ELUCIDATING THE NATURE OF NEUTRINOS WITH GERDA & LEGEND

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RAL PPD SEMINAR
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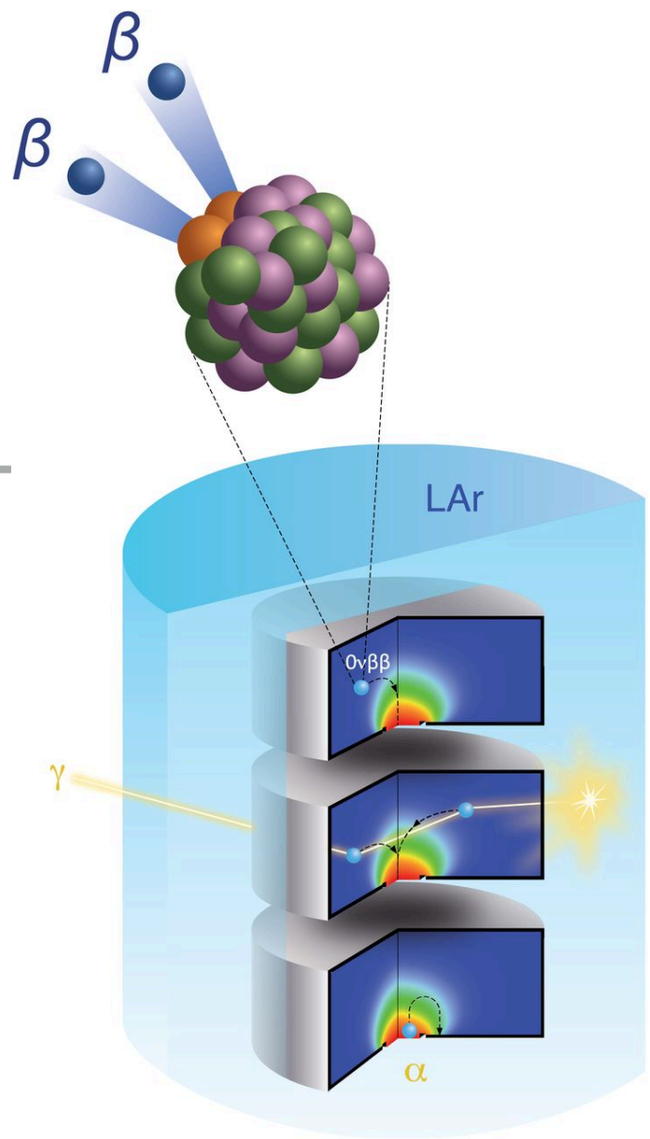
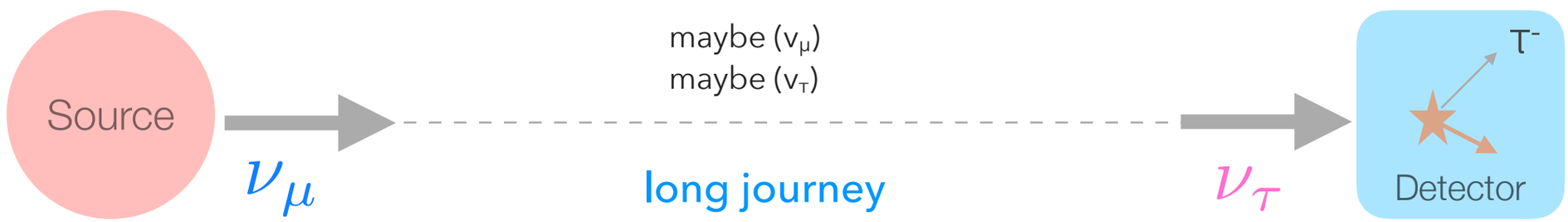


WHAT DO WE KNOW ABOUT NEUTRINOS?

- When they propagate over macroscopic distances, they oscillate between flavours



- Well-studied effect in quantum mechanics
- Flavour is not conserved over macroscopic distances: ν states with different flavours ν_α mix with ν states with different masses ν_i

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j=1}^{3} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left(-i \frac{m^2_{\nu_i} - m^2_{\nu_j}}{2E} x\right)$$

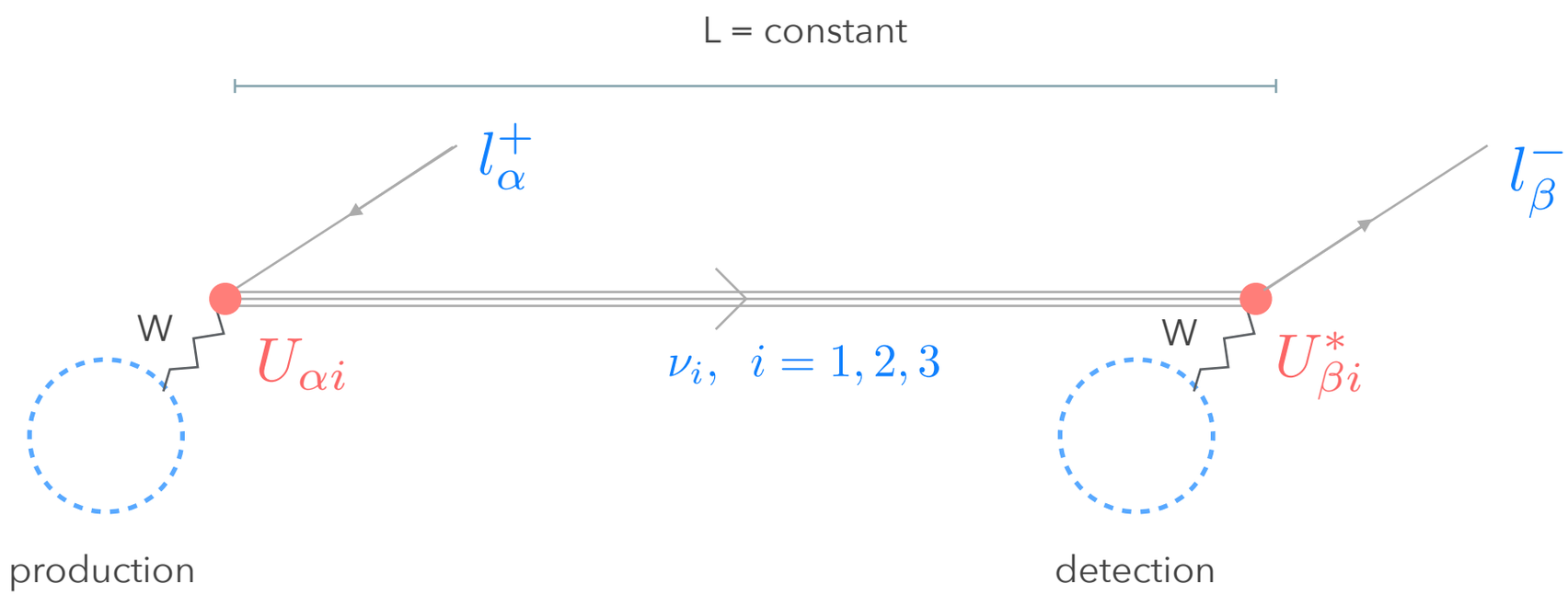
Unitary neutrino mixing matrix (PMNS matrix)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- the effect of the mass is to generate flavour oscillations as a function of distance

WHAT DO WE KNOW ABOUT NEUTRINOS?

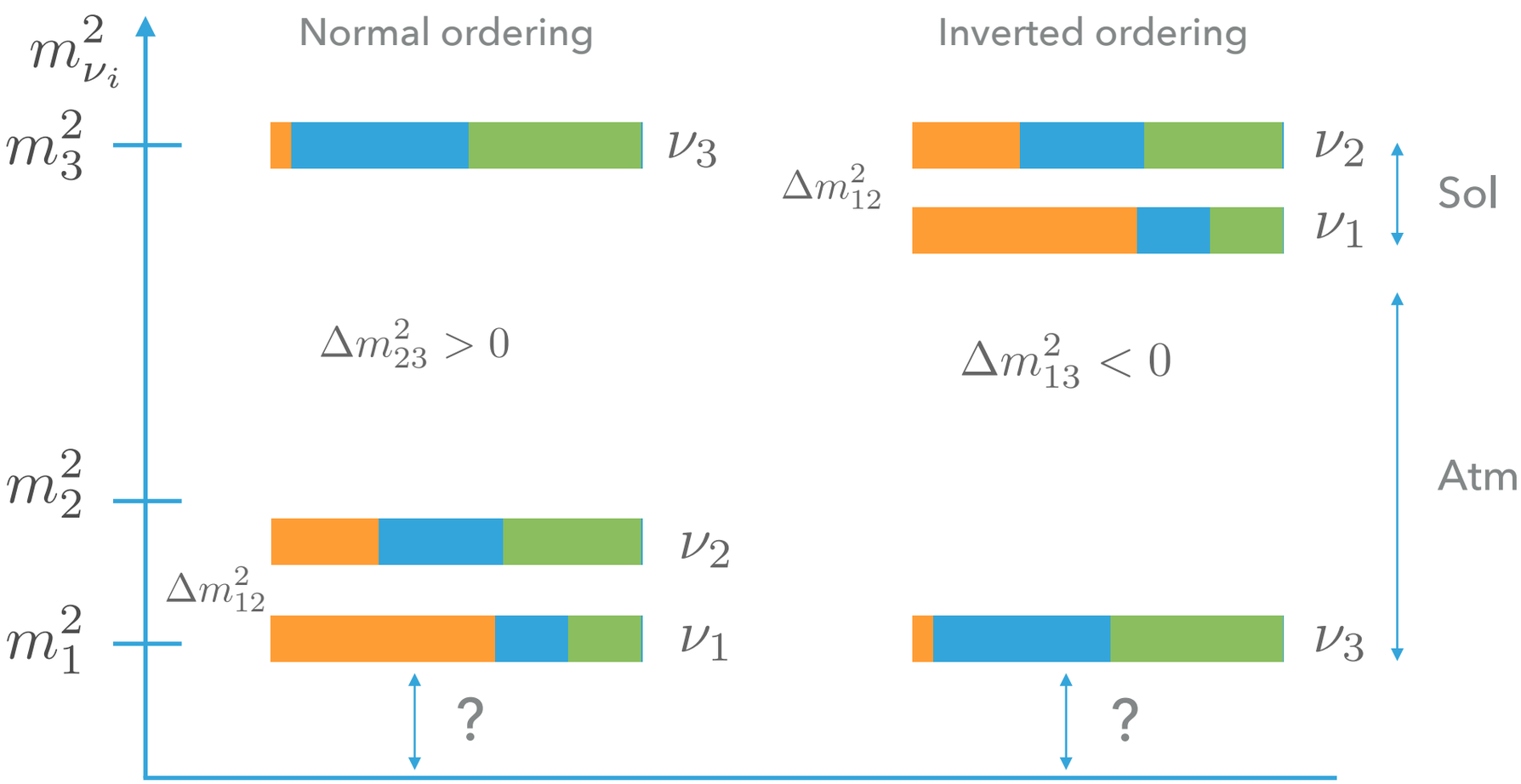
- From oscillation experiments: non-zero masses and non-trivial mixing



Nobel Prize 2015: Takaaki Kajita and Arthur McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

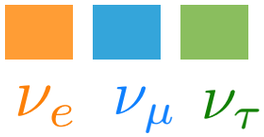
WHAT DO WE KNOW ABOUT NEUTRINOS?

- From oscillation experiments: we know the mixing angles (or the $U_{\alpha i}$) and the Δm^2
- However: 2 possible mass orderings and no information on the mass scale



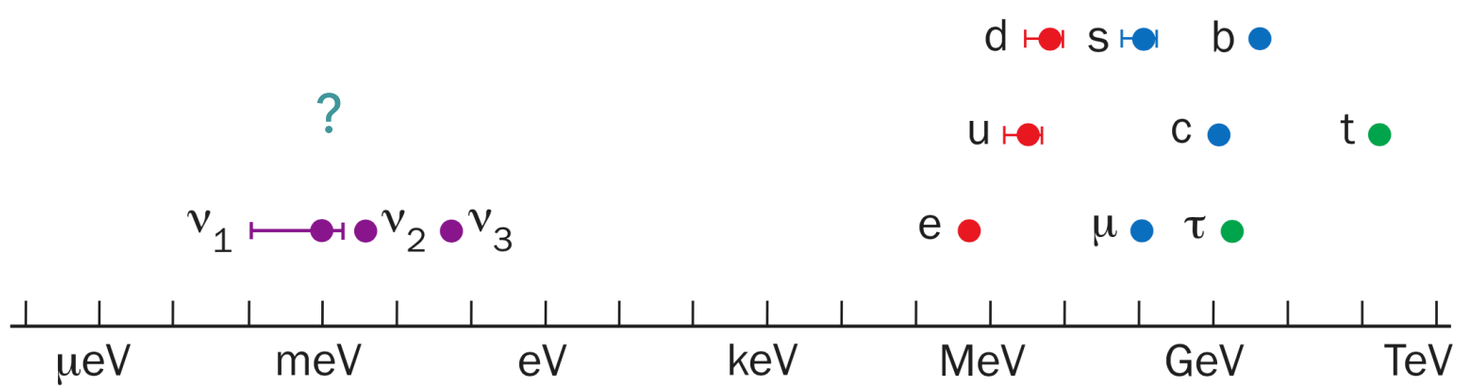
$$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$$
$$\Delta m^2_{sol} \approx 8 \times 10^{-5}\,\mathrm{eV}^2$$

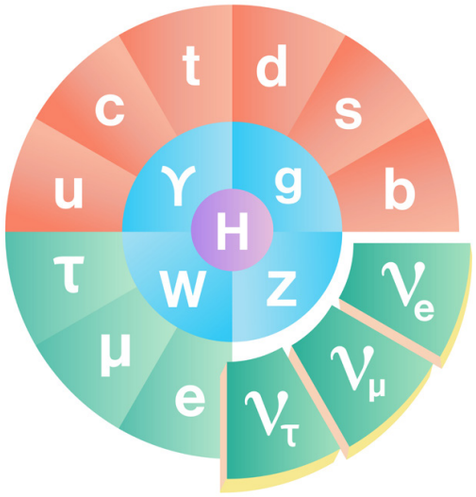
Probabilities of finding a certain neutrino flavour in each mass eigenstate ~ $|U_{\alpha i}|^2$



SOME OPEN QUESTIONS IN NEUTRINO PHYSICS

- What are the absolute values of neutrino masses, and the mass ordering?
- What is the nature of neutrinos? Are they Dirac or Majorana particles?
- What is the origin of small neutrino masses? $\frac{m_{\nu_j}}{m_{l,q}} \leq 10^{-6}$ for $m_{\nu_j} \leq 0.5\,\mathrm{eV}$
- What are the precise values of the mixing angles, and the origin of the large ν mixing?
- Is the standard three-neutrino picture correct, or do other, sterile neutrinos exist?
- What is the precise value of the CP violating phase δ?
- …





THE DOUBLE BETA DECAY

- Some of these open questions can be addressed with an extremely rare nuclear decay process
  - What are the absolute values of neutrino masses, and the mass ordering?
  - What is the nature of neutrinos? Are they Dirac or Majorana particles?
  - What is the origin of small neutrino masses?

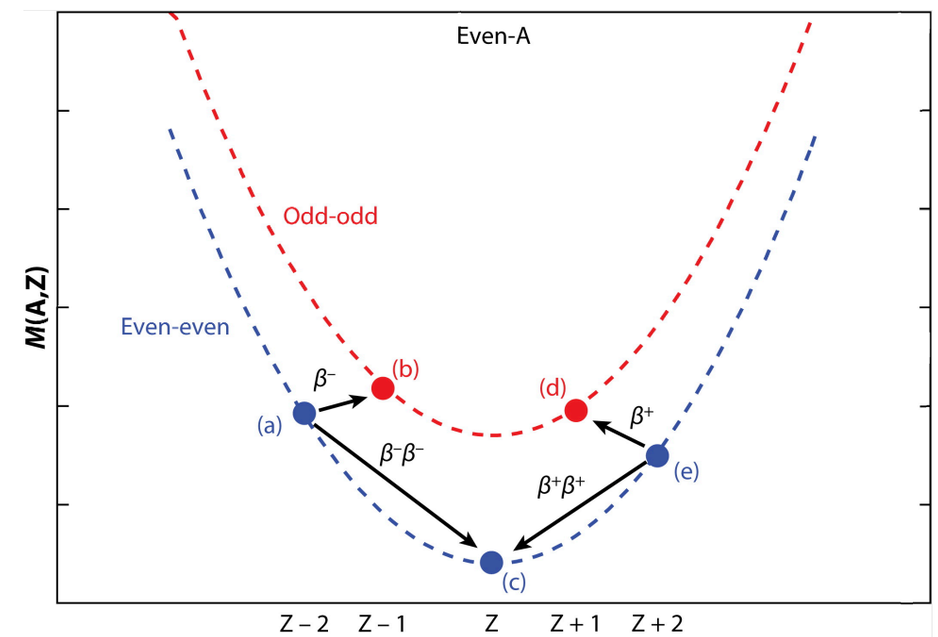
THE DOUBLE BETA DECAY

- If simple β^- or β^+-decay is forbidden on energetic grounds
- Predicted by Maria-Goeppert Mayer in 1935
- The probability for a decay is very small, the mean lifetime of a nucleus is much larger than the age of the universe ($\tau_U \sim 1.4\times10^{10}$ a)

$$\tau_{2\nu} \approx 10^{20} y$$

- Thus: a *very* rare process
- However, if a large amount of nuclei is used, the process can be observed experimentally

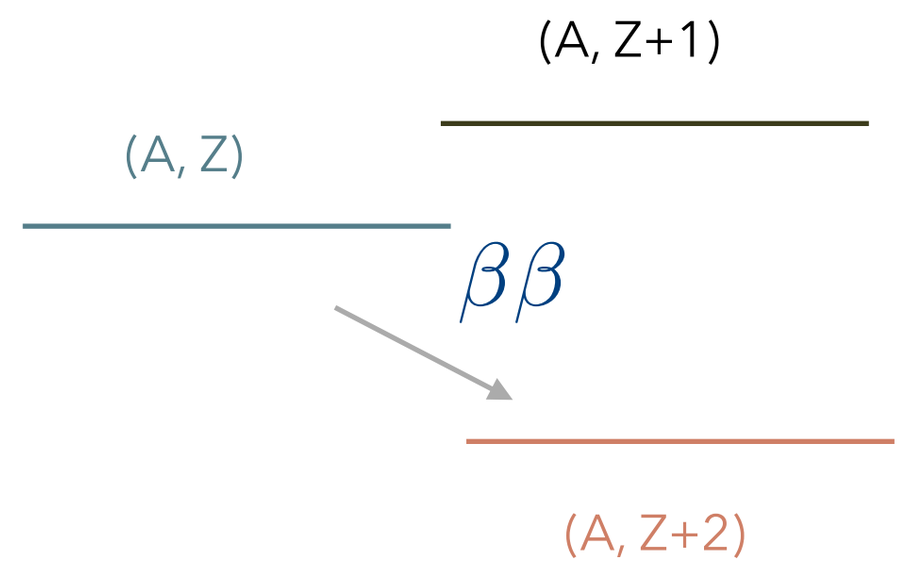
mass parabola of isobars with even A



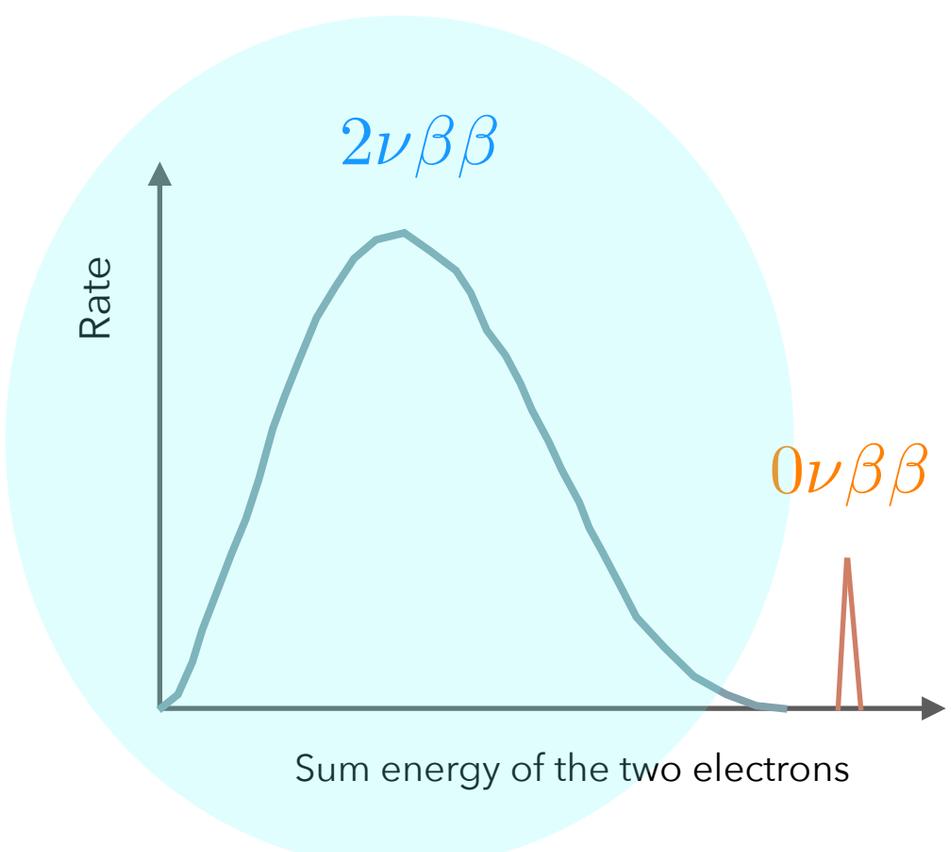
Ruben Saakyan, Annu. Rev. Nucl. Part. Sci. 63 (2013)

Nobel Prize in physics, 1963 for her discoveries concerning the nuclear shell structure

