SEARCH FOR THE NEUTRINOLESS DOUBLE BETA DECAY - STATUS AND PROSPECTS

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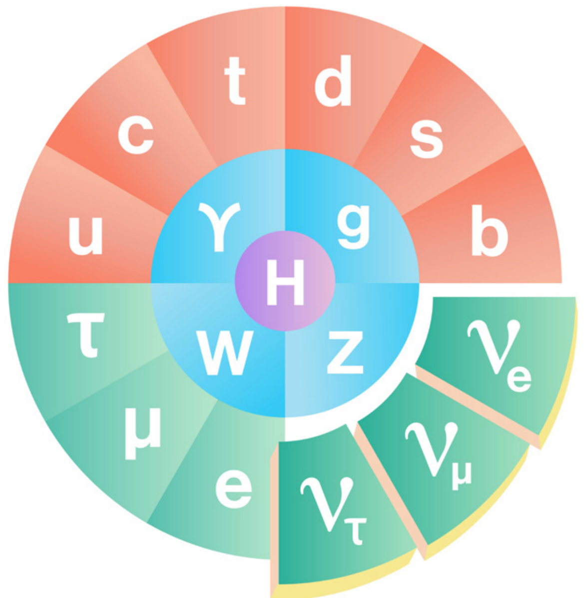
PHYSICS OF FUNDAMENTAL SYMMETRIES AND INTERACTIONS
PSI, OCTOBER 25, 2019

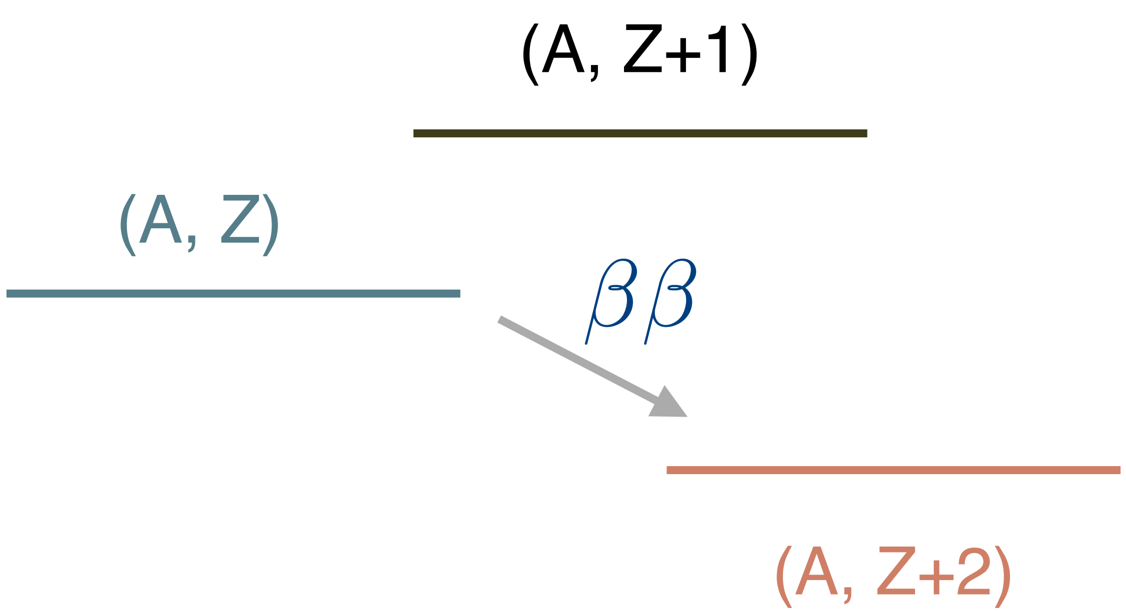
(SOME) OPEN QUESTIONS IN NEUTRINO PHYSICS

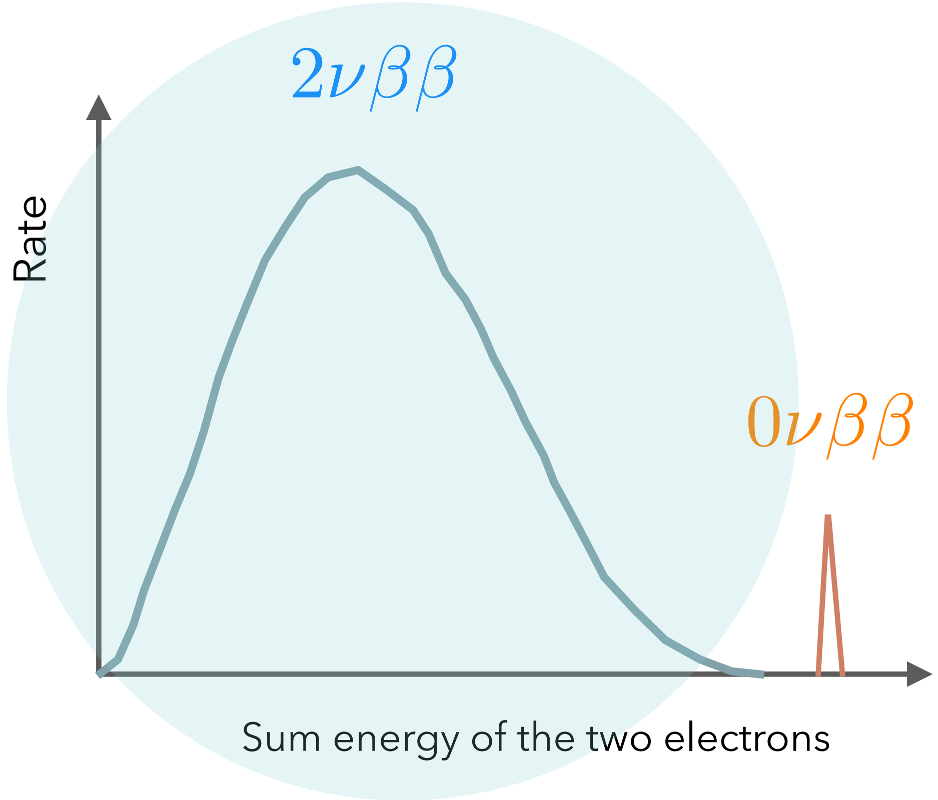


- Origin of neutrino masses beyond the SM
- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- These can be addressed with an extremely rare nuclear decay process: the double beta decay

THE DOUBLE BETA DECAY

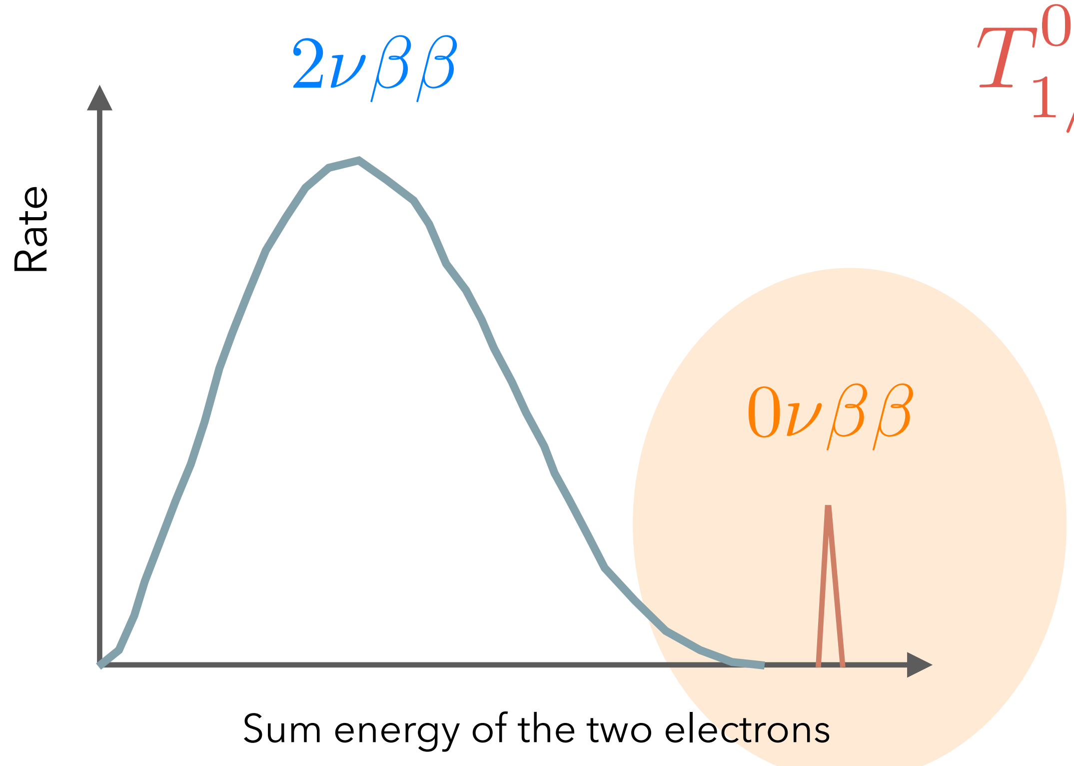
- Predicted by Maria-Goeppert Mayer in 1935
- The SM decay, with 2 neutrinos, was observed in 14 nuclei
- $T_{1/2} > 10^{18}$ y: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



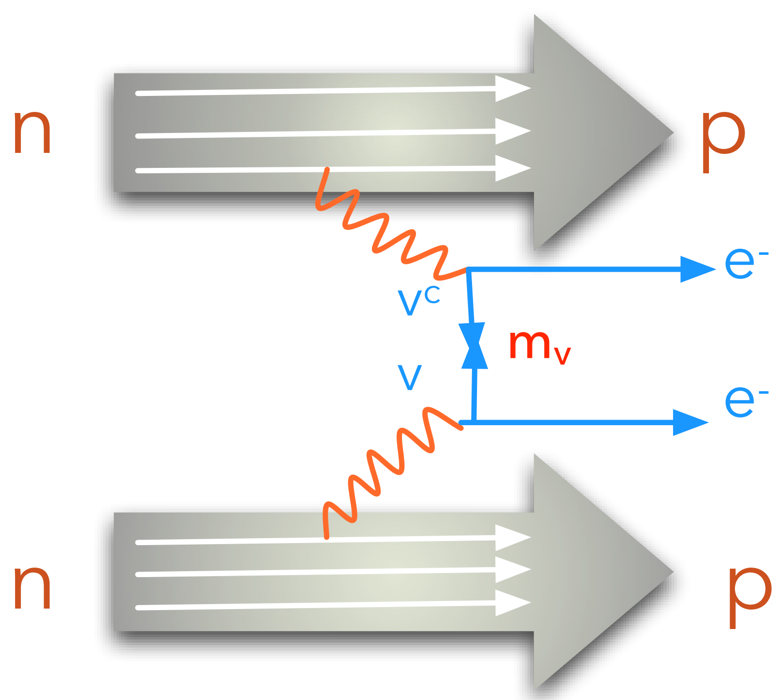


THE NEUTRINOLESS DOUBLE BETA DECAY

- Can only occur if neutrinos have mass and if they are their own anti-particles; ΔL = 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

Leptonic phase space | Axial-vector cc | Nuclear physics NME | Particle physics

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

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

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

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

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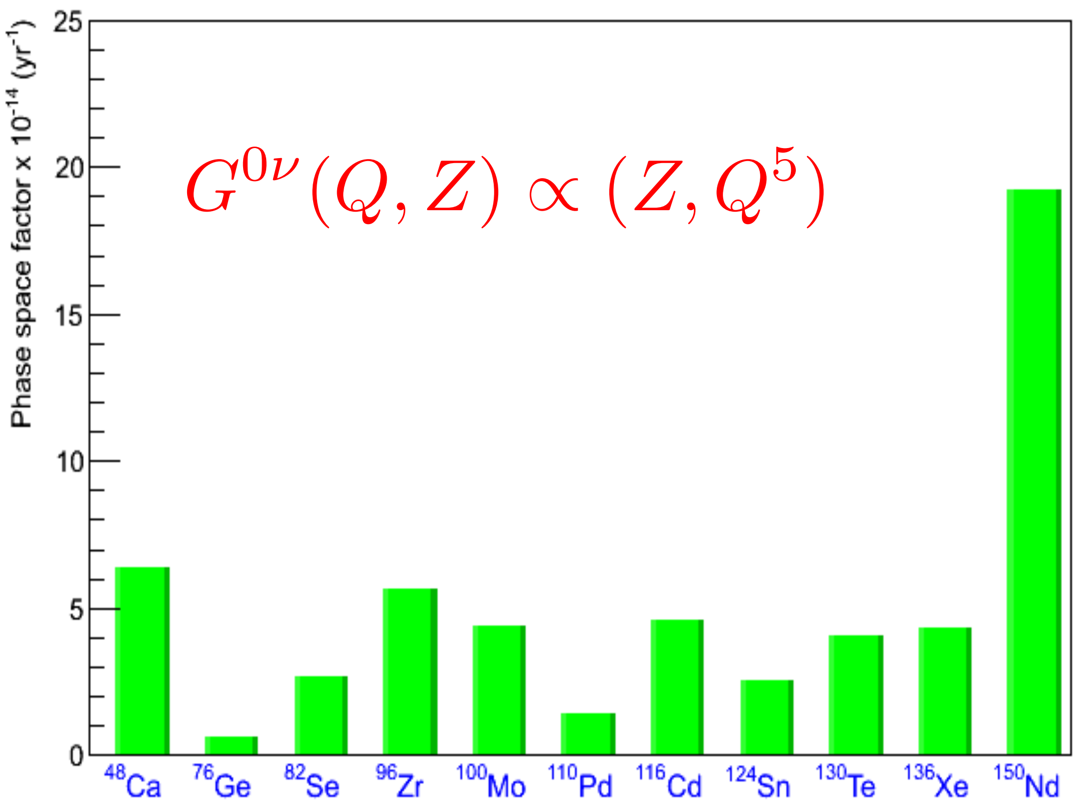
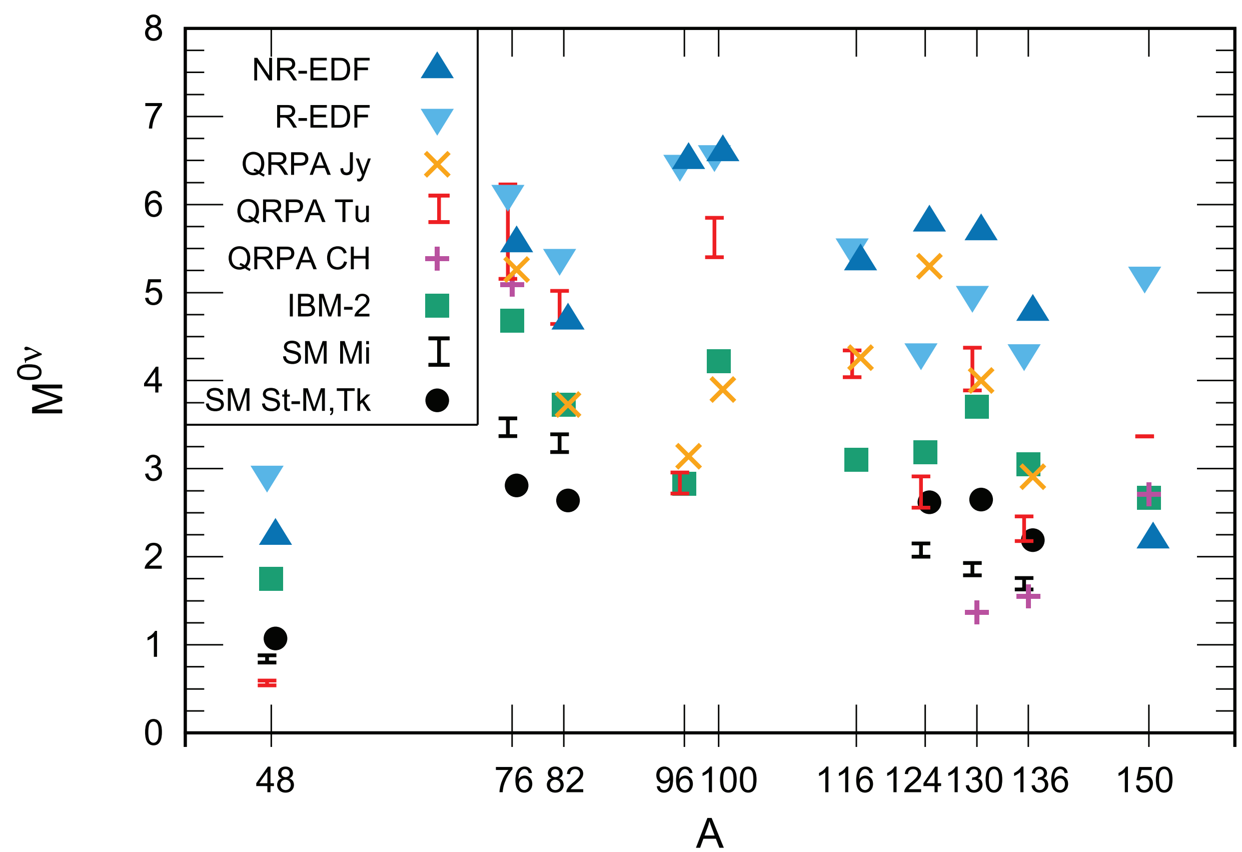
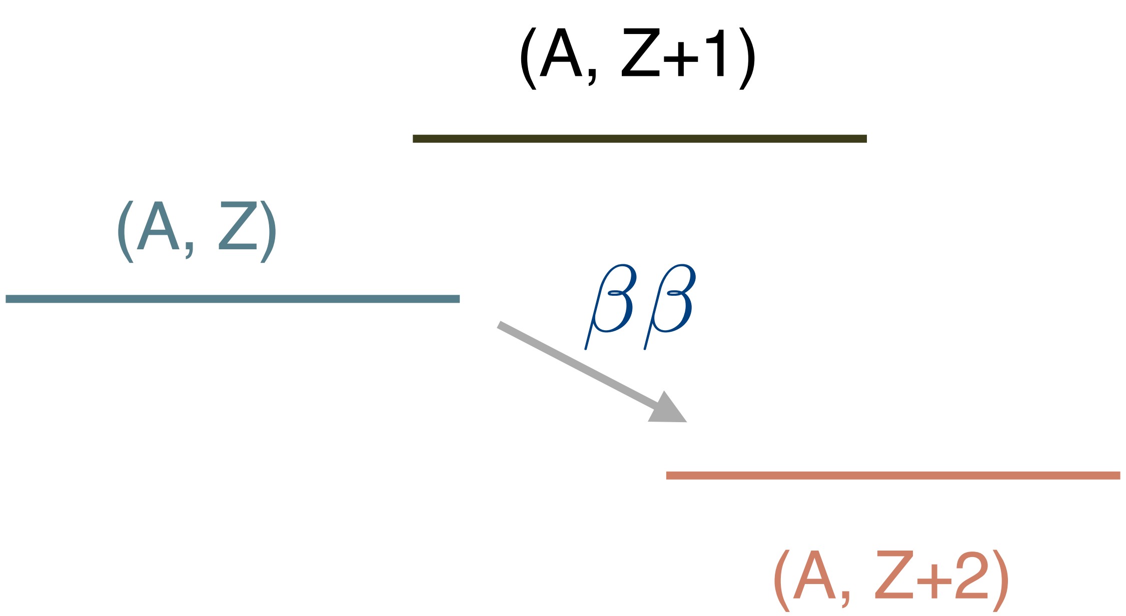




Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301

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

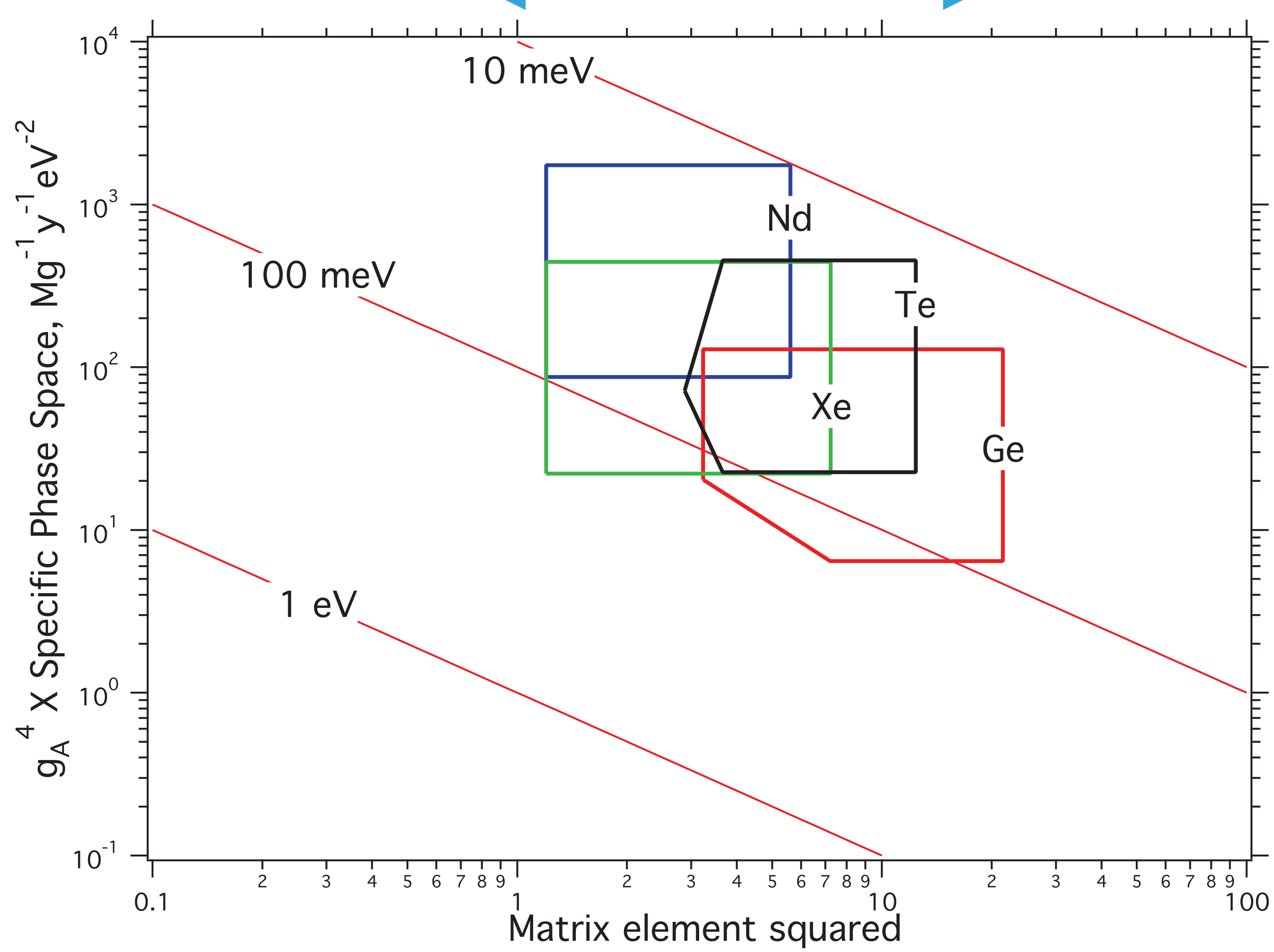
ISOTOPES AND SENSITIVITY TO THE DECAY

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

- 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

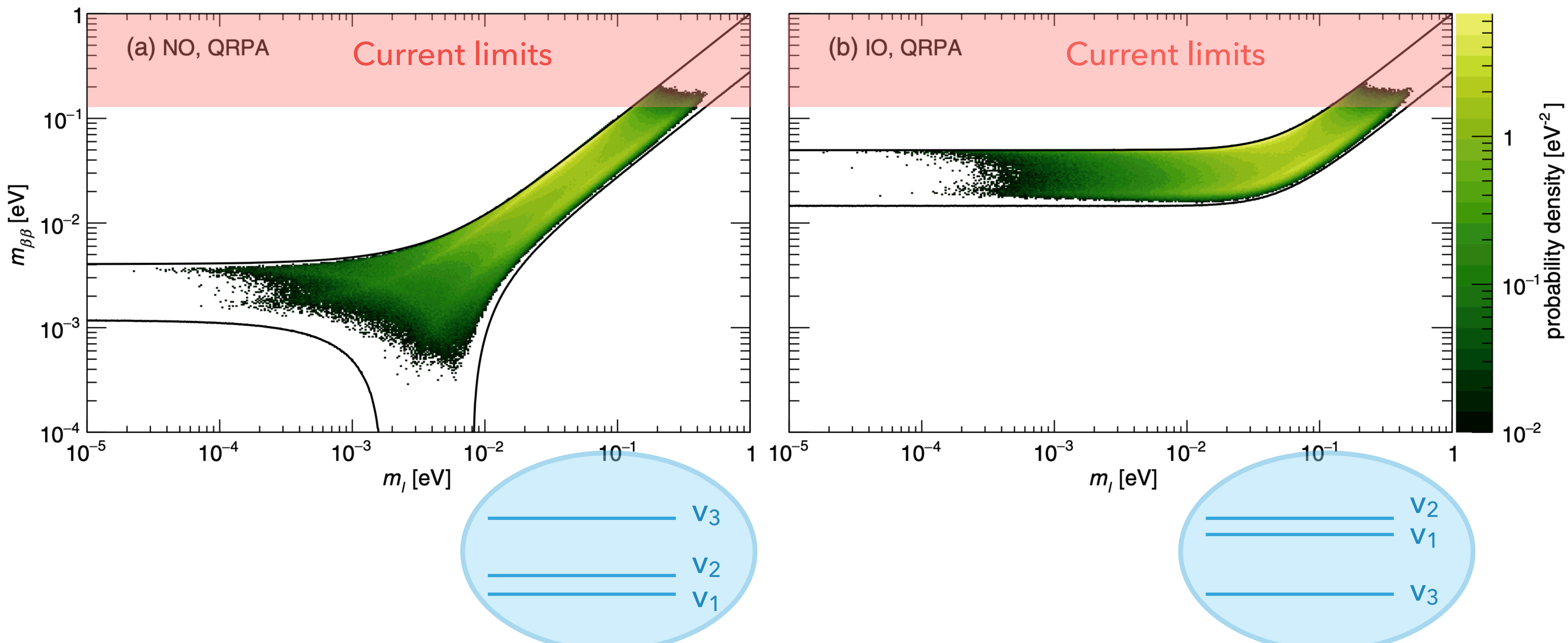
effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

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

NEUTRINO MASS EIGENSTATES AND MIXING MATRIX TERMS

- 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



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

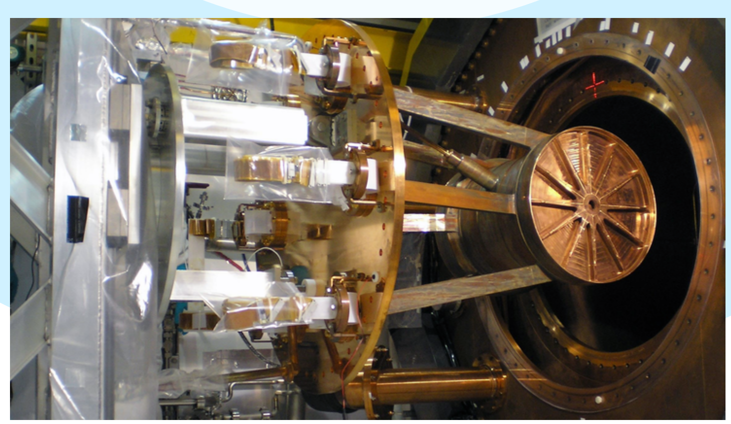
Energy of the two electrons

GERDA
MAJORANA
LEGEND
SuperNEMO

Charge

Light

KAMLAND-Zen
SNO+



nEXO, NEXT
DARWIN

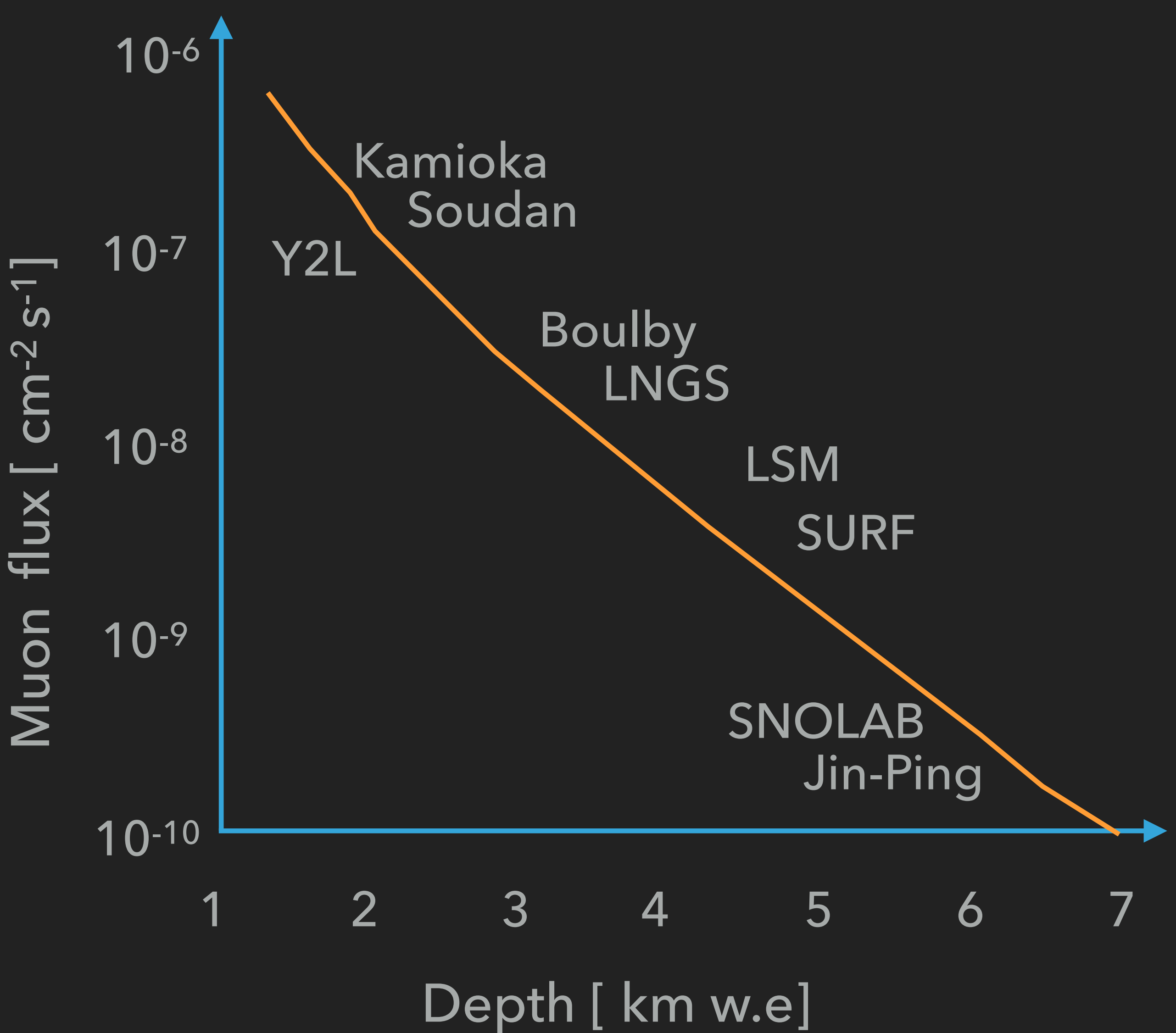
(not a complete list)

