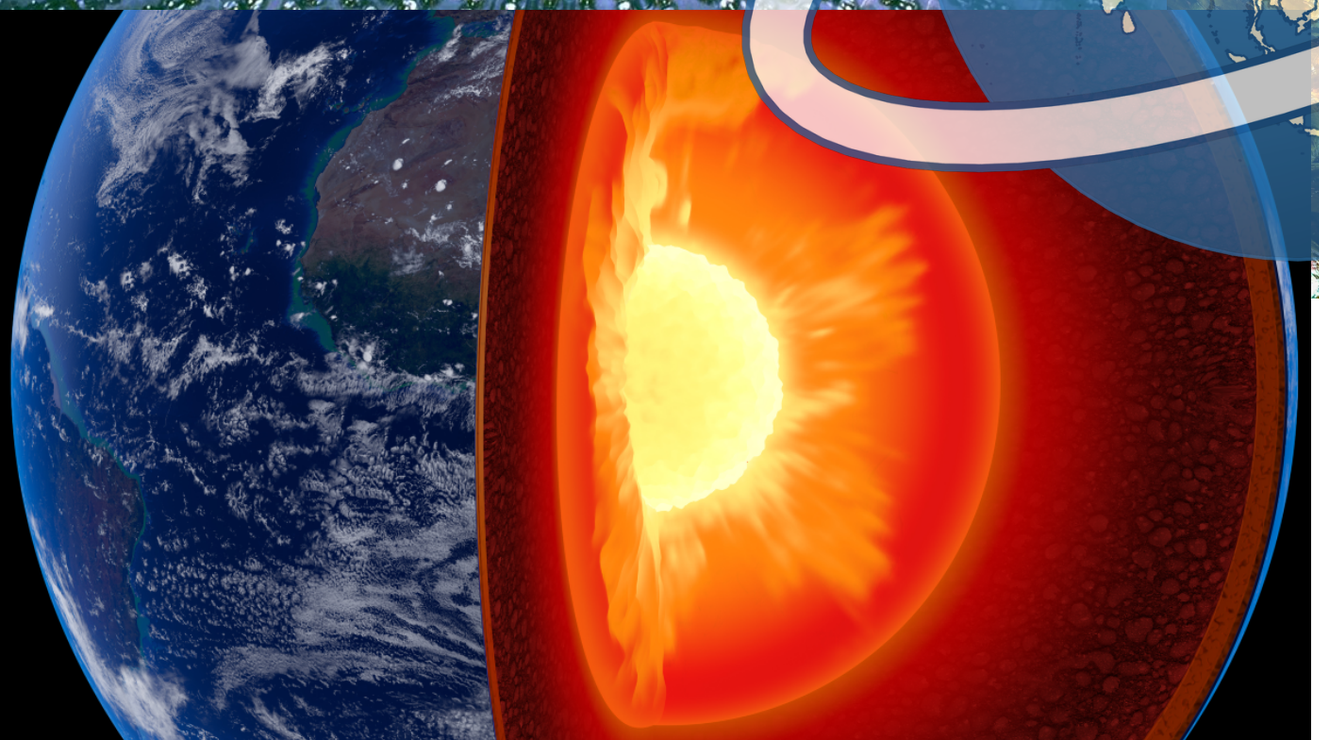
Geoneutrinos:
Two Decades of Discovery
…and the road ahead



Neutrino Geoscience 2026
November 16-19, 2026
Zhuhai, China
珠海市 中国

Mark Chen
Queen's University

Geoneutrinos: $\bar{\nu}_e$ emitted by the Earth

from the β^- decay of naturally-occurring radioactive elements in the crust and mantle

U, Th, K account for >99% of Earth's radiogenic heat production

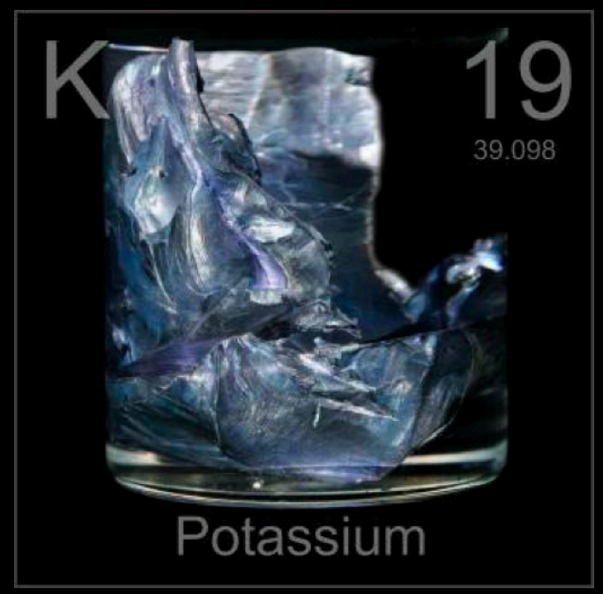
(and a large fraction ~40% of Earth's total heat flow)







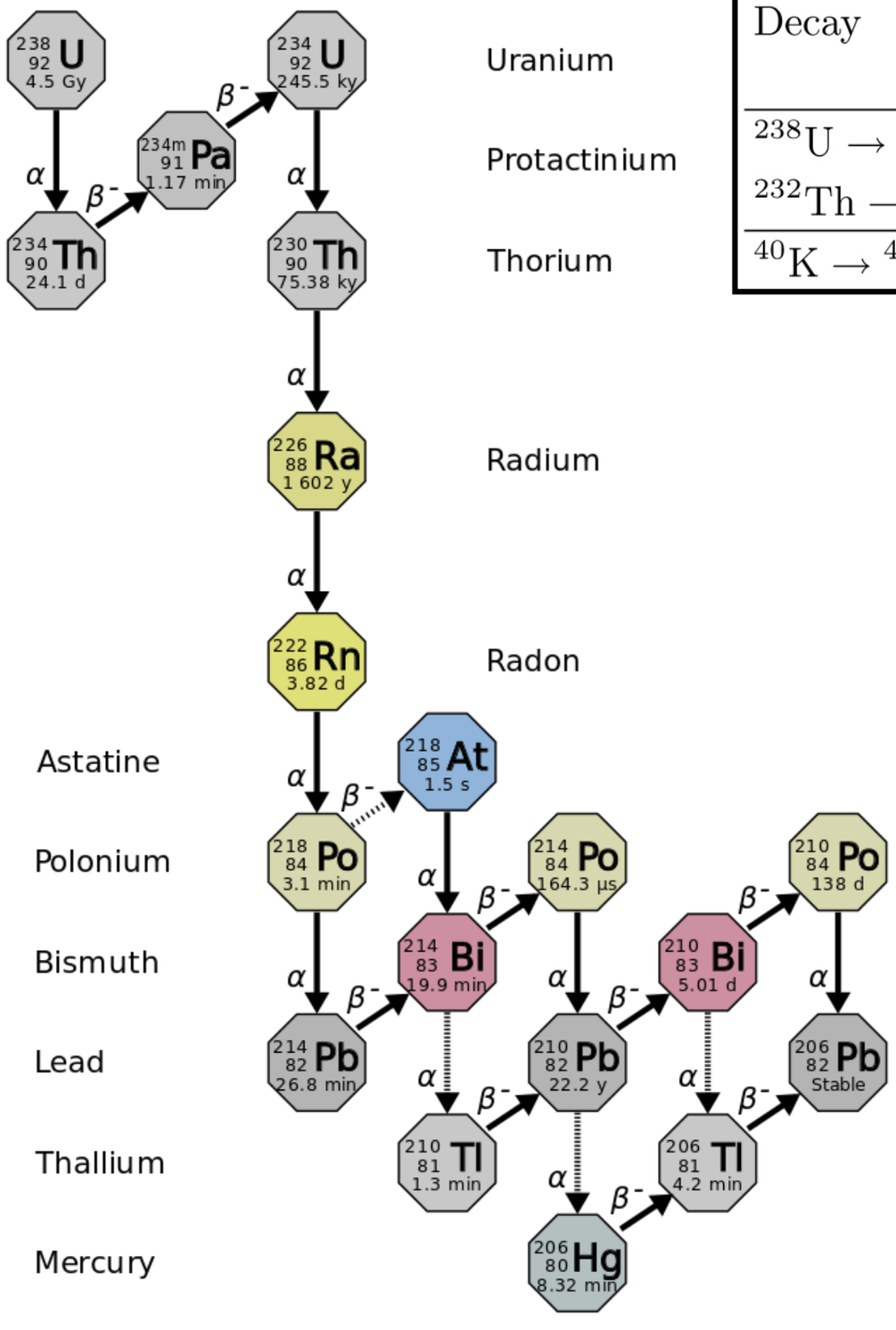




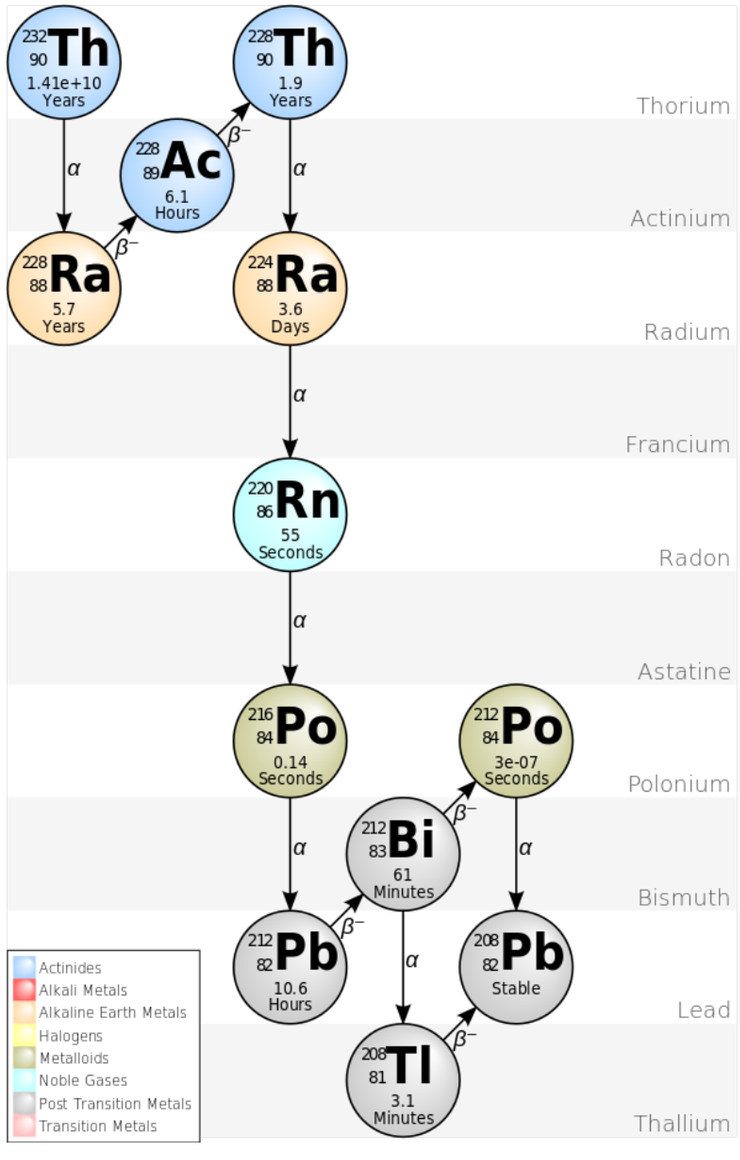
^{40}K

~20% of radiogenic heat

Uranium, Thorium and Potassium Decay



Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [kg^{-1}s^{-1}]	ε_H [W/kg]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