THE DOUBLE BETA DECAY

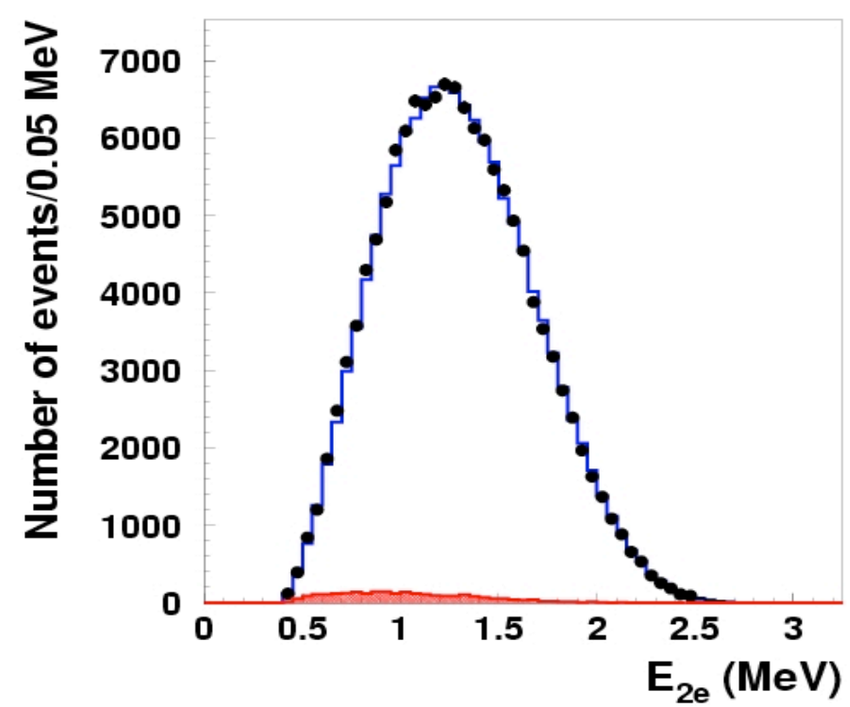


- The Standard Model decay, with 2 neutrinos, was observed in a number of nuclei
- $T_{1/2} > 10^{18}$ y: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd



^{100}Mo: $T_{1/2}=7.15\times10^{18}$ y

NEMO Experiment in Modane/Frejus



THE DOUBLE BETA DECAY

- The decay rate $\Gamma^{2\nu}$ depends on the matrix element $M^{2\nu}$ and on the phase space factor $G^{2\nu}$ (which determines the energy spectrum):

$$\Gamma^{2\nu} = \frac{\ln 2}{T_{1/2}^{2\nu}} = G^{2\nu}(Q, Z)|M^{2\nu}|^2$$

- The phase space factor (Z= charge of daughter nucleus) from the leptonic degrees of freedom:

$$G^{2\nu} \propto (G_F \cos\theta_C)^4 Q^7 \cdot \left(\frac{Q^4}{1980} + \frac{Q^3}{90} + \frac{Q^2}{9} + \frac{Q}{2} + 1\right) \propto (G_F \cos\theta_C)^4 \cdot Q^{11}$$

  - The decay rate scales with $Q^{11} \times (G_F)^4 \Longrightarrow$ we expect indeed very long $T_{1/2}$ of ~10^{20} y

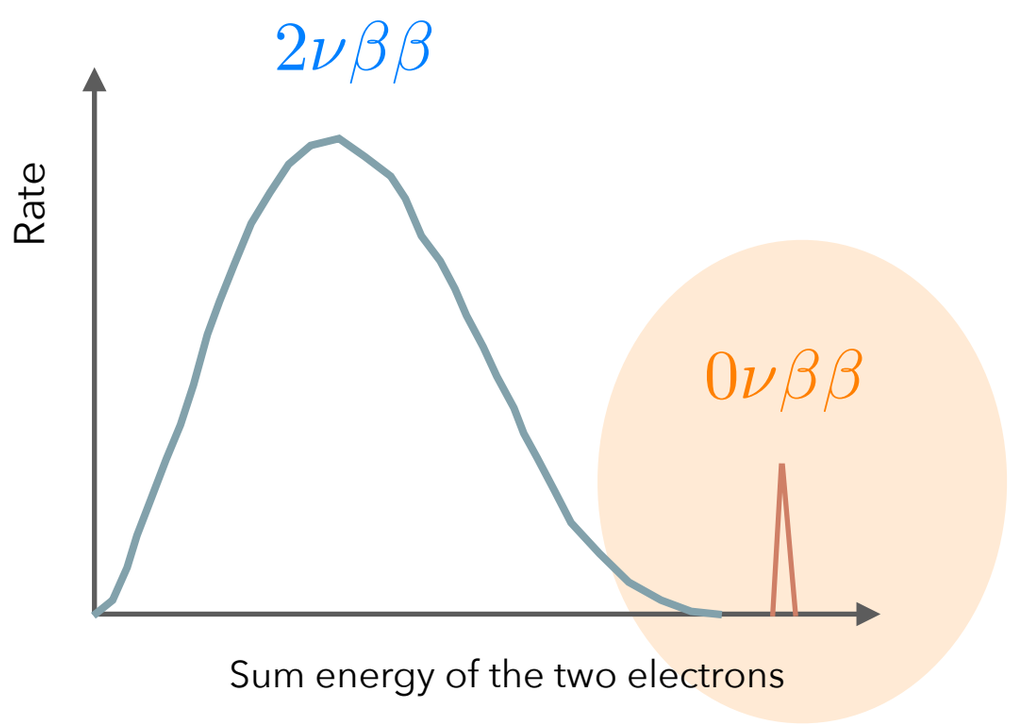
THE NEUTRINOLESS DOUBLE BETA DECAY

- More interesting: the decay *without* emission of neutrinos $\Longrightarrow$ ΔL = 2

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

- Expected signature: *sharp peak at the Q-value of the decay*

$$Q = E_{e1} + E_{e2} - 2m_e$$

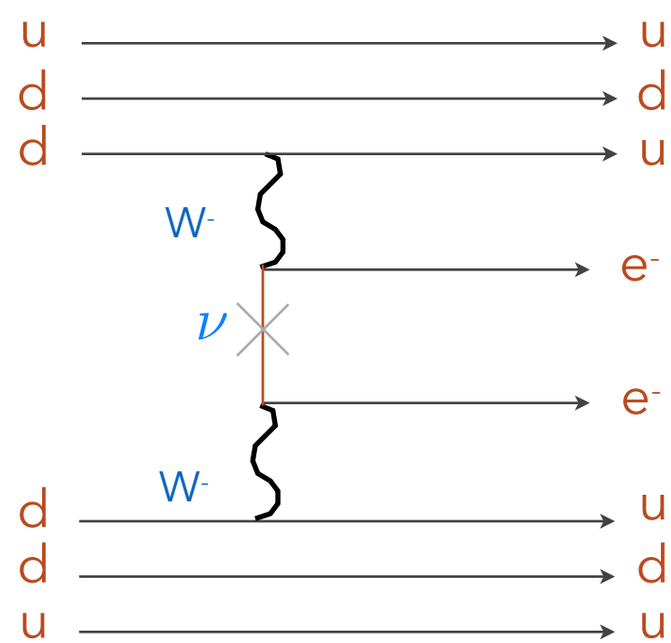


The double beta decay without neutrinos: first discussed by Wendell H. Fury in 1939

Ettore Majorana had proposed in 1937 that neutrinos could be their own antiparticles

THE NEUTRINOLESS DOUBLE BETA DECAY

- In this decay, a **light virtual neutrino could be exchanged**



Charge conjugate spinor

$$\psi^c = C\bar{\psi}^T$$

A Majorana field

$$\psi = \psi^c$$

$$\psi = \psi_L + \psi_L^c$$

has 2 spin d.o.f.

- The neutron decays under emission of a right handed 'anti-neutrino' ν_L^c
  - the ν_L^c has to be absorbed at the second vertex as left handed 'neutrino' ν_L
  - for the decay to happen: neutrinos and anti-neutrinos must be identical, thus Majorana particles
  - & the helicity must change

MAJORANA AND DIRAC NEUTRINOS

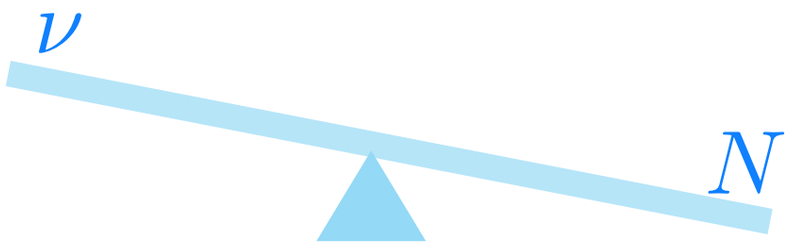
- Most general Lagrangian: both type of neutrinos masses

$$\mathcal{L}_{\mathcal{M}_\nu} = -\frac{1}{2}\left[m_D(\bar{\psi}_R^c\psi_L^c + \bar{\psi}_R\psi_L) + M\bar{\psi}_L^c\psi_L\right] + h.c.$$

- Dirac term: generated after SSB from Yukawa interactions; Majorana term: singlet of the SM gauge group and can appear as bare mass term

- Masses of physical neutrinos: from the eigenvalues of the mass matrix. In the "see saw" mechanism: $M \gg m_D \Rightarrow$ a very light neutrinos state ν and a heavy state N with masses:

$$m_\nu \approx \frac{m_D^2}{M} \qquad m_N \approx M$$



- If Dirac mass term m_D: of similar size as of other fermions & M at the GUT scale (~10^{14} GeV) $\Rightarrow$ explanation of the smallness of neutrino masses

THE NEUTRINOLESS DOUBLE BETA DECAY

- The expected rate can be calculated as:

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

from the leptonic part of the matrix element

the matrix element of the nuclear transition

- with the phase space integral (now spanned only by 2 electrons):

$$G^{0\nu} \propto (G_F \cos\theta_C)^4 \cdot \left(\frac{Q^5}{30} - \frac{2Q^2}{3} + Q - \frac{2}{5}\right) \propto (G_F \cos\theta_C)^4 \cdot Q^5$$

THE EFFECTIVE MAJORANA NEUTRINO MASS

- The effective Majorana neutrino mass parameter: embeds all the dependance on neutrino quantities

$$|m_{\beta\beta}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2\phi_1} + m_3 U_{e3}^2 e^{2i(\phi_2 - \delta)}|$$

- A mixture of m_1, m_2, m_3 $\propto$ to the U_{ei}^2 (the complex entries in the PMNS matrix)

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- φ_1,φ_2 = Majorana phases and $|U_{e1}|^2$ is for instance the probability that ν_e has the mass m_1

◉ fewer phases can be removed by redefining the fields

THE EFFECTIVE MAJORANA NEUTRINO MASS

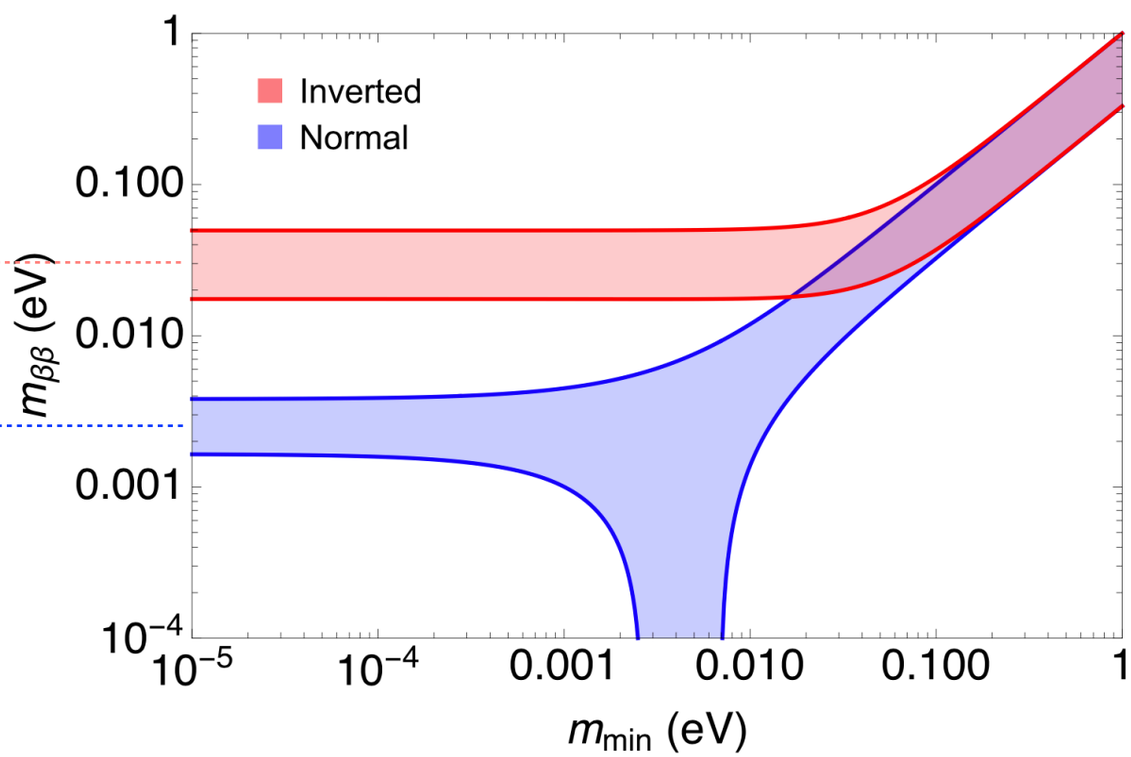
- The value of $m_{\beta\beta}$ depends critically on the neutrino mass spectrum and on the values of the two Majorana phases in the PMNS matrix
- One can express $m_{\beta\beta}$ as a function of the lightest ($m_{\rm min}$) mass state for the two mass orderings and obtain the allowed ranges

Inverted mass ordering

$m_3 \ll m_1 < m_2$

Normal mass ordering

$m_1 < m_2 \ll m_3$



Degenerate region

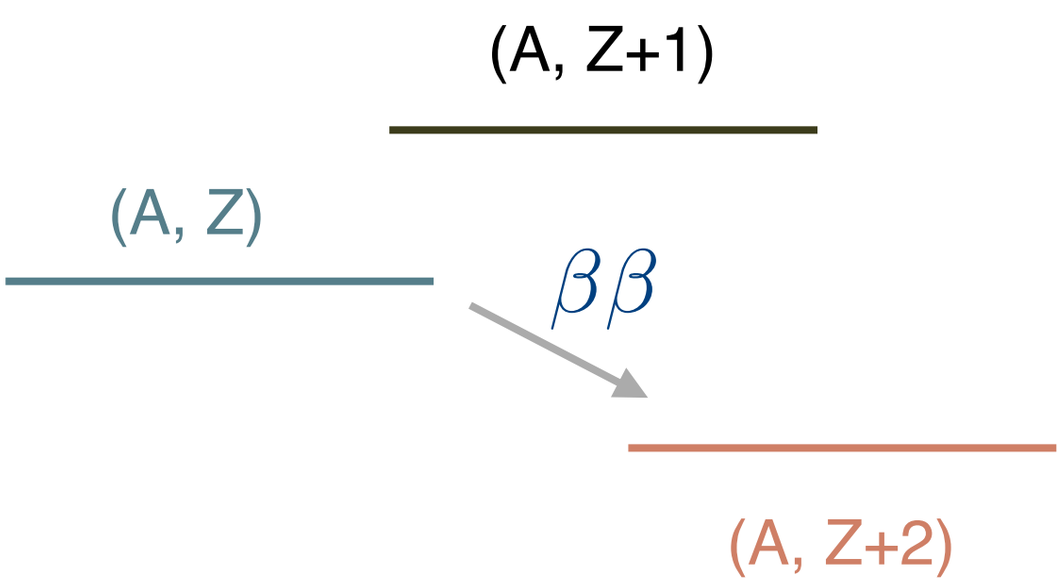
$m_{\rm lightest} \simeq m_1 \simeq m_2 \simeq m_3 \gg \sqrt{|\Delta m^2_{32}|}$

Band widths: mainly from the unknown Majorana phases φ_1, φ_2

Data from PDG Review: PTEP 8, August 2020

EMPLOYED NUCLEI IN SEARCHES

- 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

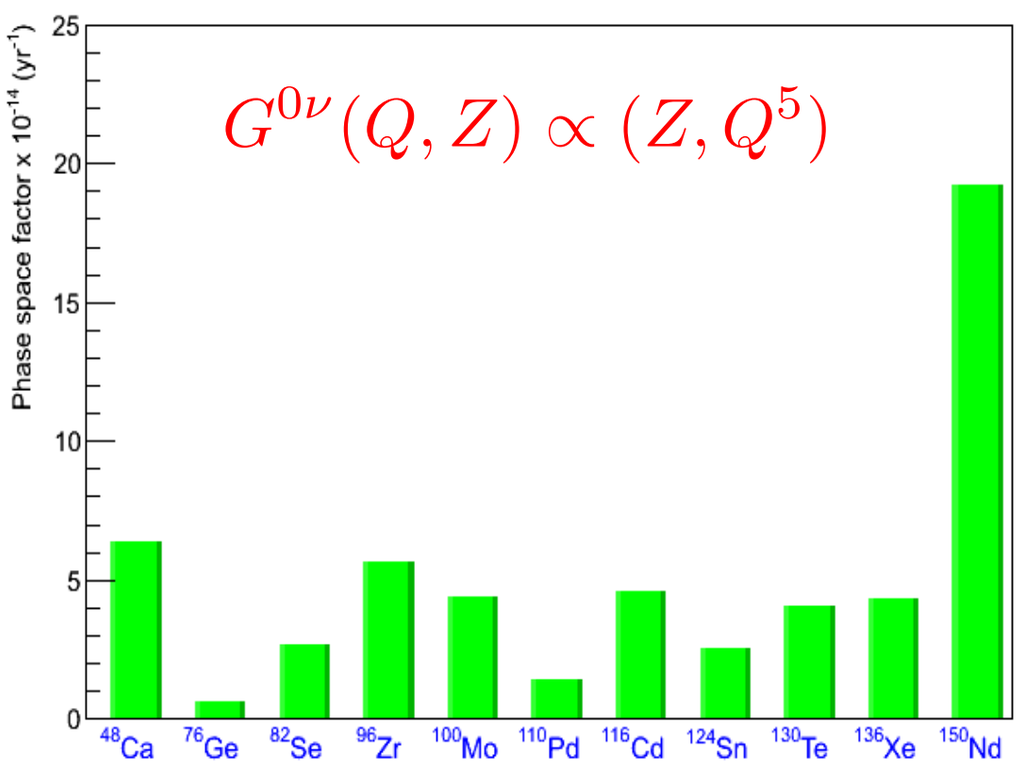
* Q-value > 2 MeV

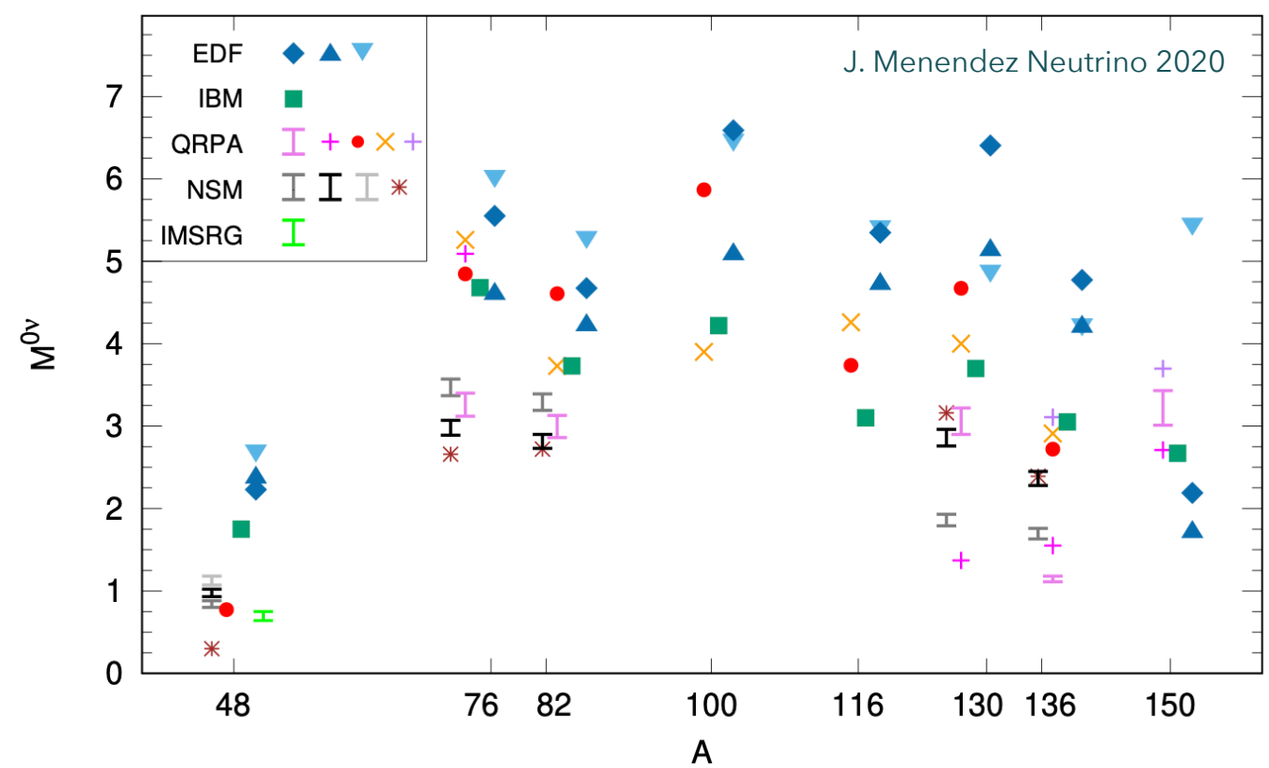
PHASE SPACE AND MATRIX ELEMENTS

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

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

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



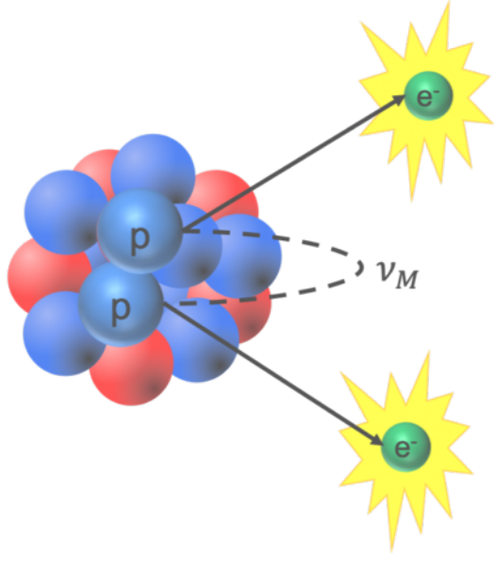


Jonathan Engel and Javier Menéndez 2017 Rep. Prog. Phys. 80 046301

Vergados, Ejiri, Simkovoc, Int. Journal of Modern Physics E, Vol 25 (2016)

