Общелабораторный семинар ЛЯП
25.03.2020

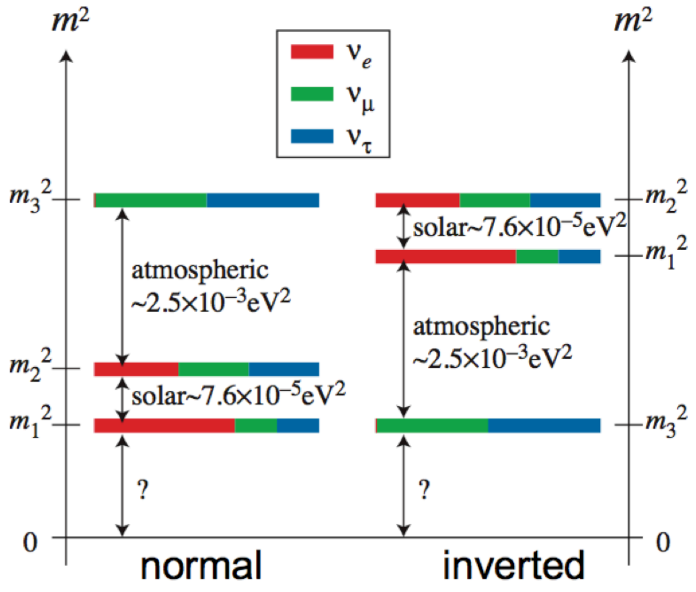
Васильев С.И.

Поиск безнейтринного двойного бета-распада (0νββ) ^{76}Ge в экспериментах MAJORANA, GERDA и LEGEND-200

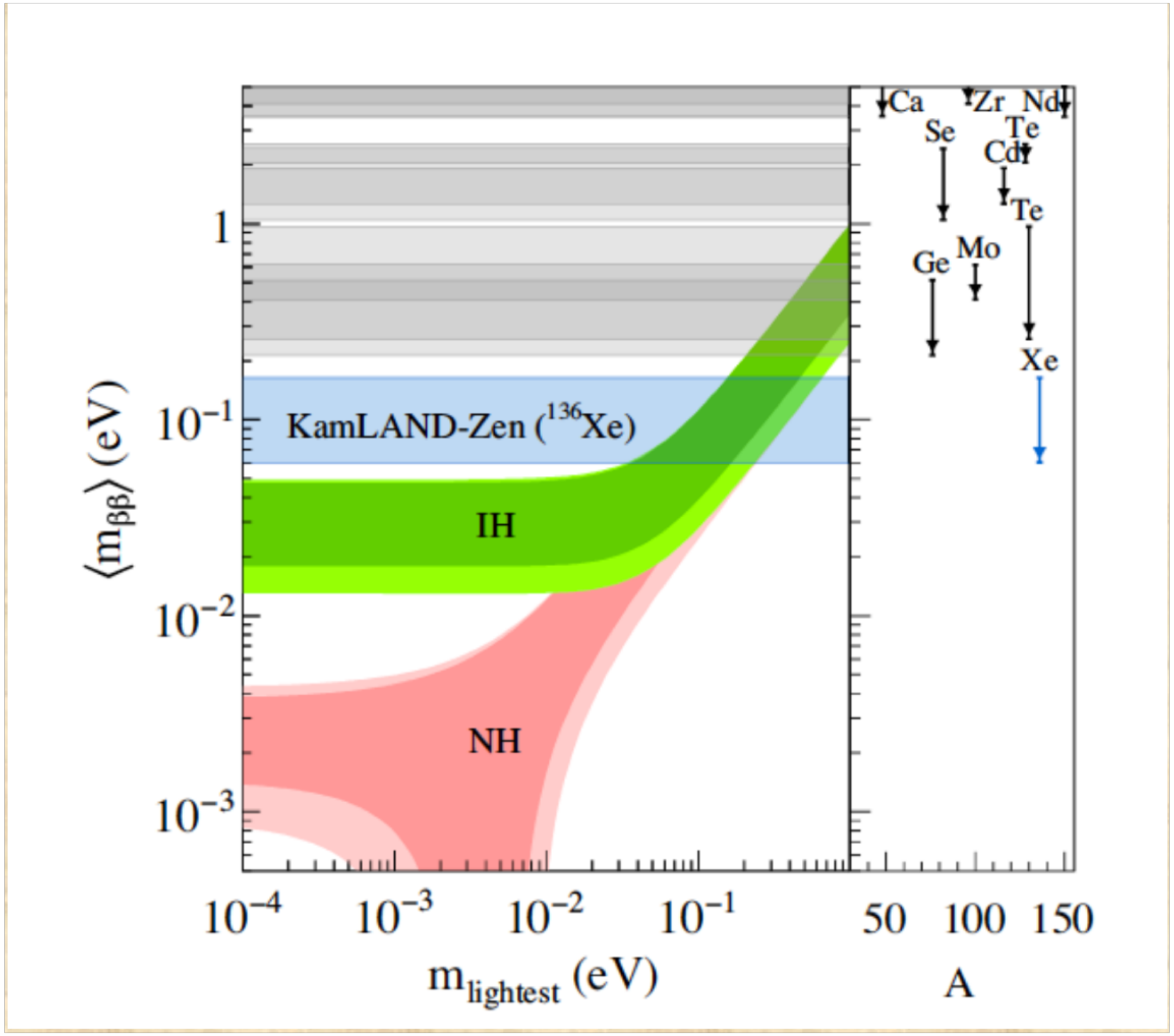
План доклада

- **Актуальность исследований 0νββ**
- **Эксперимент MAJORANA**
- **Эксперимент GERDA (кратко)**
- **Эксперимент LEGEND -200**

Neutrino questions



- What is the absolute mass scale of neutrinos?
- What is the neutrino mass hierarchy?
- Is the neutrino its own antiparticle (a Majorana particle)?
- Is lepton number a conserved quantity?

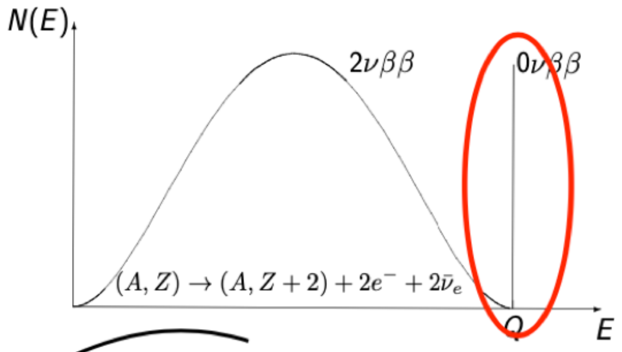


Ca
Zr
Nd
Se
Te
Cd
Te
Mo
Ge
Xe
KamLAND-Zen (^{136}Xe)
IH
NH
1
10^{-1}
10^{-2}
10^{-3}
$\langle m_{\beta\beta} \rangle$ (eV)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$m_{lightest}$ (eV)
50
100
150
A

Experimental searches of betabeta decay

Neutrinoless double beta decay can be tested in nuclei in which single beta decay is kinematically forbidden (^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe…).

It is a very rare process:



$$T_{0\nu} \propto \sqrt{\frac{M\ t}{B\ \Delta E}}$$

ton-scale

<1% at Q_{bb}

<1 cts/yr/ton/ROI

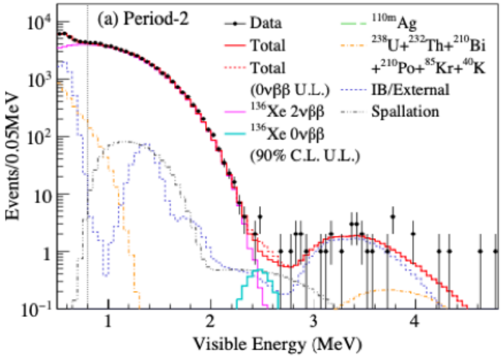
KamLAND-Zen Loaded LSc with 380 kg ^{136}Xe, $T_{1/2} > 1.07\times10^{26}$ yrs (90% C.L.), $m_{bb} <$ 61-165 meV

EXO-200 ~75 kg LXe TPC, $T_{1/2} > 3.7\times10^{25}$ yrs

GERDA 31 kg (enriched) ^{76}Ge, $T_{1/2} > 0.9\times10^{26}$ yrs

MAJORANA 26.0 kg yrs, $T_{1/2} > 0.27\times10^{26}$ yrs

CUORE ^{130}Te, ~206 kg, $T_{1/2} > 2.3\times10^{25}$ yrs

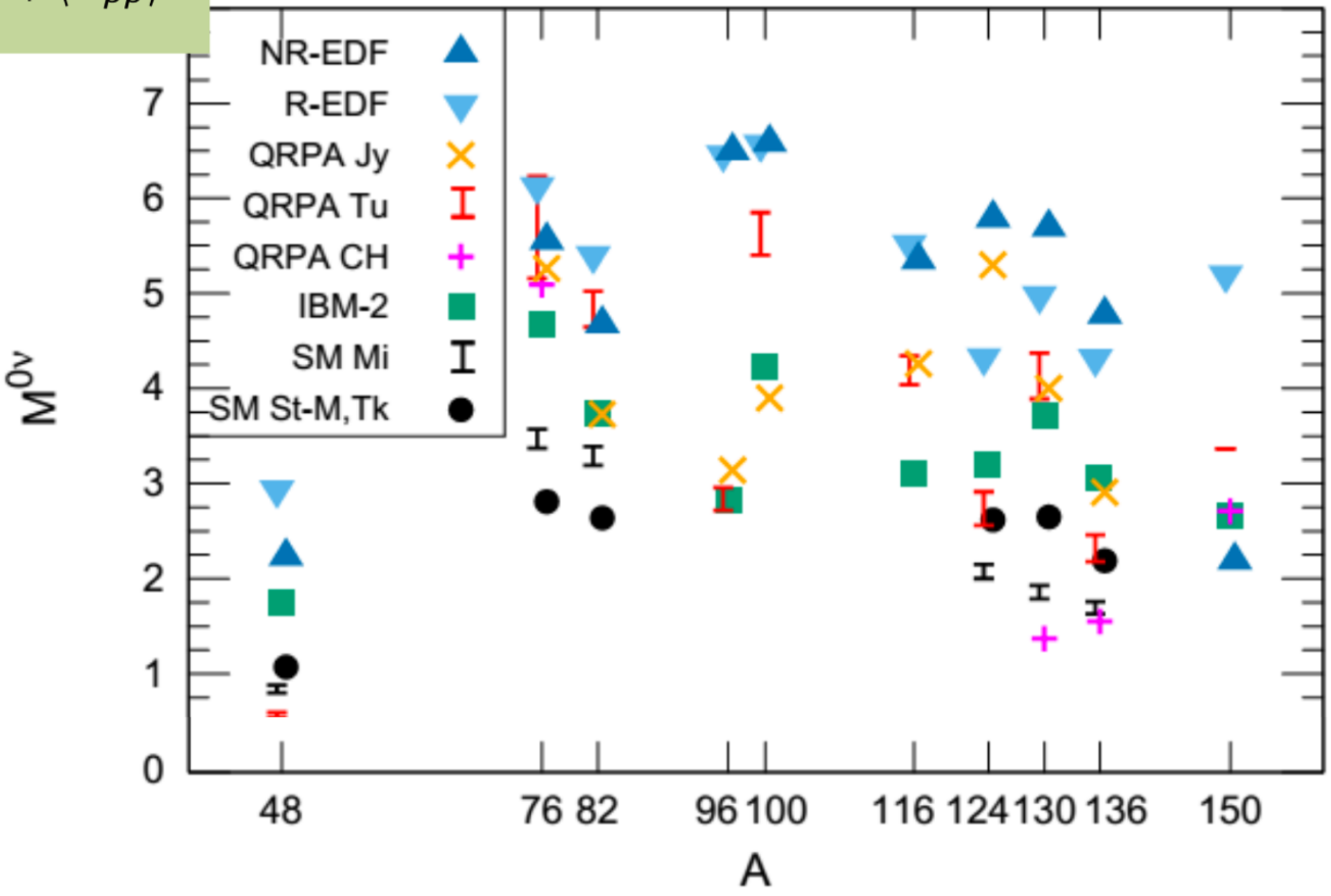


KamLAND-Zen, PRL 117 (2016)

J. Ouellet, NuPhys 2019

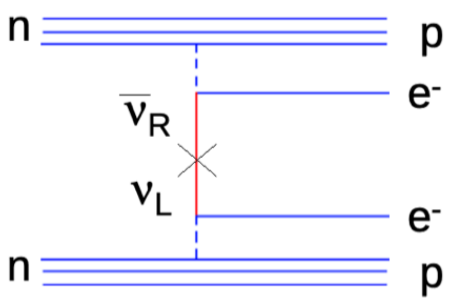
NME

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

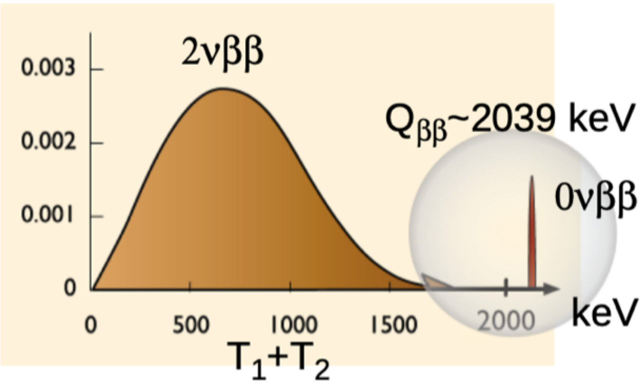


Signal and Sensitivity

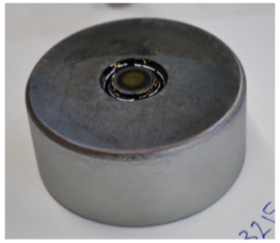
0νββ decay, ΔL=2



$^{76}Ge \rightarrow\ ^{76}Se + 2\,e^-$



Ge detector



^{76}Ge: 7% → 87%

Experiment observes $N^{0\nu} = \ln 2 \dfrac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\%CL) > \begin{cases} \dfrac{\ln 2}{2.3} \dfrac{N_A}{A} a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg}=0 \\ \dfrac{\ln 2}{1.64} \dfrac{N_A}{A} a \cdot \epsilon \sqrt{\dfrac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A = Avogadro constant
a = fraction of 0νββ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

"background-free": N^{bkg} <1 within 1xFWHM @ $Q_{\beta\beta}$ at design exposure M t

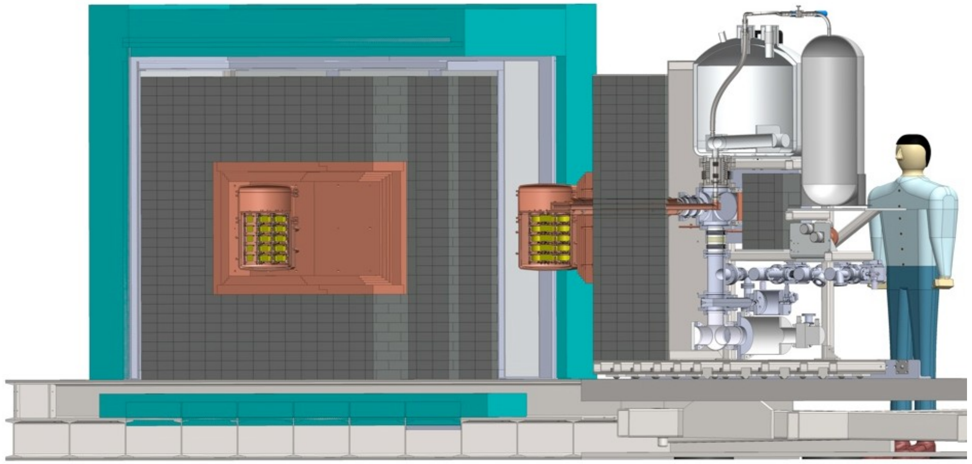
Advantages of ^{76}Ge:

- Ge diodes are intrinsically high purity
- Natural abundance of 7.4%, with demonstrated ability to enrich to > 86%
- Excellent energy resolution – 0.13% at 2039 keV
- HPGe crystals act as both source and detector (high detection efficiency)
- $Q_{\beta\beta}$ = 2.039 MeV, above most backgrounds
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.9\times10^{21}$ y)
- Powerful background rejection from pulse shape analysis

GERDA

- **Design:** Ge crystals submerged in liquid Argon at LNGS, Italy
- **Shield**: LAr, H_20
- **Phase I:** 18 kg enr-Ge (2011)
- **Phase II:** 20 kg enr-Ge (2013)

MAJORANA



- **Design:** Ge crystals in high-purity electroformed copper cryostats at Sanford Lab, US
- **Shield:** copper, lead
- **DEMONSTRATOR:** 30 kg of enr-Ge

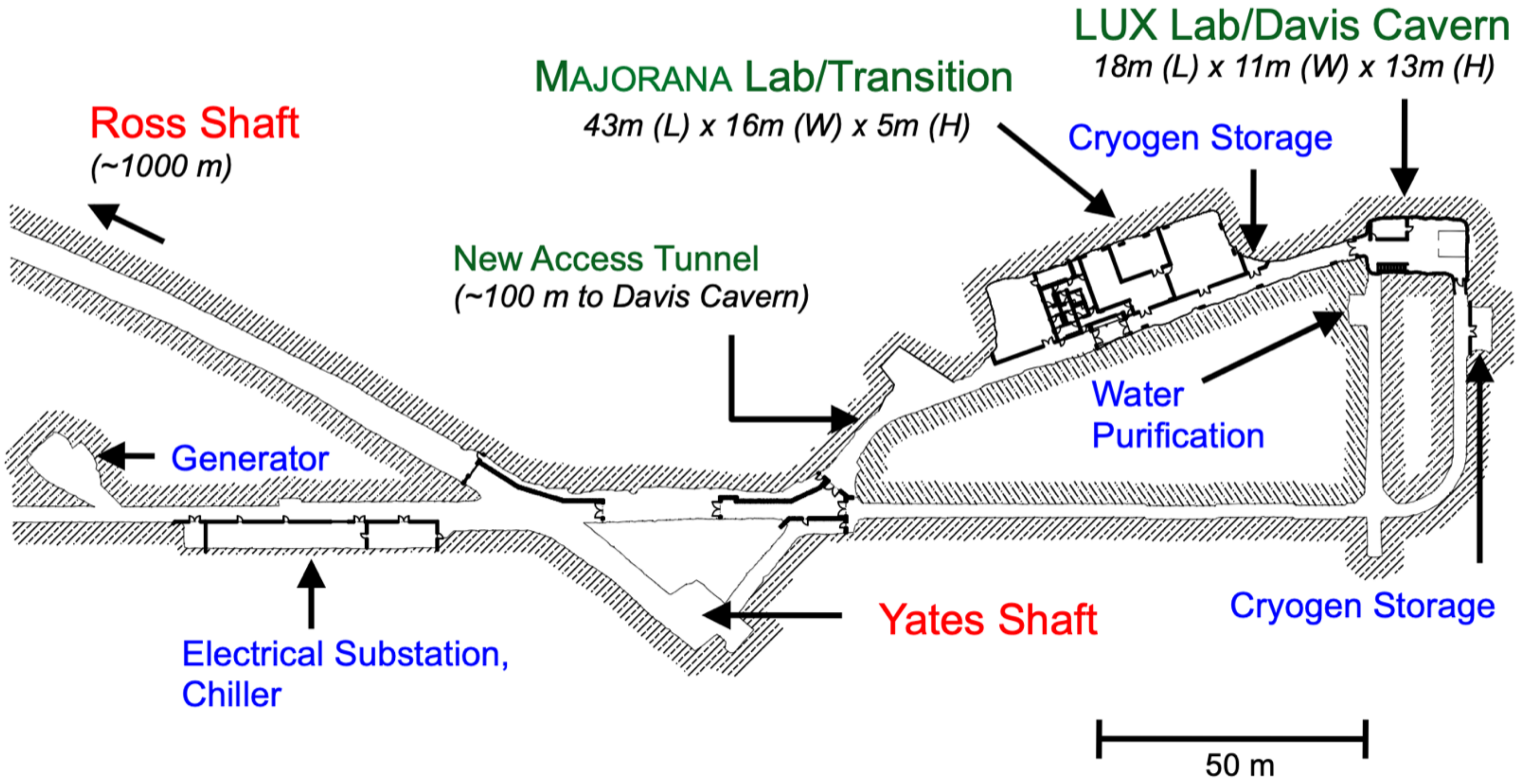
Open exchange of knowledge and technologies
Future goal: merge for tonne-scale experiment

Sanford Underground Research Facility

Lead, South Dakota, USA

SURF Science Infrastructure

4850L Davis Campus: 2,732 m² (Total) / 927 m² (Science)



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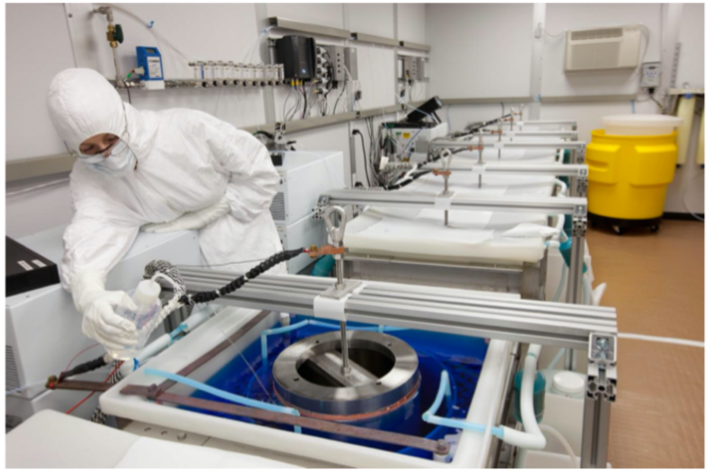
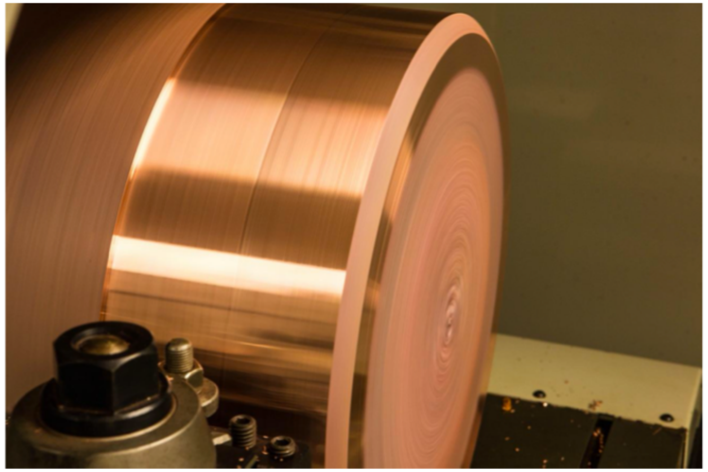
MJD's Basic Building-Block: UGEFCu

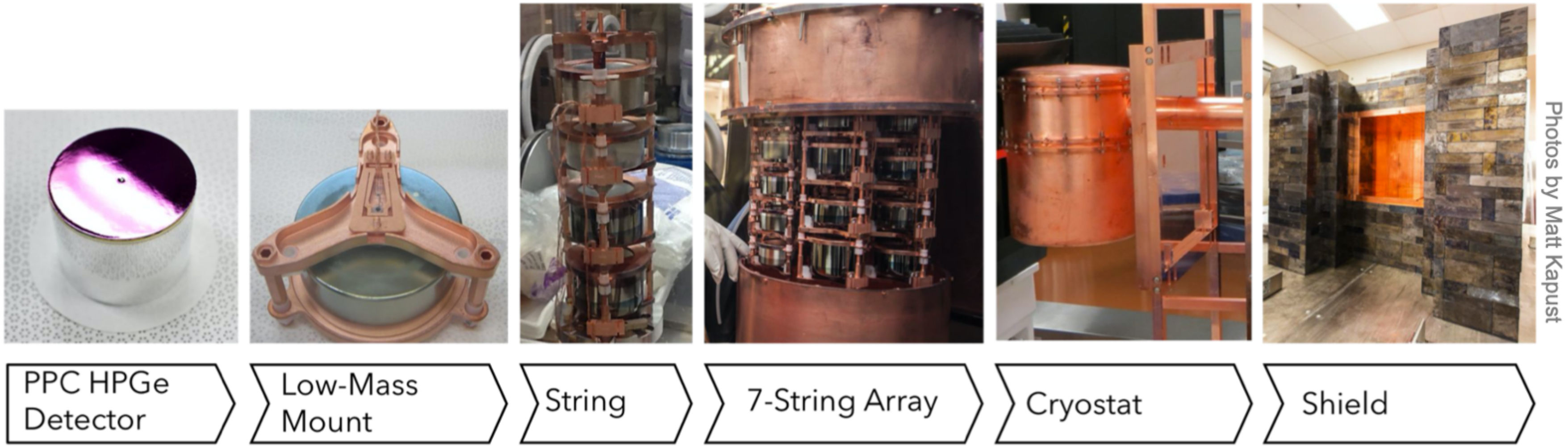
- Copper was electroformed at PNNL and SURF 4850' level
- All machining conducted underground
- Over 2 tons of copper produced, 1.2 tons in MJD
- Th decay chain ≤ 0.1 μBq/kg
- U decay chain ≤ 0.1 μBq/kg
- Etched to remove surface contamination, stored under N_2 flow





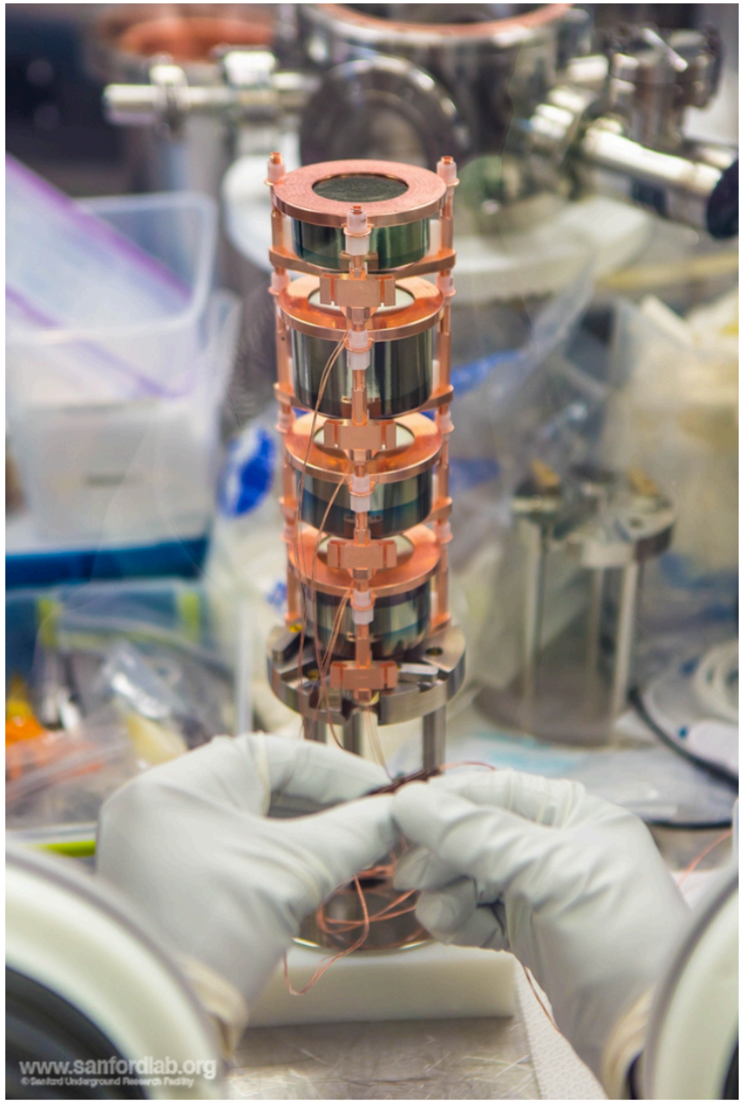
Photos by Matt Kapust

Modular Design



- Two independent cryostats in compact passive shield with active muon veto
- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
- Makes MJD design scalable for tonne-scale experiment

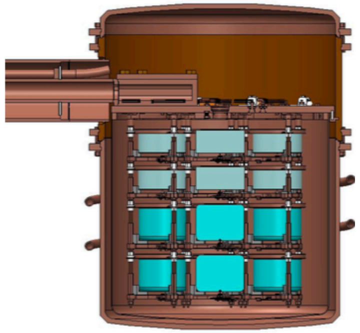
Detector Strings and Modules



The MAJORANA DEMONSTRATOR

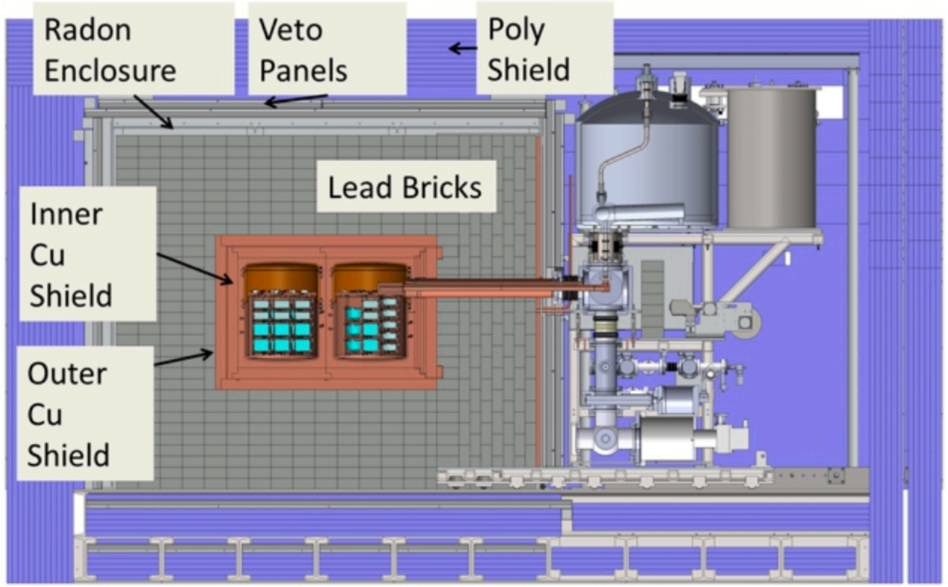
Operating underground at the 4850' Sanford Underground Research Facility

Goals:
- Demonstrating backgrounds low enough to justify building a tonne scale experiment
- Establishing feasibility to construct & field modular arrays of Ge detectors
- Searching for additional physics beyond the standard model



- Energy resolution of 2.5 keV FWHM @ 2039 keV is the best of any ββ-decay experiment
- Background Goal in the 0νββ peak after analysis cuts with the achieved resolution: 2.5 counts/(FWHM t yr)
- Projected backgrounds based on assay results ≤ 2.2 counts/(FWHM t yr)

- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of natGe
  - Detector Technology: P-type, point-contact
- 2 independent cryostats
  - Ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - Naturally scalable
- Compact Shield
  - Low-background passive Cu and Pb shield with active muon veto



Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics
with additional contributions from international collaborators.

