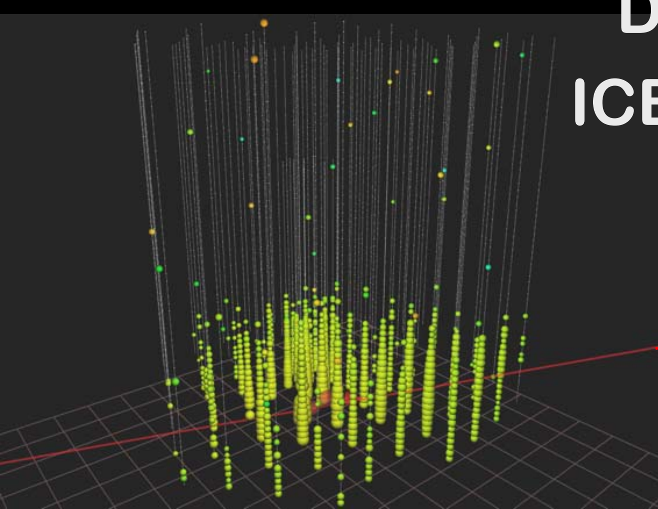
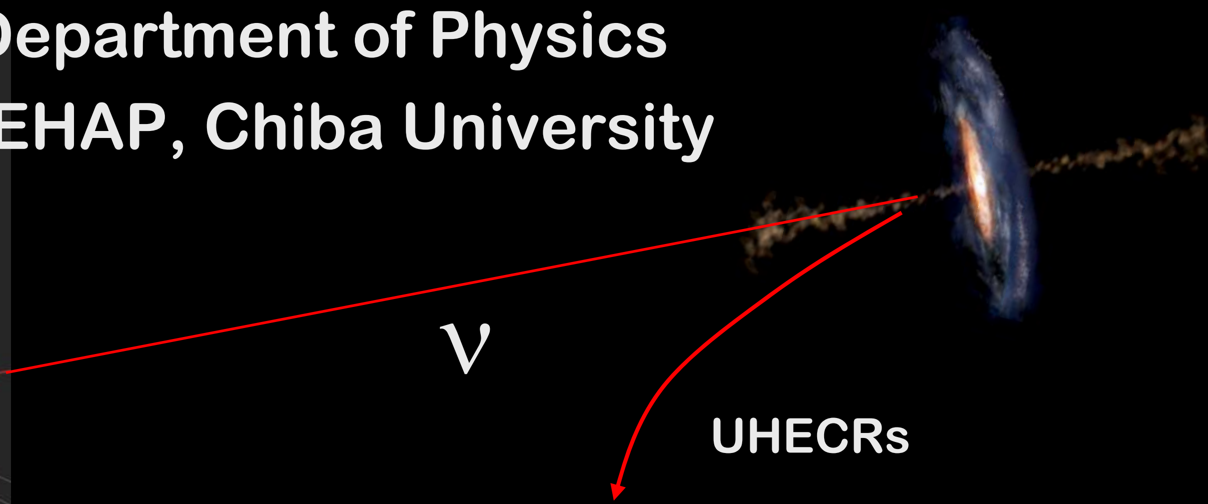
Probing the origin of UHECRs with neutrinos

The recent results from IceCube and its outlook

Shigeru Yoshida
Department of Physics
ICEHAP, Chiba University

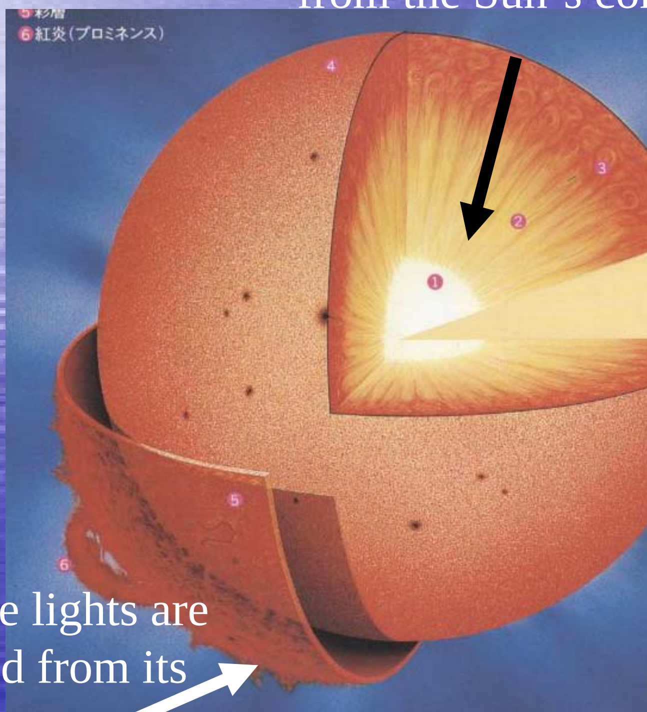




Neutrino Astronomy

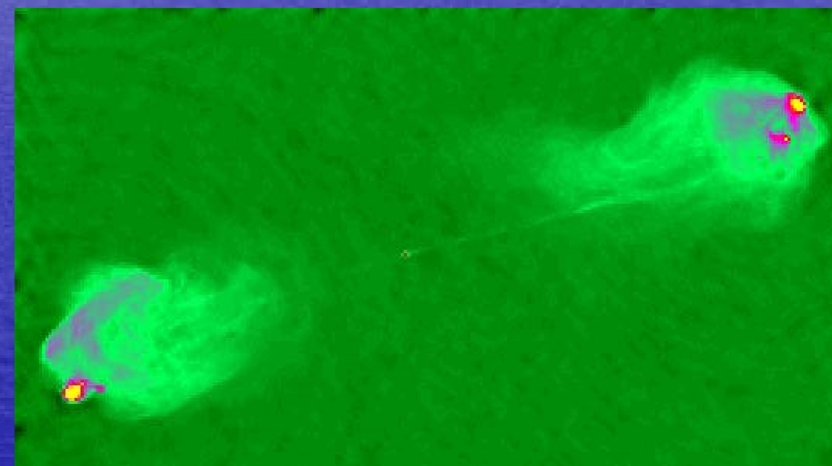
Scan star core

Solar neutrinos come from the Sun's core



Visible lights are emitted from its surface

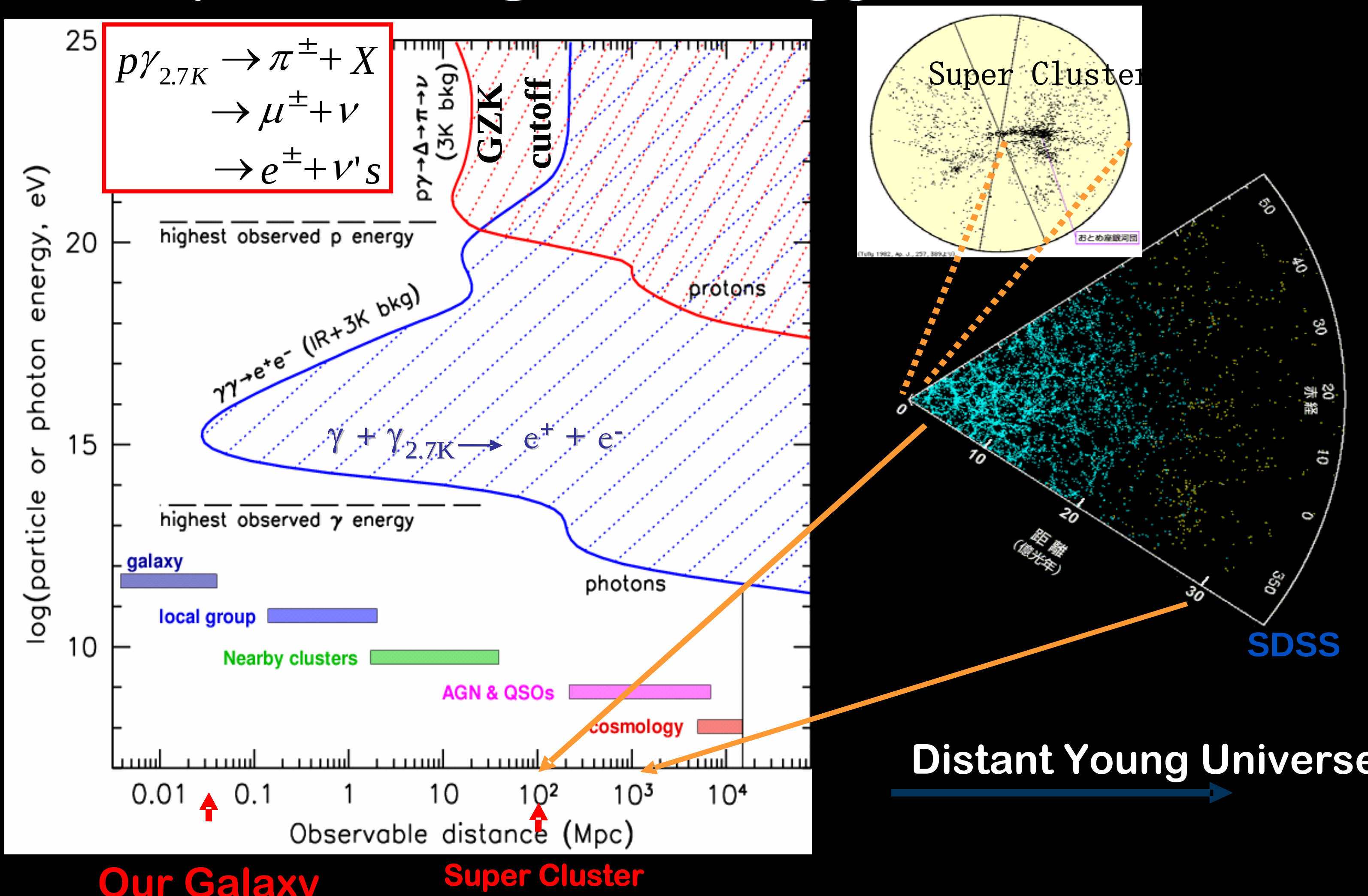
Explore the energetic phenomena in the deep universe



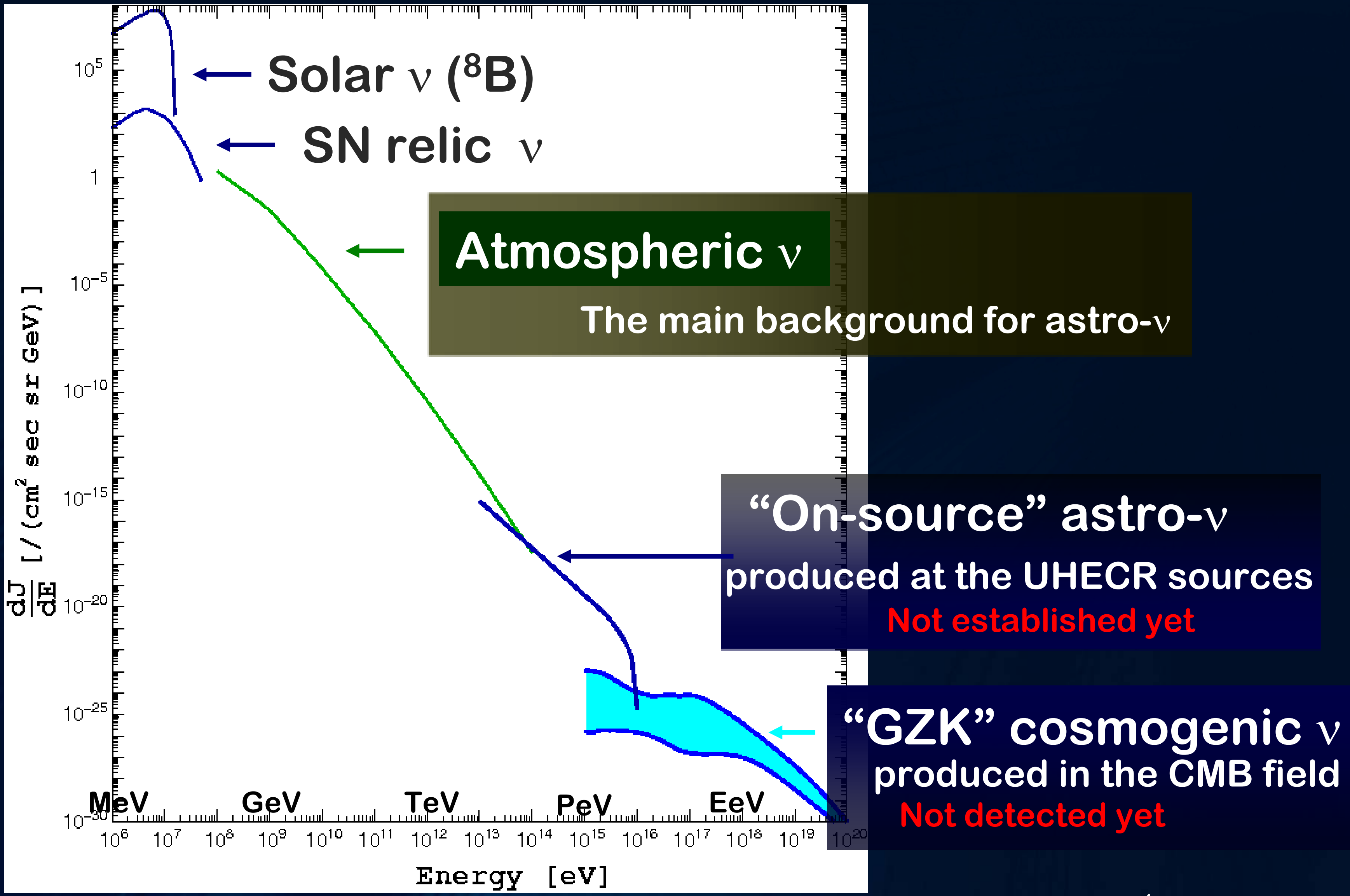
VLA image of Cygnus A

The High Energy Neutrino Astronomy

Why ν is so powerful to explore high energy universe?

