In-situ Cosmogenic Background for LEGEND

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on behalf of the LEGEND Collaboration

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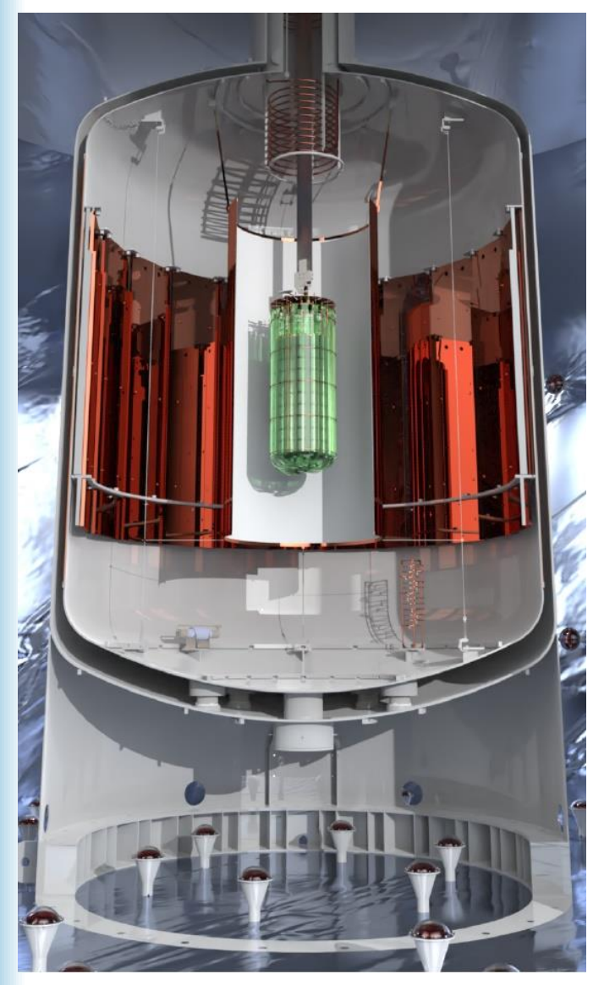
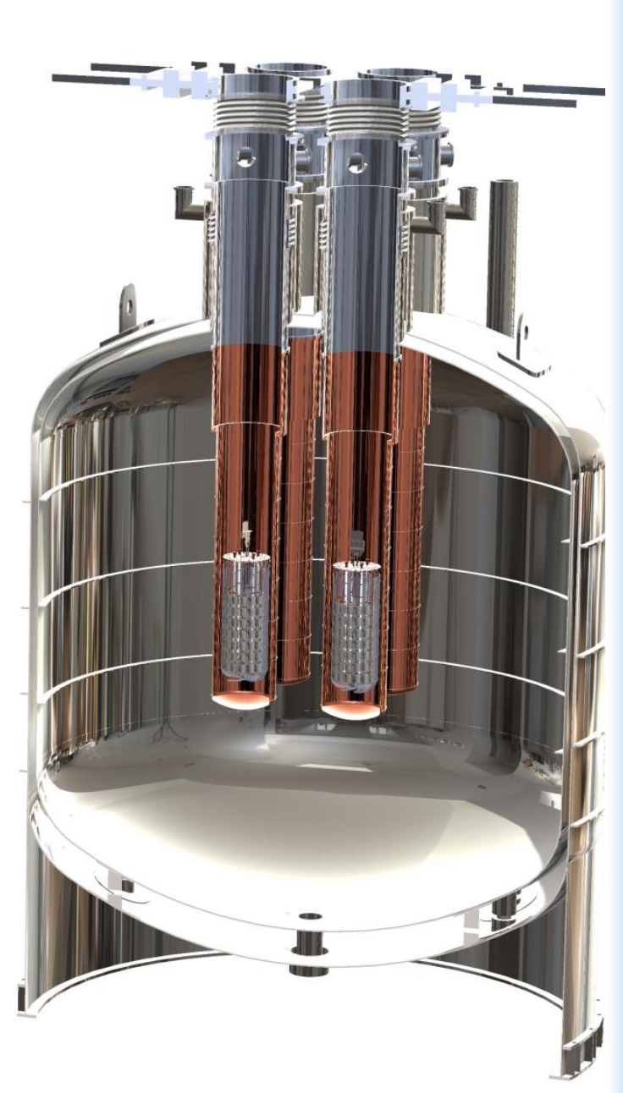
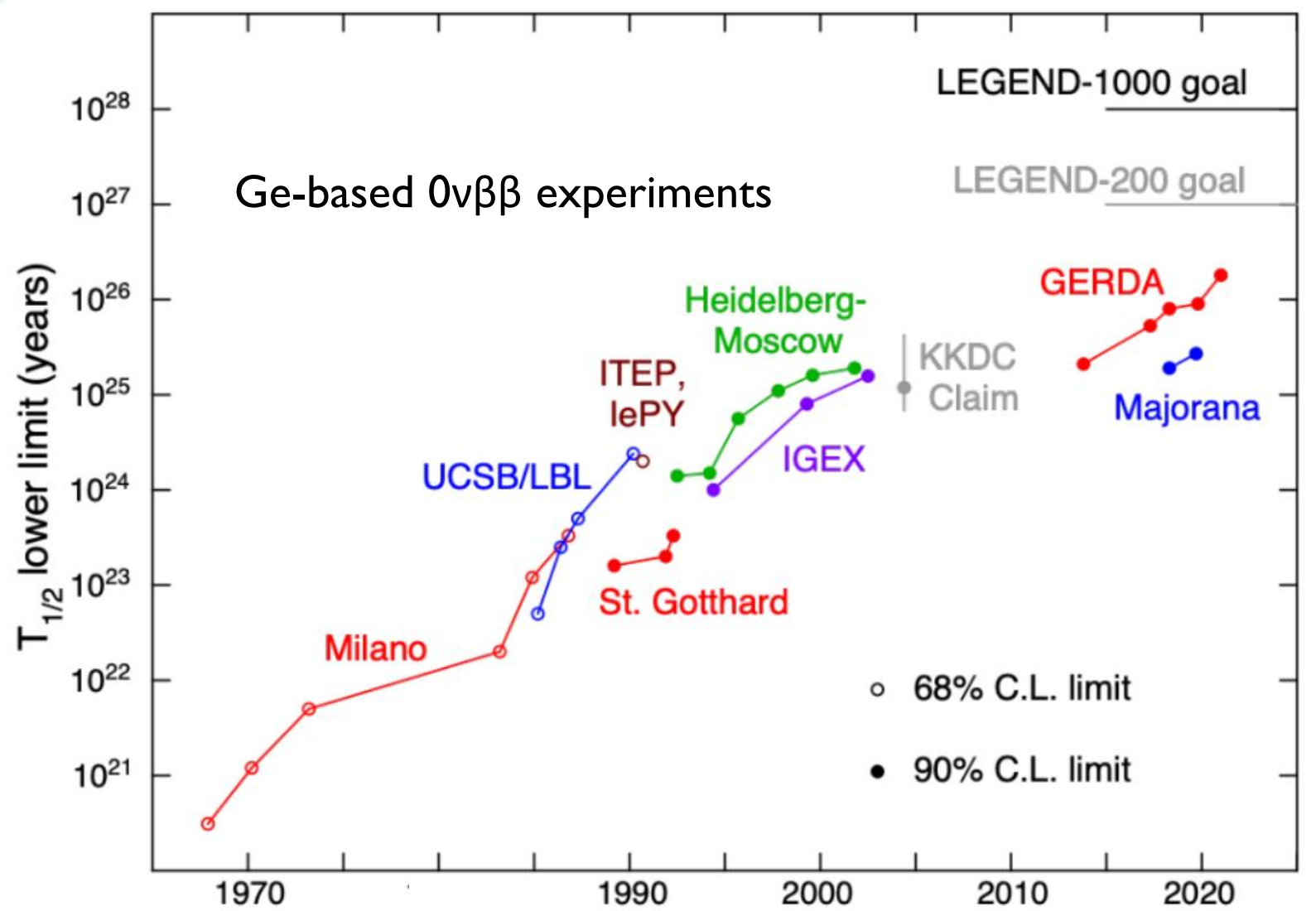
The Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND) Collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results. To meet the unprecedented background goals of a next-gen experiment, improvements in all areas of background modeling and analysis are being investigated. Geant4 simulations developed for the LEGEND Collaboration explore the prompt and delayed signals induced by cosmogenic muons and their secondaries in deep underground lab sites.

