

# **Electron Anti-neutrinos: the Nexus for Physics, Geology and Nuclear Security**

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*Electron anti-neutrinos have become the tool for understanding the Earth’s nuclear engine and the burning cycle in reactors*

Electron antineutrinos, sub-atomic particles emitted during beta-decay, are helping scientists implement a diverse range of intriguing applications. These particles are providing valuable clues about the origin and thermal history of the Earth. They are also providing critical information about the fuel cycle in nuclear reactors and, hopefully soon, new insight on heavy element production in supernova.

Kiloton-sized electron antineutrino detectors are now viewing inside the Earth, allowing us to determine the amount and distribution of the key radioactive, heat-producing elements uranium and thorium. These and much smaller detectors are monitoring from near and afar the fission furnaces of nuclear reactors. Significantly larger detectors are being considered with far-reaching applications in astroparticle physics, geology, nuclear reactor studies and fundamental particle physics.

Electron anti-neutrinos are miniscule, uncharged particles, which are ten million times lighter than an electron and have a size (interaction cross-section) that is unimaginably small [see FIGURE 1 and insert box], provide a means to peer to the very core of the Earth, enable nuclear security monitoring, and provide observations on astro-particle physics (supernovae in particular). Of course, the electron anti-neutrino is itself a subject of study in understanding fundamental particles and the phenomenon of neutrino oscillations, but we shall not dwell on that aspect herein, rather focusing on the applications in geology and nuclear security.

## **Setting**

Neutrinos were first imagined in 1930 by Wolfgang Pauli to conserve a 3-body momentum problem, though he presumed the hypothetical particles could not be detected. Some twenty-six years later the research team led by Fred Reines and Clyde Cowan first detected electron anti-neutrinos with a cubic meter scale detector placed about 10 meters from a nuclear reactor [FIGURE 2]. Thus began the science of detecting anti-neutrinos, and, in fact, monitoring what is going on inside nuclear reactors. A decade later, Ray Davis’ experiment in the Homestake mine (South Dakota, USA)

detected electron neutrinos (the matter sister particle to anti-neutrinos) originating from fusion reactions within the core of the Sun. Much more recently, it was discovered from experiments at Super Kamiokande (Super K, Japan) and the Sudbury Neutrino Observatory (SNO, Canada) that neutrinos oscillate [1, 2], and then, in 2002, the KamLAND (Kamioka Liquid AntiNeutrino Detector, Japan) team demonstrated that electron anti-neutrinos also oscillate between the three different flavor states [3], leading to the inescapable conclusion that neutrinos (and anti-neutrinos), like quarks and the charged leptons, have mass, but far less than the other fundamental fermions.

Astrophysicists have appreciated that neutrinos may play a crucial role in a variety of phenomena, including the apparent slight excess of matter over anti-matter shortly after the Big Bang, the rapid evolution and cooling of pre-white dwarf stars, the genesis of heavy elements in supernovae, and the formation of black holes. Supernova 1987A was the one and only event (so far) that led to detection of neutrinos from beyond our solar system. The 19 detection events observed from 1987A stimulated more than 200 papers, with new ones still appearing, and revealed several peculiarities that await the arrival of a new neutrino wave for resolution.

### **Putting Neutrinos to Work**

The KamLAND experiment, like the initial Rienes-Cowan experiment, was designed to study the electron anti-neutrinos emitted during the normal fuel cycle burning in nuclear reactors, with energies ranging from about 1.8 MeV to 8 MeV. Although enriched  $^{235}\text{U}$  fuel rods are used in the nuclear power reactors, these rods contain some amount of  $^{238}\text{U}$  and  $^{232}\text{Th}$ , and, early in the burning stage, the rods also produce  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$ , along with abundant other fissile and fission isotopes. Many isotopes contribute to the anti-neutrino flux from a reactor, typically from beta decays of isotopes rich in neutrons produced during nuclear fission. Nuclear reactors produce neutrinos with energies up to around 7 MeV, with a mean (event energy) of around 4 MeV. This contrasts with natural radioactive decays of generally long-lived isotopes, which tops out at 3.6 MeV [FIGURE 3]. Early in the fuel rod burning cycle, nuclear reactors produce weapons grade Pu, a product for making lightweight atomic bombs. Power reactors burn the rods until they are well worn down (but by no means totally depleted!), typically in about 18 months. A tell-tale signature of using “special nuclear material” is the frequent reactor shut-downs to allow shuffling of the rods.

