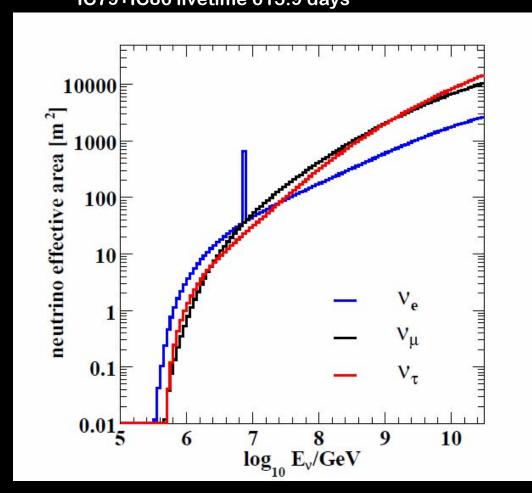
remarks

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
∨ yield from cosmic-ray nucleon	+2.2% - 2.2%	The Elbert model
prompt v model	+12.6% - 16.1%	The Enberg model perturbative-QCD



Effective Areas

Area x v flux x 4π x livetime = event rate IC79+IC86 livetime 615.9 days



V_{e} larger below 10 PeV due to effective energy deposition

by showers

 $v^{\mu \tau}$ 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)

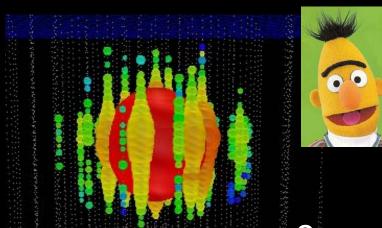
The Expected Backgrounds

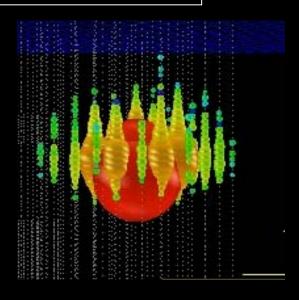
including prompt $0.082^{+0.041}_{-0.057}$

conventional only 0.050 +0.028 - 0.047

p-value 2.9x10⁻³ (2.8σ)

p-value $9.0x10^{-4}$ (3.1 σ)





Super-nicely contained cascades!

Run118545-Event63733662 August 9th 2011 ("**Bert**") NPE 6.9928x10⁴

Number of Optical Sensors 354

Run119316-Event36556705 Jan 3rd 2012 ("**Ernie**")

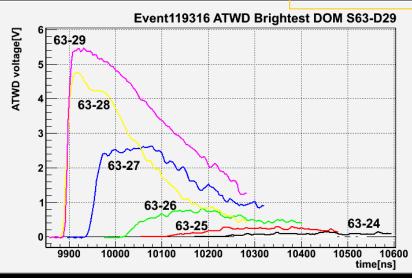
NPE 9.628x10⁴

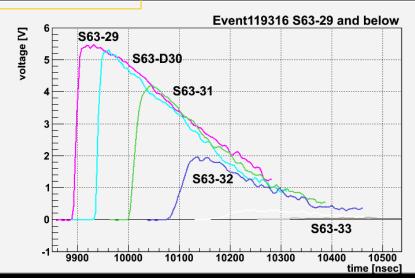
Number of Optical Sensors 312



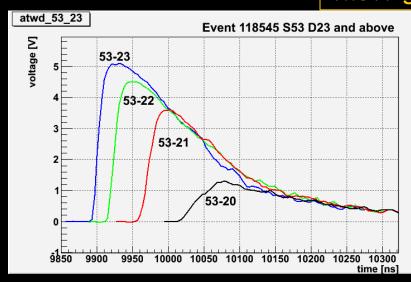
Recorded pulses Clean and luminous bulk of photons !!