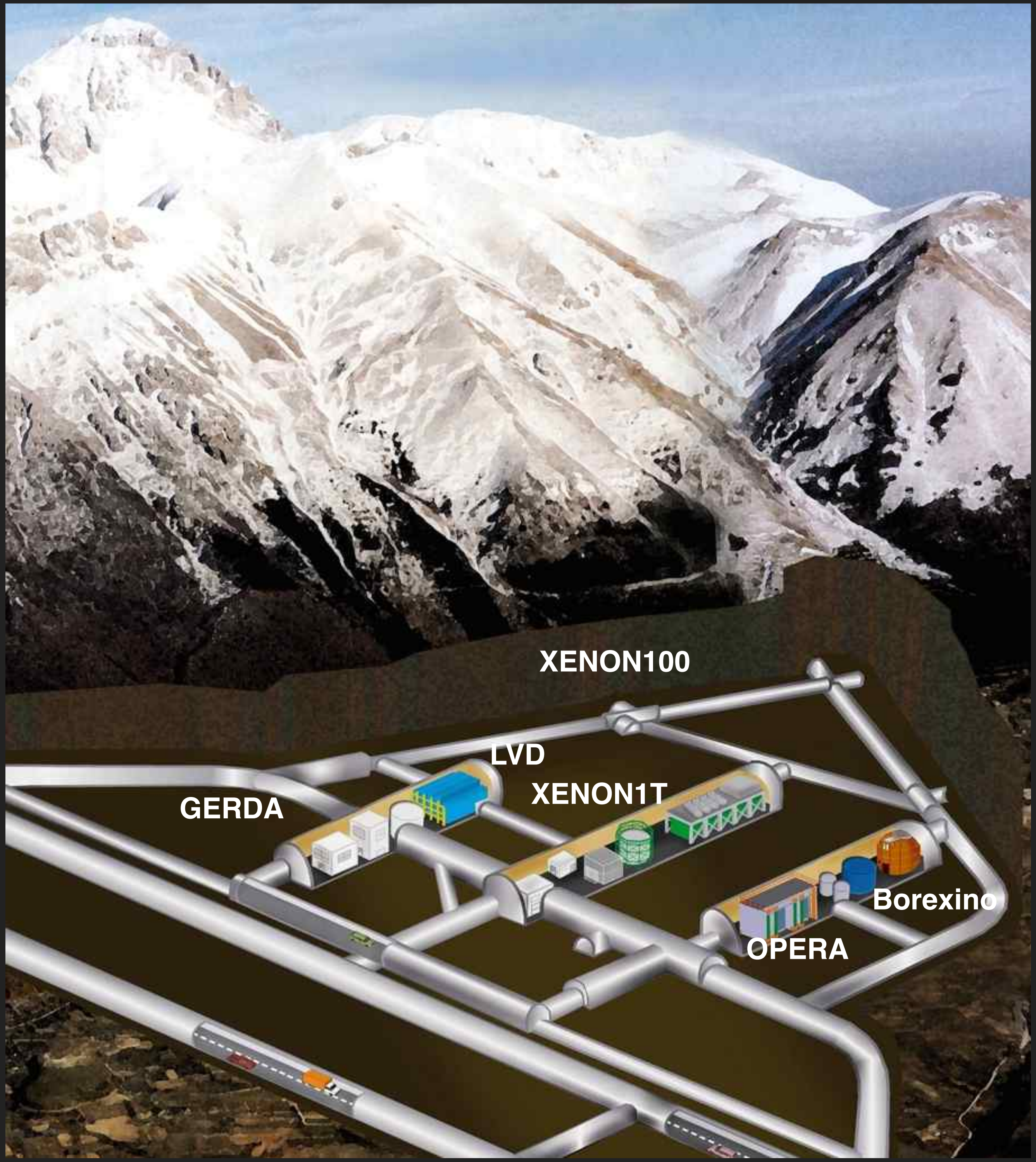
MAIN CHALLENGES

- Energy resolution (ultimate background from $2\nu\beta\beta$-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

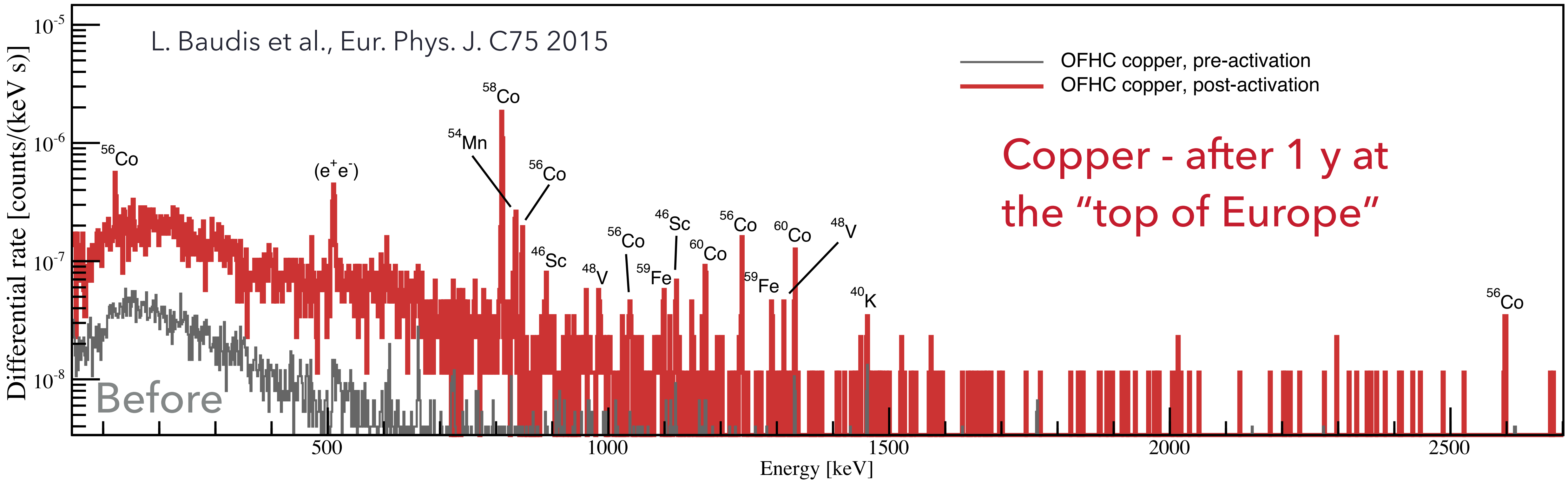
- Network of underground laboratories





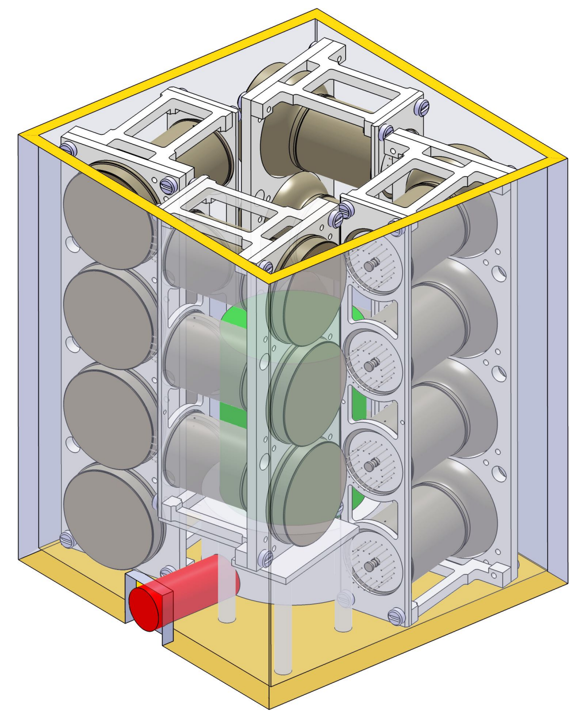
AVOID EXPOSURE TO COSMIC RAYS

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

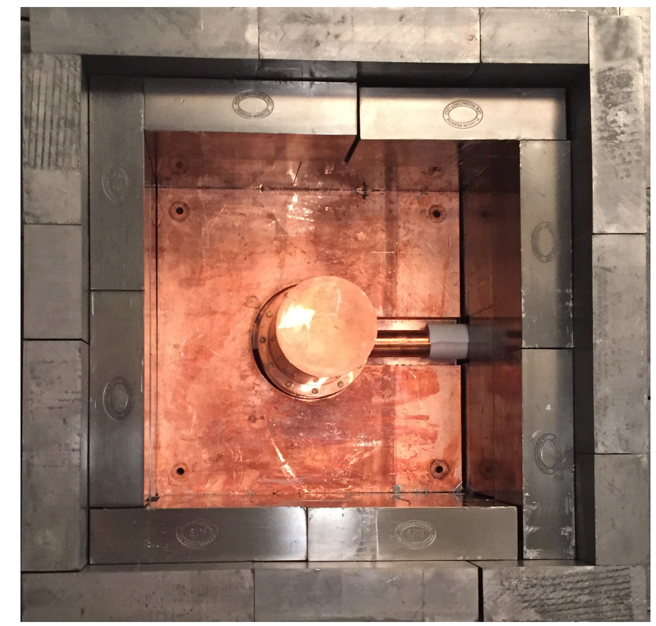


MATERIAL SCREENING AND SELECTION

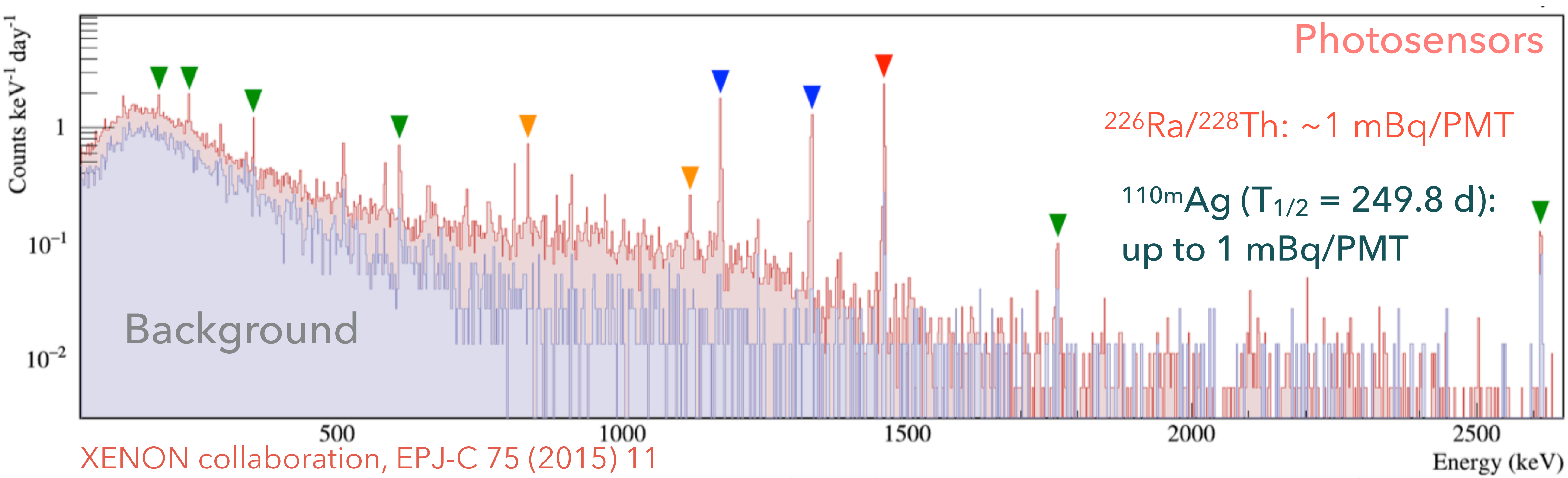
- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



Gator HPGe detector at LNGS



L. Baudis et al., JINST 6, 2011



XENON collaboration, EPJ-C 75 (2015) 11

CURRENT STATUS OF THE FIELD

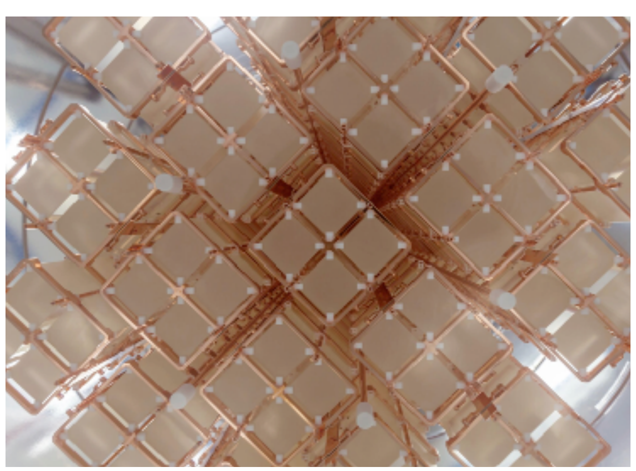
- No observation of this extremely rare nuclear decay (so far)
- Best lower limits on $T_{1/2}$: 1.07×10^{26} y (^{136}Xe), 0.9×10^{26} y (^{76}Ge), 1.5×10^{25} y (^{130}Te)

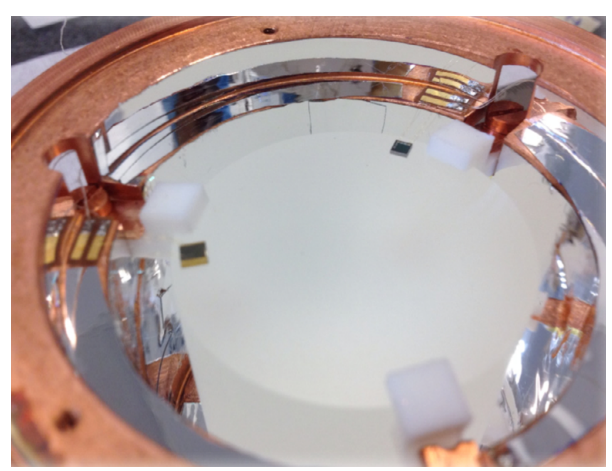
$$|\langle m_{\beta\beta} \rangle| \leq (0.07 - 0.16)\ \mathrm{eV}$$

- 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, ^{82}Se: CUPID = CUORE with light read-out
  - ^{82}Se (^{150}Nd, ^{48}Ca): SuperNEMO

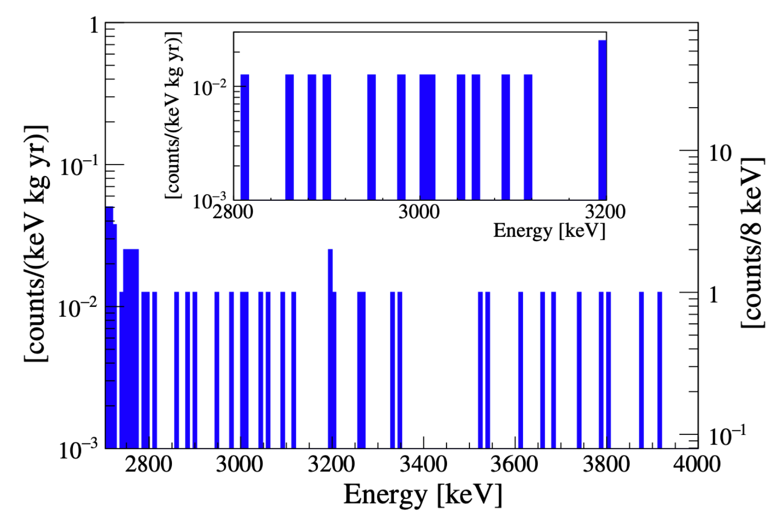
CUORE AND CUPID

- CUORE: 988 crystals (206 kg ^{130}Te assembled in towers) at LNGS
- Background level: 14 events/(keV t y); energy resolution: 0.3% FWHM (7.7 keV in ROI)
- Results: $T_{1/2} > 1.5 \times 10^{25}$ y for ^{130}Te
- CUPID: R&D for ton-scale detector using $Li_2{}^{100}MoO_4$ and $Zn^{82}Se$ crystals as scintillating bolometers (to identify major α-particle background)
- CUPID-0: pilot project at LNGS, 24 $Zn^{82}Se$ crystals, best limit of $T_{1/2}$ of ^{82}Se





CUPID-0: PRL 123, 2019



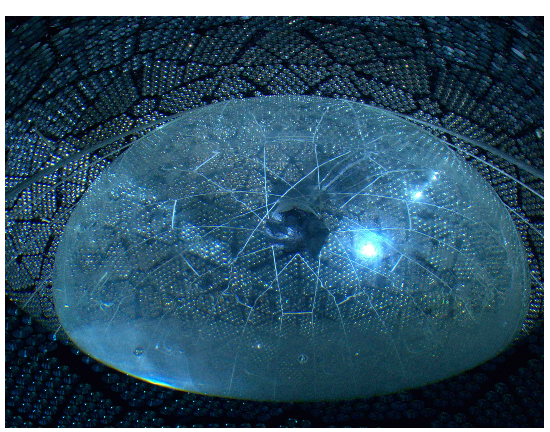
CUORE: PRL 120, 2018

Q value of ^{82}Se (2997.9 ±0.3 keV)

