The quest for LFV through $0\nu2\beta$ decays in Germanium:

LEGEND

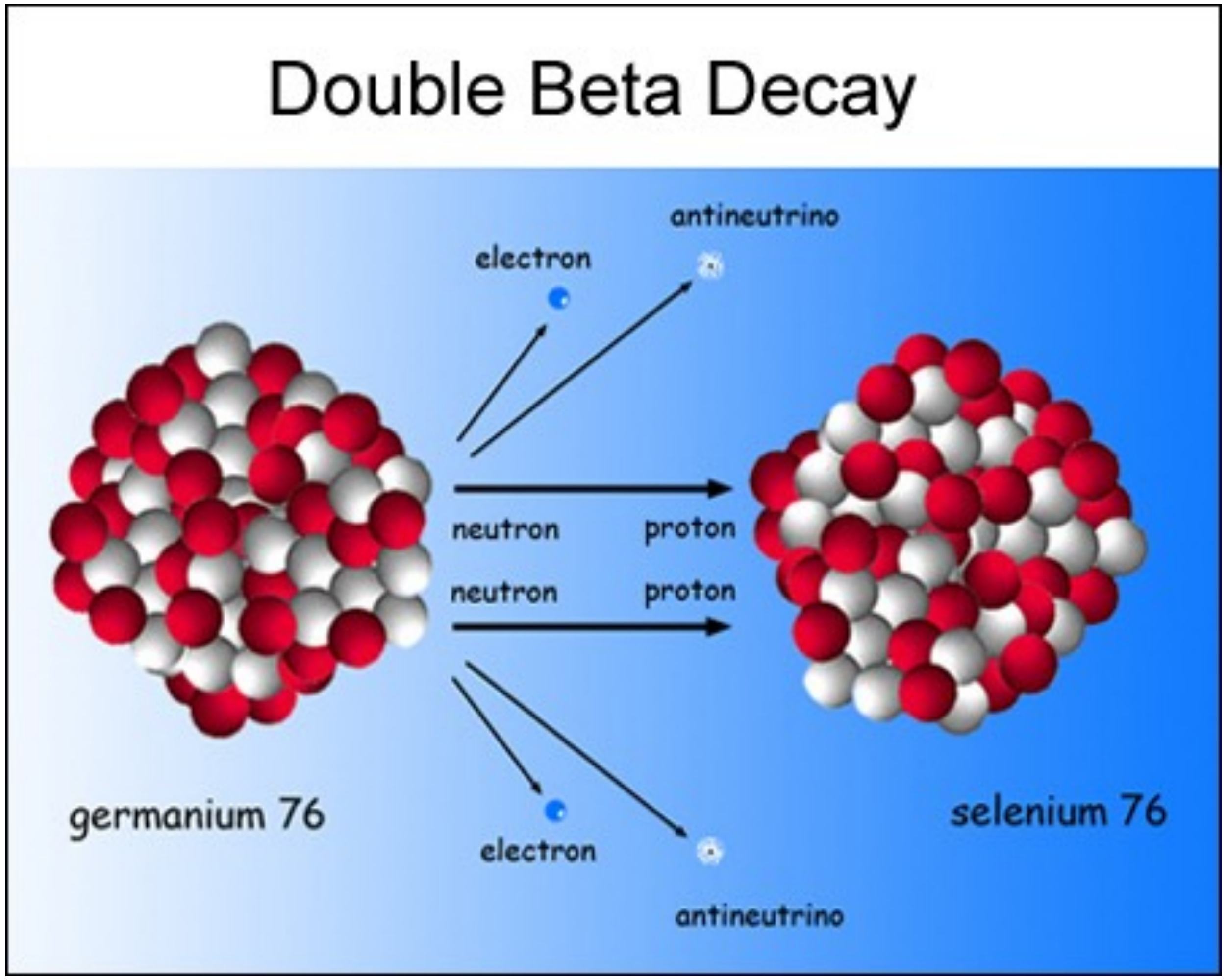
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

G. Salamanna (Roma Tre University&INFN)

KCL, April 26th, 2021

$0\nu2\beta$ decays

$\Delta L=0$



- Two β decays at the same time
- Only a few isotopes able to undergo 2β

$$2\nu\beta\beta : (A, Z) \to (A, Z+2) + 2e^- + 2\nu_e$$

2^{nd} order process, observed, $T_{1/2} \sim 10^{19}$-10^{24} yrs

^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs

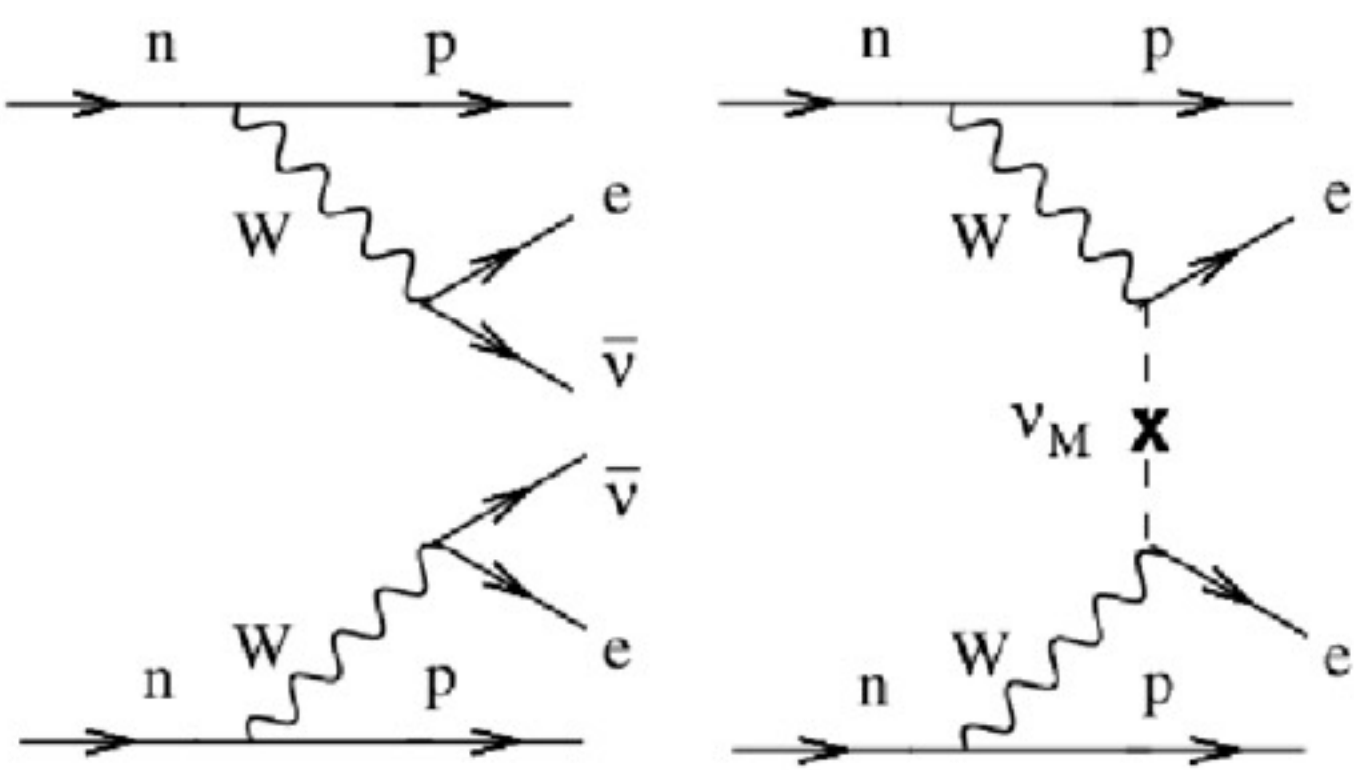
TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$$Q_{\beta\beta} = M(Z+2)-M(Z) -2m_e$$

0ν2β decays

ΔL=2



$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$

- ⇔ if neutrinos are Majorana fermions

(Majorana mass term)

- Prosaically: $\nu \equiv \bar{\nu}$
- Not only process available, but the one with the highest sensitivity
- BSM (SM only Dirac terms with L-R fermions)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

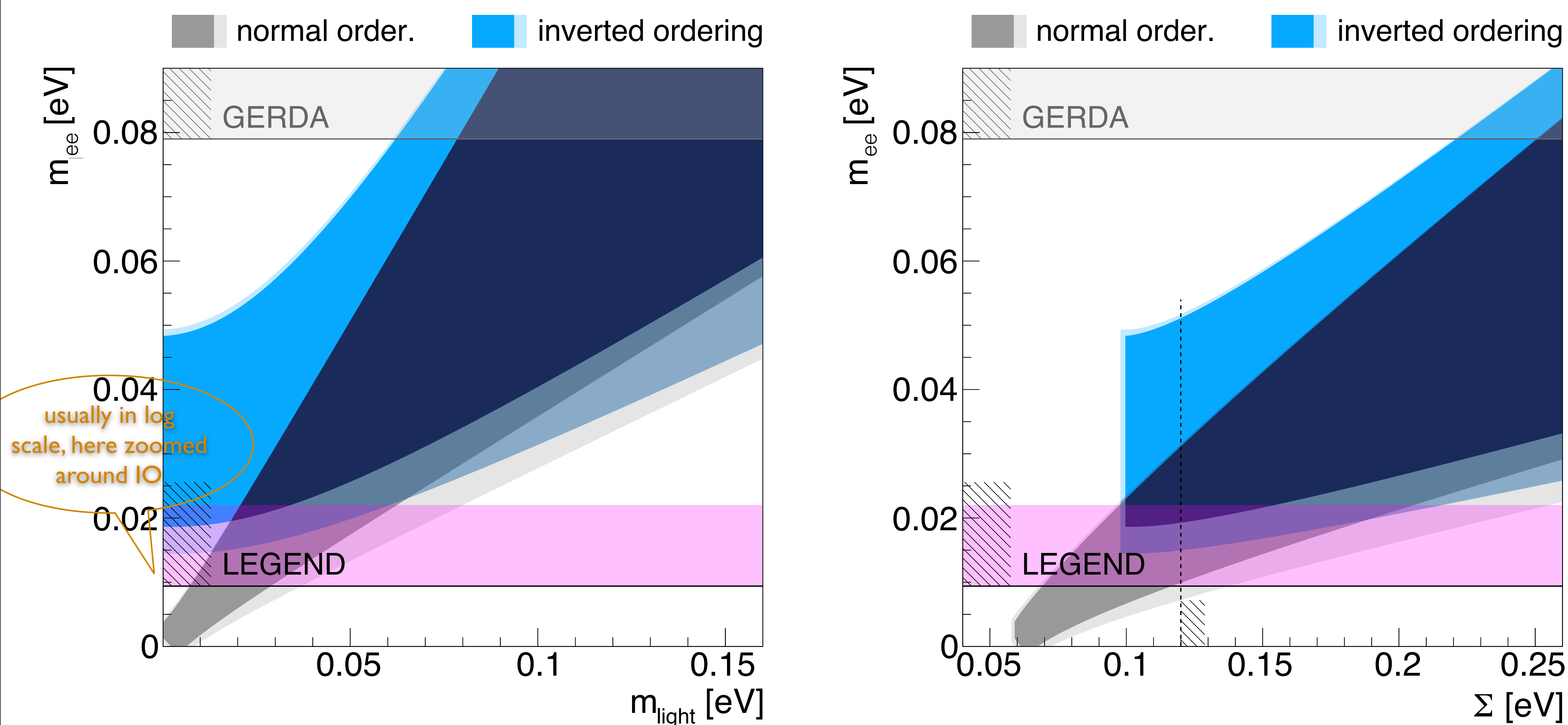
phase space factor

nuclear matrix element

effective Majorana neutrino mass

NB: experiments measure $T^{0\nu}{}_{1/2}$

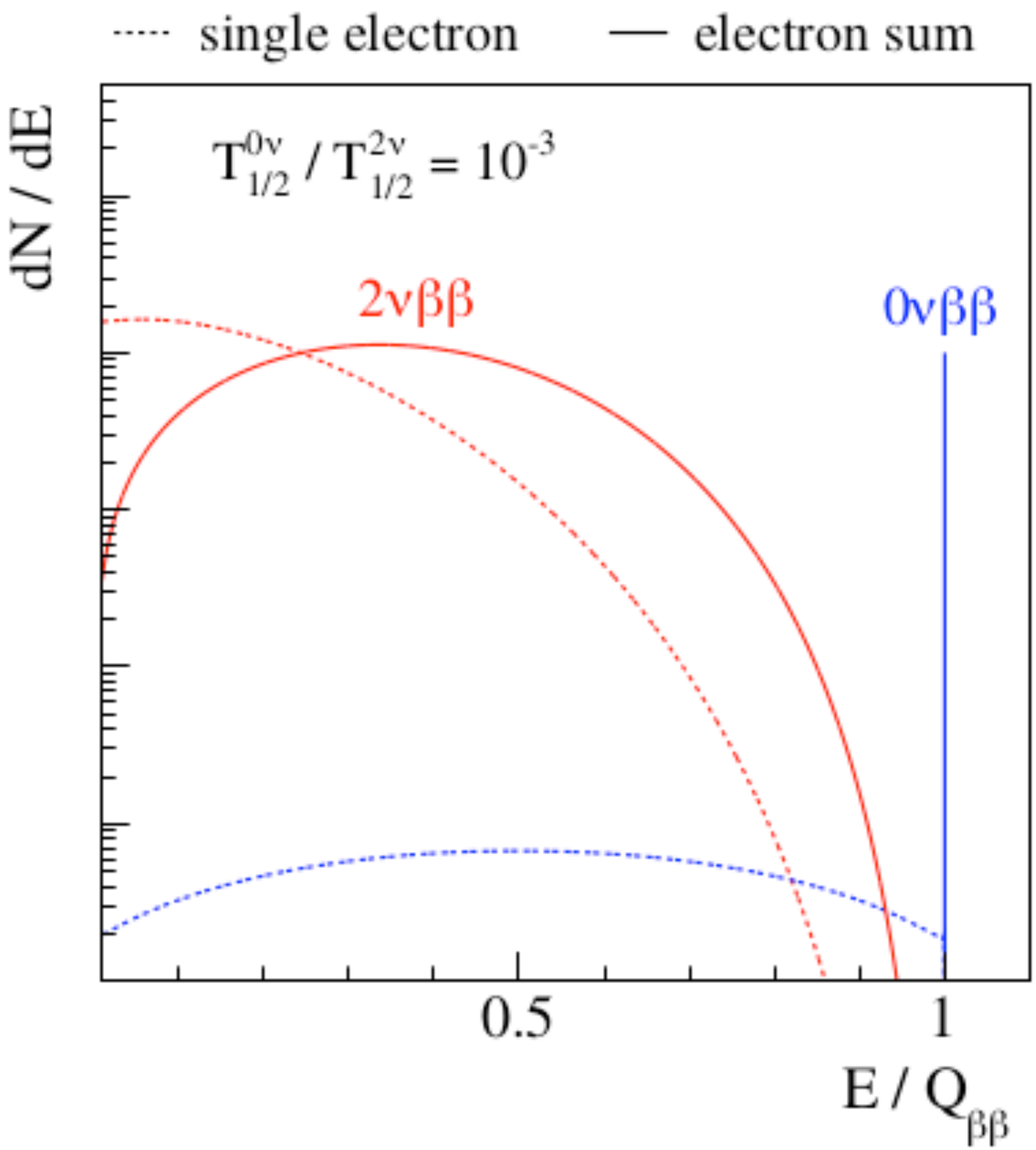
Connection with mass ordering



$$\boxed{\langle m_{ee}\rangle = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}\right|}$$

- Limits on m_{ee} from above, can try to rule out IH
  - electron flavour: mix of mass eigenstates, entering <m_{ee}> differently for the two MO
  - nuclear matrix element uncertainties: biggest spoiler in the conversion (shaded area)

The observable

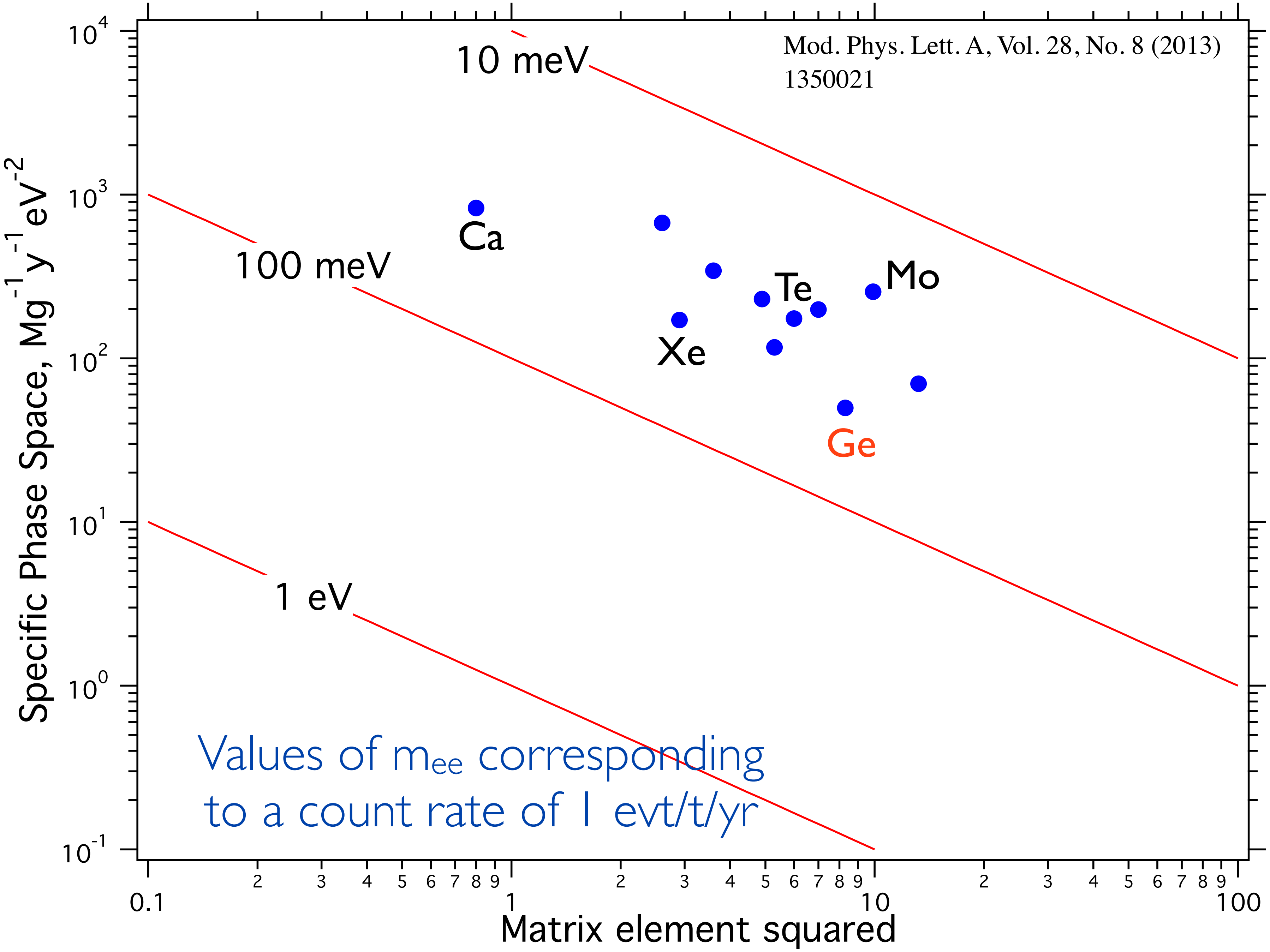


$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$

Measure overall energy of "2e" considered as "one body" in a 2-body decay → with no neutrinos it's a line at $E = Q_{\beta\beta}$

Comparing different isotopes



- No isotope "theoretically" better than another
- Phase Space and NME inversely correlated. Tend to compensate in rate

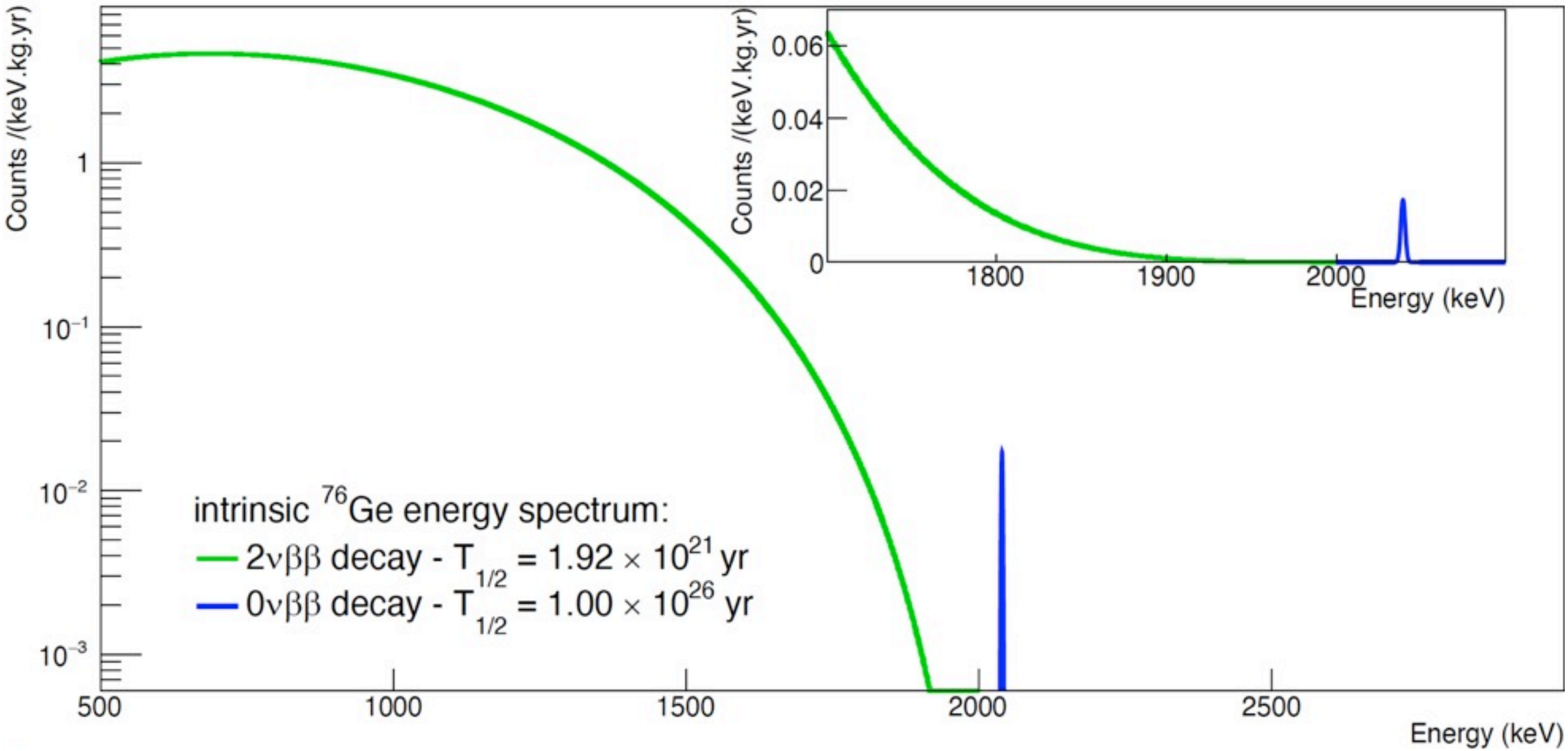
Choice informed mostly by experimental/practical criteria
- Enrichment cost
- Energy resolution
- Background levels of related material and design at Q-value
- Scalability

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \underbrace{G^{0\nu}}_{\text{phase space factor}}(Q_{\beta\beta}, Z)\,\underbrace{|M^{0\nu}|^2}_{\text{nuclear matrix element}} \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

effective Majorana neutrino mass

Alas, it's more like this...