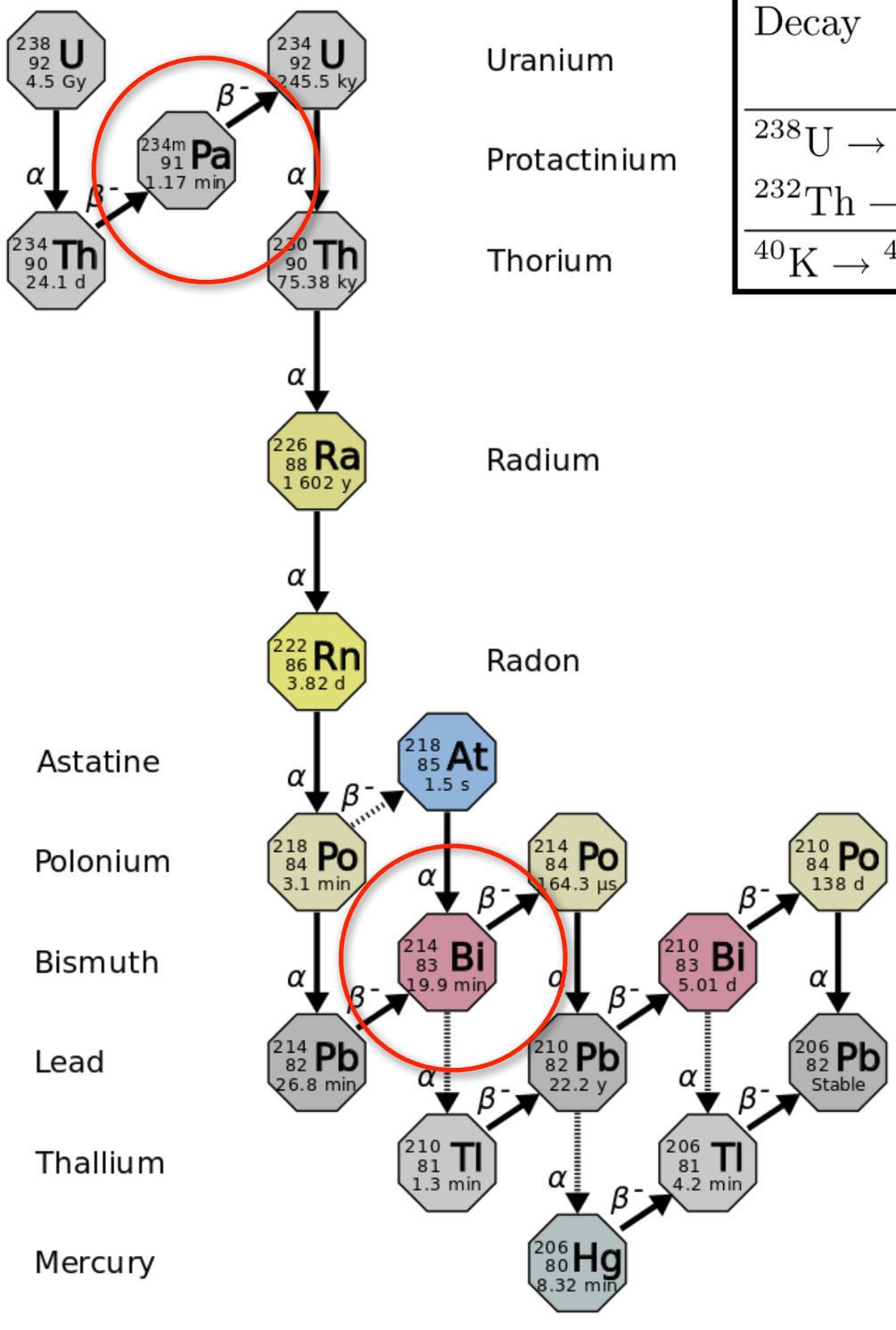


when neutron-rich heavy elements undergo beta decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

antineutrinos (electron-flavour) are emitted

Uranium, Thorium and Potassium Decay



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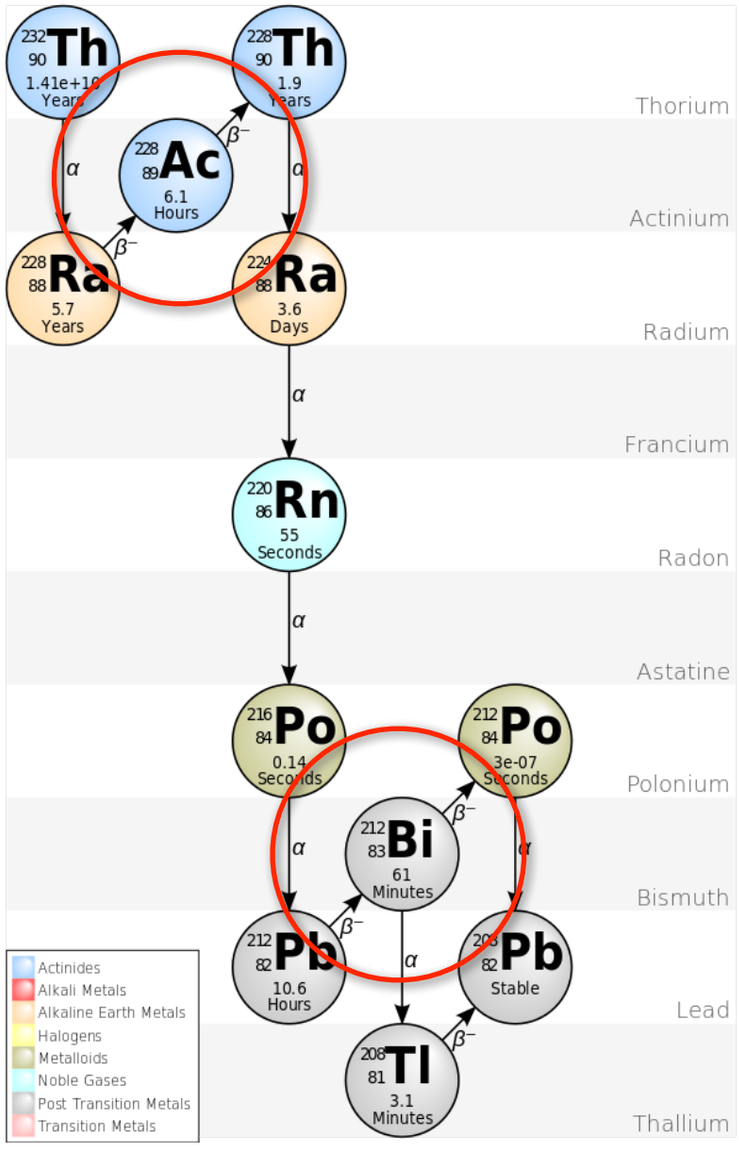

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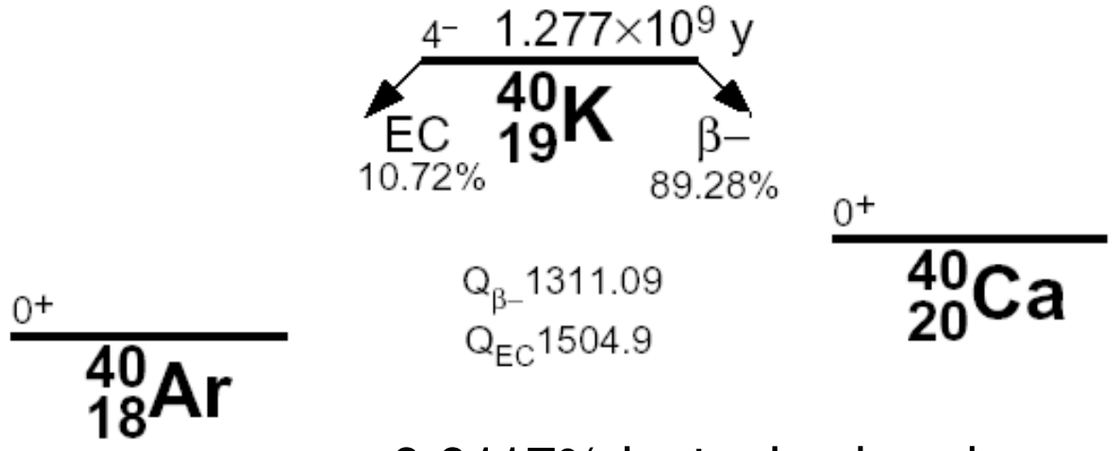
- note: ^{40}K also has a 10.72% EC branch

thus also emits neutrinos as well as antineutrinos; but the ν_e are mostly inconsequential because they have much lower energy, 44 keV (EC to an excited state of ^{40}Ar, 10.67%) or very small branching ratio, 0.05% to the ground state



0.0117% isotopic abundance

Looking back more that two decades…

to 1960 (just a few years after Reines and Cowan)

and 1965

ÜBER DIE PERSPEKTIVEN DER NEUTRINOASTRONOMIE

von

G. MARX und NÓRA MENYHÁRD

Institut für Theoretische Physik der Roland Eötvös Universität Budapest

Zentralforschungsinstitut für Physik Budapest

Aus dem Gesichtspunkte der Astronomie zählt die durch die Himmelskörper ausgesandte Neutrinostrahlung zu den intensivsten Strahlungen. Es wird hier der Charakter der Neutrinostrahlung des Erdkörpers vom geochemischen, jener der Sonne aus astrophysikalischen und der der von ausserhalb des Sonnensystems kommenden Strahlung vom kosmogonischen Standpunkt aus untersucht. Die Detektierung bildet das schwerste Problem: die derzeitige Empfindlichkeit müsste um Grössenordnungen erhöht werden, um durch die Detektierung der Neutrinostrahlung astronomische Probleme klären zu können. Als einzige Ausnahme bietet sich hiefür die Neutrinostrahlung der Sonne, deren Detektierung nunmehr als eine nahe Perspektive bevorsteht.

Die Verteilung der radioaktiven Substanzen im Innern der Erde kennen wir nicht, es ist jedoch anzunehmen, dass sie in der Erdrinde am meisten angereichert sind. Wenn wir voraussetzen, dass radioaktive Stoffe nur in der

15 km dicken oberen Rinde (deren Masse — die Ozeanenboden mitinbegriffen — $M = 2 \cdot 10^{19}$ Tonnen beträgt) vorhanden sind (der Beitrag der basischen und sonstigen Gesteine, die die unteren Schichten der Erdrinde bilden, kann vernachlässigt werden), so ist die $\tilde{\nu}$-Intensität an der Erdfläche

$$I_0 = \frac{W}{4\pi R^2} = \frac{wM}{4\pi R^2} = 6{,}7 \cdot 10^6\ \tilde{\nu}\ \mathrm{cm^{-2}\ sec^{-1}}\,.$$

TERRESTRIAL NEUTRINOS

GERNOT EDER

Institut für Theoretische Physik der Universität Giessen, Giessen, Germany

Received 11 October 1965

Abstract: Arguments are given for a remarkable abundance of radioactive elements within the earth. Methods are discussed in order to measure this abundance by neutrino experiments.

1. Introduction

The chemical composition of the interior of the earth is still quite unsure. Therefore it would be an advancement if one could measure the abundance of selected chemical elements by their neutrino emission. In this connection, potassium, thorium and uranium are of interest. Generally it is assumed that these elements are confined mainly to the earth's crust, if only for that reason that the material obtainable from the earth's mantle shows a small portion of the mentioned substances. On the other hand the exchange of material between the earth's crust and the upper mantle can give rise to a reduction of radioactive elements in this region. Further there are arguments from paleomagnetic measurements [1,2]) and from geophysical considera-

We have seen that the high abundance (1) of radioactive materials has important consequences for the chemical composition of the earth and for the dynamics of the earth during its history. Therefore it is desirable to measure the radioactivity of the earth. In sect. 2 we discuss the antineutrino and neutrino flux produced by the earth. In sect. 3 we consider the two nuclear reactions

We do not know the distribution of radioactive substances in the Earth's interior, but it can be assumed that they are most enriched in the Earth's crust. If we assume that radioactive materials are present only in the upper crust, 15 km thick (whose mass, including the ocean floor, amounts to M = 2×10^{19} tonnes), the contribution of the mafic and other rocks that form the lower layers of the crust being negligible, then the $\bar{\nu}$ (antineutrino) intensity at the Earth's surface is: $6.7 \times 10^6\ \bar{\nu}$ cm^{-2} s^{-1}.

Earth's chemical composition and heat flux

Looking back more that two decades…

there is also G. Marx, "Geophysics by neutrinos", Czech. J. Phys. B **19**, 1471 (1969)

GEOPHYSICS BY NEUTRINOS*)

G. MARX

Institute of Theoretical Physics, Roland Eötväs University, Budapest

A review of the possibilities for the chemical exploration of the central regions of the Earth is given, making use of the antineutrino flux produced by natural radioactive isotopes.

1. INTRODUCTION

It was suggested many years ago that the neutrino and antineutrino luminosity of different celestial bodies might provide means of exploring the internal structure of these objects (see e.g. [1]). Due to the enormous mean free path the neutrinos and antineutrinos provide valuable direct information, which is not available with other methods. Searching the Sun with a neutrino telescope is well under way [2]. The present paper is concentrated on the second important task of neutrino physics: the Earth. The idea of observing terrestrial antineutrinos is not a new one [1, 3, 4, 5]. Here a review of different experimental possibilities will be given.

"induced" beta decay

(a superallowed transition with a threshold as low as possible). For practical use the allowed low energy reaction

(6) $\tilde{\nu} + {}^{35}\mathrm{Cl} \rightarrow {}^{35}\mathrm{S} + \mathrm{e}^{+}$ $(E_{\min} = 1{\cdot}189\ \mathrm{MeV},\ \log ft = 4{\cdot}98)$

or the superallowed medium energy reaction [3, 4, 6]

(7) $\tilde{\nu} + {}^{1}\mathrm{H} \rightarrow \mathrm{n} + \mathrm{e}^{+}$ $(E_{\min} = 1{\cdot}804\ \mathrm{MeV},\ \log ft = 3{\cdot}13)$

may be considered. These examples show that only the high energy end of the terrestrial antineutrino spectrum is accessible with the induced β decay technique. Most antineutrinos are lost. This fact makes the value T^{-1} rather small in spite of the fact that the total terrestial intensity

(8) $$I_0 = \int_0^\infty I(\varepsilon)\, \mathrm{d}\varepsilon$$

is quite considerable. For observing the U-Th antineutrinos purely ($E_\nu > 1{\cdot}3$ MeV region) the classical target ^{1}H is convenient. The isotopes ^{234}Pa and ^{214}Bi from the U family give the largest contribution.

