ISAPP Summer School
Part 3

Carsten Rott (SKKU)

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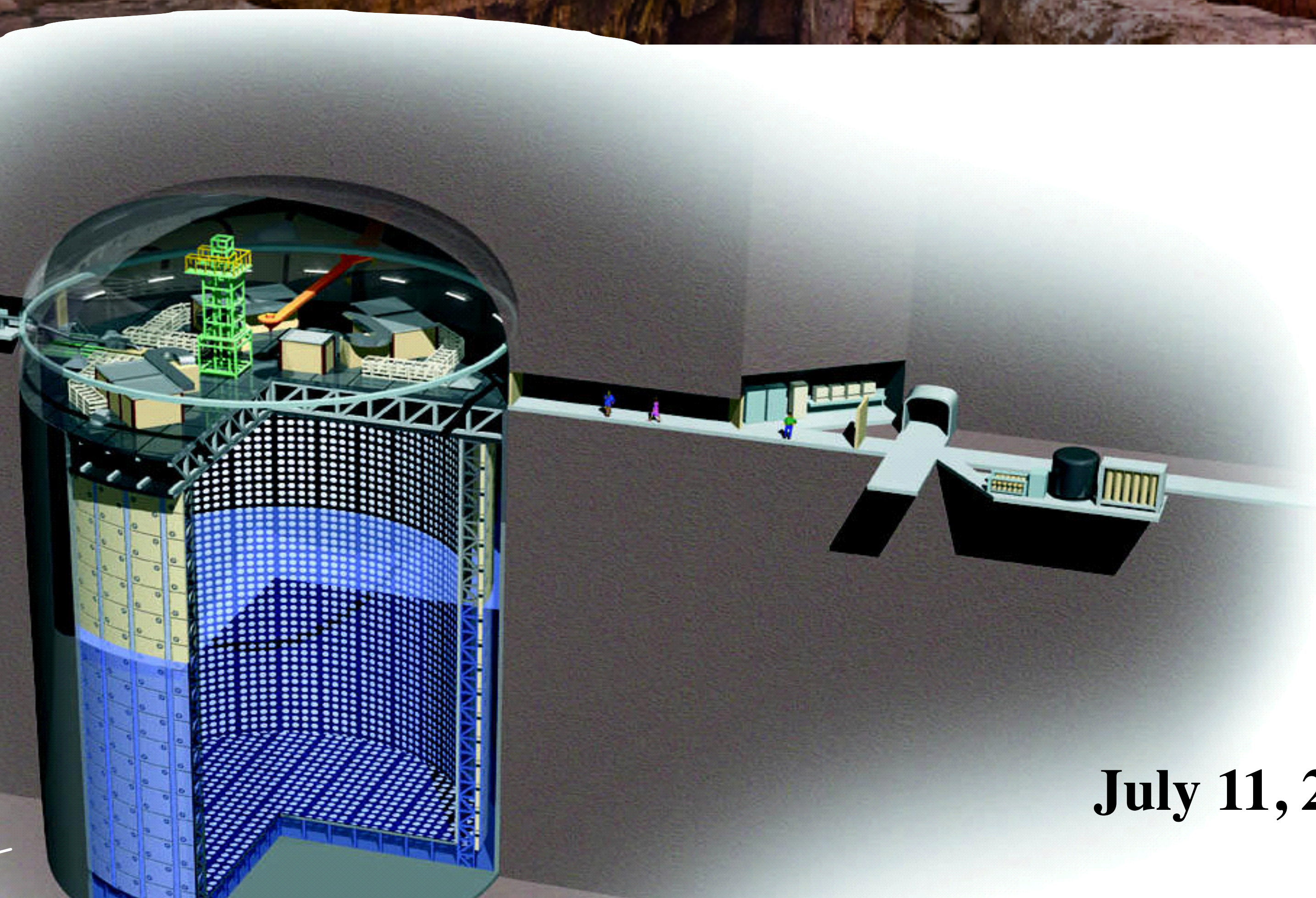
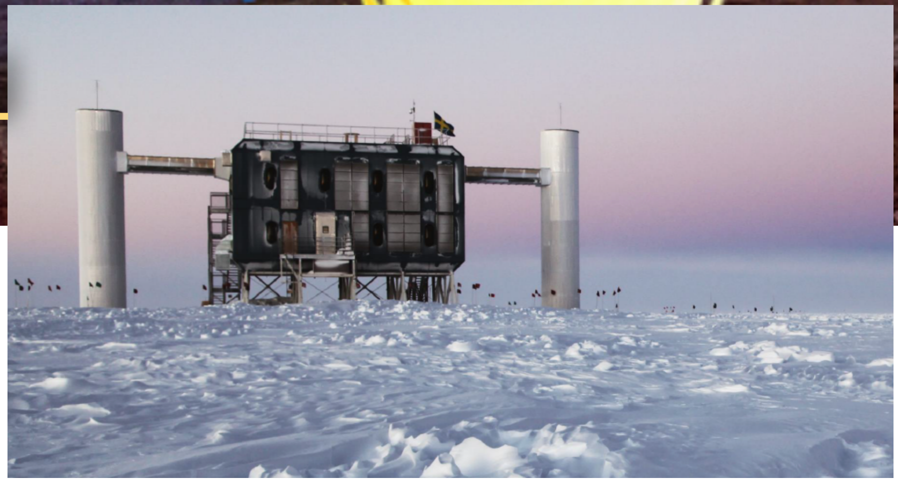
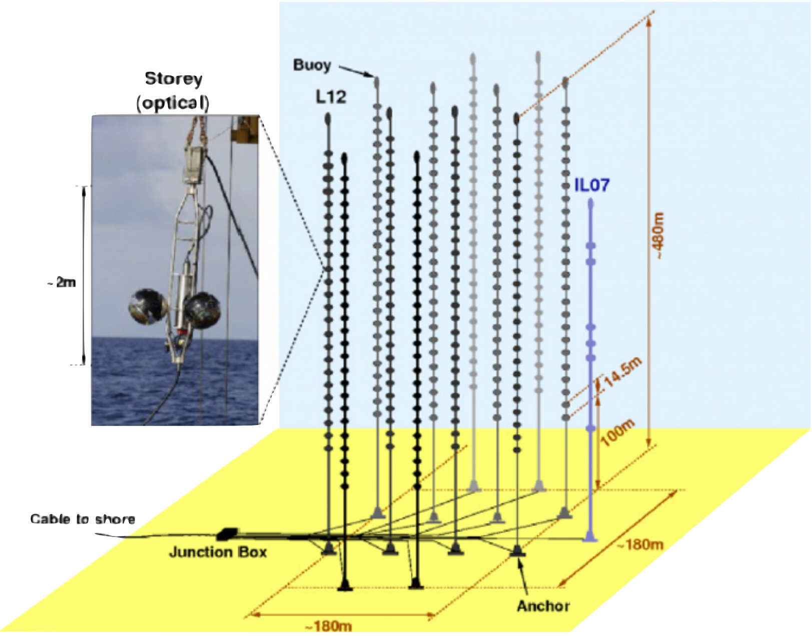






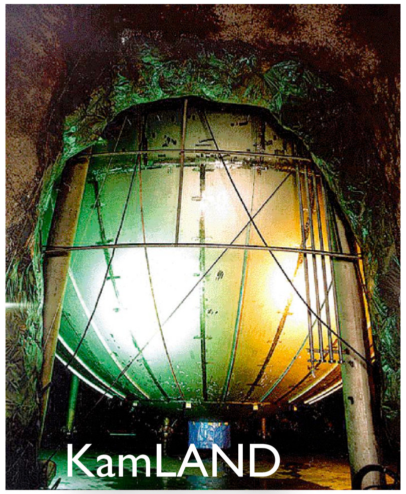
July 11, 2018

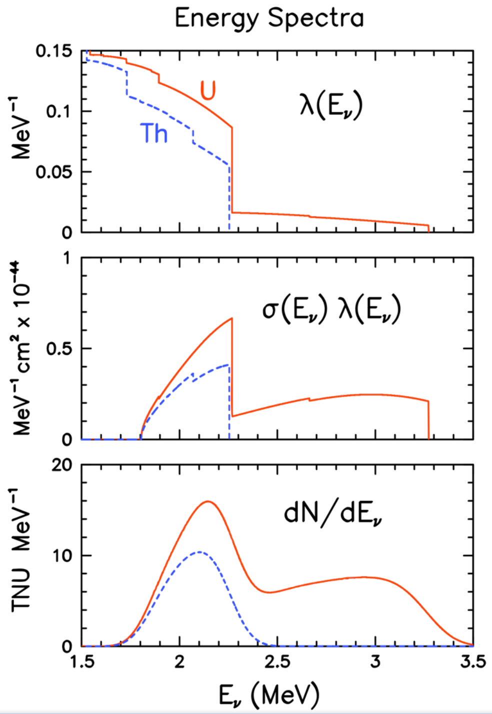
Motivation (Particle Physics ⇒ Earth Science)

- What can neutrino detectors do for Solid Earth Science ?
  - **Muon Radiography**
    - Atm. airshower muon absorption
  - **Geo-neutrinos**
    - Low-energy neutrino detection from nuclear decays
  - **Neutrino absorption tomography**
    - Atm. air shower high-energy neutrino absorption
  - **Neutrino oscillation tomography**
    - Atm. air shower neutrino oscillations

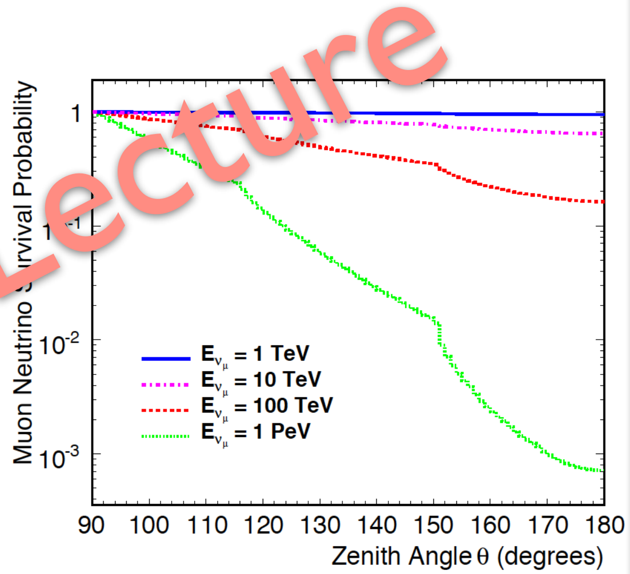
Geo-neutrinos

U and Th geo-ν

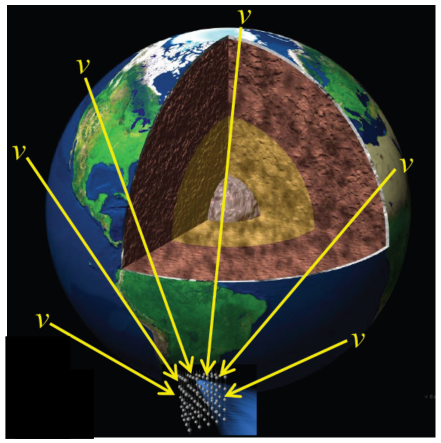


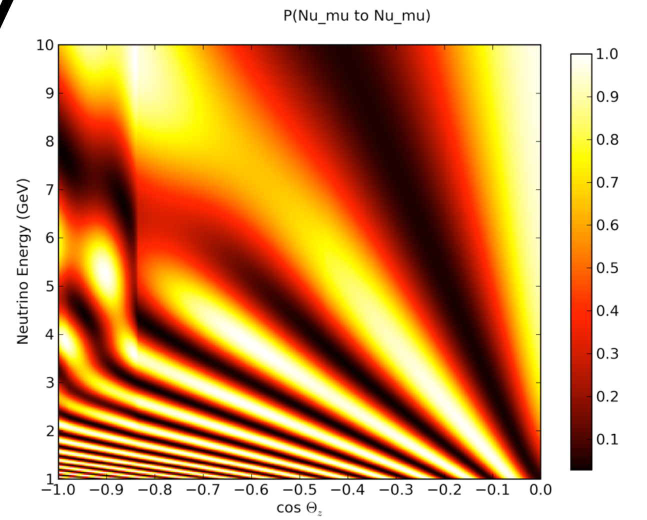


Neutrino absorption tomography



Neutrino oscillation tomography

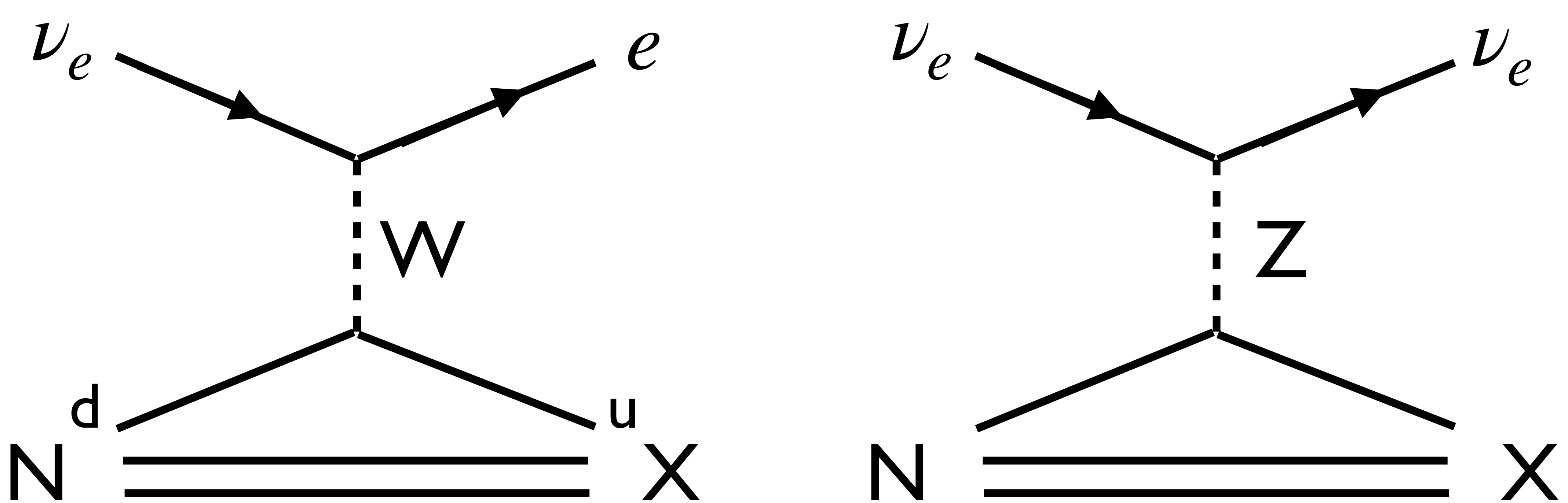




Neutrino Cross sections

Neutrino Cross Sections

- Neutrinos interact via the weak interaction (W,Z-Boson)
- Above ~1GeV Neutrinos interact via the deep inelastic scattering (DIS)
  - Charged-current (CC) $(\nu_l, \bar{\nu}_l)N \rightarrow (l^-, l^+) + X$
  - Neutral current (NC) $(\nu_l, \bar{\nu}_l)N \rightarrow (\nu_l, \bar{\nu}_l) + X$



Neutrino Cross Section

Assuming the interaction $\nu_\mu N \to \mu^- + \text{anything}$,

Differential cross section

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 [xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2]$$

Quark distribution functions
(including valence and sea quarks)

$-Q^2$ - invariant momentum transfer between the incident neutrino and outgoing muon
G_F - Fermi Constant $G_F = 1.16632\ 10^{-5}$ GeV^{-2}

Bjorken scaling variables

$x = Q^2/2M\nu$ $\qquad$ $y = \nu/E_\nu$

with

$\nu = E_\nu - E_\mu$ in the lab (target) frame

Neutrino Cross Section

Charged-current

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 [\underline{xq(x,Q^2)} + x\underline{\bar{q}(x,Q^2)}(1-y)^2]$$

Quark distribution functions
(including valence and sea quarks)

Neutral current

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M E_\nu}{2\pi}\left(\frac{M_Z^2}{Q^2+M_Z^2}\right)^2 [xq^0(x,Q^2) + x\bar{q}^0(x,Q^2)(1-y)^2]$$

Parton distribution functions
(including valence and sea quarks)
(including chiral coupling)

