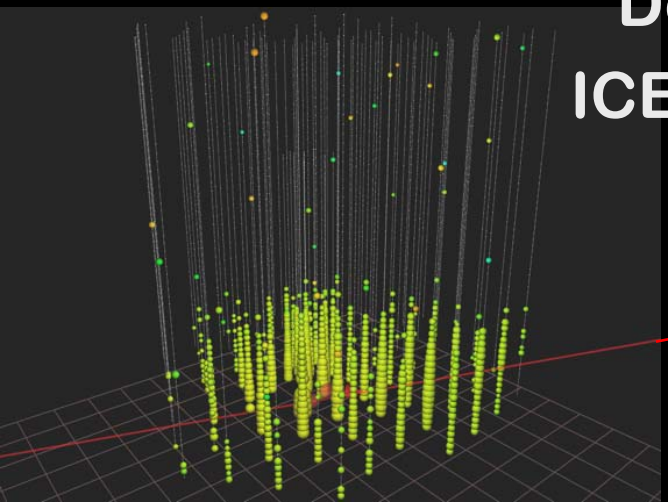
CHIBA UNIVERSITY

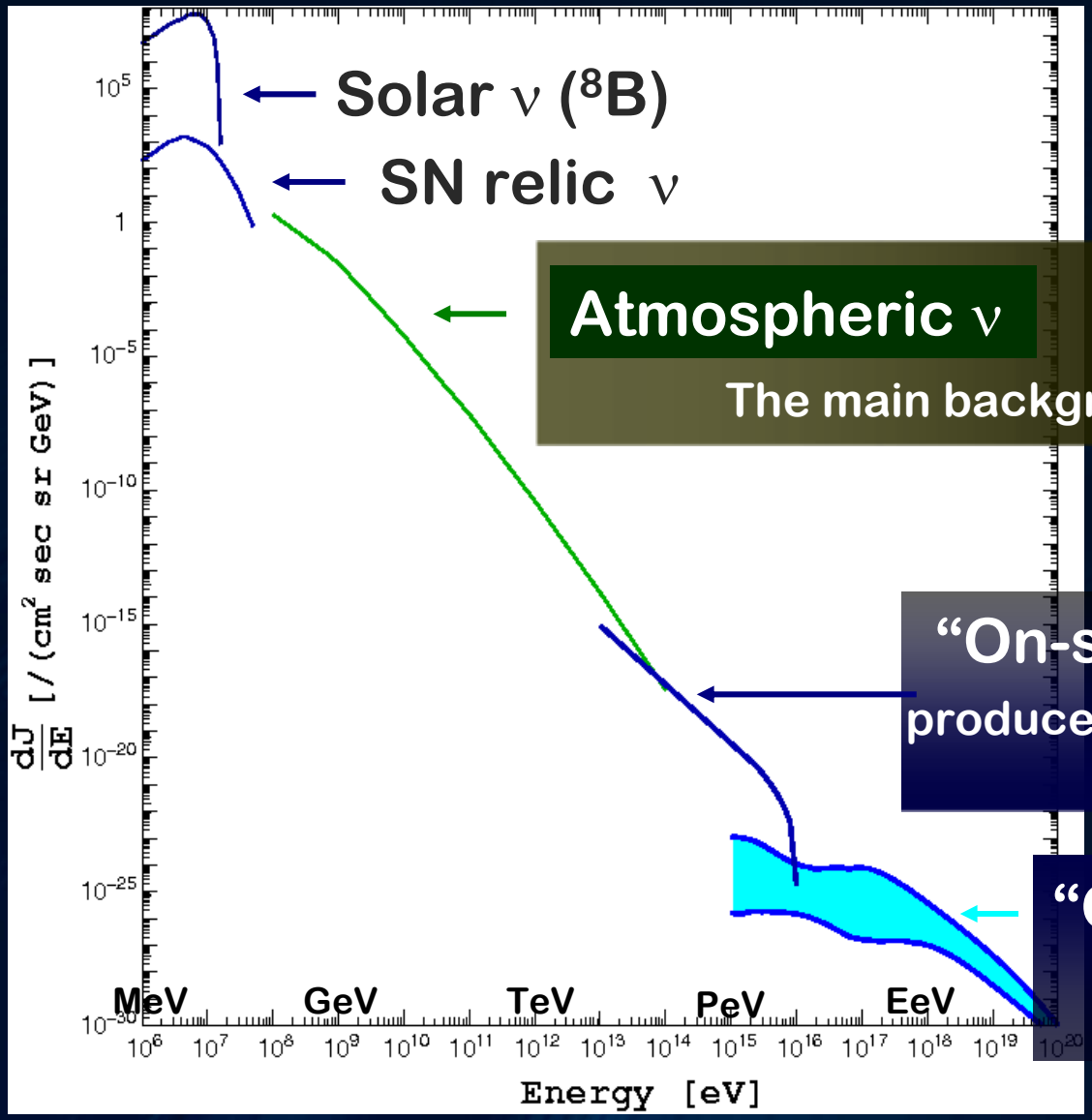
Probing the origin of UHECRs with neutrinos

The recent results from IceCube and its outlook

Shigeru Yoshida
Department of Physics
ICEHAP, Chiba University

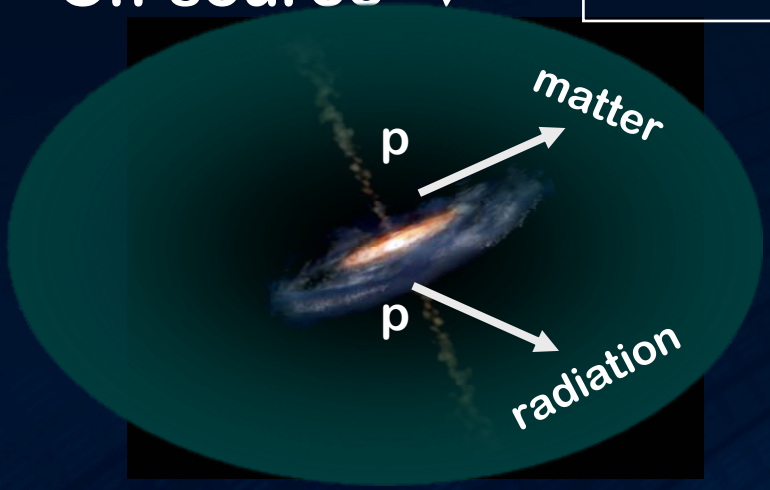


The Neutrino Flux: overview



The Cosmic Neutrinos
Production Mechanisms

"On-source" ν **TeV - PeV**

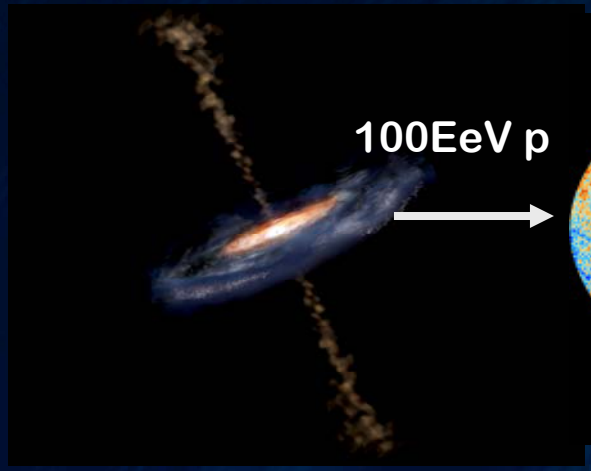


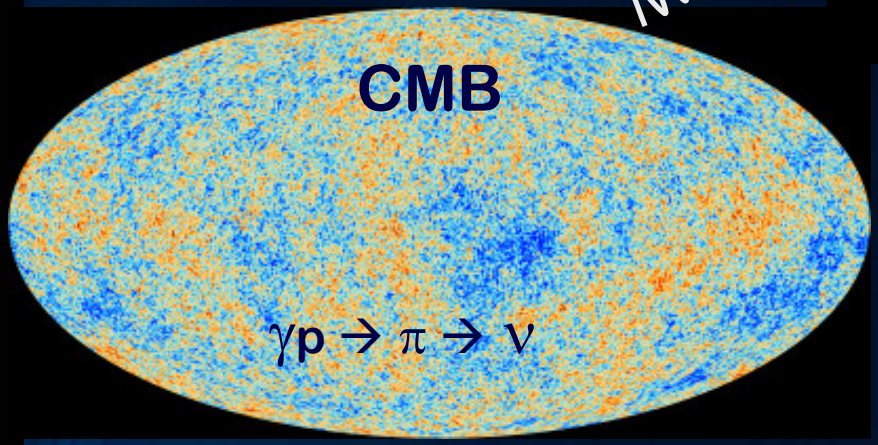
$pp \rightarrow \pi \rightarrow \nu$

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

photopion production

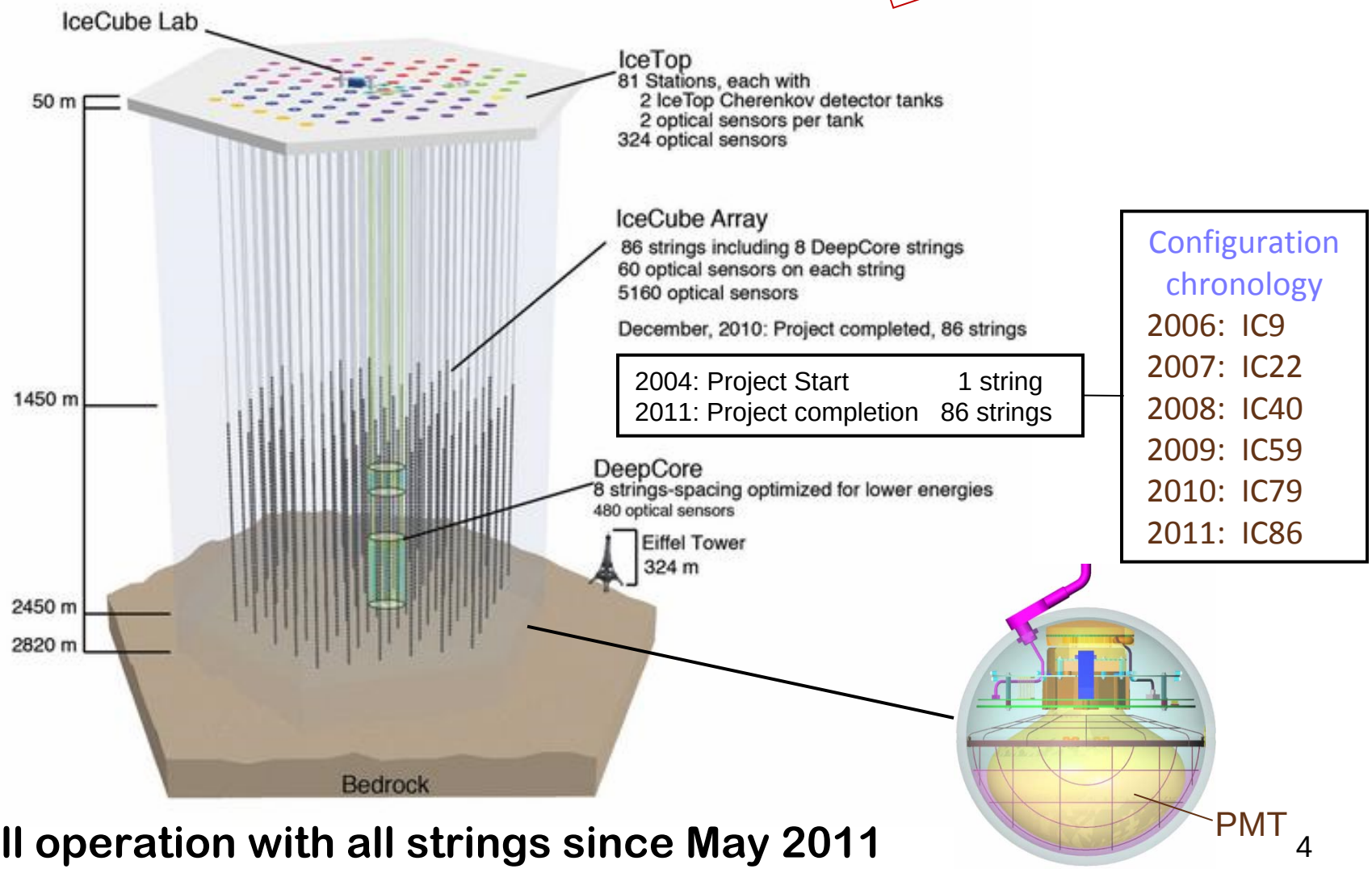
"GZK" cosmogenic ν **EeV**





The IceCube Neutrino Observatory

Completed: Dec 2010



Full operation with all strings since May 2011

Constructions 2005-2011

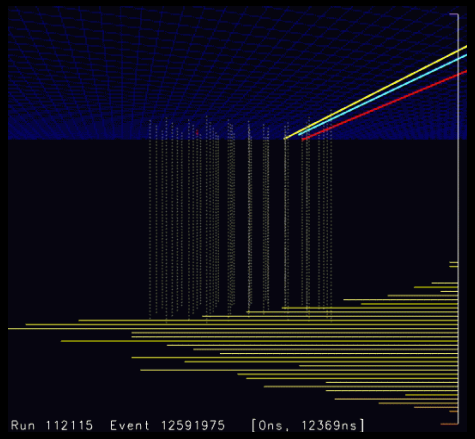
Detectors shipped from Japan

Drill House

The IceCube Lab 「Beer Can」

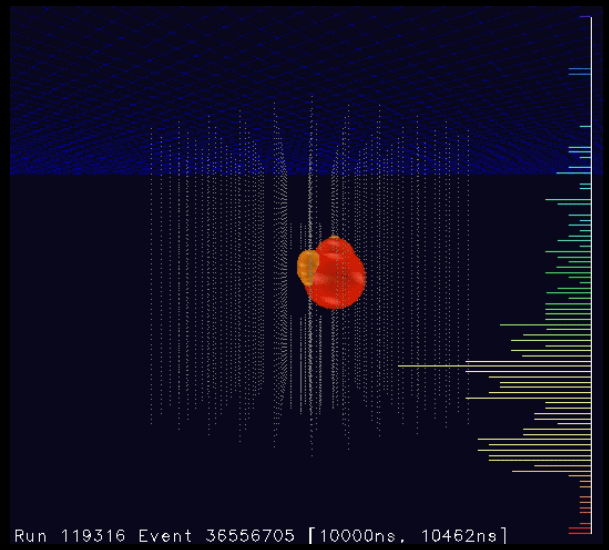
Researchers working on deployment

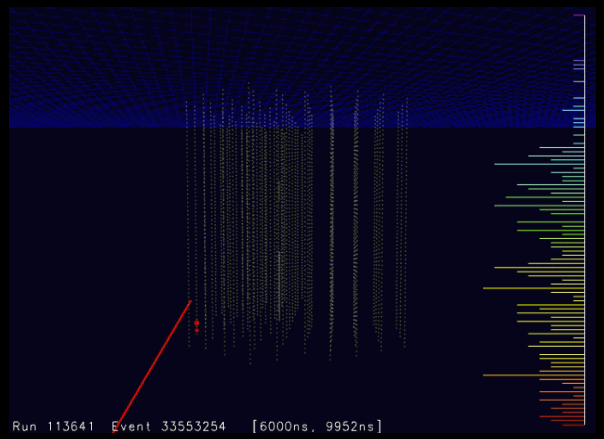
Topological signatures of IceCube events



Down-going track

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





Up-going track

- atmospheric ν_μ

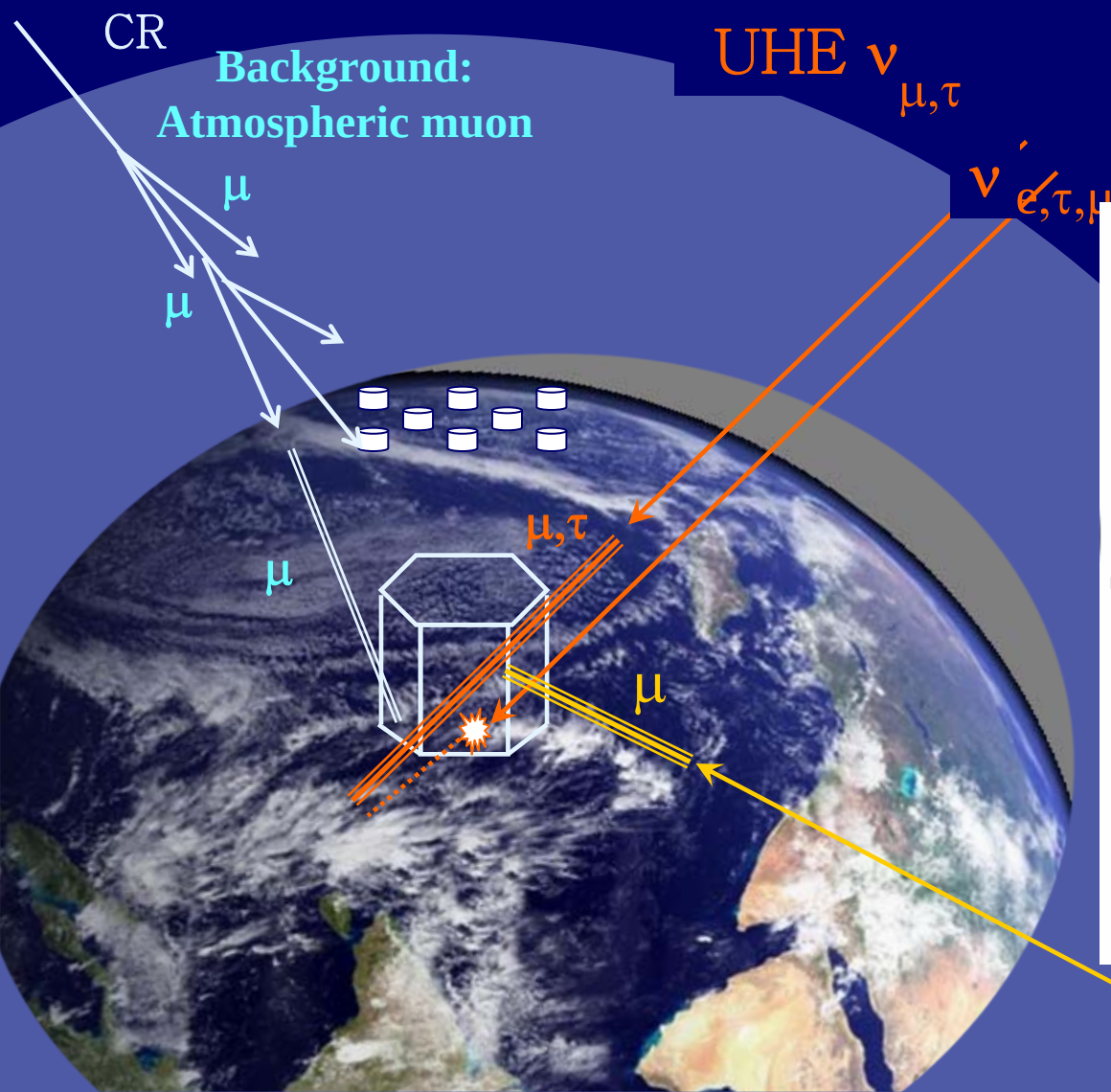
Cascade (Shower)

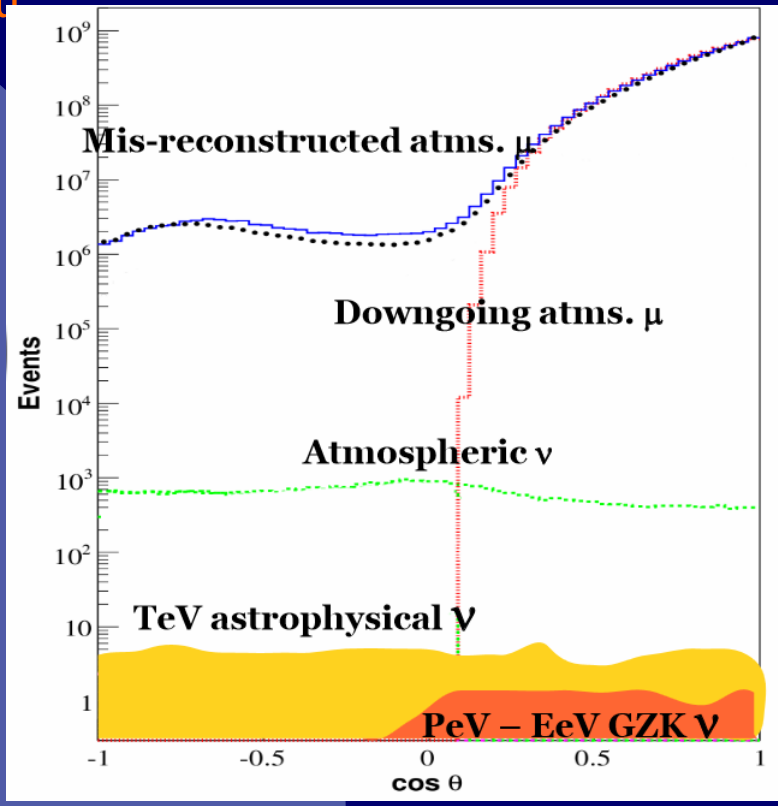
directly induced by ν
inside the detector volume

- 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)

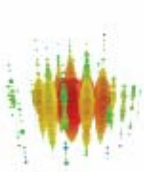




Post Bert & Ernie

The Discovery Analyses

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)]

PHYSICAL REVIEW LETTERS

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Articles published 6 July – 12 July 2013

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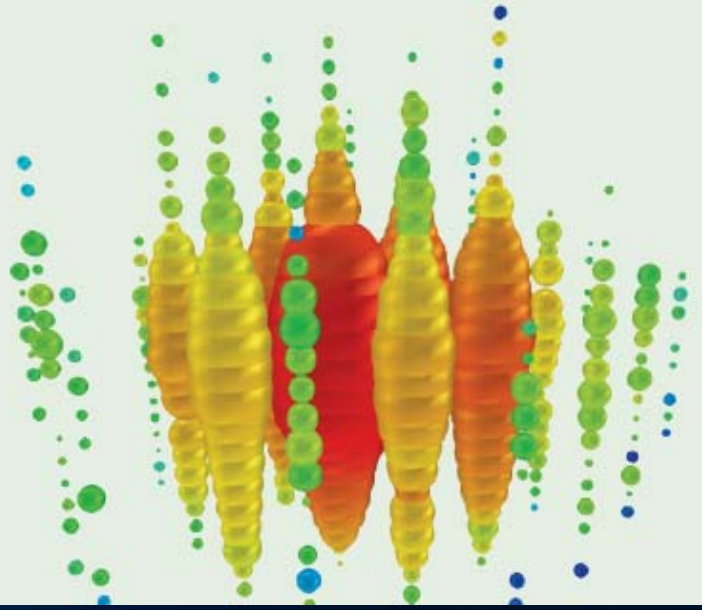
PHYSICAL REVIEW LETTERS

