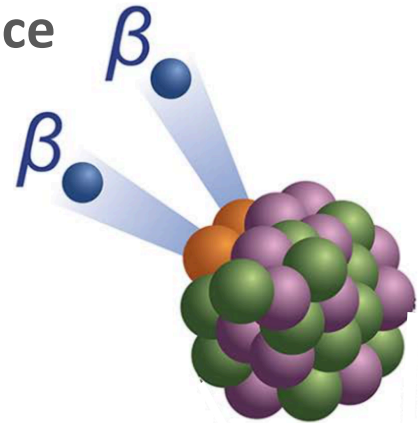
GERDA, MAJORANA and LEGEND
towards a background-free ton-scale Ge-76 experiment

Yoann KERMAÏDIC
for the GERDA, MAJORANA and LEGEND collaborations

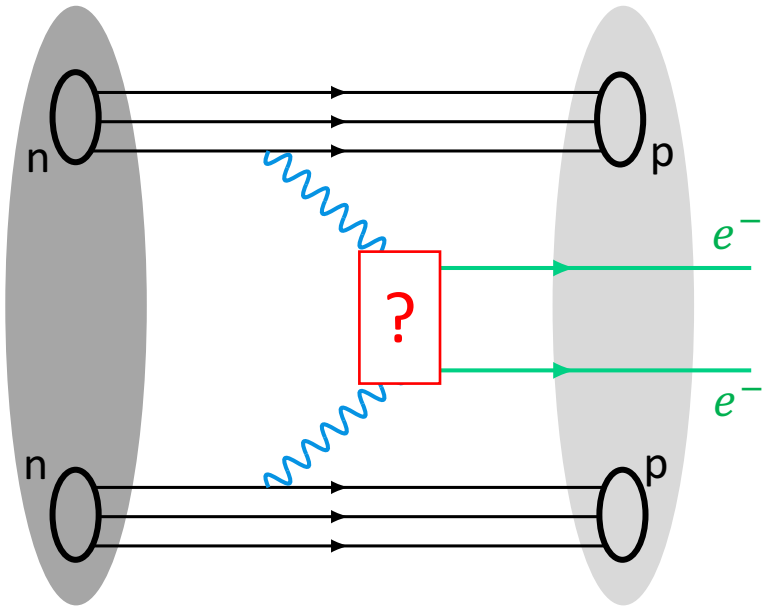
XXIX International Conference on Neutrino Physics

Virtual meeting
July 2020



Physics case: neutrinoless $\beta\beta$ decay

Search for a natural **double beta decay**
without the standard emission of **two anti-neutrinos** ($0\nu\beta\beta$)



$0\nu\beta\beta$ decay is a search for **lepton number violation**:

☞ **sheds light on Majorana nature of neutrinos**

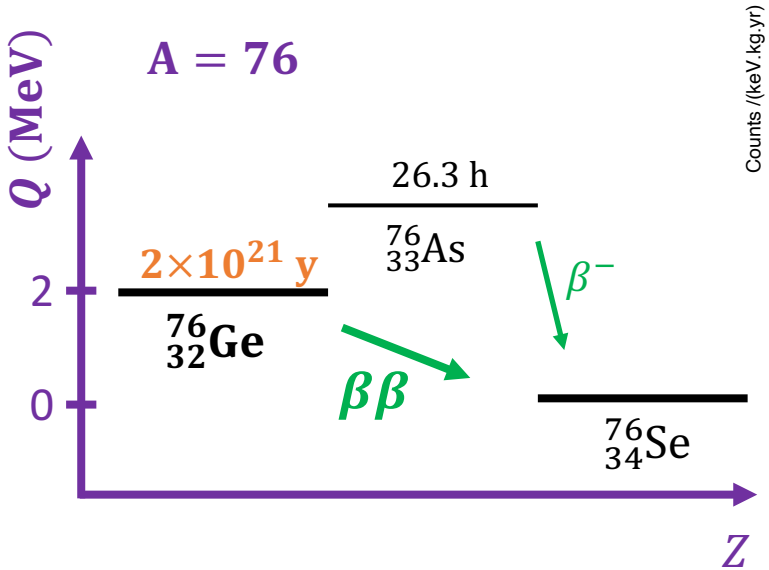
☞ **tests theories with lepton number violating interactions**

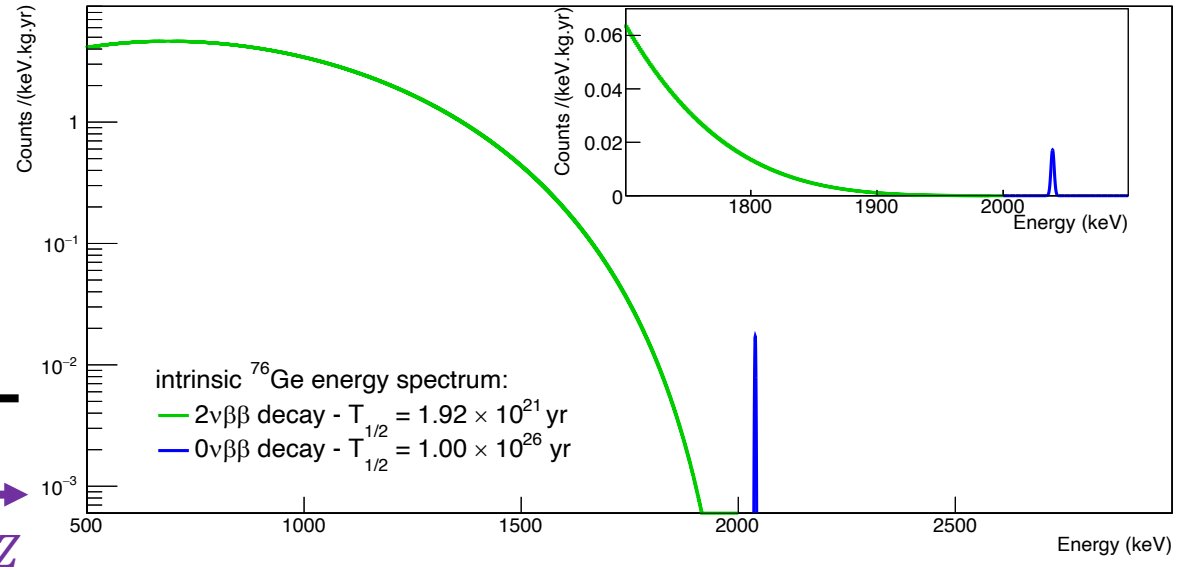
☞ **constrains baryon asymmetry scenarios**

$\beta\beta$ decay is energetically **favoured in many isotopes**:

^{76}Ge – ^{82}Se – ^{100}Mo – ^{130}Te – ^{136}Xe – …

$0\nu\beta\beta$ experimental signature in ^{76}Ge





Signature: Expected **line at the ^{76}Ge Q-value** (2039.061 $\pm$ 0.007 keV) for a given decay half-life $T_{1/2}^{0\nu}$ above measured $2\nu\beta\beta$ continuum

Why Ge detectors?:

High detection efficiency (detector = $\beta\beta$ source)

Enrichment from 7.7% to ~88% (up to ~92%)

Best proved energy resolution at the Q-value (~0.13% FWHM)

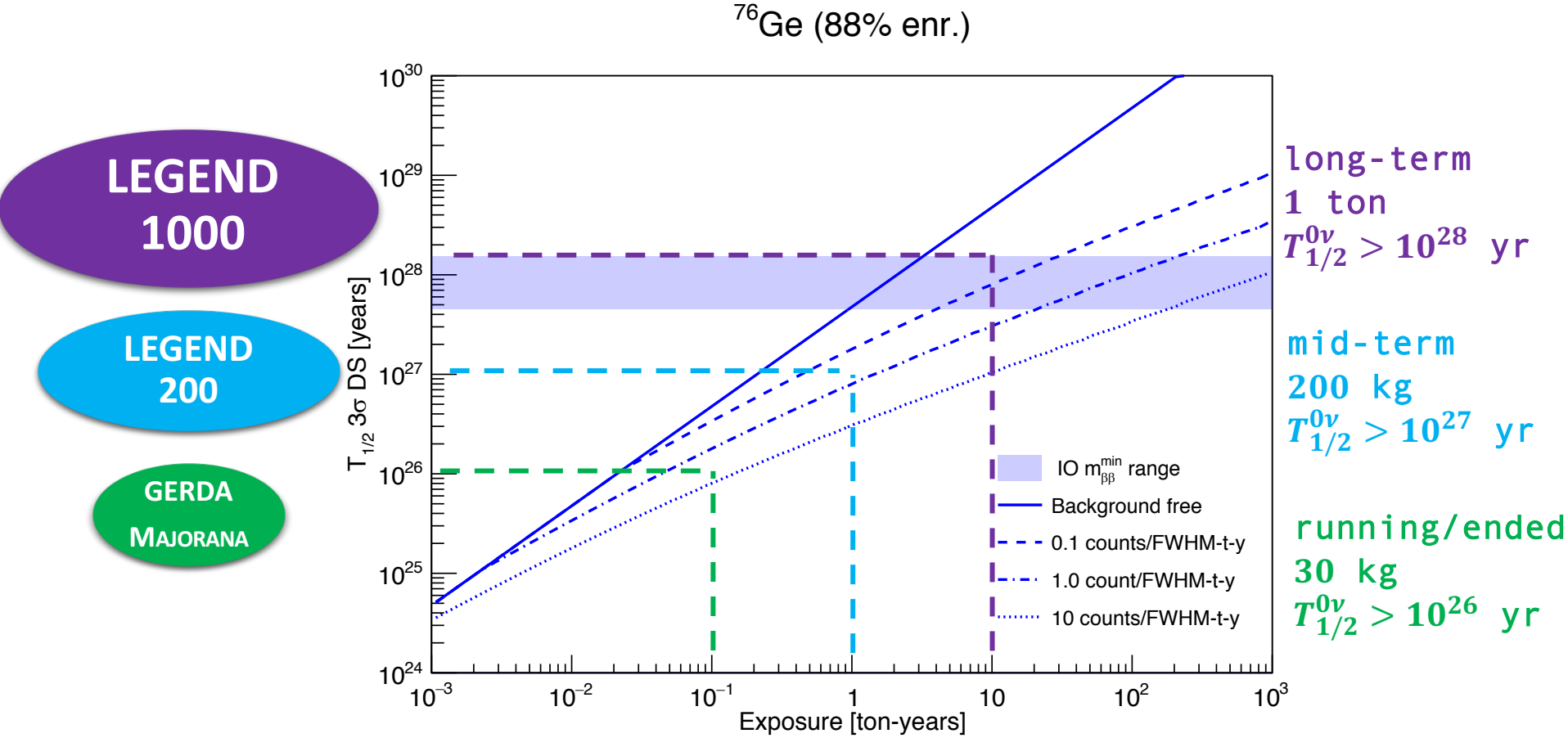
Lowest background per FWHM energy resolution in the field

[PRL **120**, 132502 (2018)]

[Nature **544**, 47–52 (2017)]
[Science **365**, 6460 (2019)]

➢ **Background-free experiment demonstrated** ($N_{\mathrm{bkg}} < 1$ @ final exposure in ROI)

Outline



1. Status of MAJORANA and GERDA data taking
2. Joint worldwide community: LEGEND
3. Prospective towards a ton-scale experiment

new results at this conference!

MAJORANA DEMONSTRATOR

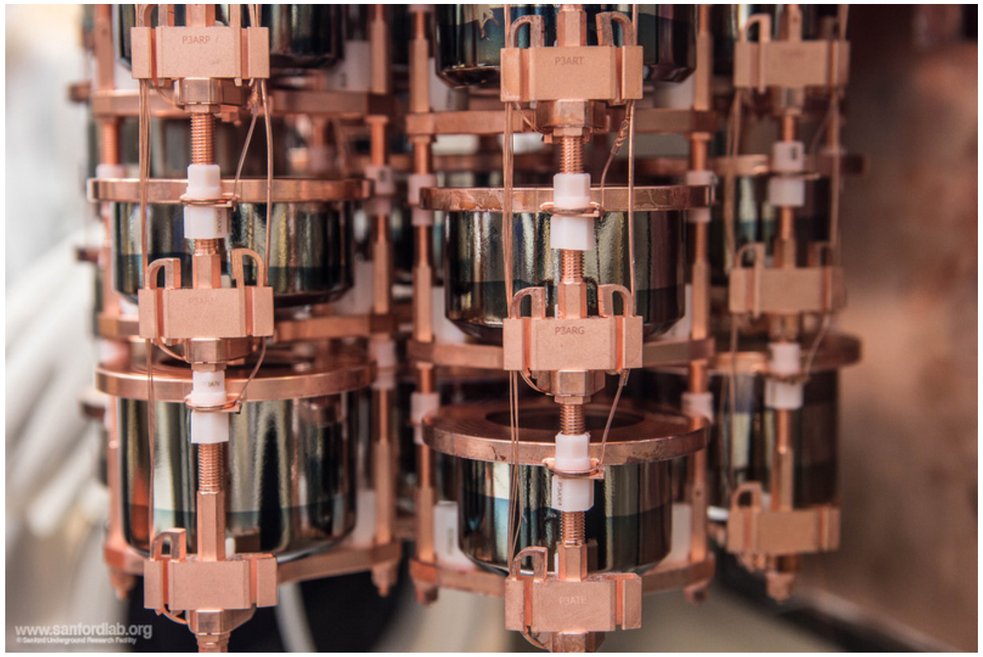
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

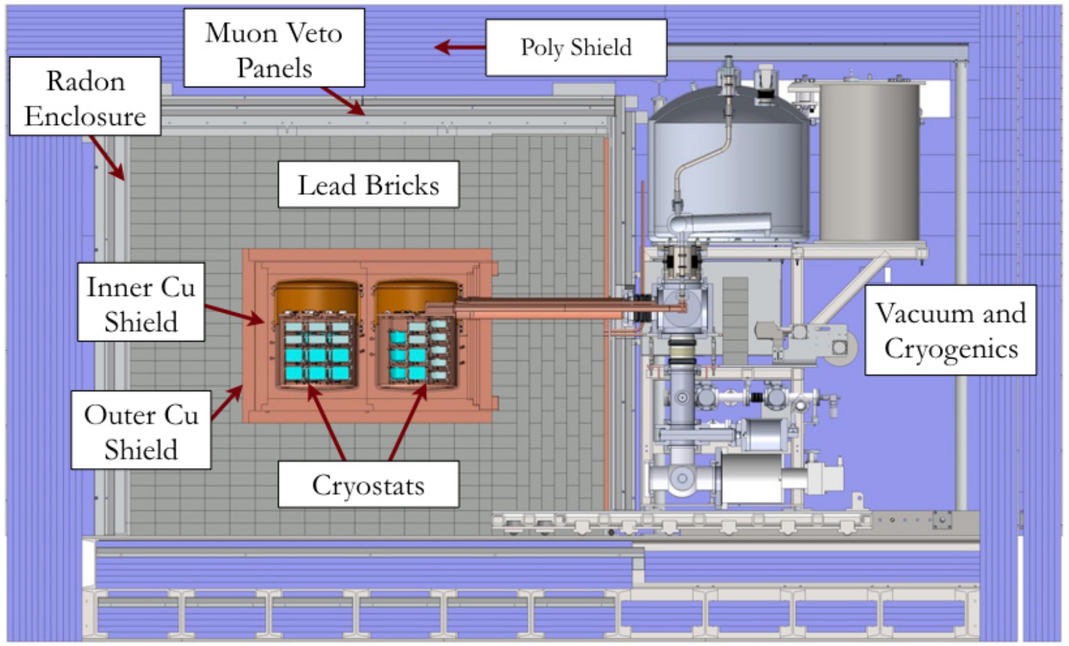
Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

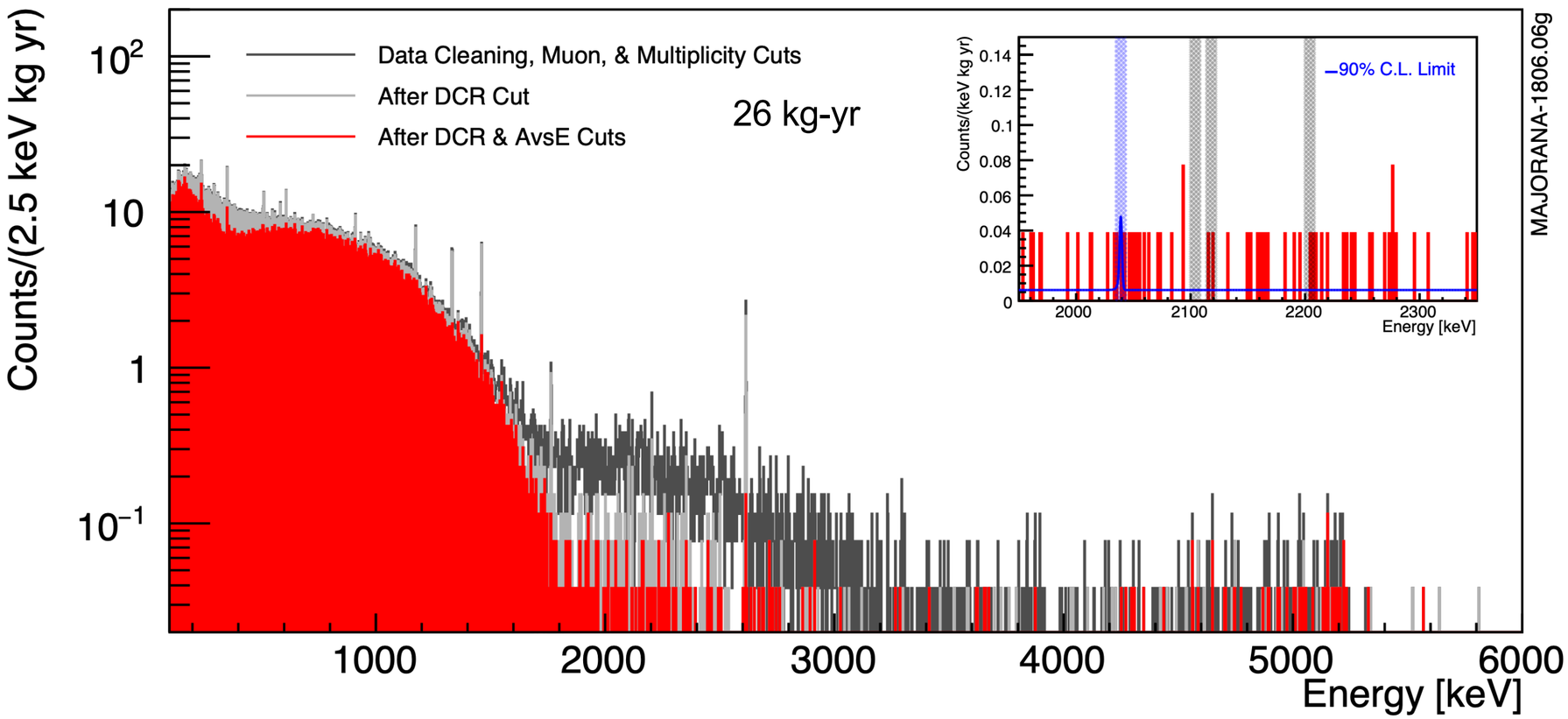
Operating underground at the 4850' level of the Sanford Underground Research Facility since 2015





MAJORANA DEMONSTRATOR 2019 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)

Latest result from 26 kg-yr (data up through April 2018)

An upcoming result with **improved analysis** and new data through Nov 2019

A combined total of ~50 kg-yr, a release later this summer

Upcoming new results on background model & beyond the standard model searches

A new result on excited state decays of ^{76}Ge

MAJORANA: Progress and Improvements

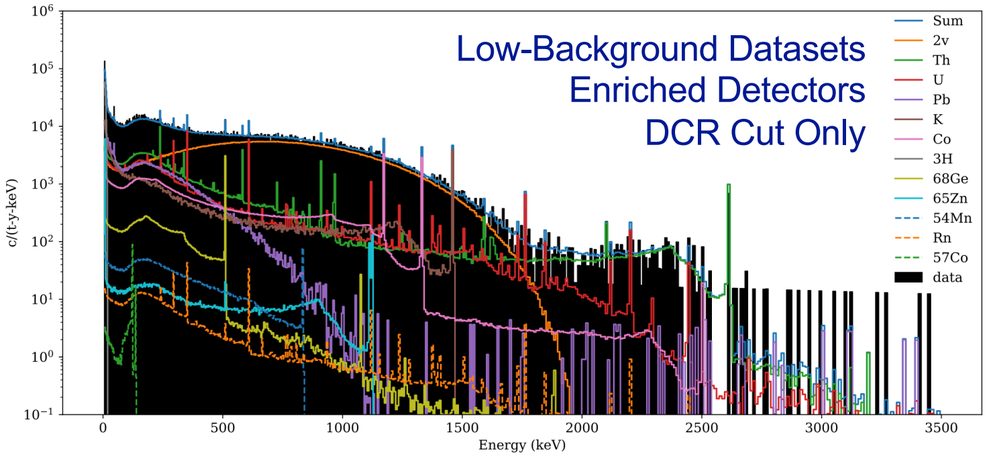
Progress towards modeling the measured background

Investigating source of excess backgrounds near $Q_{\beta\beta}$

Preliminary findings point to ^{232}Th backgrounds distant from the array

A higher fidelity modeling of distant components is underway

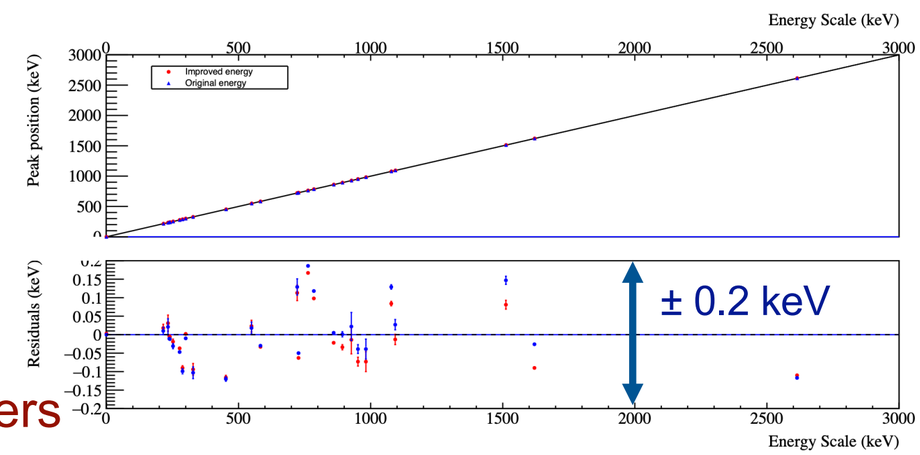
See Poster 257: An Improved Background Model for the MAJORANA DEMONSTRATOR (A. Reine, C. Haufe)



M. Buuck, UW, PhD Dissertation 2019

An upcoming result with **improved analysis** and new data through Nov 2019

A combined total of ~50 kg-yr, a release later this summer



Improved analysis

Improved energy estimator with a corrected waveform start time

Excellent energy resolution (2.5 keV FWHM at $Q_{\beta\beta}$) and improved linearity

Enhanced the stability and uniformity of background rejection parameters

Improved discrimination power of the multisite (AvsE) and surface alpha (DCR) cuts

See Poster 586: Status and Results from the MAJORANA DEMONSTRATOR Experiment (J. M. López-Castaño, N. Ruof, A. Hostiuc)

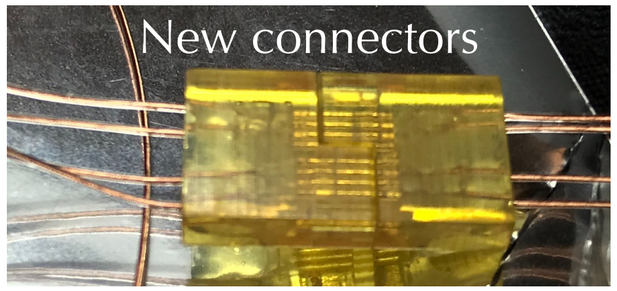
Status and run plan

2020 hardware upgrade

Improved the robustness of the signal and HV connections based on an ultra-clean, low-mass, & high-reliability design