The efficiency of the different detectors is given by their Z^3/ft values. This means that the stable daughter nuclei of the allowed β decays (leading into the nuclear ground state) at the end of the periodic system are the most convenient detectors. Some possibilities are listed as follows:

$^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H}$	$E_\nu = 0{\cdot}02$ MeV	$Z^3/ft = 0{\cdot}01$
$^{35}\mathrm{Cl} \rightarrow {}^{35}\mathrm{S}$	$0{\cdot}17$ MeV	$0{\cdot}05$
$^{45}\mathrm{Sc} \rightarrow {}^{45}\mathrm{Ca}$	$0{\cdot}25$ MeV	$0{\cdot}01$
$^{130}\mathrm{Ba} \rightarrow {}^{130}\mathrm{Cs}$	$0{\cdot}44$ MeV	$2{\cdot}42$
$^{209}\mathrm{Bi} \rightarrow {}^{209}\mathrm{Pb}$	$0{\cdot}63$ MeV	$1{\cdot}81$
$^{112}\mathrm{Sn} \rightarrow {}^{112}\mathrm{In}$	$0{\cdot}65$ MeV	$9{\cdot}93$
$^{164}\mathrm{Er} \rightarrow {}^{164}\mathrm{Ho}$	$0{\cdot}97$ MeV	$1{\cdot}98$
$^{207}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Tl}$	$1{\cdot}43$ MeV	$4{\cdot}38$
$^{206}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Tl}$	$1{\cdot}50$ MeV	$4{\cdot}38$

Jumping forward in time to 1984

and a classic reference in the field of neutrino geoscience

NATURE VOL. 310 19 JULY 1984

REVIEW ARTICLE

Antineutrino astronomy and geophysics

Lawrence M. Krauss*, Sheldon L. Glashow† & David N. Schramm‡

* Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
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‡ Department of Physics and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

Radioactive decays inside the Earth produce antineutrinos that may be detectable at the surface. Their flux and spectrum contain important geophysical information. New detectors need to be developed, discriminating between sources of antineutrinos, including the cosmic-background. The latter can be related to the frequency of supernovas.

First time the geoneutrino spectrum appeared in a paper

Numerous detection targets proposed (using radiochemical methods)

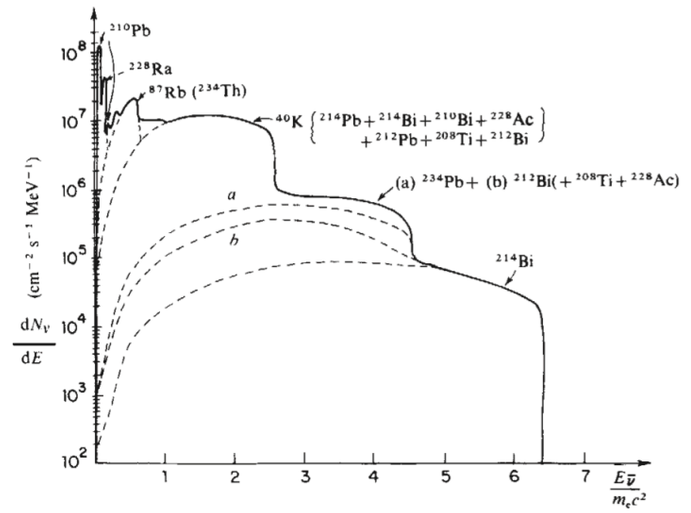

Fig. 1 Number density of antineutrinos at the Earth's surface due to abundance of chief radioactive isotopies in the lithosphere.

Jumping forward in time to 1984

and a classic reference in the field of neutrino geoscience

Table 3 Antineutrino targets with product lifetime ≥1 day and $Q_{ns} < 2$ MeV (in order of increasing log ft)

Target process	Q_B (MeV) (ground state transition)	log ft	Product lifetime	Interaction rate (TAU)	Sensitivity to terrestrial decay
$^{3}_{2}He \rightarrow {}^{3}_{1}H$	0.0186	3.1	12 yr	0.32	^{238}U, ^{40}K, ^{232}Th
$^{33}_{16}S \rightarrow {}^{33}_{15}P$	0.248	5.0	25 day	0.002	^{232}Th, ^{238}U, ^{87}Rb
$^{35}_{17}Cl \rightarrow {}^{35}_{16}S$	0.167	5.0	88 day	0.004	^{232}Th, ^{238}U, ^{87}Rb
$^{121}_{51}Sb \rightarrow {}^{121}_{50}Sn$	0.383	5.0	27 h	0.01	^{40}K, ^{238}U
$^{64}_{30}Zn \rightarrow {}^{64}_{29}Cu \rightarrow {}^{64}_{28}N_i$	0.573	5.3	Stable	0.02	^{40}K, ^{238}U, ^{232}Th
$^{77}_{34}Se \rightarrow {}^{77}_{33}As$	0.68	5.7	1.6 day		
$^{175}_{71}Lu \rightarrow {}^{175}_{70}Vb$	0.467	6.3	5.5 day	$\sim 10^{-2}$	
$^{169}_{69}Tm \rightarrow {}^{169}Er$	0.34	6.4	9.4 day		
$^{185}_{75}Re \rightarrow {}^{185}_{74}W$	0.49	6.5	75 day		
$^{177}_{72}Hf \rightarrow {}^{177}_{71}Lu$	0.497	6.6	6.7 day		
$^{63}_{29}Cu \rightarrow {}^{63}_{28}Ni$	0.067	6.7	92 yr	0.04* (0.15–0.2 MeV)	^{87}Rb, ^{232}Th
$^{153}_{63}Eu \rightarrow {}^{153}_{62}Sm$	0.801	7.2	2 day		
$^{199}_{80}Hg \rightarrow {}^{199}_{79}Au$	0.46	7.5	3.15 day		
$^{151}_{63}Eu \rightarrow {}^{151}_{62}Sm$	0.076	7.6	87 yr	0.15 (0.15–0.23 MeV)	^{87}Rb, ^{232}Th
$^{141}_{59}Pr \rightarrow {}^{141}_{58}Ce$	0.58	7.7	33 day		
$^{161}_{66}Dy \rightarrow {}^{161}_{65}Tb$	0.58	7.8	7 day		
$^{155}_{64}Gd \rightarrow {}^{155}_{63}Eu$	0.248	8.2	1.8 yr		
$^{14}_{7}N \rightarrow {}^{14}_{6}C$	0.156	9.0	5×10^3 yr		
$^{85}_{37}Rb \rightarrow {}^{85}_{36}Kr$	0.67	9.1	10.7 yr		
$^{113}_{49}In \rightarrow {}^{113}_{48}Cd$	0.58	9.2	14 yr		
$^{39}_{19}K \rightarrow {}^{39}_{18}Ar$	0.565	9.9	269 yr		
$^{204}_{82}Pb \rightarrow {}^{204}_{81}Tl$	0.765	9.9	3.8 yr		
$^{79}_{35}Br \rightarrow {}^{79}_{34}Se$	0.154	10.8	6.5×10^4 yr	0.08 (0.25 MeV)	^{87}Rb, ^{232}Th
$^{107}_{47}Ag \rightarrow {}^{107}_{46}Pd$	0.035	10.8	7×10^6 yr		

Now to 1998 forecasting the era of detection

and these important papers in the field of neutrino geoscience

VOLUME 80, NUMBER 3 PHYSICAL REVIEW LETTERS 19 JANUARY 1998

Measuring the Global Radioactivity in the Earth by Multidetector Antineutrino Spectroscopy

R. S. Raghavan,[1] S. Schoenert,[2] S. Enomoto,[3] J. Shirai,[3] F. Suekane,[3] and A. Suzuki[3]
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[3]*Tohoku University, Sendai 980-77, Japan*
(Received 15 August 1997)

We show that antineutrino ($\bar{\nu}_e$) spectroscopy in upcoming detectors in Italy and Japan can be used to measure the separate global abundances of ^{238}U and ^{232}Th, thus ~90% of the radiogenic heat in the Earth. Exploiting the unique advantage of their contrasting geological locations, they may also probe differences in U,Th areal densities in the continental and oceanic crusts and the mantle. Bearing directly on the interior of the whole Earth, such data can test, for the first time, the conceptual foundations of the geophysical structure, dynamics, and evolution of the present Earth. [S0031-9007(97)05047-3]

GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 7, PAGES 1083-1086, APRIL 1, 1998

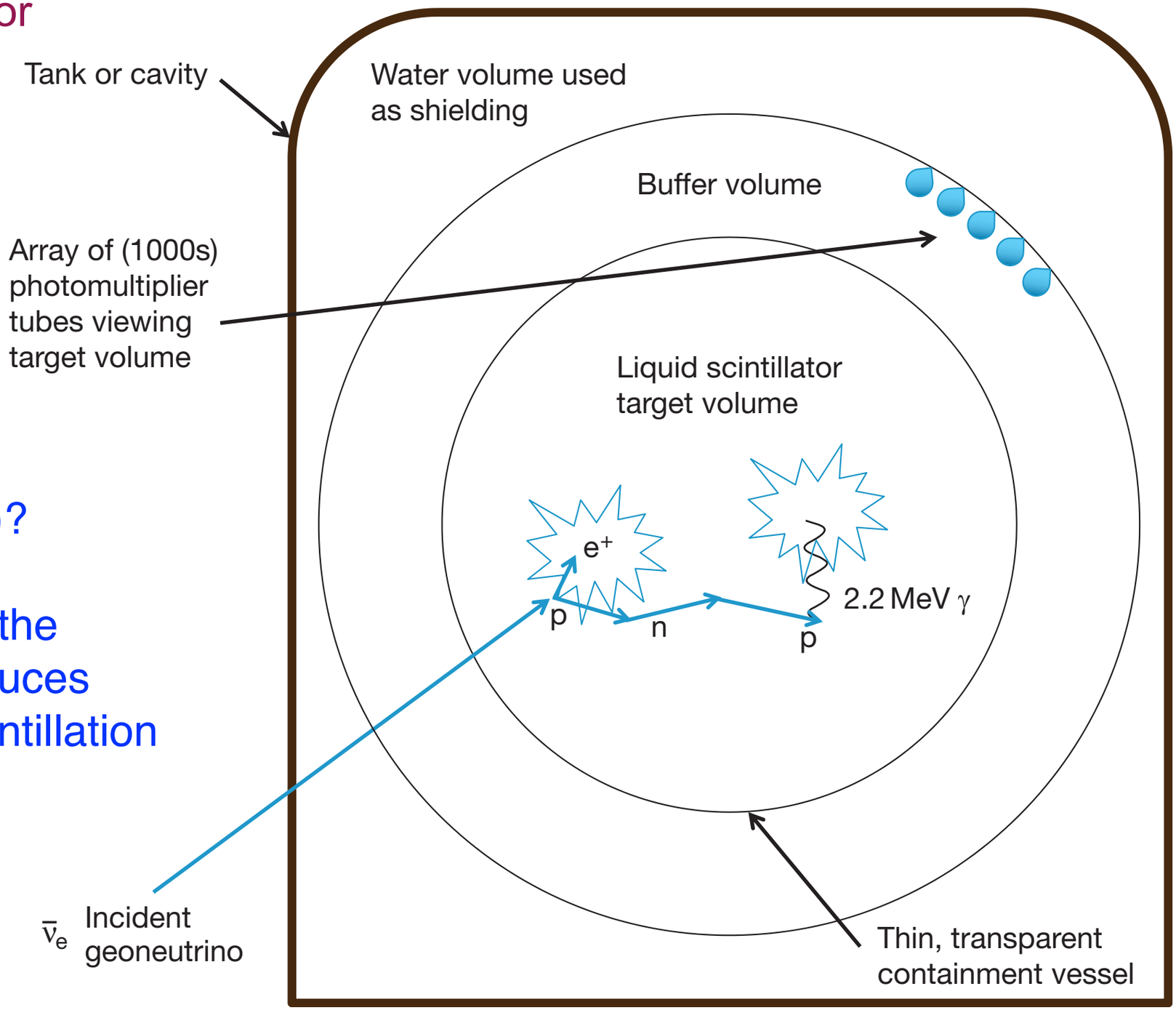
Antineutrino geophysics with liquid scintillator detectors

Casey G. Rothschild, Mark C. Chen and Frank P. Calaprice

Abstract. Detecting the antineutrinos emitted by the decay of radioactive elements in the mantle and crust could provide a direct measurement of the total abundance of uranium and thorium in the Earth. In calculating the antineutrino flux at specific sites, the local geology of the crust and the background from the world's nuclear power reactors are important considerations. Employing a global crustal map, with type and thickness data, and using recent estimates of the uranium and thorium distribution in the Earth, we calculate the antineutrino event rate for two new neutrino detectors. We show that spectral features allow terrestrial antineutrino events to be identified above reactor antineutrino backgrounds and that the uranium and thorium contributions can be separately determined.

Geoneutrino Detection

in a large liquid scintillator detector



Q: can the detection medium be water (H_2O)?

