Beyond LEGEND-1000

Semi-private thoughts

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Double Beta Decay Workshop

ISCTE – Lisbon

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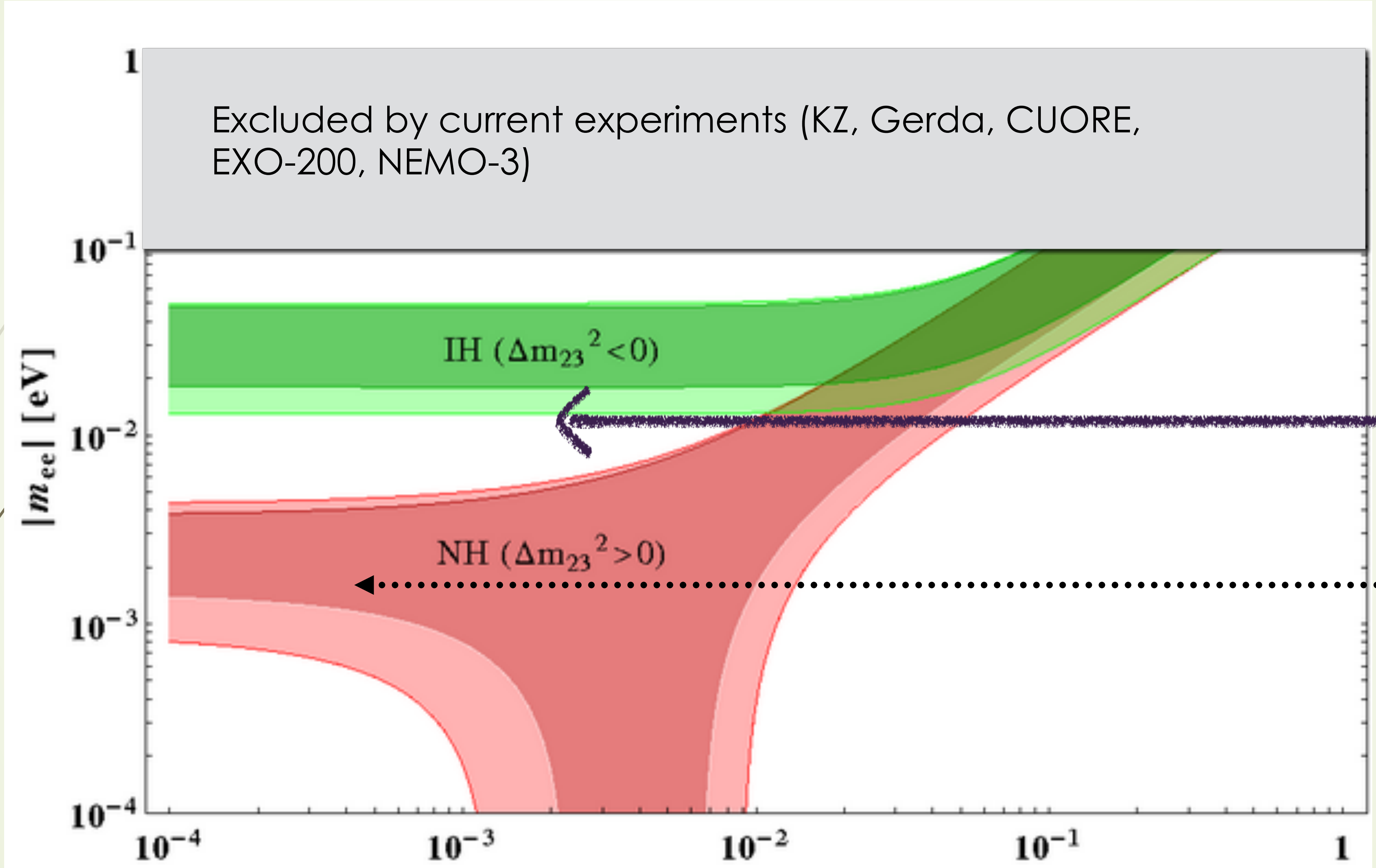
Most plots from LEGEND pCDR, arXiv:2107.11462v1

Motivation

- A rare chance for ***zero-background*** "discovery machine"
  - Unsurpassed **energy resolution** (FWHM@$Q_{\beta\beta} \leq 2.5$ keV)
  - Ge crystals intrinsically clean from ^{238}U and ^{232}Th, ***no known γ-lines*** near $Q_{\beta\beta}$=2039 keV
  - ***No contribution*** from "irreducible" $\boldsymbol{2\nu\beta\beta}$ with exposures of up ***to 100's of ton-years***
  - **^{76}Ge** isotope can be produced with **sufficient quantities**, **no monopoly**, benefit from **commercial production** of ^{72}Ge (but *cost*!)

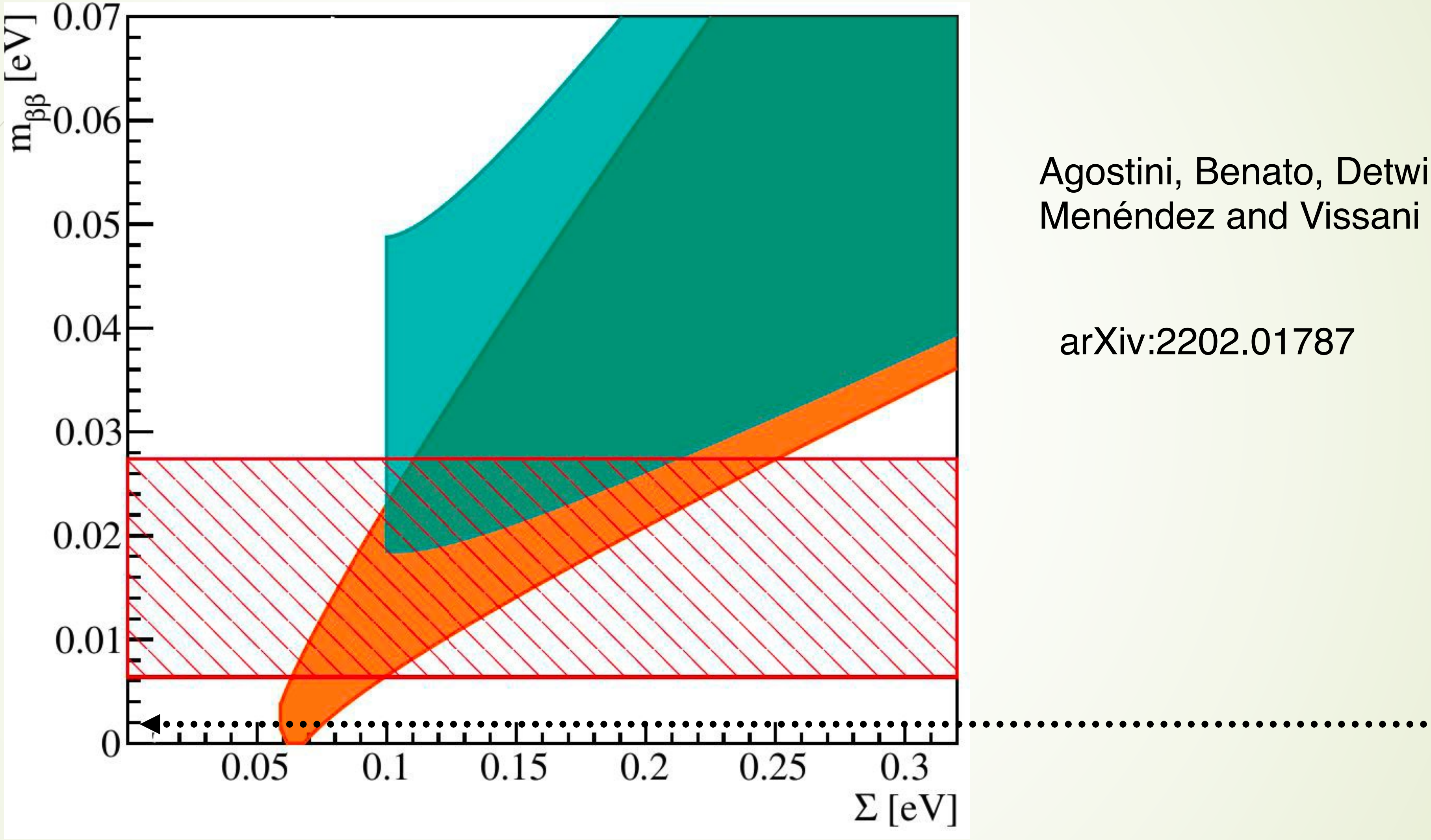
$$\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$$



upcoming (L1K, CUPID, nEXO, SNO+(II), NEXT, …

What we're here for

Cheer up with linear scale !



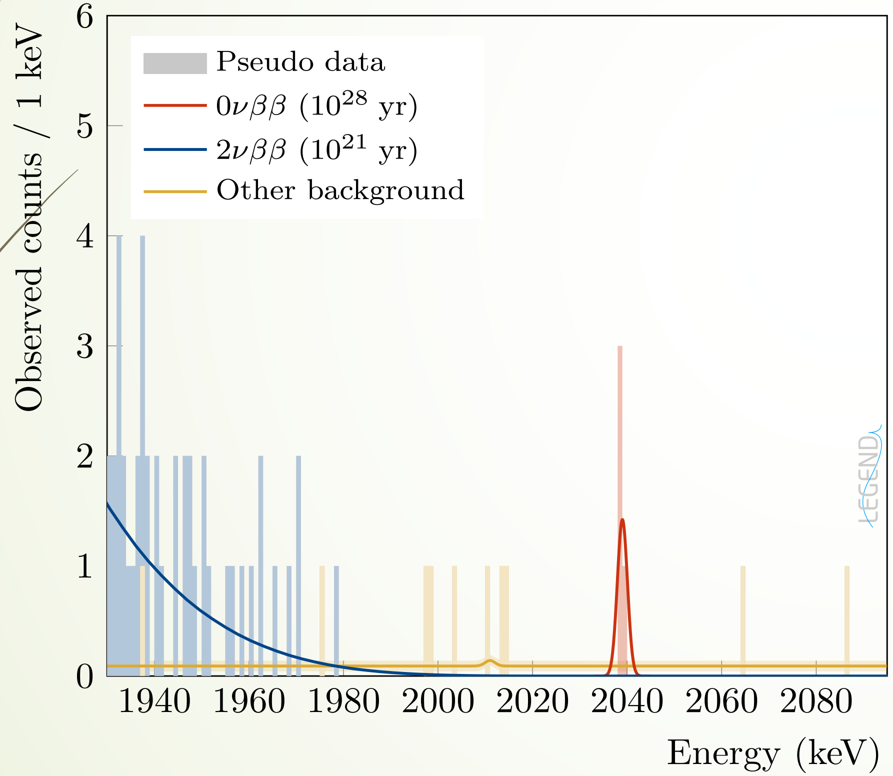
Agostini, Benato, Detwiler, Menéndez and Vissani