Achieving Ultra-Pure Materials

Material purity was central to the Majorana Demonstrator design

- The efforts of the community were very useful in our selection of components
  - i.e. radiopurity.org, the EXO assay paper [NIM **A591** (2008) 490–509]
- Initial background budget based our own certification of candidate materials

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The MAJORANA DEMONSTRATOR radioassay program

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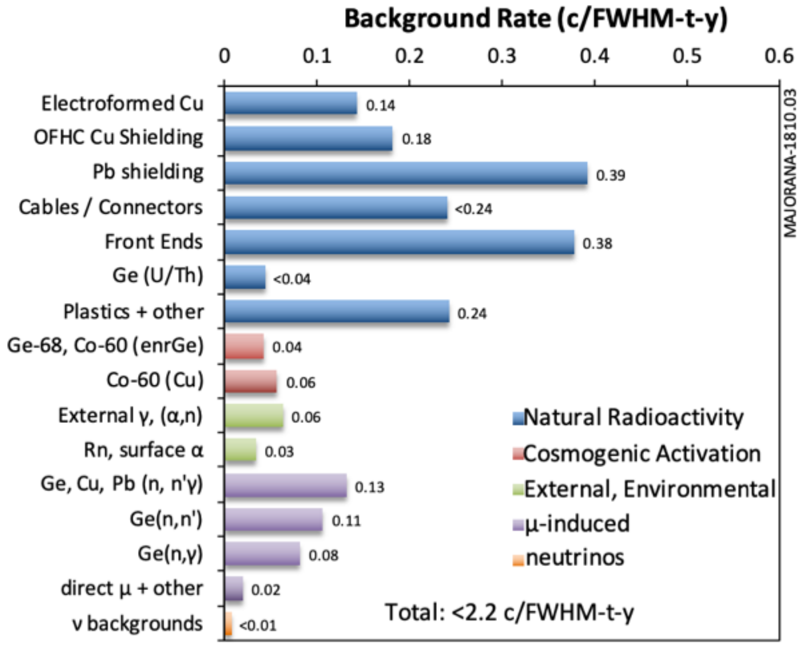
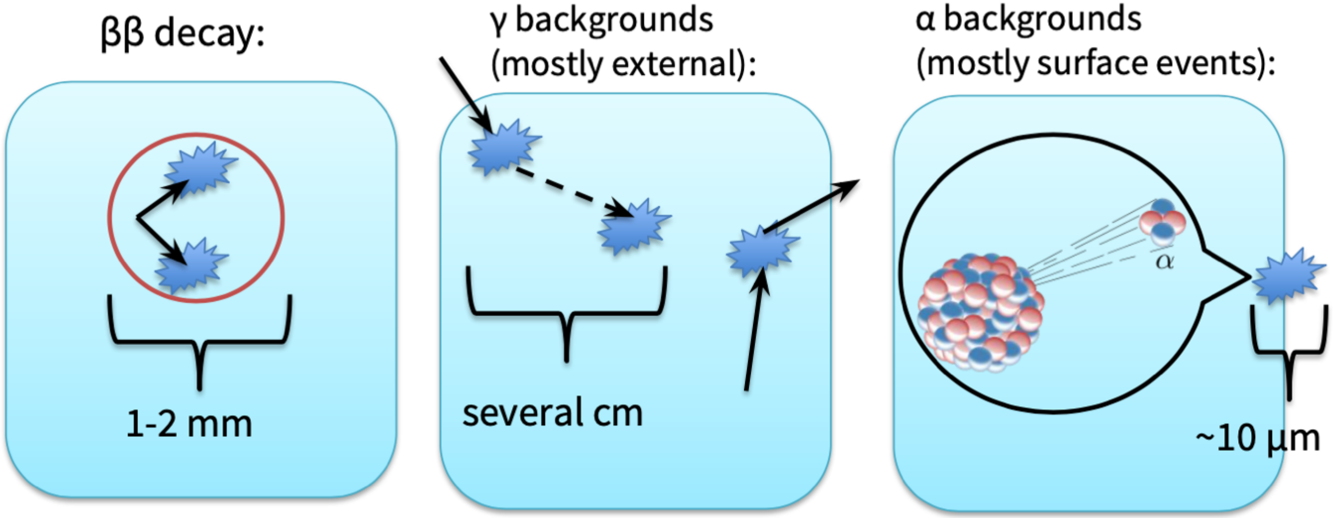
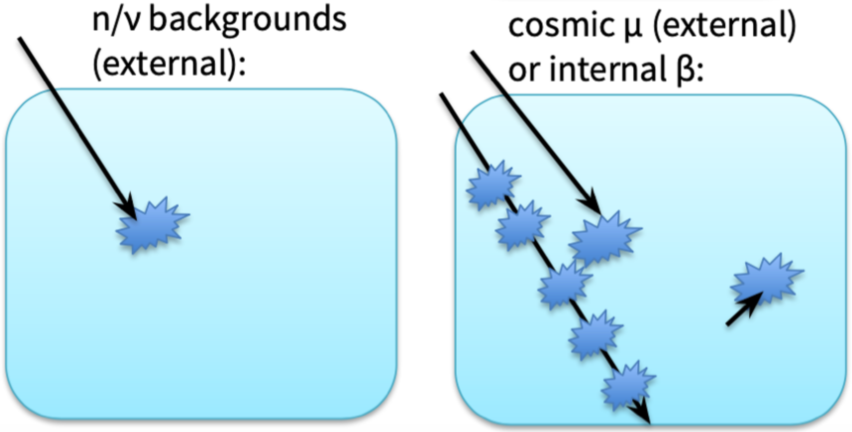
Initial assay-based background budget



NIM **A828** (2016) 22–36 arXiv:1601.03779

Signal and Backgrounds





- Differences in range and type of interaction
- γ, β, and μ interact with electrons
- α, ν, and n scatter off of nuclei

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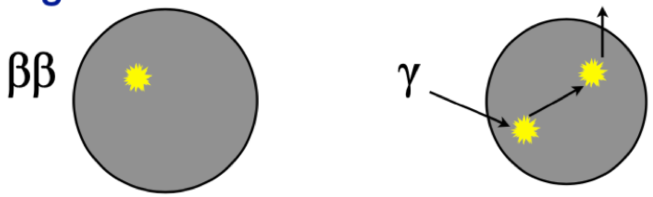
Background Rejection: Multi-Site Events

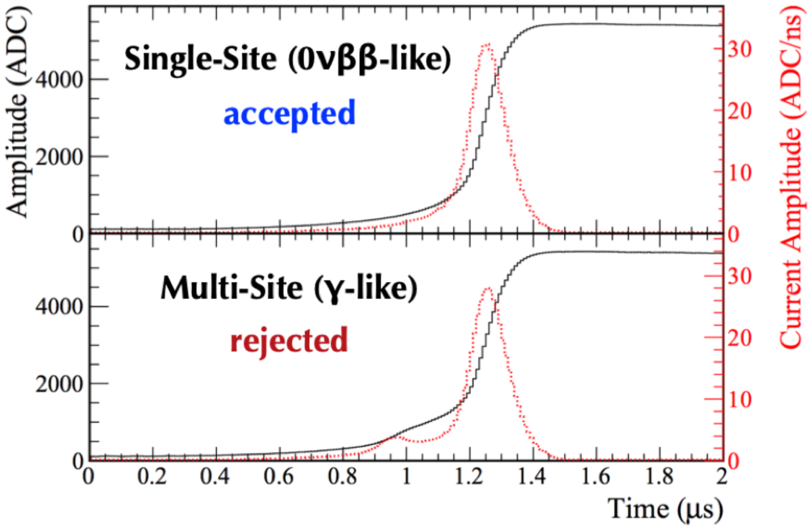
Benefit of P-type Point-Contact (PPC) style detectors for background rejection:

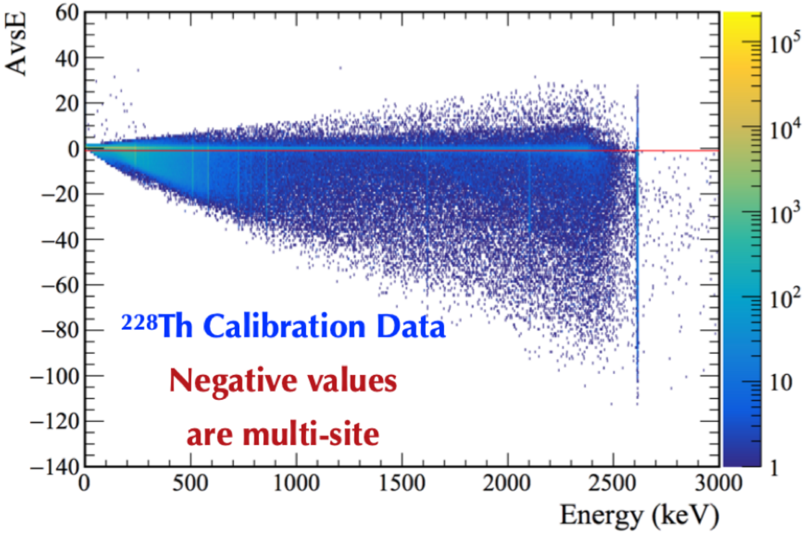
- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection

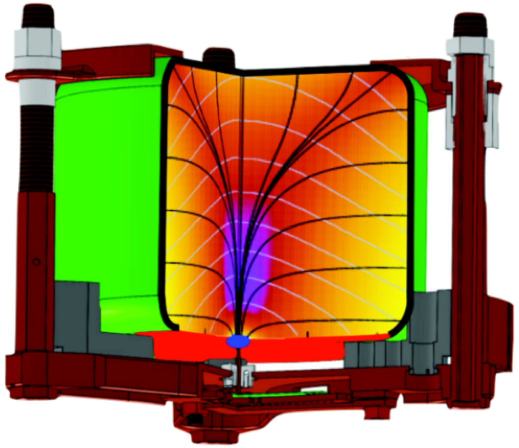
Amplitude of current pulse is reduced for a multi-site event compared to a single-site event of the same event Energy (AvsE)



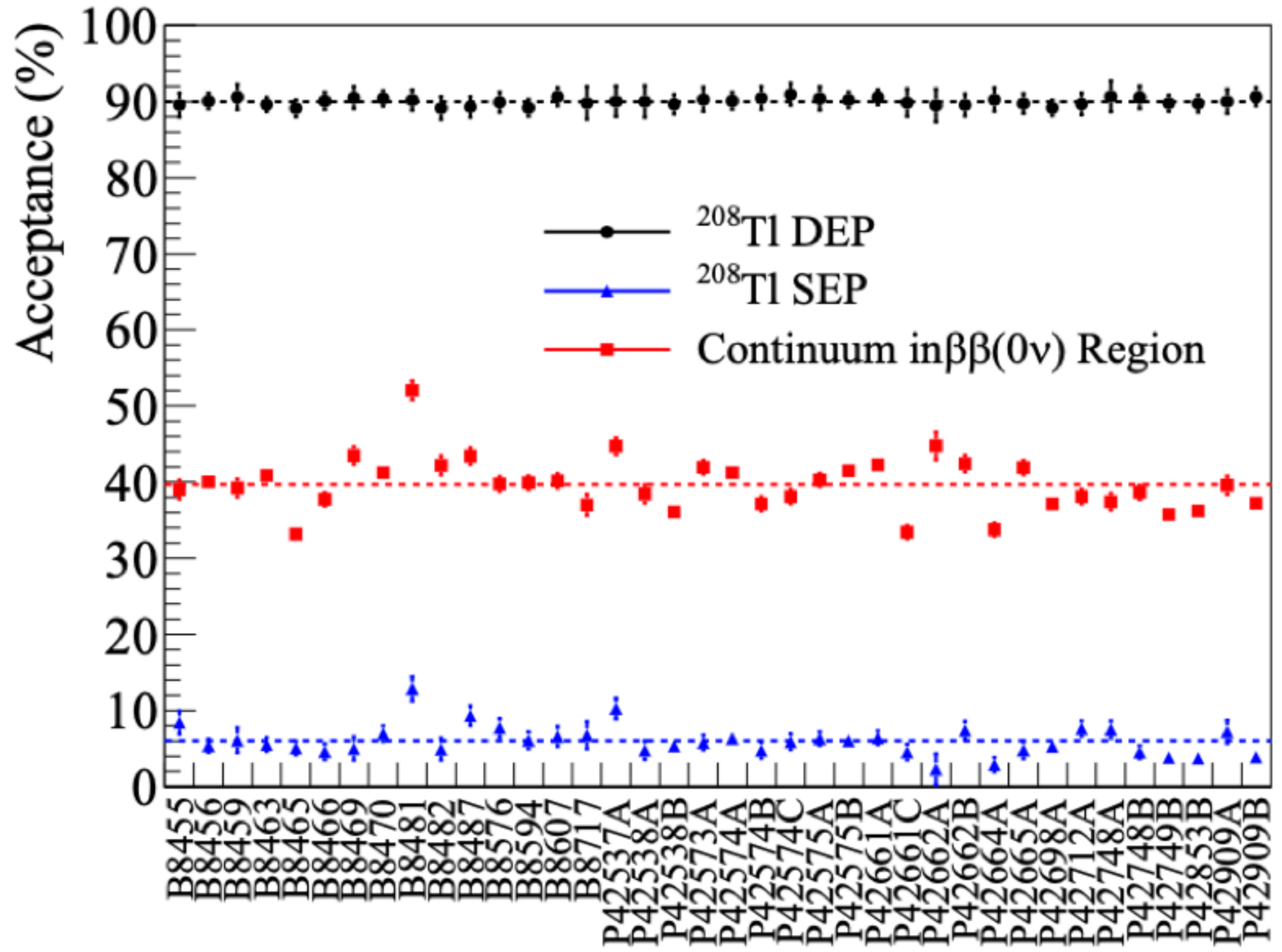
Tuned to accept 90% of single-site events







PRC 99 065501 (2019)


