University of Zurich[UZH]

Swiss National Science Foundation

GERDA

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

SEARCH FOR THE NEUTRINOLESS DOUBLE BETA DECAY WITH GERDA AND LEGEND

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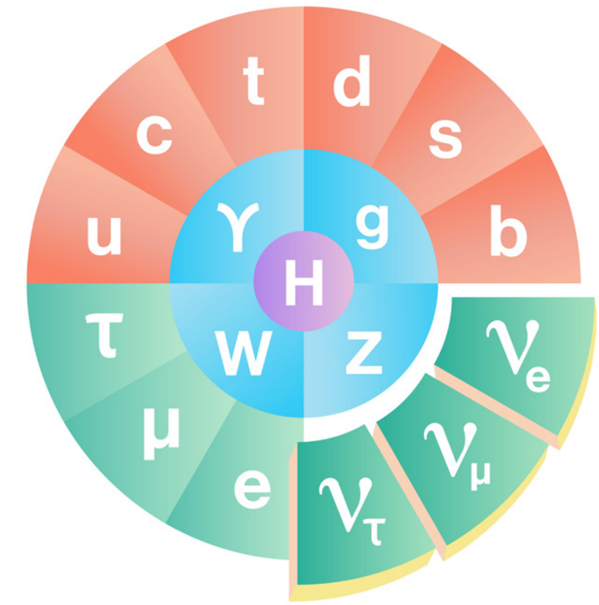
OCTOBER 9, 2019

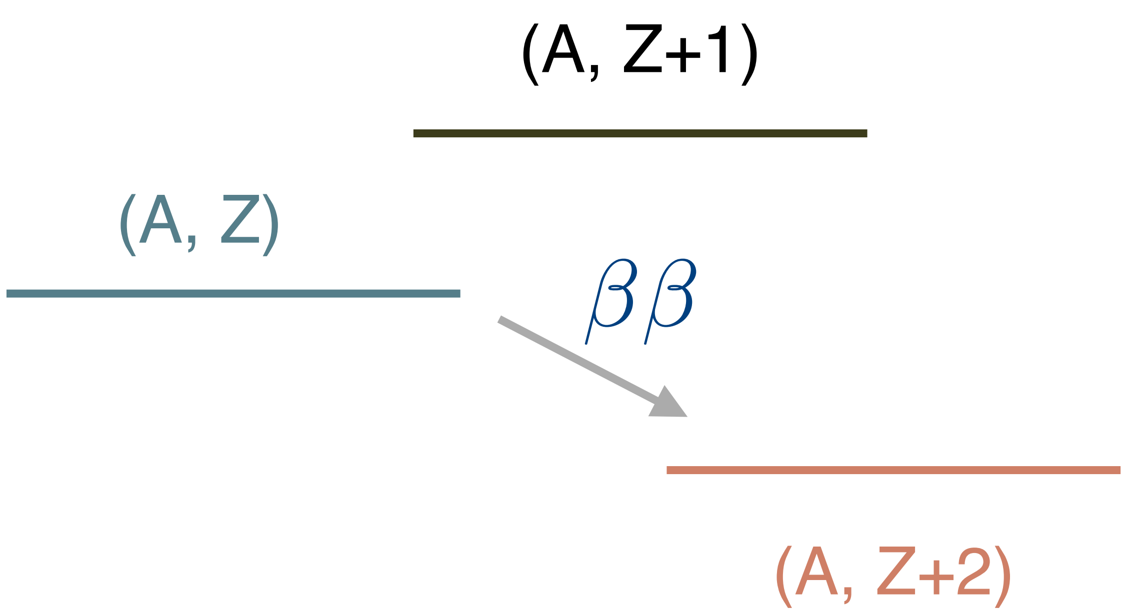
(SOME) OPEN QUESTIONS IN NEUTRINO PHYSICS

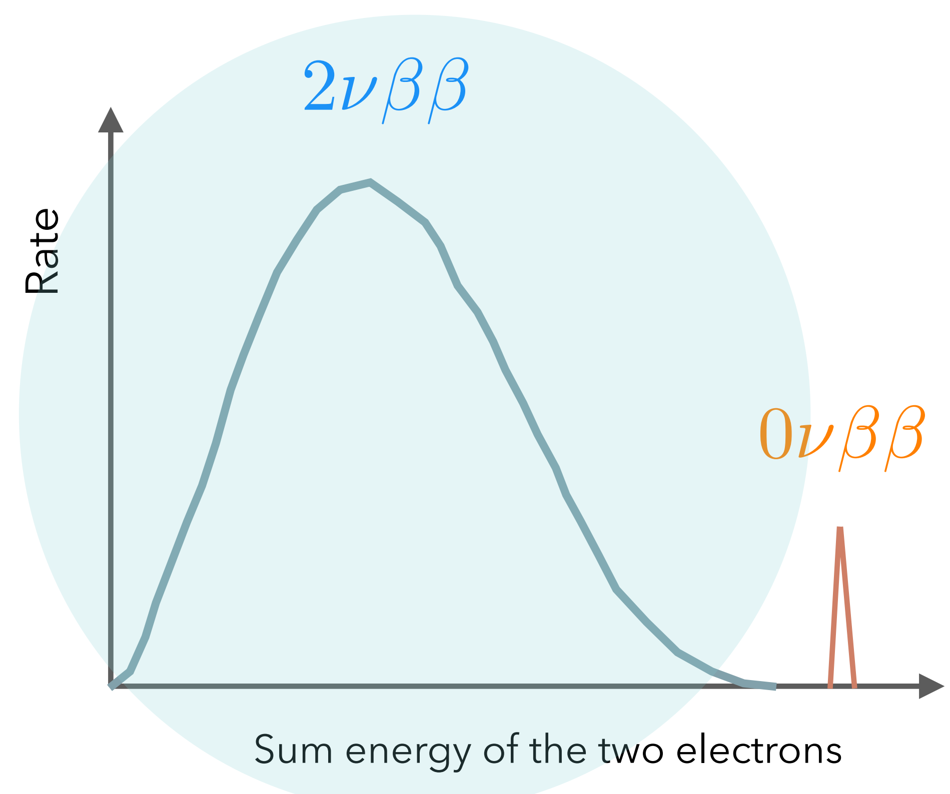


- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- These can be addressed with an extremely rare nuclear decay process: the double beta decay

THE DOUBLE BETA DECAY

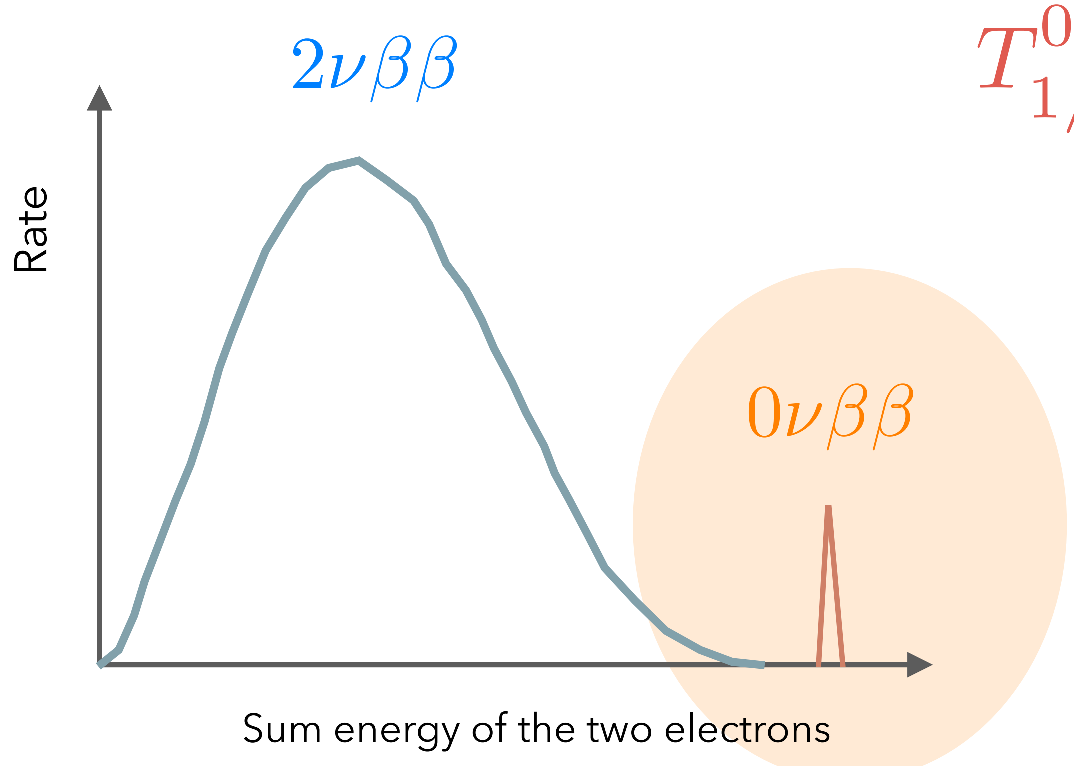
- Predicted by Maria-Goeppert Mayer in 1935
- The SM decay, with 2 neutrinos, was observed in 14 nuclei
- $T_{1/2} > 10^{18}$ y; ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



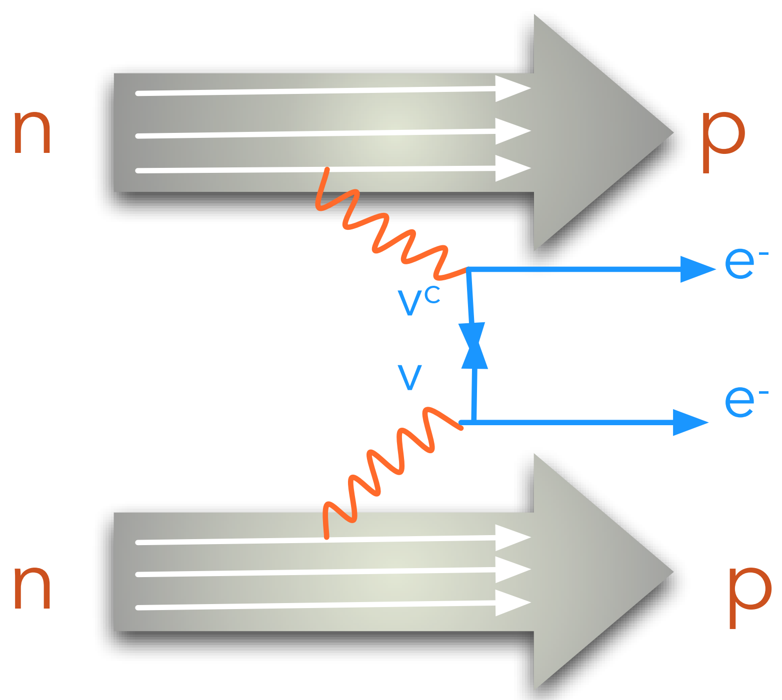


THE NEUTRINOLESS DOUBLE BETA DECAY

- Can only occur if neutrinos have mass and if they are their own anti-particles; $\Delta L = 2$
- Expected signature: sharp peak at the Q-value of the decay



$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\ \mathrm{y}$$



OBSERVABLE DECAY RATE

Phase space factor

Axial-vector cc

NME

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

Can be calculated: ~ Q^5

Difficult: factor 2-3

- With the effective Majorana neutrino mass:

$$|\langle m_{\beta\beta}\rangle| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1-\alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1-2\delta)}|$$

- a coherent sum over mass ES, with potentially CP violating phases
- a mixture of m_1, m_2, m_3, proportional to U^2

PHASE SPACE AND MATRIX ELEMENTS

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

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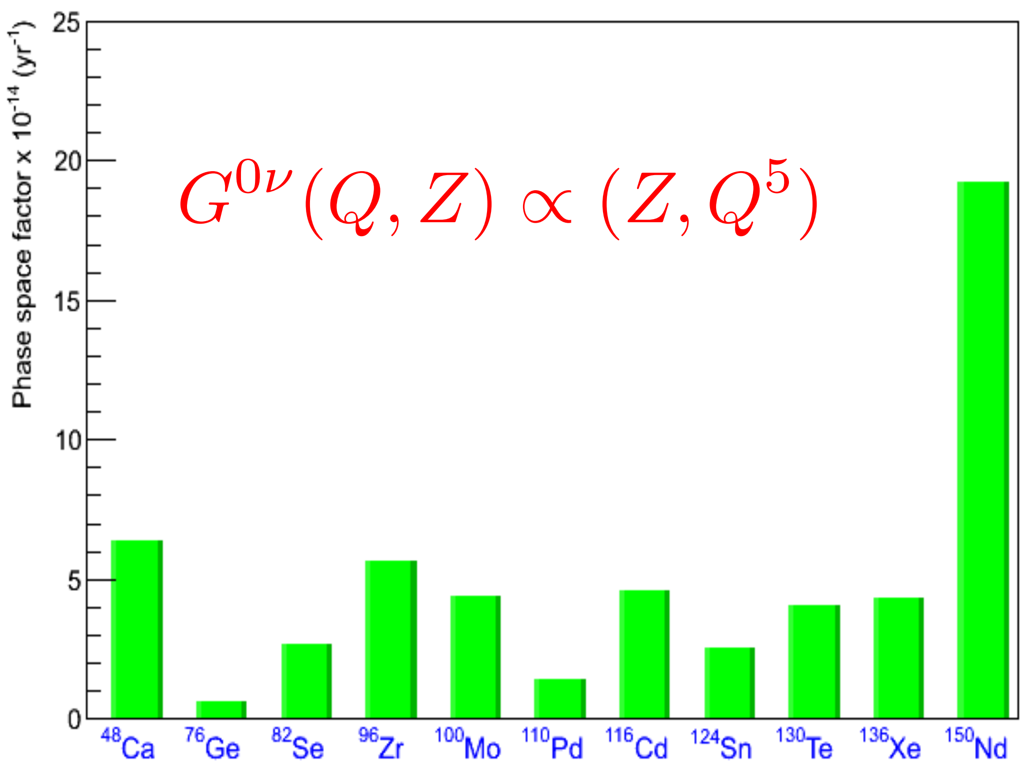
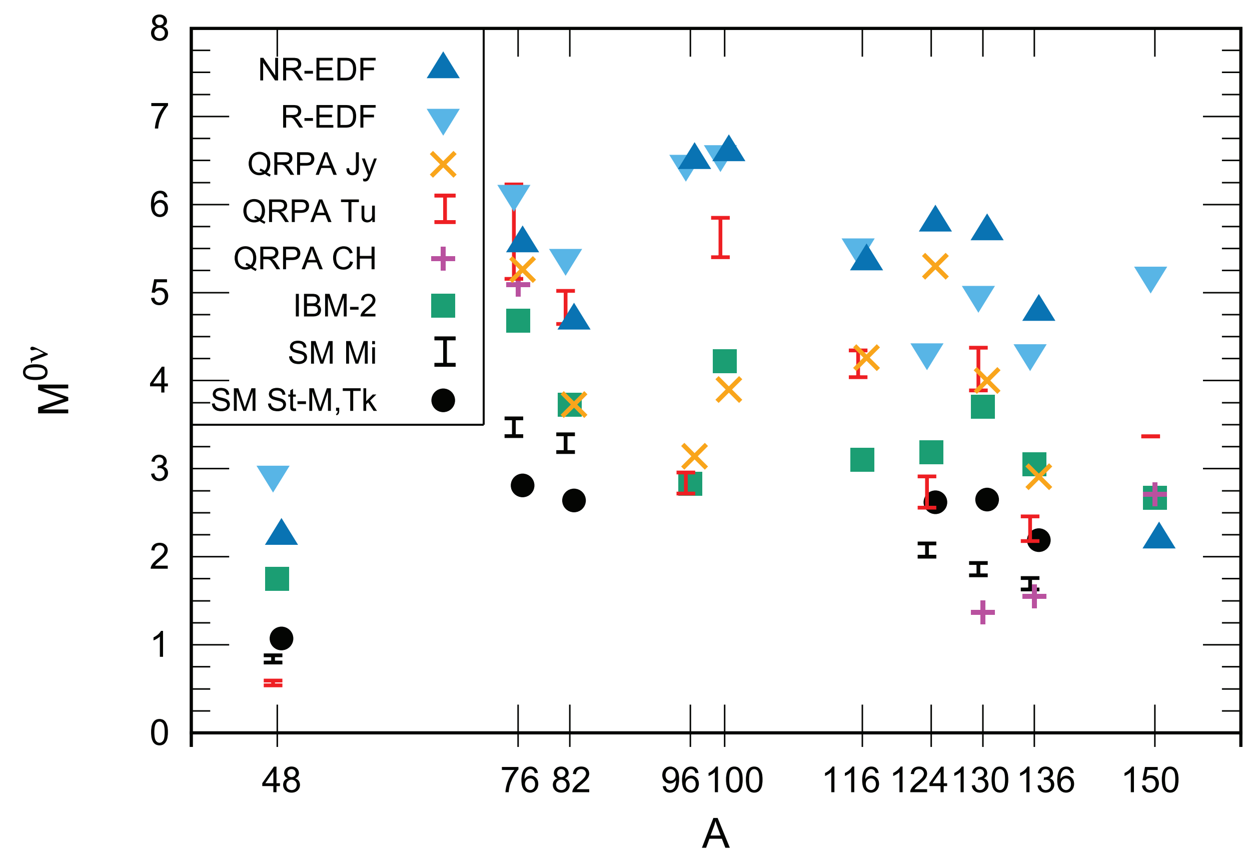


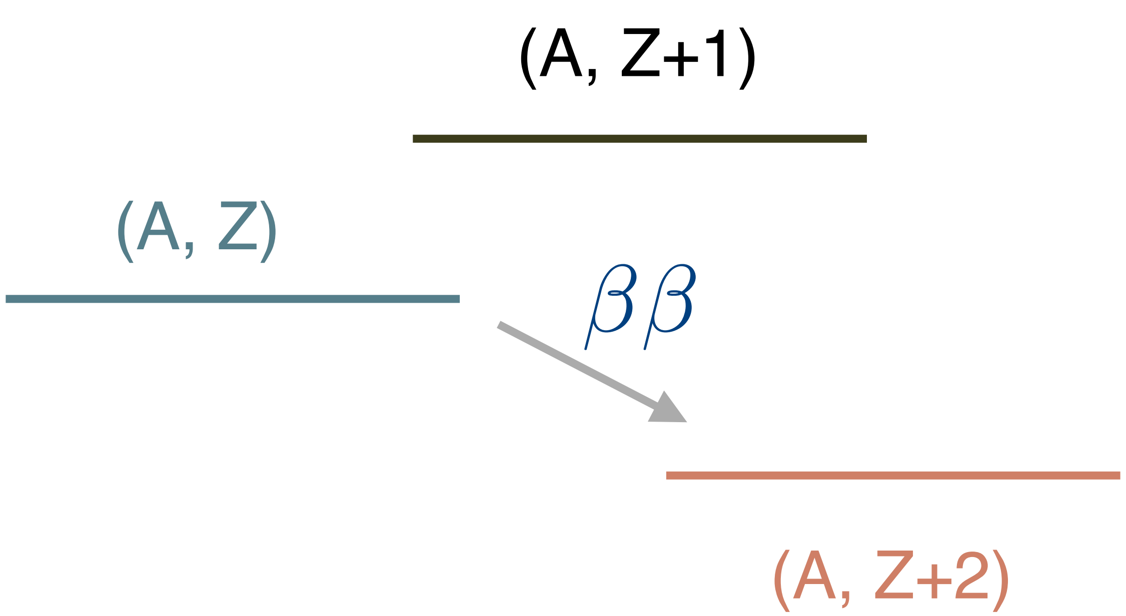


Matrix elements: vary by a factor of 2- 3 for a given A

Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301

EMPLOYED NUCLEI

- Even-even nuclei
- Natural abundance is low (except ^{130}Te)
- Must use enriched material



Candidate	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.039	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	**34.5**
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

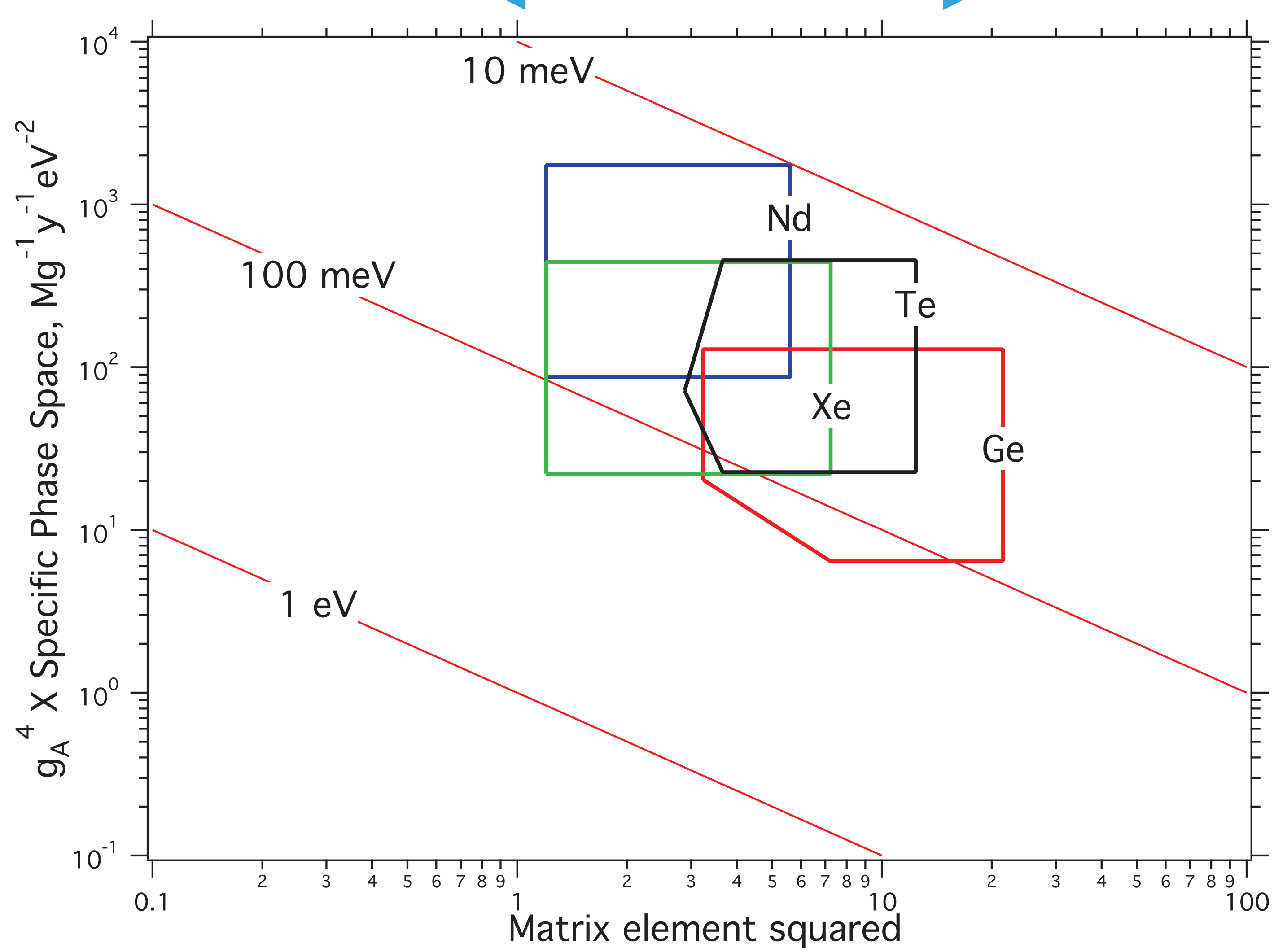
ISOTOPES AND SENSITIVITY TO THE DECAY

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

- Isotopes have comparable sensitivities in terms of rates per unit mass

|M|^2 uncertainty

$$g_A^4 \ln(2) \frac{N_A}{A m_e^2} G^{0\nu}$$



g_A^4 uncertainty

effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

R. G. H. Robertson, Mod. Phys. Lett. A28 (2013) 1350021

EXPRIMENTAL REQUIREMENTS

- Experiments measure the half-life, with a sensitivity (in the case of non-zero background)

