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Neutrinos from the Earth: Status and Perspectives

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Constraints on the Earth's composition and on its radiogenic energy budget come from the detection of geoneutrinos, i.e. electron antineutrinos produced in beta decays along the the decay chains of ^{238}U and ^{232}Th existing in the interior of our planet. The KamLAND and Borexino experiments recently reported the geoneutrino flux and other experiments are starting or planning in different countries of the world. We report here the main available results and the future perspectives about these special probes of the Earth's interior. Since reactor antineutrinos represent the main source of background in geoneutrinos detection, we also report updated evaluation of reactor antineutrino signals for the different experimental sites in the world, taking into account the most recent reactors operational data.

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1. Introduction

The relevance of neutrinos for astronomical studies was realized many years ago[1]. Low-energy neutrinos have very long mean free path and neutrinos emitted by astronomical bodies carry direct information on their internal composition and structure. Experimental detection of the solar neutrinos has already provided valuable information on radioactive processes inside the stars[2]. Unlike the Sun, Earth emits mainly antineutrinos, the so-called geoneutrinos. Some interesting reviews[9, 10] discuss in details geoneutrino properties, detection, and relevance for the Earth's structure.

These particles have been conceived during the very first attempts of neutrino detection, performed at the Hanford nuclear reactor by Reines and Cowan in 1953, where experimental results showed an unexpected and unexplained background[1]. While on board of the Santa Fe Chief Train, Georg Gamow wrote to Fred Reines: "It just occurred to me that your background may just be coming from high energy beta-decaying members of U and Th families in the crust of the Earth". In a teletype message by Reines in response to the letter of Gamow, the first estimate of geoneutrino flux was given: "Heat loss from Earth's surface is 50 erg cm^{-2} s^{-1}. If assume all due to beta decay than have only enough energy for about 10^8 one-MeV neutrinos per cm^2 and sec".

In the scientific leterature, geoneutrinos were introduced in the sixties by Eder[3] and Marx[4]. In the eighties Krauss et al. discussed their potential as probes of the Earth's interior in an extensive publication[5]. In the nineties the first paper on a geophysical journal was published by Kobayashi et al.[6]. In 1998, Raghavan et al.[7] and Rothschild et al.[8] pointed out the potential of KamLAND and Borexino for geoneutrino detection.

Geoneutrinos are mainly produced in the decays of nuclei in the ^{238}U and ^{232}Th chains and of ^{40}K inside the Earth. The main geoneutrino properties, summarized in Table 1 and Fig. 1, deserve a few comments:

1) geoneutrinos from different elements yield different energy spectra, e.g. geoneutrinos with energy E > 2.25 MeV are produced only from the uranium decay chain. Therefore the geoneutrino spectrum can provide information on the abundances of U and Th separately.

2) Only a fraction of geoneutrinos from U and Th (not those from ^{40}K) are above threshold for the classical antineutrino detection reaction, the inverse beta decay on free protons:

$$\bar{\nu} + p \to e^+ + n - 1.806\,MeV \tag{1.1}$$

Table 1: The main properties of geoneutrinos. For each parent nucleus the table presents half-life ($T_{1/2}$), antineutrino maximal energy (E_{max}), Q-value, antineutrino and heat production rates ($\varepsilon_{\bar{\nu}}$ and ε_H) for unit mass for unit mass of the isotope (the corresponding values at natural isotopic composition are obtained by multiplying the isotopic abundance), adapted from [9].

Decay	$T_{1/2}$ [10^9yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$Kg^{-1}s^{-1}$]	ε_H [W/Kg]
$^{238}U \to ^{206}Pb + 8\,^4He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	$7.46 \cdot 10^7$	$0.95 \cdot 10^{-4}$
$^{232}Th \to ^{208}Pb + 6\,^4He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	$1.62 \cdot 10^7$	$0.27 \cdot 10^{-4}$
$^{40}K \to ^{40}Ca + e + \bar{\nu}$	1.28	1.311	1.311	$2.32 \cdot 10^8$	$0.22 \cdot 10^{-4}$

[1] Such background was due to cosmic rays.

