The quest for LFV through 0ν2β decays in Germanium:

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

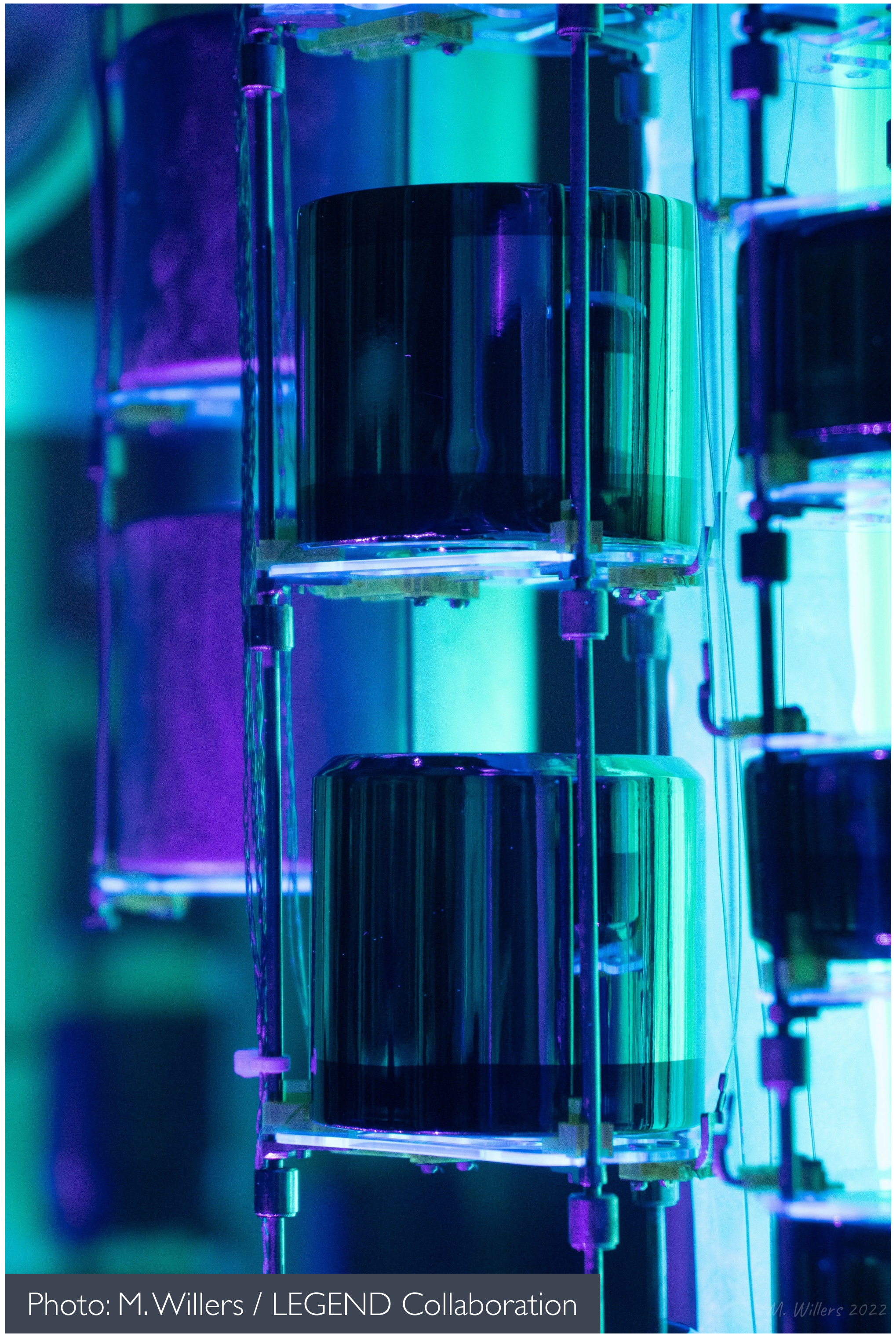


Photo: M. Willers / LEGEND Collaboration

G. Salamanna (Roma Tre University & INFN)

Le Rencontres, La Thuile, March 2023

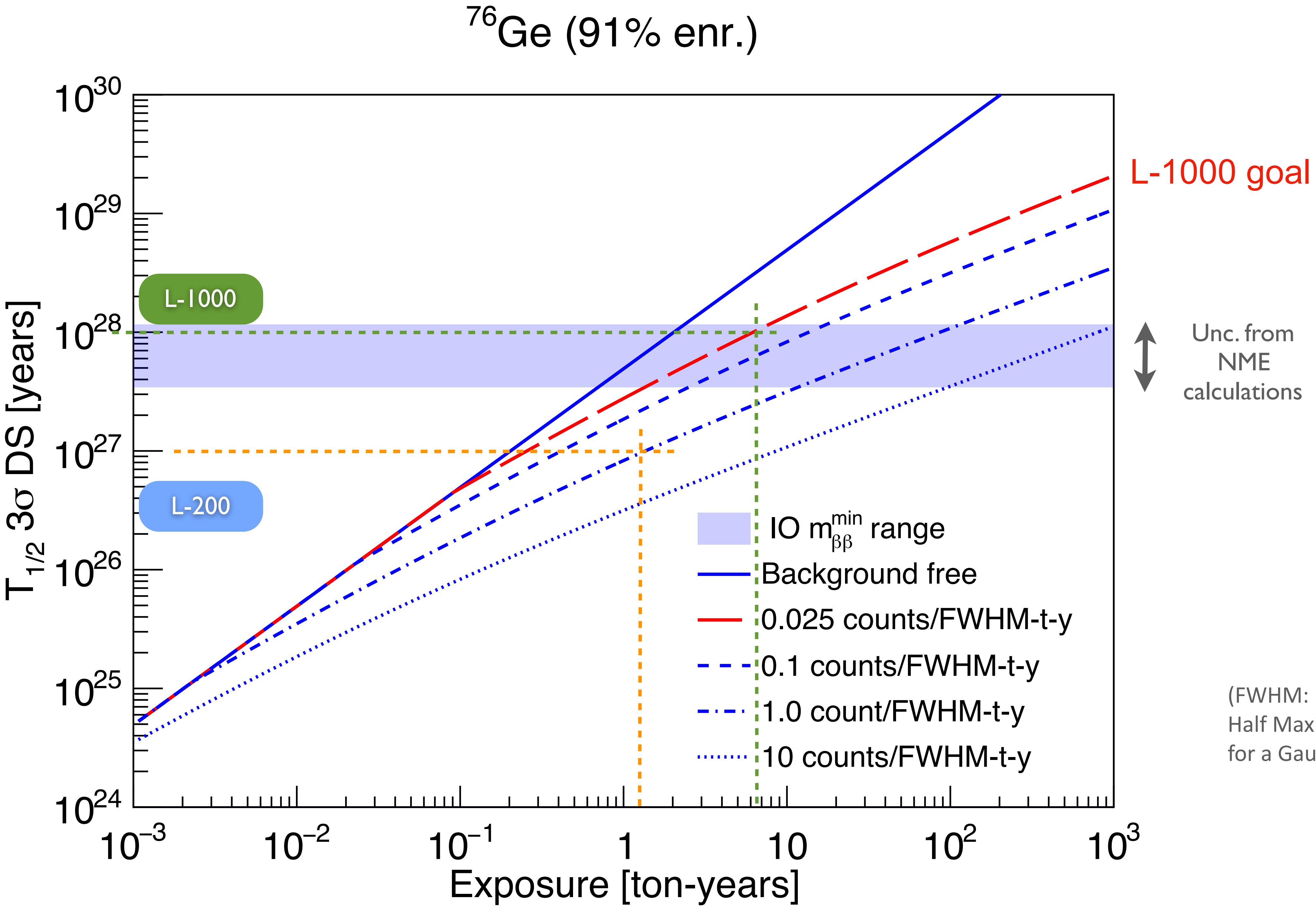
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

- Stems from previous achievements with Germanium and puts together their best in terms of technology and know-how
- Two-staged approach with a "stepping stone" of ~200 kg (**Legend-200**) towards the full-fledged experiment with one-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