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T_{1/2}^{0\nu}}}$$

Minimal requirements:

large detector masses
high isotopic abundance
ultra-low background noise
good energy resolution

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

Heat

CUORE
CUPID

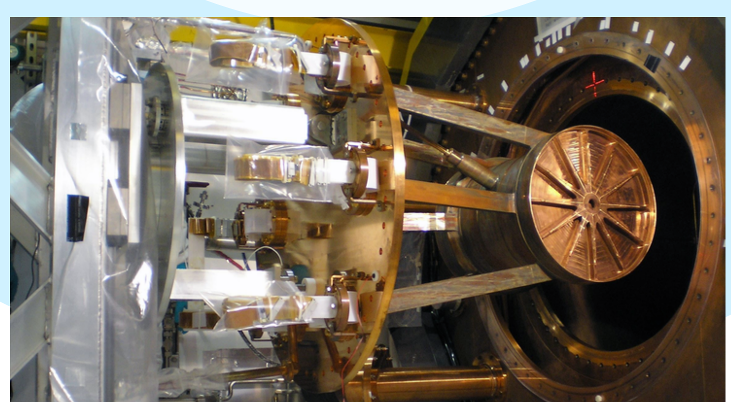
Energy of the
two electrons

GERDA
MAJORANA
LEGEND
SuperNEMO

Charge

Light

KAMLAND-Zen
SNO+



nEXO, NEXT
DARWIN

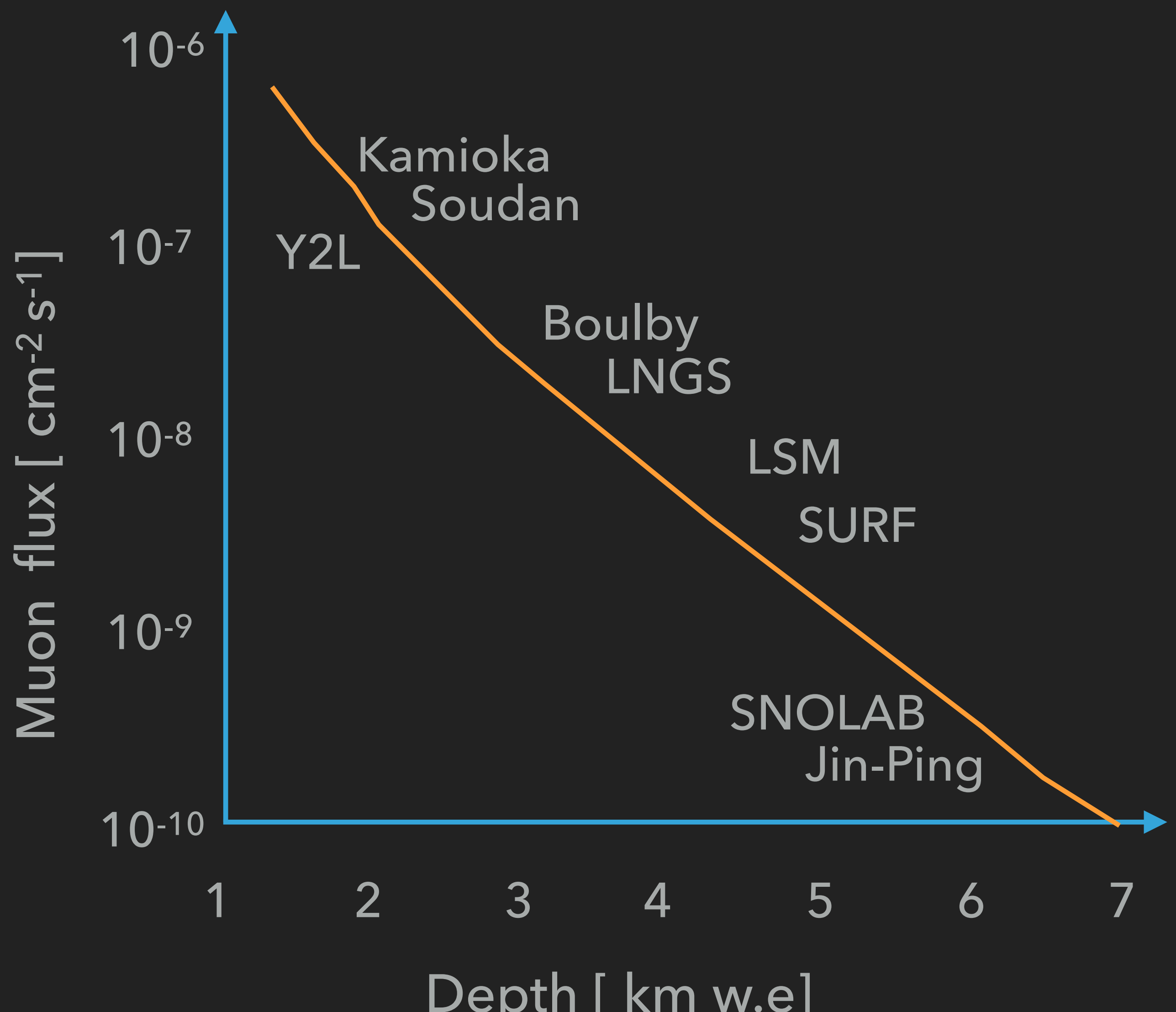
(not a complete list)

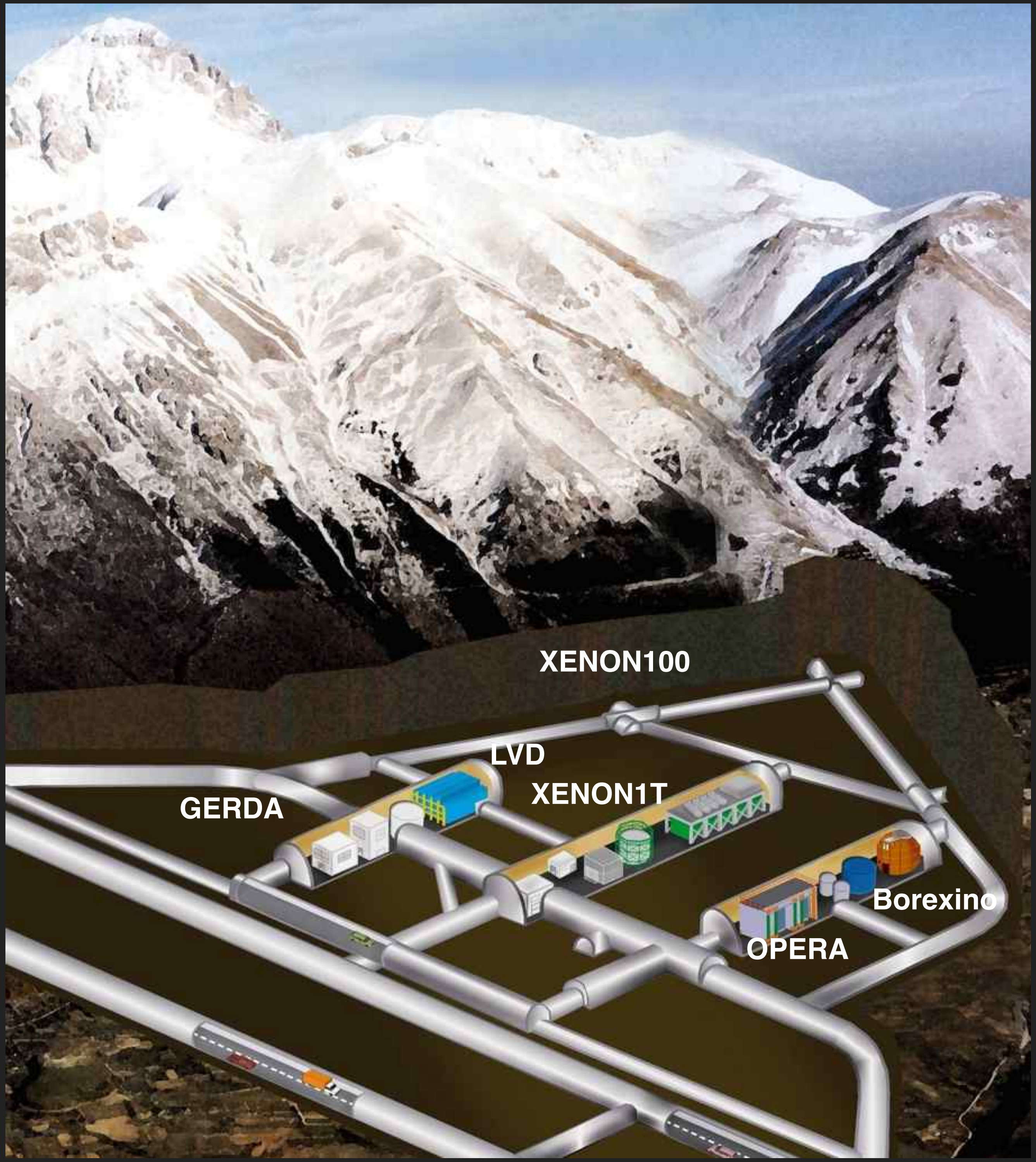
MAIN CHALLENGES

- Energy resolution (ultimate background from 2νββ-decay)
- Backgrounds
  - cosmic rays & cosmogenic activation
  - radioactivity of detector materials (^{238}U, ^{232}Th, ^{40}K, ^{60}Co, etc: α, β, γ-radiation)
  - anthropogenic (e.g., ^{137}Cs, ^{110m}Ag)
  - neutrinos: $\nu + e^- \rightarrow \nu + e^-$

GO UNDERGROUND

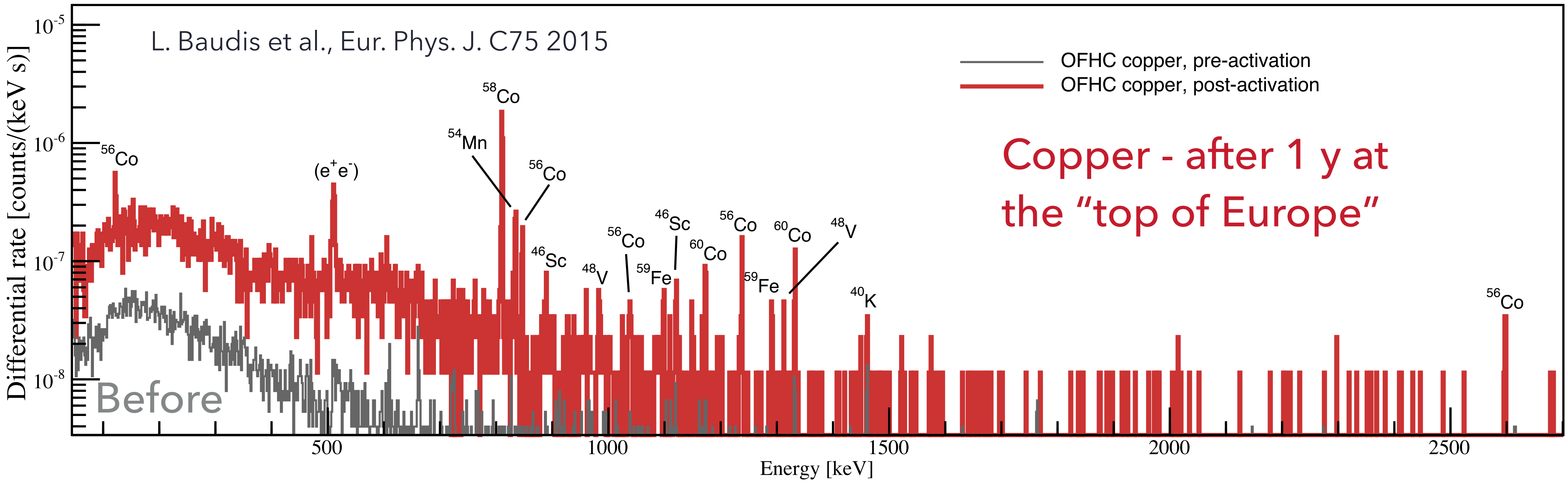
- Network of underground laboratories





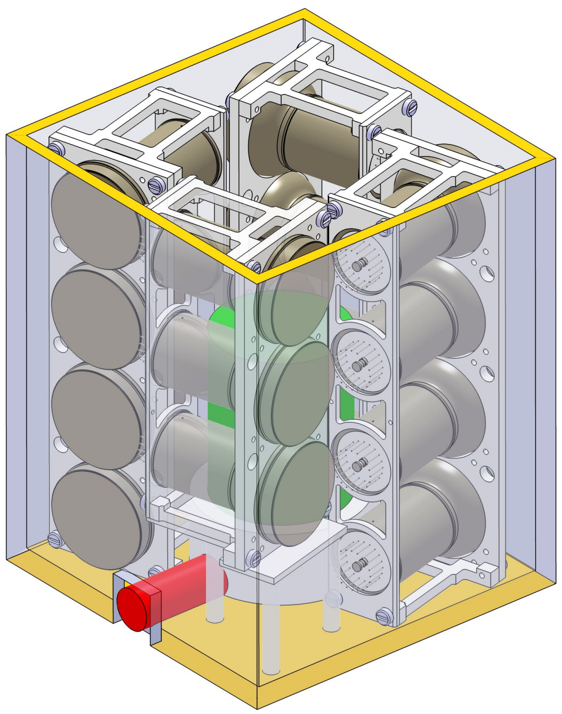
AVOID EXPOSURE TO COSMIC RAYS

- Spallation reactions can produce long-lived isotopes
- Activate and compare with predictions (Activia, Cosmo, etc)

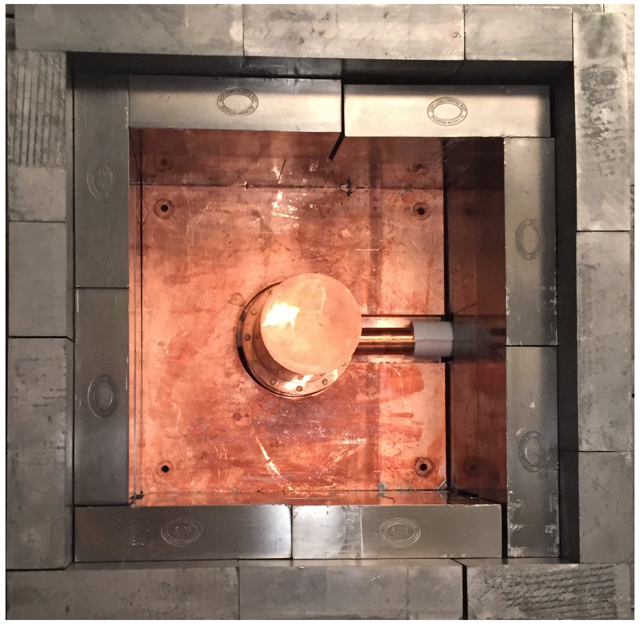


MATERIAL SCREENING AND SELECTION

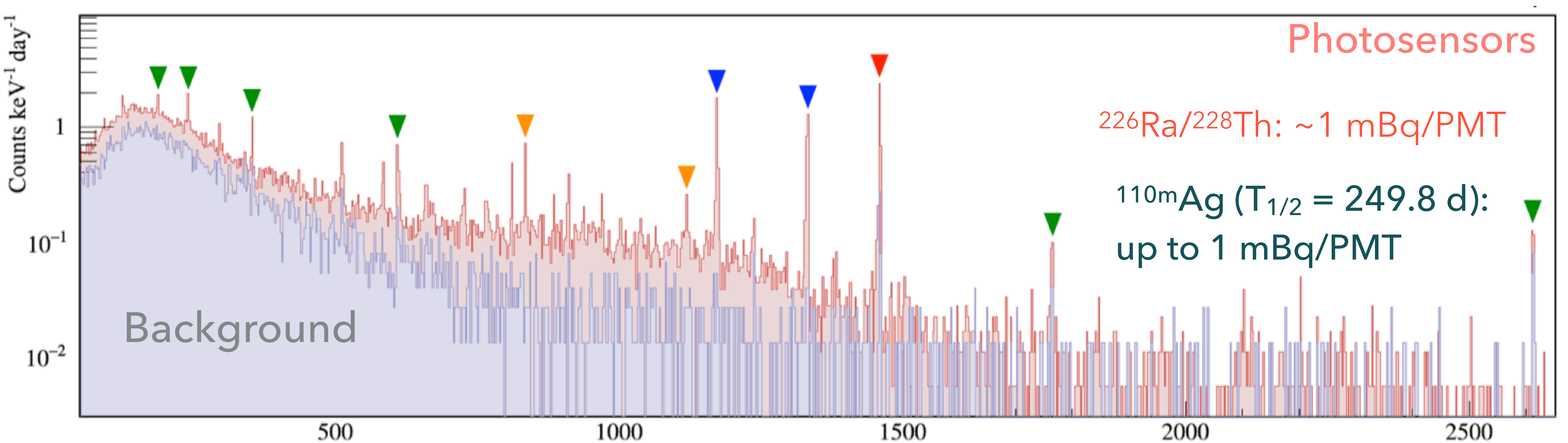
- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



Gator HPGe detector at LNGS



L. Baudis et al., JINST 6, 2011



XENON collaboration, EPJ-C 75 (2015) 11

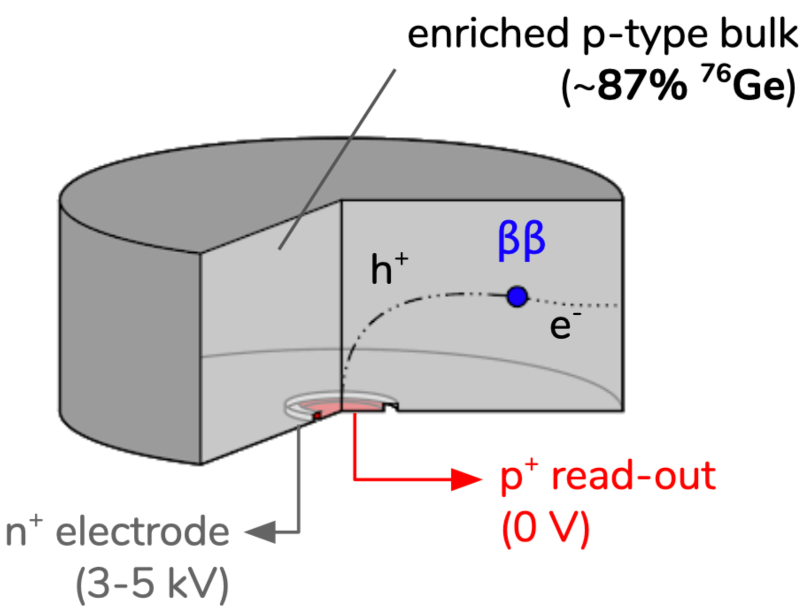
CURRENT STATUS OF THE FIELD

- No observation of this extremely rare nuclear decay (so far)
- Best lower limits on $T_{1/2}$: 1.07x10^{26} y (^{136}Xe), 0.9x10^{26} y (^{76}Ge), 2.7x10^{24} y (^{130}Te)

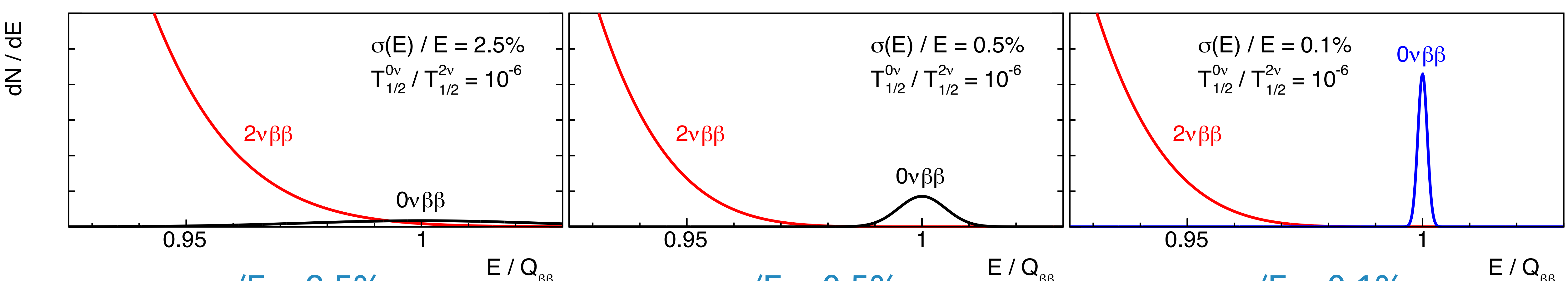
$$|\langle m_{\beta\beta}\rangle| \leq (0.07 - 0.16)\ \mathrm{eV}$$

