Neutrino tomography of Earth

Andrea Donini (IFIC, Valencia)


in collaboration with:
S. Palomares-Ruiz
J. Salvadó
What neutrinos are...

\[ \beta\text{-decay} \]

\[ n \rightarrow p + e^- + \nu_e \]

(radioactivity...)
What neutrinos are...

Standard Model of Elementary Particles

### three generations of matter (fermions)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>2.2 MeV/c²</td>
<td>1.28 GeV/c²</td>
<td>173.1 GeV/c²</td>
</tr>
<tr>
<td>d</td>
<td>4.7 MeV/c²</td>
<td>96 MeV/c²</td>
<td>4.18 GeV/c²</td>
</tr>
<tr>
<td>e</td>
<td>0.511 MeV/c²</td>
<td>105.66 MeV/c²</td>
<td>1.7765 GeV/c²</td>
</tr>
<tr>
<td>ν_e</td>
<td>&lt;2.2 eV/c²</td>
<td>&lt;0.17 MeV/c²</td>
<td>&lt;18.2 MeV/c²</td>
</tr>
</tbody>
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### interactions / force carriers (bosons)

- g: gluon
- H: higgs
- γ: photon
- Z: Z boson
- W: W boson

**β-decay**

\[ n \rightarrow p + e^- + ν_e \]

(radiusactivity...)

**Other decays**

- \( π \rightarrow μ ν_μ \)
- \( K \rightarrow μ ν_μ , e ν_e \)
- \( μ \rightarrow ν_μ e ν_e \)
- \( τ \rightarrow ν_τ μ ν_μ , ν_τ e ν_e \)
What you need to know about neutrinos....

Neutrinos only interact **WEAKLY**
(no electromagnetic interactions, no strong interactions)
What you need to know about neutrinos....

Neutrinos only interact WEAKLY
(no electromagnetic interactions, no strong interactions)

(1) Detectors must be gigantic (1 km³)!

(2) The absorption length of a 40 TeV neutrino is the Earth’s diameter
What you need to know about neutrinos....

Neutrinos only interact WEAKLY
(nonelectromagnetically, no strong interactions)

(1) Detectors must...

(2) The absorption length of a 40 TeV neutrino is the Earth's diameter 

Lipari, NeuTel 2019, Venice
Neutrinos and geophysics

GEO-NEUTRINOS... (radiogenic heat)
Neutrinos and geophysics

GEO-NEUTRINOS... (radiogenic heat)

See, for example, Dye, Rev. Geophysics 50 (2012)

https://en.wikipedia.org/wiki/Geoneutrino
Neutrinos and geophysics

GEO-NEUTRINOS... (radiogenic heat)

and ATMOSPHERIC NEUTRINOS...

https://en.wikipedia.org/wiki/Geoneutrino
Atmospheric neutrinos

Model of Primary Cosmic Ray Flux

+  

Model of the interactions of Cosmic Rays with outer layers of the atmosphere

↓

Atmospheric Neutrino Flux
Why atmospheric neutrinos?

Using neutrinos to study the Earth’s interior is an old idea, first mentioned in an unpublished CERN preprint:

A. Placci and E. Zavattini, submitted in Oct 1973 to Nuovo Cimento; rejected?... never received?....

and in a talk:


In short: make a neutrino beam, and shoot far far away!

The idea was premature for the ‘70s! ... and for the ’80, the ’90s and the ‘00s...
However: an optimal source exists!

ATMOSPHERIC NEUTRINOS!

IceCube contribution to ICRC 2015, arXiv:1510.05223
Why atmo-ν are an optimal source?

IceCube contribution to ICRC 2015, arXiv:1510.05223
Two ways to scan the Earth with v’s

- Neutrino oscillations (< 1 TeV)

\[ P_{ee}^{\pm} = 1 - \left( \frac{\Delta_{23}}{B_{\pm}} \right)^2 \sin^2(2\theta_{13}) \sin^2 \left( \frac{B_{\pm} L}{2} \right) - \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2(2\theta_{12}) \sin^2 \left( \frac{A L}{2} \right) \]
Two ways to scan the Earth with ν’s

• Neutrino oscillations (< 1 TeV)

\[
P_{ee}^{\pm} = 1 - \left(\frac{A_{23}^{\pm}}{B_{23}^{\pm}}\right)^2 \sin^2(2\theta_{13}) \sin^2\left(\frac{B_{23}^{\pm} L}{2}\right) - \left(\frac{A_{12}^2}{A}\right)^2 \sin^2(2\theta_{12}) \sin^2\left(\frac{A L}{2}\right)
\]

