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Rare Multi-Nucleon Decays in MAJORANA DEMONSTRATOR (MJD)

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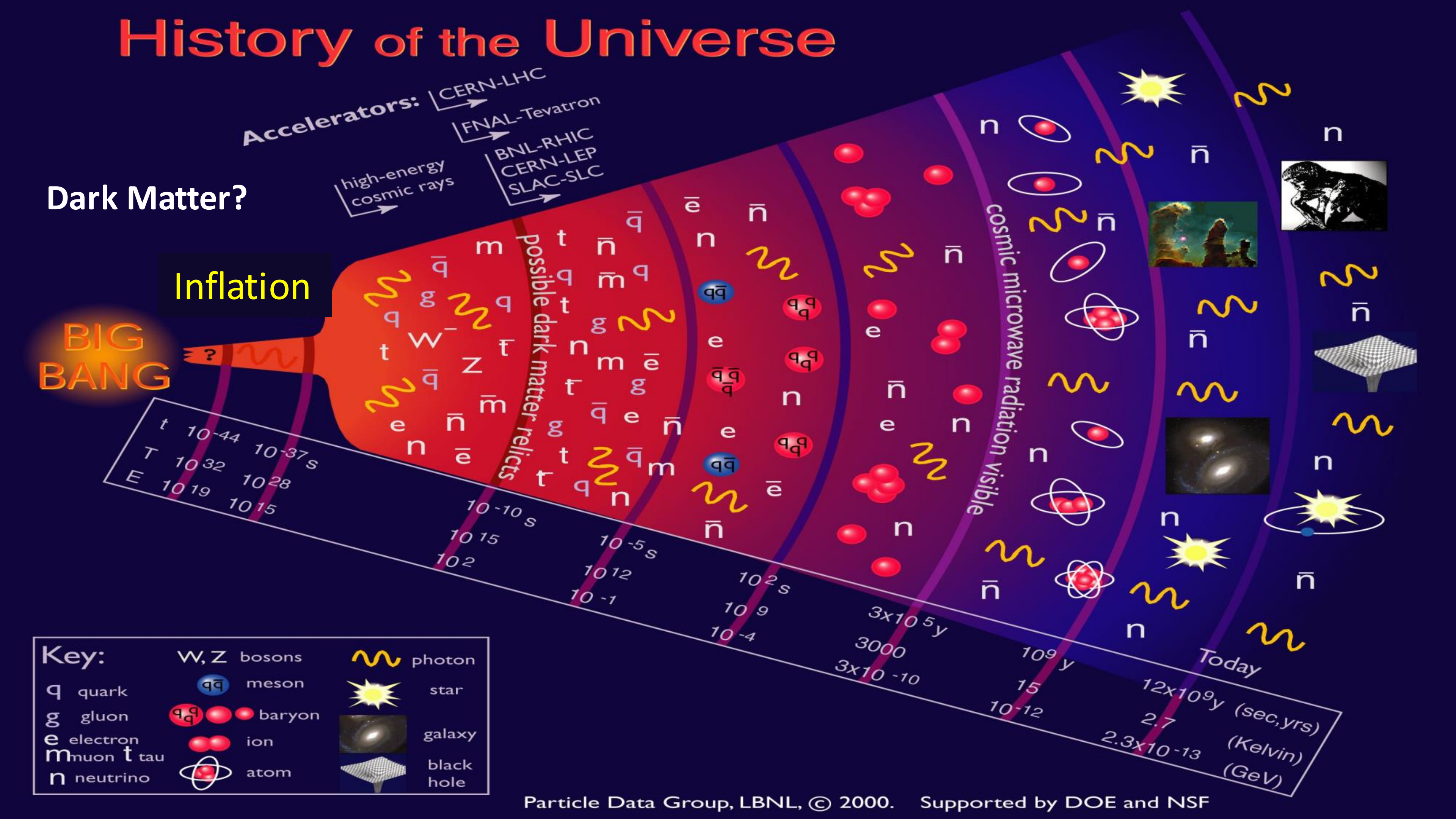
Introduction

- Understanding baryon number violation is fundamental for explaining the stability of matter and possible new physics beyond the Standard Model.
- **MAJORANA DEMONSTRATOR:**
  An ultra-low-background experiment designed to search for neutrinoless double-beta decay ($0\nu\beta\beta$) and rare multi-nucleon decay modes in high-purity germanium (^{76}Ge) detectors, located deep underground at the Sanford Underground Research Facility (SURF).
- Present results from the full dataset: the most stringent limits to date for rare multi-nucleon decay processes in germanium isotopes, probing lifetimes up to 10^{26}years.



History of the Universe
Dark Matter?
Inflation
BIG BANG
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
W, Z bosons
q quark
g gluon
e electron
m muon
t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
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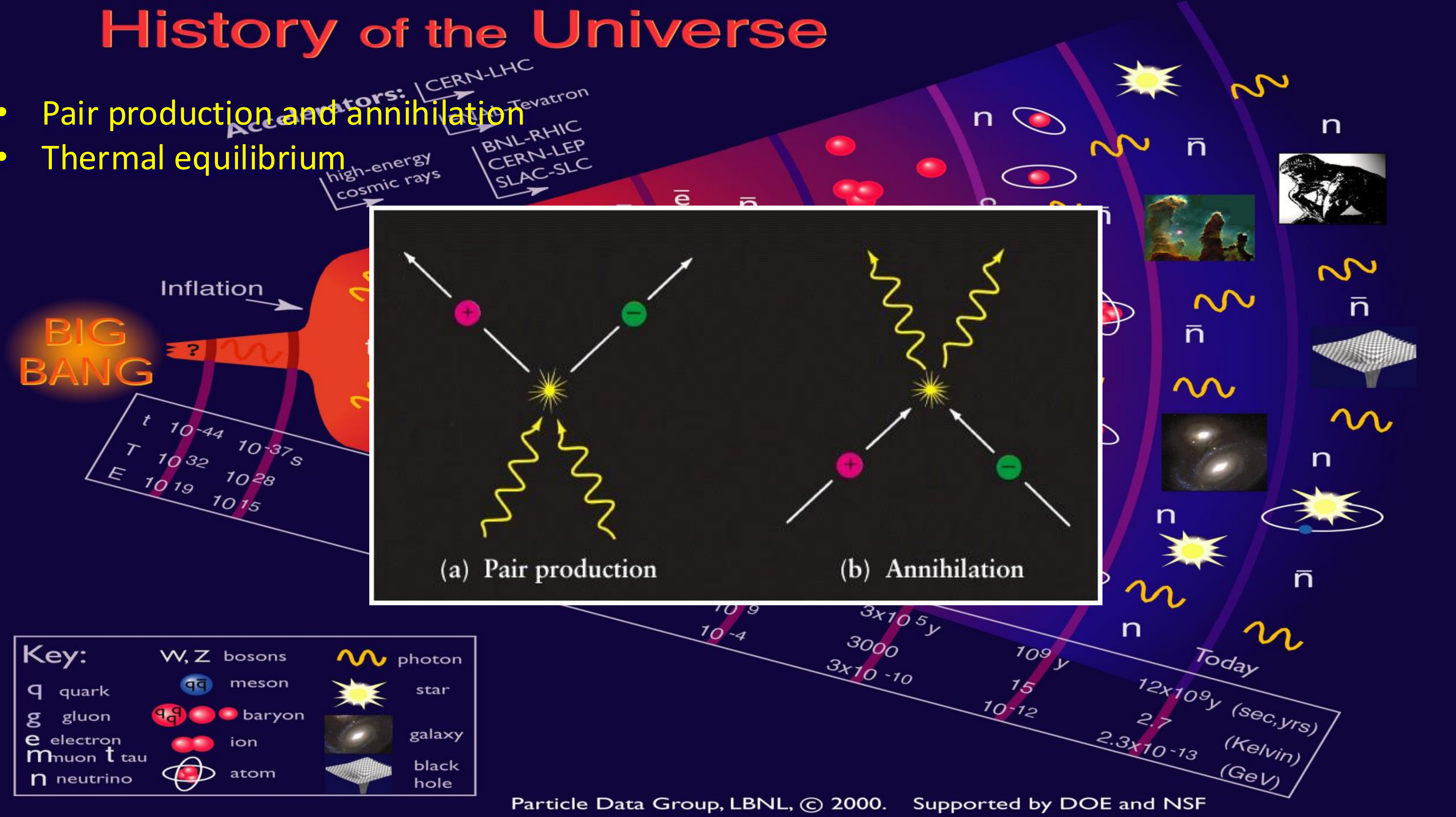
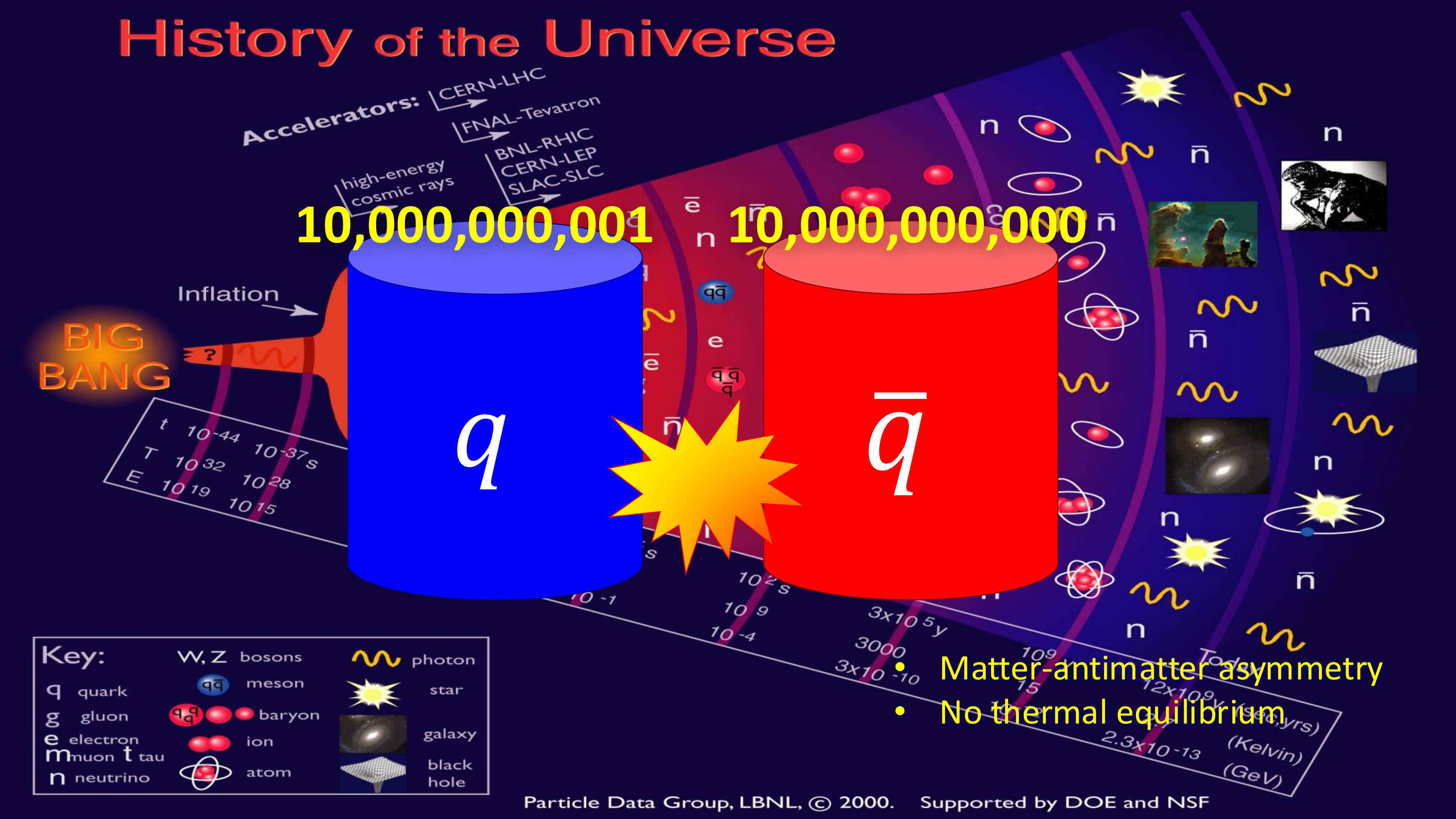
- Pair production and annihilation
- Thermal equilibrium

