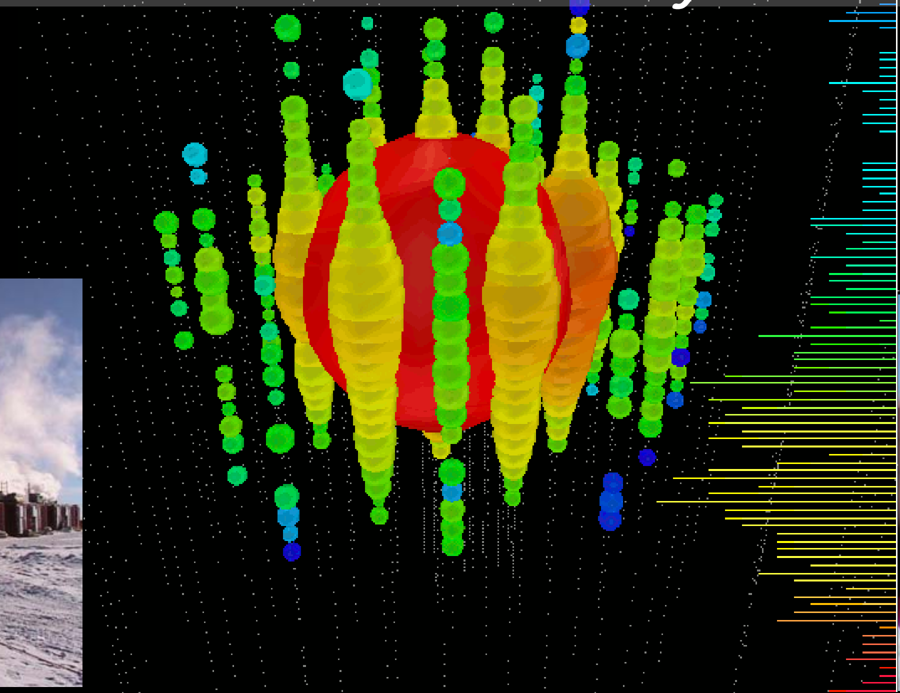
The new messengers from the universe

The 'First Light' of the high energy neutrino astronomy

Shigeru Yoshida

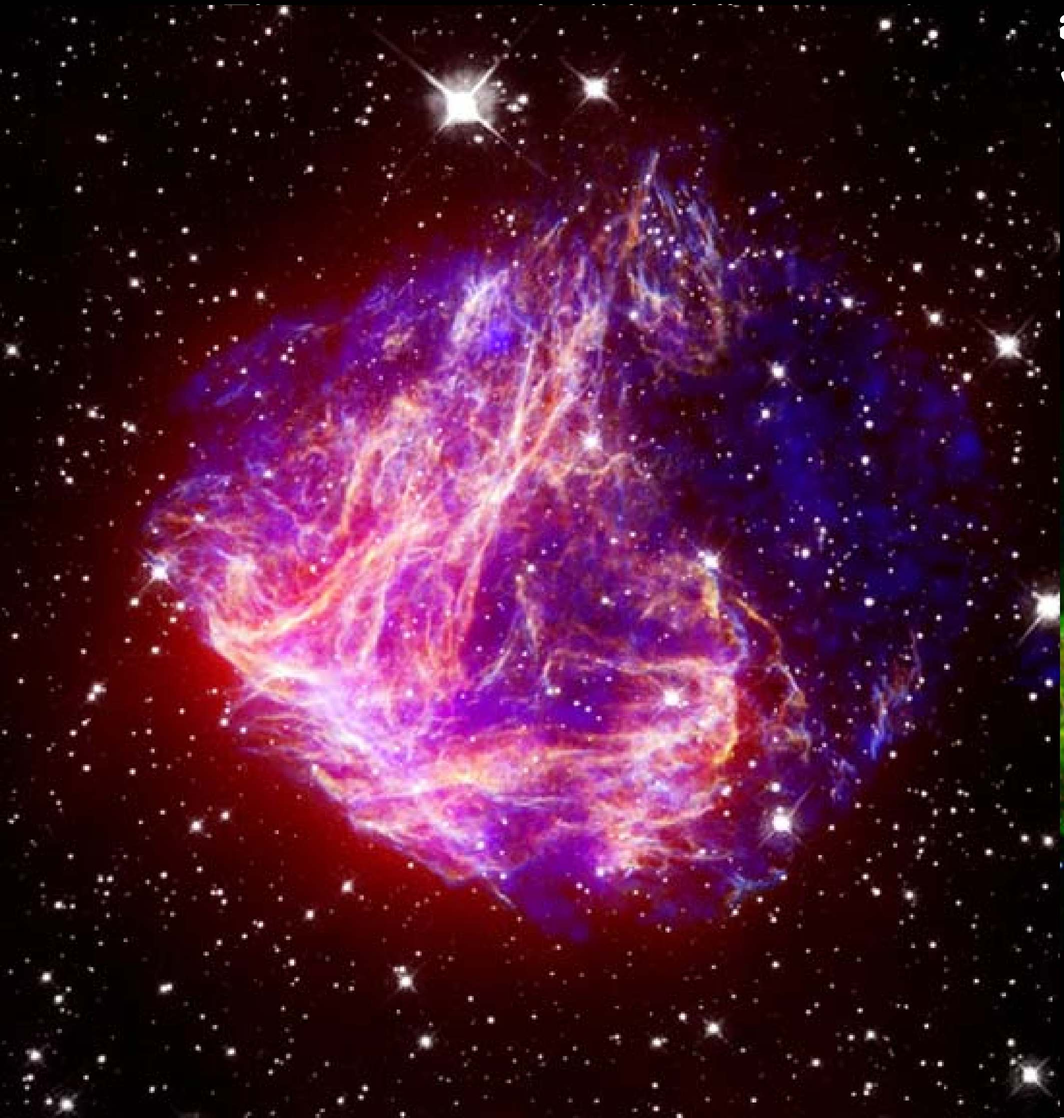
Chiba University



CHIBA UNIVERSITY

ICECUBE

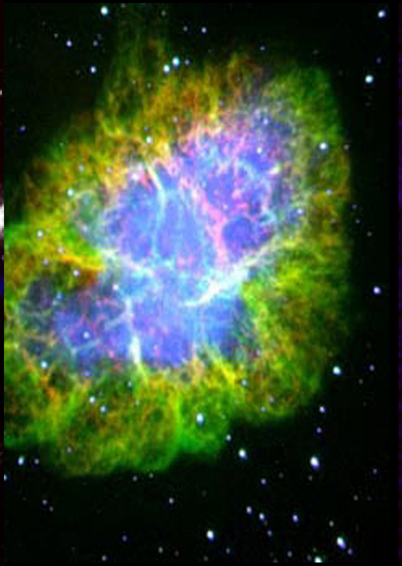
Space explored by *invisibles*



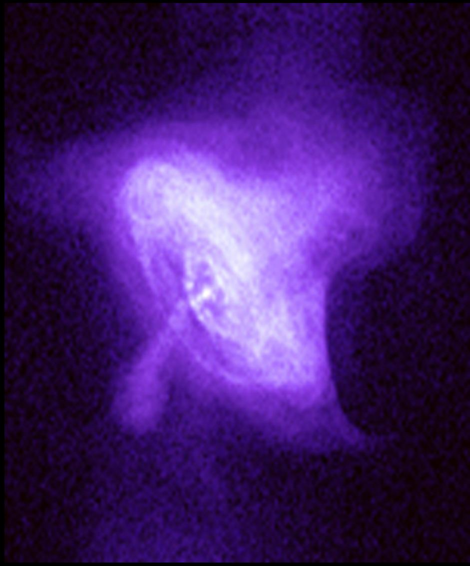
ally filled with so many ‘light’
view

Supernova NA49
white : **visible light**
blue : **x-ray**
red : **infra-red**

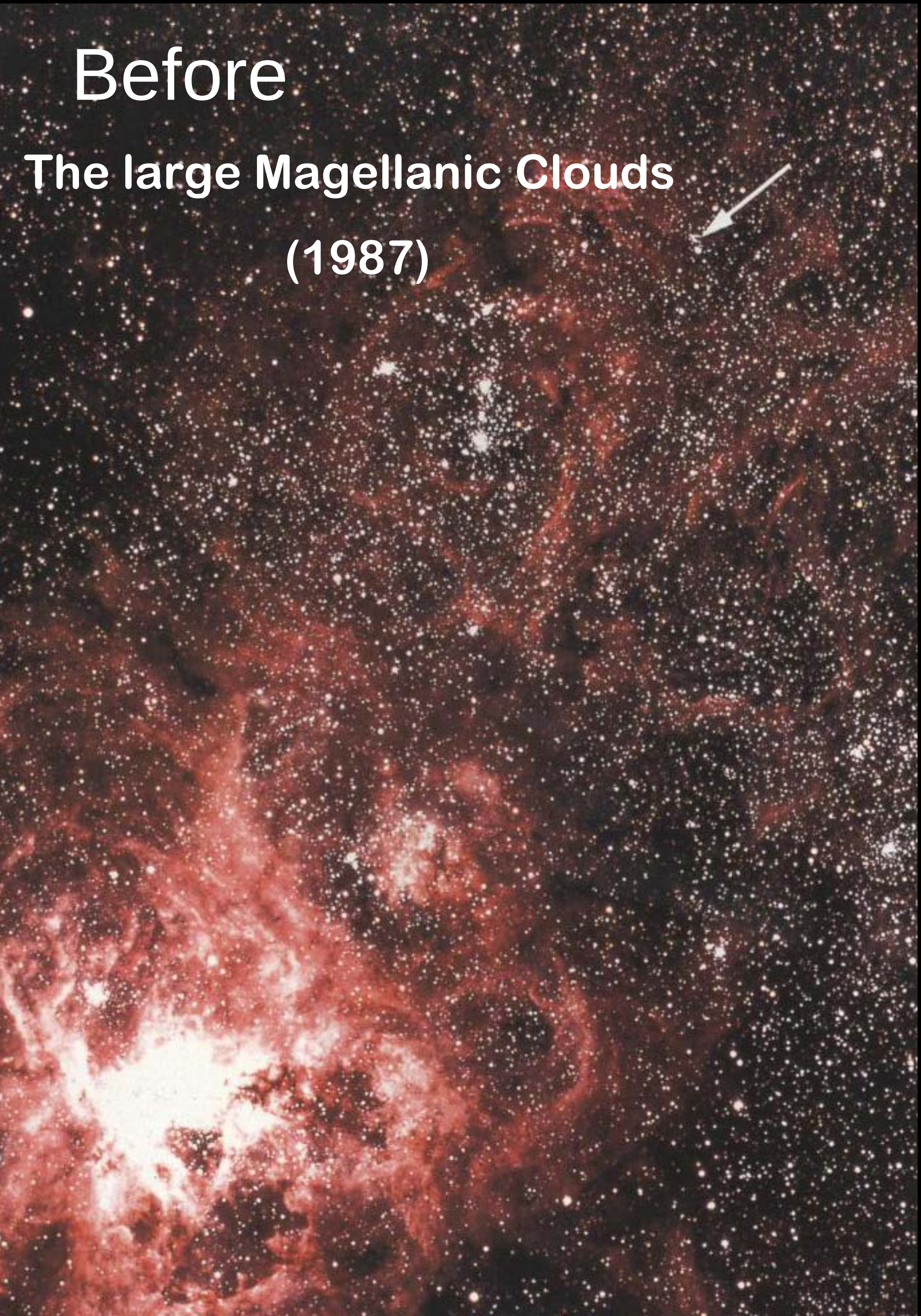
Visible light



X-rays



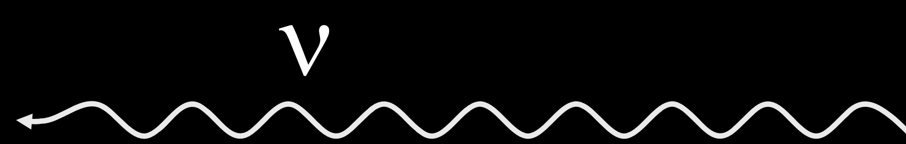
Neutrinos from Supernova



Neutrinos are "ghost" particles

$\sigma_{\nu N}$ = 10^{-38} (E_ν/GeV) cm^2 ~ $10^{-15}\sigma_{Thompson}$

→ $\lambda = (N_A \rho \sigma)^{-1} \sim 10^4 R_{earth}$

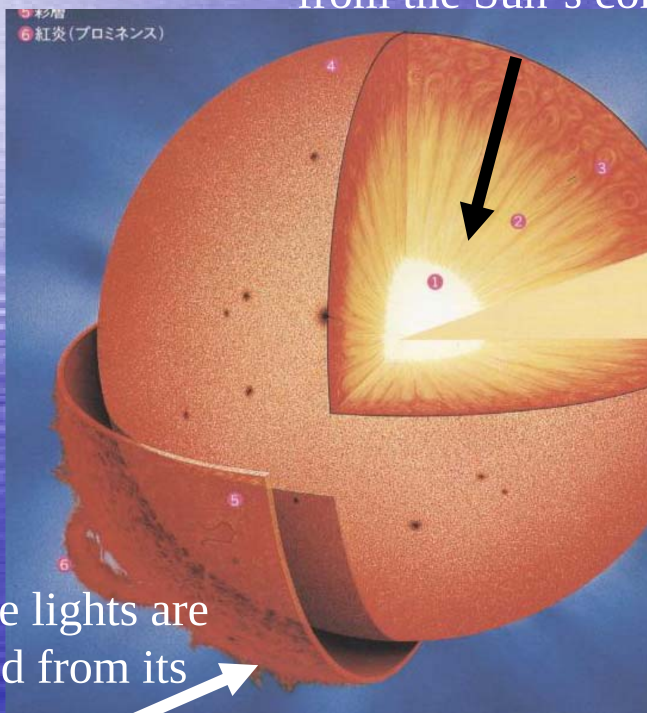


x 10,000 !!

Neutrino Astronomy

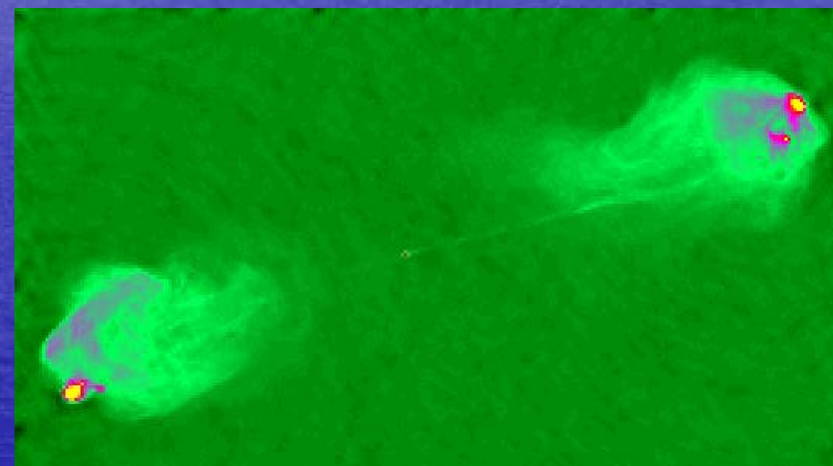
Scan star core

Solar neutrinos come from the Sun’s core



Visible lights are emitted from its surface

Explore the energetic phenomena in the deep universe



VLA image of Cygnus A

The High Energy Neutrino Astronomy

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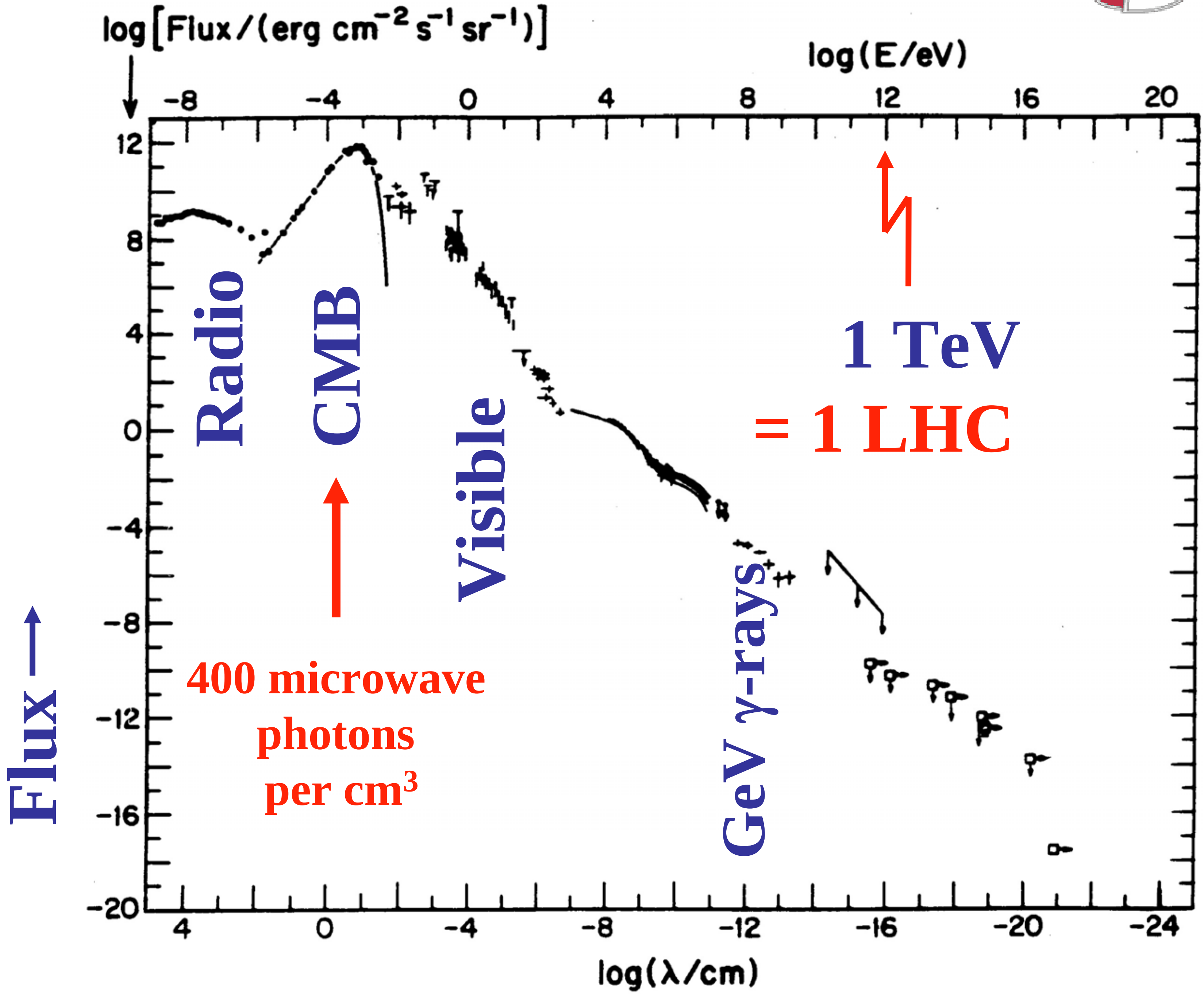


The most energetic universe

The Cosmic Rays

Mostly protons

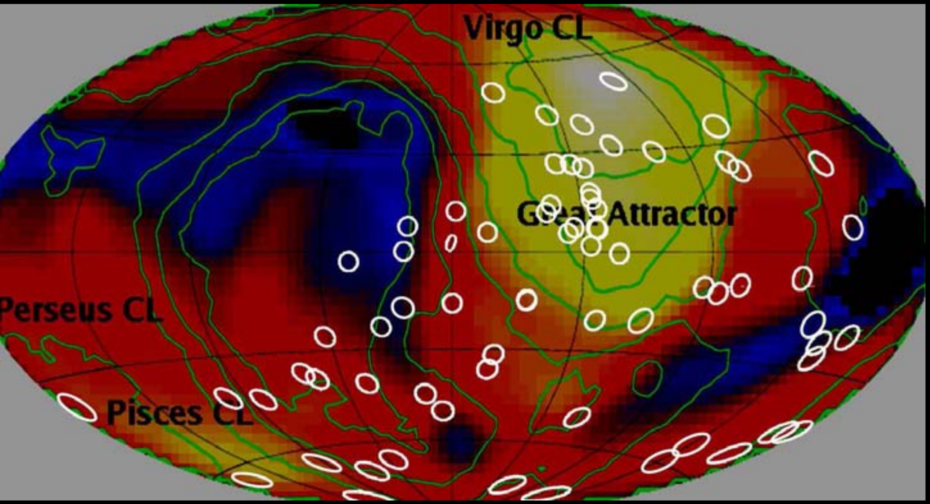
Some light nuculei
He, Li, ...

Heavy nuclei (ex. Fe) *may* dominate at higher energies

Not so sure at
at the highest energy end

Theoretically favors protons

The challenge



No clear correlations…..

Two possibilities

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

   We may not be so smart.

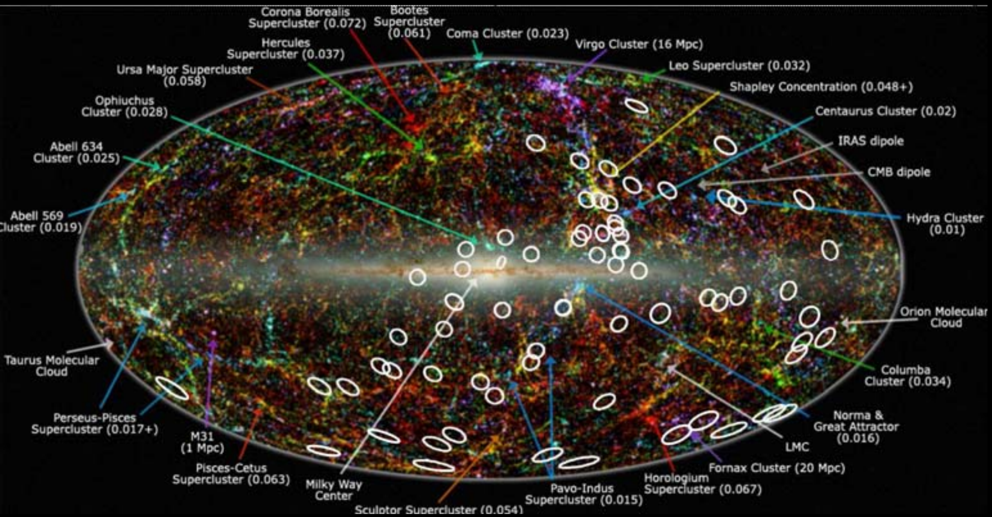
2. Cannot handle pointing them back to their radiation points

   Magnetic field?

   Particle charge?

   Proton or even iron?