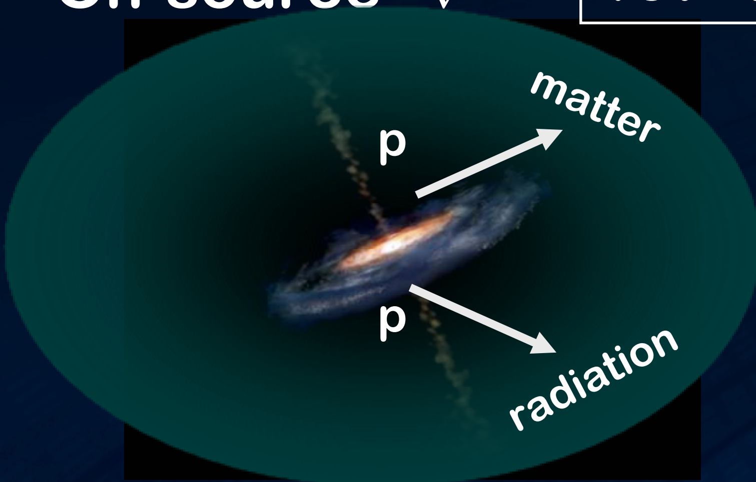


The Neutrino Flux: overview



The Cosmic Neutrinos Production Mechanisms

“On-source” ν — TeV - PeV

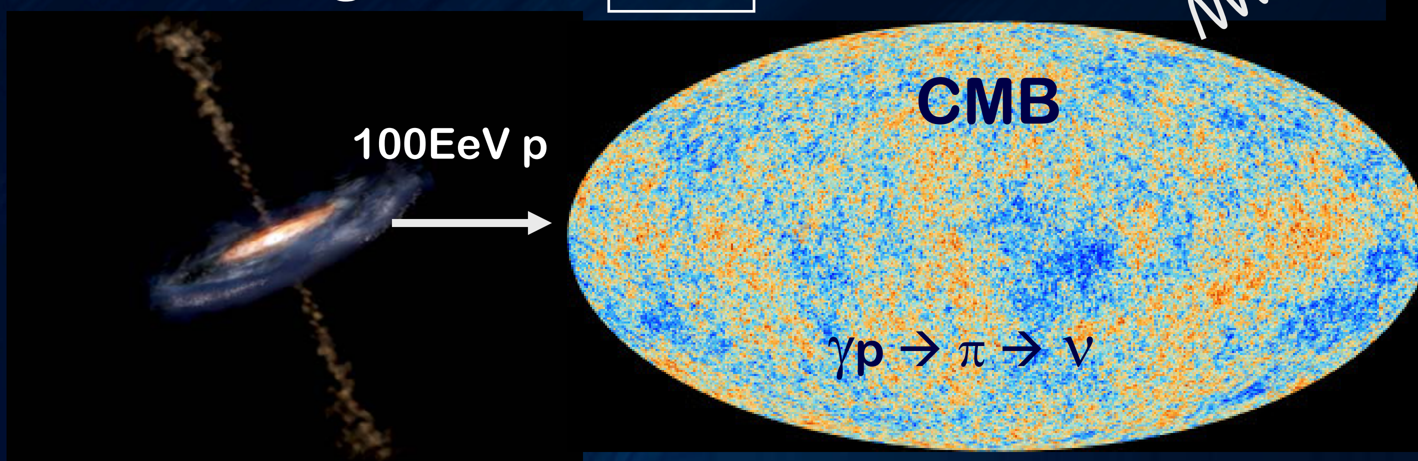


$pp \rightarrow \pi \rightarrow \nu$

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

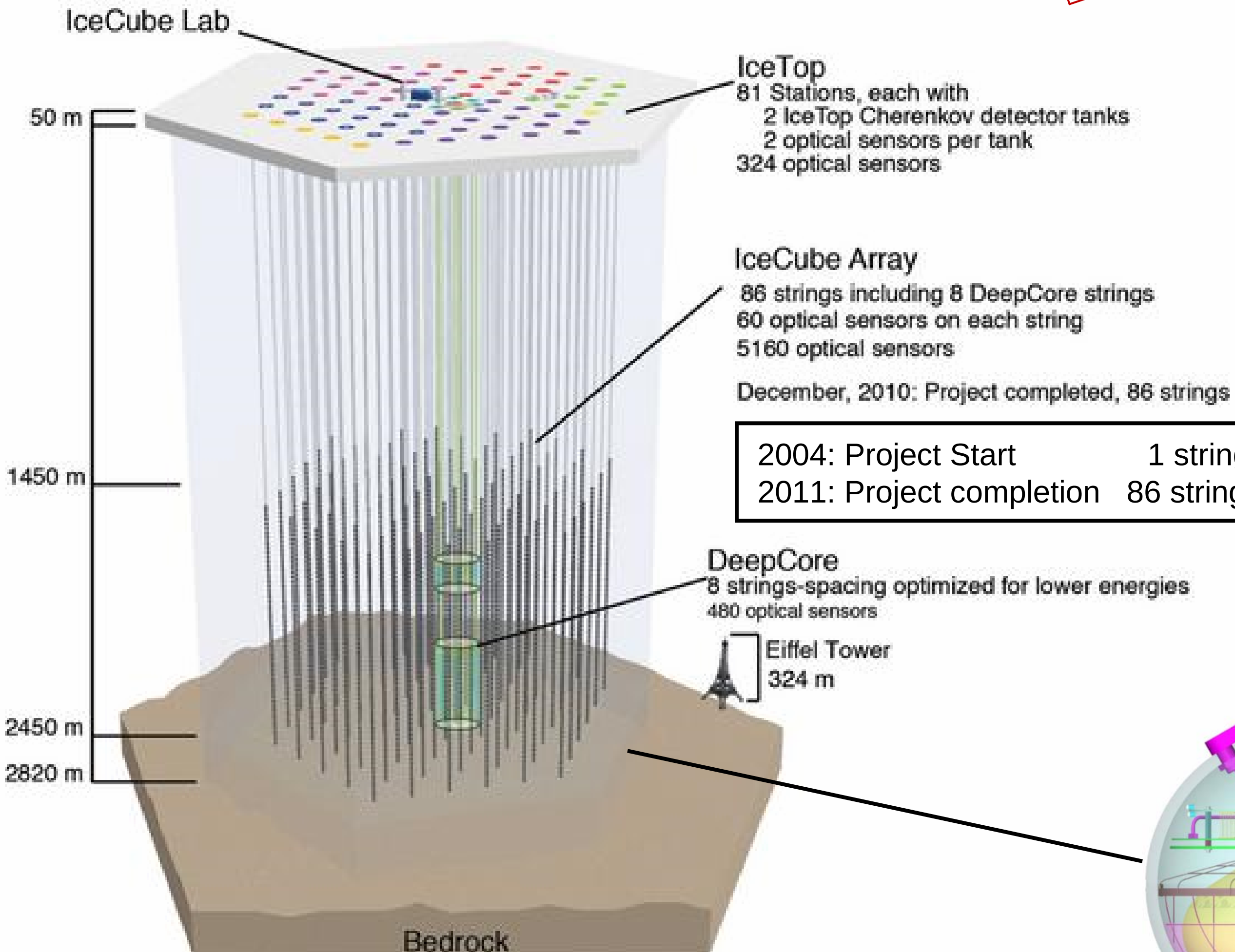
photopion production

“GZK” cosmogenic ν — EeV



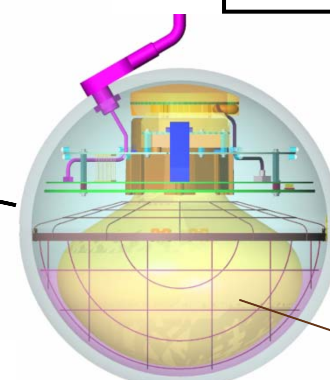
The IceCube Neutrino Observatory

Completed: Dec 2010



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

Constructions
2005-2011

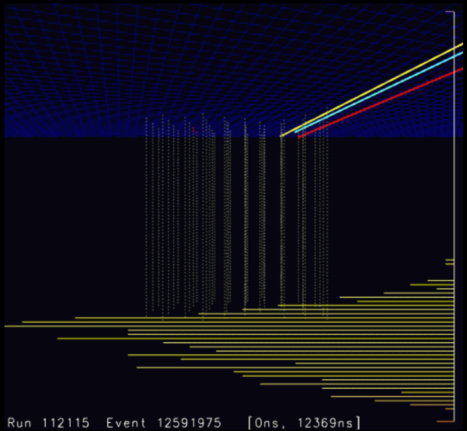
Detectors shipped from Japan

Drill House

The IceCube Lab 「Beer Can」

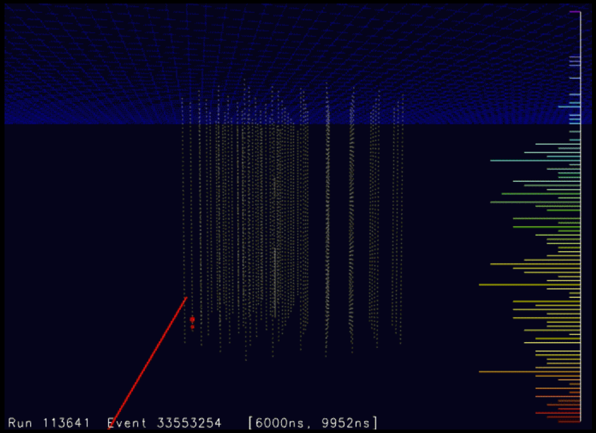
Researchers working on deployment

Topological signatures of IceCube events



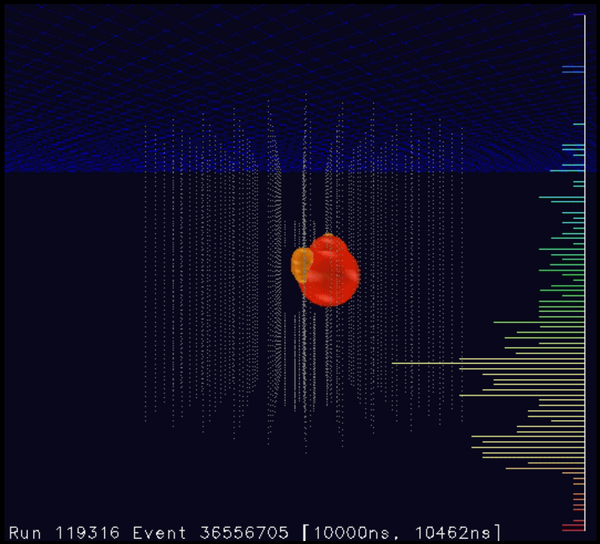
Down-going track

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



Up-going track

- atmospheric ν_μ



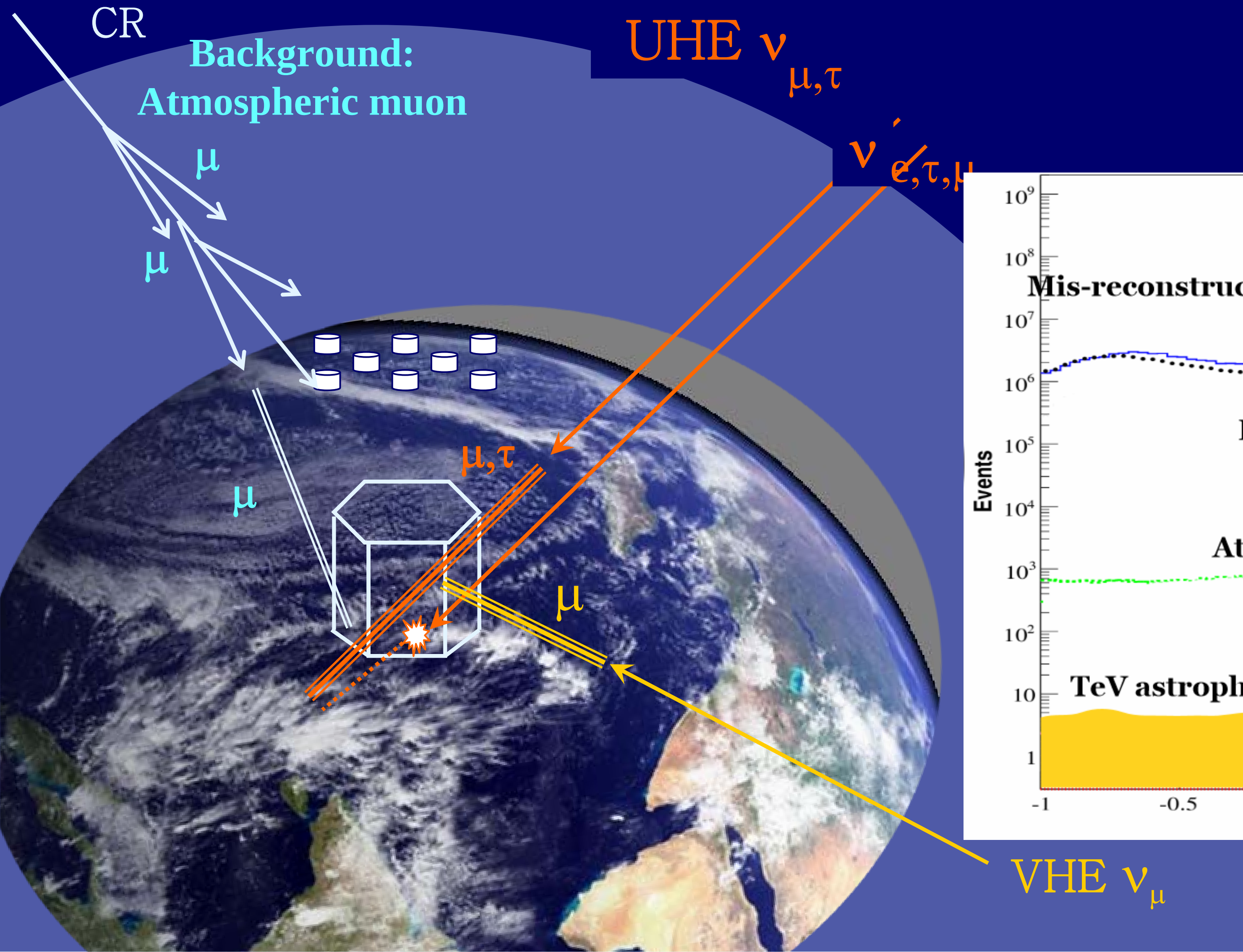
Cascade (Shower)

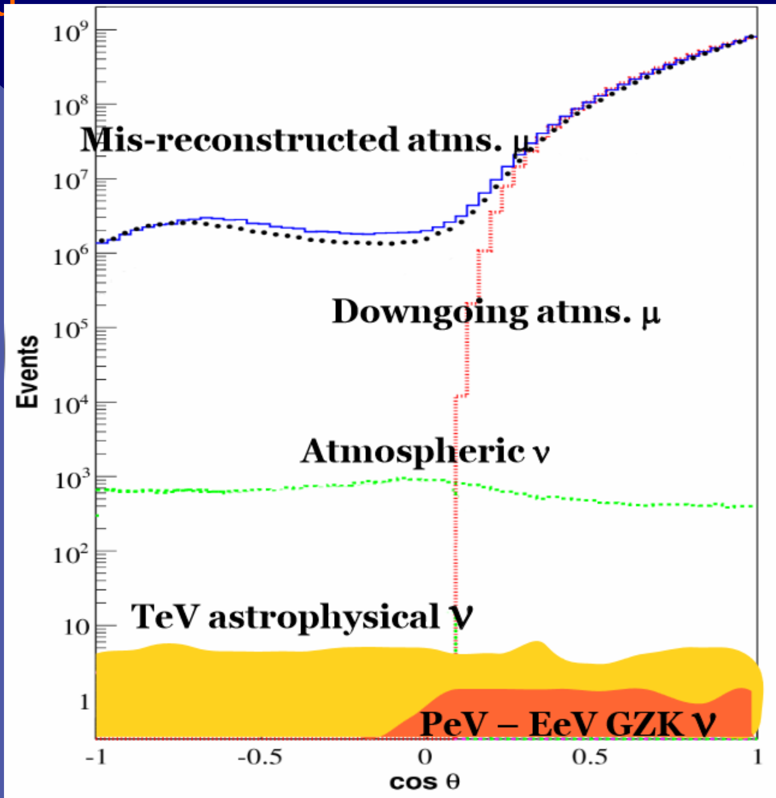
directly induced by ν
inside the detector volume

- 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)

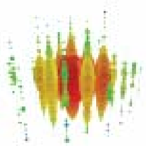




Post Bert & Ernie

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

Contents

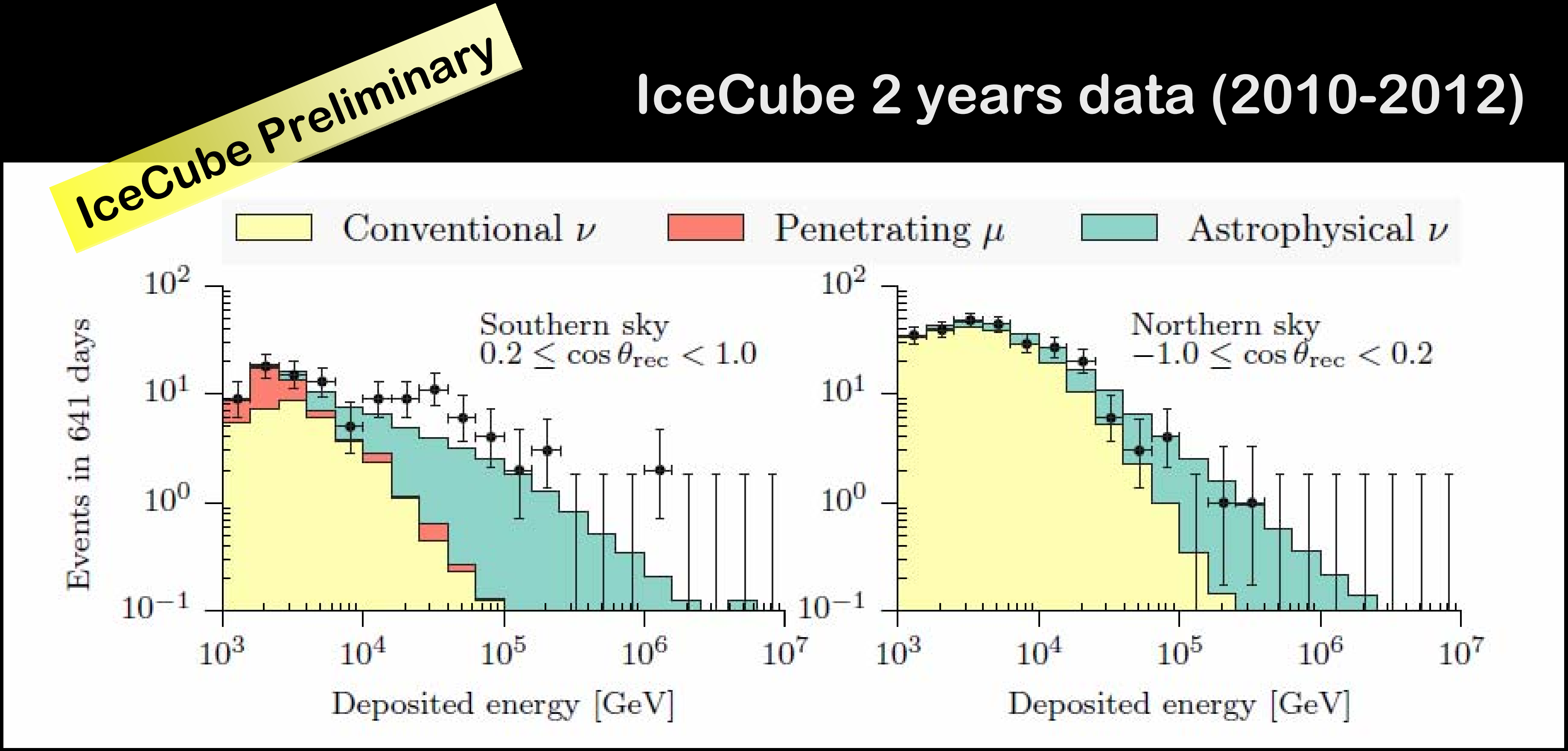
Articles published 6 July – 12 July 2013

VOLUME 111, NUMBER 2 — 12 July 2013

TeV PeV EeV

LE (<10 TeV)

IceCube 2 years data (2010-2012)

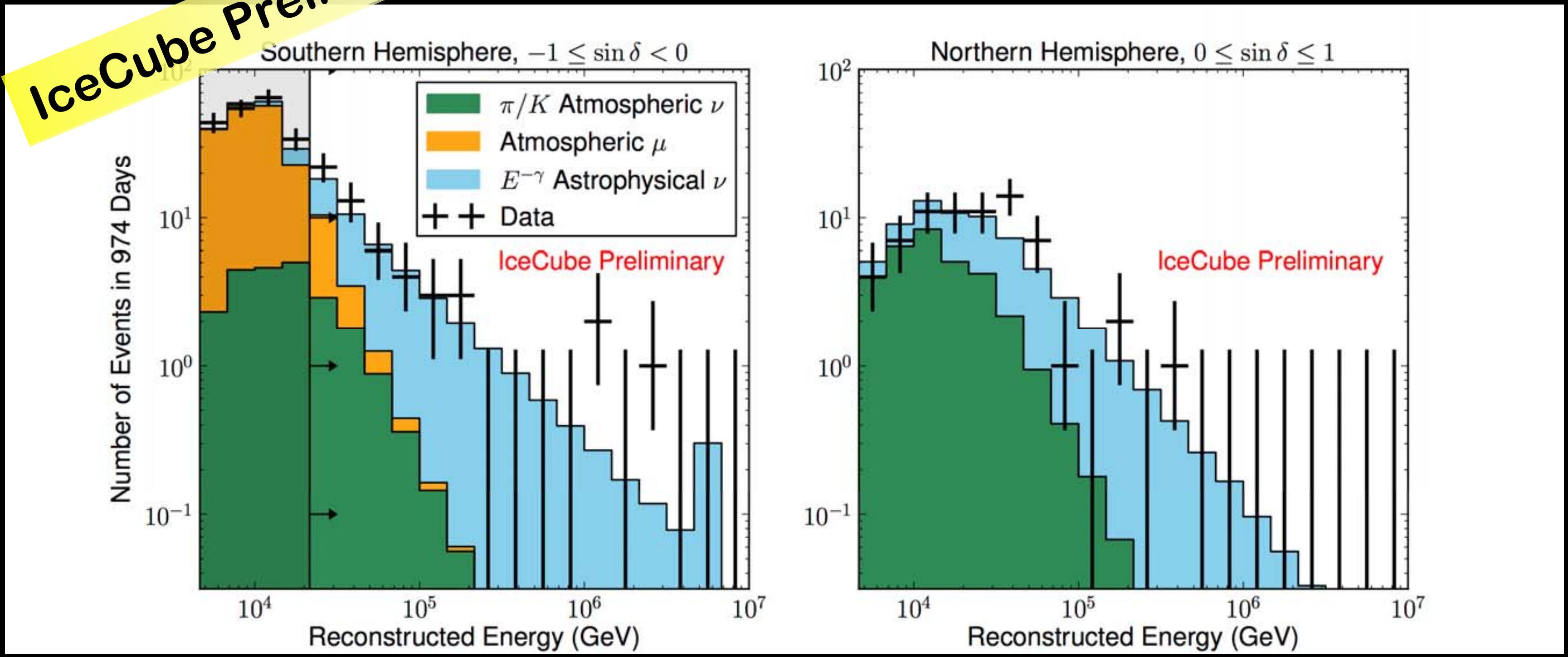


TeV PeV EeV

Mid Energy (10 TeV-)

veto + "cascade"

IceCube Preliminary

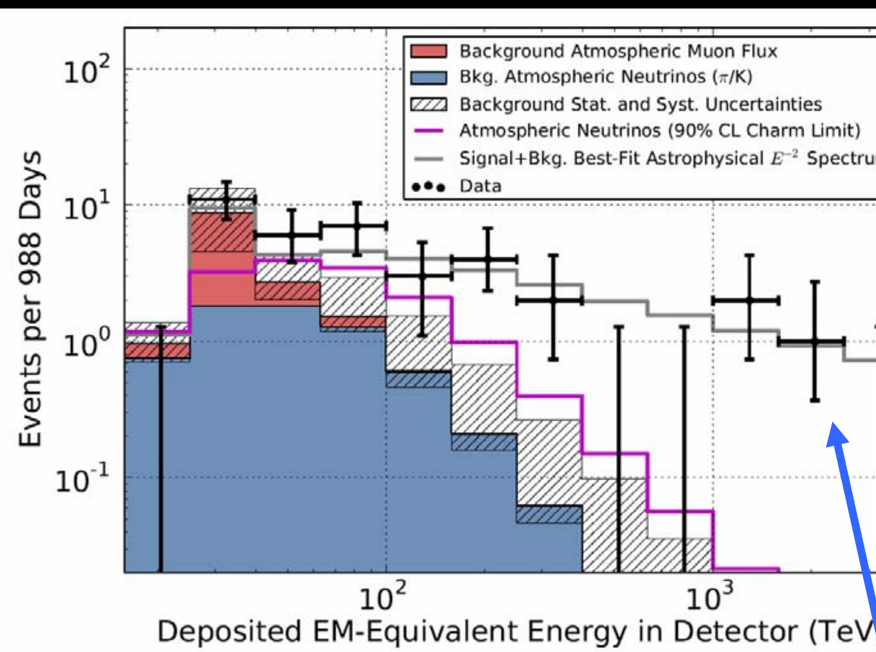


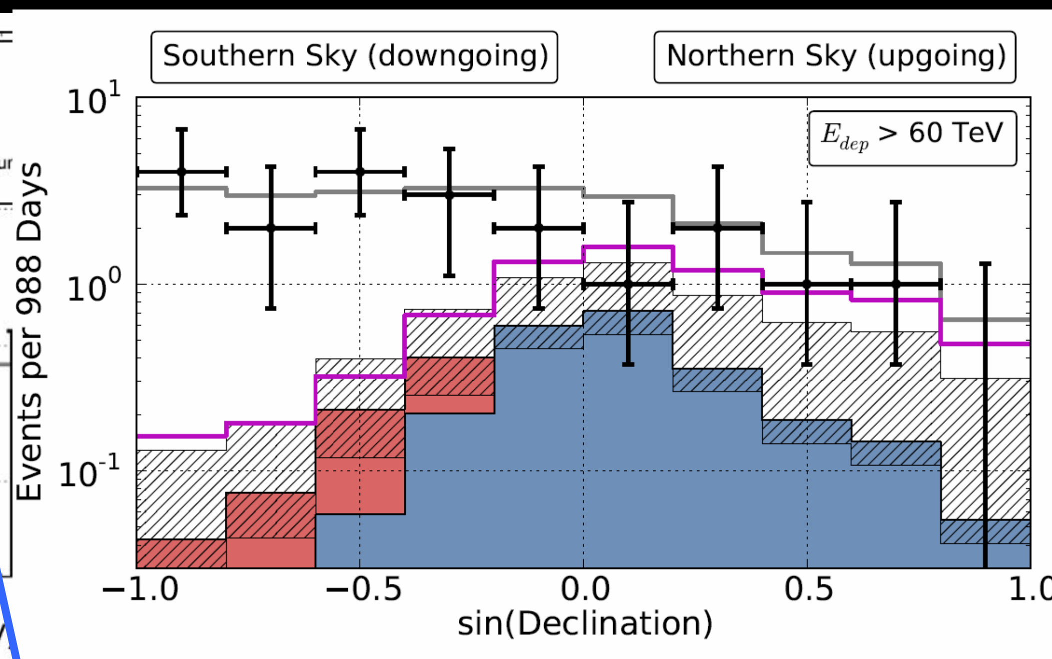
TeV PeV EeV

Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

IceCube collaboration
Phys. Rev. Lett. 113, 101101



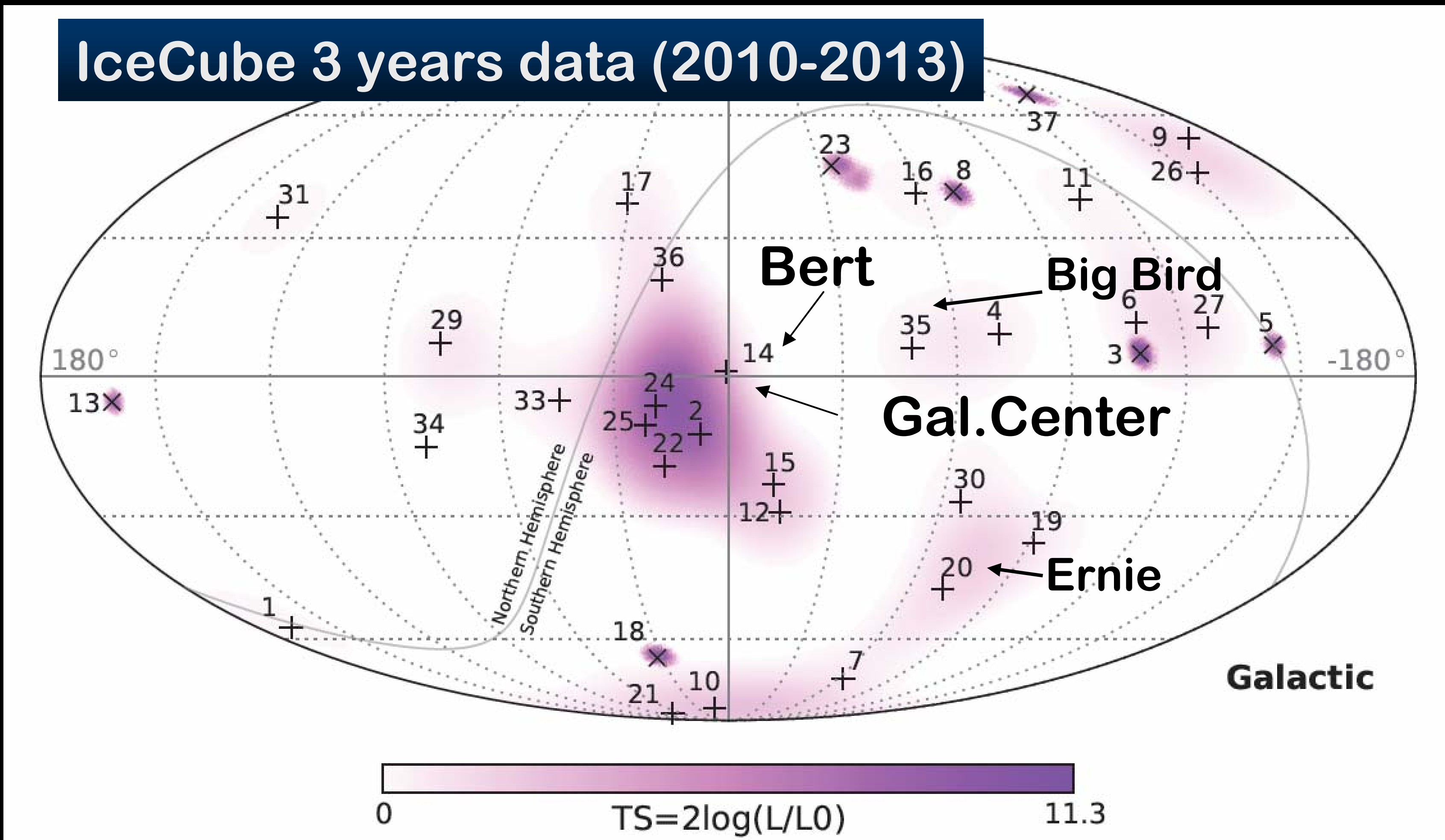


2PeV
“Big Bird”

