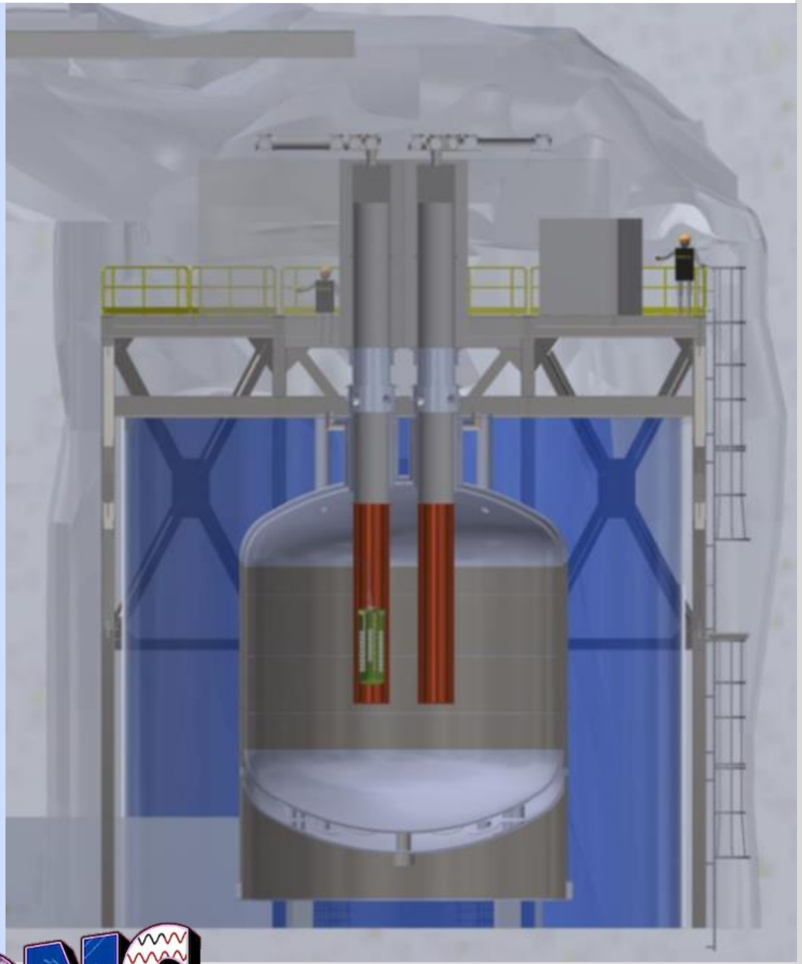
An update on muon-induced backgrounds in LEGEND-1000

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



CJ Barton, for the LEGEND collaboration
University of South Dakota

September 2022

14th Conference on the Intersections of Particle and Nuclear Physics

UNIVERSITY OF SOUTH DAKOTA

INTERSECTIONS

Part 1: LEGEND and cosmogenics

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

LEGEND-1000 Preconceptual Design Report

- arXiv:2107.11462

LEGEND overview

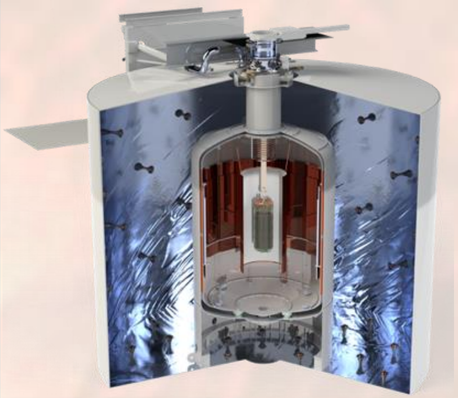
Mission: "The collaboration aims to develop a phased, **Ge-76 based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results**."

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

MAJORANA
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold
(helps reject cosmogenic background)

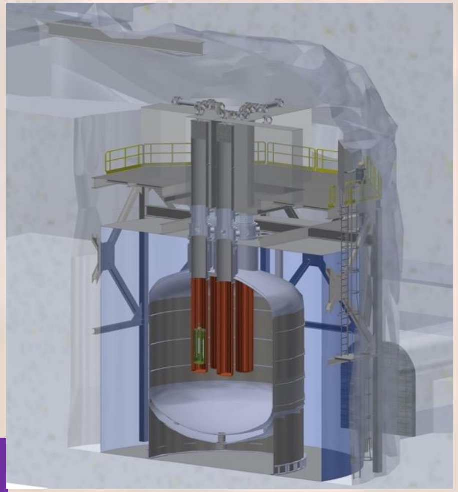
GERDA
- Liquid argon veto
- Light nuclei shield, no lead

Both
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution 0vbb experiments



First phase:
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 c /(FWMH t y)
- Discovery sensitivity at a half-life of 10^{27} years
- Currently taking commissioning data

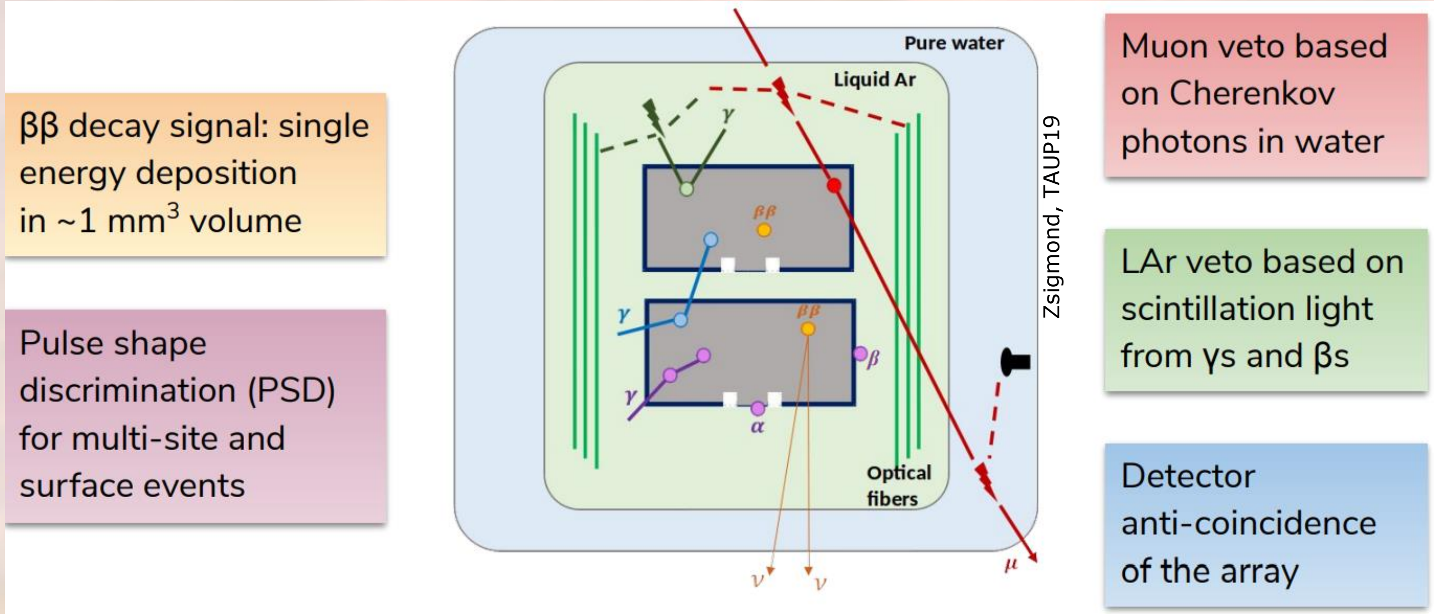
See also the overview talk "**The search of 0νββ and the LEGEND Experiment**", W. Xu, session NN6 (Saturday @3:30)



Subsequent stages:
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr)
- *Location to be selected*

Signal identification in LEGEND

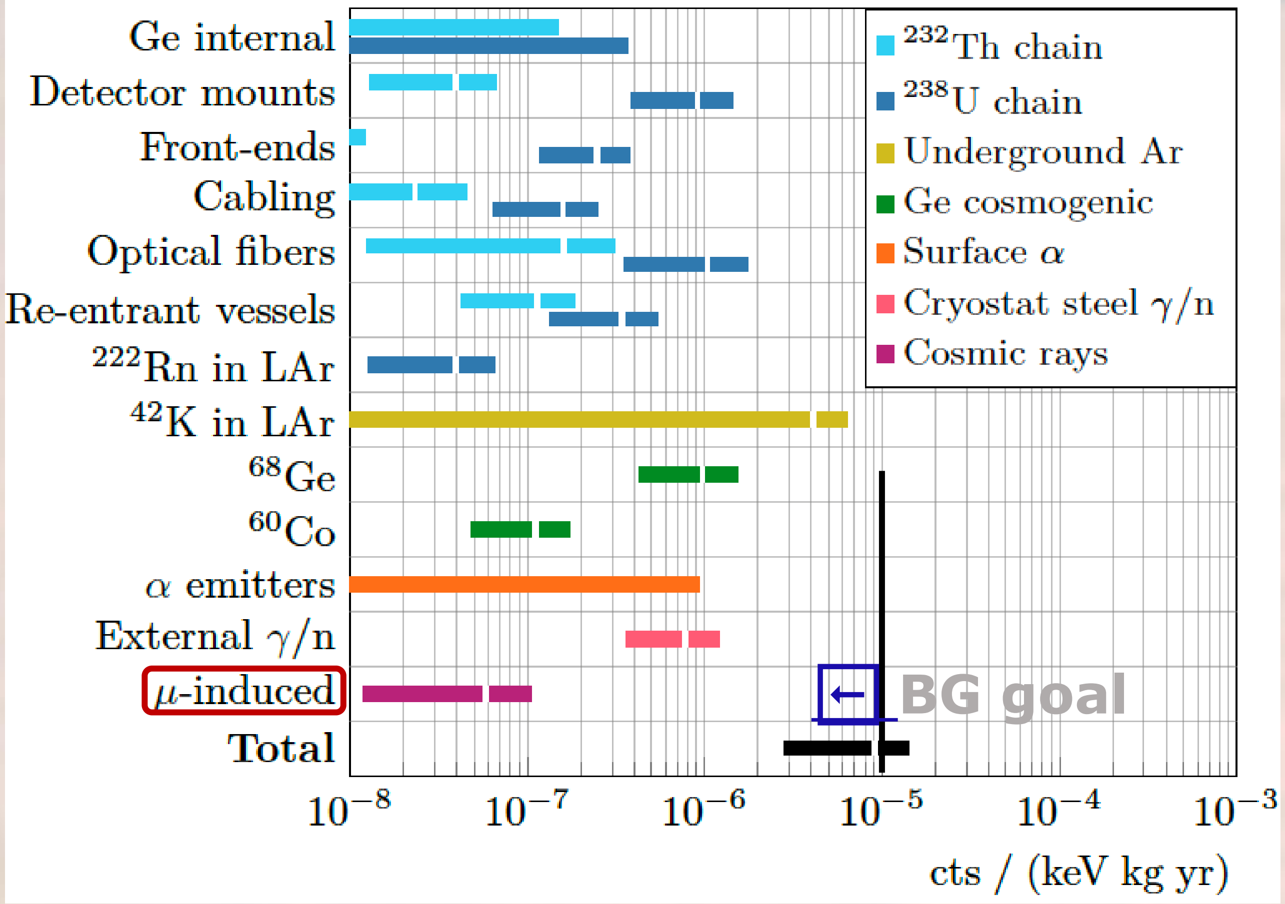
- Complementary systems identify likely sources of signals in detectors
- To qualify as 0νββ background:
  - Single or highly localized energy deposition(s)
  - Energy very close to 2039 keV Q-value (expected signal)
  - Not in coincidence with any external signals in liquid argon (LAr) or water (muon)



Muon signals and induced prompt backgrounds are rejected with exceptional efficiency

The LEGEND-1000 background model

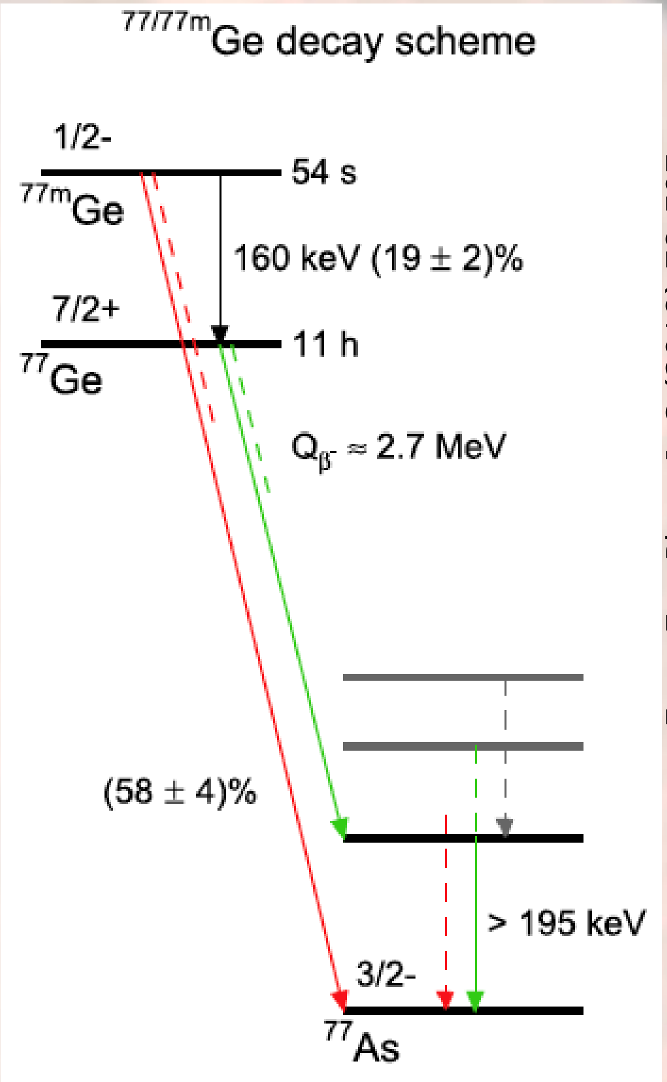
- Background model makes some assumptions
- 6000 meters water equivalent of overburden assumes placement at SNOLab as a host site
- Muon intensity increases exponentially for shallower sites



While very high energy muons are difficult to predict individually, high-statistics simulations estimate average behavior