Acceptance (%)
100
90
80
70
60
50
40
30
20
10
0
208Tl DEP
208Tl SEP
Continuum inββ(0ν) Region
B8455
B8456
B8459
B8463
B8465
B8466
B8469
B8470
B8481
B8482
B8487
B8576
B8594
B8607
B8717
P42537A
P42538A
P42538B
P42573A
P42574A
P42574B
P42574C
P42575A
P42575B
P42661A
P42661C
P42662A
P42662B
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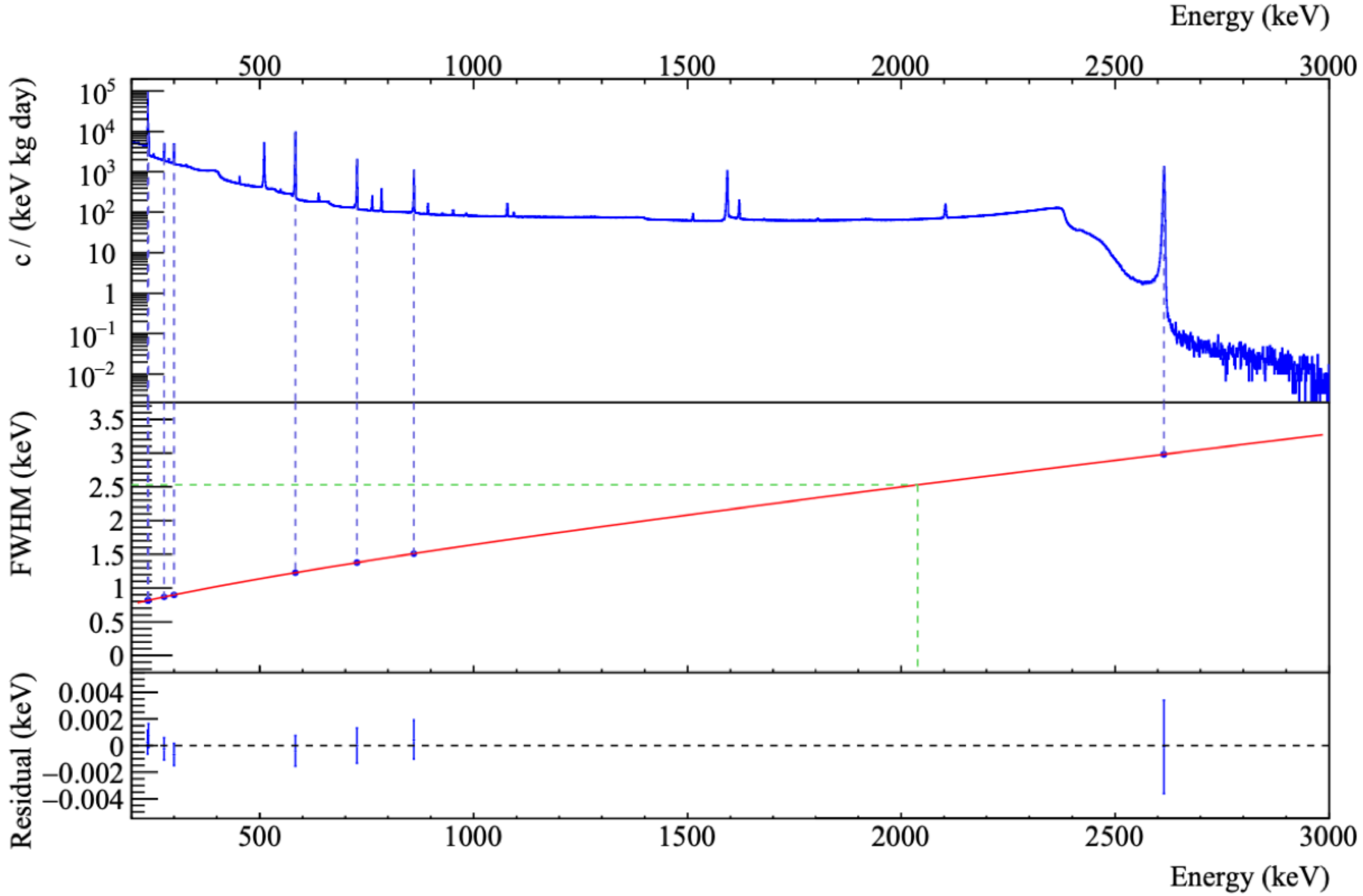
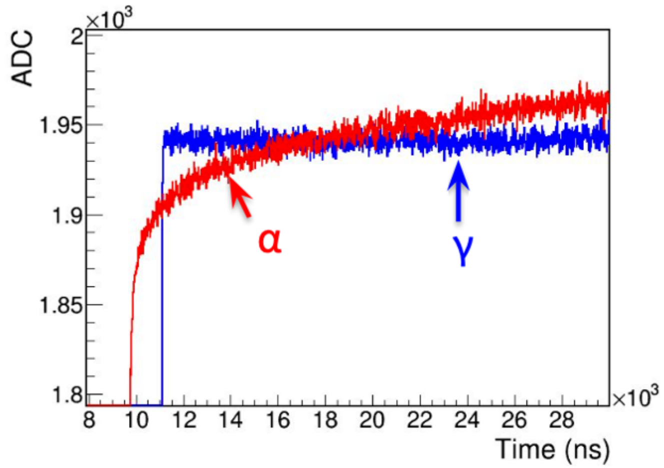
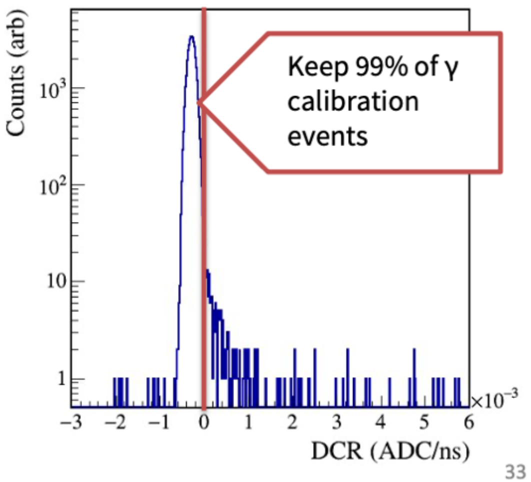
P42749B
P42853B
P42909A
P42909B


Energy (keV)
500
1000
1500
2000
2500
3000
c / (keV kg day)
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
FWHM (keV)
3.5
3
2.5
2
1.5
1
0.5
0
Residual (keV)
0.004
0.002
0
−0.002
−0.004
500
1000
1500
2000
2500
3000
Energy (keV)

The DCR PSD Parameter

- Some of the charge collected normally
- Delayed charge recovery (DCR) from:
  - Surface drift of electrons
  - Near-surface hole trapping and slow re-release
- DCR degrades energy, gives α events distinct pulse shape
- Calculate DCR parameter for each waveform:
  - Correct for decay from electronics
  - Measure slope of tail
  - Cut events with high DCR
- Use calibration Compton continuum near $Q_{\beta\beta}$ to set cut level
- α's that hit p+ contact should have no DCR





12/19/17

TABLE I. A summary of the key parameters of each data set. The exposure calculation is done independently for each detector. Symmetric uncertainties for the last digits are given in parentheses. The value of $\epsilon_{\rm res}$ varies slightly for each data set, given the measured peak shape and optimal ROI. The exposure weighted value over all data sets is $\epsilon_{\rm res} = 0.900 \pm 0.007$.

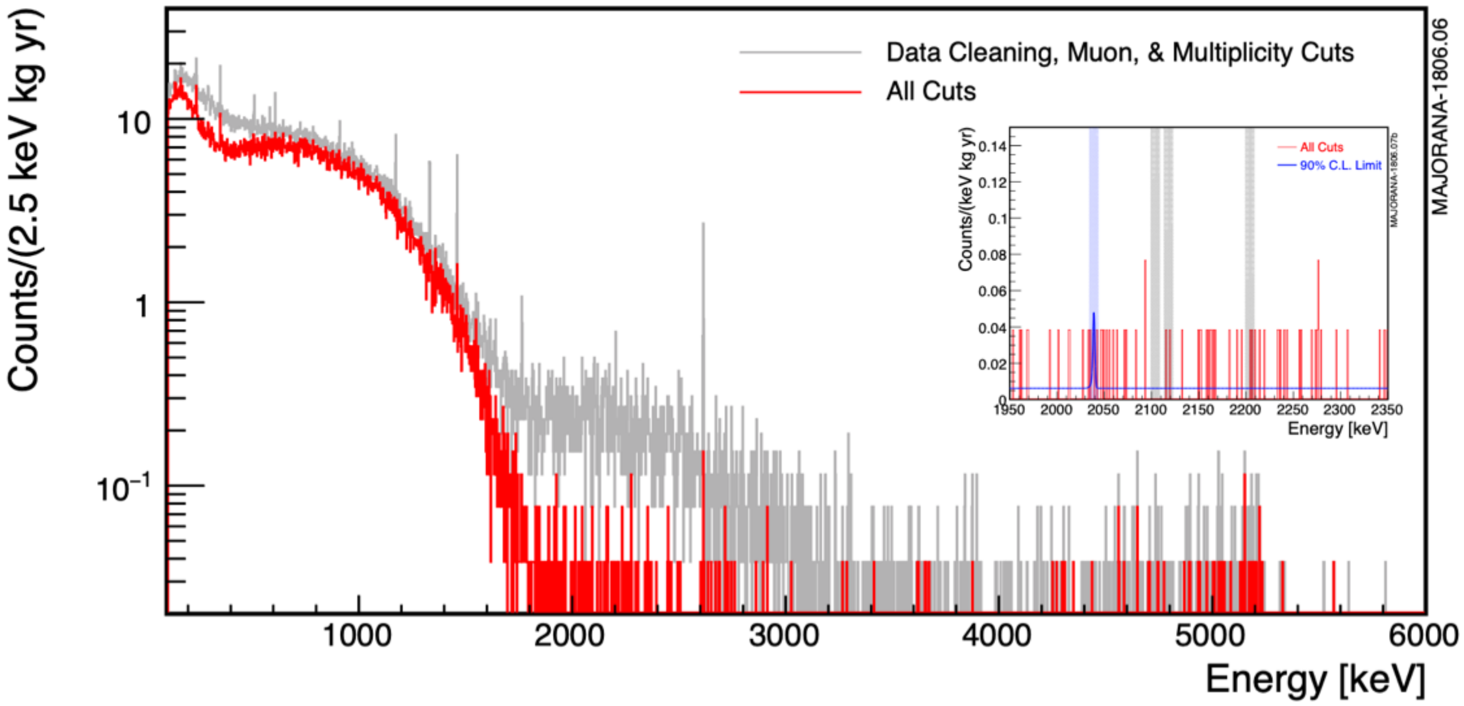
Data set	Start date	Data set distinction	Active enr. mass (kg)	Exposure (kg yr)	ϵ_{AE}	$\epsilon_{\rm DCR}$	ϵ_{cont}	$\epsilon_{\rm tot}$	$NT\epsilon_{\rm tot}\epsilon_{\rm res}$ (10^{24} atom yr)
DS0	6/26/15	No inner Cu shield	10.69(16)	1.26(02)	$0.901^{+0.032}_{-0.035}$	$0.989^{+0.009}_{-0.002}$	0.908(11)	$0.808^{+0.031}_{-0.033}$	$6.34^{+0.25}_{-0.27}$
DS1	12/31/15	Inner Cu shield added	11.90(17)	2.32(04)	$0.901^{+0.036}_{-0.040}$	$0.991^{+0.010}_{-0.005}$	0.909(11)	$0.811^{+0.035}_{-0.038}$	$11.82^{+0.53}_{-0.58}$
DS2	5/24/16	Presumming	11.31(16)	1.22(02)	$0.903^{+0.035}_{-0.037}$	$0.986^{+0.011}_{-0.005}$	0.909(11)	$0.809^{+0.034}_{-0.035}$	$6.24^{+0.28}_{-0.29}$
DS3	8/25/16	M1 and M2 installed	12.63(19)	1.01(01)	$0.900^{+0.030}_{-0.031}$	$0.990^{+0.010}_{-0.003}$	0.909(11)	$0.809^{+0.030}_{-0.030}$	$5.18^{+0.20}_{-0.20}$
DS4	8/25/16	M1 and M2 installed	5.47(08)	0.28(00)	$0.900^{+0.031}_{-0.034}$	$0.992^{+0.011}_{-0.002}$	0.908(10)	$0.809^{+0.030}_{-0.032}$	$1.47^{+0.06}_{-0.06}$
DS5a	10/13/16	Integrated DAQ (noise)	17.48(25)	3.45(05)	$0.900^{+0.034}_{-0.036}$	$0.969^{+0.013}_{-0.013}$	0.909(13)	$0.792^{+0.034}_{-0.035}$	$17.17^{+0.76}_{-0.79}$
DS5b	1/27/17	Optimized grounding	18.44(26)	1.85(03)	$0.900^{+0.031}_{-0.033}$	$0.985^{+0.014}_{-0.005}$	0.909(13)	$0.805^{+0.032}_{-0.032}$	$9.46^{+0.39}_{-0.39}$
DS5c	3/17/17	Blind	18.44(26)	1.97(03)	$0.900^{+0.031}_{-0.033}$	$0.985^{+0.012}_{-0.003}$	0.908(11)	$0.806^{+0.031}_{-0.031}$	$10.31^{+0.47}_{-0.47}$
DS6a	5/11/17	Presumming, blind	18.44(26)	12.67(19)	$0.901^{+0.032}_{-0.032}$	$0.990^{+0.008}_{-0.002}$	0.908(11)	$0.811^{+0.030}_{-0.030}$	$65.10^{+2.92}_{-2.92}$
Total	(DS0-6)			26.02(53)					133.1 ± 6.3
Total	(DS1-4,5b-6)			21.31(41)					110.0 ± 5.1

TABLE II. The background (BG) within the 360-keV window defined in the text for each data set. The background index (BI) is given in units of counts/(keV kg yr). The optimum ROI width for each data set is also given, and the final column shows the resulting expected number of background counts within that ROI. The second from last row provides a summary for all data sets, and the final row shows the combined total for the lower background data sets.