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10,000,000,001
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Inflation
BIG BANG
q
q̄
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
Matter-antimatter asymmetry
No thermal equilibrium
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q quark
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n neutrino
W, Z bosons
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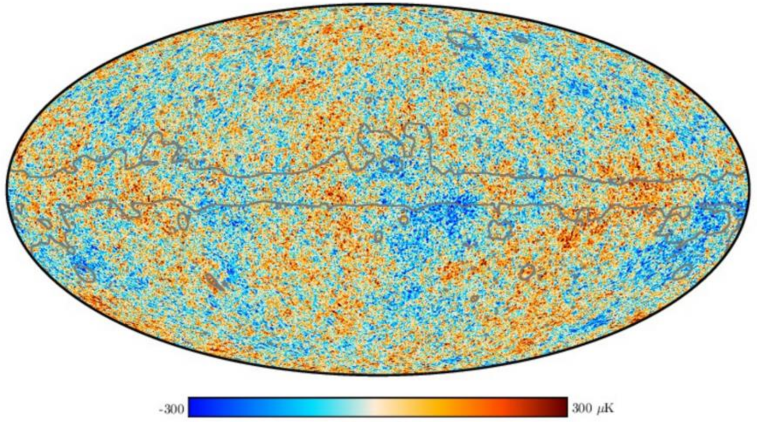
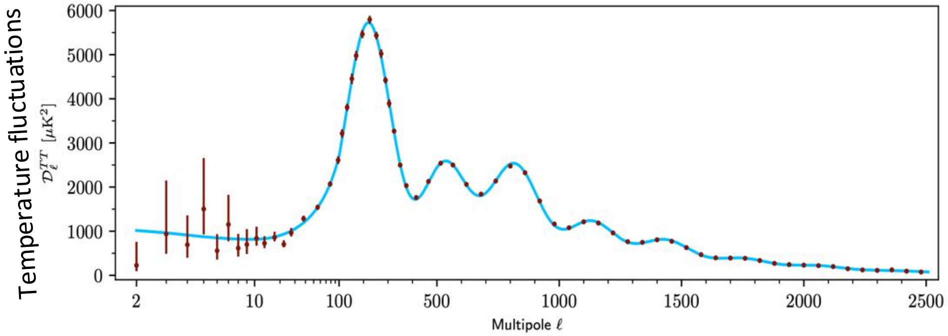
Matter-Antimatter Asymmetry

- Baryon asymmetry of Universe
  - Baryon/photon ~6×10^{-10} (Cosmic Microwave Background Radiation; Nobel Prize 2006)

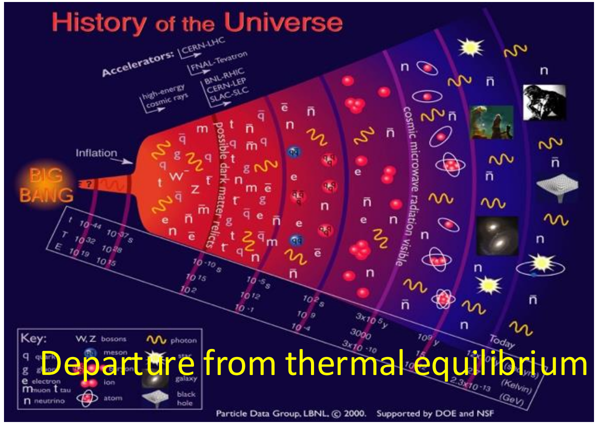




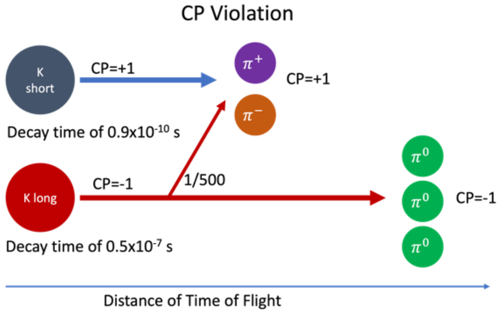
Cosmic Microwave Background Radiation (Planck, 2018, arxiv:1807.06205)

Matter-Antimatter Asymmetry

- Baryon asymmetry of Universe
  - Baryon/photon ~6×10^{-10} (Cosmic Microwave Background Radiation; Nobel Prize 2006)
- Sakharov (Nobel Peace Prize 1975) conditions
  - Departure from thermal equilibrium
  - Charge-parity(CP) violation
  - Baryon number nonconservation
- The Universe cooled now.
- CP violation only observed in kaon (Nobel Prize 1980)and B meson decays
  - Kobayashi-Maskawa mechanism in Standard Model (CKM Matrix) (Nobel Prize 2008)
  - Baryon/photon~10^{-18}
- No evidence for baryon number violation!
  - $0\beta\nu\nu$ (MJD, **PRL130.062501)**
  - Tri-nucleon Decay (MJD, **PRC112. L022501)**



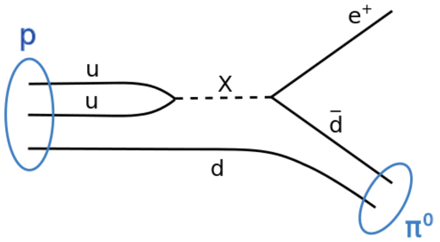
Kaon decay

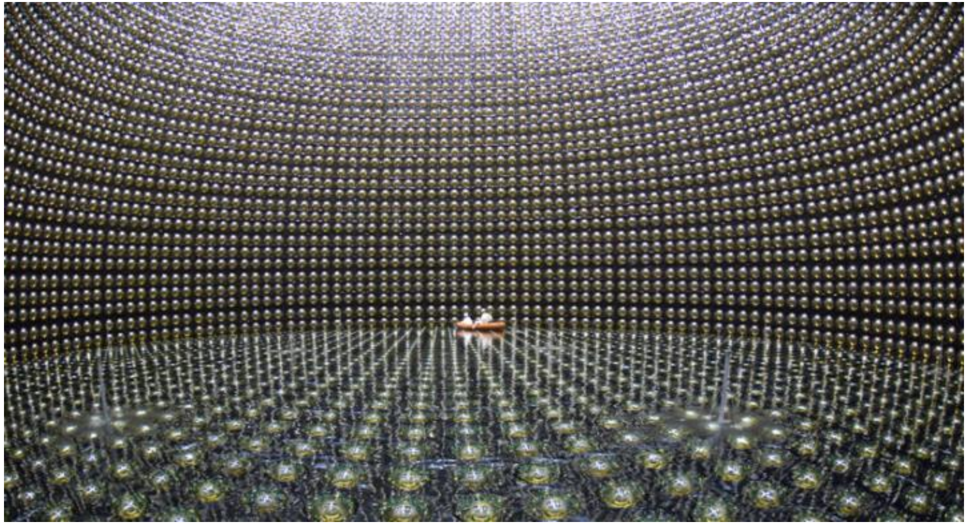


CKM Matrix
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

Origins and Early Theory of Baryon Decays

- The concept emerged in the context of **grand unified theories** (GUTs).
  - Predict proton decays
- The current limit is $\tau/B(p \rightarrow e^{+}\pi^{0}) > 2.4\times10^{34}$ yr (Super-Kamiokande, PRD 102.112011 (2020))





Experimental Efforts

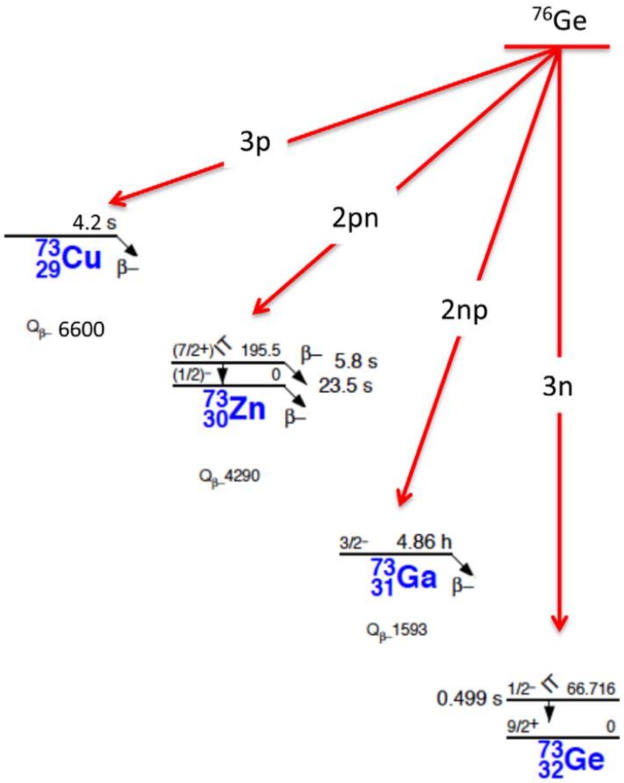
- **Proton and Nucleon Decay Searches (underground experiments)**
  - Kamiokande / Super-Kamiokande, Soudan, SNO, etc
  - $p \to e^+\pi^0, p \to \mu^+\pi^0, p \to \bar{\nu}K^+, p \to e^+K^0, p \to \mu^+K^0$
- **Collider-Based Baryon Decay Studies**
  - LHC, Belle, etc
  - $t \to l^+jj$(where l =e or μ) , $\tau^- \to \Lambda\pi^-$
- **Neutron–Antineutron Oscillation**
  - European Spallation Source, SNO, Super-Kamiokande
  - $n \to \bar{n}$

Multi-nucleon Decays

- Extension of Higgs sector or GUT-inspired models allow $\Delta B = 2$
  - Best limit is > 4.04×10^{32} yr (Super-K)
- The Z_6 model is the Standard Model extended by an additional discrete symmetry ($Z_2 \times Z_3$), i.e., the centers of SU(2) and SU(3).
  - Include the right-handed neutrinos to cancel anomalies.
  - K. S. Babu, I. Gogoladze, and K. Wang, Gauged baryon parity and nucleon stability, Phys. Lett. B 570, 32 (2003).
- This forbids all operators with $\Delta B = 1$ or $\Delta B = 2$, such as single proton decay or neutron–antineutron oscillations. Only $\Delta B = 3$(such as triple nucleon decay) is permitted, but only via extremely high-dimension (dimension 15) operators.

