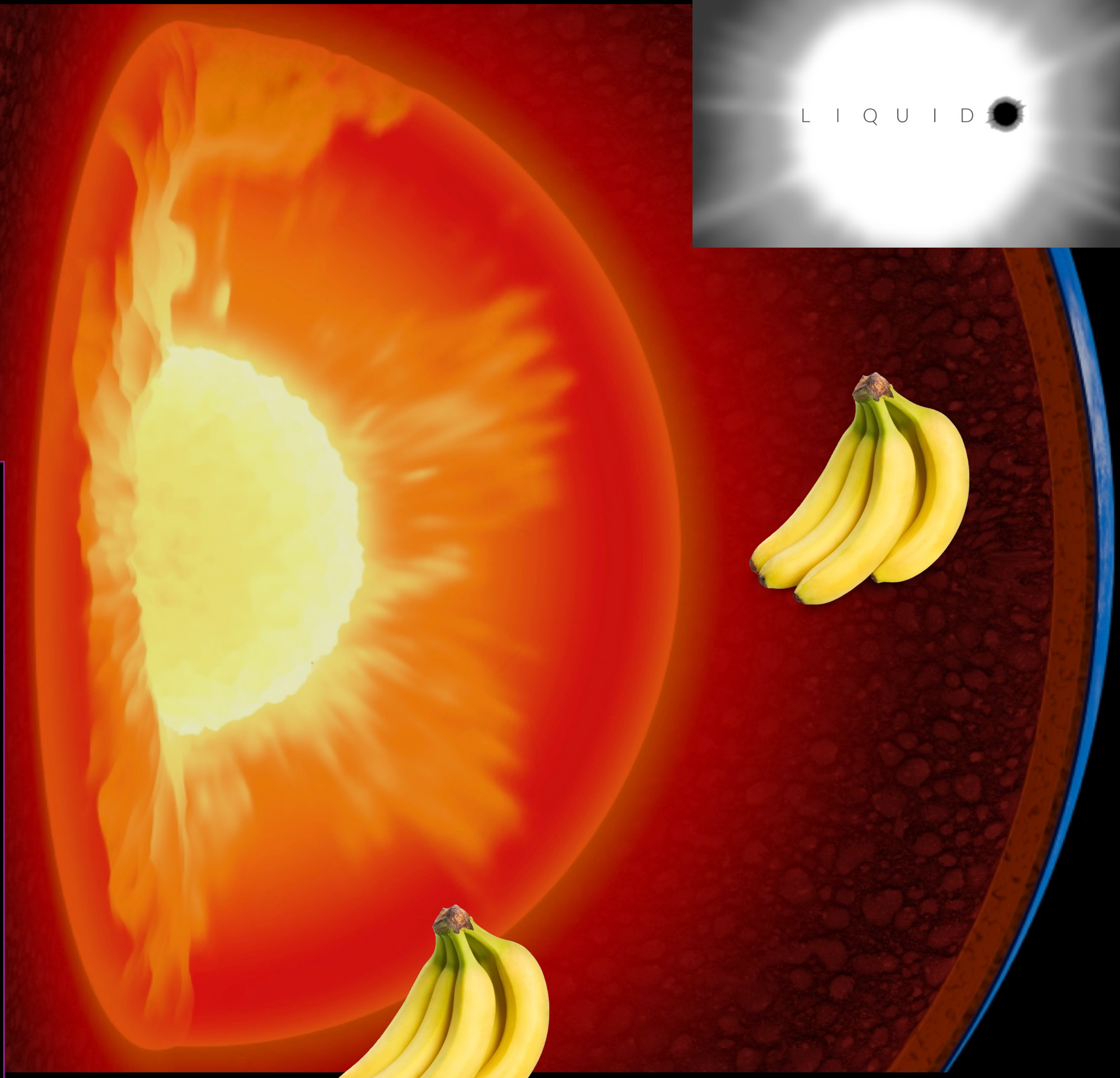
Potassium Geoneutrino Detection

Mark Chen (Queen's University and CIFAR)

Anatael Cabrera, Fabio Mantovani, Andrea Serafini, Virginia Strati *for the LiquidO Consortium*



TAUP 2023

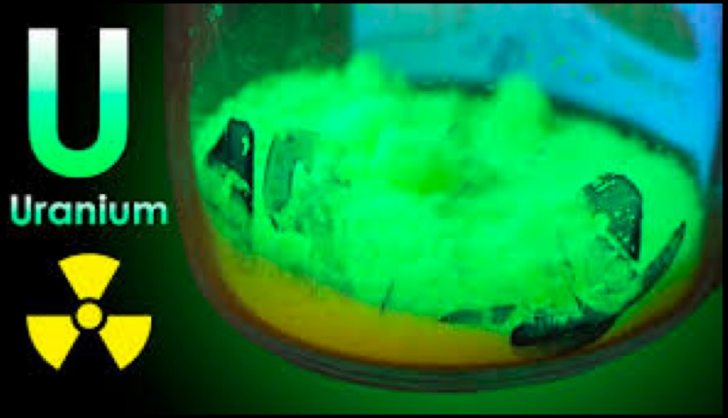
Vienna, Austria | August 28, 2023

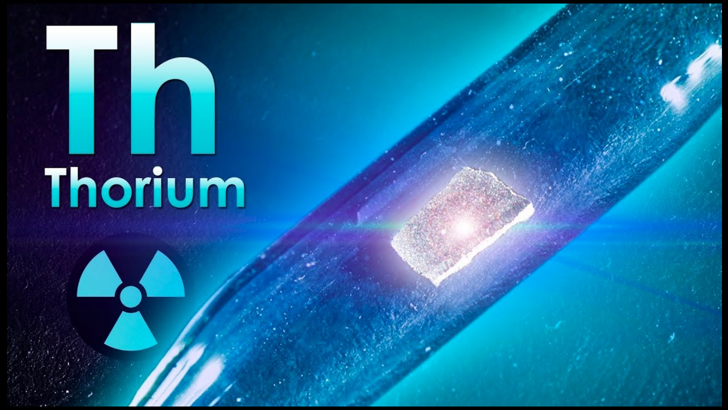
Geoneutrinos: $\bar{\nu}_e$ emitted by the Earth…

