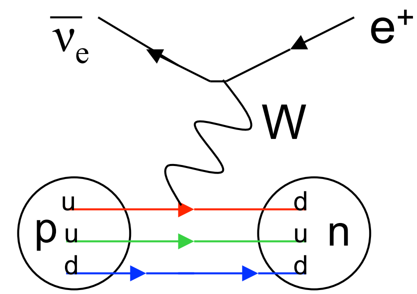

Neutrino Geosciences

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Hawaii Pacific University

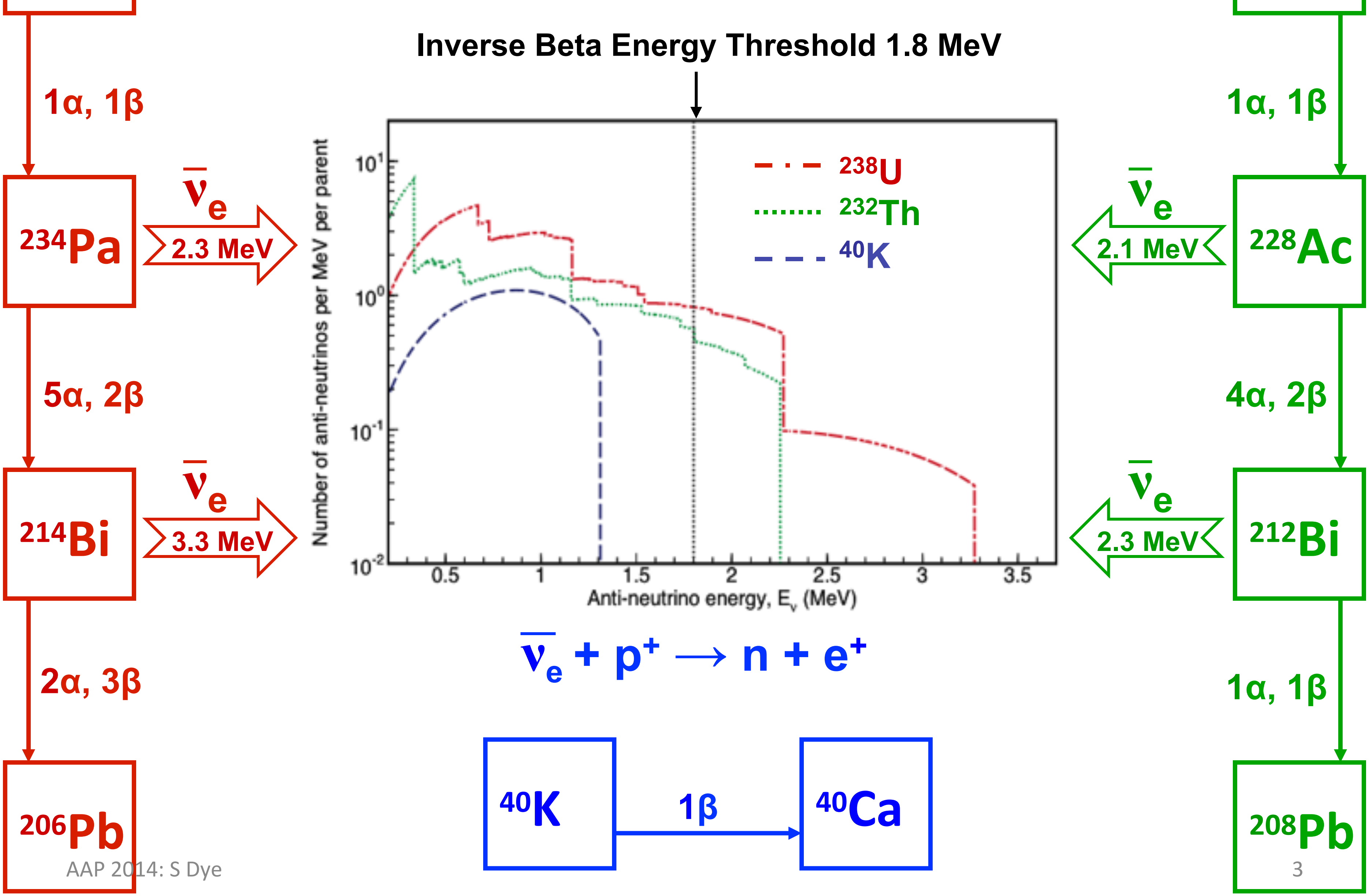
National Science Foundation
WHERE DISCOVERIES BEGIN

