Recent results and status of MAJORANA DEMONSTRATOR experiment

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University of South Dakota

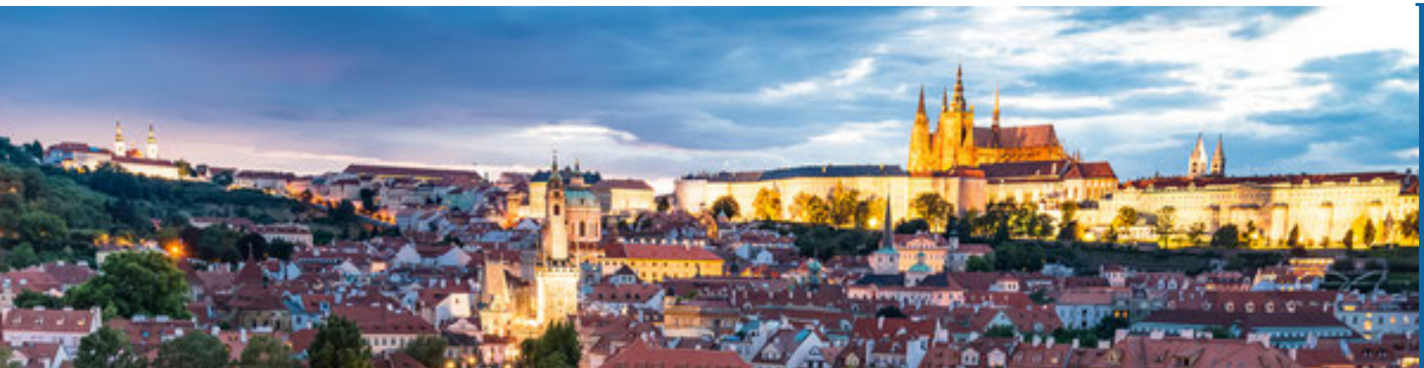
On behalf of the MAJORANA collaboration

UNIVERSITY OF SOUTH DAKOTA

Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

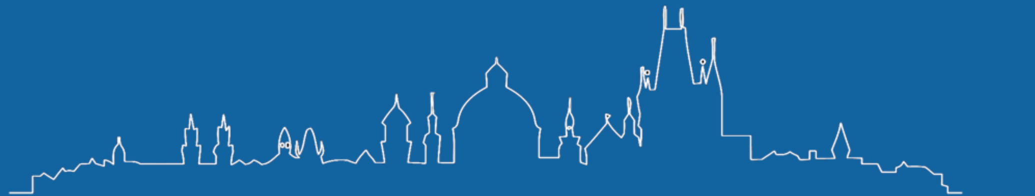
NSF



MEDEX'19

Matrix Elements for the Double beta decay Experiments

Prague 27-31 May, 2019



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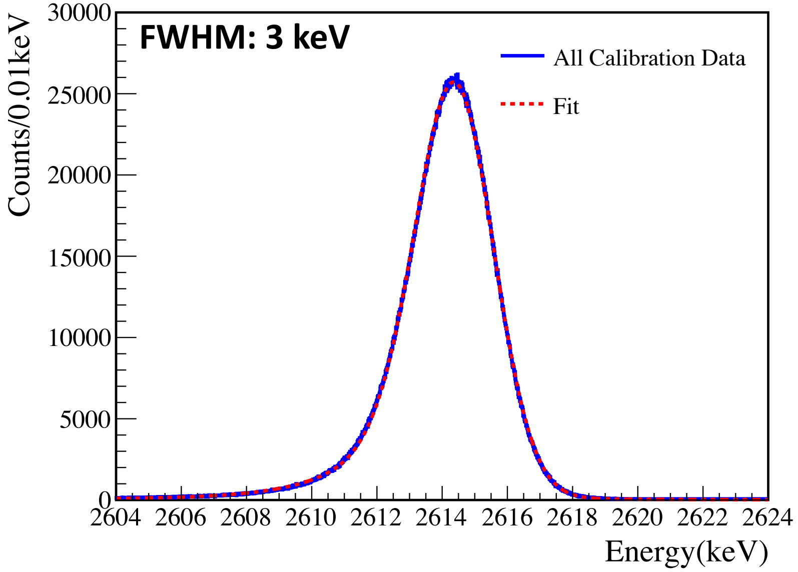
p-TYPE POINT CONTACT HIGH PURITY Ge DETECTOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

High Purity Germanium (HPGe) detectors

- Source & detector
- Demonstrated ability to enrich ^{76}Ge from 7.44% to 88%
- Excellent energy resolution
  - 2.5 keV at 2039 keV

2.614 MeV γ from ^{208}Tl

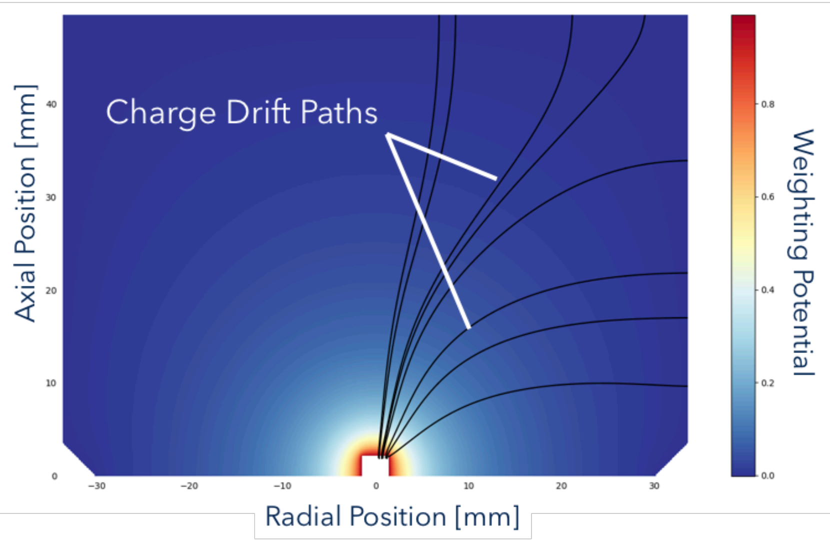


p-type point contact configuration

- Slow drift time of ionization charge cloud
- Localized weighting potential

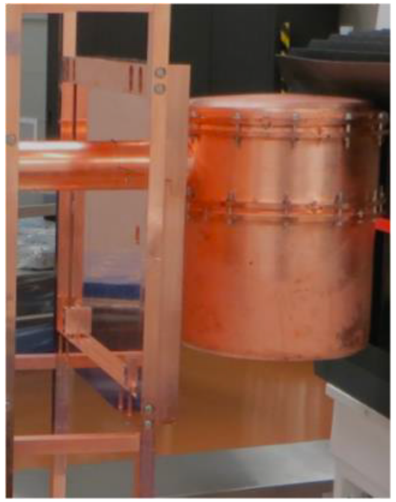
Excellent multi-site event rejection

Sample Detector Weighting Potential



MODULAR APPROACH

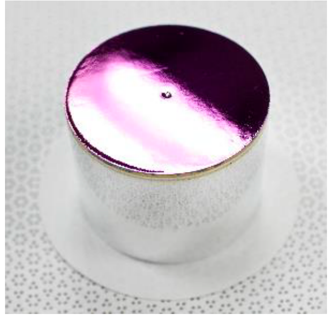
The modular approach provided a fast deployment, easy scalability and independent optimization



2 cryostats

7 strings

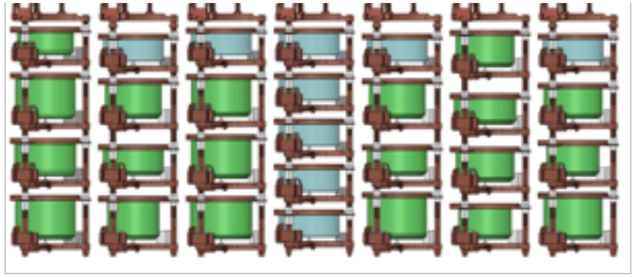
3, 4 or 5 detectors



High Purity Germanium detectors (HPGe):
0.6-1 kg
Natural or enriched

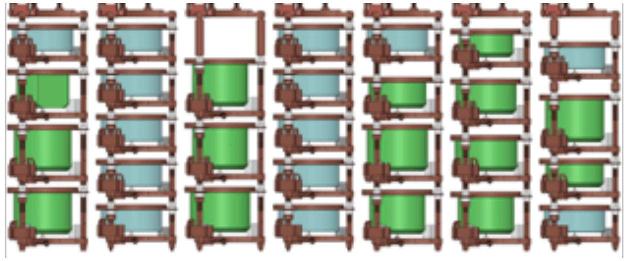
Module 1: Jun. 2015

- 16.9 kg of enriched detectors (20 units)
- 5.6 kg of natural detectors (6 units)



Module 2: Aug. 2016

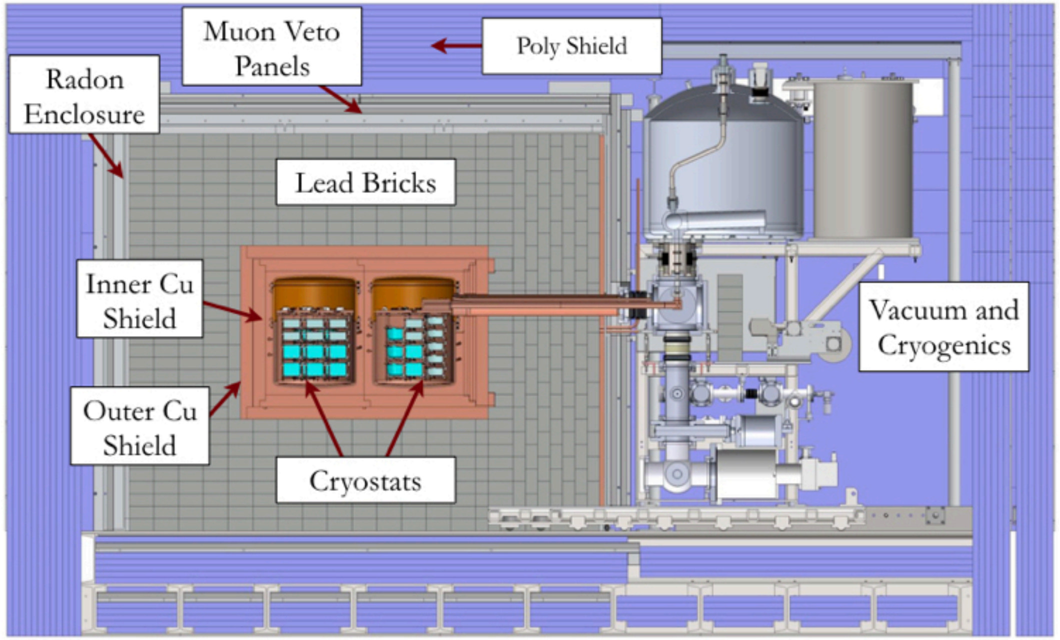
- 12.9 kg of enriched detectors (15 units)
- 8.8 kg of natural detectors (14 units)

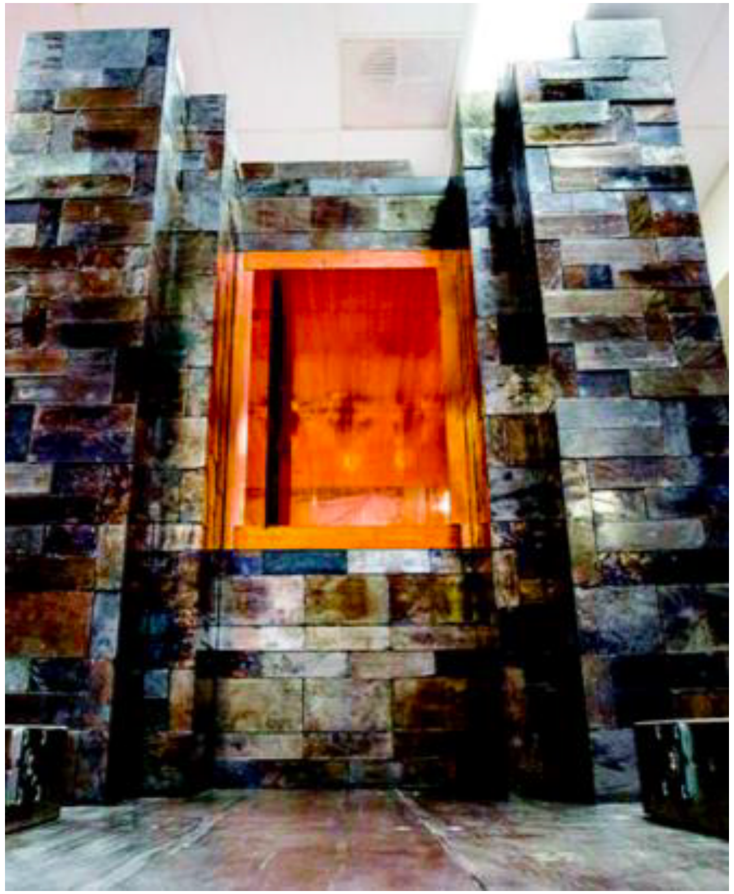


CONTROL OF BACKGROUNDS

Operating underground at the 4850' level of the Sanford Underground Research Facility