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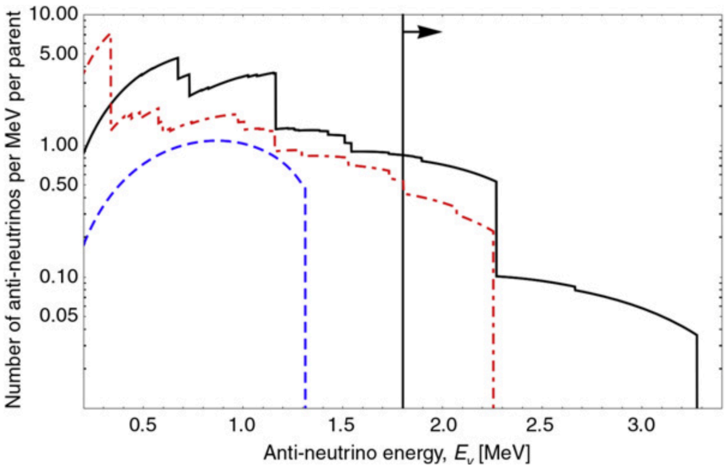

Figure 1: Energy spectra of geoneutrinos released in ^{238}U chain (solid black line), ^{232}Th chain (dashed-dotted red line) and ^{40}K decay (dashed blue line). The vertical dashed line shows the inverse beta decay threshold, from [10].

3) Antineutrinos from the Earth are not obscured by solar neutrinos, which cannot yield reaction (1.1).

Really geoneutrinos represent a new probe of the Earth interior: differently from other emissions of the planet (e.g., heat or noble gases), they escape freely and instantaneously from the Earth's interior, carrying to the surface information about the chemical composition of the whole planet and, on the radiogenic contribution to terrestrial heat production and on the validity of different geological models of the Earth, see eg. [11]

This paper is organized as follows. First we discuss the geoneutrinos detection with a particular attention to the main source of background due to antineutrino produced by nuclear power plants. Next we report some relevant implications of available experimental data. Finally we report our conclusions.

2. Reactor antineutrinos background in geoneutrinos detection

As already mentioned, antineutrinos from the Earth are detected through inverse beta decay (IBD), see Eq. (1.1). The IBD detection event in liquid scintillator produces two flashes of light: the annihilation flash, from electron-positron interaction, followed by the deuterium formation flash, which is 2.2 MeV of light that follows some 200 μs later. The delayed coincidence of these two flashes of light provides the critical identification of the antineutrino interaction and eliminates most background events a part the background due to reactor antineutrinos, i.e. electron antineutrinos emitted during the beta decays of fission products from 235U, 238U, 239Pu and 241Pu burning in nuclear power plants. The energy spectrum of reactor antineutrinos extends up to $\simeq$ 10 MeV, well beyond the end point of the geoneutrino spectrum (3.27 MeV). As a consequence, in the geoneutrino energy window, 1.8 - 3.27 MeV (or Low Energy Region, LER), there is an overlap between geoneutrino and reactor antineutrino signals, see Fig. 2: about 27% of the total reactor events are registered in the LER.

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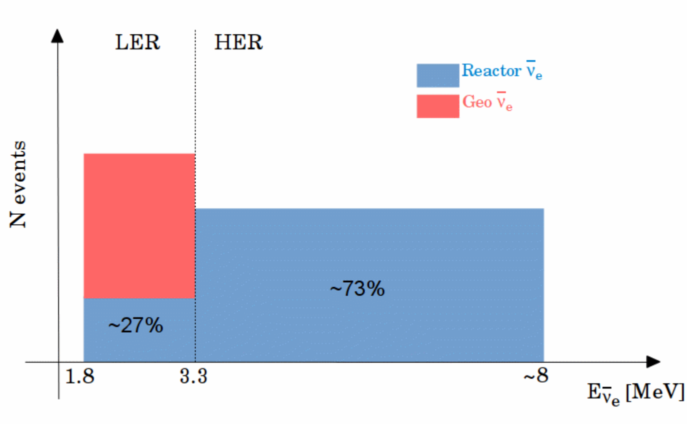

Figure 2: A schematic picture of the expected reactor signal in the Low Energy Region (LER) and in the High Energy Region (HER), from [12].

