University of Zurich[UZH]

FNSNF
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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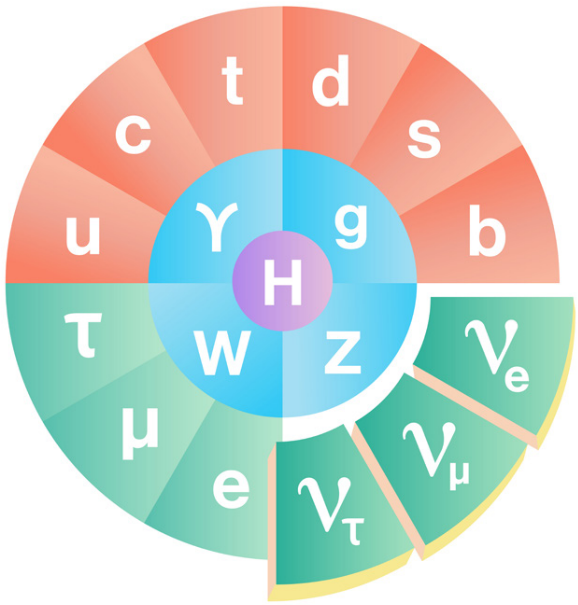
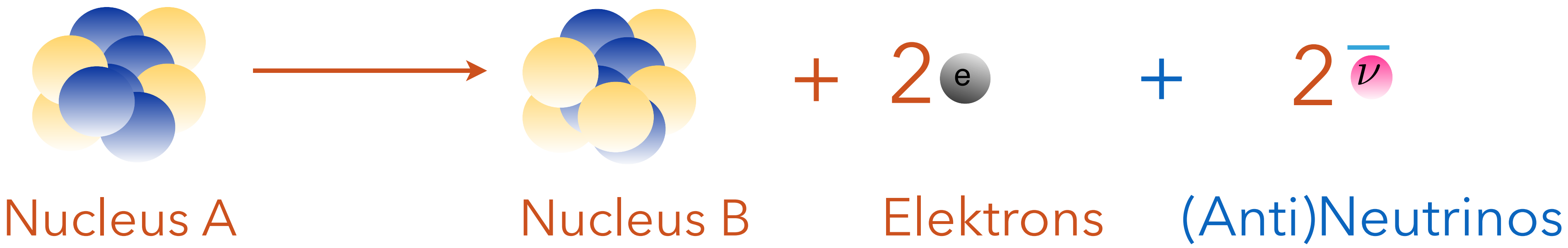
# (SOME) OPEN QUESTIONS IN NEUTRINO PHYSICS

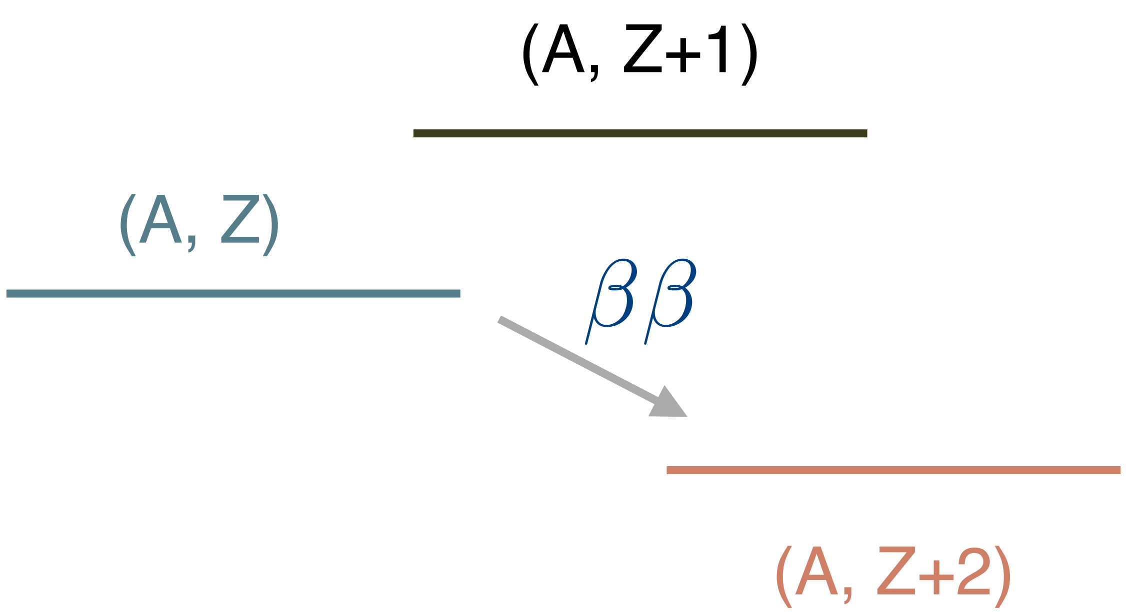


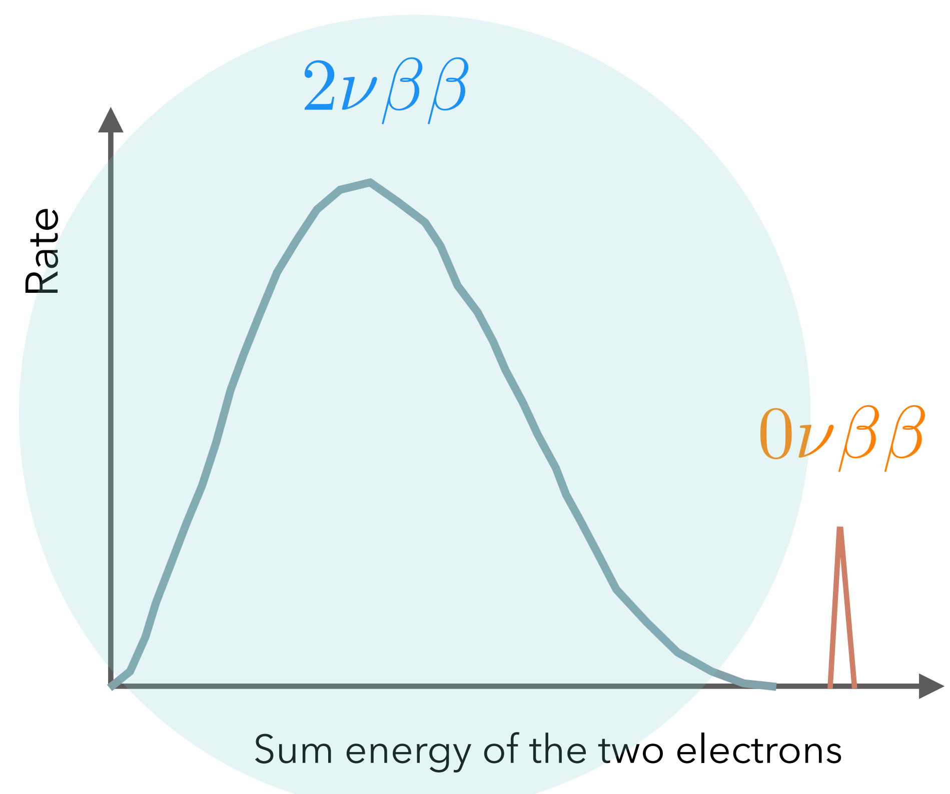

- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- These can be addressed with an extremely rare nuclear decay process: the double beta decay



# THE DOUBLE BETA DECAY

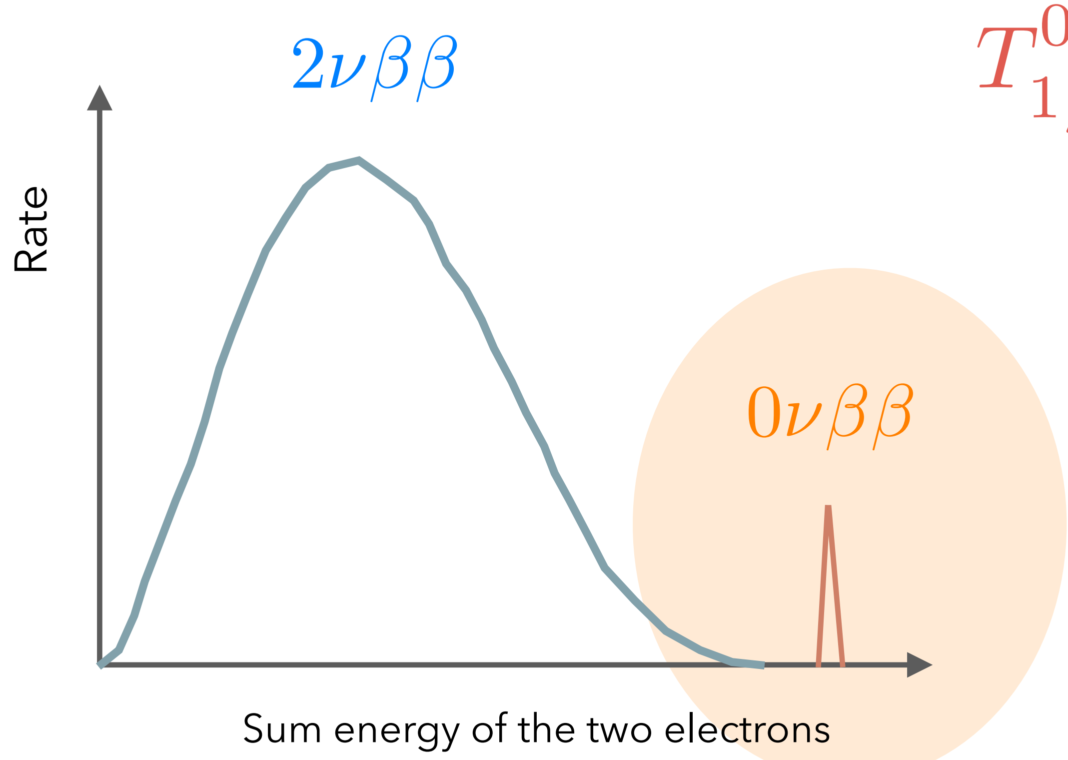

- Predicted by Maria-Goeppert Mayer in 1935
- The SM decay, with 2 neutrinos, was observed in 14 nuclei
- $T_{1/2} > 10^{18}$ y; $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{136}$Xe, $^{150}$Nd, $^{238}$U



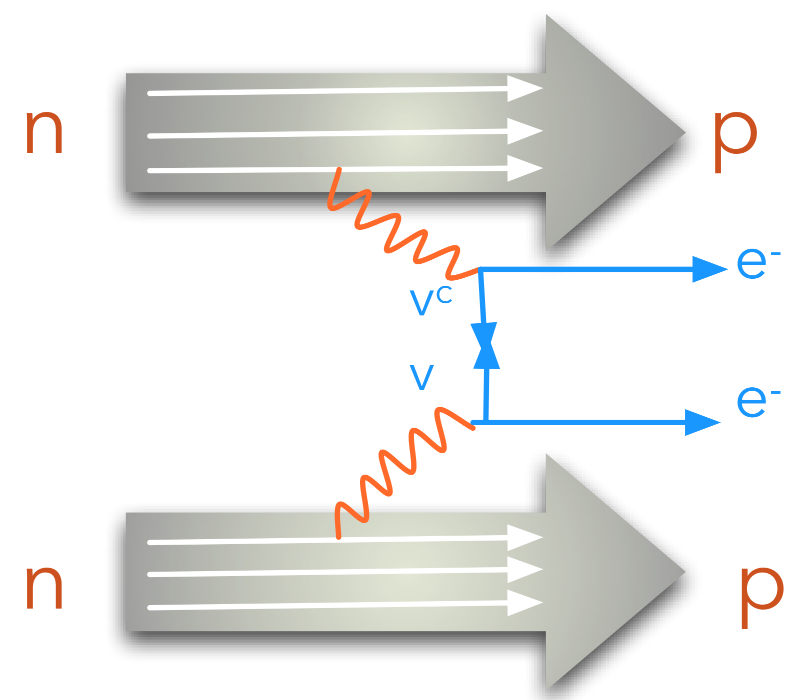



# THE NEUTRINOLESS DOUBLE BETA DECAY

- 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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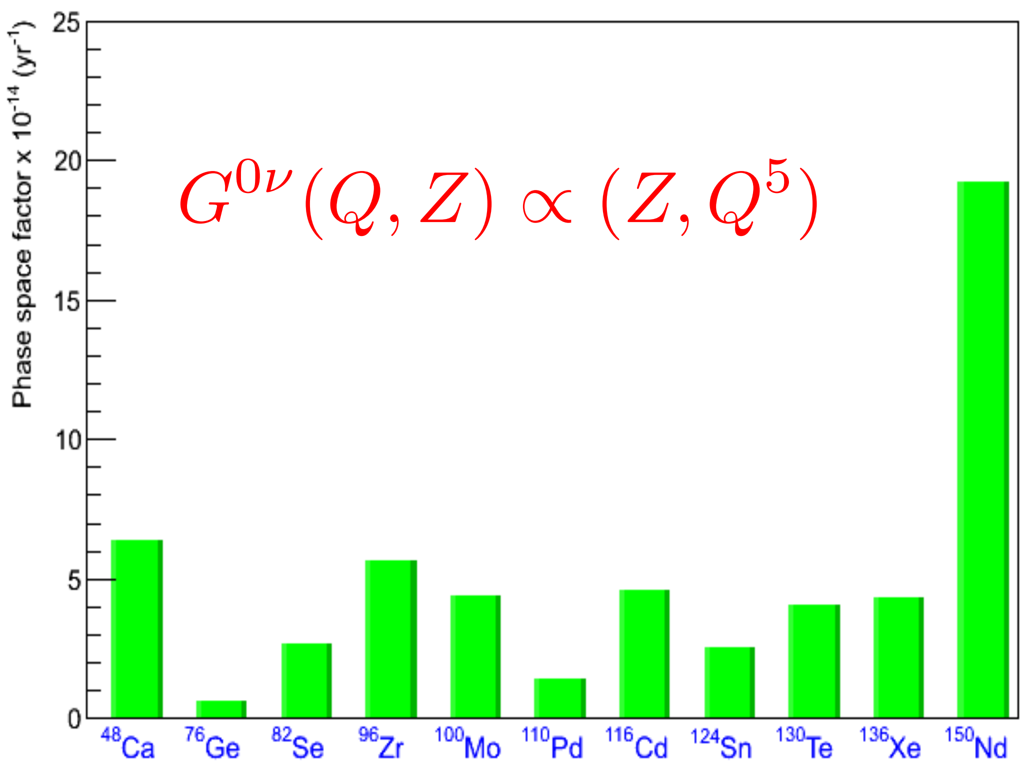
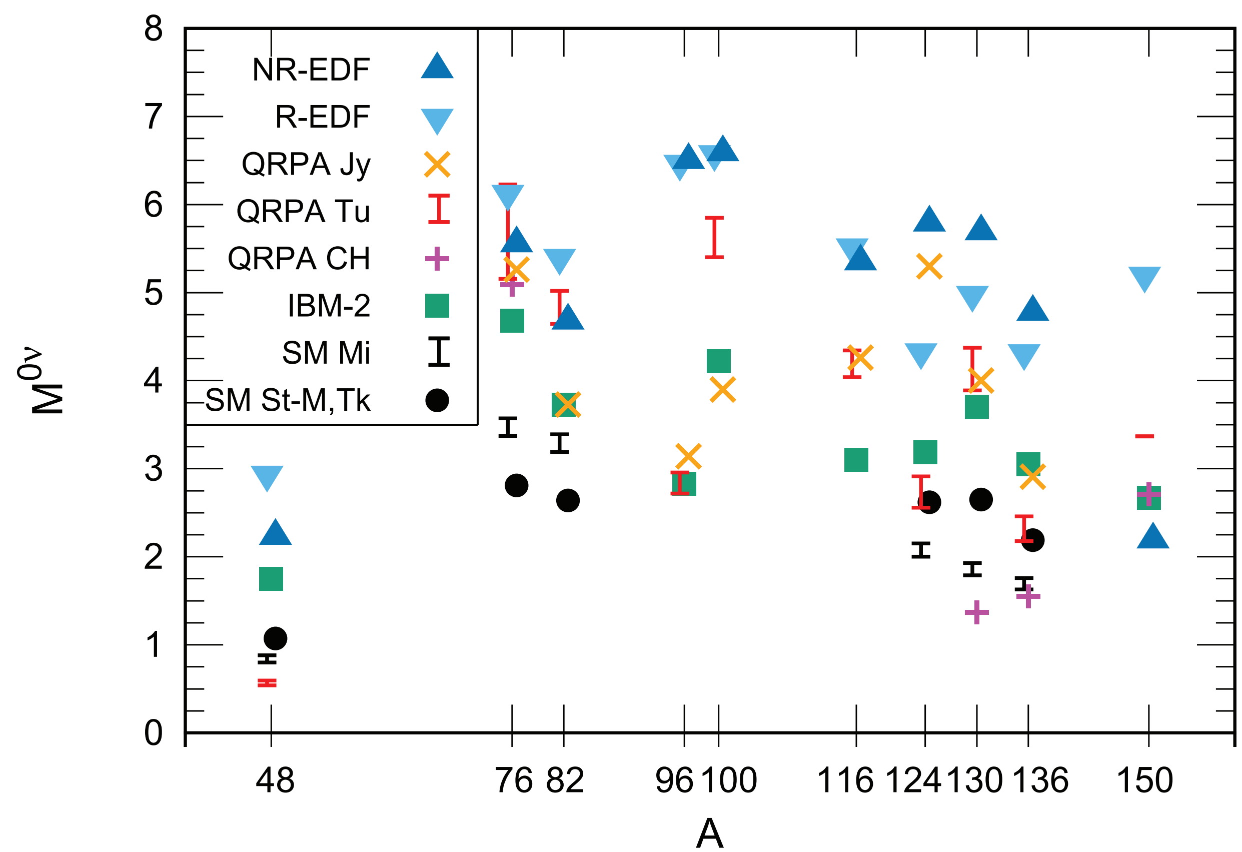


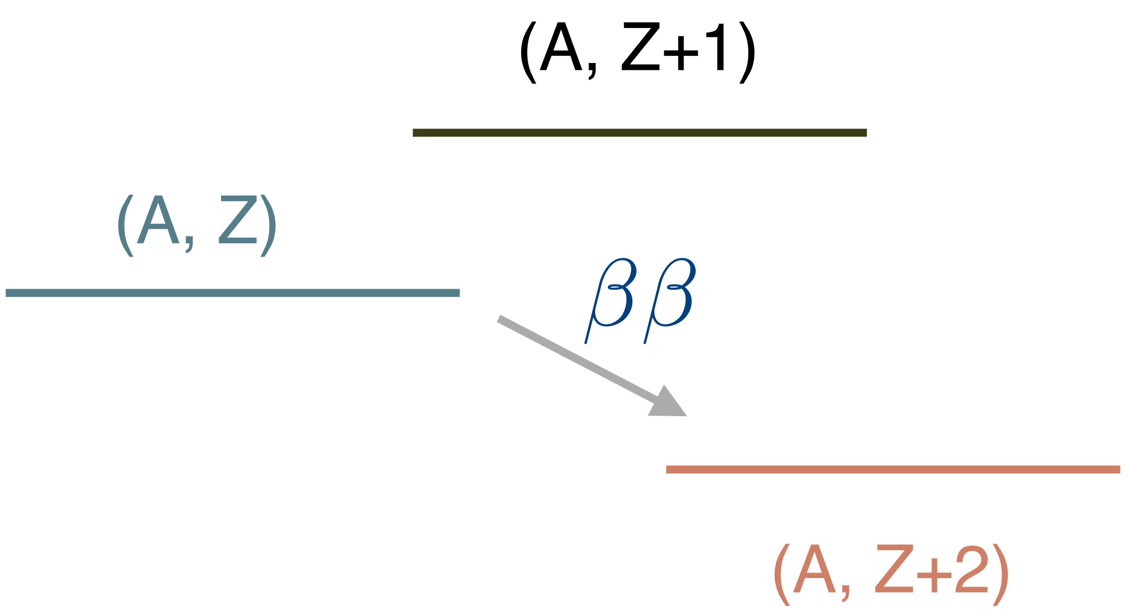




Matrix elements: vary by a factor of 2- 3 for a given A

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 |

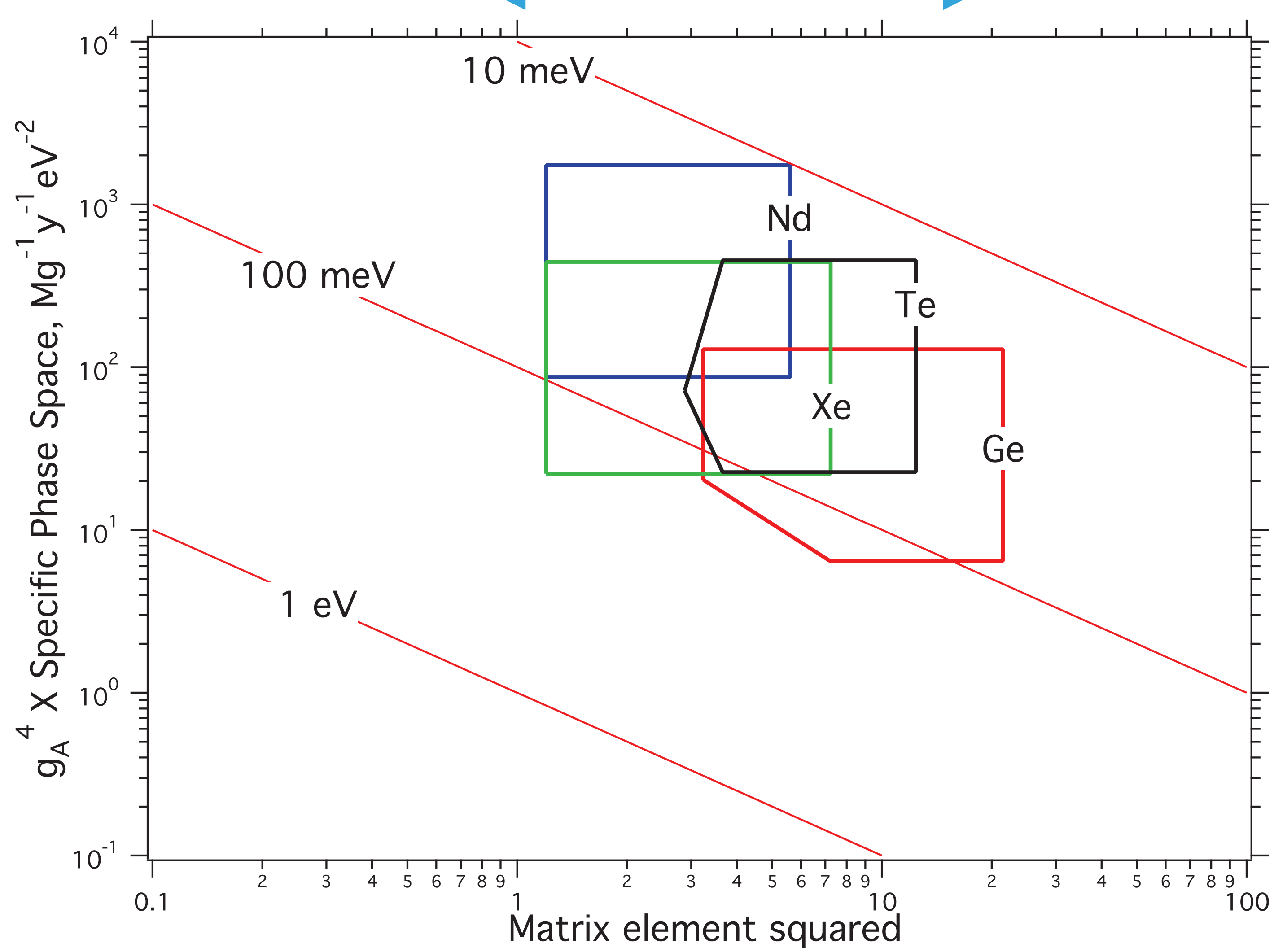
# ISOTOPES AND SENSITIVITY TO THE DECAY

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

- 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)