^{77}Ge and ^{77m}Ge

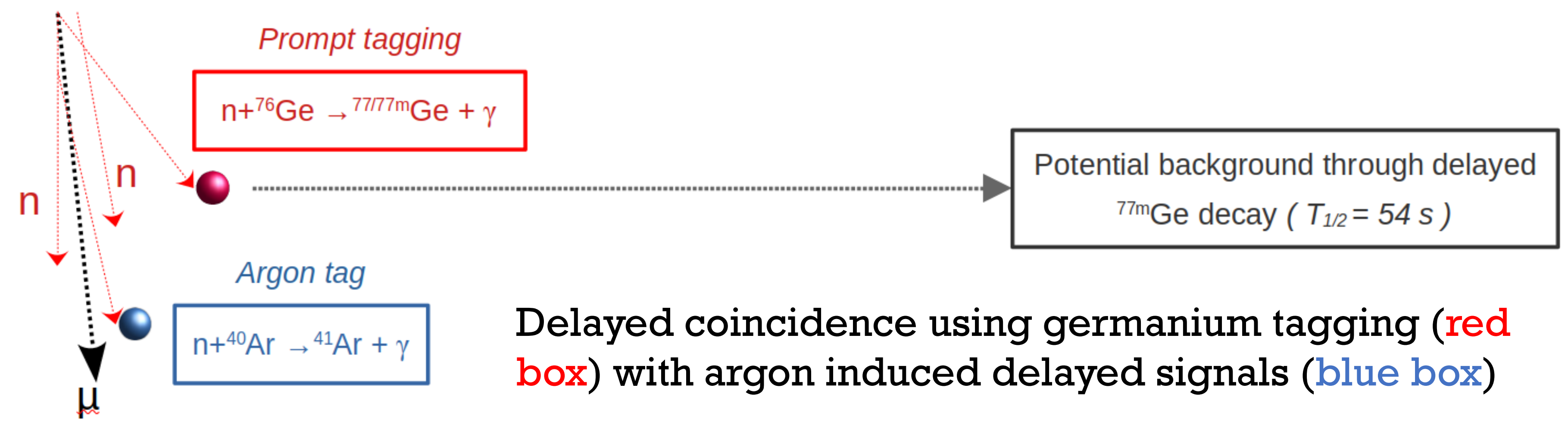
- Produced inside the sensitive detectors of LEGEND via neutron capture, primarily from muon-induced neutrons
- High β^- decay Q value can result in signals very close to 2039 keV
- Longer half-lives prevent prompt coincidence/rejection with parent muon
- ^{77m}Ge mostly undergoes ‘quiet’ decay, releasing no coincident photons



From Eur. Phys. J. C (2018) 78:597

Delayed decays of ^{77}Ge and ^{77m}Ge are identified as the dominant source of muon-induced backgrounds in LEGEND after cuts

Delayed Coincidence Cut



Delayed coincidence using germanium tagging (red box) with argon induced delayed signals (blue box)

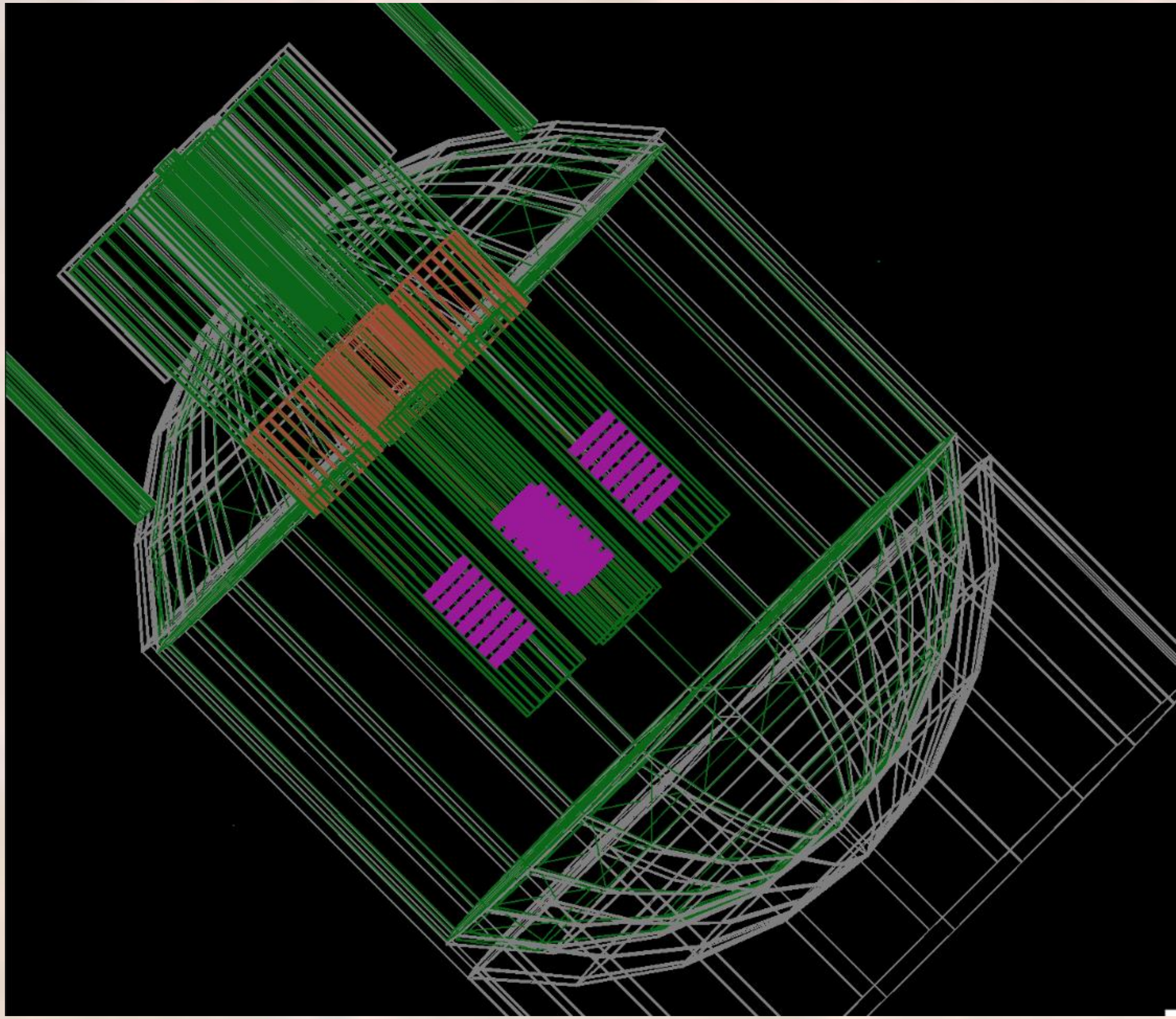
introduced in Eur. Phys. J. C (2018) 78:597

- Typical muon coincidence window is 1 second
- Extending coincidence window to 6 minutes after a potential $^{77,77m}Ge$ production event reduces the ^{77m}Ge background highly effectively
- Anti-coincidences between Ge detectors and muon-veto system identify 94% of the production events, while introducing <4% dead time for a GERDA-like experiment at LNGS

LEGEND simulations with Geant4

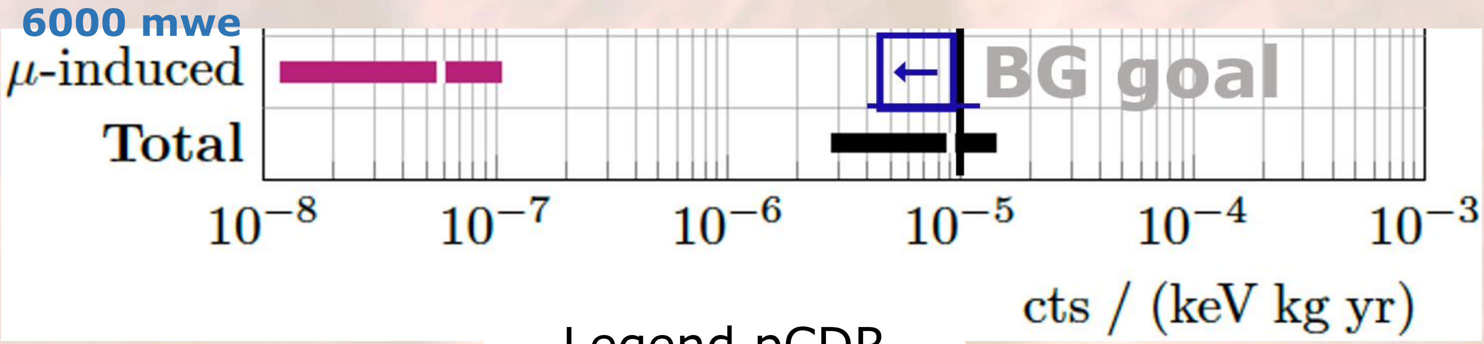
- Muon-induced background has been studied using Geant4 simulation module and analysis suite designed primarily for LEGEND-1000
- Muon sampling is either parametrized to fit depths of interest or taken from input files based on muon data from underground experiments
- LEGEND-1000-like geometry can be easily modified for testing experimental alterations
- Details can be found in LEGEND-1000 preconceptual design report (pCDR)

  arXiv:2107.11462

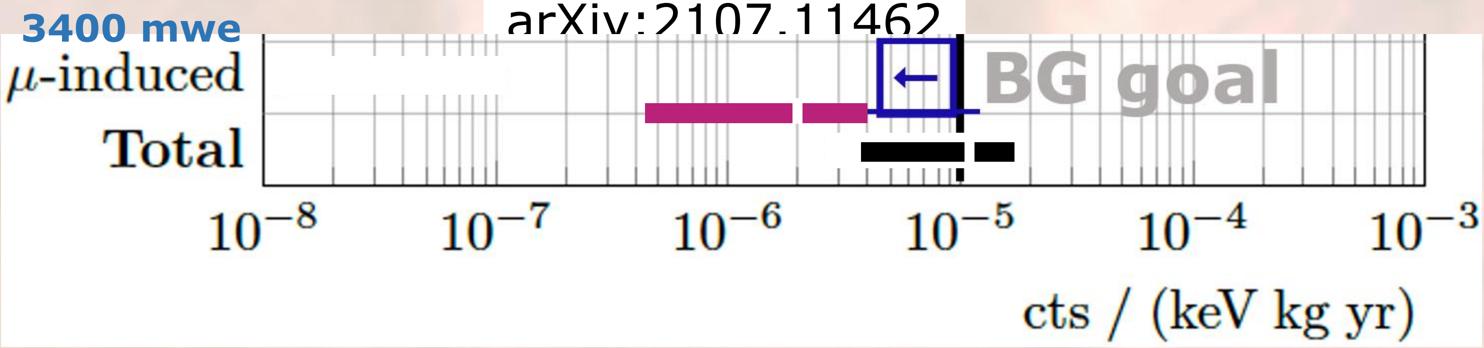


Refining cosmogenic understanding

- Background model makes some assumptions
- 6000 meters water equivalent (mwe) of overburden assumes placement at SNOLab as a host site
- For LNGS as a host site, reduced overburden (3400 mwe) results in increased muon activity



Legend pCDR arXiv:2107.11462

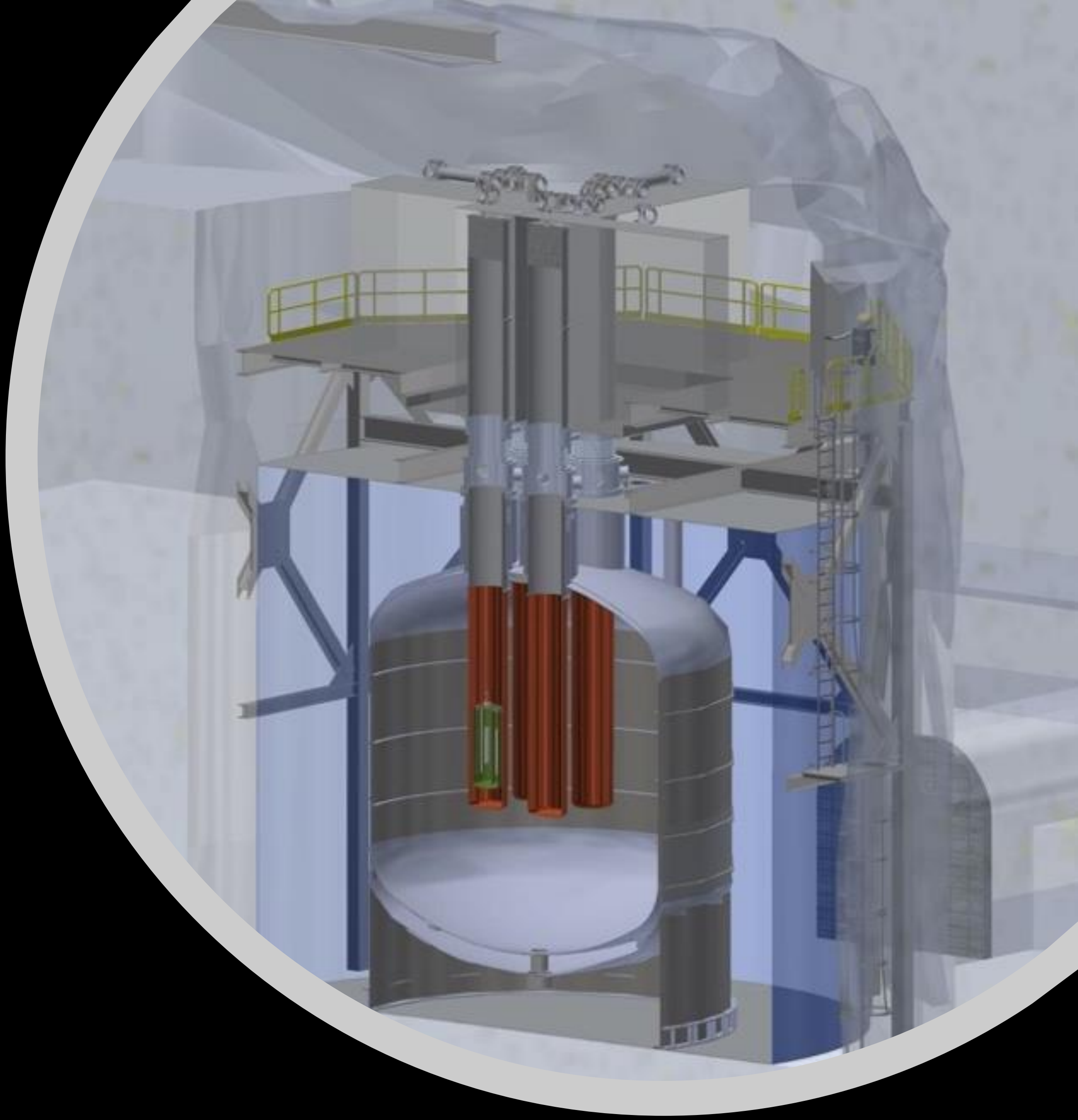


For some candidate host sites, muon background estimates have serious impact on the background model

