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^{40}K-geoneutrino detection

Revealing the missing piece in Earth's thermal puzzle

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supported by the LiquidO collaboration

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Outline

» The "Standard Model" of the Earth

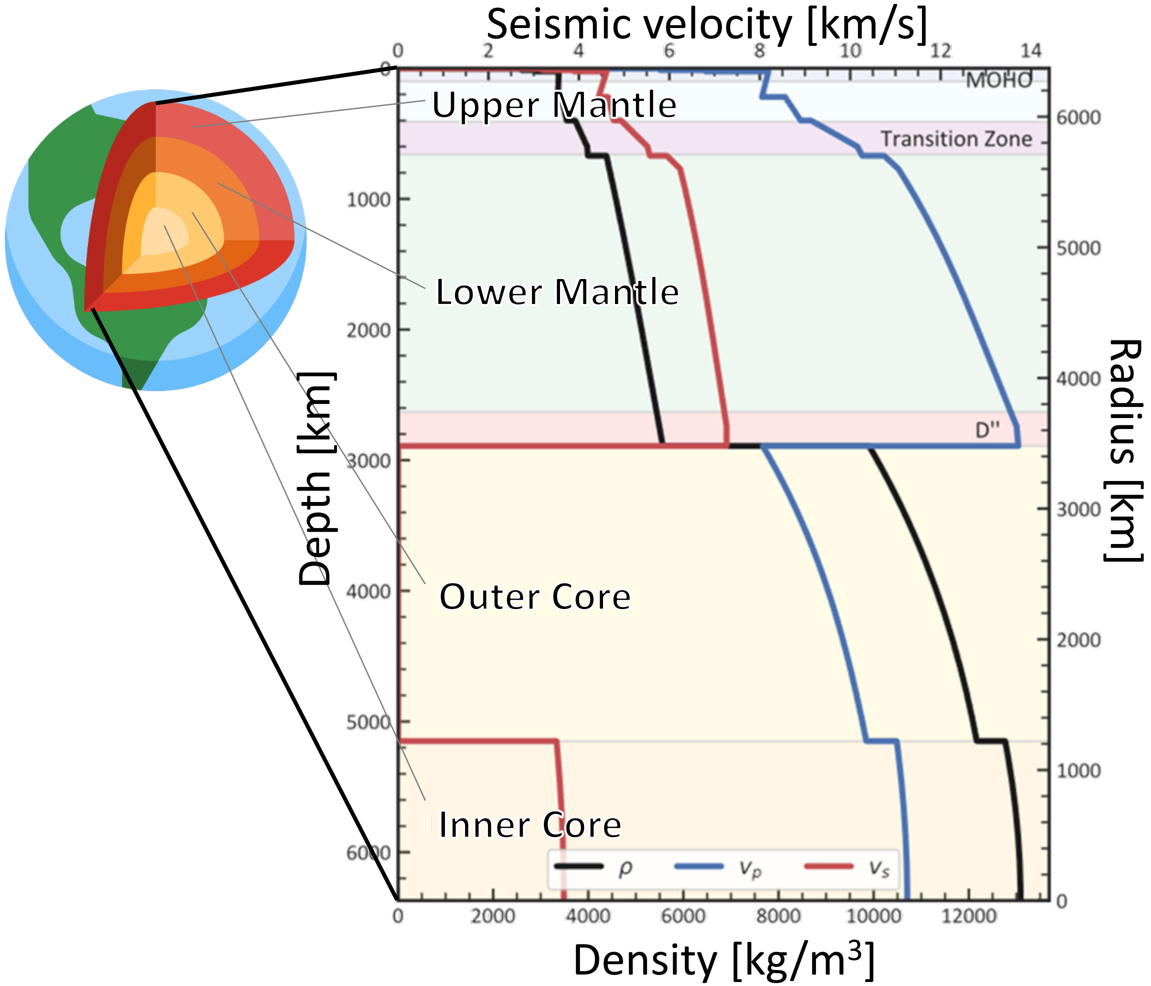
» Geoneutrinos in understanding Earth Sciences

» Insights from current geoneutrino measurements

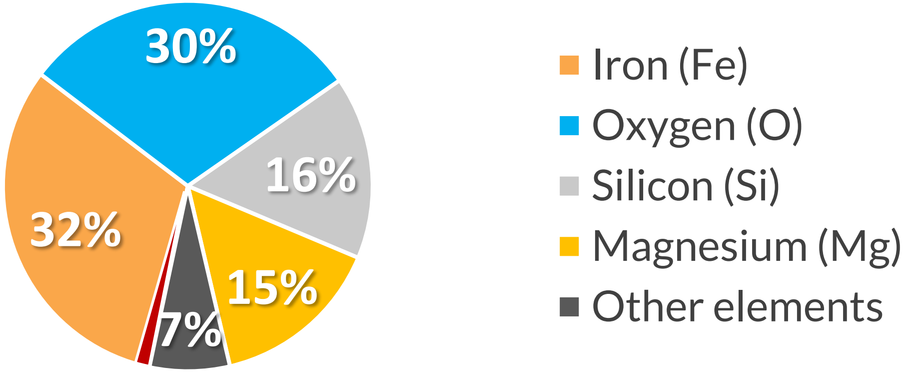
» The missing piece: ^{40}K-geoneutrinos

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** ($M_K \sim 10^{-4}\ M_{Earth}$)

Elemental properties

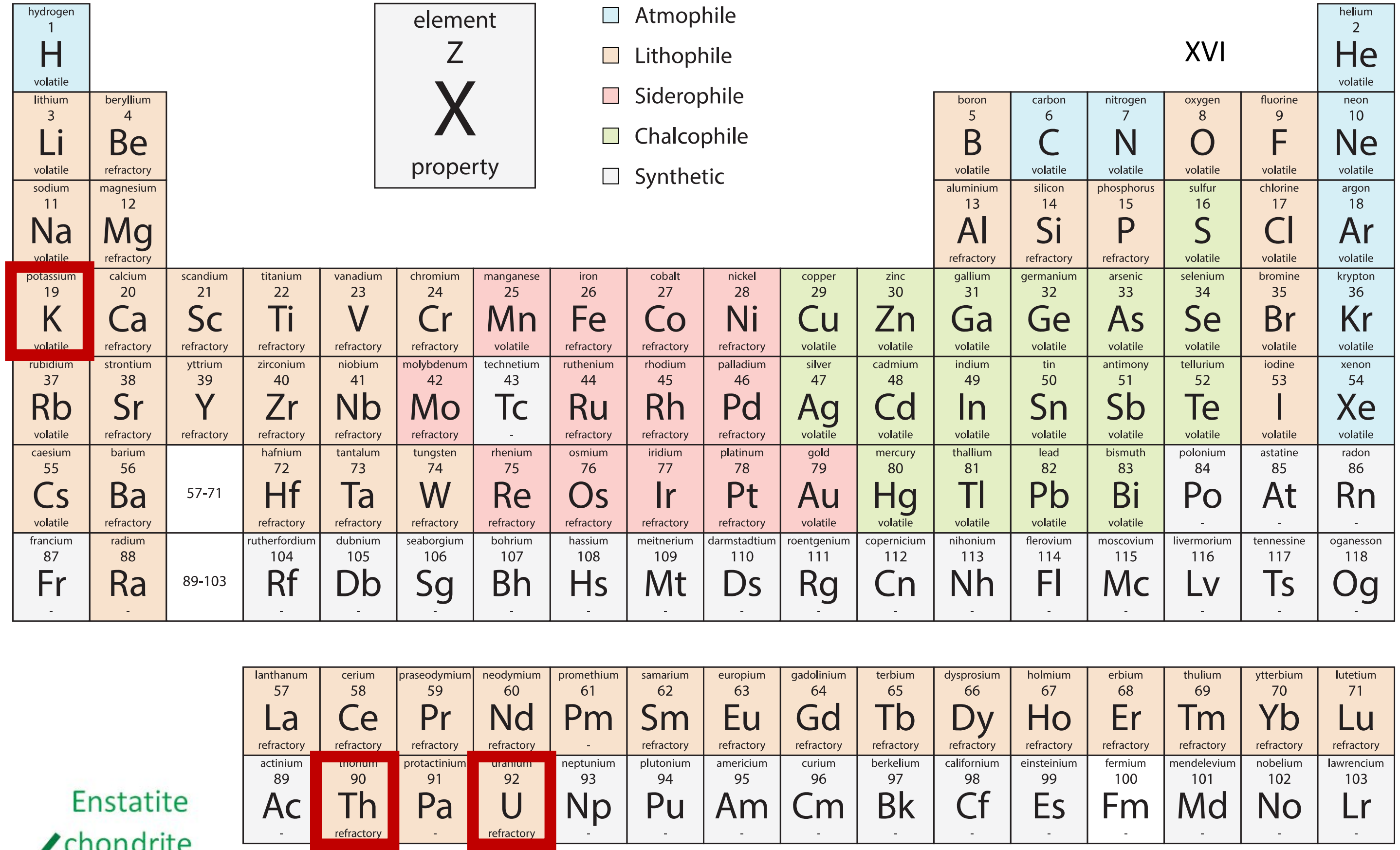
*The condensation temperatures are the temperatures at which 50% of the element will be in the form of a solid (rock) under a pressure of 10^{-4} bar.

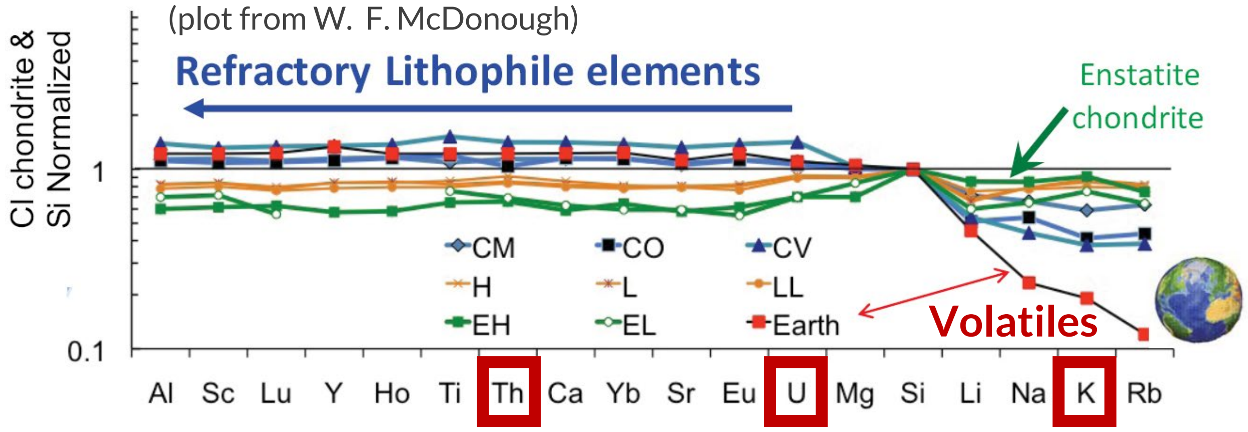
Chemical properties:

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

Condensation temperature* (T_C):

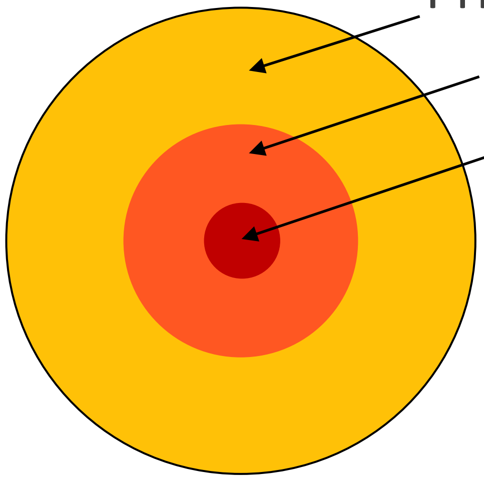
- **Volatile** ($T_C < 1300$ K)
- **Refractory** ($T_C > 1300$ K)





Earth evolution in a nutshell

1st differentiation

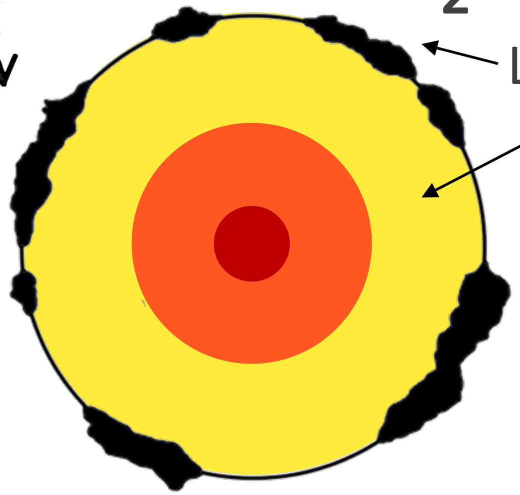


Primitive Mantle (PM) [M_{PM} ~68% M_{Earth}]
Outer Core (OC) [M_{OC} ~31% M_{Earth}]
Inner Core (IC) [M_{IC} ~1% M_{Earth}]

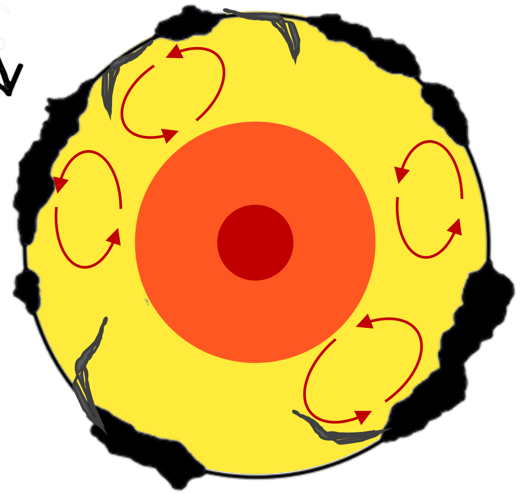
Siderophile elements
(chemical affinity with Fe)
in the Core

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

2nd differentiation

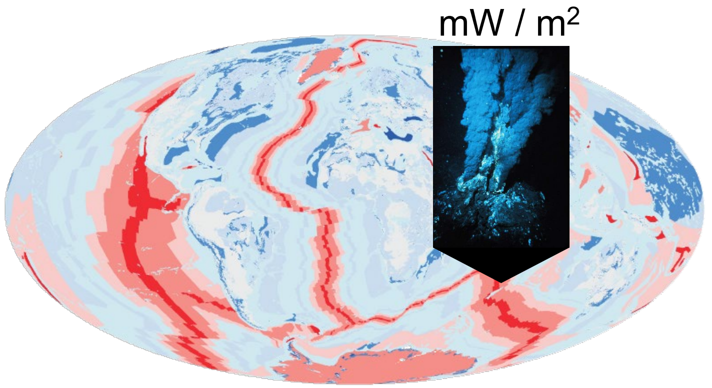


Lithosphere [M_{Lith} ~2% M_{Earth}]
Mantle [M_{Mantle} ~66% M_{Earth}]
OC+IC [M_{Core} ~32% M_{Earth}]



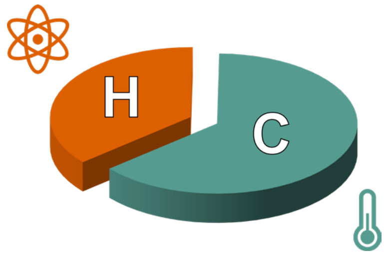
Convective and tectonic processes: formation of new crust (oceanic crust) and recycling of continental crust

