



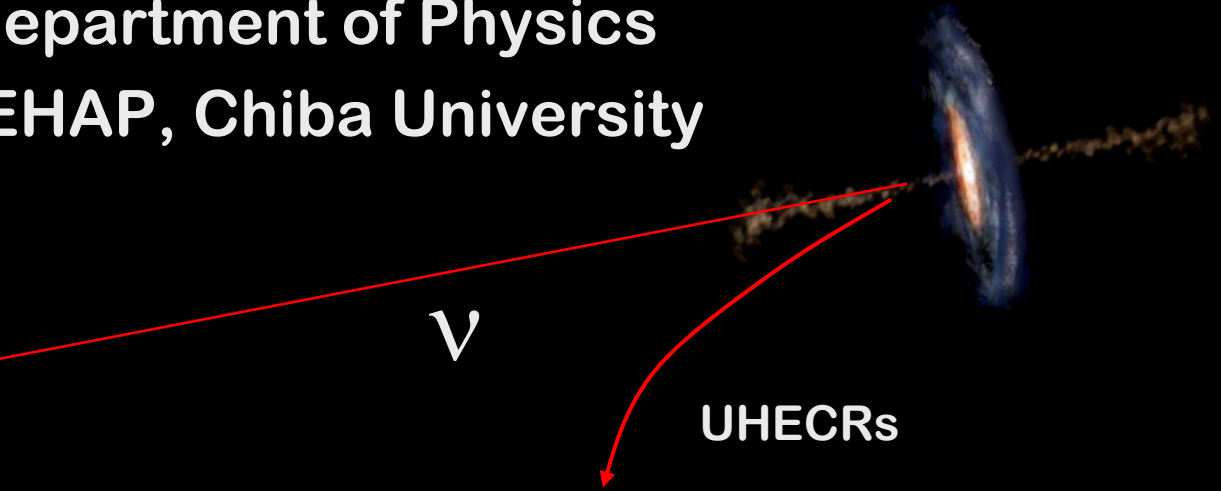
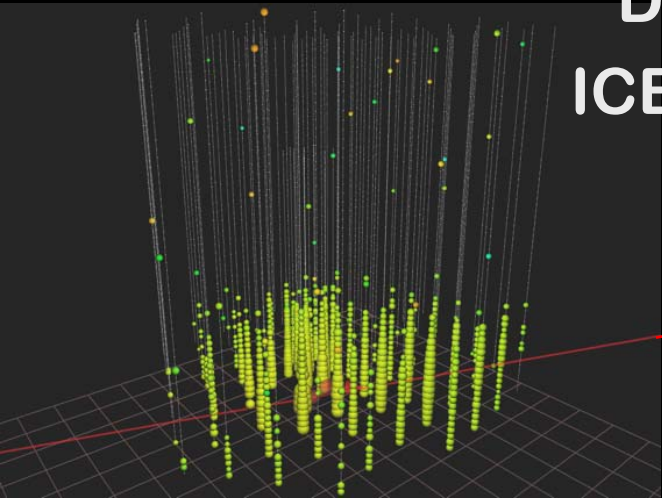
Probing the origin of UHECRs with neutrinos

The recent results from IceCube and its outlook

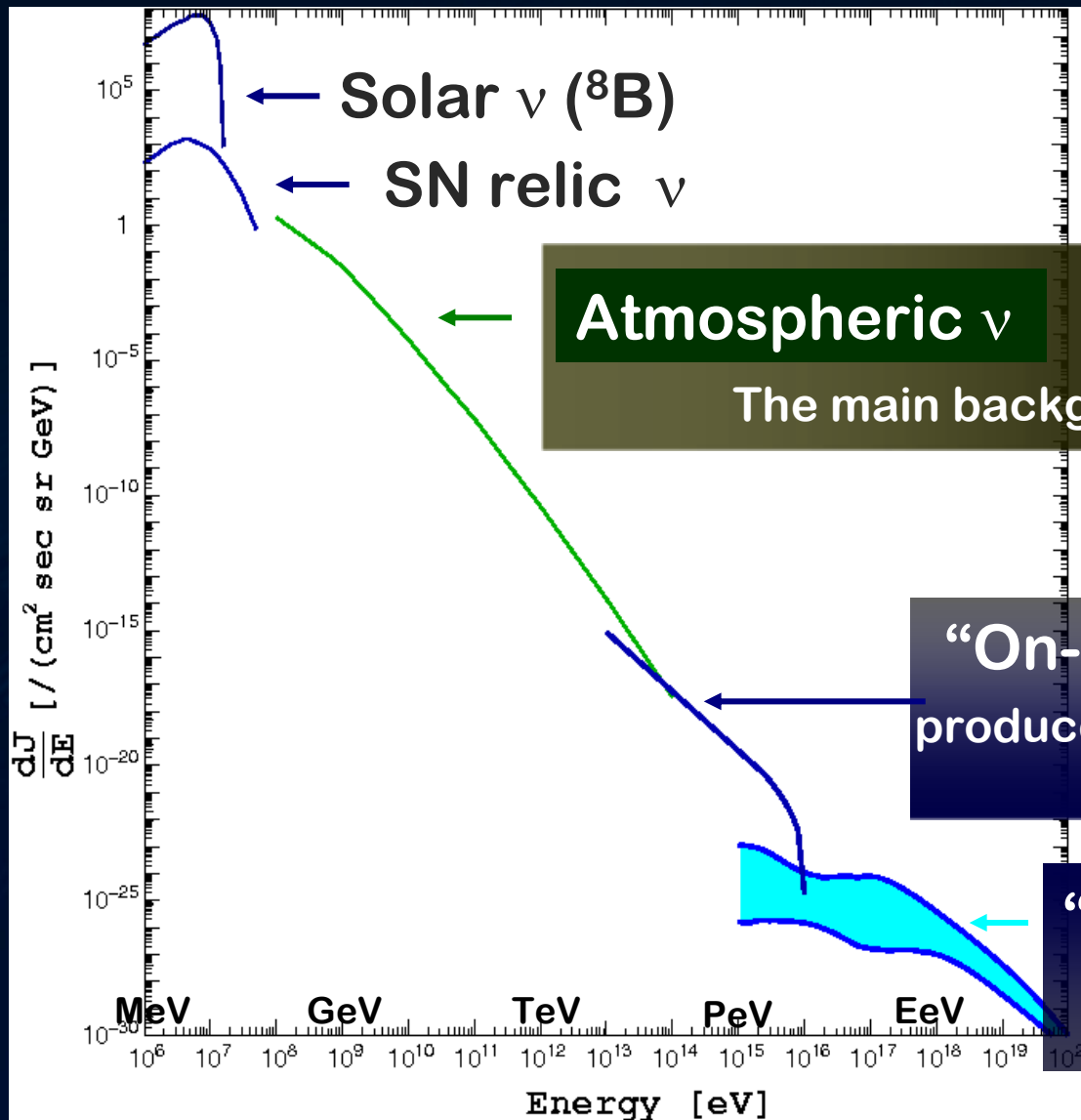
Shigeru Yoshida

Department of Physics

ICEHAP, Chiba University



The Neutrino Flux: overview



← Solar ν (^8B)

← SN relic ν

← Atmospheric ν

The main background for astro- ν

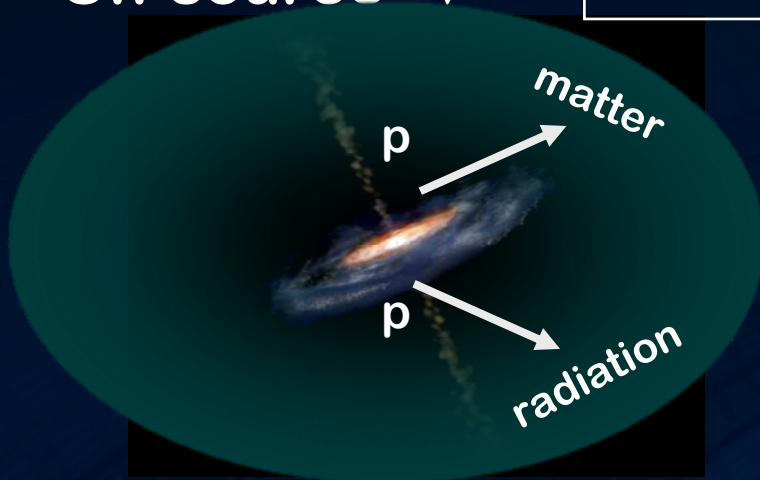
← "On-source" astro- ν
produced at the UHECR sources
Not established yet

← "GZK" cosmogenic ν
produced in the CMB field
Not detected yet

The Cosmic Neutrinos Production Mechanisms

“On-source” ν

TeV - PeV



$$pp \rightarrow \pi \rightarrow \nu$$

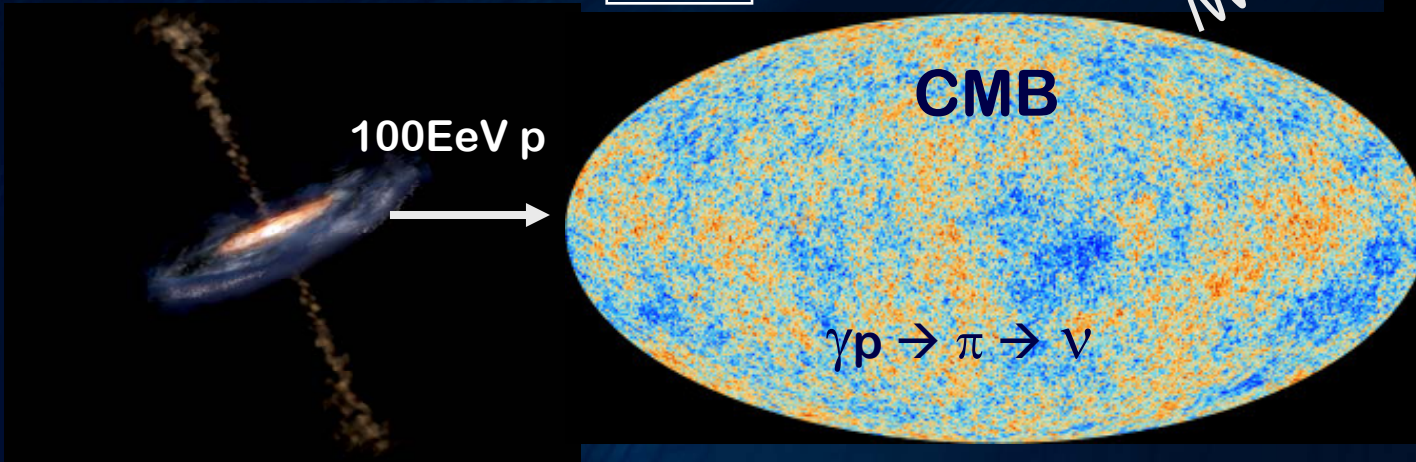
$$\gamma p \rightarrow \pi \rightarrow \nu$$

photopion production



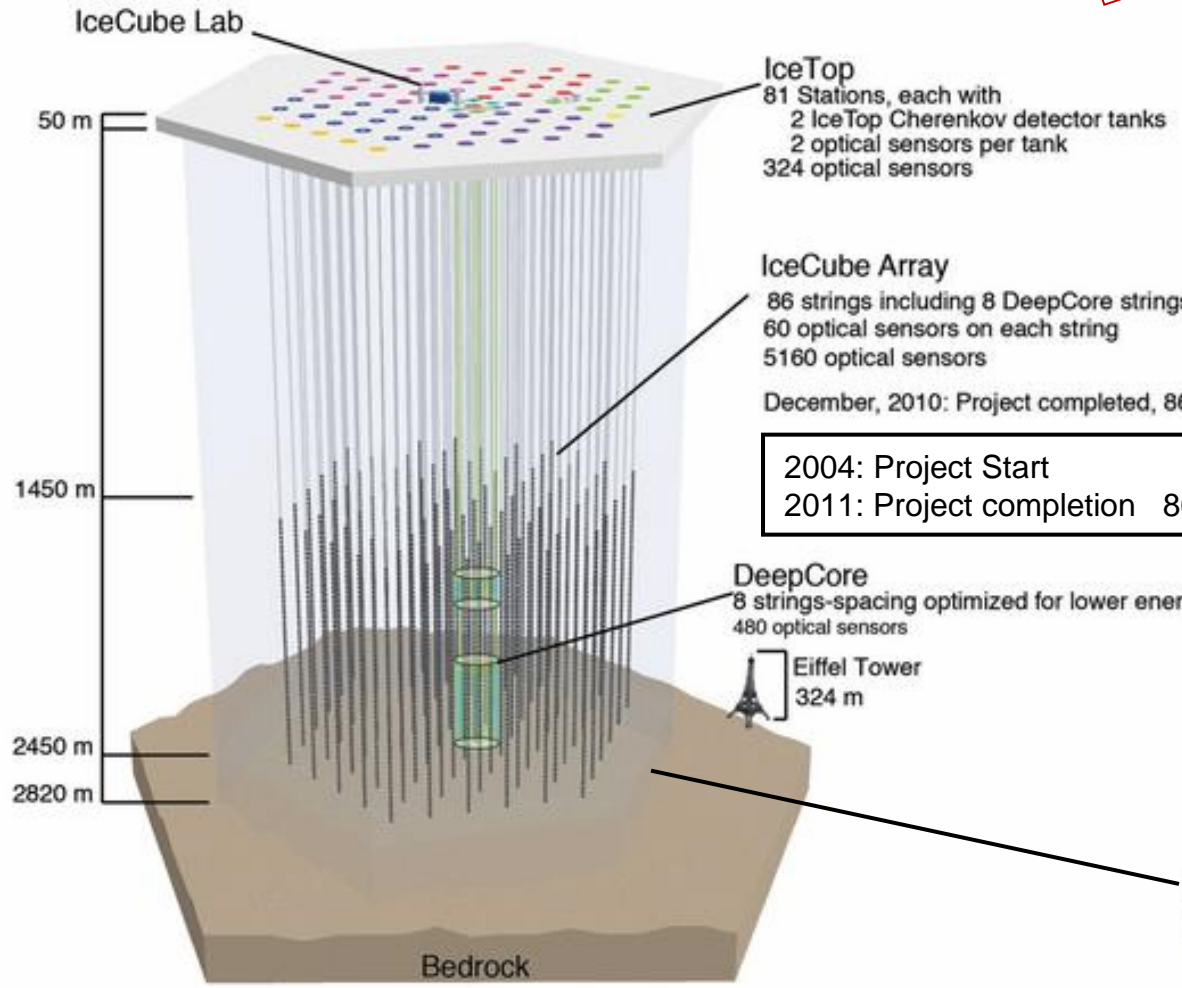
“GZK” cosmogenic ν

EeV



The IceCube Neutrino Observatory

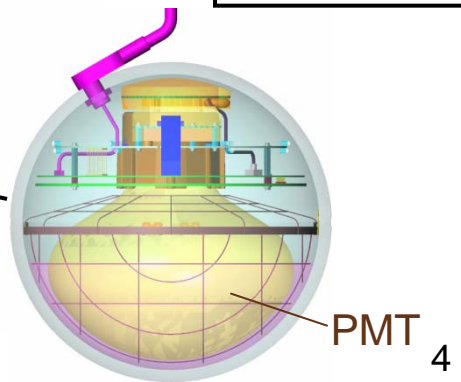
Completed: Dec 2010



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

Digital Optical Module (DOM)

Constructions 2005-2011

Detectors shipped from Japan



Drill House



Researchers working on deployment

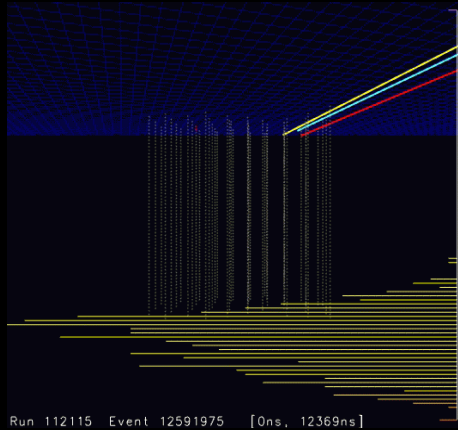


The IceCube Lab 「Beer Can」





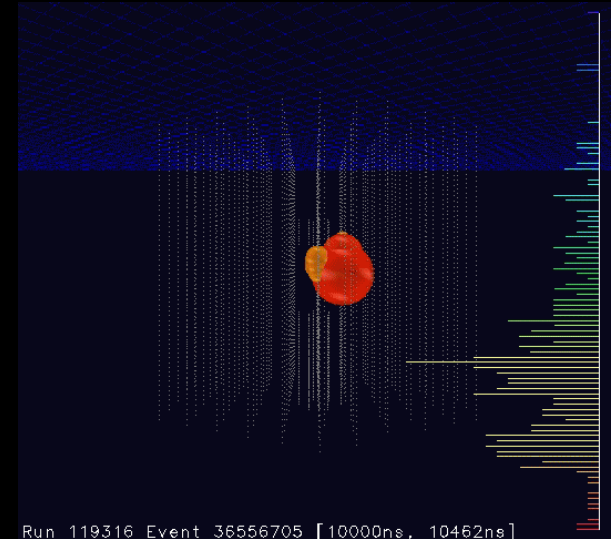
Topological signatures of IceCube events



Run 112115 Event 12591975 [0ns, 12369ns]

Down-going track

- atmospheric μ
- secondary produced μ from ν_μ
 τ from ν_τ @ \gg PeV



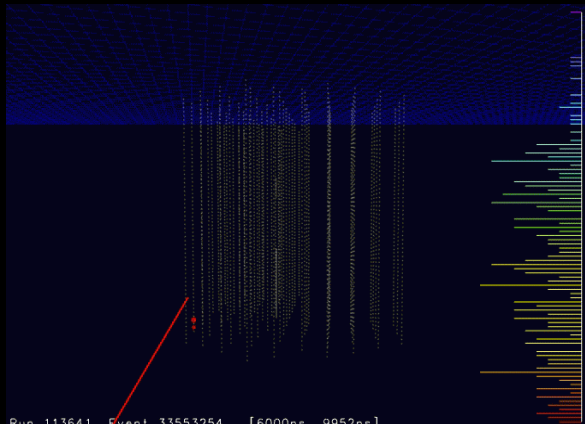
Run 119316 Event 36556705 [10000ns, 10462ns]

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



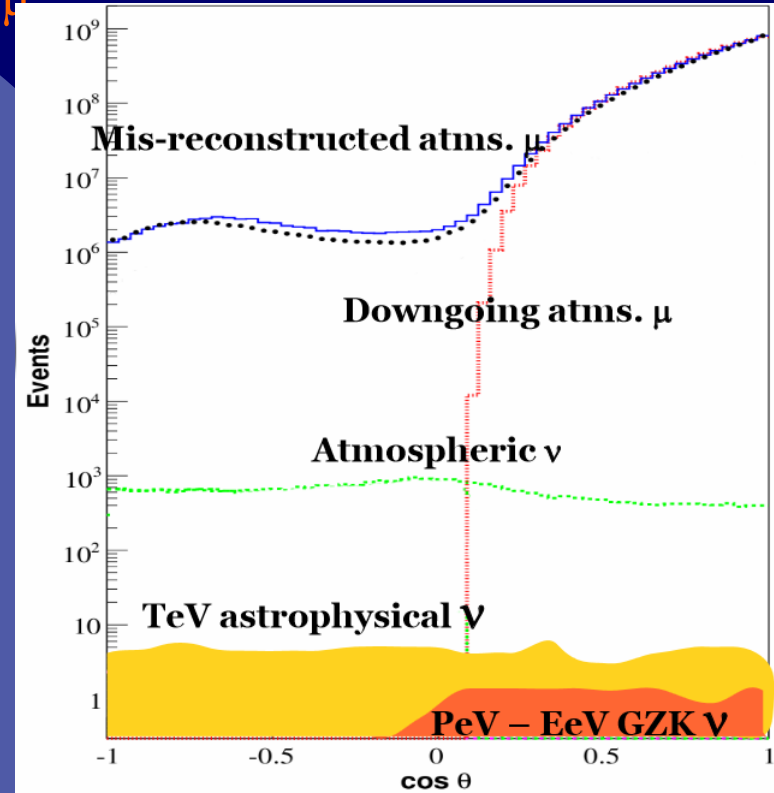
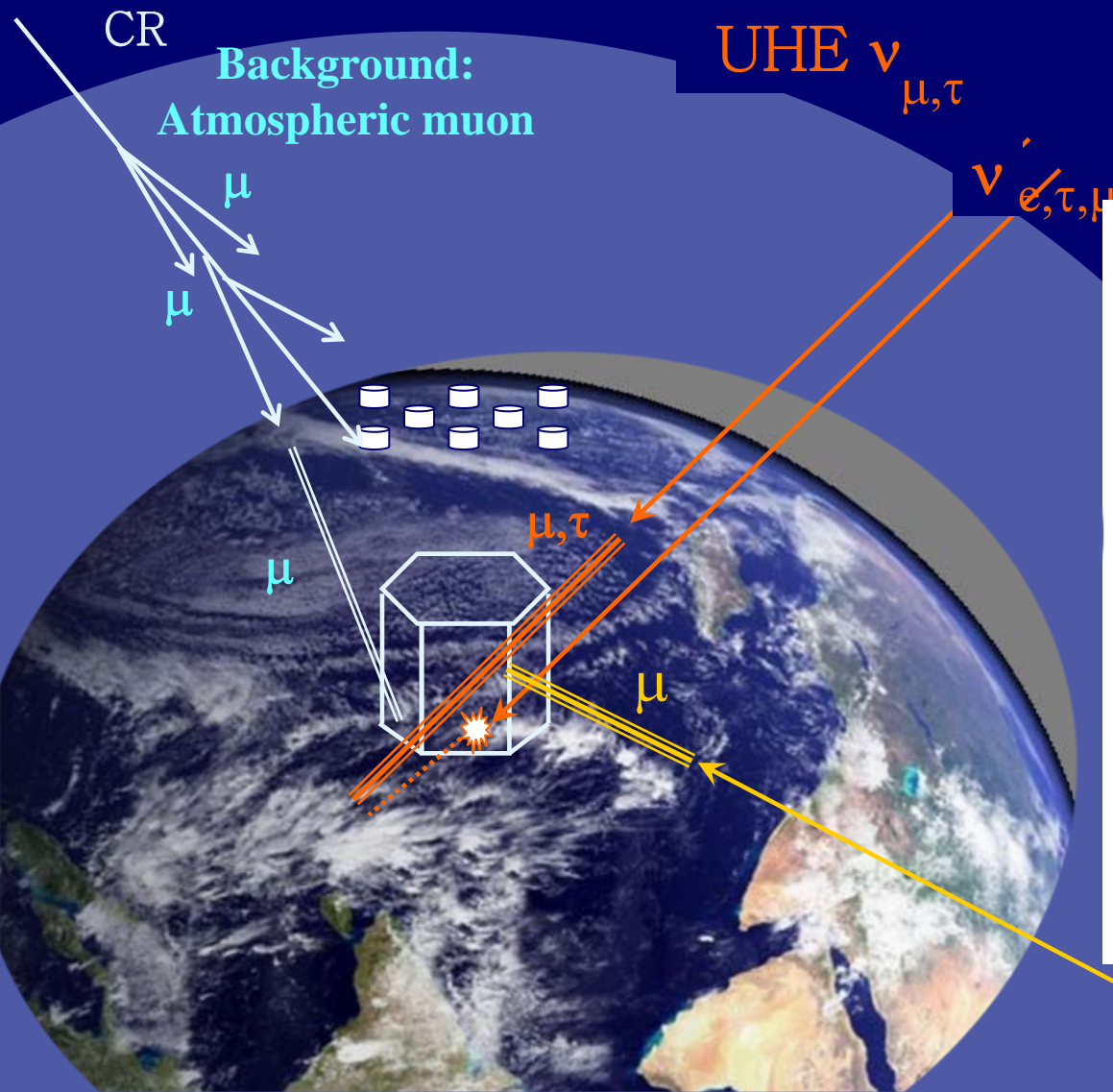
Run 113641 Event 33553254 [6000ns, 9952ns]

