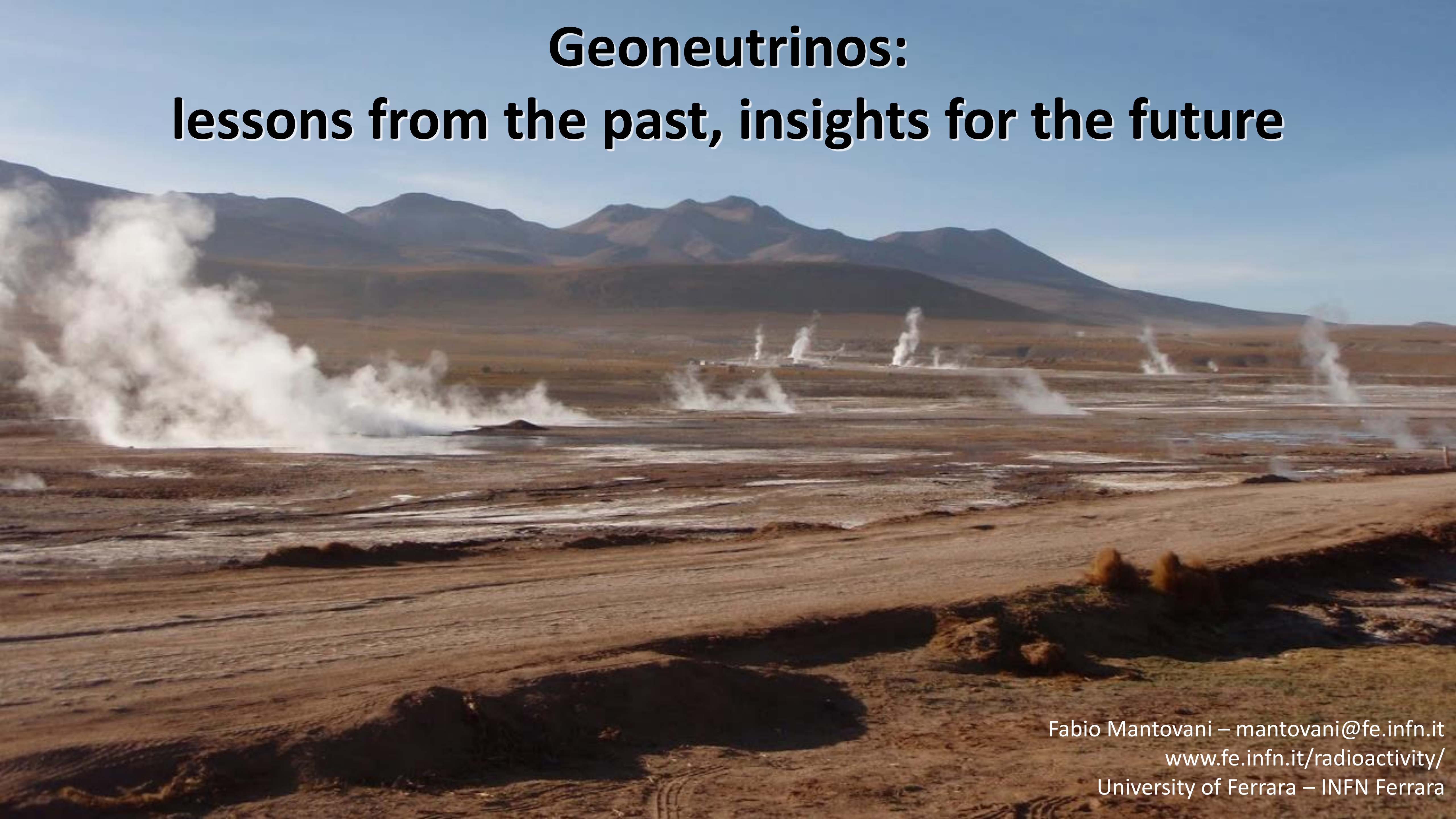
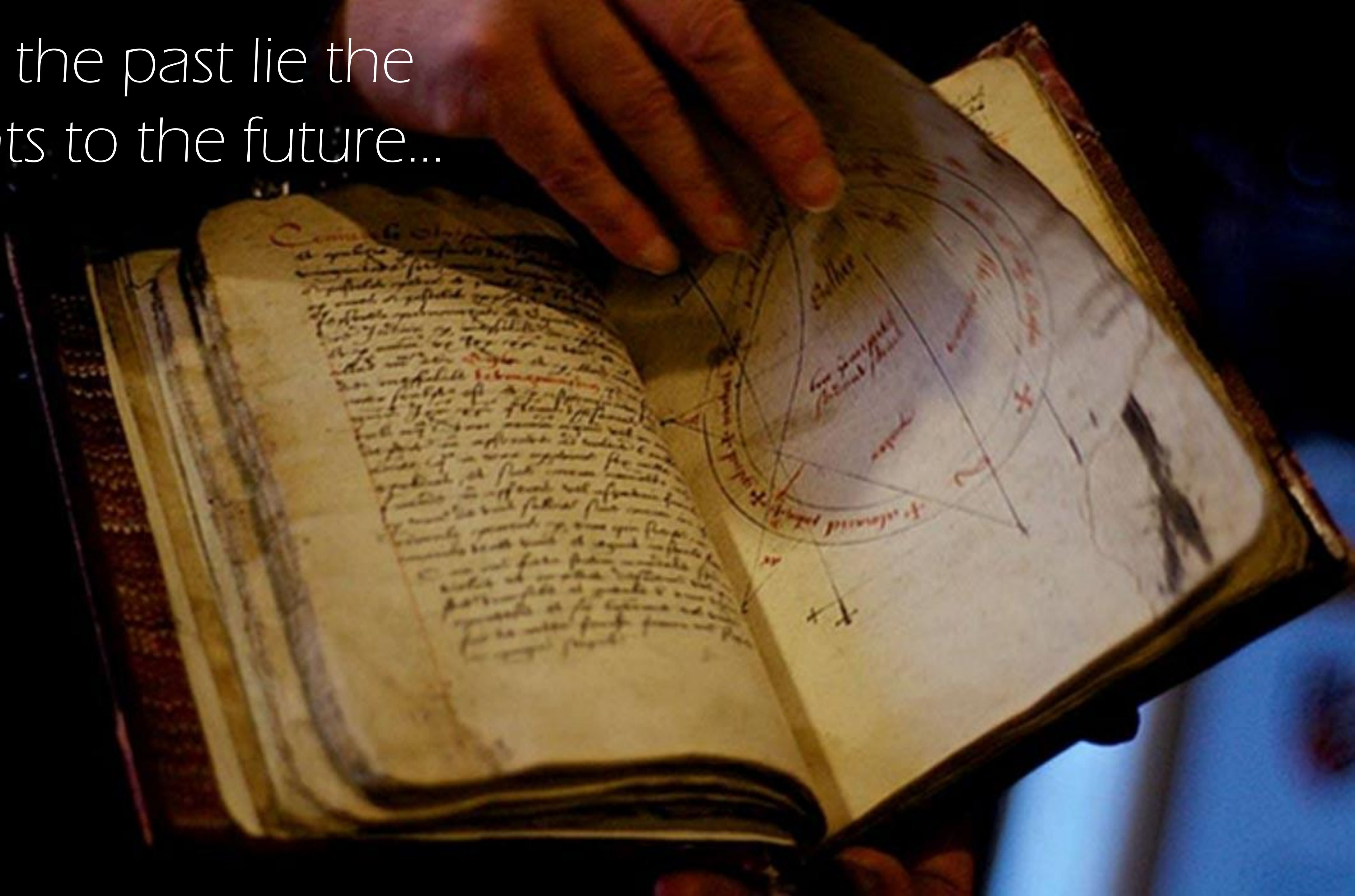


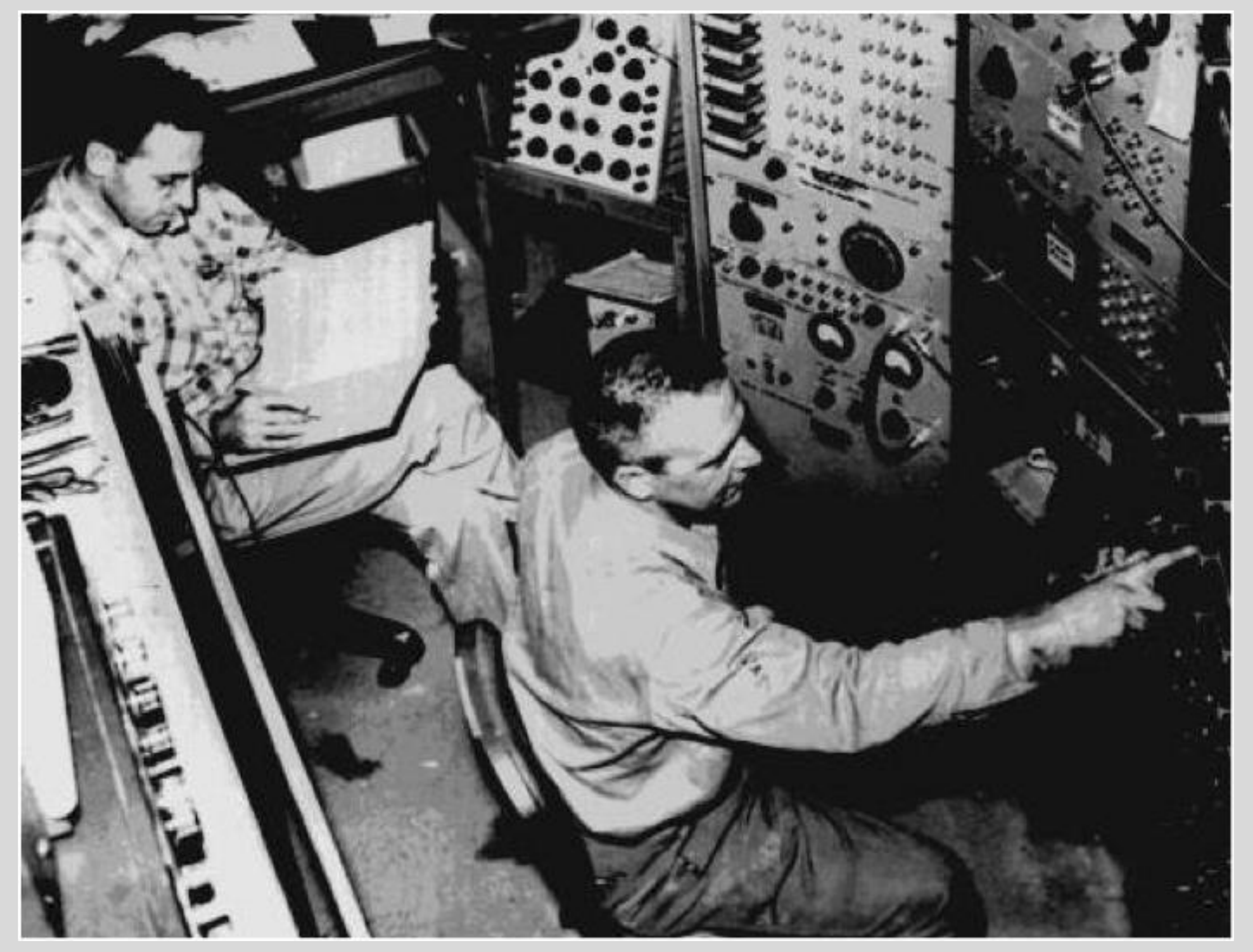
Geoneutrinos:
lessons from the past, insights for the future