Hawai'i Pacific University

Neutrino Geosciences Outline

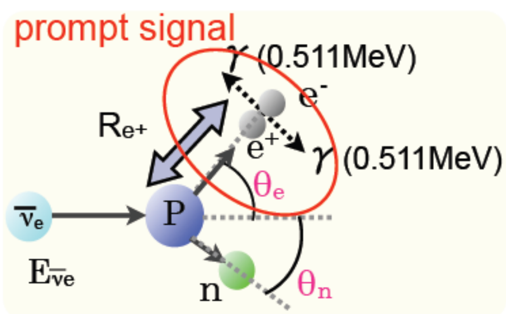
- Introduction
- Earth energetics
- Reported observations
- Observational opportunities
- Atmospheric neutrinos and core
- Conclusion

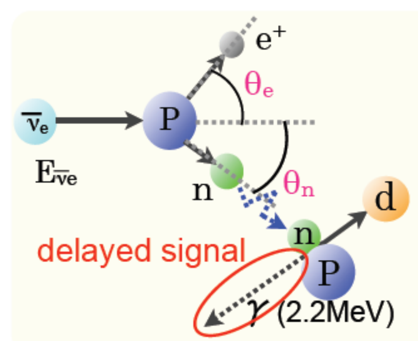
Geo-neutrinos



Geo-neutrino Detection

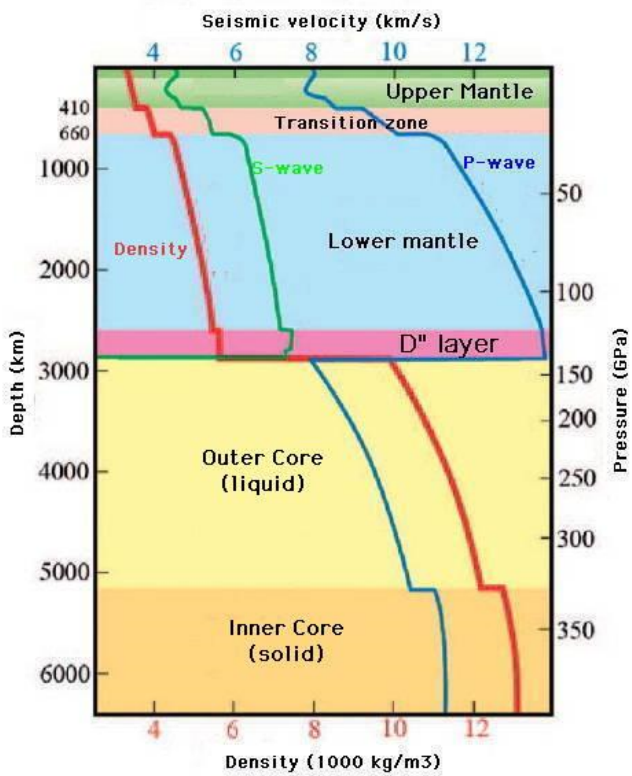
- **Geo-neutrinos: Mostly electron antineutrinos ($E \approx$ few MeV) from decay series of U, Th, K***
- **Interaction: Inverse beta decay- $\overline{\nu}_e + p \rightarrow n + e^+$**
- **Detection medium: Organic scintillating liquid**
- **Detected signal: Coincidence in space and time**