In addition to detecting reactor generated electron anti-neutrinos, the KamLAND group first reported detecting geoneutrinos (electron anti-neutrinos generated inside the Earth) in 2005 [4], albeit with a significant background reactor signal. More recently [5], this team has observed more than 100 geoneutrino events and a greatly reduced background signal, due to improvements to the detector and unanticipated reactor shutdowns.

The Borexino experiment (Gran Sasso, Italy), which is designed to detect low-energy solar neutrinos, is a second detector that is observing geoneutrinos. This team has already reported on measurements of solar neutrinos produced from  $^7\text{Be}$  and  $^8\text{B}$  [6], as well as having reported their first geoneutrinos measurements in 2010 [7]. This latter

detector has a substantially lower reactor background, given its mean baseline to the nearest nuclear reactor is 1000 km. Thus, geology is benefitting mightily from these two great experiments that are sited in markedly different geological environments and with contrasting background signals.

### **Geoneutrinos, a key to unlocking Earth's secrets**

The Earth is an anti-neutrino star emitting about six million geoneutrinos per centimeter square per second. This high flux is because the Earth is transparent to anti-neutrinos, as is all matter. Because of their minute cross sections and lack of charge, neutrinos (and anti-neutrinos) can pass through a light year's length of lead and have only a 50% chance of interacting with it during transit. Consequently, this feature of neutrinos is good and bad; good because you cannot hide or shield such emissions from reactors, and bad because these particles are very hard to detect.

Geoneutrino studies offer an opportunity to establish independently the absolute amount of U and Th in the Earth and settle a 150-year long discussion, initiated by Lord Kelvin, about the sources of heat inside the Earth. Precise detection of the surface flux of geoneutrinos will allow discrimination between competing models of the planet's bulk composition. With increasingly more precise geoneutrino data we will be able to test quantitatively (1) models that predict the candidate accretion materials from which the Earth was built (i.e., chondrites, the primitive, undifferentiated material that formed in the nebular 4.5 billion years ago and believed to be comparable to the building blocks of the planets), (2) models that predict the existence of enriched areas in the mantle, some which may have been sequestered to the core-mantle boundary early in Earth's history, (3) models that predict the relative contribution of radioactive heating to the total surface heat flow of the planet, and (4) radioactivity in the core? Beyond this, there are a host of other debates in geodynamics that can be narrowed and reshaped by the constraints derived from geoneutrino data collected on land and in the oceans.

Scientists yearn to know how much, if any, of the Earth's nuclear power is driving plate tectonics and providing power to run the geodynamo, the magnetic shield protecting the planet. Knowing how much radioactive power there is in the planet would, in turn, tell us much about the building blocks that made the Earth and the initial conditions of planetary accretion. A subject of lively debate is what proportion of the surface heat flow comes from present radioactive decay and how much is from primordial sources. These primordial sources include the kinetic energy of accretion, the gravitational energy of core formation, and the dissipation of energy associated with ancient radiogenic decays.

The Earth is radiating some  $46 \pm 3$  TW ( $10^{12}$  watts) of thermal energy [8], with about 7 TW of this heat due to radiogenic heating of the continents, based on estimates of K, Th and U in the continental crust. Radiogenic heating in the Earth, like in nuclear power plants, is produced during the decay of radioactive elements inside the Earth, with 80% of this heat coming from U and Th with each giving an equal share, 20% coming from  $^{40}\text{K}$  decay and less than 1% coming from  $^{87}\text{Rb}$  decay. These proportional contributions are set by the decay energies of these isotopes and the known abundance ratios of Th/U, K/U

and Rb/U (i.e., 4,  $10^4$  and 30 respectively) in the Earth [9], where the former ratio is established by the fixed ratio in chondrites and the latter two ratios being dependent on the fraction of volatile (K and Rb) to refractory (Th and U) elements accreted on to the Earth. [The planetary ratio of volatile to refractory elements varies markedly from the inner terrestrial planets to the outer gas giants.] Therefore, after subtracting the crustal fraction, we need to explain the source of the remaining 39 TW that radiates from the mantle.