Up-going track

- atmospheric ν_μ

Neutrino Signatures

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



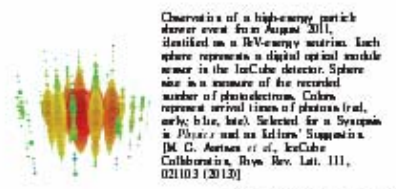


Post Bert & Ernie

The Discovery Analyses



NEWSPAPER



Observation of a high-energy particle shower event from August 2011, identified as a BeV-energy muon. 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, orange, blue, black). Selected for a Symposium in *Physics* and as Editors' Suggestion. [M. C. Aarssen *et al.*, IceCube Collaboration, *Phys. Rev. Lett.* 111, 021103 (2013)]

PHYSICAL REVIEW LETTERS[®]

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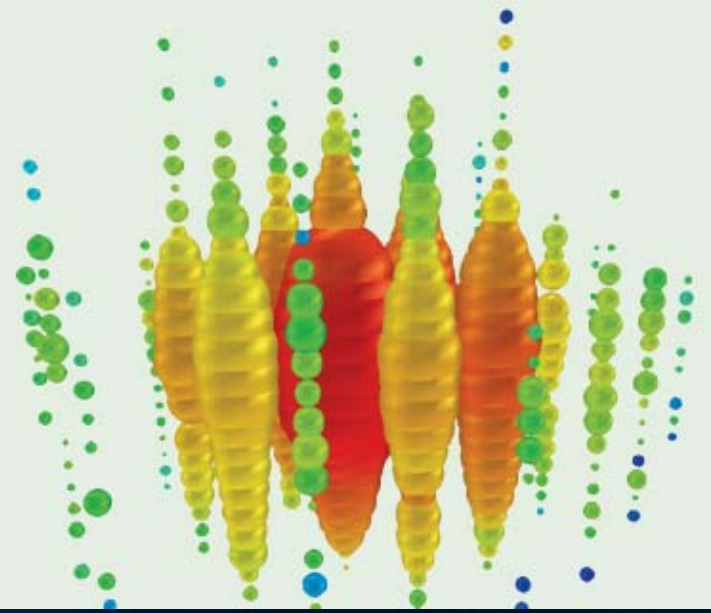
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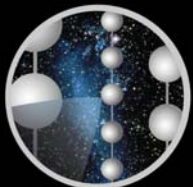
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PHYSICAL REVIEW LETTERS[®]

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ICECUBE

TeV



PeV

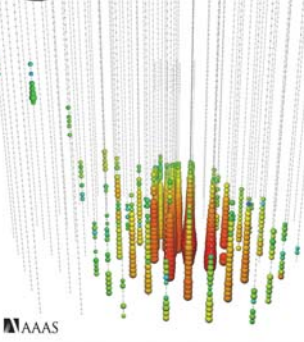
EeV

Mid Energy (60 TeV-)

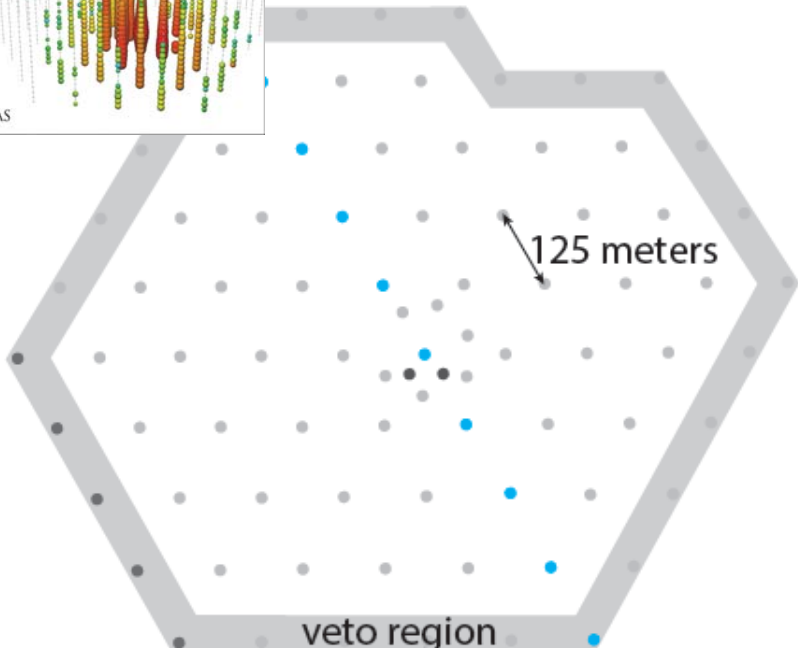
look for only events with their interaction vertices within the fiducial volume

Science

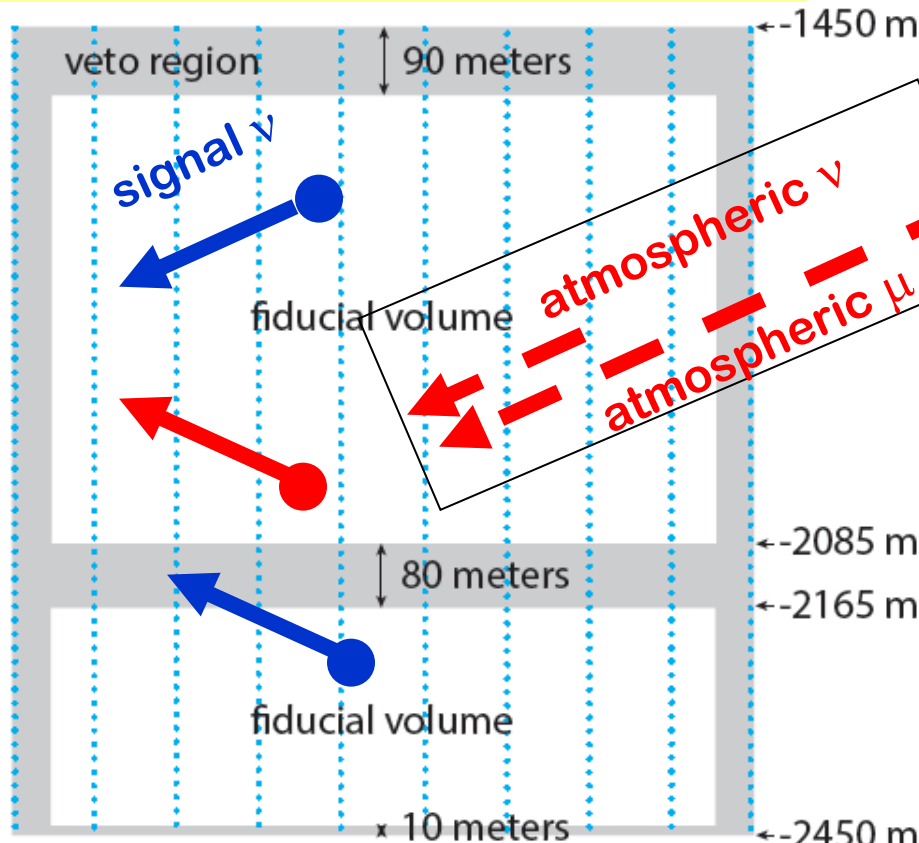
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AAAS



Top



Side

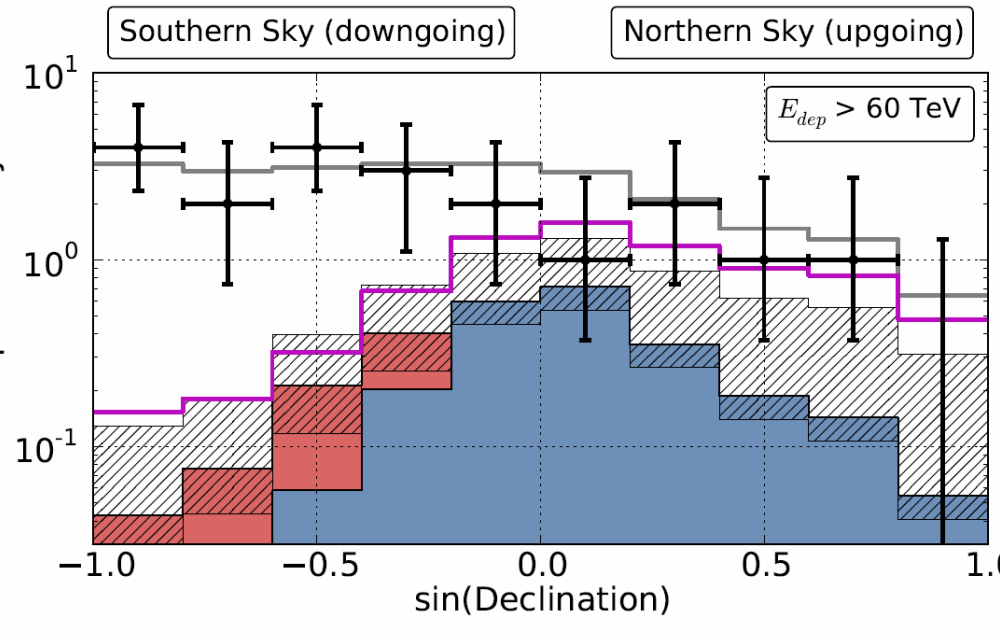
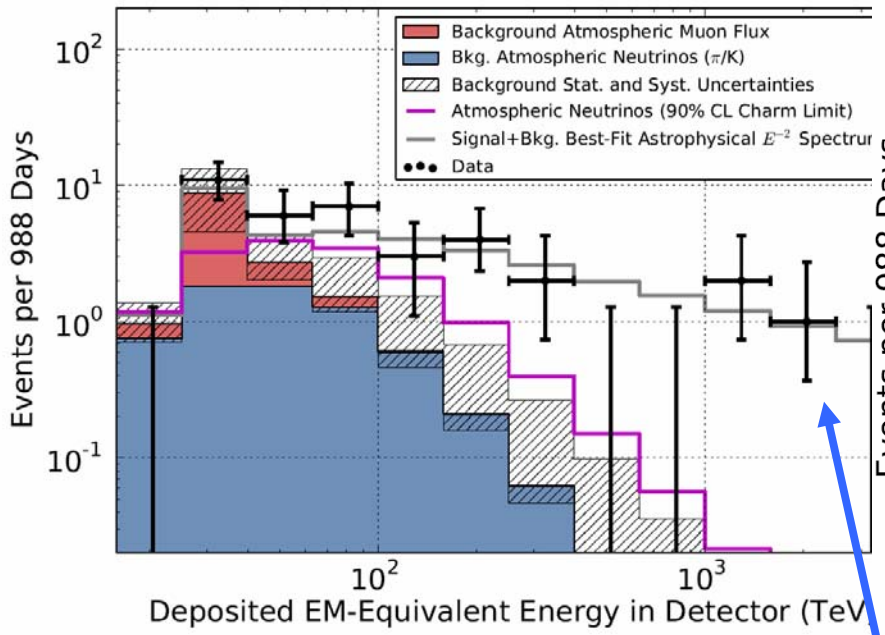


TeV PeV EeV

Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

IceCube collaboration
Phys. Rev. Lett. 113, 101101



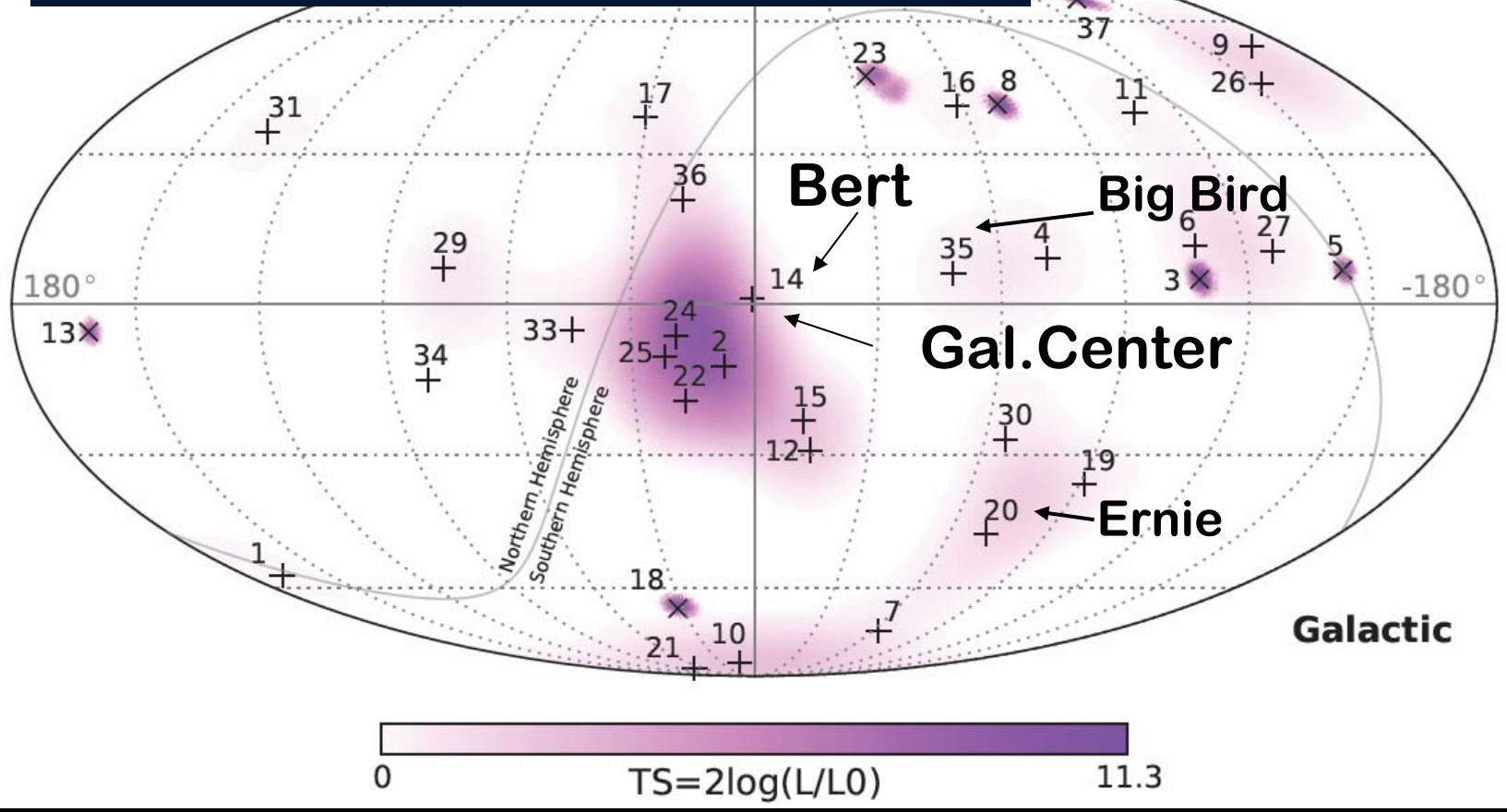
2PeV
"Big Bird"



TeV PeV EeV

Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)





TeV

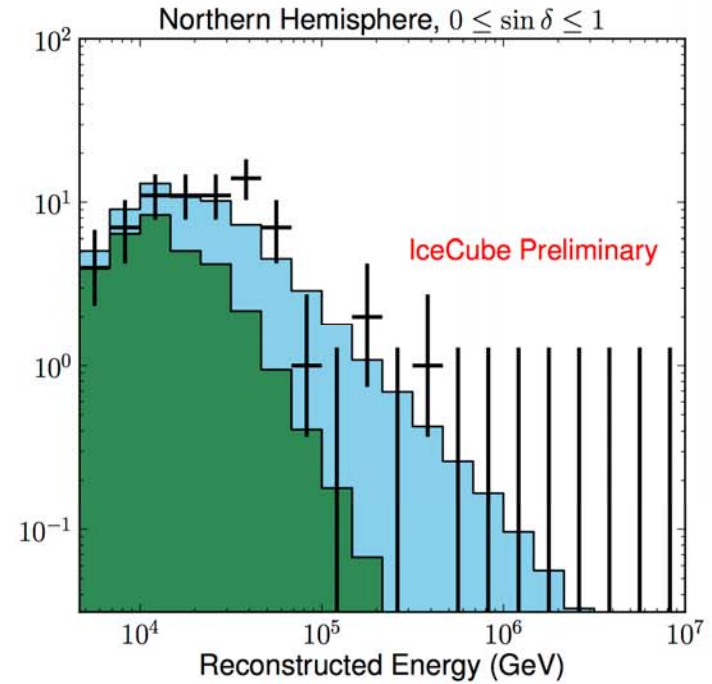
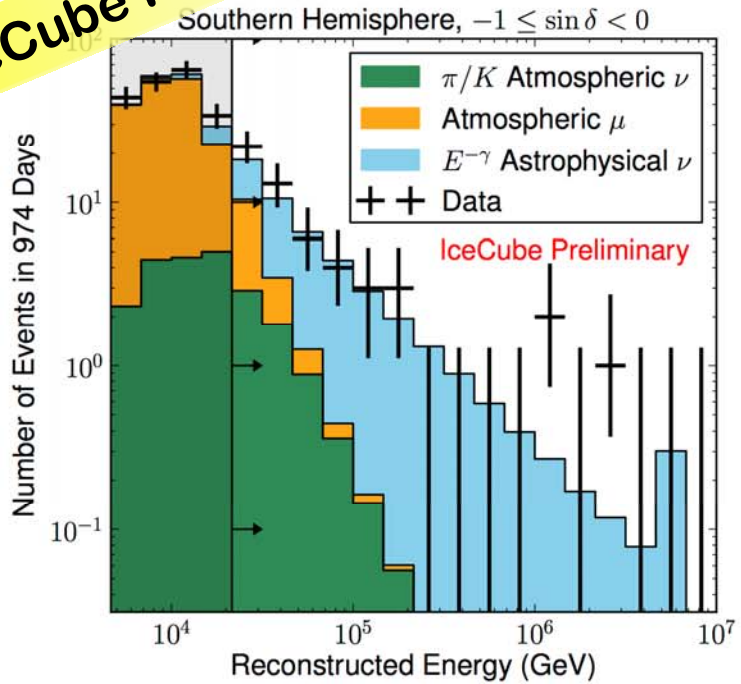
PeV

EeV

Mid Energy (10 TeV-)

veto + “cascade”

IceCube Preliminary





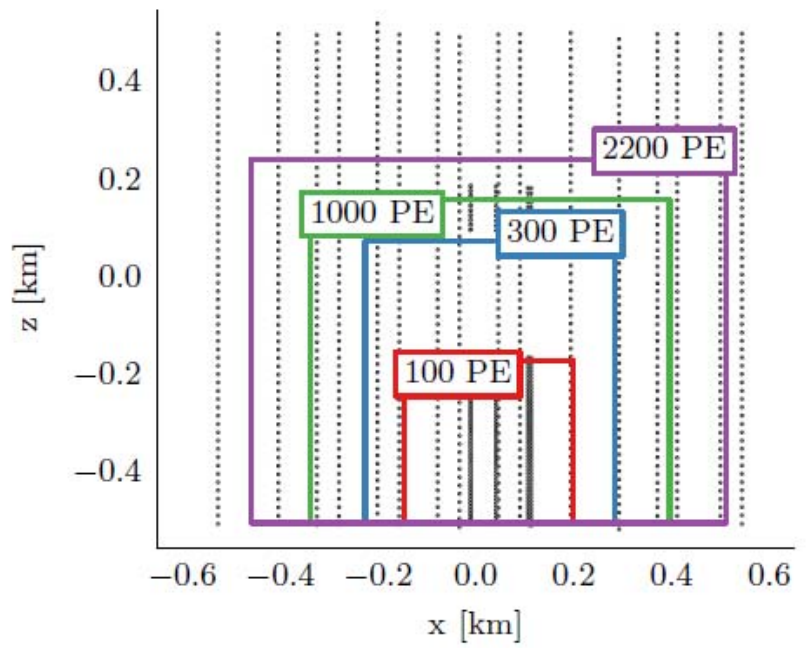
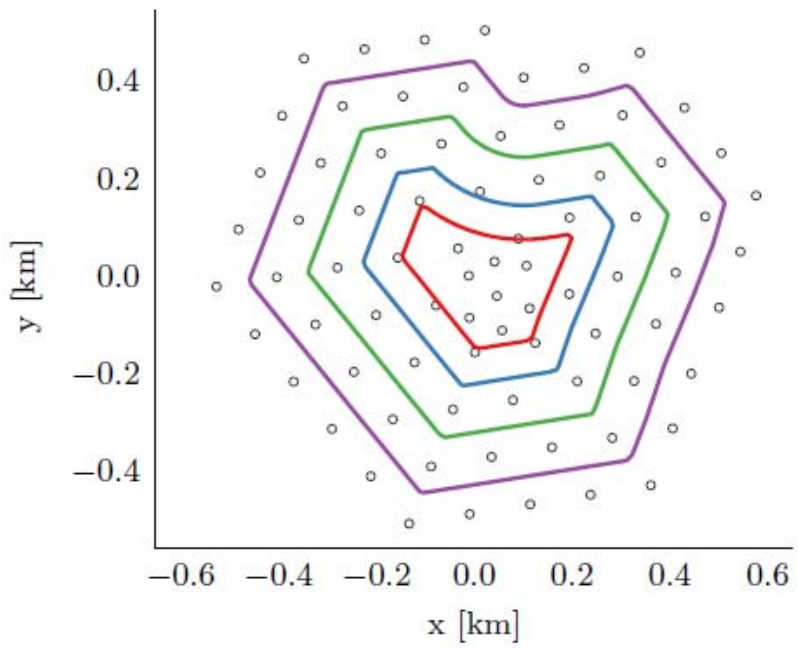
TeV

PeV

EeV

LE (<10 TeV)