SOME TIME SCALES

- ^{14}C: $T_{1/2} \sim 5.7 \times 10^4$ y
- ^{40}K: $T_{1/2} \sim 1.3 \times 10^9$ y
- ^{232}Th: $T_{1/2} \sim 1.4 \times 10^{10}$ y, ^{238}U: $T_{1/2} \sim 4.5 \times 10^9$ y
- Age of the universe: ~ 1.4×10^{10} y
- $2\nu\beta\beta$: $T_{1/2} \sim 10^{20}$ y
- $0\nu\beta\beta$: $T_{1/2} > 10^{26}$ y
- Proton decay > 10^{34} y



EXPRIMENTAL REQUIREMENTS

- Experiments measure the half-life, with a sensitivity (for 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:

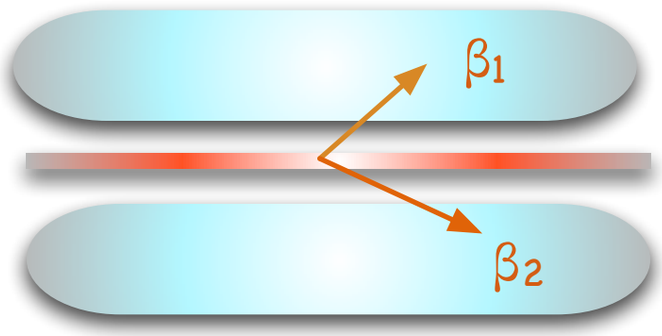
high isotopic abundance (a)
high efficiency (ε)
large detector masses (M)
ultra-low background noise (B)
good energy resolution (ΔE)

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

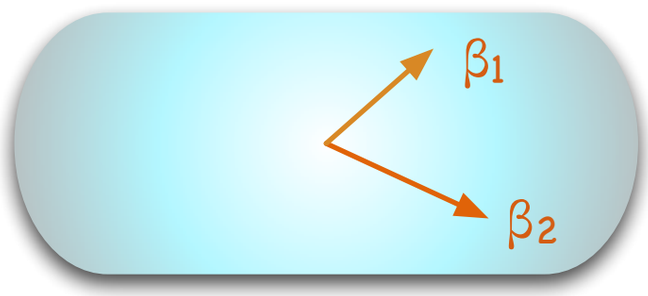
EXPERIMENTS: MAIN APPROACHES

Source ≠ Detector

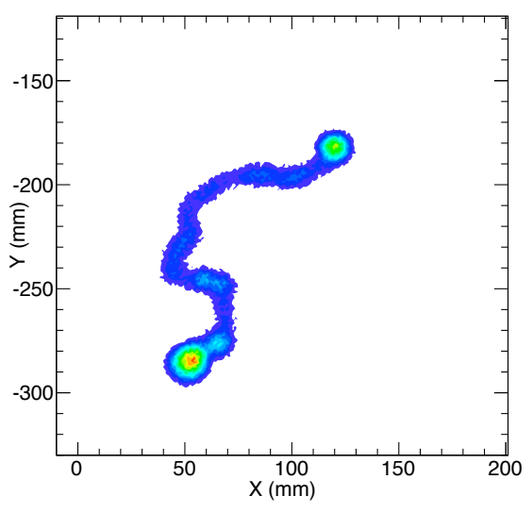


Source as thin foil
Electrons detected with: scintillator, TPC, drift chamber, semiconductor detectors
- Event topology
- Low energy resolution and detection efficiency

Source = Detector (calorimeters)



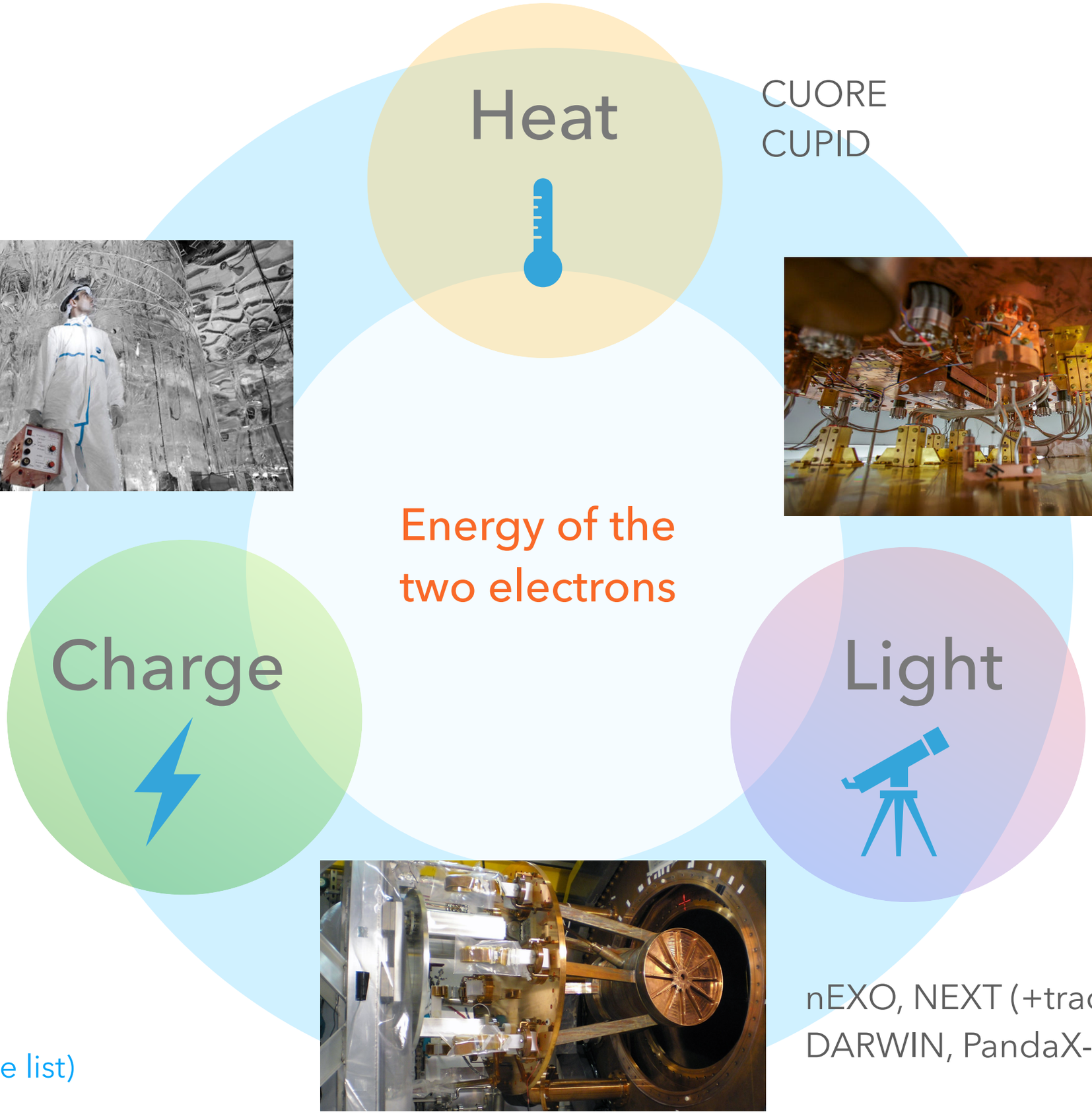
The sum of the energy of the two electrons is measured
Signature: peak at the Q-value of the decay
Scintillators, semiconductors, bolometers
- High resolution + detection efficiency
- No event topology



Source = Detector = Tracker

Source is the (high-pressure) gas of a TPC
Charge and light detected with electron multipliers and/or photosensors
- Good energy and position resolution, high efficiency
- Event topology very helpful in reducing the background and *in identifying the potential signal*

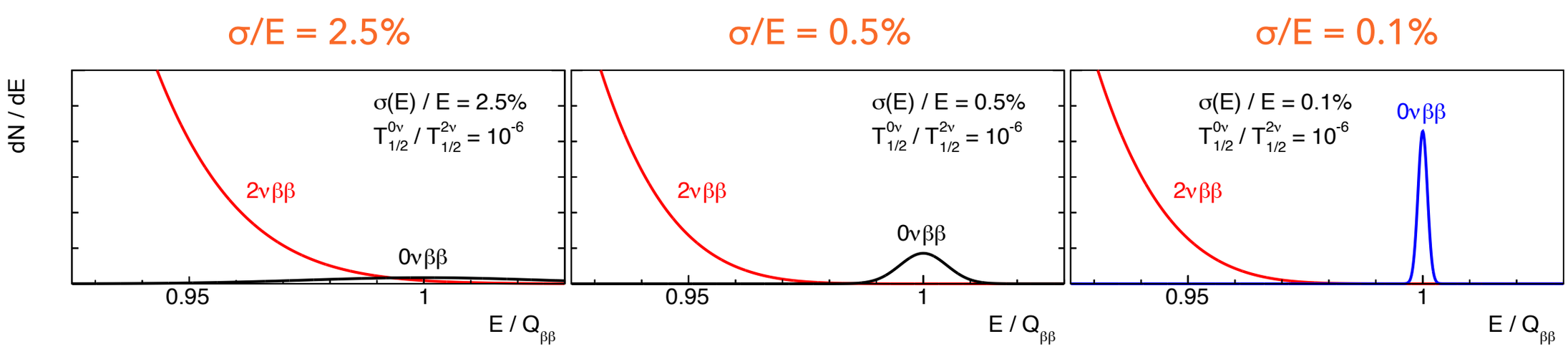
DOUBLE BETA DECAY: EXPERIMENTAL TECHNIQUES*



(*not a complete list)

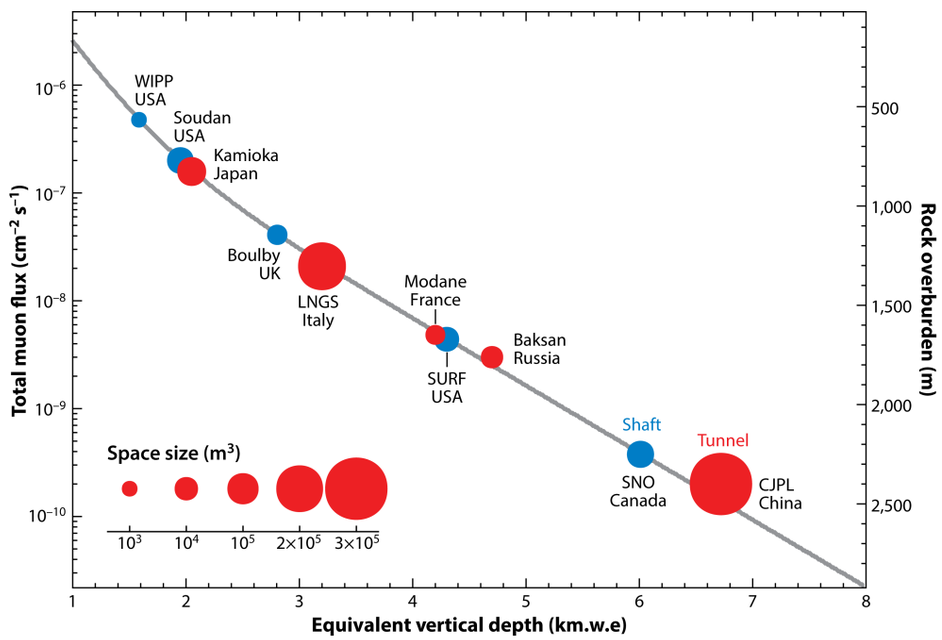
MAIN EXPERIMENTAL CHALLENGES

- Energy resolution (ultimate background from 2νββ-decay)
- Backgrounds
  - cosmic rays & cosmogenic activation (including in situ, e.g., ^{77}Ge, ^{137}Xe)
  - 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 (e.g., ^{8}B from the Sun): $\nu + e^- \rightarrow \nu + e^-$



BACKGROUND REDUCTION

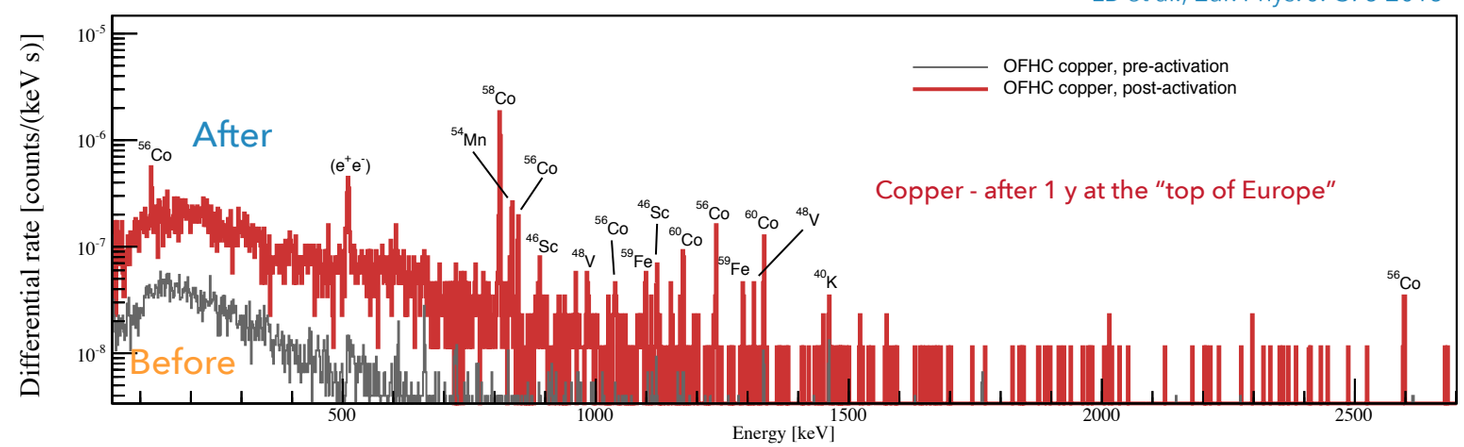
- Go deep underground



Cheng J-P, et al. 2017.
Annu. Rev. Nucl. Part. Sci. 67:231–51

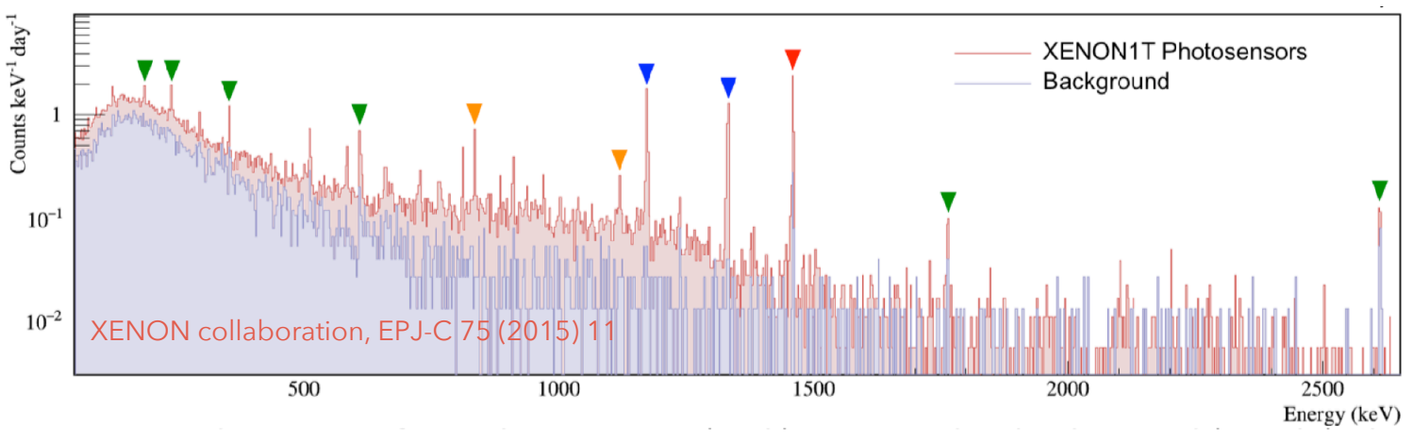
- Avoid cosmic activation

LB et al., Eur. Phys. J. C75 2015



- Use active shields

- Select low-radioactivity materials



VERY BRIEF STATUS OF THE FIELD

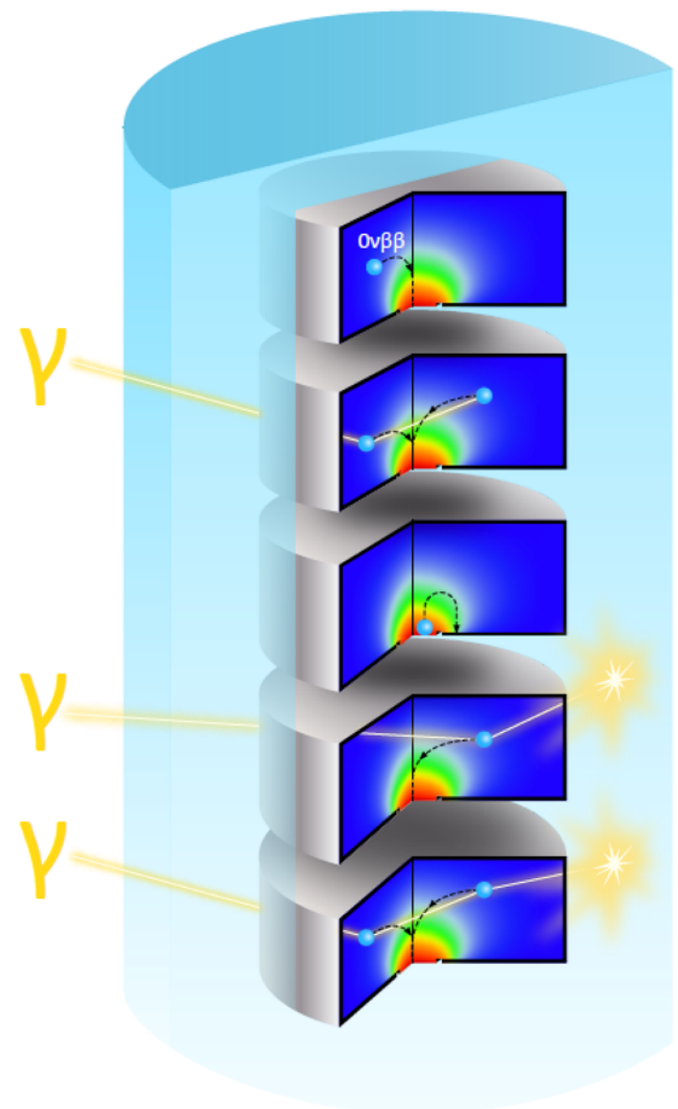
- No observation of this extremely rare nuclear decay (so far)
- Best *lower limits* on $T_{1/2}$: 1.07×10^{26} y (^{136}Xe), 1.8×10^{26} y (^{76}Ge), 3.2×10^{25} y (^{130}Te)

$$m_{\beta\beta} < (0.08 - 0.18)\,\mathrm{eV}\ (90\%\ \mathrm{C.L.})$$

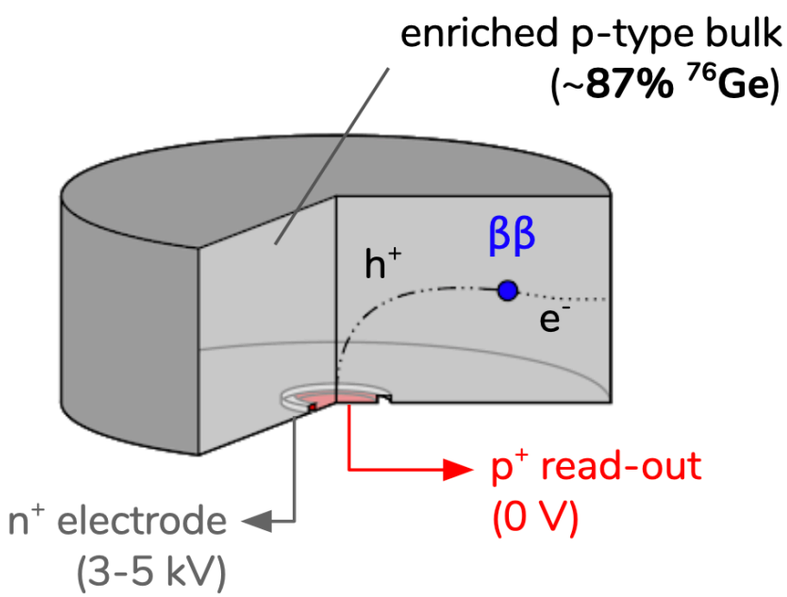
- Running and upcoming experiments (a selection)
  - ^{130}Te: CUORE, SNO+
  - ^{136}Xe: KAMLAND-Zen, KAMLAND2-Zen, EXO-200, nEXO, NEXT, DARWIN, PandaX-III
  - ^{76}Ge: GERDA Phase-II, Majorana, LEGEND (GERDA & Majorana + new groups)
  - ^{82}Se: CUPID (= CUORE with light read-out)
  - ^{82}Se (^{150}Nd, ^{48}Ca): SuperNEMO
  - ^{100}Mo: NEMO-3, AMoRE, CUPID-Mo

GERMANIUM EXPERIMENTS

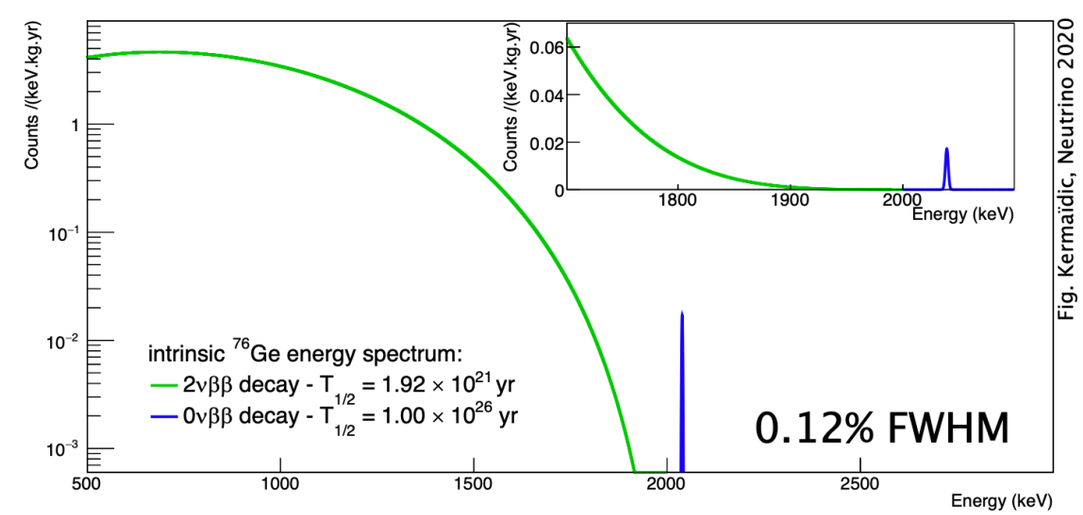
$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2\,e^{-}$$



