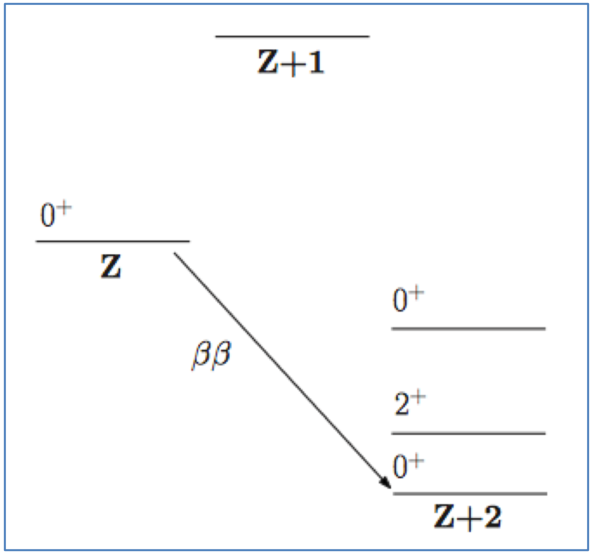
HW: Consider two flavor-mixing case involving electron and muon neutrinos. Taking:

- $\theta_{12}=32^o$
- $\Delta(m_{12})^2=8\times10^{-5}$ eV^2
- E=8 GeV

(parameters of Nova experiment), find the probability of observing electron neutrinos at L=810 km. Assume that the original neutrino beam at t=0 (L=0) consists of electron neutrinos only. What is the probability of observing electron neutrinos at L=2000 km?

Double beta decay

http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.80.481



Seen in: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{150}Nd,…

a second-order weak process
(a very weak indeed!)

$$\langle f|V_{\text{int}}|i\rangle = \sum_n \frac{\langle f|V|n\rangle\langle n|V|i\rangle}{E_i - E_n}$$

$$^{A}_{Z}X_N \rightarrow {}^{A}_{Z+2}Y_{N-2} + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

A list of the values of ννββ half-lives

Isotope	$T^{2\nu}_{1/2}$ (yr)	Isotope	$T^{2\nu}_{1/2}$ (yr)
^{48}Ca	$(4.2^{+2.1}_{-1.0})\times 10^{19}$	^{128}Te	$(2.5\pm0.3)\times 10^{24}$
^{76}Ge	$(1.5\pm0.1)\times 10^{21}$	^{130}Ba EC-EC(2ν)	$(2.2\pm0.5)\times 10^{21}$
^{82}Se	$(0.92\pm0.07)\times 10^{20}$	^{130}Te	$(0.9\pm0.1)\times 10^{21}$
^{96}Zr	$(2.0\pm0.3)\times 10^{19}$	^{150}Nd	$(7.8\pm0.7)\times 10^{18}$
^{100}Mo	$(7.1\pm0.4)\times 10^{18}$	^{238}U	$(2.0\pm0.6)\times 10^{21}$
^{116}Cd	$(3.0\pm0.2)\times 10^{19}$	^{136}Xe	2.2×10^{21}

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.107.212501

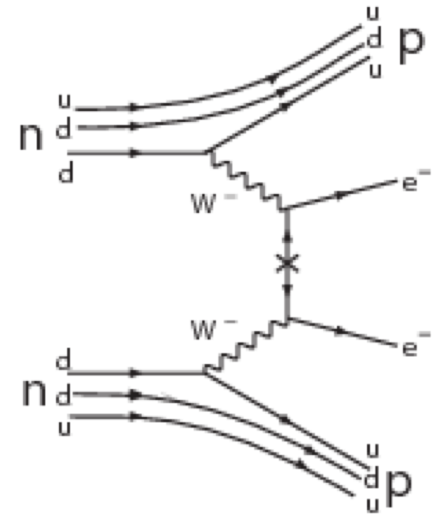
Typical lifetimes are of the order of 10^{21} years. To be compared with 13.8 billion years = $13.8\cdot 10^9$ years.