A: in principle, yes; but the Čerenkov process produces much less light than scintillation

figure from MC, Treatise on Geochemistry, 2nd edition (2013)

Now to 1998 forecasting the era of detection

and these important papers in the field of neutrino geoscience

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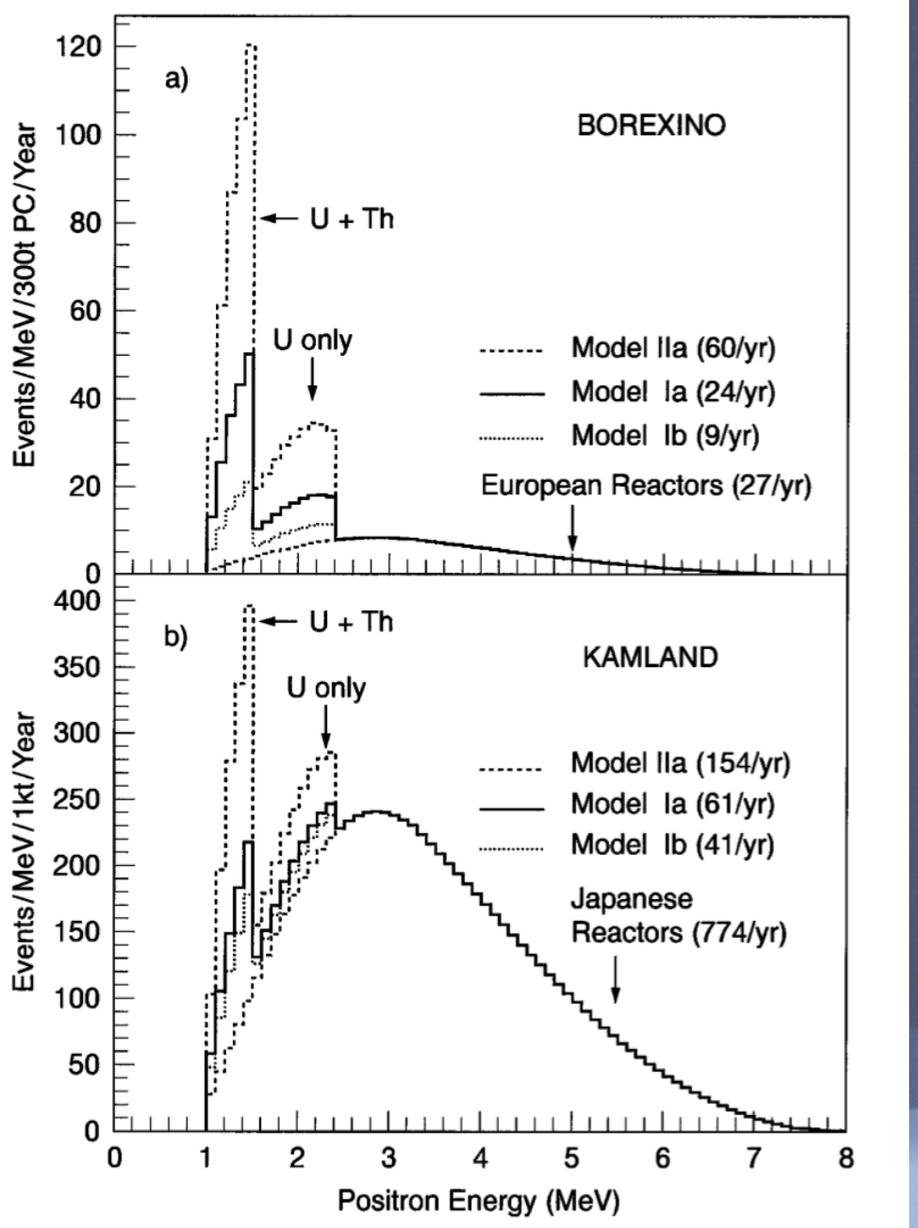
TABLE I. Abundances of ^{238}U and ^{232}Th and signal rates in model I (Th/U abundance = 4; U-Th radiogenic heat = 16 TW); Y = Rate/10^{32} p/yr; Y(Kamland; 1 Kton mineral oil = 0.86×10^{32} p) = 0.86 Y(Japan); Y(Borexino; 300 ton pseudocumene = 0.18×10^{32} p) = 0.18 Y(Italy).

Feature	Mass 10^{25} g	U ppm	N(U) g/cm^2	Y U	Y Th	Total
CC	2.3	1.8	27.5	93.5	24.8	118
OC	0.6	0.08	0.13	0.56	0.15	0.71
M	400	0.01	7.76	12.2	3.2	15.4
Ia Japan [Y_{tot}{1/2(CC + OC)} + M]						75
Ia' Japan [Y_{tot}(OC + M)]						16
Ia Italy [Y_{tot}(CC + M)]						134
Ib (uniform crustal U/Th) Japan						50
Ib (uniform crustal U/Th) Italy						50
IIa,b (40 TW U/Th radiogenic heat)						2.5Y (Ia,b)



Continental Crust: 35 km thin, spherical crustal shell
Oceanic Crust: 6.5 km thinner, spherical crustal shell
Mantle: 2900 km spherical shell

Model II is what we would call "Fully Radiogenic" these days

Now to 1998 forecasting the era of detection

and these important papers in the field of neutrino geoscience

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Antineutrino geophysics with liquid scintillator detectors

Casey G. Rothschild, Mark C. Chen and Frank P. Calaprice
Physics Department, Princeton University Princeton, New Jersey

first mention of Bulk Silicate Earth

Table 1. Uranium and thorium abundances in the Earth.

	$[^{238}U]$ in ppm	$[^{232}Th]$ in ppm
Bulk Silicate Earth [*McDonough and Sun*, 1995]	0.0203	0.0795
average continental crust [*Rudnick and Fountain*, 1995]	1.4	5.6
average oceanic crust [*Taylor and McLennan*, 1985]	0.10	0.22
present-day "residual" mantle	0.013	0.052

The difference in U and Th activity between continental and oceanic crust is substantial. Therefore, the crustal topography near an antineutrino detector is important to take into account when calculating the $\bar{\nu}_e$ flux; previous calculations did not include such a detailed analysis. We employed crust type and thickness data in the form of a global crustal map: (W. D. Mooney, G. Laske, and T. G. Masters, CRUST 5.1: A Global Crustal Model at 5° × 5°, submitted to the *Journal of Geophysical Research*, 1997; data accesible from the World Wide Web server for the U.S. Geological Survey at http://quake.wr.usgs.gov/study/CrustalStructure/). The data include 16 primary crust types with about 140 different sub-types. In our calculations, we lumped the crust classification into just continental and oceanic and used the average U and Th concentrations (from Table 1) regardless of sub-classification, but did use the crust thickness data, which range from 6–70 km.

first use of a crustal model

Table 2. Calculated $\bar{\nu}_e$ fluxes [$\times 10^6$ cm^{-2} s^{-1}] for sites around the world.

		Uranium		Thorium		Total
Site	Location	crust	mantle	crust	mantle	(U + Th)
Gran Sasso Lab (Italy)	42°N 14°E	2.5	1.2	2.2	1.0	6.9
Kamioka Mine (Japan)	36°N 137°E	0.82	1.2	0.69	1.0	3.7
Sudbury (Canada)	47°N 81°W	3.2	1.2	2.8	1.0	8.2
Central Australia	25°S 133°E	2.7	1.2	2.4	1.0	7.3
Himalayas (Tibet)	33°N 85°E	3.5	1.2	3.1	1.0	8.8
Pacific Ocean (Hawaii)	20°N 156°W	0.30	1.2	0.23	1.0	2.7
Geographic Maximum		3.5	1.2	3.1	1.0	8.8
Geographic Minimum		0.21	1.2	0.16	1.0	2.6

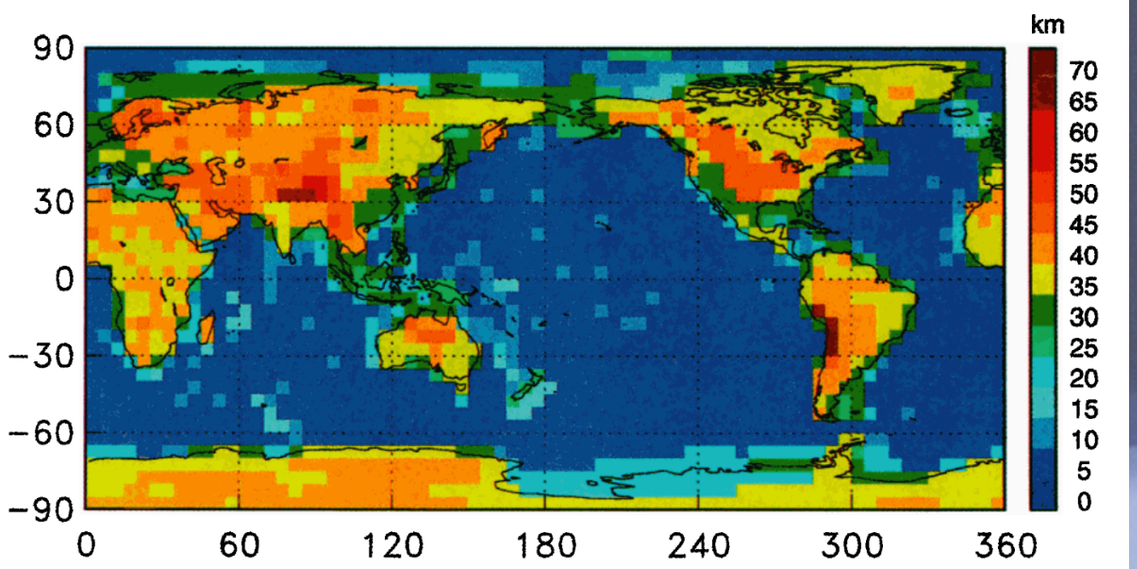

Plate 1d. Global crustal thickness, including topography above sea level but not bathymetry. The average thickness of continental crust, including shelf regions, is 38 km and varies locally from 20.5 km (extended crust) to 70 km (Tibetan Plateau).

promoting multiple sites including SNO+ and a mid-ocean site that "enables a $\bar{\nu}_e$ flux measurement to be predominantly sensitive to radioactivity from the mantle"

Concluding with this 2003 landmark paper

setting the stage, fully, for the upcoming discovery…

Neutrinos and energetics of the Earth

G. Fiorentini [a,b], F. Mantovani [c], B. Ricci [a,b]

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Received 8 December 2002; received in revised form 24 January 2003; accepted 12 February 2003

Editor: G.F. Giudice

Abstract

We estimate terrestrial antineutrino and neutrino fluxes according to different models of Earth composition. We find large variations, corresponding to uncertainties on the estimated U, Th and K abundances in the mantle. Information on the mantle composition can be derived from antineutrino flux measurements after subtracting the crust contribution. This requires a good description of the crust composition in the region of the detector site. Measurements of terrestrial antineutrinos will provide a direct insight on the main sources of Earth's heat flow.
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Later work by Gianni, Fabio and others in the Ferrara group built these "reference models" – later still, collaborating with Bill and the Maryland group establishing the geology modelling "standard"

- introduced the Terrestrial Neutrino Unit (TNU) # of events yr^{-1} per 10^{32} proton targets (at 100% efficiency)

Concluding with this 2003 landmark paper

setting the stage, completely, for the upcoming discovery…

Table 1
Main radiogenic sources. We report the Q-values, the half lives ($\tau_{1/2}$), the maximal energies (E_{max}) and (anti)neutrino production rates ($\epsilon_{\bar{\nu}/\nu}$) per unit mass for *natural* isotopic abundances. Neutrinos from electron capture are monochromatic

Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	E_{max} [MeV]	$\epsilon_{\bar{\nu}/\nu}$ [kg^{-1} s^{-1}]
$^{238}U \rightarrow {}^{206}Pb + 8\ {}^4He + 6e + 6\bar{\nu}$	51.7	4.47	3.26	7.41×10^7
$^{232}Th \rightarrow {}^{208}Pb + 6\ {}^4He + 4e + 4\bar{\nu}$	42.8	14.0	2.25	1.63×10^7
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$	1.321	1.28	1.31	2.69×10^4
$^{40}K + e \rightarrow {}^{40}Ar + \nu$	1.513		1.51	3.33×10^3

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Table 2
Masses, heat and neutrino production rates. M, H and L are in units of 10^{17} kg, 10^{12} W and 10^{24} s^{-1}, respectively. H_{NR} is defined as the difference between total heat flow $H_\oplus$ and the radiogenic production

