Università degli Studi di Ferrara

Laboratory for Nuclear Technologies Applied to the Environment

Exploiting ^{40}K radioactivity to probe the Earth and the environment

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Tutor:

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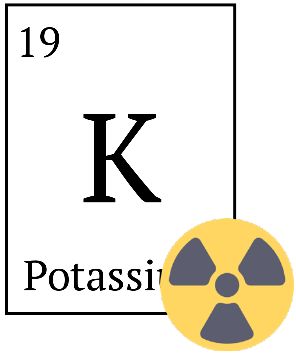
Outline

» The peculiarities of potassium



» Potassium radioactivity as a probe for the Earth and the environment

» The role of geoneutrinos in the deep Earth's investigation

» Understanding Earth's energetics with KamLAND and Borexino

» Geoneutrinos from ^{40}K: a new challenge

Why potassium is important?

Potassium

$^{40}_{19}K$

Necessary to life

K is a necessary element for life. It is a major constituent within all living cells in the animal and plant worlds.

Abundant

K is the 8th most abundant element in Earth's crust (2% of its mass) and occurs in considerable amounts in most soils.

Chemically interesting

K is volatile and lithophile, with siderophile characteristic under extreme conditions. It is interesting to understand Earth's composition.

Radioactive

Among its naturally occurring isotopes, K has ^{40}K, one of the most abundant radioisotopes in nature.

Long-lived

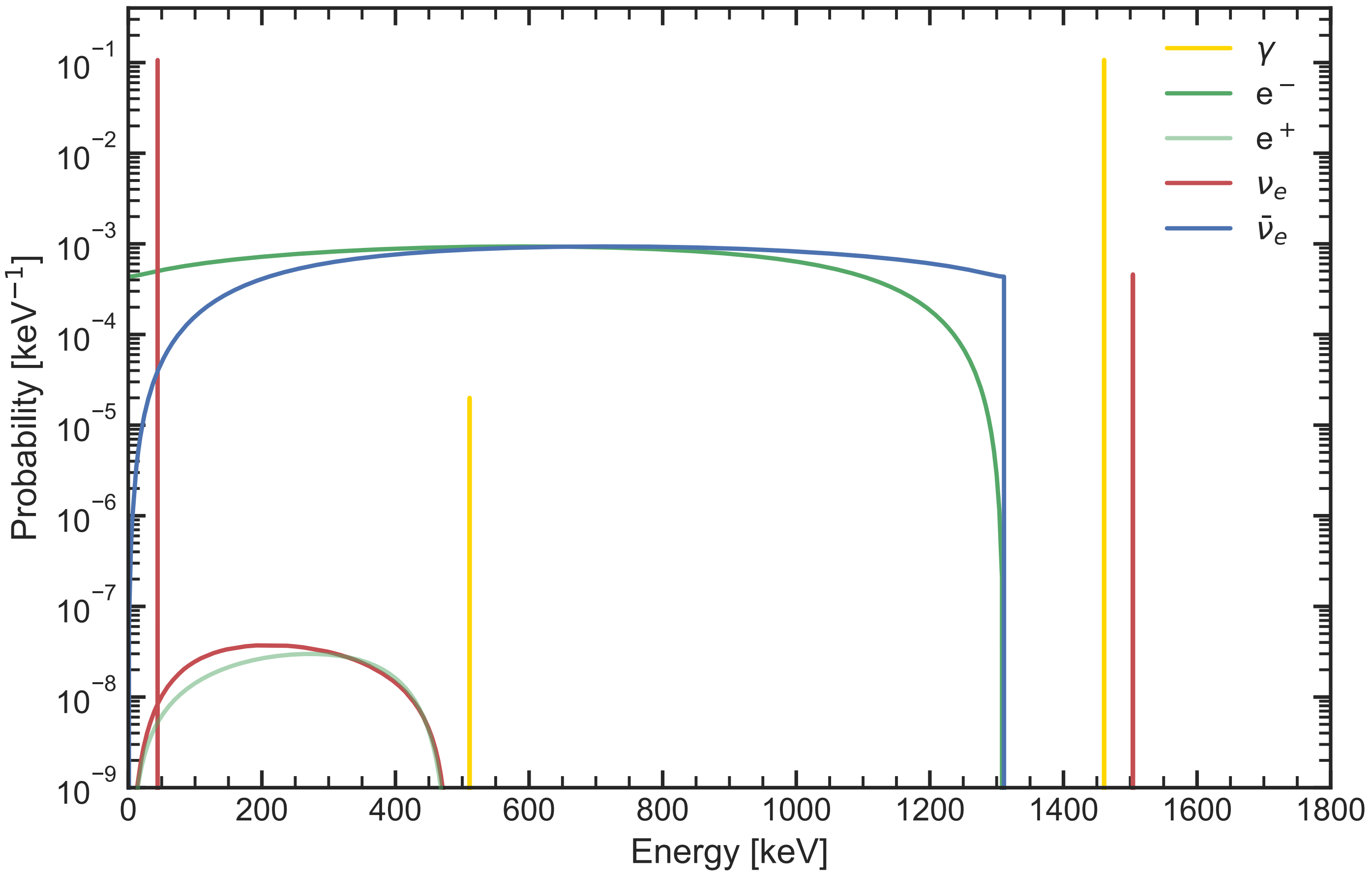
^{40}K has a half-life >1 Gy. It has accompanied our planet during its formation and evolution.

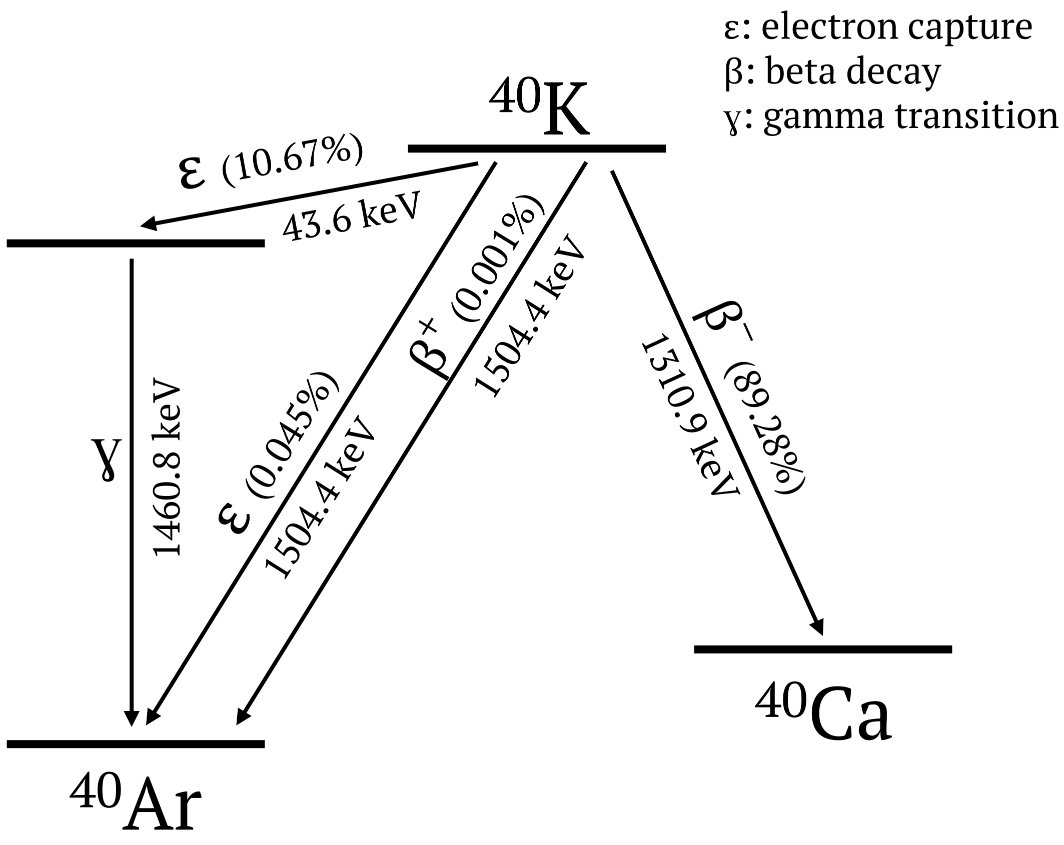
Heat producer

During its decays, ^{40}K releases energy, which heats and provides energy to the inner Earth, contributing to the so called "radiogenic heat".

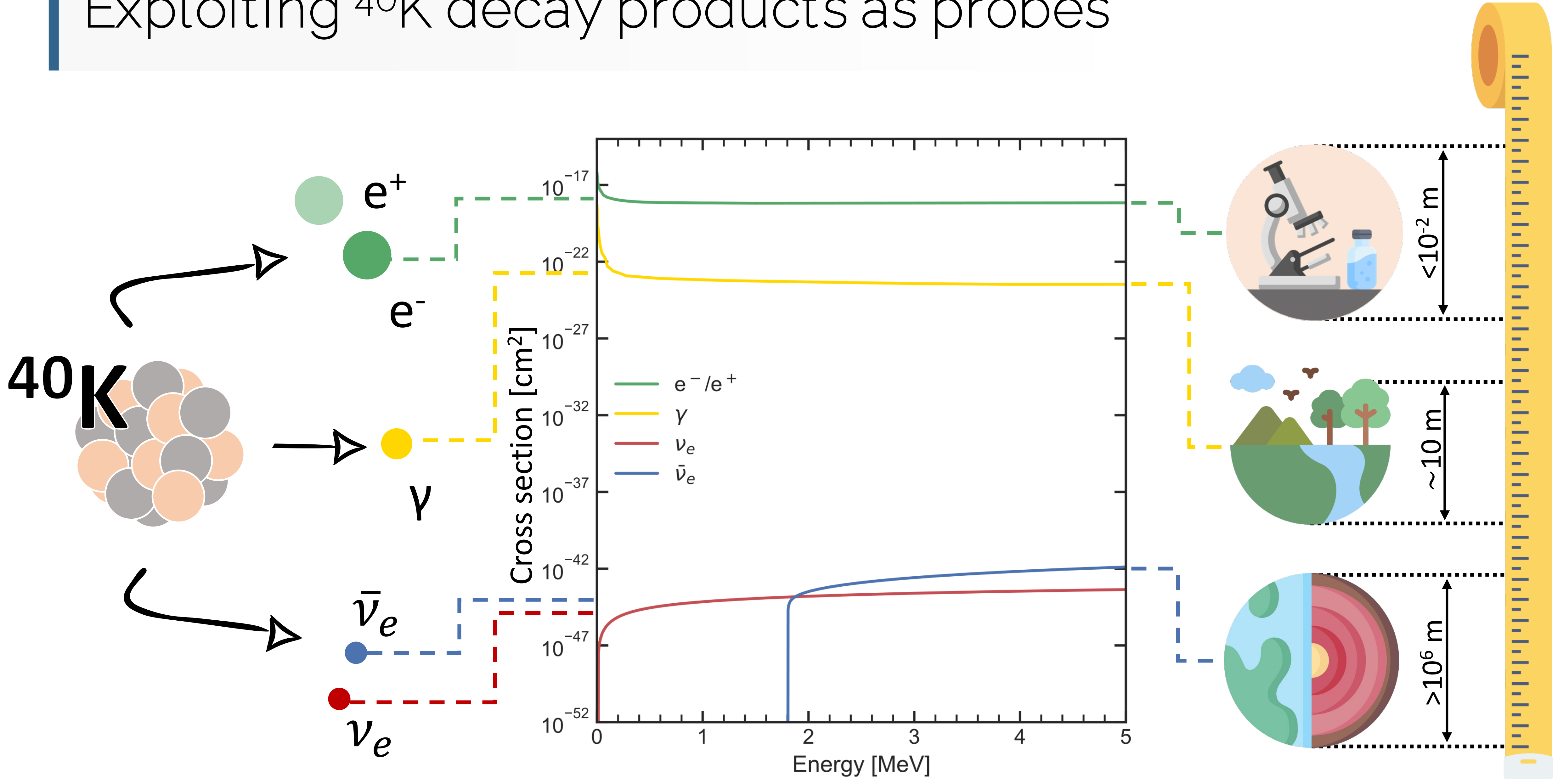
^{40}K decay properties

During its **decays**, **^{40}K** produces electrons (e^-), positrons (e^+), **photons (γ)**, neutrinos (ν_e), and **antineutrinos ($\bar{\nu}_e$)** through electron captures (ε), beta decays (β) and gamma transitions (γ).

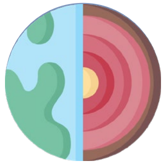




Exploiting ^{40}K decay products as probes



My contribution to the study of the Earth and the environment



Geoneutrinos
(basic science)

Electron antineutrinos originating from the β^- decays of ^{238}U, ^{232}Th and ^{40}K inside our planet are a precious tool for **exploring the inner Earth**.

In my thesis:

» I exploited latest Borexino and KamLAND experimental results (^{238}U and ^{232}Th) to recover information on deep Earth energetics.

» I identified and proposed a novel methodology to enable the detection of the still undetected ^{40}K geoneutrinos.