Data set	Window counts	BI 10^{-3}	ROI (keV)	ROI BG (counts)
DS0	11	$24.3^{+8.4}_{-7.0}$	3.93	0.120
DS1	5	$6.0^{+3.4}_{-2.7}$	4.21	0.058
DS2	2	$4.6^{+5.1}_{-2.9}$	4.34	0.024
DS3	0	<3.6	4.39	0.000
DS4	0	<12.7	4.25	0.000
DS5a	10	$8.0^{+3.1}_{-2.6}$	4.49	0.125
DS5b	0	<1.9	4.33	0.000
DS5c	5	$7.0^{+4.0}_{-3.2}$	4.37	0.061
DS6a	24	$5.3^{+1.2}_{-1.0}$	3.93	0.262
Total	57	6.1 ± 0.8	4.13	0.653
DS1-4,5b-6	36	4.7 ± 0.8	4.14	0.529

2018 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution



Initial Release:

- 9.95 kg-yr open data
- **[PRL 120 132502 (2018)]**

Latest Release:

- First unblinding of data
- 26 kg-yr exposure
- **[PRC 100 025501 (2019)]**

Median $T_{1/2}$ Sensitivity:

- 4.8×10^{25} yr

Full Exposure Limit:

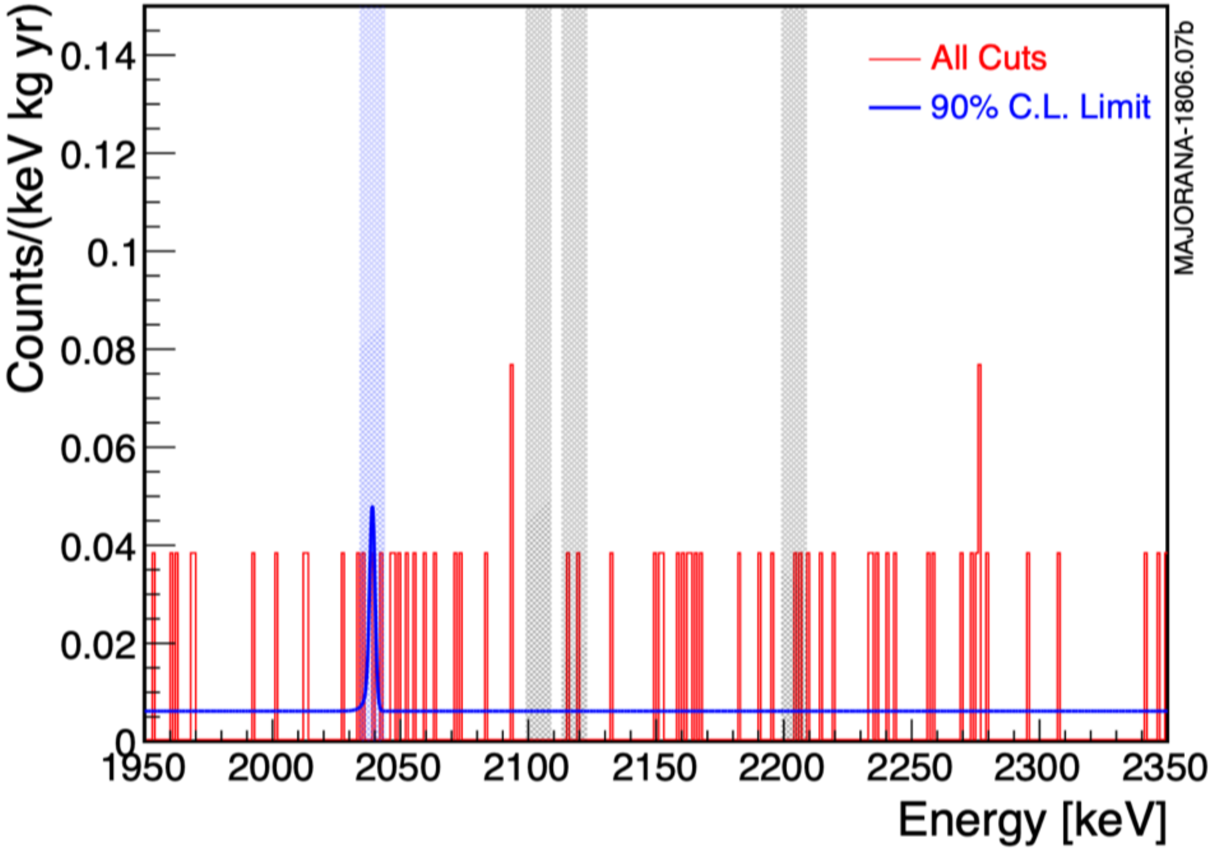
- $T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Background Index at 2039 keV in lowest background config:

- 11.9 ± 2.0 cts/(FWHM t yr)

2018 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution



Matthew P. Green - TAUP 2019 - Toyama, Japan

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- 11.9 ± 2.0 cts/(FWHM t yr)

Background Model Development

Initial assay measurements with early simulations of expected detector configuration

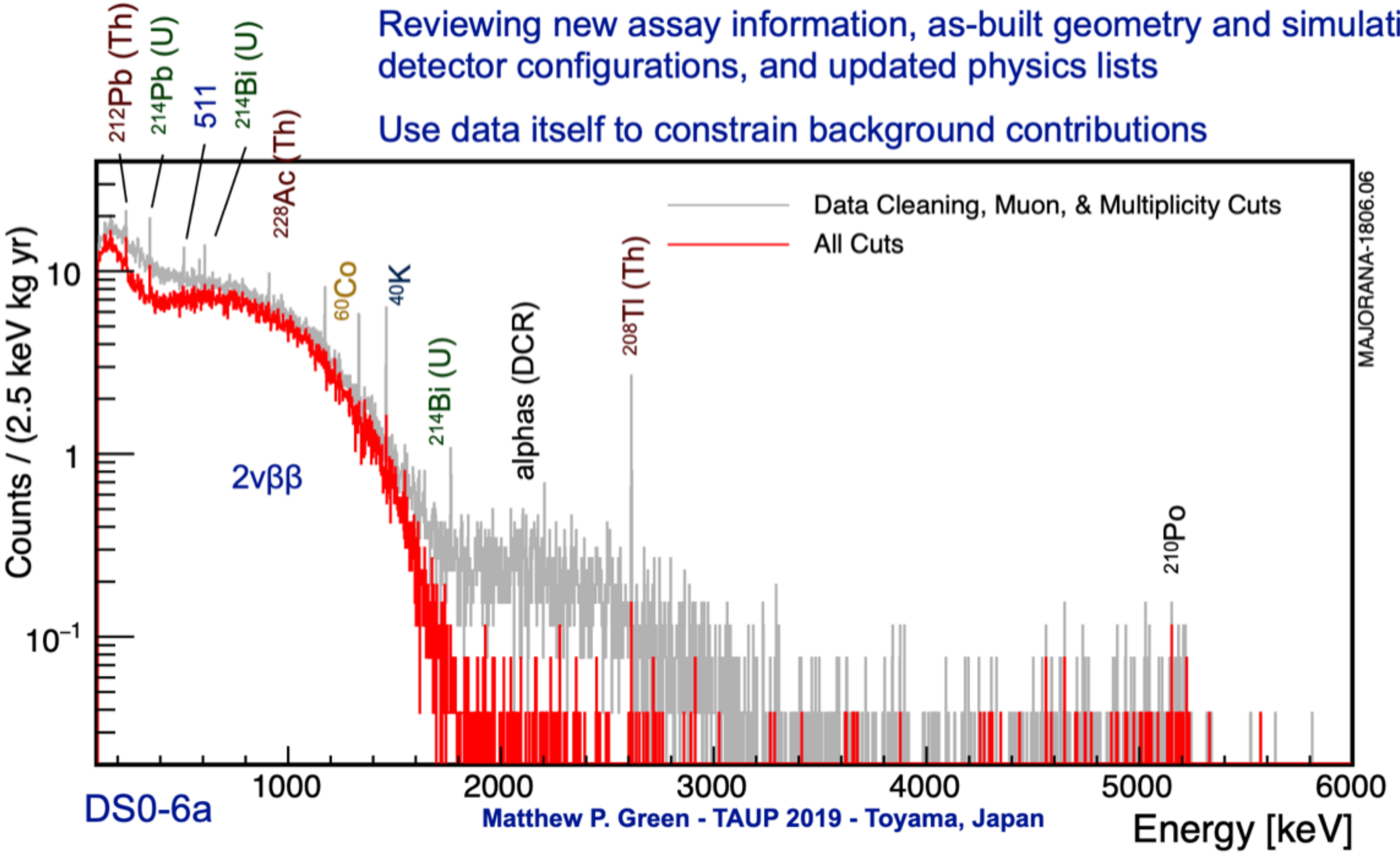
Initially predicted < 2.2 cts/(FWHM t y) at $Q_{\beta\beta}$

Measured Background: 11.9 ± 2.0 cts/(FWHM t y)

PRC **100** 025501 (2019)

Reviewing new assay information, as-built geometry and simulations, detector configurations, and updated physics lists

Use data itself to constrain background contributions



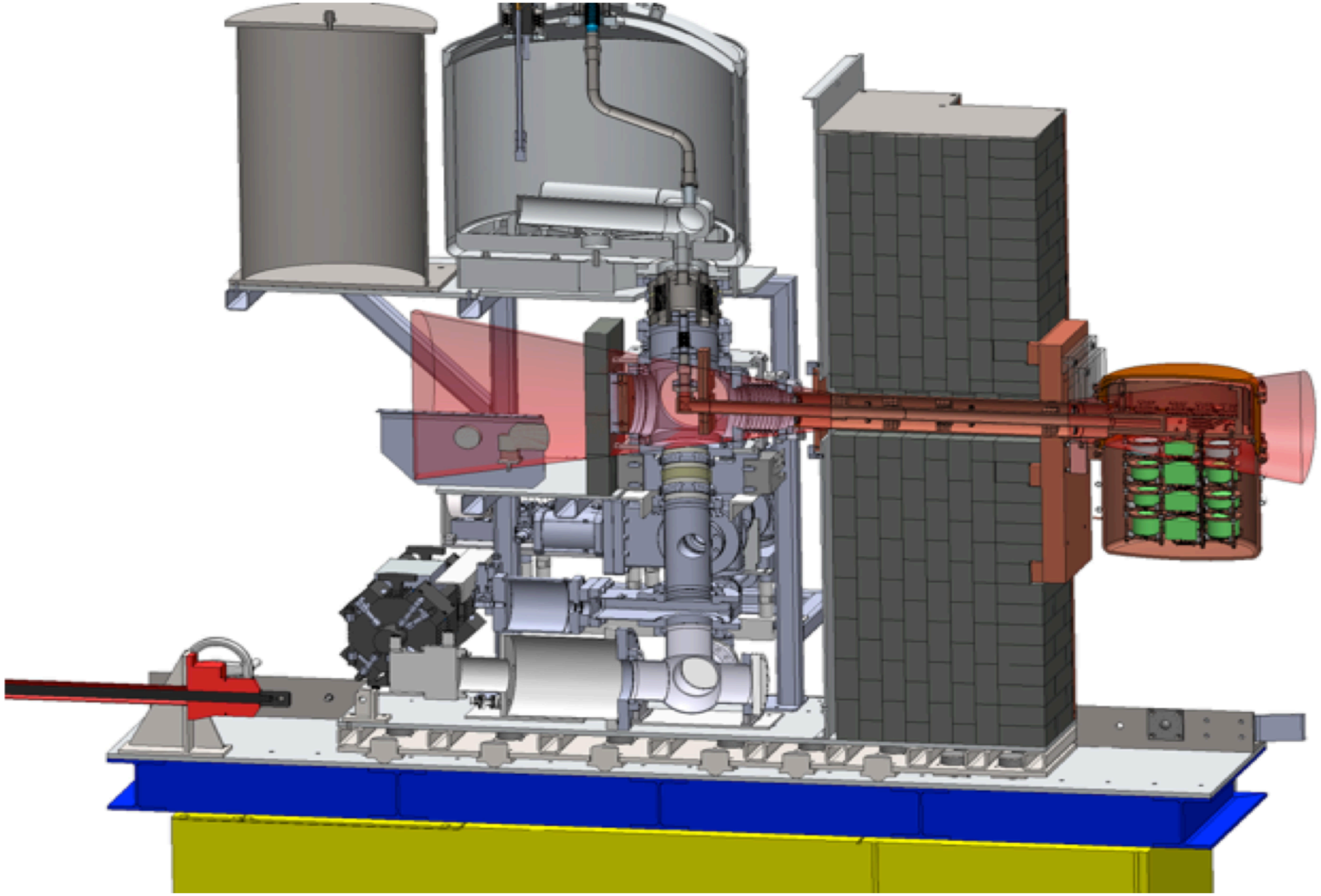
In order to convert the limit on $T_{1/2}$ to limits on $\langle m_{\beta\beta} \rangle$

$$(T_{1/2}^{0\nu})^{-1} = g_A^4 \times G_{0\nu} \times |M_{0\nu}|^2 \times |\langle m_{\beta\beta} \rangle / m_e|^2$$

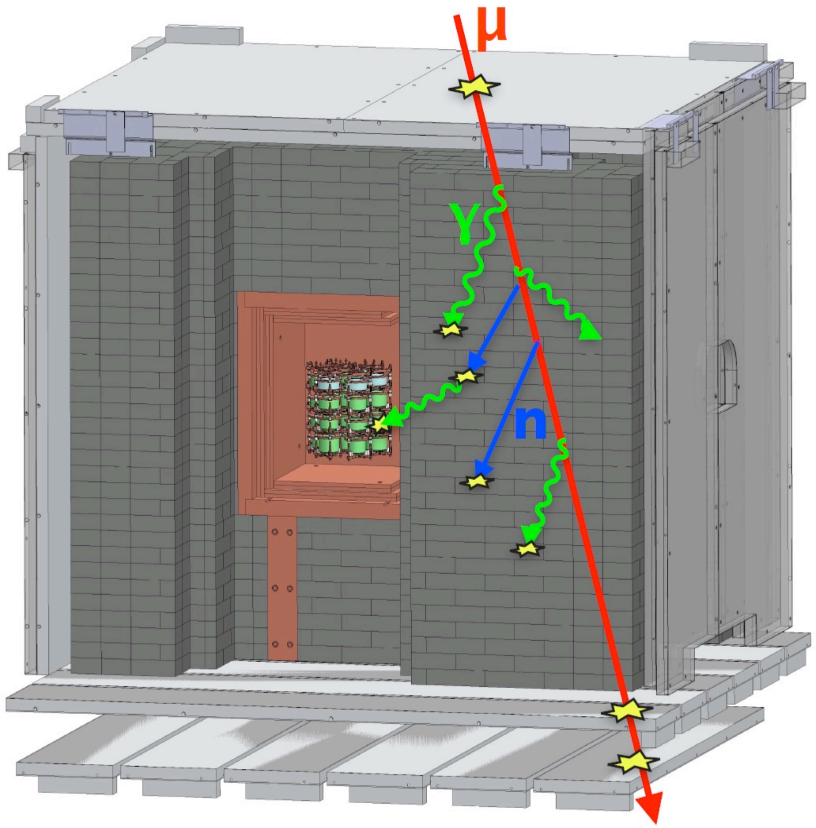
- $T_{1/2} > 2.7 \times 10^{25}$ yr (90 % CL)
- $2.81 < M_{0\nu} < 6.13$
- $G_{0\nu} = (2.36 - 2.37) \times 10^{-15}$/ yr
- $g_A = 1.27$

$\langle m_{\beta\beta} \rangle < (200 - 433)$ meV (90% CL)

