Geo-neutrino Introduction

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Geo-neutrino Overview

• Earth’s **neutrino luminosity** is \((3\pm2)\times10^{19} \text{ erg/s}\)
• Earth radiates \(60 \pm 40\) moles of **neutrinos per second** from the decay of **potassium, thorium, and uranium**
• Decays of **potassium, thorium, and uranium** generate \(15 \pm 10\) TW of **radiogenic heating**
• Large uncertainties: models and observations
• Earth surface **heat flux** \(\sim0.1\) W/m\(^2\) but solar constant \(\sim1000\) W/m\(^2\)
• Geo-neutrinos important for geoscience but not related to climate change
Geo-neutrino Status

• **Two significant detections of U/Th flux**
  – ~140 recorded interactions
  – Rate and energy measured NOT direction
  – Separate U and Th flux not resolved yet
  – Measured signals are consistent
  – Model inputs required for geological analysis
  – Combined results begin to resolve mantle

• **K not measured**

• **View of lower mantle possible!**
Geo-neutrino Primer

• Terminology
  – DM (depleted mantle not dark matter)
  – CMB (core-mantle boundary not cosmic microwave background)
  – HPE (heat-producing element: U, Th, K)
  – BSE (bulk silicate Earth)

• Unit
  – TNU (Terrestrial antiNeutrino Unit: 1 event per $10^{32}$ free proton targets per year)
Earth Energy Budget

Terrestrial Power Balance

\[ P_{\text{surface}} \approx P_{\text{rad}} + P_{\text{CMB}} + P_{\text{man_cool}} \]

Present Status

Surface heat flow \( P_{\text{surf}} = 47 \pm 3 \text{ TW} \)

- Radiogenic heating \( P_{\text{rad}} = 15 \pm 10 \text{ TW} \)
- Heat flow across CMB \( P_{\text{CMB}} = 13 \pm 3 \text{ TW} \)

\[ = \text{Rate of mantle cooling} P_{\text{man_cool}} = 19 \pm 11 \text{ TW} \]

Constrain thermal evolution

\[ \frac{\partial T}{\partial t} = \frac{Aq}{M_c} (M_h/A_q - 1) = -(50 \text{ to } 150) \text{ K/Ga} \]
Talk Outline

- Introduction
- Neutrinos
- Geo-neutrino status
- Developments
- Conclusions
Neutrinos

**Properties**

- **Mass**: $\sum m_\nu < 2 \text{ eV} \sim 4 \times 10^{-36} \text{ kg}$
- **Charge**: $q_\nu < 10^{-21} \text{ e} \sim 2 \times 10^{-40} \text{ C}$
- **Magnetic dipole moment**: $\mu_\nu < 3 \times 10^{-11} \mu_B$
- **Lifetime**: $\tau_\nu > 10^{20} \text{ s}$
- **Spin**: $s_\nu = \frac{1}{2}$
- **Oscillations**: => Flavor and Mass states
- **Majorana or Dirac?**
- **Mass Hierarchy**: $(m_\nu^3 > m_\nu^2 \text{ or } m_\nu^3 < m_\nu^1)$?
Neutrino Oscillations: Survival Probability

\[ P_{\nu_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 (2\theta_{12}) \sin^2 (1.27\delta m^2_{21} L / E_{\nu_e}) \]
\[ - \sin^2 (2\theta_{13}) \cos^2 \theta_{12} \sin^2 (1.27\delta m^2_{31} L / E_{\nu_e}) \]
\[ - \sin^2 (2\theta_{13}) \sin^2 \theta_{12} \sin^2 (1.27\delta m^2_{32} L / E_{\nu_e}) \].

