Università
degli Studi
di Ferrara

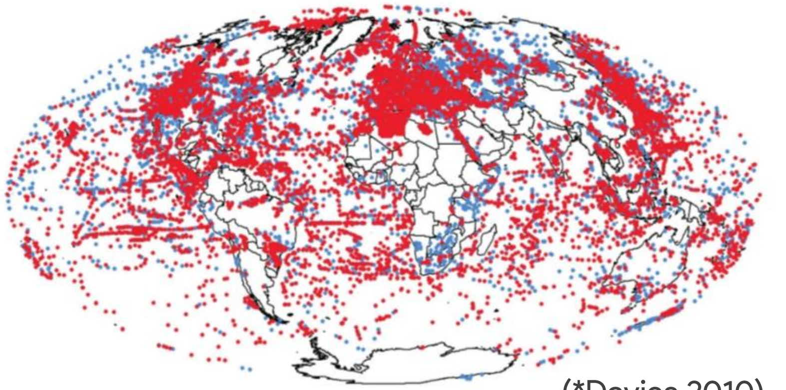
Dipartimento
di Fisica
e Scienze della Terra

Andrea Serafini, *Baldoncini M., Cabrera A., Chen M., Grassi M., Mantovani F., Strati V., Wagner S.*

(On behalf of LiquidO collaboration)

Detecting ^{40}K geoneutrinos with LiquidO

Why is ^{40}K so important?



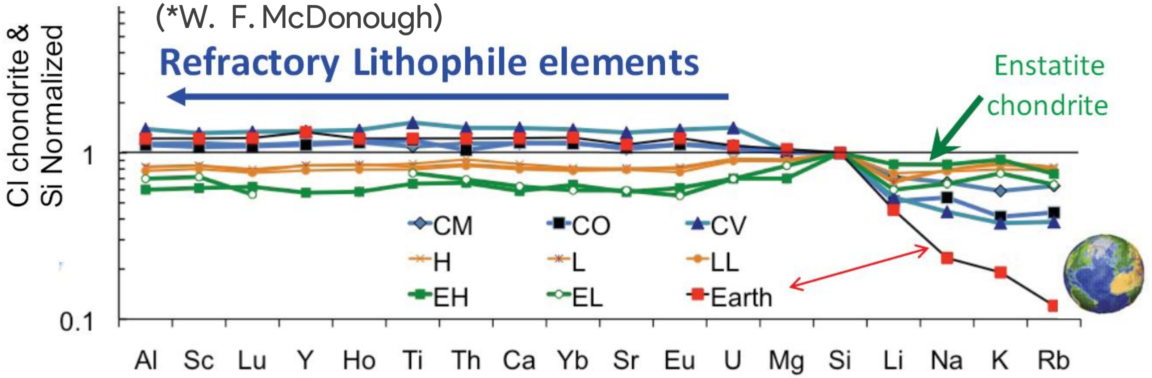
(*Davies 2010)

1. K, together with U and Th, is one of the three **Heat Producing Elements** (HPEs) that contribute to the 47 ± 2 TW heat power.
2. According to Earth models, ^{40}K radiogenic power varies from **2.0-4.7 TW**.
3. Our planet seems to contain **10%-30% K respect to** the enstatitic (EH) and carbonaceous (CI) **chondrites** meteorites, respectively.
4. 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)

5. 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.

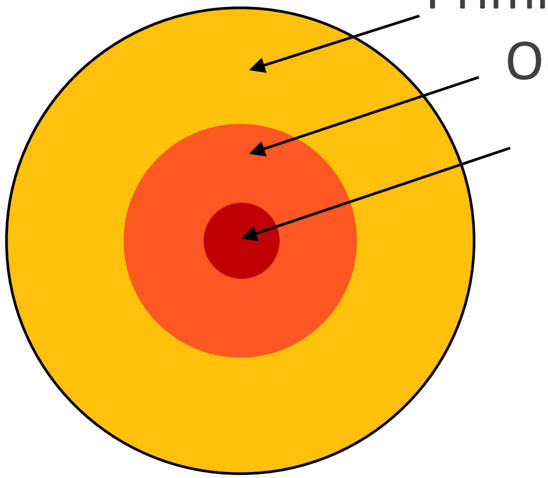


(*W. F. McDonough)

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

Earth evolution

1st differentiation



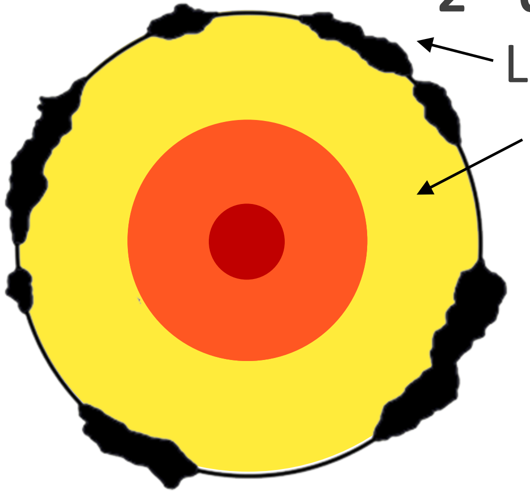
Primitive Mantle (PM) [M_{PM} ~68% M_{Earth}]

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

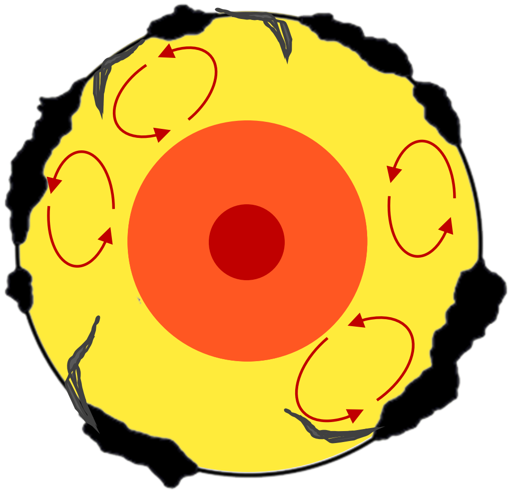


Lithosphere [M_{Lith} ~2% M_{Earth}]

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

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

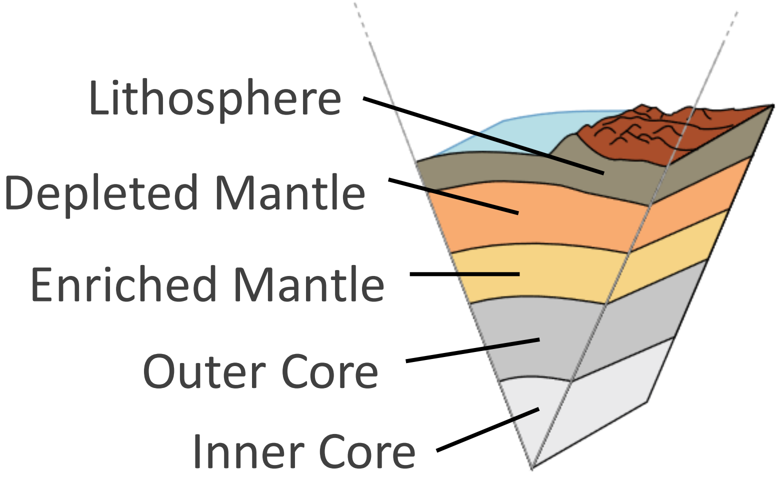
Lithophile elements
(chemical affinity with O)
in the Lithosphere (e.g. U, Th, K)

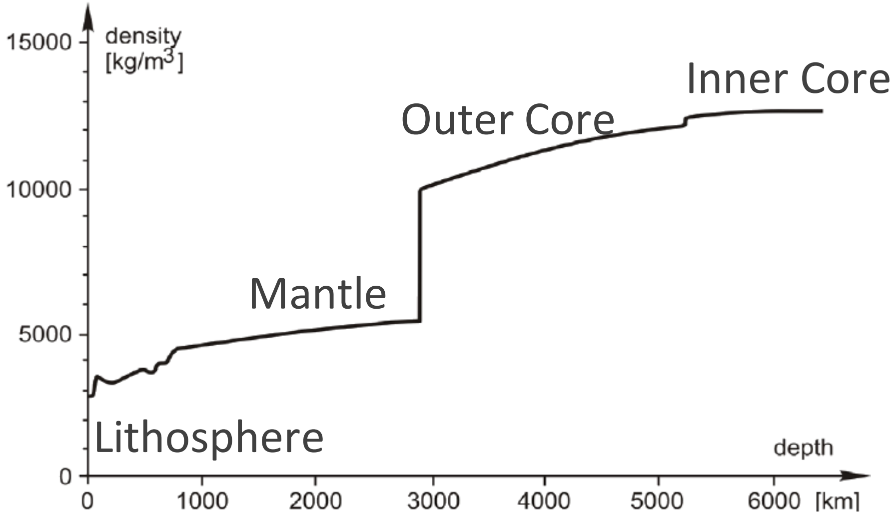


Convective and tectonic processes: formation of new crust (oceanic crust) and recycling of continental crust (up to 10 times)

