Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

International School of Nuclear Physics - 43rd Course

Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

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Geoneutrino experiments: status and prospects

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Outline

» The "Standard Model" of the Earth

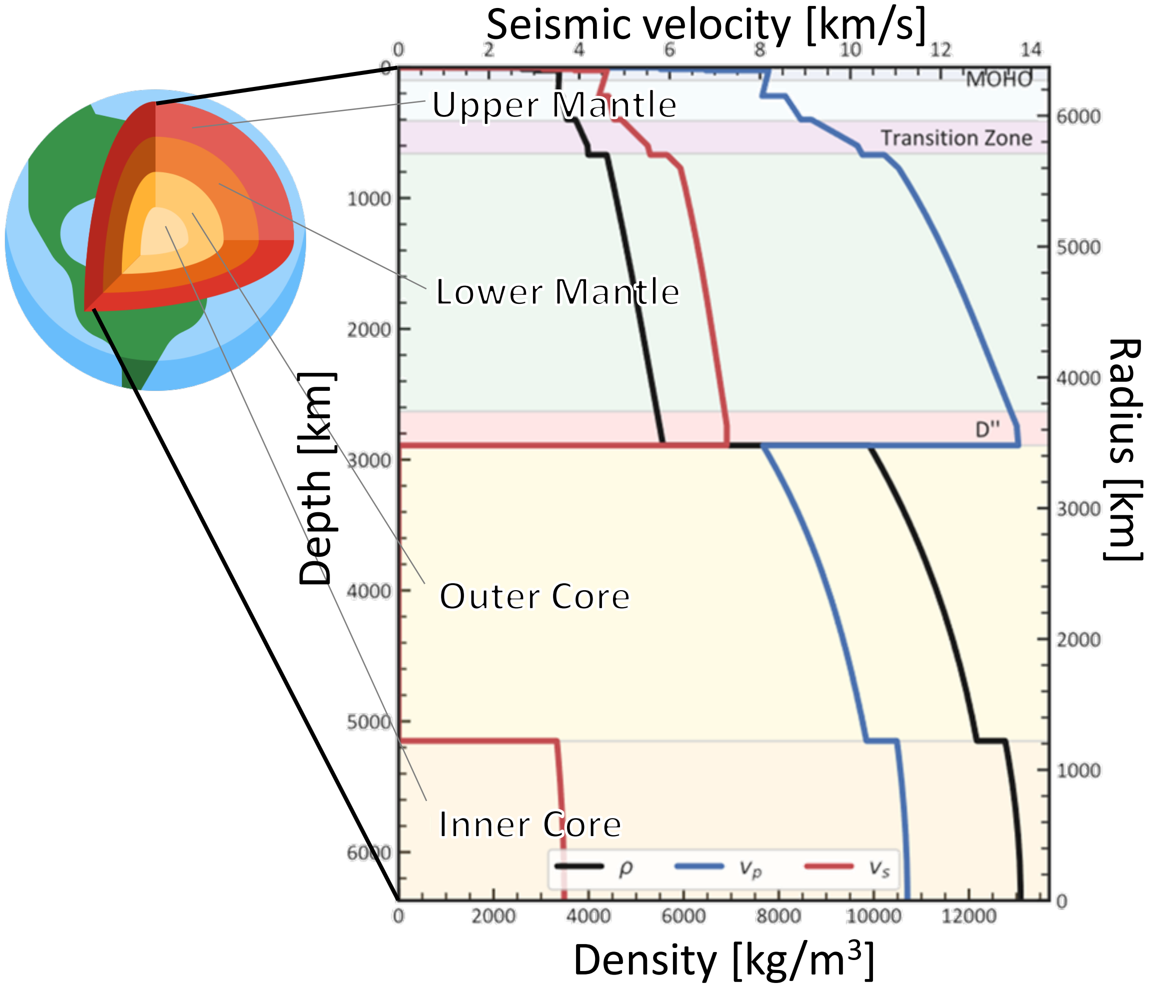
» Geoneutrinos in understanding Earth Sciences

» Insights from current geoneutrino measurements

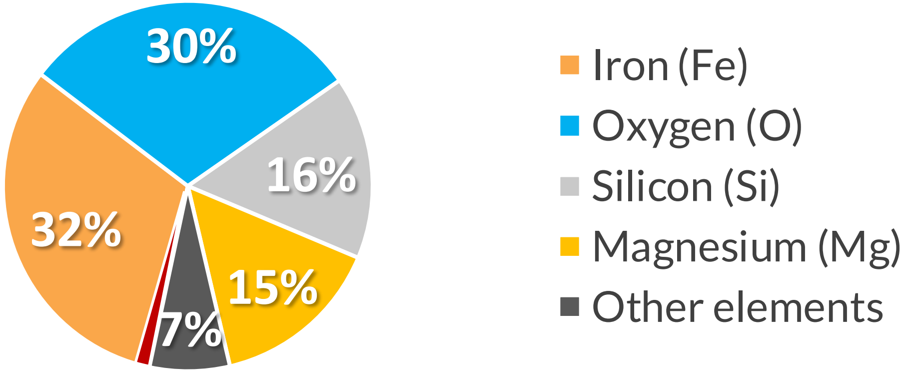
» Future prospects in the geoneutrino field

The "Standard Model" of the Earth

Earth has a well-established **layered** structure, visible from its **density profile**:



The Bulk Earth's **mass composition** for **main elements** is well known:



About 0.02% of Earth's mass is composed of radioactive **Heat Producing Elements (HPEs)**.

The most important for activity, abundances and half-life time (comparable to Earth's age) are:

- **Uranium U** ($M_U \sim 10^{-8} M_{Earth}$)
- **Thorium Th** ($M_{Th} \sim 10^{-8} M_{Earth}$)
- **Potassium K** ($M_K \sim 10^{-4} M_{Earth}$)

*The condensation temperatures are the temperatures at which 50% of the element will be in the form of a solid (rock) under a pressure of 10^{-4} bar.

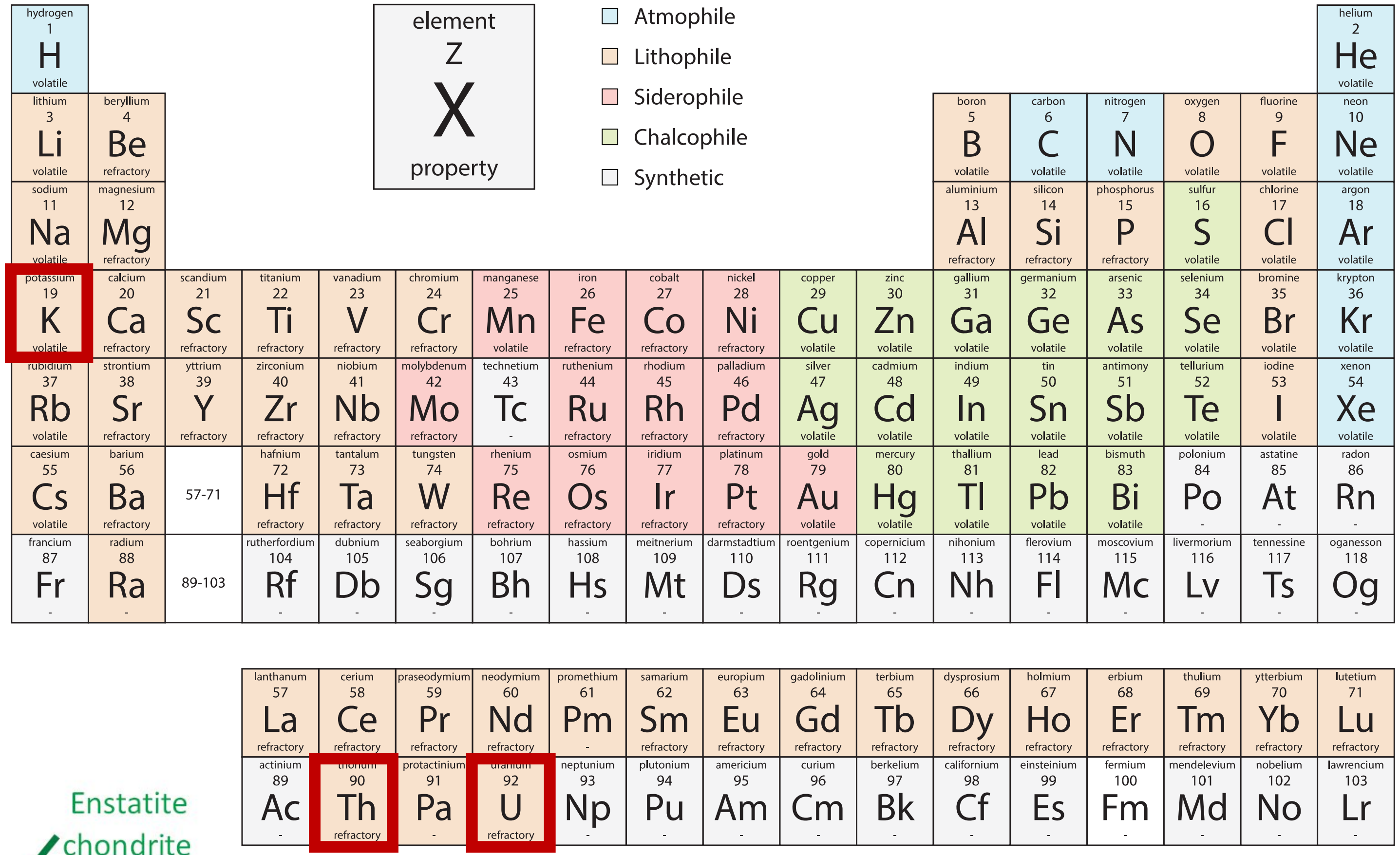
Elemental properties

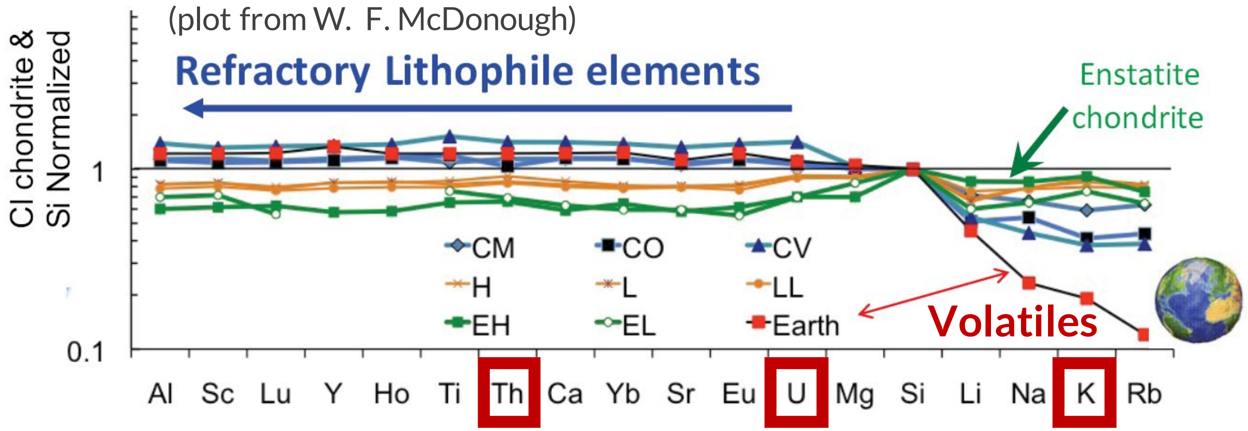
Chemical properties:

- **Siderophiles**: dissolve in iron
- **Lithophiles**: bind with oxygen
- **Chalcophiles**: combine with XVI
- **Atmophile**: do not combine

Condensation temperature* (T_C):

- **Volatile** (T_C < 1300 K)
- **Refractory** (T_C > 1300 K)





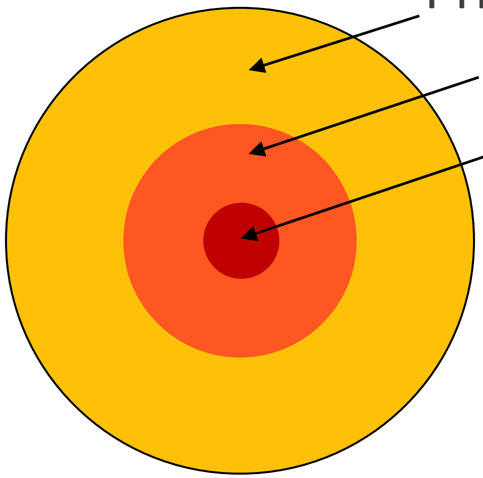
Earth evolution in a nutshell

1st differentiation

Primitive Mantle (PM) [M_{PM} ~68% M_{Earth}]

Outer Core (OC) [M_{OC} ~31% M_{Earth}]

Inner Core (IC) [M_{IC} ~1% M_{Earth}]



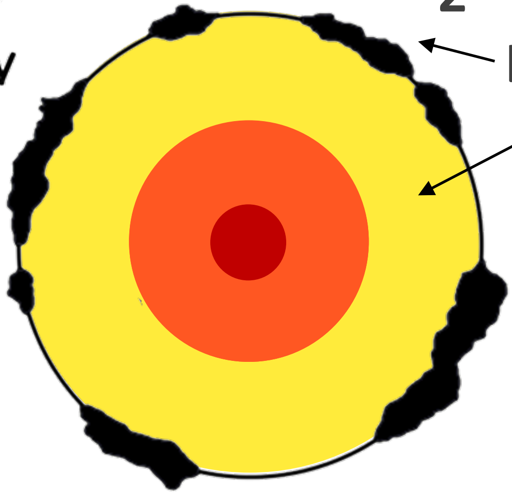
Siderophile elements
(chemical affinity with Fe)
in the Core

2nd differentiation

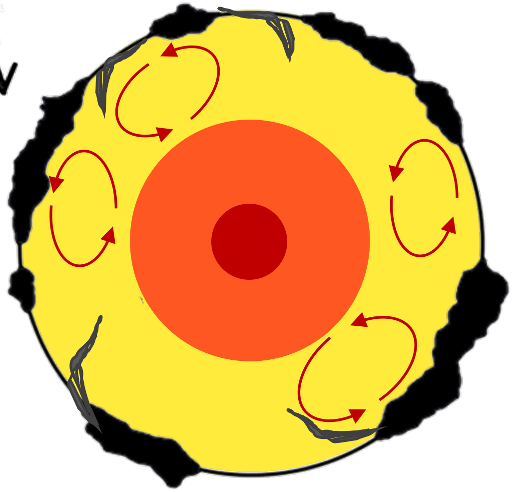
Lithosphere [M_{Lith} ~2% M_{Earth}]