Deployment of larger inverted-coax point-contact detectors and measure performance

Final running to yield an ultimate integrated exposure of ~60 kg-yr



MAJORANA: Beyond the Standard Model Searches

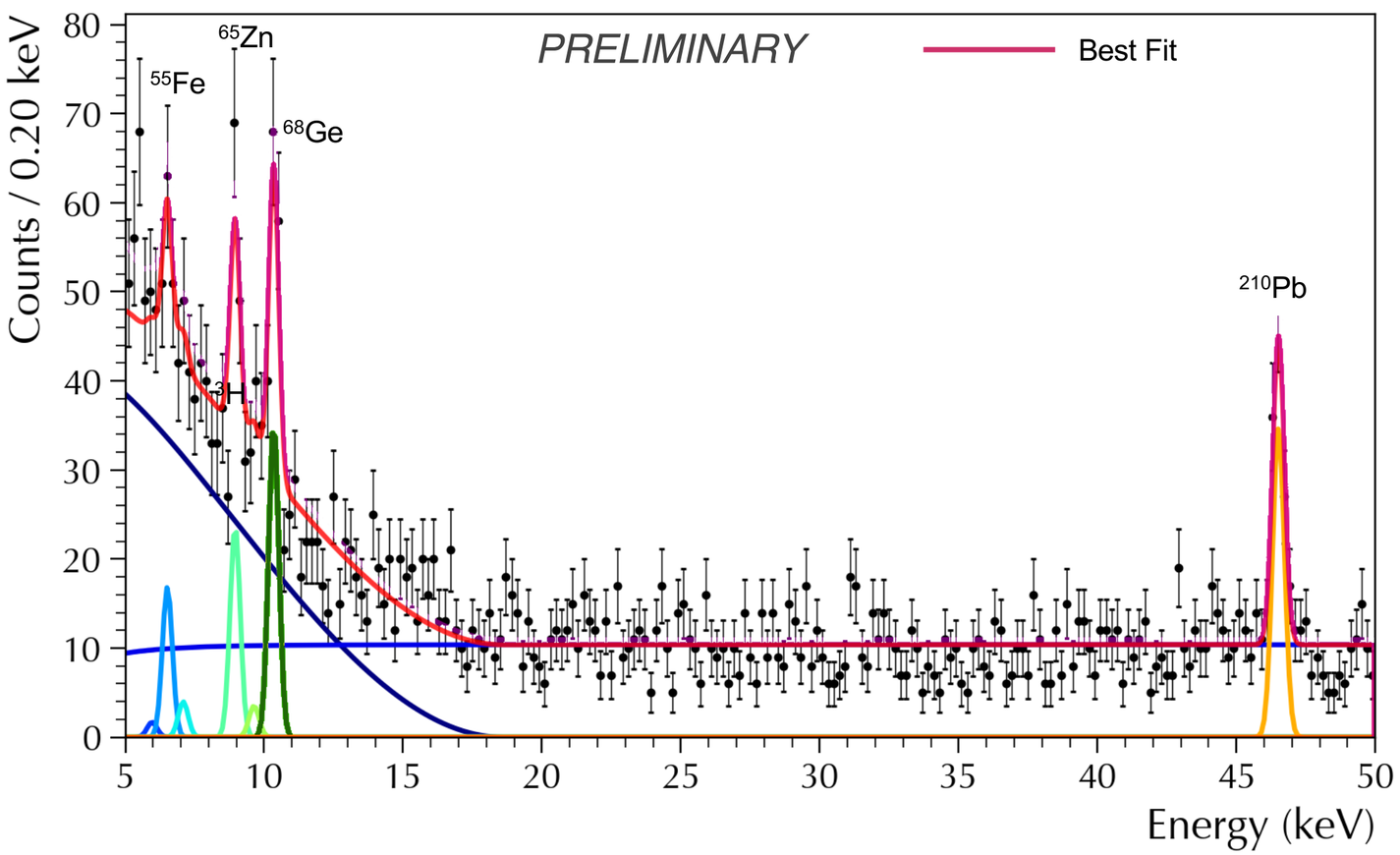
The low backgrounds, low threshold, high resolution spectra allows additional physics searches

Controlled surface exposure of enriched material to minimize cosmogenics

Upcoming updates to beyond the standard model searches

Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

Progress towards a low-E background model:



Low energy spectra from 14.9 kg-yr of low-background open physics running (DS1-6a)

Low-energy physics searches

pseudoscalar dark matter

vector dark matter,

14.4-keV solar axion

PRL **118** 161801 (2017)

Updated limits to be released after unblinding

C. Wiseman, J. Phys. Conf. Ser. 1468, 012040 (2020)

Search for tri-nuclean decay

A test of baryon number violation

PRD **99** 072004 (2019)

Lightly ionizing particles

First limit for charge as low as *e*/1000

PRL **120** 211804 (2018)

New Result: Double Beta Decay to Excited States

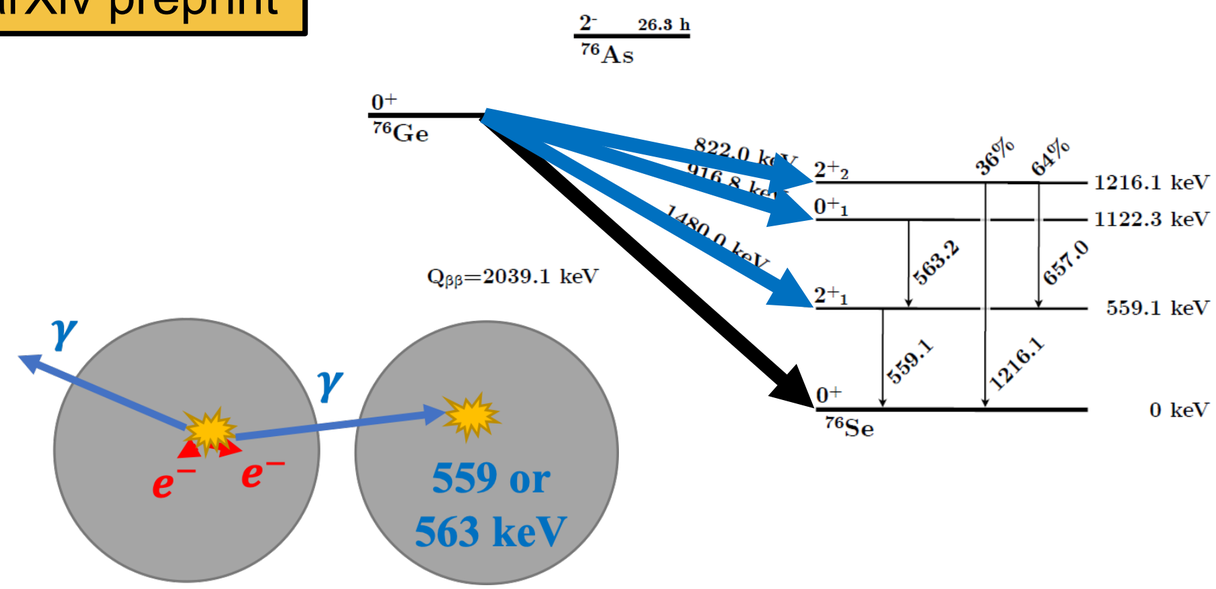
Forthcoming arXiv preprint

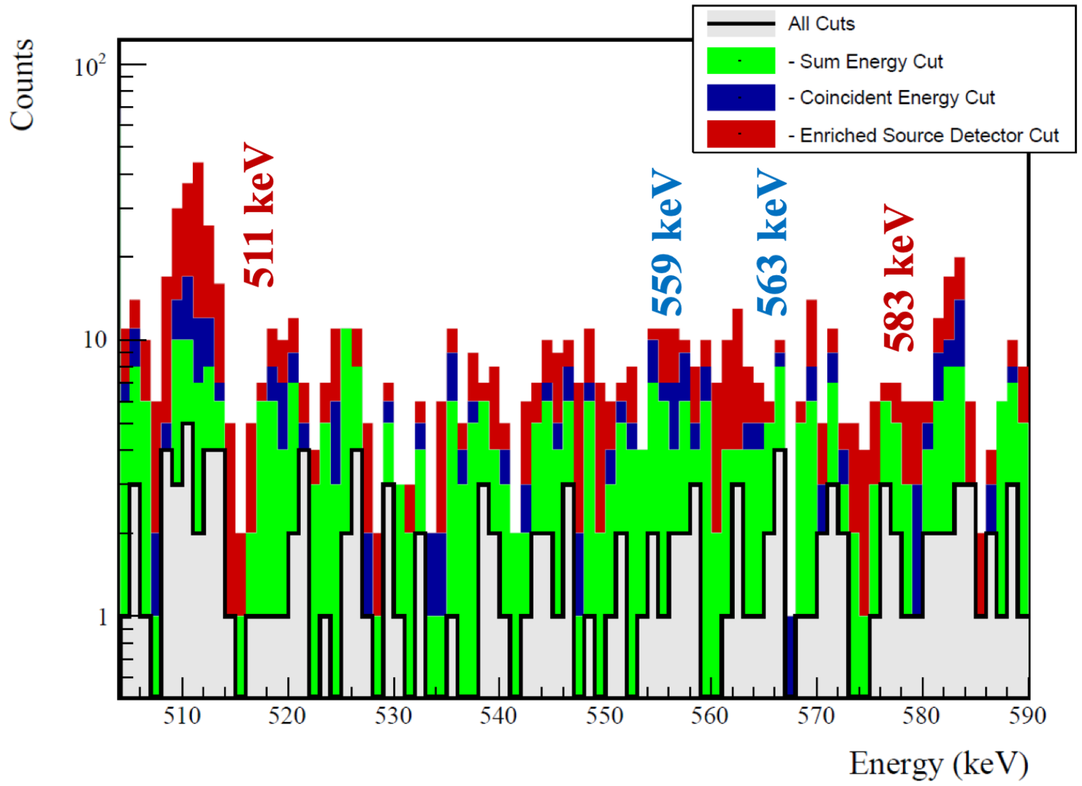
An inherently multi-site signal topology:

A "source" detector will have a broad energy spectrum from ββ

The "gamma" detector will measure energy peaked at the γ energies

41.9 kg y of isotopic exposure
(20.6 kg y of which was blinded)





Decay Mode	Det. efficiency (M1, M2)	$T_{1/2}$ prev. limit (90% CI)	$T_{1/2}$ new limit (90% CI)	$T_{1/2}$ sensitivity (90% CI)
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	2.4%, 1.0%	$> 3.7 \cdot 10^{23} y$ [5]	$> \mathbf{7.5 \cdot 10^{23} y}$	$> \mathbf{10.5 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	1.4%, 0.6%	$> 1.6 \cdot 10^{23} y$ [5]	$> \mathbf{7.7 \cdot 10^{23} y}$	$> \mathbf{10.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	2.2%, 0.8%	$> 2.3 \cdot 10^{23} y$ [5]	$> \mathbf{12.8 \cdot 10^{23} y}$	$> \mathbf{8.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	3.0%, 1.2%	$> 1.3 \cdot 10^{22} y$ [6]	$> \mathbf{39.9 \cdot 10^{23} y}$	$> \mathbf{39.9 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	1.6%, 0.7%	$> 1.3 \cdot 10^{23} y$ [7]	$> \mathbf{21.2 \cdot 10^{23} y}$	$> \mathbf{21.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	2.3%, 1.0%	$> 1.4 \cdot 10^{21} y$ [8]	$> \mathbf{9.7 \cdot 10^{23} y}$	$> \mathbf{18.6 \cdot 10^{23} y}$

The most stringent limits to date for ββ to each excited state of ^{76}Se due to:

Operating an array in vacuum: high detection efficiency

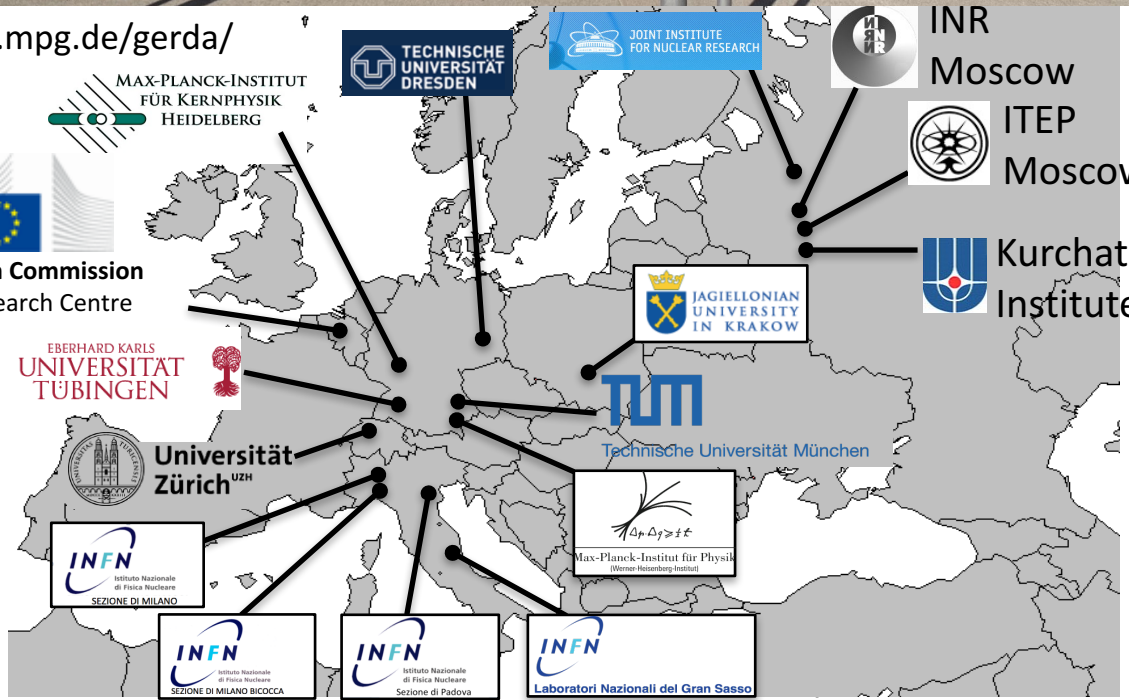
Exquisite energy resolution for identifying peaks

Low environmental backgrounds & analysis cuts

See Poster 254: New results from Majorana Demonstrator's search for Double-Beta Decay of ^{76}Ge to Excited States of ^{76}Se (I. Guinn)

GERDA at Laboratori Nazionali del Gran Sasso in Italy

http://www.mpi-hd.mpg.de/gerda/



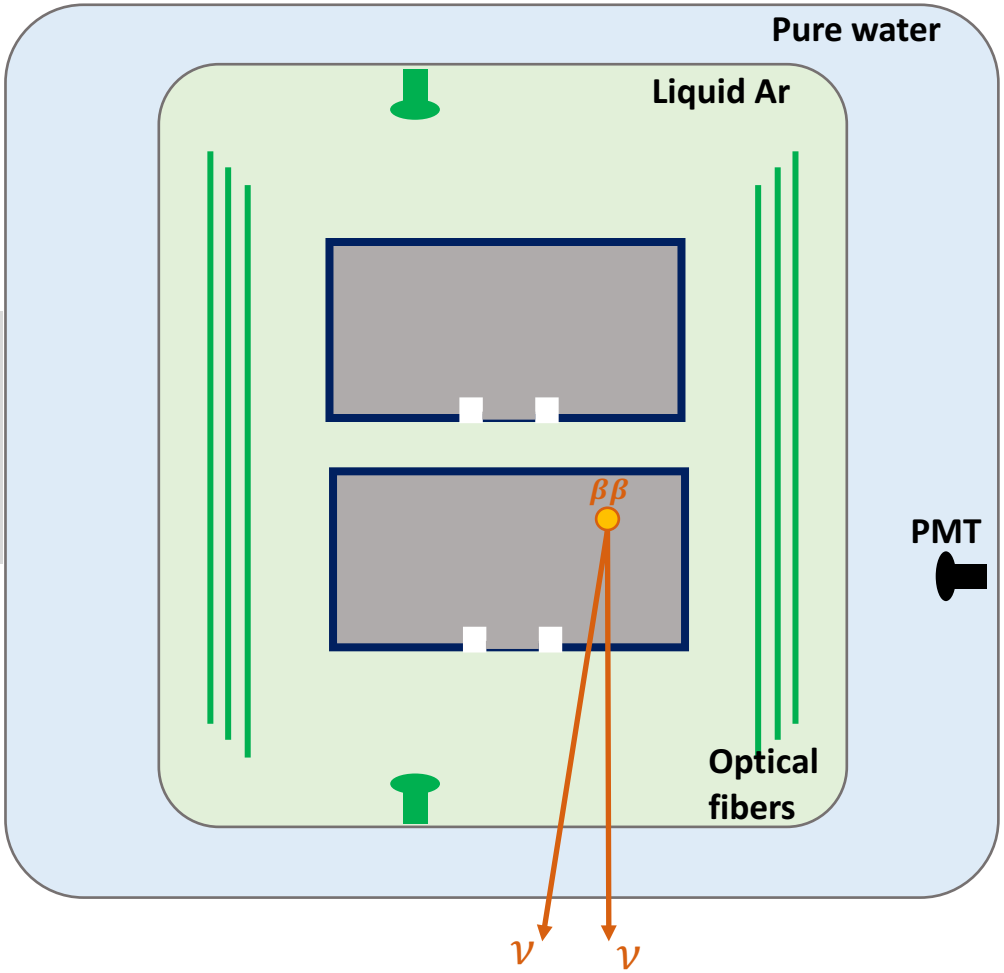
About 100 scientists from Europe

Background-free experiment design

[Eur. Phys. J. C (2018) 78:388]

- signal topology

$\beta\beta$ decay signal: single-site event energy deposition in a 1 mm^3 volume

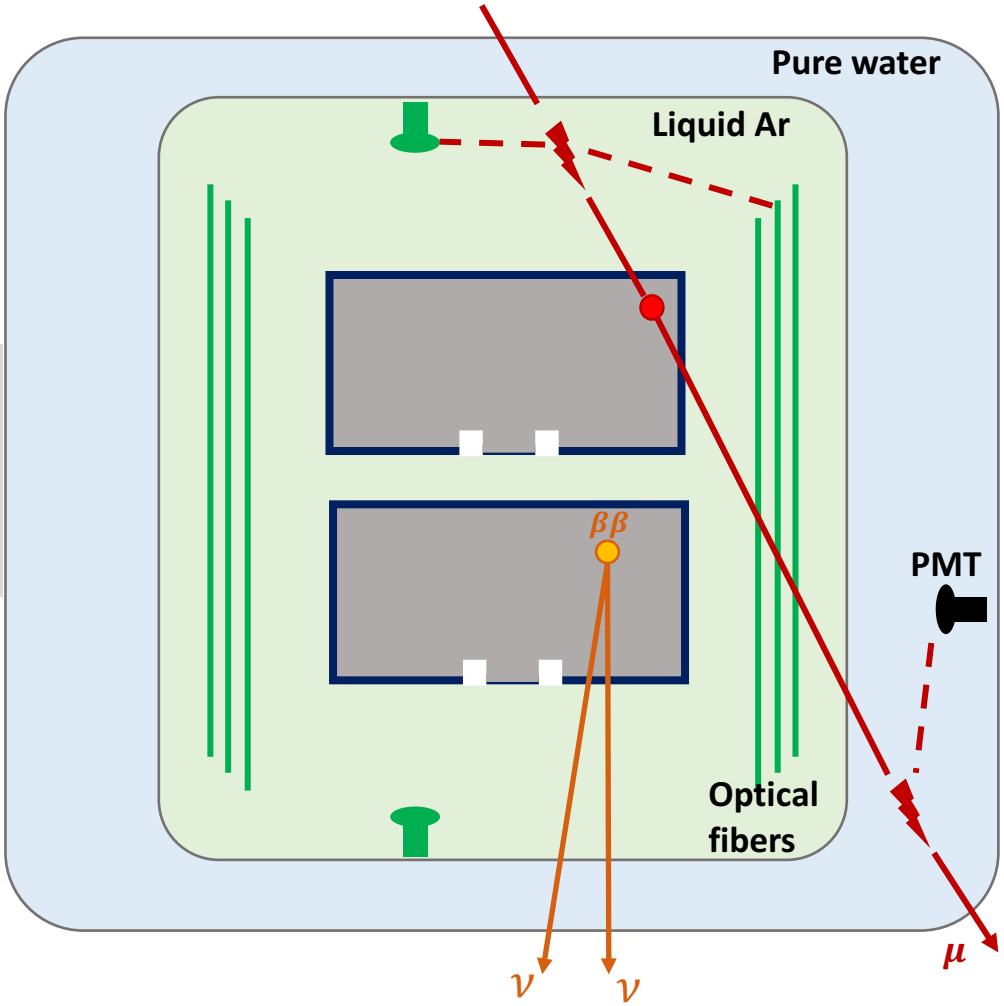


Background-free experiment design

[Eur. Phys. J. C (2018) 78:388]

- background mitigation

$\beta\beta$ decay signal: single-site event energy deposition in a 1 mm^3 volume



Muon veto based on Cherenkov light and plastic scintillator

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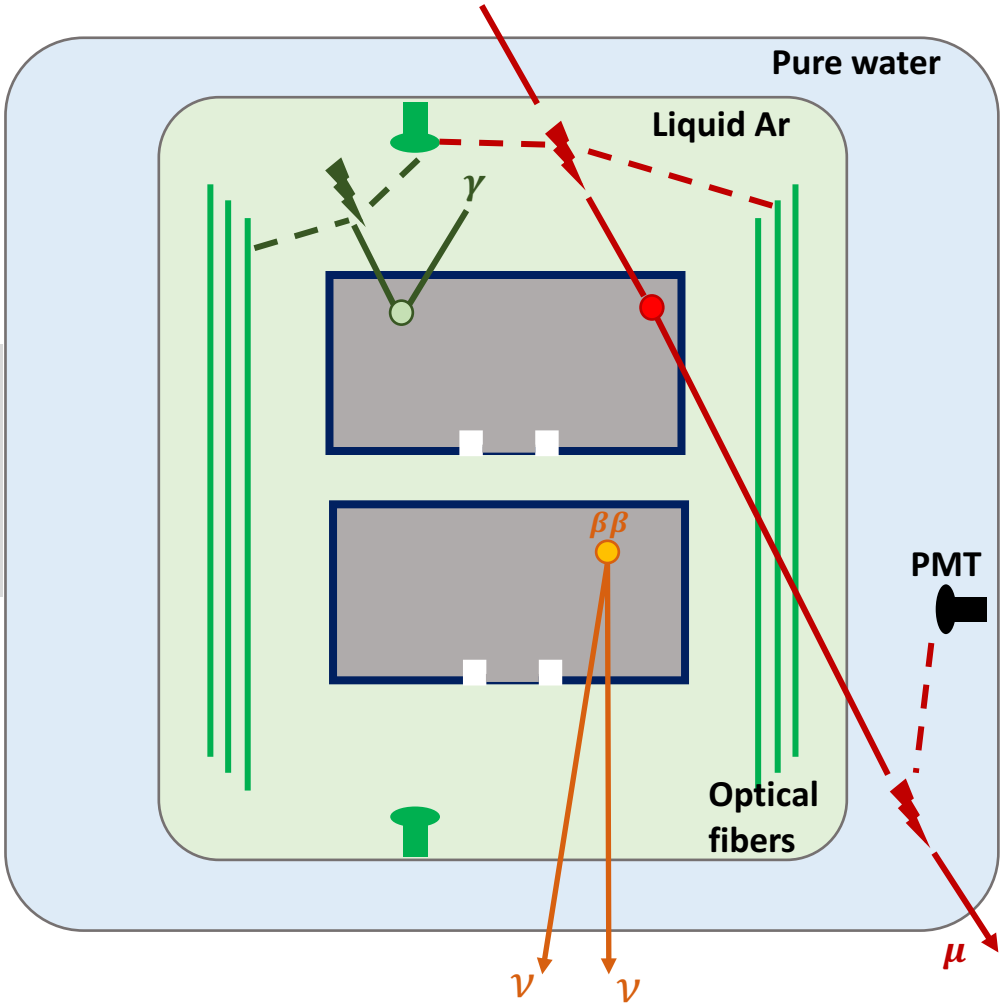