Neutrinoless double beta decay

It was suggested that neutrino can be identical or different to its charge conjugate:

$$\mathcal{C}|\upsilon\rangle \equiv |\overline{\upsilon}\rangle = |\upsilon\rangle \quad \text{(Majorana particle)}$$

$$\mathcal{C}|\upsilon\rangle \equiv |\overline{\upsilon}\rangle \neq |\upsilon\rangle \quad \text{(Dirac particle)}$$

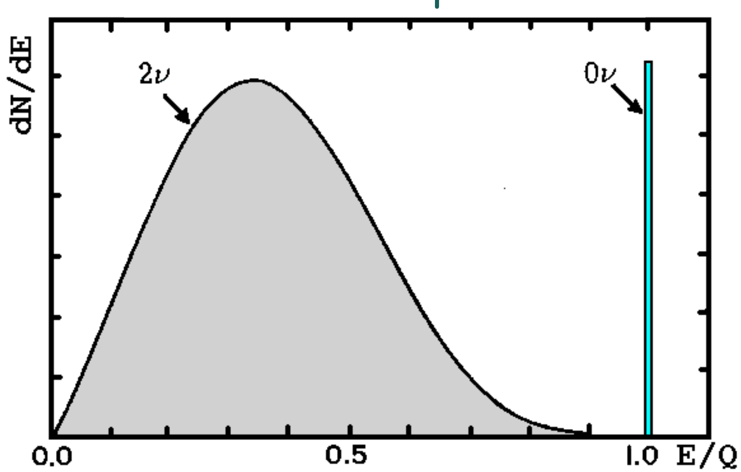


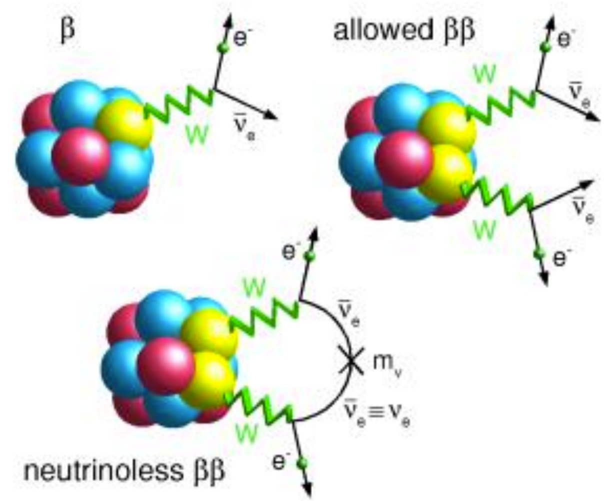
Majorana particles appear in a natural way in GUT theories that unify the strong and electroweak interactions with the possibility that *the lepton number is no longer conserved*, since now the emitted antineutrino could be absorbed as neutrino.

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + e^{-} + e^{-} $$

The estimated transition probability for the 0νββ decay is more than 10^5 shorter than the 2νββ decay