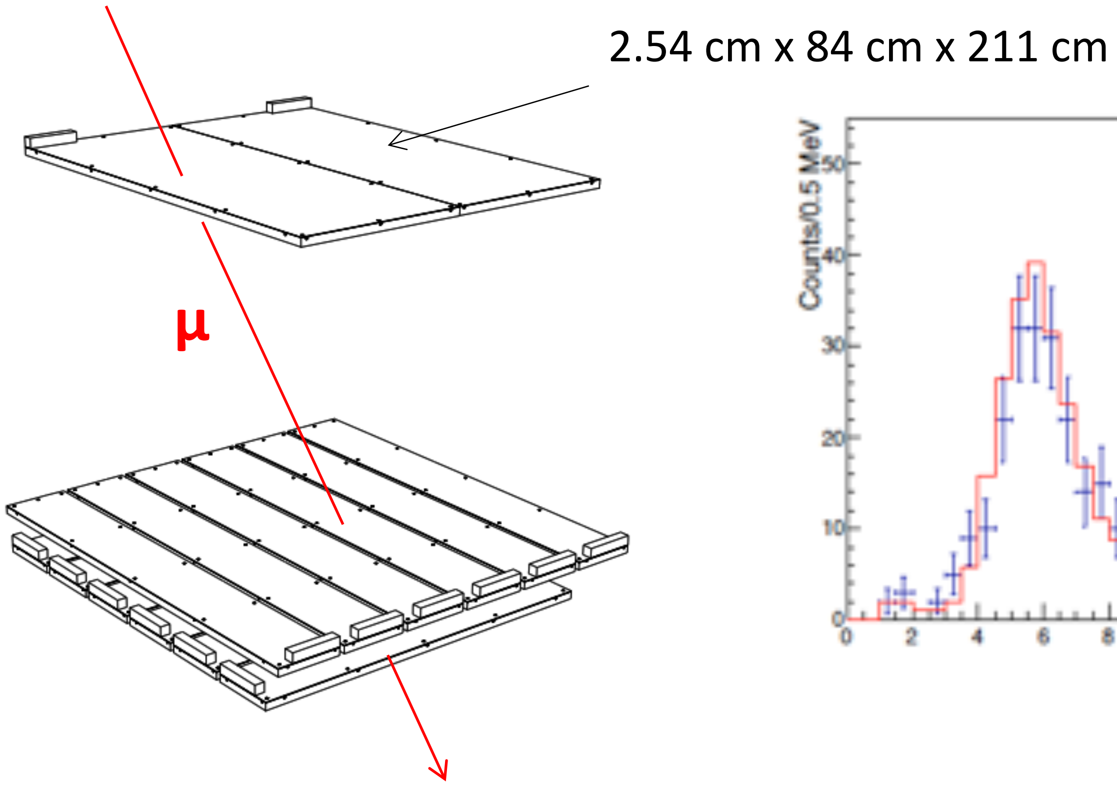
Shine Path through Cross arm

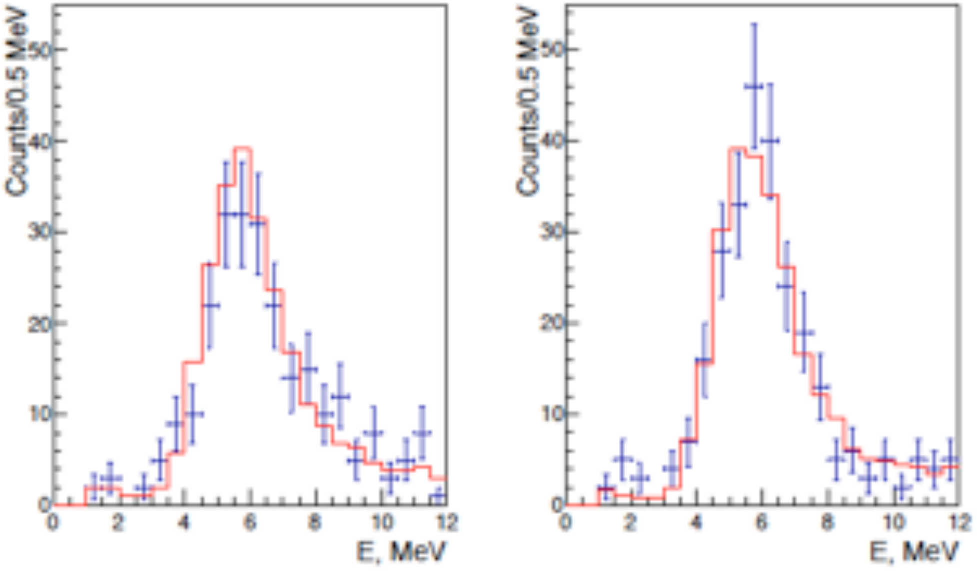


Muon flux measurements at 4850' (4300 m w.e.)



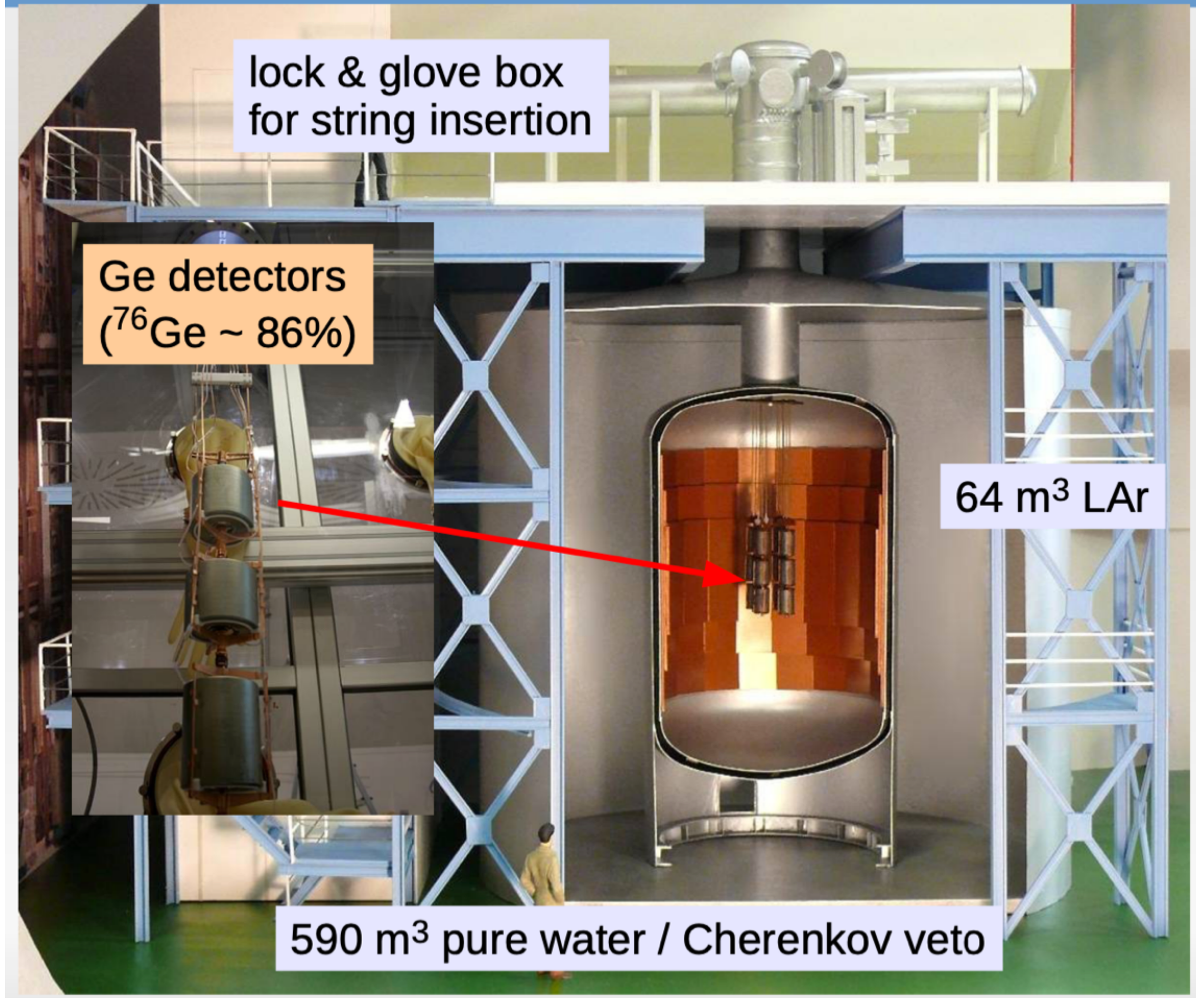
Three-Fold Coincidence





F = (5.31±0.17)x10^{-9} s^{-1} cm^{-2} (Astroparticle Physics, Volume 93, July 2017, p. 70 -75)

GERDA: Ge in LAr @ Gran Sasso



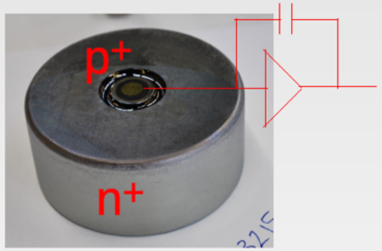
Phase I (2011-13):

$T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)

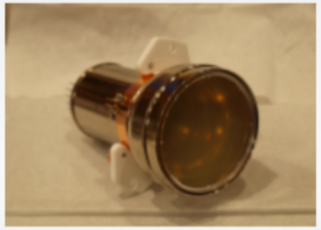
^{76}Ge $0\nu\beta\beta$ decay, PRL 111 122503

Phase II:

2x Ge mass (30 BEGe det.)



LAr scint. light readout



started end 2015

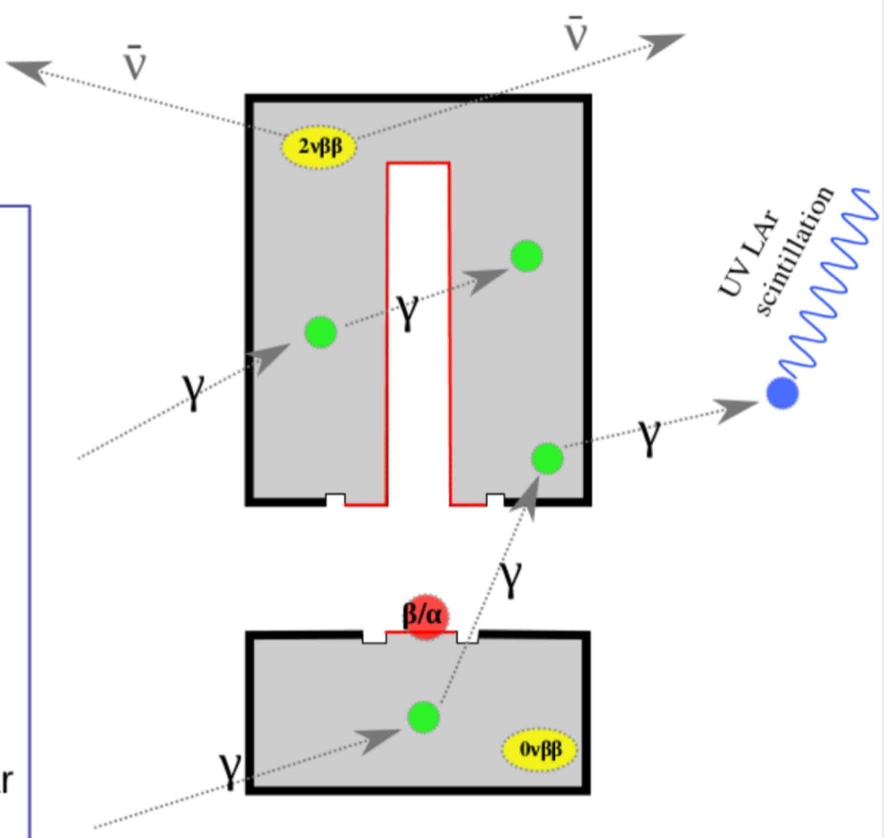
Background reduction techniques

ββ event

- local energy deposition (SSE) in single detector

background event

- energy deposition in multiple locations (MSE) in single detector or on detector surface (α/β)
  → **pulse shape discrimination**
- coincident energy deposition in more than one detector
  → **detector anti-coincindence**
- additional energy deposition in LAr
  → **LAr veto**



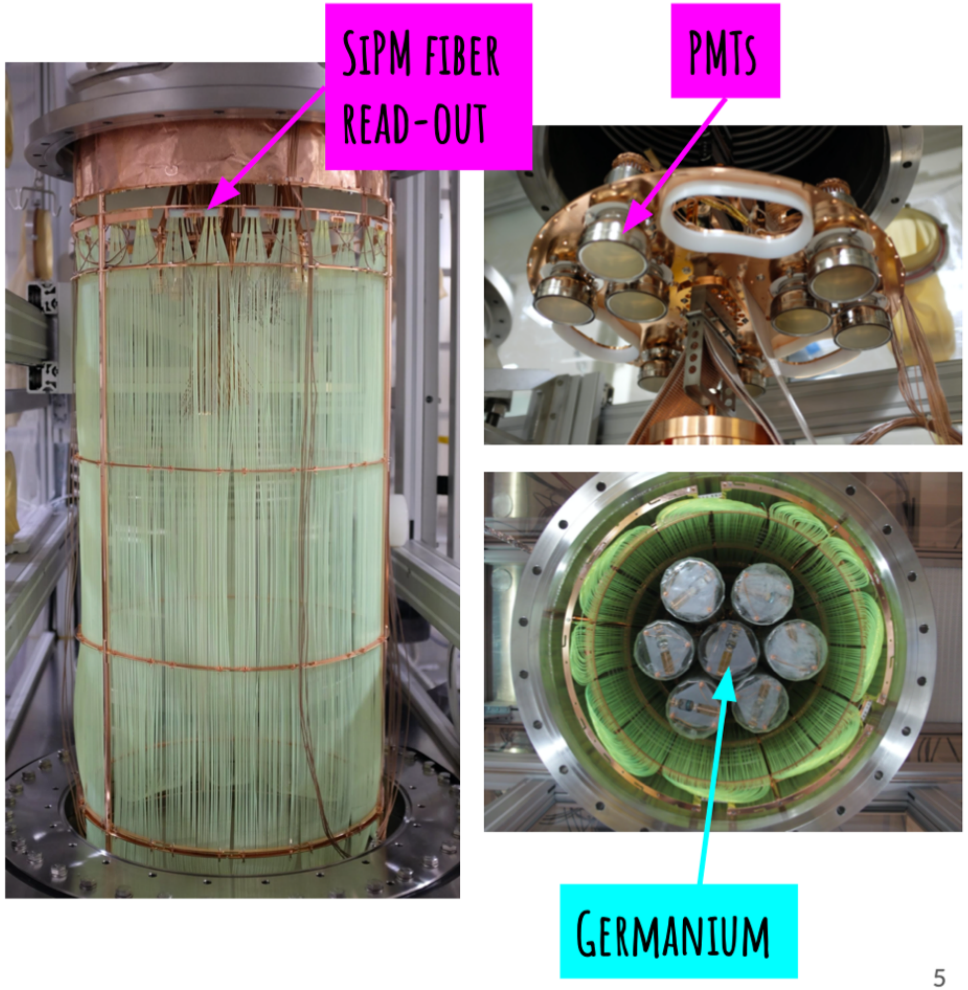
slide by Victoria Wagner

The LAr veto

LAr veto hybrid solution

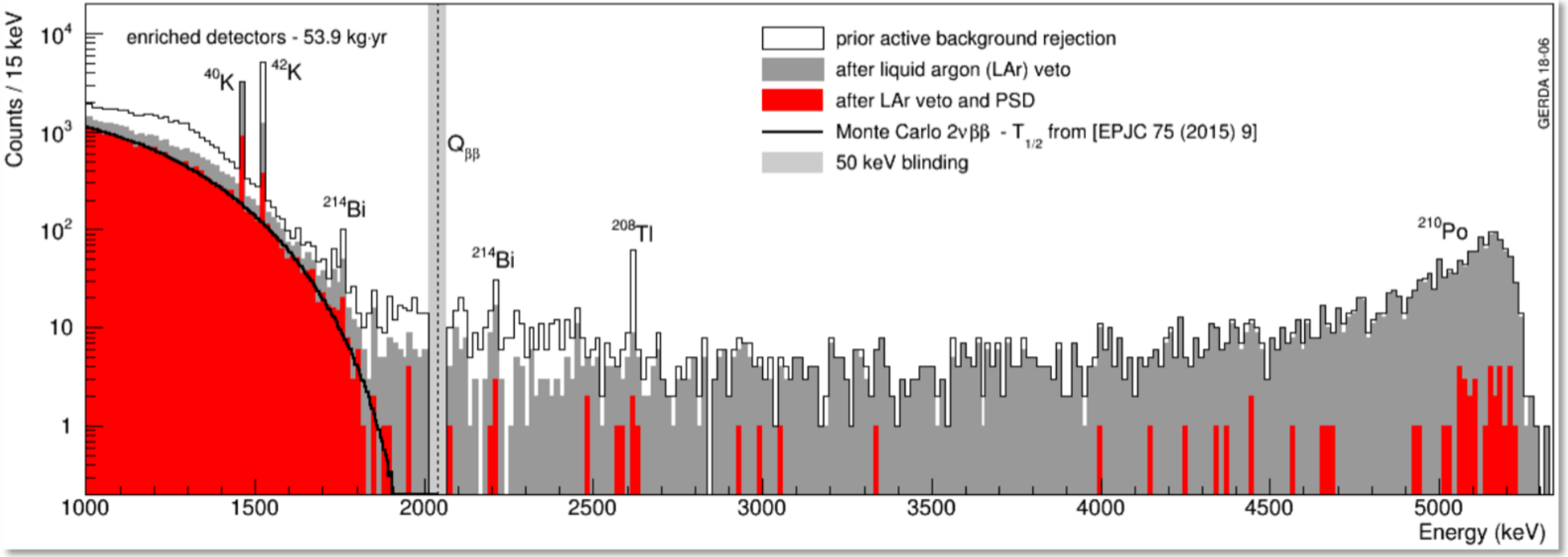
- use LAr scintillation light
- 800m light guiding fibers coated with WLS + 90 SiPM readout channels
- 2 PMT arrays (9 top + 7 bottom)
- each detector string enclosed in a WLS coated nylon mini-shroud