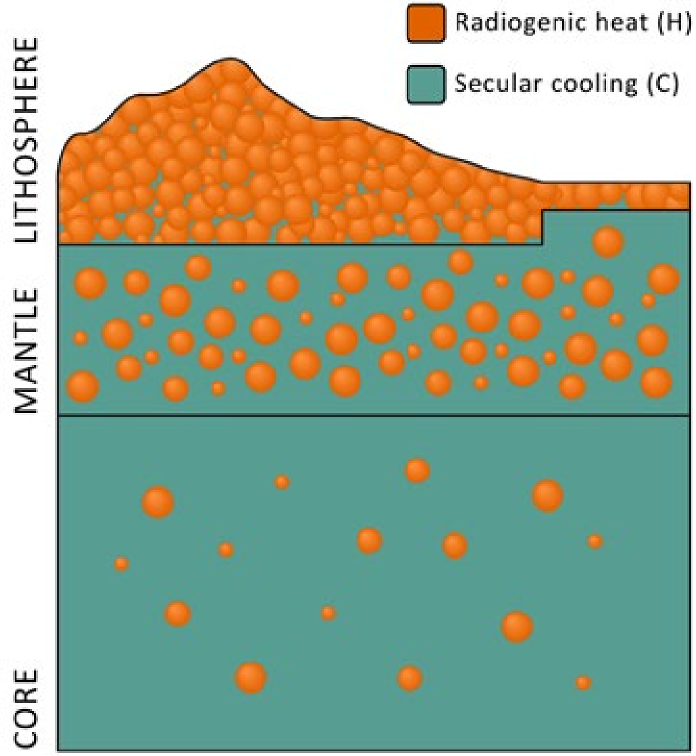
Earth's heat budget



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

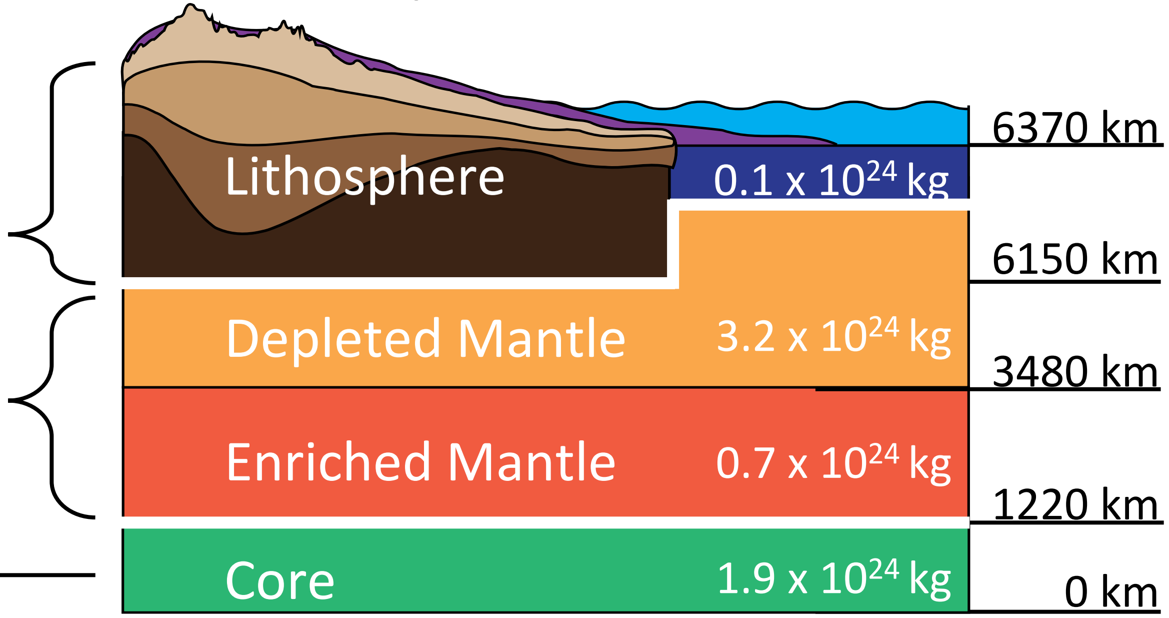
Despite deep Earth's structure is well understood, its chemical composition is not.

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

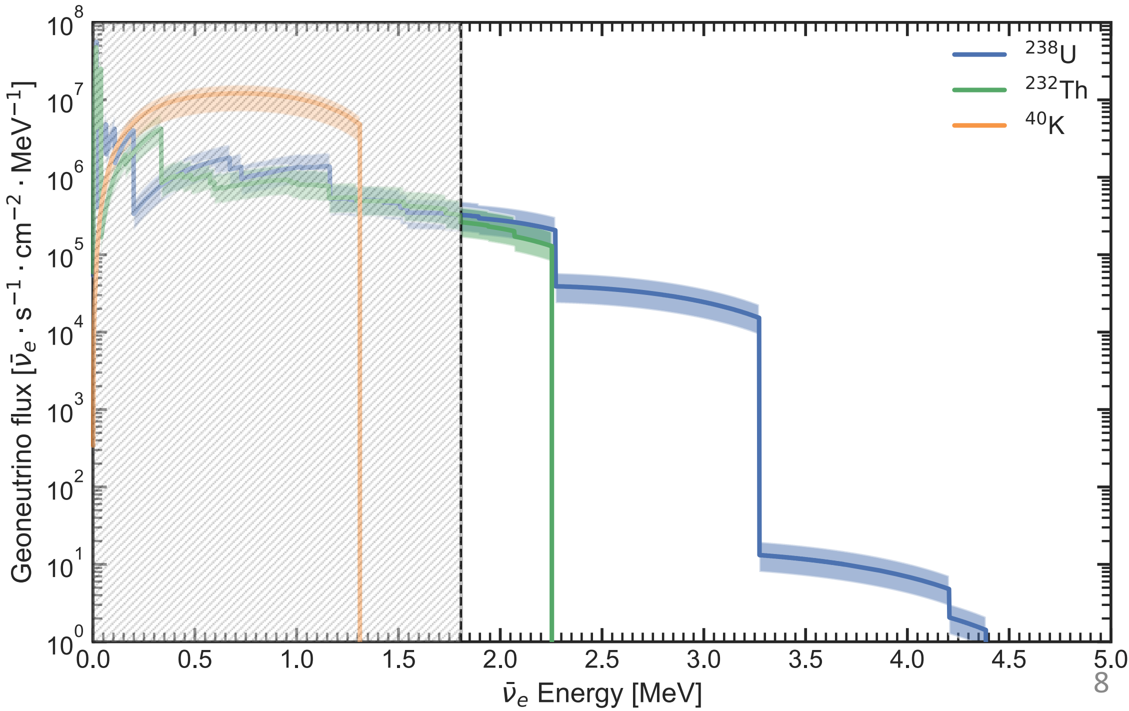
» Earth emits (mainly) $\bar{\nu}_e$ ($\Phi \backsim 10^7$ cm^{-2} s^{-1}) whereas Sun shines in ν_e ($\Phi \backsim 10^{11}$ cm^{-2} s^{-1})

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

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

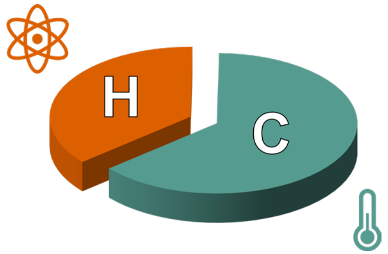
» Different components can be distinguished due to different energy spectra

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



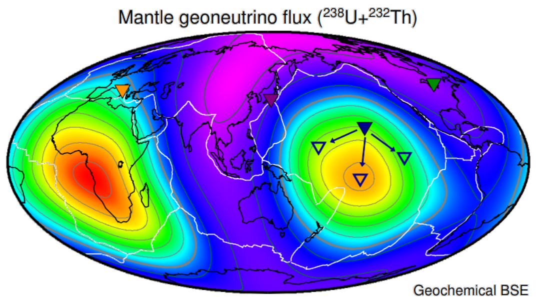
Open questions geoneutrinos can answer

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



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

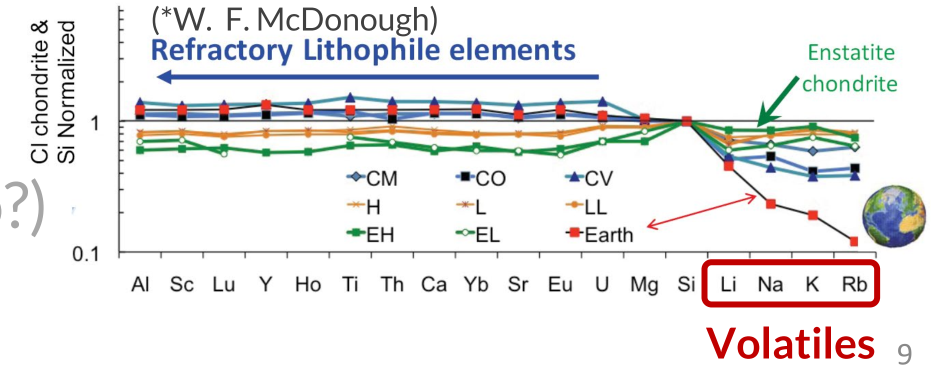
» What's the distribution of reservoirs in the mantle?



(Sramek et al. 2012)

» Are there any radiogenic elements in the core?

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

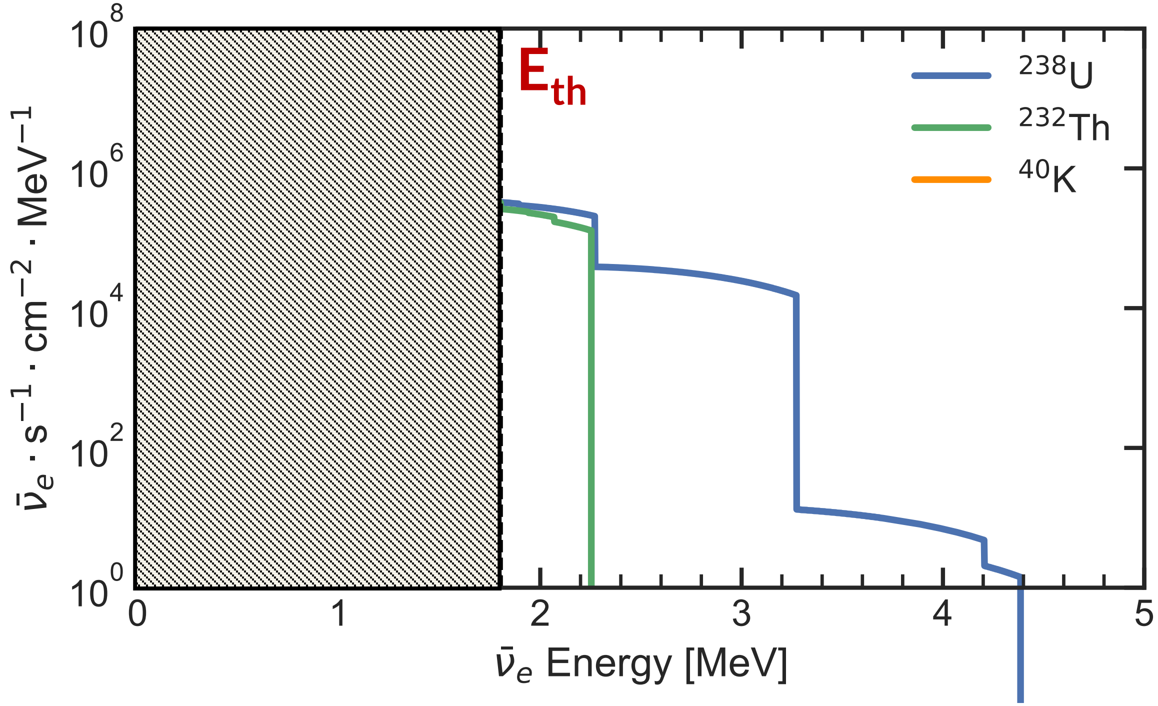


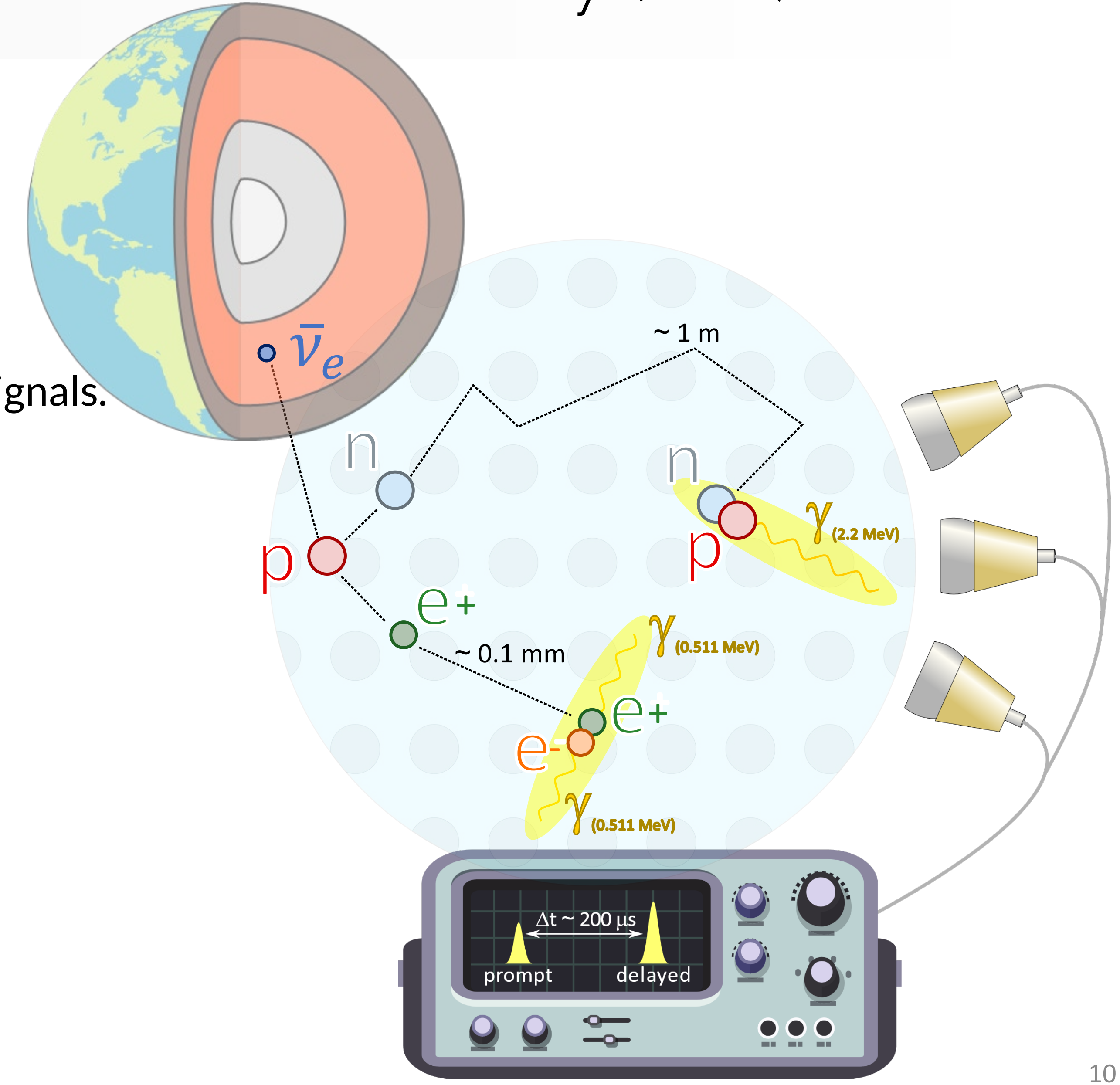
Detecting geoneutrinos: Inverse Beta Decay (IBD)