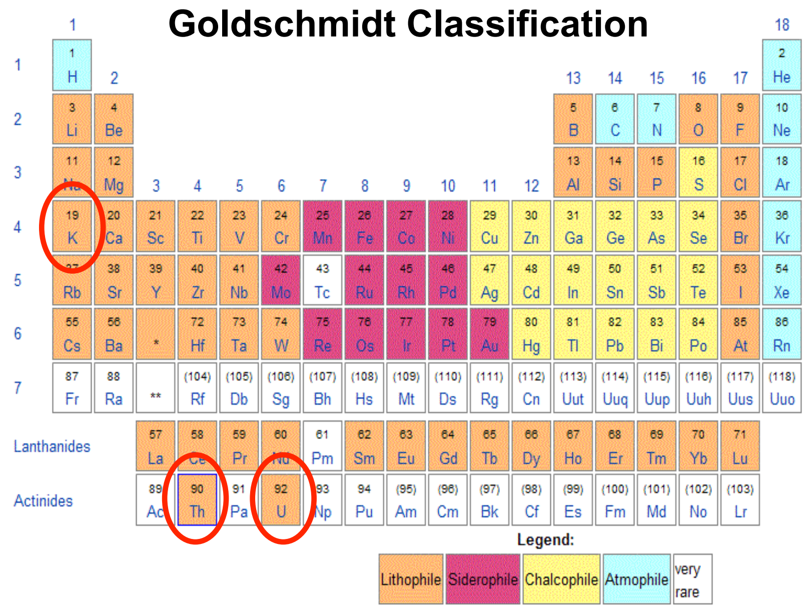




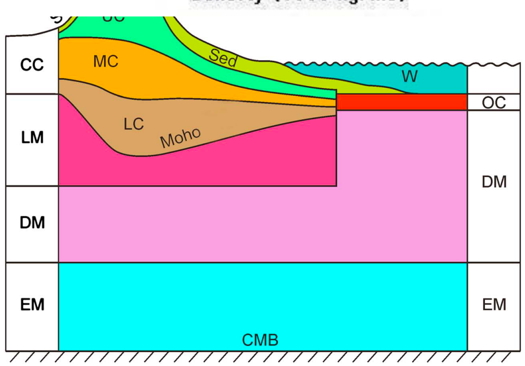
- **Measure $\overline{\nu}_e$ energy spectrum NOT direction**
- **Observations: Neutrino geosciences**

Earth- crust, mantle, core





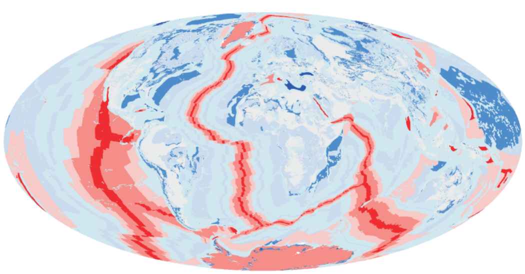
Lithophilic- "rock-loving"



Geochemistry strongly suggests geo-neutrinos from U, Th, & K in mantle and crust only

Why Geo-neutrinos?

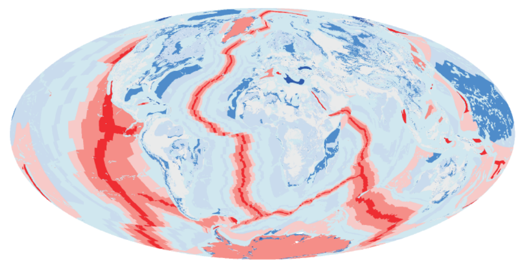
- **Earth radiogenic power: Understand heat engine**
  - **Surface power loss well measured: 47 ± 3 TW**
  - **Radiogenic power now resolved: 16 ± 8 TW**
    - **Lithosphere radiogenic power: 8 ± 1 TW (model)**
    - **Mantle radiogenic power: 8 ± 8 TW (geo-nu)**
  - **Informs thermal evolution of planet by defining mantle cooling (secular heat)**
  - **Constrains parent material of Earth: U & Th content**



Planetary Energy Conservation

- **Terrestrial Power Balance**
  - $P_{surface} \approx P_{rad} + P_{CMB} + P_{man\_cool}$

- **Present Status**
  - $P_{surf} = 47 \pm 3$ TW
    (Davies and Davies 2010)
  - $P_{rad} = 16 \pm 8$ TW
    (Dye 2014)
  - $P_{CMB} = 13 \pm 3$ TW
    (Wu et al. 2011)
  - $P_{man\_cool} = 18 \pm 9$ TW



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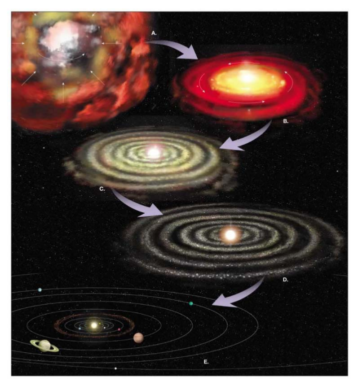