Mantle [M_{Mantle} ~66% M_{Earth}]

OC+IC [M_{Core} ~32% M_{Earth}]

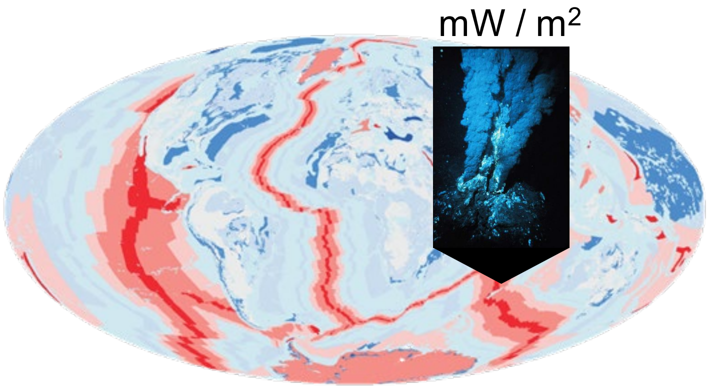


Lithophile elements
(chemical affinity with O)
in the Lithosphere (e.g. U, Th, K)



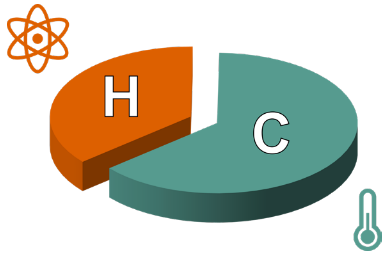
Convective and tectonic processes: formation of new crust (oceanic crust) and recycling of continental crust

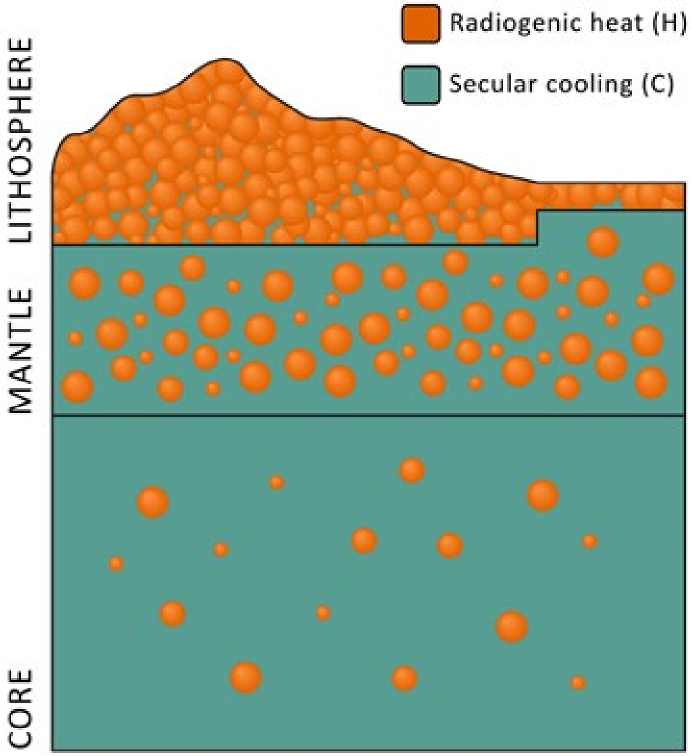
Earth's heat budget



The **total heat power (Q)** of the Earth is well established and is 47 ± 2 TW.
What has still to be understood is in which fraction this heat is due to:

- **Secular Cooling (C)**: cooling down caused by the initial hot environment of early formation's stages
- **Radiogenic Heat (H)**: due to naturally occurring decays of U, Th and K (HPEs) inside our planet.





H_{CC} = radiogenic power of the continental crust

H_{CC} = radiogenic power of the continental crust

H_{CLM} = radiogenic power of the continental lithospheric mantle

$$C = Q - H$$
$$C_M = Q - H - C_C$$
$$H_M = H - H_{LS} - H_C$$
$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$
$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$

	Range [TW]	Adopted [TW]
H	[10 ; 37]	19.3 ± 2.9
H_{LS}	[6 ; 11]	$8.1^{+1.9}_{-1.4}$
H_M	[0 ; 31]	$11.0^{+3.3}_{-3.4}$
H_C	[0 ; 5]	0

	Range [TW]	Adopted [TW]
C	[8 ; 39]	28 ± 4
C_{LS}	~ 0	0
C_M	[1 ; 29]	17 ± 4
C_C	[5 ; 17]	11 ± 2

» The mass of the lithosphere (~ 2% of the Earth's mass) contains ~ 40% of the total estimated HPEs and it produces H_{LS} ~ 8 TW.

» Radiogenic power of the mantle H_M and the contributions to C from mantle (C_M) and core (C_C) are model dependent.

The main reservoirs of the Earth

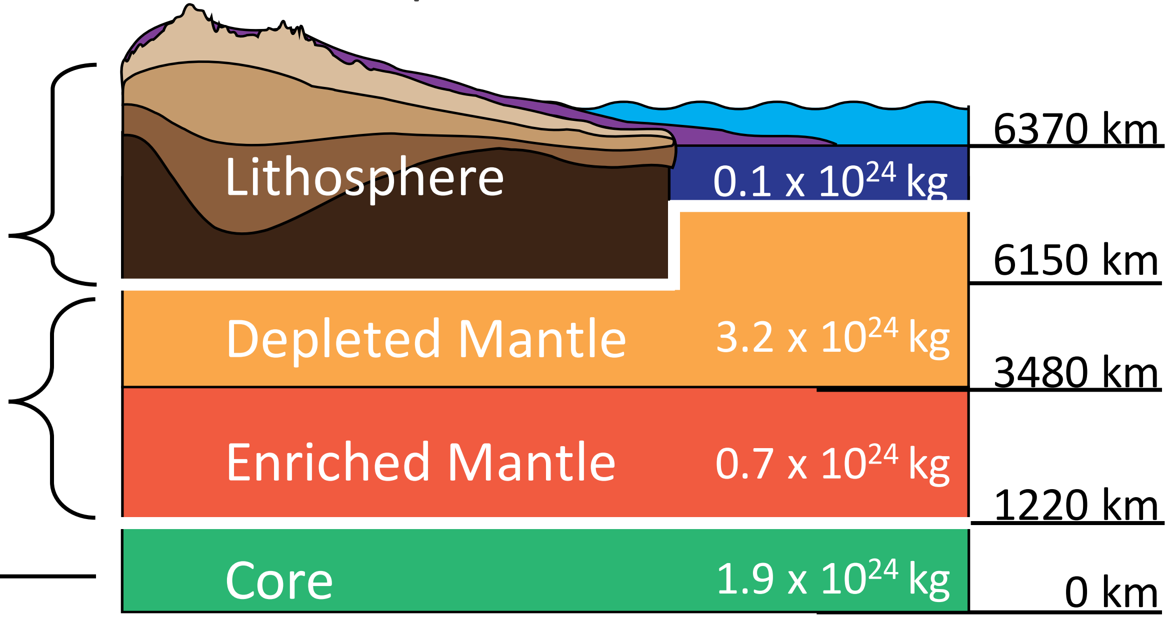
Despite deep Earth's structure is well understood, its chemical composition is not.

Samples from Lithosphere permit to study its compositions with a statistical significance.

Lithosphere rich in HPEs, directly measurable.

Mantle inaccessible to direct measurements.

Core inaccessible and void of HPEs



	a(U) *[μg/g]*	a(Th) *[μg/g]*	a(K) *[10^{-2}g/g]*
Lithosphere	$0.25^{+0.07}_{-0.06}$	$1.08^{+0.37}_{-0.23}$	$0.28^{+0.07}_{-0.06}$
Depleted Mantle	*?*	*?*	*?*
Enriched Mantle	*?*	*?*	*?*

Geoneutrinos: anti-neutrinos from the Earth

^{238}U, ^{232}Th and ^{40}K in the Earth release heat together with $\bar{\nu}_e$ in a well-fixed ratio:

Decay	$T_{1/2}$ [10^9 y]	$E_{max}(\bar{\nu})$ [MeV]	$\epsilon_{\bar{\nu}}$ [10^7 kg^{-1} s^{-1}]	ϵ_H [10^{-5} W kg^{-1}]
$^{238}U \rightarrow ^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e$	4.47	3.36	7.5	9.5
$^{232}Th \rightarrow ^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e$	14.0	2.25	1.6	2.6
$^{40}K \rightarrow ^{40}Ca + e^- + \bar{\nu}_e$ (89%)	1.28	1.31	23.7	2.9

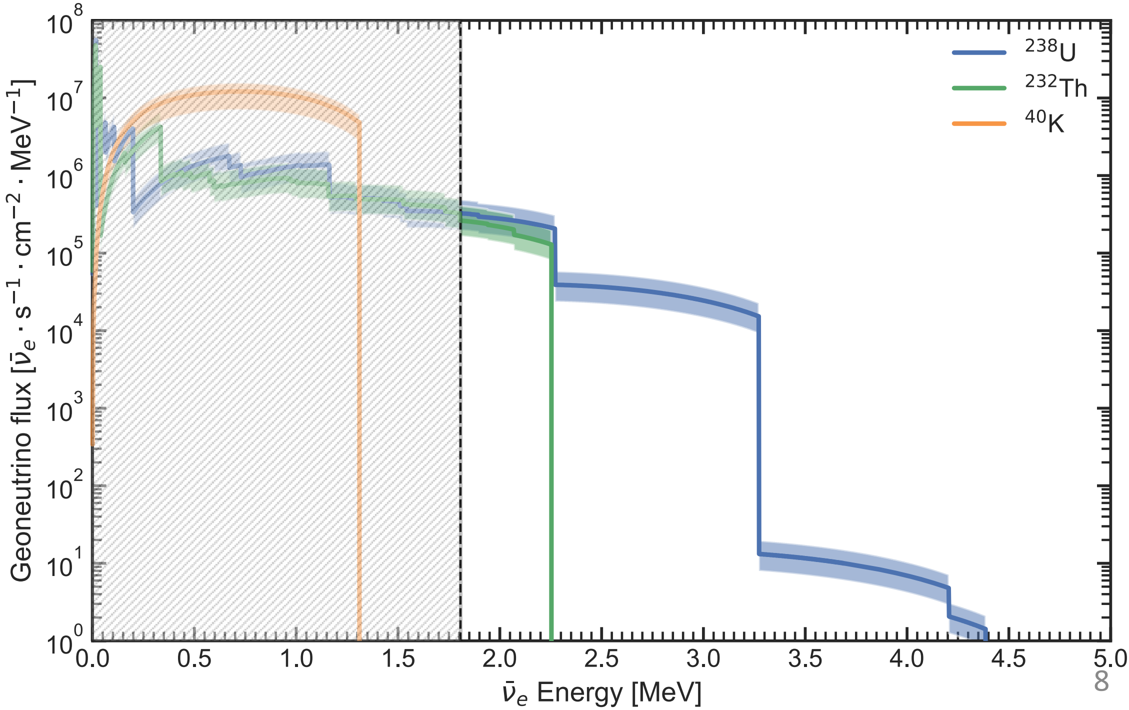
» Earth emits (mainly) $\bar{\nu}_e$ ($\Phi \backsim 10^7$ cm^{-2} s^{-1}) whereas Sun shines in ν_e ($\Phi \backsim 10^{11}$ cm^{-2} s^{-1})

» A fraction of geoneutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons:

$$\bar{\nu}_e + p \rightarrow e^+ + n - 1.8\ MeV$$

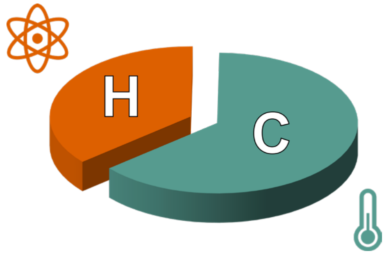
» Different components can be distinguished due to different energy spectra

» Signal unit: 1 TNU = one event per 10^{32} free protons/year



Open questions geoneutrinos can answer

» What is the radiogenic contribution to Earth's heat budget?

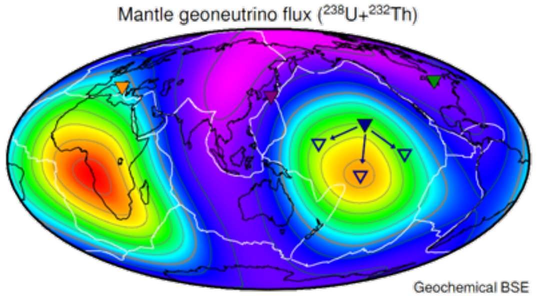


» Are the fundamental ideas about Earth's chemical composition correct?

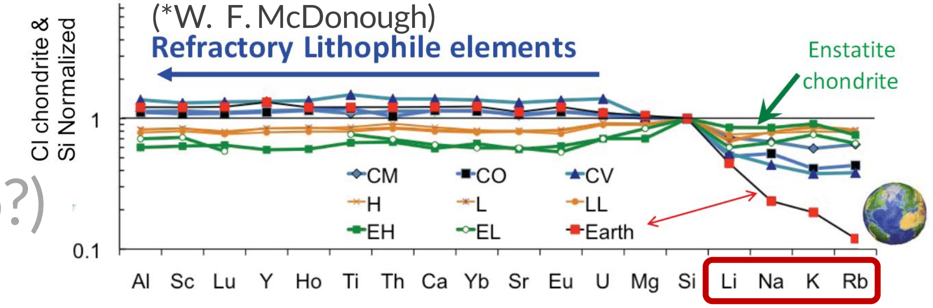
» What's the distribution of reservoirs in the mantle?

» Are there any radiogenic elements in the core?

» What is the volatility slope of the Earth? (K/U ratio?)