Neutrino Cross Sections

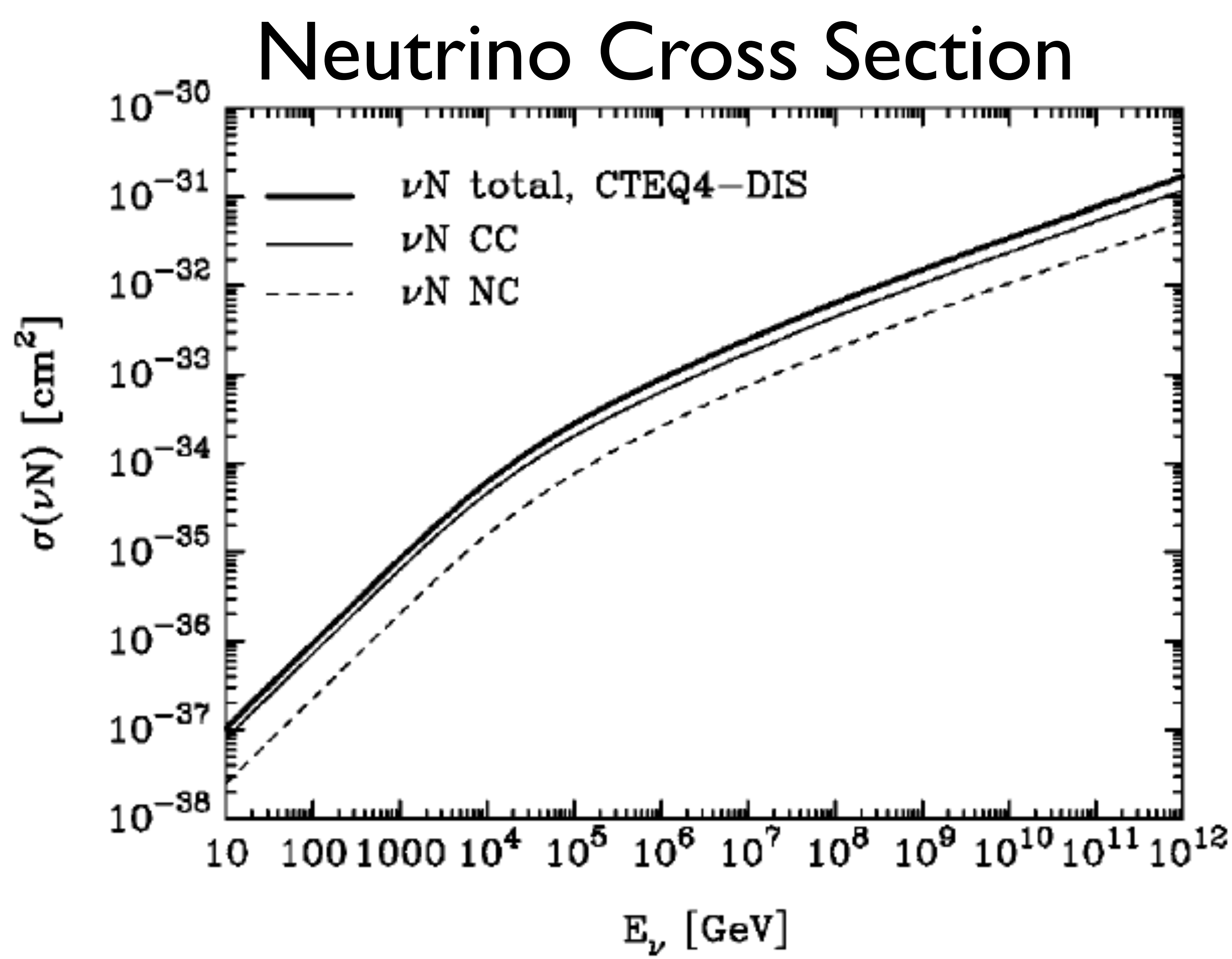


FIG. 1. Cross sections for $\nu_l N$ interactions at high energies, according to the CTEQ4-DIS parton distributions: dashed line, $\sigma(\nu_l N \rightarrow \nu_l + \text{anything})$; thin line, $\sigma(\nu_l N \rightarrow l^- + \text{anything})$; thick line, total (charged-current plus neutral-current) cross section.

Scaling

Below 10TeV linear with energy

Energies exceeding 10 TeV the cross section is damped by the W -boson propagator

GANDHI, QUIGG, RENO, AND SARCEVIC

Anti-Neutrino Cross Section

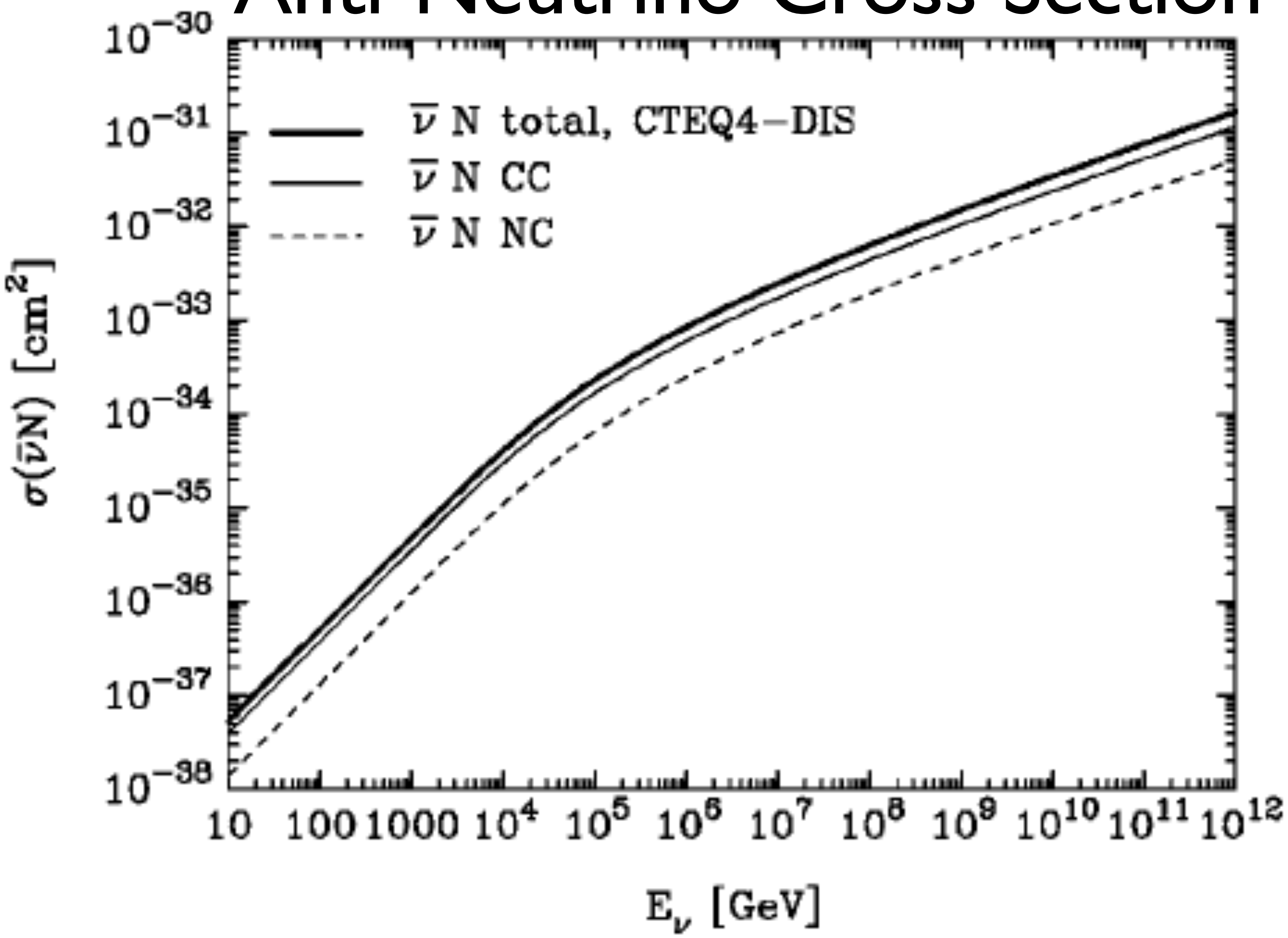


FIG. 3. Cross sections for $\bar{\nu}_l N$ interactions at high energies, according to the CTEQ4-DIS parton distributions: dashed line, $\sigma(\bar{\nu}_l N \to \bar{\nu}_l + \text{anything})$; thin line, $\sigma(\bar{\nu}_l N \to l^+ + \text{anything})$; thick line, total (charged-current plus neutral-current) cross section.

Above 10^6 GeV the valence quarks in the parton distribution function become irrelevant and neutrino and anti-neutrino cross sections are equal

Neutrino Interaction Length

GANDHI, QUIGG, RENO, AND SARCEVIC   PHYSICAL REVIEW D 58 093009

Neutrinos

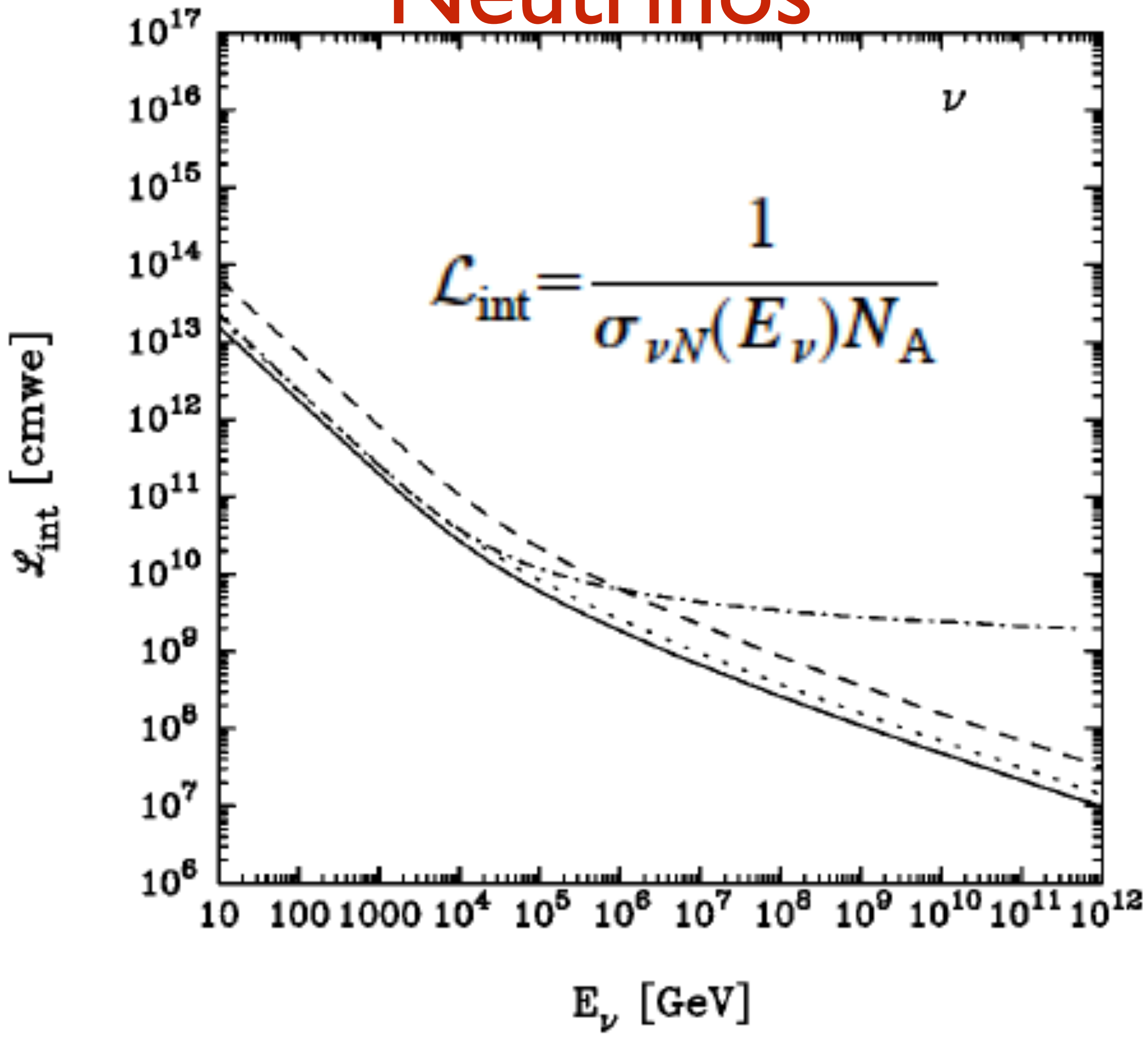


FIG. 6. Interaction lengths for neutrino interactions on nucleon targets: dotted line, charged-current interaction length; dashed line, neutral-current interaction length; solid line, total interaction length, all computed with the CTEQ4-DIS parton distributions. The dot-dashed curve shows the charged-current interaction length based on the EHLQ structure functions with Q^2 held fixed at $Q_0^2 = 5\ \mathrm{GeV}^2$.

Anti-Neutrinos

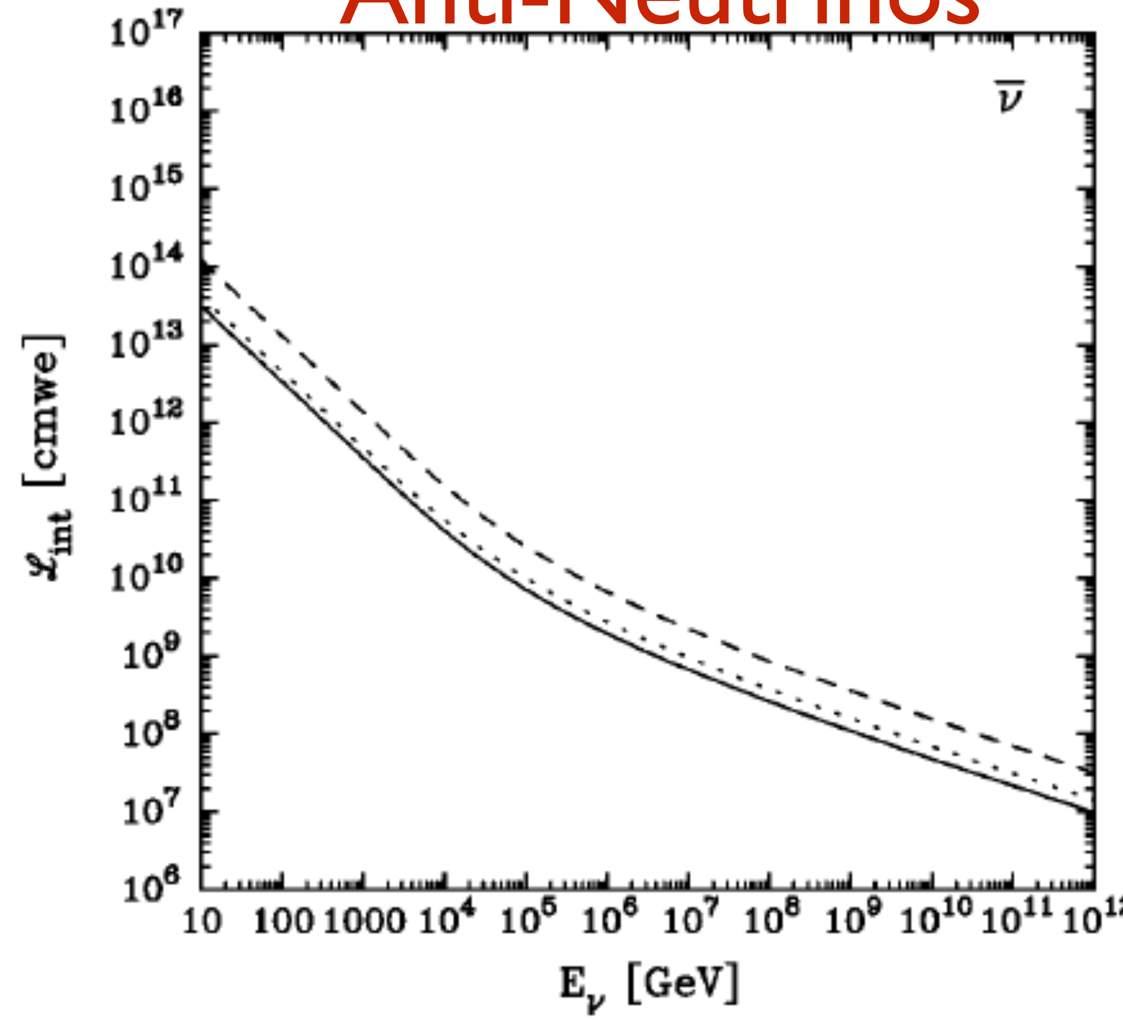


FIG. 7. Interaction lengths for antineutrino interactions on nucleon targets: dotted line, charged-current interaction length; dashed line, neutral-current interaction length; solid line, total interaction length, all computed with the CTEQ4-DIS parton distributions.