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

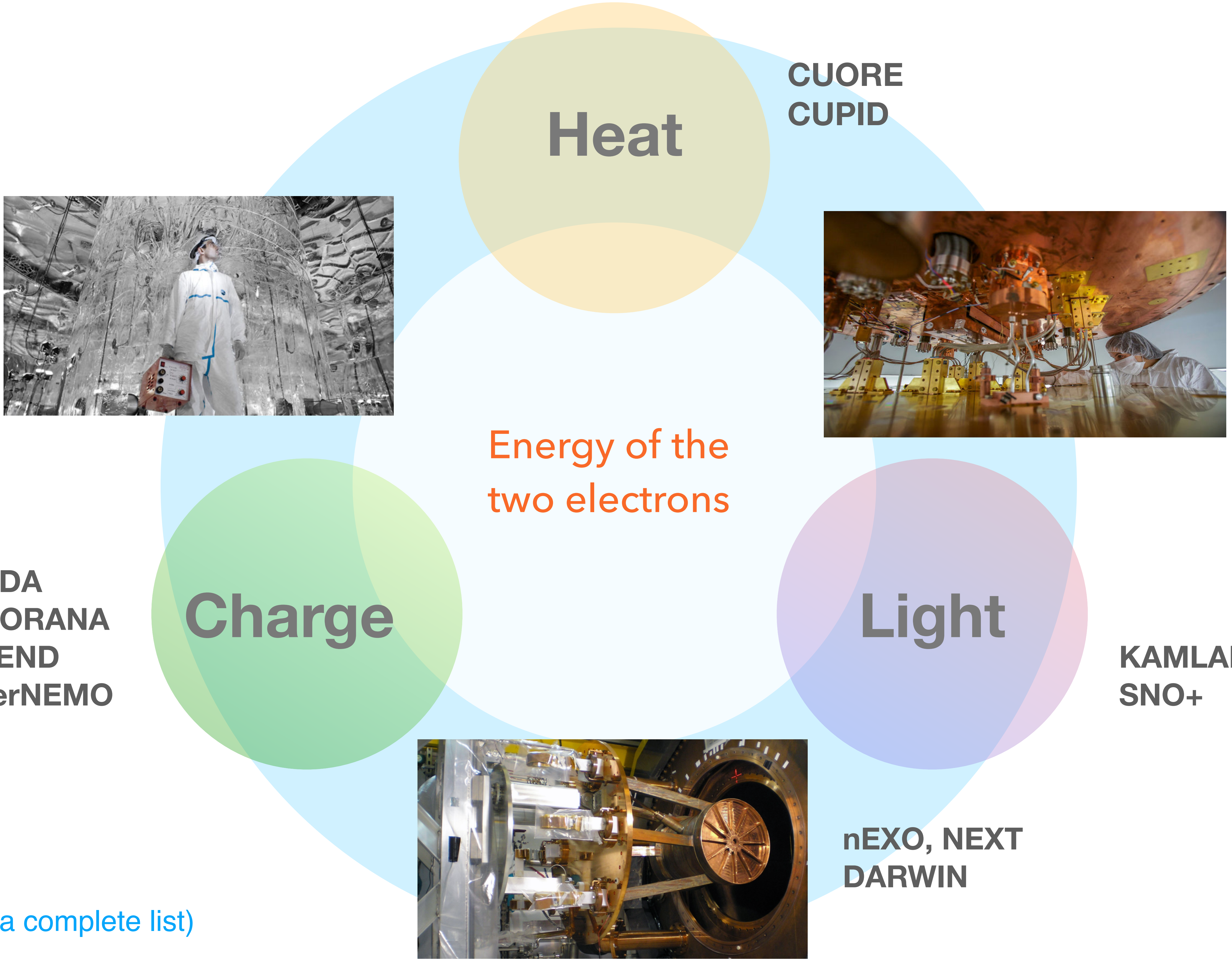
$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

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




CUORE
CUPID

GERDA
MAJORANA
LEGEND
SuperNEMO

KAMLAND-Zen
SNO+

nEXO, NEXT
DARWIN

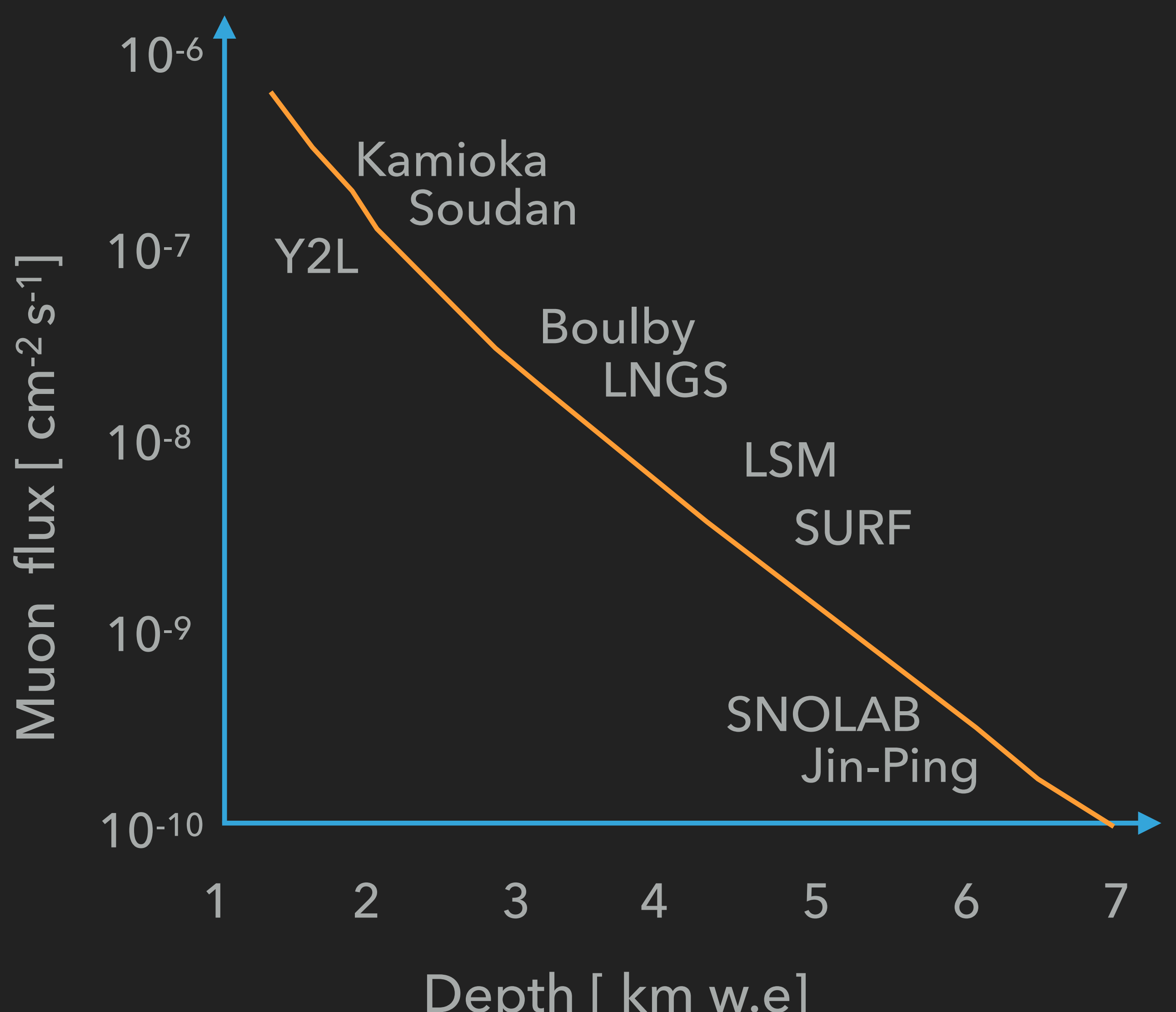
(not a complete list)

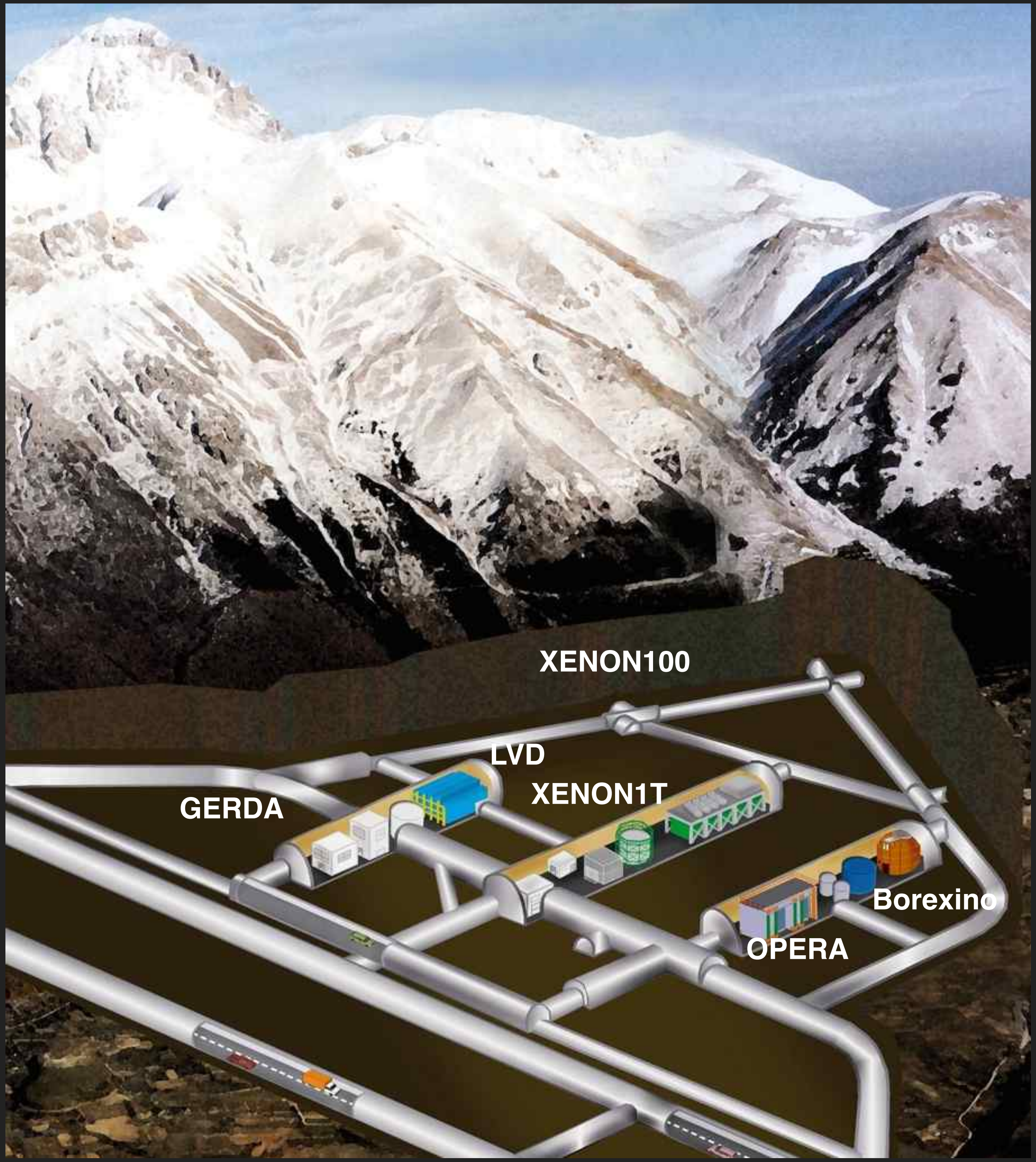
# MAIN CHALLENGES

- 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

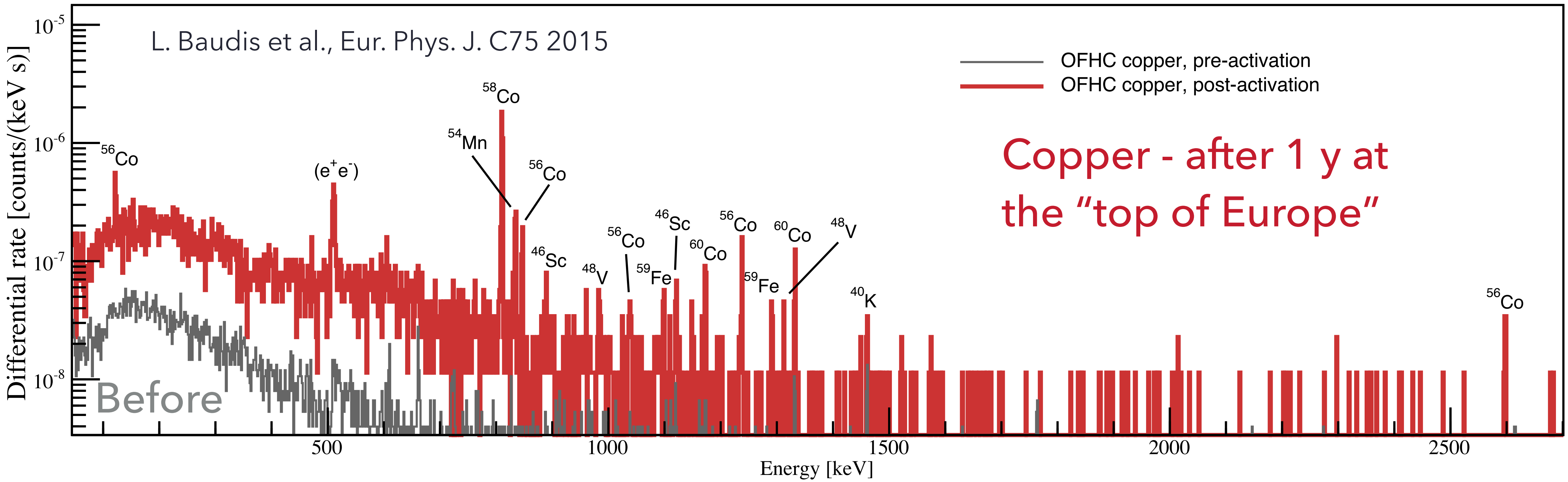
- Network of underground laboratories



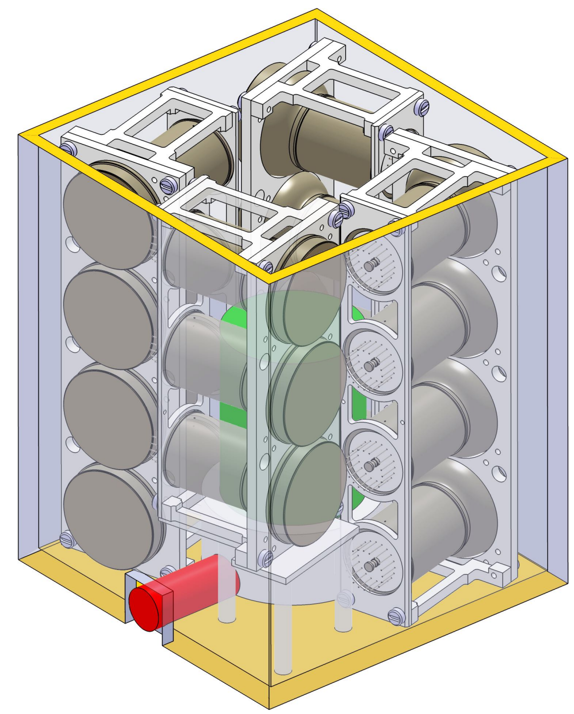
# AVOID EXPOSURE TO COSMIC RAYS

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

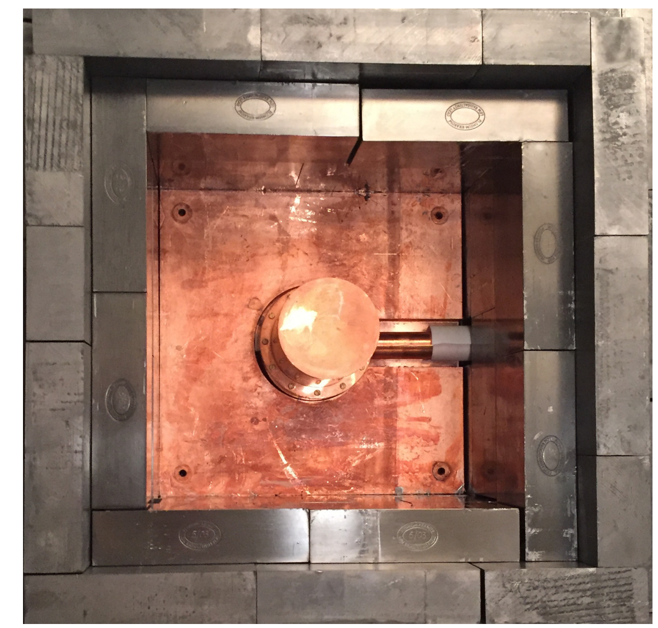



# MATERIAL SCREENING AND SELECTION

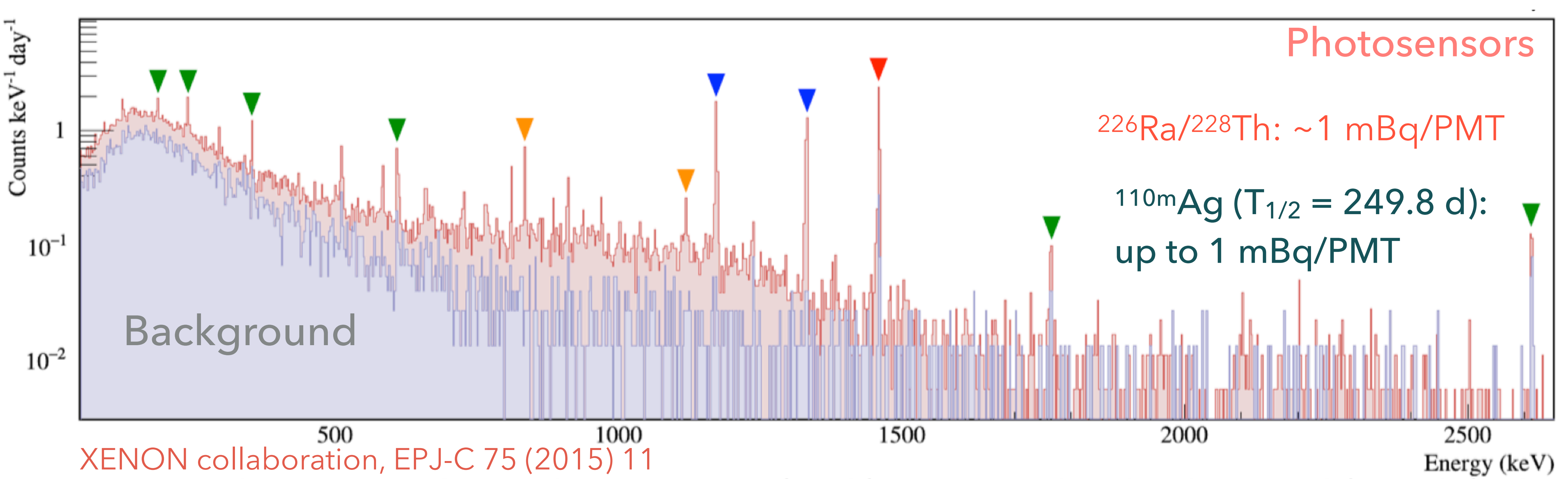
- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