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

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

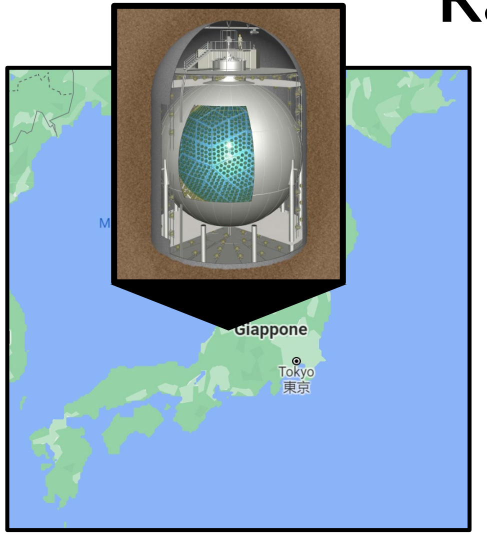
Detection requires the coincidence of 2 delayed light signals.
It does not permit to observe ^{40}K-$\bar{\nu}_e$

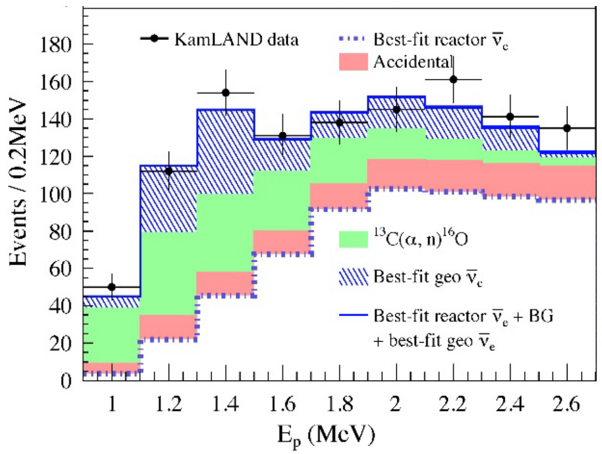




Borexino and KamLAND geoneutrino results

KamLAND



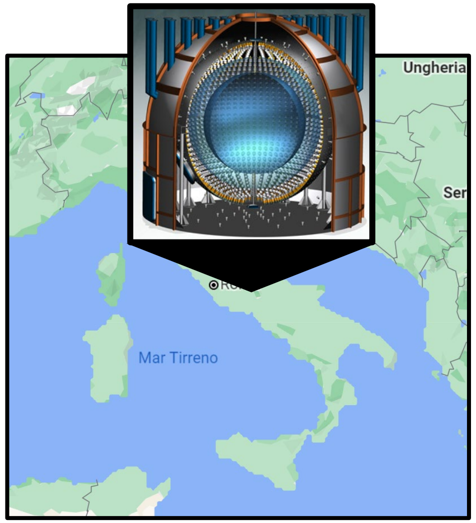


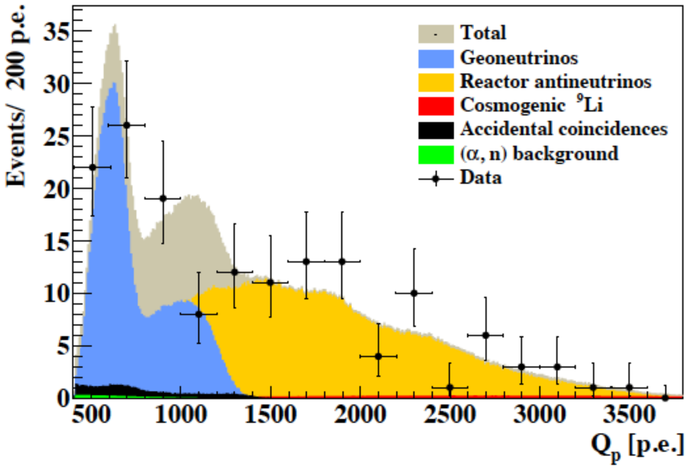
KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17” PMTs and 554 20” PMTs

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





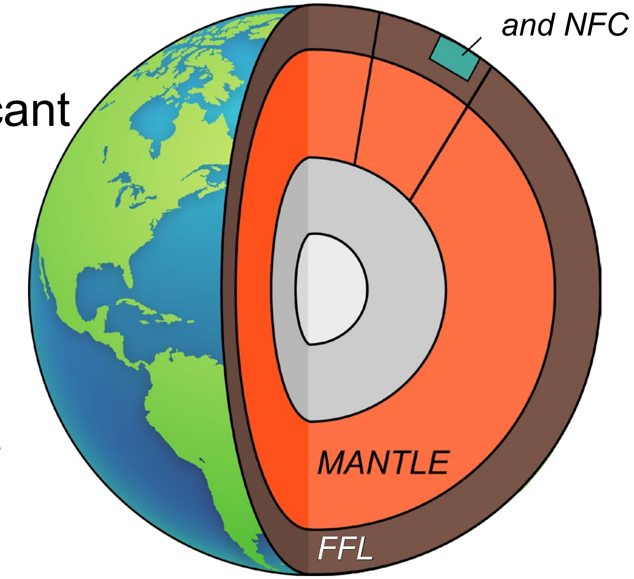
Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8” PMTs.

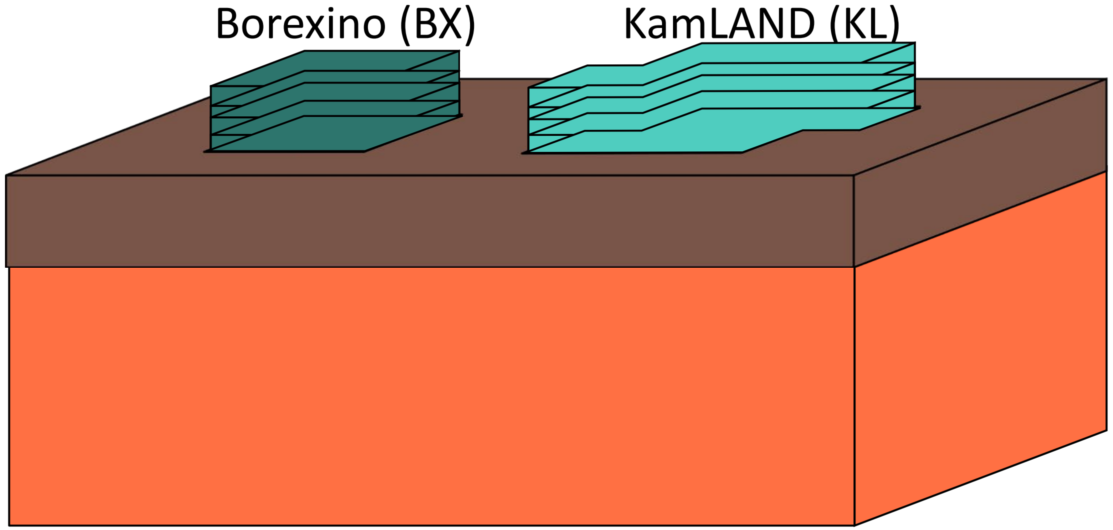
Data-taking: 2007-2019			
	U	Th	U+Th
Events	$41.1^{+7.5}_{-7.1}$	$11.5^{+2.2}_{-1.9}$	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$36.3^{+6.7}_{-6.2}$	$10.5^{+2.1}_{-1.7}$	$\mathbf{47.0^{+8.6}_{-8.1}}$

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**

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

Extracting the mantle signal: the rationale

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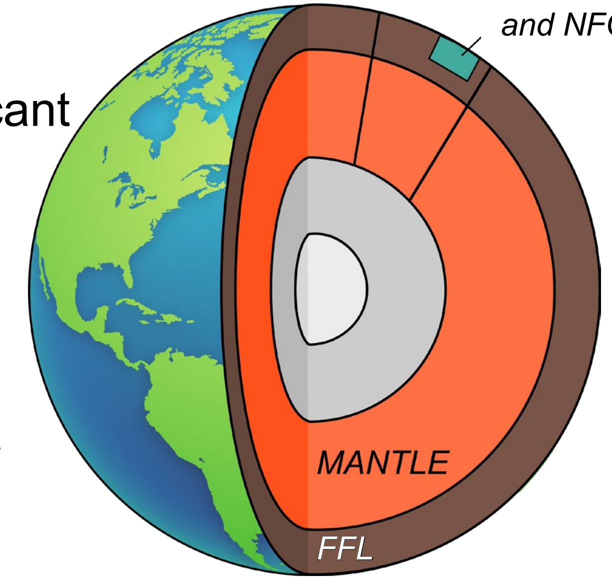
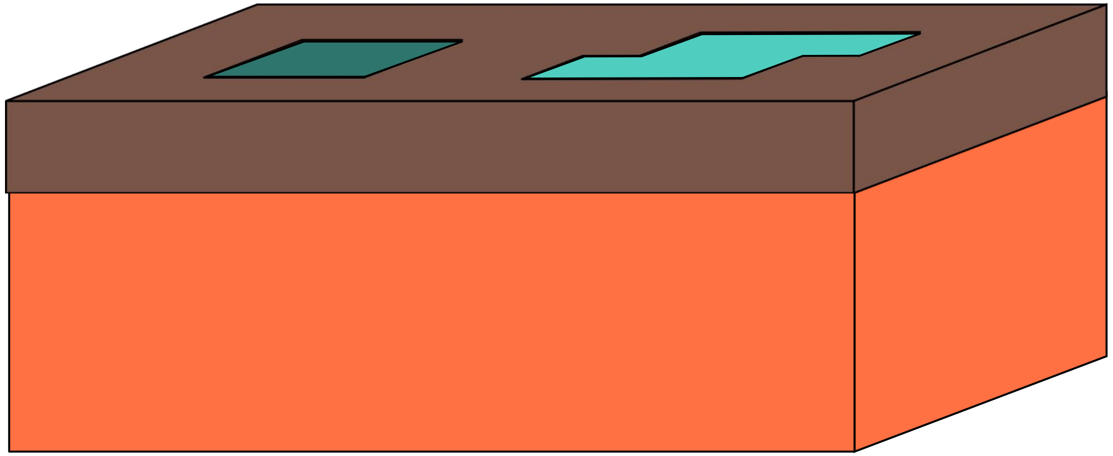




To be modeled

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

The geological models need to comply with the following constraints:

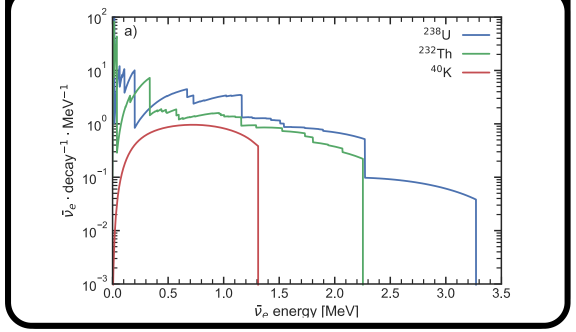
- **FFC** model needs to be the same for each *i*-th detector for avoiding biases.
- **NFC** should be built with geochemical and/or geophysical information typical of the local regions.
- **NFC** must be geometrically complementary to the FFC.

Modeling the geoneutrino signal

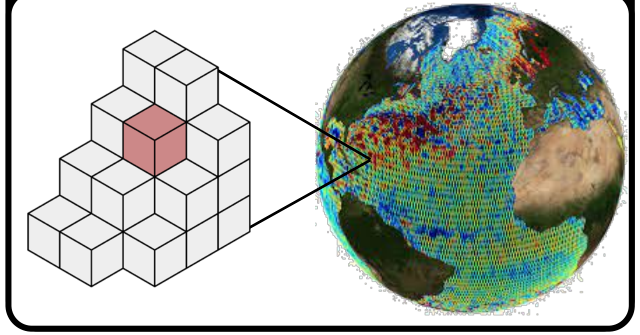
Production | **Propagation** | **Detection**