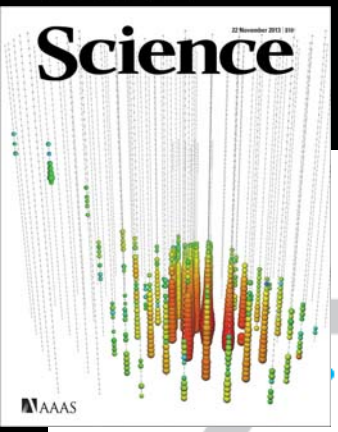
Articles published week ending 12 JULY 2013

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

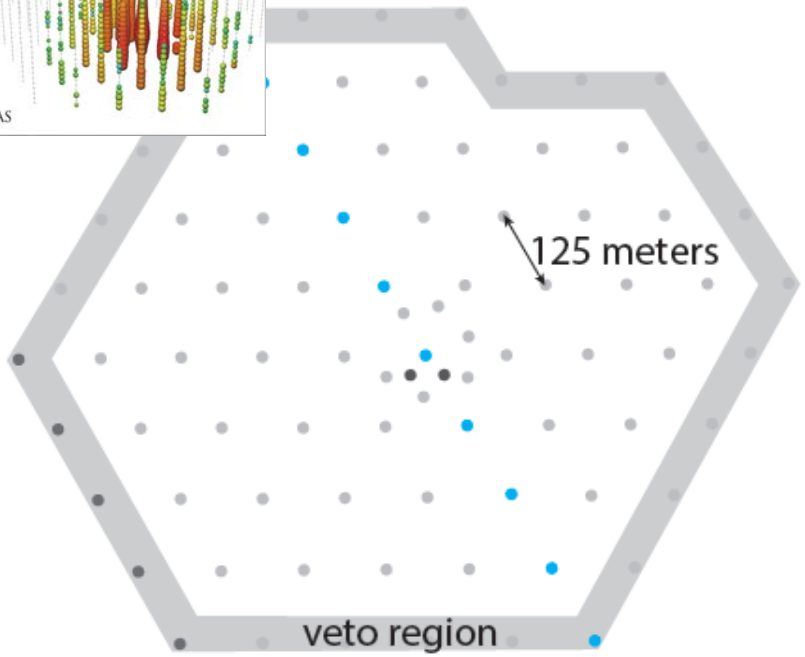


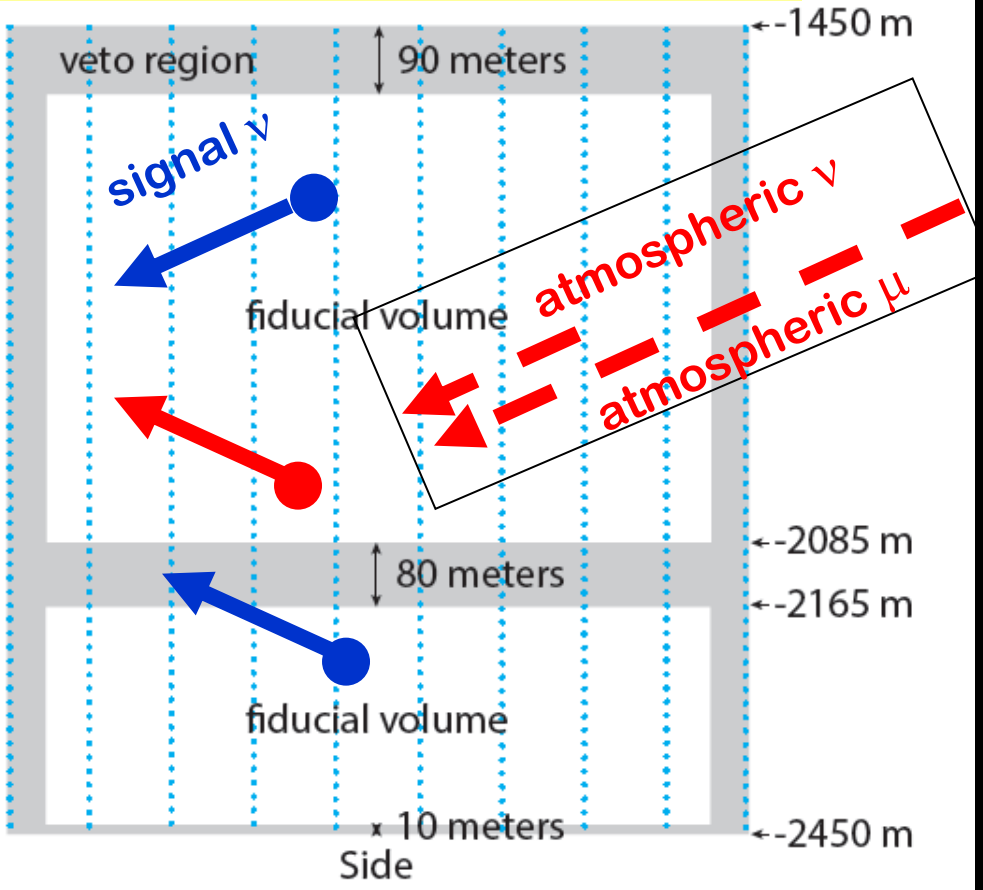
TeV PeV EeV

Mid Energy (60 TeV-)



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

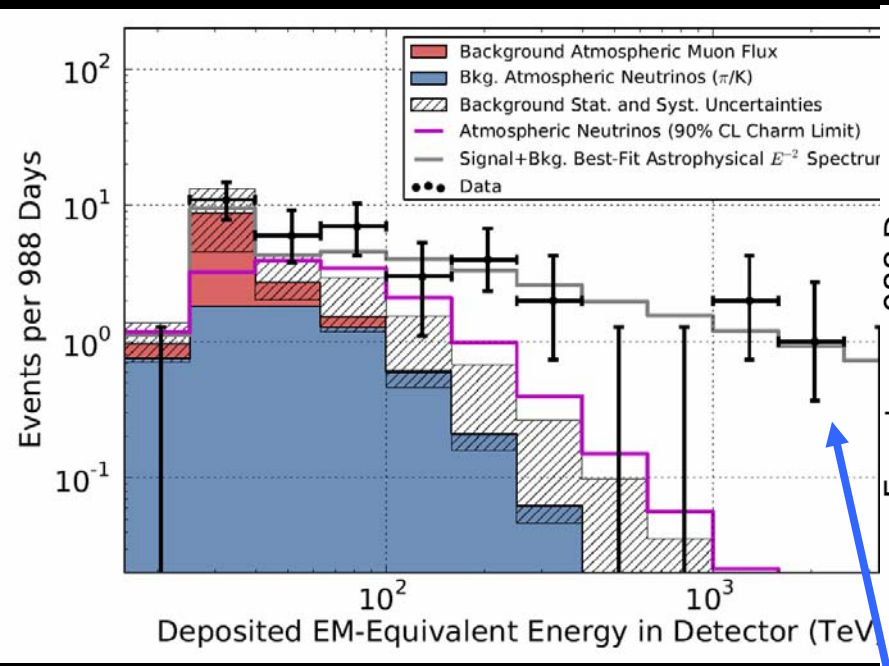


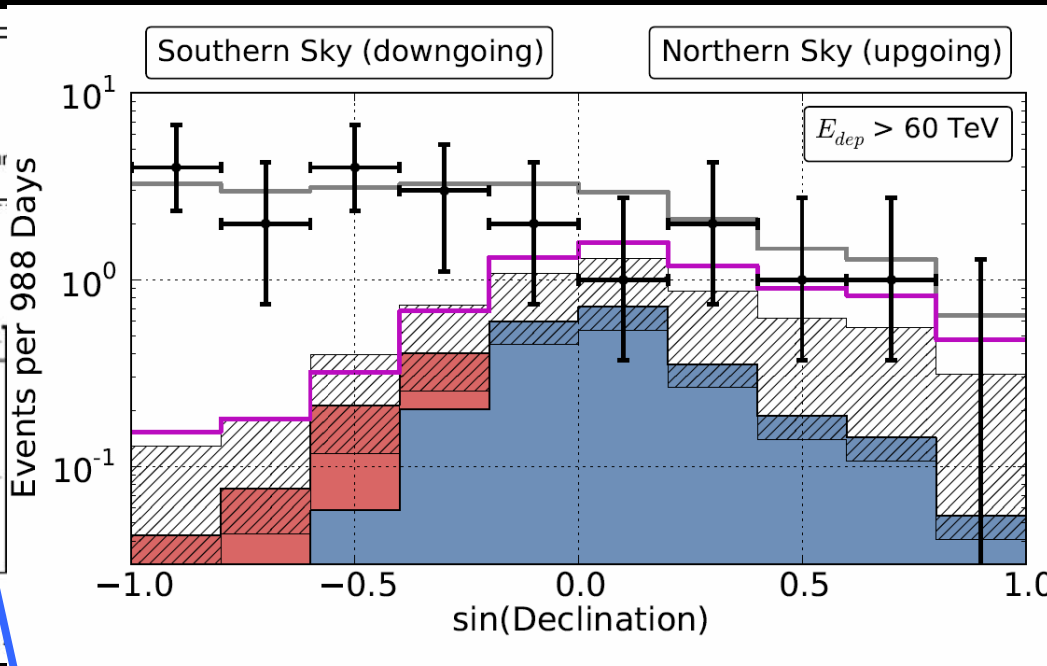


Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

IceCube collaboration
Phys. Rev. Lett. 113, 101101

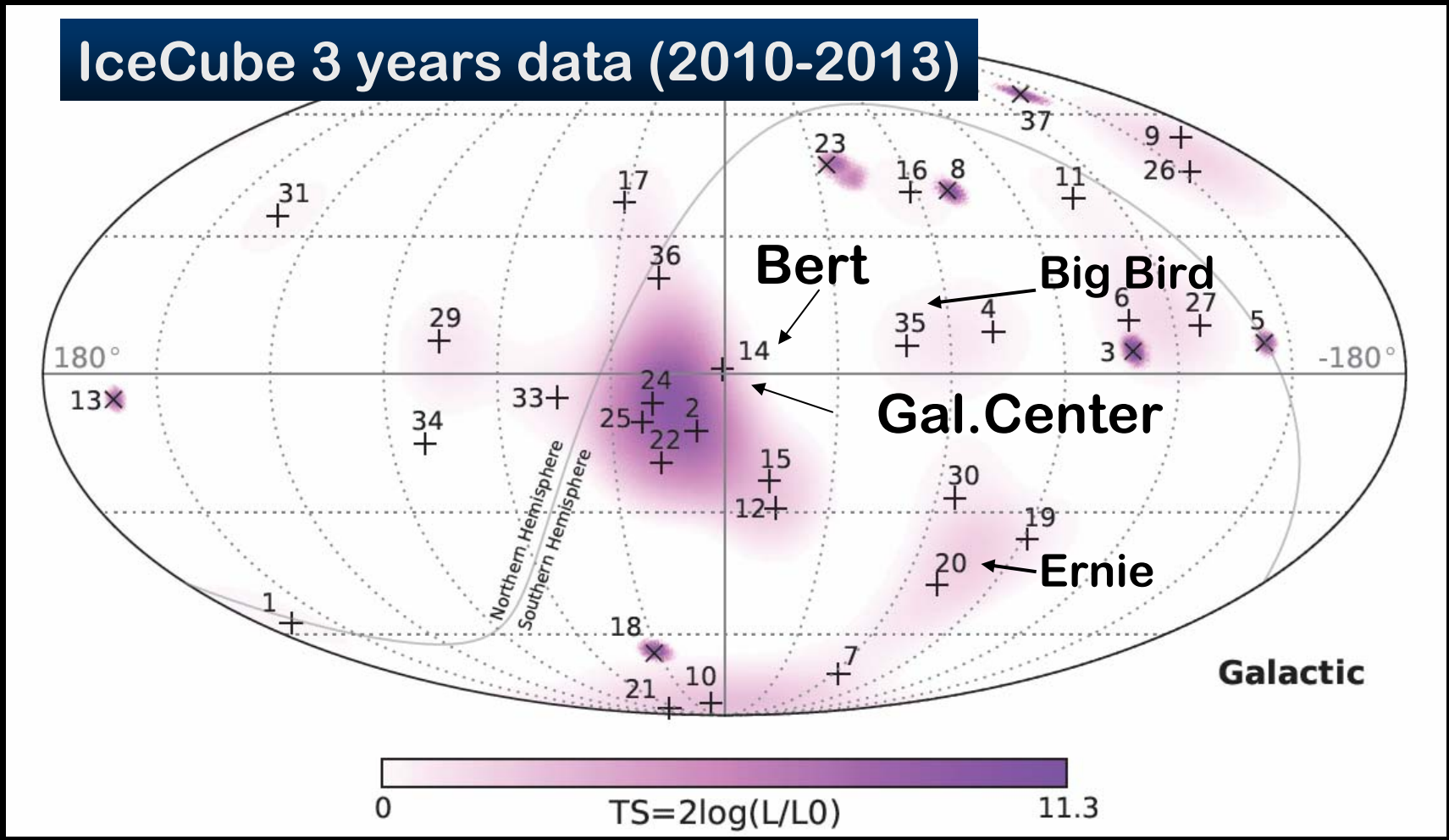




2PeV "Big Bird"

TeV PeV EeV

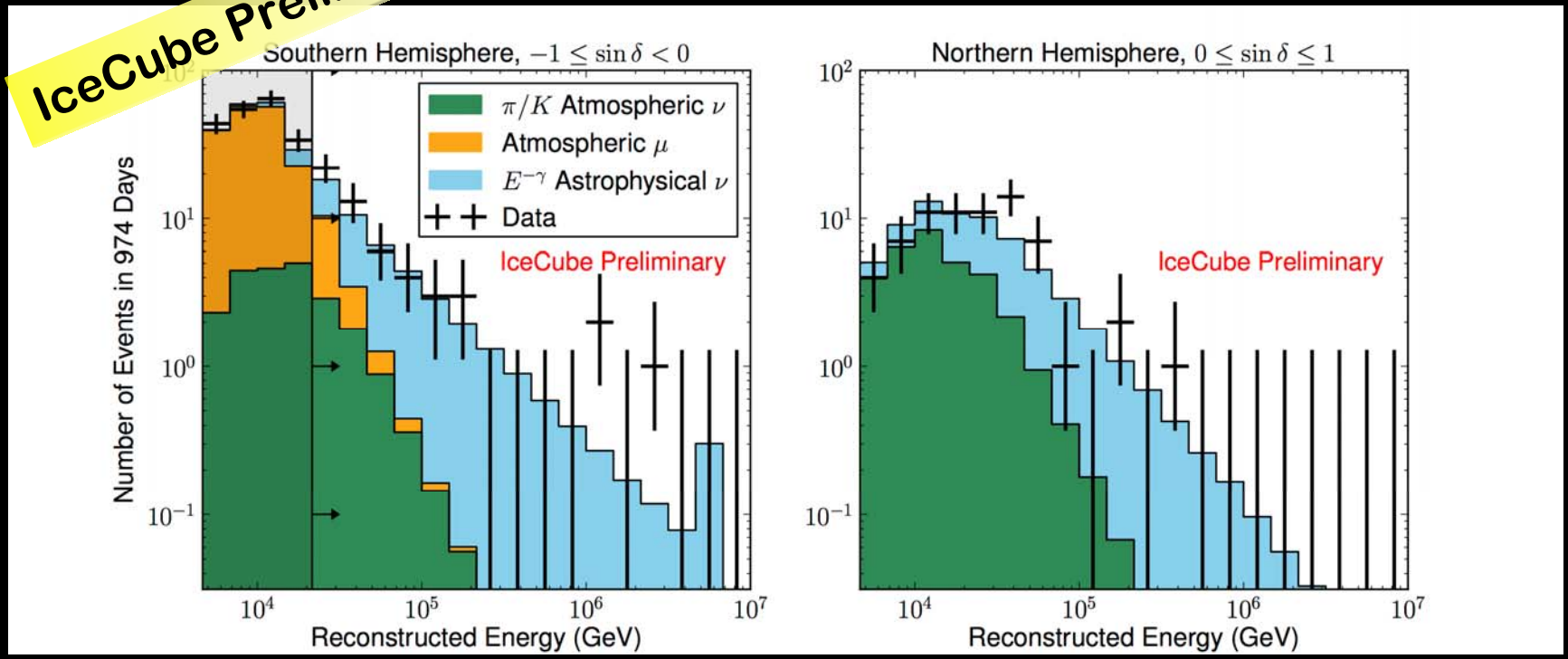
Mid Energy (60 TeV-)



Mid Energy (10 TeV-)

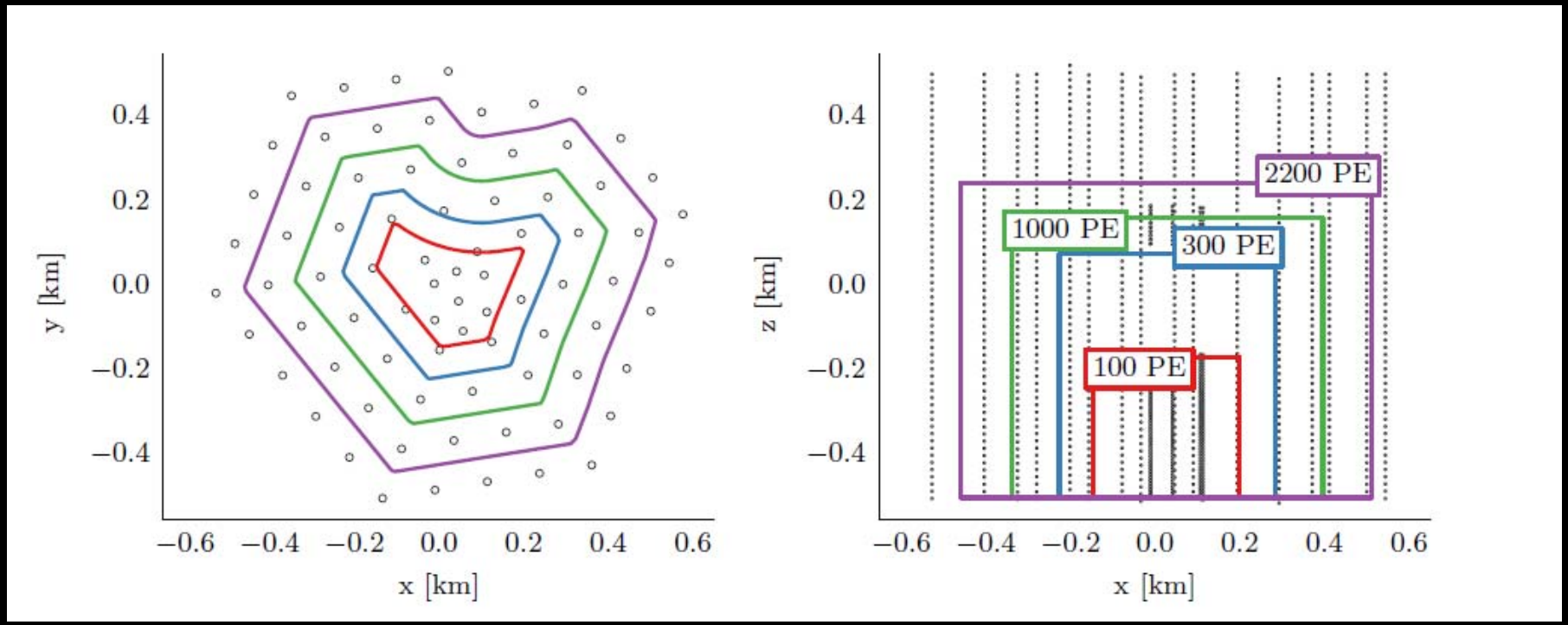
veto + "cascade"

IceCube Preliminary



LE (<10 TeV)

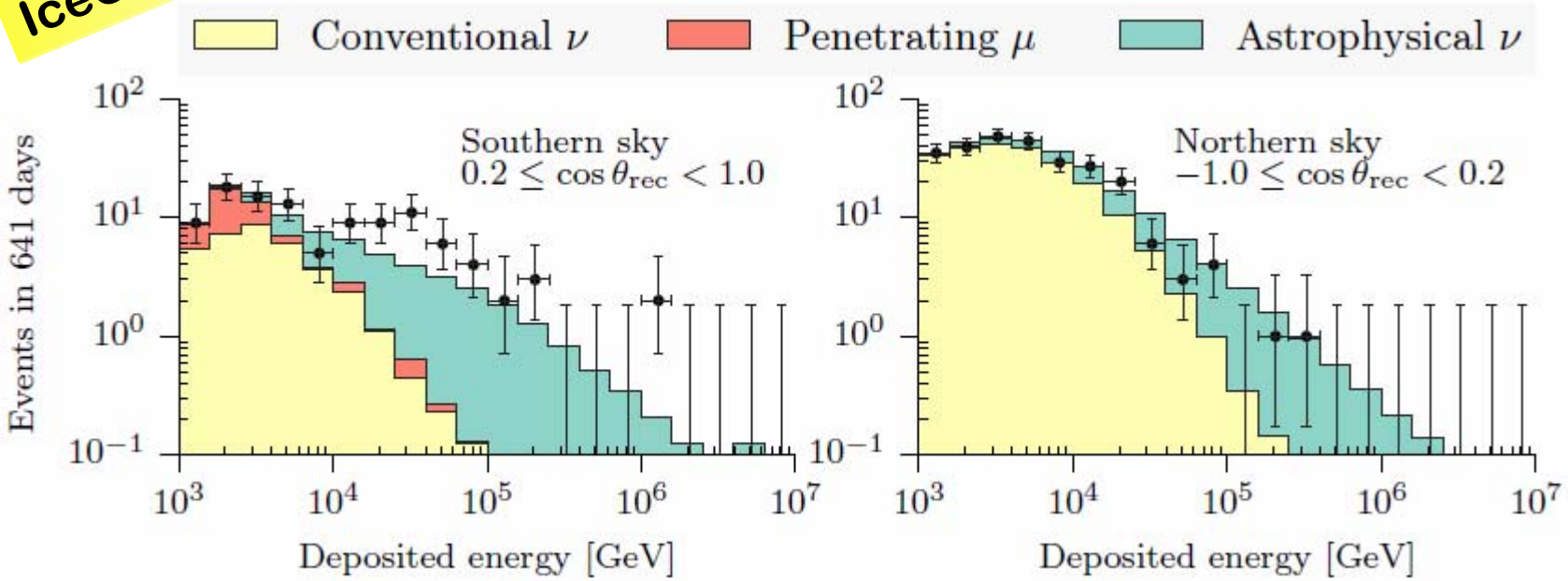
Energy-dependent active veto



LE (<10 TeV)