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)



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

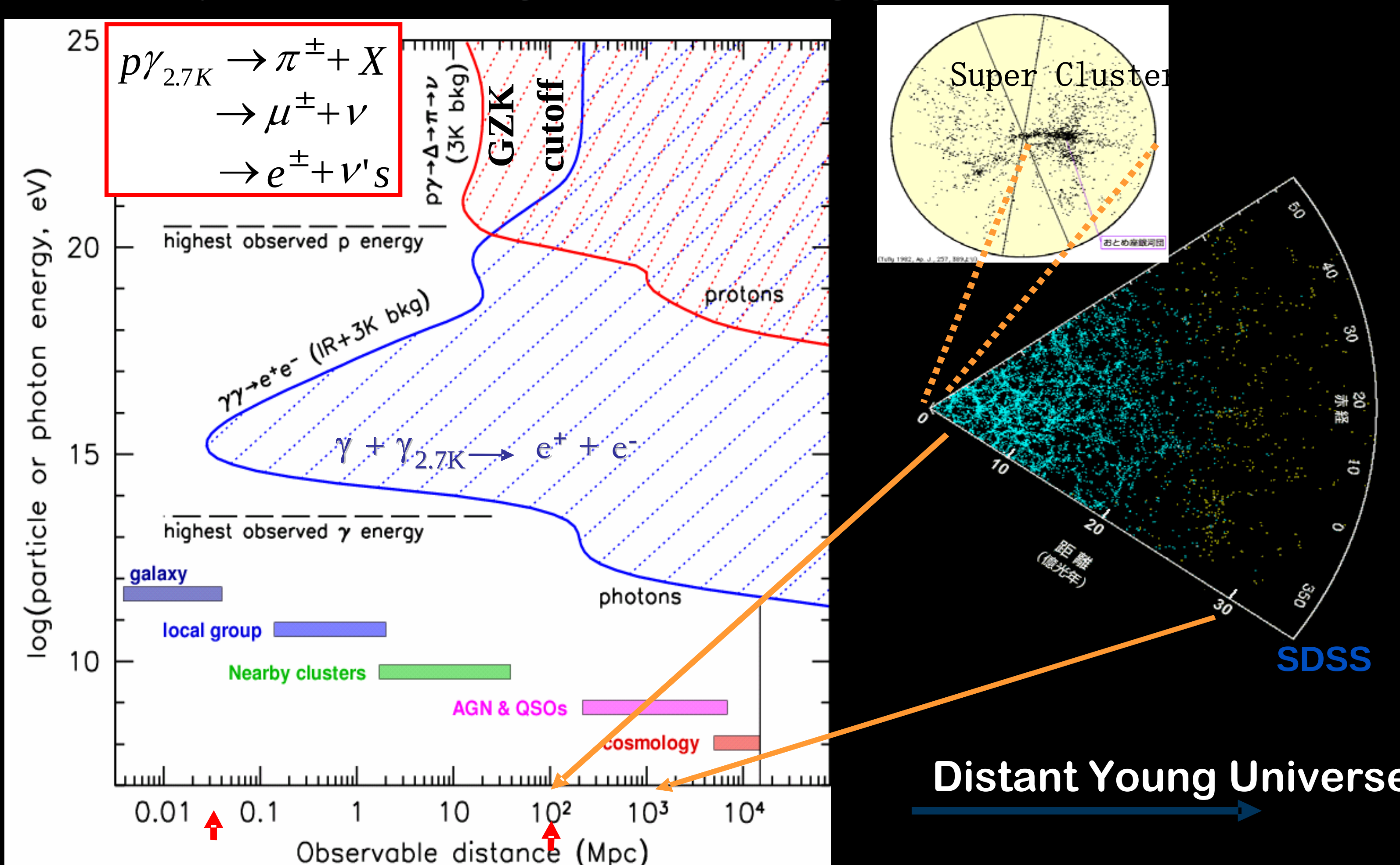
   Highly complementary – ν can travel over a LONG distance

   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

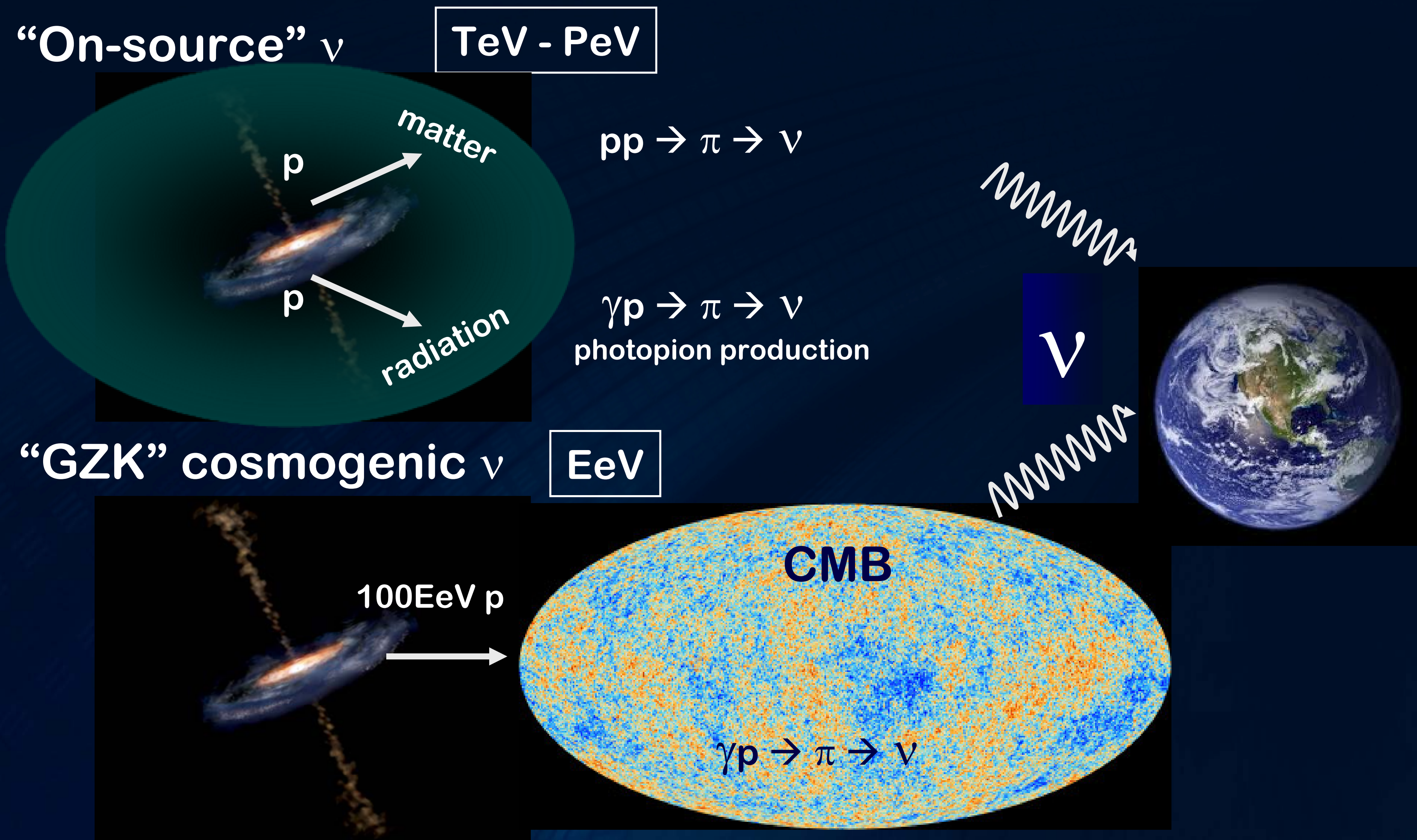
Why ν is so powerful to explore high energy universe?



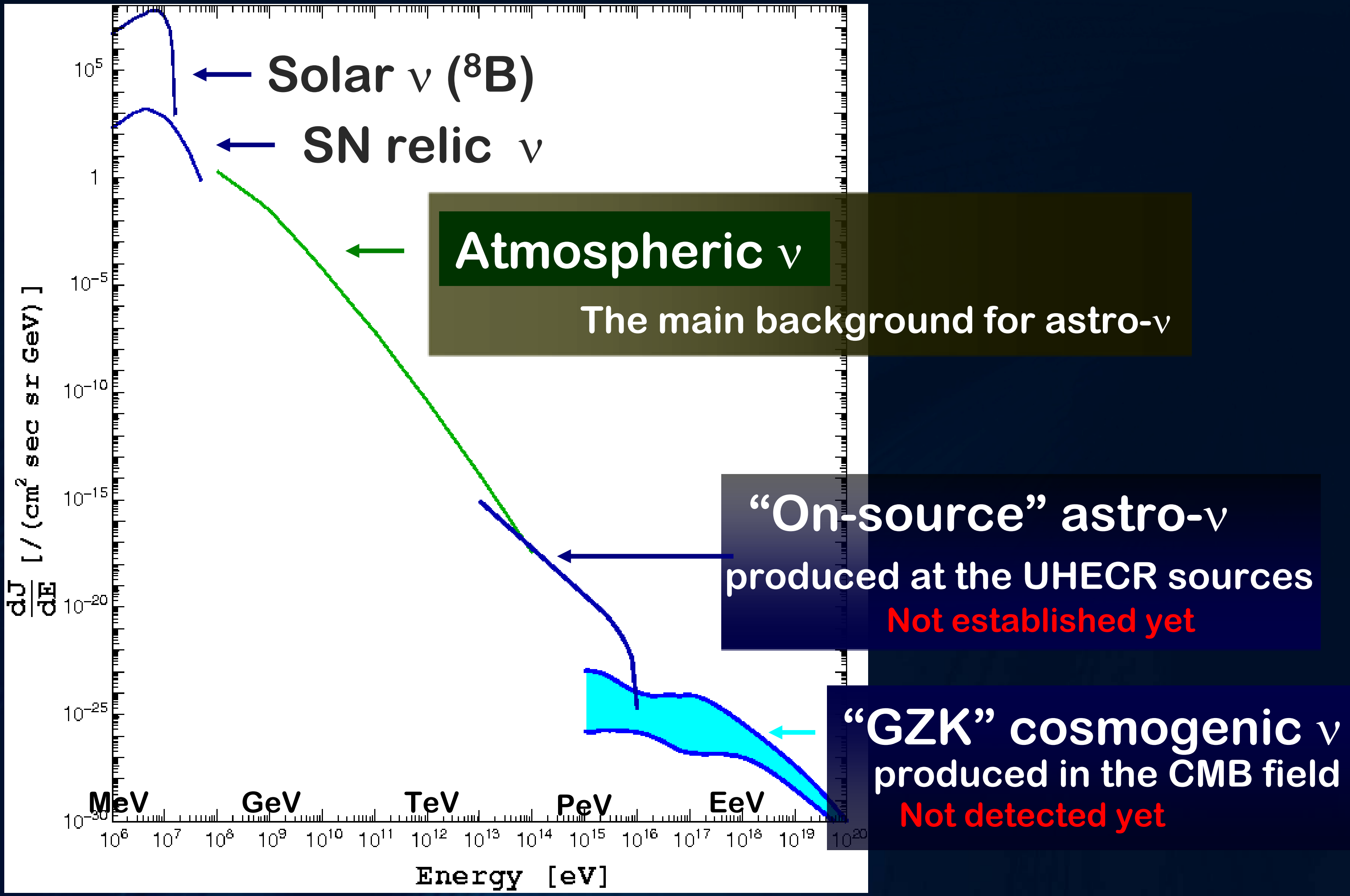
Our Galaxy

Super Cluster

The Cosmic Neutrinos Production Mechanisms

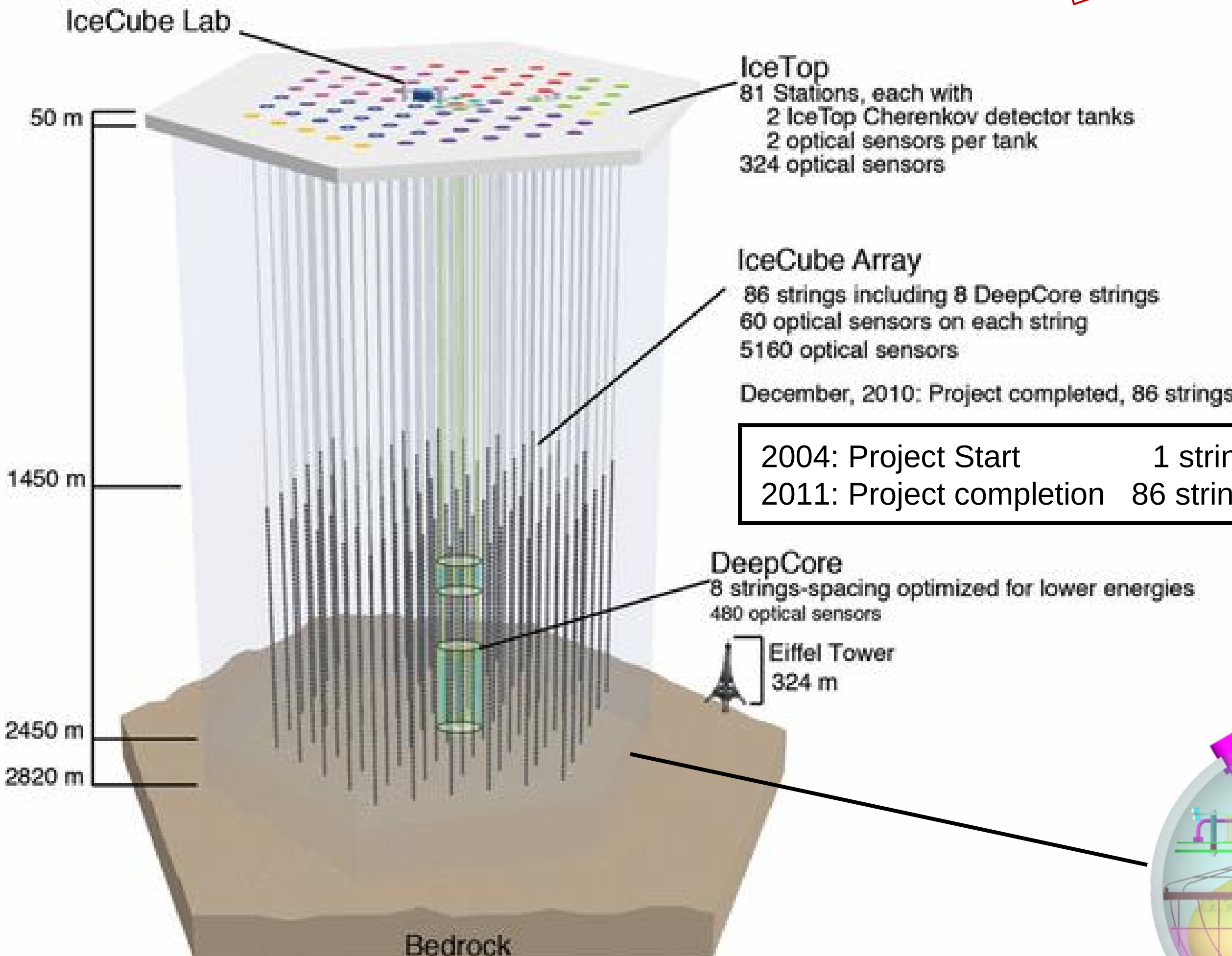


The Neutrino Flux: overview



The IceCube Neutrino Observatory

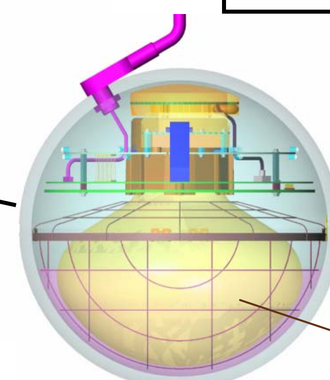
Completed: Dec 2010



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

Configuration chronology

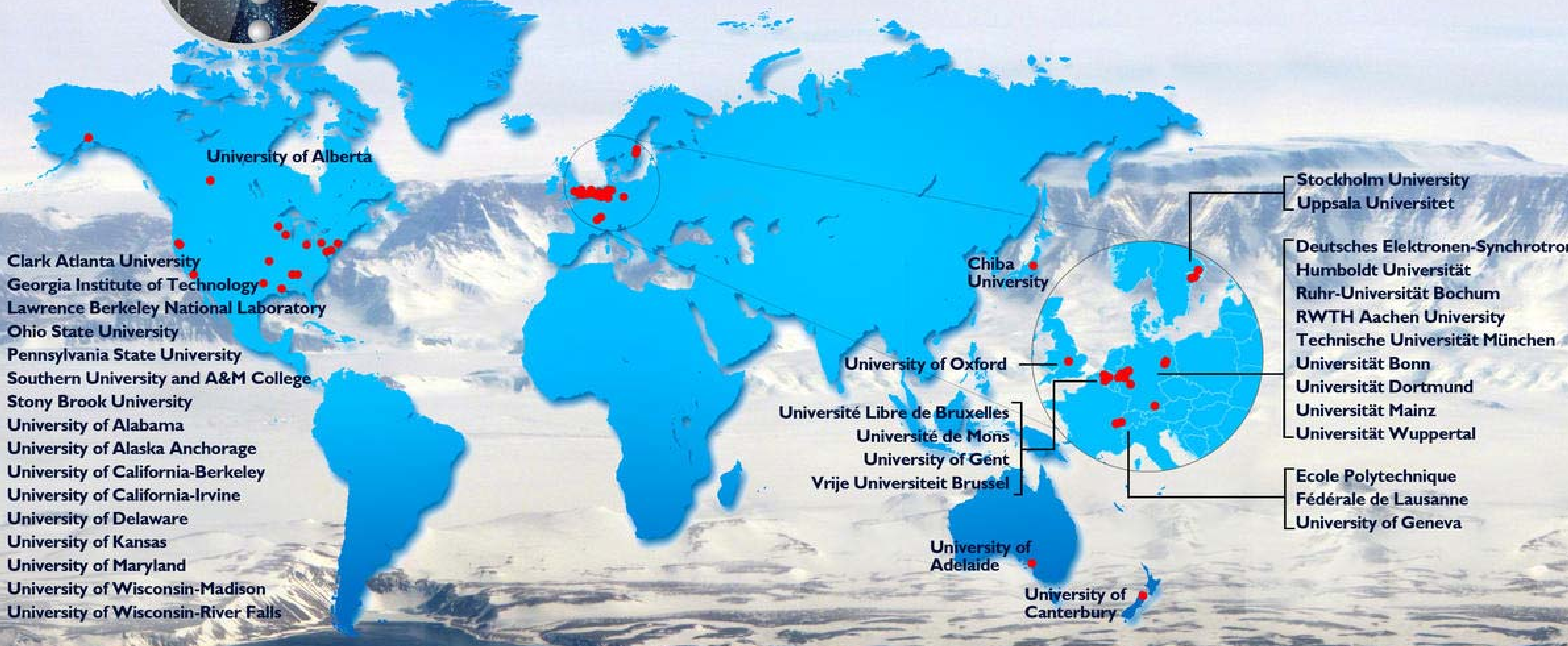
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Digital Optical Module (DOM)

Full operation with all strings since May 2011

The IceCube Collaboration

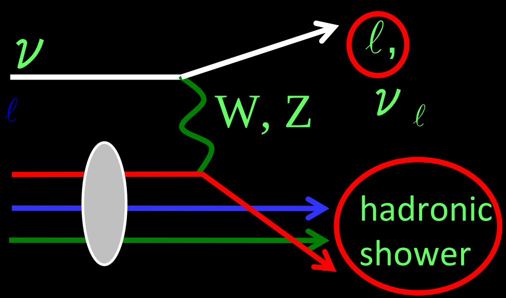


International Funding Agencies

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)

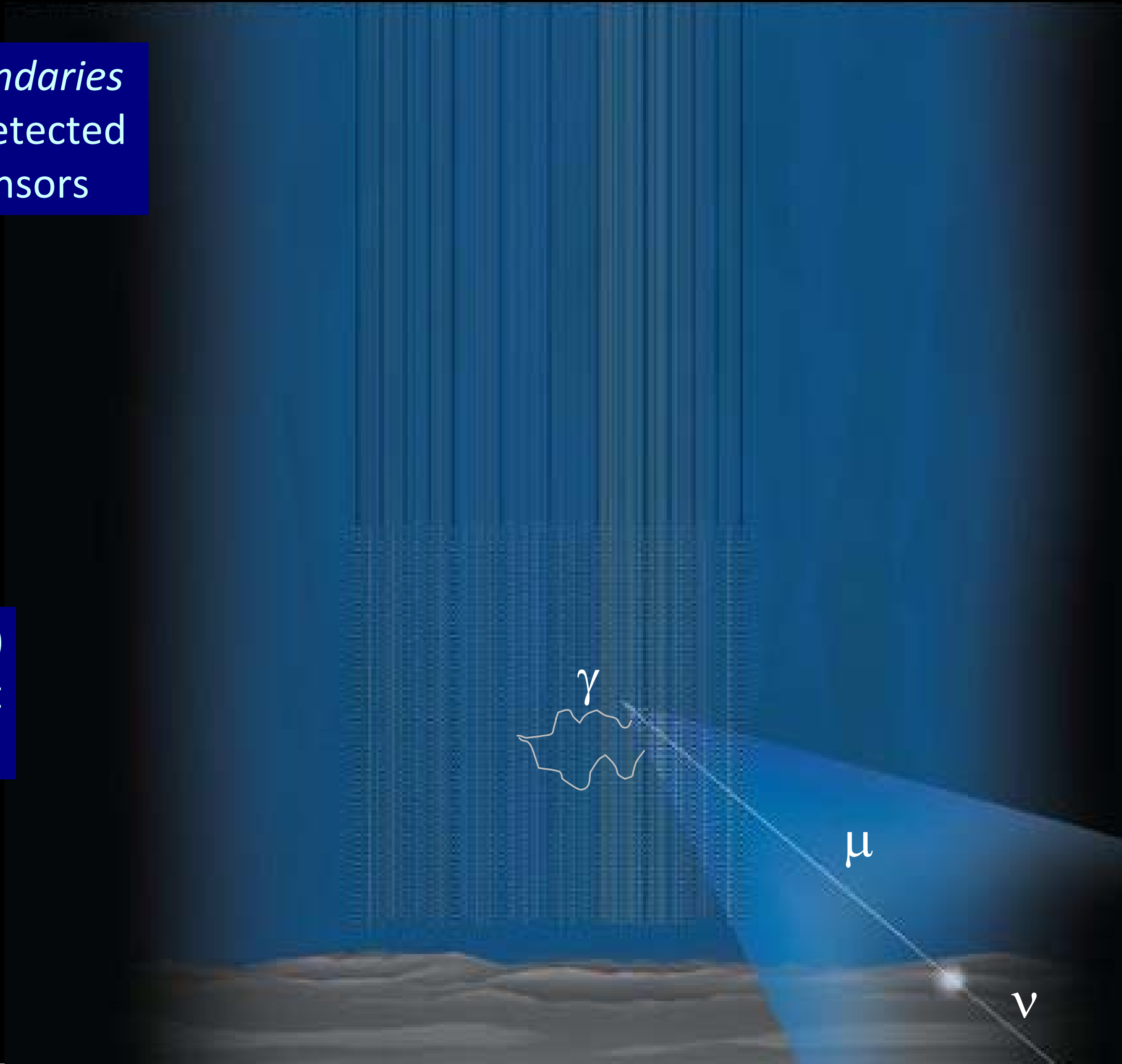
Neutrino Detection Principle

Observe the charged *secondaries* via Cherenkov radiation detected by a 3D array of optical sensors

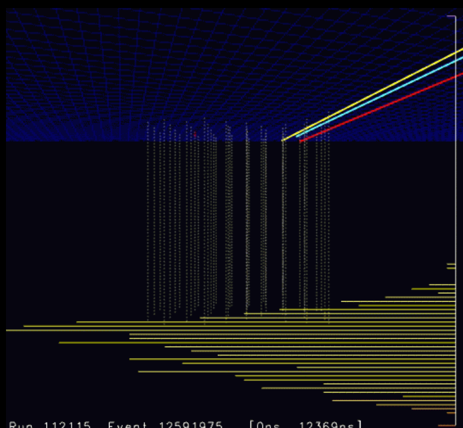


Need a huge volume (km³) of an optically transparent detector material

Antarctic ice is the most transparent natural solid known
(absorption lengths up 200 m)

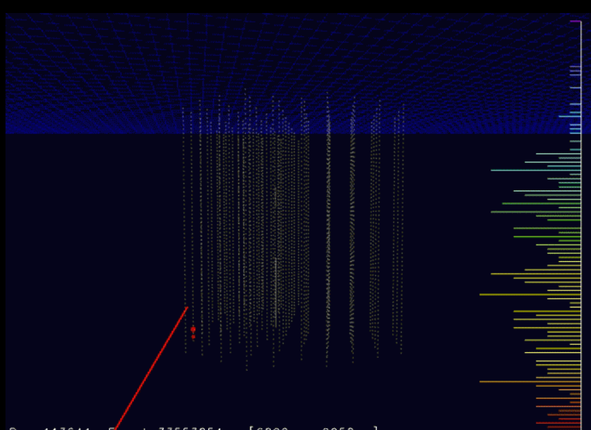


Topological signatures of IceCube events



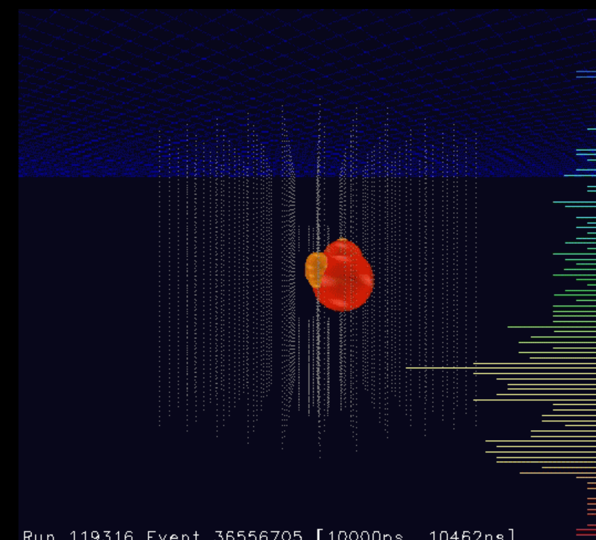
Down-going track

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



Up-going track

- atmospheric ν_μ



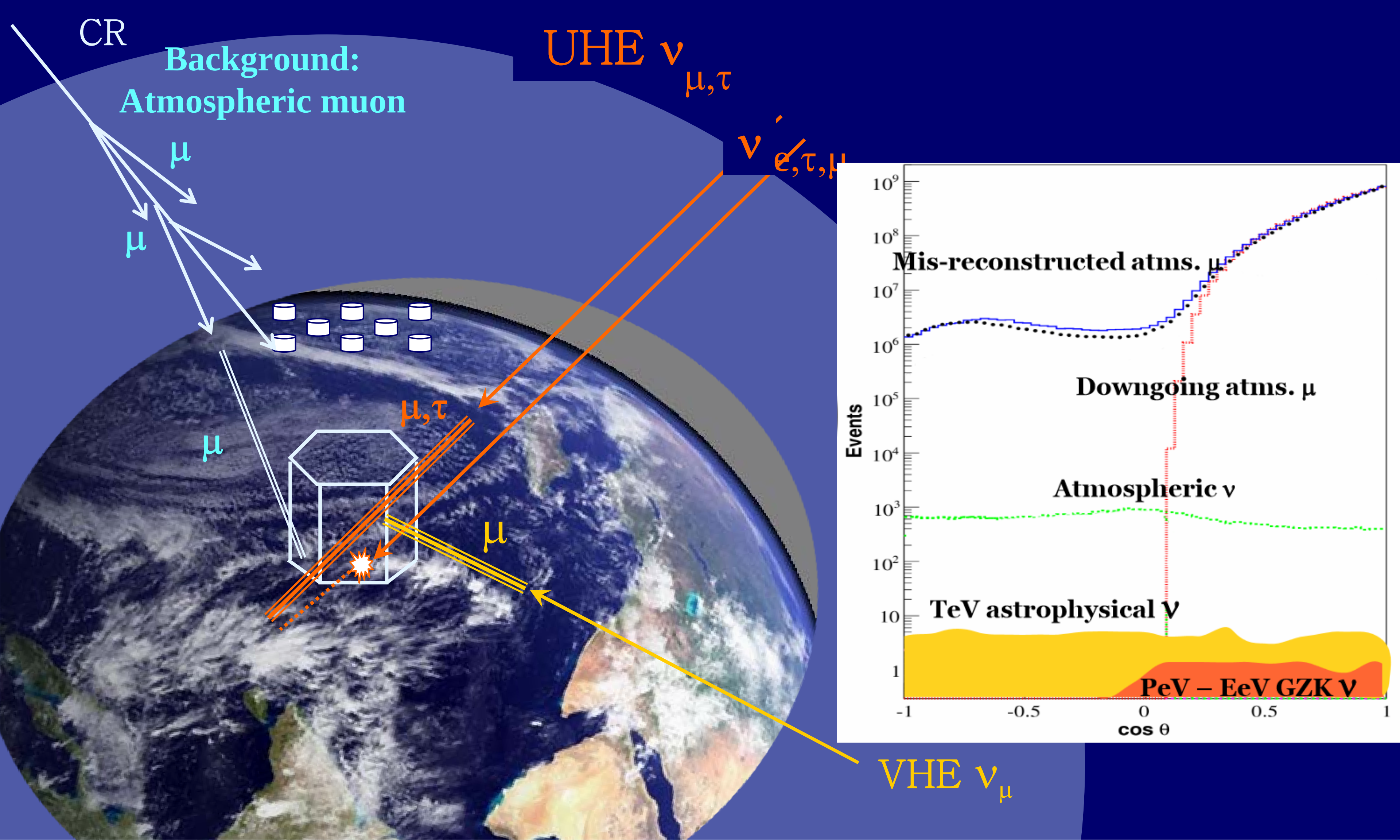
Cascade (Shower)

directly induced by ν
inside the detector volume

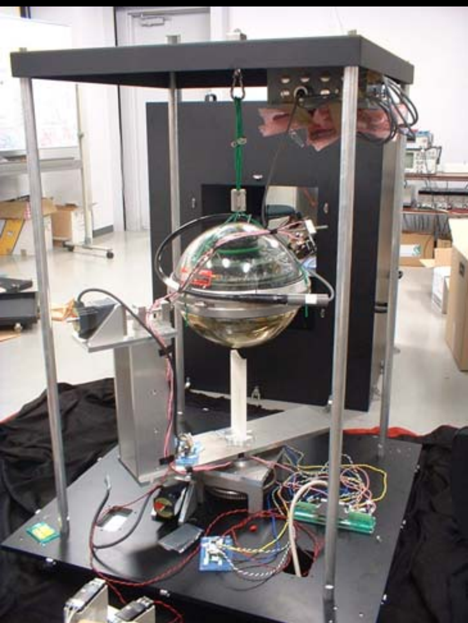
- via CC from ν_e
- via NC from ν_e, ν_μ, ν_τ