(Sramek et al. 2012)

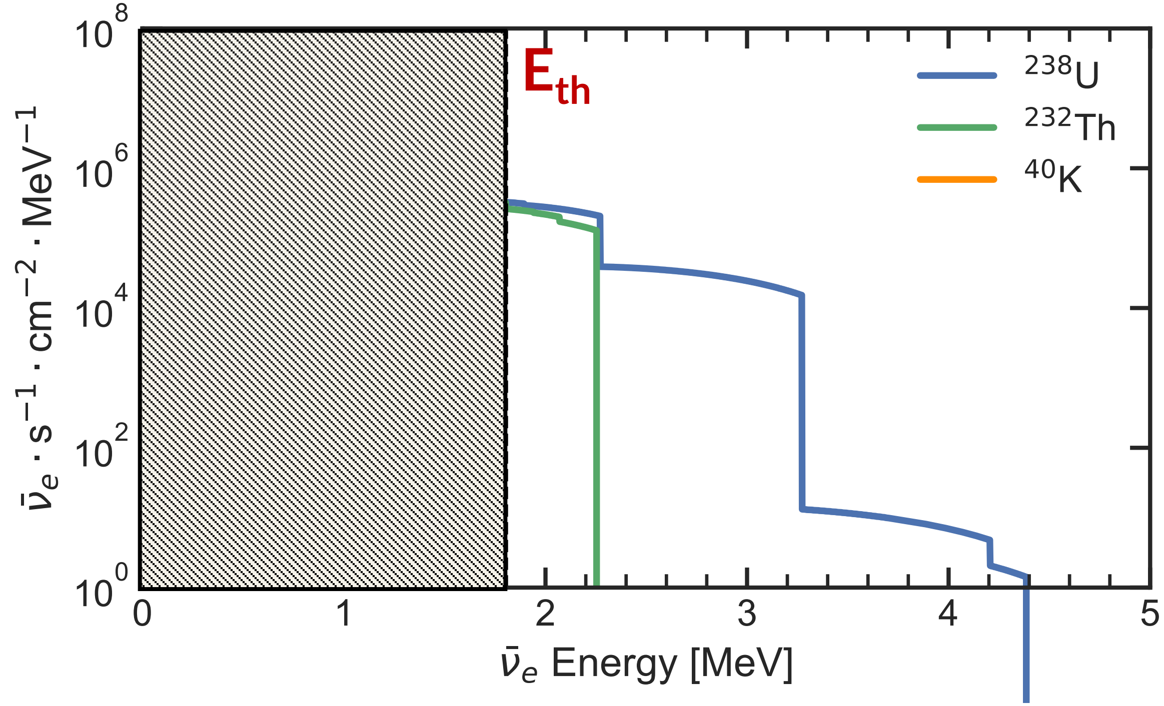


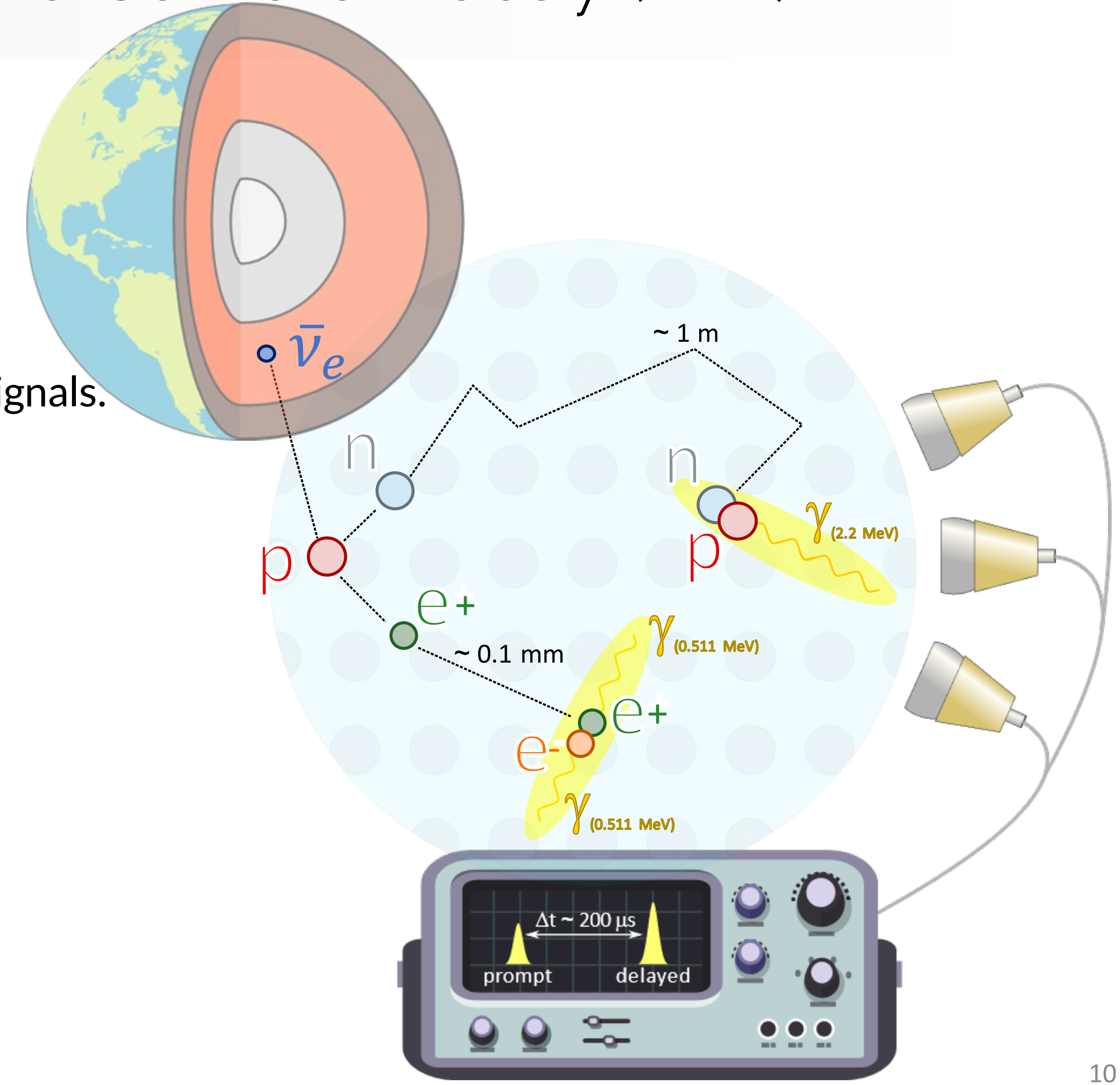
Detecting geoneutrinos: Inverse Beta Decay (IBD)

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

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

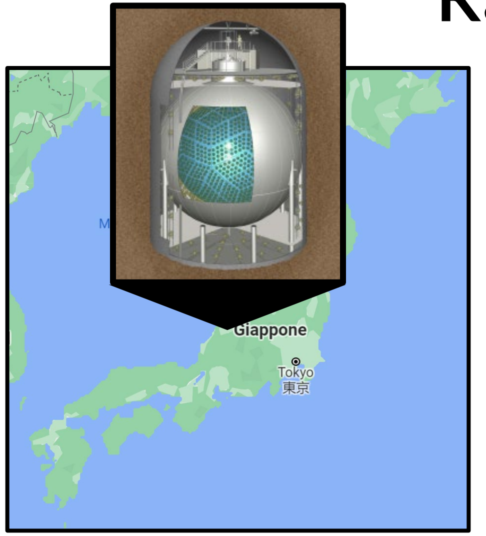
Detection requires the coincidence of 2 delayed light signals.
It does not permit to observe ^{40}K-$\bar{\nu}_e$

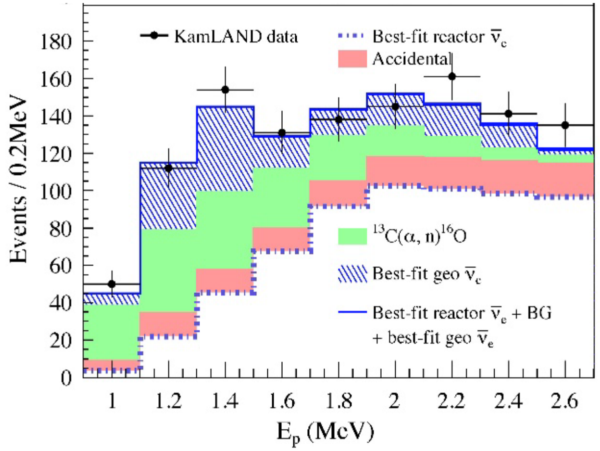




Borexino and KamLAND geoneutrino results

KamLAND



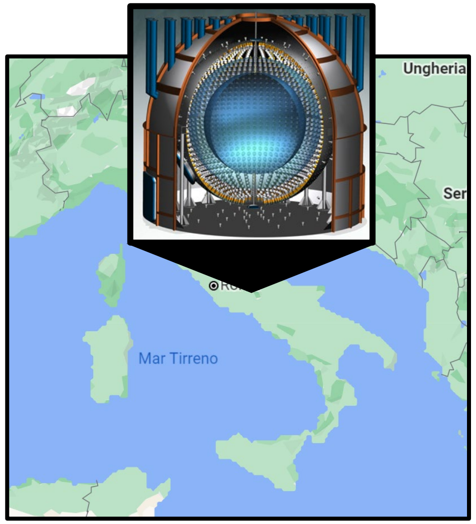


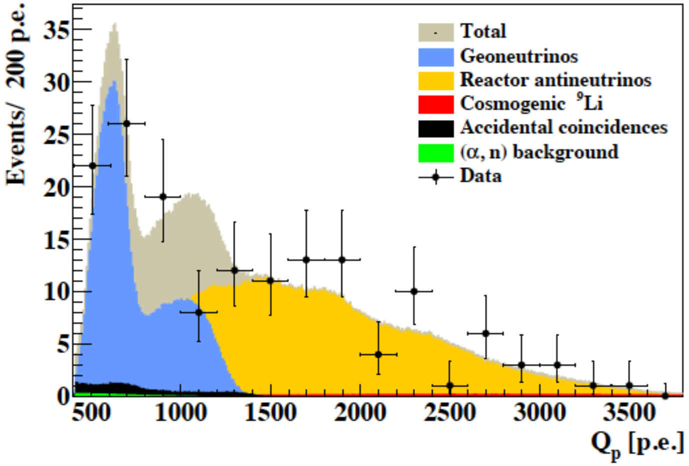
KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17” PMTs and 554 20” PMTs

Data-taking: 2002-2019*			
	U	**Th**	**U+Th**
Events	$138.0^{+22.3}_{-20.5}$	$34.1^{+5.4}_{-5.1}$	$168.8^{+26.3}_{-26.5}$
Signal [TNU]	$26.1^{+4.2}_{-3.9}$	$6.6^{+1.1}_{-1.0}$	$\mathbf{32.1^{+5.0}_{-5.0}}$

*new release 11th August 2022

Borexino





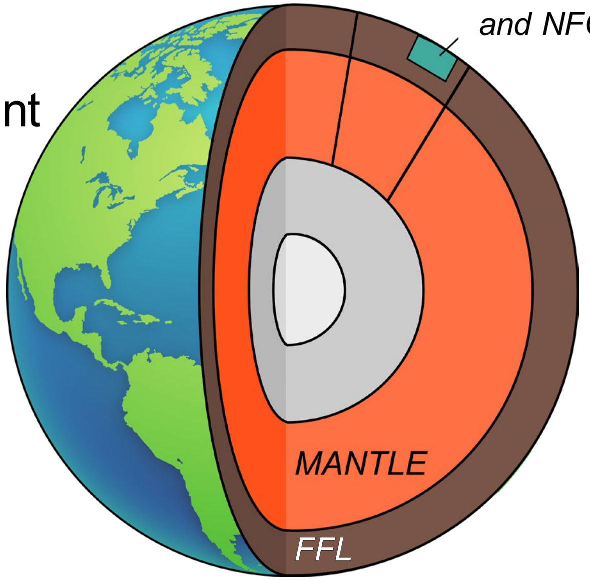
Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8” PMTs.

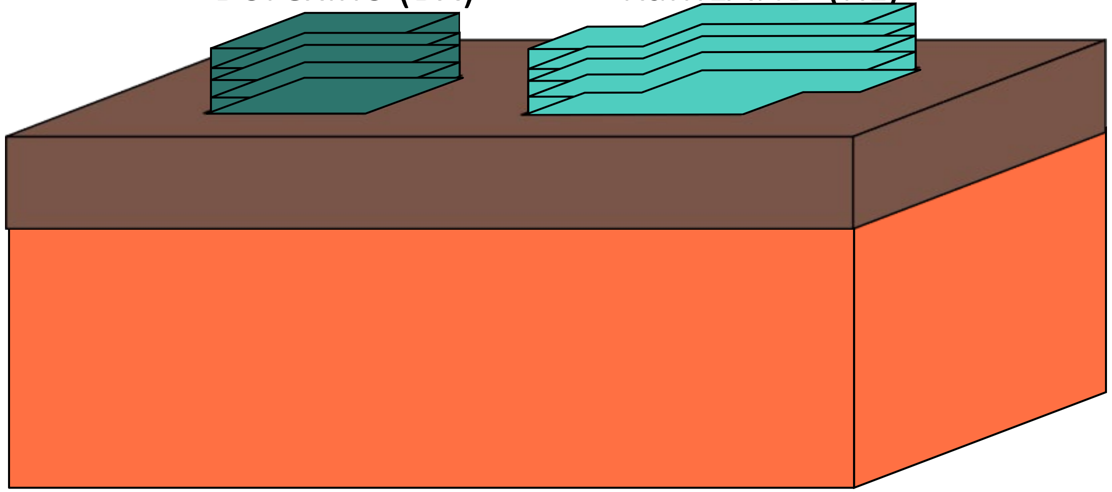
Data-taking: 2007-2019			
	U	**Th**	**U+Th**
Events	$41.1^{+7.5}_{-7.1}$	$11.5^{+2.2}_{-1.9}$	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$36.3^{+6.7}_{-6.2}$	$10.5^{+2.1}_{-1.7}$	$\mathbf{47.0^{+8.6}_{-8.1}}$

Extracting the mantle signal: the rationale

U and Th distributed in the **Near Field Crust (NFC)** gives a significant contribution to the signal (~ 50%).

The **Far Field Lithosphere (FFL)** is the superficial portion of the Earth including the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM).