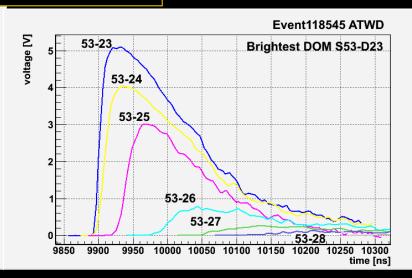
The Jan 2012 event - Ernie





The Aug 2011 event - Bert



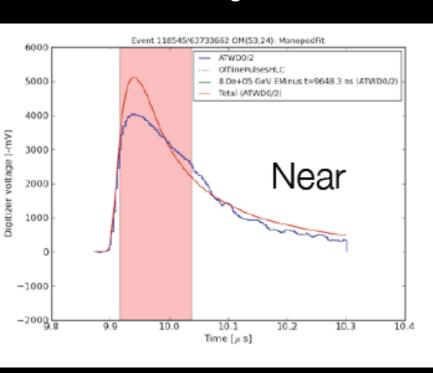


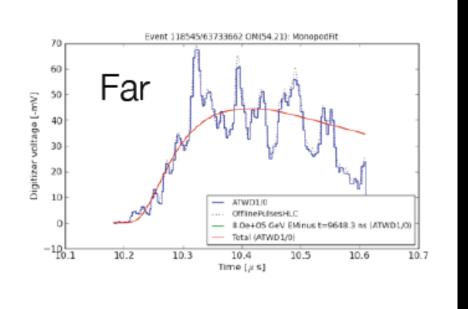




What are their energies?

Maximizing the Poisson likelihood based on the recorded waveforms





Estimated Energy Deposit

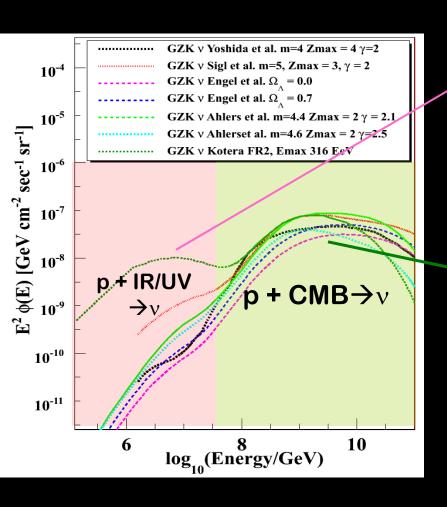
+- 15% accuracy

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

A PeV shower



The GZK cosmogenic v?



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 **v**
- EeV (=10⁹ GeV) is the key energy region



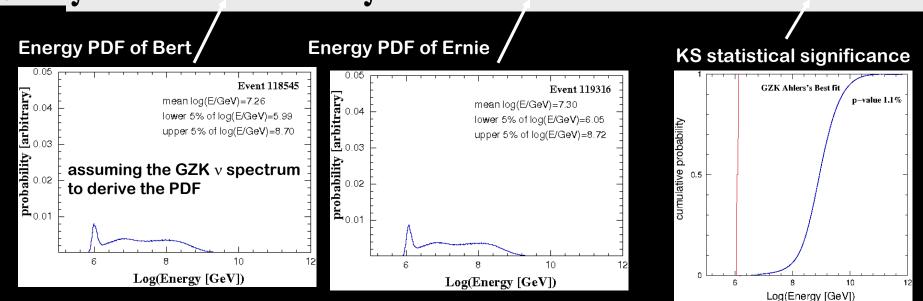
The KS Test

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

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



The standard GZK

The low energy GZK

p-value 7.5x10⁻²

p-value 3.9x10⁻²

inconsistent at >90% C.L.