ICECUBE

TeV PeV EeV

Mid Energy (60 TeV-)



TeV PeV EeV

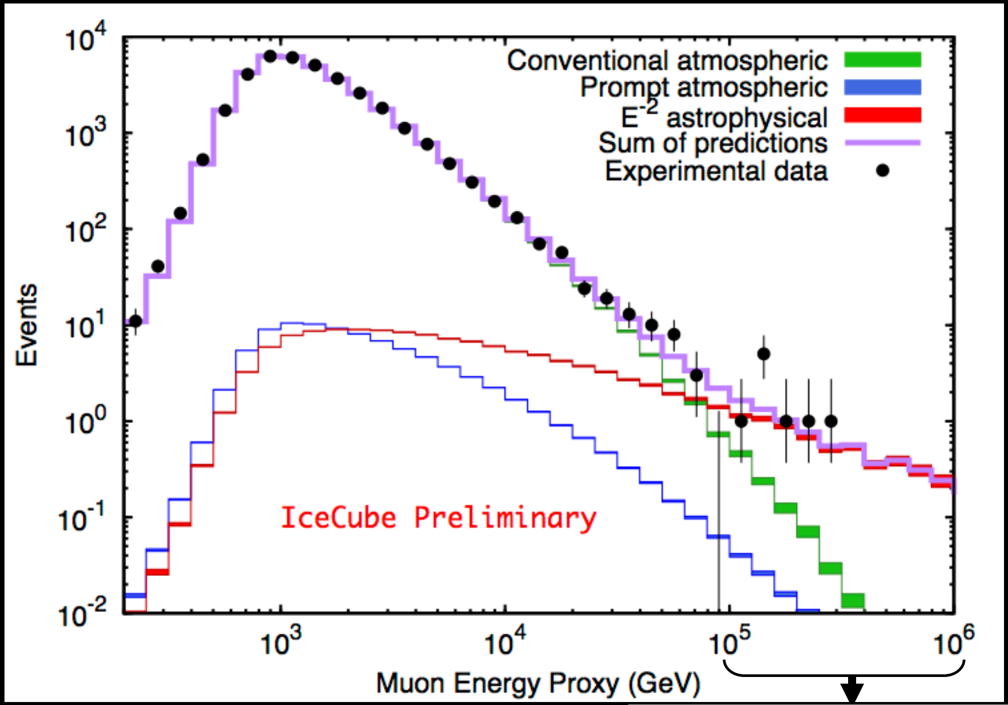
VHE (100 TeV-PeV)

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



$E_\nu = O(100TeV)$

3.9 σ excess over the atmospheric BG

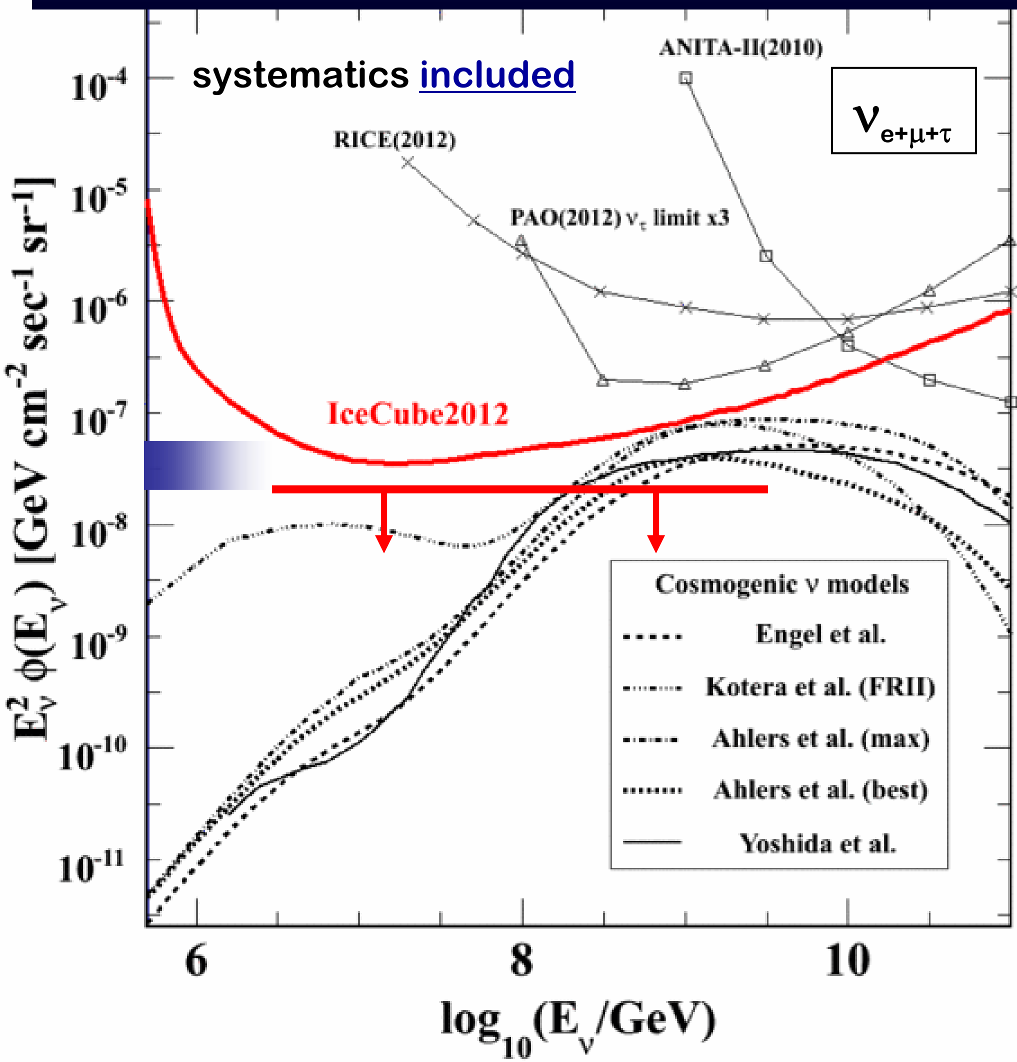
$E^2\ \phi_{\nu_\mu}(E) \sim 9.6 \times 10^{-9}$ [GeV/cm^2 sec sr]

TeV PeV EeV

UHE (PeV-EeV)

The model-independent upper limit on flux

IceCube 2 years data (2010-2012)



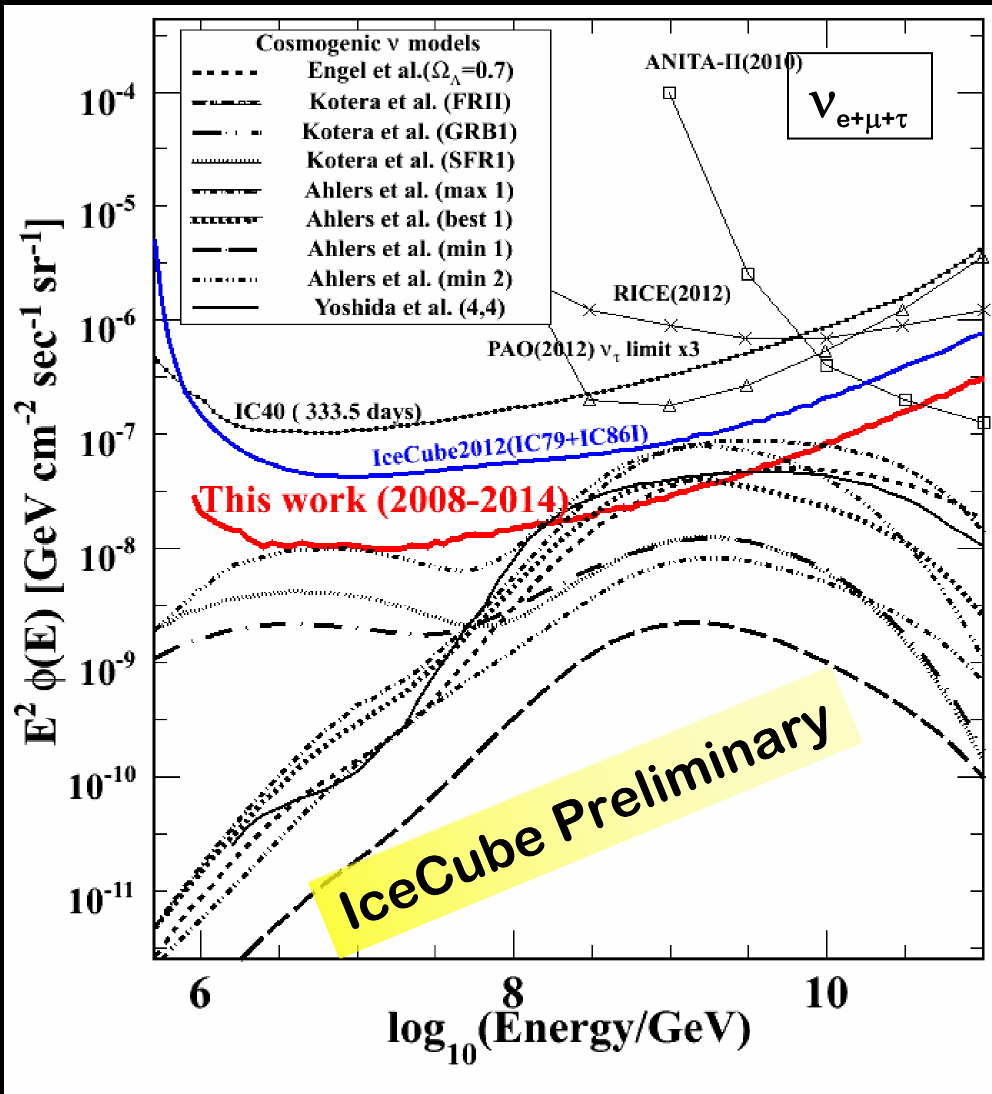
IceCube collaboration
Phys. Rev. D 88, 112008

any model adjacent to the limit is disfavored by the observation

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

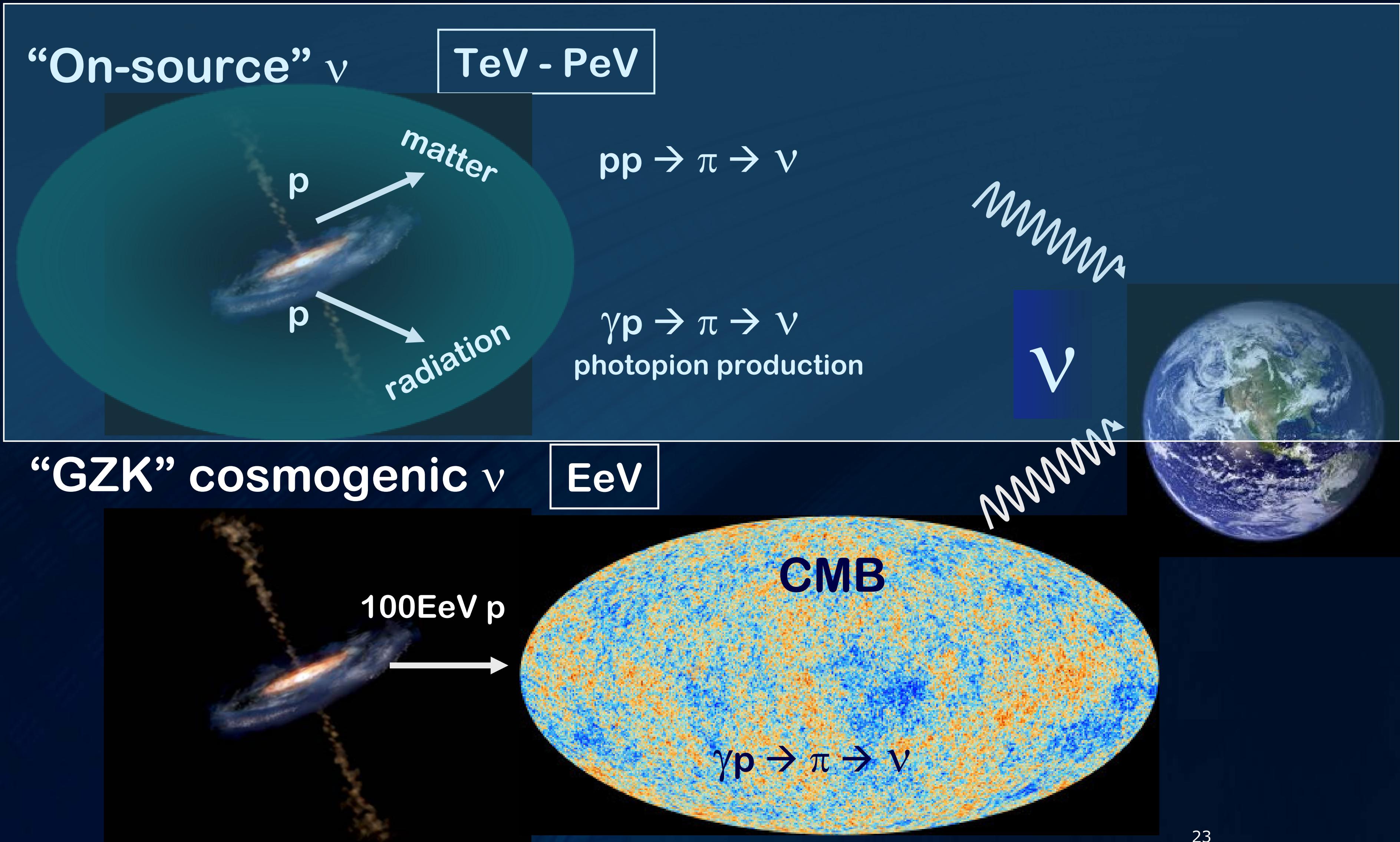
UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined

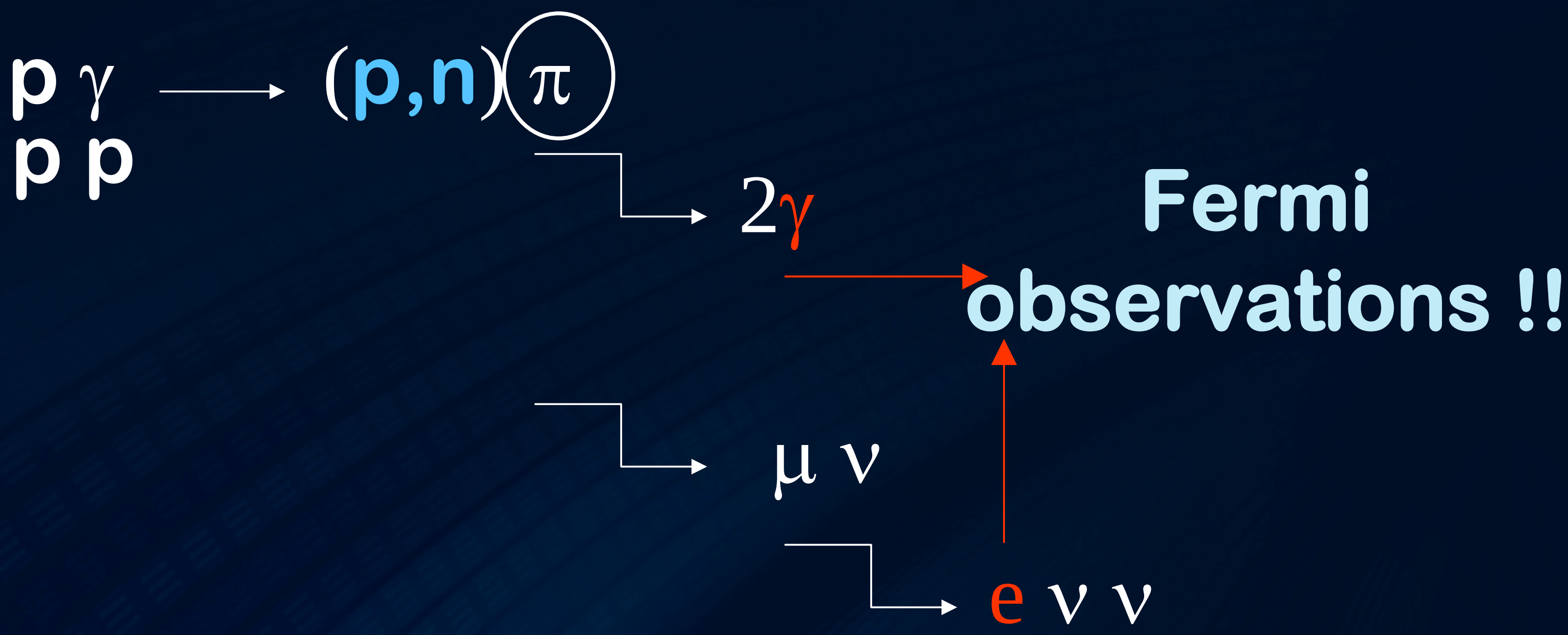
IceCube Confidential

Search Results coming soon

The Cosmic Neutrinos Production Mechanisms

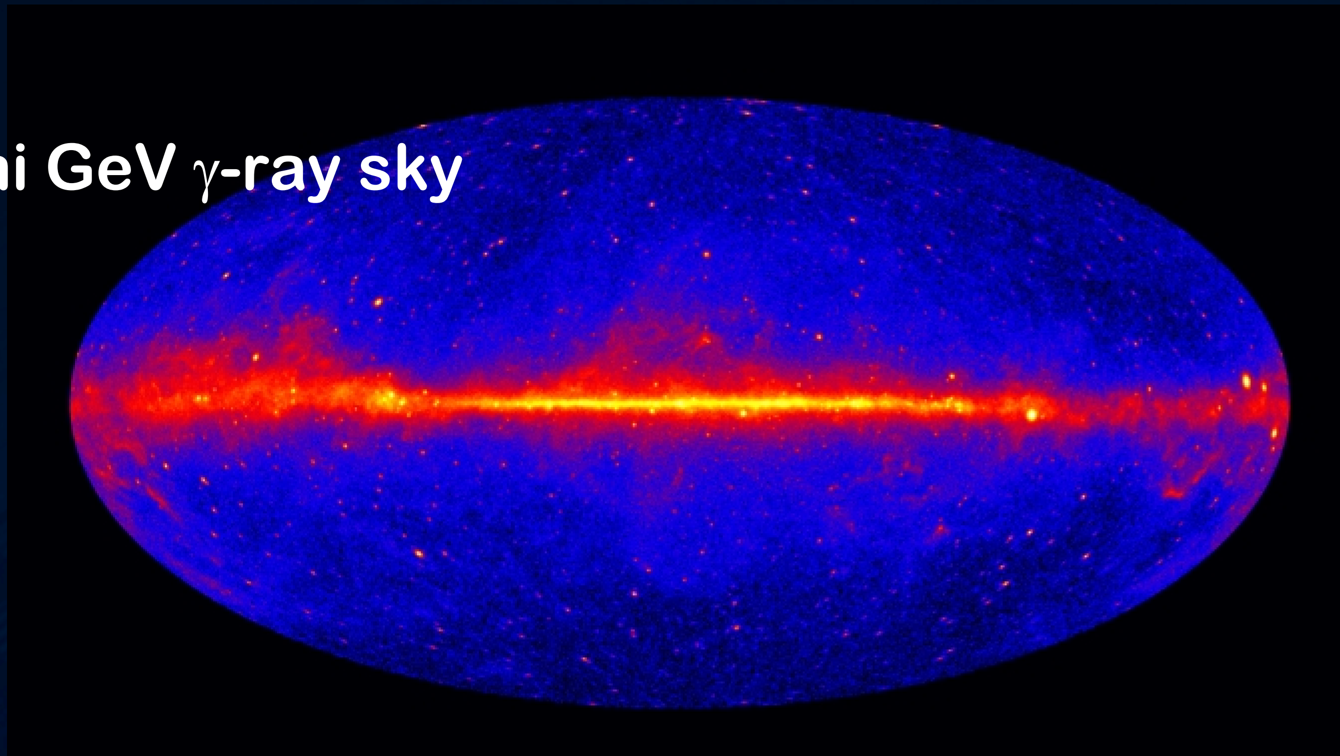


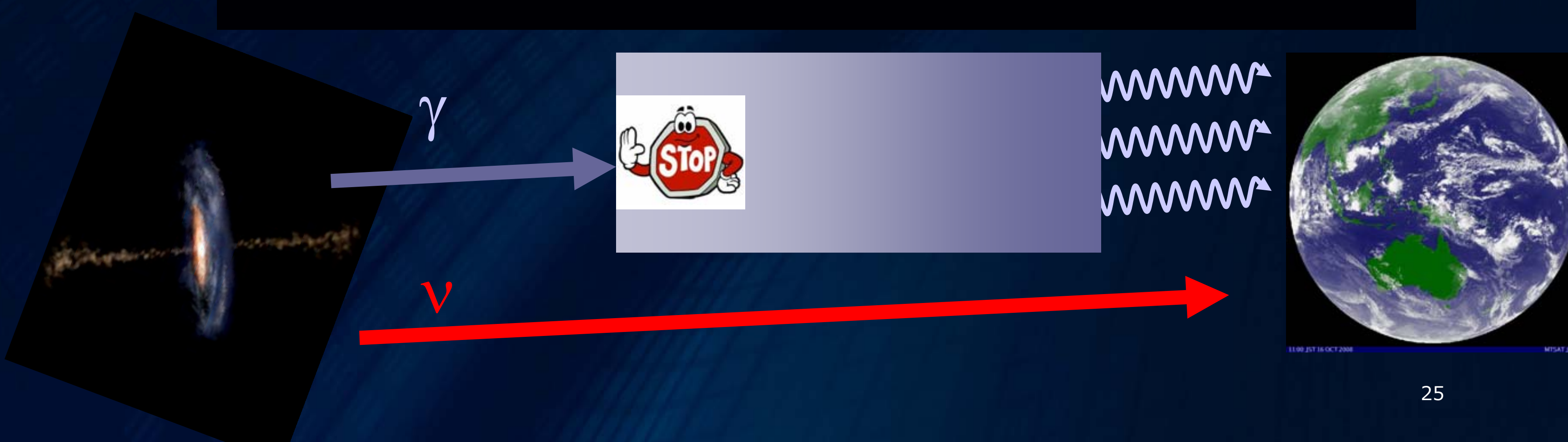
ν emission always accompanies γ



γ-ray sky bounds high energy ν emission

Fermi GeV γ-ray sky





EBL cools energetic γ

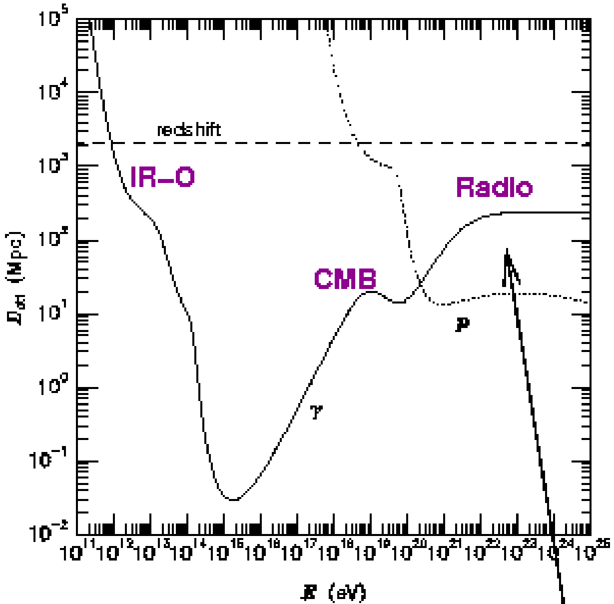
Extra-galactic Background Light

EM cascades recycle eγ energies
to GeV

$\gamma\,\gamma_{rad} \rightarrow ee$ $\quad E_{th} = \frac{m_{electron}}{E_{rad}} = 2.6 \times 10^{14} \left(\frac{E_{rad}}{10^{-3} eV}\right)^{-1} eV$

$e\,\gamma_{rad} \rightarrow e\gamma$

$e\,B \rightarrow e\,\gamma B$



$$\frac{d\sigma}{d\eta} \sim \frac{2\pi m^2 r_e^2}{s} \left(\frac{1-\eta}{\eta} + \frac{\eta}{1-\eta}\right)$$

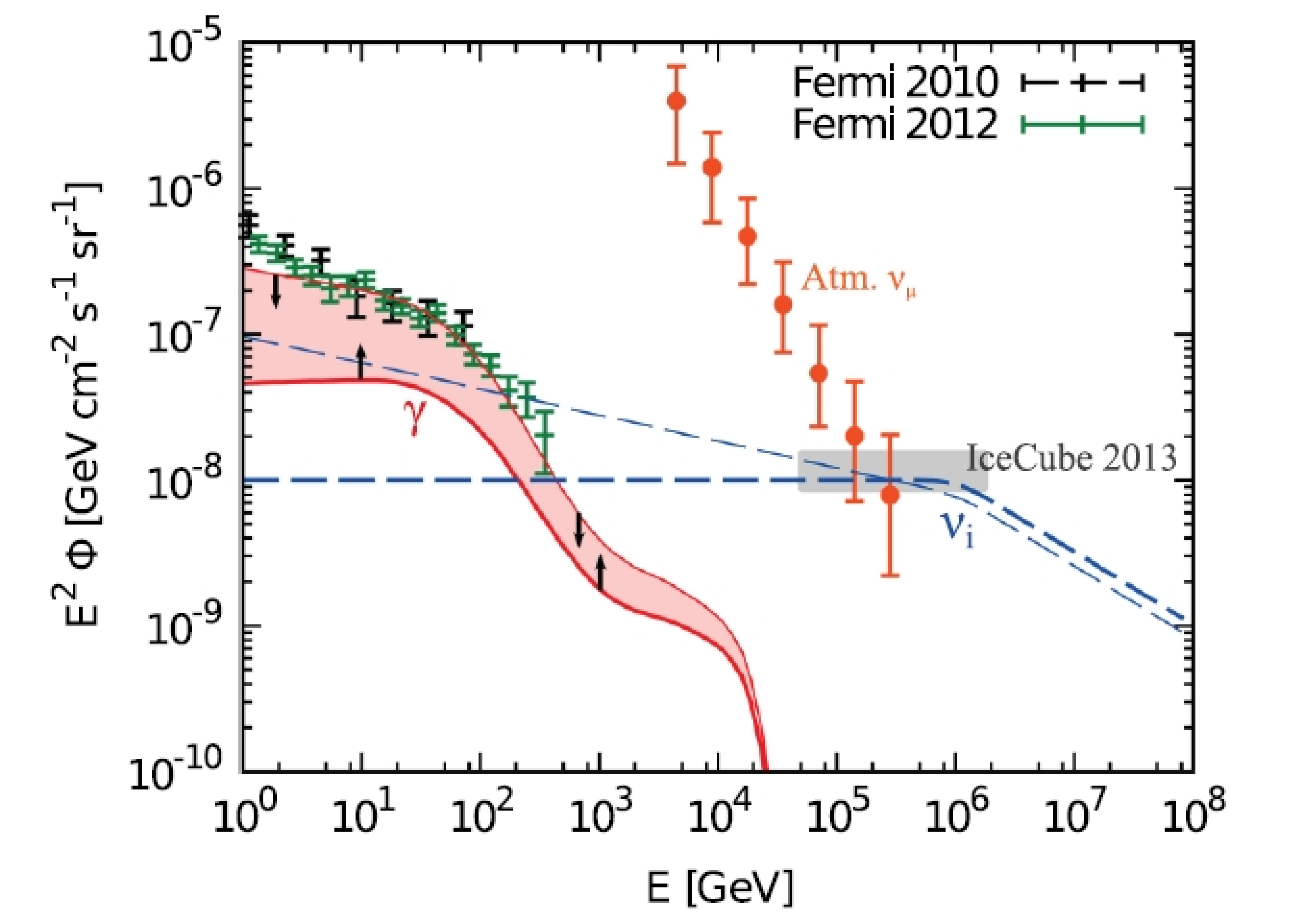
$$\eta = \frac{E_-}{E_\gamma}$$

→ "leading" particles
carry most faction of the photon energy

10 times larger
then D_{proton}

Bounds on pp→ν by Fermi

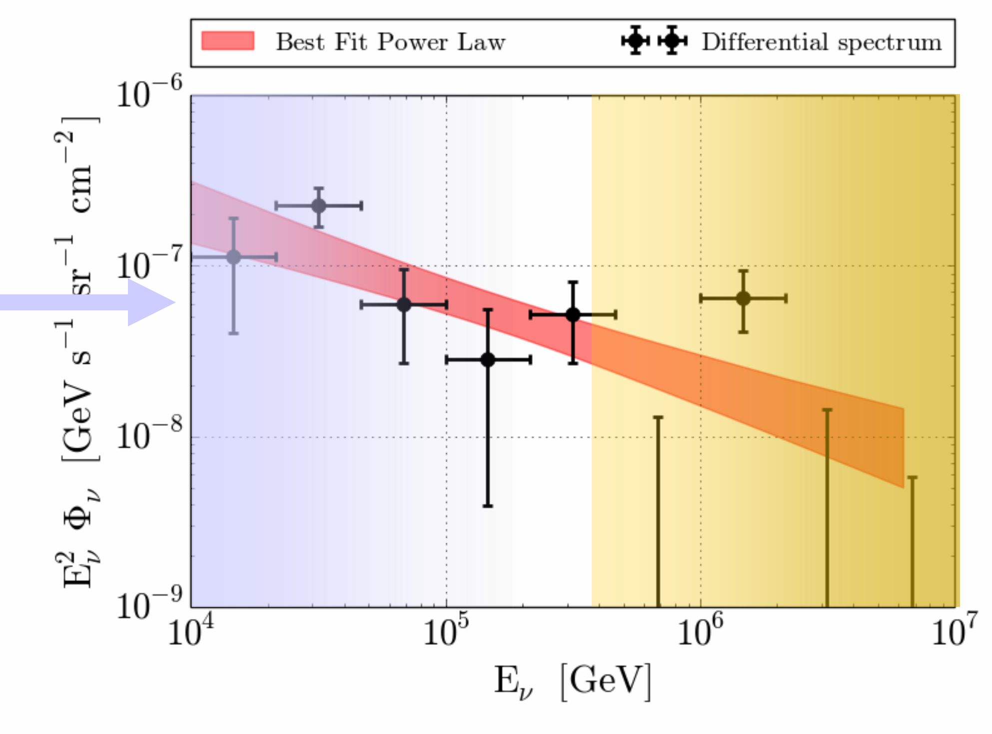
Murase, Ahlers, Lacki, PRD 2013



if pp→ν

a tension with Fermi

if pγ→ν



no rich target photons (~ X-rays) to yield TeV ν's

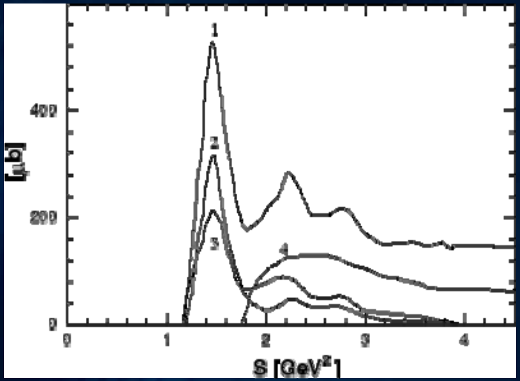
pγ→ν

$$E_\nu \sim 1\ \text{PeV} \left(\frac{E_\gamma}{10\text{eV}}\right)^{-1}$$

target γ visible light/IR Ly α

$$E_\nu \sim 10\text{TeV} \left(\frac{E_\gamma}{1\text{keV}}\right)^{-1}$$

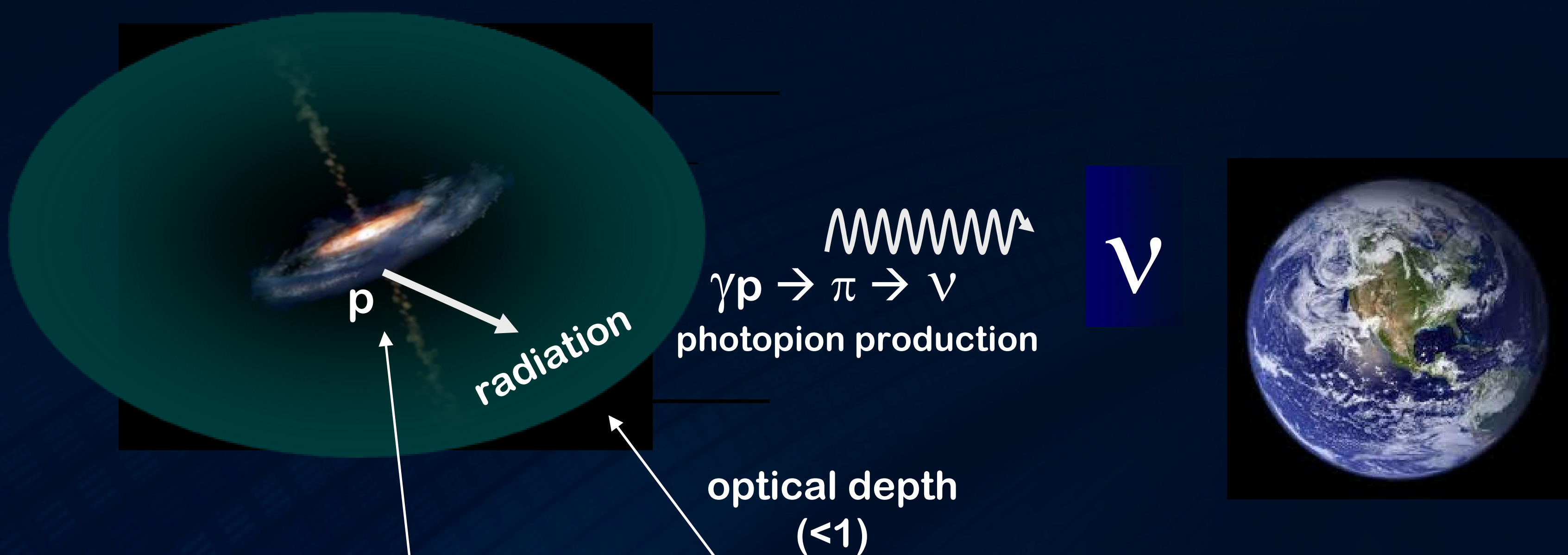
@ obs. frame



threshold effect of the pγ reaction

Any other generic constraints?

Constraints on the optical depth and extra-galactic CR flux

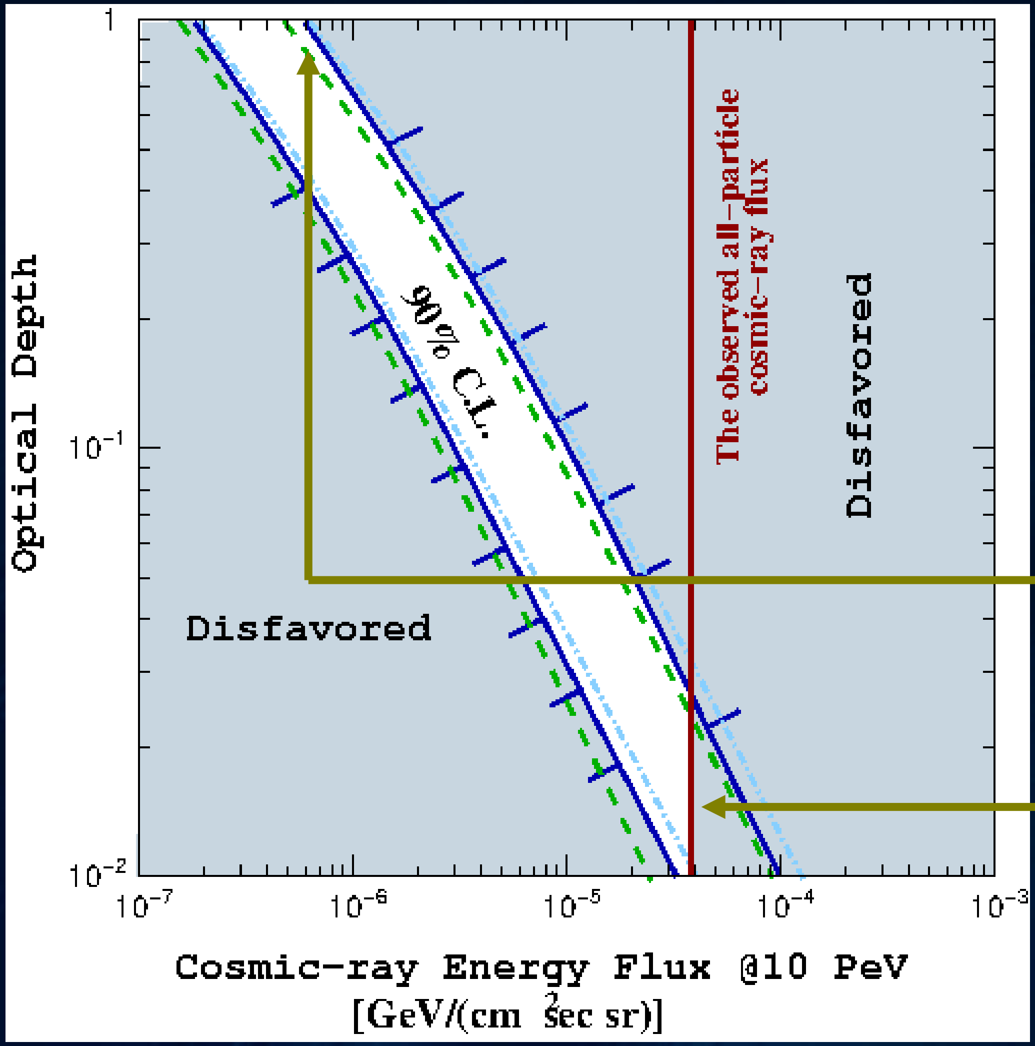


$$\frac{dJ_\nu}{dE} \sim F_{GZK\ CR}\frac{R_{cosmic}}{R_{GZK}}\,\mathbf{E}^{-\alpha}\ \tau(E)\ \zeta(z, m, z_{max}, E)$$

Constrain them by the IceCube 100TeV-PeV observation

Fixed to the Star Formation Rate

Constraints on the optical depth and extra-galactic CR flux

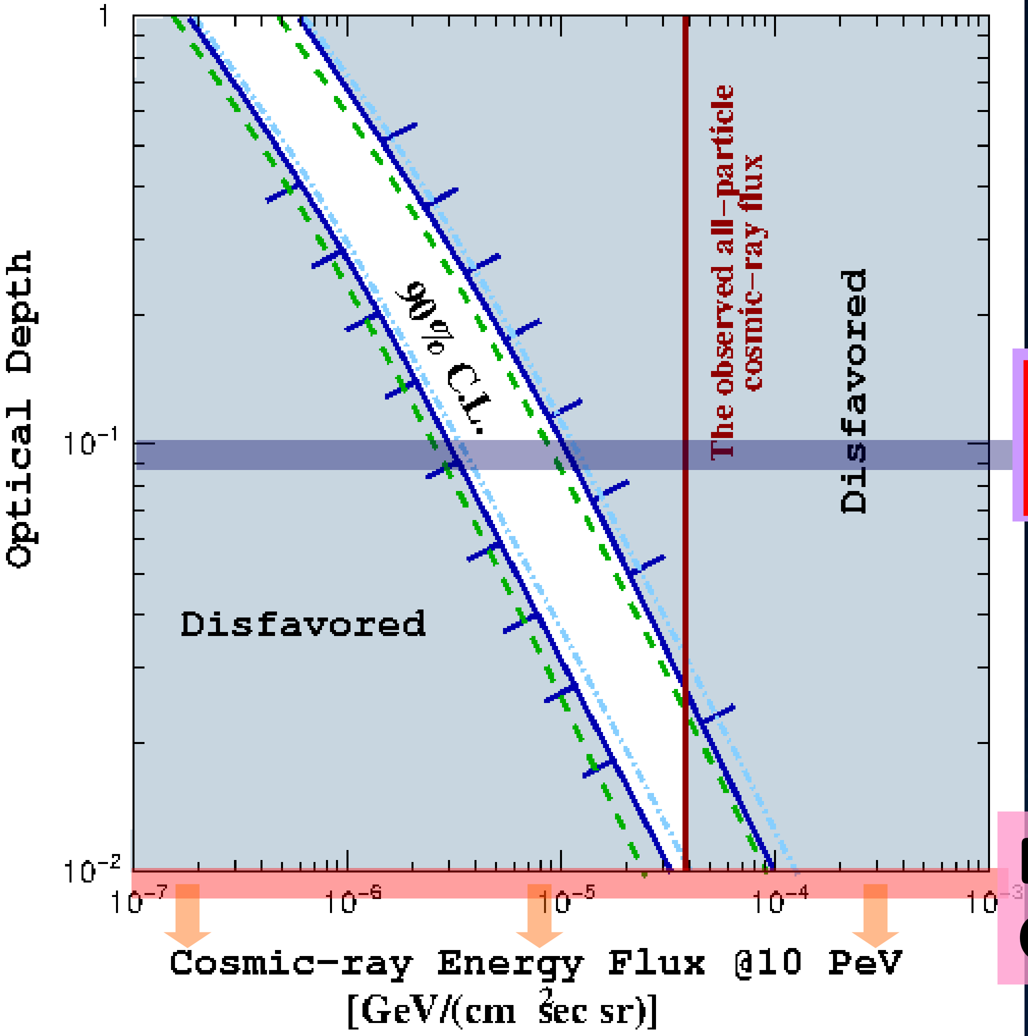


Yoshida, Takami
PRD (2014)