Eur.Phys.J.C 78 (2018) 388



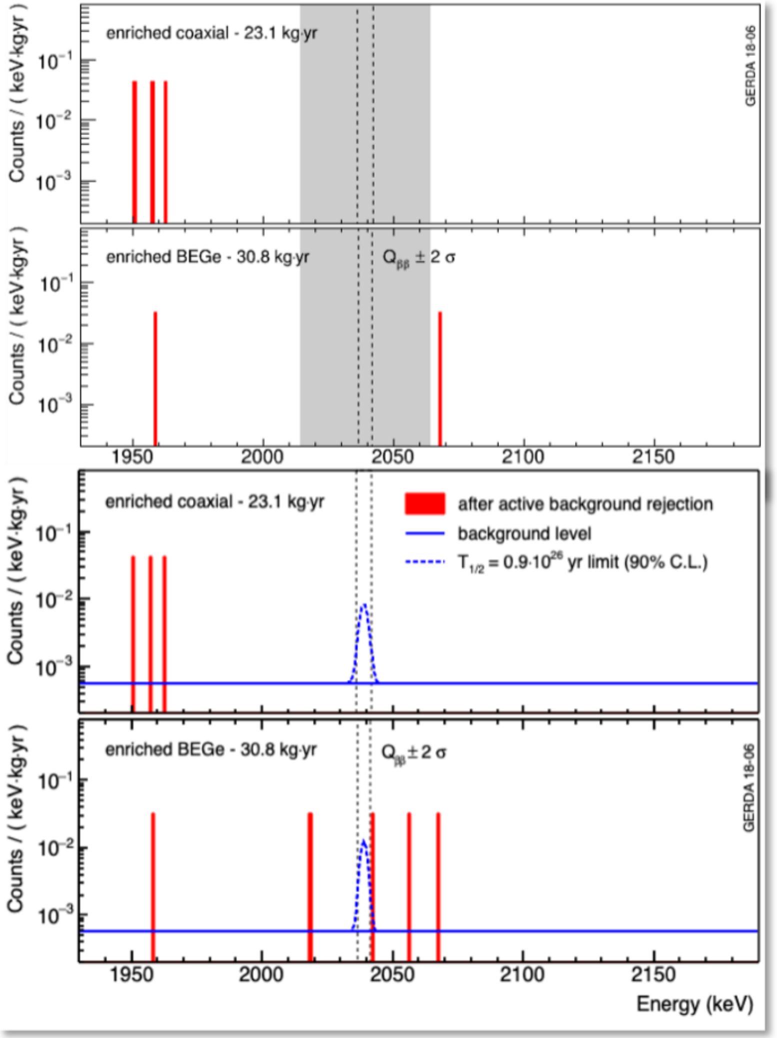
GERDA **Phase II**

Physics spectrum



GERDA **Phase II**

Background index and limits



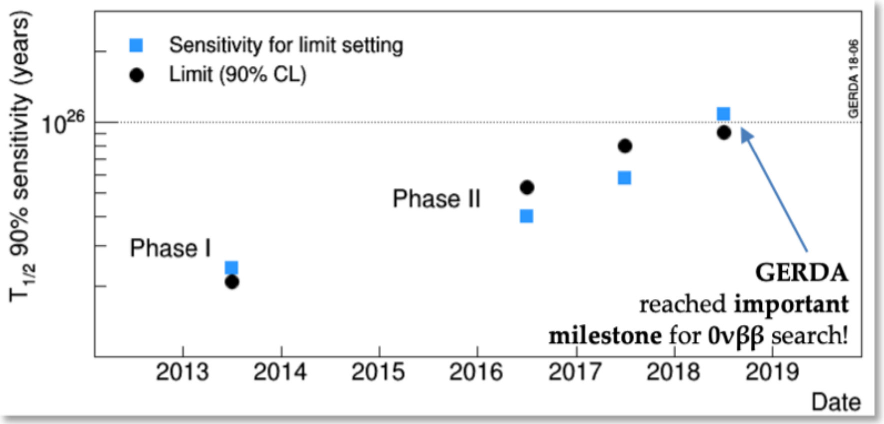
Unique background indices achieved:

- ✓ Coax: $\mathbf{5.7^{+4.1}_{-2.6} \times 10^{-4}}$ cts/(keV·kg·yr)
- ✓ BEGe: $\mathbf{5.6^{+3.4}_{-2.4} \times 10^{-4}}$ cts/(keV·kg·yr)

***best** in the field when normalized to FWHM!*

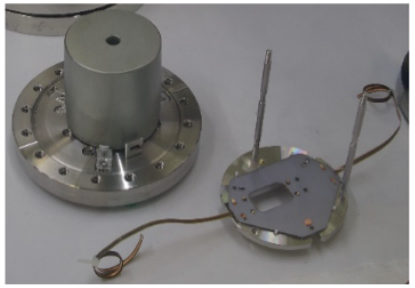
Actual GERDA Phase II limits:

- ✓ Median sensitivity for limit setting:
  $\mathbf{1.1 \times 10^{26}}$ **yr** (world best!)
- ✓ Best fit → no signal
  $\boldsymbol{T^{0\nu}_{1/2} > 0.9 \times 10^{26}}$ **yr** (90% CL) ➡ $\langle m_{\beta\beta} \rangle <$ (104 - 228) meV
- ✓ Probability to have stronger limit 63%



GERDA **Phase II+**

Upgrade 2018



Upgrade of the GERDA experiment aims to:

- ✓ Test the novel detectors + increase the mass of ^{76}Ge
- ✓ Show the possibility to improve the background index
- ✓ Prove the robustness and reproducibility of the GERDA approach

Upgrade included:

- New LAr veto:
  - ✓ new fiber curtain (improved light collection) + central module to read out hidden Ar volume
- Installation of 5 novel **inverted coaxial detectors** made from **^{76}Ge**
- Exchange of all signal and HV cables by new ones with better radiopurity
- New signal cable routing to reduce the cross-talk and improve resolution
- Repairing of broken electronic channels and installation of protective diodes

old curtain

810 fiber ends, 90 SiPMs

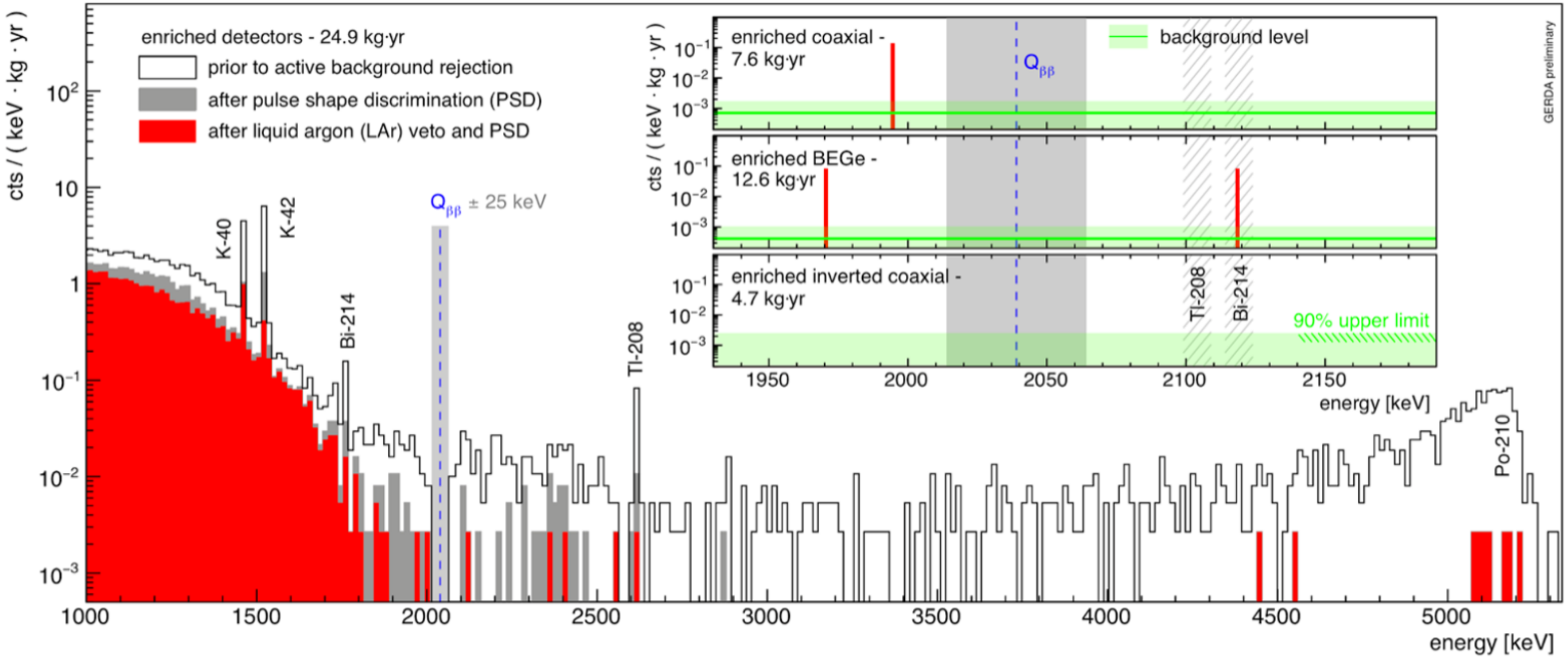
new curtain

1215 fiber ends, 135 SiPMs

Central module

GERDA **Phase II**

Alfa rates and background indices



New background indices:

✓ Coax: $\mathbf{0.7^{+1.0}_{-0.5} \times 10^{-3}}$ cts/(keV·kg·yr)

✓ BEGe: $\mathbf{0.4^{+0.6}_{-0.3} \times 10^{-3}}$ cts/(keV·kg·yr)

✓ InvCoax: $\mathbf{< 2.6 \times 10^{-3}}$ cts/(keV·kg·yr)

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

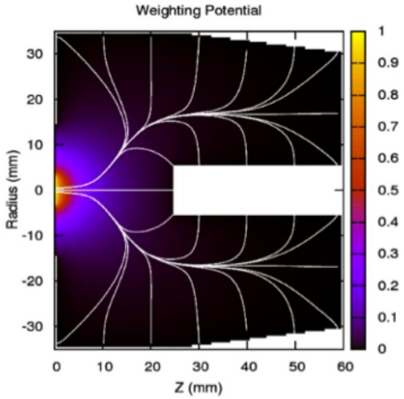
LEGEND

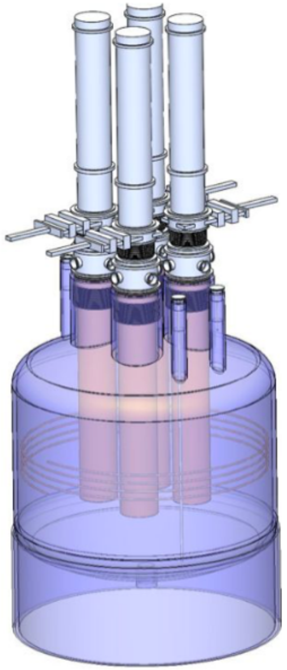
First phase: LEGEND-200

- (Up to) 200 kg, using the existing GERDA infrastructure
- Background goal of 0.6c/(FWHM t yr): x5 improvement
- Start by ~2021

Subsequent stages

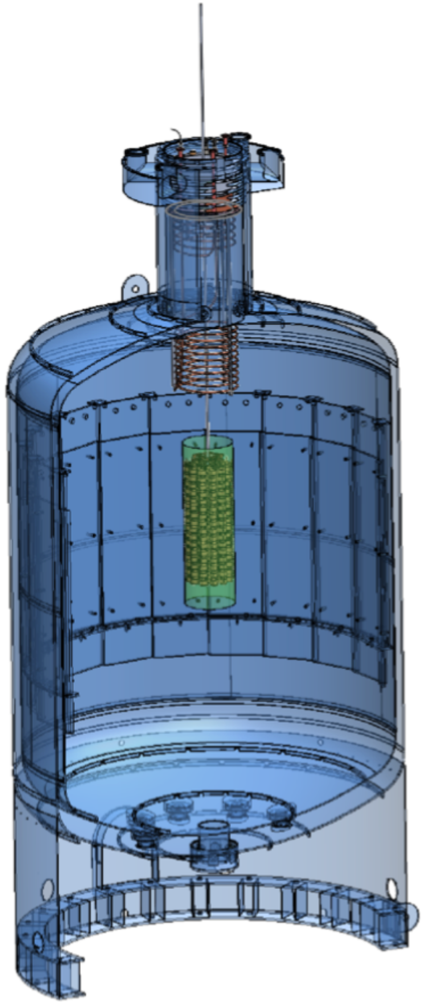
- 1000 kg (staged)
- Background goal of <~0.1c/(FWHM t yr): x30 improvement
- New, larger mass detectors being studied
- Location and timeline TBD



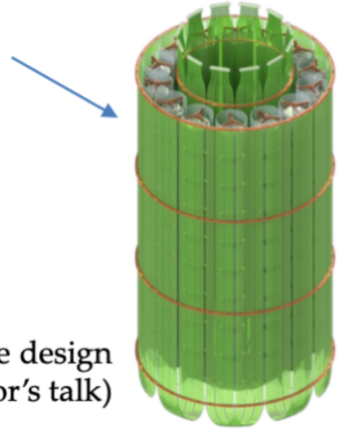


LEGEND-200

200 kg in GERDA setup



- ✓ Reuse existing GERDA infrastructure at LNGS
- ✓ Modifications of internal cryostat piping so can accommodate up to 200 kg of detectors
- ✓ Improvements
  - use some larger Ge detectors
  - improve LAr scintillator light collection
  - lower mass, cleaner cables
  - lower noise electronics
- ✓ Estimate background improvement by ~ x5 over GERDA/MAJORANA (goal 0.6 cnt /(FWMH t yr)):
  - intrinsic : including ^{68}Ge/^{60}Co all OK
  - external Th/U: cleaner materials based on those used in DEMONSTRATOR
  - surface events : α & β rejection via PSD
  - ^{42}Ar : better suppression & mitigation
  - muon induced : OK