It's critical to understand project risks and explore options for muon background mitigation

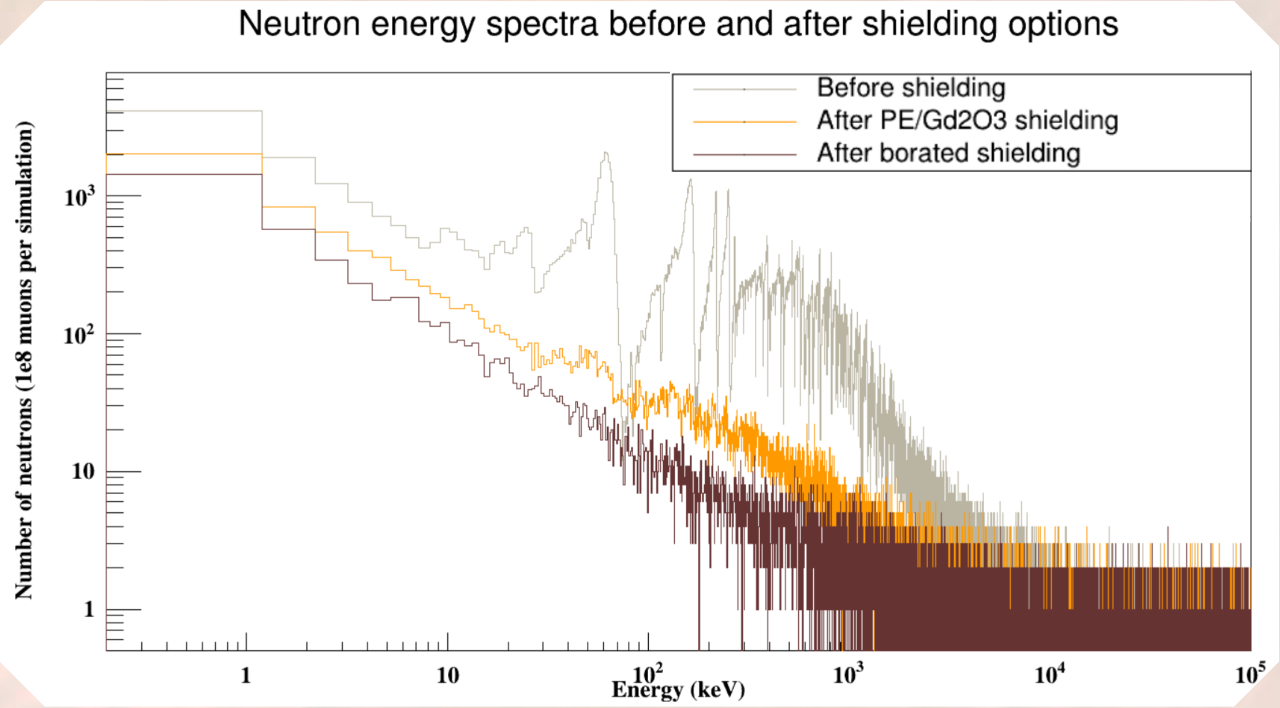
Part 2: Suppression of cosmogenic background via neutron moderation and absorption

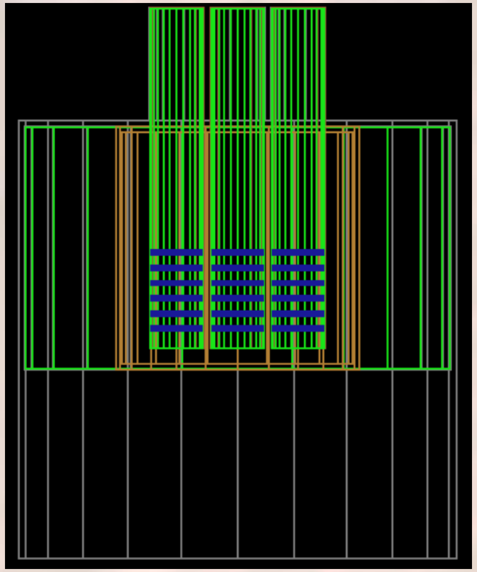
- Updates beyond the LEGEND-1000 baseline design in the pCDR



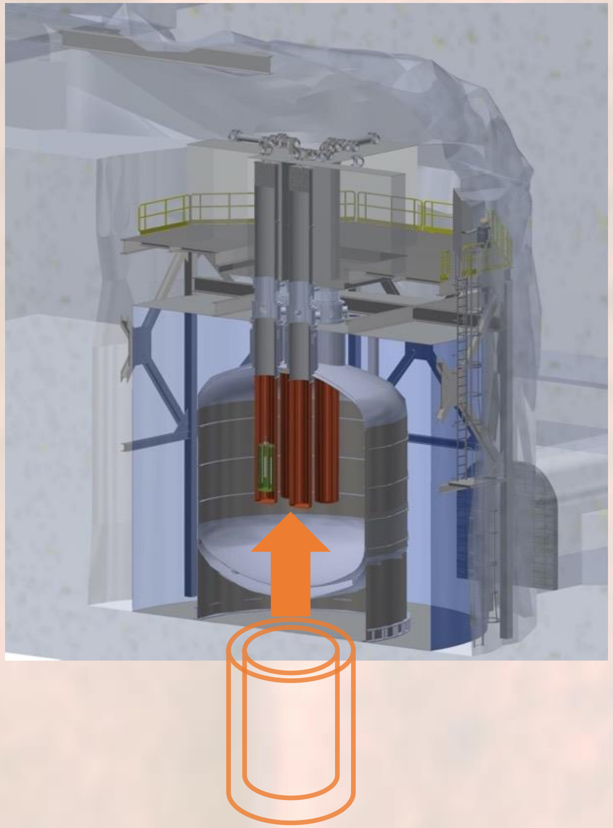
Solid shield neutron moderators

- Large solid moderators made of low-Z materials have been investigated
- Often with a neutron absorbing layer
- Challenges: sourcing radiopure materials, deploying the solid shield

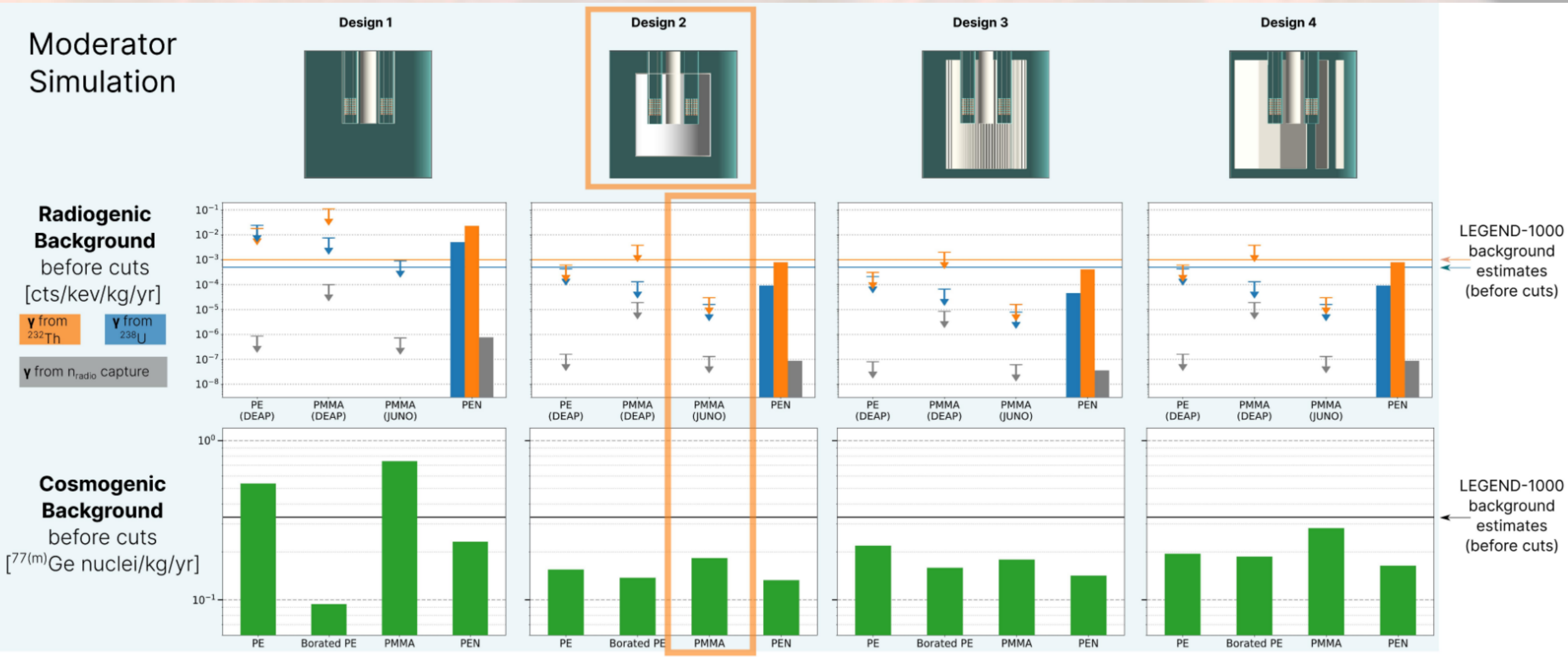




A borated polyethylene (PE) shield (brown) implemented in an older geometry for LEGEND-1000



See C. Barton, PANIC 2021 proceedings
DOI: 10.22323/1.380.0288

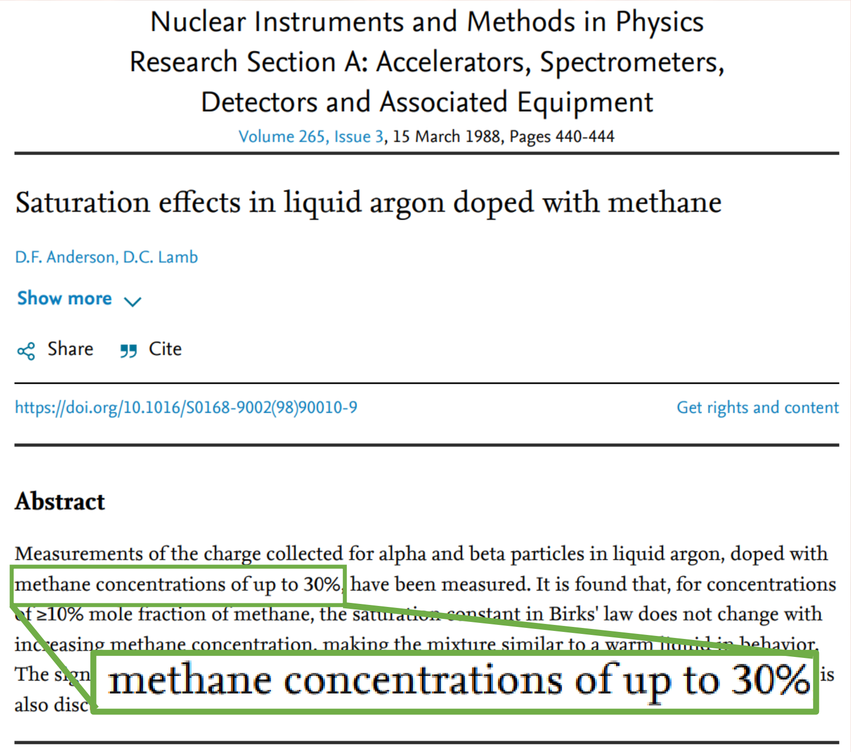


Solid shield design and choice of materials optimization achieve a cosmogenic background reduction factor of ~2, with a small increase in radiogenic background

Adapted from M. Neuberger, M. Morella et al. (TUM, Munich, DE) presentation at Neutrino 2022

Doping liquid argon with a neutron moderator

- Methane (CH_4) has a high hydrogen content, making for an excellent neutron moderator
- Add 1-20% molar fraction methane (0.3-10% mass fraction) to outer LAr tank in LEGEND-1000
  - Scintillation detection in inner tanks would be unaffected by addition of methane in uninstrumented outer tank
- Both the argon and hydrogen atoms can absorb neutrons at sufficiently low energies, removing need for solid neutron absorber


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 265, Issue 3, 15 March 1988, Pages 440-444

Saturation effects in liquid argon doped with methane

D.F. Anderson, D.C. Lamb

Show more

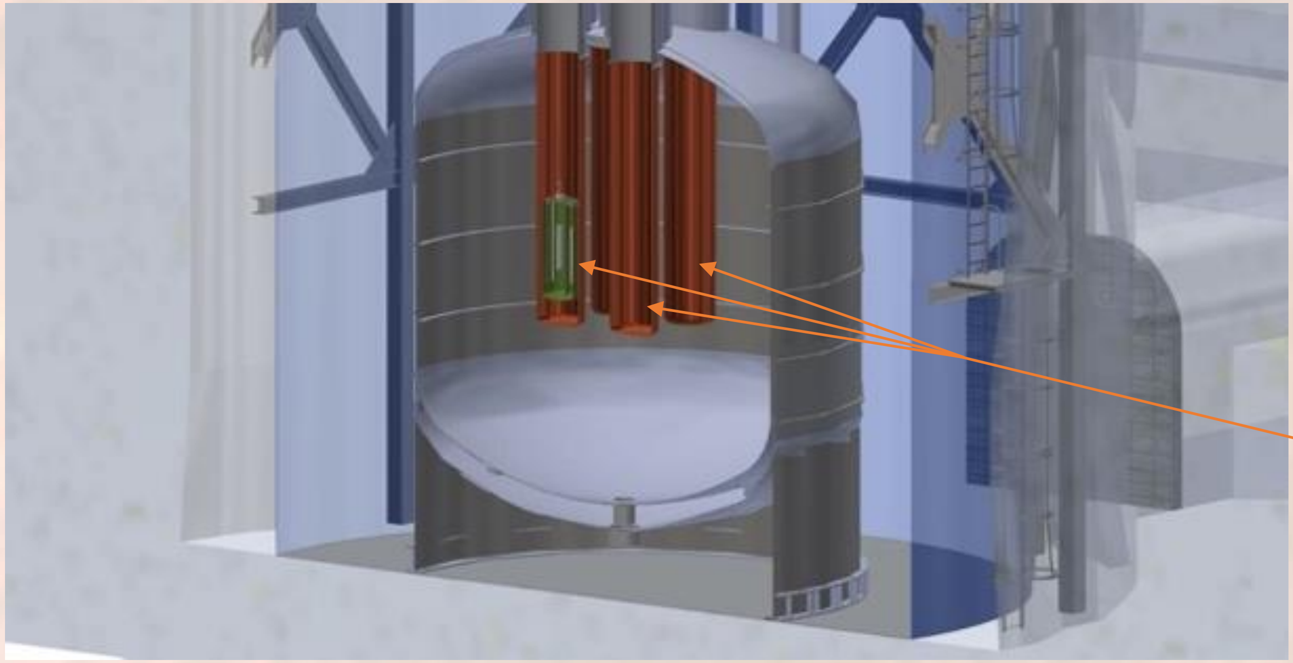
Share Cite

https://doi.org/10.1016/S0168-9002(98)90010-9 Get rights and content

Abstract

Measurements of the charge collected for alpha and beta particles in liquid argon, doped with methane concentrations of up to 30% have been measured. It is found that, for concentrations of ≥10% mole fraction of methane, the saturation constant in Birks' law does not change with increasing methane concentration, making the mixture similar to a warm liquid in behavior. The sign... is also disc...