Therefore, a careful analysis of the expected reactor antineutrino event rate at a given experimental site is mandatory. In particular, the comparison between the predicted reactor antineutrino signal in the LER and the expected geoneutrino signal can be considered an important tool to access the potentiality of a geoneutrino detector. Note also that the reactor contribution to the signal changes according to the different reactor operational conditions, while the geoneutrino component is, in principle, time independent.

Analyses of reactor antineutrino signals have been presented in the past, for instance see ref. [9] and [13]. Recently in [12] a reference worldwide model for antineutrinos from reactors has been published, including uncertainties related to reactor antineutrino production, propagation, and detection processes, estimated using a Monte Carlo-based approach.

Clearly several ingredients occurring in the signal calculation, spanning from nuclear physics (energy released for fission, reactor neutrino spectra) to neutrino properties (neutrino oscillation mechanism, IBD cross section), passing through our knowledge of the nuclear plant operation procedure (thermal power, fuel composition...) and position .

In Table 2 we present our updated results on expected reactor antineutrino signal for several sites in the world, compared with the prediction of geoneutrino signals calculated according to [14]. We perform signal (and uncertainty) calculations as in [12] but for the operational Load Factor of nuclear cores: we use here the most recent values referred to operational year 2014 [15].

As the antineutrino detection depends on several experimental parameters (e.g. the fiducial volume), expressing both geoneutrino and reactor antineutrino signals in terms of detector independent quantities allows the comparison of signals measured at different experiments and originating from different sources. Therefore, event rates are quoted in Terrestrial Neutrino Units (TNU) [9], corresponding to one event per 10^{32} target protons per year, which are practical units as liquid scintillator mass is on the order of one kton ($\sim 10^{32}$ free protons) and the exposure times are typically on the order of a few years.

In Table 2, the ratio R_{LER}/G between the predicted reactor signal in the Low Energy Region and the expected geoneutrino signal can be considered as a figure of merit for assessing the discrimination power on geoneutrinos detection at a specific location. In particular, with respect the

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Sites	Experiment	R_{FER} [TNU]	R_{LER} [TNU]	G [TNU]	R_{LER}/G
GRAN SASSO	Borexino	$85.2^{+2.0}_{-1.8}$	$22.9^{+0.6}_{-0.5}$	$40.3^{+7.3}_{-5.8}$	0.6
SUDBURY	SNO+	$193.9^{+4.7}_{-4.5}$	$48.8^{+1.7}_{-1.5}$	$45.4^{+7.5}_{-6.3}$	1.1
KAMIOKA	KamLAND	$27.4^{+0.6}_{-0.6}$	$7.4^{+0.2}_{-0.2}$	$31.5^{+4.9}_{-4.1}$	0.2
DONGKENG	JUNO	214.4^{+11}_{-10}	$53.9^{+3.0}_{-2.7}$	$39.7^{+6.5}_{-5.2}$	1.4
GUEMSEONG	RENO-50	1176^{+75}_{-72}	190^{+22}_{-20}	$38.3^{+6.1}_{-4.9}$	5.0
HAWAII	Hanohano	$3.4^{+0.08}_{-0.07}$	$0.9^{+0.02}_{-0.02}$	$12^{+0.7}_{-0.6}$	0.1
PHYASALMI	LENA	$69.5^{+1.7}_{-1.6}$	$18.0^{+0.5}_{-0.5}$	$45.5^{+6.9}_{-5.9}$	0.4
BOULBY	LENA	1056^{+29}_{-30}	210^{+10}_{-10}	$39.2^{+6.3}_{-4.9}$	5.4
CANFRANC	LENA	237^{+6}_{-5}	$67.7^{+1.5}_{-1.6}$	$40.0^{+6.4}_{-5.1}$	1.7
FREJUS	LENA	$558.1^{+11.4}_{-10.6}$	$129.1^{+5.5}_{-5.0}$	$42.8^{+7.6}_{-6.4}$	3.0
SLANIC	LENA	$114.9^{+2.8}_{-2.7}$	$31.3^{+0.76}_{-0.72}$	$45.1^{+7.8}_{-6.3}$	0.7
SIEROSZOWICE	LENA	$154.8^{+3.7}_{-3.5}$	$42.2^{+1.0}_{-1.1}$	$43.4^{+7.0}_{-5.6}$	1.0
HOMESTAKE		$31.8^{+0.8}_{-0.7}$	$8.5^{+0.2}_{-0.2}$	$48.7^{+8.3}_{-6.9}$	0.2
BAKSAN		$37.4^{+0.9}_{-0.8}$	$9.96^{+0.28}_{-0.27}$	$47.2^{+7.7}_{-6.4}$	0.2