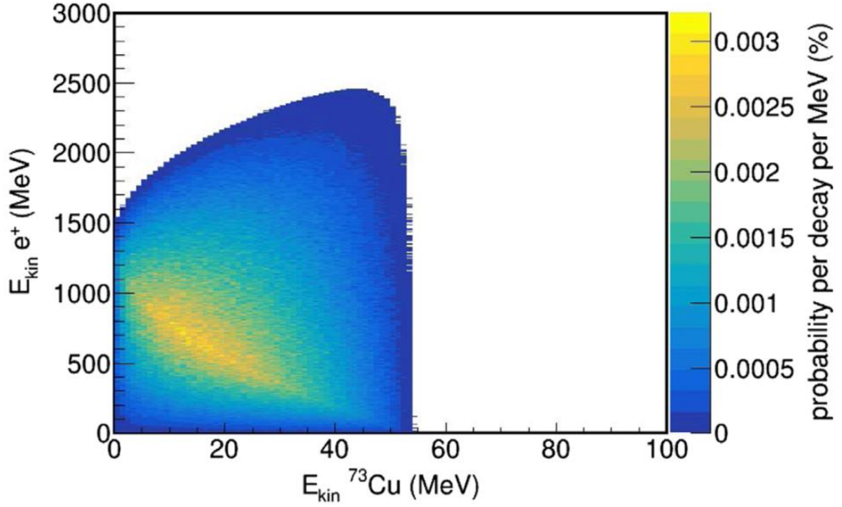
Three-nucleon Decays in MAJORANA DEMONSTRATOR

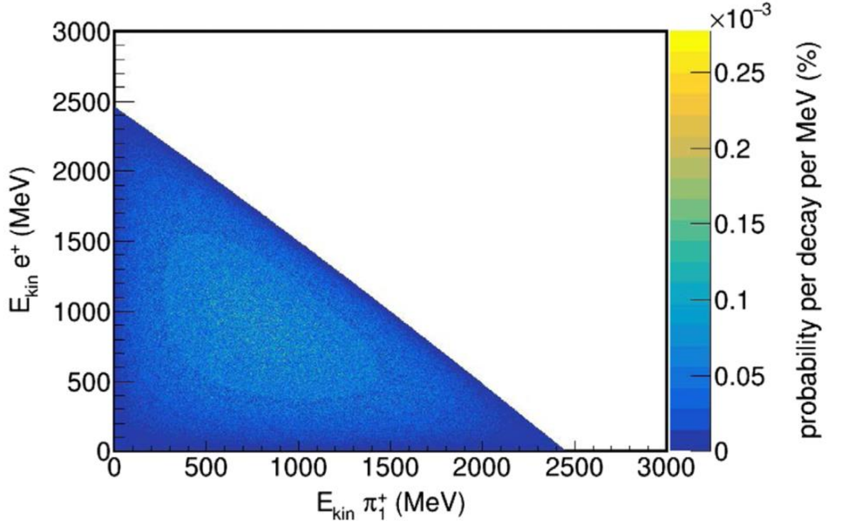
- Semi-inclusive visible modes
  - $ppp \to e^+\pi^+\pi^+, ppn \to e^+\pi^+, pnn \to e^+\pi^0, nnn \to \bar{\nu}\pi^0$
  - Deposit large energy in the detectors
  - Cannot distinguish positrons or pions in MJD
  - The excited daughter can emit gammas (multiple detectors)
  - Search for emission of enormous energy and the following daughter isotope decay
- Fully inclusive modes
  - ${}^{76}\mathrm{Ge}(ppp) \to {}^{73}Cu + X, {}^{76}\mathrm{Ge}(ppn) \to {}^{73}Zn + X,$
  - ${}^{76}\mathrm{Ge}(pnn) \to {}^{73}Ga + X, {}^{76}\mathrm{Ge}(nnn) \to {}^{73}Ge + X$
  - X can deposit energy in detectors (visible) or escape from detectors (invisible)
  - Search for the daughter isotope decays and the grand-daughter isotope decays
- Don't consider the proton or neutron emission (excited daughter isotopes). Calculate partial lifetime.



Semi-inclusive Visible Modes : Event Selection 1

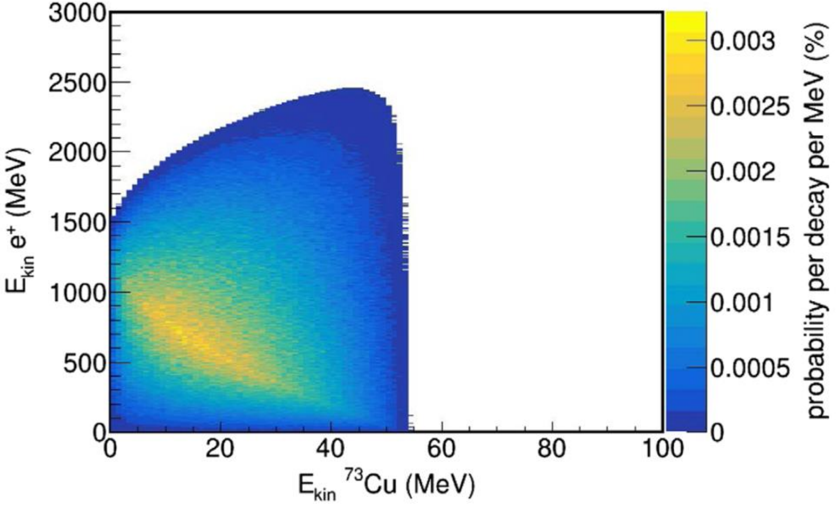
- $ppp \rightarrow e^+\pi^+\pi^+, ppn \rightarrow e^+\pi^+, pnn \rightarrow e^+\pi^0, nnn \rightarrow \bar{\nu}\pi^0$
- Visible particles (e.g., positrons, pions) deposit large amounts of energy *in* germanium detectors (three-nucleon mass ≈ 3 GeV).
- Event selection (Step 1): identify high-energy deposits (>10 MeV) — saturated events not tagged as muons (Ge detector energy threshold ~10–11 MeV).

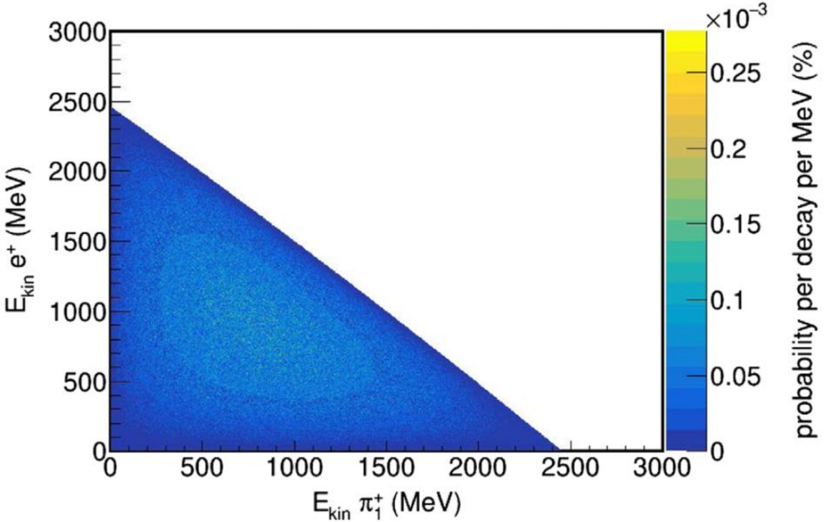




Semi-inclusive Visible Modes : Event Selection 1

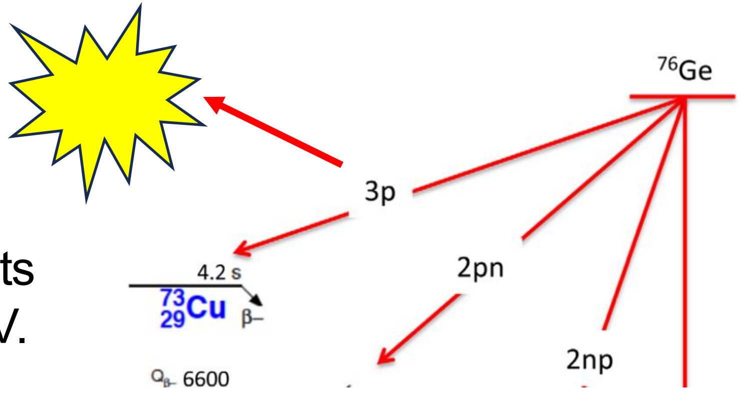
- Selection efficiency: ~99%. Calculated using GEANT4 simulations.
  - Simulate energy release from 3-nucleon decays
  - Track daughter particles (isotopes, positrons, pions, etc.)
  - Propagate particles within germanium detectors
  - Calculate fraction of events depositing >10 MeV (ϵ_0)

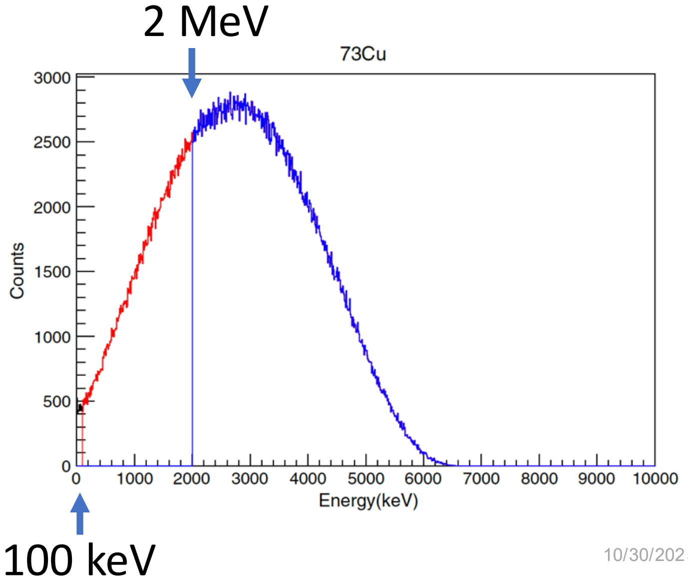




Semi-inclusive Visible Modes : Event Selection 2

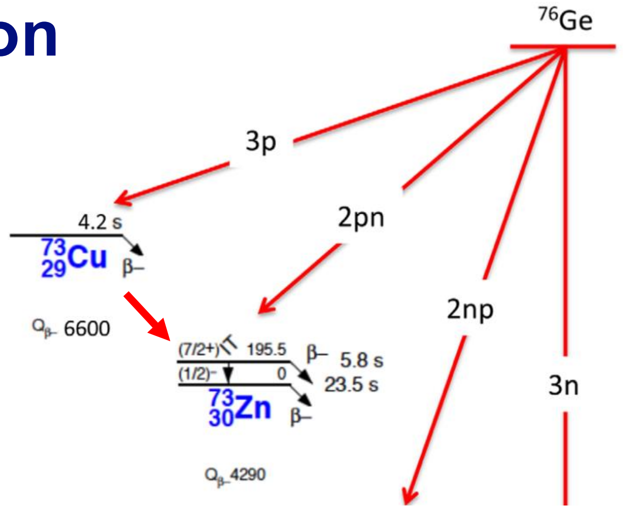
- Daughter isotopes are unstable.
- After the first saturated event, select events within 5 × half-life where energy > 100 keV.
  - The $5 \times T_{1/2}$ window corresponds roughly to a 5σ coverage (ϵ_{τ_1}). Must account for run gaps due to calibrations, detector downtime, or power outages.
  - Example: for ^{73}Cu, $T_1/_2$ = 4.2 s → search window = 4.2 × 5 = 21 s.
  - Calculate the energy efficiency from 100 keV up to Q-value for each decay channel. (ϵ_{E_1})
- This approach is possible because the first events are very rare (thanks to the highly efficient muon tagging), and the MJD background is extremely low.