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

γ spectroscopy
(applied science)

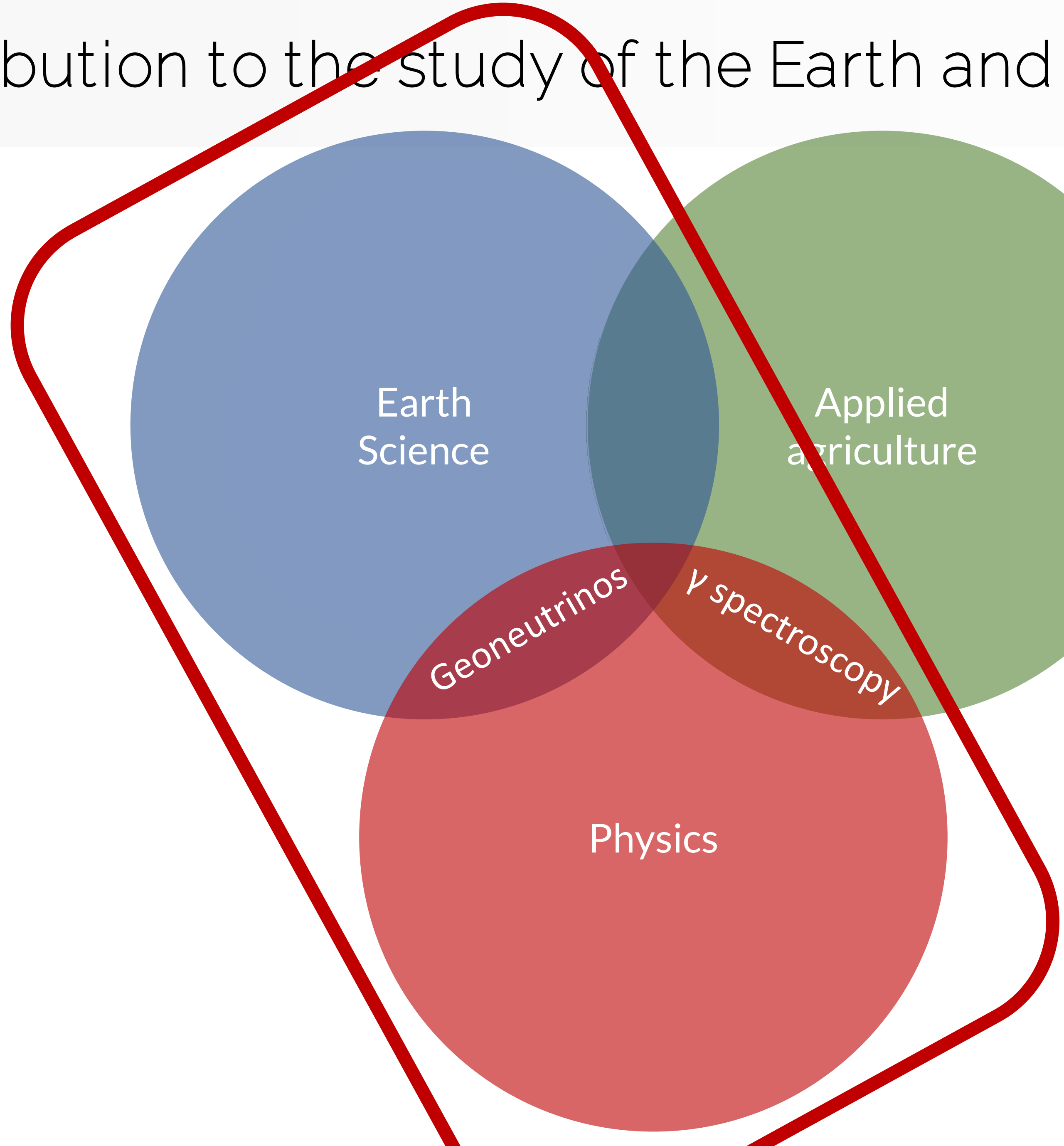
The **gamma photons** emitted in the underground decays of ^{40}K are attenuated proportionally to soil density and are consequently sensitive to **soil water content**. In my thesis:

» I showed how the time evolution of ^{40}K gamma counts can be used to recover soil water content at field scale (~25 m).

» I demonstrated how the simultaneous observation of ^{40}K and ^{214}Pb temporal variations in a gamma spectrum can be used to distinguish rain from irrigation.

Proximal Gamma Ray Spectroscopy: an effective tool to discern rain from irrigation. **Serafini** et al., Remote Sens. 2021, 13(20), 4103;

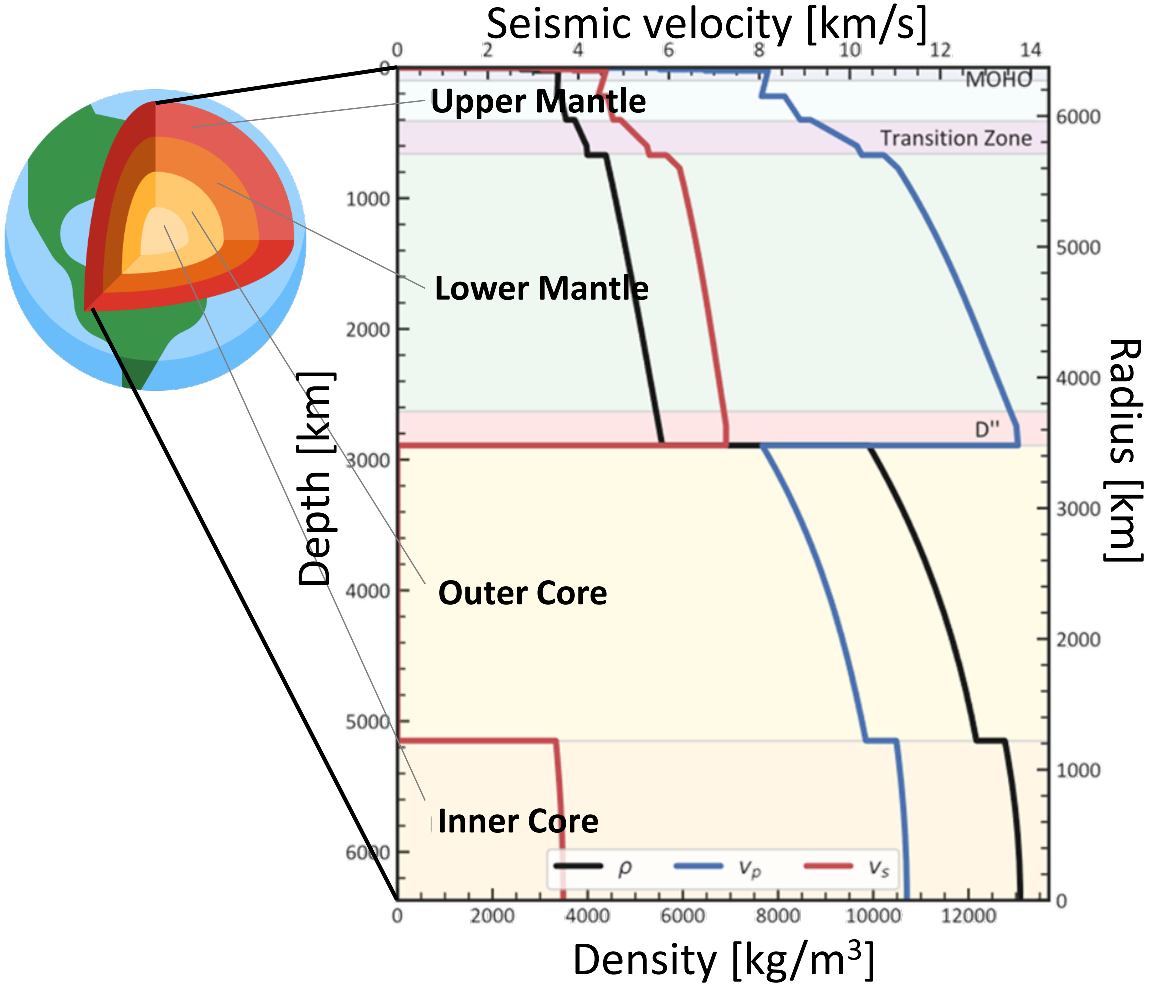
My contribution to the study of the Earth and the environment



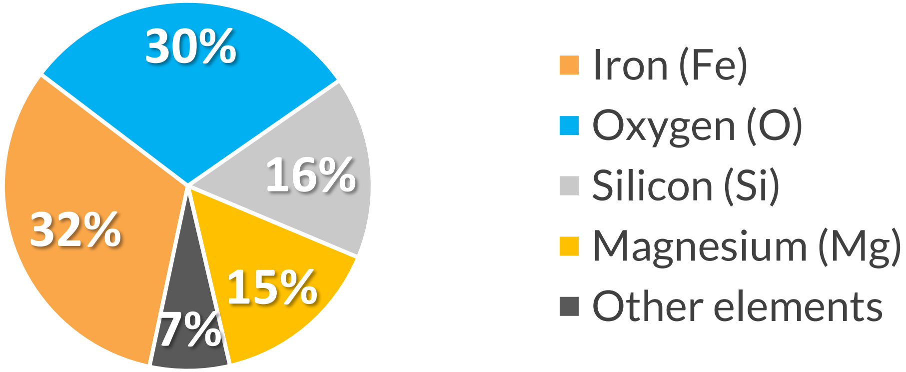
Ask questions if you are interested!

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:

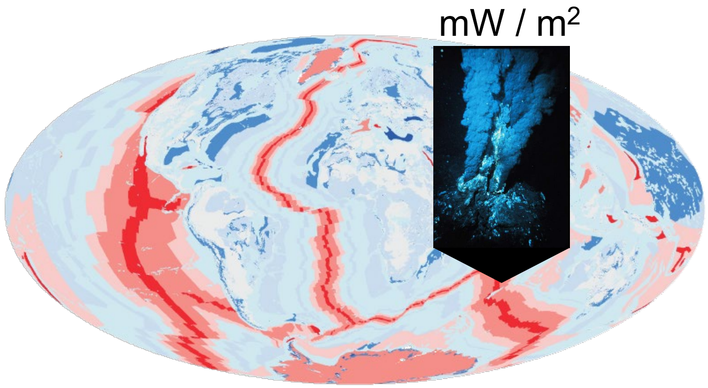


About 0.02% of Earth's mass is made out of radioactive **Heat Producing Elements (HPEs).**

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

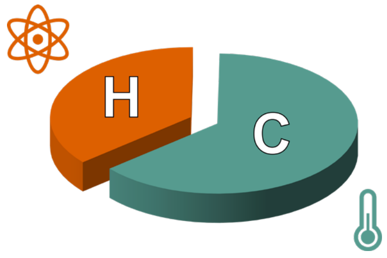
- **Uranium U** ($M_U \sim 10^{-8} M_{Earth}$)
- **Thorium Th** ($M_{Th} \sim 10^{-8} M_{Earth}$)
- **Potassium K** ($M_K \sim 10^{-4} M_{Earth}$)

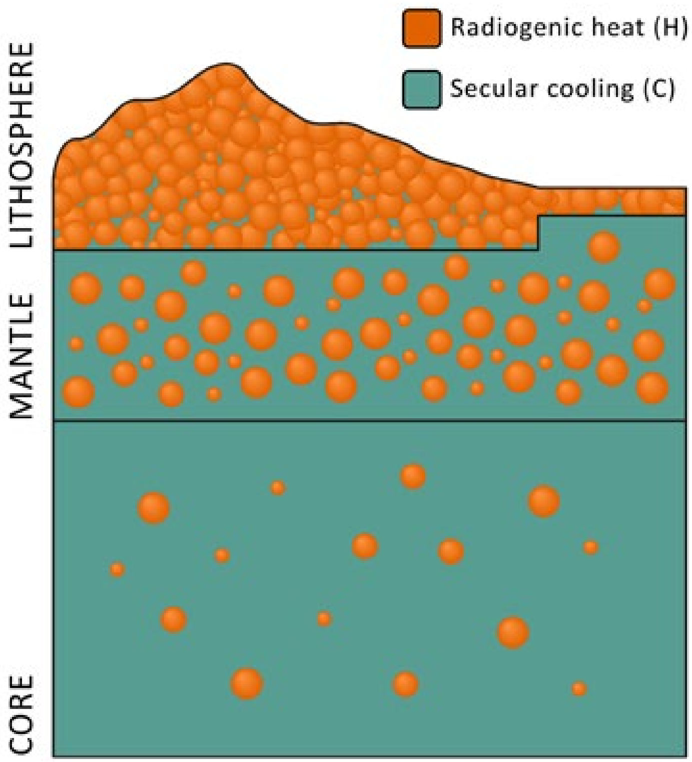
Earth's heat budget



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.