These results apply for $\nu_e N$ (or $\bar{\nu}_e N$) and $\nu_\mu N$ (or $\bar{\nu}_\mu N$)

Neutrino - electron scattering

- In the energy range of interest to atmospheric and astrophysical neutrino, neutrino-electron scattering can be generally be neglected
- Anti-electron neutrinos are an exception due to a resonance at ~6.3PeV
  - This is known as the Glashow resonance

$$\bar{\nu}_e e \rightarrow W^- \rightarrow \bar{\nu}_\mu \mu \text{ and } \bar{\nu}_e e \rightarrow W^- \rightarrow \text{hadrons}$$

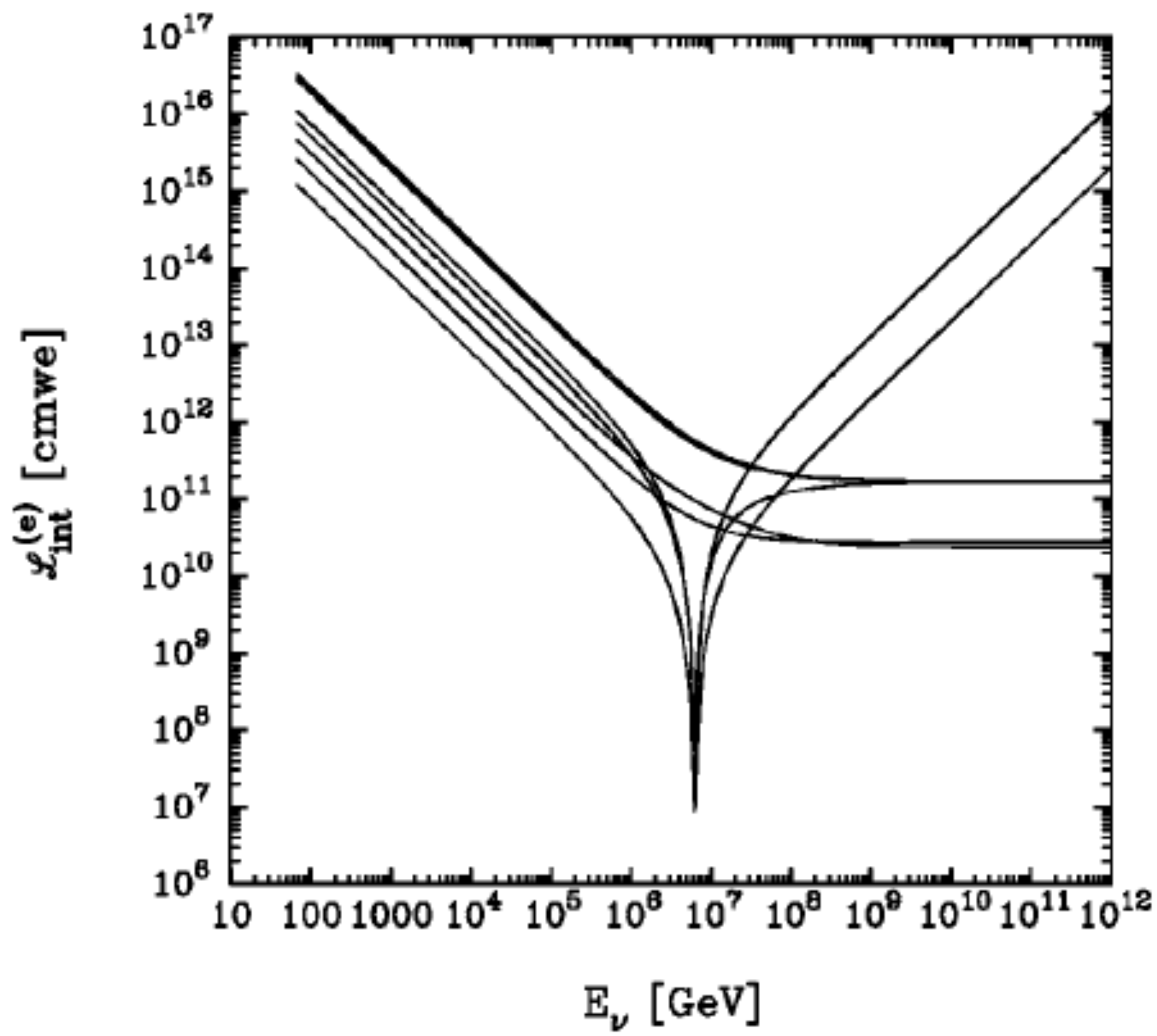
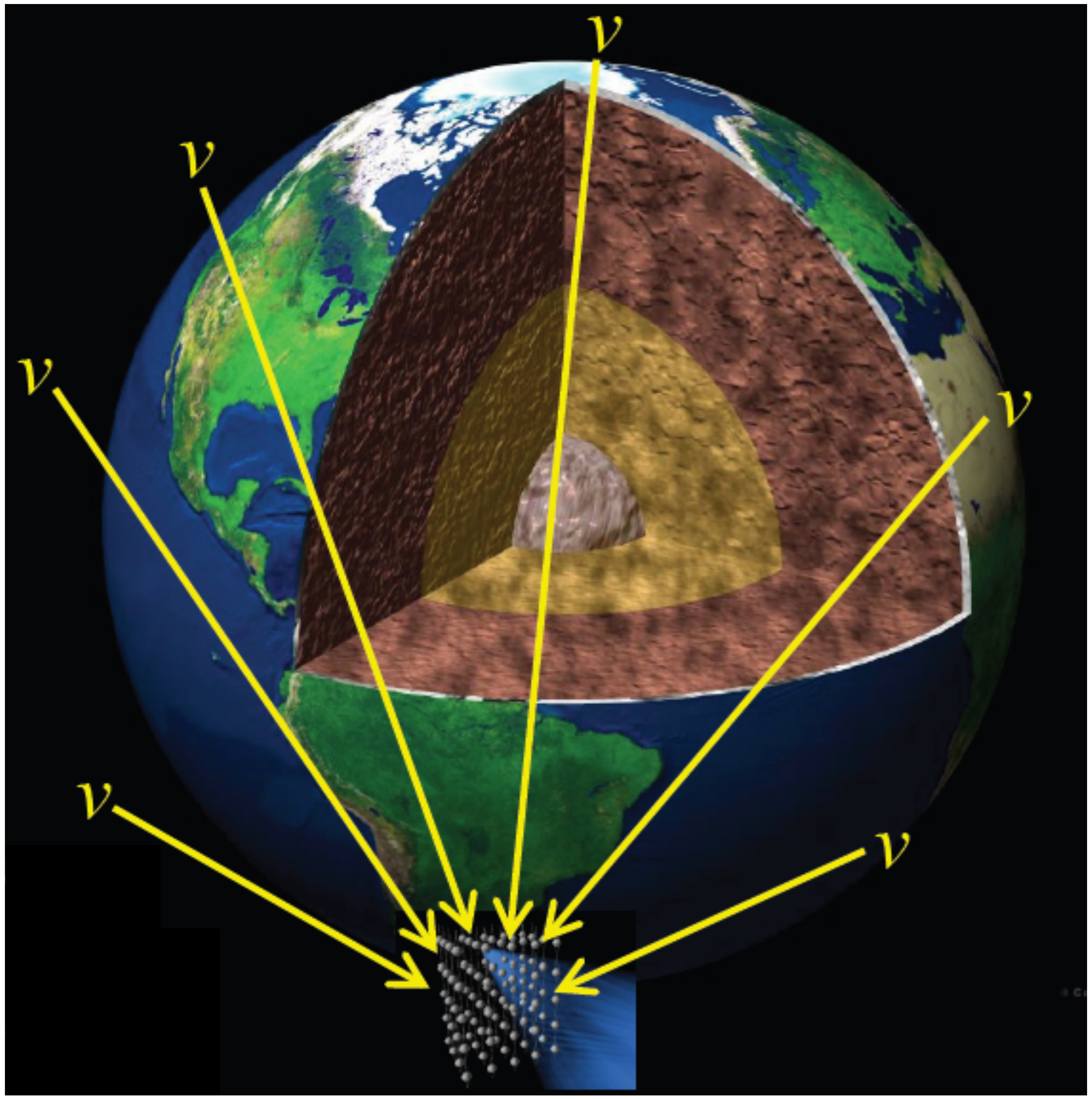
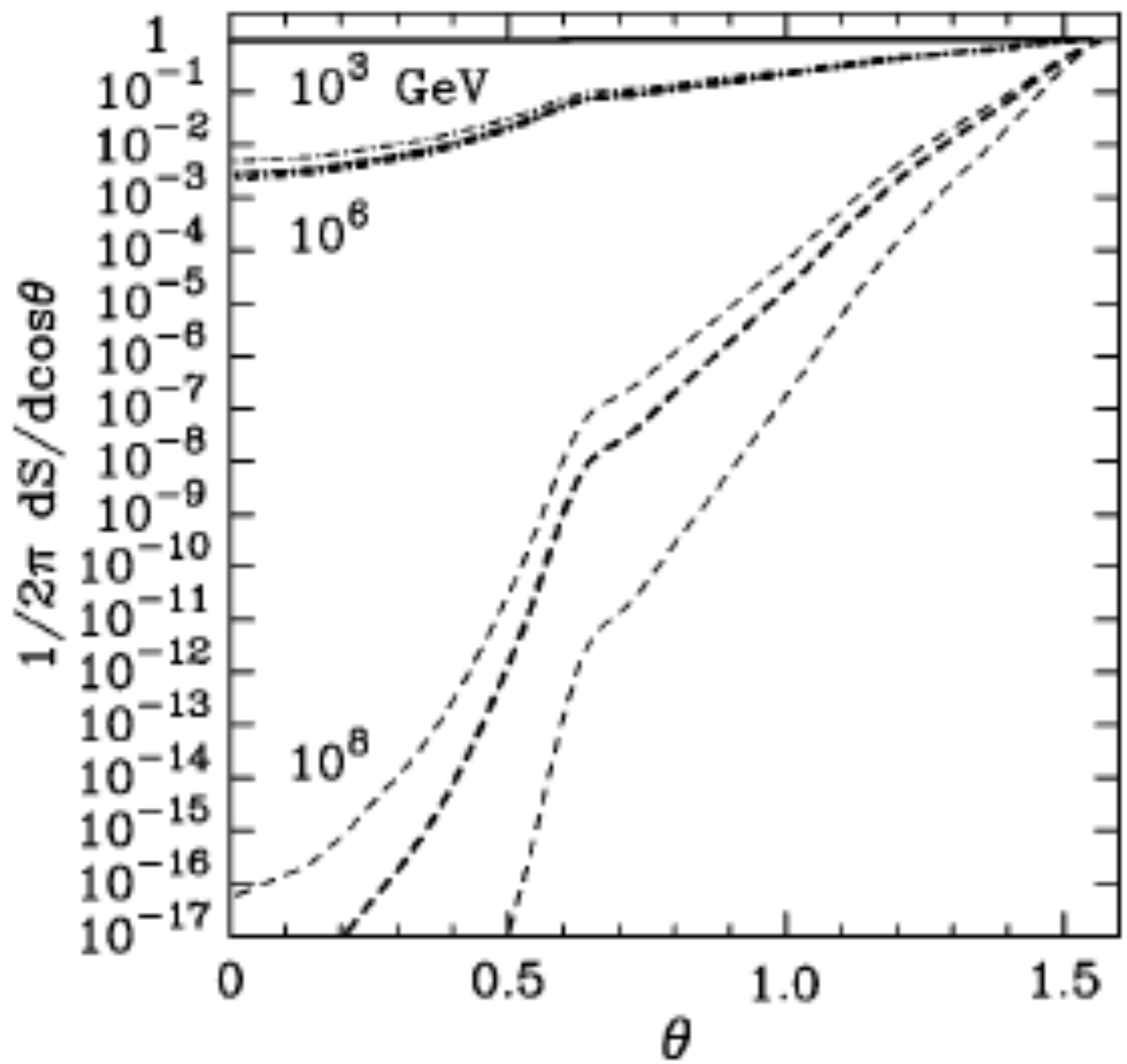


FIG. 8. Interaction lengths for neutrino interactions on electron targets. At low energies, from smallest to largest interaction length, the processes are (i) $\bar{\nu}_e e \rightarrow$hadrons, (ii) $\nu_\mu e \rightarrow \mu \nu_e$, (iii) $\nu_e e \rightarrow \nu_e e$, (iv) $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$, (v) $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$, (vi) $\nu_\mu e \rightarrow \nu_\mu e$, (vii) $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ (from Ref. [12]).

Neutrino Absorption in the Earth





With neutrino telescopes measure the arrival direction (and neutrino energy). Use muon neutrinos for good pointing

Neutrino Absorption in the Earth

- Ingredients to study neutrino absorption in the Earth
  - Neutrino flux (Flux Model)
  - Neutrino propagation through the Earth
  - Interactions with nucleons
  - Detector simulation
  - Experimental data

A prediction …

Radiography of the Earth's Core and Mantle with Atmospheric Neutrinos
M.C. Gonzalez-Garcia, Francis Halzen, Michele Maltoni, and Hiroyuki K.M. Tanaka
Phys. Rev. Let. (100) (2008)

Method
Use atmospheric muon neutrino absorption in the Earth to detect the core

Observation time

Differential Muon neutrino flux after propagation through the Earth

$$N_{\rm ev}^{\nu_\mu} = T\int_{-1}^{1} d\cos\theta \int_0^\infty dl'_{\rm min} \int_{l'_{\rm min}}^\infty dl \int_{E_\mu^{\rm fin,min}}^\infty dE_\mu^{\rm fin} \int_{E_\mu^{\rm fin}}^\infty dE_\mu^0 \int_{E_\mu^0}^\infty dE_\nu \frac{d^2\phi_{\nu_\mu}}{dE_\nu\, d\cos\theta}(E_\nu,\cos\theta) \frac{d\sigma_{CC}^\mu}{dE_\mu^0}(E_\nu, E_\mu^0)\, n_T\, F(E_\mu^0, E_\mu^{\rm fin}, l)\, A_{\rm eff}^0 \quad (1)$$

Neutrino cross section

Number density of targets

Muon propagation to detector

Muon effective area

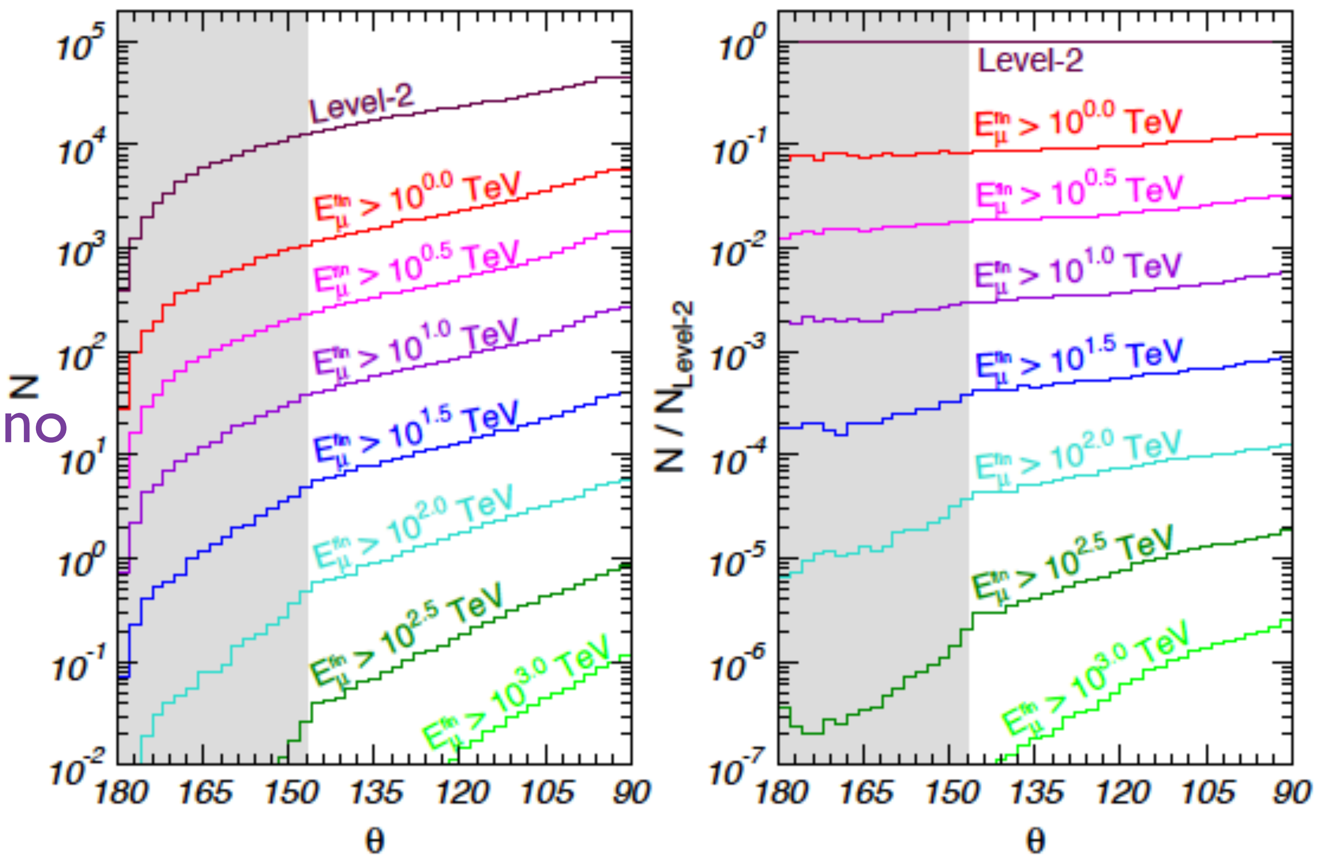


FIG. 1: (a) Expected zenith angle distribution of ATM ν_μ induced events in IceCube for different energy thresholds $E_\mu^{\rm fin,min}$ for the PREM. θ is the neutrino angle (which at these energies is collinear with the detected muon) as measured from the vertical direction (upgoing-ν corresponding to $\theta = 180$). (b) Ratio of the zenith angle distribution of ATM ν_μ induced events in IceCube for different energy thresholds $E_\mu^{\rm fin,min}$ over the corresponding one for L2 cuts only. The shadow areas cover the angular size of the Earth core.