An excellent energy resolution crucial to separate SM from BSM type around Q-value

Experimental sensitivity

- This is essentially a counting exercise in the presence of background
- Sensitivity is dominated by Poisson counting around the Q-value (ROI)

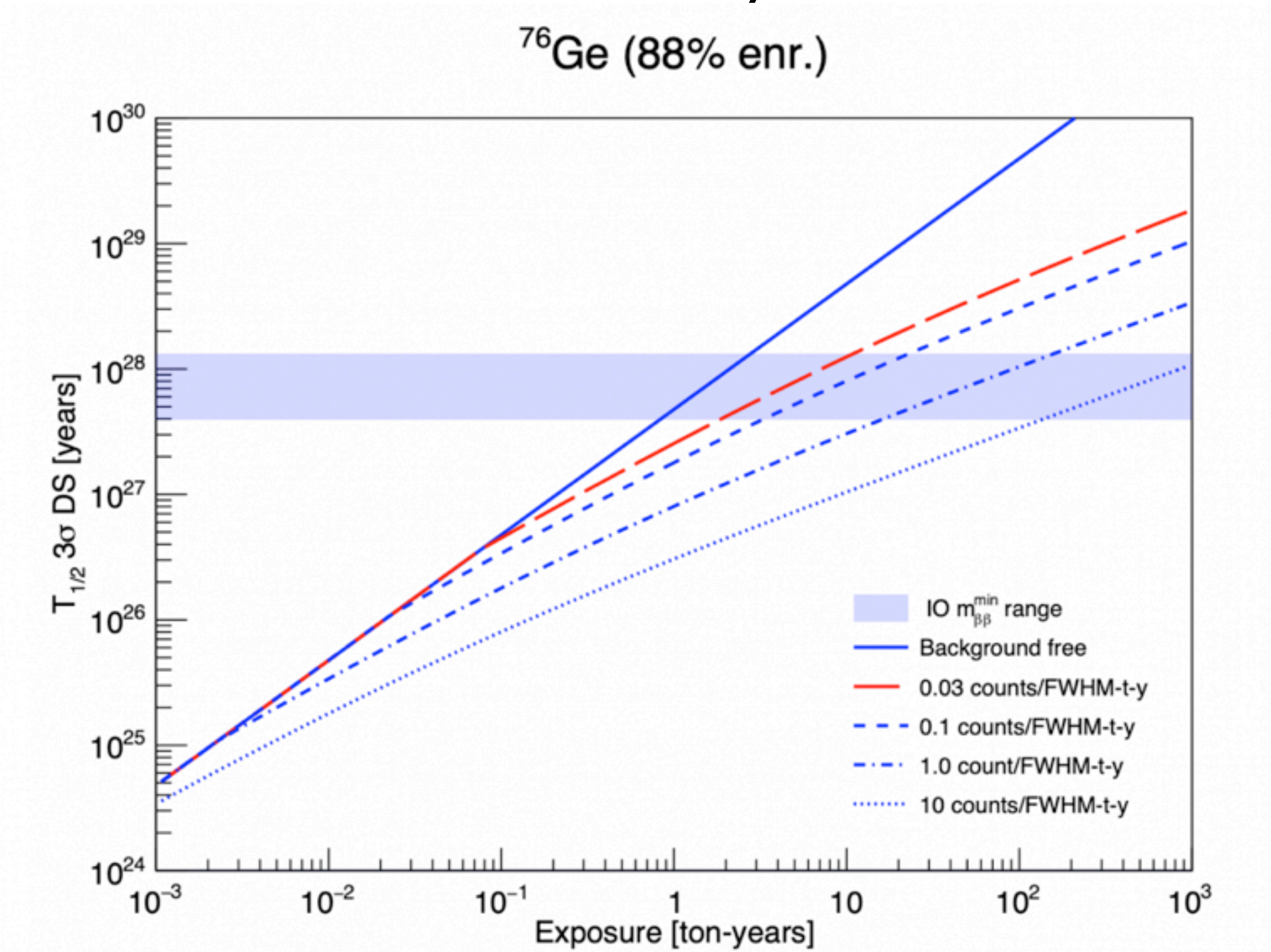
$$\mathbf{S} \sim \epsilon \cdot \mathbf{f} \cdot \sqrt{\frac{\mathbf{M} \cdot \mathbf{t}_{\mathbf{run}}}{\mathbf{BI} \cdot \Delta \mathbf{E}}}$$

non-zero background

S: sensitivity
ε: efficiency
f: abundance of 0νββ isotope
M: detector mass

t_{run}: measurement time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

What sensitivity looks like



- Value of $T_{1/2}$ for which a ^{76}Ge-enriched experiment has a 50% chance to observe a signal above background with 3σ significance
  - for various scenarios of BI=N_{bkg}

The pros and cons of Germanium

$$S \sim \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t_{run}}{BI \cdot \Delta E}}$$

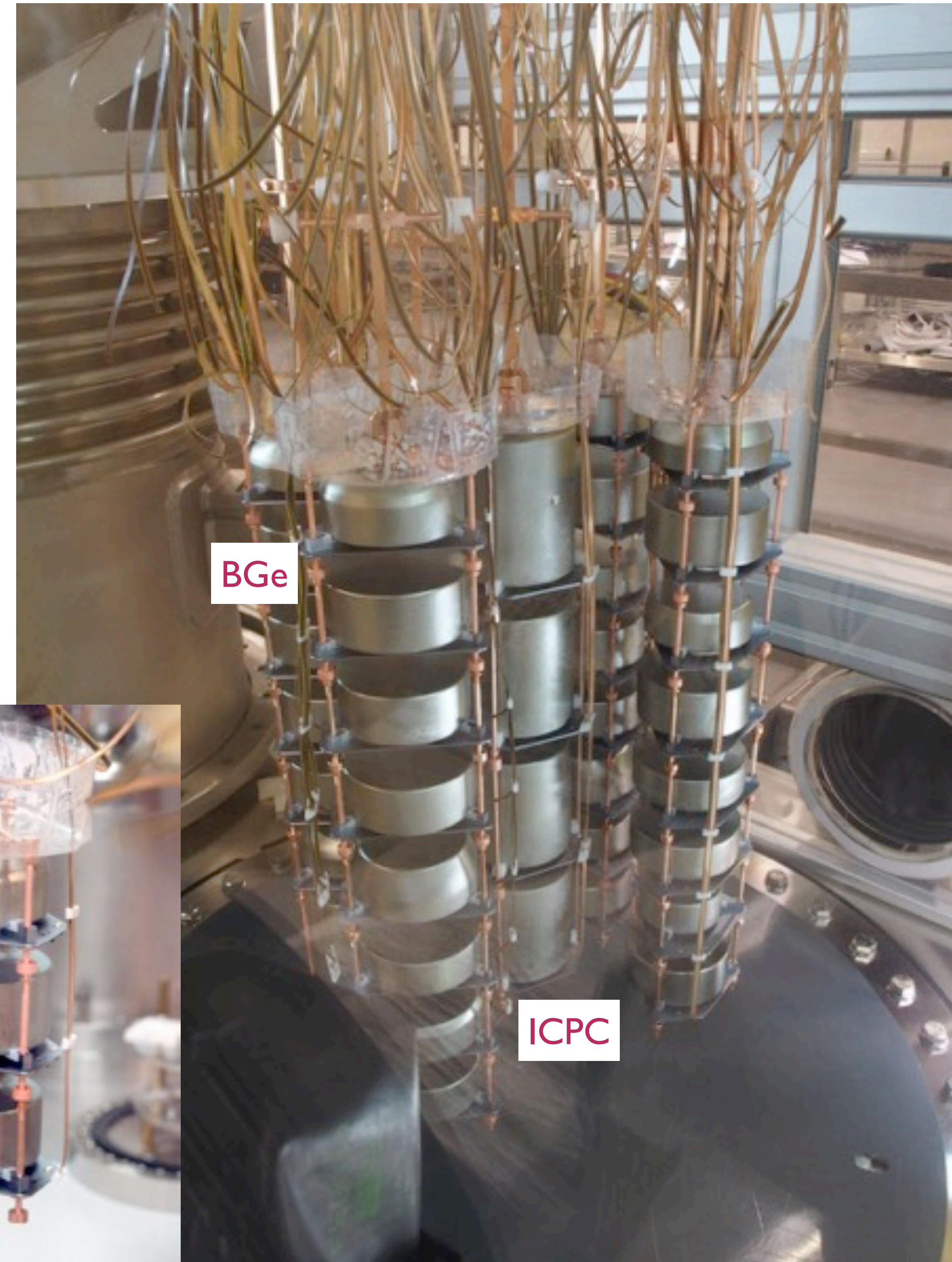
non-zero background

S: sensitivity
ε: efficiency
f: abundance of 0νββ isotope
M: detector mass

t_{run}: measurement time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

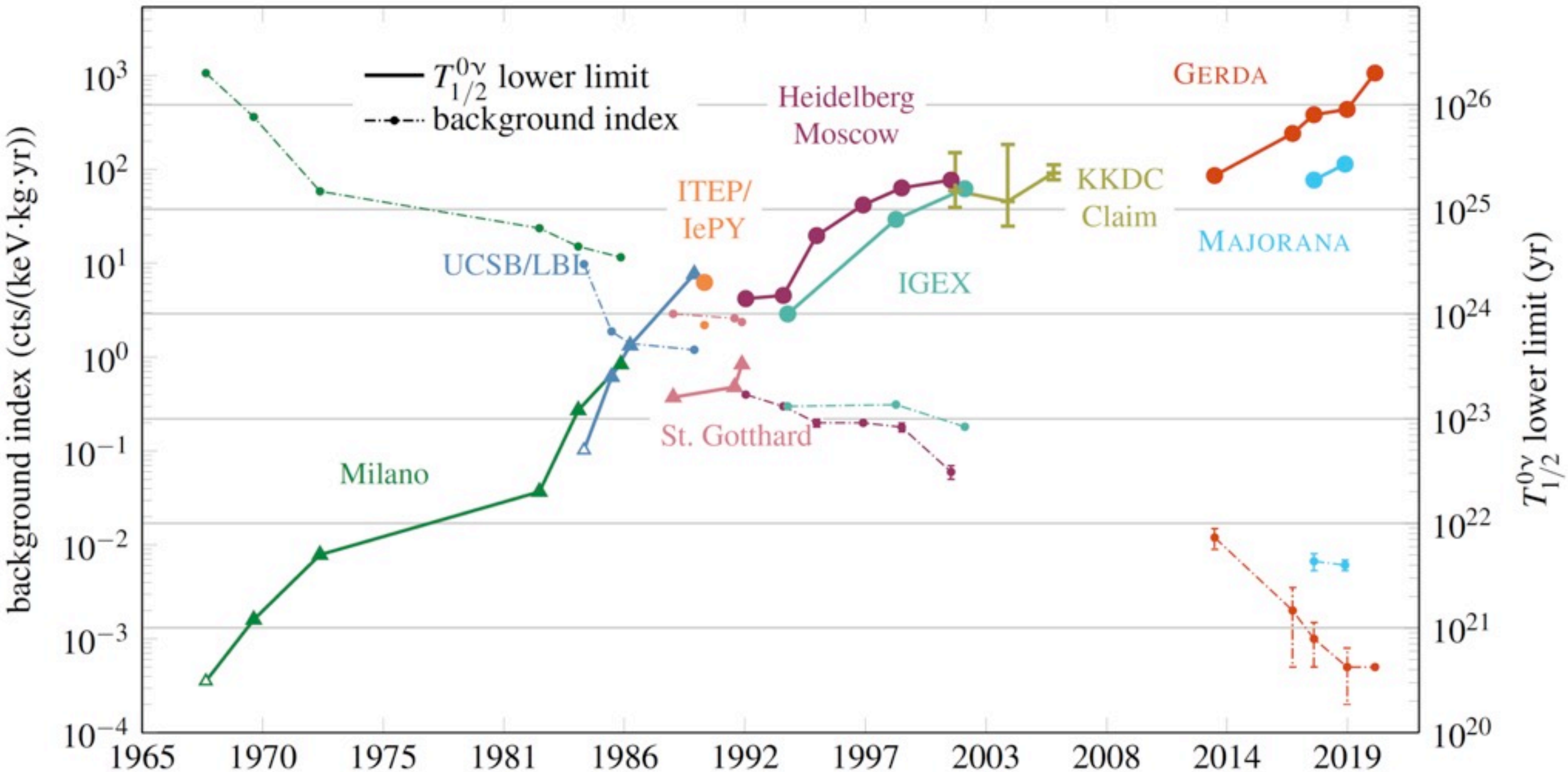
- Source ≡ detector
- semiconductor detectors provide excellent E_{reso} (2.5 keV FWHM @ 2039 keV)
- low intrinsic BI in HPGe
- Bkg rejection capabilities from solid state detectors organized in arrays
- scalable thanks to high demand of HPGe for various applications

- Low isotopic abundance in natural Ge means higher cost to enrich it
- Small phase space



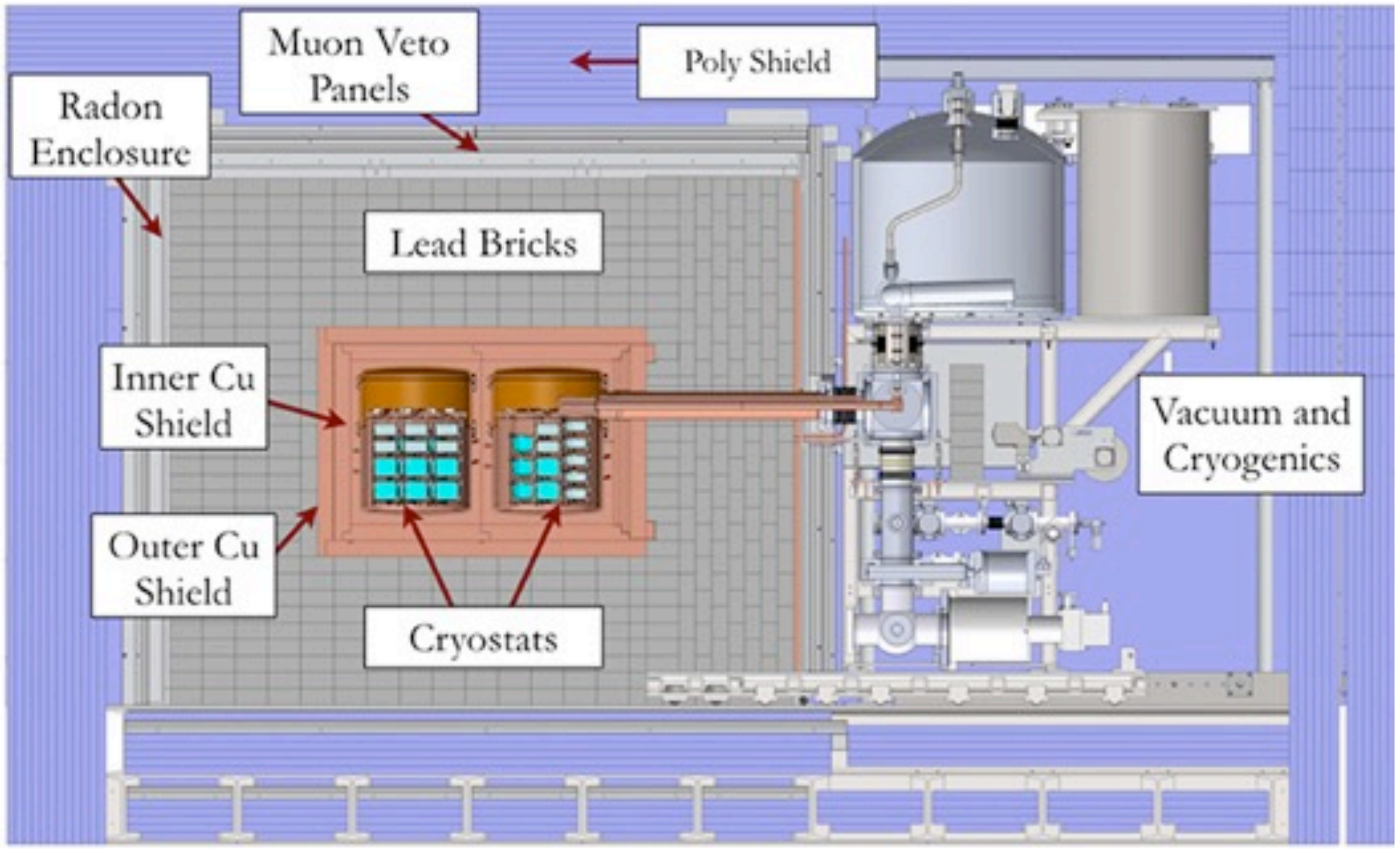
A plot can tell a story...

Y.Kermaidic, Neutrino '20



- Searches with Ge have a long tradition and established technique
- GERDA+Majorana Demonstrator=LEGEND

LEGEND's pa and ma



Majorana demonstrator (SURF)

- Conventional screening with passive material (Pb)
- Low noise electronics for better PSD and energy resolution (2.5 keV FWHM @ $Q_{\beta\beta}$)
- Lower threshold for more physics searches
- 29.7 kg of 88% enriched ^{76}Ge crystals (PPC detectors)

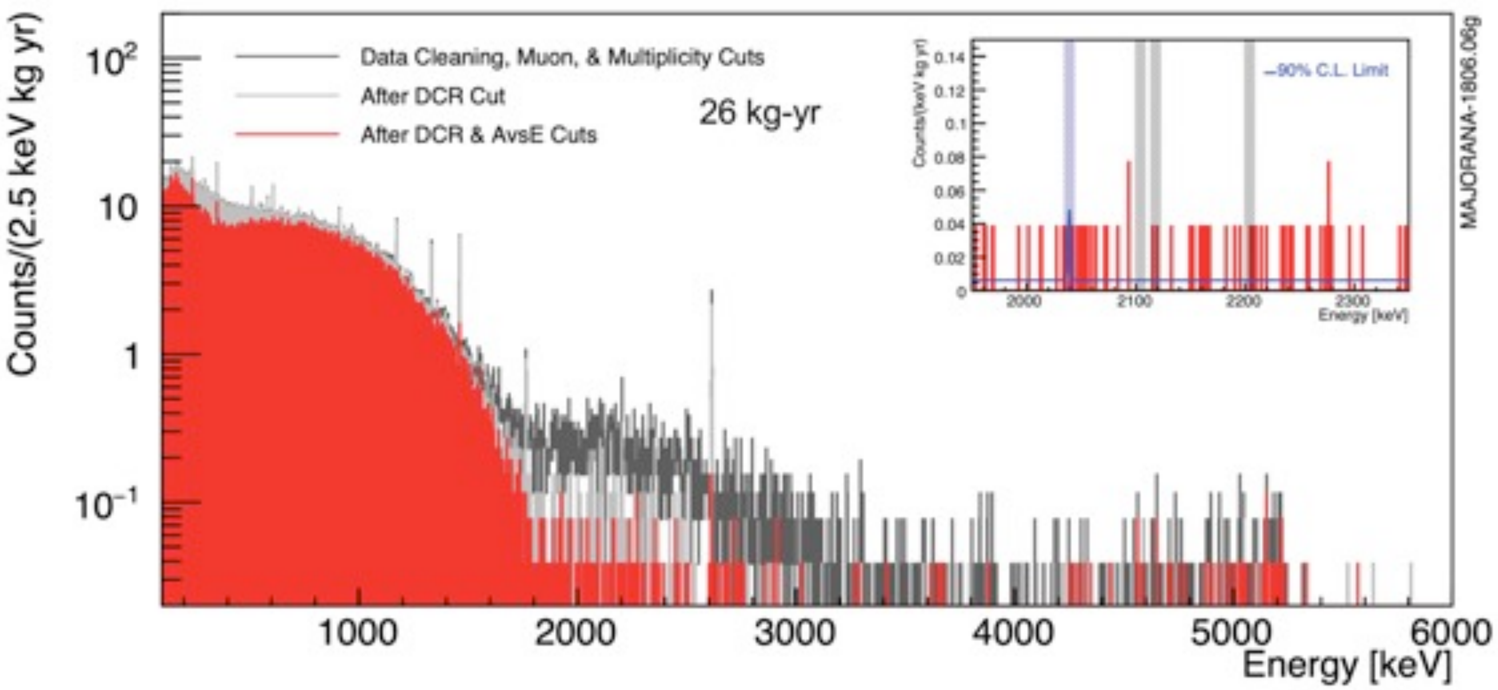
GERDA (LNGS)

- New idea implying active LAr-based screening
→exploit bkg topologies to detect scintillation and apply coincidences btw LAr and Ge dipped within
- E reso: 2.6-2.9 keV FWHM @ $Q_{\beta\beta}$
- 44.2 kg of 88% enriched ^{76}Ge crystals (coax+BEGe+ICPC detectors)

<u>In common</u>: careful control of radioactive bkg at material fabrication and specialized analysis techniques (material+ambient)

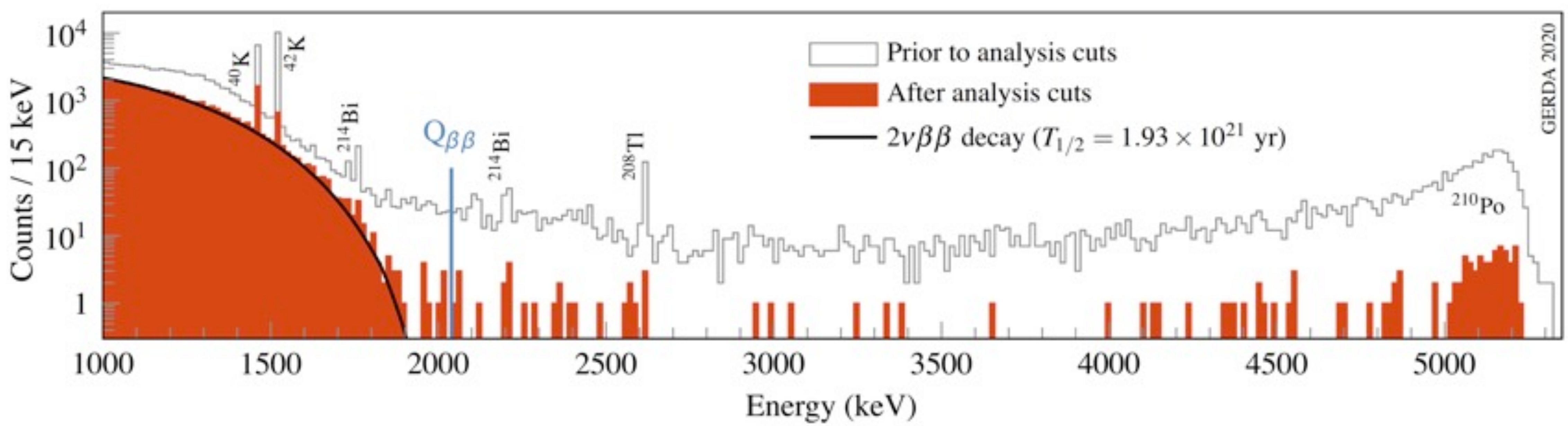
⇒ Lowest bkg rate and best E reso for any $0\nu2\beta$ expt

LEGEND's pa and ma



Majorana demonstrator (SURF)

- Exposure: 26 kg yr
- BI@Q: 47.0×10^{-4} counts/(keV kg yr)
- Median $T_{1/2}$ Sensitivity: 4.8 10^{25} yr
- Full Exposure Limit: $T_{1/2}$ > 2.7 10^{25} yr (90% CL)
- `PRC 100 025501 (2019)`



GERDA (LNGS)

- Exposure: 104 kg yr
- BI@Q: 5.2×10^{-4} counts/(keV kg yr)
- Median $T_{1/2}$ Sensitivity: 1.8 10^{26} yr
- Full Exposure Limit: $T_{1/2}$ > 1.8 10^{26} yr (90% CL)
- `Phys. Rev. Lett. 125, 252502 (2020)`

LEGEND

Large Enriched
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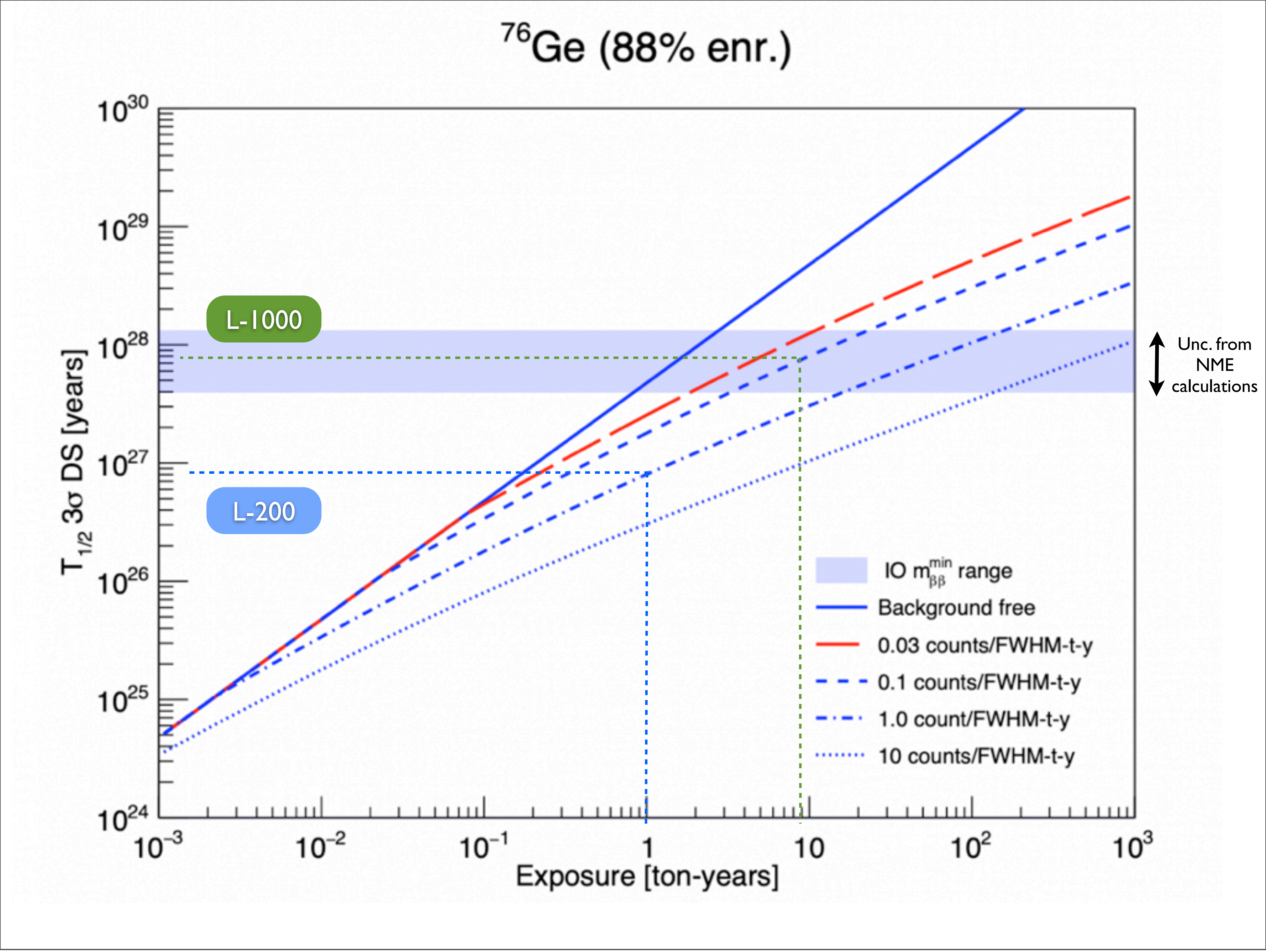
for Neutrinoless ββ Decay

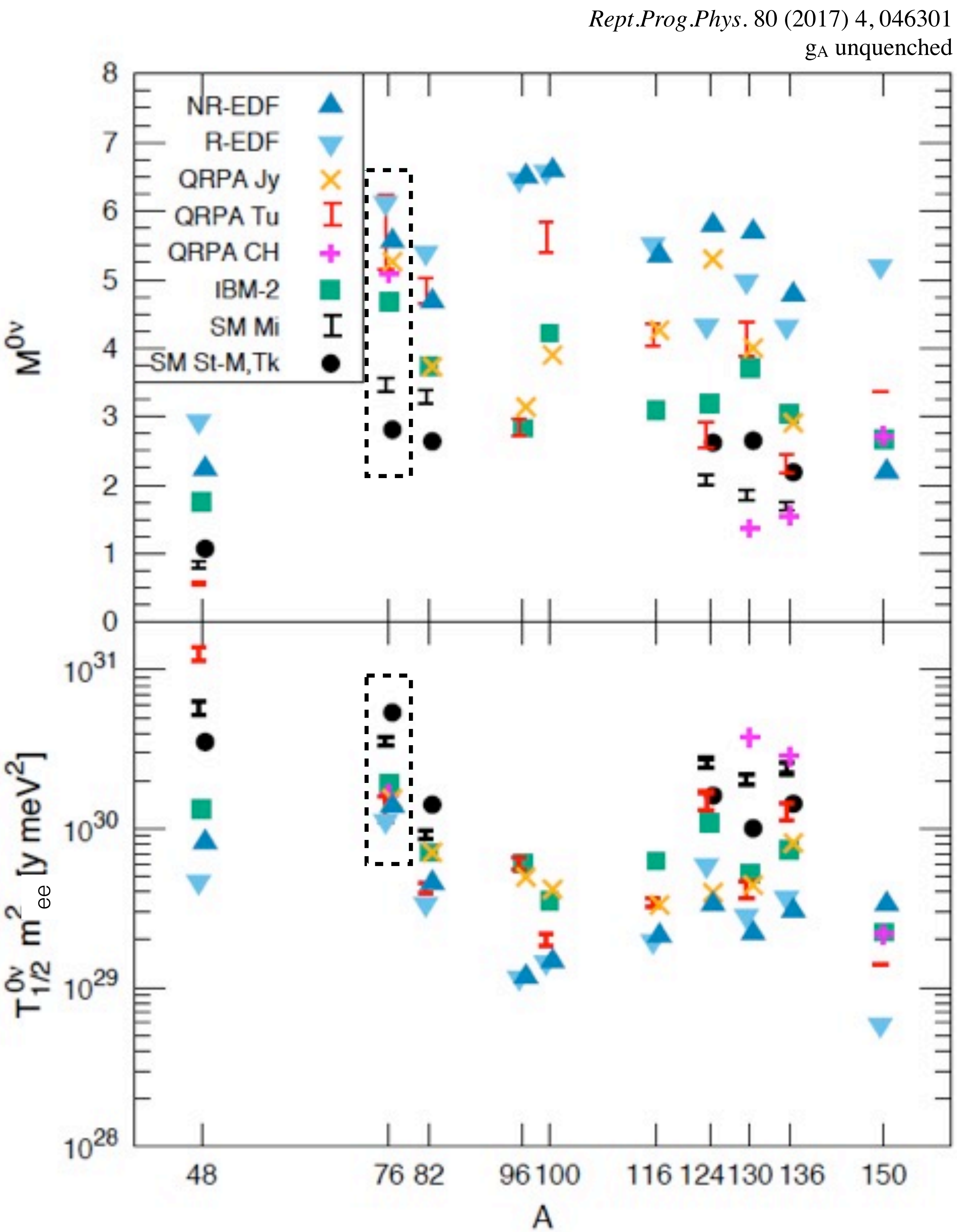
- Stems from such achievements and puts together best of both in terms of technology and know-how (*+ some new-comers like me...)*
- Two-staged approach with a "demonstrator" of ~200 kg (**Legend-200**) towards the full-fledged experiment with 1 ton scale (**Legend-1000**)
- What's to "*demonstrate*"? Development of large Point-contact detectors, layout can be scaled up, bkg reduction can be taken even farther aggressively (incl. cosmogenic activation)