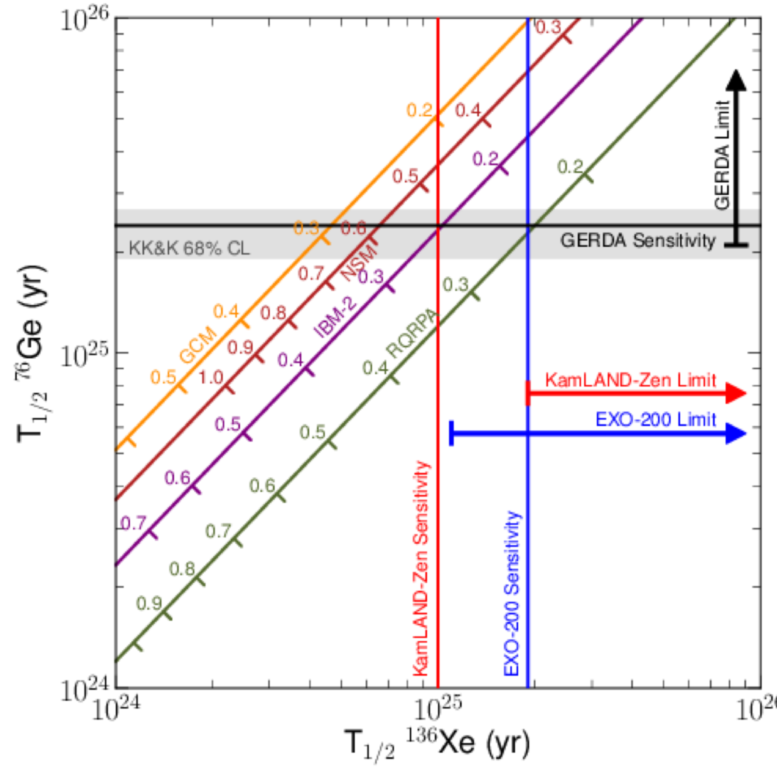
two-electron spectrum





The Enriched Xenon Observatory (EXO-200) uses large amounts of ^{136}Xe

Recent searches carried out with ^{76}Ge (the GERDA experiment) and ^{136}Xe (the KamLAND-Zen and EXO (Enriched Xenon Observatory)-200 experiments) have established the lifetime of this decay to be longer than 10^{25} years, corresponding to a limit on the neutrino mass of 0.2–0.4 electronvolts. Recently, EXO-200 found no statistically significant evidence for 0$\nu\beta\beta$ decay and set a half-life limit of 1.1×10^{25} years at the 90 per cent confidence level.



http://www.nature.com/nature/journal/v510/n7504/full/nature13432.html

http://physicsworld.com/cws/article/news/2014/jun/11/exo-200-narrows-its-search-for-majorana-neutrinos

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.109.032505

The MAJORANA Neutrinoless Double-beta Decay Experiment

http://www.npl.washington.edu/majorana/

The MAJORANA Collaboration proposes to search for neutrinoless double-beta decay using an array of germanium crystals enriched in ^{76}Ge. Of the candidate isotopes for 0νββ, ^{76}Ge has some of the most favorable characteristics. Germanium-diode detectors are a well established technology, and in searches for 0νββ of ^{76}Ge, the detectors can work as both source and detector.

KamLAND-Zen uses 13 tons of ^{136}Xe

The KamLAND-Zen collaboration boosted their experimental sensitivity to neutrinoless double-beta decays through a combination of factors. The researchers deployed clean detectors with very low background noise. And they used an unprecedented amount of xenon-136, which they purified to remove any radioactive contaminants that could produce unwanted signals in the detectors. Combining data from several years, they improved the limit on the probability of neutrinoless double-beta decay by sixfold compared to previous searches. This probability corresponds to a decay lifetime whose staggering value exceeds 10^{26} years. This measurement allowed the researchers to set the most stringent upper limit on the possible mass of Majorana neutrinos (the particle must be lighter than 61–165 meV).

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.117.082503
http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.117.082503