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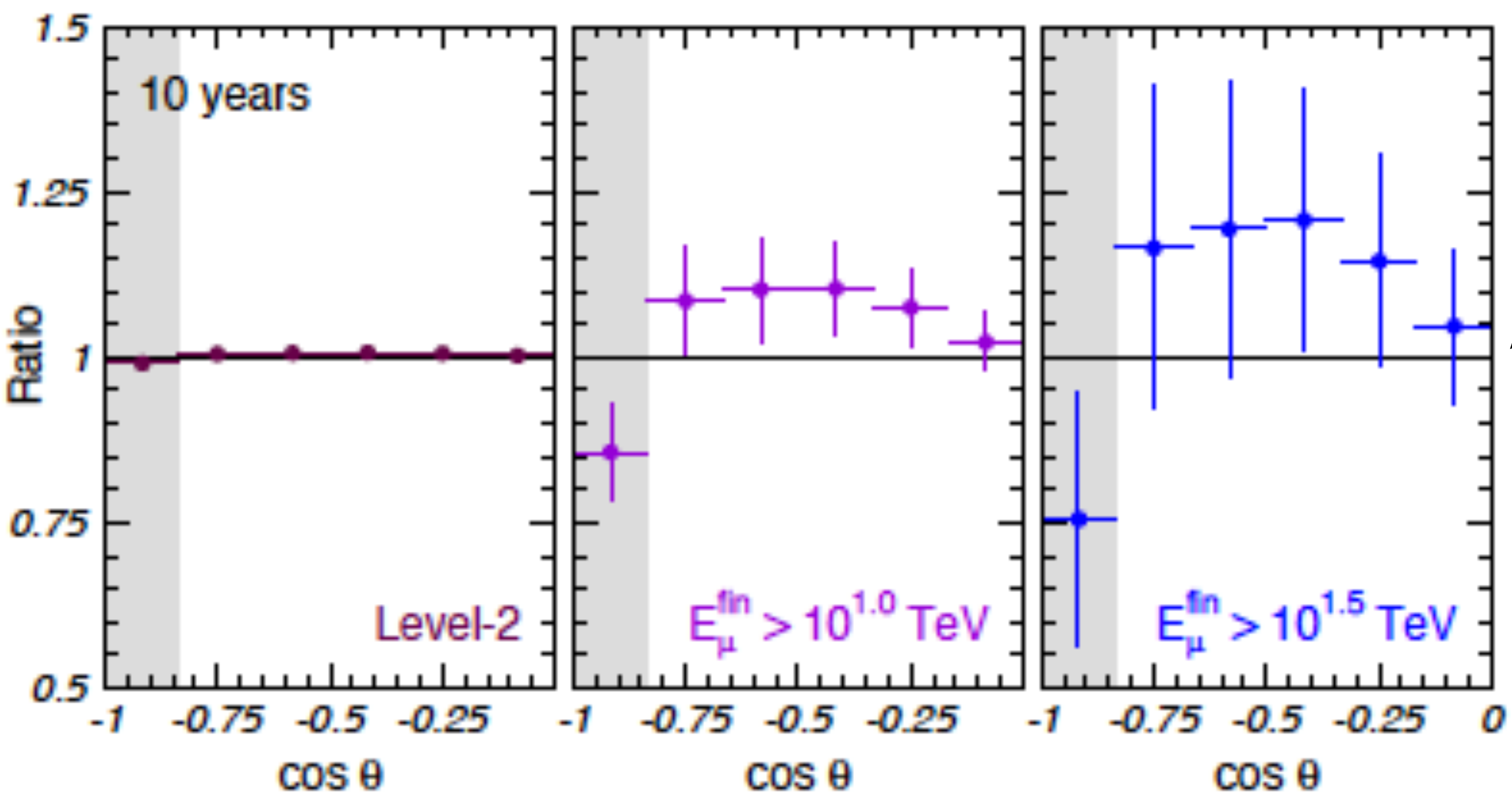
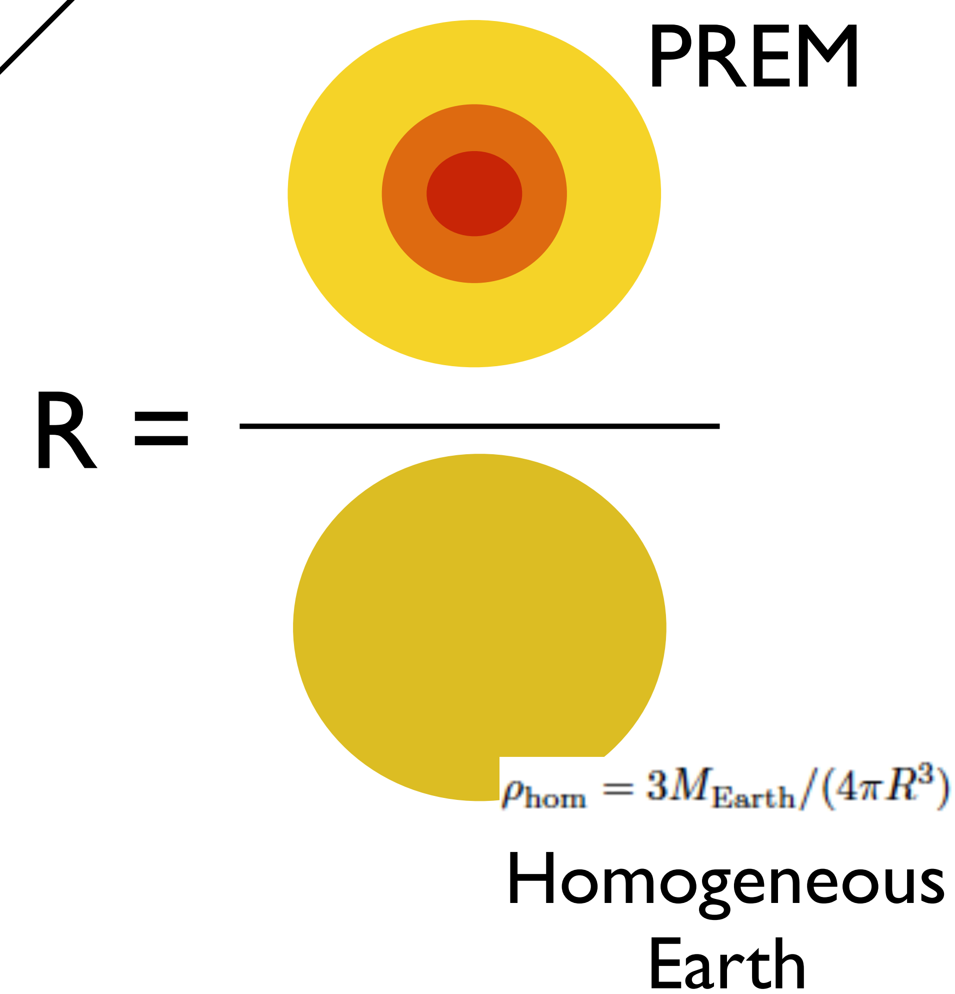


FIG. 2: Ratio of zenith angle distribution of expected events for the PREM over the expectations with an homogeneous Earth matter distribution for different values of the energy threshold of the events. The error bars in the figure show the expected statistical error in 10 years of IceCube.

$$R = \frac{N_\mu(E_\mu^{\rm fin} > E_\mu^{\rm fin,min},\, \cos\theta,\, \rho_{\rm PREM})}{N_\mu(E_\mu^{\rm fin} > E_\mu^{\rm fin,min},\, \cos\theta,\, \rho_{\rm hom})}$$



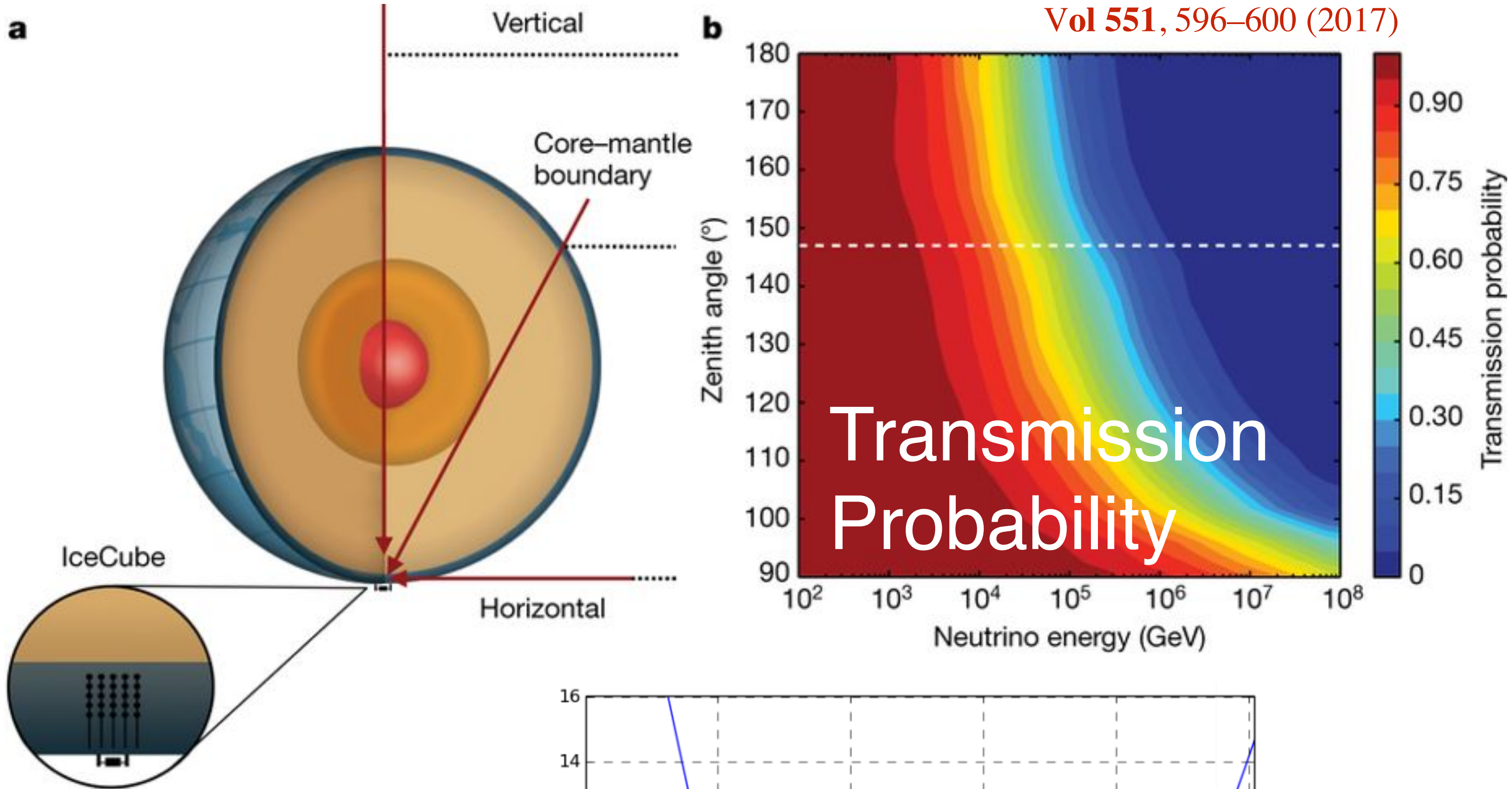
A prediction:
IceCube can directly observe the core-mantle transition at the 5σ level in 10 years.

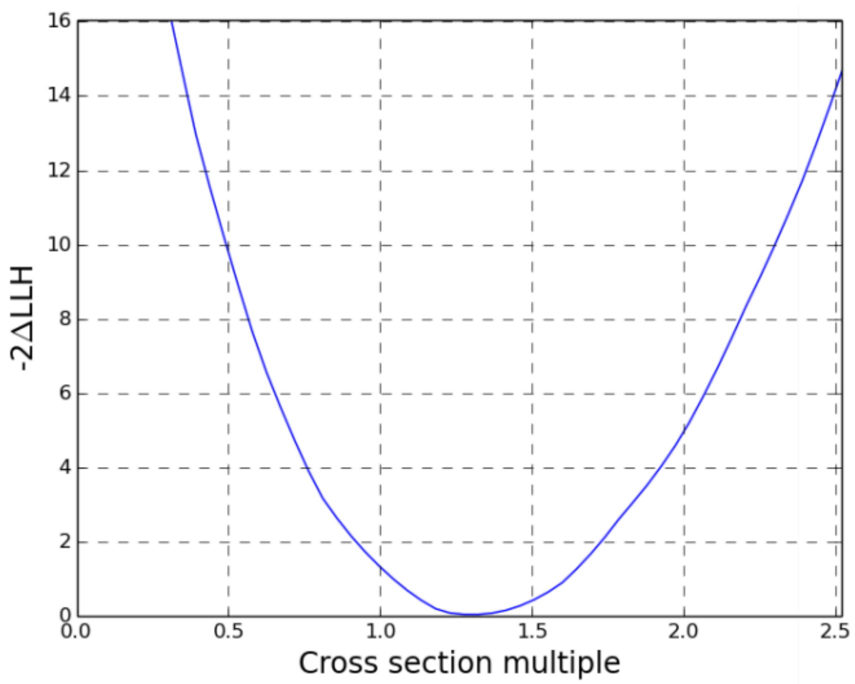
Neutrino Absorption in the Earth

Neutrino absorption in the Earth / Neutrino Cross section measurement

IceCube Collaboration - *Nature* **Vol 551**, 596–600 (2017)

- One year of IceCube data
  - Data acquisition period 2009-2010
- IceCube Detector configuration
  - IC79 (nearly completed detector with 79-strings installed)
- Data sample
  - 10,784 energetic upward-going neutrino-induced muons
- Neutrino energy range
  - E_ν = 6.3–980 TeV





$$\frac{\sigma_{\text{meas.}}}{\sigma_{SM}} = 1.30^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$$

Neutrino absorption in the Earth / Neutrino Cross section measurement

Neutrino Tomography / Neutrino Cross Section Measurements

- 2 orders of magnitude higher in energy than previous accelerator based measurements
- Measurement reflects a flux-weighted sum of neutrinos and antineutrinos
- First measurement where the DIS cross section is no longer linear in energy
- Consistent with current Standard Model calculations
- 6 more years of data are available and could reduce uncertainties below 20% and enable a binned measurement across energy

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Nachrichten > Wissenschaft > Natur > Neutrinos > Neutrinos im IceCube-Experiment: Erde verschluckt Geisterteilchen

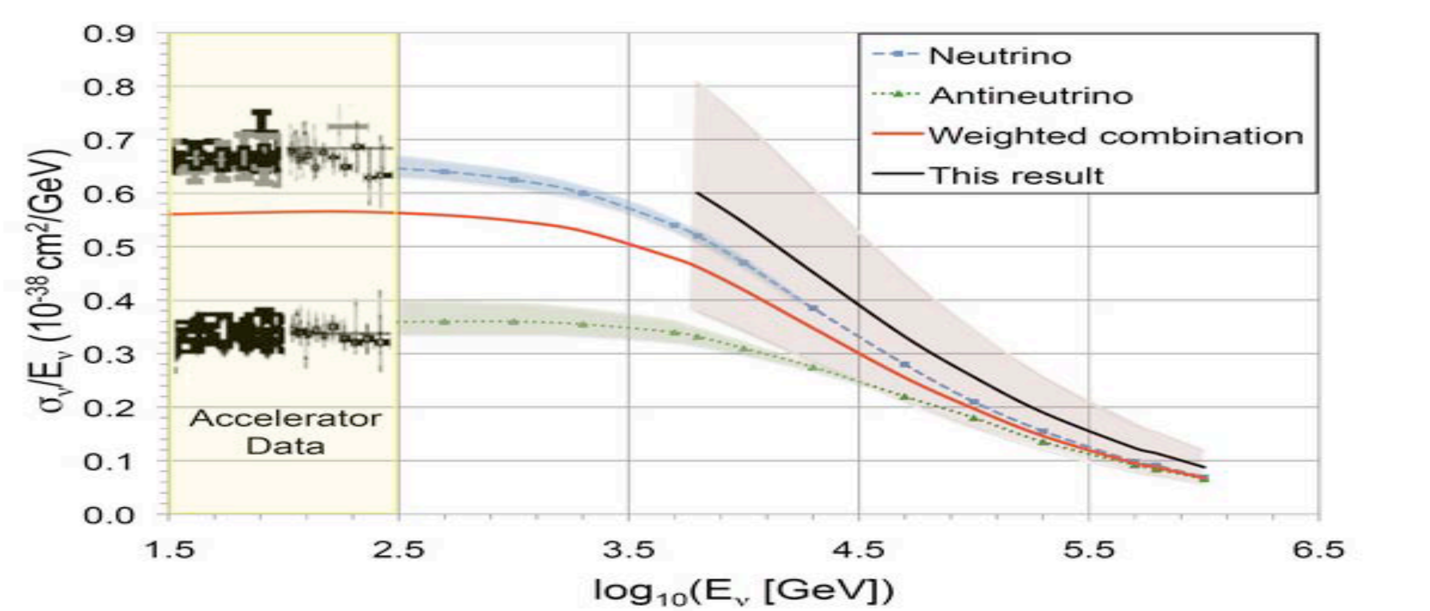
Neutrino-Experiment

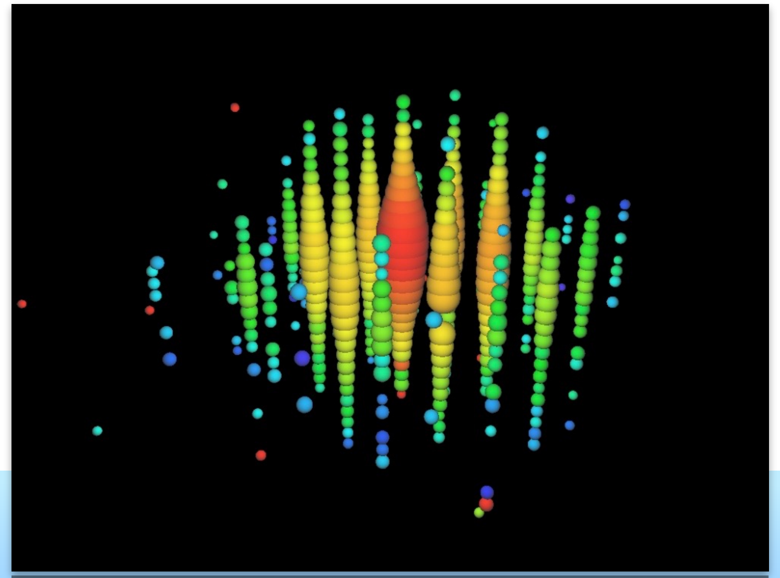
Erde verschluckt geheimnisvolle Geisterteilchen

Neutrinos rasen weitgehend ungestört durchs All, weil sie fast nicht mit normaler Materie interagieren. Aber nur fast. Ausgerechnet unsere Erde ist ein effizienter Neutrino-Killer, wie ein Experiment beweist.