Suppression of flux and distortion of energy spectrum for point source
Geo-neutrino Emission Tomography

- Fast- near instantaneous `picture’
- Straight- undistorted `picture’
- No energy loss- parents identified by spectrum
- Oscillations averaged- spectrum undistorted
- Detection methods-
  - U, Th by IBD free proton; U, Th, K by elastic scattering
Antineutrino Global Map: AGM 2015
Antineutrino Spectral Slices
Earth Model: Crust + Mantle
Crust Model

• Physical structure from seismology: CRUST 1.0
  – http://jgppweb.ucsd.edu/~gabi/rem.html

• Potassium, thorium, uranium concentrations from geochemistry: Rudnick and Gao (2003); Huang et al. 2013

• Refinements clearly possible
Crust Model: 8-layer profile
Crust Model: Geo-neutrino Th/U Ratio

~7 TW of radiogenic heating

Now add mantle signal constrained by bulk Earth $Th/U = 3.9$
Mantle Model Observationally Derived

- Derived from geo-neutrino observations at Japan (KamLAND) and Italy (Borexino)
- Mantle estimate = Total observed – Crust predicted
- Assume homogeneous mantle composition
- Take weighted average of two mantle estimates
- Undersea exposure best to reduce uncertainties
Mantle Signal Depends on Model

Homogeneous

Layered
Mantle Signal Discriminates Models

Bulk Earth
Th/U = 3.9
16 TW U+Th

Total mantle heating
U+Th+K, add 20%

Pacific Ocean has greatest sensitivity
Large-scale Mantle Heterogeneity?

Mantle geoneutrino flux ($^{238}\text{U}+^{232}\text{Th}$)

Sudbury ▼ Kamioka ▼ Gran Sasso ▼ Hawaii

Geochemical BSE A&McD DM % surf.ave.

88 92 96 100 104 108 112 116 120 124

0.90 0.95 1.00 1.05 1.10 1.15 1.20 1.25 cm$^{-2}$ μs$^{-1}$

Sramek et al., 2012
Geo-neutrino Production
$\beta^-$ decay: $[A,Z] \rightarrow [A,Z+1] + e^- + \nu_e \pm Q_\beta$
Antineutrino Interactions

**Electron elastic scattering**
- $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$
- Electron target
  - No energy threshold
- Cross-section
  - $\sigma(E_\nu) \sim 4.0 \times 10^{-45} \ E_\nu \ \text{cm}^2$

**Inverse-β decay**
- $\bar{\nu}_e + p \rightarrow n + e^+$
- Proton target
  - $E_{\text{thresh}} \approx 1.8 \ \text{MeV}$
- Cross-section
  - $\sigma(E_\nu) \sim 9.5 \times 10^{-44} \ (E_\nu - 1.3)^2 \ \text{cm}^2$
Inverse Beta Decay (IBD)

\[ p^+ + \bar{v}_e \rightarrow e^+ + n^0 \]
Geo-neutrino Parents, Spectra

\[ \bar{\nu}_e + p^+ \rightarrow n + e^+ \]

1.8 MeV Energy Threshold

\[ 238^\text{U} \]
\[ 1\alpha, 1\beta \]
\[ 232^\text{Th} \]
\[ 1\alpha, 1\beta \]

\[ 234^\text{Pa} \]
\[ \bar{\nu}_e \]
\[ 2.3 \text{ MeV} \]
\[ 228^\text{Ac} \]
\[ 4\alpha, 2\beta \]

\[ 214^\text{Bi} \]
\[ \bar{\nu}_e \]
\[ 3.3 \text{ MeV} \]
\[ 212^\text{Bi} \]
\[ 1\alpha, 1\beta \]

\[ 206^\text{Pb} \]
\[ 2\alpha, 3\beta \]
\[ 208^\text{Pb} \]

\[ 40^\text{K} \]
\[ 1\beta \]
\[ 40^\text{Ca} \]

\[ 2.3 \text{ MeV} \]
\[ 2.1 \text{ MeV} \]

\[ 11/16/16 \]

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Antineutrino Cross Sections

Nue-bar elastic scattering observed in 1976 by Reines, Gurr, Sobel

Sensitivity below 1.8 MeV; no tag

4 e^- / p^+ in CH₂ LS

Resolve e^- direction to find signal?