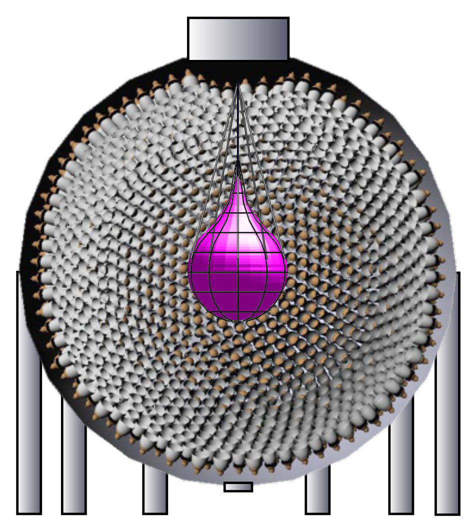
$T_{1/2} > 3.5 \times 10^{24}$ y

SNO+ AND KAMLAND-ZEN

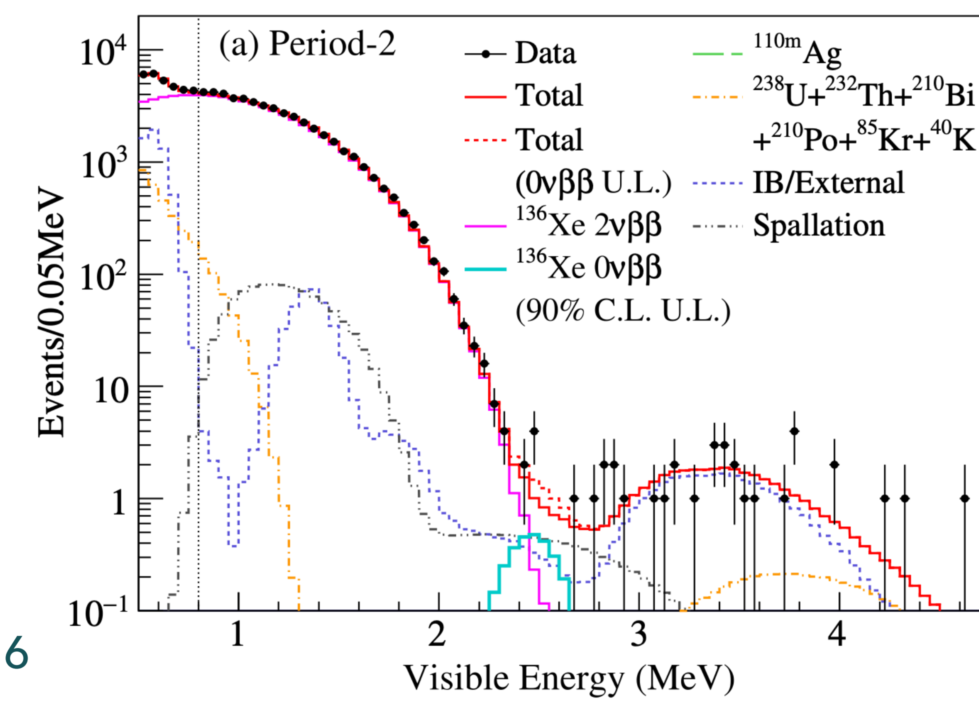
- SNO+: goal is 0.5% ^{nat}Te (~1330 kg ^{130}Te) in LS at SNOLAB
  - Scintillator fill in Nov 2018; Te loading planned for late 2019
- KamLAND-Zen: 745 kg ^{136}Xe in LS at Kamioka, ongoing; KamLAND2-Zen: 1t
  - Background: Energy resolution: 270 keV
  - Results: $T_{1/2} > 1.07 \times 10^{26}$ y



SNO+ J.Phys.Conf.Ser. 1137 (2019): aim is $T_{1/2} > 1.9 \times 10^{26}$ y after 5 y of data

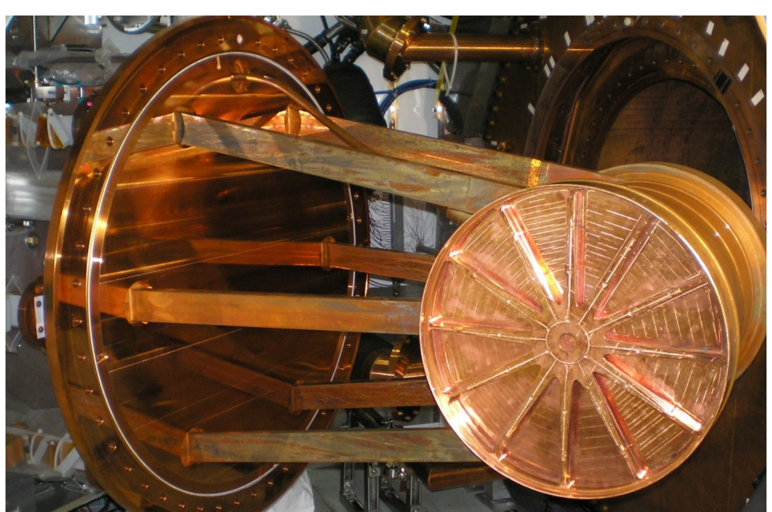


KamLAND-Zen: PRL 117, 2016



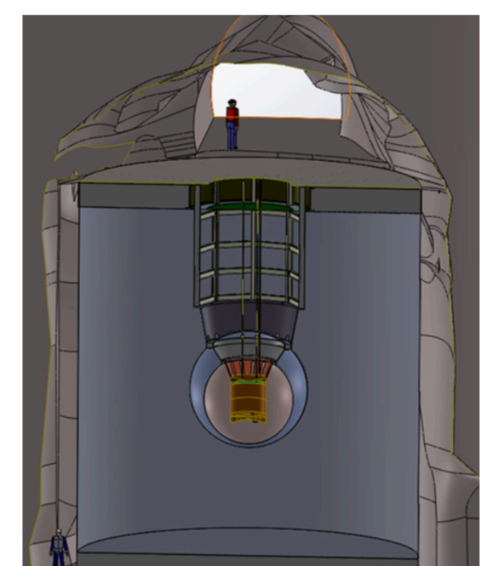
EXO-200, NEXO AND NEXT

- EXO-200: 75 kg ^{136}Xe in fiducial region of TPC, $\sigma/E = 1.1\%$; $T_{1/2} > 3.5 \times 10^{25}$ y
- nEXO: 5 t of liquid xenon enriched in ^{136}Xe, goal $T_{1/2} \sim 5.7 \times 10^{27}$ y
- NEXT: high-pressure ^{136}Xe gas -> tracking; 5 kg demonstrator at Canfranc (2015-2019)
  - NEXT demo achieved $\sigma/E = 0.43\%$; NEXT-100: data in 2020, $T_{1/2} \sim 6 \times 10^{25}$ y after 3 y
- R&D on Ba ion tagging ongoing



EXO-200: PRL 123, 2019

NEXT arXiv:1910.07314



nEXO arXiv:1805.11142 preCDR

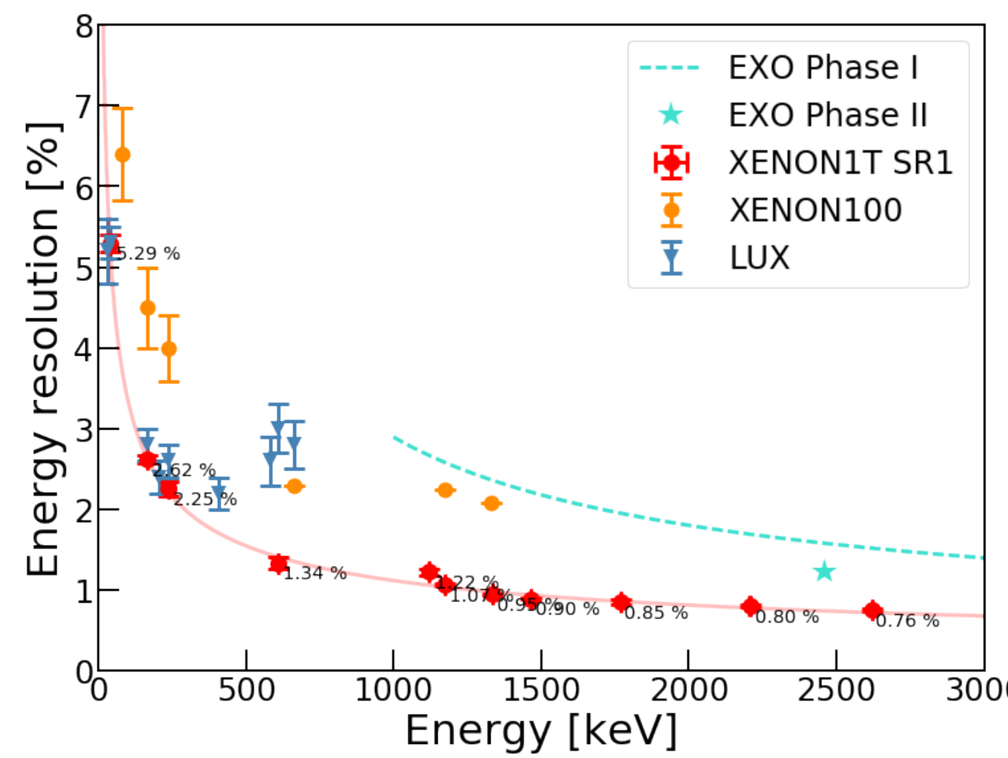
DARWIN

- TPC with 40 t ^{nat}Xe (50 t in total) for DM searches; 8.9% ^{136}Xe
- Goal: $T_{1/2}$ ~ few x 10^{27} y
- Energy resolution: E/σ = 0.8% (achieved in XENON1T)

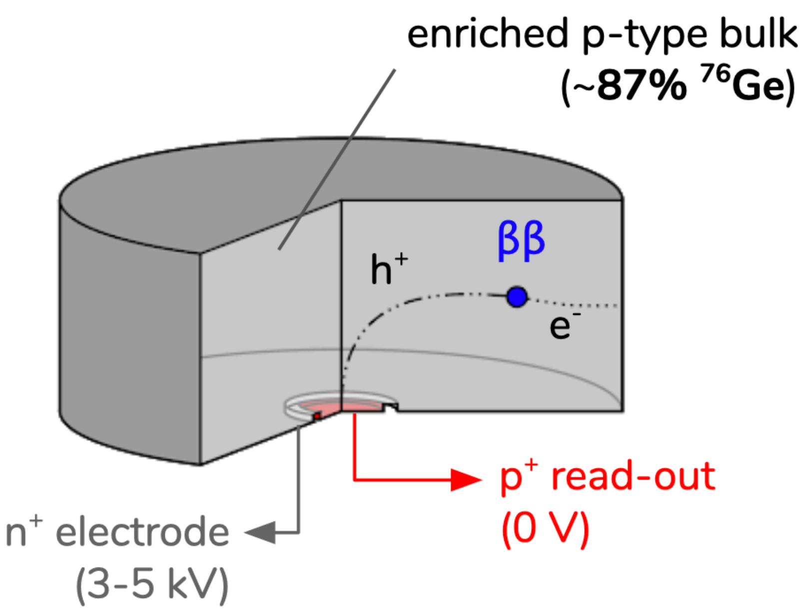
DARWIN: JCAP 1611 (2016) 017

2.6 m TPC demonstrator at UZH

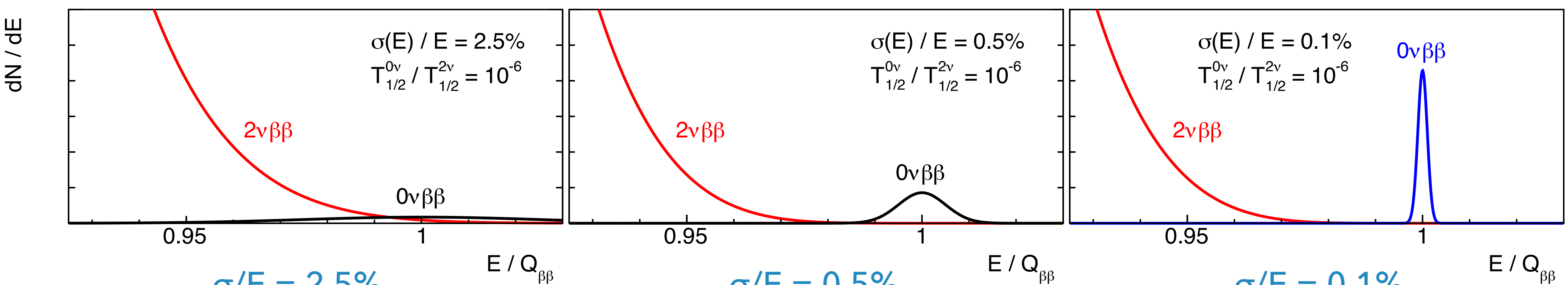
XENON1T: σ/E=0.8% at 2.5 MeV



GERMANIUM IONISATION DETECTORS

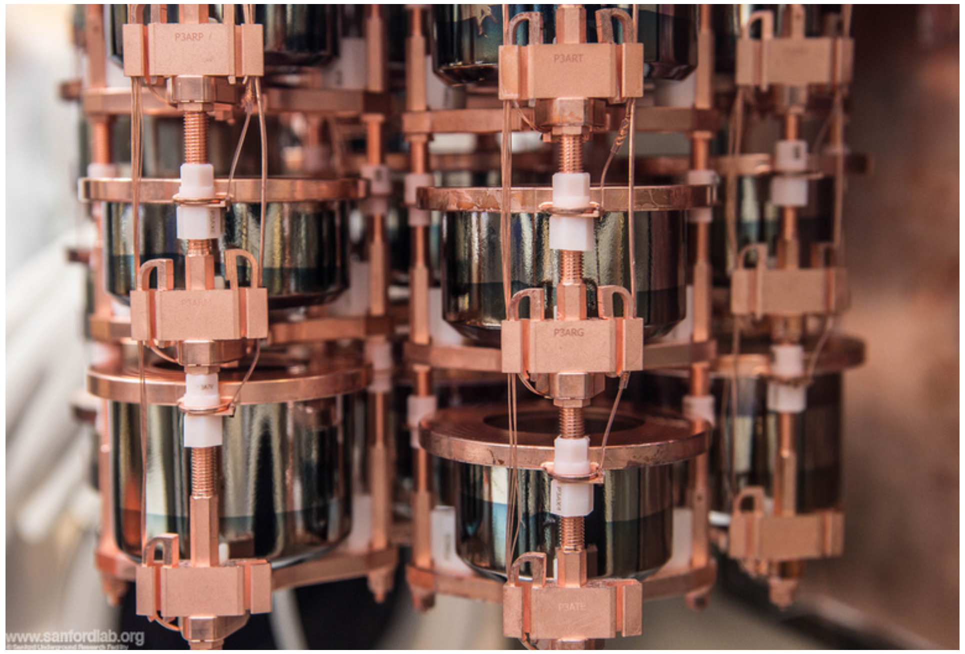


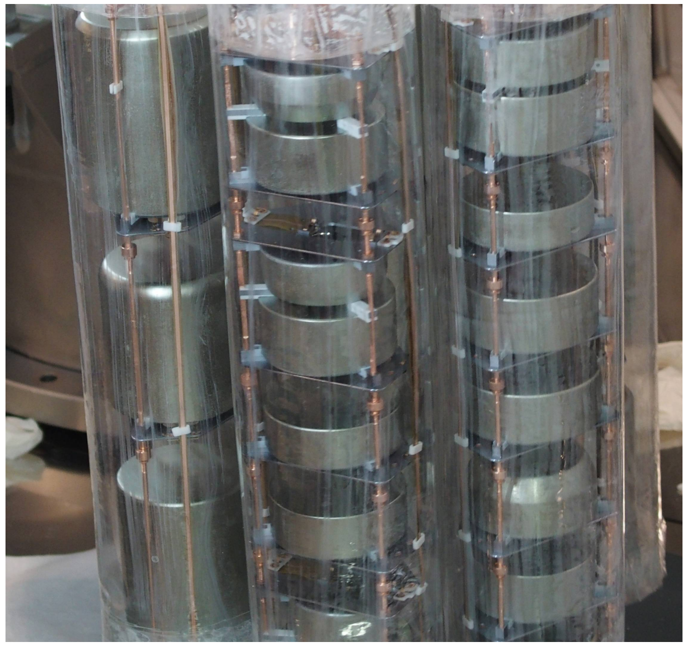
- HPGe detectors enriched in ^{76}Ge
  - Source = detector: high detection efficiency
  - High-purity material: no intrinsic backgrounds
  - Semiconductor: energy resolution σ/E < 0.1% at $Q_{\beta\beta}$ = 2039.061 ± 0.007 keV
  - High stopping power: β absorbed within O(1) mm