Summarized statements on the origin of the 2 events

if astrophysical (very likely, but not conclusive)

They are unlikely to be GZK cosmogenic

v 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

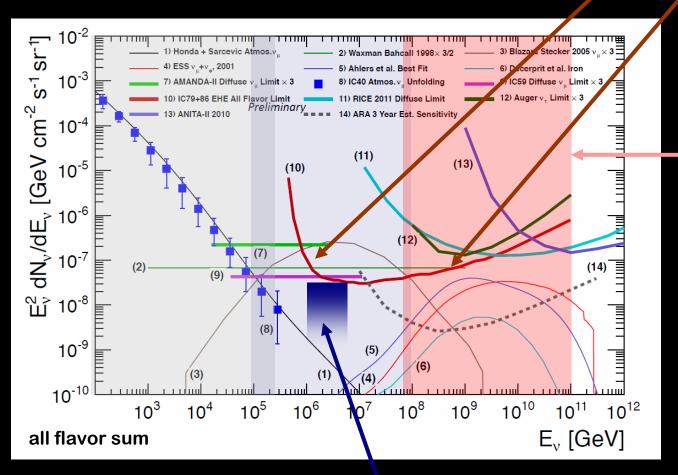
V_{e+μ+τ} intensity of ~ 10⁻⁸ GeV/cm2 sec sr

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

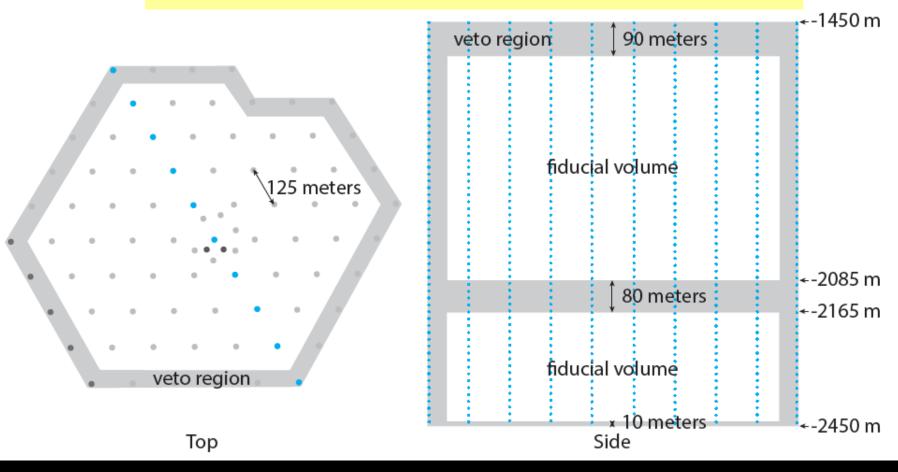
- radio-loud AGN jets
- m>4 for (1+z)m
- \bullet emission maximally allowed by the Fermi γ

Bert & Ernie 2.8 σ excess over atmospheric



A search for events originated within the detector interior

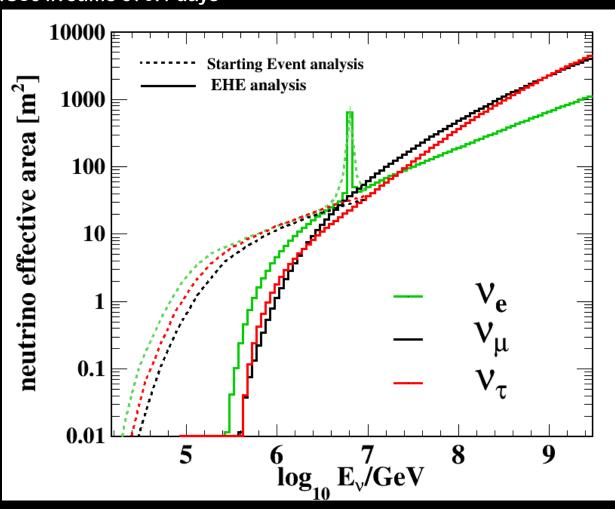
look for only events with their interaction vertices within the fiducial volume