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Nue-bar quasi-elastic scattering used by Reines and Cowan in 1950’s

Coincidence counting; weak direction

Works great for geo-nu

Uncertainties small
Antineutrino Event Spectra

Earth

Few $10^6 \nu_e$ bars/cm$^2$/s

Reactors

$\sim 1.8 \times 10^{20} \nu_e$ bars/s/GW$_{th}$
Reactor Antineutrino Overview

• **435 reactor cores** generate $870 \text{ GW}_{th}$
• Reactor **antineutrino luminosity** is $4 \times 10^{17} \text{ erg/s}$
• Global reactors radiate $0.27 \pm 0.02$ moles of **antineutrinos per second**
• Main uncertainty is reactor power output (on/off)
\[ E = \Delta mc^2 \]

Nucleus (smaller mass) + Binding energy \rightarrow Separated nucleons (greater mass)
Nuclear Fission

6 $\nu_e$ bars/fission
205 MeV/fission
Typical power $\sim 3$ GW$_{th}$
$\sim 1.8 \times 10^{20} \nu_e$ bars/s/GW$_{th}$
Detecting IBD on Free Proton

Antineutrino ($E_\nu > 1.8$ MeV) interacts with free proton

Prompt event deposits energy of $E_\nu - 0.8$ MeV

Delayed event deposits energy of 2.2 MeV

PMTs measure vertex location and deposited energy
Operating Geo-neutrino Detectors

KamLAND- Kamioka, Japan
- 1 kT LS
- 80% dodecane
- 20% PC
- w/ 1.36 g/l PPO
- ~1800 PMTs
- 34% solid angle
- ~250 pe/MeV\textsubscript{vis}
- $(5.98 \pm 0.12) \times 10^{31}$ p

Borexino- Gran Sasso, Italy
- 0.278 kT PC
- w/ 1.5 g/l PPO
- 2212 8-in PMTs
- ~30% solid angle
- ~500 pe/MeV\textsubscript{vis}
- ~$0.17 \times 10^{31}$ p

Both existing detectors are in Eurasia at ~40° N and separated in longitude by ~120°.
Reported Geo-neutrino Measurements

• **KamLAND: 2002 – 12 at Japan**
  - Exposure = $4.90 \pm 0.10$ TNU$^{-1}$
  - Positive detection: p-value $2 \times 10^{-6}$
  - Reported flux: $3.4(+0.8/-0.8)$ cm$^{-2}$ μs$^{-1}$
  - Rate ($Th/U = 3.9$): $30.6 \pm 7.2$ TNU

• **Borexino: 2007 – 15 at Italy**
  - Exposure = $0.55 \pm 0.03$ TNU$^{-1}$
  - Positive detection: p-value $3.6 \times 10^{-9}$
  - Reported rate: $43.5(+12.1/-10.7)$ TNU
  - Flux ($Th/U = 3.9$): $5.0 \pm 1.3$ cm$^{-2}$ μs$^{-1}$
Geo-neutrino Measurements Consistent

Huang et al., 2013

Geo-neutrino measurements have not yet observed the predicted variation at the surface of Earth

Th/U ratio not yet measured
Geo-neutrino Signal Rate Variation

KamLAND & Borexino signals are consistent

Plot shows exposure needed to observe signal deviation at $\pm 1\sigma$ from KL signal

Pacific Ocean (0.1 TNU$^{-1}$) offers the best opportunity
Oceanic Observatory

- Model predictions: $\sim 0.1 \text{ kT-}y$ observes signal different than KL; $\sim 4 \text{ kT-}y$ for 5σ mantle signal
- Tow to site on special barge
- Deploy at site
- Operate buoyed off bottom

Feasibility/engineering studies completed
Technology demonstration needed
Geo-neutrino Energy Spectrum: $Th/U$

- Challenging measurement
- Requires $\sim 10^3$ events
- Large exposure
- KL limit: $Th/U < 19$
Direction: Inverse Beta Decay

Initial: $p_{trans} = 0$

Final: $p_{trans} = 0$

$\nu_e \rightarrow p + e^+$

$\nu_e \rightarrow n + e^+$

Neutron angle, degrees vs. Positron angle, degrees

Neutron Kinetic Energy [keV] vs. 8MeV, 5MeV, 3MeV, 2MeV

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Direction: Electron Elastic Scattering

K Geo-neutrino Angular Distribution

1 pW/kg core
KL+BX homogeneous mantle
SS DMM KL+BX D^−
Geo-neutrino direction

Information for harvesting with advanced detectors
## Geo-neutrino Experimental Status