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

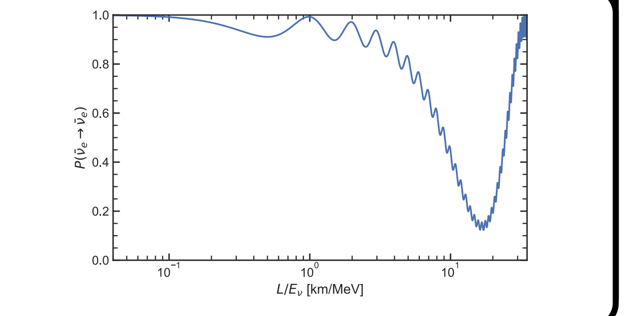
Isotopic β- spectra



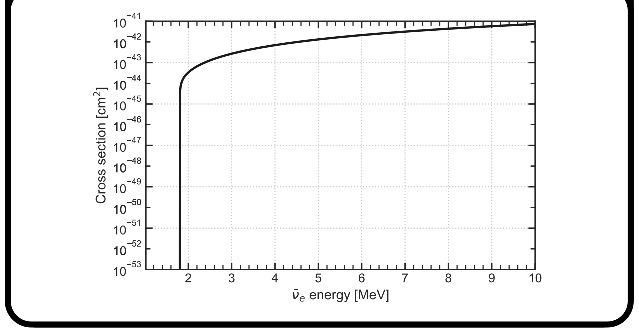
3D Earth model



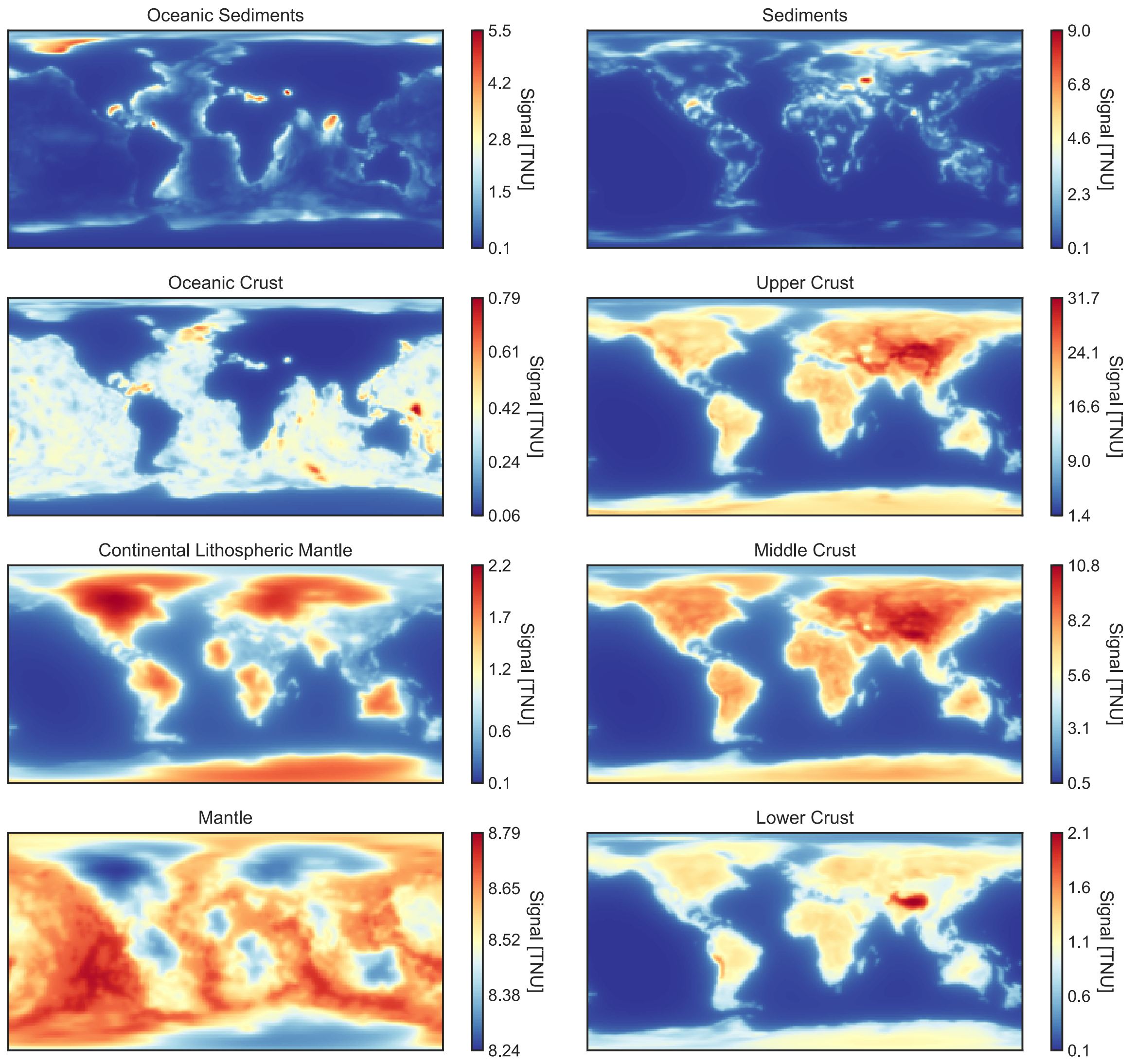
Survival probability

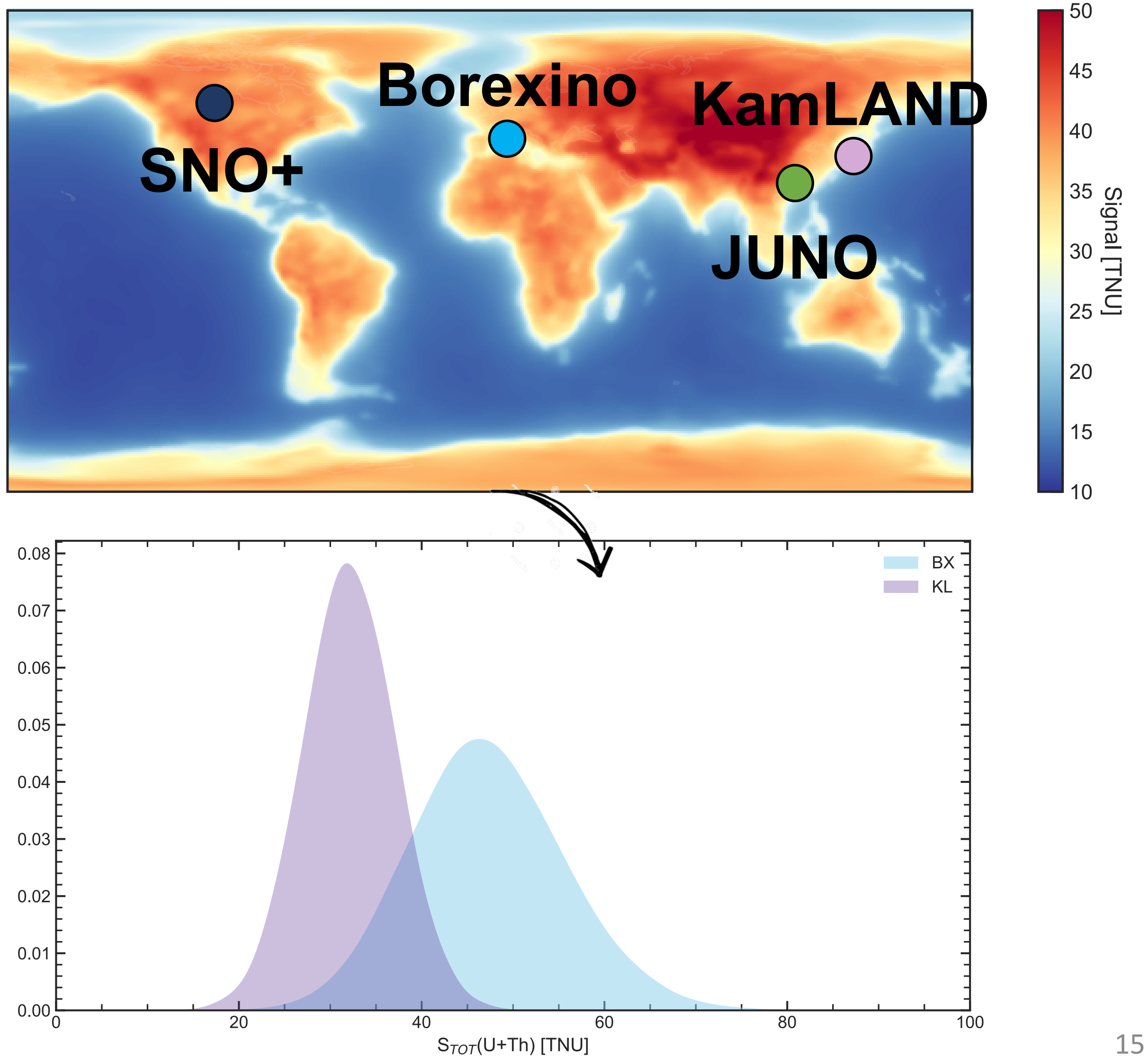


IBD cross section



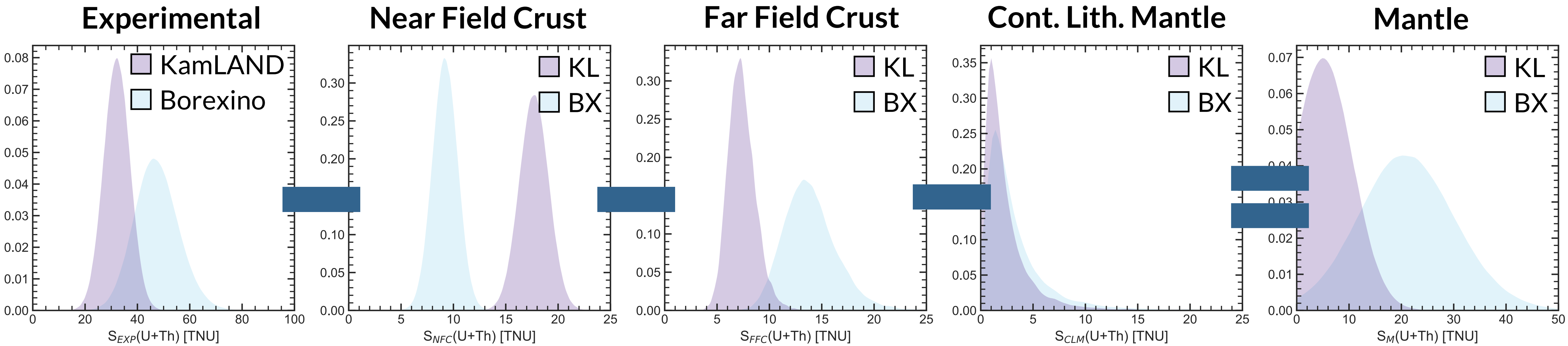
Modeling the geoneutrino signal for different reservoirs





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:



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

		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:

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

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

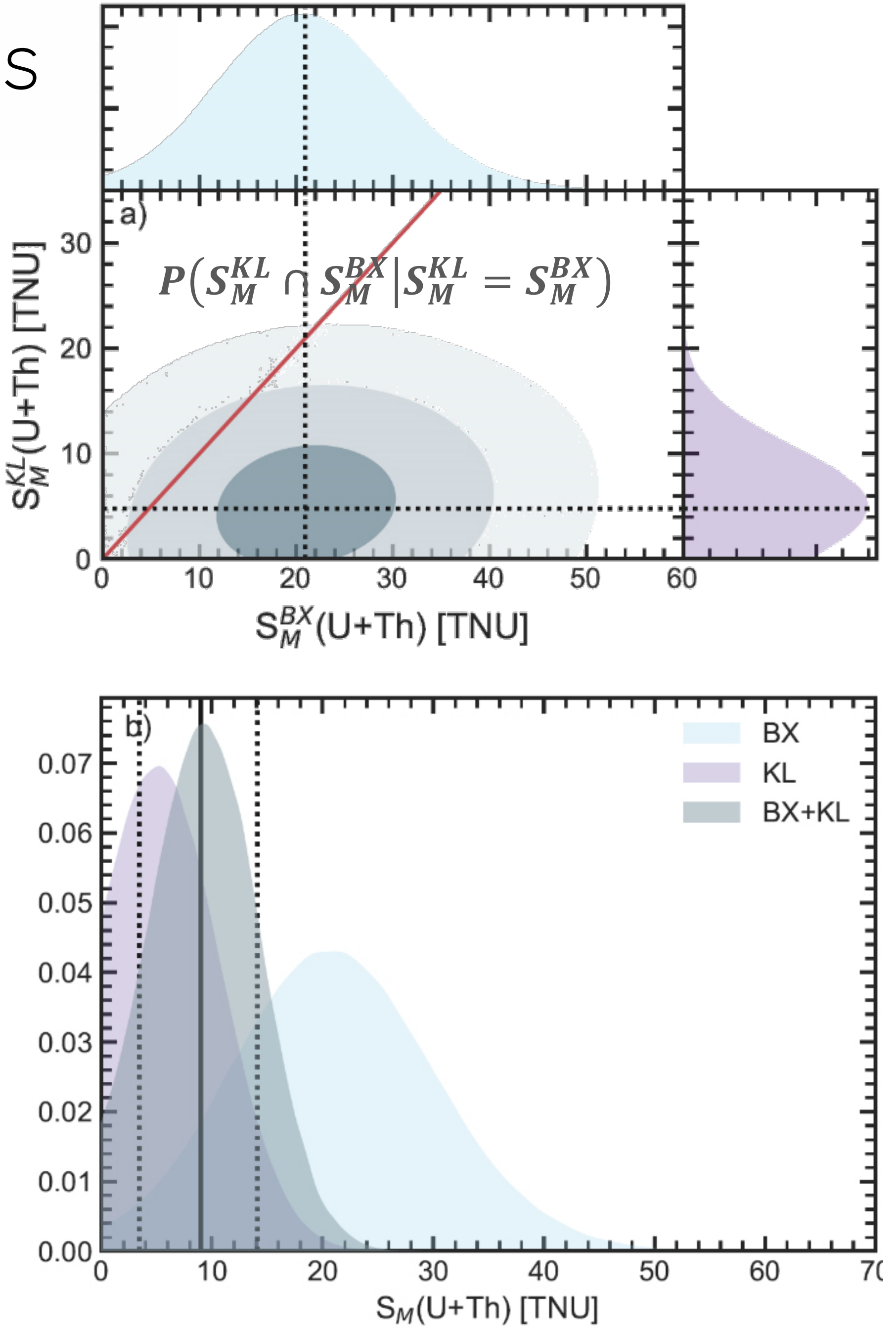
$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ TNU$$

Where correlations need to be properly accounted for:

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

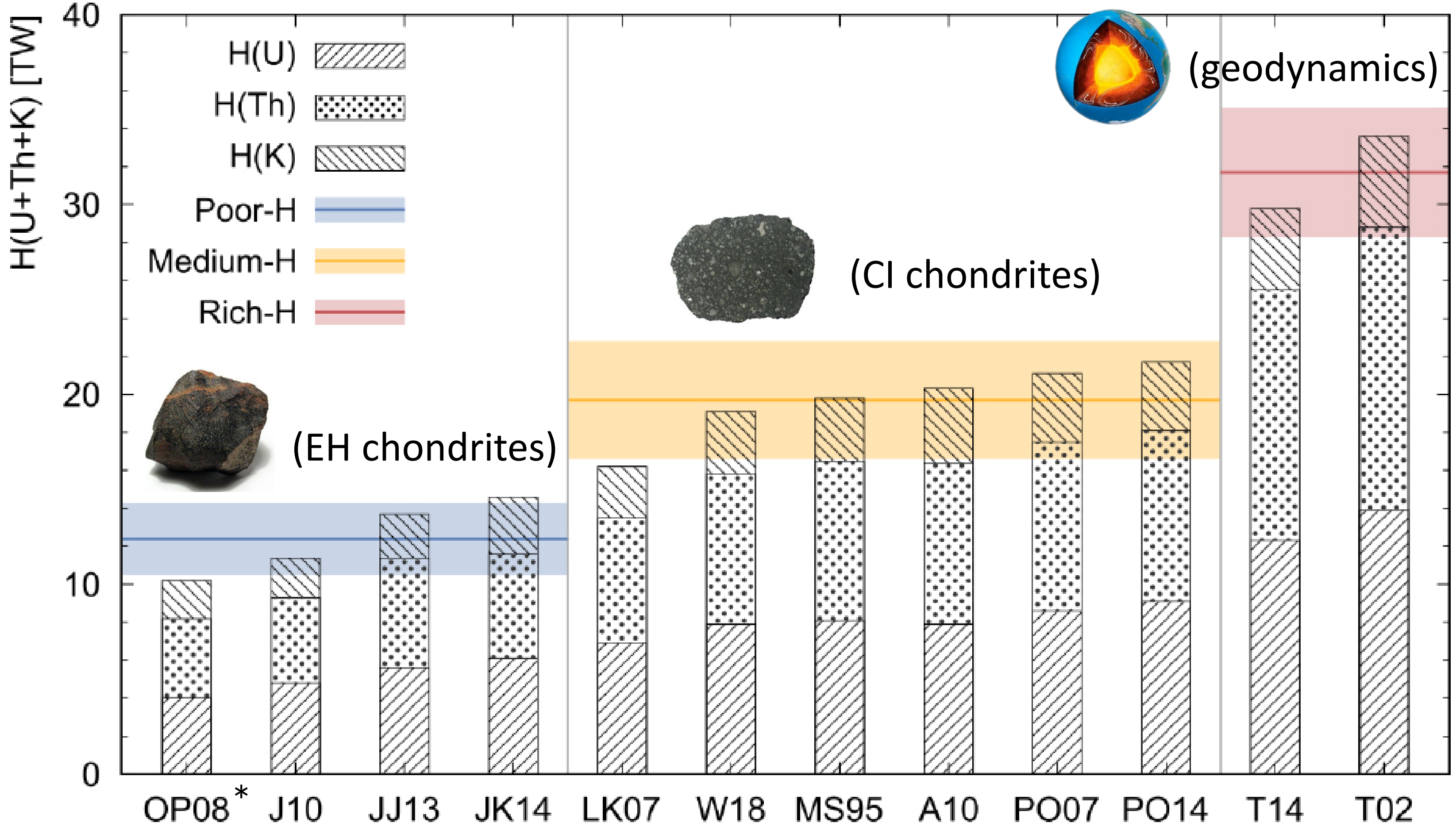
» $S_{CLM}^{KL}(U+Th) \propto S_{CLM}^{BX}(U+Th)$