Energy-dependent active veto





TeV

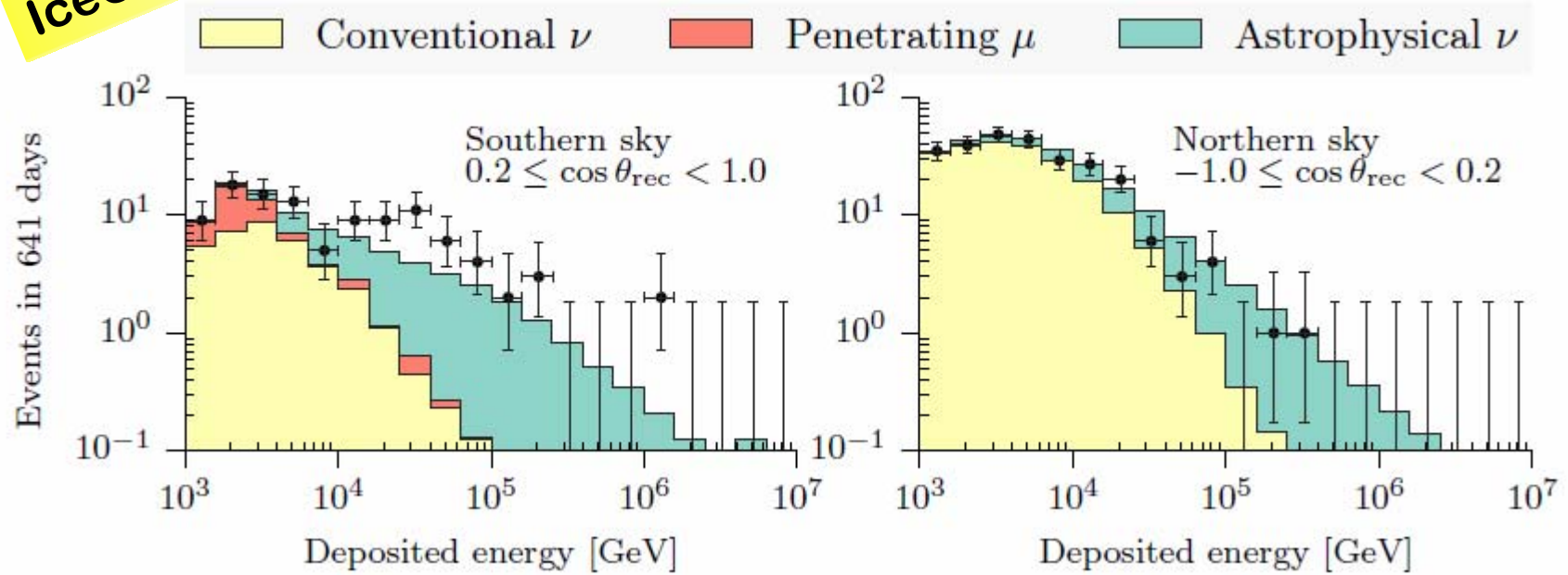
PeV

EeV

LE (<10 TeV)

IceCube Preliminary

IceCube 2 years data (2010-2012)





TeV

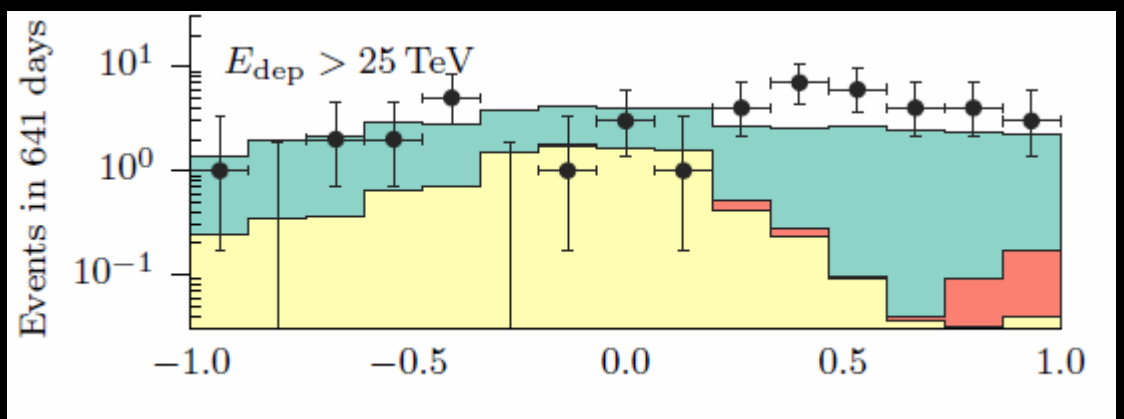
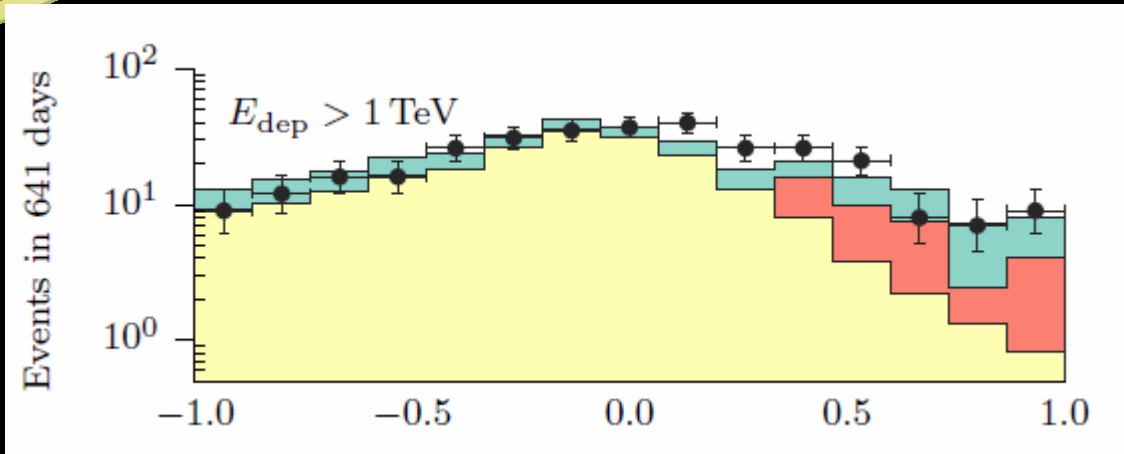
PeV

EeV

LE (<10 TeV)

IceCube Preliminary

IceCube 2 years data (2010-2012)





TeV PeV EeV

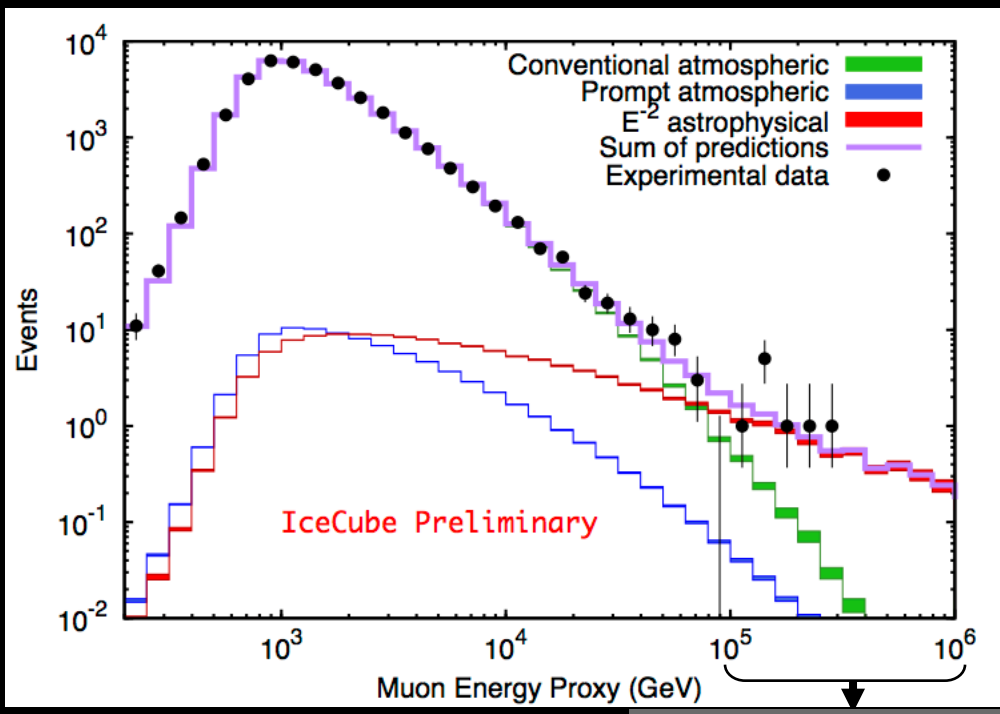
VHE (100 TeV-PeV)

The “traditional” ν_μ search
looking into upgoing tracks

IceCube 2 years data (2010-2012)

$\nu_\mu \rightarrow \mu$ detected as upgoing track

IceCube Preliminary



3.9 σ excess
over the atmospheric BG

$$E^2 \phi(E) \sim 9.6 \times 10^{-9} \text{ [GeV/cm}^2 \text{ sec sr]}$$

ν_μ

$E_\nu = O(100\text{TeV})$



TeV

PeV

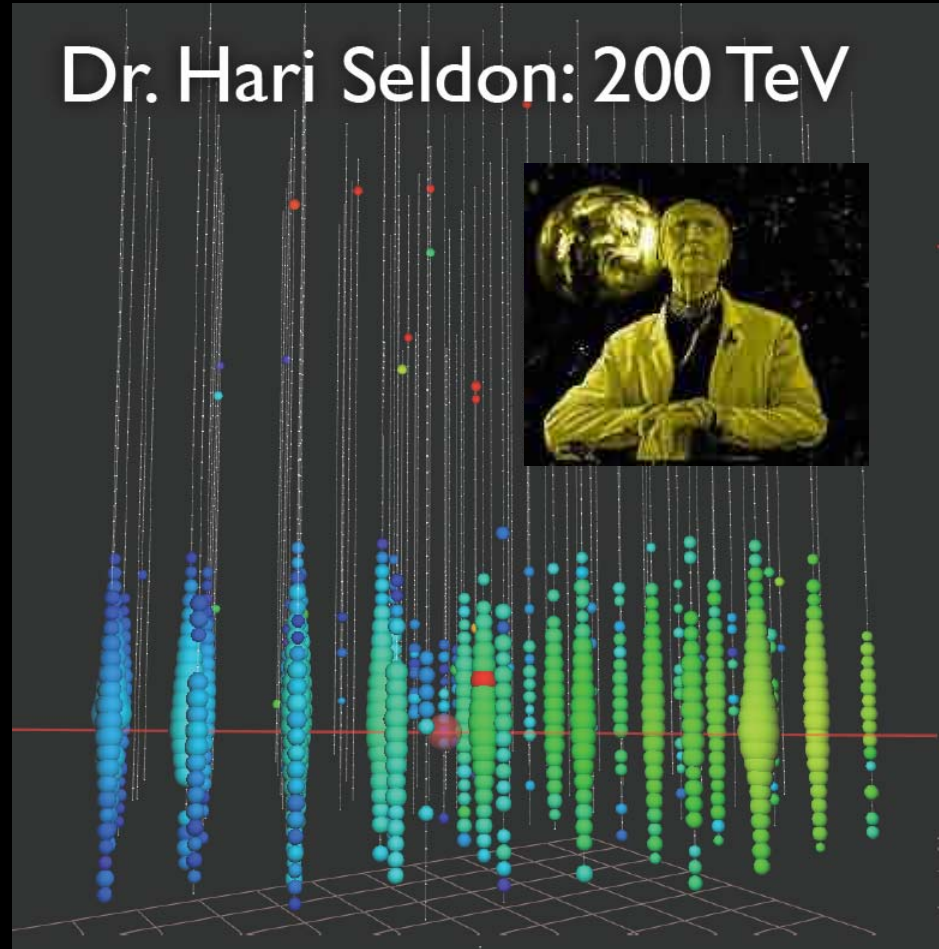
EeV

VHE (100 TeV-PeV)

The “traditional” ν_μ search
looking into upgoing tracks

IceCube Preliminary

Dr. Hari Seldon: 200 TeV

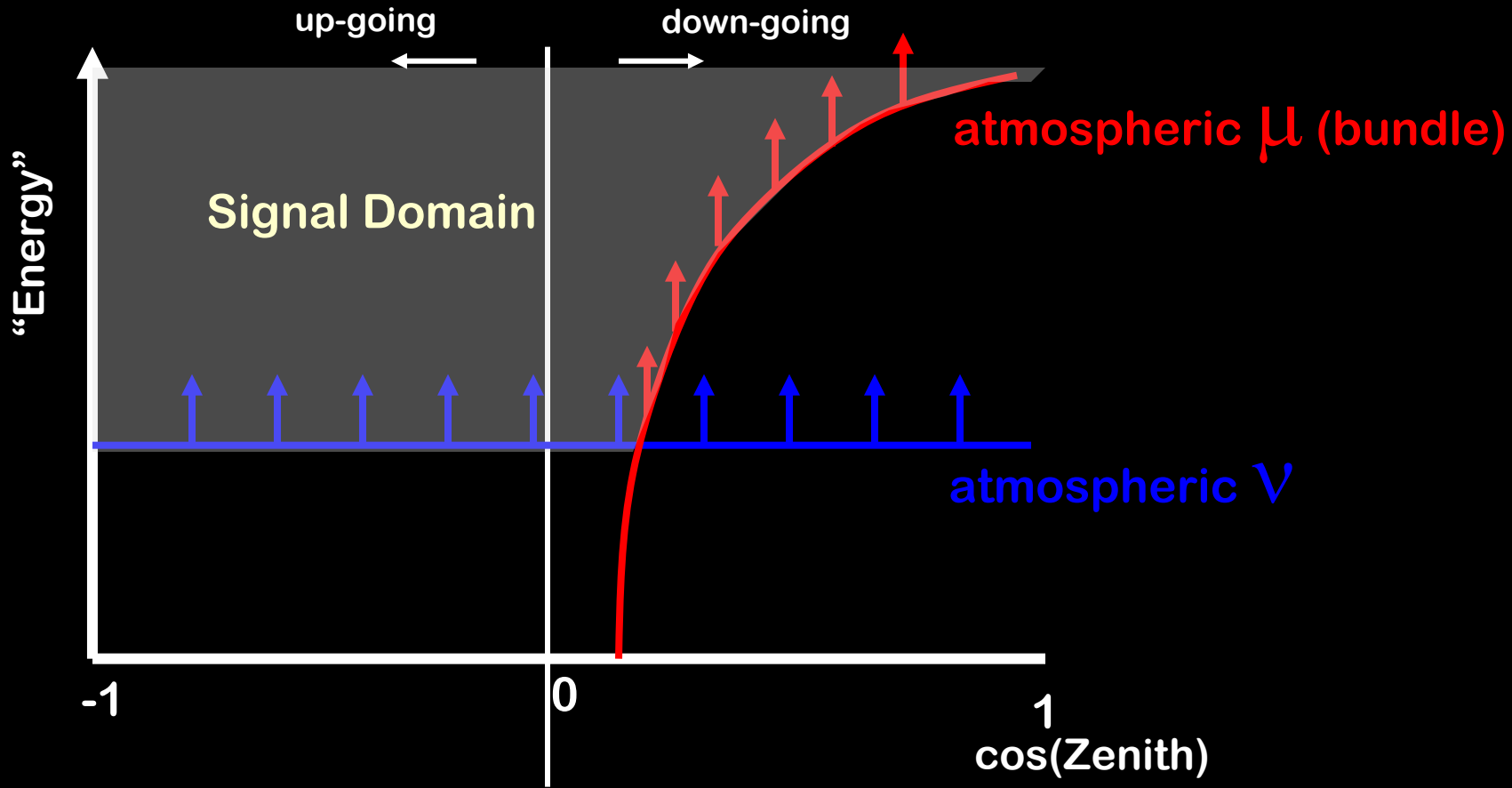




TeV PeV EeV

UHE (PeV-EeV)

Detection Principle – All flavor sensitive





TeV

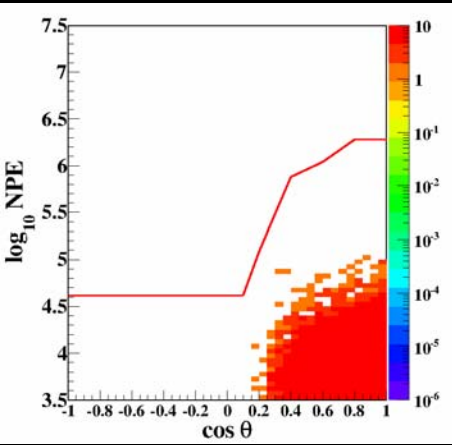
PeV

EeV

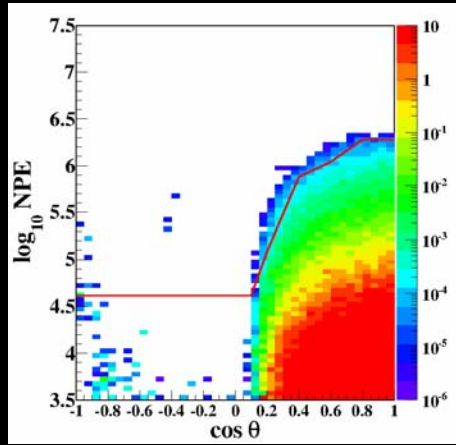
UHE (PeV-EeV)

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

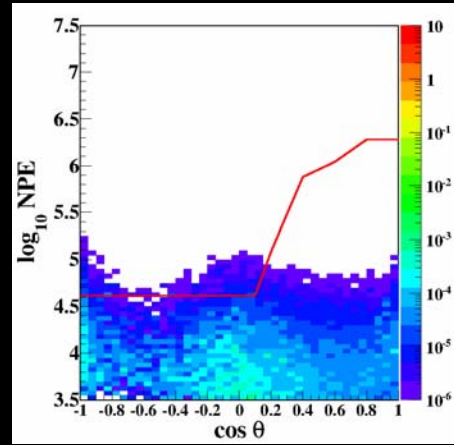
test-sample data
IceCube2010



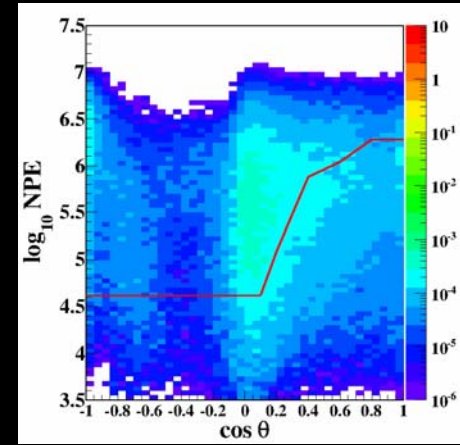
atmospheric μ



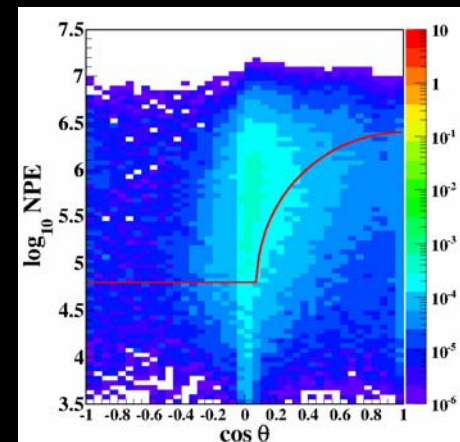
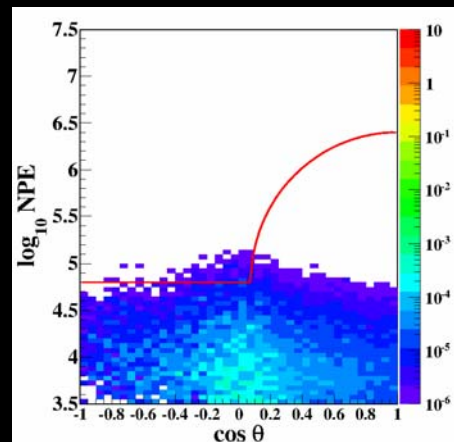
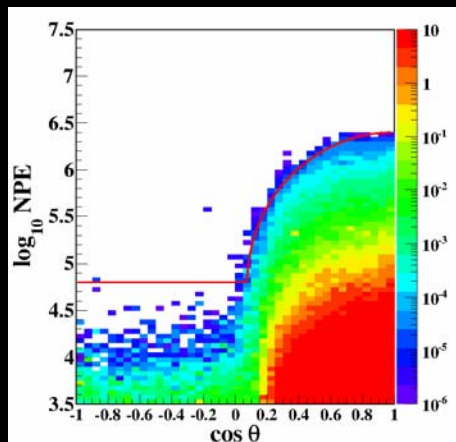
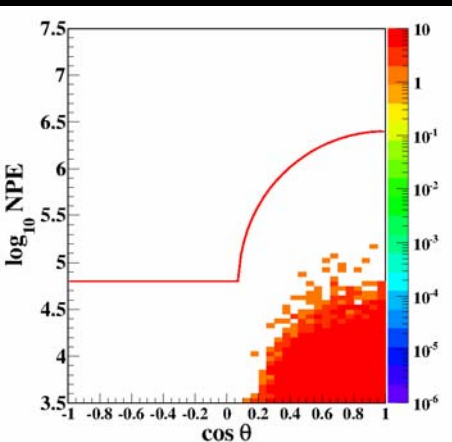
atmospheric ν
conventional only



signal GZK ν



IceCube2011





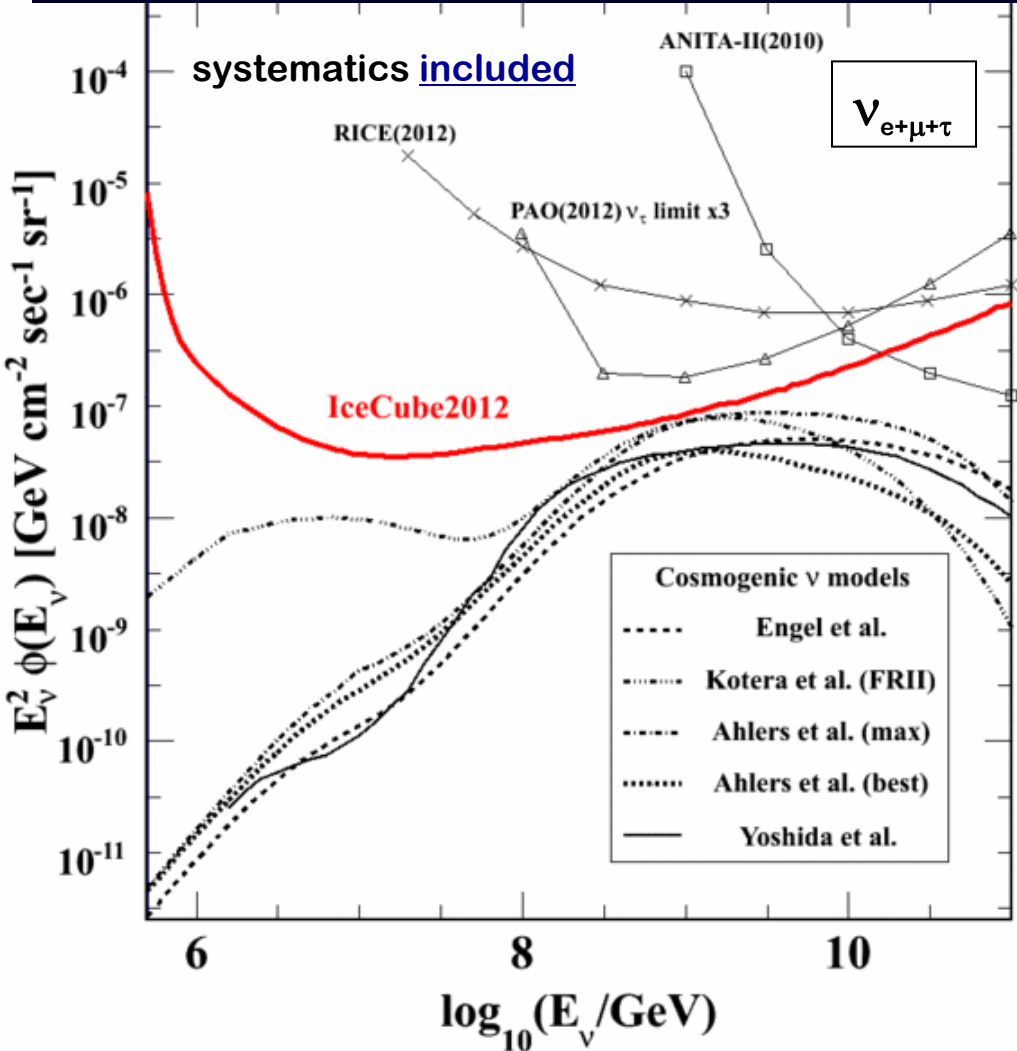
TeV PeV EeV



UHE (PeV-EeV)