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

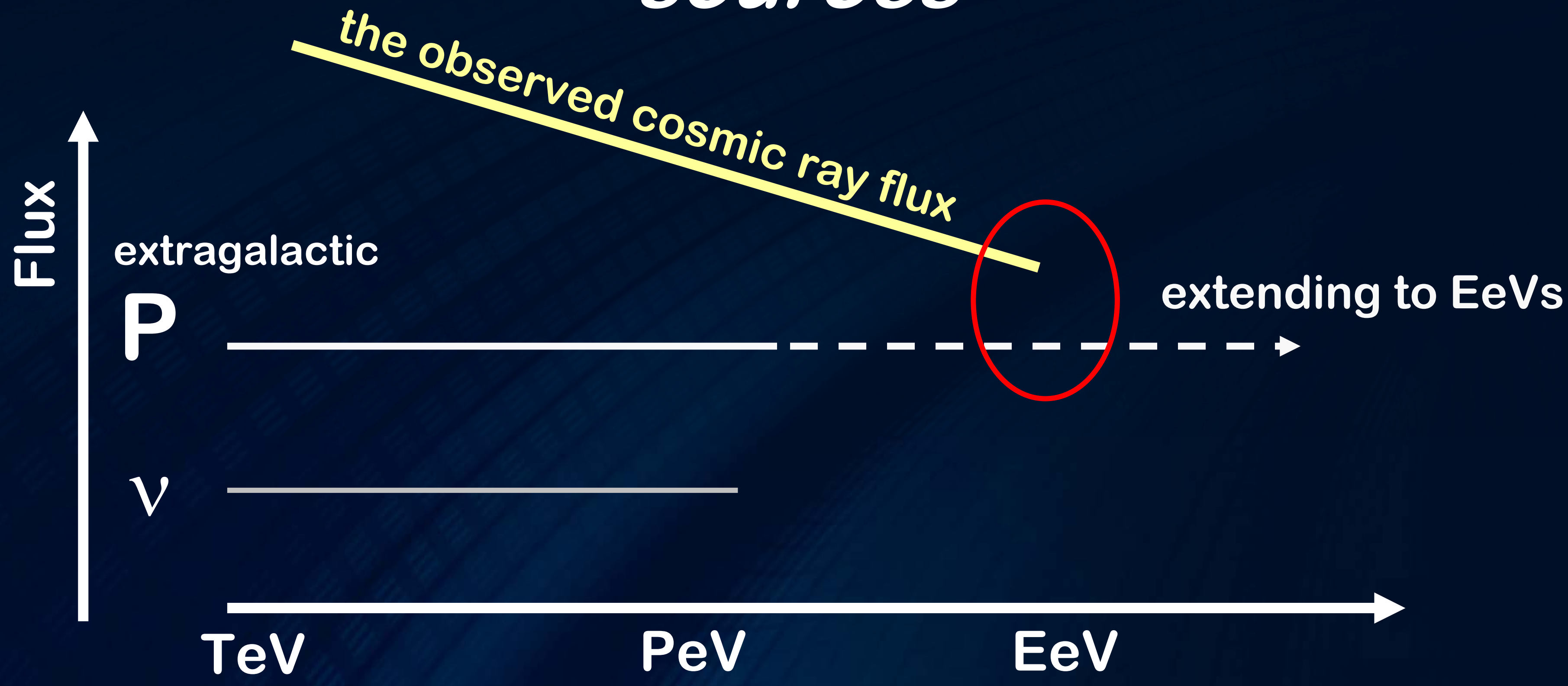
GRBs (internal shock)

energetics

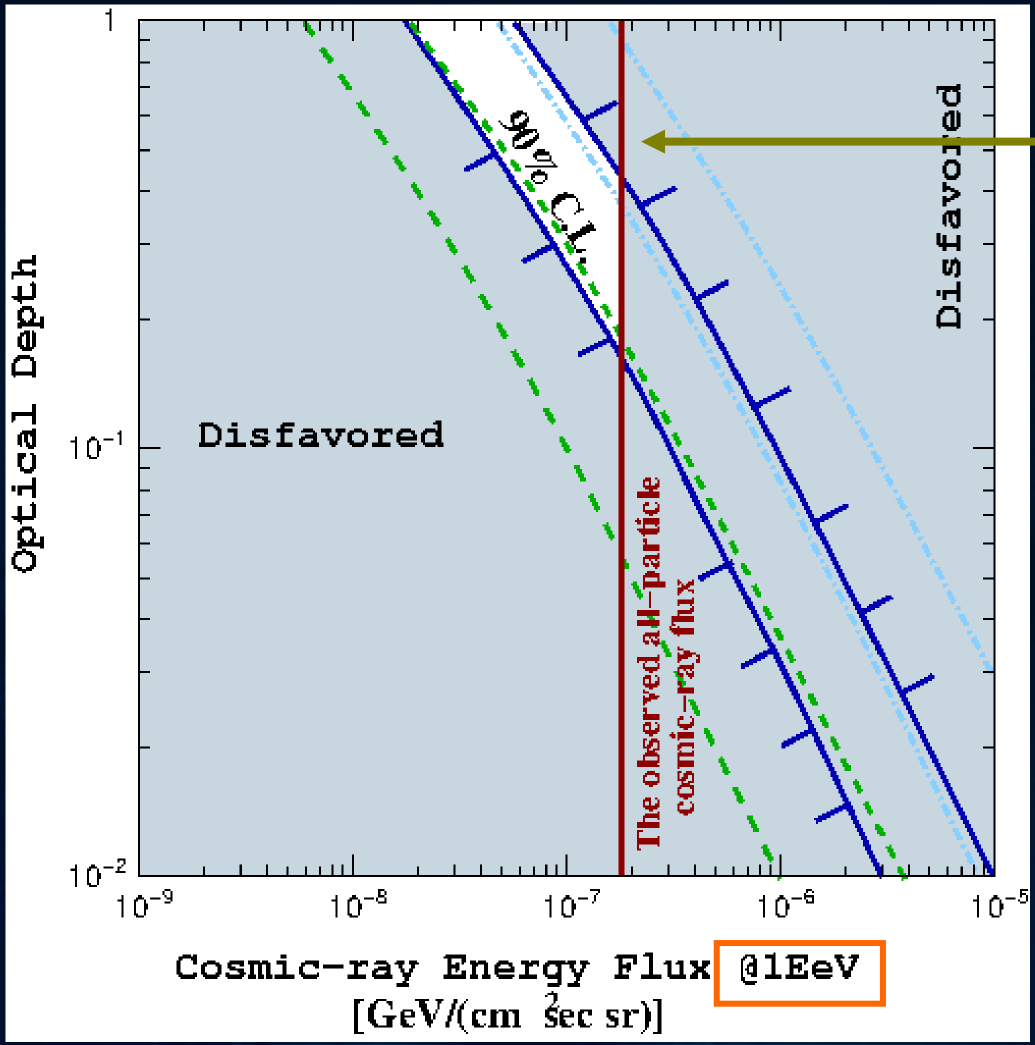
BL Lac/FR-I

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

The numbers to challenge

Requirements

@ 10PeV

γp optical depth ~ 0.1

Proton emission energy budget

$O(10\%) \times L_{CR}^{10PeV} \sim 10^{45}$ erg/Mpc^3 yr

The numbers to challenge

Requirements

@ 10PeV

γp optical depth ~ 0.1

Proton emission energy budget

$O(10\%) \times L_{CR}^{10PeV} \sim 10^{45}$ erg/Mpc^3 yr

@EeV=1000PeV

if emitted proton spectrum extends further to this energy
(this is *probably* easy to achieve)

γp optical depth ~ 1

Proton emission energy budget

$\sim L_{CR}^{1EeV} \sim 10^{44}$ erg/Mpc^3 yr

$L_\gamma > 10^{45}$ erg/s

The numbers to challenge

GRBs

@ 10PeV

○ γp optical depth ~ 0.1

× Proton emission energy budget

$O(10\%) \times L_{CR}^{10PeV} \sim 10^{45}$ erg/Mpc^3 yr

@EeV=1000PeV

if emitted proton spectrum extends further to this energy
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× γp optical depth ~ 1

○ Proton emission energy budget

$\sim L_{CR}^{1EeV} \sim 10^{44}$ erg/Mpc^3 yr

◎ $L_\gamma > 10^{45}$ erg/s

The numbers to challenge

Blazars (BL Lac)

@ 10PeV

× γp optical depth ~ 0.1

△ Proton emission energy budget

$O(10\%) \times L_{CR}^{10PeV} \sim 10^{45}$ erg/Mpc^3 yr

@EeV=1000PeV

if emitted proton spectrum extends further to this energy
(this is *probably* easy to achieve)

× γp optical depth ~ 1

○ Proton emission energy budget

$\sim L_{CR}^{1EeV} \sim 10^{44}$ erg/Mpc^3 yr

○ $L_\gamma > 10^{45}$ erg/s

The numbers to challenge

Blazars (FSRQs)

@ 10PeV

○ γp optical depth ~ 0.1

△ Proton emission energy budget

$O(10\%) \times L_{CR}^{10PeV} \sim 10^{45}$ erg/Mpc^3 yr

@EeV=1000PeV

if emitted proton spectrum extends further to this energy
(this is *probably* easy to achieve)

× γp optical depth ~ 1

○ Proton emission energy budget

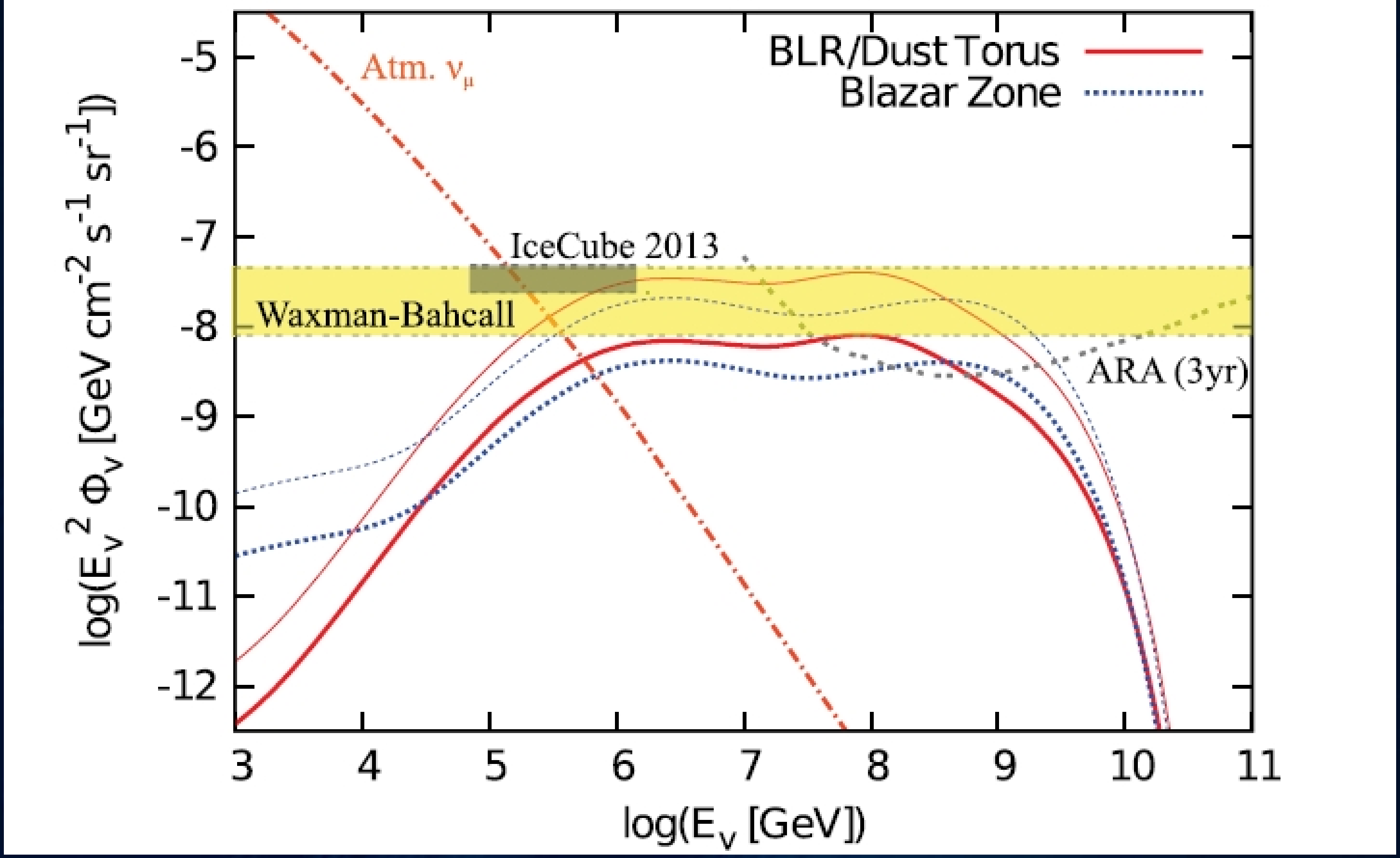
$\sim L_{CR}^{1EeV} \sim 10^{44}$ erg/Mpc^3 yr

◎ $L_\gamma > 10^{45}$ erg/s

An example of $\gamma p \rightarrow \nu$ models

ν emission from Blazars (FSRQs)

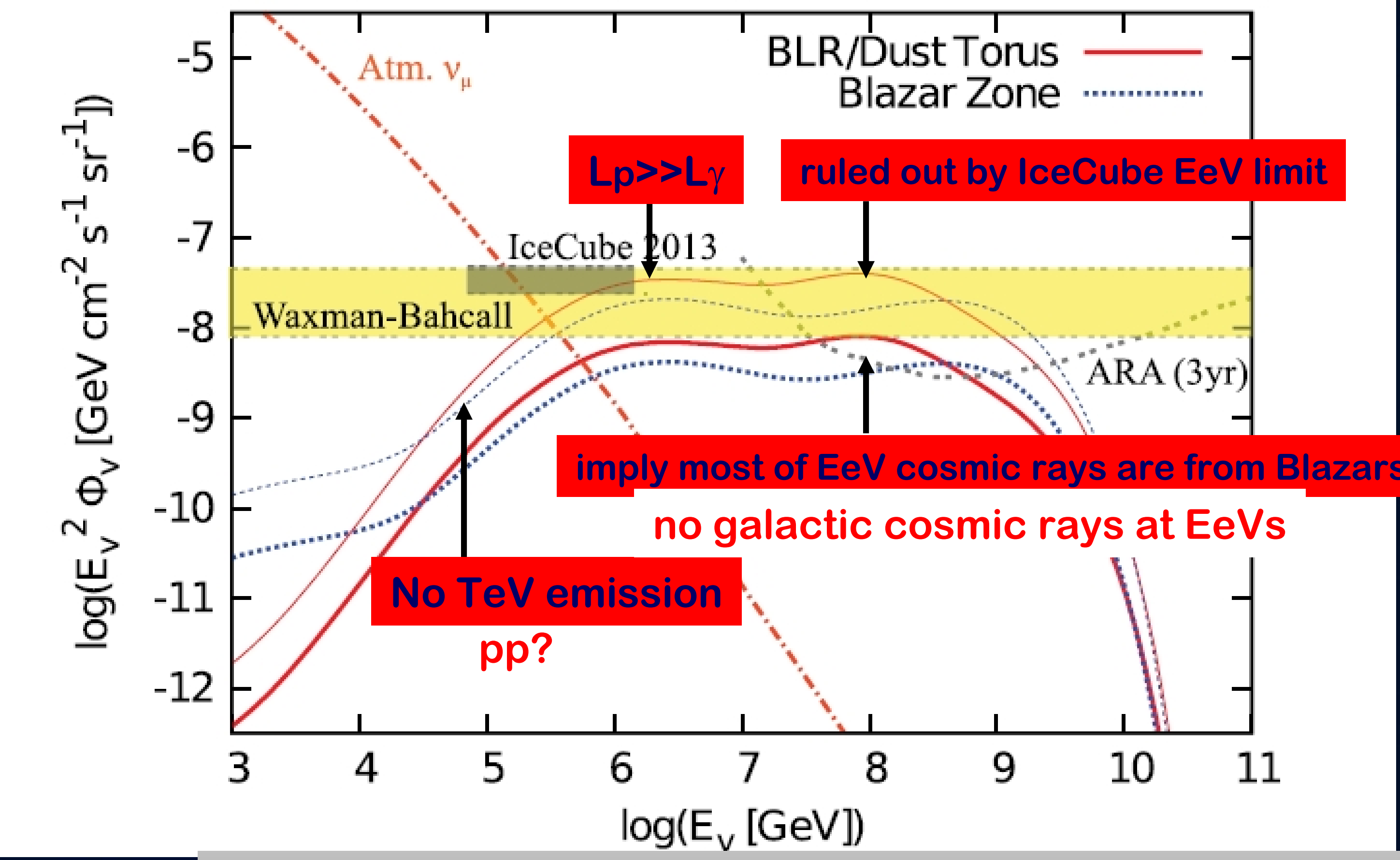
Murase, Inoue, Dermer, PRD 2014



An example of γp→ν models

ν emission from Blazars (FSRQs)