Fabio Mantovani – mantovani@fe.infn.it
www.fe.infn.it/radioactivity/
University of Ferrara – INFN Ferrara

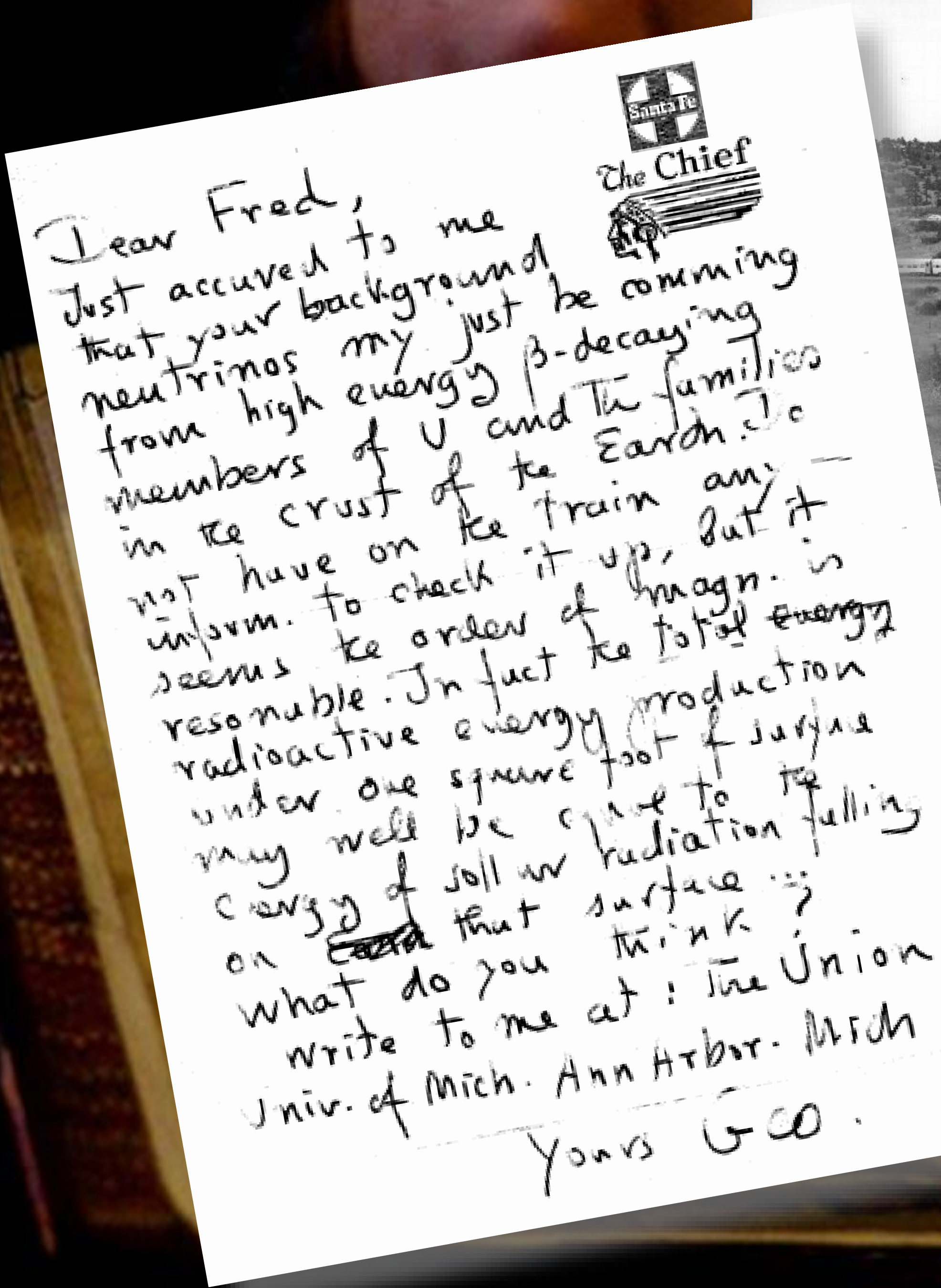


…within the past lie the footprints to the future…

…1953…



In **1953** G. **Gamow** wrote to F. 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.”



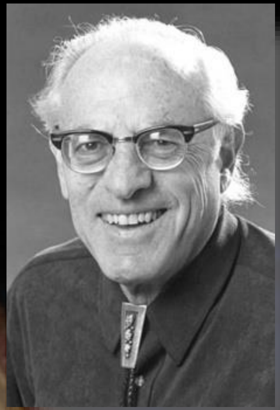
Santa Fe
The Chief

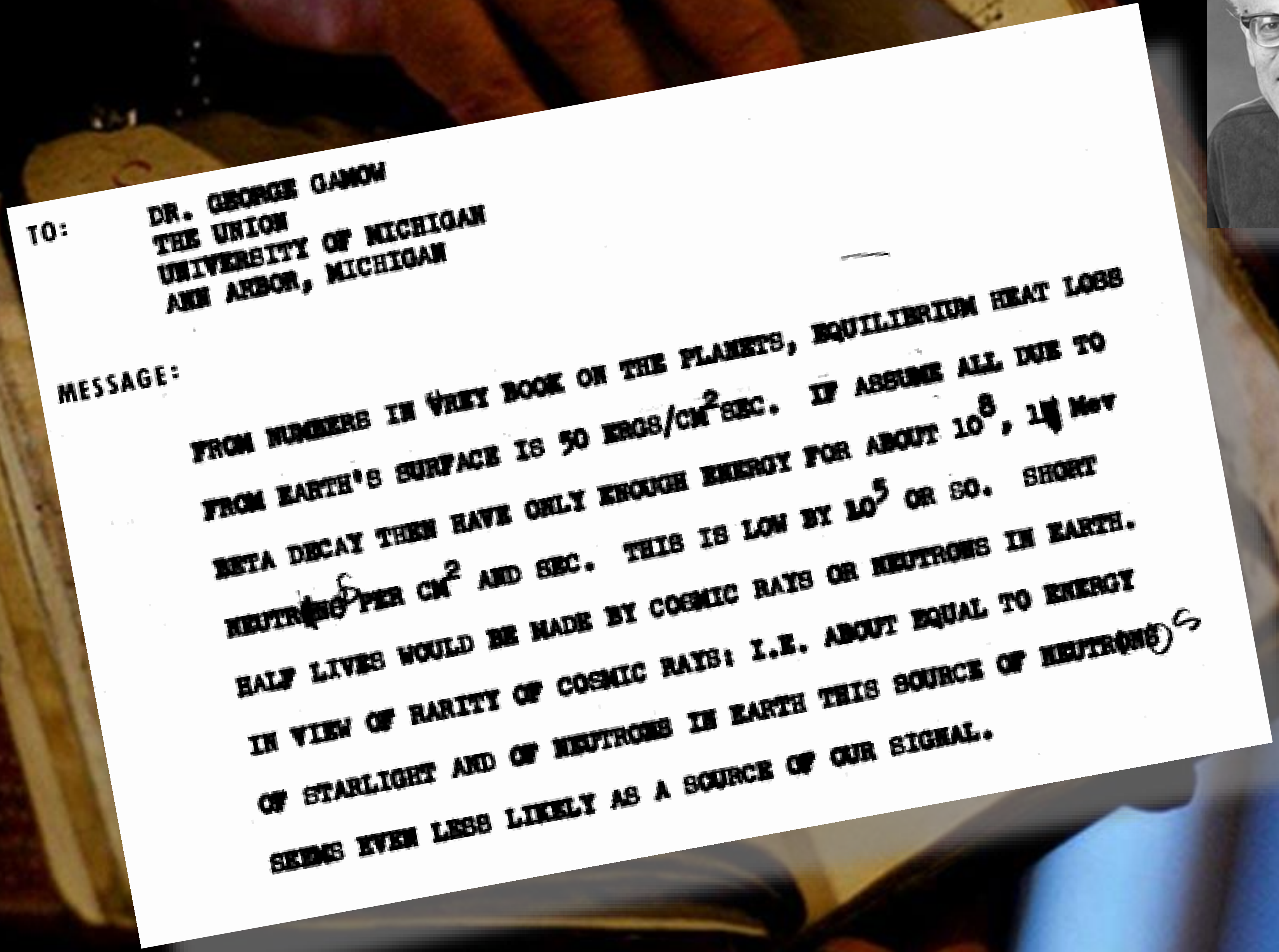
Dear Fred,
Just accured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. I do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fact the total ~~energy~~
radioactive energy production
under one square foot of surface
may well be equal to the
energy of soll ar radiation falling
on ~~Earth~~ that surface.
what do you think?
write to me at: The Union
Univ. of Mich. Ann Arbor. Mich

Yours Geo.