- Low mass design
- Ultra-clean material selection
- Assembly and parts storage in N_2 purged environment
- Graded shields
  - Underground electroformed Cu for the inner Cu shield
- Muon veto panels





RUN TIME

		Enriched germanium exposure time (kg-yr)	
Start date	**Comments**	Blind data	Open data
June 2015	Module 1: No inner shield	-	1.26
Dec 2015	Module 1: Inner shield	0.51	1.81
May 2016	Module 1: Multisampling	0.93	0.29
Aug 2016	Module 1 & 2: Separate DAQ	-	1.29
Oct 2016	Module 1 & 2: Combined DAQ	-	3.45
Jan 2017	Module 1 & 2: Construction complete	-	1.85
March 2017	Module 1 & 2: Blindness implemented	1.49	0.48
May 2017	Module 1 & 2: Multisampling	8.93	3.74
		11.86	14.17

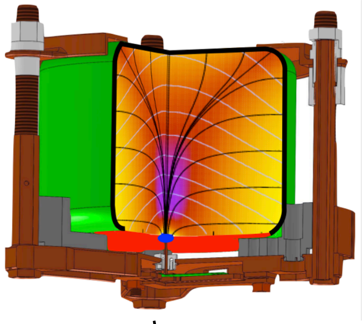
9.95 kg-yr: PRL 120 132502 (2018)

26 kg-yr: arXiv **1902**.02299

The data collected on June 2015-December 2015 and October 2016-January 2017 were taken with a higher background configuration

Ge DETECTOR WAVEFORMS

An interacting particle produces an energy deposition, generating a cloud of charge which is collected in the point of contact

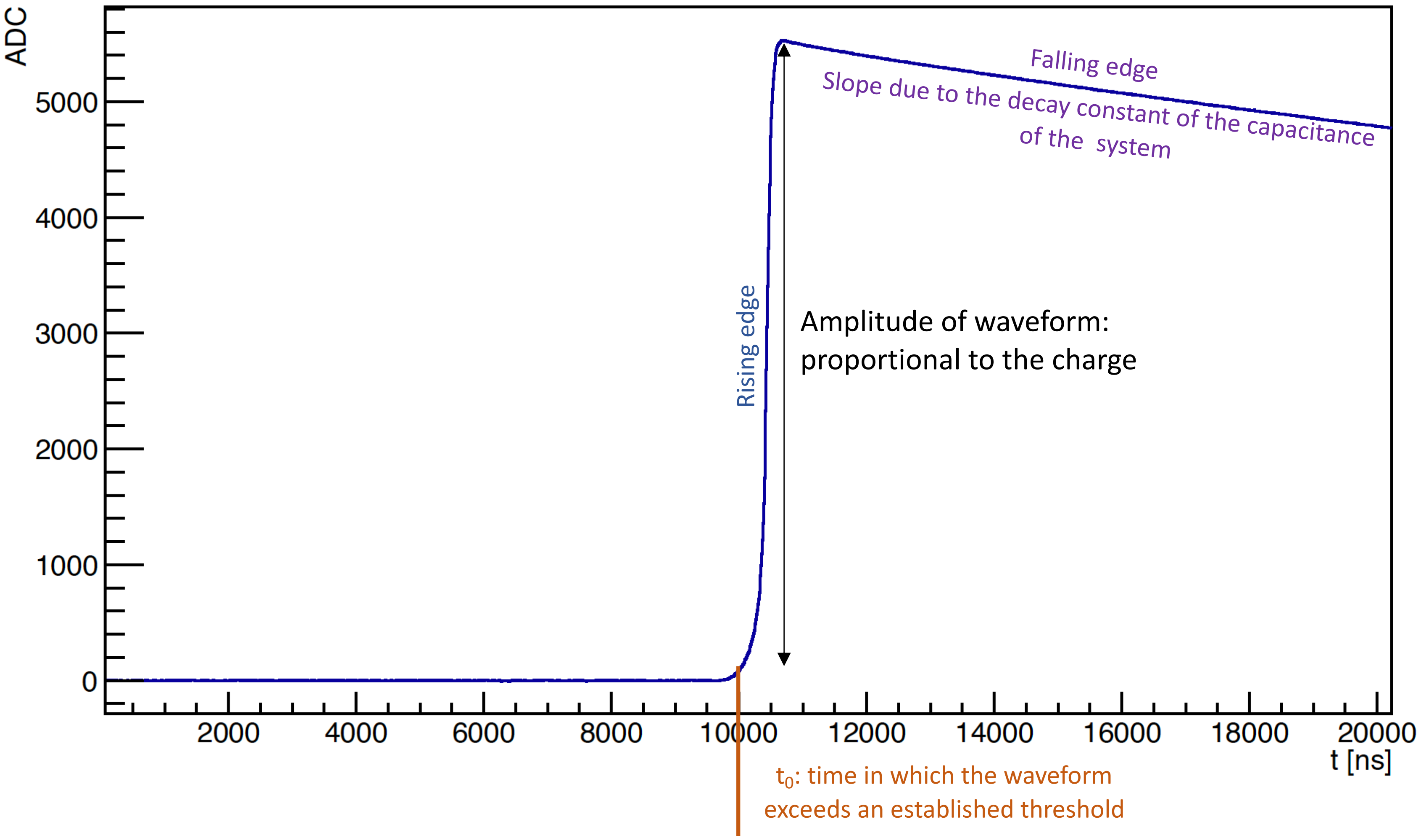


14 bit 100 MS/s digitizers

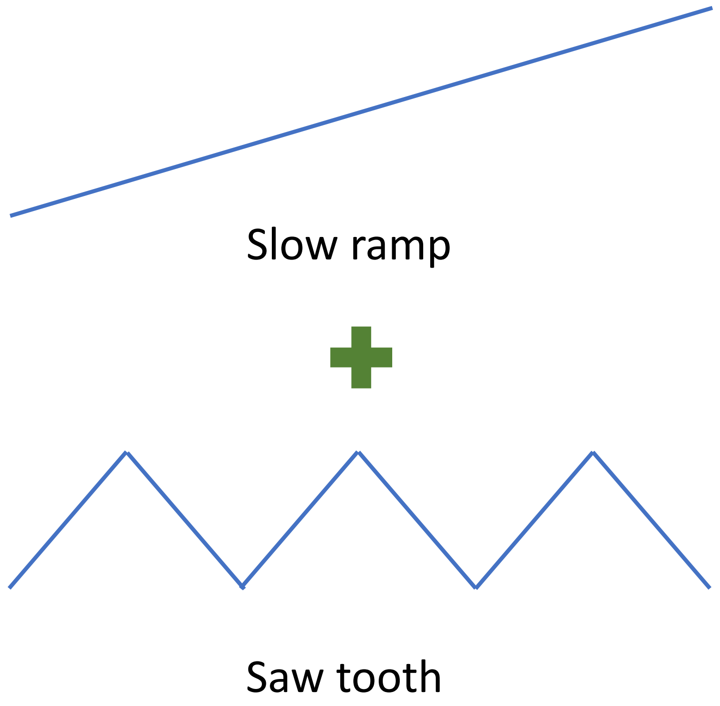
Low gain channel (amplif: ~ 3 times)

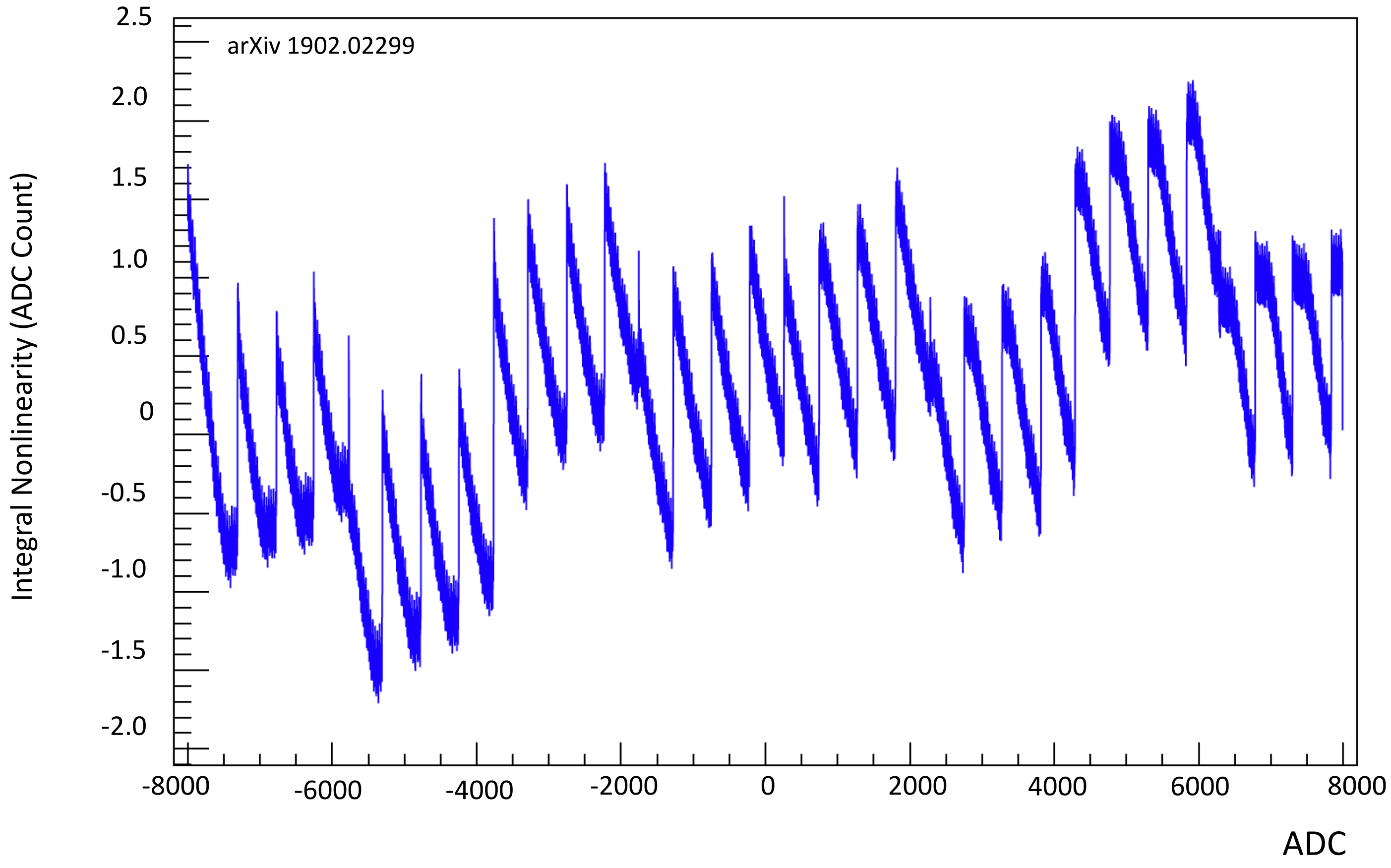
High gain channel (amplif: ~ 10 times)

2 different outputs for each detector



ELECTRONIC NON-LINEARITY





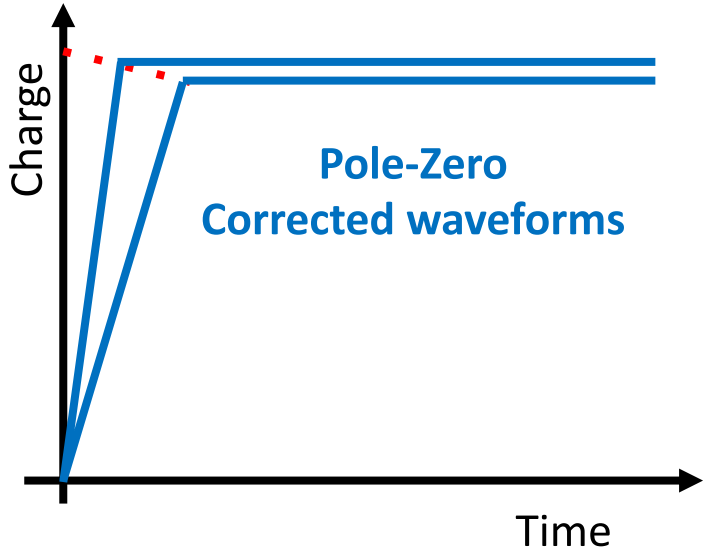
- The **ADC non-linearity** associated to the electronics modifies the output of each sample
- They have to be corrected sample by sample
- An external pulser is used to determine this correction

ENERGY DETERMINATION

The energy is determined using a <u>trapezoidal filter</u> (4μs–2.5μs–4μs) with a decay constant applied

$$\frac{1}{\tau} = \frac{1}{\tau_{PZ}}$$

- PZ (Pole Zero): Intrinsic correction due to the pre-amp (70 μs)

