

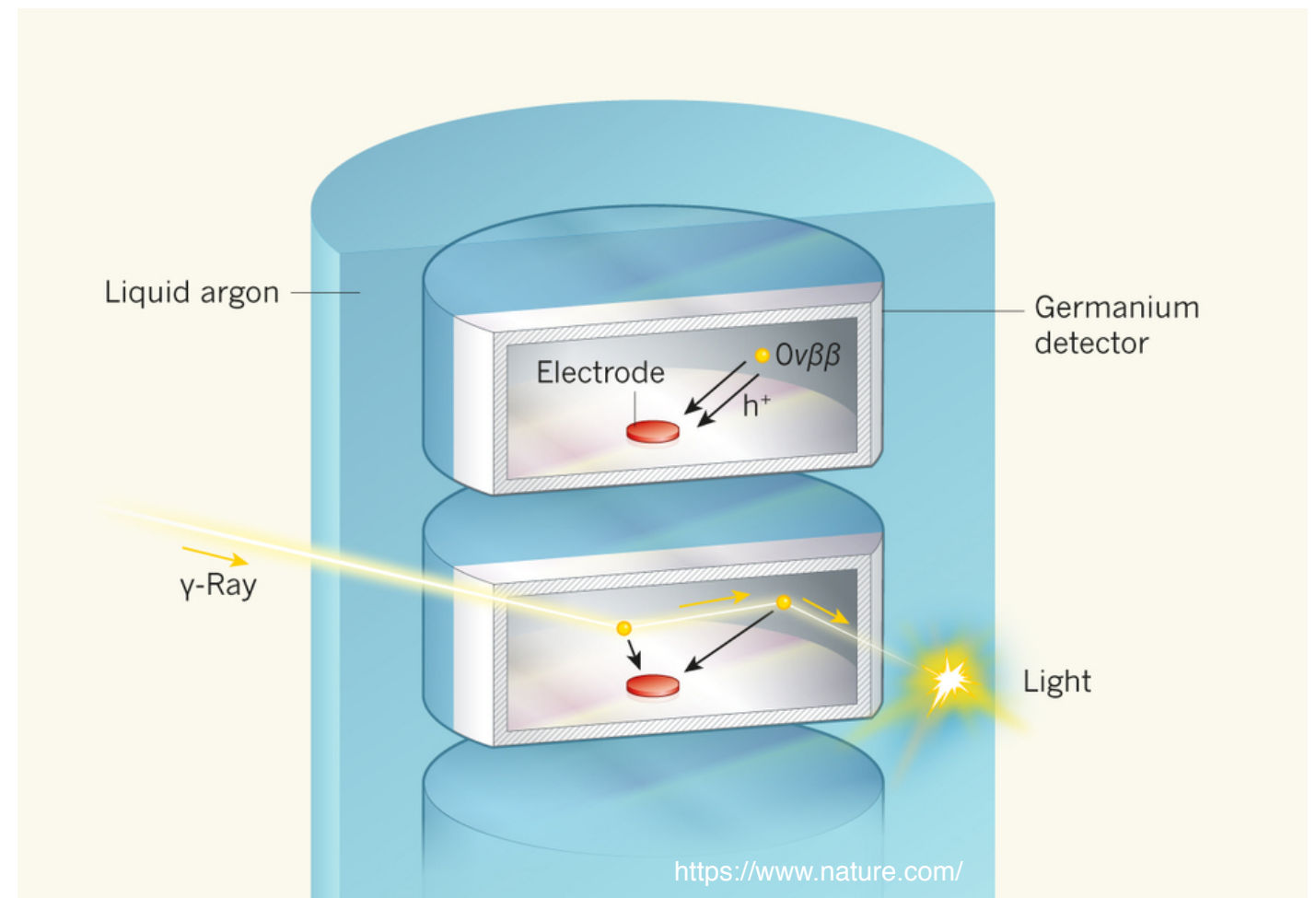


Neutrinoless Double Beta Decay

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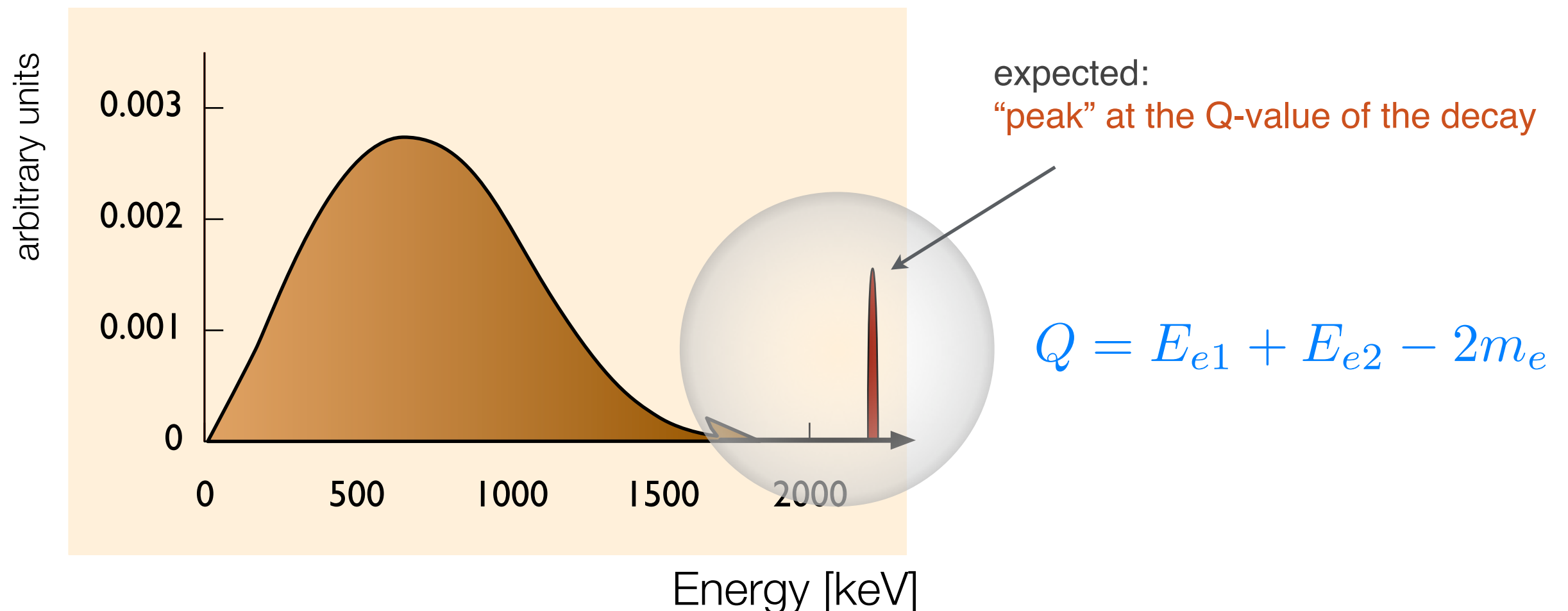
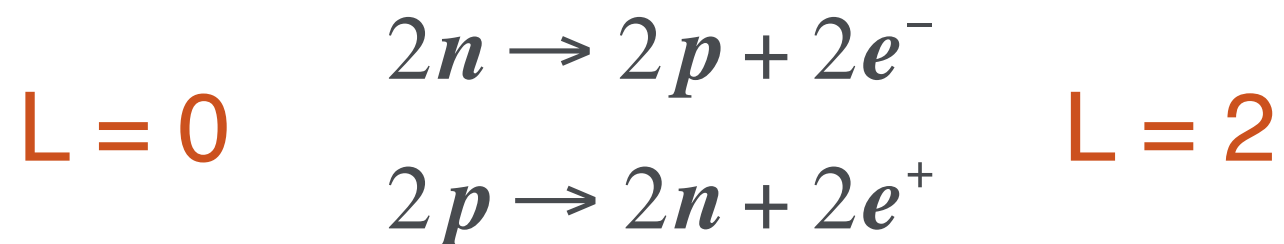
SWICH2 Workshop

Fribourg, September 14, 2018



Neutrinoless double beta decay

- Nuclear decay mode without emission of neutrinos (“forbidden” in the SM, since the lepton number is violated: $\Delta L = 2$)



Neutrinoless double beta decay

- Why is this decay mode interesting?
 - ➡ it can provide information about the nature of neutrinos
- Decision:
 - ➡ neutrinos and antineutrinos are distinct particles (Dirac particles) or
 - ➡ neutrinos are their own antiparticles (Majorana particles)



Paul Dirac



Ettore Majorana

What is the observable decay rate?

$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = \overset{\substack{\text{Phase} \\ \text{space} \\ \text{factor}}}{G^{0\nu}} \overset{\substack{\text{Axial-} \\ \text{vector} \\ \text{cc}}}{g_A^4} \overset{\text{NME}}{|M^{0\nu}|^2} \frac{|\langle m_{eff} \rangle|^2}{m_e^2}$$

Can be calculated: $\sim Q^5$
Difficult: factor 2-3

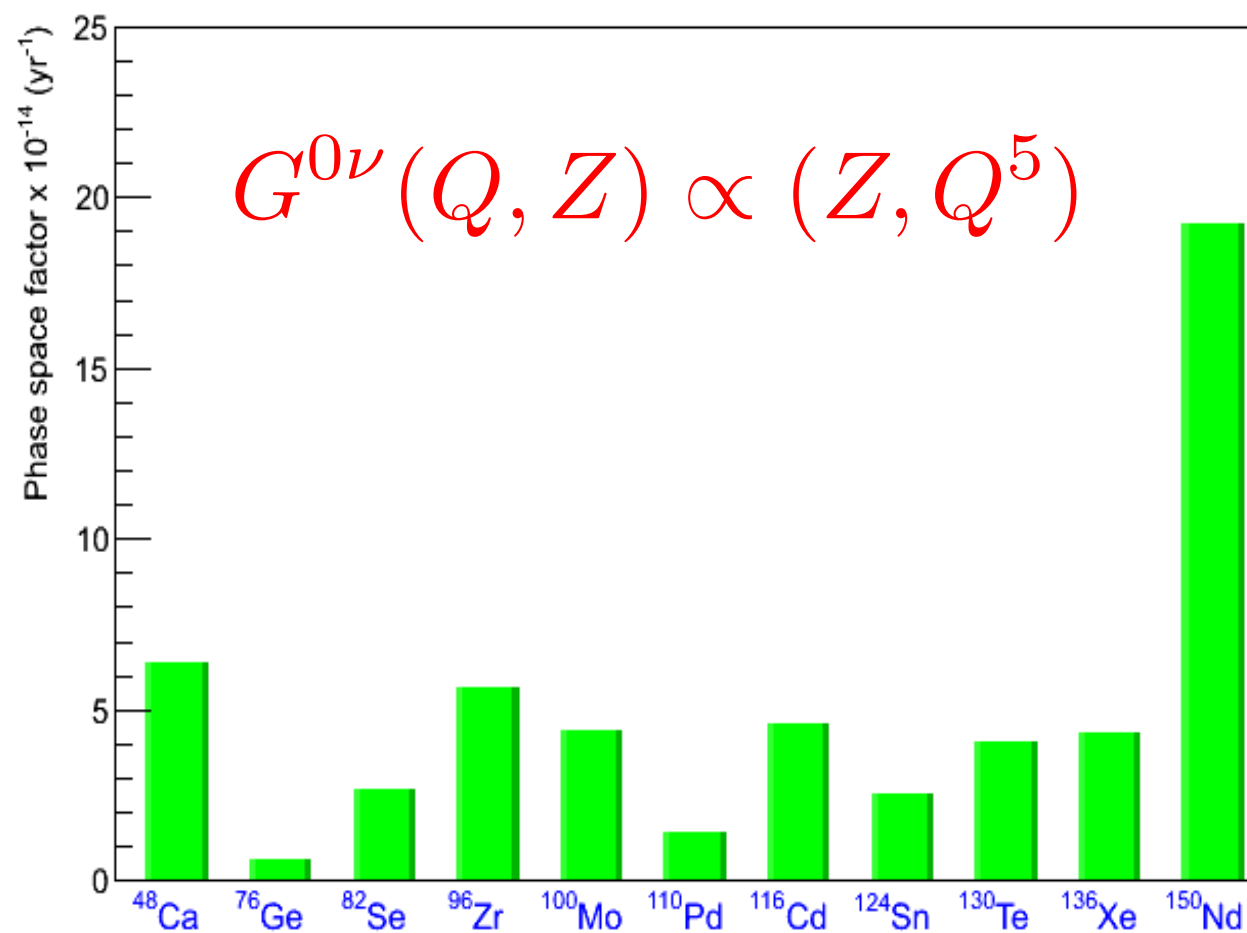
- with the *effective Majorana neutrino mass*:

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

- ➡ a coherent sum over mass eigenstates with potentially CP violating phases
- ➡ a mixture of m_1, m_2, m_3 , proportional to the U_{ei}^2 , with $\alpha_1, \alpha_2 =$ Majorana CPV phases

Phase space

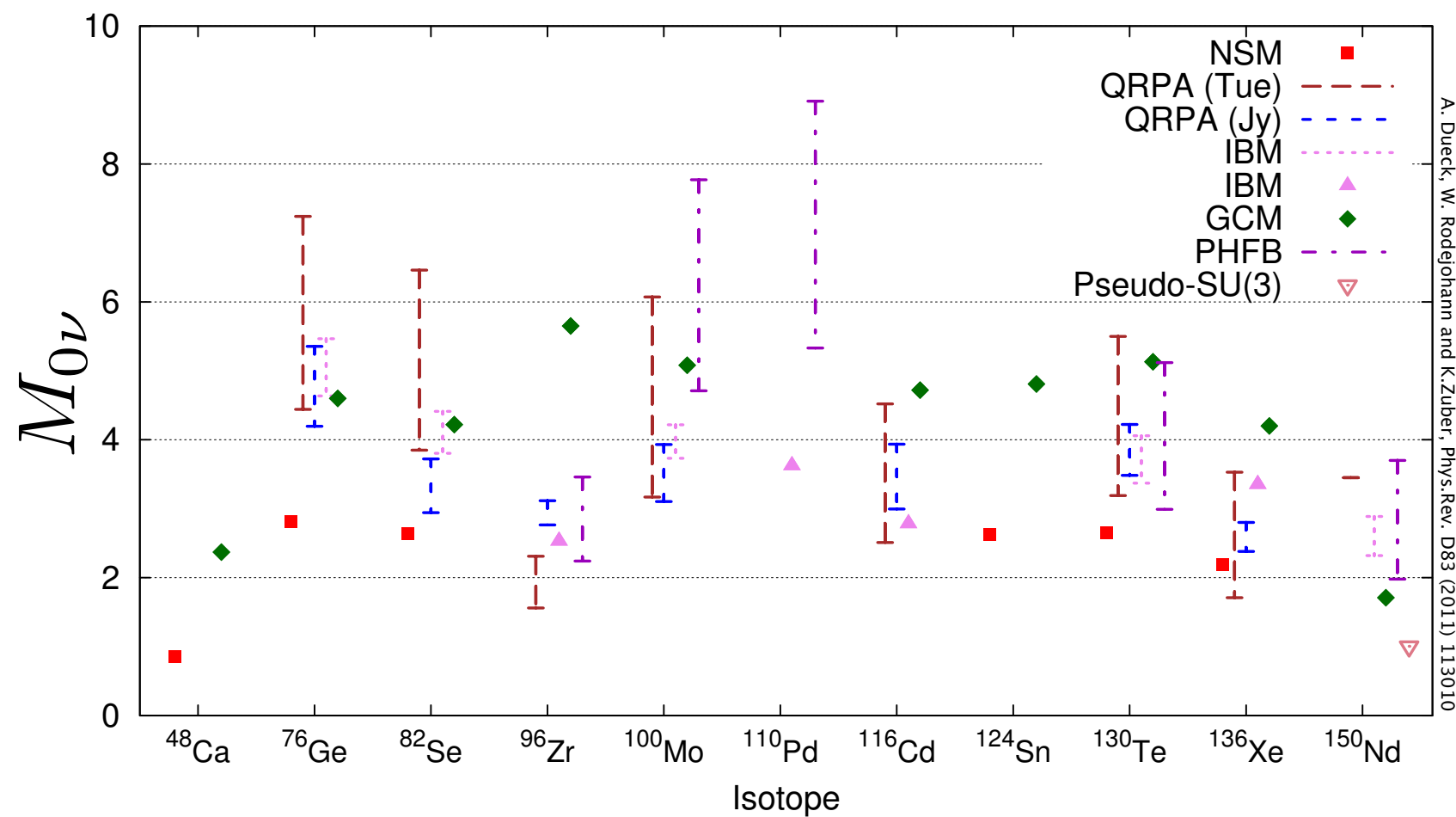
$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$