- Running and upcoming experiments (a selection)
  - ^{130}Te: CUORE, SNO+
  - ^{136}Xe: KAMLAND-Zen, KAMLAND2-Zen, EXO-200, nEXO, NEXT, DARWIN
  - ^{76}Ge: GERDA Phase-II, Majorana, LEGEND (GERDA & Majorana + new groups)
  - ^{100}Mo AMoRE, LUMINEU; ^{82}Se: LUCIFER, CUPID = CUORE with light read-out
  - ^{82}Se (^{150}Nd, ^{48}Ca): SuperNEMO

SEARCH FOR THE NEUTRINOLESS DECAY OF ^{76}GE

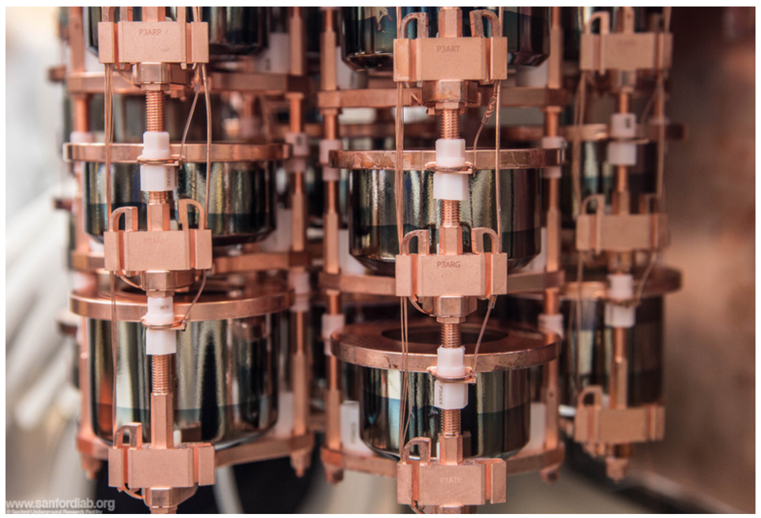
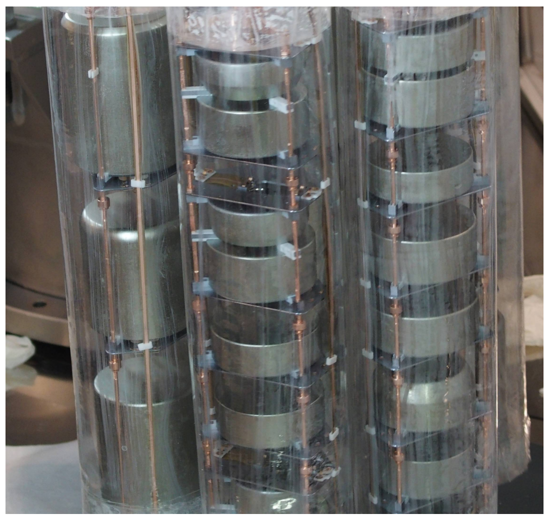
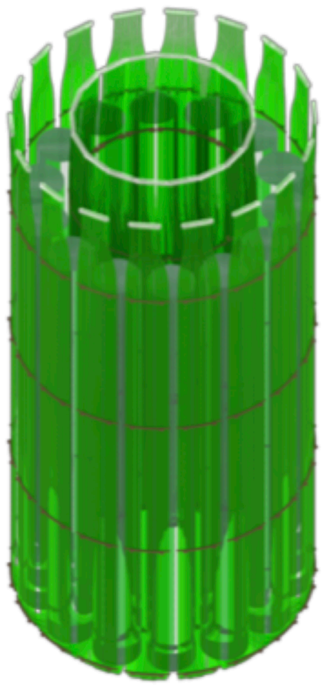


- HPGe detectors enriched in ^{76}Ge
  - Source = detector: high detection efficiency
  - High-purity material: no intrinsic backgrounds
  - Semiconductor: energy resolution σ/E < 0.1% at $Q_{\beta\beta}$ (2039.061 ± 0.007 keV)
  - High stopping power: β absorbed within O(1) mm



σ/E = 2.5%   σ/E = 0.5%   σ/E = 0.1%

EXISTING AND FUTURE GERMANIUM EXPERIMENTS

LEGEND-1t

Goal: $T_{1/2}$ ~ 1 x 10^{28} y (90% CL)

Location: tbd

MAJORANA at SURF

29.7 kg of 88% enriched ^{76}Ge crystals

2.5 keV FWHM at 2039 keV

26 kg y exposure; PRL 120 (2018)

$T_{1/2}$ > 2.7 x 10^{25} y (90% CL)

GERDA at LNGS

35.6 kg of 86% enriched ^{76}Ge crystals

3.0 keV FWHM at 2039 keV

58.9 kg y exposure; published in Science 2019

$T_{1/2}$ > 0.9 x 10^{26} y (90% CL)

LEGEND-200 at LNGS

200 kg of ^{76}Ge crystals at LNGS

Goal: 1 tonne year exposure

Goal: $T_{1/2}$ ~ 1 x 10^{27} y (90% CL)

Start in 2021

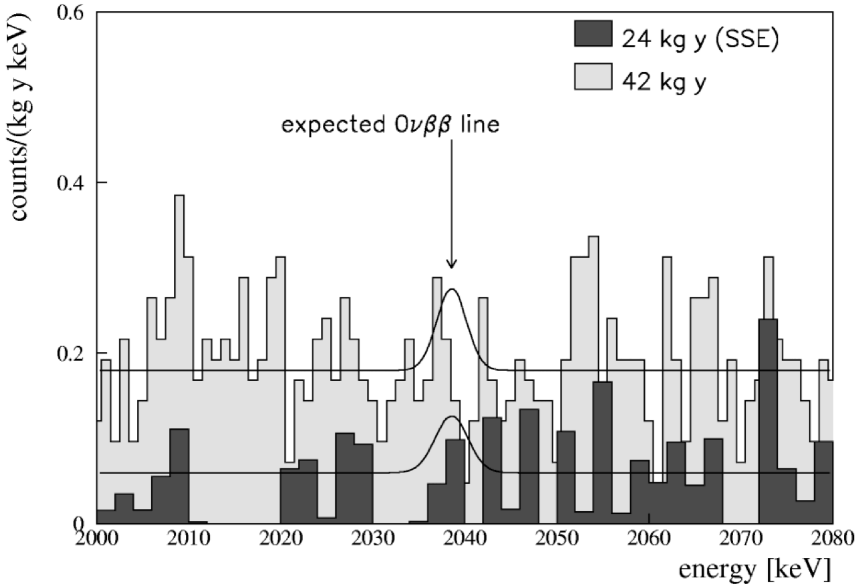
THE HEIDELBERG-MOSCOW EXPERIMENT

- Detectors in conventional shield: five ^{76}Ge detectors, mass 10.96 kg
- Concept to operate directly in cryogenic liquid: Genius - now GERDA

A first "bare" HPGe detector

GENIUS background and technical studies:
L. Baudis et al, NIM A 426 (1999)

Heidelberg-Moscow detector in conventional shield



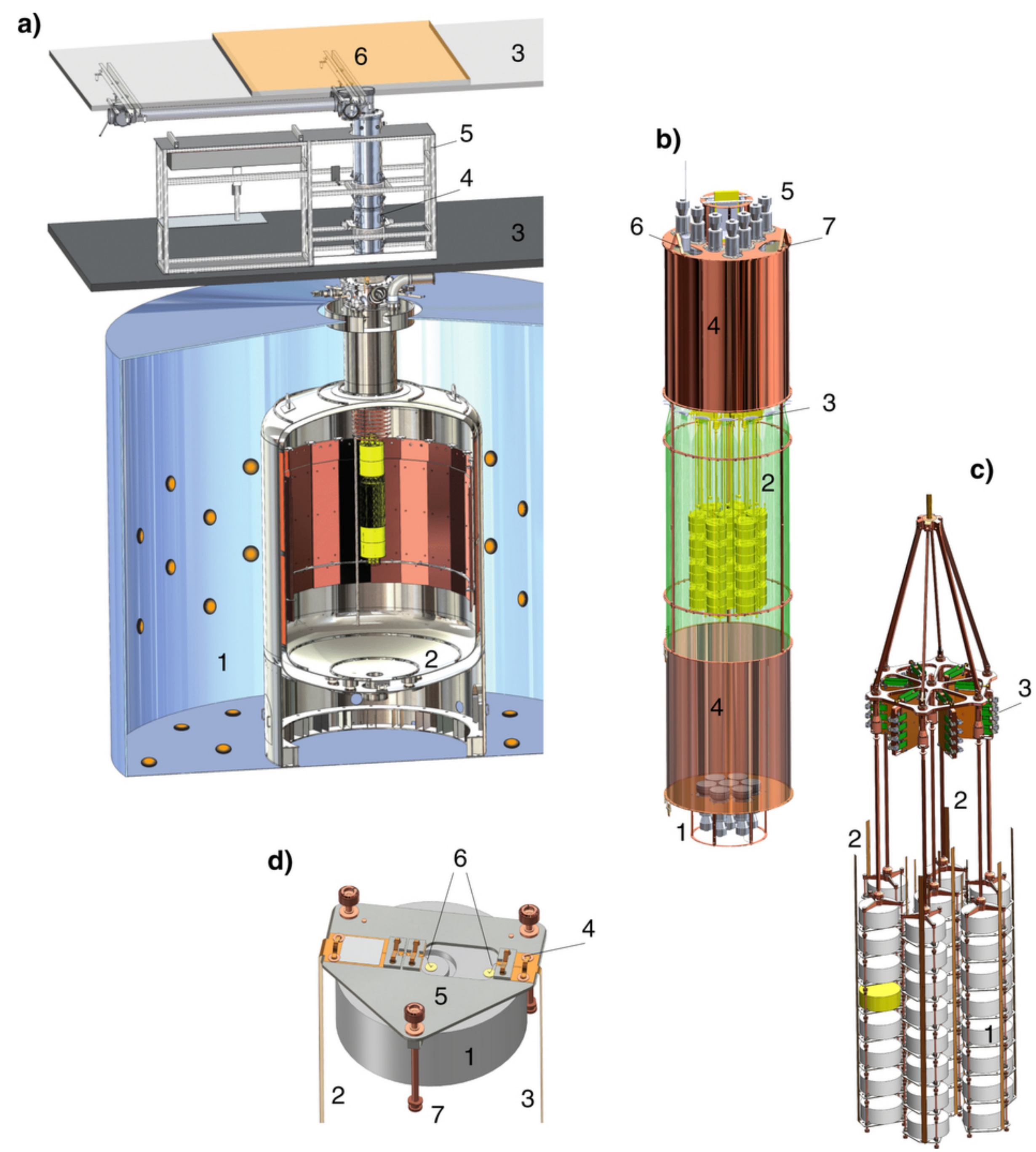
Limits on the Majorana neutrino mass in the 0.1 eV range,
L. Baudis et al., Phys. Rev. Lett. 83, 1999

Sensitivity $T_{1/2} > 1.6 \times 10^{25}$ y 90% C.L.

THE GERDA EXPERIMENT

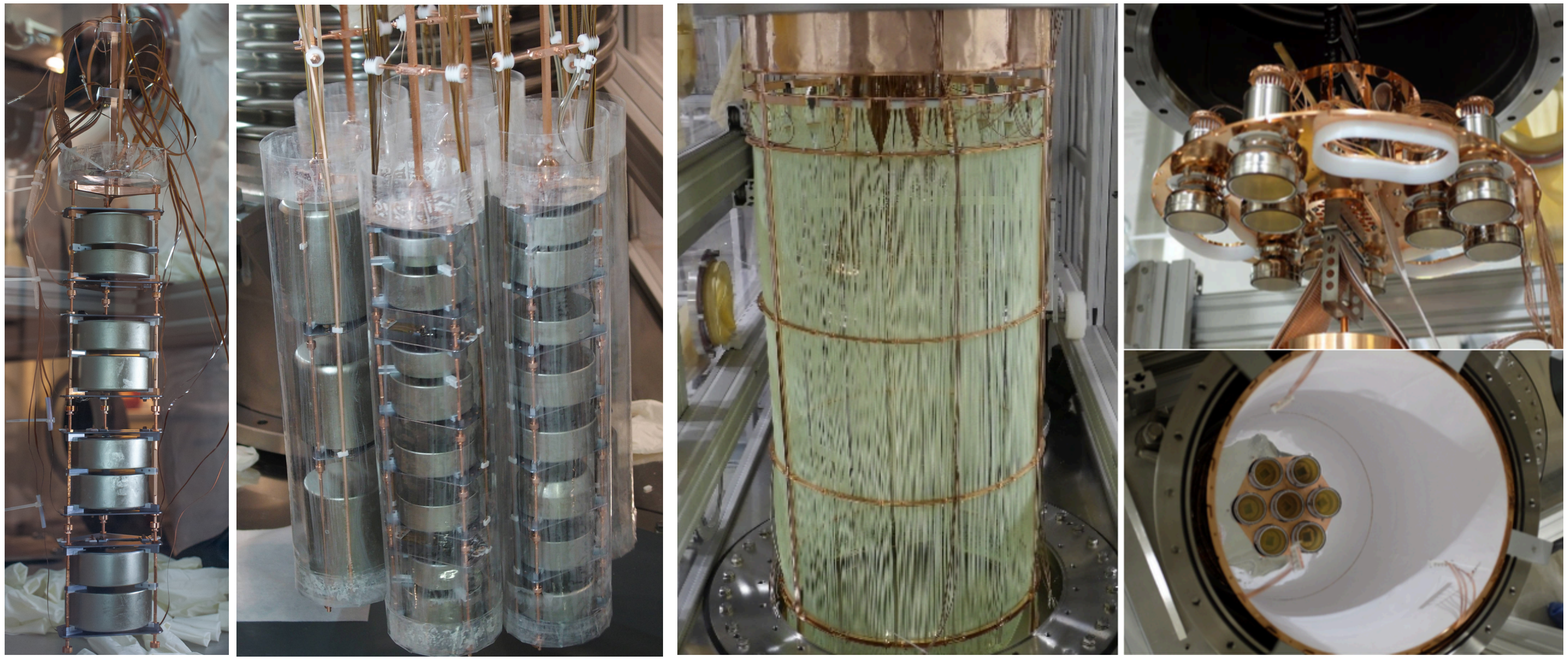
GERDA collaboration, EPJ C78 (2018) no.5

- Liquid Ar (64 m³) as cooling medium and shielding, surrounded by 590 m³ of ultra-pure water as muon Cherenkov veto
- U/Th in LAr < 7×10^{-4} µBq/kg
- A minimal amount of surrounding material
  - Phase I: 2011-2014
  - Phase II: 2015-2019



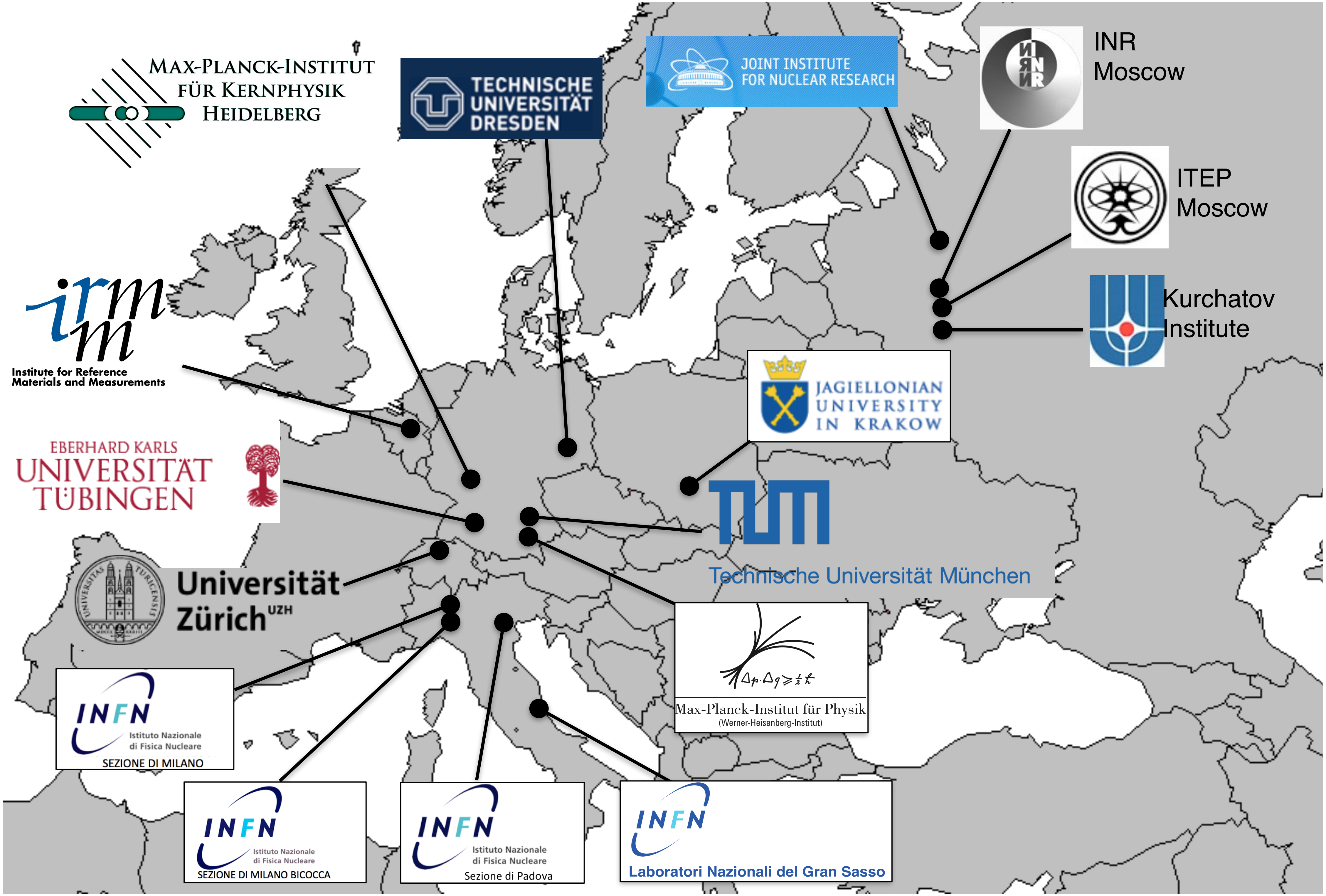
THE GERDA PHASE II PROJECT

- Seven string with 40 detectors (30 BEGe*, 7 coaxial, 3 natural coaxial -> enriched IC)
- Liquid argon veto, equipped with optical fibres and SiPMs, plus 2 arrays of 3-inch PMTs
- Science run started in December 2015
- Summer 2018: central string replaced with enriched, inverted coaxial detectors



* GERDA collaboration, Characterisation of 30 ^{76}Ge enriched Broad Energy Ge detectors for GERDA Phase II; arXiv:1901.0650