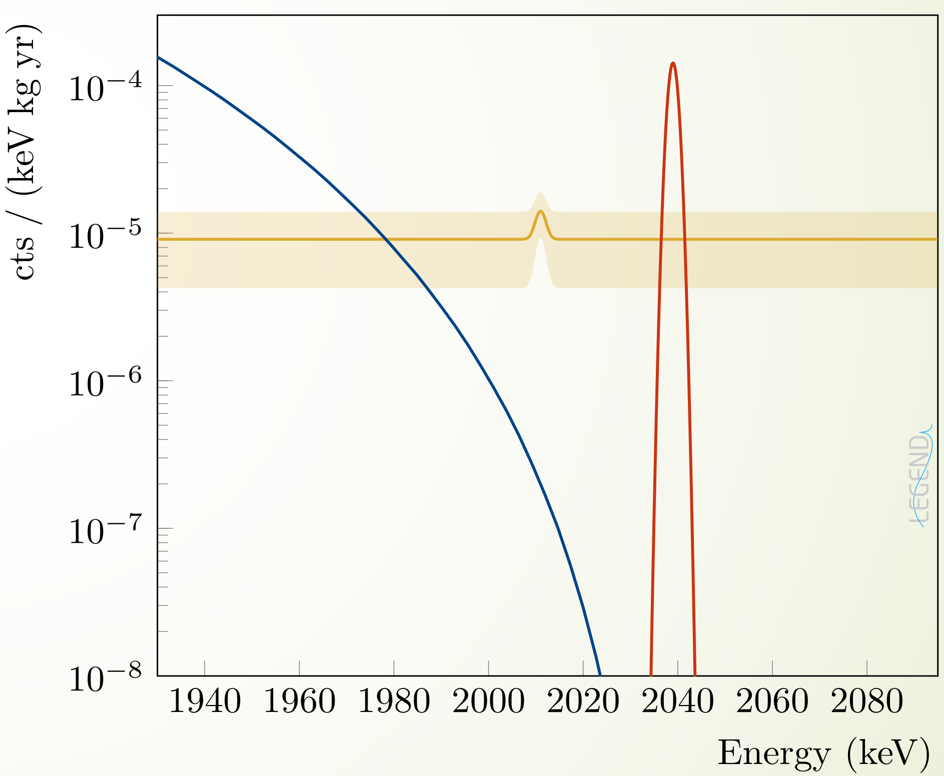
arXiv:2202.01787

Will look into

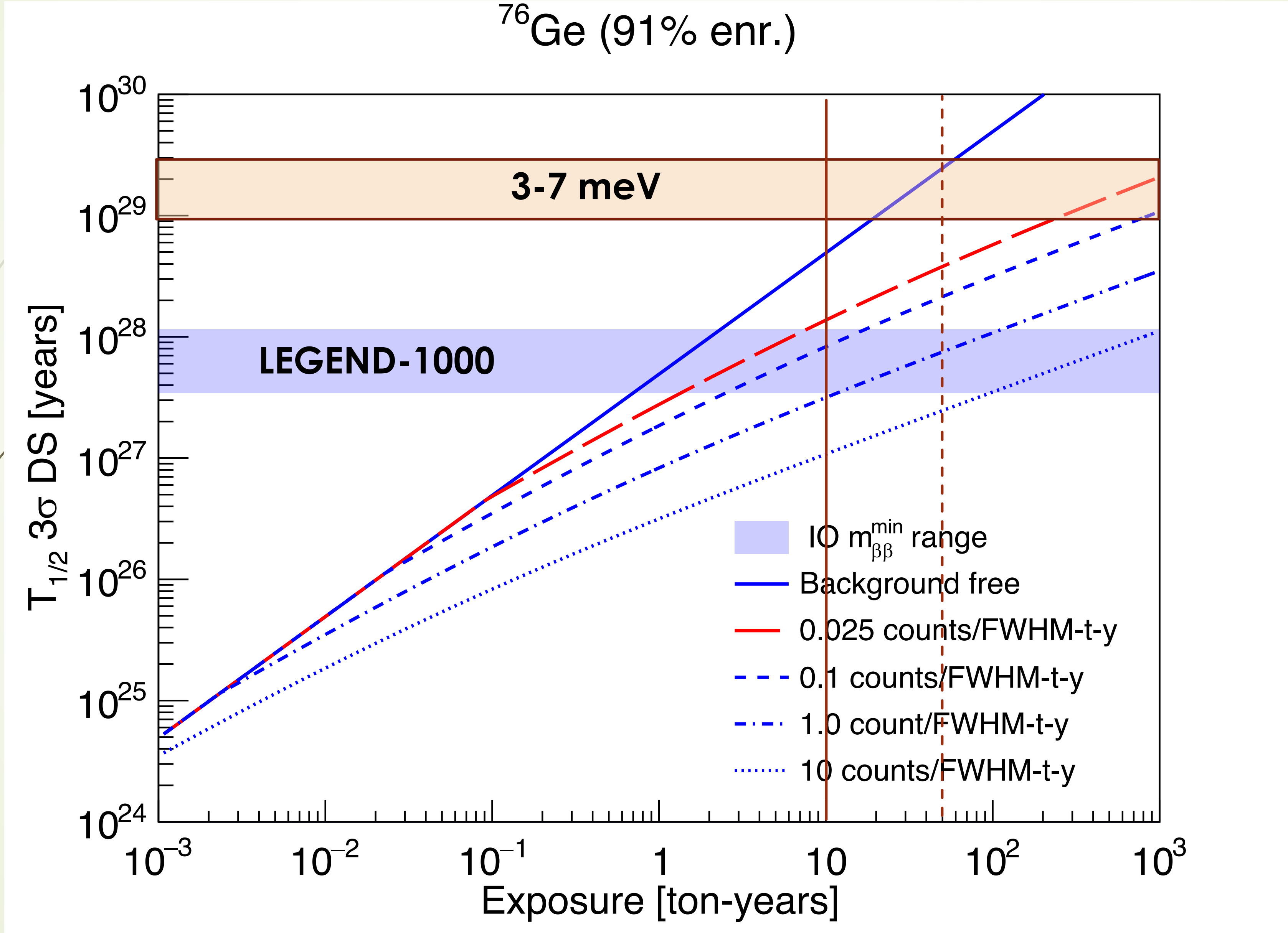
- Feasibility for a **LEGEND-type** detector to reach ***few meV discovery potential***
  - Aiming at $T_{1/2} \sim 10^{29}$ yr, ➔ $<m_{\beta\beta}> \sim$ 3-7 meV