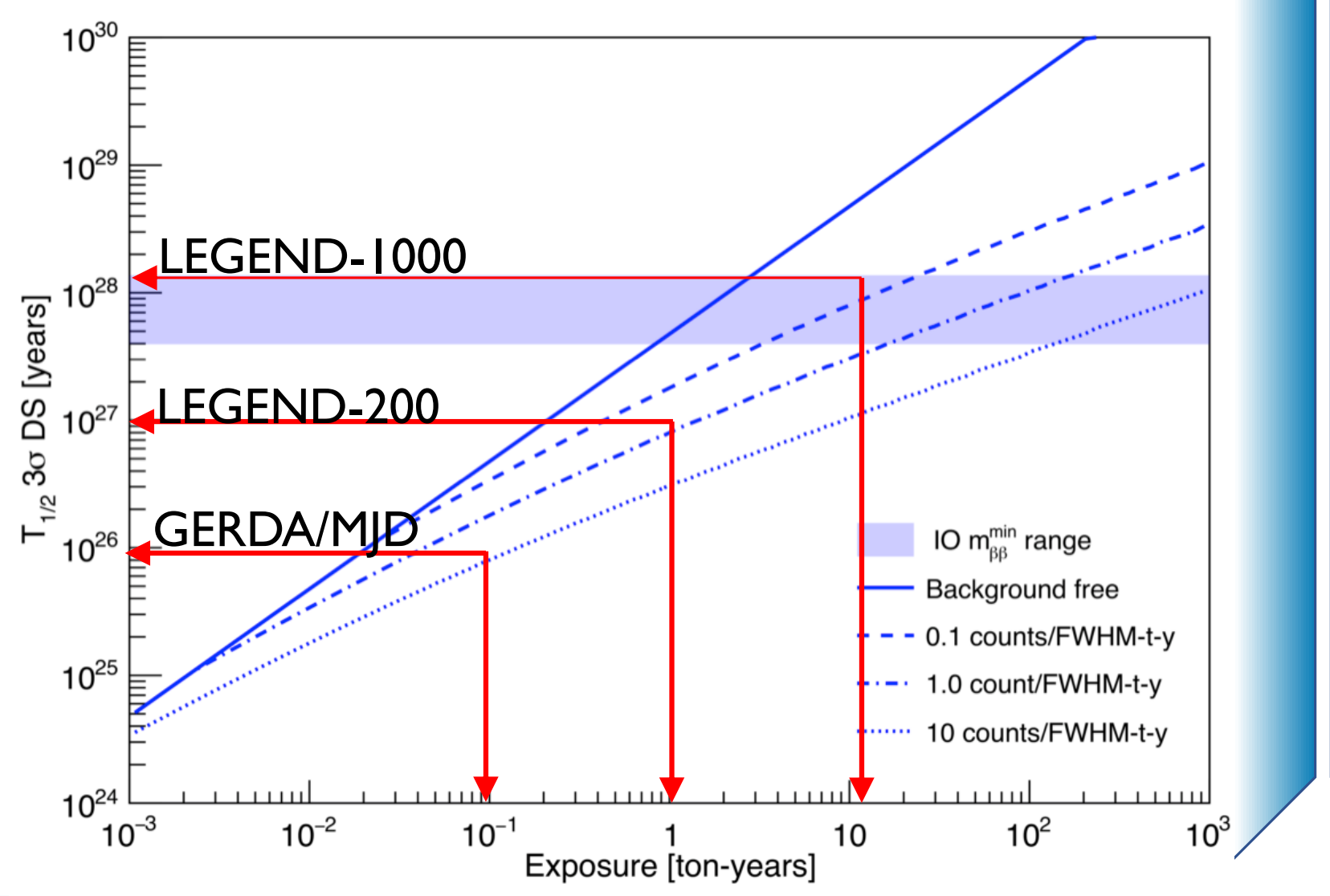
LEGEND goals and sensitivity



LEGEND-200		LEGEND-1000
200	Active detector mass kg	1000
5	Expected runtime yrs	10
10^{27}	$T_{1/2}$ sensitivity yrs	10^{28}
34 – 78	mββ upper limit meV	9 – 21
$2x10^{-4}$	Background index cts/(keV kg yr)	$1x10^{-5}$