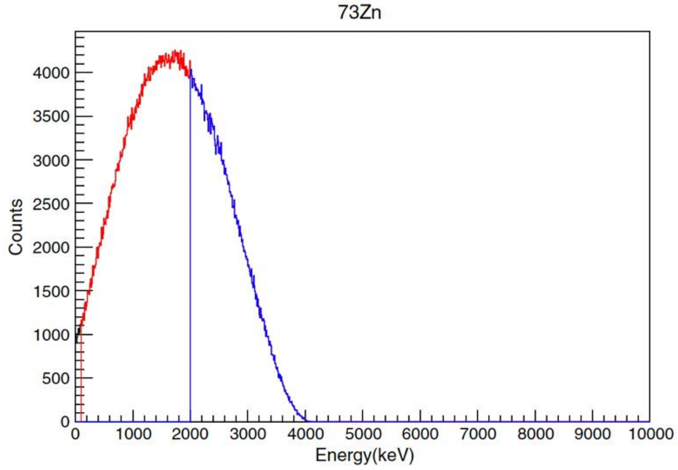




Fully Inclusive Modes: Event Selection

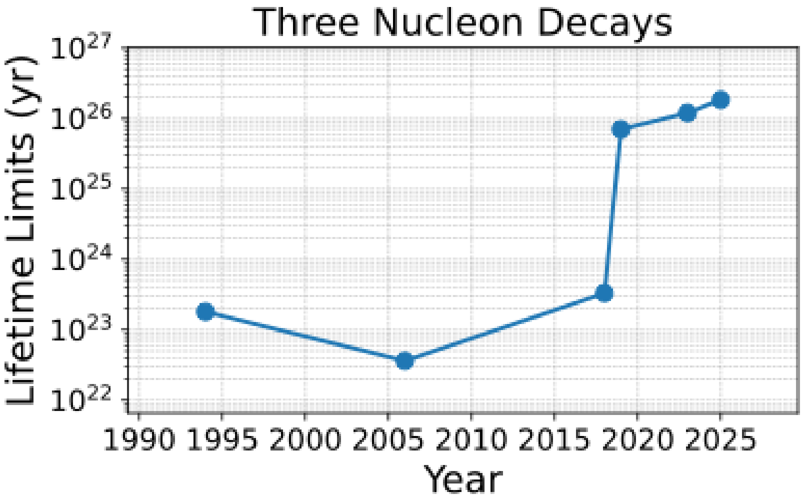
- ${}^{76}\text{Ge}(ppp) \rightarrow {}^{73}Cu + X, {}^{76}\text{Ge}(ppn) \rightarrow {}^{73}Zn + X,$
- ${}^{76}\text{Ge}(pnn) \rightarrow {}^{73}Ga + X, {}^{76}\text{Ge}(nnn) \rightarrow {}^{73}Ge + X$
- X can deposit energy in detectors (visible) or escape from detectors (invisible)
- We don't consider X but the decays of the daughter isotopes and the following grand-daughter isotopes.
- For example, ^{73}Cu can decay to ^{73}Zn and ^{73}Zn can decay to ^{73}Ga.
- Select the first event of energy > 2 MeV. There are more low energy backgrounds. (ϵ_{E_1})
- After the 5×$T_{1/2}$ window of the grand-daughter isotope (ϵ_{τ_2}), search for the second event of energy > 2MeV. (ϵ_{E_2})
- Calculate the energy efficiency from 2 MeV up to Q-value for each decay channel. Exclude the multi-site events because of the multi-site cuts.





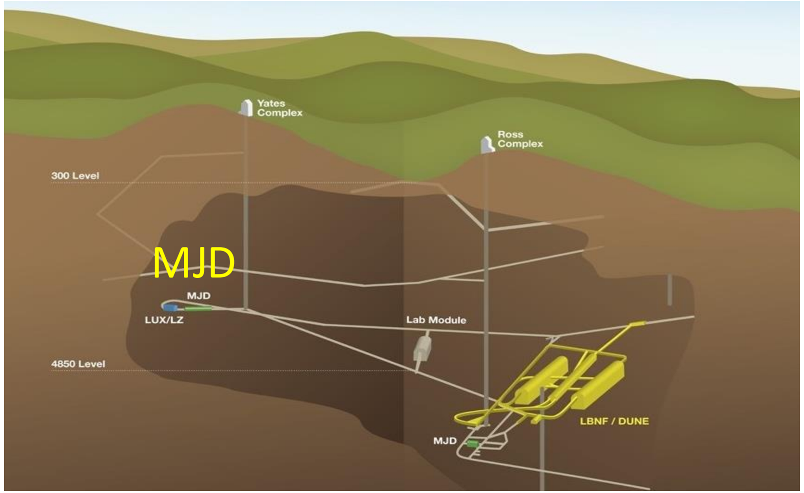
Experimental Efforts for Three-nucleon Decays

Experiment	Isotope	Channels	Lifetime Limits (10^{23} yr)	Year
NaI(Tl)	^{127}I	nnn (invisible)	1.8	(1994)
DAMA/ LXe	^{136}Xe	pnn (invisible)	0.14	(2006)
		ppn (invisible)	0.27	
		ppp (invisible)	0.36	
EXO-200	^{136}Xe	ppn (invisible)	1.9	(2018)
		ppp (invisible)	3.3	
MJD	^{76}Ge	ppn ($e^+\pi^+$)	703	(2019)
		ppp ($e^+\pi^+\pi^+$)	678	
GERDA	^{76}Ge	ppp, ppn,pnn (All inclusive)	1200	(2023)
MJD	^{76}Ge	ppn ($e^+\pi^+$)	1827	(2025)
		ppp ($e^+\pi^+\pi^+$)	1836	



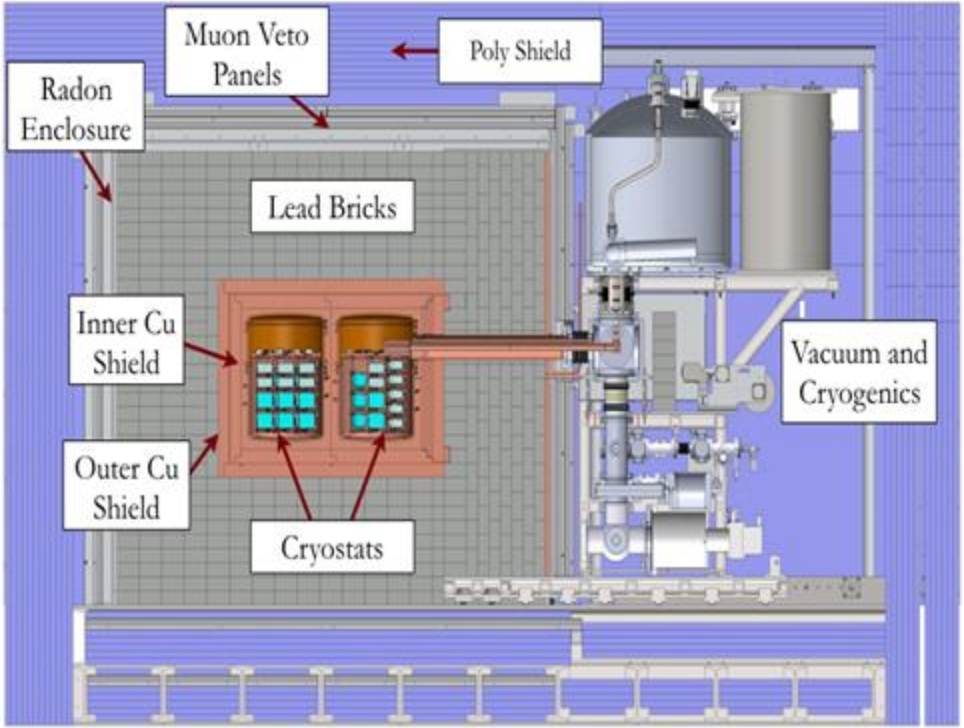
Location

- **Earth shielding blocks cosmic rays**
- Sanford Underground Research Facility (SURF): Located in Lead, SD, at a depth of 1480 m
- Equivalent to ~4300 m water overburden (m.w.e.)
- Muon flux reduced from ~10^{-2} /cm²/s (surface) to ~5×10^{-9} /cm²/s (underground)
- **Site of the historic Homestake experiment** — Ray Davis's pioneering solar neutrino detection (Nobel Prize 2002)



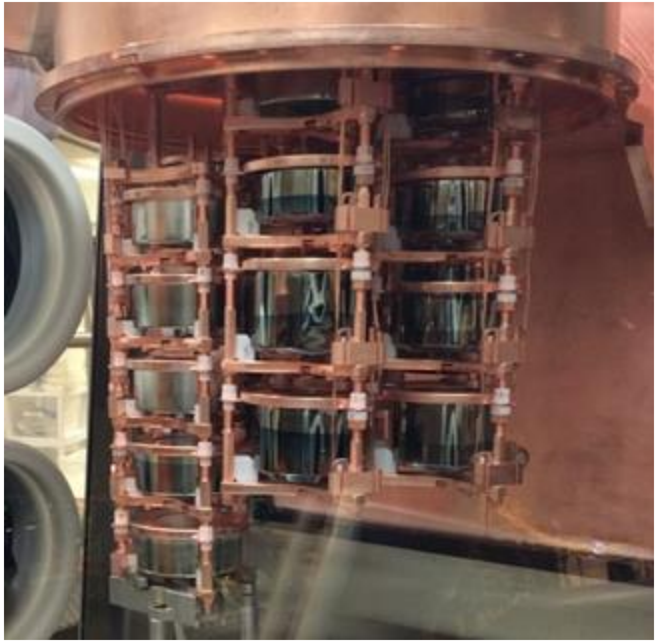
Low Background

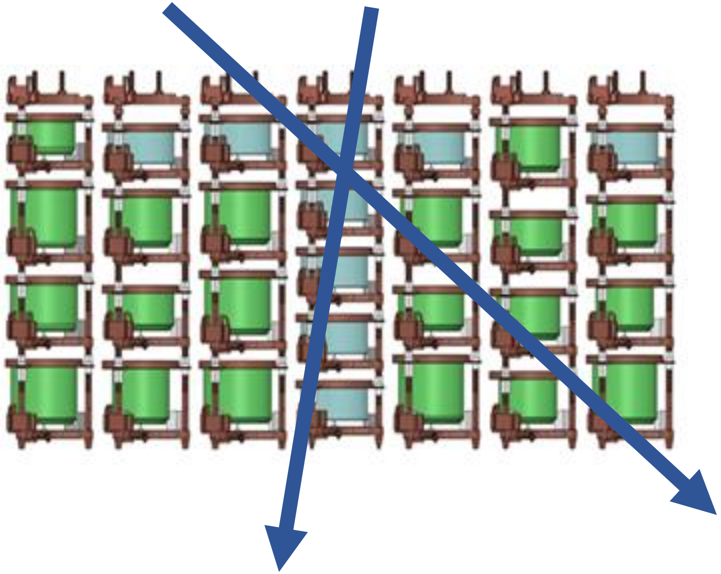
- **Active veto:** muon detection panels
- **Passive shielding:** polyethylene, underground lead, commercial + electroform copper layers
- **Radon suppression:** continuous nitrogen purge