<table>
<thead>
<tr>
<th></th>
<th>Rate</th>
<th>Spectrum</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>U and Th</td>
<td>p &lt; $10^{-9}$</td>
<td>Th/U &lt; 19</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crust</td>
<td></td>
<td>model</td>
<td></td>
</tr>
<tr>
<td>Mantle</td>
<td></td>
<td>model</td>
<td></td>
</tr>
<tr>
<td>Lower mantle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>Demonstrated/Completed</th>
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<tbody>
<tr>
<td></td>
<td>Limits or Model-dependent results</td>
</tr>
<tr>
<td></td>
<td>Opportunity</td>
</tr>
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</table>
Geo-neutrino Conclusions

• Add observatories, SNO+, others
• Increase exposure
• Resolve Th geo-neutrinos and measure $Th/U$ ratio
• Verify surface variation with geo-nu measurement
• Improve geochemical crust model- $a$(HPE)
• Develop and implement direction capability
• Detect K geo-neutrinos
• Build and deploy deep ocean observatory
Geophysical Response

• Define geophysical response $G$ at field point $P$ due to mass $m$ at source point $S$ at distance $r$

• $G = m/(4\pi r^2)$ in units of g/cm$^2$

Consider three field points
• Kamioka
  • 36.427 N, 137.300 E
  • 358 m.a.s.l.
• Gran Sasso
  • 42.450 N, 13.567 E
  • 936 m.a.s.l.
• Sudbury
  • 46.475 N, -81.201 E
  • -1761 m.a.s.l.
Three Field Points: Observatories

Consider three field points

- **Kamioka, Japan**
  - 36.427 N, 137.300 E
  - 358 m.a.s.l.

- **Gran Sasso, Italy (LNGS)**
  - 42.450 N, 13.567 E
  - 936 m.a.s.l.

- **Sudbury, Canada (SNOLab)**
  - 46.475 N, -81.201 E
  - -1761 m.a.s.l.
Earth Formation and Differentiation

- Earth formation releases gravitational potential energy sufficient to melt planet
- Short-lived radioisotopes (i.e. $^{26}$Al) keep proto-Earth hot
- Dense molten Fe-Ni with siderophile elements sinks beneath primitive silicate mantle with lithophile elements
- Igneous processes form continental crust
- Erosion makes sediments
- Sea-floor spreading makes oceanic crust
Stones from Space- Clues to Composition

Chondrites are primitive, undifferentiated, stony meteorites

**Enstatite Chondrite- EH**
- O isotopic composition
- High metallic Fe content
- Low in oxidized Fe
- $P_{\text{rad}} = 14.6 \pm 1.3$ TW
- $R_{\text{man}} = 5.1 \pm 1.0$ TNU
  
  Javoy & Kaminski 2014

**Carbonaceous Chondrite- CI**
- Composition solar photosphere
- Low metallic Fe content
- High in oxidized Fe
- $P_{\text{rad}} = 20 \pm 4$ TW
- $R_{\text{man}} = 9 \pm 3$ TNU
  
  After McDonough & Sun 1995

Is one an Earth composition analogue?
Earth Origin

Schematic perspective of the early Earth (a) as a homogeneous mixture with no continents or oceans. In the process of differentiation, iron sank to the center and light material floated upward to form a crust (b). As a result, the Earth is zoned (c) with a dense iron core, a surficial crust of light rock, and, between them, a residual mantle. The upper mantle consists of two zones which are important in explaining many geologic phenomena: an outer solid, strong lithosphere underlain by a partially molten, weak asthenosphere.

Ken Sims, CETUP 2011
Core-Mantle Separation

Silicate Primitive Mantle

Fe-Ni Core
K, Th, U
assumed absent

Total Earth allotment
of K, Th, U
Earth Structure: Layered by Differentiation

The interior of Earth is layered:

- Lithosphere
  - Continental crust
  - Oceanic crust
- Upper mantle (DM)
  - Lower lithosphere, upper asthenosphere
- Lower mantle
- CMB
- Outer core (liquid)
- Inner core (solid)
Geochemical Affinity

Goldschmidt Classification

Lithophilic - “rock-loving”