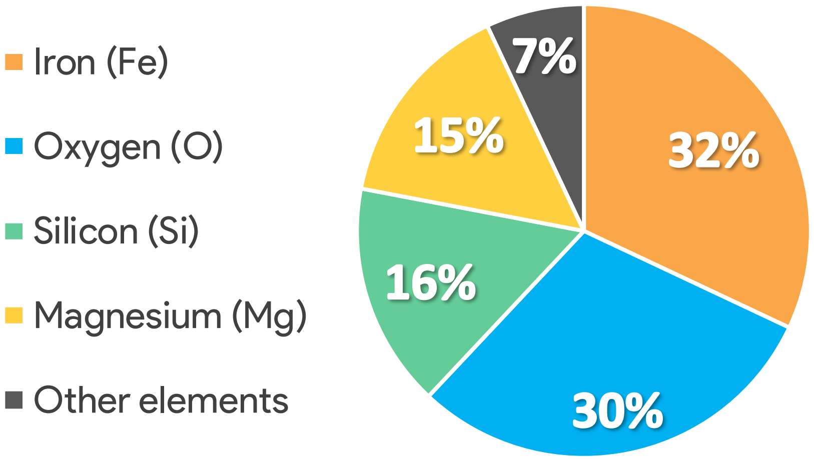
A Standard Model of the Earth

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





Bulk Earth's mass composition



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

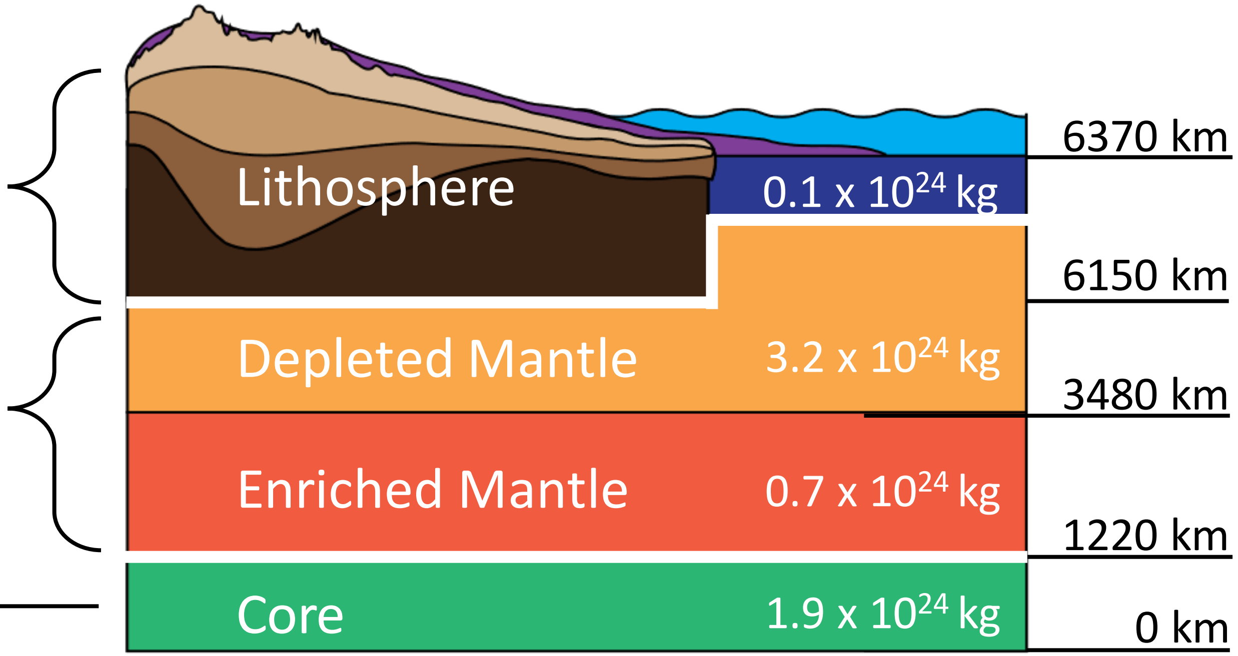
The most important for activity, abundances and half-life time (comparable to Earth's age) are:

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

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	*?*	*?*	*?*

Bulk Silicate Earth (BSE) Models

The Primitive Mantle's composition is described by the paradigm of the BSE.

Among the several models proposed, these are the ones predicting the **minimum**, the **standard** and the **maximum** values for HPEs' masses

Cosmochemical Model (CCM)

- Enstatitic composition
- Low HPEs content

Geochemical Model (GCM)

- Carbonaceous composition
- Medium HPEs content

Geodynamical Model (GDM)

- Based on Earth dynamics
- High HPEs content

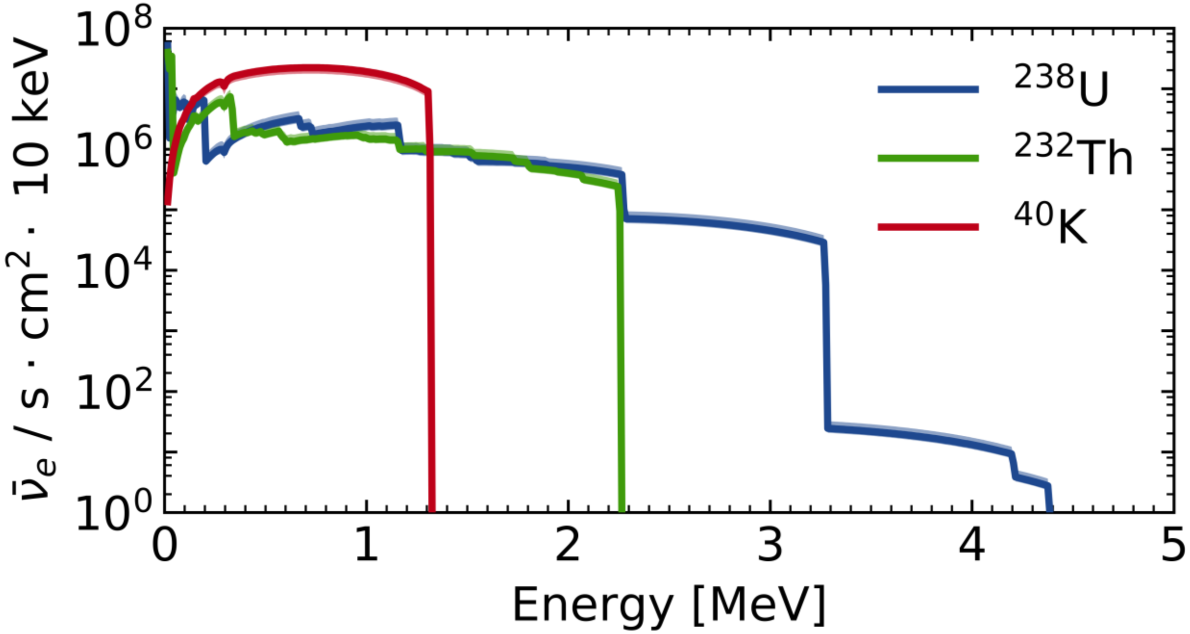
	CCM	GCM	GDM
M(U) *[10^{16} kg]*	*4.8*	*8.1*	*14.1*
M(Th) *[10^{16} kg]*	*17.4*	*32.3*	*56.5*
M(K) *[10^{19} kg]*	***58.9***	***113.0***	***141.2***

Individual models' uncertainties are typically ~20%, of second order compared to a factor ~3 variability among models.

Geoneutrinos: main physical properties

- Geoneutrinos are $\bar{\nu}_e$ produced in naturally occurring β^- decays of HPEs in the Earth.
- HPEs release heat together with geo-$\bar{\nu}_e$ (ε) in a well-fixed ratio.
- They can cross the entire planet **almost without interacting**, bringing instantaneous information on the Earth's composition.
- Geo-$\bar{\nu}_e$ from **^{40}K** could represent an important tool thanks to their **high luminosity**.