Two ways to scan the Earth with ν’s

- Neutrino oscillations (< 1 TeV)

\[ P_{ee}^{\pm} = 1 - \left( \frac{\Lambda^{23}}{B_{\pm}} \right)^2 \sin^2(2\theta_{13}) \sin^2\left( \frac{B_{\pm} L}{2} \right) - \left( \frac{\Lambda^{12}}{A} \right)^2 \sin^2(2\theta_{12}) \sin^2\left( \frac{A L}{2} \right) \]


- Neutrino flux attenuation (> 1 TeV)

\[ \frac{d\phi_\nu(E, \tau)}{d\tau} = -\sigma_{tot}(E) \phi_\nu(E, \tau) \]
Two ways to scan the Earth with ν’s

• Neutrino oscillations (< 1 TeV)

\[ P_{ee}^\pm = 1 - \left( \frac{\Lambda_{\nu 3}^2}{B_{\nu \pm}} \right)^2 \sin^2(2\theta_{13}) \sin^2\left(\frac{B_{\nu \pm} L}{2}\right) - \left( \frac{\Lambda_{\nu 12}^2}{A} \right)^2 \sin^2(2\theta_{12}) \sin^2\left(\frac{A L}{2}\right) \]


• Neutrino flux attenuation (> 1 TeV)

\[ \frac{d\phi_\nu(E, \tau)}{d\tau} = -\sigma_{tot}(E)\phi_\nu(E, \tau) \]

\[ \sigma_{tot} = \sigma_{\nu N} \times \rho \]

The IceCube Experiment

Halzen, NeuTel 2019, Venice

EGU 2019 General Assembly, 9-4-2019
The IceCube Experiment

- Deployed in glacial ice at the South Pole
- Array size 1 km³, 86 strings, 60 optical sensors (DOMs) per string
The IceCube IC86 data sample

- Data taking: 2011-2012
- 20145 muons
- $E_\mu = [400 \text{ GeV} \div 20 \text{ TeV}]$
- Good reconstruction of $\nu$ energy and direction
- PUBLICLY AVAILABLE!
- 7 more years of data are not (yet) available.....

C. de los Heros, NeuTel 2019, Venice
Raw data as a function of $E_\mu$ and $\theta$
Comparison with expectations

- Atmospheric Neutrino Flux
- Propagation through Earth
- Interaction with nucleons
- Detector simulation
Our Earth’s model

5 spherical layers

Inner Core, one layer
$L_1 = 1242$ km

Outer Core, two layers
$L_2 = 2373$ km,
$L_3 = 3504$ km

Mantle, two layers
$L_4 = 4938$ km,
$L_5 = 6371$ km

No crust!
Our Earth’s model

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No crust!

ICB and CMB fixed!
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 by ν’s

FIRST ELECTROWEAK MEASUREMENT OF THE EARTH’S MASS

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

Gravitational measurement of the Earth’s mass

\[ M_{\text{earth-\text{grav}}} = (5.9722 \pm 0.0006) \times 10^{24} \text{ kg} \]
The Earth’s mass by ν’s

Gravitational measurement of the Earth’s mass

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

NO (SIGNIFICANT AMOUNT OF) DARK MATTER INSIDE THE EARTH!
The Earth’s moment of inertia

Electro-weak measurement of the Earth’s moment of inertia

\[ I_{\text{earth-v}} = (6.9 \pm 2.4) \times 10^{37} \text{ kg m}^2 \]

Gravitational measurement of the Earth’s moment of inertia

\[ I_{\text{earth-grav}} = (8.01736 \pm 0.00097) \times 10^{37} \text{ kg m}^2 \]
Earth’s non-homogeneity

Electro-weak measurement of the Core-Mantle discontinuity

\[ \Delta \rho_{\text{CMB-\nu}} = (13^{+5.8}_{-6.3}) \text{ g/cm}^3 \]

A homogenous Earth has a p-value \( p = 0.01 \) !!!

2008 Claim: IceCube could reject a homogeneous Earth at 5\( \sigma \) in ten years
The Earth’s core mass

Electro-weak measurement of the Earth’s core mass

\[ M_{\text{core-\nu}} = (2.7^{+1.0}_{-0.9}) \times 10^{24} \text{ kg} \]
1-d density profile with 10 years

SIMULATED DATA (FROM PREM)!
Conclusions

AN EPIPHANITY:
It is eventually possible to make a neutrino tomography of the Earth: first 1-dimensional density profile (with just one year of IceCube data)!

\[
M_{\text{earth}}, I_{\text{earth}}, \Delta \rho_{\text{CMB}}, M_{\text{core}}
\]

Precision will hugely increase as soon as 7 other years of IceCube data will become accessible! We hope to present the new results here NEXT YEAR!
Outlook

New Neutrino Telescopes are under construction:
1) Increase in statistics will be ~ 10 x faster;
2) We will look at the Earth’s interior from both emispheres (test of anisotropies)

By ~ 2030: 6-8 km$^3$ optical detectors in the Southern and Northern emispheres
Complementarity with Geophysics

**Neutrino Physics** may provide *independent constraints* on the mass distribution inside the Earth that may be used by seismological modeling.