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

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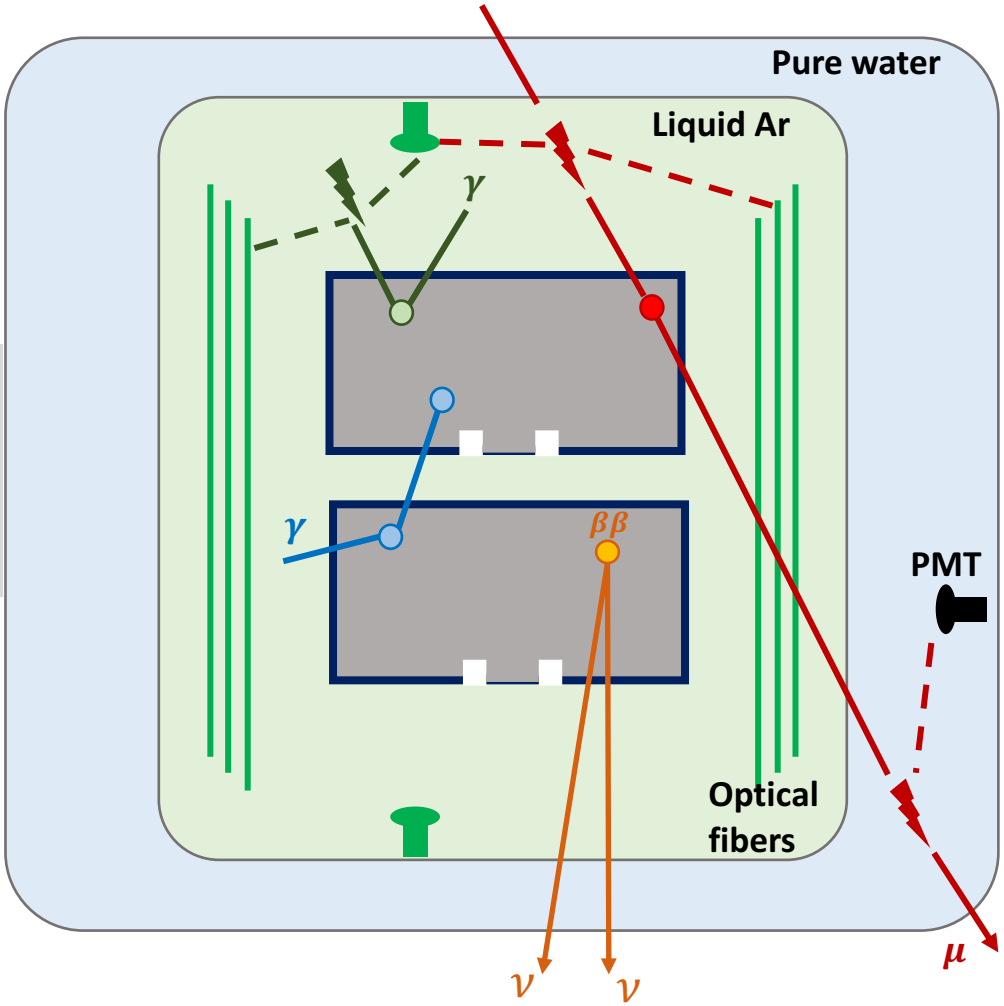

Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

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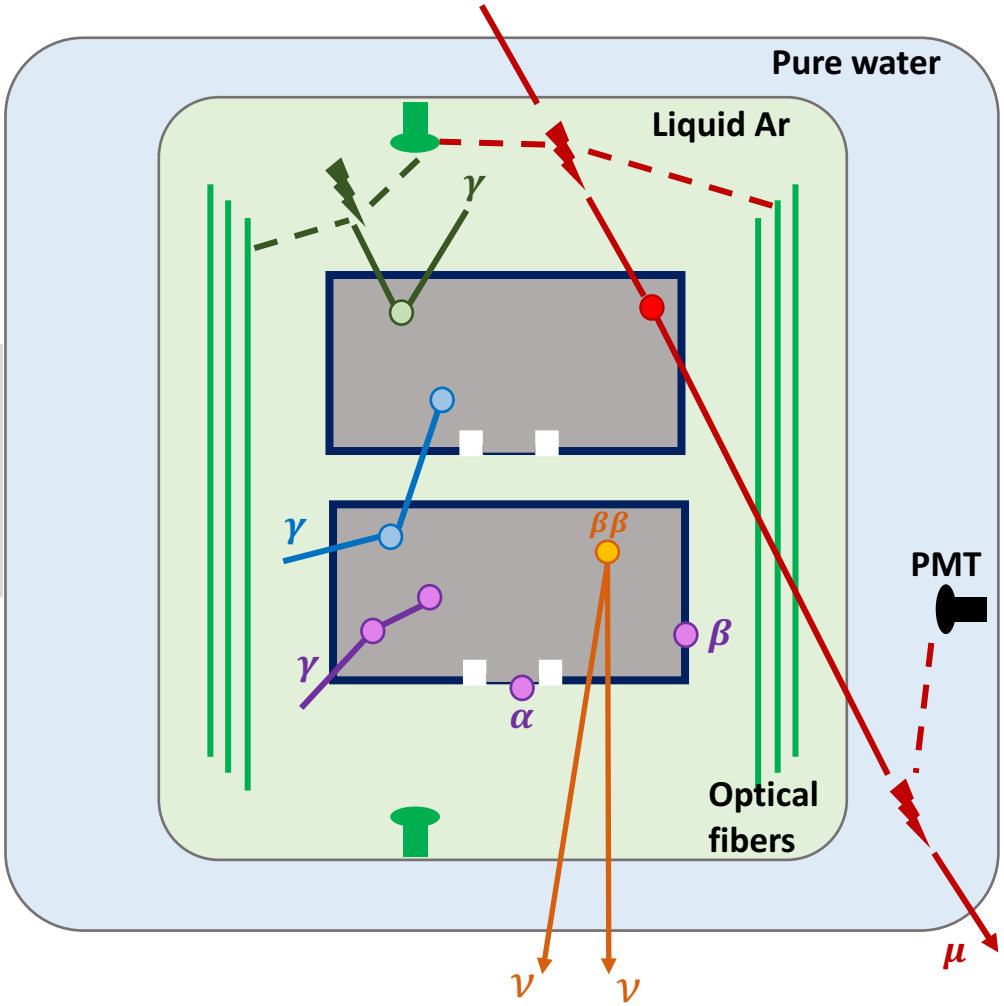


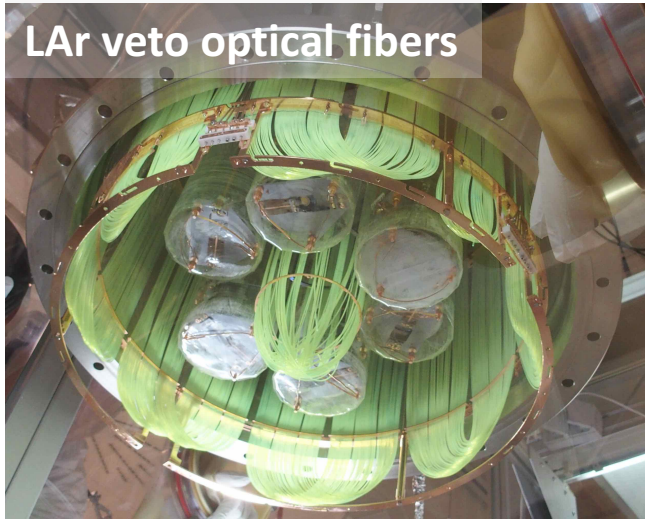
Pulse shape discrimination (PSD) for multi-site and surface α, β events

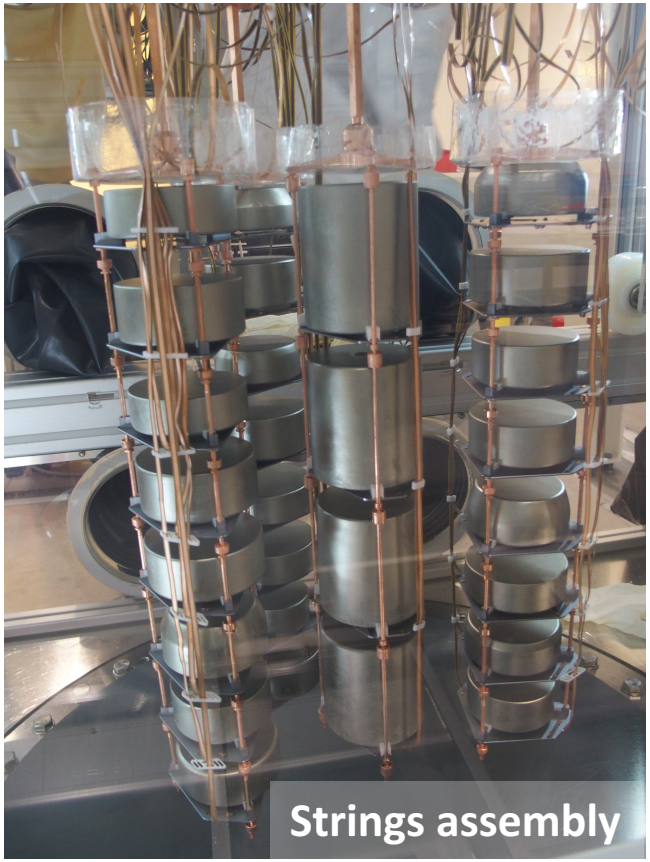
Ge detector anti-coincidence

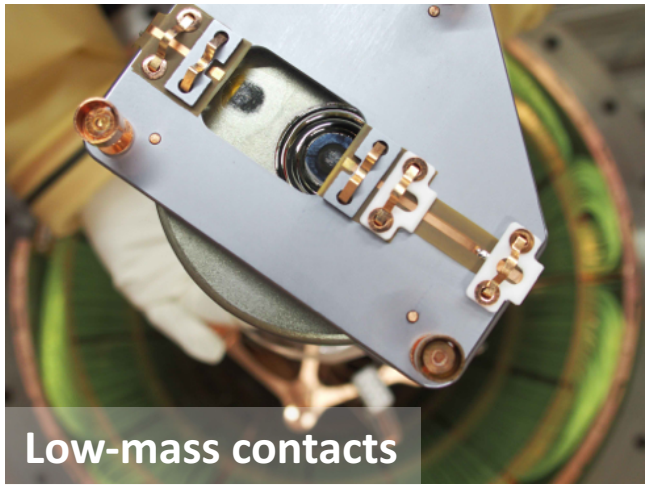
LAr veto based on Ar scintillation light read by fibers and PMT

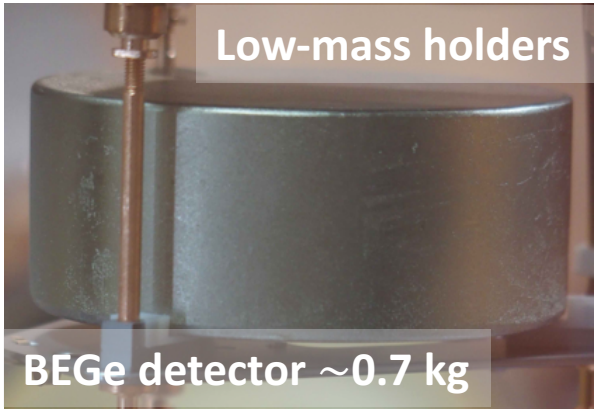
Muon veto based on Cherenkov light and plastic scintillator

The phase II Ge detector array



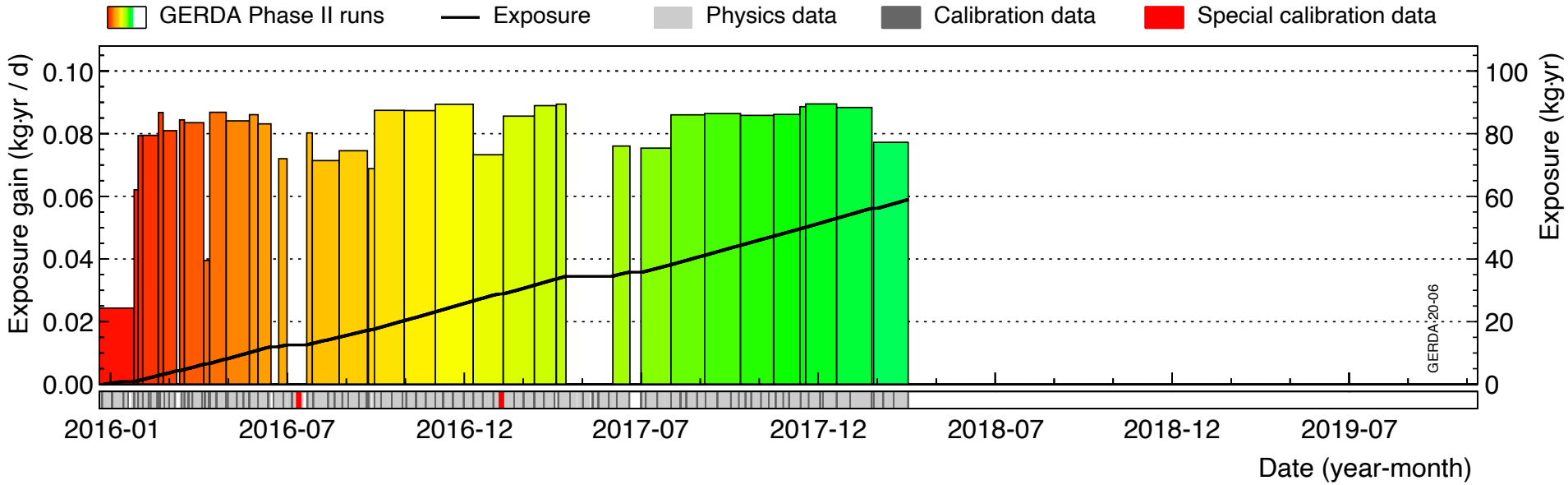




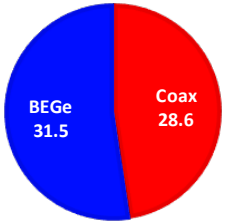


- Up to **41 enriched detectors** deployed from **Dec. 2015 to Dec. 2019**
- Three detectors type (Coaxial, BEGe and IC)
- Two data taking periods with an **upgrade in May 2018** in between
- Total enriched detectors mass: **35.6 kg/44.2 kg**

Final phase II data collection summary



- **data collection split in pre/post upgrade periods**
  - pre-upgrade: data released at Neutrino2018 [Science **365**, 6460 (2019)]
  - cumulated exposure $58.9\ \mathrm{kg} \cdot \mathrm{yr}$



- **upgrade:** new LAr veto system + new IC detector string TAUP2019

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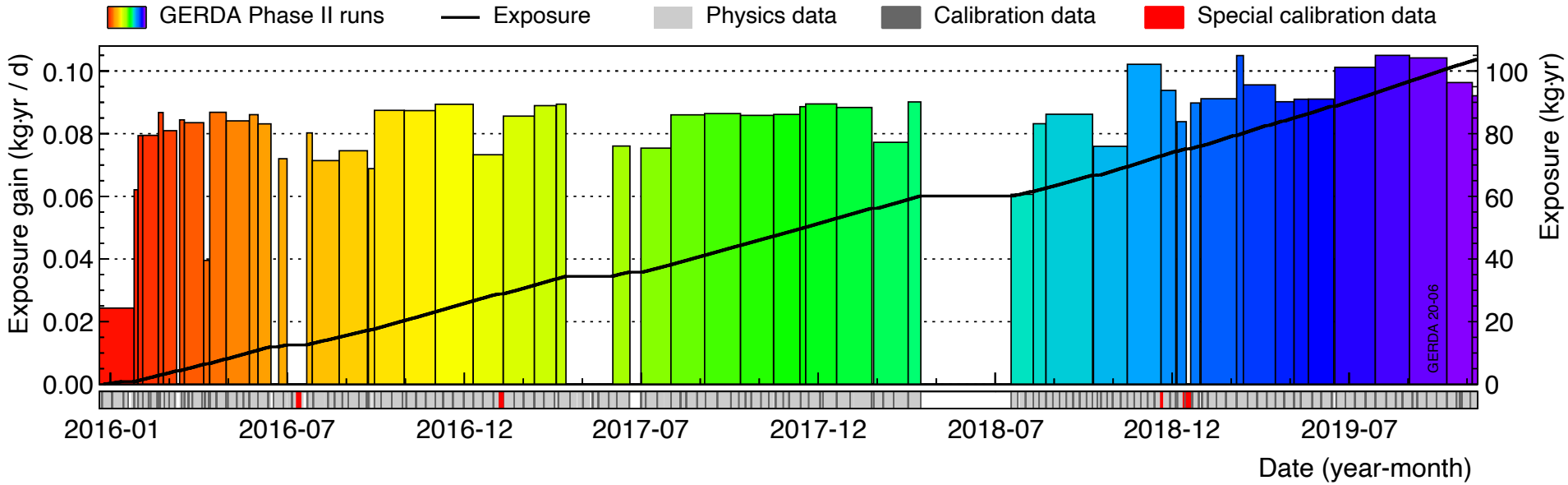

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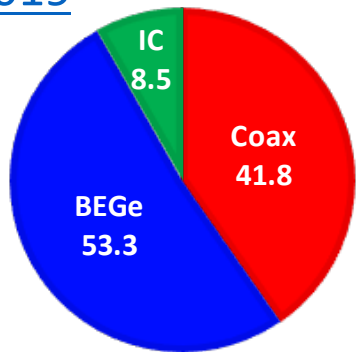
- **this talk:**
  - **final exposure:** $\mathbf{103.7\ kg \cdot yr}$ (original design: $100\ \mathrm{kg} \cdot \mathrm{yr}$)
  - **full data collection analysed**



^{76}Ge detector calibration

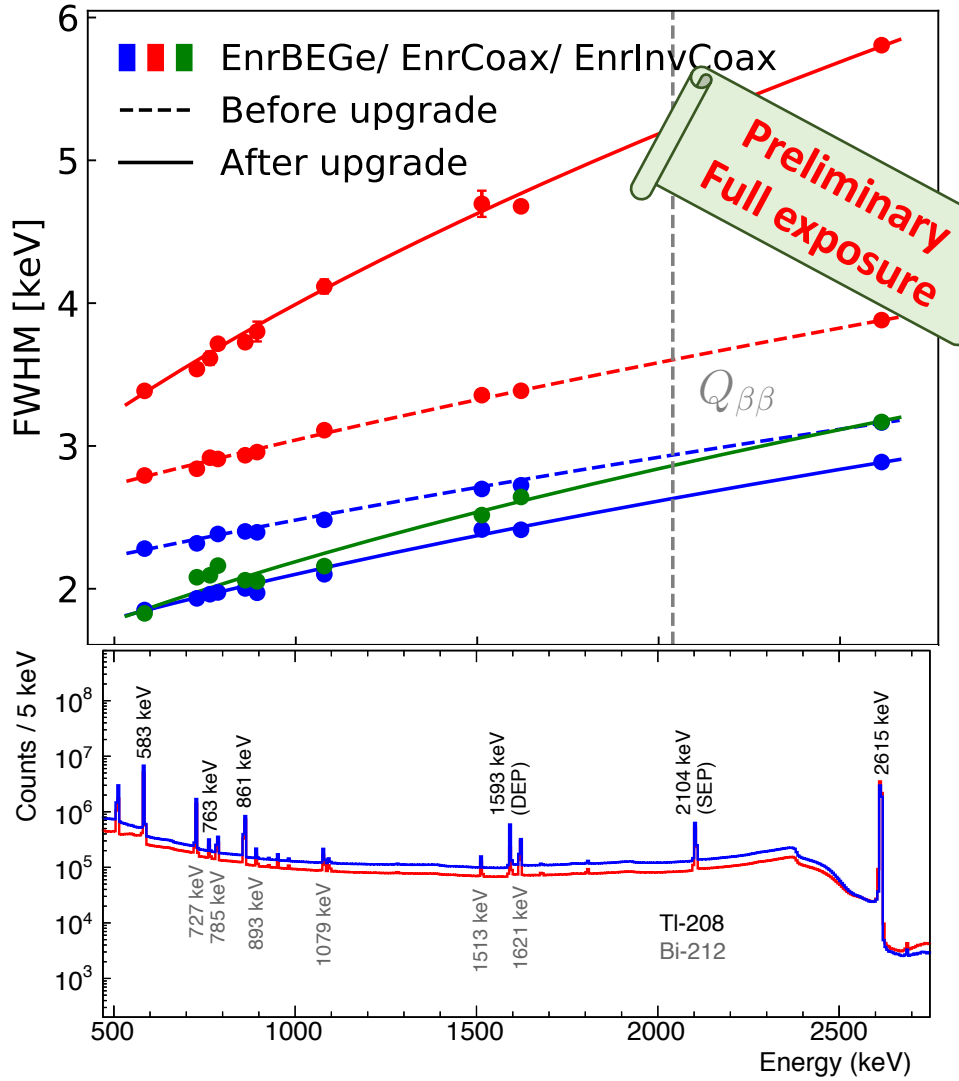
- weekly calibrations with ^{228}Th sources
- every 20 s **test pulse** injection for gain stability measurement

FWHM resolution @ $Q_{\beta\beta}$ (keV)

period	BEGe*	Coax**	IC
pre-upgrade	2.9 ± 0.3	3.6 ± 0.3	
post-upgrade	2.6 ± 0.2	5.2 ± 1.9	2.9 ± 0.1

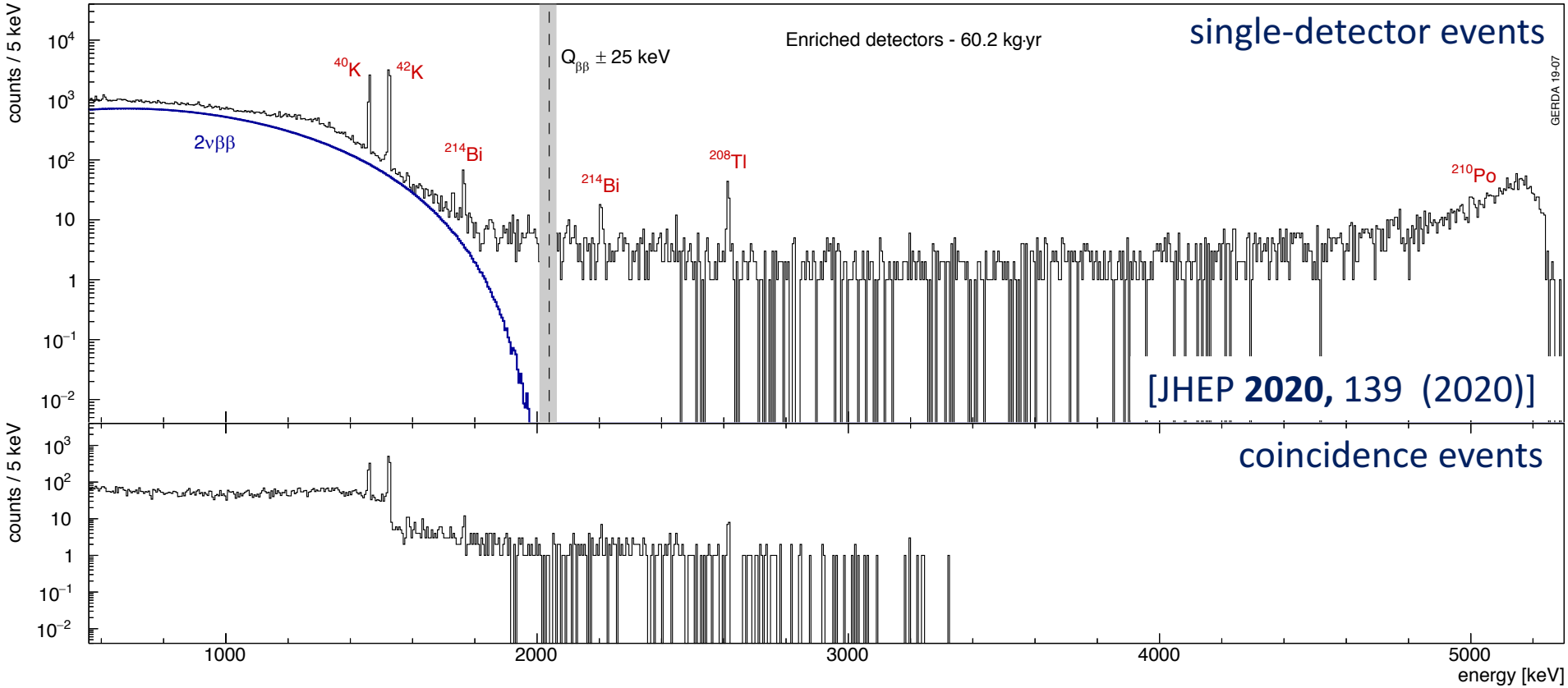
- Statistical analysis based on **detectors-wise partitioning** over stable periods