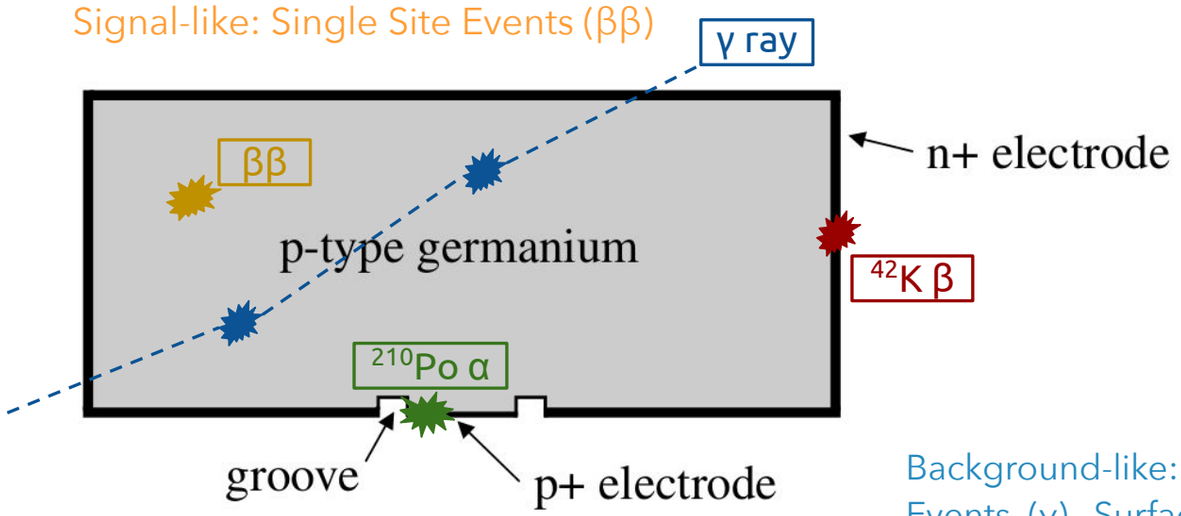
GERMANIUM IONISATION DETECTORS



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

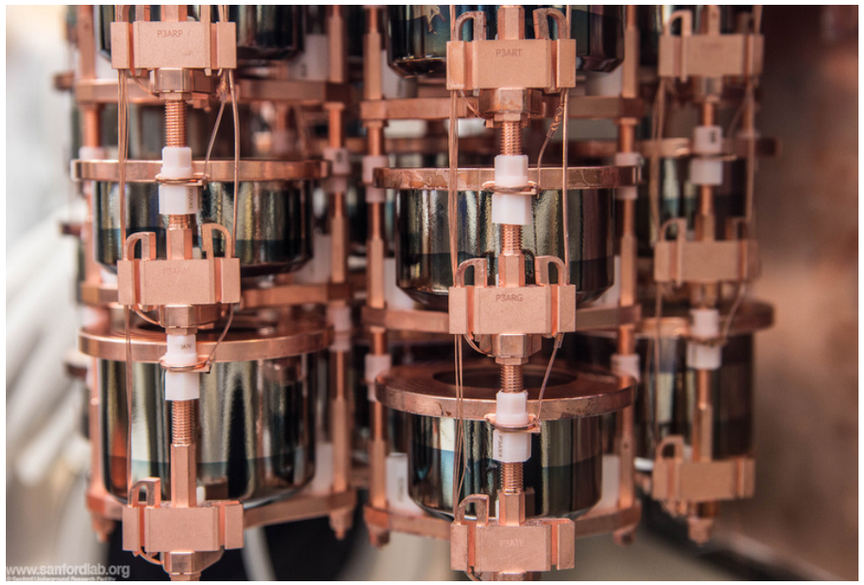


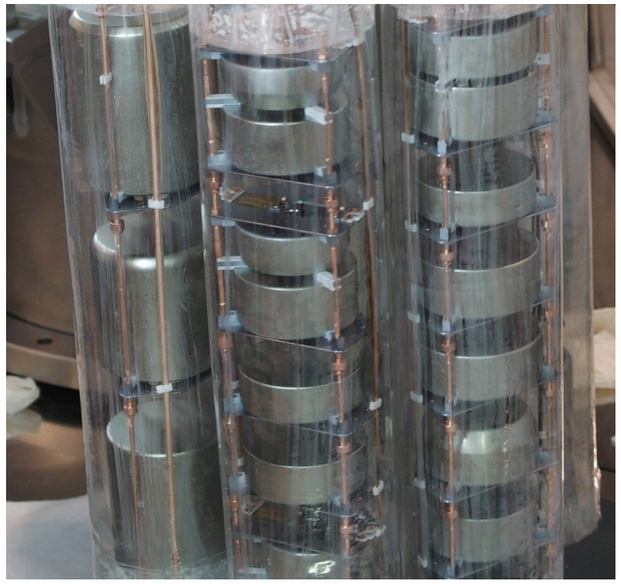
Signal-like: Single Site Events (ββ)

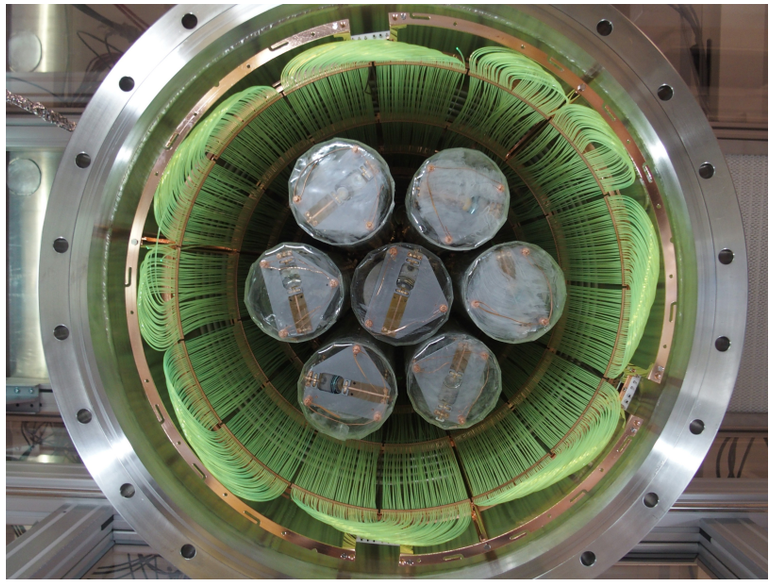


Background-like: Multiple Site Events (γ), Surface events (α,β)

RECENT 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 in LAr

3.0 keV FWHM at 2039 keV

127.2 kg y exposure; PRL 125, 2020

$T_{1/2} > 1.8 \times 10^{26}$ y (90% CL)

$Q_{\beta\beta} = 2039.061 \pm 0.007$ keV

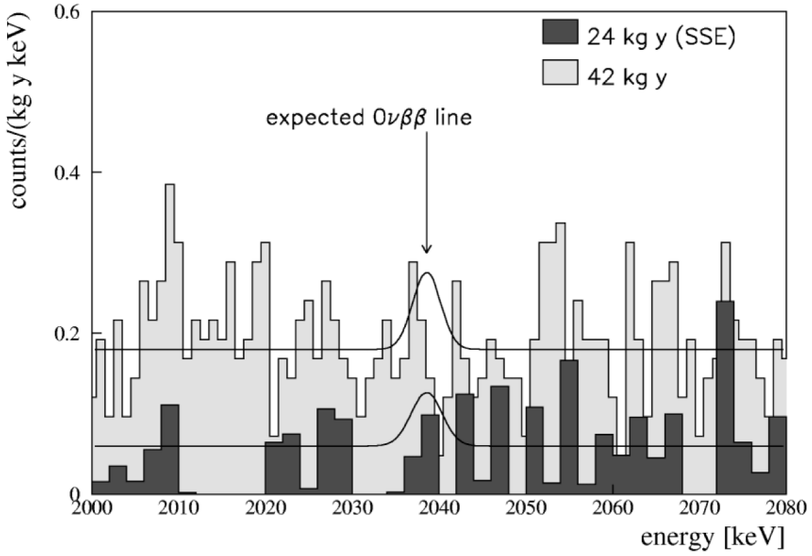
THE HEIDELBERG-MOSCOW EXPERIMENT

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

A first "bare" HPGe detector

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

Heidelberg-Moscow HPGe detector in conventional shield

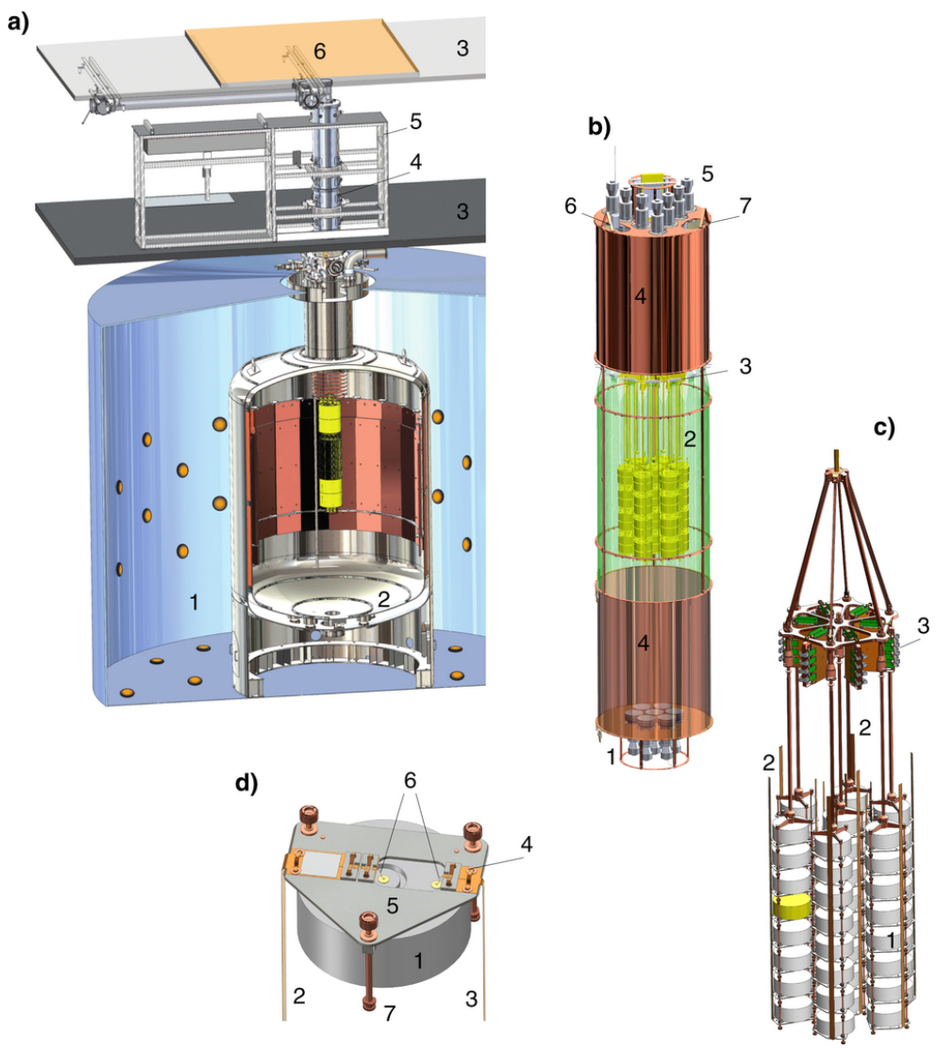


Limits on the Majorana neutrino mass in the 0.1 eV range, L. Baudis et al., Phys. Rev. Lett. 83, 1999

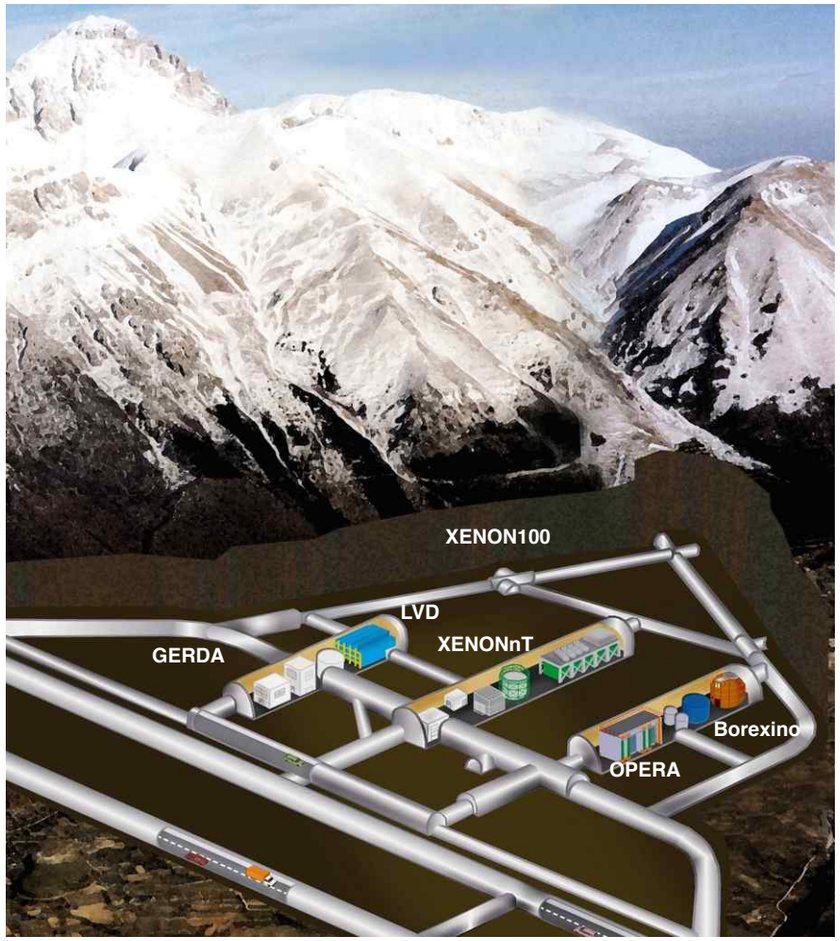
$$T_{1/2} > 1.6 \times 10^{25}\ \mathrm{y}\ 90\%\ \mathrm{C.L.}$$

Sensitivity

THE GERDA EXPERIMENT



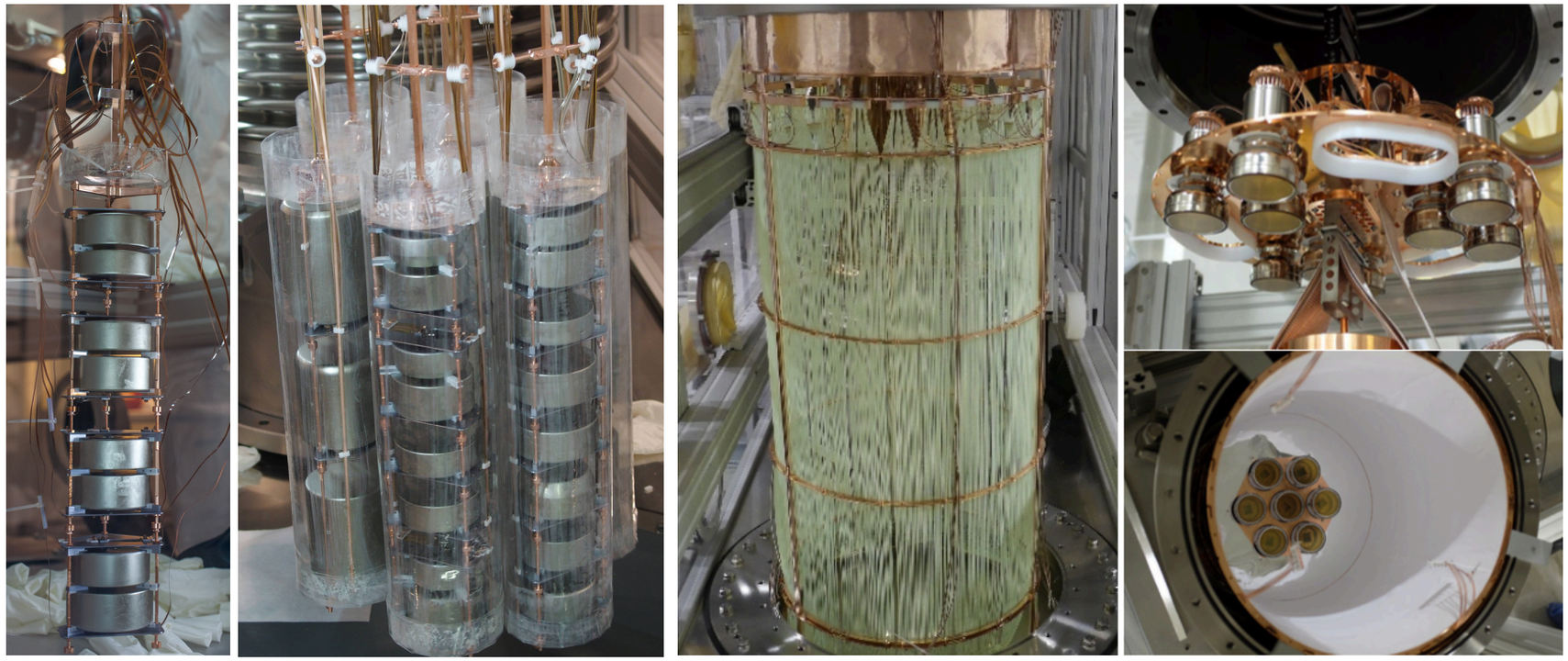
GERDA collaboration, EPJ-C 78 (2018) 5



- LNGS at ~ 3600 mwe
- 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 < 7×10^{-4} μBq/kg
- A minimal amount of surrounding material
- Data taking: 2011-2019

THE GERDA EXPERIMENT

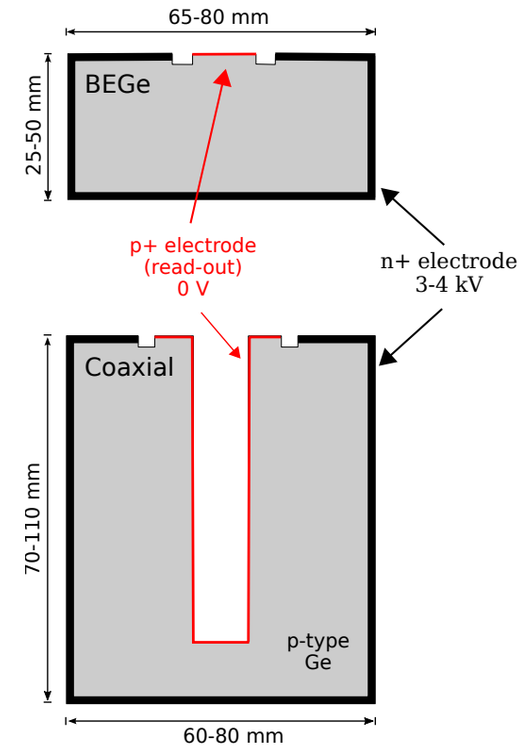
- Seven string with 40 detectors (30 BEGe, 7 coaxial, 3 natural coaxial → enriched IC)
- Liquid argon veto, equipped with optical fibres and SiPMs, plus 2 arrays of 3-inch PMTs
  - Science run (phase II) started in December 2015
  - Summer 2018: central string replaced with enriched, inverted coaxial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

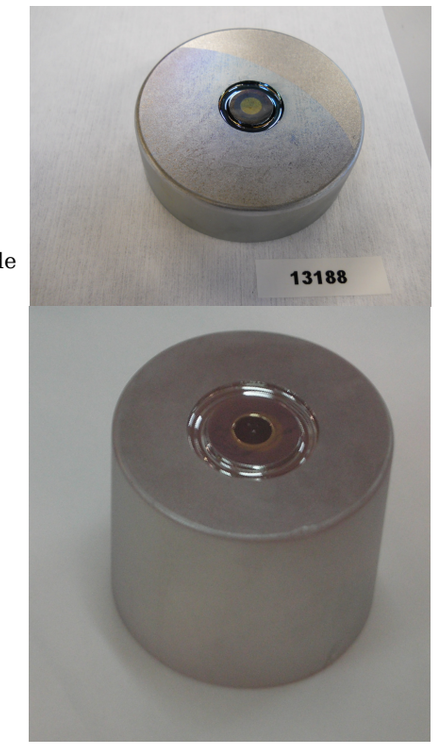


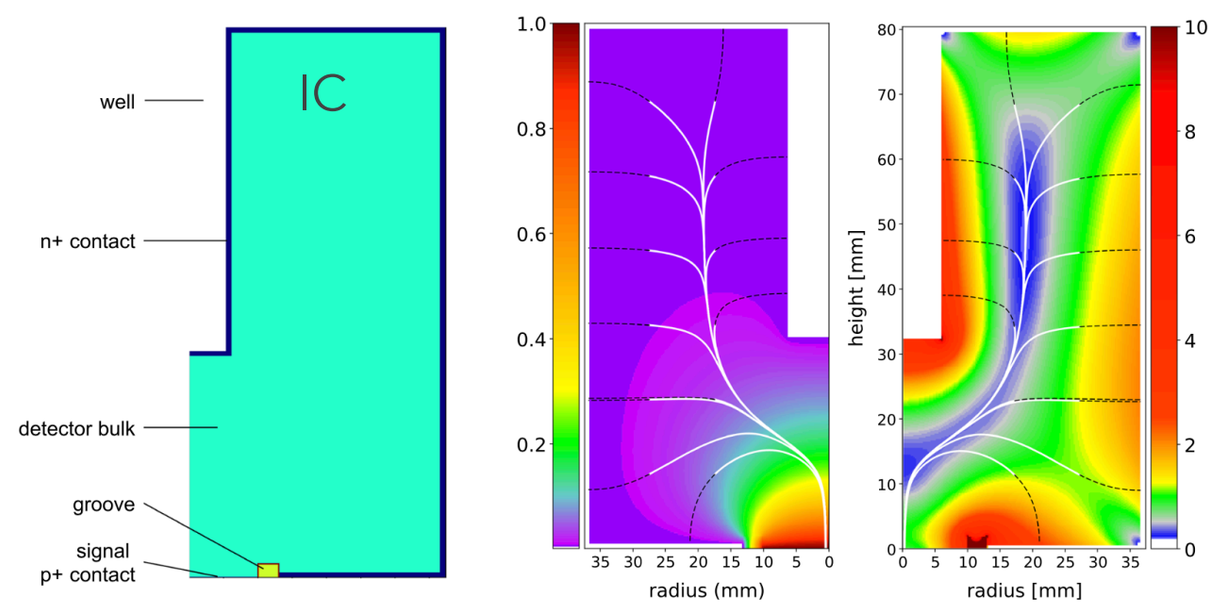
GERDA collaboration, Characterisation of 30 ^{76}Ge enriched Broad Energy Ge detectors for GERDA Phase II, EPJ-C 79, 2019; Characterisation of inverted coaxial ^{76}Ge detectors in GERDA for future double beta decay experiments, EPJ-C 81, 2021