Model	Chondritic	BSE	Fully radiogenic
M(U)	0.65	0.84	1.7
M(Th)	2.5	3.4	6.5
M(K)	4.6×10^4	0.84×10^4	1.7×10^4
H(U)	6.2	7.9	16.3
H(Th)	6.7	8.6	17.6
H(K)	16.4	3.0	6.1
H_{NR}	10.7	20.5	0
$L_{\bar{\nu}}$(U)	4.8	6.2	12.7
$L_{\bar{\nu}}$(Th)	4.0	5.2	10.6
$L_{\bar{\nu}}$(K)	123	22.5	46.0
L_ν(K)	15.2	2.8	5.7

distribution in the mantle is important

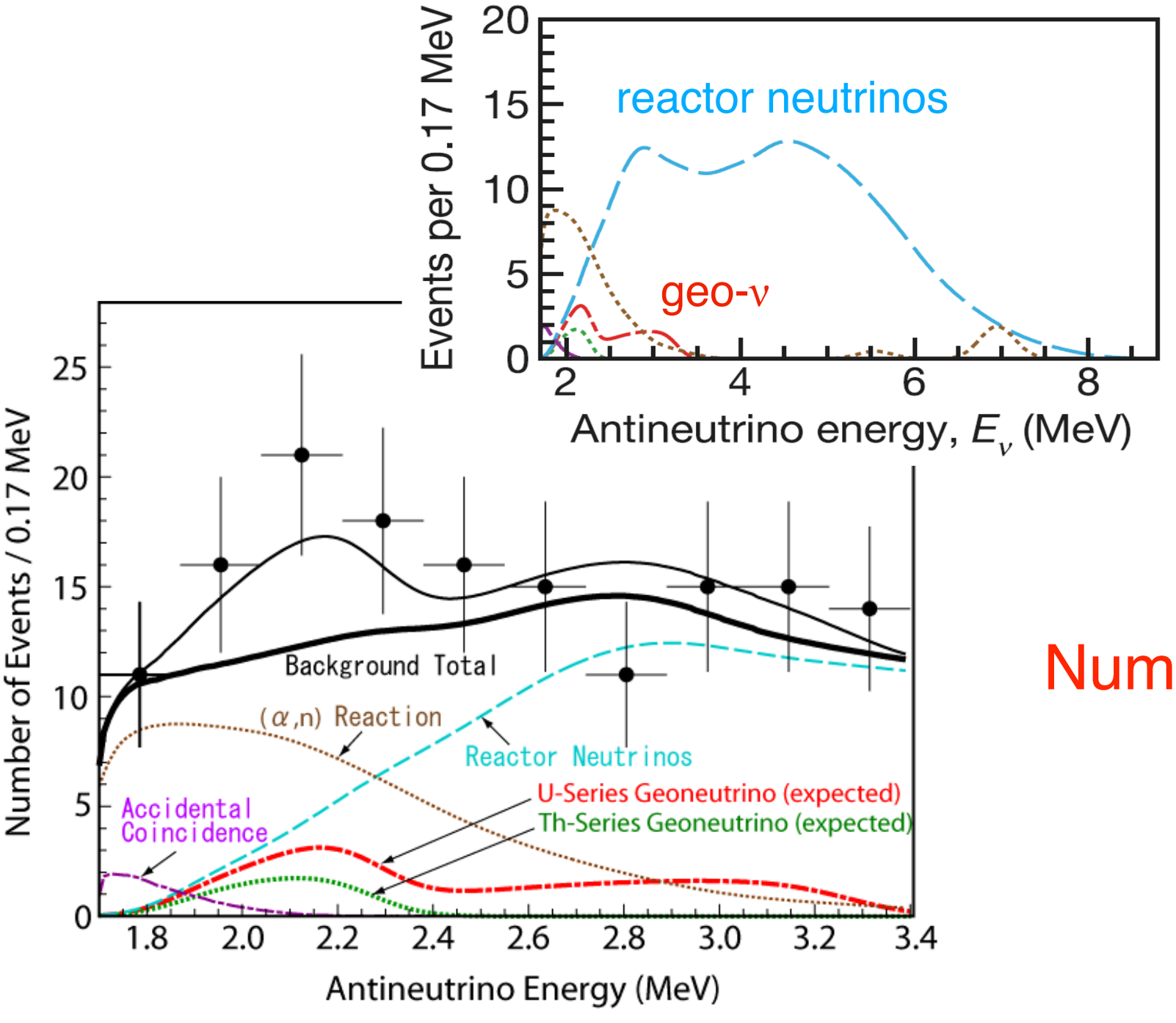
Table 4
Flux dependence on uranium abundance in the crust and distribution in the mantle. Fluxes are calculated for $M_{crust+mantle}(U) = 0.84 \times 10^{17}$ kg. The total flux Φ(tot) is the sum of the contribution from the crust, upper mantle and transition zone + lower mantle. Same units as in Table 3

	Uranium		
	High a_{CC}	Low a_{CC}	Depleted upper mantle
M(crust)	0.42	0.21	0.42
M(upper mantle)	0.06	0.09	0
M(transition + lower mantle)	0.36	0.54	0.42
Φ(crust)	2.1	1.0	2.1
Φ(upper mantle)	0.21	0.32	0
Φ(transition + lower mantle)	0.79	1.2	0.92
Φ(tot)	3.1	2.5	3.0

What can we learn from geoneutrinos?

- Flux of geoneutrinos is related to Earth's energetics (present-day heat flow) and thermal history, that also depends on ↓↓…
- Insights into Earth's bulk chemical composition through U, Th and K
- Testing Earth origin models and ideas: chondritic, BSE, …
- Distribution of radiogenic heat producing elements (HPEs) – in the crust and mantle
  - Testing models of the composition of the crust and depletion of lithophile elements in the mantle (enriching the crust in U and Th)
  - Crust models are needed to calculate the local crustal contribution to the geoneutrino signal measured by any detector in order to extract ↓↓…
- Information about the **deep Earth**
  - Mantle Urey ratio (ratio radiogenic heat production in the mantle)
  - Reservoirs in the mantle: is the mantle homogeneous? layered? lateral variability? (e.g. mantle plumes)
- Anything about the core??? → we need our friends doing neutrino tomography

KamLAND First Detection in 2005



Expected Geoneutrinos

- U-Series: 14.9
- Th-Series: 4.0

Backgrounds

- Reactor: 82.3±7.2
- (α,n): 42.4±11.1
- Accidental: 2.38±0.01

BG total: 127.4±13.3
Observed: 152

Number of Geoneutrinos:

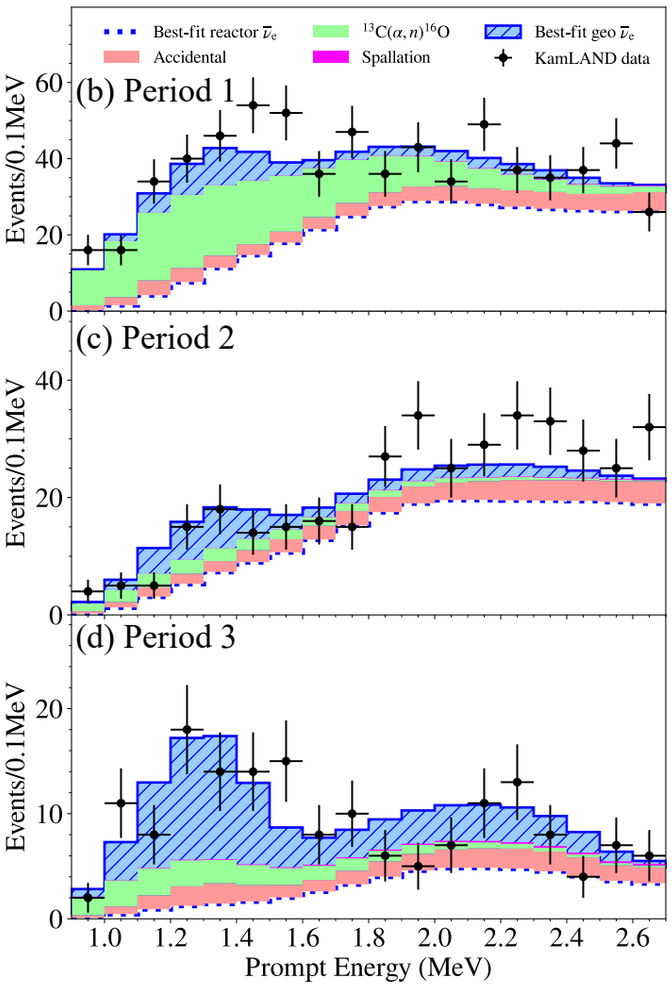
25^{+19}_{-18}

“expected” geoneutrinos means from BSE models



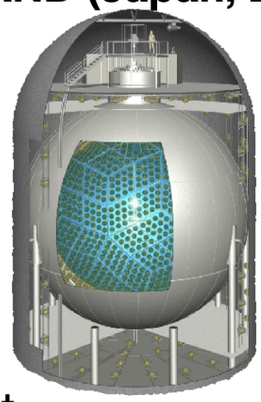
KamLAND Latest Geoneutrino Result

ended 2024 to upgrade to KamLAND2

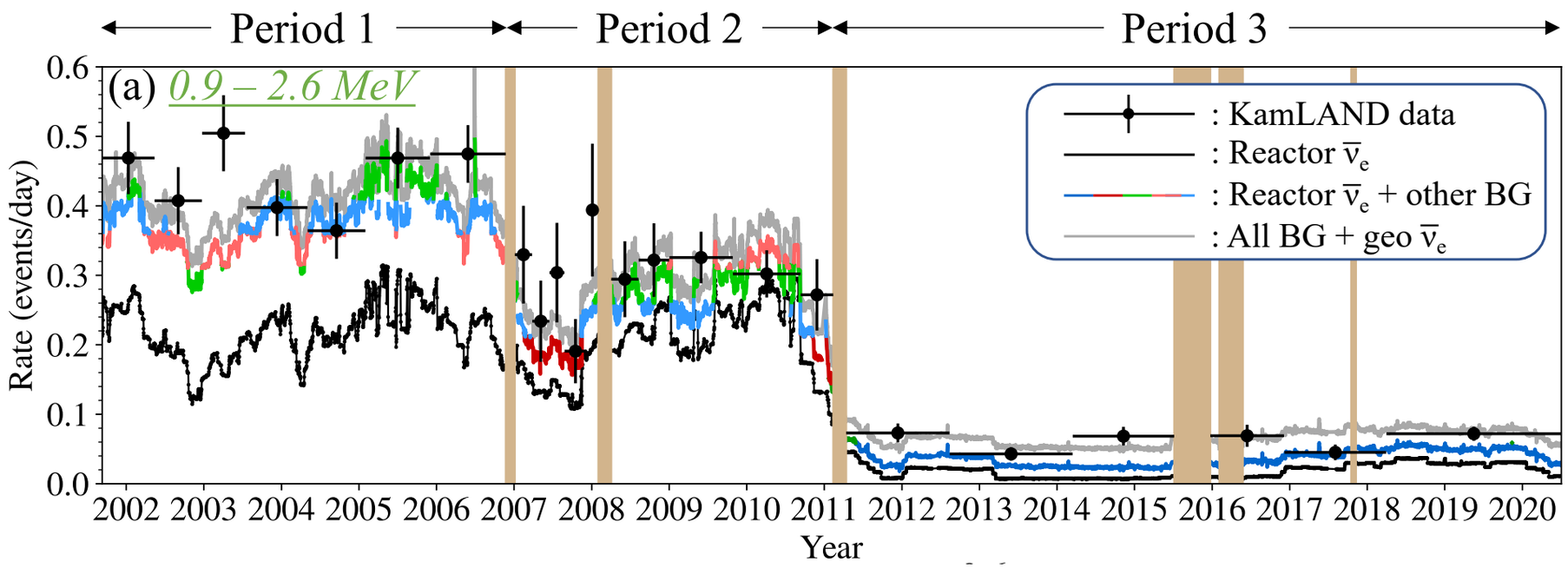


6.39 × 10^{32} proton-years, 14.3 live-time years
1178 candidate events (in the geo-ν region)
183^{+29}_{-28} geoneutrinos

KamLAND (Japan, 2002~)

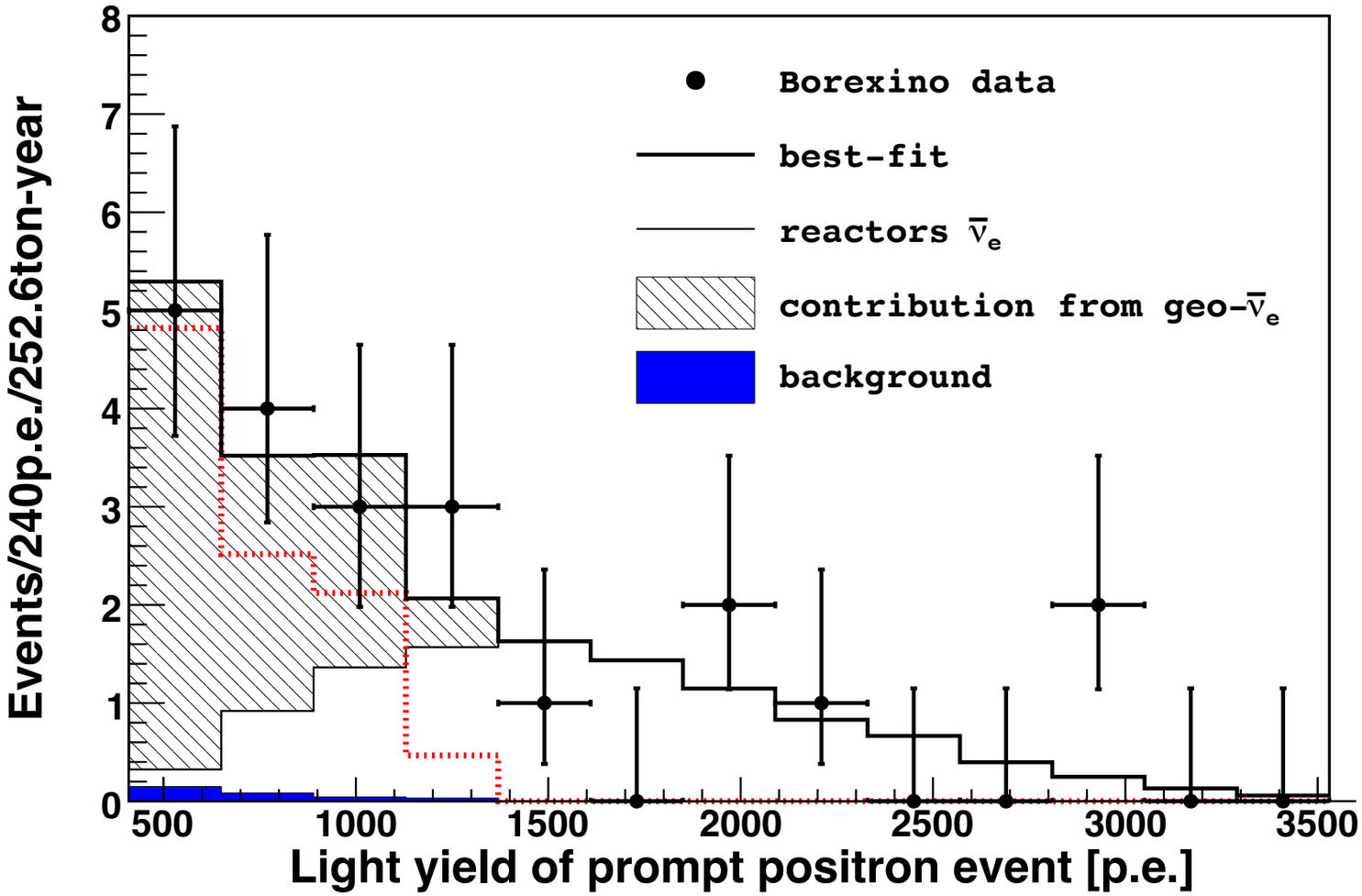


- *LS : 1000 t
- *Depth : 2700 m.w.e.
- *expected event ratio
  reactor/geo ~**6.7** (up to 2010)
  ~**0.4** (2011~)
  w/o Japanese reactors