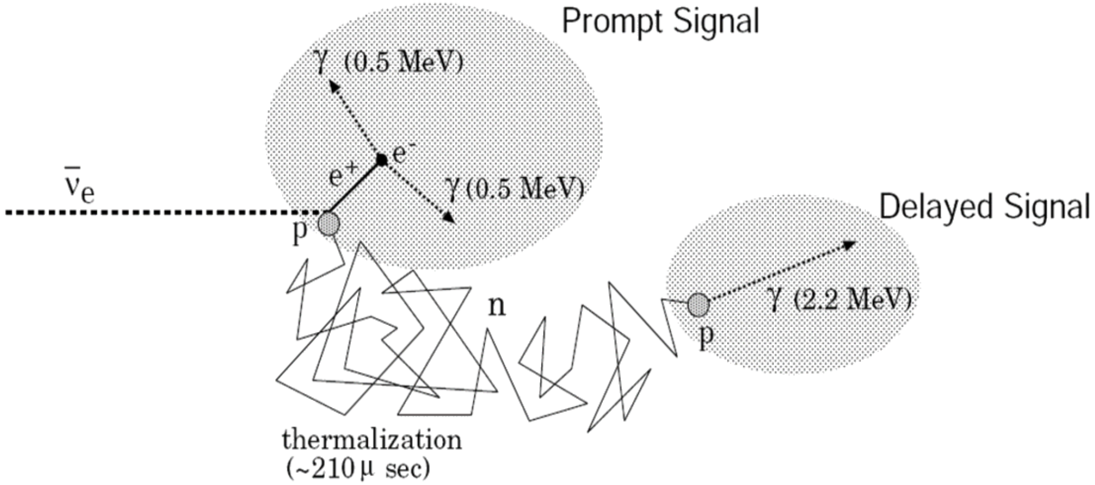
Decay	$T_{1/2}$ [10^9 y]	$\varepsilon(\bar{\nu})$ [$10^7 kg^{-1} s^{-1}$]	$E_{max}(\bar{\nu})$ [MeV]
$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6\beta^-$	4.47	7.5	3.36
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4\beta^-$	14.0	1.6	2.25
$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$ (89%)	1.28	**23.2**	1.31



Inverse Beta Decay (IBD) detection

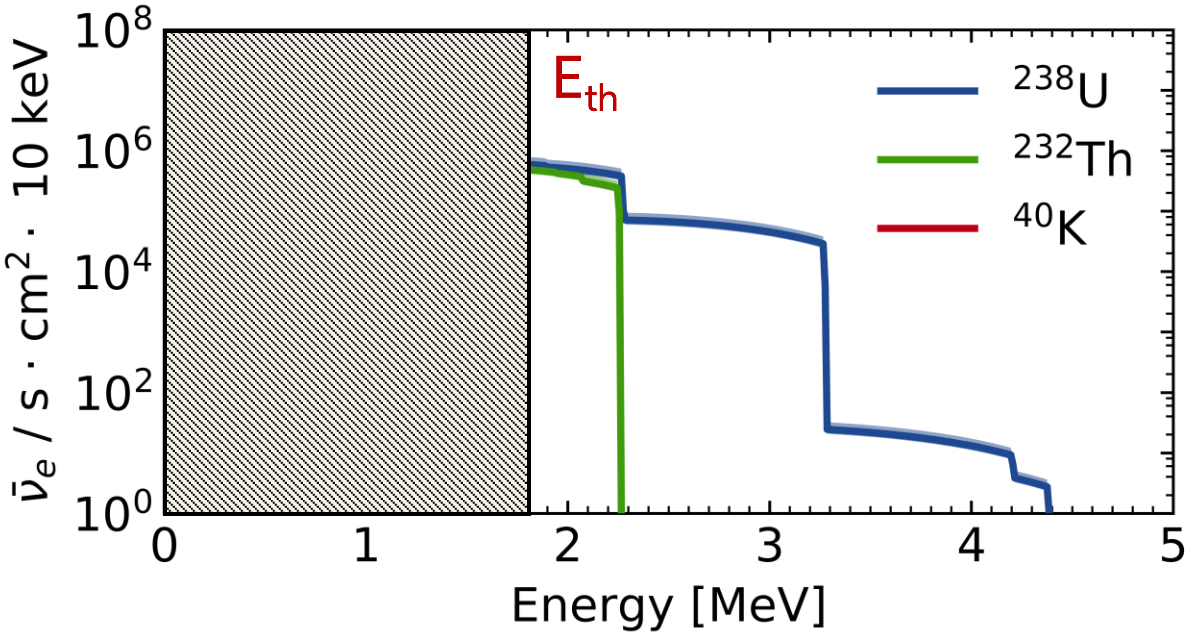
Geoneutrinos are **detected by IBD** in **~kton** Liquid Scintillation Detectors.

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



Detection requires the coincidence of 2 delayed light signals.

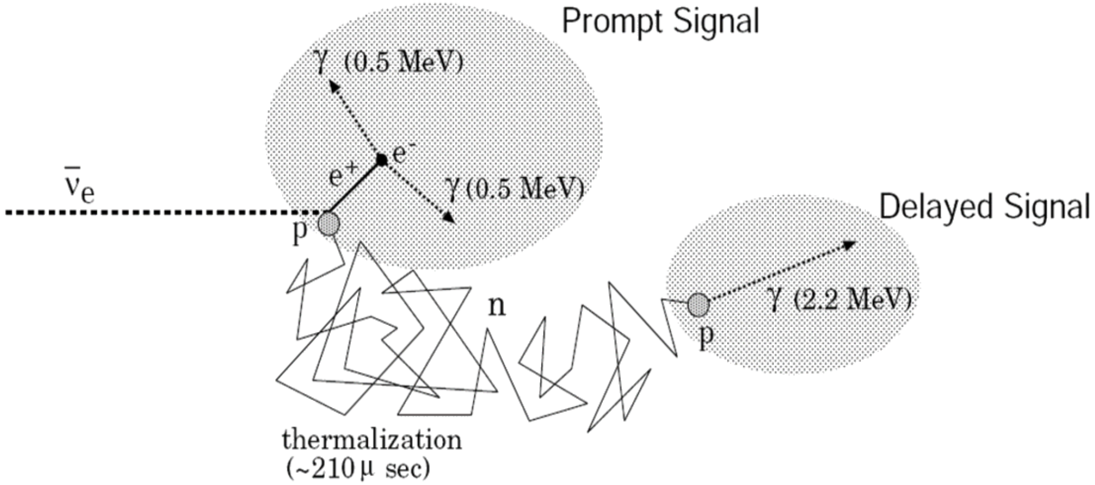
It does not permit to observe ^{40}K-$\bar{\nu}_e$



Inverse Beta Decay (IBD) detection

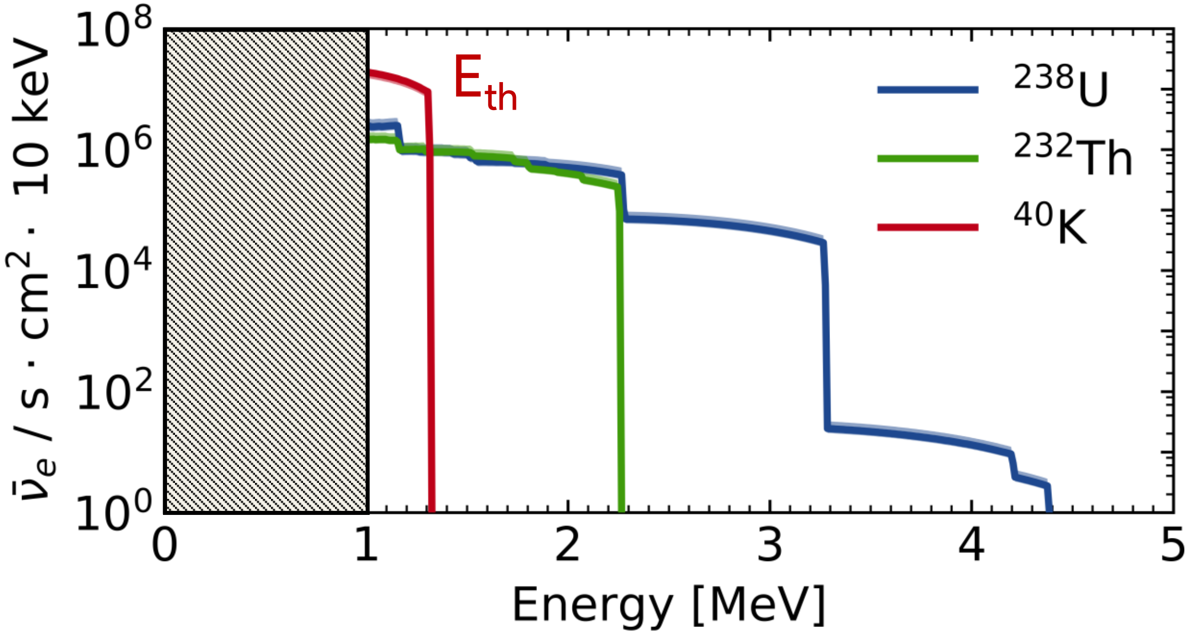
Geoneutrinos are **detected by IBD** in **~kton** Liquid Scintillation Detectors.

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



Detection requires the coincidence of 2 delayed light signals.