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



*AAYY – Author year acronym

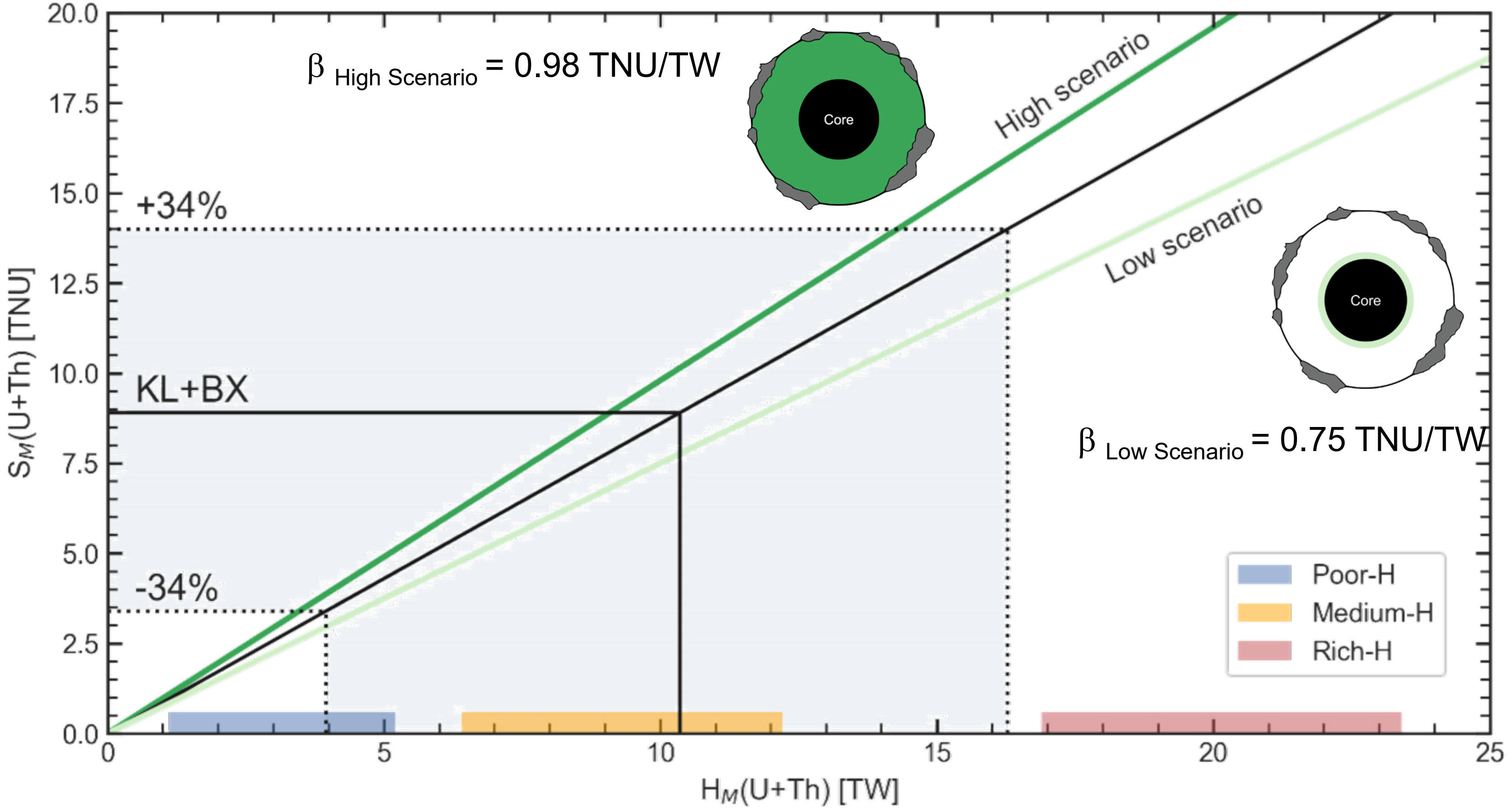
Bulk Silicate Earth Models



	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 $H_M(U+Th)$:

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

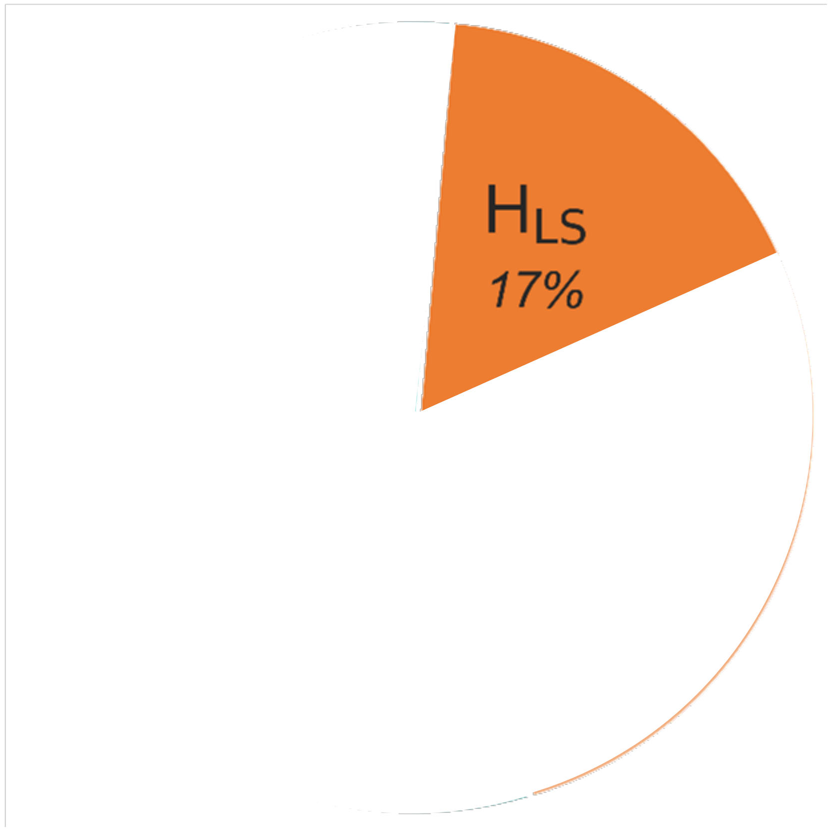
	Poor-H	Medium-H	Rich-H	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

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



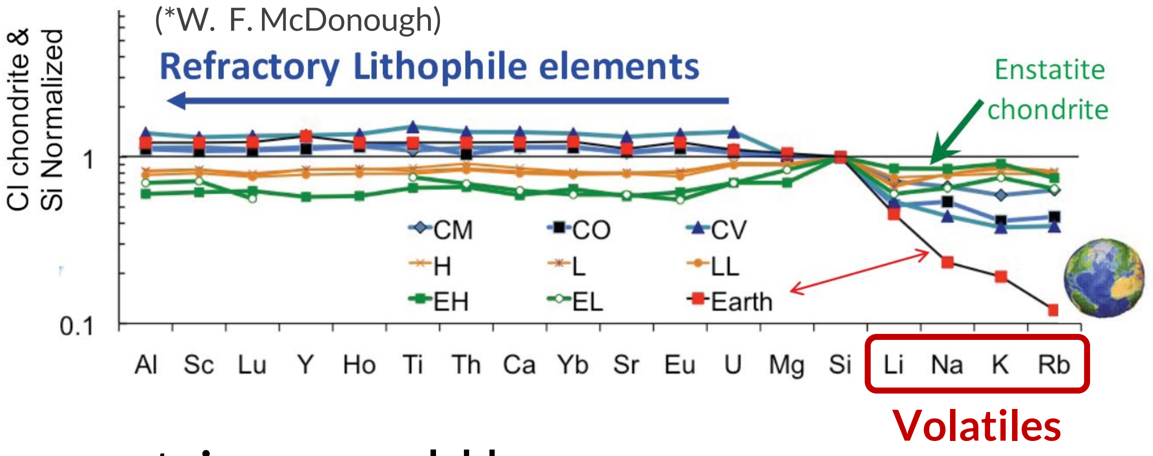
Geoneutrinos and geoscience: an intriguing joint-venture
Bellini et al.
Riv. Nuovo Cim. 45, 1–105 (2022).

^{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.

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.

A quick summary

» 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 feasible experimental path identified for their detection

^{40}K-geoneutrino detection

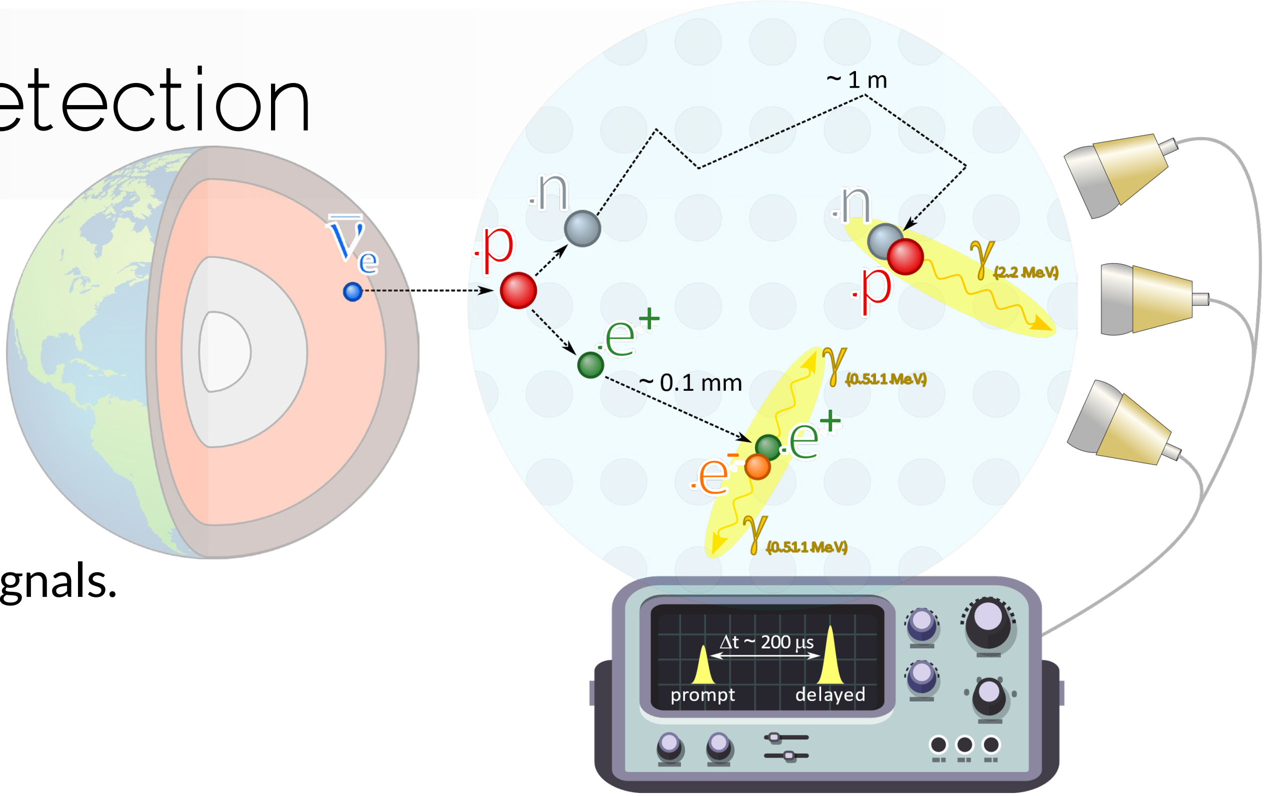
Revealing the missing piece in Earth's thermal puzzle

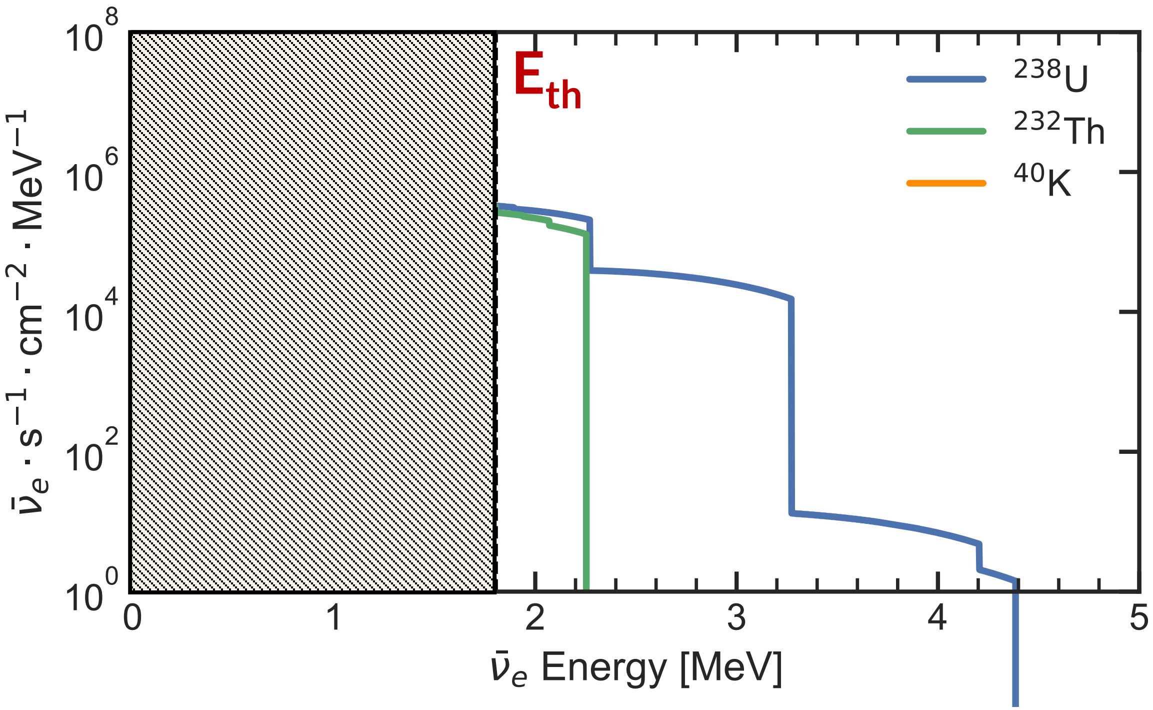
Inverse Beta Decay (IBD) detection

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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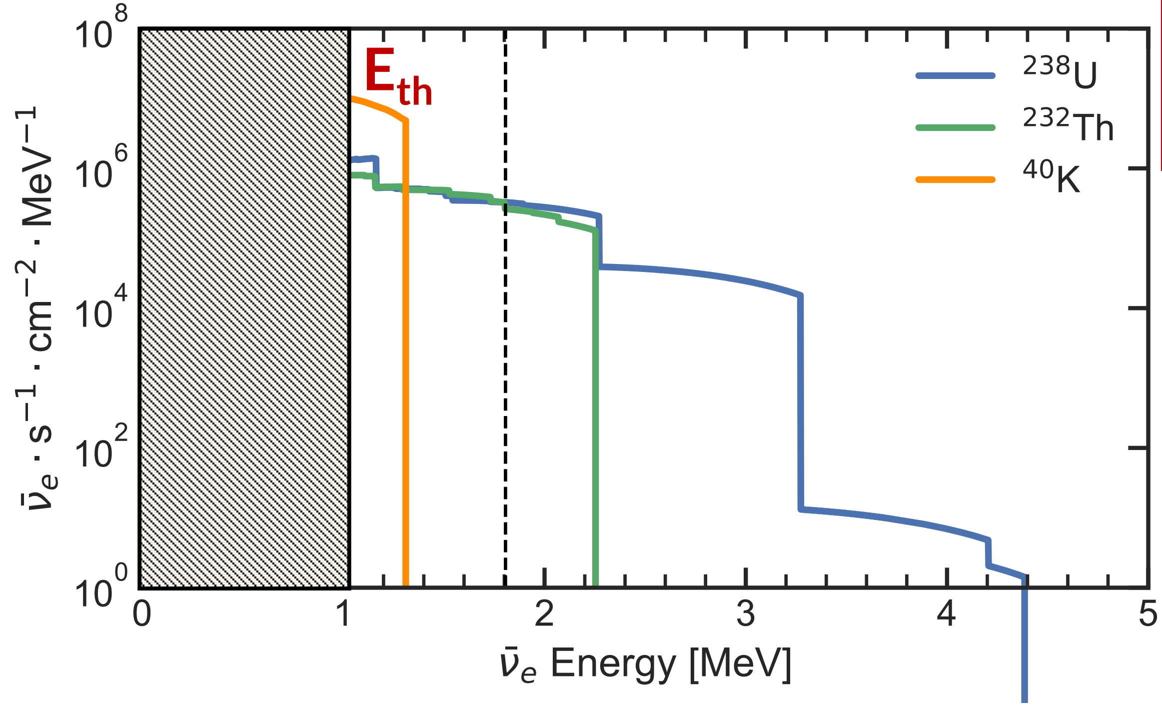