Collab Meeting Seattle Dec 2019



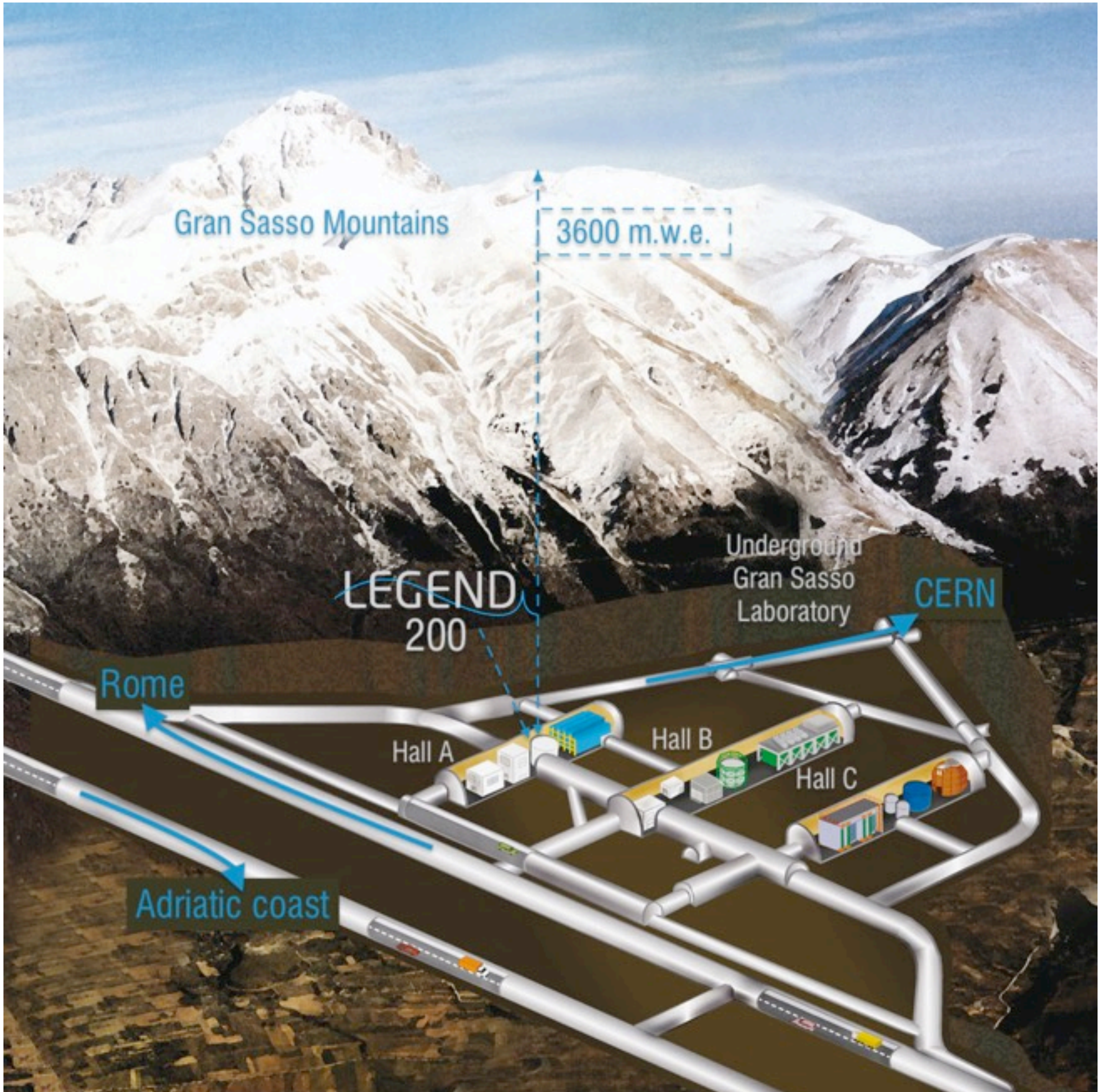
^{76}Ge (88% enr.)
L-1000
L-200
Unc. from NME calculations
$T_{1/2}$ 3σ DS [years]
Exposure [ton-years]
IO $m_{\beta\beta}^{min}$ range
Background free
0.03 counts/FWHM-t-y
0.1 counts/FWHM-t-y
1.0 count/FWHM-t-y
10 counts/FWHM-t-y

Nuclear Matrix Element values from various nuclear models



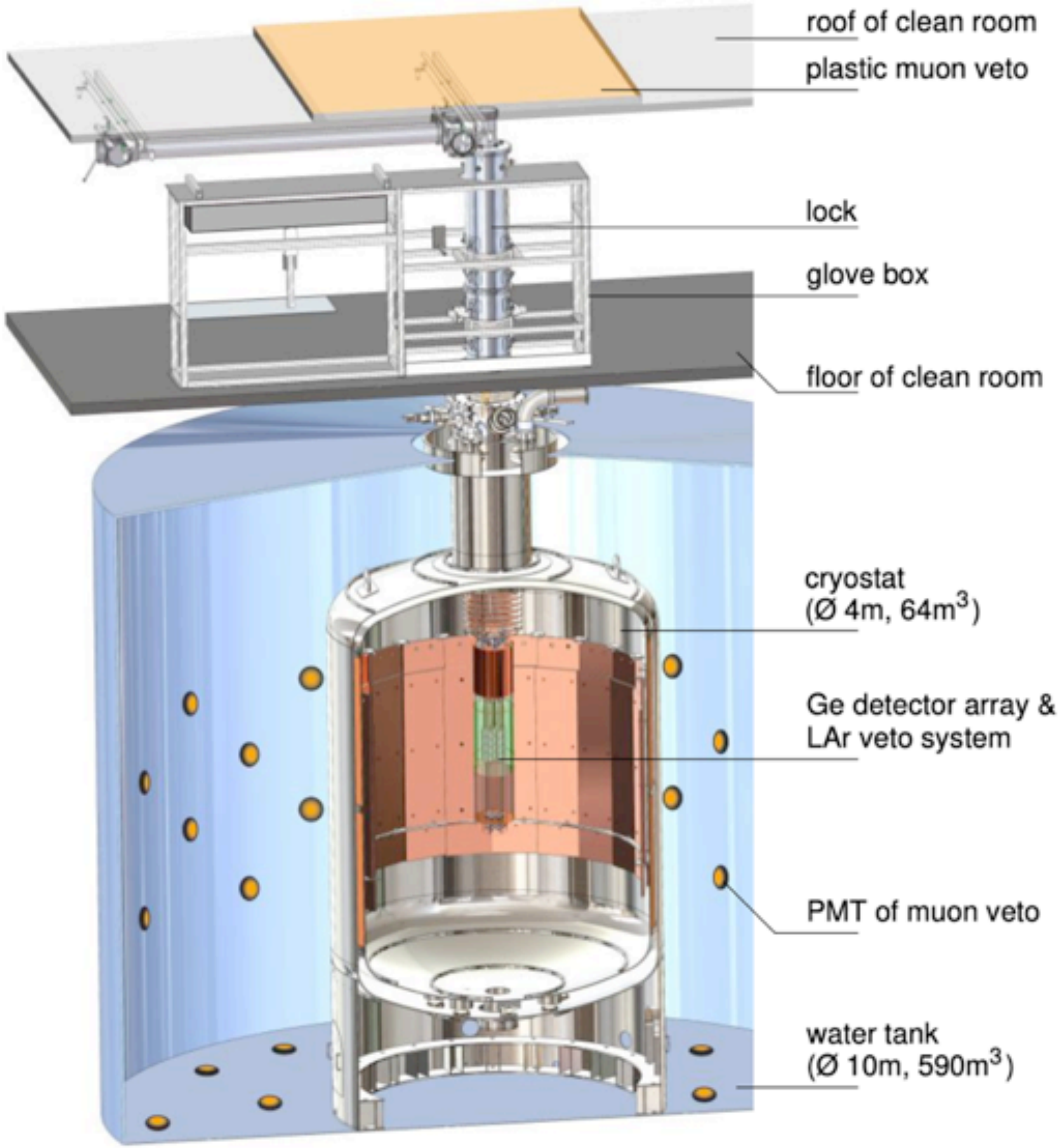
- Various models predict quite different values, throughout the isotope A range
- Affects the conversion from $T_{1/2}$ to m_{ee}

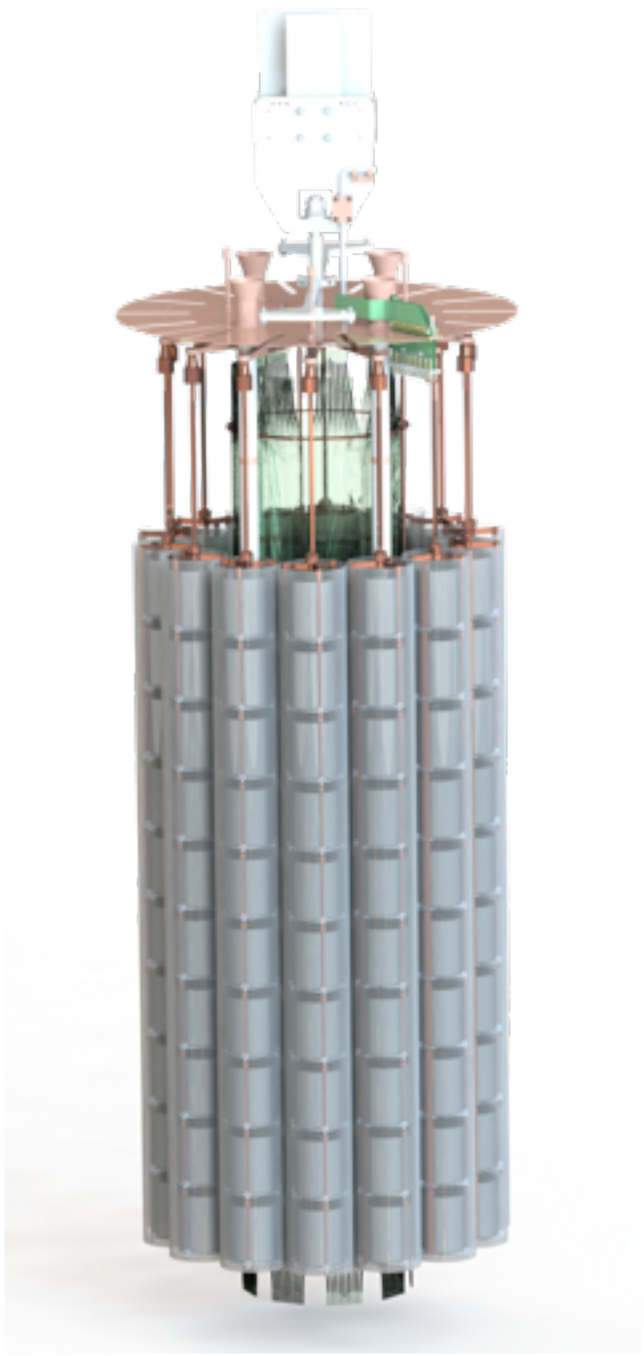
LEGEND-200 site: LNGS



- L-200 will use GERDA infrastructure at LNGS
- Same concept of Ge detectors dipped within LAr in pre-existing cryostat
- Mountain provides screening against cosmic rays

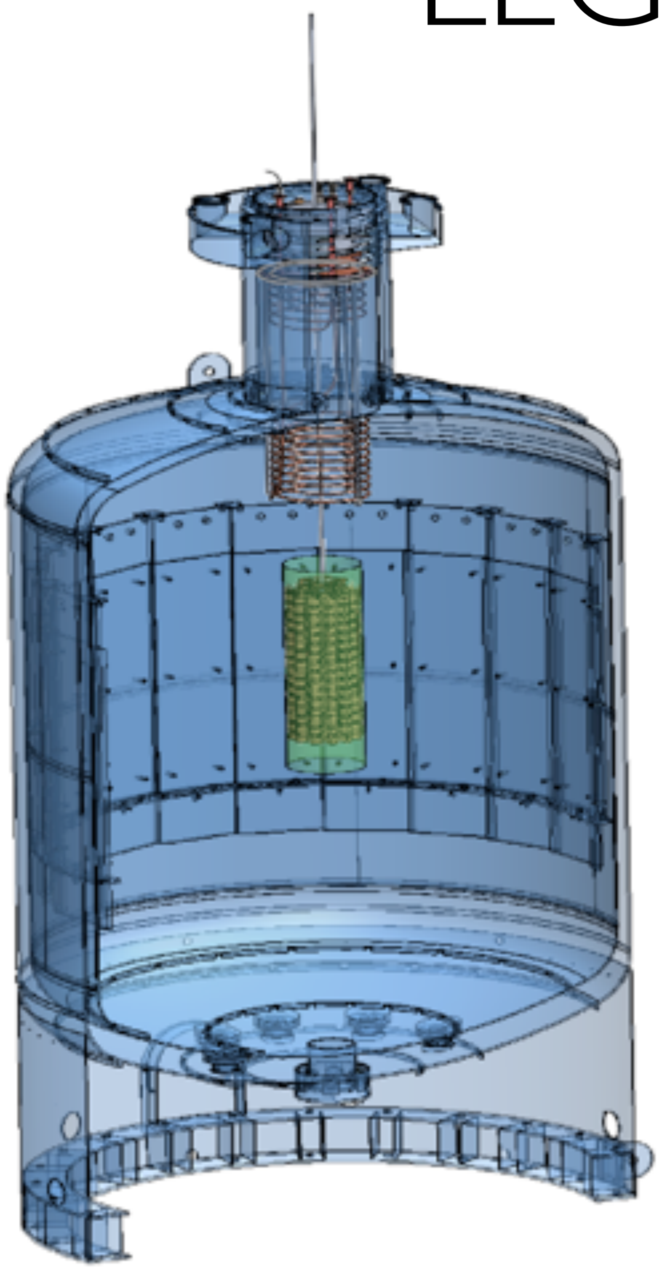
- Expected sources of external bkg include γ from U/Th decays, neutrons, remaining cosmic rays (prompt and delayed)
- Intrinsic: radioactive surface contamination, ^{39}Ar decays, cosmogenic activation of isotopes





- high-purity germanium (HPGe) detectors enriched in ^{76}Ge to (86–88)%: source + detector
- detectors mounted on low-mass holders (to minimize radioactive bkg)
- embedded in liquid argon (LAr): cryogenic coolant and absorber against external radiation
- ultrapure water tank: buffer around cryostat as additional absorber + Cherenkov veto

LEGEND-200: what's new



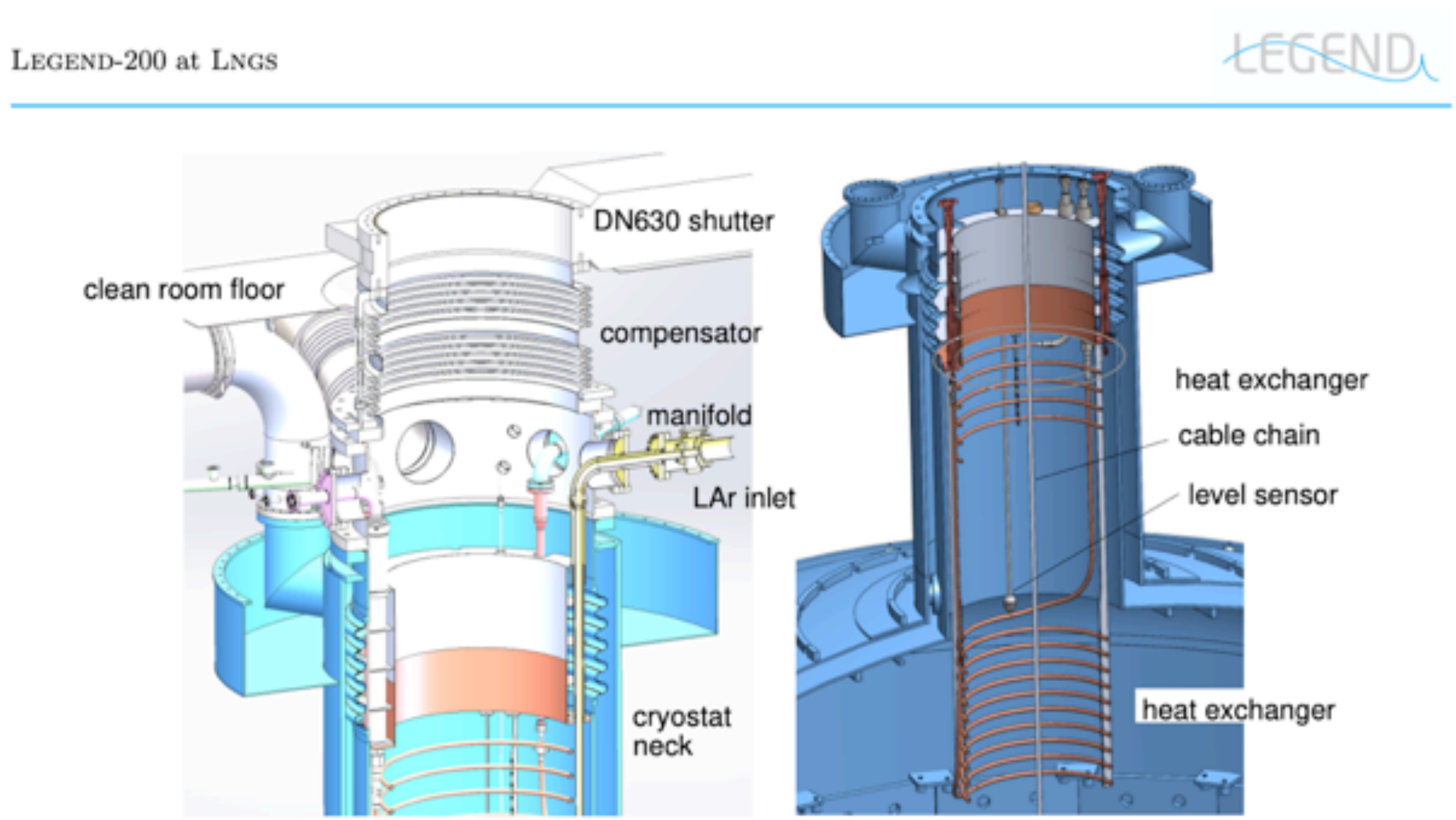


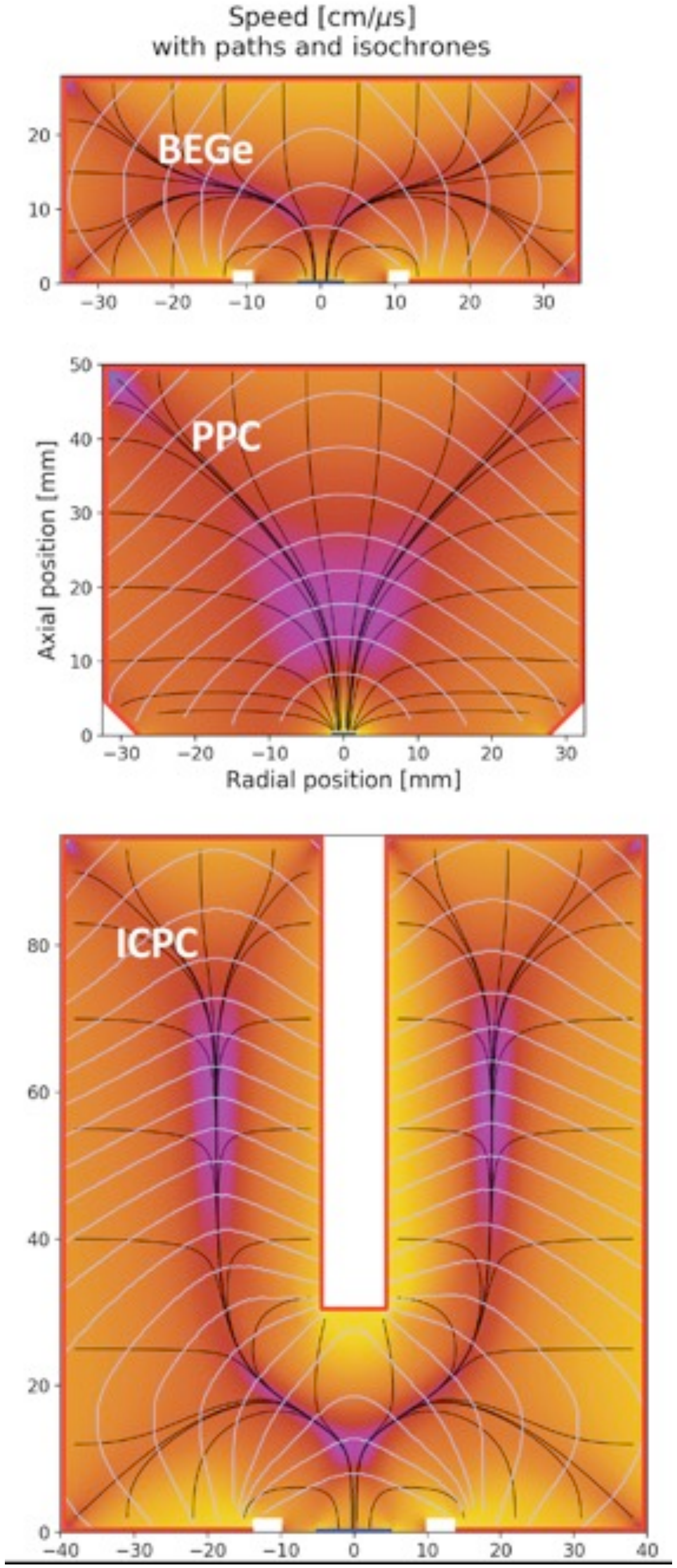
FIG. 6. Cross section through the cyrogenic infrastructure at the cryostat. Left: between the DN630 shutter and the cryostat (compensator and manifold with feedthroughs). Right: inside the cryostat (heat exchanger, fill level measurement).