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



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

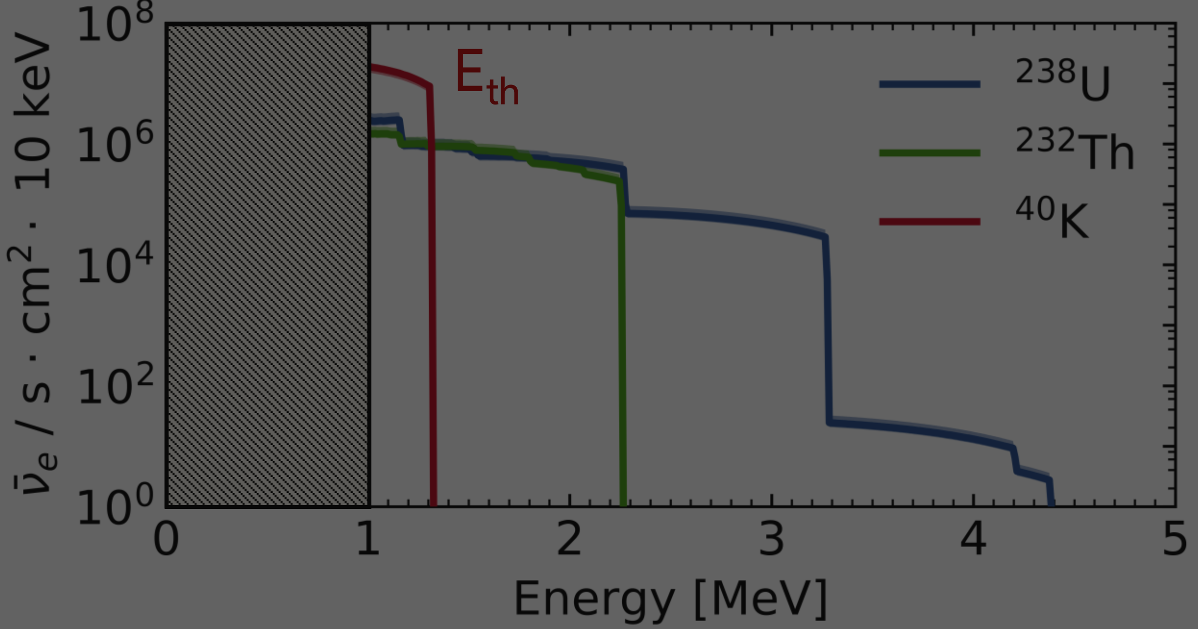
Inverse Beta Decay (IBD) detection

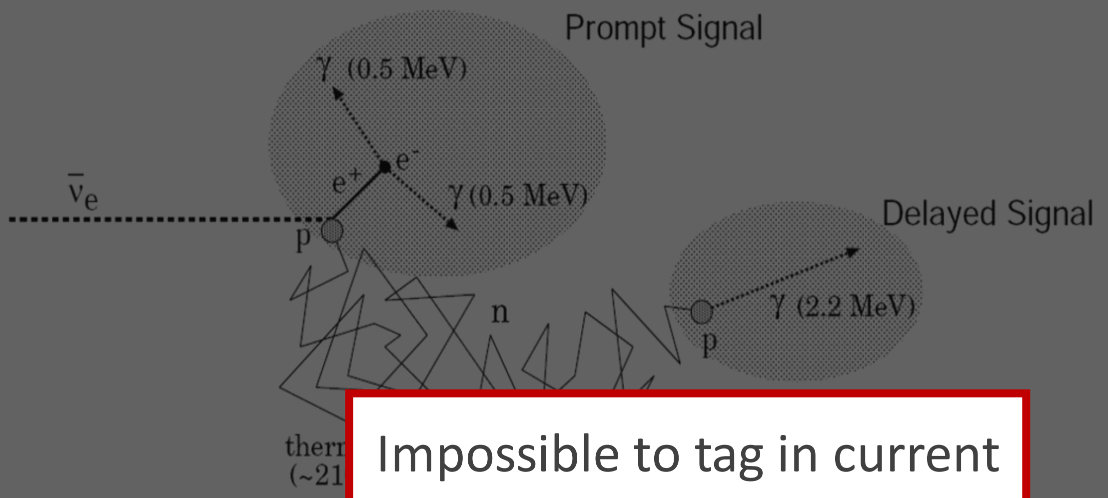
Geoneutrinos are **detected by IBD** in **~kton** Liquid Scintillation Detectors.

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

Detection requires the coincidence of 2 delayed light signals.

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





Impossible to tag in current Liquid Scintillator Detector

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

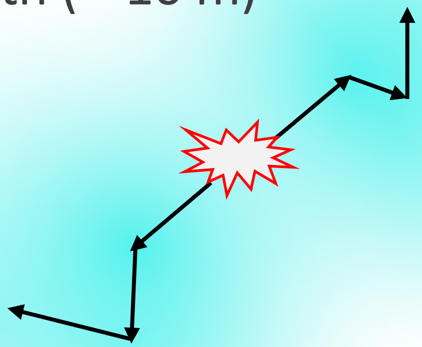
$$\bar{\nu}_e + {}_{Z+1}^{\ A}Y \rightarrow {}_{Z}^{A}X + \boxed{e^+} - E_{th}$$

We shall require:

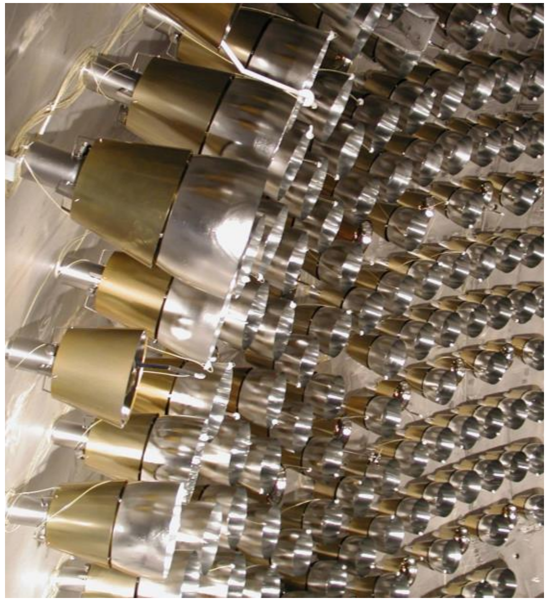
- E$_{th}$ < *1.3 MeV*
- High cross-section
- High Y natural isotopic abundance

Transparent vs. opaque detector

Very long scattering length (~ 10 m)

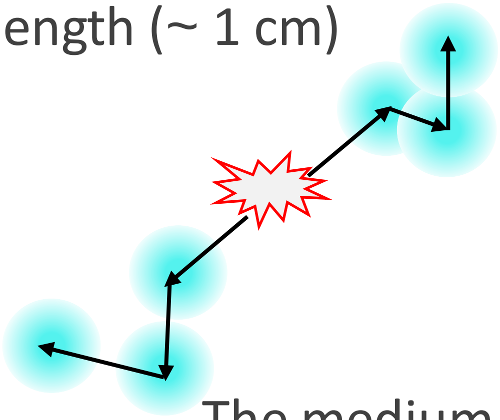


The medium is transparent to scintillation photons

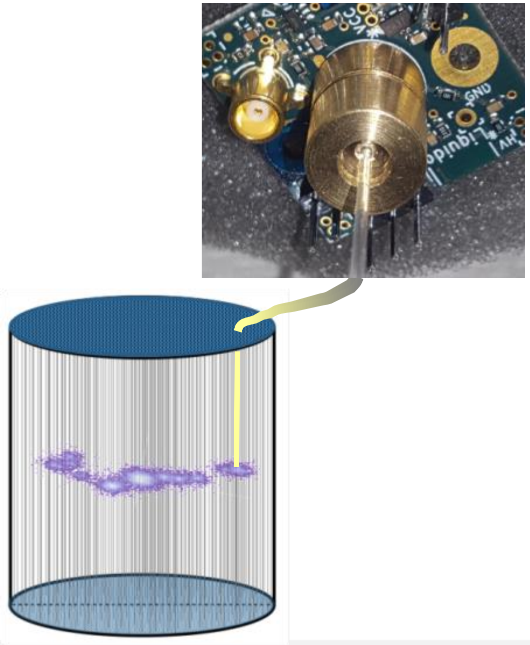


- Scintillation light reaches the surrounding 10^3-10^4 PMTs
- Slow time resolution (~ ns)
- Poor spatial resolution on light deposition (~ 10 cm)
- High photon detection efficiency (~ 20%)

Very short scattering length (~ 1 cm)