Table 2: For current and proposed neutrino experimental sites we report the redicted antineutrino signals from nuclear power plants in the Full Energy Region (R_{FER}) and in the Low Energy Region (R_{LER}) obtained with 2014 reactor operational data, together with the expected geoneutrino signals (G) [14]. The R_{LER}/G ratios is also shown.

previous results reported in [12] one can observe that:
1) In year 2014 KamLAND experiment reached a very high sensitivity in geoneutrino detection. In fact during this year all nuclear power plant were closed down, leaving Japan without any nuclear power for the third time in 40 years. We expect that near in the future KamLAND collaboration will provide new interesting measurements on geoneutrino flux.
2)Conversely, in China the nuclear power plant near JUNO site are becoming more and more operative, providing an increase of the ratio R_{LER}/G. As reported in [12] in year 2020 the ratio will increase of about one order of magnitude. But nevertheless due to the huge mass ($\simeq$ 20 kt), the collection of a high statistic could provide interesting results on geoneutrinos, in particular during the temporary switching off for ordinary plants maintenance, see [16].

3. Geo-neutrinos measurements and implications

The first observation of geoneutrinos in 2005 by KamLAND experiment [26] demonstrated that geoneutrino detection was possible. In 2010 Borexino collaboration presented the first observation of geoneutrinos at Gran Sasso National Laboratory with more than 4σ C.L [27]. These achievements were the consequence of two fundamental developments: extremely-low-background neutrino detectors and progress on the understanding neutrino propagation. In the last years both experiments updated their first results with larger statistics and lower background [26, 27] and new measurements of geoneutrino fluxes are highly awaited from experiments entering operation, such as SNO+ [19], or proposed to the scientific community, such as Juno [20], RENO-50 [21], LENA [22], Hanohano [23], Homestake [24] and Baksan [25]. In Fig. 3 we report the location of existing

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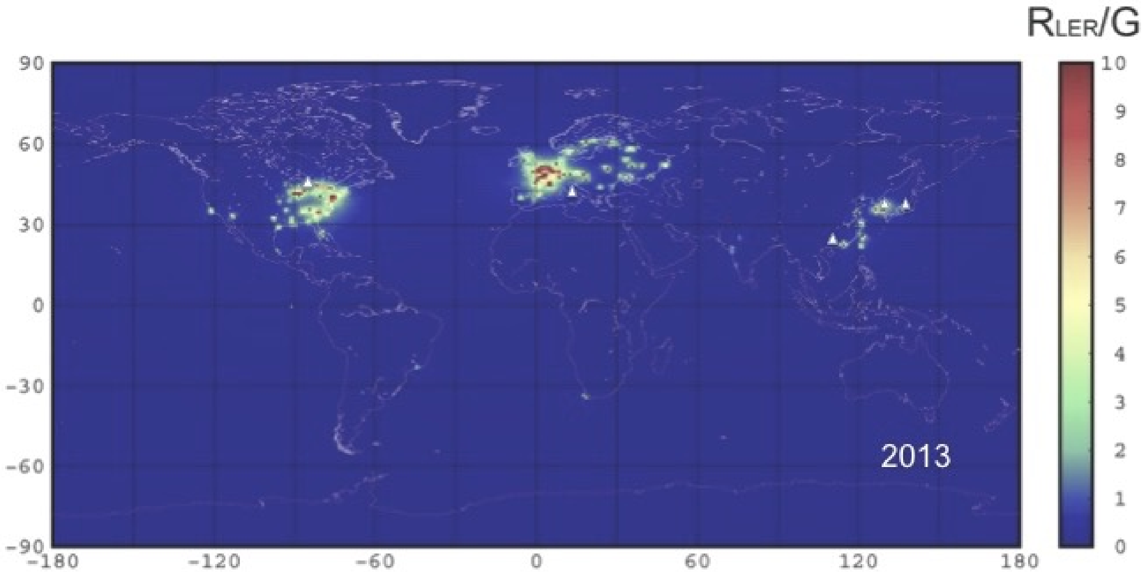