Transition	G [10^{-14} yr^{-1}]	Q [keV]
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	6.35	4373.7
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	0.63	2039.1
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.7	2995.5
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	4.36	3035
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	4.62	2809
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	4.09	2530.3
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	4.31	2461.9
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	19.2	3367.3

Matrix elements

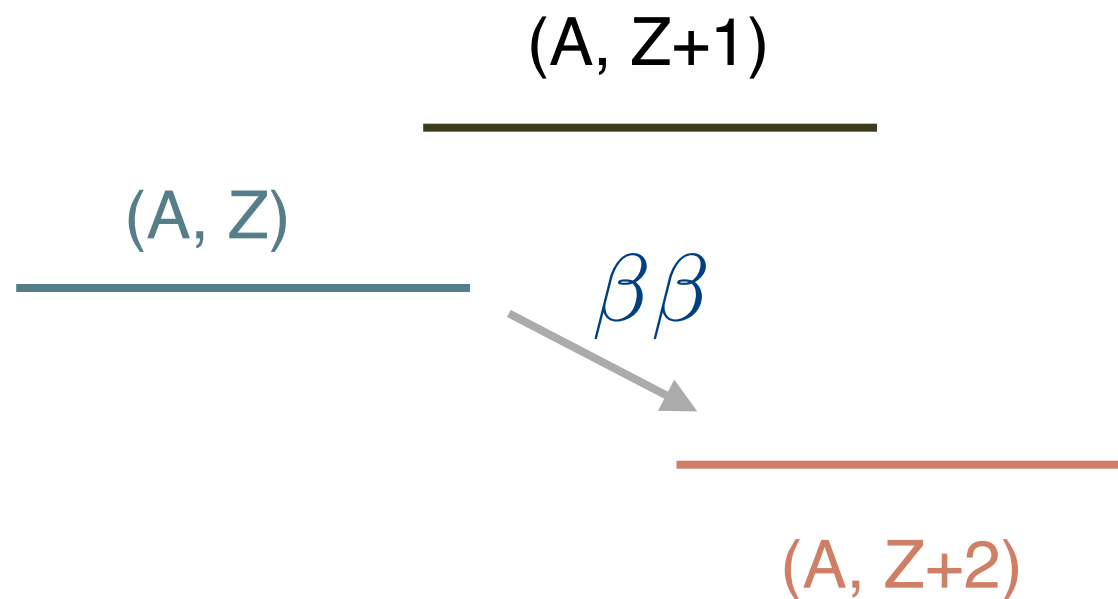
$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$



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

Which nuclei can decay via $0\nu\beta\beta$?

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



Candidate*	Q [MeV]	Abund [%]
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	3.350	2.8
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.034	9.6
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	2.228	5.64
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	2.530	34.5
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	2.479	8.9
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	3.367	5.6

* Q-value > 2 MeV

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$ 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:

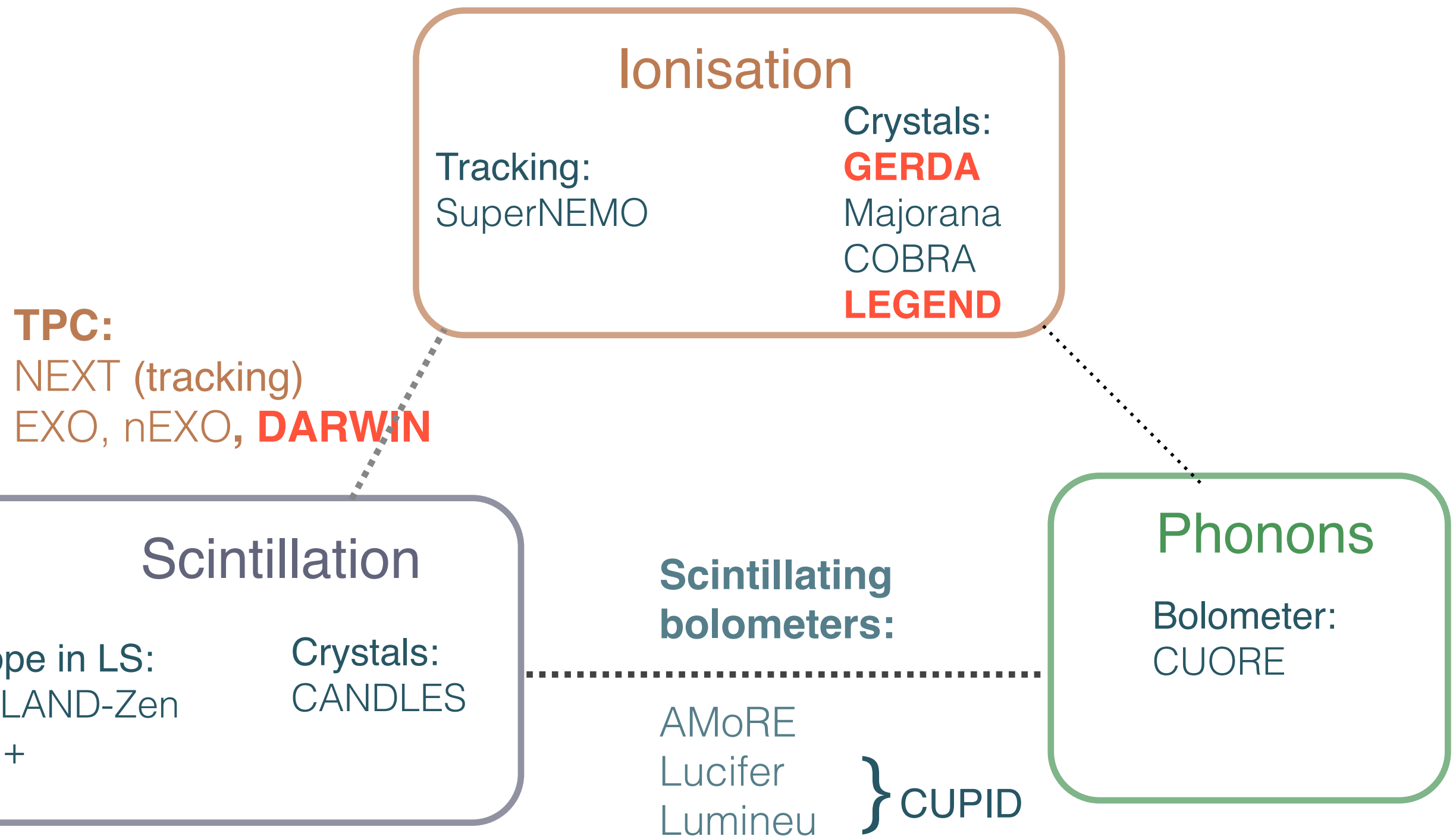
large detector masses
high isotopic abundance
ultra-low background noise
good energy resolution



Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

Experimental techniques



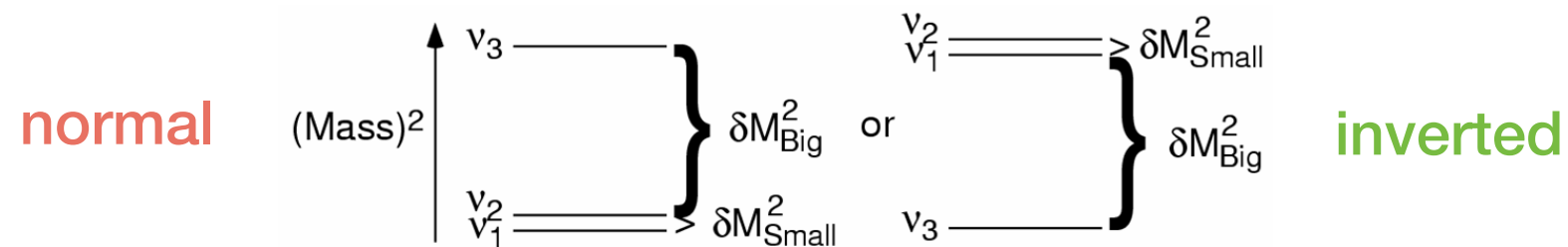
One Slide Current Status of the Field

- *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), 2.7×10^{24} y (^{130}Te)

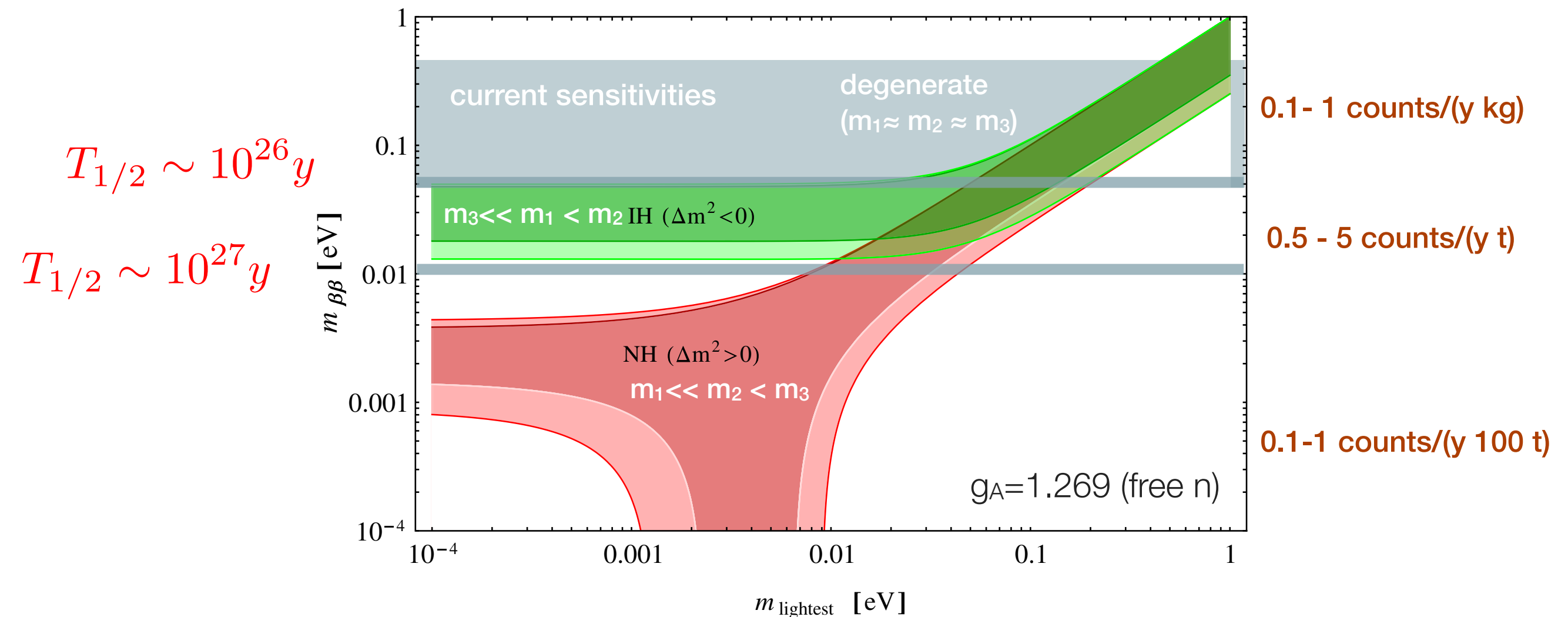
$$|\langle m_{eff} \rangle| = |\sum_i U_{ei}^2 m_i| \leq 0.06 - 0.4 \text{ eV}$$

- 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

Effective Majorana neutrino mass

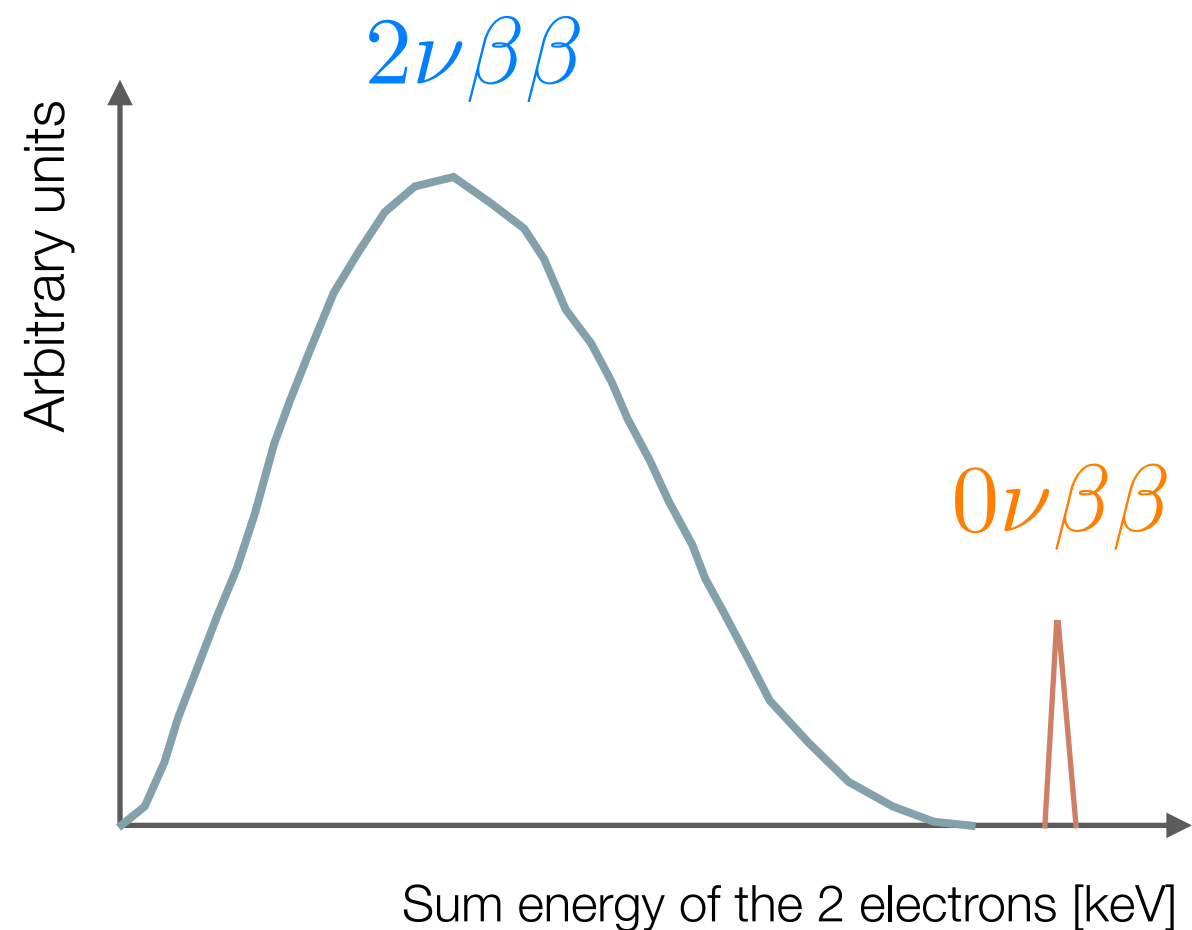


Del'Oro, Marocci, Vissani, PRD 90, 2014



Physics goal of GERDA and LEGEND

- Search for the neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge
- Observe the 2 final-state e^- , expect sharp “peak” at the Q-value
- Excellent energy resolutions and ultra-low background: *essential for a discovery*