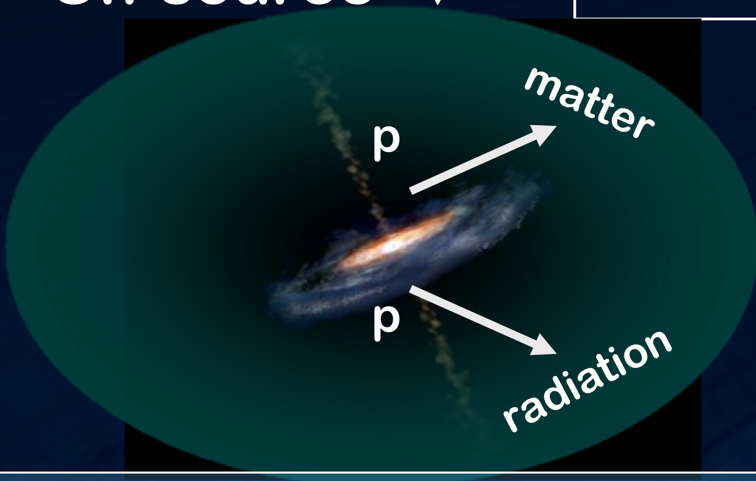
Murase, Inoue, Dermer, PRD 2014



Not naturally explain the IceCube observations

The Cosmic Neutrinos Production Mechanisms

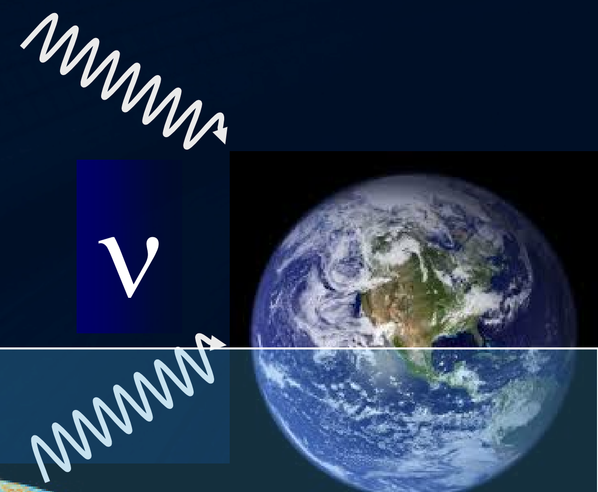
“On-source” ν TeV - PeV



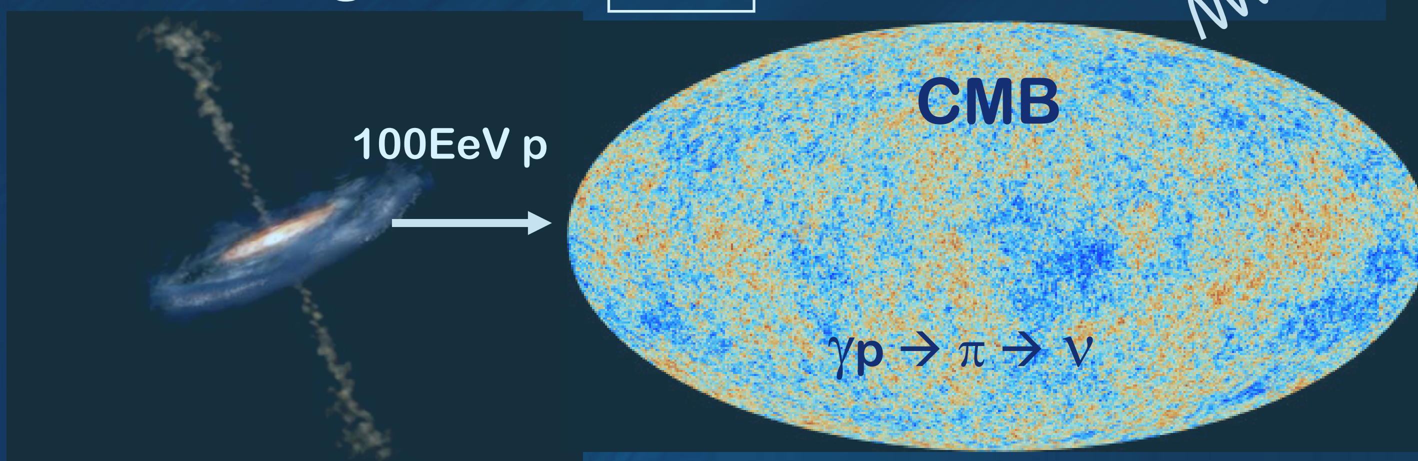
$pp \rightarrow \pi \rightarrow \nu$

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

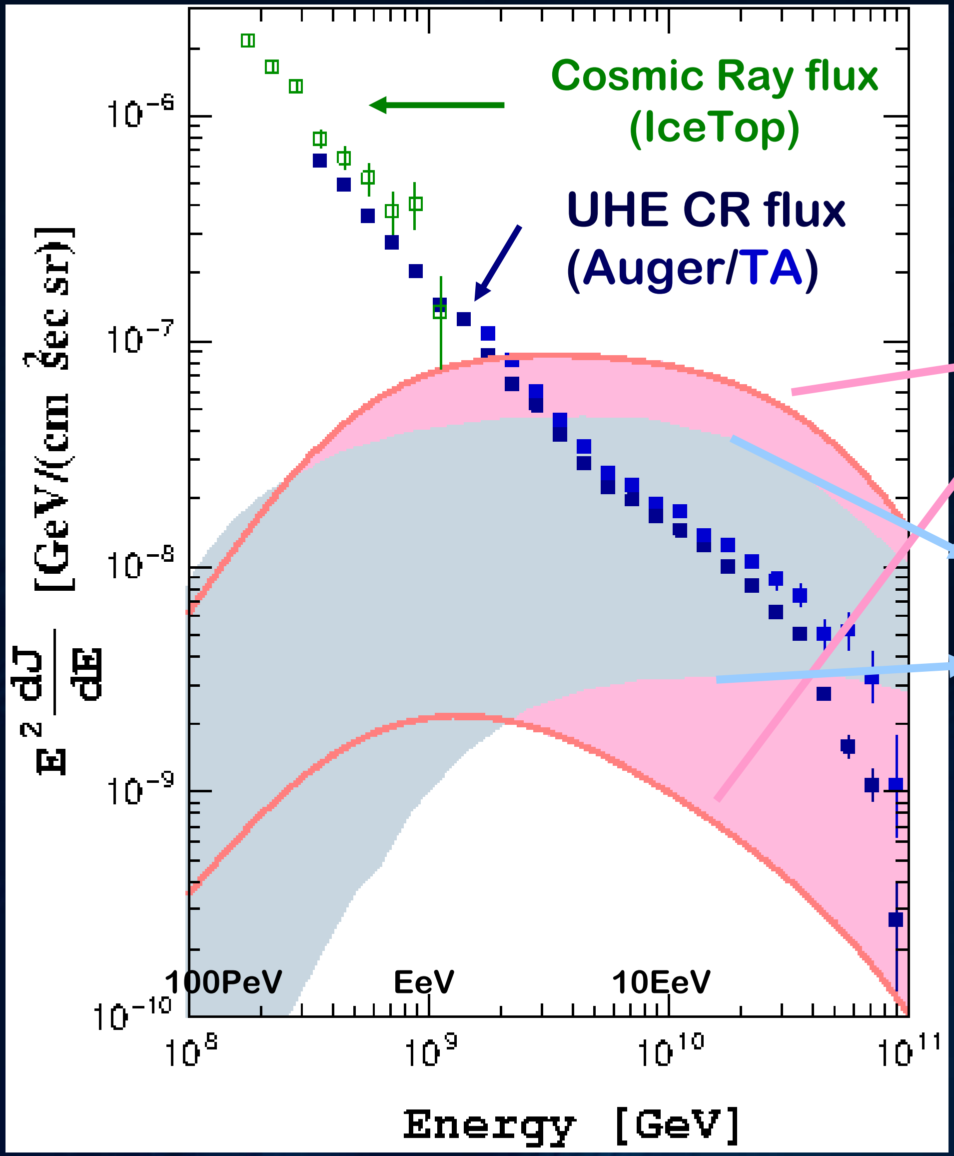
photopion production



“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?

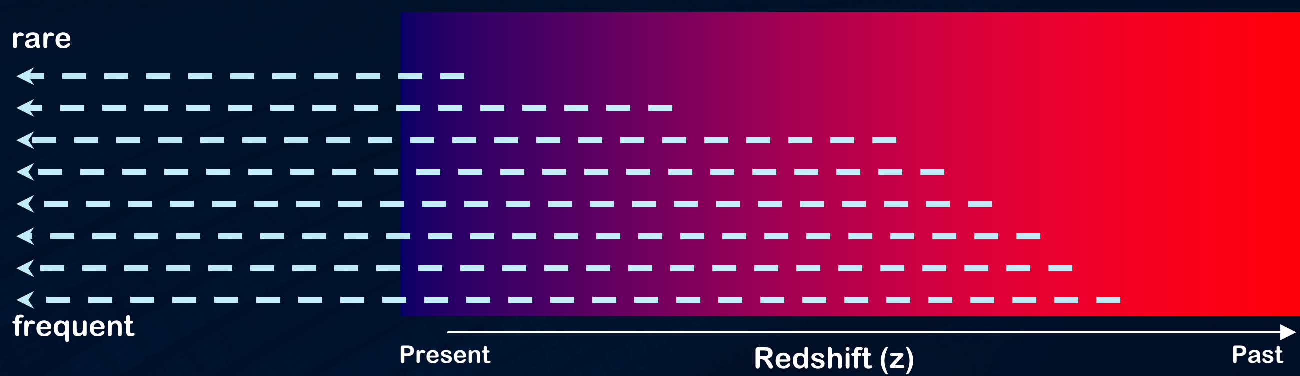
Tracing *history* of the particle emissions with ν flux

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

ν

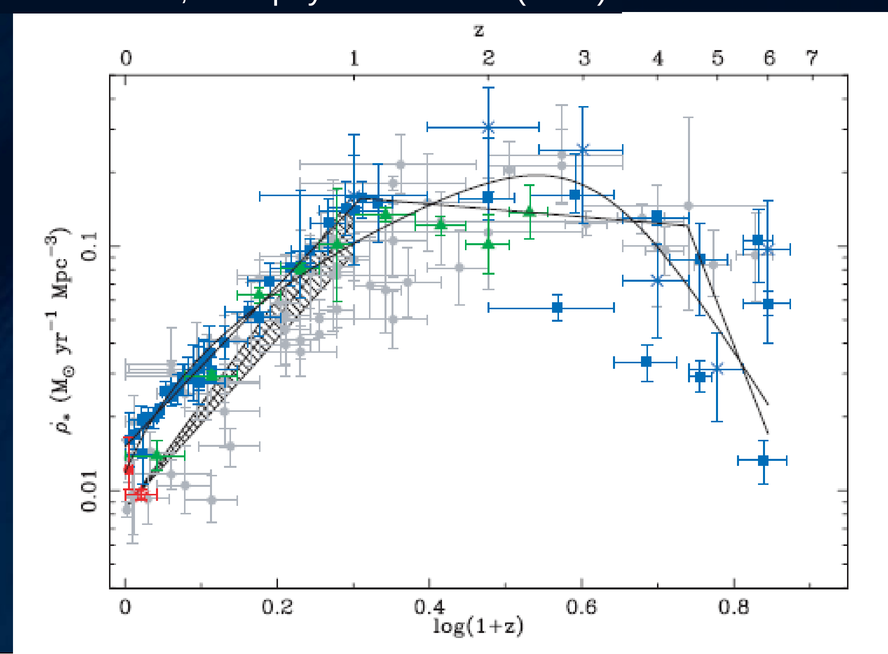


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→

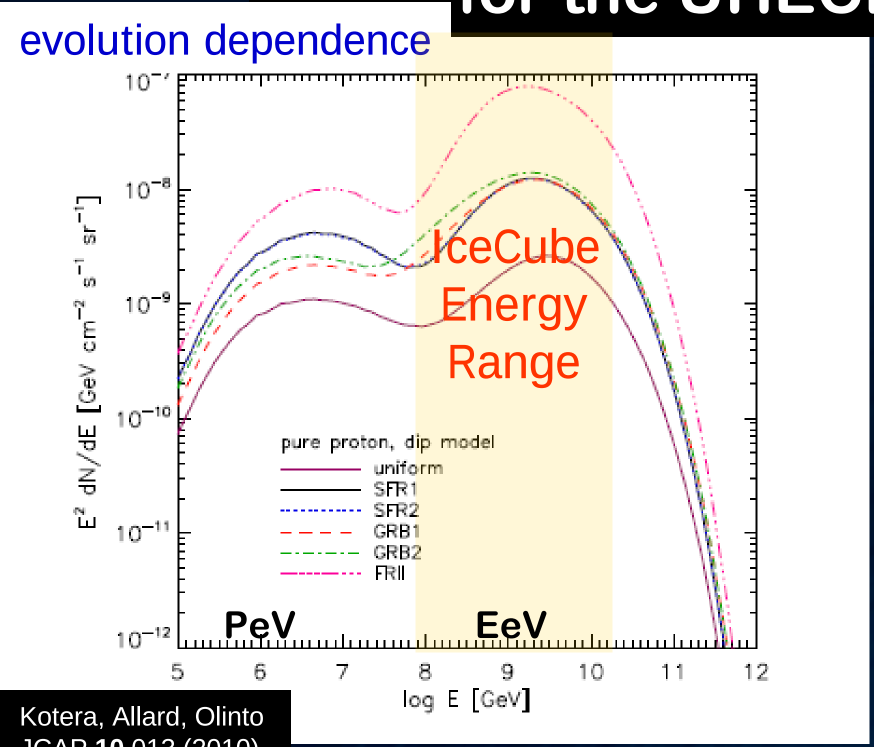


The spectral emission rate

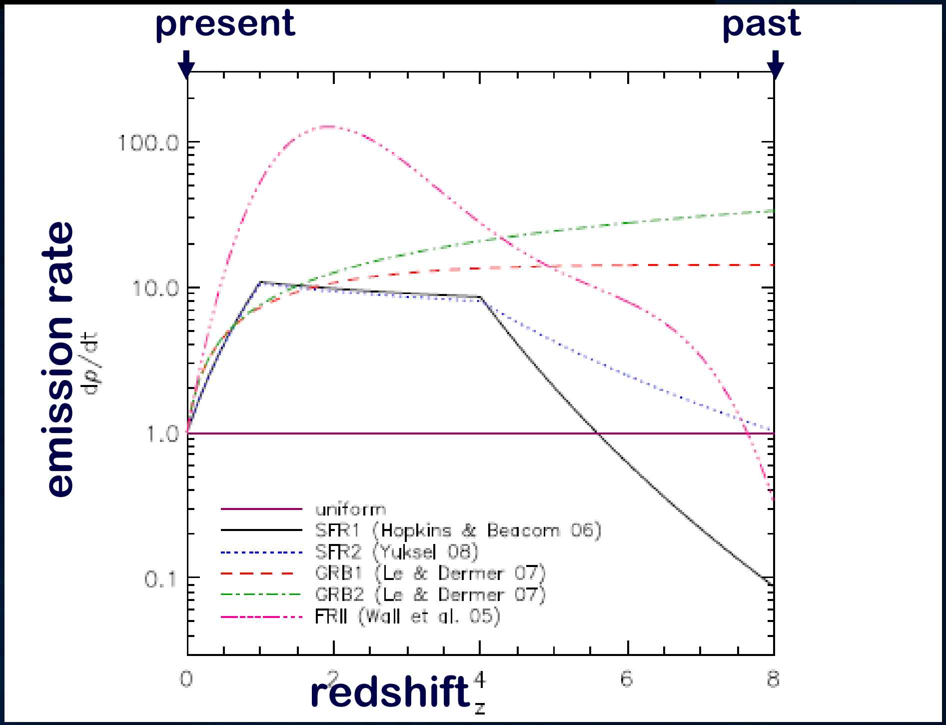
$$\rho(z) \sim (1+z)^m$$

m= 0 : No evolution

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



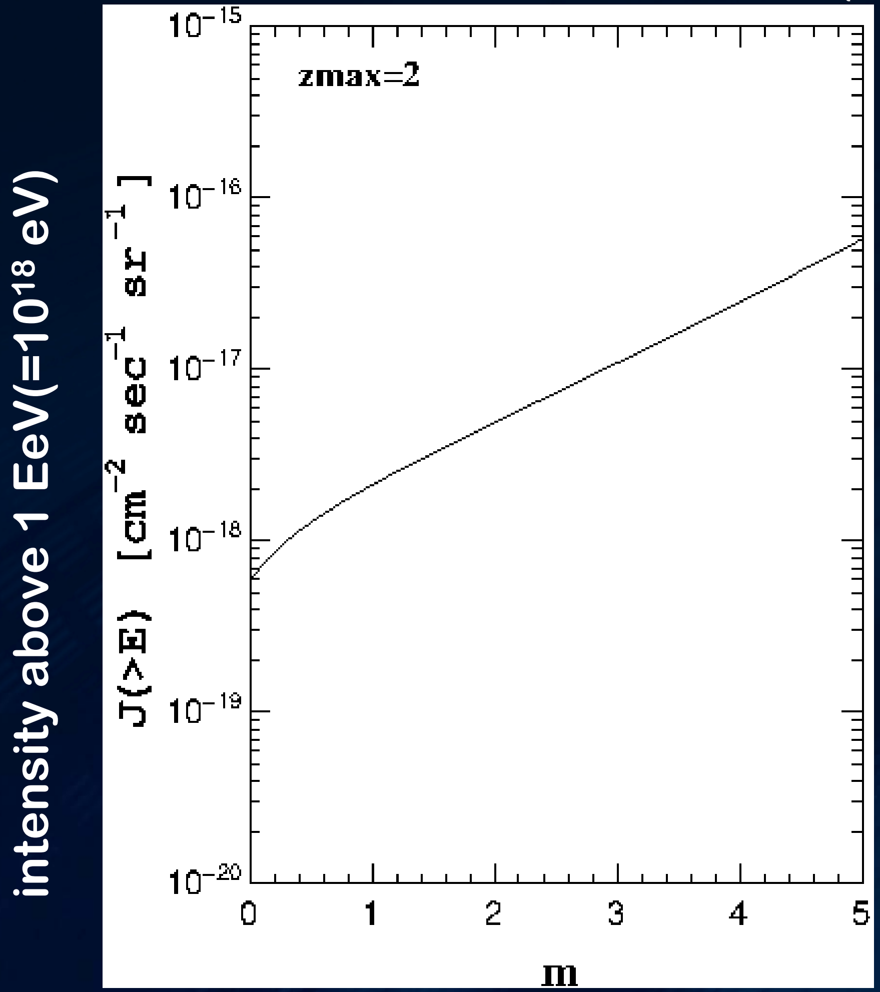
Kotera, Allard, Olinto
JCAP **10** 013 (2010)



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)



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 <u>85</u>, 063002 (2012)