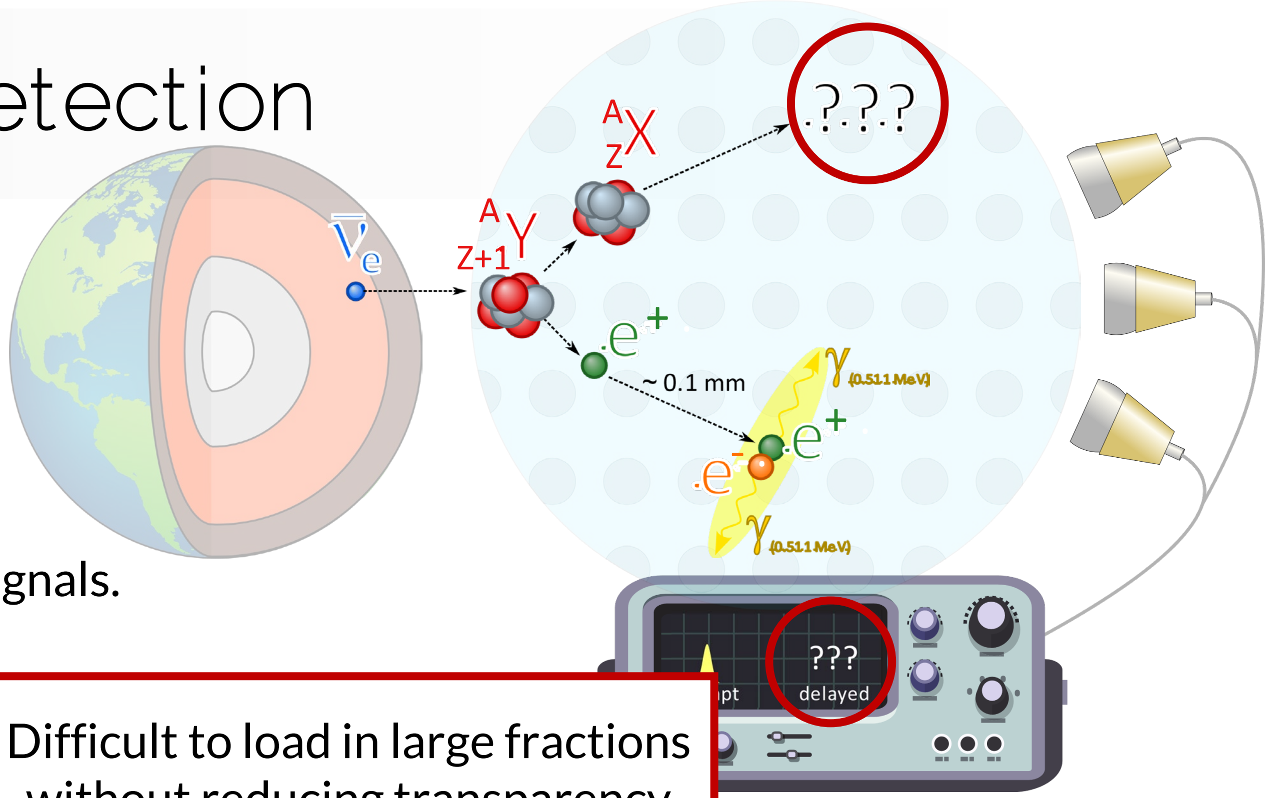

Difficult to load in large fractions without reducing transparency

e 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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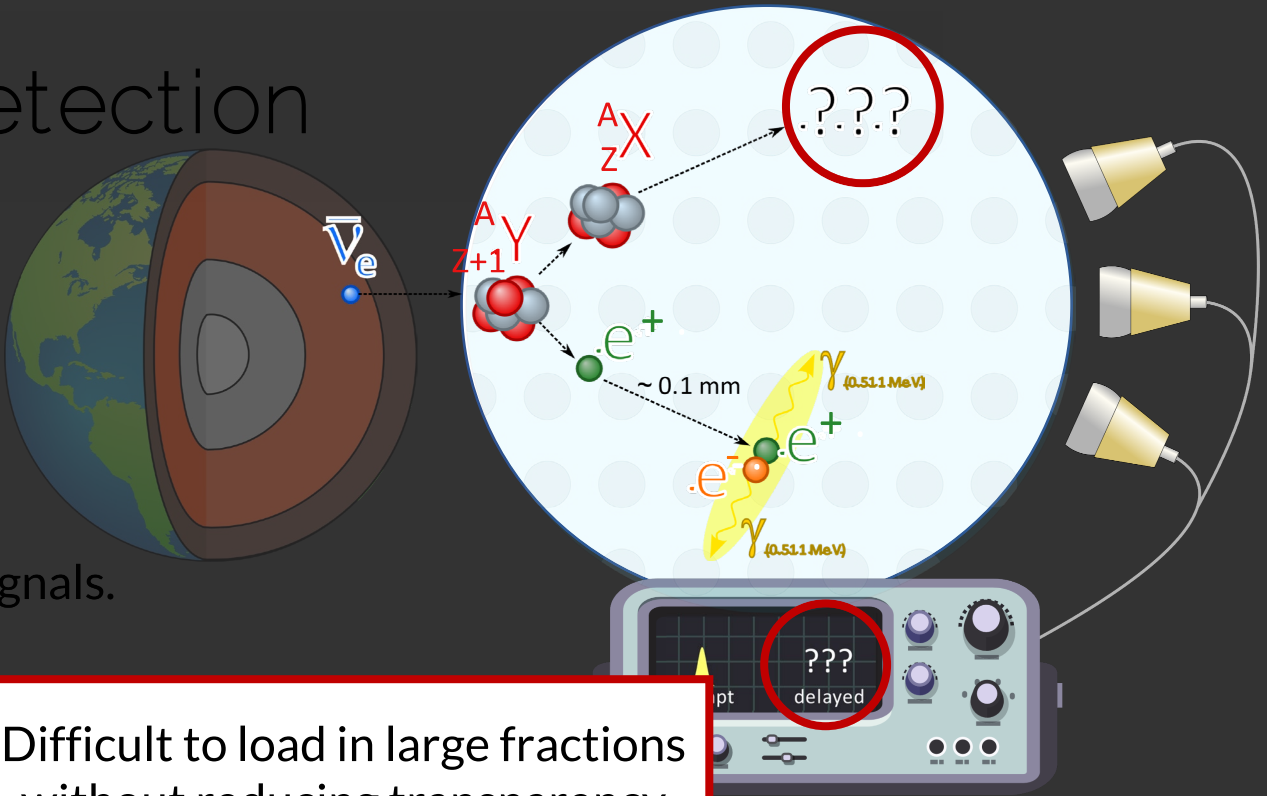

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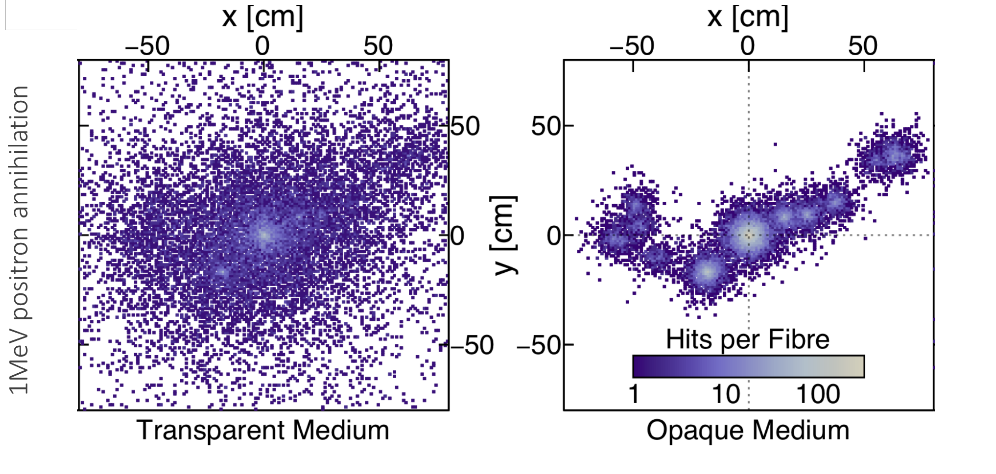
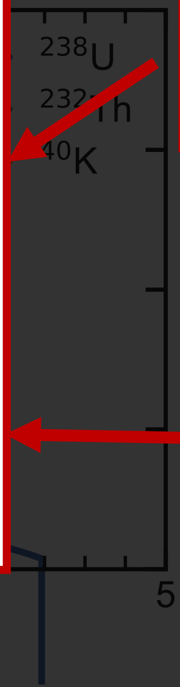


Neutrino physics with an opaque detector.
Cabrera et al.
Commun. Phys. 4, 273 (2021)



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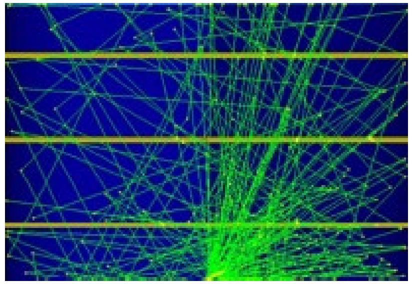
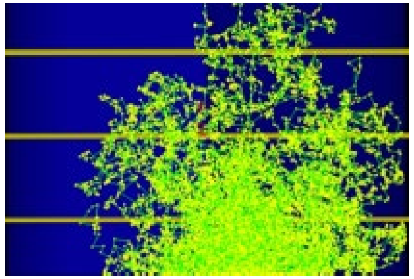
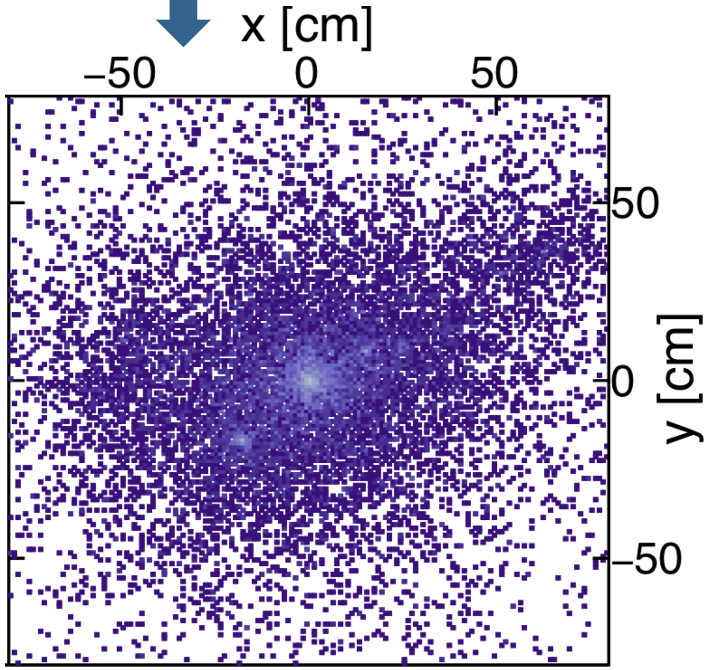
LiquidO: a new detection technique

Long scattering length (>10 m)

Short scattering length (<1 cm)



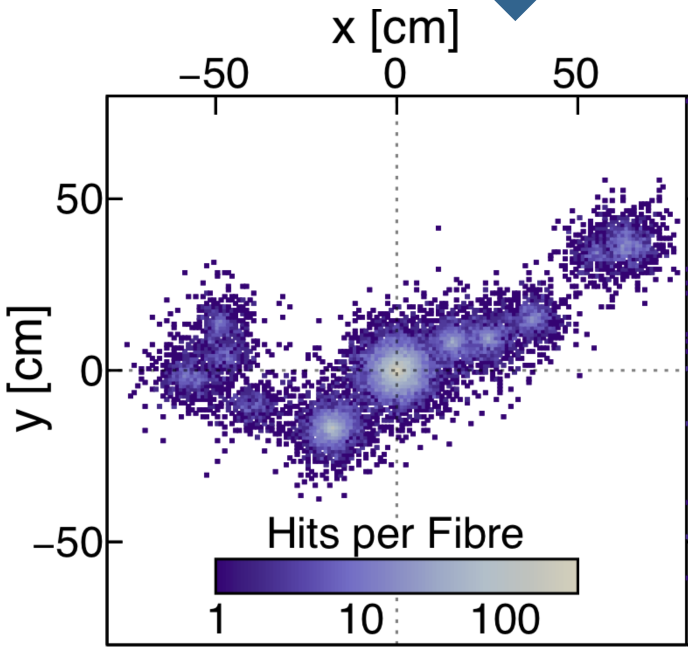




Transparent Medium

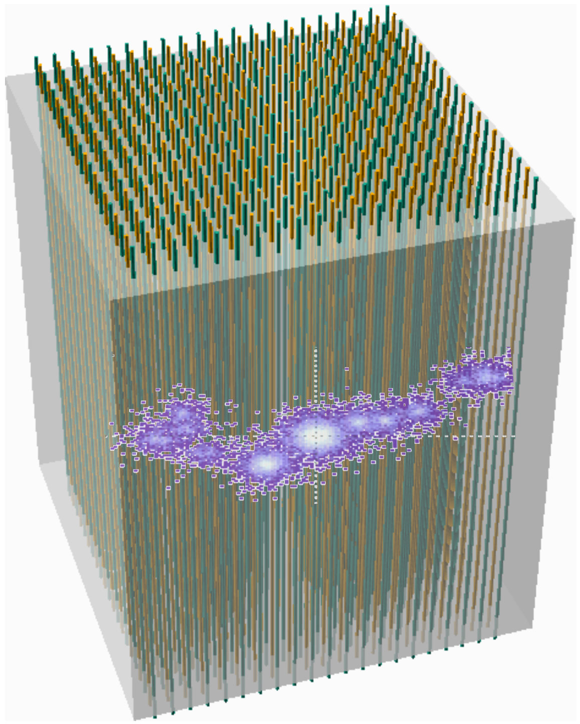
Stochastic light confinement
(self-segmentation)