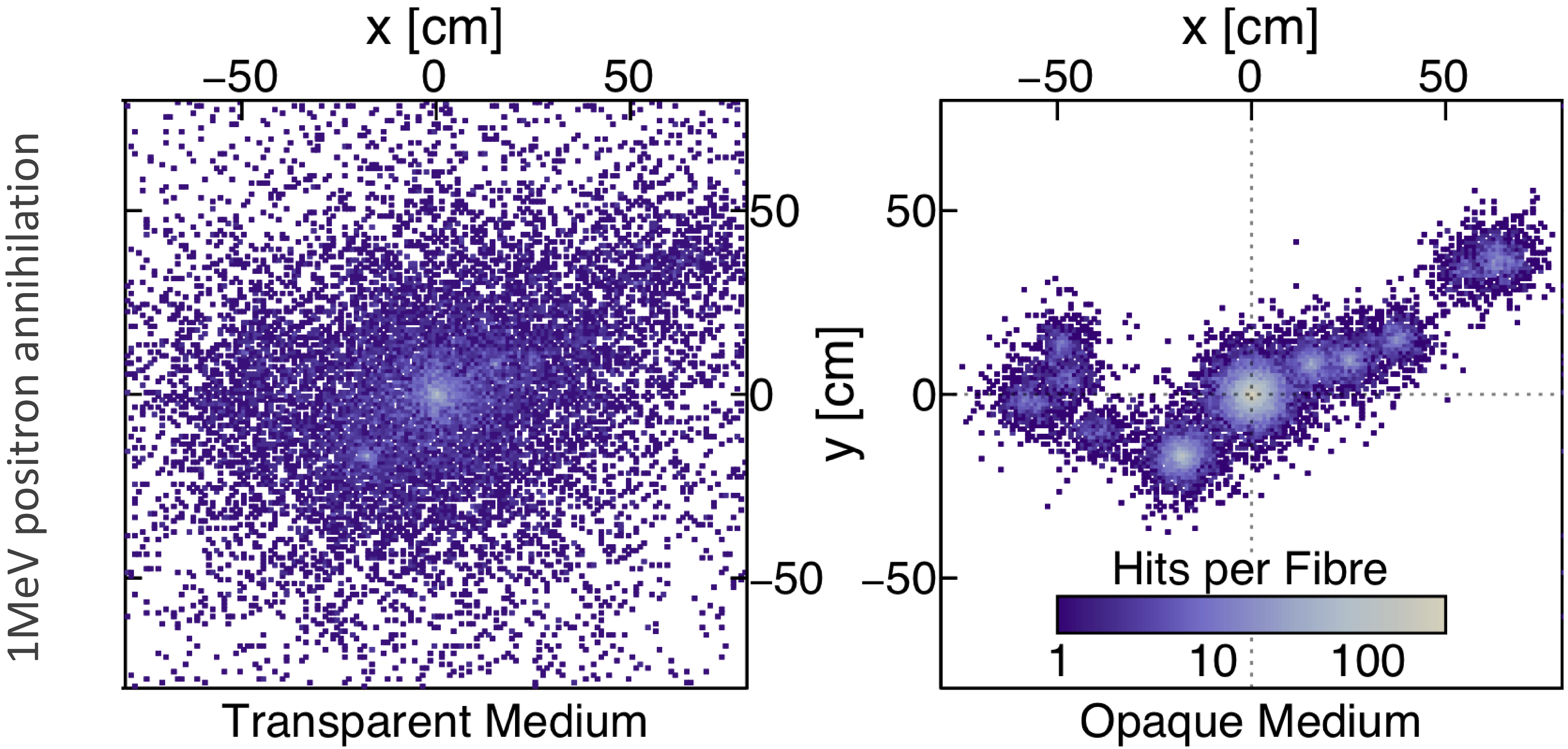


The medium is opaque to scintillation photons



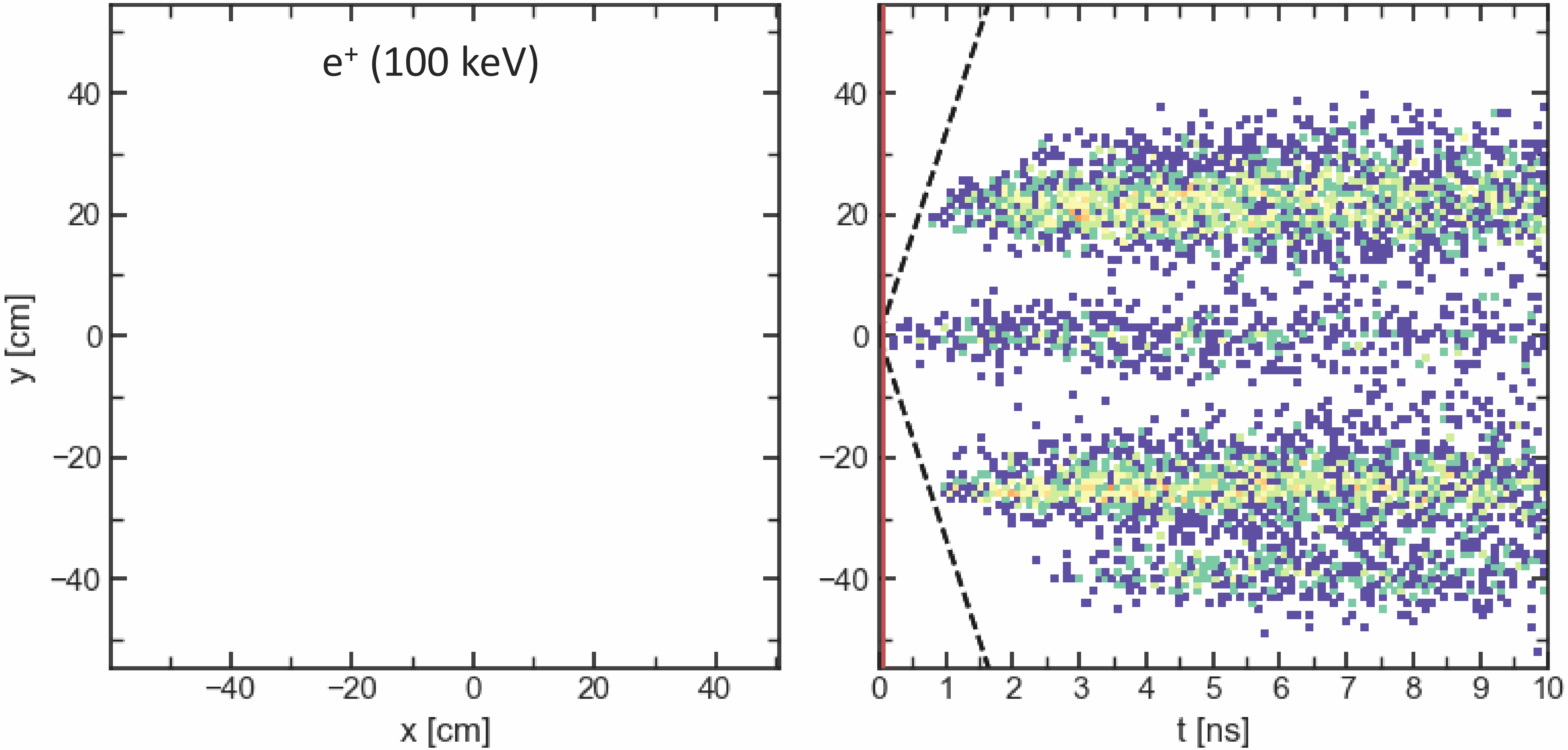
- The light is extracted by an array of optical fibers connected to SiPMs
- Fast time resolution (~ 0.3 ns)
- Excellent spatial resolution on light deposition (~ 1 cm)
- Poor photon detection efficiency (~ 5%)

Simulated scintillation light deposition



(*credits to Marco Grassi)