$$\Delta L = 2$$

$$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e = 2039 \text{ keV}$$

The GERDA Experiment: Overview

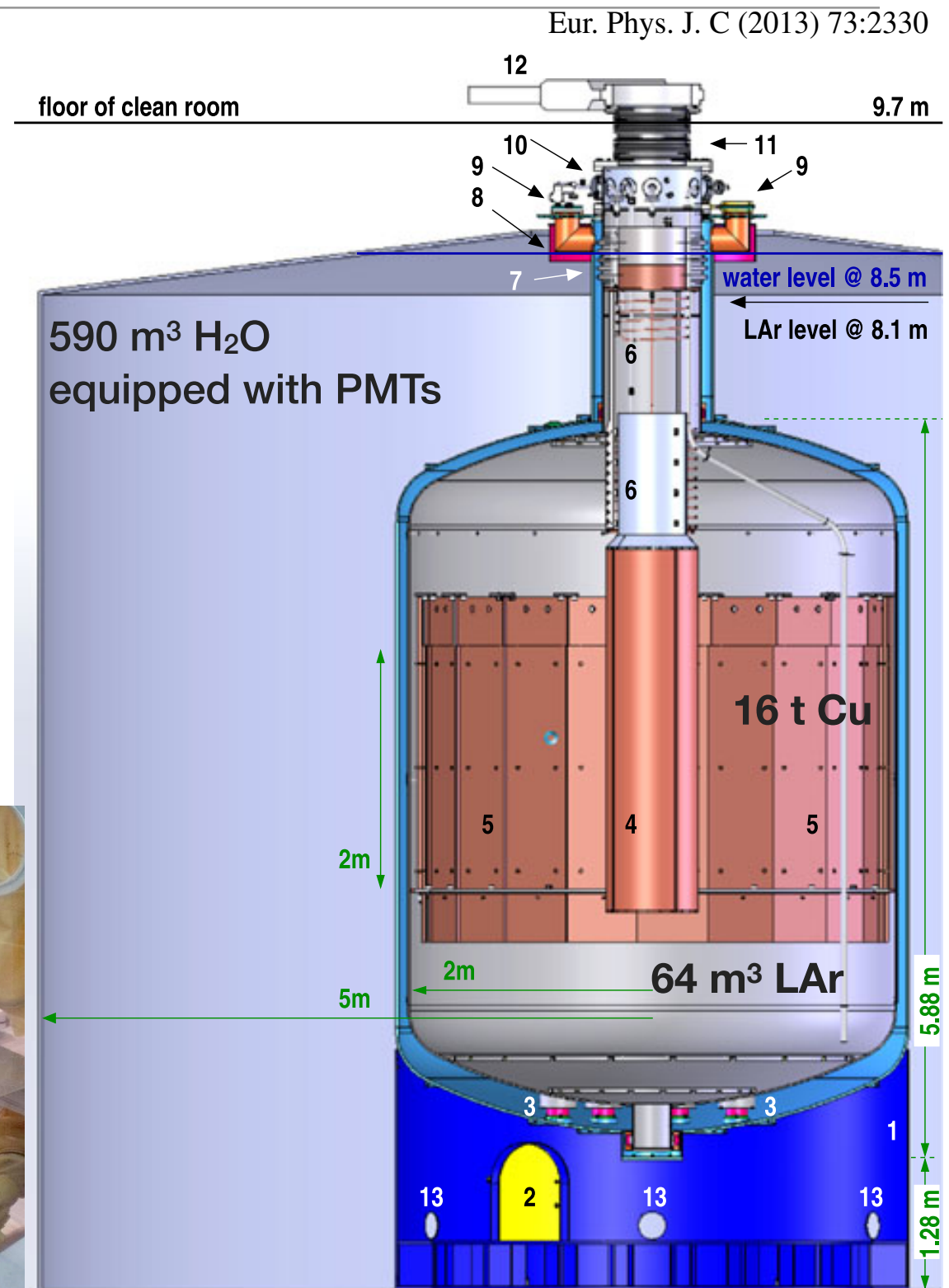
HPGe detectors, enriched to $\sim 86\%$ in ^{76}Ge
Liquid argon as cooling medium and shielding
(U/Th in LAr $< 7 \times 10^{-4} \mu\text{Bq/kg}$)
A minimal amount of surrounding materials

Phase I (2011-2014)

~ 18 kg HPGe detectors

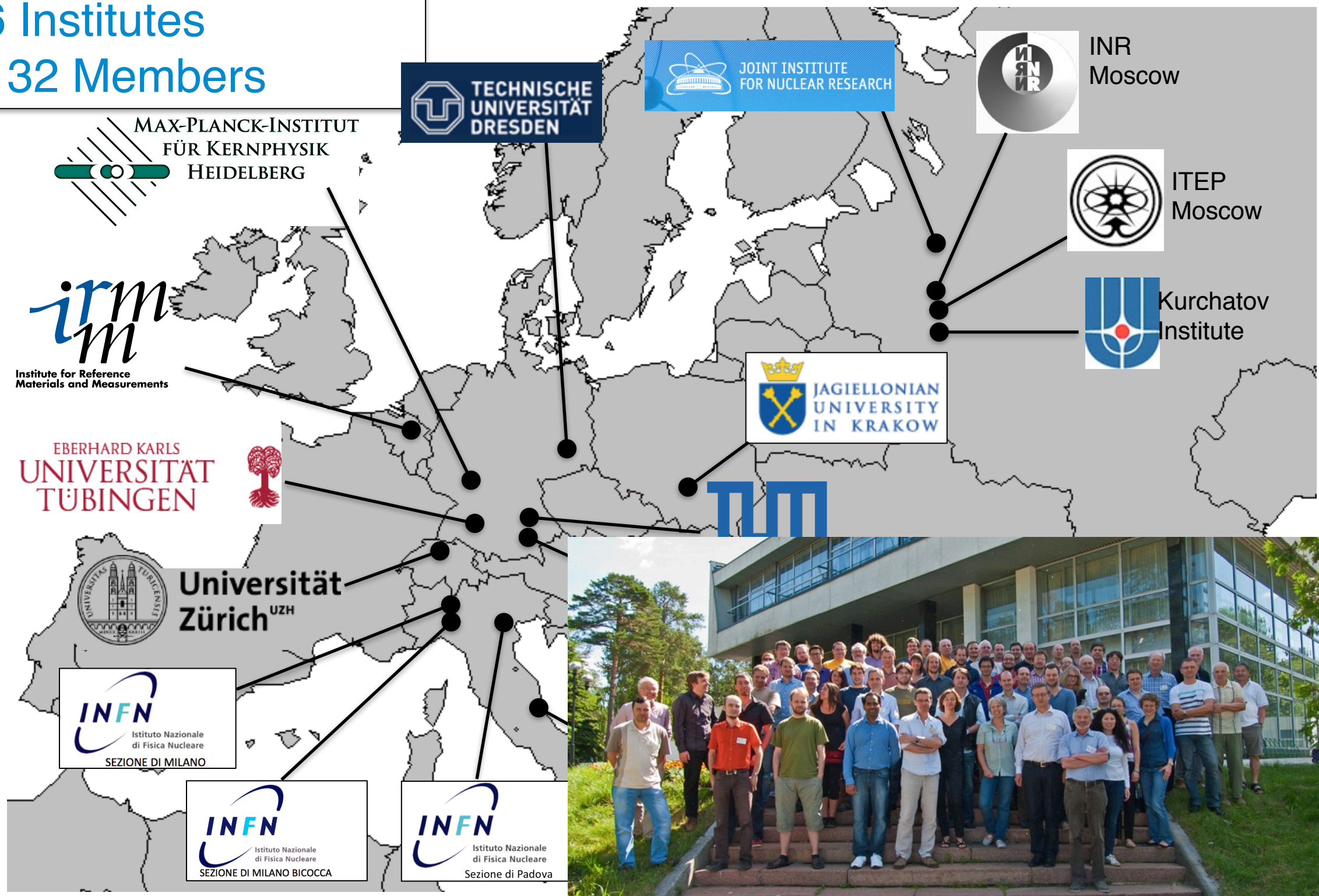
Phase II (2015-2019)

~ 36 kg HPGe detectors



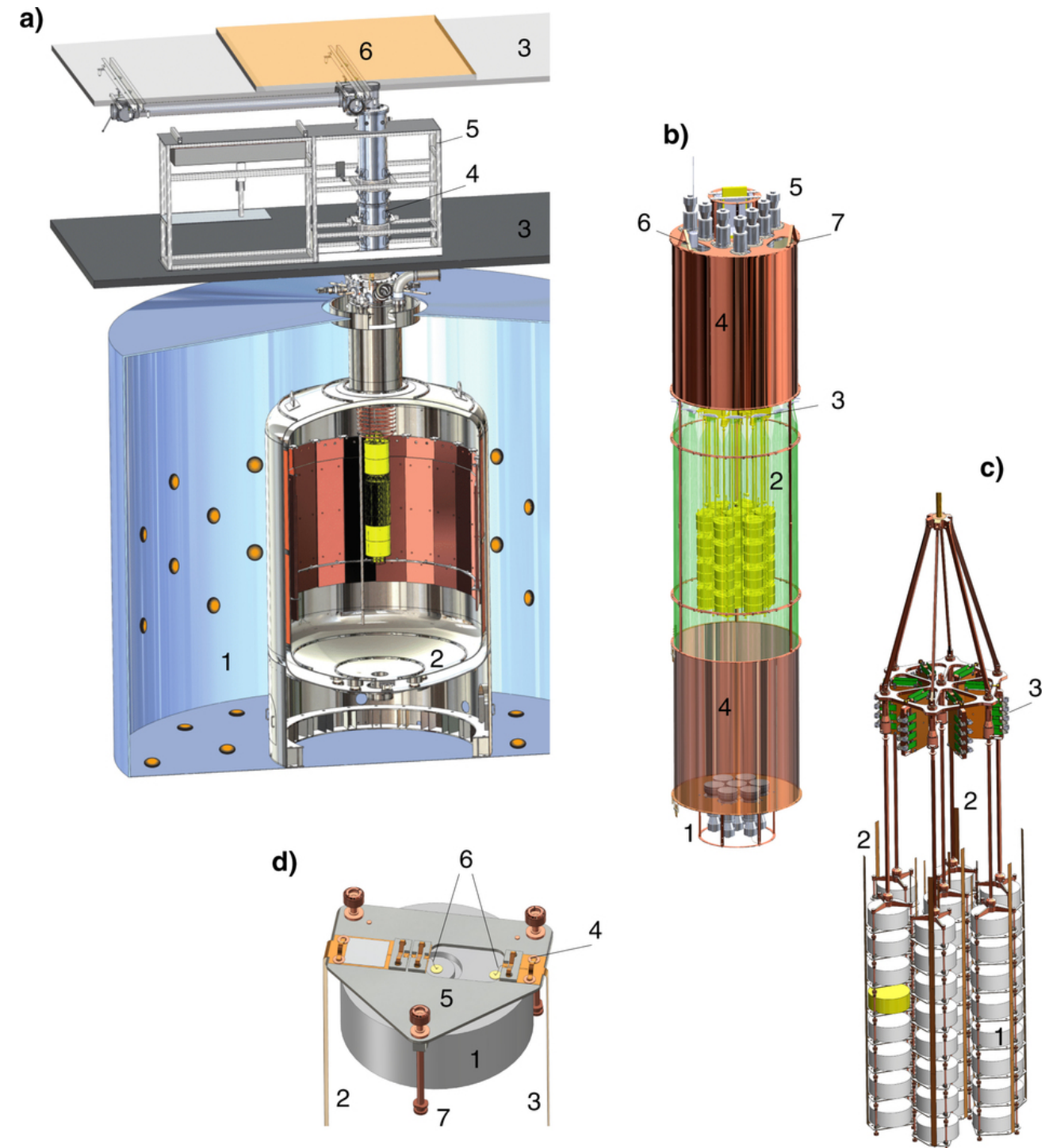
The GERDA Collaboration

16 Institutes
~132 Members



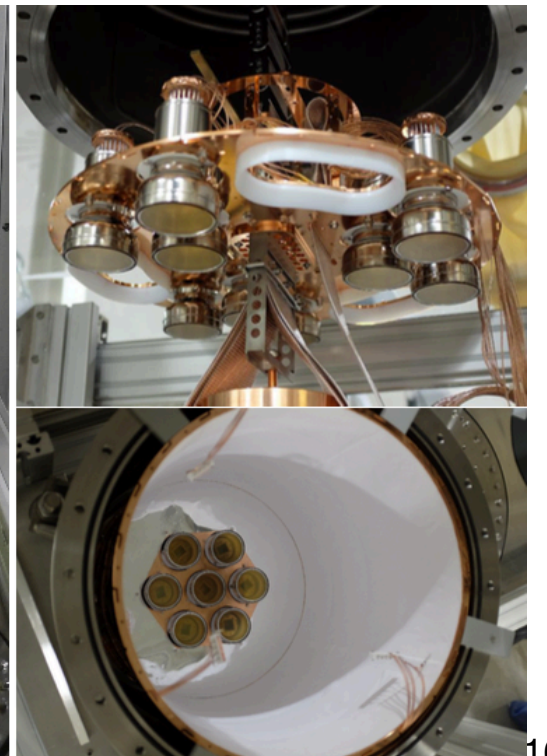
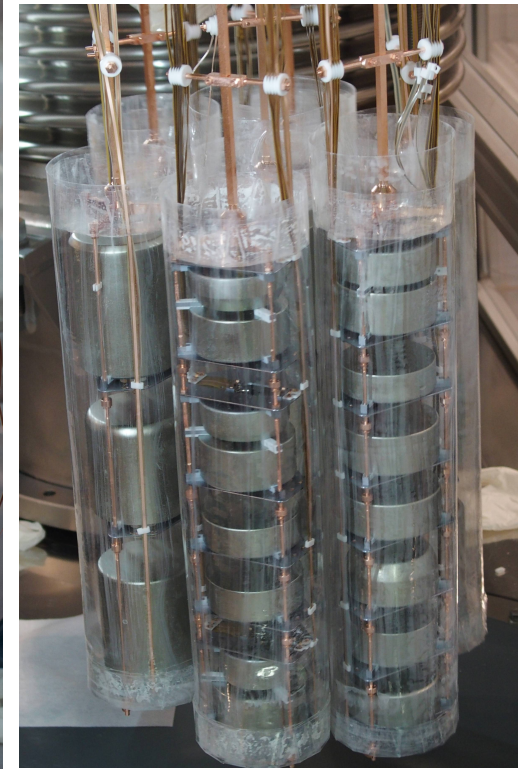
GERDA Phase II

- Started science run in December 2015
- 37 detectors (35.6 kg) enriched in ^{76}Ge
- Improve phase I sensitivity by factor 10:
 - 100 kg y exposure
 - background: 0.001 events/(kg y keV)
- LAr veto: 0.5 m diameter, 2 m high
- Viewed by optical fibres + SiPMs and 16 (7 + 9) 3-inch PMTs (R11065-10/20)
- 7 detector strings (one out of $^{\text{nat}}\text{Ge}$ detectors) fully operational