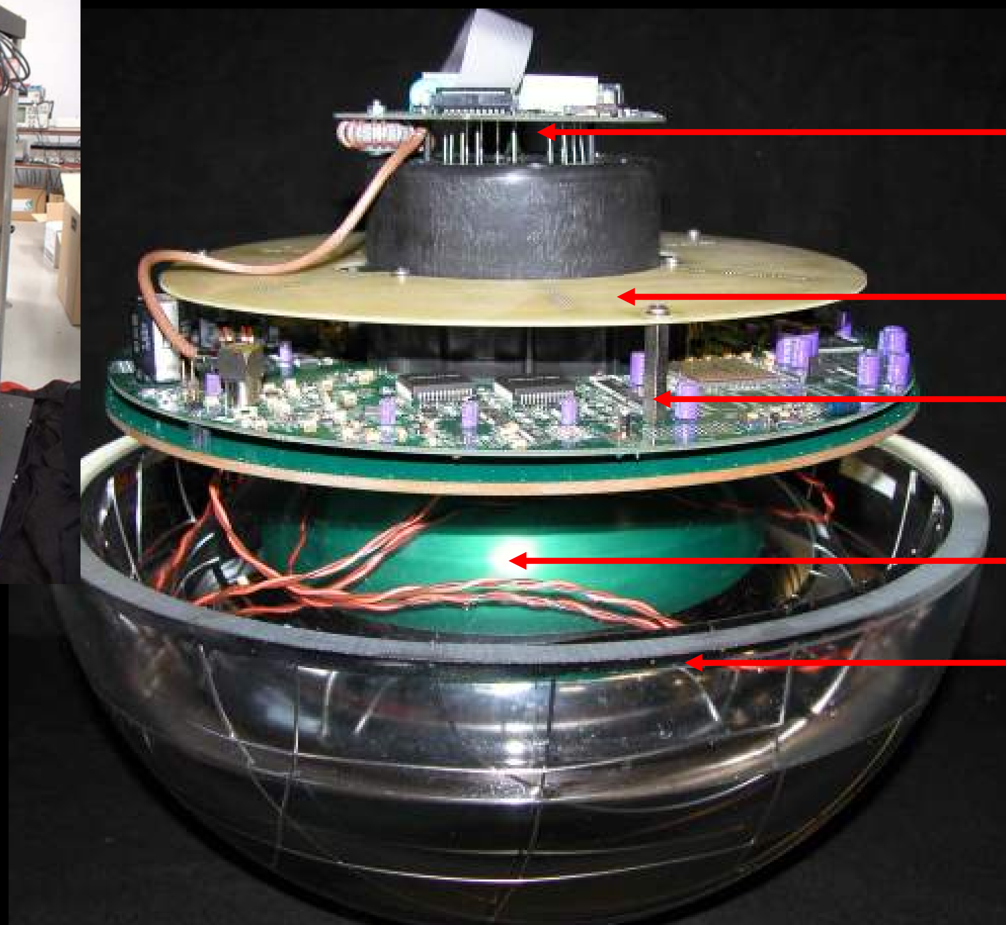
all 3 flavor sensitive

Neutrino Signatures
UHE (>100 PeV) VHE(>100 TeV)



DOM
Digital Optical Module





HV Base

“Flasher Board”

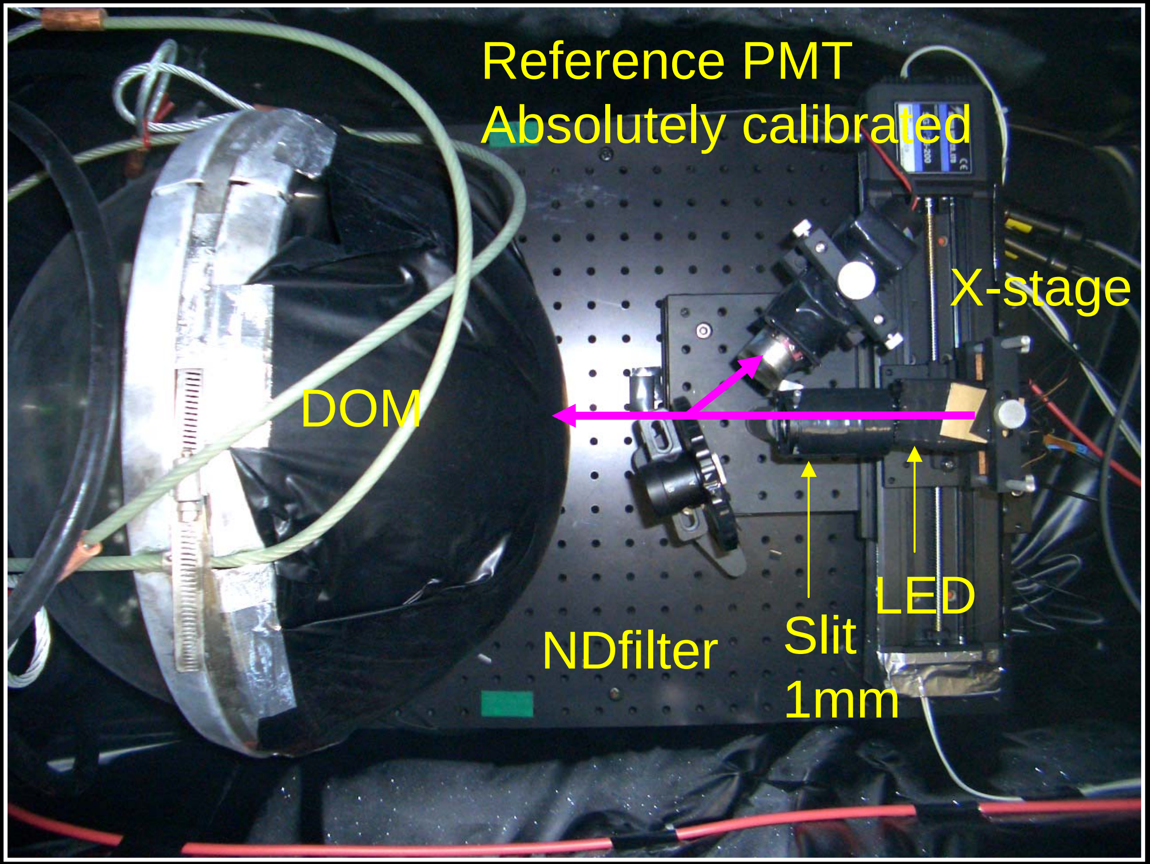
Main Board
(DOM-MB)

10” PMT

13” Glass
(hemi)sphere

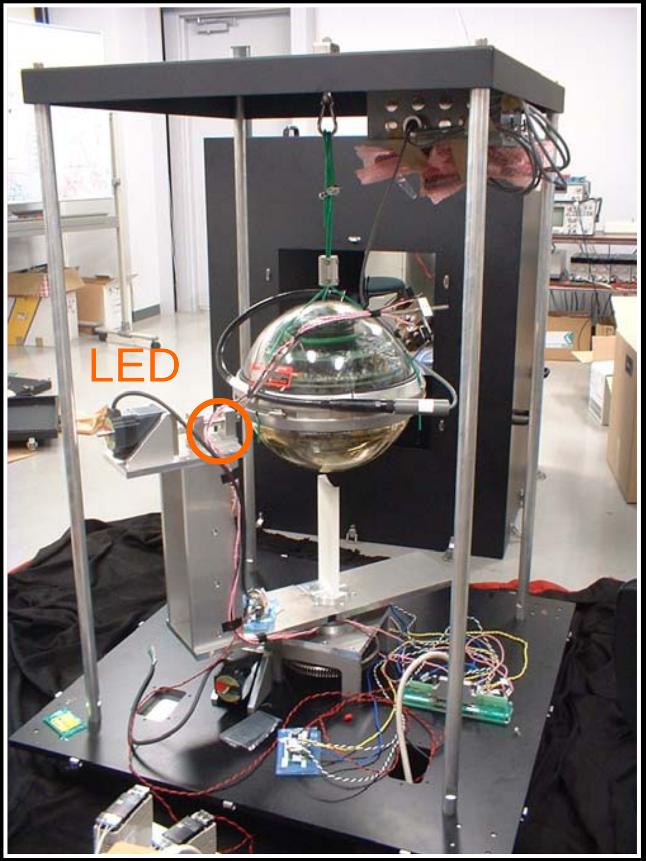
Calibration of DOM

Effective detection area



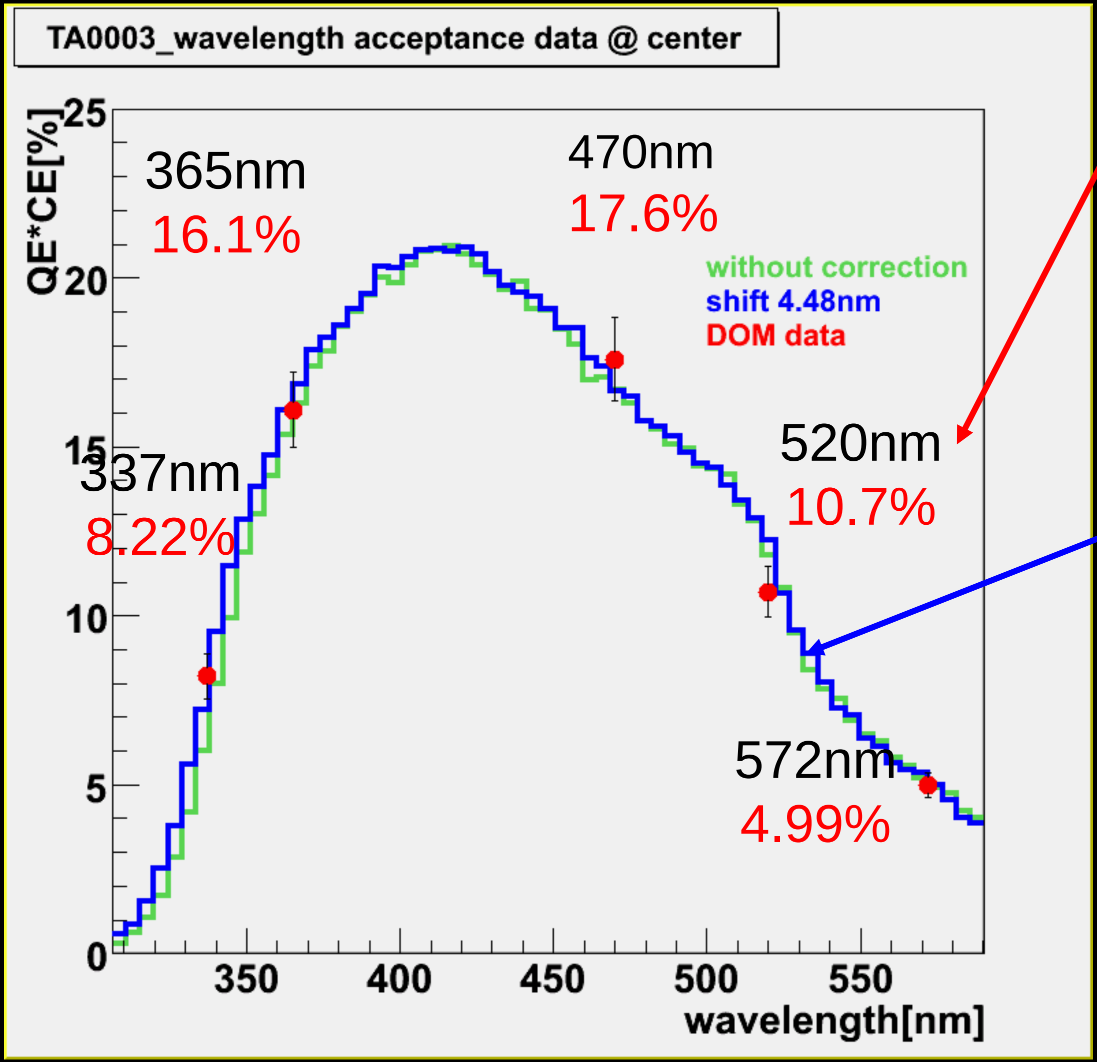
Reflectivity : 14.5%±0.73
Transmission : 50.7%±2.54

4 π mapping

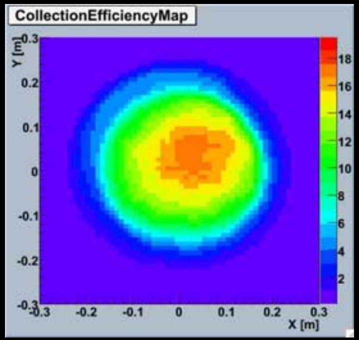


Systematic error ~7% @ room

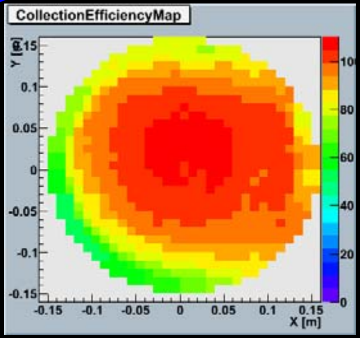
Photon Detection Efficiency

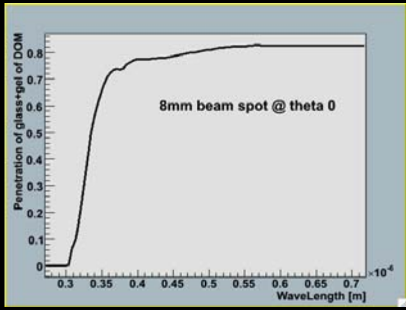


Absolute calibration of DOM



PMT + Glass/Gel





Good agreements over the wavelengths.

Constructions
2005-2011

Detectors shipped from Japan

Drill House

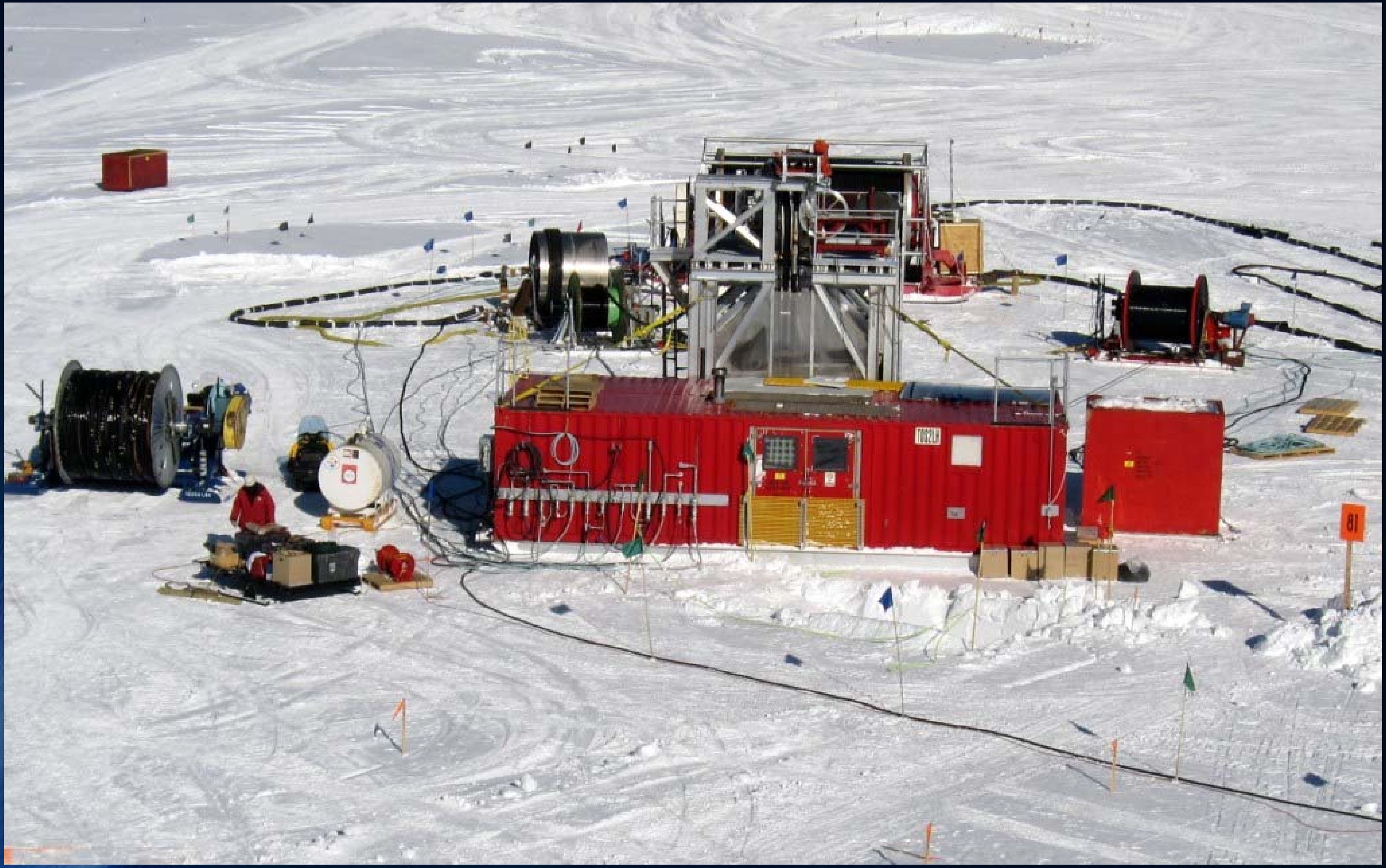
The IceCube Lab 「Beer Can」

Researchers working on deployment

The Construction

The Construction

The Construction



The Construction

The Construction

The Construction

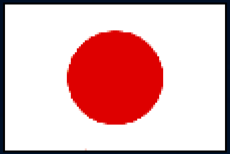
The Construction

The Construction

The Construction

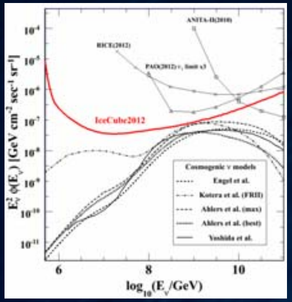
UHE-UltraHigh Energy ν search

> PeV = 10^{15} eV

 's flagship mission

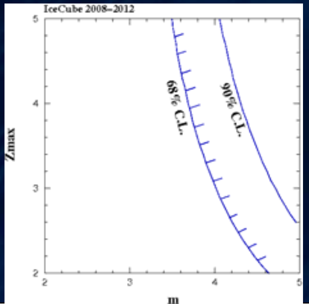
Phys. Rev. Lett. 111, 021103

The 1st evidence of *astrophysical* ν



Phys. Rev. D 88, 112008

The stringent constraints on cosmic ν fluxes at PeV and EeV(=1000 PeV)



The 1st astrophysically meaningful constraints on UHE cosmic ray origin by ν

The dataset

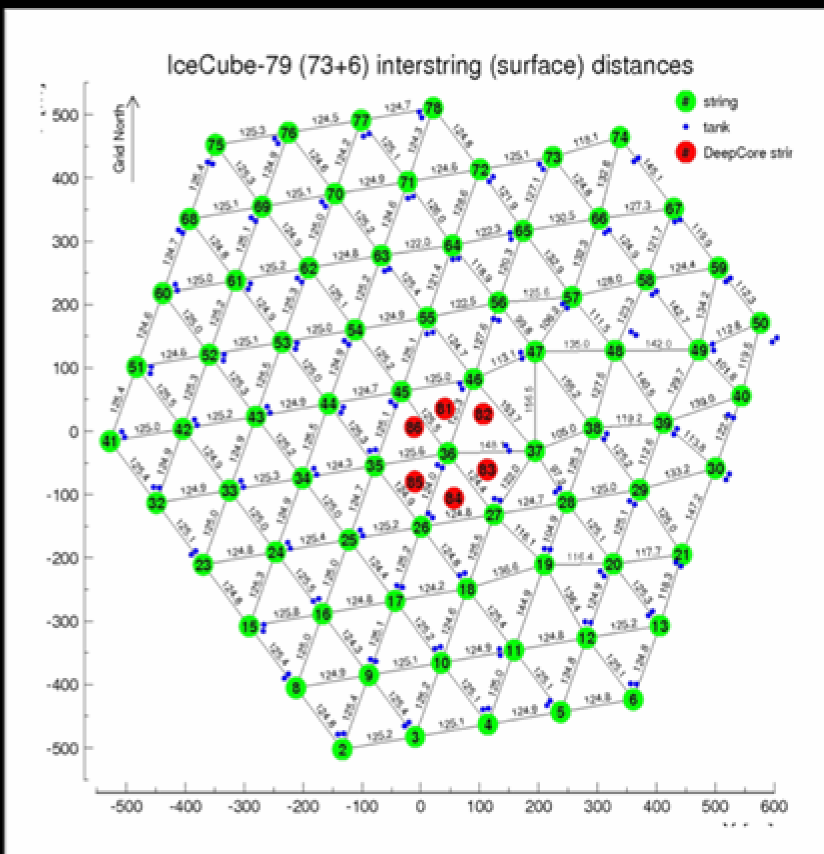
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

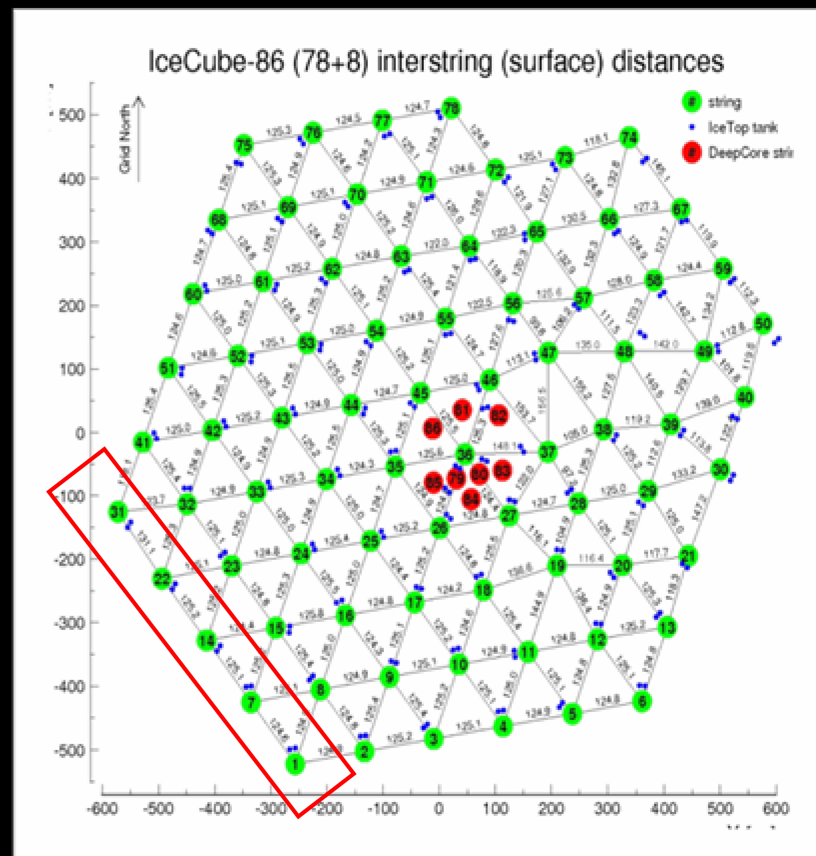
"IC79"