What fraction of the Earth's deep power of 39 TW is due to decay of K, Th and U? The answer to this question relates to how much K, Th and U there is in the planet and compositional models for the Earth's formation. Models for the Earth are developed from constraints set by geodetic and seismological data, for they describe the body as it exists today. Determining the initial state of the Earth is a challenge. There are three different approaches used for estimating the composition of the Earth: cosmochemistry, geochemistry, and geophysics. Each method has its relative strengths and weaknesses. However, in the end these three approaches predict the amount of uranium, a proxy for the total heat production in the planet, at somewhere between  $0.5 \times 10^{17}$  and  $1.3 \times 10^{17}$  kg in the bulk silicate Earth. The remainder of heat production from Th and K is projected from the planetary ratios of Th/U of 4 and K/U of  $10^4$ .

The approach taken by cosmochemists is to use chondritic meteorites to find a match between their chemical and isotopic compositions and that of the Earth. The strongest proponent of this concept comes from the Paris group led by Marc Javoy [10], which highlights that enstatite chondrites and the Earth share the same isotopic compositions for many elements. They concluded that the Earth is made from these essential building blocks and it has a markedly low content of heat producing elements (e.g.,  $0.5 \times 10^{17}$  kg U). A consequence of using these meteoritic materials is that the lower two thirds of the mantle has a markedly different chemical and mineralogical composition from that of the upper mantle. Many, however, would reject this view of large scale chemical heterogeneity in the mantle, as it is inconsistent with seismological images of subducting oceanic plates that plunge into the deep mantle, stirring the entire convecting mantle.

An alternative modeling approach used by geochemists is based on deconvolution of compositional data from samples of the mantle and crust to estimate the concentration of elements in the primitive mantle, the silicate Earth prior to generation of continental and oceanic crust [11]. These models predict about  $0.8 \times 10^{17}$  kg U in the silicate Earth and conclude that the mantle has a relatively homogeneous bulk composition throughout. These models are consistent with elasticity models of the mantle and broader chondritic compositional models of the planet. The shortcoming of these geochemical studies is that rocks from the Earth's mantle sample depths of only a few hundred kilometers and do not tell us if these rocks have resided at greater mantle depths in the past.

Finally, using the present day boundary condition given by the surface heat flux, geophysical models for the Earth attempt to find satisfactory solutions to the thermal evolution of the planet that critically evaluate the relative contributions of primordial heat and heat production to maintain a reasonable fit to the secular cooling record [12]. These

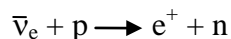
models parameterize mantle convection in terms of the force balance between buoyancy and viscosity versus thermal and momentum diffusivities, while recognizing that the convective state of mantle greatly exceeds its critical Rayleigh number, which marks the onset of convection. Typically these models predict up to about  $1.3 \times 10^{17}$  kg U in the silicate Earth, requiring more than 50% of the present heat flow is due to radiogenic heating. Consequently, these models are at odds with cosmochemical and geochemical models for the structure and the amount and distribution of heat producing elements in the Earth.

Since the initial 2005 report remarkable progress has been made in detecting geoneutrinos [4,5,7], with results [FIGURE 4] revealing an ever improving signal to noise ratio for the KamLAND findings. Within uncertainties the values overlap and their results are consistent with most Earth models. Notable, the most recent findings from the KamLAND group provides promise for discriminating the various models and rules out a fully radiogenic model for the Earth at the 67% confidence level.

Soon a third geoneutrino detector will come on line, the Canadian SNO+ detector (a wholly redeployed SNO detector in Sudbury, Canada), which is scheduled to begin counting in early 2013 and is designed to detect neutrinoless double beta decays and low energy solar neutrinos [13]. Relative to the KamLAND detector this detector, because of its location, will have more than a factor of two higher count rates for geoneutrinos and a lower reactor background signal. Thus, we are at an exciting stage of discovery where, with enhance precision, these studies will soon critically evaluate models of the amount of planetary nuclear power inside the Earth.