Same LEGEND strategy: quasi-background free discovery oriented search

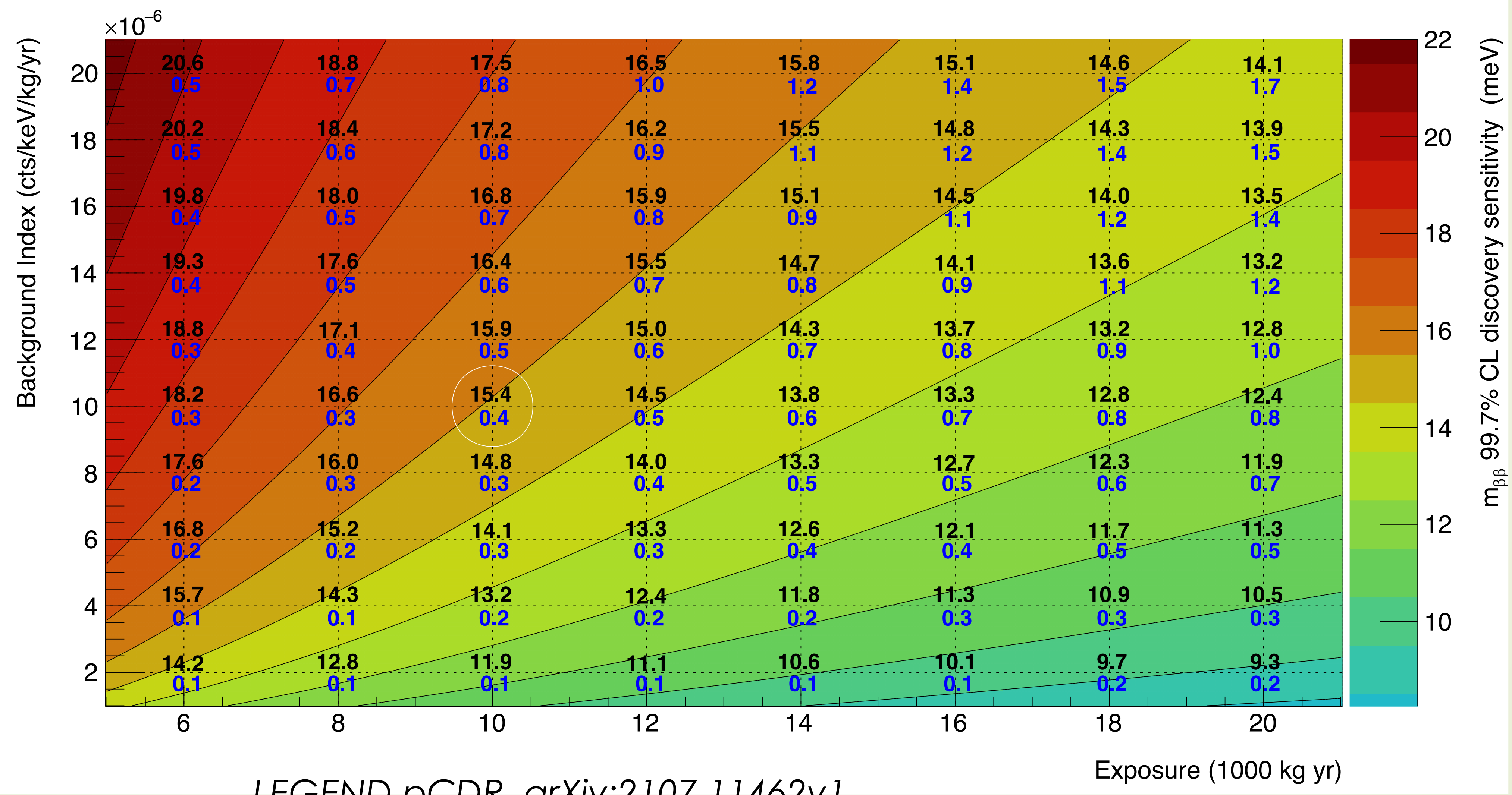




LEGEND Sensitivity



LEGEND-1000 Discovery Sensitivity (3σ) and Background Projections

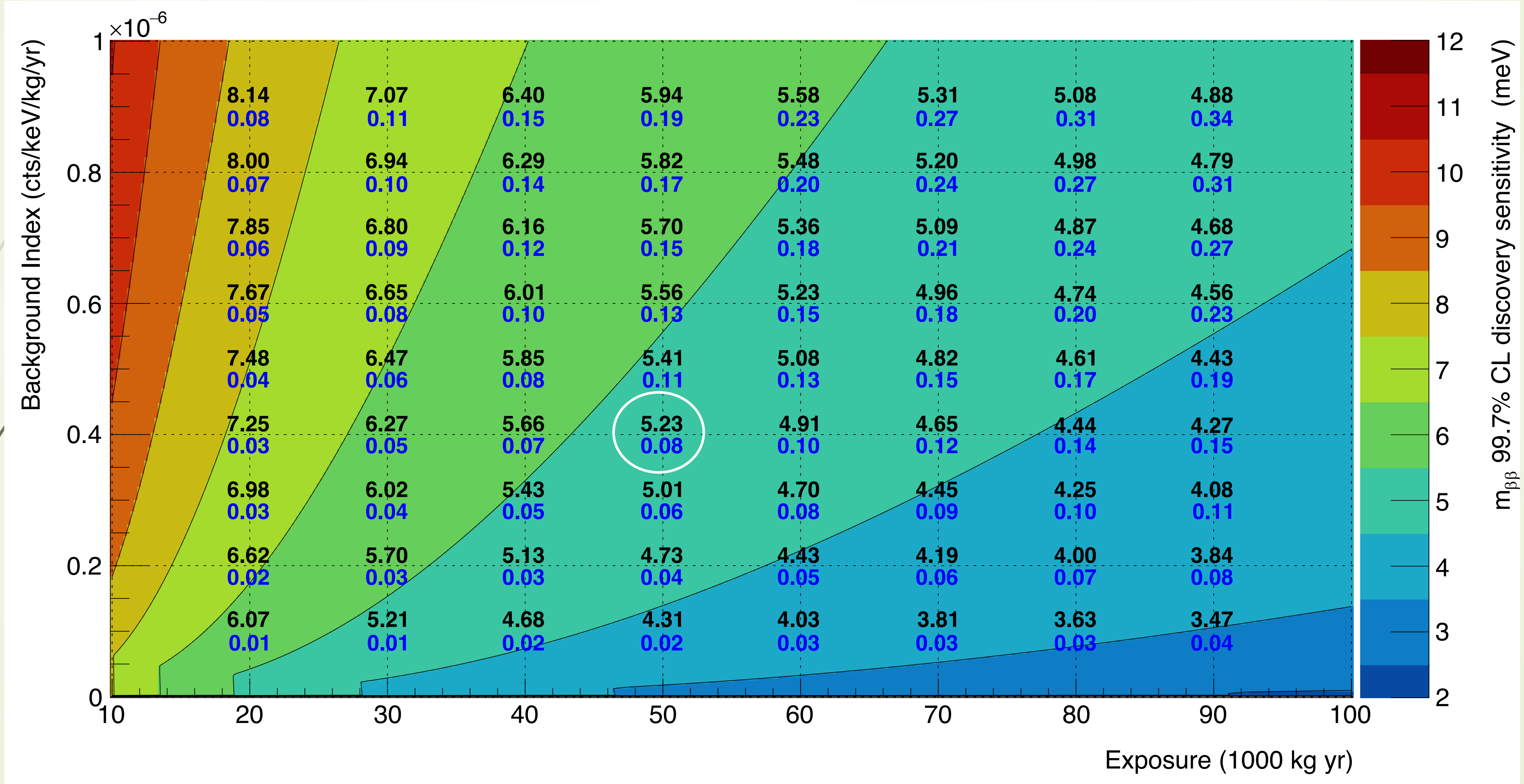


LEGEND pCDR, arXiv:2107.11462v1

Beyond L1K Discovery Sensitivity (3σ) and Background Projections

Preliminary

Credit: M. Agostini

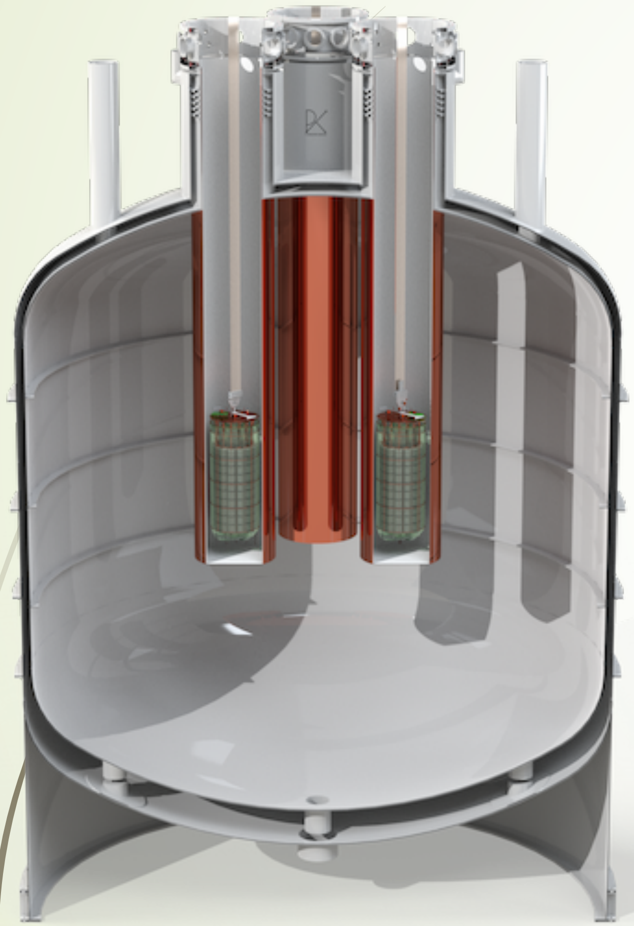


Take home

- 3-7 meV 3σ discovery potential requires $T_{1/2}$~10^{29} yr for ^{76}Ge
- Lowering background to 0.001 cnts/FWHM-t-y allows reaching 3-7 meV with 50 t-y exposure,
- Could be accommodated with ~L1K tank with some modifications (discussed below) → 5-ton of HP^{76}Ge over 10 yr.
- NB: L1000 goal is 0.025 cnts/FWHM-t-y

How to reach ~0.001 cnts/FWHM-t-y?

Same overall design concept



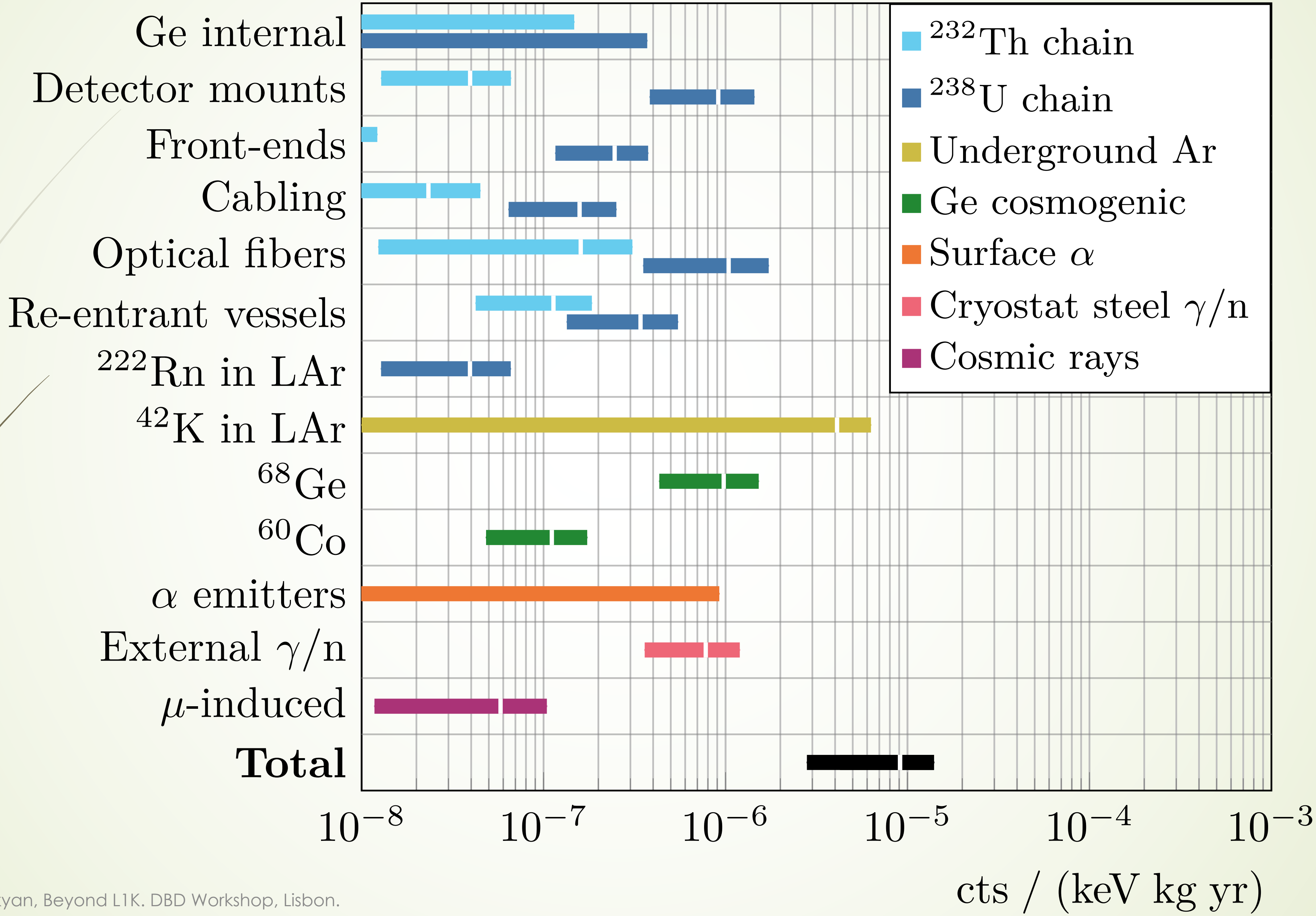
With significant modifications to improve performance of current baseline design (subject of ongoing R&D)

E.g.