THE GERDA COLLABORATION

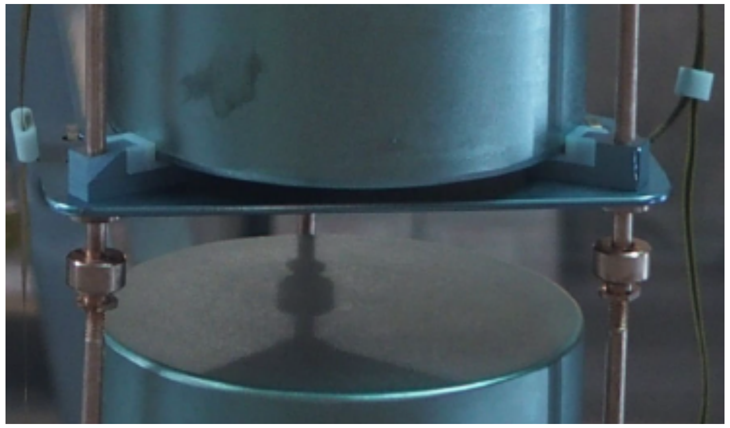


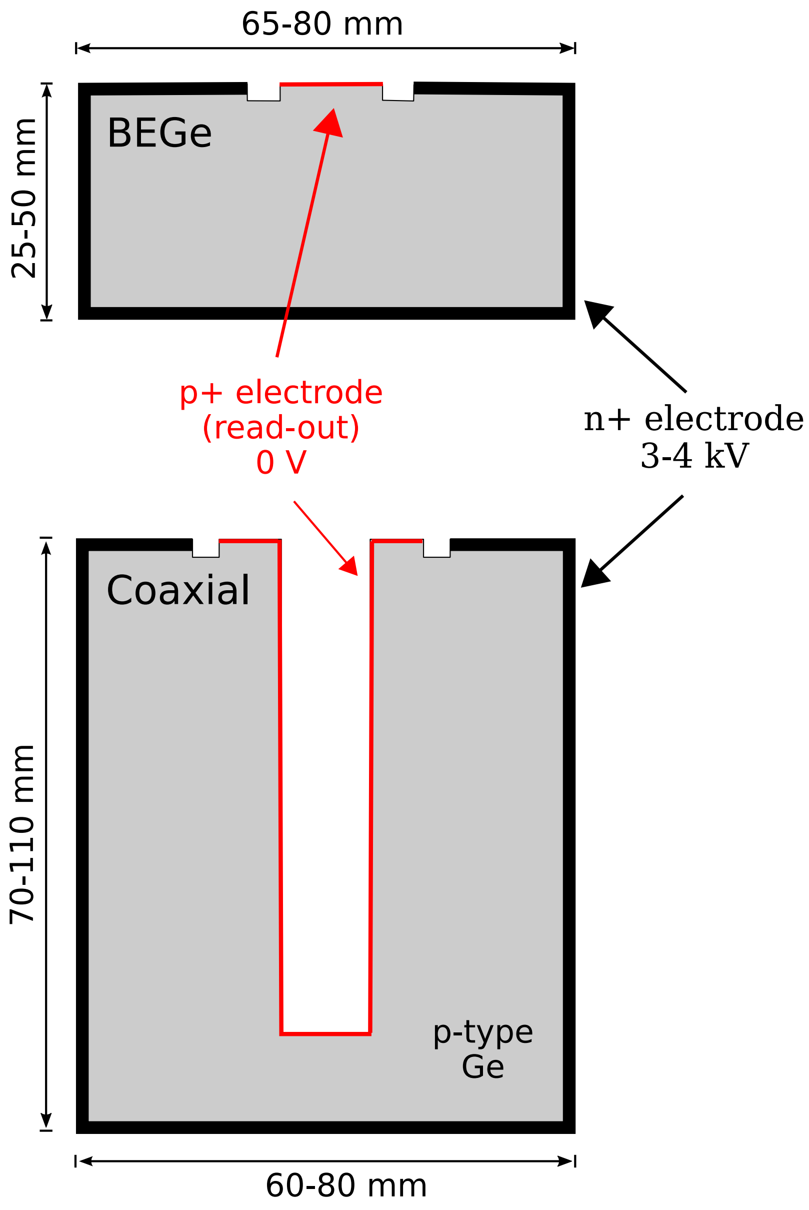
THE GERDA COLLABORATION

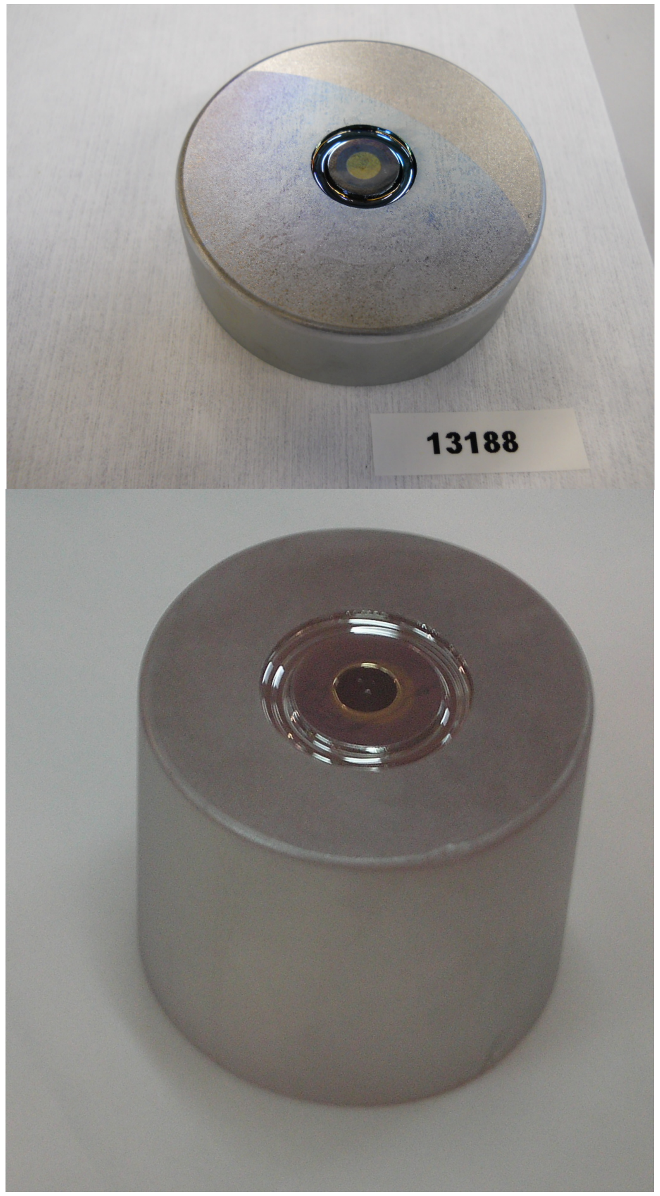
COLLABORATION MEETING IN ZURICH, JUNE 2019

GERDA PHASE-II DETECTORS

- BEGe and coaxial
- p+ electrodes:
  - 0.3 μm boron implantation
- n+ electrodes:
  - 1-2 mm lithium layer (biased up to +4.5 kV)
- Low-mass detector holders (Si, Cu, PTFE)

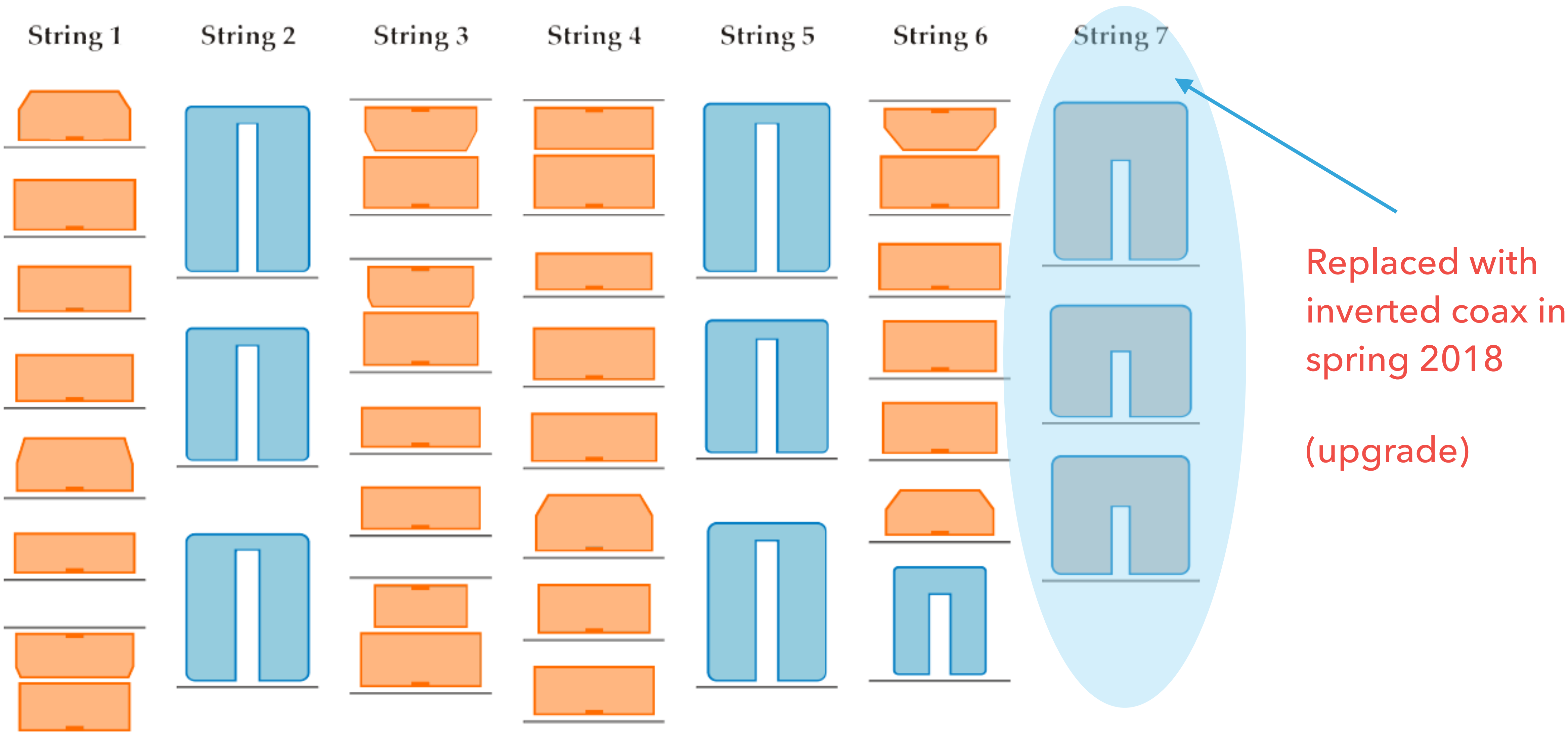






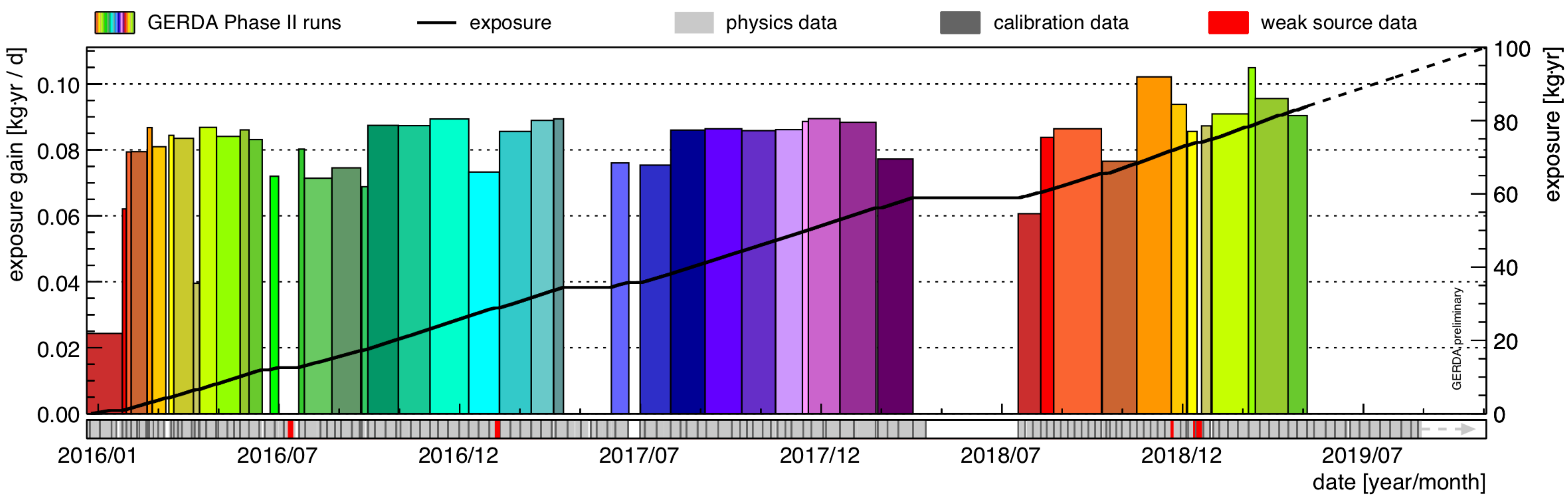
GERDA PHASE-II DETECTORS

- 7 strings, 40 detectors in total:
  - 7 semi-coax (15.8 kg), 30 BEGe (20 kg), 3 nat semi-coax (7.6 kg) s



PHASE II DATA TAKING

100 kg y, end 2019



Start Dec 2015

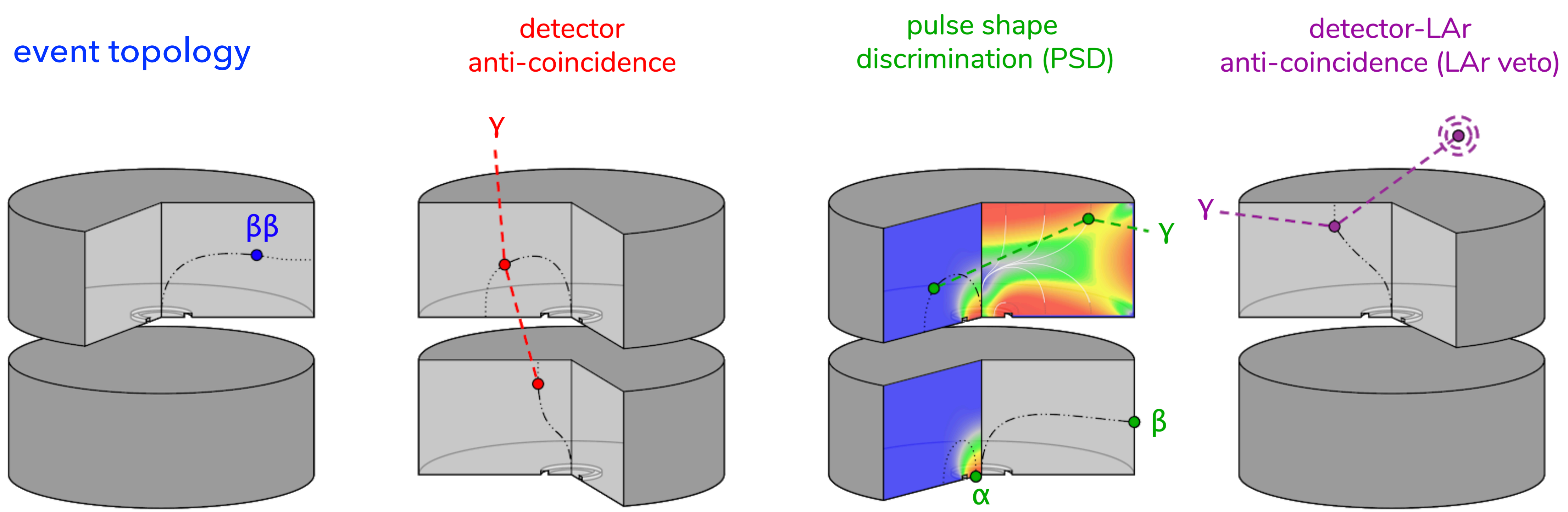
Upgrade

24.9 kg y in
May 2019 blind

58.9 kg y unblind

BACKGROUND SUPPRESSION

- Event topology + anti-coincidence between HPGe detectors + pulse shape discrimination + liquid argon veto



differentiate **point-like** (single-detector, single-site) ββ topology from:

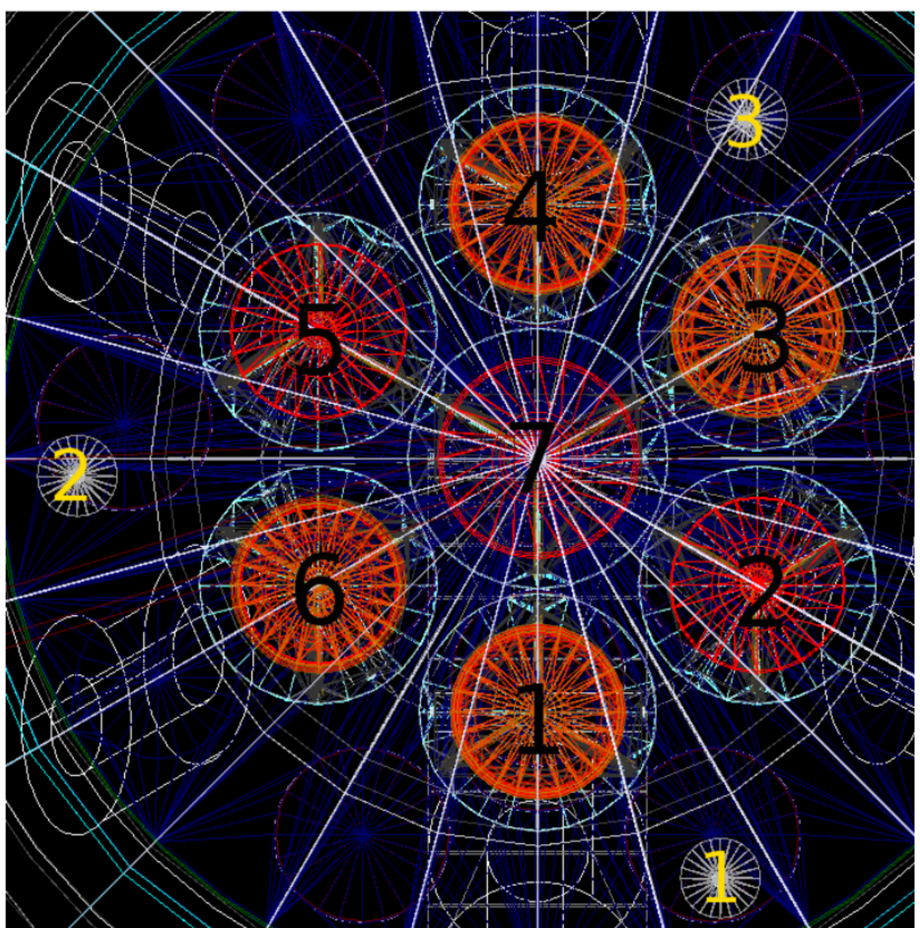
multi-detector interactions

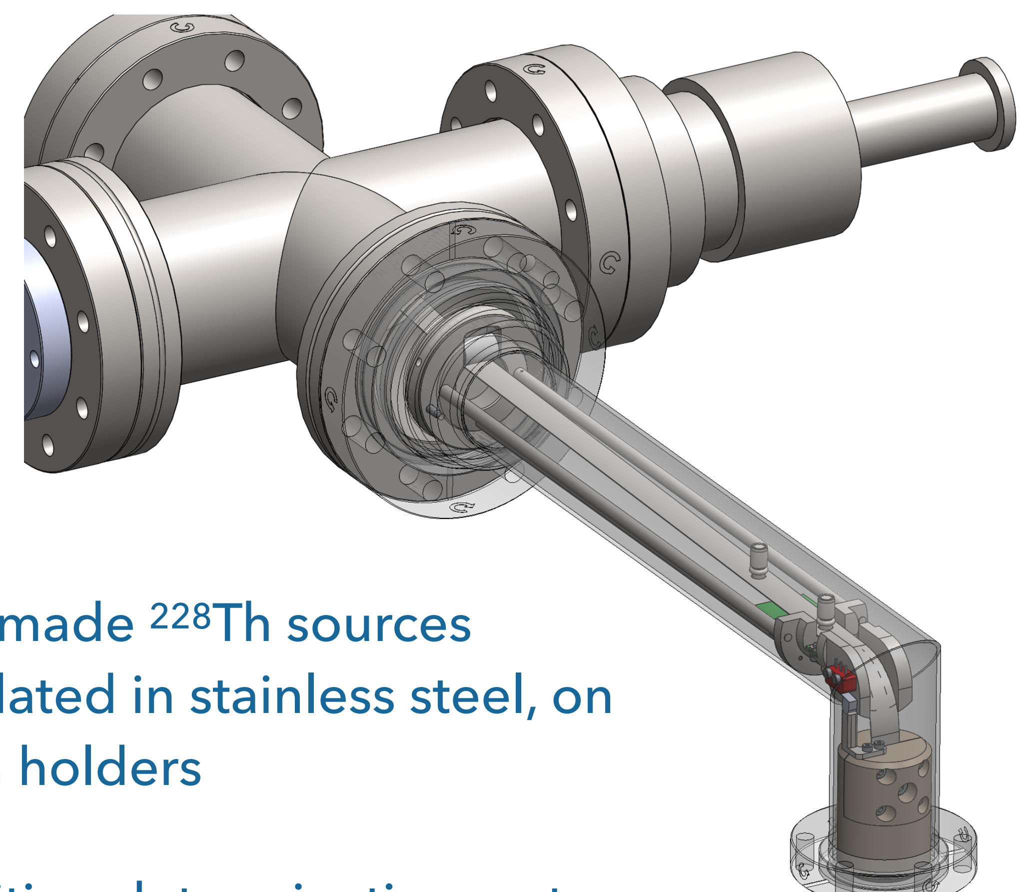
multi-site/surface interactions

interactions with **coincident energy deposition** in surroundings

ENERGY CALIBRATION

- Three low neutron-emission ^{228}Th sources in SIS, deployed once every week
- FWHM at $Q_{\beta\beta}$: (3.0 ± 0.1) keV for BEGe, (3.6 ± 0.1) keV for coaxial detectors





Custom-made ^{228}Th sources encapsulated in stainless steel, on tantalum holders