### **Evolving detector technologies**

Each generation of detector are getting better in that they are higher purity (low intrinsic background events) devices that are more environmentally friendly, using linear alkylbenzene (the base for liquid soap) for liquid scintillation. Neutrino detectors, although not as big as those in the High Energy Field (think of the LHC at CERN, which cost is at least an order of magnitude greater), are still substantial in size. The KamLAND device is one-kiloton of liquid scintillation. The Borexino detector, which has an exquisitely clean background and is in a deep location, is about half KamLAND's size. The one-kiloton SNO+ detector will be our deepest detector, almost 2 km beneath the surface, and is likely to be as clean as that of Borexino. The hydrocarbon based scintillation fluid provides the needed free protons used to detect an electron anti-neutrino via an inverse beta-decay process



An electron anti-neutrino carrying more than 1.8 MeV of energy [see Figure 2] is capable of converting a proton into a neutron and a positron. The positron produces a prompt flash of light due to annihilation with an electron. The positron carries with it most of the kinetic energy from the initial proton-neutrino interaction and thus carries the energy-tag used to identify which beta-decay was responsible for its generation. The neutron travels

ahead, with the equivalent nudge of a ping-pong ball on a bowling ball, resulting in a delayed (~200-250 micro-s) light flash: the neutron thermalizes (going from some keVs of kinetic energy to eVs) and then merges with a proton to form deuterium, with the subsequent emission of a 2.2 MeV de-excitation gamma which can be detected. This double-flash event within a specific time window, nearby in space and with the second flash having a specified energy eliminates nearly all of the background.

Future experiments include developments in detection technologies that will have applications in particle physics, geology, national security and astro-particle physics. A proposed European experiment (LENA, low energy neutrino astronomy [14]) envisages a 50-kiloton scintillation detector, sited either in the vicinity of a reactor or further afield, with the former having benefits for understanding fundamental aspects of anti-neutrinos and the latter providing a platform for long baseline neutrino beam studies and studies of understanding the Earth's anti-neutrino emission spectra. A proposed US experiment (Hanohano, Hawaiian anti-neutrino observatory, stated twice in Hawaiian tradition) envisages a mobile detector, between 10 and 50-kilotons that would operate at the bottom of the ocean and could be deployed at different distances from nuclear reactors or out in the middle of the ocean, far removed from continental crustal radioactivity [15]. The former application would be ideally suited for examining neutrino oscillation phenomena and reactor spectra, whereas the later application would reveal the nature of radioactive elements in the mantle. An exciting deployment would be to place a detector in the middle of the south Pacific positioned 3000 km away from South America, Australia and the Earth's core-mantle boundary, thus providing a complementary signal to that from land-based instruments. All of these detectors are also always available for recording supernova waves of neutrinos and a range of other exotic ephemeral phenomena, as well as searching for the sum of all past supernovae (SN relic neutrinos).

### **Directionality, a Grand Goal**

Identifying the source direction of detected electron anti-neutrinos is of paramount importance to both the needs of the geological and national nuclear security communities that wish to monitor the position where the signal originates. At present, all detectors are blind to the arrival direction of the electron anti-neutrino. The Chooz (France) and Palo Verde (Arizona) experiments did achieve 20 degree statistical directionality with a few thousand events and at distances of about 1 km from the well known source [Figure 5]. This result was achieved by summing the vectors between positron annihilation and neutrino absorption signals.

We hope that one can do much better and in a project at the University of Hawaii we are developing a tiny neutrino detector which can observe both the neutrino interaction point to a few millimeters precision and similarly the neutron absorption point (in a scintillator doped with highly neutron absorbing material). The present-day spatial resolution in KamLAND sized detectors is greater than 10 cm, meaning that directional information is lost.

Directionality greatly enhances the remote monitoring capability by identifying the neutrinos one wants and rejecting those coming from other reactors and from the Earth or random background events (which do not point). Directionality might have applicability in allowing real imaging of the reactor burning distribution. In geology the interest is in making neutrino tomography images of the mantle and pointing to areas of higher levels of Th and U contents. And for physics purposes, anything which enhances the signal-to-noise will improve studies such as for neutrino oscillations. For these reasons we expect a significant push in this area in the coming years.