Gator HPGe detector at LNGS



L. Baudis et al., JINST 6, 2011




XENON collaboration, EPJ-C 75 (2015) 11

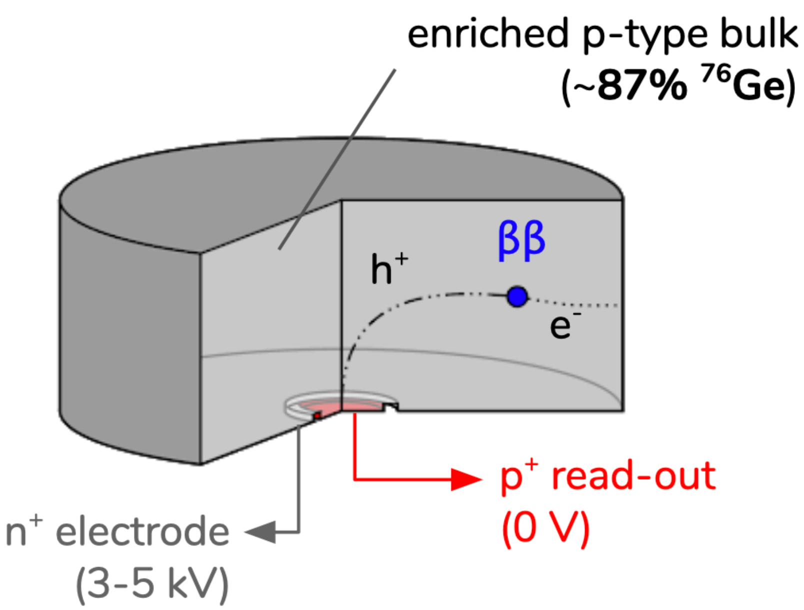
# CURRENT STATUS OF THE FIELD

- No observation of this extremely rare nuclear decay (so far)
- Best lower limits on $T_{1/2}$: 1.07x$10^{26}$ y ($^{136}$Xe), 0.9x$10^{26}$ y ($^{76}$Ge), 2.7x$10^{24}$ y ($^{130}$Te)

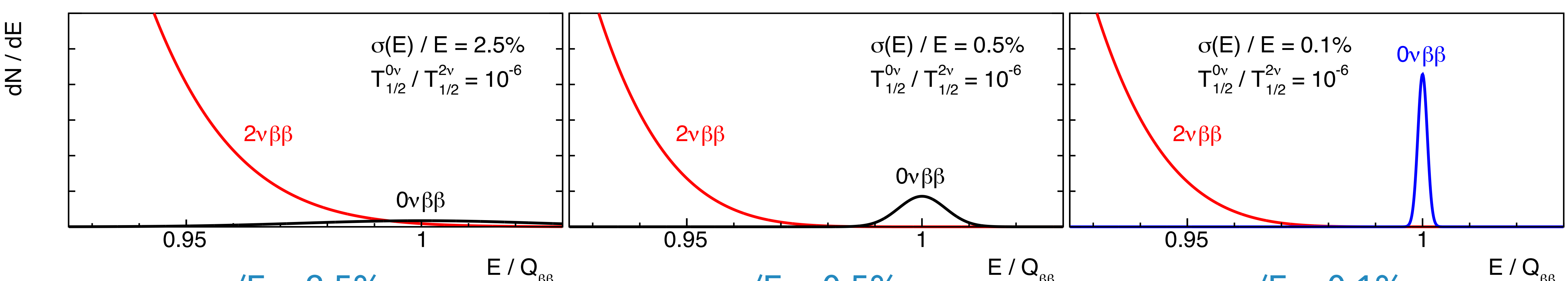
$$0.07 \text{ eV} \leq |\langle m_{\beta\beta} \rangle| \leq 0.16 \text{ eV}$$

- 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

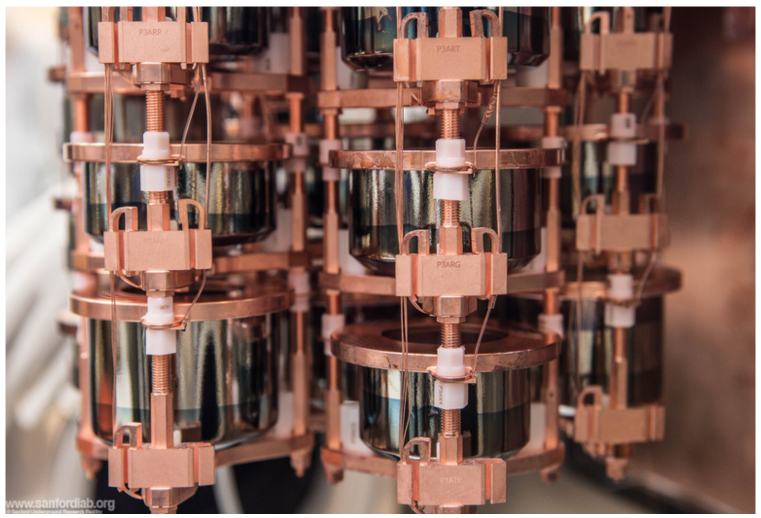



- HPGe detectors enriched in $^{76}$Ge
  - Source = detector: high detection efficiency
  - High-purity material: no intrinsic backgrounds
  - Semiconductor: energy resolution σ/E < 0.1% at $Q_{\beta\beta}$ (2039.061 ± 0.007 keV)
  - High stopping power: β absorbed within O(1) mm




σ/E = 2.5% σ/E = 0.5% σ/E = 0.1%

# EXISTING AND FUTURE GERMANIUM EXPERIMENTS



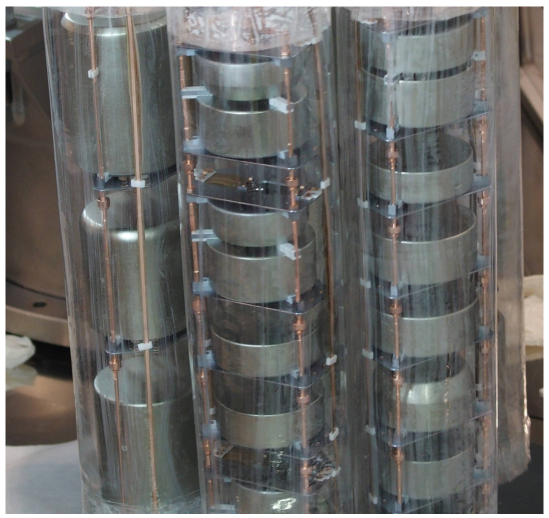

MAJORANA at SURF

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

2.5 keV FWHM at 2039 keV

26 kg y exposure; PRL 120 (2018)

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



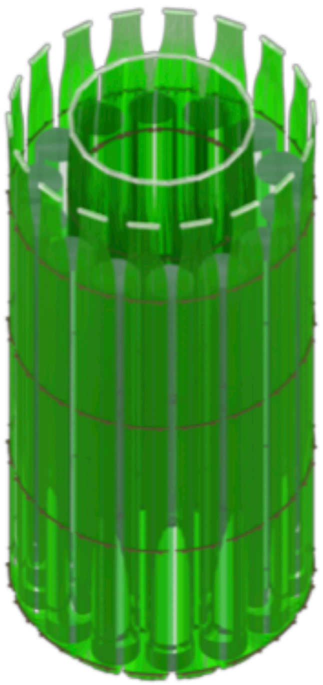
GERDA at LNGS

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

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



LEGEND-1t

Goal: $T_{1/2} \sim 1 \times 10^{28}$ y (90% CL)

Location: tbd

LEGEND-200 at LNGS

200 kg of $^{76}Ge$ crystals at LNGS

Goal: 1 tonne year exposure

Goal: $T_{1/2} \sim 1 \times 10^{27}$ y (90% CL)

Start in 2021

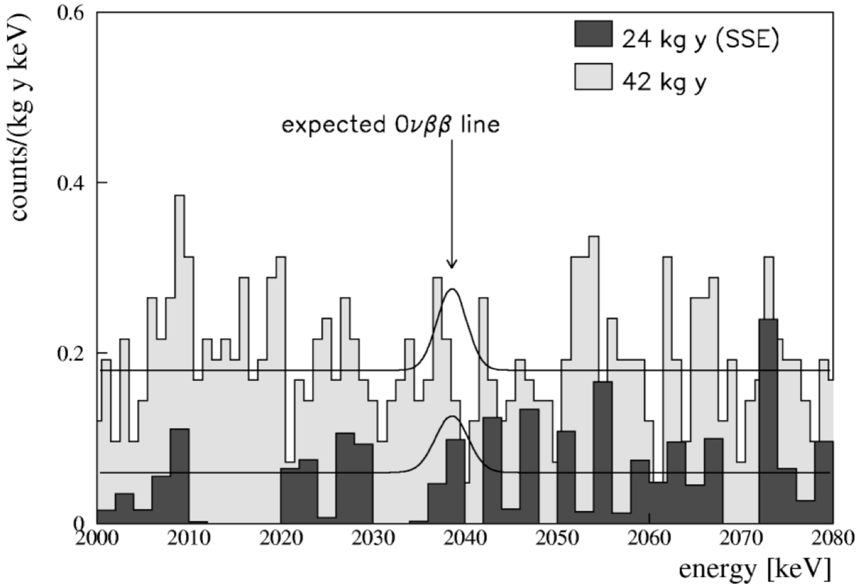
# THE HEIDELBERG-MOSCOW EXPERIMENT

- 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



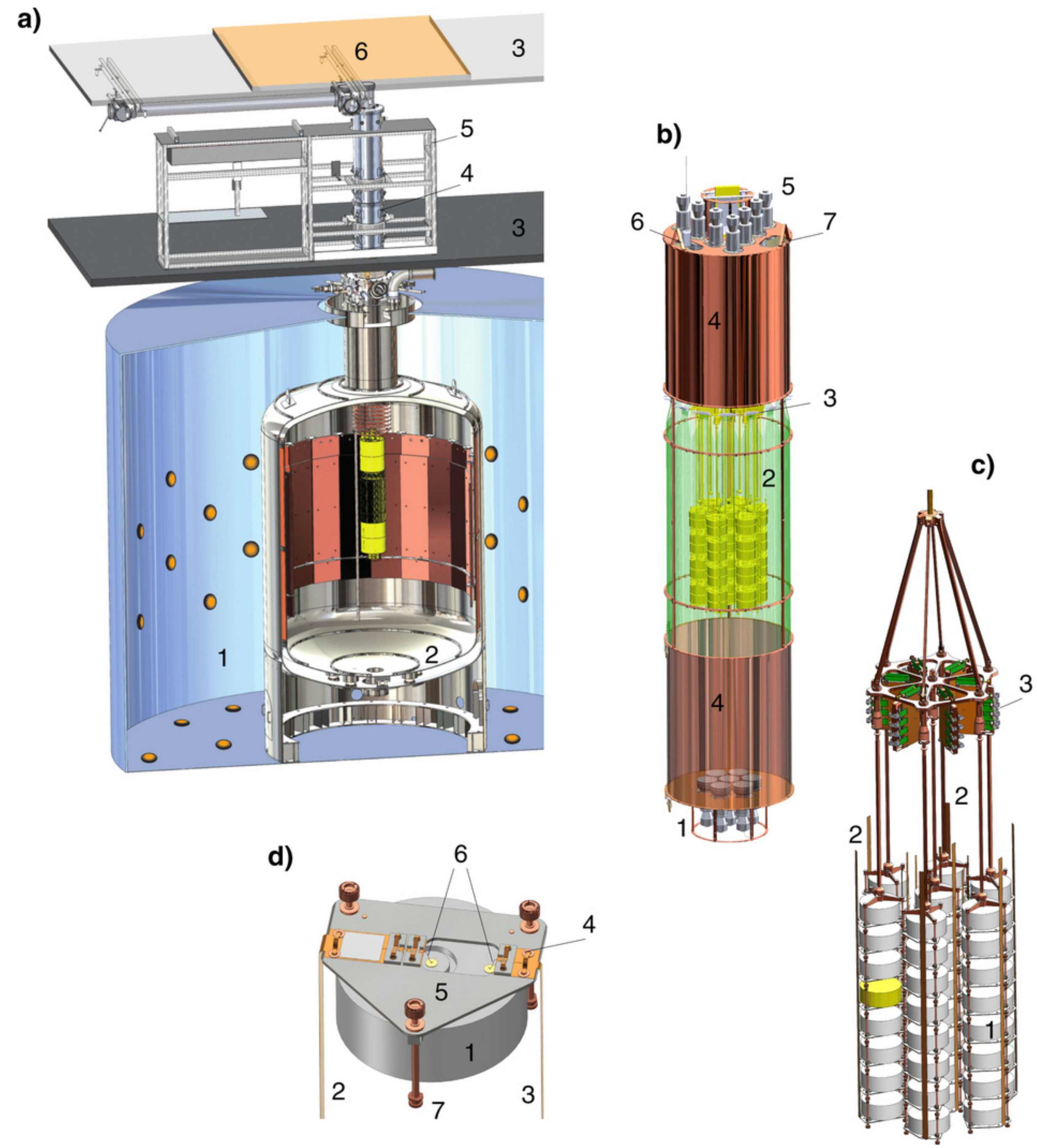

Limits on the Majorana neutrino mass in the 0.1 eV range,
L. Baudis et al., Phys. Rev. Lett. 83, 1999

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

# THE GERDA EXPERIMENT

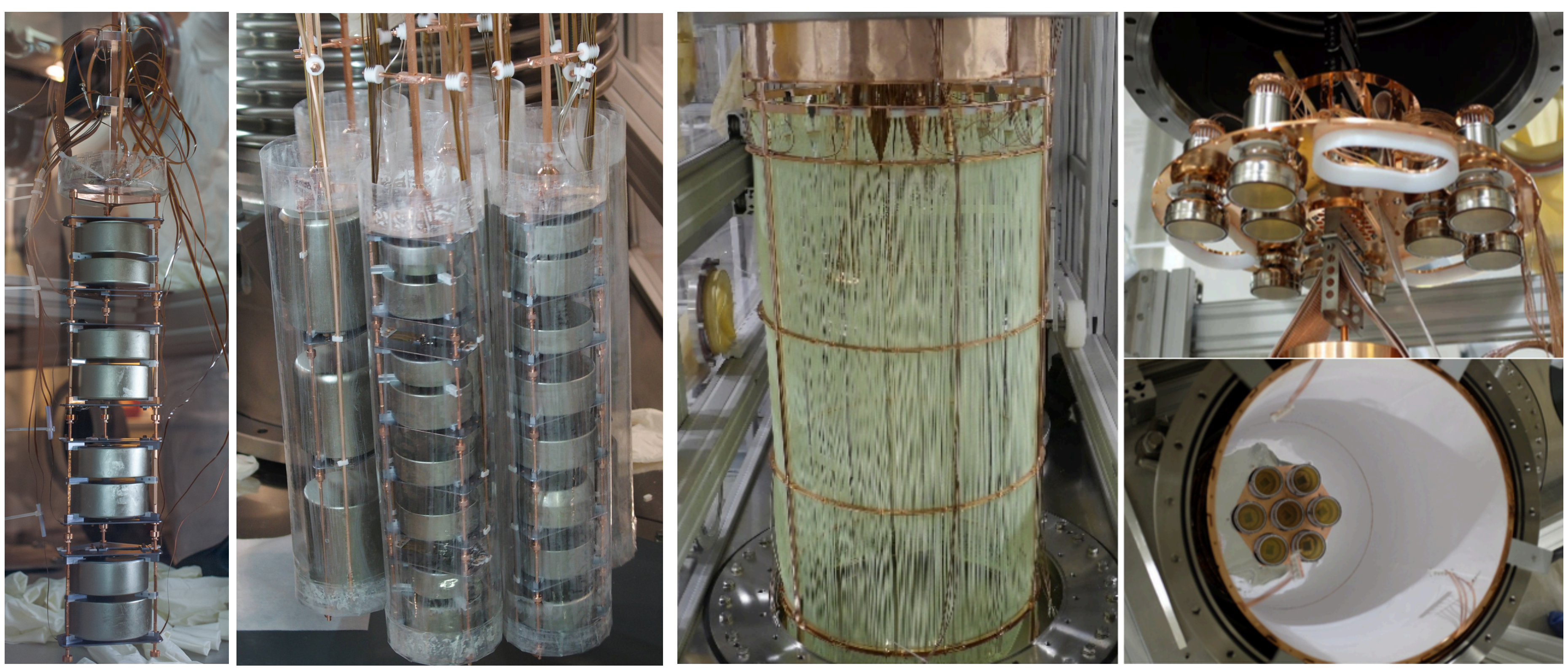
GERDA collaboration, EPJ C78 (2018) no.5

- Liquid Ar (64 m$^3$) as cooling medium and shielding, surrounded by 590 m$^3$ of ultra-pure water as muon Cherenkov veto
- U/Th in LAr < 7x10$^{-4}$ µBq/kg
- A minimal amount of surrounding material
  - Phase I: 2011-2014
  - Phase II: 2015-2019