Different for different detectors **Common to detectors**

$$S^i_{Exp}(U+Th) = \boxed{S^i_{NFC}(U+Th) + S^i_{FFC}(U+Th) + S^i_{CLM}(U+Th)} + \boxed{S^i_{M}(U+Th)}$$

Extracting the mantle signal: the rationale

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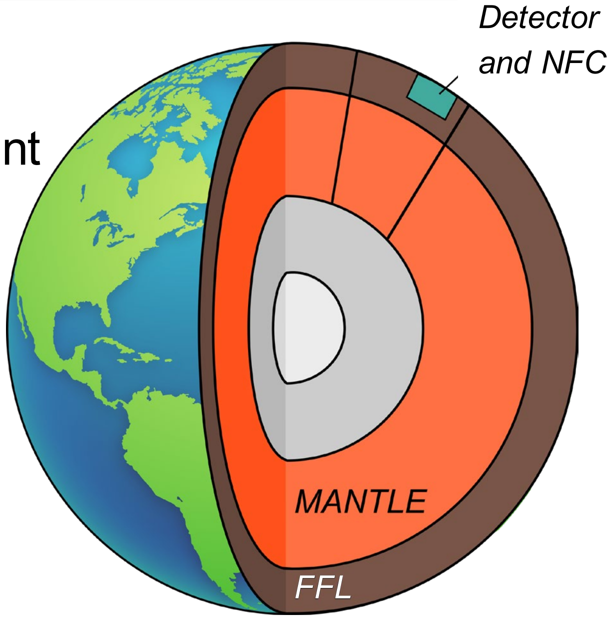
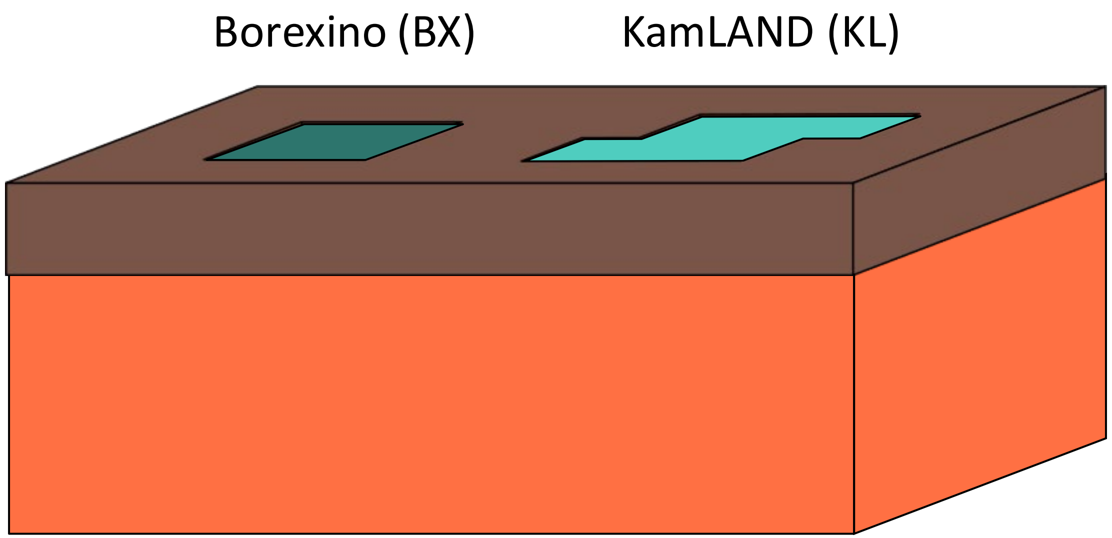




$$S^i_{Exp}(U+Th) - S^i_{NFC}(U+Th) - S^i_{FFC}(U+Th) - S^i_{CLM}(U+Th) = S^i_{M}(U+Th)$$

The geological models need to comply with the following constraints:

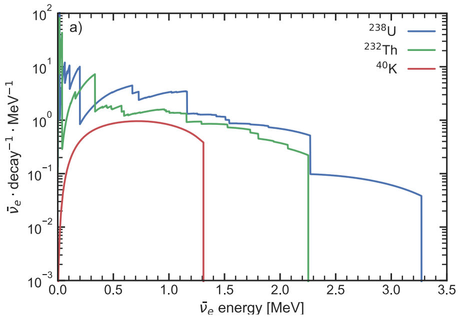
- **FFC** model needs to be the same for each *i*-th detector for avoiding biases.
- **NFC** should be built with geochemical and/or geophysical information typical of the local regions.
- **NFC** must be geometrically complementary to the FFC.

Modeling the geoneutrino signal

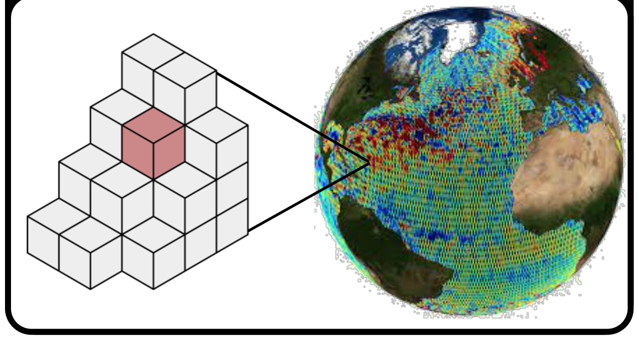
Production | **Propagation** | **Detection**

$$S_{i,n} \propto Sp_i(E) \otimes \Phi_i(m,\vec{r}) \otimes P_{ee}(E,\vec{r}) \otimes \sigma_n(E) \otimes N_{target,n} \otimes T$$

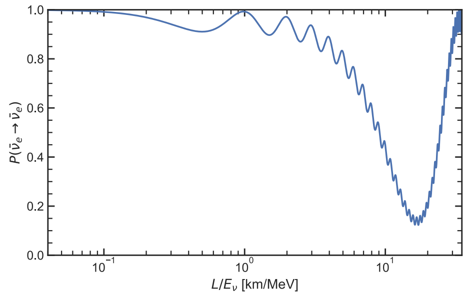
Isotopic β⁻ spectra



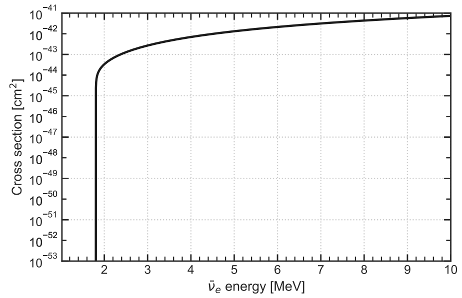
3D Earth model



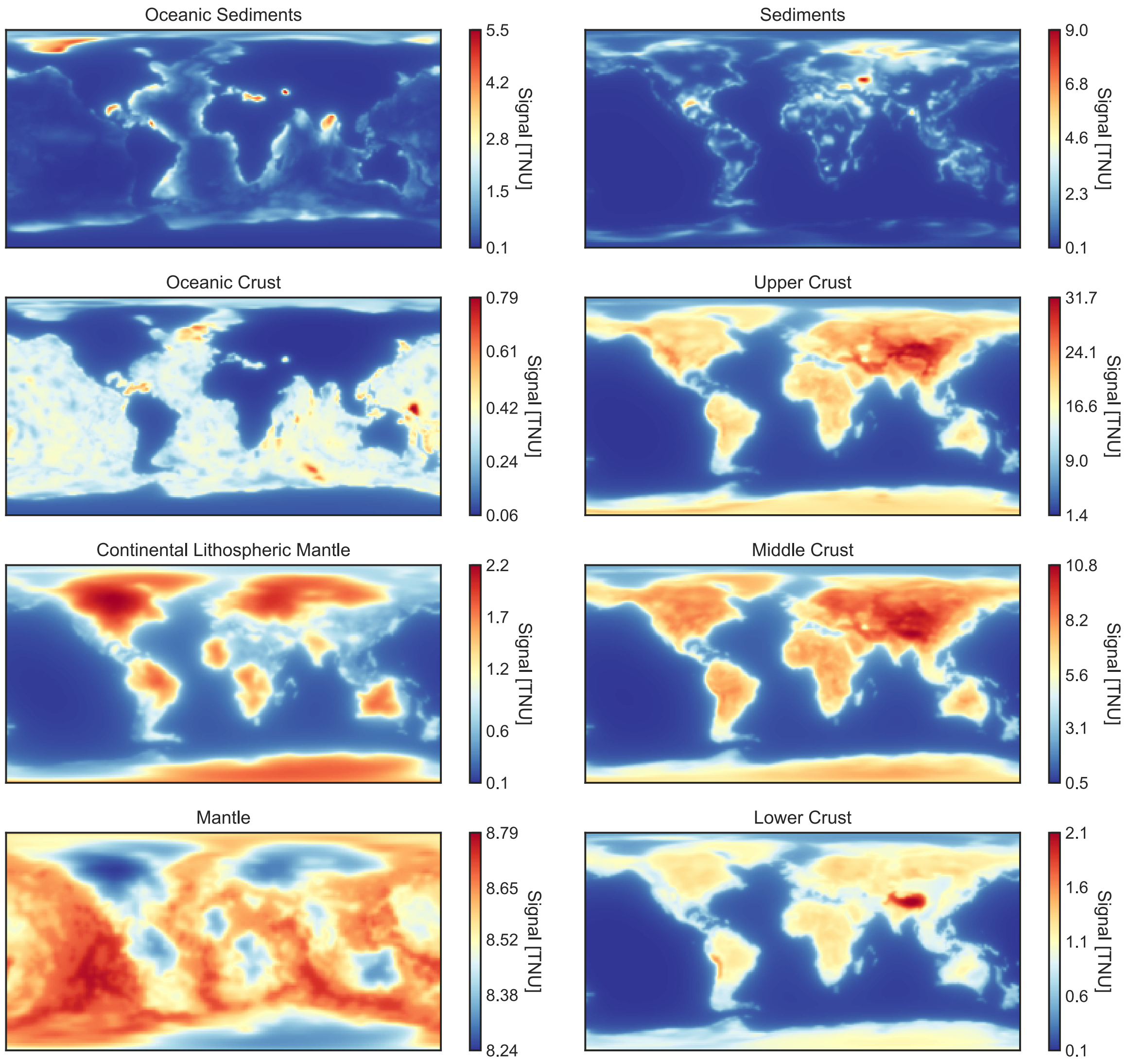
Survival probability

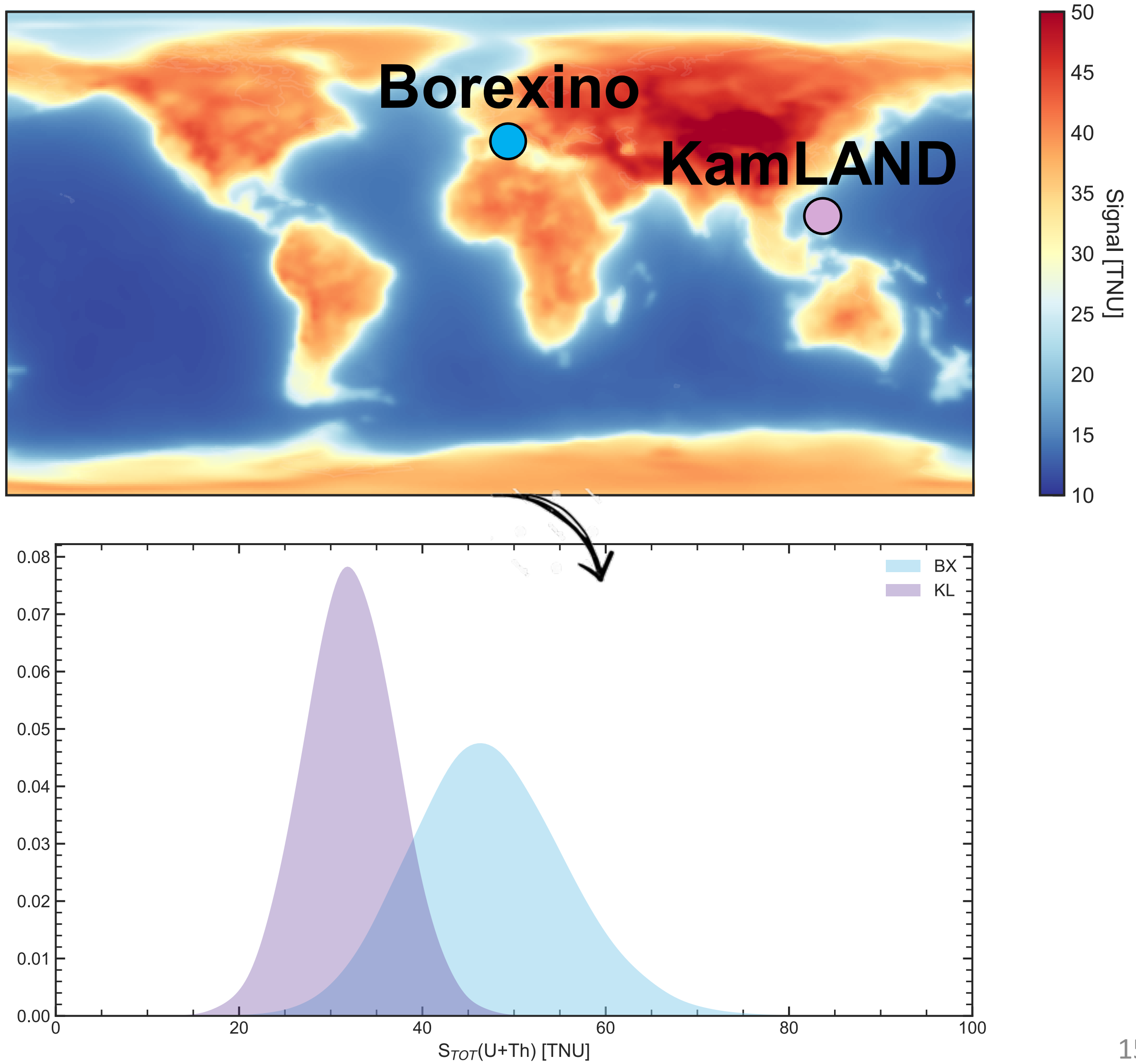


IBD cross section



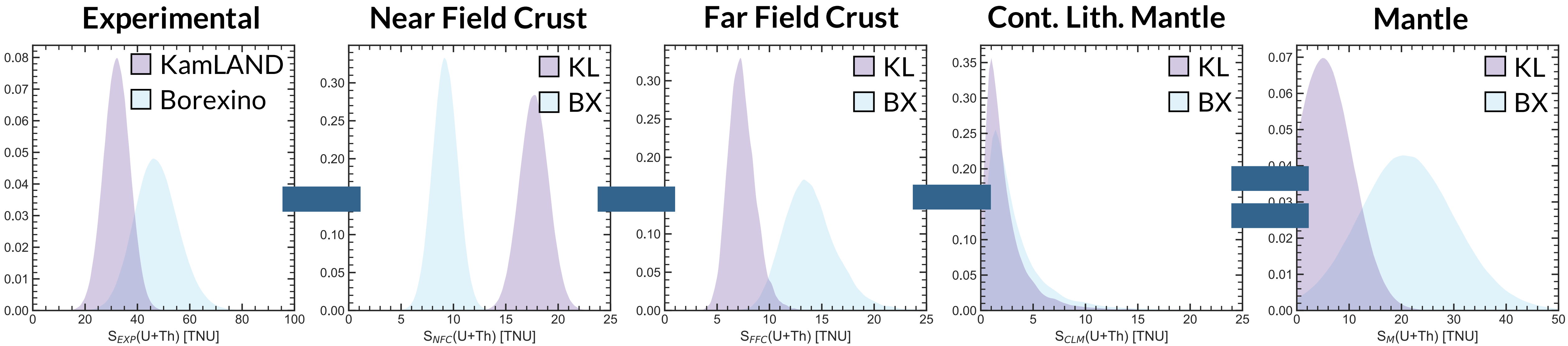
Modeling the geoneutrino signal for different reservoirs