Legend:
- Lithophile
- Siderophile
- Chalcophile
- Atmosphere

very rare

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50
Geochemical Reservoirs: K, Th, U

- All derive from primitive mantle
- Continental crust (CC) ~40 km, t ~Gy
  - Upper (UC), middle (MC), lower (LC) layers
- Lithospheric mantle (LM)
  - Pasted on bottoms of continents
- Sediments
- Oceanic crust (OC) 6-8 km, t < 200 My
- Mantle
  - Remnants of primitive mantle, additions from subduction, mass transfer across CMB(?)
  - Deep seismic structures- LLSVP, ULVZ
Variation of Continental Crust
Geophysical Response: UC

TABLE II. Total Geophysical Response from UCC

<table>
<thead>
<tr>
<th></th>
<th>LNGS</th>
<th>Kamioka</th>
<th>SNOLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>g cm$^{-2}$</td>
<td>$1.04 \times 10^7$</td>
<td>$8.46 \times 10^6$</td>
<td>$1.15 \times 10^7$</td>
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</table>
Geophysical Response: MC

TABLE III. Total Geophysical Response from MCC

<table>
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<th>LNGS</th>
<th>Kamioka</th>
<th>SNOLab</th>
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<tbody>
<tr>
<td>g cm$^{-2}$</td>
<td>$7.24 \times 10^6$</td>
<td>$5.87 \times 10^6$</td>
<td>$9.74 \times 10^6$</td>
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</table>
Geophysical Response: LC

TABLE IV. Total Geophysical Response from LCC

<table>
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<th>LNGS</th>
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<th>SNOLab</th>
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<tbody>
<tr>
<td>g cm$^{-2}$</td>
<td>$6.50 \times 10^6$</td>
<td>$5.49 \times 10^6$</td>
<td>$8.07 \times 10^6$</td>
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</table>
Geophysical Response: LM

<table>
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<th>Kamioka</th>
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<tbody>
<tr>
<td>$g , cm^{-2}$</td>
<td>$2.85 \times 10^7$</td>
<td>$2.53 \times 10^7$</td>
<td>$2.66 \times 10^7$</td>
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</table>

TABLE V. Total Geophysical Response from CLM

CRUST1.0 Lithospheric Mantle

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Geophysical Response: Sediments

TABLE VII. Total Geophysical Response from Sediments

<table>
<thead>
<tr>
<th></th>
<th>LNGS</th>
<th>Kamioka</th>
<th>SNOLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>g cm⁻²</td>
<td>1.68×10⁶</td>
<td>4.70×10⁵</td>
<td>5.22×10⁵</td>
</tr>
</tbody>
</table>
Geophysical Response: OC

TABLE VIII. Total Geophysical Response from Oceanic Crust

<table>
<thead>
<tr>
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<th>LNGS</th>
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<th>SNOLab</th>
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<tbody>
<tr>
<td>g cm$^{-2}$</td>
<td>$1.94 \times 10^6$</td>
<td>$2.45 \times 10^6$</td>
<td>$1.35 \times 10^6$</td>
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</table>

Map is boring
Geophysical Response: Mantle

<table>
<thead>
<tr>
<th></th>
<th>LNGS</th>
<th>Kamioka</th>
<th>SNOLab</th>
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</thead>
<tbody>
<tr>
<td>g cm(^{-2})</td>
<td>$1.140 \times 10^9$</td>
<td>$1.147 \times 10^9$</td>
<td>$1.141 \times 10^9$</td>
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</tbody>
</table>

Map is boring
Geophysical Response: LLSVP

LLSVP (kT/m^2)

Geological Response to LLSVP (10^6 g/cm^2)

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Geophysical Response: ULVZ

<table>
<thead>
<tr>
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<th>SNOLab</th>
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<tbody>
<tr>
<td>g cm$^{-2}$</td>
<td>$2.68 \times 10^5$</td>
<td>$1.51 \times 10^5$</td>
<td>$2.06 \times 10^5$</td>
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</tbody>
</table>
Geophysical Response: ULVZ

Geological Response to ULVZ (10^6 g/cm^2)
Isotopic Geo-neutrino Flux

• $\phi = G \cdot l \cdot a \cdot NA \cdot <P_{ee}>$

• $G$ is geophysical response (g/cm$^2$)

