Atmospheric neutrino oscillations for Earth Tomography

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DESY, Zeuthen

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Manifestation of a new paradigm: precision physics in lepton sector

Where else can this lead us to? Neutrino tomography of Earth?

Nobel prize 2015: Neutrino oscillations

Nobel prize 2015: Neutrino oscillations
Impressions from Neutrino 2016
Neutrino tomography: Principle approaches

Matter effects in neutrino oscillations

> Coherent forward scattering in matter leads to phase shift

> Net effect on electron flavor:

\[ \nu_e \rightarrow e^- \]

\[ e^- \rightarrow \nu_e \]

(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

(Earth matter does not contain muons and taus!)

> Depends on \( n_e \sim Y \rho/m_N \),
Y=Z/A ~ 0.5 (electrons per nucleon)
Somewhat composition-dependent!

> Relevant energy ~3-6 GeV (later)

Relevant for \( E \gg 10 \text{ TeV} \)
Competitive scenarios?
See e. g. Gonzalez-Garcia et al, PRL 100 (2008) 061802

Neutrino absorption of energetic neutrinos

Matter profile of the Earth
... as seen by a neutrino

(PREM: Preliminary Reference Earth Model)
Neutrino oscillations in matter [for two flavors, constant matter density]

> Oscillation probabilities in
vacuum: \[ P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \]
matter: \[ P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E} \]

\[ \Delta \tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi}, \]
\[ \xi \equiv \sqrt{\sin^2 2\theta + \left( \cos 2\theta - \tilde{A} \right)^2}, \]
\[ \tilde{A} = \frac{2E\nu}{\Delta m^2} = \pm 2\sqrt{2E}G_F n_e \frac{\Delta m^2}{\Delta m^2} \Rightarrow \text{MO} \]

Resonance energy (from \( \tilde{A} \rightarrow \cos 2\theta \)):
\[ E_{\text{res}} \ [\text{GeV}] \sim 13 \, 200 \cos 2\theta \frac{\Delta m^2 \ [\text{eV}^2]}{\rho \ [\text{g/cm}^3]} \]

For \( \nu_\mu \) appearance, \( \Delta m_{31}^2 \):
- \( \rho \sim 4.7 \, \text{g/cm}^3 \) (Earth’s mantle): \( E_{\text{res}} \sim 6.4 \, \text{GeV} \)
- \( \rho \sim 10.8 \, \text{g/cm}^3 \) (Earth’s outer core): \( E_{\text{res}} \sim 2.8 \, \text{GeV} \)
Mantle-core-mantle profile


> Probability for L=11810 km

- Core resonance energy
- Mantle resonance energy

Threshold effects expected at:
- 2 GeV
- 4-5 GeV

Oscillation length ~ mantle-core-mantle structure

Parametric enhancement.

Best-fit values from arXiv:1312.2878

Naive L/E scaling does not apply!
Neutrino oscillations with varying profiles, numerically

> Evolution operator method:

\[ \mathcal{V}(x_j, n_j) = e^{-iH(n_j)x_j} \]

\( H(n_j) \): Hamilton operator in constant electron density \( n_j \)

> Matter density from \( n_j = Y \frac{\rho_j}{m_N} \), \( Y \): electrons per nucleon (\( \sim 0.5 \))

> Probability:

\[ P_{\alpha\beta} = \left| \langle \nu_\beta | \mathcal{V}(x_m, n_m) \cdots \mathcal{V}(x_1, n_1) | \nu_\alpha \rangle \right|^2 \]

> NB: There is additional information through *interference* compared to absorption tomography because

\[ [\mathcal{V}(x_i, n_i), \mathcal{V}(x_j, n_j)] \neq 0 \text{ für } n_i \neq n_j \]
Example: structural resolution with a single baseline (11750 km) [genetic algorithm reconstruction method used]

Some characteristic examples close to $1\sigma$, $2\sigma$, $3\sigma$ (14 d.o.f.)

Can reconstruct mantle-core-mantle profile

Fluctuations on short scales ($\ll L^{\text{osc}}$) cannot be resolved

Cannot localize mantle-core-boundary

Cannot resolve very small density contrasts

Towards realistic applications

- Need very large number of neutrinos in relevant energy range.
  **Point towards oscillations of atmospheric neutrinos**

- Assumption: Cannot afford any additional equipment; spin-off from other measurement.
  **Use Mt-sized density upgrades of neutrino telescopes (PINGU, ORCA)**

See talks by J. Koskinen and J. Barrios-Marti on Monday

- Key issue: complicated analysis; need to deal with multi-parameter correlations for “proof of principle”
Towards realistic applications

> Layers inspired by REM model: where highest sensitivity?