Modifications wrt GERDA infrastructure:

- 14 strings of (mostly) ICPC detectors
- new electronics
- raise clean room roof, new lock
- new cabling, detector suspension, feedthroughs
- Improved LAr light collection

A heart of (High Purity) Germanium

- p-type diodes with point-contact (vs extended contact, *see next slides*)
- Charge collection at p^+ electrode (Boron-implanted), polarization potential applied at n^+ electrode (diffused Li)



BEGe (from GERDA) and PPC (from MJD)

- A part of the original suite of diodes from the past are retained in L-200: about 60 kg
- High E resolution
- Well established PSD technique exploiting stable field configuration across volume to reject bkg
- but small mass ≤1 kg each

ICPC (new) R. Cooper et al., NIM A665, 25 (2011)]

- Most of remaining 140 kg are of this type
- Larger mass (1.5-2.0 kg, up to <2.5> kg for L-1000)
- but retaining similar charge drift times across volume
- Reduced surface-to-volume ratio (α and β), less dirty cables, pre-amps
- Lower cost per kg, higher efficiency
- Ordered since 2019, production and characterization on-going

R. Cooper et al., NIM A665, 25 (2011)]

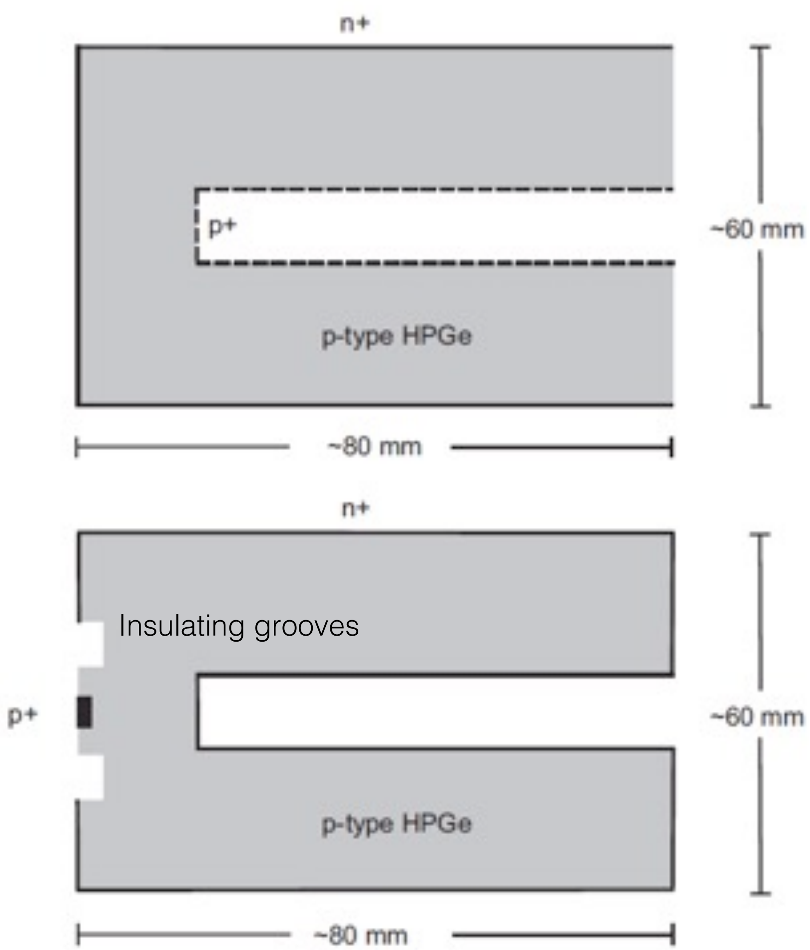
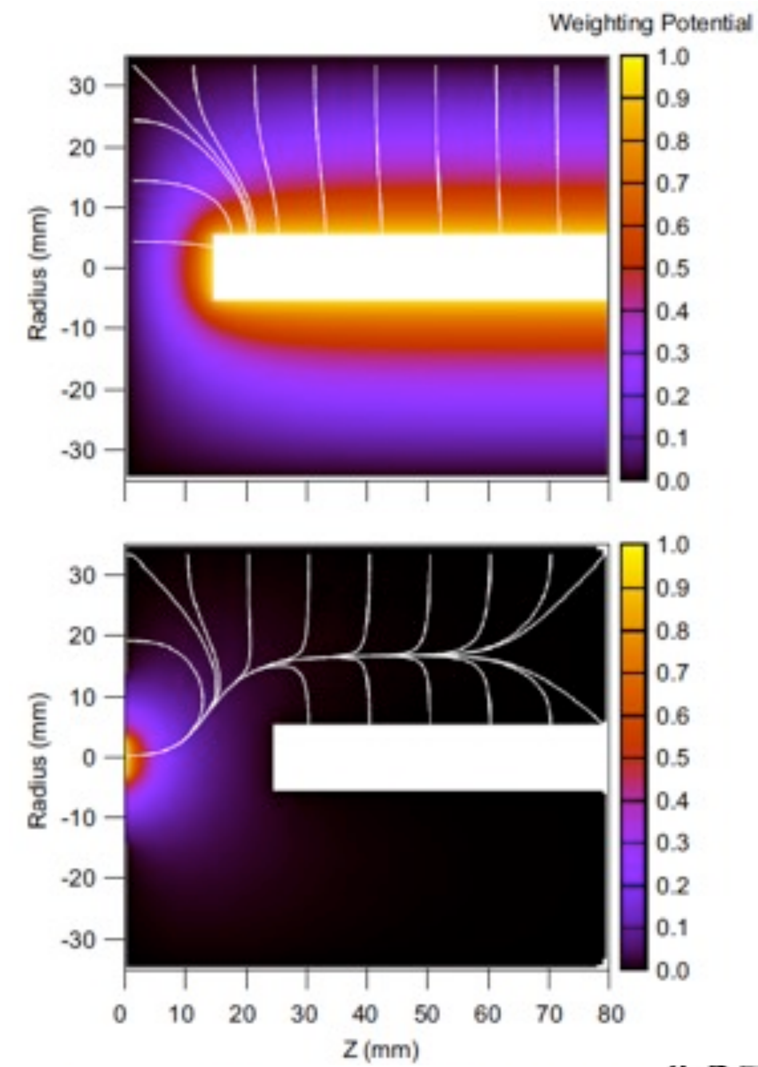
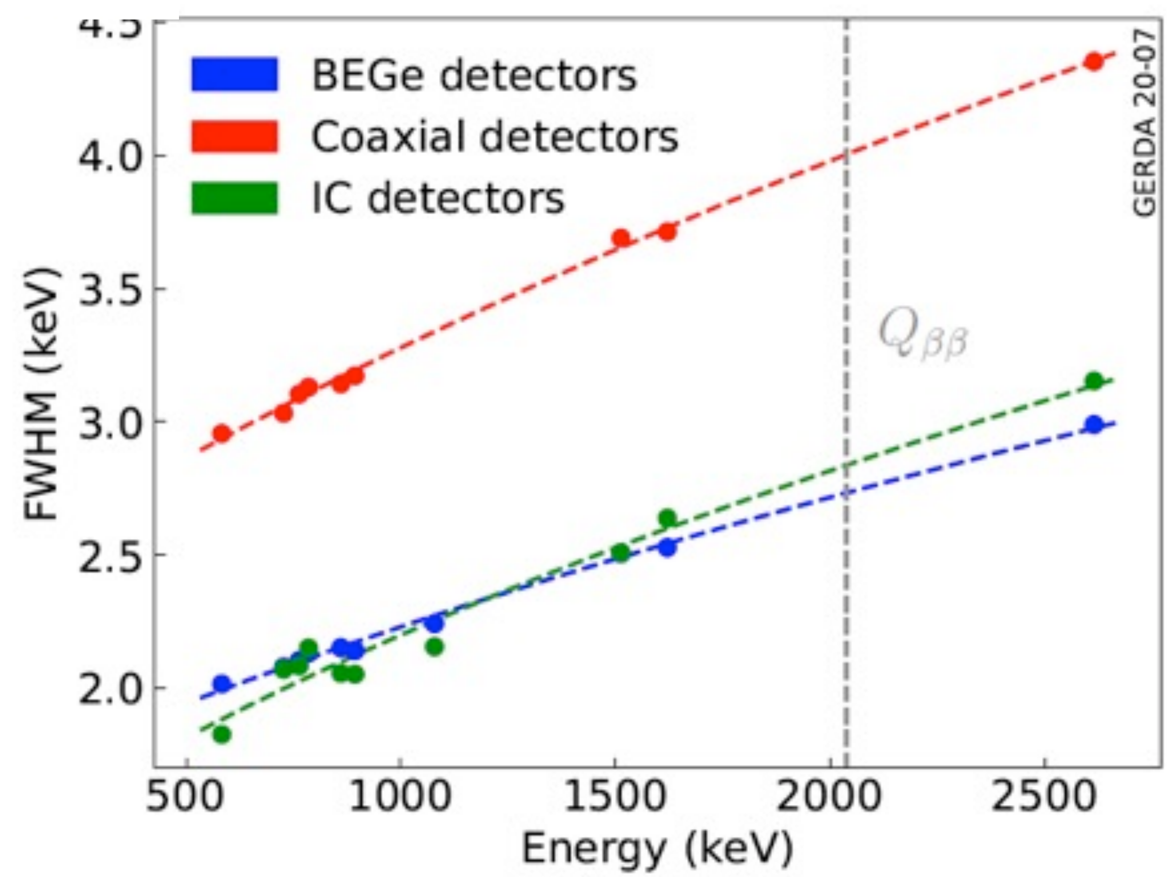


Fig. 1. Schematic diagrams of a closed-end coaxial p-type HPGe detector (top) and the new geometry Inverted Coaxial detector (bottom).



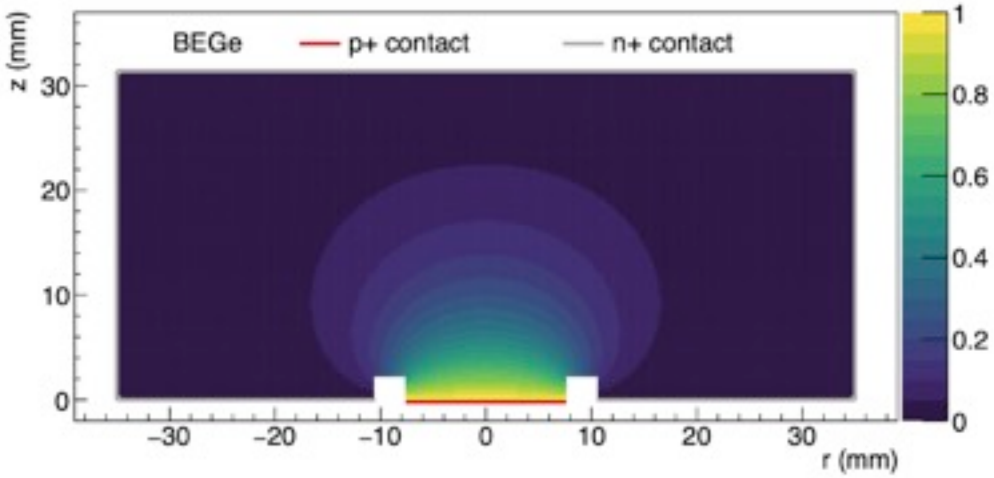
Notice more uniform weighting potential across volume = more uniform response of diverse classes of bkg happening at various sites = better PSD

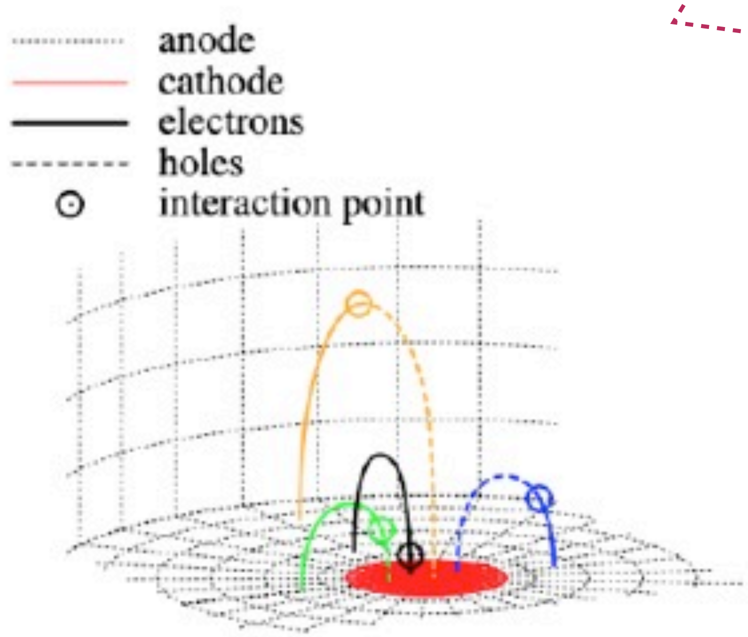


PC also offer better E_{reso} than extended contact (coaxial) thanks to reduced electrode size (smaller capacitance, ~pF)

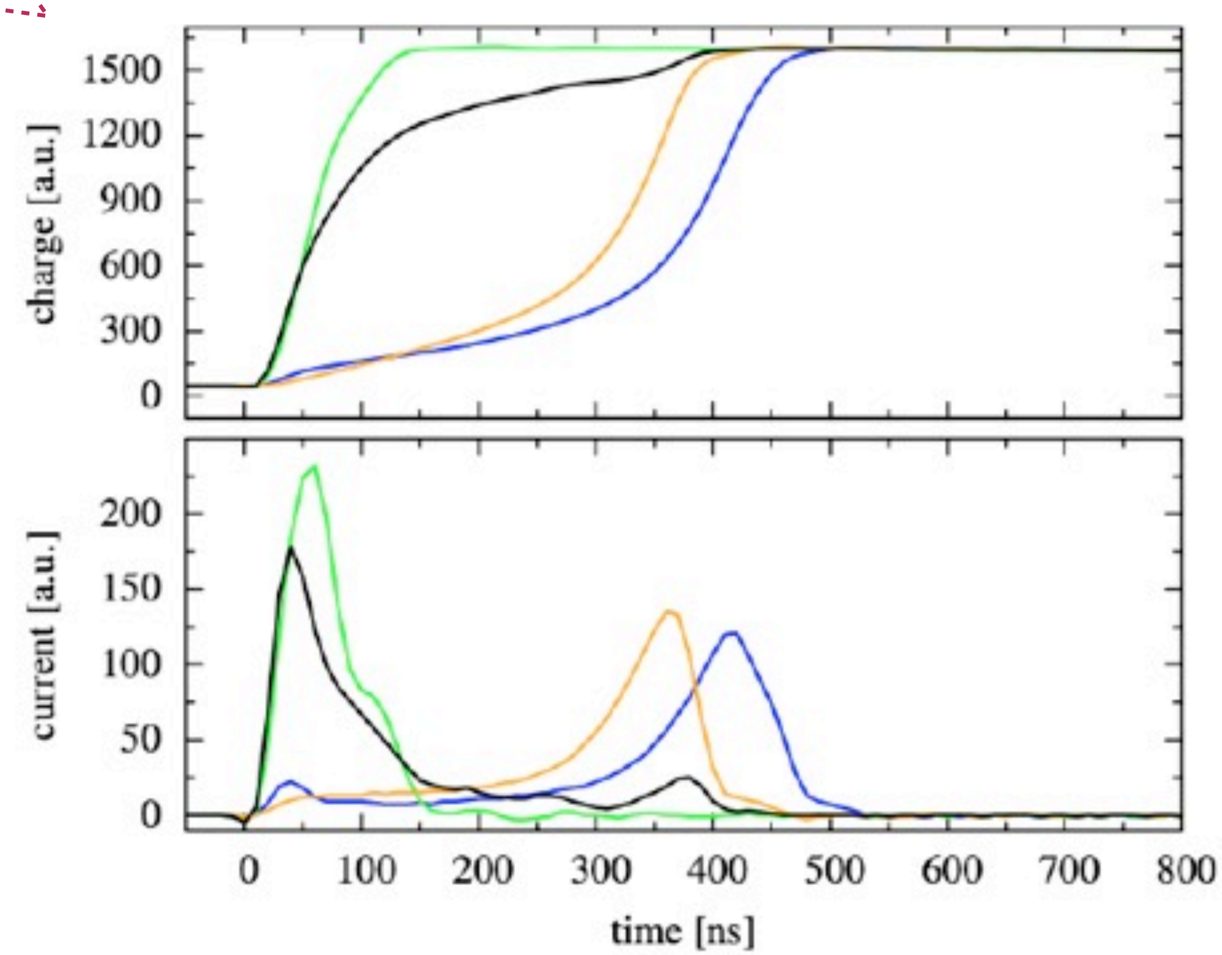
PSD in Ge: concept

See also: Nucl.Instrum.Meth.A 891 (2018) 106-110





• Markedly different Q and A spectra according to where energy deposition occurs in crystal

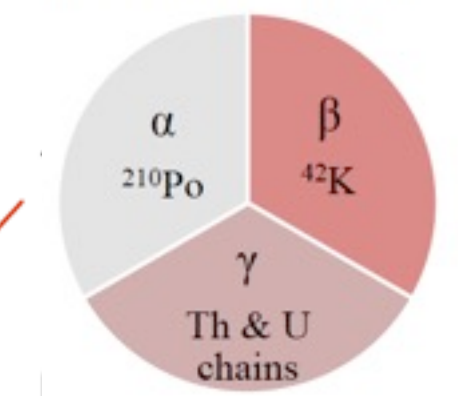


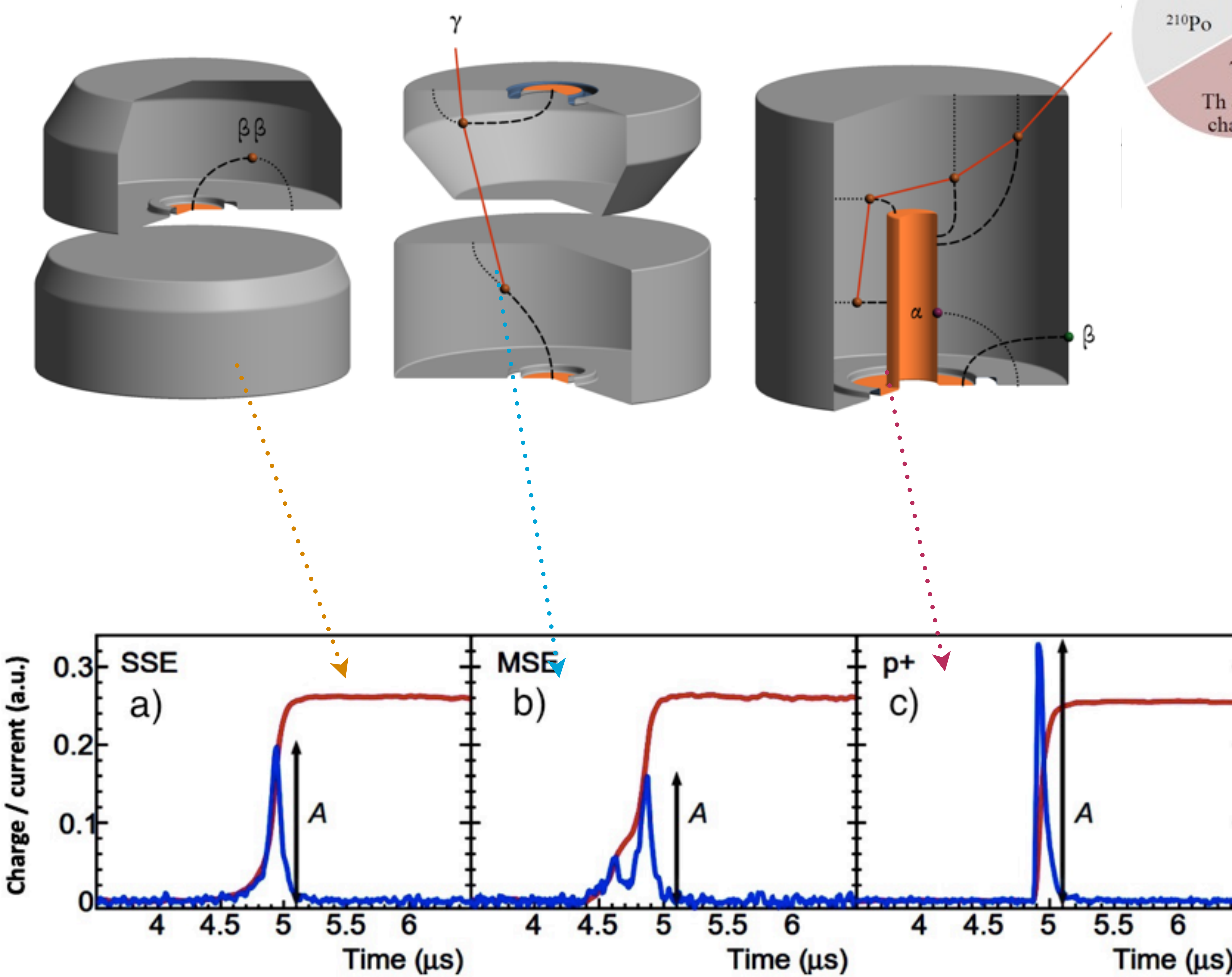
• Uniform configuration of weighting potential in PC enhances (>90%) "**yellow**" type wrt others

- If all ionization happens in single site (SSE), Q and A proportional and compatible with single cluster
- If ionization is diffused (Bethe-Bloch or Compton, MSE), total Q is split in smaller peaks of A

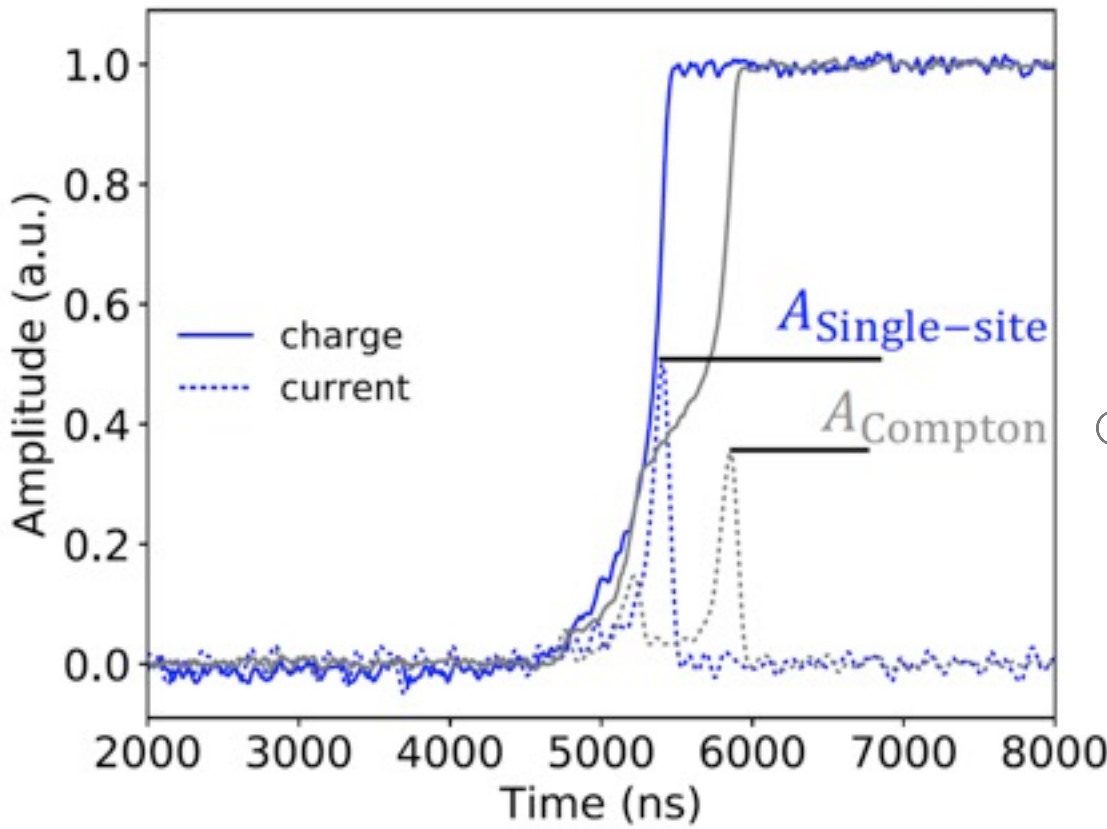
Why is PSD important?

GERDA Background Estimate:





BEGe and IC detectors: A/E



^{208}Tl γ (2614 keV)

DEP from diode

Compton in diode

Y.Kermaidic, Neutrino '20

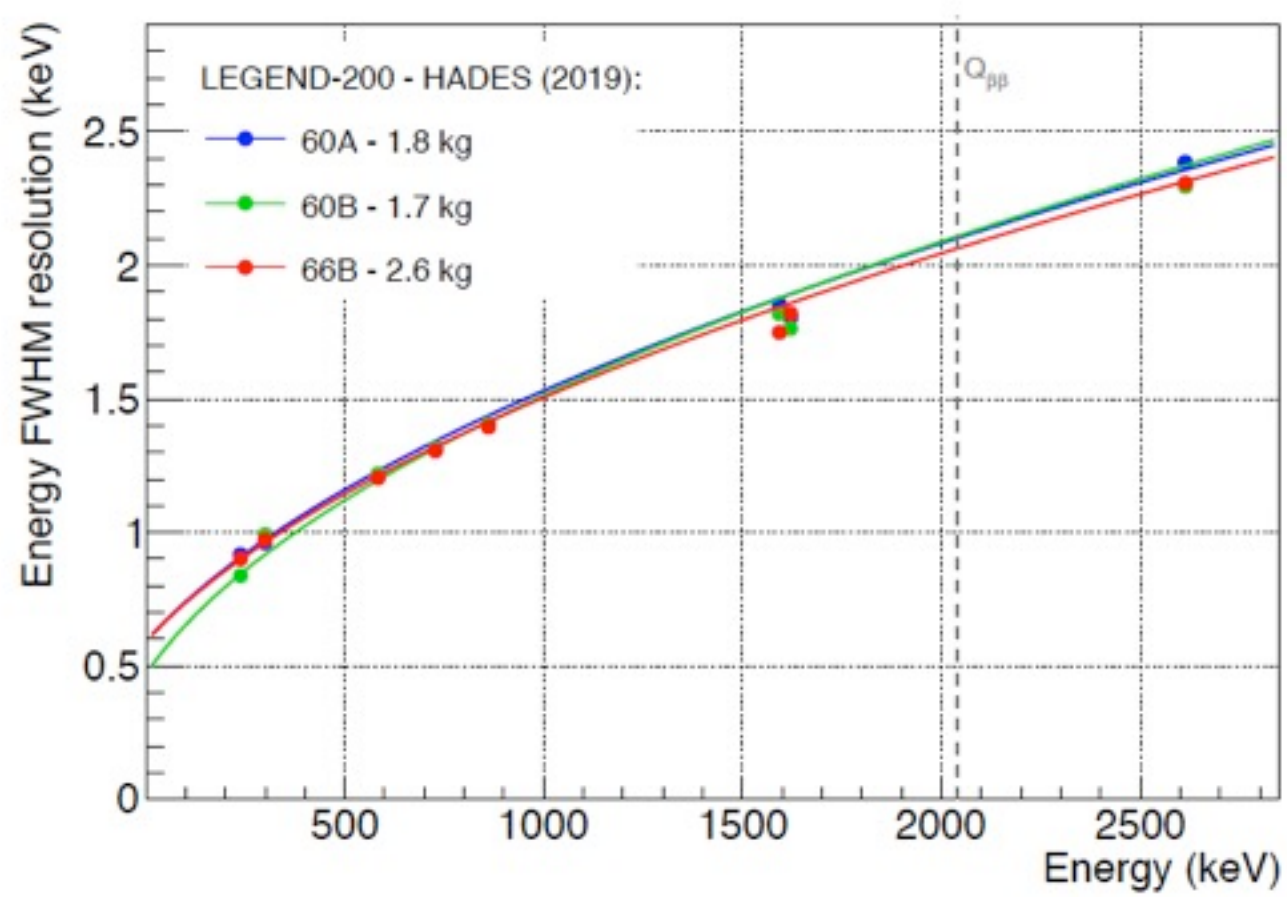
GERDA

$0\nu\beta\beta$ decay signal efficiency:

- $\epsilon_{PSD}^{BEGe} = (88.7 \pm 3.2)\%$
- $\epsilon_{PSD}^{IC} = (90.0 \pm 1.7)\%$
- $\epsilon_{PSD}^{Coax} = (68.9 \pm 3.1)\%$

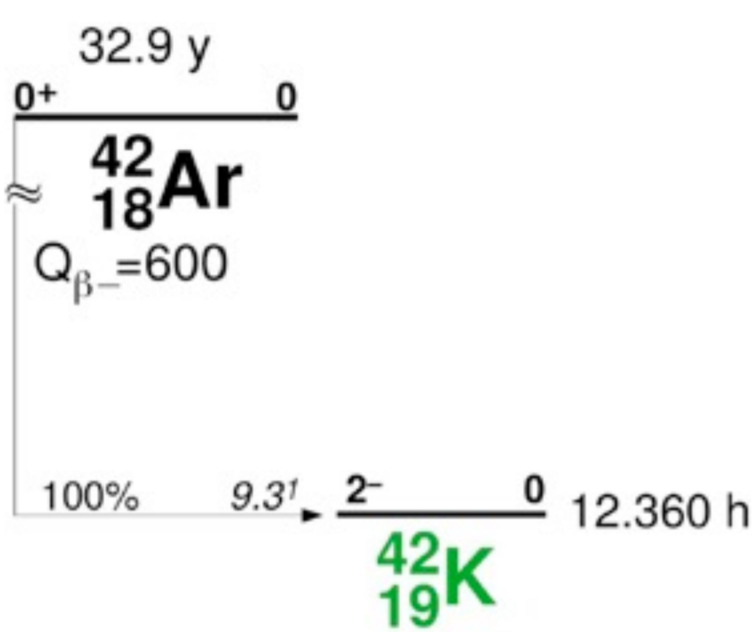
Each new batch of ICPC is characterized at dedicated underground stands in ORNL (US) and HADES (BE), where resolution, bkg, PSD performance are evaluated