**Direct testing of the Inner Core**: equation of state, composition, density jump....

**Neutrino Data** useful for Earth’s Tomography will pour out FOR FREE, as neutrino telescopes are being built for other purposes.
Backup slides
The Earth’s gravitational acceleration profile
The Earth’s gravitational profile is needed to compute $\rho(r)$ from earthquake waves velocities.

Free-fall acceleration of Earth

The diagram shows the acceleration in m/s² as a function of the radius in 1000 km. The Earth's gravitational profile is indicated with different density models, including PREM and constant density curves. The core, mantle, and space regions are color-coded for clarity.
The Earth’s gravitational profile is needed to compute $\rho(r)$ from earthquake waves velocities.
The Earth’s gravitational profile is needed to compute $\rho(r)$ from earthquake waves velocities.
The Earth's gravitational profile is needed to compute $\rho(r)$ from earthquake velocities.

A GOOD NEUTRINO MEASUREMENT OF $g(r)$ COULD BE ADDED TO SEISMOLOGY AS A CONSTRAINT TO REDUCE ERRORS.
Older Forecasts
“Recent” forecasts, 1

After 10 years of data taking at PINGU or ORCA using neutrino oscillations

Winter, Nucl. Phys B908 (2016)
“Recent” forecasts, 1

After 10 years of data taking at PINGU or ORCA using neutrino oscillations

Winter, Nucl. Phys B908 (2016)
“Recent” forecasts, 2

After 10 years of data taking at IceCube using neutrino attenuation

Claim: IceCube could reject a homogeneous Earth at 5σ in ten years

Our Forecast with 10 years of data

A much finer modelling of the Earth could be done

Test of the Inner-Outer Core discontinuity

Independent localization of the Core-Mantle Boundary
Data analysis
Neutrino propagation

Propagation through the Earth with v-SQuIDs


- Neutrino Oscillations: evolution Hamiltonian in matter (dominant below 1 TeV)
- Neutrino Attenuation: inelastic CC and NC interactions with matter (dominant above 1 TeV)
- Neutrino regeneration due to tau decays
- Migration to lower energy bins due to NC interactions
Neutrino-nucleon interaction

Parton distribution functions: HERAPDF

$vN$ ($\bar{v}N$) cross-sections at 2-3% (4-10%) errors

ICECUBE MEASUREMENT

$1.30^{+0.21}_{-0.19}$ (stat) $^{+0.39}_{-0.43}$ (syst) $\times \sigma_{SM}$

We use the official IceCube MC to map $E_\mu^{\text{obs}}, \theta_\mu^{\text{obs}}$ into $E_\nu^{\text{rec}}, \theta_\nu^{\text{rec}}$. 

Detector simulation
The IC86 Data Sample: $N_{\text{data}}/N_{\text{noatt}}$

Full sample

For $\cos \theta > -0.6$, attenuation can be as large as 50%
Systematics
Systematics importance

- **DOM efficiency**
- **Flux continuous parameters**
  - spectral index
  - $\pi/K$ ratio
  - $\nu/\bar{\nu}$ ratio Full Implementation
- Air shower hadronic models *Marginally irrelevant* precise check
- Primary cosmic ray fluxes *Marginally irrelevant* precise check
- Hole Ice *Irrelevant*
- Neutrino cross sections *Irrelevant*
- Bulk ice scattering/absorption *Irrelevant*

*continuous systematics*
*discrete systematic*
Systematics importance

- **DOM efficiency**
- **Flux continuous parameters**
  - spectral index
  - $\pi/K$ ratio
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- Air shower hadronic models Marginally irrelevant precise check
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- Hole Ice Irrelevant
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- Bulk ice scattering/absorption Irrelevant

**continuous systematics**
**discrete systematic**
Systematics importance

- DOM efficiency
- Flux continuous parameters
- Air shift
- Primaries
- Hole
- Neutrals
- Bulk ice

Irrelevant

Not taken into account:
OPTICAL PROPERTIES OF THE ICE

continuous systematics
discrete systematic
Flux dependence, IC86
Results for different models