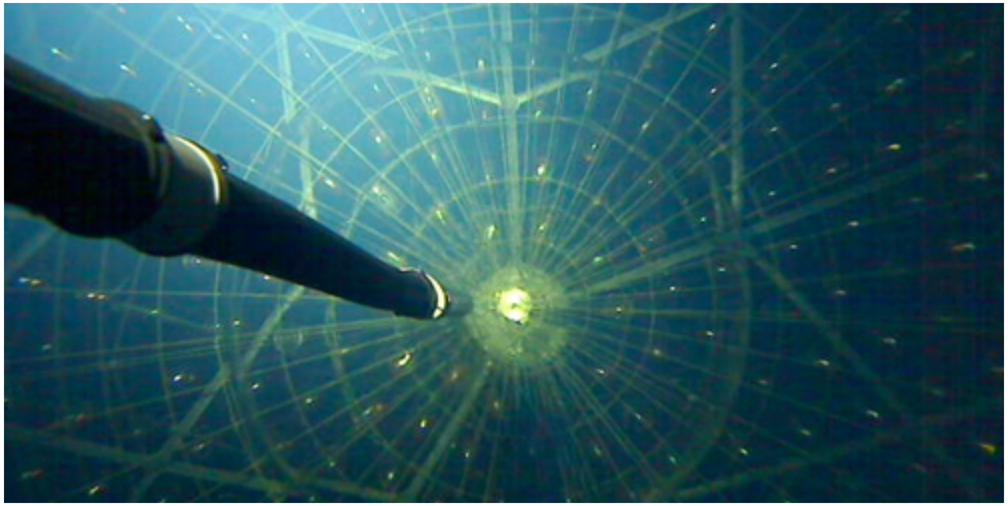
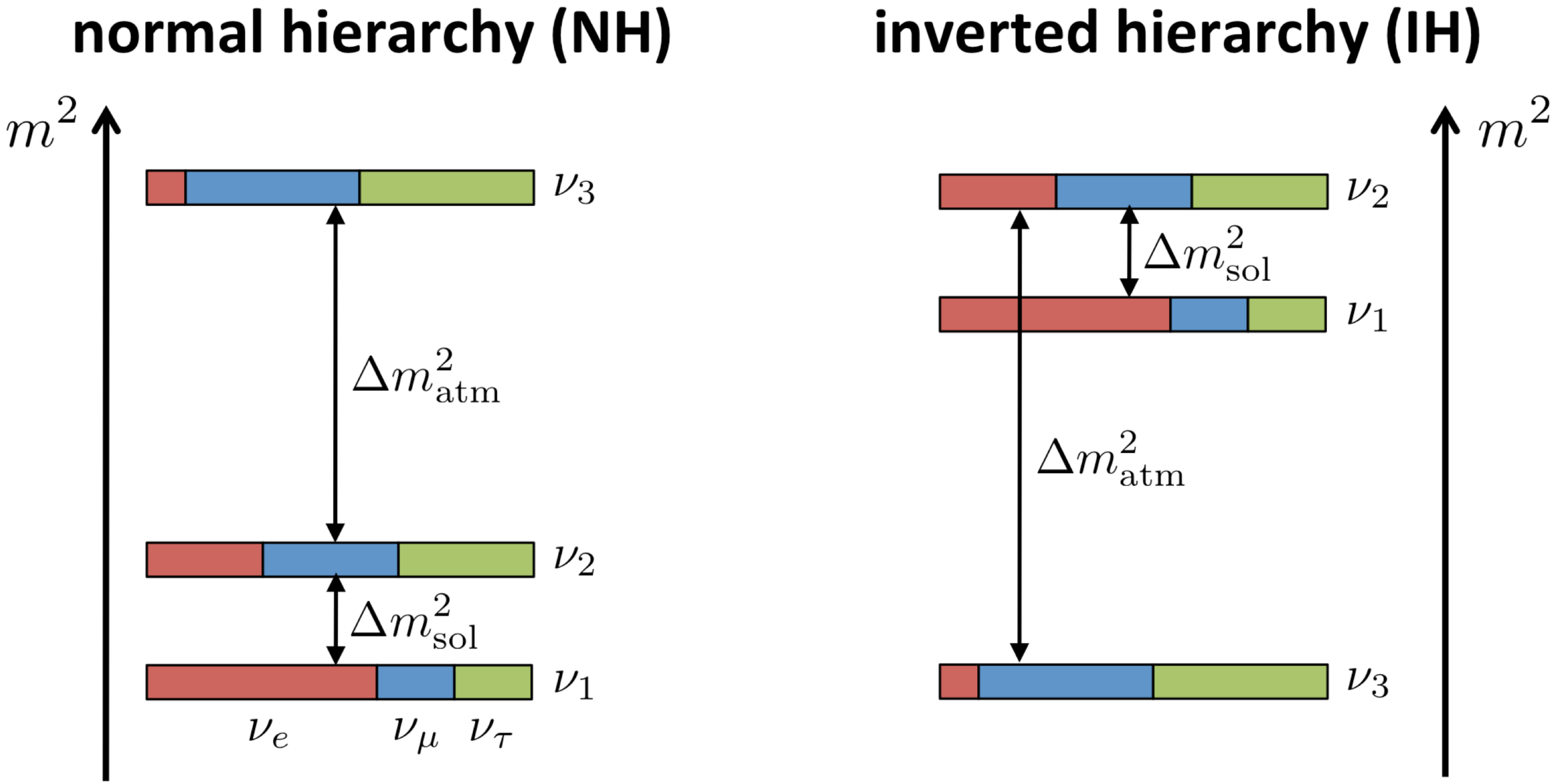