Extracting the mantle signal

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	$13.7^{+2.8}_{-2.3}$	$2.2^{+3.1}_{-1.3}$	$\mathbf{20.8^{+9.4}_{-9.2}}$

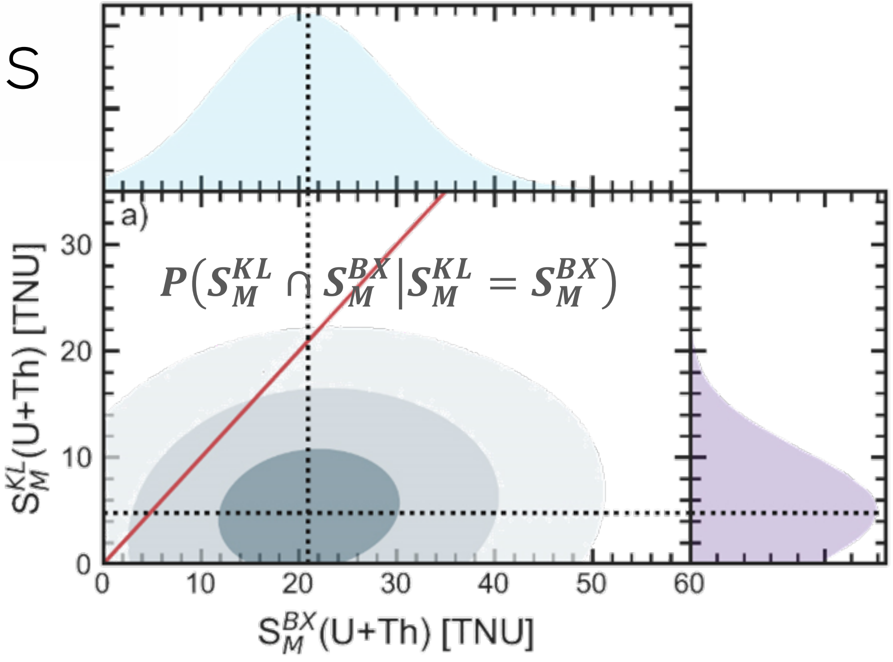
Combining KamLAND and Borexino results

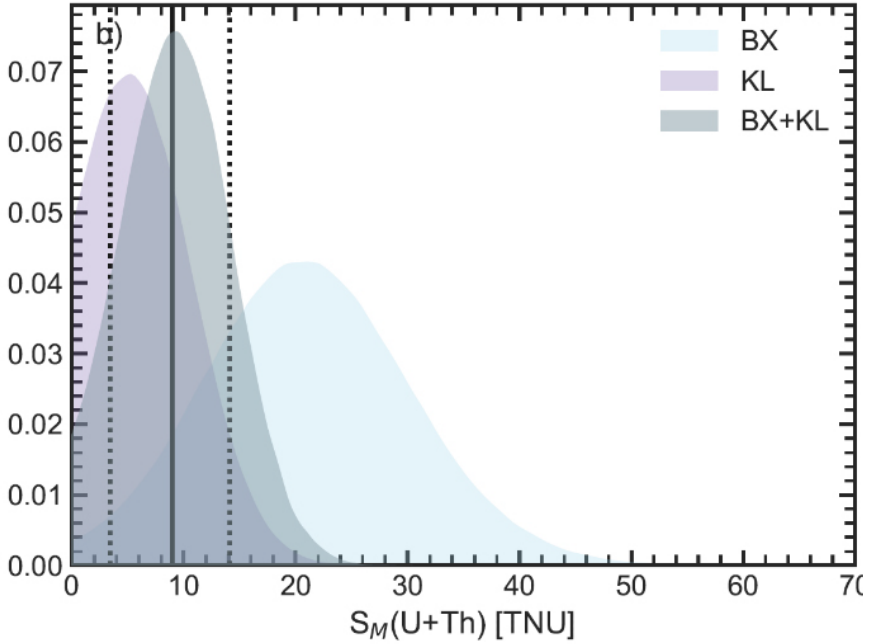
The joint distribution $S_M^{KL+BX}(U+Th)$ can be inferred from the mantle signal's PDFs of the two experiments by requiring that:

$$S_M^{KL}(U+Th) = S_M^{BX}(U+Th)$$

$4.8^{+5.6}_{-5.9}$ $\quad\quad$ $20.8^{+9.4}_{-9.2}$

$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ TNU$$





Where correlations need to be properly accounted for:

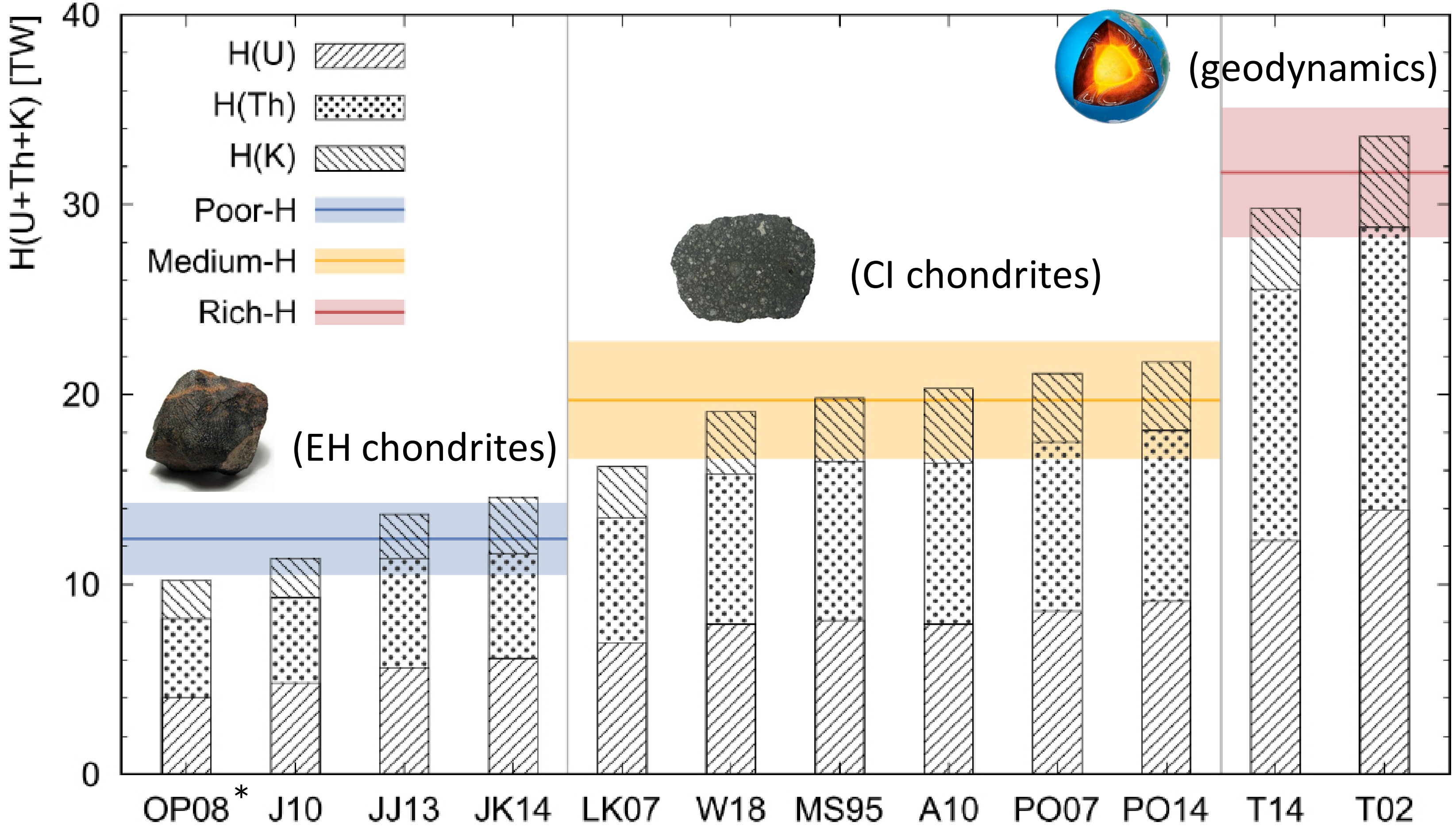
» $S_{FFC}^{KL}(U+Th) \propto S_{FFC}^{BX}(U+Th)$

» $S_{CLM}^{KL}(U+Th) \propto S_{CLM}^{BX}(U+Th)$

are fully correlated, since they are derived from the same geophysical and geochemical model

*AAYY – Author year acronym

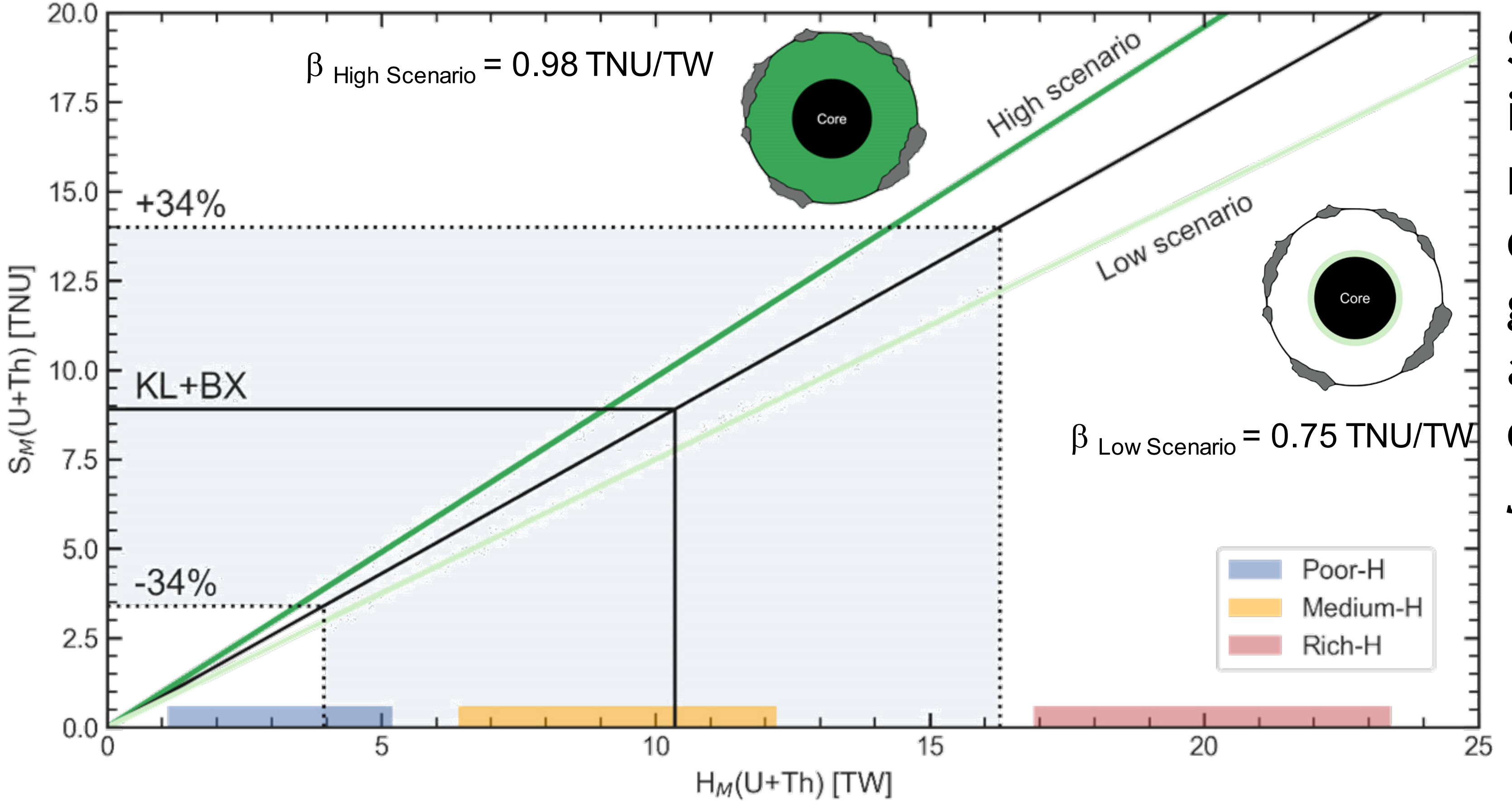
Bulk Silicate Earth Models



	Poor-H	Medium-H	Rich-H
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4

- The **BSE** describes the primordial, non-metallic Earth condition that followed planetary accretion and core separation, prior to its differentiation into a mantle and lithosphere.
- Different author proposed a **range of BSE models** based on different constraints (carbonaceous chondrites, enstatite chondrites, undepleted mantle, etc.)

Mantle radiogenic power from U and Th



Since $\boldsymbol{H_{LS}(U+Th) = 8.1^{+1.9}_{-1.6}}$ **TW is independent from the BSE model**, the discrimination capability of the combined geoneutrino measurement among the different BSE models can be studied in the space $S_M(U+Th)$ vs $H_M(U+Th)$:

$$\boldsymbol{S_M(U+Th) = \beta \cdot H_M(U+Th)}$$

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

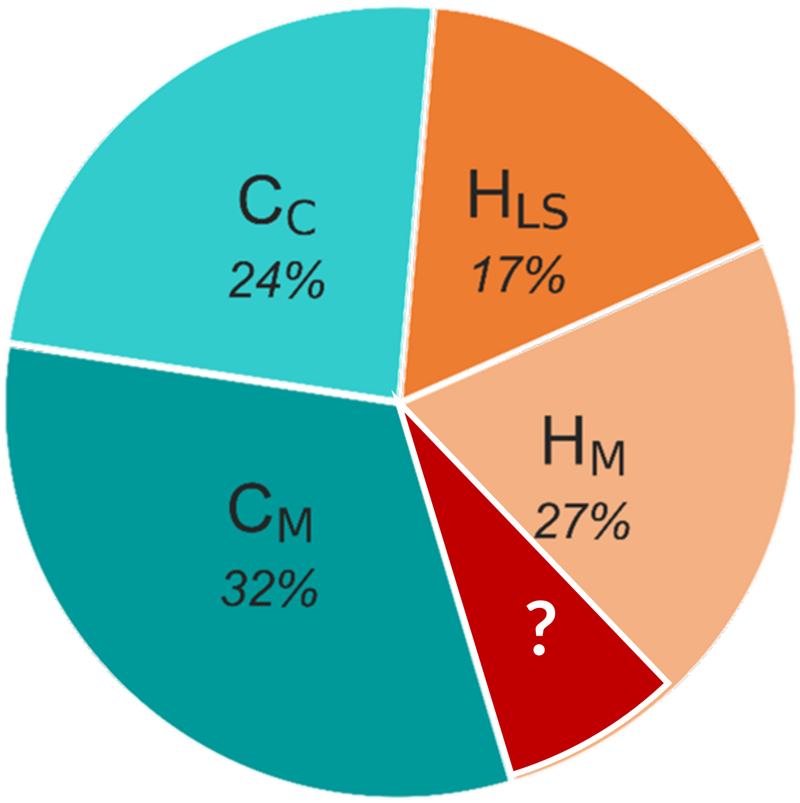
Understanding the Earth's heat budget with geoneutrinos

???