σ/E = 2.5% σ/E = 0.5% σ/E = 0.1%

EXISTING 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

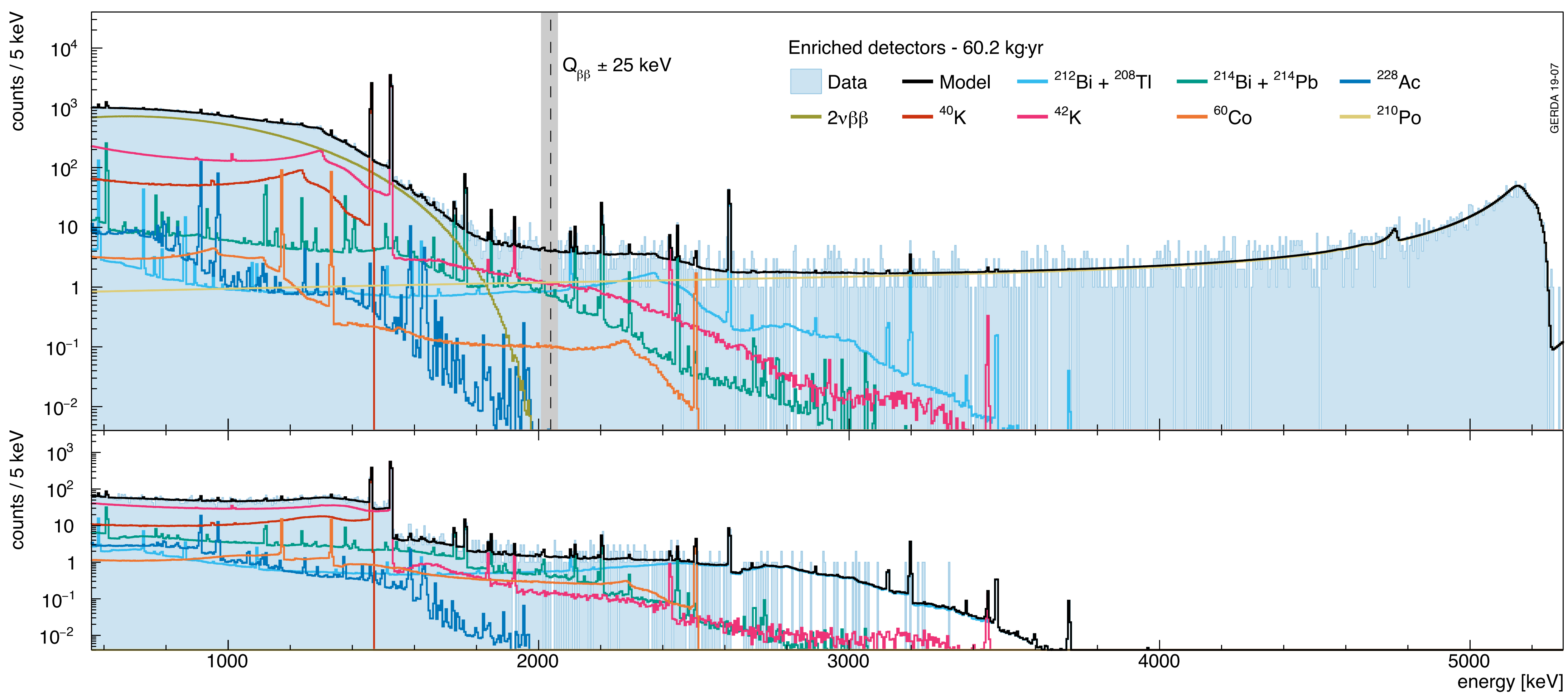
3.0 keV FWHM at 2039 keV

58.9 kg y exposure; Science 2019

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

BACKGROUND MODEL IN GERDA

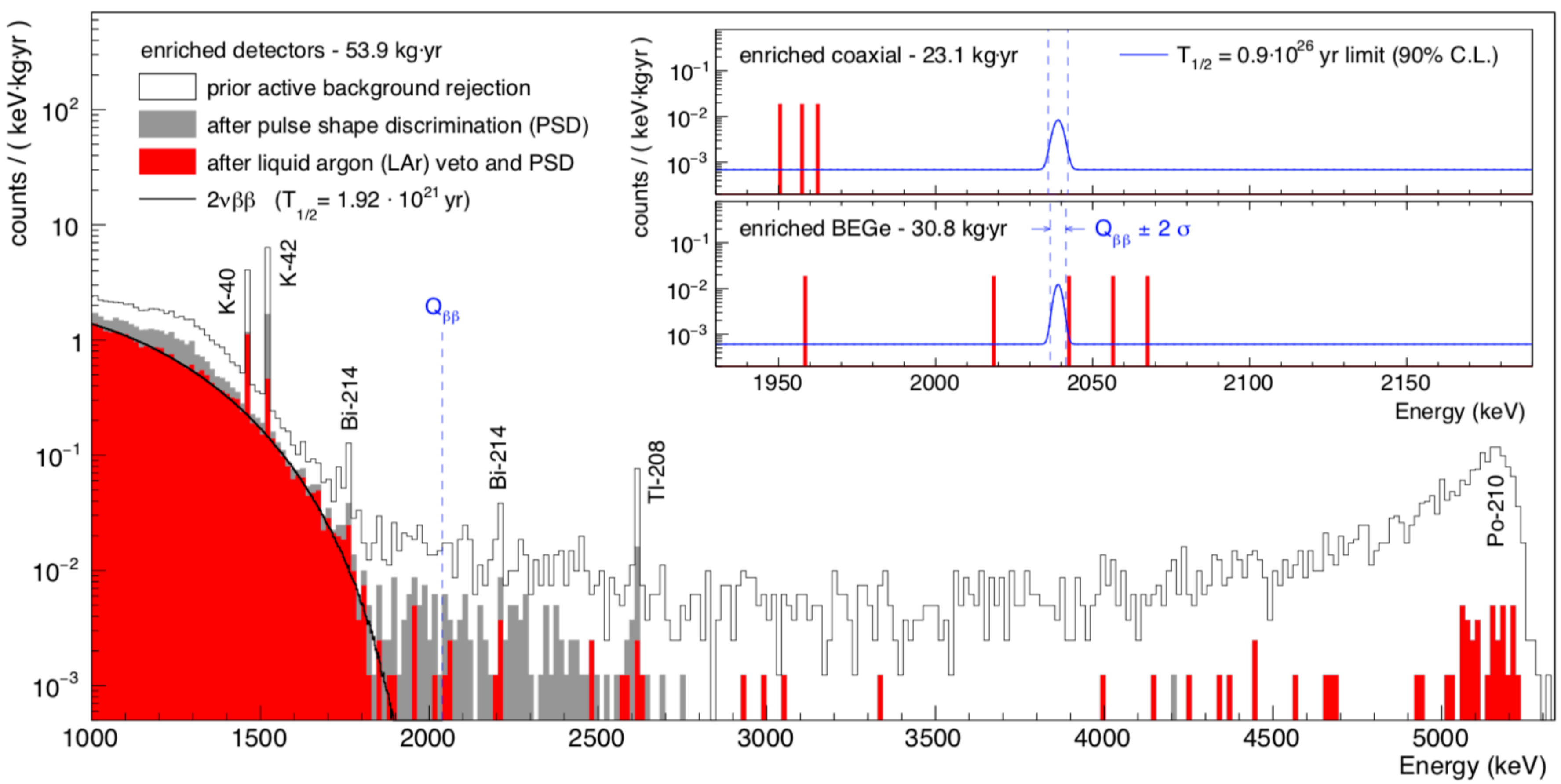
- Intrinsic 2νββ-events, ^{39}Ar, ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact



GERDA collaboration, arXiv:1909.02522

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

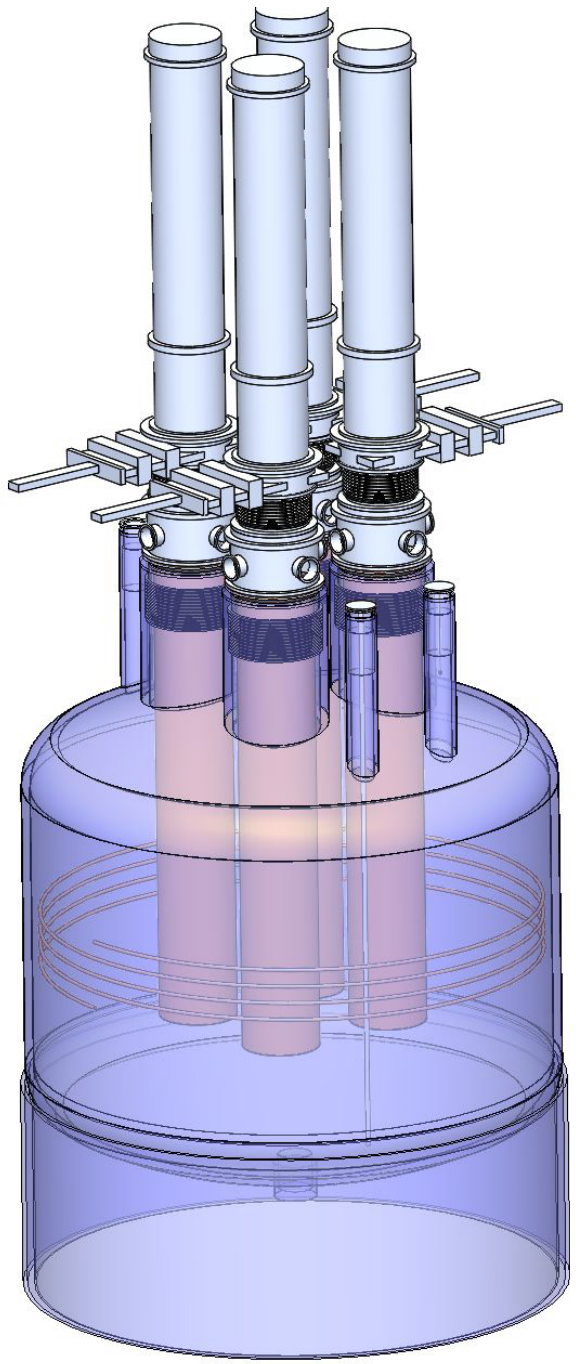
$$T^{0\nu}_{1/2} > 1.1 \times 10^{26}\,\mathrm{y}\ (90\%\mathrm{C.L.})$$

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

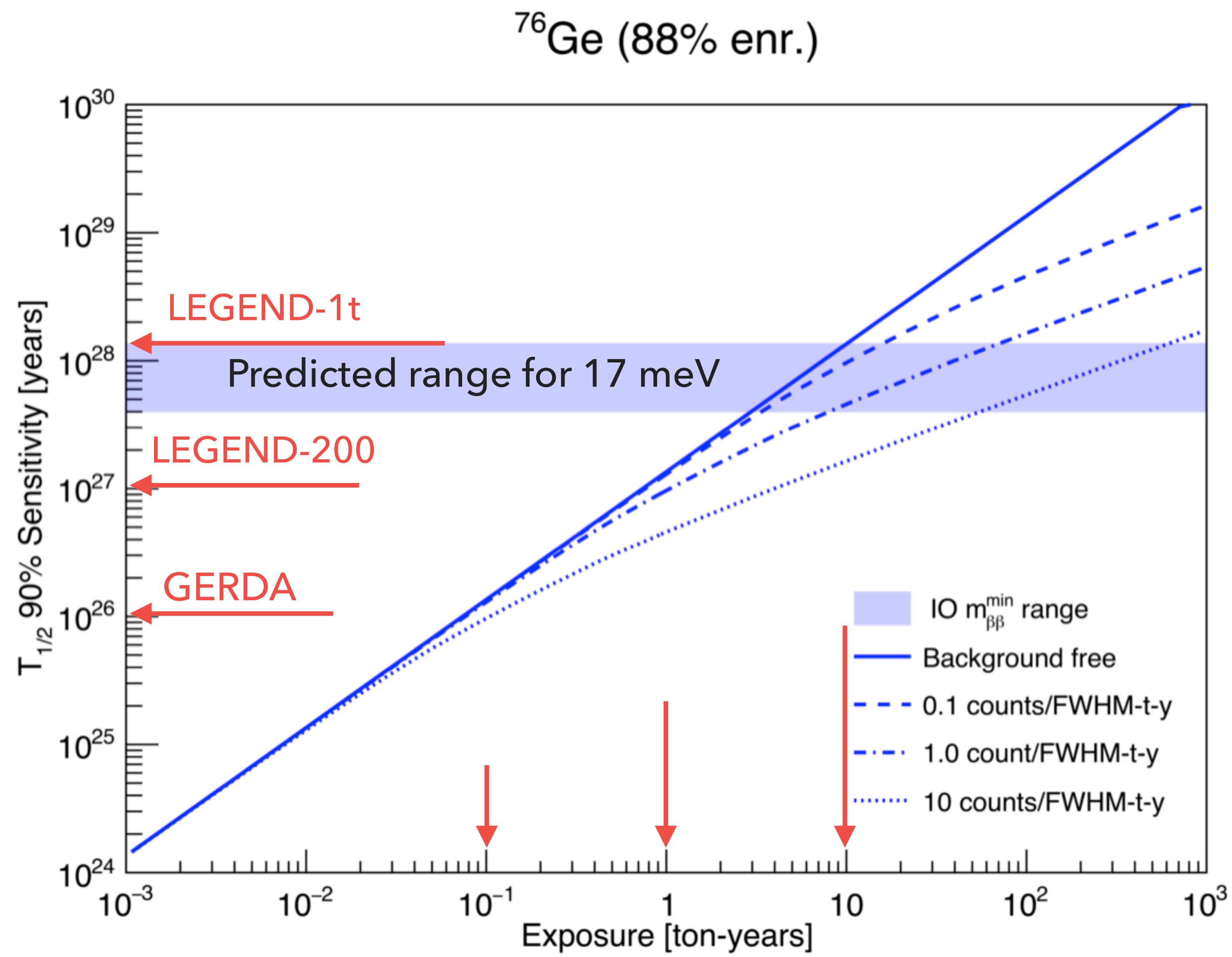
THE FUTURE: LEGEND

- 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, start in 2021
  - Background goal: 0.6 events/(FWHM t y)
  - **LEGEND-1t:** 1000 kg, staged
  - Background goal: 0.1 events/(FWHM t y)



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)

LEADING RESULTS: OVERVIEW

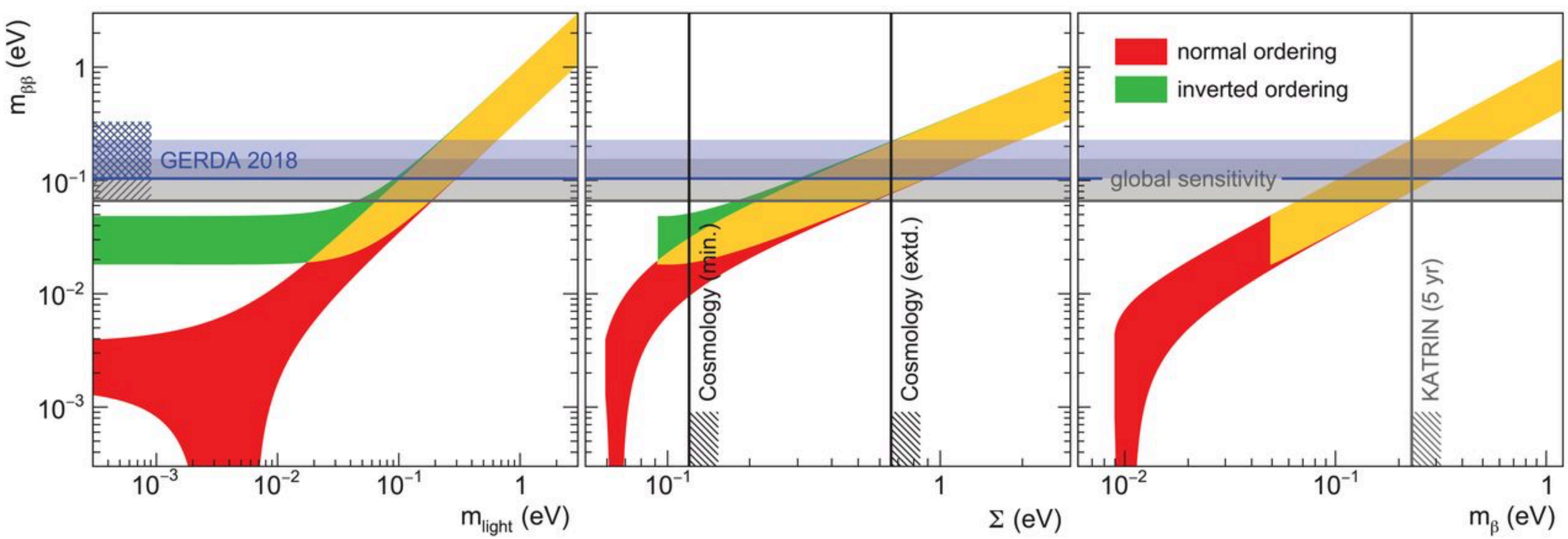
Experiment	Isotope	FWHM [keV]	$T_{1/2}$ [10^{26} y]	$m_{\beta\beta}$ [meV]
CUORE	^{130}Te	7.4	0.15	162-757
CUPID-0	^{82}Se	23	0.024	394-810
EXO-200	^{136}Xe	71	0.18	93-287
KamLAND-Zen	^{136}Xe	270	1.1	76-234
GERDA	^{76}Ge	3.3	0.9	104-228
Majorana	^{76}Ge	2.5	0.27	157-346