Detecting e^+ from ^{40}K geonu in LiquidO

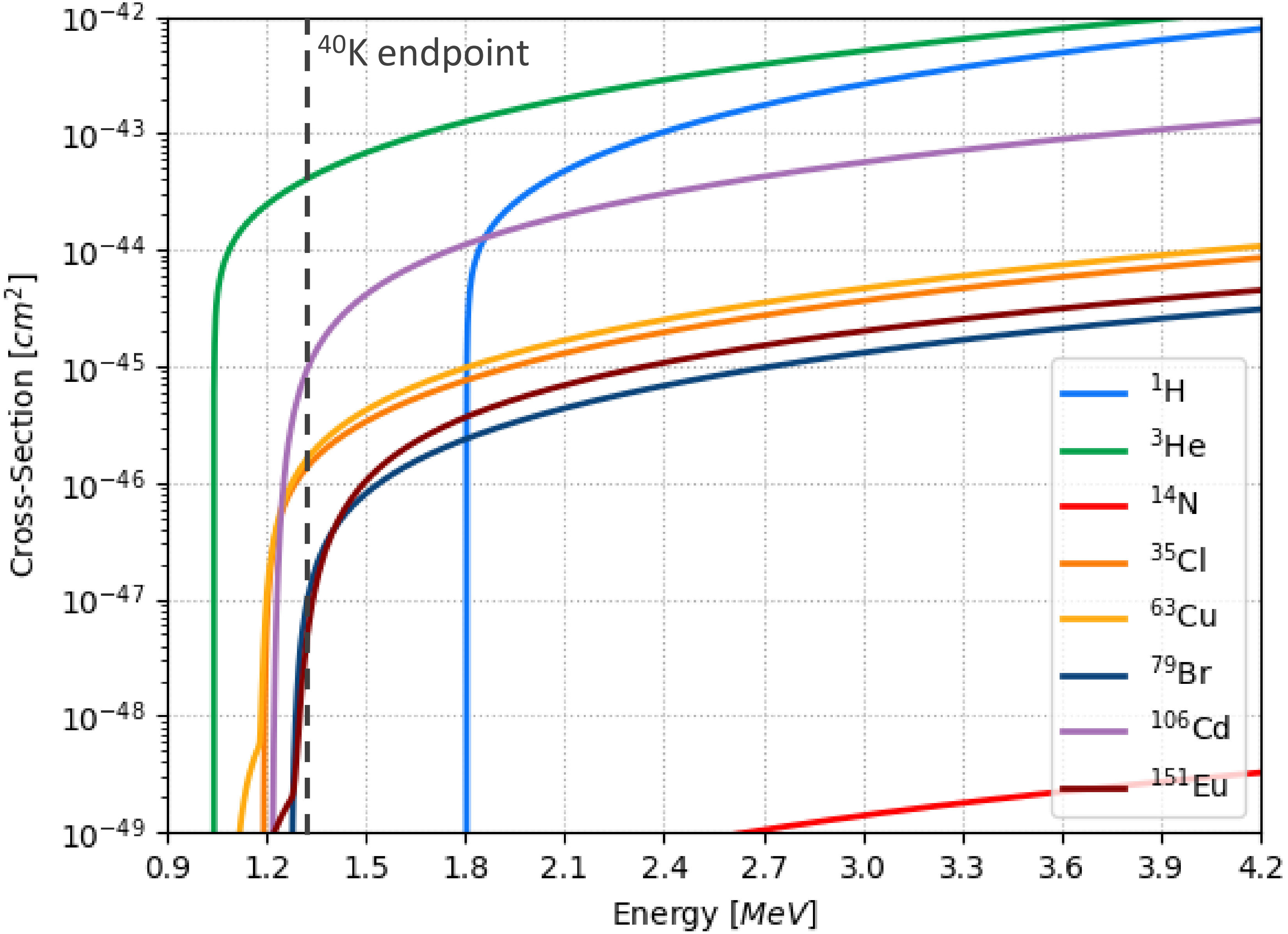


IBD target isotopes for ^{40}K detection

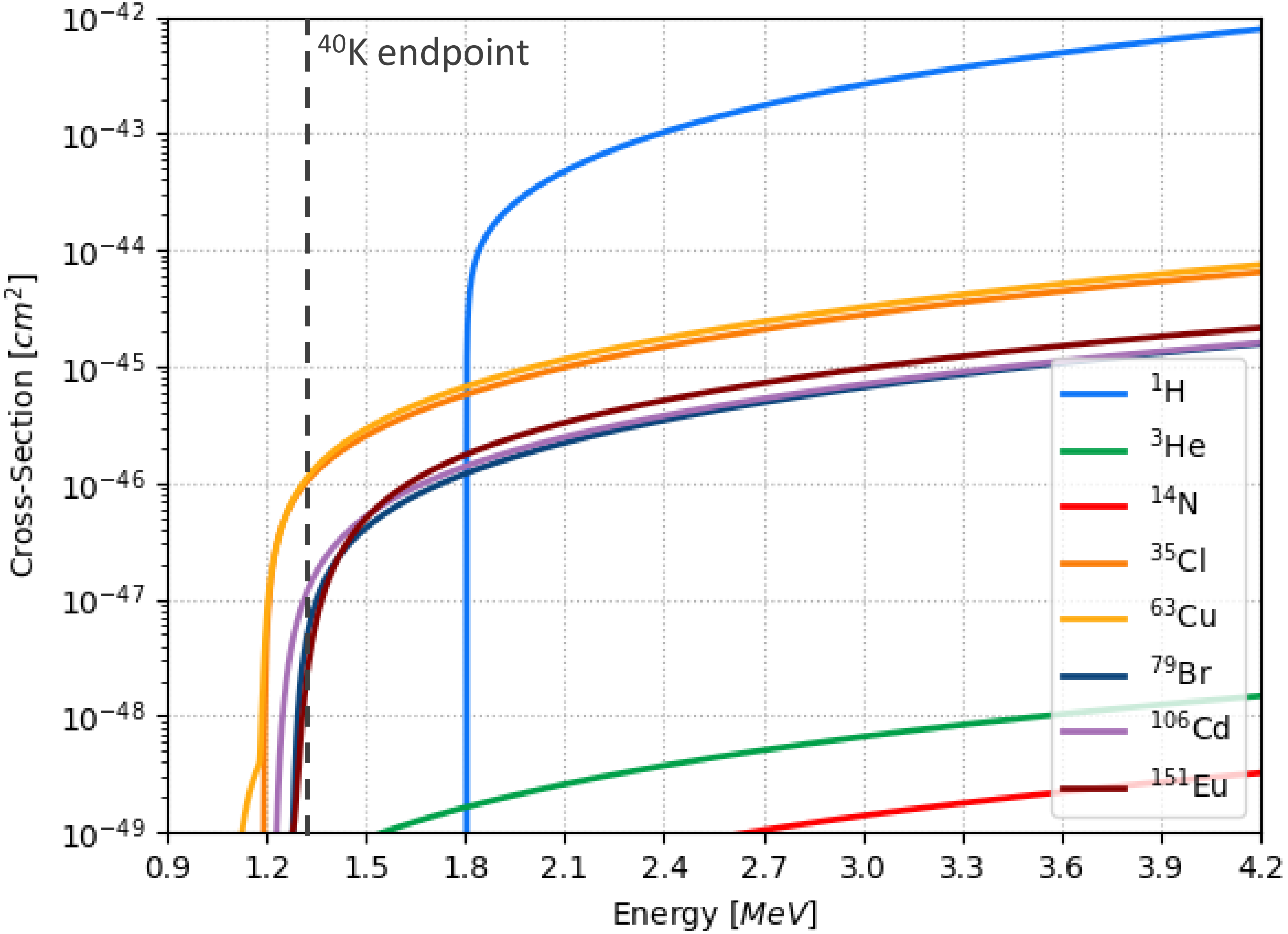
Data from ENSDF database

Target process	Isotopic abundance [%]	E_{th} [MeV]	Log *ft*
$^{1}H \rightarrow {}^{1}n$	99.99	1.806	3.0
$^{3}He \rightarrow {}^{3}H$	$1.34 \cdot 10^{-4}$	1.041	3.1
$^{14}N \rightarrow {}^{14}C$	99.64	1.178	9.0
$^{35}Cl \rightarrow {}^{35}S$	75.76	1.189	5.0
$^{63}Cu \rightarrow {}^{63}Ni$	69.15	1.089	6.7
$^{63}Cu \rightarrow {}^{63}Ni^{*}$		1.176	5.0
$^{79}Br \rightarrow {}^{79}Se$	50.69	1.173	10.8
$^{79}Br \rightarrow {}^{79}Se^{*}$		1.268	5.0
$^{106}Cd \rightarrow {}^{106}Ag$	1.25	1.212	4.1
$^{151}Eu \rightarrow {}^{151}Sm$	47.81	1.099	7.5
$^{151}Eu \rightarrow {}^{151}Sm^{*}$		1.266	5.0

IBD cross-sections on single target isotopes



IBD cross-sections weighted with isotopic abundance



- **^{3}He**, which seemed the perfect candidate, is disfavored by its **abundance**

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

- **^{63}Cu** seems to be as promising as ^{35}Cl, but not equally reliable (*ft* not experimentally measured)

Building geoneutrino signals

The ingredients for modeling the three geoneutrino life stages are:

- **production** inside the Earth
- **propagation** to the detector site
- **detection** in liquid scintillator detectors

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

Nuclear

- $Sp_i(E)$ = $\bar{\nu}_e$ emission spectra
  where i = ^{238}U, ^{232}Th, ^{40}K

Geology

- $\Phi_i(m_i,\vec{r})$ = unoscillated $\bar{\nu}$ flux at surface, where m_i is the mass of the *i-th* HPE placed at a distance $\vec{r}$ from the detector

Detector

- $N_{target,\ n}$= number of target nuclei where n runs over the IBD target candidates
- T = acquisition time