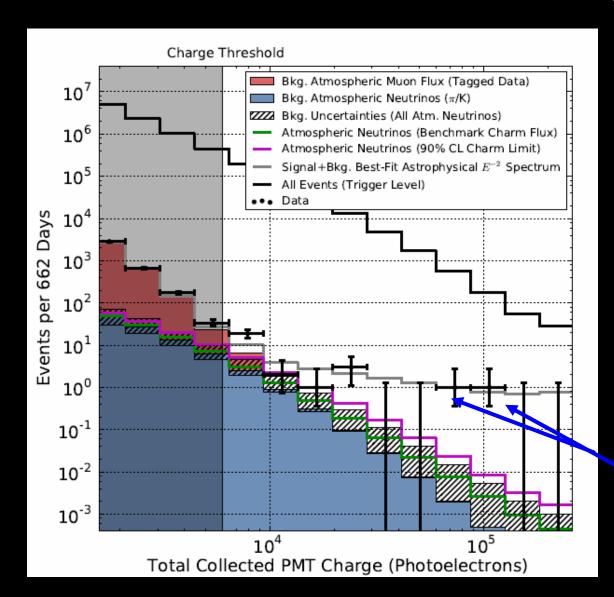
Effective Areas expanding down to 100 TeV's

Area x v flux x 4π x livetime = event rate IC79+IC86 livetime 670.1 days





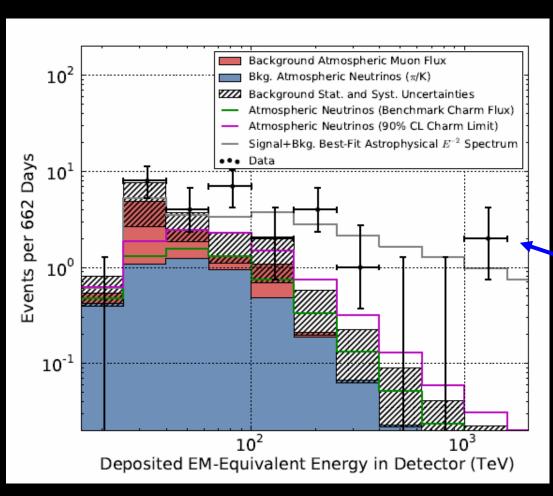
sub-PeV v samples



Bert & Ernie



sub-PeV v samples



28 events observed against bg of 10.6 +5.0

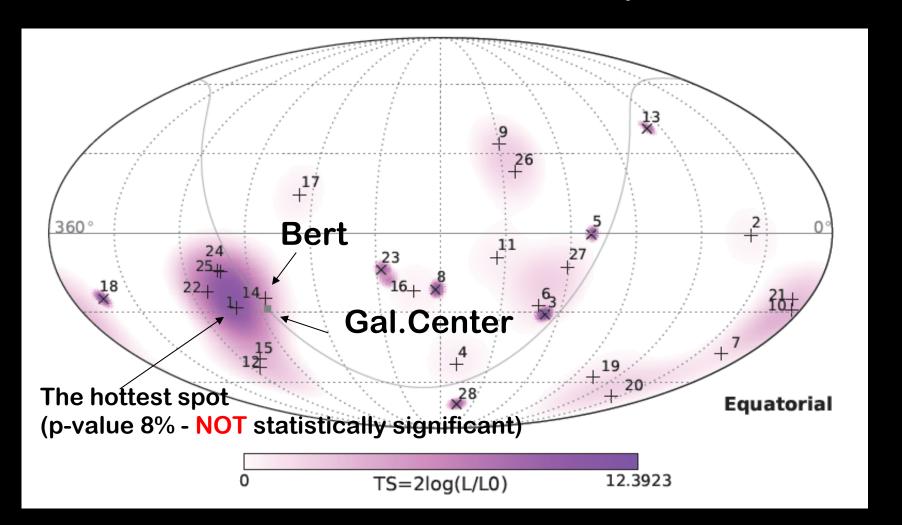
 $(4.1\sigma \text{ excess})$

Bert & Ernie

$$E^2 \oint_{\text{C}} (E) \sim (3.6^{+}1.2) \times 10^{-8}$$
 [GeV/cm² sec sr]