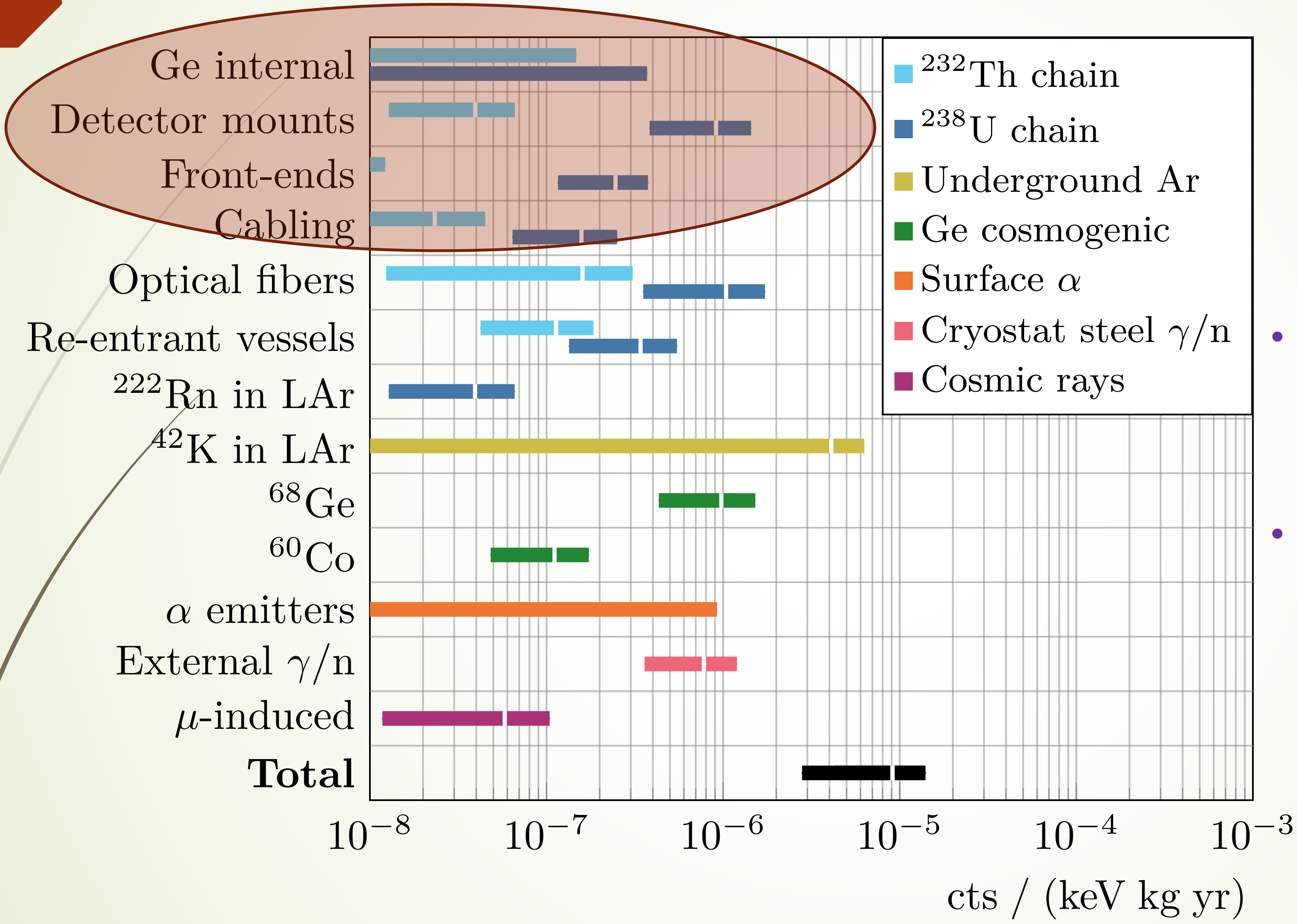
- HPGe detector innovation
- No re-entrant vessels
- detector encapsulation
- different LAr readout
- …

Addressing backgrounds based on experience from GERDA and MJD, and expectations for L200 and L1000

LEGEND-1000 Background Model



How to drop background by another order of magnitude?



- ***Increase HPGe mass without compromising performance***
- ***Use cleaner and active materials***

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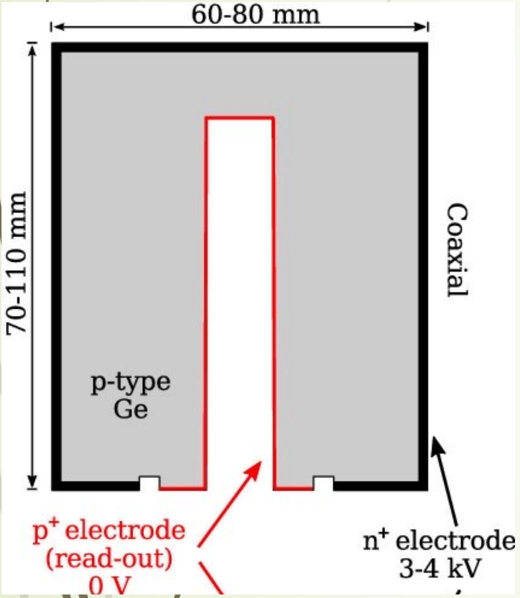
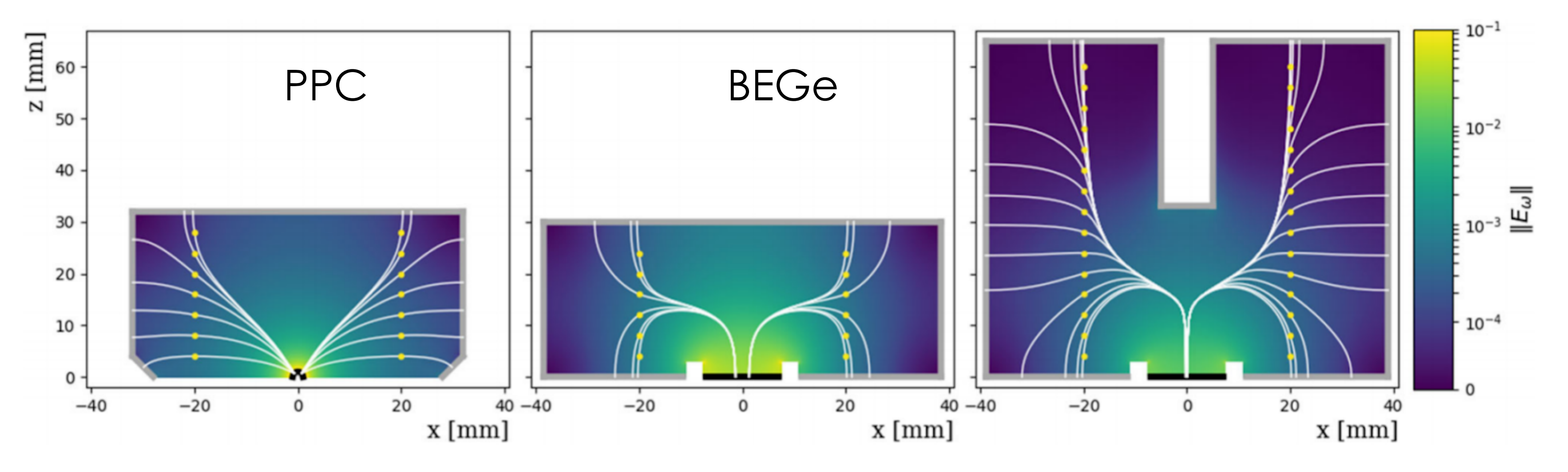
Innovation in HPGe detectors has been key to success of ^{76}Ge technology in double beta decay field giving it the competitive edge.

0.7-0.8 kg

ICPC (2-2.5 kg)

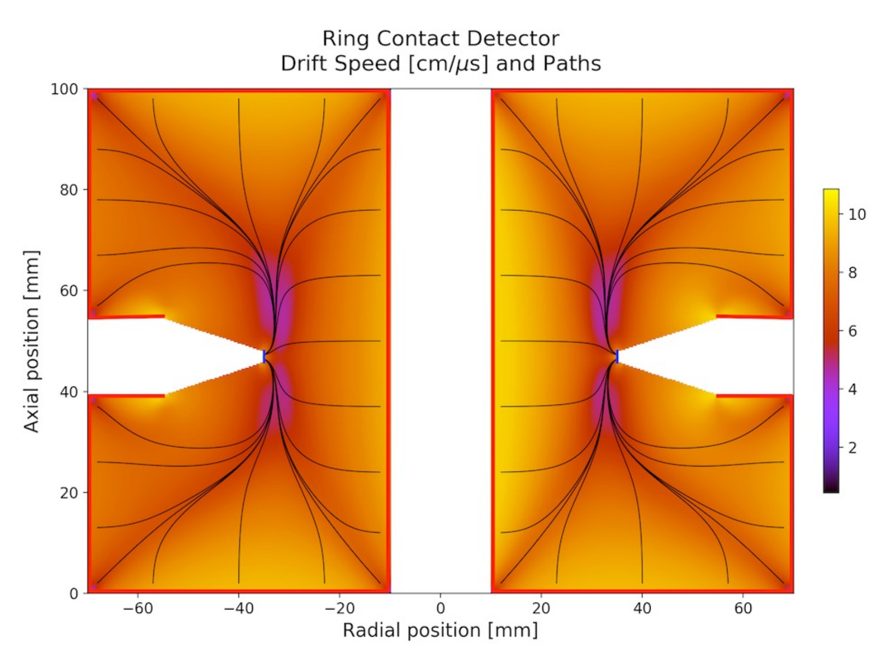




"Traditional"

MJD + GERDA → LEGEND

Significant effort in pushing to even larger HPGe detector without compromising performance in close collaboration with industry (Mirion, Ortec, etc)