<table>
<thead>
<tr>
<th></th>
<th>Piecewise flat Earth's profile</th>
<th>PREM Earth's profile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>HG-GH-H3a + QGSJET-II-04</td>
<td>HG-GH-H3a + SIBYLL2.3</td>
</tr>
<tr>
<td>$M'_\oplus$ [10^{24} kg]</td>
<td>6.0^{+1.6}_{-1.3}</td>
<td>5.5^{+1.5}_{-1.3}</td>
</tr>
<tr>
<td>$M^\nu_{\text{core}}$ [10^{24} kg]</td>
<td>2.72^{+0.97}_{-0.89}</td>
<td>2.79^{+0.98}_{-0.85}</td>
</tr>
<tr>
<td>$I^\nu_{\oplus}$ [10^{37} kg cm^2]</td>
<td>6.9 ± 2.4</td>
<td>5.4^{+2.3}_{-1.9}</td>
</tr>
<tr>
<td>$\bar{\rho}^\nu_{\text{core}} - \bar{\rho}^\nu_{\text{mantle}}$ [g/cm^3]</td>
<td>13.1^{+5.8}_{-6.3}</td>
<td>14.0^{+6.0}_{-5.9}</td>
</tr>
<tr>
<td>$p$ value</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>mantle denser than core</td>
<td></td>
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</tbody>
</table>
Flux dependence, 10 years forecast
Earth’s profile dependence, IC86
Impact of systematics on the error
Errors
What are the dots in the 1d profile?

“Central values” represent the Maximum of the Posterior Probability
Asymmetric credibility intervals

\[ \rho_1 \text{ [g cm}^{-3}\text{]} \]

\[ \rho_5 \text{ [g cm}^{-3}\text{]} \]
Asymmetric credibility intervals

“Credibility intervals” are the shortest intervals covering 68% of the posterior probability.
Constrained fits
Impact of external constraints

• Gravitational measurement of the Earth’s mass

\[ M_\oplus = \frac{4\pi}{3} \int_0^{R_\oplus} drr^2 \rho(r) = 5.972 \times 10^{24} \text{kg} \]

• A derived quantity: Earth’s mean moment of inertia

\[ I_\oplus = \frac{8\pi}{3} \int_0^{R_\oplus} drr^4 \rho(r) = 0.3307144M_\oplus R^2_\oplus \]

A constant density would give \[ I_\oplus(\rho(r) = \rho_0) = 0.4 M_\oplus R^2. \]
Impact of external constraints

Adding the gravitational Earth’s mass as an external constraint, results in fixing the mantle density:

$$\rho_5 = [1.22-4.78] \text{ g/cm}^3 \rightarrow [4.43-4.79] \text{ g/cm}^3$$

Rather small impact on the core density, instead:

$$\rho_{\text{core}} = [10.2-20.8] \text{ g/cm}^3 \rightarrow [9.7-18.6] \text{ g/cm}^3$$
What I know about seismology
How densities are measured?

seismology

O(100)/year earthquakes with magnitude larger than 6
Density at different depths

Earth’s average density: $\rho = 5.5148 \text{ g/cm}^3$

(granite density is 2.7 g/cm$^3$)
1-dimensional density profile

Preliminary Reference Earth Model

Uncertainties on the core density...

Uncertainties on the crust density...

Density variation in the CRUST for different parameter choices: 3-5%

The Earth’s core

The OUTER CORE IS LIQUID, whereas the INNER CORE IS SOLID (source of the geodynamo)

IT IS VERY DIFFICULT TO HAVE DIRECT INFORMATIONs from the INNER CORE

Mostly through global constraints and extrapolations
Strong dependence of the IC density on temperature, pressure and composition

Estimated temperature range still very large: 4000-10000 K

Composition guessed (iron-nickel?)

Missing Xenon problem

Nice pictures
Events at IceCube

de los Heros, NeuTel 2019, Venice
Near-term improvements to calibration and low-energy sensitivity
IceCube has provided an amazing sample of events, but is still limited by the small number of events few 10’s of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument up to an order of magnitude larger volume

Kopper, NeuTel 2019, Venice
Largest underwater neutrino telescope running since 2007 (complete 2008) in the Mediterranean Sea.

12 lines -> 350 m height surface area 0.1 km²
KM3NeT: ORCA & ARCA

Ref: KM3NeT LoI - J.Phys. G43 (2016) no.8, 084001

Cities and Sites of KM3NeT

ORCA:
1 DENSE BUILDING BLOCK
OPTIMISED FOR INTERMEDIATE ENERGIES (1-100 GEV)

ARCA:
2 SPARSE BUILDING BLOCKS
OPTIMISED FOR HIGH ENERGIES (>1 TEV)

Domi, NeuTel 2019, Venice
Suvorova, NeuTel 2019, Venice