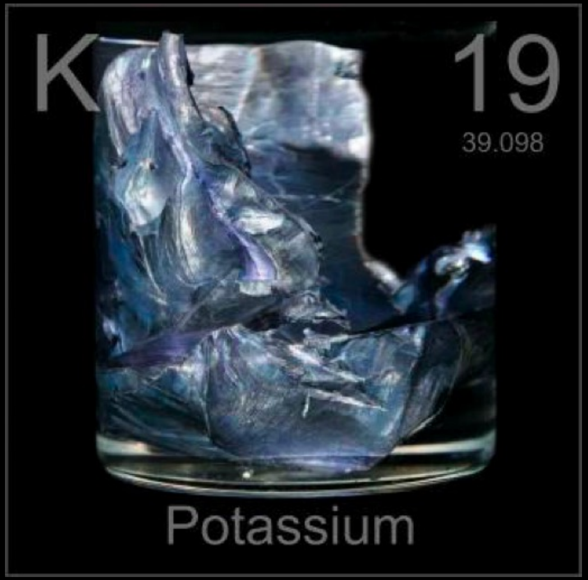
from the β⁻ decay of naturally-occurring radioactive elements in the crust and mantle

U, Th, K account for >99% of Earth's radiogenic heat production

(and a large fraction ~50% of Earth's total heat flow)





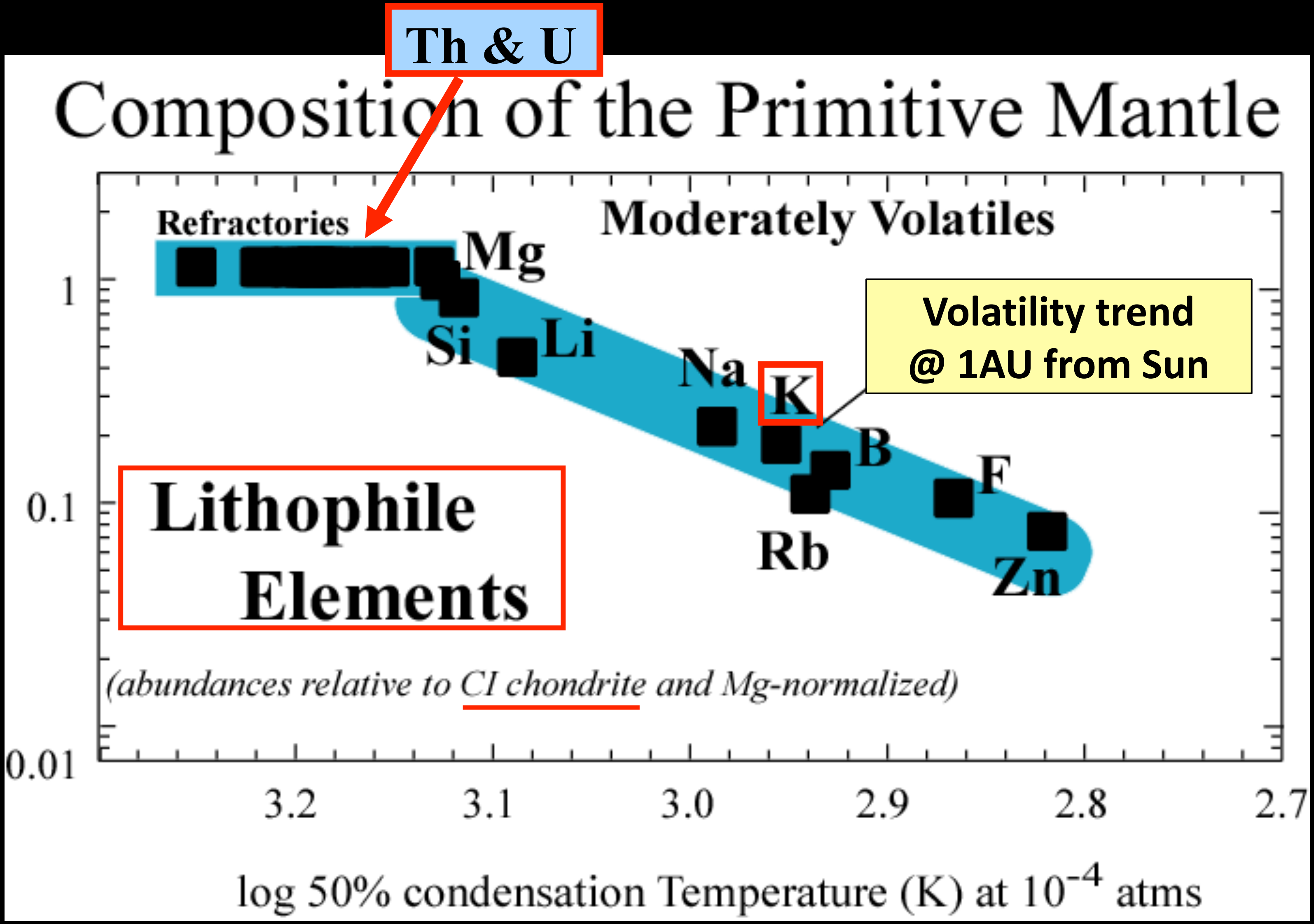


^{40}K

~20% of radiogenic heat

? ? ?

Bulk Earth Chemical Composition from Models



Abundance of K in the silicate Earth ranges from 130 to 280 ppm in compositional models

Measured K abundance only ~1/3 to ~1/8 of amounts in carbonaceous chondrites

Where is the missing potassium?

- lost to space due to moderate volatility?
- segregated in the Earth's core?