Two position determination systems

L. Baudis et al., JINST 10 (2015) no. 12

ENERGY CALIBRATION

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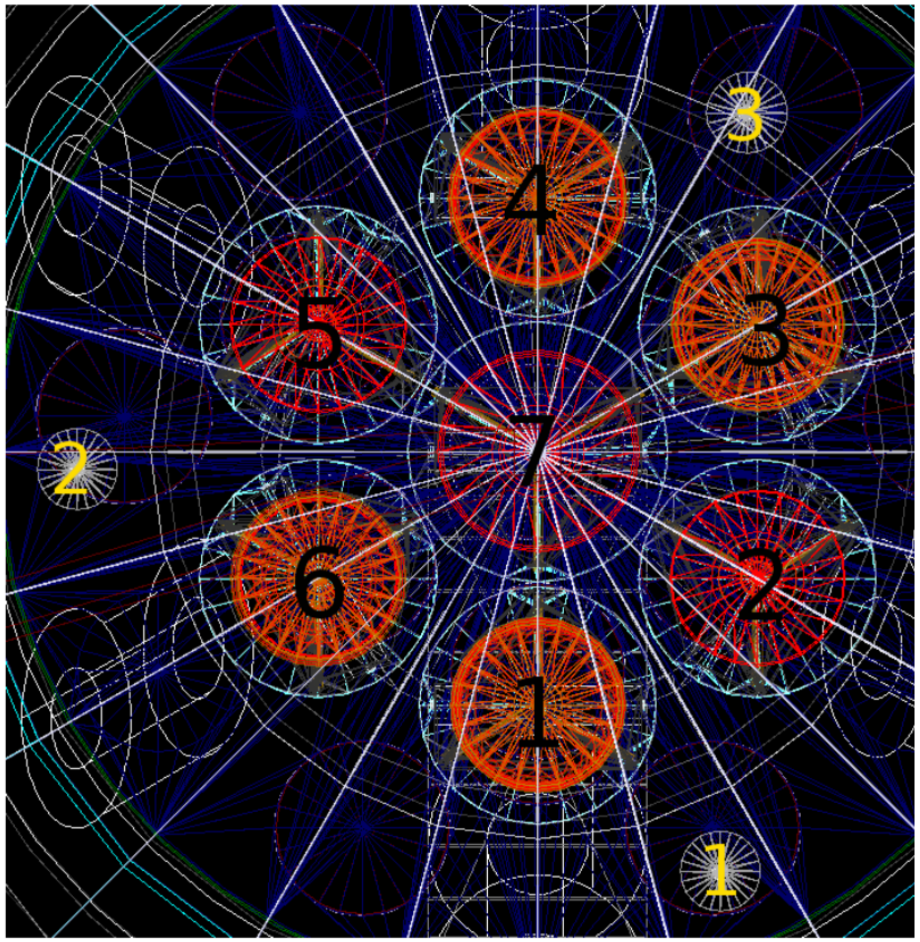
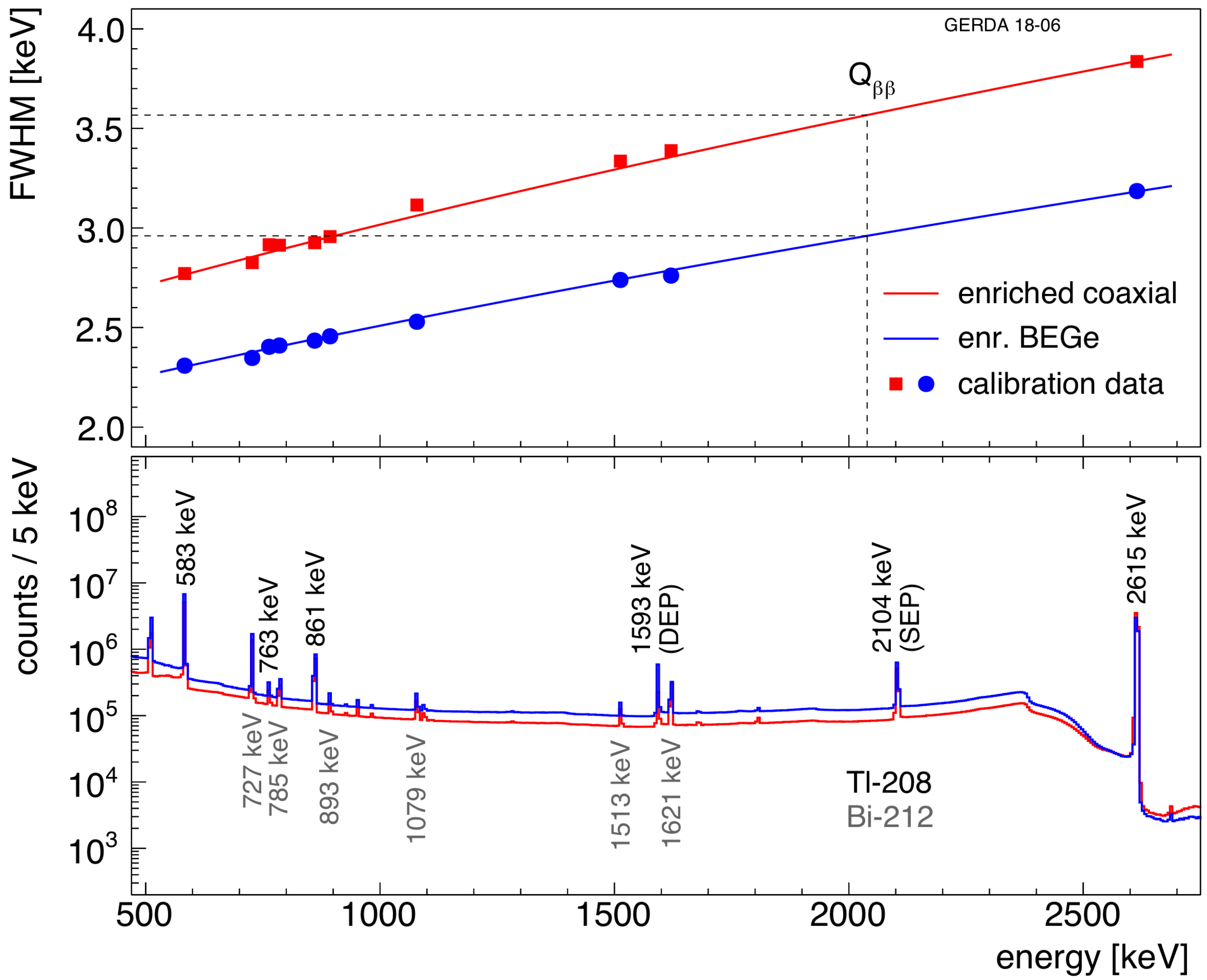
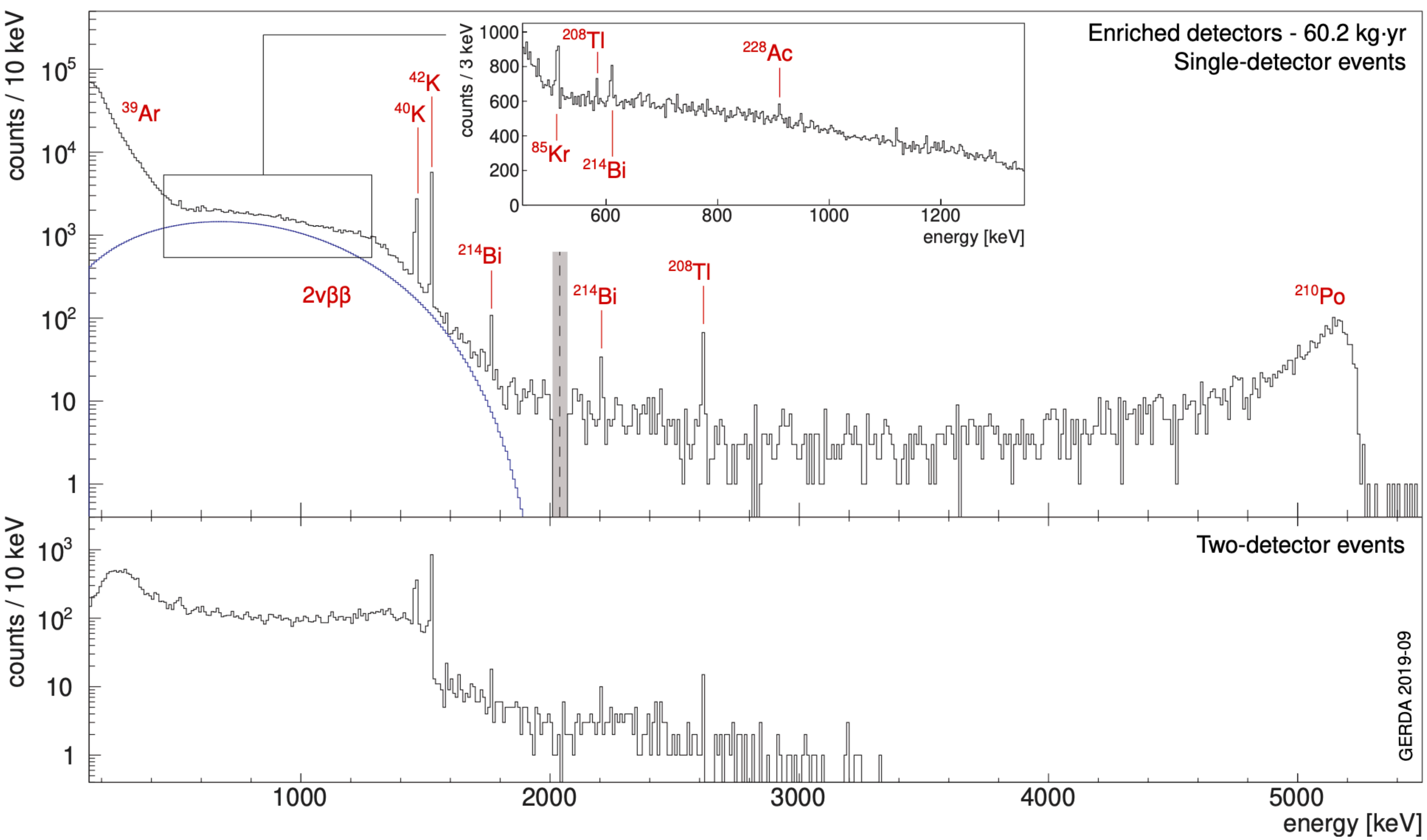




ENERGY SPECTRA

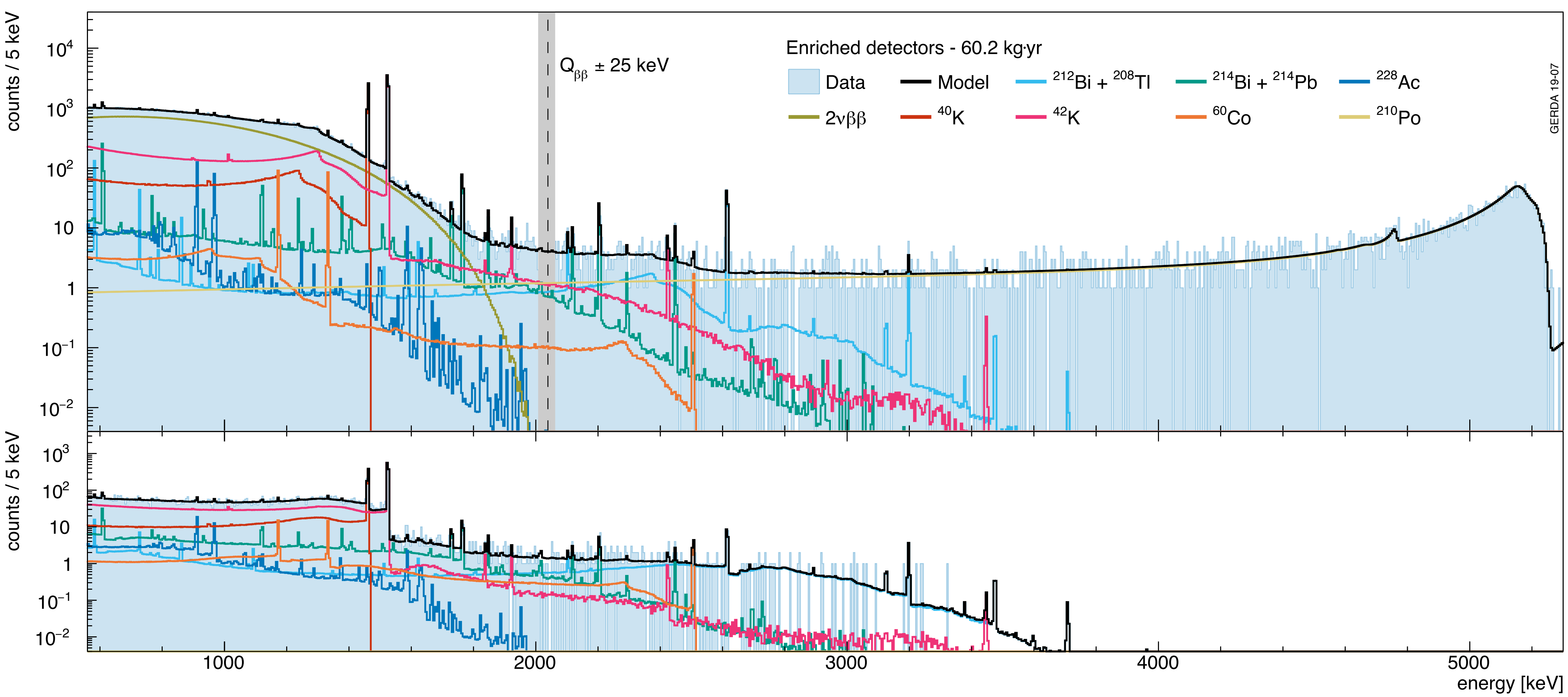
- Intrinsic 2νββ-events, ^{39}Ar, ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact



GERDA collaboration, arXiv:1909.02522

BACKGROUND MODEL

- Intrinsic 2νββ-events, ^{39}Ar, ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact

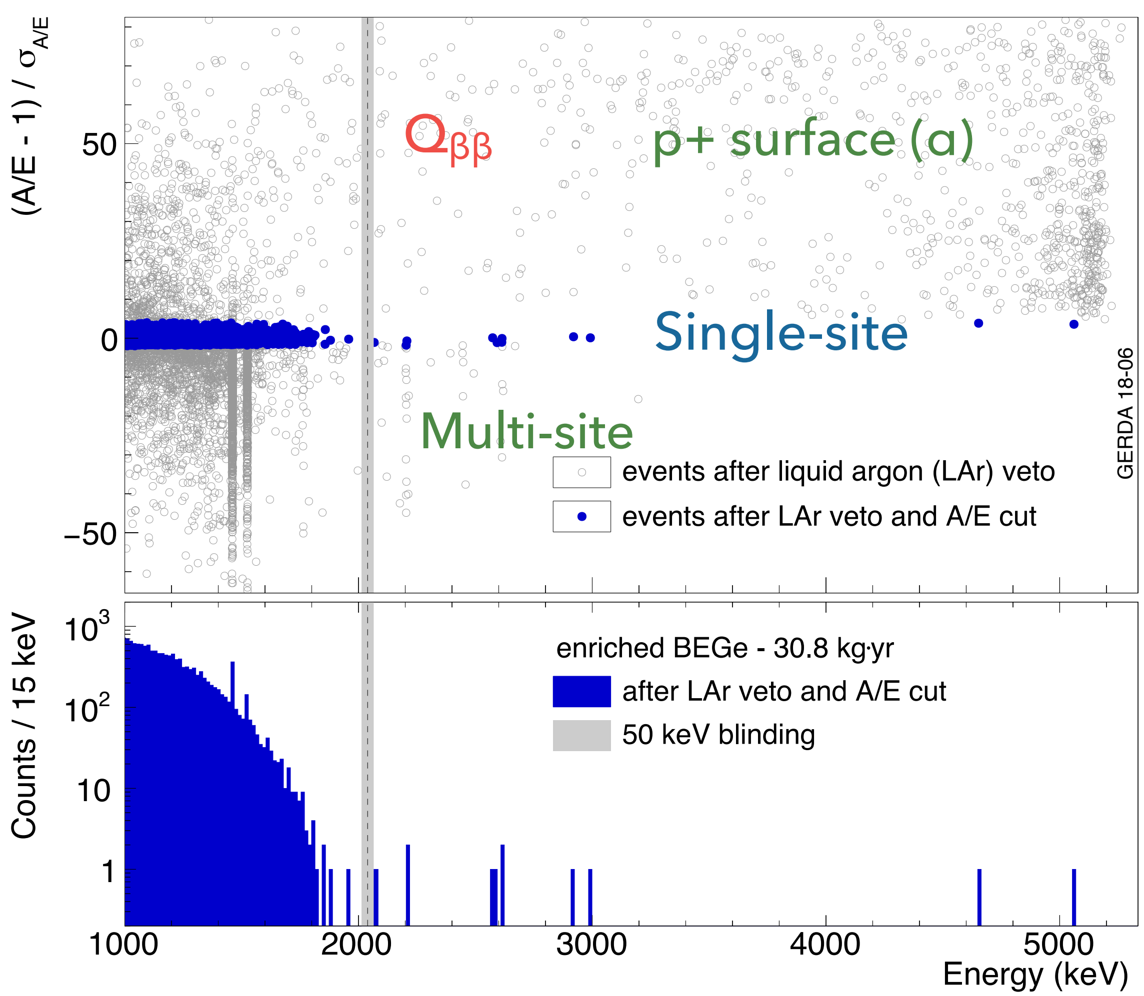


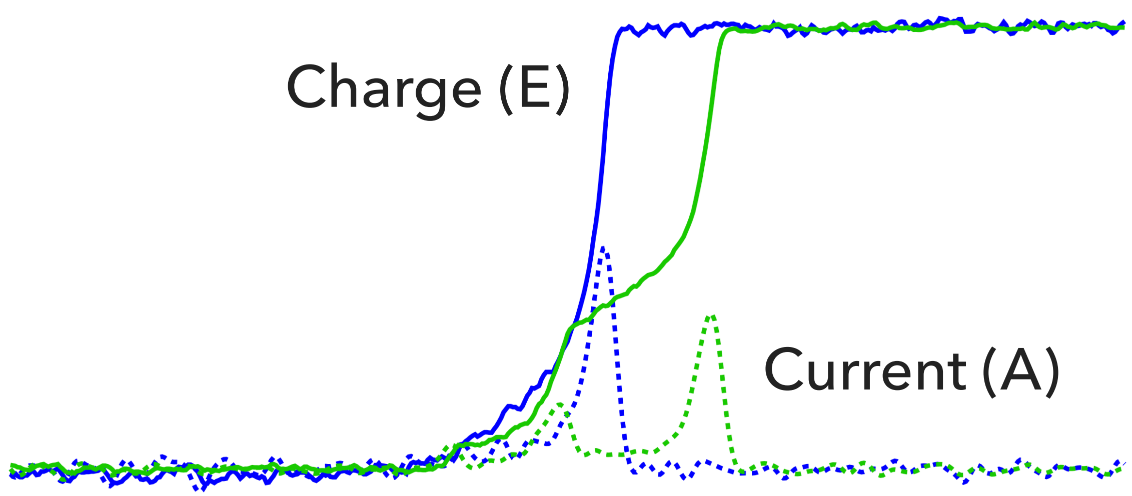
GERDA collaboration, arXiv:1909.02522

GERDA collaboration, Nature 544 (2017) 47

PULSE SHAPE DISCRIMINATION

- Cut based on 1 parameter: max of **current pulse (A)** normalised to **total energy (E)** (BEGe)
- Tuned on calibration data (90% ^{208}Tl DEP acceptance)
- Acceptance at 0νββ: **(87.6±2.5)%**





PSD parameter: (A/E -1)/$\sigma_{A/E}$

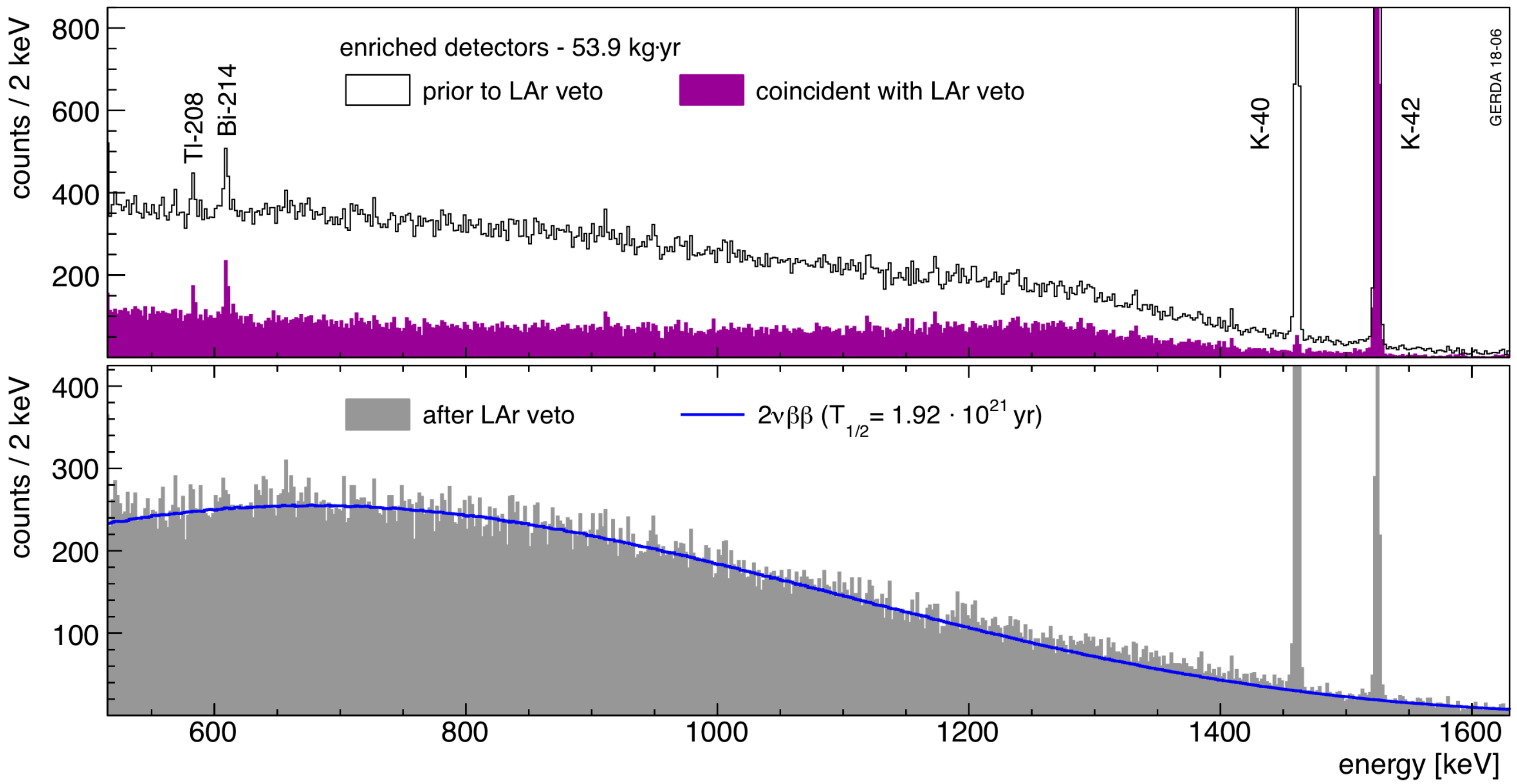
Mean and resolution corrected for E-dependance