Figure 3: The ratio R_{LER}/G between the predicted reactor signal in the Low Energy Region [12] and the expected geoneutrino signal [14] is shown. Note that R_{LER} is obtained with 2013 reactors operational data. The location of existing and some future experiments are also shown (withe triangles): SNO+, Borexino, JUNO, RENO-50, KamLAND (from west to est).

experiments and some future planned experiments, together with the ratio R_{LER}/G signal all over the world, adapted from [12].

At the moment the available geoneutrino experimental results are: 116^{+28}_{-27} observed events in a total live-time of 2991 days for KamLAND and 14.3 $\pm$ 4.4 geoneutrino events in 1353 days for Borexino, corresponding to 39 $\pm$12 TNU and to 30 $\pm$ 7 TNU respectively. Let us see how these experimental results can help in the knowledge of the Earth interior, in particular in testing different geological models, in the the determination of the radiogenic heat power and in understanding the the distribution of radioactive elements inside our planet (we summary here the main highlights and we remand to cited references for extensive analysis).

Up until now the debate about the terrestrial heat flow is still open: estimates over the last 40 years for the Earth's surface heat flow are between 30 and 50 TW, with recent estimates being 47 $\pm$ 2 [28]. Combining the present day surface flux and independent estimates of the radiogenic heat production allows one to estimate the amount of primordial heat remaining in the Earth.

As widely described in [9, 17, 10], one can extract the radiogenic heat power from U and Th decays, H(T+U), from geoneutrino experimental data, although it is not so straightforward. Actually, the measured geoneutrino signal does not depend only on the absolute mass abundances of U and Th, but also on their distribution throughout the Earth. Therefore, the radiogenic heat power extracted from a measured geoneutrino signal is Earth-model dependent. In Fig. 4 the expected geoneutrino signal in Borexino (left) and KamLAND (right) are shown, as a function of the produced radiogenic heat [10]. The red and blue lines contain the region of all possibile signals, taking into account the errors in the prediction of the signal due to U and Th existing

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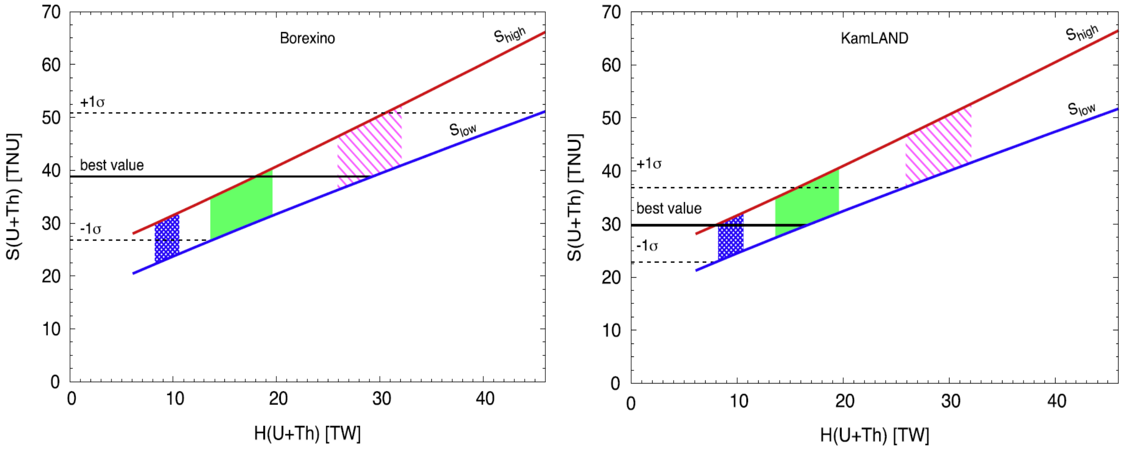

