Reference Models for Lithospheric Geoneutrino Signal

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\textit{with additional contributions from Laura Sammon (UMD)}

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Radiogenic heat flux \( \sim 20 \text{ TW} \)

Geoneutrino flux \( 10^{25} \bar{\nu}_e \text{ s}^{-1} \)

Heat Production

- \( ^{238}\text{U} \)
- \( ^{235}\text{U} \)
- \( ^{232}\text{Th} \)
- \( ^{40}\text{K} \)
- \( ^{147}\text{Sm} + ^{87}\text{Rb} \)

Geoneutrino Luminosity

- \( ^{238}\text{U} \)
- \( ^{235}\text{U} \)
- \( ^{232}\text{Th} \)
- \( ^{40}\text{K} \)
- \( ^{87}\text{Rb} \)
- \( ^{87}\text{Rb} \)
- \( ^{40}\text{K} \)
- \( ^{\nu_e} \)

21 October 2019

Geoneutrinos and Quantitative Geochemical Modeling
Weekly geoneutrino teleconference: particle physics & geology

**Nodes:** Sudbury, Beijing, California, Prague, Sendai, Maryland

Now running for 5 years, with 3 years for the bigger group!
importance of accuracy

- Which model is most accurate?

- Implications for what’s in the mantle

*Intercept = mantle flux!*
Constructing a 3-D reference Earth model for geoneutrino emission calculation
assigning chemical and physical states to Earth voxels

\[
\frac{d\phi(E_\nu, r)}{dE_\nu} = A \frac{dn(E_\nu)}{dE_\nu} \int_{V_\oplus} d^3 r' \frac{a(r') \rho(r') P(E_\nu, |r - r'|)}{4\pi |r - r'|^2}
\]
Estimating the distribution and abundance of U & Th in the Earth

Local Crust (~500 km): contributes 50% of signal, and most of that signal comes from the Upper Continental crust (UC)

Globally
- 40% LOC
- 35% ROC
- 25% Mantle

mass fraction BSE

<table>
<thead>
<tr>
<th>Layer</th>
<th>Mass Fraction</th>
<th>U (10^-6 kg/kg)</th>
<th>Th/U</th>
<th>K/U</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>~0.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>~2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UC</td>
<td>~80%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sed</td>
<td>~0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM</td>
<td>~20%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>EM</td>
<td></td>
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</tr>
</tbody>
</table>

Geoneutrinos and Quantitative Geochemical Modeling
*Detailed near field (NF) models of the upper 1/3 of the crust are critically important for **accuracy** and **precision** of signal predictions*

*Our study has not built a field-based detailed NF model*
Continental crustal thickness

Predictions by different global geophysical models
- CRUST 2.0
- CRUST 1.0
- LITHO 1.0

Avg cont. crust $41.0 \pm 6.2$
Christensen & Mooney 1995
Global Crust: physical models
- CRUST 2.0
- CRUST 1.0
- LITHO 1.0
Estimating Crustal Contributions to Geoneutrino Signal

Crustal signal is predicted by using...

- for the deep Crust: global density and velocity models CRUST1.0/LITHO1.0, and compositional data for amphibolite and granulite facies rocks
- THEN calculate density and K, Th, U abundances and geoneutrino flux

... recent focus on Deep Crust (middle and lower)
Procedure for finding consistent crustal models

Inputs:
- Vs
- Temperature
- Depth
- Composition (Perple_X)

Whole rock compositions - local granulite facies lithologies

Seismic Velocities

Moho Temperatures

Moho Depths

Temperature Gradient

Composition, depth, temperature combinations that satisfy all inputs

Minerals

Densities

Seismic Velocities

High Resolution Seismic Wave Data

Thermodynamic Relationships
SiO$_2$ vs Vp: granulite facies rocks

Granulite Facies Lithologies

Low (500°C)
Medium (650°C)
High (750°C)

$y = 0.000524x^2 - 0.102x + 11$

Quadratic norm of residuals = 10.7073
Amphibolite and granulite facies rocks middle and lower crust samples

\[ \text{SiO}_2 \text{ wt\%} \]

... on average most samples are mafic to intermediate, not felsic
Amphibolite and granulite facies rocks
middle and lower crust samples

Mg#

... on average most samples are mafic to intermediate, not felsic
U content of deep crust: global crust models

Granulite U distributions

Amphibolite U distributions

SiO₂ bins (wt%)

- 40 - 45
- 45 - 50
- 50 - 55
- 55 - 60
- 60 - 65
- 65 - 70
- 70 - 75
- 75 - 80

SiO₂ bins (wt%)

- 45.0 - 49.4
- 49.4 - 53.8
- 53.8 - 58.1
- 58.1 - 62.5
- 62.5 - 66.9
- 66.9 - 71.3
- 71.3 - 75.6
- 75.6 - 80.0
HPE of deep crustal rocks: U vs Th

All deep crustal rocks

Amphibolite, Granulite, Eclogite Facies Lithologies

$y = 1.002x + 1.243$

Just granulite rocks

Granulite Facies Lithologies

$y = 1.084x + 1.433$

Th/U = 3.47

N = 4082

N = 1836

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Geoneutrinos and Quantitative Geochemical Modeling
SiO$_2$ – U Joint Probability Analysis

Increases in SiO$_2$ correlates with increases in mean and median U content.