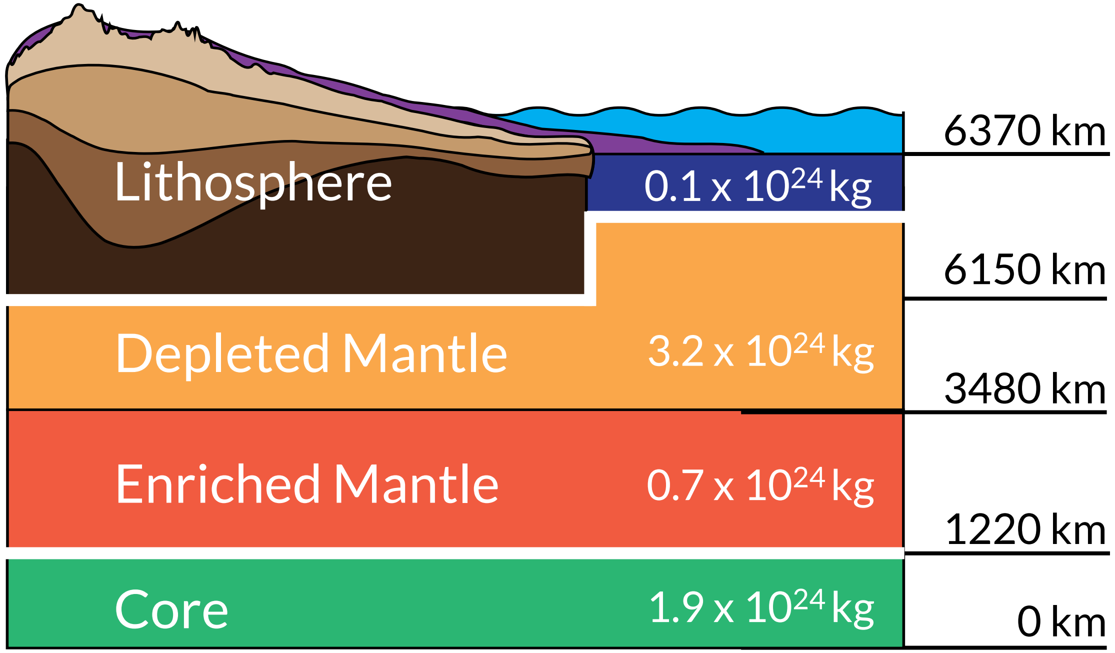
The main reservoirs of the Earth

Despite deep Earth's structure is well understood, its chemical composition is not. Samples from Lithosphere permit to statistically study its compositions.

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

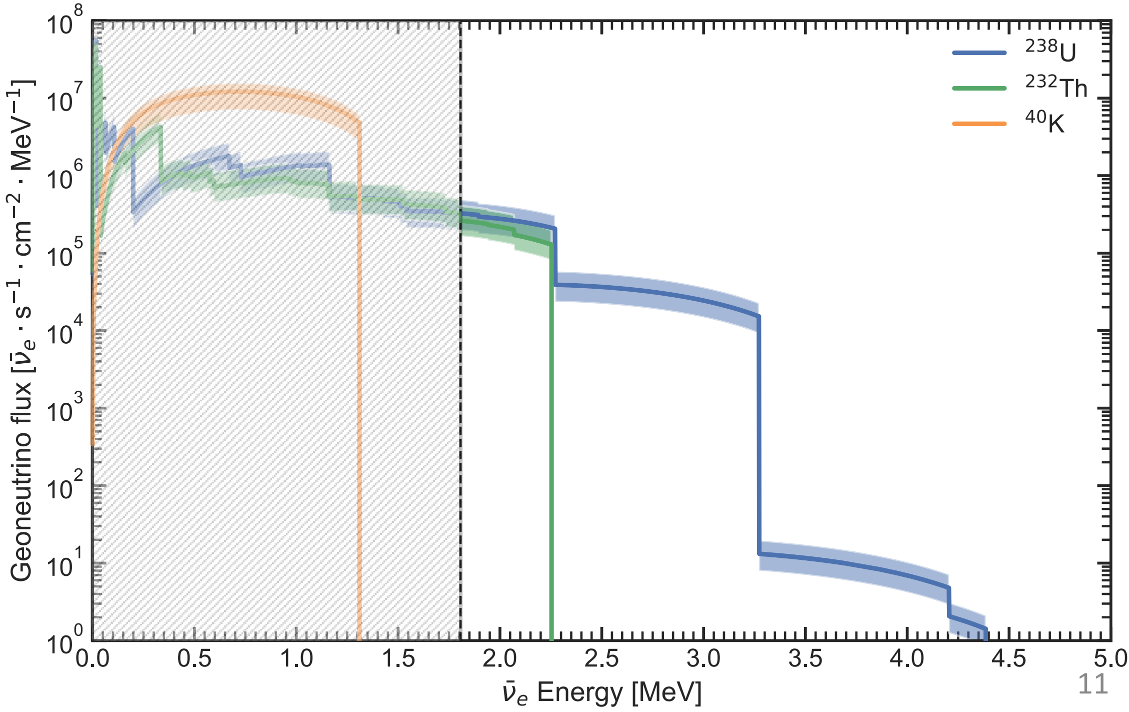
» Earth emits (mainly) $\bar{\nu}_e$ ($\Phi \backsim 10^7$ cm^{-2} s^{-1}) whereas Sun shines in ν_e ($\Phi \backsim 10^{11}$ cm^{-2} s^{-1})

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

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

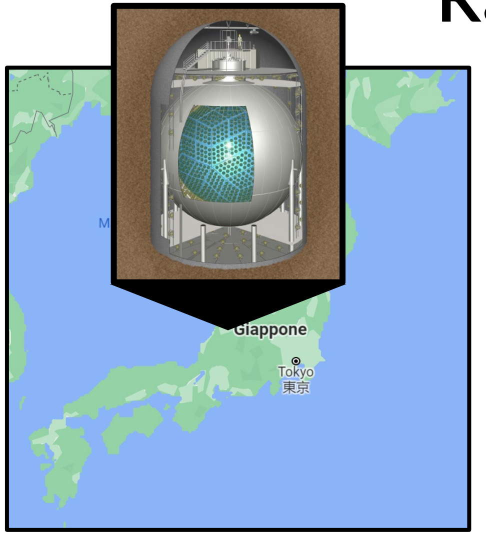
» Different components can be distinguished due to different energy spectra

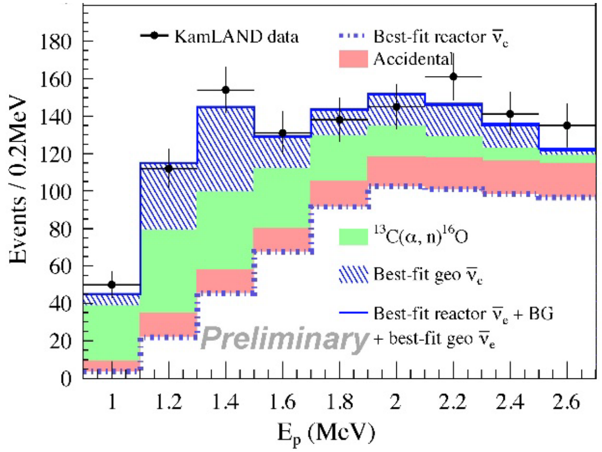
» Signal unit: 1 TNU = one event per 10^{32} free protons/year



Borexino and KamLAND geoneutrino results

KamLAND

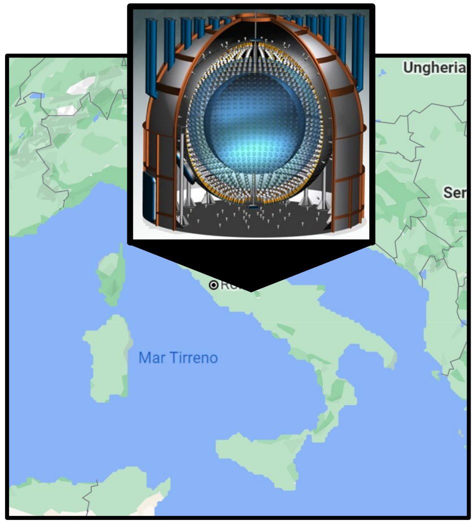


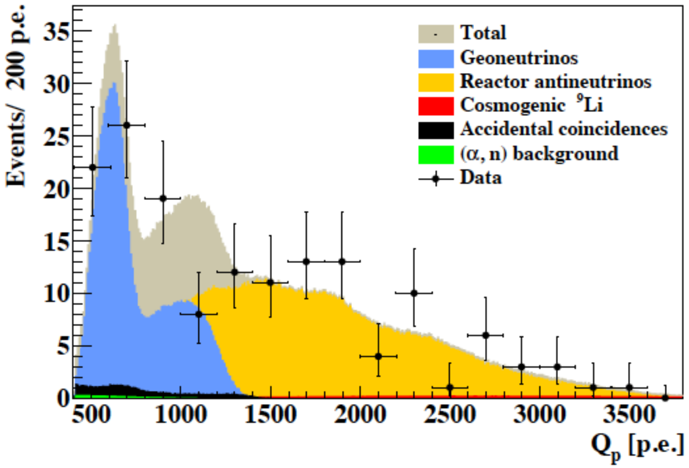


KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17” PMTs and 554 20” PMTs

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]	$26.1^{+4.2}_{-3.9}$	$6.6^{+1.1}_{-1.0}$	$\mathbf{32.1^{+5.0}_{-5.0}}$

Borexino





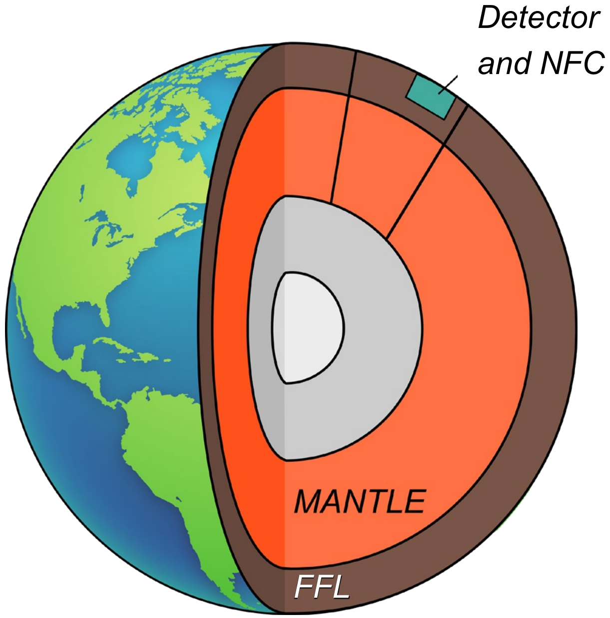
Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8” PMTs.

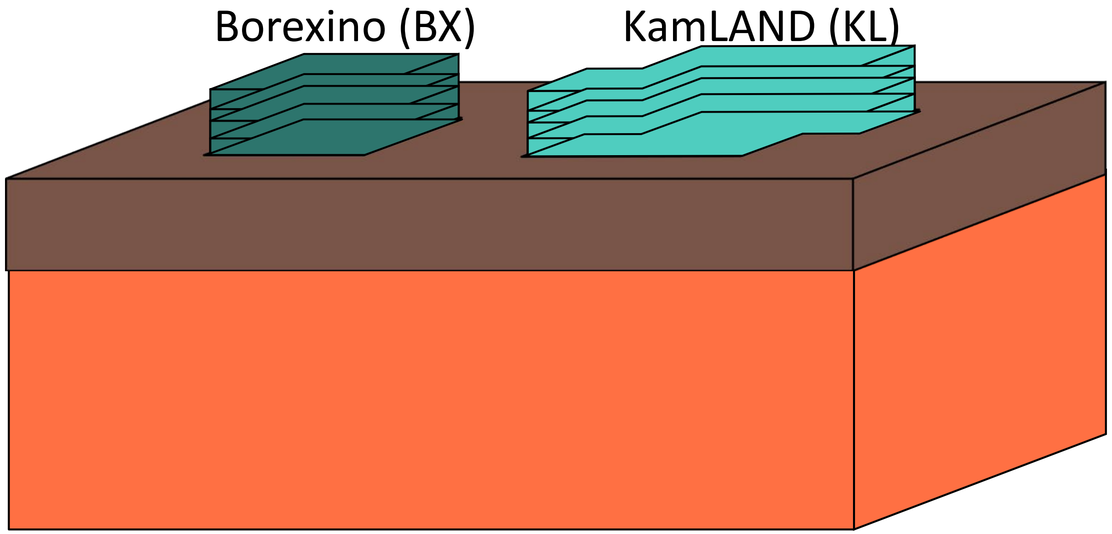
Data-taking: 2007-2019			
	U	Th	U+Th
Events	$41.1^{+7.5}_{-7.1}$	$11.5^{+2.2}_{-1.9}$	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$36.3^{+6.7}_{-6.2}$	$10.5^{+2.1}_{-1.7}$	$\mathbf{47.0^{+8.6}_{-8.1}}$