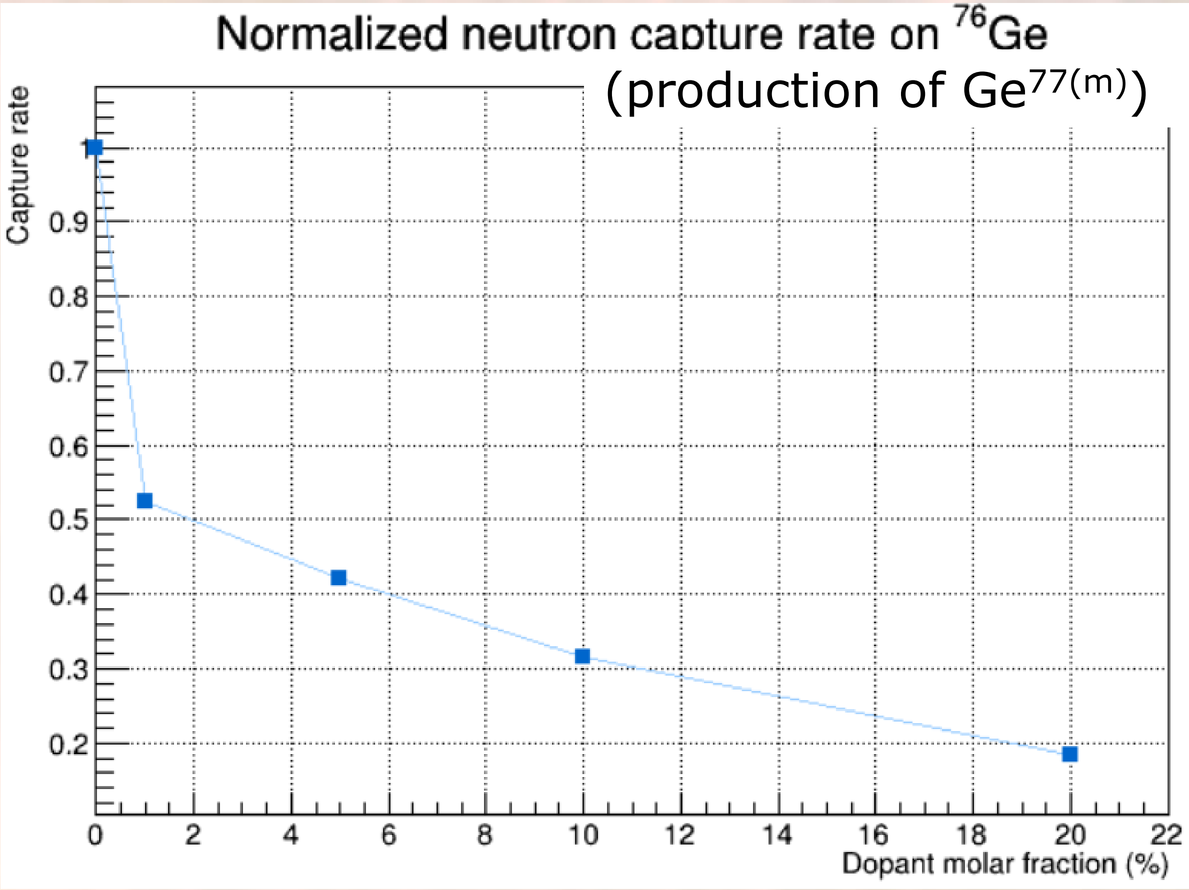
methane concentrations of up to 30%

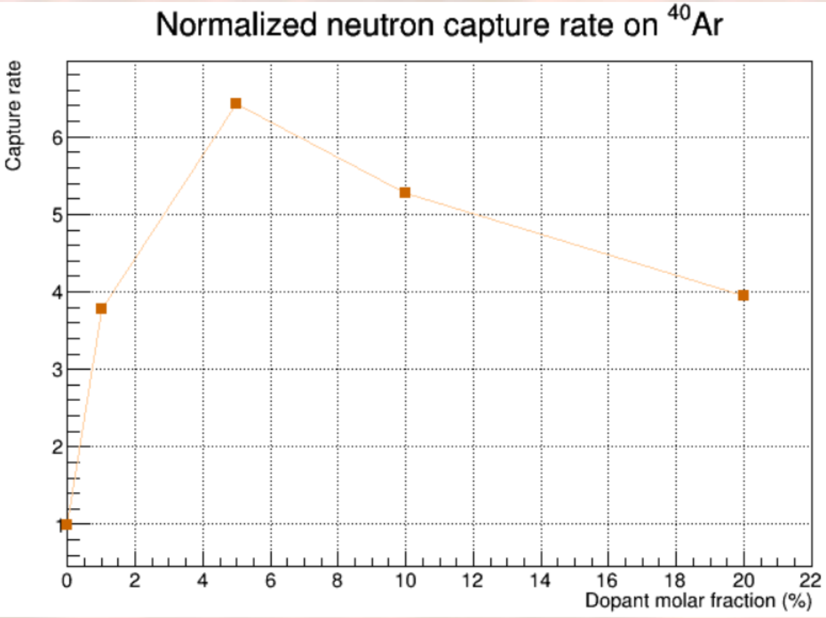


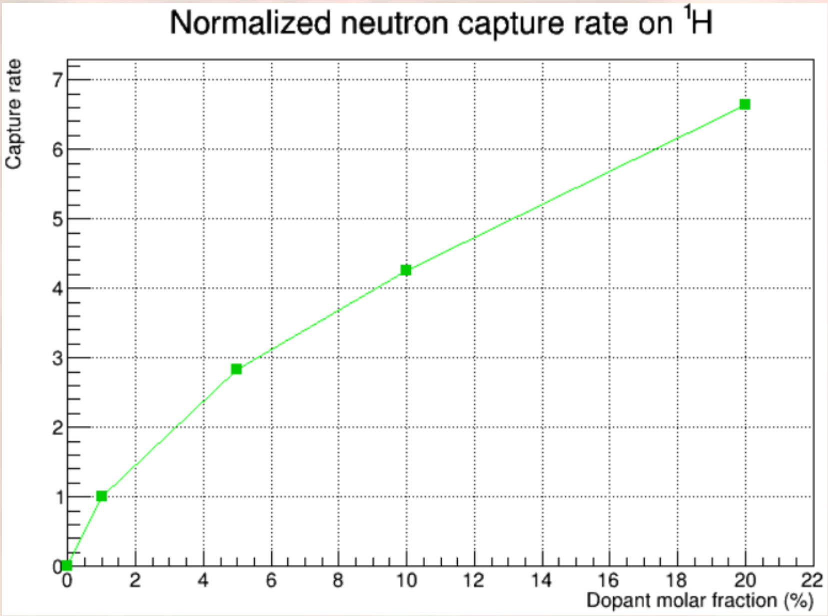
- Technical feasibility under investigation
- A risk reduction option that could be implemented post-assembly

Inner tanks still have undoped underground liquid argon (UGLAr)

Doping liquid argon with a neutron moderator

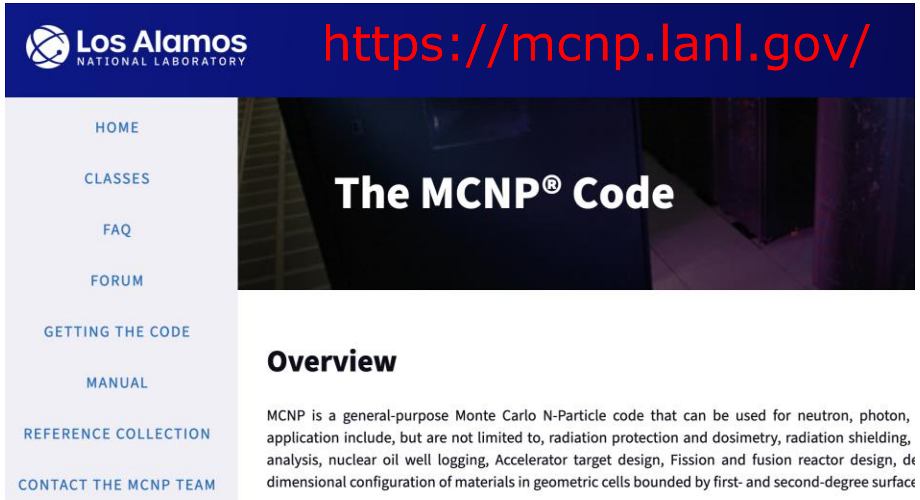






Neutrons are captured more on argon or hydrogen instead of germanium with increased doping

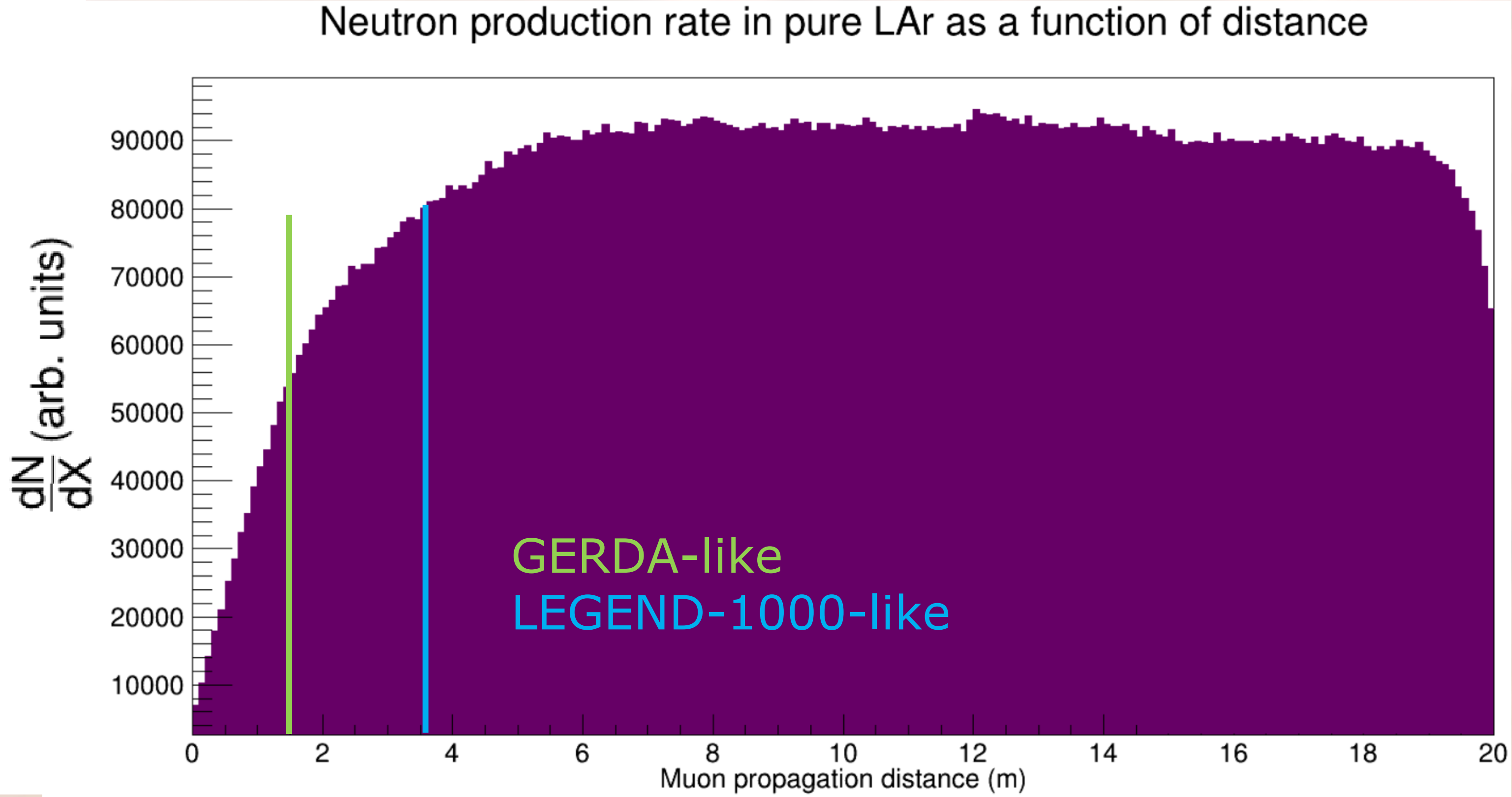
Part 3: validation and estimating uncertainty



Comparing with published study

- ^{76}Ge neutron capture rate previously simulated in a GERDA-like geometry with additional detectors (Eur. Phys. J. C (2018) 78:597)
- LEGEND-like simulations yield ~2x the capture rate
  - ✓Understood as additional argon in LEGEND increases the development of neutron cascades via muon showering
  - ✓GERDA-size geometry in this simulation yields results consistent with the reference