J. Huang poster
Energy Calibration for the GERDA experiment



*post-upgrade improvement due to better cable routing, less xtalk
**worsening driven by one detector featuring higher leakage current

Phase II physics data before cuts



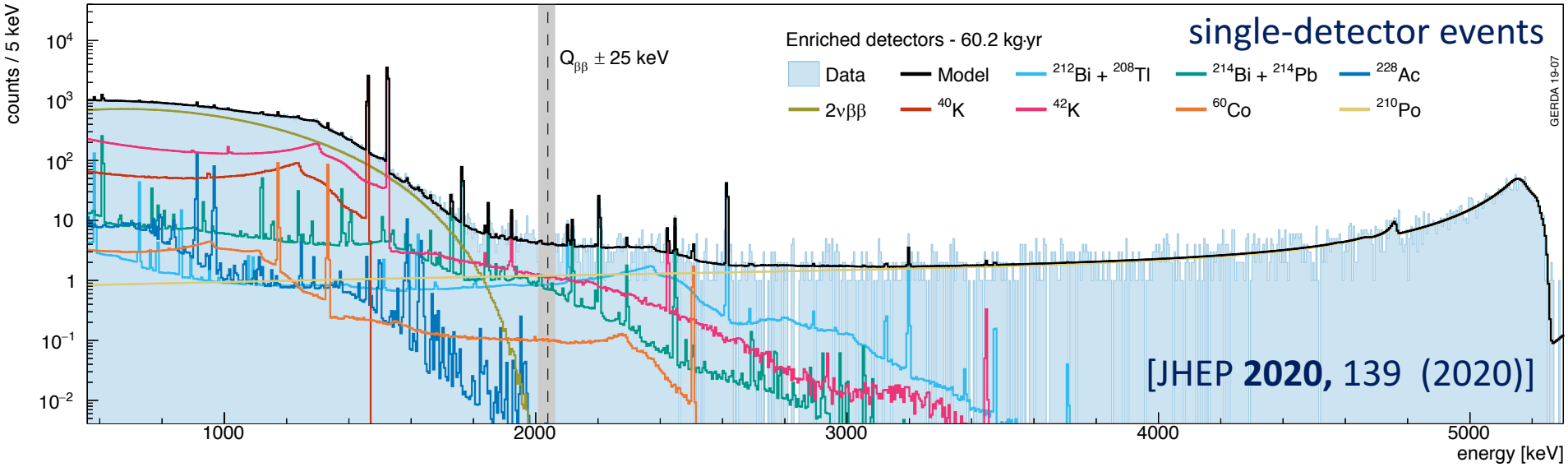
Published data collection: from Dec. 2015 to April 2018

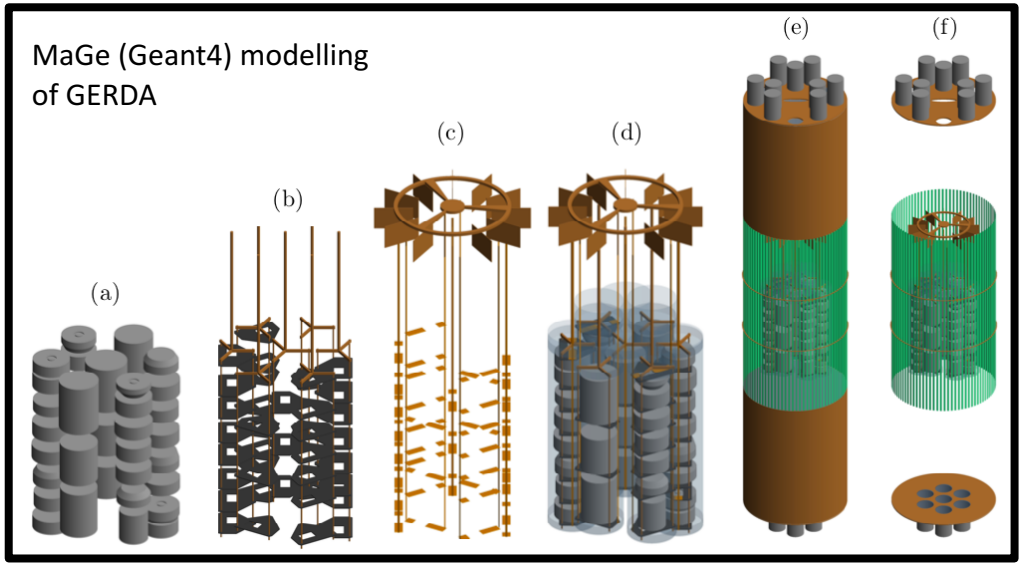
Blinding strategy: Keep events falling in $Q_{\beta\beta} \pm 25$ keV blinded

Data quality cuts + **muon veto** applied

Energy range above ^{39}Ar spectrum ($Q_\beta = 565$ keV)

Phase II physics data modeling before cuts





K. Von Sturm poster
Modeling of
GERDA Phase II data

Fine modelling of all individual parts:

Priors: Constraints from screening measurements

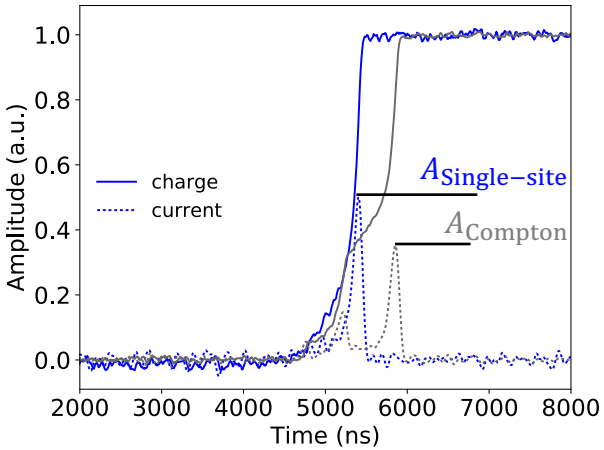
Weakness: Fairly high spatial degeneracy of some components (K, ^{214}Bi)

Main outcome: no full energy peak or other structures close to $Q_{\beta\beta}$

Phase II pulse shape discrimination

Analysis of the charge collection time profile informs about event type (bulk single/multi-site, surface events)

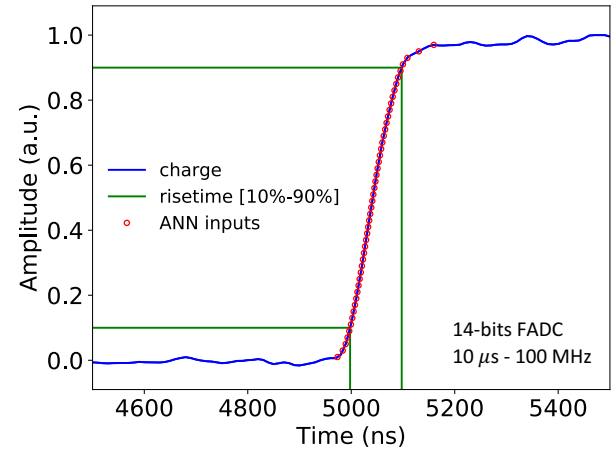
BEGe and IC detectors: A/E

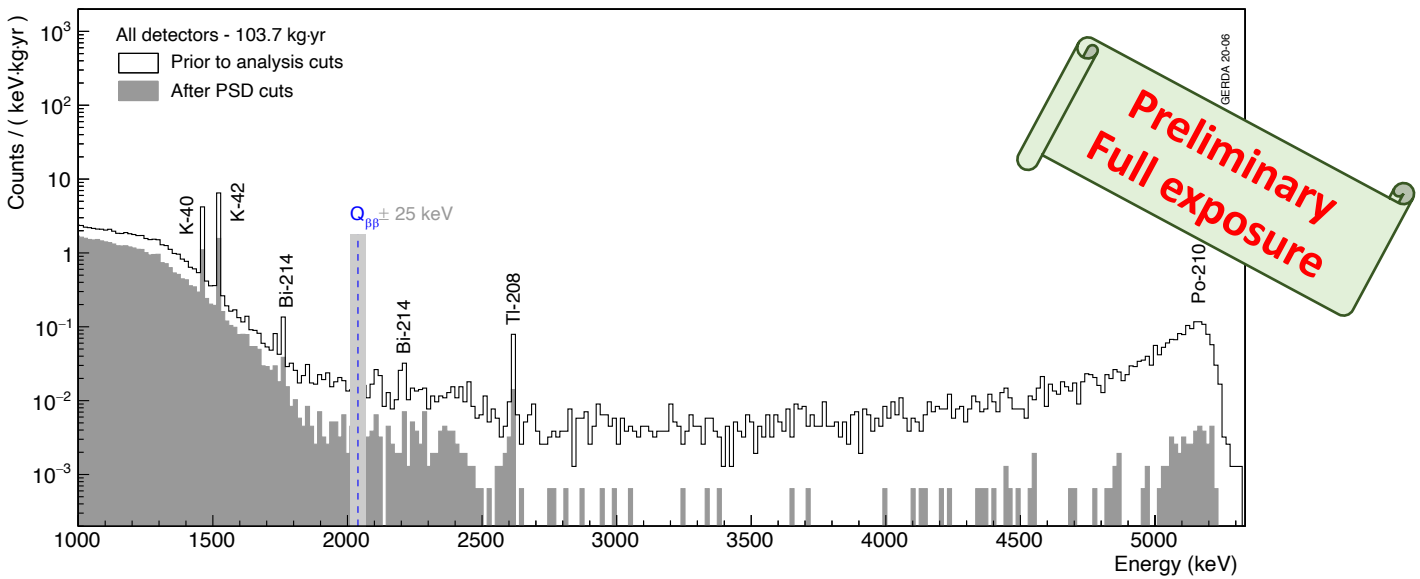


$0\nu\beta\beta$ decay signal efficiency:

- $\epsilon_{\text{PSD}}^{\text{BEGe}} = (88.7 \pm 3.2)\%$
- $\epsilon_{\text{PSD}}^{\text{IC}} = (90.0 \pm 1.7)\%$
- $\epsilon_{\text{PSD}}^{\text{Coax}} = (68.9 \pm 3.1)\%$

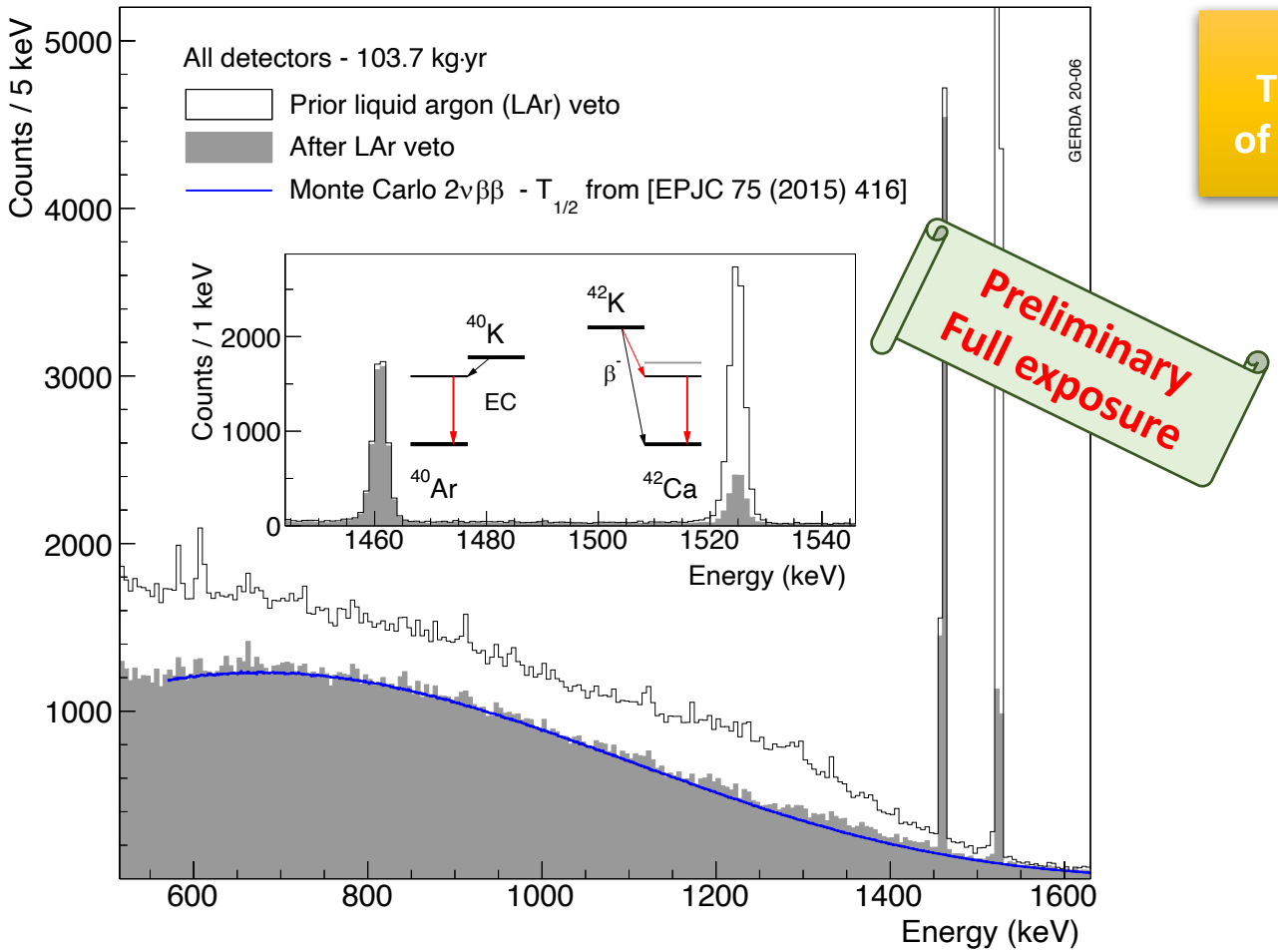
Coaxial detectors: ANN + risetime



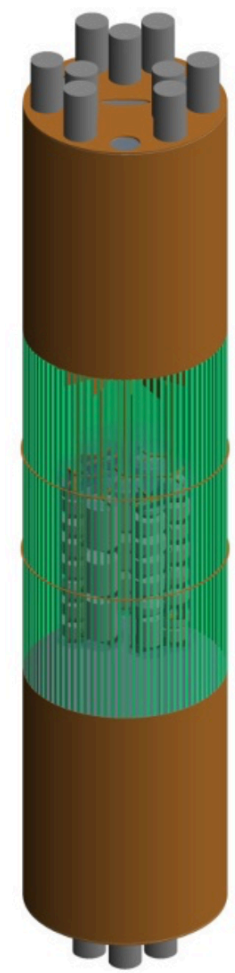


No high energy alphas survive A/E – **bkg suppression close to $Q_{\beta\beta}$: ÷ 5 in the ROI**

Phase II liquid argon veto performances

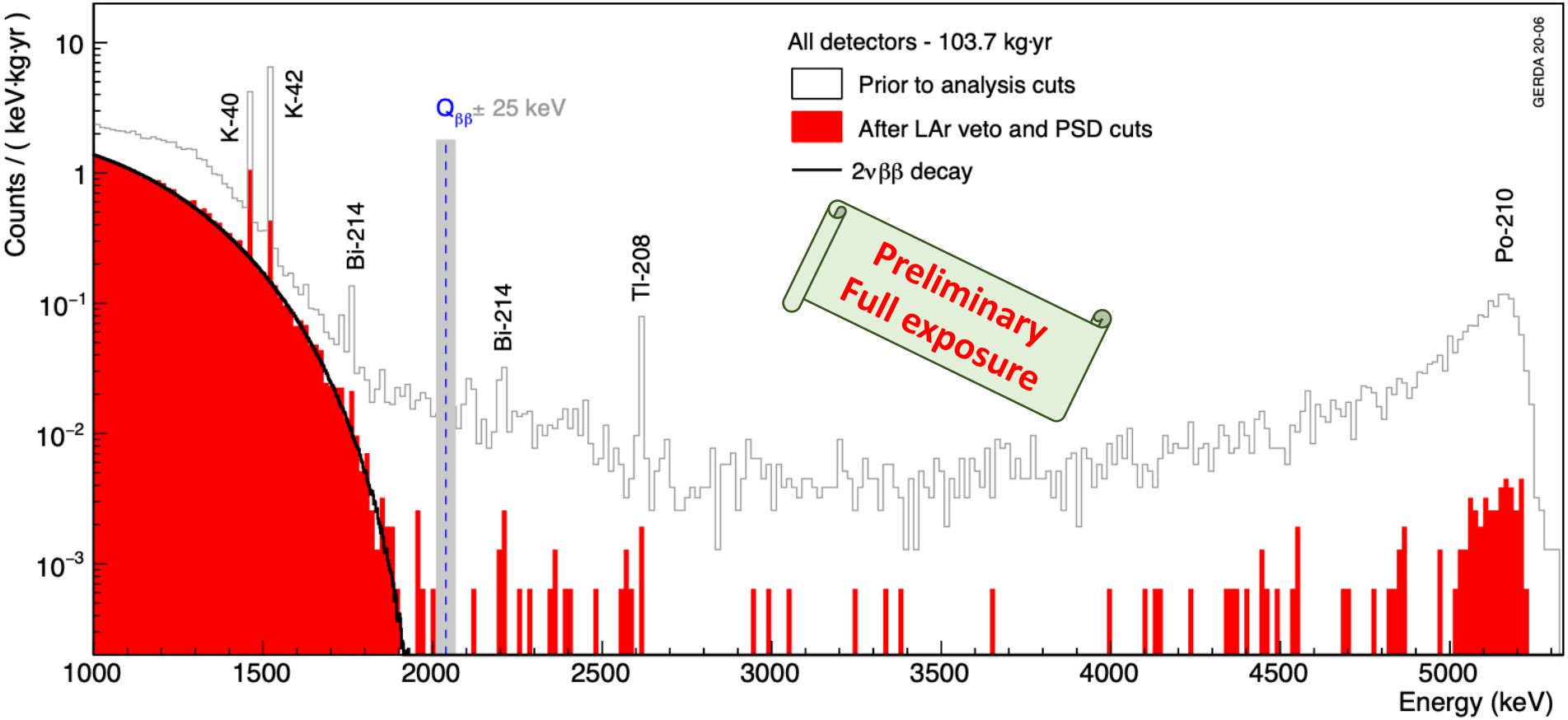


P. Krause poster
The LAr instrumentation of GERDA and LEGEND-200



- **Stable operations** over 4 years of data taking
- $0\nu\beta\beta$ decay signal efficiency: $\boldsymbol{\epsilon_{\mathrm{LAr}} = (97.9 \pm 0.1)\%}$
- Crucial role in **background suppression after PSD: ÷ 6 in the ROI**

Phase II physics spectra after all analysis cuts



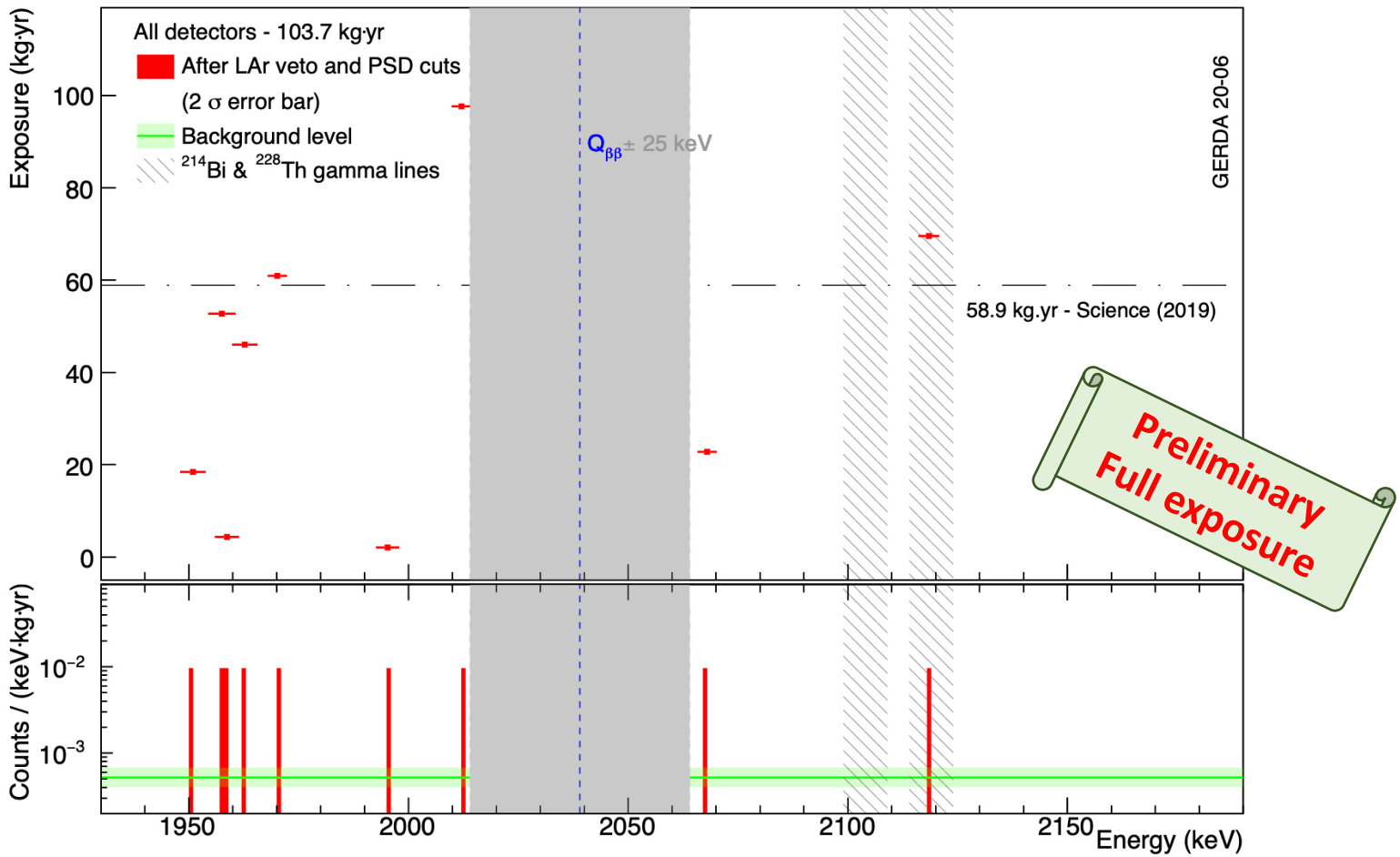
- [600 - 1900] keV – Almost pure $2\nu\beta\beta$ **decays** sample
- [1450 - 1530] keV – Strong suppression of **^{40}K and ^{42}K gamma lines** (LAr veto + MSE)
- [1900 - 2620] keV – Strong suppression of **^{214}Bi and ^{228}Th gamma lines** + Compton
- > 3500 keV – Suppression of almost all α **events** (p+ contact)