• $l$ is isotopic antineutrino luminosity (gs)$^{-1}$

• $a$ is geo-neutrino parent isotope abundance

• NA is isotopic natural abundance

• $<P_{ee}>$ is average neutrino survival probability

\[ \delta x/x \approx 1\% \]

\[ \delta x/x < 5\% \quad \text{Error estimates} \]

\[ \delta x/x \approx 10s\% \]
Geo-neutrino Isotopes

Potassium, thorium, and uranium are lithophile (rock-loving) elements

**TABLE I. Isotopic Factors**

<table>
<thead>
<tr>
<th></th>
<th>$^{40}$K</th>
<th>$^{232}$Th</th>
<th>$^{235}$U</th>
<th>$^{238}$U</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(gs)^{-1}$</td>
<td>$2.31 \times 10^5$</td>
<td>$1.62 \times 10^4$</td>
<td>$3.20 \times 10^5$</td>
<td>$7.46 \times 10^4$</td>
</tr>
<tr>
<td>% n.a.</td>
<td>0.0117</td>
<td>100.0</td>
<td>0.7204</td>
<td>99.27</td>
</tr>
</tbody>
</table>
Geochemical Abundances: UC, MC, LC, LM

Note uncertainty increases with depth

Lateral variations in abundances probably large

### TABLE VI. Element Abundances in Continental Crust

<table>
<thead>
<tr>
<th></th>
<th>Potassium (wt.%)</th>
<th>Thorium (µg/g)</th>
<th>Uranium (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCC</td>
<td>2.33 ± 0.19</td>
<td>10.5 ± 1.0</td>
<td>2.7 ± 0.6</td>
</tr>
<tr>
<td>MCC</td>
<td>1.91 ± 0.25</td>
<td>6.5 ± 0.5</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>LCC</td>
<td>0.7 ± 0.3</td>
<td>1.3 ± 0.9</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>CLM</td>
<td>0.04 ± 0.03</td>
<td>0.3 ± 0.2</td>
<td>0.05 ± 0.04</td>
</tr>
</tbody>
</table>

Adapted from Rudnick and Gao (2003); Huang et al. (2013)
Geochemical Abundances: Sed, OC

<table>
<thead>
<tr>
<th>TABLE IX. Element Abundances in SED and OCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium (wt.%)</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>SED</td>
</tr>
<tr>
<td>OCR</td>
</tr>
</tbody>
</table>

Adapted from Rudnick and Gao (2003); Huang et al. (2013)

Lateral variations in abundances probably not large
**Predicted Crust Geo-neutrino Fluxes**

<table>
<thead>
<tr>
<th></th>
<th>$\phi(K)$</th>
<th>$\phi(Th)$</th>
<th>$\phi(U)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNGS</td>
<td>6.98 ± 1.02</td>
<td>1.67 ± 0.24</td>
<td>1.82 ± 0.47</td>
</tr>
<tr>
<td>Kamioka</td>
<td>5.47 ± 0.83</td>
<td>1.30 ± 0.19</td>
<td>1.42 ± 0.38</td>
</tr>
<tr>
<td>SNOLab</td>
<td>7.90 ± 1.18</td>
<td>1.84 ± 0.26</td>
<td>2.00 ± 0.54</td>
</tr>
</tbody>
</table>

Uncertainty: $\approx 15\%$ on K, Th; $\approx 25\%$ on U
Observed Geo-neutrino Fluxes

<table>
<thead>
<tr>
<th></th>
<th>LNGS</th>
<th>Kamioka</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi(\text{Th})$</td>
<td>$2.3 \pm 0.6$</td>
<td>$1.5 \pm 0.4$</td>
</tr>
<tr>
<td>$\phi(\text{U})$</td>
<td>$2.7 \pm 0.7$</td>
<td>$1.9 \pm 0.4$</td>
</tr>
</tbody>
</table>

Bellini et al. (2015); Gando et al. (2013)

$\approx 25\%$ uncertainty on Th and U fluxes
Statistical and systematic
Estimated Mantle Abundances