F. Reines answered to G. Gamow:

“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 cm^{-2} and s.”



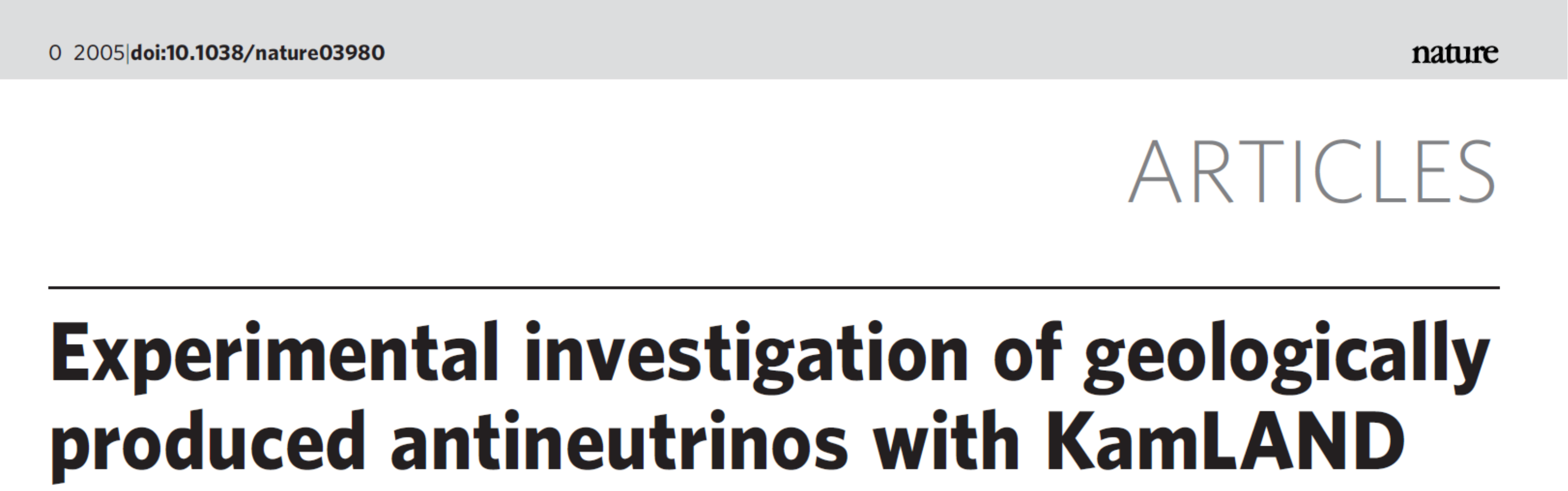


TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:

FROM NUMBERS IN VREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/CM^2SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 MEV NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^5 OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS; I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRINOS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

Lesson 1 – Patience is key in geoneutrino research



0 2005|**doi:10.1038/nature03980** nature

ARTICLES

Experimental investigation of geologically produced antineutrinos with KamLAND

28 July 2005 | www.nature.com/nature | £10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

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EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

After **749.1 ± 0.5 days** of detector live-time, the KamLAND experiment measured **25 geoneutrino candidates** from ^{238}U and ^{232}Th decay chains. With geological input adjustments (Th/U mass ratio of 3.9), the estimated event count is $28^{+26.2}_{-23.5}$ at the 90% confidence level.

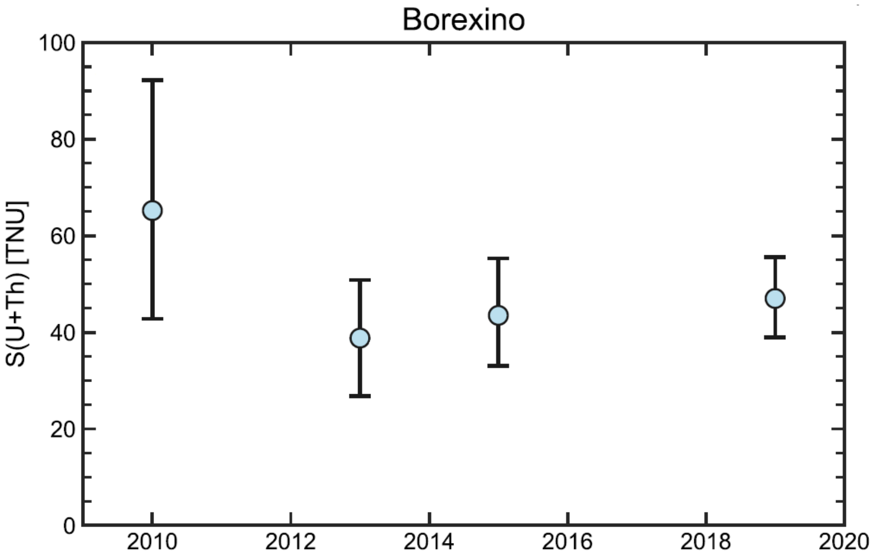
Borexino and KamLAND geoneutrinos results

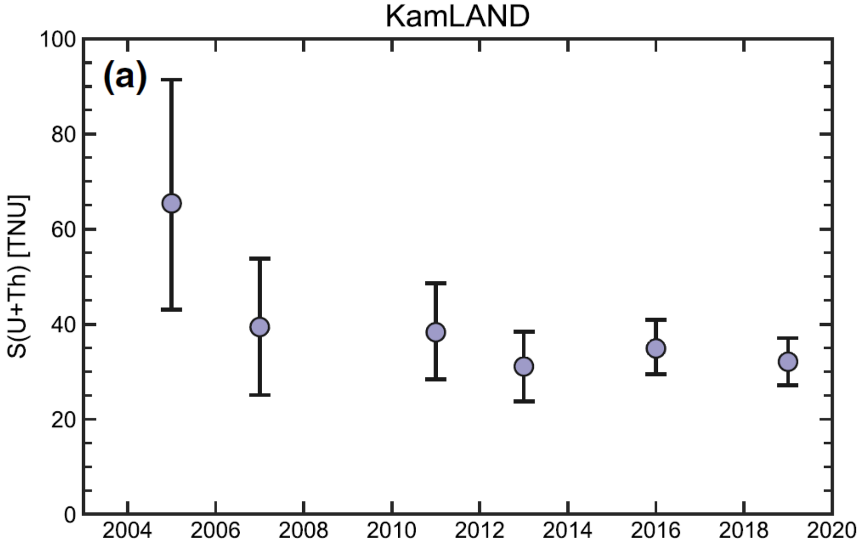
Borexino

- Period: 2007 – 2019
- Geo-ν events: $52.6^{+7.4}_{-6.3}$
- Signal: $47.0^{+8.7}_{-7.9}$ TNU

KamLAND

- Period: 2002 – 2019
- Geo-ν events: $168.8^{+26.3}_{-26.5}$
- Signal: 32 ± 5 TNU





In principle, we have two independent observatories measuring Earth’s total radioactivity.

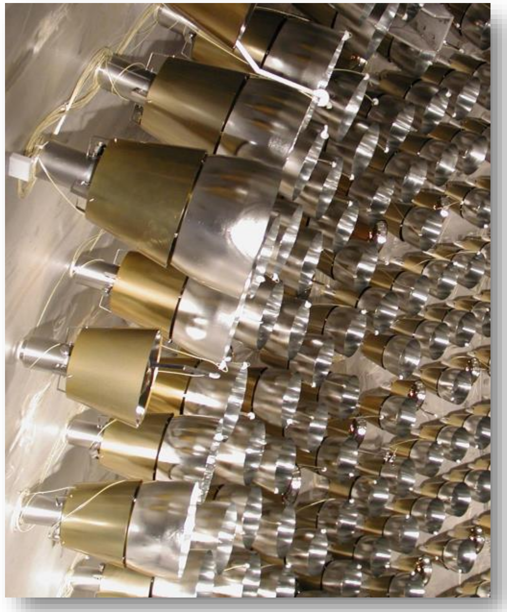
But what can we learn from these measurements?