Extracting the mantle signal: the rationale

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

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





Different for different detectors **Common to detectors**

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

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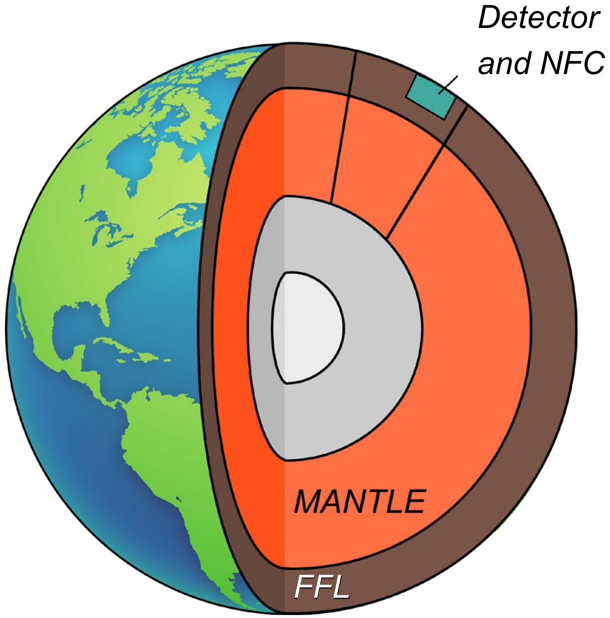
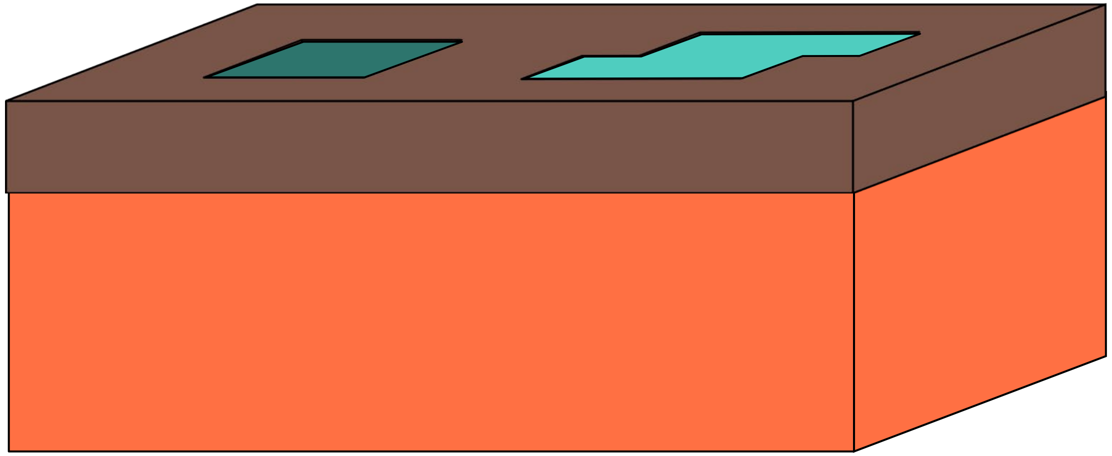




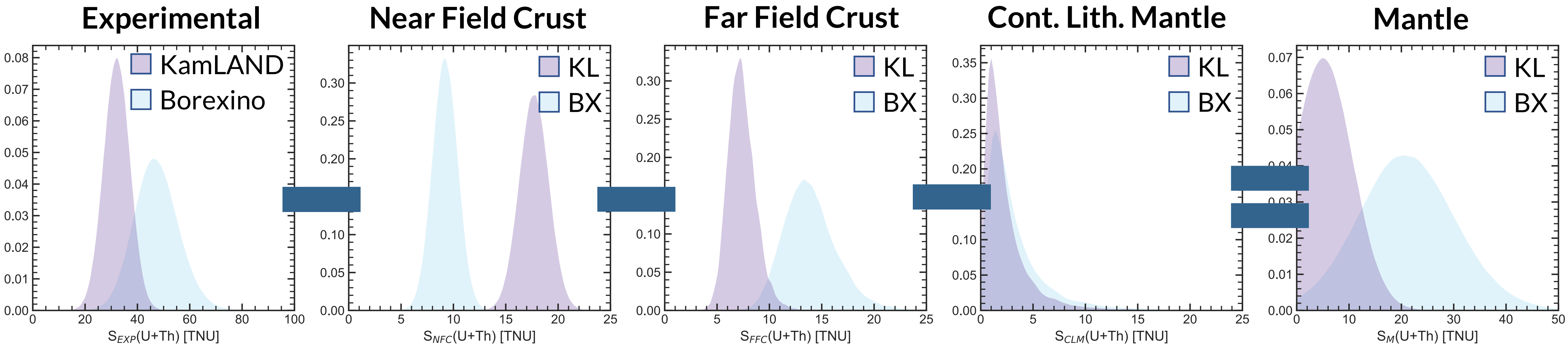
$$S^i_{Exp}(U+Th) - S^i_{NFC}(U+Th) - S^i_{FFC}(U+Th) - S^i_{CLM}(U+Th) = S^i_M(U+Th)$$

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.

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:

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

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

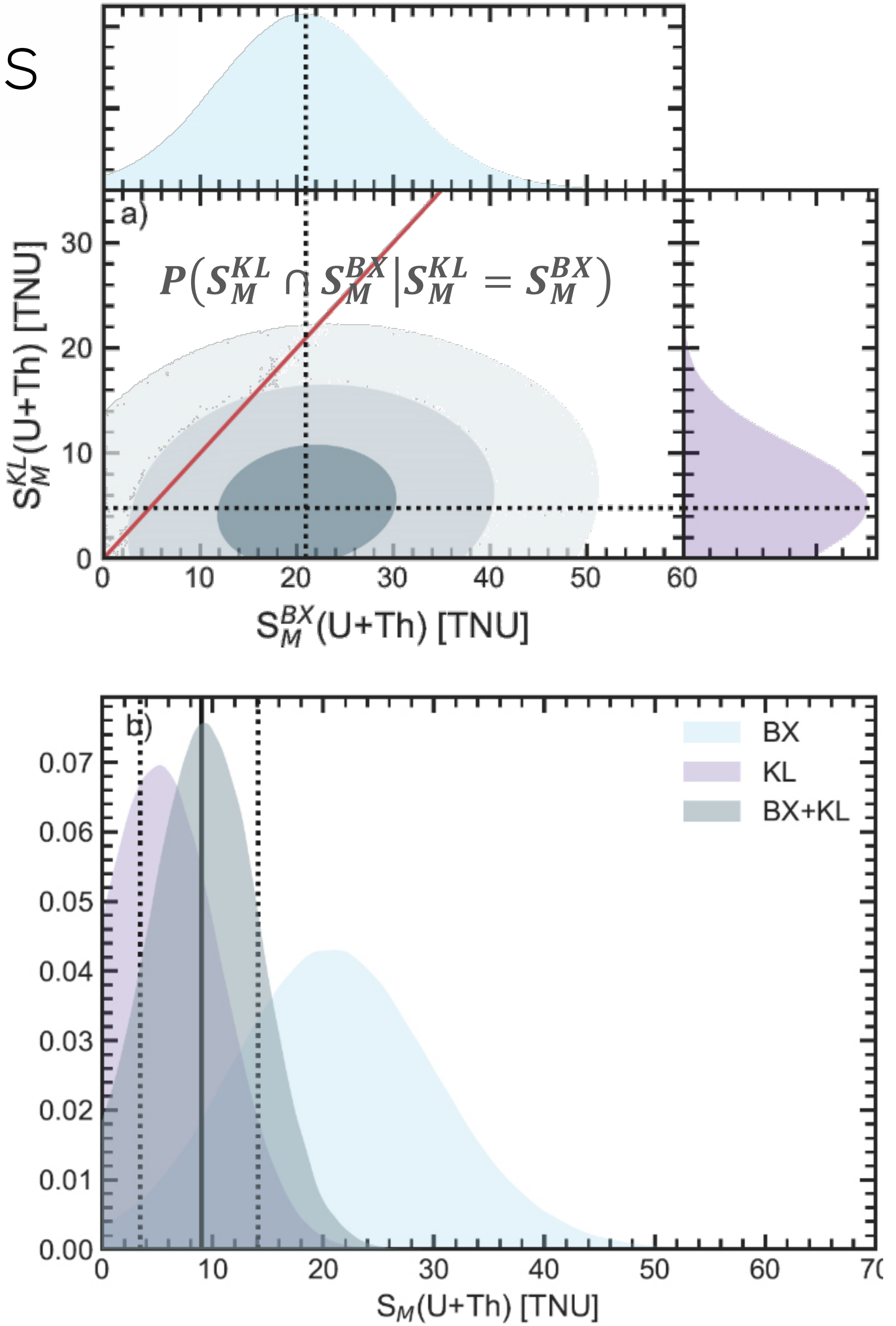
$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ TNU$$

Where correlations need to be properly accounted for:

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

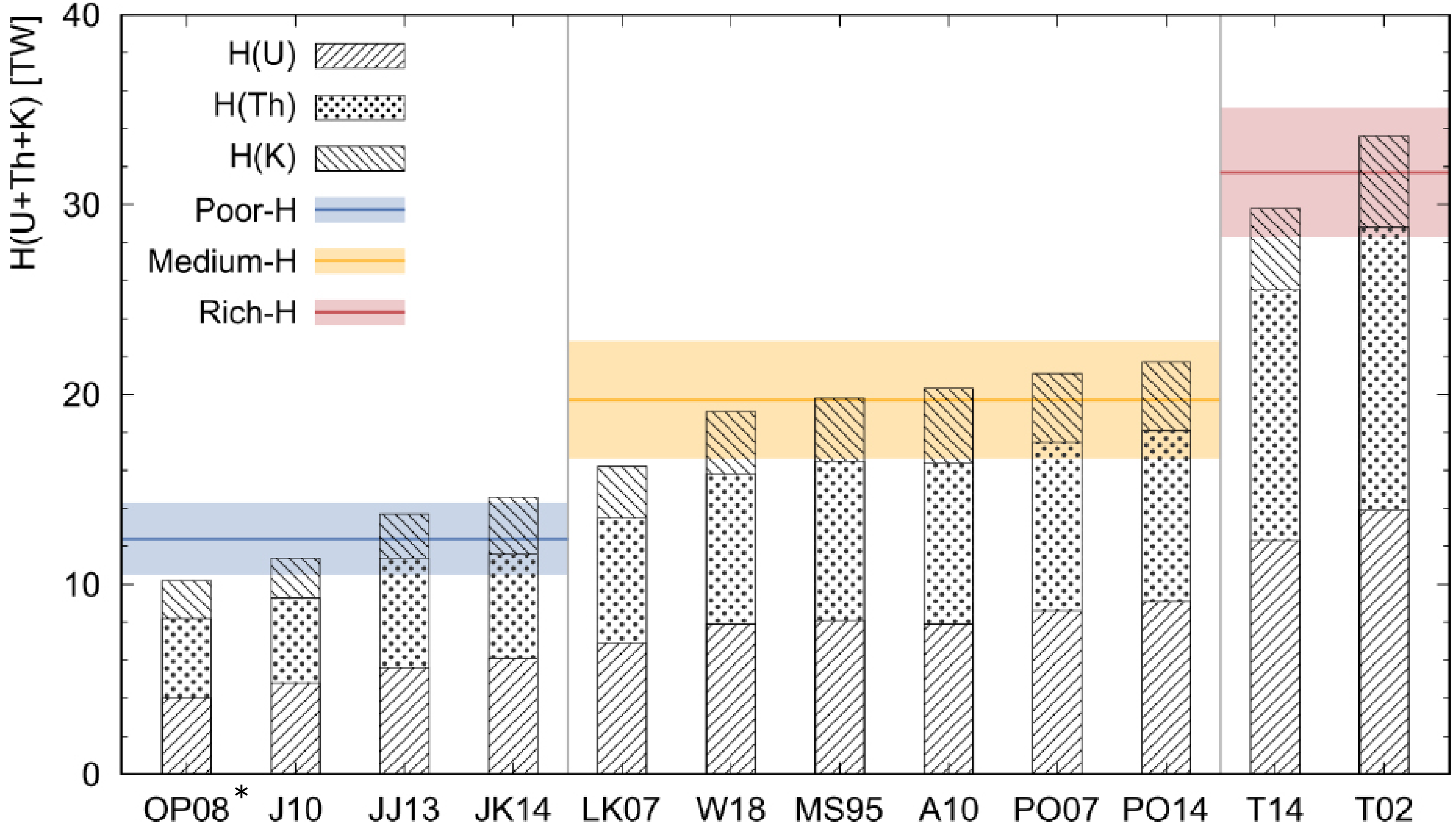
» $S_{CLM}^{KL}(U+Th) \propto S_{CLM}^{BX}(U+Th)$