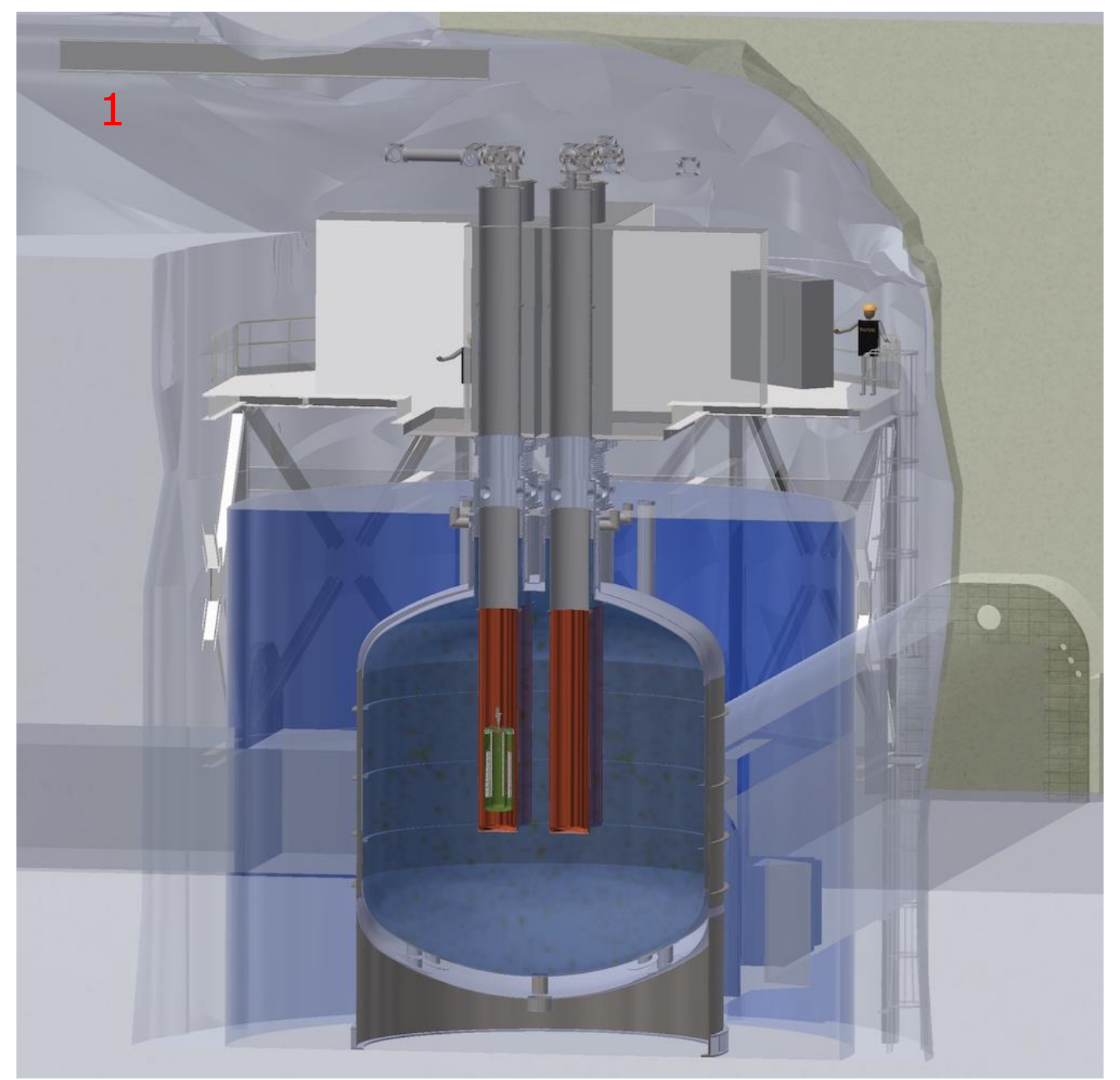


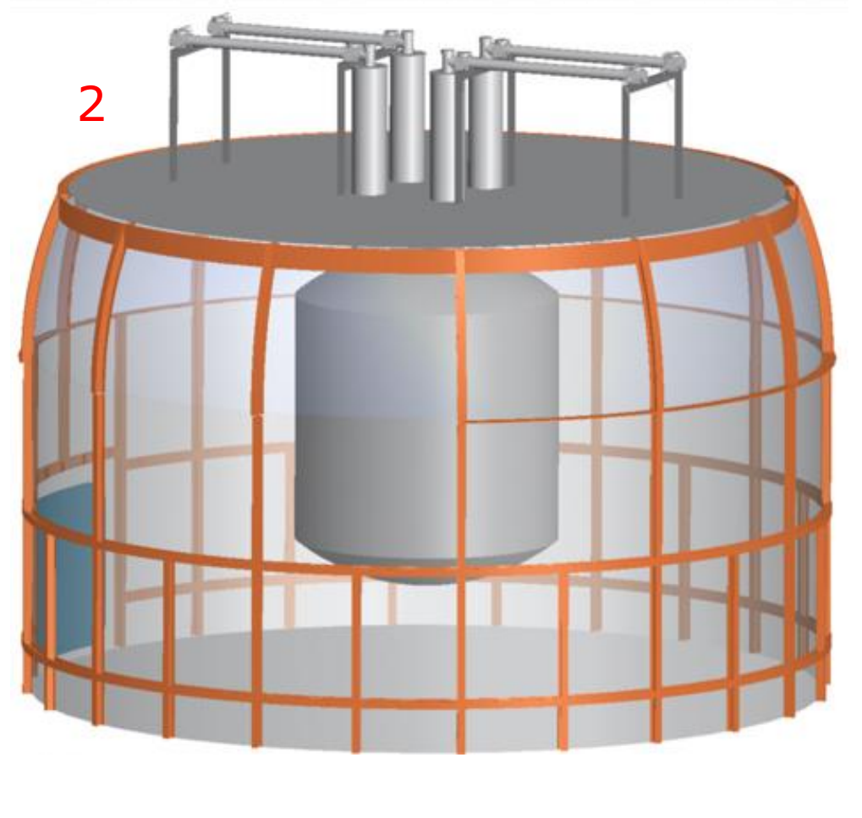


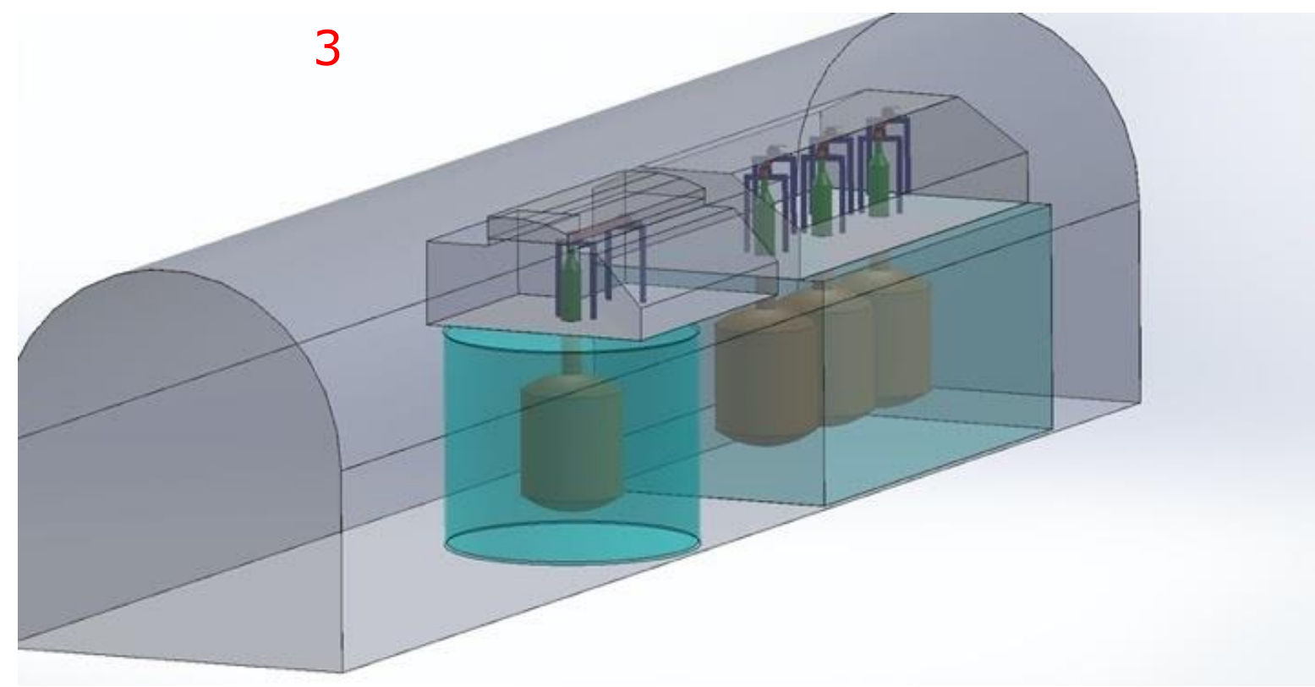


LEGEND-1000 design options

1) Baseline design (primary)
   - Designed for SNOLab's cryo-pit in Sudbury, Ont, CA
   - 4 modules, EFCu re-entrant tubes
   - Cryostat filled with liquid argon (LAr)
   - Tubes filled with underground sourced LAr
   - Encased in a large water shield
2) Borexino water tank (if available)
   - Baseline design, housed in water tank used for Borexino
   - Located at LNGS in L'Aquila province, Italy