Thermal Evolution and History of Earth

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

Present temperature decrease rate:

$$\partial T/\partial t = Aq/Mc\ (Mh/Aq - 1) = 50 \text{ to } 150 \text{ K/Ga}$$

Rate of cooling poorly constrained

Present primordial heat loss rate:

$$Aq - Mh = 22 \text{ to } 40 \text{ TW}$$

Rate of primordial heat loss poorly constrained

Rates of cooling & primordial heat loss poorly constrained due to uncertainty of radiogenic heating

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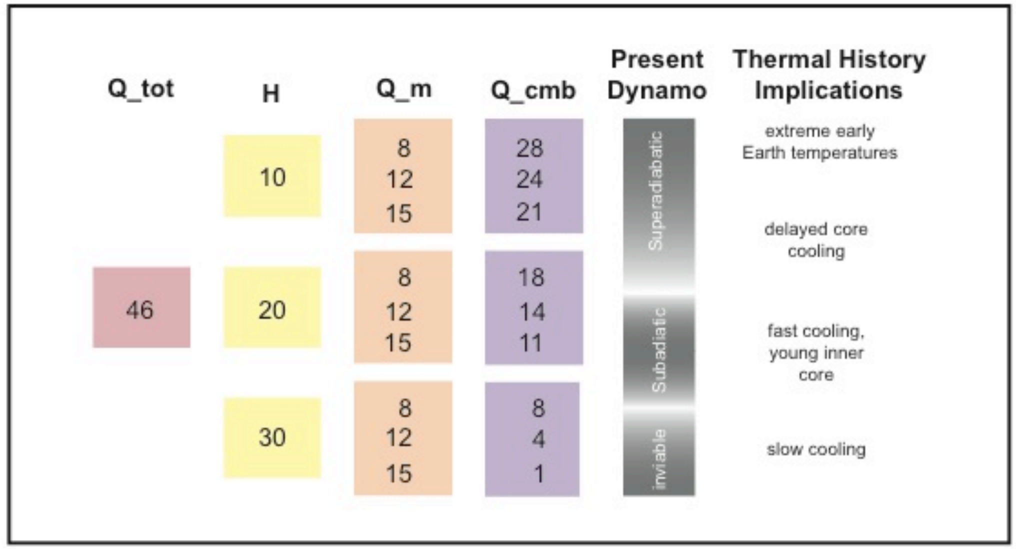
Geological Consequences

Geo-neutrinos constraining thermal evolution

Geo-neutrinos
16 ± 8 TW



Greater exposure to geo-neutrinos improves precision of radiogenic heating estimate

Reported Observations: 2013

KamLAND

- Operation- 3/02 to 11/12
- Exposure- (4.9 ± 0.1) TNU^{-1}
- Events- 116 $^{+28}/_{-27}$
- Flux- (3.4 ± 0.8) x 10^6 $cm^{-2}s^{-1}$
- Rate- (30 ± 7) TNU
- Publication- A. Gando et al. PRD 88 (2013) 033001

Borexino

- Operation- 12/07 to 8/12
- Exposure- (.369 ± .016) TNU^{-1}
- Events- 14.3 ± 4.4
- Flux- (4.3 ± 1.3) x 10^6 $cm^{-2}s^{-1}$
- Rate- (39 ± 12) TNU
- Publication- G. Bellini et al. PLB 722 (2013) 295

Main assumption: Th/U = 3.9

Combined Mantle Signal: 2013

KamLAND

- Total Rate- (30 ± 7) TNU
- Crust prediction- (26 ± 4) TNU
- Mantle signal- (4 ± 8) TNU

Borexino

- Total Rate- (39 ± 12) TNU
- Crust prediction- (25 ± 4) TNU
- Mantle signal- (14 ± 13) TNU

Weighted Average (KL + BX)

$$x_{best} = (w_A x_A + w_B x_B)/(w_A + w_B);$$
$$w_A = 1/\sigma_A^2 \text{ and } w_B = 1/\sigma_B^2$$

- **Combined mantle signal- (7.1 ± 6.7) TNU**

Dominant uncertainty: Total rate

Assumptions: No signal core, homogeneous mantle

Model Predictions of R_{man}

CI- Earth (McDonough & Sun)