IceCube Preliminary

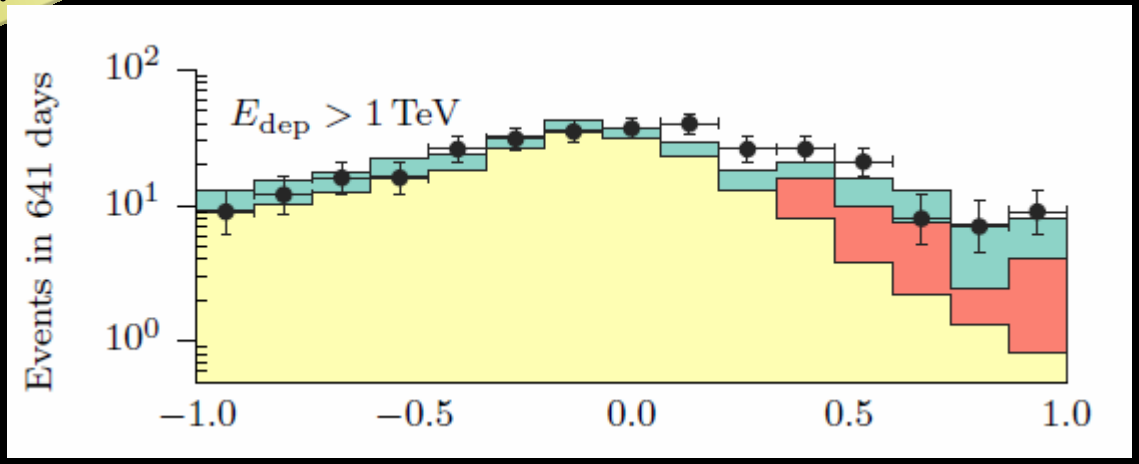
IceCube 2 years data (2010-2012)

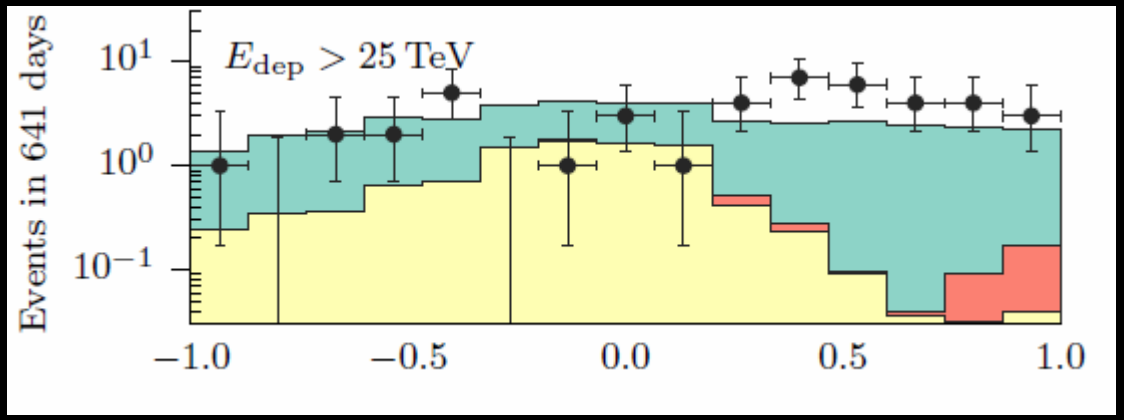


LE (<10 TeV)

IceCube Preliminary

IceCube 2 years data (2010-2012)



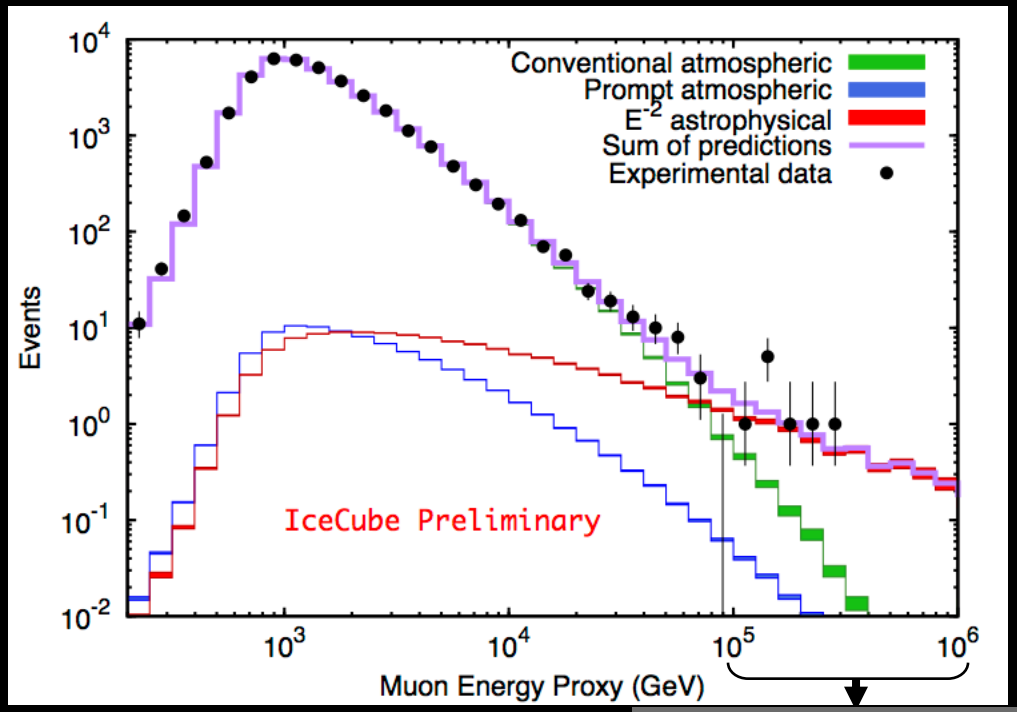


VHE (100 TeV-PeV)

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

$E^2 \phi_{\nu_\mu}(E) \sim 9.6 \times 10^{-9}$ [GeV/cm² sec sr]

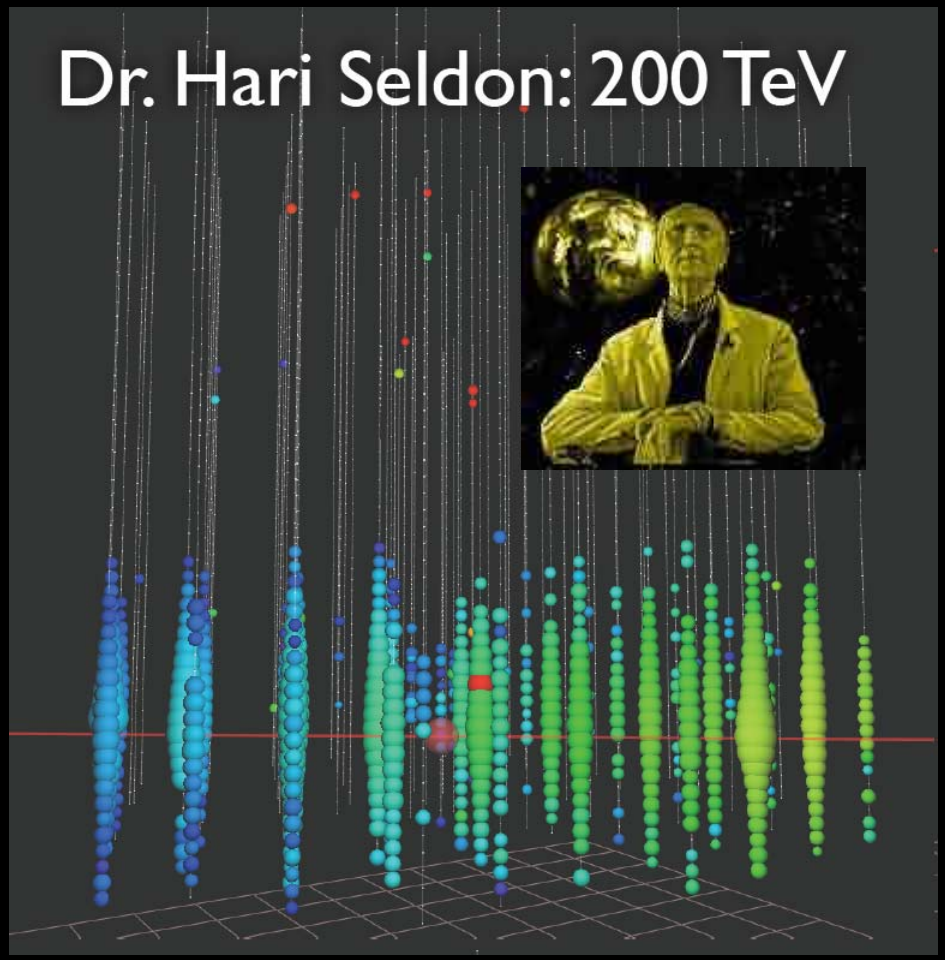
E_ν = O(100TeV)

TeV | PeV | EeV

VHE (100 TeV-PeV)

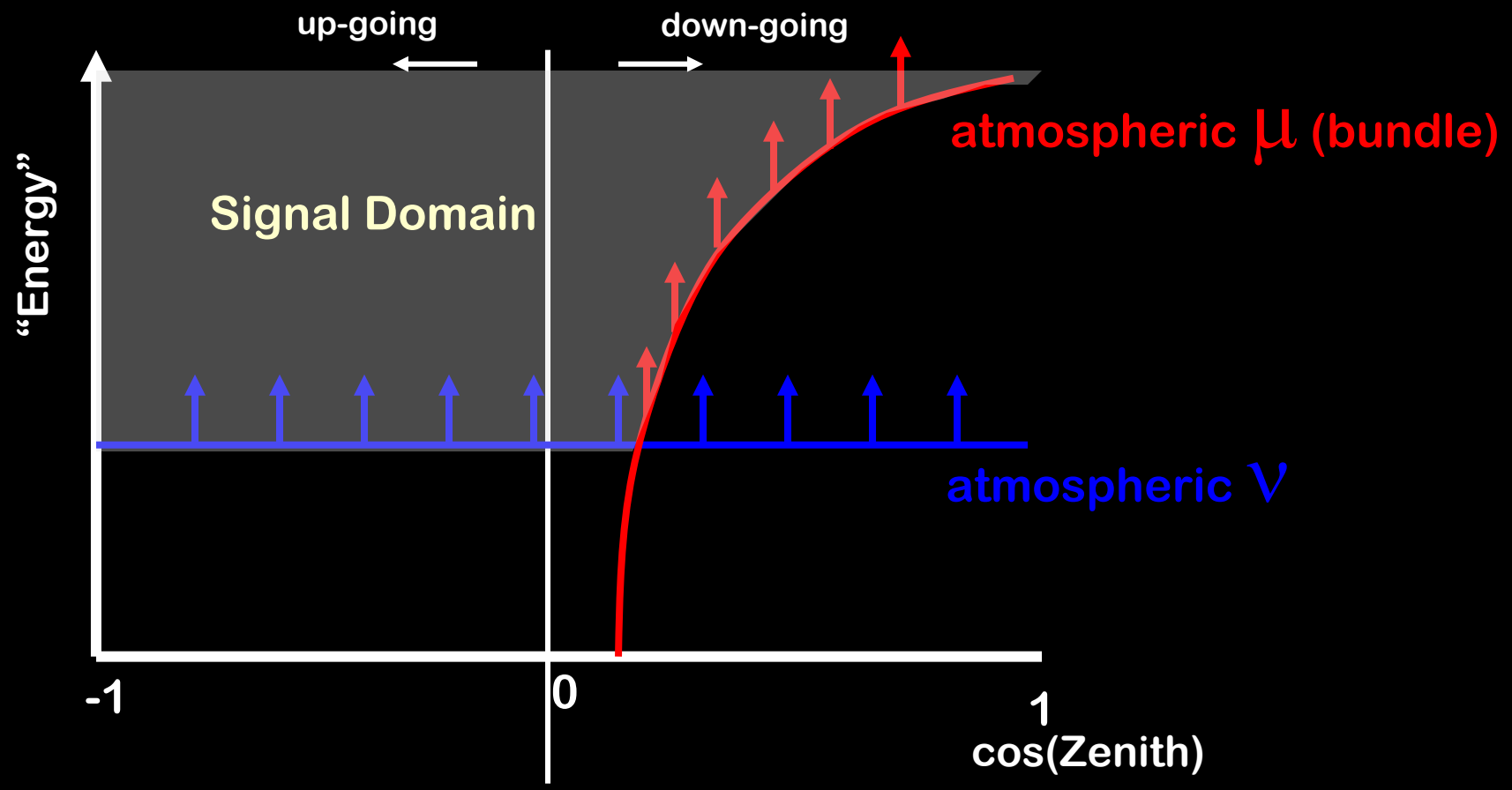
The "traditional" ν_μ search looking into upgoing tracks

IceCube Preliminary



UHE (PeV-EeV)

Detection Principle – All flavor sensitive

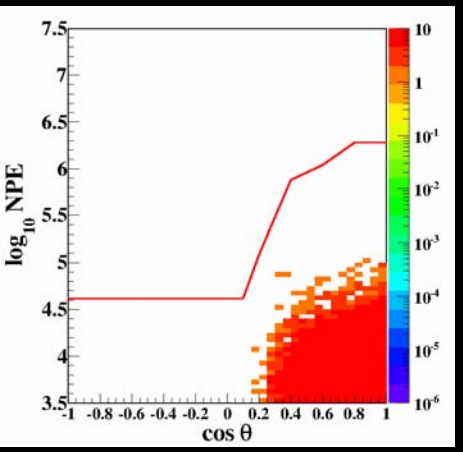


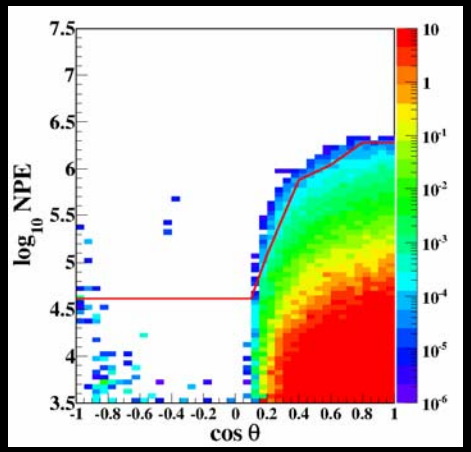
UHE (PeV-EeV)

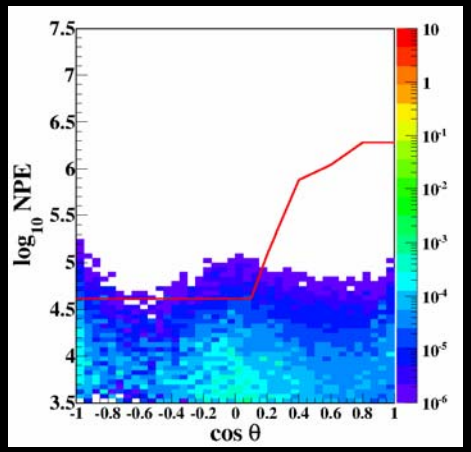
Number of events (z-axis) per the test-sample livetime

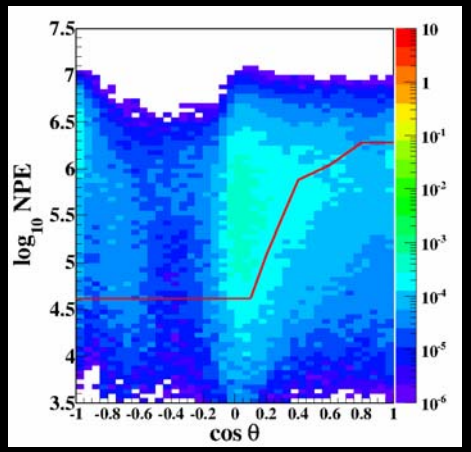
test-sample data	atmospheric μ	atmospheric ν conventional only	signal GZK ν

IceCube2010

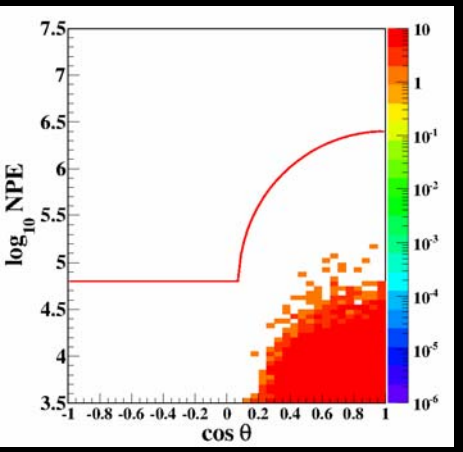


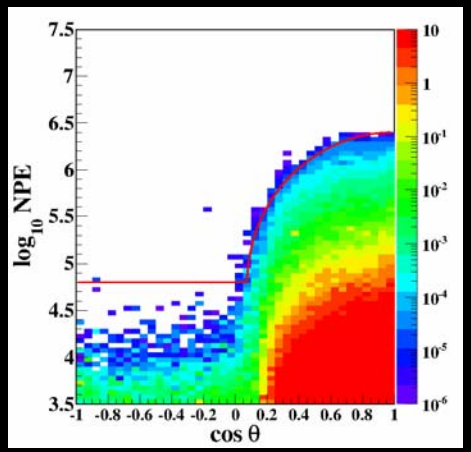


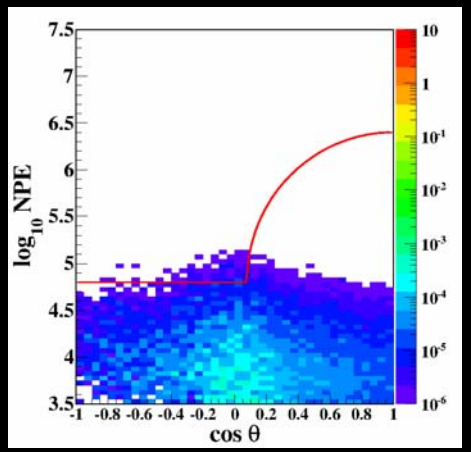


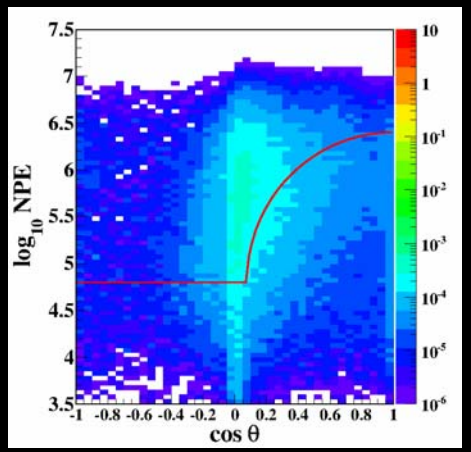


IceCube2011





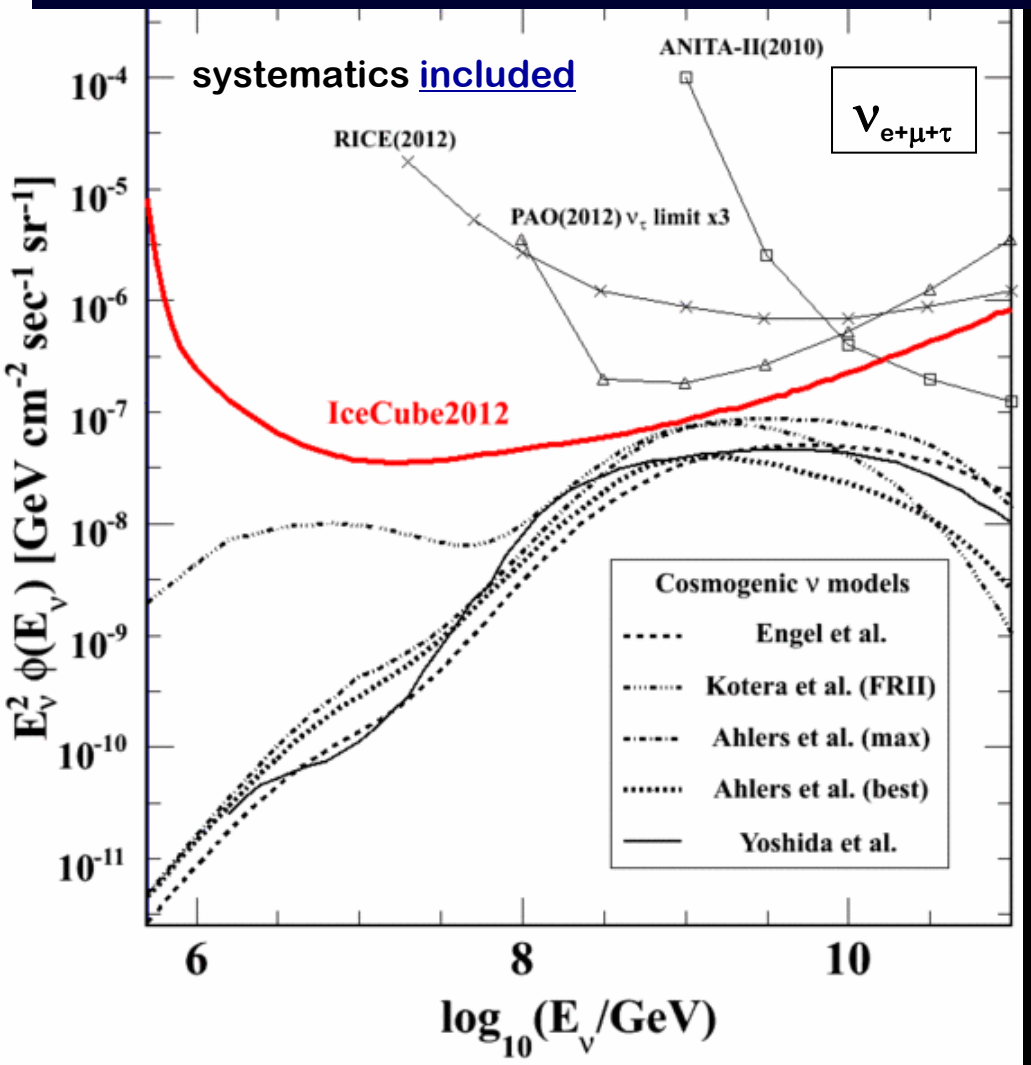




UHE (PeV-EeV)