Von Christoph Seidler

Fotos



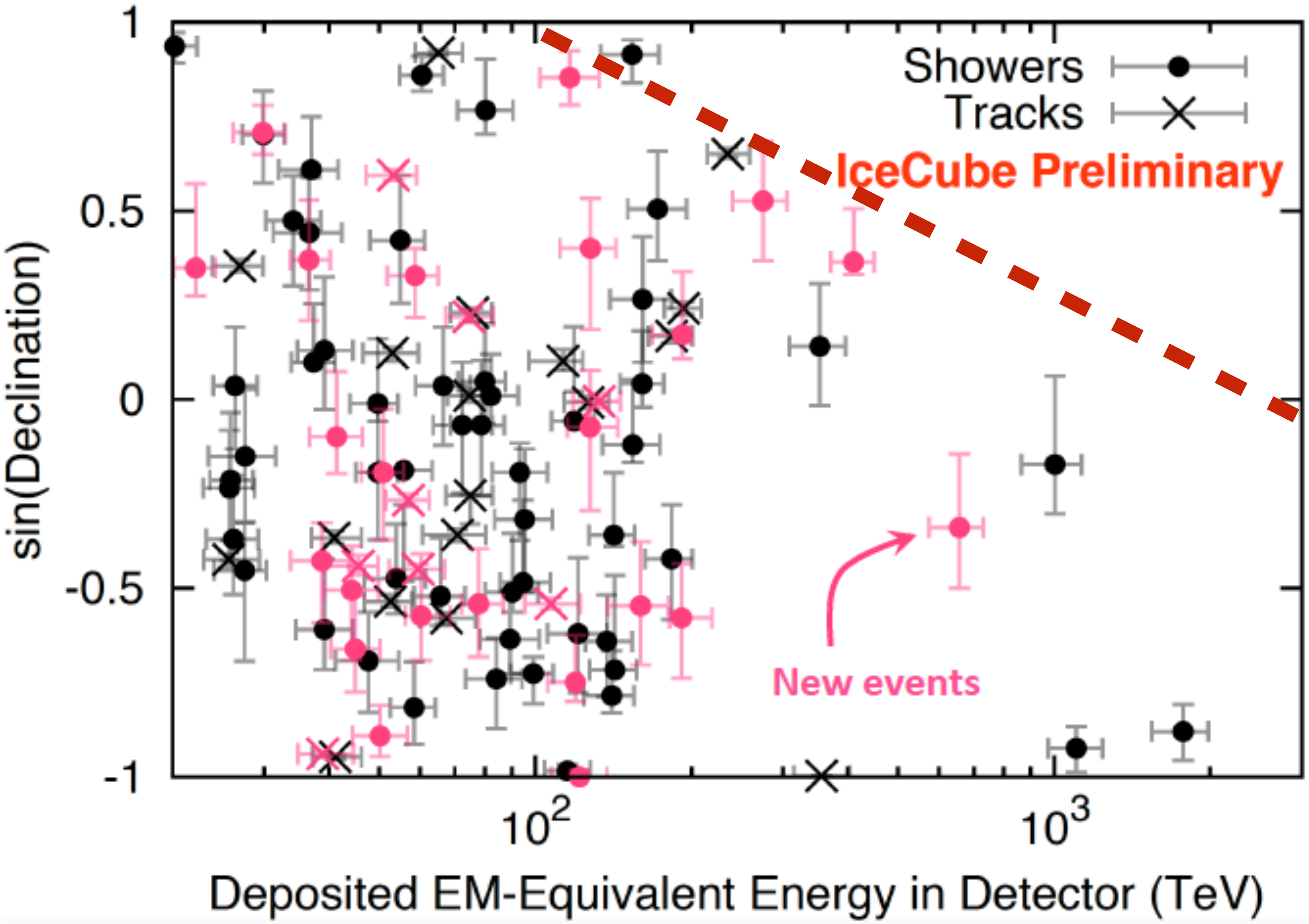


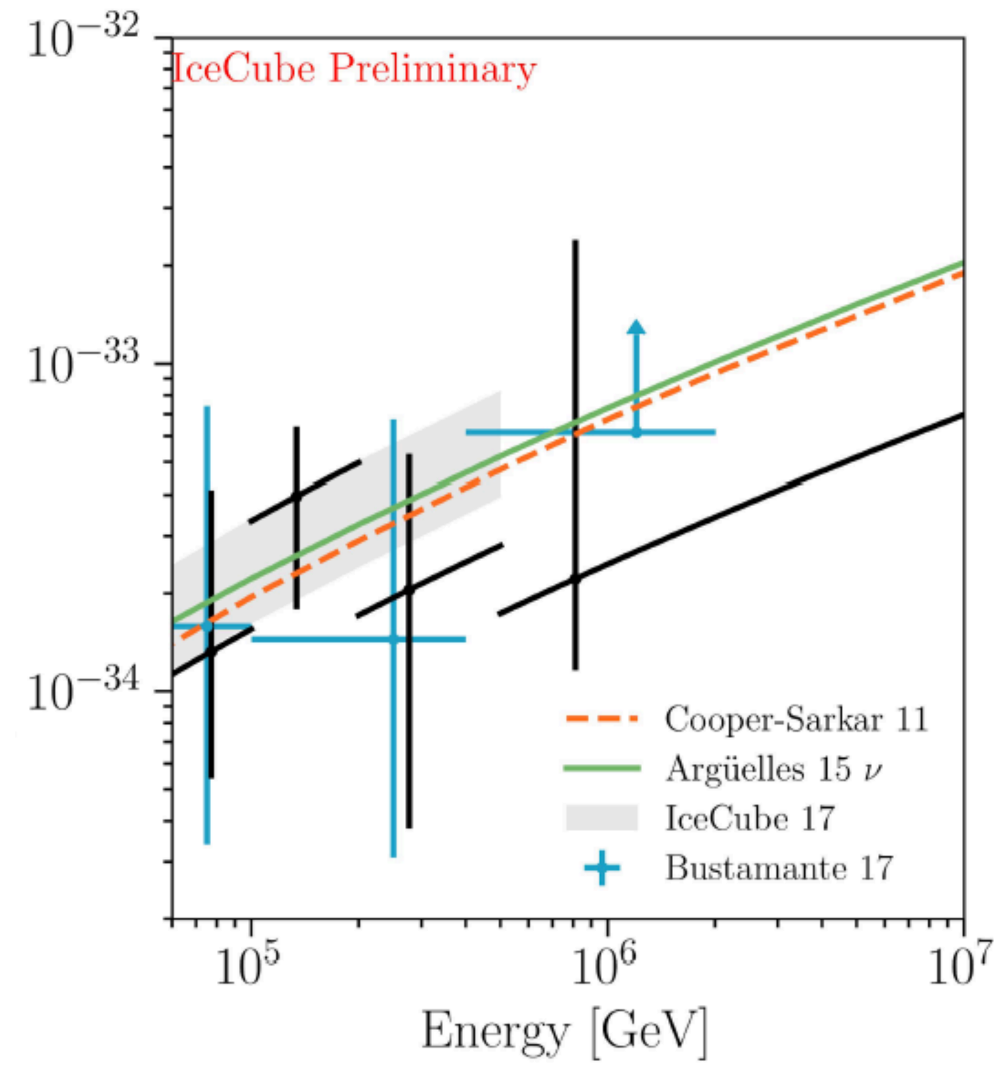
Astro-physical Neutrino Search - … and neutrino absorption

HESE7.5yrs results

High-Energy Starting Events (HESE) – 7.5 yr

IceCube Collaboration, *Science* 342, 1242856 (2013)





1803.05901

Neutrino tomography of the Earth

A. Donini[1], S. Palomares-Ruiz[1] and J. Salvado[1,2]

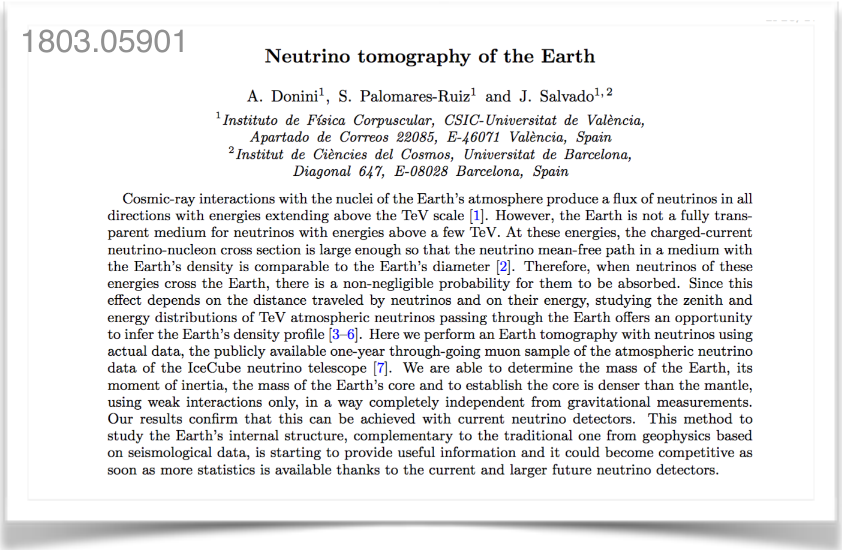
[1] *Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 València, Spain*

[2] *Institut de Ciències del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*

Cosmic-ray interactions with the nuclei of the Earth's atmosphere produce a flux of neutrinos in all directions with energies extending above the TeV scale [1]. However, the Earth is not a fully transparent medium for neutrinos with energies above a few TeV. At these energies, the charged-current neutrino-nucleon cross section is large enough so that the neutrino mean-free path in a medium with the Earth's density is comparable to the Earth's diameter [2]. Therefore, when neutrinos of these energies cross the Earth, there is a non-negligible probability for them to be absorbed. Since this effect depends on the distance traveled by neutrinos and on their energy, studying the zenith and energy distributions of TeV atmospheric neutrinos passing through the Earth offers an opportunity to infer the Earth's density profile [3–6]. Here we perform an Earth tomography with neutrinos using actual data, the publicly available one-year through-going muon sample of the atmospheric neutrino data of the IceCube neutrino telescope [7]. We are able to determine the mass of the Earth, its moment of inertia, the mass of the Earth's core and to establish the core is denser than the mantle, using weak interactions only, in a way completely independent from gravitational measurements. Our results confirm that this can be achieved with current neutrino detectors. This method to study the Earth's internal structure, complementary to the traditional one from geophysics based on seismological data, is starting to provide useful information and it could become competitive as soon as more statistics is available thanks to the current and larger future neutrino detectors.

Neutrino Absorption Study with public data

IceCube Public Data Analysis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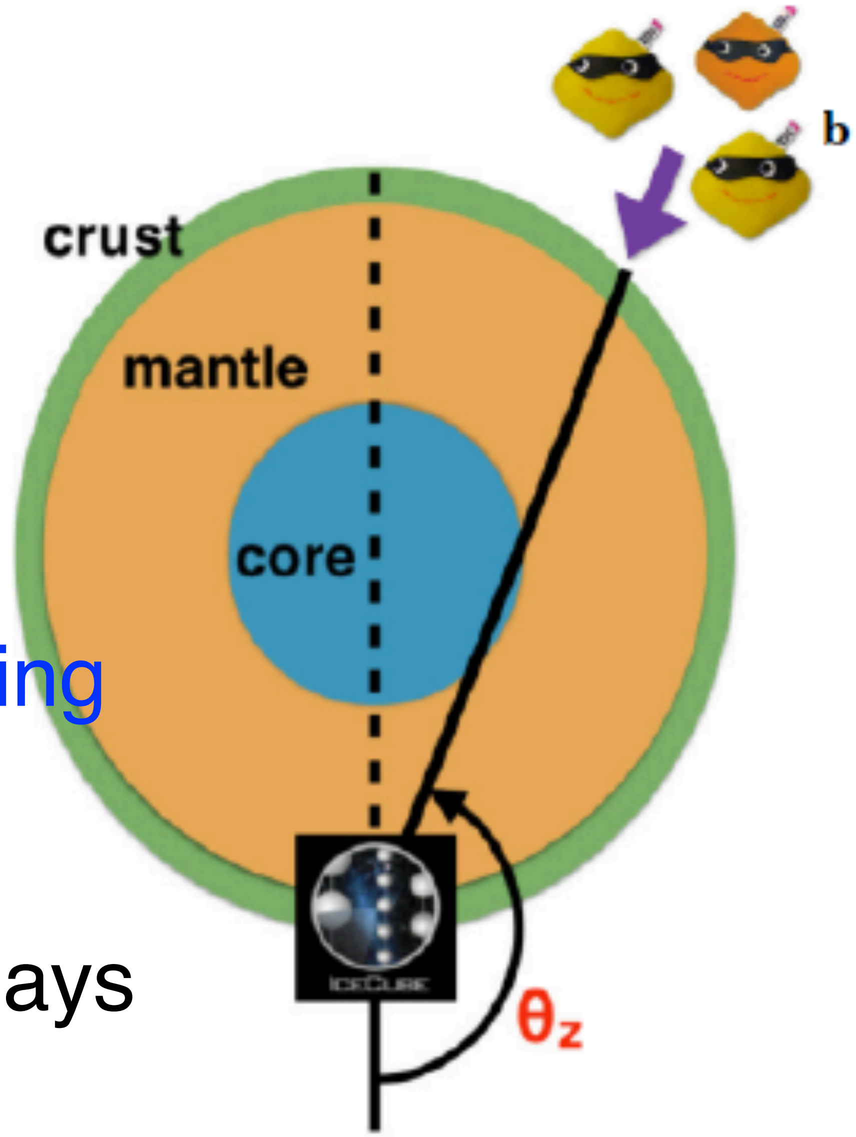
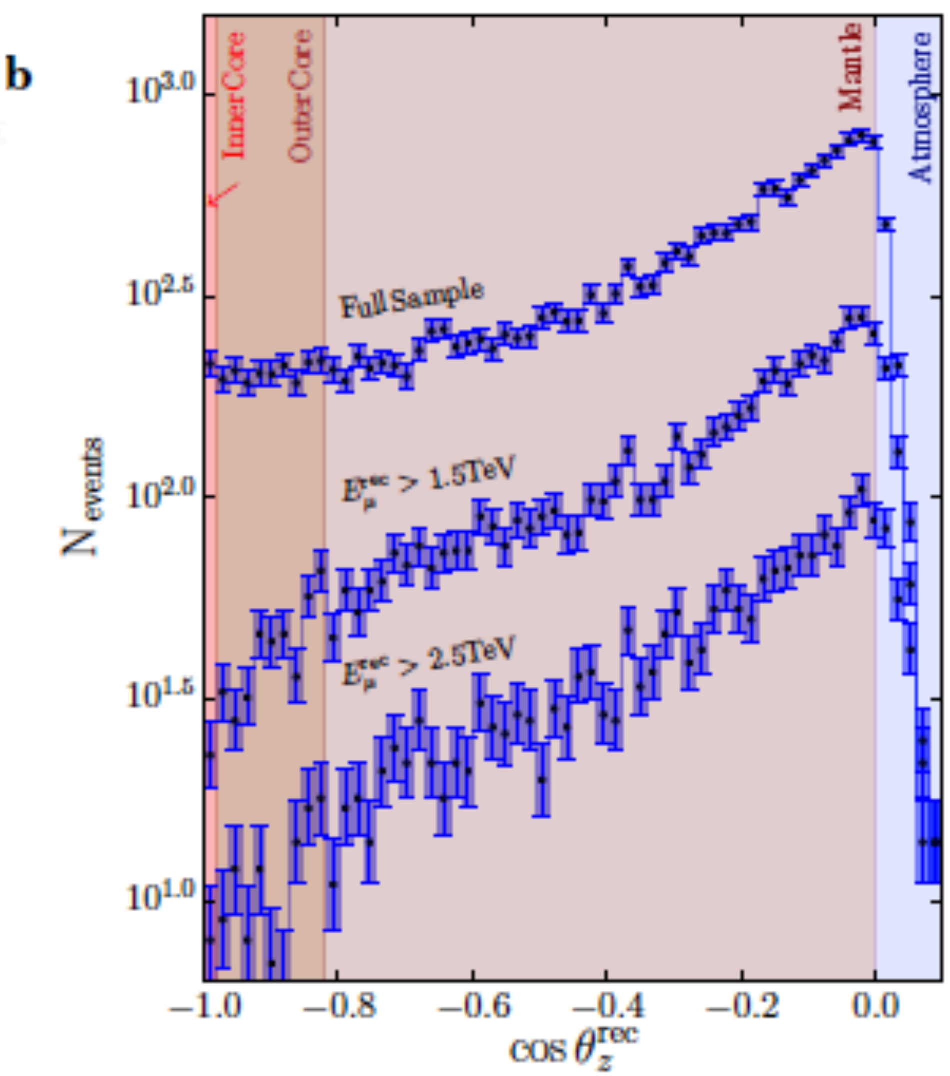
Data as a function of E_μ and θ_z