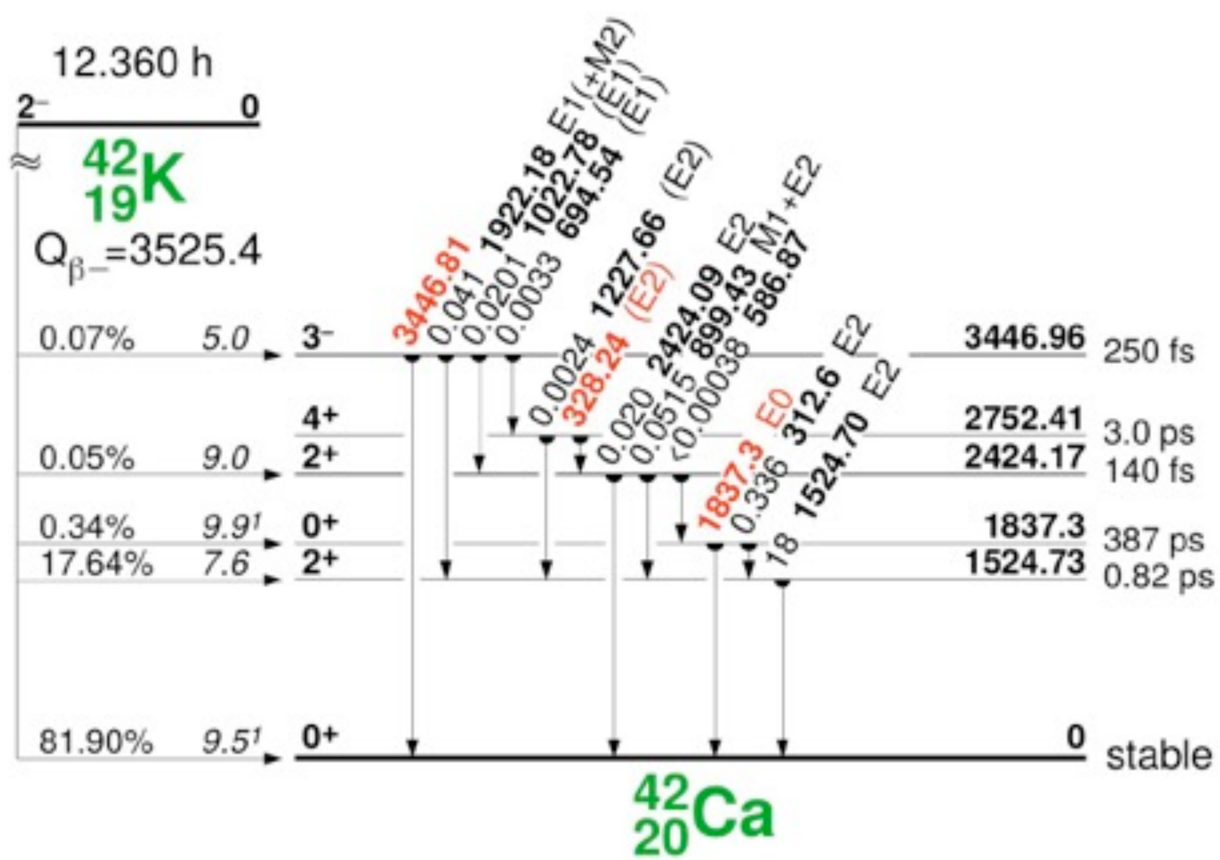
Example from first batch in 2019 with excellent E_{reso}



Origin of radioactive bkgs

- α comes from ^{210}Po (τ=138 days) coming from ^{238}U chain on diode surface and attracted to migrate towards p^+ electrode by its strong field
- γ comes from
  - various branches of U and Th chain on materials (FETs, cables, Cu mounts);
  - and from $^{40/42}Ar \rightarrow {}^{40/42}K \rightarrow {}^{40/42}Ca^*$ decays (K ion drifted by LAr convective motion and electric field lines towards n^+ dead layer = SSE)
- β mainly from $^{40/42}$K decays close to diodes, same as above





MITIGATION measures of radioactive bkgs

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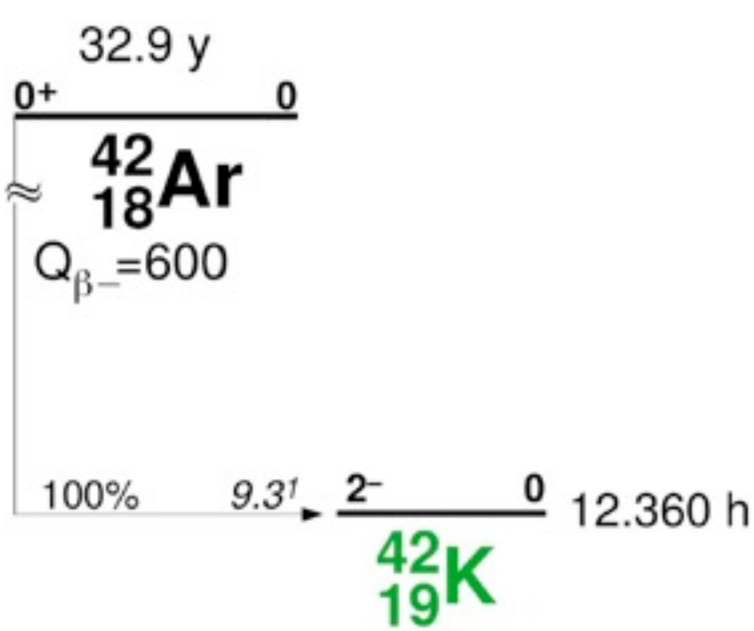
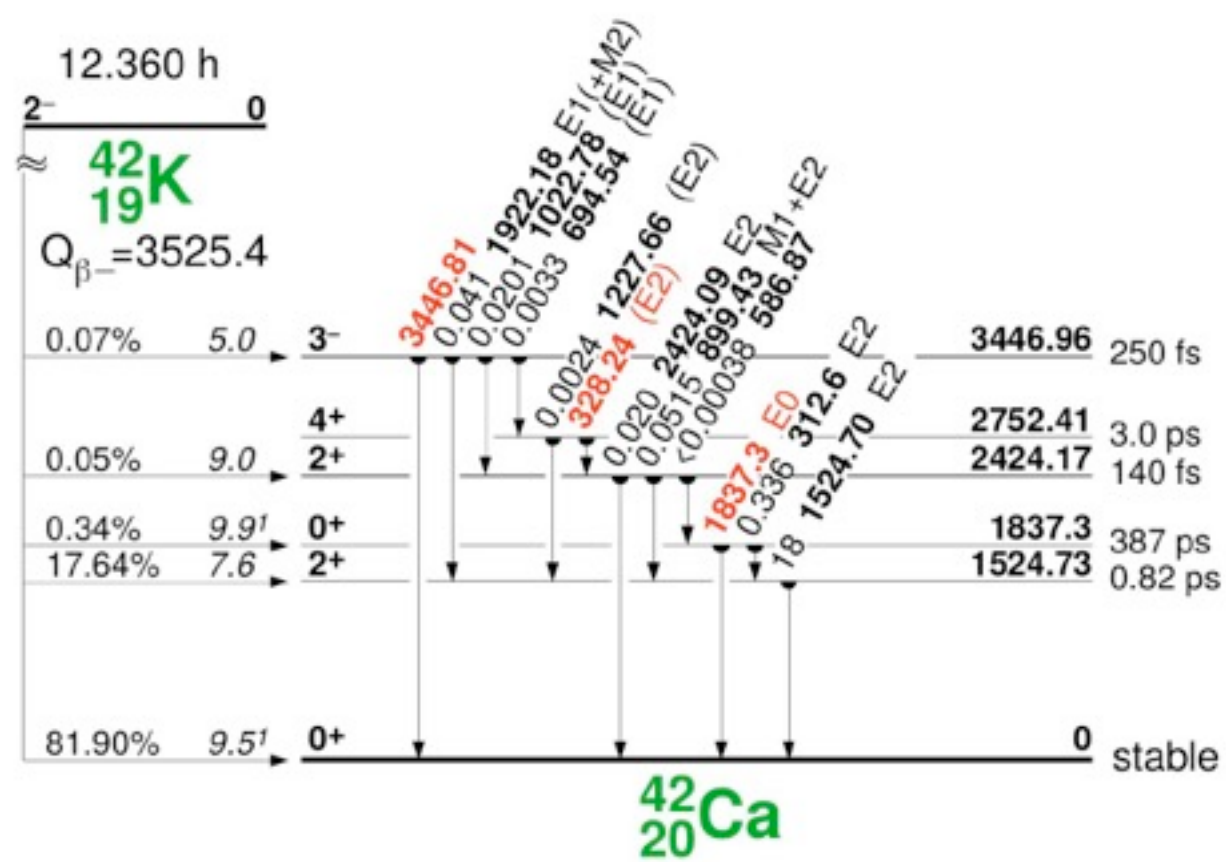
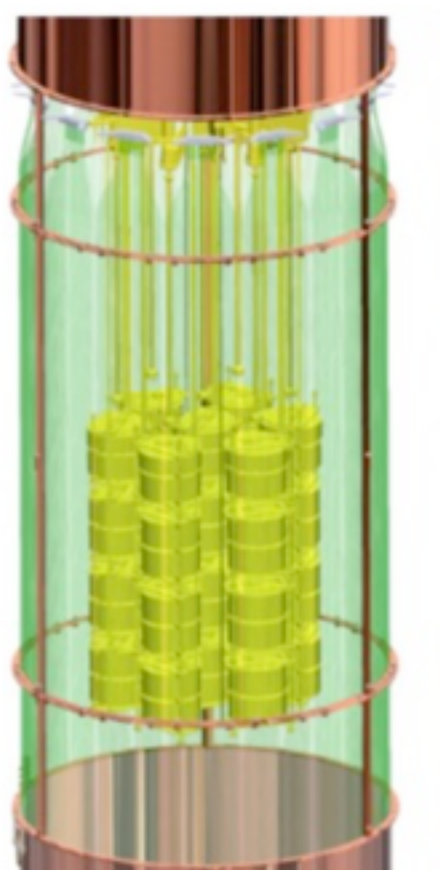




UG electro-formed copper

- Applies experience of MJD, which used 1.2 tons of UGEFCu because of its radio-purity ($\leq$ 0.1 μBq/kg Th/U chains, very low in cosmogenic ^{60}Co)
- 3 new EF baths were constructed at SURF to supply clean Cu for detector housing components
- Advancements in the understanding of post machining contamination of plastics and metals will feed into L-1000 effort

LEGEND-200 at LNGS



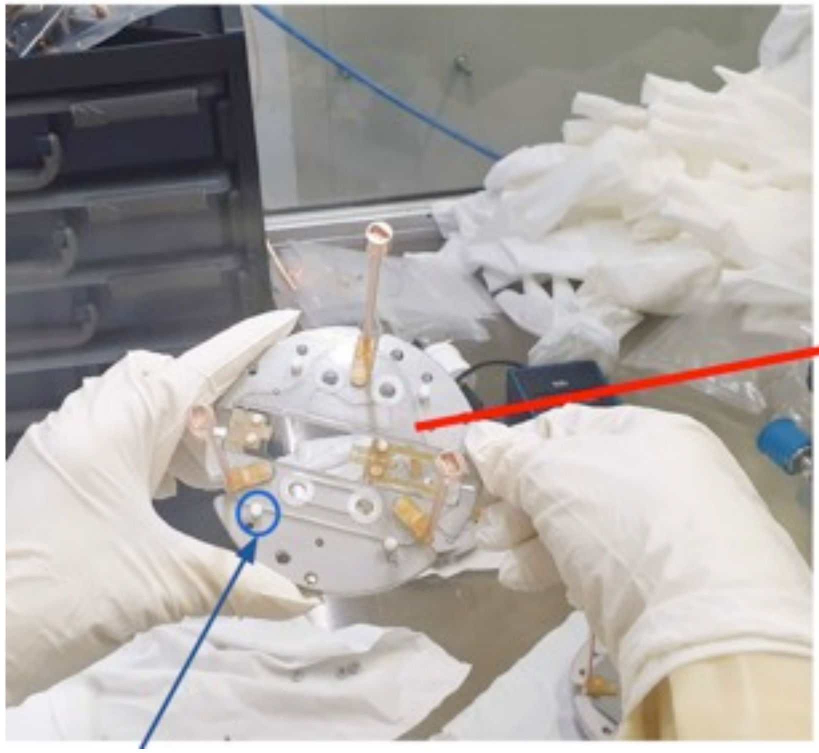
EFCu can be placed next to detectors, in LAr: improves signal/noise and, consequently, PSD

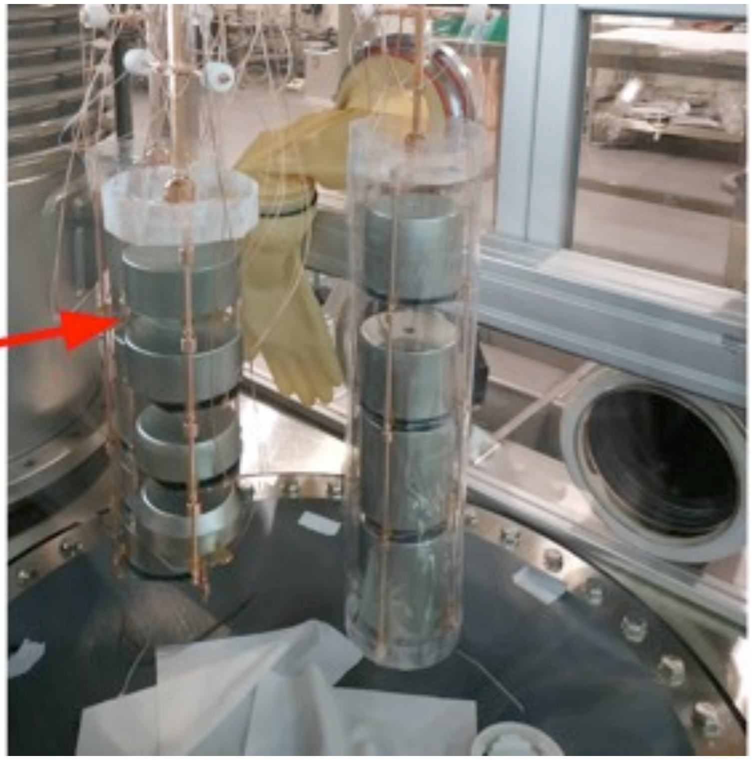
PEN plates: veto yourself !

- PEN — Poly(ethylene 2,6-naphthalate) is a scintillating plastic (1/3 LY of conventional plastic scintillators)
    - wavelength-shifts to ~450 nm the 128 nm photons from LAr
- Mechanically stronger than silicon, stronger than Cu at cryogenic temperatures (T=87 K)
- Meets radio-purity req. ≤ 1 μBq/piece for Ra/Th

Low (5-7 g) mass geometry optimized for L-200

- Replaces Si plates (GERDA)
- PEN holders deployed in LEGEND "post-GERDA test" at LNGS in first half of 2020 (despite COVID...)
- On-going further R&D for additional cleanliness and improved optical properties for L-1000





Plates fitting read-out electronics

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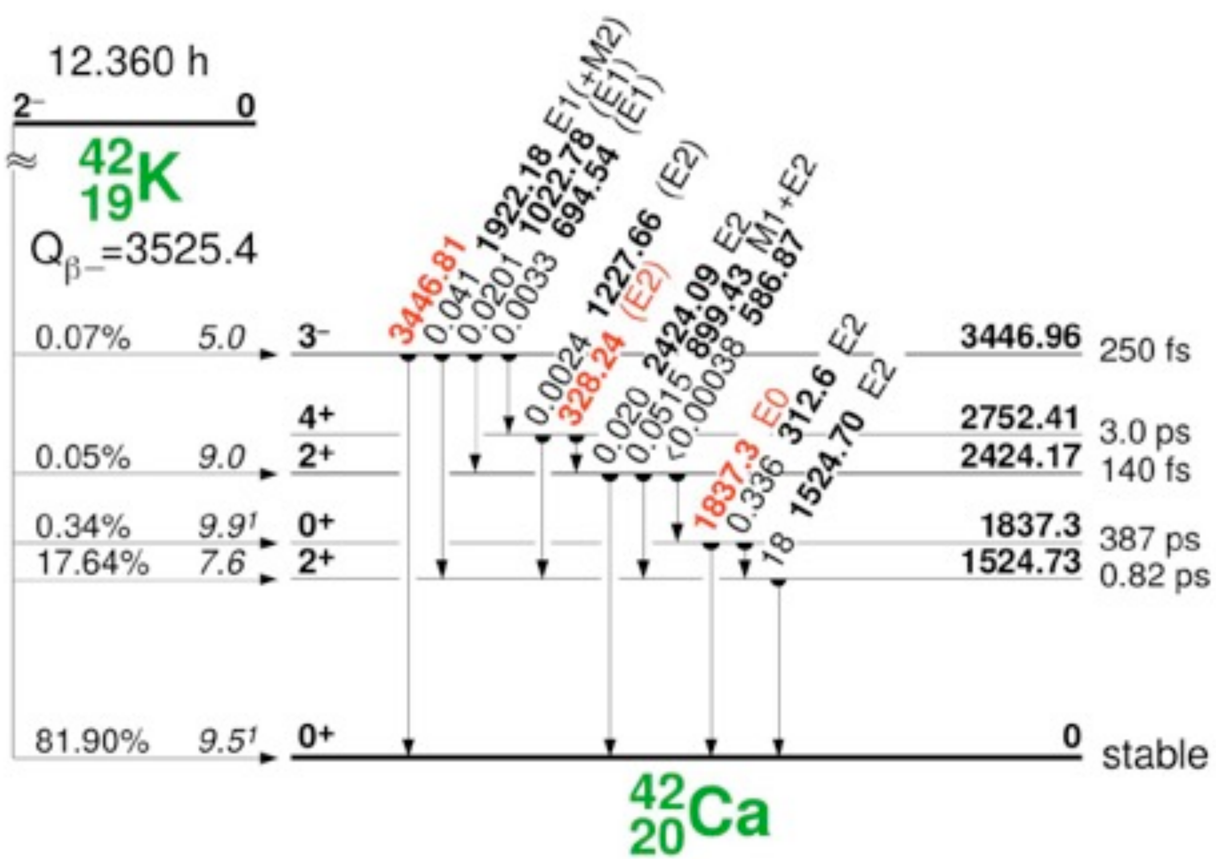
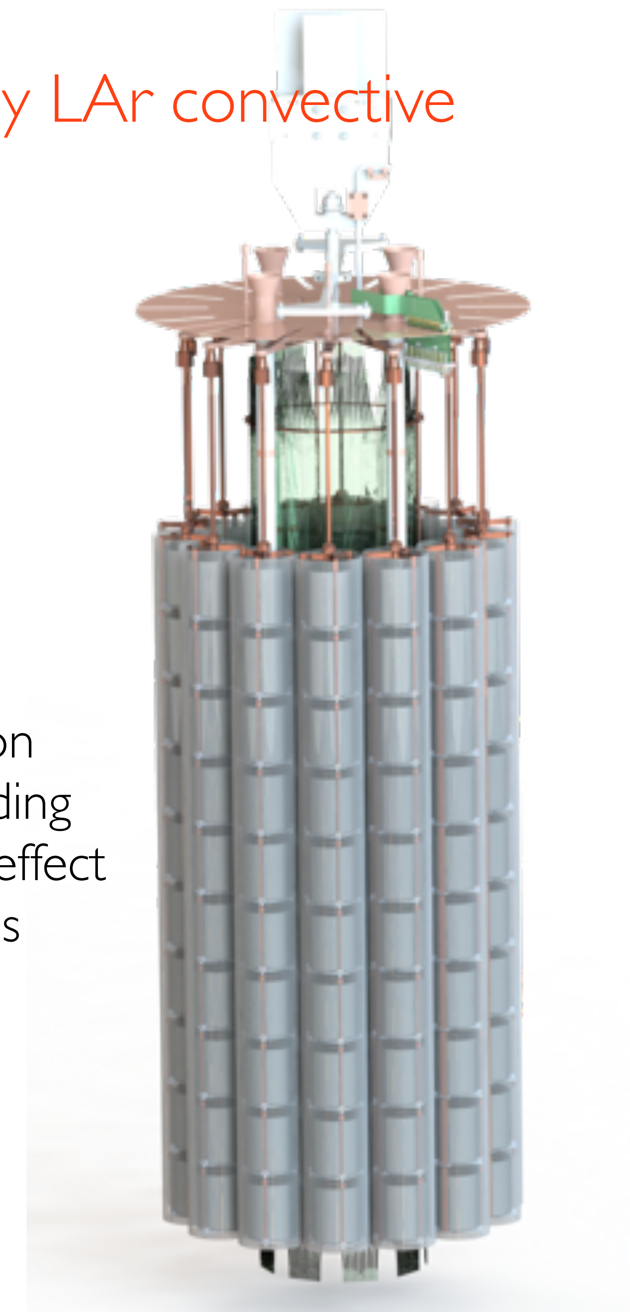
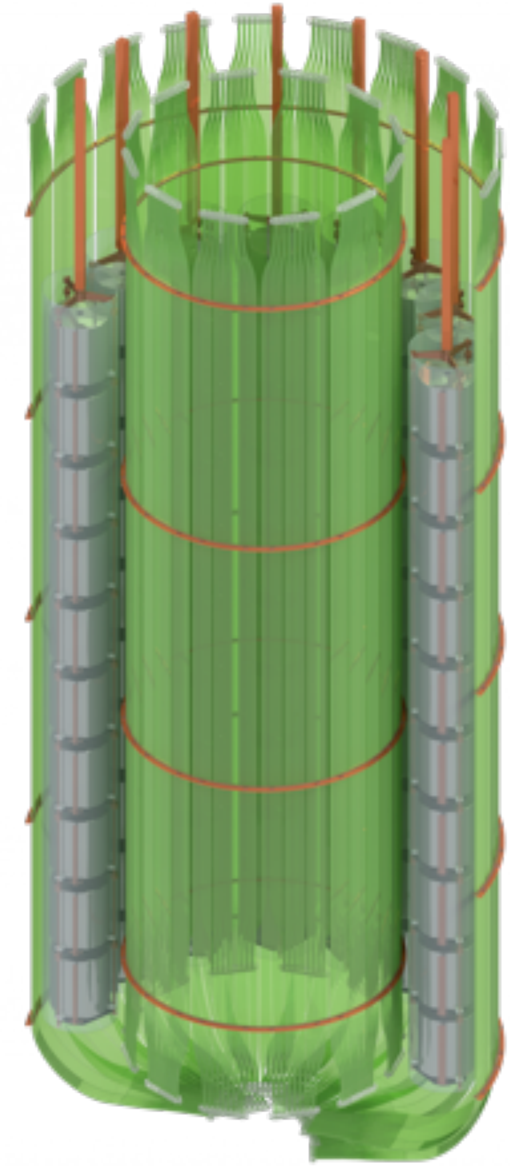


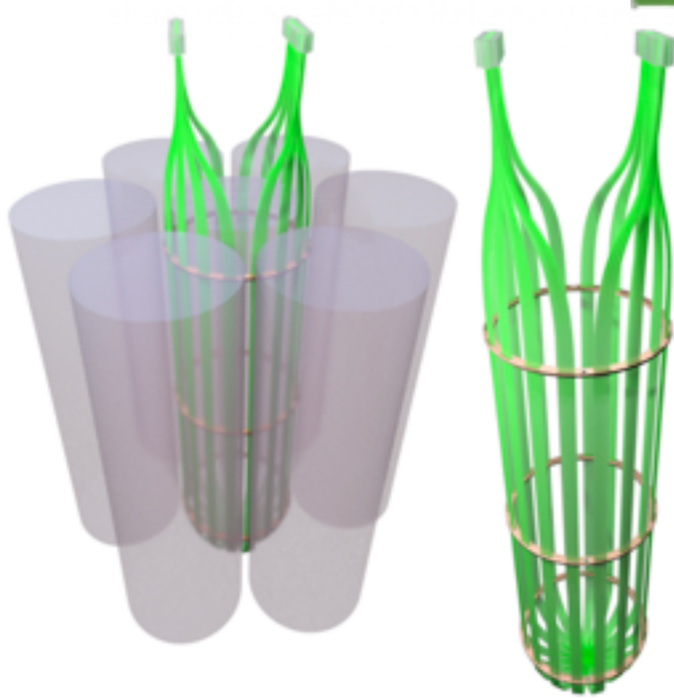
TPB-coated nylon cylinders surrounding each string to limit effect of drifting K-ions



LAr active veto

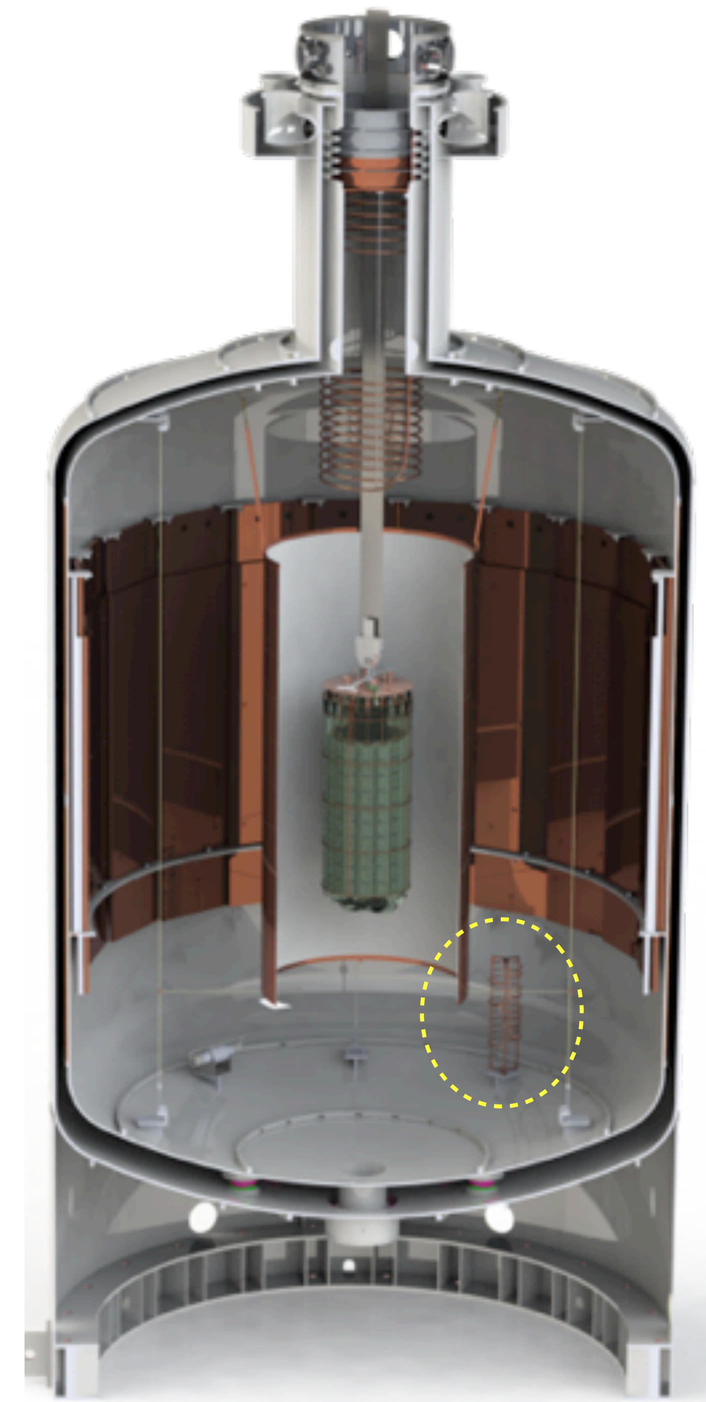
- Retain a crucial element of GERDA: instrument LAr volume to read out light from scintillation
  - 2 shrouds of optical fibers for enhanced coverage coated in TBP as WLS
  - connected SiPM with new FE electronics for SPE resolution
  - Reflective foil around outer shroud to increase light collection
- Actively vetoes incoming radiation from U/Th/K in coincidence with diodes
- But introduces bkg itself:
  - radioactivity from fibers, SiPM
  - high-activity β decays of sub-dominant isotope ^{39}Ar *[1.41 Bq/l (e.g. NIM A 574 83)]*