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

6×10^7 m^2 days sr @ 1EeV

= 0.2 km^2 sr year

Note: ϕ_{CR}(>1EeV) ~ 20/km^2 sr year

ν with CR comparable flux should have been detected

TeV PeV EeV

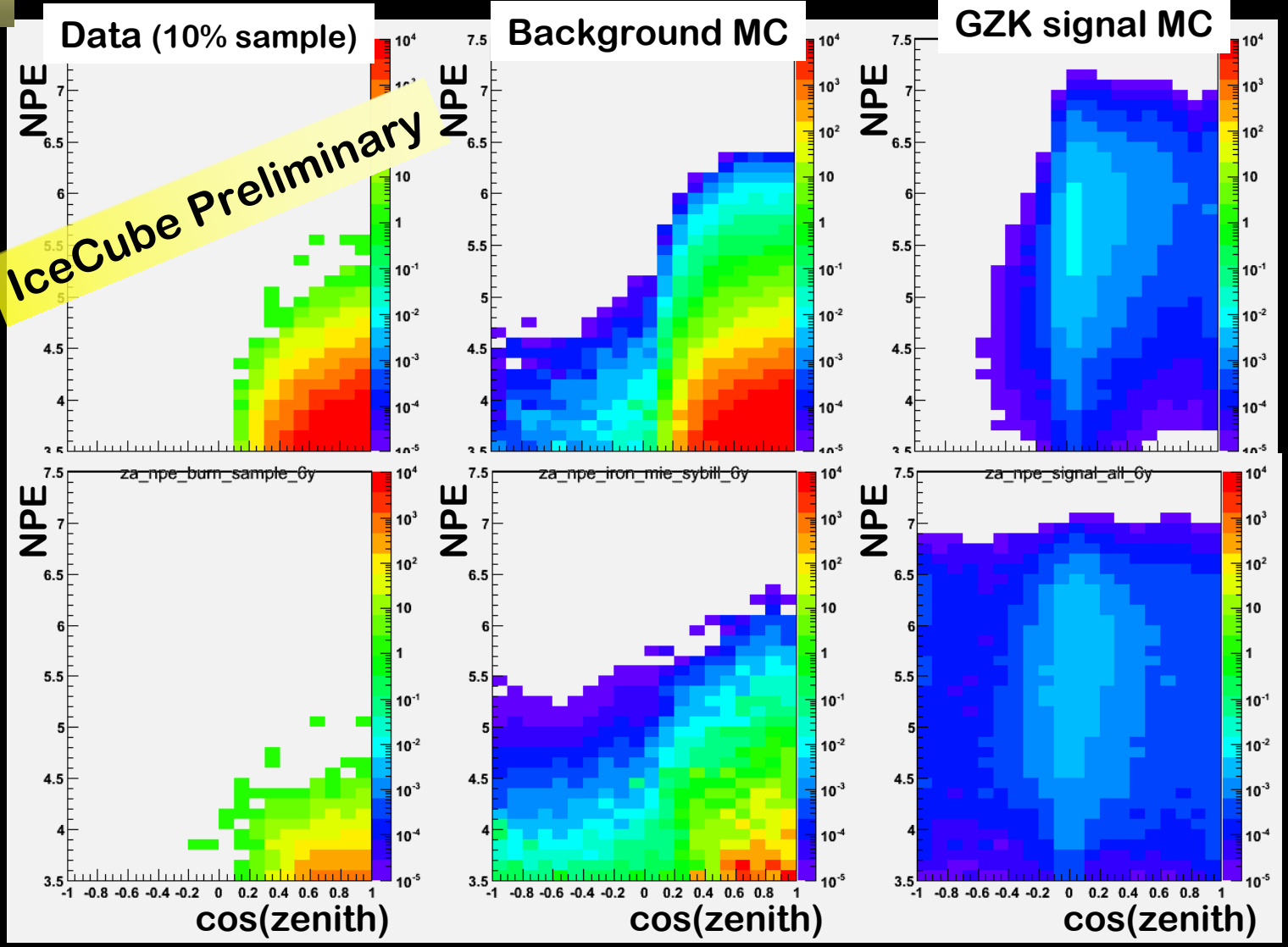
UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined

New

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

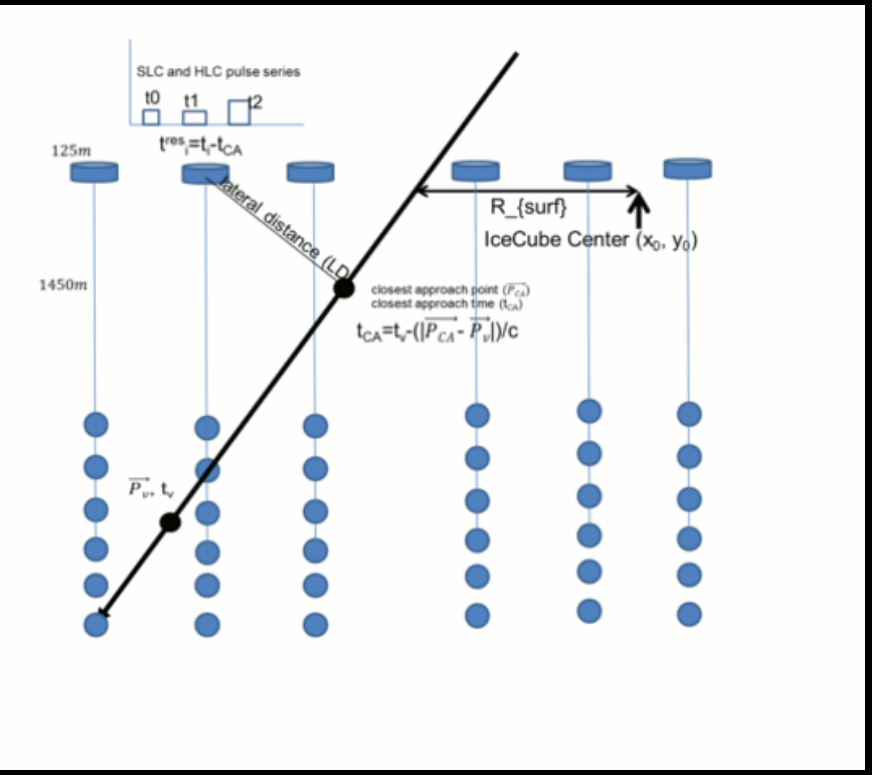
$\nu_{e,\mu,\tau}$ non track-like

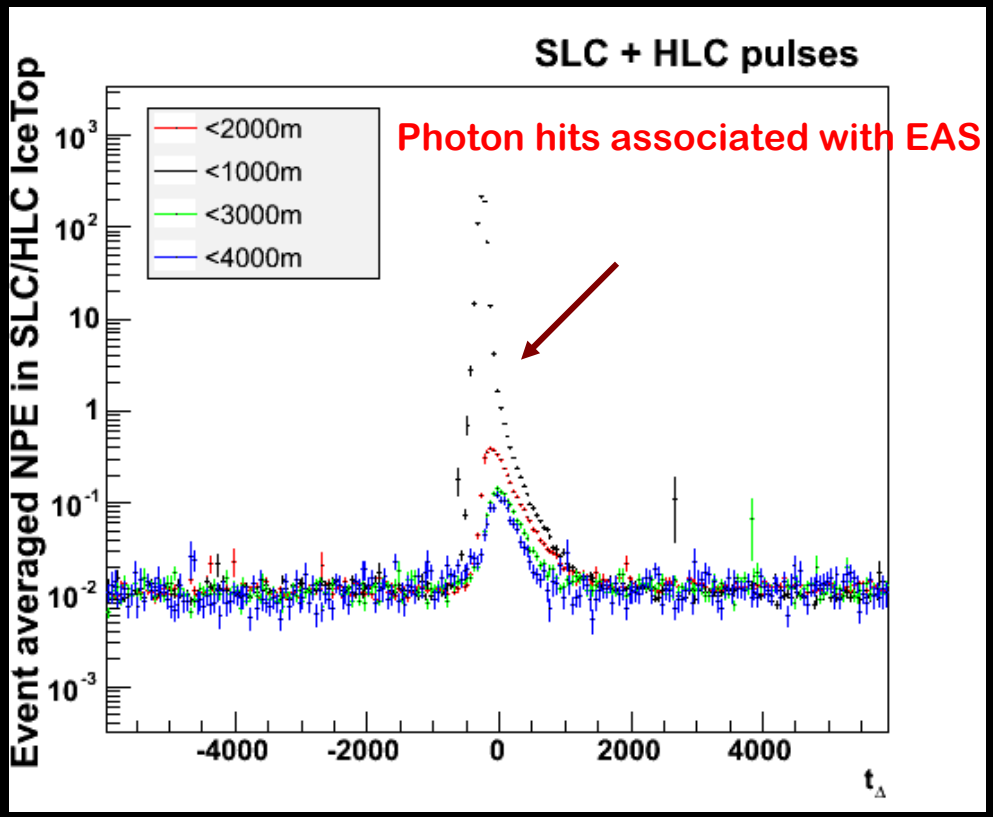


New

UHE (PeV-EeV)

Veto by arshower array (IceTop)

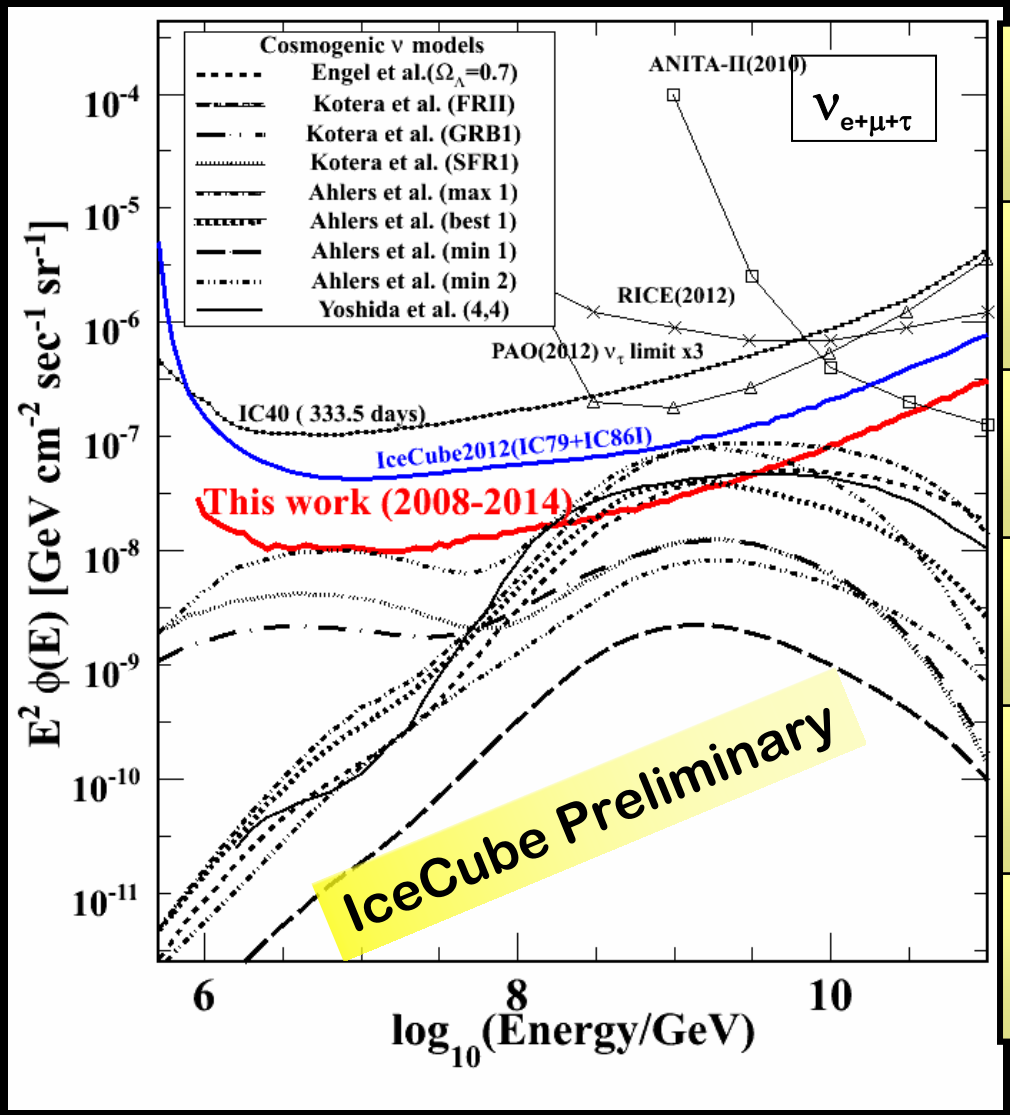




TeV PeV EeV

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

UHE (PeV-EeV)

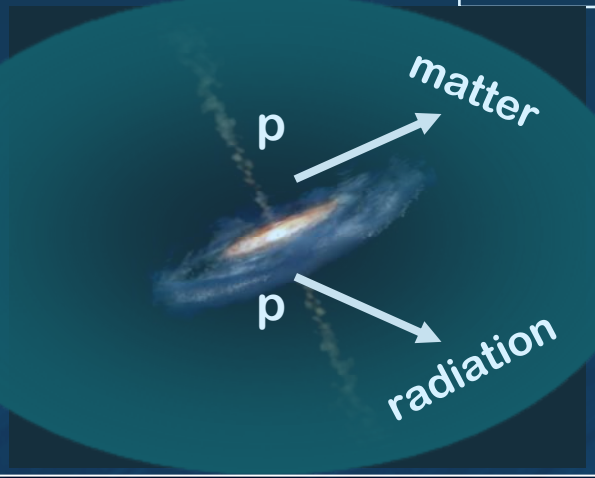
IceCube 6 years data (2008-2014) all combined

IceCube Confidential

Search Results coming soon

The Cosmic Neutrinos
Production Mechanisms

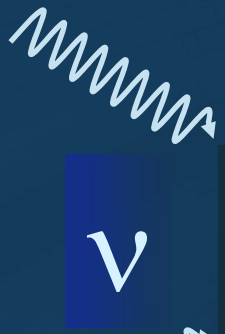
"On-source" ν **TeV - PeV**



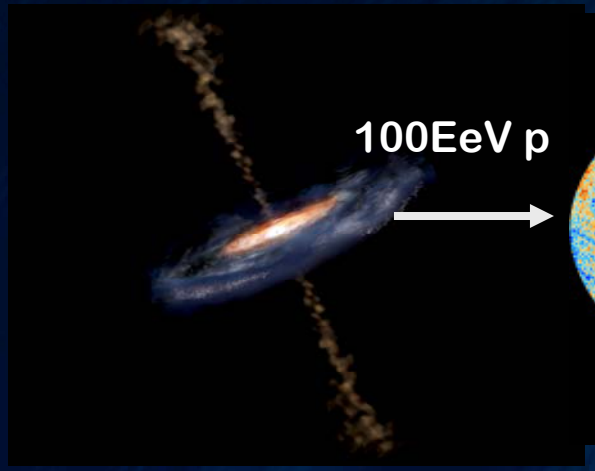
$pp \rightarrow \pi \rightarrow \nu$

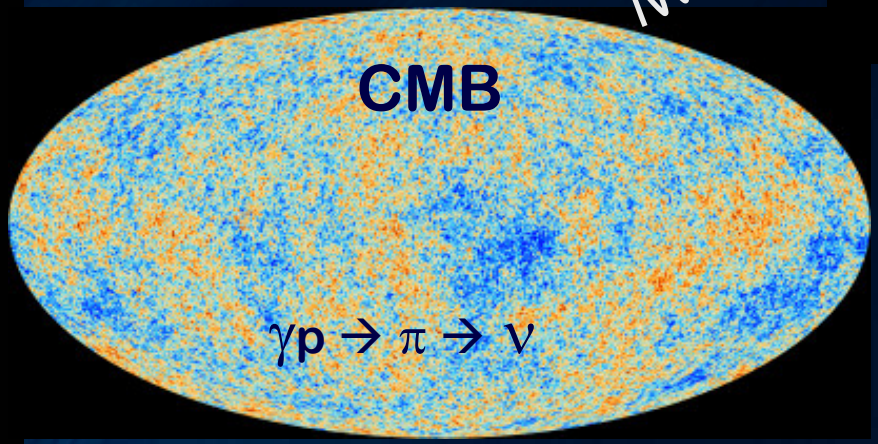
$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production

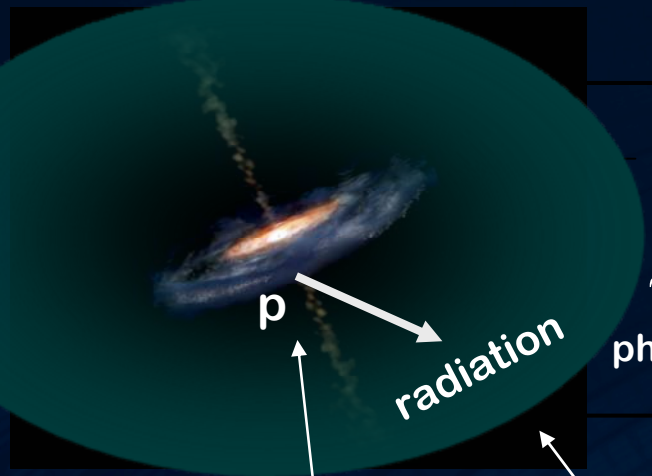


"GZK" cosmogenic ν **EeV**





Constraints on the optical depth and extra-galactic CR flux



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

photopion production

ν

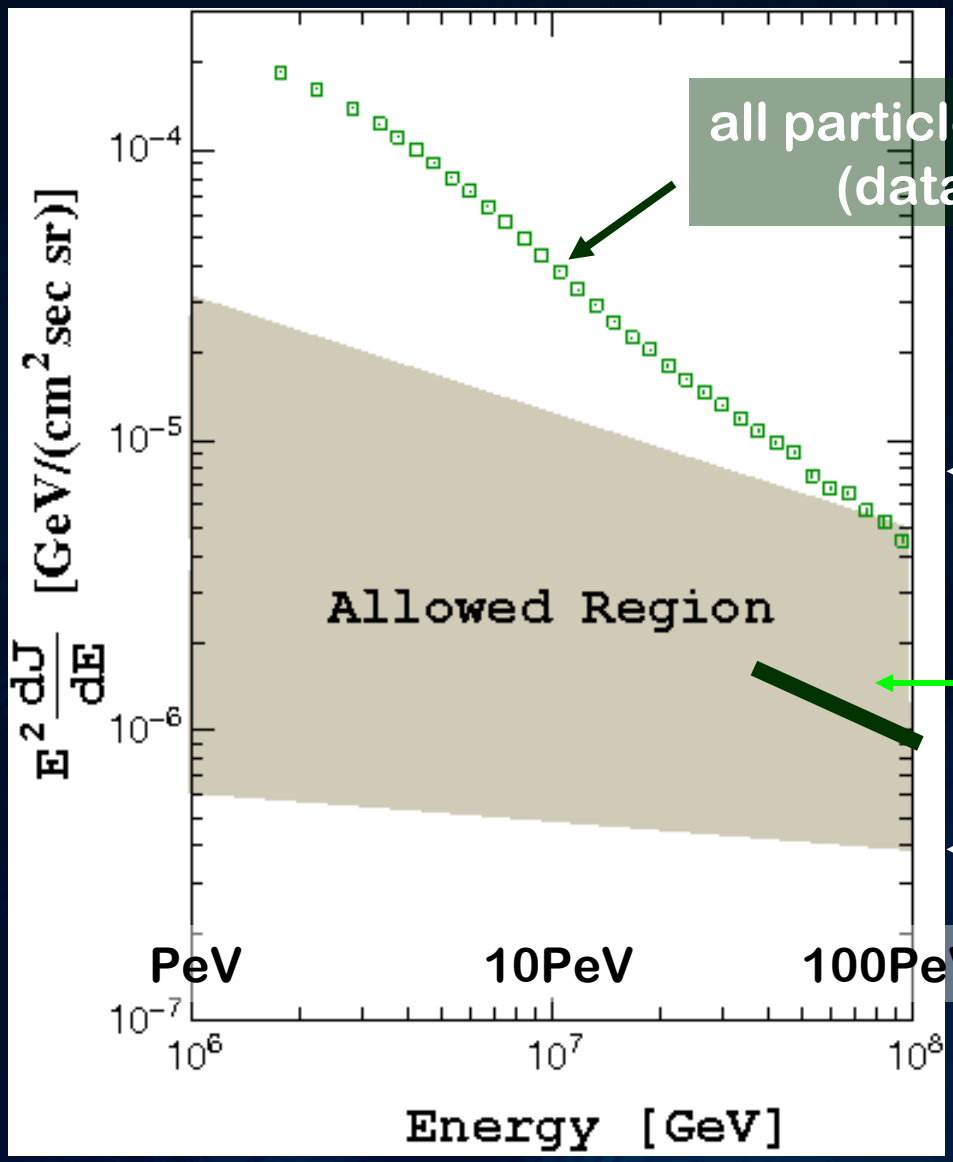
optical depth (<1)