- **BSE_{rad} = 20 ± 3 TW**
- **R_{man} = 9 ± 3 TNU**

E-Earth (Javoy & Kaminski)

- **BSE_{rad} = 13 ± 2 TW**
- **R_{man} = 5 ± 1 TNU**

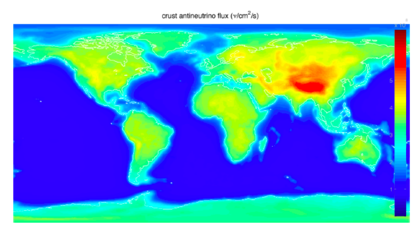
Predictions are marginally consistent
Challenging to resolve models

KL + BX combined mantle signal- (7 ± 7) TNU

Present geo-neutrino measurement is consistent with model predictions

Geo-neutrino Rate to Power: 2013

- (KL + BX) mantle signal- (7.1 ± 6.7) TNU
- 1.206 TW/TNU (Th/U=3.9; K/U=12,000)
- (KL + BX) mantle heating- H_{man}=(8.5 ± 8.0) TW
- Total radiogenic- (16 ± 8) TW
  - Mantle (8.5 ± 8.0) TW
  - Crust (7.5 ± 1.9) TW



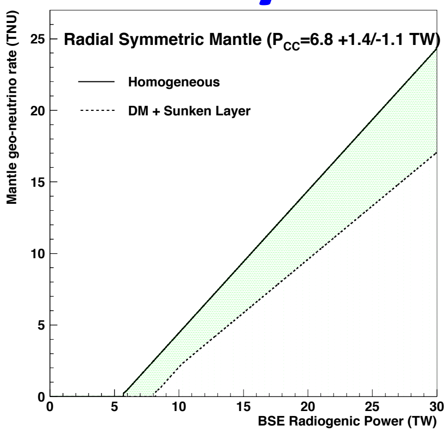
Huang et al. 2013

Assumptions: Homogeneous mantle, K/U = 12,000

Error: Dominated by geo-neutrino measurement

Inhomogeneous U, Th Distribution

- **Crust + Upper mantle (DM) complementary**
- **Lower mantle (EM) primitive**
- **Same R_{man} but more P_{rad}**
- **Estimate +2 TW**



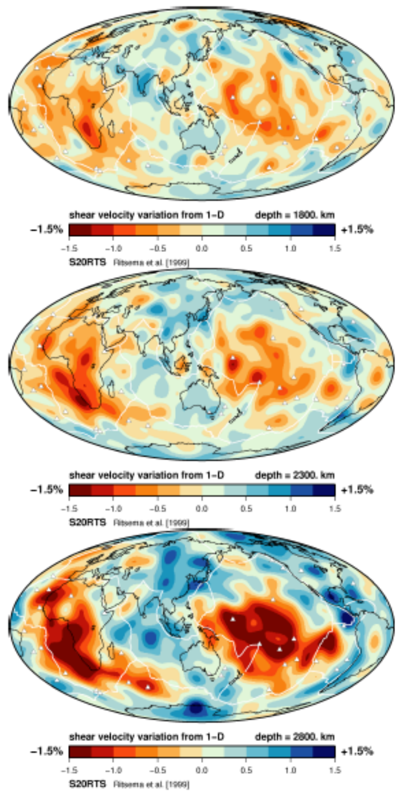
- **Core radioactivity**
- **pW/kg ~ 2 TW**
- **R_U ~ 2 TNU**
- **Estimate -2 TW**

	a(X) ng/g	m(X) 10^{16} kg	Φ(X) 10^5 cm^{-2}s^{-1}	S(X) TNU	P(X) TW
U	10.1	1.87	1.63	2.14	1.84
Th	38.1	7.00	1.29	0.52	1.84
^{40}K	35.1	6.47	17.1	n.a.	1.84