The model-independent upper limit on flux

IceCube 2 years data (2010-2012)



IceCube collaboration
Phys. Rev. D 88, 112008

any model adjacent to the limit is disfavored by the observation

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

$6 \times 10^7 \text{ m}^2 \text{ days sr @ 1 EeV}$

= 0.2 km² sr year

Note: $\phi_{CR}(>1\text{EeV}) \sim 20/\text{km}^2 \text{ sr year}$
 ν with CR comparable flux should have been detected



TeV PeV EeV

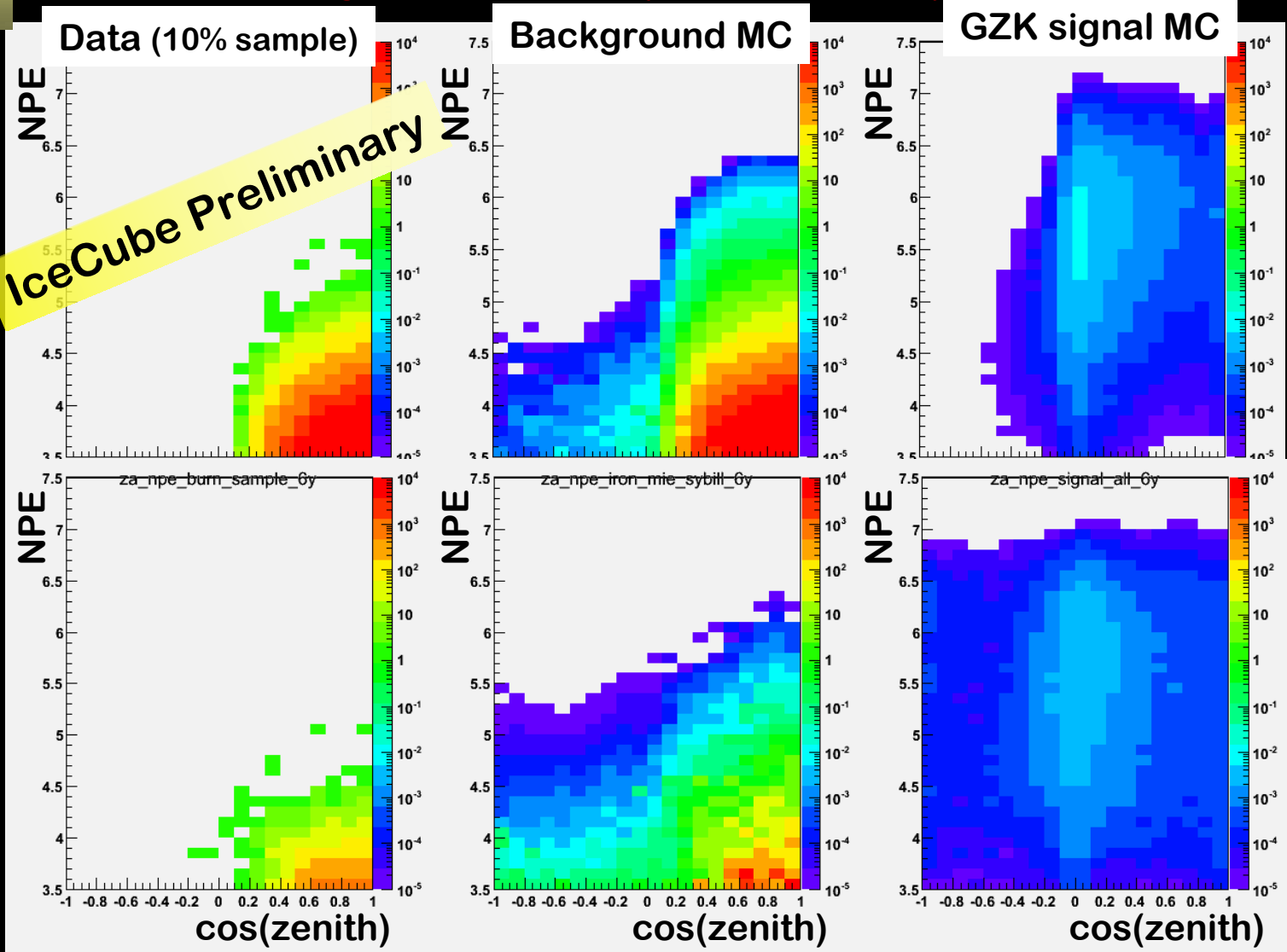


UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined

New

$\nu_{\mu, \tau}$ track-like
 $\nu_{e, \mu, \tau}$ non track-like





TeV

PeV

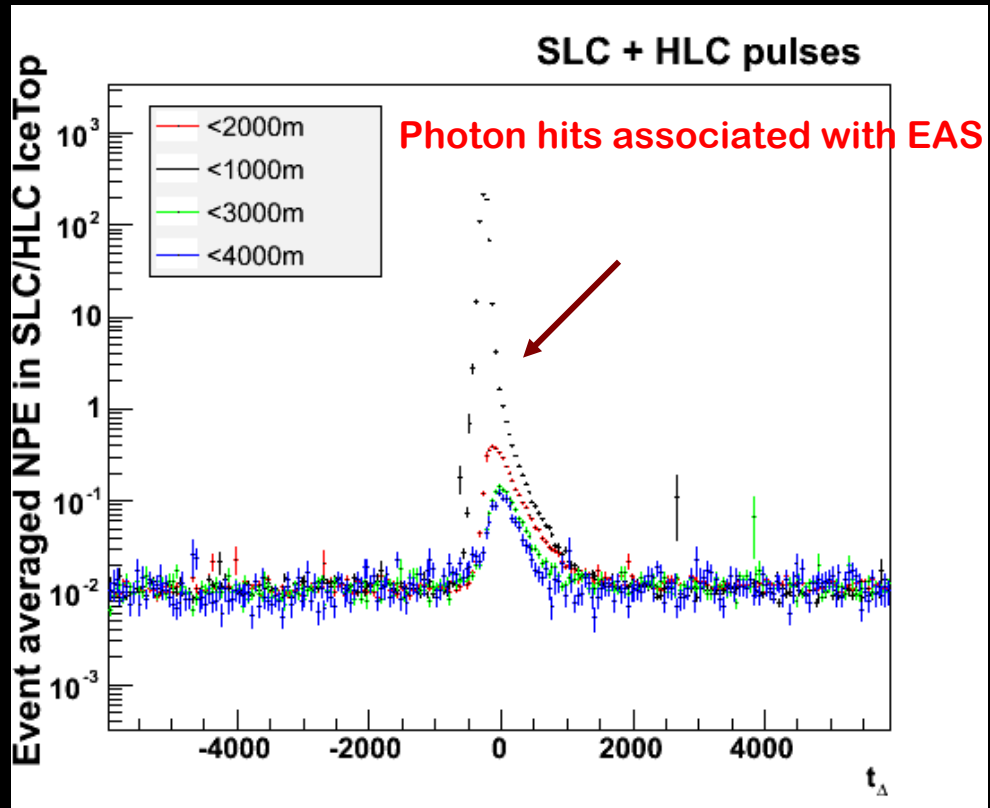
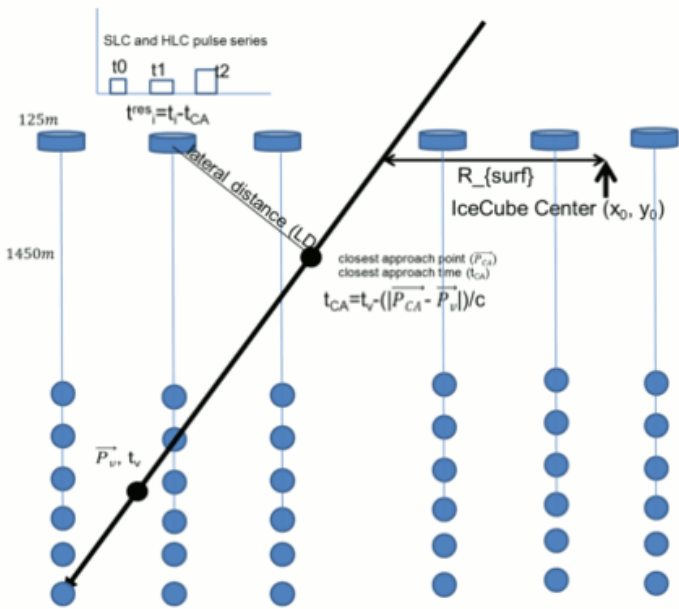
EeV



UHE (PeV-EeV)

Veto by arshower array (IceTop)

New



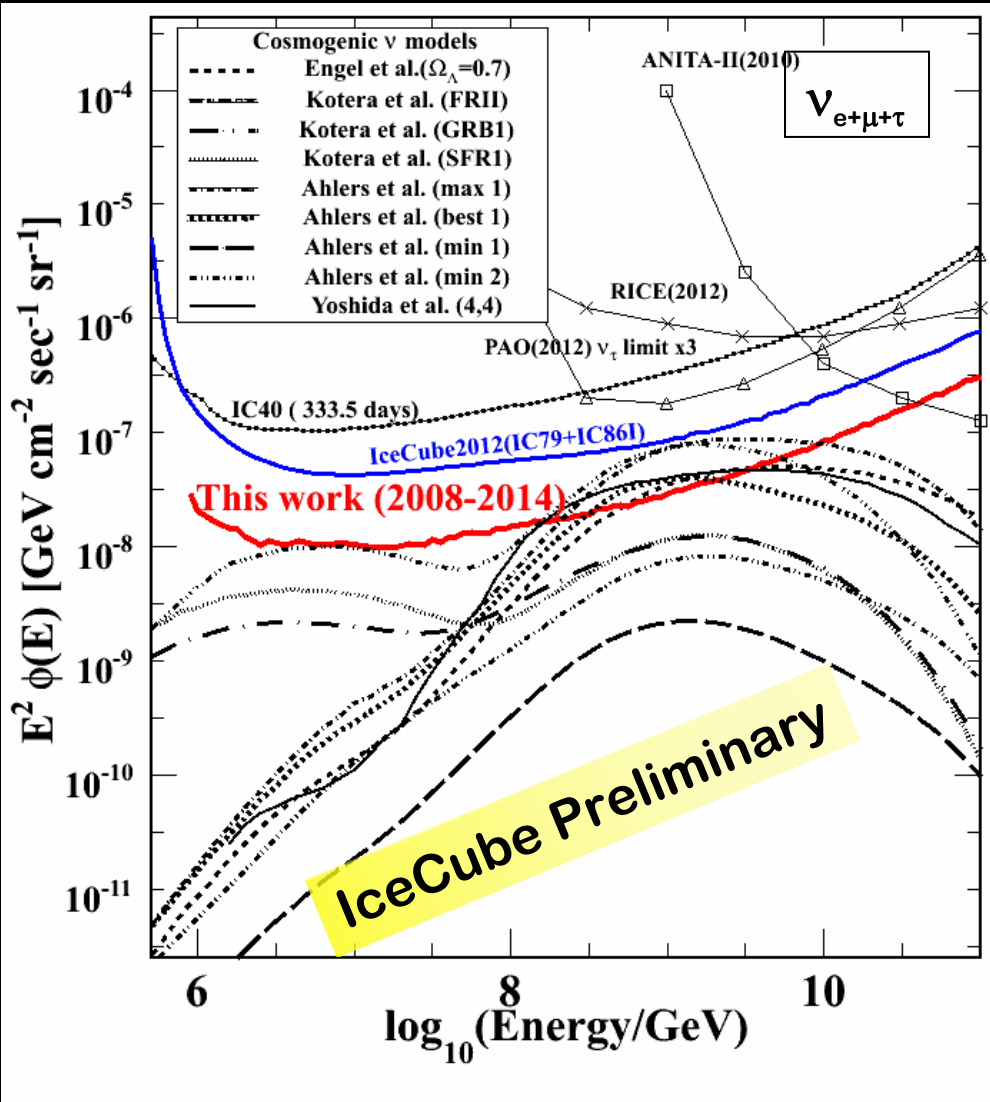


TeV PeV EeV



UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined



Model	Event Rate [/(2008-20014)]
Yoshida (FR-II compat.)	6.5
Ahlers (Best fit to HiRes)	5.0
Ahlers (Minimum)	1.1
Kotera (GRB)	3.9
Kotera (STF)	2.9



TeV PeV EeV



CHIBA
UNIVERSITY

UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined

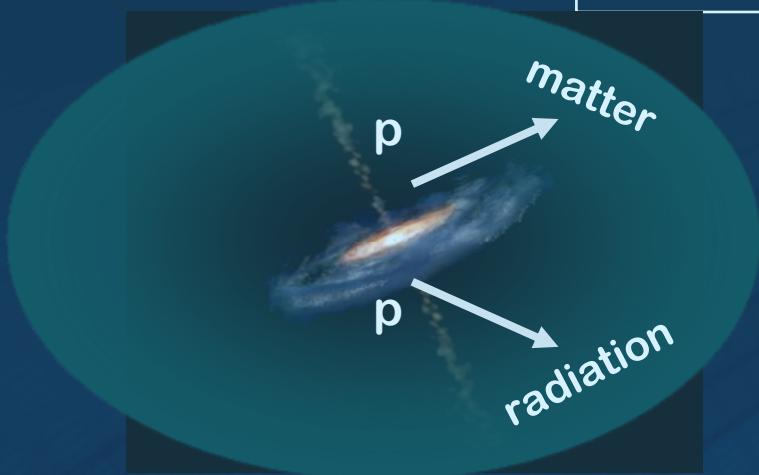
IceCube Confidential

Search Results coming soon

The Cosmic Neutrinos Production Mechanisms

“On-source” ν

TeV - PeV



$$pp \rightarrow \pi \rightarrow \nu$$

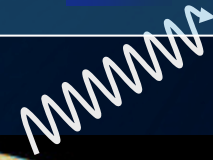
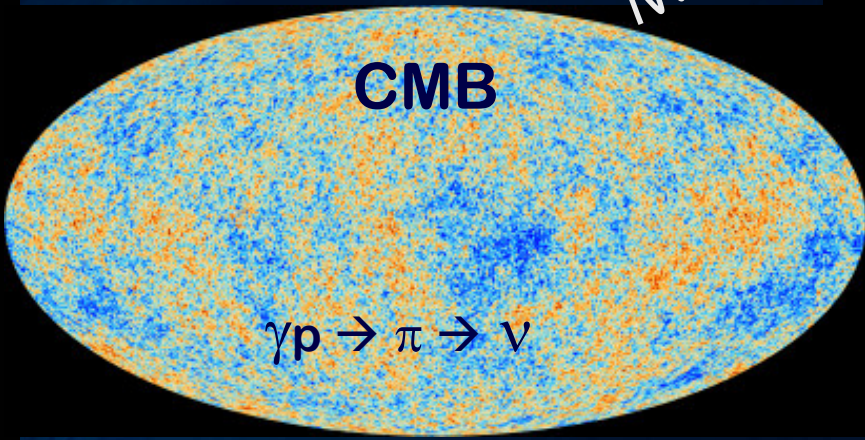
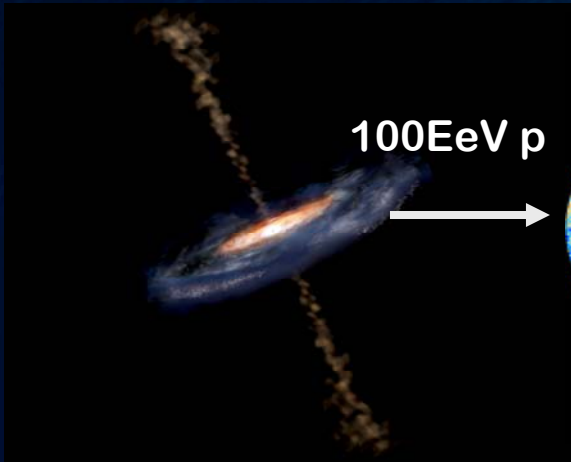
$$\gamma p \rightarrow \pi \rightarrow \nu$$

photopion production

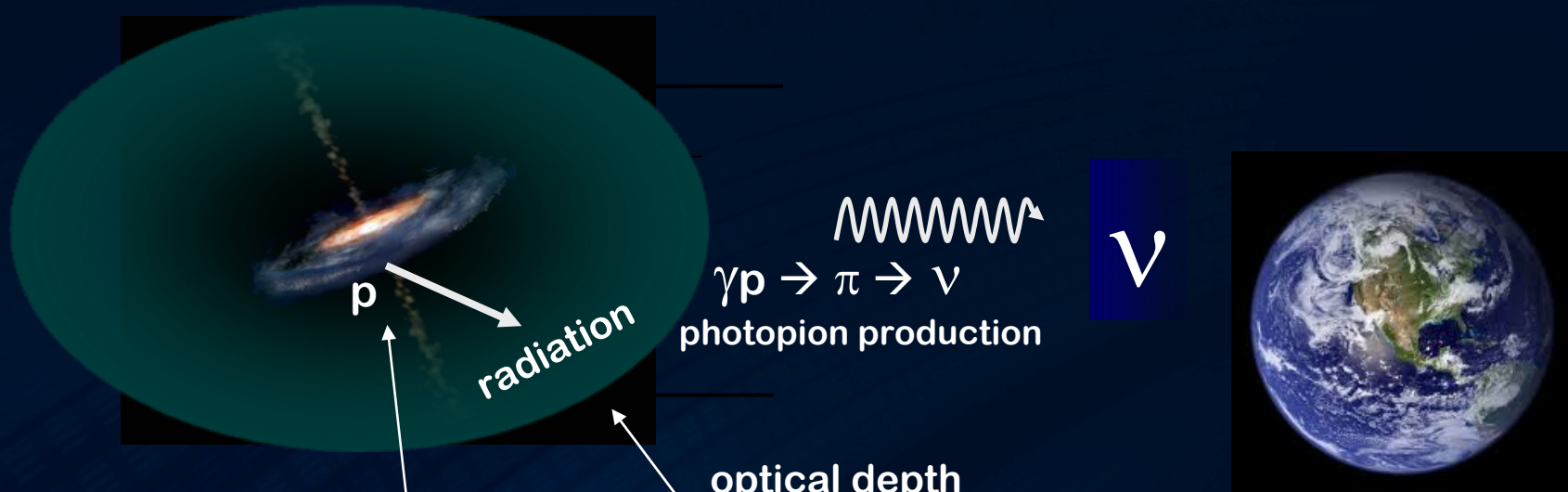


“GZK” cosmogenic ν

EeV



Constraints on the optical depth and extra-galactic CR flux



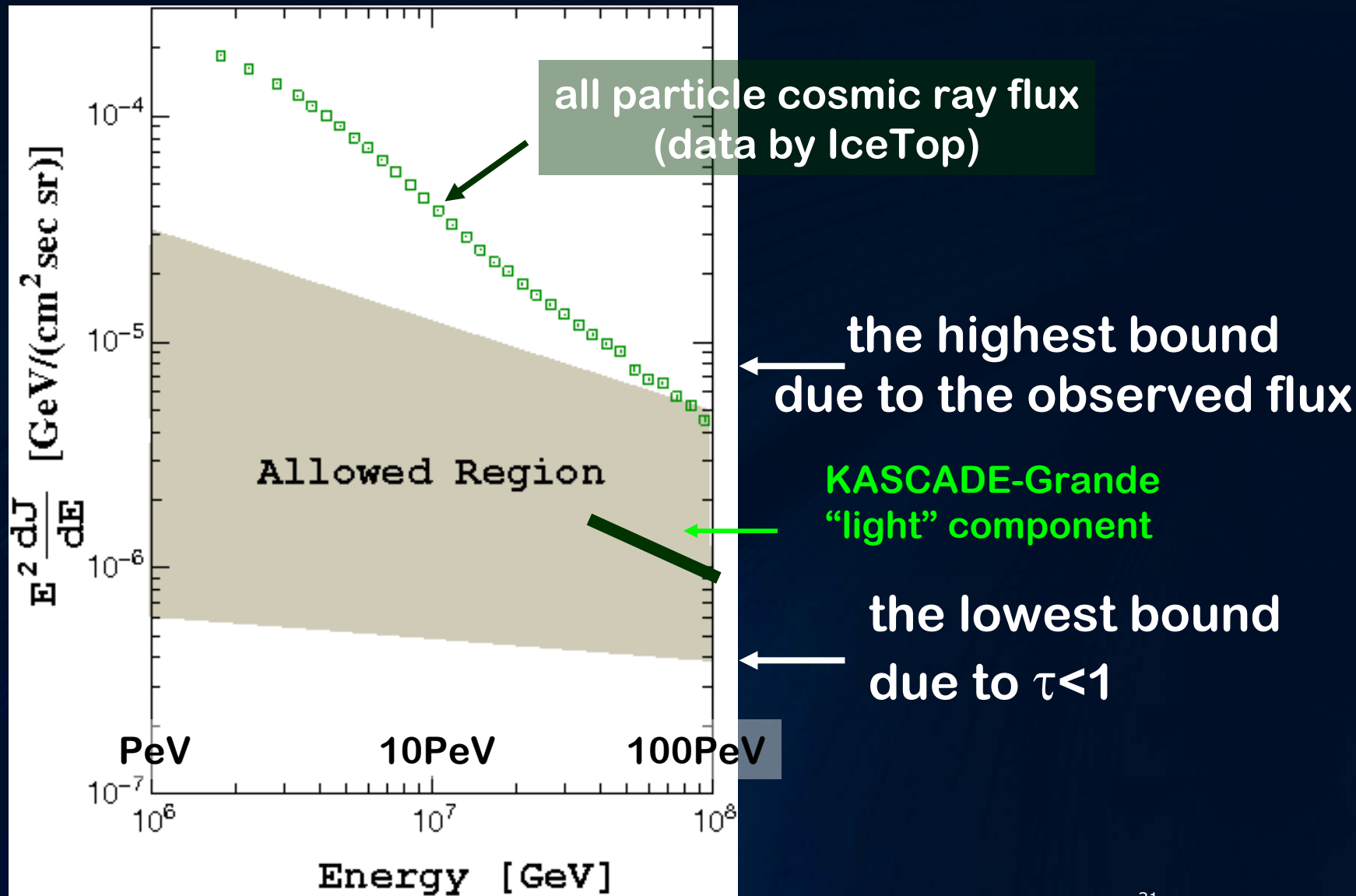
optical depth (<1)