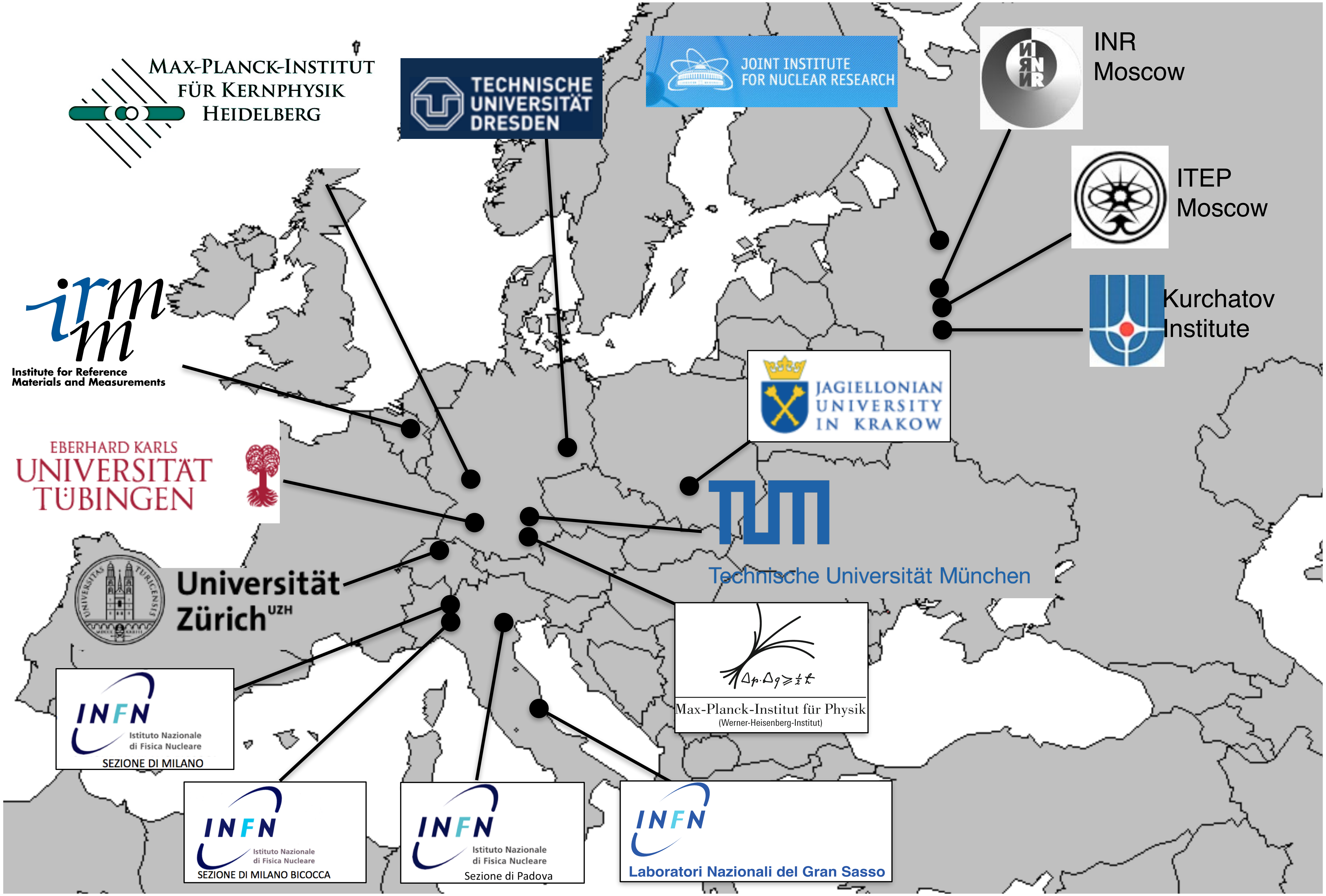
# THE GERDA PHASE II PROJECT

- 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

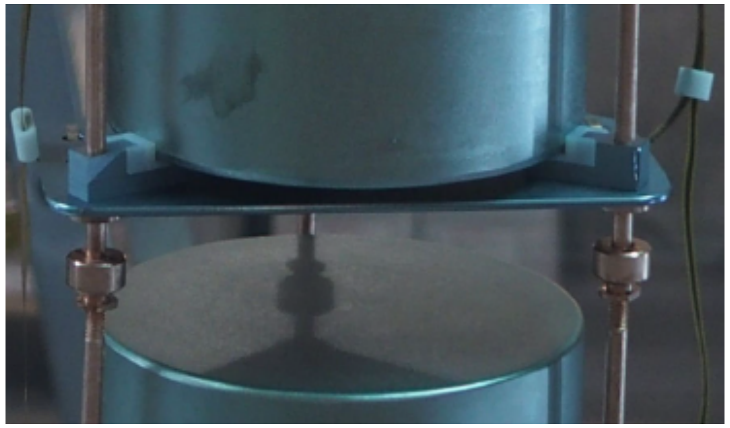


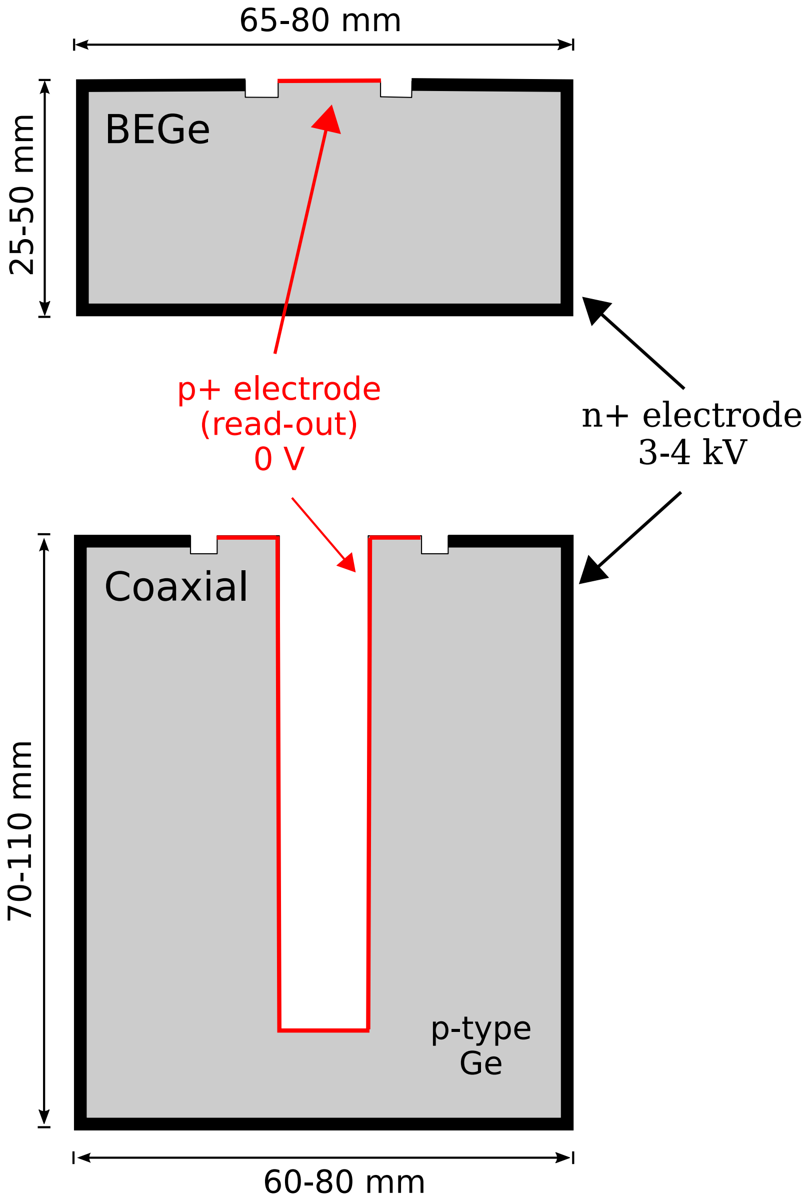
# THE GERDA COLLABORATION

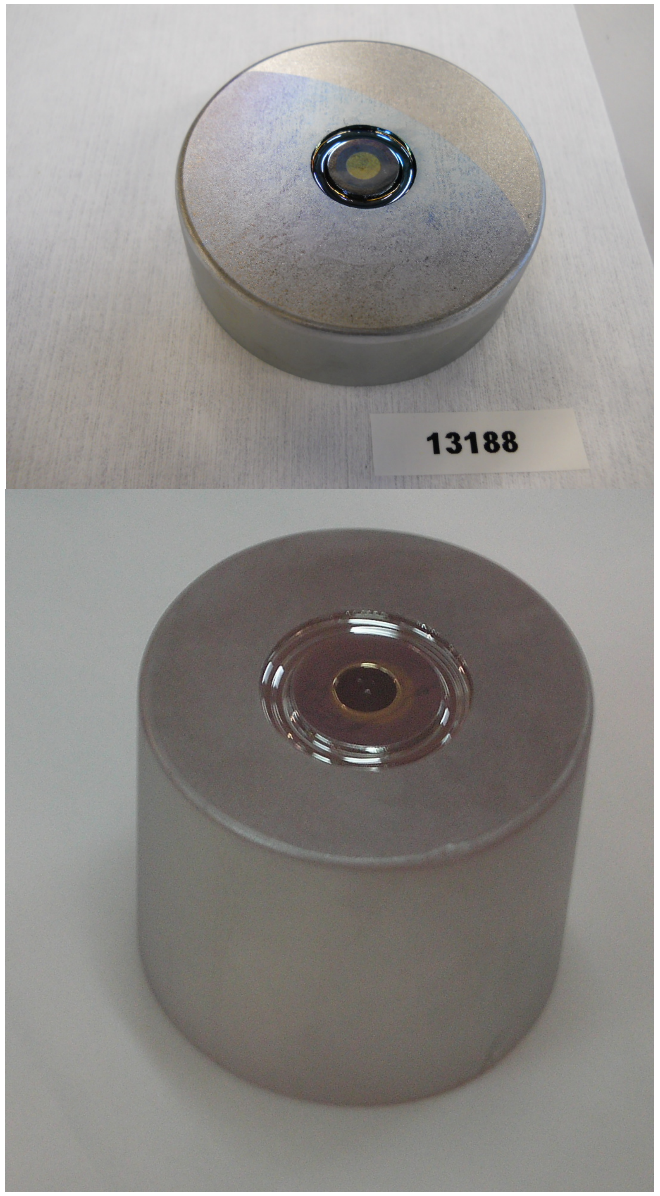
COLLABORATION MEETING IN ZURICH, JUNE 2019

# 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)

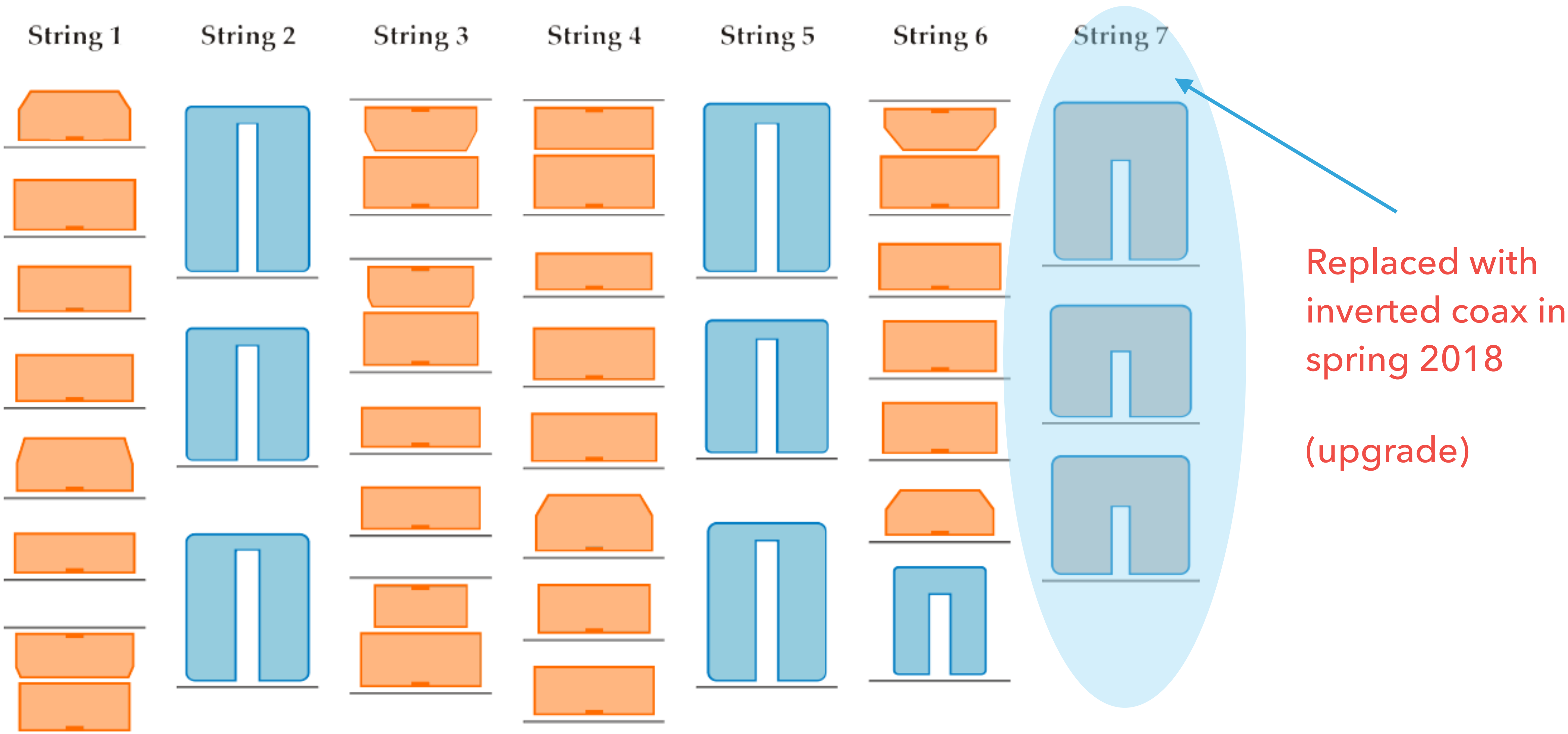




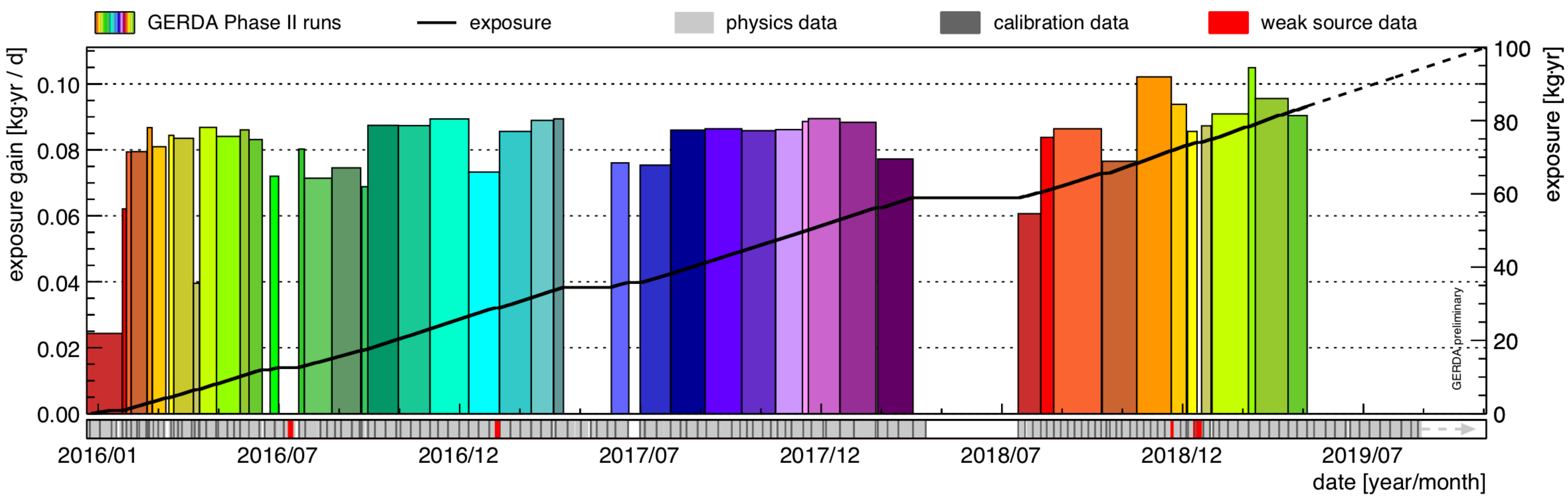
# GERDA PHASE-II DETECTORS

- 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

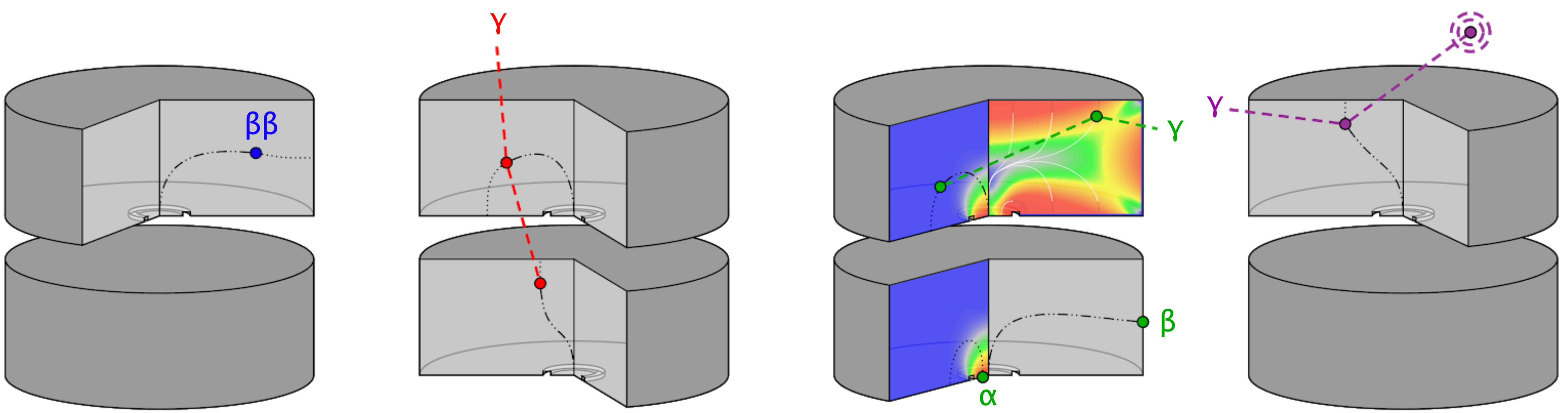
24.9 kg y in May 2019 blind

58.9 kg y unblind

# BACKGROUND SUPPRESSION

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

event topology | detector anti-coincidence | pulse shape discrimination (PSD) | detector-LAr anti-coincidence (LAr veto)




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

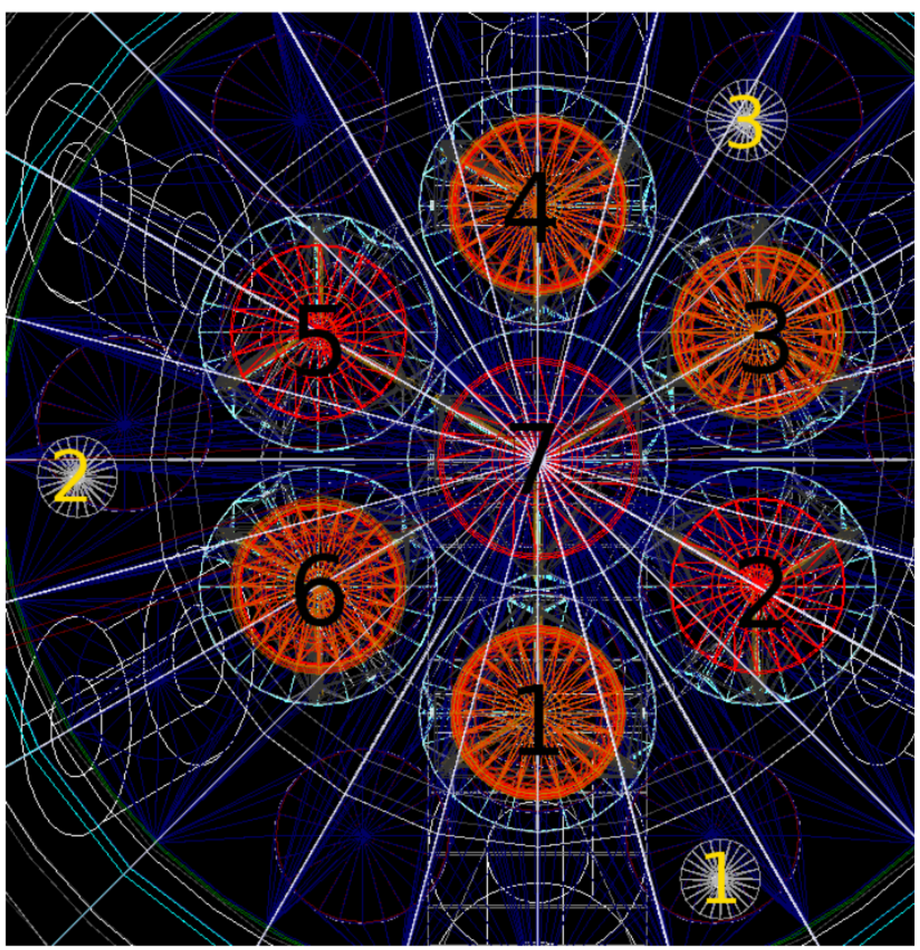
**multi-detector** interactions

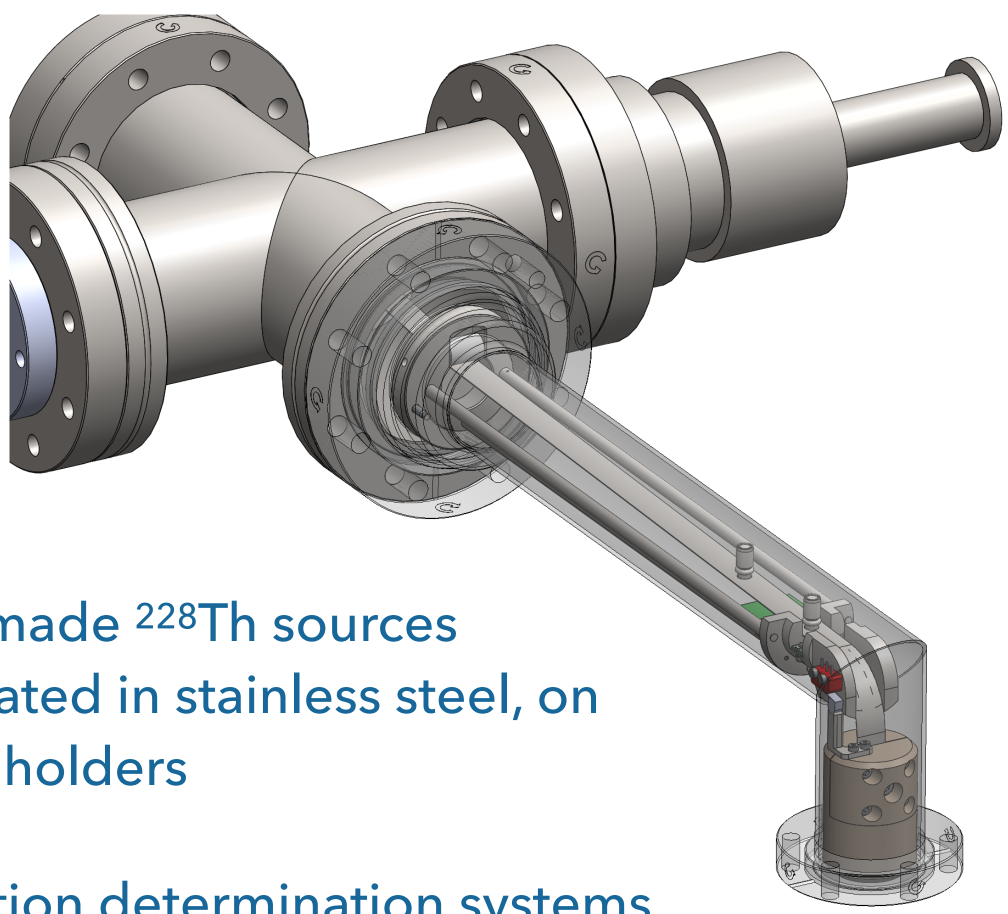
**multi-site/surface** interactions

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



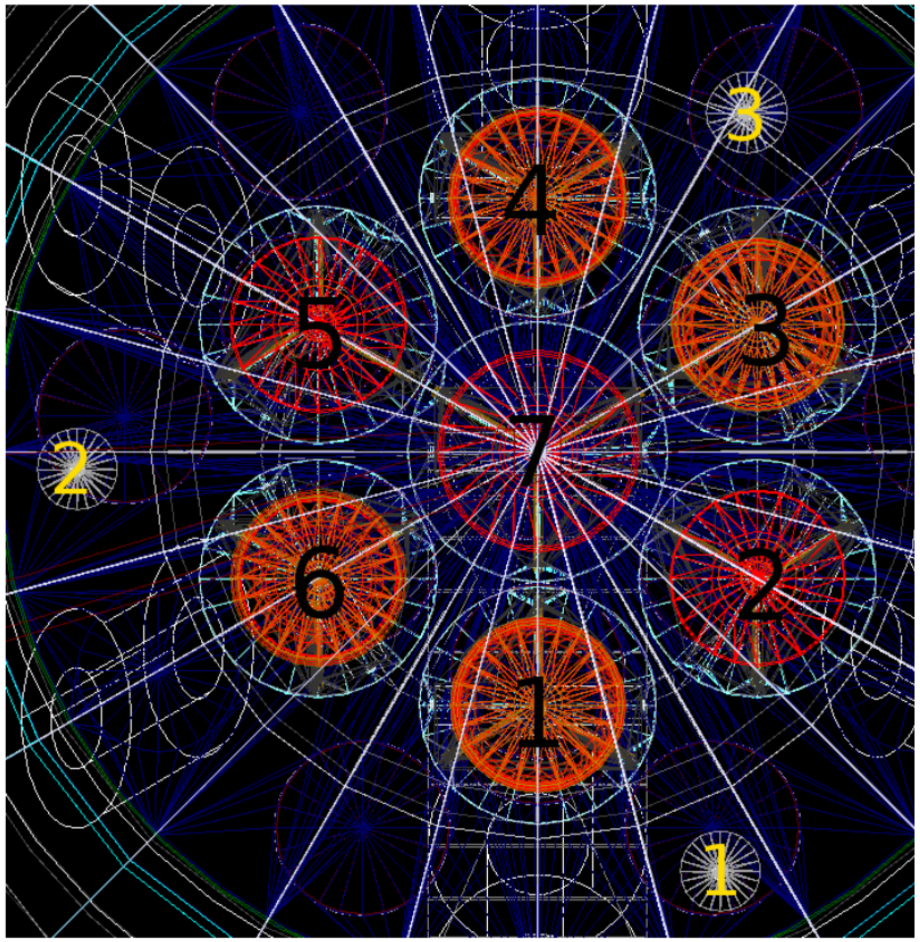
Custom-made $^{228}$Th sources encapsulated in stainless steel, on tantalum holders