Big Detector Arrays

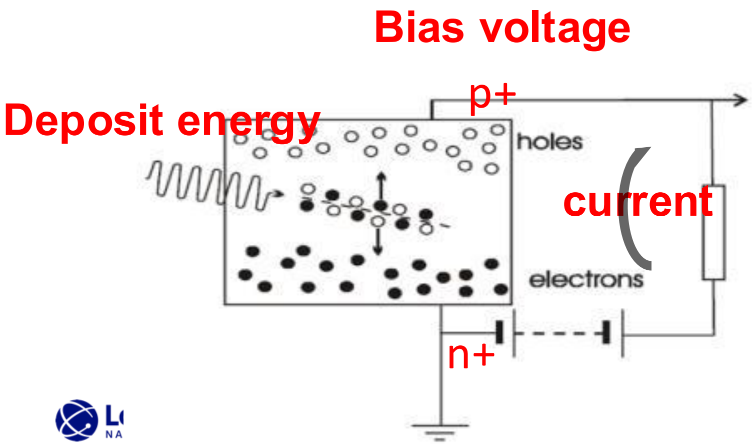
- Sensitive to events of strange patterns

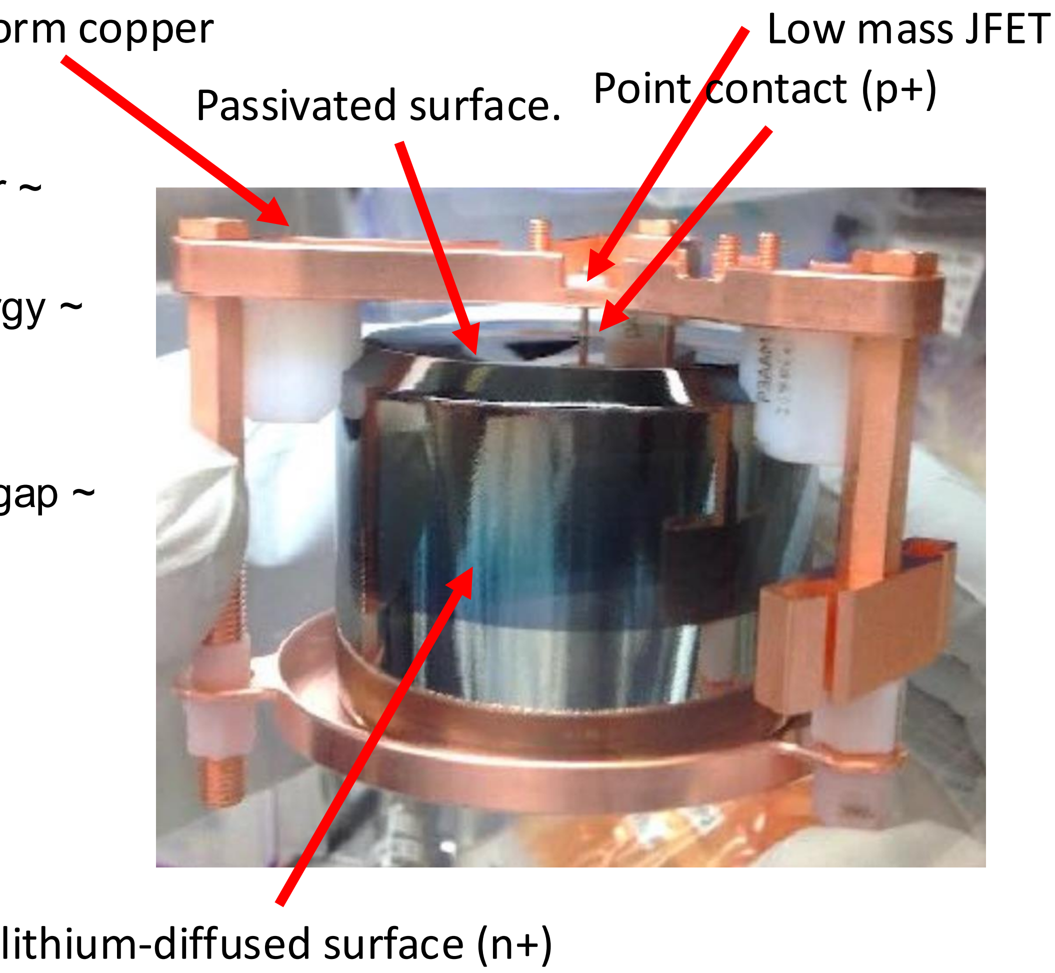




Detectors

- Enriched Germanium (^{76}Ge) detector ~ 88% ^{76}Ge enrichment
- Excellent resolution: peak width/energy ~ 0.1%
- Low threshold ~ 1 keV
- High-purity semiconductor: Ge bandgap ~ 0.8 eV

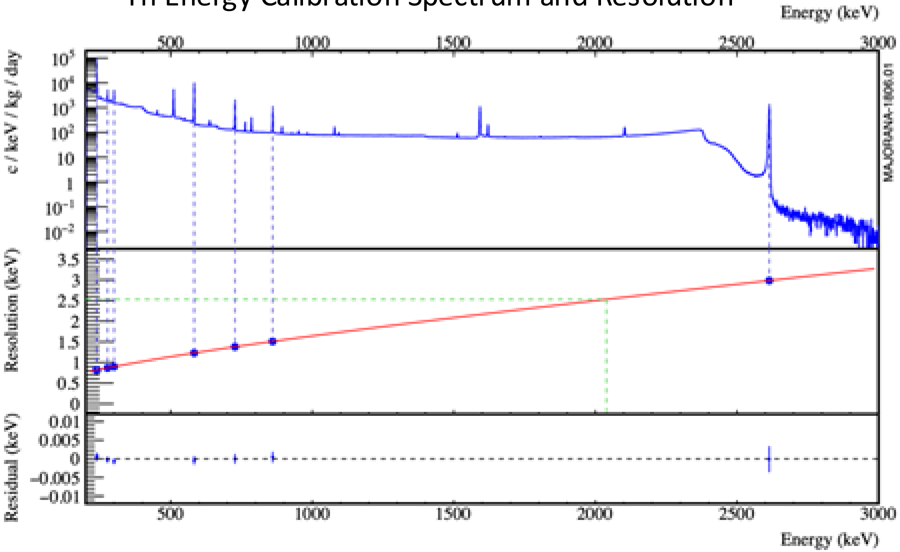




Energy Reconstruction

- Calibrated on weekly ^{228}Th calibration data, retuned on full data set
- Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected traces with charge-trapping correction
- Energy resolution (2.5 keV FWHM @ 2039 keV) and linearity (< 0.2 keV up to 3 MeV) a record for neutrinoless double-beta decay searches
- Charge trapping correction improves resolution at 2039 keV from 4 keV to 2.5 keV FWHM

^{228}Th Energy Calibration Spectrum and Resolution



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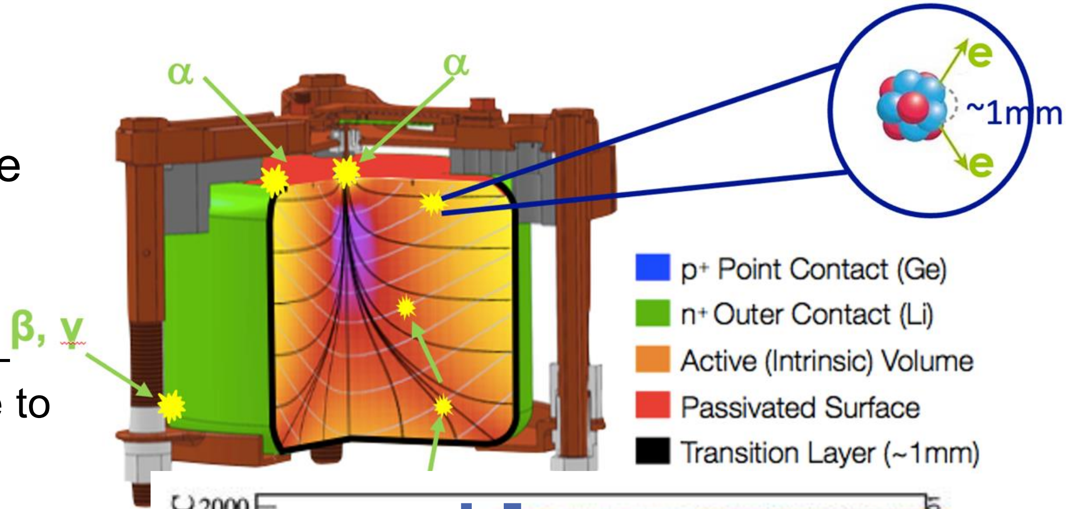
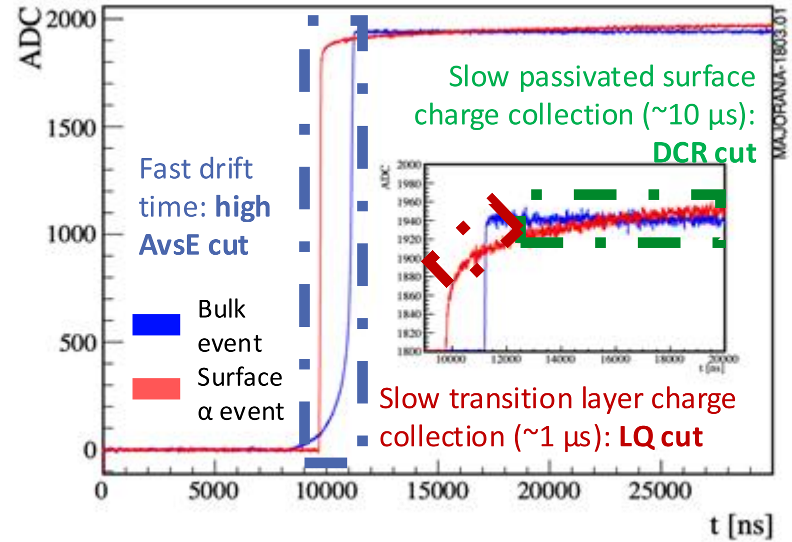
Background Rejection

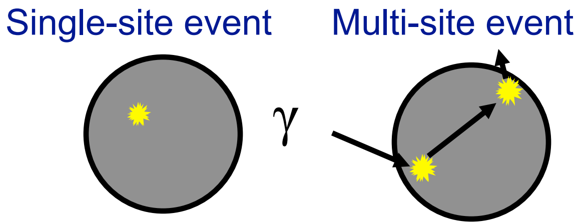
- **Point-contact HPGe detectors** are essential for background rejection.
- **Pulse-shape analysis (PSD):**
  - **AvsE:** multiple-site event rejection — compares maximum waveform slope to energy, primarily rejects external γ events.
  - **DCR (Delayed Charge Recovery):** identifies slow charge collection from surface α contamination (mainly from radon decay chain).
  - **LQ (Late Charge):** flags partial charge collection in the transition layer, often from β or γ interactions.