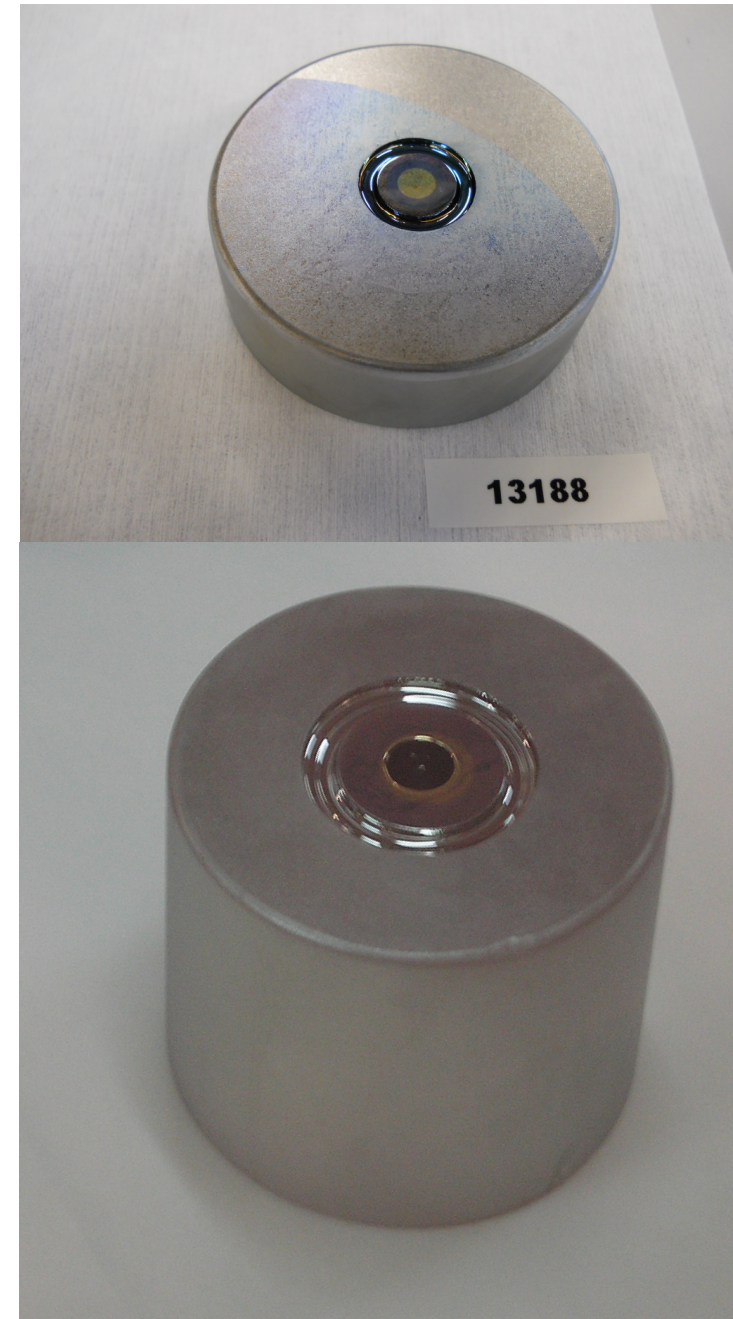
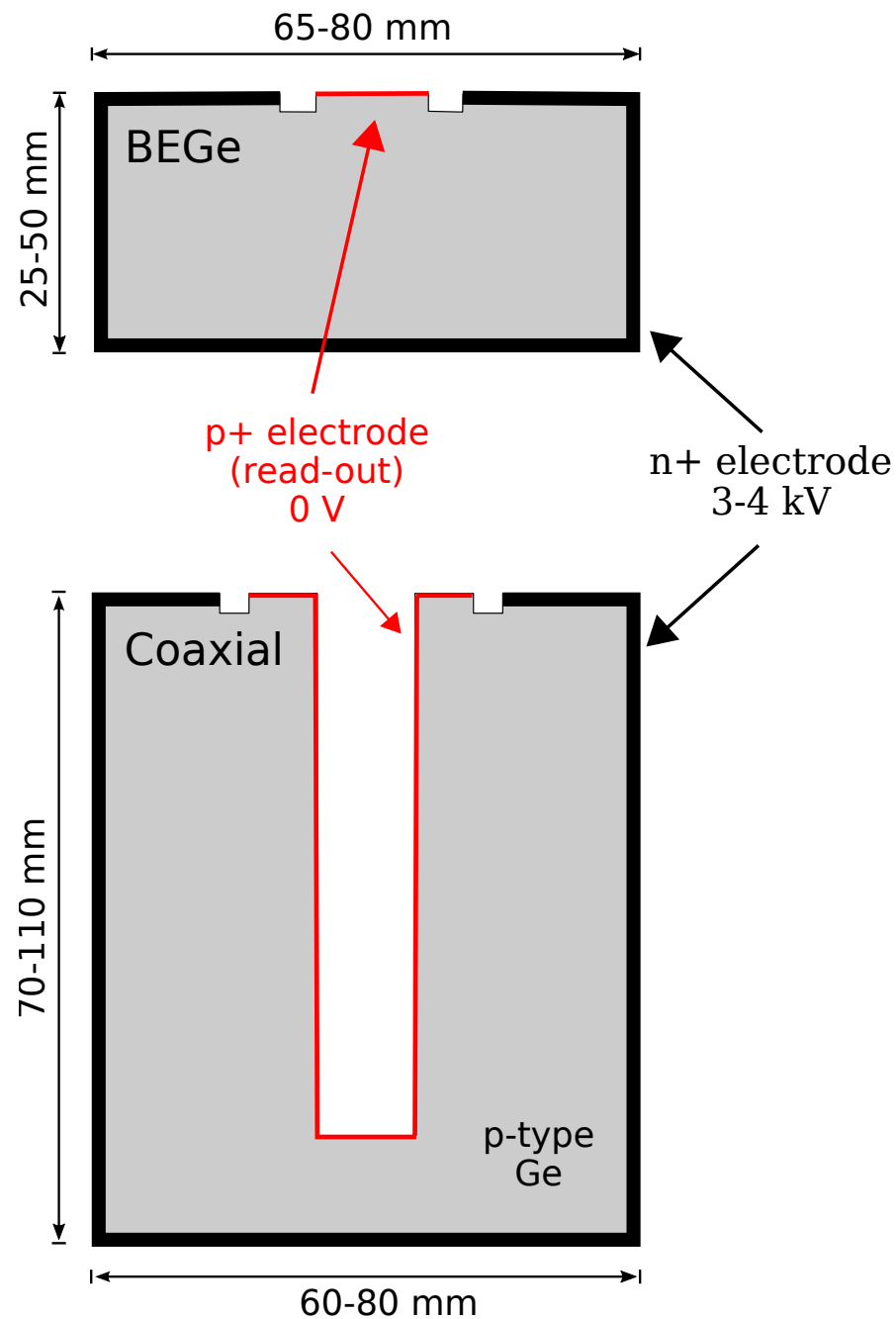
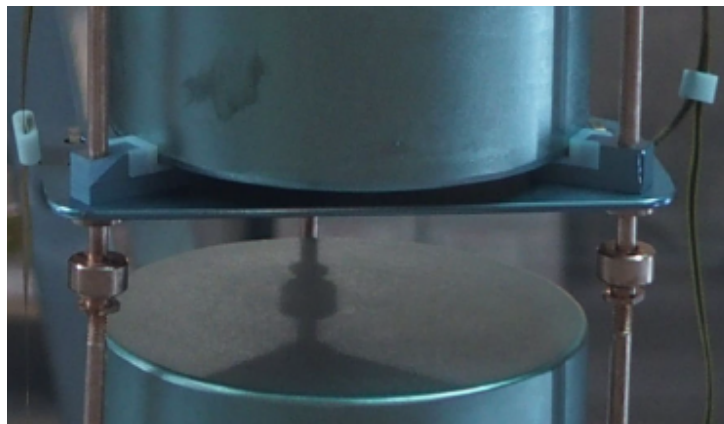
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GERDA Detectors

- 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)



Background Suppression Methods

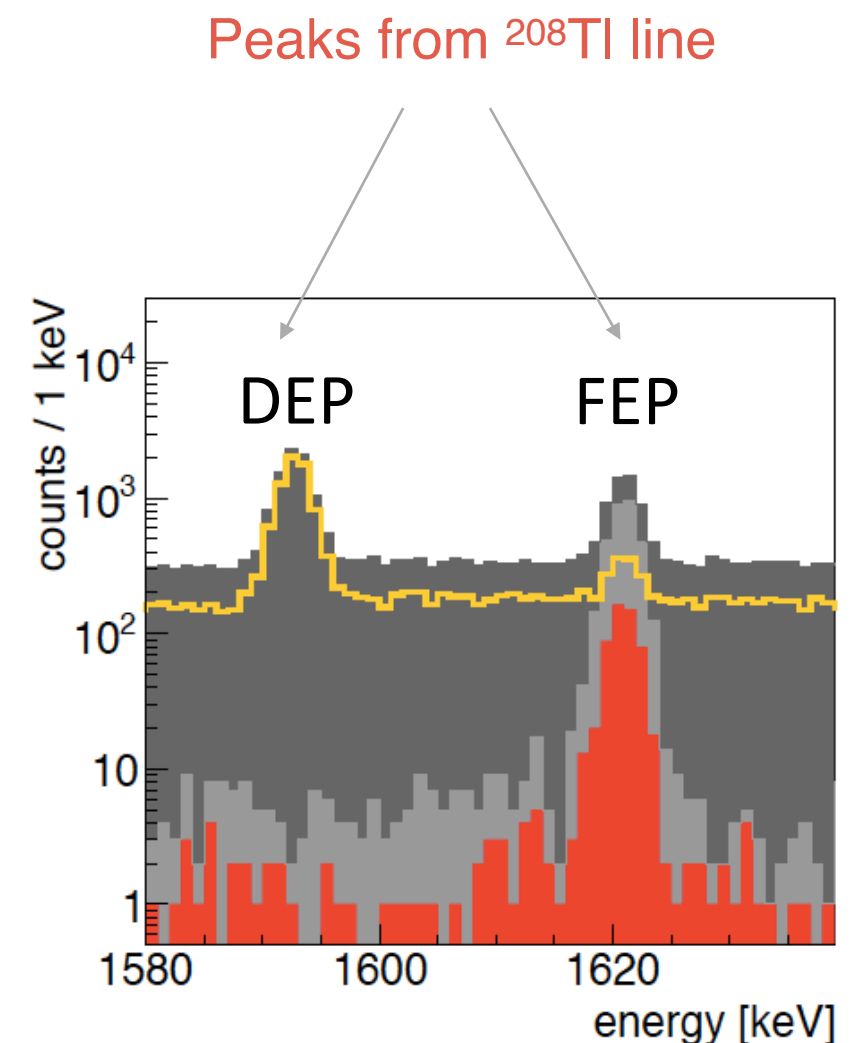
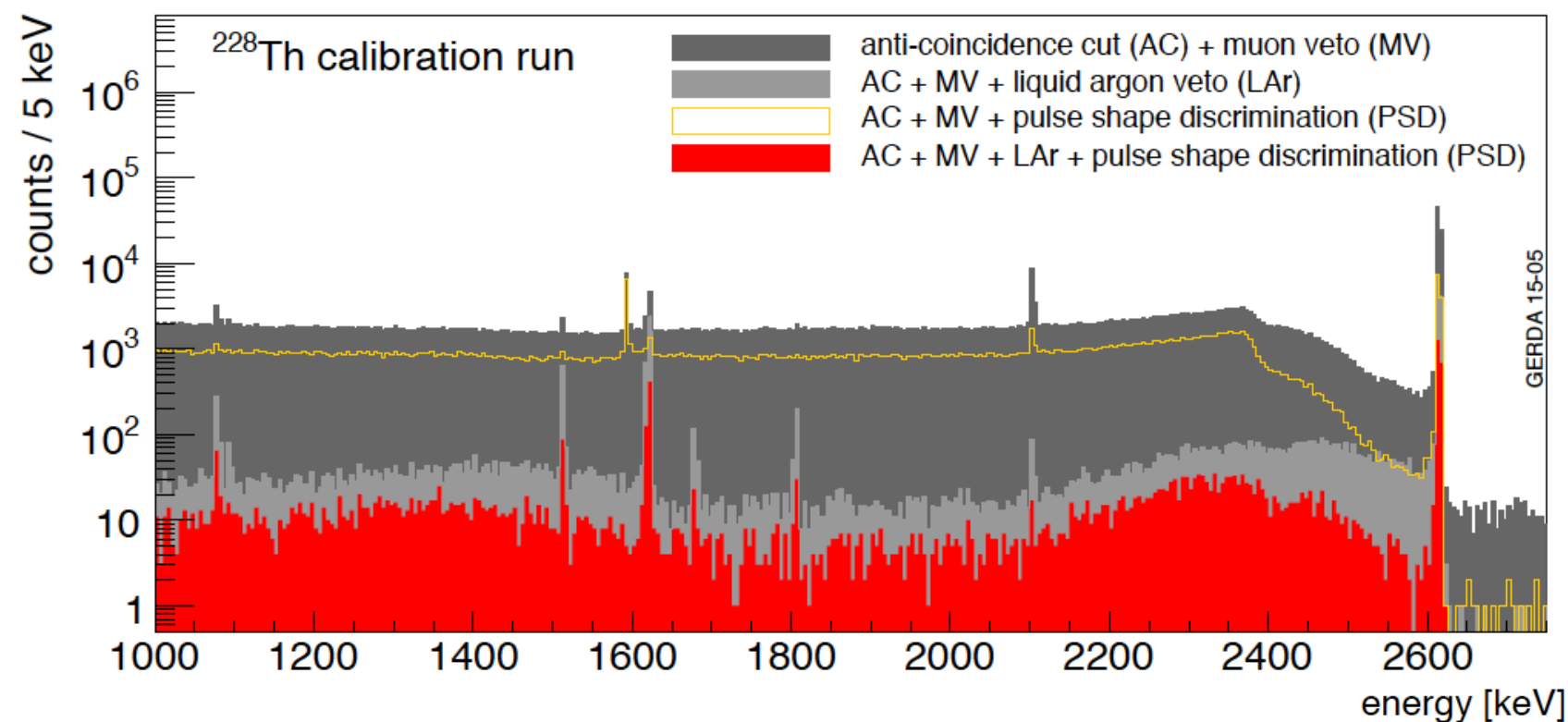
- Example: calibration data with ^{228}Th sources, background rejection via:

➔ Muon Veto (MV)

➔ Anti-coincidence detector array (AC)

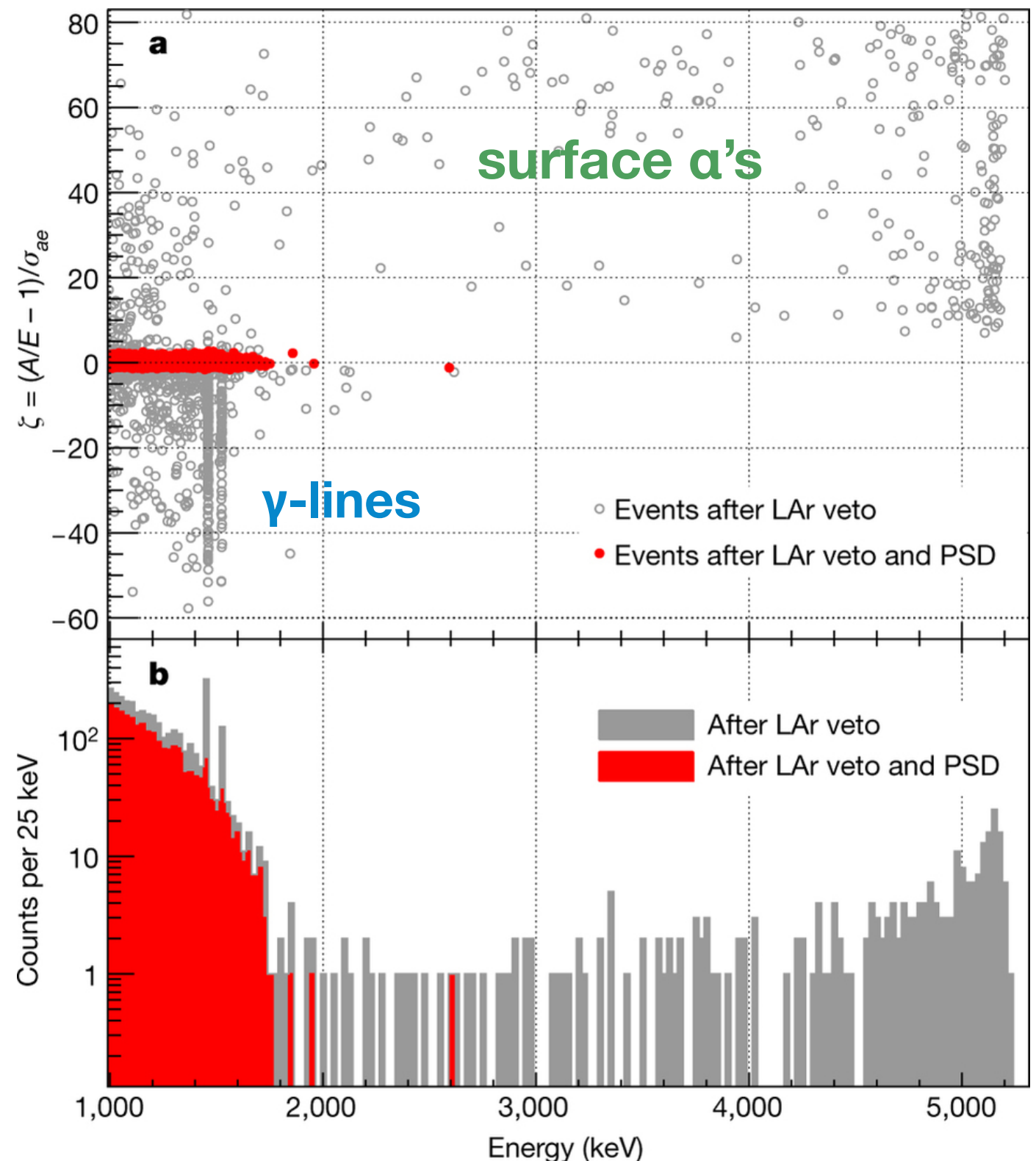
➔ Anti-coincidence liquid argon veto (LAr)

➔ Pulse shape discrimination (PSD)