LAr active veto, related specs

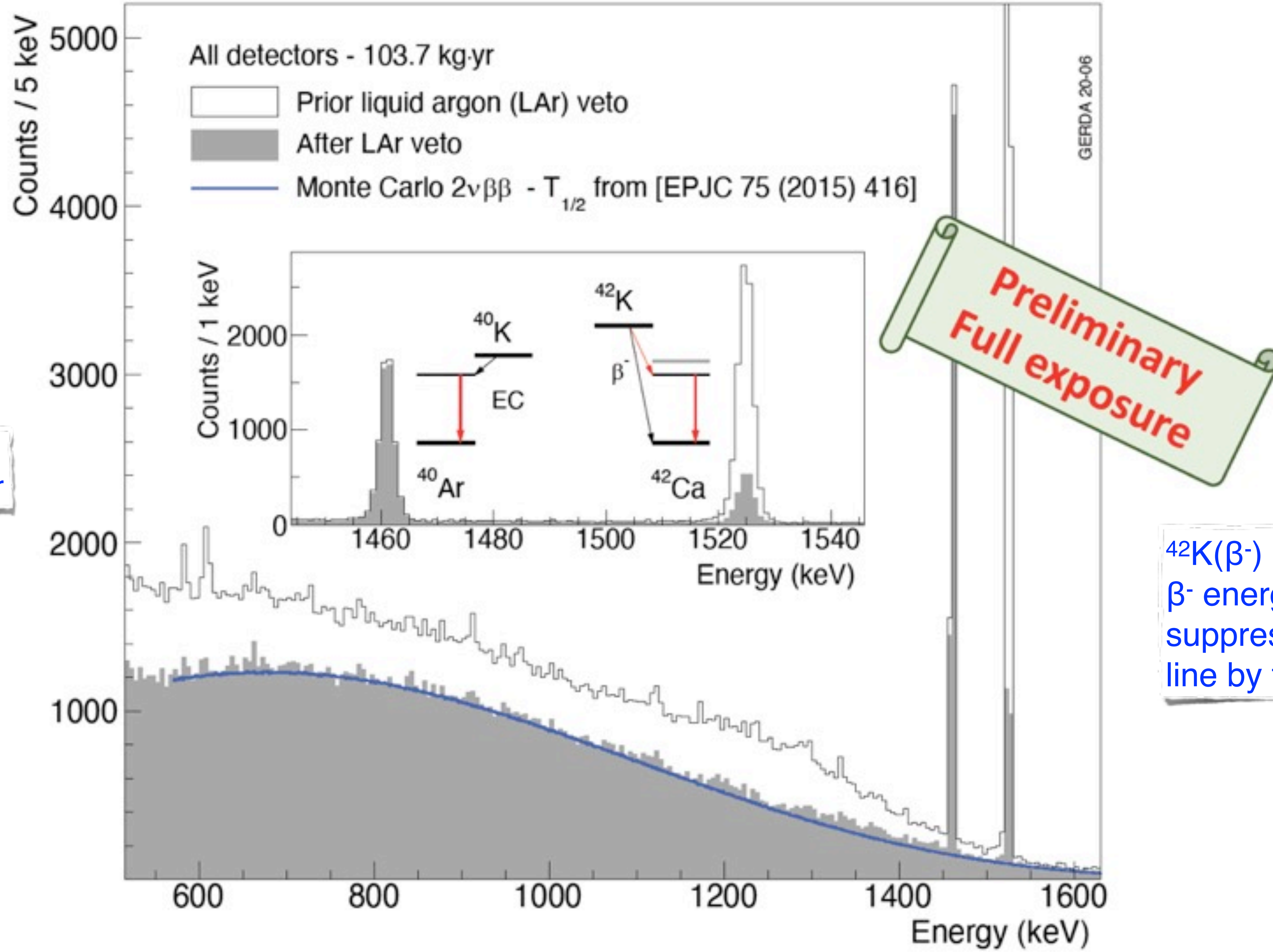
- Ar_2 excimer scintillates at 128 nm (VUV), LY O(10k photons/MeV deposited), singlet and triplet states mix in fast (~few ns) and slow (~1.5 μs) components



- triplet attenuation highly depends on recombination with impurities (N, O, Xe ppm-to-ppb) sneaking at Ar distillation
- "class 5.5" LAr from plant + in place at LNGS ad-hoc system to purify LAr as it flows between tank and cryostat
- Expected to result in $\lambda_{att} \lesssim 1$m, small wrt cryostat radius

LLAMA device in LAr will monitor in time attenuation and triplet lifetime

Benefit of active veto (lesson from GERDA)

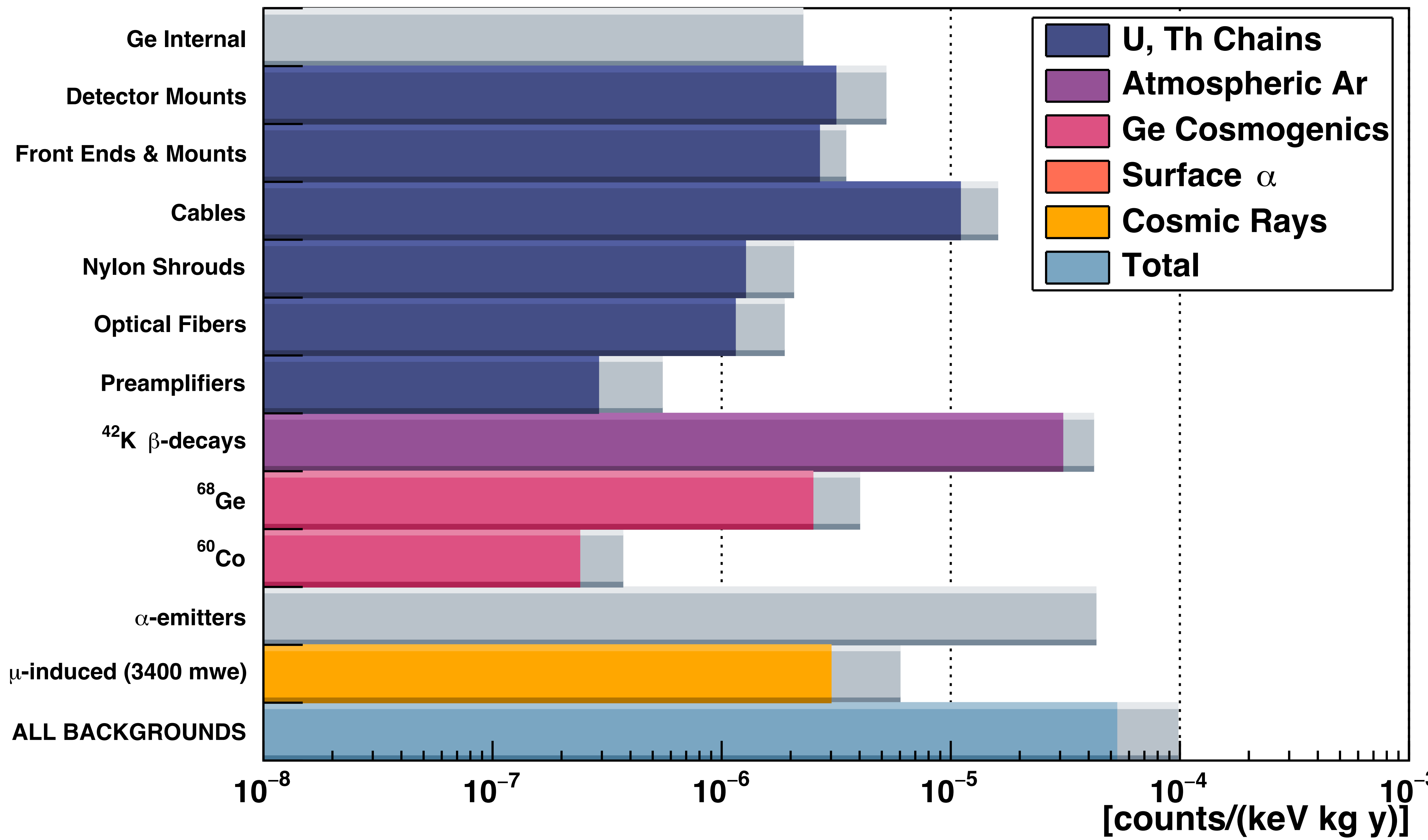


^{40}K(EC)
no energy in LAr

^{42}K(β^-)
β^- energy in LAr suppresses ^{40}Ca γ line by factor ~5

- 0ν2β decay signal efficiency: $\varepsilon_{LAr} = (97.9 \pm 0.1)\%$
- Accidental coincidences give 2.3% dead time
- Factor 6 bkg reduction in the ROI (1930 keV to 2190 keV) on top of PSD

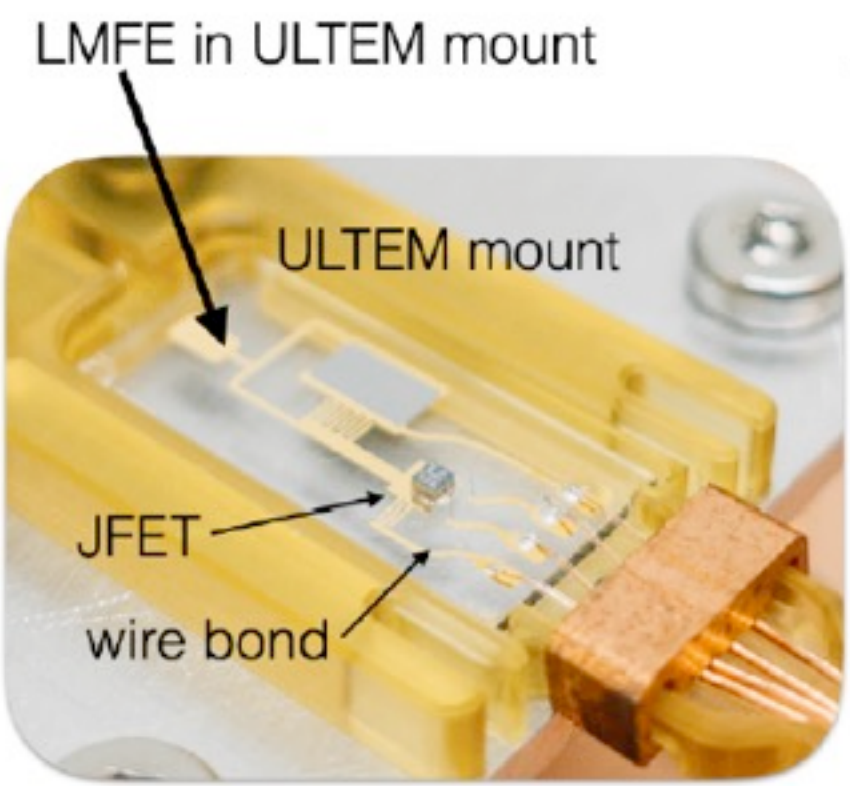
Expected bkg budget L-200

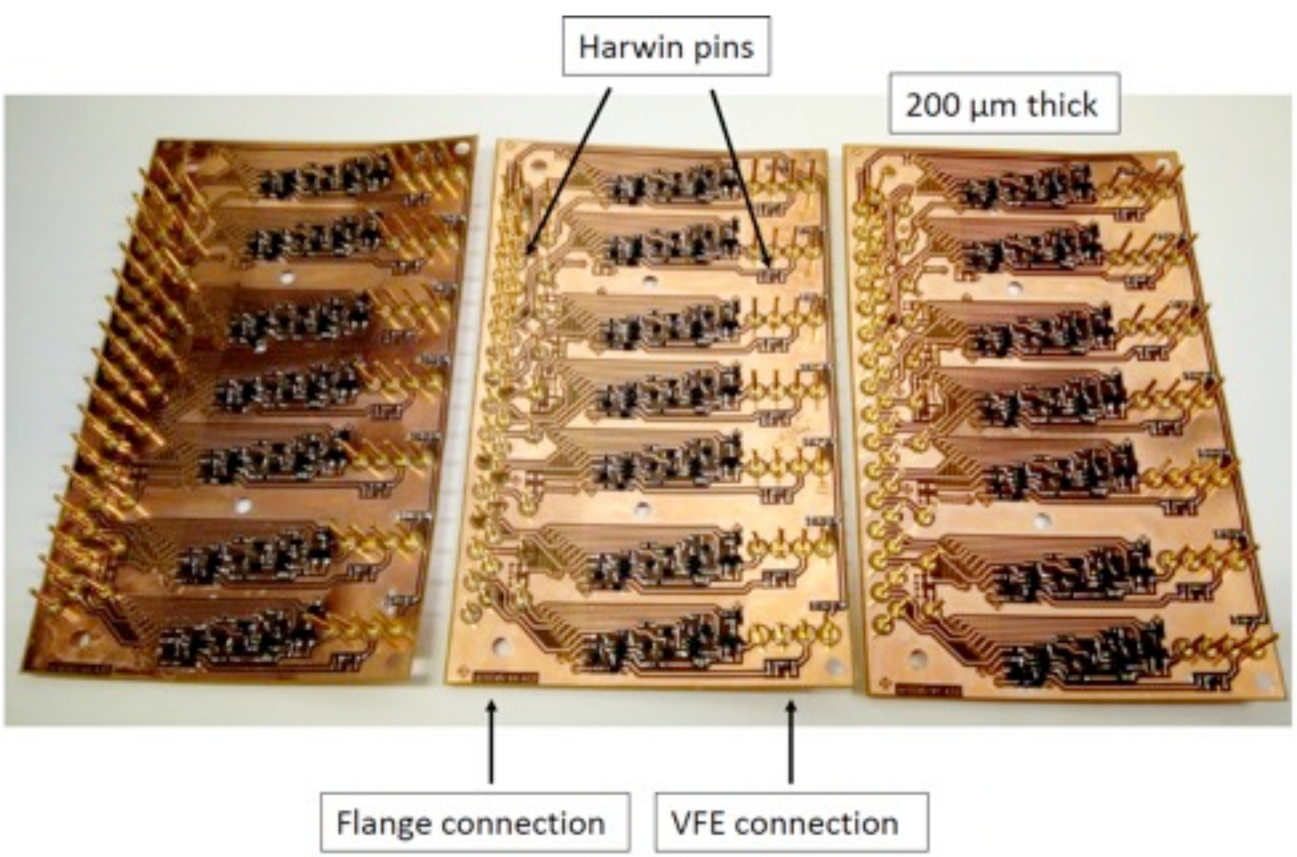


~ 2-3 times lower BI than GERDA

Front-End electronics

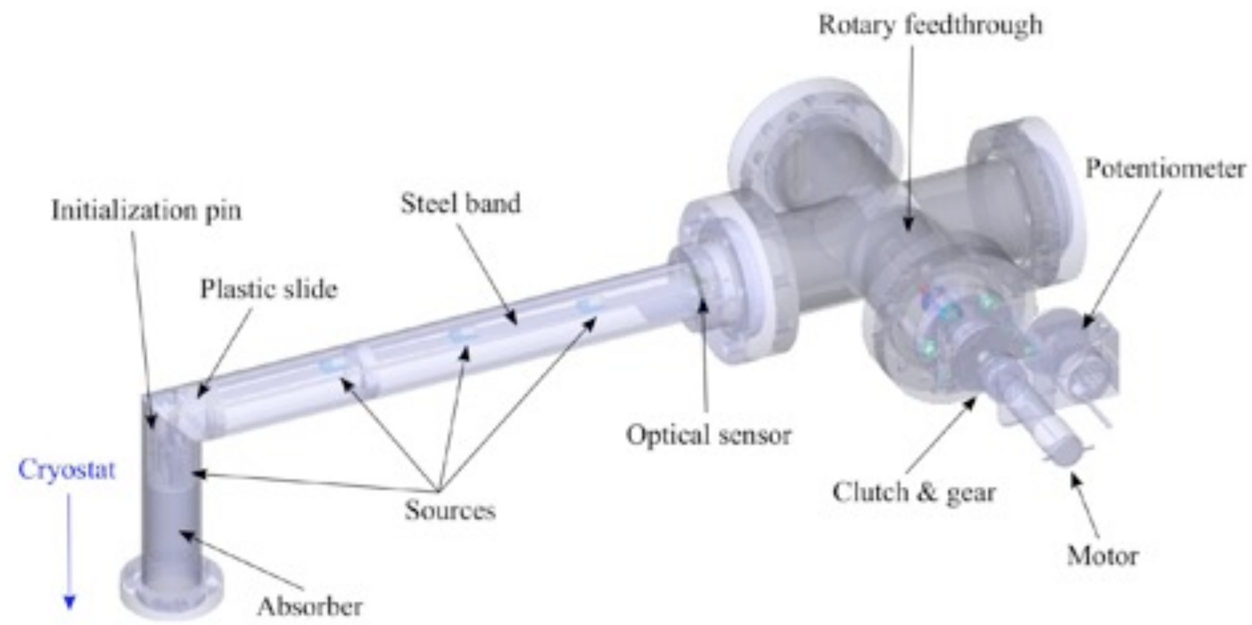
- Low-Mass (radio-pure) FE on ULTEM inert plastic *(a la MJD)* feeding into "CC4" CSA pre-amp *(a la GERDA)*
- LMFE: production tested in "Post-GERDA" tests last year, ok -> production/ shipment to LNGS being finalized
- CC4: ~2.7V output to flange/air, production complete, random screening to be performed

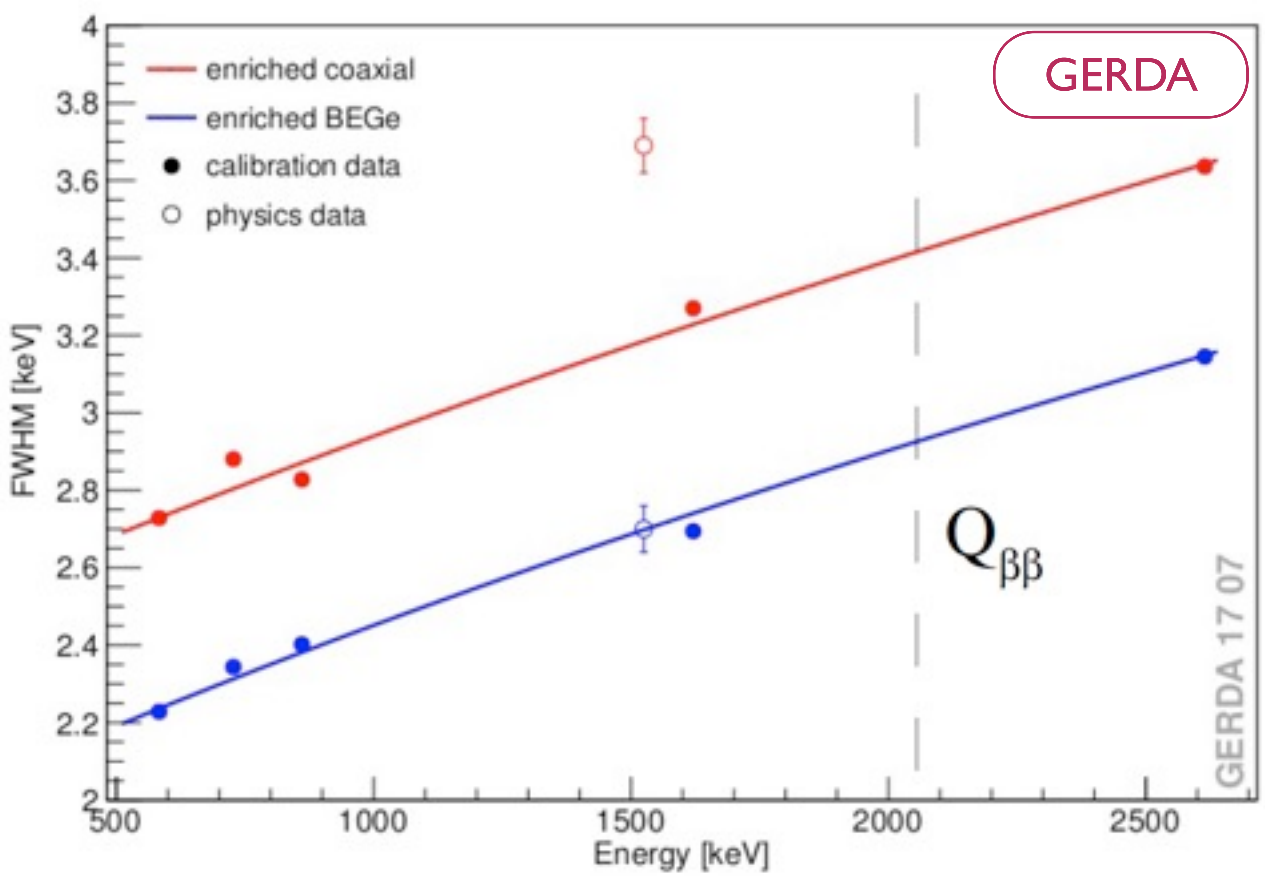


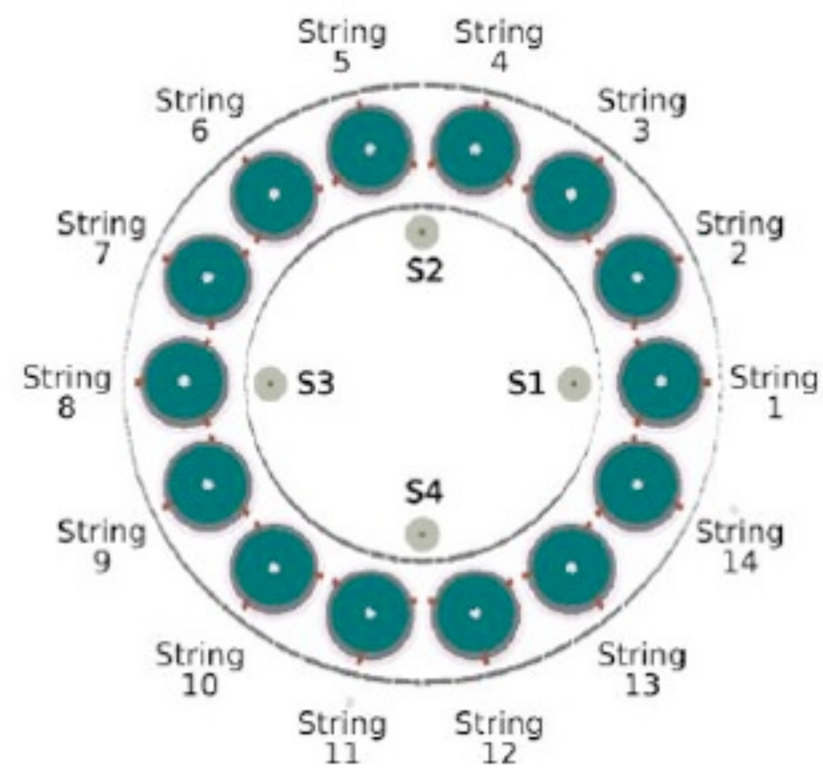


Energy calibration

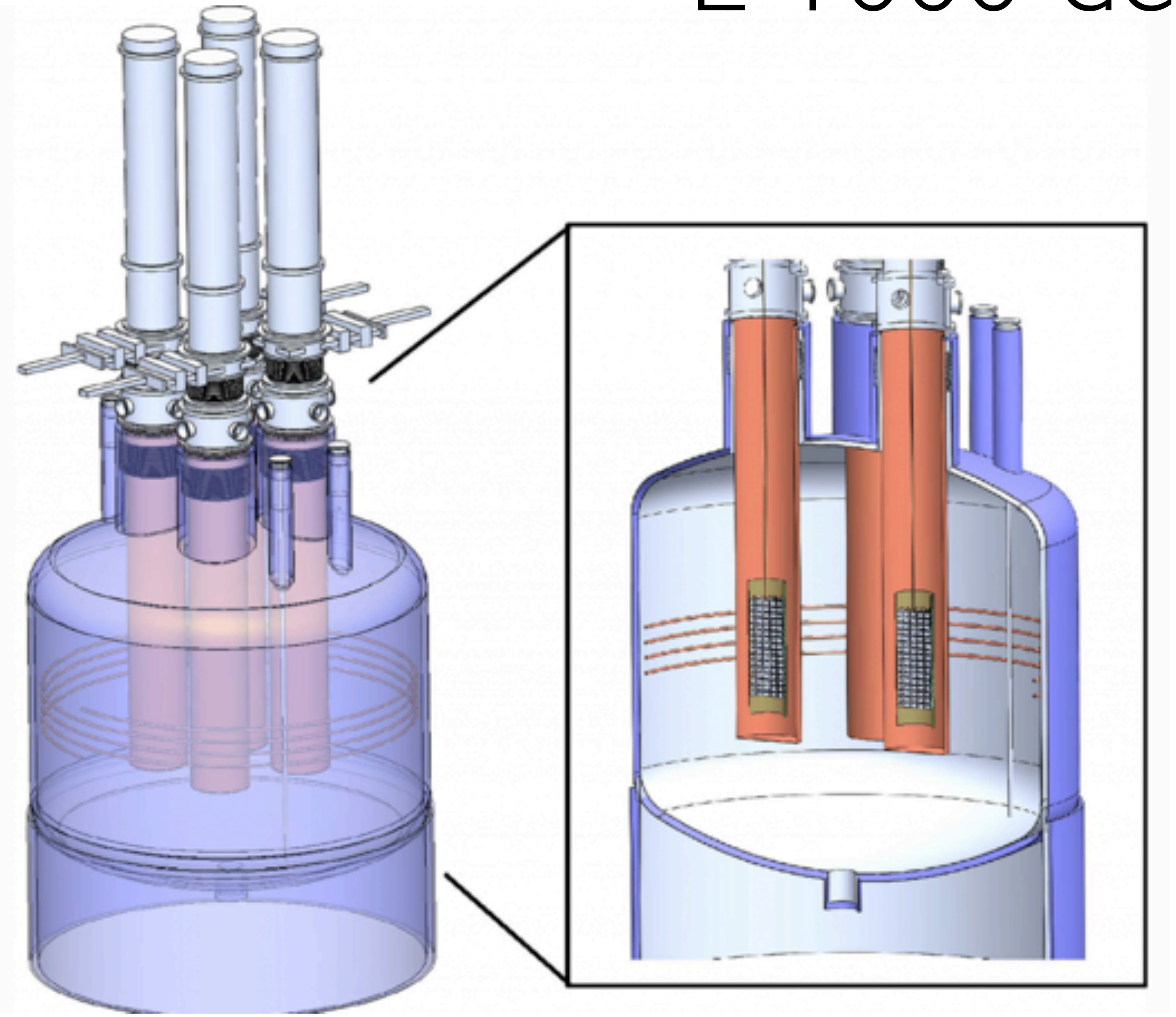
- 16 ^{228}Th sources ($T_{1/2}$=1.9 yr, A~5 kBq/source) for use in cold
- Away during data-taking and inserted by 4 dedicated motorized units
- Response checked at various energies periodically