3) 4-tank design
   - Designed for use in Hall A of LNGS
   - Re-uses the tank currently in use for LEGEND-200 (front)
   - 4 separate cryostats







*LEGEND-1000 preconceptual design is publicly available arXiv: 2107.11462

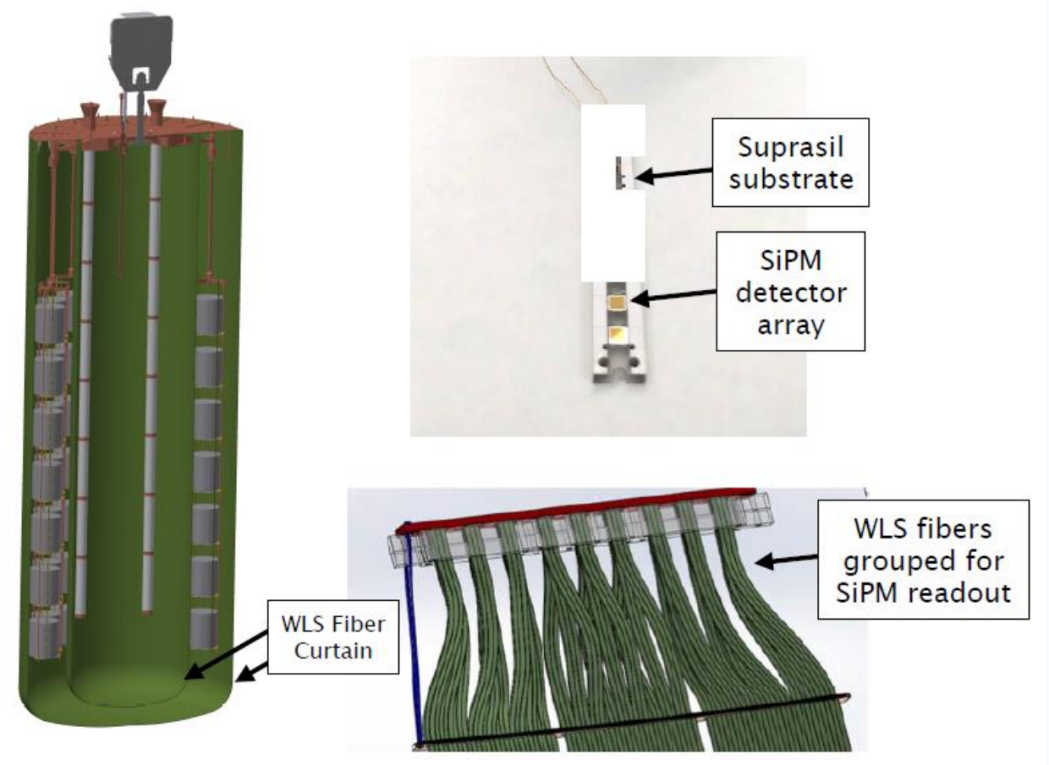
Prompt cosmogenic backgrounds at SNOLAB

Expectation for the baseline design

- GERDA-style water Cherenkov muon veto shown to be >99% efficient K. Freund et al., Eur. Phys. J. C 76, 298 (2016)
- Veto window of 1 second, negligible deadtime
- LAr scintillation veto increases veto efficiency even further