ν phisics

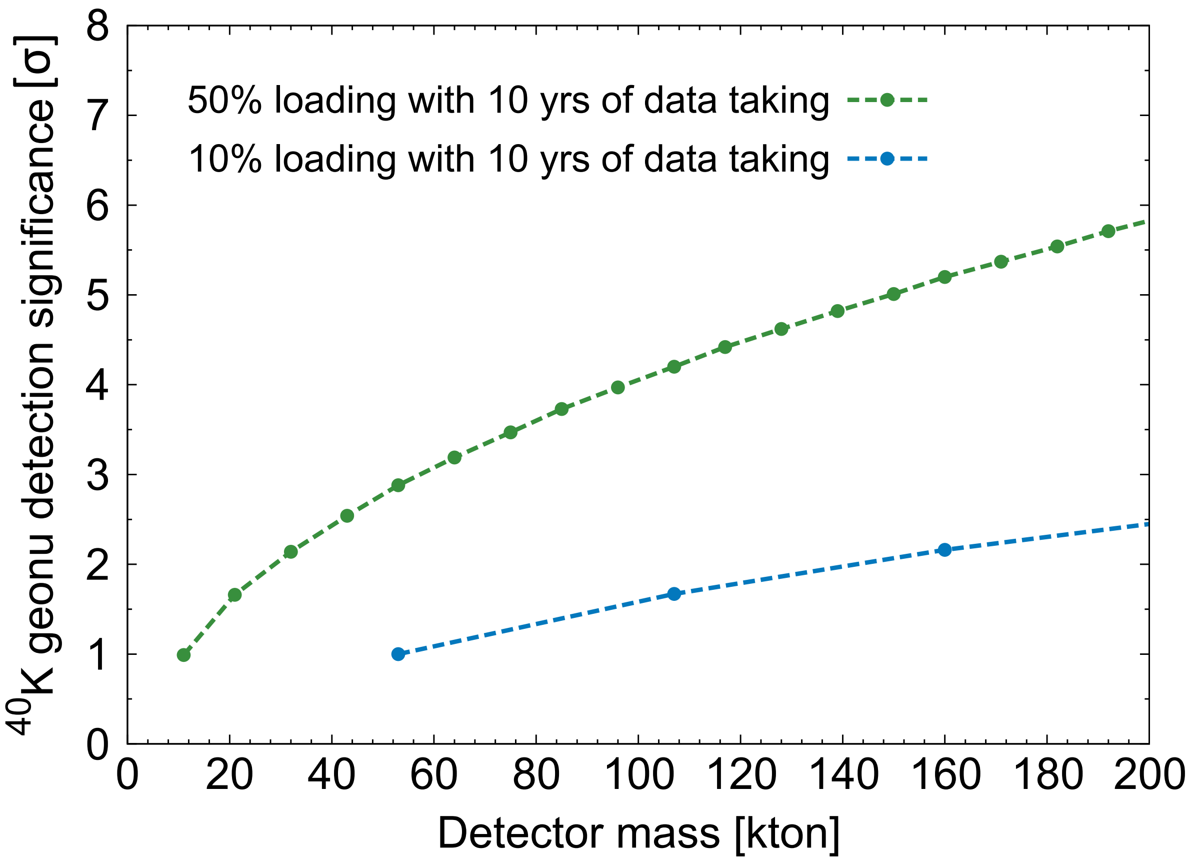
- $P_{ee}(E,\vec{r})$ = $\bar{\nu}_e$ survival probability
  $<P_{ee}>$ = 0.55 for | $\vec{r}$ |>50 km
- $\sigma_n(E)$ = IBD cross-section on nucleus target n

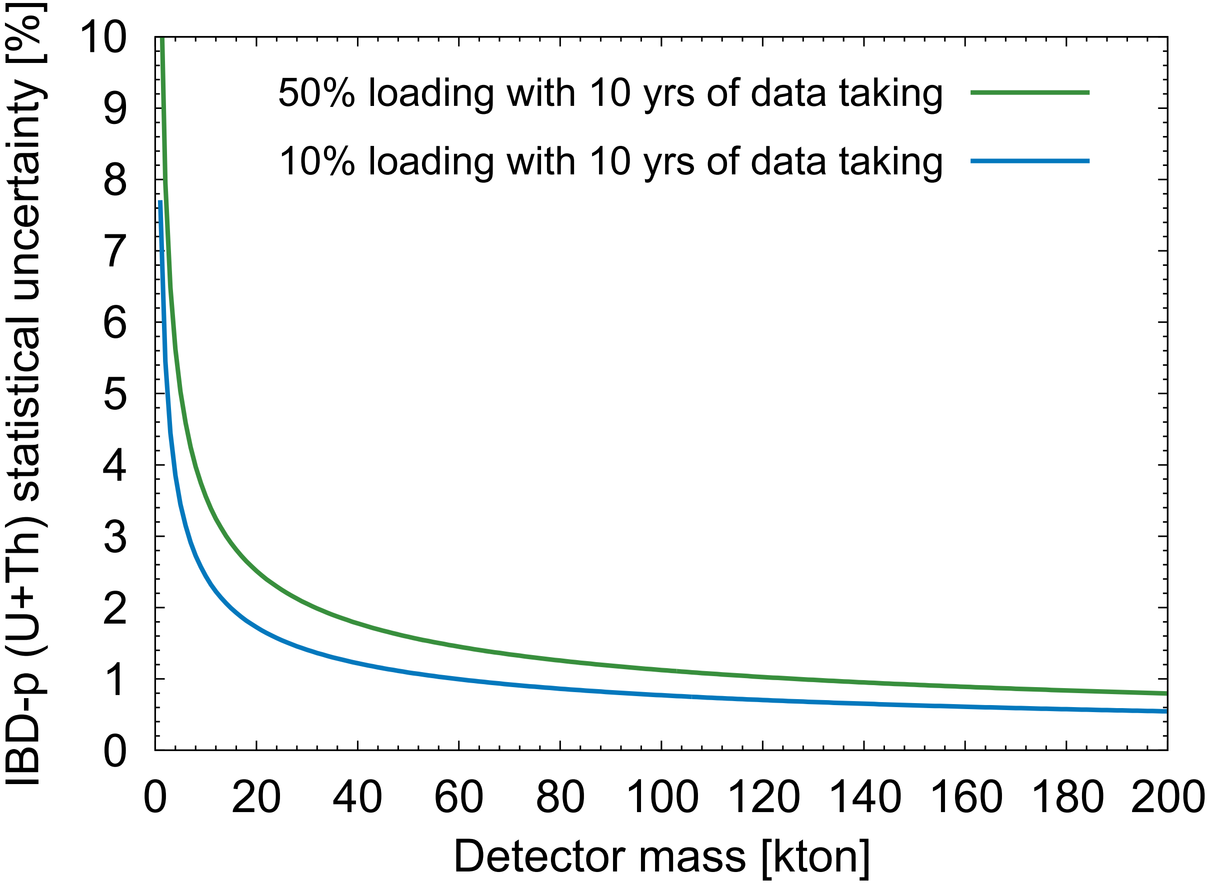
^{40}K geoneutrino expected signals

- Signals are expressed in TNU: 1 geoneutrino event per 10^{32} element target per year
- The signal variability range embraces all possible geochemical models and potassium distribution in the Earth.
- Present geoneutrino signals measured in Borexino and KamLAND on ^{1}H are S(U+Th)~40 TNU

	S(^{40}K) [TNU]	
Target	**Gran Sasso**	**Kamioka**
^{63}Cu	***0.10 [0.06, 0.13]***	***0.07 [0.05, 0.10]***
^{35}Cl	***0.09 [0.06, 0.12]***	***0.07 [0.05, 0.09]***
^{106}Cd	*4.9 [3.2, 6.5]× 10^{-3}*	*3.7 [2.4, 4.9]× 10^{-3}*
^{79}Br	*8.1 [4.4, 10.8]× 10^{-4}*	*6.0 [3.3, 8.1]× 10^{-4}*
^{151}Eu	*3.1 [2.0, 4.1]× 10^{-4}*	*2.3 [1.5, 3.1]× 10^{-4}*
^{3}He	*1.6 [1.0, 2.1]× 10^{-4}*	*1.2 [0.8, 1.6]× 10^{-4}*
^{14}N	*7.7 [5.0, 10.1]× 10^{-6}*	*5.8 [3.7, 7.6]× 10^{-6}*

Expected statistical uncertainties in a ^{35}Cl loaded LiquidO





- **Passive scheme**: mix of chlorine (C_2Cl_4) and LAB (Cl weight fraction up to 85%)
- **Active scheme**: chlorine-based scintillators such as dichlorobenzene $C_6H_4Cl_2$ (Cl weight fraction of 48%)