The IceCube IC86 public data sample

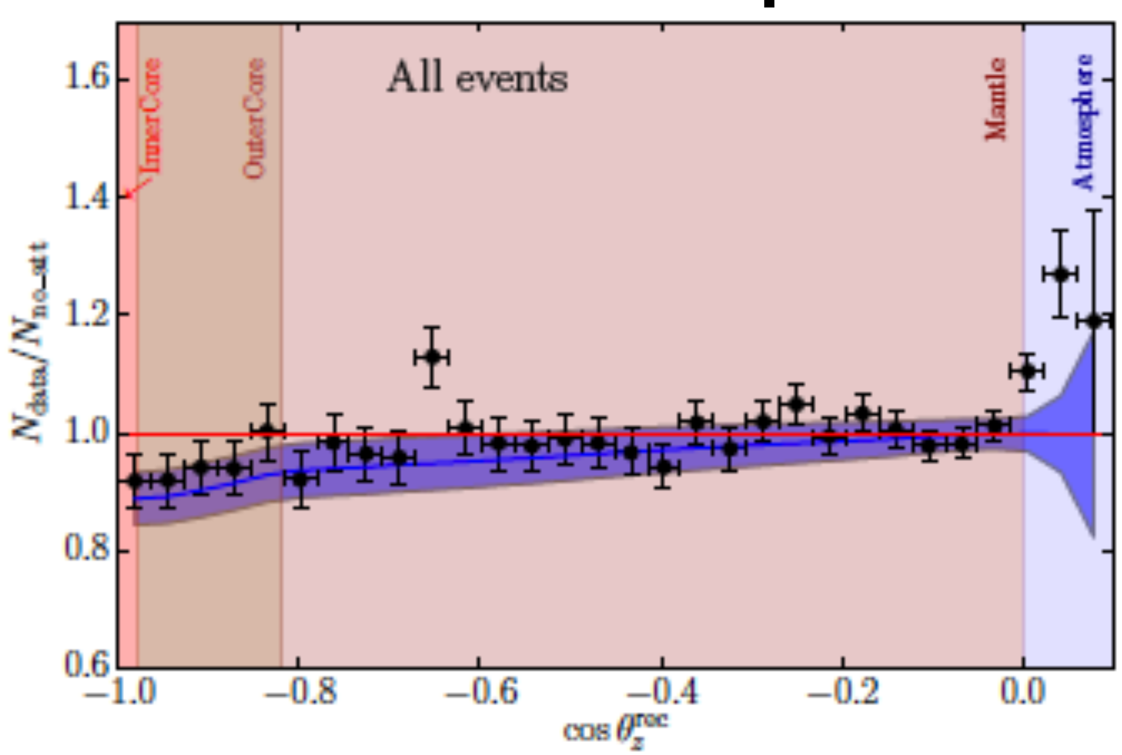
- One year of data taking (2011-2012)
- 20145 muon events collected over 343.7 days
- E_μ =[400GeV-20TeV]
- The muon direction is a very good proxy of the neutrino direction, with $\Delta\cos\theta_z < 0.01$





IceCube Public Data Analysis

a Full Sample



b Energy cut E>5TeV

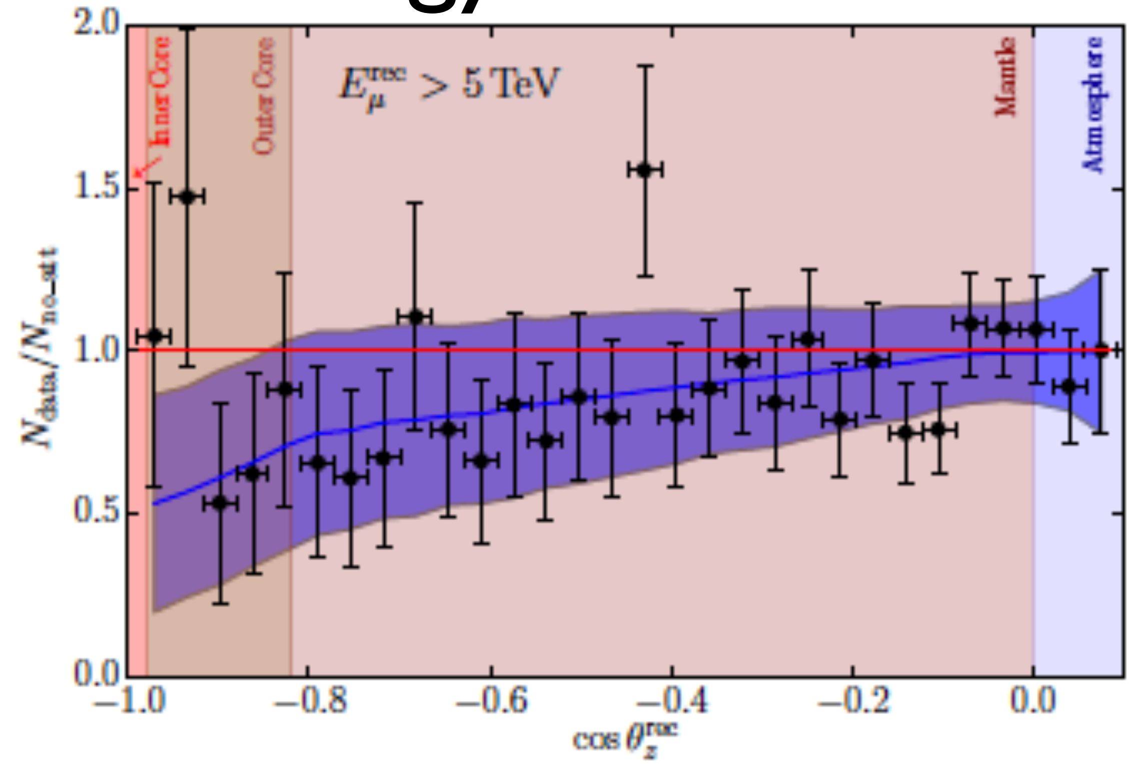
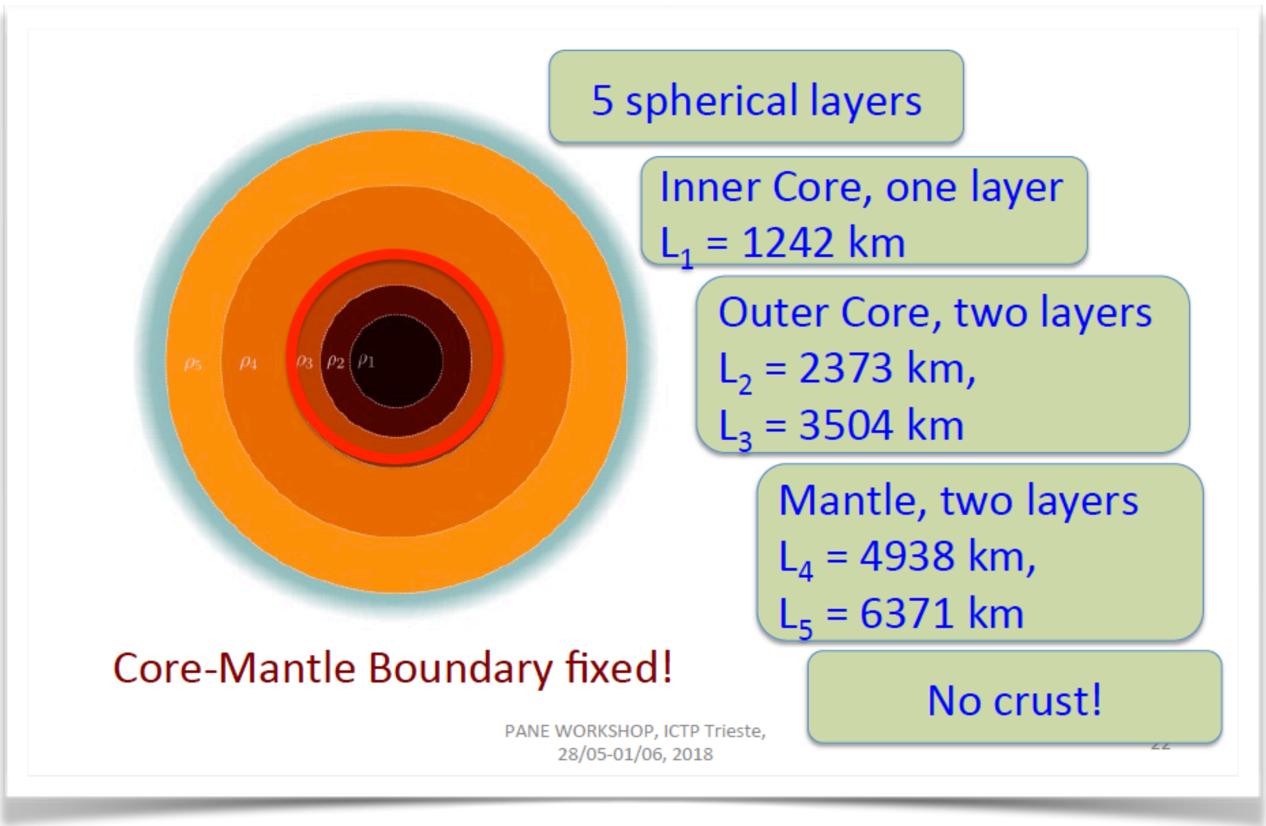


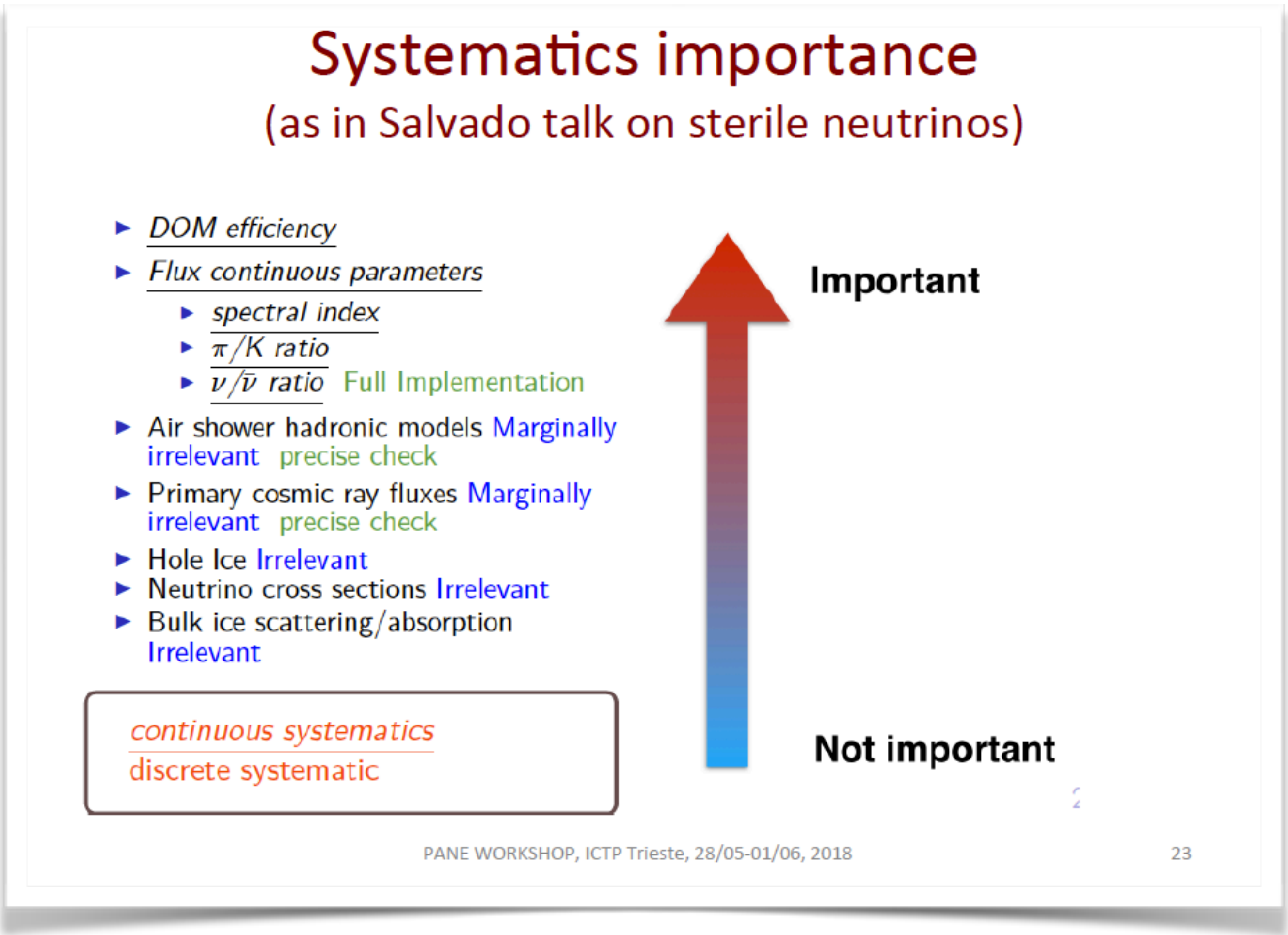
FIG. 2. **Ratio of the number of observed events in the IC86 sample to the number of expected events without including Earth attenuation.** **a,** Zenith distribution of the ratio, including all events in the IC86 sample. **b,** Zenith distribution of the ratio, but only considering events with a minimum reconstructed muon energy of 5 TeV. In both panels, the solid blue line represents the expectation using the PREM [43] for the density profile, with its statistical expected error represented by the blue band.

Bin by bin variation seem inconsistent with statistical uncertainty …

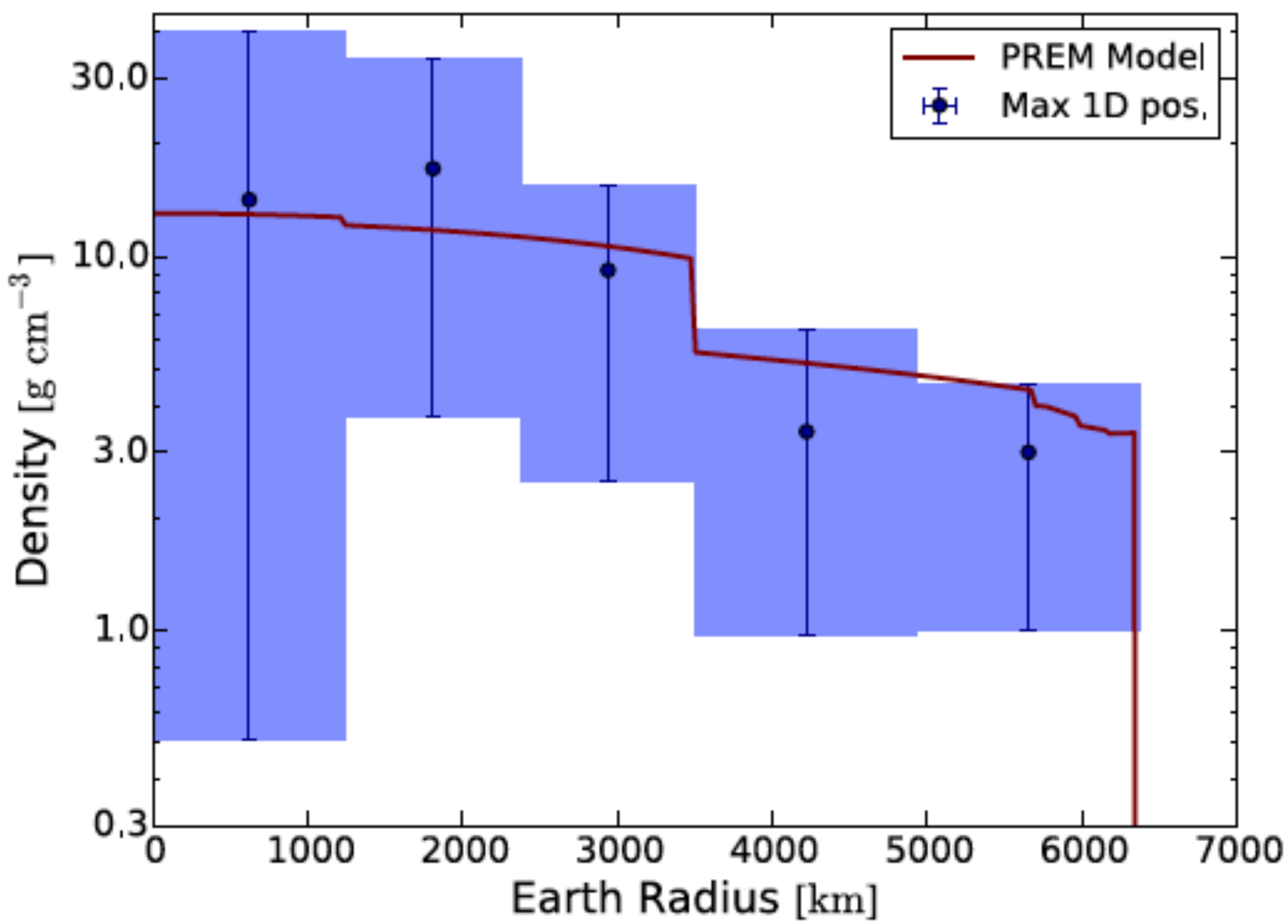
Binned log likelihood analysis

$$\ln \mathcal{L}(\boldsymbol{\rho};\boldsymbol{\eta}) = \sum_{i\in \mathrm{bins}} \left(N_i^{\mathrm{data}} \ln N_i^{\mathrm{th}}(\boldsymbol{\rho};\boldsymbol{\eta}) - N_i^{\mathrm{th}}(\boldsymbol{\rho};\boldsymbol{\eta})\right) - \sum_j \frac{(\eta_j - \eta_j^0)^2}{2\sigma_j^2}$$