> Self-consistent simulation of mass ordering sensitivity and matter profile sensitivity

Include systematics (12), correlations among matter layers (7) and with oscillation parameters (6)
Expected matter profile precision – proof of principle

<table>
<thead>
<tr>
<th>Layer</th>
<th>PINGU</th>
<th>ORCA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Crust (1)</td>
<td>No sens.</td>
<td>No sens.</td>
</tr>
<tr>
<td>Lower Lithosphere (2)</td>
<td>No sens.</td>
<td>No sens.</td>
</tr>
<tr>
<td>Upper Mesosphere (3)</td>
<td>$-53.4/ + 55.0$</td>
<td>No sens.</td>
</tr>
<tr>
<td>Transition zone (4)</td>
<td>$-79.2/ + 38.3$</td>
<td>No sens./ + 72.2</td>
</tr>
<tr>
<td>Lower Mesosphere (5)</td>
<td>$-5.0/ + 5.2$</td>
<td>$-10.5/ + 11.6$</td>
</tr>
<tr>
<td>Outer core (6)</td>
<td>$-7.6/ + 8.2$</td>
<td>$-40.2$/ No sens.</td>
</tr>
<tr>
<td>Inner core (7)</td>
<td>No sens.</td>
<td>No sens.</td>
</tr>
</tbody>
</table>

Matter profile sensitivity. Example: ORCA

- Highest precision in lower mantle (5)
- Outer core sensitivity suffers from detection threshold
- Inner core requires better resolutions

Outlook: Core composition measurement

- Same relative precisions apply to composition (degeneracy: $n_e \sim Y \rho$)
- Very difficult measurements, as core composition models deviate in $Y$ (electron fraction) by at most one percent

<table>
<thead>
<tr>
<th>Model name</th>
<th>Z/A ratio</th>
<th>Si(wt%)</th>
<th>O(wt%)</th>
<th>S(wt%)</th>
<th>C(wt%)</th>
<th>H(wt%)</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-light-element model (maximum abundance)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe+18wt%Si</td>
<td>0.4715</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Poirier $^{29}$</td>
</tr>
<tr>
<td>Fe+11wt%O</td>
<td>0.4693</td>
<td>-</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Poirier $^{29}$</td>
</tr>
<tr>
<td>Fe+13wt%S</td>
<td>0.4699</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>Li and Fei $^4$</td>
</tr>
<tr>
<td>Fe+12wt%C</td>
<td>0.4697</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
<td>Li and Fei $^4$</td>
</tr>
<tr>
<td>Fe+1wt%H</td>
<td>0.4709</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>Li and Fei $^4$</td>
</tr>
<tr>
<td>Multiple-light-element model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allegre2001</td>
<td>0.4699</td>
<td>7</td>
<td>5</td>
<td>1.21</td>
<td>-</td>
<td>-</td>
<td>Allègre et al. $^{26}$</td>
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<tr>
<td>McDonough2003</td>
<td>0.4682</td>
<td>6</td>
<td>0</td>
<td>1.9</td>
<td>0.2</td>
<td>0.06</td>
<td>McDonough $^{27}$</td>
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<tr>
<td>Huang2011</td>
<td>0.4678</td>
<td>-</td>
<td>0.1</td>
<td>5.7</td>
<td>-</td>
<td>-</td>
<td>Huang et al. $^{28}$</td>
</tr>
</tbody>
</table>

(from: Rott, Taketa, Bose, Nature Scientific Reports 15225, 2015)

- Reason: for heavier stable isotopes proton number $\sim$ neutron number
- Beyond precisions of PINGU and ORCA; requires a detector with a lower threshold (around 1 GeV), new technology
Open issues (instead of conclusions …)

➢ Geophysical “smoking gun” contribution from neutrinos? Can one really learn something qualitatively or quantitatively new?

➢ Is it worth to develop new dedicated technology? Or should one rely on spin-offs only?

➢ Required improvements (especially lower threshold) to achieve sensitivity to the inner core?

➢ Synergies between two experiments (PINGU/ORCA)? 3D models?

➢ How does one best combine geophysical and neutrino data? Statistical interpretation of geophysical methods?

➢ Impact of total mass and rotational inertia constraints?