S. Abe et al., Geophys. Res. Lett. **49,** e2022GL099566 (2022)

Borexino First Detection in 2010

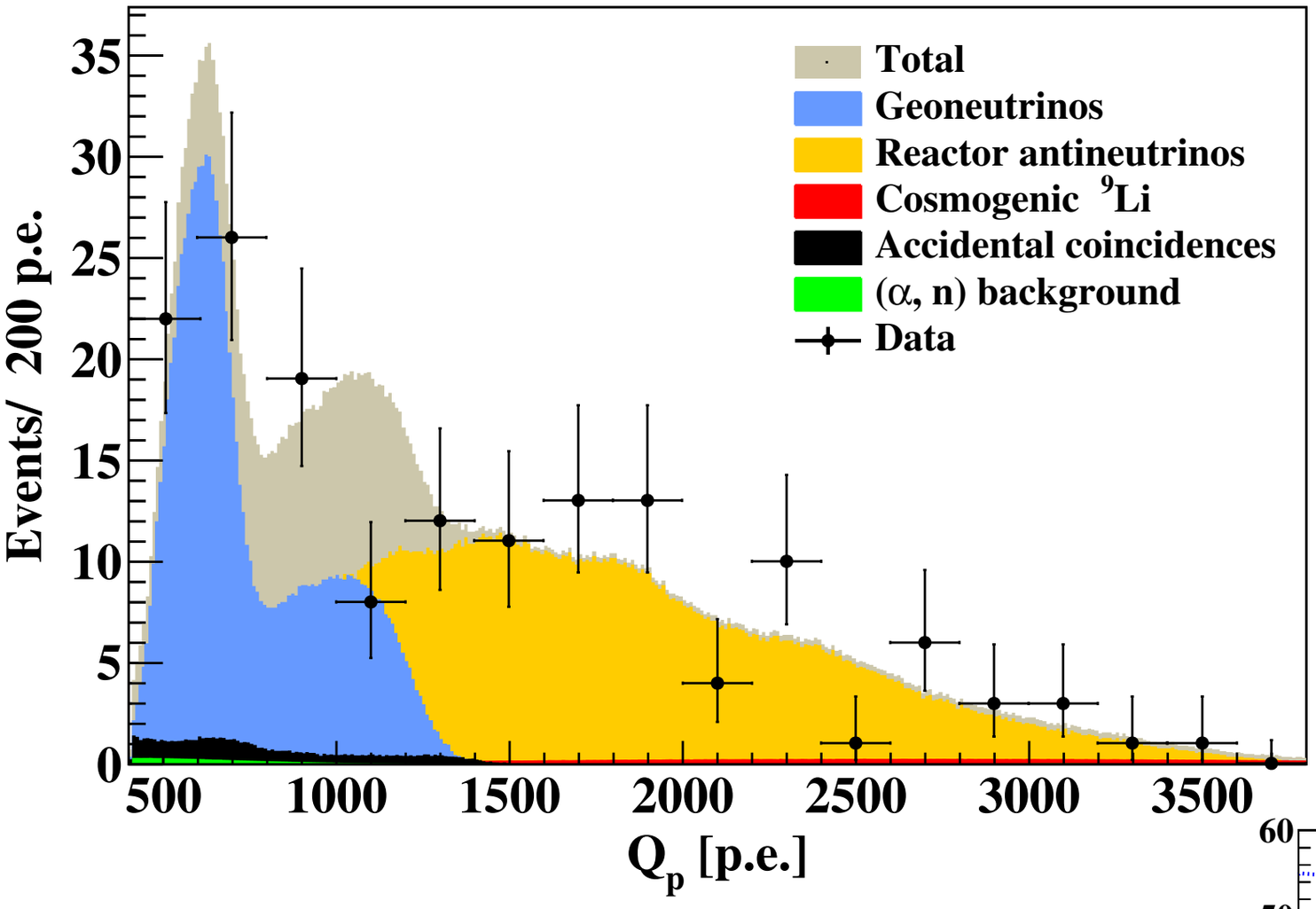


21 candidate $\bar{\nu}_e$ events
with 0.31±0.05 background events

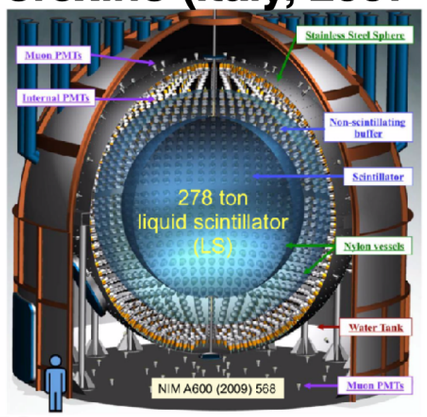
$N_{\rm geo}=9.9^{+4.1}_{-3.4}(^{+14.6}_{-8.2})$ and $N_{\rm react}=10.7^{+4.3}_{-3.4}(^{+15.8}_{-8.0})$

Borexino Final Geoneutrino Result

ended 2021
decommissioned

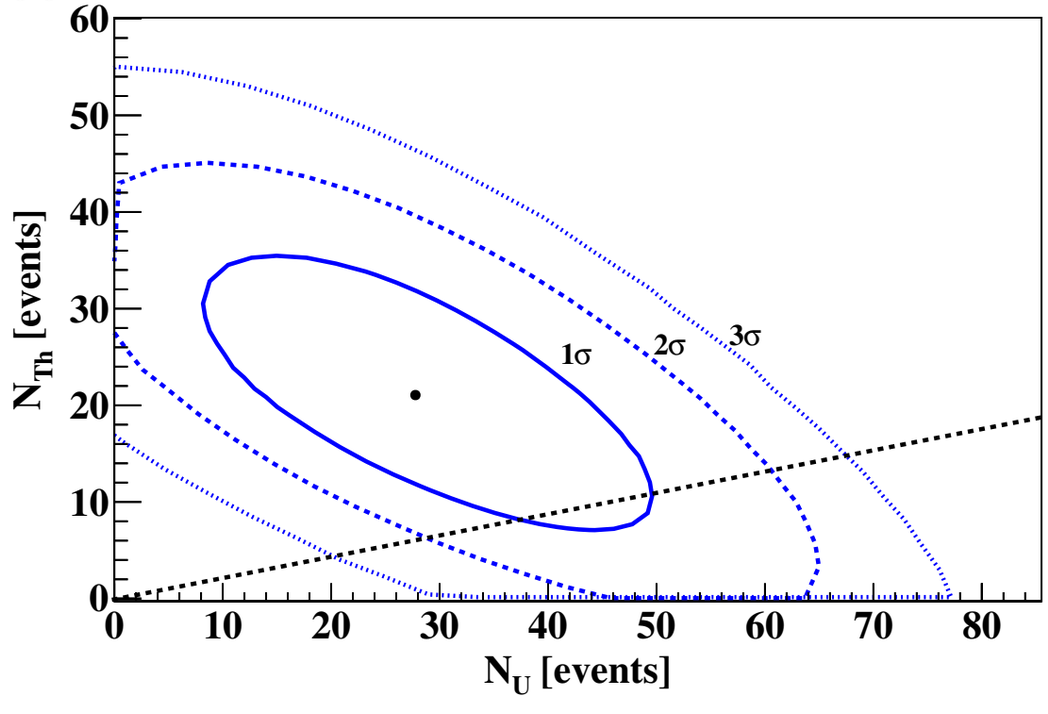


Borexino (Italy, 2007~)



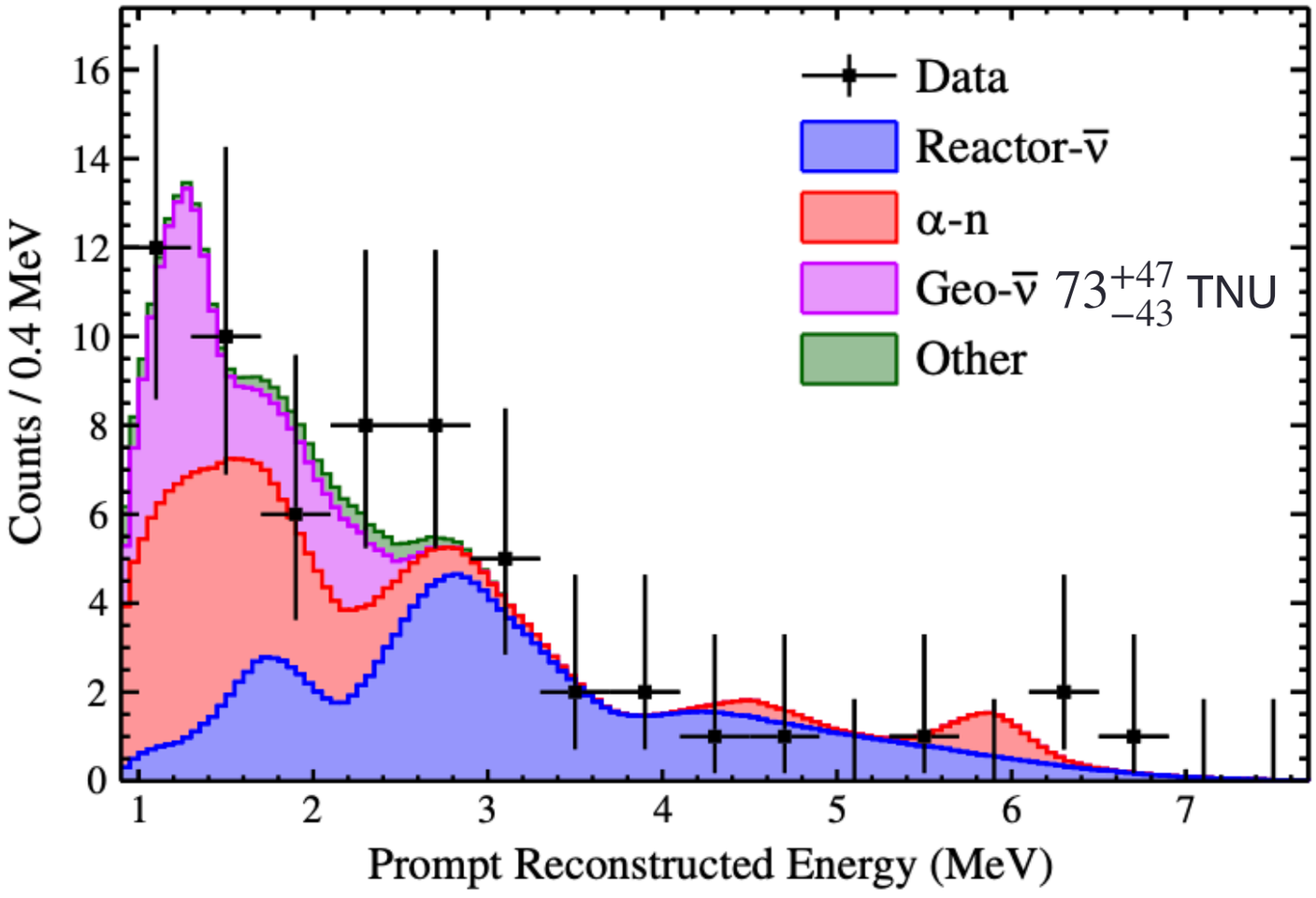
*LS : 278 t
*Depth : 3800 m.w.e.
*expected event ratio
reactor/geo ~**0.3** (2007~)

1.29 × 10^{32} proton-years,
8.7 live-time years
154 IBD candidate events
(~90 in the geo-ν region)
$52.6^{+9.4}_{-8.6}$ geoneutrinos



