Earth tomography with KM3NeT/ORCA

Lukas Maderer
Neutrino GeoScience workshop, Prague, 21/10/2019

On behalf of the KM3NeT collaboration

Work done in collaboration with Edouard Kaminski, IPGP
Outer core density ~10% below pure Iron => lighter elements present
Mantle: density anomalies?

- Composed of Pyrolite
- S-wave velocity anomalies
  => different densities
Reason: Temperature or composition
Atmospheric neutrinos

\[ E^2 \Phi_{\nu} \text{[GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

- IC-59 $\nu_\mu$ Unfolding
- AMANDA $\nu_\mu$ unfolding
- IC-79 $\nu_\mu$ flux
- ANTARES $\nu_\mu$
- Honda H3a + ERS
- Honda H3a
- Frejus $\nu_\mu$
- Frejus $\nu_\mu$ model
- Frejus $\nu_\mu$ model
- Honda $\nu_e$

arxiv.1409.4535

~1 particle/(cm$^2$ sec sr)

cosmic radiation (p, He, ...)

$\mu^-$

$\pi^-$

$\nu_\mu$

$\bar{\nu}_e$

$\pi^+$

$\pi^0$

$\gamma$

$\gamma$

$e^-$

hadronic shower

electromagnetic shower

$h=10$ to $20$ km

Lukas Maderer, Neutrino GeoScience, 21/10/2019
Earth surface * atm. neutrino flux:
~$10^{17}$ neutrinos pass through the Earth every second

Detection of neutrinos can provide information about the Earth’s interior

=> **Earth tomography with neutrinos**
Neutrino oscillations

• Neutrino oscillations: flavour changes during propagation

• Eigenstates of interaction (flavour) and propagation (mass) different

• Two possible neutrino mass hierarchies

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{\alpha,i} \times \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

"KM3NeT LoI" (2016)
Neutrino oscillations

\[ P(\alpha \rightarrow \beta; t) = \delta_{\alpha\beta} - 4 \sum_{j > i} U_{\alpha i} U_{\alpha j} U_{\beta i} U_{\beta j} \sin^2 \frac{\Delta_{ij}}{2} \]

\[ \Delta_{ij} = \frac{E_i - E_j}{\hbar} t = 2.534 \frac{\Delta m_{ij}^2}{\text{eV}^2} \cdot \frac{L}{\text{km}} \frac{1}{E/\text{GeV}} \]

Example:

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\Theta_{13} \sin^2 \Theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) \]
Oscillation tomography

- Interaction between $\nu_e$ and $e$ in Earth:

$$P_{3\nu}^{m}(\nu_{\mu} \rightarrow \nu_{e}) \approx \sin^{2}\theta_{23} \sin^{2}2\theta_{13}^{m} \sin^{2}\left(\frac{\Delta m^{2}L}{4E_{\nu}}\right)$$

$$\sin^{2}2\theta_{13}^{m} \equiv \sin^{2}2\theta_{13} \left(\frac{\Delta m_{31}^{2}}{\Delta m_{m}^{2}}\right)^{2}$$

$$\Delta m_{m}^{2} \equiv \sqrt{(\Delta m_{31}^{2} \cos 2\theta_{13} - 2E_{\nu}A)^{2} + (\Delta m_{31}^{2} \sin 2\theta_{13})^{2}}$$

- Impact on oscillation probability:

- Resonance effects for $E_{res} \equiv \frac{\Delta m_{31}^{2} \cos 2\theta_{13}}{2\sqrt{2}G_{F}N_{e}}$

  $$\approx 3 \text{ GeV (core)}$$

  $$\approx 7 \text{ GeV (mantle)}$$
Oscillation tomography: core

Measured in neutrino oscillation patterns

\[ N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{\text{matter}} \]

Constrain Z/A in core

Typical values of Z/A for chemical elements or alloys present in the Earth

- 0.39: Pb
- 0.4656: pure Fe
- 0.4957: alloy Fe + light elements
- 0.56: pyrolite
- 1: H