Figure and labels from Bill McDonough

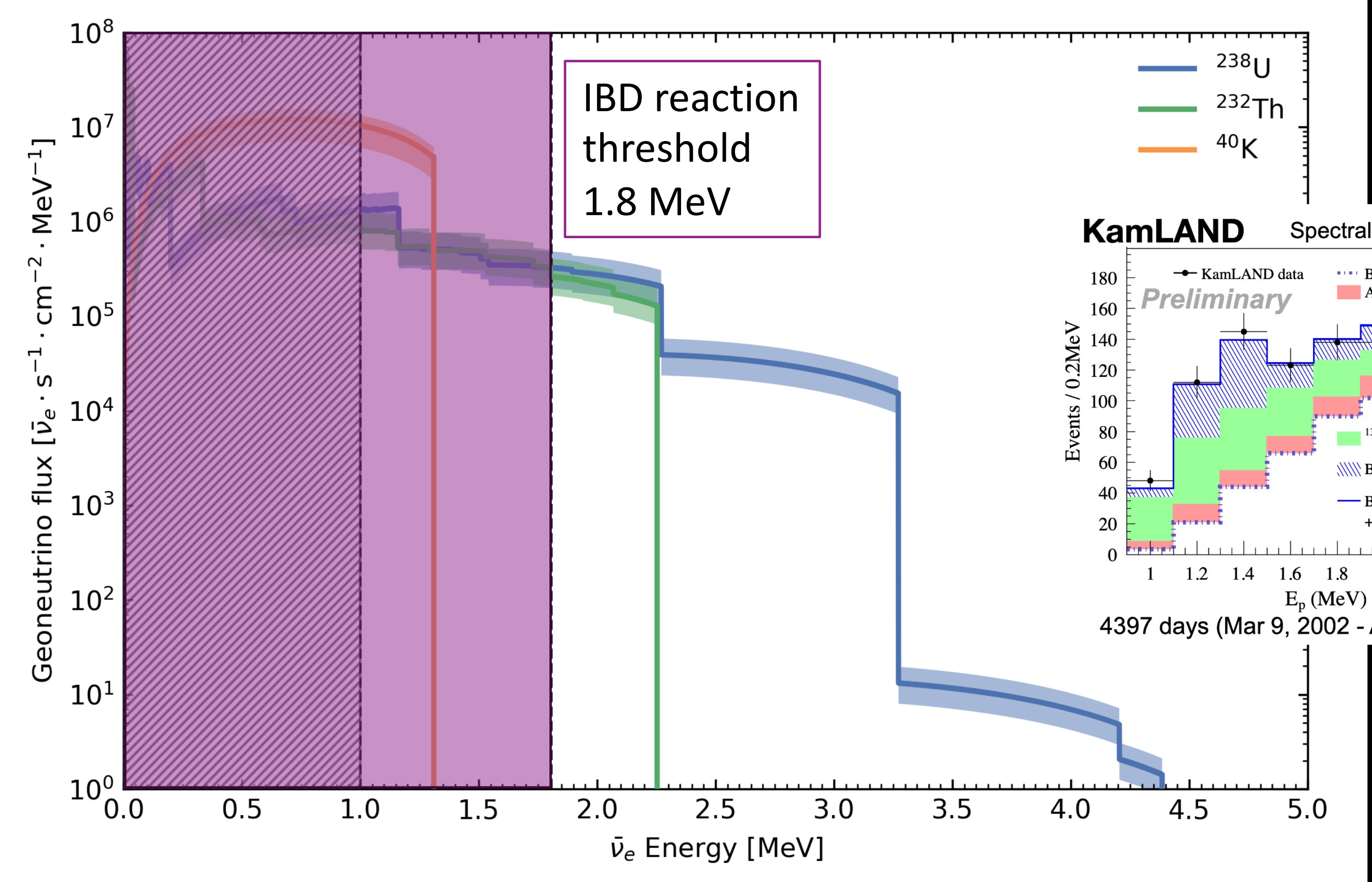
U and Th Geoneutrinos

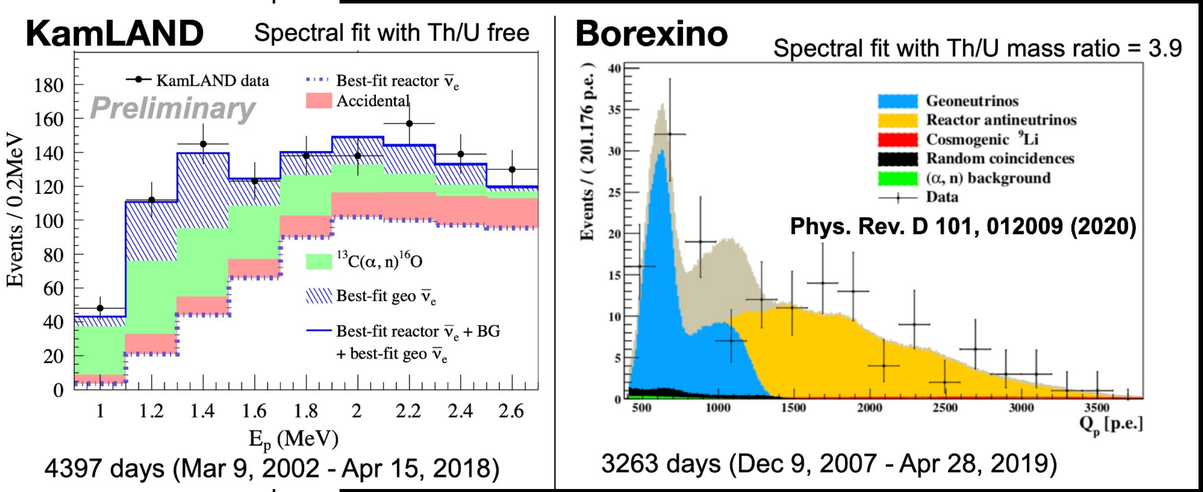
results have contributed to our understanding of U and Th radiogenic heat

Detected by KamLAND and Borexino (SNO+ results coming soon; JUNO will also be starting in the near future)