GERDA DETECTORS

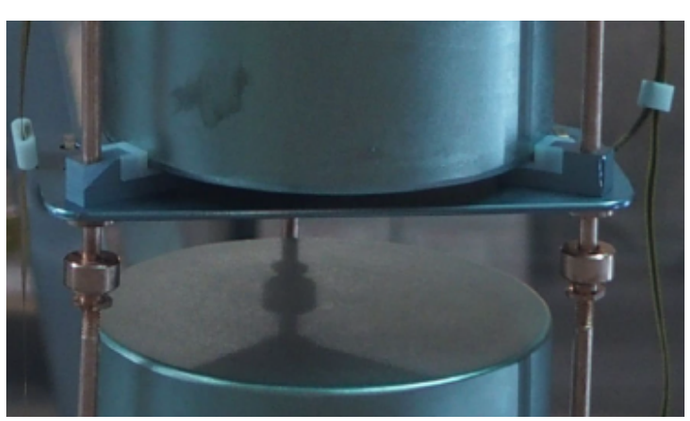
- BEGe, coaxial and IC
- p+ electrodes:
  - 0.3 μm boron implantation
- n+ electrodes:
  - 1-2 mm lithium layer (biased up to +4.5 kV)
- Low-mass holders (Si, Cu, PTFE)





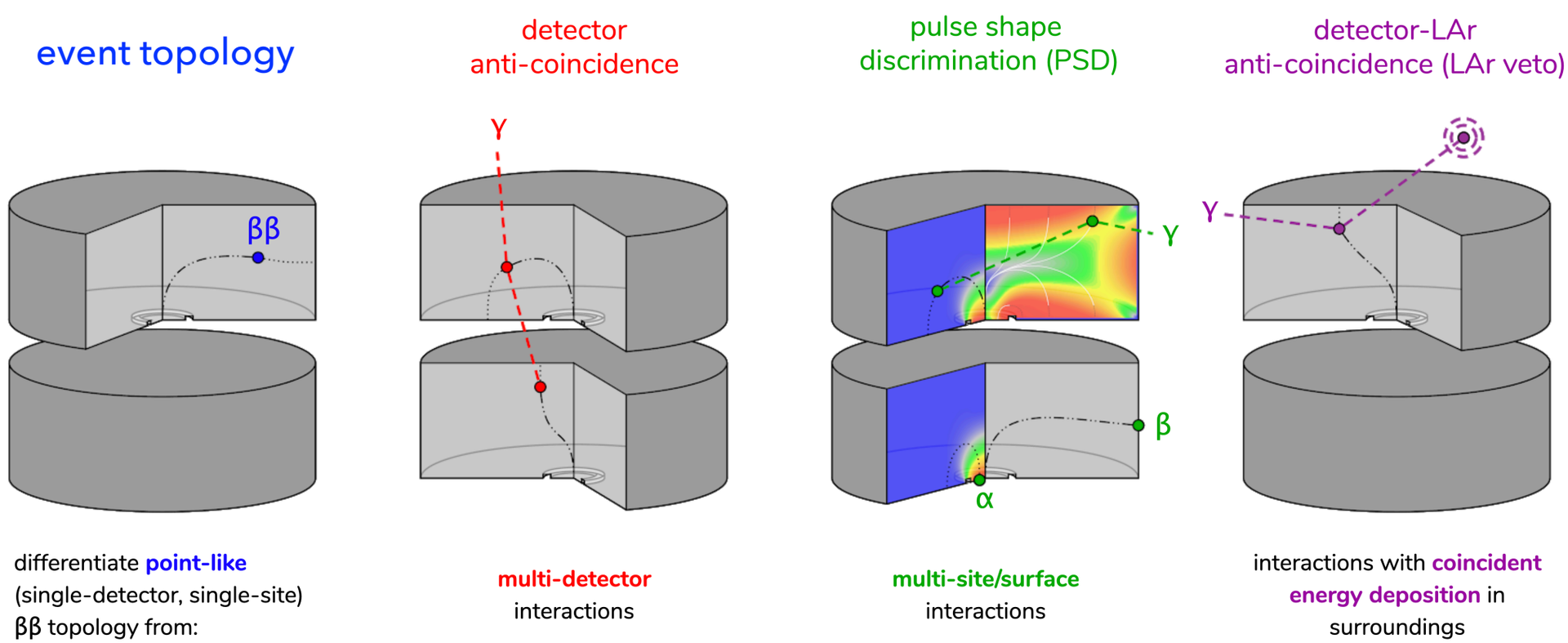


IC weighting potential and E-field in kV/cm; black: e^- drift paths, ending at n+ contact; white: hole drift paths to signal contact



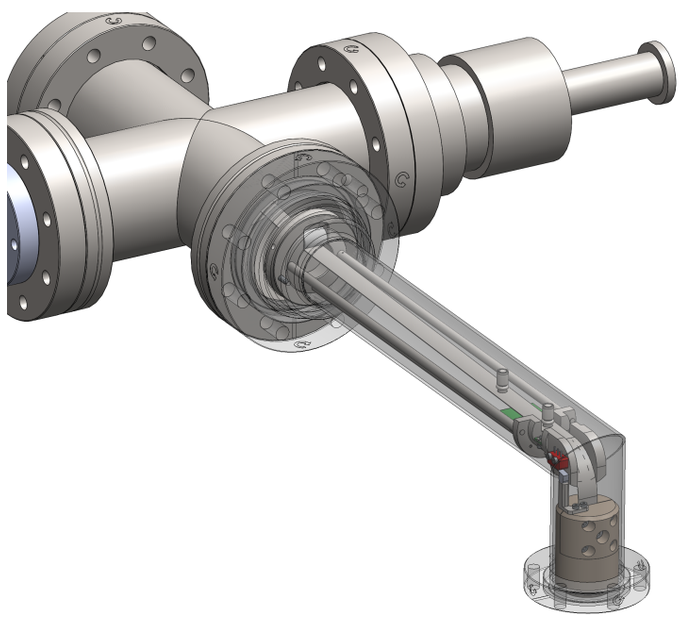
BACKGROUND SUPPRESSION

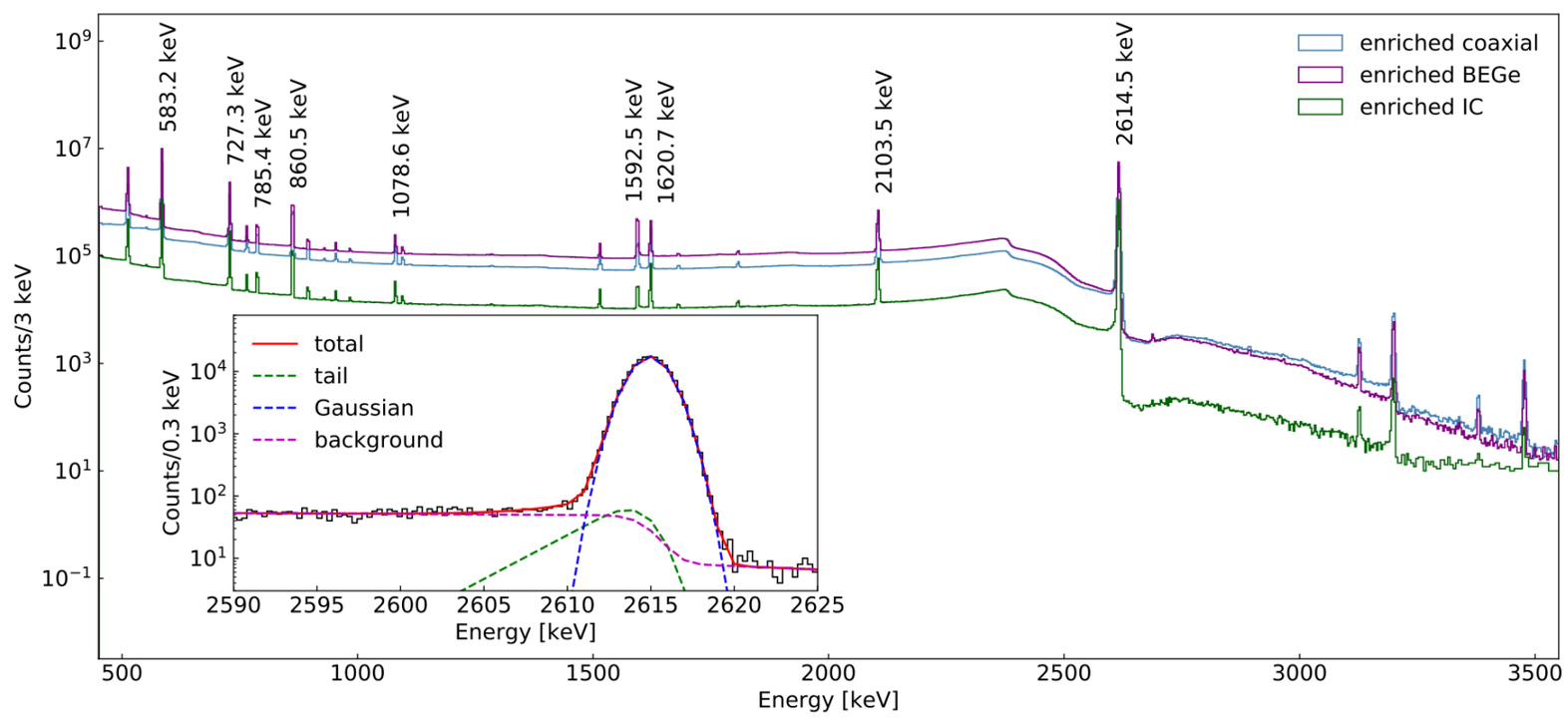
- Several handles:
  - Event topology + anti-coincidence between HPGe detectors + pulse shape discrimination + liquid argon veto



ENERGY CALIBRATION

- Three low neutron-emission ^{228}Th sources in source insertion system, deployed once every week
- FWHM at $Q_{\beta\beta}$: (2.8 ± 0.3) keV for BEGe, (4.0 ± 1.3) keV for coaxial, (2.9 ± 0.1) keV for IC detectors





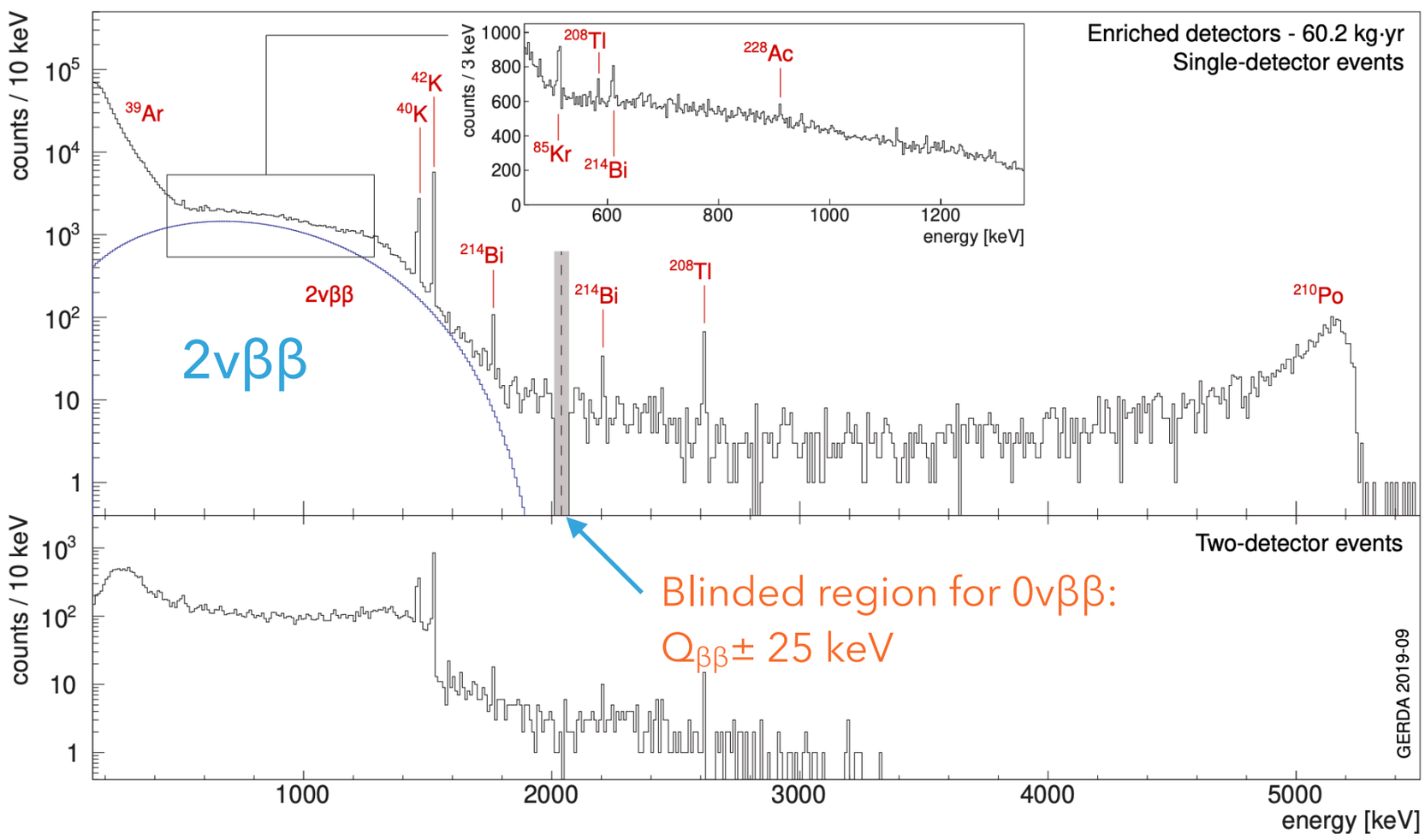
Custom-made ^{228}Th sources encapsulated in stainless steel, on Ta holders, two position determination systems

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

GERDA collaboration, arXiv:2103.13777 [physics.ins-det], accepted in EPJ-C

BACKGROUND MODEL IN GERDA

- Intrinsic 2νββ-events, ^{39}Ar ($T_{1/2}$ = 269 y), ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr ($T_{1/2}$ = 11 y) in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact



Sum spectrum, single-detector events

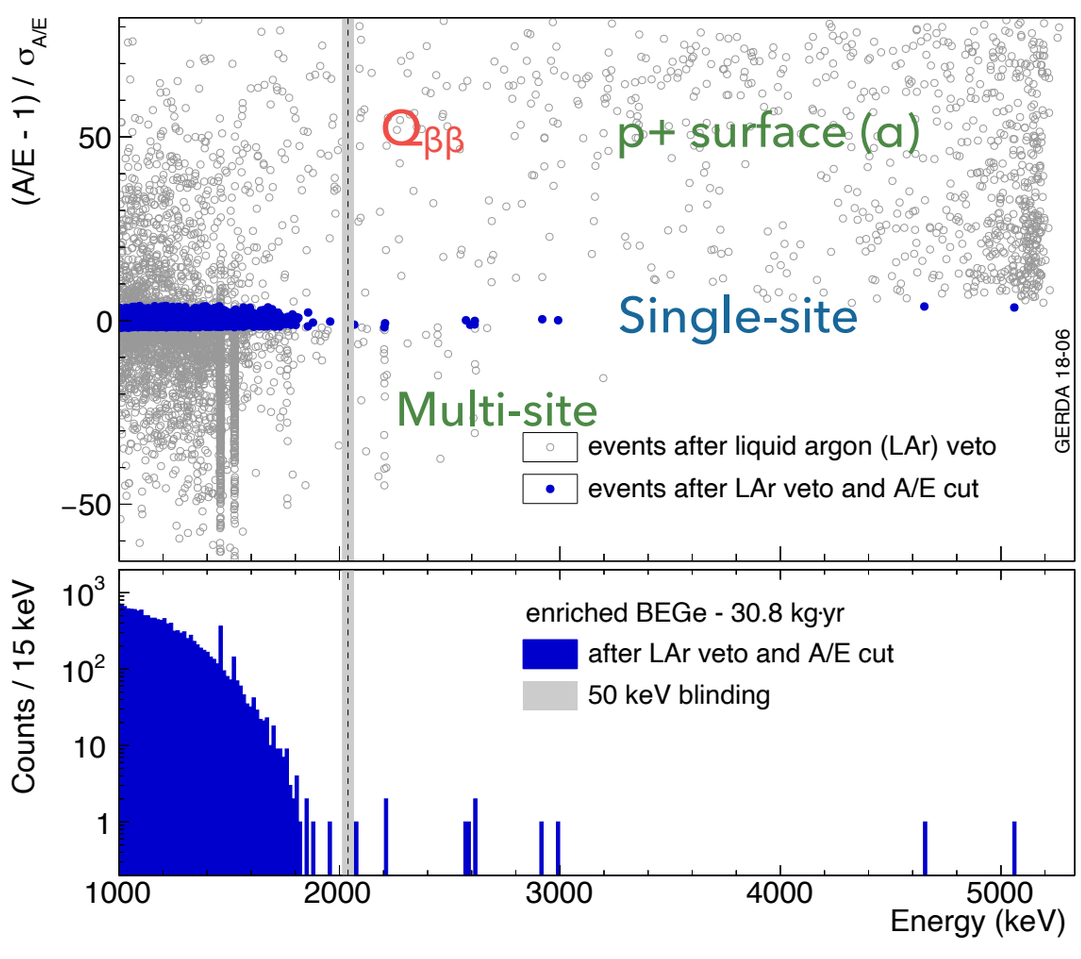
Sum spectrum, two-detector events

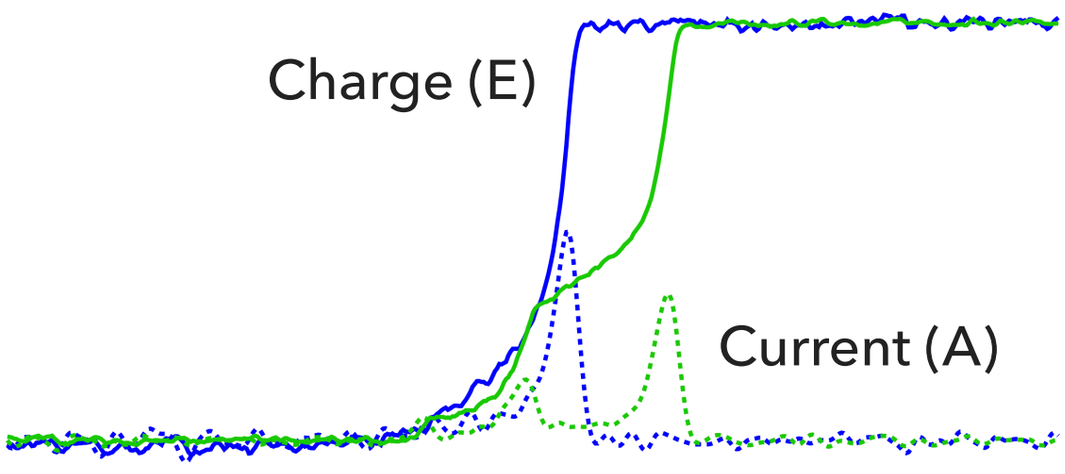
GERDA collaboration, JHEP 03 (2020)

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 double escape peak acceptance)
- Acceptance at 0νββ: (87.6±2.5)%