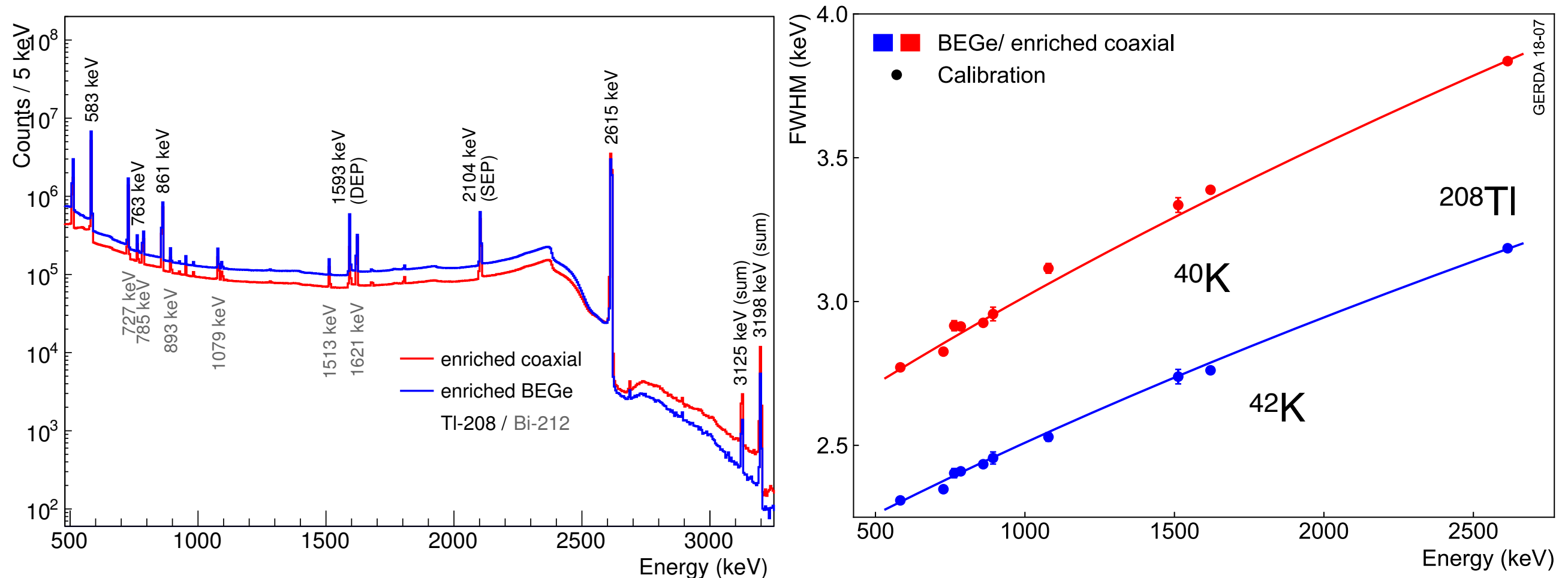


BEGe Pulse Shape Spectra

- Mono-parametric event selection based on A/E :
 - ➔ current pulse amplitude A
 - ➔ total energy E
- Tuned by calibration data (DEP from 2615 keV)
- Efficiencies:
 - ➔ DEP: ~87%
 - ➔ $2\nu\beta\beta$: ~85%
- All surface α 's removed
- γ -lines: factor 6 lower



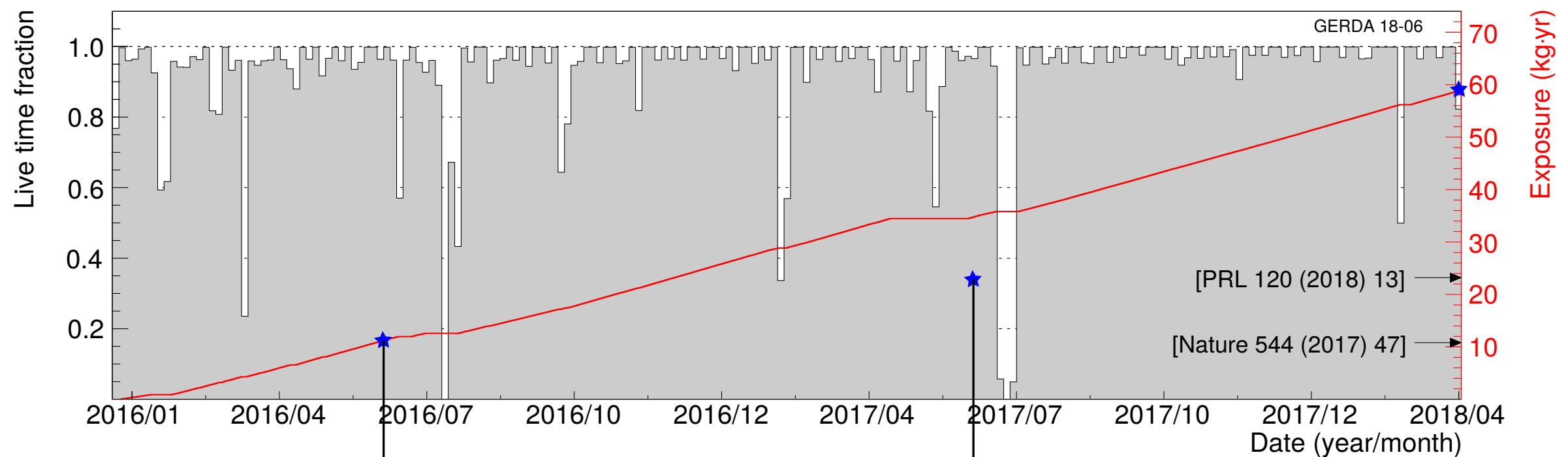
Calibration: Stability and Energy Resolution



- Weekly calibration with three ^{228}Th sources
- FWHM at $Q_{\beta\beta}$: (3.0 ± 0.1) keV for BEGe, (3.6 ± 0.1) keV for coaxial

Data taking and analysis overview

- Total exposure for June 2018 release: 82.4 kg y
- Blind analysis: events at (2039 ± 25) keV unmasked after selections frozen



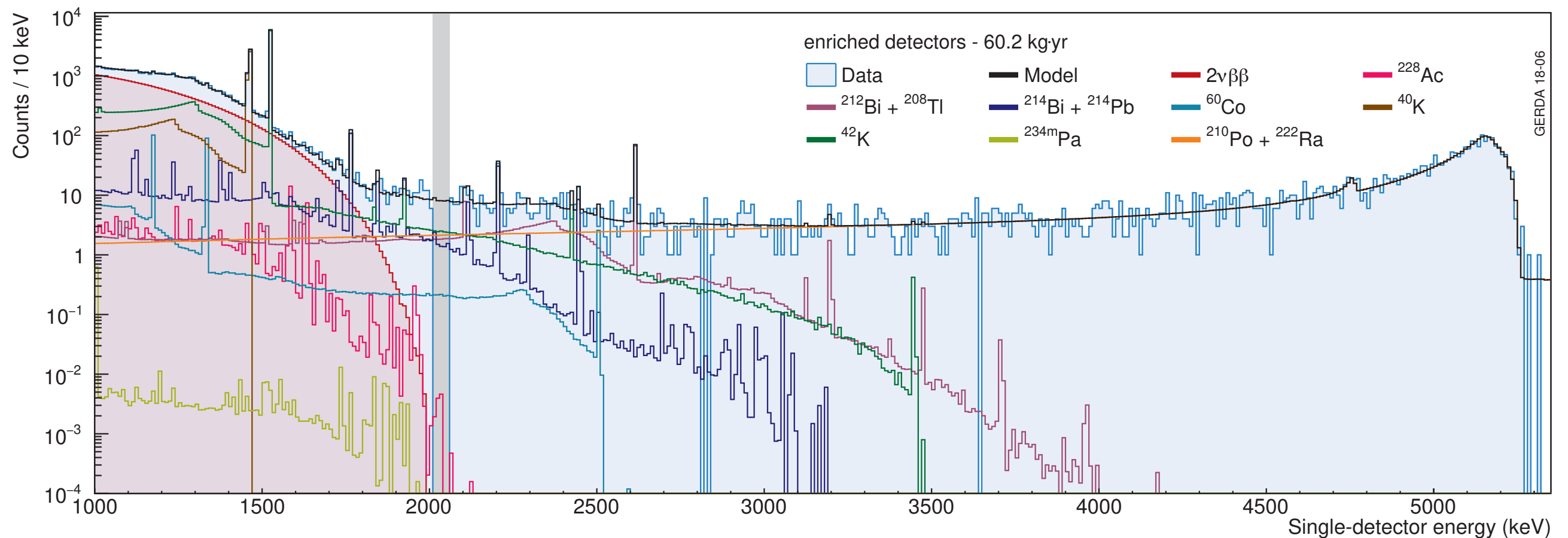
June 2016
10.8 kg yr
Nature 554, 47

June 2017
23.2 kg yr
PRL 120, 132503

June 2018
58.9 kg yr

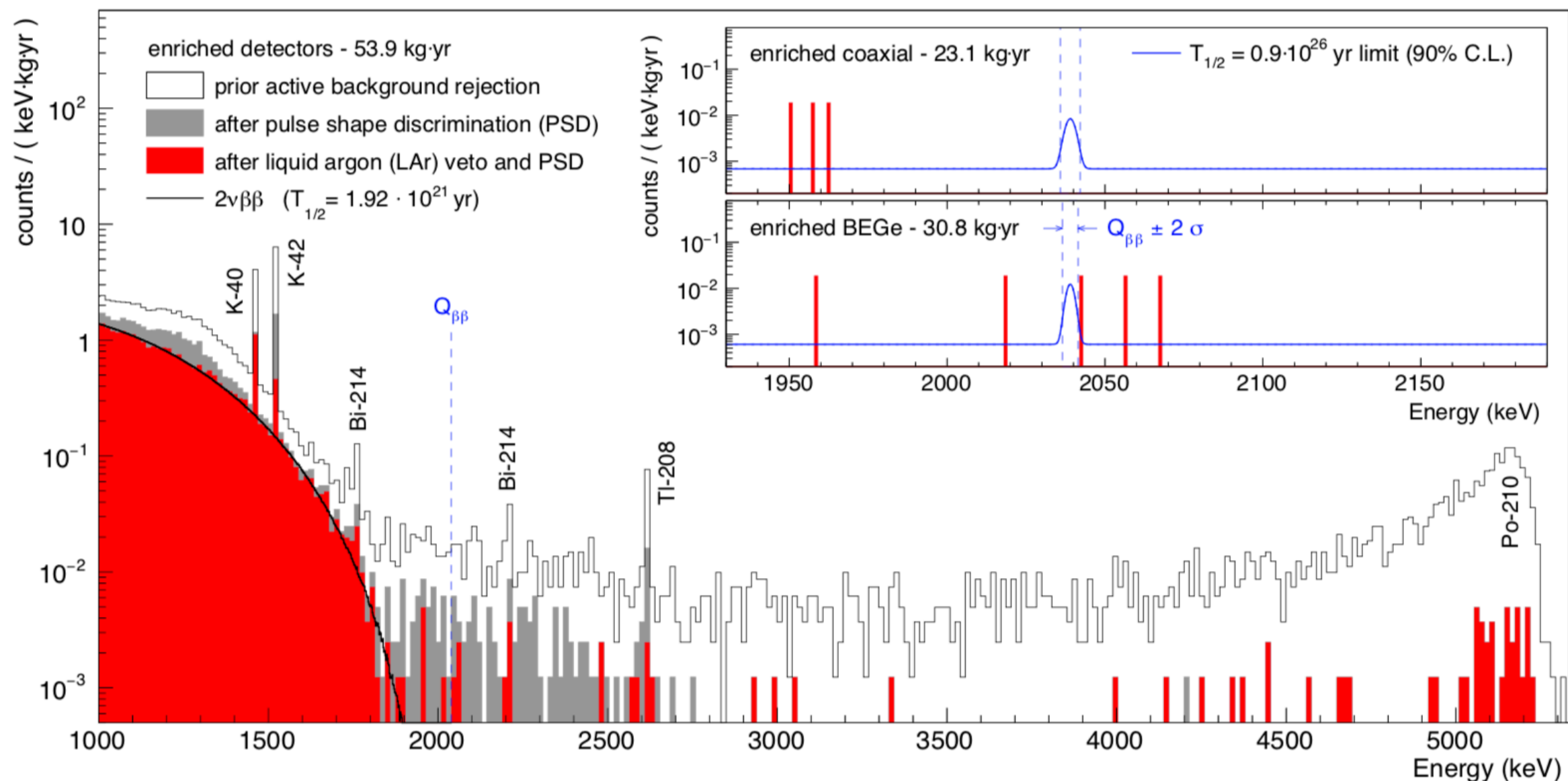
Background model

- Dominant background at $Q_{\beta\beta}$:
 - degraded alphas, betas from ^{42}K , gammas from U/Th chain



Energy Spectra in Phase II: 53.9 kg y

- Measured half-life of the $2\nu\beta\beta$ - decay: 1.92×10^{21} y
- LAr veto effect: $\sim$ factor 5 background suppression at 1525 keV (^{42}K)



Latest results

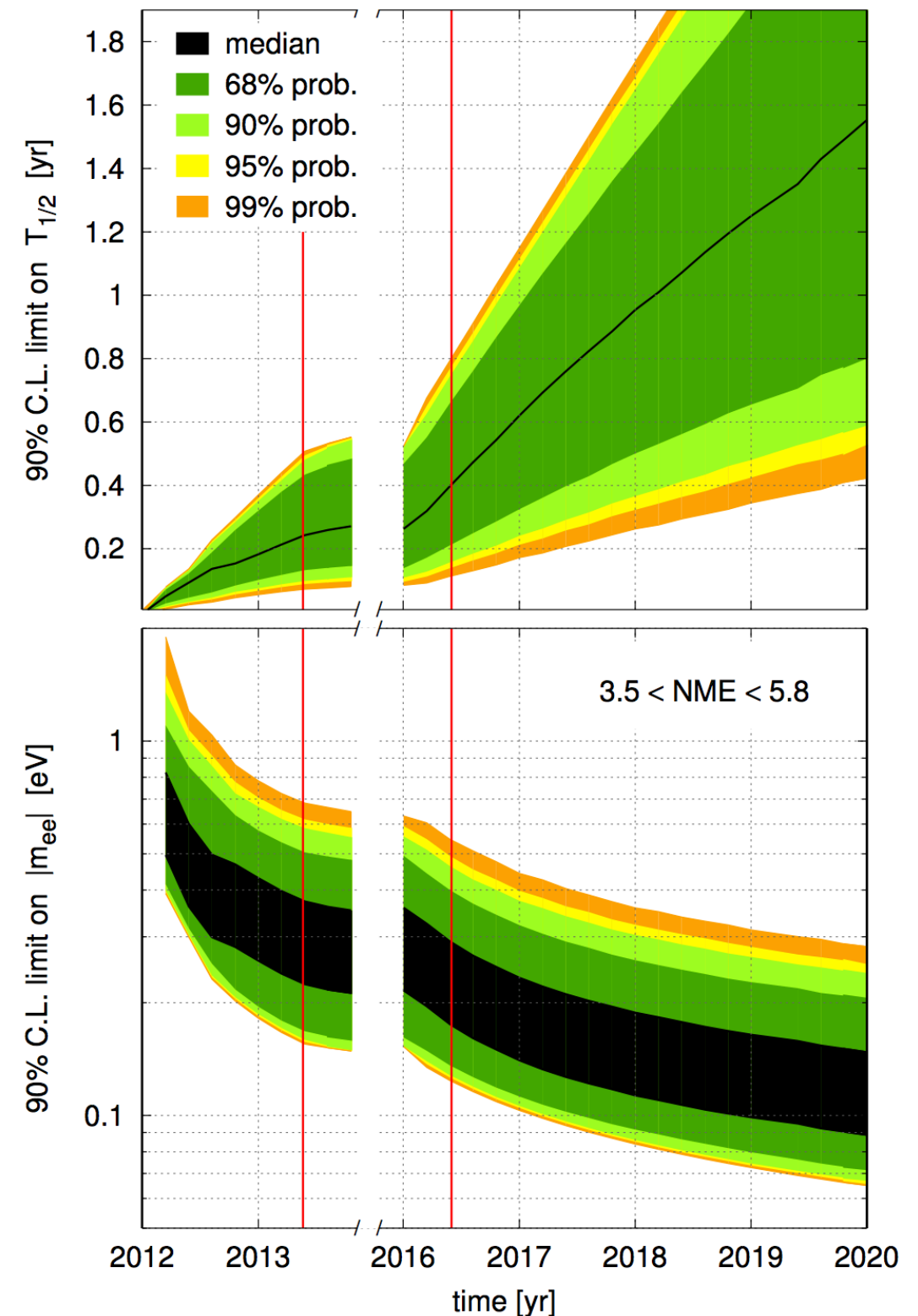
- Blind analysis: 82.4 kg y
- New limit on the $0\nu\beta\beta$ -decay of ^{76}Ge

$$T_{1/2}^{0\nu} > 0.9 \times 10^{26} \text{ y (90\%C.L.)}$$

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

- New background index:
 - 5.6×10^{-4} events/(keV kg y)
 - in 230 keV energy window around $Q_{\beta\beta}$
- *GERDA will stay “background-free” hence the motivation for LEGEND-200*
- Current median sensitivity:

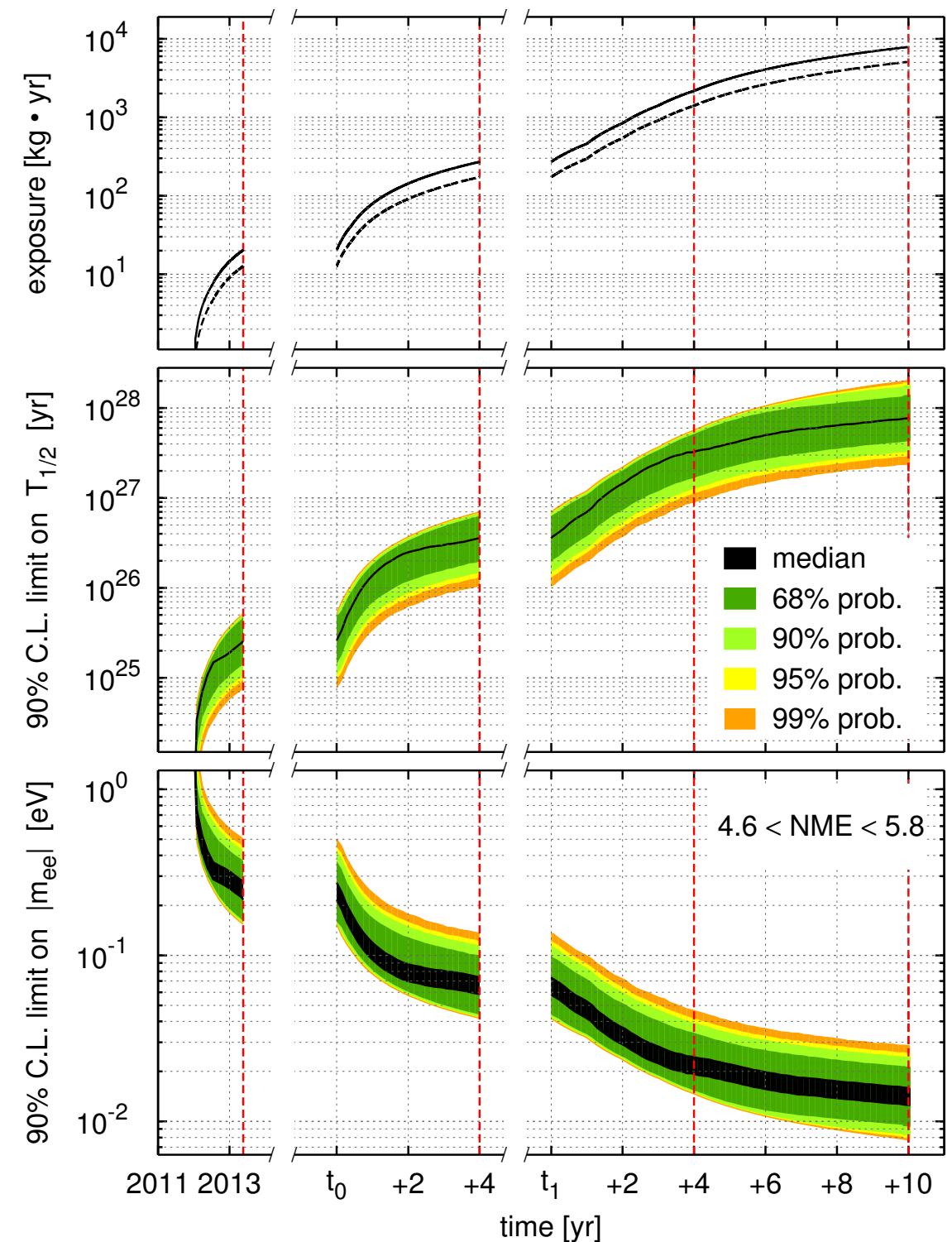
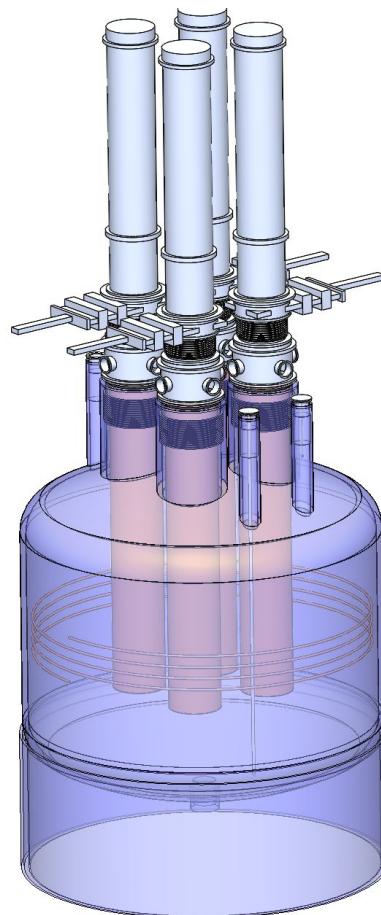
$$T_{1/2}^{0\nu} > 1.1 \times 10^{26} \text{ y (90\%C.L.)}$$



Beyond GERDA: LEGEND

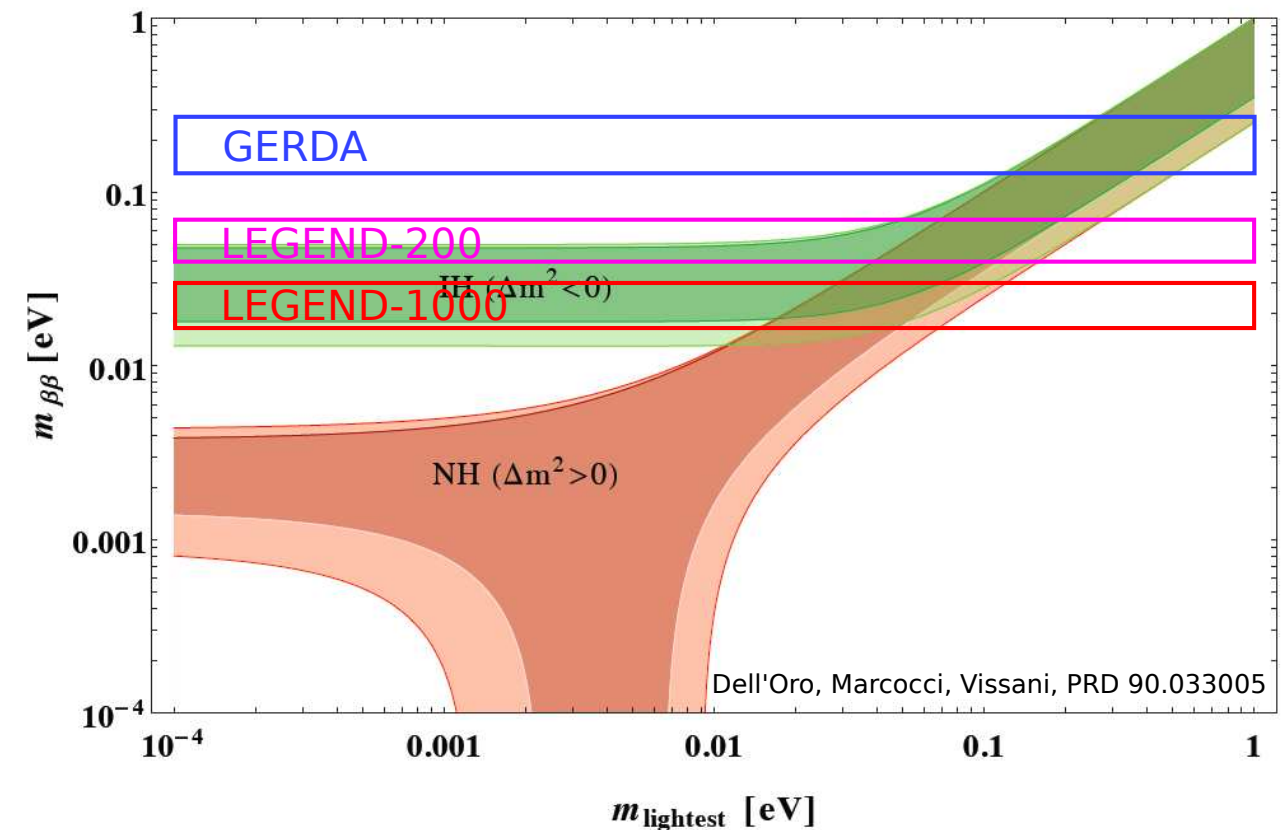
- *Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay*
- Collaboration formed in October 2016
- 219 members, 48 institutions, 16 countries (legend-exp.org)
- Background goal:
 $\sim 10^{-4}$ events/(kg y keV)
- Detector mass: 200 kg $\rightarrow$ 1 t
- Discovery potential:

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



Beyond GERDA: LEGEND

- *First stage: LEGEND-200 at LNGS*
- Reuse GERDA infrastructure
- Start data taking in 2021
- Obtain 1 ton x year exposure
- Mass sensitivity
- 30 - 70 meV discovery potential

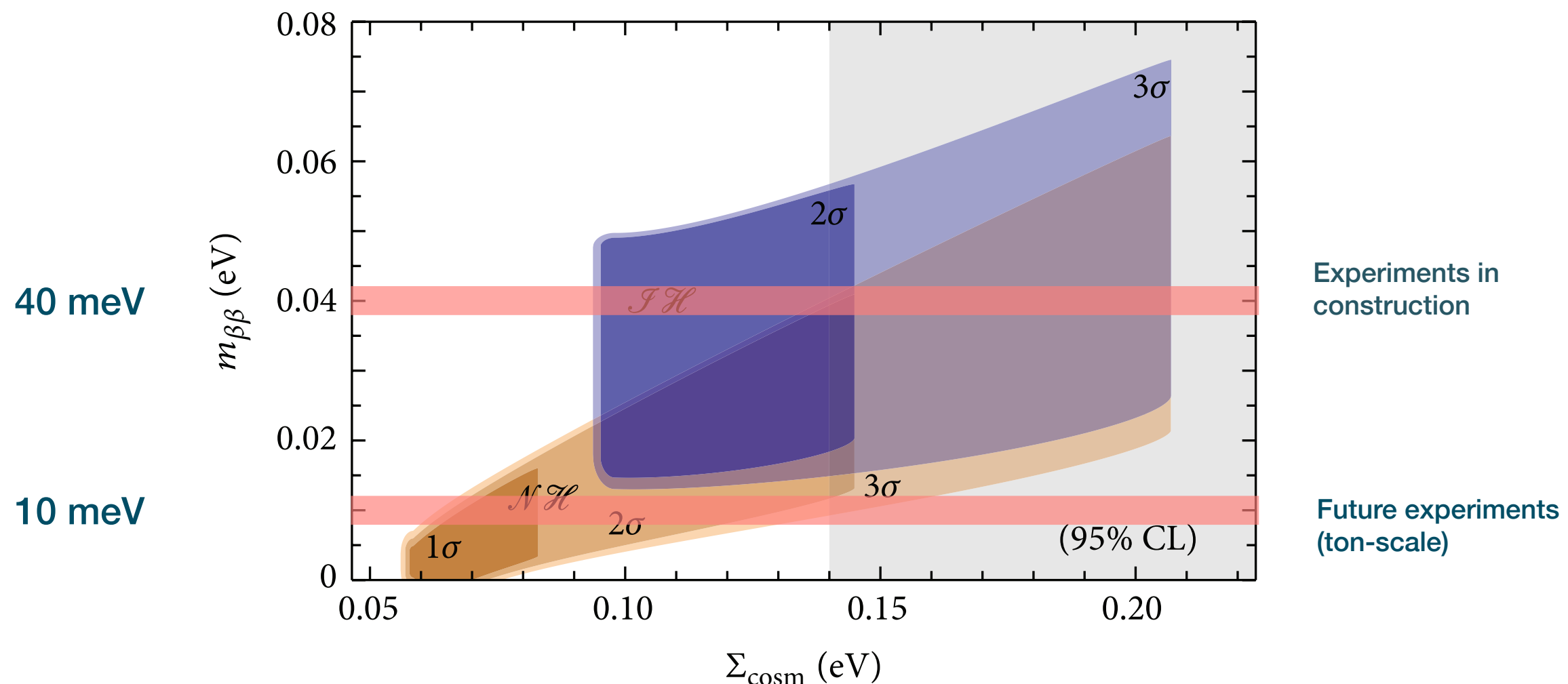


LEGEND and other experiments

Experiment	Iso	Iso. mass [kg]	FWHM [keV]	BI [cts/(FWHM·t·yr)]	$T_{1/2}^{0\nu}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]
LEGEND-200	^{76}Ge	175	3	0.6	10^{27}	34 – 74
LEGEND-1000	^{76}Ge	873	3	0.1	$6 \cdot 10^{27}$	14 – 30
SuperNEMO	^{82}Se	100	120	6	10^{26}	58 – 144
CUPID	^{82}Se	336	5	0.02	$2.1 \cdot 10^{27}$	13 – 31
AMoRE-I	^{100}Mo	2.5	5	5	$2.8 \cdot 10^{25}$	74 – 126
AMoRE-II	^{100}Mo	100	5	0.5	10^{27}	12 – 21
CUPID	^{130}Te	543	5	0.02	$2.6 \cdot 10^{27}$	8 – 38
SNO+ Phase I	^{130}Te	1357	193	23	$1.9 \cdot 10^{26}$	31 – 139
SNO+ Phase II	^{130}Te	7960	134	5.4	$7.4 \cdot 10^{26}$	16 – 71
KamLAND-Zen 800	^{136}Xe	750	268	64.3	$4.6 \cdot 10^{26}$	24 – 77
KamLAND2-Zen	^{136}Xe	1000	141	3.3	$1.4 \cdot 10^{27}$	14 – 44
nEXO	^{136}Xe	4507	59	0.4	$6 \cdot 10^{27}$	7 – 21
NEXT-100	^{136}Xe	91	18	7.2	$8.5 \cdot 10^{25}$	56 – 180
PandaX-III 200	^{136}Xe	180	73	7.3	$1.3 \cdot 10^{26}$	45 – 145
PandaX-III 1000	^{136}Xe	901	24	0.8	$1.3 \cdot 10^{27}$	14 – 46