### **Reactor Monitoring for Anti-Proliferation**

Finally, new substantially smaller, dedicated detectors are being developed specifically for monitoring electron anti-neutrino emissions from nuclear reactors. One such model is essentially a modern version of the original Reines-Cowan experiment, a 1-cubic meter liquid scintillation device, which has been successfully deployed at giga-watt nuclear power plants. Such devices are independent of control-room information have demonstrated the capability to observe the power cycles of nuclear reactors on a daily basis, as well as fuel cycle evolution. In contrast to deep underground kiloton detectors that enjoy a substantial measure of overburden shielding from cosmic rays, the near reactor cubic-meter detectors operate at surface or near-surface conditions, which means that they are flooded with cosmic ray flux. However, nuclear reactors are very bright electron anti-neutrino sources ( $\sim 10^{21}$  electron anti-neutrino per second for a 1 giga-watt power plant, so signal to noise ratios are favorable the closer you are to the reactor, falling as distance squared). Positioned at distance of about 10-20 meters typical signal may be thousand events per day per ton of detector.

IAEA endorsement of modern compact, stand-alone neutrino detectors would represent a major step forward for reactors monitoring. These detectors can be operated independent of the reactor infrastructure (for example, no tapping into the plumbing to monitor heat flow). Many think that neutrino detectors near cooperating reactor facilities will become commonplace in the future, and such may even offer potential economic gain as one may be able to better tune the reactor for maximal power output. In a disaster situation, such as occurred in Japan in March 2011, such detectors could have tallied the signature of shutting down (or not) of the nuclear burning, allaying fears of the dreaded China Syndrome.

### **Finale**

There is a great deal we do not understand about the origin of the deep Earth's heating. We know that radioactive decays contribute much to the Earth's thermal evolution, and as the recent results demonstrate, there remains a degree of secular cooling or primordial heat. The biggest unknown is the distribution of the radioactive material inside the Earth and here is where antineutrinos can come to the rescue.

We hope the reader has glimpsed the excitement of this new era in neutrino studies where the ghostly neutrino has gone from peripheral curiosity in particle physics to a prominent

role even on the cosmic scale. And now we are entering an era where we can begin to use these fundamental constituents of the universe in applications such as unimpeachable monitoring of nuclear reactors, and as a means to probe the otherwise inaccessible deep interior of our planet.

**Figures:**

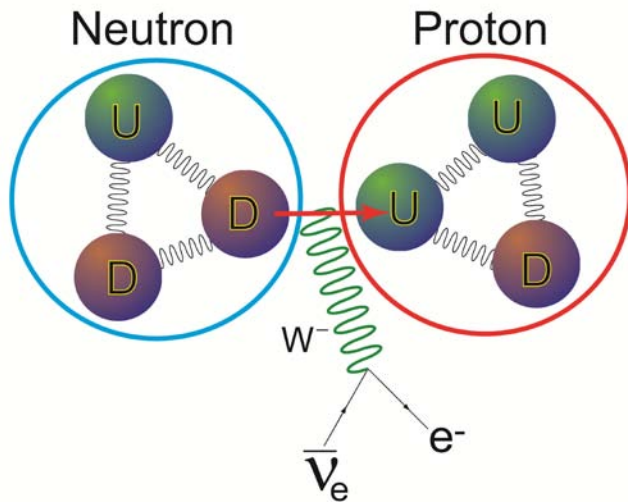


Figure 1: Production of an electron anti-neutrino ( $\bar{\nu}_e$ ) involves the decay of a down quark in a neutron to an up quark, thus transmuting the neutron to a proton. This decay is mediated by the emission of a  $W^-$  boson, an electron ( $e^-$ ) and an electron anti-neutrino. The opposite process of transmutation a proton to neutron yields a  $W^+$  boson, a positron ( $e^+$ ) and an electron neutrino ( $\nu_e$ ).