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

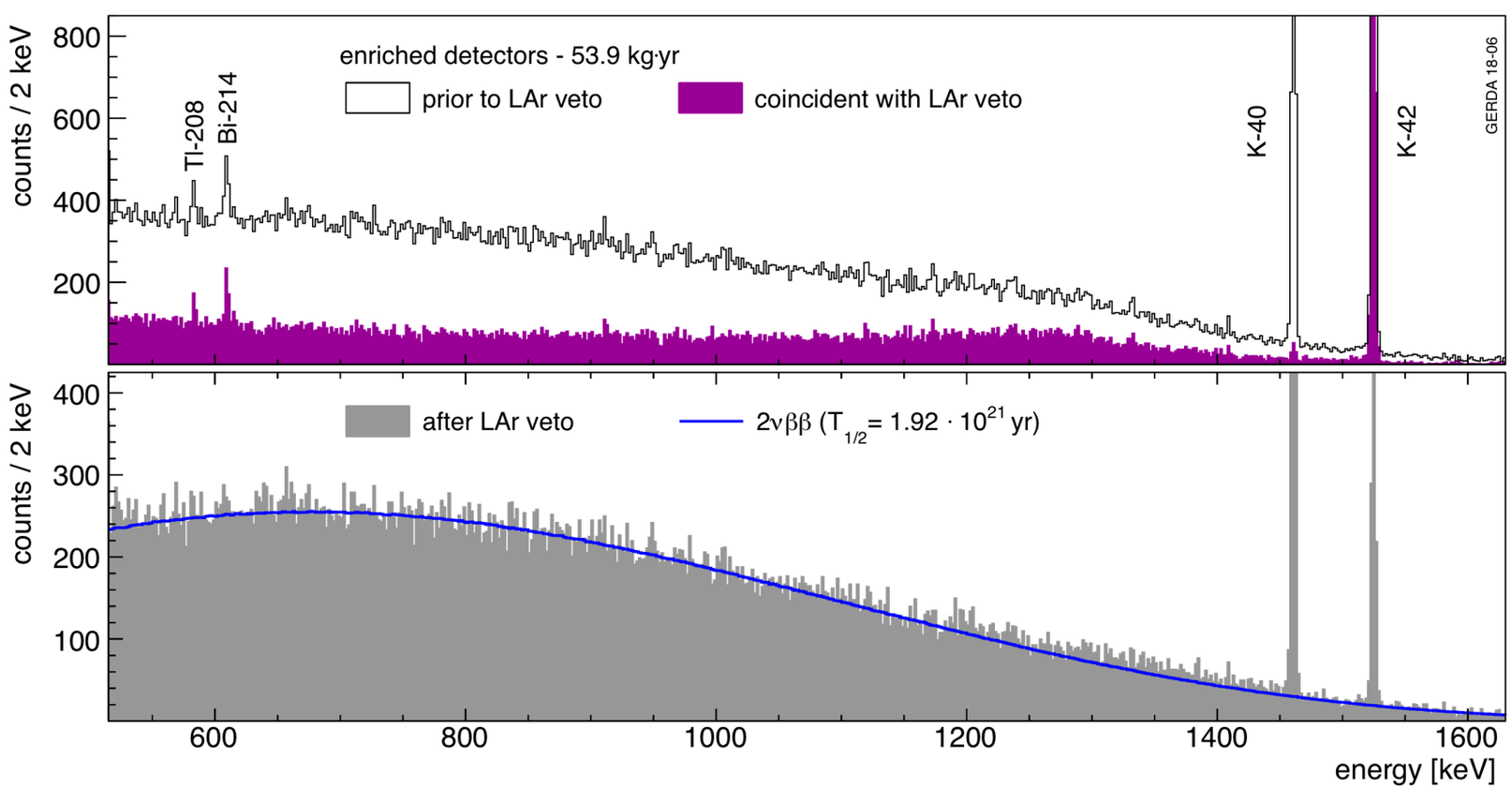
Mean and resolution corrected for E-dependance

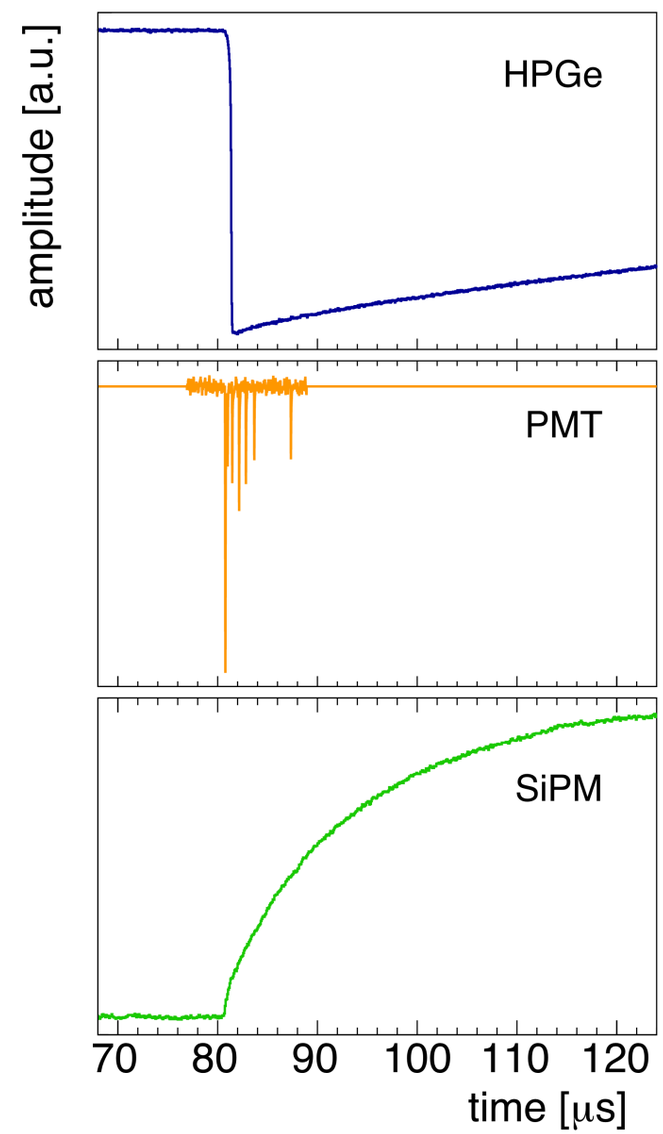
A/E normalised to 1

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 0νββ: (97.7±0.1)%

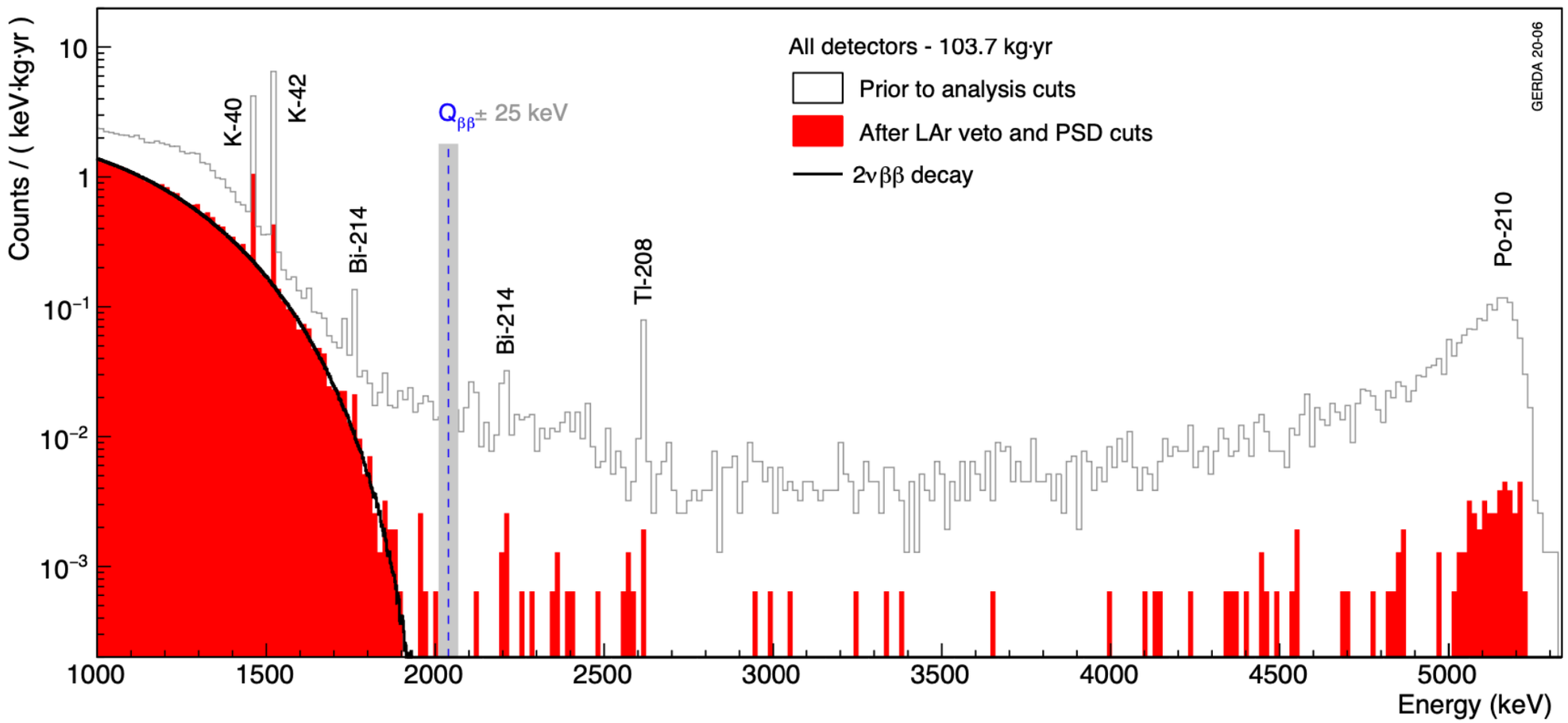




GERDA collaboration, PRL 125, 2020

DOUBLE BETA DECAY FINAL RESULTS

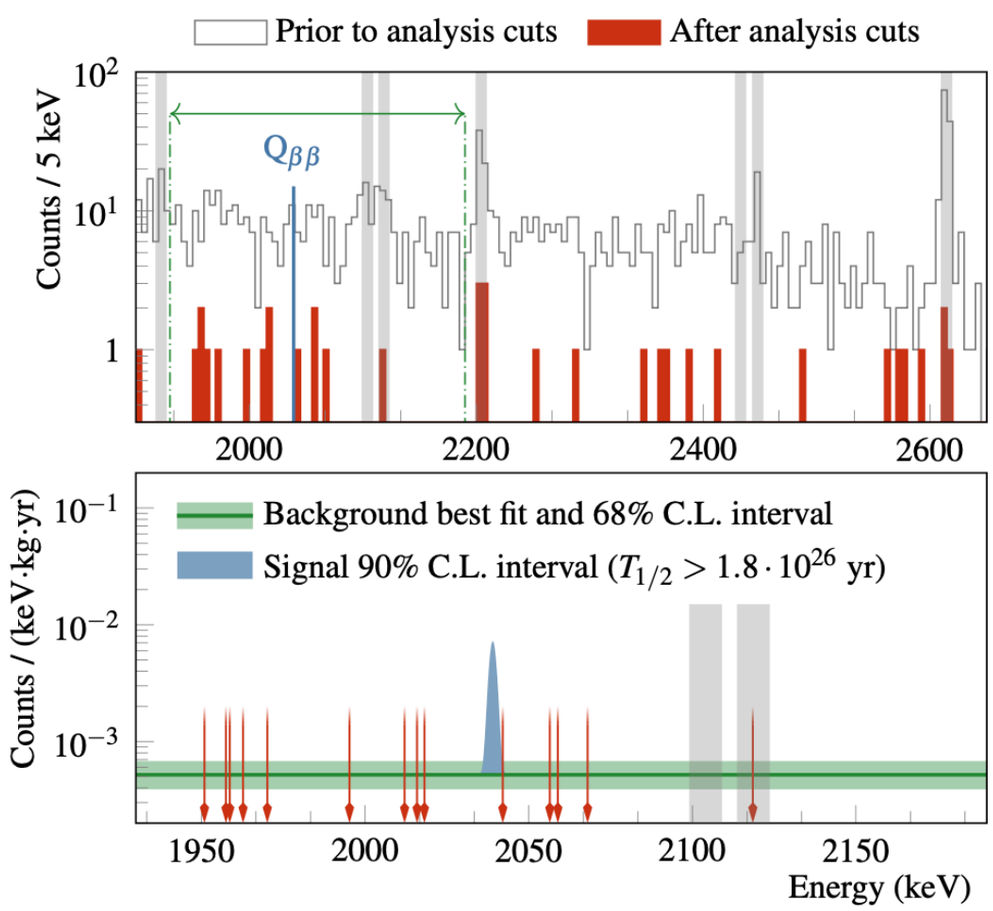
- Analysis cuts: liquid argon veto, pulse shape discrimination
- Background at low energies: dominated by 2νββ decay of ^{76}Ge
- $Q_{\beta\beta}$ ± 25 keV for blind analysis



GERDA collaboration, PRL 125, 2020

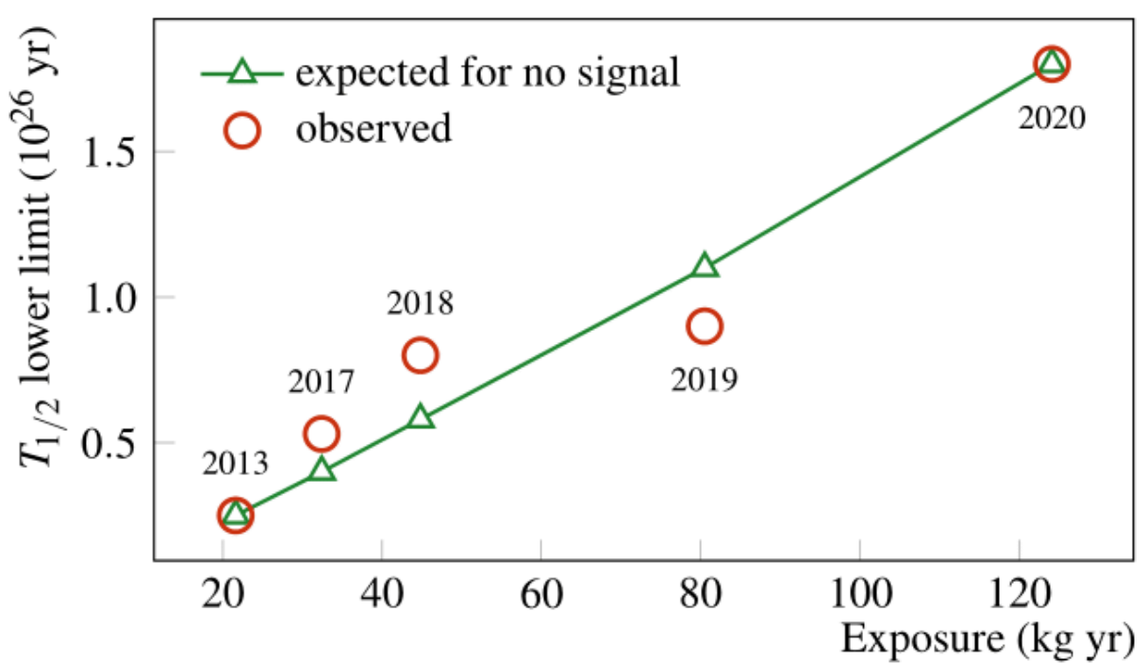
DOUBLE BETA DECAY FINAL RESULTS

- Measured $T_{1/2}$ of the 2νββ-decay: (1.926±0.094) x 10^{21} y
- Background level: 5.2 x 10^{-4} events/(keV kg y) in 230 keV window around Q-value



Constraints on the ^{76}Ge 0νββ-decay

$T_{1/2} > 1.8 \times 10^{26}$ y (90% CL); $m_{\beta\beta} < 80 - 182$ meV

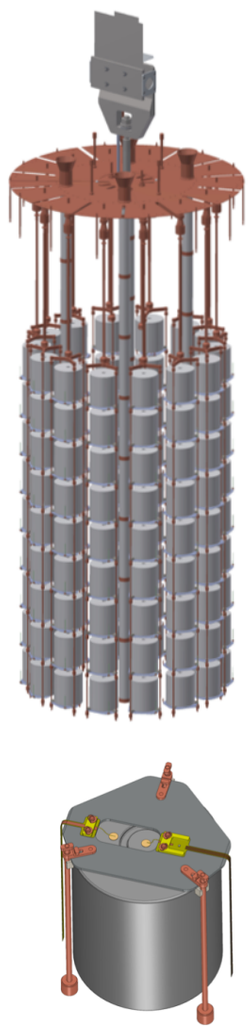


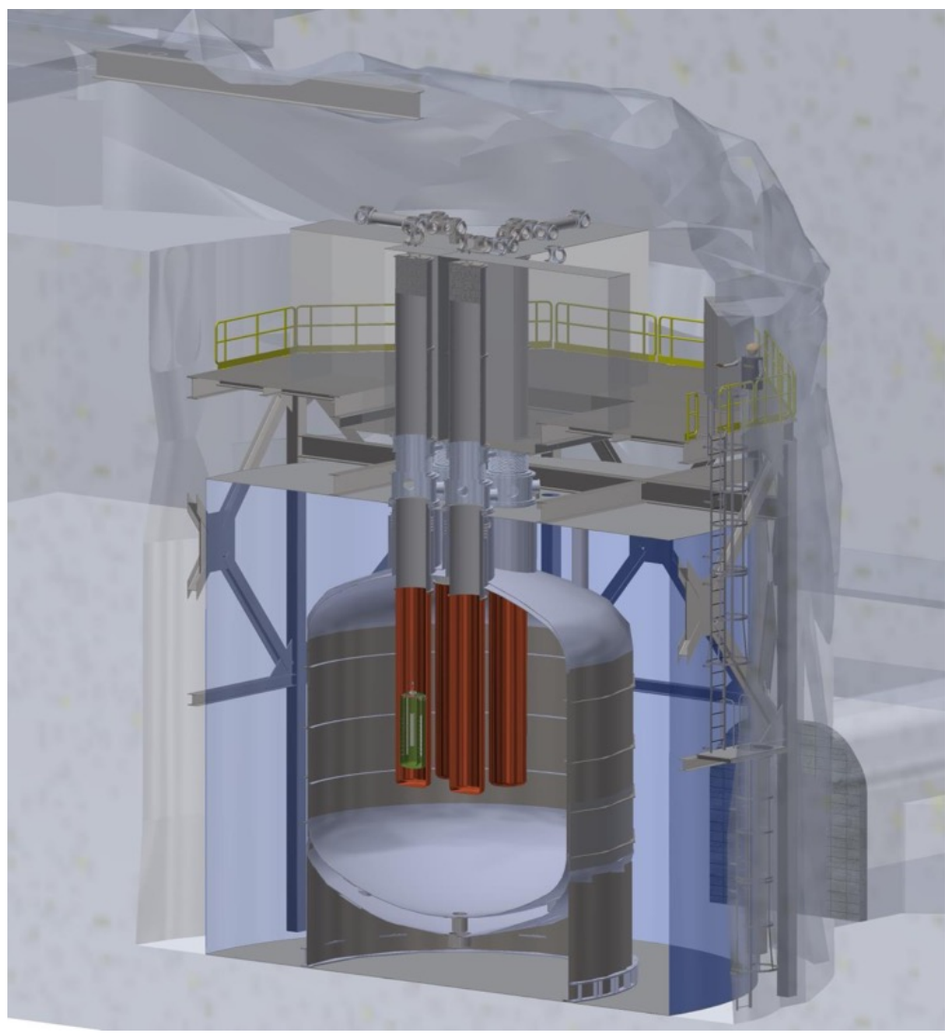
THE FUTURE: LEGEND

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

- Large enriched germanium experiment for 0νββ decay
- GERDA + Majorana + new groups
  - LEGEND-200: 200 kg in existing (upgraded) GERDA infrastructure at LNGS
  - Background goal: 0.6 events/(FWHM t y)
  - LEGEND-1000: 1000 kg, staged, 4 modules
  - Background goal: 0.025 events/(FWHM t y)



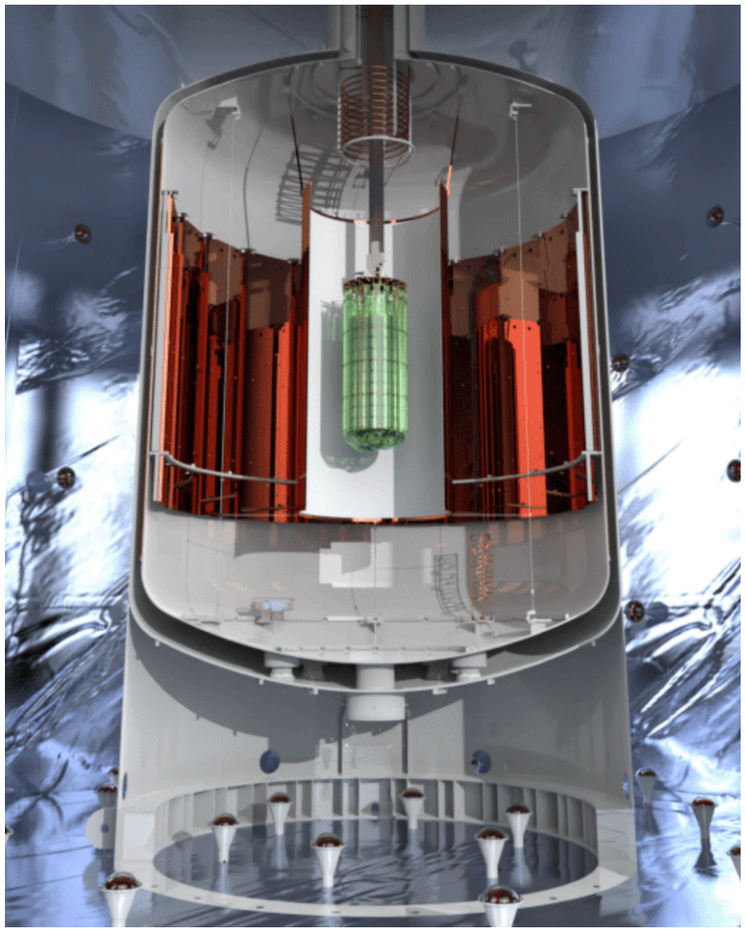


LEGEND-1000 at SNOLAB

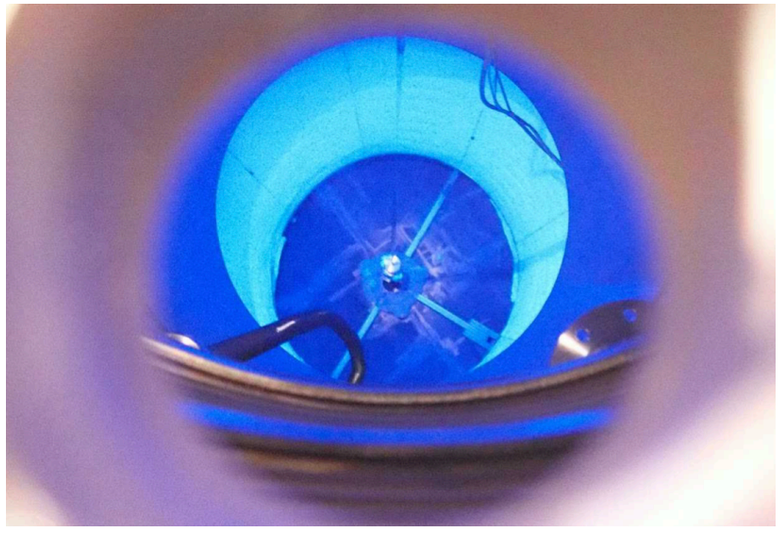
STATUS OF LEGEND-200

- Under construction at LNGS in modified GERDA infrastructure
- 70 kg from GERDA & Majorana, plus 130 kg newly produced ICPC detectors
- Fist run to start in late 2021 or early 2022