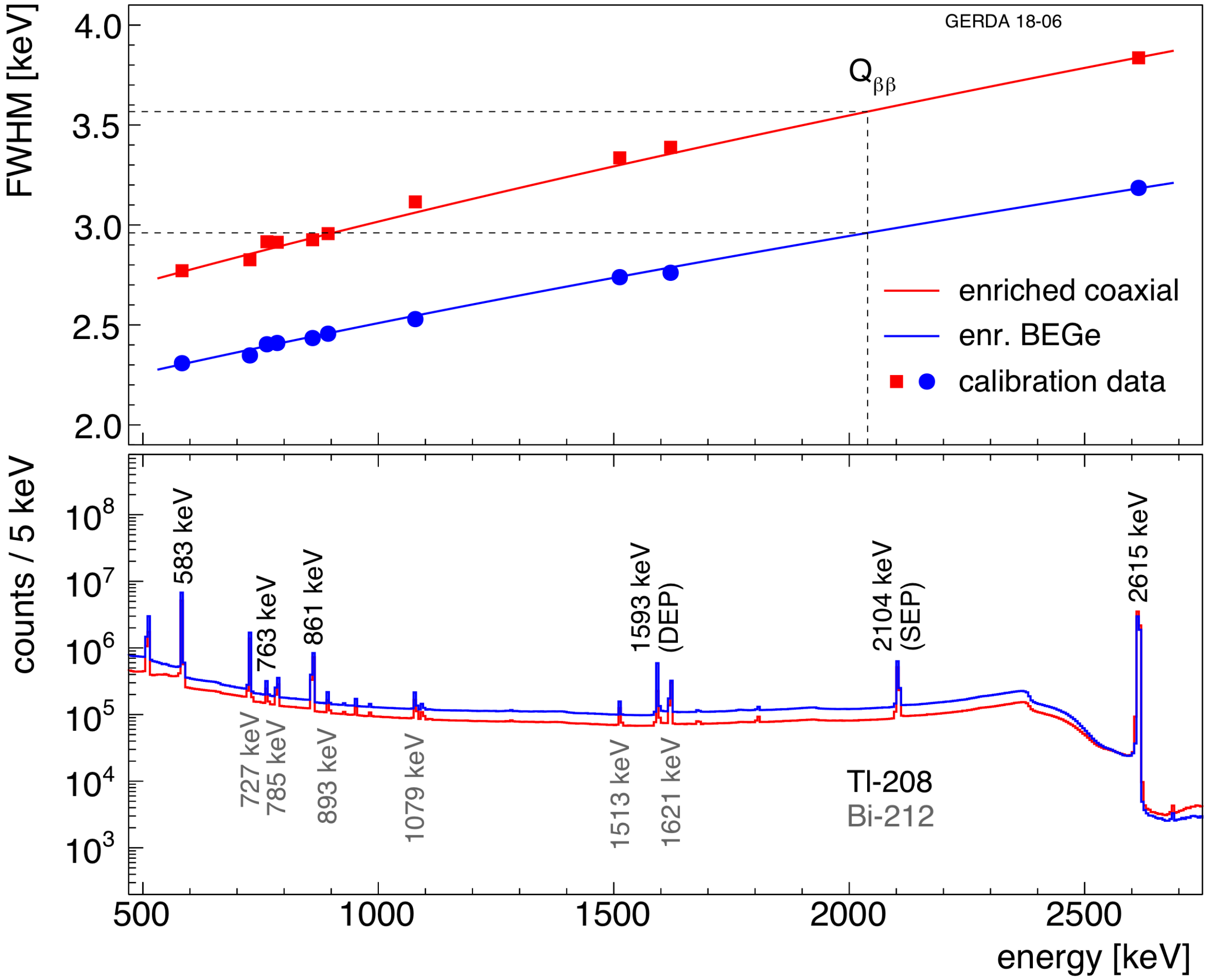
Two position determination systems

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

# ENERGY CALIBRATION

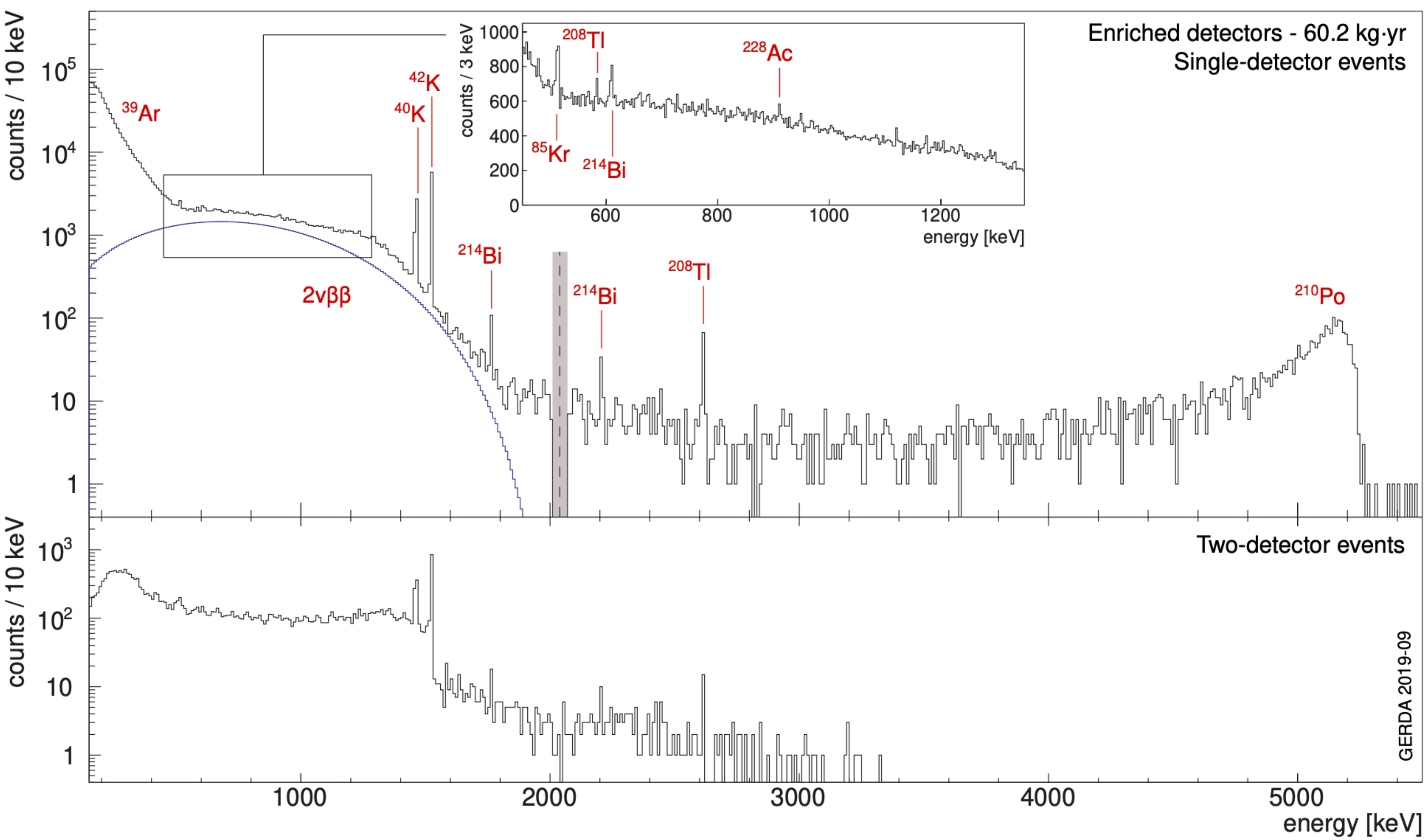
- Three low neutron-emission $^{228}$Th sources in SIS, deployed once every week
- FWHM at $Q_{\beta\beta}$: (3.0 ± 0.1) keV for BEGe, (3.6 ± 0.1) keV for coaxial detectors



# ENERGY SPECTRA

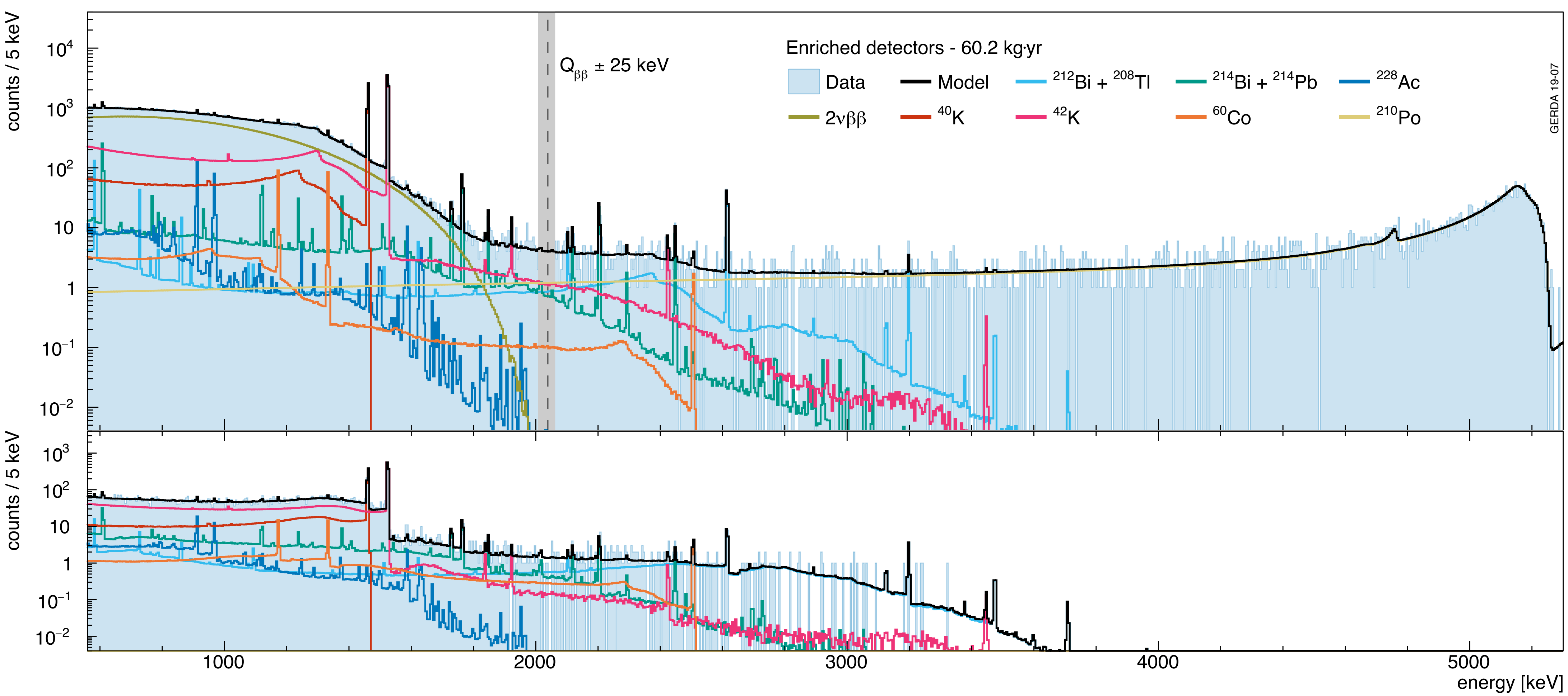
- Intrinsic 2νββ-events, $^{39}$Ar, $^{42}$Ar ($T_{1/2}$ = 33 y) and $^{85}$Kr in liquid argon
- $^{60}$Co, $^{40}$K, $^{232}$Th, $^{238}$U in materials, α-decays ($^{210}$Po) on the thin p⁺ contact




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

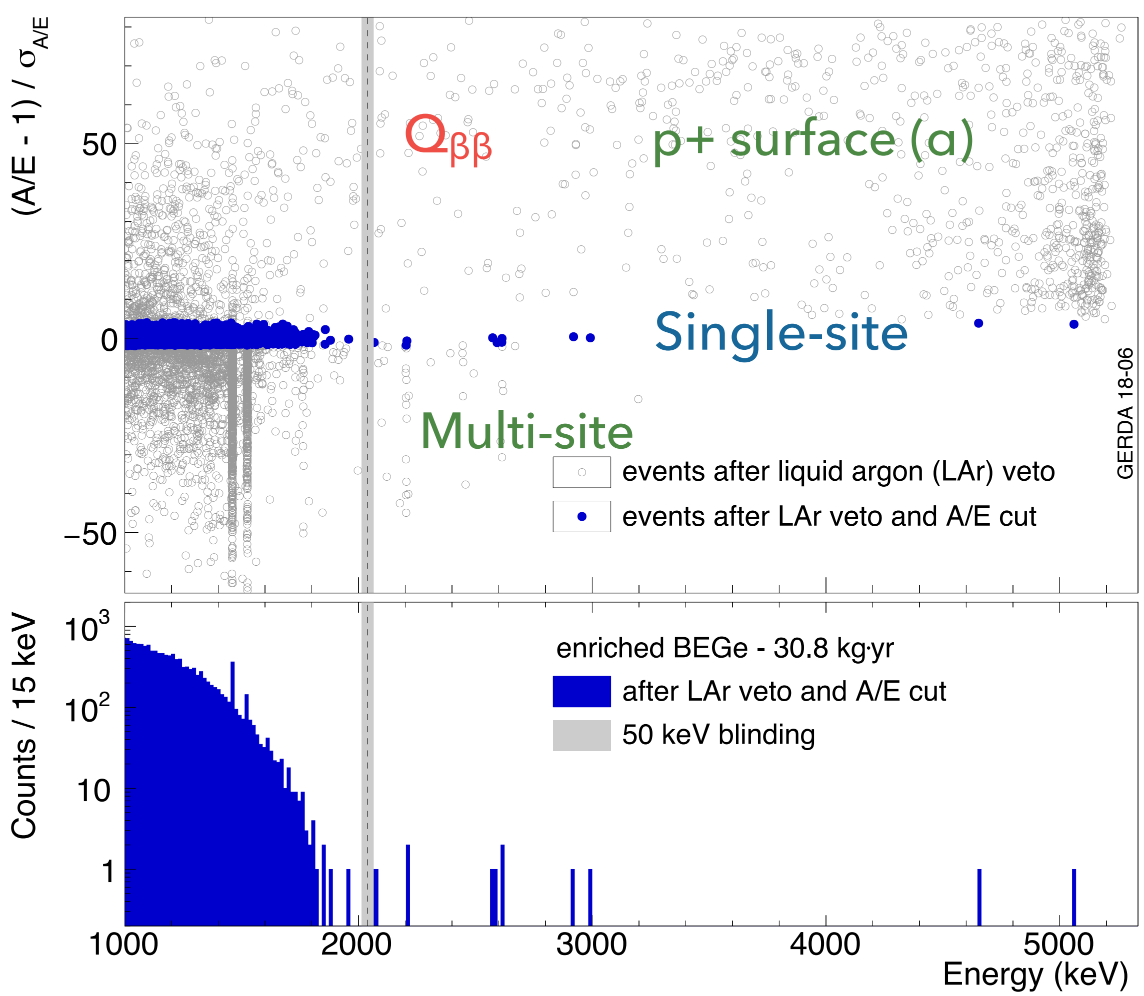


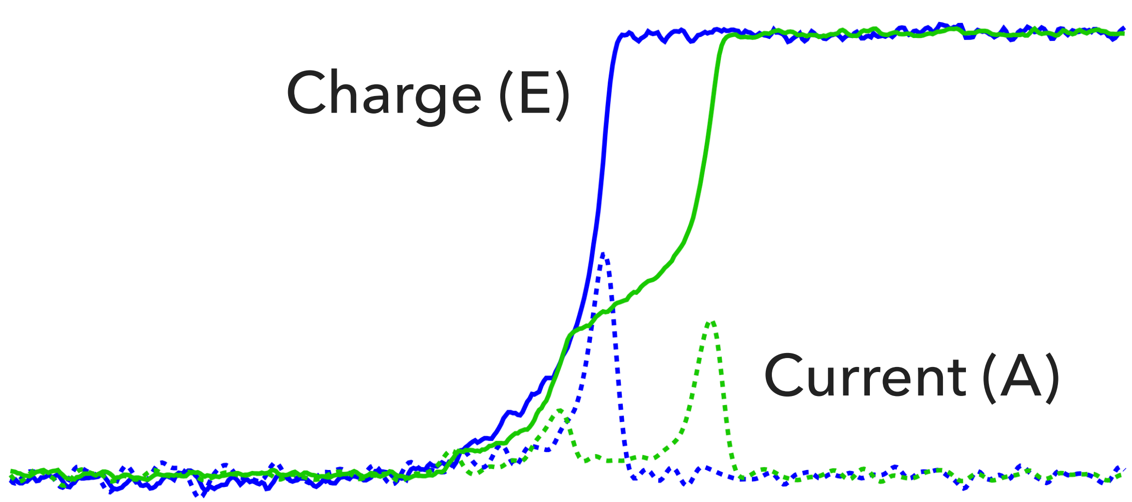

GERDA collaboration, arXiv:1909.02522

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

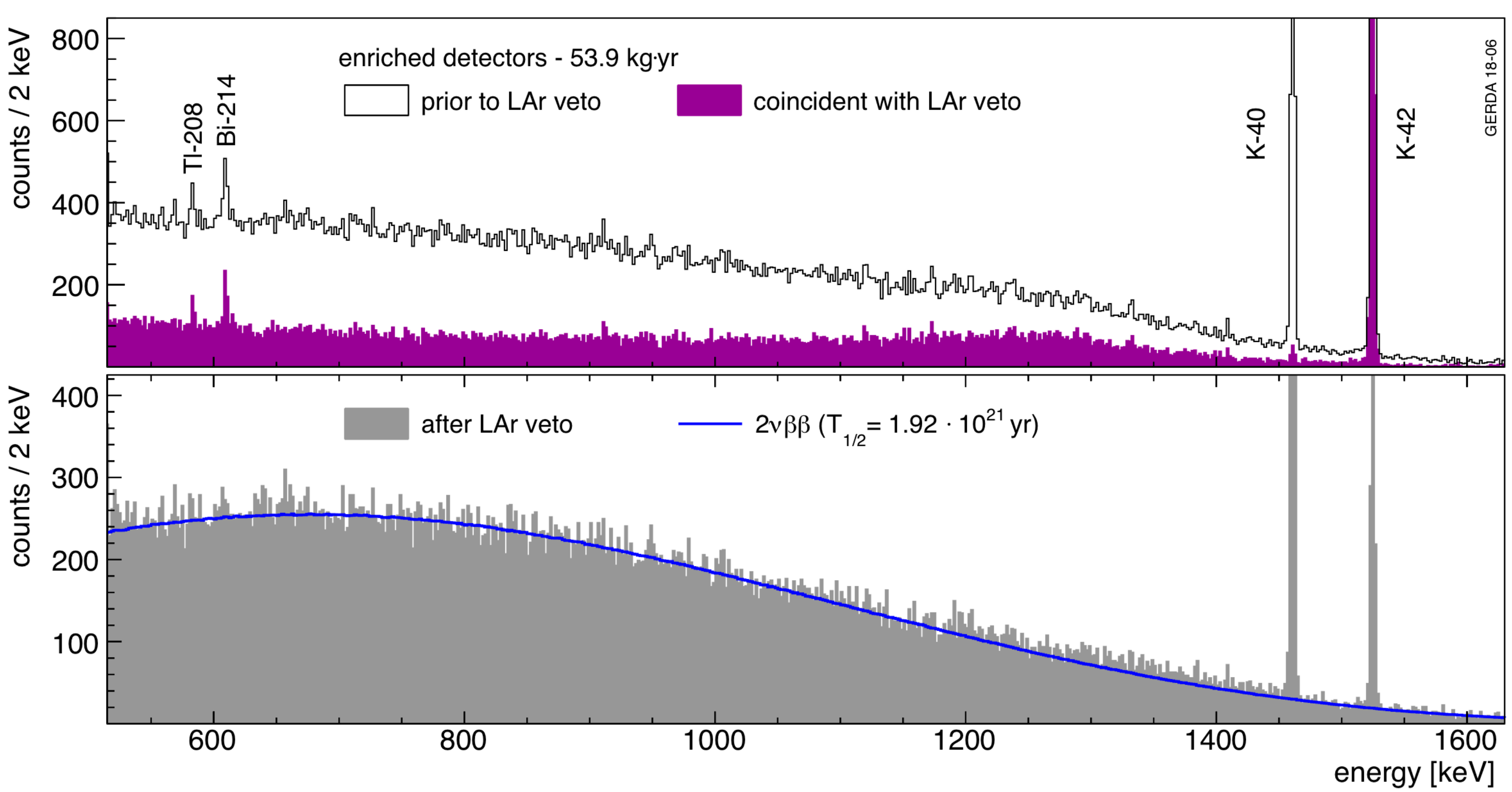
Mean and resolution corrected for E-dependance