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

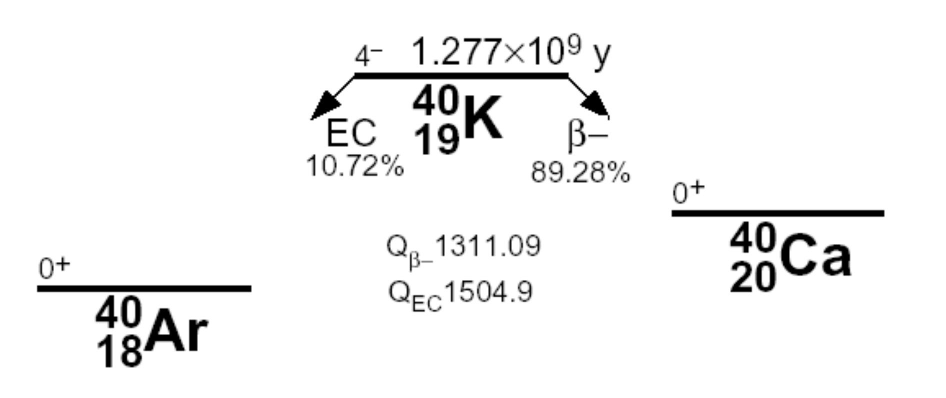
delayed coincidence signal

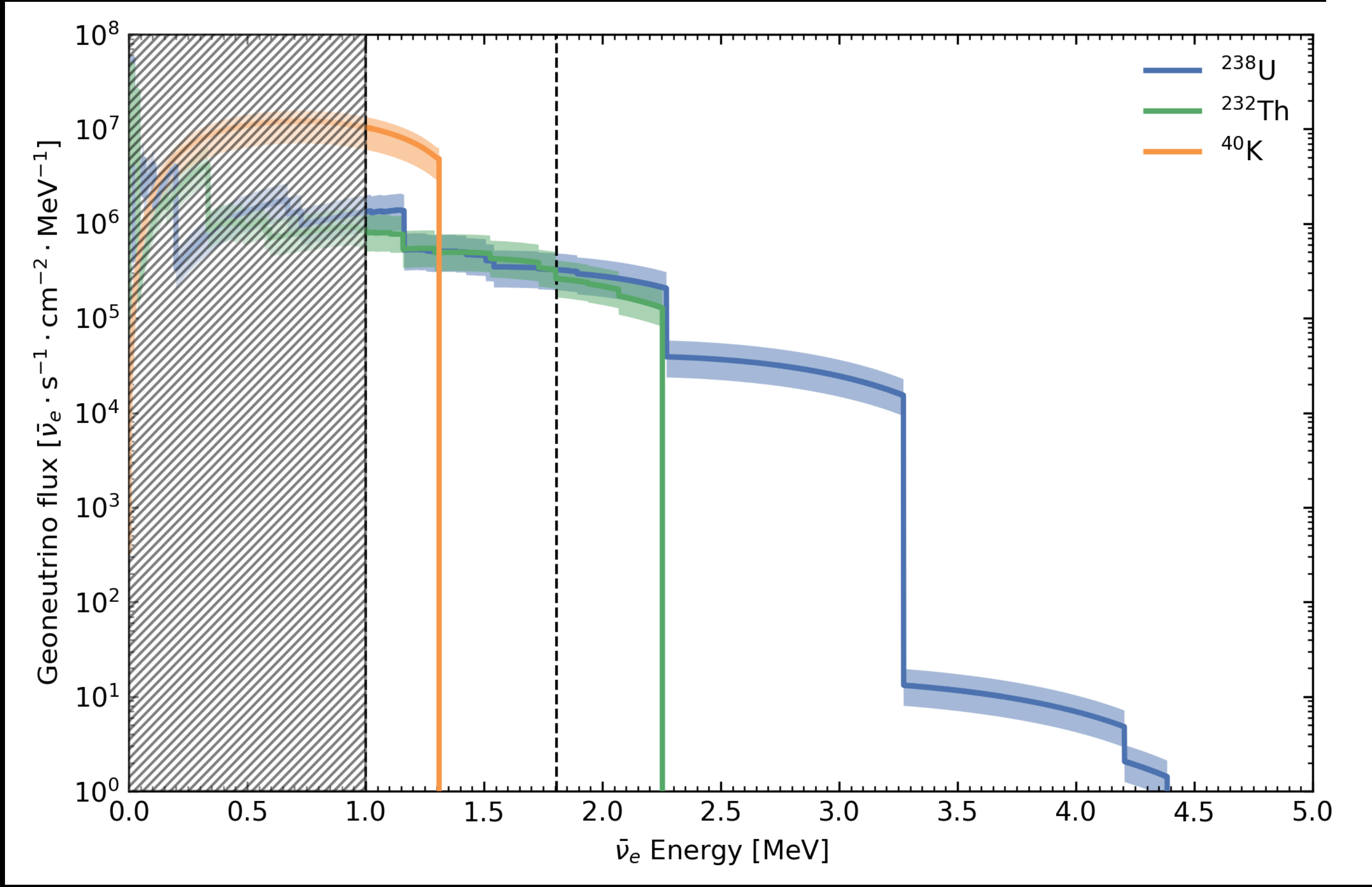




KamLAND and Borexino figure from Hiroko Watanabe Neutrino 2020

Potassium Geoneutrinos





Need a CC reaction target with energy threshold < 1.3 MeV

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

My talk @ Neutrino Geoscience 2005 in Hawaii presented all possible reactions for ^{40}K geoneutrino detection

- CC nuclear target
- ν-e⁻ ES scattering
- coherent ν-nucleus scattering
- NC nuclear excitation

- a few have been studied since

- the main problem (often ignored in those studies) are backgrounds in the proposed detection scheme

^{40}K geoneutrino detection via charged-current reactions and positron identification

arXiv > physics > arXiv:2308.04154

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[Submitted on 8 Aug 2023 (v1), last revised 23 Aug 2023 (this version, v2)]

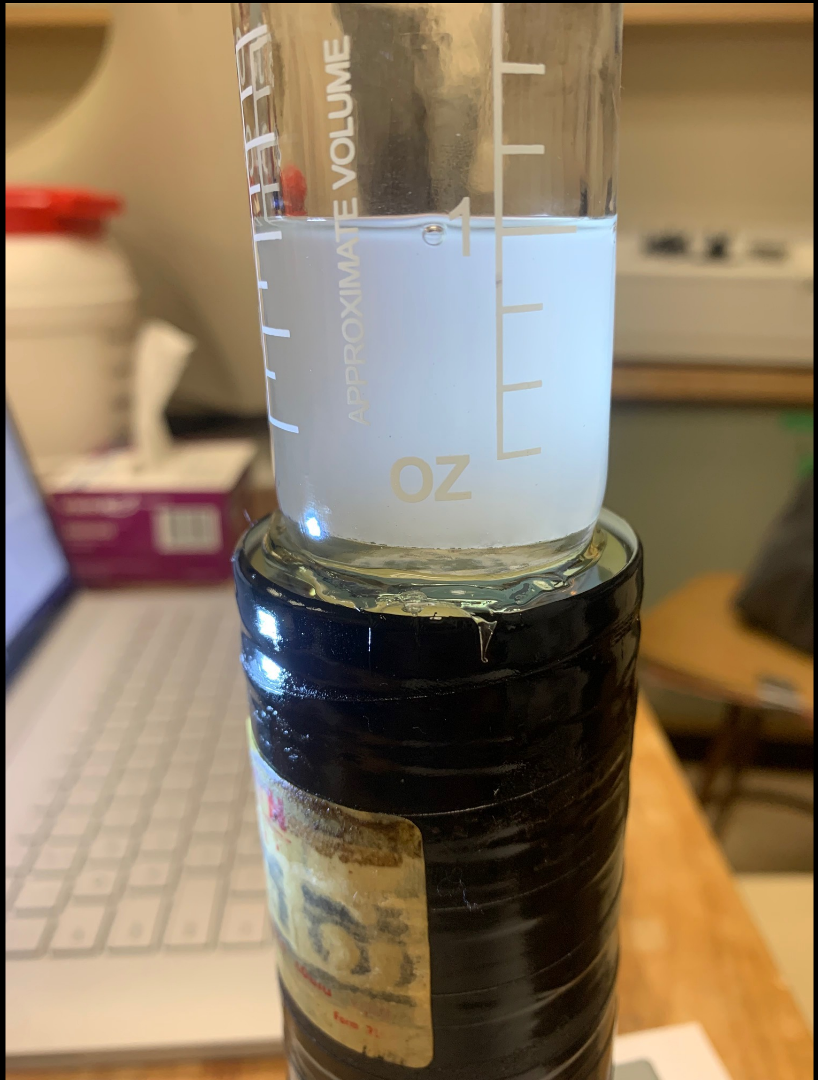
Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