LEGEND-200 at LNGS



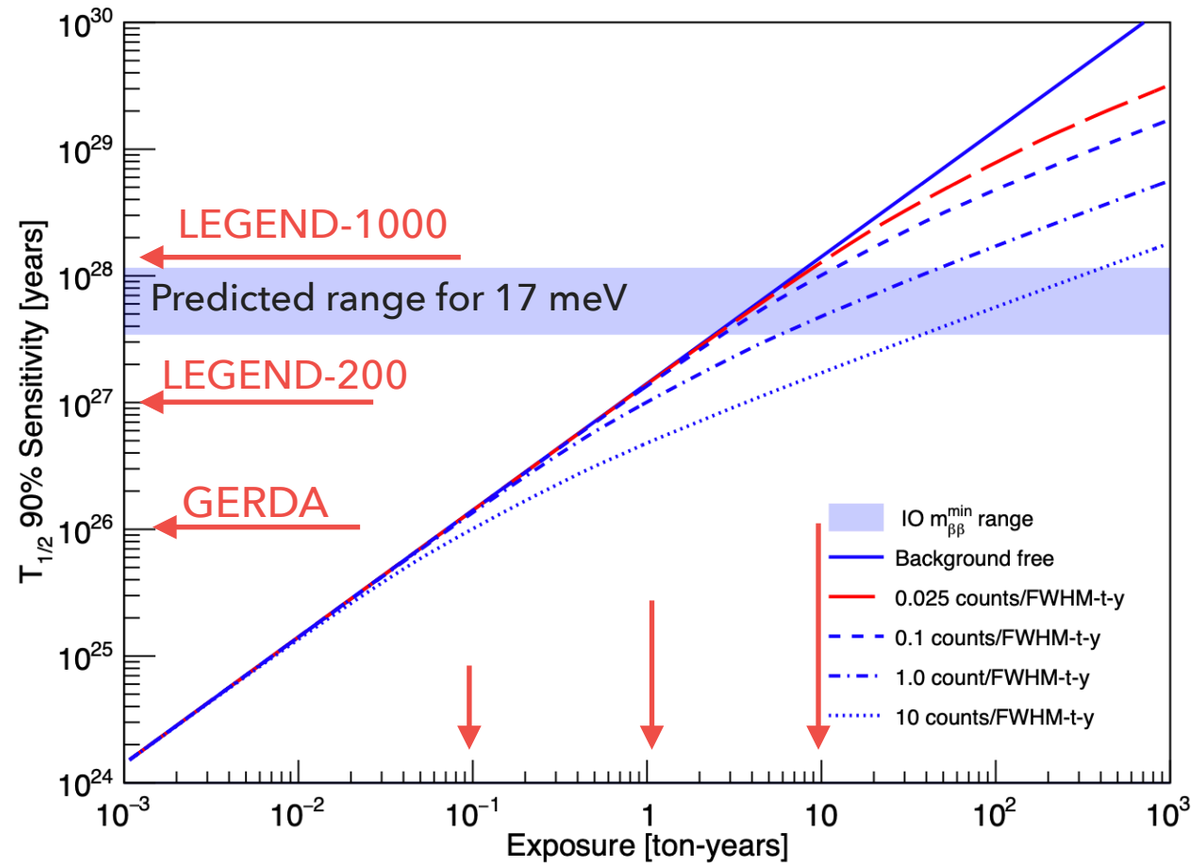
New calibration systems



In situ TPB evaporation on the WLSR

EXPECTED SENSITIVITY

- LEGEND-200: $T_{1/2} \sim 10^{27}$y
- LEGEND-1000: $T_{1/2} \sim 10^{28}$ y
- $m_{\beta\beta} \sim 17$ meV (for worst case NME)



Conceptual design of LEGEND-1000

4 independent 250 kg modules (130 kg from LEGEND-200 + 870 kg new detectors)

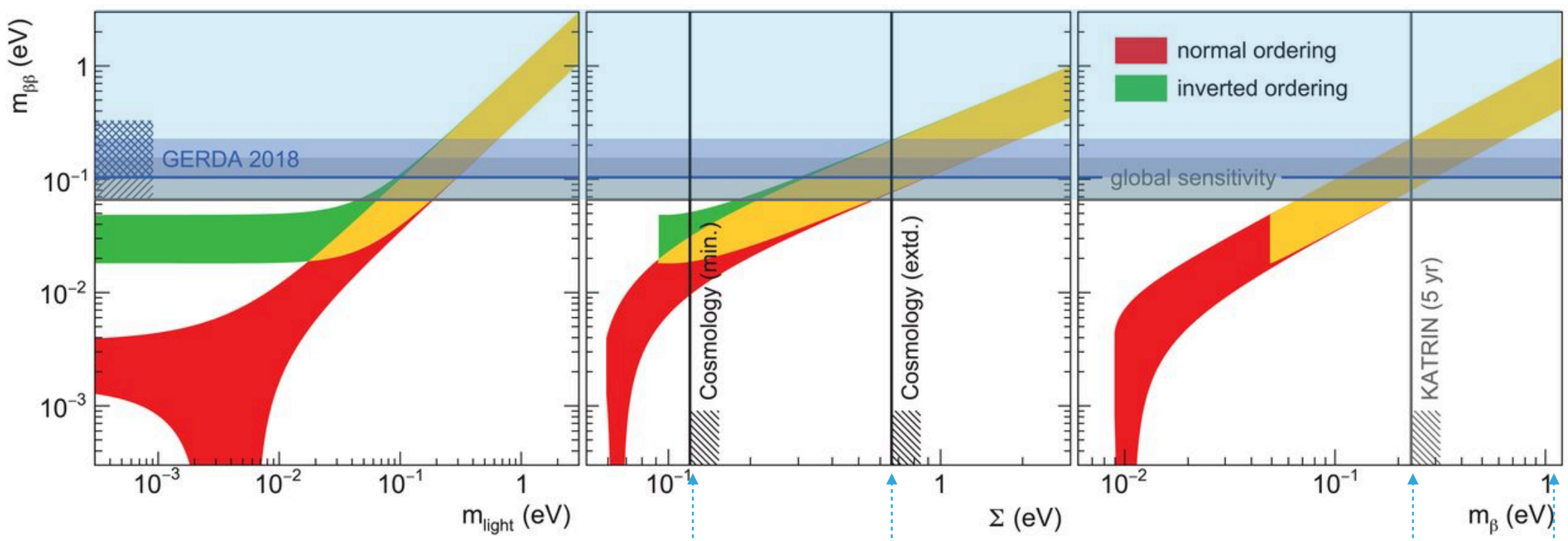
Background

GERDA: 3 events/(FWHM t y)
LEGEND-200: 0.6 events/(FWHM t y)
LEGEND-1000: 0.025 events/(FWHM t y)

MASS OBSERVABLES AND GLOBAL SENSITIVITY

- Constraints in the $m_{\beta\beta}$ parameters space in the 3 light ν scenario
- Global sensitivity from 0νββ-experiments & constraints from direct searches & cosmology

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



$$\Sigma = \sum_i m_i$$

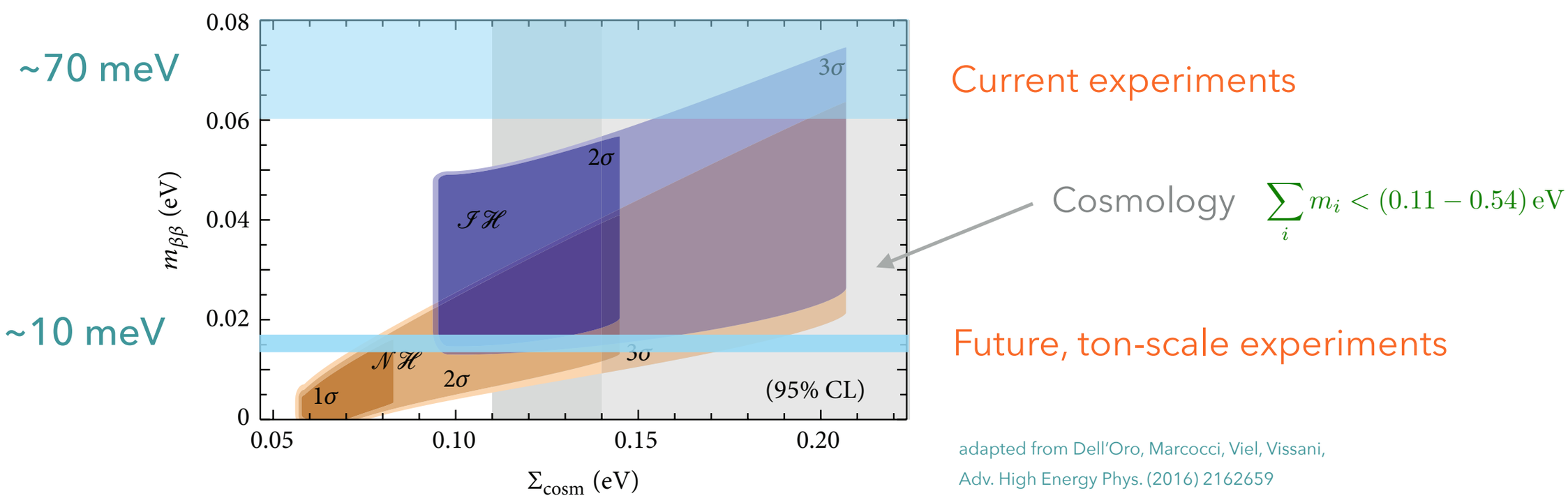
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

0.11 eV 0.66 eV 0.23 eV 1.1 eV

GERDA collaboration, Science 365, Sept 2019

SUMMARY AND OUTLOOK

- Ninety years after Pauli postulated his *"silly child"*: many open questions in neutrino physics
- 0νββ-decay: excellent tool to test LNV and the nature of neutrinos (Dirac vs Majorana)
- Existing experiments probe $T_{1/2}$ up to ~ 1.8 x 10^{26} years, with $T_{1/2} \sim (0.1\ \mathrm{eV}/m_\nu)^2 \times 10^{26}$ y
- Ton-scale experiments are required to cover the **inverted mass ordering scenario**
  - Several technologies move into this direction
- Much larger experiments needed to probe the **normal mass ordering**



adapted from Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

THANK YOU

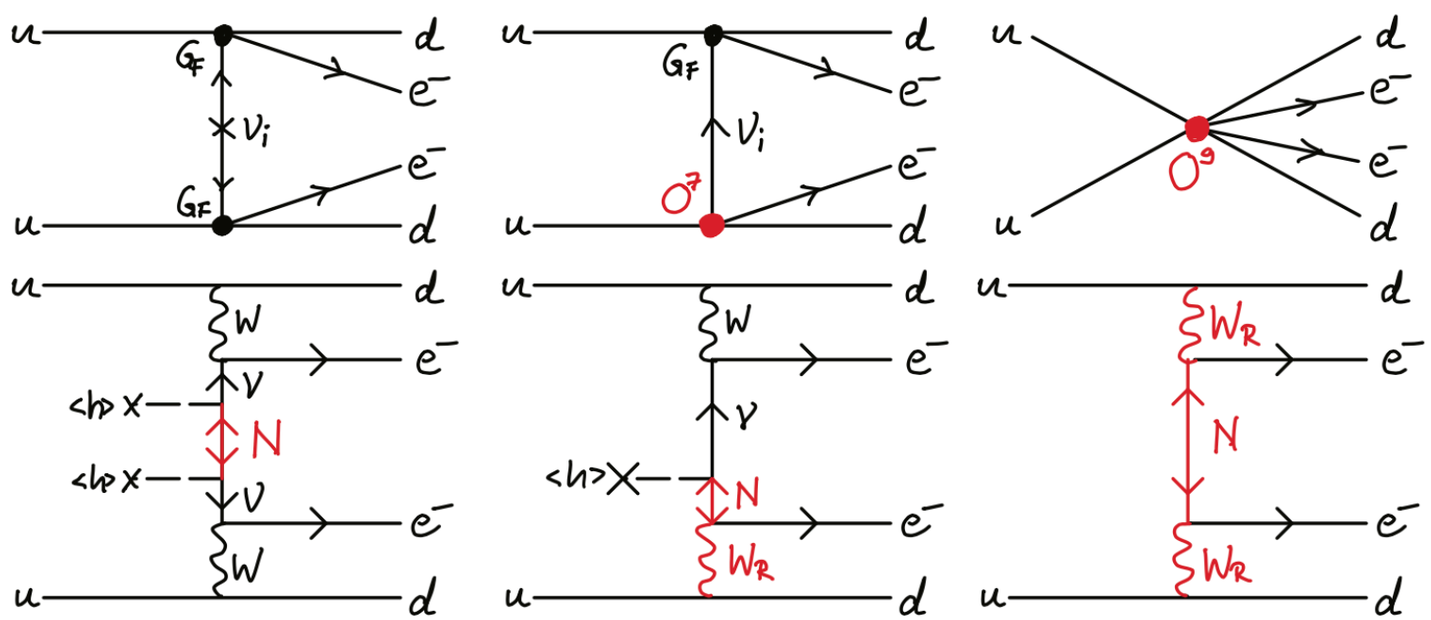
OTHER MECHANISMS FOR DOUBLE BETA DECAY

- LNV processes in extensions of the Standard Model generically contribute to 0νββ-decay (light or heavy sterile neutrinos, LR symmetric models, R-parity violating SUSY, leptoquarks, etc)
- Often classified as short- and long range processes, depending on the mass of the particles mediating the process (whether lighter or heavier than the momentum exchange scale ~ O(100 MeV))
- In the effective Lagrangian picture, the effects at low energies can be summarised in terms of higher order operators, added to the SM Lagrangian

5-dim Weinberg operator, standard mechanism

7-dim operator, long-range contributions

9-dim operator, short-range contributions

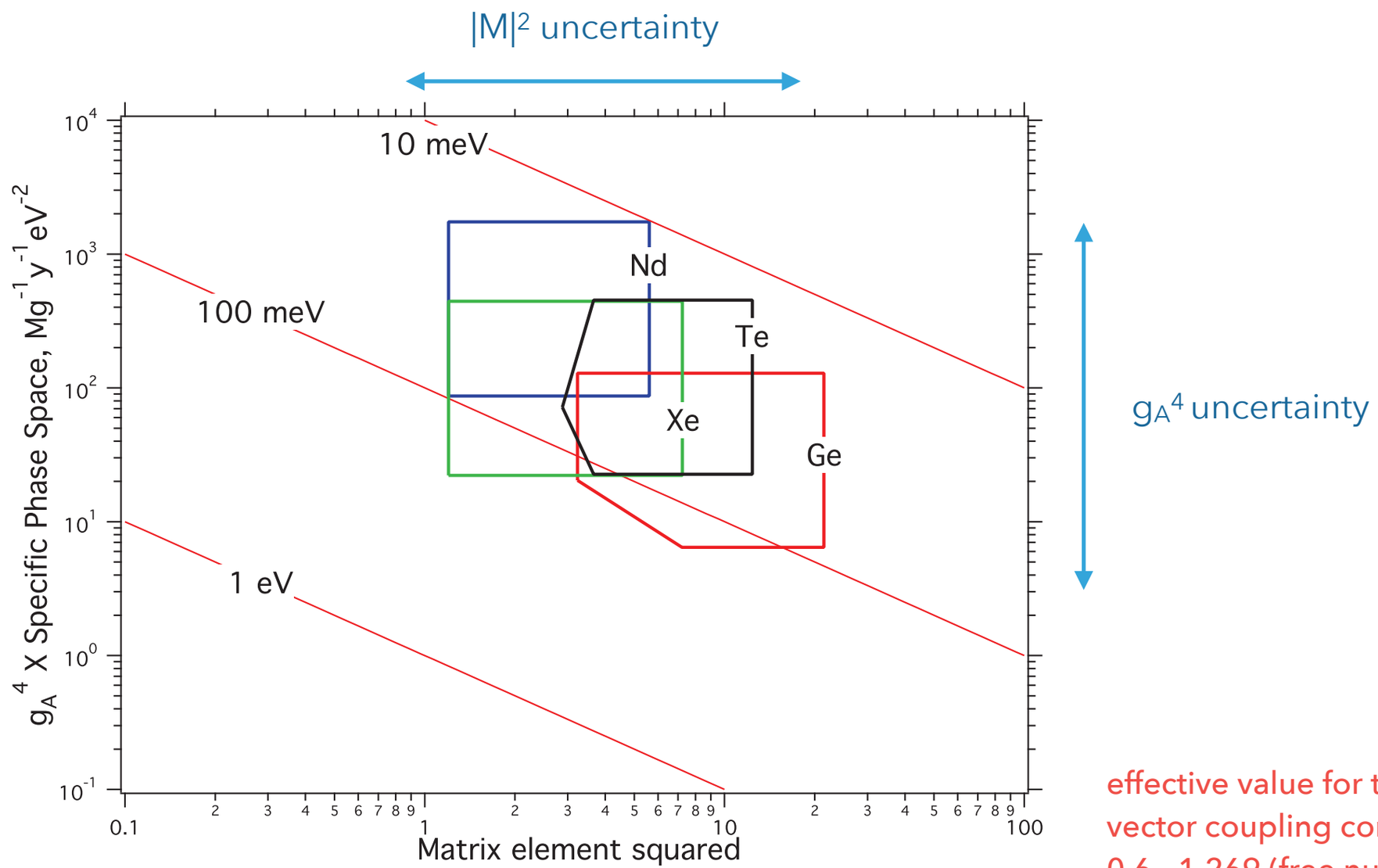


Examples from F. Deppisch, A modern introduction to neutrino physics: the lowest-order contributions beyond the standard mechanism

ISOTOPES AND SENSITIVITY TO DOUBLE BETA DECAY

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

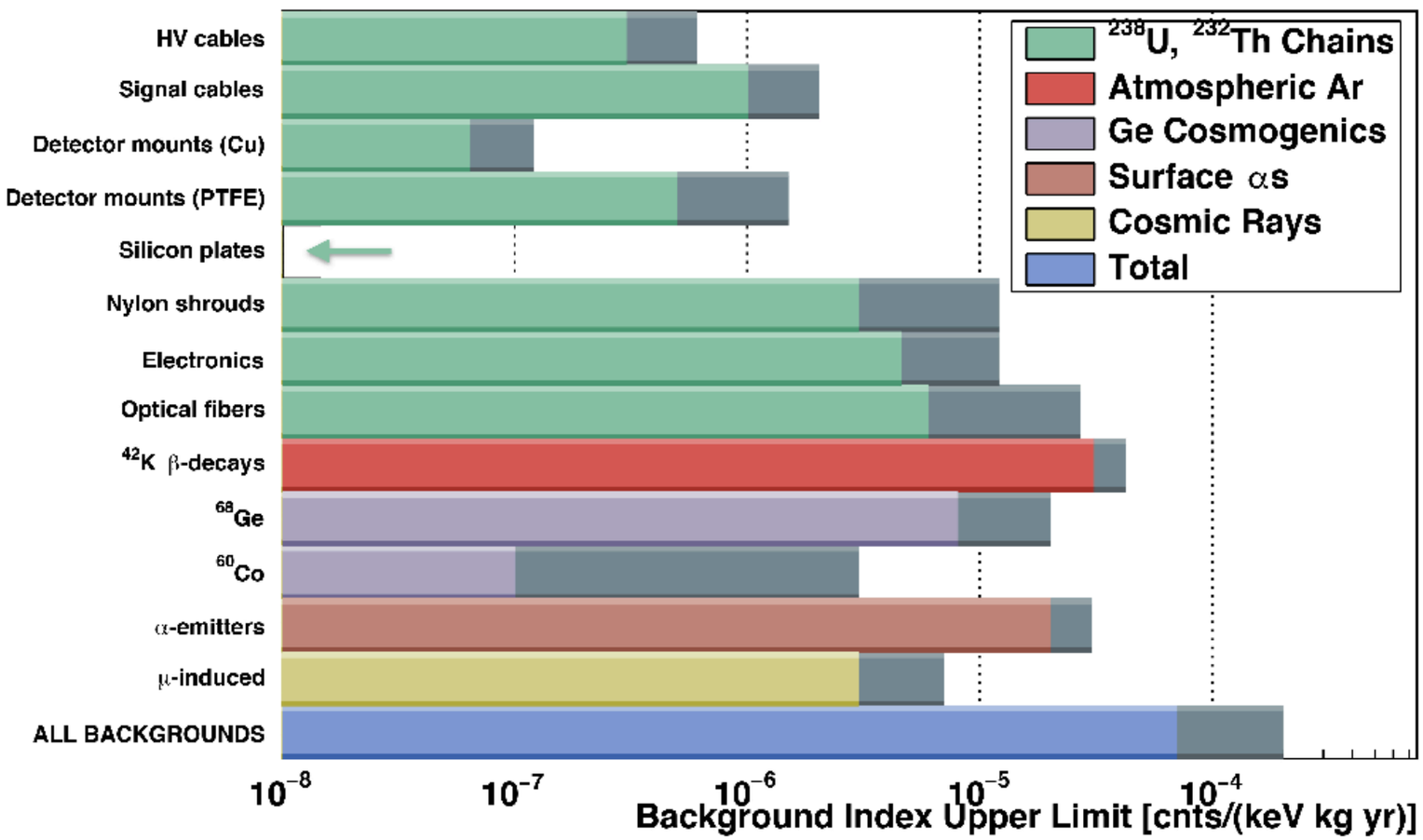
$$g_A^4 \ln(2) \frac{N_A}{A m_e^2} G^{0\nu}$$



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

BACKGROUND EXPECTATION IN LEGEND-200



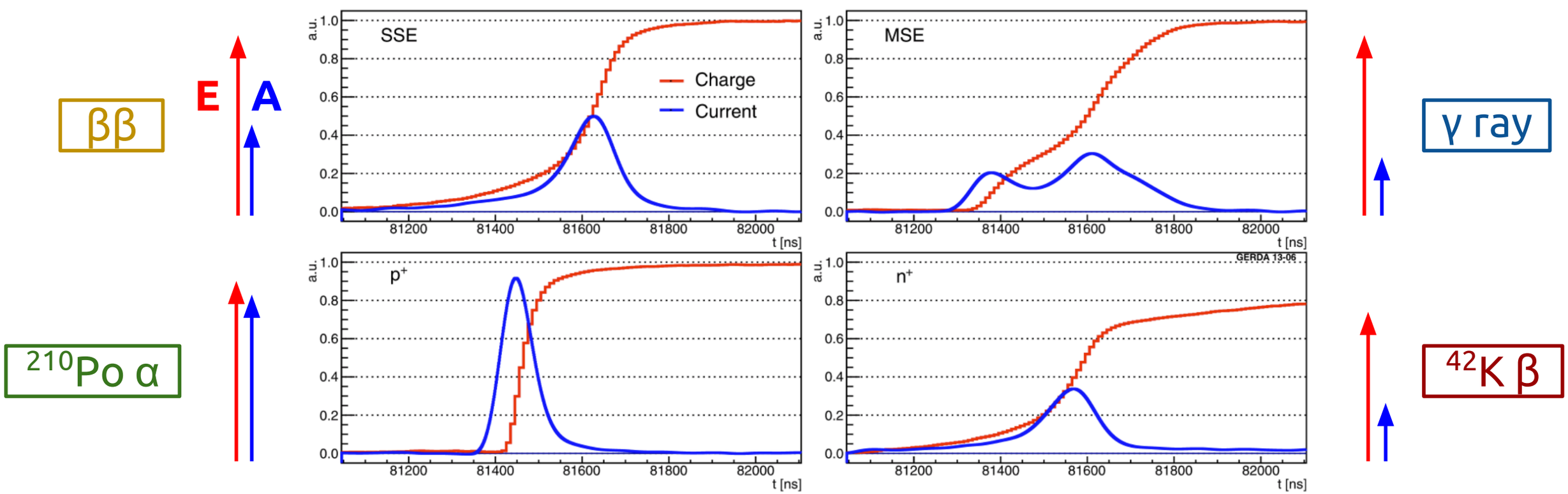
Monte Carlo simulations based on experimental data and material assays. Background rate after anti-coin., PSD, LAr veto cuts.