???

Assuming a K contribution to the radiogenic heat of 17% from geochemical arguments, the combined geoneutrino analysis of **KL and BX** results **constrains**:

	Expected	**Combined KL + BX**
Q [TW]	47 ± 2	
H_{LS} [TW]	$8.1^{+1.9}_{-1.6}$	
H_M [TW]	$11.3^{+3.3}_{-3.4}$	$12.5^{+7.1}_{-7.7}$
H [TW]	$\mathbf{19.3 \pm 2.9}$	$\mathbf{20.8^{+7.3}_{-7.9}}$
C [TW]	**27 ± 4**	$\mathbf{26 \pm 8}$



Geoneutrinos and geoscience: an intriguing joint-venture
Bellini et al.
Riv. Nuovo Cim. 45, 1–105 (2022).

^{40}K in Earth Science

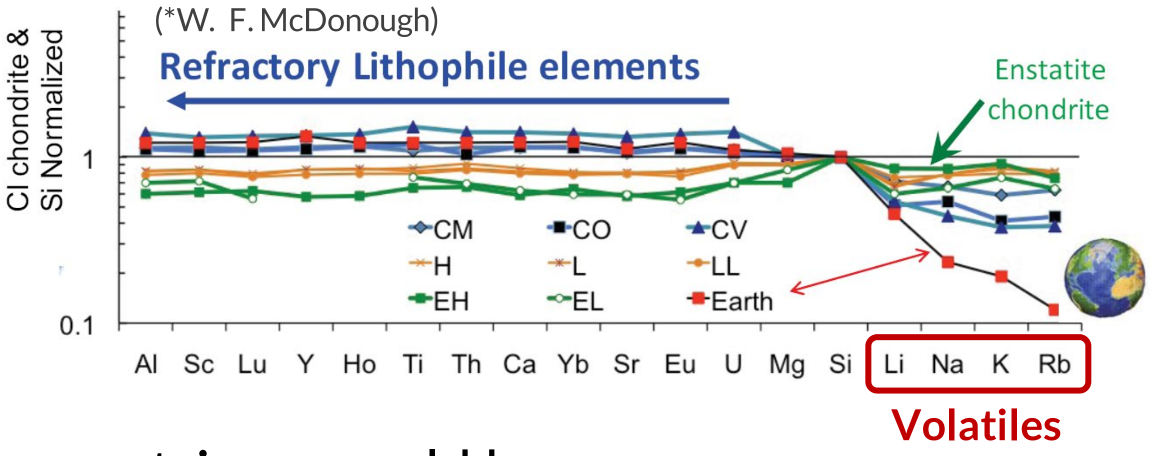
1. Our planet seems to contain **10%-30% K respect to** the enstatitic (EH) and carbonaceous (CI) **chondrites** meteorites, respectively.


(EH)


(CI)

2. Two theories on the fate of the mysterious "**missing K**" include **loss to space** during accretion or **segregation into the core**, but no experimental evidence has been able to confirm or rule out any of the hypotheses, yet.

3. Being moderately volatile, K is representative of the depletion of **volatile elements** on Earth. Volatiles' abundances are required to understand deep H_2O cycle and ^{40}K-^{40}Ar system in the Earth.



A direct measurement of the still undetected ^{40}K geoneutrinos would be a breakthrough in the comprehension of the Earth's origin and composition.

Possible detection channels for ^{40}K (anti)neutrinos

Inverse Beta Decay (IBD) $\bar{\nu}_e + {}_{Z+1}^{A}Y \rightarrow {}_{Z}^{A}X + e^{+}$

The currently employed reaction has an energy threshold at 1.8 MeV. Its current detection relies on a double coincidence rejecting most backgrounds.

Elastic Scattering on electrons (ES) $\bar{\nu}_X + e^{-} \rightarrow \bar{\nu}_X + e^{-}$

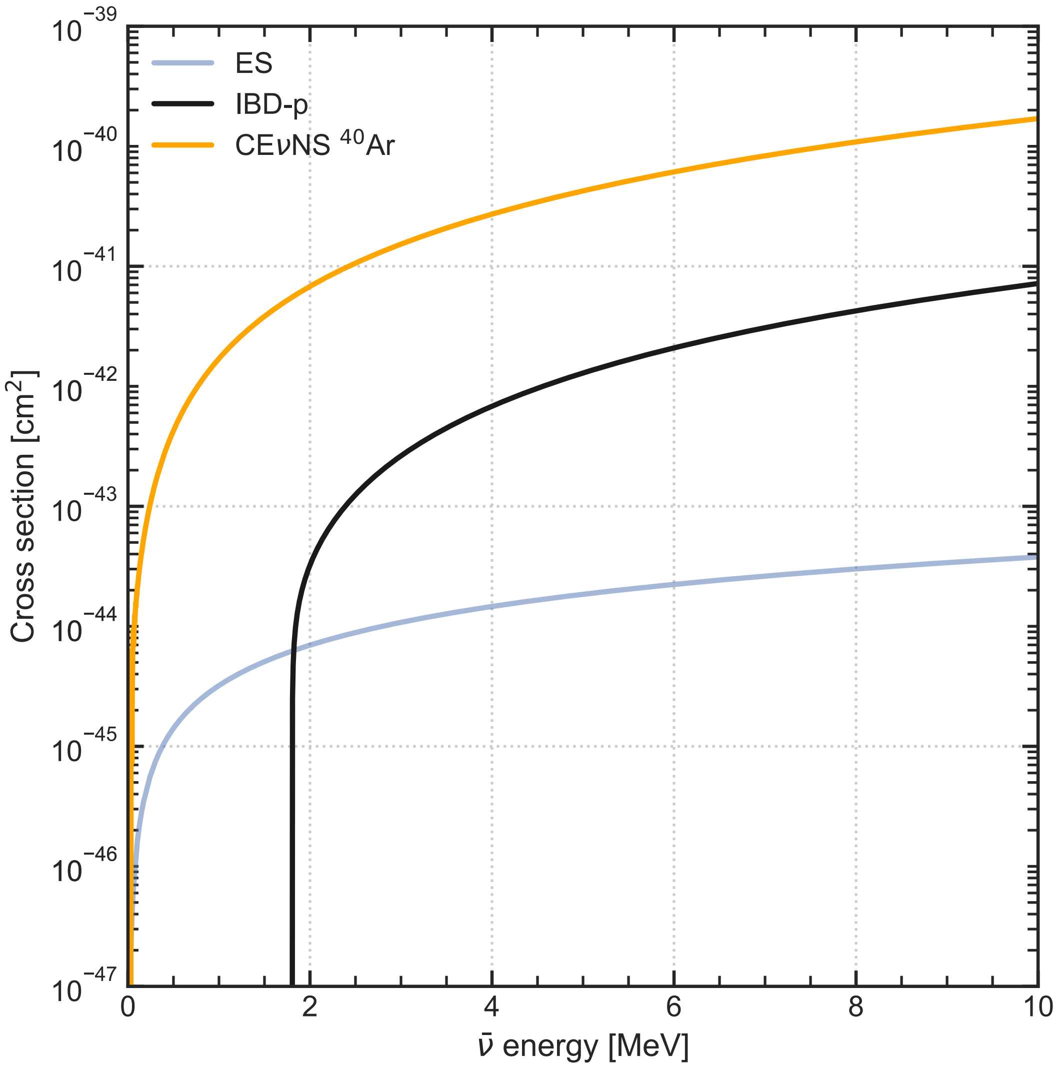
It has no energy threshold (apart from our capability to detect electron recoil). It does not allow to distinguish flavors, or to separate neutrinos from antineutrinos (in the absence of directional information).

Coherent neutrino-nucleus scattering (CEvNS)

$$\bar{\nu}_X + {}_{Z}^{A}N \rightarrow \bar{\nu}_X + {}_{Z}^{A}N$$

It has no energy threshold (apart from our capability to detect nuclear recoil… which is almost always too small). It does not allow to distinguish flavors, or to separate neutrinos from antineutrinos

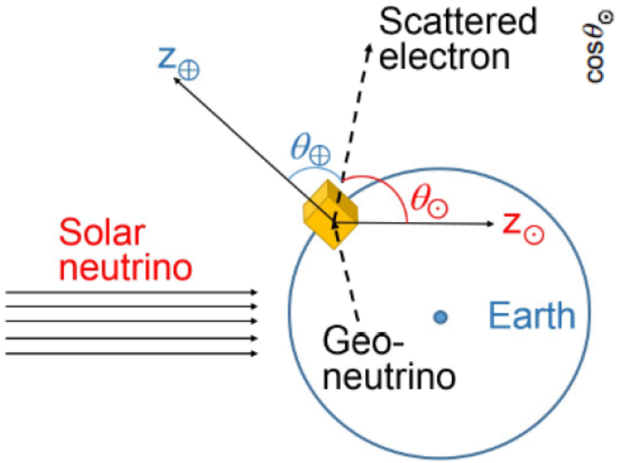
Geo-$\bar{\nu}_e$ ($\Phi \backsim 10^7$ cm^{-2} s^{-1}) - Solar ν_e ($\Phi \backsim 10^{11}$ cm^{-2} s^{-1})

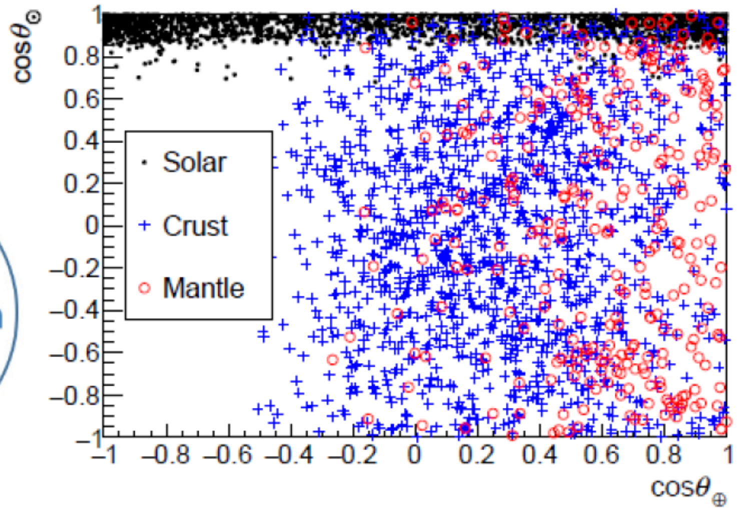


Electron scattering directionality*

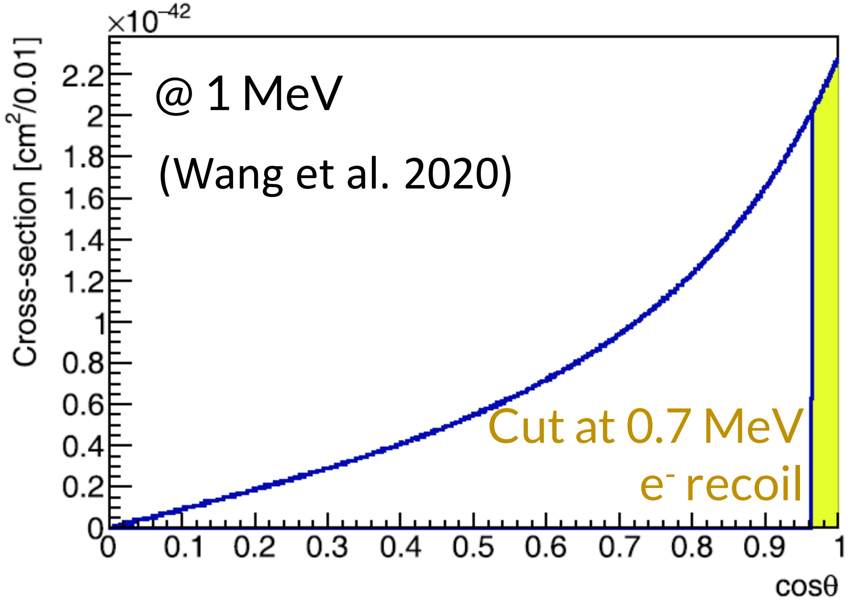
Hunting potassium geoneutrinos with liquid scintillator Cherenkov neutrino detectors.
Wang et al. Chinese Physics C (2020)

Solar neutrinos and terrestrial antineutrinos come from different directions:





- ES interaction retains **information of** incoming antineutrino **direction**.
- Using a slow scintillator and Cherenkov light it could be possible to recover both e⁻ direction and energy.



Without assuming additional backgrounds:

→5σ ^{40}K significance with 10y of data taking and 40 kton.