Figure 2: The Poltergeist project team of Fred Reines, Clyde Cowan and collaborators (<http://www.ps.uci.edu/physics/reinesphotos.html>). The shielded liquid scintillation detector at the Savannah River Plant (now the Savannah River National Laboratory) was eleven meters from the reactor and 12 meters underground.

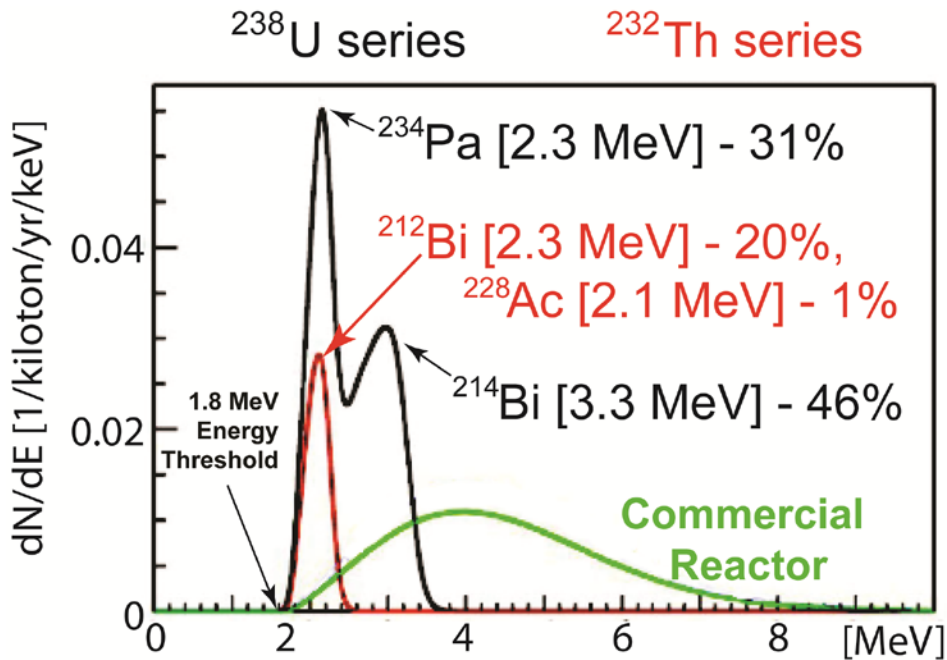


Figure 3: The  $^{238}\text{U}$  series decay chain involves the generation of 8  $\alpha$  and 6  $\beta^-$  products ( $\bar{\nu}_e$  and  $e^-$ ). Two of these decay steps  $^{234}\text{Pa}$  and  $^{214}\text{Bi}$  emit electron anti-neutrinos with more than 1.8 MeV, the energy needed to transmute a proton to a neutron and a positron. The  $^{232}\text{Th}$  series decay chain involves the generation of 6  $\alpha$  and 4  $\beta^-$  products, with the  $^{228}\text{Ac}$  and  $^{212}\text{Bi}$  decay steps producing electron anti-neutrinos with more than 1.8 MeV. Notably the total event yield is a function of the electron anti-neutrino energy, with larger signal coming from the  $^{238}\text{U}$  series. The green curve represents a typical range of electron anti-neutrinos from a commercial nuclear reactor.