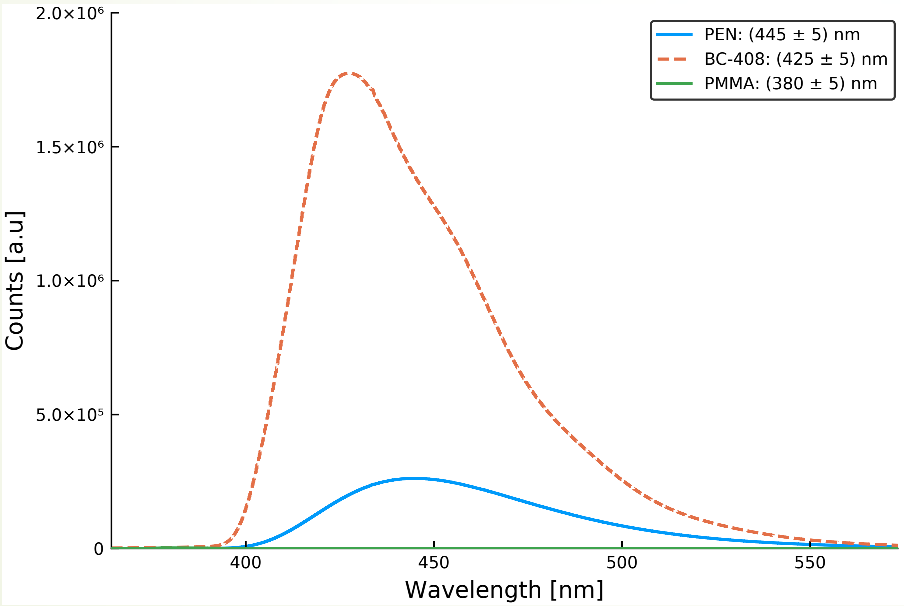


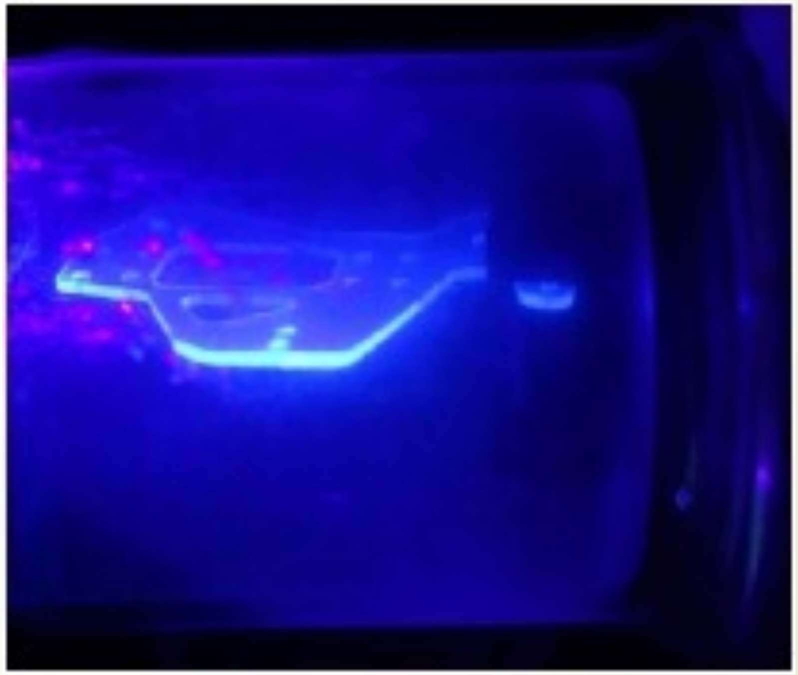
- Maintain topological and particle ID capabilities for background discrimination
- Maintain energy resolution of ≤ 2.5 keV@$Q_{\beta\beta}$
  - Small readout electron capacitance

- Ongoing effort towards **4-6kg** detectors by introducing ***conceptual*** changes in **geometry** of **crystal** and **electrodes**
- *Subject to ongoing patent application*
- *Potential game changer, watch this space!*

Detector mounts from fully active materials

- Structural scintillating plastic, such as PEN, [$C_{14}H_{10}O_4$]
- Will be thorough tested already in L200, and further in L1000
- Shows exceptionally good radiopurity levels and good scintillating properties (veto)
- Fabrication with SLA 3D printing





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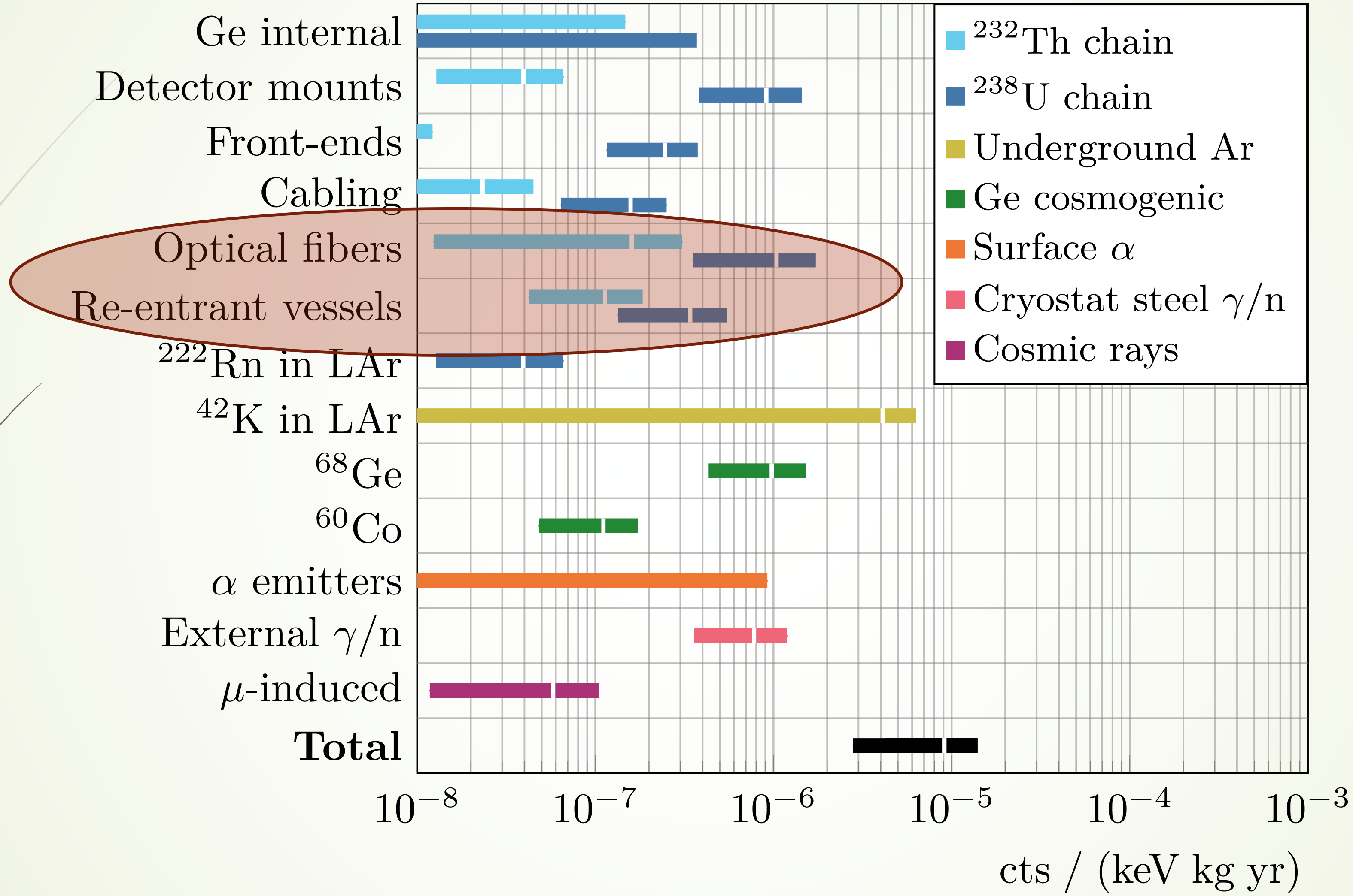
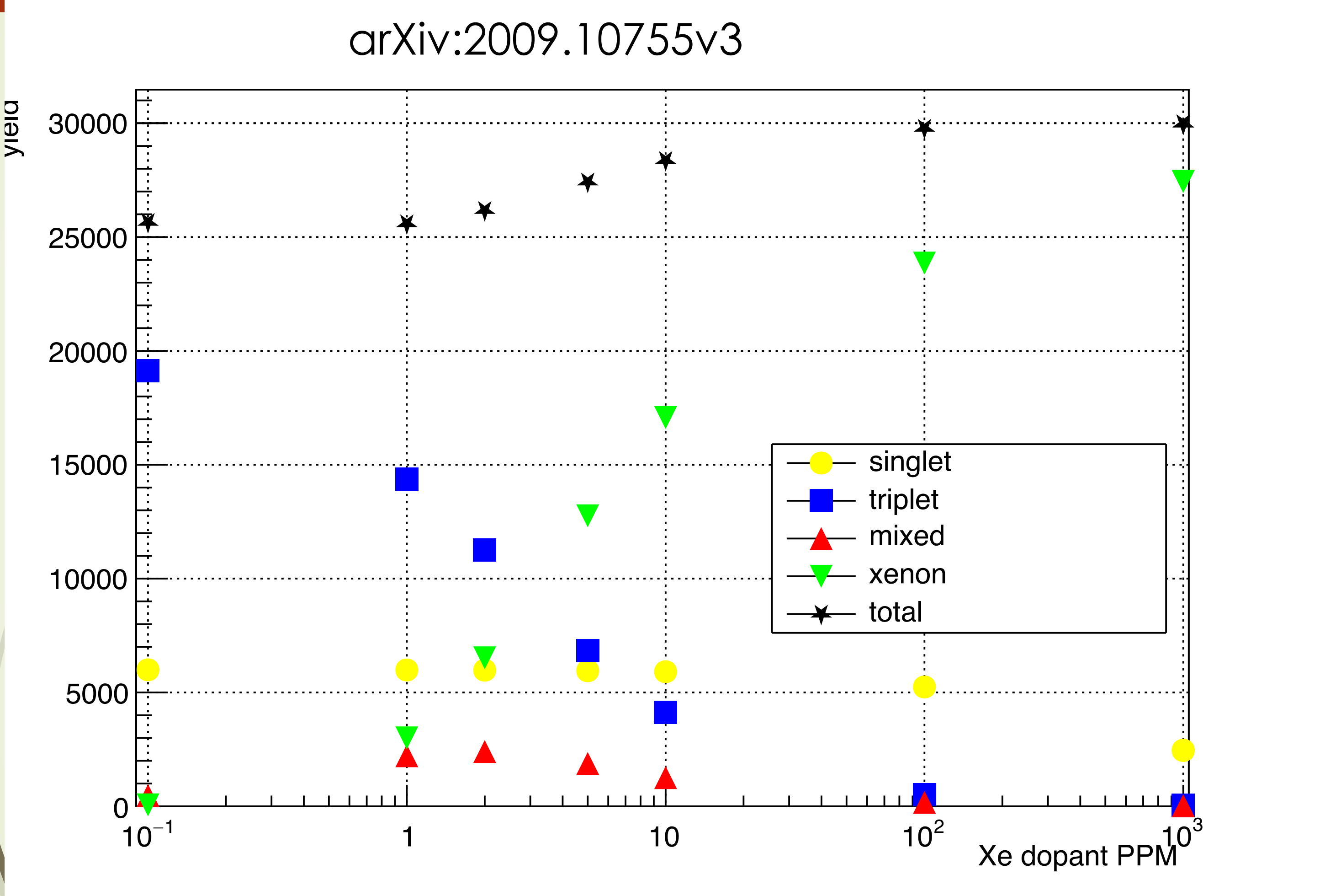


From WLS fibres to Xenon doping of Liquid Argon veto



Increased light yield by x2

Shifting wavelength to 175 nm

WLS plates/cylinders are also under study. Potentially higher radiopurity and light yield.