TABLE XV. Estimated Mantle Element Abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>95 ± 74 µg/g</td>
</tr>
<tr>
<td>Th</td>
<td>18 ± 20 ng/g</td>
</tr>
<tr>
<td>U</td>
<td>7 ± 5 ng/g</td>
</tr>
</tbody>
</table>

K/U of 13,800±1300 from Arevalo et al. (2009)

≈100% errors on a(K), a(Th), and a(U)
ULVZ Geo-neutrino Fluxes

TABLE XVI. Predicted ULVZ Geo-neutrino Fluxes

<table>
<thead>
<tr>
<th></th>
<th>$\phi(K)$</th>
<th>$\phi(Th)$</th>
<th>$\phi(U)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNGS</td>
<td>$169 \pm 14$</td>
<td>$46 \pm 4$</td>
<td>$55 \pm 12$</td>
</tr>
<tr>
<td>Kamioka</td>
<td>$95 \pm 8$</td>
<td>$26 \pm 2$</td>
<td>$31 \pm 7$</td>
</tr>
<tr>
<td>SNOLab</td>
<td>$130 \pm 11$</td>
<td>$35 \pm 3$</td>
<td>$42 \pm 9$</td>
</tr>
</tbody>
</table>

Assumes abundances same as UC
Main Uncertainty: Abundances of K, Th, U

- $\alpha$(HPE) in UC model no lateral variation
- $\alpha$(HPE) in deep crust (MC, LC) model possible lateral variation by $V_p$ (Huang et al. 2013)
  - Personal assessment: method not robust
- Modeling is key to advancing neutrino geoscience
- How to improve?
Oceanic Observatory

- Tow to site on specially designed barge
- Deploy at site
- Operate buoyed off bottom

Feasibility/engineering studies completed
Technology demonstration needed

11/16/16
Tohoku Forum Creativity
<table>
<thead>
<tr>
<th>PROS</th>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No excavation</td>
<td>• PMT pressure housings</td>
</tr>
<tr>
<td>• Freedom of access to ~2/3 of planet surface</td>
<td>• Energy/implosion high</td>
</tr>
<tr>
<td>• External neutron rate ~5x less than equivalent depth underground site</td>
<td>• Undersea cable for data/power link</td>
</tr>
<tr>
<td>• Reduced PMT dark noise</td>
<td>• Special deployment barge</td>
</tr>
<tr>
<td>• Completed feasibility and preliminary design studies</td>
<td>• ⁴⁰K background</td>
</tr>
<tr>
<td></td>
<td>• Floatation</td>
</tr>
<tr>
<td></td>
<td>• Risk of fishing accident</td>
</tr>
</tbody>
</table>

Cons straightforward to address
Submarine Cables as of 2015

Many unused/retired cables available
Shallow Demonstration Site

- Utilize existing cabled observatory at Monterey
- Depth 890 m
- User fee $5k/mo
- R/V + ROV ~$30k/day
- Power
  - 48 VDC 100 W, 375 VDC 500 W
- Data
  - 10/100 Base-T Ethernet TCP/IP
  - 100 Mbps
- Timing
  - 1 Hz precision pulse
- Comprehensive report
Deep Demonstration Site

- Utilize Aloha Cabled Observatory (ACO)
- Depth 4800 m
- User fee $6k/mo
- R/V + ROV thru UH/UNOLS
- Power
  - 48 VDC 100 W, 400 VDC 500 W
- Data
  - 100 Base- T Ethernet TCP/IP
  - 100 Mbps
- Timing
  - Better than 1 ms w/ IRIG time code

More information
http://aco-ssds.soest.hawaii.edu/
Optical Module

13-inch Benthos sphere w/ 10-inch PMT + HV Base
Detector Configuration
Underwater Testing in Laboratory

- SURF #6 Winze at 4850L
- Access to 8000L
- Flooded to ~5500’
- 800 m water depth
- 7.2 km w.e. overburden
- 90° F
#6 Winze
Undersea Demonstrator Plan

- Build and test prototype in laboratory
- Test at SURF 80 atm. warm, fresh water
- Deploy at MARS 90 atm. cold, sea water
- Deploy at ACO 480 atm. cold, sea water
- Technology demonstration complete
Backup slides
Antineutrino Cross Sections

\[ \bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \]

\[ T_{\text{max}} = \frac{E_{\bar{\nu}_e}}{1 + \frac{m_e}{2E_{\bar{\nu}_e}}} \]