Tolerance to opacity



Opaque Medium

LiquidO PID capabilities



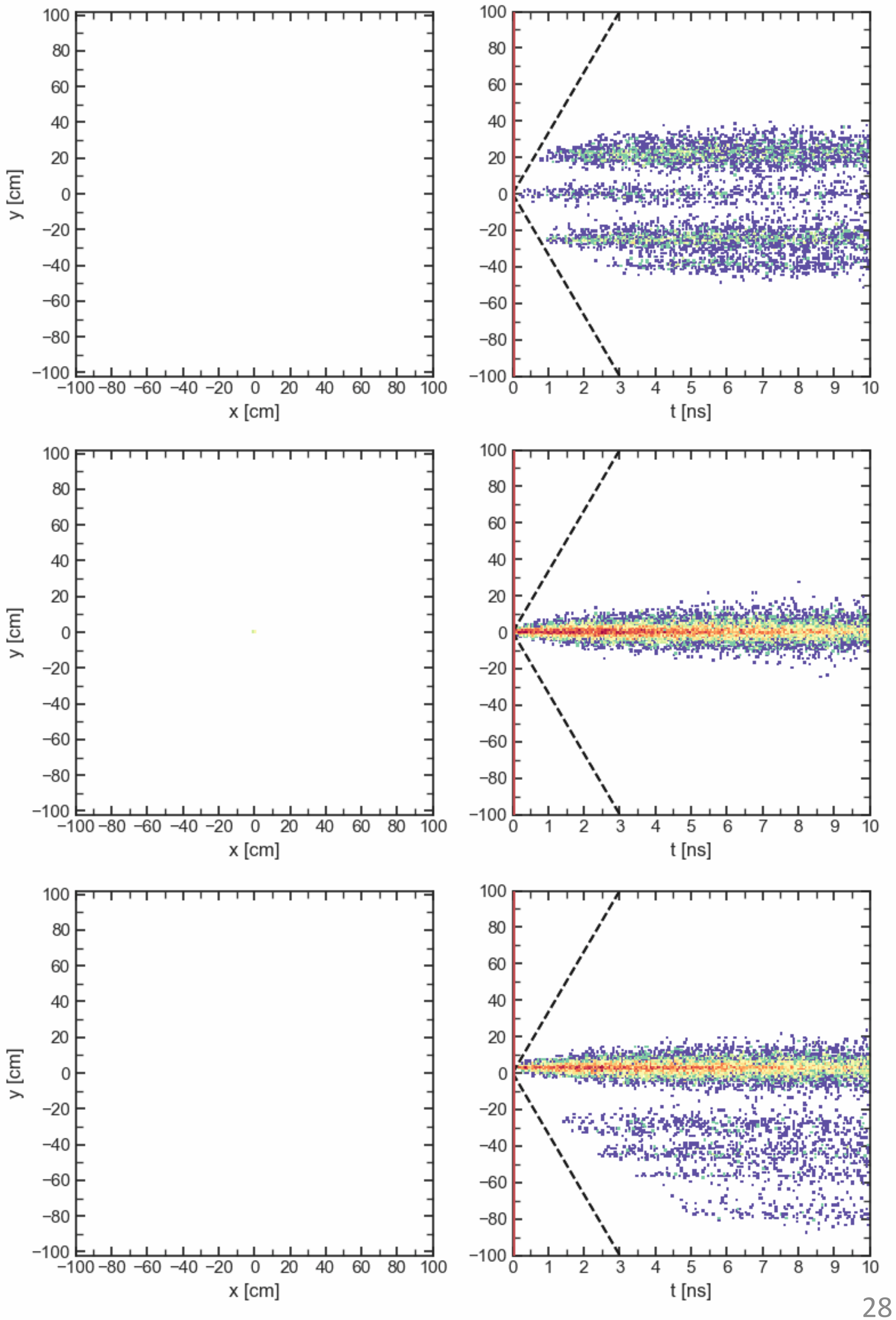
The idea: array of fibers read out by SiPMs

Several possible configurations:
(X,Y and possibly Z): topology → mm resol.
(T): timing → <100 ps resol.

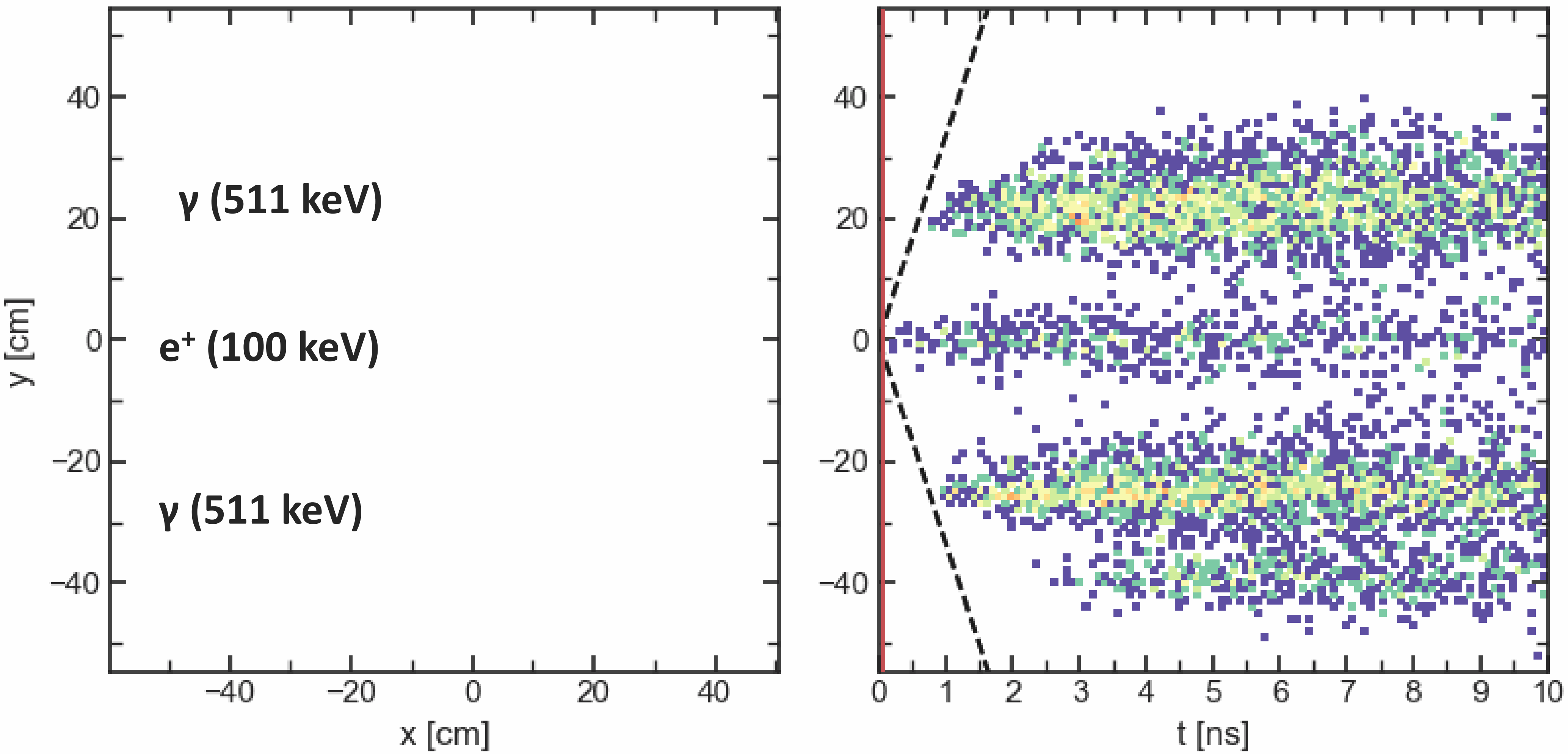
e^+ (100 keV)

e^- (2.1 MeV)

γ (2.1 MeV)



Detecting single e⁺ in LiquidO



→ **5D imaging**: space (x, y, z), time (t) and energy (E)

Looking for possible ^{40}K-geoneutrino IBD targets

List of ingredients for ^{40}K geoneutrino detection:

- Methodology to load heavy isotopes → **LiquidO tolerance to opacity** ✓
- Capability to detect single e^+ → **LiquidO PID capabilities** ✓
- Isotope capable of IBD with threshold < 1.3 MeV (^{40}K endpoint) → ?

β^- reaction and IBD share the **same matrix element** (dominated by the ft parameter)

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

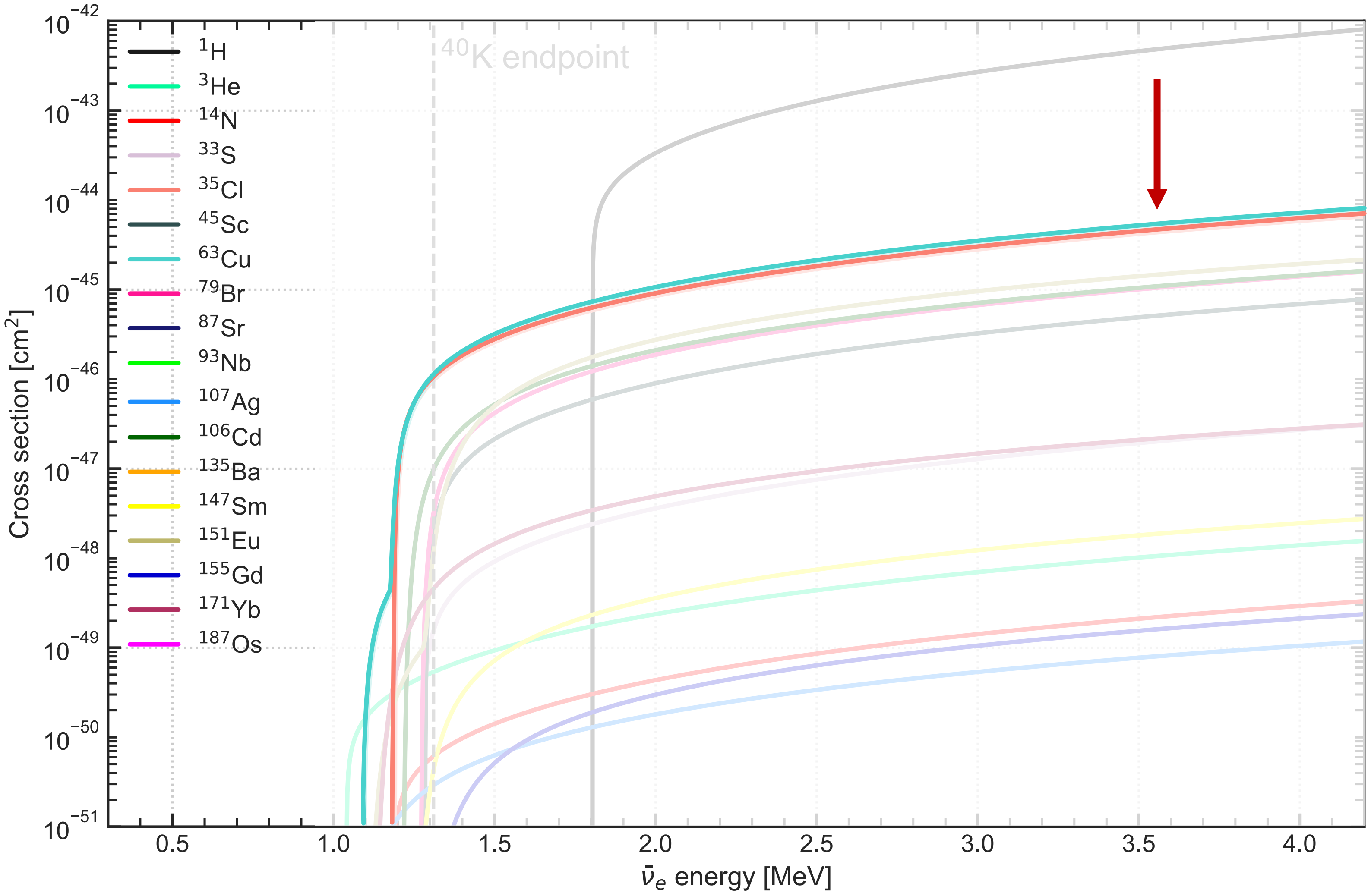
$$\bar{\nu}_e + {}_{Z}^{A}X \rightarrow e^+ + {}_{Z-1}^{A}Y - (Q_\beta + 1.022\ MeV)$$

$$ft \longrightarrow \sigma(E) = \frac{2\pi^2 \ln 2}{ft\, m_e^5}\, p_e E_e F(Z,E,R) \frac{(2J_f + 1)}{(2J_i + 1)}$$

Scan of all β^- emitters with Q_β<0.3 MeV → **17 candidates found:**
^{3}He, ^{14}N, ^{33}S, ^{35}Cl, ^{45}Sc, ^{63}Cu, ^{79}Br, ^{87}Sr, ^{93}Nb, ^{106}Cd, ^{107}Ag, ^{135}Ba, ^{147}Sm, ^{151}Eu, ^{155}Gd, ^{171}Yb and ^{187}Os

Previously only 9 of these have been known/considered (Krauss, L. et al., Nature, 1984)

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)

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

There are only **few possible irreducible 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 → **can be reduced with purification**
  - natural β^+ emitting isotopes in the target element → **irreducible**

^{35}Cl

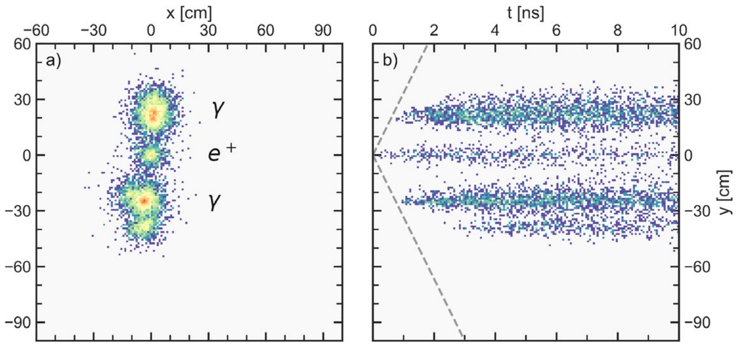
- can be loaded as solut[illegible]he LS or as chlorinated benzene scintillating c[illegible]unds ✓
- Cl contains ^{36}Cl (~1[illegible]), wh[illegible] produces ~10^{10} e^+ per year per 10^{32} chlo[illegible]ne atoms ✗