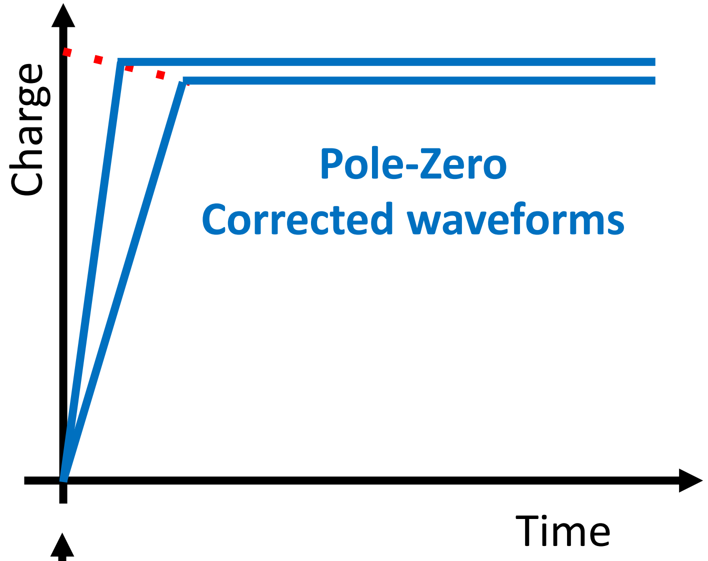


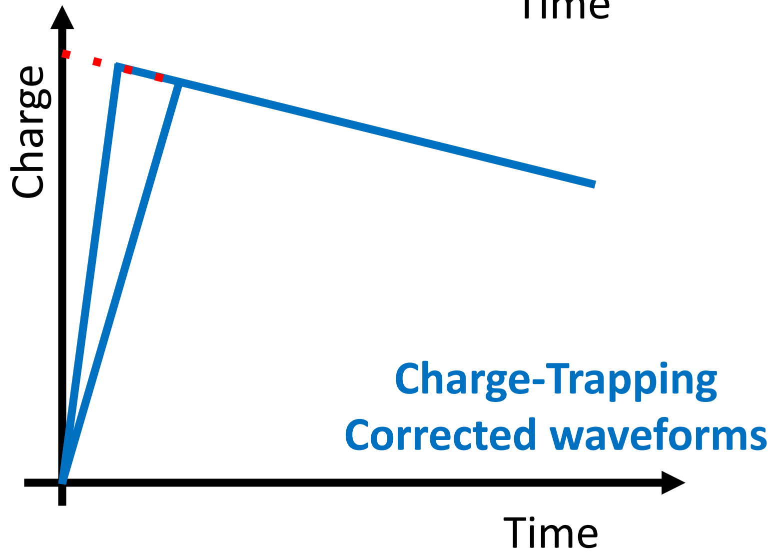
ENERGY DETERMINATION

The energy is determined using a trapezoidal filter (4μs–2.5μs–4μs) with a decay constant applied

$$\frac{1}{\tau} = \frac{1}{\tau_{PZ}} + \frac{1}{\tau_{CT}}$$

- PZ (Pole Zero): Intrinsic correction due to the pre-amp (70 μs)
- CT (Charge Trapping): The detector impurities capture part of the charge before it is collected



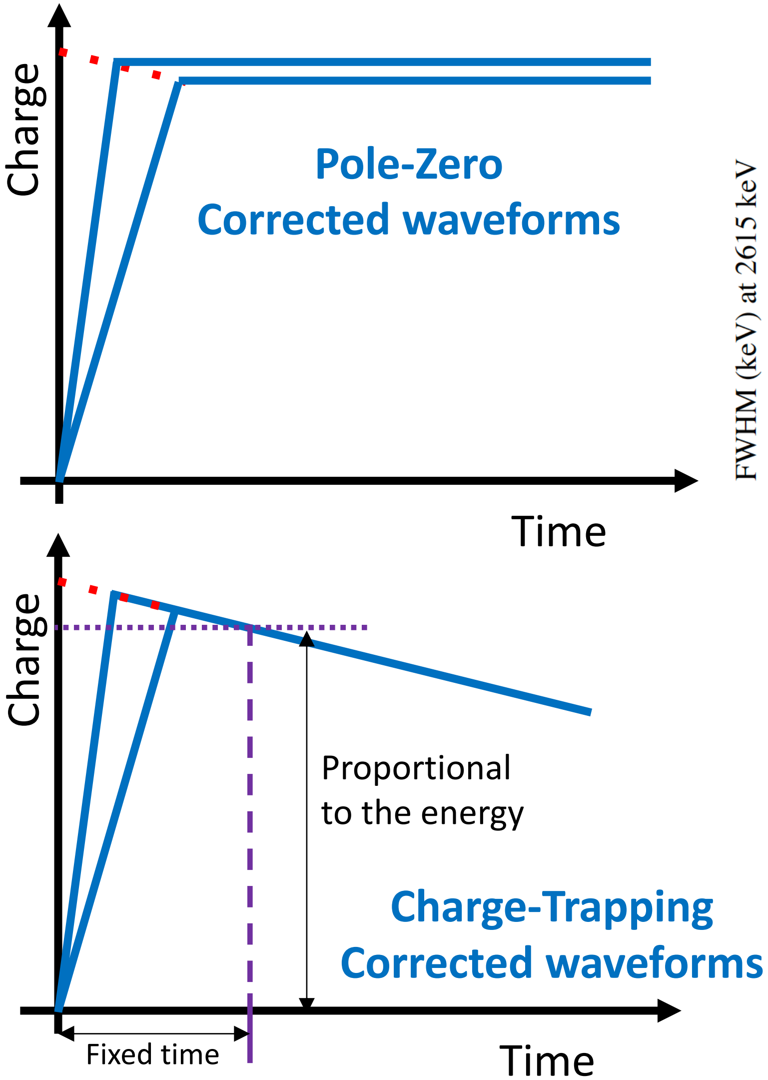


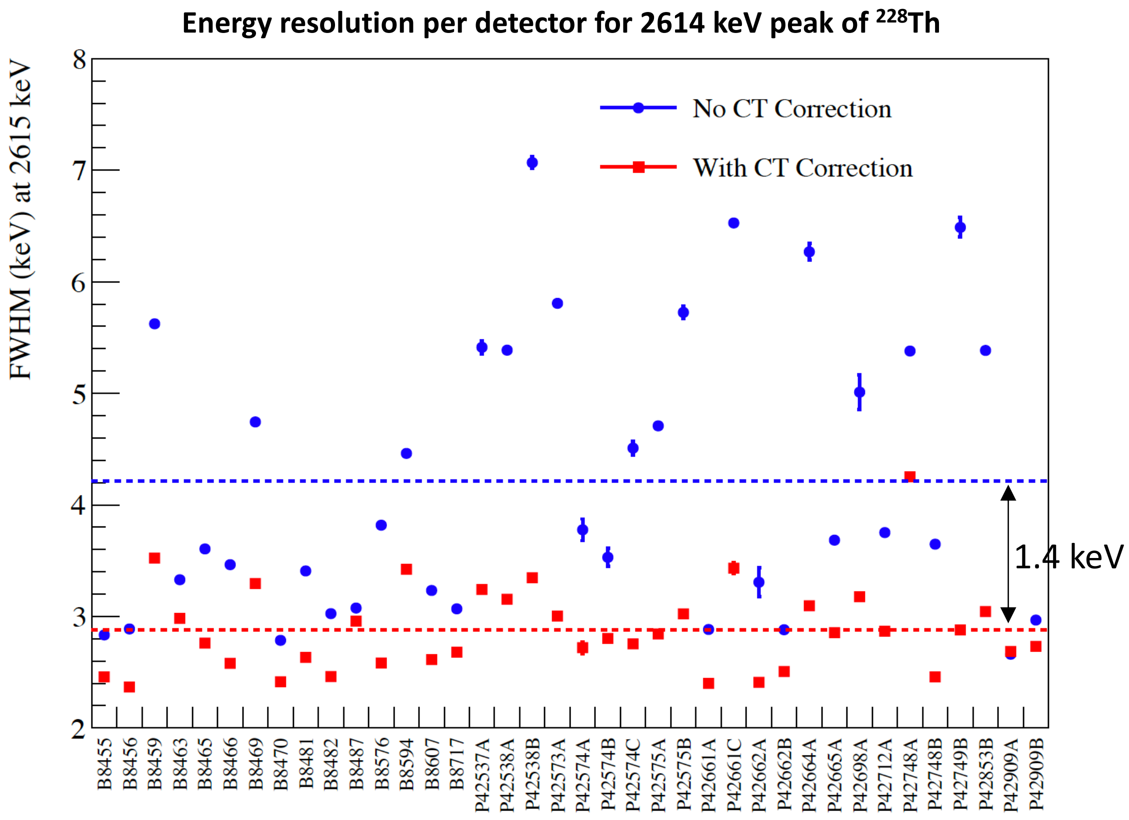
ENERGY DETERMINATION

The energy is determined using a trapezoidal filter (4μs–2.5μs–4μs) with a decay constant applied

$$\frac{1}{\tau} = \frac{1}{\tau_{PZ}} + \frac{1}{\tau_{CT}}$$

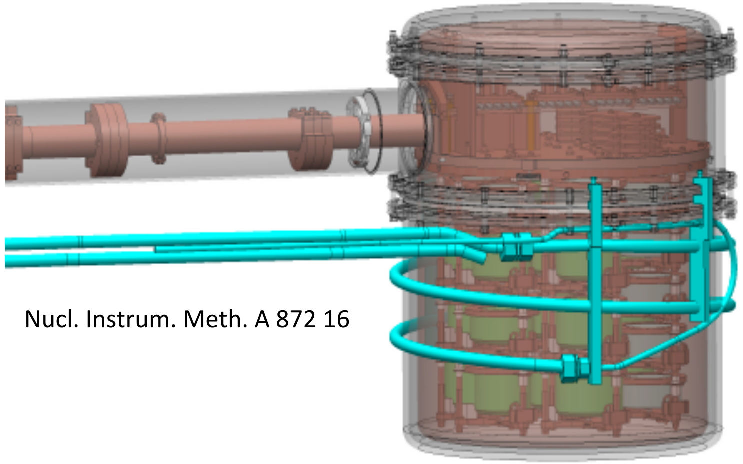
- PZ (Pole Zero): Intrinsic correction due to the pre-amp (70 μs)
- CT (Charge Trapping): The detector impurities capture part of the charge before it is collected
- τ is varied to find the value which minimizes the FWHM in calibration data





ENERGY CALIBRATION I

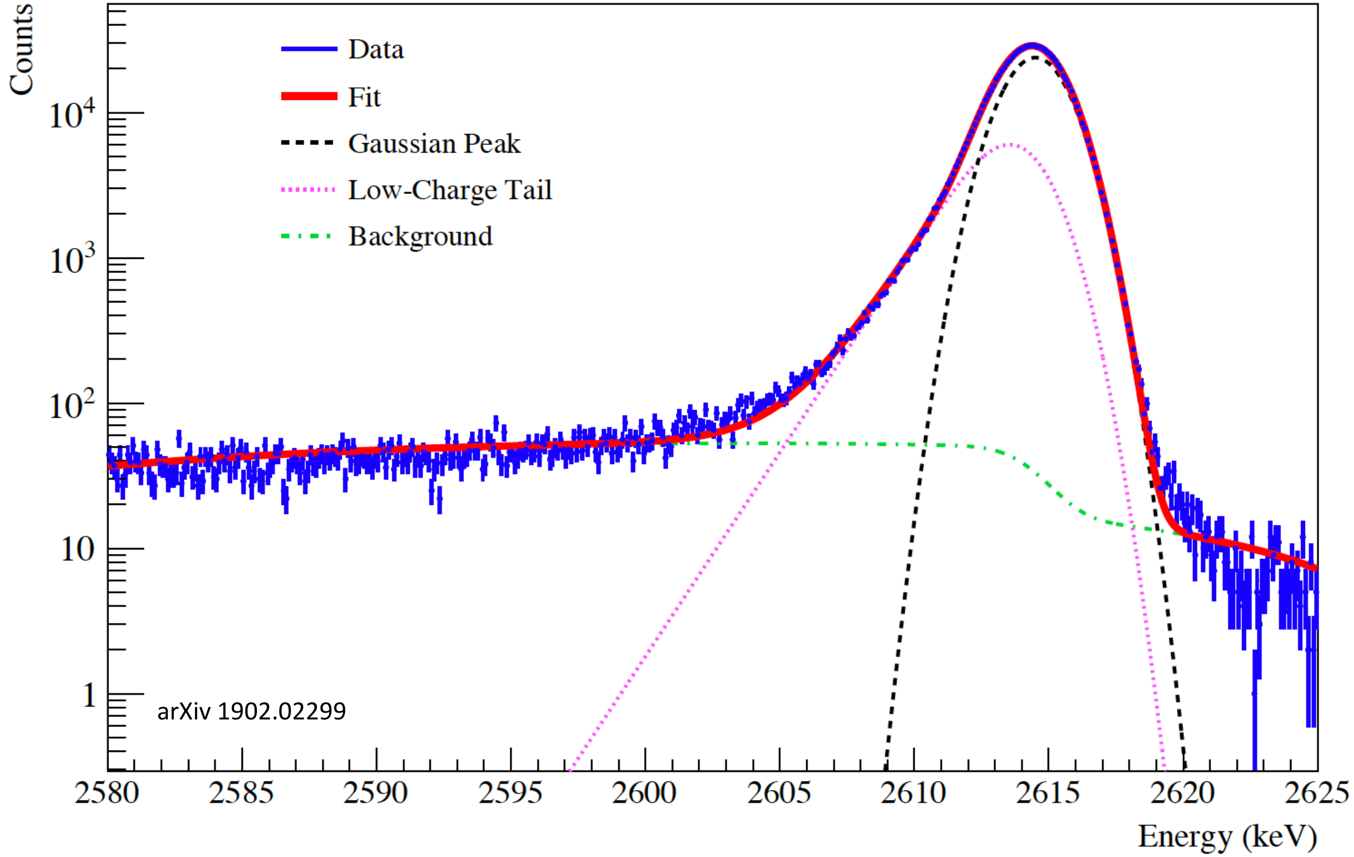
Calibration system



Nucl. Instrum. Meth. A 872 16

The ^{228}Th source is used to take weekly energy calibration

Initial calibration: zero energy + 2614 keV



Flat beackground + peak (gaussian, tail + step function)