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

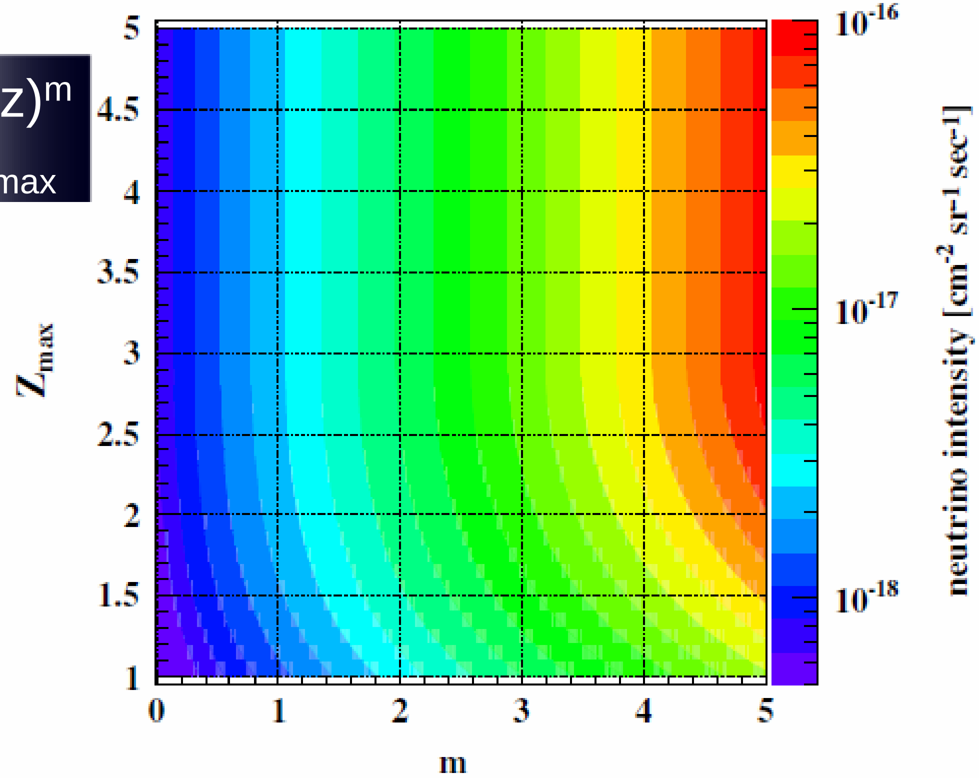


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

x IceCube Exposure

Number of events we should have detected

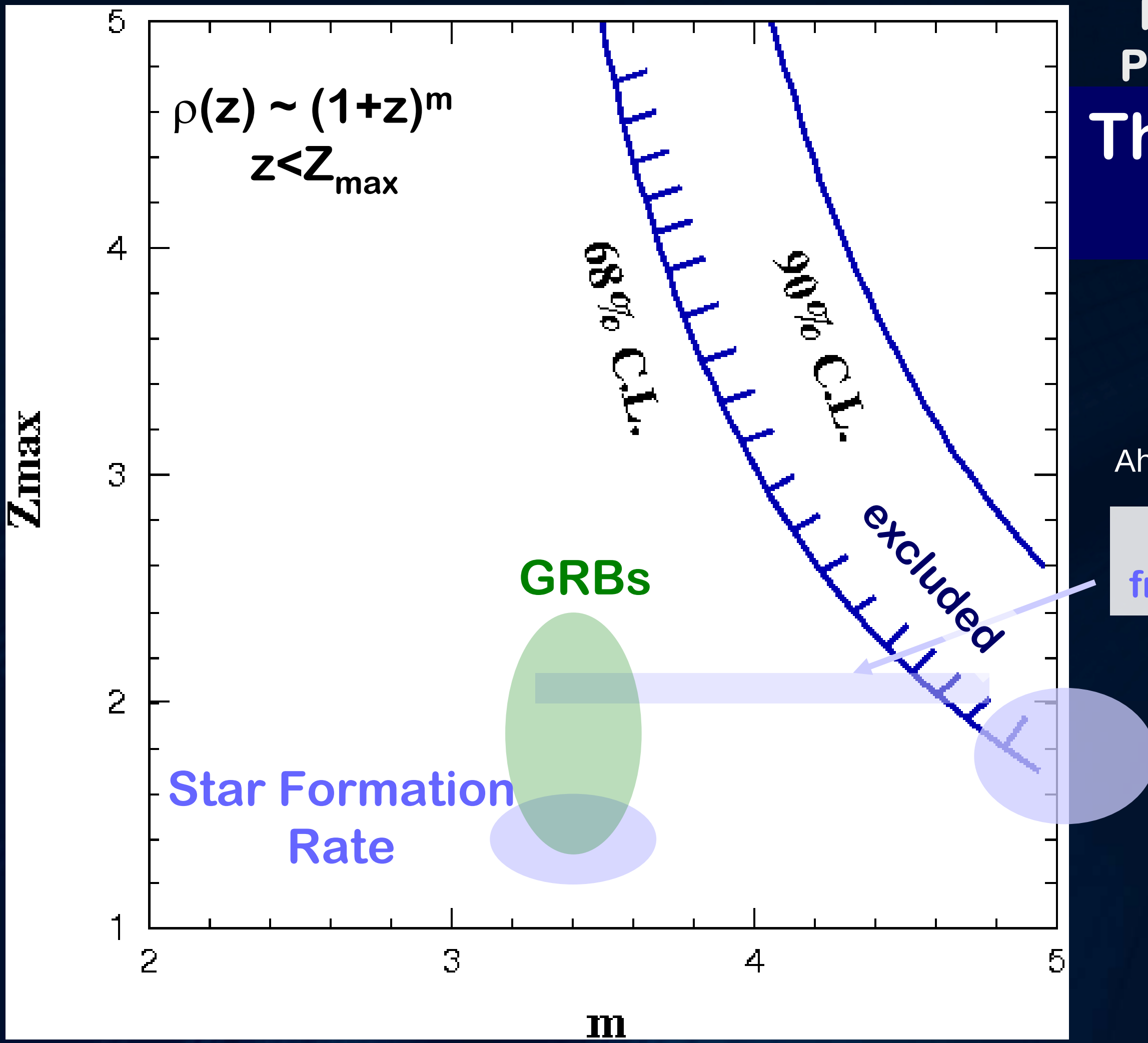
↕

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

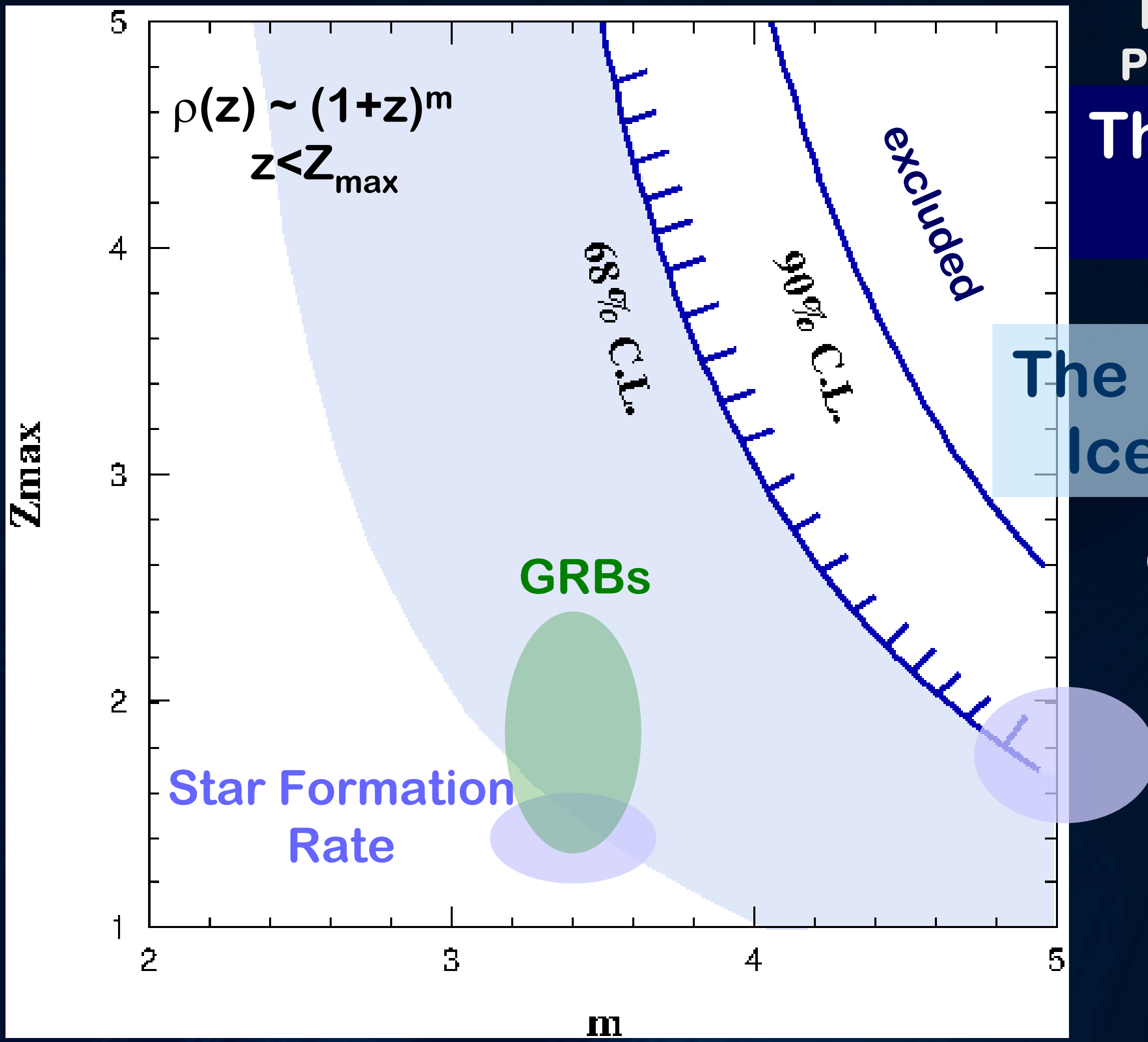


Ahlers et al, Astropart.Phys. **34** 106 (2010)

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

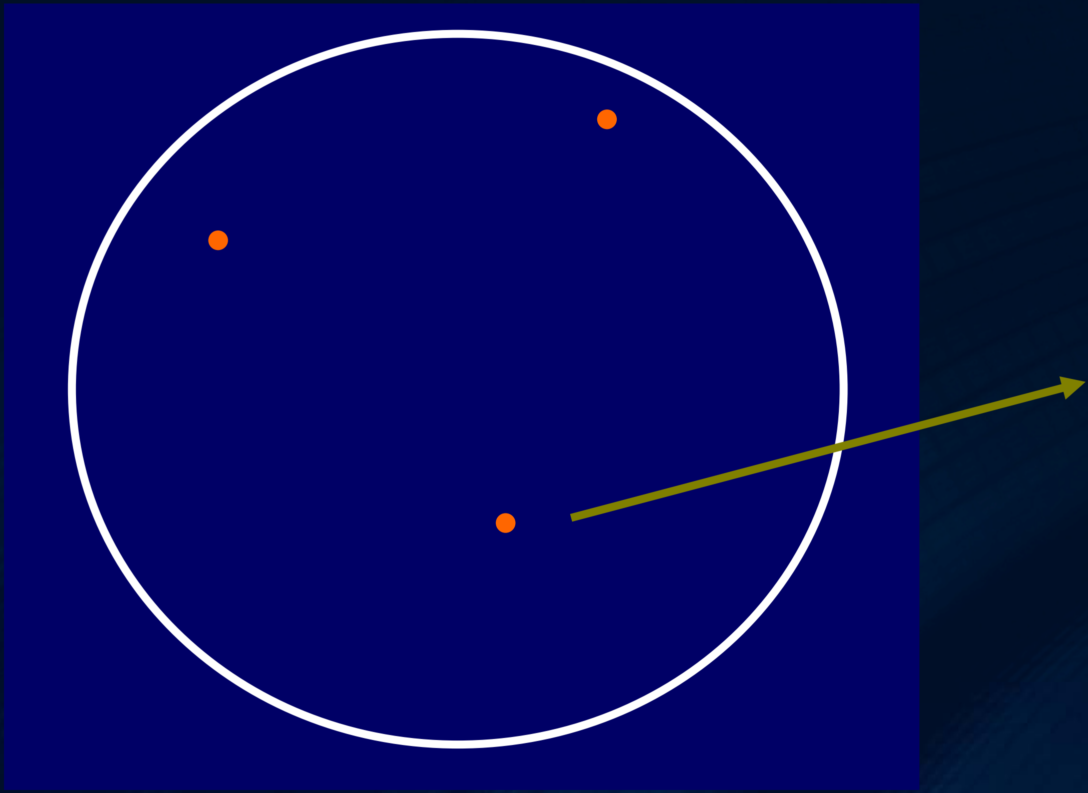
The solid bound by the GZK ν

The region scanned by IceCube 2008-2014

coming soon!

AGNs with radio-loud jets

The Multi Messengers:
UHE ν → γ (or any other messengers)



look up this direction!

ν "GFU" γ

TeV PeV EeV

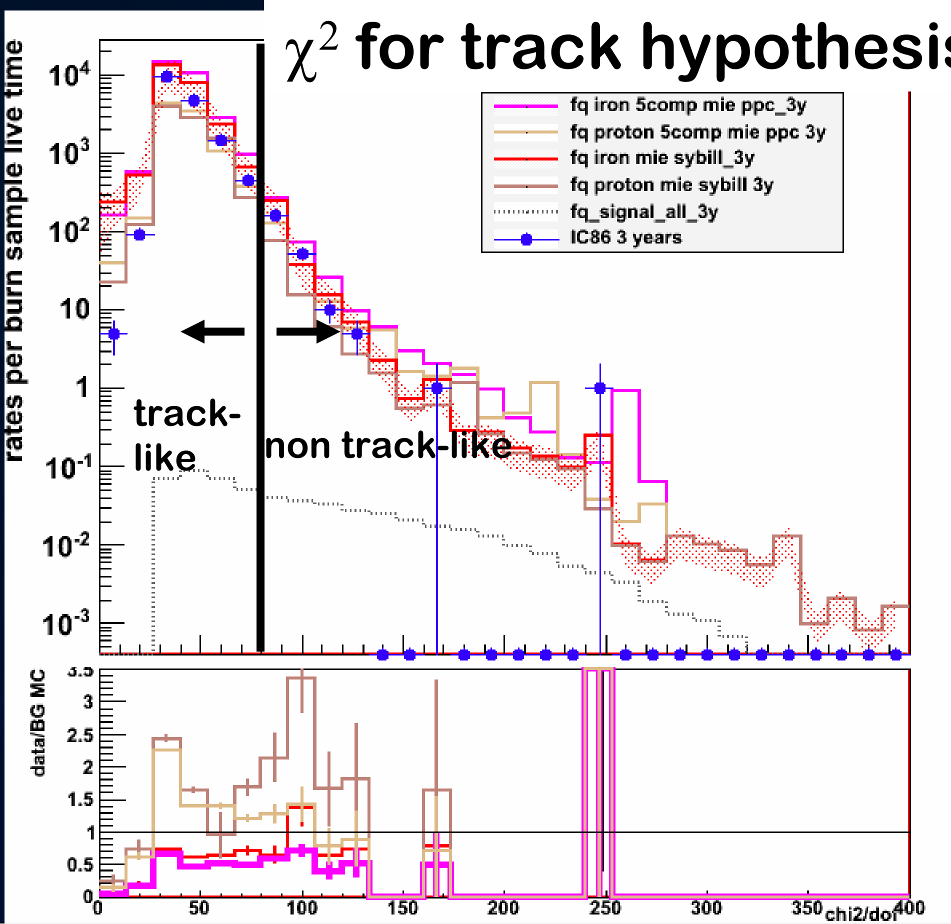
UHE (PeV-EeV)

Online Analysis for γ-ray/optical follow-up

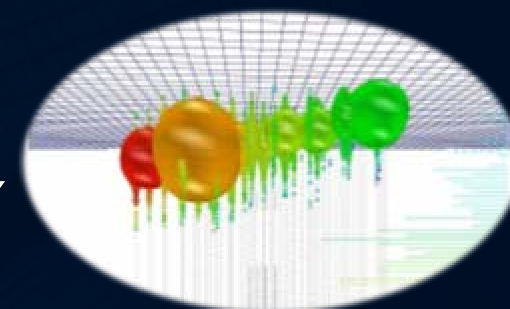
new

event topology separation

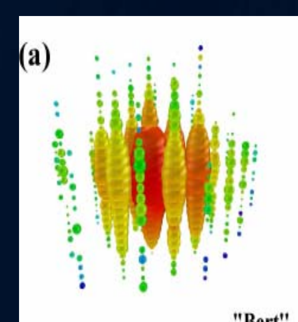
χ^2 for track hypothesis



track



cascade (non track-like)

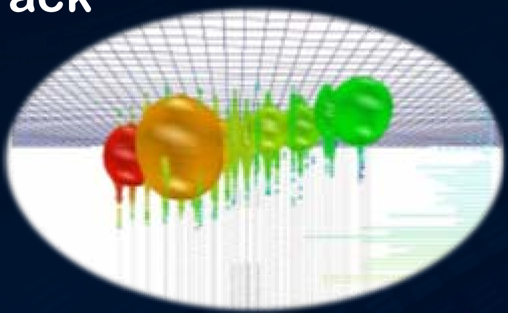


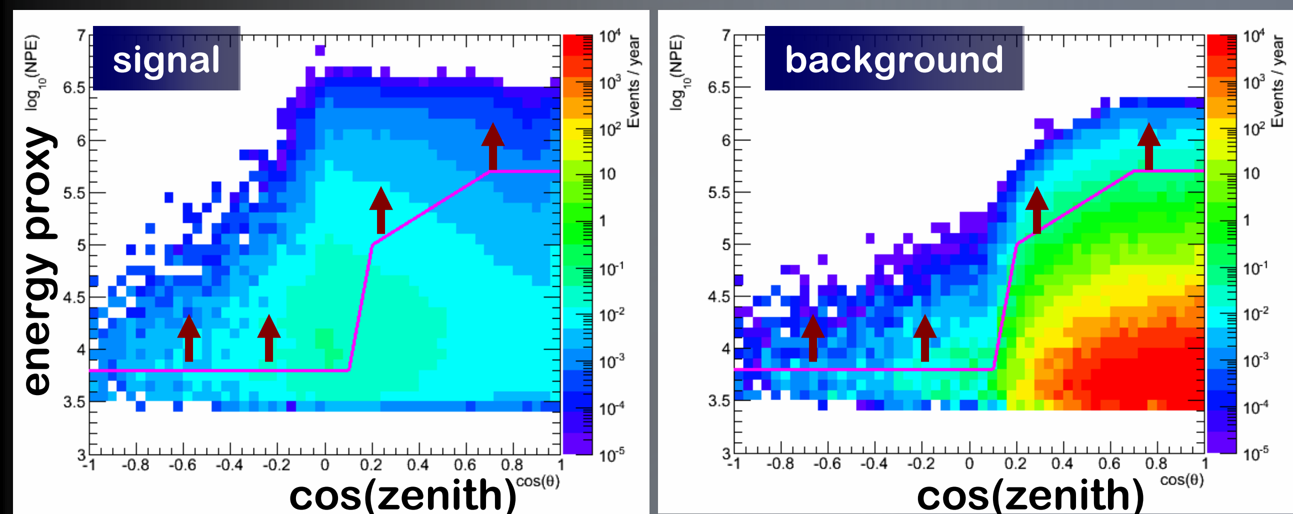
TeV PeV EeV

UHE (PeV-EeV)

Online Analysis for γ-ray/optical follow-up

track





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

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

GZK: ~ 0.3-0.9 event/year

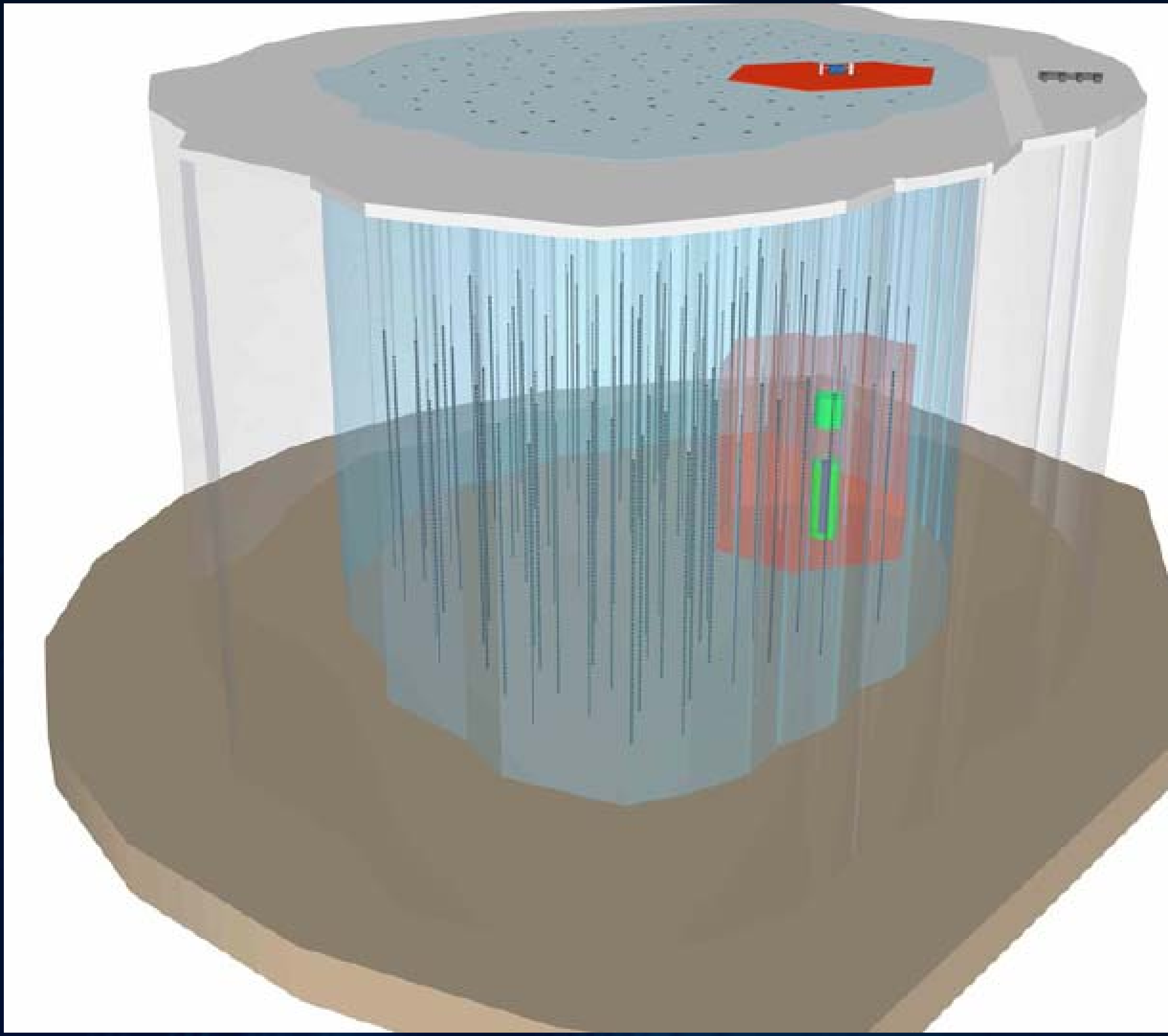
BG: ~ 2-3 event/year

We will send you:

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

$\Delta\theta$~0.3 deg

Next Generation: IceCube HEX

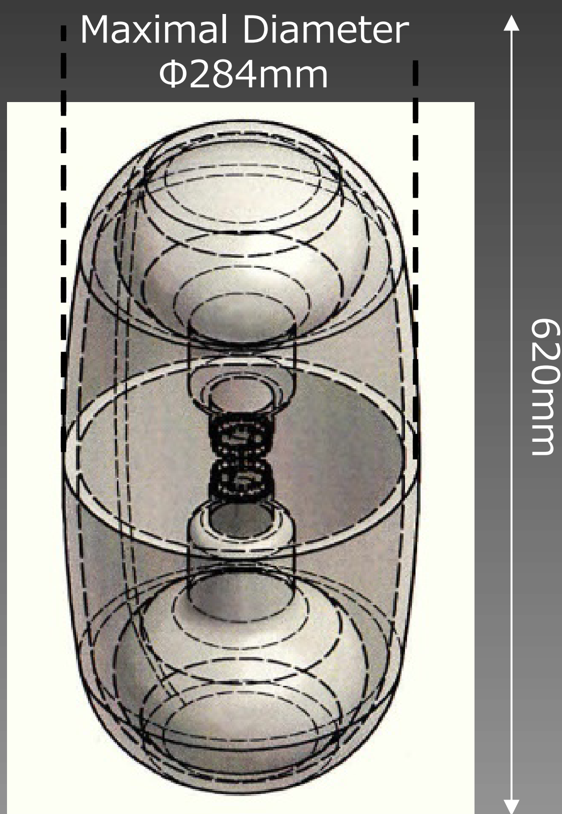


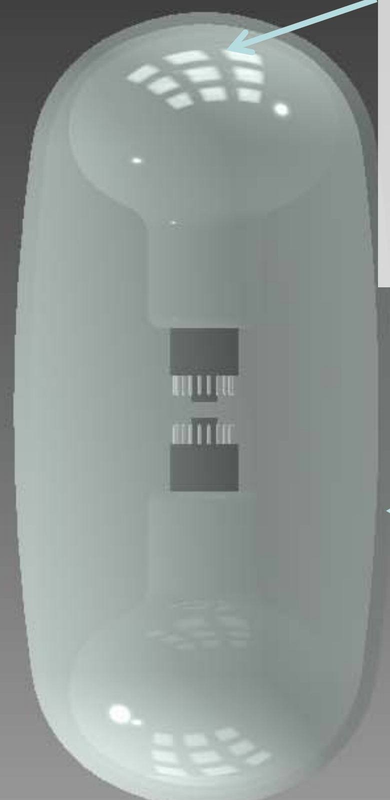
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