Larger liquid argon shields produce more neutrons faster than linearly

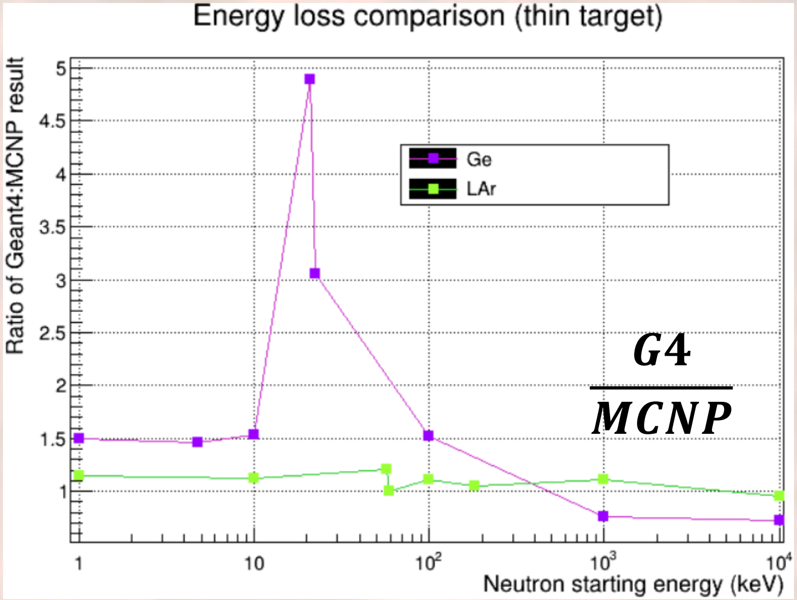


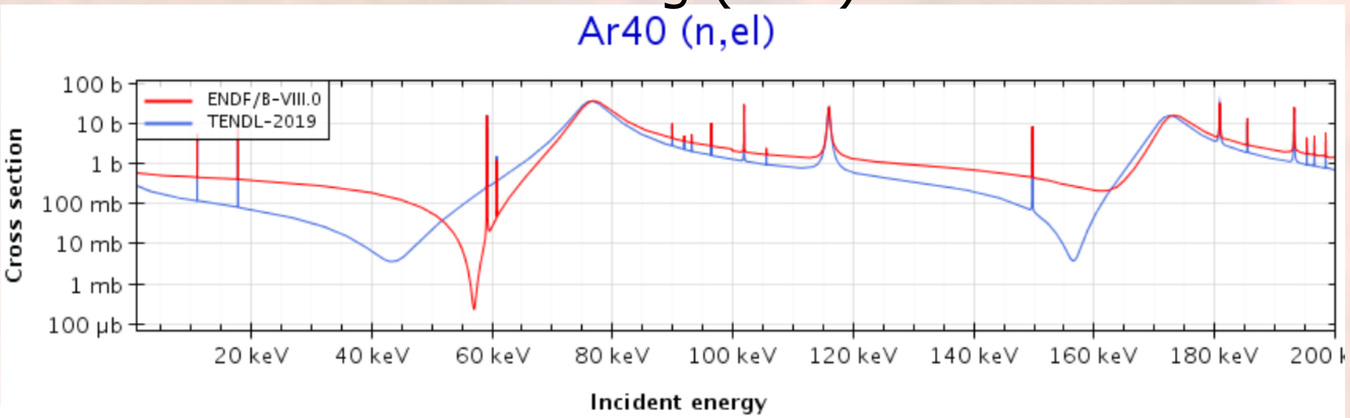
See C. Barton, ICHEP 2020 proceedings
DOI: 10.22323/1.390.0195

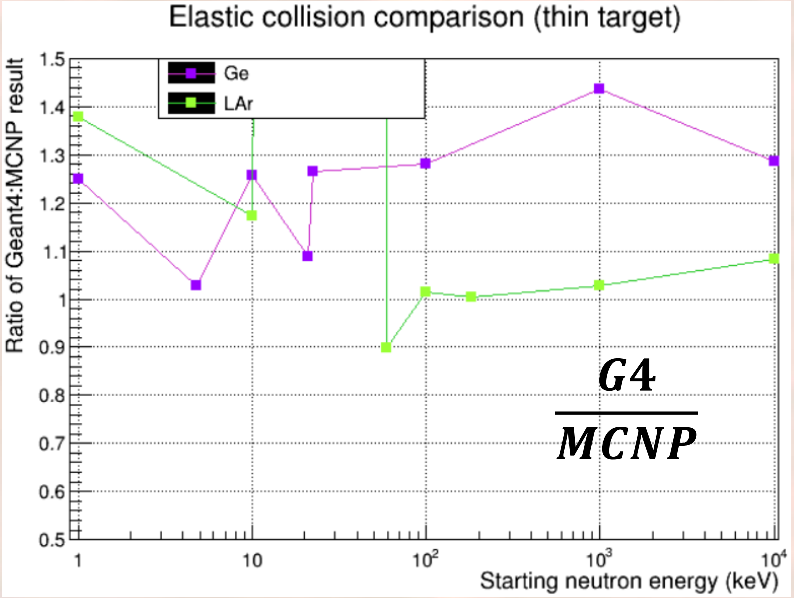
Systematic comparisons of Geant4 and MCNP

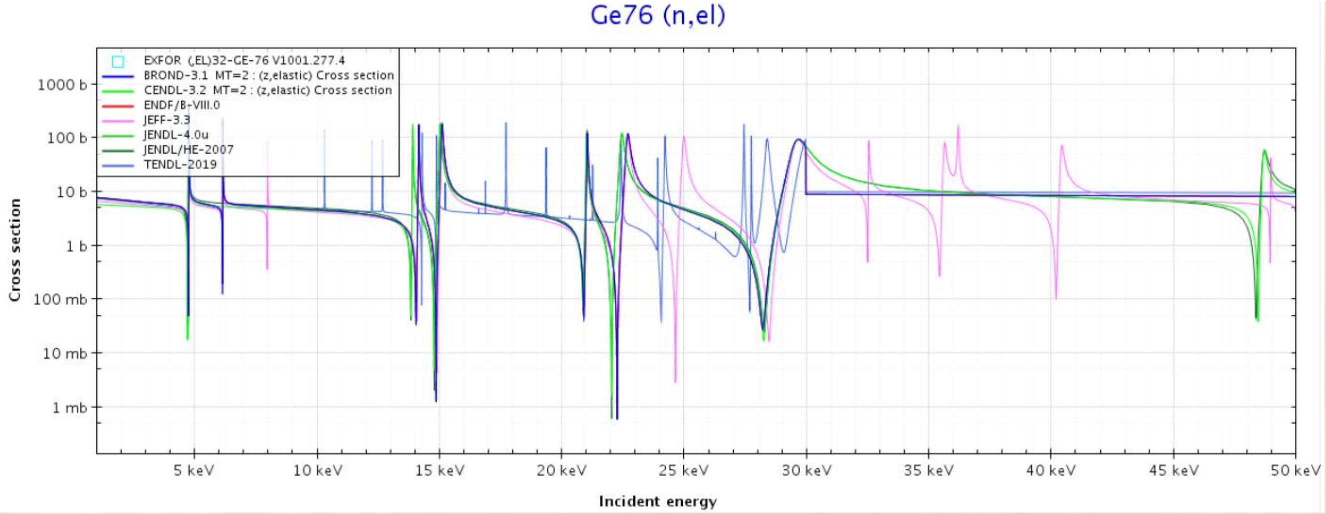
MCNP® -> **M**onte **C**arlo **N-P**article simulation software

- First, use thin target simulations (right) to compare single neutron scattering
- Typically, higher scatter rate in Geant4
- Largest differences at scattering (anti)resonances





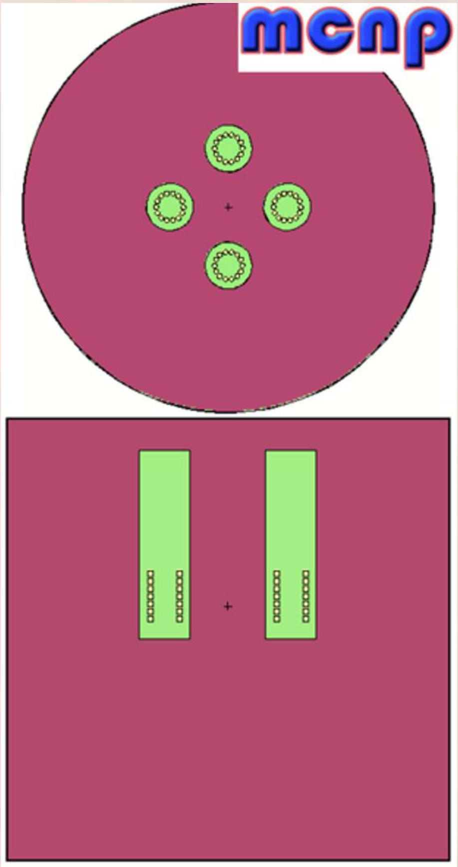


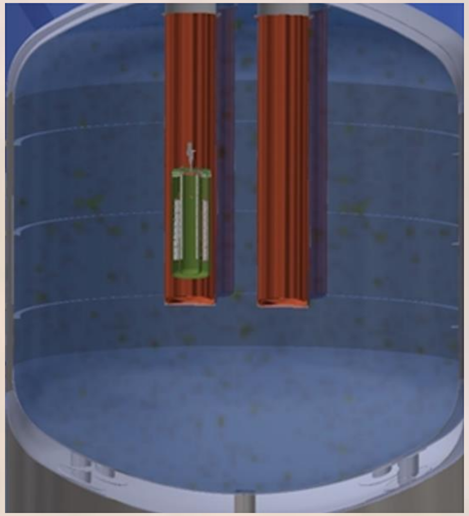


Representative LEGEND-1000 Geometry

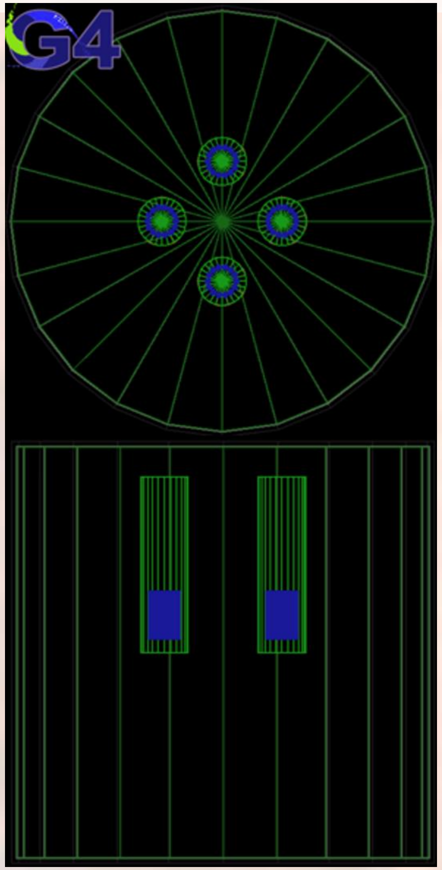
MCNP® -> **M**onte **C**arlo **N**-**P**article simulation software

Goal: simulate realistic muon-induced neutrons using identical "LEGEND-like" setups in Geant4 and MCNP simulation packages to address systematic uncertainties





CAD drawing of LEGEND-1000 reference design cryostat



Muon-induced neutrons

Muons are simulated in Geant4 in step 1, and any neutrons created in the cryostat are saved to a file, to be used as an input for MCNP/Geant4 simulations in step 2

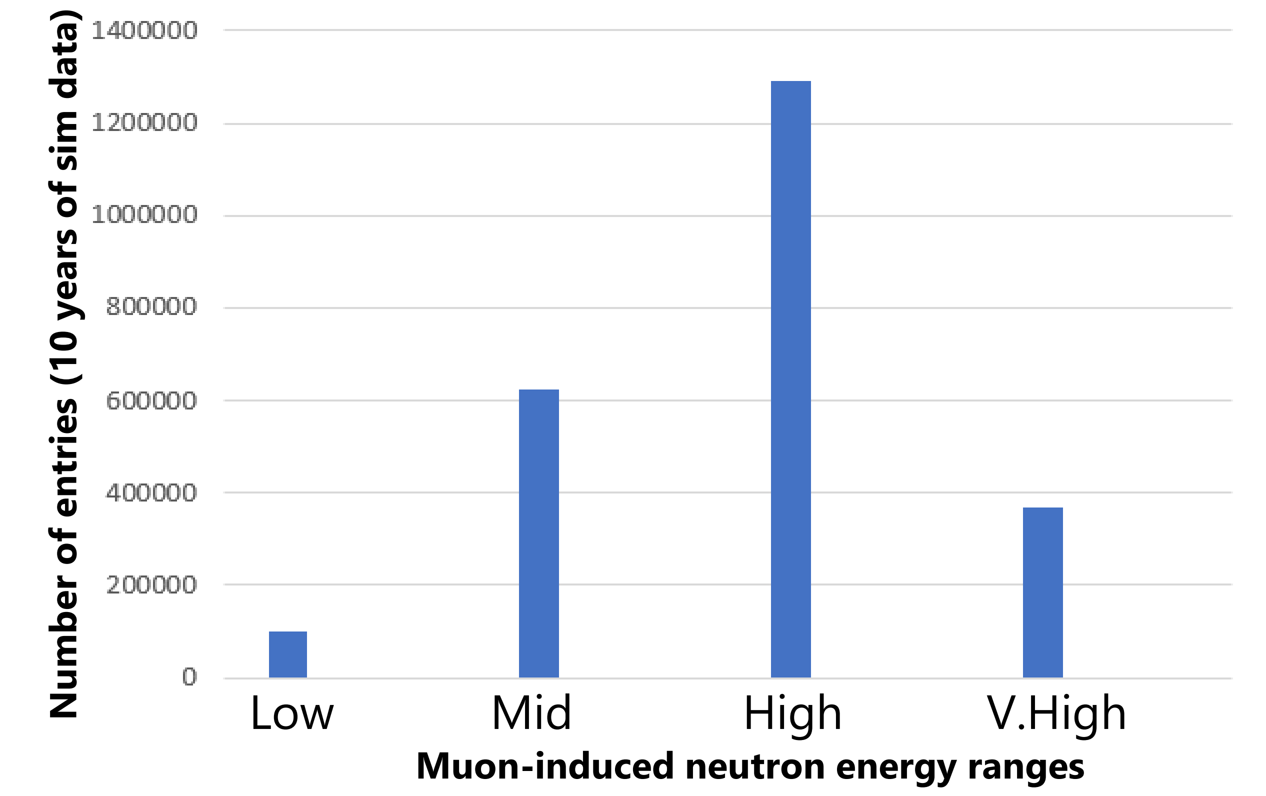
Incident muons:

Sampled for LNGS laboratory

Generated by MUSUN simulation software

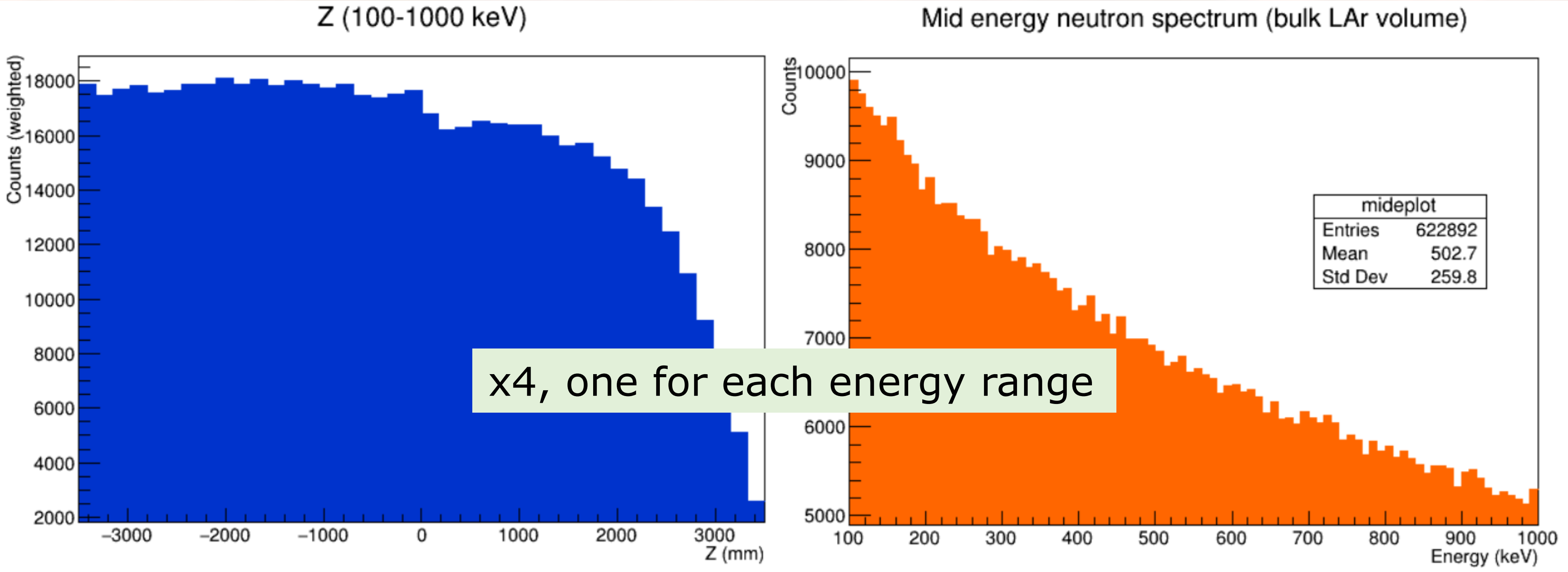
10 years’ worth of sim data

Neutrons saved in **4 energy ranges**:
Low – 0-100 keV
Mid – 100-1000 keV
High – 1-10 MeV
Very high – 10-100 MeV



Muon-induced neutrons

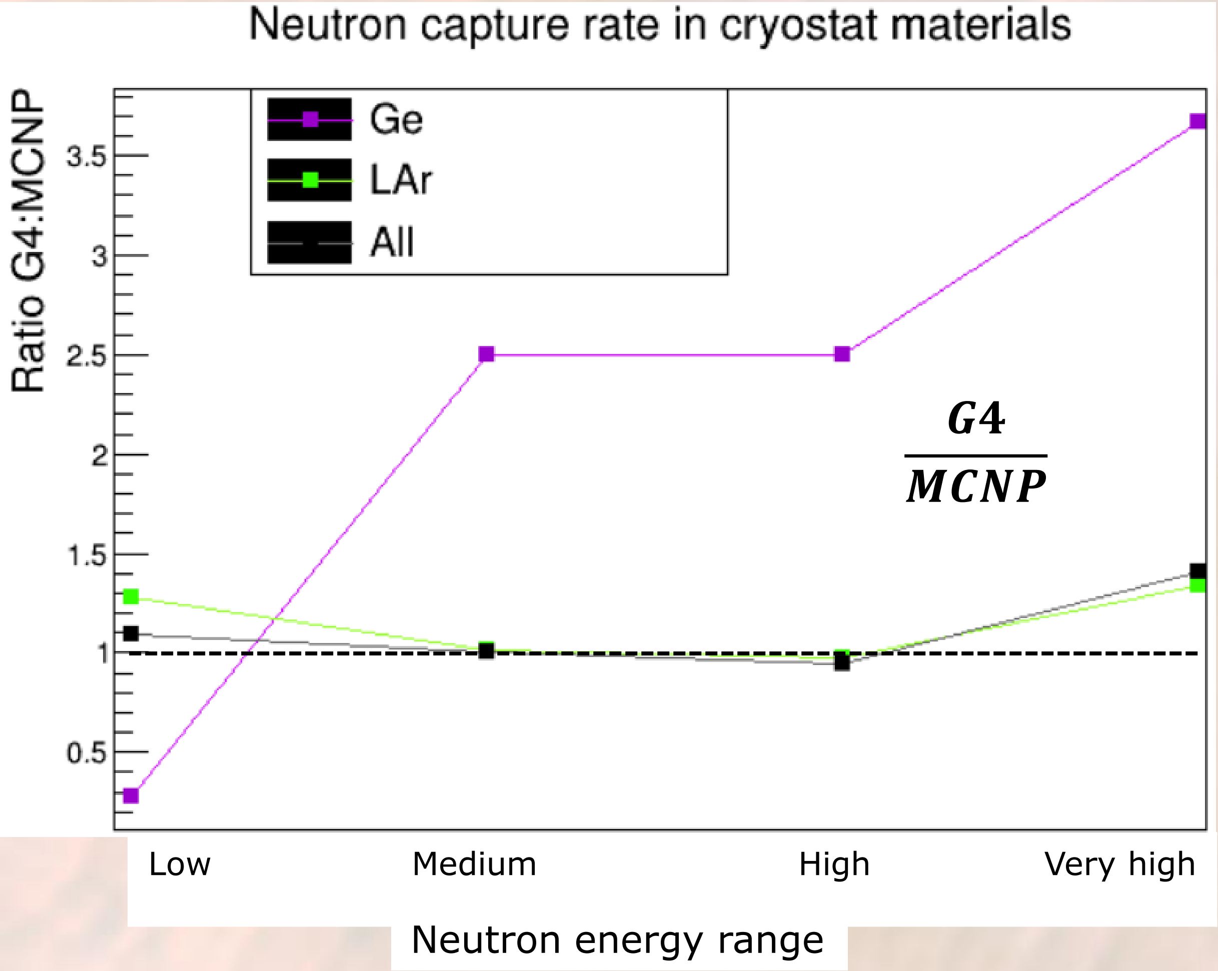
Neutron parameters are saved to histograms but sampled as distributions, for consistency

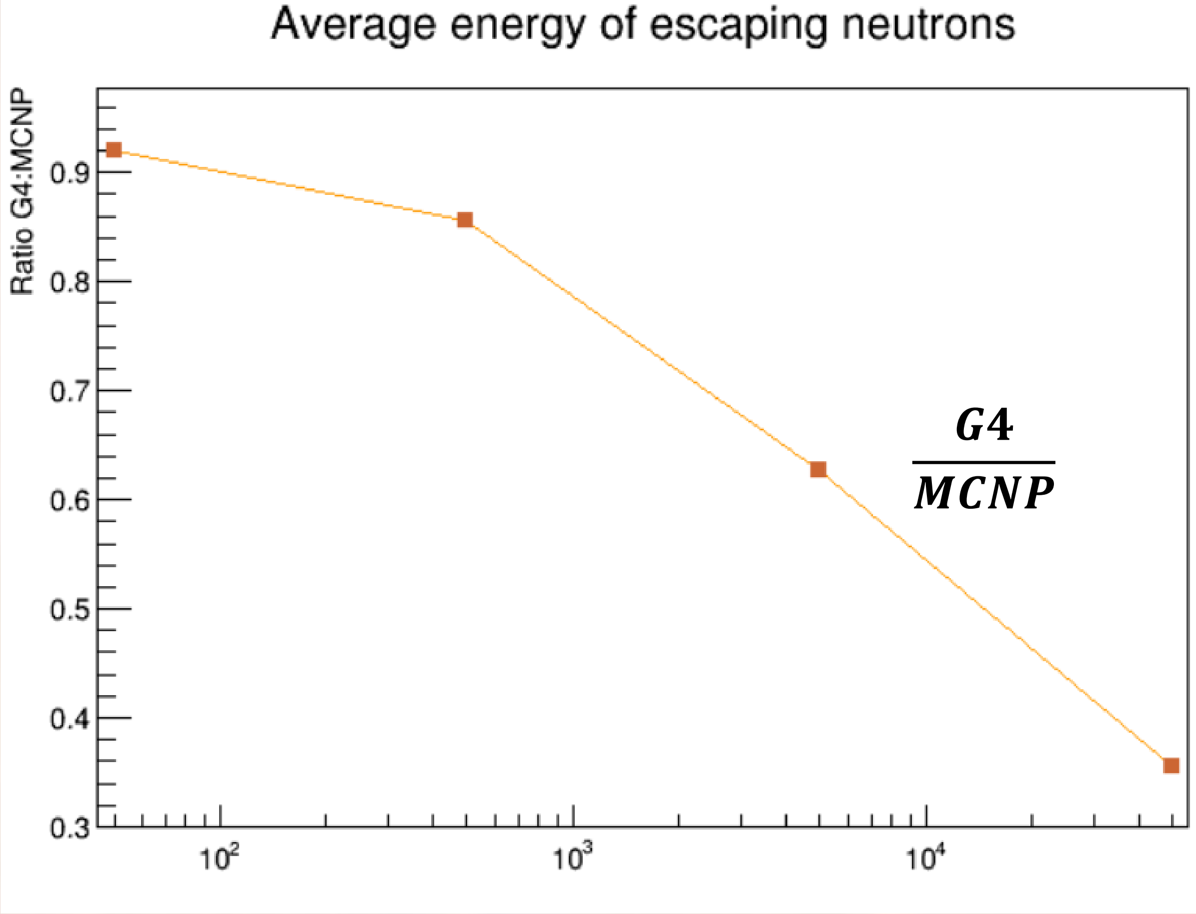


x and y distributions assumed flat
Angular momentum distribution assumed isotropic

Comparison study results

Neutron scattering rate and energy loss trended higher in Geant4, resulting in lower energy neutrons, which are captured more effectively





Outlook

LEGEND is progressing with LEGEND-200 in commissioning and LEGEND-1000 being actively pursued

LEGEND-1000 preconceptual design report determines muons-induced delayed backgrounds negligible for deep lab (SNOLAB), sizeable for shallower lab (LNGS)

To reduce project risk:

Alternative options are studied with Geant4 simulations

Solid neutron moderator is promising and extensively studied for effectiveness and radiogenic backgrounds

Doping un-instrumented part of LAr shield with low-Z material such as methane is potential risk-reduction option. Effectiveness, technical feasibility are under study

Neutron simulations are cross-checked using MCNP. MCNP predicts lower background than Geant4 predictions

With design optimizations and new analysis techniques, the performance of LEGEND at shallower depths can be improved

The LEGEND collaboration


Seattle, Dec. 2019

CIPANP 2022

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Indiana University
Comenius University
Simon Fraser University

University of North Carolina
University of South Carolina
Tennessee Tech University
University of Warwick
Jagiellonian University
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University

Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute, Heidelberg
Queens University
University Tennessee
Lancaster University
University Liverpool
University College London
Los Alamos National Lab.

INFN Milano Bicocca
Milano University and Milano INFN
Institute Nuclear Research Russ. Acad. Sci.
National Research Center Kurchatov Inst.
Lab. Exper. Nucl. Phy. MEPhI
Max Planck Institute, Munich
Technical University Munich
Oak Ridge National Laboratory
Padova University
Padova INFN

Czech Technical University Prague
North Carolina State University
South Dakota School Mines Tech.
University Washington
University Tübingen
University South Dakota
Williams College
University Zurich

Thanks for listening!

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1812356. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s)and do not necessarily reflect the views of the National Science Foundation.
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education for the DOE under contract number DE-SC0014664. Special thanks to Dr. Ralph Massarczyk at Los Alamos National Laboratory for being an excellent host.