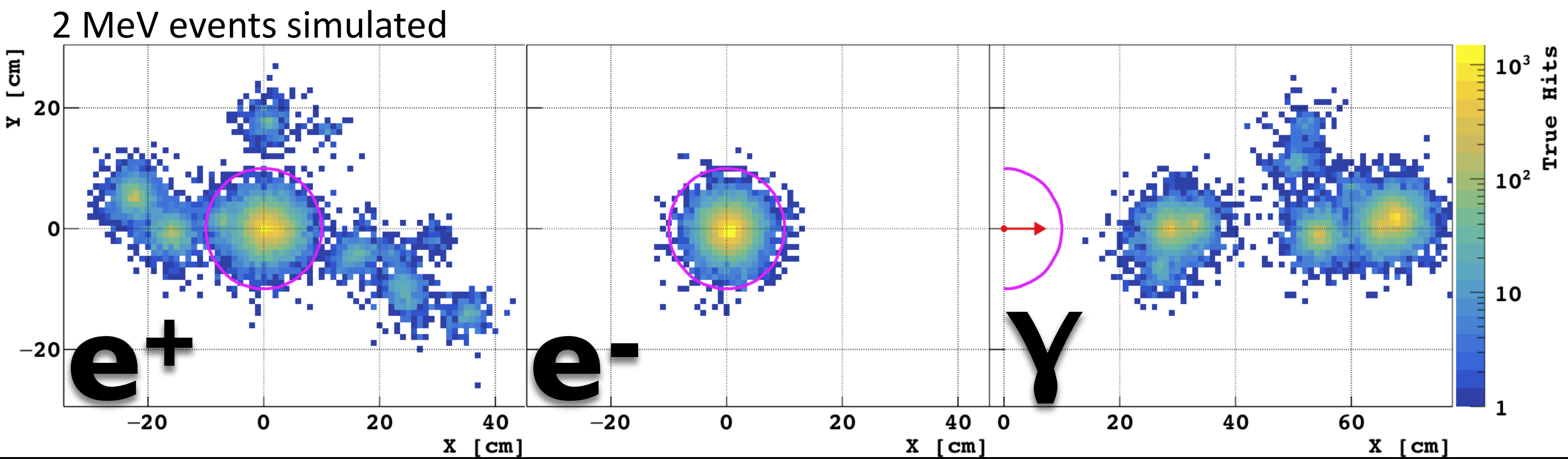
LiquidO Consortium: A. Cabrera, M. Chen, F. Mantovani, A. Serafini, V. Strati, J. Apilluelo, L. Asquith, J.L. Beney, T.J.C. Bezerra, M. Bongrand, C. Bourgeois, D. Breton, M. Briere, J. Busto, A. Cadiou, E. Calvo, V. Chaumat, E. Chauveau, B.J. Cattermole, P. Chimenti, C. Delafosse, H. de Kerret, S. Dusini, A. Earle, C. Frigerio-Martins, J. Galán, J. A. García, R. Gazzini, A. Gibson-Foster, A. Gallas, C. Girard-Carillo, W.C. Griffith, F. Haddad, J. Hartnell, A. Hourlier, G. Hull, I. G. Irastorza, L. Koch, P. Laniéce, J.F. Le Du, C. Lefebvre, F. Lefevre, F. Legrand, P. Loaiza, J. A. Lock, G. Luzón, J. Maalmi, C. Marquet, M. Martínez, B. Mathon, L. Ménard, D. Navas-Nicolás, H. Nunokawa, J.P. Ochoa-Ricoux, M. Obolensky, C. Palomares, P. Pillot, J.C.C. Porter, M.S. Pravikoff, H. Ramarijaona, M. Roche, P. Rosier, B. Roskovec, M.L. Sarsa, S. Schoppmann, W. Shorrock, L. Simard, H.Th.J. Steiger, D. Stocco, J.S. Stutzmann, F. Suekane, A. Tunc, M.-A. Verdier, A. Verdugo, B. Viaud, S. M. Wakely, A. Weber, F. Yermia

Could a single positron signal be used for ^{40}K geoneutrino detection?
What possible nuclear targets?
Which one is best?
What are possible single e^+ backgrounds?
→ fewer than single e^- backgrounds

LiquidO – "Opaque" Liquid Scintillator

see talk on LiquidO by
Cloé Girard-Carillo later today





short light scattering length stochastically confines scintillation photons
energy deposition pattern can be imaged by collecting light with grid of wavelength-shifting fibres