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

Constrain them by the IceCube 100TeV-PeV observation

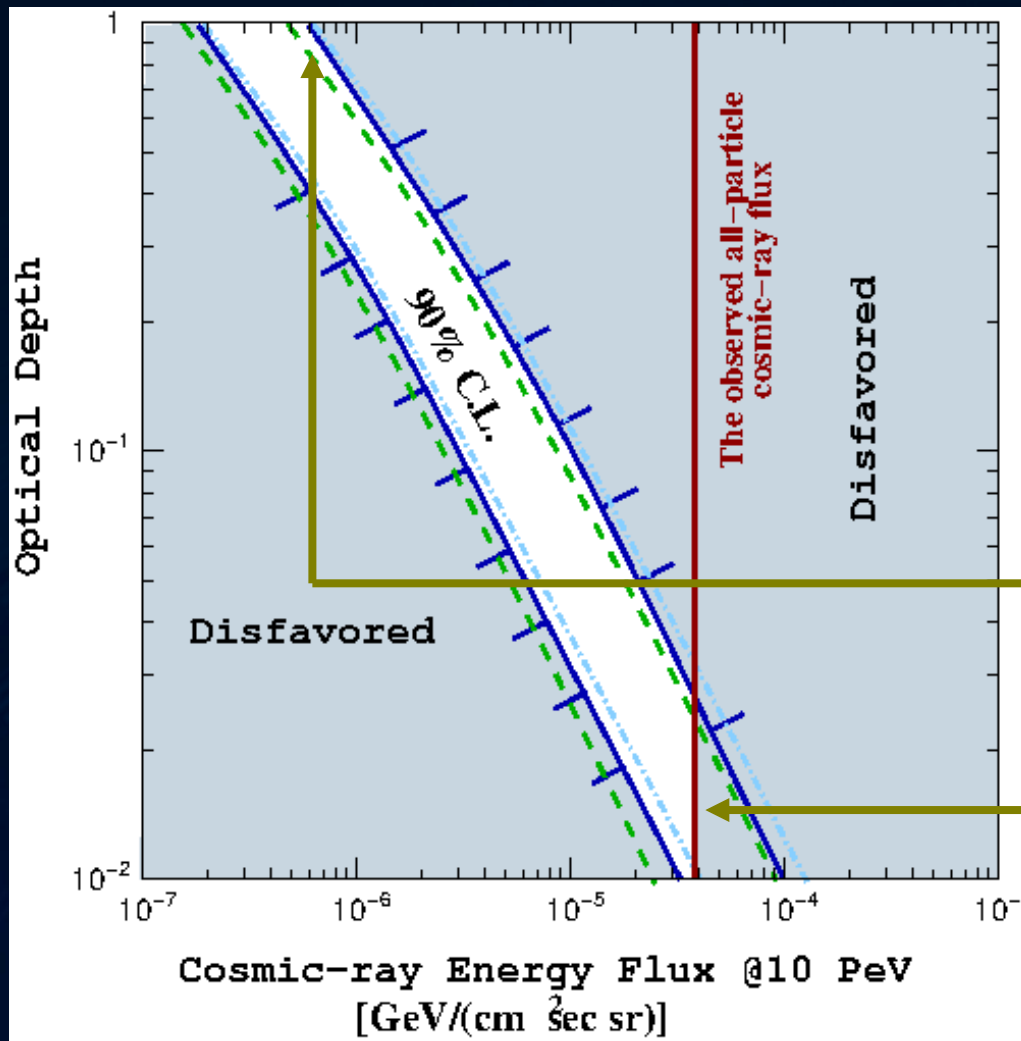
Fixed to the Star Formation Rate

Constraints on the optical depth and extra-galactic CR flux



Constraints on the optical depth and extra-galactic CR flux

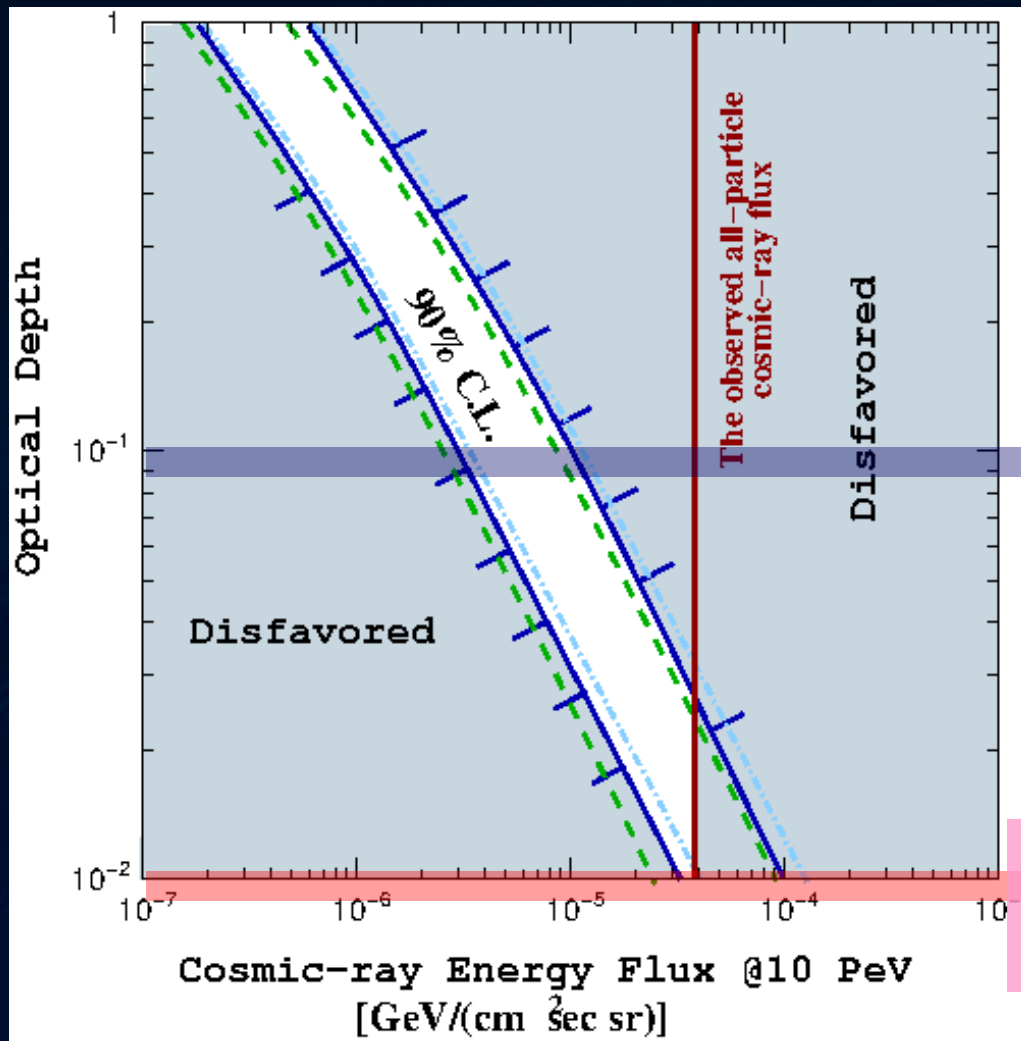
Yoshida, Takami
arXiv:1409.2950



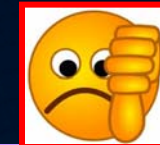
extra-galactic proton flux
must be $> 10^{-2}$ of
the all-particle CR flux
@ 10 PeV

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

Constraints on the optical depth and extra-galactic CR flux



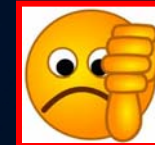
if they are also
100EeV CR sources



strong
evolution

Quasars/FR-II

GRBs (internal shock)



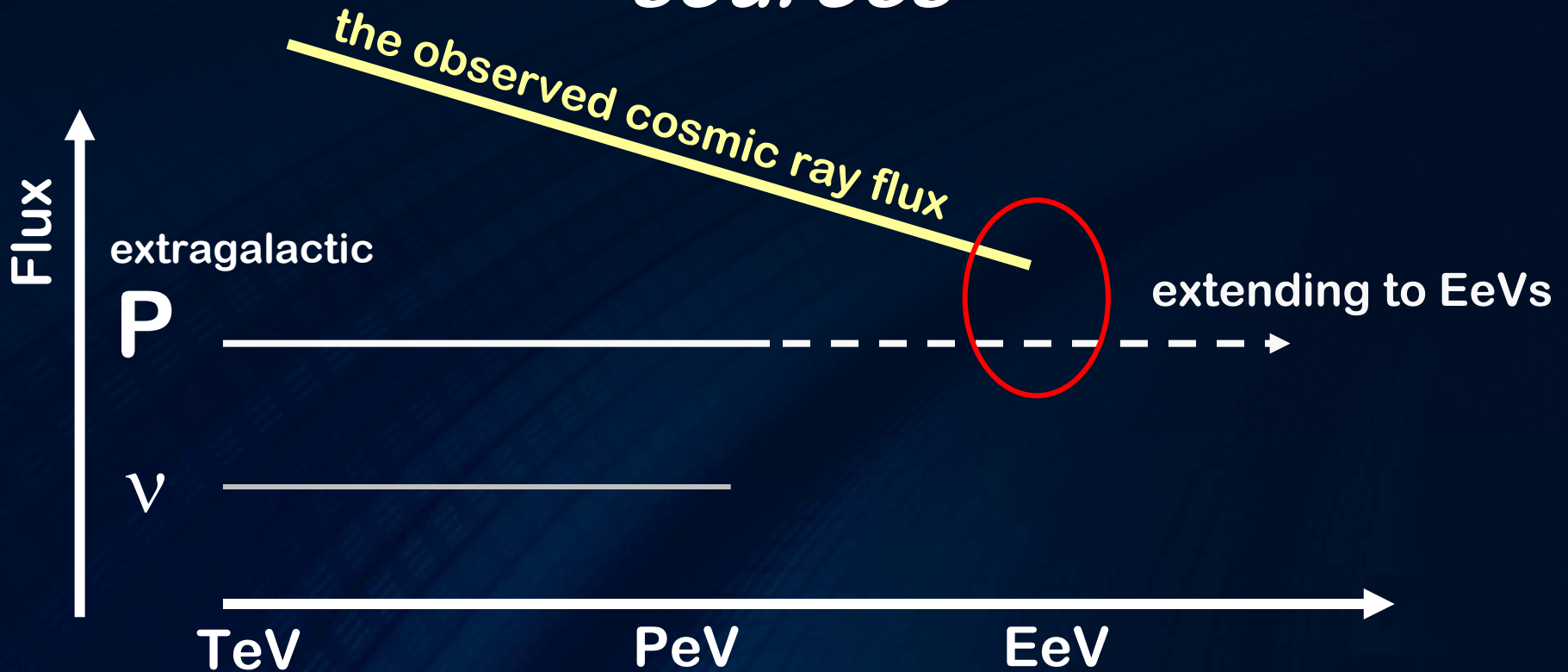
energetics



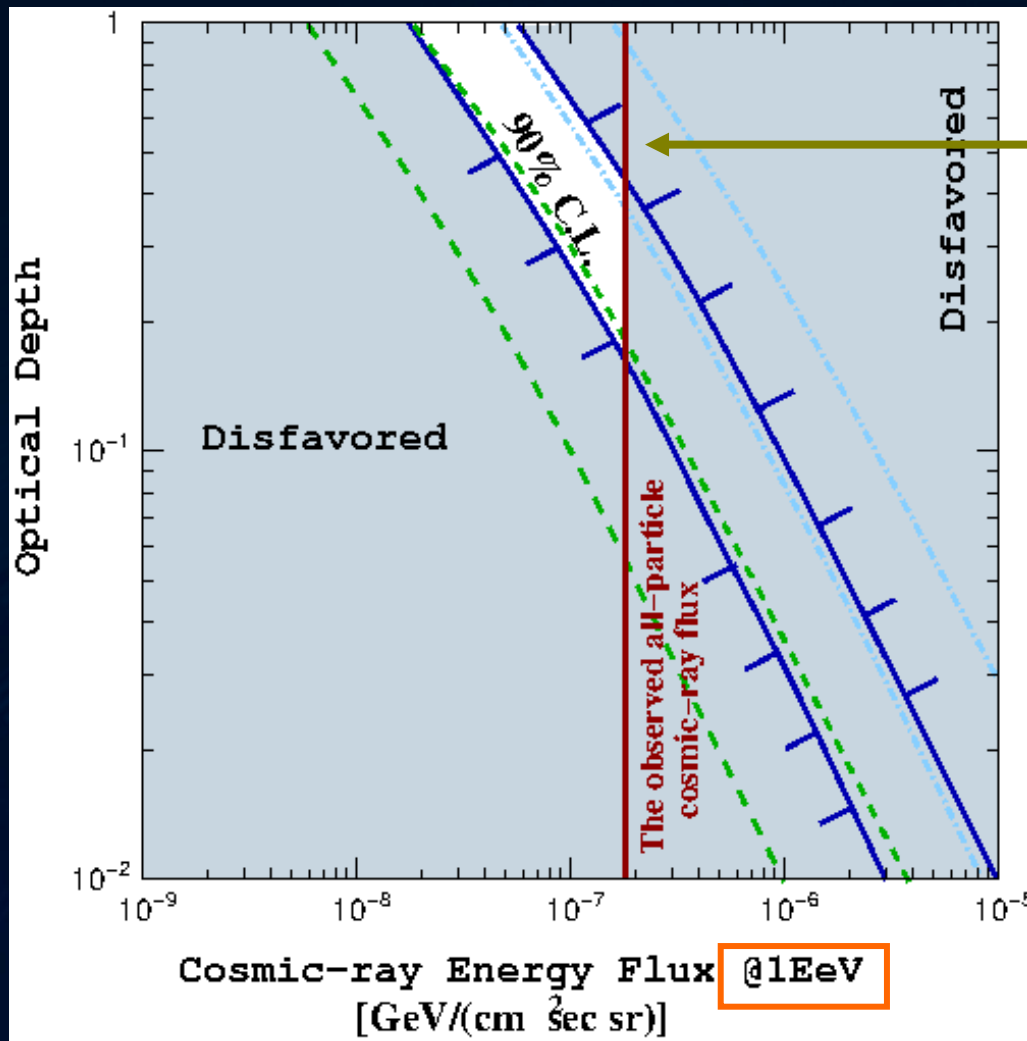
BL Lac/FR-I

GRBs (external shock)

Suppose the PeV ν emitters
are *also UHECR ($E \sim 100 \text{ EeV}$)*
sources



Constraints on the optical depth and extra-galactic CR flux

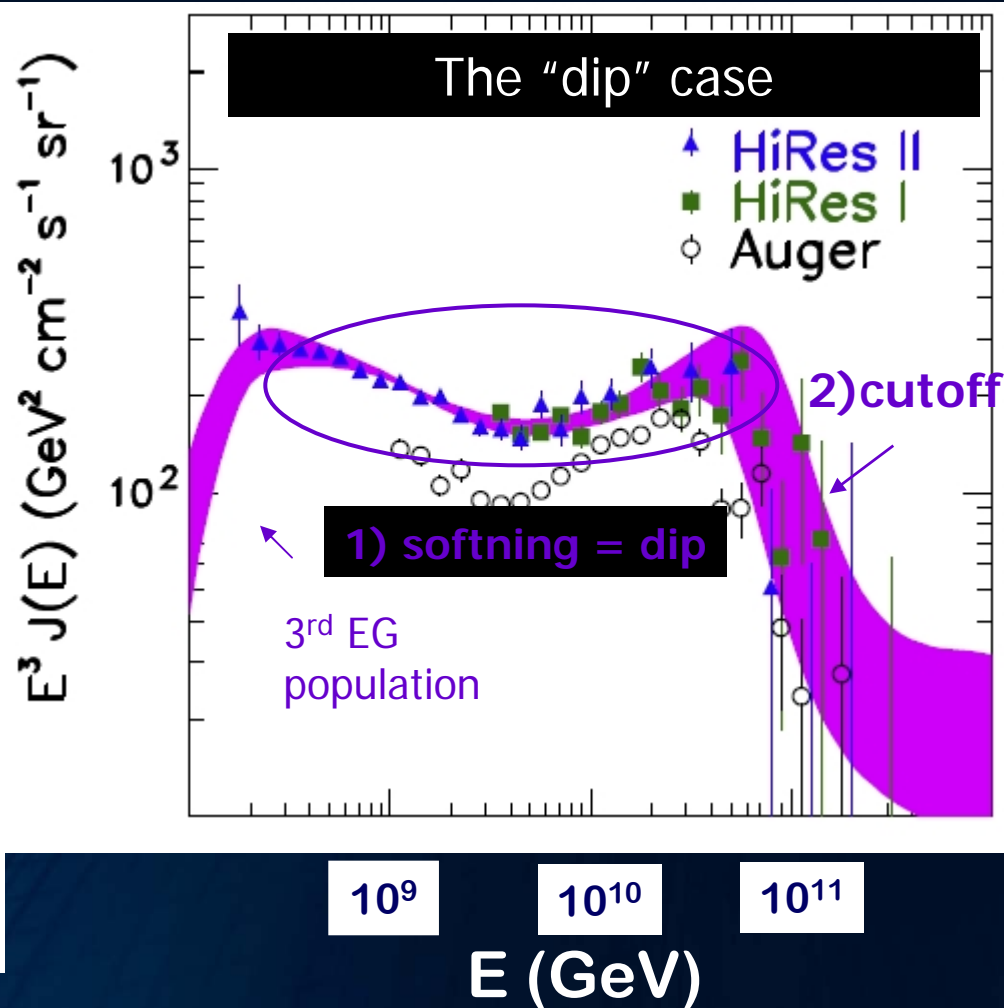
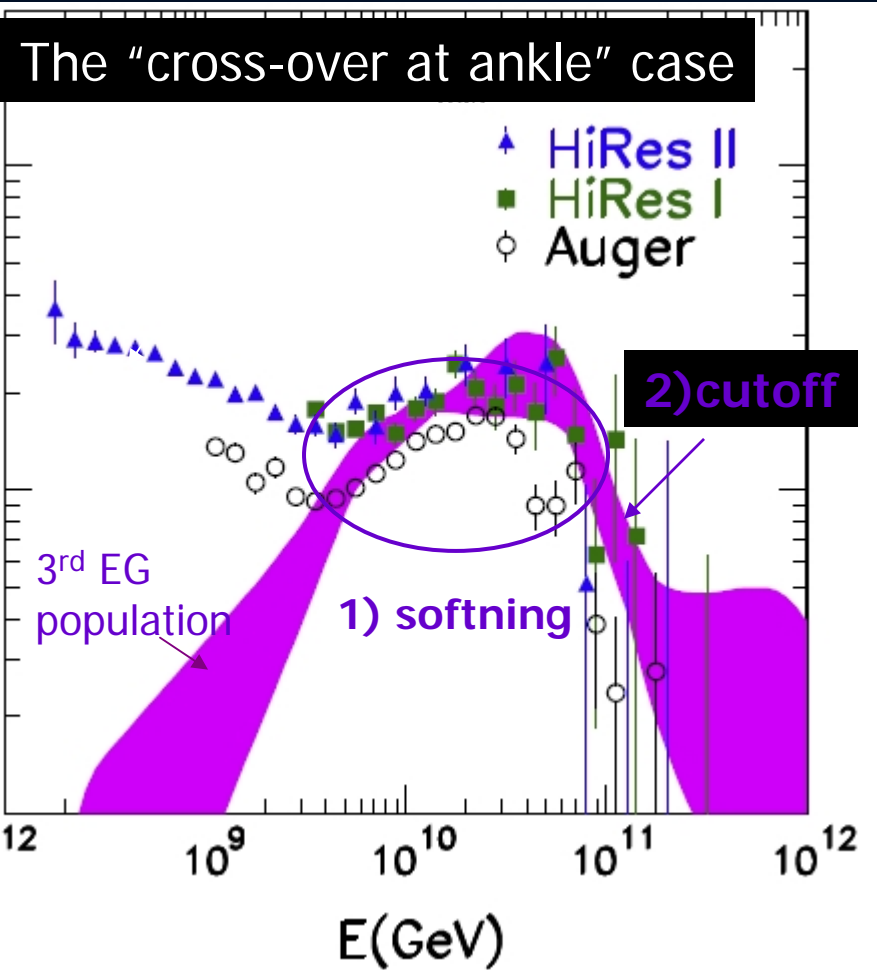


- extra-galactic proton flux must **dominate** in the all-particle CR flux @ 1 EeV(=1000PeV)
- optical depth must be **~1**

How the 3rd population (extragalactic?)