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

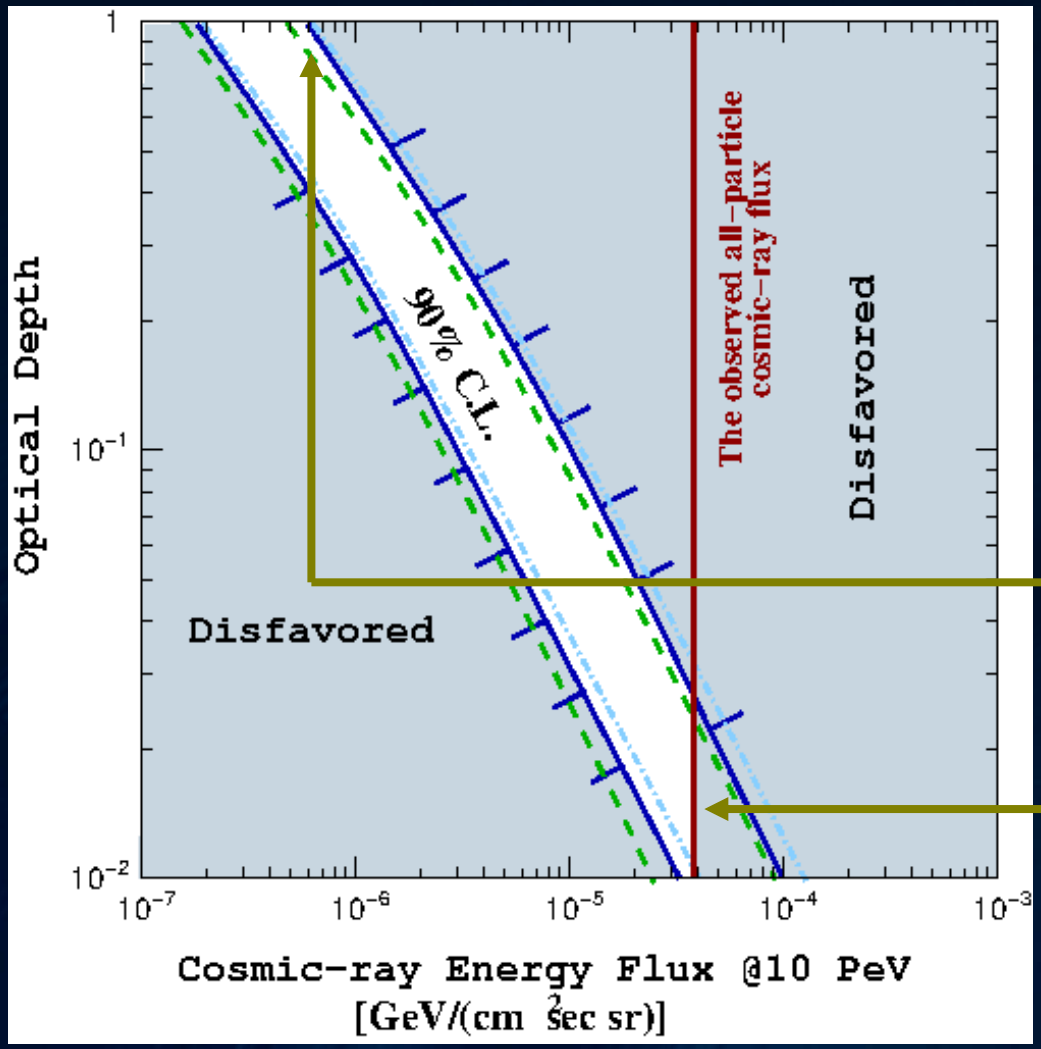
Fixed to the Star Formation Rate

Constrain them by the IceCube 100TeV-PeV observation

Constraints on the optical depth and extra-galactic CR flux



Constraints on the optical depth and extra-galactic CR flux

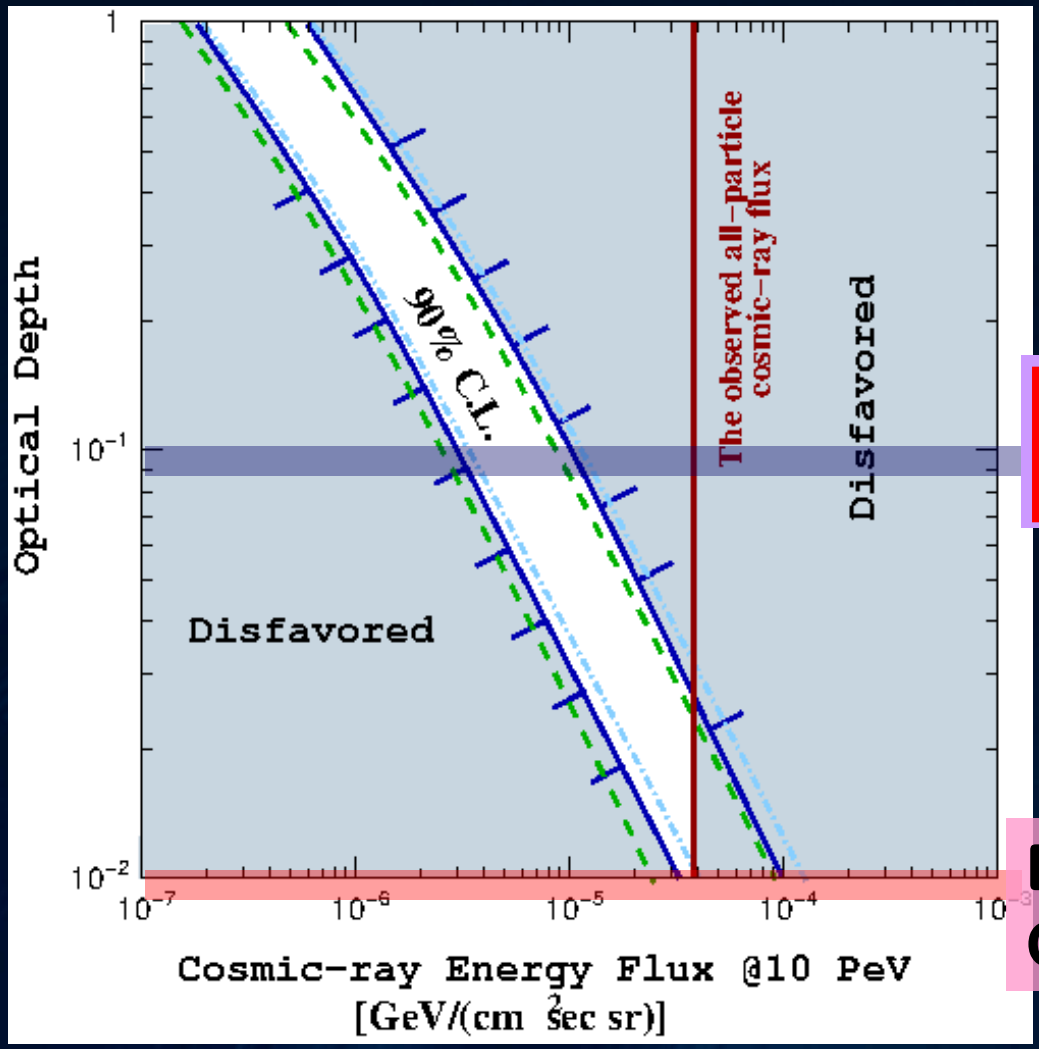


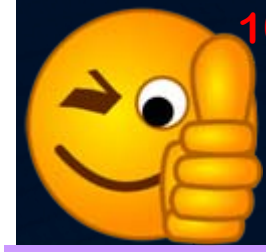
Yoshida, Takami
arXiv:1409.2950

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

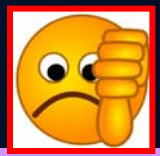
optical depth must be $\gtrsim 10^{-2}$

Constraints on the optical depth and extra-galactic CR flux





if they are also 100EeV CR sources

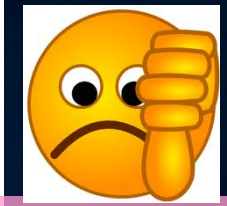


strong evolution

Quasars/FR-II

GRBs (internal shock)

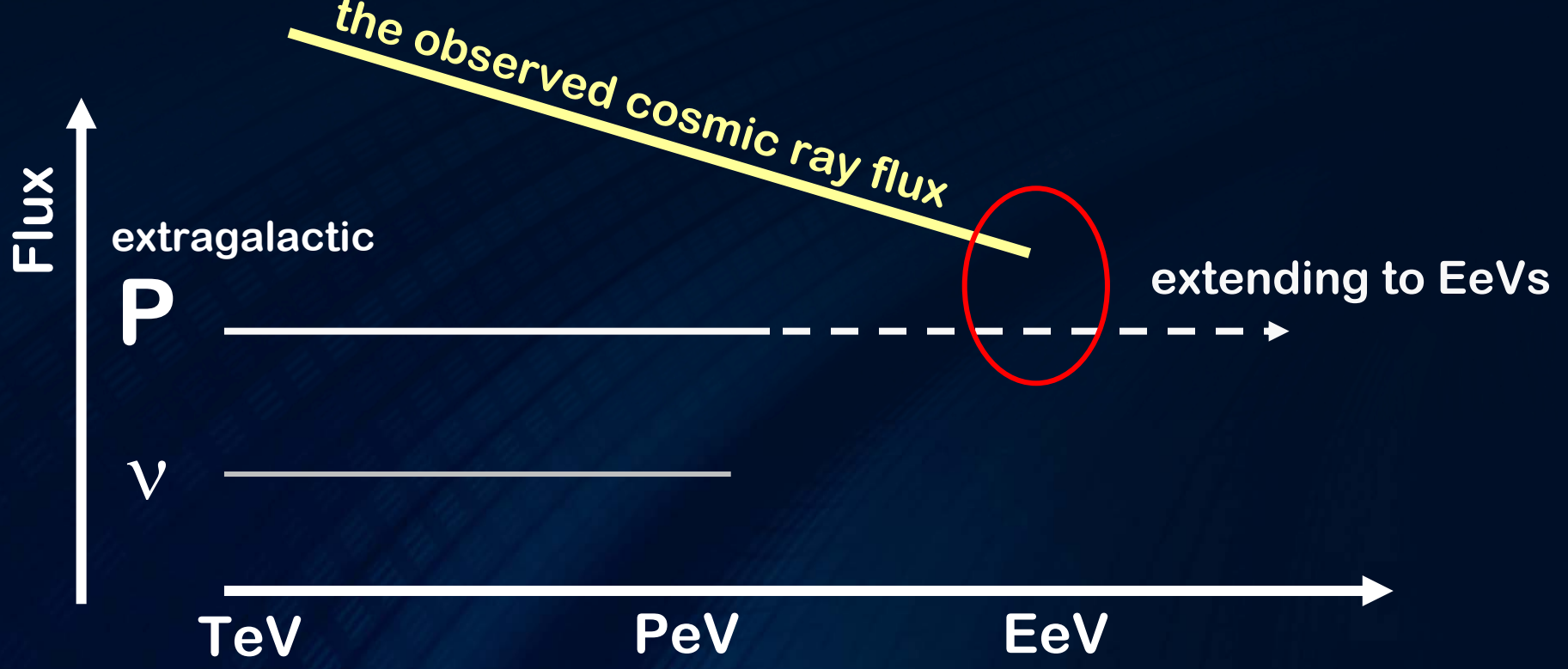
energetics



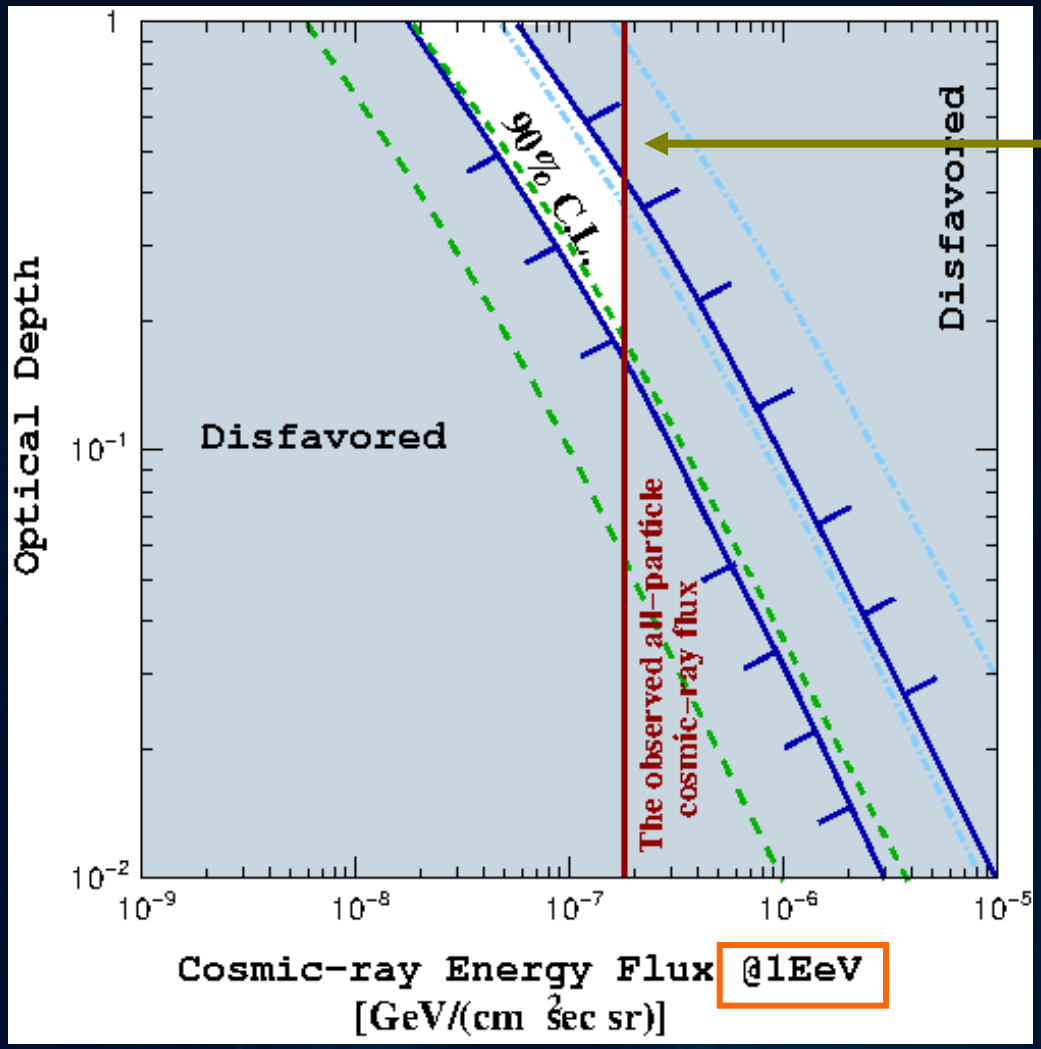
BL Lac/FR-I

GRBs (external shock)

Suppose the PeV ν emitters are *also UHECR (E~100EeV) sources*



Constraints on the optical depth and extra-galactic CR flux

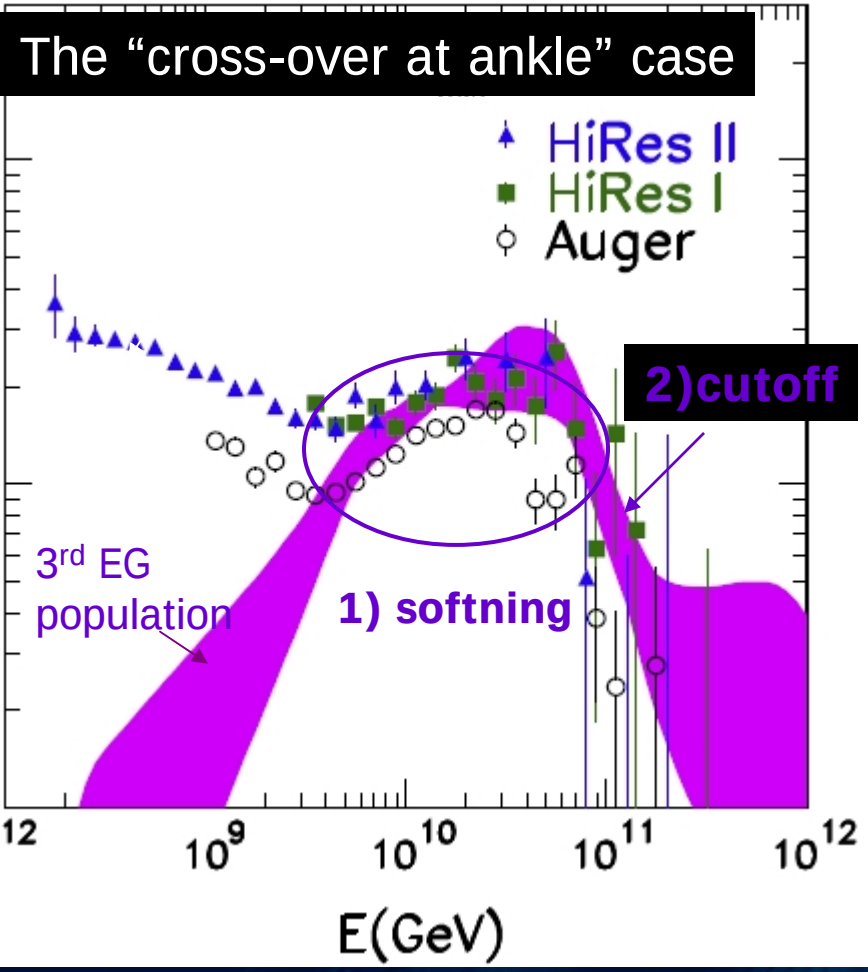


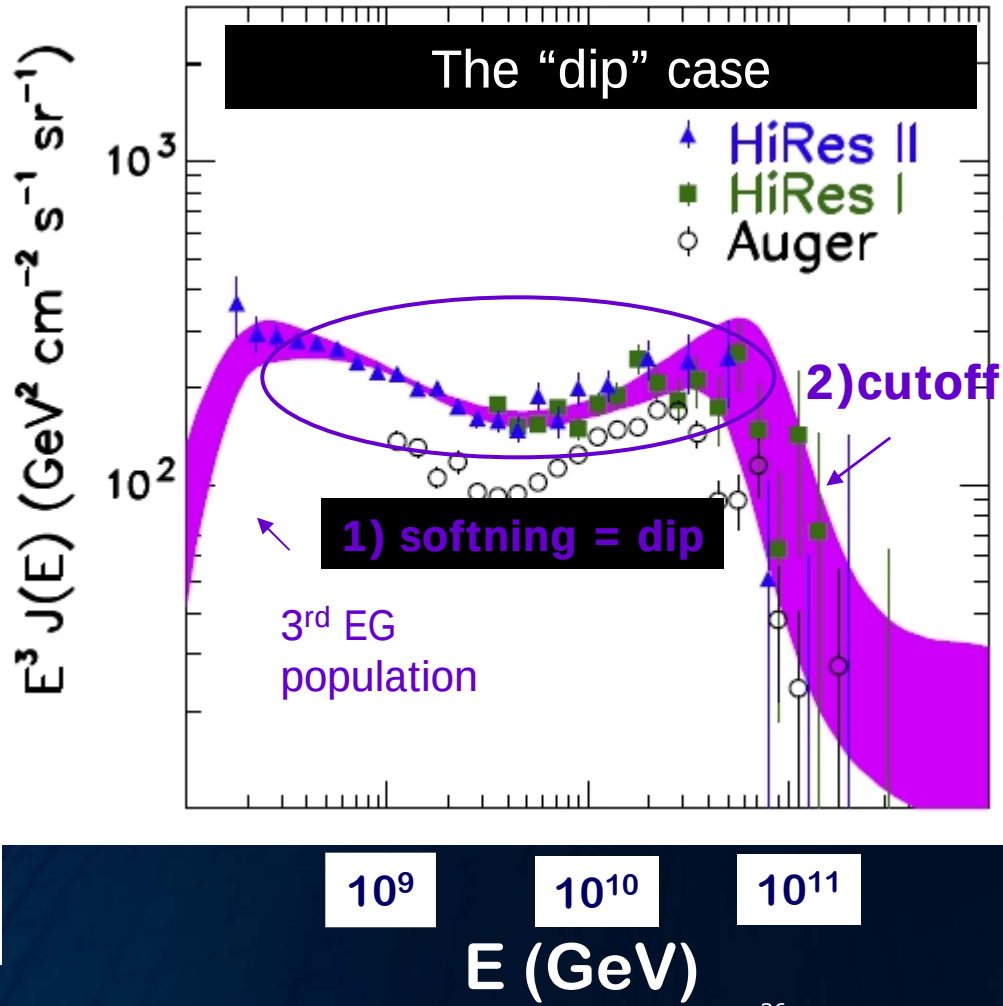
- extra-galactic proton flux must *dominate* in the all-particle CR flux @ 1 EeV(=1000PeV)
- optical depth must be ~1

How the 3rd population (exrtagalactic?)