Main limitation is scintillator density
→ degrades angular resolution
→ gaseous detector? (Leyton et al. 2017)

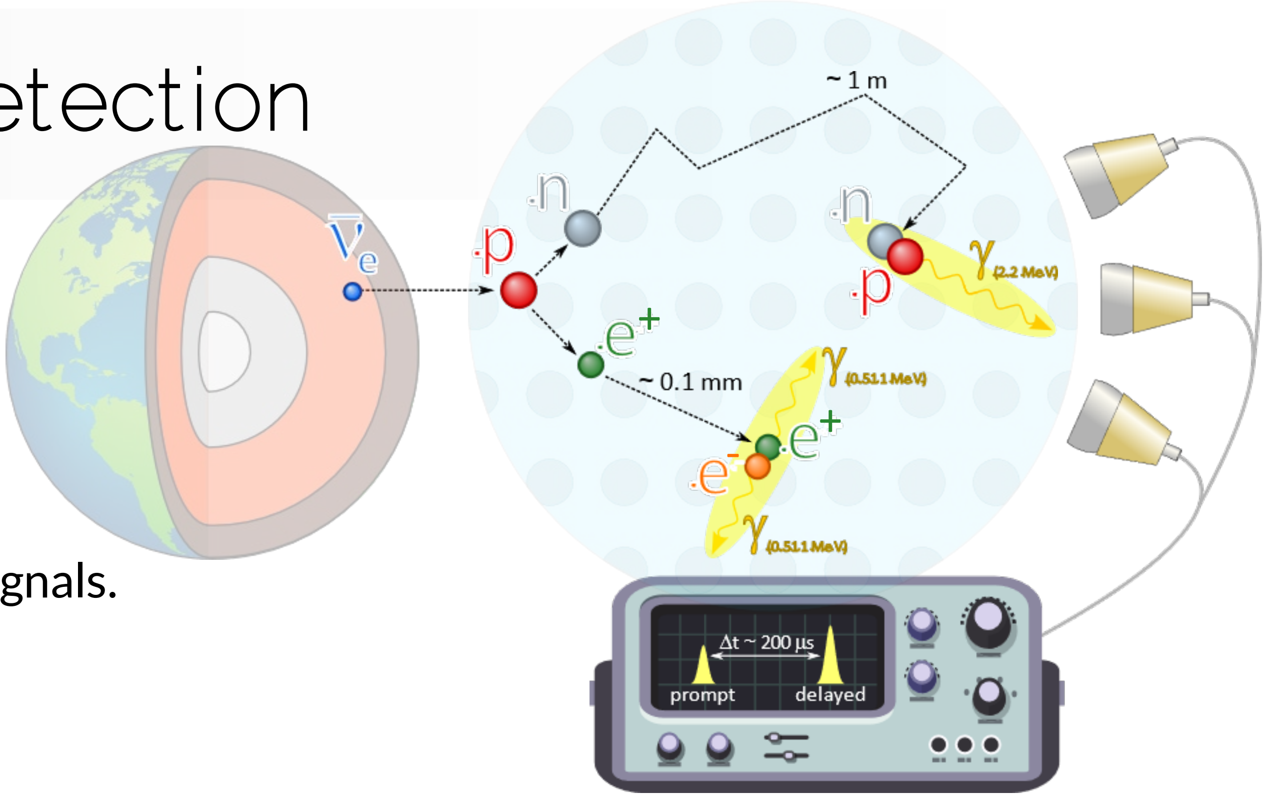
* even IBD retains some directional info, but doesn't permit to observe ^{40}K

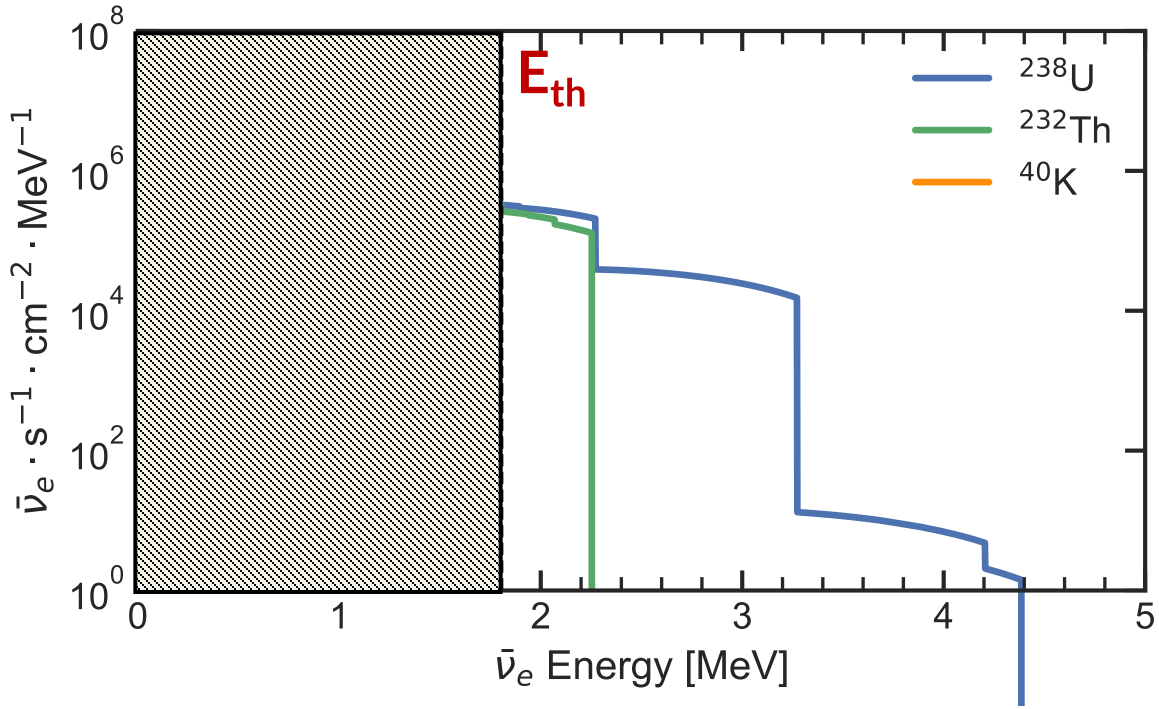
Inverse Beta Decay (IBD) detection

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

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

Detection requires the coincidence of 2 delayed light signals.
It does not permit to observe ^{40}K-$\bar{\nu}_e$





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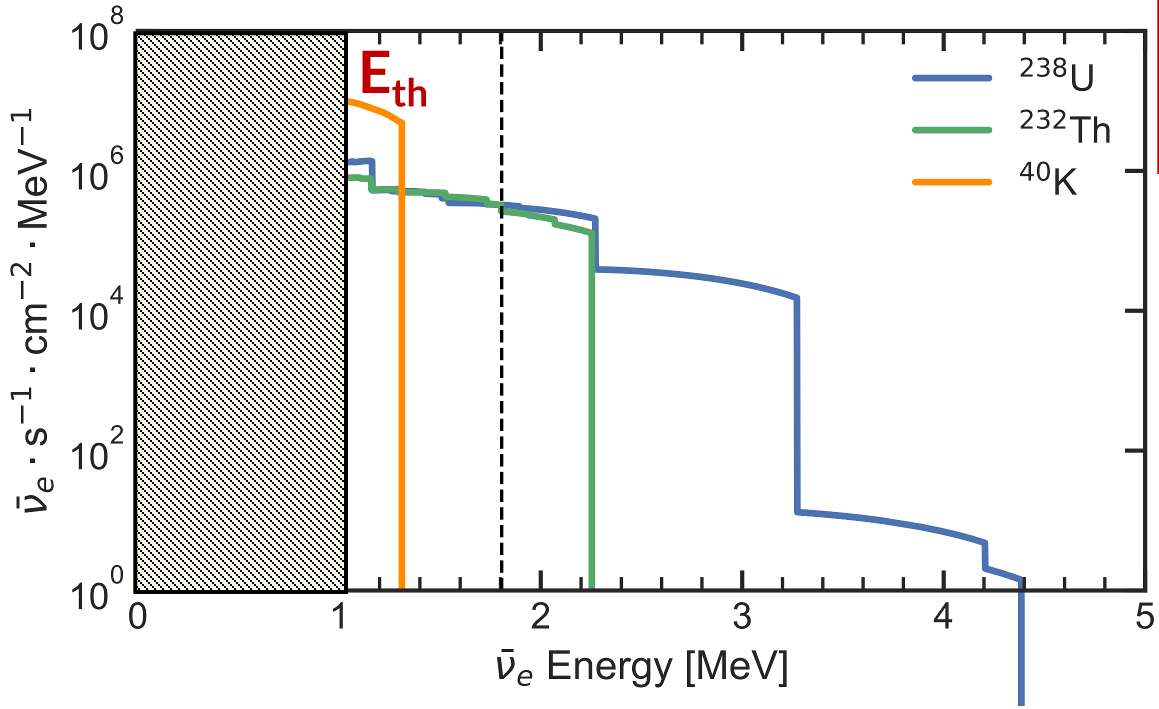

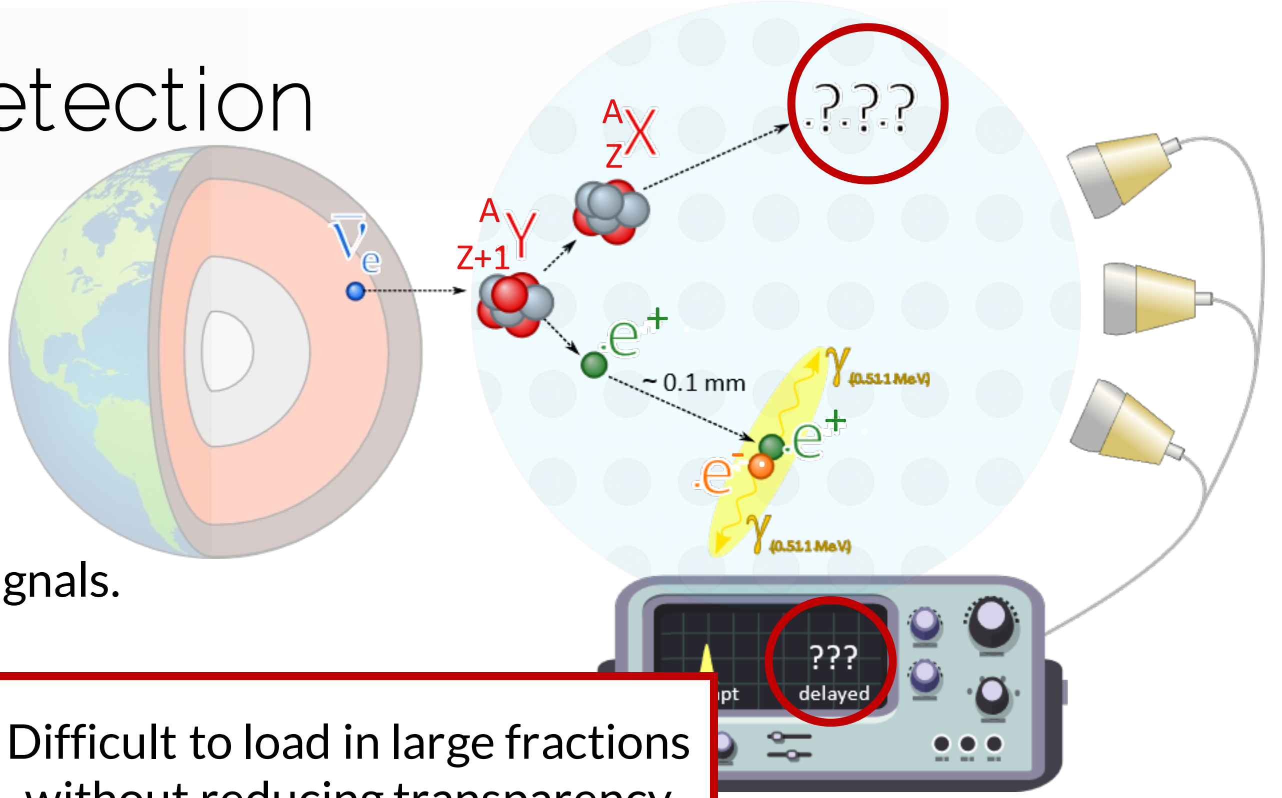

Difficult to load in large fractions without reducing transparency

could use:

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

Impossible to tag in current Liquid Scintillator Detector

We shall require

- E_{th} < *1.3 MeV*
- High cross-se
- High Y natural isotopic abundance

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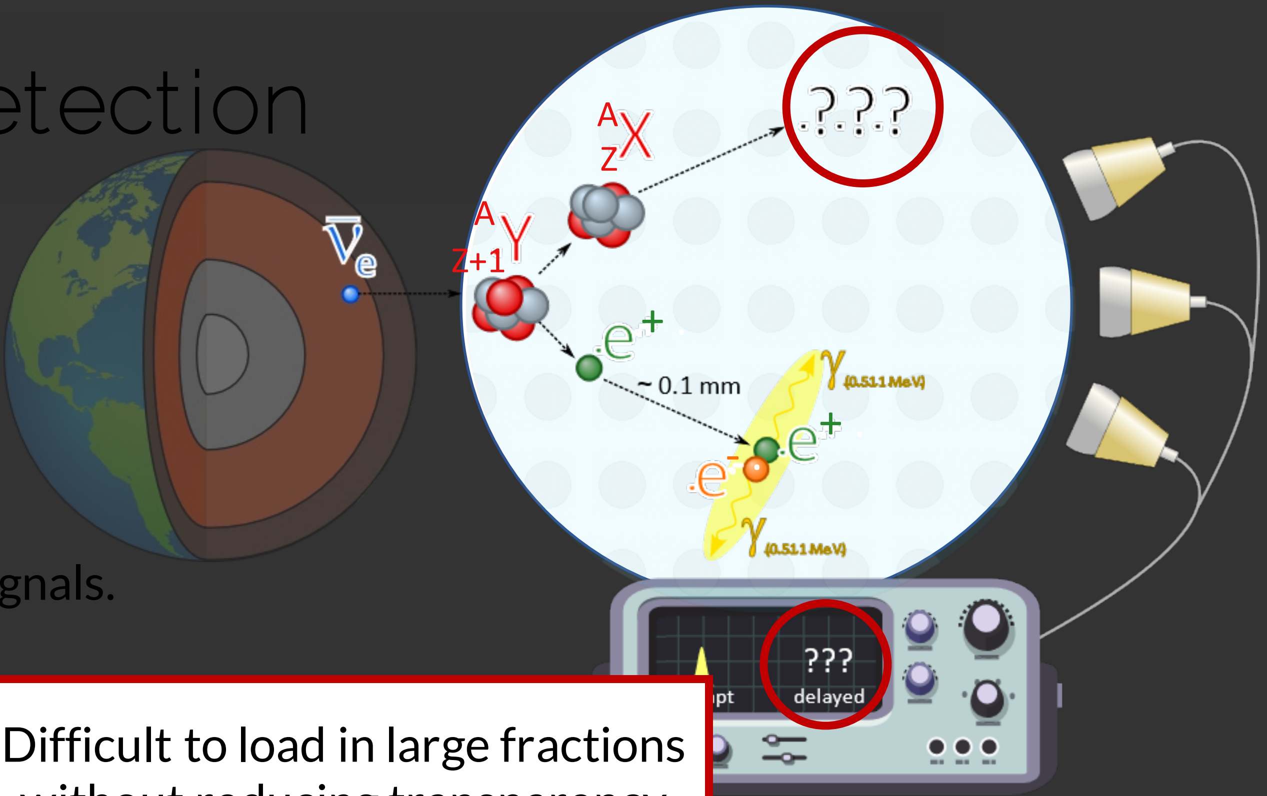

ed light signals.