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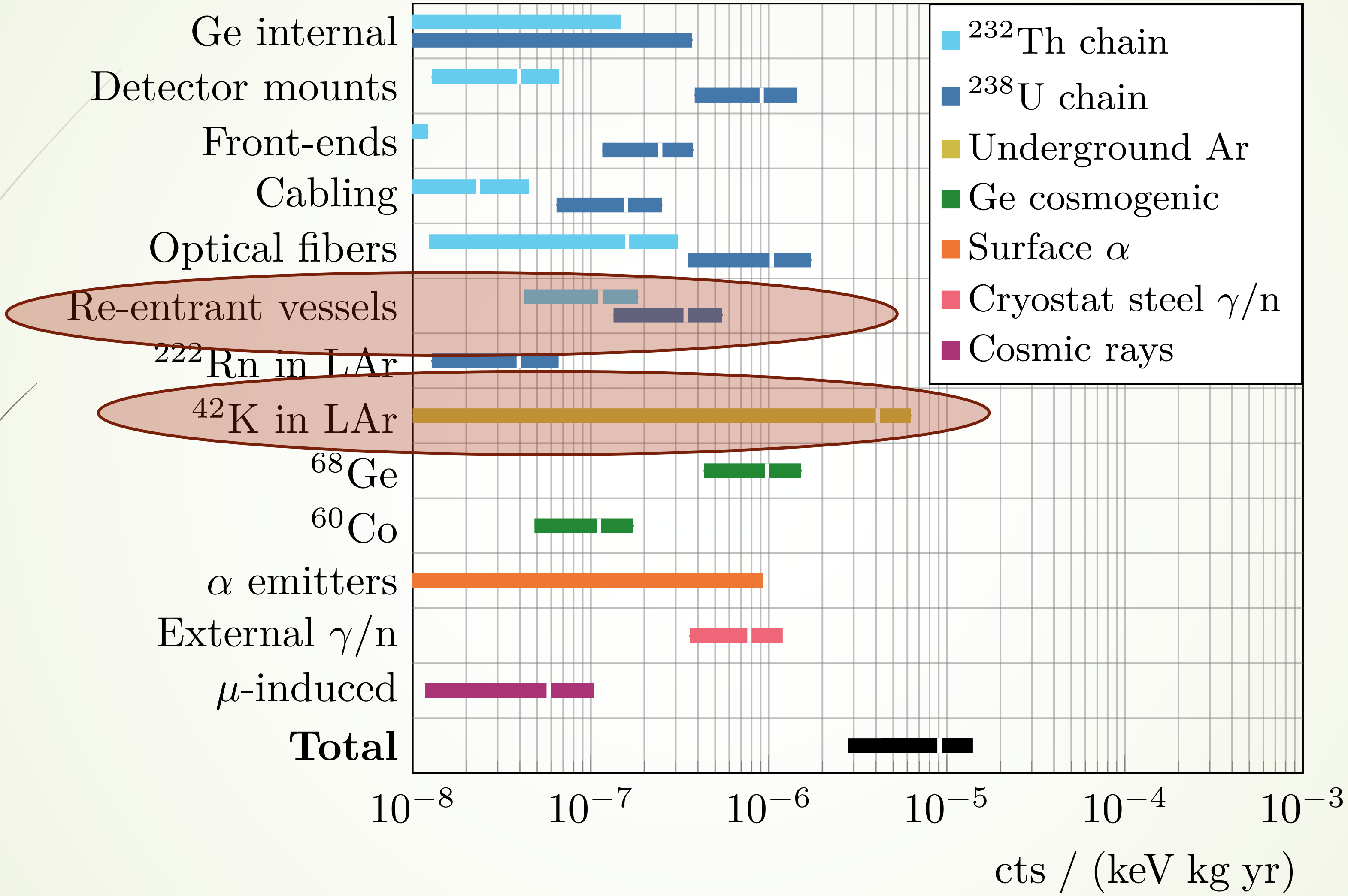
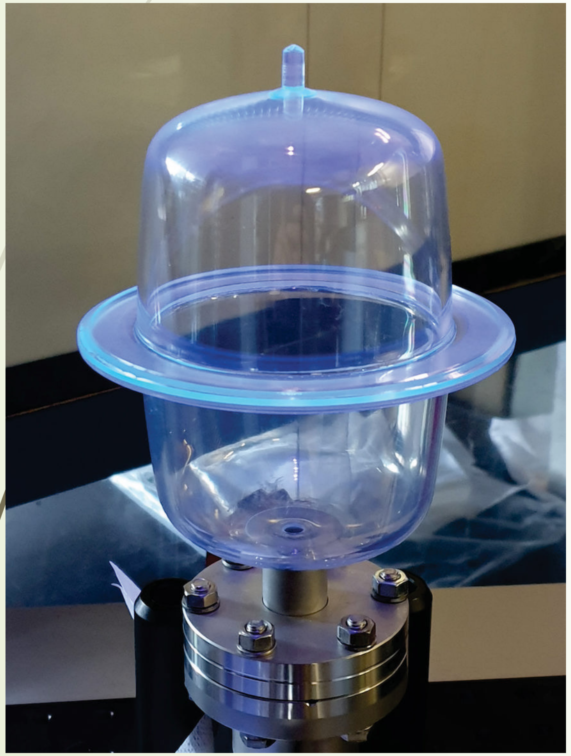
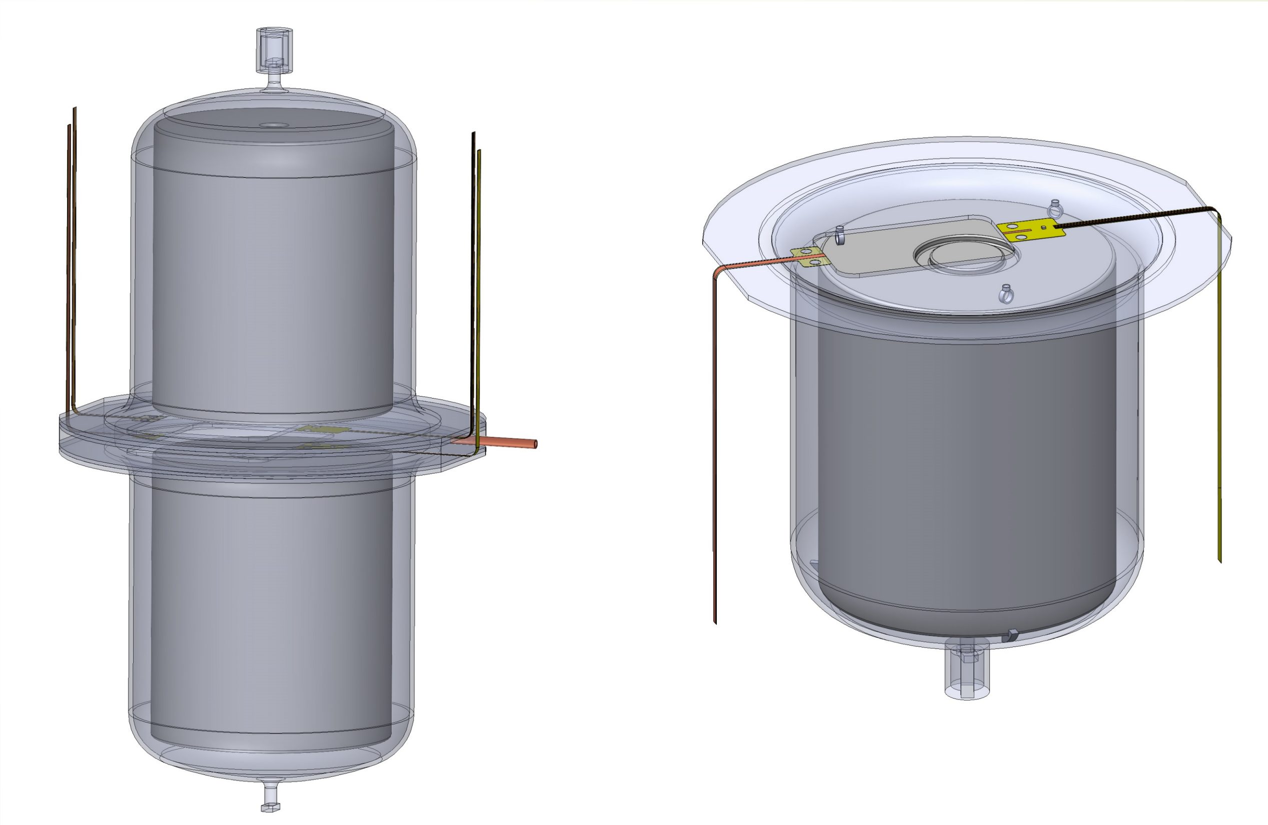


HPGe detector encapsulation

- Made of active (scintillating) material, e.g. PEN
- Block ^{42}K ions (from ^{42}Ar) drifting to detector surfaces
- Potential to use atmospheric LAr only
- Removes the need for re-entrant Cu vessels

NB: optimisation of n+ dead layer thickness is another mitigation tool for ^{42}K background