Quantities: pW/kg radiogenic heating in outer core

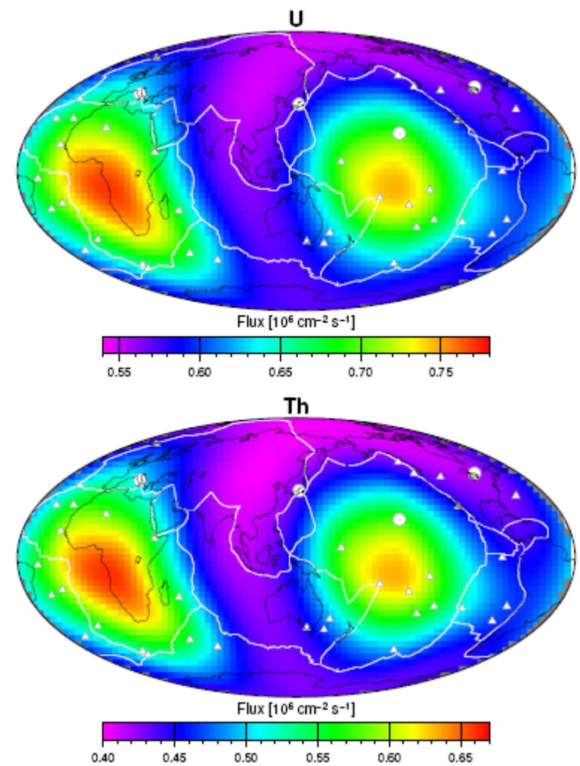
Radial inhomogeneity of U, Th introduces ± 2 TW uncertainty to H_{man}

Non-radial Inhomogeneity of U, Th



Seismically-resolved deep mantle features

Sound speed slow due to composition, temperature, or both? If composition, then possible geo-neutrino signal



Sramek et al. 2013

Potential source of uncertainty
Features resolvable?

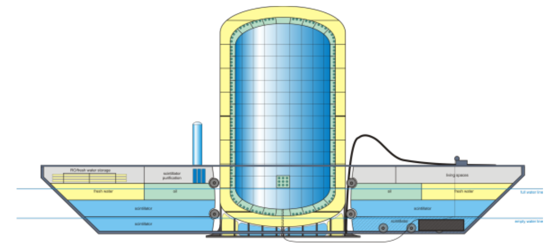
Mantle Signal Measurements

Which…???

Continental Network

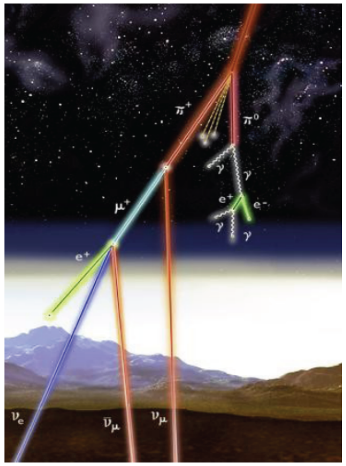
5 more years of each
Predict error ±3.6 TNU
Equivalent ±4.3 TW
(homogeneous)
Total 11.8 TNU^{-1}

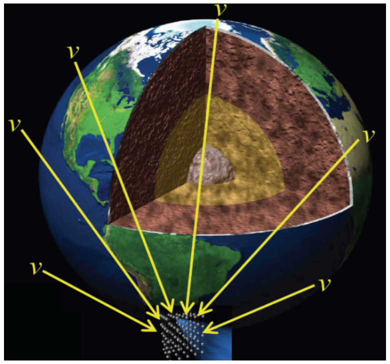
Oceanic Rover

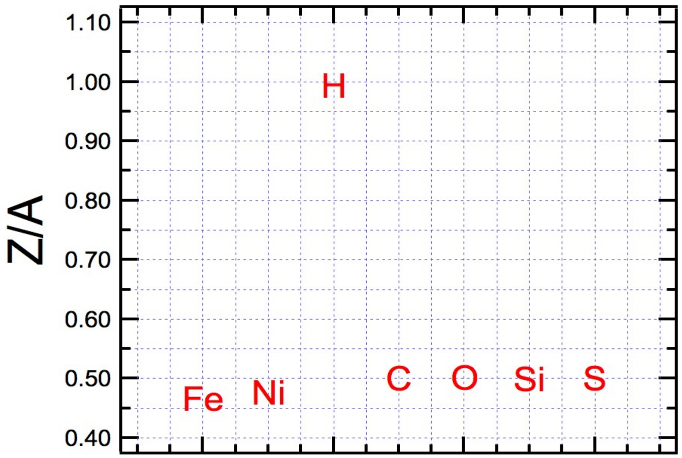


1.7 years of 10 kT
Predict error ±1.3 TNU
Equivalent ±1.6 TW
(homogeneous)