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

Extremely High Energy
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

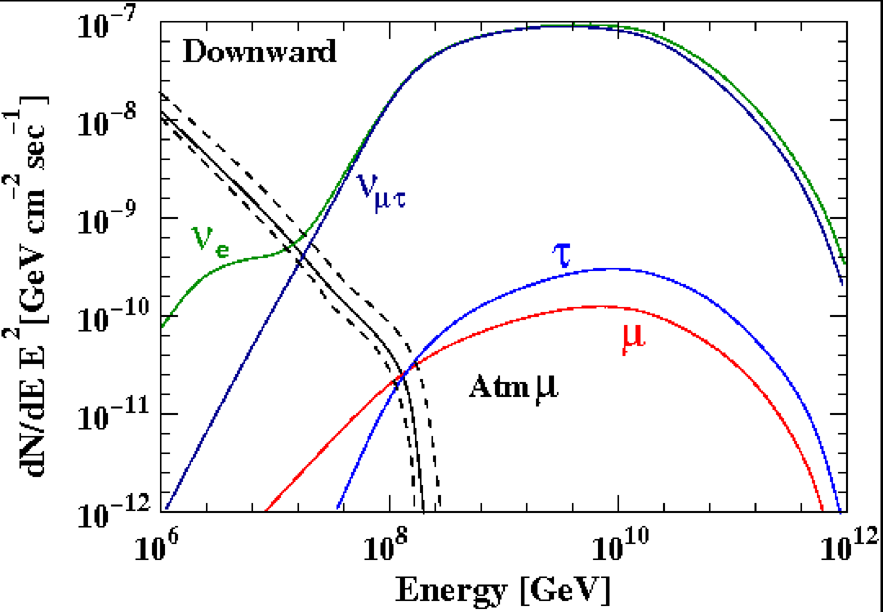
To Northern Hemisphere

千葉大学
Chiba University

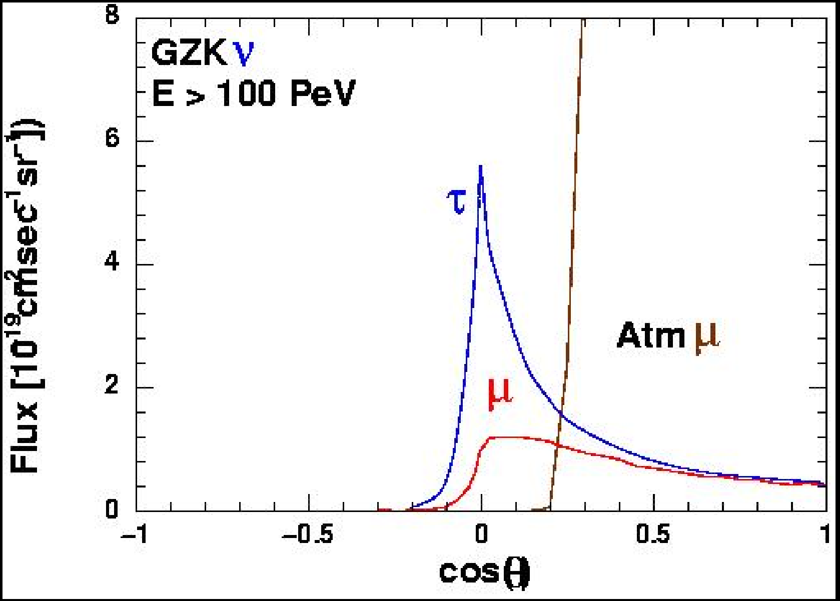
Ultra-high Energy ν search

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

And tracks arrive **horizontally**

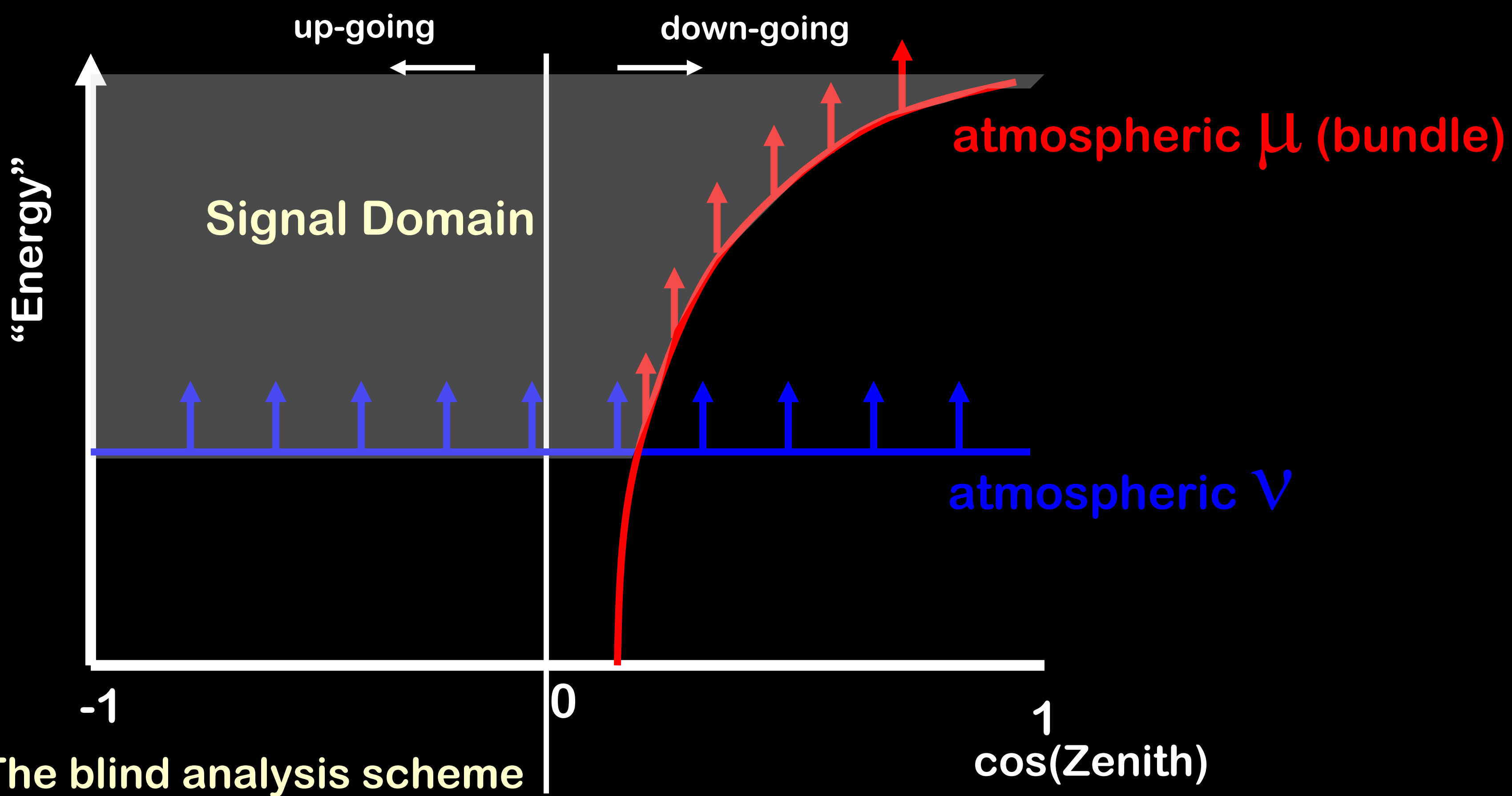
starting track/ cascade

Directly induced events from ν

→ Sensitive to ν_e ν_μ ν_τ

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

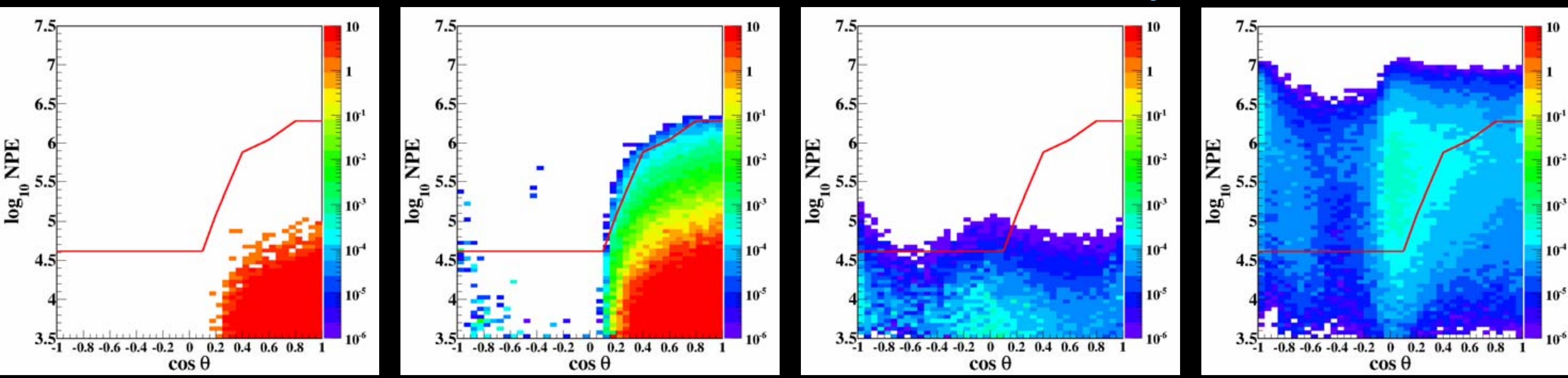
On the Analysis level

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

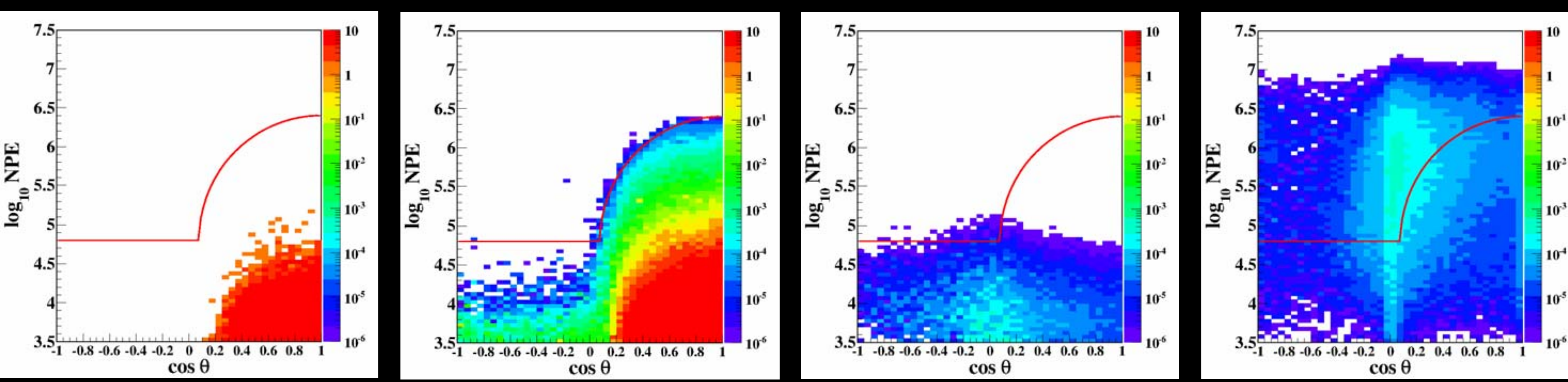
Number of events (z-axis) per the test-sample livetime

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

IC79



IC86



Two events passed the final criteria

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

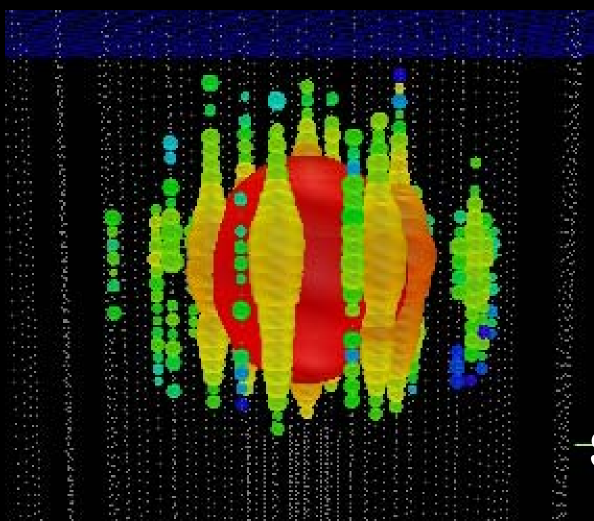
The Expected Backgrounds

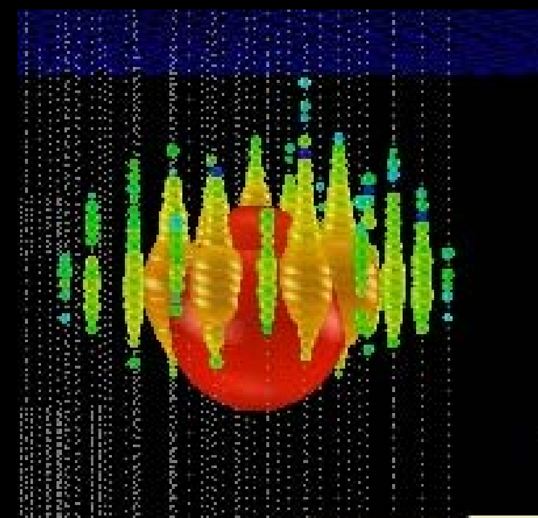
including prompt **0.082** $^{+0.041}_{-0.057}$

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

p-value 2.9×10^{-3} (2.8σ)

p-value 9.0×10^{-4} (3.1σ)

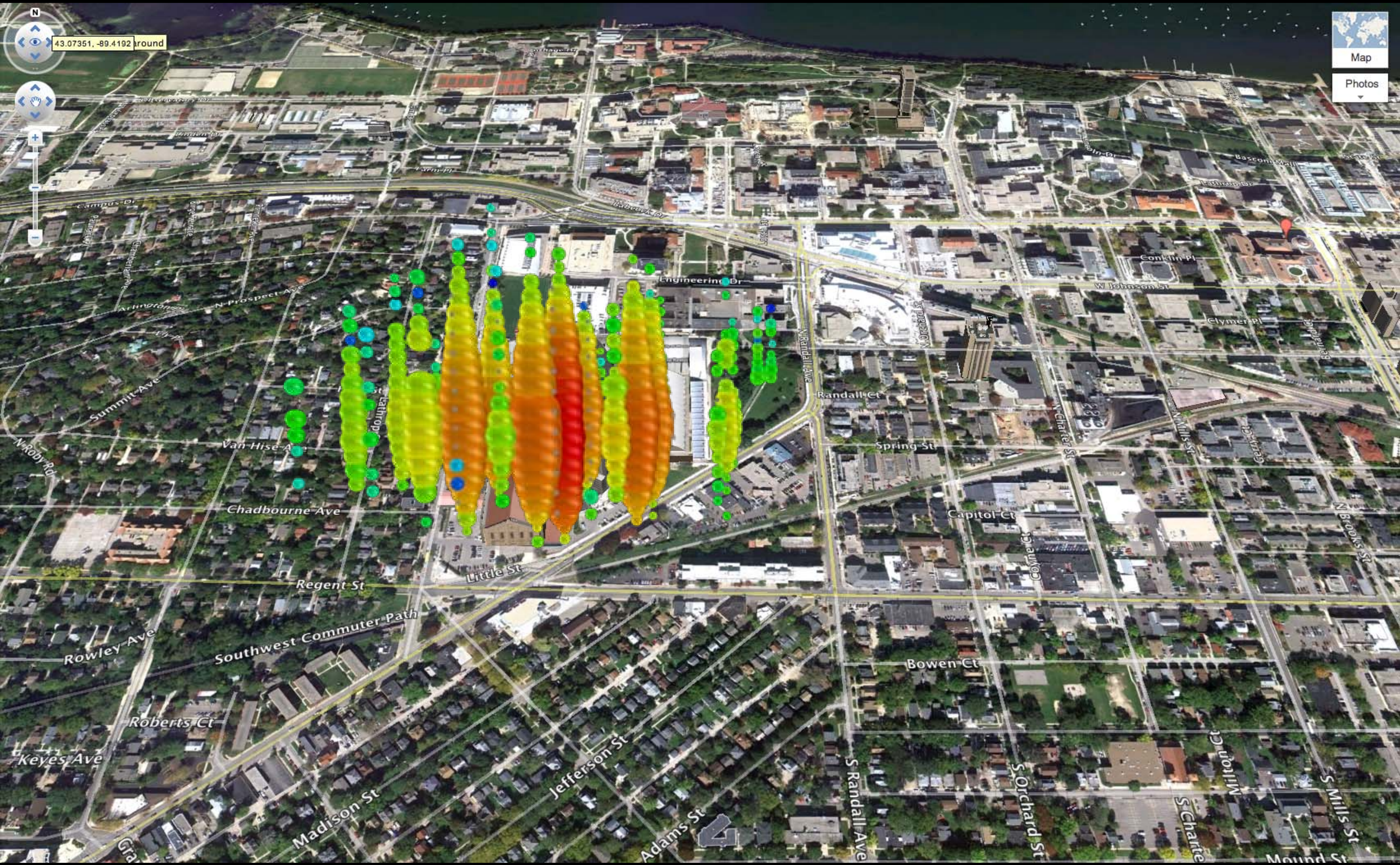




Super-nicely contained cascades!

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



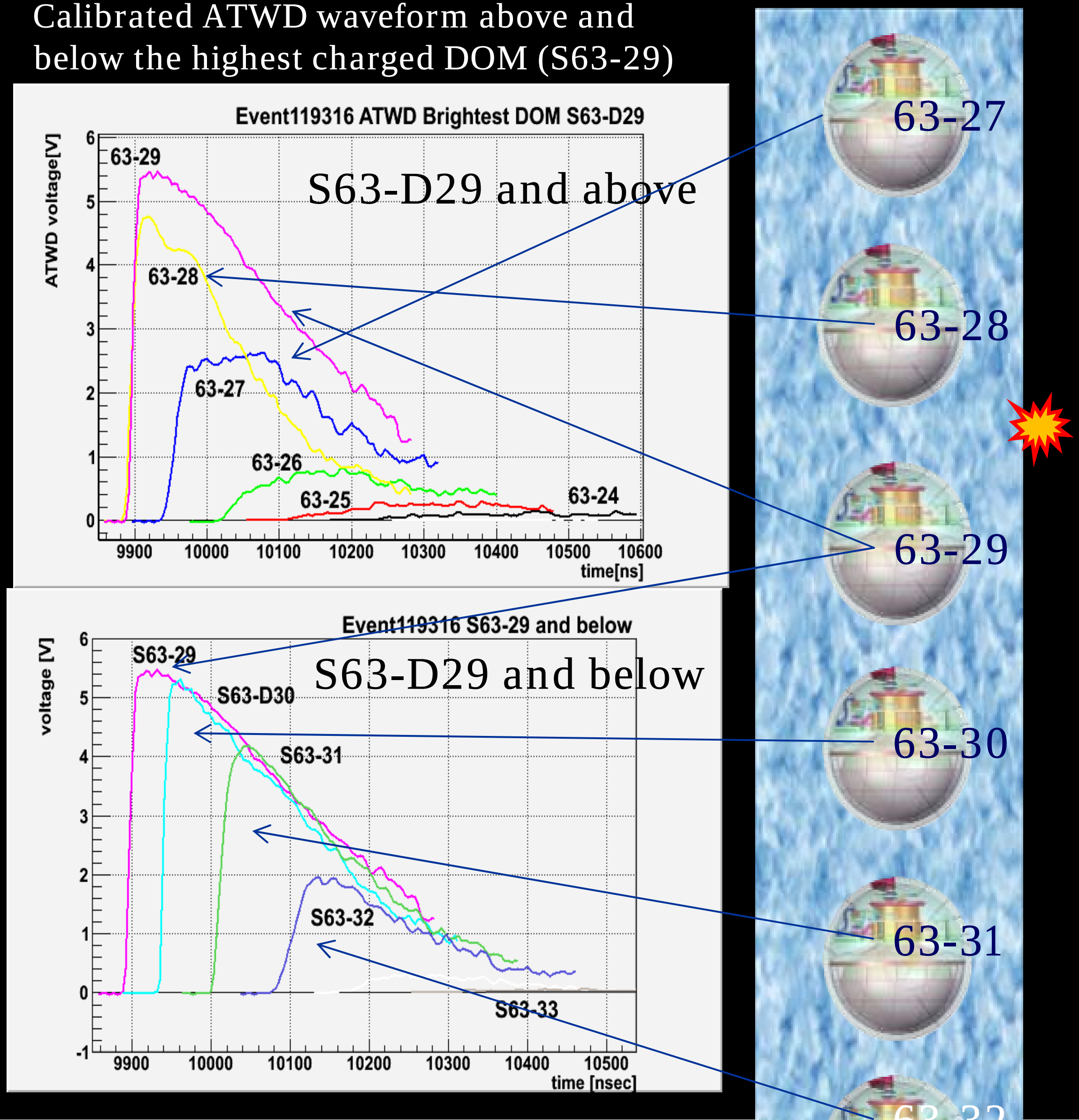
N
43.07351, -89.4192
round
Map
Photos
Campus Dr
Engineering Dr
W Johnson St
Conklin Pl
Clymer Pl
N Randall Ave
Randall Ct
Spring St
Capitol Ct
Regent St
Little St
Chadbourne Ave
Van Hise Ave
Summit Ave
N Prospect Ave
N Roby Rd
Southwest Commuter Path
Rowley Ave
Roberts Ct
Keyes Ave
Madison St
Jefferson St
Adams St
S Randall Ave
S Orchard St
S Charter St
S Mills St
Bowen Ct
Mound St

We can still reconstruct the directions they came from

More scattered Cherenkov light in the backward direction

EHE-Jan-2012 “Ernie”

Calibrated ATWD waveform above and below the highest charged DOM (S63-29)



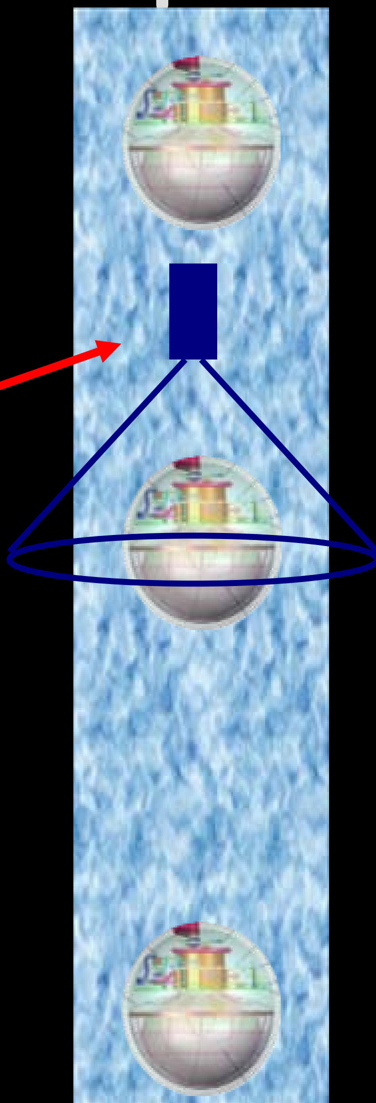
Zenith Angles

Bert ~ 70 deg
Ernie ~ 20 deg

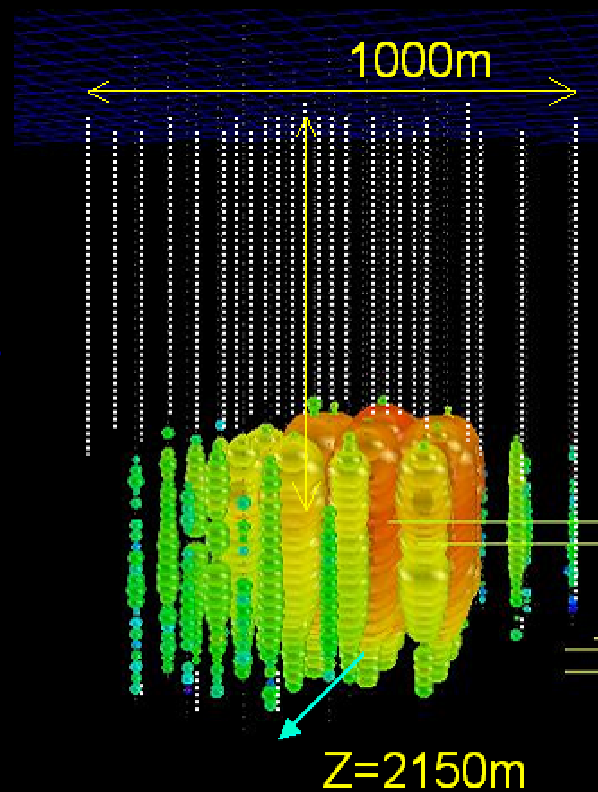
$\Delta\theta$ ~ 20 deg

The in-situ verification on the photon measurement

337 nm pulsed Nitrogen Laser

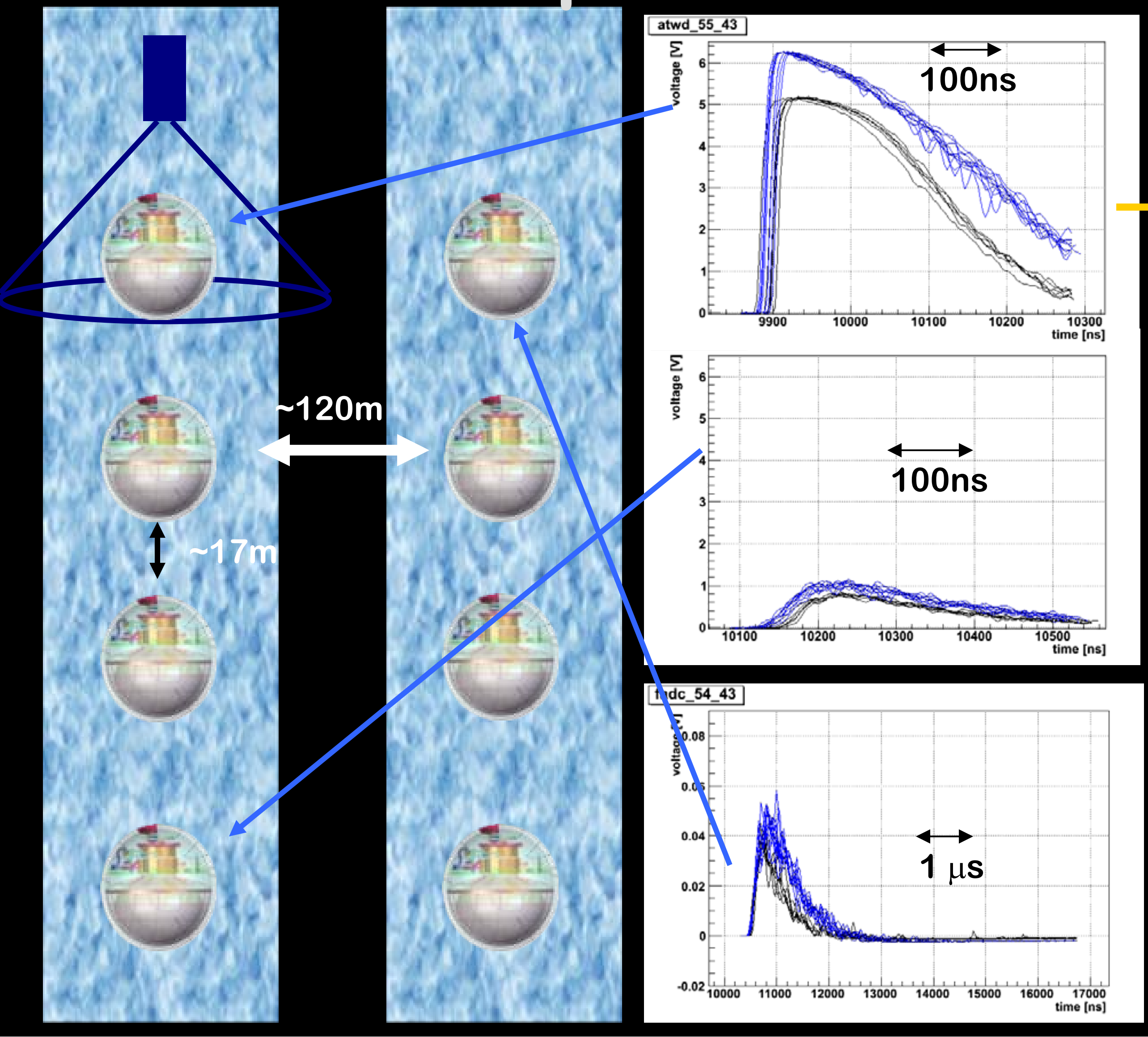


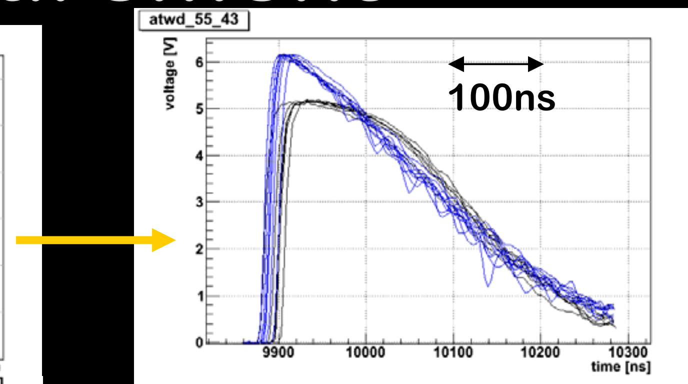
Laser shot event view



Experimentally "simulate" cascade events

The in-situ verification on the photon measurement



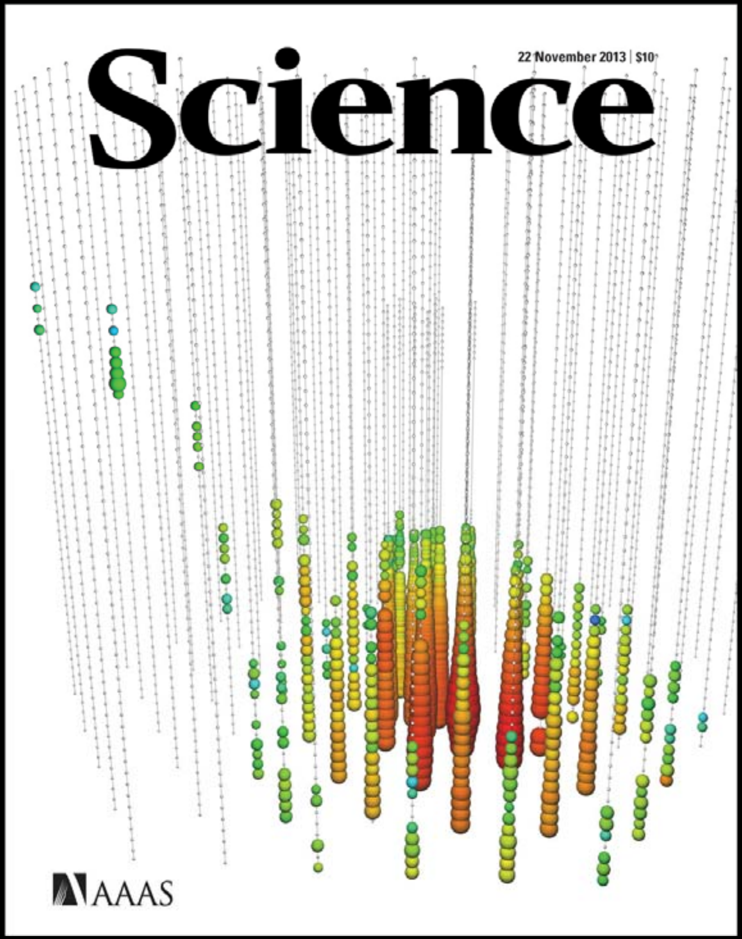


Improving the ice model

The data/MC agreement involves….