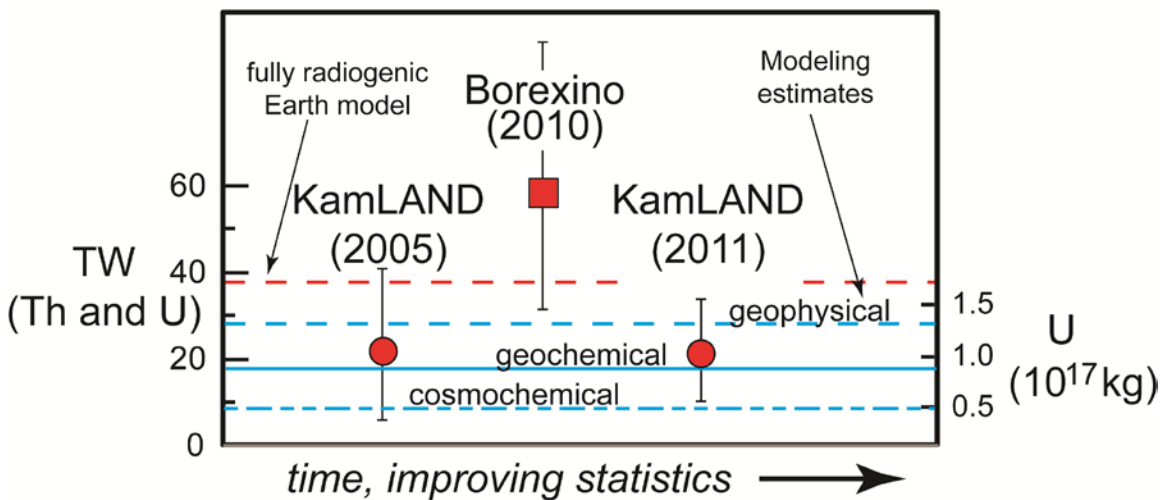


Figure 4: Data (most recent to the right [4,5,7]) from geoneutrino experiments in terms of equivalent radioactive power output from Th plus U decays (TW,  $10^{12}$  watts). The y-axis on the right reports the equivalent amount of uranium in the Earth. The three blue lines represent different estimates for abundance of U and total radiogenic power of the Earth. The red dashed line illustrates what would be the contribution from Th and U if the total surface heat flow was produced by radioactive elements in the Earth.

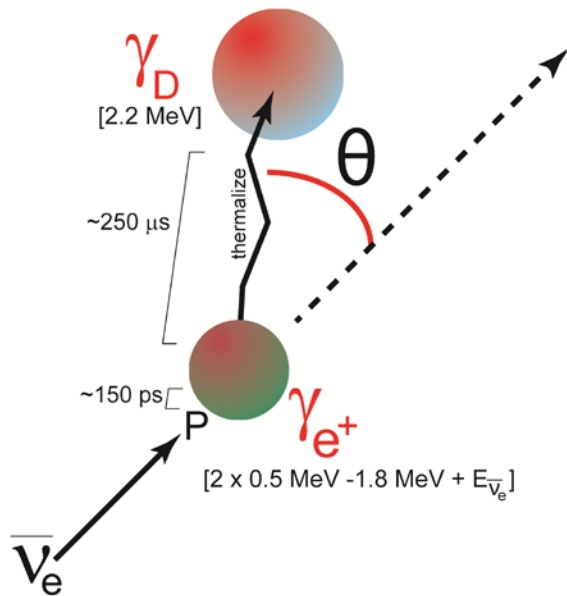


Figure 5: Directionality measurement from the inverse beta-decay process ( $\bar{\nu}_e + p \rightarrow e^+ + n$ ). The interaction of an electron anti-neutrino and a free proton in the hydrocarbon scintillation device produces two flashes of light (positron annihilation and deuterium formation) that are close in space ( $\sim 1\text{m}$ ) and separated by about 250 microseconds, with the positron light carrying the signature energy tag of the electron anti-neutrino. A resolution of  $\sim 20$  degree statistical directionality has been achieved with a few thousand events from a reactor source that is  $\sim 1$  km away.

### INSET Side-box: The neutrino

The standard model has three generations of neutrinos, electron ( $\nu_e$ ), muon ( $\nu_\mu$ ), and tau ( $\nu_\tau$ ), according to their increasing mass, although there may also exist a heavy, sterile neutrino. Each of these leptons has an anti-matter cousin, the electron anti-neutrino, muon anti-neutrino and tau anti-neutrino. Among the leptons, neutrinos stand out because of their extremely small size and neutral state.

Neutrino production occurs during proton-proton fusion in the core of the sun, where the transformation of an *up* to a *down* quark is mediated via the weak interaction involving the exchange of a  $W^+$  boson and the two particles, a positron and an electron neutrino. More locally, anti-neutrino production occurs during  $\beta^-$  decay, a common decay branch for many long-lived radioactive elements (e.g., U, Th, K, Rb, Lu, Re), where the transformation of a *down* to an *up* quark also mediated via the weak interaction involving the exchange of a  $W$  boson and the two particles, an electron and an electron anti-neutrino [see Figure 1].