GERDA collaboration, Science 365, Sept 2019

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



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

FUTURE PROJECTS: A SELECTION

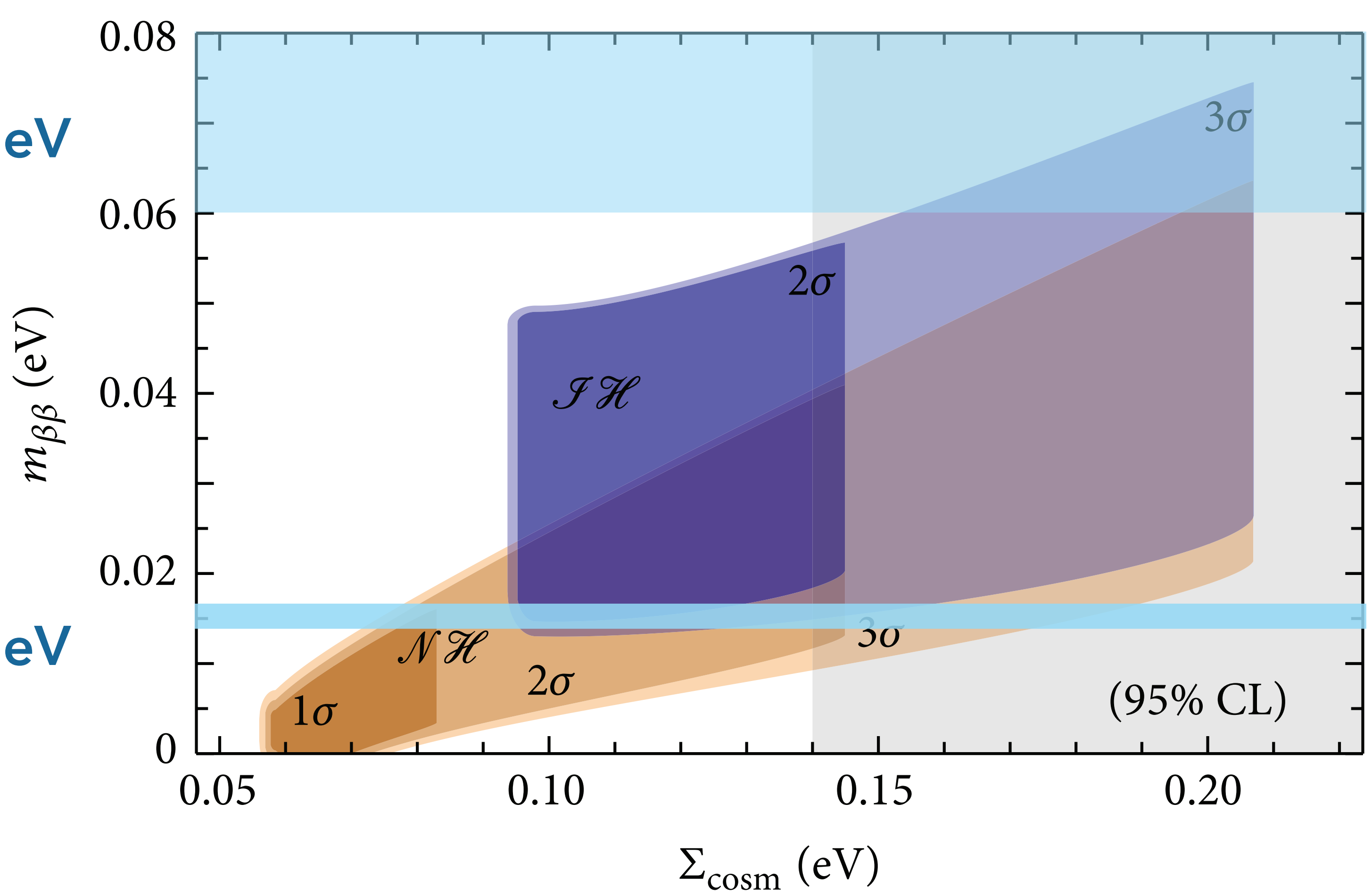
Experiment	Isotope	Iso mass [kg]	FWHM [keV]	$T_{1/2}$ [10^{27} y]	$m_{\beta\beta}$ [meV]
CUPID	^{130}Te	543	5	2.1	13-31
CUPID	^{82}Se	336	5	2.6	8-38
nEXO	^{136}Xe	4500	59	6	7-21
KamLAND2-Zen	^{136}Xe	1000	141	1.4	14-44
DARWIN	^{136}Xe	1068	20	1.4	14-44
PandaX-III	^{136}Xe	901	24	1.3	14-46
LEGEND-200	^{76}Ge	175	3	1	34-74
LEGEND-1t	^{76}Ge	873	3	6	14-30
SuperNEMO	^{82}Se	100	120	0.1	58-144

SUMMARY

- Ton-scale experiments are required to probe the IH scenario
- Several technologies move into this direction
- Much larger experiments required to probe the NH scenario

70 meV

10 meV



Current experiments

Future, ton-scale experiments

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

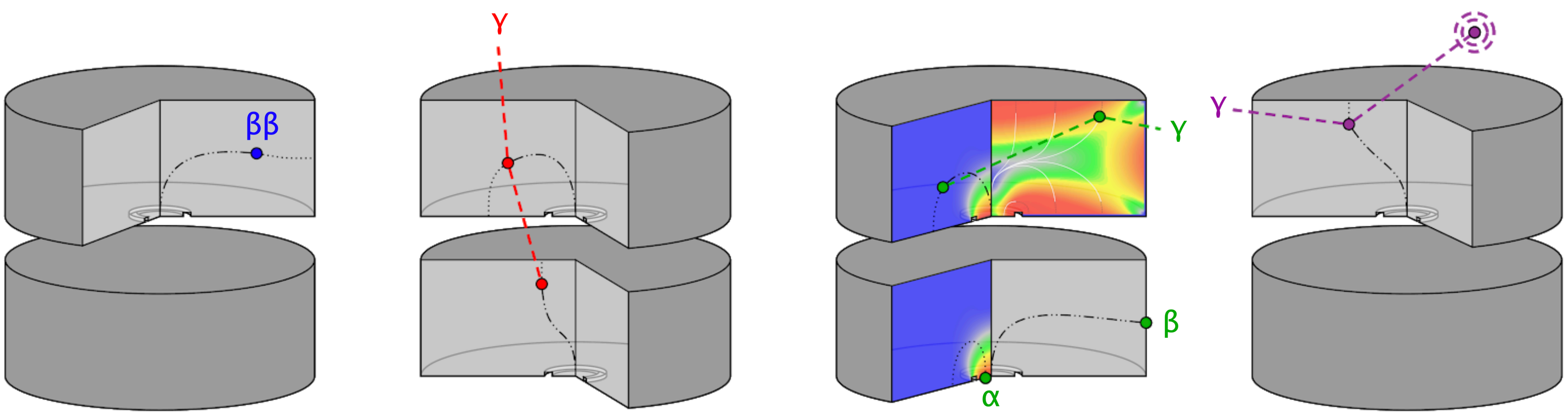
Report available at arXiv:1910.04688

ADDITIONAL MATERIAL

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:

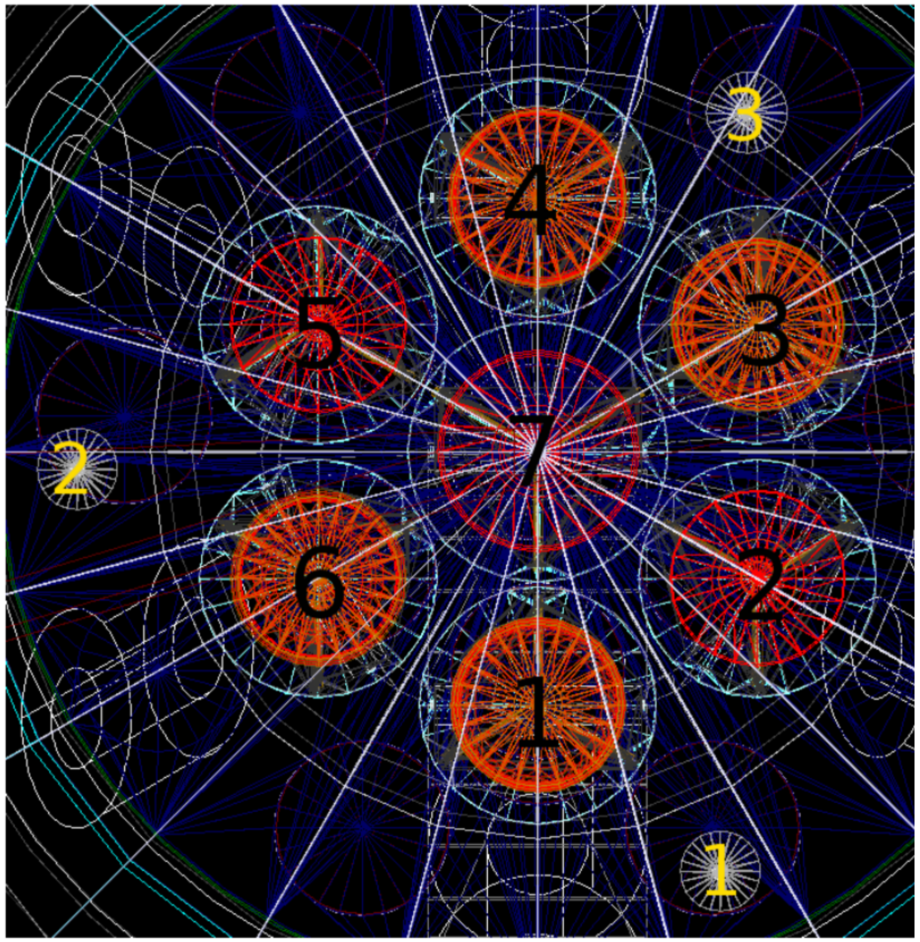
multi-detector interactions

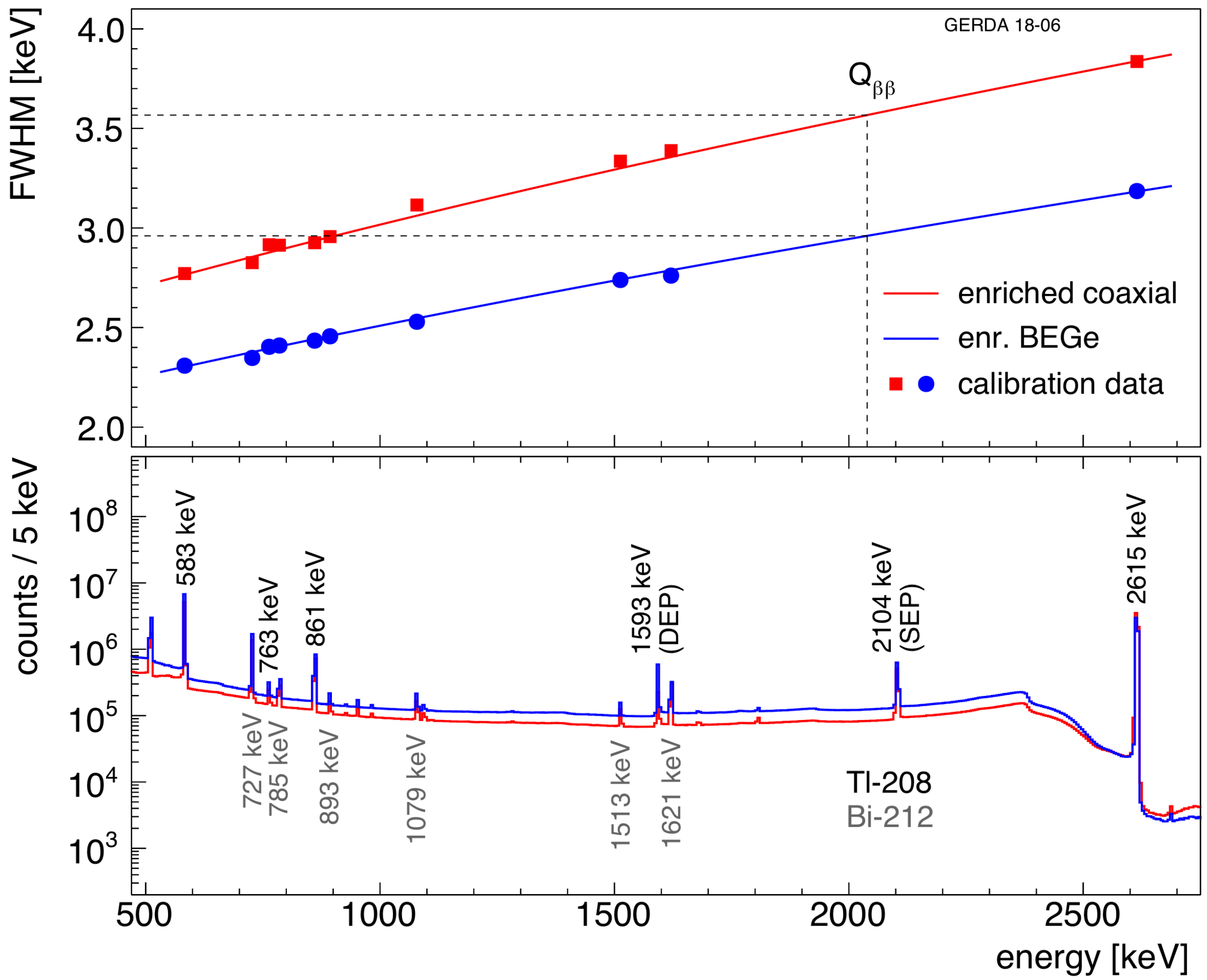
multi-site/surface interactions

interactions with **coincident energy deposition** in surroundings

ENERGY CALIBRATION

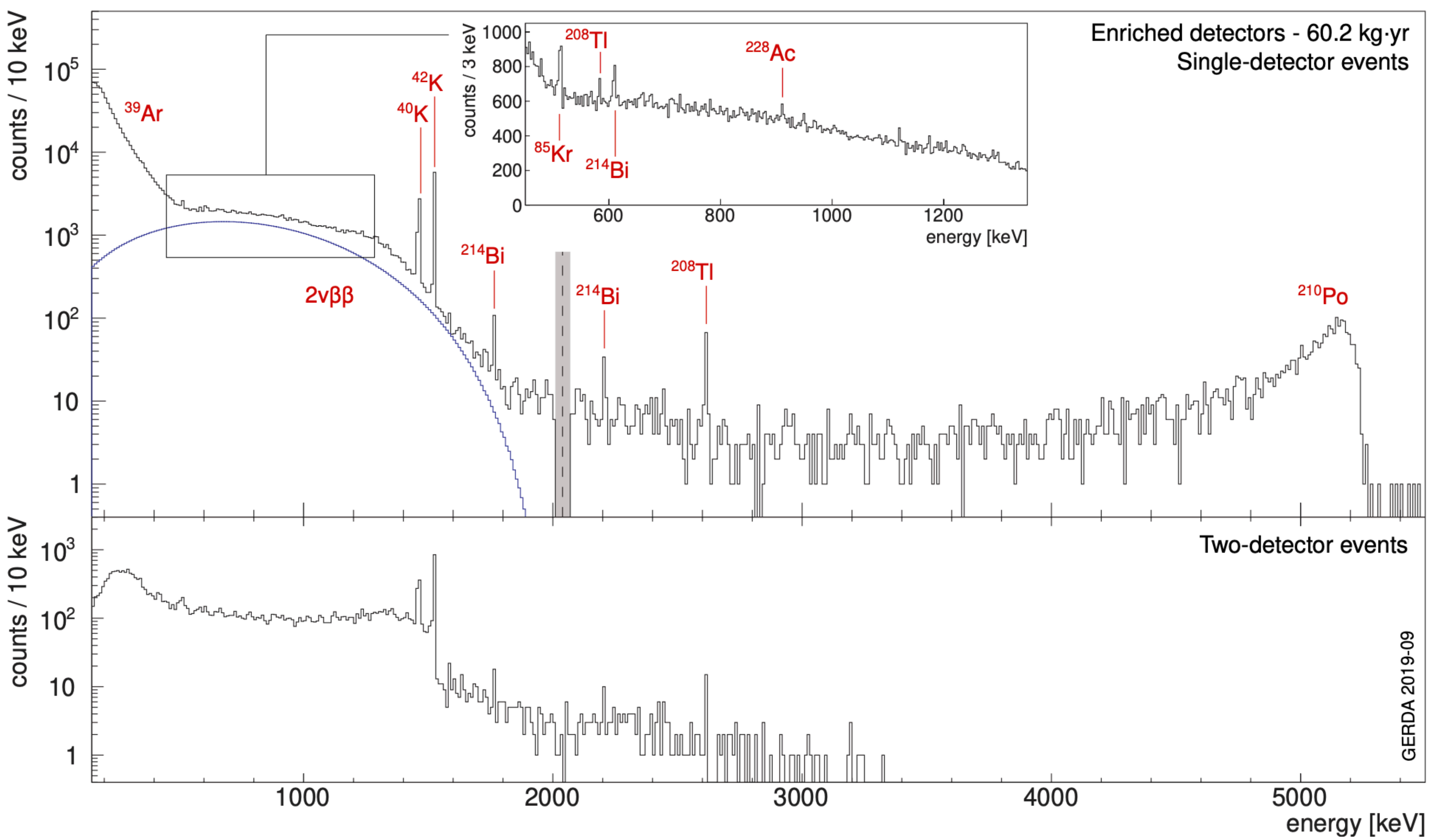
- Three low neutron-emission ^{228}Th sources in SIS, deployed once every week
- FWHM at $Q_{\beta\beta}$: (3.0 ± 0.1) keV for BEGe, (3.6 ± 0.1) keV for coaxial detectors





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

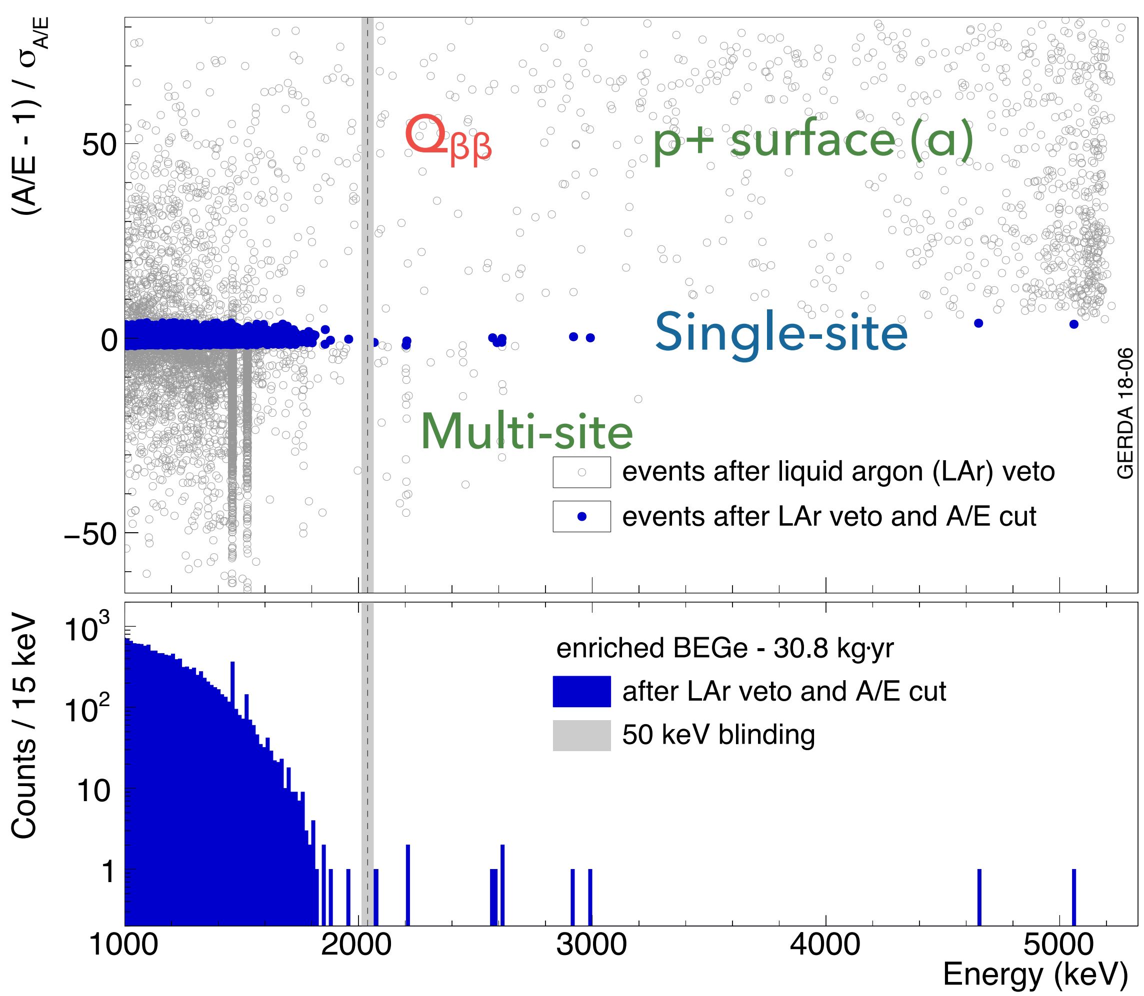


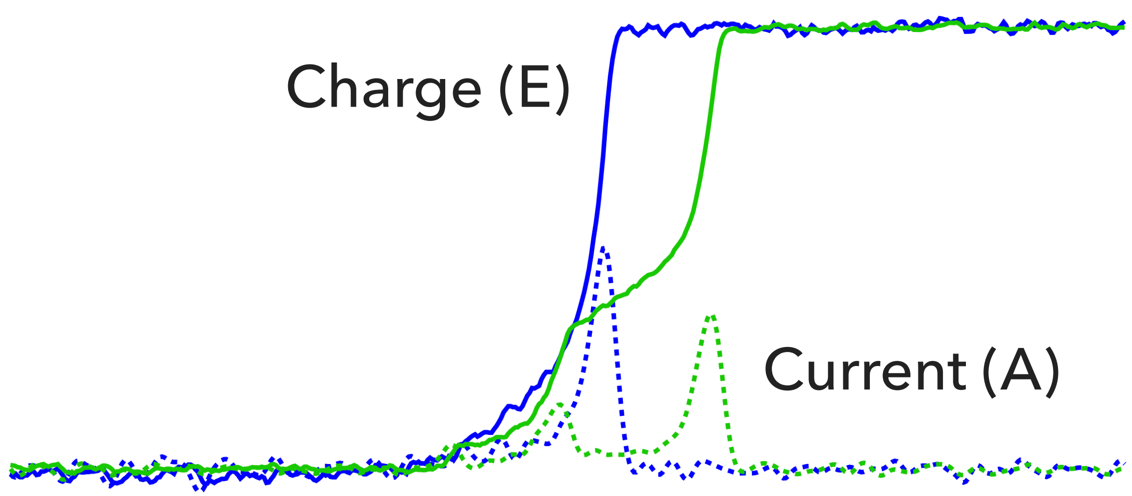
GERDA collaboration, arXiv:1909.02522

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

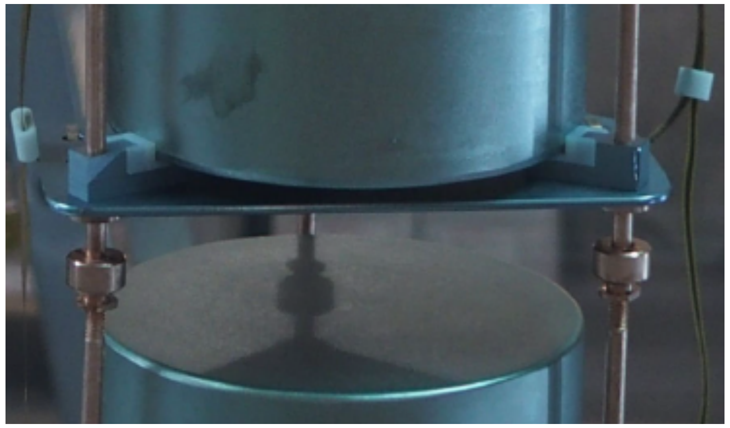
Mean and resolution corrected for E-dependance

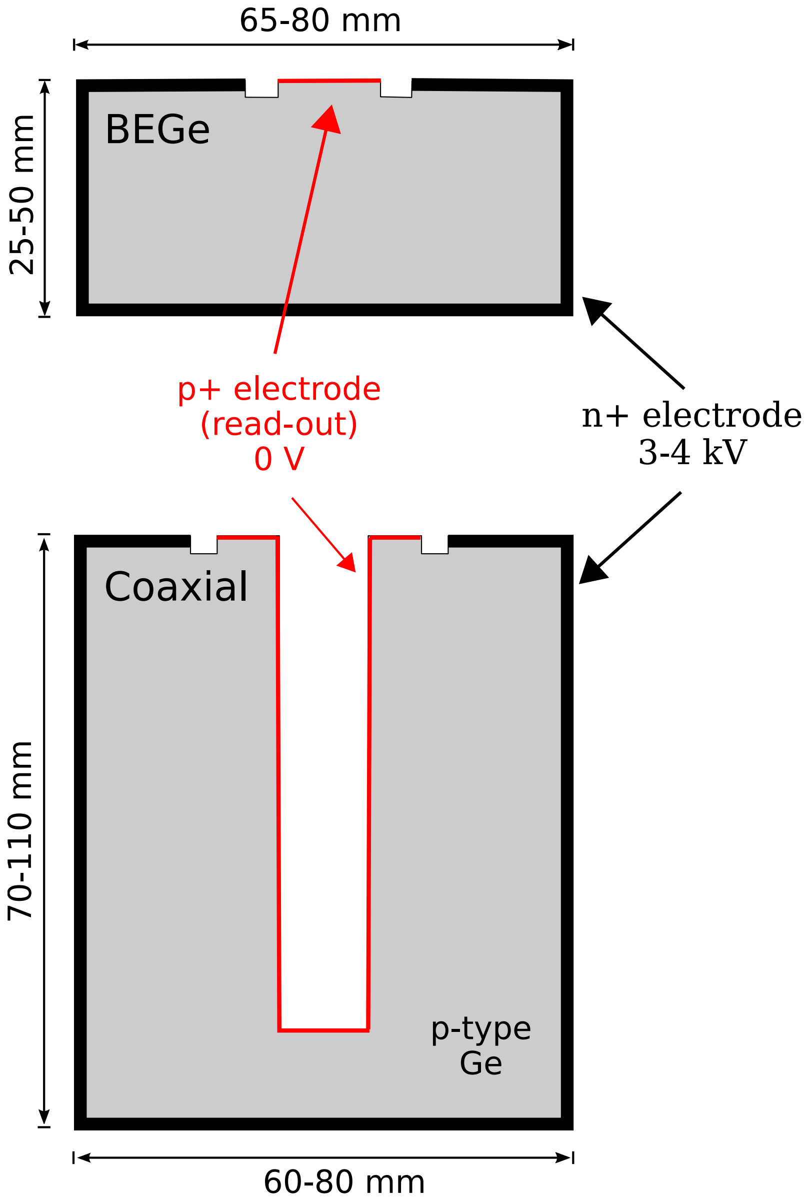
A/E normalised to 1

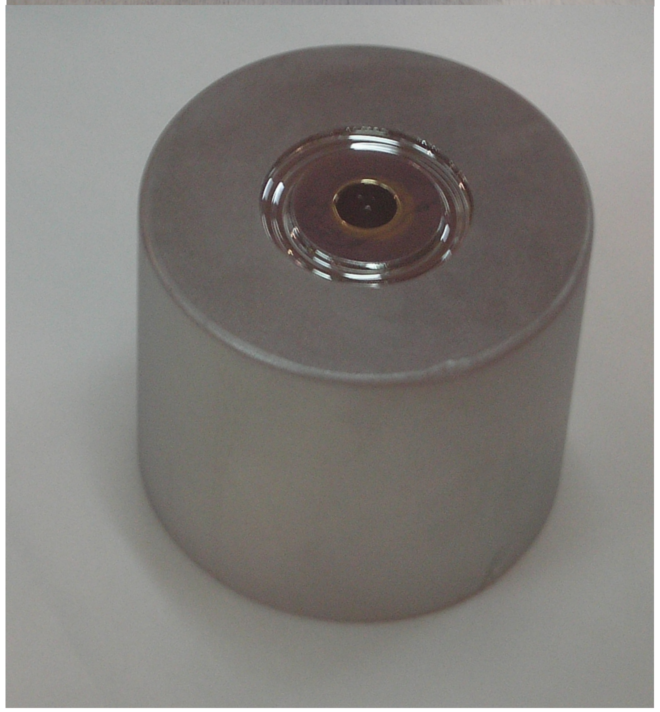
Accept events around **$(A/E - 1)/\sigma_{A/E} = 0$**

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)