- **Extremely powerful complementarity between LAr veto and PSD cuts!**

Zoom around the region of interest

Dec. 2019

Dec. 2015

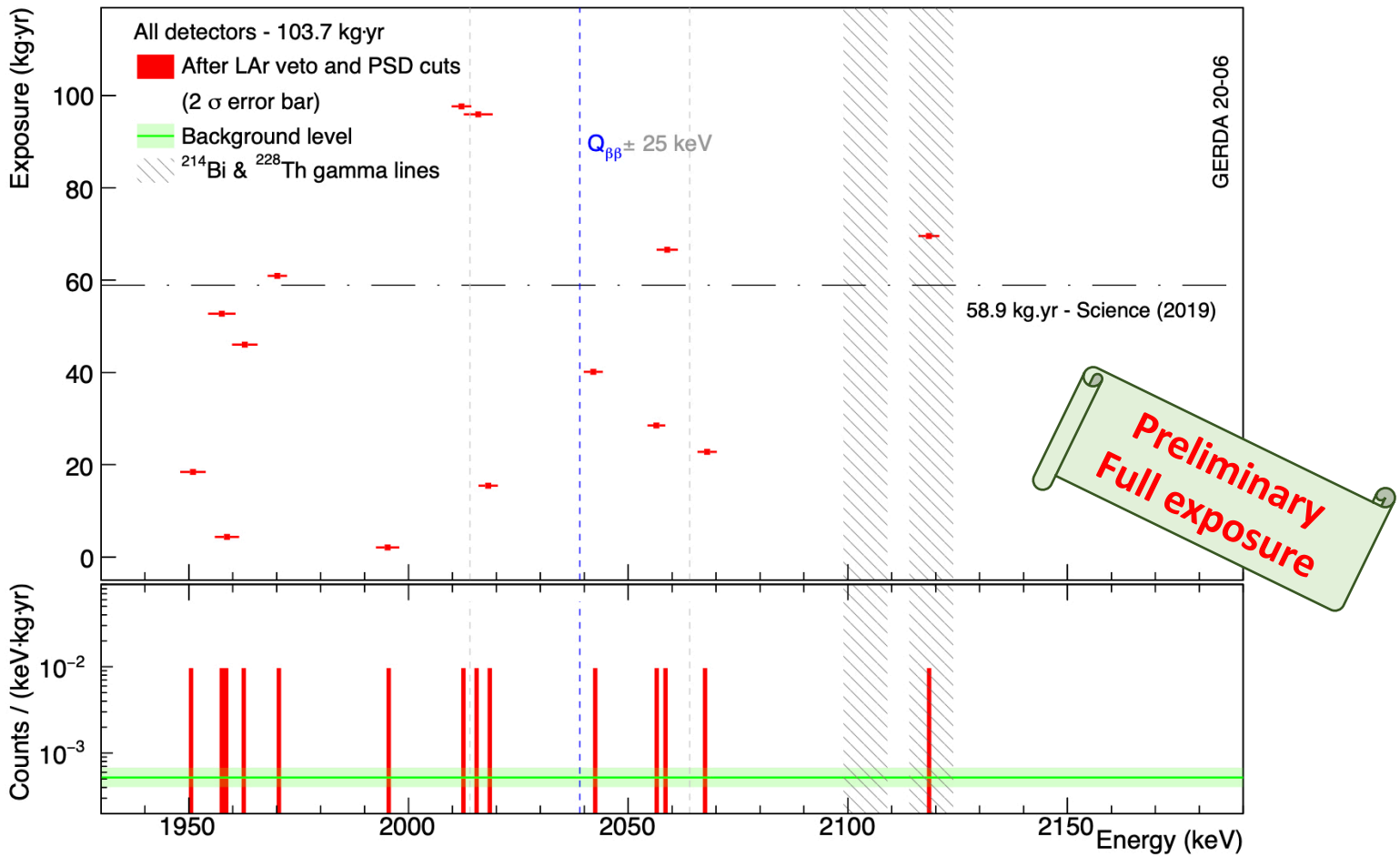


- Bkg index (BI) analysis window: [1930-2190] keV with the exclusion of ^{208}Tl SEP and ^{214}Bi FEP lines and $Q_{\beta\beta} \pm 25$ keV
- Prior to analysis cuts, $\mathrm{BI} = 143^{+9}_{-8} \times 10^{-4}\ \mathrm{cts/(keV \cdot kg \cdot yr)}$ ÷ 30!
- **After all cuts: $\mathbf{BI} = \mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}\ cts/(keV \cdot kg \cdot yr)}$** at the final exposure of $\mathbf{103.7\ kg \cdot yr}$

Phase II energy spectrum after unblinding!

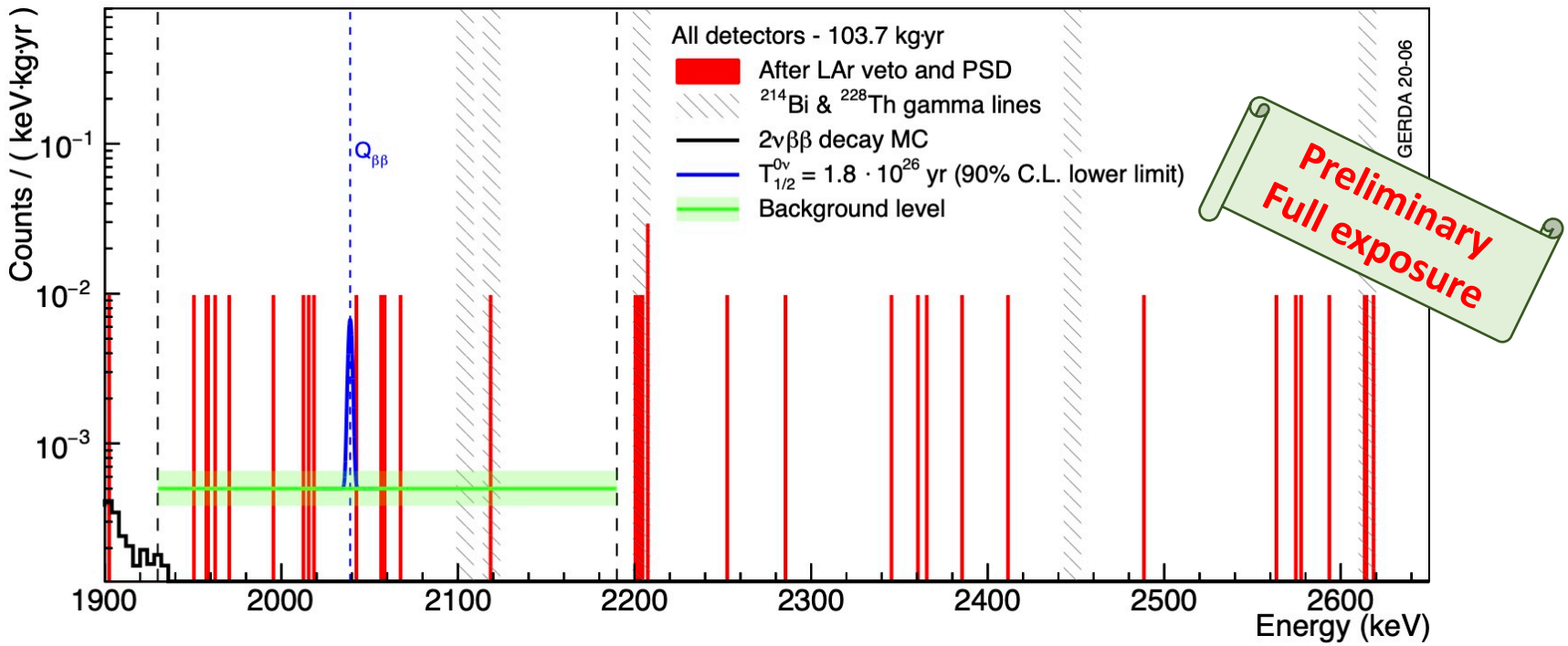
Dec. 2019

Dec. 2015



- Two new counts entering the $Q_{\beta\beta} \pm 25$ keV blinding window since the last data release
- **But still no count within $Q_{\beta\beta} \pm 2\sigma$ …**

Statistical analysis and interpretation



Frequentist analysis*:

- Median sensitivity for limit setting:
  $\mathbf{1.8 \times 10^{26}\ yr\ (90\%\ C.L.)}$
  - Best fit → no signal
  - 90% C. L. lower limit:
    $\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}\ yr}$

Bayesian analysis with uniform prior*:

- Median sensitivity for limit setting:
  $1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$
  - $T^{0\nu}_{1/2} > 1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$

L. Shtembari poster
Statistical methods for the new data release of GERDA

Statistical treatment found in* [Nature **544, 47–52 (2017)]
+ includes 23.5 kg·yr phase I exposure

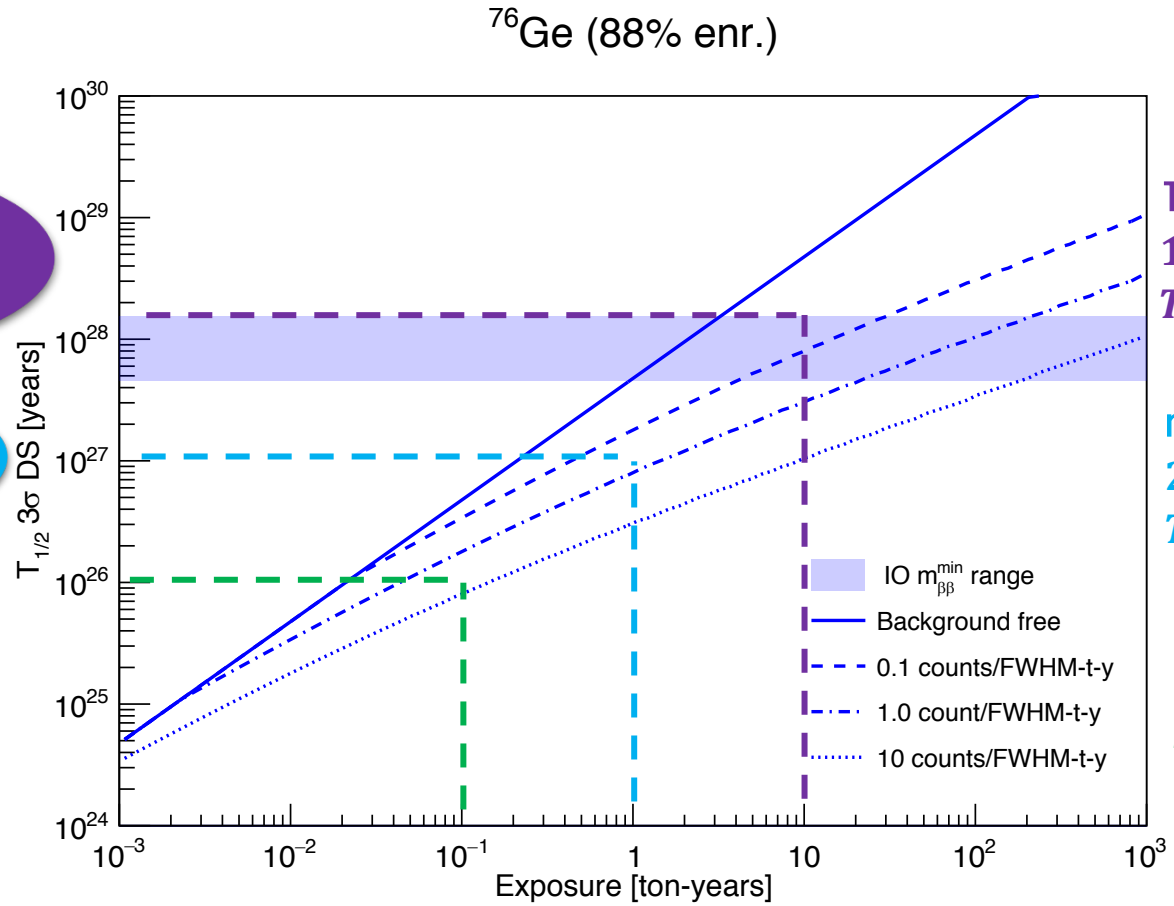
Moving forward

LEGEND 1000

LEGEND 200

GERDA

MAJORANA



long-term
1 ton
$T_{1/2}^{0\nu} > 10^{28}$ yr

mid-term
200 kg
$T_{1/2}^{0\nu} > 10^{27}$ yr

running/ended
30 kg
$T_{1/2}^{0\nu} > 10^{26}$ yr

LEGEND: A worldwide joint effort

LEGEND mission:
"The collaboration aims to develop a phased, ^{76}Ge 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."

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University
University of North Carolina
University of Warwick
Sichuan University

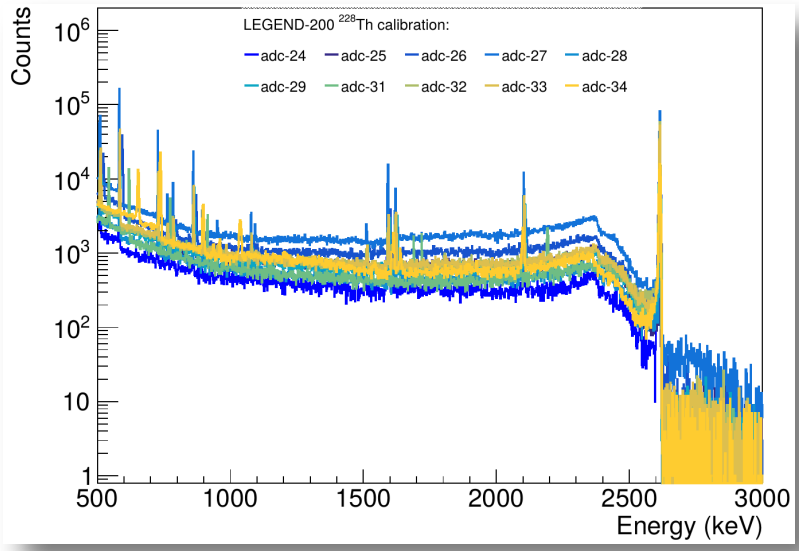
University of South Carolina
Tennessee Tech University
Jagiellonian University
University of Dortmund
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University
Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute for
Nuclear Physics, Heidelberg
Queens University

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 for Physics, 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
Academia Sinica
University Tübingen
University South Dakota
University of Zurich
Roma Tre University and INFN

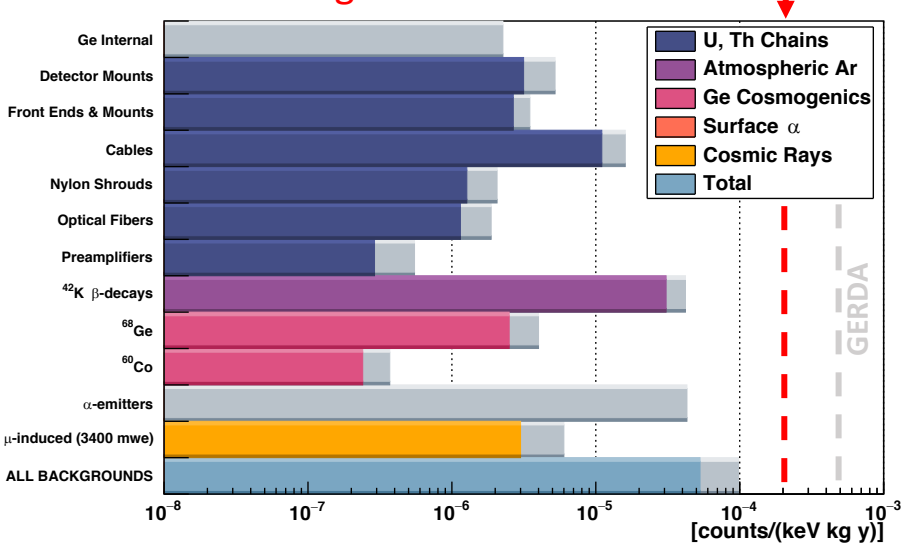
LEGEND-200 ongoing LNGS program

First calibration spectra in March 2020



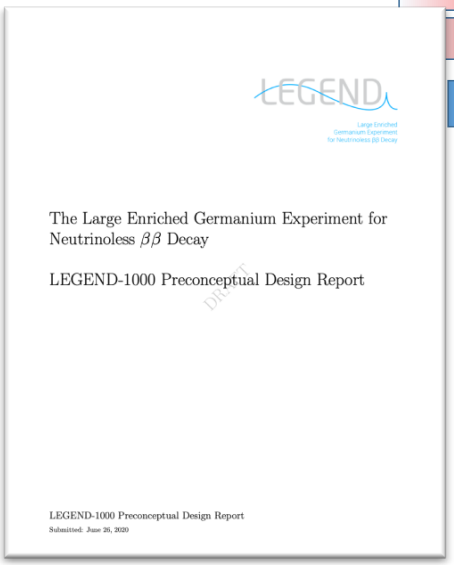
- Ongoing since Feb 2020
- **GERDA detectors + 4 L200 ICPC + 5 MJD PPC detectors operating in liquid argon**
- First tests of new DAQ, calibration system under real conditions
- First spectra taken using new head electronics
- Data taking still ongoing while LNGS activities are impacted by COVID

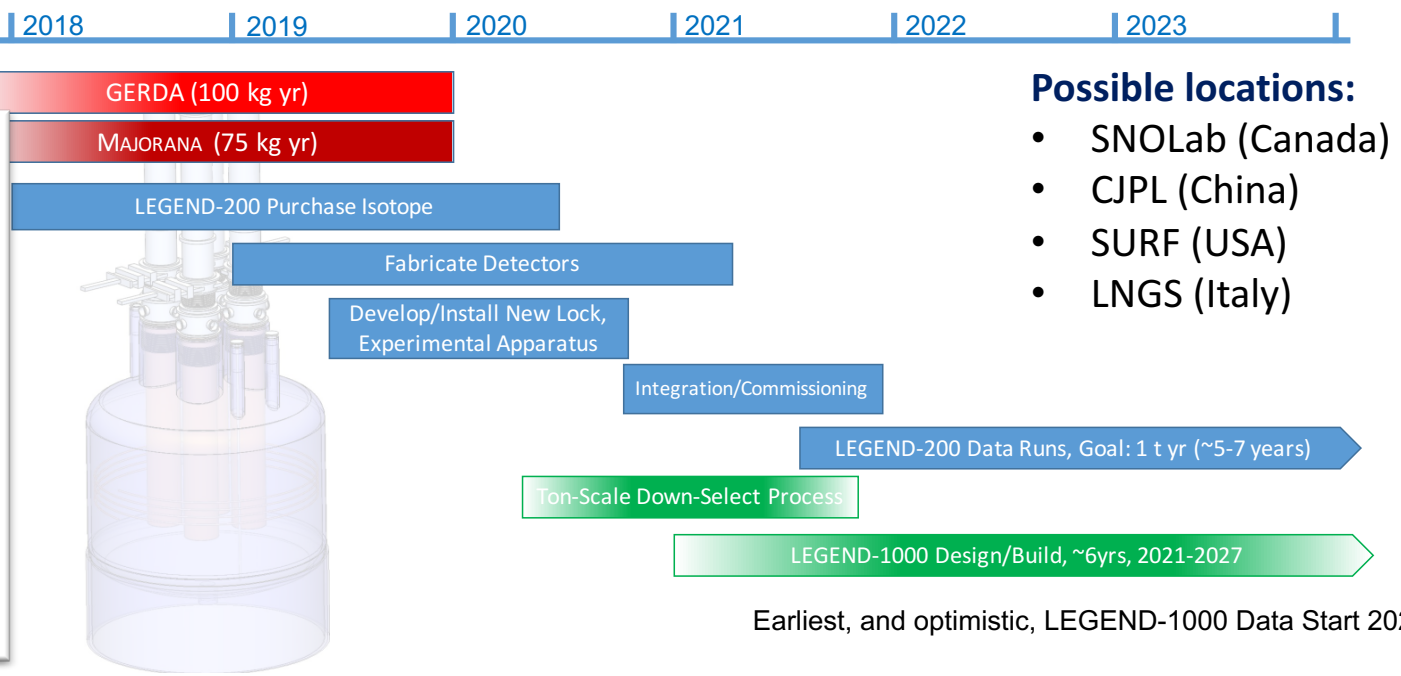
LEGEND-200 background Goal



- **Background contributions near $Q_{\beta\beta}$ after all cuts** *(NB: design exposure = 1 t · yr)*
- Monte Carlo + data-driven projections of Ge U/Th, ^{42}K, α based on GERDA, MJD data
- All others: Monte Carlo + assay-based projections
- Grey bands indicate uncertainties in assays and background rejection

LEGEND-1000: Toward a ton-scale experiment



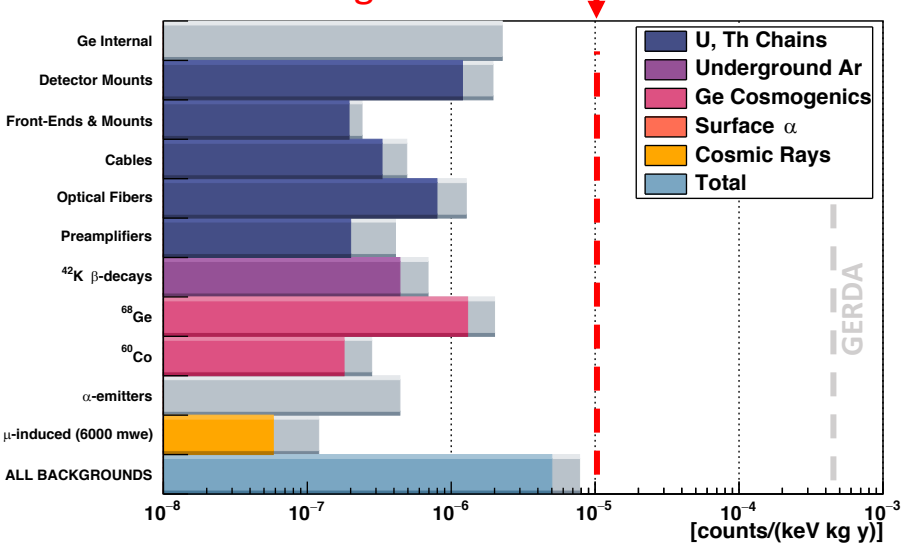


Possible locations:

- SNOLab (Canada)
- CJPL (China)
- SURF (USA)
- LNGS (Italy)

Earliest, and optimistic, LEGEND-1000 Data Start 2025/6

LEGEND-1000 background Goal



Reductions for LEGEND-1000:

- **U/Th**: optimized array spacing, minimize opaque materials, larger detectors, better light collection, cleaner materials
- **^{42}Ar**: strong suppression by using udg. sourced Ar
- **μ-induced**: improved shielding, SNOLab depth assumed
- **Surface α's**: assumes achieved UL for BEGes and ICPCs in GERDA