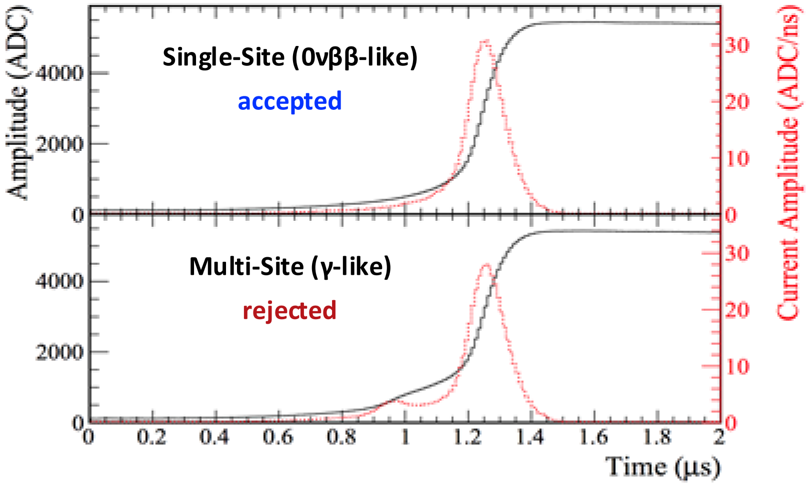




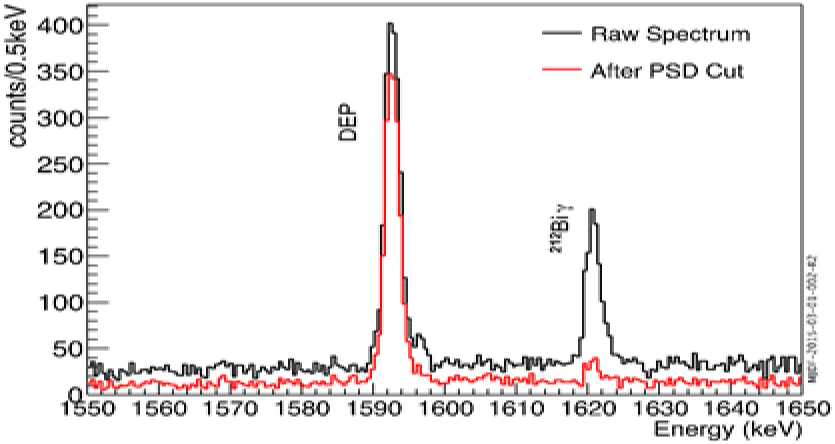
Multi-Site Events Cut (AvsE)

- Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event Energy (AvsE)
- Tuned on ^{228}Th calibration data to accept 90% of single-site DEP events. Rejects >50% of the Compton continuum near $Q_{\beta\beta}$





^{228}Th calibration data



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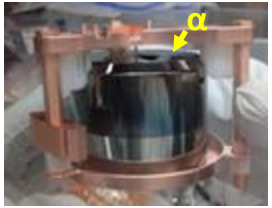
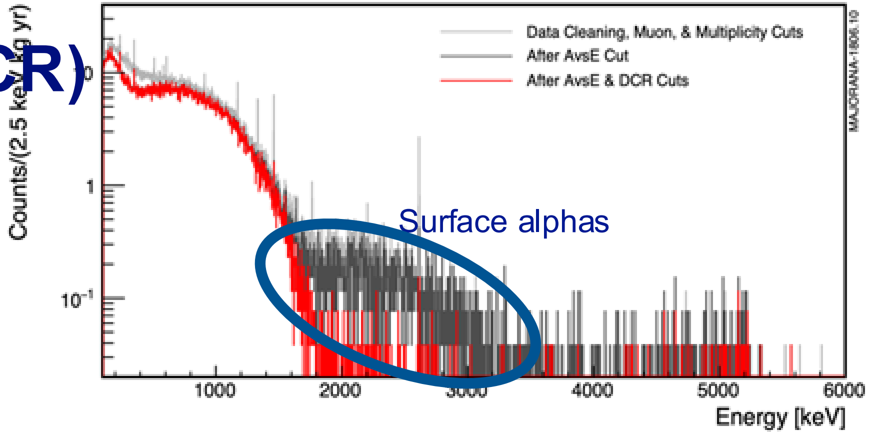
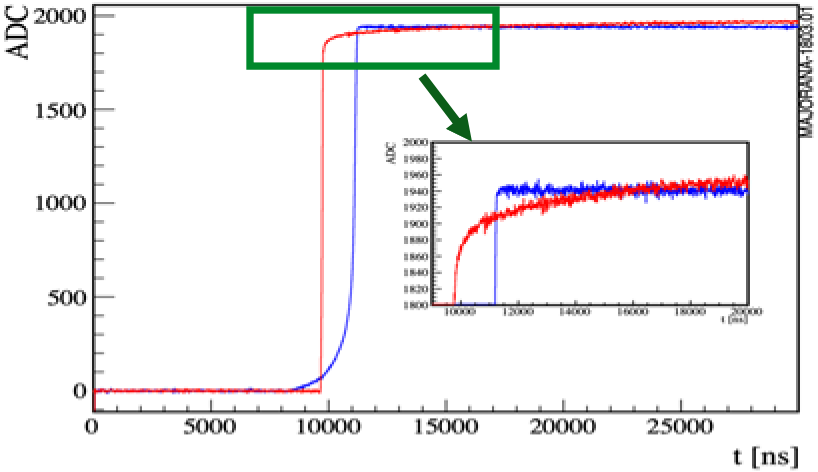
Passivated Surface Events (DCR)

- Alpha particles incident on the passivated surfaces have a degraded energy reconstruction and can fall near $Q_{\beta\beta}$.





- Charge trapped at passivated surface is slowly rereleased (~10s of μs): Delayed Charge Recovery (DCR)
  - Cut using slope of tail after rising edge
  - Tuned to keep 99% of bulk events
- Suspect α contamination near passivated surface ^{210}Po from ^{222}Rn exposure



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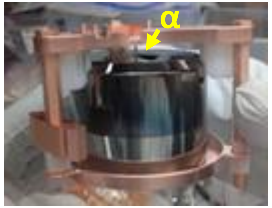
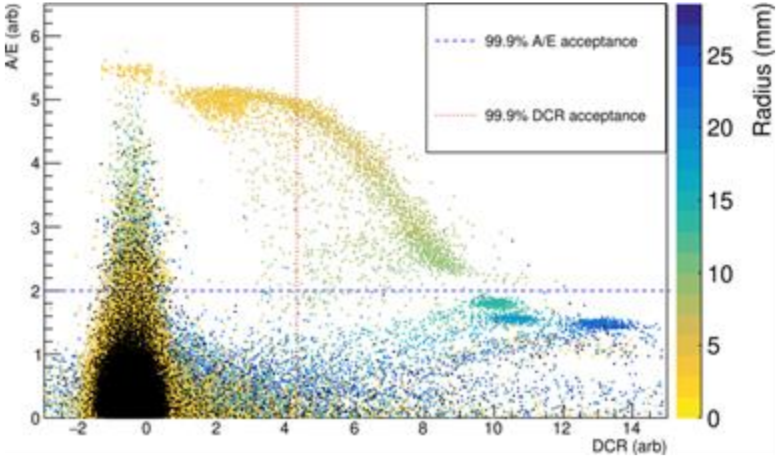
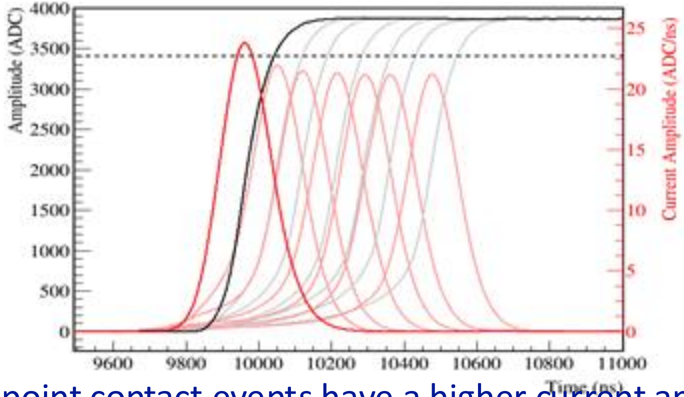
Surface Cuts:
Point-Contact Events (AvsE)

- Alphas incident on the point contacts release less delayed charge and evade the DCR cut.
- But they have steeper rising edges, so the higher current amplitude events can be removed using the AvsE cut.





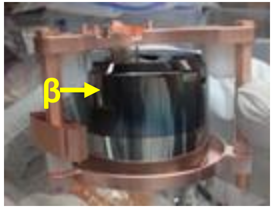
Joint A/E-DCR spectrum from TUBE scanner, with an α-source scanning across the passivated surface of a PPC detector

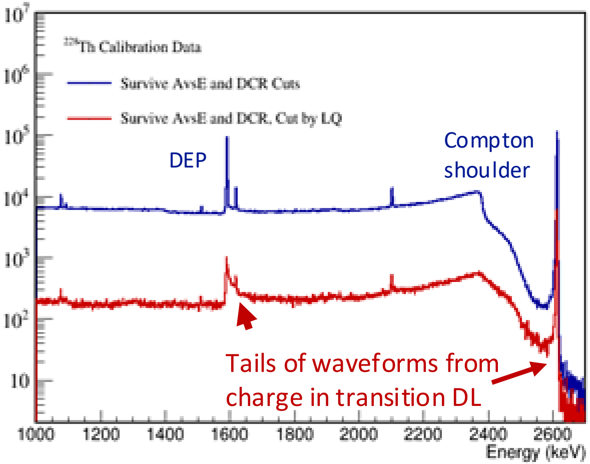


Near point contact events have a higher current amplitude

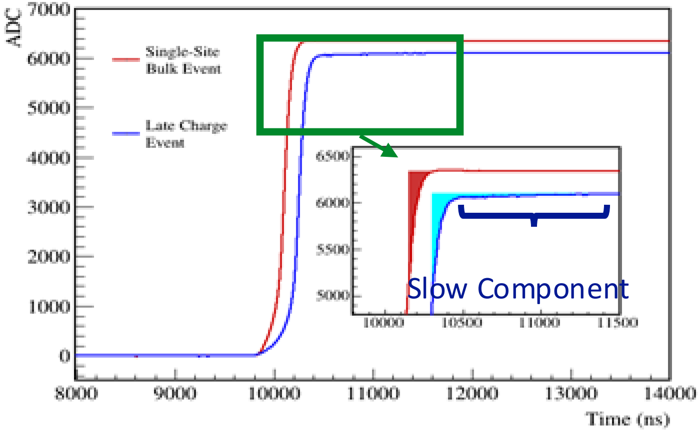
Surface Cuts: Transition Dead-Layer Events (LQ)

- Events in lithiated n-plus surfaces experience severe energy degradation and slow (~1-2 μs) rerelease of charge. Events with a partial charge deposit in this transition layer are potential backgrounds!
- Cut waveforms with a slow component using “Late Charge” (LQ): area above rising edge of waveform after 80% of charge is collected
- Tune to keep >99% of single-site bulk events using ^{208}Tl double escape events