turns over is still open question

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

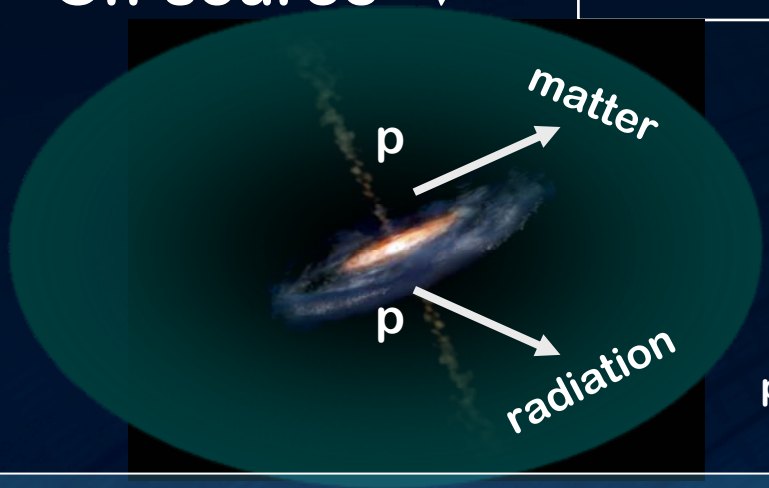




Structures 1) and 2) are consequence of propagation in extra-galactic space

The Cosmic Neutrinos
Production Mechanisms

"On-source" ν **TeV - PeV**

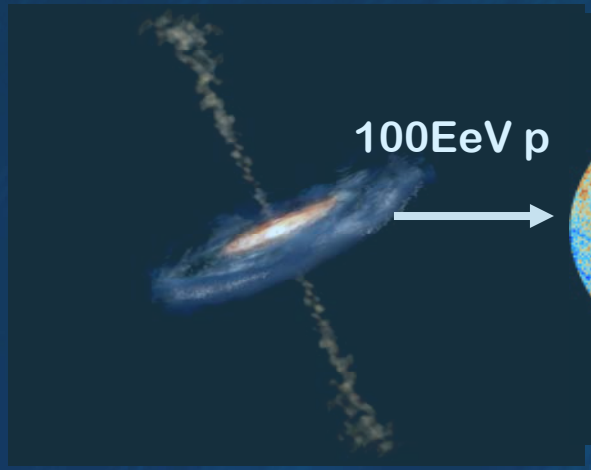


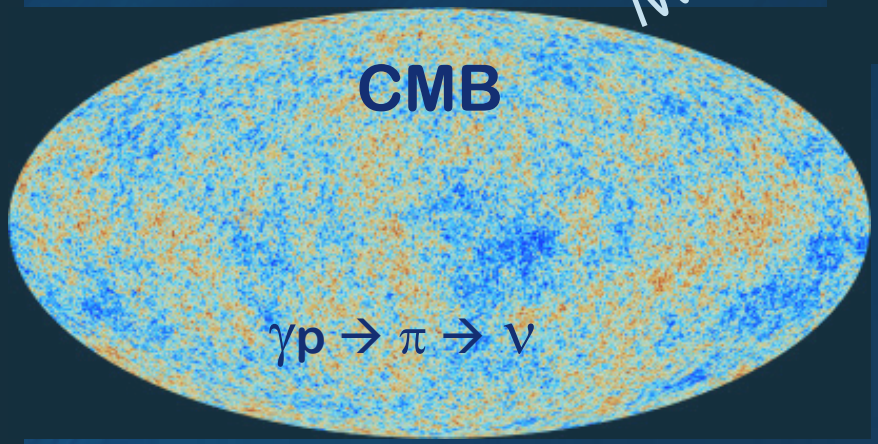
$pp \rightarrow \pi \rightarrow \nu$

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

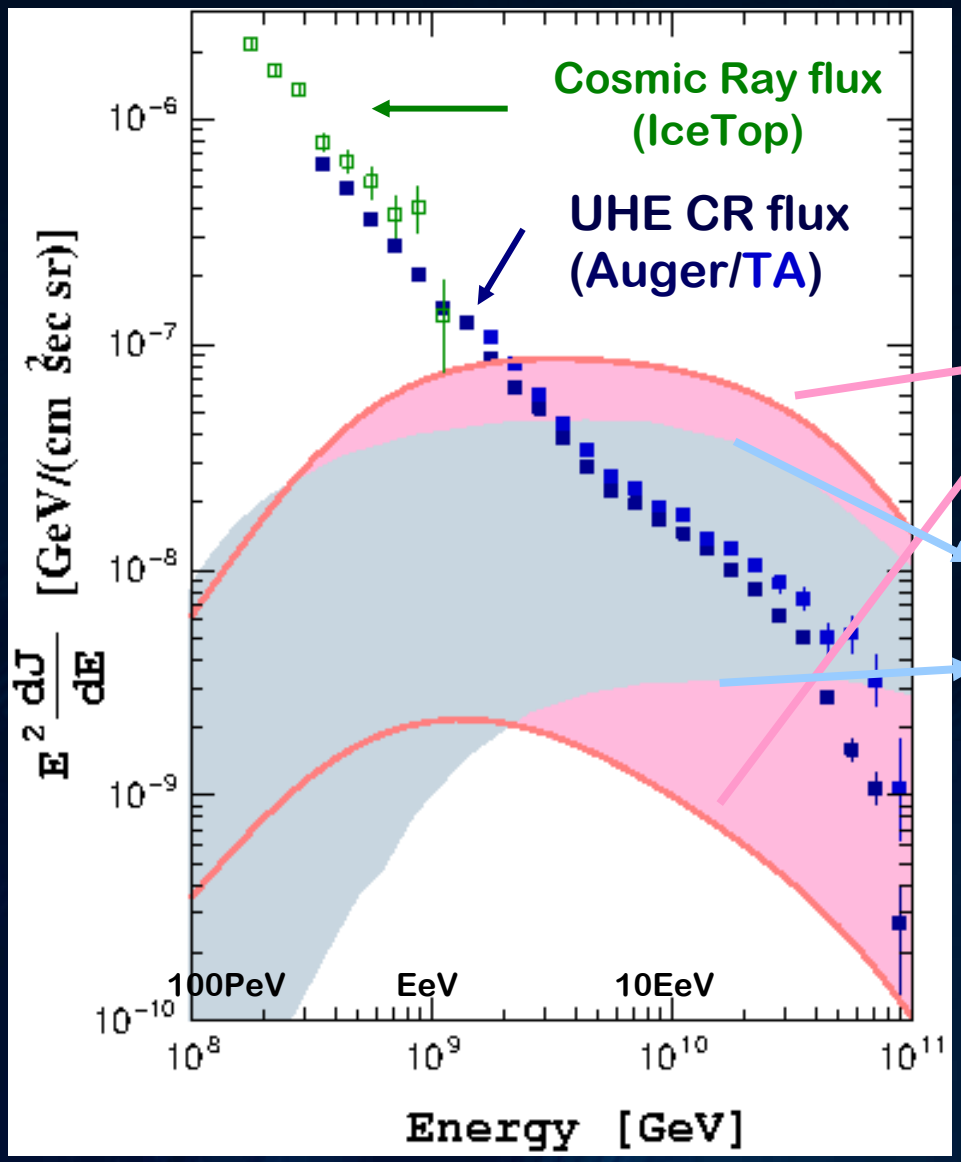
photopion production

"GZK" cosmogenic ν **EeV**





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

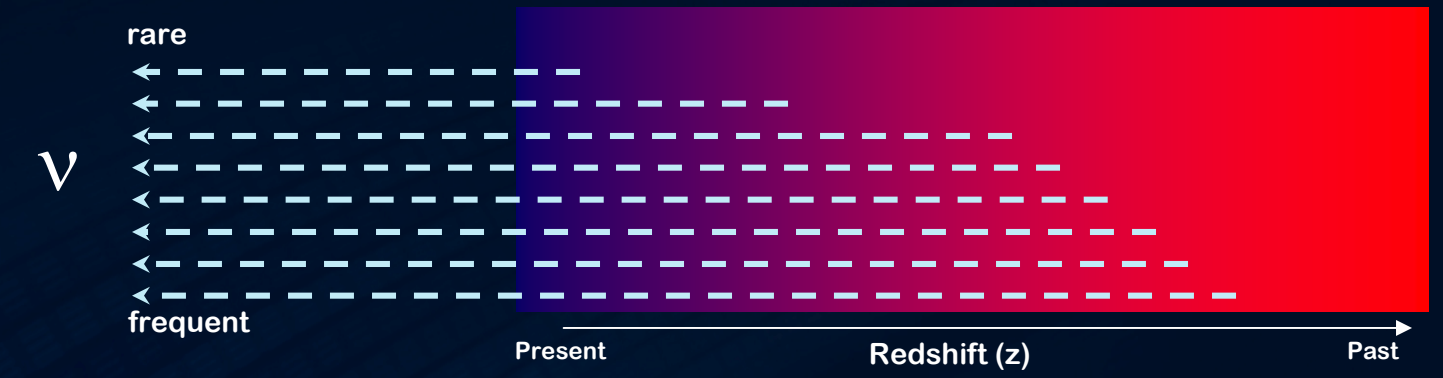
why?

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 <u>active</u> in the past

because ν beams are penetrating over cosmological distances

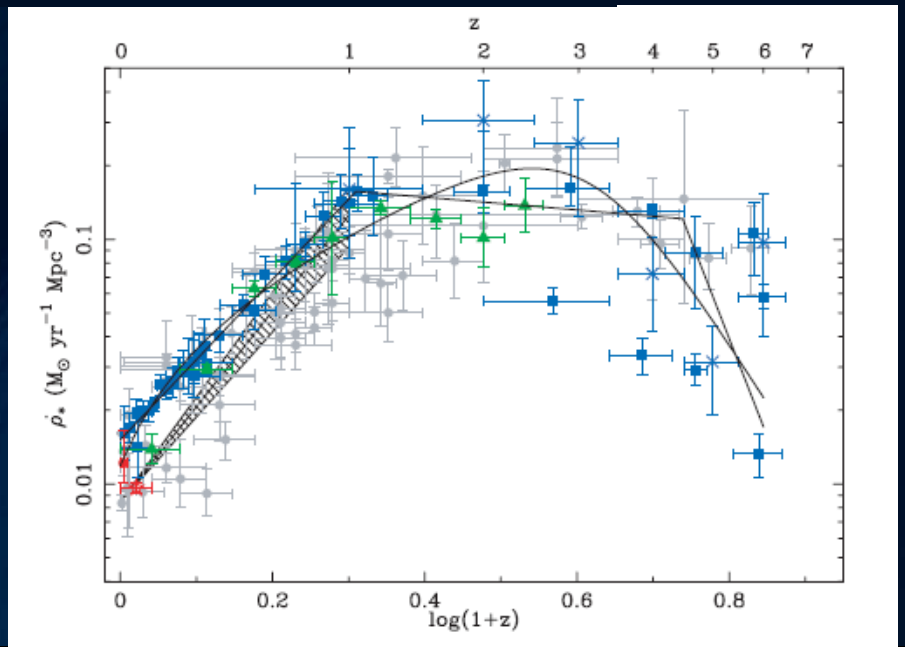


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→



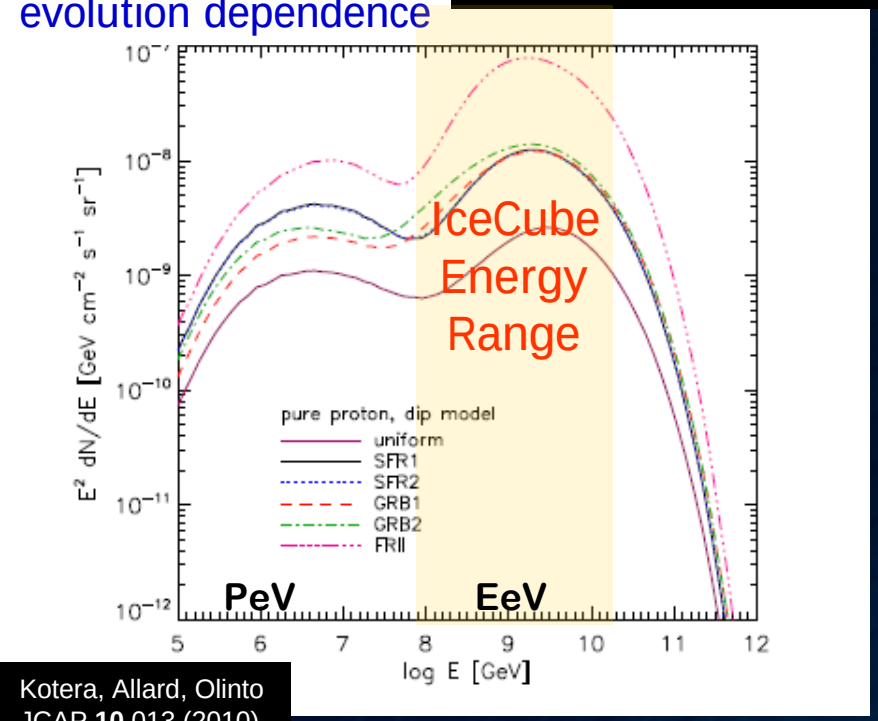
The spectral emission rate

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

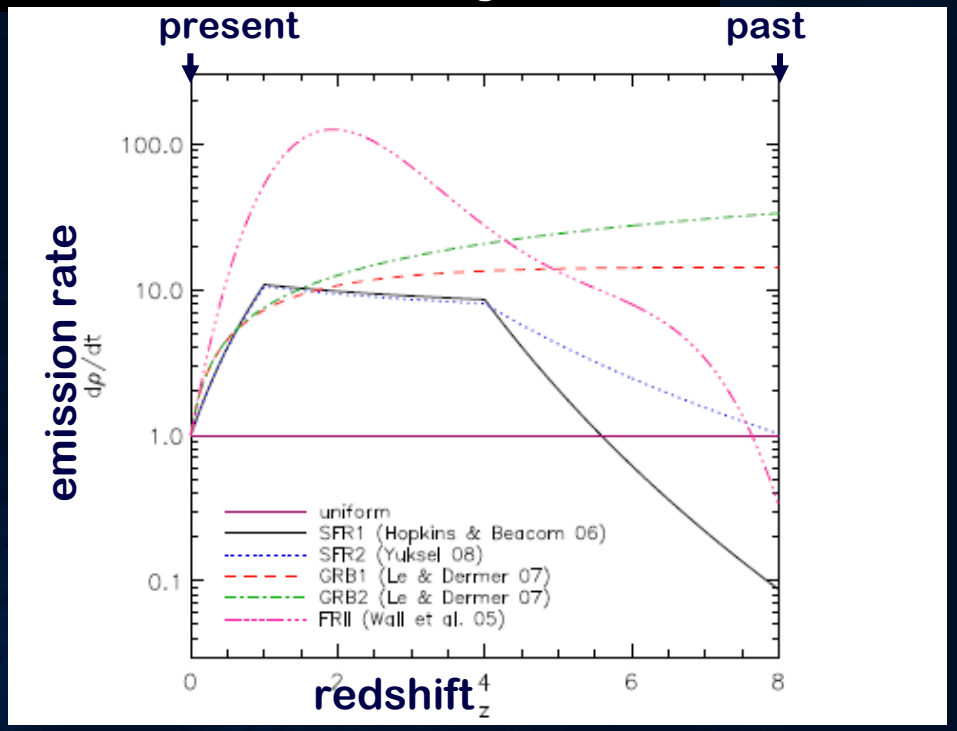
m= 0 : No evolution

I_{GZK} $_{\nu}$ @ 1EeV is an excellent indicator for the UHECR emission history

evolution dependence



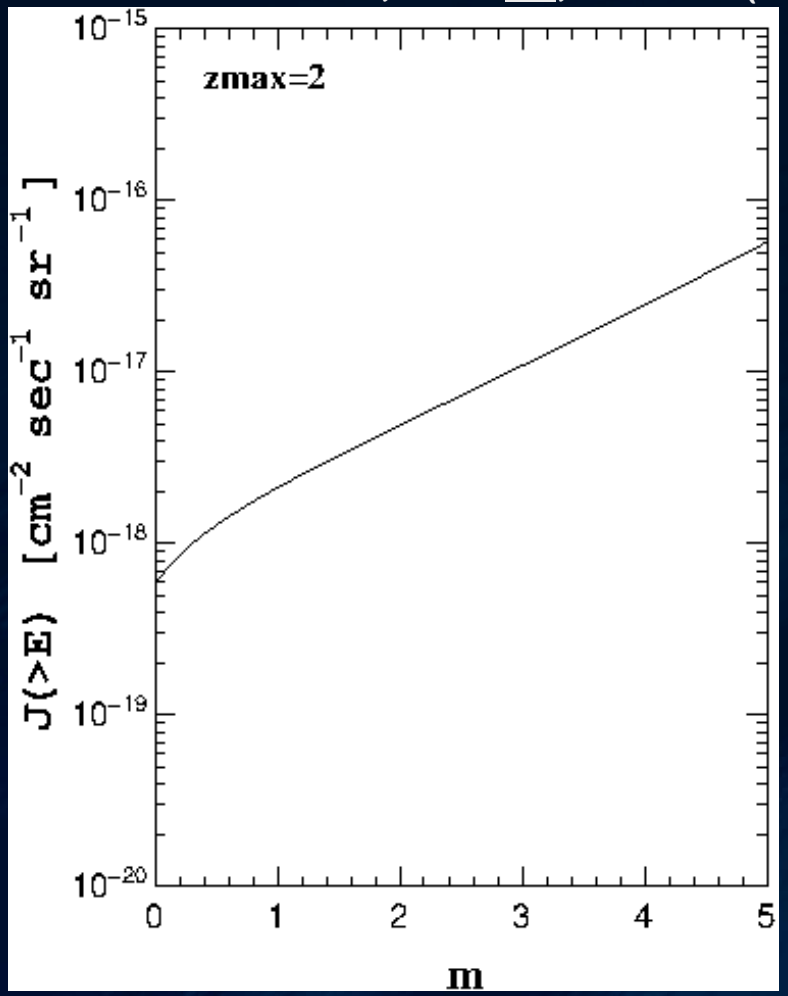
Kotera, Allard, Olinto
JCAP **10** 013 (2010)



ν = early history of cosmic radiation!

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

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

Yoshida and Ishihara, PRD 85, 063002 (2012)

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

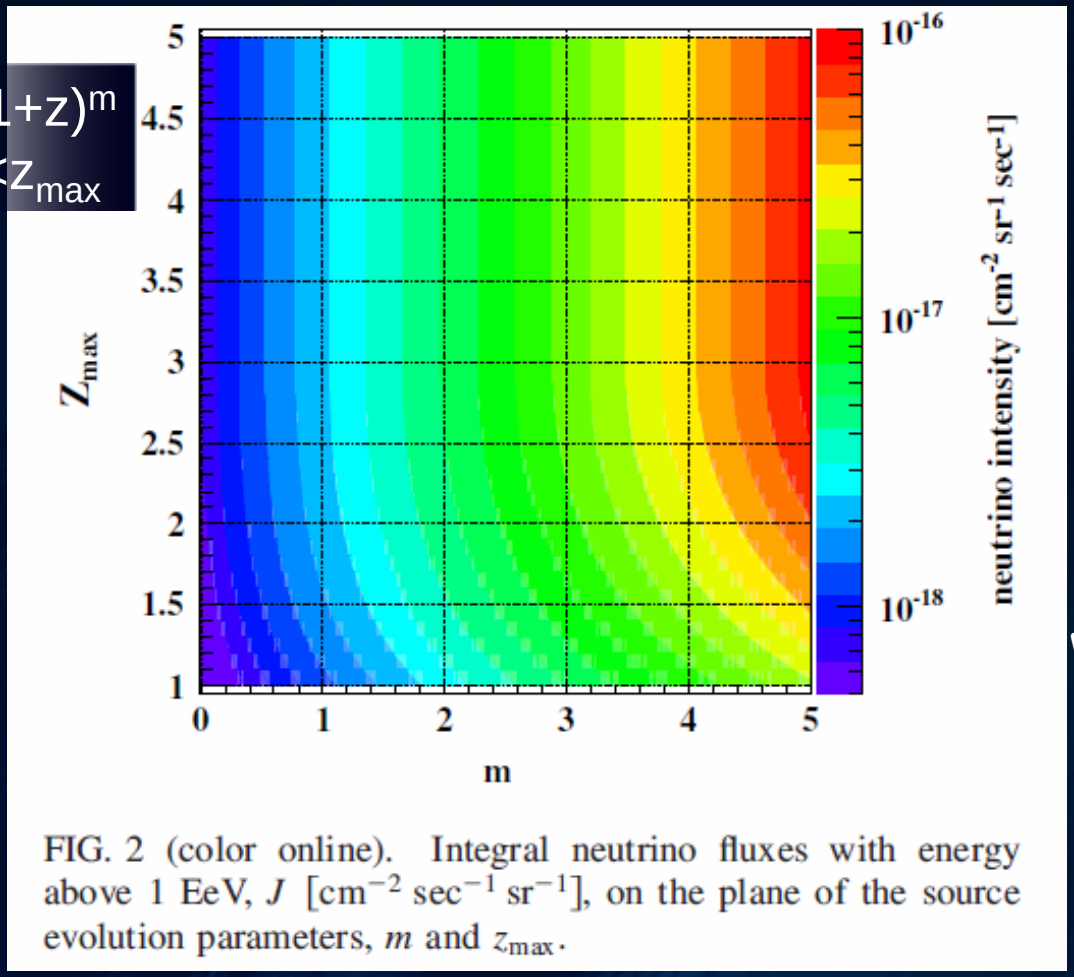


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

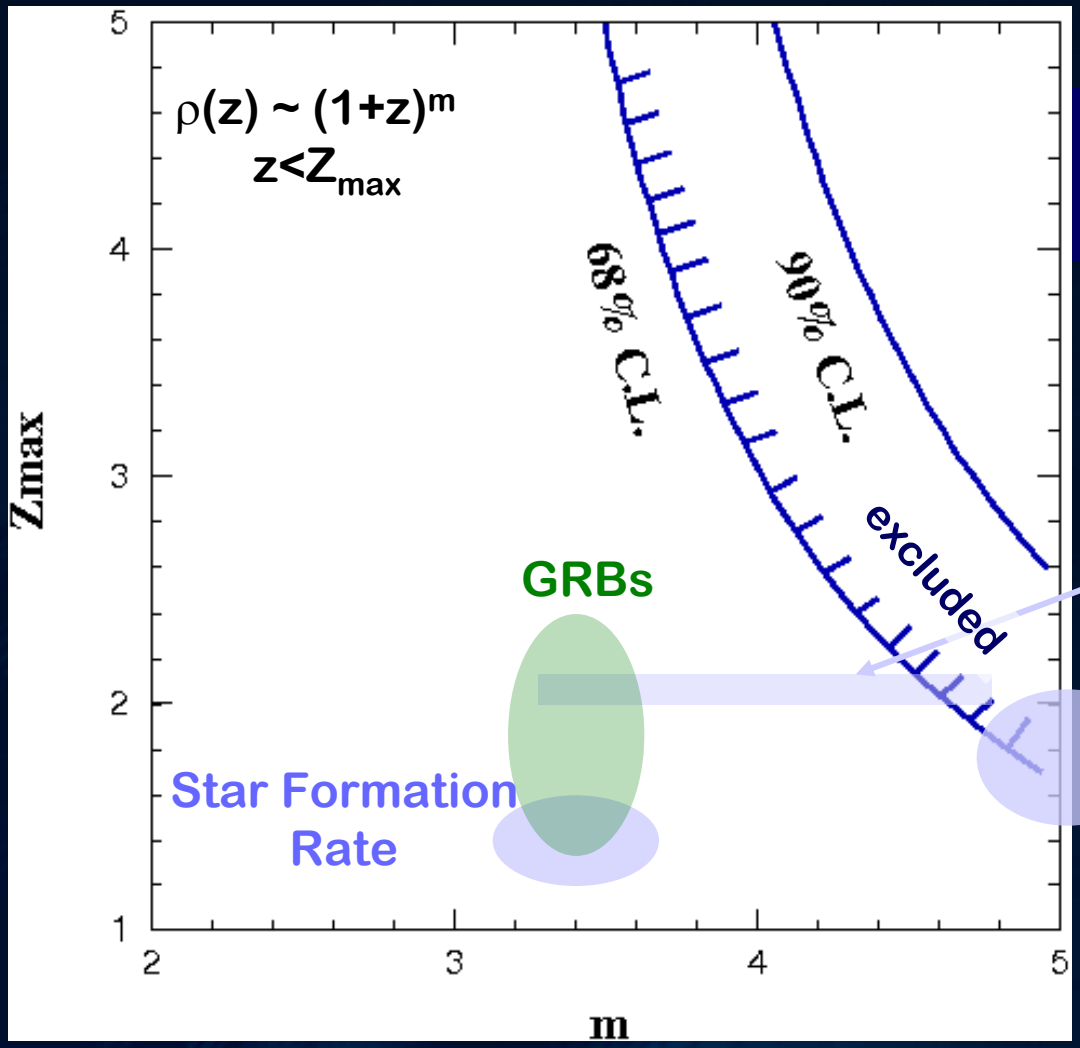
↓ x IceCube Exposure

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

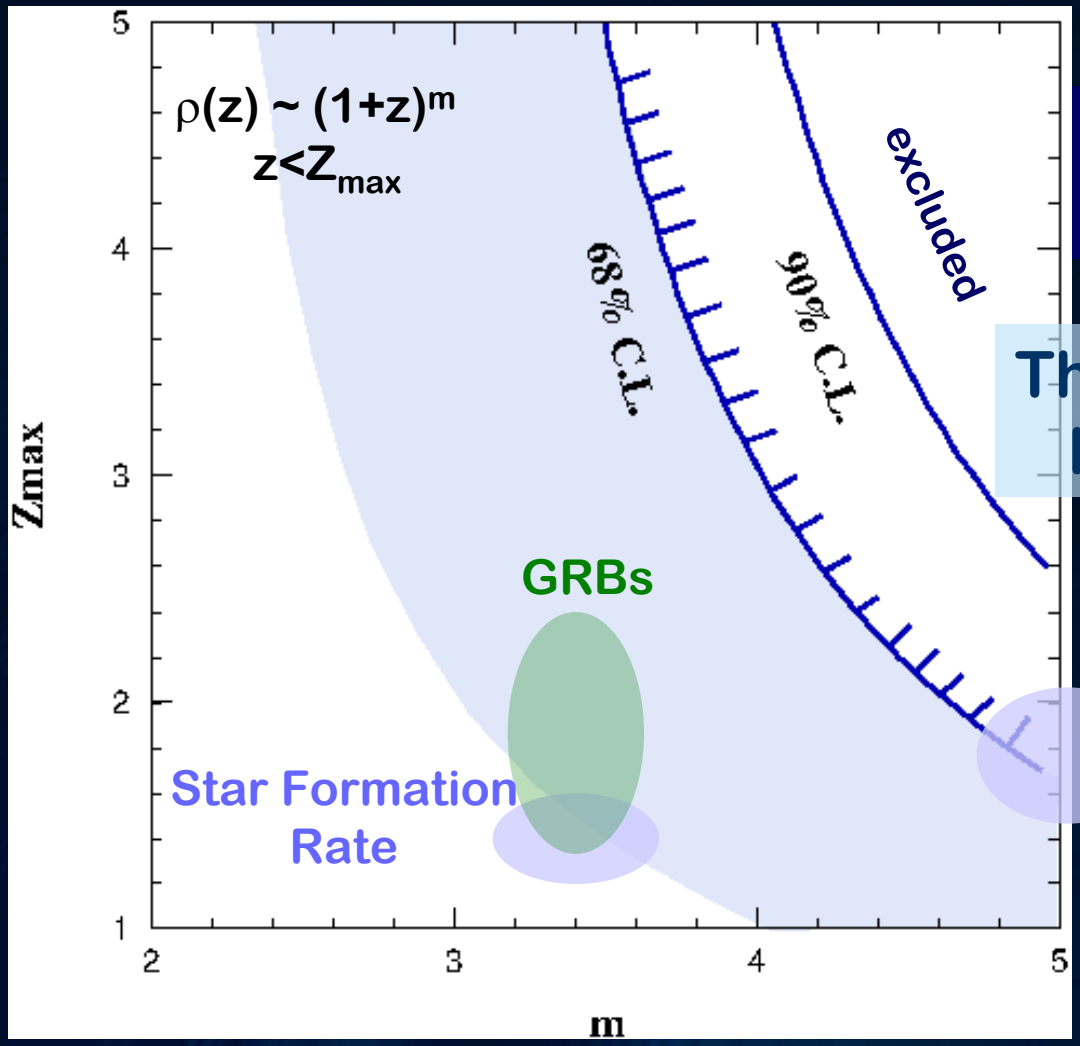
The solid bound by the GZK ν

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



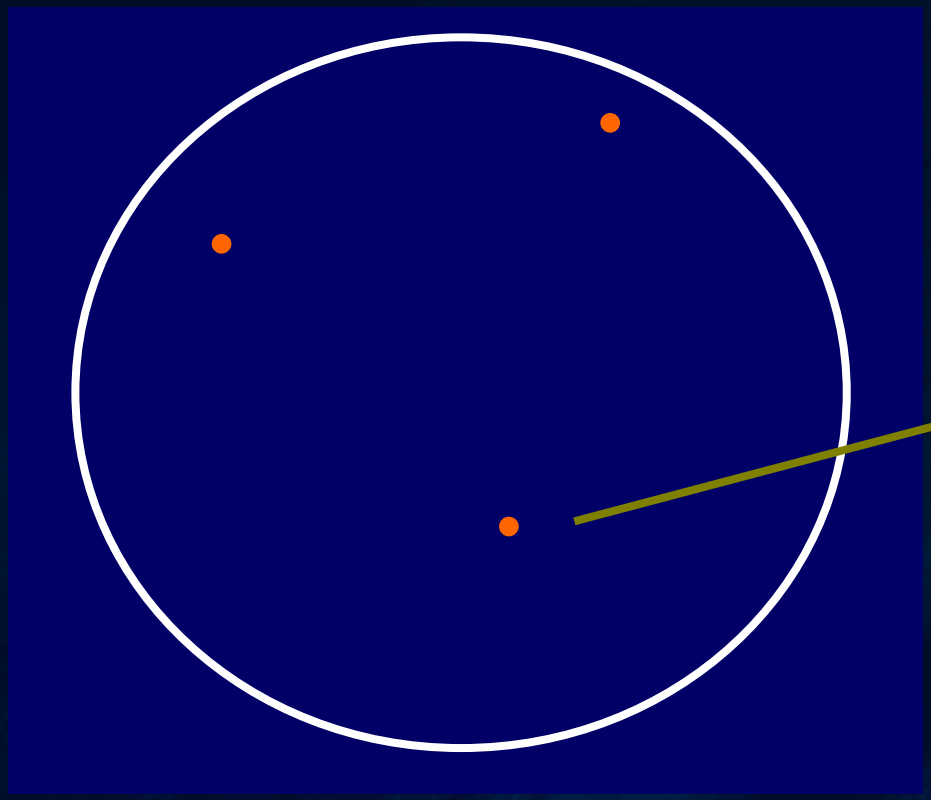
IceCube collaboration
Phys. Rev. D 88, 112008

The solid bound by the GZK ν

The region scanned by IceCube 2008-2014

coming soon!