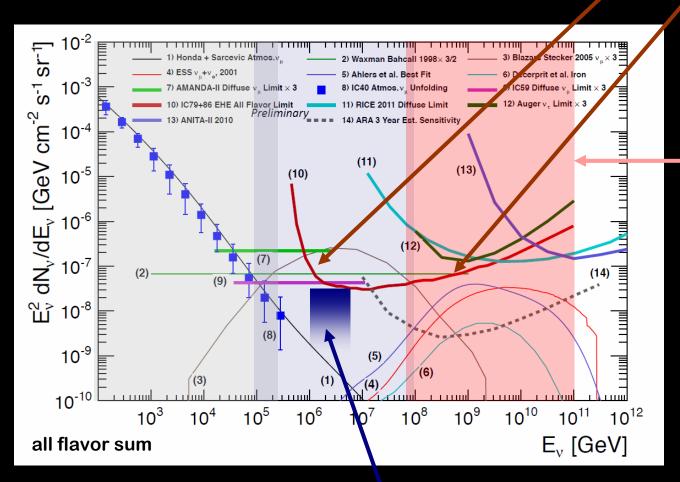
sub-PeV v samples





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
- \bullet emission maximally allowed by the Fermi γ

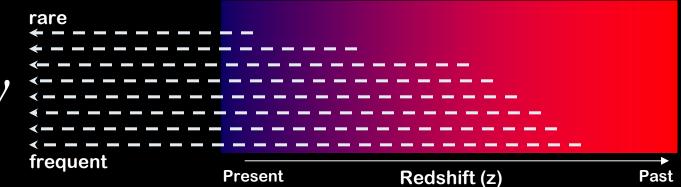
Bert & Ernie + O(10) sub-PeV events
4.1 σ excess over atmospheric

Tracing *history* of the particle emissions with v flux

color: emission rate of ultra-high energy particles

Intensity gets higher if the emission is more active in the past

because v beams are penetrating over cosmological distances



The cosmological evolution

Many indications that the past was more active.

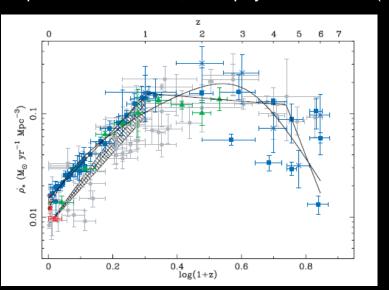
Star formation rate →

The spectral emission rate

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

m= 0: No evolution

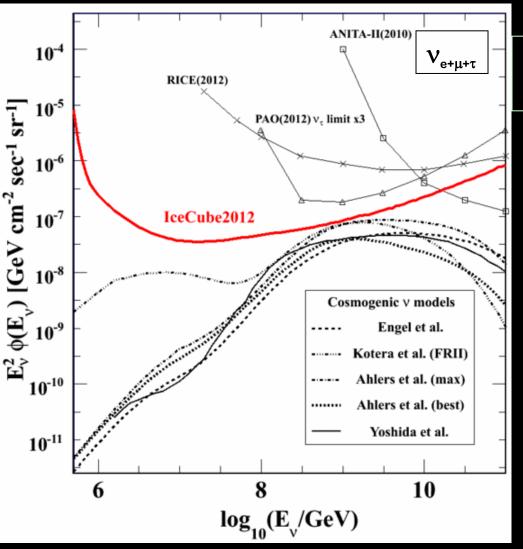
Hopkins and Beacom, Astrophys. J. 651 142 (2006)





Constraints on UHECR origin

The model-independent upper limit on flux



any model adjacent to the limit is disfavored by the observation

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

 $6x10^7 \text{ m}^2 \text{ days sr } @ 1\text{EeV}$ = $0.2 \text{ km}^2 \text{ sr year}$

(6 x Auger v_{τ} exposure)