Backups

Motivation for LEGEND

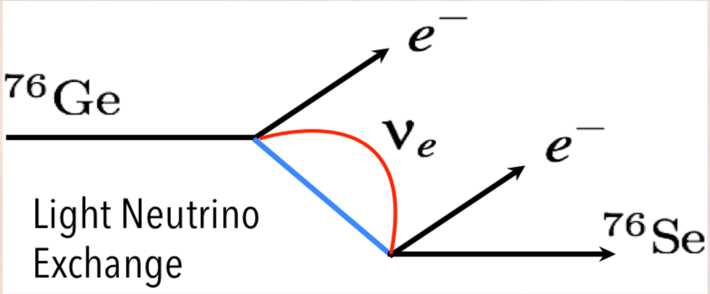
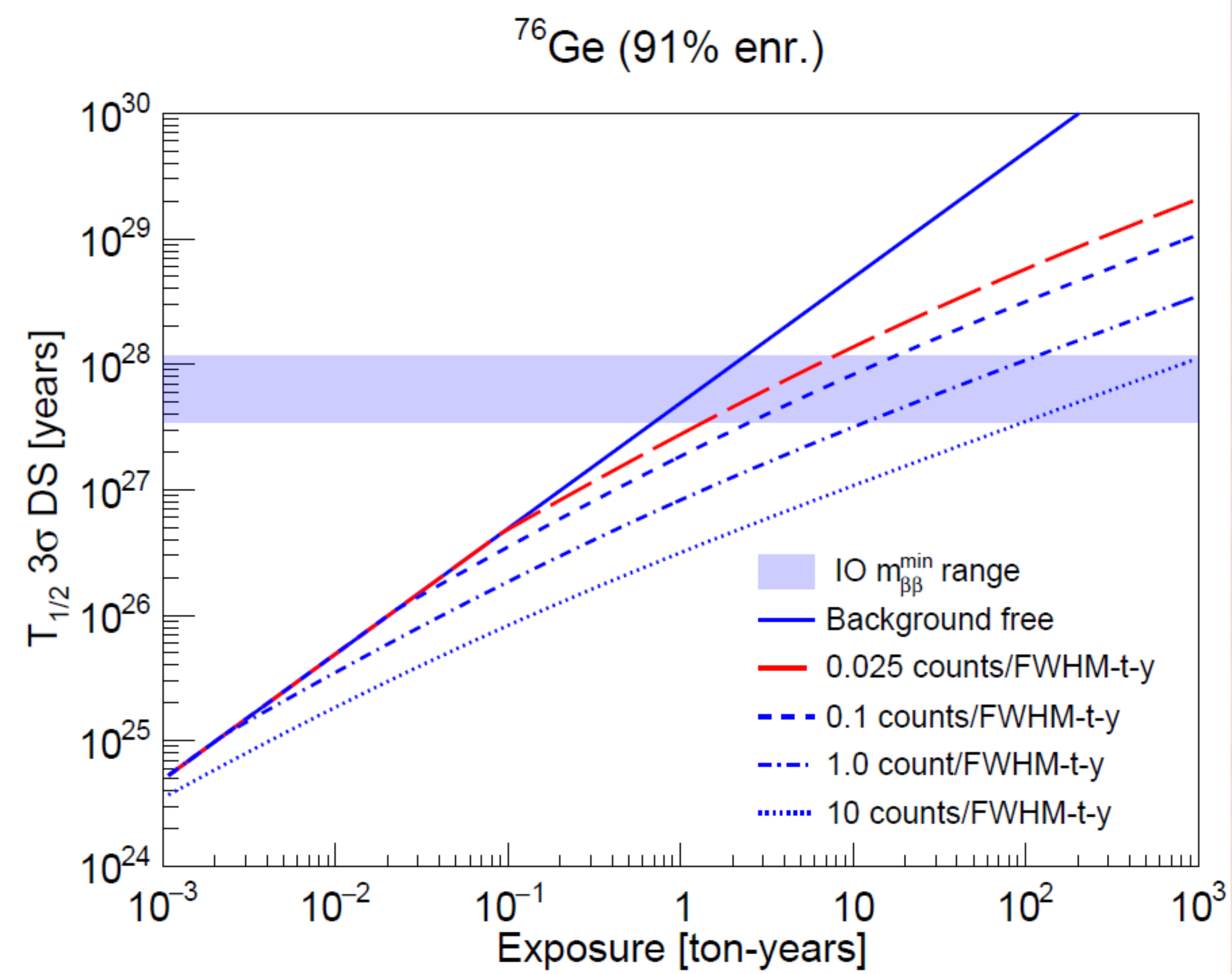


Diagram of 0νββ in ^{76}Ge

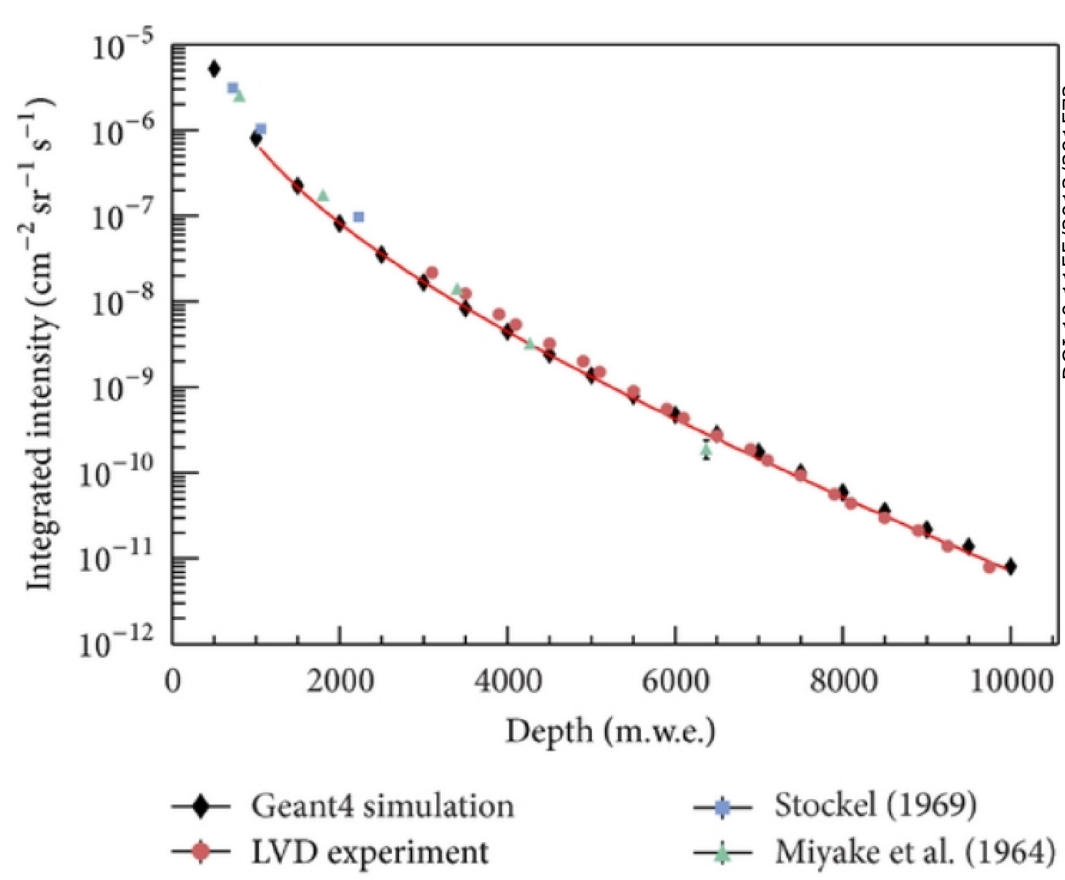
- Searches for neutrinoless double beta decay (0νββ) only experimentally viable method for establishing neutrino's Majorana nature
- MAJORANA DEMONSTRATOR and GERDA have proven feasibility of a large-scale ^{76}Ge-based 0νββ experiment
  - World's lowest backgrounds in the ROI, best energy resolutions at Q-value
- GERDA limit [1]: $T^{0\nu}_{1/2} > 9.0 \times 10^{25}\ yr$
- MJD limit [2]: $T^{0\nu}_{1/2} > 2.7 \times 10^{25}\ yr$
- To cover entire inverted mass ordering phase space, need to probe half-life beyond 10^{28} yr
  - Requires improvements in background rate and exposure



$T_{1/2}$ discovery potential vs. exposure for a few background rates, with projected results for each phase.

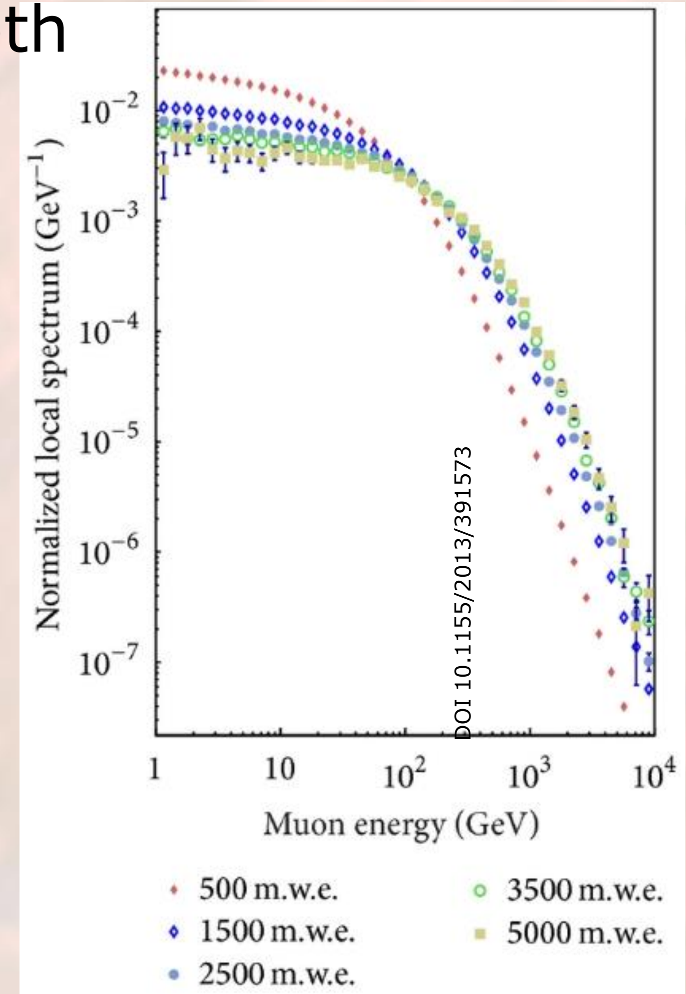
[1,2] Results available at 10.1126/science.aav8613 (2019) and Phys. Rev. C 100 025501 (2019), respectively

Muons and deep underground sites



DOI 10.1155/2013/391573

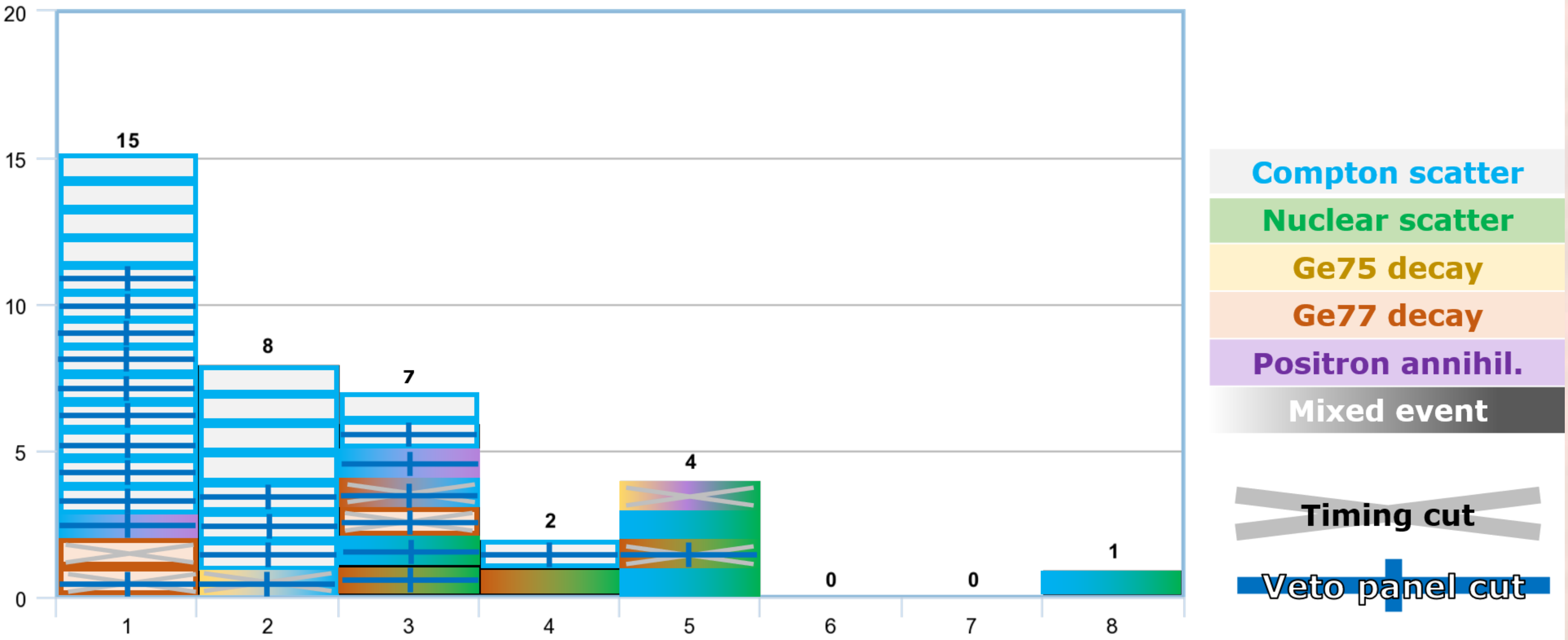
- Muon flux drops exponentially with increasing depth
- Surface profile can have an effect, decreasing with depth



For very deep sites, average muon energy slowly increases, but stays in the 100s of GeV range