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



look up this direction!

ν **"GFU"** γ

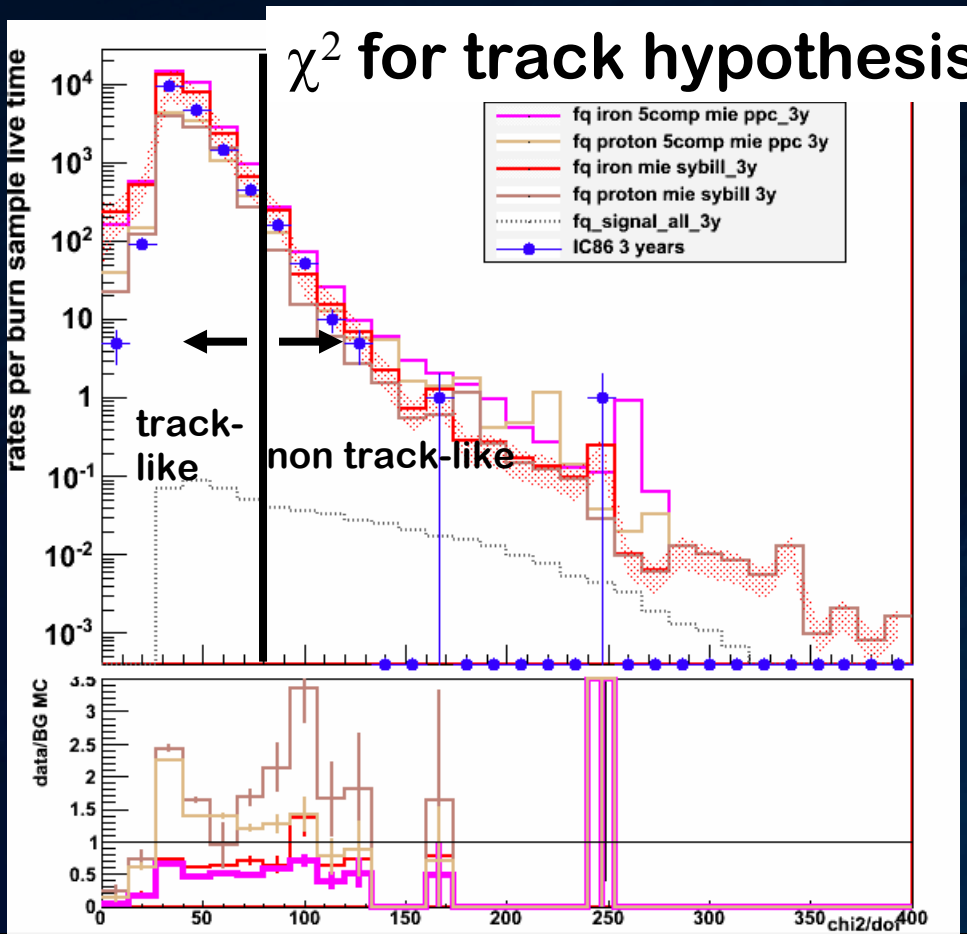
TeV PeV EeV

UHE (PeV-EeV)

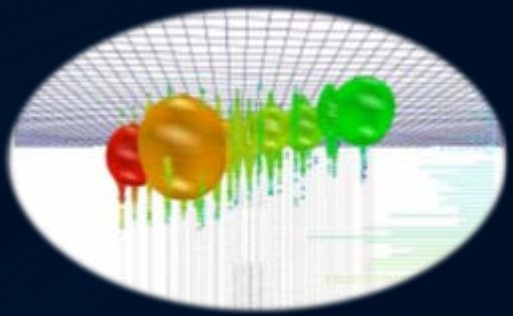
Online Analysis for γ-ray/optical follow-up

new

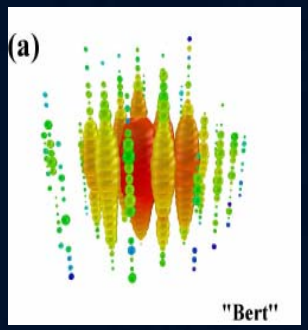
event topology separation



track



cascade (non track-like)

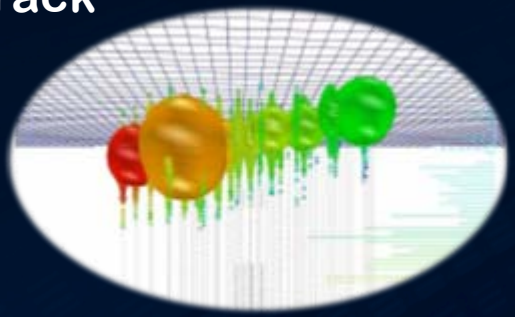


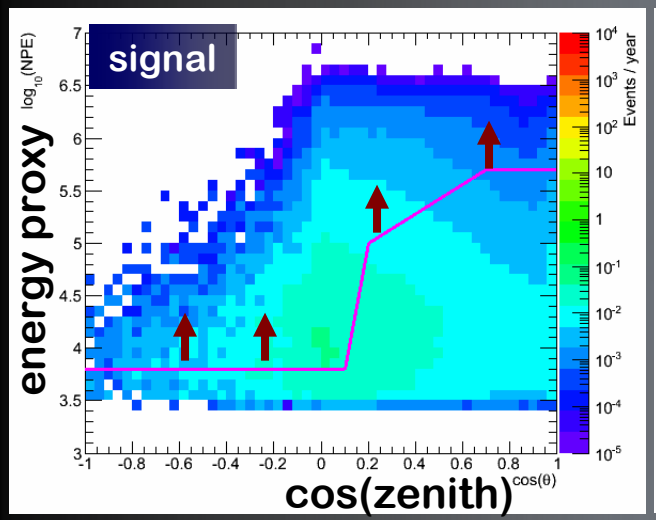
TeV PeV EeV

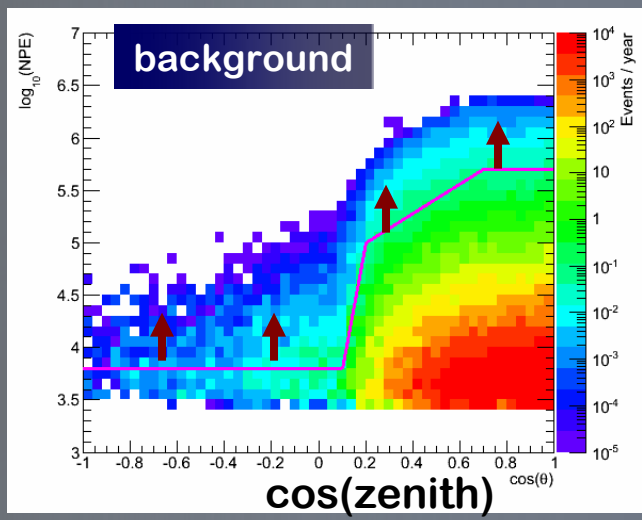
UHE (PeV-EeV)

Online Analysis for γ-ray/optical follow-up

track





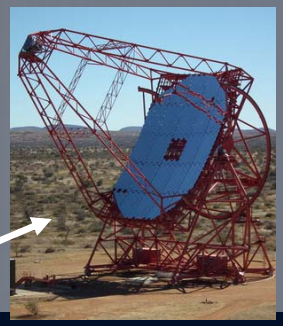


3.8 event/year for $\nu_{e+\mu+\tau}$ of

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

GZK: ~ 0.3-0.9 event/year

BG: ~ 2-3 event/year

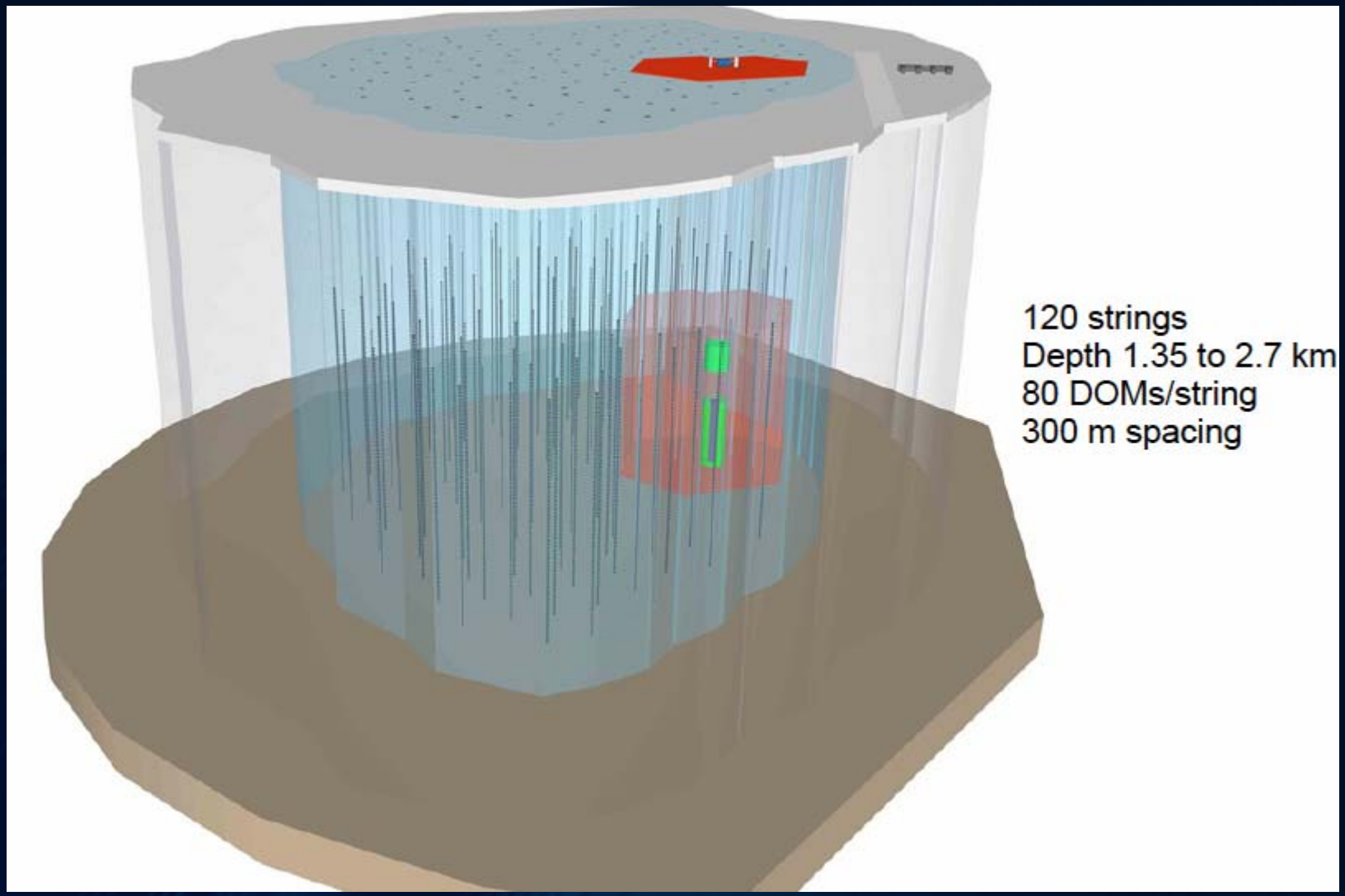


We will send you:

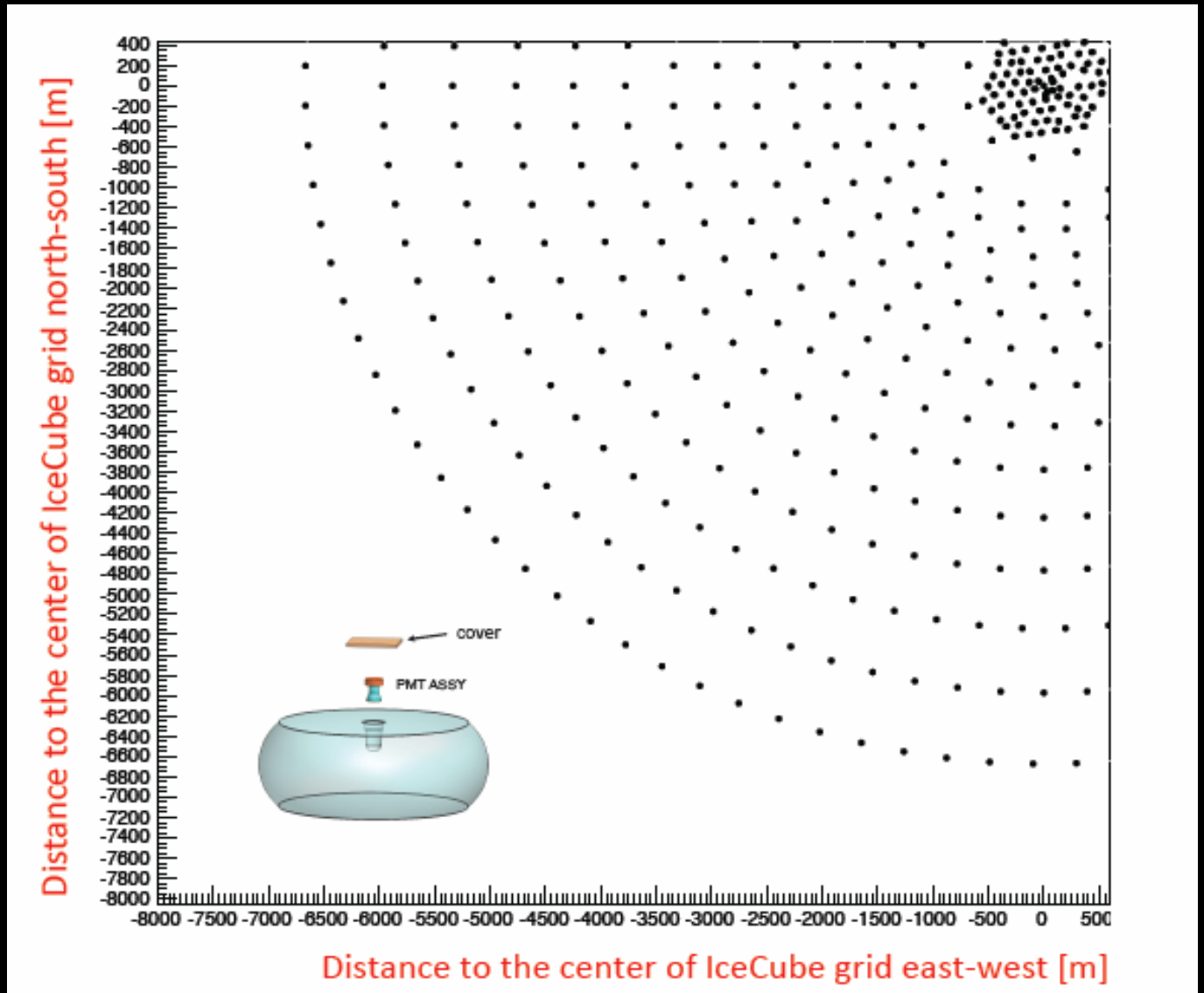
- direction
- Energy (proxy)
- rating of signal-likelihood

$\Delta\theta$~0.3 deg

Next Generation: IceCube HEX



A veto airshower array



Next Generation: IceCube HEX

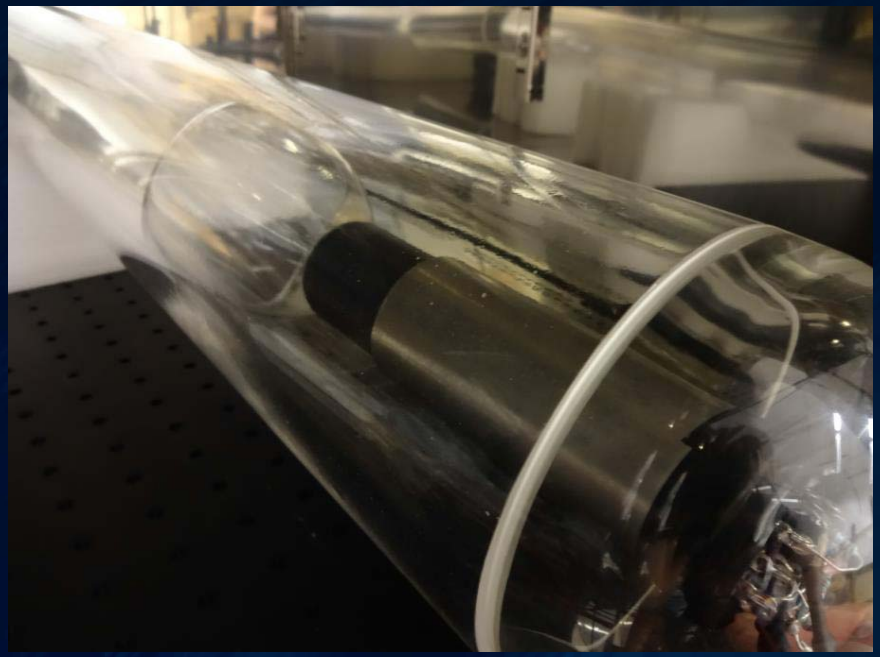
Photo-detector development

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Wavelength shifter coated tube