➢ New neutrino analyses in geophysicist’s language?
Earth’s interior: What we know

Mantle: Probed by seismic waves; parameterization relative to REM
(Reference Earth Model, Dziewonski, Anderson, 1981)

Velocities among 3D models consistent within percentage errors:

Outer core: Liquid (as no seismic shear waves)

[Probably least known part …]

Seismic wave reflection/refraction

Zones with local anomalies in seismic wave velocities

Density constrained by collective constraints from mass and moment of inertia

\[ M = 2\pi \int r^2 \rho(r) \, dr, \quad I = 2\pi \int (x^2 + y^2) r^2 \rho(r) \, dr \]

… and free oscillation modes at percent level

(http://igppweb.ucsd.edu/~gabi/rem.html)
# Ideas using absorption tomography

<table>
<thead>
<tr>
<th>Isotropic flux</th>
<th>TeV beam</th>
<th>Astro point source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(cosmic diffuse, atmospheric)</td>
<td><img src="Diagram.png" alt="Diagram" /></td>
<td><img src="Diagram.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Sources available**
  - Atmospheric neutrinos: low statistics at $E>10$ TeV
  - Diffuse cosmic flux: low statistics, unknown flux normalization

- **Potentially high precision**
  - Build and safely operate a TeV neutrino beam (need FCC-scale accelerator); moving decay tunnel + detector?

- **Earth rotation ➔ different baselines**
  - No sources resolved yet; most probably low statistics

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- Jain, Ralston, Frichter, 1999; Reynoso, Sampayo, 2004; Gonazales-Garcia, Halzen, Maltoni, 2005; …
- De Rujula, Glashow, Wilson, Charpak, 1983; Askar’yan, 1984; Borisov, Dolgoshein, Kalinovskii, 1986; …
- Wilson, 1984; Kuo, Crawford, Jeanloz, Romanowicz, Shapiro, Stevenson, 1994; …
<table>
<thead>
<tr>
<th><strong>Ideas using oscillation tomography</strong></th>
<th><strong>Isotropic flux</strong> (atmospheric, diffuse cosmic)</th>
<th><strong>Neutrino beam</strong></th>
<th><strong>Astro point source</strong> (supernova, Sun)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sources available, atmospheric ν just right</strong></td>
<td>Sources available, atmospheric ν just right</td>
<td>Potentially high precision</td>
<td>Earth rotation → different baselines</td>
</tr>
<tr>
<td><strong>Diffuse cosmic flux: too high neutrino energies</strong></td>
<td>Moving decay tunnel+ detector? Or: new dedicated experiment?</td>
<td><strong>Supernovae</strong> in neutrinos are rare events</td>
<td>Solar neutrinos have somewhat too low E</td>
</tr>
<tr>
<td>Rott, Taketa, Bose, 2015; Winter, 2016 + some earlier ideas; …</td>
<td>Ohlsson, Winter, 2002; Winter, 2005; Gandhi, Winter, 2007; Arguelles, Bustamante, Gago, 2015; …</td>
<td>Lindner, Ohlsson, Tomas, Winter, 2003; Akhmedov, Tortola, Valle, 2005; …</td>
<td></td>
</tr>
</tbody>
</table>
Emerging technologies: mass ordering with atm. neutrinos

- Plans for high-density atmospheric neutrino detectors in ice (PINGU) and sea water (ORCA)
- Mton-size volume in relevant energy range:

\( V_{\text{eff}}(\nu_\mu) \)

Resolution of cavities = zones with a density contrast

- Low-energy (300-500 MeV) superbeam
- The cavity can be located if long enough and density contrast strong enough (here: water)
- There is some positional information (one baseline!)

(from Ohlsson, Winter, Europhys. Lett. 60 (2002) 34; see also Arguelles, Bustamante, Gago, 2015)
Matter profile inversion problem

Some approaches for direct inversion:

- Simple models, such as one zone (cavity) with density contrast
  (Nicolaidis, 1988; Ohlsson, Winter, 2002; Arguelles, Bustamante, Gago, 2015)
- Linearization for low densities (Akhmedov, Tortola, Valle, 2005)
- Discretization with many (N) parameters:
  Use non-deterministic methods to reconstruct these parameters
  (e. g. genetic algorithm in Ohlsson, Winter, 2001)
Comparison to geophysical methods

- Especially free oscillations of Earth effective for “direct” access to density profile
- Similar issues: degeneracy between target precision and length of layers averaged over (i.e., one needs some “external” knowledge/smoothing …)
- Precision claimed at the percent level from deviation of reconstructed profiles; but: rigid statistical interpretation?
- Yet unclear how data can be combined, and what effect mass and rotational inertia constraints would have

(Ensemble averages, lower mantle, Kennett, 1998)