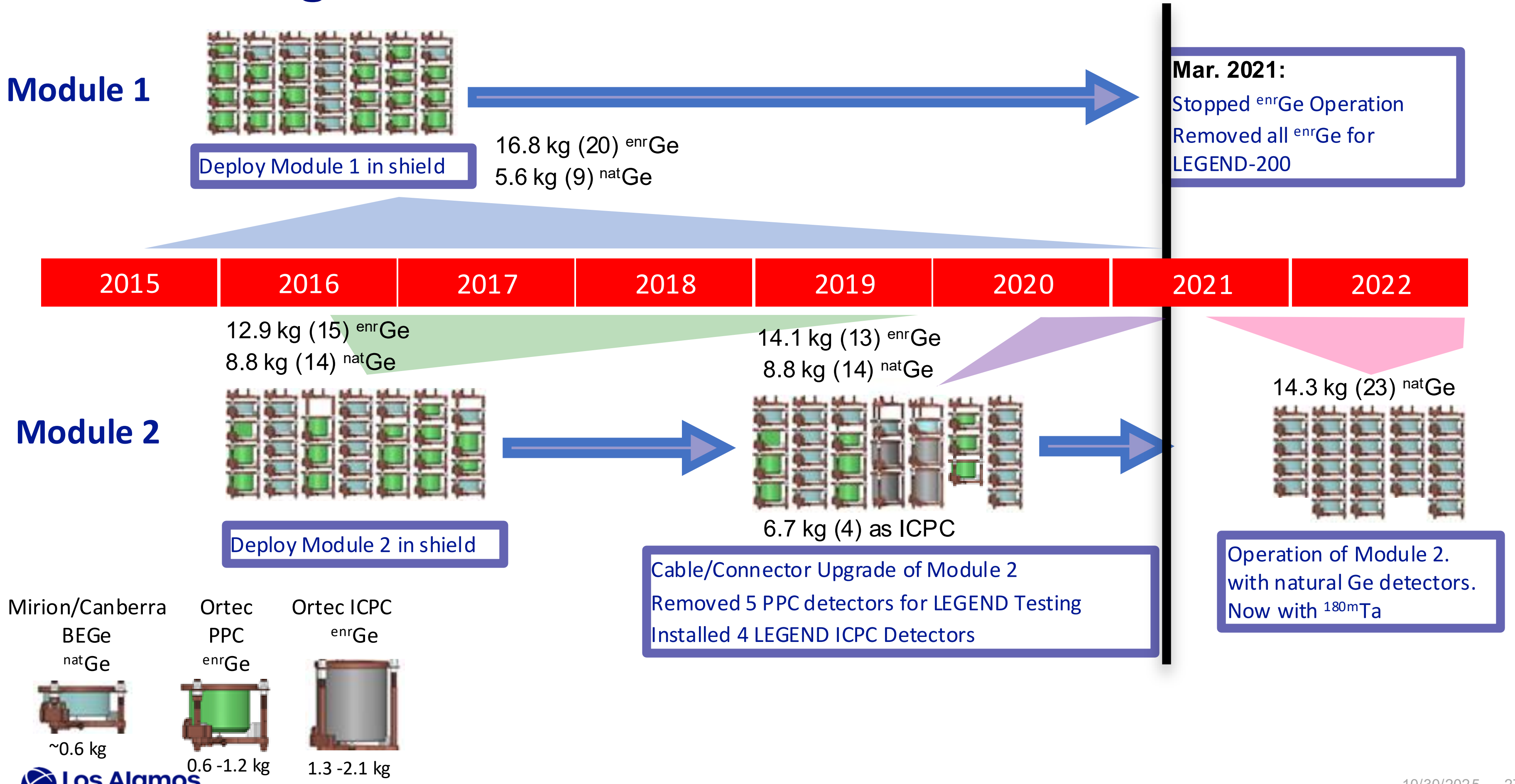




LQ cut leaves bulk single-site structures in ^{228}Th calibration data intact



Run Configuration and Timeline



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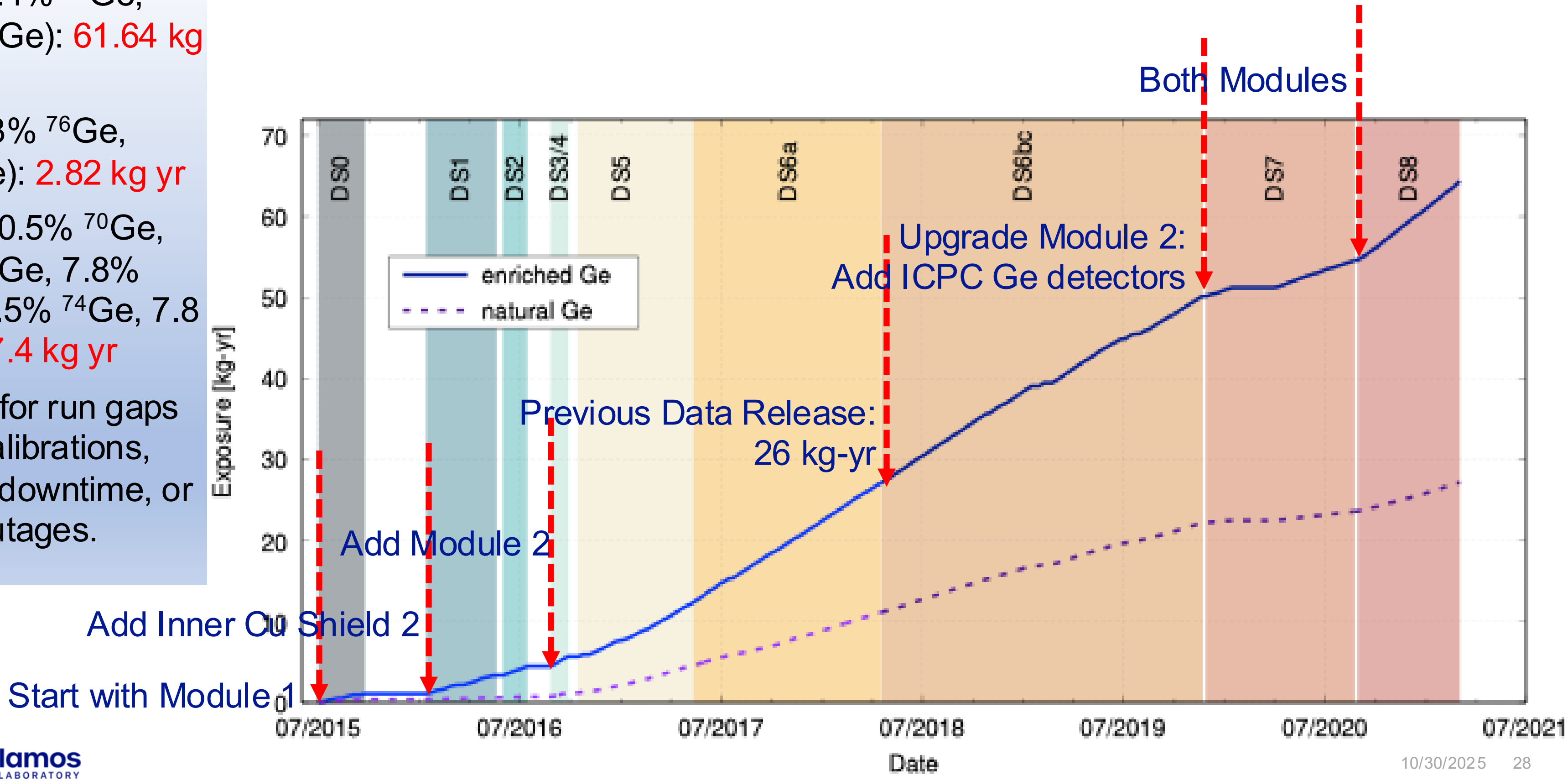
Exposure

- PPC (87.4% ^{76}Ge, 12.6% ^{74}Ge): 61.64 kg yr
- ICPC (88% ^{76}Ge, 12%^{74}Ge): 2.82 kg yr
- BEGe (20.5% ^{70}Ge, 27.4% ^{72}Ge, 7.8% ^{73}Ge, 36.5% ^{74}Ge, 7.8 ^{76}Ge): 27.4 kg yr
- Account for run gaps due to calibrations, detector downtime, or power outages.



Search Candidates for Semi-inclusive Visible

- The longest $T_{1/2}$ is 1268.4 s so $5xT_{1/2}$ is 6342 s.
- One potential event for semi-inclusive visible mode
  - Energy of first event > 11558 keV
  - Energy of second event: 147 keV
  - Time difference between first and second events: 1712 s
  - Satisfy
    - **$^{76}Ge(pn) \rightarrow {}^{74}Ga + \pi^0 + \pi^+$**
    - **$^{73}Ge(pnn) \rightarrow {}^{70}Ga + e^+ + \pi^0$**
    - **$^{72}Ge(pn) \rightarrow {}^{70}Ga + \pi^0 + \pi^+$**
    - **$^{70}Ge(nnn) \rightarrow {}^{67}Ge + \bar{\nu} + \pi^0$**

Isotope	$T_{1/2}$ (s)	Q (MeV)
^{73}Cu	4.2	6.6
^{73}Zn	24.5	4.1
^{74}Zn	95.6	2.3
^{74}Ga	487.2	5.4
^{71}Cu	19.4	4.6
^{71}Zn	147	2.8
^{70}Cu	44.5	6.6
^{70}Ga	1268.4	1.7
^{69}Cu	171	2.7
^{67}Ge	1134	4.2

Search Candidates for Fully Inclusive

- One potential event for fully inclusive mode
  - Energy of first event: 2294 keV
  - Energy of second event: 2614 keV
  - Time difference between first and second events: 1657 s
  - Satisfy no channels

Isotope	$T_{1/2}$ (s)	Q (MeV)
^{73}Cu	4.2	6.6
^{73}Zn	24.5	4.1
^{74}Zn	95.6	2.3
^{74}Ga	487.2	5.4
^{71}Cu	19.4	4.6
^{71}Zn	147	2.8
^{70}Cu	44.5	6.6
^{70}Ga	1268.4	1.7
^{69}Cu	171	2.7
^{67}Ge	1134	4.2

The Partial Lifetime Limit

- The partial lifetime limit is calculated as
  - $\tau > \frac{NT\epsilon_{tot}}{S}$
  - NT is exposure, ϵ is the efficiency and S is the signal upper limit corresponding to Feldman-Cousins 90% confidence level.
- In this study, we considered all detectors including enriched and natural detectors; need to calculate PPC, ICPC, BEGe separately (And each has its own efficiency study).
- The data cleaning cuts discard nonphysical waveforms, pileup waveforms, pulser events.
- The Pulse-shape analysis (PSD) cuts, including AvsE, DCR, and LQ, discard background events.

I	PPC	ICPC	BEGe
NT_i	61.64 kg yr	2.82 kg yr	27.383 kg yr
$\epsilon_{DC,i}$	99.1%	99.9%	99.9%
$\epsilon_{PSD,i}$	86.1%	81.0%	86.1%

Final Results for Semi-inclusive Visible Mode

- $NT\epsilon_{Tot} = (\sum_i^{PPC,ICPC,BEGe} NT_i\epsilon_{DC,i})\epsilon_0\epsilon_{\tau_1}\epsilon_{E_1}$

For semi-inclusive visible mode, we only consider the data cleaning cuts to the daughter isotope decay (>100 keV events).