Oscillation tomography is sensitive to Earth core composition

assumed known matter density profile from PREM model

Lukas Maderer, Neutrino GeoScience, 21/10/2019
Oscillation tomography: mantle

Measured in neutrino oscillation patterns

\[ N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{\text{matter}} \]

Constrain inhomogenities in matter density profile

Assumed known for mantle on average

Oscillation tomography is sensitive to density inhomogenities
Neutrino detection
Neutrino detection

• Light signature dependent on neutrino flavour and interaction type (CC or NC)
• Algorithms reconstruct energy and direction of the neutrino
• Particle identification (PID) with machine learning: shower-, track-like

Taken from arXiv:1207.4952
ORCA detector

• 115 strings in the Med. Sea
  - Length: 200m
  - Horizontal spacing 23m
  - Instrumented volume $\sim 5.5 \times 10^6 \, m^3$
  - 2450m depth
  - 18 DOMs per string

• Digital Optical Module (DOM):
  - 42cm diameter
  - 31 photo-sensors
  - Vertical spacing 9m
  - Detection of Cherenkov light

• Status: 4 strings deployed
ORCA: core & mantle tomography

- Earth density profile: 42-steps PREM model
- 3 chemical layers
- Log-likelihood ratio analysis for outer core and mantle
Example: outer core tomography

1. Assume a ’’true’’ Z/A
2. Compare to a hypothetical Z/A
3. Calculate difference
   => Confidence level for excluding hypothesis

See also:
PINGU LoI, arXiv:1401.2046
ORCA: outer core (interacting events)

Z/A varied by 5% in outer core only: ORCA 10 years, perfect detector

\[
\text{signed } \chi^2(\text{bin } i) = \frac{(n^i_A - n^i_B) \times |n^i_A - n^i_B|}{n^i_A}
\]
ORCA: detector response

- Theoretical signal more visible in muon (track) channel and for outer core
- Detector effects described by response matrix from full MC simulations:
  
  - True \((E, \cos \theta_\zeta, Y_{\text{Bj}})\)
  - True channel:
    - CC \(\nu_e/\bar{\nu}_e, \nu_\mu/\bar{\nu}_\mu, \nu_\tau/\bar{\nu}_\tau\)
    - NC \(\nu/\bar{\nu}\)

  Reconstruction & Classification
  - Reco \((E, \cos \theta_\zeta, Y_{\text{Bj}})\)
  - Event classification ("flavour ID"):
    - Track / Cascade / \(\mu_{\text{atm}}\)

  ➢ Both channels end up with comparable contributions to \(\chi^2\) (outer core):

Track-like id., \(\chi^2 = 0.3\) (10 years)

Shower-like id., \(\chi^2 = 0.4\) (10 years)
ORCA: sensitivity

Single layer fit uncertainties for 10 years livetime:
- Mantle: > 3.1%
- Outer core: > 5.7%

Combined measurement shows no correlation
=> No "shielding" by outer layers

Lukas Maderer, Neutrino GeoScience, 21/10/2019
Summary and outlook

Oscillation tomography
• inform on Earth composition (actually on $\rho \times Z/A$), main systematics: atmospheric neutrino flux, detector response
• to resolve first the neutrino mass hierarchy need

Outlook
• Opportunity for combined measurements: reconstruction of 3D density profiles →Possibility to resolve large-scale inhomogeneities in the lower mantle
• needs large statistics of events at $\sim$GeV energies: next Generation detectors?
Also see poster of Véronique van Elewyck
Backup
Neutrino oscillations

- Oscillation probability depends on:
  - $\Delta m_{ij}^2$, $U_{i\alpha}$
  - Propagation length $L$
  - Neutrino energy
- Red: $\nu_e$, Blue: $\nu_\mu$
- Solid: NH assumed
  Dashed: IH assumed

"KM3NeT LoI" (2016)
Event example
Atmospheric neutrinos

• Hadronic showers in the atmosphere due to cosmic rays:
  main contribution from pion decay: \( \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \)