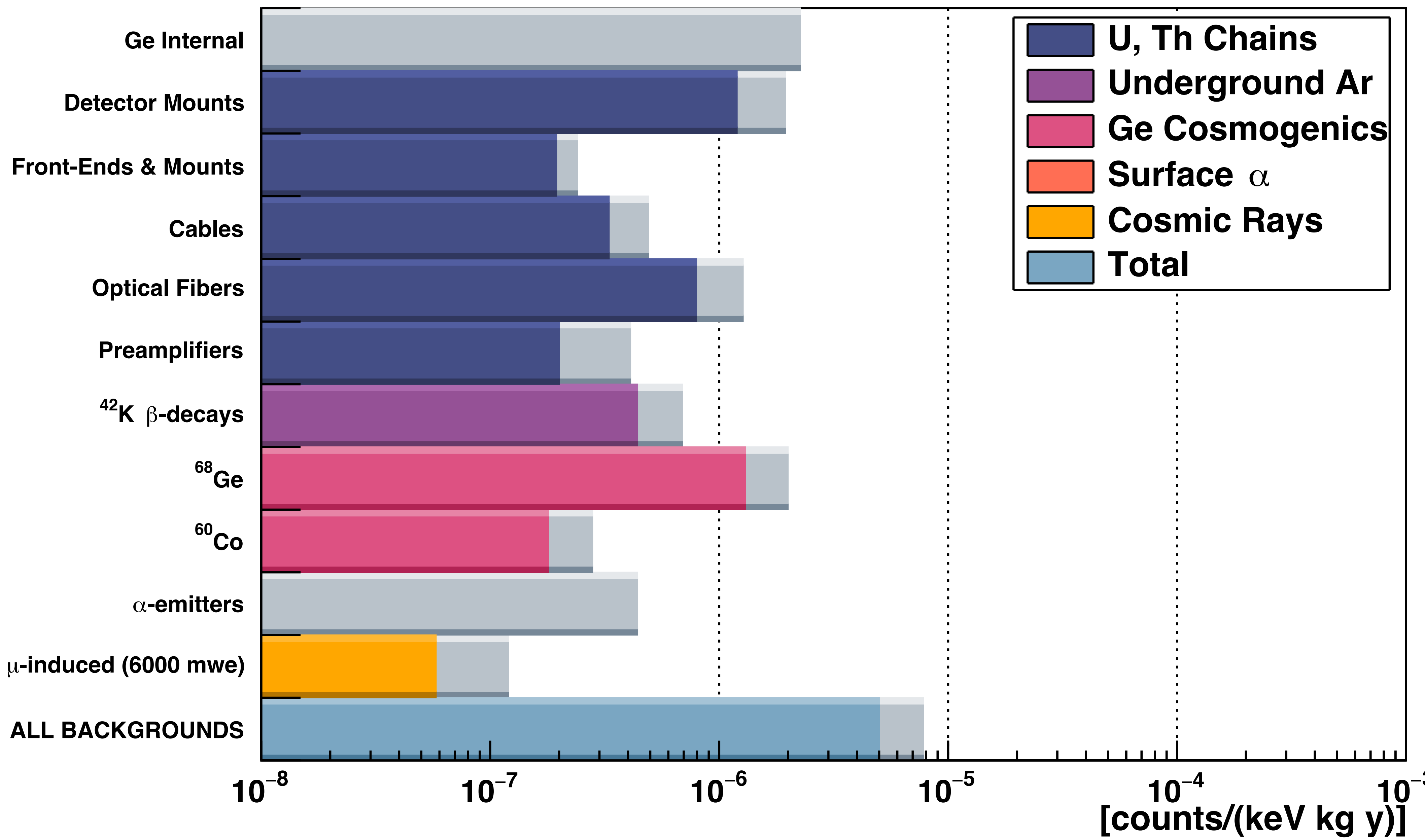
L-1000 design



- String concept replicated in 4 payloads, in total ~400 detectors
- Each re-entrant tube (UGEFCu) hosts 14 strings in dedicated UAr cryostat, ~3m^3 in volume
- Modest-sized LAr cryostat in "water tank" (6 m Ø LAr, 2-2.5 m layer of water) or large LAr cryostat w/o water (9 m Ø)
  - Other options still remain under investigation (e.g. LN_2)

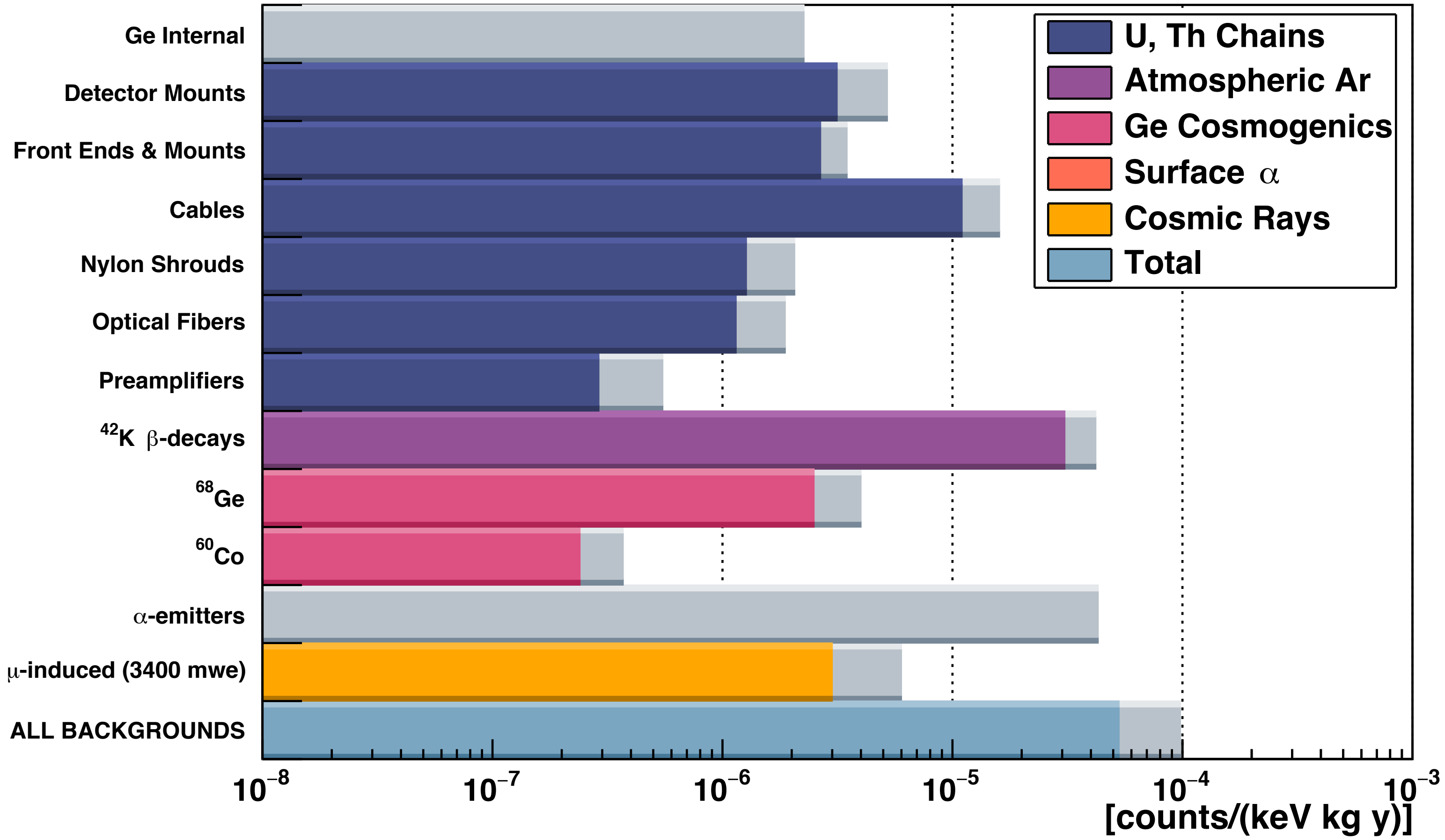
- Site yet TBD (LNGS? SNO? SURF?): all offer some advantages and some limitations
- Staged data-taking in payloads (2025-2030?) as detector production progresses
- R&D on-going on several crucial improvements

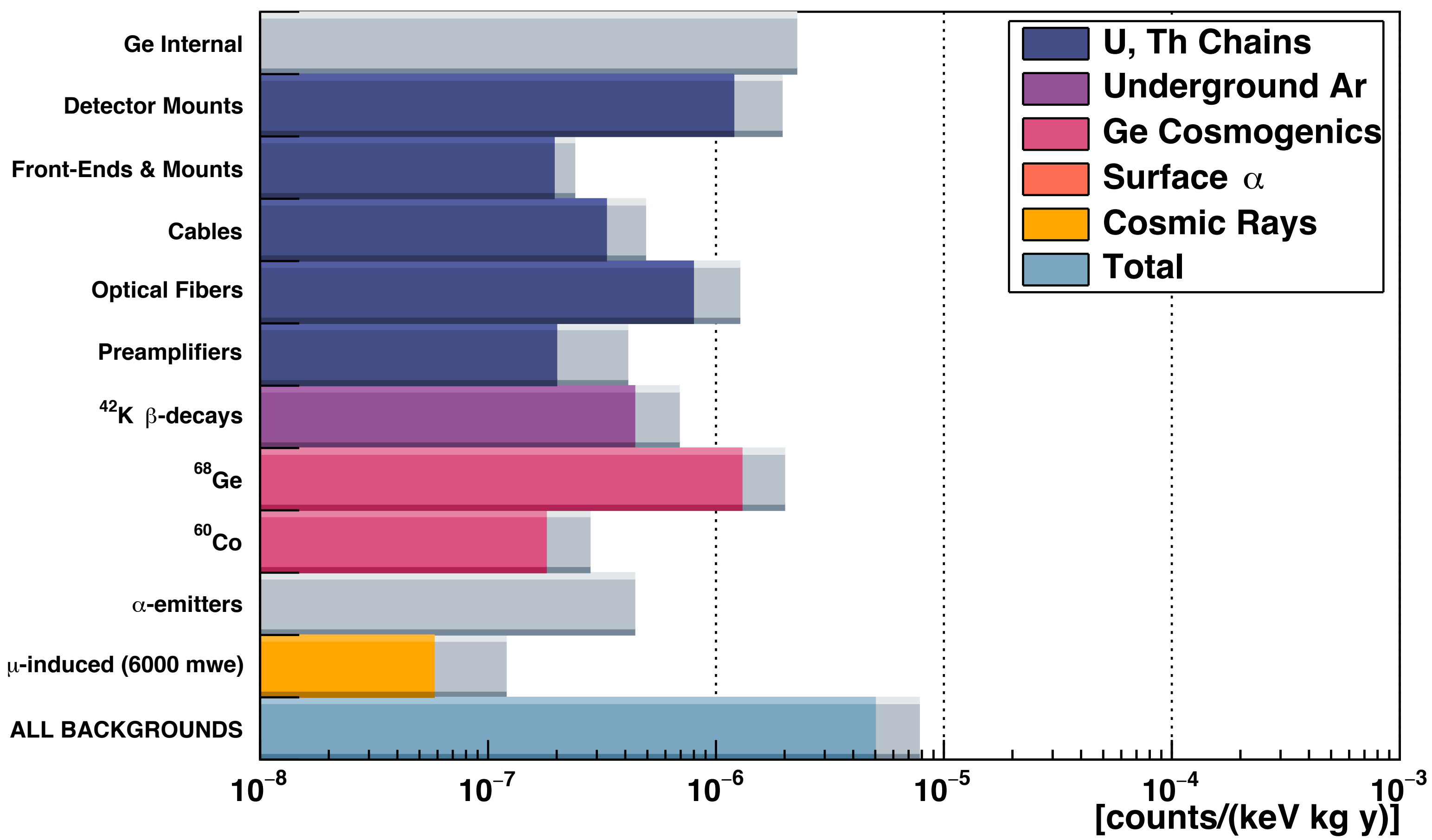
Expected bkg budget L-1000 (*preliminary*)



~ 50 times lower BI than GERDA

L-200 → L-1000





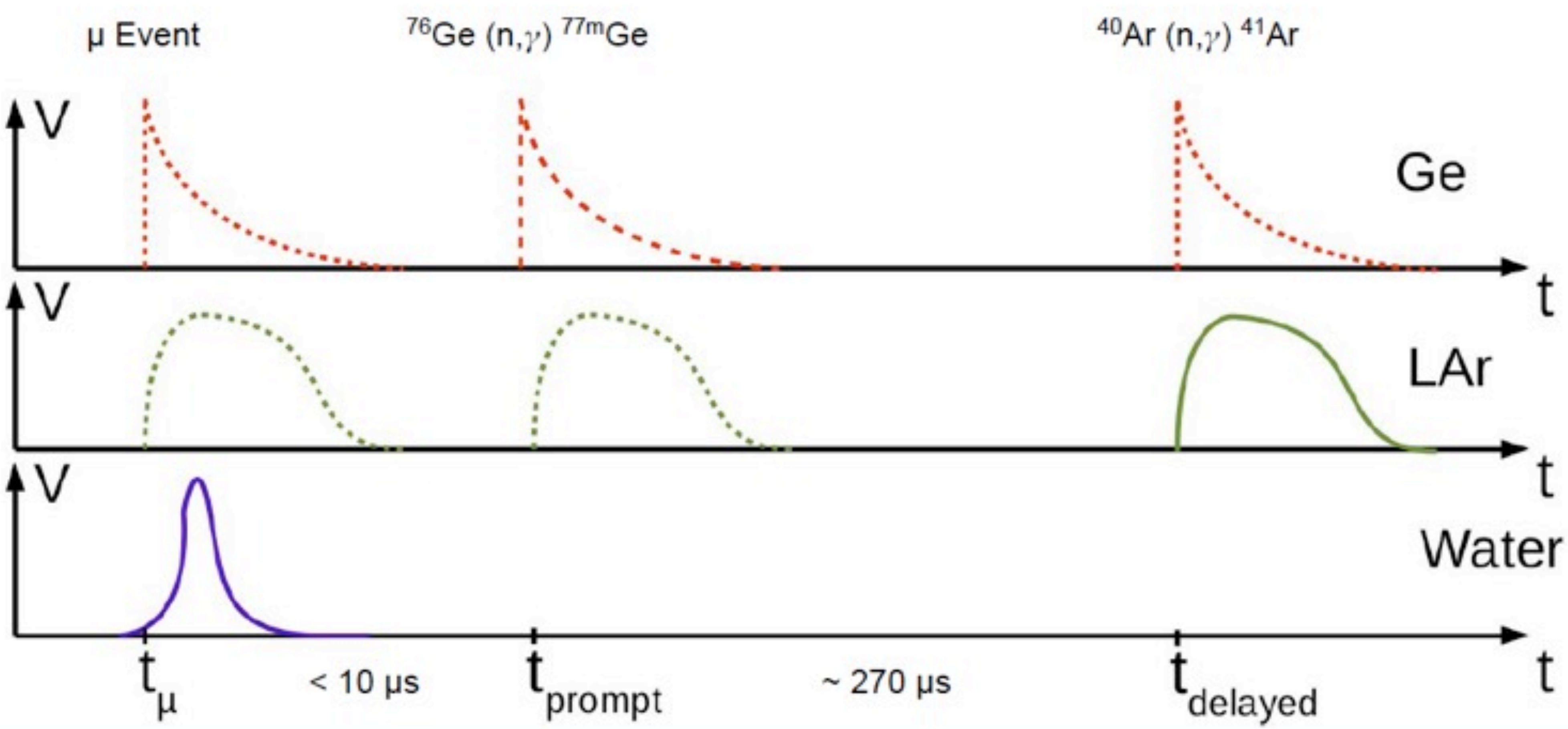
- Largest reductions are on ^{42}K, **α**, **μ**
- + “trimming” here and there on radio-purity of materials, esp. cables

UGAr to reduce ^{42}Ar/^{42}K

- ^{42}K from β decay of ^{42}Ar resulting from cosmogenic activation in various processes [e.g. PRD 100, 072009 (2019)]
    - low fraction in atmospheric Ar, but high enough activity
- Underground Ar significantly less subject to CR activation → highly depleted in such isotopes (down by factors ~10^4)
- Proposed to use part of the production from the ARIA plant, estimated need 21 tons (from 2023): use only in payload cryostats, AAr in outer volume
- Ion collection depends on n^+ dead-layer thickness: to be optimized
- Use of nylon cylinders around strings for further screening under discussion
    - shields, but only partially; self-vetoes, but only partially
    - could be good enough (after PSD and LAr veto), several studies done and on-going for GERDA and L-1000 [e.g. EPJC 75, 506 (2015)]
    - Else PEN? Encapsulated detectors (no LAr)? Xe-doped LAr for charge-exchanges?

Cosmic muons

- While "prompt" events in time with muon passage can be effectively rejected (95 to 99%) by water or LAr veto, delayed effects can generate disturbance
- Particularly production of Ge isotopes from capture of spallated neutrons (^{77,m}Ge)
- At SNO depth w/o further shielding expect ~5 10^{-8} cts/kev/kg/yr (1% of desired BI)
  - at LNGS x100, but gain "virtual" depth operating the LAr active veto with an independent trigger for delayed detection of n capture on ^{40}Ar (factor of ×10 reduction in **μ**-induced ^{77,m}Ge decays?) [Eur.Phys.J. C78 (2018) no.7, 597]
  - developments (using also ML) will be tested at L-200



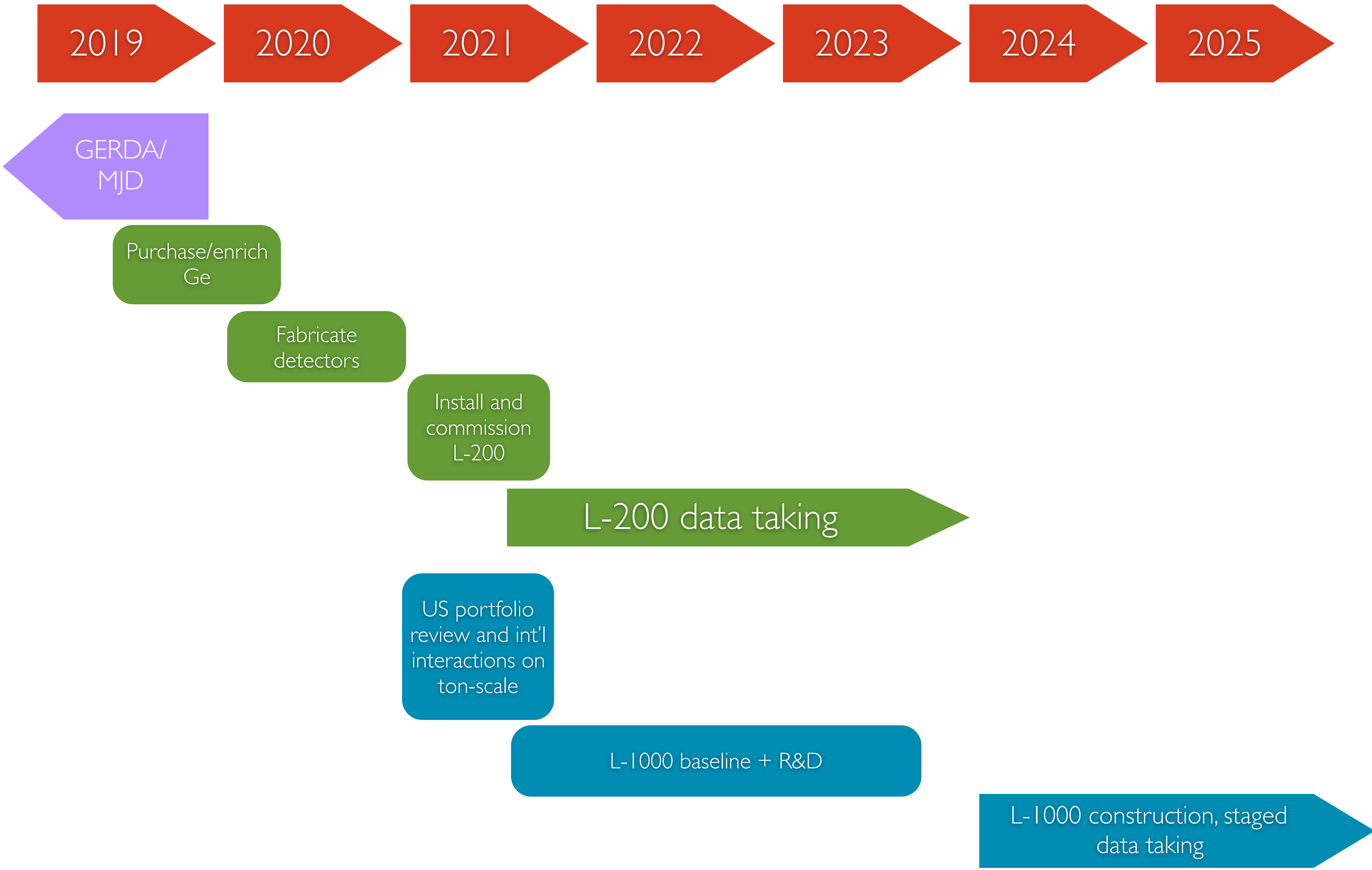
Alpha

- Those α depositing on diode surface making it through the p^+ electrode or the this-surfaced insulating grooves
  - most of the surface is a too-thick n^+
- Hard to estimate a priori (consider upper limits from previous experiments)
- PSD, PSD and yet improved PSD
  - complementary techniques in GERDA and MJD more or less effective depending on charge diffusion in detector geometry (BEGe vs PPC)
  - therefore, design the LEGEND-1000 ICPC detector electrode geometry based on the relative size of the detector's passivated surface

Selection of additional R&D

- Larger mass detectors: different configurations with similar weighting potential being still pursued as alternatives to baseline, but need time
- Material:
  - clean manufacturing of alloys and plastics by laser-excitation additive "3-D printing" (SLA)
  - In-house synthesis of more radio-pure PEN
- FE: Reduced front-end substrate and connector mass, related to new ASIC radio-pure boards (JINST15 P09022)
- All signal cables in re-entrant tube from clean Kapton (incl Diode HV)
- Active veto: variants include Xe-doped LAr, walls of SiPM instead of "dirtier" fibres

(Approx) timeline



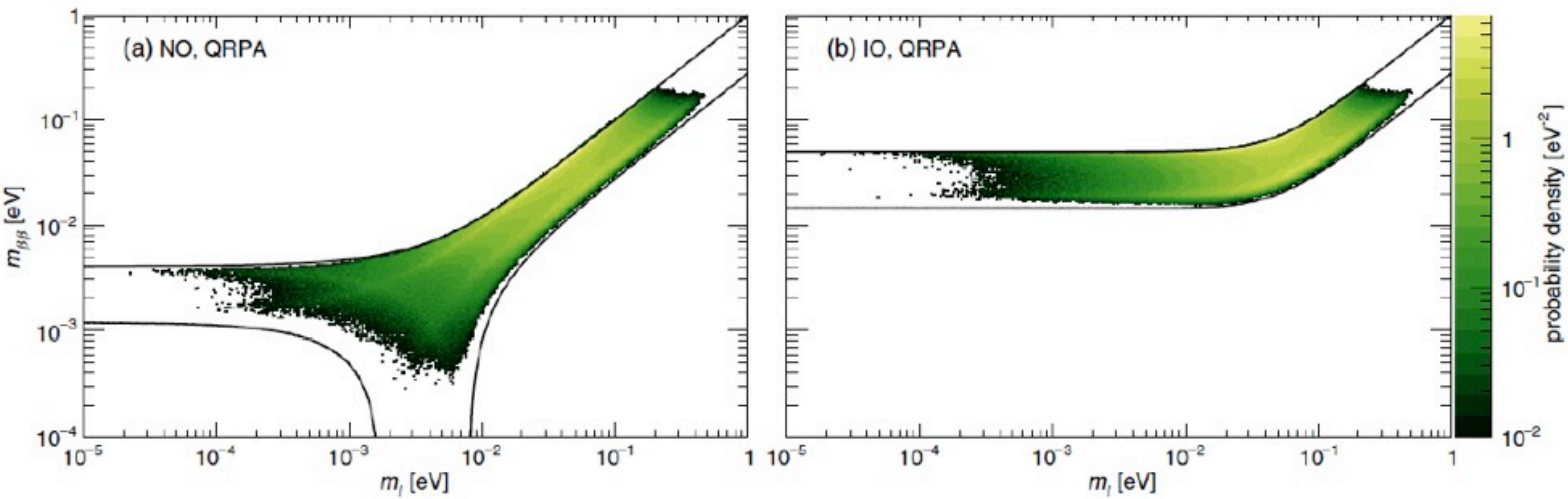
Back-up

MO separation

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

$$= \left|m_0 c_{12}^2 c_{13}^2 + \sqrt{m_0^2 + \delta m_{\rm sol}^2}\, s_{12}^2 c_{13}^2 e^{2i(\alpha_2-\alpha_1)} + \sqrt{m_0^2 + \delta m_{\rm sol}^2 + \delta m_{\rm atm}^2}\, s_{13}^2 e^{-2i(\delta_{\rm CP}+\alpha_1)}\right| \quad \text{NO}$$

$$= \left|m_0 s_{13}^2 + \sqrt{m_0^2 - \delta m_{\rm atm}^2}\, s_{12}^2 c_{13}^2 e^{2i(\delta_{\rm CP}+\alpha_2)} + \sqrt{m_0^2 - \delta m_{\rm sol}^2 - \delta m_{\rm atm}^2}\, c_{12}^2 c_{13}^2 e^{2i(\delta_{CP}+\alpha_1)}\right| \quad \text{IO.}$$



Phys. Rev. D 96, 053001

Active veto optical parameters

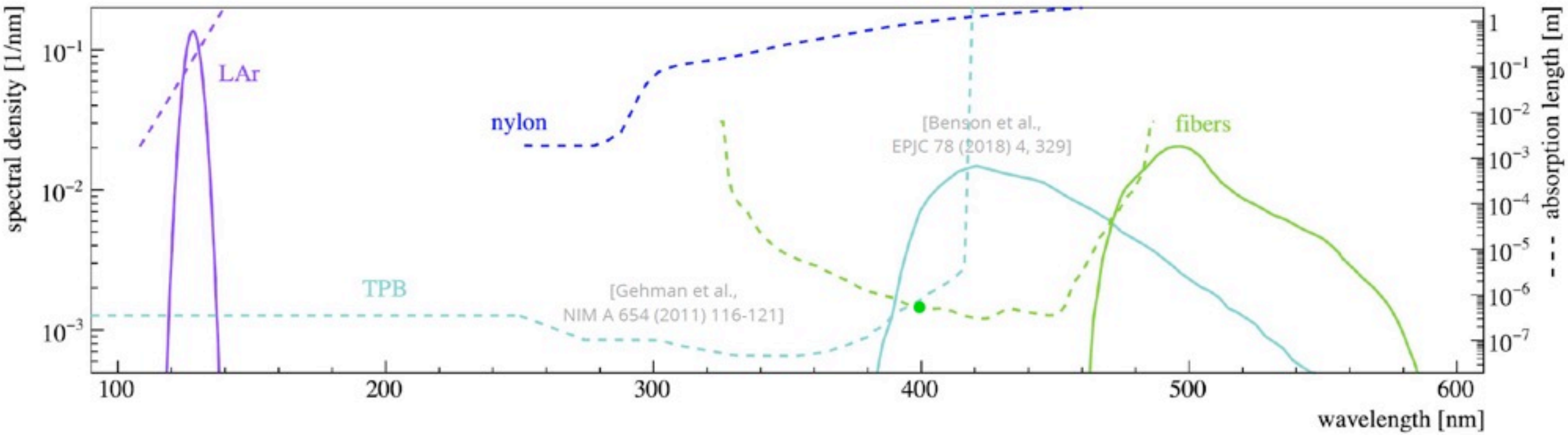


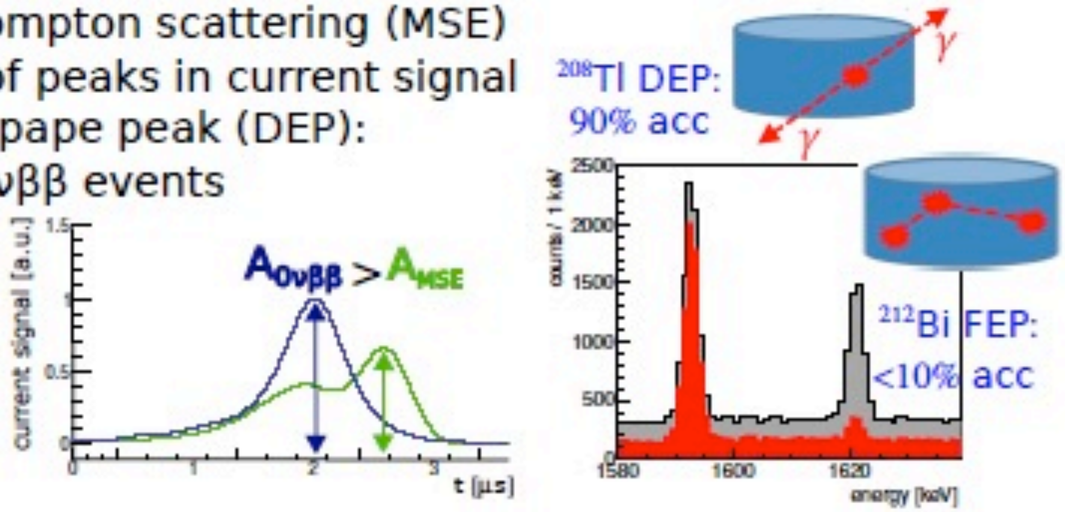
TABLE XV. The relevant properties of PEN.