Neutrino Oscillation- Electron Density







Normal mass hierarchy more favorable

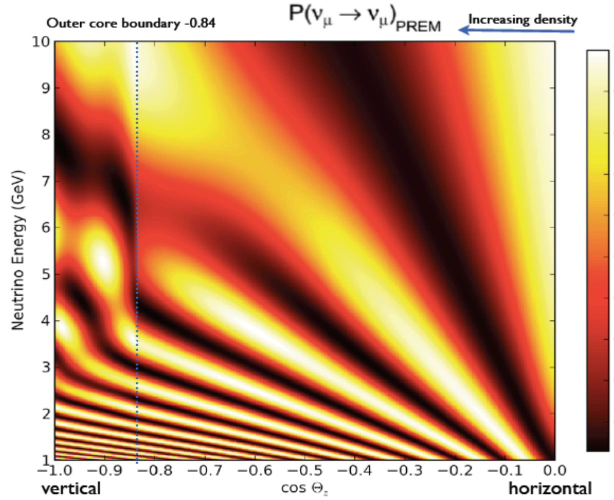
matter effect

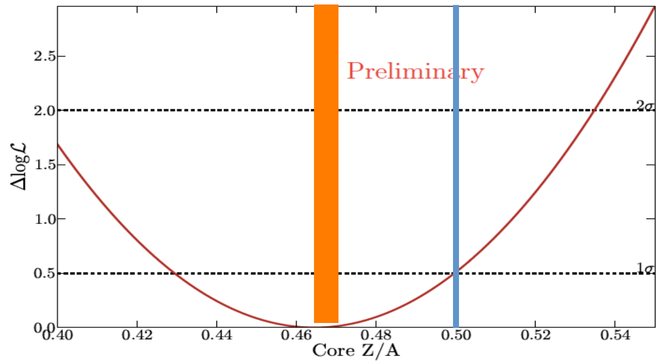
electron density = mass density • Z/A

Z/A = sum(x_i•Z_i)/sum(x_i•A_i)

where x_i is the atomic fraction, Z_i is the atomic number, and A_i is the mass of element

Neutrino Oscillation Tomography





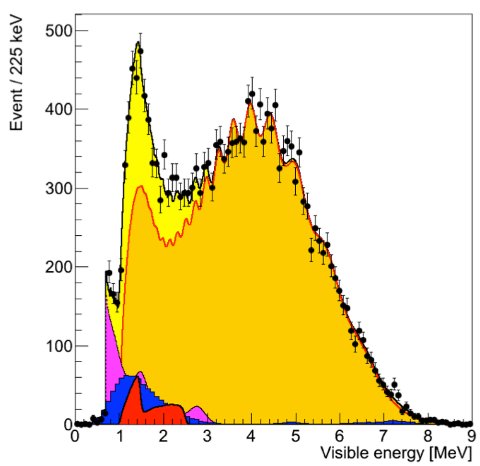
PINGU LOI- 5 years

Outer Core	Fe	Fe-Ni	Fe-Ni-S	Fe-Ni-Si	Fe-Ni-O	Fe-Ni-C	Fe-Ni-H	Huang11 Rubie11	Badro14	McDonough14
Z/A	0.4656	0.4661	0.4694	0.4694	0.4684	0.4680	0.4710	0.4695	0.4680	0.4692

Greater exposure and lower energy threshold help probe geologically relevant models
Possible synergy with nuclear monitoring

Current Activities

- http://www.geol.umd.edu/~mcdonoug/KITP%20Website%20for%20Bill/index.html
  - Whitepaper
  - CIDER-funded
- geoneutrinos.org/model/
  - Browser-based modeling
  - NSF-funded
- JUNO modeling
  - arXiv, YB



Conclusions

- **Geo-neutrinos estimate mantle radiogenic power**
- **Constraints on thermal evolution of Earth**
- **Observational opportunities**
  - **Network of Continental Observatories**
  - **Oceanic Observatory?**
  - **Address systematic errors- radial distribution U, Th**
- **Atmospheric neutrinos probe light elements in core**
- **Joint projects: Geology and Nuclear Monitoring**