Figure 4: The expected geoneutrino signal in Borexino (left panel) and KamLAND (right panel) from U and Th as a function of radiogenic heat released in radioactive decays of U and Th. The three filled regions delimit, from the left to the right, the cosmochemical, geochemical and geodynamical Earth models. The 2013 Borexino and KamLAND results are indicated by the horizontal lines; from [10].

into the Earth's crust, as well as different U and Th distributions through the Earth's mantle, see [10] for details. The three filled areas in Fig. 4 represent the predictions of three main classes of Earth models: cosmochemical, geochemical, and geodynamical, according to the classification from [18]. The horizontal lines represent the 2013 results of Borexino and KamLAND. At 1σ level the geodynamical models seem disfavored by KamLAND results, whereas Borexino data are compatible with all the models.

Furthermore, from Fig. 4 one can see that H(U+Th) consistent with present Borexino (KamLand) results, lies in the interval 13–45 TW (8–25 TW). More refined analysis [10] gives : H(U+Th)= 23±14 TW (13±9 TW). Such determinations will be constrained in the future by new experimental data and surely represent a valuable determination of the radiogenic heat flux.

In addition, geoneutrinos are a real time probe of the Earth's distribution of U and Th naturally present in the crust and in the mantle, which are thought to be the main reservoirs of these radioisotopes [9]. In particular, the crustal contribution to the geoneutrino signal can be inferred from direct geochemical and geophysical surveys, see e.g. [14, 29], while the mantle contribution is totally model-dependent. Hence from the experimental determination of geoneutrinos signal, by subtracting the crustal contribution, one can derive the the mantle contribution in an independent way. In Bellini et al 2013 [27], from Borexino data a mantle geoneutrino signal of S(Mantle)=15.4 ±12.3 TN has been extracted, by considering the geoneutrino signal from the crust S(Crust) = (23.4 ± 2.8) TNU, this last obtained by combining the study of the Local Crust in the region around the Gran Sasso laboratory of [29] together with the calculation of the contribution from the Rest Of the Crust of [14]. Furthermore, the Borexino and KamLAND results have been combined, by assuming a homogeneous mantle and thus the same signal from the mantle geoneutrinos on the Earth surface, resulting into S(Mantle)=14.1 ± 8.1 TNU. In Gando et al. 2013 [26], using KamLAND 2013 data and subtracting out the crust contribution determined by [30] in the hypothesis that U and Th are uniformly distributed throughout the mantle, the total mantle radiogenic heat production is calculated to be 11.2±7.9 TW [112].

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4. Conclusions and perspectives

Really geoneutrinos represent a new probe of the Earth interior: they escape freely and instantaneously from the Earth's interior carrying to the surface precious information on important quantities such as the radiogenic contribution to terrestrial heat production, the abundances of U and Th inside the Earth, and on the validity of different geological models of the Earth.

At the moment two independent experiments, far about 10^4 km each other, measure a geoneutrino signal essentially in agreement with the expectations. These experimental results, together with the big effort in geoneutrino signal calulation accomplished in the last years and to a better knowledge of the backgrounds due to antineutrinos produced by reactor power plant, allow us to estimate the amount of radioactive elements in the most deeper region of our planet, otherwise inaccessible.

All of these measurements need further confirmations and refinements, which can be achieved with an increase of statistical significance. In this respect future geoneutrino detectors, like JUNO, even bigger than the current ones are really suitable.

One of the most exciting question is the measurement of the geoneutrino signal from the mantle: a geoneutrino detector placed in Hawaii, where the crustal contribution to geoneutrino signal is minimal and easily estimated, can improve our knowledge on the radioactive composition of the mantle. Furthermore due to the absence of nearby power reactors, the geoneutrino signal can be measured with small errors, allowing a better discrimination among different models for terrestrial heat generation.

At Sudbury, SNO+ experiment will have excellent opportunities to determine the uranium mass in the crust, which accounts for about 80% of the geo-neutrino signal. This will provide an important test about models for the Earth's crust.

For the very long term future, one can speculate about completely new detectors, capable of providing (moderately) directional information. These should allow the identification of the different geo-neutrino sources (crust, mantle and possibly core) in the Earth.

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