TABLE II A summary list of the $\beta\beta(0\nu)$ proposals and experiments. The Q-Value is the available energy for the decay as referenced in the text.

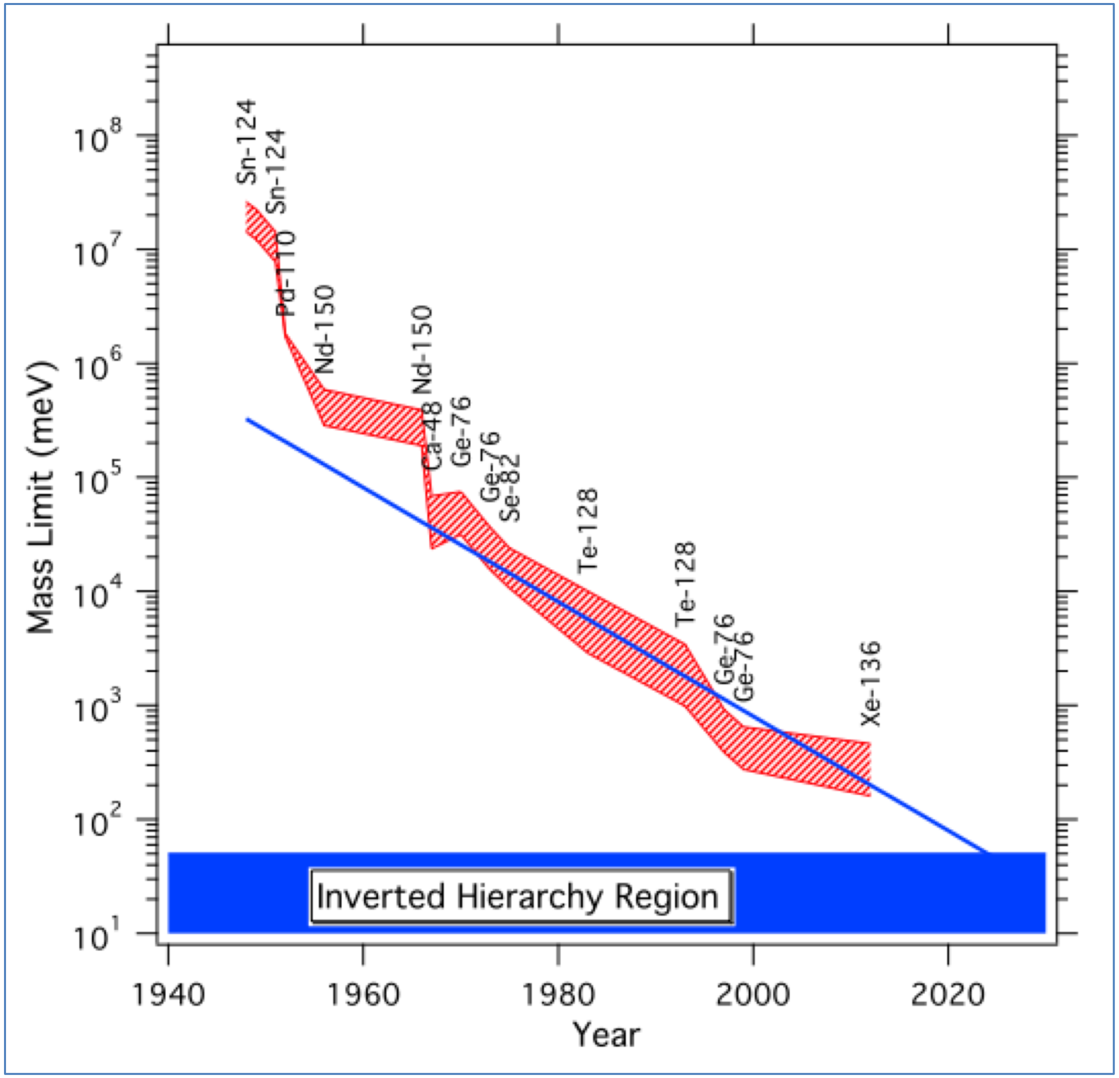
Isotope	Q-Value (MeV)	Technique	Collaborations
^{48}Ca	4.274	CaF_2 scintillating crystals	CANDLES(Umehara et al., 2008), CARVEL(Zdesenko et al., 2005)
^{82}Se	2.995	ZnSe scintillating bolometers Thin foils and tracking	LUCIFER(Arnaboldi et al., 2011) SuperNEMO(Barabash et al., 2012)
^{76}Ge	2.039	high purity Ge semiconductor detectors	GERDA(Agostini et al., 2013), MAJORANA(Abgrall et al., 2013)
^{100}Mo	3.034	$CaMoO_4$bolometers Thin foils and tracking $ZnMoO_4$bolometers	AMoRE(Lee et al., 2011) MOON(Ejiri et al., 2000) Mo Bolometer(Beeman et al., 2012)
^{116}Cd	2.809	CZT semiconductor detectors	COBRA(Dawson et al., 2009)
^{130}Te	2.528	TeO_2bolometers Te disolved in scintillator	CUORE(Alessandria et al., 2011) SNO+(Hartnell, 2012)
^{136}Xe	2.458	liquid Xe time projection chamber Gaseous Xe time projection chamber Xe dissolved in scintillator Scint. liq. Xe within Graphene sphere	EXO-200(Auger et al., 2012), nEXO, LZ(Akerib et al., 2013a) NEXT(Gómez et al., 2011) KamLAND-Zen(Gando et al., 2013) GraXe(Gómez-Cadenas et al., 2012)
^{150}Nd	3.371	thin foils and tracking	DCBA(Ishihara et al., 2000)
^{160}Gd	1.730	Cd_2SiO_5:Ce scint. crystals in liq. scint.	GSO(Wang et al., 2002)
Various		Quantum dots in liquid scintillator	Quantum Dots(Aberle et al., 2013; Winslow and Simpson, 2012)

RMP Colloquium on Majorana fermions:
http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.87.137
http://arxiv.org/abs/1403.4976