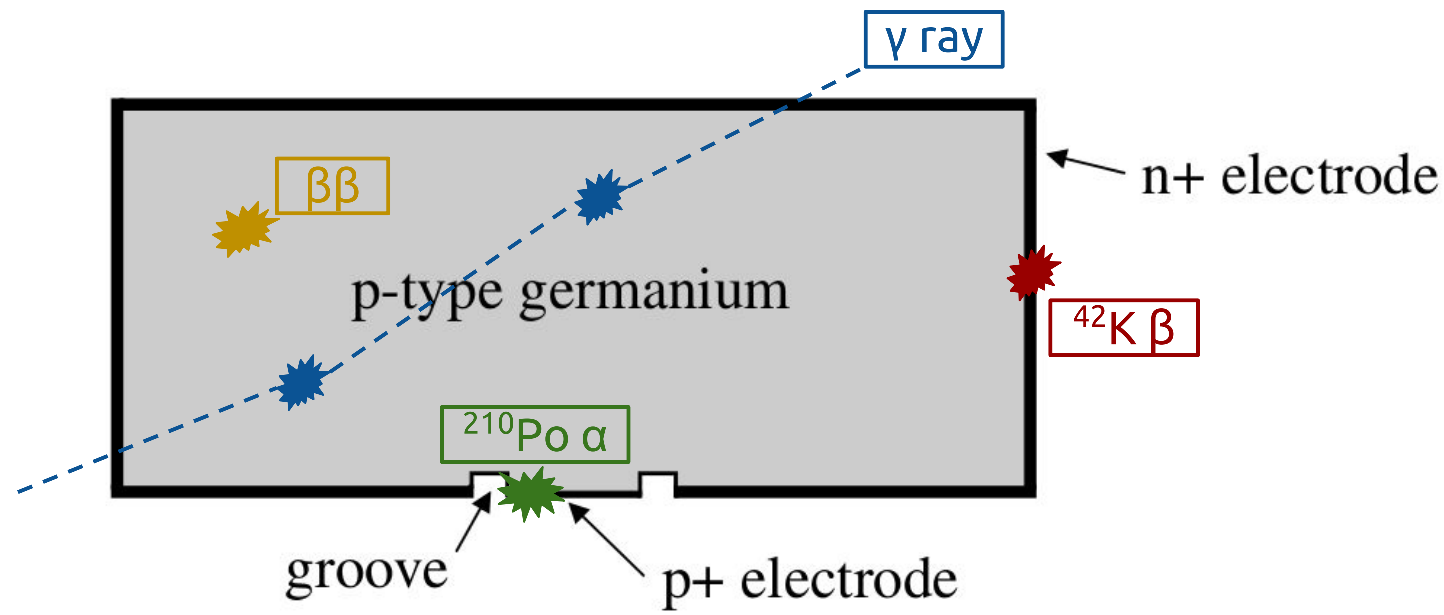


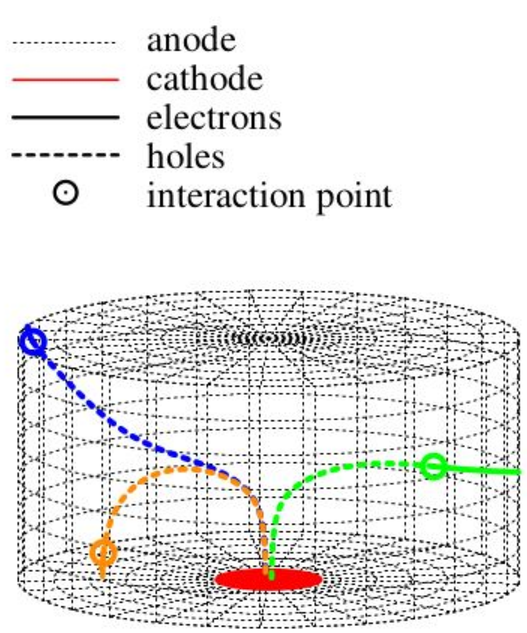


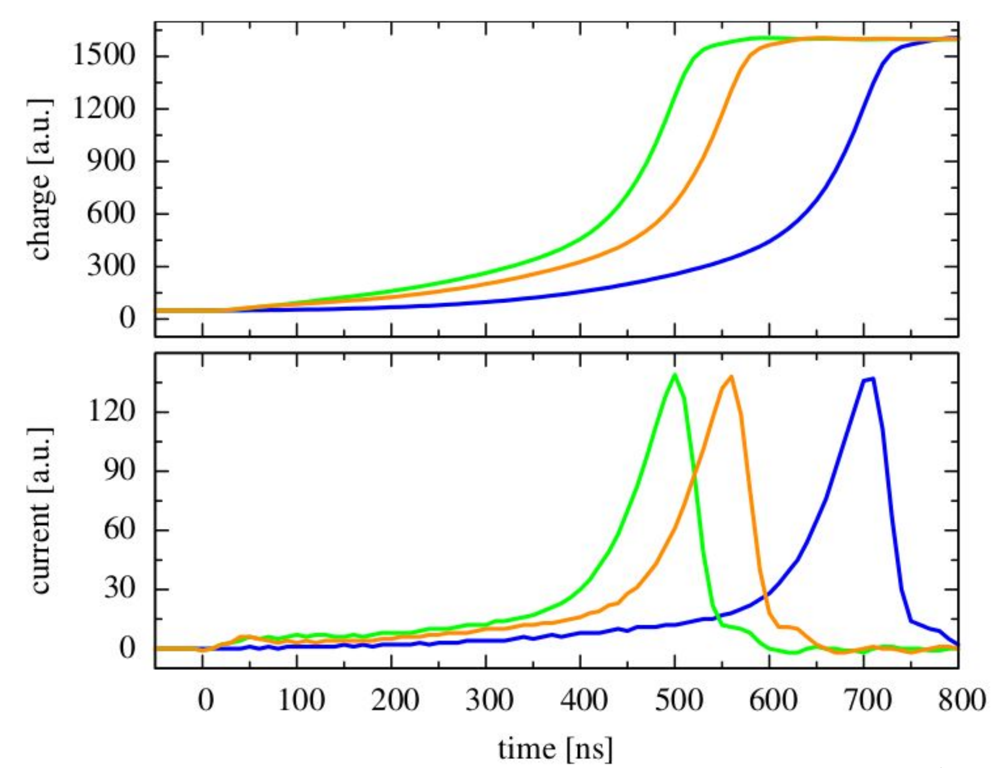


GERDA PULSE SHAPE DISCRIMINATION

- 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

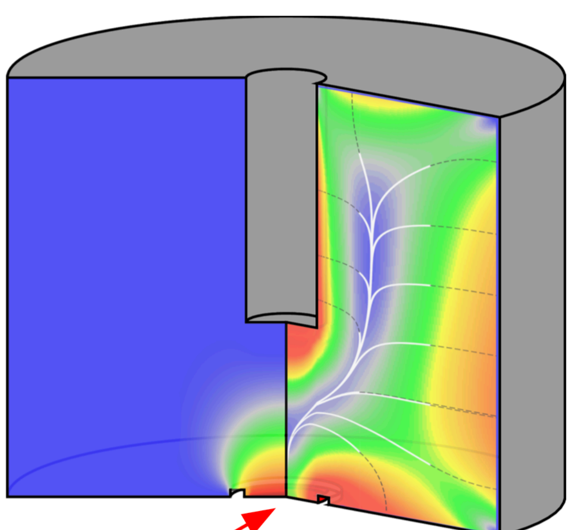




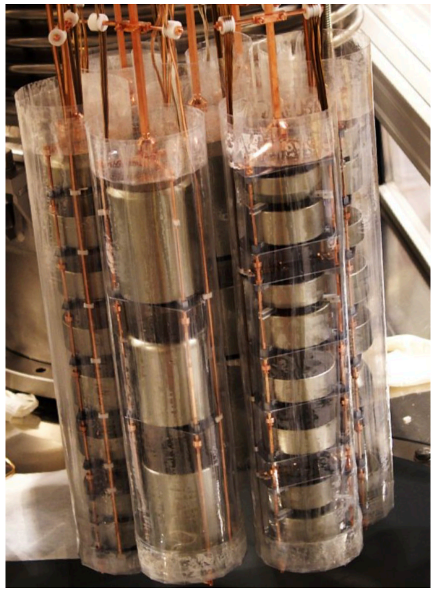


UPGRADE: INVERTED COAXIAL DETECTORS

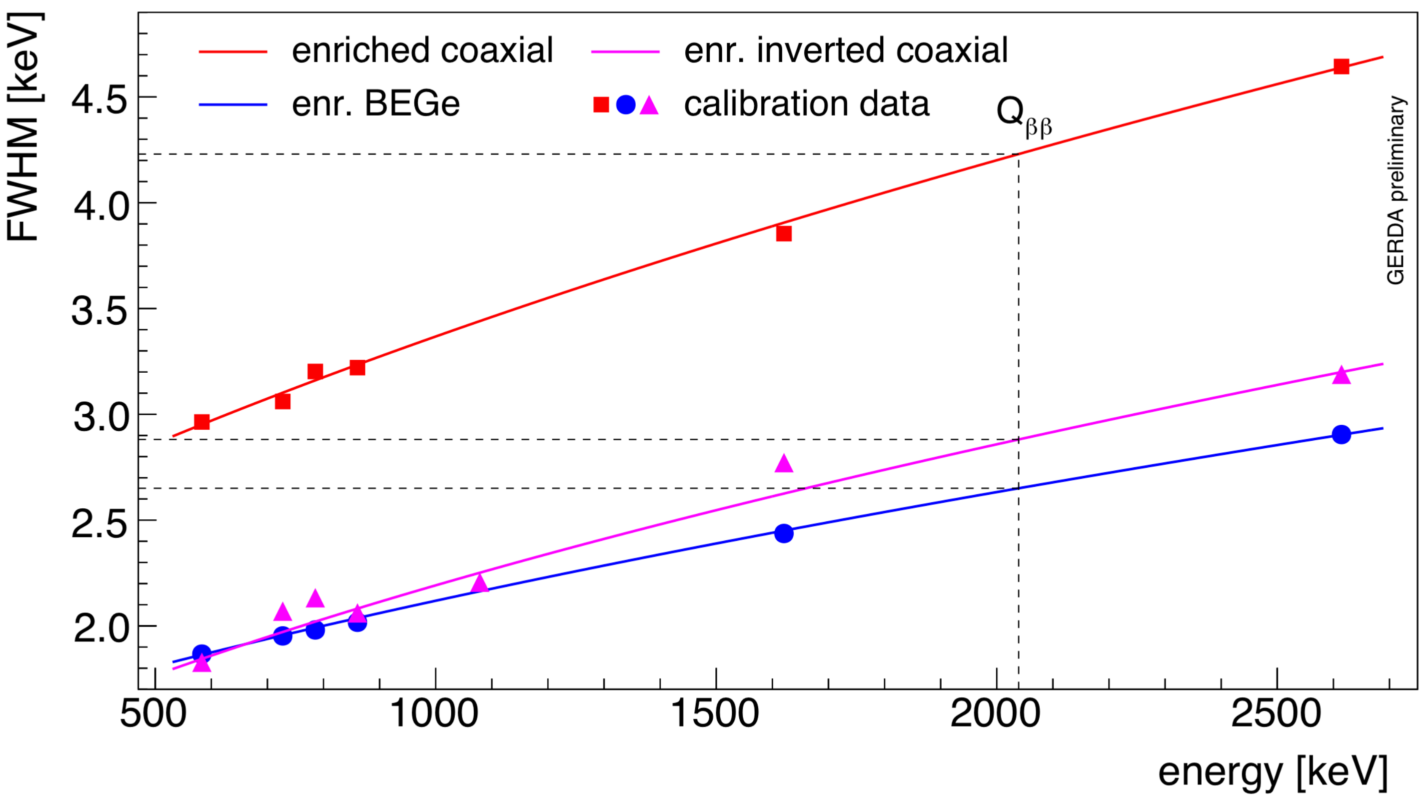
- Large point-contact detectors with ~ 3 kg mass, excellent PSD performance
- First 5 enriched IC detectors installed in spring 2018; baseline for LEGEND



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

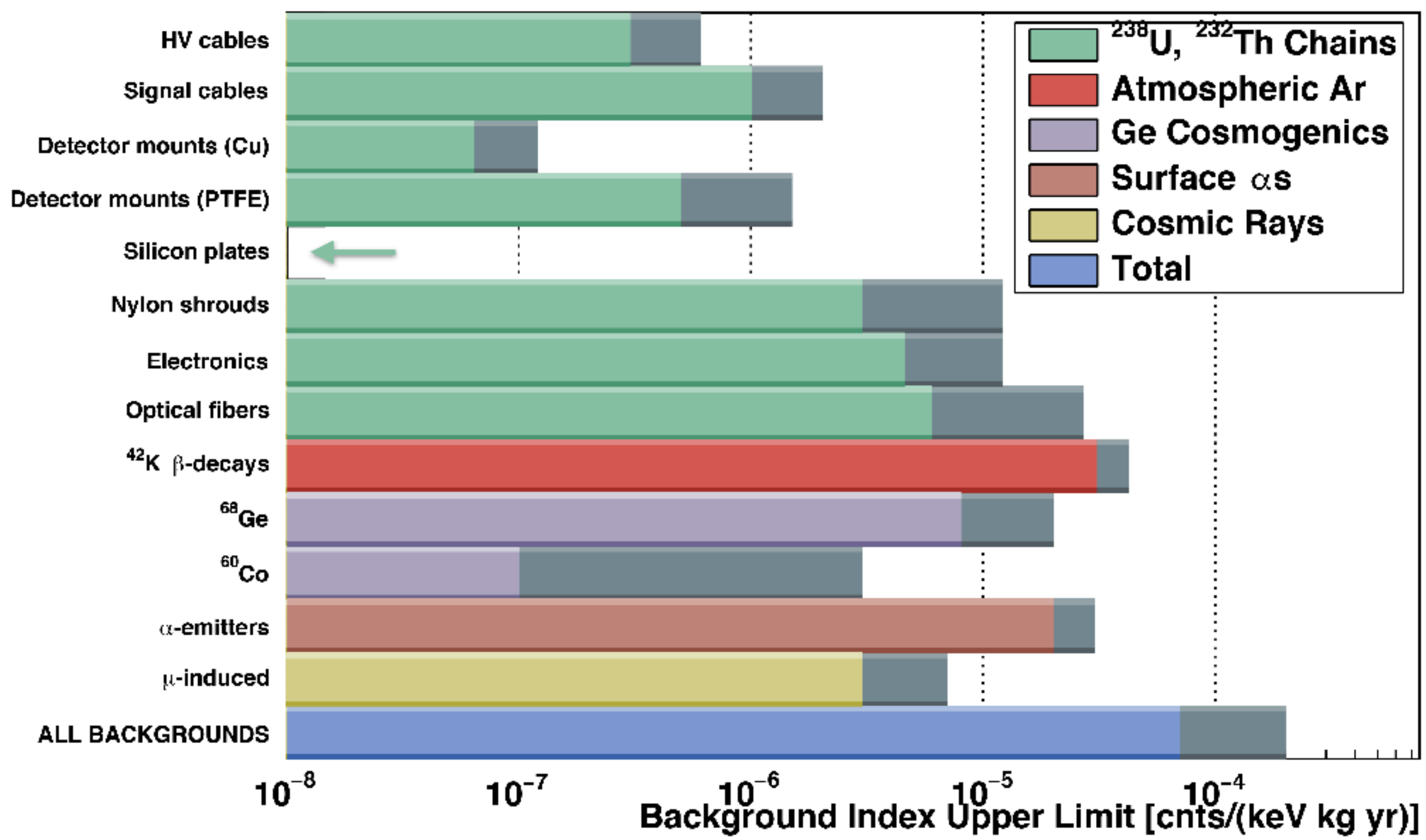


Detector mass increase: 35.6 kg -> 44.2 kg



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

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)

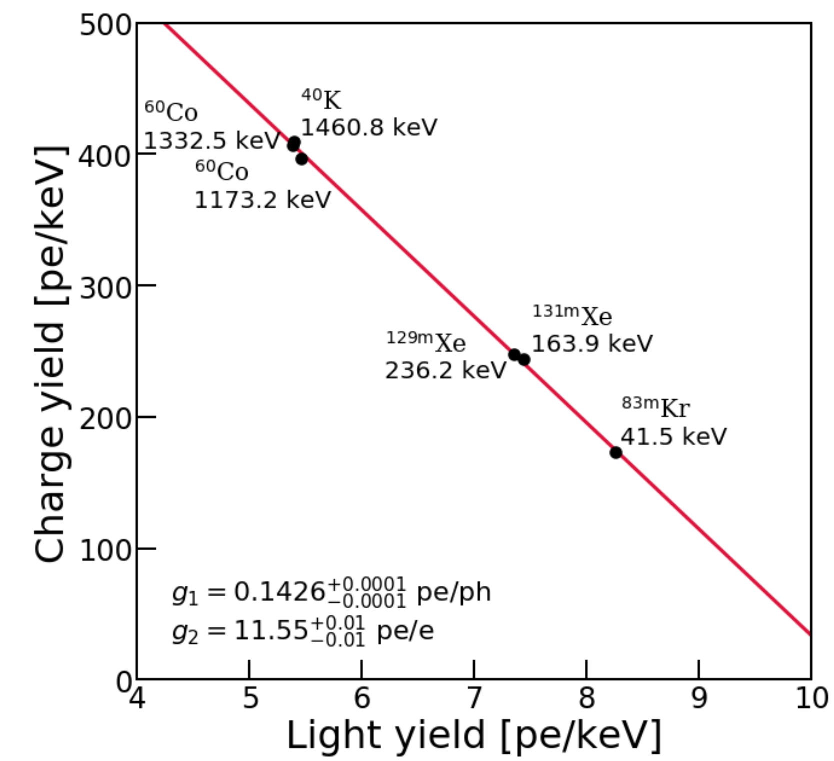
ENERGY RESOLUTION

- Anti-correlation between light (S1) and charge (S2)
- Energy scale uses linear combination of S1 and S2
- Photon gain: g_1 (pe/photon), electron gain: g_2 (pe/electron)

$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W$$

W-value = 13.7 eV

$$\frac{S2}{E} = \frac{g_2}{W} - \frac{g_2}{g_1}\frac{S1}{E}$$



Example for XENON1T:

0.8% relative energy resolution (σ/E) around 2.5 MeV