Note: $\phi_{CR}(>1EeV) \sim 20/km^2 \text{ sr year}$

v 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

V Model	GZK Y&T m=4,zmax=4	GZK SigI 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	1.4x10 ⁻¹	4.6x10 ⁻²	2.2x10 ⁻¹	4.4x10 ⁻²	5.2x10 ⁻²	6.7x10 ⁻¹	2.1x10 ⁻²

Excluded



Mildly Excluded



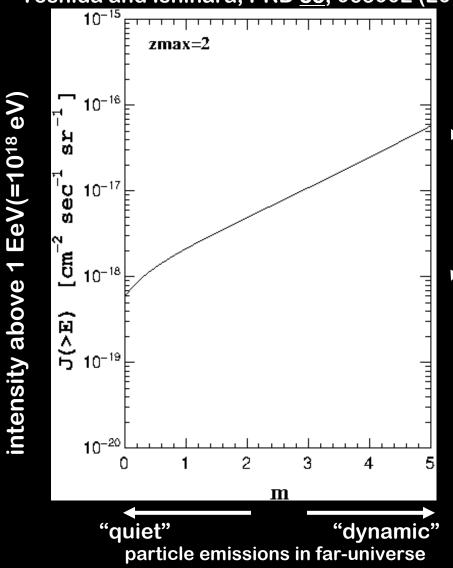
Consistent

Maximal ν flux allowed by the Fermi γ-ray measurement

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

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

Yoshida and Ishihara, PRD 85, 063002 (2012)



more than an order of magnitude difference

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

Yoshida and Ishihara, PRD <u>85</u>, 063002 (2012)

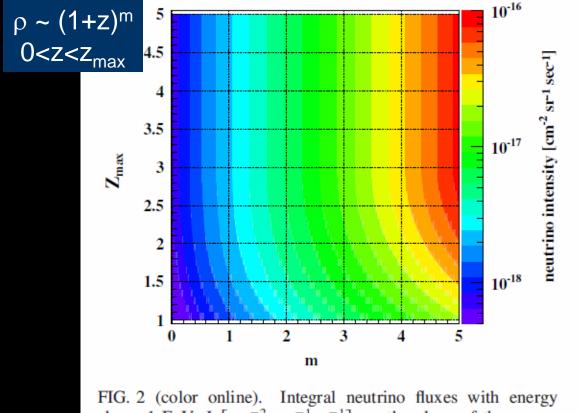
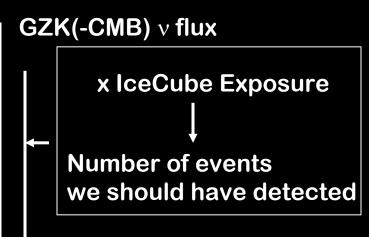


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm⁻² sec⁻¹ sr⁻¹], on the plane of the source evolution parameters, m and z_{max} .



Evolution of UHECR sources

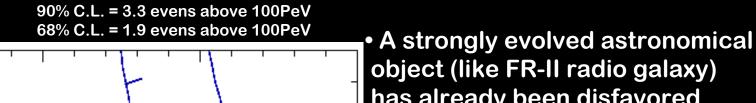
Identify classes of astronomical objects responsible for UHECRs