M. Agostini et al., PRD 101, 012009 (2020)

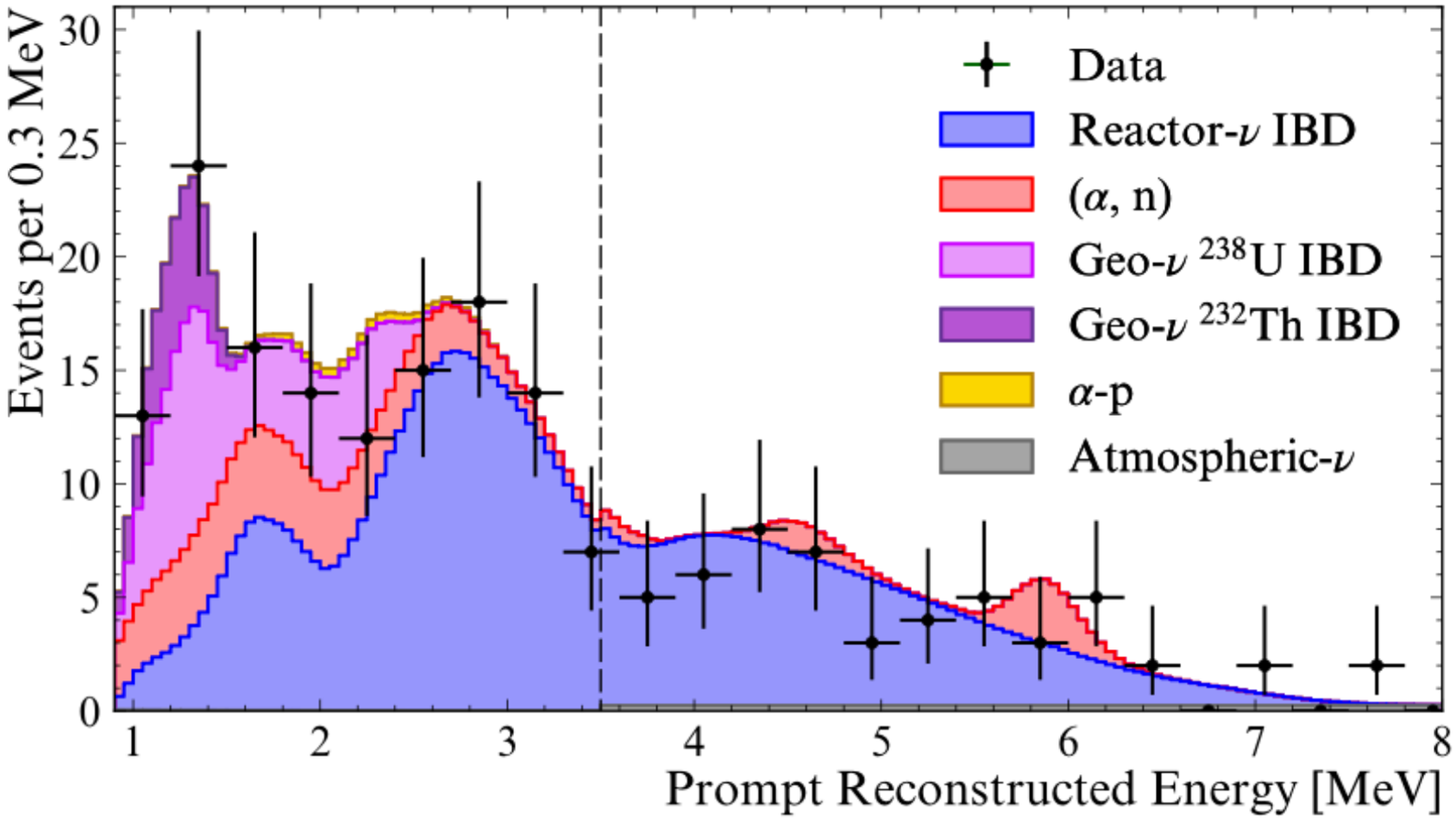
SNO+ First Detection in 2024



	Expectation	Fit (Uncon.)	Fit (Con.)
Reactor-$\bar{\nu}$ IBD	27.9 ± 0.8	$25.1^{+6.4}_{-2.1}$	27.5 ± 0.9
(α, n)	18.2 ± 5.2	$17.2^{+4.5}_{-4.4}$	$17.2^{+4.5}_{-4.4}$
Geo-$\bar{\nu}$ IBD	7.2	$12.0^{+7.4}_{-6.8}$	$11.1^{+7.1}_{-6.6}$
^{214}BiPo-like	1.1 ± 1.1	1.2 ± 1.1	1.2 ± 1.1
Accidental	0.3 ± 0.0	0.3 ± 0.0	0.3 ± 0.0
Total	54.7	55.8	57.3
Observed	59	59	59

significant background from $^{13}C(\alpha, n)$

SNO+ Latest Geoneutrino Result



PRL **137**, 101807 (2026)

1.46 kilotonne-years (live) of SNO+ Scintillator Phase data, with the LAB+PPO dataset and +bis-MSB dataset analyzed separately (due to different detector performance)

combined together in simultaneous fit with *correlations included*

Geoneutrinos U and Th total of 41 events corresponding to a flux/rate:

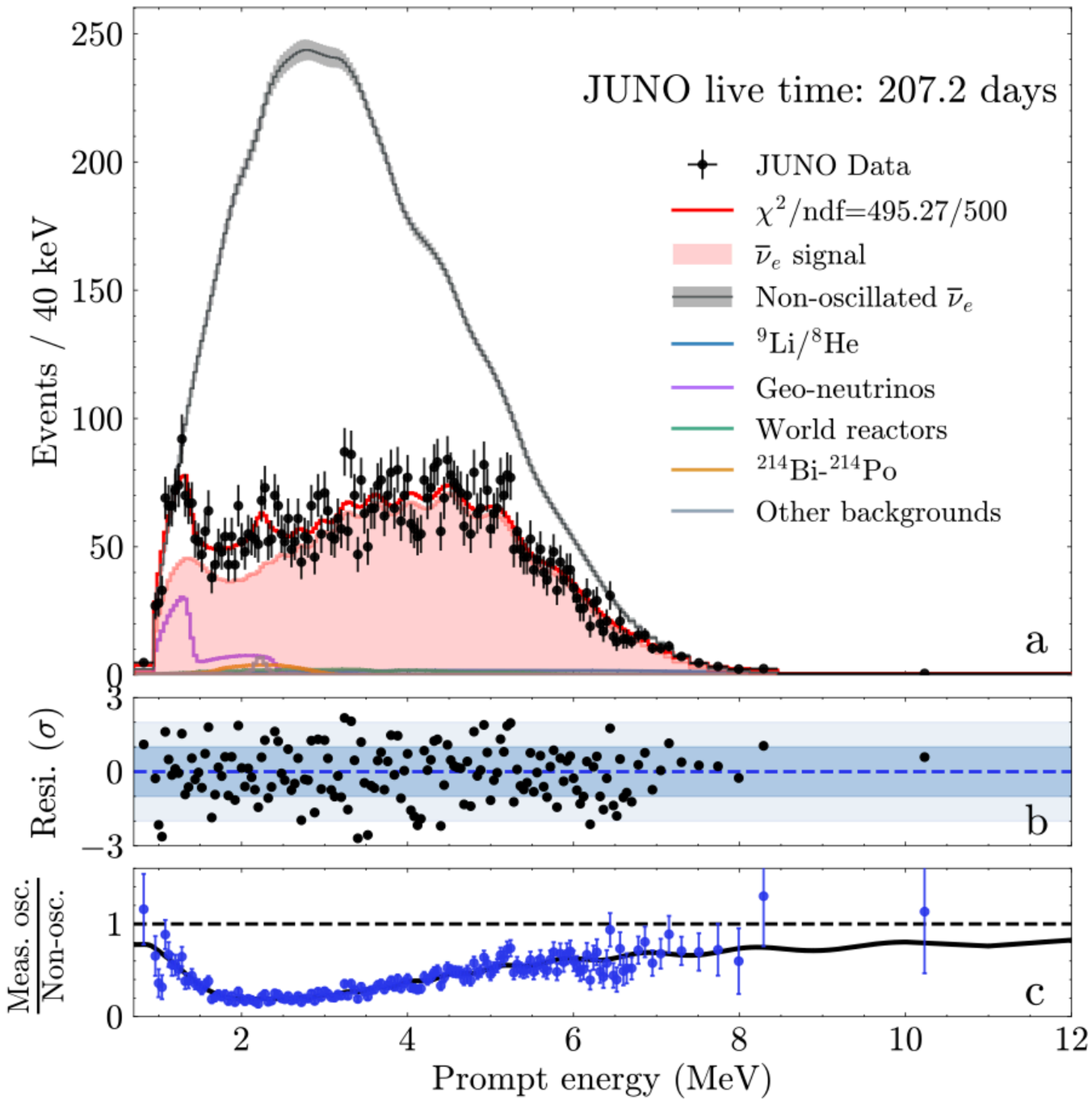
48^{+14}_{-12} TNU

U/Th ratio constrained by expectation from chondritic Earth models

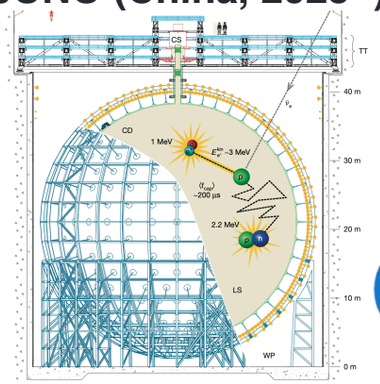
U/Th signal ratio constraint: 3.8 ± 1.3 (34%)

JUNO First Detection in 2026

arXiv:2609.37895



JUNO (China, 2025~)





* LS : 20 kt
* Depth : 1800 m.w.e.
* expected event ratio reactor/geo ~**9**

2.12 ± 0.32 counts per day

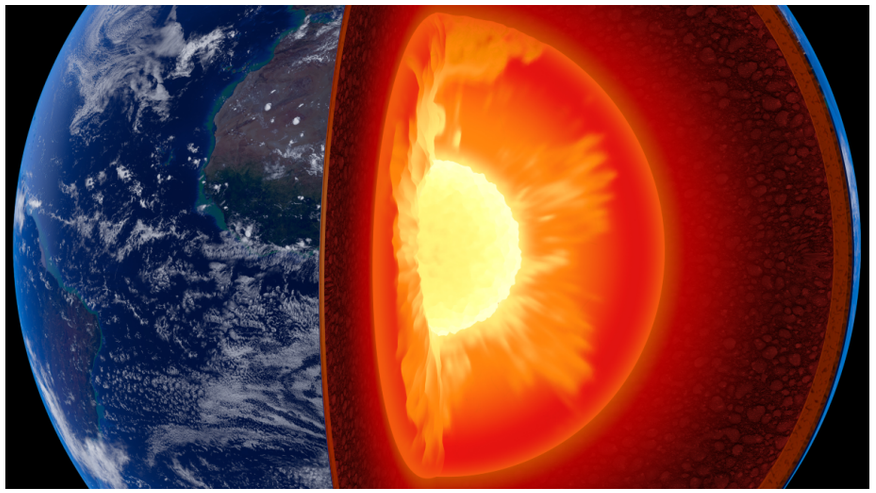
that's 439 events detected!
(geoneutrino events extracted from reactor data)

good backgrounds!
$^{13}C(\alpha, n)$ seems not a problem!

Th/U signal ratio constraint: $0.29 \pm 10\,\%$ = U/Th of 3.45

Signals from the Deep Earth

the mantle



Detailed study of local geology needed to calculate its contribution to the total geoneutrino signal
- the difference between total measured $\bar{\nu}_e$ and predicted local component represents the mantle

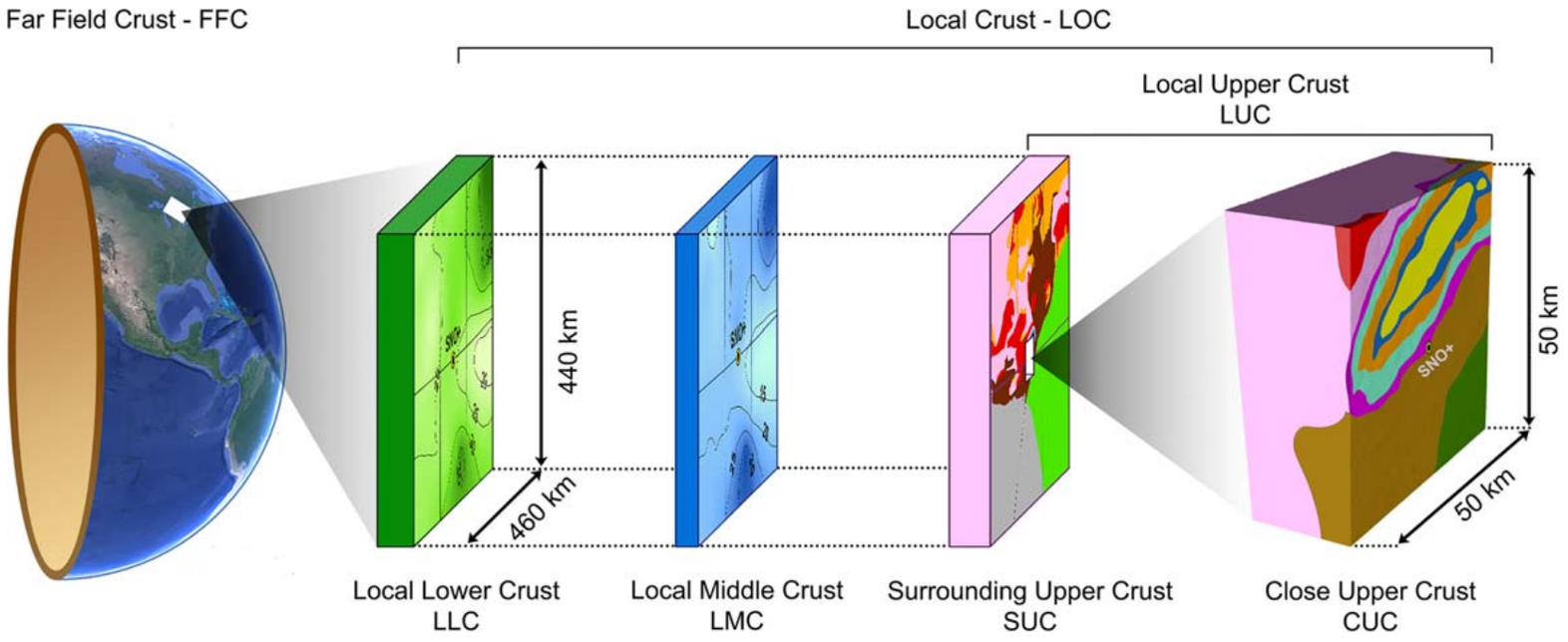


figure from V. Strati et al., G3 **18**, 4326 (2017)
(local geology structures studied for SNO+)