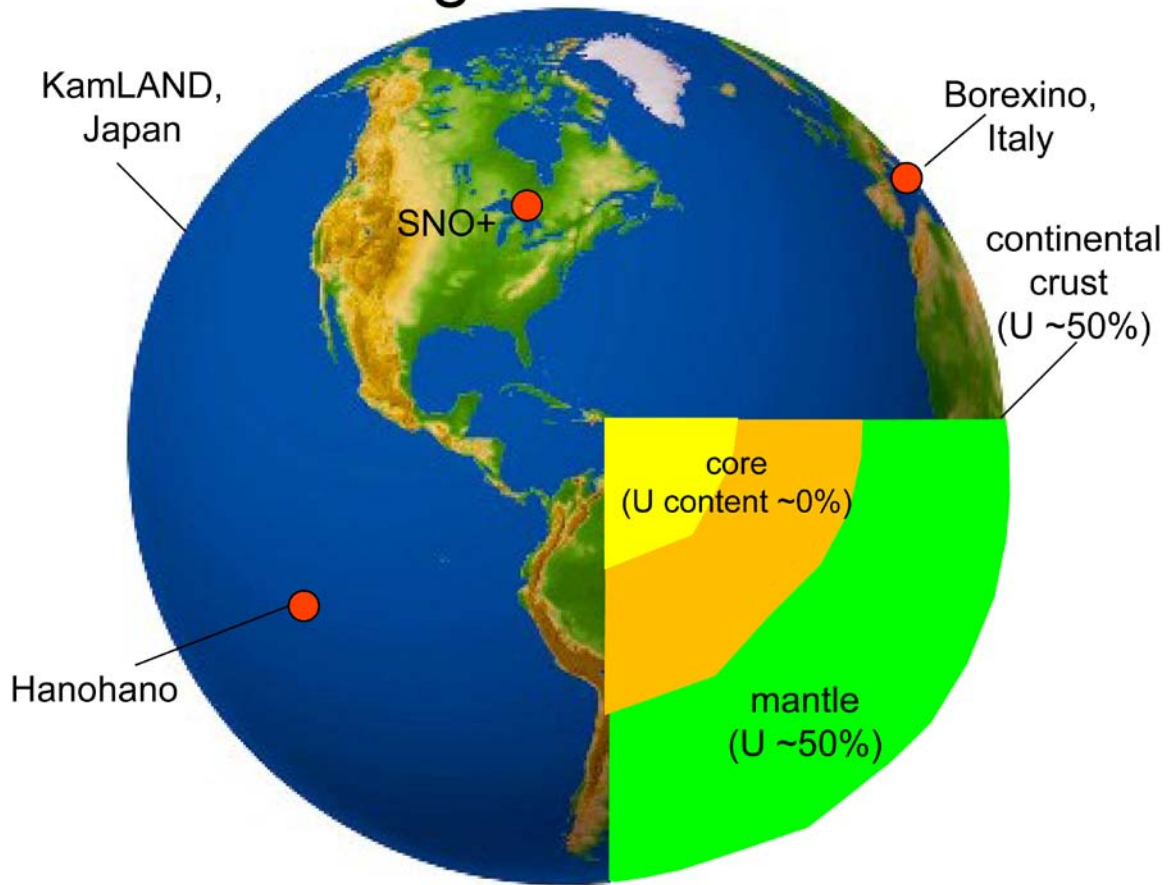
Are they Dirac or Majorana particles? This question arises, because, unlike charged fermions, neutrinos with their negligible mass and a neutral state, presents the possibility that a neutrino is its own antiparticle, which would make them a Majorana particle.

Majorana particles have only two distinct states, whereas Dirac particles have four distinct states given the helicities of their different charge states.

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# Detectors measuring the Earth's geoneutrino flux



Cover Figure: [“albeit a crude version”] A telescope into the Earth’s interior via electron anti-neutrino detectors that surround the global and serve the needs of physics, geology and nuclear security communities.