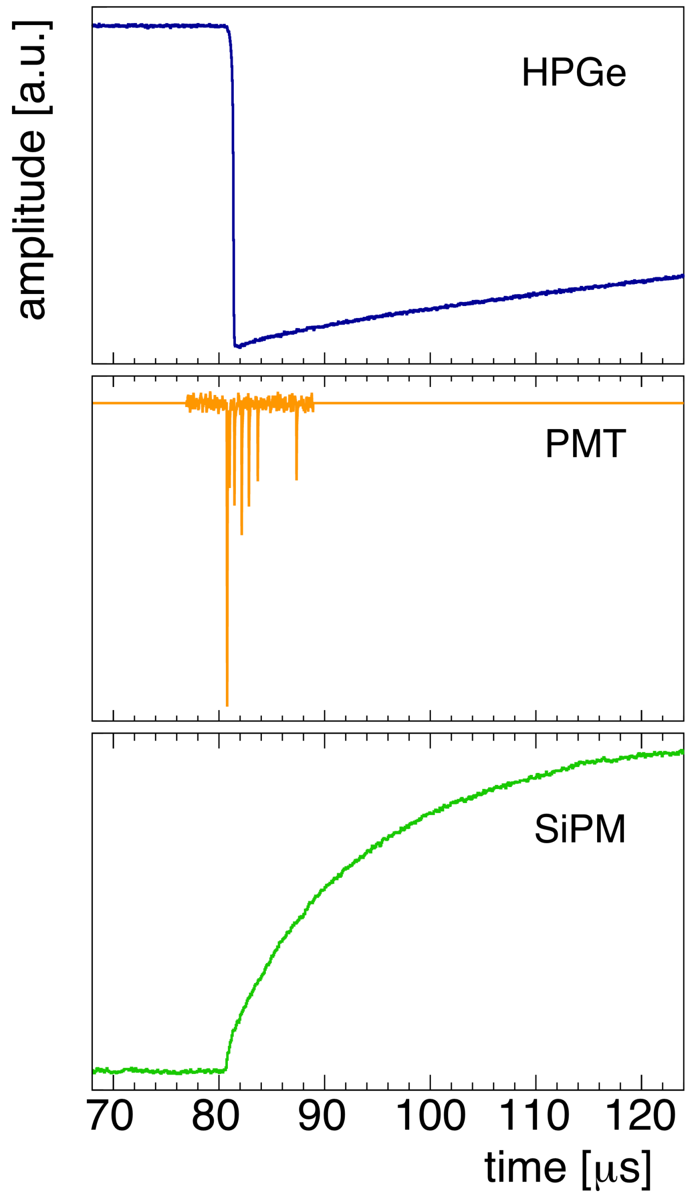
A/E normalised to 1

Accept events around **(A/E -1)/$\sigma_{A/E}$ =0**

LIQUID ARGON VETO

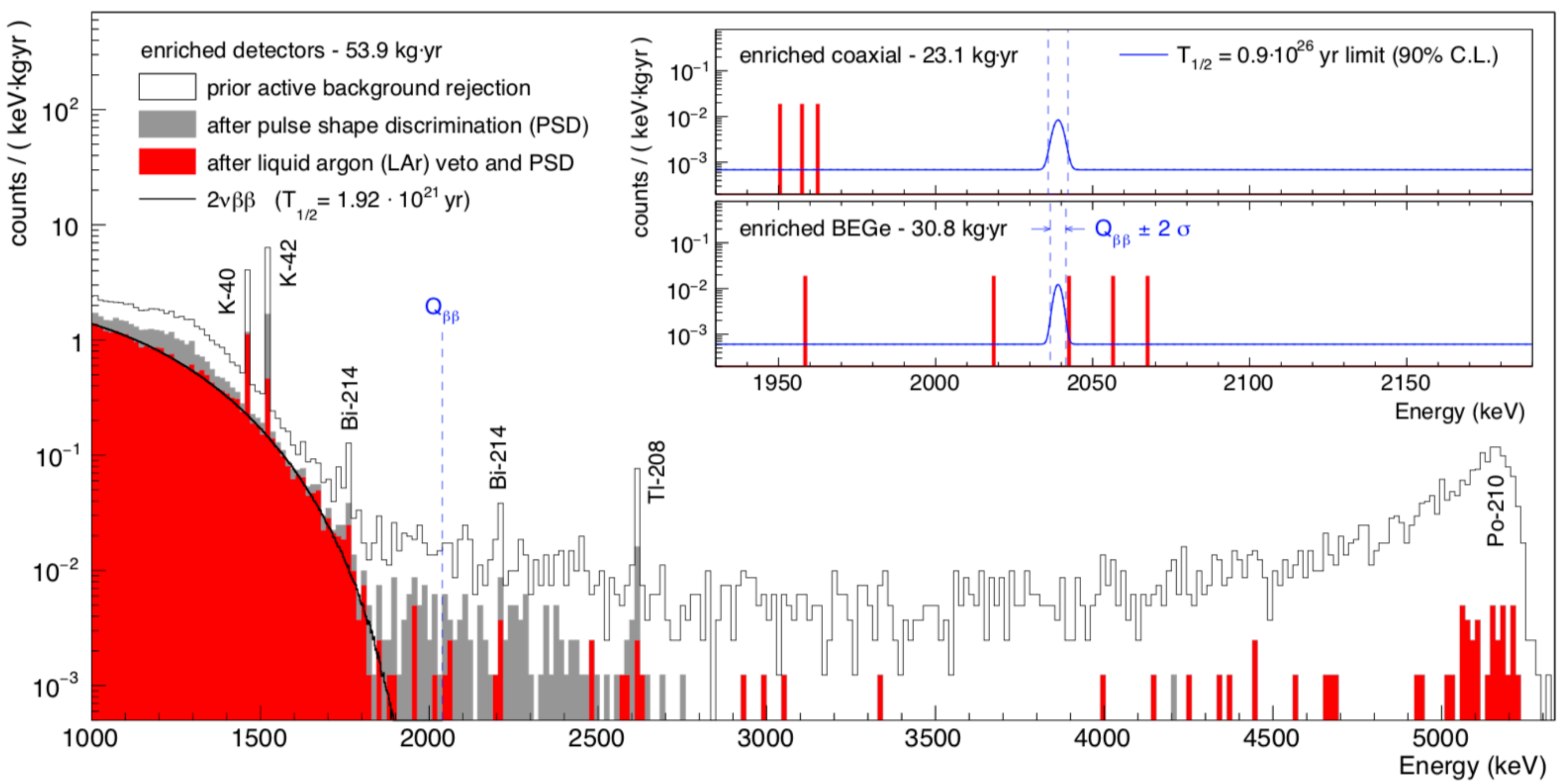
- Anti-coincidence with signals in PMTs and SiPMs (0.5 p.e. threshold)
- Acceptance at $0\nu\beta\beta$: $(97.7\pm0.1)\%$





DOUBLE BETA DECAY RESULTS

- Measured $T_{1/2}$ of the 2vββ-decay: 1.92×10^{21} y
- LAr veto: factor 5 background suppression at 1525 keV (^{42}K line)
- Background level: 5.6×10^{-4} events/(keV kg y) in 230 keV window around Q-value



New constraints on the 0vββ-decay of ^{76}Ge

$$T^{0\nu}_{1/2} > 0.9 \times 10^{26}\,\mathrm{y}\ (90\%\mathrm{C.L.})$$

$$m_{\beta\beta} < 0.11 - 0.26\,\mathrm{eV}\ (90\%\mathrm{C.L.})$$

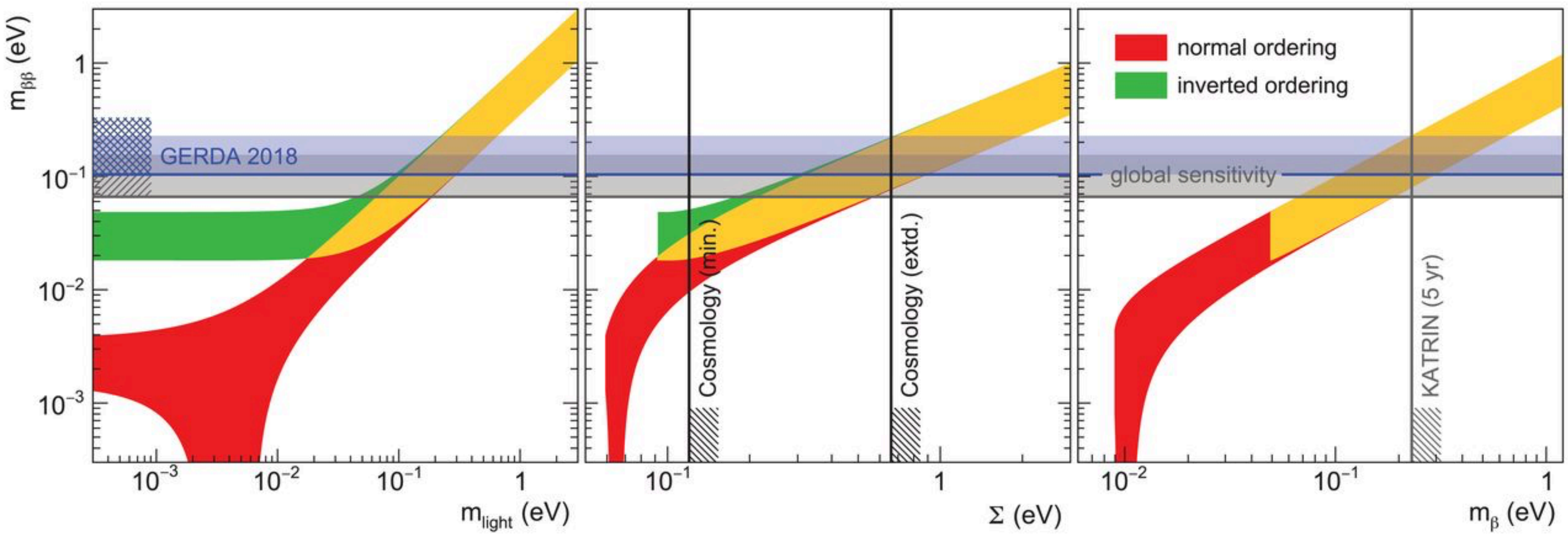
Median sensitivity

$$T^{0\nu}_{1/2} > 1.1 \times 10^{26}\,\mathrm{y}\ (90\%\mathrm{C.L.})$$

GERDA collaboration, Science 365, Sept 2019

MASS OBSERVABLES

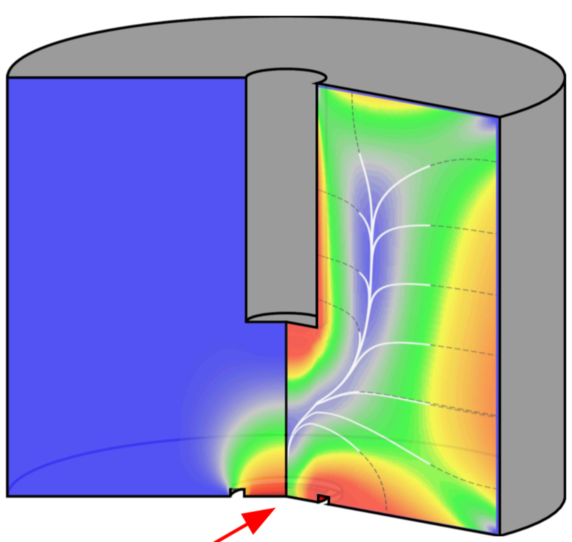
- Constraints in the $m_{\beta\beta}$ parameters space in the 3 light ν scenario
- GERDA + leading experiments in the field



$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \qquad \Sigma = \sum_i m_i \qquad m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

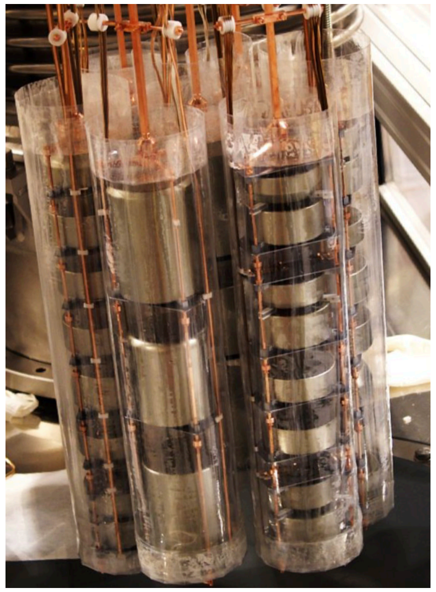
UPGRADE: INVERTED COAXIAL DETECTORS

- Large point-contact detectors with ~ 3 kg mass, excellent PSD performance
- First 5 enriched IC detectors installed in spring 2018; baseline for LEGEND

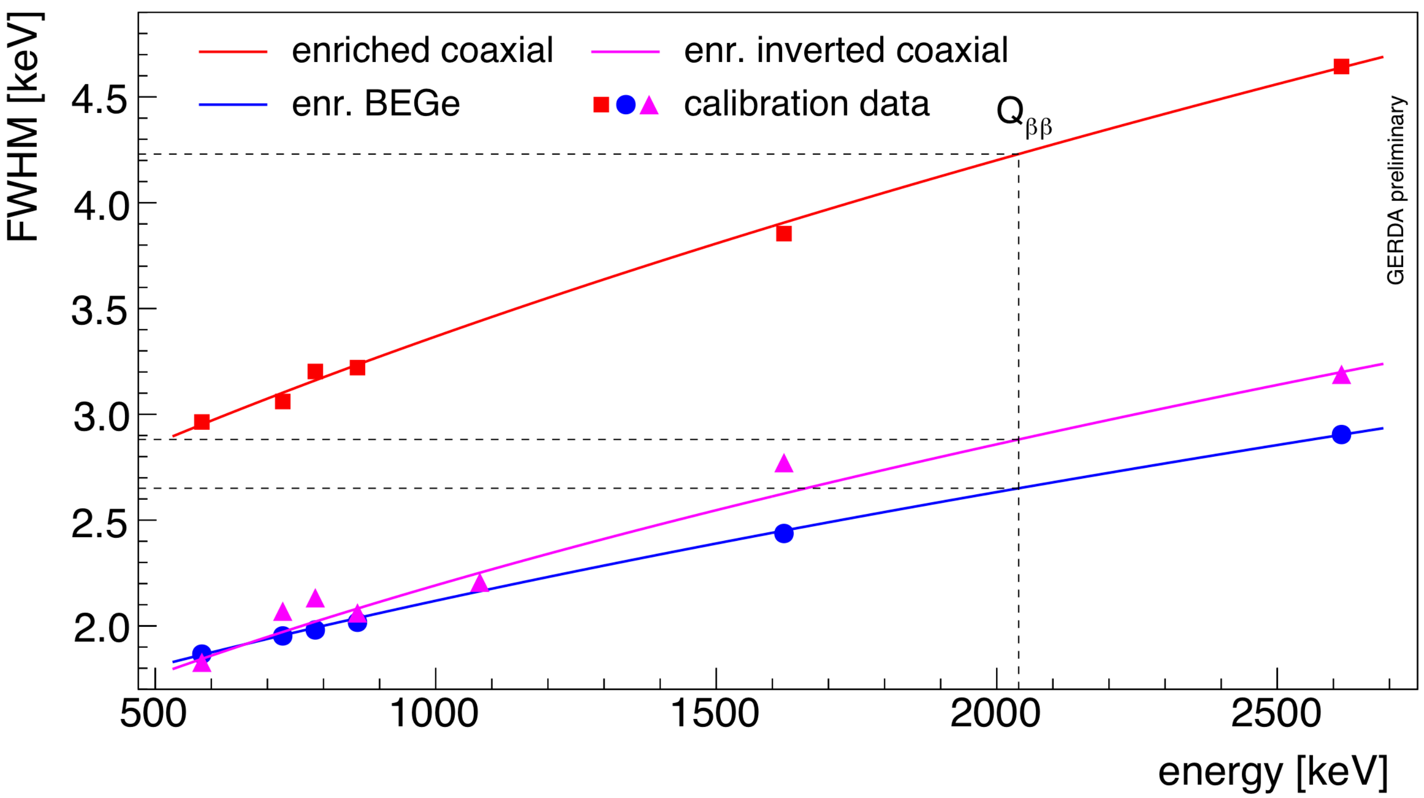


point contact

R.J Cooper et al.,
NIM A 665 (2011) 25



Detector mass increase: 35.6 kg -> 44.2 kg



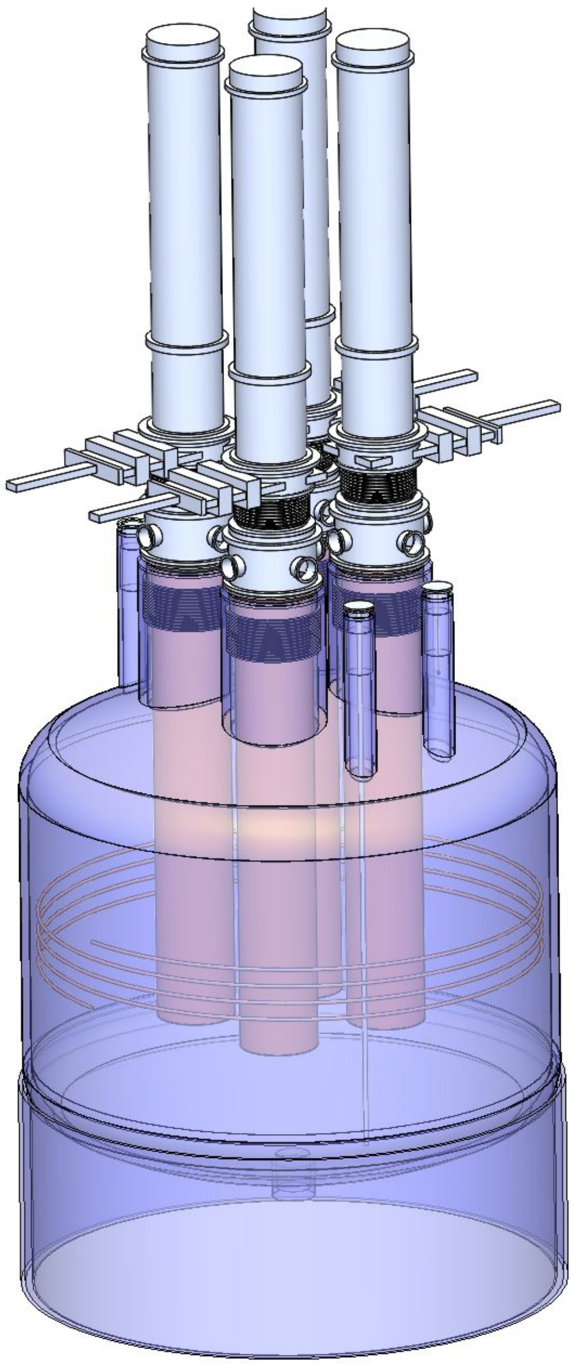
FWHM at $Q_{\beta\beta}$ [keV]: 4.2±0.1 coax; 2.7 ± 0.1 BEGe; 2.9±0.1 IC

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

THE LEGEND EXPERIMENT

- Large enriched germanium experiment for neutrinoless double beta decay
- Collaboration formed in October 2016
- 2019 members, 48 institutions, 16 countries
  - **LEGEND-200**: 200 kg in existing (upgraded) infrastructure at LNGS
  - Background goal: 0.6 events/(FWHM t y)
  - **LEGEND-1t:** 1000 kg, staged
  - Background goal: 0.1 events/(FWHM t y)

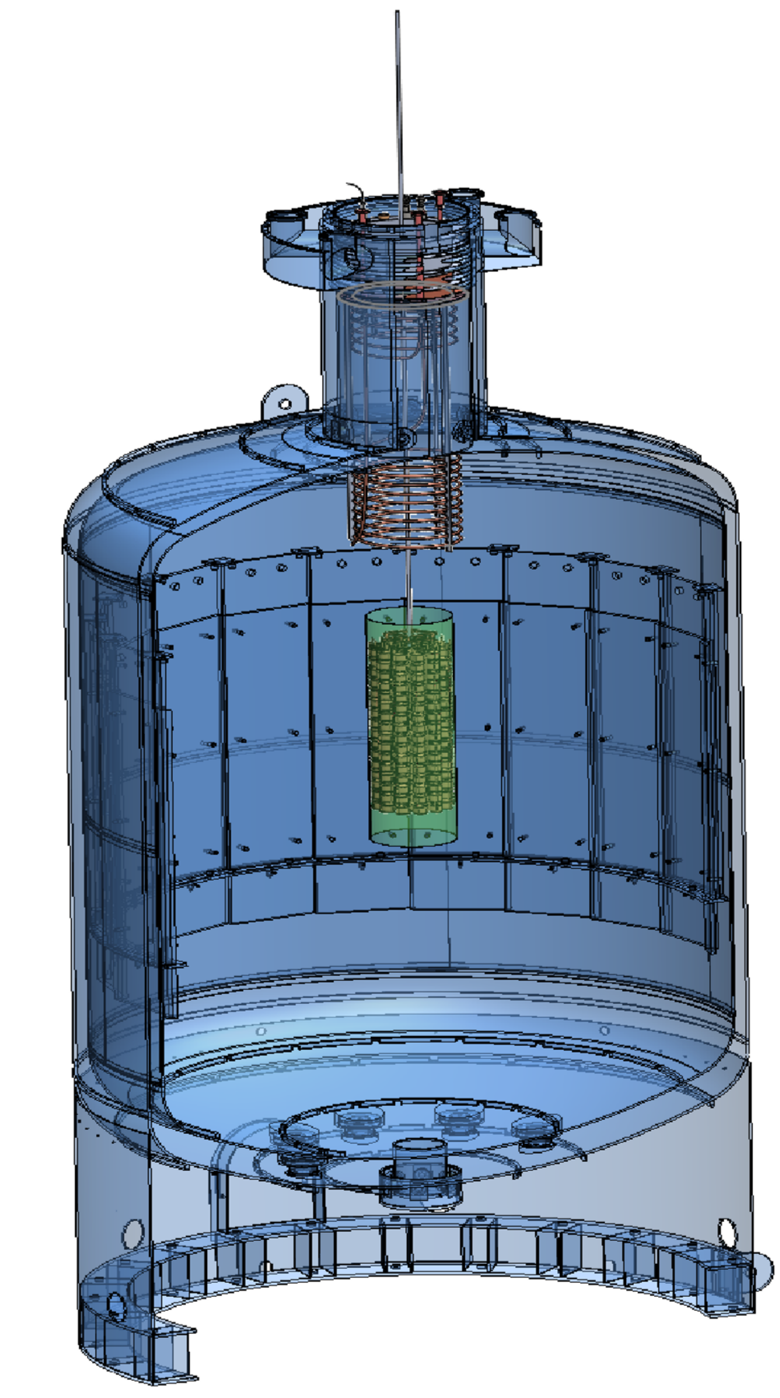


LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

LEGEND-200

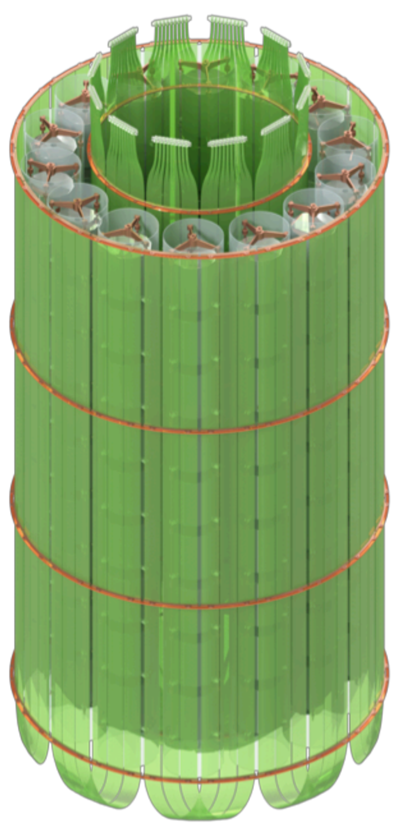
- 200 kg HPGe in existing (upgraded) infrastructure at LNGS
- Ge detectors from Majorana & GERDA & new inverted coaxials
- Background reduction: factor 5 compared to GERDA (reduce ^{42}K, ^{214}Bi, ^{208}Tl background)
- Discovery sensitivity:

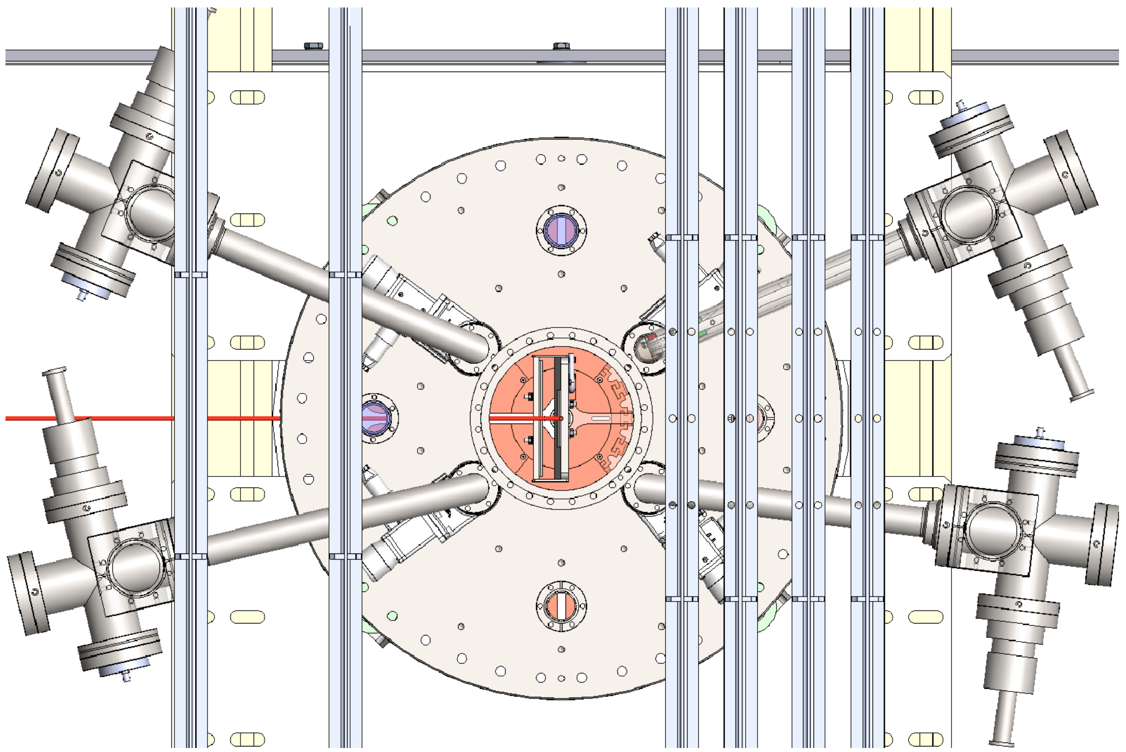
$$T_{1/2}^{0\nu} > 10^{27}\ \mathrm{y}$$



LEGEND-200

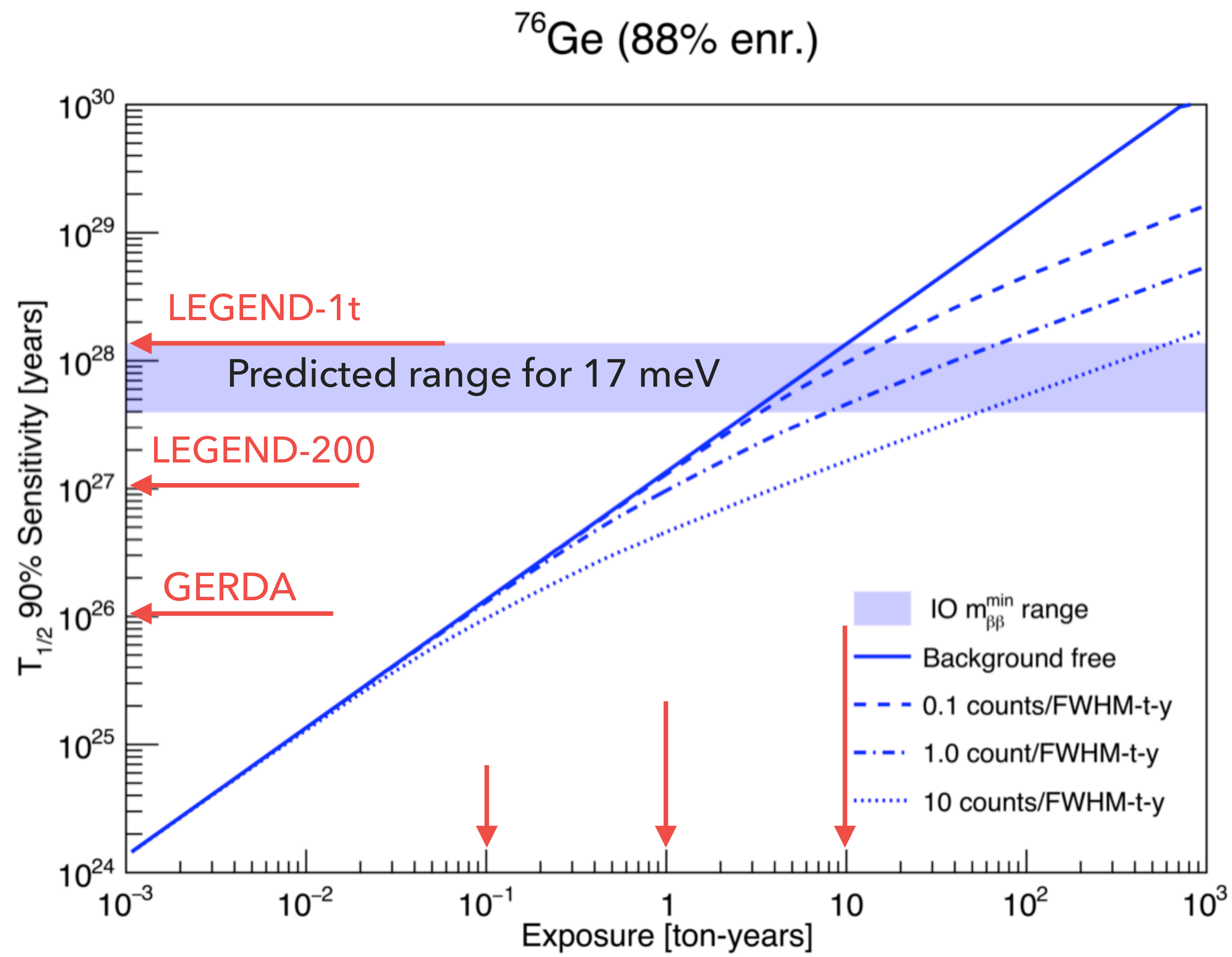
- Existing GERDA infrastructure sufficient (800 mm cryostat neck)
- New lock system, new cabling & feedthroughs
- 19 string, 4 calibration systems with multiple ^{228}Th sources





EXPECTED SENSITIVITY

- LEGEND-200: 10^{27}y
- LEGEND-1t: 10^{28} y
- $m_{\beta\beta}$ = 17 meV (for worst case ME = 3.5)

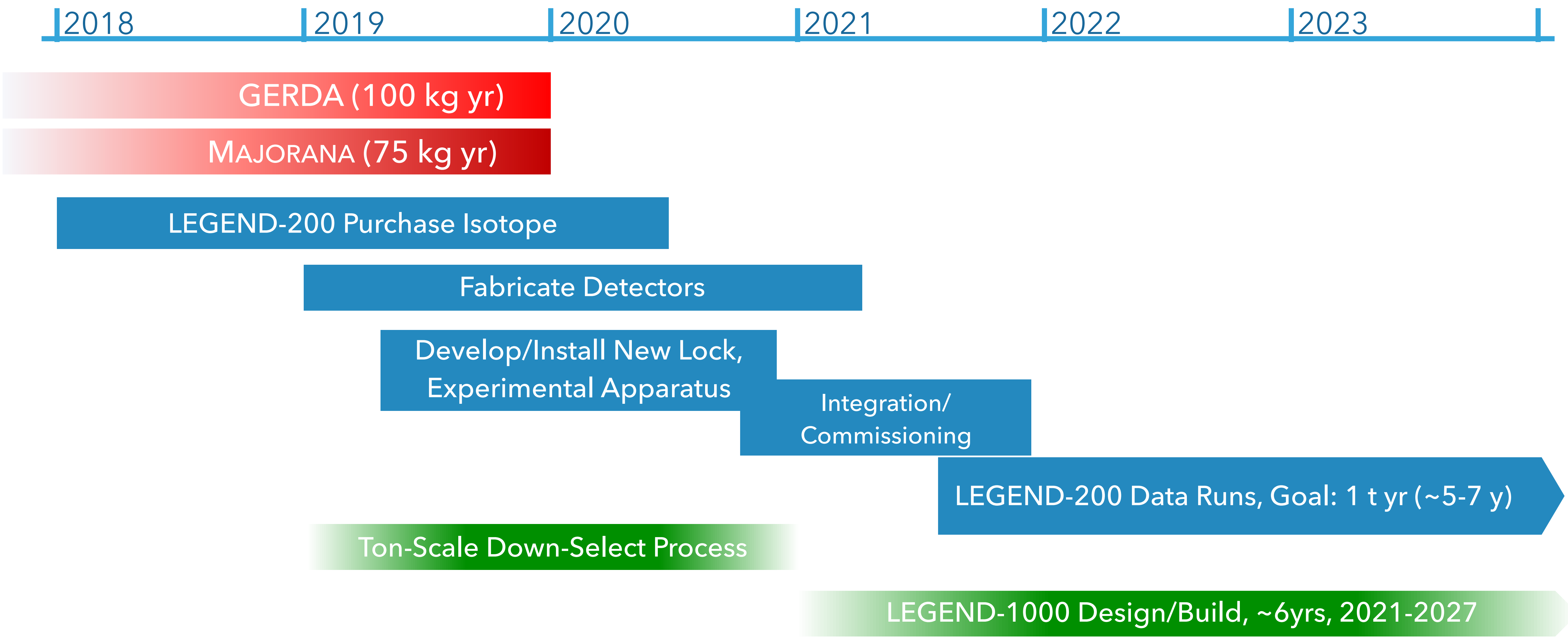


Background

GERDA: 3 events/(ROI t y)
LEGEND-200: 0.6 events/(ROI t y)
LEGEND-1t: 0.1/(ROI t y)

Abgrall et al., The large enriched germanium experiment for neutrinoless double beta decay. AIP Conf. Proc. **1894**(1), 020027 (2017)

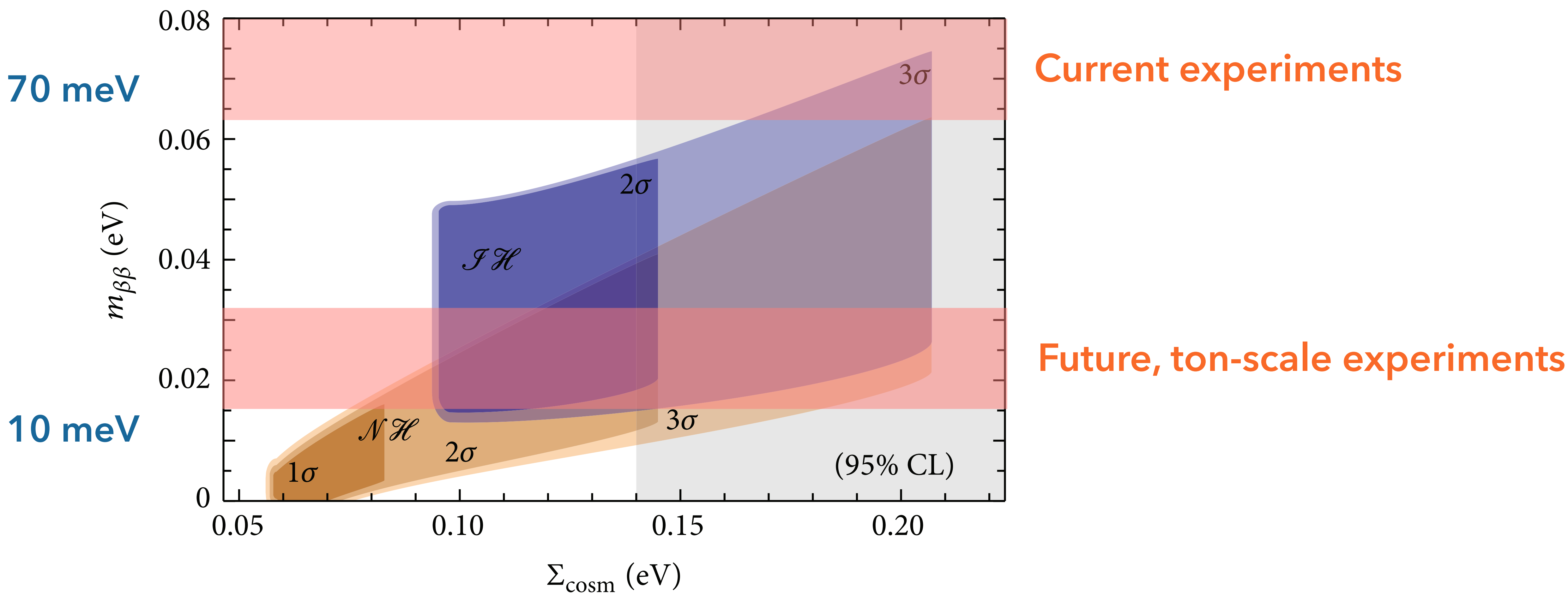
TIME SCALE



Earliest LEGEND-1t Data Start: 2025/6

SUMMARY

- Ton-scale experiments are required to probe the IMO scenario
- ^{76}Ge experiments: excellent resolution and very low background levels
- GERDA will reach 100 kg y by the end of 2019
- LEGEND-200 on track to start in 2021; LEGEND-1t being designed



OF COURSE, “THE PROBABILITY OF SUCCESS IS DIFFICULT TO ESTIMATE, BUT IF WE NEVER SEARCH, THE CHANCE OF SUCCESS IS ZERO”

G. Cocconi & P. Morrison, Nature, 1959

ADDITIONAL MATERIAL

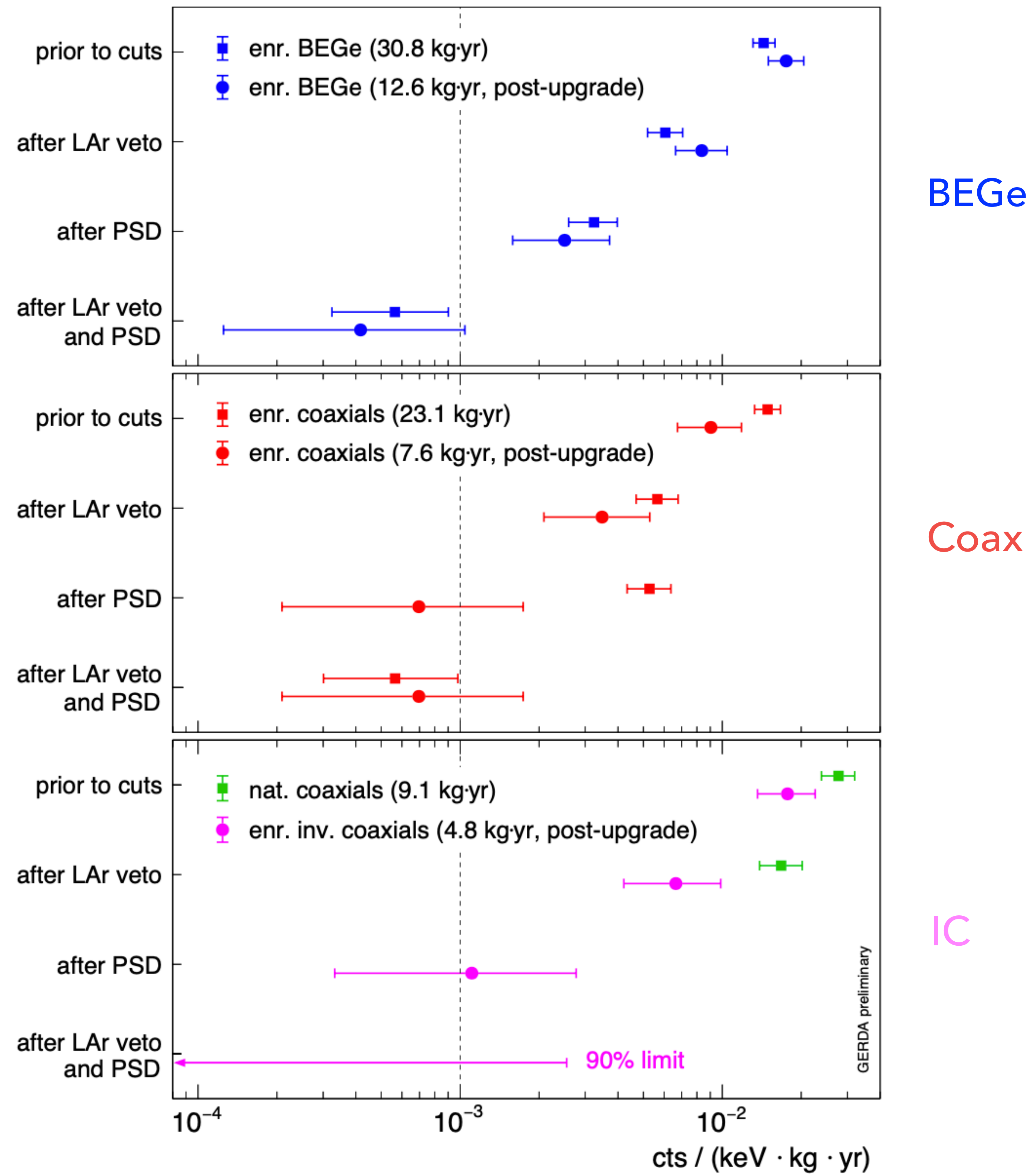
GERDA AND OTHER EXPERIMENTS

Table 1. Comparison of present and prior experiments. Lower half-life limits $L(T_{1/2})$ and sensitivities $S(T_{1/2})$, both at 90% C.L., reported by recent $0\nu\beta\beta$ decay searches with indicated deployed isotope masses M_i and FWHM energy resolutions. Sensitivities $S(T_{1/2})$ have been converted into upper limits of effective Majorana masses $m_{\beta\beta}$ using the nuclear matrix elements quoted in (*20*).

Experiment	Isotope	M_i (kmol)	FWHM (keV)	$L(T_{1/2})$ (10^{25} years)	$S(T_{1/2})$ (10^{25} years)	$m_{\beta\beta}$ (meV)
GERDA (this work)	^{76}Ge	0.41	3.3	9	11	104 to 228
MAJORANA (*27*)	^{76}Ge	0.34	2.5	2.7	4.8	157 to 346
CUPID-0 (*28*)	^{82}Se	0.063	23	0.24	0.23	394 to 810
CUORE (*29*)	^{130}Te	1.59	7.4	1.5	0.7	162 to 757
EXO-200 (*30*)	^{136}Xe	1.04	71	1.8	3.7	93 to 287
KamLAND-Zen (*21*)	^{136}Xe	2.52	270	10.7	5.6	76 to 234
Combined						66 to 155

GERDA BACKGROUNDS

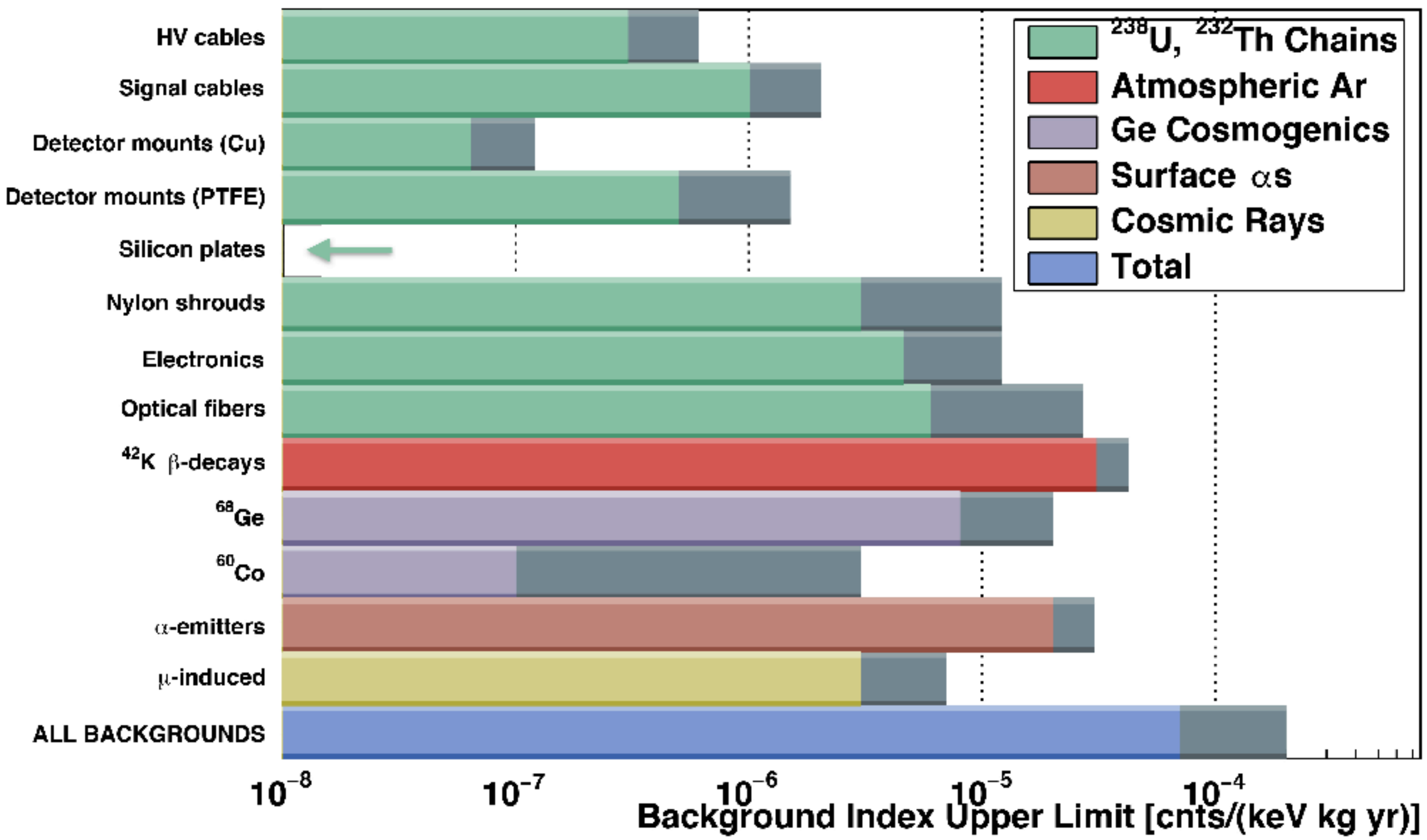
- Background levels in the 3 detector types before & after various cuts