- the optical characteristics of the glacier
- detector response to a luminous photon bulk

The Follow-up analysis

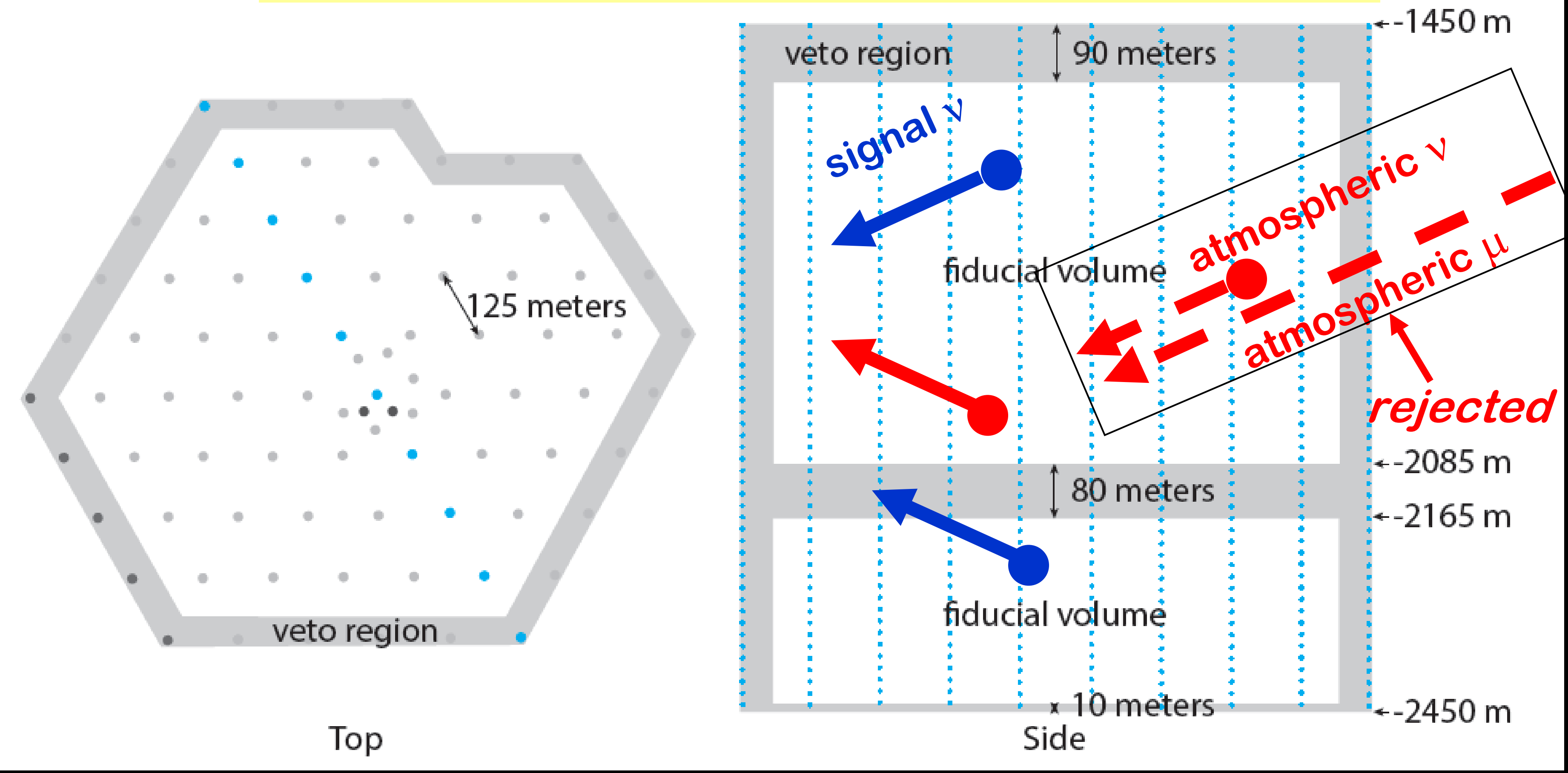


Mr. Snuffleupagus

250TeV

A search for events originated within the detector interior

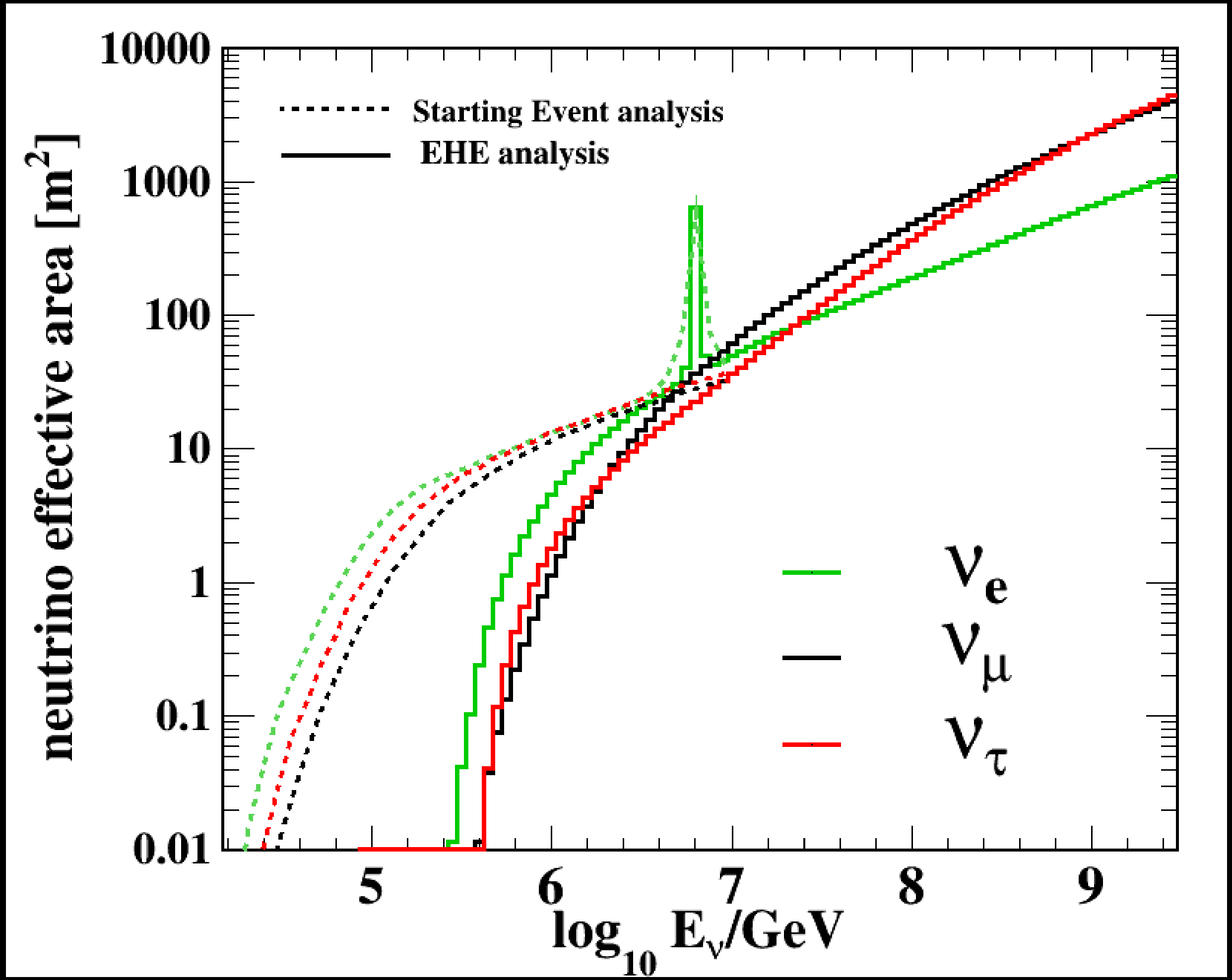
look for only events with their interaction vertices within the fiducial volume



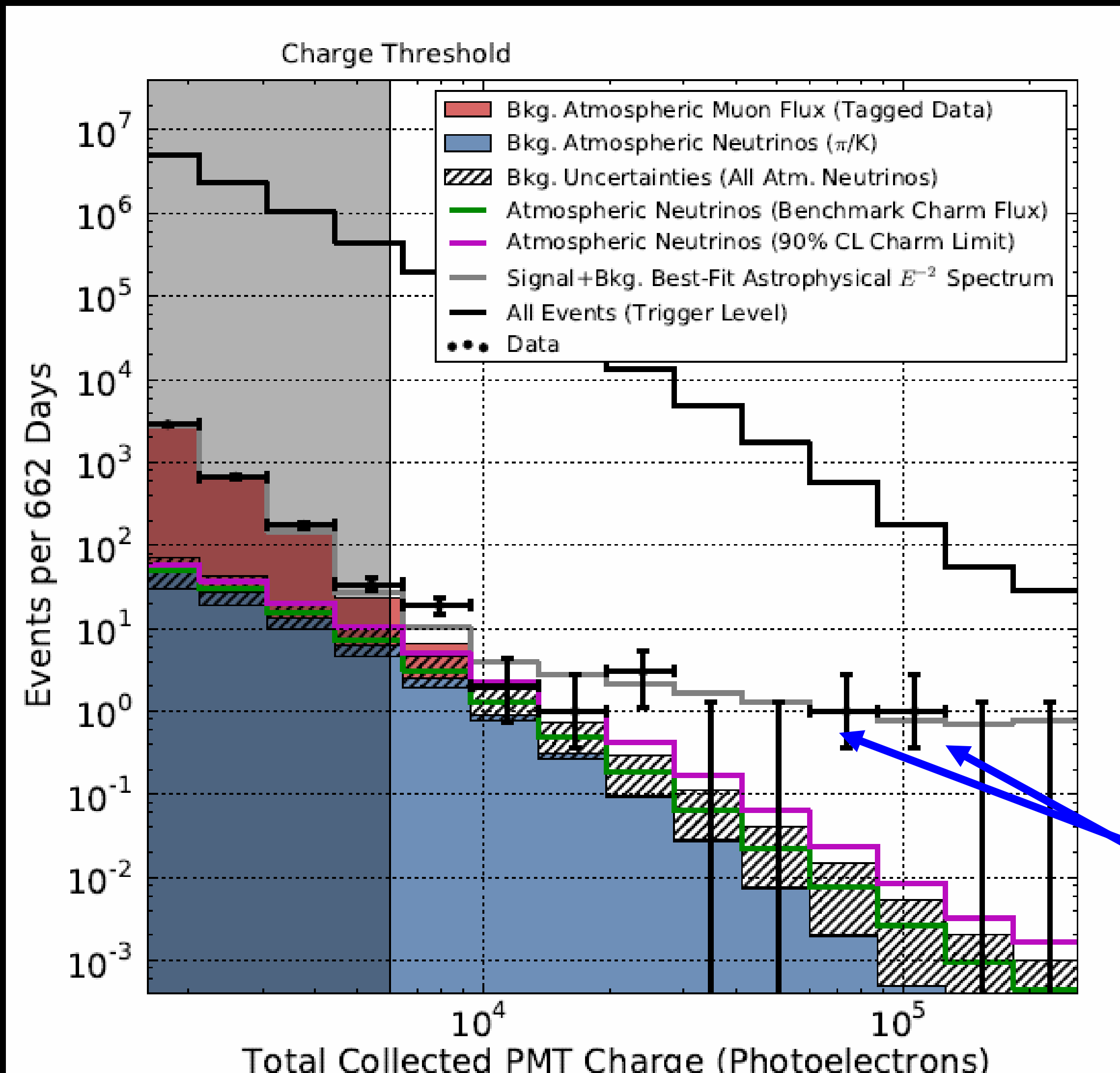
Effective Areas expanding down to 100 TeV's

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

IC79+IC86 livetime 670.1 days

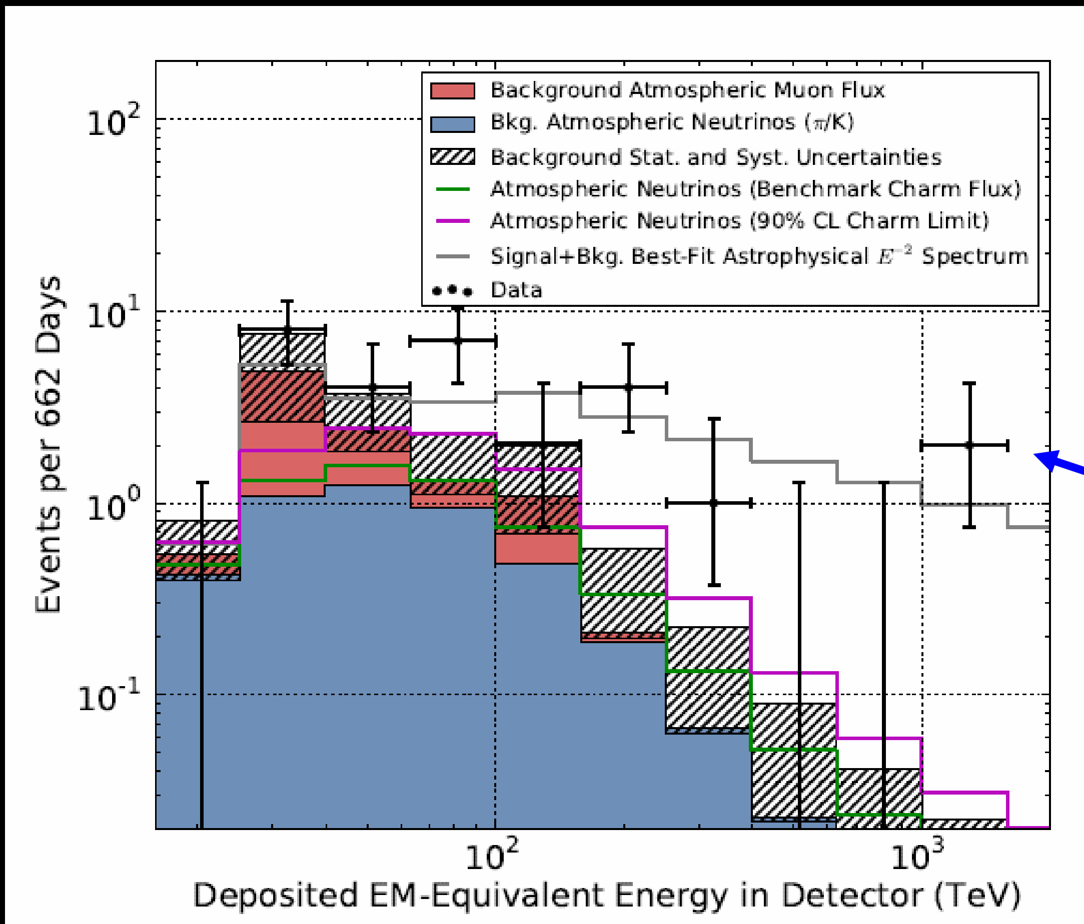


sub-PeV ν samples



Bert & Ernie

sub-PeV ν samples



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

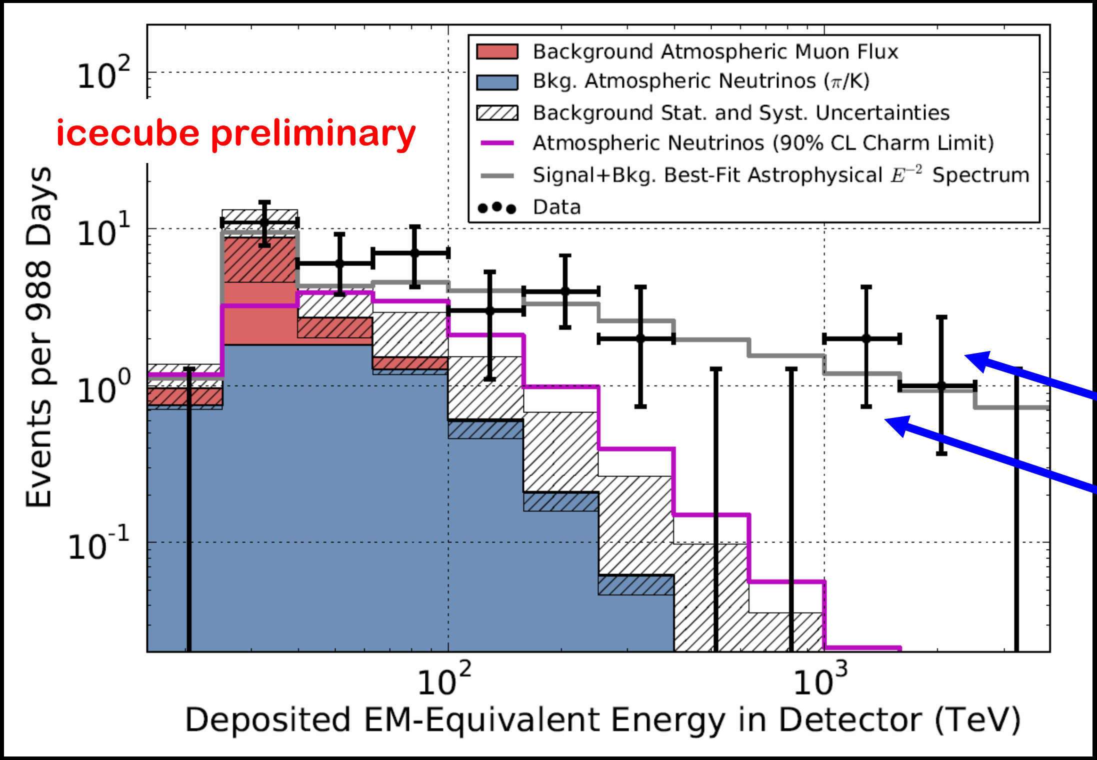
Bert & Ernie

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

[GeV/cm^2 sec sr]

sub-PeV ν samples

+ additional 2013 data = 988 day sample



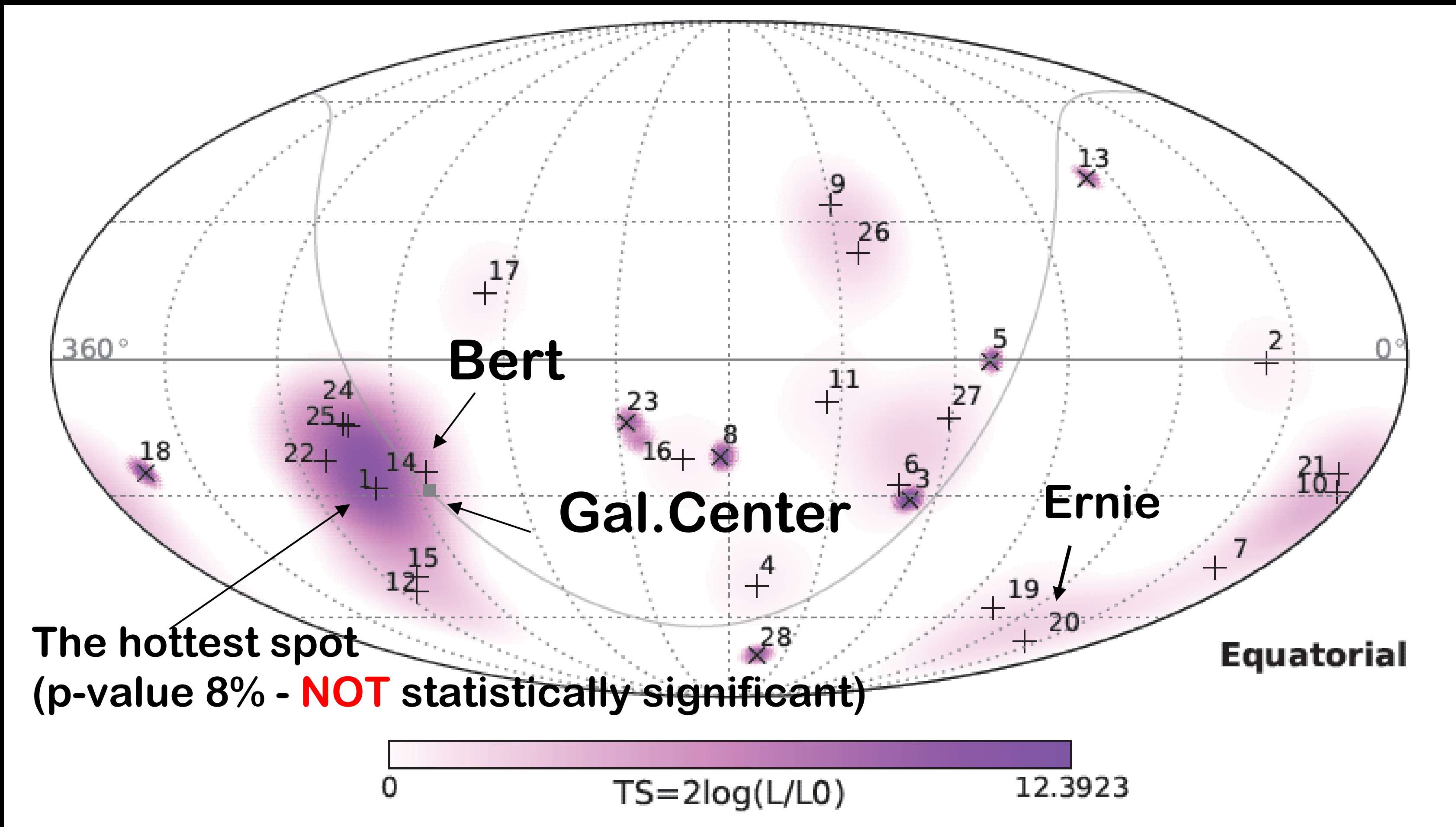
37 events observed against bg of $14.0^{+7.2}_{-4.5}$ (5.7σ excess)

Big Bird (2 PeV)