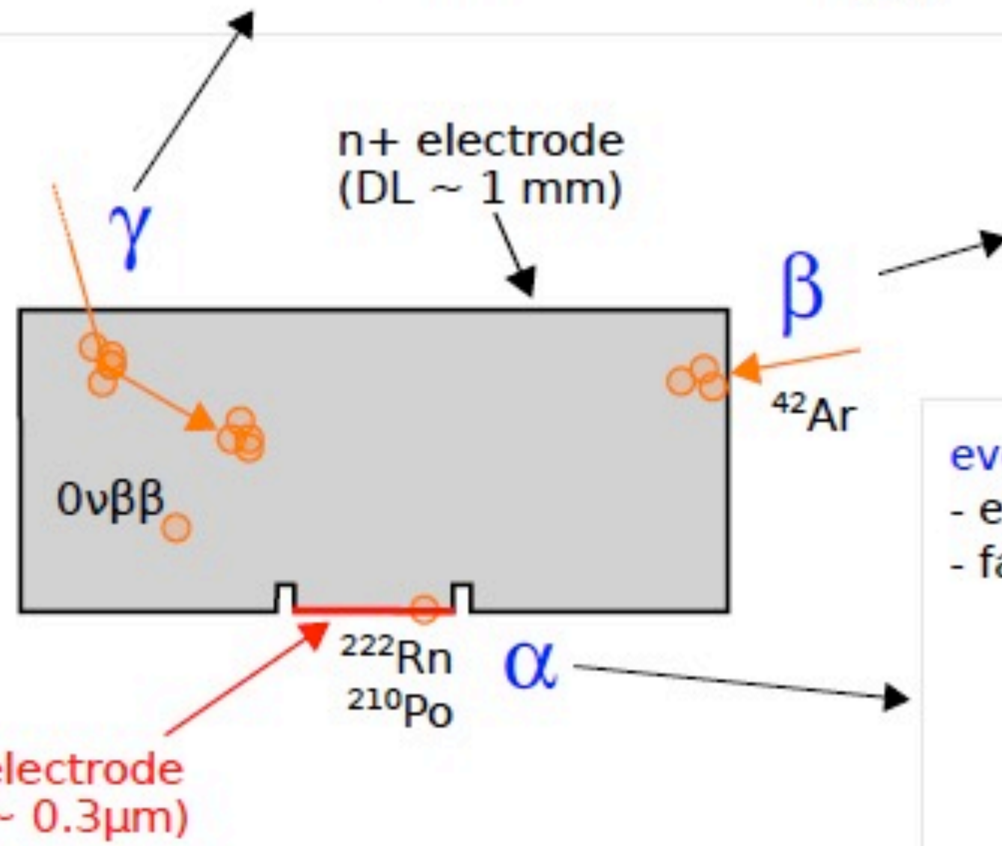
Property	Value	
Atomic composition	$[C_{14}H_{10}O_4]_n$	
Density: δ	$1.35\,g/cm^3$	
Melting point	$270°C$	
Peak emission λ	$445\pm5\,nm$	
Light yield	≈ 4000 photons/MeV	
Decay constant	34.91 ns	
Attenuation length	$\approx 5\,cm$	
Young's modulus: E [GPa]	1.855 ± 0.011 (296 K)	3.708 ± 0.084 (77 K)
Yield strength: σ_{el} [MPa]	108.6 ± 2.6 (296 K)	209.4 ± 2.8 (77 K)

Phase II upgrade: BEGe detectors

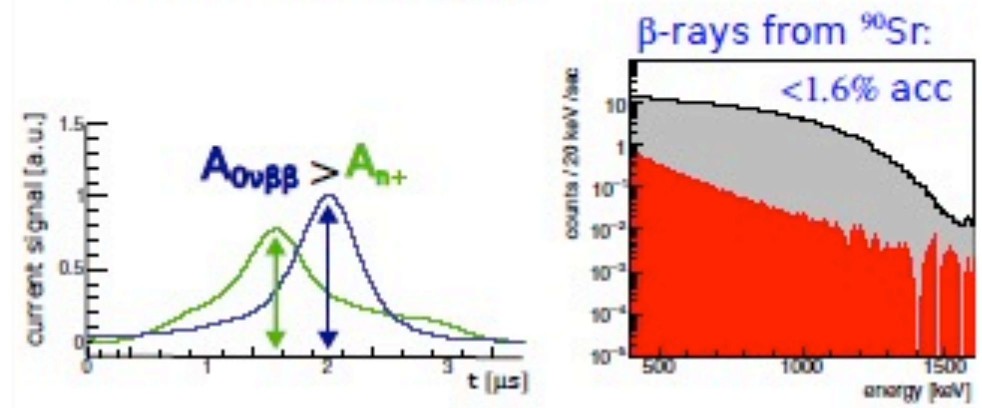
Broad Energy Germanium

γ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for 0νββ events

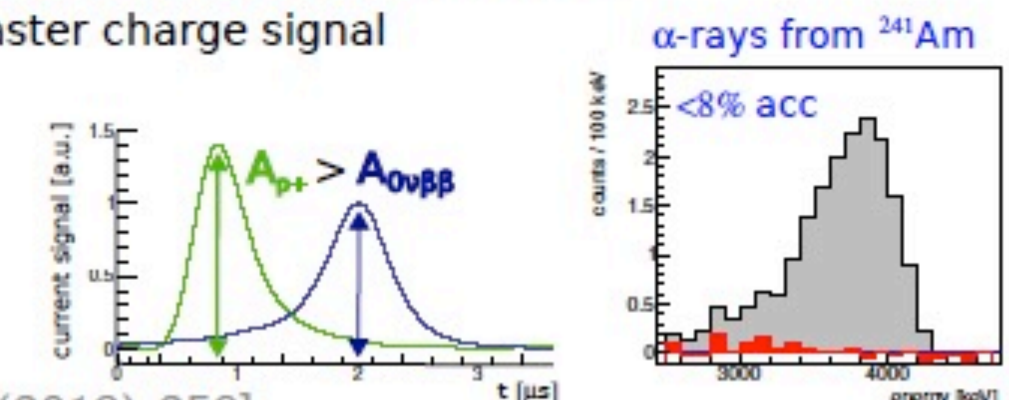




events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal



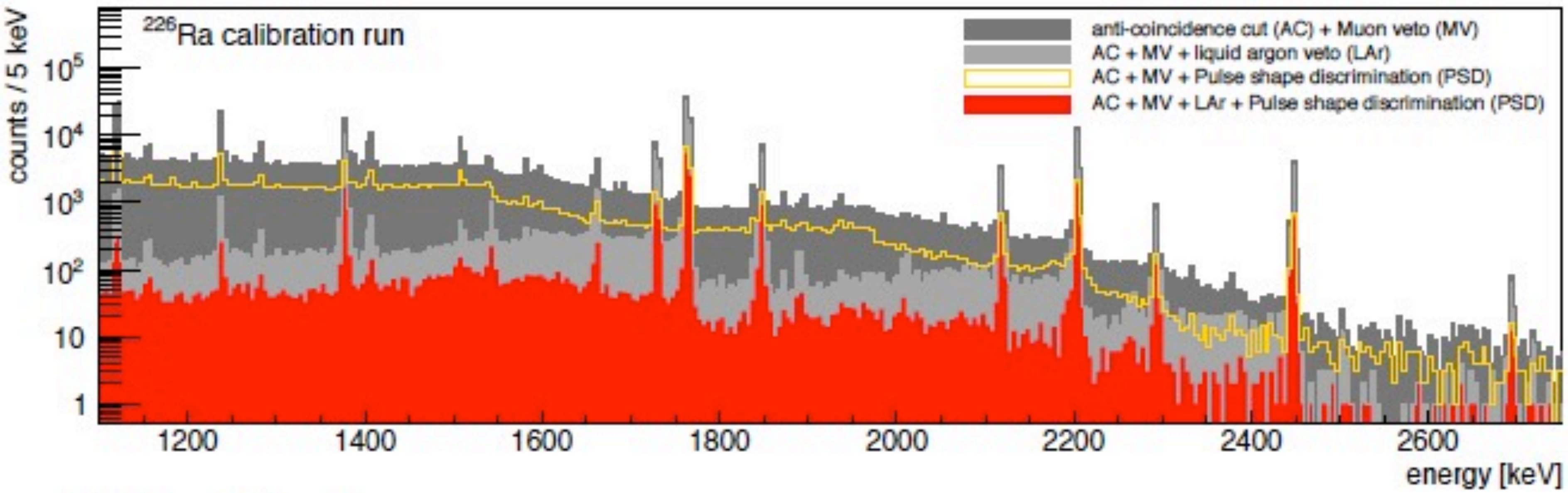
events on p+ electrode:
- electron drift faster then holes
- faster charge signal



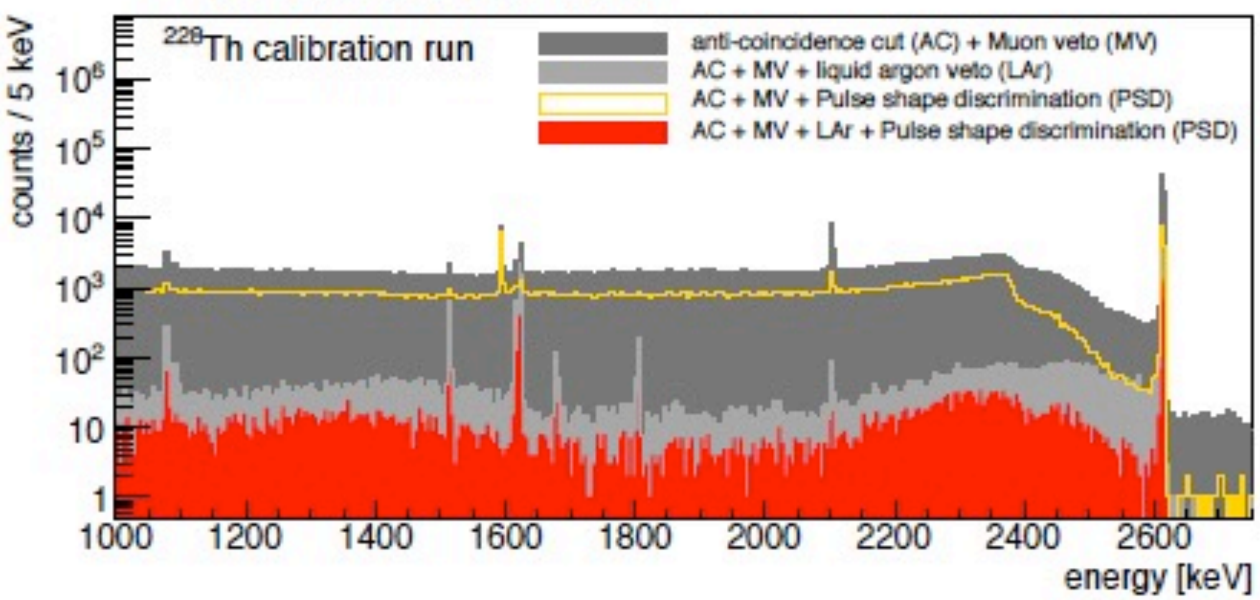
[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

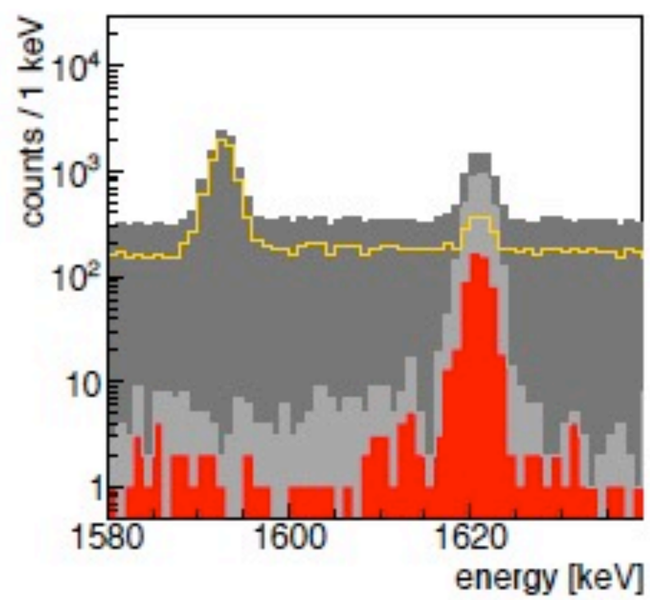
PSD and LAr veto during Phase II commissioning

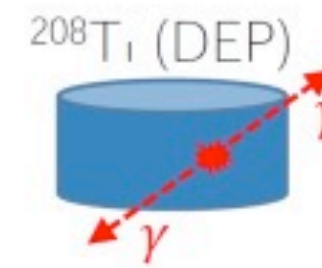
^{226}Ra calibration run (single BEGe string in GERDA):



^{228}Th calibration run:





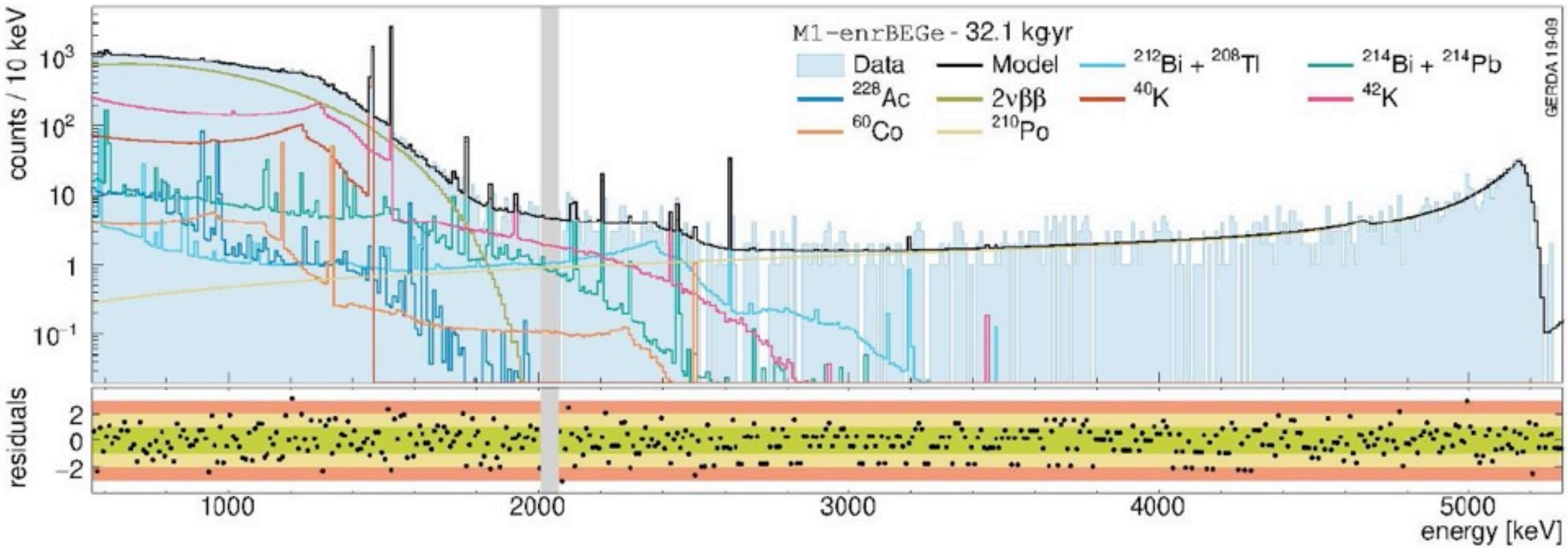


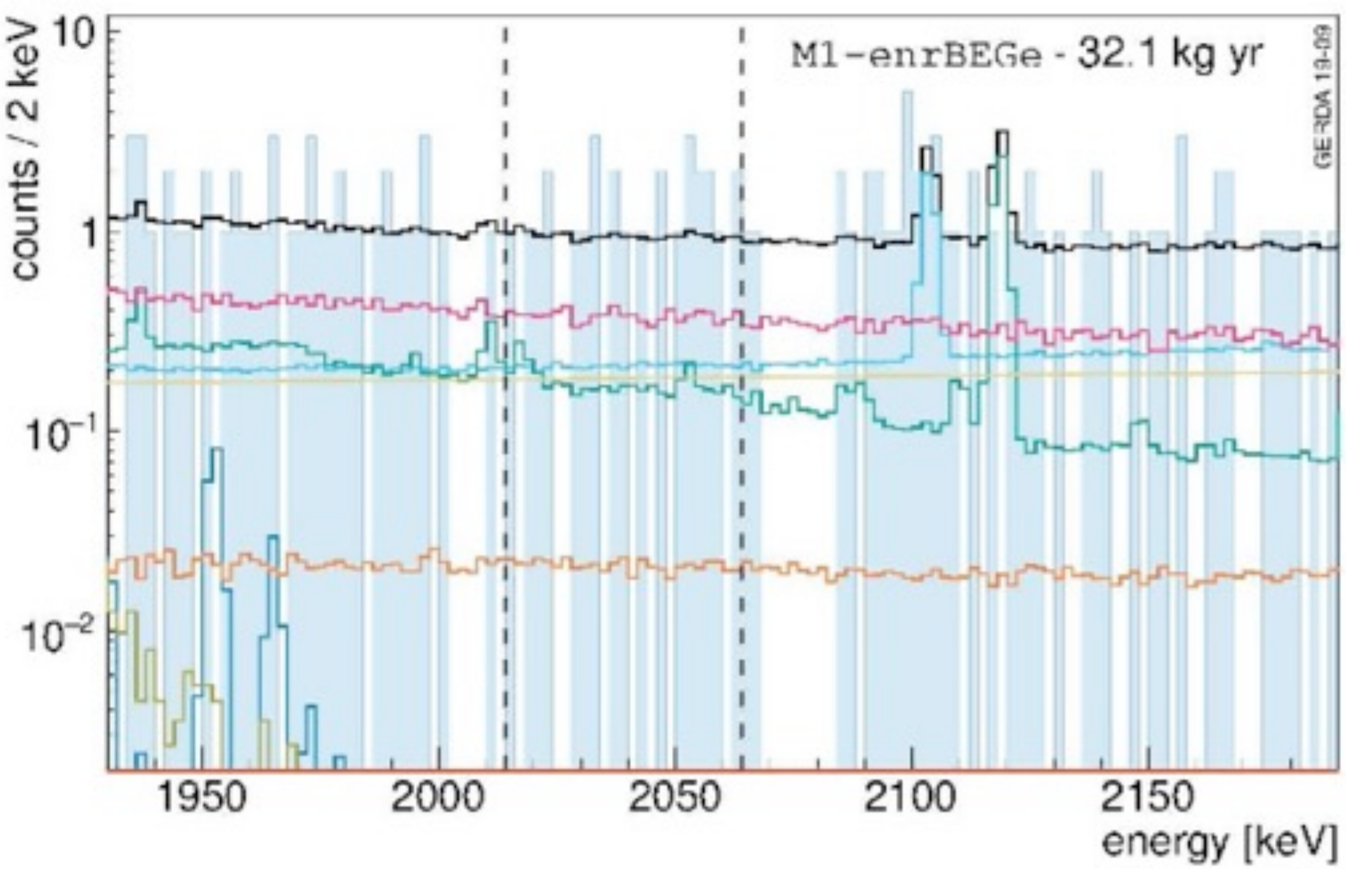
Combined suppression factors: 27±2 (for ^{226}Ra) and 300±28 (for ^{228}Th)

Suppression depends on isotope, location and detector configuration

main components before LAr veto/PSD:
- α from ^{210}Po, ^{226}Ra
- β from ^{42}K
- γ from ^{214}Bi, ^{208}Tl

Gerda





JHEP 2020, 139 (2020)

- same isotopes as in Phase I
- Th/Ra contributions consistent with screening results
- main components before LAr veto/PSD:
  - α from ^{210}Po,^{226}Ra
  - β from ^{42}K
  - γ from ^{214}Bi,^{208}Tl
- flat background in the ROI

https://arxiv.org/pdf/1205.5608.pdf

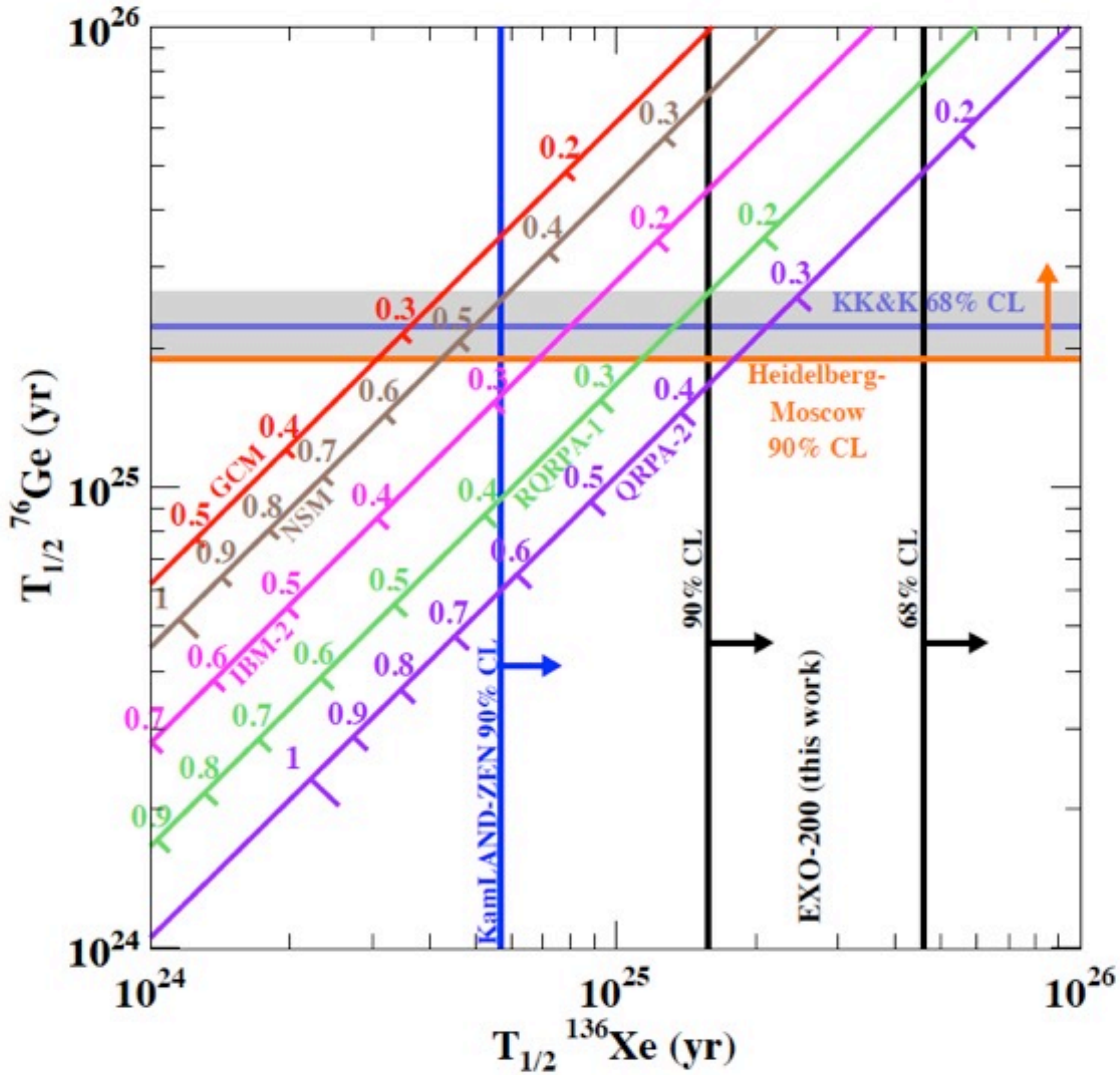


FIG. 6: Relation between the $T_{1/2}^{0\nu\beta\beta}$ in ^{76}Ge and ^{136}Xe for different matrix element calculations (GCM [20], NSM [21], IBM-2 [22], RQRPA-1 [23] and QRPA-2 [5]). For each matrix element $\langle m \rangle_{\beta\beta}$ is also shown (eV). The claim [4] is represented by the grey band, along with the best limit for ^{76}Ge [19]. The result reported here is shown along with that from [7].

Phase II final array configuration

- Deployed in Dec 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

⇒ 35.8 kg of enr detectors