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



*AAYY – Author year acronym

Bulk Silicate Earth Models

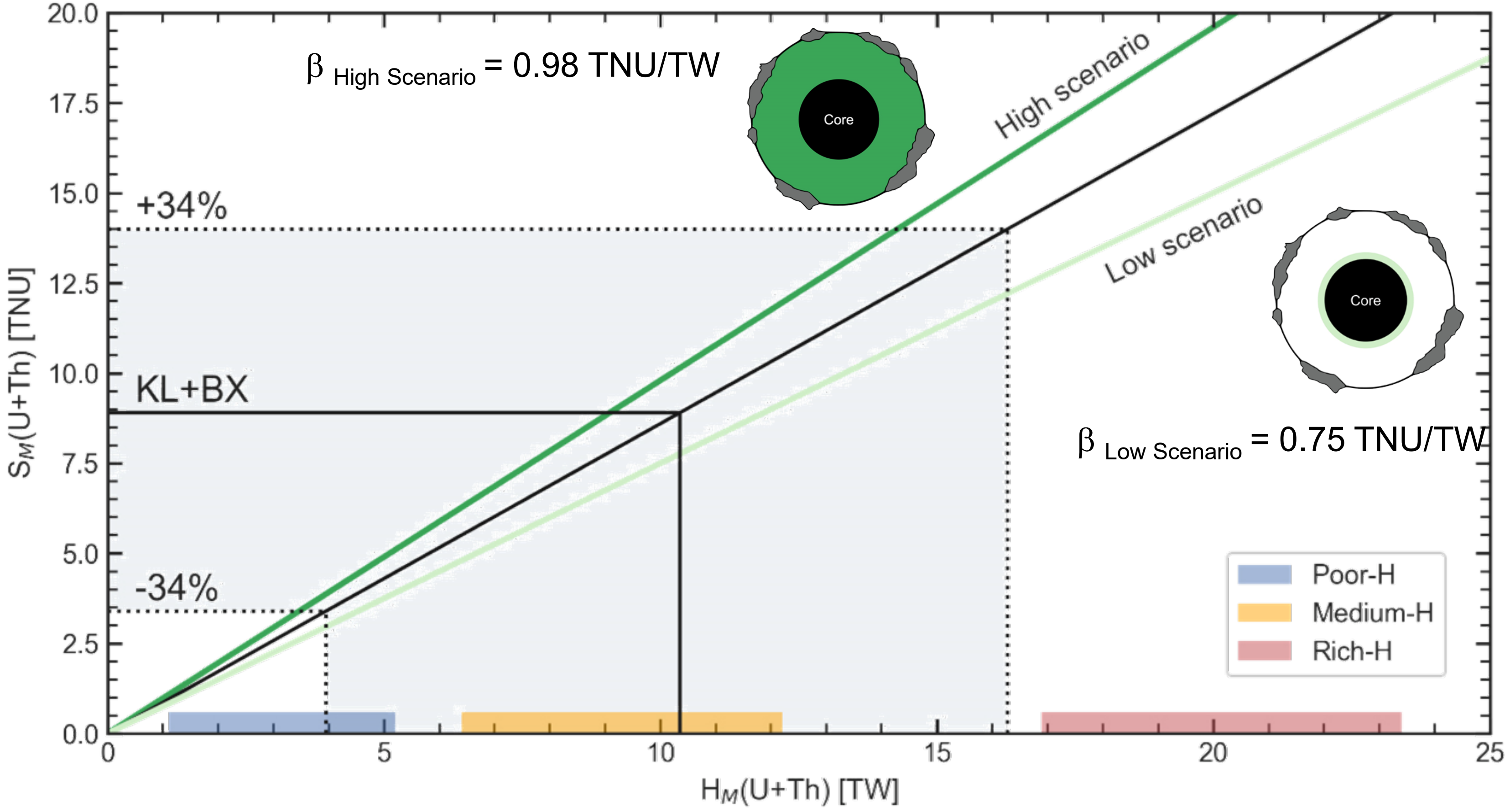


	Poor-H	Medium-H	Rich-H
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4

» 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 $H_M(U+Th)$:

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

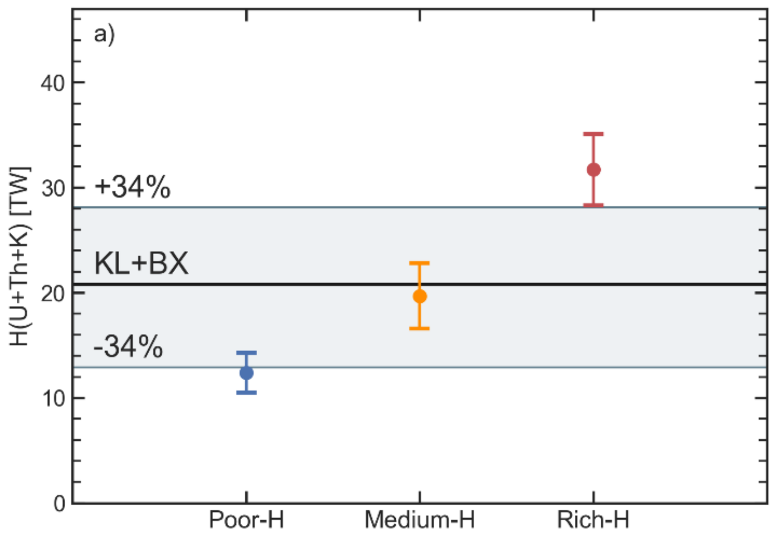
	Poor-H	Medium-H	Rich-H	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

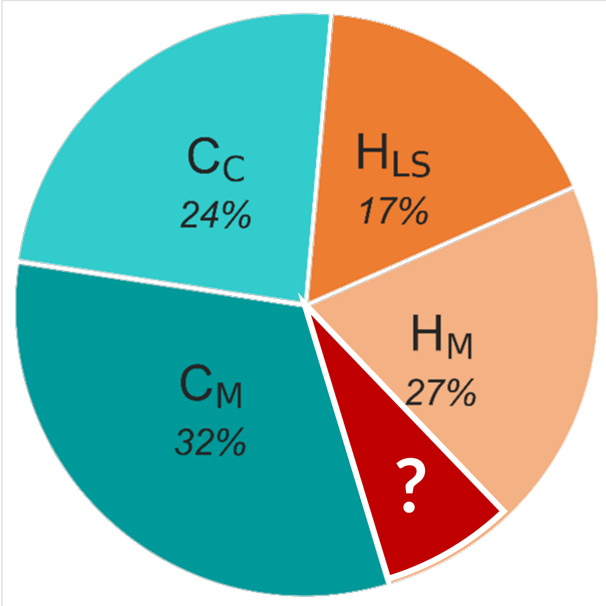
Understanding the Earth's heat budget with geoneutrinos

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

- the **radiogenic heat** $H^{KL+BX} = 20.8^{+7.3}_{-7.9}\ TW$
- the **secular cooling** $C^{KL+BX} = 26 \pm 8\ TW$

	Adopted	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**	$\mathbf{26 \pm 8}$





^{40}K in Earth Science

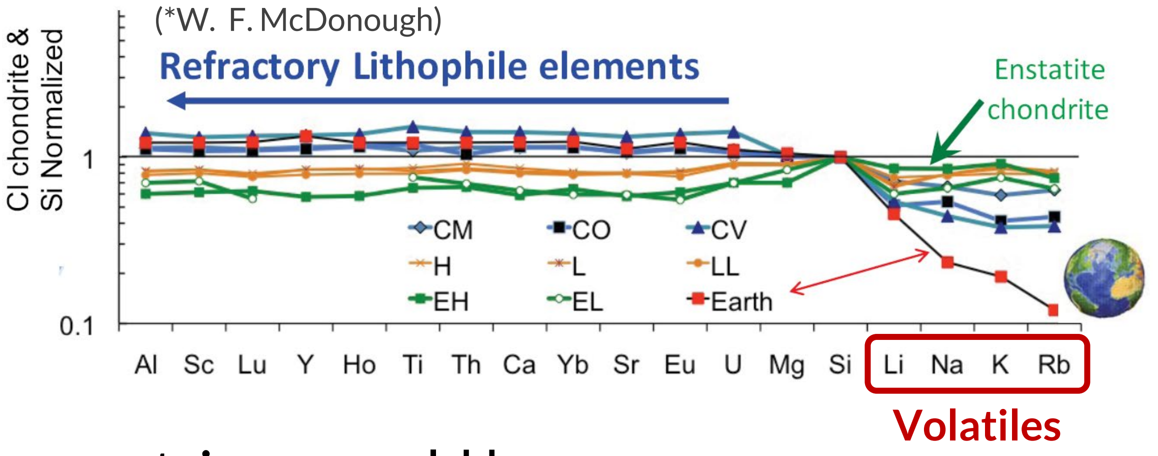
1. Our planet seems to contain **10%-30% K respect to** the enstatitic (EH) and carbonaceous (CI) **chondrites** meteorites, respectively.

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.

(EH)

(CI)

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)** $\bar{\nu}_X + e^- \rightarrow \bar{\nu}_X + e^-$~~

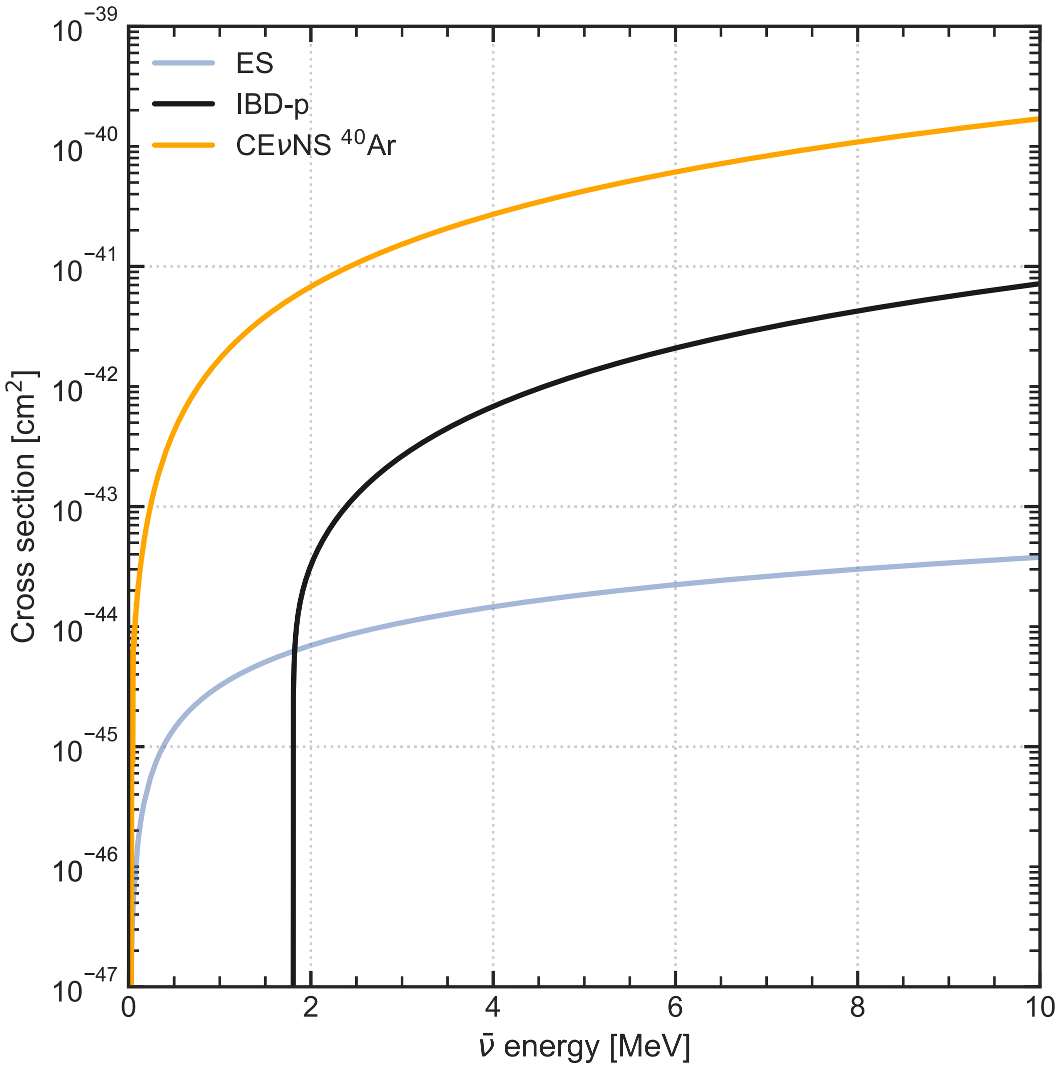
~~It has no energy threshold (apart from our capability to detect electron recoil). It does not allow to distinguish flavors, or to separate neutrinos from antineutrinos (in the absence of directional information).~~