turns over is still open question

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

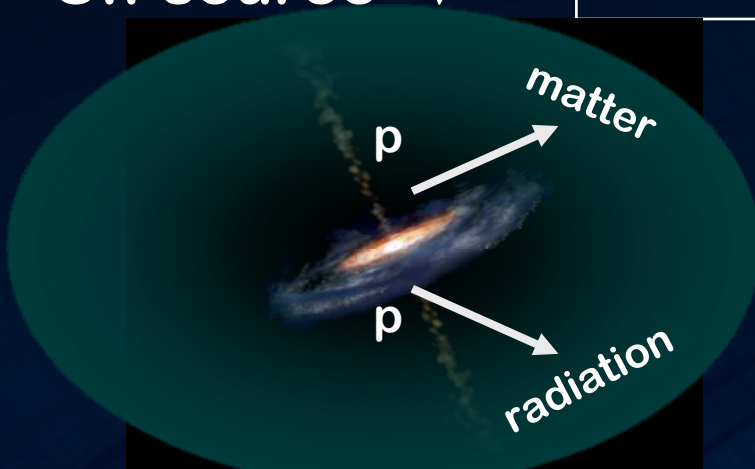


Structures 1) and 2) are consequence of propagation in extra-galactic space

The Cosmic Neutrinos Production Mechanisms

“On-source” ν

TeV - PeV



$$pp \rightarrow \pi \rightarrow \nu$$

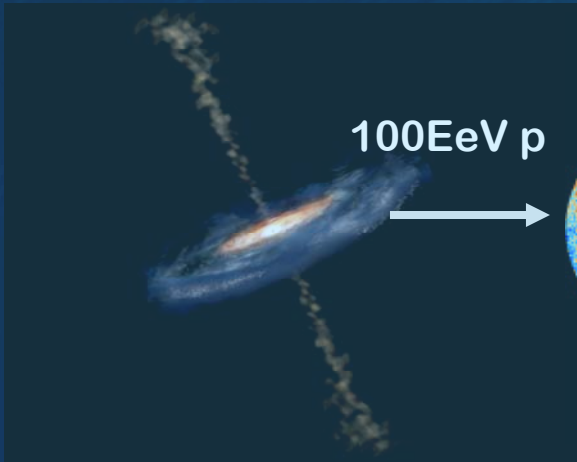
$$\gamma p \rightarrow \pi \rightarrow \nu$$

photopion production



“GZK” cosmogenic ν

EeV

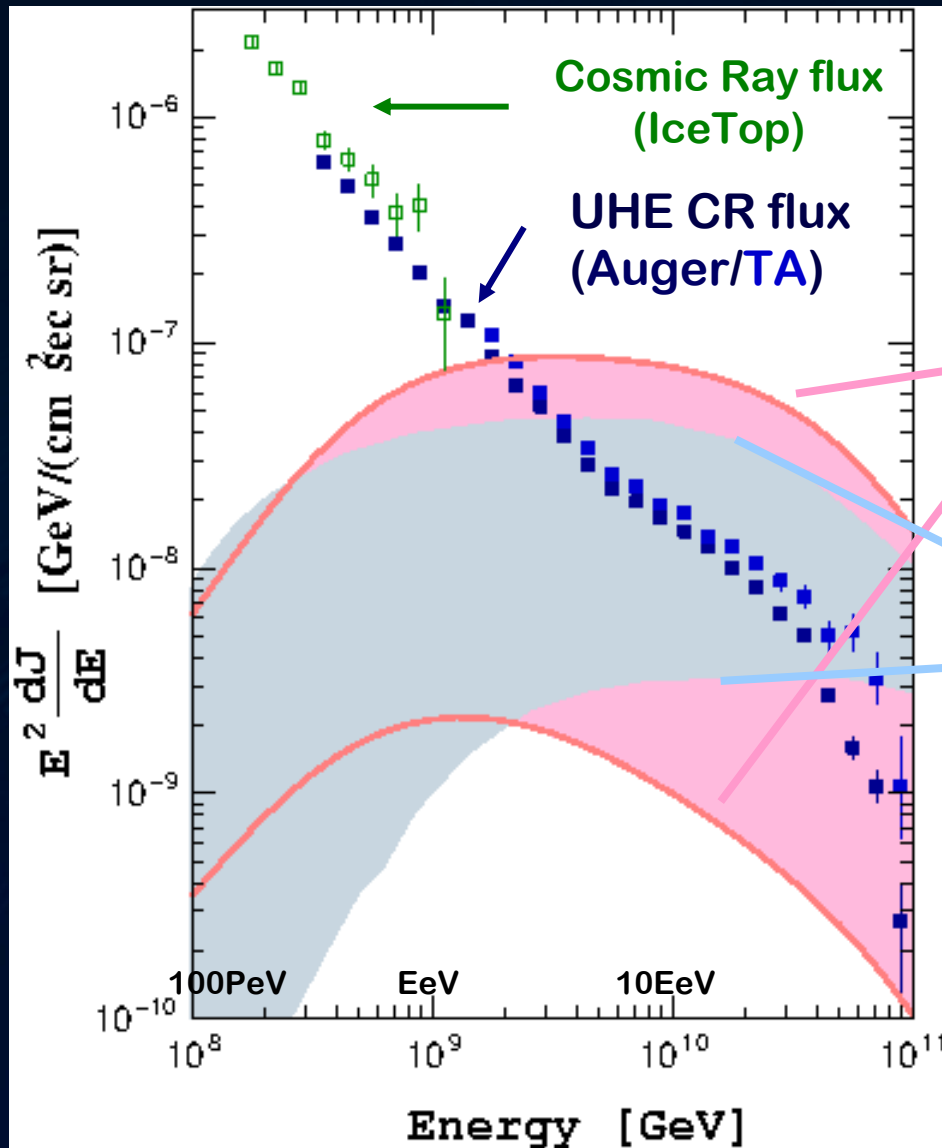


CMB

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



UHE cosmic ray and GZK ν fluxes



GZK cosmogenic ν 's

allowed range of the ν flux

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

the ν fluxes from strongly evolved and no evolved sources

SY et al, *Prog.Theo.Phys.* **89** 833(1993)

Ranges more than an order of magnitude

why?

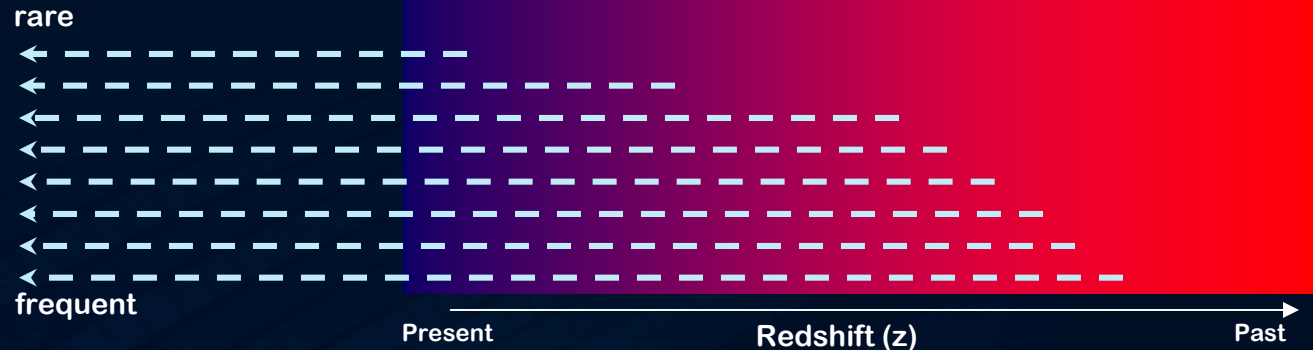
Tracing *history* of the particle emissions with ν flux

color : emission rate of ultra-high energy particles

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

ν

because ν beams are penetrating over cosmological distances



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

The cosmological evolution

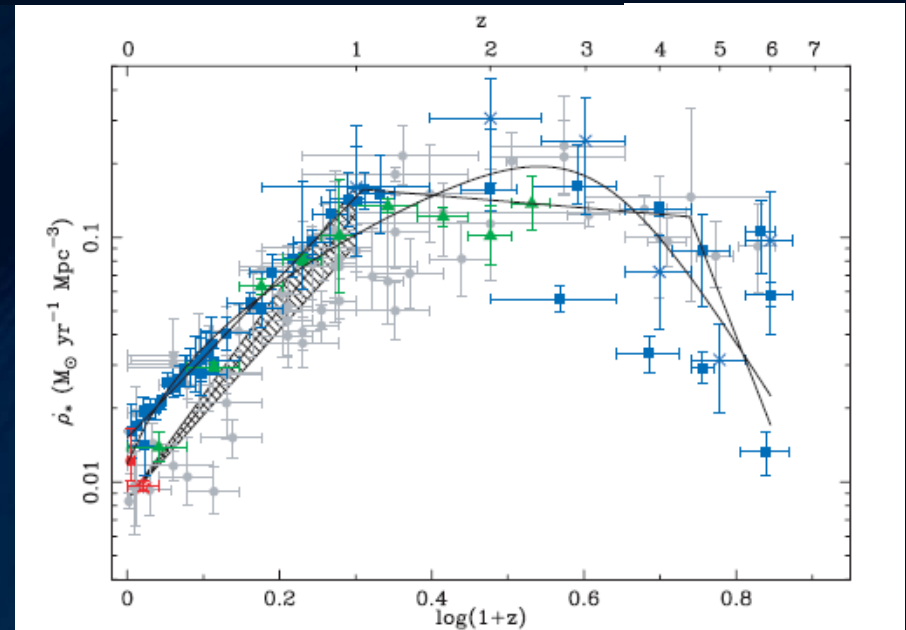
Many indications that the past was more active.

Star formation rate \rightarrow

The spectral emission rate

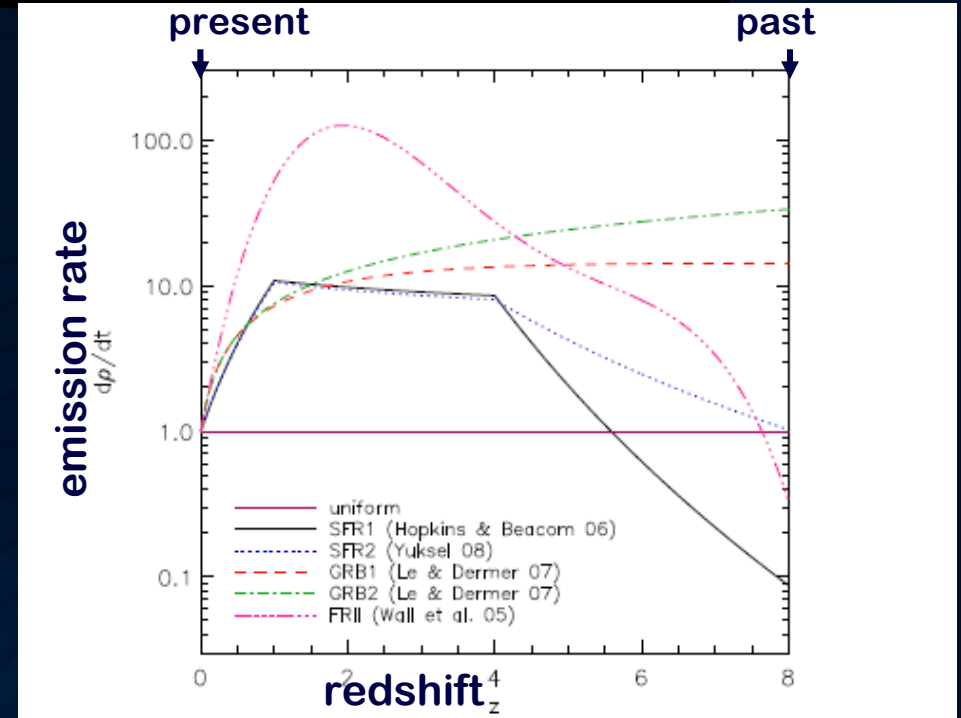
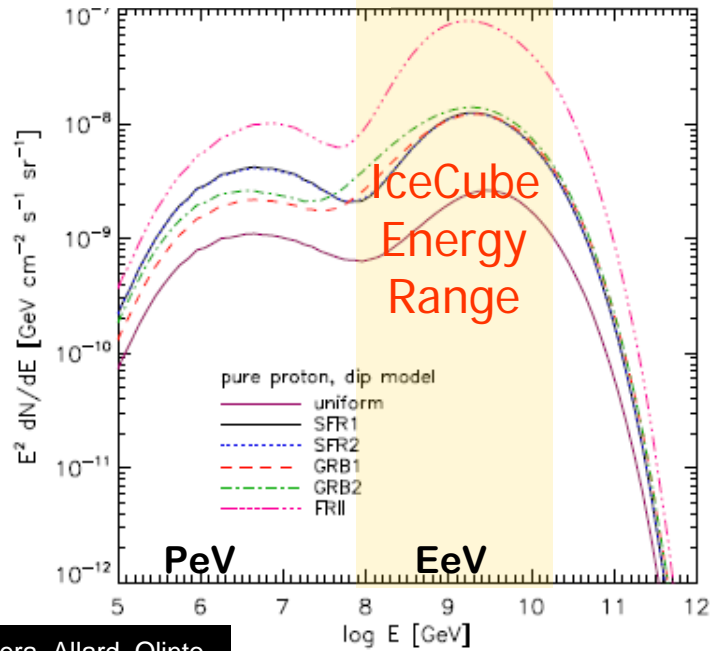
$$\rho(z) \sim (1+z)^m$$

$m=0$: No evolution



I_{GZK}^{ν} @ 1 EeV is an excellent indicator for the UHECR emission history

evolution dependence

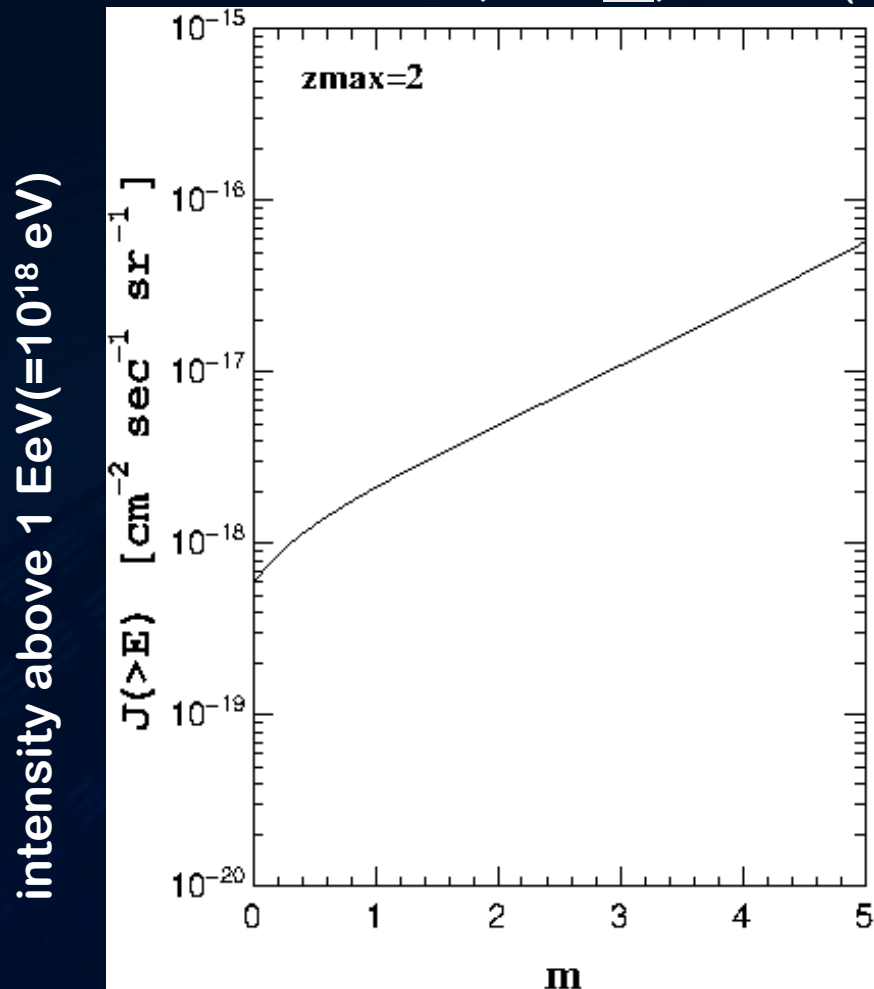


ν = early history of cosmic radiation!

Kotera, Allard, Olinto
JCAP 10 013 (2010)

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

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

“quiet”

particle emissions in far-universe

“dynamic”

GZK cosmogenic ν intensity @ 1EeV in the phase space of the emission history

Yoshida and Ishihara, PRD 85, 063002 (2012)

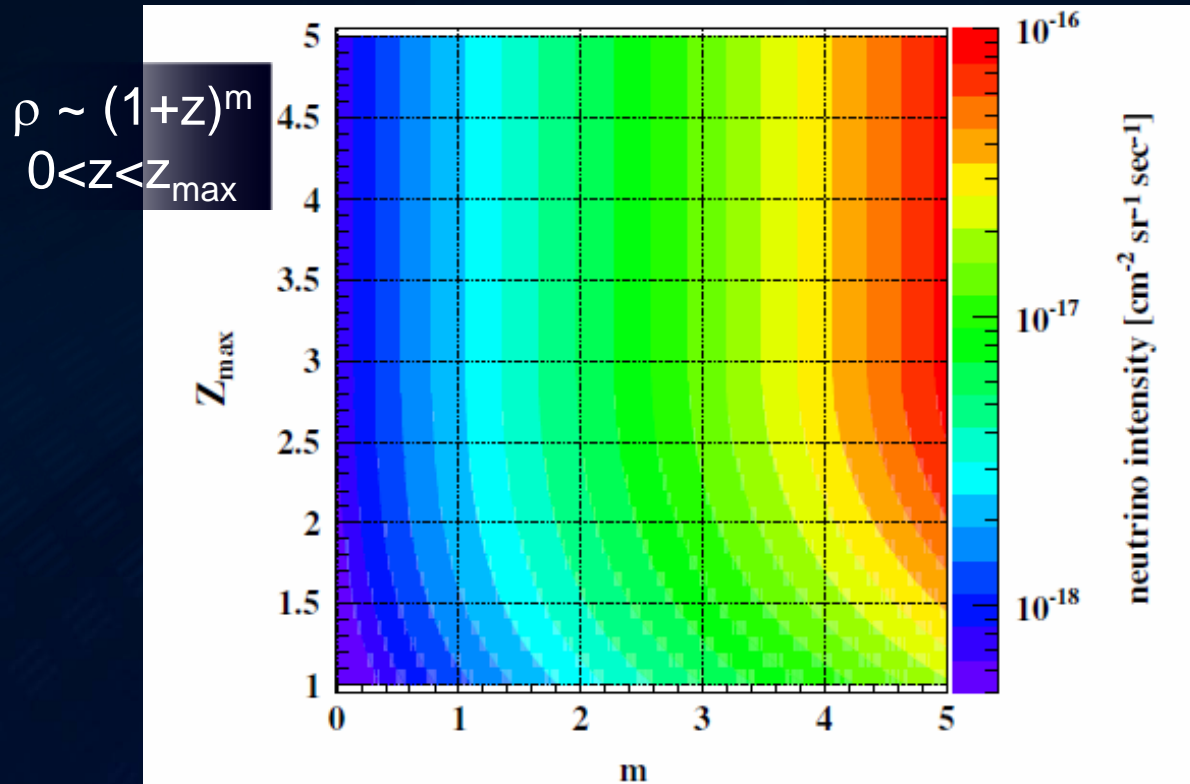


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [$\text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$], on the plane of the source evolution parameters, m and z_{\max} .

GZK ν flux $\phi = (m, z_{\max})$

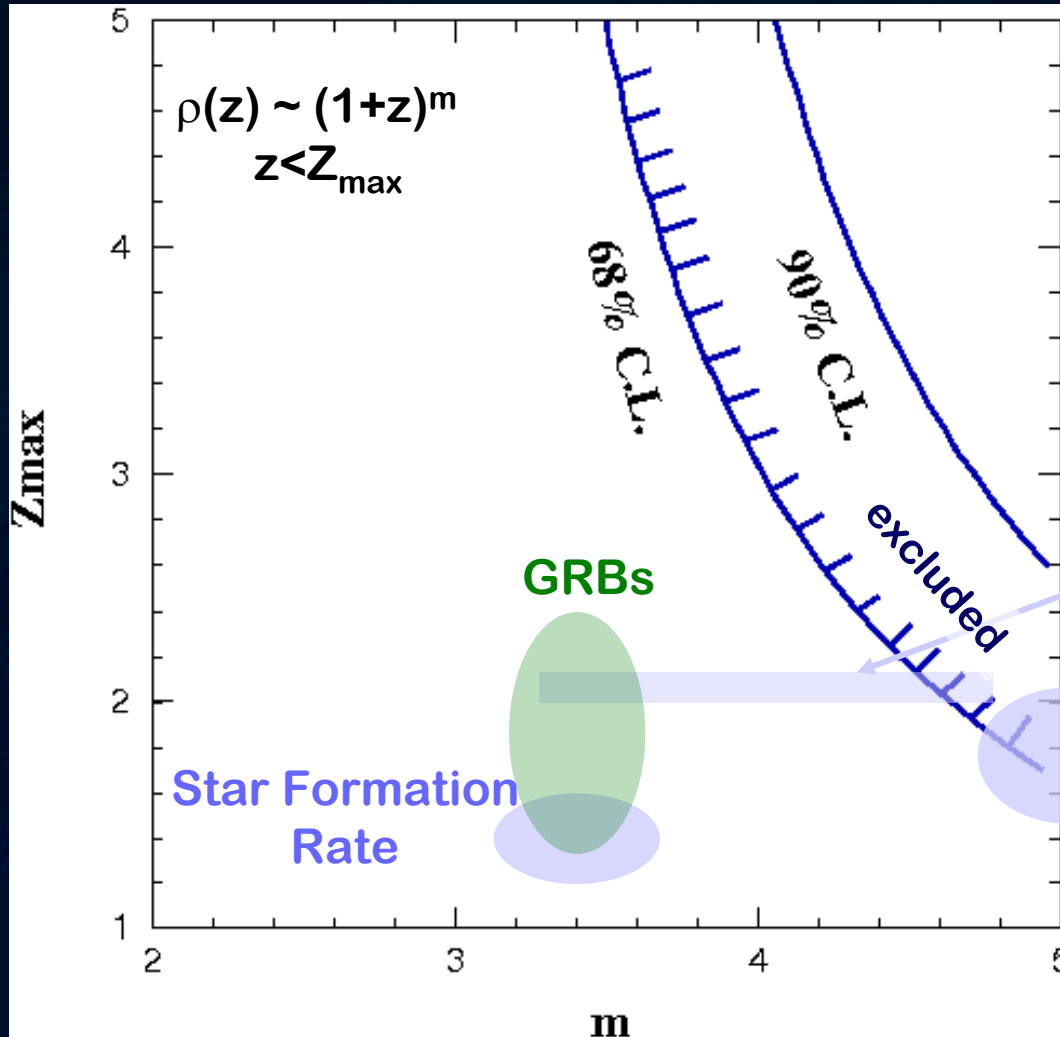
x IceCube Exposure

Number of events
we should have detected



We have seen null events

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

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

The best guess
from the cosmic ray spectrum

AGNs with
radio-loud jets

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

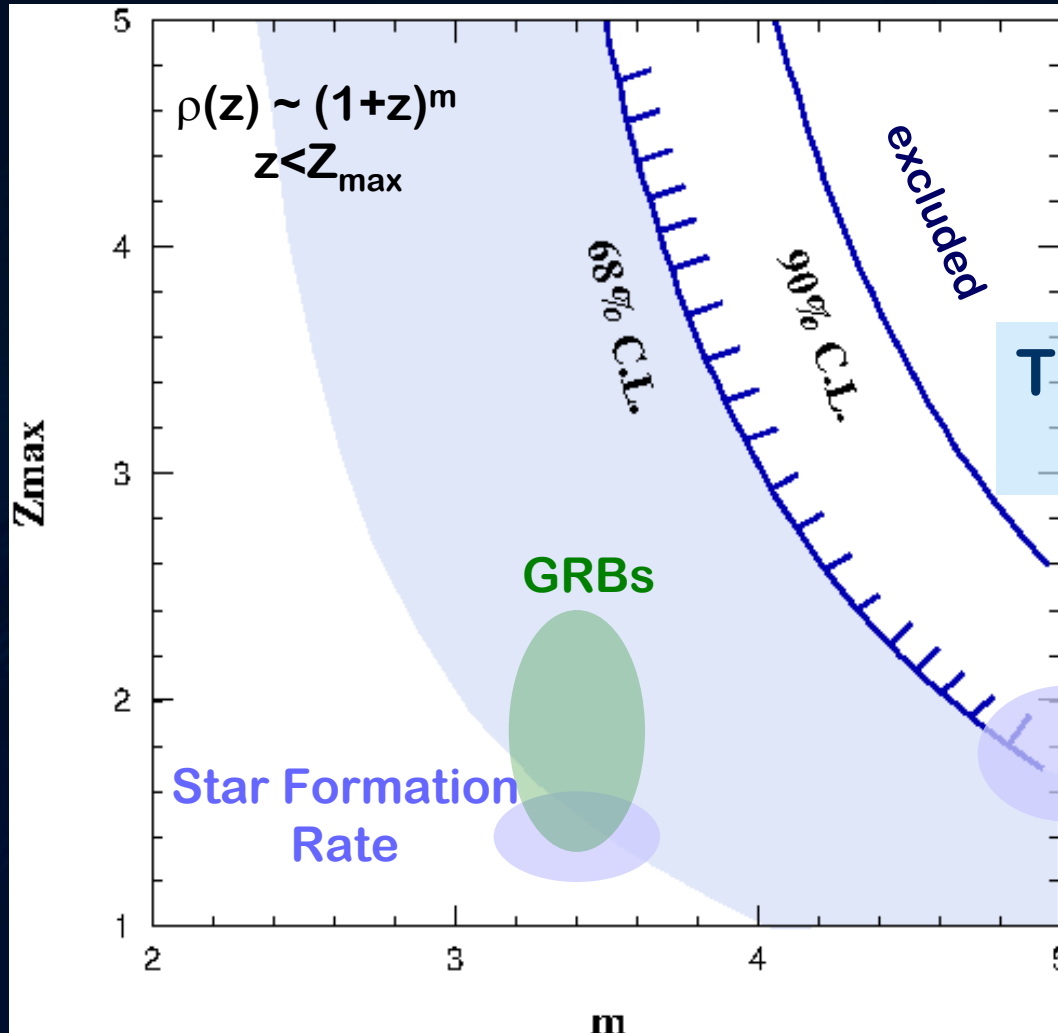
IceCube collaboration
Phys. Rev. D 88, 112008