Summary

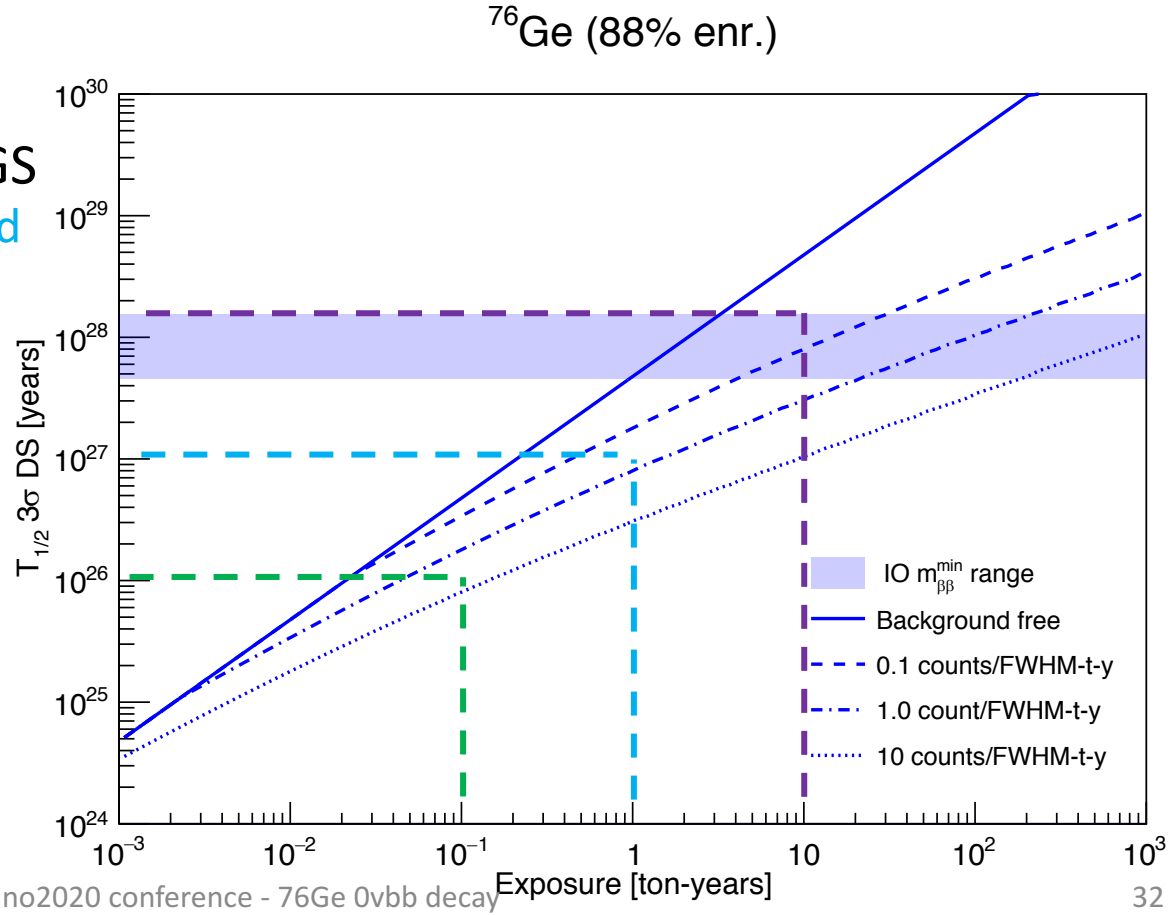
- **MAJORANA:** doubled exposure $(50\ \mathrm{kg} \cdot \mathrm{yr})$ to be released this year
  most stringent limits on $\beta\beta$ decay to ^{76}Se excited states at this conference

- **GERDA** data taking completed in Dec. 2019 – $104\ \mathrm{kg} \cdot \mathrm{yr}$ collected
  no signal observed @ $Q_{\beta\beta}$ – new lower limit on ^{76}Ge $0\nu\beta\beta$ decay half-life:

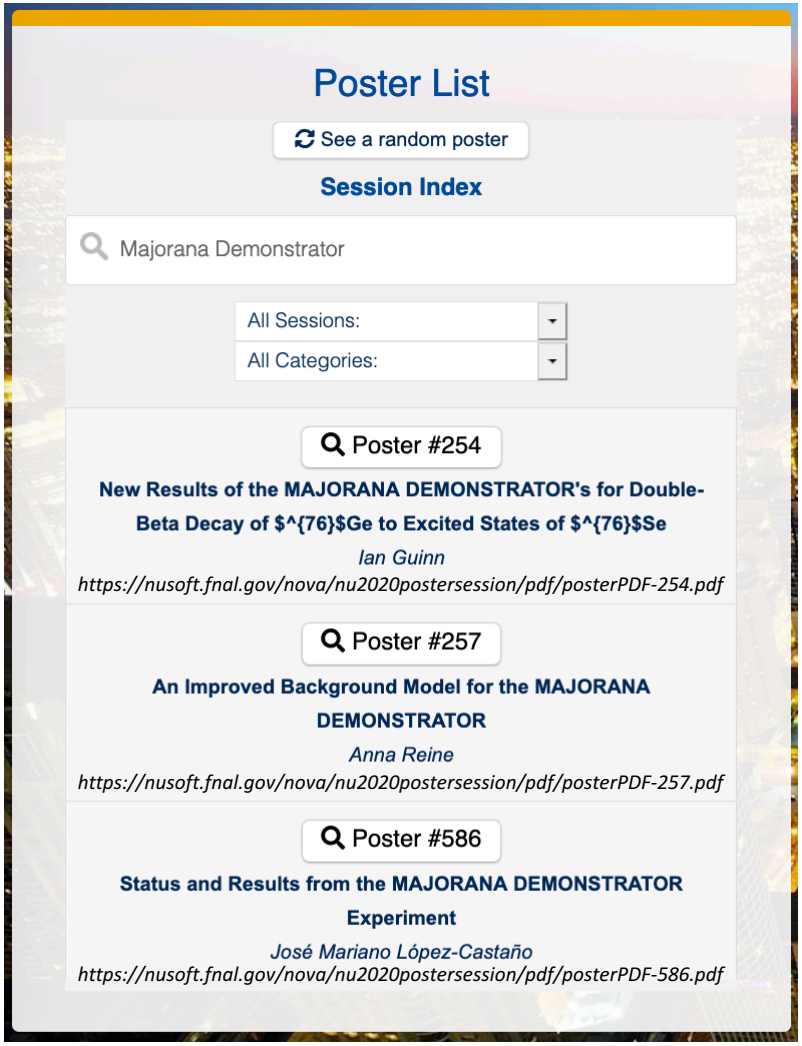
$$T_{1/2}^{0\nu} > 1.8 \times 10^{26}\ \mathrm{yr} \quad @\ 90\%\ \mathrm{C.L.}$$

- **LEGEND-200** already using GERDA infrastructure at LNGS
  - Test of prototype electronics and DAQ started in existing cryostat,
  - to be followed by infrastructure upgrade.
  - Data-taking will begin in 2021

- **LEGEND-1000**: ton-scale experiment achievable with modest evolution of LEGEND-200 design
  - goal to reach the 10^{28} yr discovery potential sensitivity



List of MAJORANA DEMONSTRATOR related posters

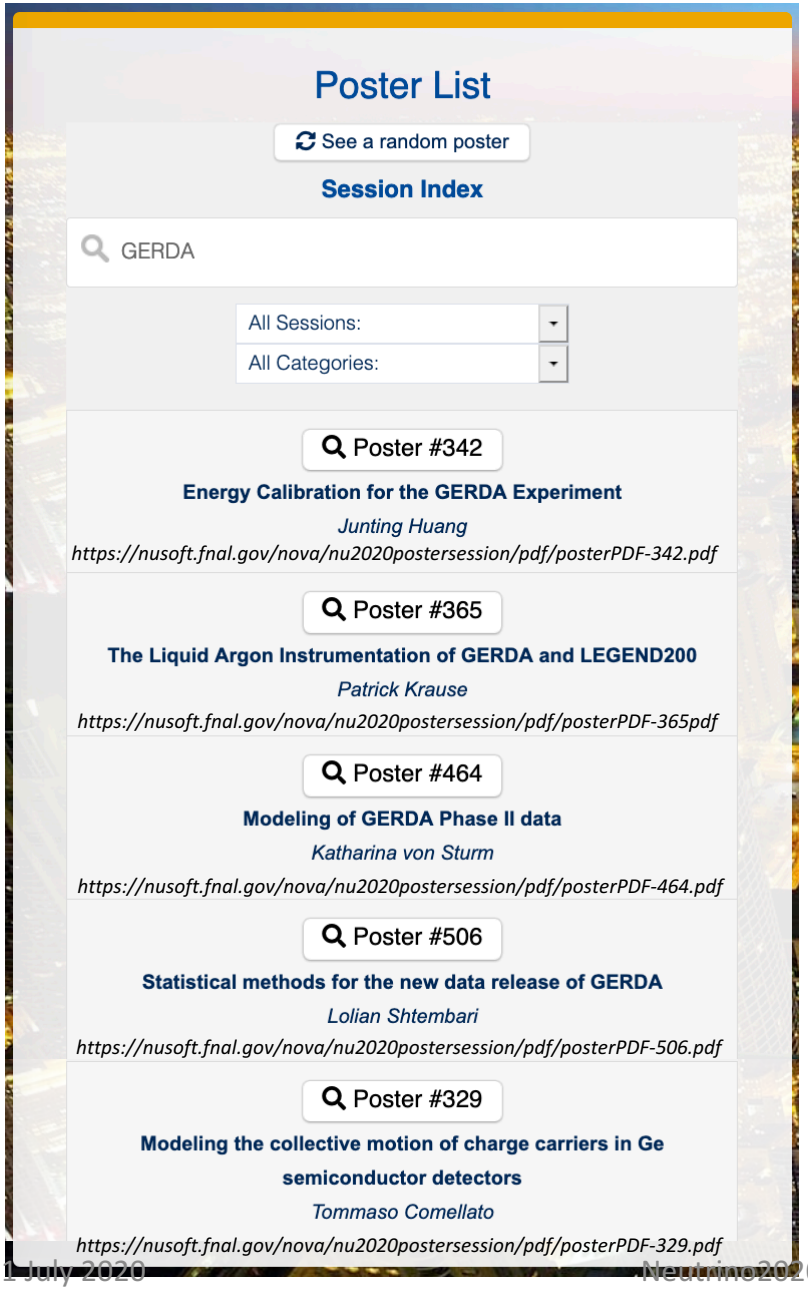


Go to:
https://nusoft.fnal.gov/nova/nu2020postersession/

Search for: "Majorana Demonstrator"
in "All Sessions"

You'll find up to 3 posters!

List of GERDA related posters

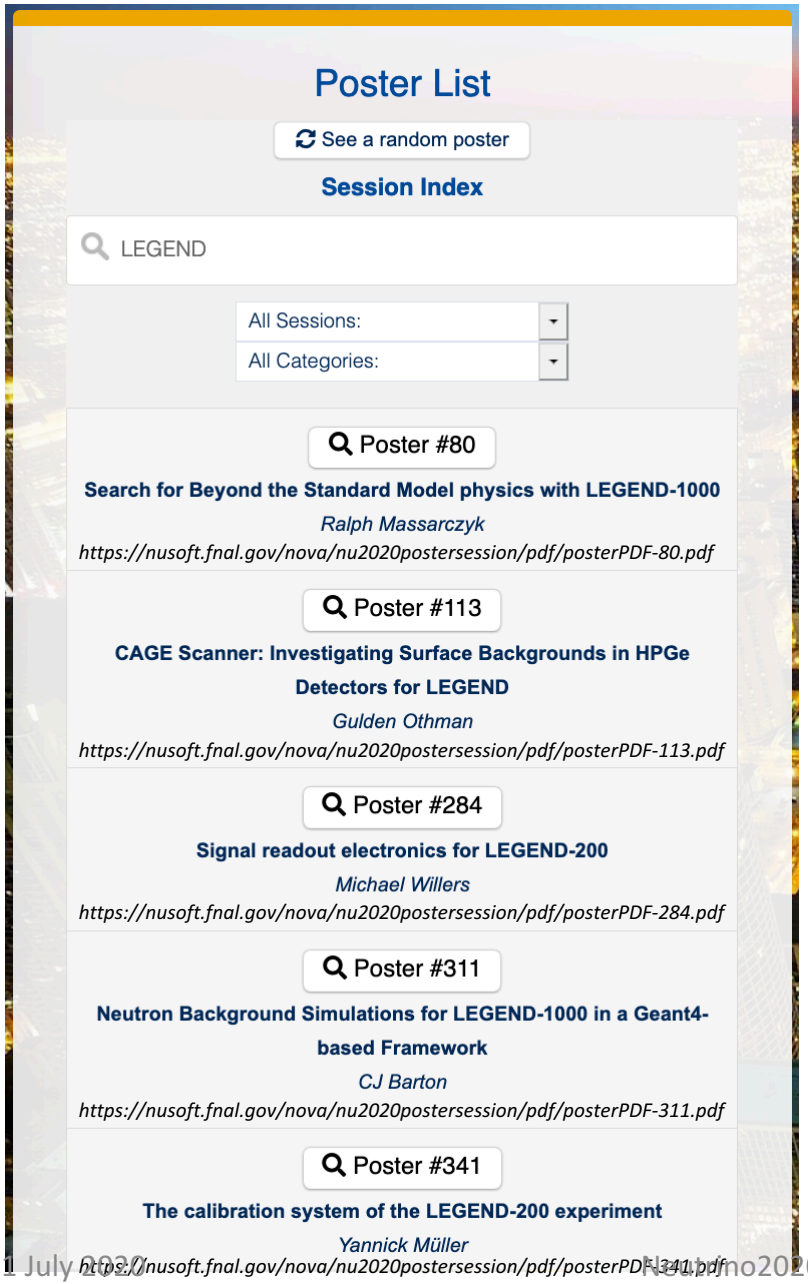


Go to:
https://nusoft.fnal.gov/nova/nu2020postersession/

Search for: “GERDA” & ”in Ge” in “All Sessions”

You’ll find up to 5 posters!

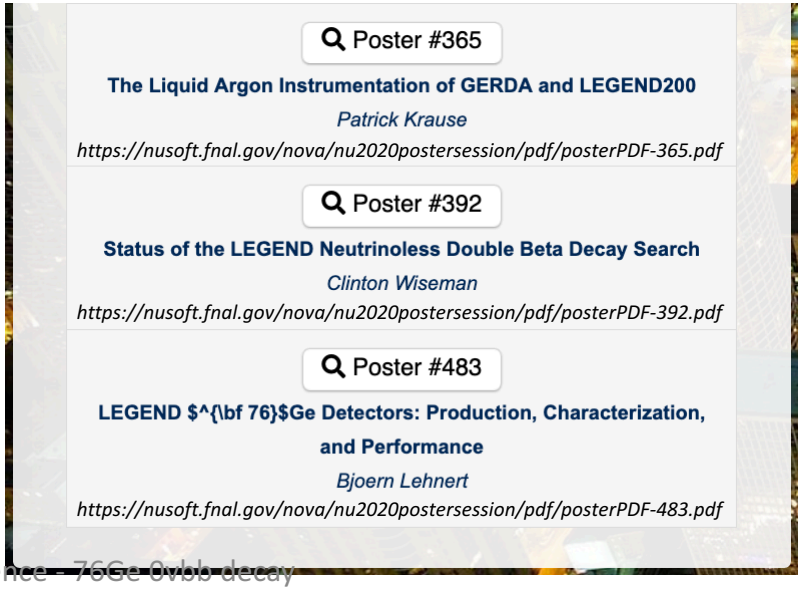
List of LEGEND related posters



Go to:
https://nusoft.fnal.gov/nova/nu2020postersession/

Search for: “LEGEND” in “All Sessions”

You’ll find up to 8 posters!

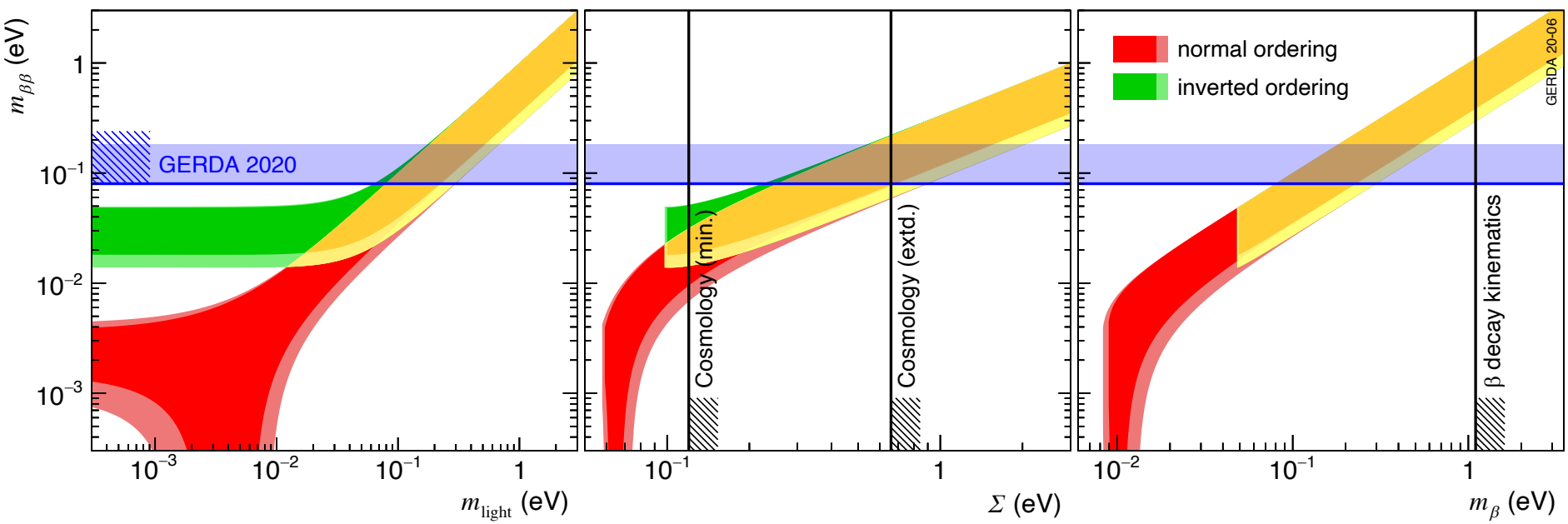


The end

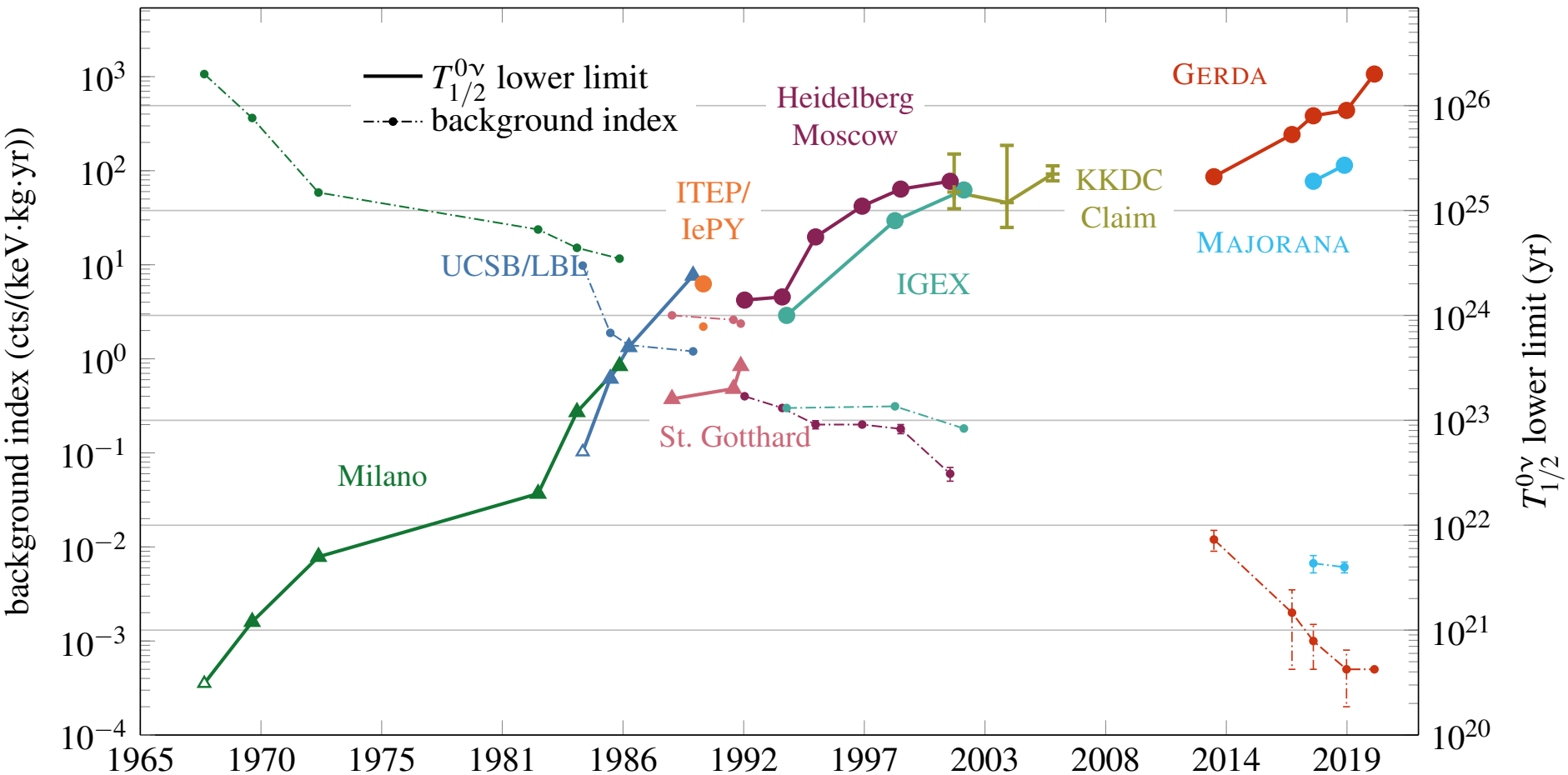
Upper limit on $m_{\beta\beta}$ within 3ν flavor model

$$1/T^{0\nu}_{1/2} = g_A^4\, G^{0\nu}\, \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

- Lower 90% C. L. limit: $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr
- Converted into upper limit on: $m_{\beta\beta} < [80 - 182]$ meV
- Other inputs:
  - $g_A = 1.27$
  - ^{76}Ge NME $\in [2.66 - 6.04]$ min NME from Coraggio et al. 2020
    max NME from Song et al. 2017