\( \sigma_e(E_{\bar{\nu}_e}) = 0.43 \left[ x^2 T_{\text{max}} + (x + 1)^2 \frac{E_{\bar{\nu}_e}}{3} \left\{ 1 - \left(1 - \frac{T_{\text{max}}}{E_{\bar{\nu}_e}}\right)^3 \right\} - x(x + 1) \frac{m_e T_{\text{max}}^2}{2E_{\bar{\nu}_e}^2} \right] \times 10^{-44} \)

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

\( \sigma_p(E_{\bar{\nu}_e}) = 9.52(E_{\bar{\nu}_e} - \Delta)^2 \sqrt{1 - \frac{m_e^2}{(E_{\bar{\nu}_e} - \Delta)^2}} \times 10^{-44} \)

\( T_e = E_{\bar{\nu}_e} - \Delta - m_e \)

11/16/16

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Geo-neutrinos

<table>
<thead>
<tr>
<th>Element</th>
<th>$^{238}$U series</th>
<th>$^{232}$Th series</th>
<th>$^{235}$U series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>$^{234}$Pa</td>
<td>$^{238}$Th</td>
<td>$^{236}$Pa</td>
</tr>
<tr>
<td>Protactinium</td>
<td>$1.18$</td>
<td>$1.91$</td>
<td>$7.64e8$</td>
</tr>
<tr>
<td>Thorium</td>
<td>$234$Th</td>
<td>$232$Th</td>
<td>$227$Ac</td>
</tr>
<tr>
<td>Actinium</td>
<td>$5.75$ min</td>
<td>$3.66$ day</td>
<td>$21.8$ yr</td>
</tr>
<tr>
<td>Radium</td>
<td>$1.60e3$ yr</td>
<td>$223$Rn</td>
<td>$229$Rn</td>
</tr>
<tr>
<td>Francium</td>
<td>$3.32$ day</td>
<td>$209$Rn</td>
<td>$3.96$ sec</td>
</tr>
<tr>
<td>Radon</td>
<td>$222$Rn</td>
<td>$220$Rn</td>
<td>$219$Rn</td>
</tr>
<tr>
<td>Astatine</td>
<td>$219$Po</td>
<td>$217$Po</td>
<td>$211$Bi</td>
</tr>
<tr>
<td>Polonium</td>
<td>$218$Bi</td>
<td>$216$Po</td>
<td>$208$Pb</td>
</tr>
<tr>
<td>Bismuth</td>
<td>$3.05$ min</td>
<td>$138$ day</td>
<td>$207$Pb</td>
</tr>
<tr>
<td>Lead</td>
<td>$210$Pb</td>
<td>$10.5$ hr</td>
<td>$206$Tl</td>
</tr>
<tr>
<td>Thallium</td>
<td>$26.8$ min</td>
<td>$22.3$ yr</td>
<td>$207$Tl</td>
</tr>
</tbody>
</table>

- $^{234}$Pa: routinely analyzed by TIMS
- $^{238}$Th: techniques in development (by alpha counting)
- $^{236}$Pa: routine analysis by TIMS

Ken Sims, CETUP 2011
Surface Heat Flow

Pollack et al., 1993
Added for Davies, Davies, 2010

Heat flow probe - thermal conductivity, $dT/dx$

Heat conduction - $q = -k \, dT/dx$

Total Heat Flow $47 \pm 2$ TW
Planetary Power

\[ Aq = Mh - Mc(\partial T/\partial t) \]

Surface heat flow - *Aq*

Internal heating - *Mh*

Heat to change temperature - *Mc*(\(\partial T/\partial t\))

Temperature change rate:
\[ \partial T/\partial t = Aq/Mc \left( Mh/Aq - 1 \right) \]

Planetary Urey ratio - *U* = *Mh*/*Aq*
Neutrino Geoscience Goals

• Measure mantle geo-neutrinos
• Constrain Earth models
• Estimate mantle radiogenic heating
• Constrain thermal history and composition

Diagram from D. Stegman, L. Ziegler