~~**Coherent neutrino-nucleus scattering (CEvNS)**~~

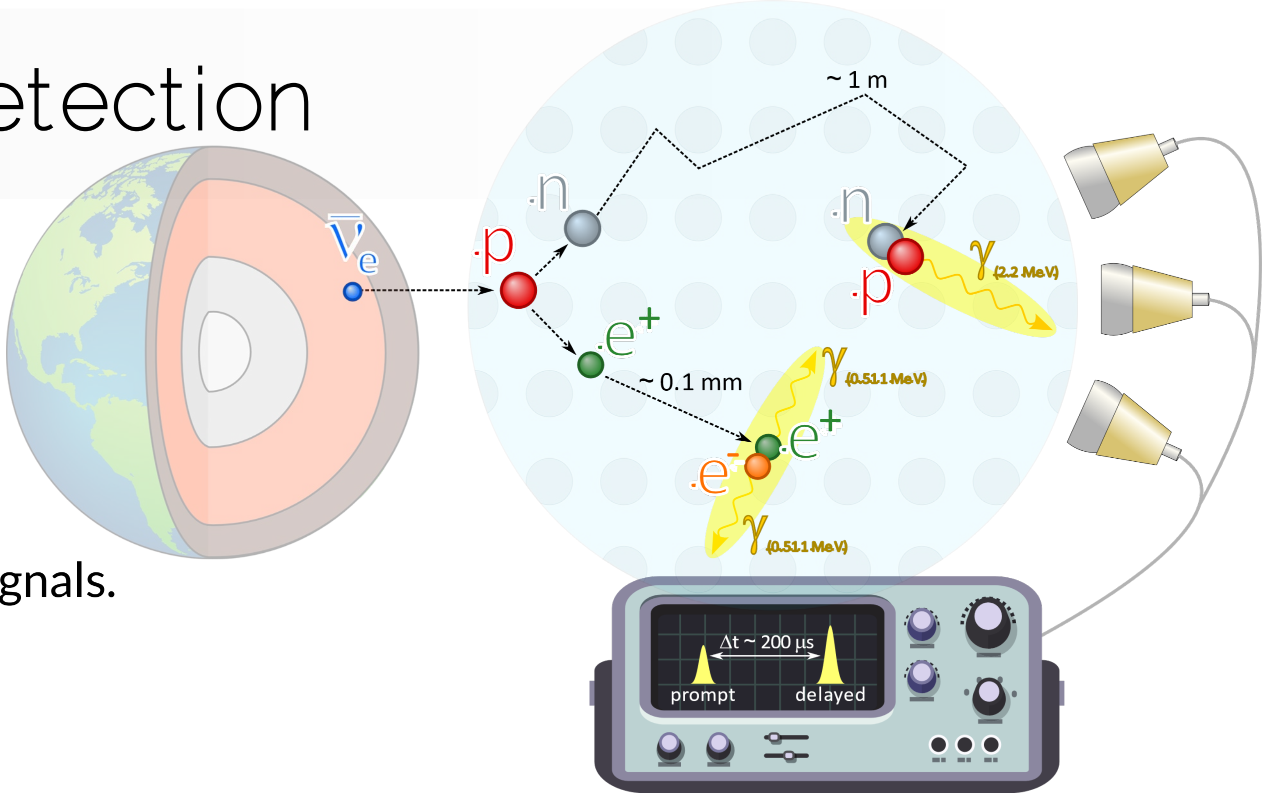
$$\bar{\nu}_X + {}_{Z}^{A}N \rightarrow \bar{\nu}_X + {}_{Z}^{A}N$$

~~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})



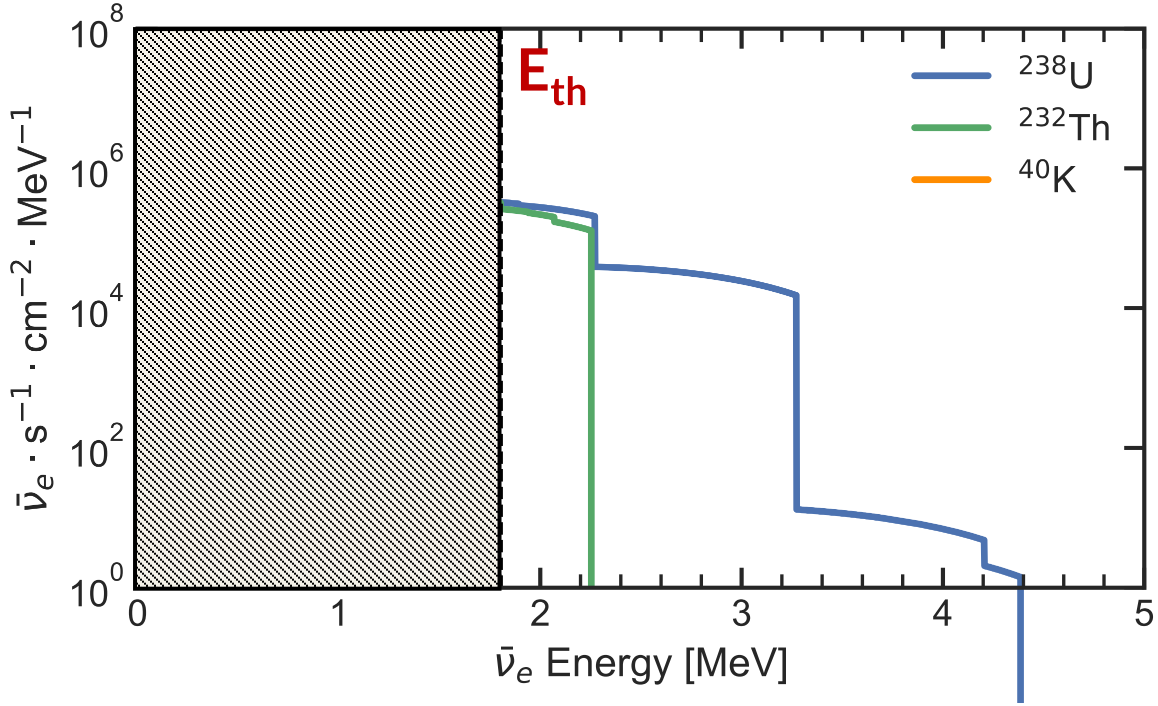
Inverse Beta Decay (IBD) detection



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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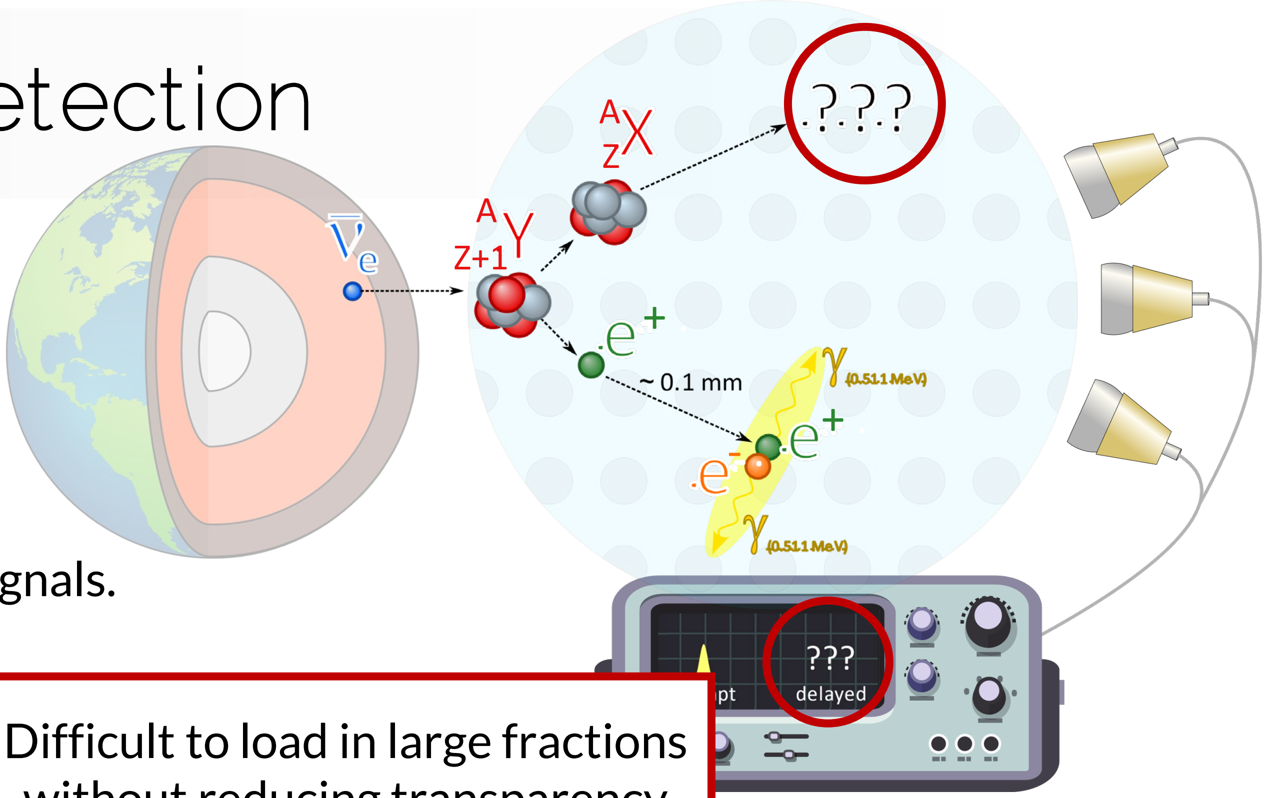

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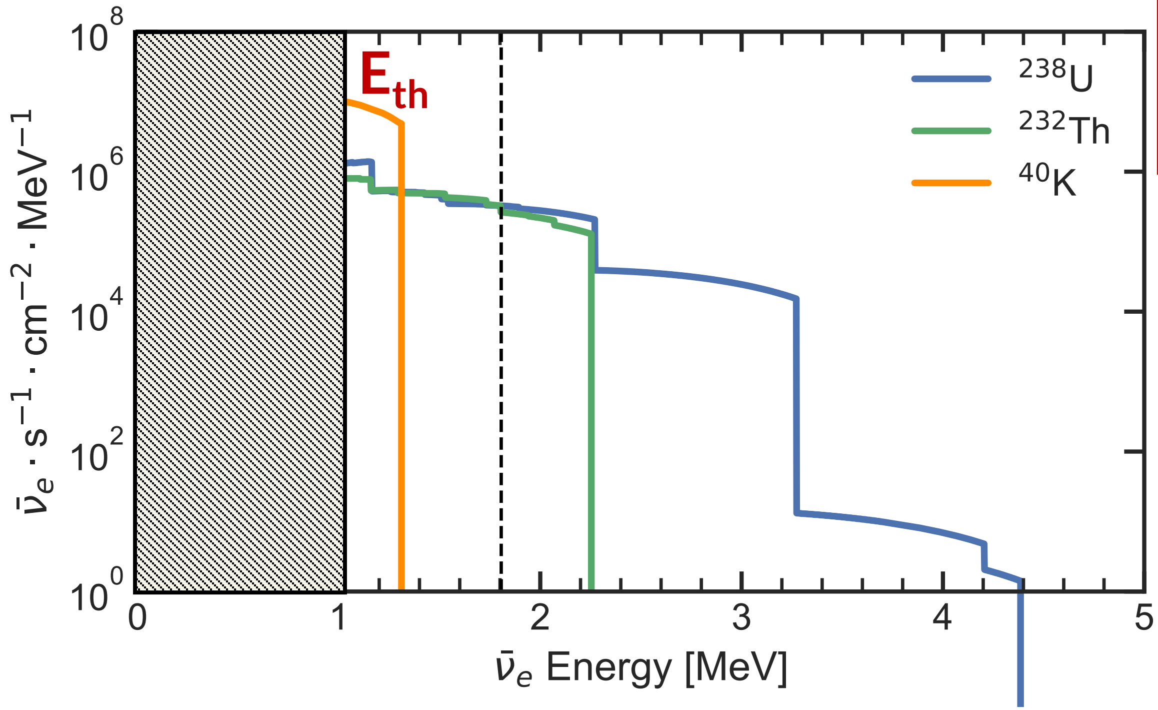


Difficult to load in large fractions without reducing transparency

... could use:

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

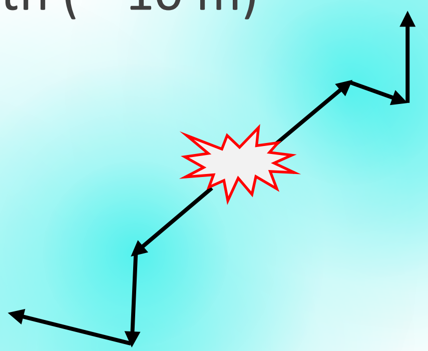
Impossible to tag in current Liquid Scintillator Detector

We shall require

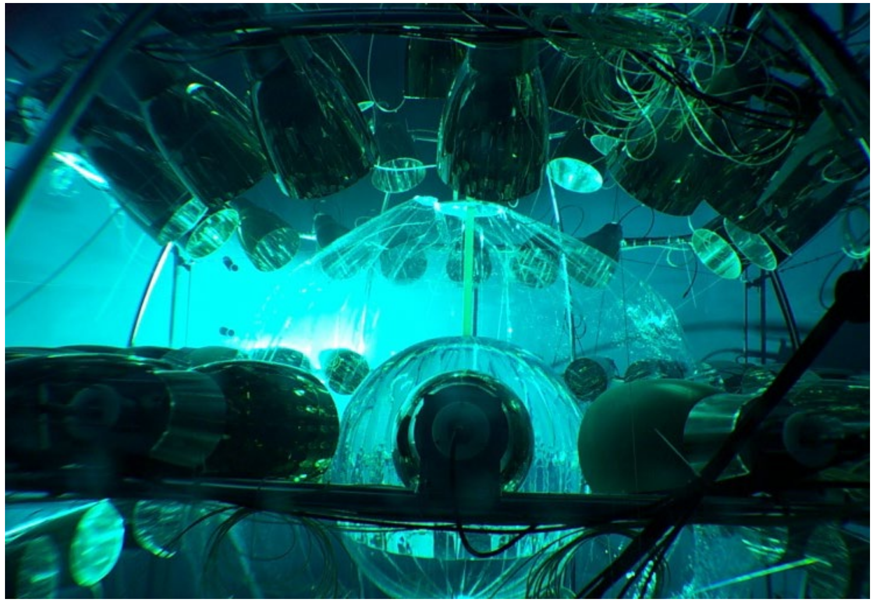
- E_{th} < *1.3 MeV*
- High cross-se...
- High Y natural isotopic abundance