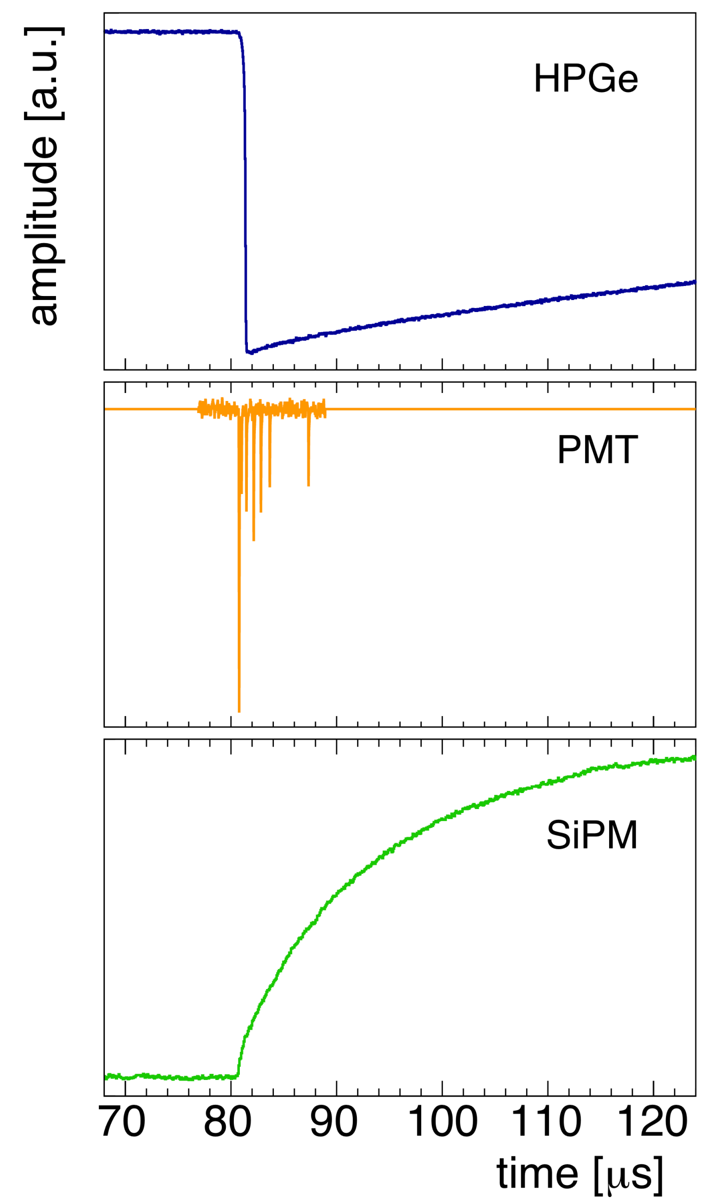
A/E normalised to 1

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

# LIQUID ARGON VETO

- Anti-coincidence with signals in PMTs and SiPMs (0.5 p.e. threshold)
- Acceptance at 0νββ: (97.7±0.1)%

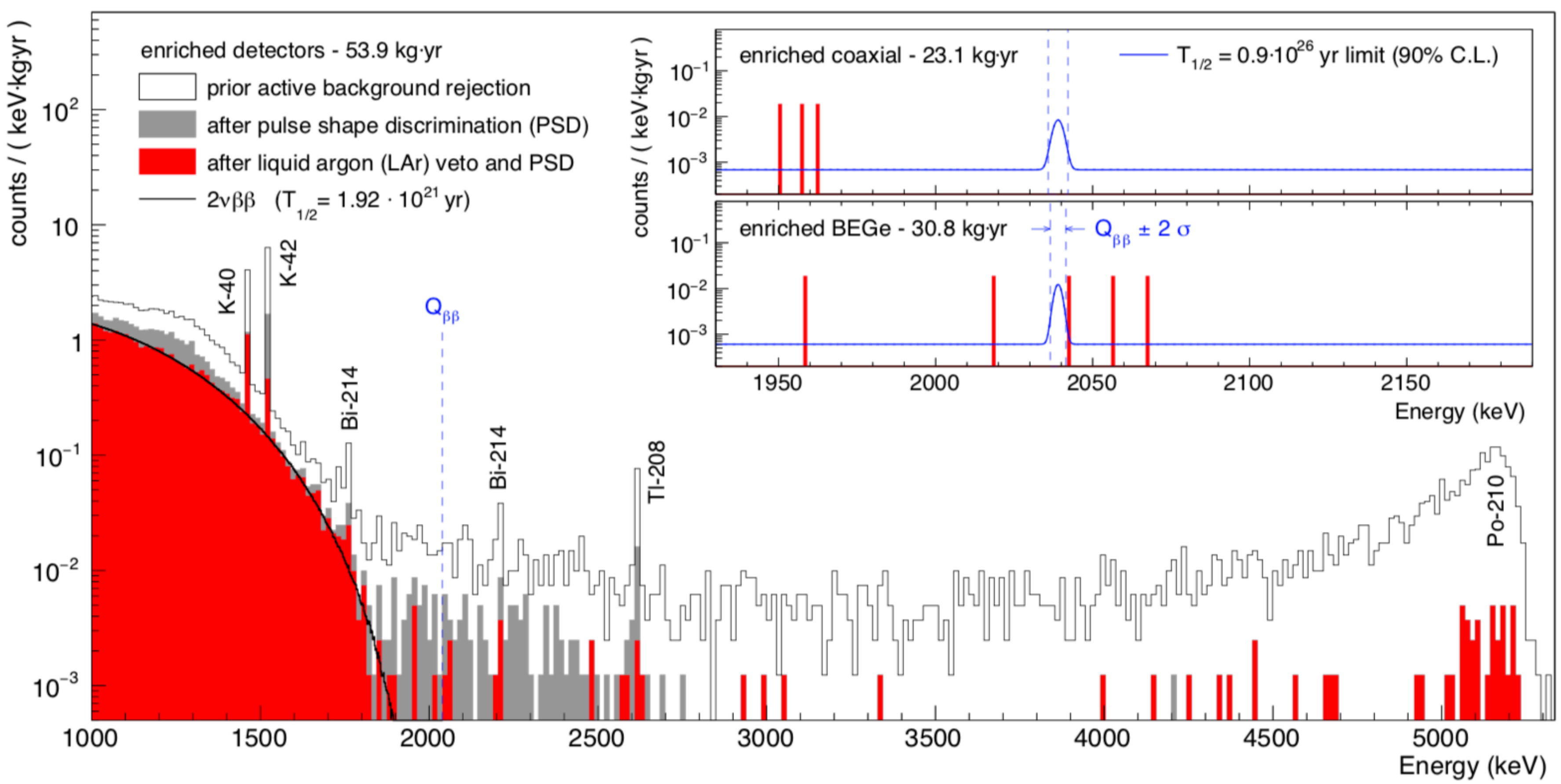


GERDA collaboration, Science 365, Sept 2019

# DOUBLE BETA DECAY RESULTS

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




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

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

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

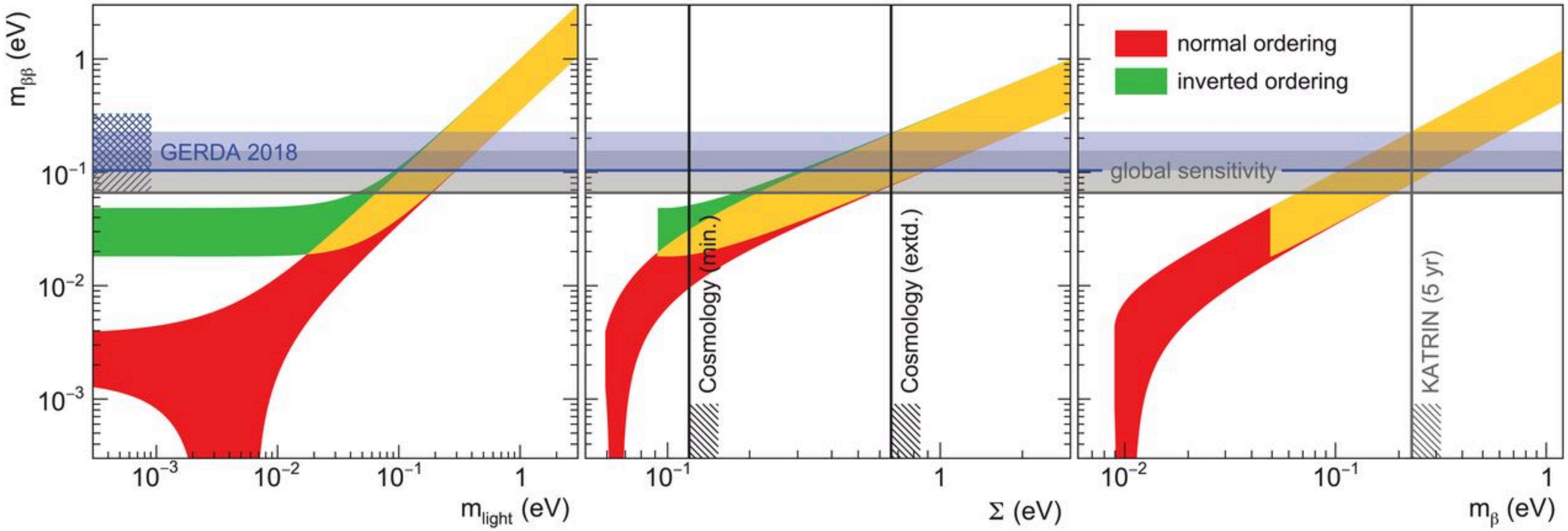
Median sensitivity

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

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



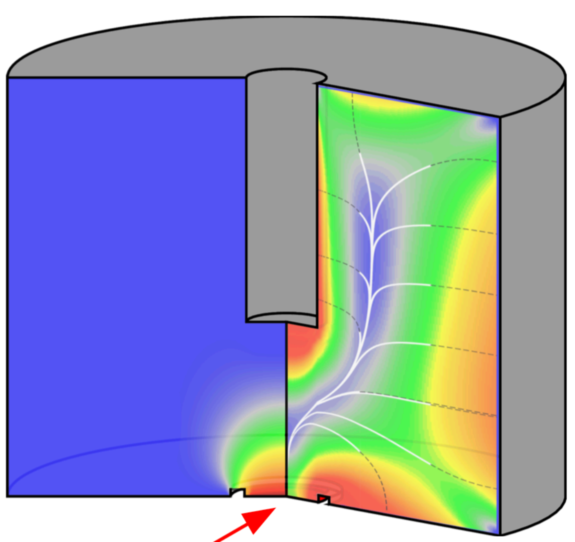

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$\Sigma = \sum_i m_i$$

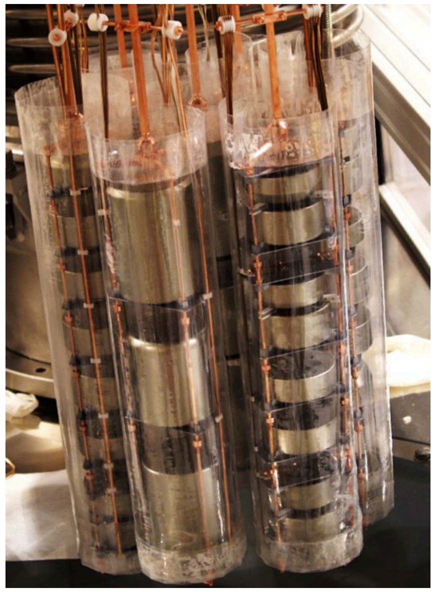
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

# UPGRADE: INVERTED COAXIAL DETECTORS

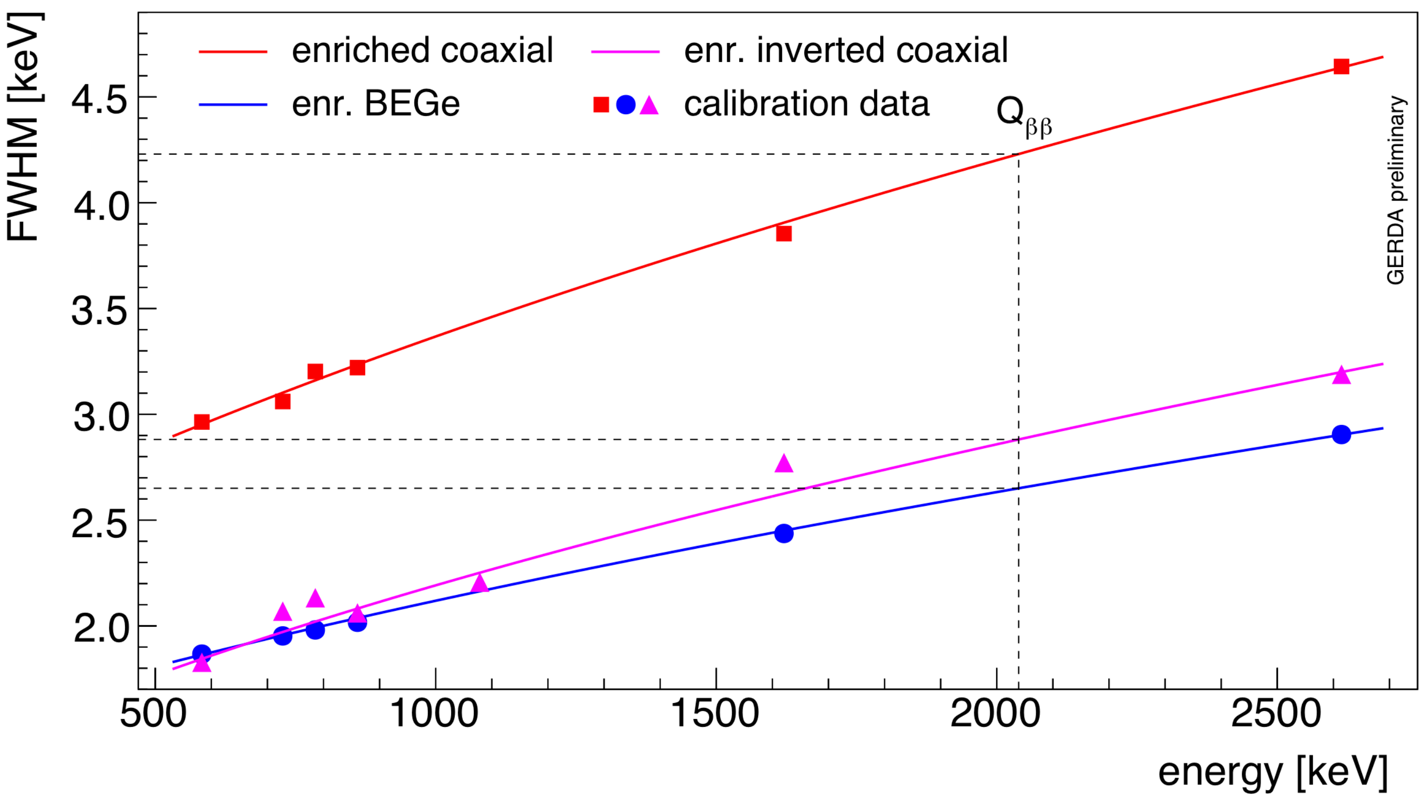
- Large point-contact detectors with ~ 3 kg mass, excellent PSD performance
- First 5 enriched IC detectors installed in spring 2018; baseline for LEGEND




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



Detector mass increase: 35.6 kg -> 44.2 kg



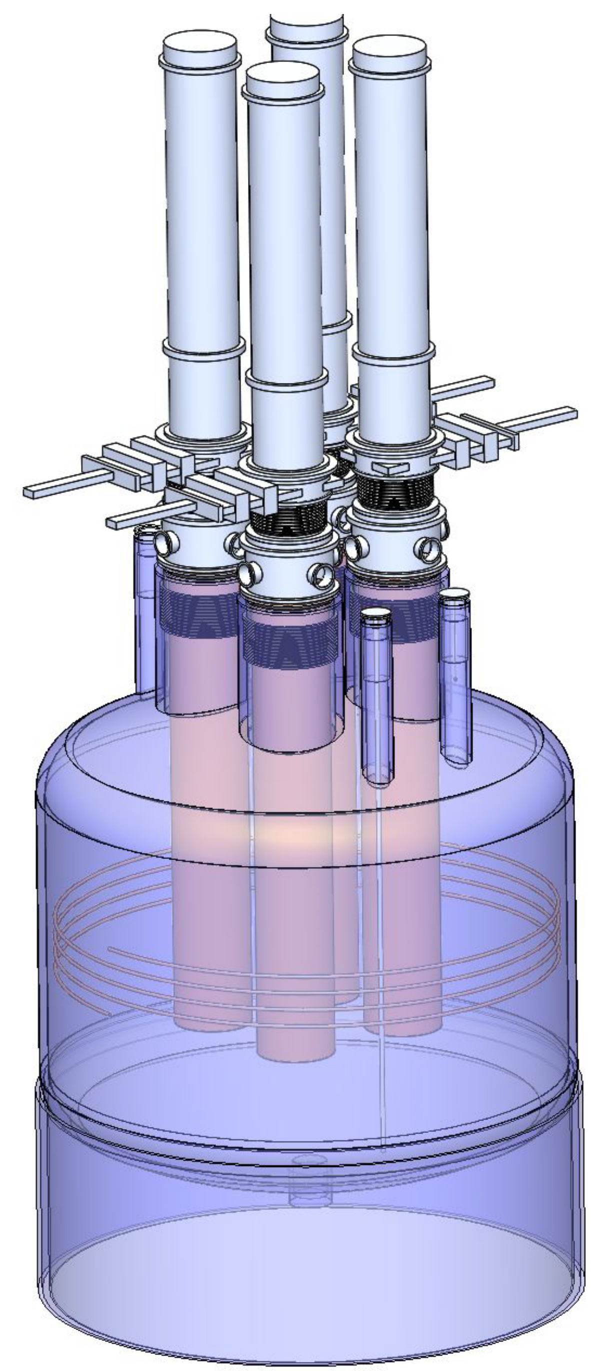

**FWHM at $Q_{\beta\beta}$ [keV]: 4.2±0.1 coax; 2.7 ± 0.1 BEGe; 2.9±0.1 IC**

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)



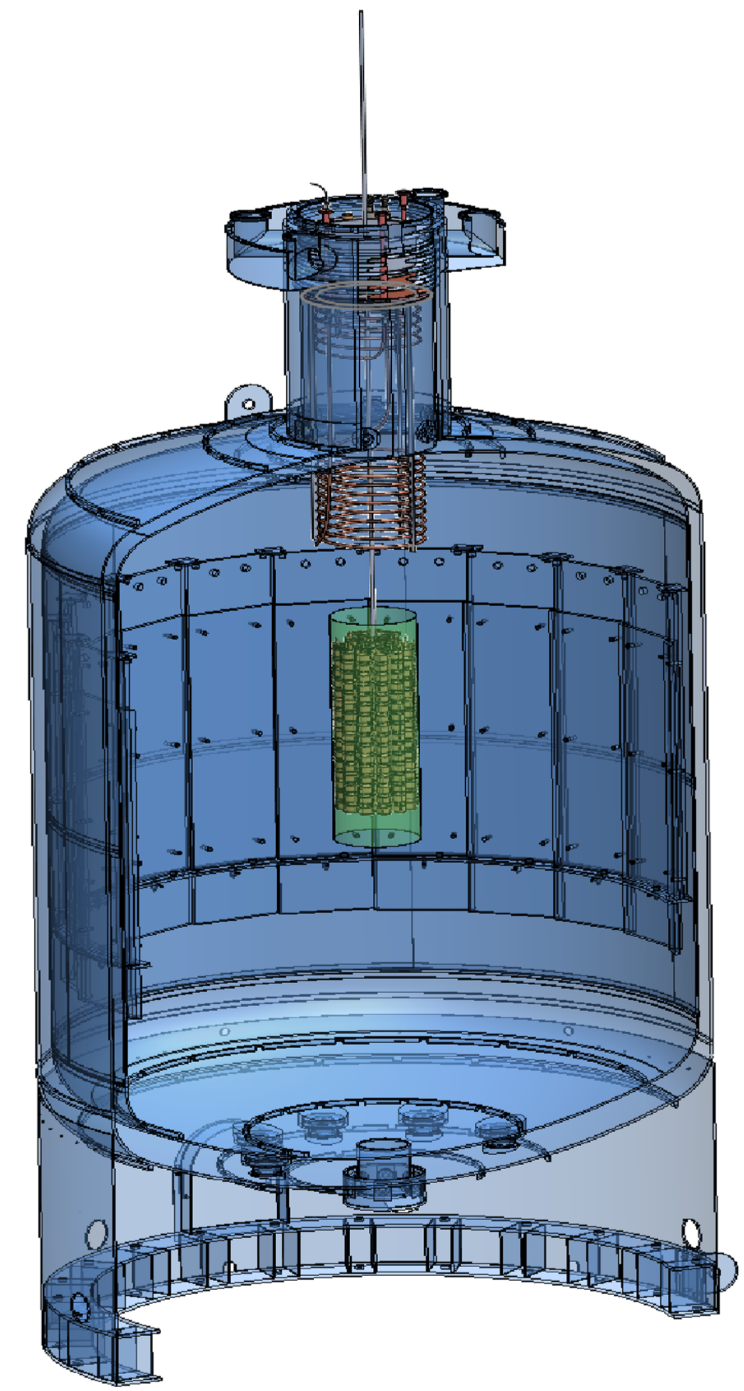
LEGEND

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:

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

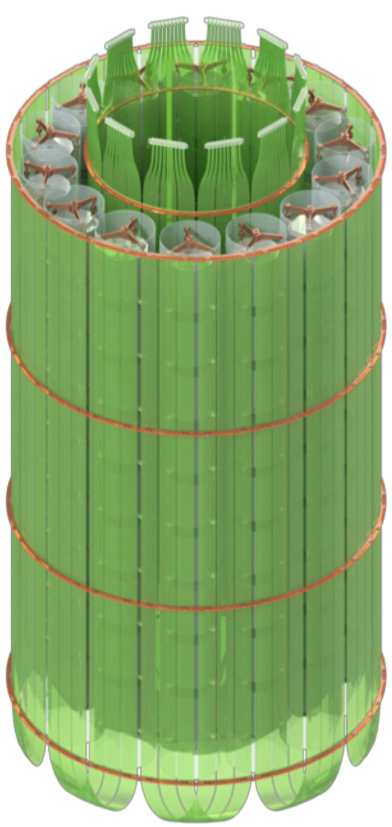


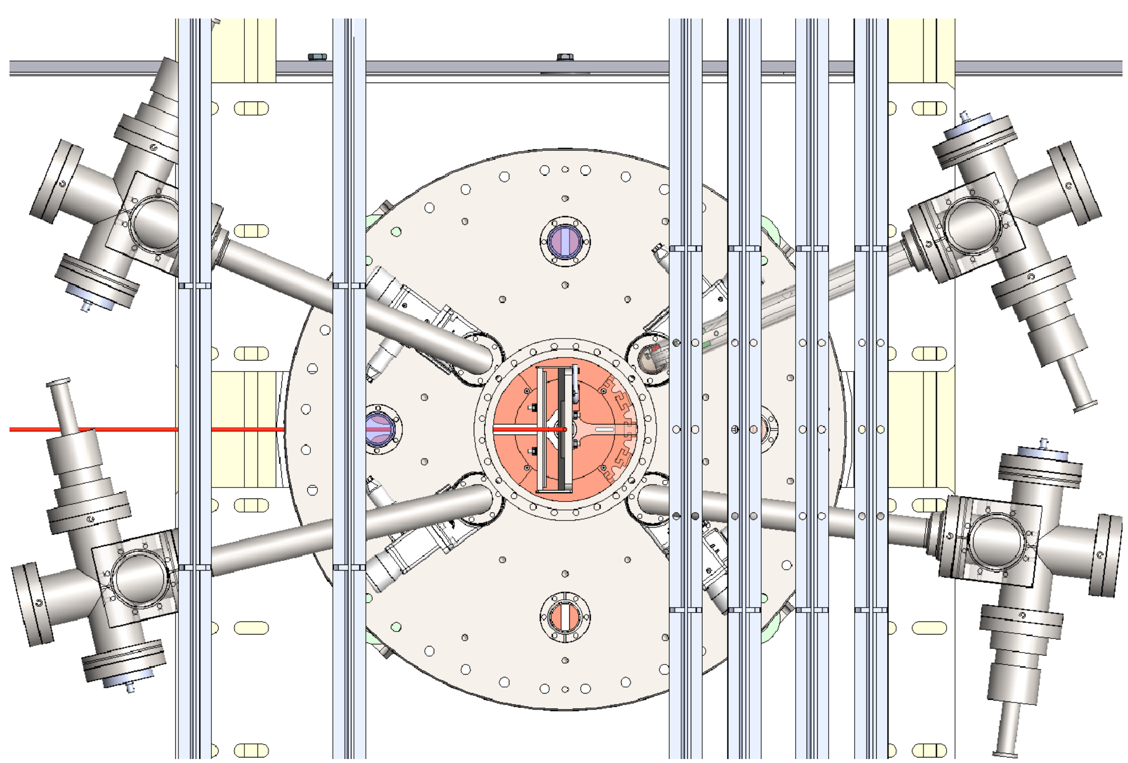
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

# LEGEND-200

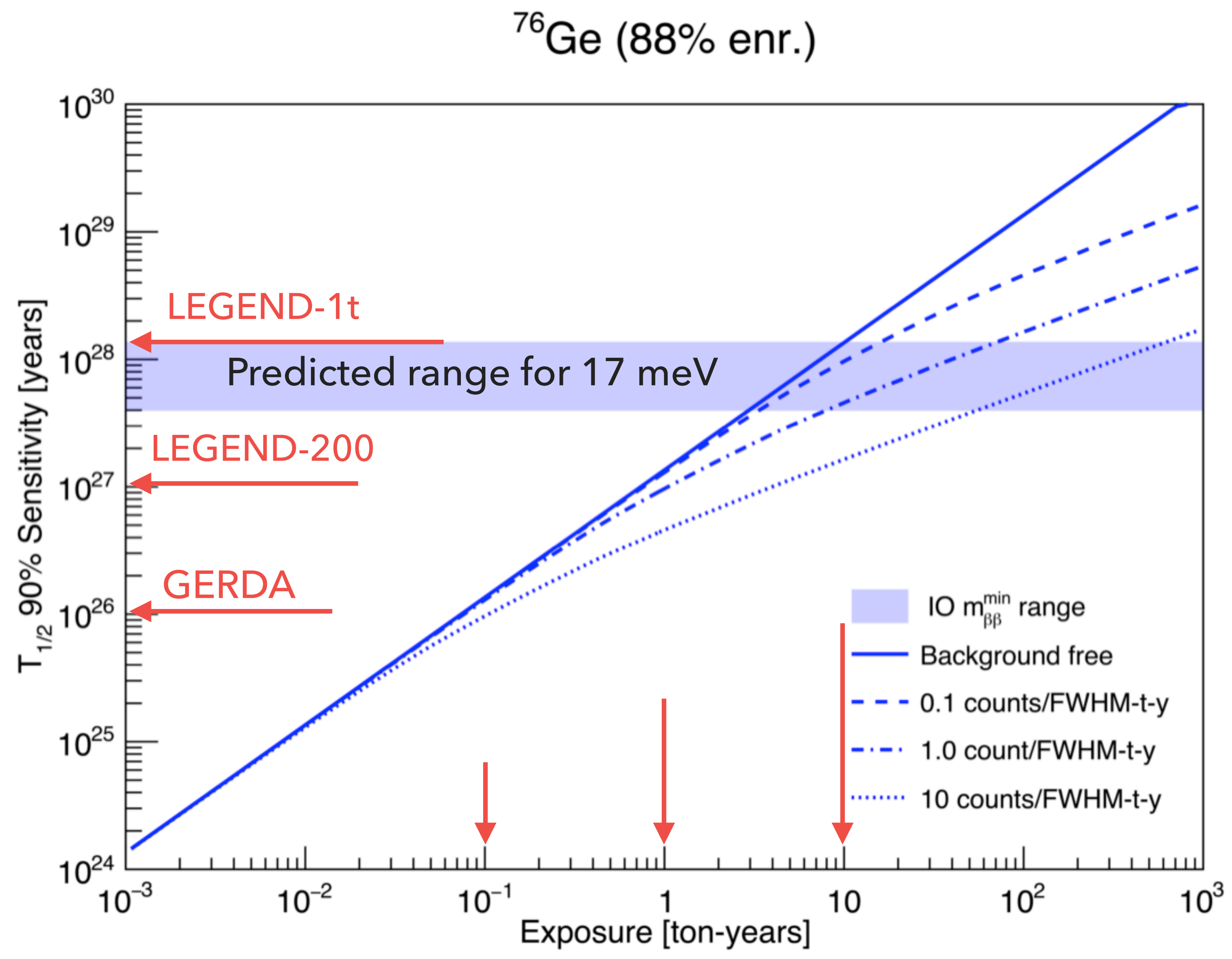
- Existing GERDA infrastructure sufficient (800 mm cryostat neck)
- New lock system, new cabling & feedthroughs
- 19 string, 4 calibration systems with multiple $^{228}$Th sources





# EXPECTED SENSITIVITY

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

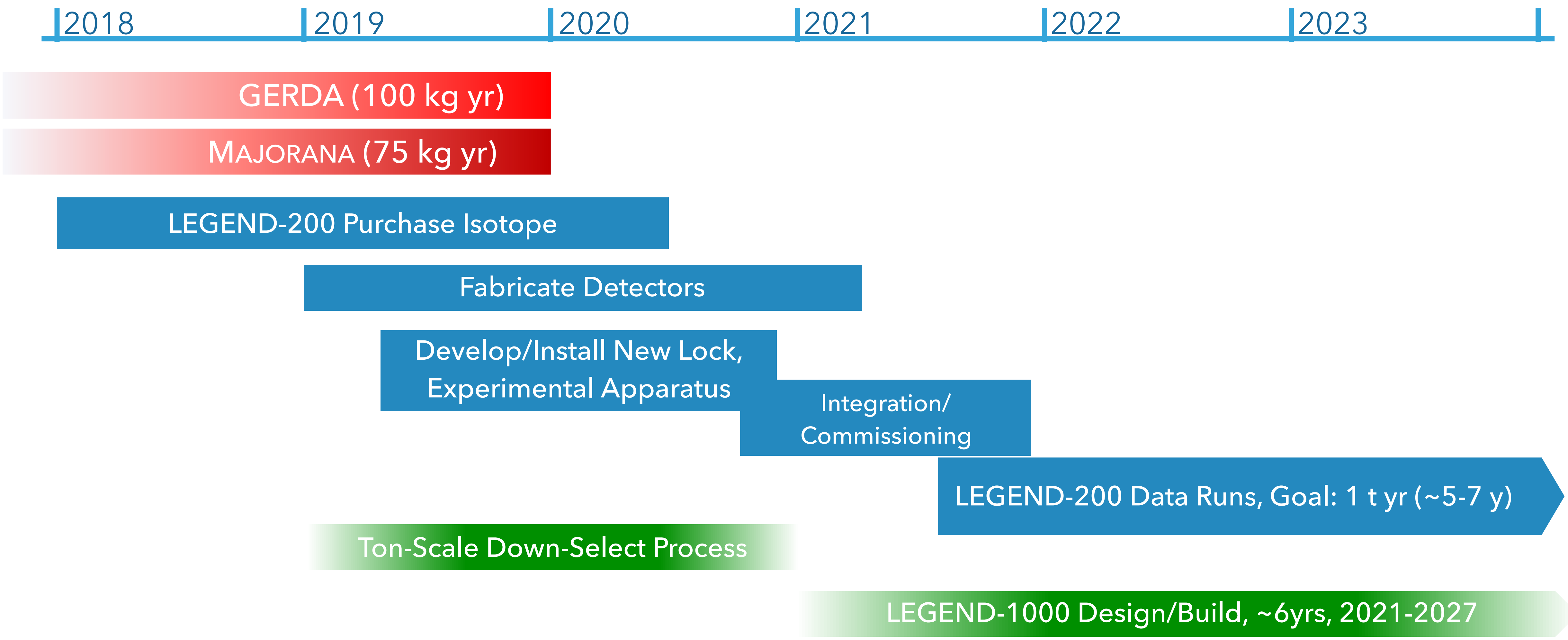



Background

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)

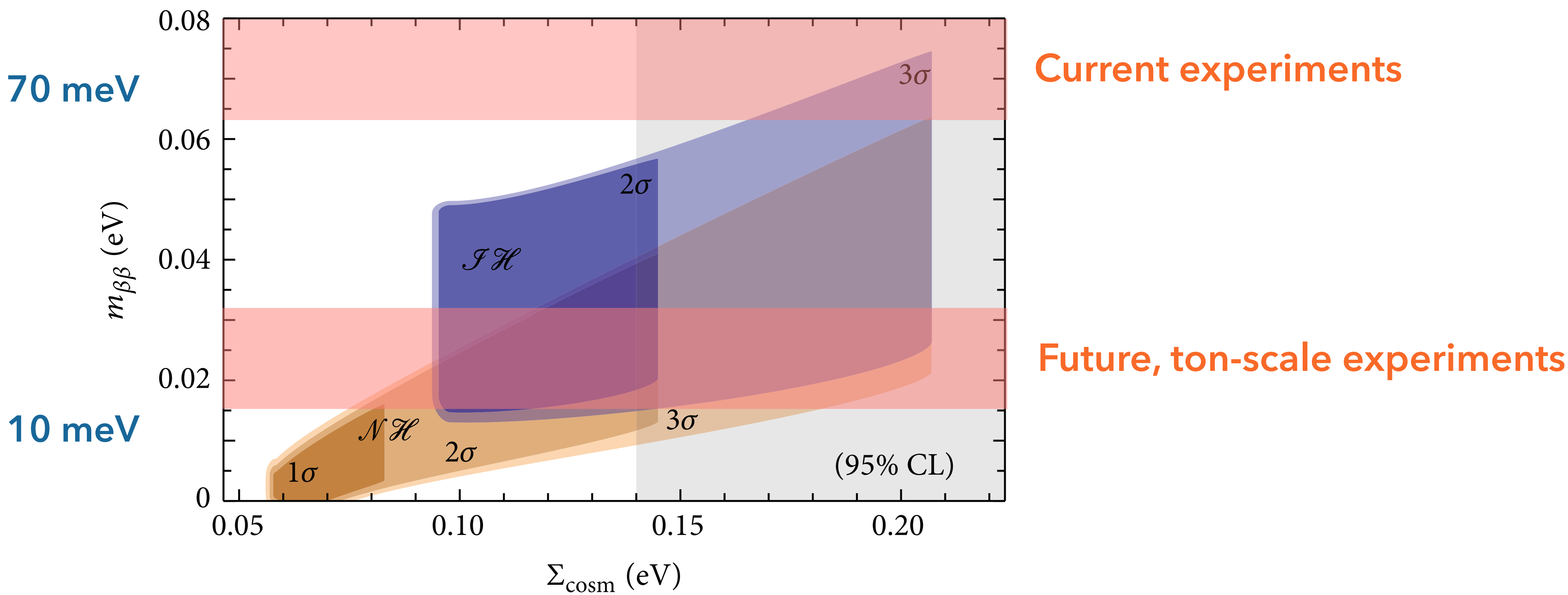
# TIME SCALE




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

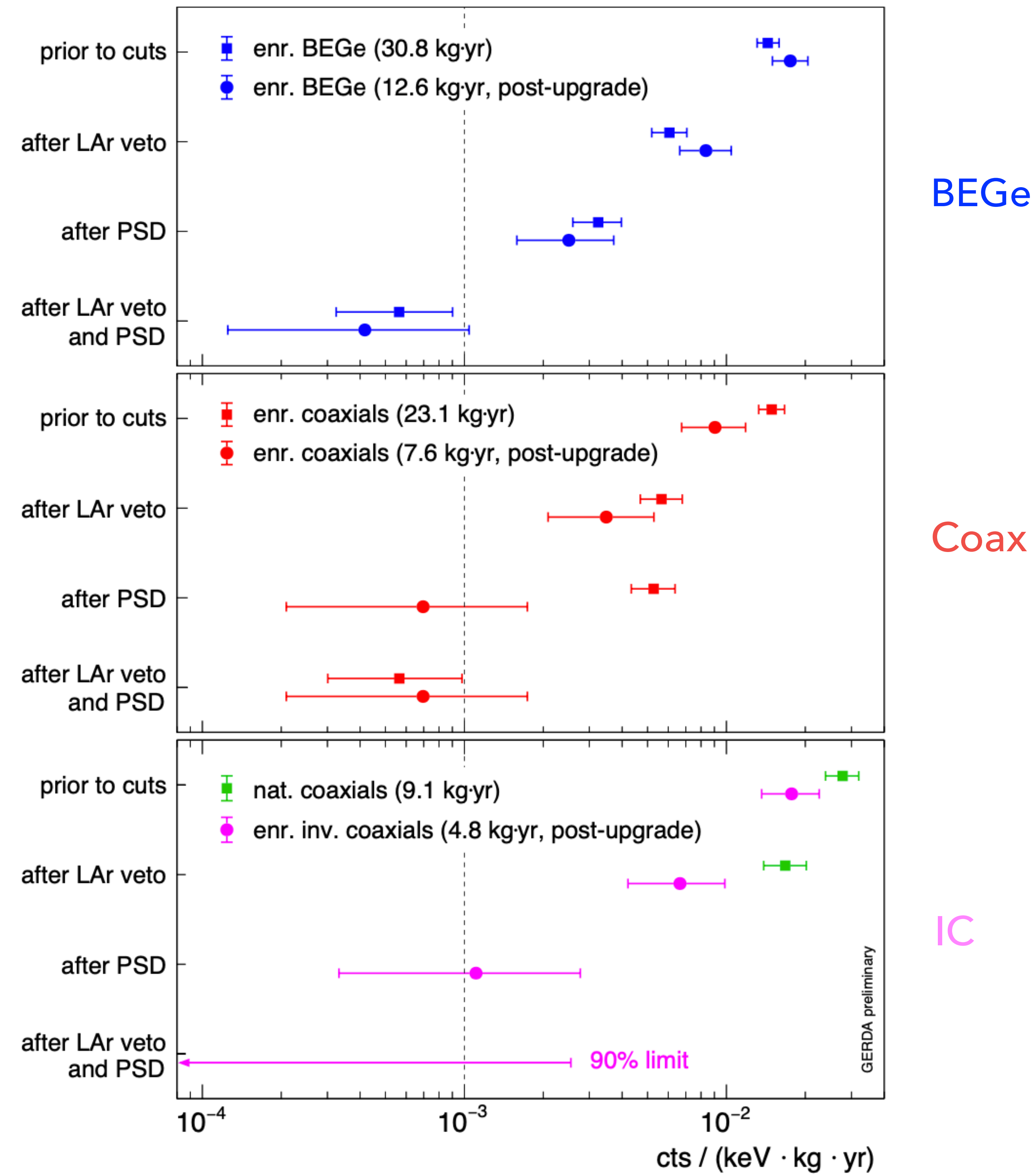
# GERDA AND OTHER EXPERIMENTS

**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

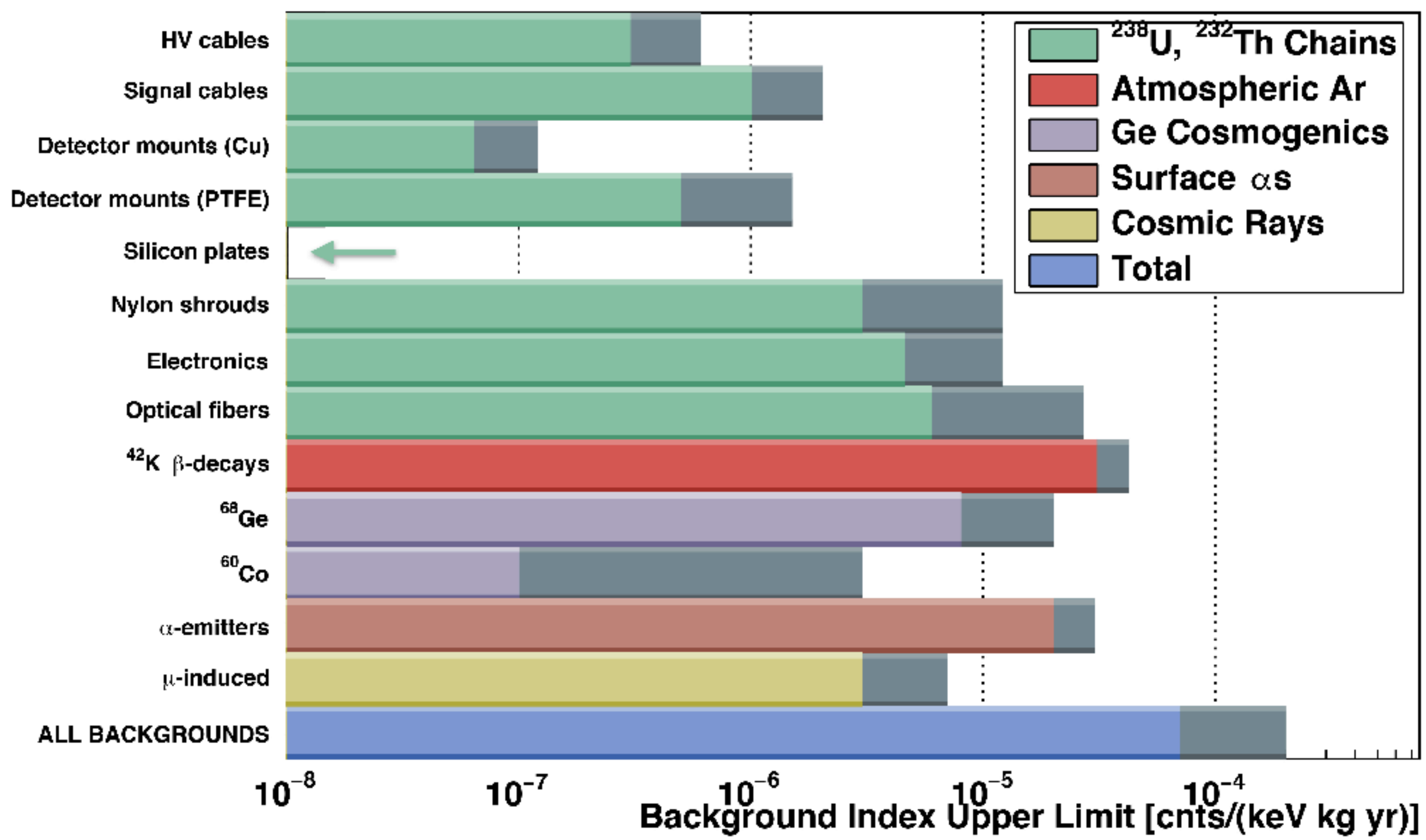
- Background levels in the 3 detector types before & after various cuts