Imaging and Positron ID

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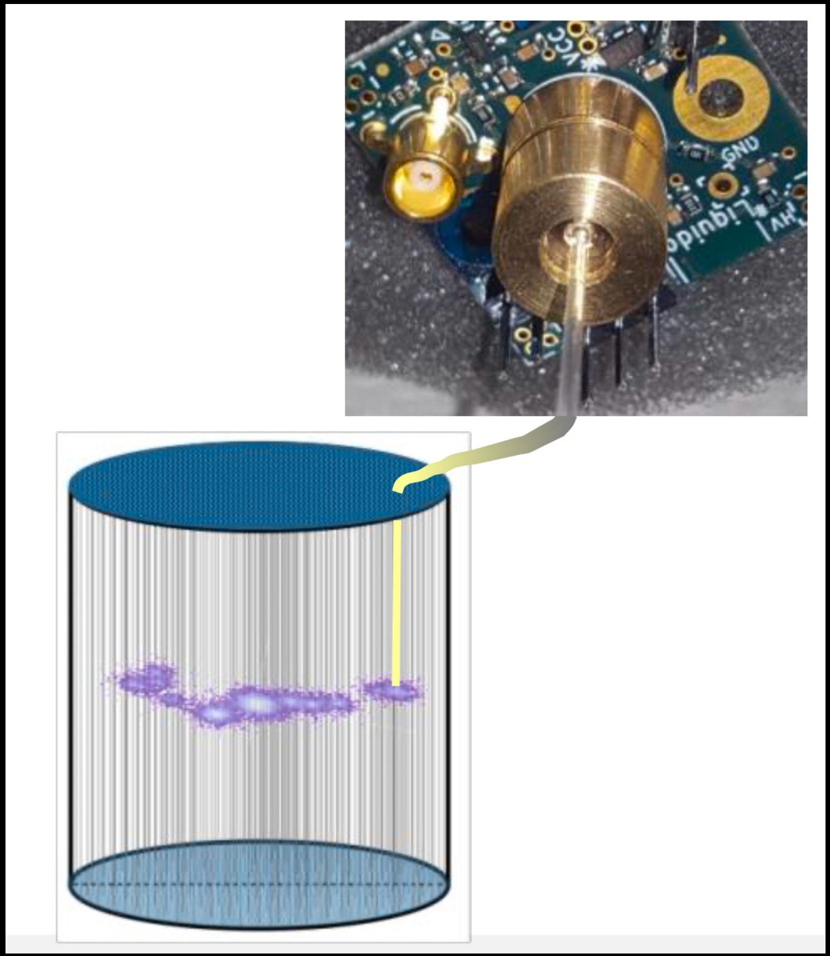