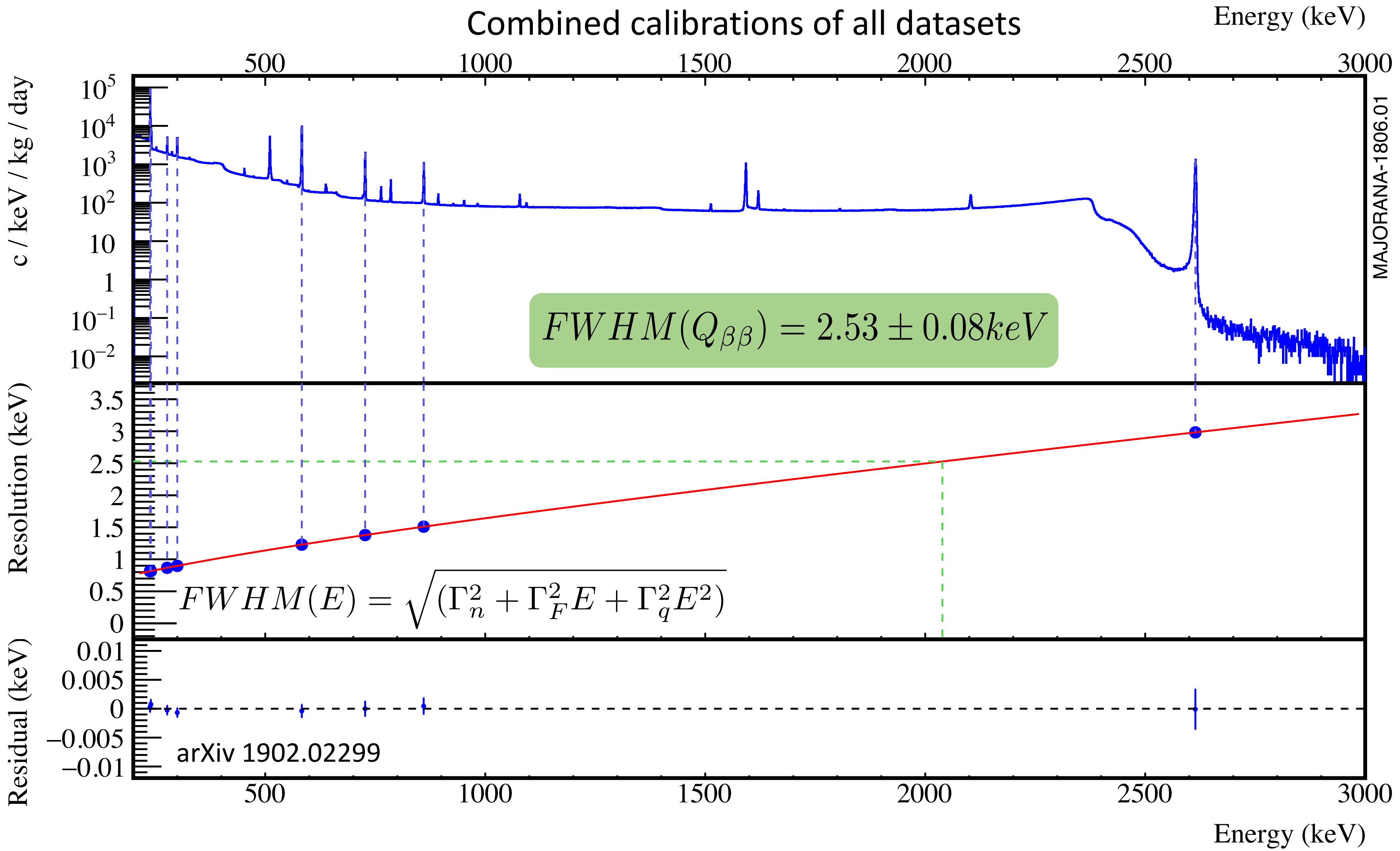
ENERGY CALIBRATION II

Second step: simultaneous fit and combined statistics (by each period)

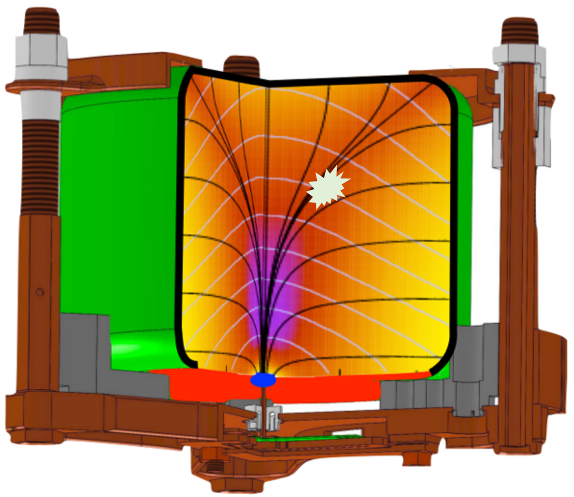
Peaks:

- 238.6 keV
- 241.0 keV
- 277.4 keV
- 300.1 keV
- 583.2 keV
- 727.3 keV
- 860.6 keV
- 2614 keV

Combined calibrations of all datasets

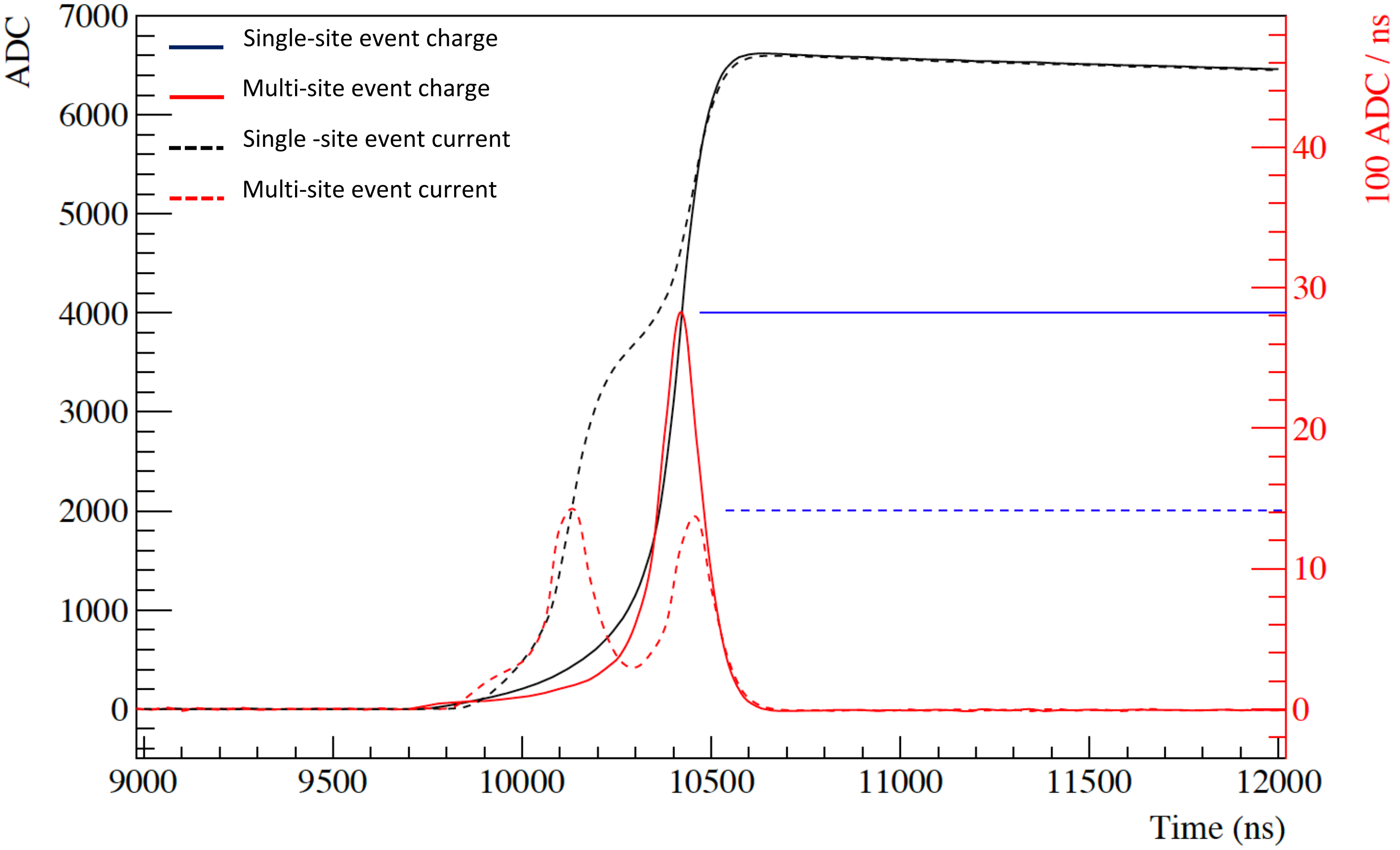


BACKGROUND REJECTION

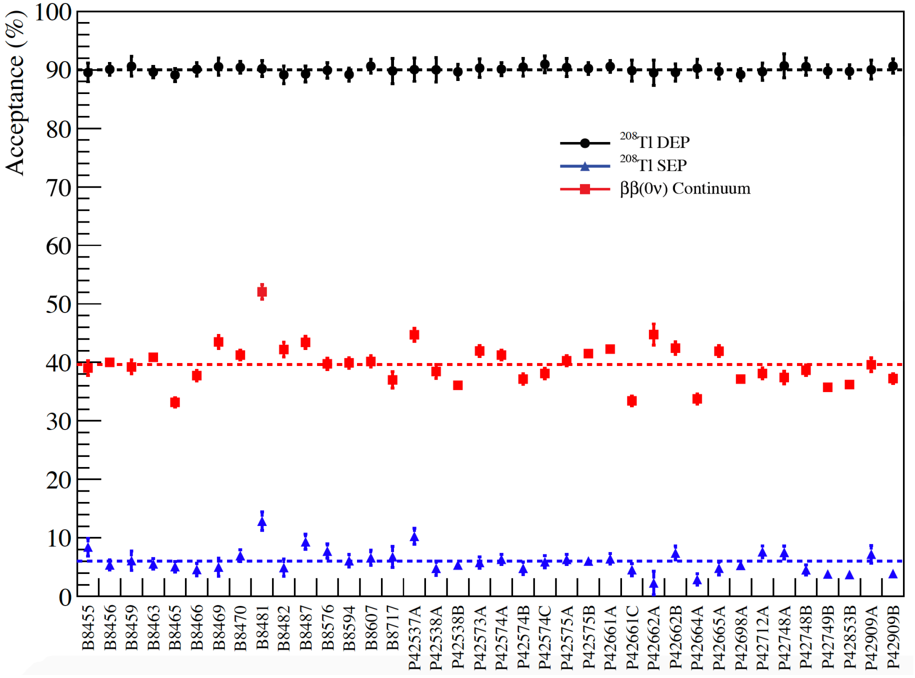


Neutrinoless double beta decay features	**Associated cuts**
It is a real signal (obviously) →	Data cleaning Non-physical signal removal
It is collected in a unique detector →	Multiplicity cut High multiplicity processes, like Compton
It is not produced by muon →	Muon veto Events rejected within 1s after a muon trigger
It is a single-site energy deposition →	AvsE (next slides)
It is not an alpha particle →	DCR (next slides)