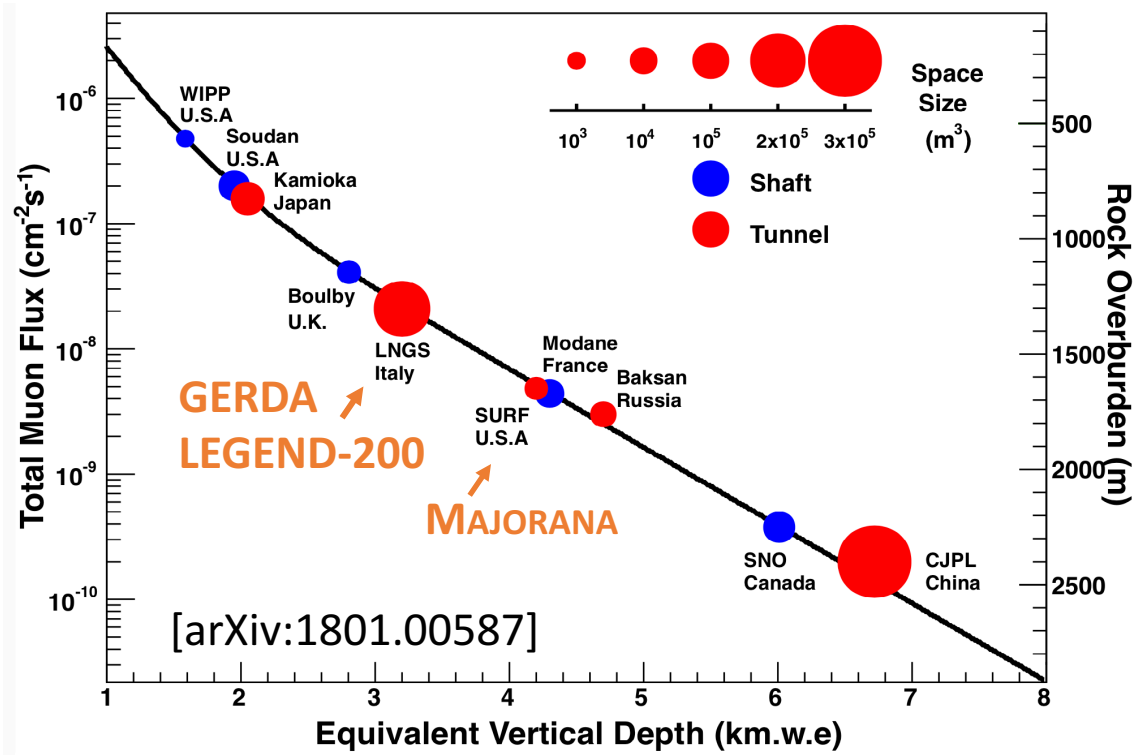


^{76}Ge $0\nu\beta\beta$ decay search history



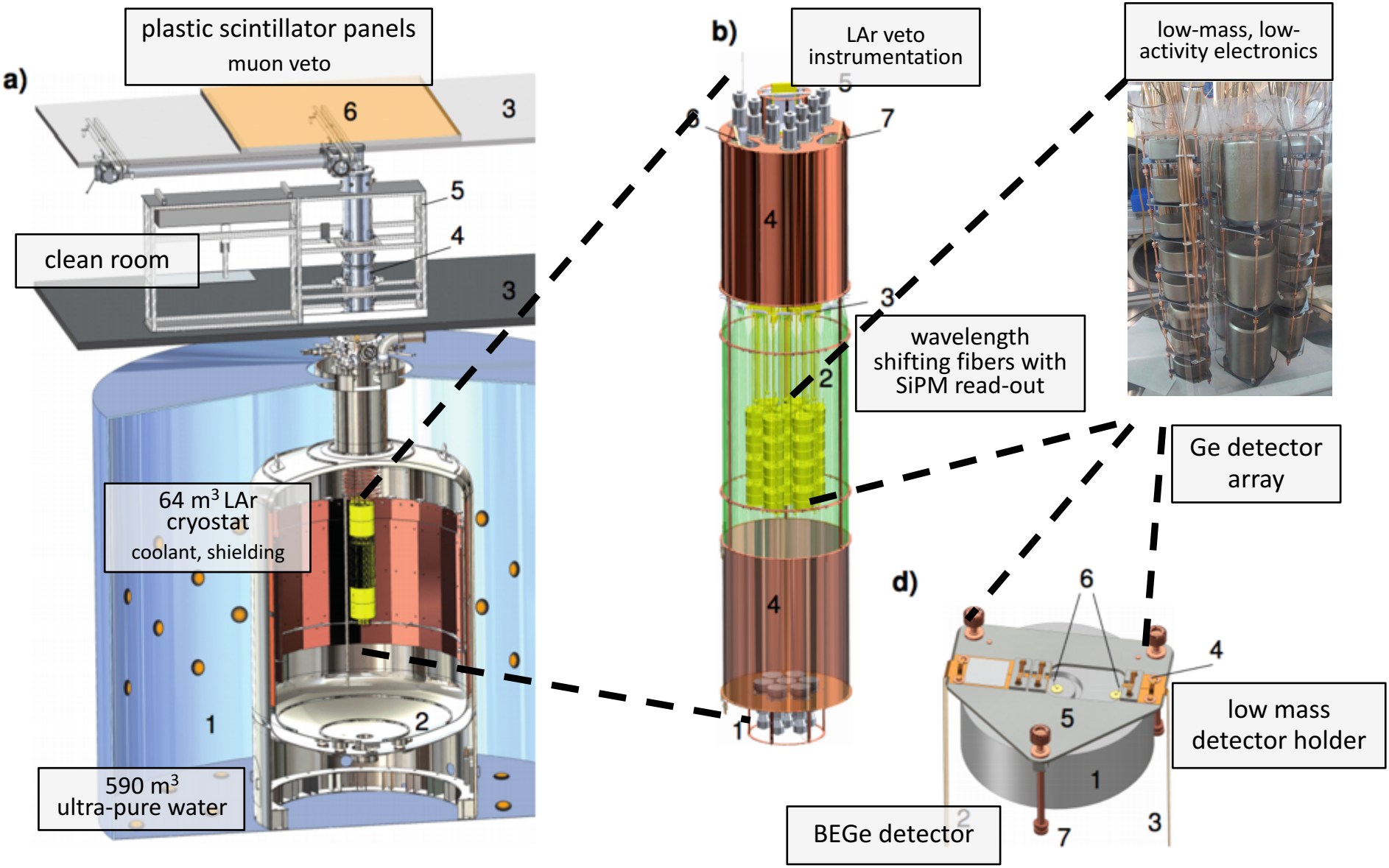
Underground laboratories worldwide

see J. Heise talk

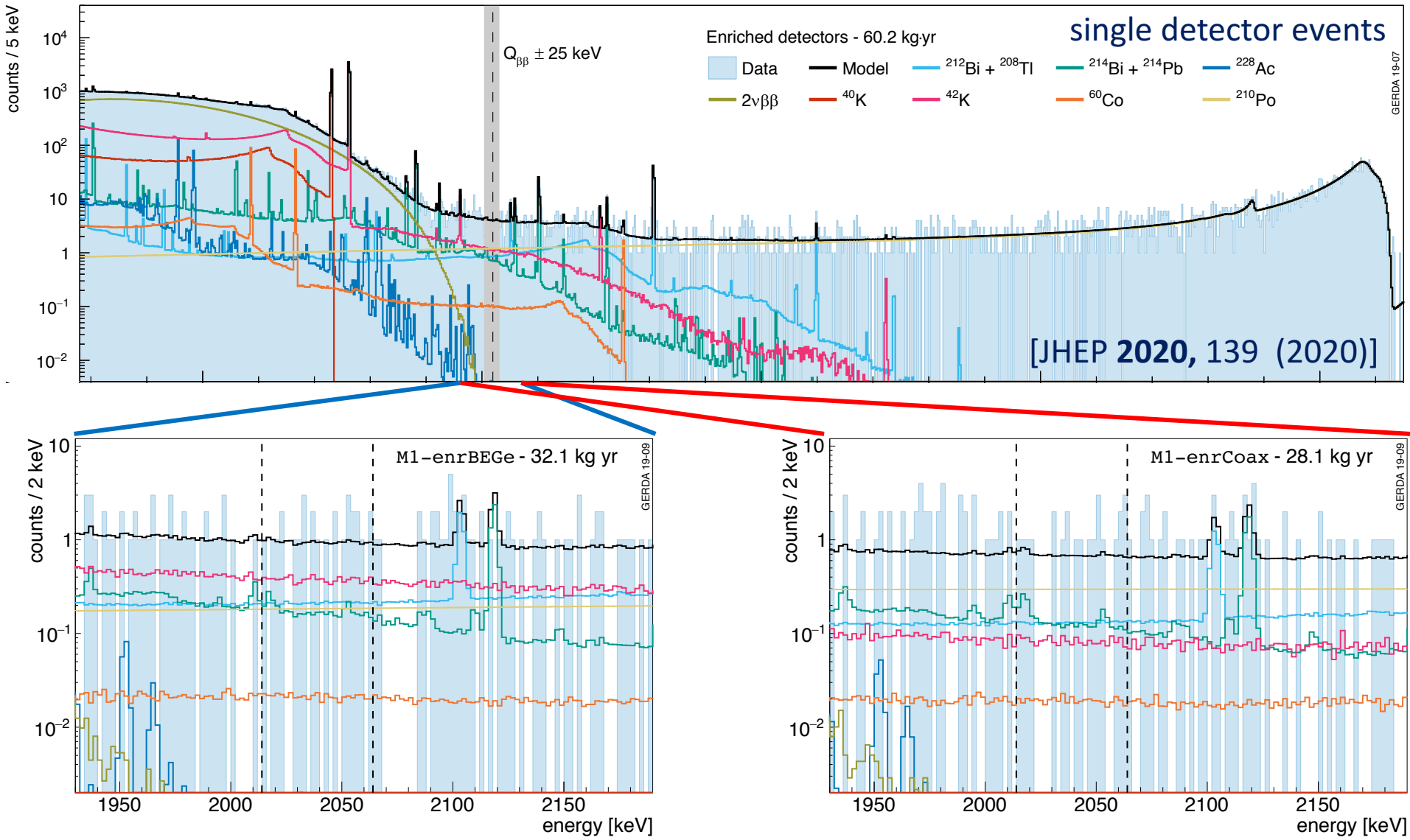


- Underground = passive background suppression for « free »
- Isotopic activation suppression (neutron capture – e.g. $^{76}\mathrm{Ge} + n \rightarrow {}^{77\mathrm{m}}\mathrm{Ge} \rightarrow {}^{77}\mathrm{As}$ + **2.7 MeV**)
- Large experimental infrastructure required (shielding, cryostat, instrumentation)
- Size/depth/access compromise taken into account by the collaborations

Phase II: From concept to design

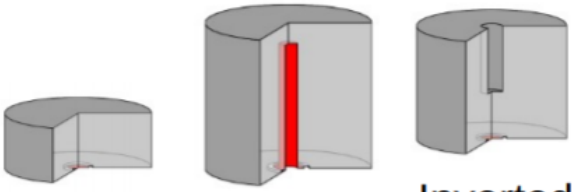


Phase II physics data modeling before cuts



Main outcome: no full energy peak or other structures close to $Q_{\beta\beta}$

GERDA overall exposure summary

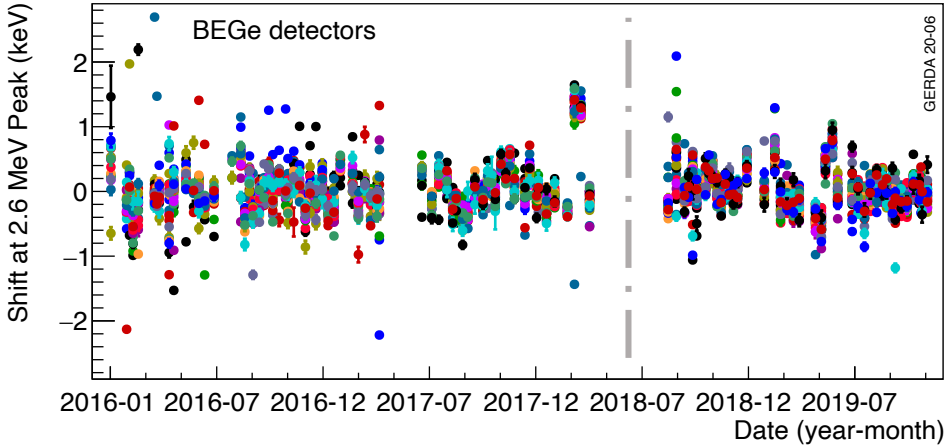


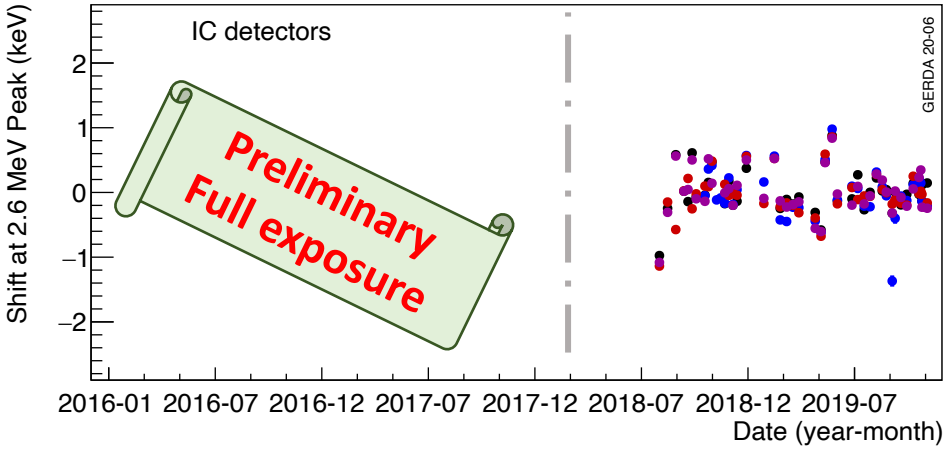
	BEGe	Coaxial	Inverted Coaxial	[kg·yr]
pre-upgrade:	31.5	28.6		60.1
post-upgrade:	21.9	13.2	8.5	43.6
	53.3	**41.8**	**8.5**	**103.7**
Phase I:	2.4	21.1		**127.2**

Calibration stability

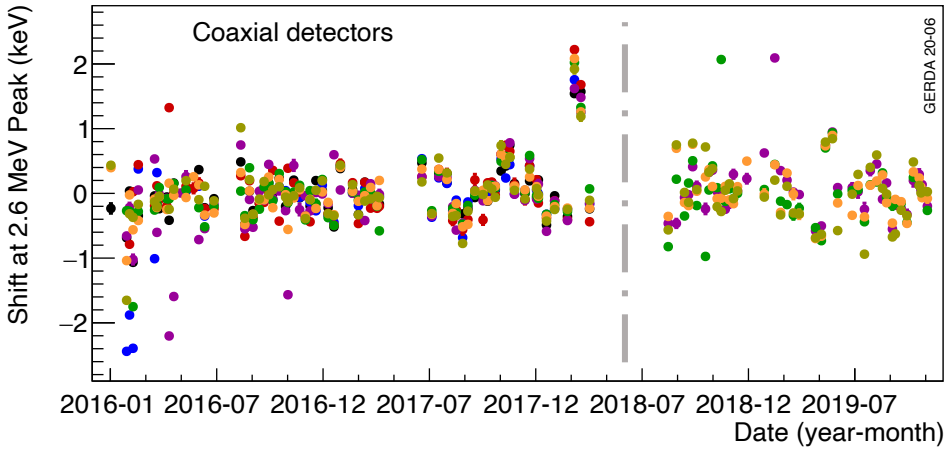
- **small contact detectors:**

— · May 2018 upgrade





- **coaxial detectors:**

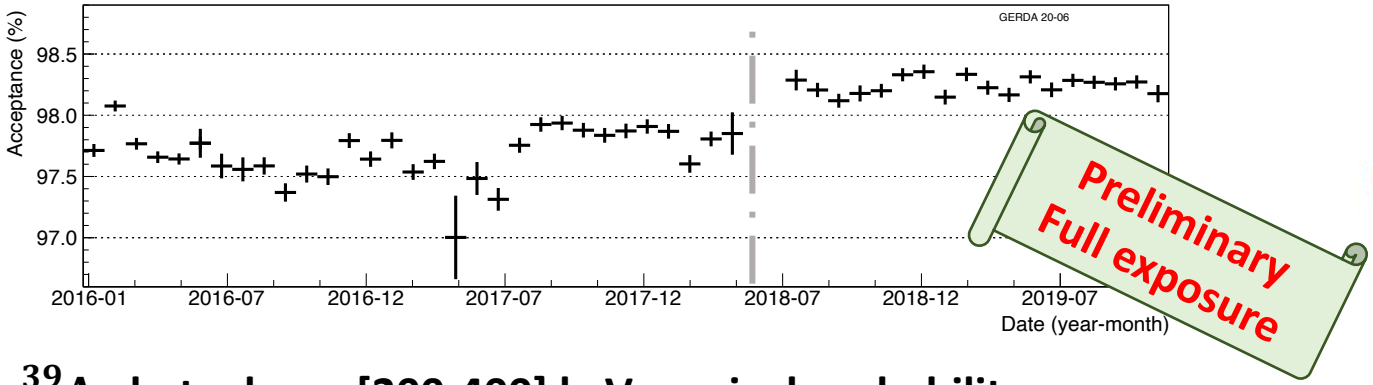


Check for the 2.6 MeV gamma line shift from ^{228}Th calibration source in each consecutive valid period of time