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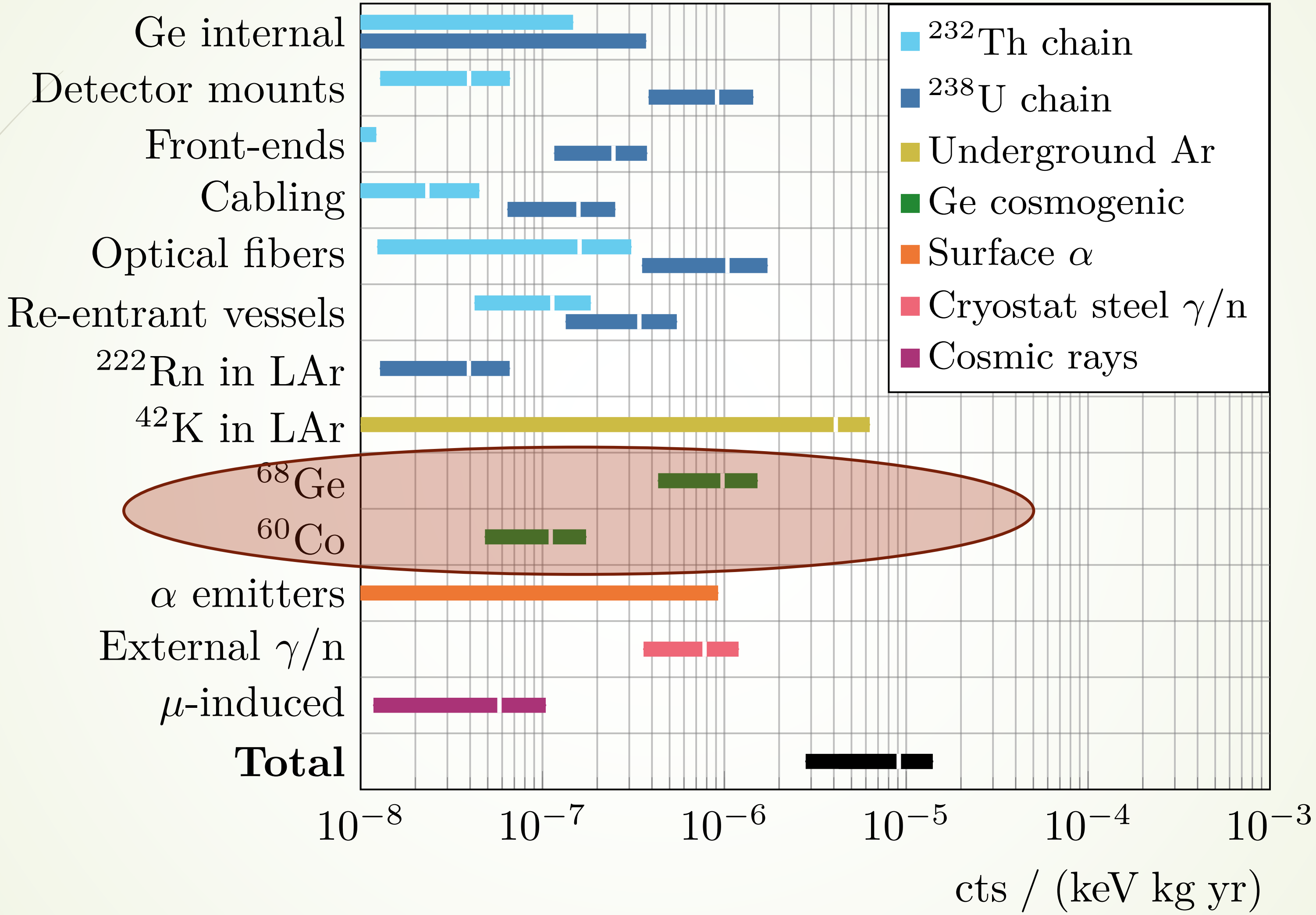
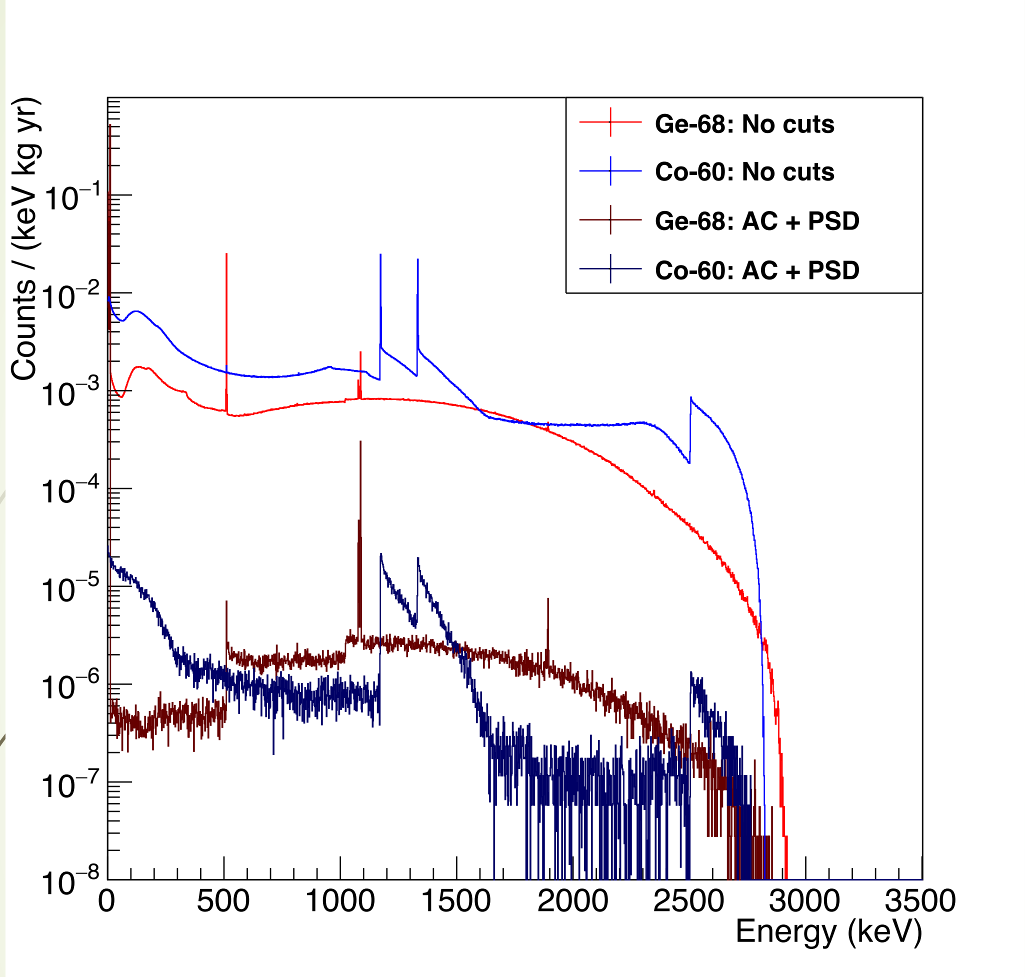
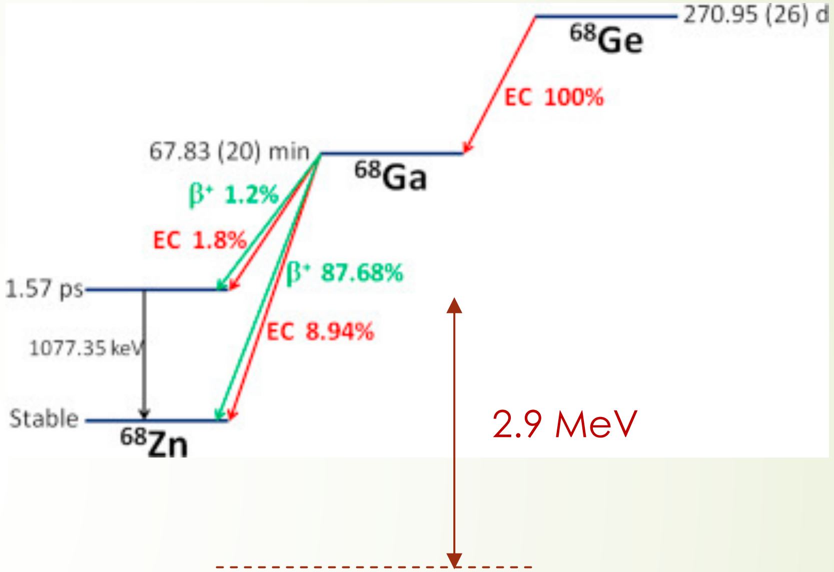




^{60}Co not a concern, ^{68}Ge slightly more so



^{68}Ge mitigation

- Minimise surface time during crystal pulling/detector production
- Low energy threshold and background allows to tag 10keV and 1 keV x-rays

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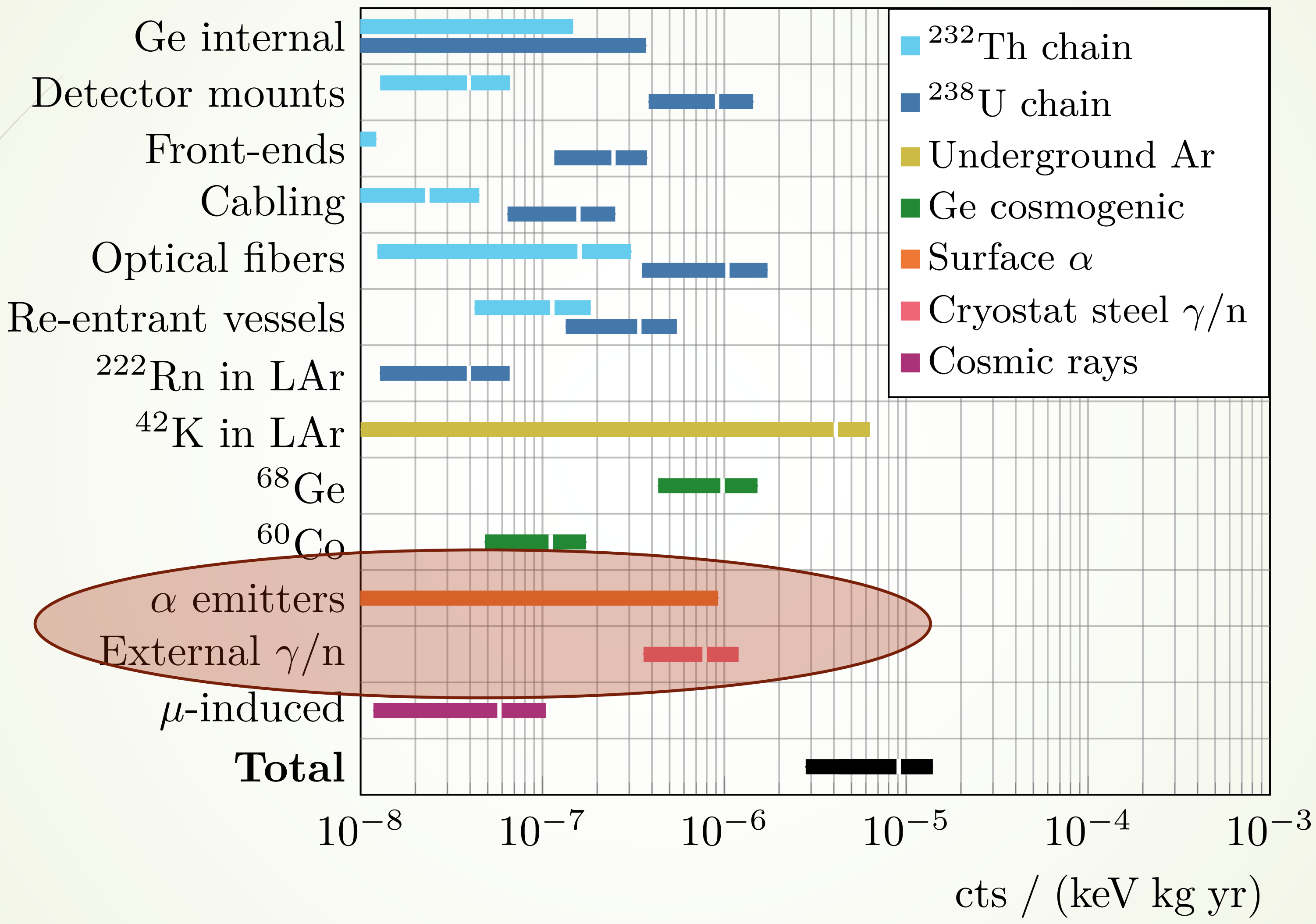