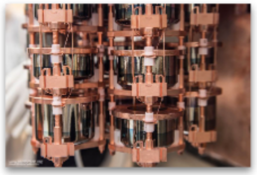
LEGEND-200 LAr veto possible design (see Egor's talk)

Best of MAJORANA and GERDA

LEGEND

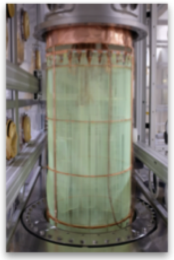
MAJORANA

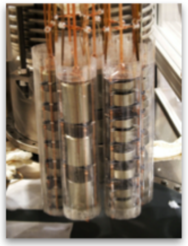
- Radiopurity of nearby parts (cables, copper mounts, etc.)
- Low noise electronics
- Low energy threshold



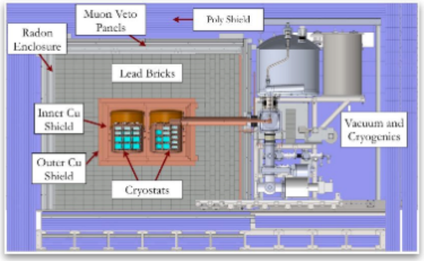
GERDA

- Liquid Argon (LAr) veto
- Low A shield, no lead





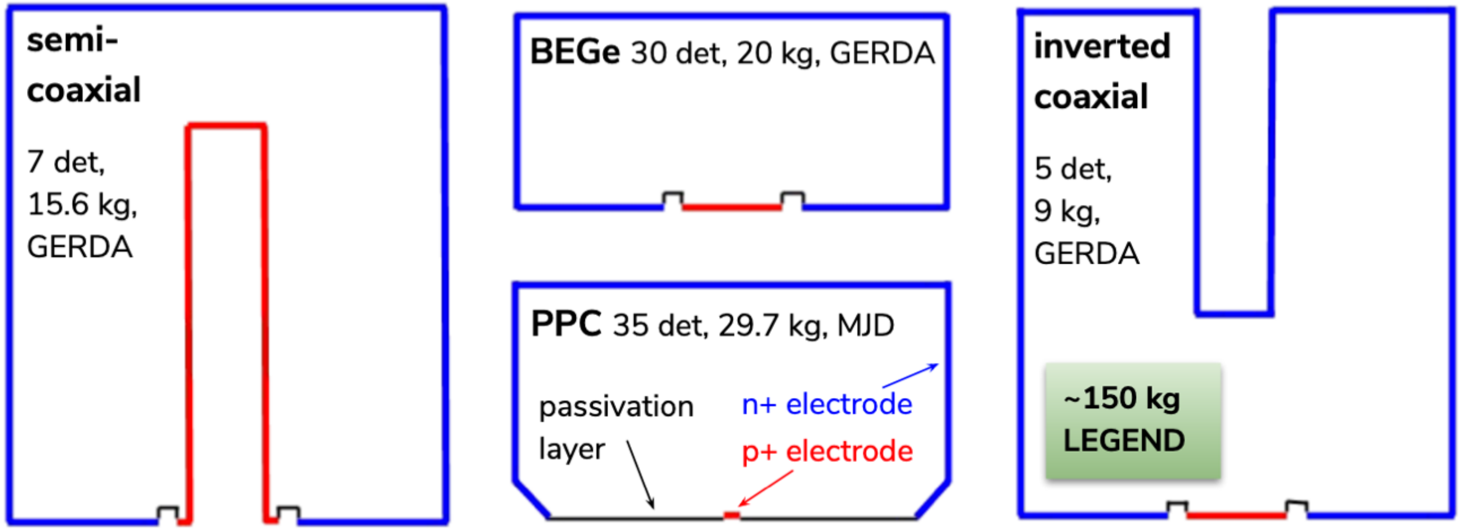
Both



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

Germanium detectors

LEGEND



- 4 types of detectors from GERDA and MAJORANA
- Production of new enriched material and new inverted coaxial detectors is ongoing

Inverted-coax detectors

A novel HPGe detector for gamma-ray tracking and imaging

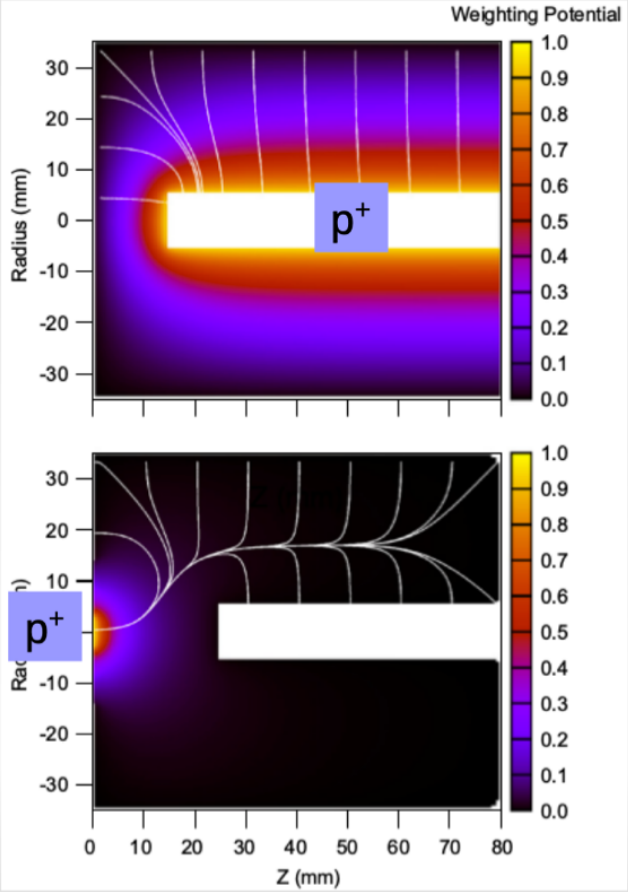
R.J. Cooper [a,*], D.C. Radford [b], P.A. Hausladen [c], K. Lagergren [a]

NIMA 665 (2011) 25

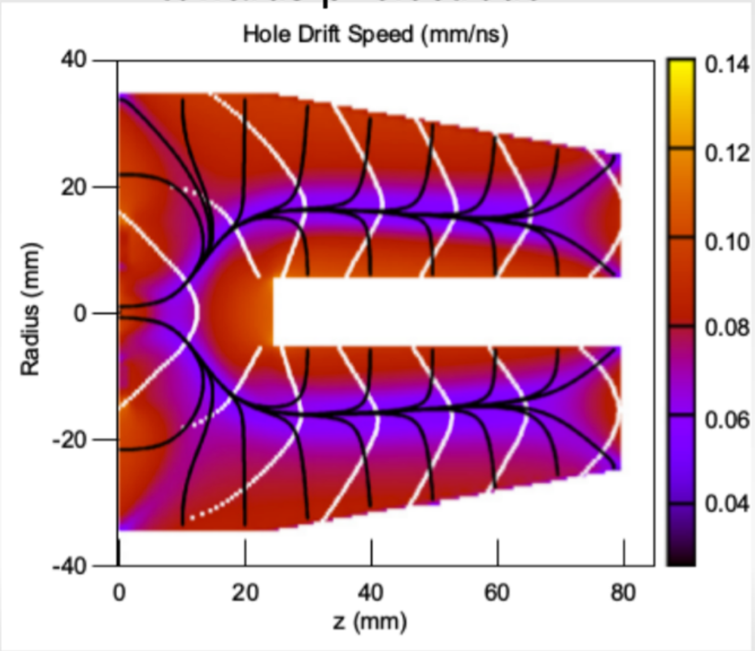
Motivation: 700 g / BEGe
→ 2-3 kg / inverted-coax
→ fewer cable / holder
→ lower background

normal coax

inverted coax

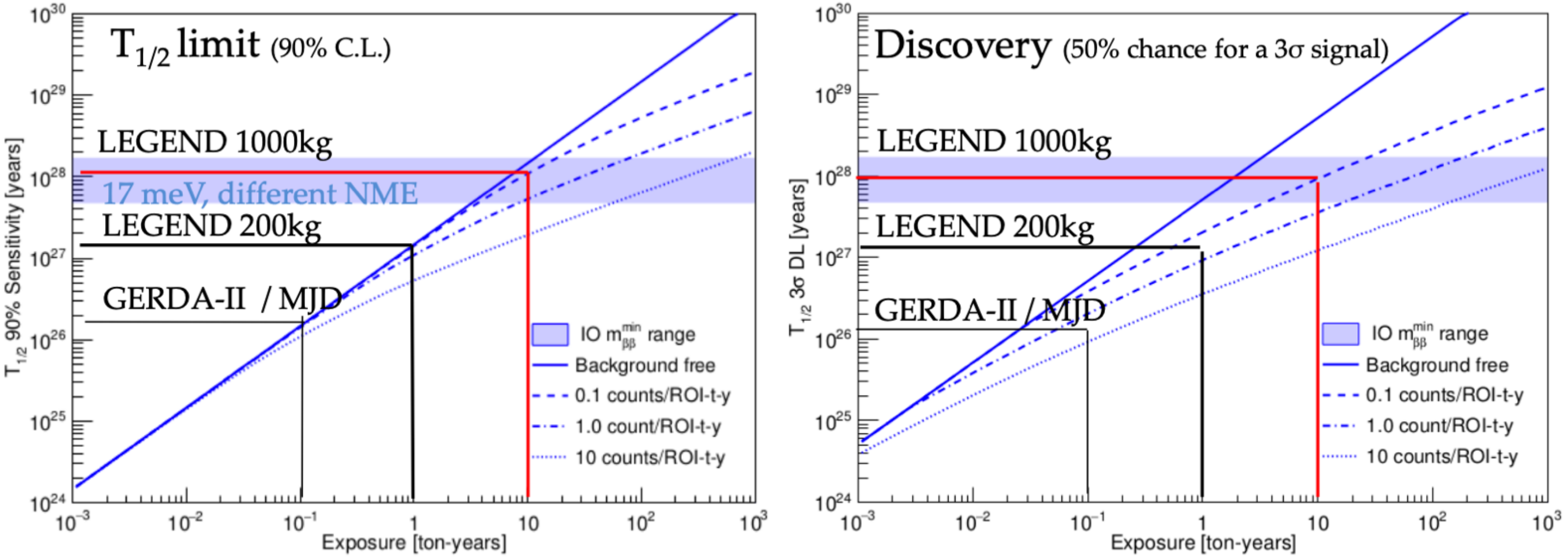


hole drift paths + velocity towards p⁺ electrode



LEGEND

Sensitivity



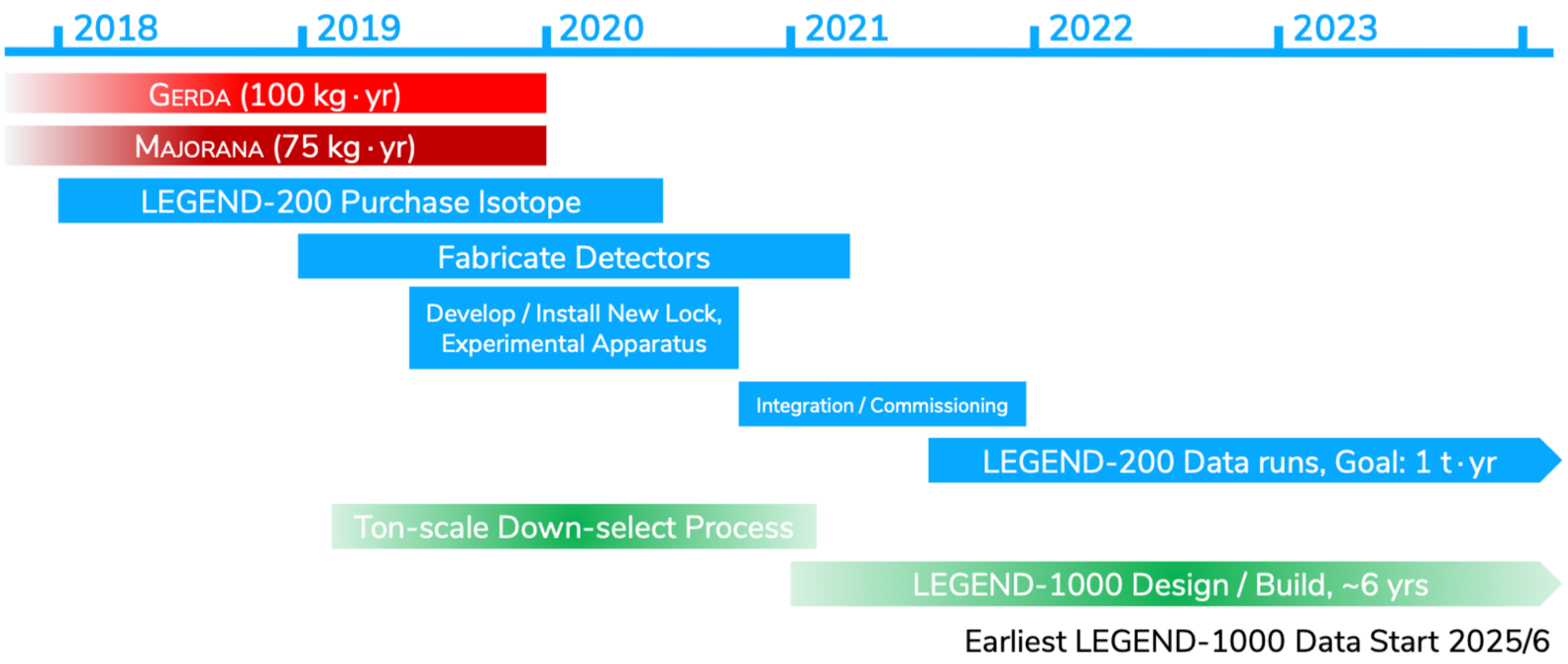
- ✓ $T_{1/2}$ unknown, BSM → 'around corner'
- ✓ background reduction in steps → phased approach

- ✓ inputs: 60% efficiency (GERDA number)
- ✓ Background: GERDA/MJD ~ 3 cts/(FWHM t yr)
  200 kg ~ 0.6 cts/(FWHM t yr)
  1000 kg ~ 0.1 cts/(FWHM t yr)

N.B.: background-free operation is a prerequisite for a discovery

Schedule

LEGEND



AJ Zsigmond TAUP 2019 15

LEGEND-200
Present status

- Nearly all funding in place for LEGEND-200.
- All isotope is either in-hand, on-order, or orders being prepared. Deliveries from 2 suppliers.
- Ge detector fabrication from two suppliers has begun.
  - Front-end electronics being tested. Detector unit designs being tested.
  - Plan to characterize detectors at HADES, ORNL and SURF.
  - About 80 inverted coax detectors (1.5-2 kg), about 150 kg
  - 28 BEGe's (0.7 kg) about 20 kg
  - 5 ICPC's (2.0 kg) about 10 kg
  - 35 PPC's (0.8 kg) about 28 kg
  - Semi Co-Ax detectors (either use as is, or recycle) about 15 kg
  - Total ~200 kg
- Lock is being produced and new deployment hardware is well underway. Testing of new hardware continues.
- LAr veto is under construction with all parts delivered or on order.
- Assay program is well underway.
- LEGEND-200 is on track to start data taking mid 2021.

Спасибо за внимание !