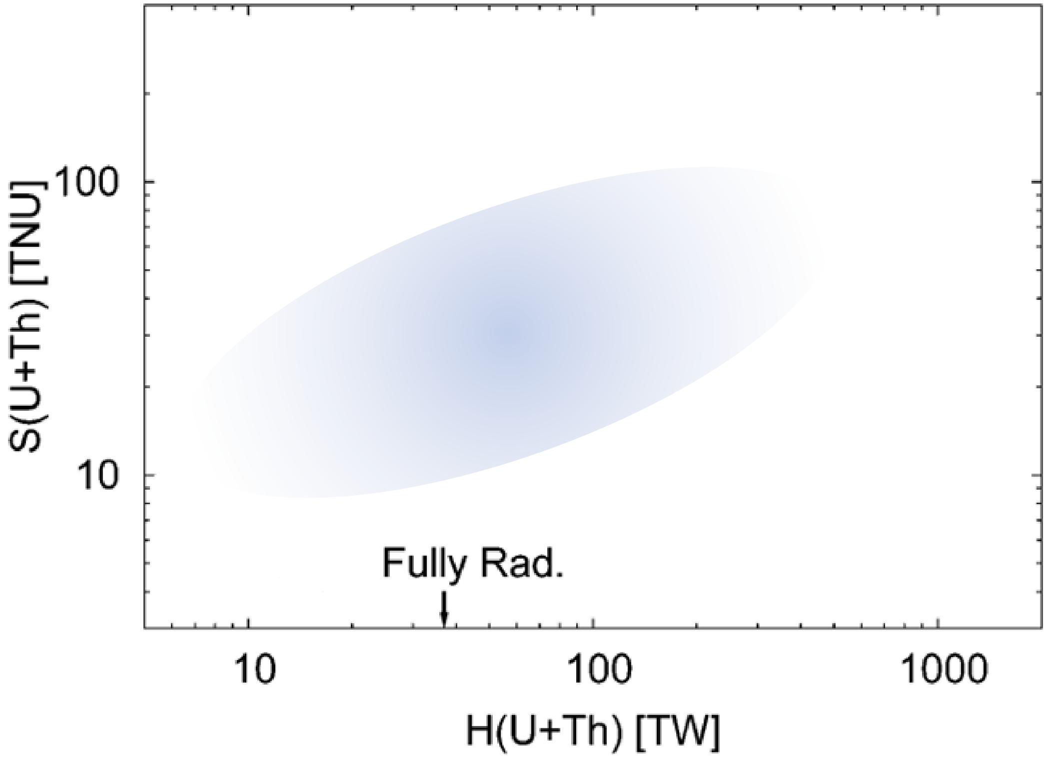
Borexino collaboration, 2020 - PRD – 101 (1)

KamLAND collaboration, 2019 – NGS Prague 2019

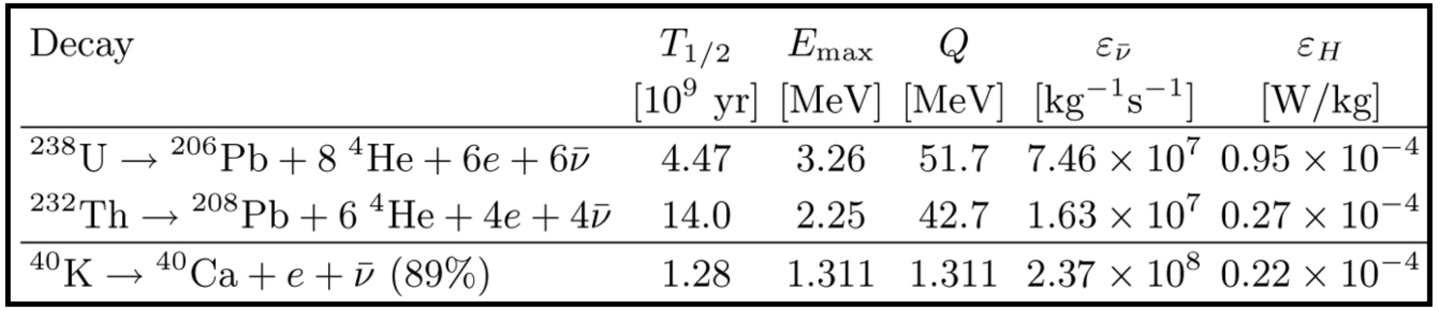
Lesson 2 – Geoneutrino signals need geological models

Signal is measured in 1 TNU = 1 event per 10^{32} free protons/year





U, Th and ^{40}K in the Earth release heat together with anti-ν, in a well-fixed ratio



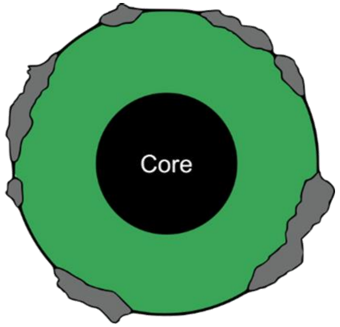
Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.63×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.37×10^8	0.22×10^{-4}

REFERENCE	Earth power
	Q (TW)
Pollack et al., 1993	44 ± 1
Hofmeister and Criss, 2005	31 ± 1
Jaupart et al., 2015	46 ± 2
Davies and Davies, 2010	47 ± 2
Davies, 2013	45
Lucazeau, 2019	44

Mantle radiogenic power from KamLAND and Borexino

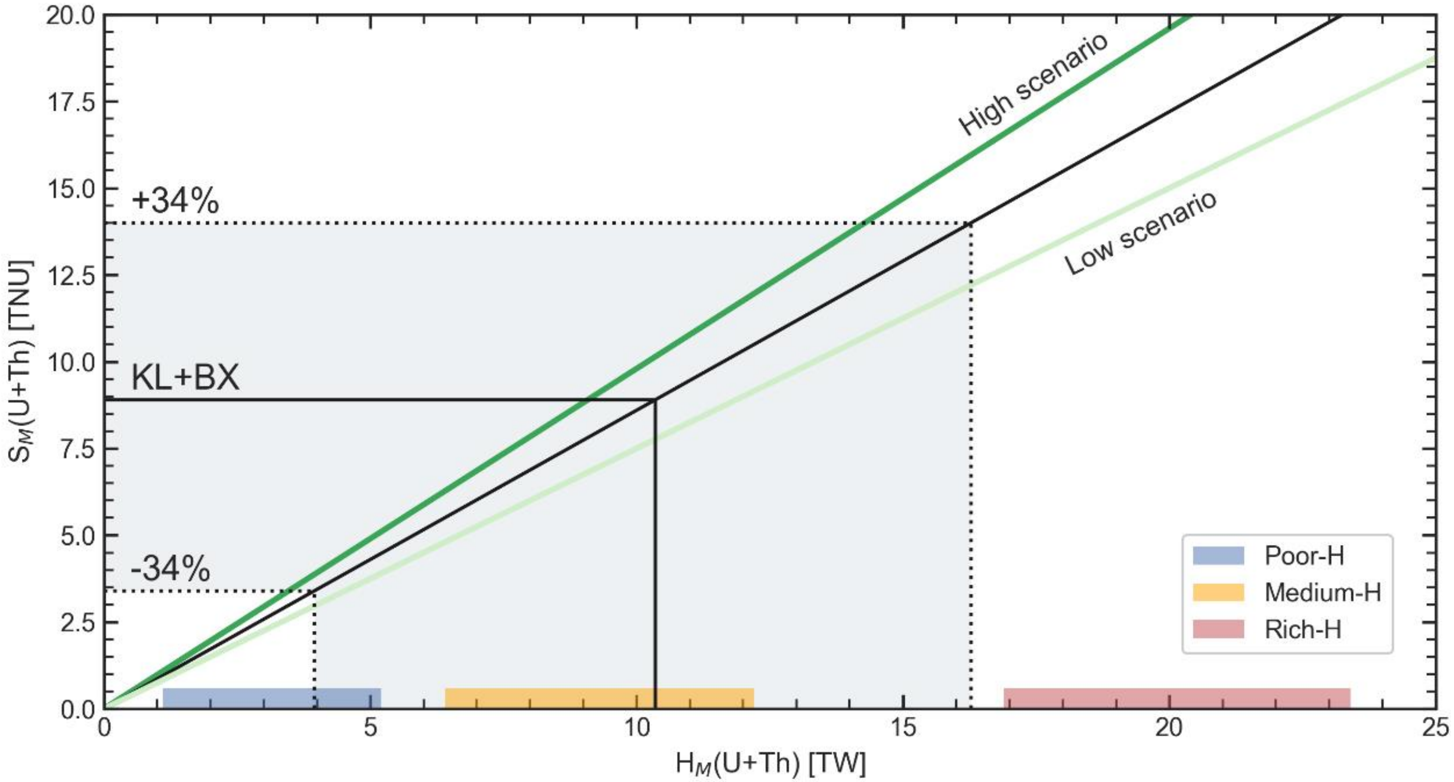
$$S_M(U+Th) = \beta\, H_M(TH+U)$$

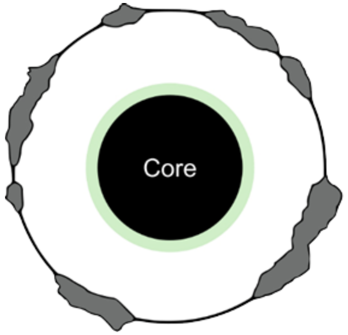
The coefficient β depends only on the distribution of U and Th in the mantle.



β_{High} = 0.98 TNU/TW

By combining signals from Borexino and KamLAND, a mantle geoneutrino signal of $8.9^{+5.1}_{-5.5}$ TNU* can be extracted





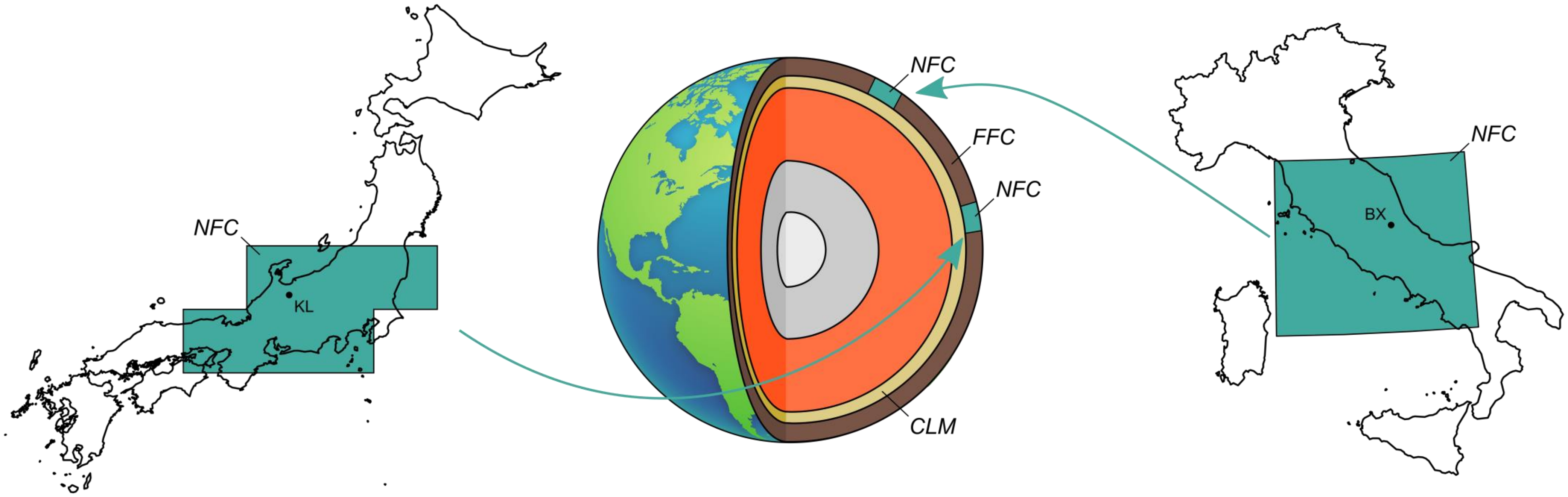
β_{Low} = 0.75 TNU/TW

	Geochemical mantle models			
	Poor (U+Th)	Medium (U+Th)	Rich (U+Th)	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

* Bellini et al. - Riv. Nuovo Cim. 45, 1–105 (2022)

How can extract the mantle signal from experimental data?