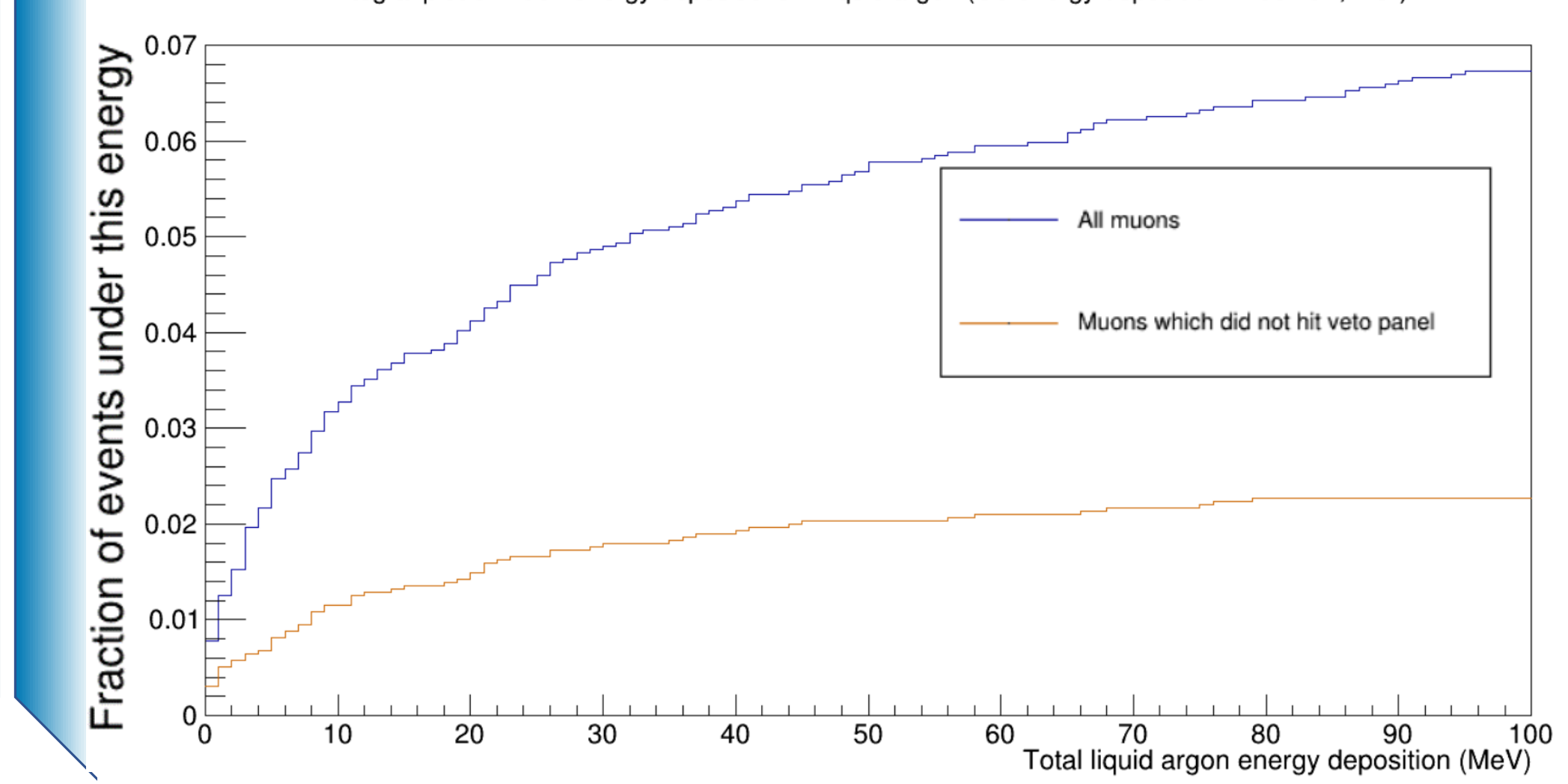
Alternative design: LAr veto only

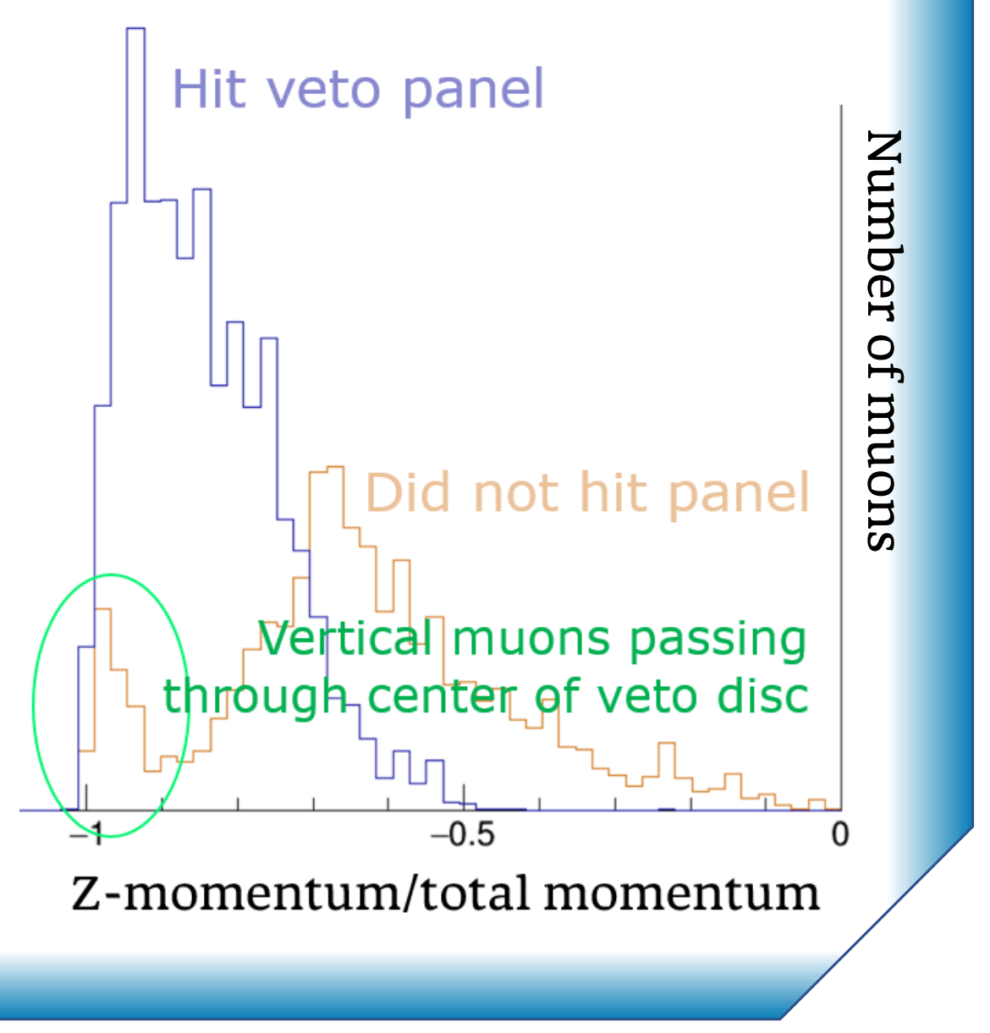
- Simulation of coincident muon-induced energy depositions in LAr and Ge detectors for LEGEND-200-like geometry
  - Conversion of LAr energy depositions to expected number of photoelectrons detected handled by a separate simulation
- Conservative cuts on Ge and LAr energy depositions suggest <1% background contribution at SNOLAB
- Plastic veto panel above the water tank could be added to detect >60% of incoming muons independently