The solid bound by
the GZK ν

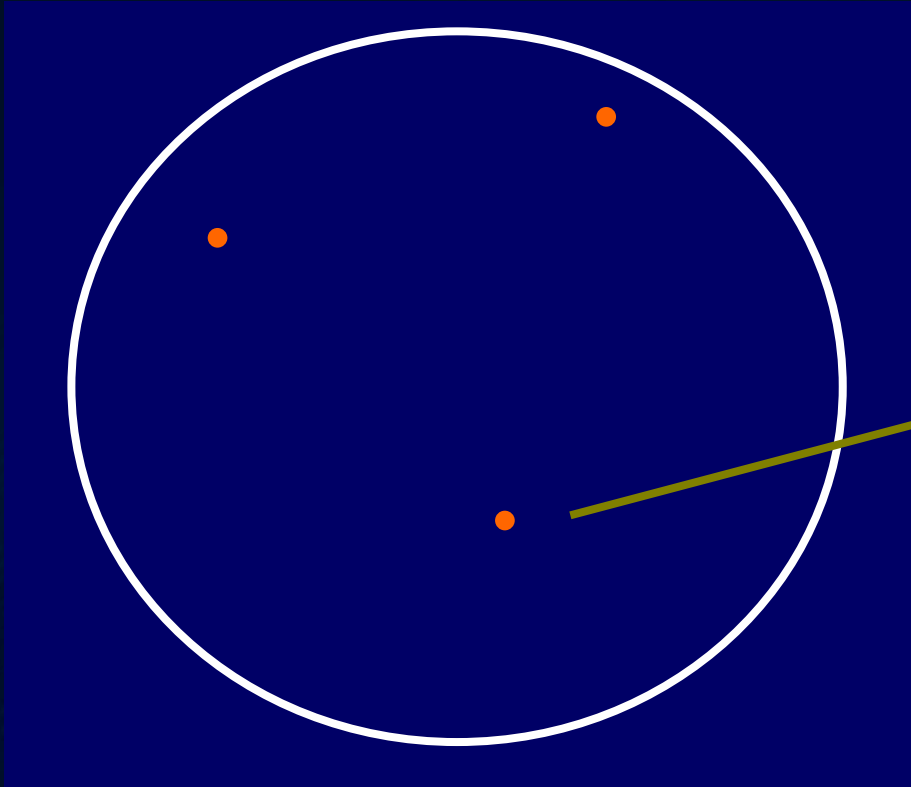
The region scanned by
IceCube 2008-2014

coming soon!

AGNs with
radio-loud jets



The Multi Messengers: UHE $\nu \rightarrow \gamma$ (or any other messengers)



look up this direction!

ν

“GFU”

γ

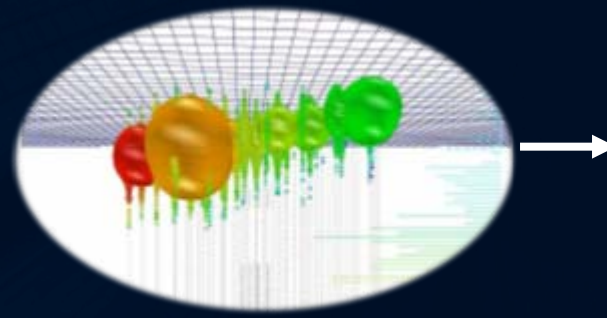
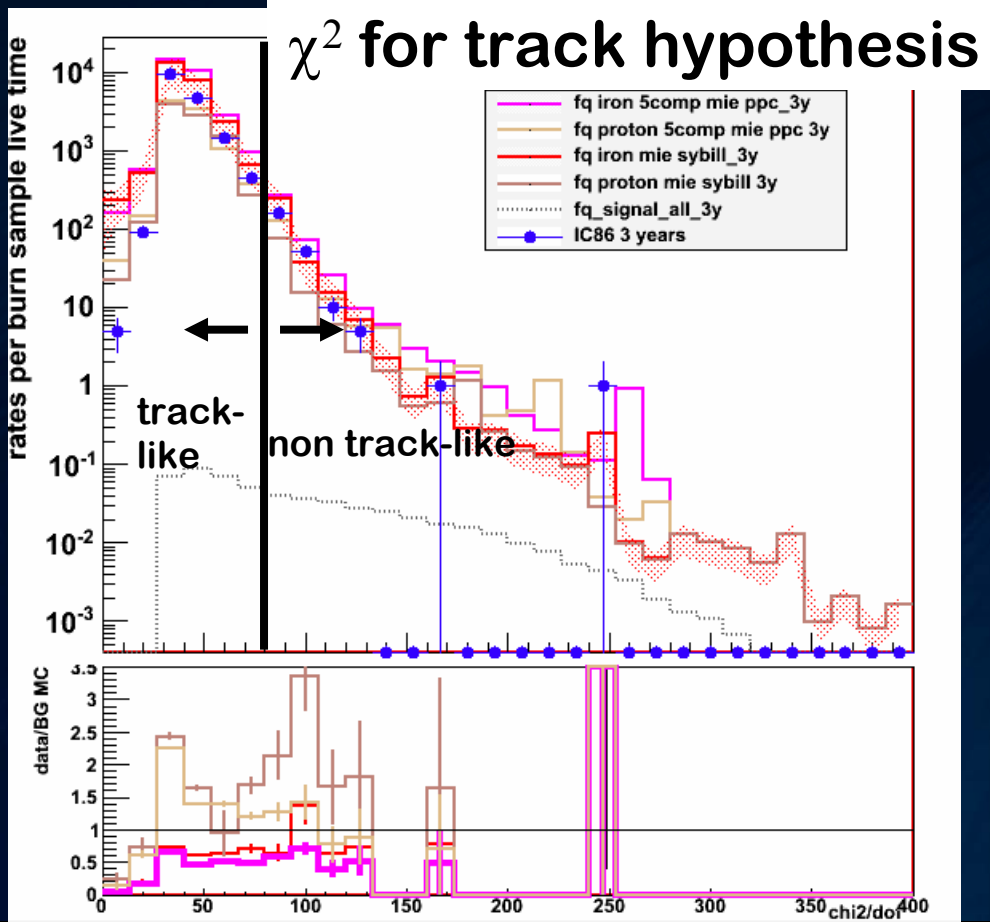
UHE (PeV-EeV)

Online Analysis for γ -ray/optical follow-up

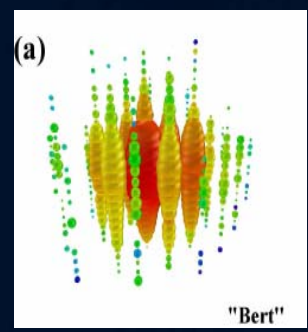
new

event topology separation

track



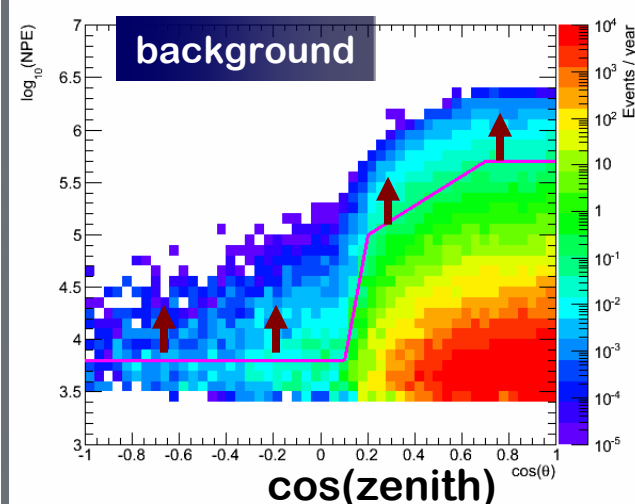
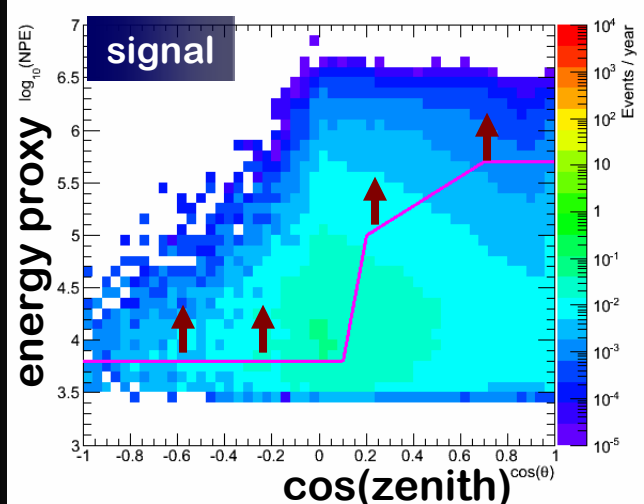
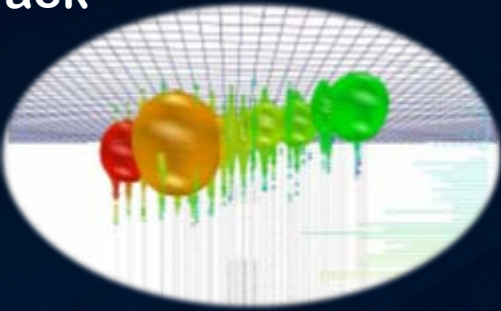
cascade (non track-like)



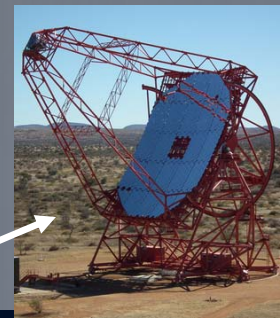
UHE (PeV-EeV)

Online Analysis for γ -ray/optical follow-up

track



3.8 event/year for $\nu_{e+\mu+\tau}$ of
 $E^2\phi = 3 \times 10^{-8} \text{GeVm}^{-2}\text{sec}^{-1}\text{sr}^{-1}$
GZK: ~ 0.3-0.9 event/year
BG: ~ 2-3 event/year



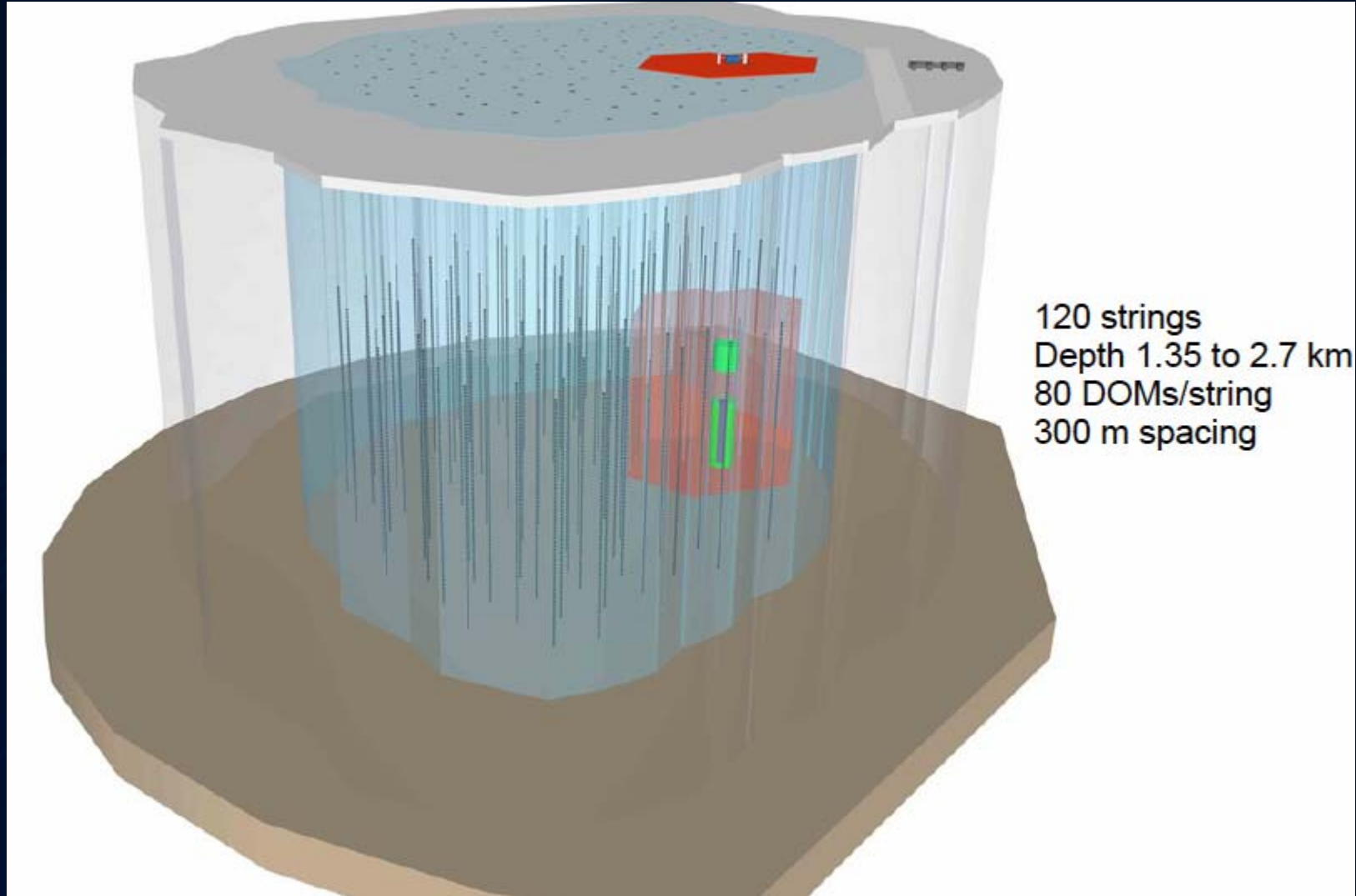
We will send you:

- direction
- Energy (proxy)
- rating of signal-likelihood

$\Delta\theta \sim 0.3 \text{ deg}$

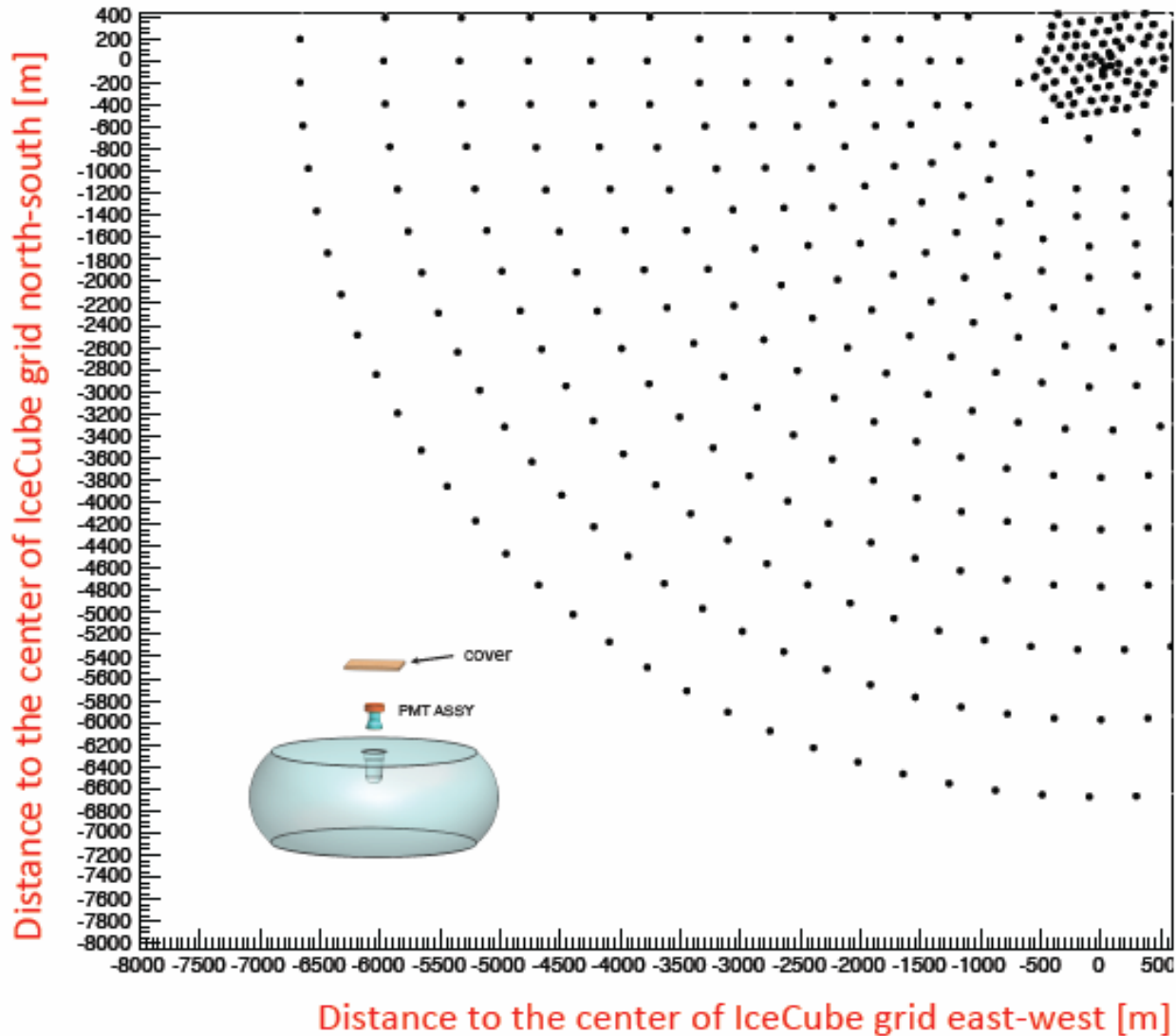


Next Generation: IceCube HEX





A veto airshower array



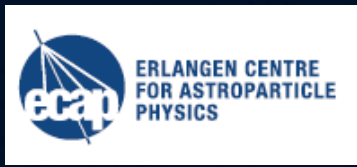


Next Generation: IceCube HEX

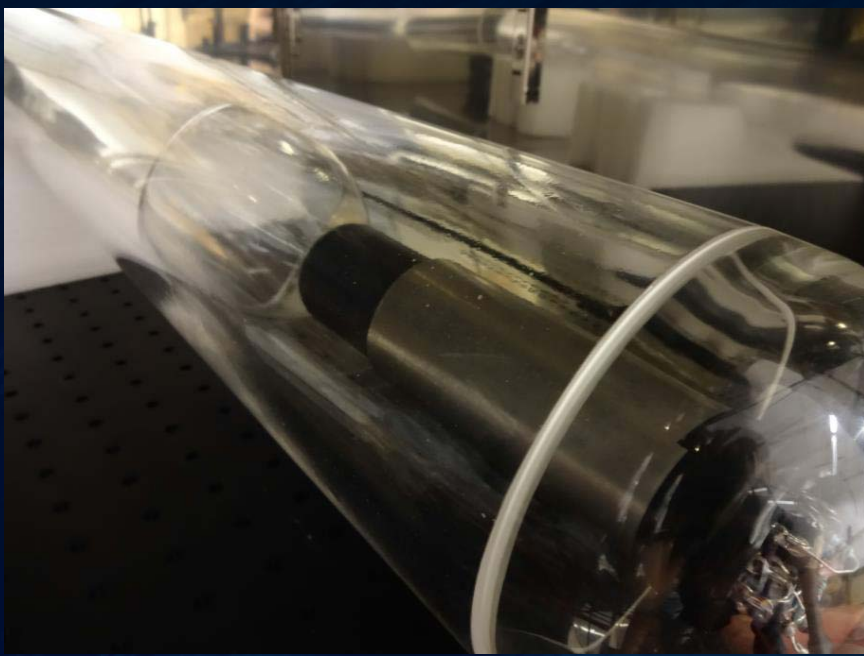
Photo-detector development



Wavelength shifter coated tube



A la KM3Net



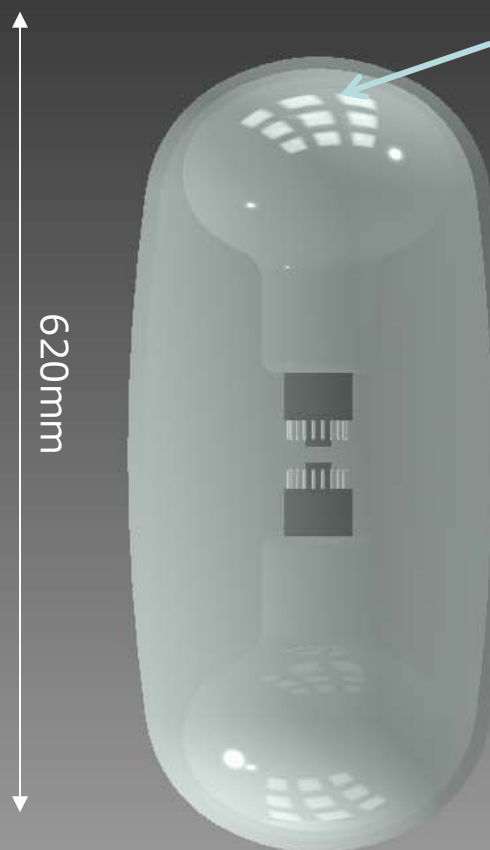
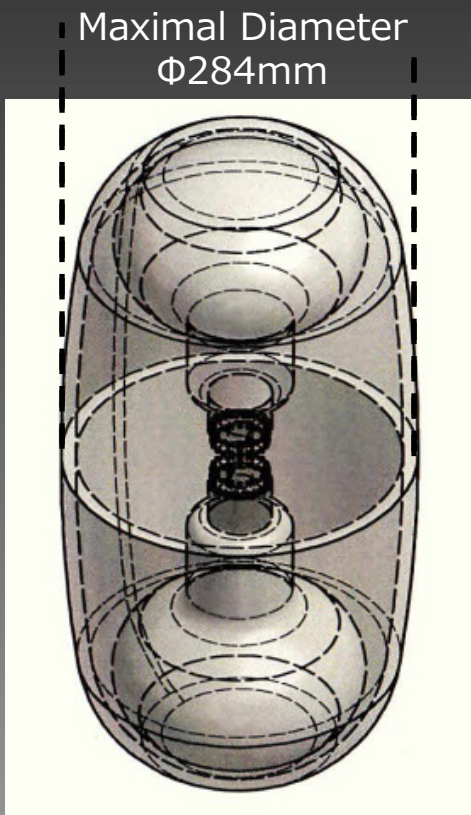