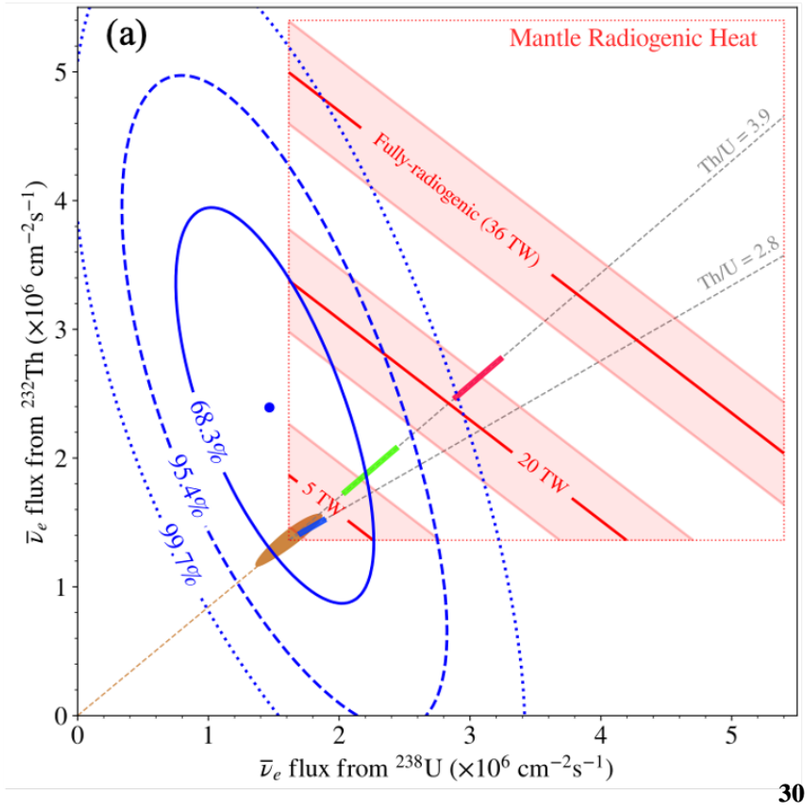
Our geoneutrino community needs to examine together the local geology details for all of the experiments…
…to extract the most information from each geological interpretation separately and jointly!

I will leave the presentation of the geology interpretation from each experiment to the upcoming speakers from their respective collaborations…

What we are learning – two decades

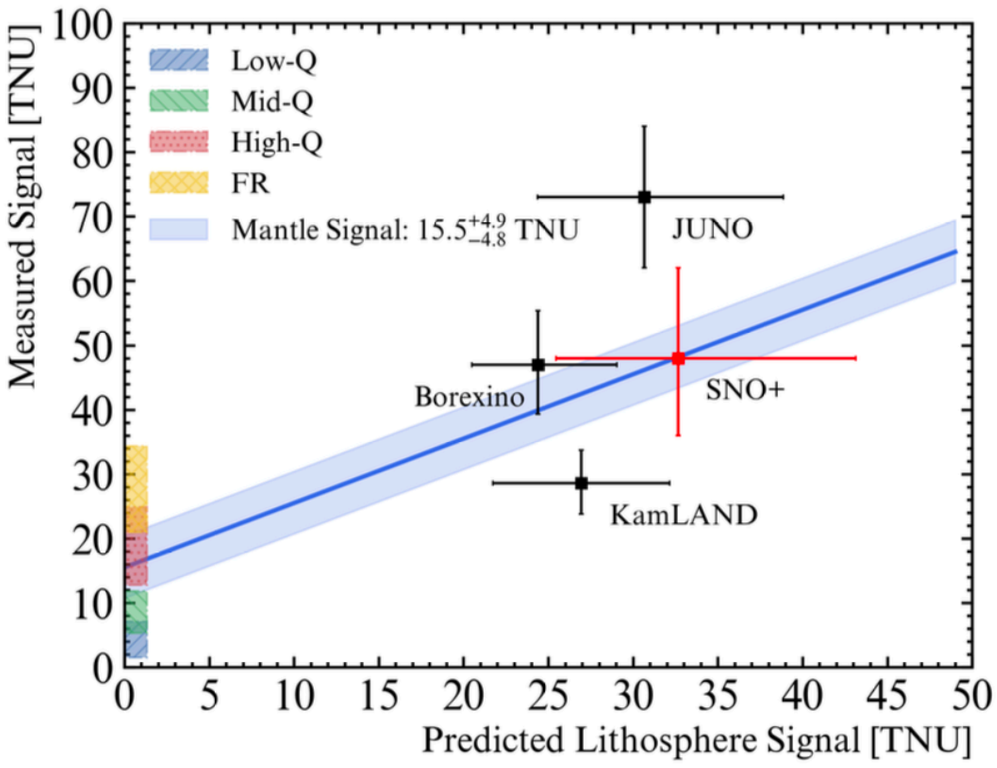
I will leave the presentation of the geology interpretation from each experiment to the upcoming speakers from their respective collaborations…

From KamLAND mantle radiogenic heat and Th/U

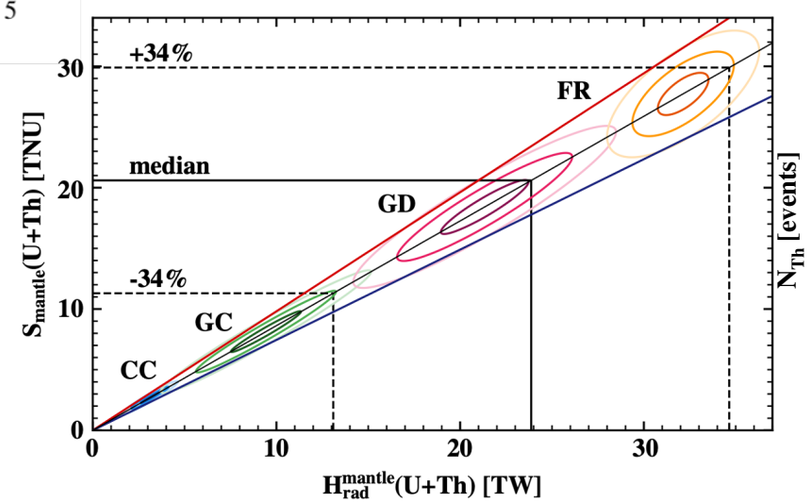


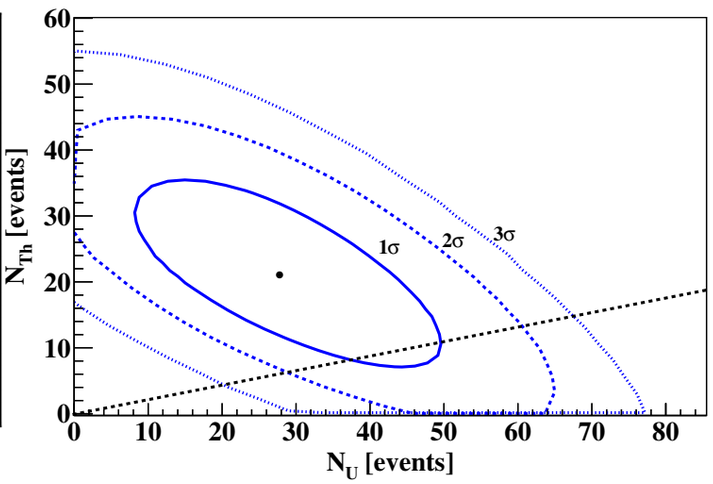
Measured geoneutrino fluxes are broadly consistent with expectations from Earth composition models and radiogenic HPE abundances

From SNO+ combined fit for the mantle signal



From Borexino testing Earth composition models from inferred mantle signal …and Th/U





The Road Ahead

Where do we want to go in neutrino geoscience… geoneutrino studies

[I leave the topic of **neutrino tomography of the Earth** to the appropriate experts.]

With more detectors around the globe, we can try to explore **mantle heterogeneity**

- requires **better constrained local models** (is that possible?)
- directionality can help

Mantle geoneutrino detection

- requires **Ocean Bottom Detector**

U/Th ratio

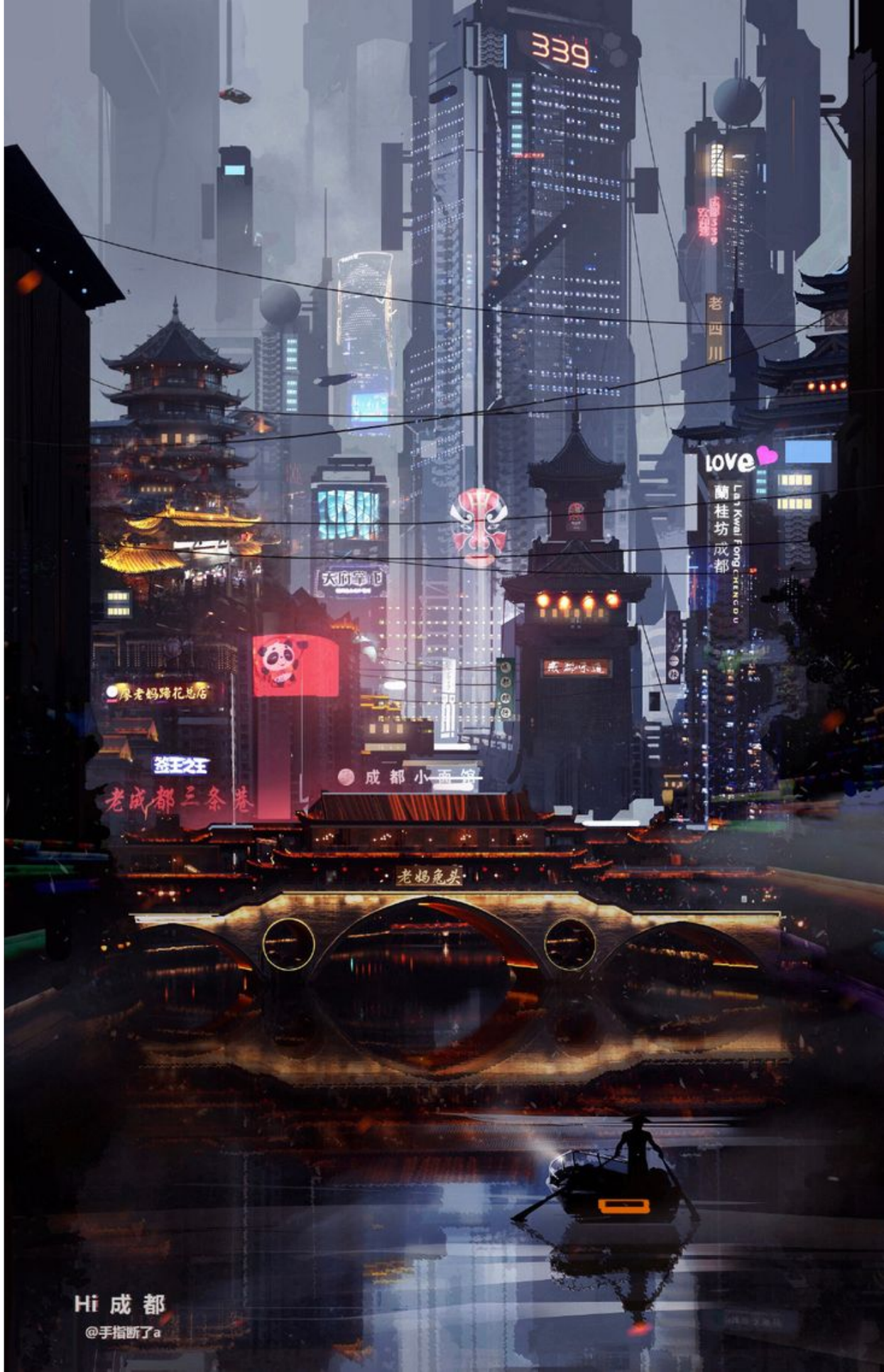
- requires **statistics** (JUNO leads here)

^{40}K geoneutrinos are super interesting for geoscience

is it feasible?

w/elastic scattering

w/Cu-doping in LiquidO



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w/Cu-doping in LiquidO

A. Cabrera, M. Chen, F. Mantovani, A. Serafini, V. Strati et al., Commun. Phys. **9**, 95 (2026)