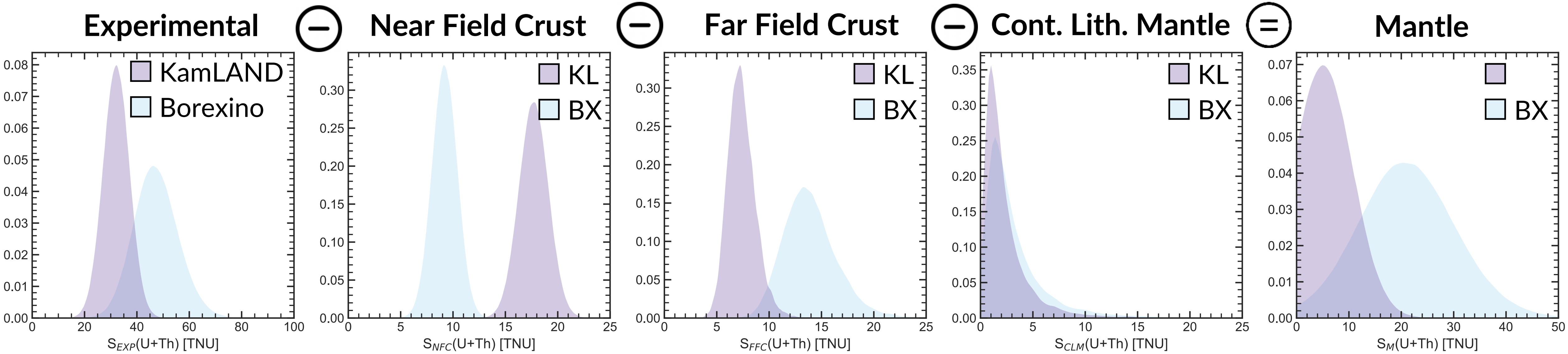
$$S_M(U+Th) = S_{Exp}(U+Th) - S_{NFC}(U+Th) - S_{FFC}(U+Th) - S_{CLM}(U+Th)$$



- U and Th distributed in the **Near Field Crust (NFC)** (i.e. ~ 500 km within the detector) gives a significant contribution to the signal (~ 50% of the total). The modeling of the **NFC** should be built with local geochemical and/or geophysical information
- The signal of **the Far Field Crust (FFC)** and of the **Continental Lithospheric Mantle** (**CLM**) is modeling based on global reference models.

Lesson 3 – The better we know the crust, the better we can infer the mantle

The mantle signals $S_M^{BX}(U+Th)$ and $S_M^{KL}(U+Th)$ can be inferred by subtracting the estimated lithospheric components from the experimental total signals using their reconstructed PDFs:

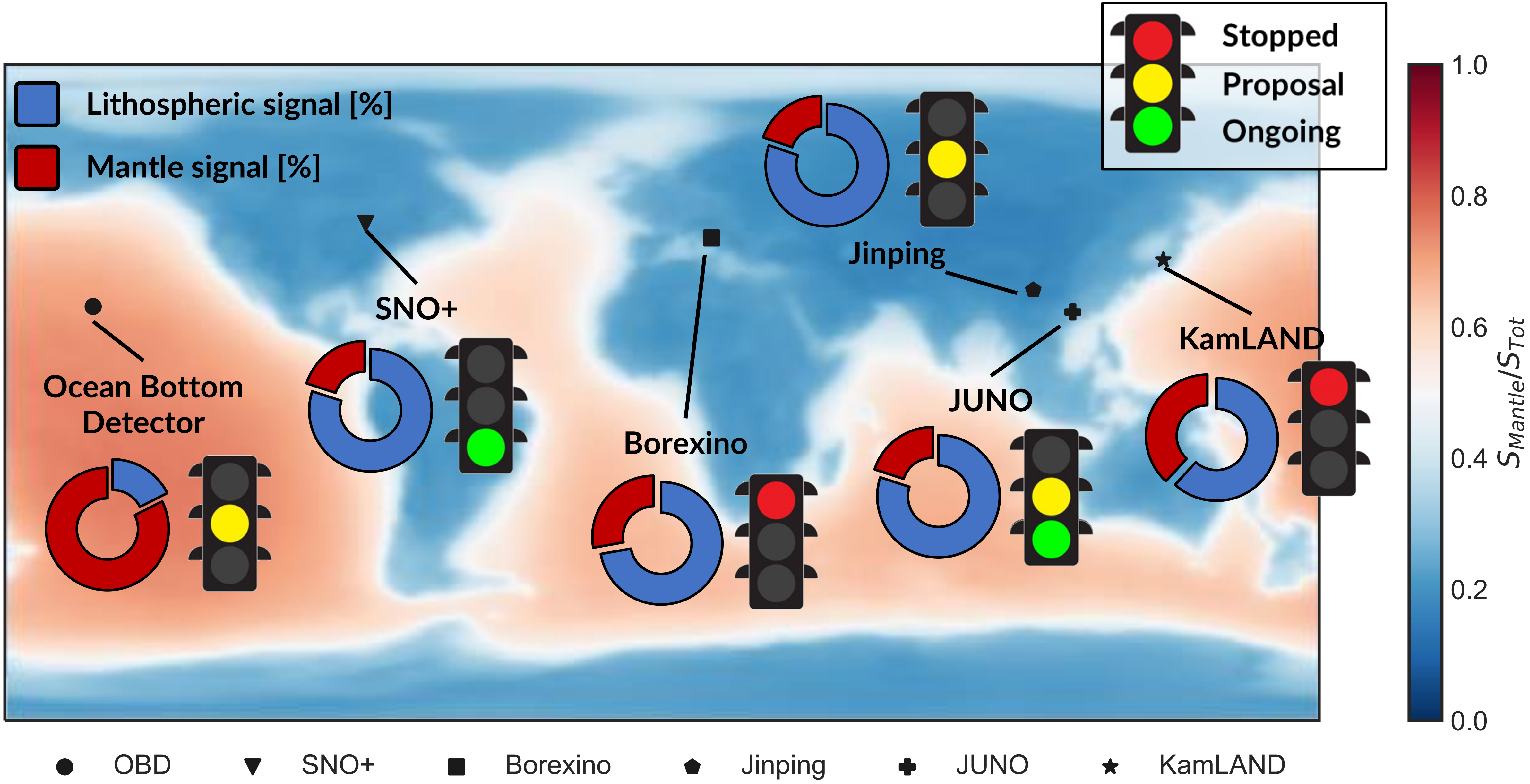


$$S^i_{Exp}(U+Th) - S^i_{NFC}(U+Th) - S^i_{FFC}(U+Th) - S^i_{CLM}(U+Th) = S^i_M(U+Th)$$

		S_{Exp}(U+Th) [TNU]	S_{NFC}(U+Th) [TNU]	S_{FFC}(U+Th) [TNU]	S_{CLM}(U+Th) [TNU]	S_M(U+Th) [TNU]
🟪	KL	32.1 ± 5.0	17.7 ± 1.4	$7.3^{+1.5}_{-1.2}$	$1.6^{+2.2}_{-1.0}$	$\mathbf{4.8^{+5.6}_{-5.9}}$
🟦	BX	$47.0^{+8.6}_{-8.1}$	9.2 ± 1.2	$13.7^{+2.8}_{-2.3}$	$2.2^{+3.1}_{-1.3}$	$\mathbf{20.8^{+9.4}_{-9.2}}$

Bellini et al. - Riv. Nuovo Cim. 45, 1–105 (2022)