MULTI-SITE EVENT REJECTION



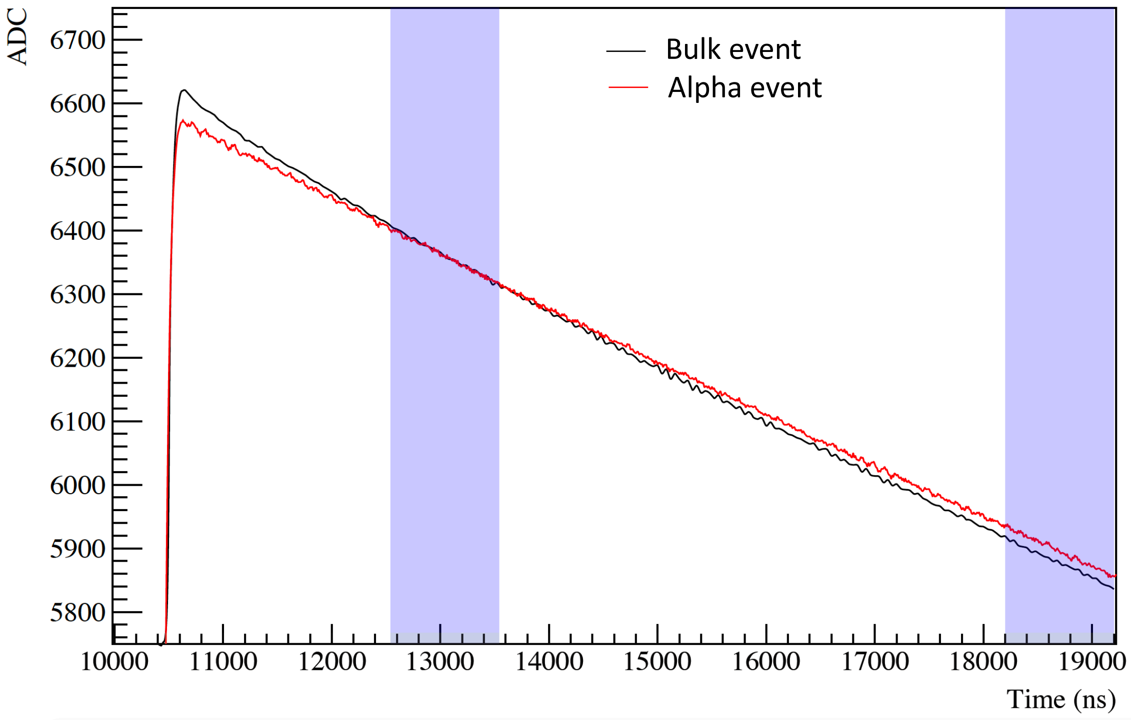
- Slow drift: depositions in different positions are collected at different times
- For the same energy: the maximal current of multi-site events is smaller (AvsE)

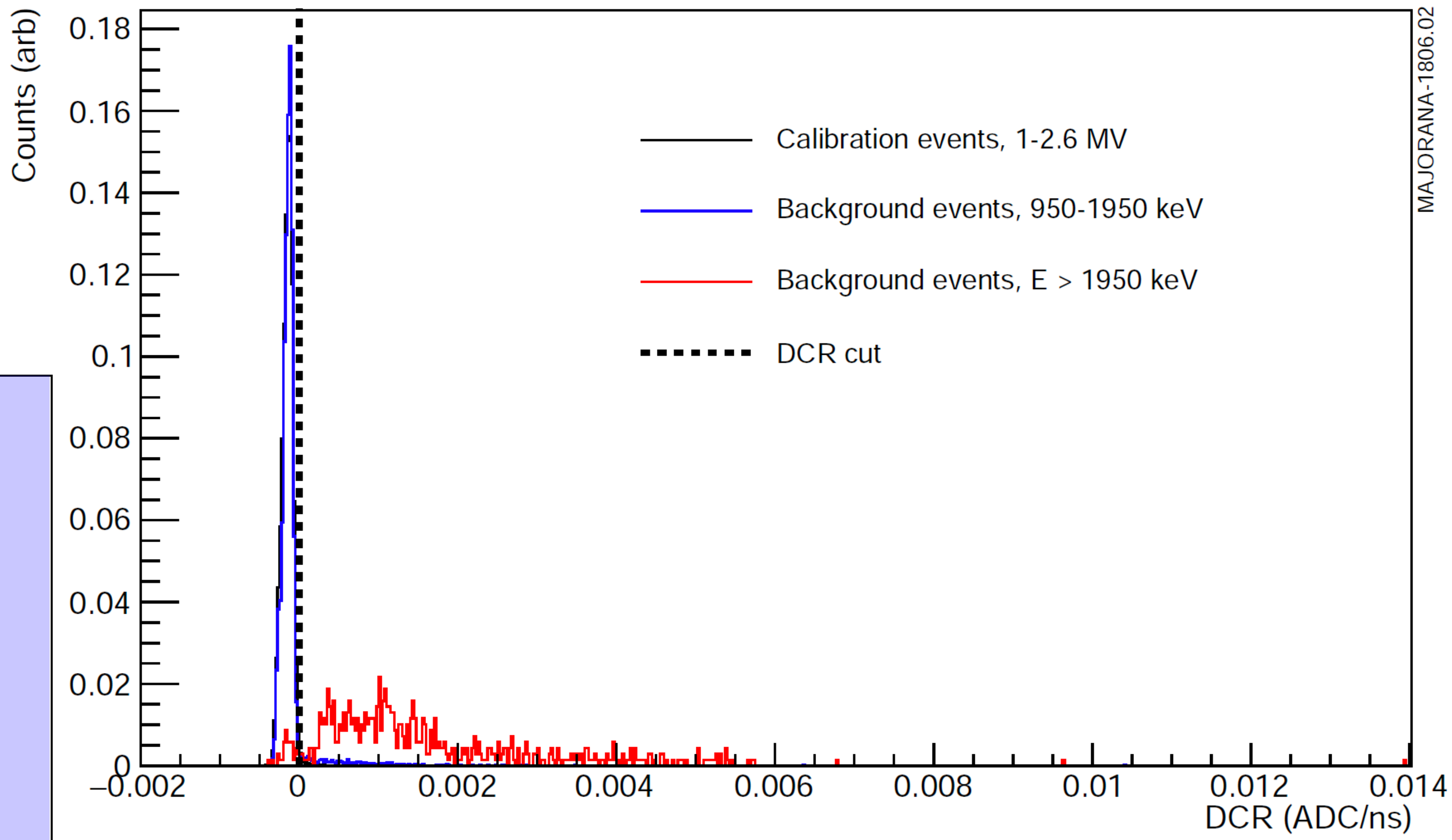


The cut is established to accept a 90% of the double escape events of the 2614 keV photons

SURFACE ALPHA DISCRIMINATION

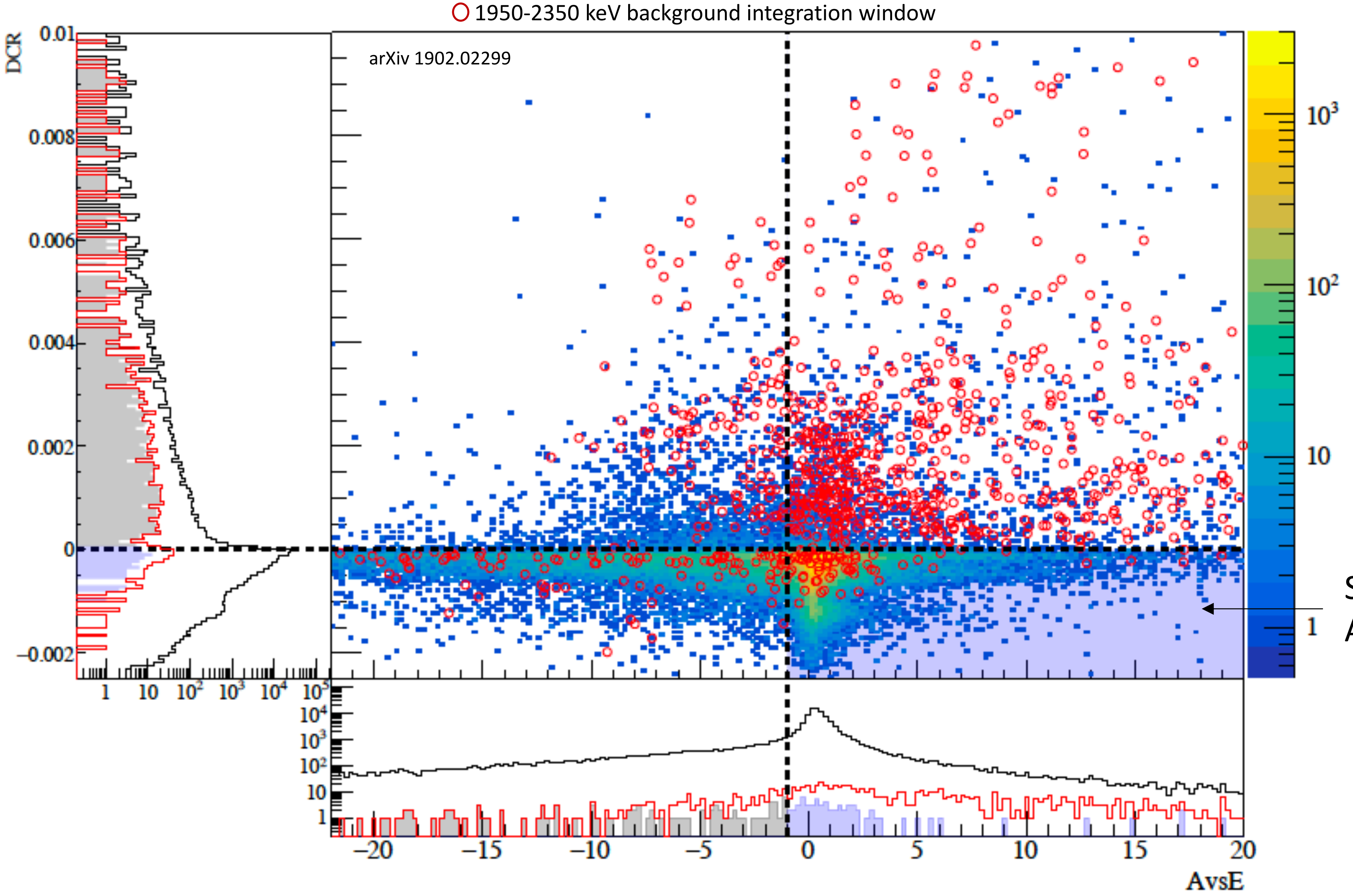
- α impinging on the n+ contact cannot penetrate the dead layer of the detector
- Energy deposition in the vicinity of the passivated surface results in trapping of charges which are slowly released into the bulk
- The slope of the waveform after the initial charge collection is used as a simple discriminant: delayed charge recovery (DCR)