• Flux uncertainties \( \sim 15\% \)

KM3NeT LOI (2016)

Honda et al. (2015)
Z/A varied by 5% in outer core only: ORCA 10 years, perfect detector

\[ \chi^2(\text{bin } i) = \frac{(n_A^i - n_B^i) \times |n_A^i - n_B^i|}{n_A^i} \]
### Treatment of parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>treatment</th>
<th>true value</th>
<th>prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta M^2</td>
<td>(\text{eV}^2)$</td>
<td>fitted</td>
</tr>
<tr>
<td>$\Delta m^2_{21} (\text{eV}^2)$</td>
<td>fix</td>
<td>$7.53 \cdot 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$\theta_{13} (^\circ)$</td>
<td>fitted</td>
<td>8.42</td>
<td>0.26</td>
</tr>
<tr>
<td>$\theta_{12} (^\circ)$</td>
<td>fix</td>
<td>33.4</td>
<td>–</td>
</tr>
<tr>
<td>$\theta_{23} (^\circ)$</td>
<td>fitted</td>
<td>$38 - 52$</td>
<td>free</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>fitted</td>
<td>0 – $2\pi$</td>
<td>free</td>
</tr>
<tr>
<td>Flux spectral tilt</td>
<td>fitted</td>
<td>0</td>
<td>free</td>
</tr>
<tr>
<td>$\nu/\bar{\nu}$ skew</td>
<td>fitted</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Tracks normalisation</td>
<td>fitted</td>
<td>1</td>
<td>free</td>
</tr>
<tr>
<td>Cascades normalisation</td>
<td>fitted</td>
<td>1</td>
<td>free</td>
</tr>
<tr>
<td>NC events normalisation</td>
<td>fitted</td>
<td>1</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Neutrino cross section

Formaggio et al. (2013)
Log-likelihood-ratio analysis

\[ L_{\text{hyp}}(d | \eta) = \prod_{i=0}^{N_{\text{class}}-1} \prod_{b=0}^{N_{\text{bins}}-1} \exp \left[ - (\mu_{\text{hyp}})_b^i \right] \frac{[(\mu_{\text{hyp}})_b^i]^{n_b^i}}{n_b^i!} \]

\[ \Delta \chi^2 = -2\ln T = \min_{\eta} \left[ -2\ln L_{\text{NH}}(d | \eta) \right] - \min_{\eta} \left[ -2\ln L_{\text{IH}}(d | \eta) \right] \]

\[ -2\ln L_{\text{hyp}} = \sum_{i=0}^{N_{\text{class}}-1} \sum_{b=0}^{N_{\text{bins}}-1} \left[ - (\mu_{\text{hyp}})_b^i + n_b^i \ln(\mu_{\text{hyp}})_b^i - \ln(n_b^i!) \right] \]

\[ \chi^2_{\text{hyp}}(d | \eta) = \sum_{i=0}^{N_{\text{class}}-1} \sum_{b=0}^{N_{\text{bins}}-1} \left[ (\mu_{\text{hyp}})_b^i - n_b^i + n_b^i \ln \left( \frac{n_b^i}{(\mu_{\text{hyp}})_b^i} \right) \right]. \]

\[ \Delta \chi^2 = \min_{\eta} \left[ \chi^2_{\text{NH}}(d | \eta) \right] - \min_{\eta} \left[ \chi^2_{\text{IH}}(d | \eta) \right] \]

\[ \eta = \text{nuisance parameters} \]

\[ d = \text{data} \]
ORCA: sensitivity

Single layer fit uncertainties for 10 years livetime:

- Outer core: > 3.1%
- Mantle: > 5.7%

Test Z/A mantle
- Fit Z/A core only
- core + 3 osc.
- core + 4 osc. + 8 syst.

Test Z/A outer core
- Fit Z/A mantle only
- mantle + 3 osc.
- mantle + 4 osc. + 8 syst.

KM3NeT Preliminary

Pure Iron

KM3NeT Preliminary

True NH

True IH