Next Generation: IceCube HEX

Photo-detector development



- Two 8' Hamamatsu R5912 High-QE PMTs
- up/down symmetry: good for veto, reco etc
- two PMTs instead of one: Better saturation response



customized glass shape/curvature

- designed best match curvature to our PMT
- less thickness top/bottom part (9mm-10mm where PMT acceptance) for better light transmittance

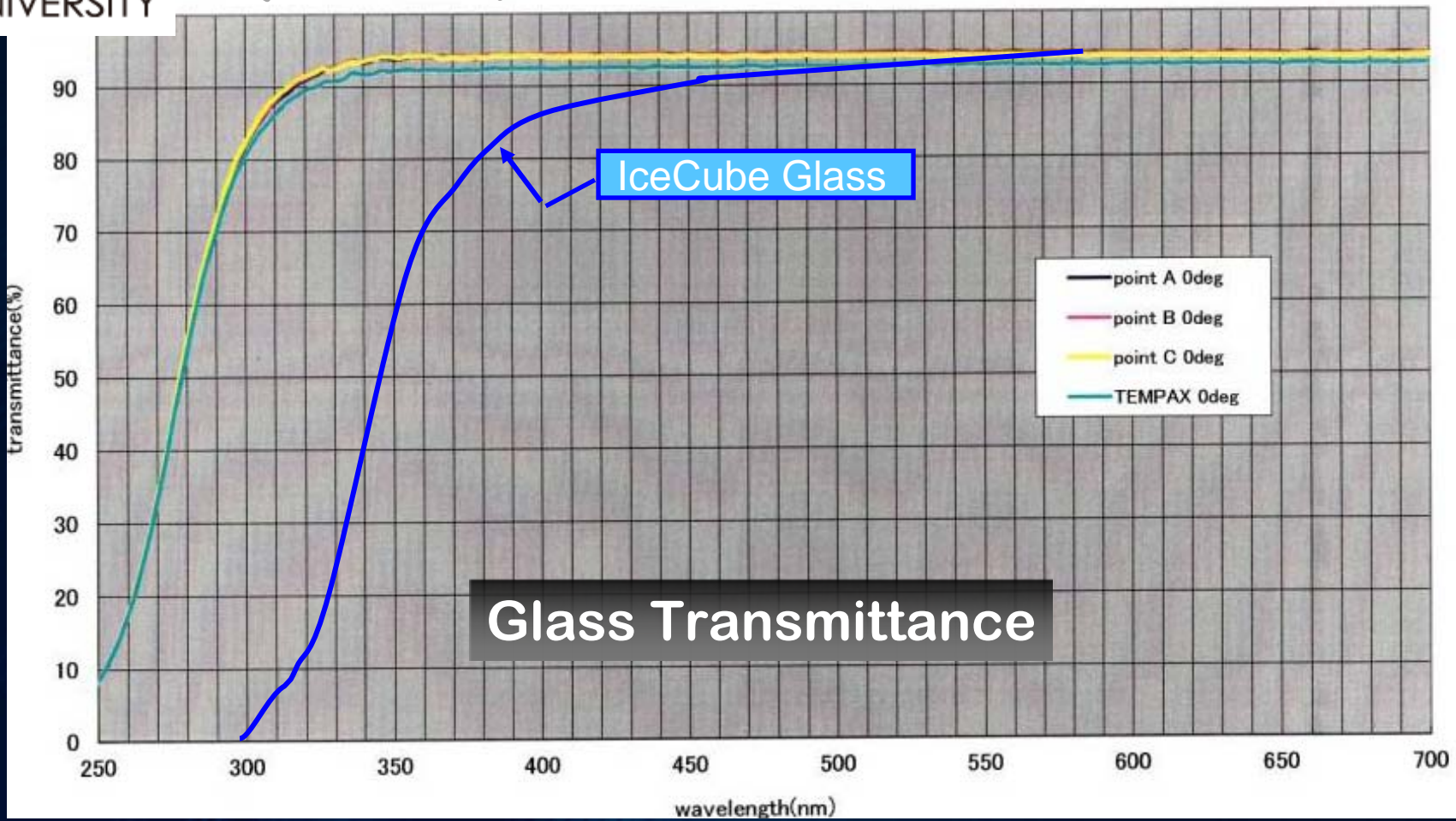
Slightly enhanced diameter and glass thickness in the middle for a mechanical strength



Next Generation: IceCube HEX Photo-detector development



A god improvements in 300nm-400nm



Glass Transmittance

IceCube Glass

- point A 0deg
- point B 0deg
- point C 0deg
- TEMPAX 0deg

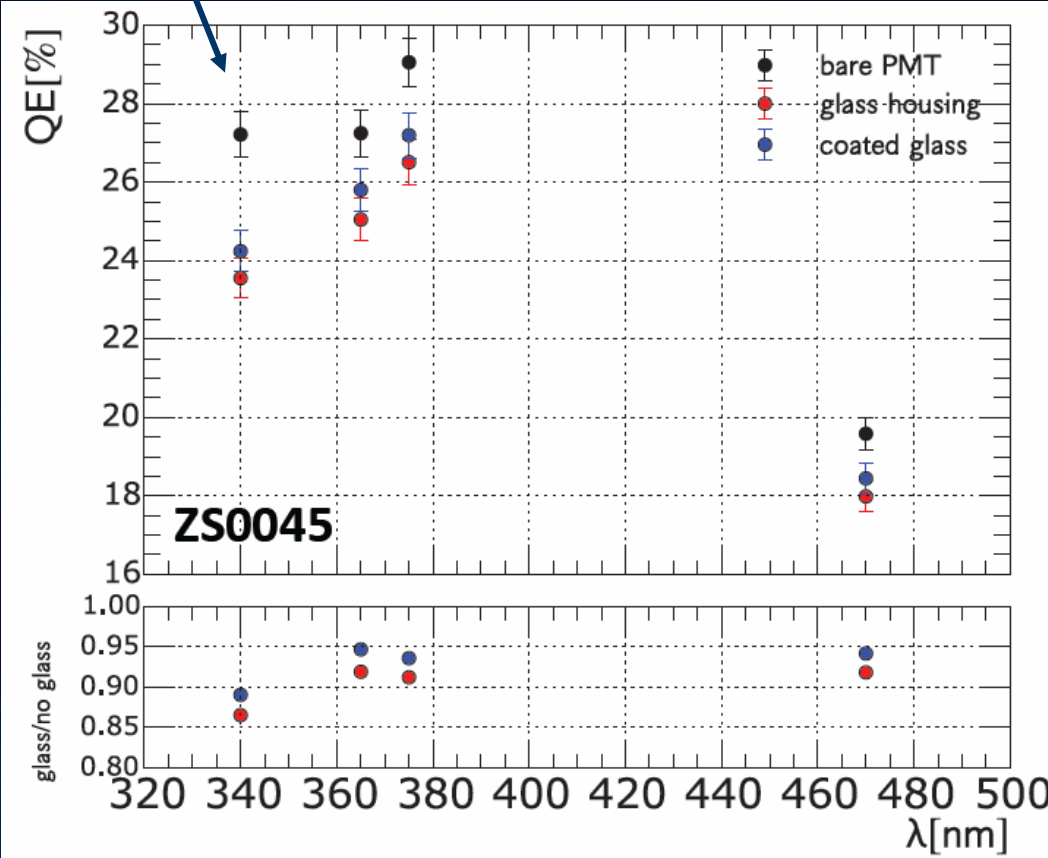
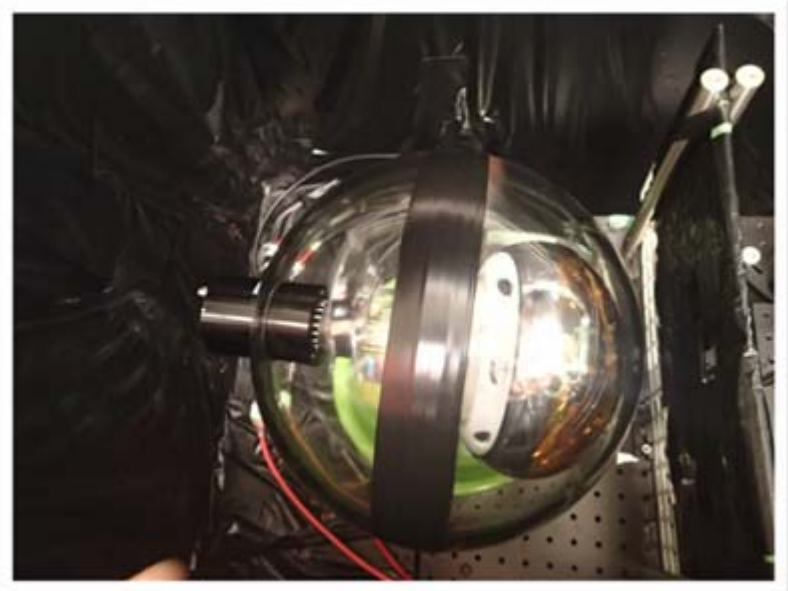


Next Generation: IceCube HEX Photo-detector development



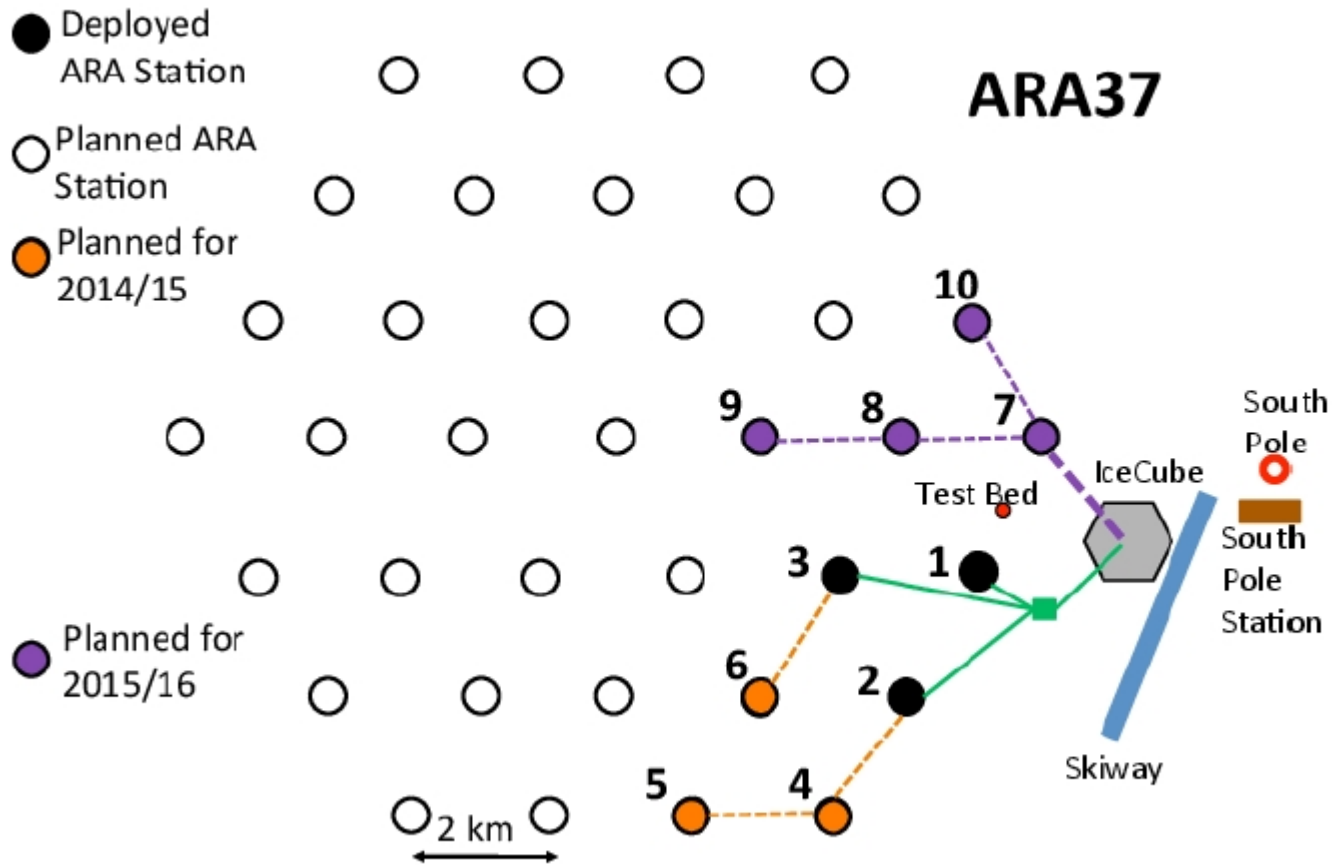
QE@340nm

7% (present icecube) → 24%





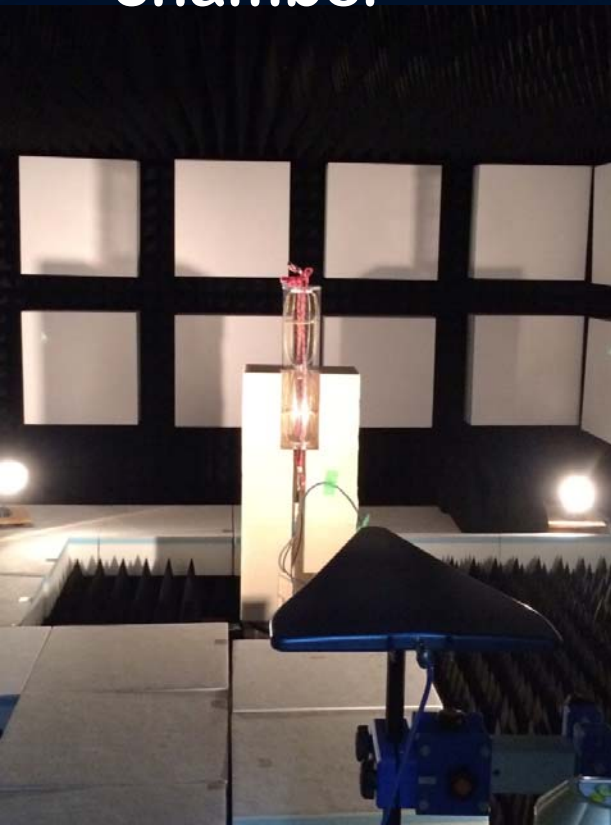
Next Generation: ARA



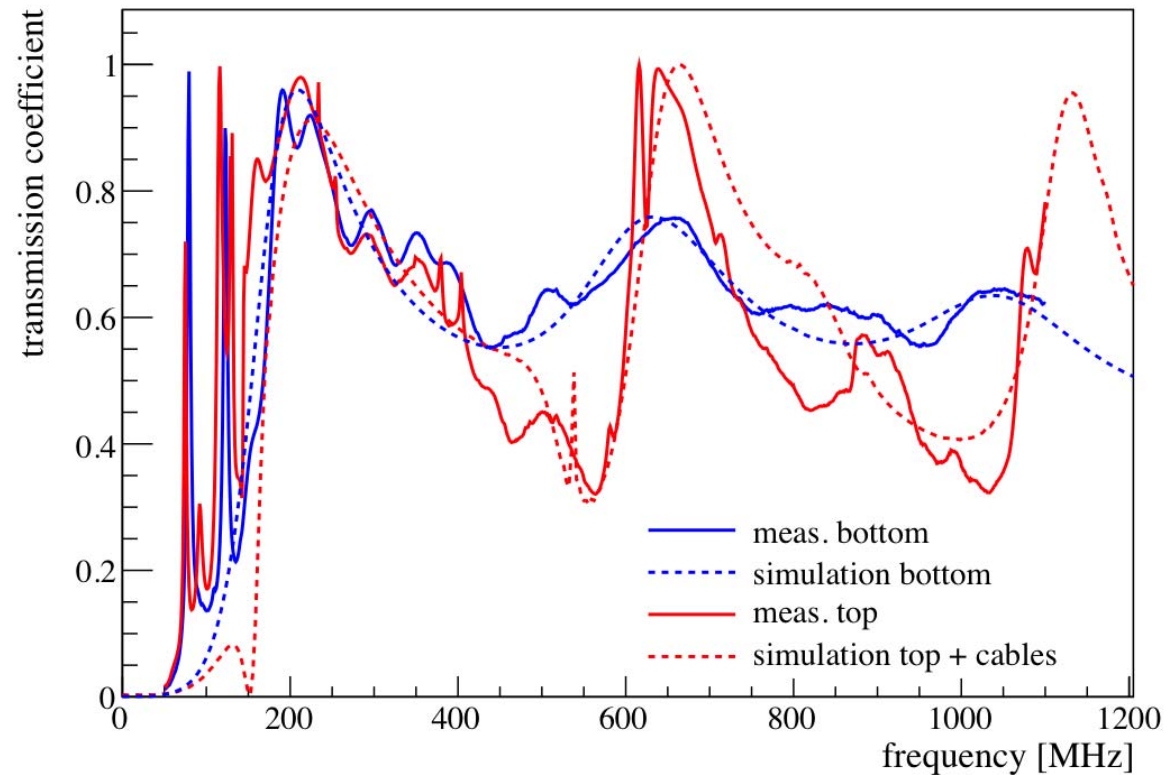
Next Generation: ARA

Antenna Assembly and calibration

chamber



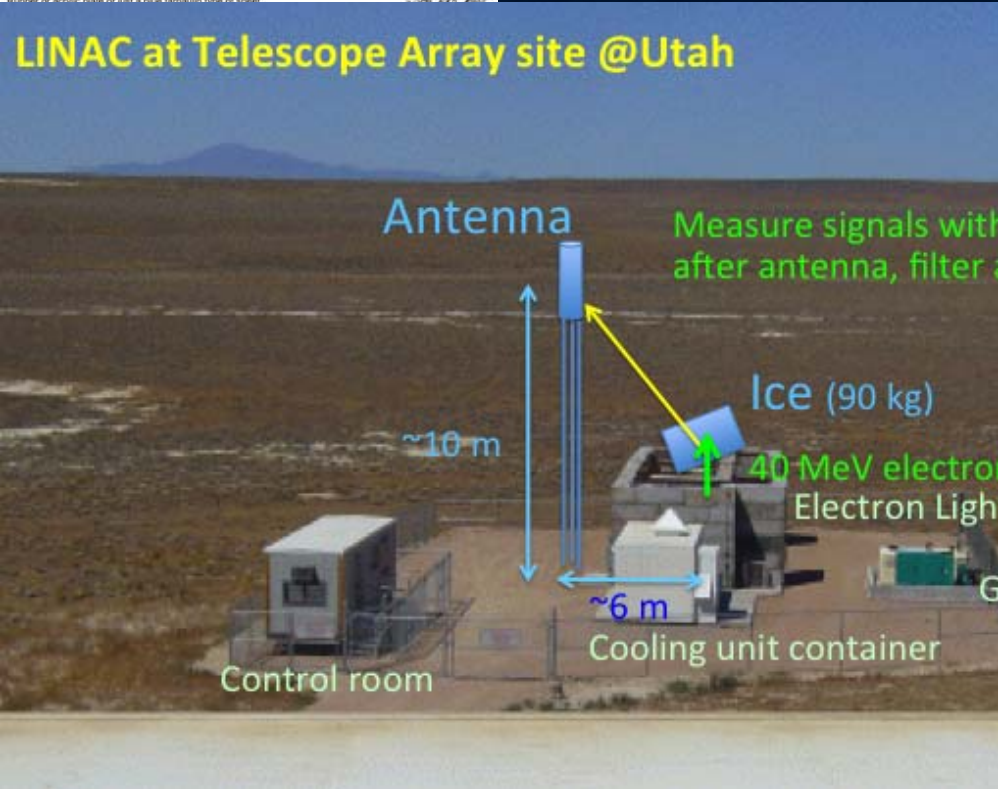
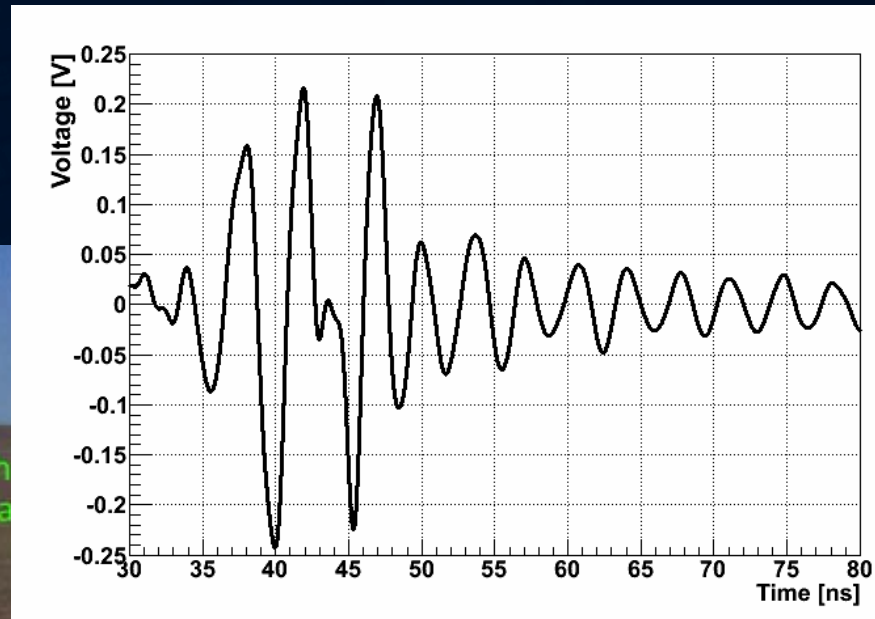
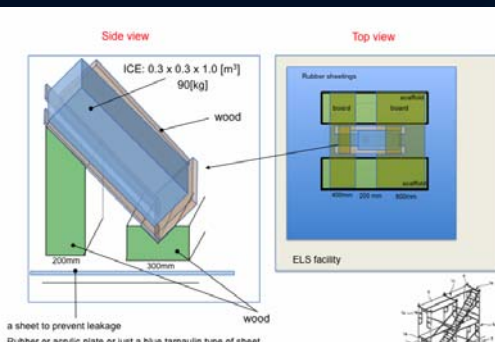
transmission coefficient





Next Generation: ARA

“end-to-end” calibration



Expected signals from ice

Executive Summary

$v = \text{THE smoking gun}$