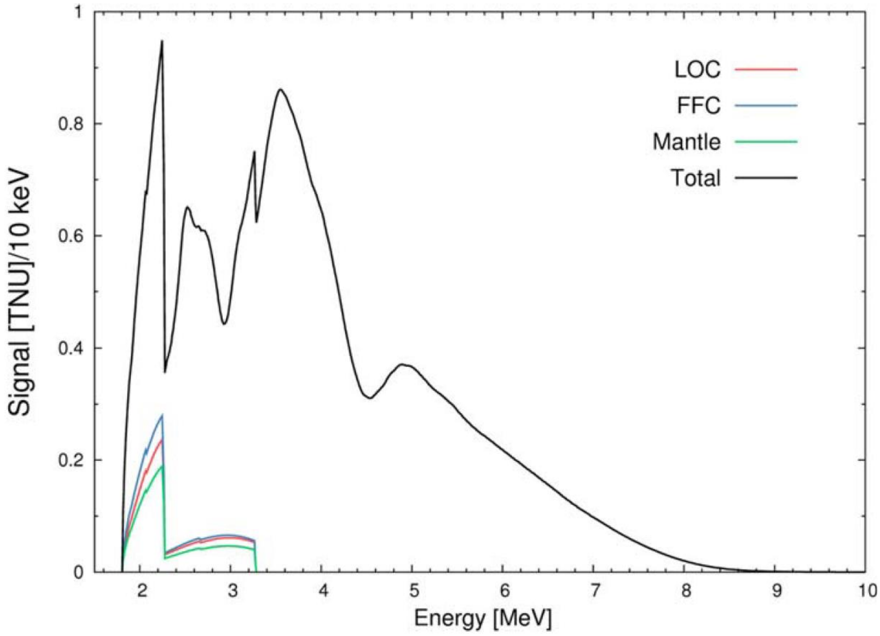
Present and next generation detectors

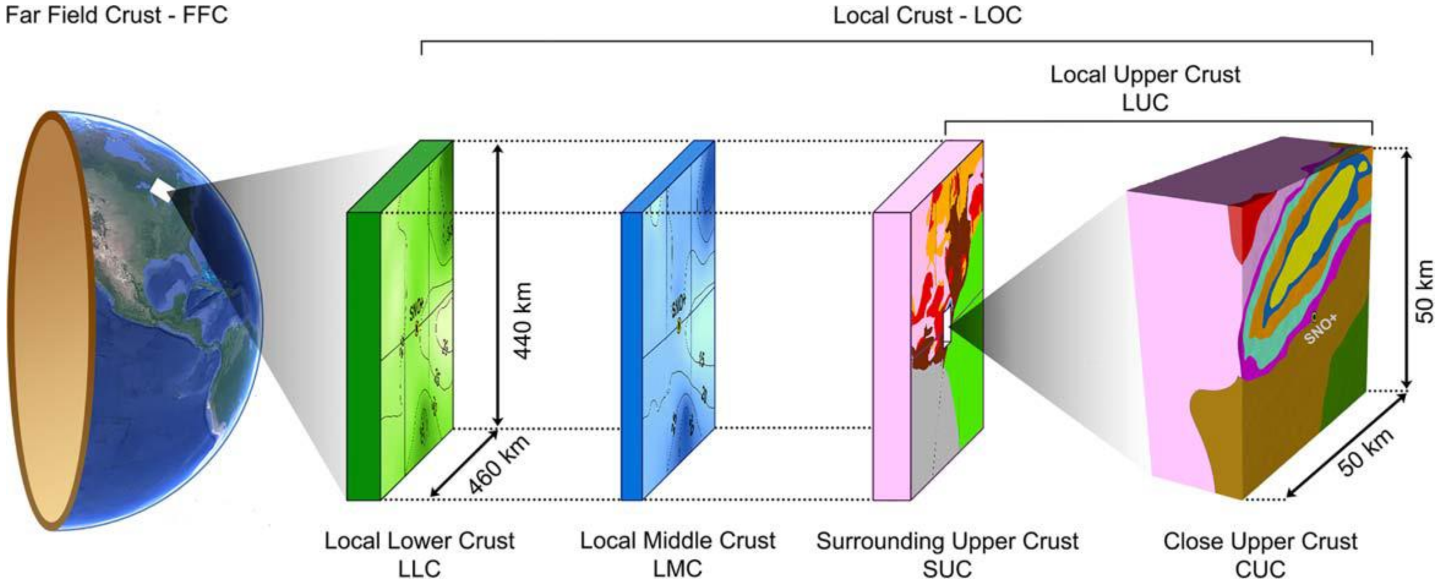


● OBD ▼ SNO+ ■ Borexino ⬟ Jinping ✚ JUNO ★ KamLAND

Expected geoneutrino signal at SNO+

- In the geoneutrino energy window [1.8–3.3 MeV], an expected reactor antineutrino signal of $48.5^{+1.8}_{-1.5}$ TNU.
- Two distinct 3D models of the SNO+ crust, impacted by a meteorite ~ $1.9\ 10^9$ yr ago, were developed at different resolutions using geological, geophysical, and geochemical data.
- U and Th in the main 9 upper crust (UC) units were characterized with 112 samples.





Huang et al. Geochem. Geophys. Geosyst., 2014 – Strati et al. Geochem. Geophys. Geosyst,.2017

	S(U+Th) TNU
LOC	$15.3^{+7.7}_{-3.3}$
FFC	$15.2^{+2.7}_{-2.4}$
CLM	$2.1^{+3.0}_{-1.3}$
Lithosphere	$34.2^{+9.2}_{-5.3}$

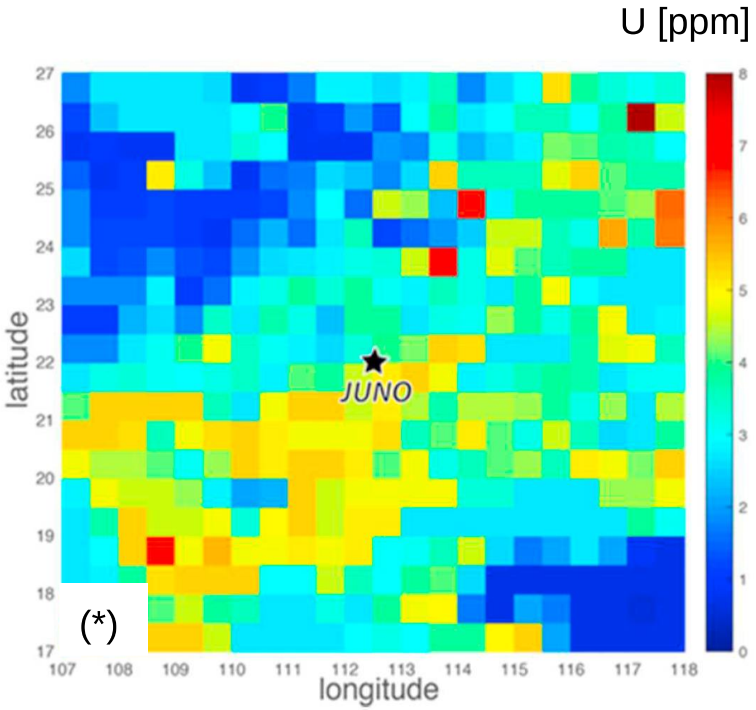
The total expected geoneutrino signal at SNO+ is estimated at 42 ± 8 TNU

Expected geoneutrino signal at JUNO

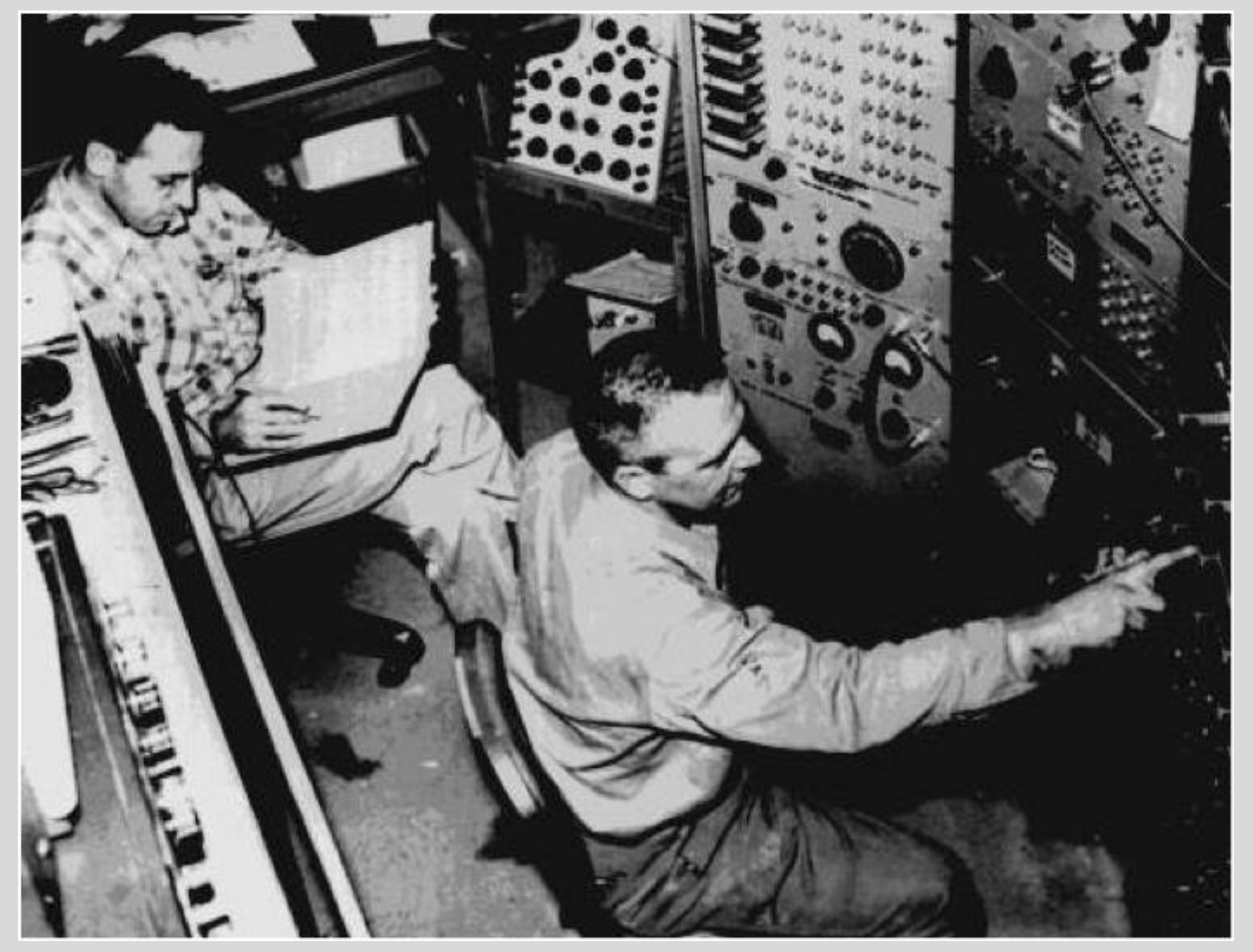
- JUNO is a 20 kton LS detector surrounded by ~18.000 20” PMT
- Expected geo-ν ~ 400 events/year (~ 40 TNU)
- Expected react-ν in [1.8-3.3 MeV] ~ 260 TNU (S_{rea} / S_{geo} ~ 7)