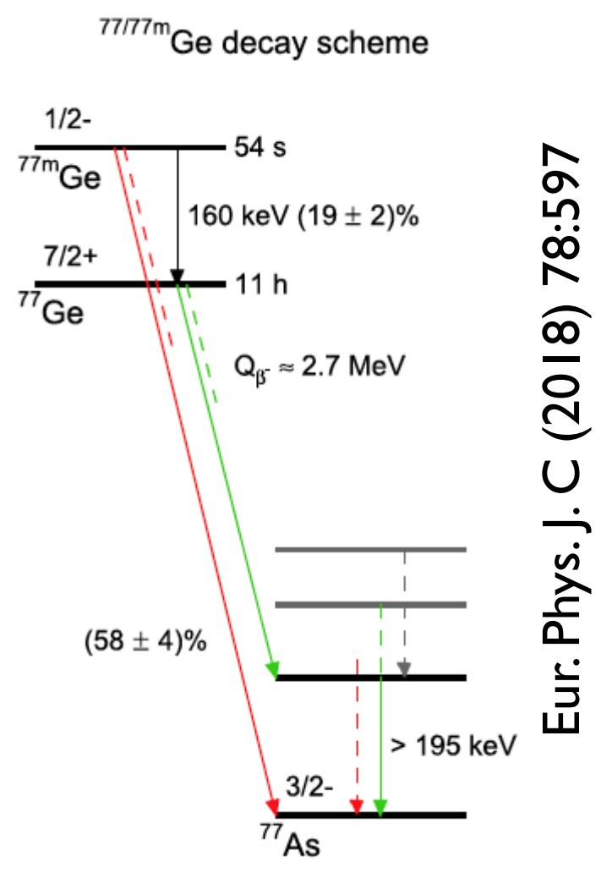
Drawing of the LAr scintillation detection system for LEGEND-1000

Integral plot of muon energy depositions in liquid argon (Ge energy deposition >200 keV, ROI)





Delayed cosmogenic backgrounds at SNOLAB



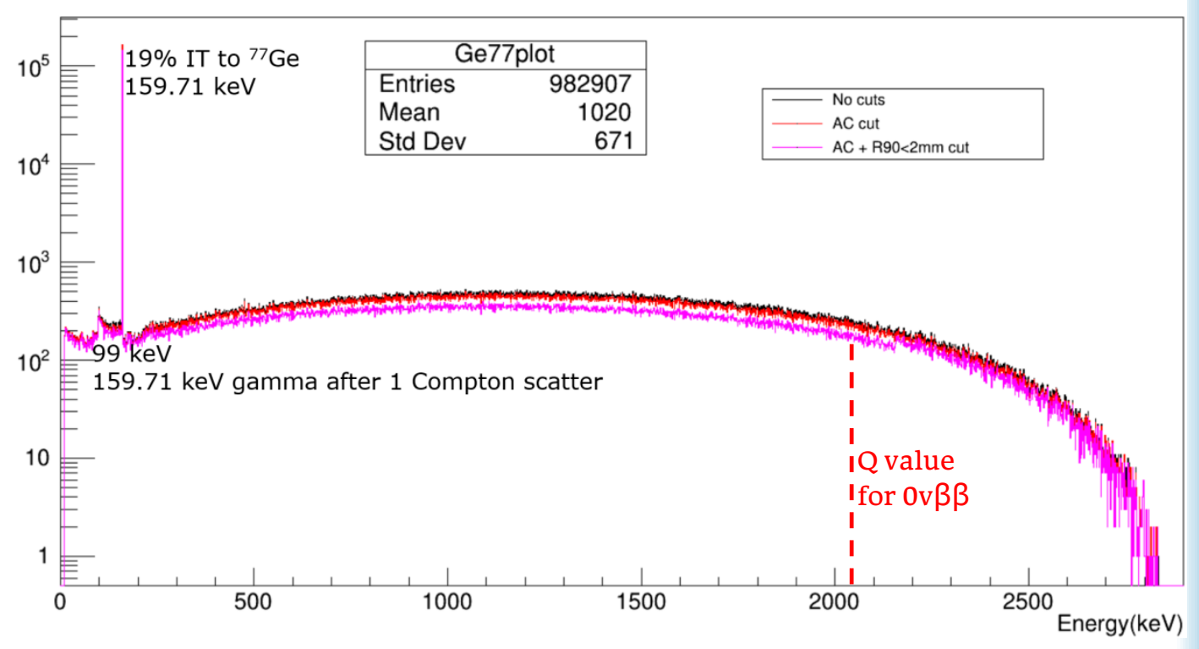
- Primarily caused by ^{77}Ge and ^{77m}Ge, created in-situ via neutron capture
  - ^{77m}Ge decay usually has no coincident gammas, ^{77}Ge half-life is long
  - Large LAr shielding leads to higher production rate, see proceedings from neutron talk, PoS(ICHEP2020)195
- A range of analysis cuts, including granularity, LAr veto, pulse shape, and delayed coincidence, can mitigate delayed backgrounds
- Efficiencies were initially studied in Eur. Phys. J. C (2018) 78:597 with a GERDA-like geometry

Efficiencies studied in representative LEGEND-200, LEGEND-1000 geometries

Breakdown of the effectiveness of each analysis cut on $^{77/77m}$Ge
The delayed coincidence cut only affects the metastable state

Delayed signal cut	Reduction factor $[Ge^{77}]/[Ge^{77m}]$	Reduction factor Comparison to Eur. Phys. J. C (2018) 78:597
$\pm 200 keV Q_{\beta\beta}$	-	-
Granularity	1.5 [1.99/1.07]	1.09 [1.2/1.04]
LAr veto heuristic	1.11 [1.38/1]	1.15 [1.4/1.06]
Multi-site	1.7 [8.25/1.27]	1.58 [6.25/1.25]
Delayed coincidence	7.49 [0/15]	7.22 [0/15]