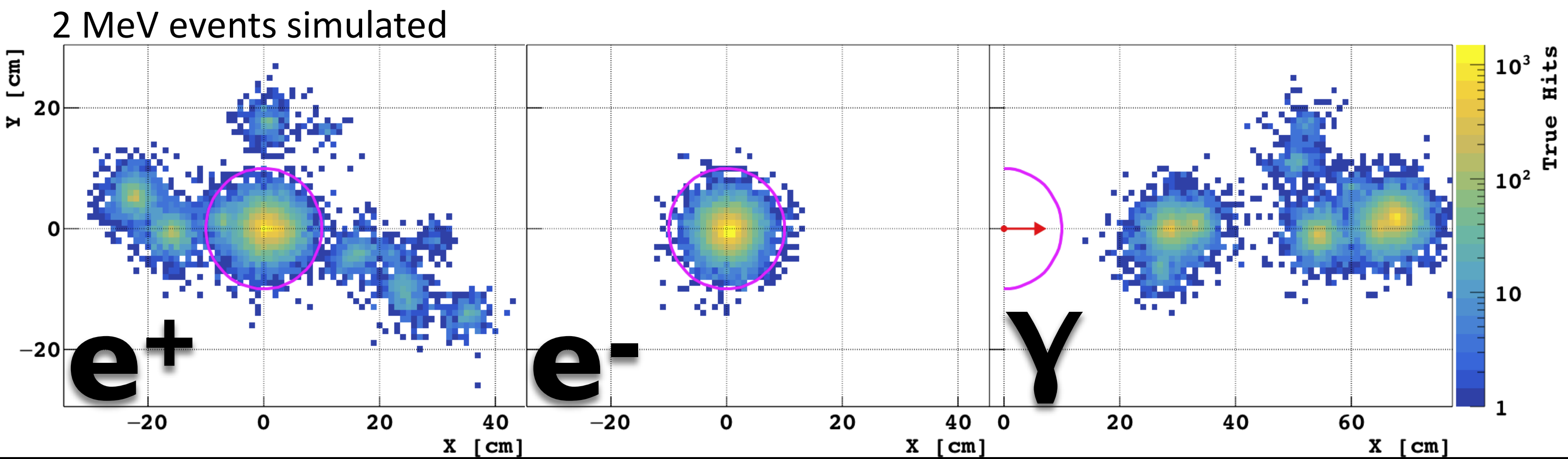

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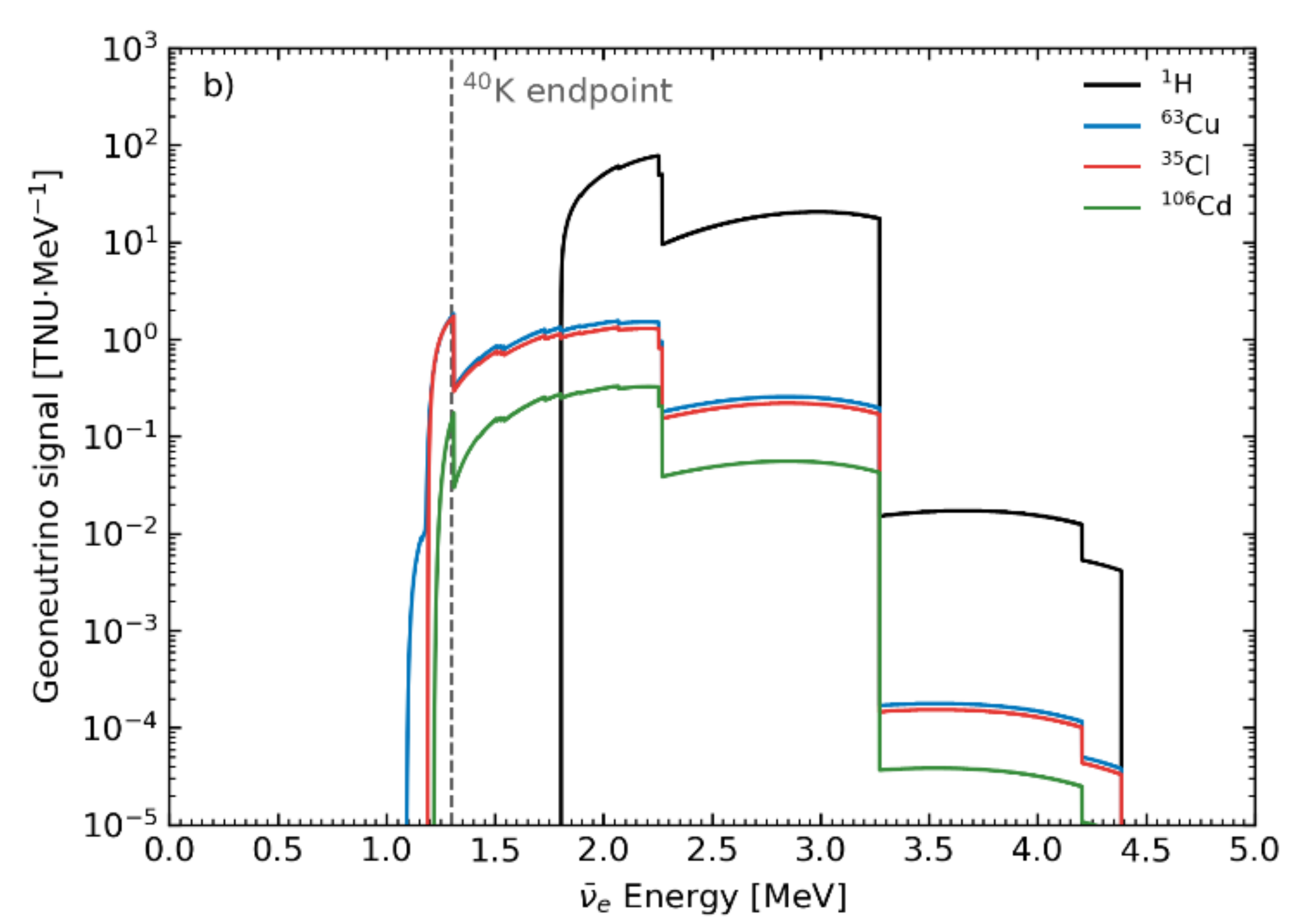
LiquidO's relaxed transparency condition facilitates high doping (of CC nuclear target)

Best Nuclear Targets
Cross Section Weighted by Isotopic Abundance



^{35}Cl and ^{63}Cu are the best, followed by ^{106}Cd
75.76%, 69.15% and 1.25% natural abundance, respectively

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

^{63}Ni* decays with 87 keV gamma ray
1.67 μs lifetime – a delayed coincidence!

Both the LiquidO positron identification and the delayed coincidence would strongly suppress backgrounds!