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**



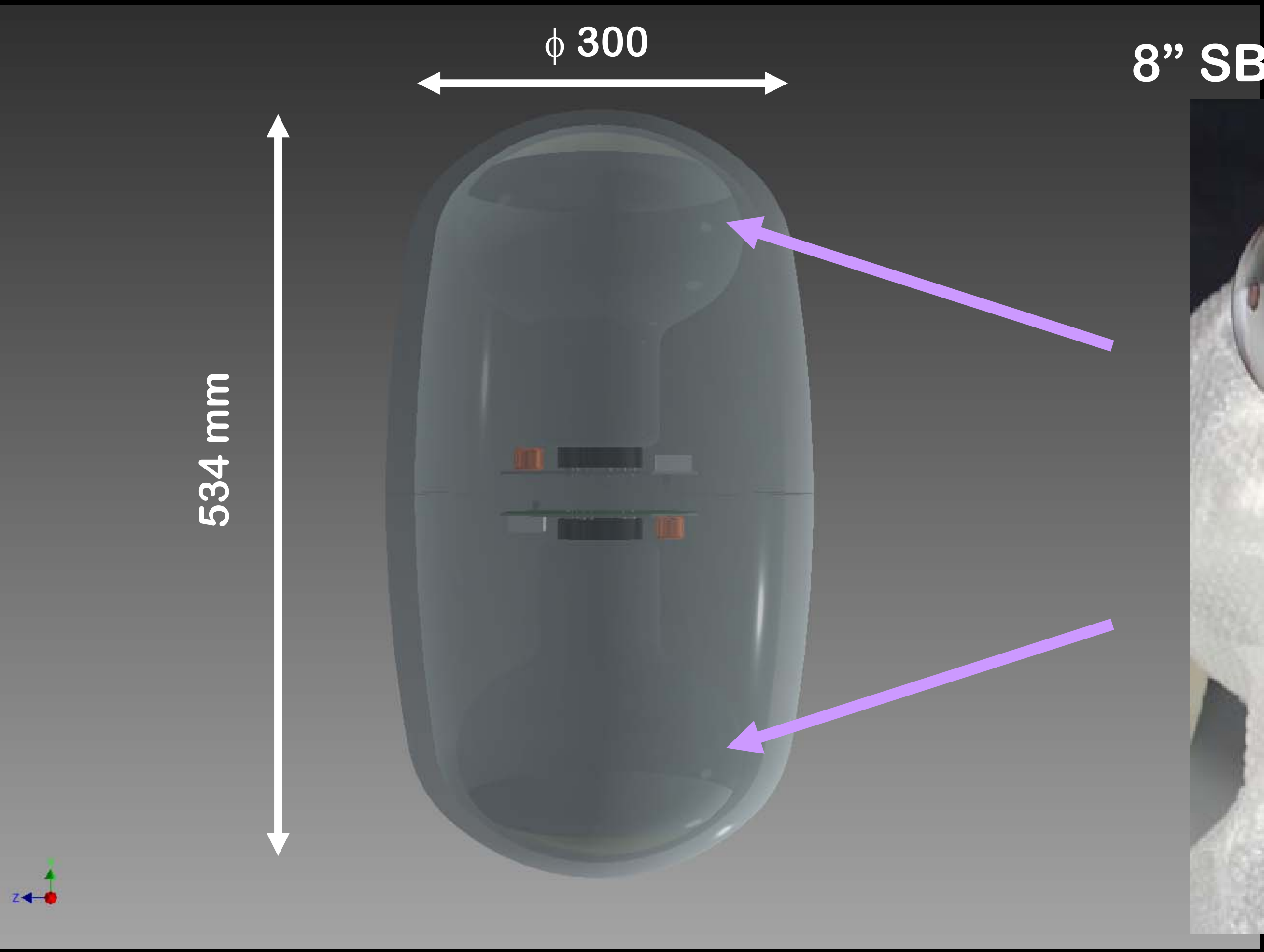


customized glass shape/curvature
- **designed best match curvature to our PMT**
- **less thickness top/bottom part (9mm-10mm where PMT cceptance) for better light transmittance**

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

Two-PMT Optical Module

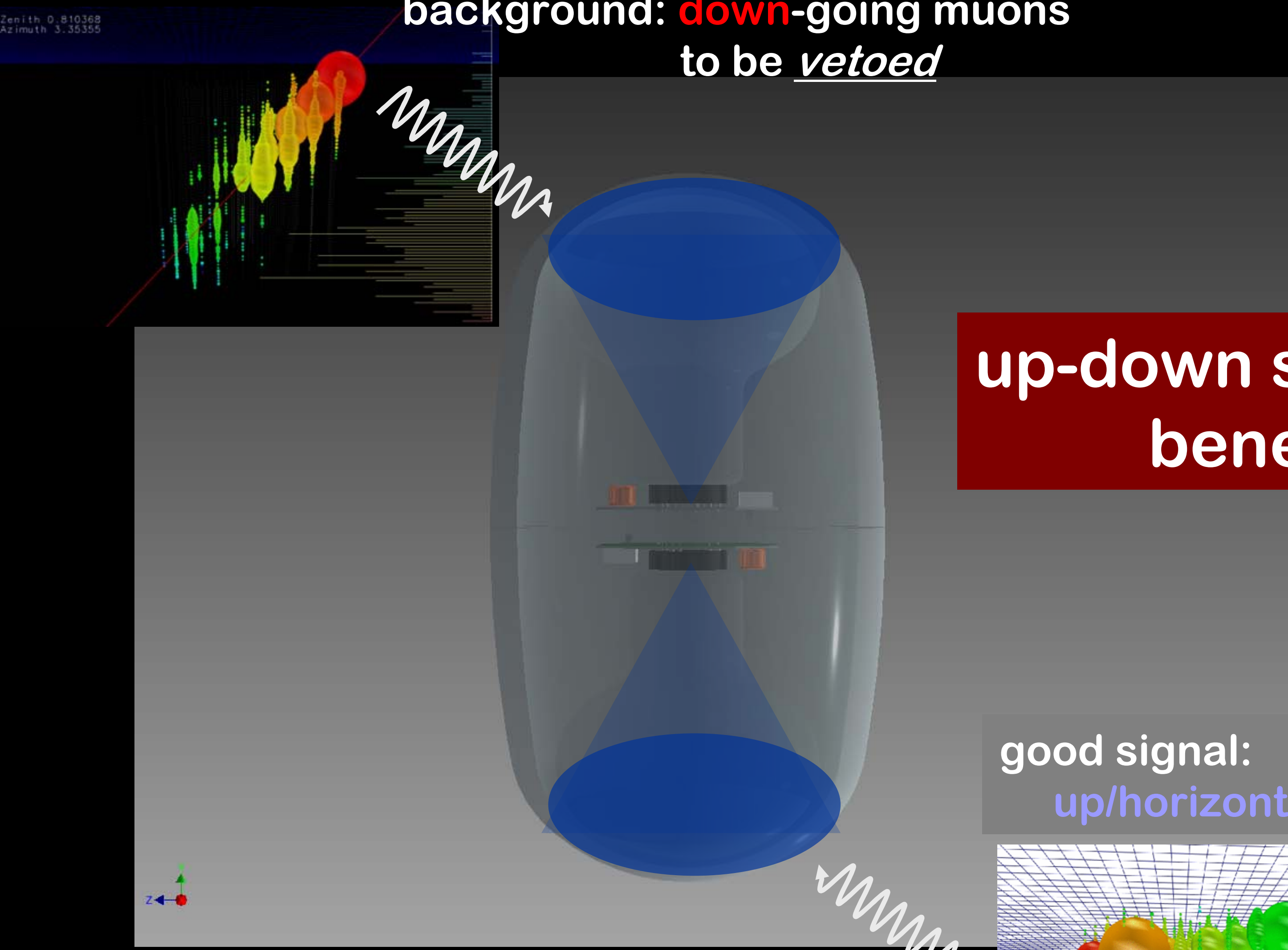
A baseline design



8” SBA PMT R5912-100

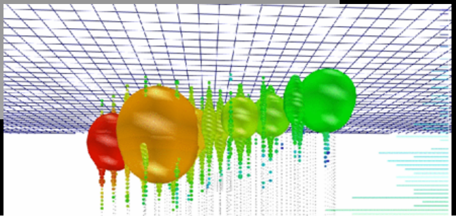
Two-PMT Optical Module

background: down-going muons
to be *vetoed*



up-down symmetry is beneficial.

good signal:
up/horizontally-going track



Next Generation: IceCube HEX

Photo-detector development

8' high-QE PMT

Silicon gel

Glass + PMT assembly

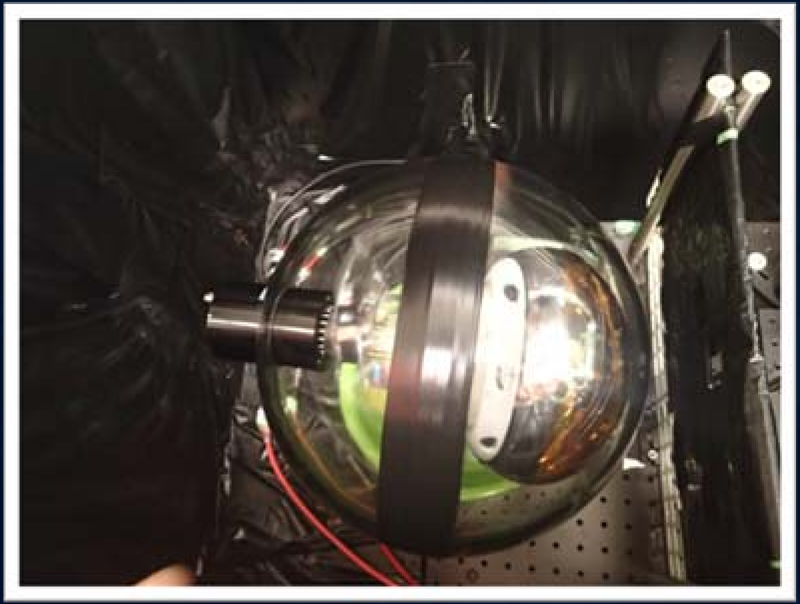
Lovely ball

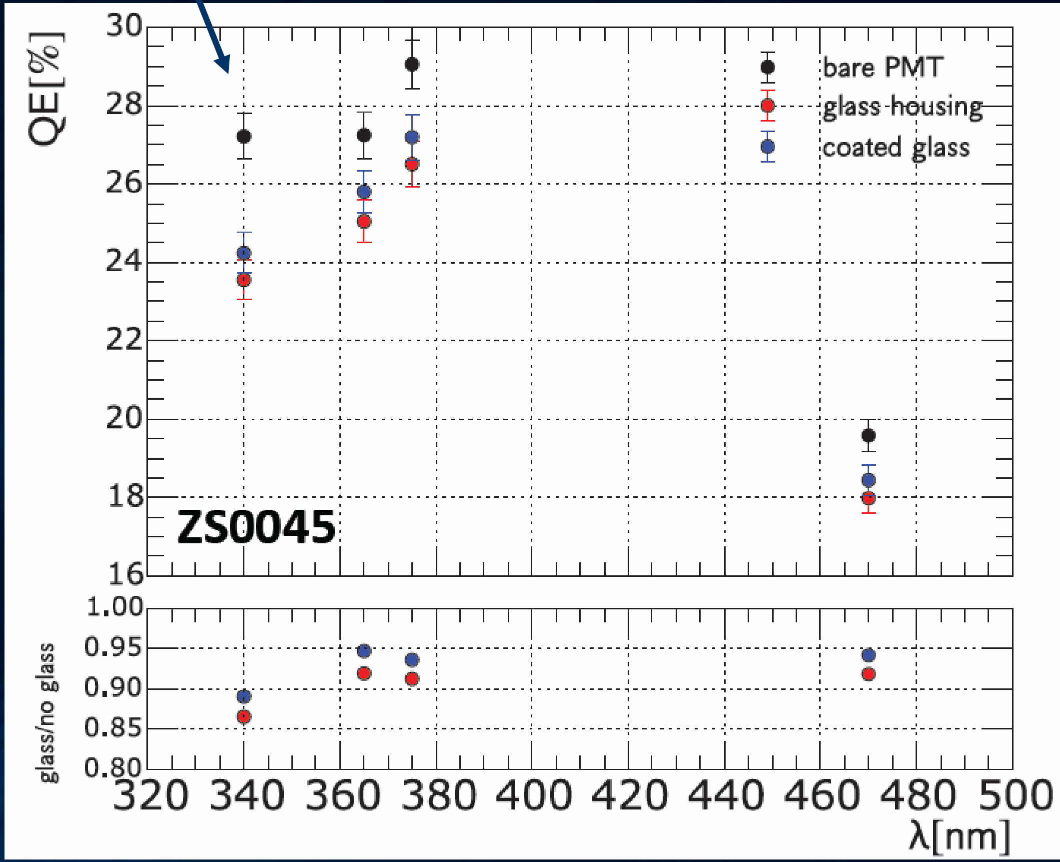
Next Generation: IceCube HEX

Photo-detector development

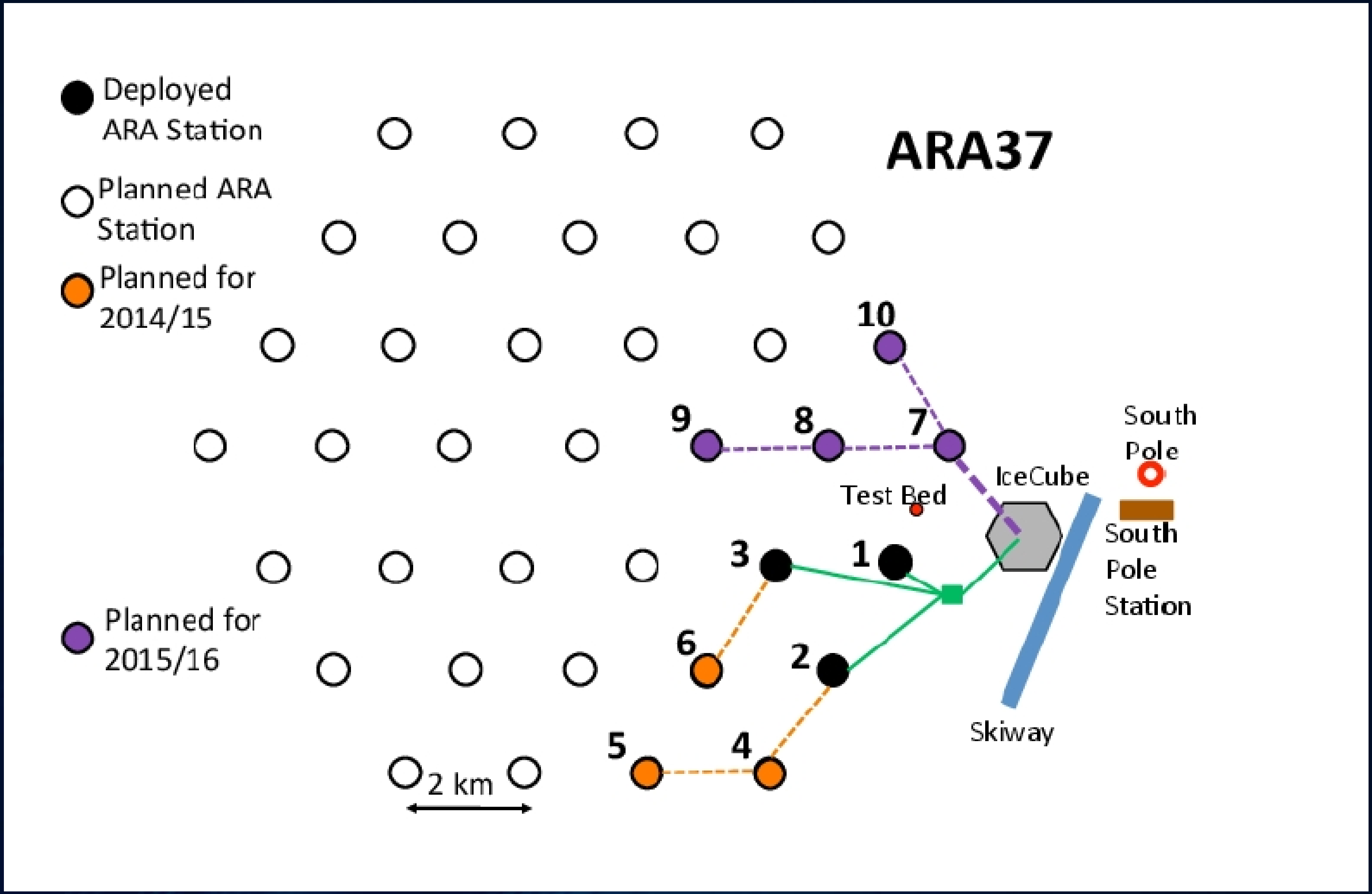
QE@340nm

7% (present icecube) → 24%



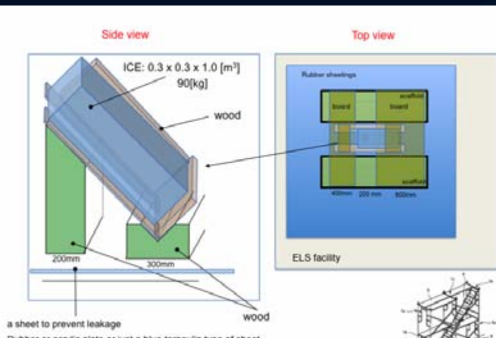


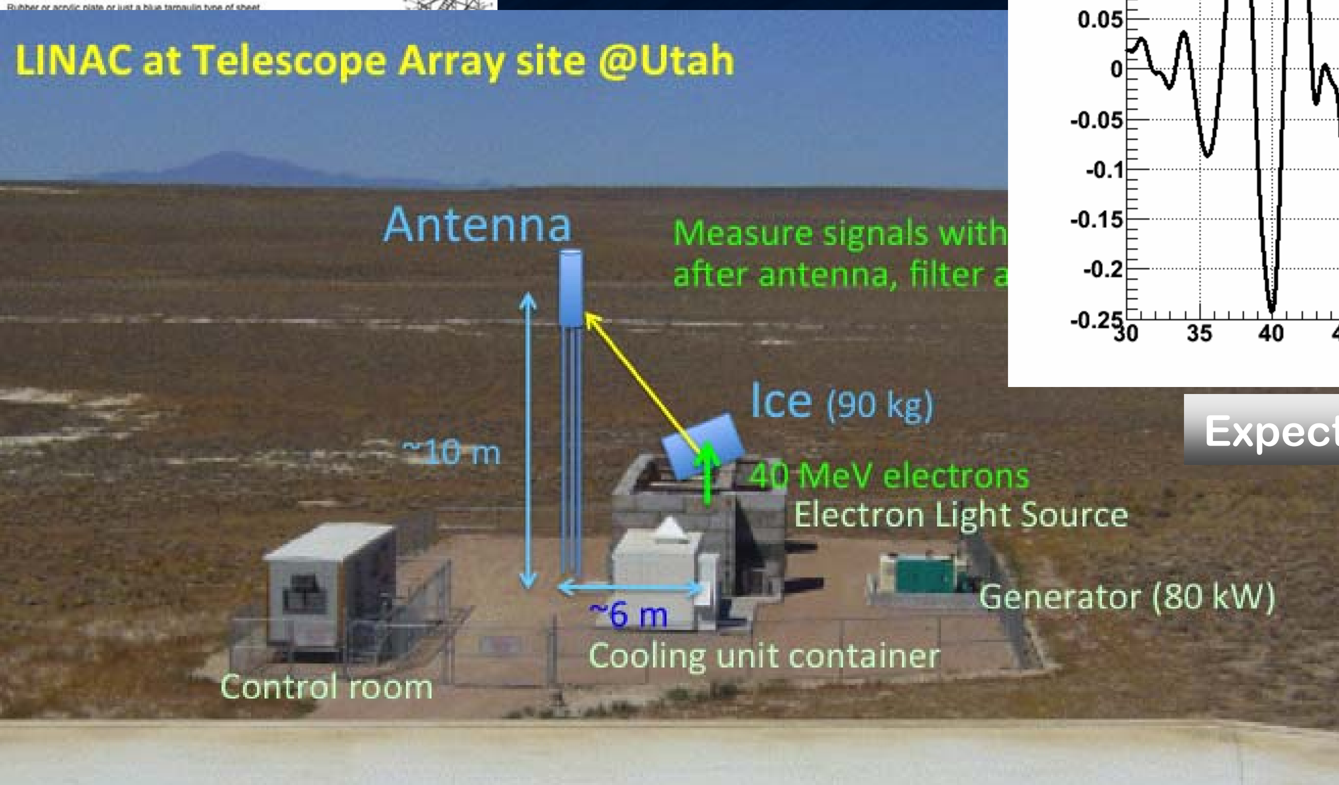
Next Generation: ARA

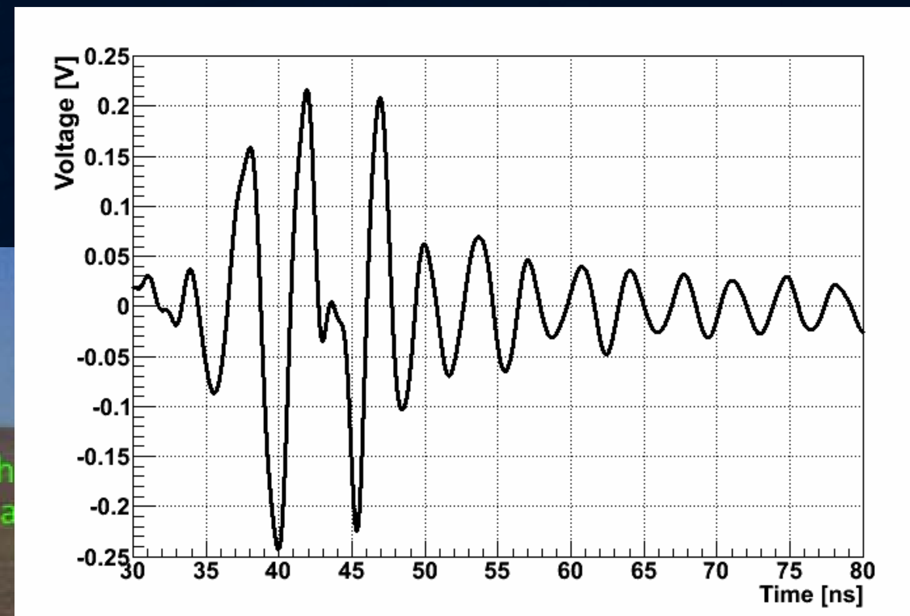


Next Generation: ARA

"end-to-end" calibration







Expected signals from ice

Executive Summary

ν = THE smoking gun