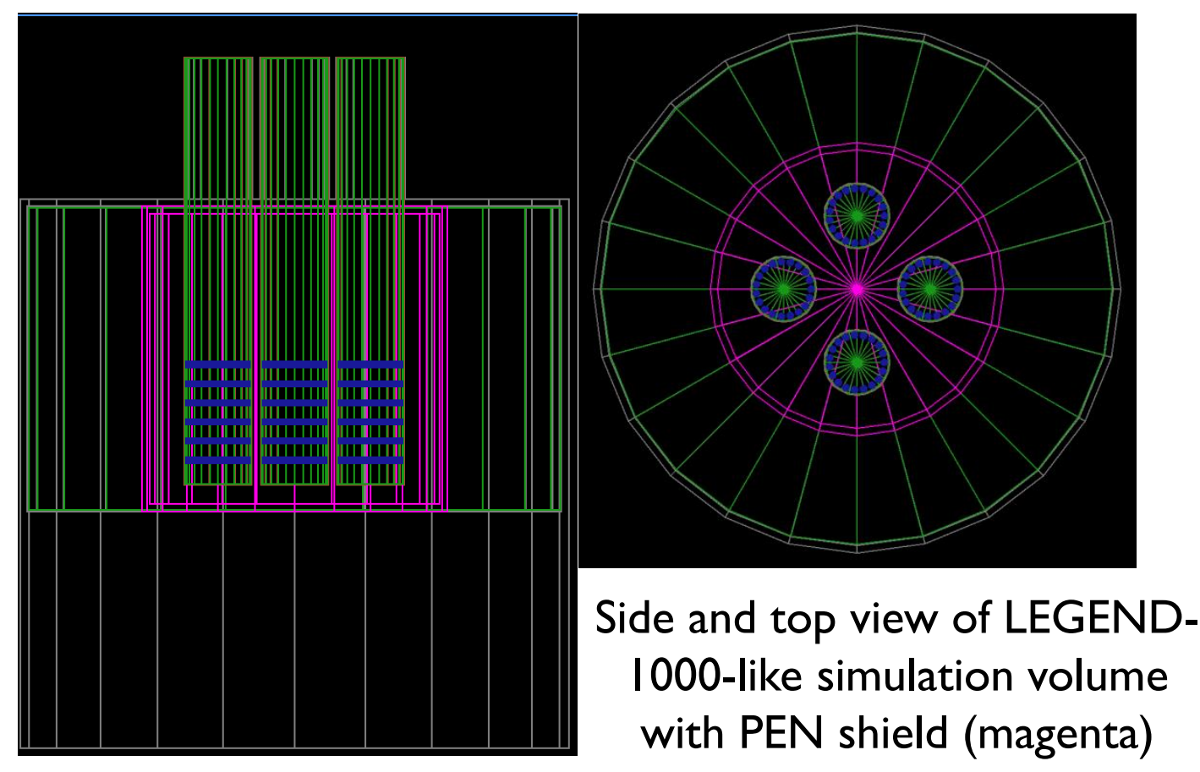
Ge^{77m} spectrum in Geant4 10.2.02 LEGEND-200-like geometry



Further reduction of delayed backgrounds

Additional neutron shielding options

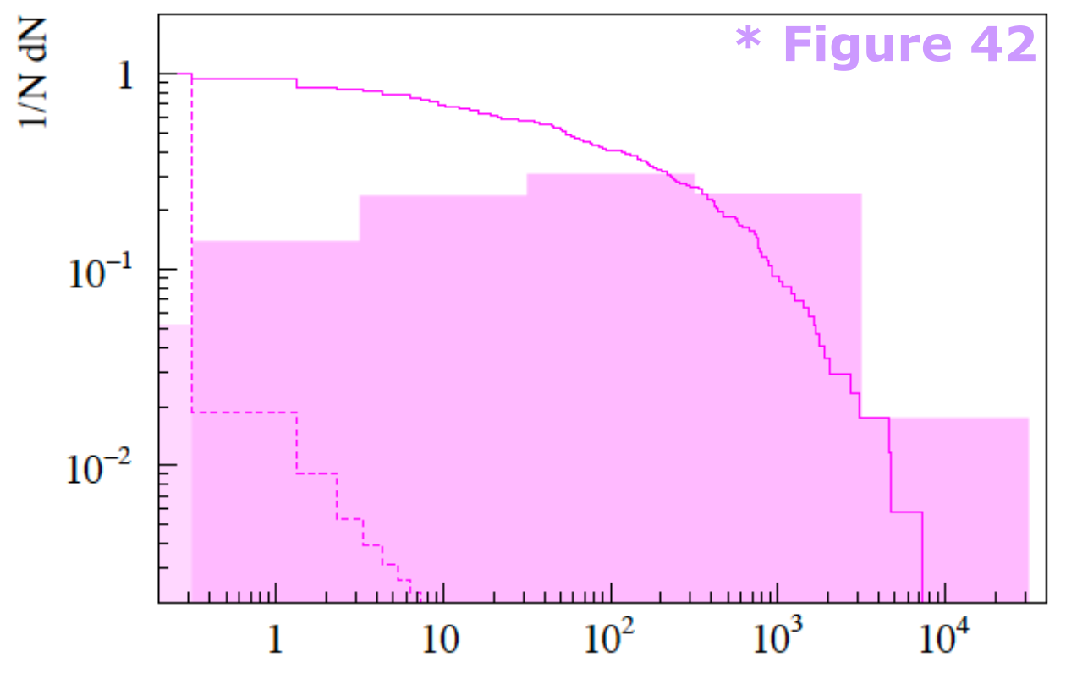
- Polyethylene naphthalate (PEN) $(C_{14}H_{10}O_4)_n$
  - Scintillating, transparent
  - Can waveshift LAr scintillation
  - Being studied for detector mounting in LEGEND-1000
  - Can be produced with high radiopurity <100 µBq/kg U&Th
- Two Geant4 simulations of LEGEND-1000-like geometry
  - Copper re-entrant tubes replaced with 10 cm thick PEN tube
  - 10 cm thick PEN shield placed farther away, around tubes
- Neutron stopping power/$^{77/77m}$Ge production rate evaluated
  - 100% *increase* in $^{77/77m}$Ge production for tube simulations
  - 50% *decrease* in $^{77/77m}$Ge production for shield simulations
- PEN moderates neutrons well, but relies on liquid argon to absorb neutrons, so can't be too close to the Ge



Side and top view of LEGEND-1000-like simulation volume with PEN shield (magenta)

Active Ge77 reduction with new techniques

- Doping LAr with neutron absorber
- Tagging sibling neutrons in LAr
- Gd-loaded water shield
- Using topology information
- Potential to achieve background index of < 1 x 10^{-6} cts /keV/kg/yr at LNGS depth