Potassium Geoneutrino Event in LiquidO

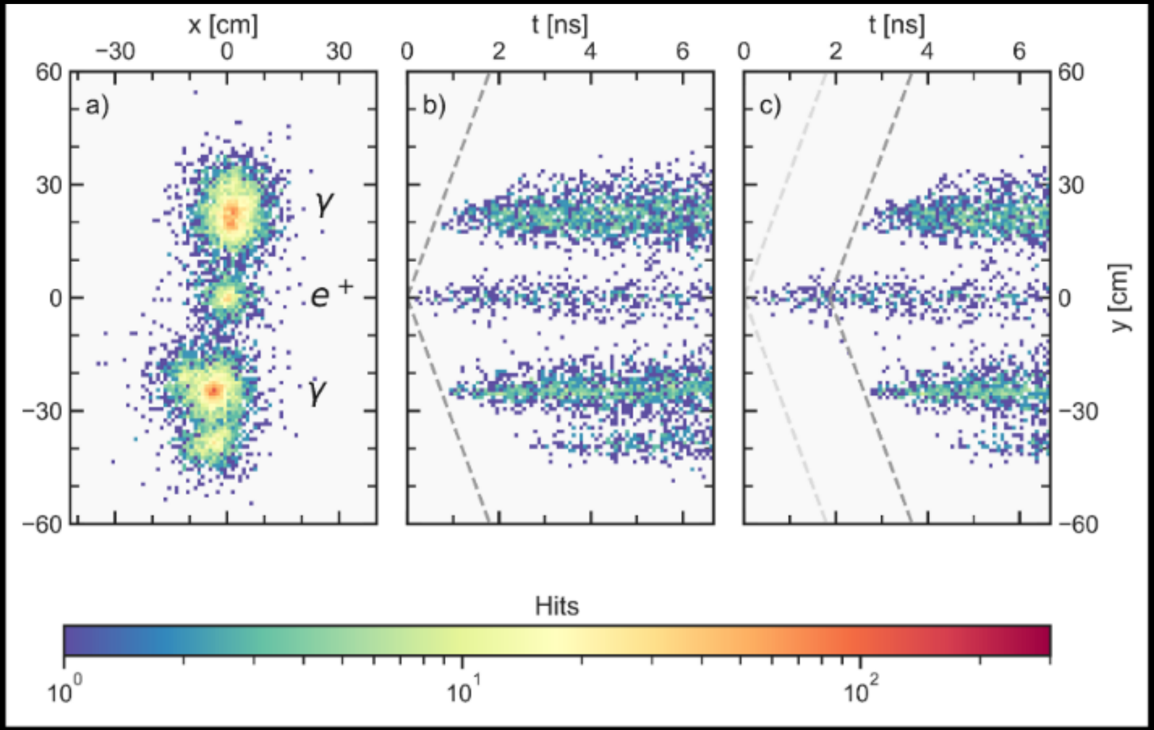
a) positron event imaging

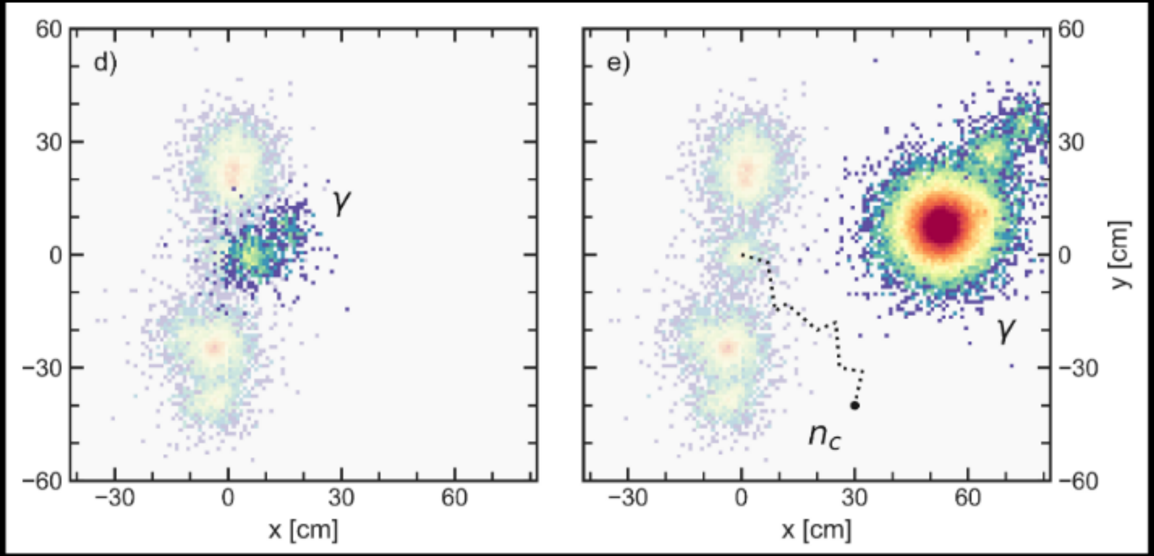
b) energy-time flow confirms 2γ's

c) orthopositronium formation provides another e^+ tag

d) delayed 87 keV γ from $^{63}Ni^*$ decay

e) IBD (on proton) event from U, Th, reactor $\bar{\nu}_e$'s can be distinguished





Positron Backgrounds
(and how to deal with them)

e$^+$ Backgrounds		
Source	**Expectation**	**Suppression**
IBD(^{A}X) of U and Th geoneutrinos	~1/5 rate of predicted ^{40}K geoneutrinos in K energy interval	Irreducible but measured by IBD(p)
IBD(^{A}X) of reactor antineutrinos	~1/60 rate of predicted ^{40}K geoneutrinos in K energy interval	Irreducible but measured by IBD(p)
β^+ decays of naturally occurring ^{40}K in the detector	~10^{-5} e$^+$ per year per ton	Use of decay energy spectrum to constrain
β^+ decays of cosmogenic isotopes	Similar to β^+ isotope production in current experiments	Cosmic muon veto and energy spectrum for further suppression
Pair production (e$^+$-e$^-$) by gamma rays (conversion)	Pair production cross section in the [1.022; 1.144] MeV range is ~10^{-3} times the Compton scattering cross section that dominates in current experiments	Gamma rays make other interactions prior to converting; *LiquidO* event pattern helps reject
Multiple Compton scattering (fake e$^+$ signal)	e$^+$ signal is still very distinctive compared to gamma-ray-induced single electron recoils	Monte Carlo study of rejection of gamma rays using event pattern and energy flow

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In our paper, we found that a cosmogenic background, ^{36}Cl production, rules out the possibility to use ^{35}Cl as the target.

We emphasize the importance of fully studying cosmogenic backgrounds in rare event experiments.

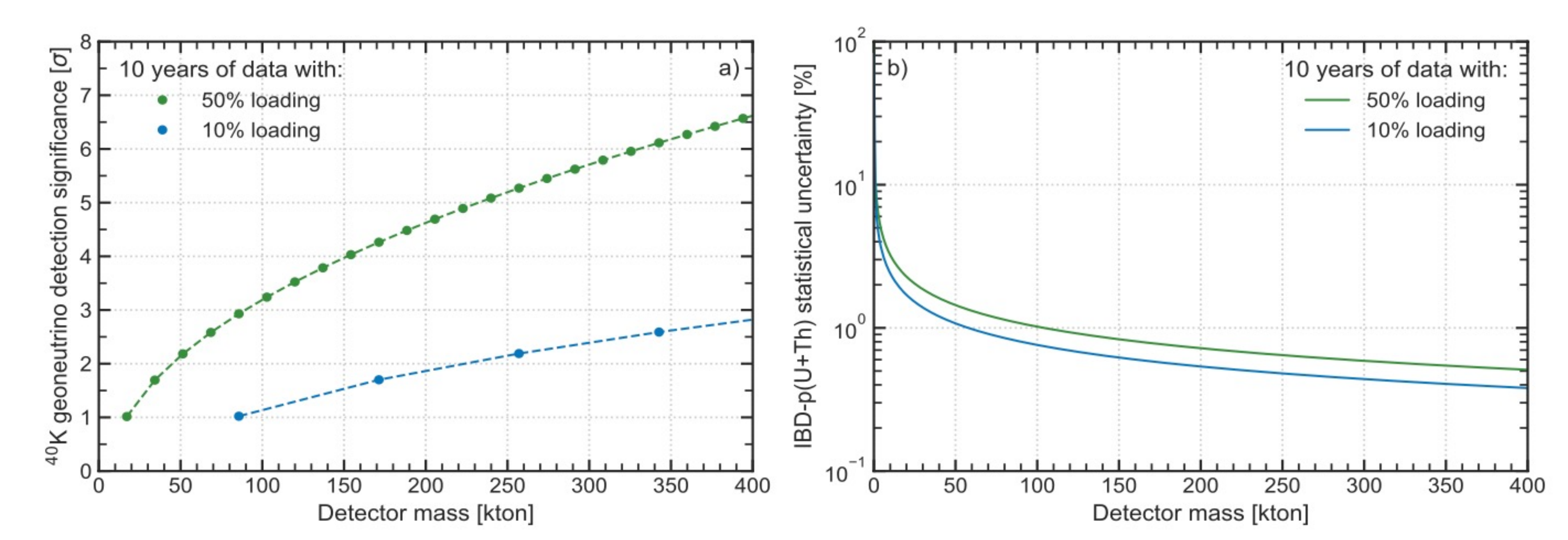
What's the Event Rate?

Signal at LNGS	[TNU]
^{40}K geo	0.10
U+Th IBD(p)	40.5
U+Th IBD(Cu)	1.34
U+Th in ^{40}K window IBD(Cu)	0.02

- 1 event/yr/100 kton of Cu

  yes, I know… proton decay searches are at this scale too 😉

  Including backgrounds (that are expected to be very low) and their uncertainties, the discovery significance versus detector size is:



Conclusions

- Potassium geoneutrino detection is hard!
- Exploiting the antimatter signature (e^+ identification like in LiquidO) provides a handle for suppressing backgrounds for this rarest of neutrino signals
- ^{63}Cu is the ideal and only feasible CC nuclear target, out of all that have been studied, and provides a delayed coincidence signal