DCR cut is highly efficient, accepting 99% of signal-like events

DCR vs AvsE

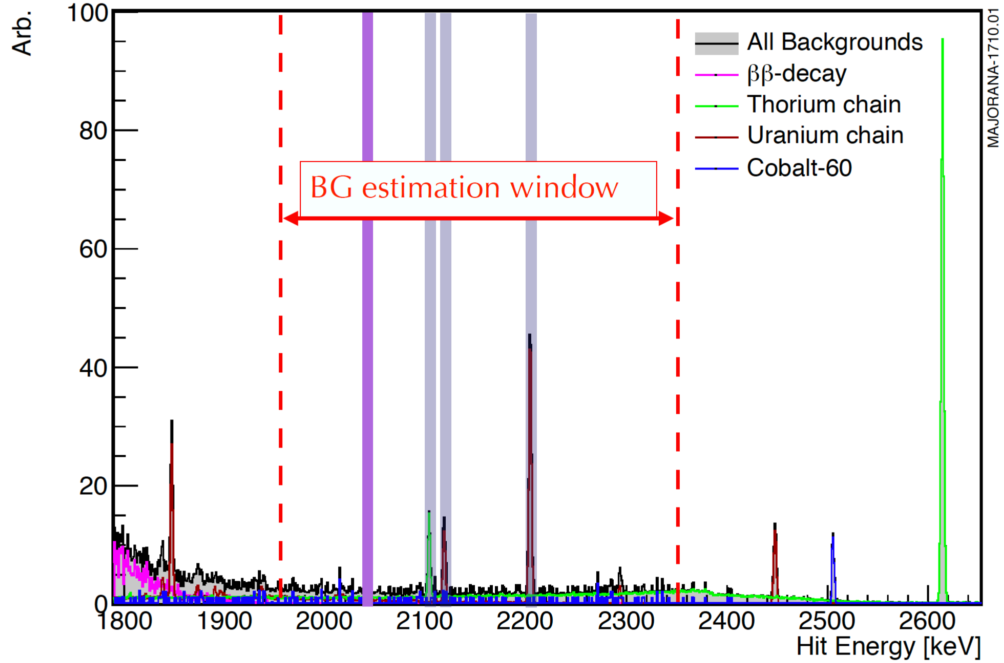


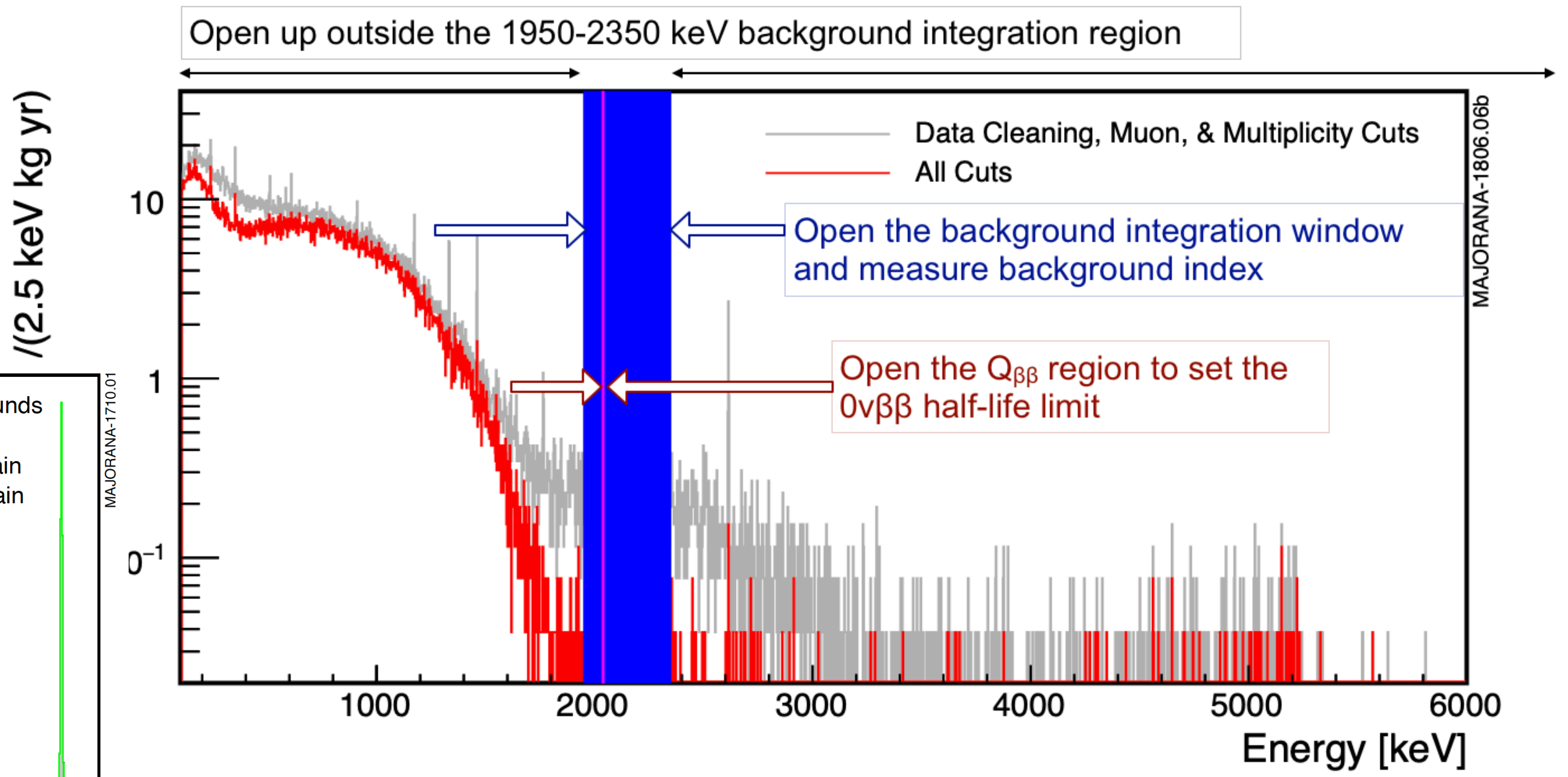
Shadow region:
Accepted events

BLINDING IMPLEMENTATION

Sequential process:

1. Open outside 1950-2350 keV
   - Sanity, exposure, …
2. Open outside 2034-2044 keV
   - Calculate the background index
3. Open everything
   - Calculate the half-life



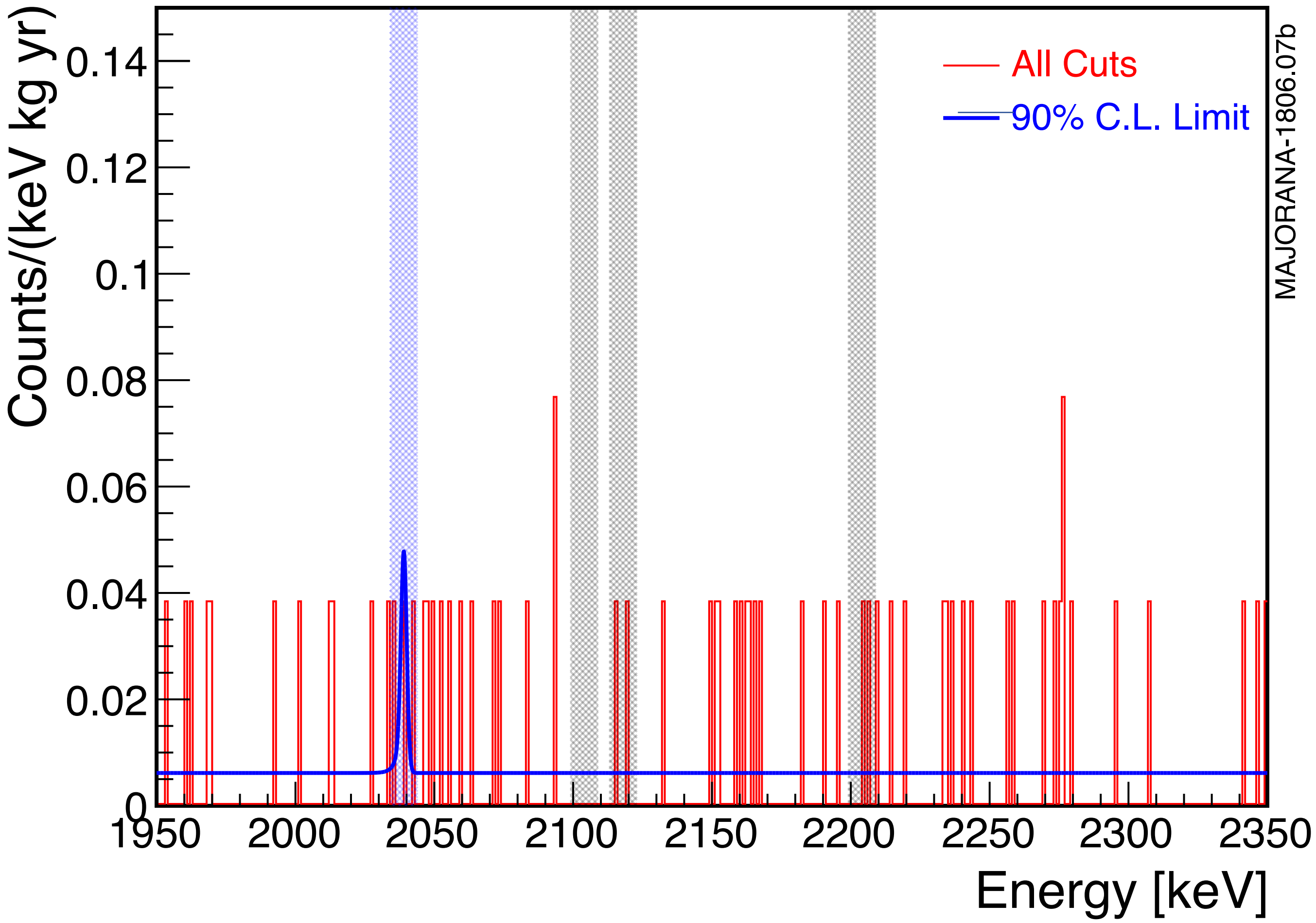


SUMMARY OF EXPOSURE AND EFFICIENCY

Start date	Exposure (kg-yr)	Eff_{AE}	Eff_{DCR}	Eff_{count}	Eff_{tot}	$NTEff_{tot}Eff_{res}$ (10^{24} atom yr)*
June 2015	1.26(2)	$0.901^{+0.032}_{-0.035}$	$0.989^{+0.009}_{-0.002}$	0.908(11)	$0.808^{+0.031}_{-0.033}$	$6.34^{+0.25}_{-0.27}$
Dec 2015	2.32(4)	$0.901^{+0.036}_{-0.040}$	$0.991^{+0.010}_{-0.005}$	0.909(11)	$0.811^{+0.035}_{-0.038}$	$11.82^{+0.53}_{-0.58}$
May 2016	1.22(2)	$0.903^{+0.035}_{-0.037}$	$0.986^{+0.011}_{-0.005}$	0.909(11)	$0.809^{+0.034}_{-0.035}$	$6.24^{+0.28}_{-0.29}$
Aug 2016 (M1)	1.01(1)	$0.900^{+0.030}_{-0.031}$	$0.990^{+0.010}_{-0.003}$	0.909(11)	$0.809^{+0.030}_{-0.030}$	$5.18^{+0.20}_{-0.20}$
Aug 2016(M2)	0.28(0)	$0.900^{+0.031}_{-0.034}$	$0.992^{+0.011}_{-0.002}$	0.908(10)	$0.809^{+0.030}_{-0.032}$	$1.47^{+0.06}_{-0.06}$
Oct 2016	3.45(5)	$0.900^{+0.034}_{-0.036}$	$0.969^{+0.013}_{-0.013}$	0.909(13)	$0.792^{+0.034}_{-0.035}$	$17.17^{+0.76}_{-0.79}$
Jan 2017	1.85(3)	$0.900^{+0.031}_{-0.033}$	$0.985^{+0.014}_{-0.005}$	0.909(13)	$0.805^{+0.032}_{-0.032}$	$9.46^{+0.39}_{-0.39}$
March 2017	1.97(3)	$0.900^{+0.031}_{-0.033}$	$0.985^{+0.012}_{-0.003}$	0.908(11)	$0.806^{+0.031}_{-0.031}$	$10.31^{+0.47}_{-0.47}$
May 2017	12.67(19)	$0.901^{+0.032}_{-0.032}$	$0.990^{+0.008}_{-0.002}$	0.908(11)	$0.811^{+0.030}_{-0.030}$	$65.10^{+2.92}_{-2.92}$
	26.02(53)					133.1 (6.3)
Without colored periods	21.31(41)					110.0 (5.1)

*The efficiency due to the resolution varies slightly. The exposure weighted value over all data sets is 0.900(7).

0νββ RESULTS (26 kg-yr)



Start date	Window counts	BI 10^{-3} (keV kg yr)	ROI (keV)	ROI BG (counts)
June 2015	11	$24.3^{+8.4}_{-7.0}$	3.93	0.120
Dec 2015	5	$6.0^{+3.4}_{-2.7}$	4.21	0.058
May 2016	2	$4.6^{+5.1}_{-2.9}$	4.34	0.024
Aug 2016 (M1)	0	< 3.6	4.39	0.000
Aug 2016(M2)	0	< 12.7	4.25	0.000
Oct 2016	10	$8.0^{+3.1}_{-2.6}$	4.49	0.125
Jan 2017	0	< 1.9	4.33	0.000
March 2017	5	$7.0^{+4.0}_{-3.2}$	4.37	0.061
May 2017	24	$5.3^{+1.2}_{-1.0}$	3.93	0.262
	57	6.1 ± 0.8	4.13	0.653
Low Bg	36	4.7 ± 0.8	4.14	0.529

Full exposure: (15.4 ± 2.0) c/(FWHM t yr)

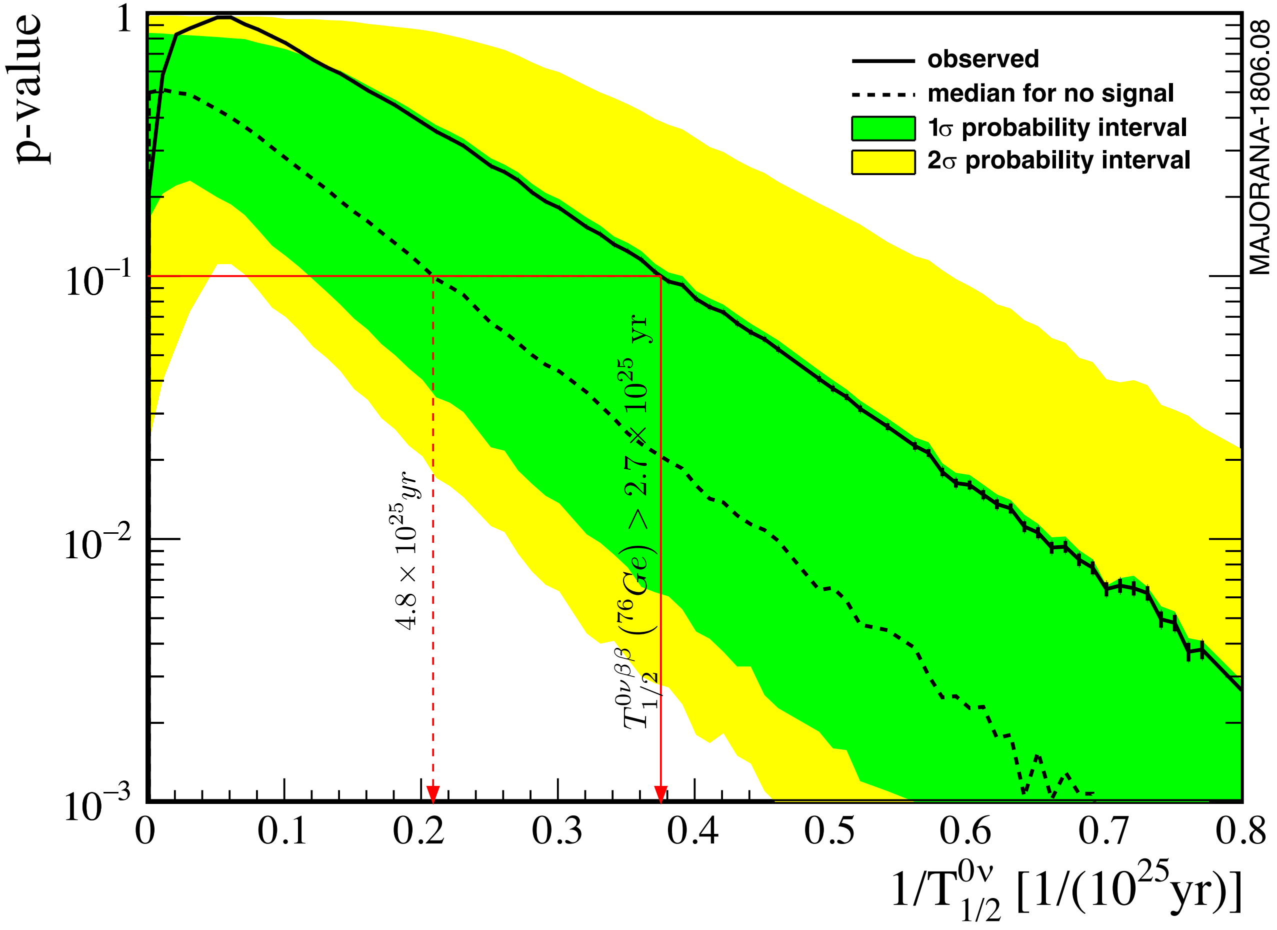
Low bkg configuration: (11.9 ± 2.0) c/(FWHM t yr)