Decay Mode	ϵ_0	ϵ_{τ_1}	ϵ_{E_1}	ϵ_{τ_2}	ϵ_{E_2}	$\sum_i \mathrm{NT}_i\epsilon_i$ (10^{24} atom yr)	$\mathrm{NT}\epsilon_{\mathrm{Tot}}$ (10^{24} atom yr)	Total candidates Observed	S (counts)	τ (10^{24} yr)
Semi-inclusive Visible										
^{76}Ge$(ppp) \to {}^{73}$Cu $e^+\pi^+\pi^+$	0.998	0.969	0.996	N.A.	N.A.	465.1	448.0	0	2.44	>183.6
^{76}Ge$(ppn) \to {}^{73}$Zn $e^+\pi^+$	0.999	0.969	0.990	N.A.	N.A.	465.1	445.8	0	2.44	>182.7
^{76}Ge$(pp) \to {}^{74}$Zn $\pi^+\pi^+$	0.994	0.968	0.972	N.A.	N.A.	465.1	435.0	0	2.44	>178.3
^{76}Ge$(pn) \to {}^{74}$Ga $\pi^0\pi^+$	0.979	0.964	0.991	N.A.	N.A.	465.1	435.0	1	4.36	>99.8
^{74}Ge$(ppp) \to {}^{71}$Cu $e^+\pi^+\pi^+$	0.998	0.969	0.993	N.A.	N.A.	147.2	141.3	0	2.44	>57.9
^{74}Ge$(ppn) \to {}^{71}$Zn $e^+\pi^+$	0.999	0.967	0.982	N.A.	N.A.	147.2	139.6	0	2.44	>57.2
^{73}Ge$(ppp) \to {}^{70}$Cu $e^+\pi^+\pi^+$	0.998	0.968	0.996	N.A.	N.A.	17.6	16.9	0	2.44	>6.9
^{73}Ge$(pnn) \to {}^{70}$Ga $e^+\pi^0$	0.999	0.958	0.867	N.A.	N.A.	17.6	14.6	1	4.36	>3.3
^{73}Ge$(pp) \to {}^{71}$Zn $\pi^+\pi^+$	0.994	0.967	0.982	N.A.	N.A.	17.6	16.6	0	2.44	>6.8
^{72}Ge$(ppp) \to {}^{69}$Cu $e^+\pi^+\pi^+$	0.998	0.967	0.973	N.A.	N.A.	62.1	58.4	0	2.44	>23.9
^{72}Ge$(pn) \to {}^{70}$Ga $\pi^0\pi^+$	0.979	0.958	0.867	N.A.	N.A.	62.1	50.5	1	4.36	>11.6
^{70}Ge$(nnn) \to {}^{67}$Ge $\bar{\nu}\pi^0$	0.952	0.959	0.972	N.A.	N.A.	46.5	41.3	1	4.36	>9.5

Final Results for Fully Inclusive Mode

- $NT\epsilon_{Tot} = (\sum_{i}^{PPC,ICPC,BEGe} NT_i \epsilon_{PSD,i}^2)\epsilon_{E_1}\epsilon_{\tau_2}\epsilon_{E_2}$

For fully inclusive mode, we consider all pulse-shape analysis for the daughter isotopes and the grand-daughter isotopes decays.

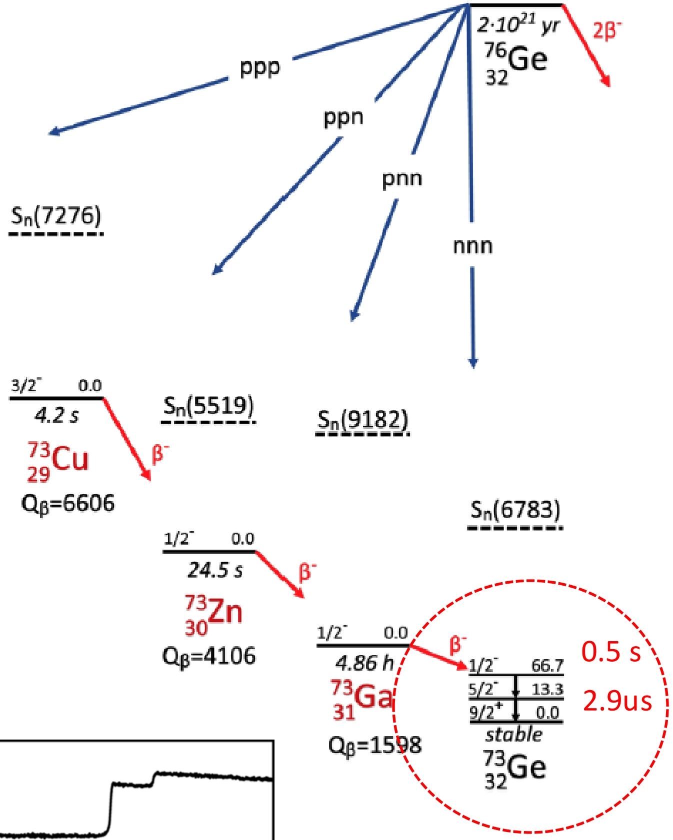
Decay Mode	ϵ_0	ϵ_{τ_1}	ϵ_{E_1}	ϵ_{τ_2}	ϵ_{E_2}	$\sum_i \mathrm{NT}_i\epsilon_i$ (10^{24} atom yr)	$\mathrm{NT}\epsilon_{\mathrm{Tot}}$ (10^{24} atom yr)	Total candidates Observed	S (counts)	τ (10^{24} yr)
$^{76}\mathrm{Ge}(ppp) \rightarrow {}^{73}\mathrm{Cu} + X$	N.A.	N.A.	0.445	0.969	0.350	343.5	51.84	0	2.44	>21.2
$^{74}\mathrm{Ge}(ppp) \rightarrow {}^{71}\mathrm{Cu} + X$	N.A.	N.A.	0.114	0.969	0.050	109.0	0.60	0	2.44	>0.2

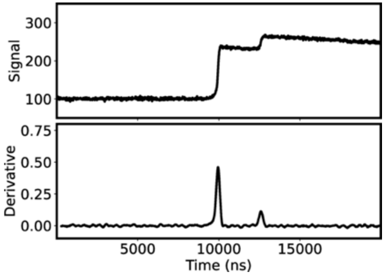
Background: Semi-Inclusive Visible Mode

- **Main Background Sources:**
  - Muon-induced saturated events not tagged by the veto system.
  - Random time coincidences with unrelated events.
- **Random Coincidence Rate:**
  - Event rate (>100 keV) ≈ 10^{-4} Hz in the MJD.
  - Expected random events after saturation: **≈ 0.6** (6342 × 10^{-4}).
  - Must occur in the **same detector** as the saturated event (0.6/35) **≈ 0.017 counts** across ~35 detectors.
- **Muon Veto System:**
  - High efficiency with near-4π coverage.
- **6 out of 492** saturated events not tagged; 2 likely due to electrical issues (electrical breakdown), 3 lack of the corresponding daughter events.
- **One non-muon-veto saturated event** meets all analysis criteria.
- If more such events match the **β-decay half-life** of daughter isotopes, it would **strengthen rare decay signal evidence**.

Comparison with GERDA Experiment

- Set a **partial lifetime limit** of **~1.2 × 10^{26} years** for **fully inclusive tri-nucleon decays** of ^{76}Ge. Used an exposure of **61.89 kg·yr**.
- All tri-nucleon decays will end with ^{73m}Ge decay.
- Developed an algorithm to detect **two-step waveforms** from ^{73m}Ge decay.
- **No events** observed matching ^{73m}Ge decay signature.
- **MJD observed several events** consistent with ^{73m}Ge decay detected, likely stem from **cosmogenic ^{73}As decay**. Phys. Rev. C **105**, 014617 (2022)





Summary

- Using a full dataset with a total exposure of **MAJORANA DEMONSTRATOR**, the experiment set the one of the **most stringent limits to date** for rare multinucleon decay processes.
- New partial lifetime limits were established, including a record
  - **1.836×10^{26} yr** for the $^{76}Ge(ppp) \rightarrow ^{73}Cu\ e^{+}\pi^{+}\pi^{+}$ decay mode,
  - **1.827×10^{26} yr** for the $^{76}Ge(ppn) \rightarrow ^{73}Zn\ e^{+}\pi^{+}$ decay mode.
- These new limits significantly advance the search for physics beyond the Standard Model and highlight the potential of the HPGe detector technology for future experiments such as LEGEND-1000.

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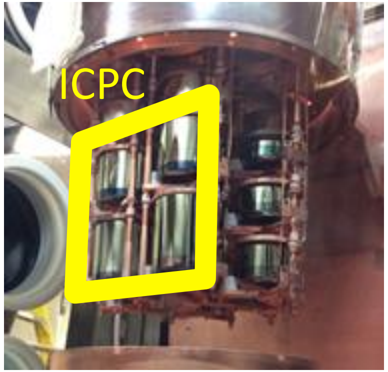
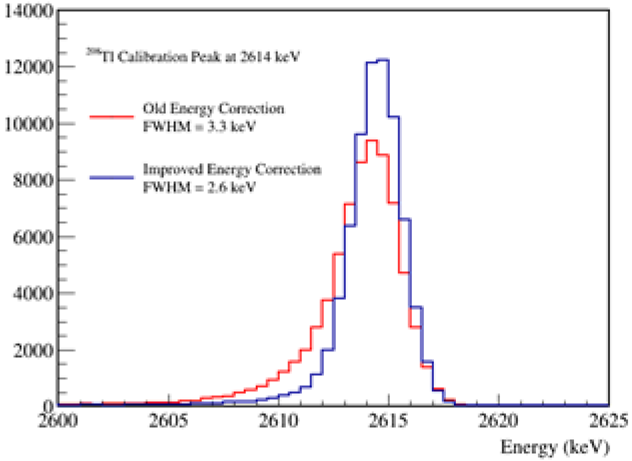
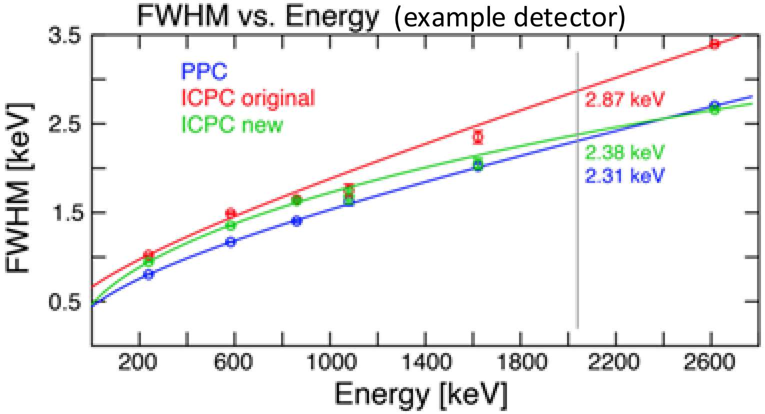
Inverted Coaxial Point Contact Detectors

- Inverted coaxial point contact (ICPC) detectors are larger (>3 kg) than PPC detectors (up to 1.2 kg). MAJORANA operated 4 ICPCs from Aug. 2020 to Mar 2021
  - Beneficial for background reduction in LEGEND
  - Larger range of drift times requires more refined analysis techniques
  - MAJORANA has demonstrated comparable performance with ICPCs and PPCs. Best energy resolution for ICPCs to date!







New charge trapping correction improves combined energy resolution of ICPC detectors