Average neutron multiplicity for muons which create Ge^{77} in simulations

Summary

- After cuts, estimate of muon-induced in-situ background <1% of background goal at SNOLAB
- At LNGS, could be up to 20% with alternative detector design, more in the baseline design
- There is the possibility to achieve the LEGEND-1000 background goal at LNGS with techniques that may lead to additional detector dead time
- Reduced construction time might permit increased exposure, re-establishing the sensitivity

LEGEND-1000 aims for a "quasi-background-free" regime
Most likely outcome: no background events

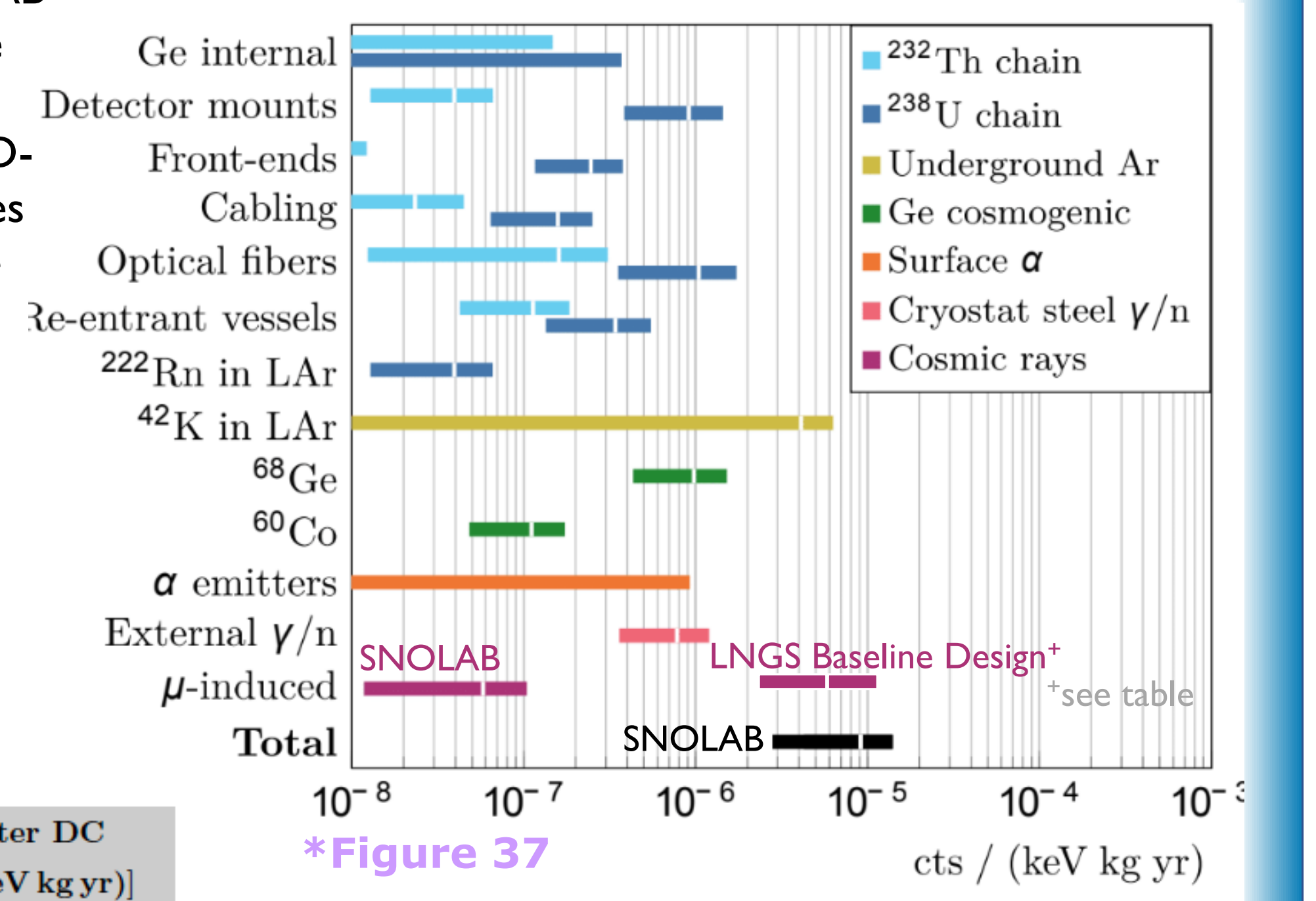


*Table XII

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}

Background estimates for the baseline design at various host lab sites

- Simulations of muon-induced neutrons have large uncertainties, real data cross-checks are needed
- LEGEND-200 will measure ^{77,77m}Ge production, tag sibling neutrons, and test mitigation strategies

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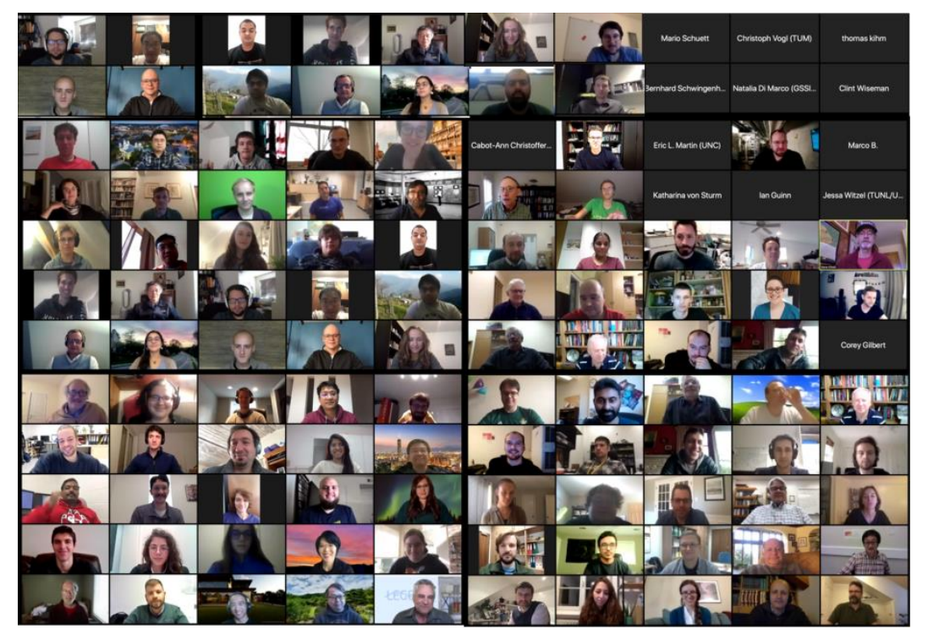

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