Detecting geoneutrinos in a ^{35}Cl loaded LiquidO

IBD(^{35}Cl)

$$\bar{\nu}_e + {}^{35}Cl \rightarrow {}^{35}S + e^+$$

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

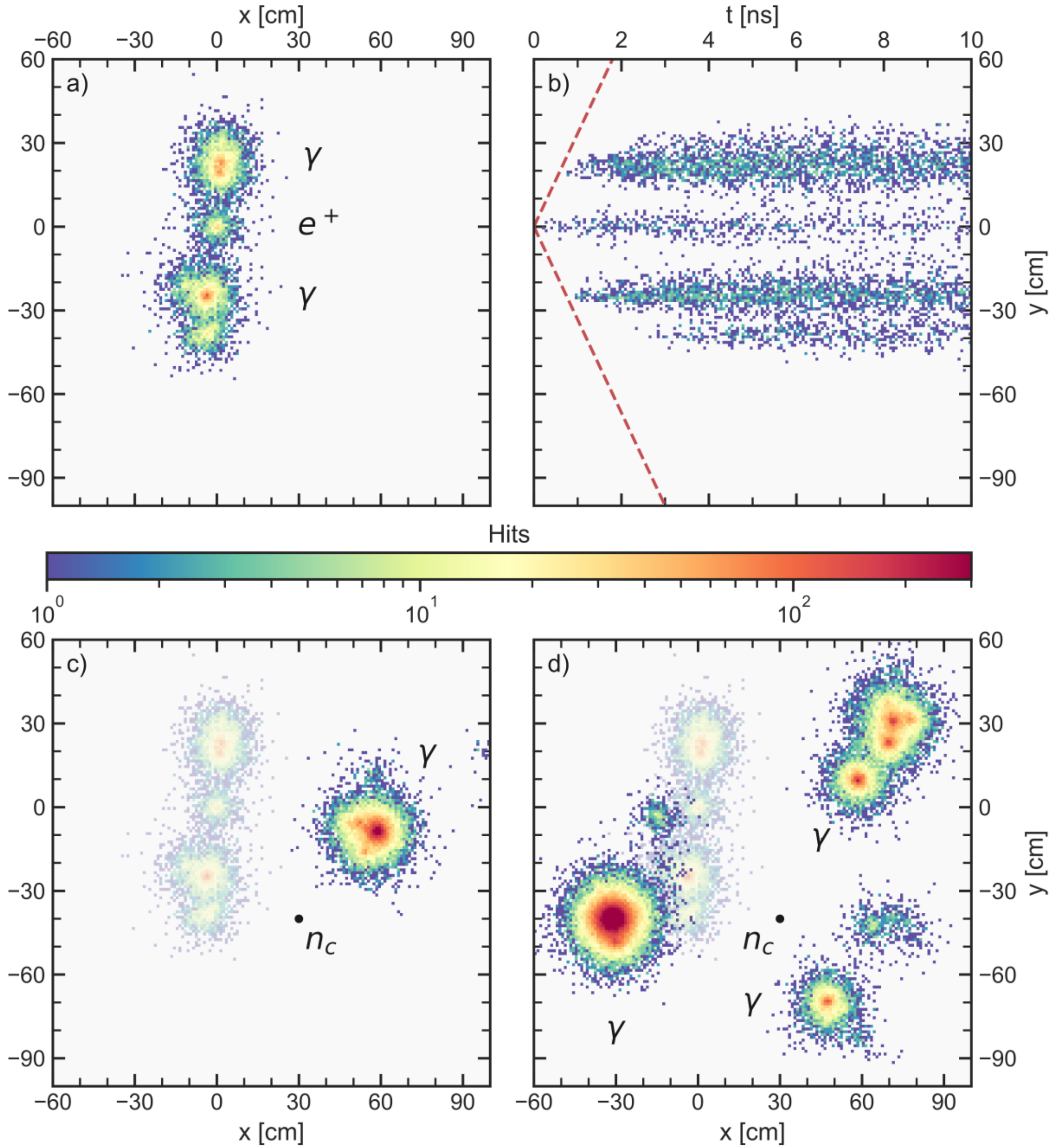
IBD-proton

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

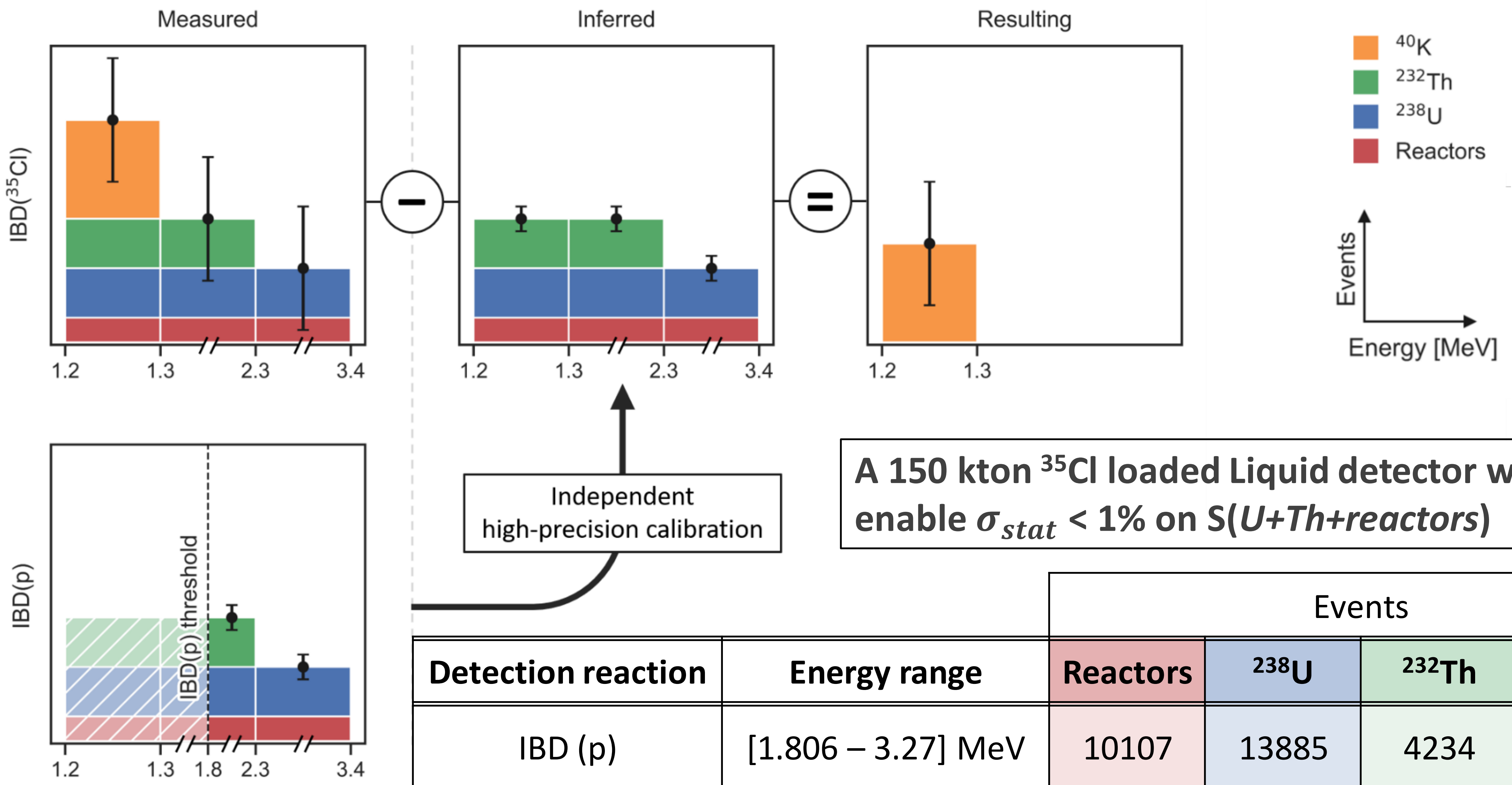
$$\rightarrow e^+ + e^- \rightarrow 2\gamma$$

$$\rightarrow n + p \rightarrow d + \gamma$$

$$\rightarrow n + {}^{35}Cl \rightarrow {}^{36}Cl + 3\gamma$$



Detecting ^{40}K geoneutrinos in a ^{35}Cl loaded LiquidO



Independent
high-precision calibration

A 150 kton ^{35}Cl loaded Liquid detector would enable $\sigma_{stat} < 1\%$ on S(*U+Th+reactors*)

		Events			
Detection reaction	**Energy range**	**Reactors**	**^{238}U**	**^{232}Th**	**^{40}K**
IBD (p)	[1.806 – 3.27] MeV	10107	13885	4234	/
IBD (^{35}Cl)	[1.189 – 1.311] MeV	0.2	1.1	1.1	11.9

Take away messages

- 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"**.

- Considering geochemical and geophysical uncertainties we estimated that the **expected ^{40}K geo-$\bar{\nu}_e$ signal** at surface **varies of a factor x2** according to different Earth's compositional models.

- LiquidO enables a **clear identification of single positrons** from both the time pattern and the spatial topology of the event →Detection of **^{40}K-$\bar{\nu}_e$** via CC now possible!!

- At the present time, K-$\bar{\nu}_e$ remains undetected. A list of **seven candidate isotopes** (^{3}He,^{14}N,^{35}Cl,^{63}Cu,^{79}Br,^{106}Cd, ^{151}Eu) suitable **for ^{40}K-$\bar{\nu}_e$ IBD detection** have been identified.

- Considering IBD cross sections and isotopic abundances, **^{63}Cu** and **^{35}Cl** resulted the **best candidates**.
  → The poor reliability of ^{63}Cu log *ft* value calls for refined nuclear physics inputs

- A **50 kton** (150 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 geoneutrino detection**.

Than^{40}Ks for your attention