Neutrino mass hierarchy

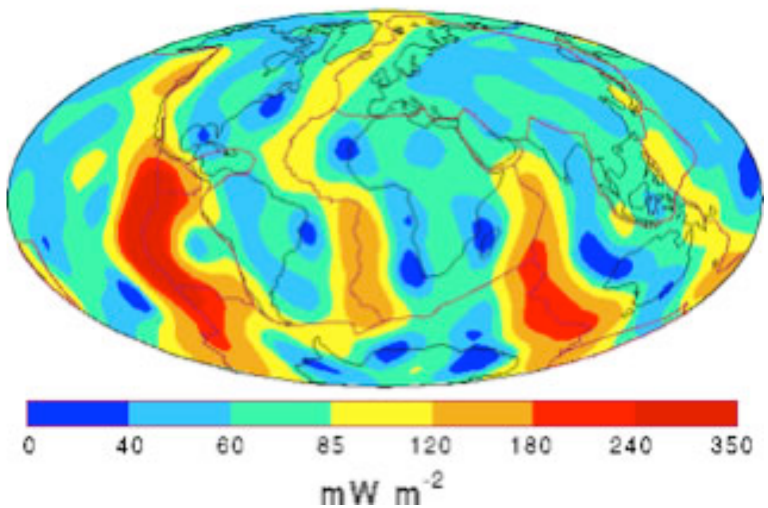


The limit improves by about a factor of 2 every 6 years. If this trend continues, the inverted-hierarchy goal for the Majorana mass sensitivity below 50 meV should be explored during the coming decade or so. Within the next few years, the presently operating experiments and those due to come online should extend the reach below 100 meV.



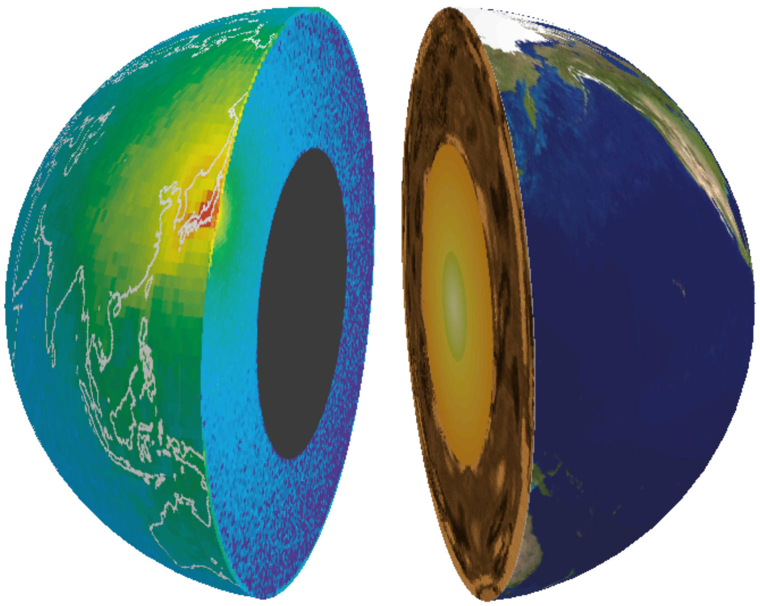
Neutrino as a tool

The total heat flow from the Earth is an estimated 40 tera-watts. Geologists believe that the most significant sources of this heat—and therefore, the likely driving force for plate tectonics, earthquakes, and the geomagnetic field— are the natural decays of uranium and thorium distributed throughout the Earth.



Distribution of the Earth's heat flow. Reviews of Geophysics 31, 267 (1993)

Geoneutrinos



Left: the production distribution for the geoneutrinos detected at KamLAND; Right: the geologic structure. Nature 436, 499 (2005). Geoneutrinos offer the only known method to directly measure the chemical composition at depths greater than a few miles.

Using antineutrinos to monitor nuclear reactors

http://physicsworld.com/cws/article/news/2014/aug/12/using-antineutrinos-to-monitor-nuclear-reactors

Neutrino Test of Lorentz Invariance

http://physics.aps.org/synopsis-for/10.1103/PhysRevD.91.052003

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.052003

A search for neutrino oscillations induced by Lorentz violation has been performed using 4,438 live-days of Super-Kamiokande atmospheric neutrino data. The Lorentz violation is included in addition to standard three-flavor oscillations using the nonperturbative standard model extension (SME), allowing the use of the full range of neutrino path lengths, ranging from 15 to 12,800 km, and energies ranging from 100 MeV to more than 100 TeV in the search. No evidence of Lorentz violation was observed, so limits are set on the renormalizable isotropic SME coefficients in the eμ, μτ, and eτ sectors, improving the existing limits by up to 7 orders of magnitude and setting limits for the first time in the neutrino μτ sector of the SME