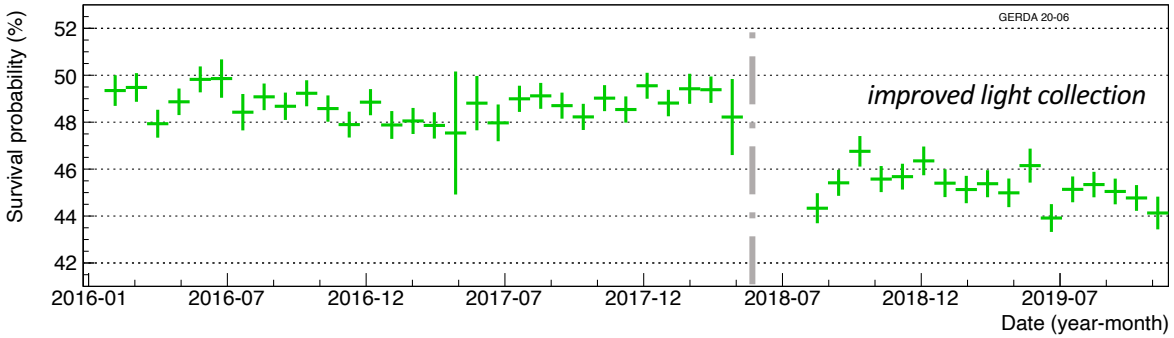
Liquid argon veto stability

- **$0\nu\beta\beta$ decay signal acceptance:**

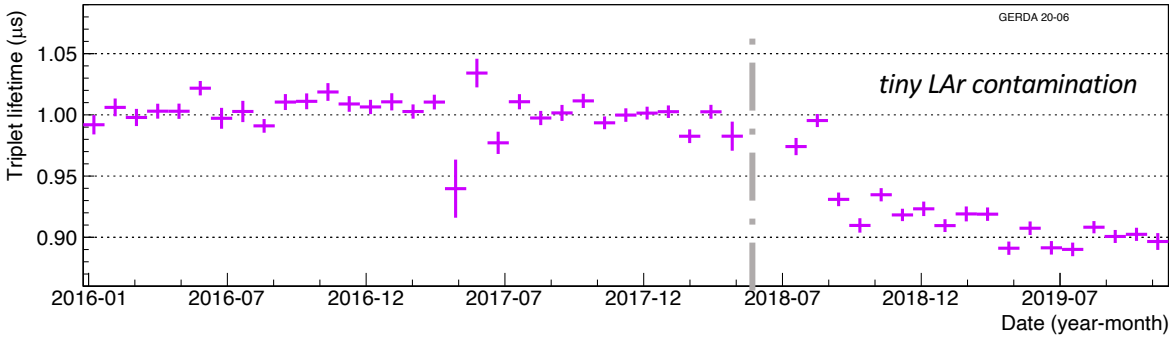
— · May 2018 upgrade

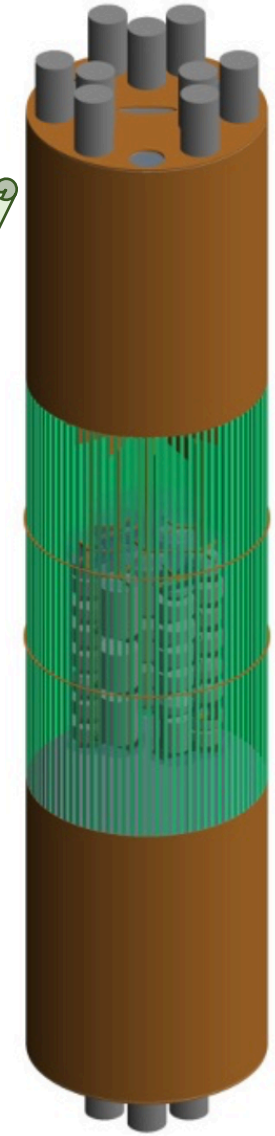


- **^{39}Ar beta decay [200-400] keV survival probability:**



- **GERDA liquid argon triplet lifetime:**

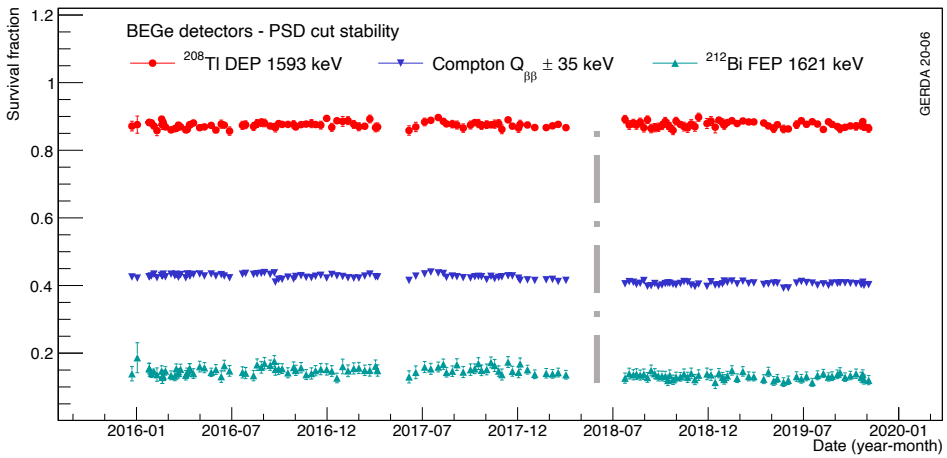


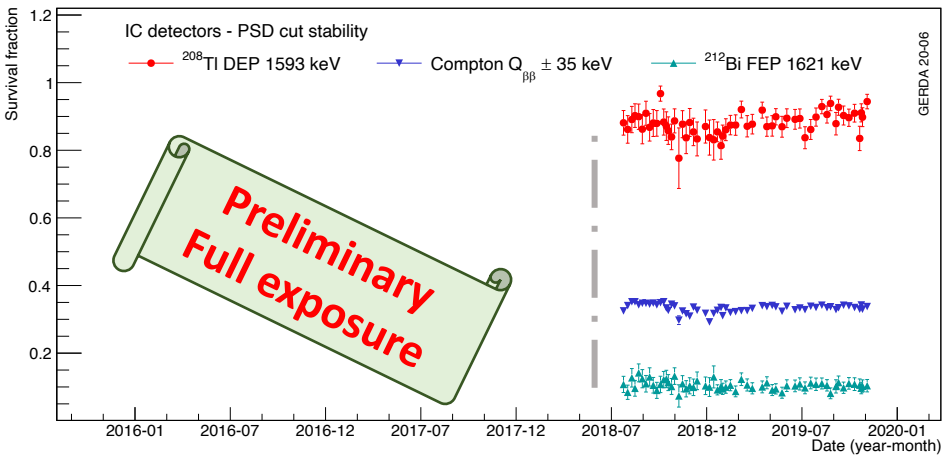


PSD efficiencies stability

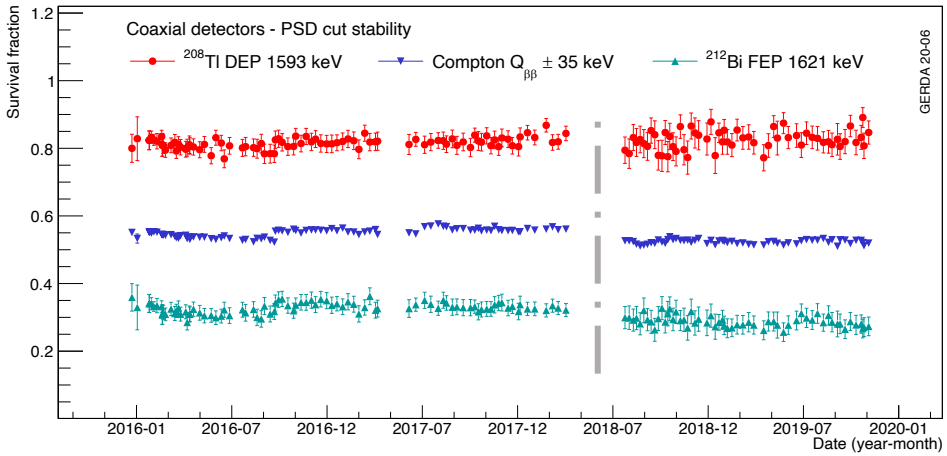
- **small contact detectors:**

— · May 2018 upgrade





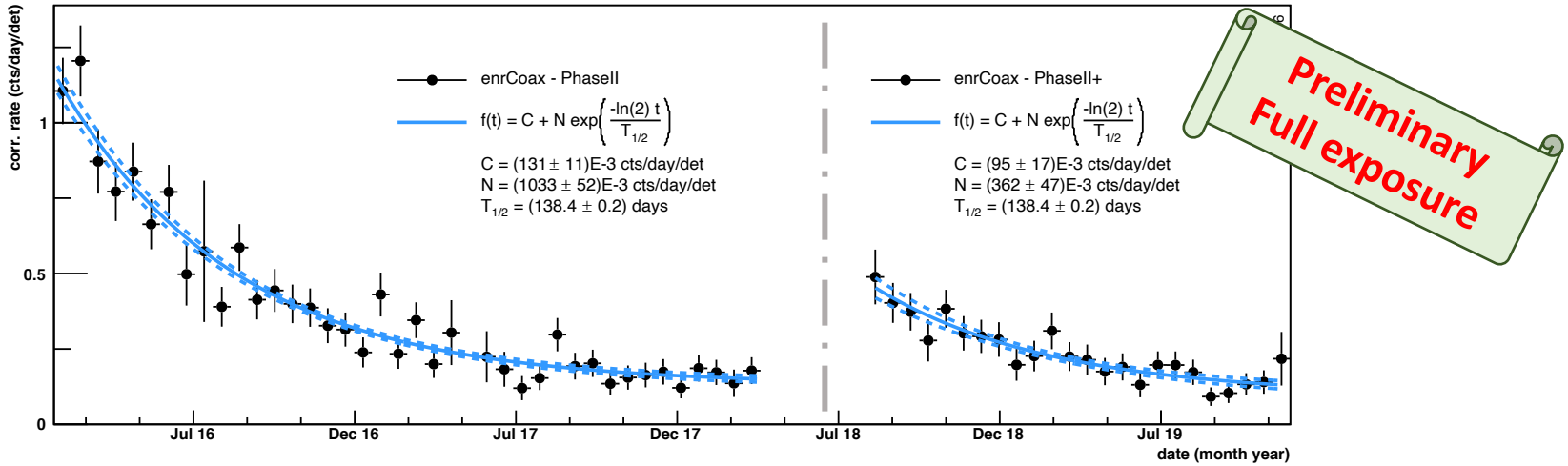
- **coaxial detectors:**



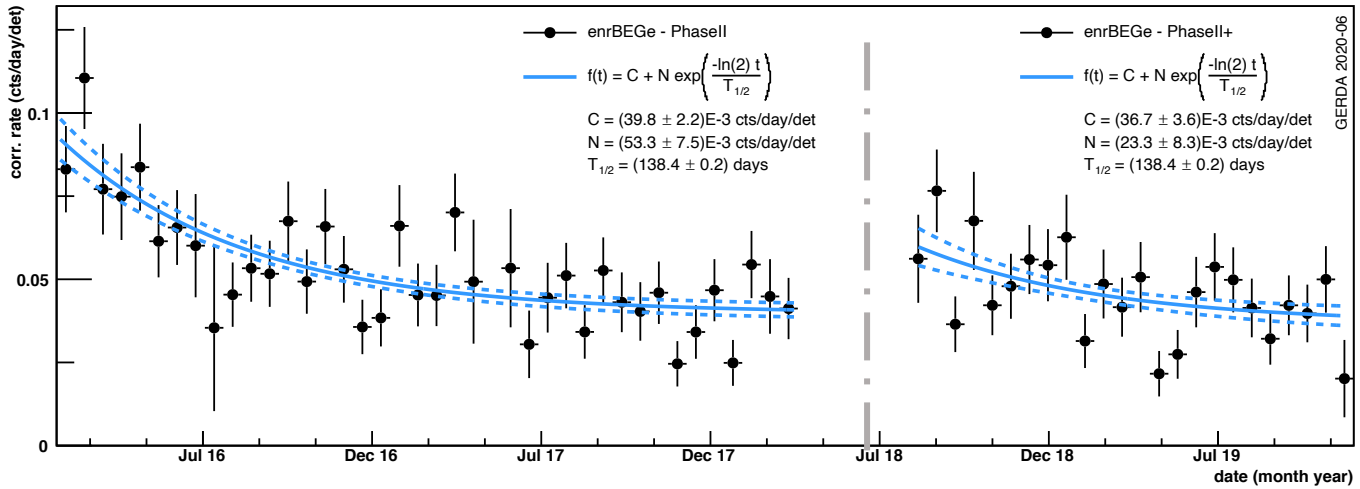
PSD time stability checked by looking at gamma lines survival fraction from individual calibration runs

Time evolution of Alpha background

- **Coax detectors α background (energy > 3500 keV) before cuts:**

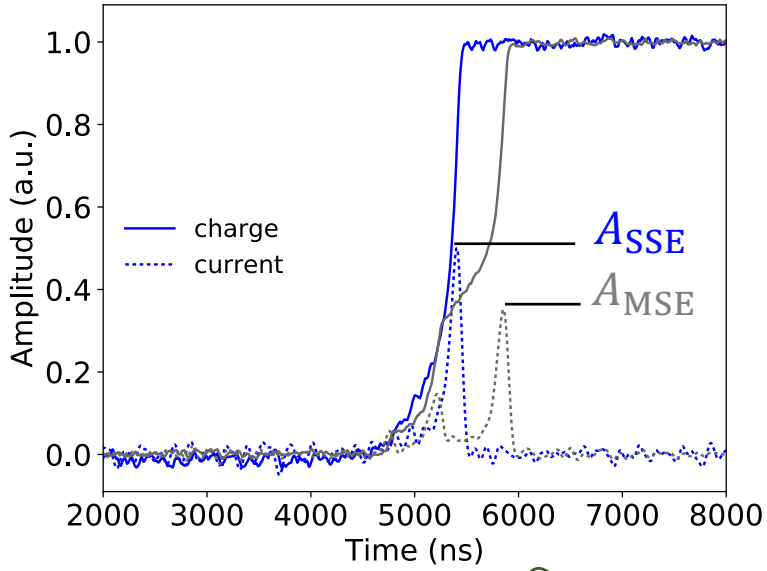


- **BEGe detectors α background (energy > 3500 keV) before cuts:**

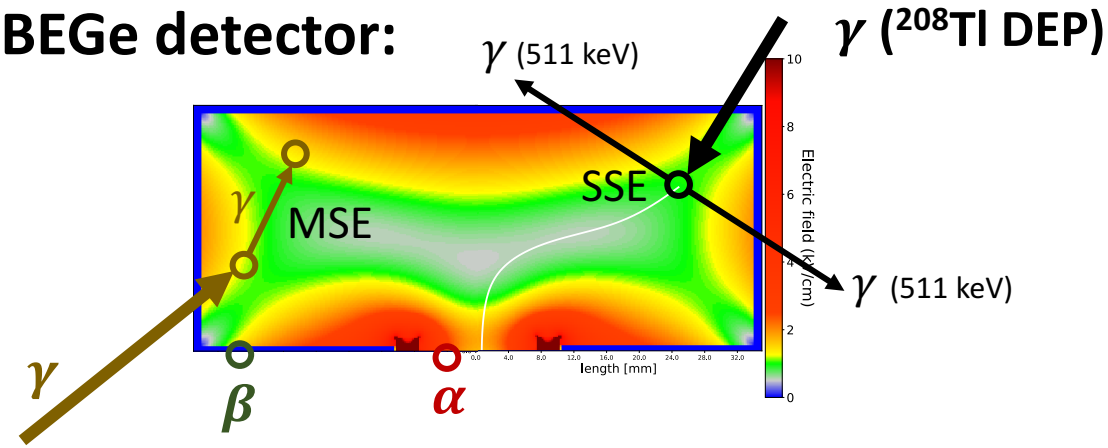


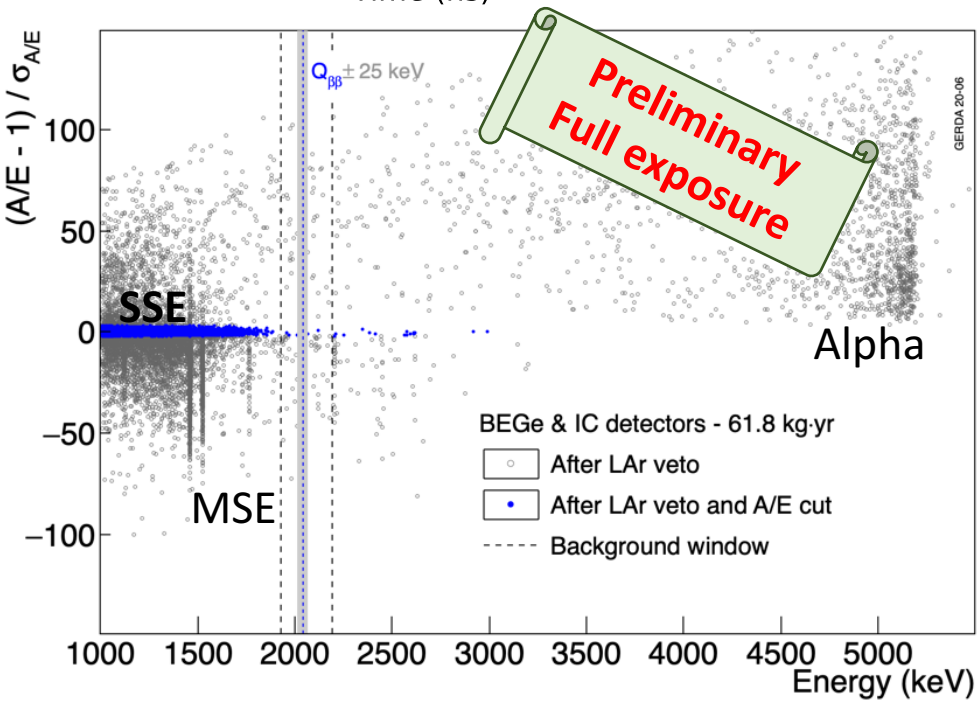
Main outcome: No critical recontamination of BEGe small-contact detector during the upgrade
Detector handling procedure OK for LEGEND-200

Pulse Shape Discrimination #1



BEGe detector:



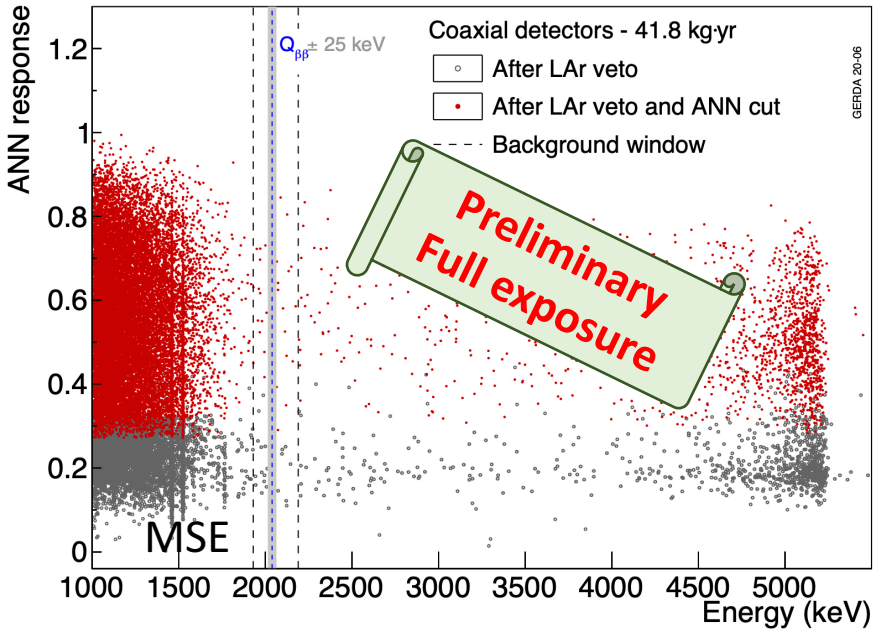


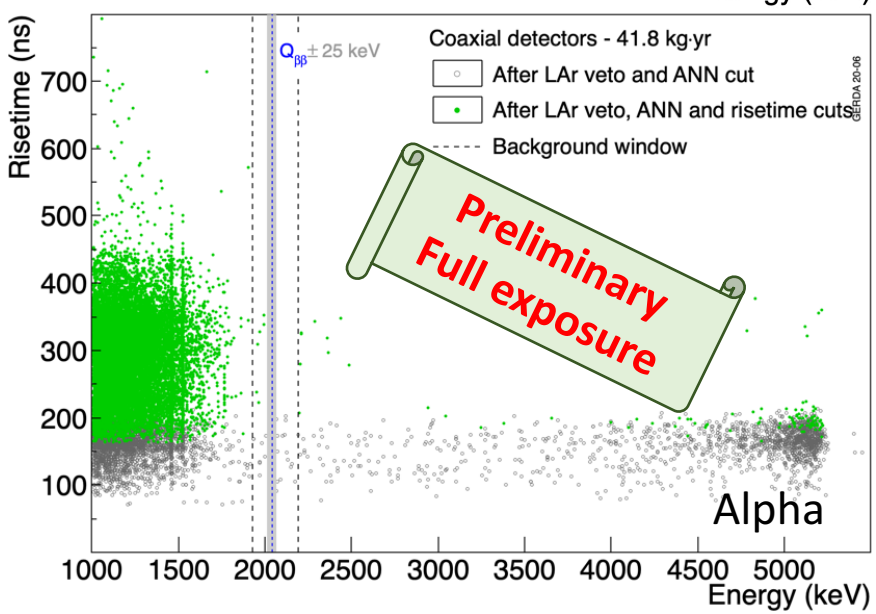
- **MSE cut**: Low A/E cut set to accept 90% of ^{208}Tl DEP from cal.
- **Alpha cut**: High A/E cut set to $+3\sigma$ of SSE A/E band
  No high energy alpha (E>3.5 MeV) survive
- $\epsilon_{PSD}^{BEGe} = (88.7 \pm 3.2)\%$
- $\epsilon_{PSD}^{IC} = (90.0 \pm 1.7)\%$

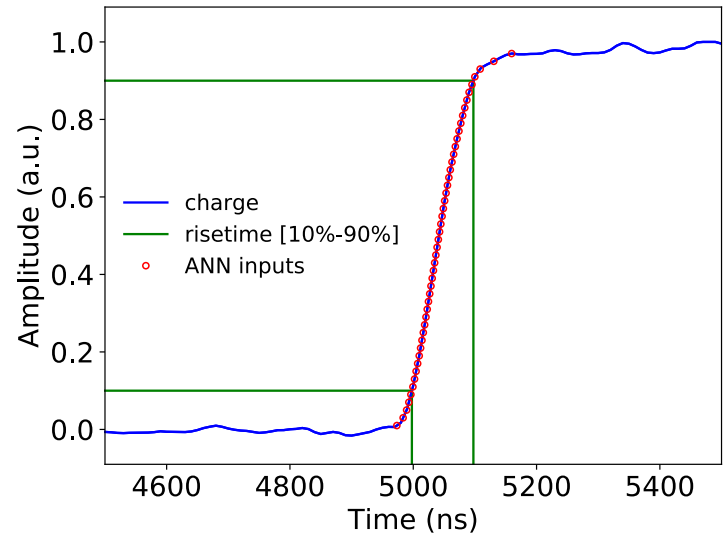
PSD uncertainties are systematics dominated

T. Comellato poster
Modelling the collective motion of charge carrier in Ge detectors

Pulse Shape Discrimination #2



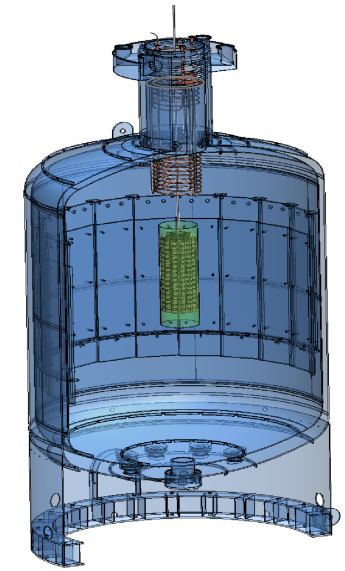




- **MSE cut**: **Artificial Neural Network** fed with SSE and MSE **proxies from cal.** (^{208}Tl DEP and ^{212}Bi FEP)
  cut set @ 90% acc. of ^{208}Tl DEP events
  $\epsilon_{\mathrm{ANN}} = (82.3 \pm 3.1)\%$
- **Alpha cut**: Charge collection risetime [10%-90%]. **Cut optimized from $2\nu\beta\beta$ and α samples**:
  cut set @ $\max[\epsilon_{2\nu\beta\beta} \cdot (1 - \epsilon_{\alpha})]$
  $\epsilon_{\mathrm{RT}} = (85.5 \pm 1.0)\%$
- $\boldsymbol{\epsilon_{\mathrm{PSD}}^{\mathrm{Coax}} = (68.9 \pm 3.1)\%}$

PSD uncertainties are systematics dominated

The Best of MAJORANA & GERDA



MAJORANA

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

MAJORANA achieved best energy resolution: 2.5 keV FWHM at $Q_{\beta\beta}$

Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$ experiments

GERDA

- LAr veto
- Low-A shield, no Pb

GERDA achieved the lowest background index:
5×10^{-4} cts/(keV · kg · yr)
LEGEND-200 needs only x3-5 better.

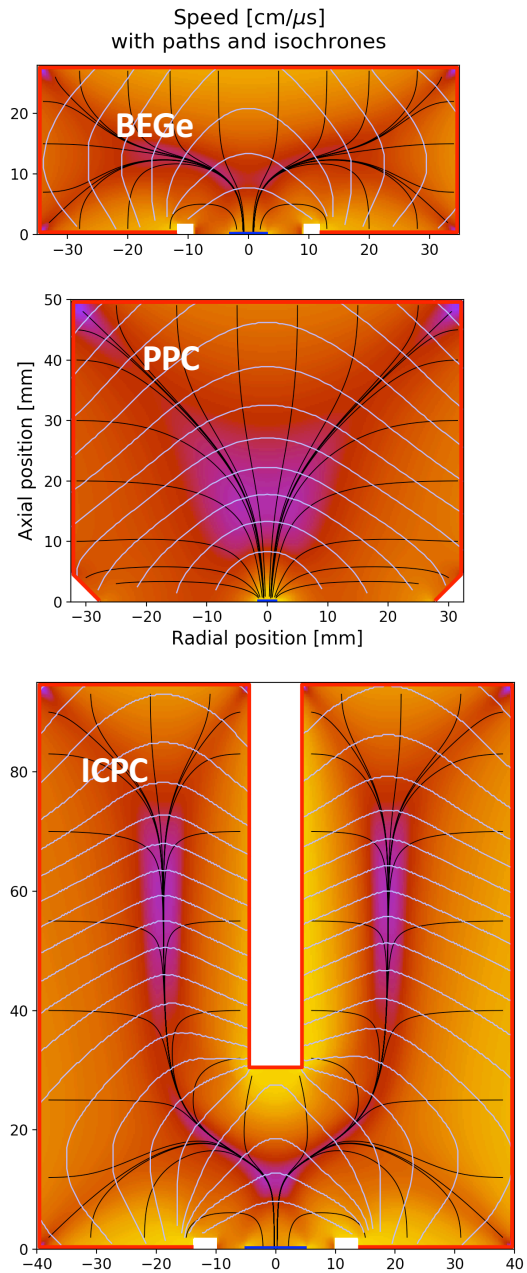
Ge Detectors for LEGEND-200

GERDA BEGes and MAJORANA PPCs

- ✓ Excellent energy resolution
- ✓ Superb pulse-shape sensitivity to reject multi-site and surface background events
- • But relatively small: <m> = 0.66 and 0.85 kg, respectively

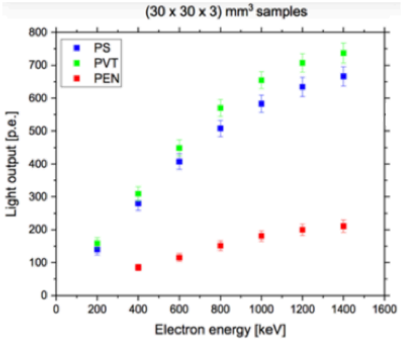
New Inverted-Coaxial Point Contact detectors

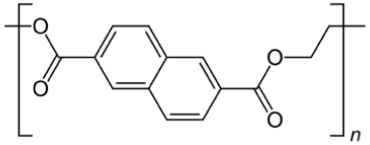
- ✓ First design proposed in 2011
  [R. Cooper et al., NIM A665, 25 (2011)]
- ✓ Large active mass up to 3 kg
- ✓ Excellent resolution and pulse shape discrimination performance [A. Domula et al., NIM A891, 106 (2018)]
- ✓ Lower surface to volume ratio
- ✓ Reduced background due to lower number of channels per mass of ^{76}Ge
- ✓ Production started early 2019
  About 60 detectors expected by fall 2021



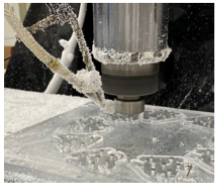
PEN — self-vetoing structural material

- **PEN — Poly(ethylene 2,6-naphthalate)**
  - Scintillates, providing veto to potential backgrounds
  - Light yield ~1/3 of conventional plastic scintillators
  - Particle identification using pulse shape discrimination (PSD) possible
  - Functions as a wavelength shifter of LAr scintillation photons (128 nm)
  - Transparent in the visible range
  - Mechanically stronger than silicon, stronger than Cu at cryogenic temps.

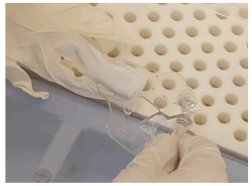




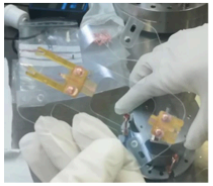
- **Production of LEGEND-200 low-background detector holder plates**
  - Possible replacement of Si detector holder plates
  - Plates produced via CNC machining using clean procedures
  - PEN holders deployed in LEGEND "post GERDA test" at LNGS



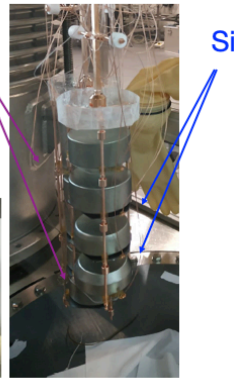
CNC Machining



Cleaning

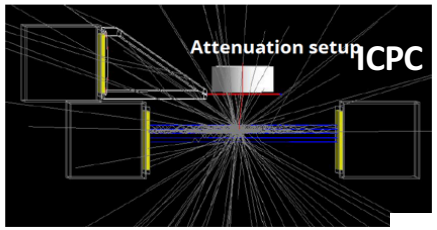


PEN Plate

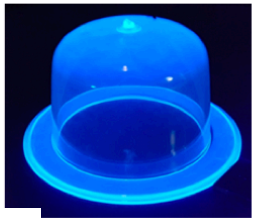


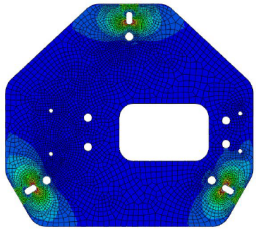
Deployed

- **R&D Activities**
  - Enhanced cleanliness,
  - Dedicated test stands and simulations to further study optical properties:
  - WLS, Light yield, attenuation, surface effects
  - Injection molded components (encapsulation of objects)



PEN crystal capsule





Design