First 1-d density profile with neutrinos



Analysis performed with MultiNest

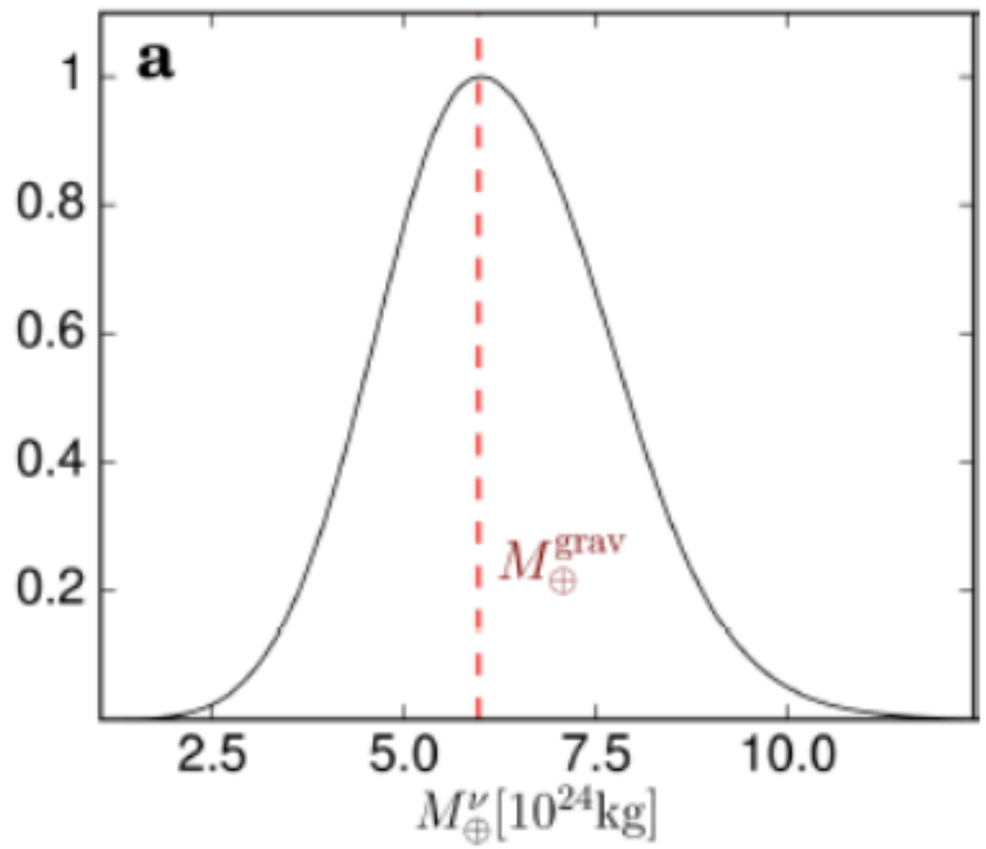
5 Earth layers densities

and

4 systematic errors:

- Flux normalization
- Pion-to-kaon ratio
- Spectral shape
- DOM Efficiency

The Earth's mass



First Electro-weak measurement of the Earth's mass

$M_{earth-\nu} = (6.0\ ^{+1.6}_{-1.3}) \times 10^{24}$ kg

Gravitational measurement of the Earth's mass

$M_{earth-grav} = (5.9722 \pm 0.0006) \times 10^{24}$ kg

PANE WORKSHOP, ICTP Trieste, 28/05-01/06, 2018

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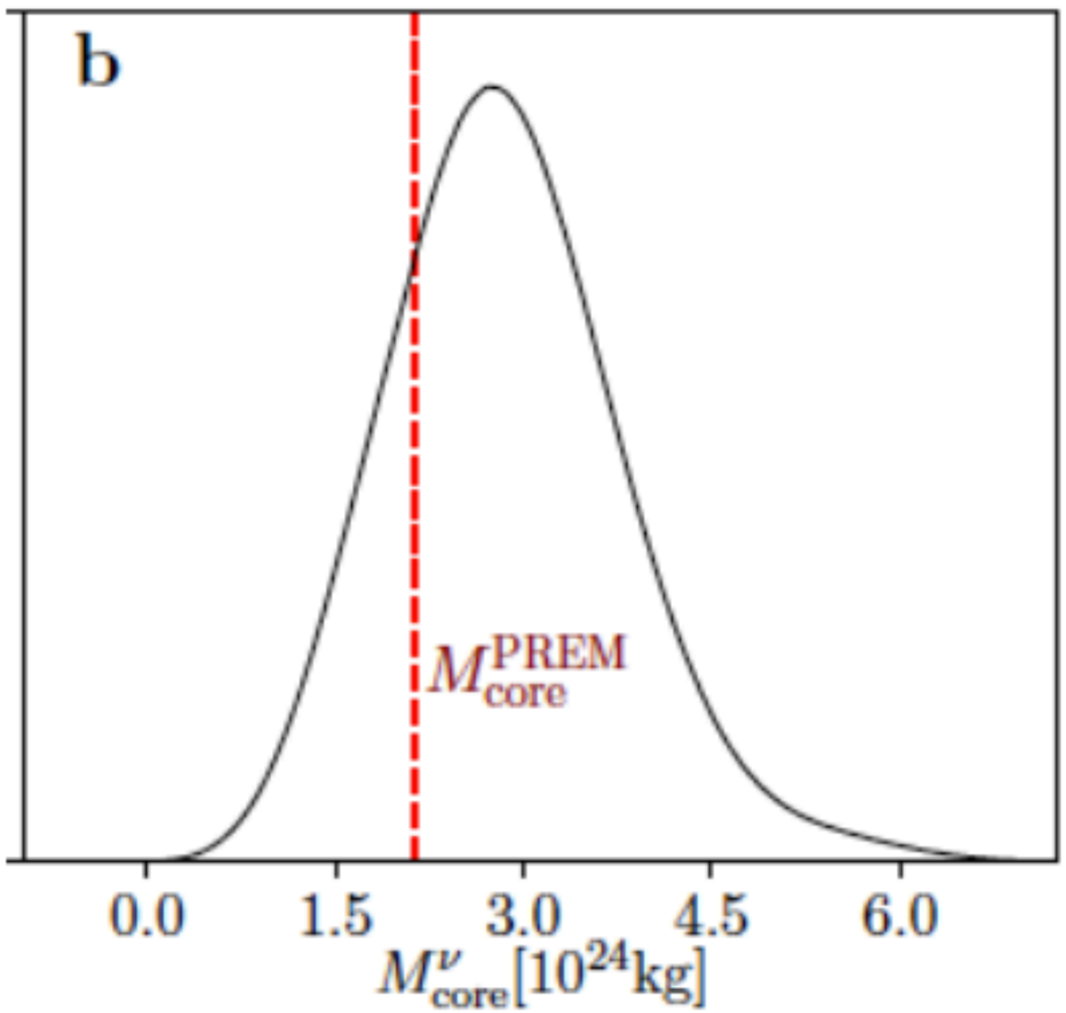
The Earth's core mass

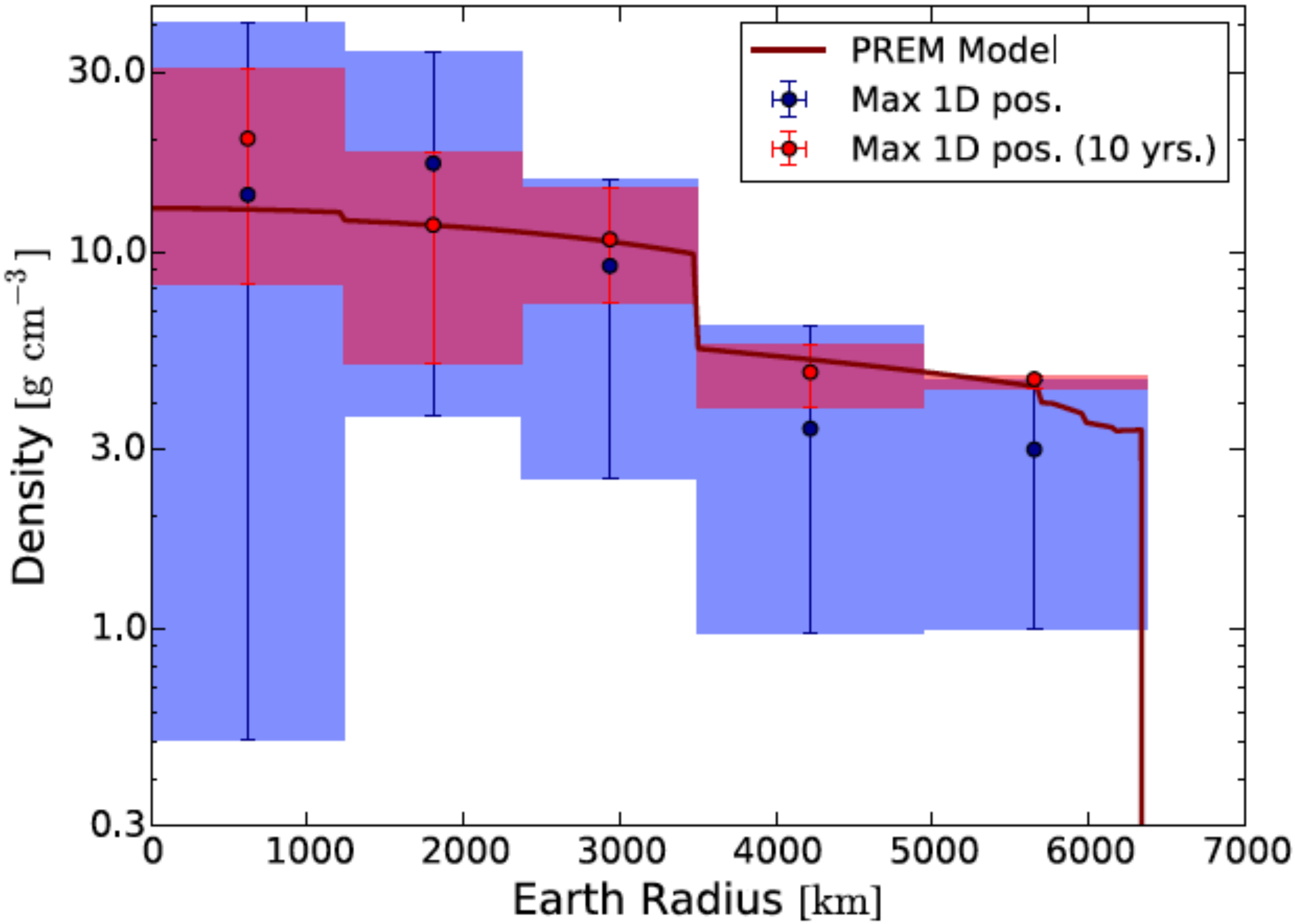


Electro-weak measurement of the Earth's core mass

$M_{core\text{-}\nu} = (2.7\ ^{+1.0}_{-0.9}) \times 10^{24}$ kg

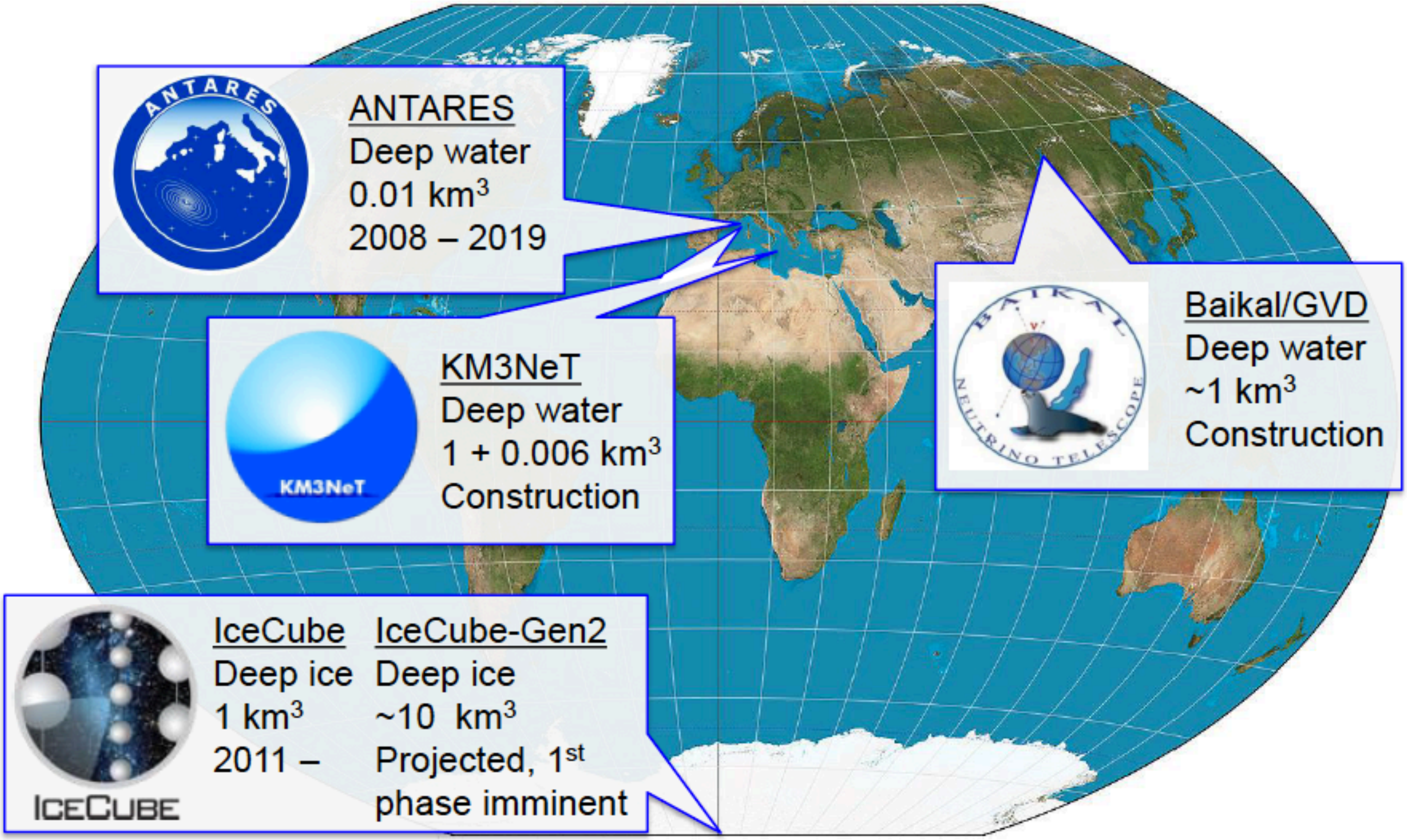
This quantity may be used as a new constraint in seismological analyses