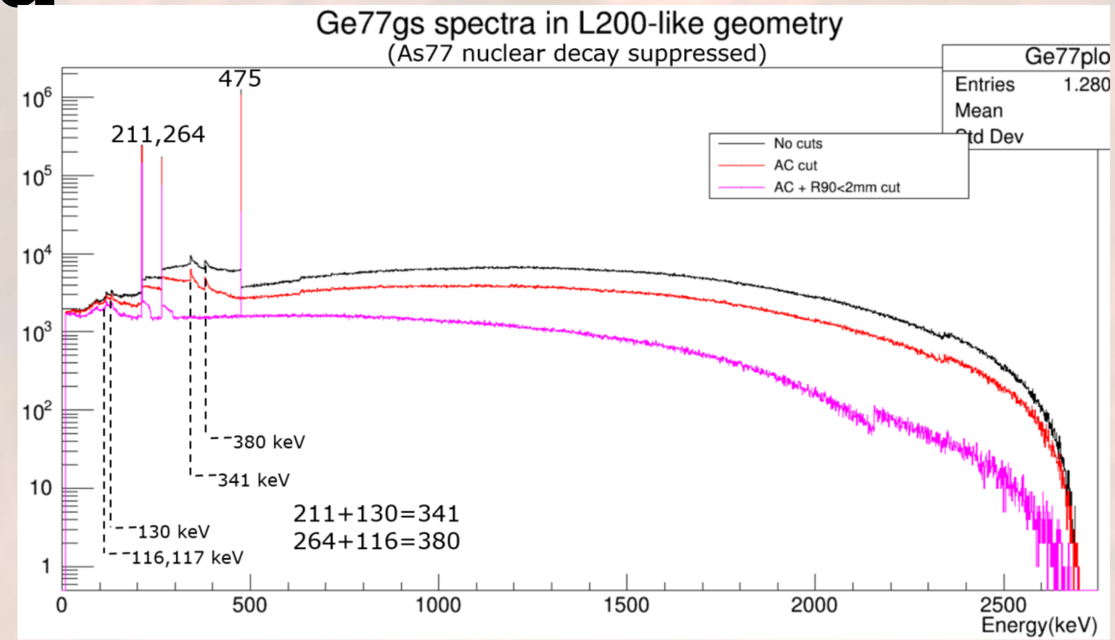
Prompt muon signals

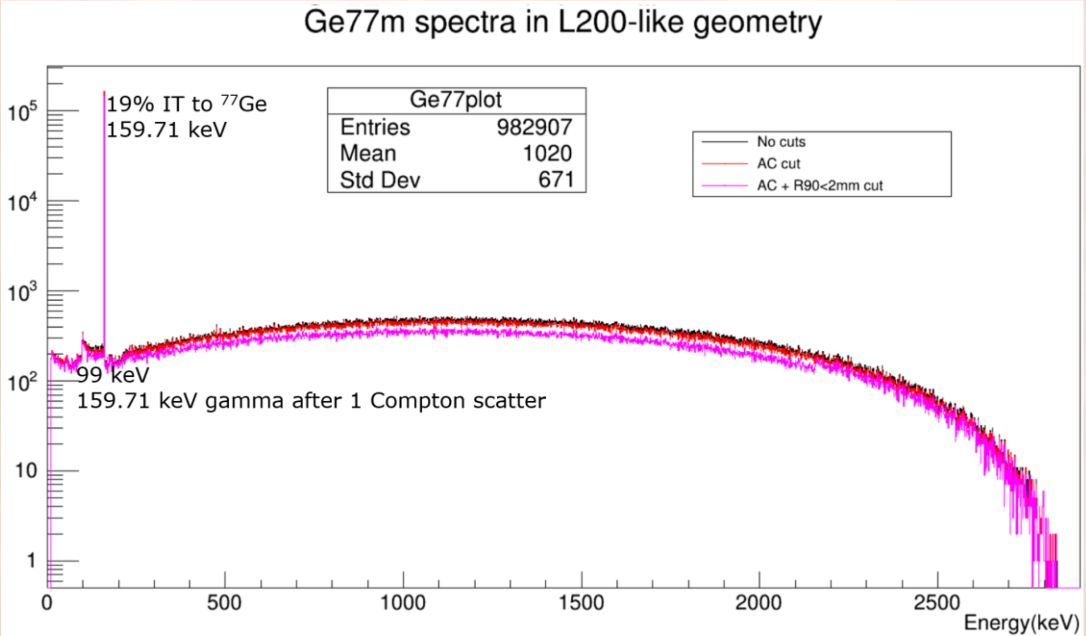
Prompt signal events investigated without water shield veto
If water shield is included, background contribution <0.5% of total budget



Ge^{77}+Ge^{77m} decay spectra

- ^{77}Ge produces several de-excitation gammas upon decay, which are very likely to cause signal rejection by multi-site or liquid argon veto cuts
- ^{77m}Ge decay tends to be 'quiet', possibly necessitating the use of preemptive cuts such as the delayed coincidence cut





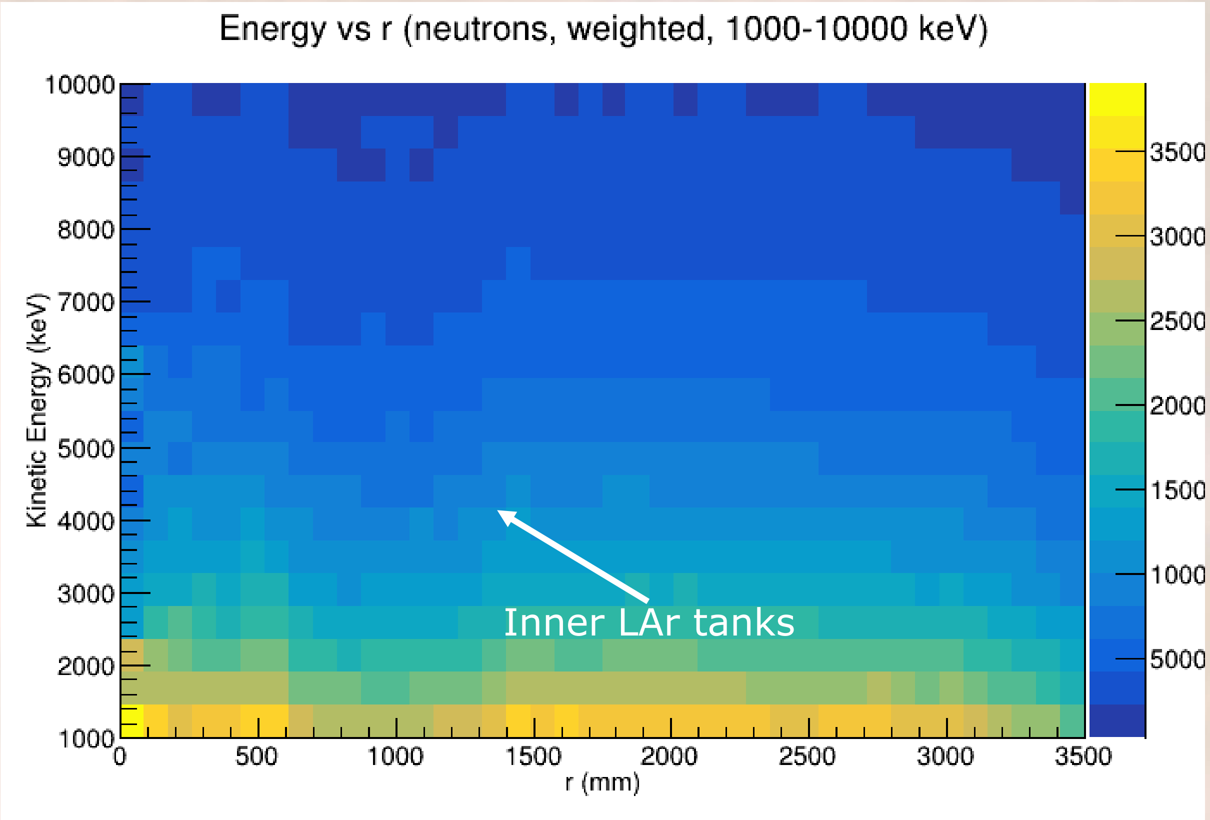
Other cosmogenic isotopes

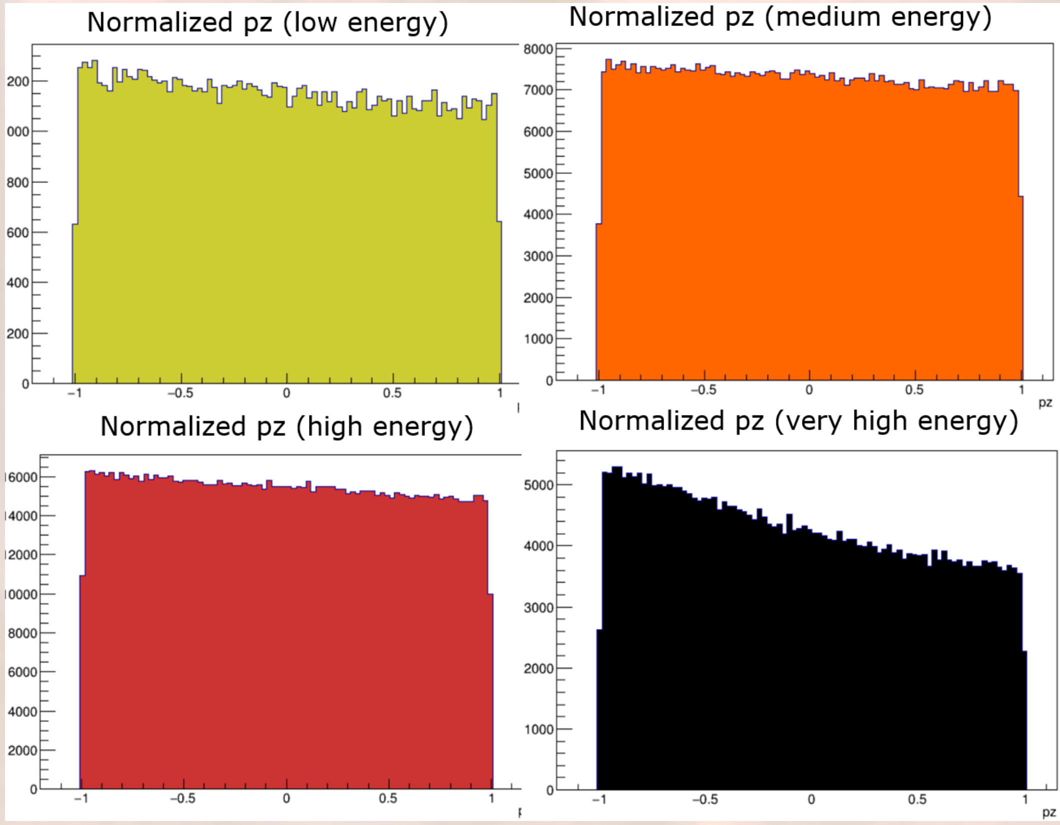
- All other isotopes with delayed decay times produced at less than half the rate of $^{77/77m}Ge$ when *combined*
- β^+ decay isotopes produce annihilation gammas and are rejected efficiently
- Electron capture decay isotopes produce x-rays which should be detectable

isotope	natural detectors (10^{-2} cts /keV/t/yr)	enriched detectors (10^{-2} cts /keV/t/yr)
^{58}Co	0.02	< 0.01
^{60}Co	0.09	0.01
^{61}Cu	0.02	< 0.01
^{62}Cu	0.17	0.08
^{66}Cu	0.22	0.16
^{62}Zn	0.26	< 0.01
^{63}Zn	0.19	< 0.01
^{71}Zn	0.2	0.02
^{73}Zn	0.04	0.15
^{74}Zn	0.01	0.04
^{66}Ga	0.75	0.2
^{68}Ga	4.94	0.27
^{70}Ga	0.12	< 0.01
^{72}Ga	0.28	1.07
^{73}Ga	0.47	1.00
^{74}Ga	0.03	0.11
^{75}Ga	2.19	1.18
^{76}Ga	0.05	0.19
^{66}Ge	0.03	0.01
^{67}Ge	0.6	0.15
^{69}Ge	3.29	0.03
$^{77/77m}Ge$	2.55	9.56

Neutron distributions in G4/MCNP

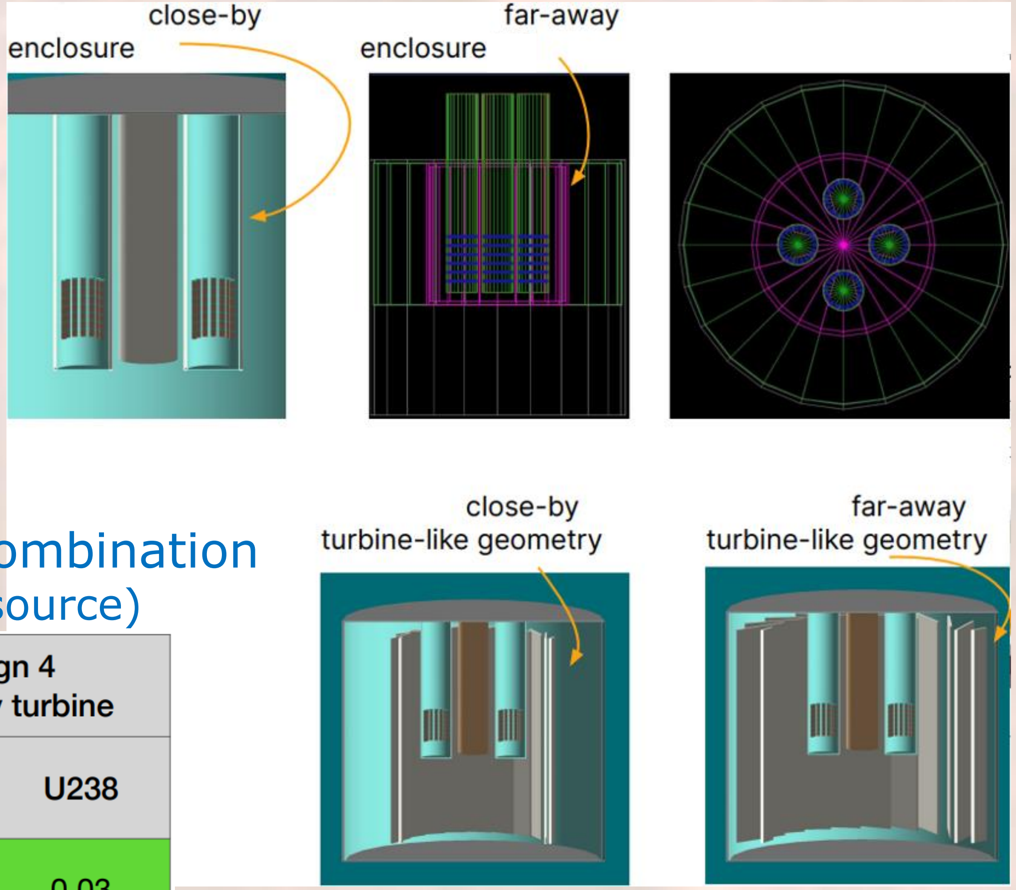
- To simplify simulation, radial position and angular momentum distributions were assumed to have no features
- Inner LAr tanks not tallied
- Assumption accurate to within ~20%





Optimizing solid shield designs

- Best configuration reduces cosmogenic backgrounds by a factor of ~2, while introducing an additional ~3% radiogenic background



Radiogenic background contribution of each design/material combination
(expressed as fraction of total allowable background from each source)

	Design 1 Close-by enclosure		Design 2 Far away enclosure		Design 3 Close-by turbine		Design 4 Far away turbine	
	Th232	U238	Th232	U238	Th232	U238	Th232	U238
(Borated) PE	18	48	0.6	0.9	0.3	0.4	0.04	0.03
PMMA (DEAP)	110	15	4	0.3	2	0.1	0.2	0.01
PEN	23	10	0.8	0.2	0.4	0.09	0.05	7E-03
PMMA (JUNO)	0.9	1.8	0.03	0.03	0.02	0.02	2E-03	1E-03

Big Cylinder + JUNO Acrylic