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)

GERDA PULSE SHAPE DISCRIMINATION

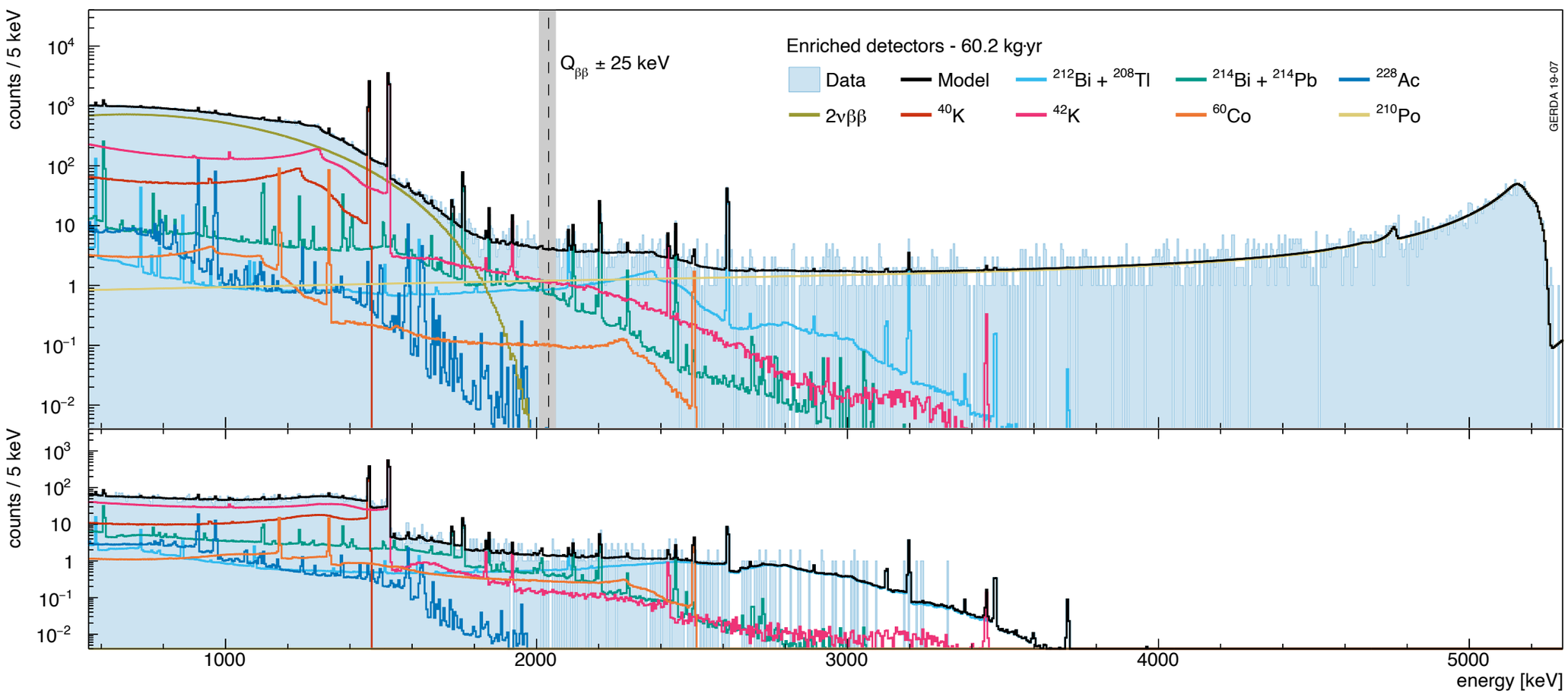
- A/E: amplitude of the current pulse over energy
- Multiple energy depositions: multiple peaks in current pulse => decreasing A/E
- p+ surface events: shorter signals => higher A/E



EPJC 73 (2013) 2583

GERDA BACKGROUND MODEL

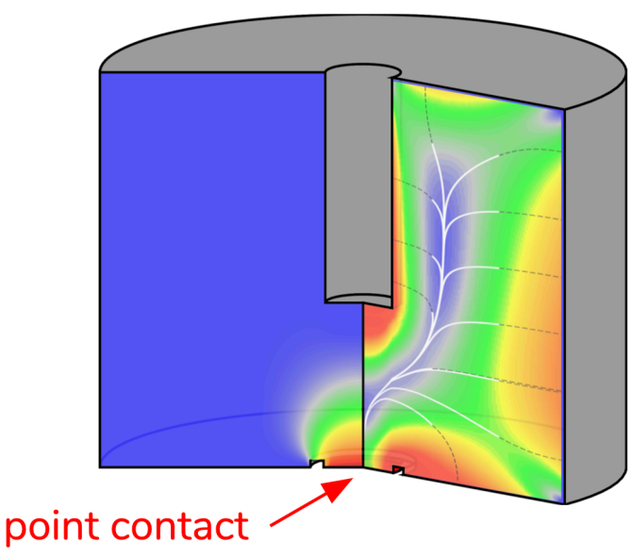
- Intrinsic 2νββ-events, ^{39}Ar, ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact



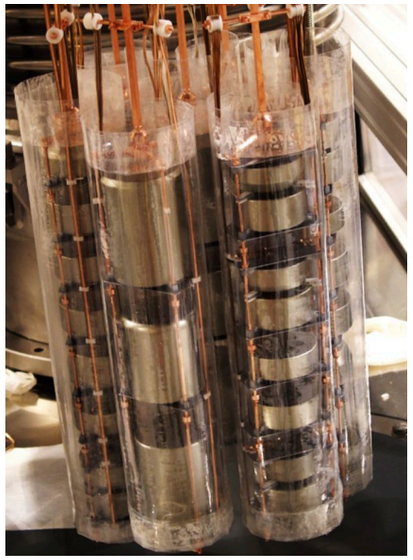
GERDA collaboration, arXiv:1909.02522

INVERTED COAXIAL DETECTORS

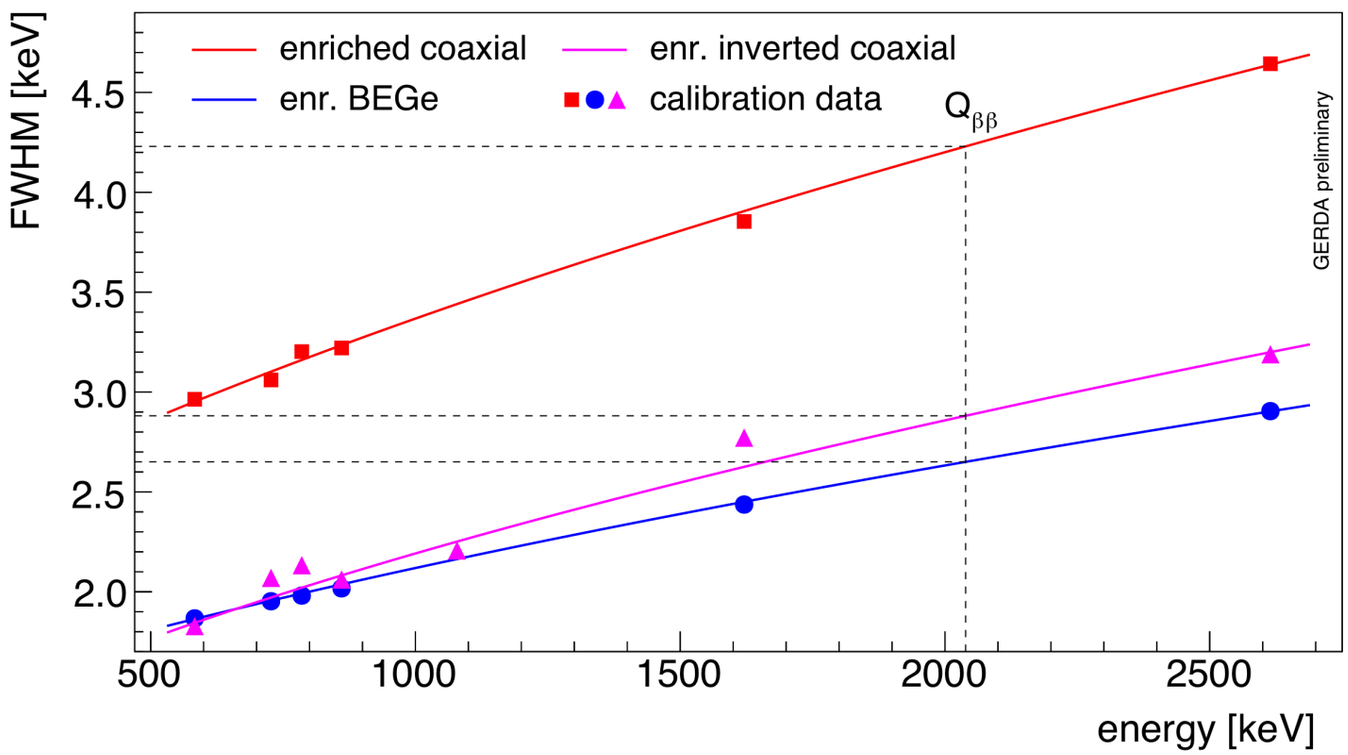
- Large point-contact detectors with ~ 3 kg mass, excellent PSD performance
- First 5 enriched IC detectors installed in GERDA spring 2018; baseline for LEGEND



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

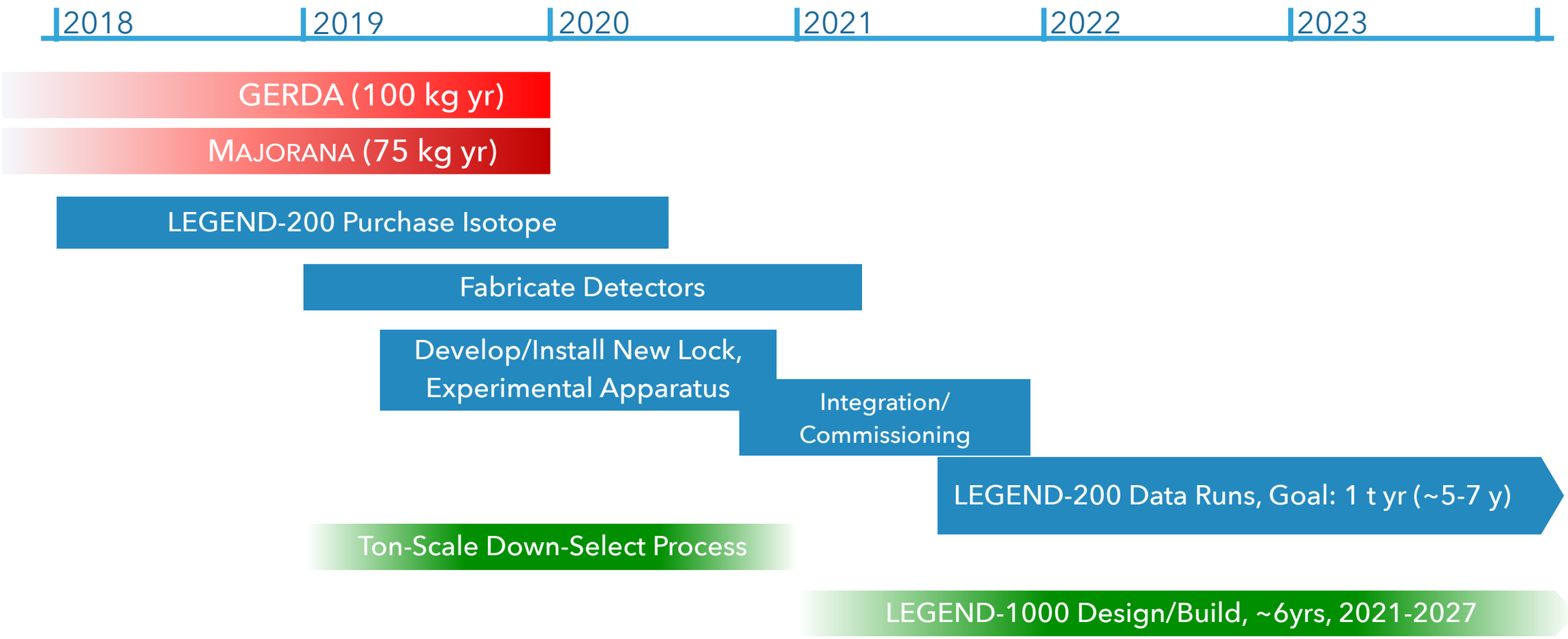


Detector mass increase: 35.6 kg -> 44.2 kg



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

TIME SCALE FOR GERDA, MAJORANA AND LEGEND



Earliest LEGEND-1000 Data Start: 2025/6

LEADING RESULTS: OVERVIEW

Experiment	Isotope	FWHM [keV]	$T_{1/2}$ [10^{26} y]	$m_{\beta\beta}$ [meV]
CUORE	^{130}Te	7.4	0.15	162-757
CUPID-0	^{82}Se	23	0.024	394-810
EXO-200	^{136}Xe	71	0.18	93-287
KamLAND-Zen	^{136}Xe	270	1.1	76-234
GERDA	^{76}Ge	3.3	1.8	80-182
Majorana	^{76}Ge	2.5	0.27	157-346

FUTURE PROJECTS: A SELECTION

$$|m_{\beta\beta}| \propto \left(\frac{B \cdot \Delta E}{M \cdot t}\right)^{\frac{1}{4}}$$

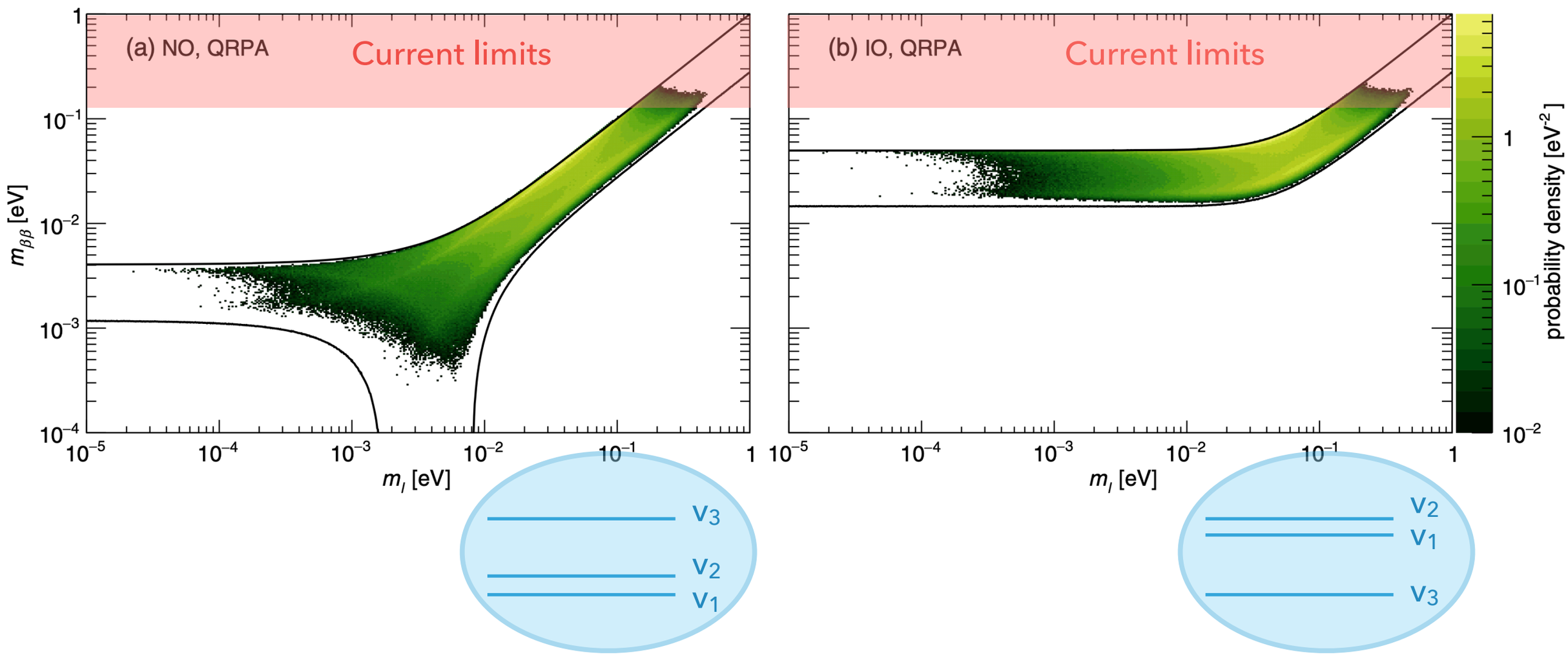
Experiment	Isotope	Iso mass [kg]	FWHM [keV]	$T_{1/2}$ [10^{27} y]	$m_{\beta\beta}$ [meV]
CUPID	^{130}Te	543	5	2.1	13-31
CUPID	^{82}Se	336	5	2.6	8-38
nEXO	^{136}Xe	4500	59	9	7-21
KamLAND2-Zen	^{136}Xe	1000	141	0.6	25-70
DARWIN	^{136}Xe	1068	20	2.4	11-46
PandaX-III	^{136}Xe	901	24	1.0	20-55
LEGEND-200	^{76}Ge	175	3	1	34-74
LEGEND-1000	^{76}Ge	873	3	6	11-28
SuperNEMO	^{82}Se	100	120	0.1	58-144

- Reminder
  - Large exposures: 10 tonne x year, low background rates < 1 event/(FWHM tonne x year)
  - Good energy resolution, large Q-value, high efficiency, demonstrated technology, etc
- Essential to use multiple isotopes to make a convincing case for **LNV**

THE EFFECTIVE MAJORANA NEUTRINO MASS

- Probability distribution of $m_{\beta\beta}$ via random sampling from the distributions of mixing angles and Δm^2
- Flat priors for the Majorana phases

Agostini, Benato, Detwiler, PRD 96, 2017



NEUTRINO MASSES

- Three main methods: direct mass measurements, 0νββ-decay, cosmology
  - the observation of flavour oscillations imply *a lower bound on the mass of the heavier neutrino*
  - depending on the mass ordering, this lower bound is ≈ 0.05 eV

- The most direct probe: precision measurements of β-decays

$$^{3}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + e^{-} + \bar{\nu}_e$$

- The effect of a non-zero neutrino masses is observed kinematically: when a ν is produced, some of the energy exchanged in the process is spent by the non-zero neutrino mass

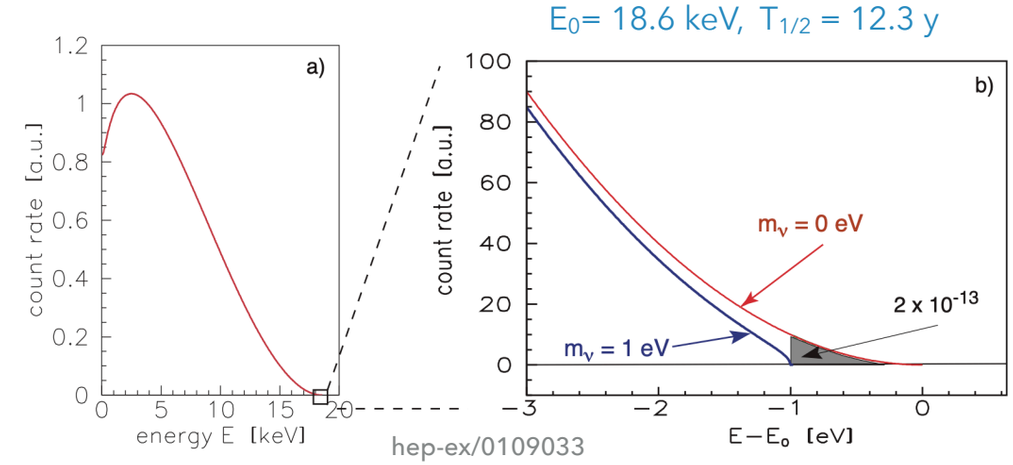
- The effects are however very small & difficult to observe

- KATRIN will probe the eff. ν_e mass down to 0.2 eV


Eur. Phys. J. C (2020) 80:264
https://doi.org/10.1140/epjc/s10052-020-7718-z
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics
First operation of the KATRIN experiment with tritium

$$m^2_{\nu_e} = \sum_i |U_{ei}|^2 m_i^2$$

E_0= 18.6 keV, $T_{1/2}$ = 12.3 y



hep-ex/0109033

NEUTRINO MASSES

- Three main methods: direct mass measurements, 0νββ-decay, cosmology
  - the observation of flavour oscillations imply *a lower bound on the mass of the heavier neutrino*
  - depending on the mass ordering, this lower bound is ≈ 0.05 eV

- Cosmology: neutrinos influence the LSS and the CMB (with the ν density ratio):

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{eff} \left(\frac{4}{11}\right)^{4/3}$$

N_{eff} = 3 ~ number of active neutrinos

- The constraints are on the sum of neutrino masses

$$\sum_i m_i$$

- Dependent on the parameters of the cosmological model (ΛCDM)
- In general, depending on which data is included (see e.g., review in PDG2020)

$$\sum_i m_i < (0.11 - 0.54)\,\mathrm{eV}$$