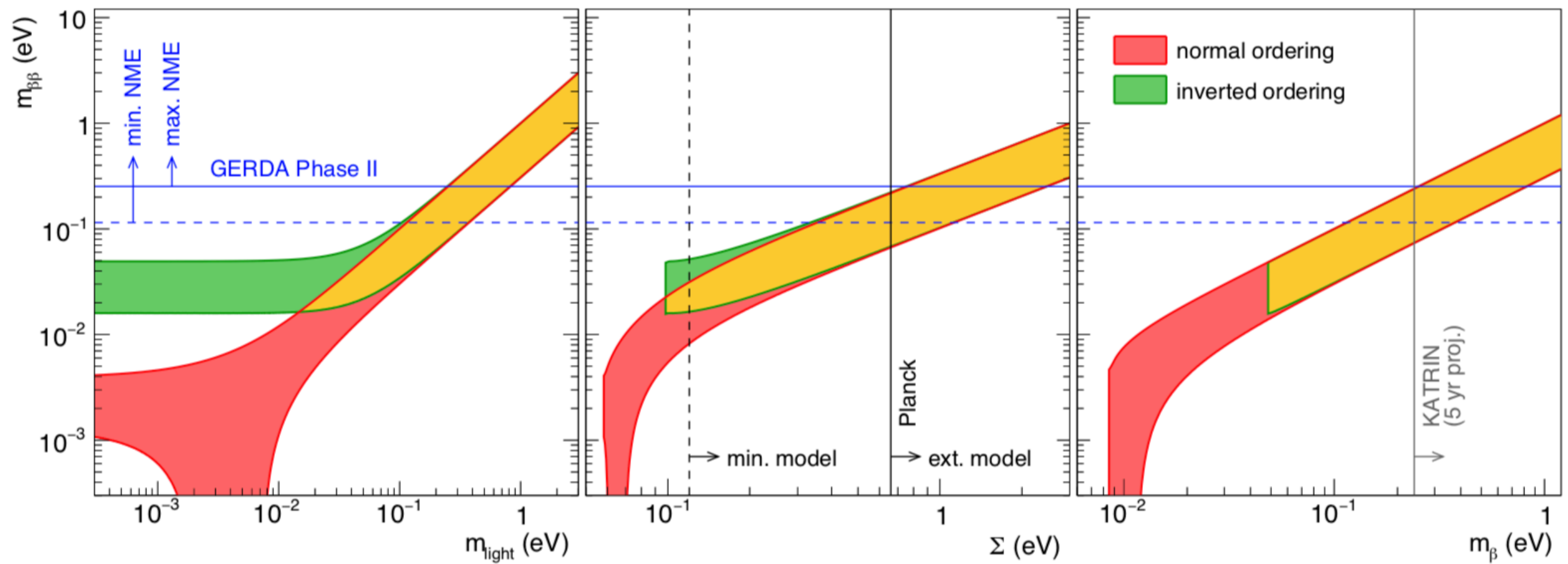
LEGEND: Physics Reach

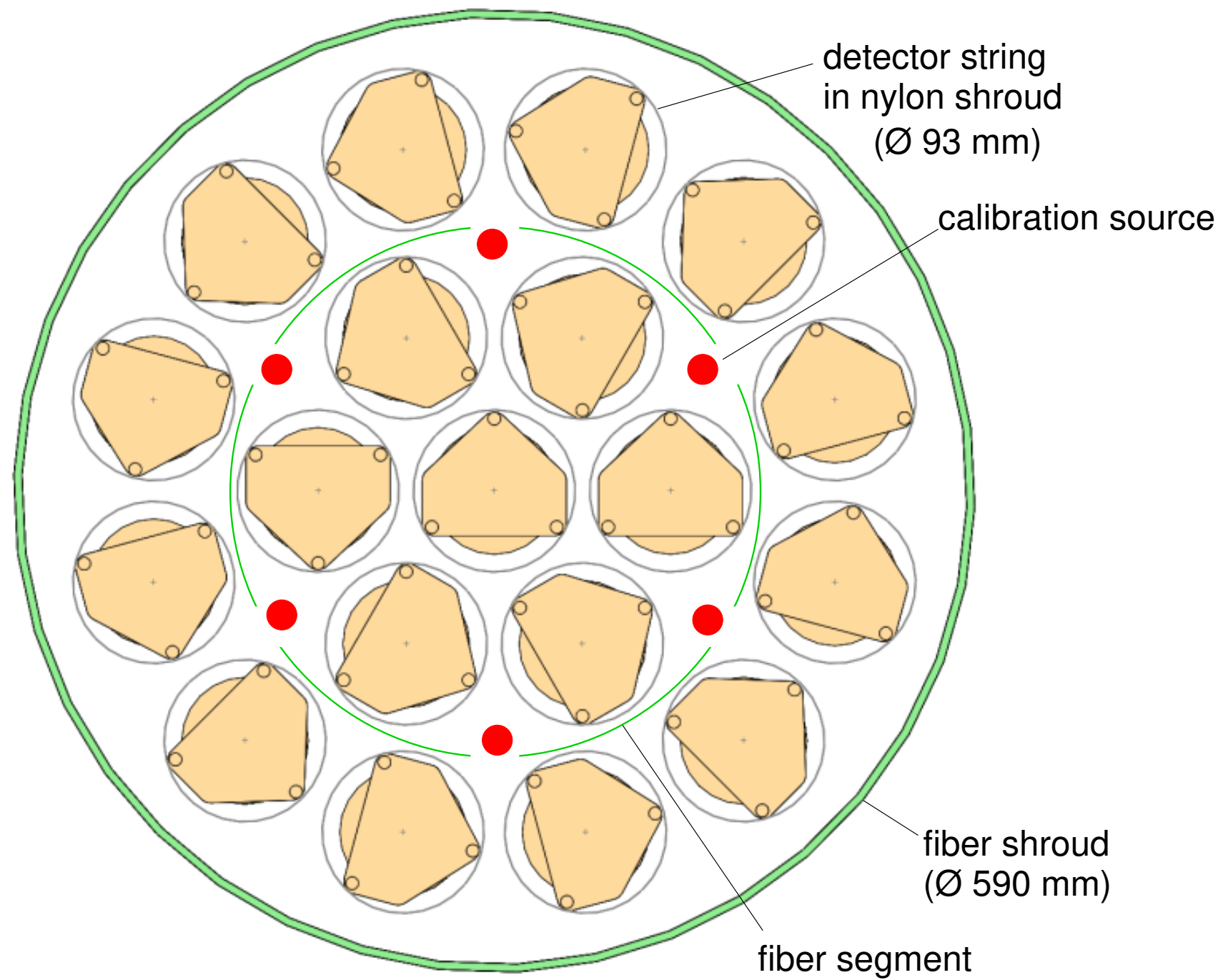
- Ton-scale experiments are indeed required to explore the inverted mass hierarchy scale
- Several other technologies also move into this direction
- ^{76}Ge experiments: the advantage of an excellent energy resolution coupled to ultra-low backgrounds



The end

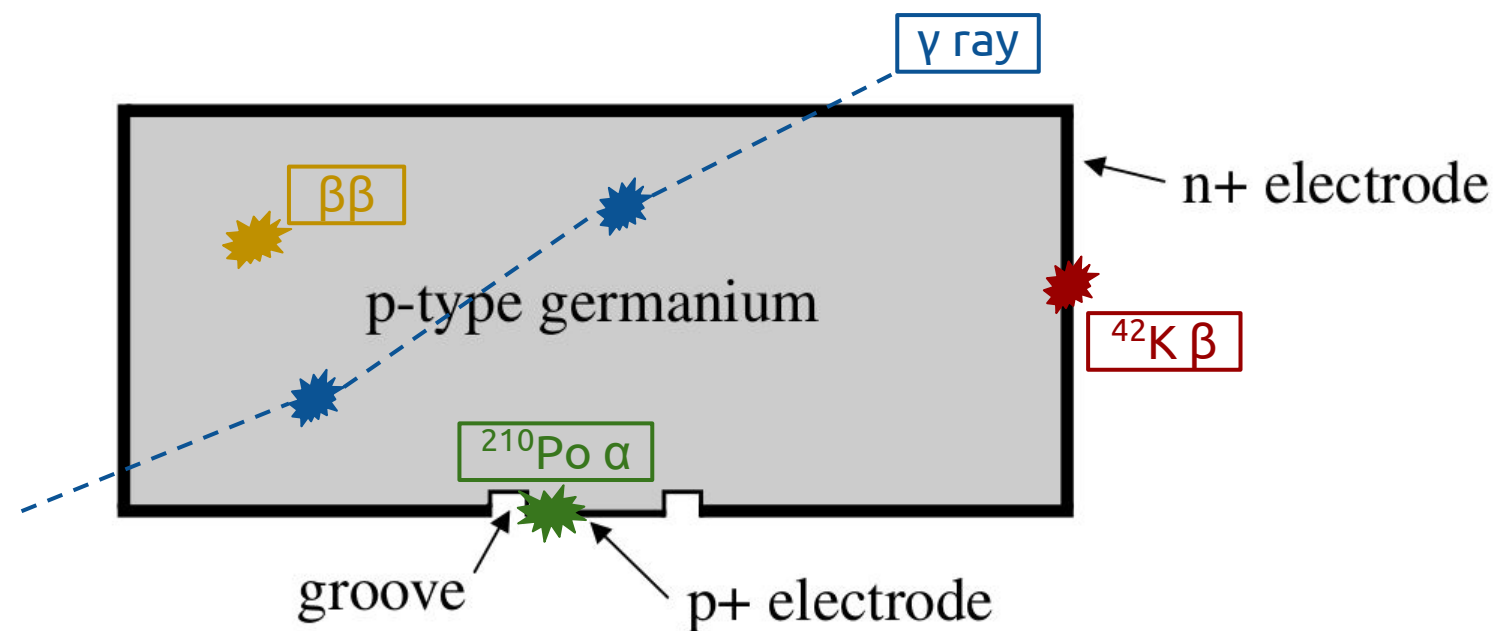
Allowed parameter space for $m_{\beta\beta}$



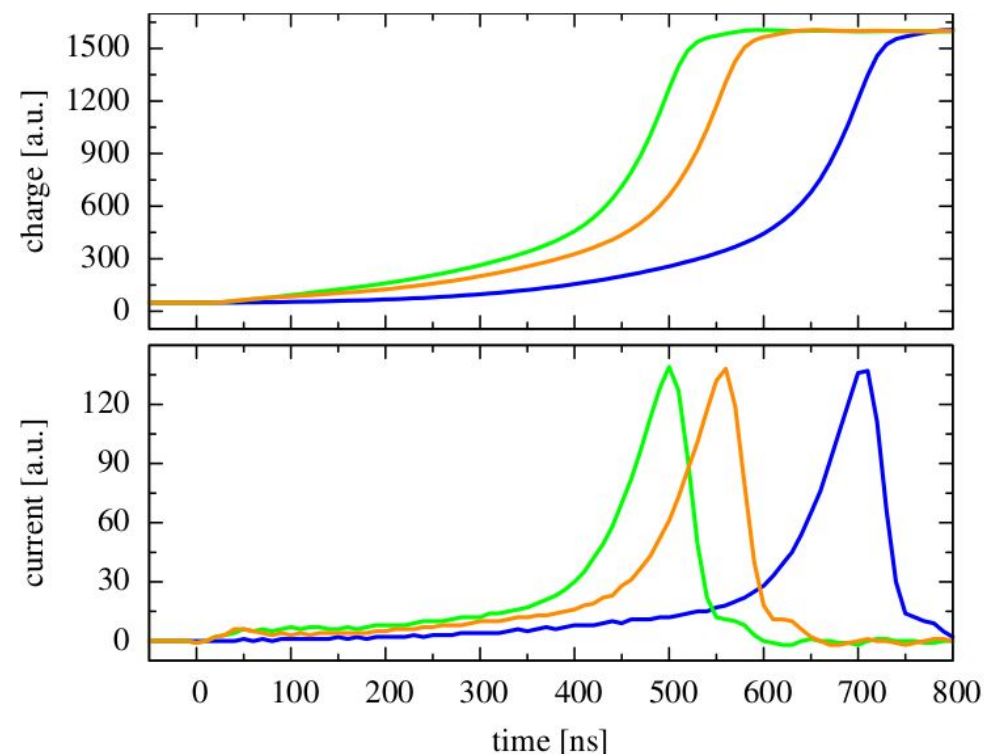
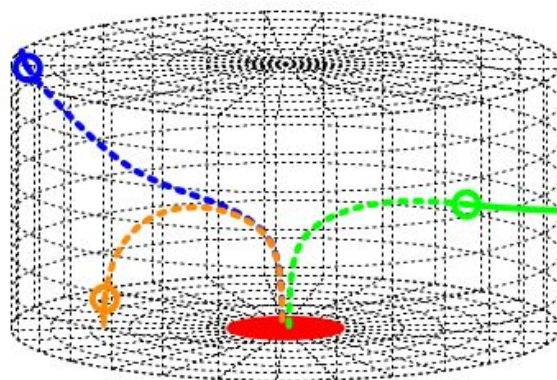