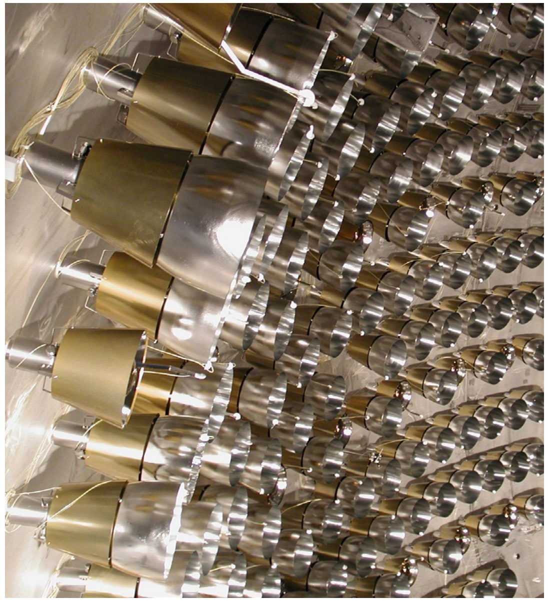
Neutrino physics with opaque scintillators

Very long attenuation length (~ 10 m)

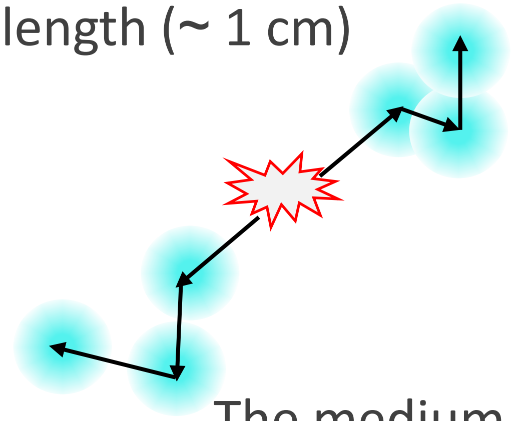


The medium is transparent to scintillation photons

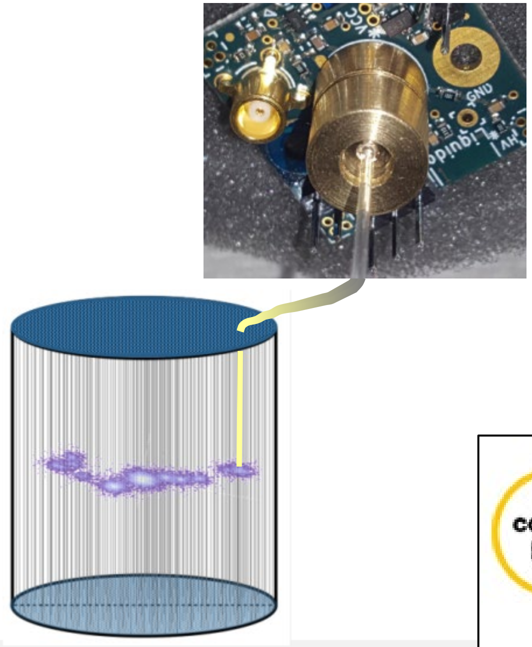




Very short scattering length (~ 1 cm)



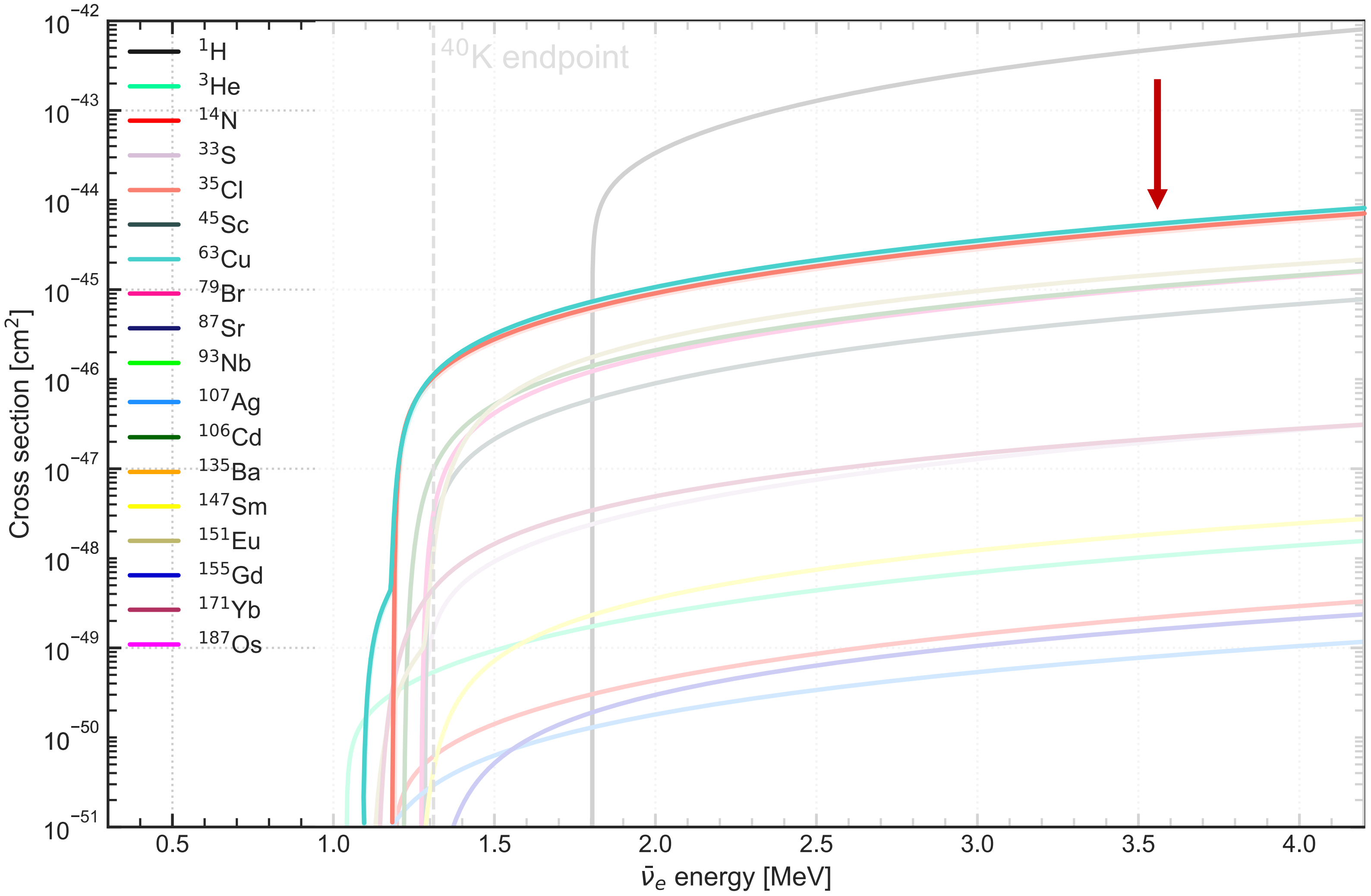
The medium is opaque to scintillation photons



- Tolerance to opacity → high loading
- **Technology under R&D**

Neutrino physics with an opaque detector. Cabrera […], **Serafini** et al. Commun. Phys. 4, 273 (2021)

IBD cross-sections weighted by isotopic abundance



$$\bar{\nu}_e + \boldsymbol{^{35}Cl} \rightarrow {}^{35}S + e^+ - 1.189 \text{ MeV}$$

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

^{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)

The golden candidates: ^{35}Cl and ^{63}Cu

There are only **few possible backgrounds** for ^{40}K geoneutrinos detection via IBD:

- true antineutrino events (U, Th and reactors) → **can be independently estimated via IBD-p!**
- β^+ emitting background sources:
  - ^{40}K contamination of the LS
  - natural β^+ emitting isotopes in the target element → **irreducible**

^{35}Cl

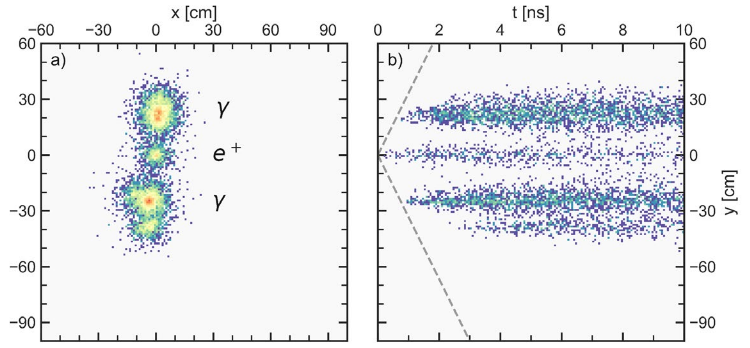
- can be loaded as solu[illegible] the LS or as chlorinated benzene scintillating c[illegible]unds ✓
- Cl contains ^{36}Cl (~1[illegible]), wh[illegible] produces ~10^{10} e^+ per year per 10^{32} chlo[illegible]ne atoms ✗

^{63}Cu

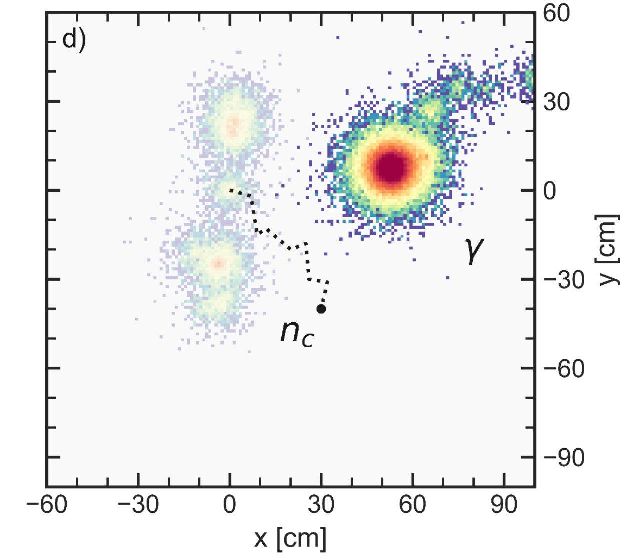
- can be loaded in aqueous solution in scintillator cocktails miscible with water ✓
- has no natural β^+ emitters and provides an additional delayed gamma coincidence ✓

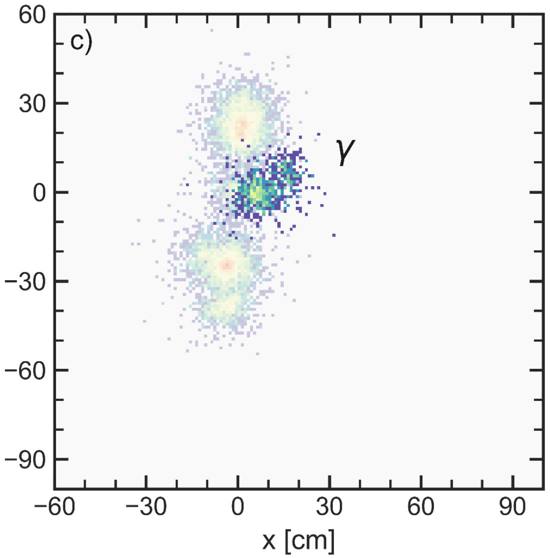
^{63}Cu: two distinct detection channels

A scintillator loaded with copper will offer **two distinct detection channels**: IBD on protons (IBD-p) and IBD on copper itself IBD-^{63}Cu