GERMANIUM DETECTOR PRODUCTION

- GeO_2 material from Urenco and ECP
- Reduction/refinement processing at PPM; diode fabrication: Mirion & Ortec
- Detector type: p-type IC detectors [R.J. Cooper et al., NIM A 665 (2011)] Li outer electrode, B implantation for p^+ contact
  - Large active mass up to 3 kg
  - Excellent pulse shape discrimination performance
  - Lower surface to volume ratio
  - Reduced background due to lower number of channels per mass of ^{76}Ge
  - Production started early 2019, ~60 detectors expected by fall 2021

BACKGROUND EXPECTATION

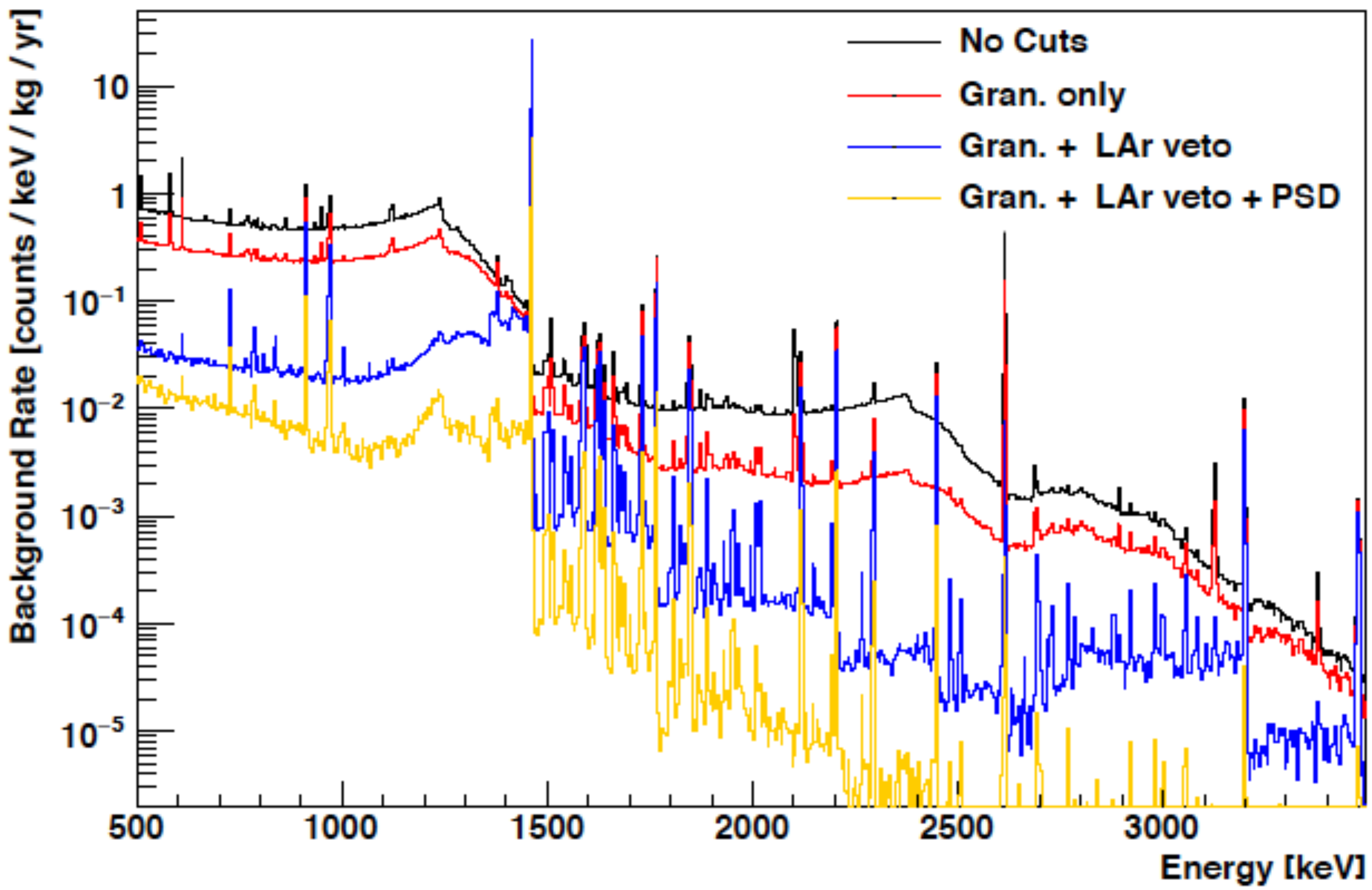


Monte Carlo simulations based on experimental data and material assays. Background rate after anti-coin., PSD, LAr veto cuts.

Assay limits correspond to the 90% CL upper limit. Grey bands indicate uncertainties in overall background rejection efficiency

$Q_{\beta\beta}$ BI ≤ (0.7–2.)x10^{-4} events/(keV kg yr) = 0.2-0.5 events/(FWHM t yr)

BACKGROUND EXPECTATION



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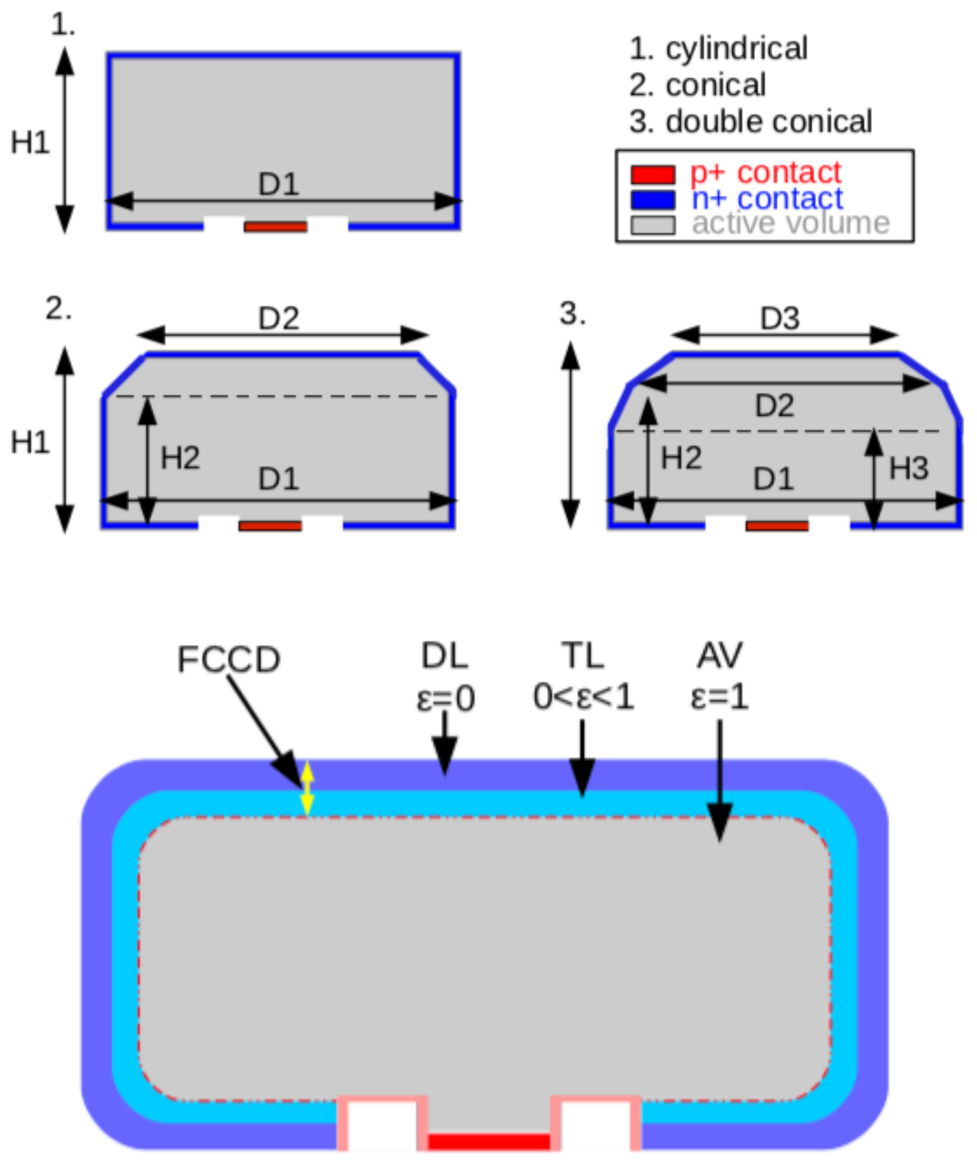
$Q_{\beta\beta}$ BI ≤ (0.7–2.)x10^{-4} events/(keV kg yr) = 0.2-0.5 events/(FWHM t yr)

BACKGROUND GOAL

- LEGEND-200 background: ~ equal contributions of U/Th, ^{42}Ar, surface α before analysis cuts
- LEGEND-1000: background lower by ~ x6 than LEGEND-200.
- U/Th: reduced by optimising array spacing, minimising opaque materials, larger detectors, better light collection, cleaner materials, improved active suppression
- ^{42}Ar: eliminated by using underground sourced Ar
- Surface α: reduced by improved process control (hypothesis Rn in air at detector fabrication facility)
- Larger detectors have a better surface to volume ratio
- Higher isotope fraction is now cost effective.

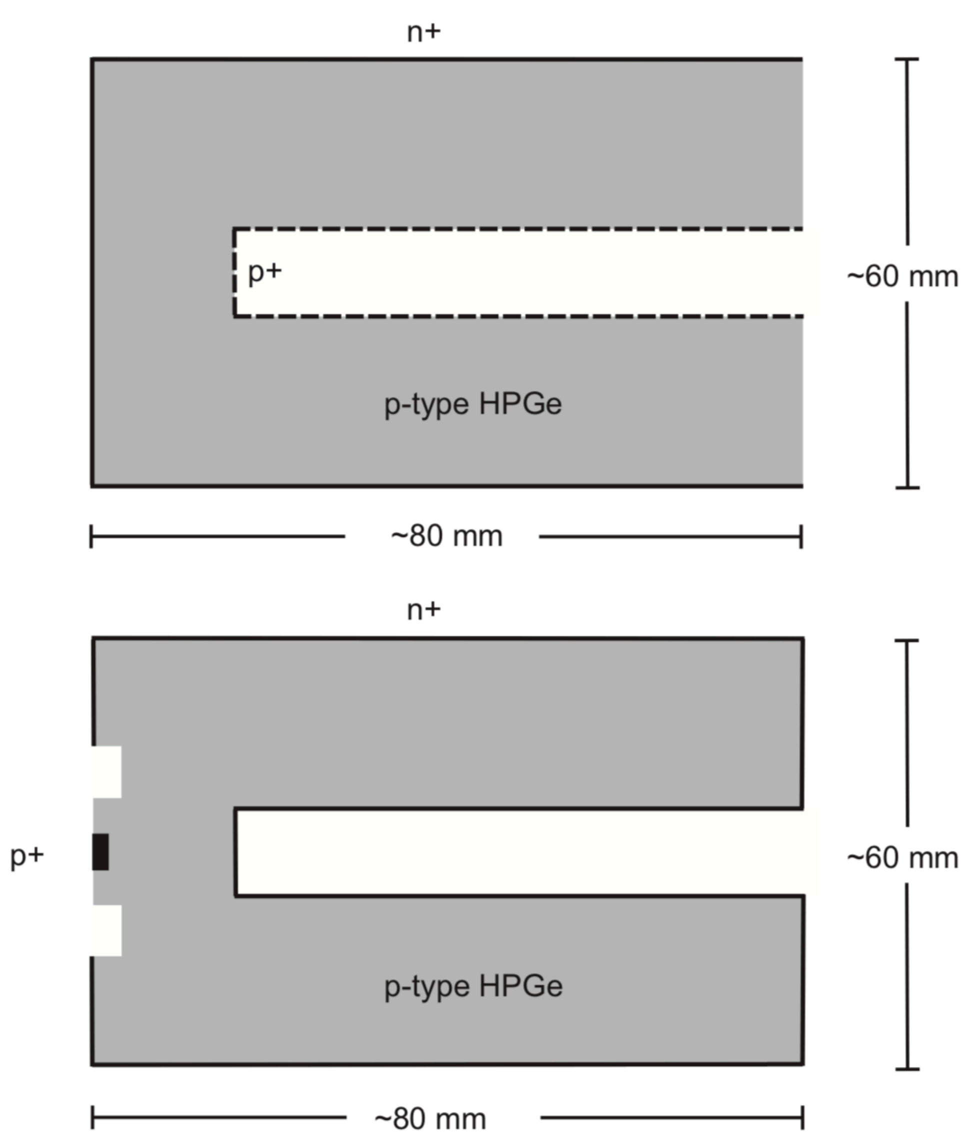
GERDA PHASE-II DETECTORS

BEGe detectors



GERDA collaboration, arXiv:1901.0650

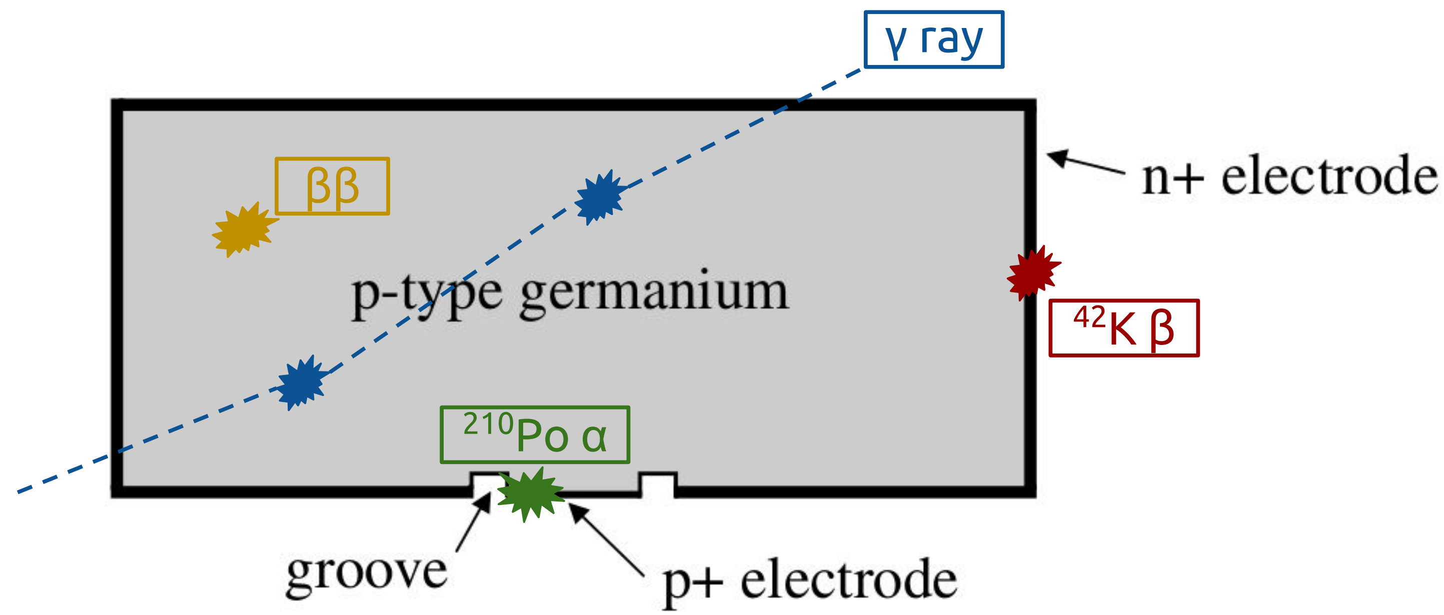
IC detectors

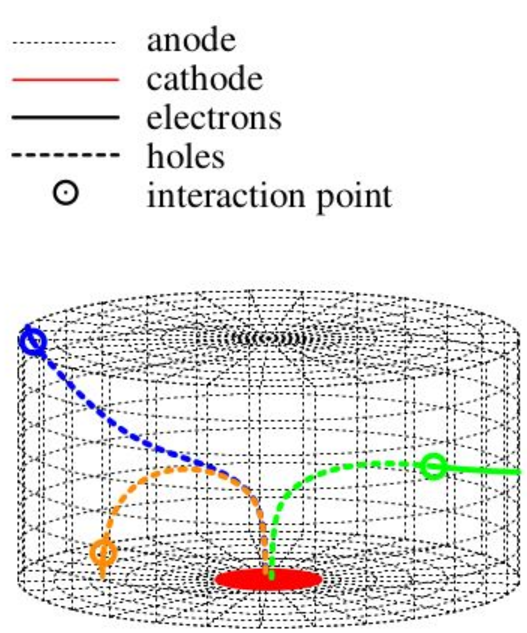


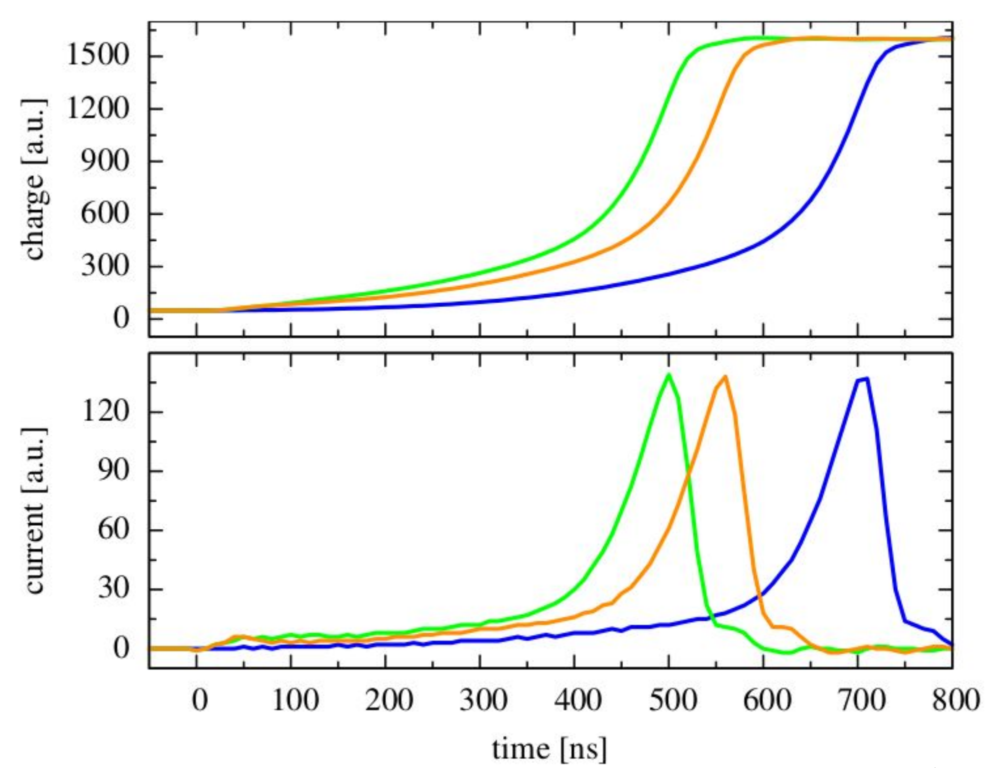
R.J. Cooper et al., NIM A 665 (2011) 25-32

GERDA PULSE SHAPE DISCRIMINATION

- Signal-like: Single Site Events (SSE)
- Background-like: Multiple Site Events (MSE)
- BEGe detectors: E-field and weighting potential has special shape: pulse-height nearly independent of position

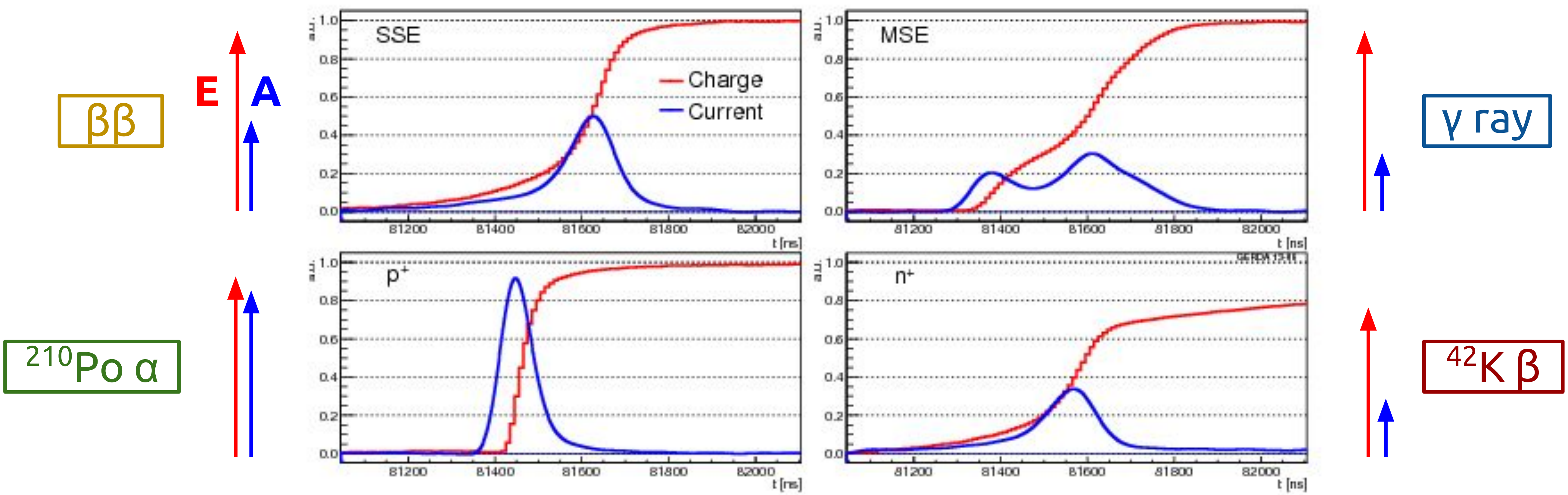






GERDA PULSE SHAPE DISCRIMINATION

- A/E: amplitude of the current pulse over energy
- Multiple energy depositions: multiple peaks in current pulse => decreasing A/E
- p+ surface events: shorter signals => higher A/E



EPJC 73 (2013) 2583

COSMOGENIC ACTIVATION FOR LEGEND

- ^{77}Ge production: n-capture by ^{76}Ge
- ^{77}Ge: $T_{1/2}$ = 11.3 h; $Q_{\beta-}$ = 2.7 MeV
- ^{77m}Ge: $T_{1/2}$ = 53 s; $Q_{\beta-}$ = 2.86 MeV