	N° of cores	Thermal power/core
Yangjiang	6	2.9 GW
Taishan	2	4.6 GW

	S(U+Th) [TNU]
Strati et al., 2015 (using global crustal model)	$39.7^{+6.5}_{-5.2}$
Wipperfurth et al., 2020 (using global crustal models)	$41.3^{+7.5}_{-6.3}$
	$41.2^{+7.6}_{-6.4}$
	$40.0^{+7.4}_{-6.2}$
Gao et al., 2020 (*) (combining global crustal model and local geological data)	$49.1^{+5.6}_{-5.0}$



…1953 -> 2024



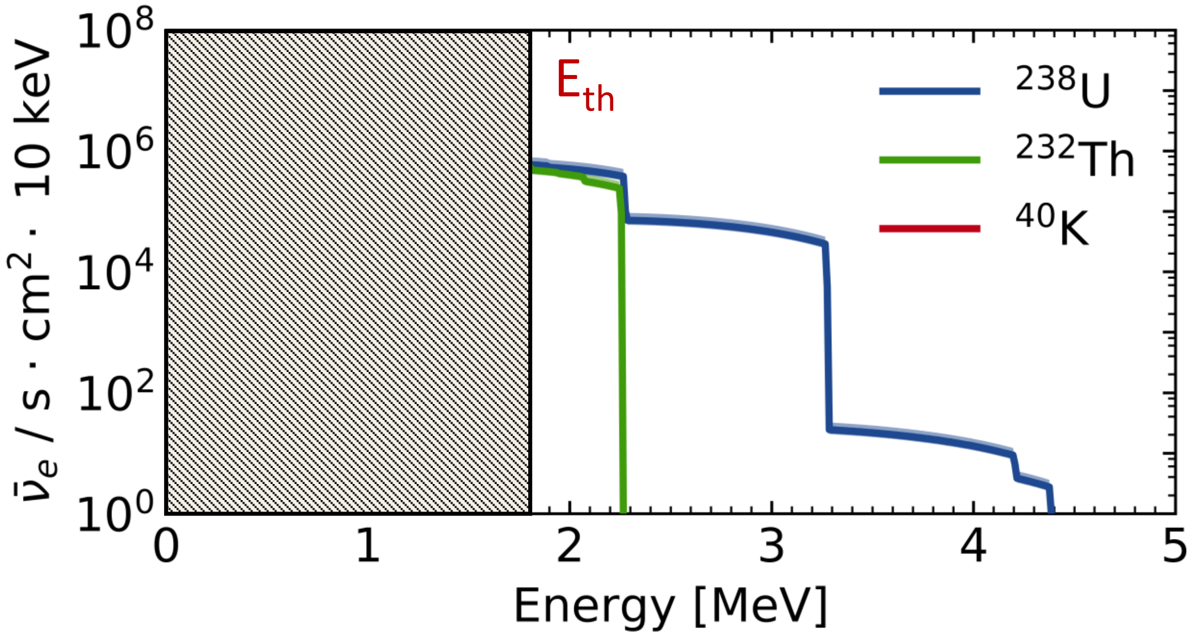
Inverse Beta Decay (IBD) detection

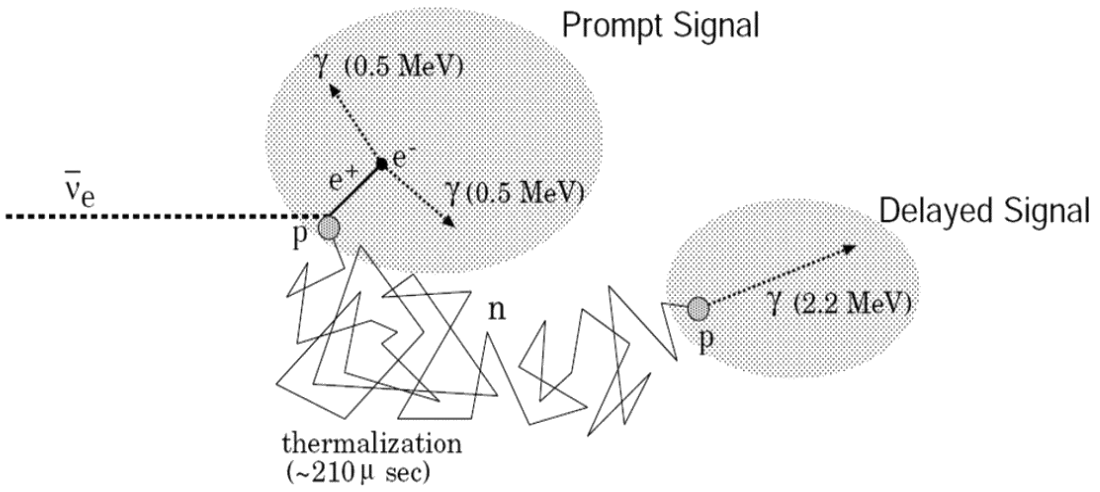
Geoneutrinos are **detected by IBD** in **~kton** Liquid Scintillation Detectors.

$$\bar{\nu}_e + p \rightarrow n + e^+ - 1.806\ MeV$$

Detection requires the coincidence of 2 delayed light signals.

It does not permit to observe ^{40}K-$\bar{\nu}_e$





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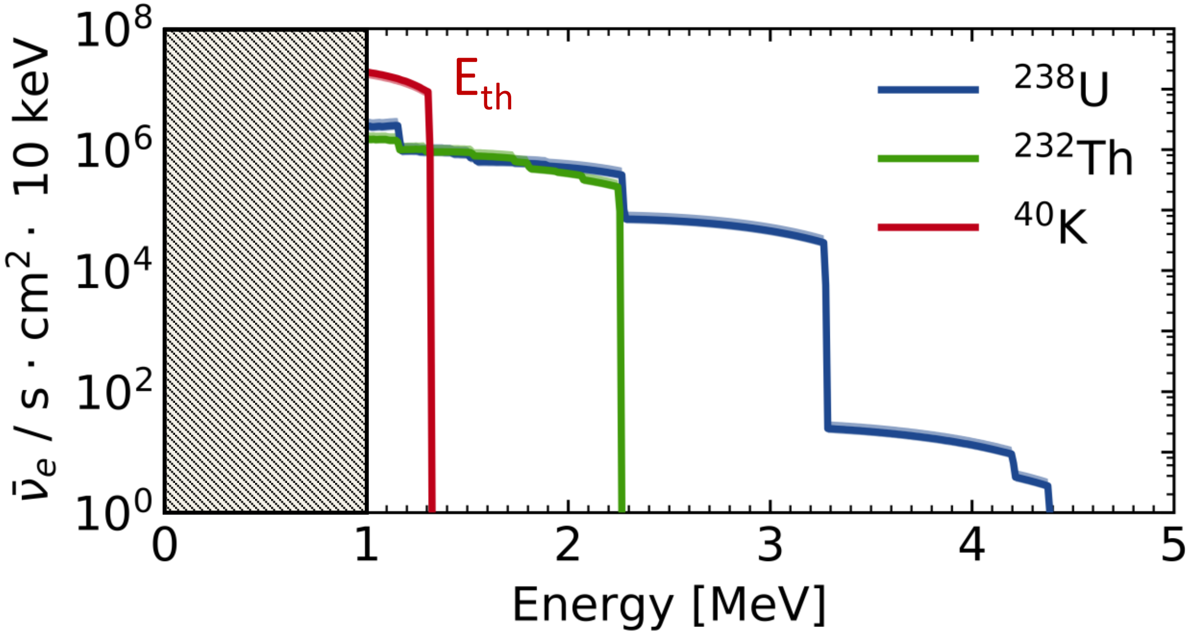
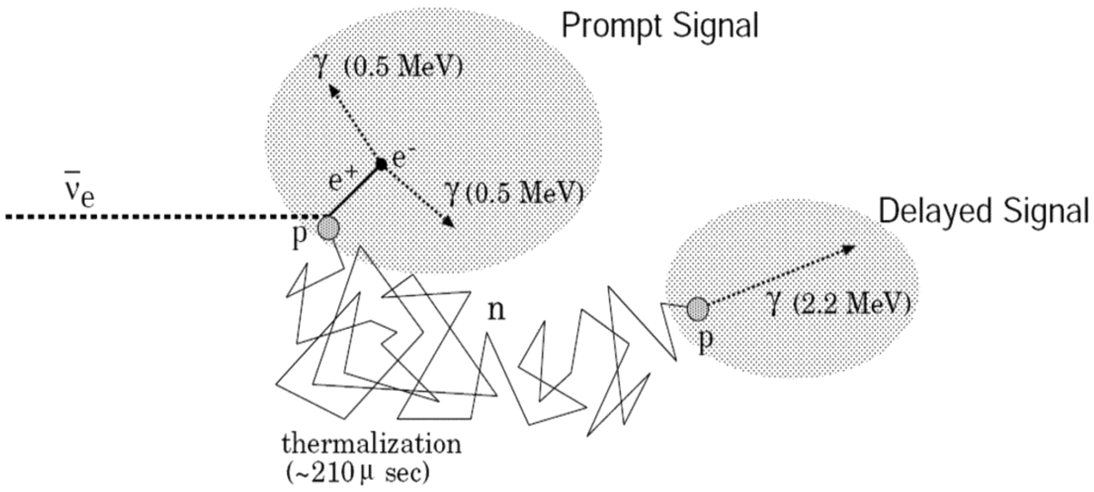




In order to detect ^{40}K- $\bar{\nu}_e$ we could use:

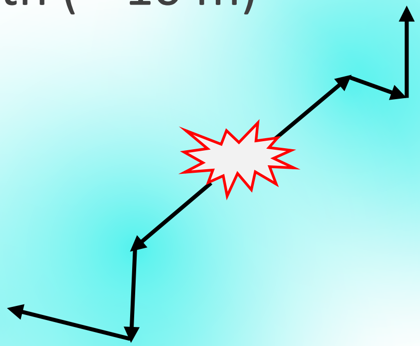
$$\bar{\nu}_e + {}_{Z+1}^{A}Y \rightarrow {}_{Z}^{A}X + e^+ - E_{th}$$

We shall require:

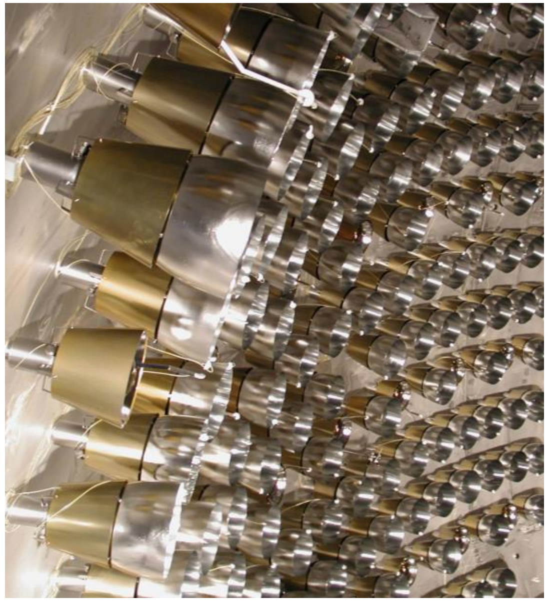
- $E_{th} < 1.3\ MeV$
- High cross-section
- High Y natural isotopic abundance

Transparent vs. opaque detector

Very long scattering length (~ 10 m)

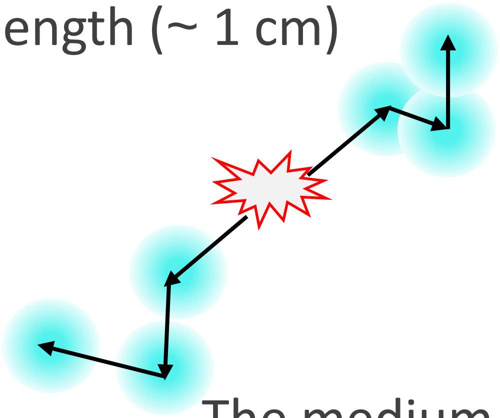


The medium is transparent to scintillation photons

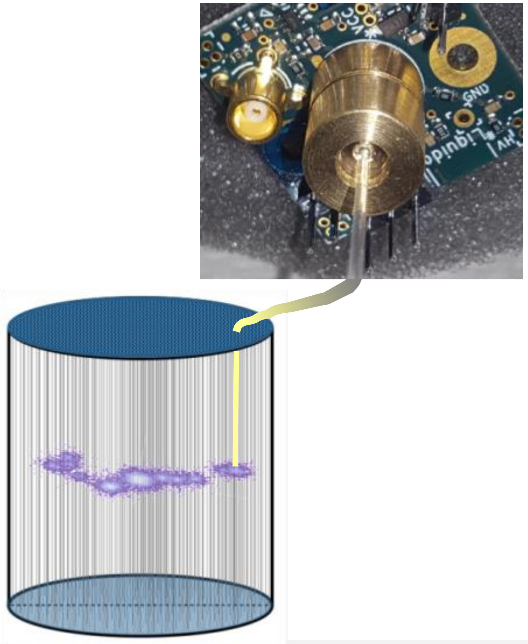


- Scintillation light reaches the surrounding 10^3-10^4 PMTs
- Slow time resolution (~ ns)
- Poor spatial resolution on light deposition (~ 10 cm)
- High photon detection efficiency (~ 20%)

Very short scattering length (~ 1 cm)

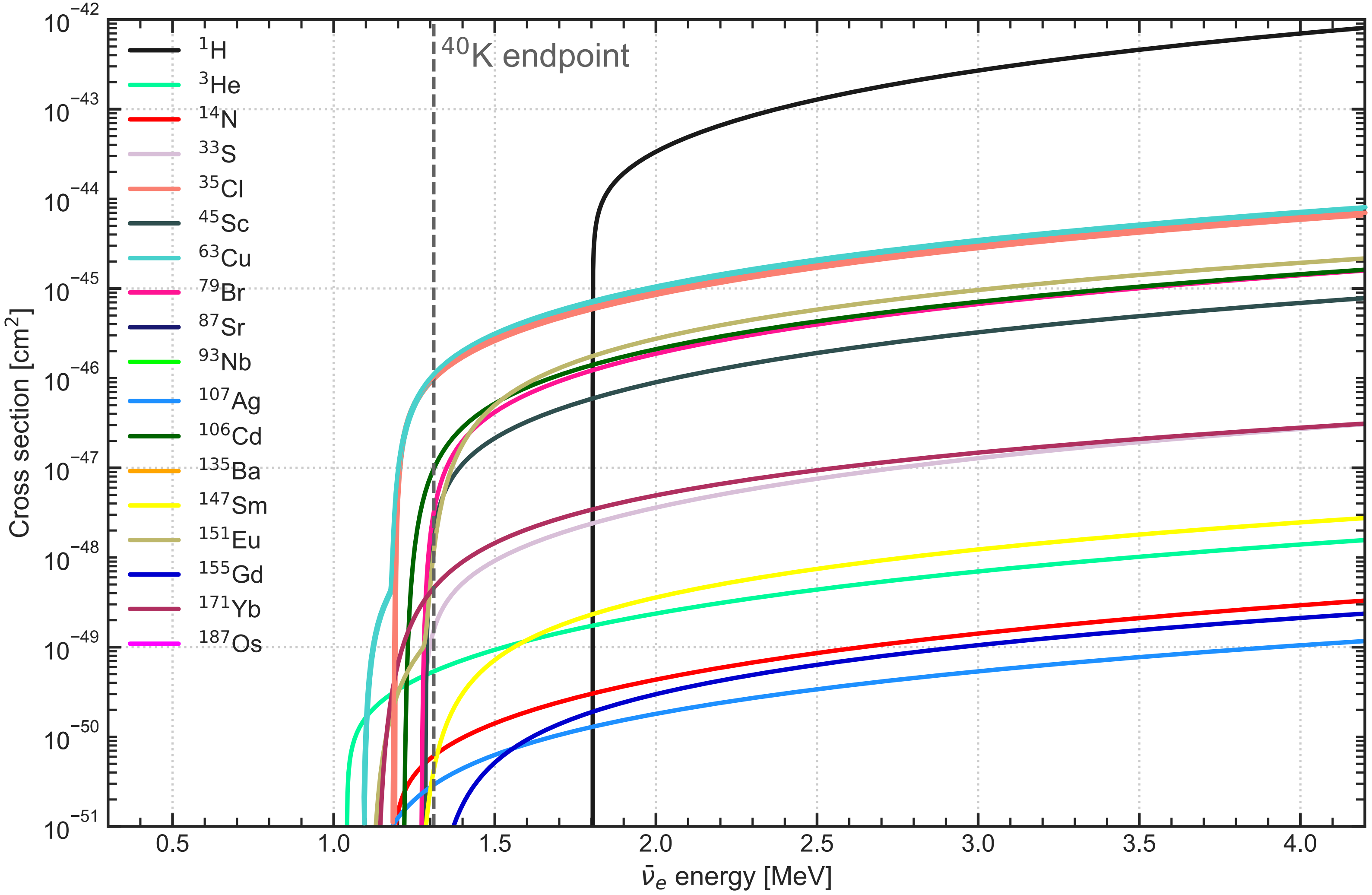


The medium is opaque to scintillation photons

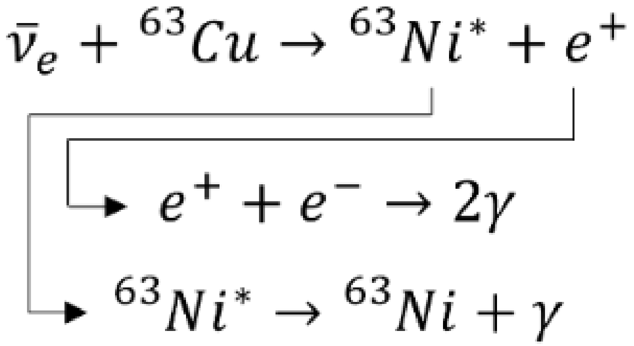


- The light is extracted by an array of optical fibers connected to SiPMs
- Fast time resolution (~ 0.3 ns)
- Excellent spatial resolution on light deposition (~ 1 cm)
- Poor photon detection efficiency (~ 5%)

IBD cross-sections weighted by isotopic abundance



^{63}Cu (Isotopic Abundance = 69%) appears to be a promising target for ^{40}K geoneutrinos due to its transition to an excited state in ^{63}Ni* (E_{MAX} = 1.176 MeV; $t_{1/2}$ = 1.67 μs), offering potential double-coincidence capability ($E\gamma$ = 87 keV).



$$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$$

$$e^+ + e^- \rightarrow 2\gamma$$

$$^{63}Ni^* \rightarrow {}^{63}Ni + \gamma$$

Cabrera et al. - Probing Earth’s Missing Potassium using the Unique Antimatter Signature of Geoneutrinos - arXiv:2308.04154

Conclusions & perspectives

- We learn three lessons from past research:
  - patience is essential in geoneutrino studies;
  - interpreting geoneutrino signals requires geological models;
  - the better we understand the crust, the more accurately we can infer mantle properties.
- The "multi-site detection" era for U+Th geoneutrinos is underway, with new data from SNO+ and JUNO soon reinforce constraints on mantle composition and Earth's radiogenic heat.
- The development of new technologies (i.e. opaque liquid-based detectors) may open opportunities for detecting potassium geoneutrinos.