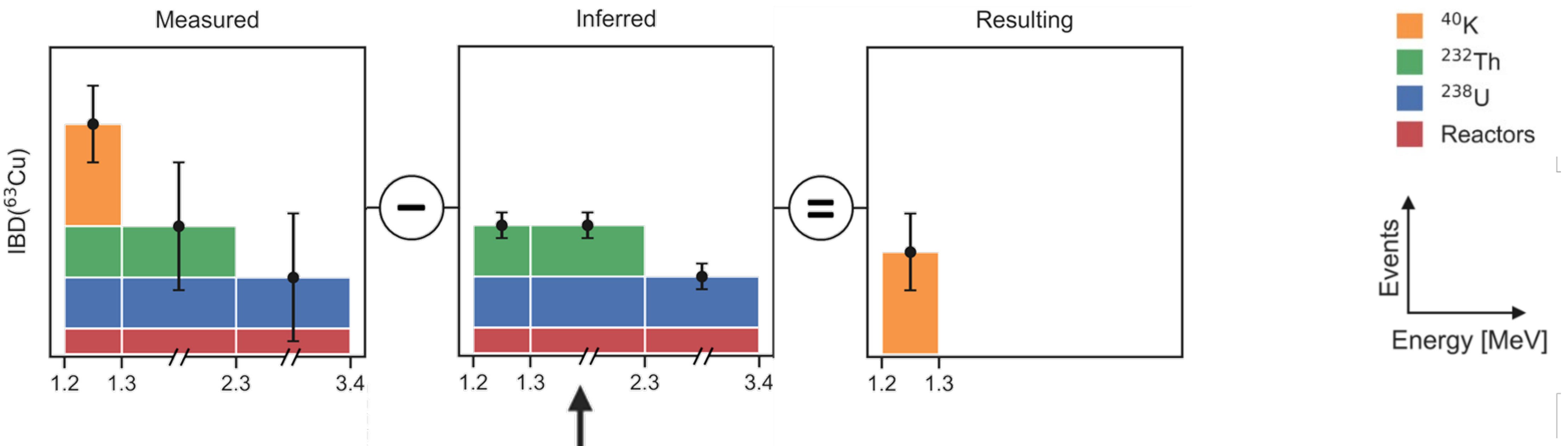


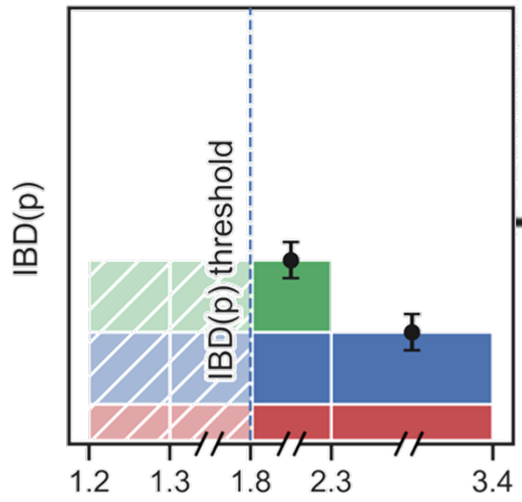
	IBD-p	IBD-^{63}Cu
Reaction	$\bar{\nu}_e + p \rightarrow n + e^+$	$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$
Prompt	$e^+ + e^- \rightarrow 2\gamma$ $(511\ keV)$	$e^+ + e^- \rightarrow 2\gamma$ $(511\ keV)$
Delayed	$n + p \rightarrow d + \gamma$ $(2.2\ MeV)$	${}^{63}Ni^* \rightarrow {}^{63}Ni + \gamma$ $(87\ keV)$
	$\sim 200\ \mu s$	$\sim 2\ \mu s$

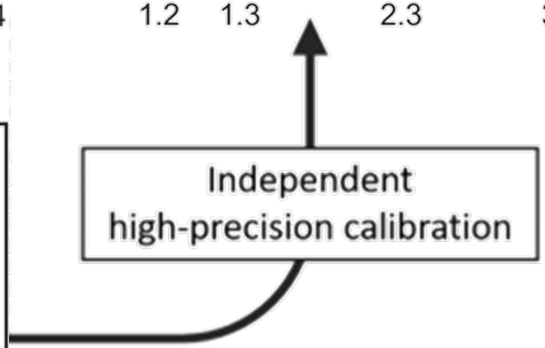




Rationale for signal extraction







Side effect: $\boldsymbol{\sigma}_{stat}$ < 1% on S(*U+Th+reactors*)

		Events/10y/240kton			
Detection reaction	**Energy range**	**Reactors**	**^{238}U**	**^{232}Th**	**^{40}K**
IBD(p)	[1.806 – 3.27] MeV	19530	27750	7948	/
IBD(^{63}Cu)	[1.176 – 1.311] MeV	0.2	1.1	1.1	11.7

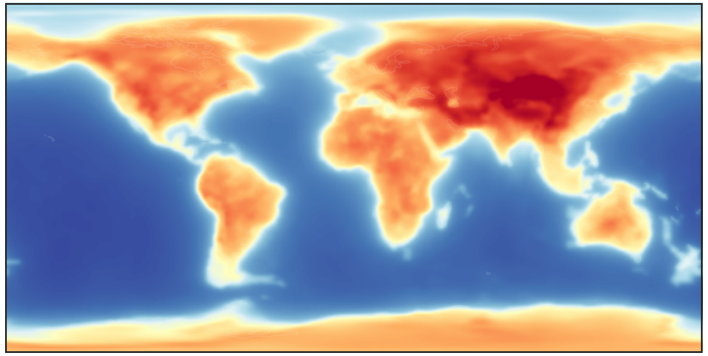
Final remarks

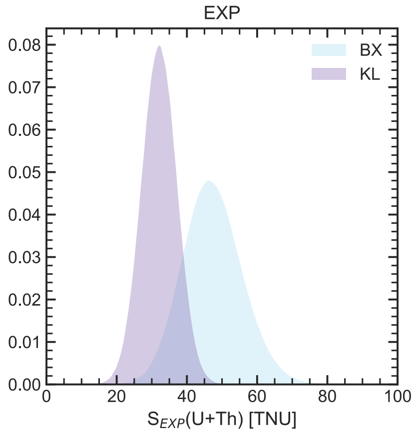
$^{40}_{19}\mathrm{K}$

Geoneutrinos

» Promising tool to explore the inaccessible Earth:

- comprehension of geodynamical processes of our planet
- expected new data from next generation SNO+ (Canada) and JUNO (China) antineutrino experiments.
- synergy between experimental physics and geochemical and geophysical modeling





» $^{40}\mathrm{K}$-$\bar{\nu}_e$ detection would be a breakthrough in Earth Science.

- a methodology for their detection has been identified!

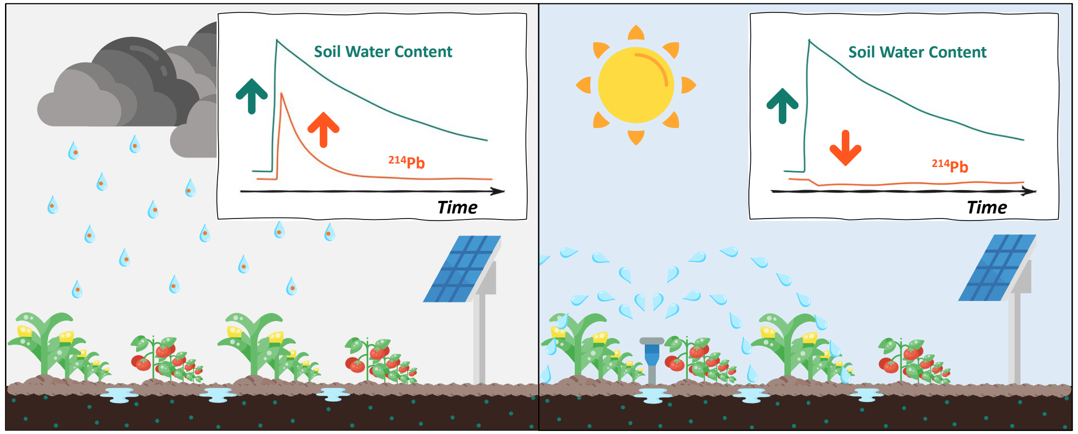
γ spectroscopy

» Mature technique for proximal remote sensing applied to precision agriculture:

- Estimation of soil water content
- Discrimination of rain and irrigation

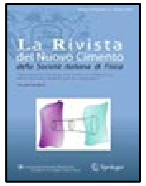
→ management of water resources

→ scheduling of irrigations

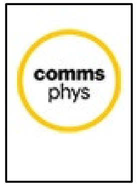


Thank you!

Some of my publications:

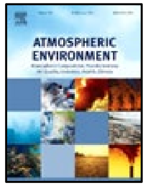


Geoneutrinos and geoscience: an intriguing joint-venture
Bellini […] **Serafini** et al.
Rivista del Nuovo Cimento (2021)

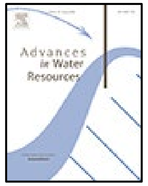


Neutrino physics with an opaque detector
Cabrera […] **Serafini** et al.
Communications Physics, 4, 273 (2021)

Proximal Gamma-Ray Spectroscopy: An Effective Tool to Discern […]
Serafini et al.
Remote Sensing, 13(20), 4103 (2021)



Rain rate and radon daughters' activity
Bottardi […] **Serafini** et al.
Atmospheric Environment, 238, 117728 (2020)



Soil moisture as a potential variable for tracking and quantifying […]
Filippucci […] **Serafini** et al.
Advances in Water Resources, 136, 103502 (2020)

Final remarks

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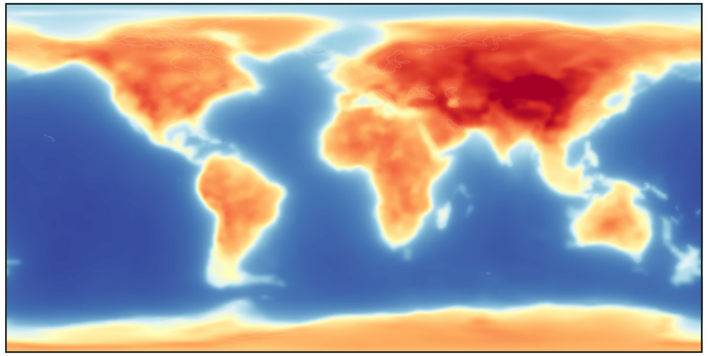

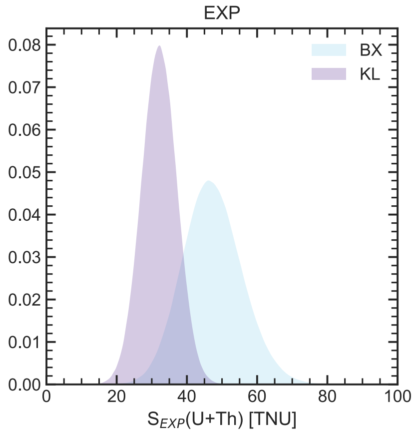

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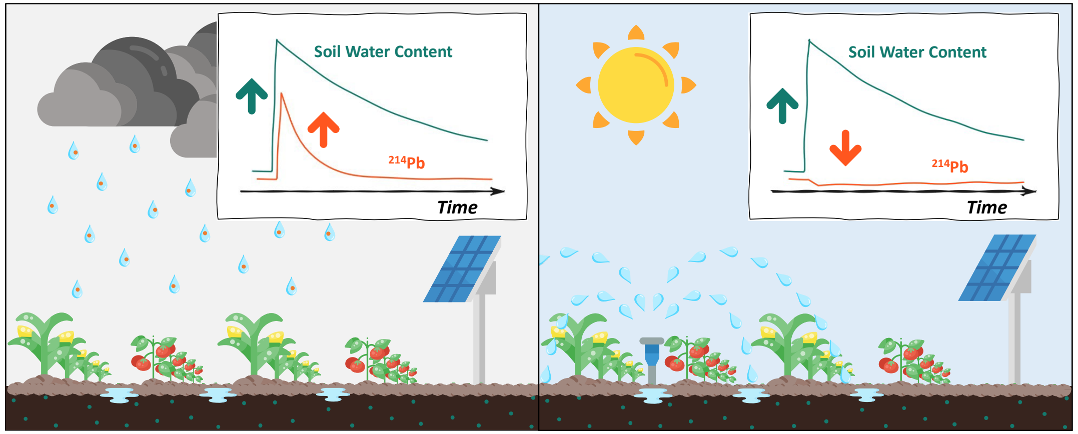

Backup

Thank you!

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Bellini […] Serafini et al.
Accepted by La Rivista del Nuovo Cimento (2021)

Proximal Gamma Ray Spectroscopy: an effective tool to discern rain from irrigation
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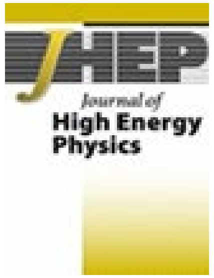
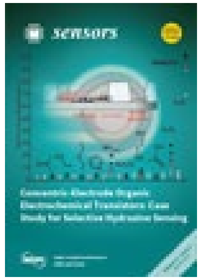


Calibration strategy of the JUNO experiment
Abusleme […] Serafini et al. (JUNO collaboration)
Journal of High Energy Physics, 4 (2021)

FPGA Implementation of NCO based CDR for the JUNO Front-End Electronics
Marini et al. (JUNO collaboration)
IEEE Transactions on Nuclear Science (2021)

Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO
Abusleme et al. (JUNO collaboration)
Chinese Physics C, 45(2) (2021)



An Easily Integrable Industrial System for Gamma Spectroscopic Analysis and Traceability of Stones and Building Materials
Marini et al. (CORSAIR project)
Sensors, 21(2), 352 (2021)

Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector
Abusleme et al. (JUNO collaboration)
Nuclear Instruments and Methods in Physics Research Section A, 988, 164823 (2021)

Embedded Readout Electronics R&D for the Large PMTs in the JUNO Experiment
Bellato et al. (JUNO collaboration)
Nuclear Instruments and Methods in Physics Research Section A, 985, 164600 (2021)