Observed counts in the optimal ROI (4.17keV): 1 →

$$T_{1/2}^{0\nu\beta\beta}\left({}^{76}Ge\right) > 2.7 \times 10^{25}\ \text{yr}$$

arXiv:1902.02299, accepted by PRC

$0\nu\beta\beta$ RESULTS (26 kg-yr)



Method	Exclusion limit
Nominal profile likelihood	$2.7 \times 10^{25} yr$
Feldman-Cousins	$2.5 \times 10^{25} yr$
Modified profile likelihood (CLS)	$2.5 \times 10^{25} yr$
Bayesian flat decay rate prior	$2.5 \times 10^{25} yr$

Median sensitivity (90% CL)

$$4.8 \times 10^{25} yr$$

Using:

$$g_A = 1.27$$

$$G_{0\nu} = (2.36 - 2.37) \times 10^{-15} yr^{-1}$$

$$M_{0\nu} = 2.81 - 6.13$$

$$\langle m_{\beta\beta} \rangle < (200 - 433)\,\text{meV}$$

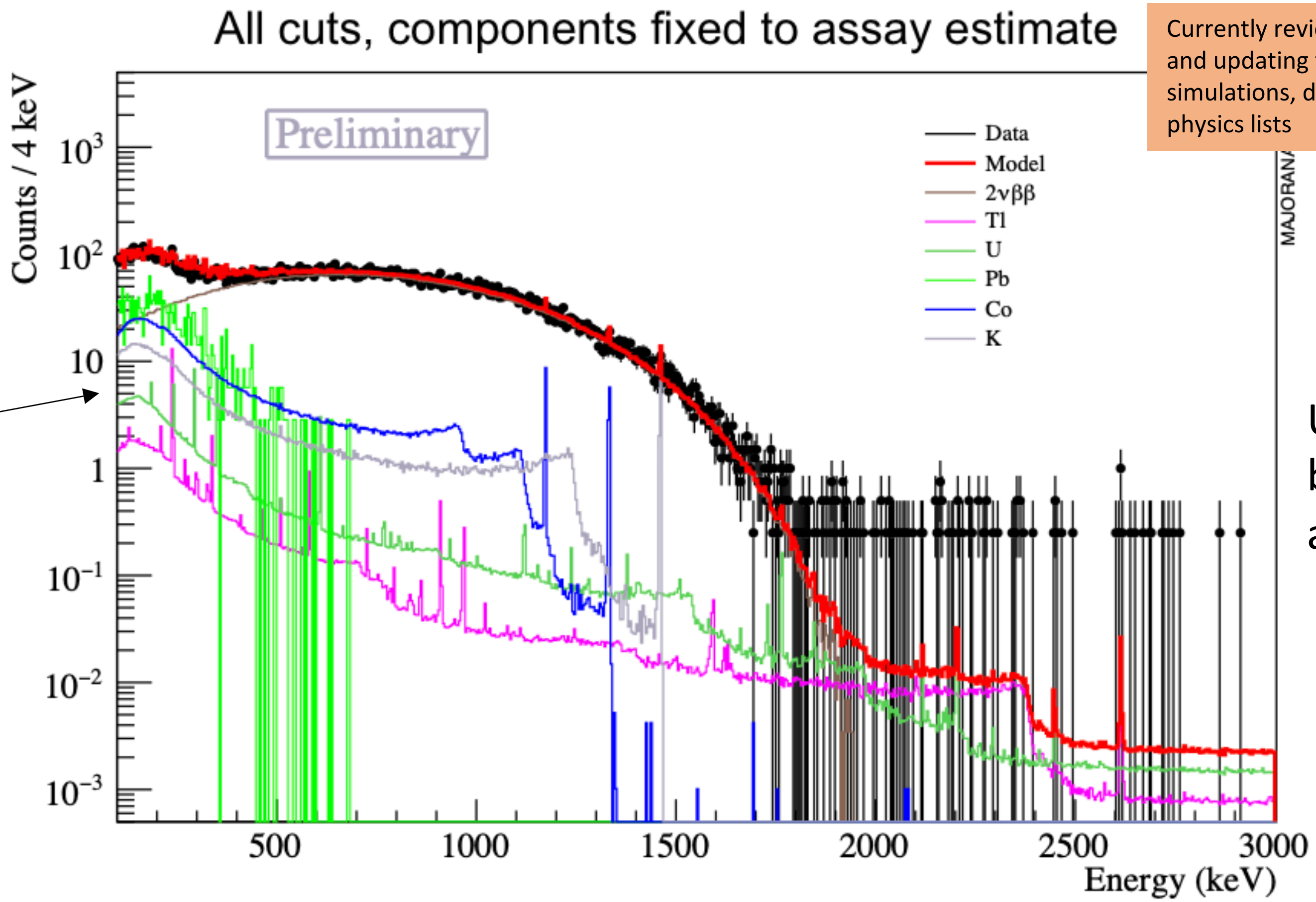
arXiv:1902.02299, accepted by PRC

BACKGROUND MODEL

- Ratio of ^{208}Tl 2614 keV to low energy peaks suggests **missing activity**
- Initial analysis suggests source of excess **is not nearby the detectors**
- Coincidences between 583 keV and 2614 keV gammas (^{208}Tl to ^{208}Pb): **1 observed vs 5-10 expected for nearby components**
- Complete background model fit under development

Sum over the components for decay chain contributions

Assume secular equilibrium

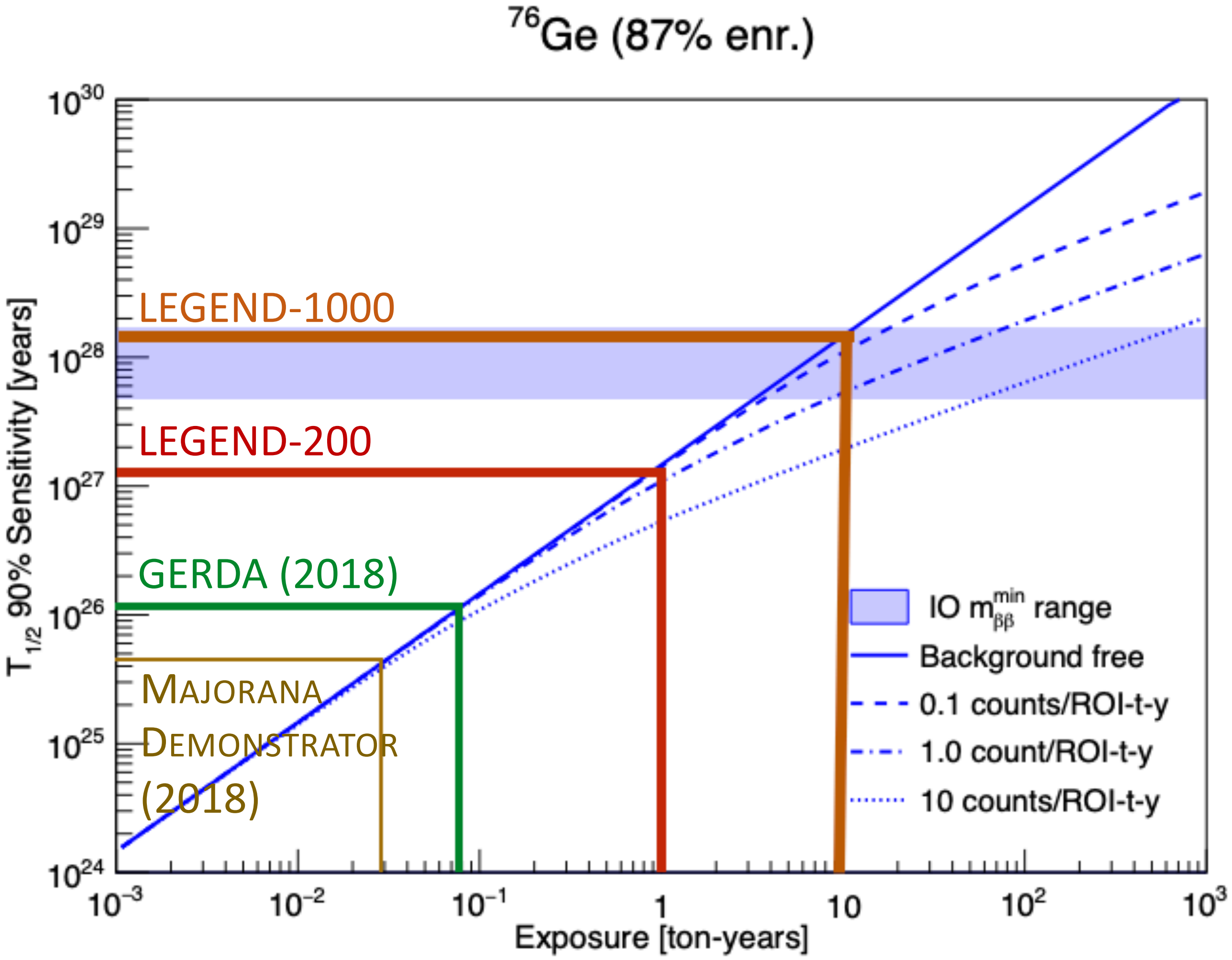


Currently reviewing available assay information and updating the assay-based model with as-built simulations, detector configurations, and updated physics lists

Under-predicted backgrounds seem attributable to ^{232}Th

^{76}Ge 0νββ NEXT EXPERIMENT GENERATION

Next generation ^{76}Ge: LEGEND (Large Enriched Germanium Experiment for Neutrinoless ββ Decay)
52 institutions, about 250 members



First stage:

200 kg ^{76}Ge (GERDA + MAJORANA + New)
Location: LNGS
Start data: 2021
BG goal: 0.6 count/(FWHM*kg-yr)

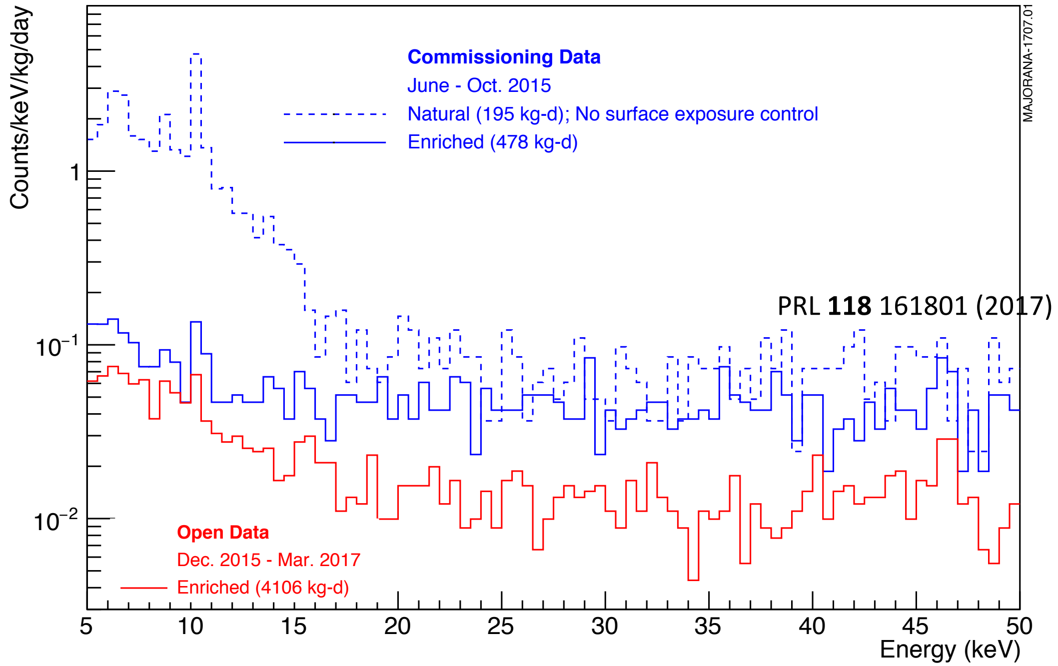
Subsequent stages:

1 ton ^{76}Ge (200 kg + New)
Location: TBD
BG goal: <0.1 count/(FWHM*kg-yr)

BEYOND THE STANDARD MODEL SEARCHES

The low backgrounds, low threshold, high resolution spectra allows additional searches