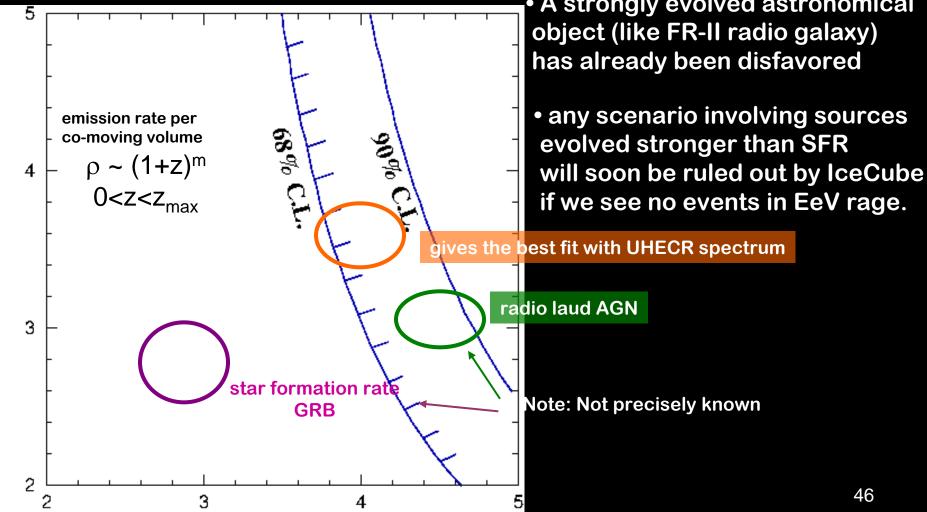


Zmax



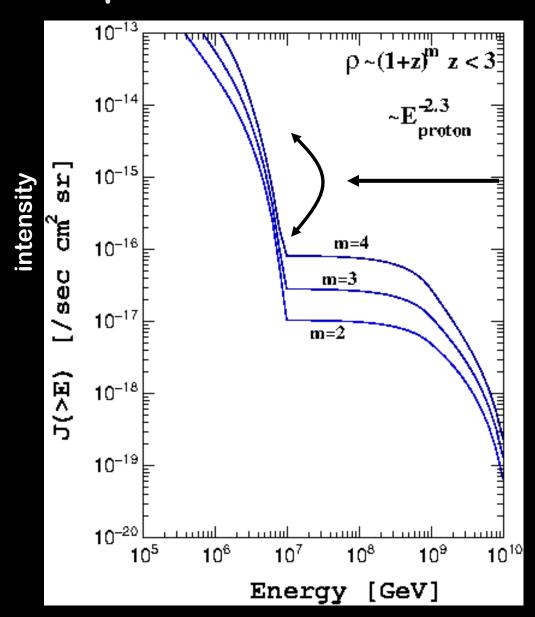
Constraints on the evolution





m

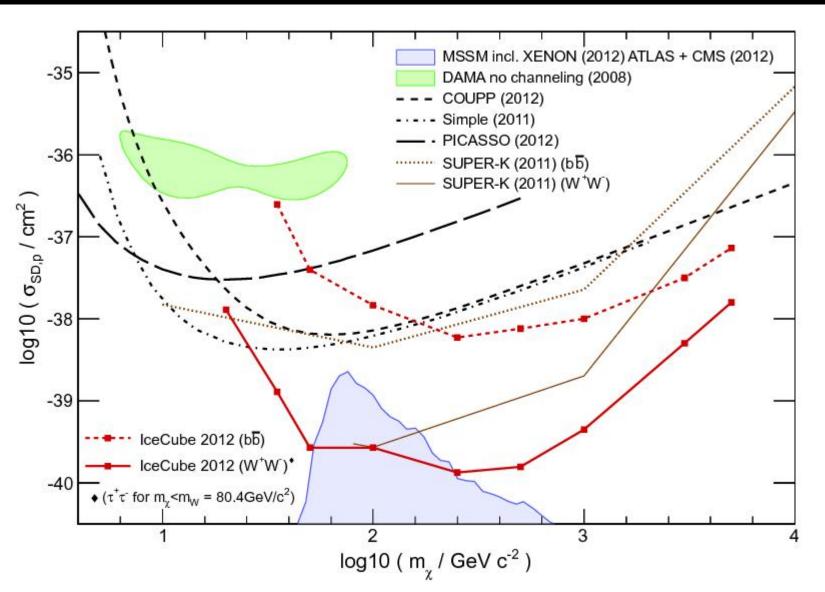
Ultra-high energy v intensity depends on the emission rate in far-universe



more than an order of magnitude difference



WIMP from Sun





WIMP from Sun