GERDA Pulse Shape Discrimination

- 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

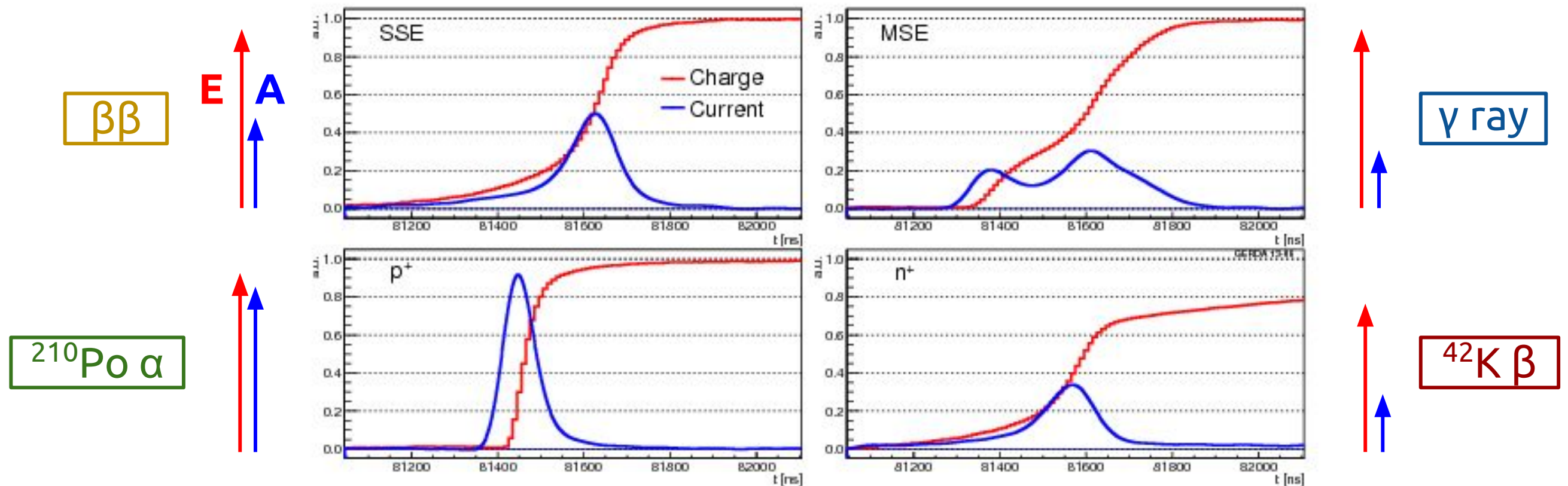


..... anode
— cathode
— electrons
- - - holes
⊙ interaction point



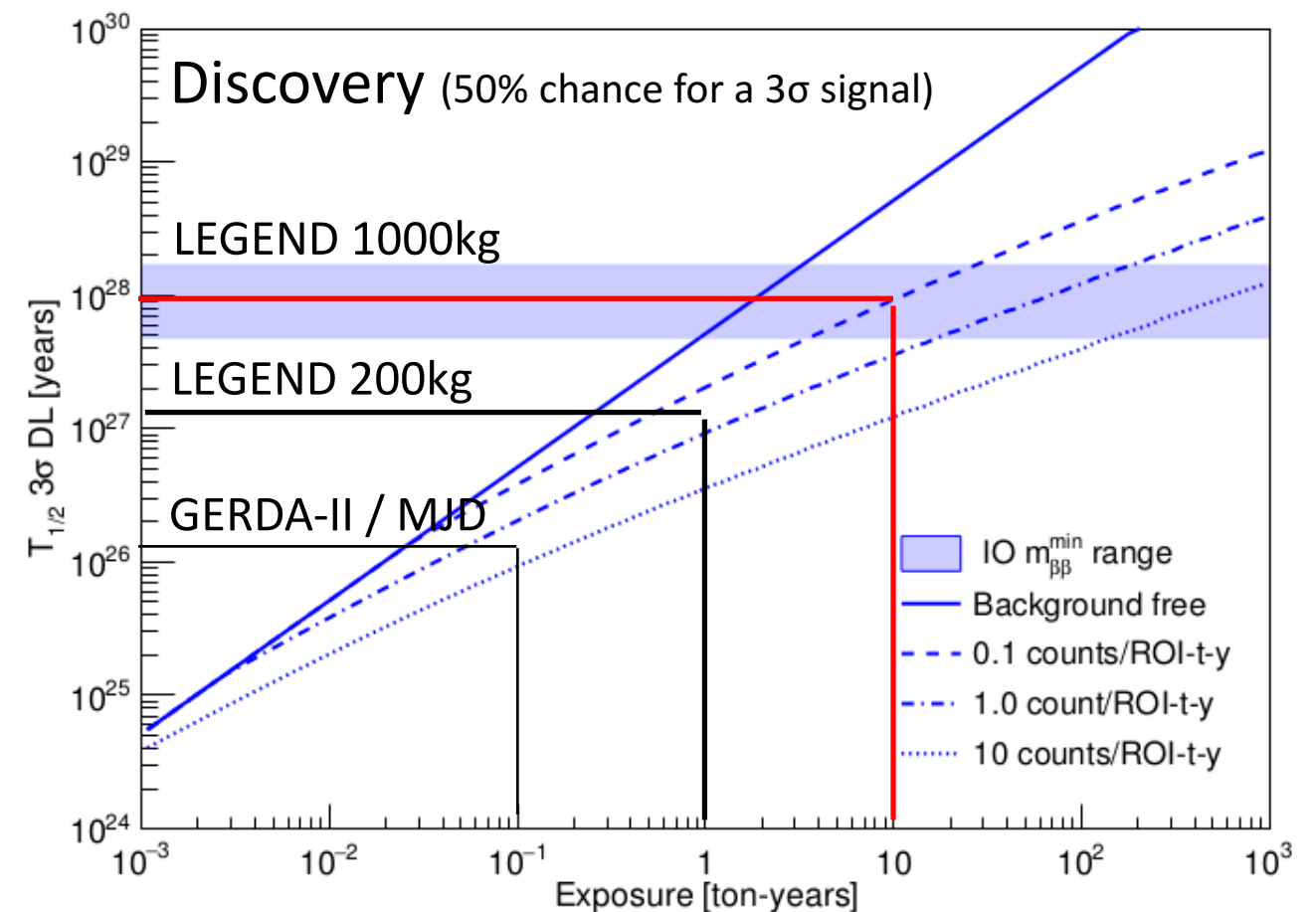
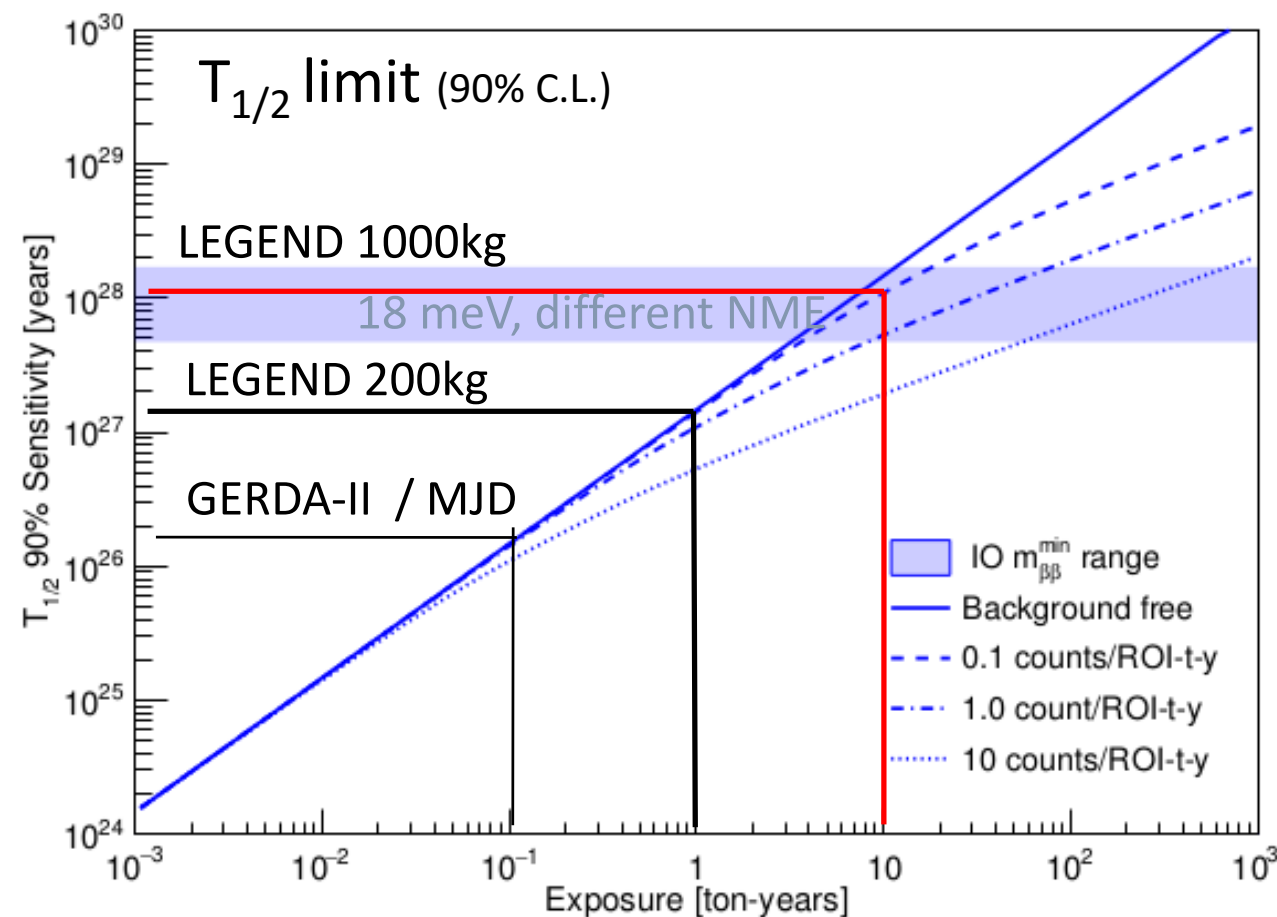
GERDA Pulse Shape Discrimination

- 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



LEGEND Physics Reach

- 60% efficiency, including isotope fraction, active volume fraction, analysis cuts
- GERDA-II/MJD: 3 events/(ROI t y)
- LEGEND-200 (LEGEND-1000): 0.6 events/(ROI t y) (0.1 events/(ROI t y))

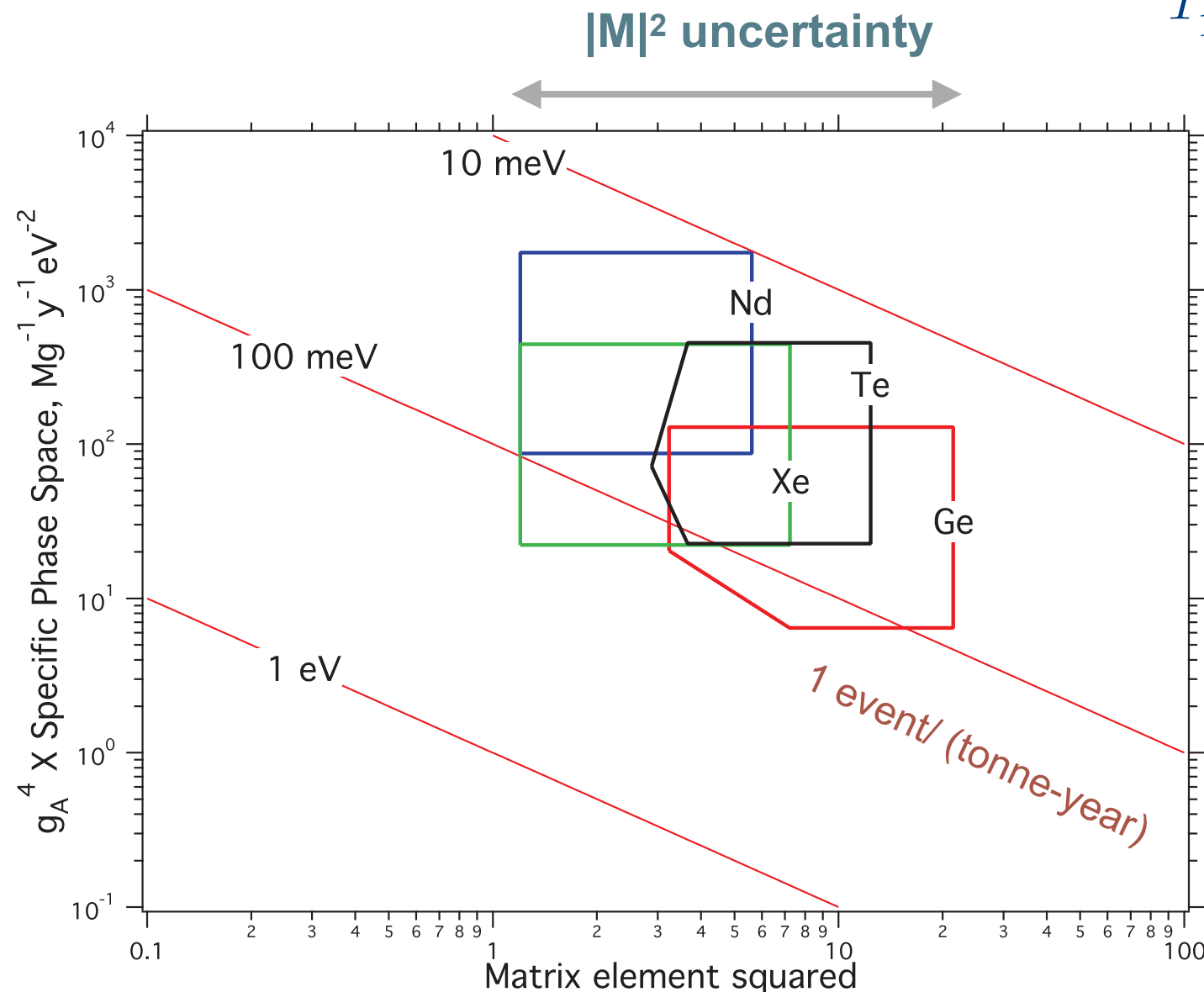


Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

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

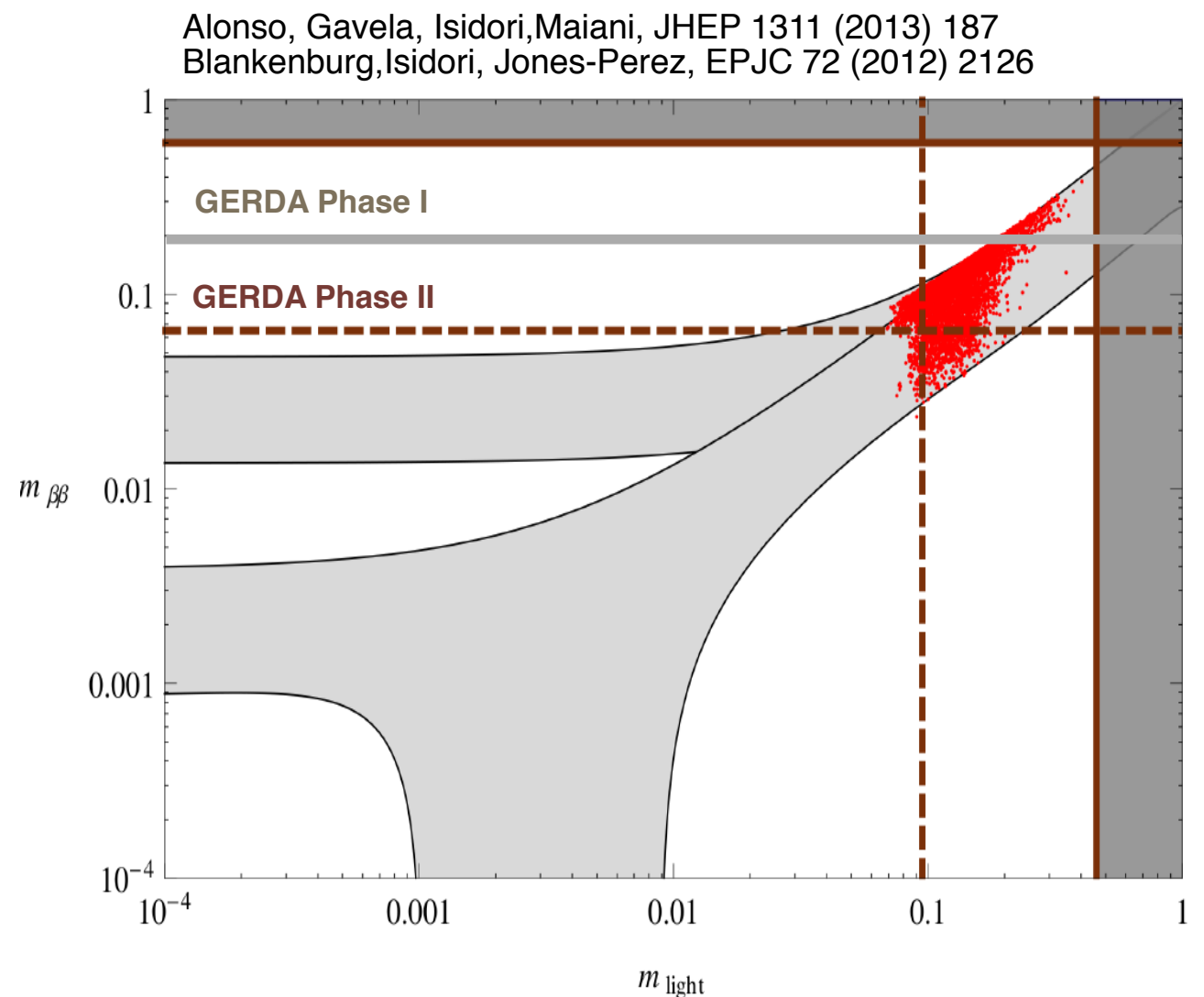
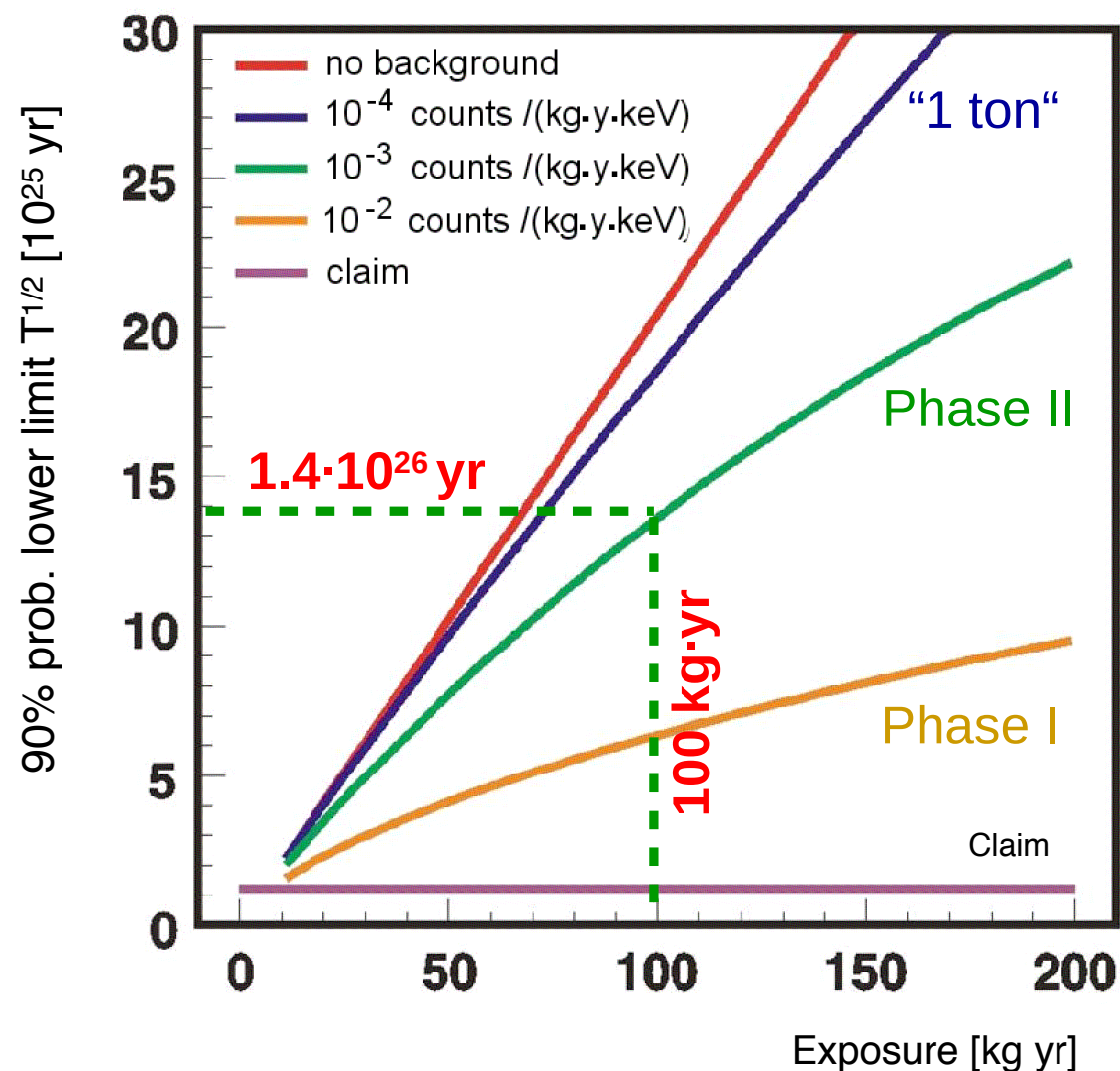
$$g_A^4 \ln(2) \frac{N_A}{A m_e^2} G^{0\nu}$$



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

GERDA phase II and beyond

- Demonstrated that a background of $\leq 10^{-3}$ events/(keV kg yr) is feasible
- Will explore $T_{1/2}$ values in the 10^{26} yr range, probing the degenerate mass region
- LEGEND, a ton-scale experiment (in collaboration with Majorana) is in design phase



Theory: neutrino mixing and masses from a minimum principle