^{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

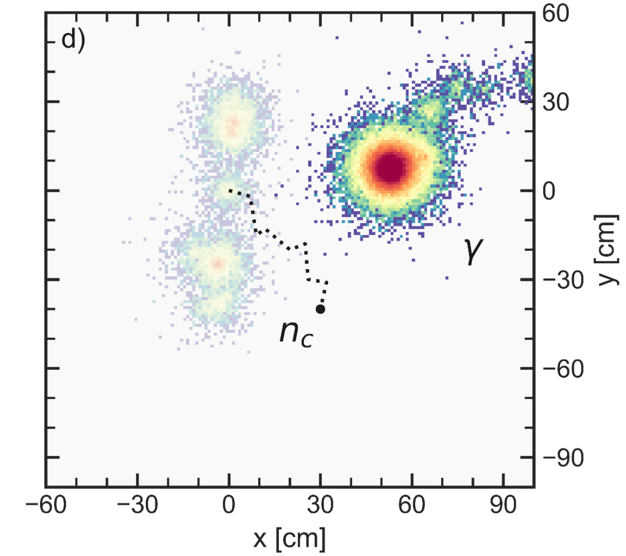
A scintillator loaded with copper will offer **two distinct detection channels**:
IBD on protons (IBD-p) and IBD on copper itself IBD-^{63}Cu

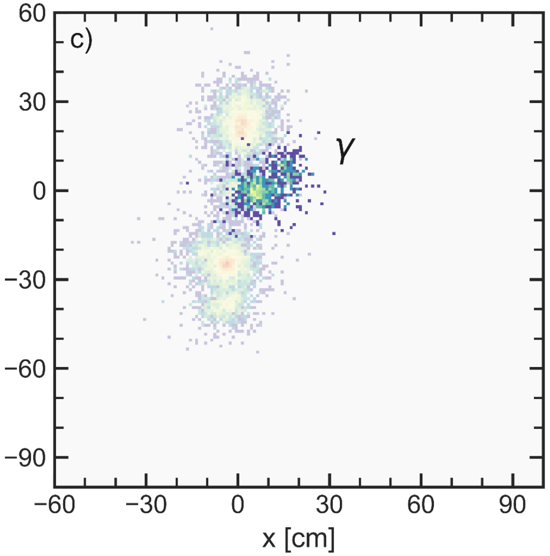


	IBD-p	IBD-^{63}Cu
Reaction	$\bar{\nu}_e + p \rightarrow n + e^+$	$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$
Prompt	$e^+ + e^- \rightarrow 2\gamma$ $(511\ keV)$	$e^+ + e^- \rightarrow 2\gamma$ $(511\ keV)$
Delayed	$n + p/Cu \rightarrow d/Cu + \gamma$ $(> 2.2\ MeV)$	${}^{63}Ni^* \rightarrow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

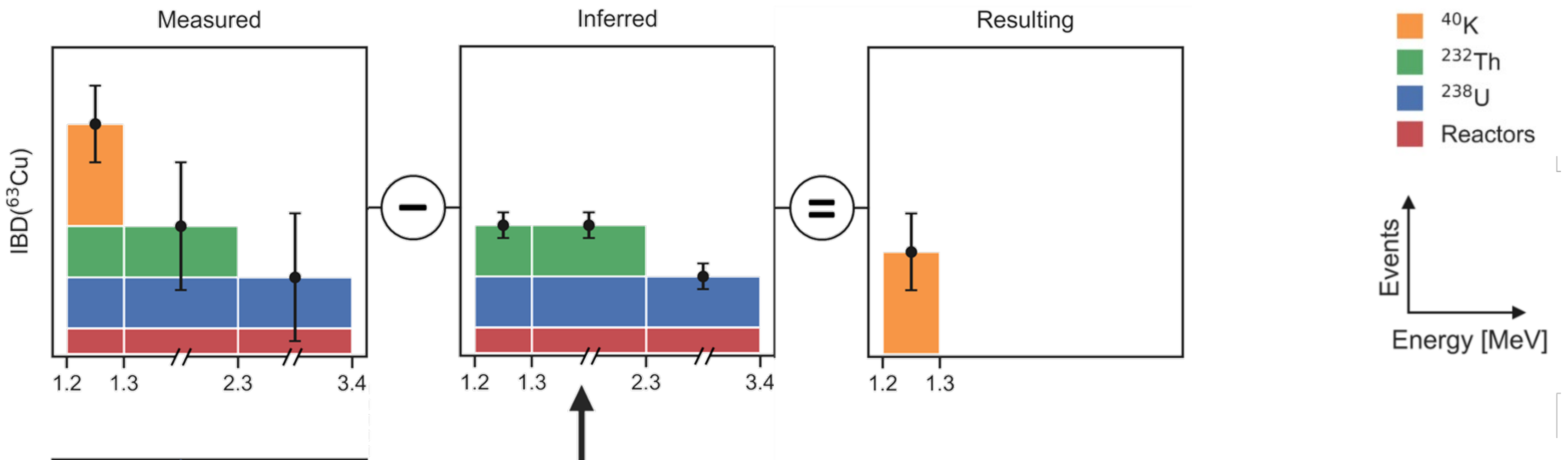
$\sim 200\ \mu s$ (IBD-p, prompt to delayed)

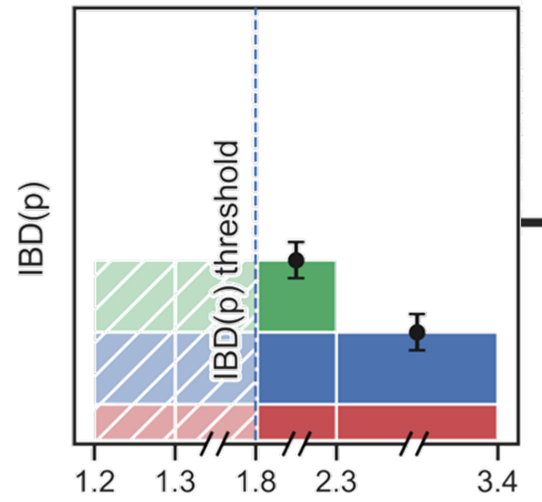
$\sim 2\ \mu s$ (IBD-^{63}Cu, prompt to delayed)

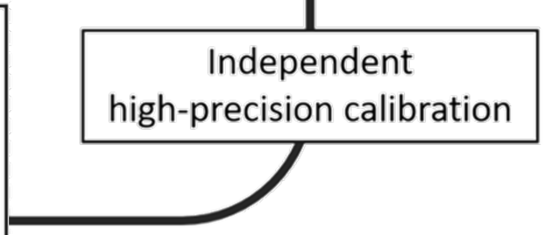




Rationale for signal extraction







Side effect: σ_{stat} < 1% on S(*U+Th+reactors*)

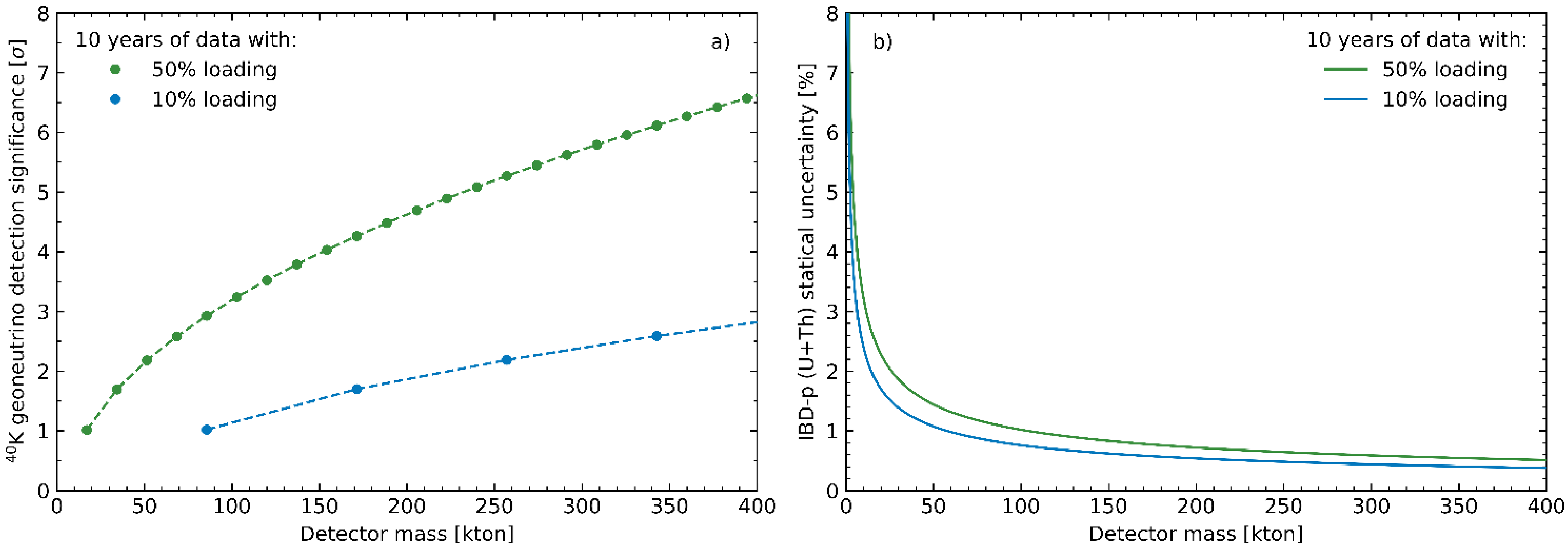
		Events/10y/240kton			
Detection reaction	**Energy range**	**Reactors**	^{238}**U**	^{232}**Th**	^{40}**K**
IBD(p)	[1.806 – 3.27] MeV	19530	27750	7948	/
IBD(^{63}Cu)	[1.176 – 1.311] MeV	0.2	1.1	1.1	11.7

Detection significance

The **detection significance** can be calculated from a **Poisson probability** of the hypothetical observation of N or greater events compared to the null hypothesis that the experimental observation came from only backgrounds.

Statistical and "systematic" uncertainties

$$\sum_{n=N}^{\infty} P(n;\ \mu + \Delta\mu)$$



Experimental roadmap

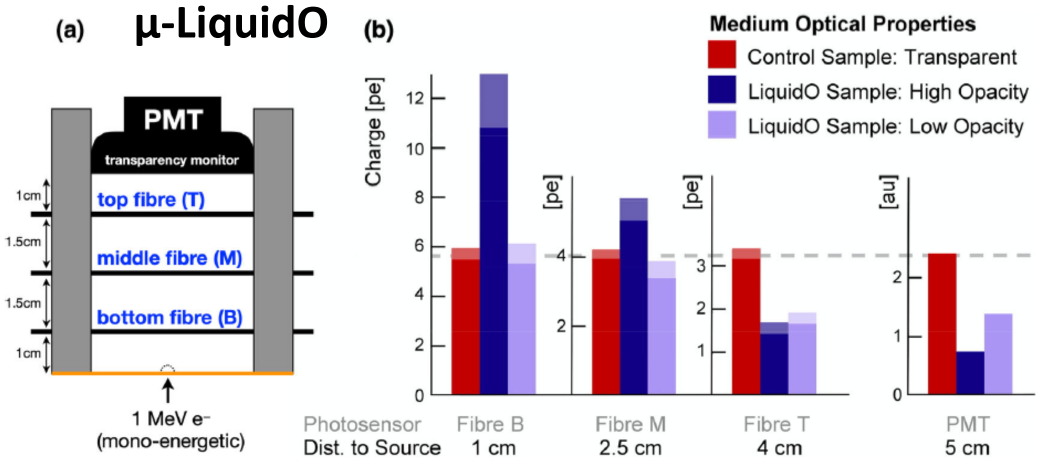
^{40}K geoneutrino detection is **challenging**, but **no showstopper** a priori. Methodology relies on new **LiquidO** technology, under **R&D**:

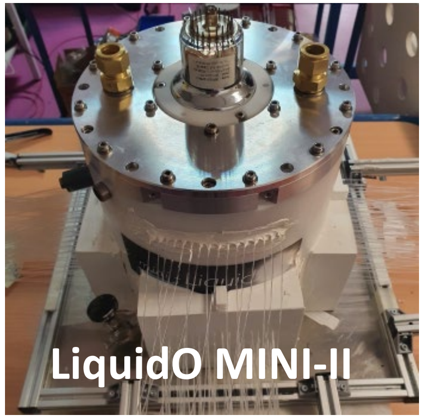
2020
μ-LiquidO – proof of principle (light confinement)

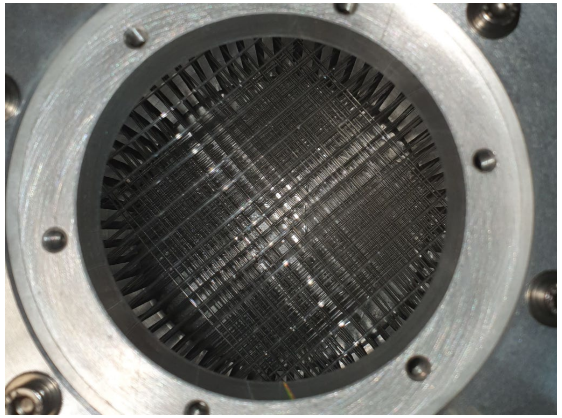
2021 - present
LiquidO's MINI-II prototype

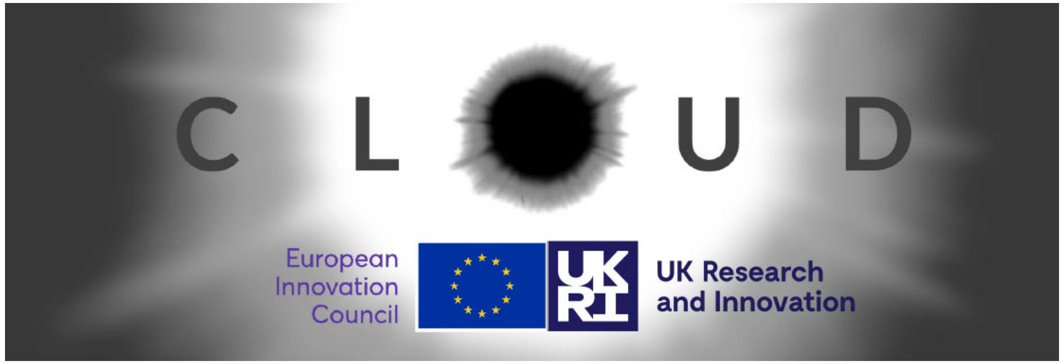
Future (present)
CLOUD project funded and headed to construction
https://liquido.ijclab.in2p3.fr/nucloud/

→ testing ^{63}Cu cross-section with reactors
→ testing full methodology with reactor IBDs (different loading, scintillator R&D, etc.)









Final remarks

K is essential in understanding Earth's **thermal evolution** and **volatility** pattern.
A direct ^{40}K-$\bar{\nu}_e$ detection would rule out exotic scenarios on the fate of "**missing K**".

At present time, K-$\bar{\nu}_e$ remains undetected:

- **17 isotopes** suitable **for ^{40}K-$\bar{\nu}_e$ IBD detection** identified
- **^{63}Cu** resulted as **golden candidates**
  → poor reliability of ^{63}Cu cross section calls for refined nuclear physics inputs (or experimental validation)
- A **100 kton** (240 kton) LiquidO detector would detect **^{40}K-$\bar{\nu}_e$ with 3σ** (5σ) significance **in 10 years**.
  (It would also enable sub-percent uncertainties on U and Th geoneutrinos)

Despite challenging, this methodology proves feasible and experimentally testable