Bert & Ernie

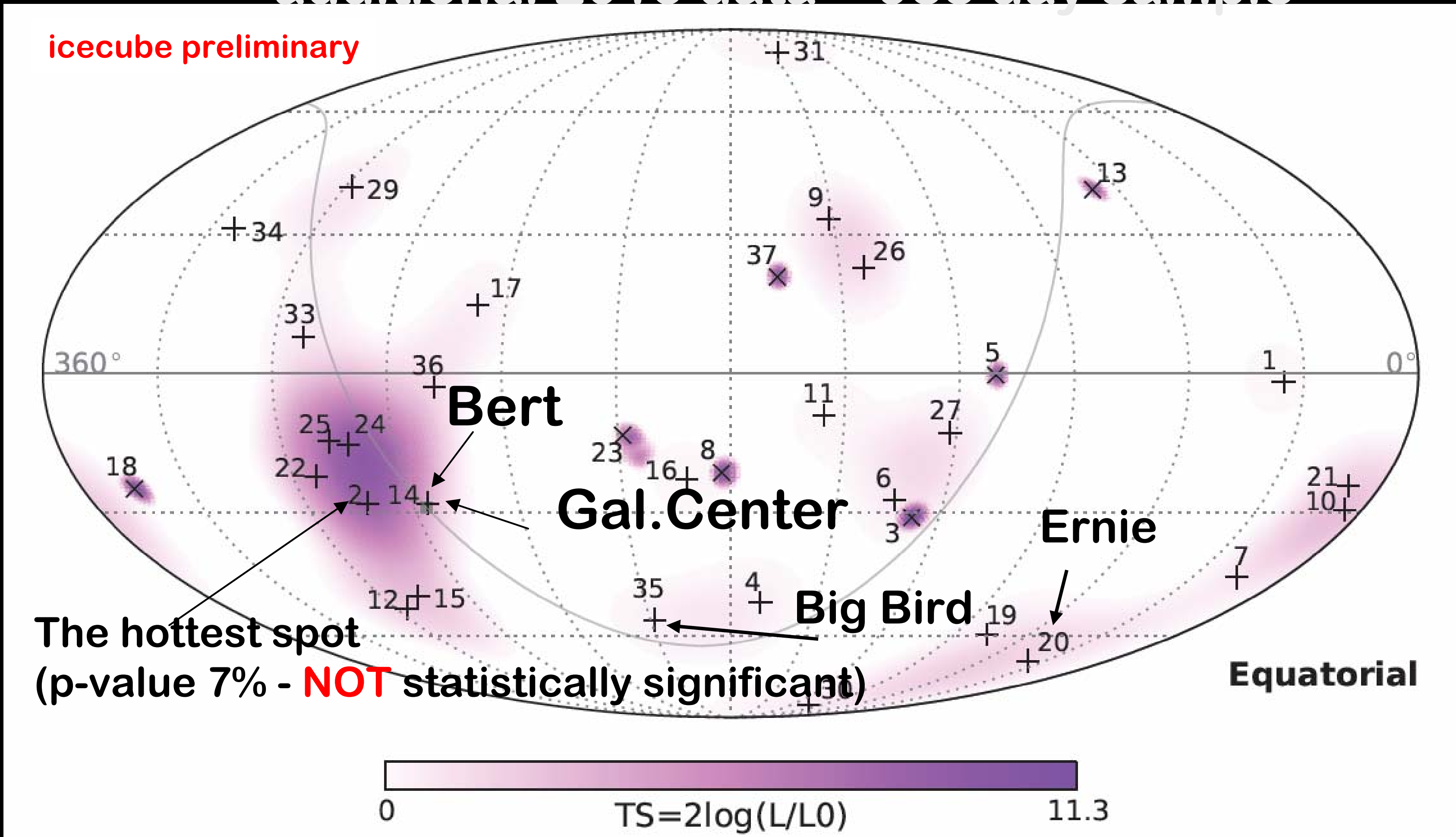
$E^2 \phi_{\nu_{e+\mu+\tau}}(E) \sim (2.9 \pm 0.9) \times 10^{-8}$ [GeV/cm² sec sr]

sub-PeV ν samples



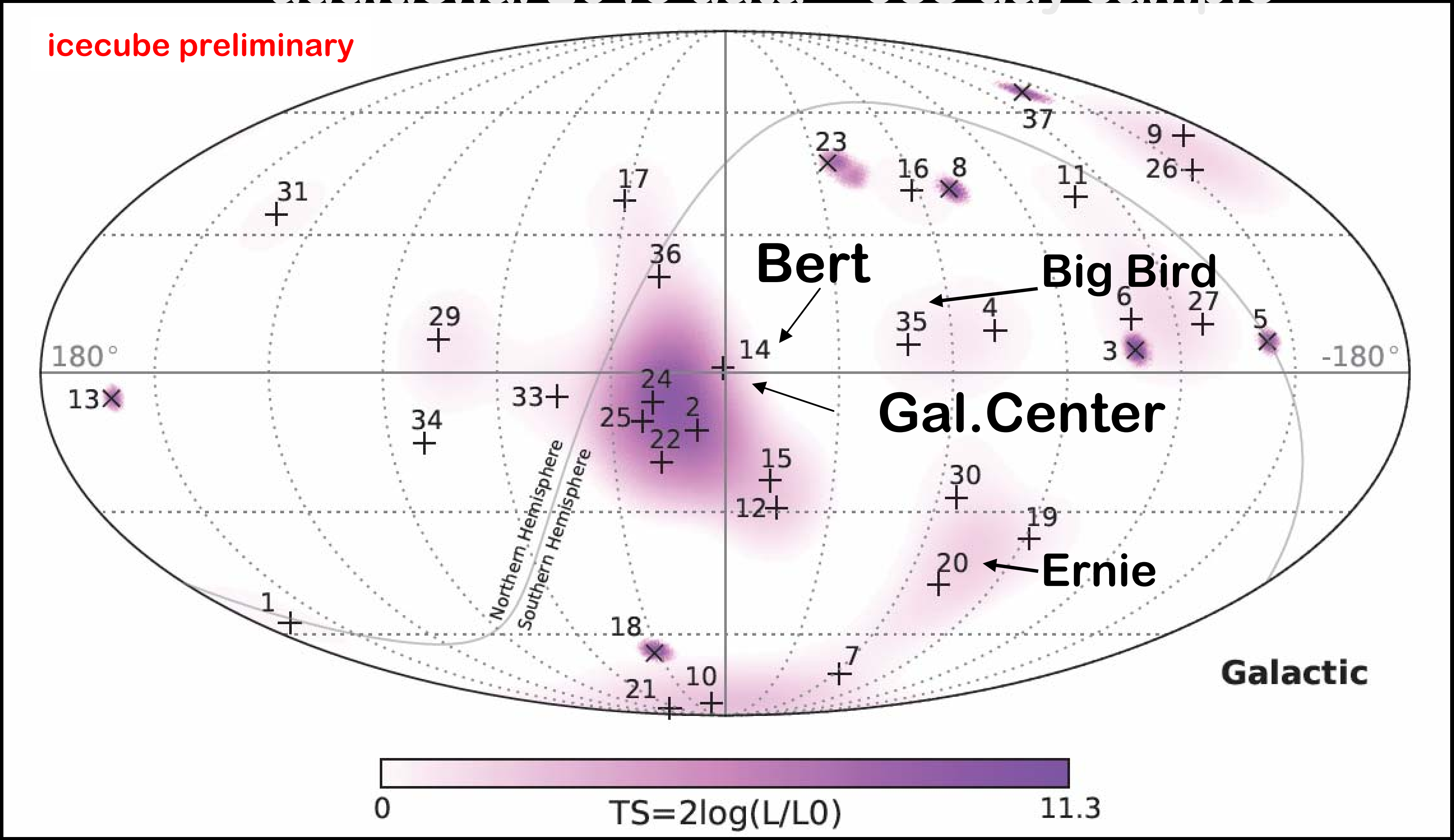
sub-PeV ν samples

+ additional 2013 data = 988 day sample



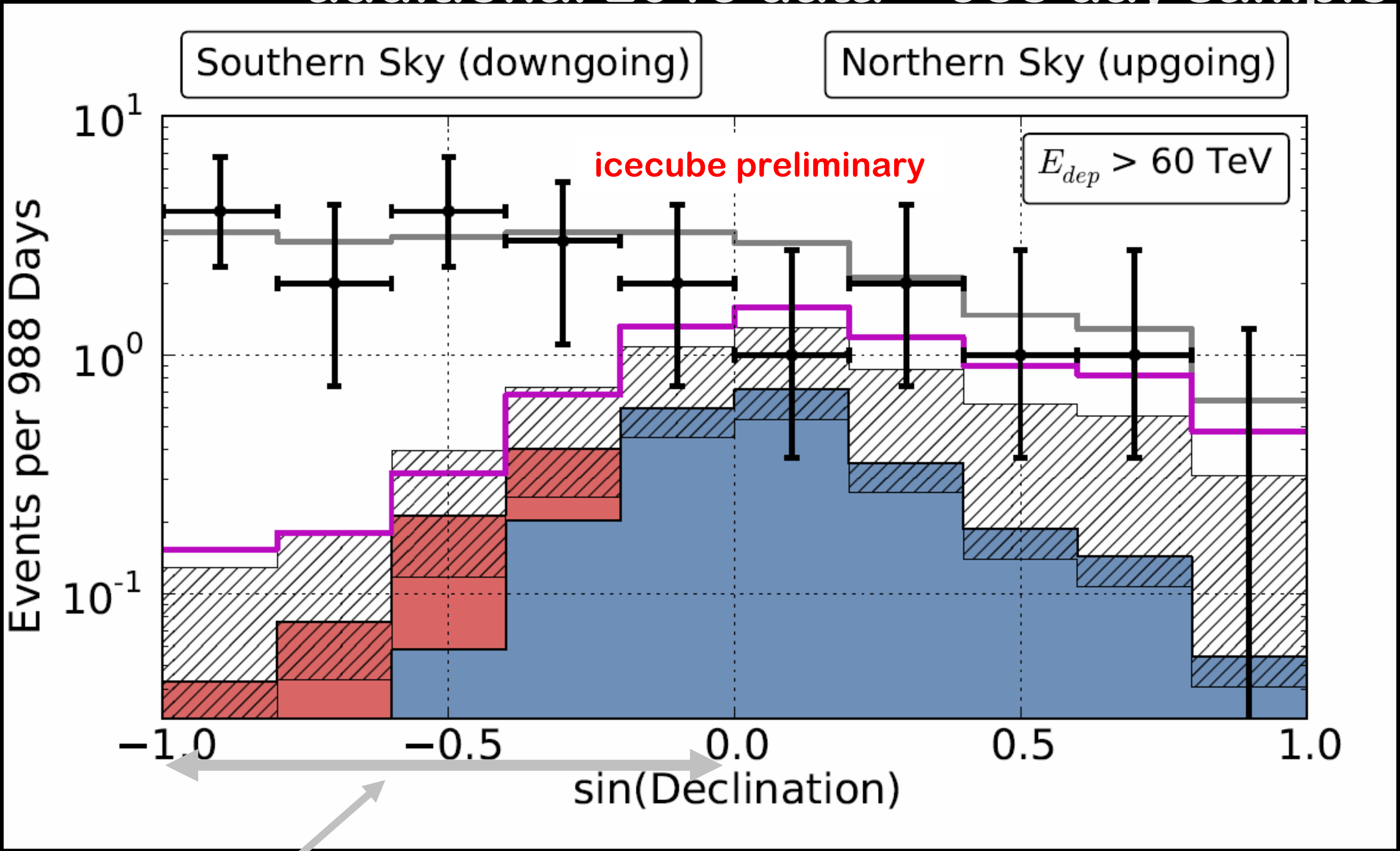
sub-PeV ν samples

+ additional 2013 data = 988 day sample



sub-PeV ν samples

+ additional 2013 data = 988 day sample

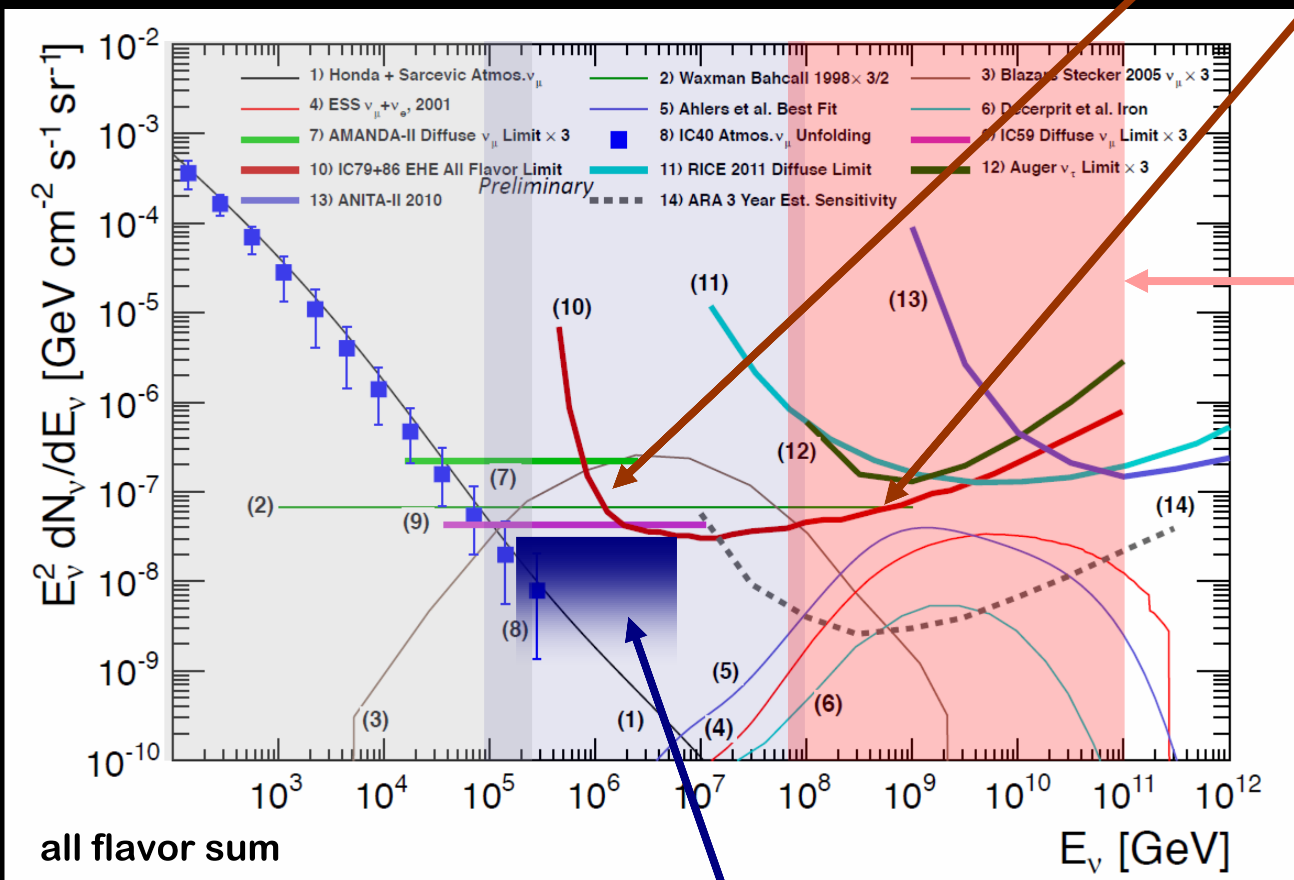


less background in Southern Sky due to the atmospheric background veto

→ better sensitivity for Southern Sky

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

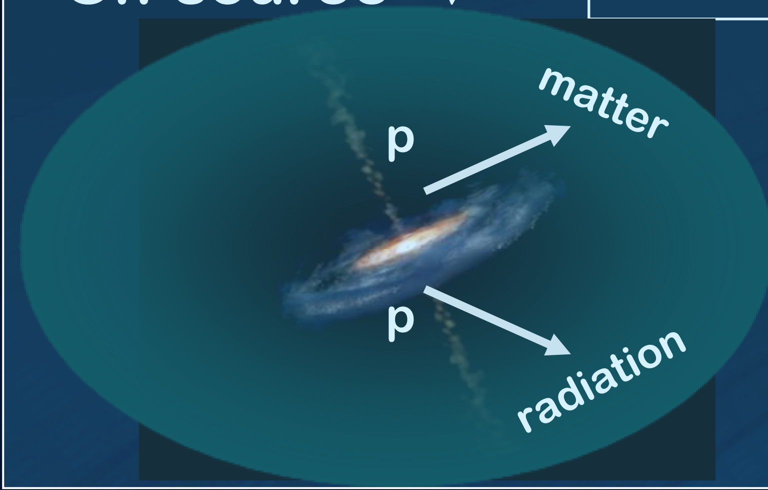
Bert & Ernie + O(10) sub-PeV events

4.1 σ excess over atmospheric

The Cosmic Neutrinos
Production Mechanisms

"On-source" ν

TeV - PeV



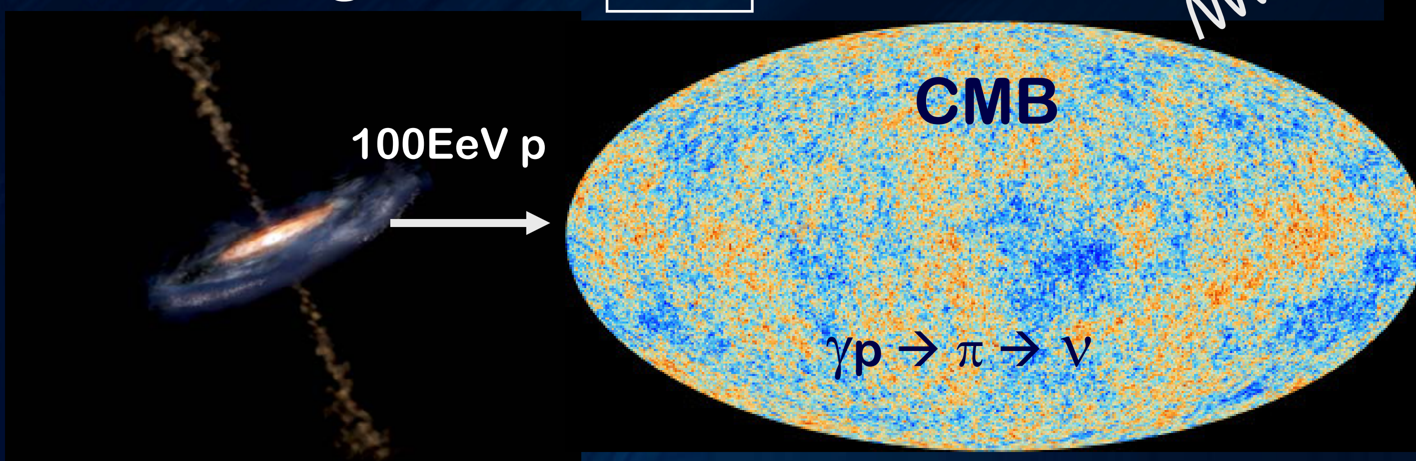
$pp \rightarrow \pi \rightarrow \nu$

$\gamma p \rightarrow \pi \rightarrow \nu$

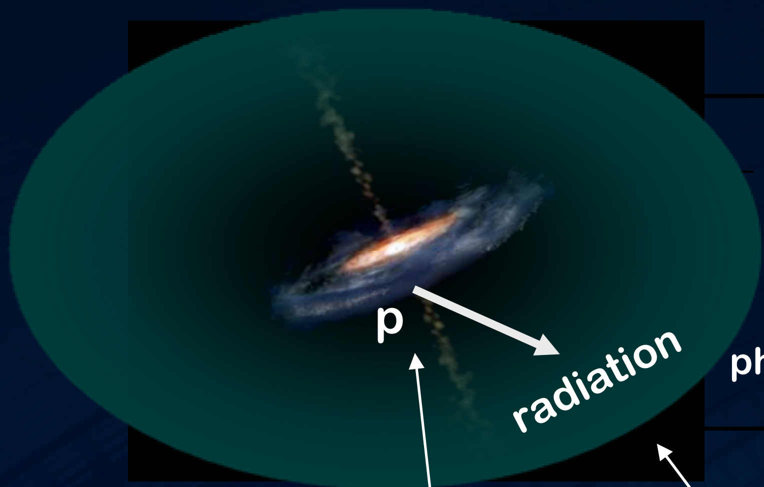
photopion production

"GZK" cosmogenic ν

EeV



On-source ν flux estimates: model-independent analytical approach



$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production

ν

optical depth (<1)

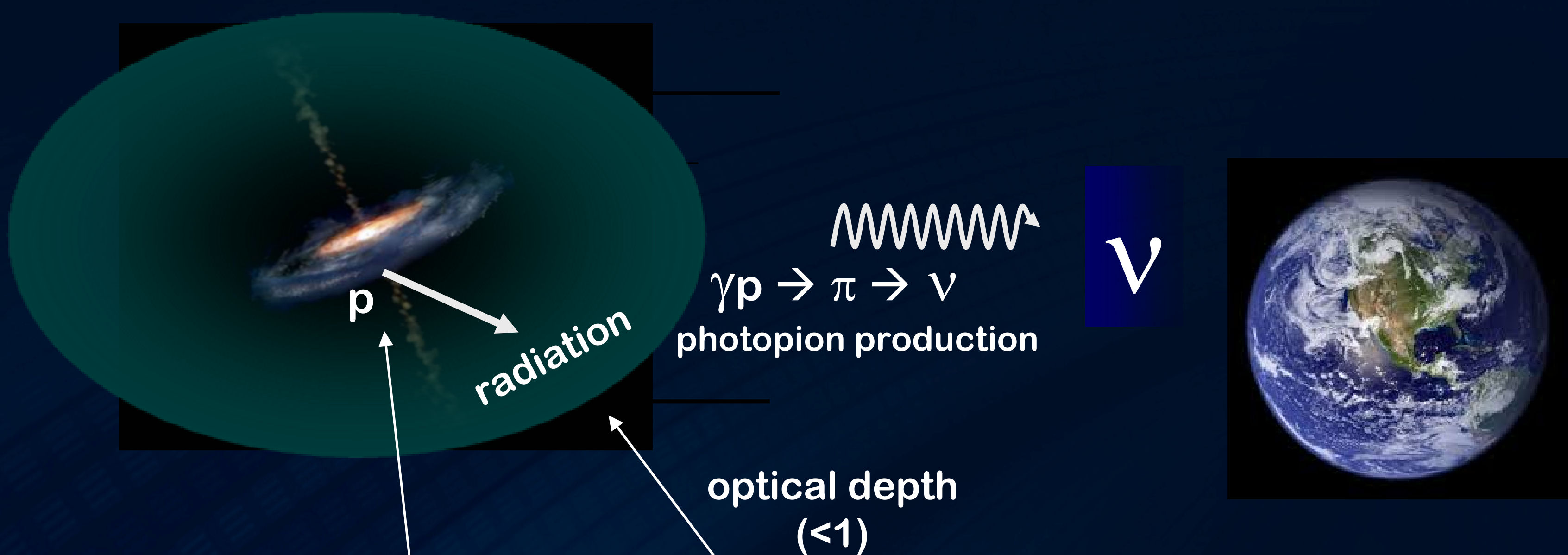
$$\frac{dJ_\nu}{dE} \sim F_{GZK\ CR}\,\frac{R_{cosmic}}{R_{GZK}}\,E^{-\alpha}\;\tau(E)\;\zeta(z,\ m,\ z_{max},\ E)$$

Primary Extragalactic CR proton flux $\sim E^{-\alpha}$

The cosmological term to account the source evolution

We do NOT know how large: strongly depends on α

Constraints on the optical depth and extra-galactic CR flux

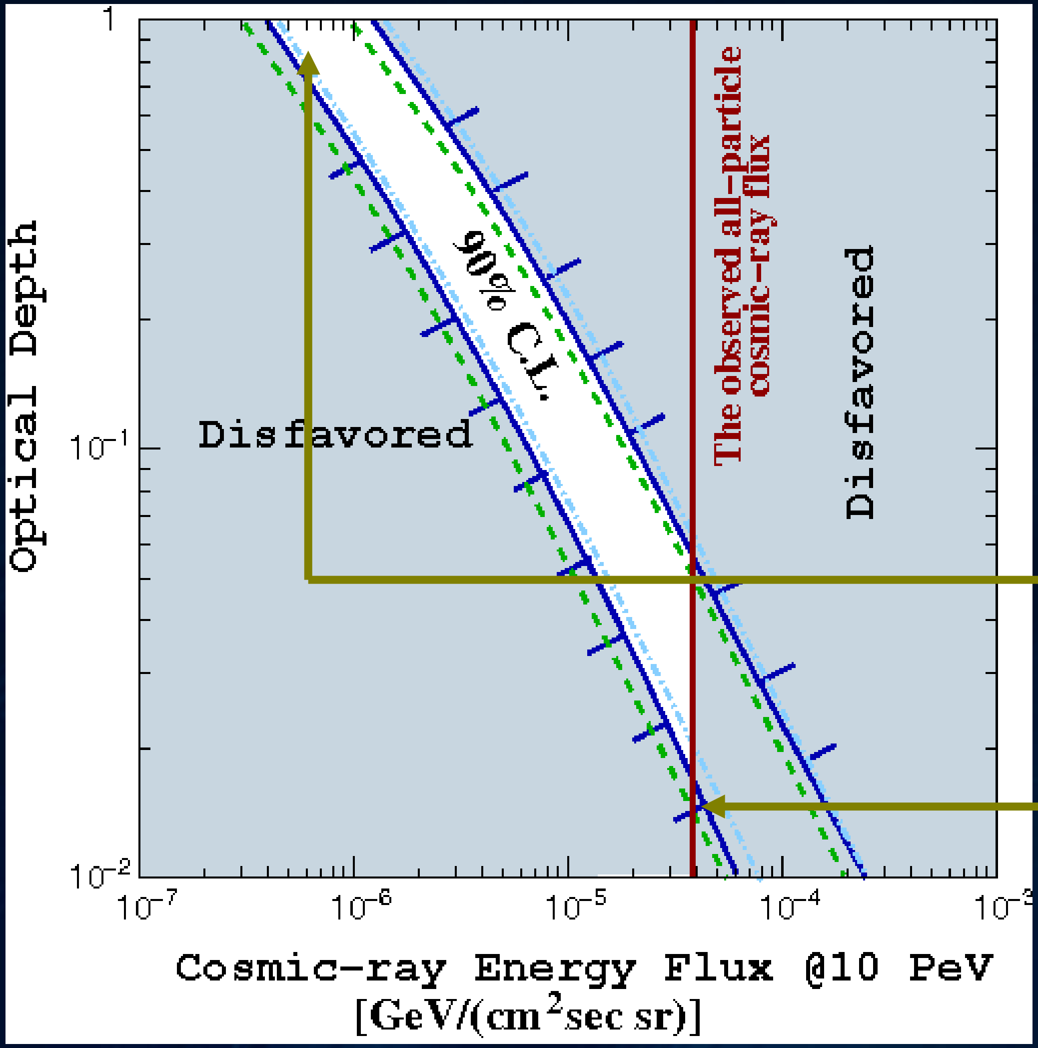


$$\frac{dJ_\nu}{dE} \sim F_{GZK\ CR} \frac{R_{cosmic}}{R_{GZK}} \mathbf{E}^{-\alpha} \; \tau(E) \; \zeta(z,\ m,\ z_{max},\ E)$$