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

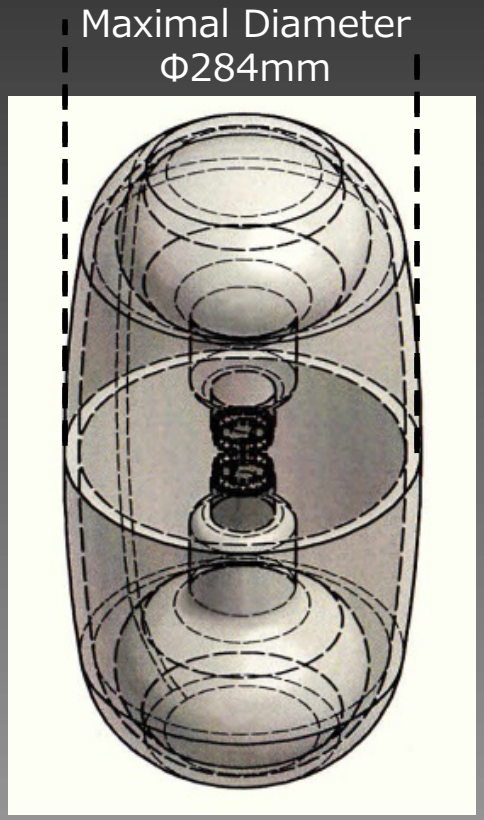
A la KM3Net

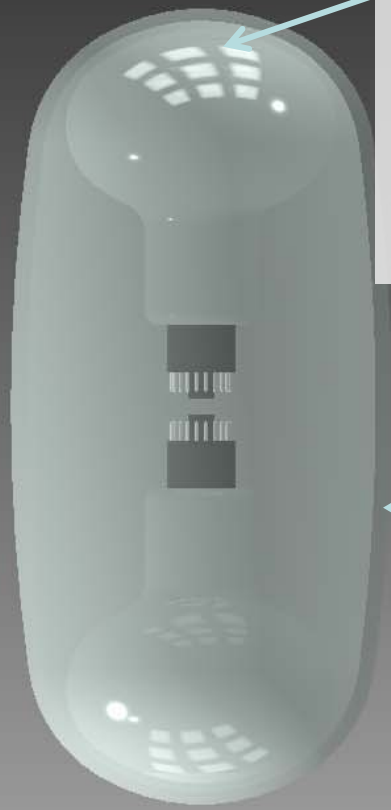


Next Generation: IceCube HEX

Photo-detector development

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





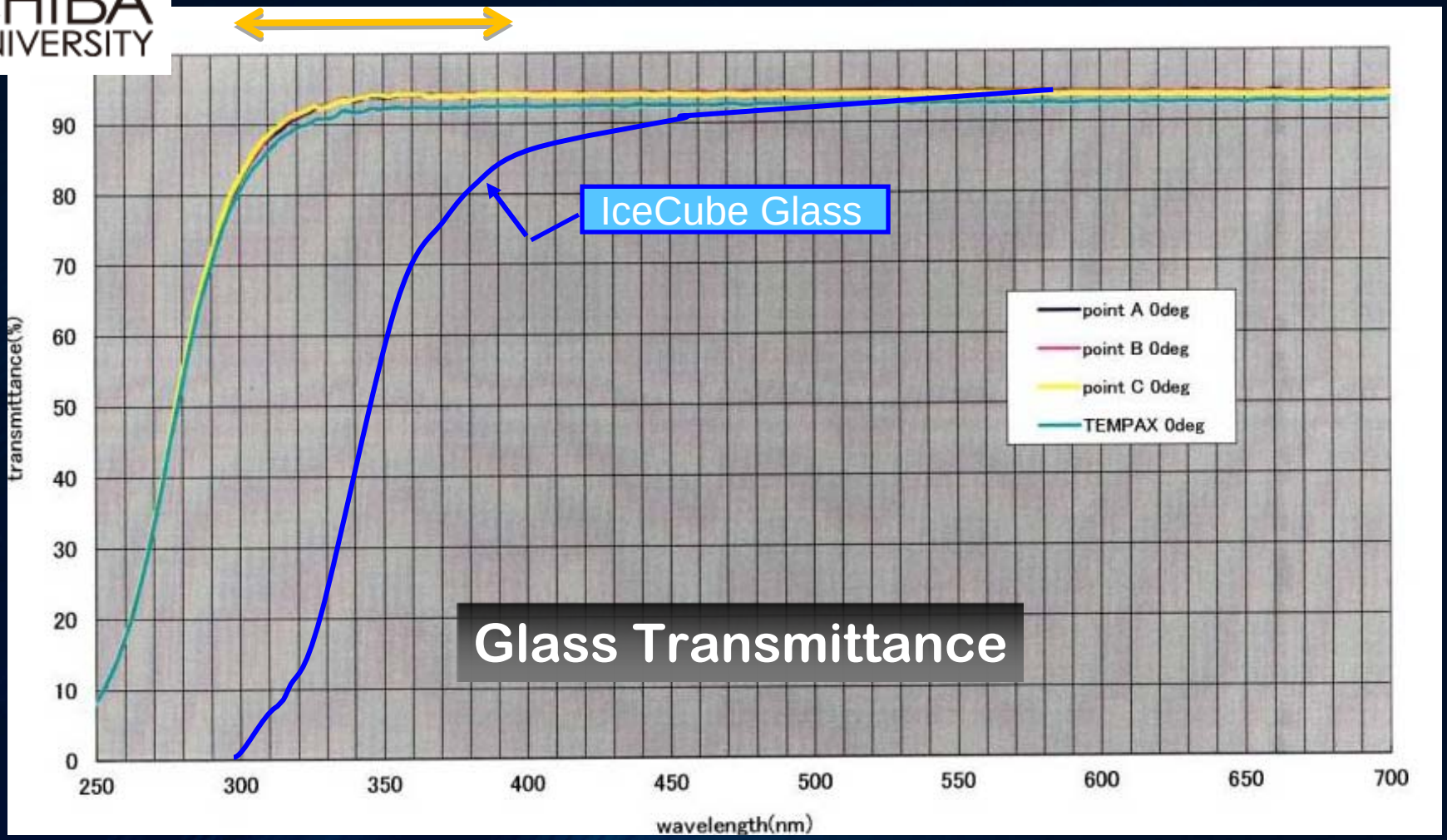
customized glass shape/curvature
- **designed best match curvature to our PMT**
- **less thickness top/bottom part (9mm-10mm where PMT cceptance) for better light transmittance**

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

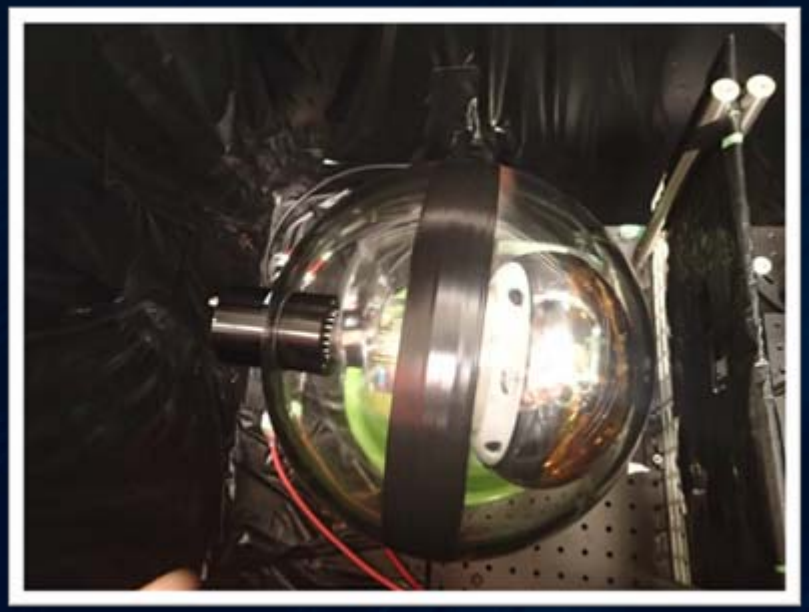


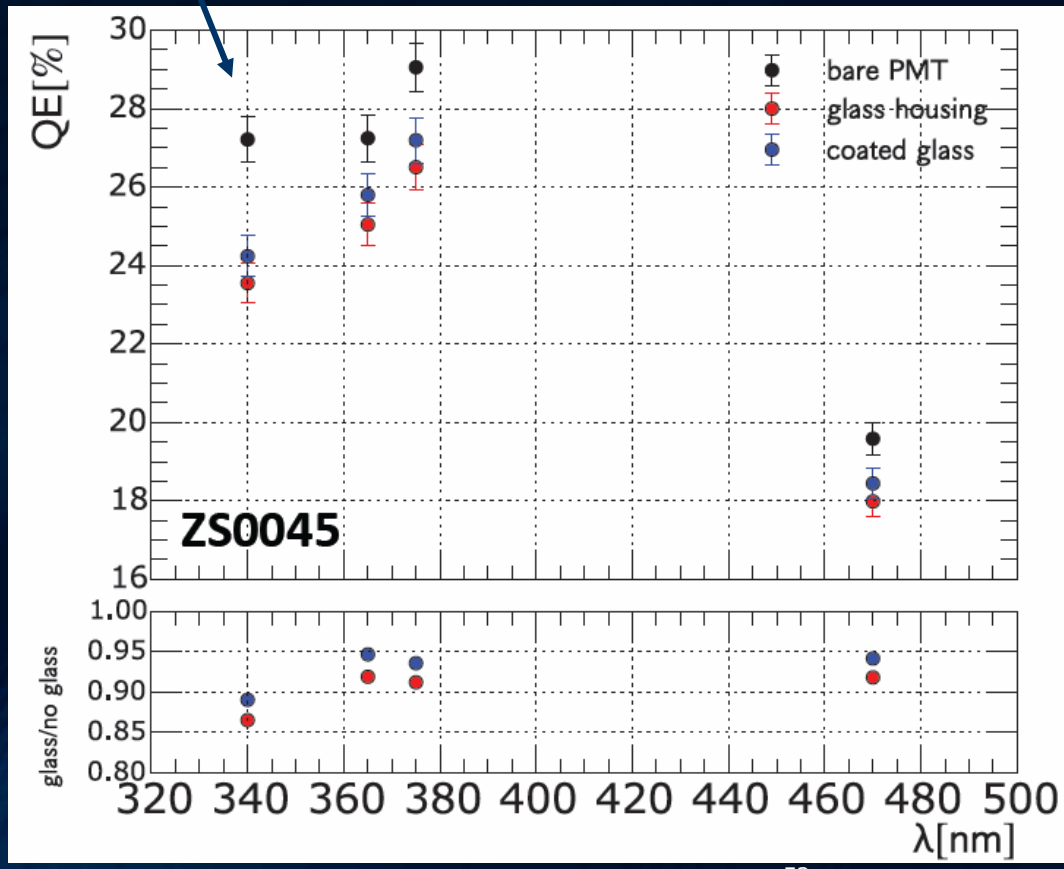
Next Generation: IceCube HEX

Photo-detector development

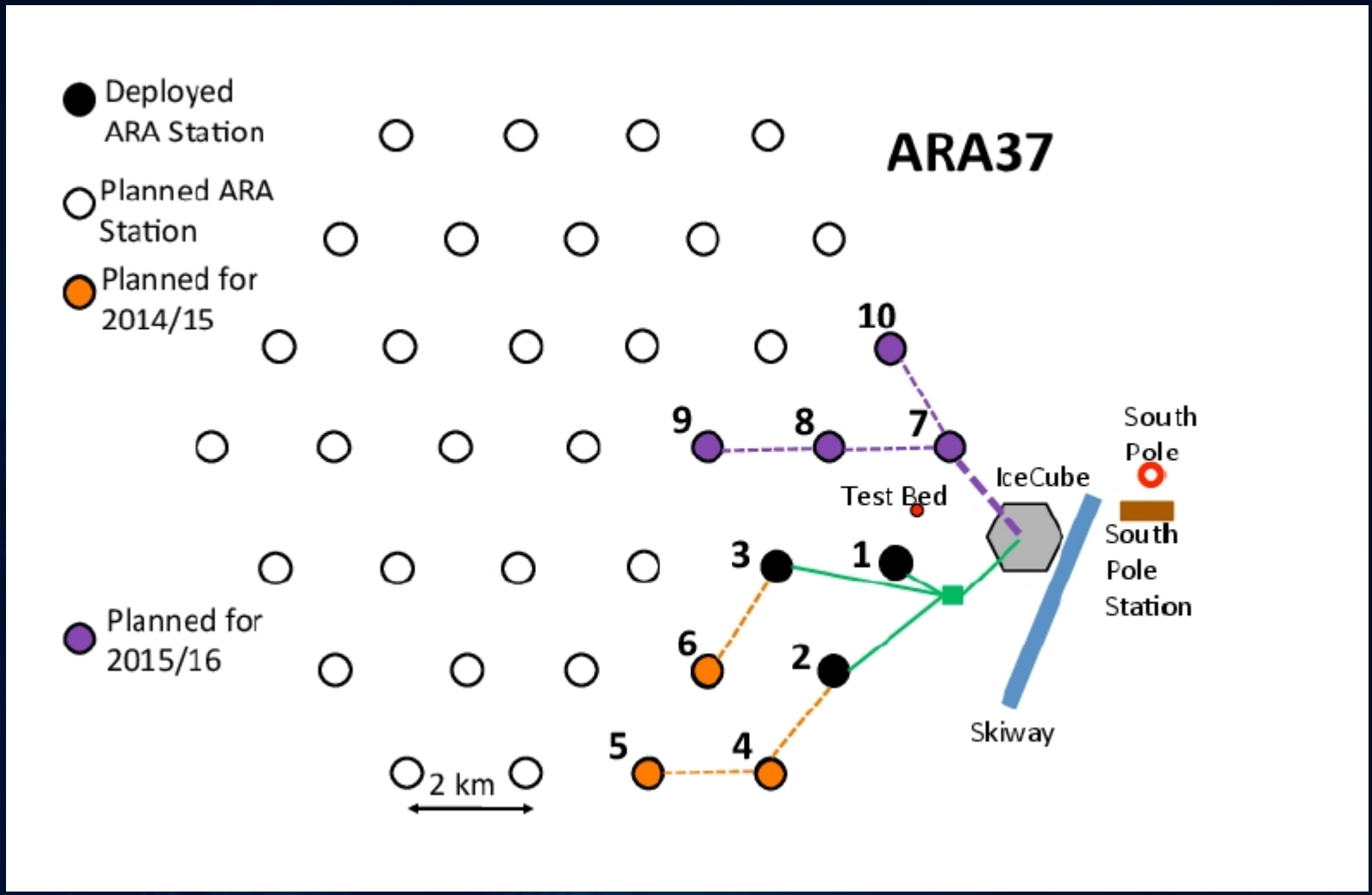
QE@340nm

7% (present icecube) → 24%





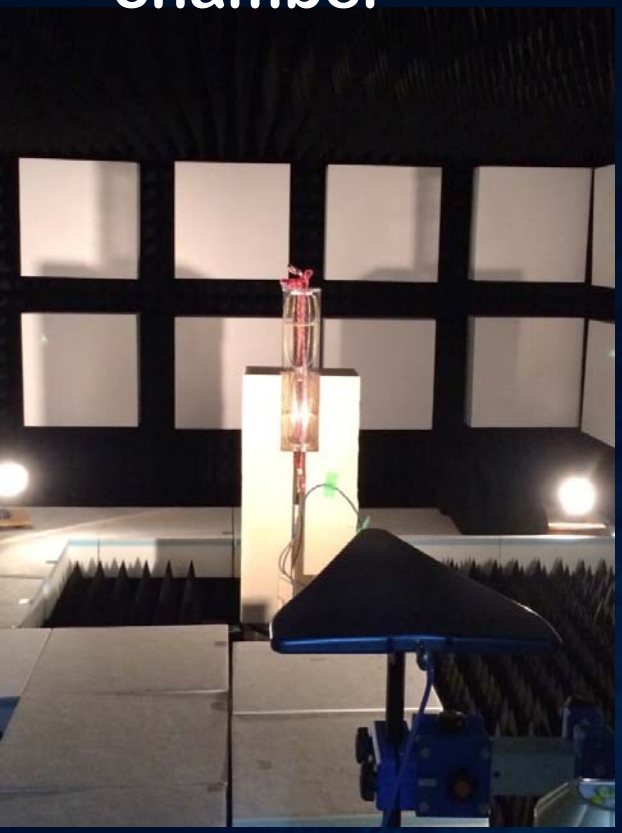
Next Generation: ARA



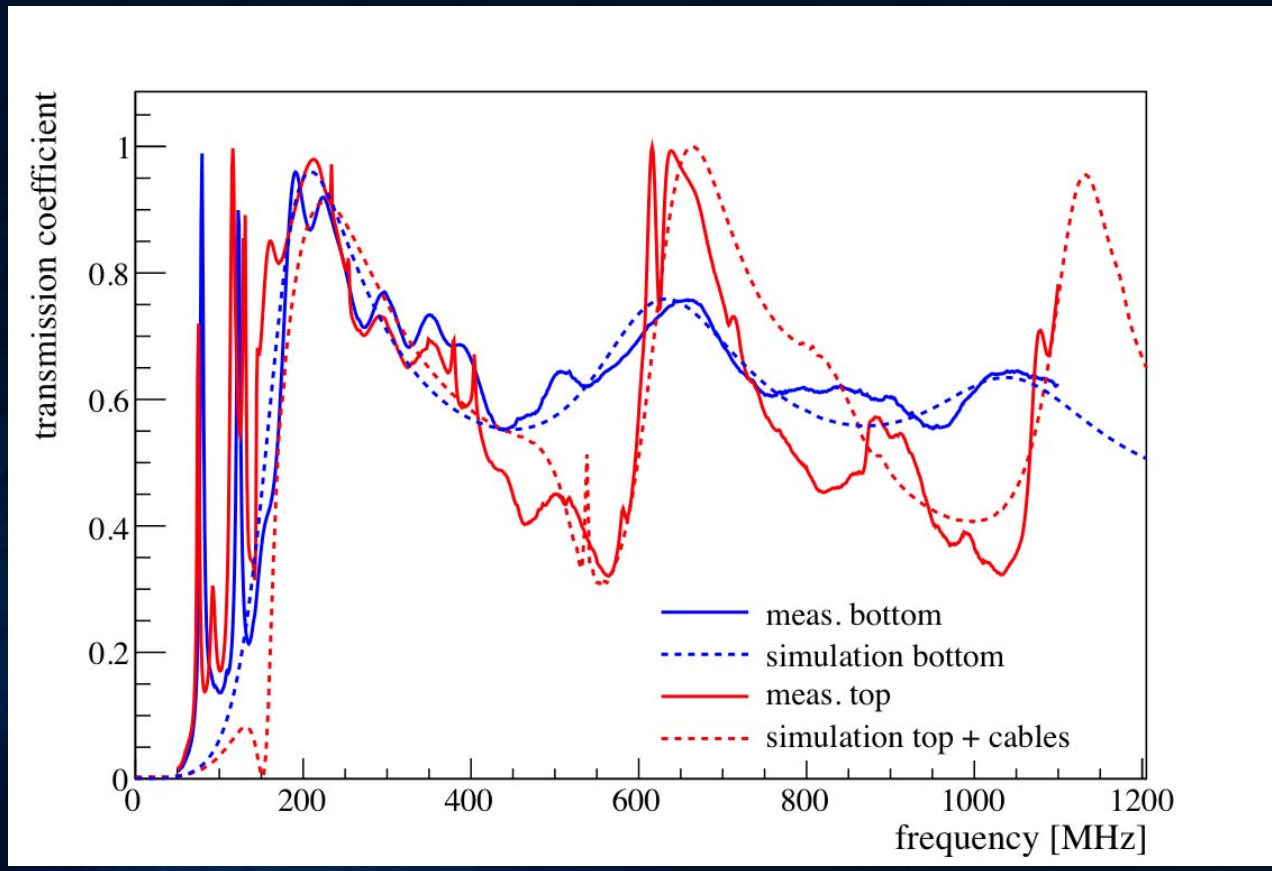
Next Generation: ARA

Antenna Assembly and calibration

chamber

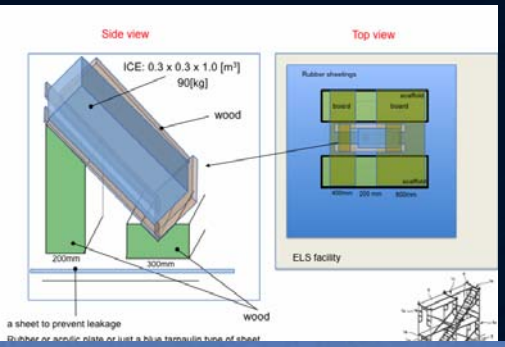


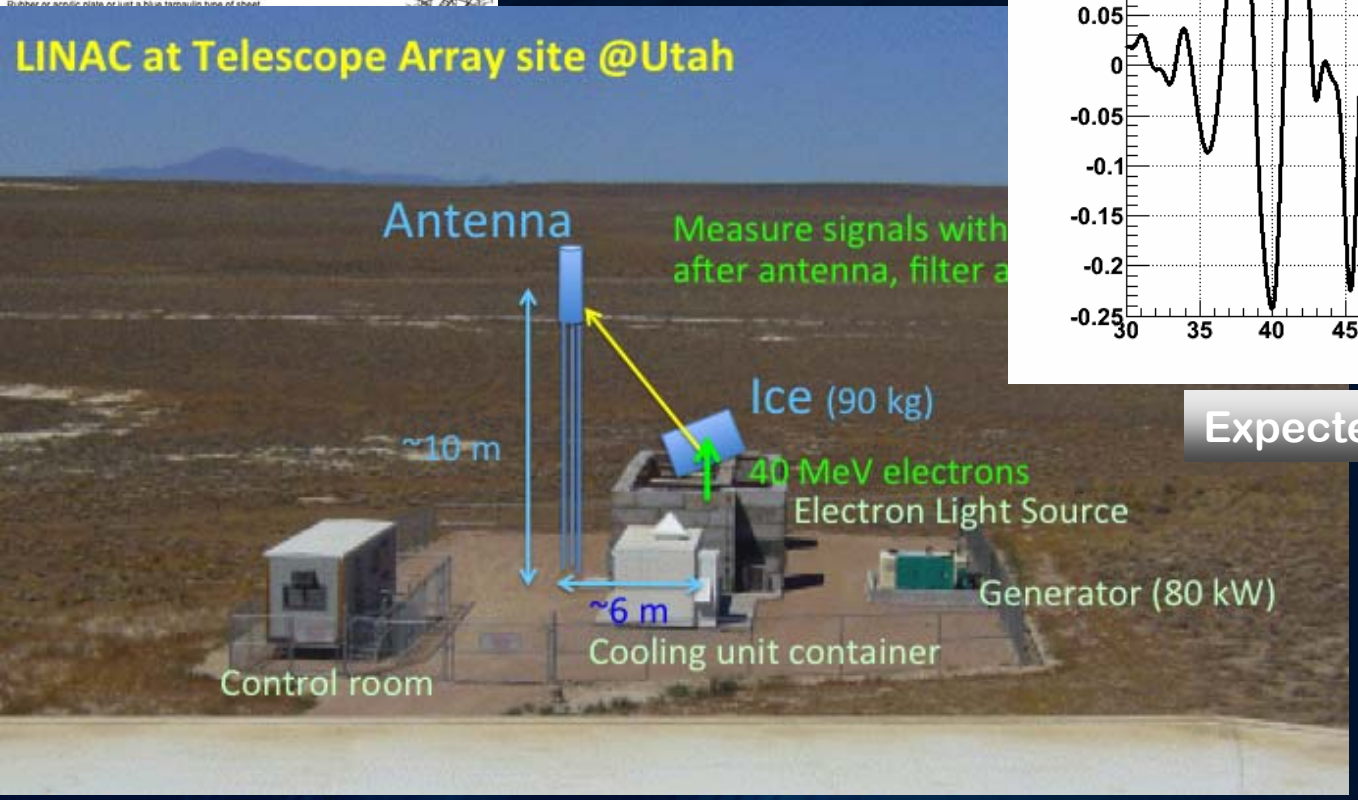
transmission coefficient

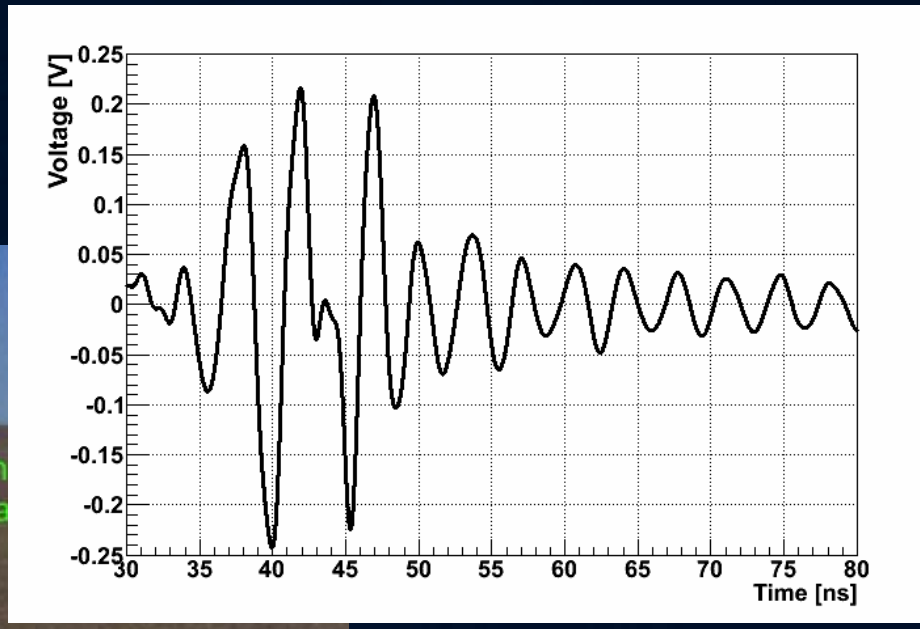


Next Generation: ARA

"end-to-end" calibration







Expected signals from ice

CHIBA UNIVERSITY

Executive Summary

ν = THE smoking gun