1-d density profile with 10 years

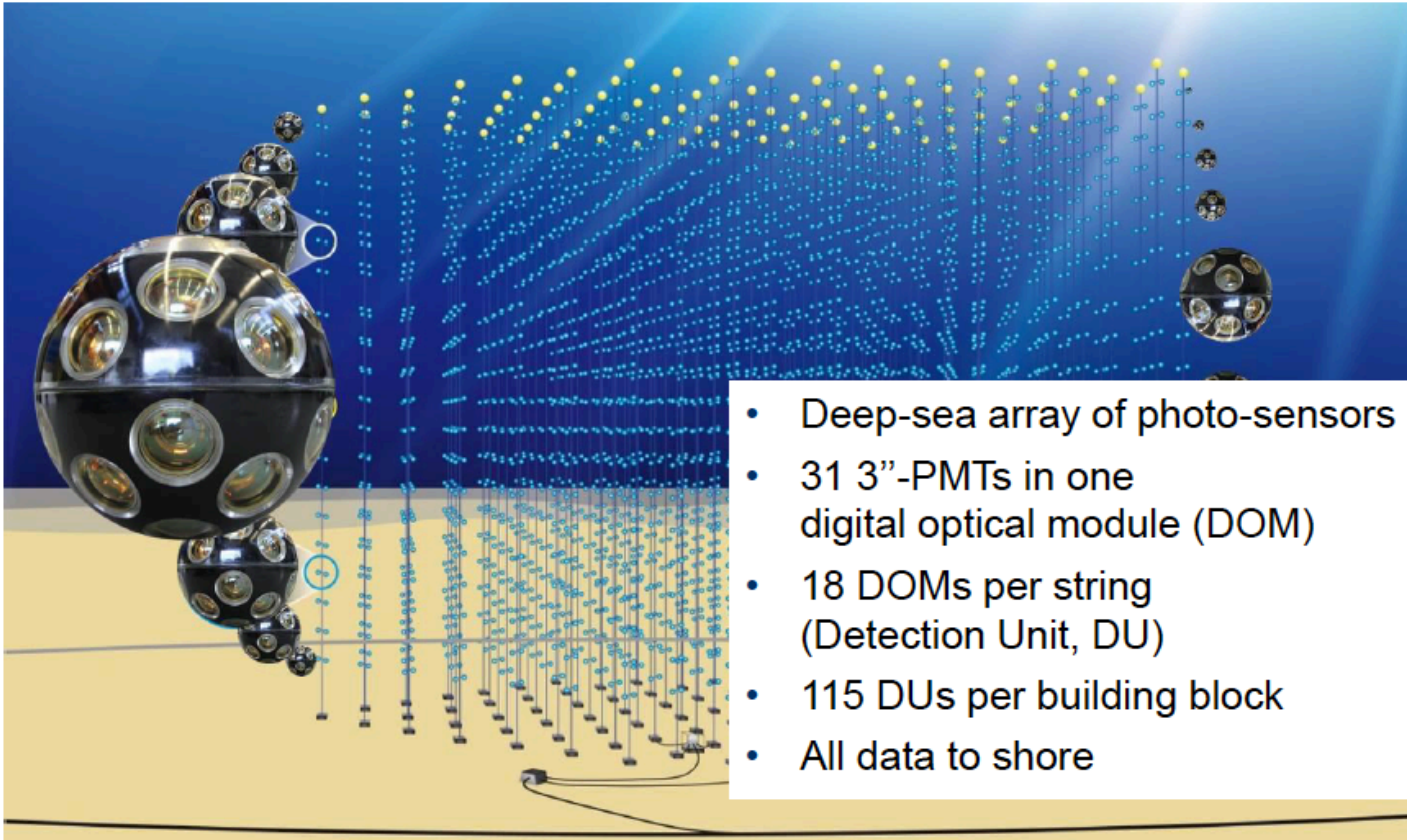


Next generation large volume neutrino detectors

The neutrino telescope world map 2018



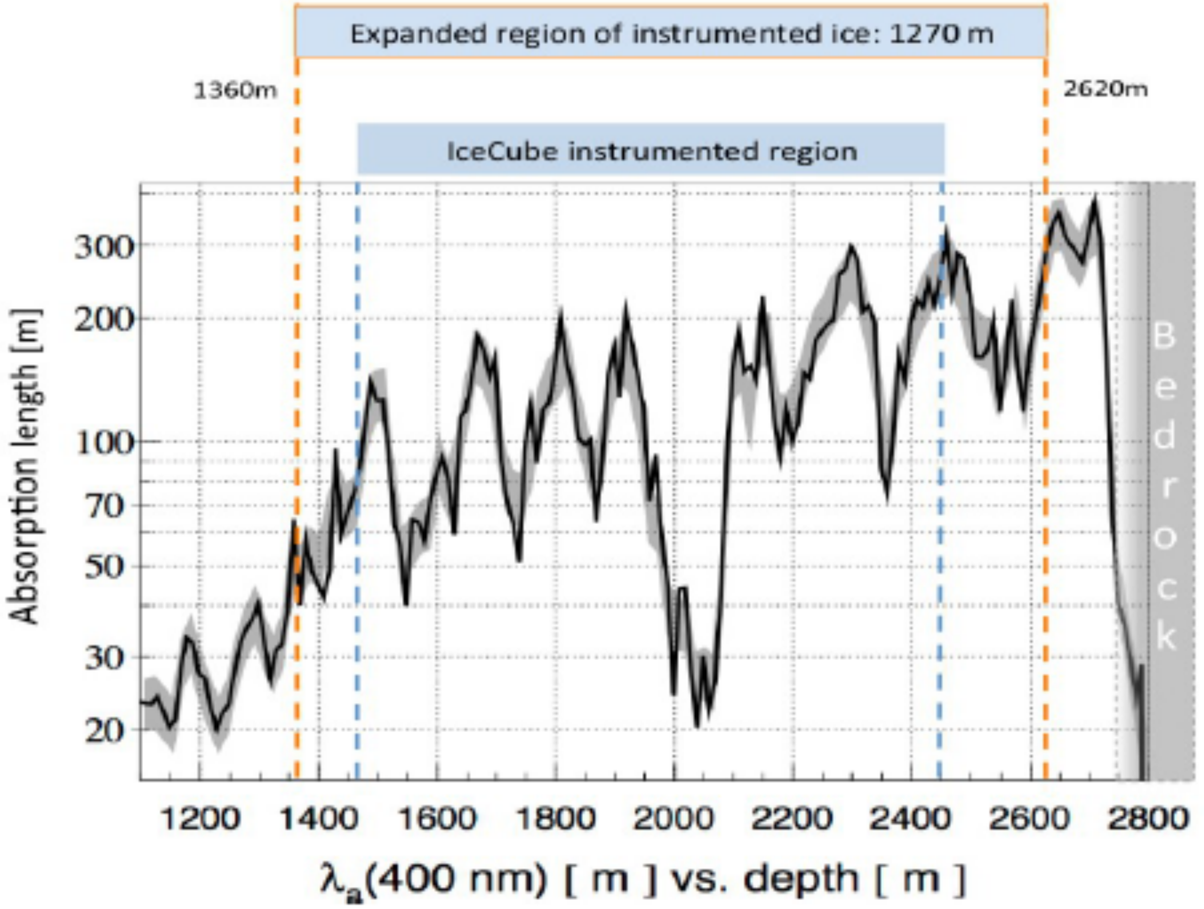
KM3NeT: the concept

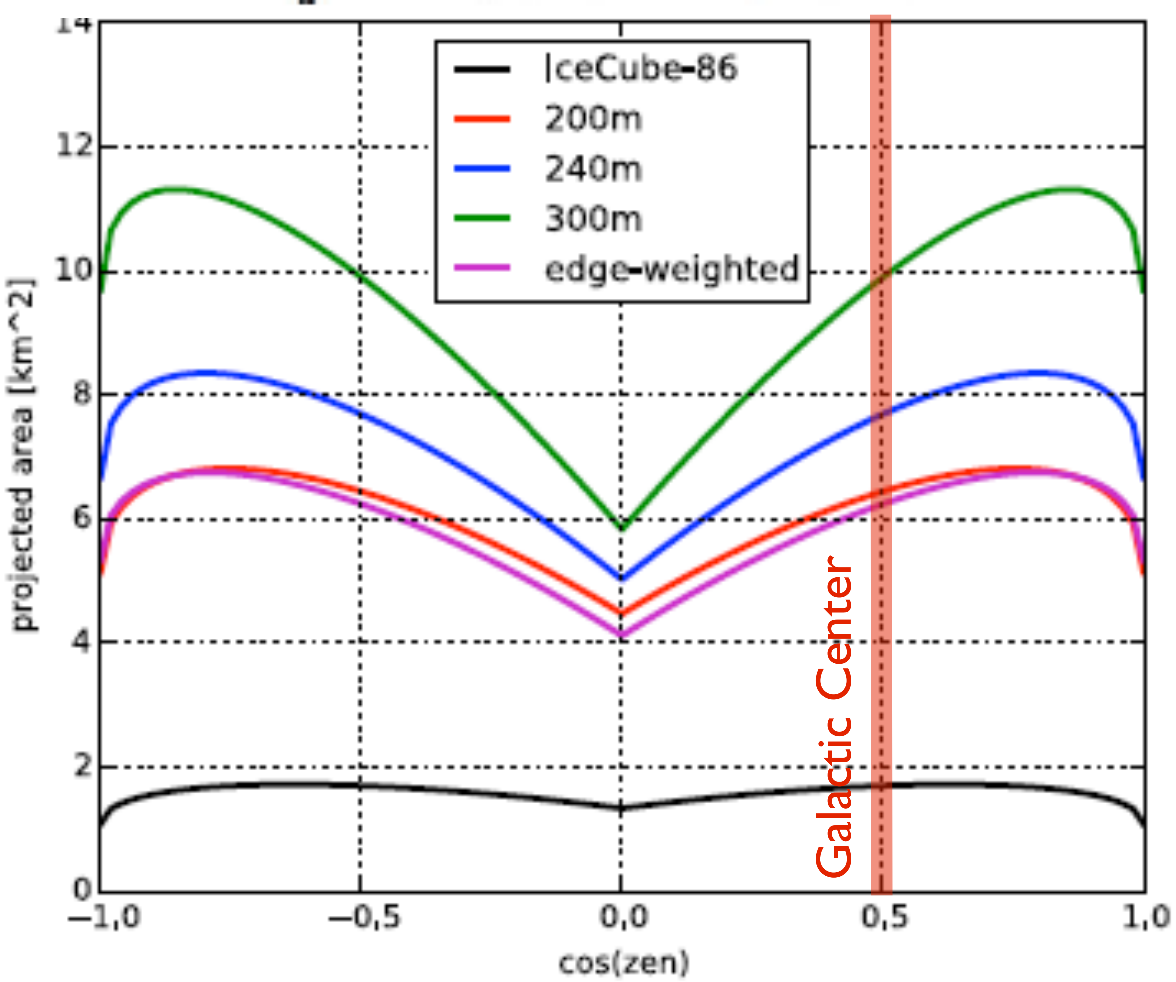


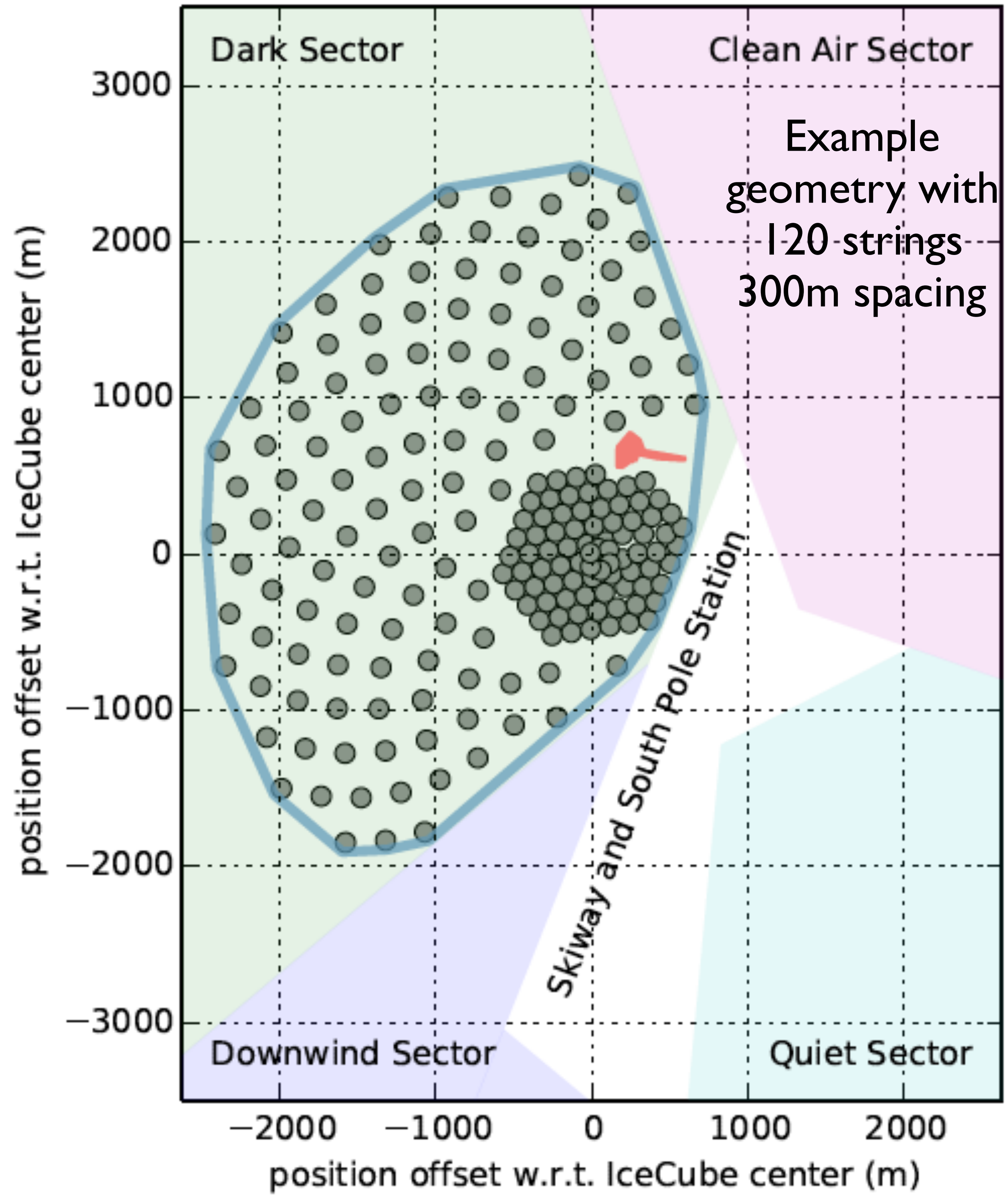
- Deep-sea array of photo-sensors
- 31 3"-PMTs in one digital optical module (DOM)
- 18 DOMs per string (Detection Unit, DU)
- 115 DUs per building block
- All data to shore

IceCube Gen 2

IceCube Coll. Gen2 LOI [arXiv:1412.5106]





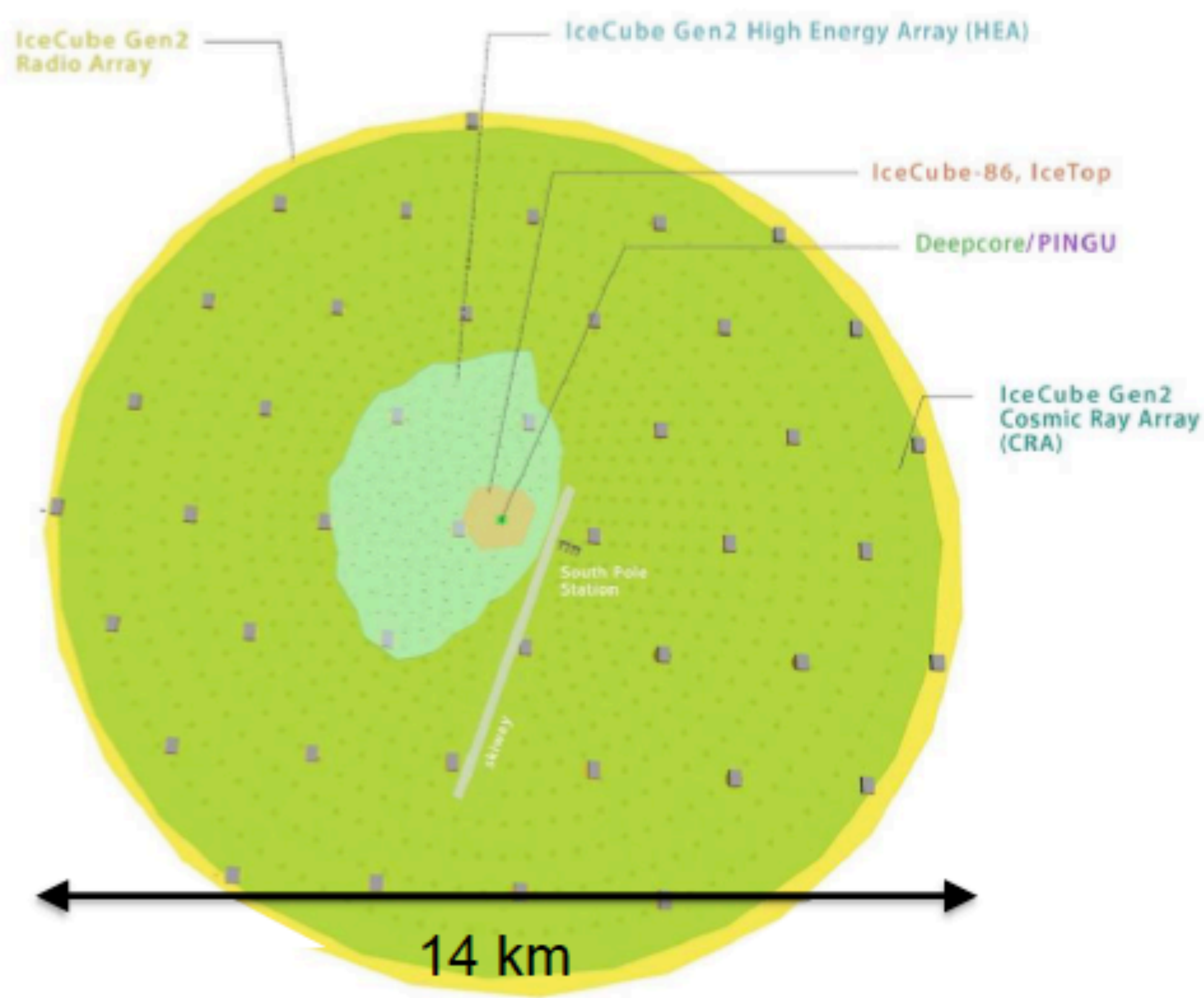


IceCube-Gen2

- Next-generation neutrino observatory at South Pole, with
  - High-energy deep-ice detector (High-energy array, HEA)
  - Cosmic-ray and veto surface array (CRA)
  - Radio array (RA)
  - High-density core for low-energy neutrinos (PINGU)
- Funding application expected in NSF MREFC scheme (~2020)

Deployment 2025-31 → time

The IceCube Gen2 Facility



Conclusions

Conclusions

- Neutrinos above 40TeV are expected to be absorbed in the Earth
- Neutrino absorption has been observed for the first time (IceCube Collaboration - Nature Vol 551, 596–600 (2017)) and neutrino cross sections measured in the TeV range
- Neutrino absorption measurements are more important to study high-energy neutrino cross sections
- Next generation large volume neutrino detectors are expected to allow for more precise Earth density profile measurements


Thanks !