# 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

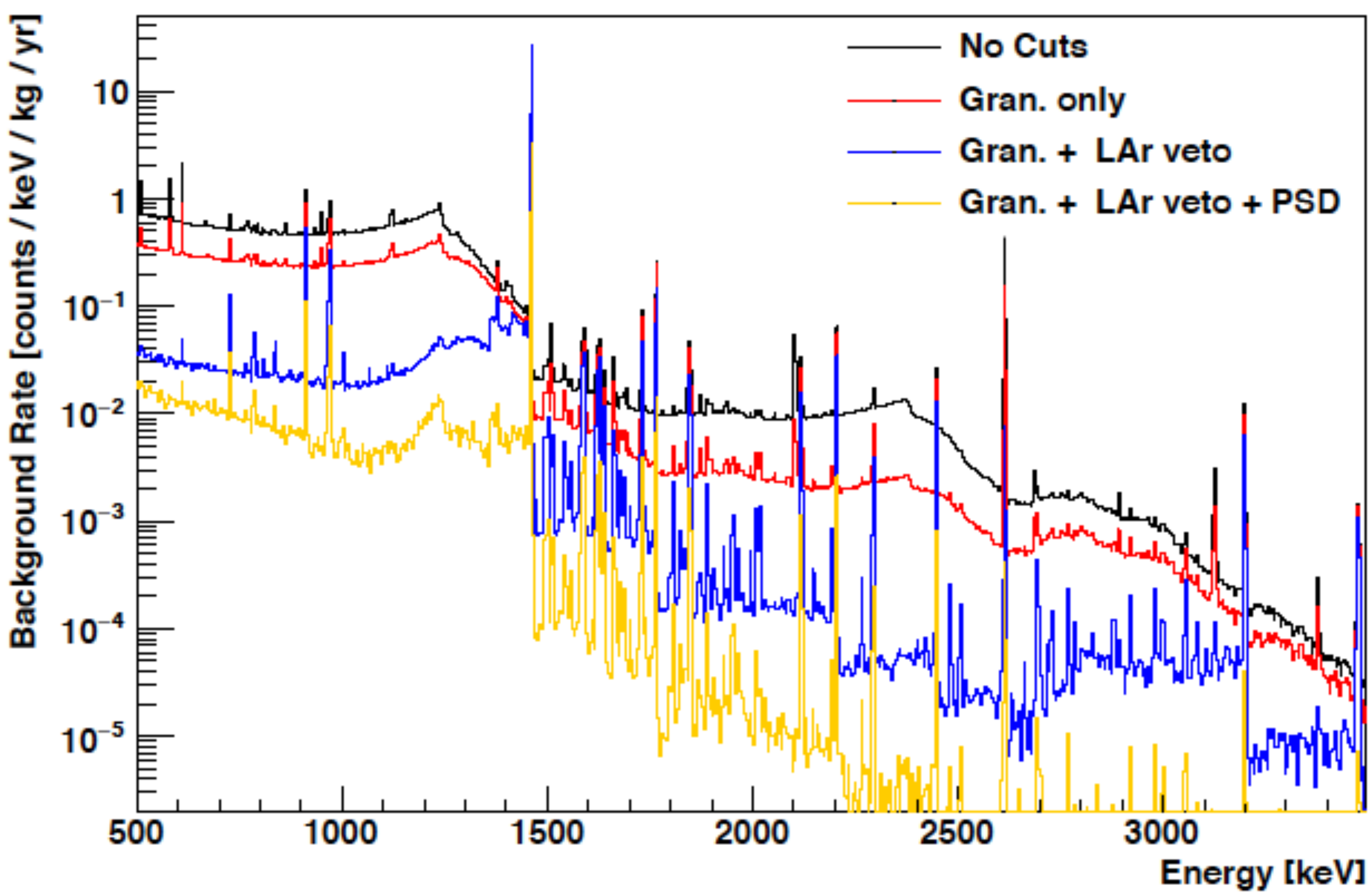



Monte Carlo simulations based on experimental data and material assays. Background rate after anti-coin., PSD, LAr veto cuts.

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.)x$10^{-4}$ events/(keV kg yr) = 0.2-0.5 events/(FWHM t yr)

# BACKGROUND EXPECTATION

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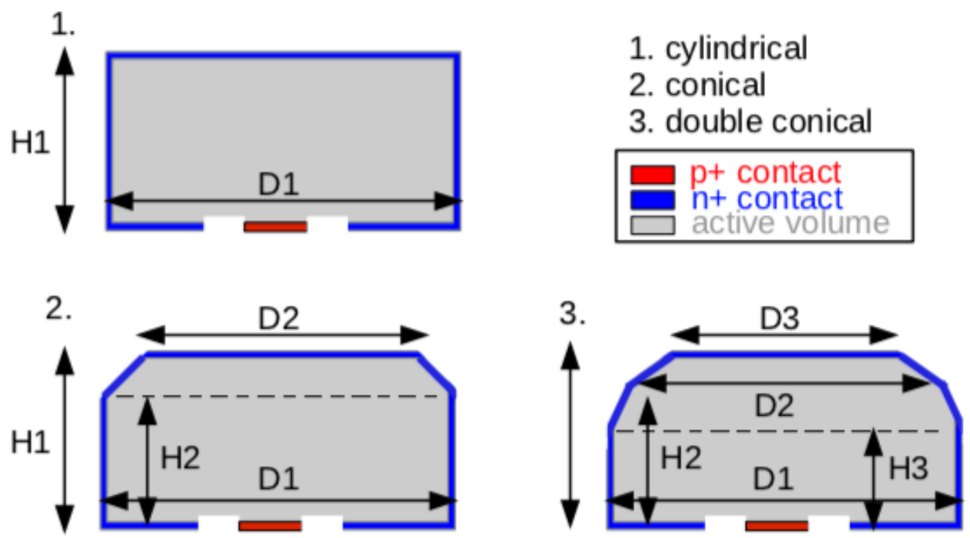
$Q_{\beta\beta}$ BI ≤ (0.7–2.)x$10^{-4}$ events/(keV kg yr) = 0.2-0.5 events/(FWHM t yr)

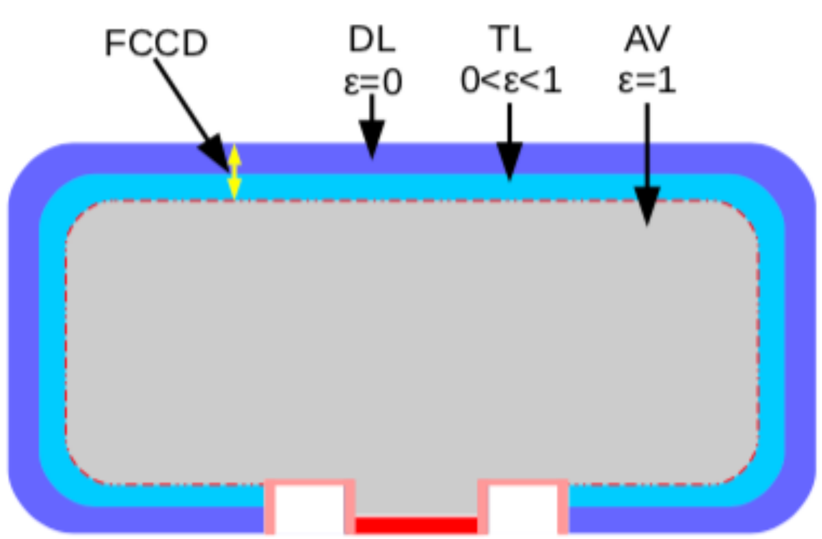
# BACKGROUND GOAL

- LEGEND-200 background: ~ equal contributions of U/Th, $^{42}Ar$, surface $\alpha$ 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 $\alpha$: 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

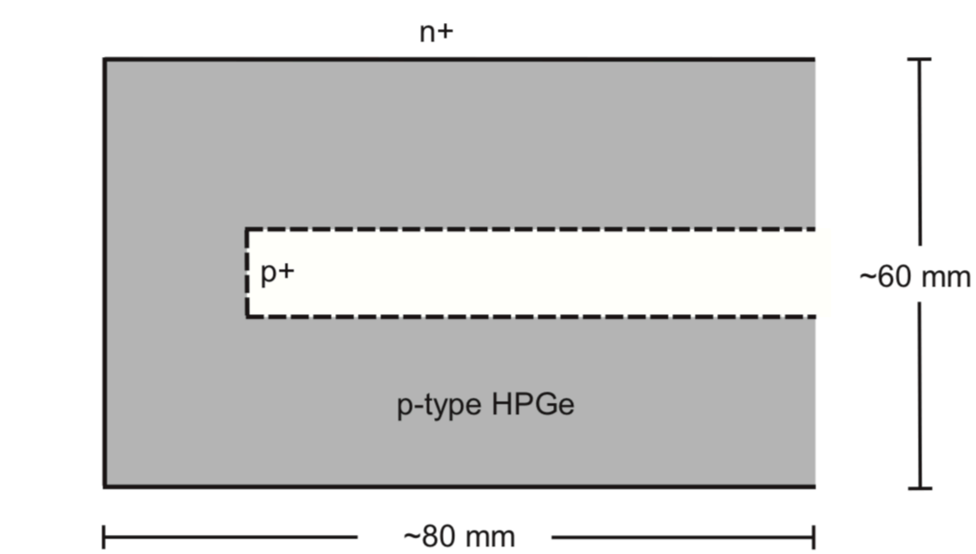
## BEGe detectors

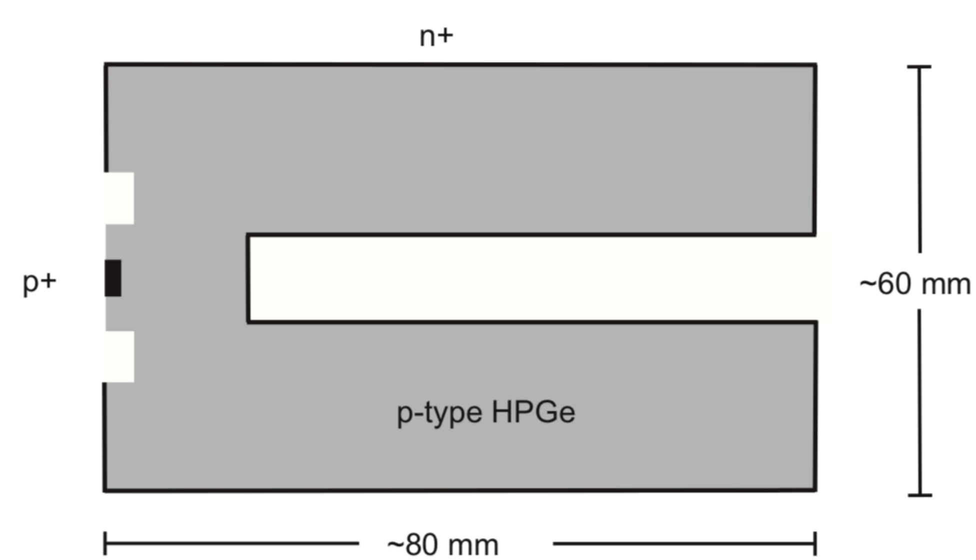



GERDA collaboration, arXiv:1901.0650

## IC detectors

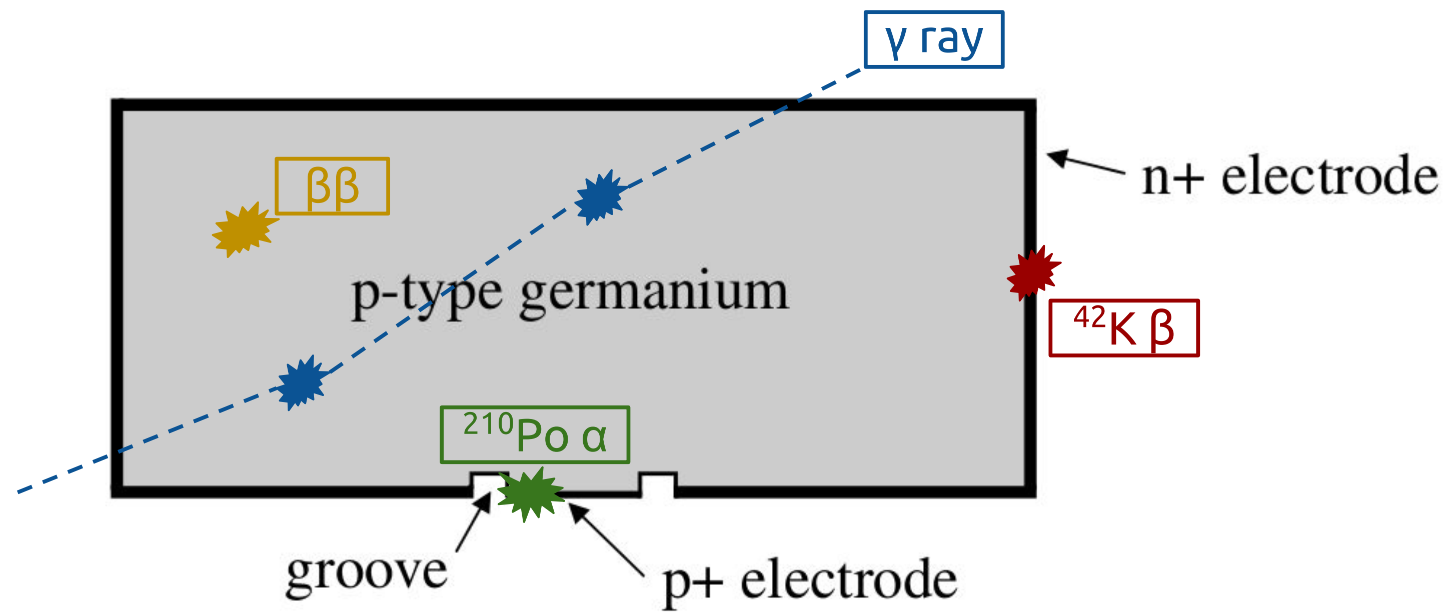


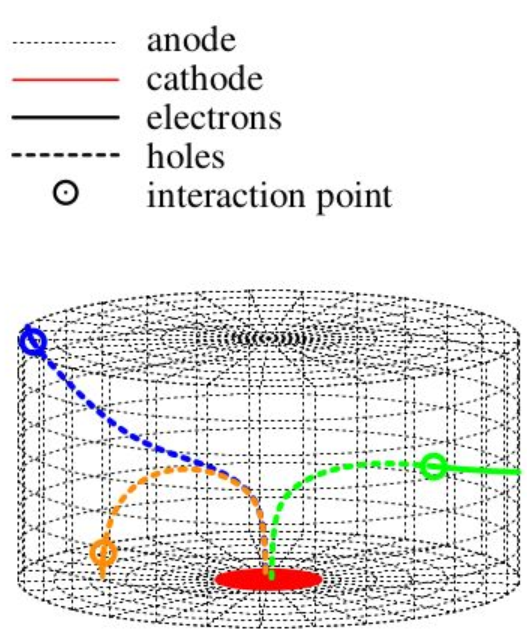



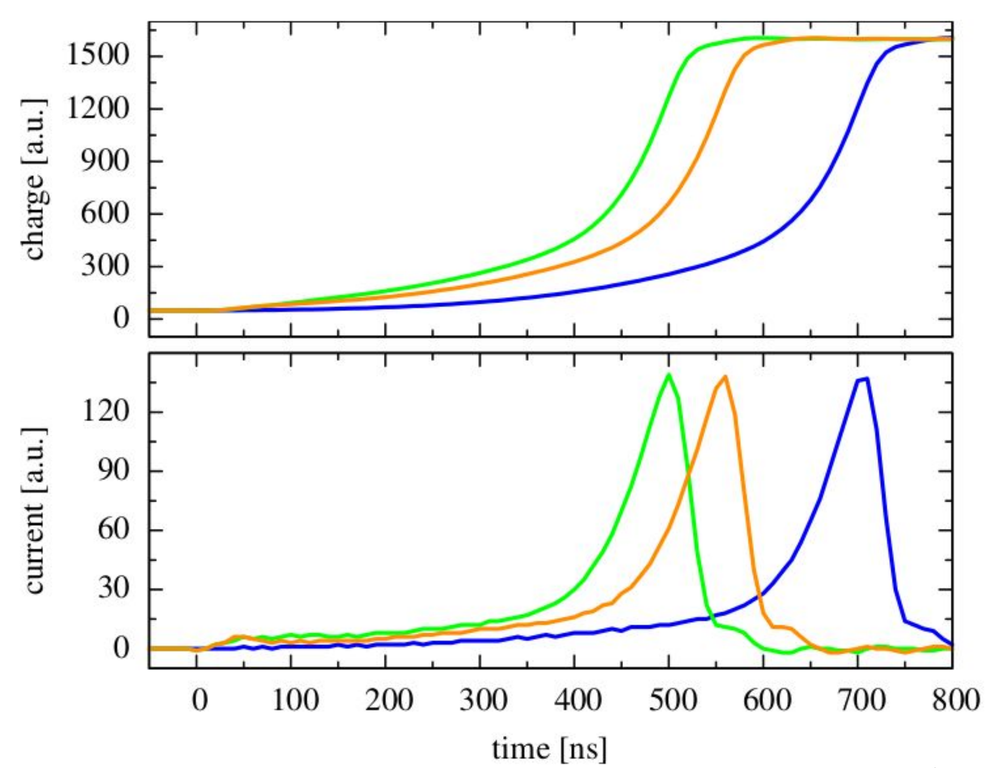

R.J. Cooper et al., NIM A 665 (2011) 25-32

# 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

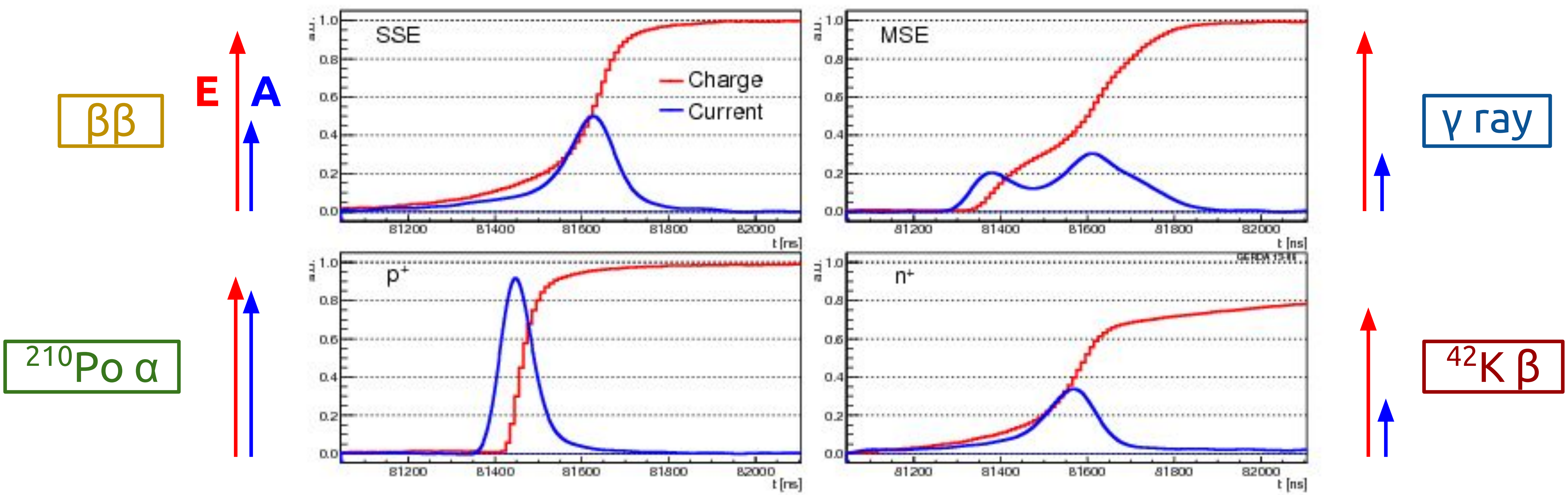


# GERDA PULSE SHAPE DISCRIMINATION

- 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
-