Fixed to the Star Formation Rate

Constrain them by the IceCube 100TeV-PeV observation

Constraints on the optical depth and extra-galactic CR flux

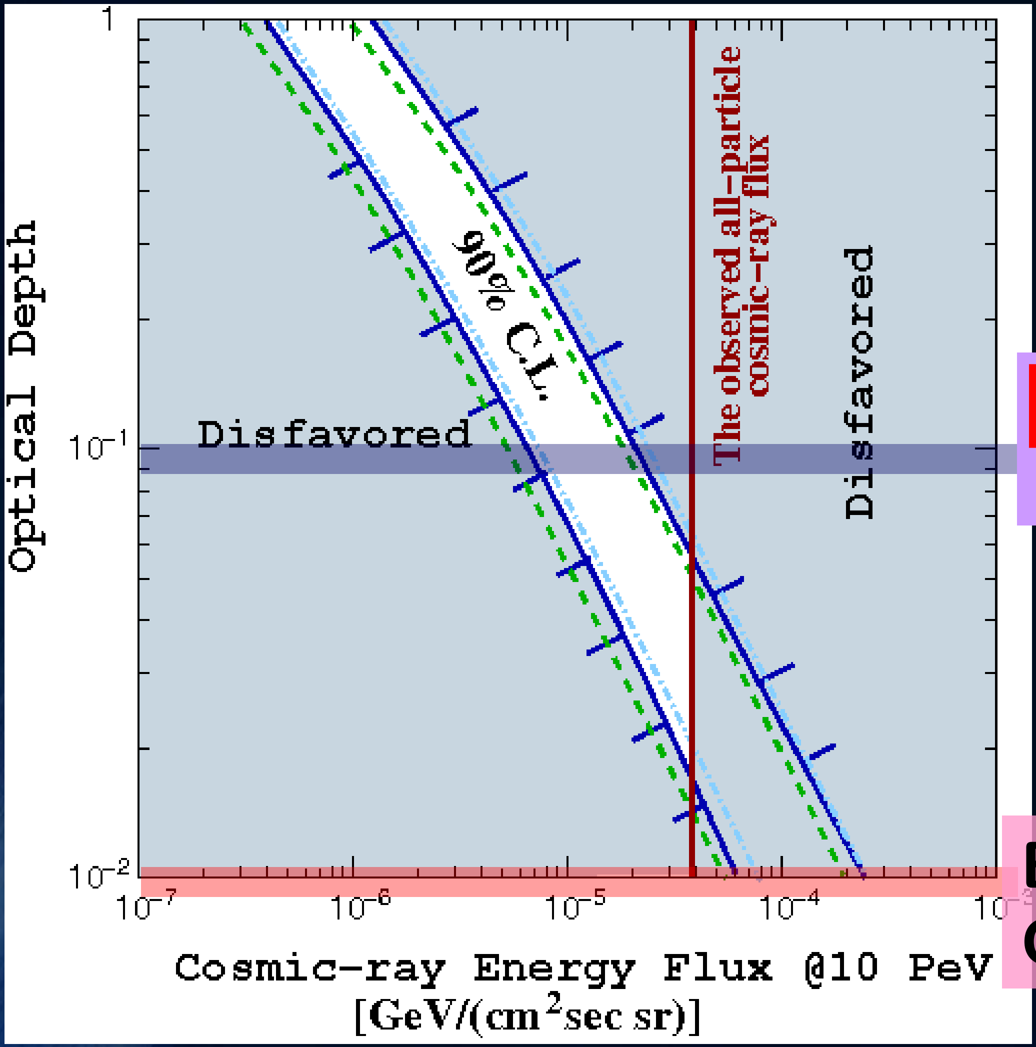


Yoshida, Takami
in preparation

extra-galactic proton flux must be > 10^{-2} of the all-particle CR flux @ 10 PeV

optical depth must be $\gtrsim 10^{-2}$

Constraints on the optical depth and extra-galactic CR flux



strong evolution

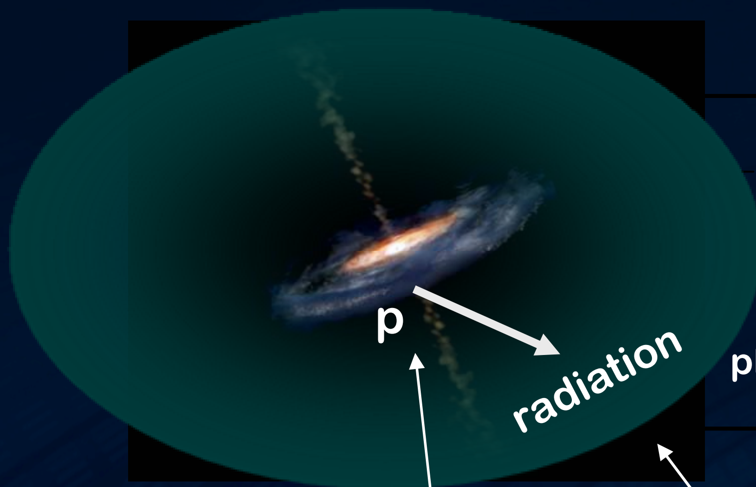
Quasars/FR-II

GRBs (internal shock)

BL Lac/FR-I

GRBs (external shock)

The Constraints on evolution (=emission history) of UHE cosmic ray sources



$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production

ν

optical depth (<1)

$$\frac{dJ_\nu}{dE} \sim F_{GZK\,CR} \frac{R_{cosmic}}{R_{GZK}} \mathbf{E}^{-\alpha} \; \tau(E) \; \zeta(z,\, m,\, z_{max},\, E)$$

Fixed to $E^{-2.3}$

Constrain them by the IceCube 100TeV-PeV observation

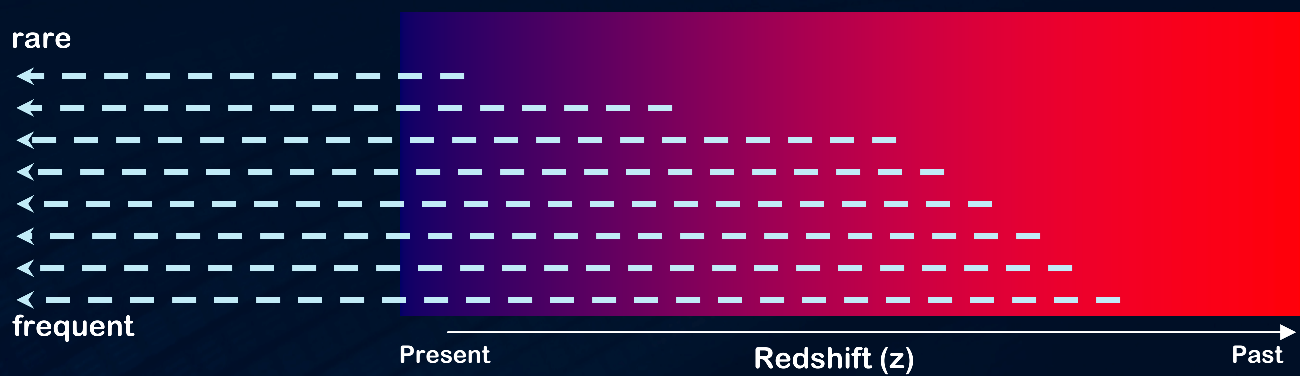
Tracing *history* of the particle emissions with ν flux

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

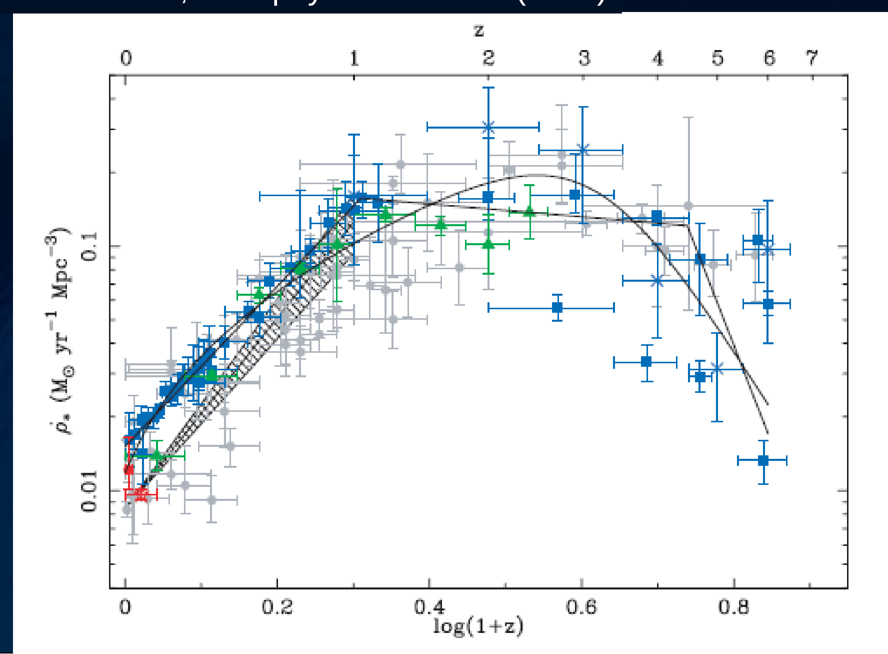


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→

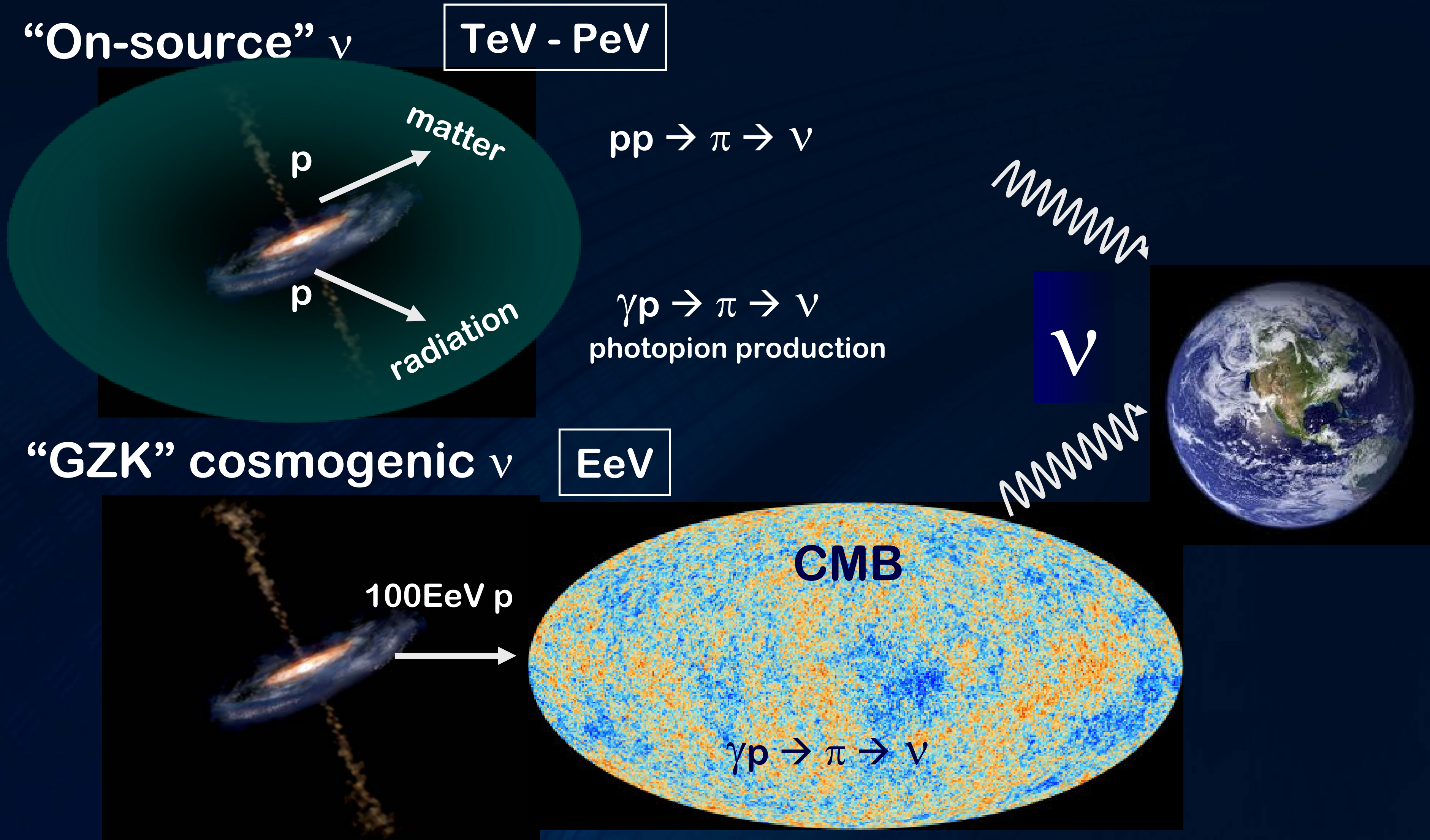


The spectral emission rate

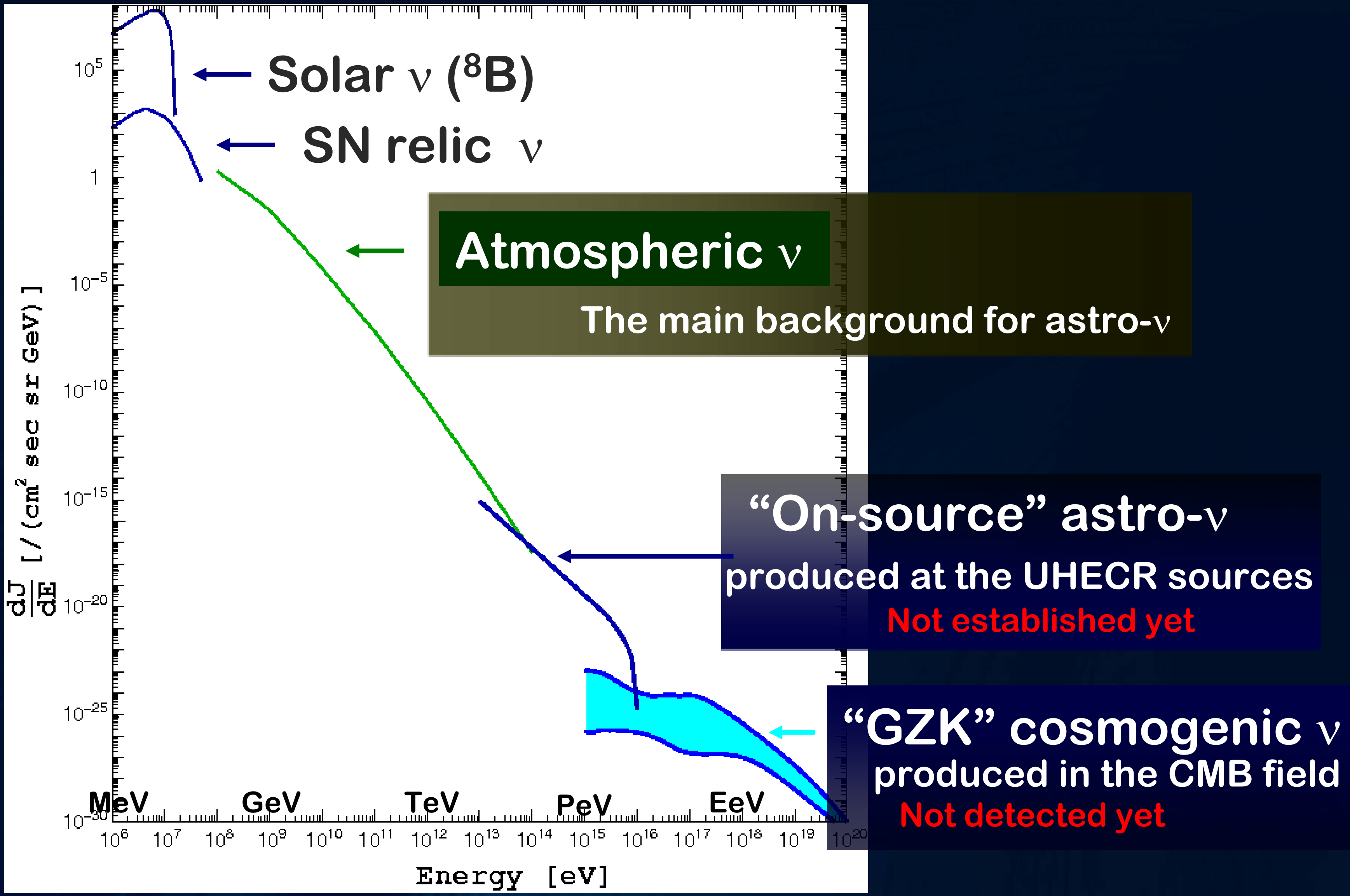
$$\rho(z) \sim (1+z)^m$$

m= 0 : No evolution

The Cosmic Neutrinos Production Mechanisms



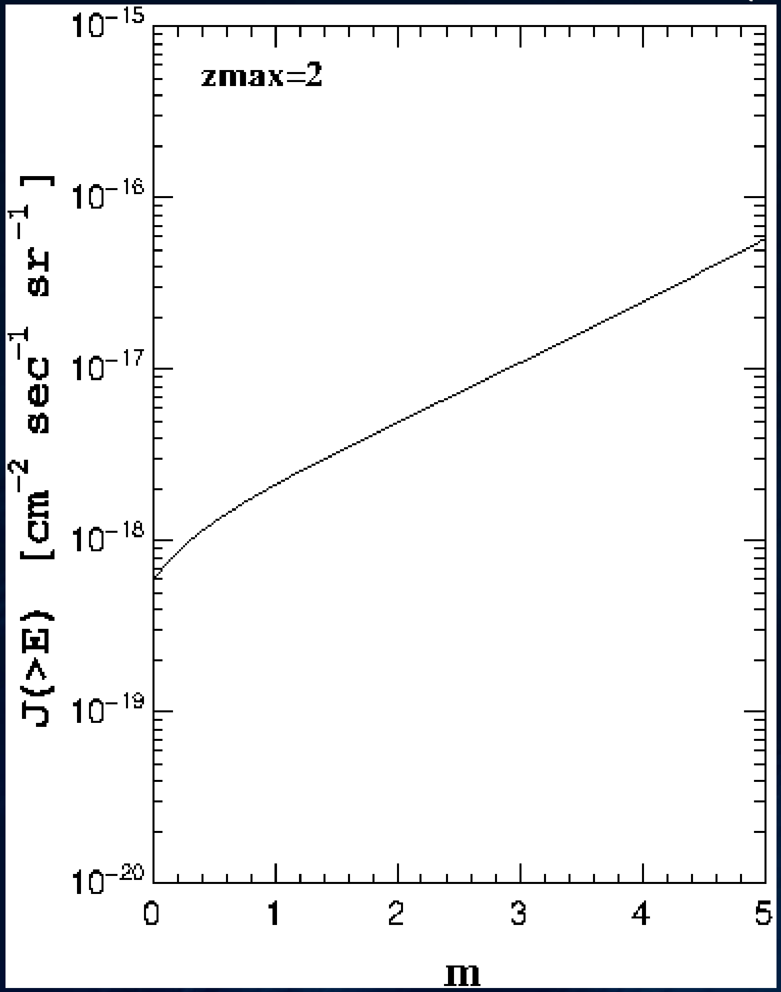
The Neutrino Flux: overview



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

Yoshida and Ishihara, PRD 85, 063002 (2012)

intensity above 1 EeV(=10^{18} eV)



more than an order of magnitude difference

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

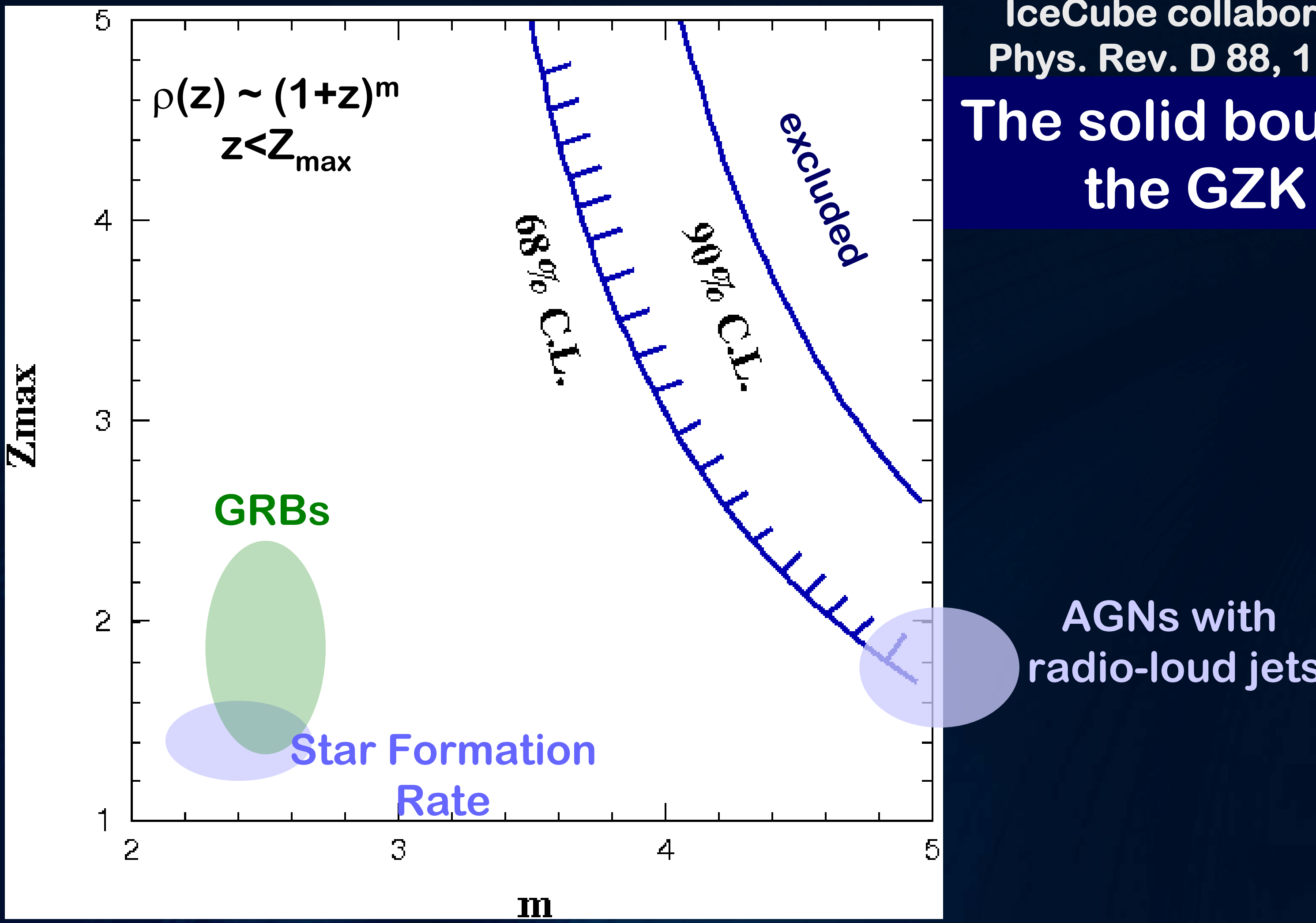
"quiet" "dynamic"

particle emissions in far-universe

The Constraints on evolution (=emission history) of UHE cosmic ray sources

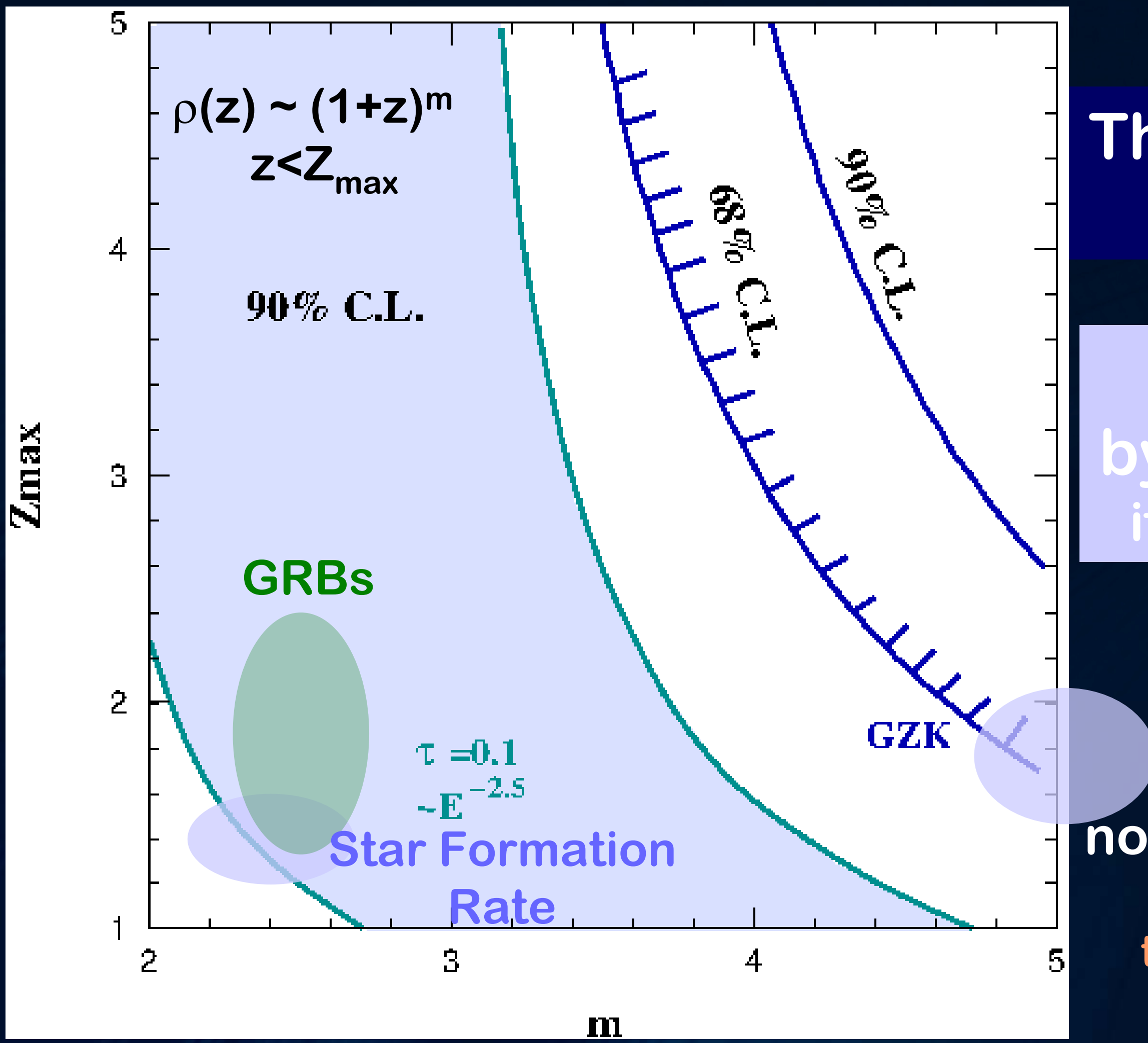
IceCube collaboration
Phys. Rev. D 88, 112008