Controlled surface exposure of enriched material to minimize cosmogenics



Low energy spectra during commissioning (blue) and first low-background physics runs (red)

Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

Ongoing effort on:

- low energy data cleaning, de-noising
- low energy cut development & efficiencies

Permits low-energy physics

- Pseudoscalar and vector dark matter
- 14.4-keV solar axion,
- $e^- \rightarrow 3\nu$,
- Pauli Exclusion Principle

PRL **118** 161801 (2017)

- First limit on the direct detection of lightly ionizing particles for electric charge as low as e/1000

  PRL **120** 211804 (2018)

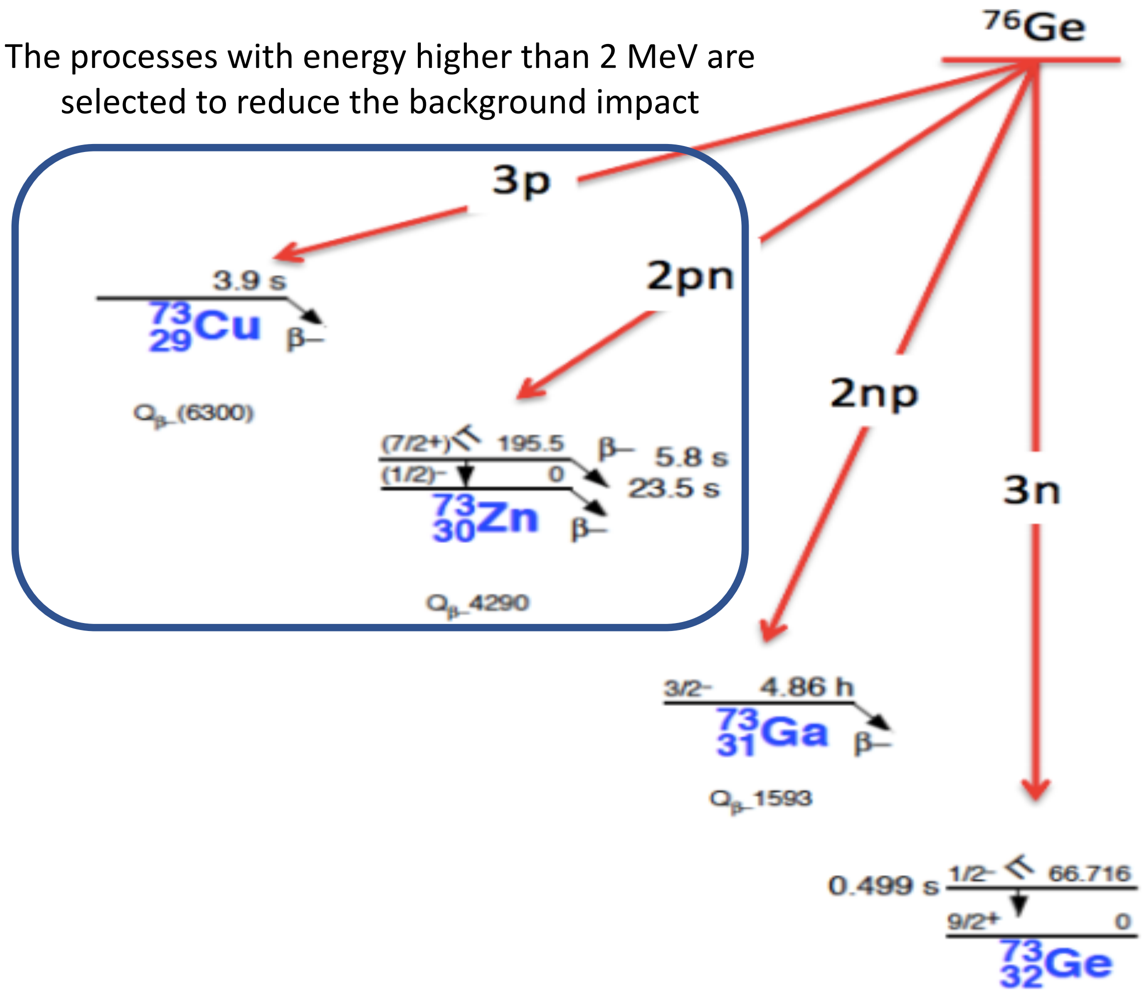
- Tri-Nucleon decay (test of baryon number violation)

  PRD 99 (2019) 072004

TRINUCLEON DECAY

PRD 99 (2019) 072004

The processes with energy higher than 2 MeV are selected to reduce the background impact



- The anomaly free Z_6 symmetry of SM can be cancelled by right-handed neutrinos
  - $\Delta B=1$ or $\Delta B=2$ processes are forbidden
  - $\Delta B=3$ are not forbidden
- If the daughter is unstable, its decay rate can be interpreted in terms of the trinucleon decay half life
- Two different analyses:
  - Invisible mode
  - Specific decay mode

	Eff (%)	**Half-Life (10^{25} yr)**
^{76}Ge(ppp)	92	>4.7
^{76}Ge(ppn)	96	>4.9

90% CL

TRINUCLEON DECAY

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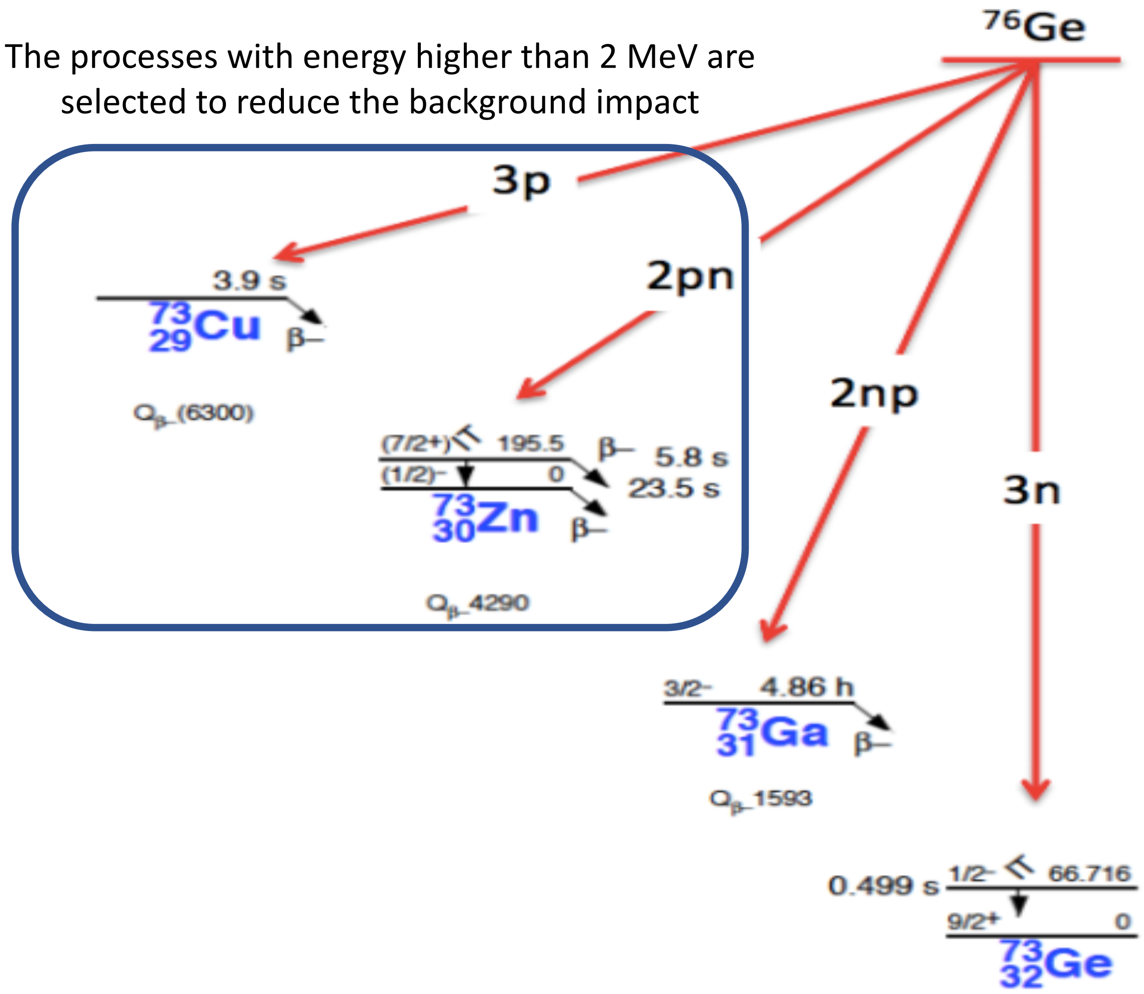
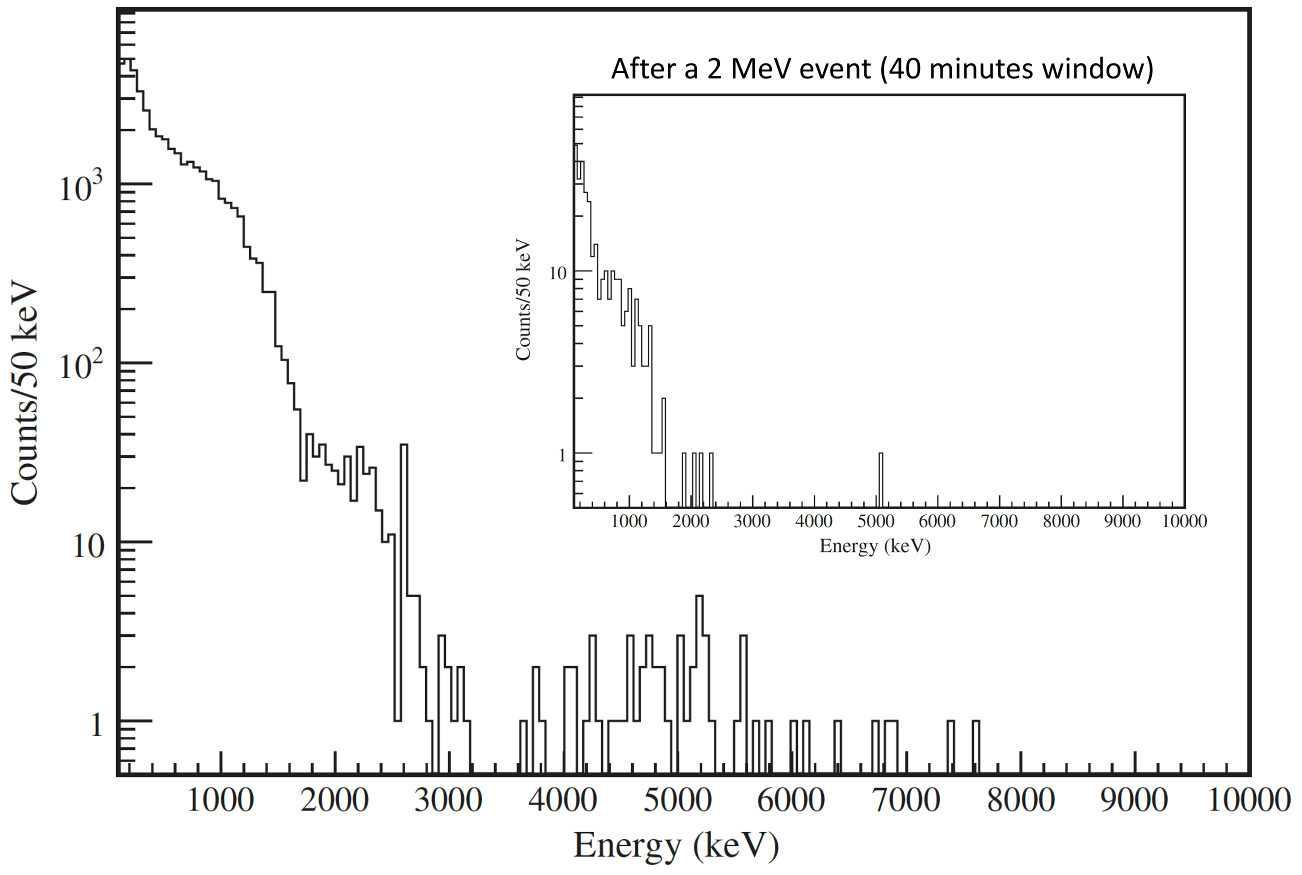


After a 100 keV event (40 minutes window)



SUMMARY

- MAJORANA DEMONSTRATOR has been taking data since June 2015 and, in its final configuration since Spring 2017
- The HPGe detectors and the energy calibration algorithm of MAJORANA DEMONSTRATOR allow to reach the best energy resolution for $0\nu\beta\beta$: $2.53 \pm 0.08\ \mathrm{keV}$ in the ROI
- Algorithms to reject multi-site events and alpha events have been developed and are currently being improved for further background rejection
- A complete background model is under development
- Latest $0\nu\beta\beta$ measurement (arXiv:1902.02299, accepted by PRC) with 26 kg-year :

$$T_{1/2}^{0\nu\beta\beta}\left({}^{76}Ge\right) > 2.7 \times 10^{25}\ \mathrm{yr}$$

- Low background + low threshold allows for broad physics program
- The experience with the different technologies used by MAJORANA DEMONSTRATOR is a valuable information for the next generation experiment: LEGEND

THANKS

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