238U
232Th
40K
0
1
2
3
4
5
$\bar{\nu}_e$ Energy [MeV]

Difficult to load in large fractions without reducing transparency

could use:

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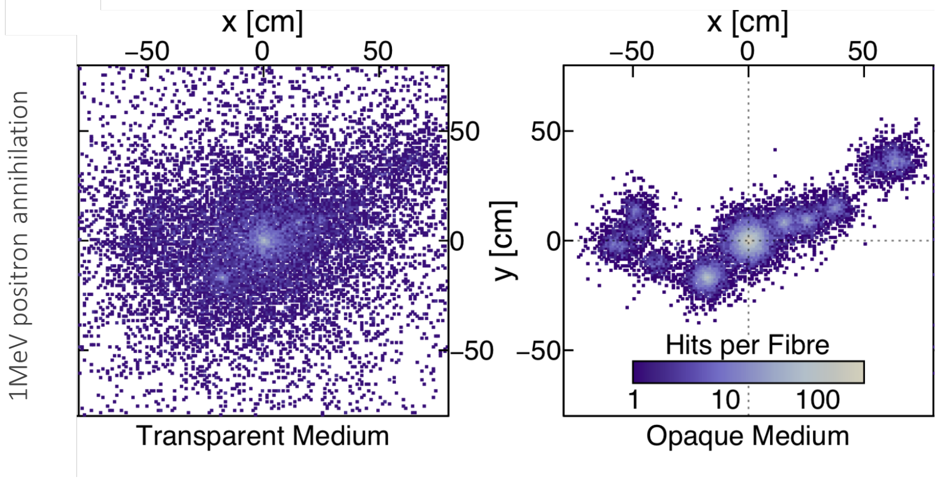
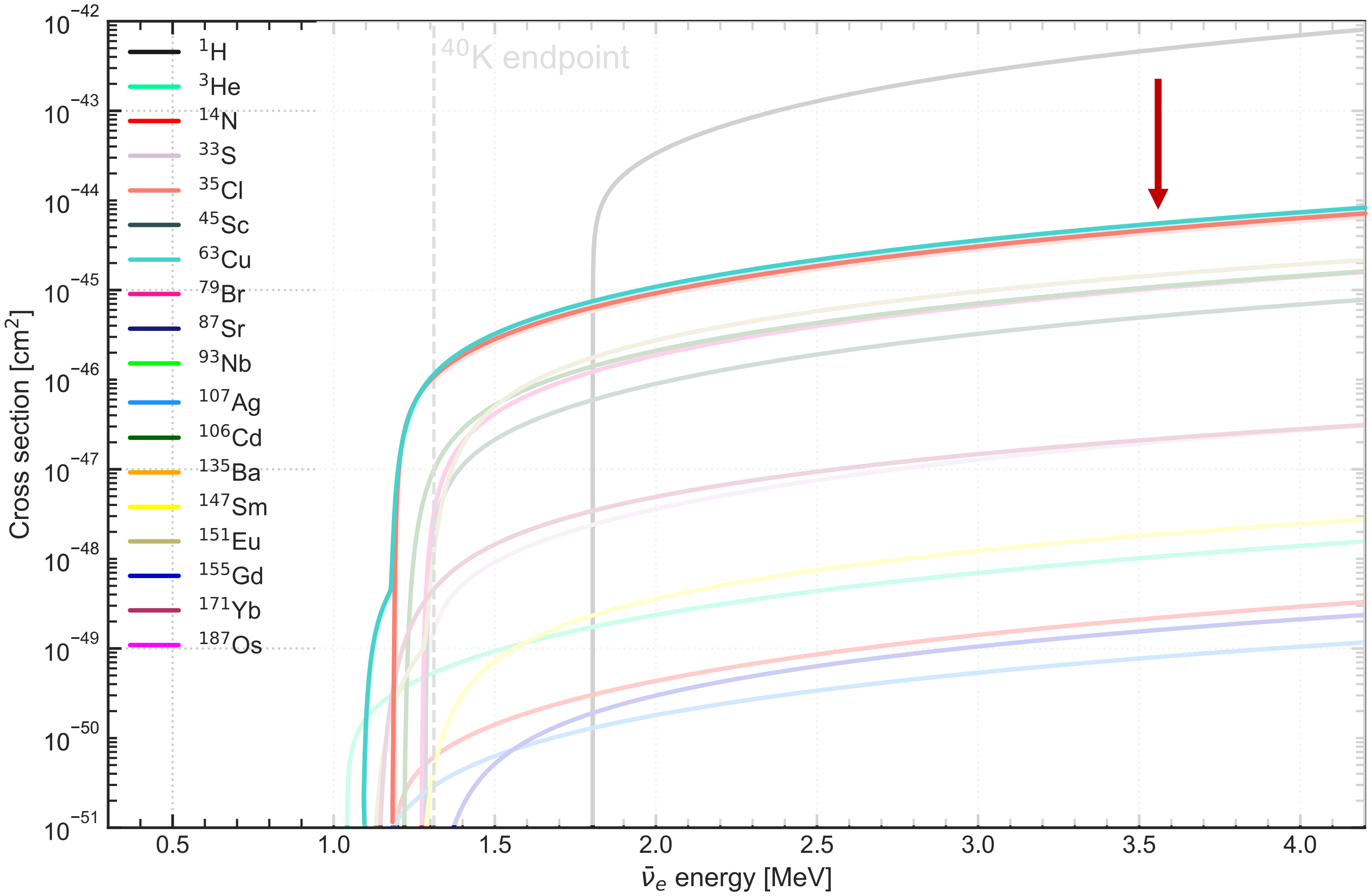


Neutrino physics with an opaque detector.
Cabrera et al.
Commun. Phys. 4, 273 (2021)

IBD cross-sections weighted by isotopic abundance



$$\bar{\nu}_e + {}^{35}\boldsymbol{Cl} \rightarrow {}^{35}S + e^+ - 1.189\text{ MeV}$$
$$\bar{\nu}_e + {}^{63}\boldsymbol{Cu} \rightarrow {}^{63}Ni^* + e^+ - 1.176\text{ MeV}$$

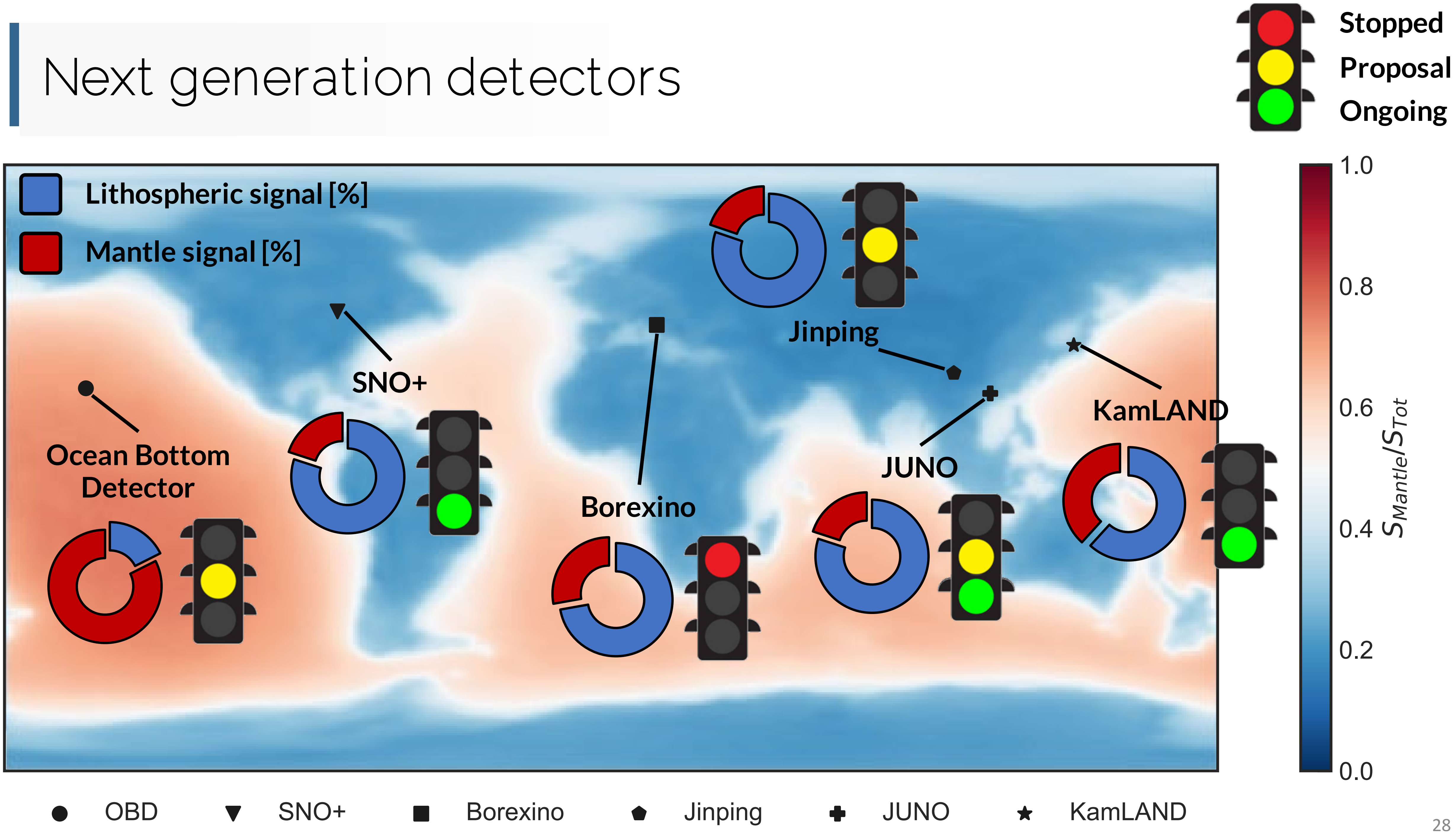
^{35}Cl has both a **low threshold** and a **good weighted cross-section**

^{63}Cu seems to be as promising as ^{35}Cl, and additionally lands to an excited level in the final state (possible double coincidence capability)

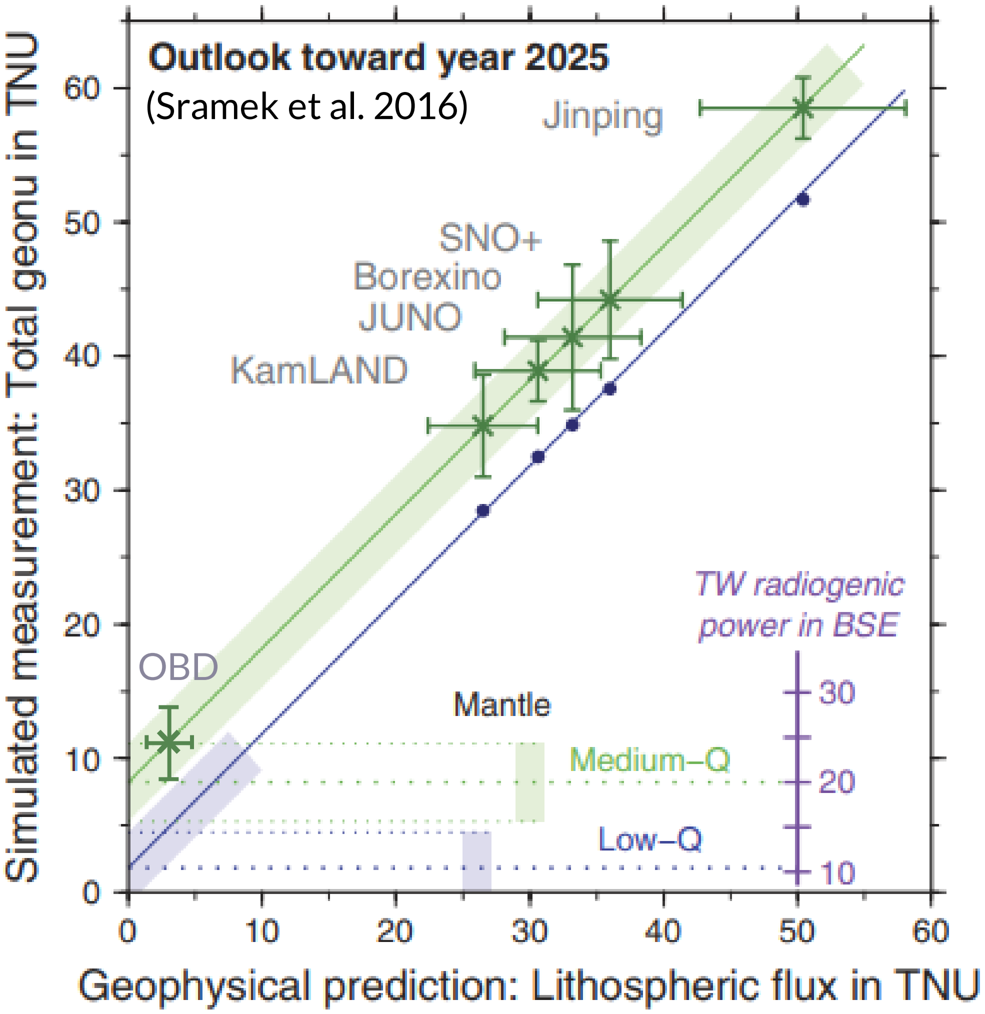
→5σ ^{40}K significance with 10 y of data taking and 240 ktons.

preliminary

Next generation detectors



Multi site detection



In the next decade, several other experiments will join KamLAND and Borexino:

→bigger detectors, lower statistical uncertainties

→different sites, more handles to disentangle mantle signal

An equally large effort is required to geophysical/geochemical modeling:

→lithospheric signal is usually ~80% of the total signal

→mantle signal estimates (and uncertainties) highly dependent on models!

Final remarks

» Geoneutrinos are a promising tool to explore the inaccessible Earth:
  - synergy between experimental physics and geochemical/geophysical modeling
  - comprehension of radiogenic production of our planet
  - handle to discriminate Bulk Silicate Earth models

» ^{40}K-$\bar{\nu}_e$ detection would be a breakthrough in Earth Science:
  - missing piece to heat budget of our planet
  - indicative of volatiles' behavior during Earth formation and evolution
  - new methodologies identified for their detection

» New generation detectors are on their way:
  - more statistics, lower uncertainties, multi site detection

We can glimpse a bright future for the geoneutrino field!

Thank you!