The solid bound by the GZK ν



The Constraints on evolution (=emission history) of UHE cosmic ray sources

Yoshida, Takami
in preparation



The solid bound by the GZK ν

+ by the on-source ν if optical depth ~0.1

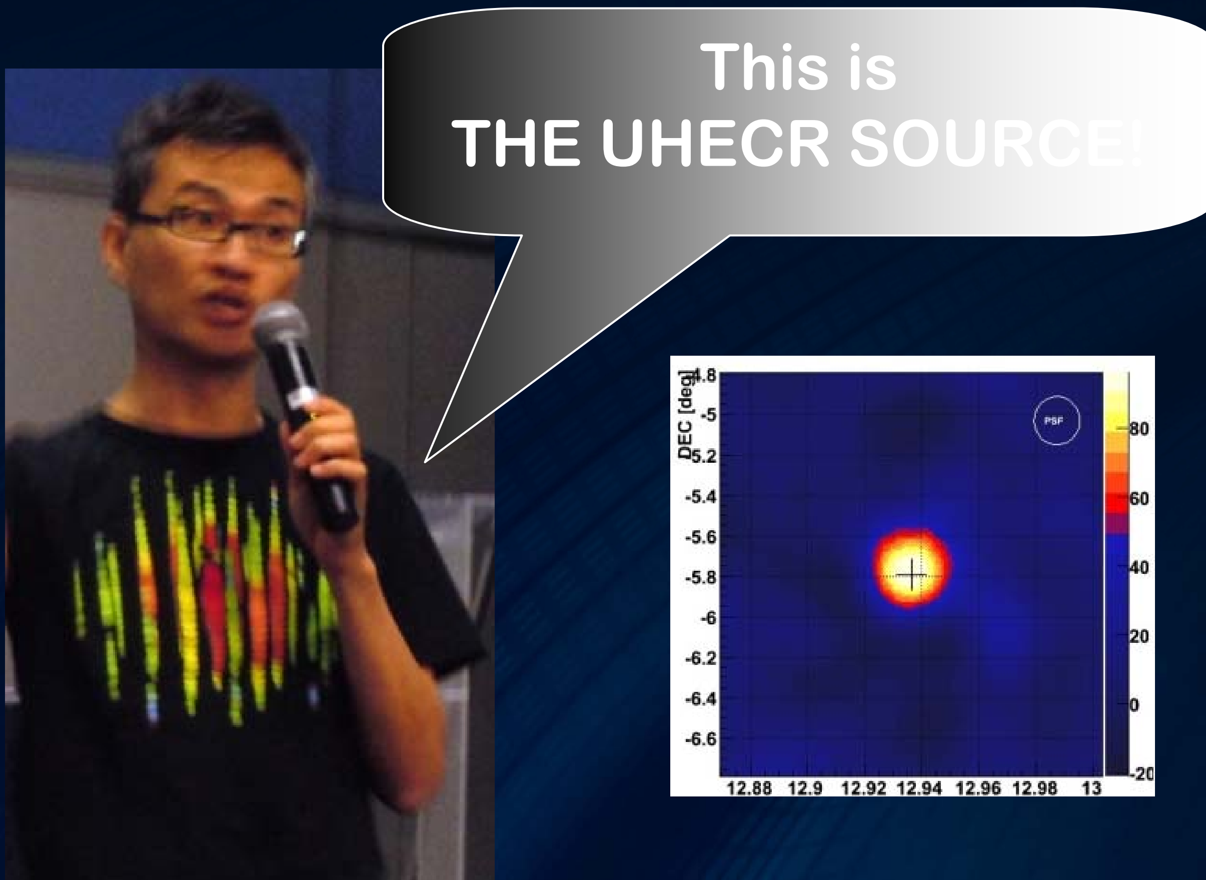
AGNs with radio-loud jets

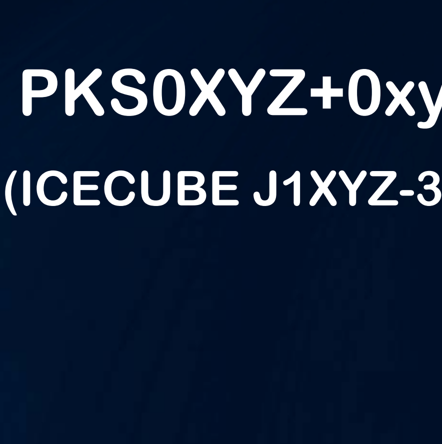
no high-redshift emission

consistent with the star formation rate

A Personal View:
Diffuse Search Vs. Point Sources

But we want to ID a source(s) in the end!

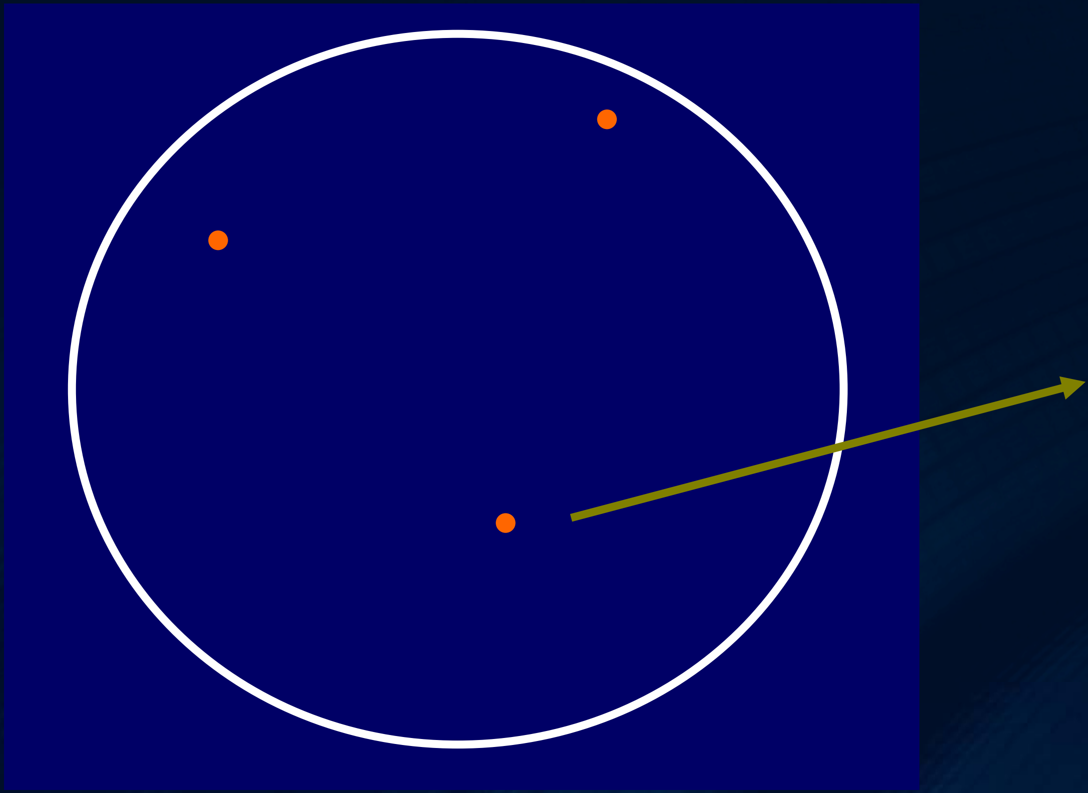




PKS0XYZ+0xy

(ICECUBE J1XYZ-3xy)

The Multi Messengers:
UHE $\nu \rightarrow \gamma$

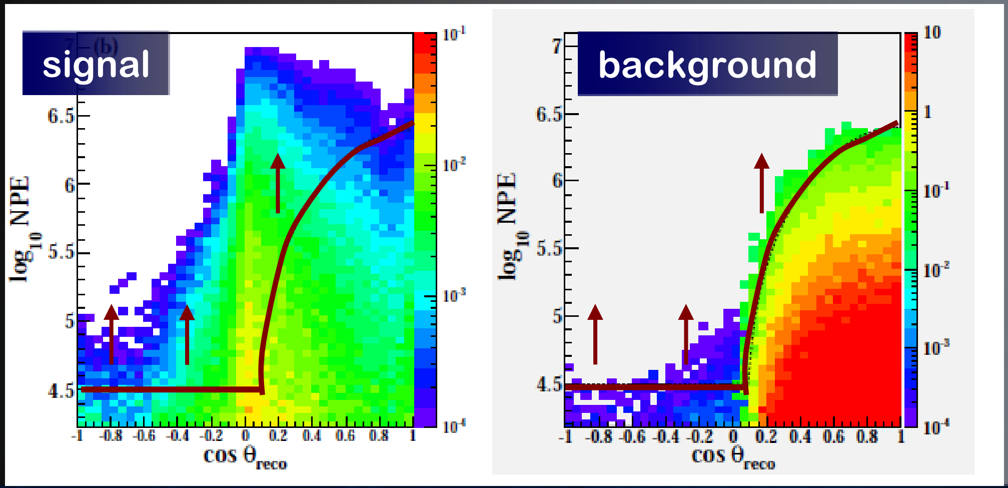


look up this direction!

ν **"GFU"** γ

The Multi Messengers:
UHE $\nu \rightarrow \gamma$

The IceCube UHE ν search



- sensitive to ν > O(10PeV)
- the robust algorithm

~ 2 events/year for $\nu_{e+\mu+\tau}$ of

$E^2\phi = 3\times10^{-8} GeV m^{-2} sec^{-1} sr^{-1}$

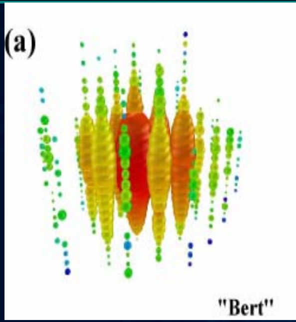
BG: ~ 0.1 event/year

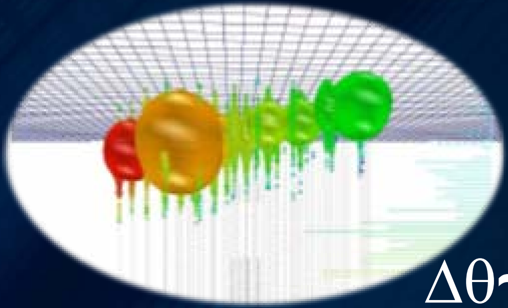
cascade

track

new

event topology separation

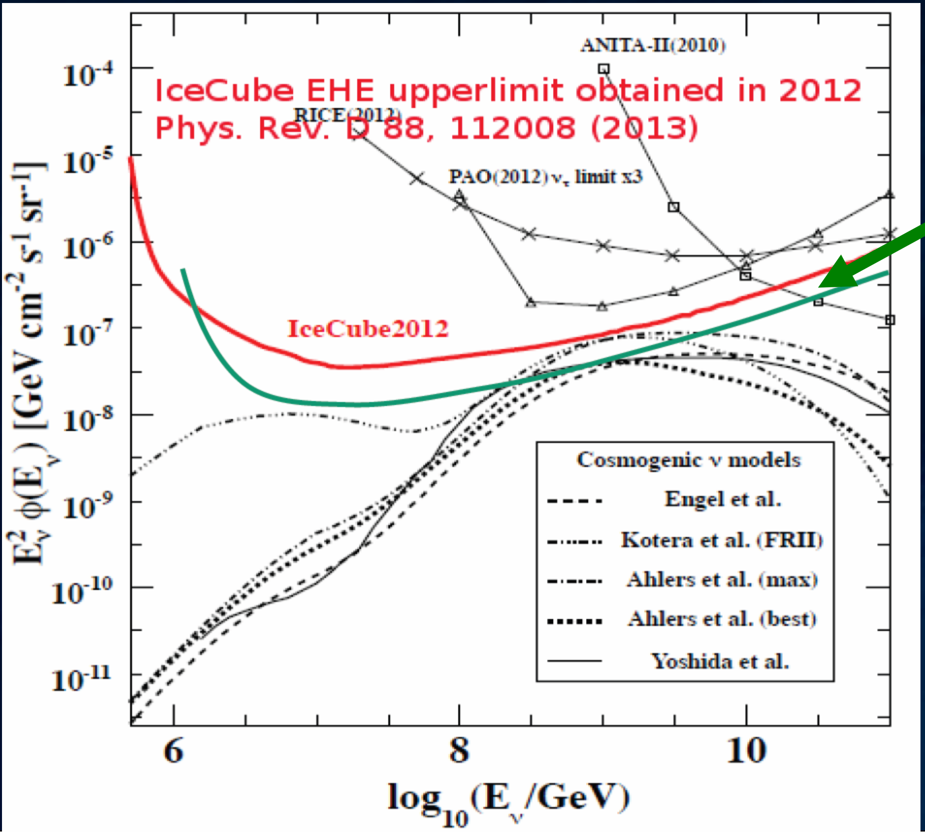




$\Delta\theta$~1deg

Outlook for IceCube and Neutrino Astronomy

- UHE (> PeV) ν → γ multi-messenger
- Super UHE (~ EeV) ν search with 2013-2014 data
  GZK ν search → understanding of the origin of highest energy cosmic rays



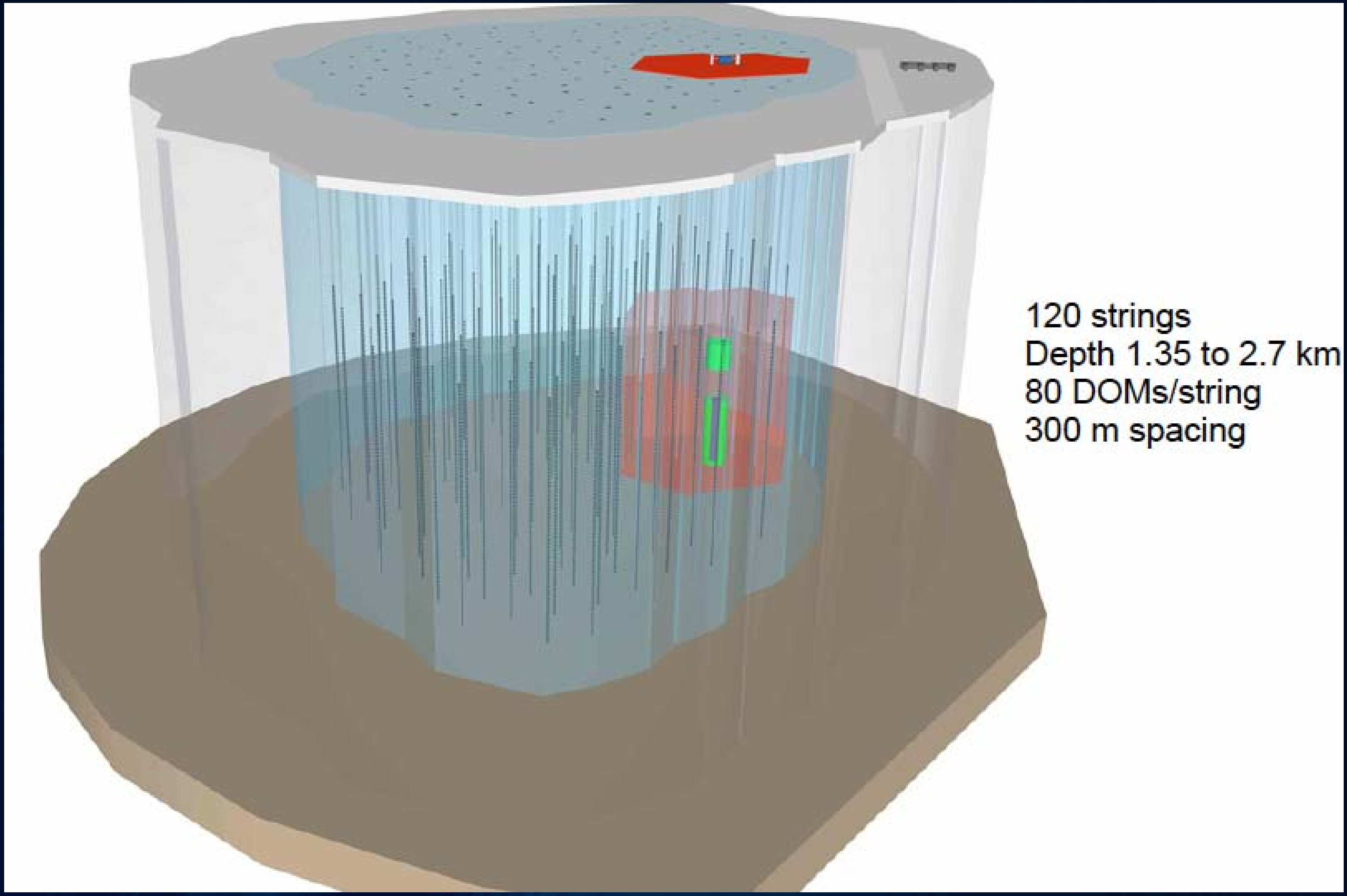
the projected sensitivity

some technical improvements
- track ←→ cascade separation
- airshower veto

A fair chance to see 100PeV-EeV ν with $\delta\theta \lesssim$ 2deg

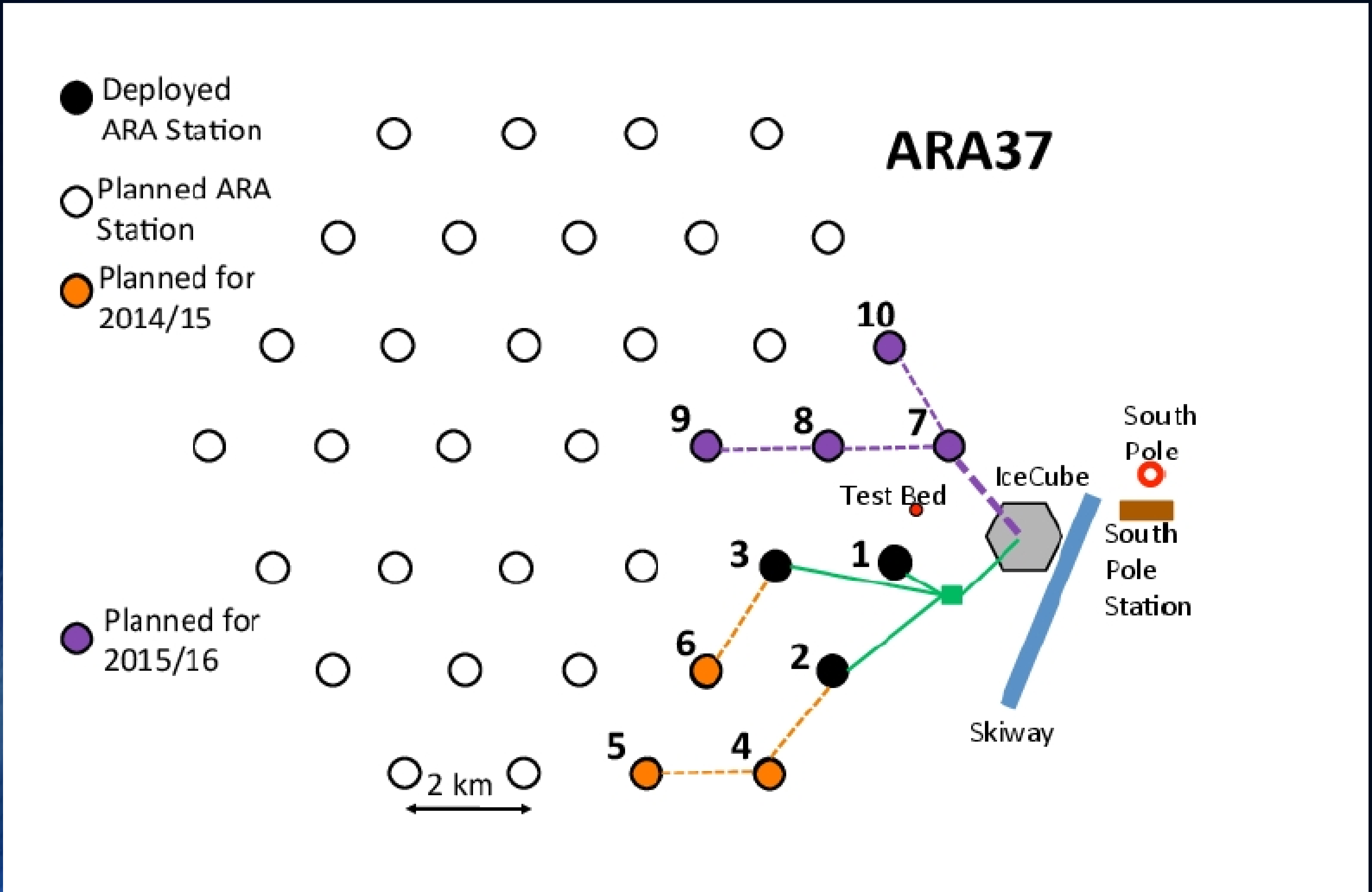
Outlook for IceCube and Neutrino Astronomy

bigger, and get more events…..



Outlook for IceCube and Neutrino Astronomy

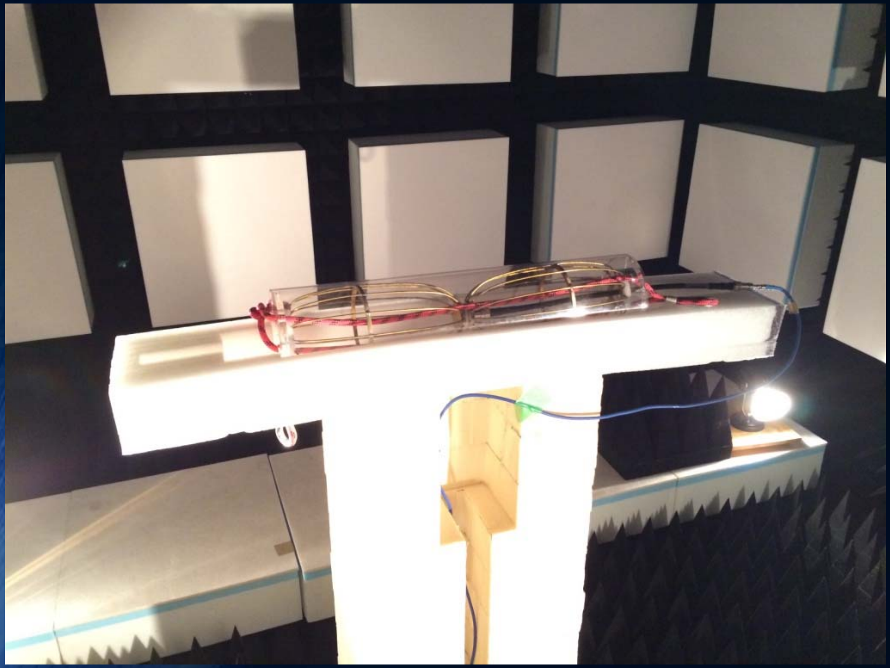
bigger, and get more events…..



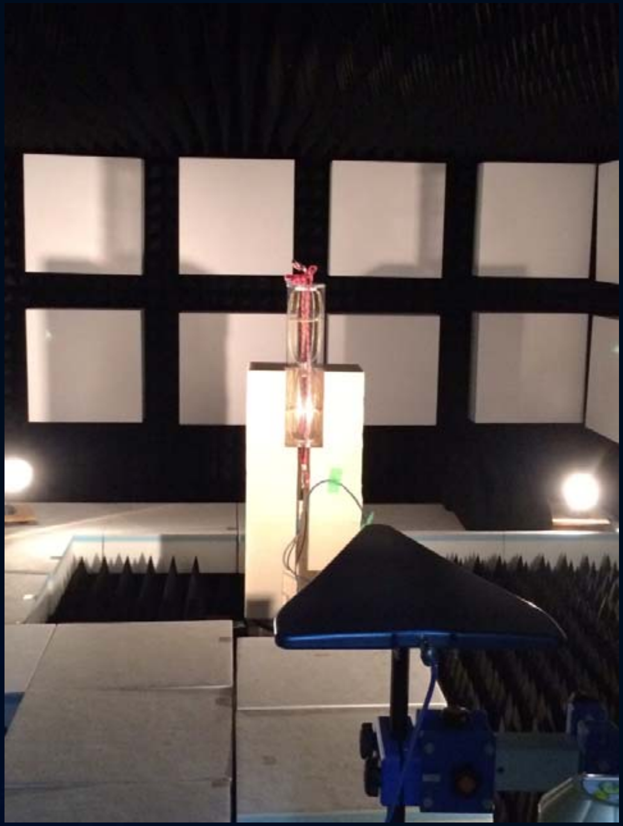
ARA detector assembly and calibration

PeV (可視光の千兆倍のエネルギー)よりもっと高エネルギーな宇宙ニュートリノ探索

目指せ 1000 PeV： GZK ν detection!



製作したARA実験用検出器の信号応答を
電波暗室中で測定



どんなサイエンスをねらうか？

研究の価値とは

$$V = I \times C$$

value(価値)　Importance(重要性)　Completeness(達成度)

I ~ C が理想的。I<C でも OK

私の方程式

$$V = \exp[I] \times C$$

I < C じゃだめ。I > C くらいじゃないと。

I >> C になってしまうリスクをとって対策を講じておく。