Surface alpha backgrounds

- Careful handling in Rn-mitigated environments
- Significant room for improvement with modelling surface α-events and advanced PSD, including ML methods. Input from L200 and L1000 critical.

External γ–ray and neutron backgrounds

- Dominant background from 2615 keV line (^{208}Tl) from cryostat stainless steel. Conservative 1mBq/kg assumed and can be improved. Larger LAr shielding possible.
- Neutrons and gammas from water tank and laboratory are effectively shielded by water, should not be a concern.

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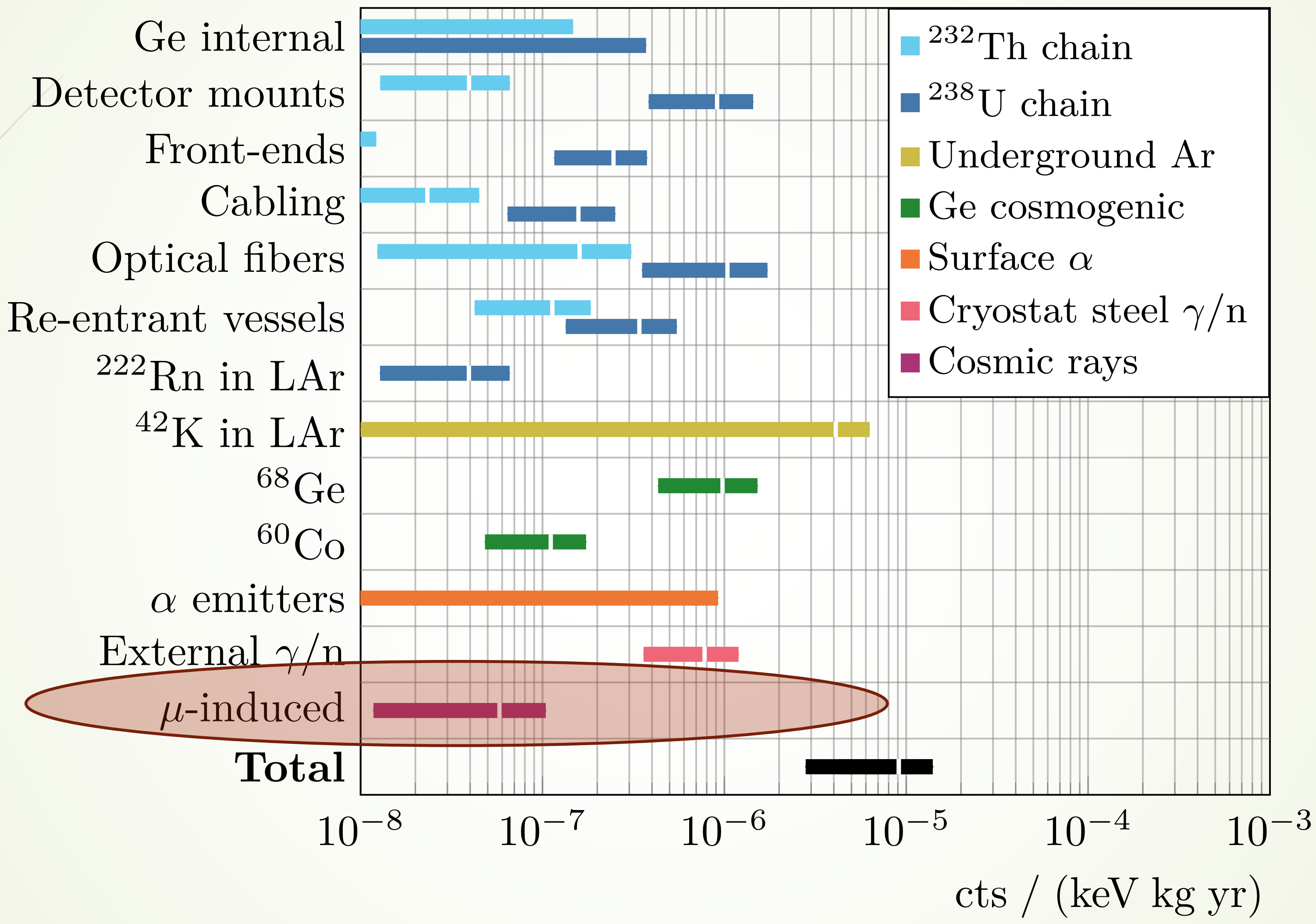
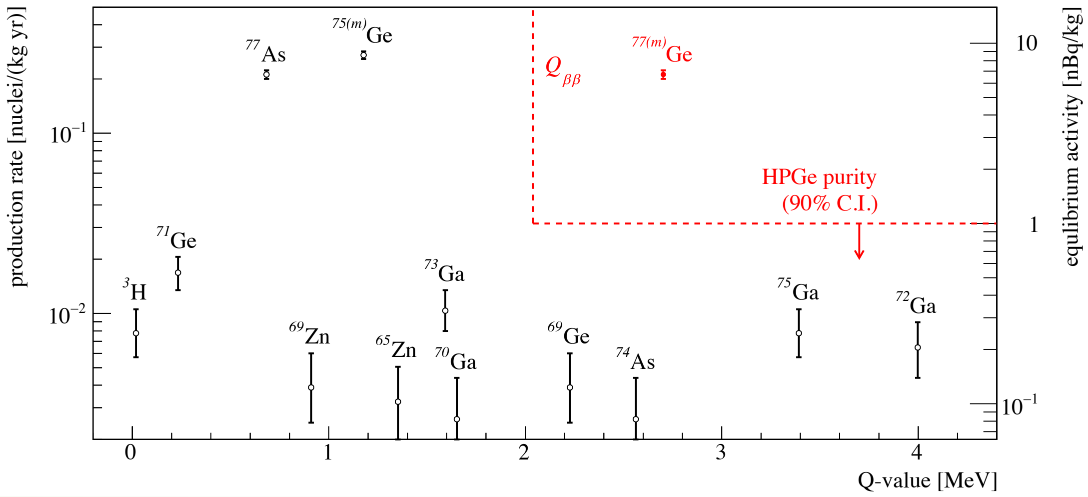
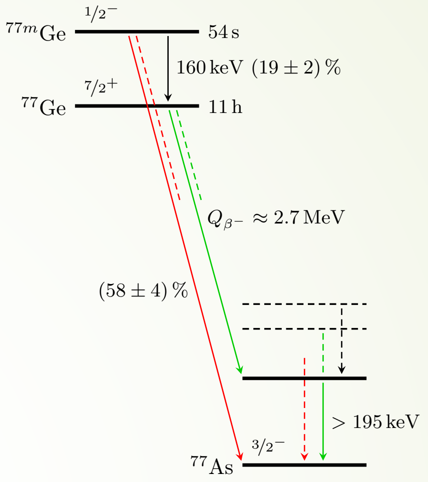


In-situ muon-induced background





Not a problem at SNOlab depth. Moreover, additional mitigation (delayed coincidences) investigated for LNGS option of L1000 appears to be powerful

Source	Location	BI before DC [cts/(keV kg yr)]	BI after DC [cts/(keV kg yr)]
^{77}Ge	SNOLAB	3.2×10^{-8}	N/A
^{77}Ge	SURF	5.0×10^{-7}	N/A
^{77}Ge	LNGS	3.0×10^{-6}	N/A
^{77m}Ge	SNOLAB	3.9×10^{-7}	2.6×10^{-8}
^{77m}Ge	SURF	6.0×10^{-6}	4.0×10^{-7}
^{77m}Ge	LNGS	3.6×10^{-5}	2.4×10^{-6}

Ge Enrichment and International Landscape

- Ge enrichment is an industrial scale business, primarily for $^{72}GeF_4$, $^{76}GeF_4$ is a "by-product"
- There is a reliable European vendor, URENCO in The Netherlands, that currently invests in "hundreds of kg per year" capacities
- Ge enrichment remains the chief capital costs (more than half of enriched HPGe detector costs)
- This is similar for many other $0\nu\beta\beta$ experiments.
- A number of roadmaps and reviews on $0\nu\beta\beta$ released in recent years. Close coordination between Europe and North America
  - APPEC Report on DBD Strategy, US DOE Portfolio Review, Europe-North America Summit
- A vision for global approach to investment in $0\nu\beta\beta$ science.
- Establishing an international facility for stable isotope production can be a great showcase for such cooperation.

Concluding Remarks

- HP^{76}Ge offers **best energy resolution** and **lowest background** among all existing $0\nu\beta\beta$ technologies.
- **No irreducible background "floor"** such as $2\nu\beta\beta$ or solar neutrinos for 100's t-y exposures.
- Ongoing R&D for a **quasi-background-free discovery** oriented search down to $\langle m_{\beta\beta}\rangle$~3-7 meV ($T_{1/2}$~$10^{29}$ yr)
- **No show stoppers so far**. HPGe **detector innovation** could be (once again) a game changer.
- Together with **other innovative solutions** w.r.t. LEGEND baseline design
  - Xenon doping of LAr, Fully active materials for detector support, active detector encapsulation
- **Enrichment** costs present a significant challenge for many future $0\nu\beta\beta$ projects and may/should(?) be addressed by a **global approach** to investment in $0\nu\beta\beta$ science.