$U = 0.11^{+0.20}_{-0.07}$ ppm

$U = 0.25^{+0.57}_{-0.18}$ ppm
Based on results of Watanabe, 2016

**Best fit**

Radiogenic power

\[ R_{BSE} = 20 \text{ TW} \]
Based on results of Agostini et al., 2015

Best fit
Radiogenic power
$R_{BSE} = 24 \text{ TW}$

$\text{Borexino}$

Measurement: $43.5 \pm 11.8 \pm 10.4$
### Negligible difference in crustal models

**Geoneutrino signal calculated from global crust models**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Geoneutrino Flux (TNU)</th>
<th>Overlapping Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRUST2</td>
<td>CRUST1</td>
</tr>
<tr>
<td>KamLAND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk CC</td>
<td>22.7±5.9</td>
<td>24.2±6.7</td>
</tr>
<tr>
<td>Total</td>
<td>34.7±5.0</td>
<td>36.6±6.5</td>
</tr>
<tr>
<td>Borexino</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.5±8.1</td>
<td>29.9±8.0</td>
</tr>
<tr>
<td></td>
<td>43.2±8.0</td>
<td>42.9±7.9</td>
</tr>
<tr>
<td>SNO+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>37.5±10.2</td>
<td>32.9±9.6</td>
</tr>
<tr>
<td></td>
<td>49.8±9.7</td>
<td>45.7±9.3</td>
</tr>
<tr>
<td>JUNO</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28.1±7.5</td>
<td>28±7.1</td>
</tr>
<tr>
<td></td>
<td>40.5±7.4</td>
<td>40.7±7.6</td>
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<tr>
<td>Jinping</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.5±11.5</td>
<td>47.2±12.7</td>
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<tr>
<td></td>
<td>55.0±10.9</td>
<td>59.9±12.1</td>
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<tr>
<td>Hawaii</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3±0.7</td>
<td>2.1±0.6</td>
</tr>
<tr>
<td></td>
<td>12.9±2.8</td>
<td>12.9±2.8</td>
</tr>
</tbody>
</table>

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Geoneutrinos and Quantitative Geochemical Modeling
## Physical properties of crustal models

<table>
<thead>
<tr>
<th>Layer</th>
<th>( \rho ) (g/cm(^3))</th>
<th>( d ) (km)*</th>
<th>( M ) (10(^{21}) kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRUST2.0</td>
<td>CRUST1.0</td>
<td>LITHO1.0</td>
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<tr>
<td>Sed</td>
<td>2.2</td>
<td>2.18 ± 2.1</td>
<td>0.8 ± 0.1</td>
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<tr>
<td>UC</td>
<td>2.75</td>
<td>11.60 ± 3.9</td>
<td>7.0 ± 0.9</td>
</tr>
<tr>
<td>MC</td>
<td>2.84</td>
<td>11.18 ± 3.4</td>
<td>7.2 ± 0.9</td>
</tr>
<tr>
<td>LC</td>
<td>3.02</td>
<td>9.93 ± 2.9</td>
<td>6.7 ± 0.8</td>
</tr>
<tr>
<td>Bulk CC</td>
<td>2.9</td>
<td>34.25 ± 8.8</td>
<td>21.8 ± 2.6</td>
</tr>
<tr>
<td>OC</td>
<td>Sed</td>
<td>1.9</td>
<td>1.86 ± 0.2</td>
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<tr>
<td></td>
<td>C</td>
<td>6.80 ± 1.5</td>
<td>5.6 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>LM</td>
<td>3.34</td>
<td>139.9 ± 75</td>
</tr>
<tr>
<td></td>
<td>DM</td>
<td>4.4</td>
<td>1966</td>
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<td>5.4</td>
<td>750</td>
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<tr>
<td>BSE</td>
<td>4.45</td>
<td>2891</td>
<td>4035</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2891</td>
<td>4036</td>
</tr>
</tbody>
</table>
importance of accuracy

Our latest model for predicting the mantle signal

measured KL signal (Watanabe, 2016)
measured BX signal (Agostini et al. 2015)
Predicted signals (Wipperfurth et al. 2019)
Combining data from the global array

Future is Bright

2025 and beyond

- Physics continues to count
- Much to be learned
- More geoneutrino data!
- Benefits for astrophysics
- Importance of an ocean measurement!

Prediction based on 1.5 kt, 4 yr exposure, ± 20%

Šrimek et al. (2016) model (SREP 6, 33034 (2016))
Conclusions

• Contributions to the geoneutrino signal:
  • 40% local crustal model
  • 35% global continental lithosphere
  • 25% mantle

• Estimated total signal uncertainties 20%, with 6% from geophysics + 14% from geochemistry

• Calculations using CRUST2.0, CRUST1.0 and LITHO1.0 yield physical uncertainties that overlap each other

• Bulk continental crust has (7 ± 2) TW