Collaboration Meeting, GSSI Oct 2022

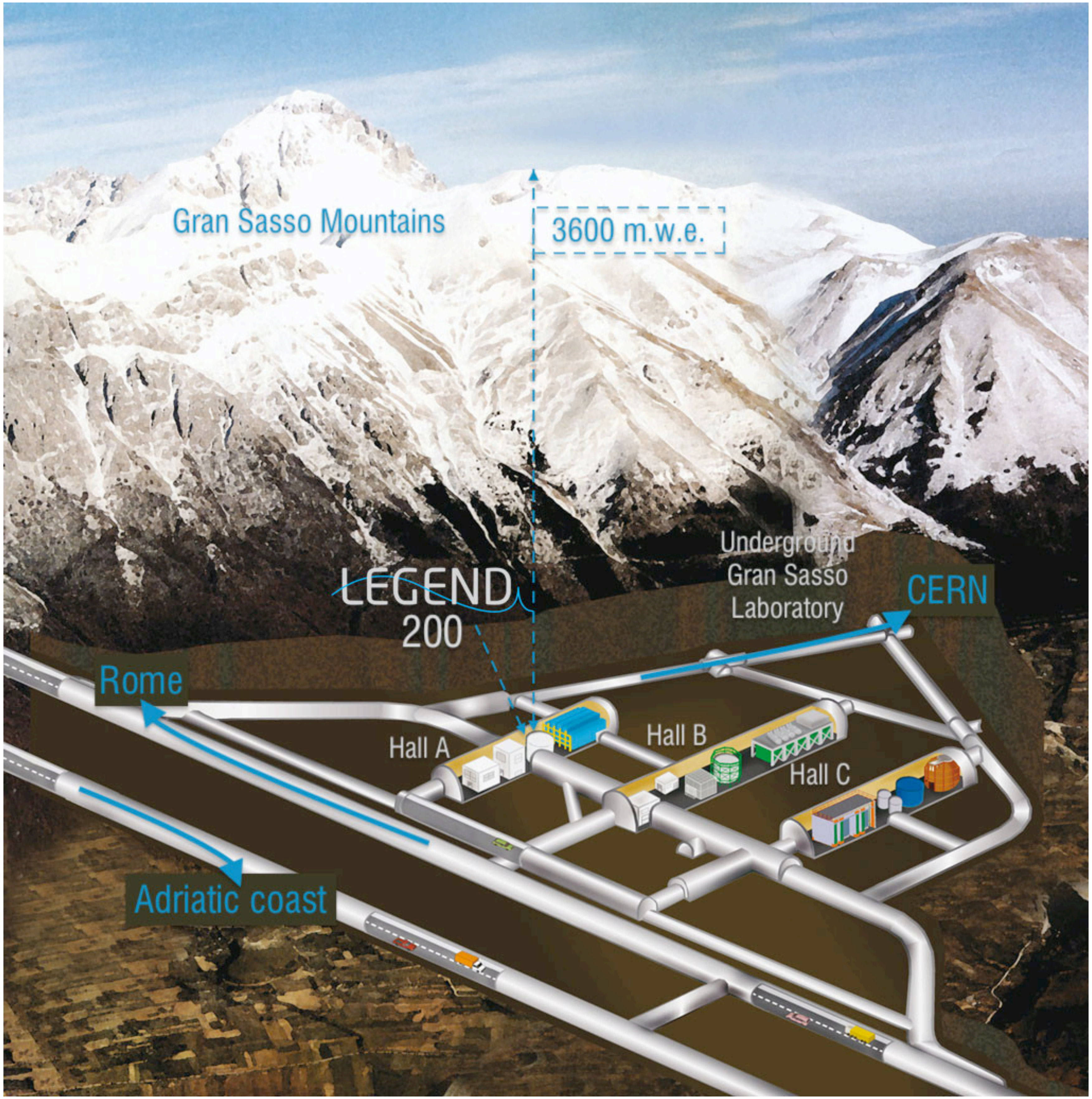
How far can we go?



(FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)

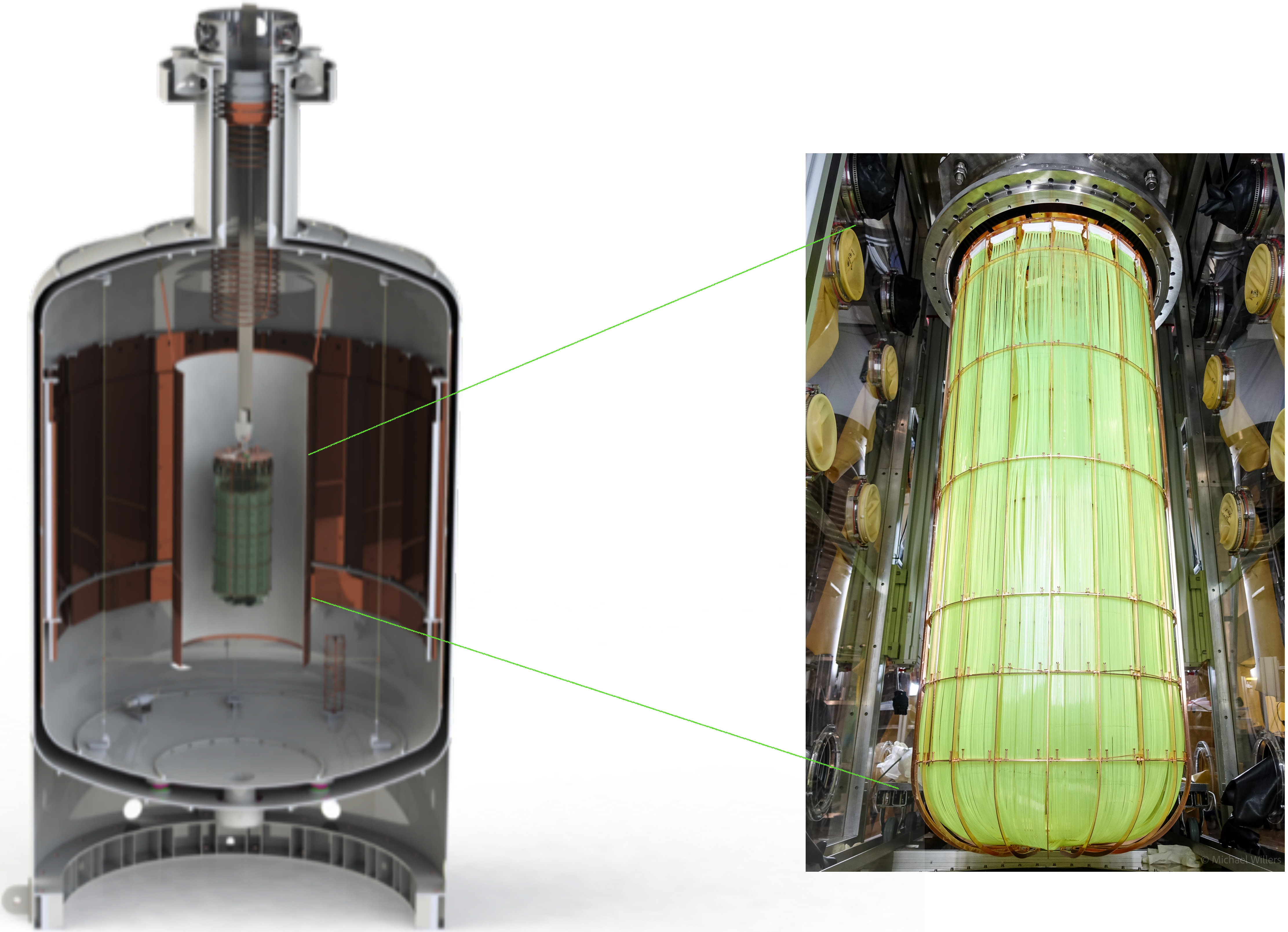
- Value of $T_{1/2}$ for which a ^{76}Ge-enriched experiment has a **50%** chance to observe a signal above background with **3σ** significance
- *Less than one background count* expected in a 4σ Region of Interest (ROI) with 10 t y exposure

LEGEND-200 site: LNGS



- L-200 uses GERDA infrastructure at LNGS
- Ge detectors "dipped" in LAr in pre-existing cryostat
- Mountain provides screening against cosmic rays

- Expected external bkg sources:
  - 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 detector** against external radiation
- ultrapure water tank: buffer around cryostat as additional **absorber** + Cherenkov veto

A heart of (High Purity) Germanium

General concept

- p-type diodes with point-contact
- Charge collection at p⁺ electrode (Boron-implanted),

polarization potential applied to n⁺ electrode (diffused Li)

ICPC

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

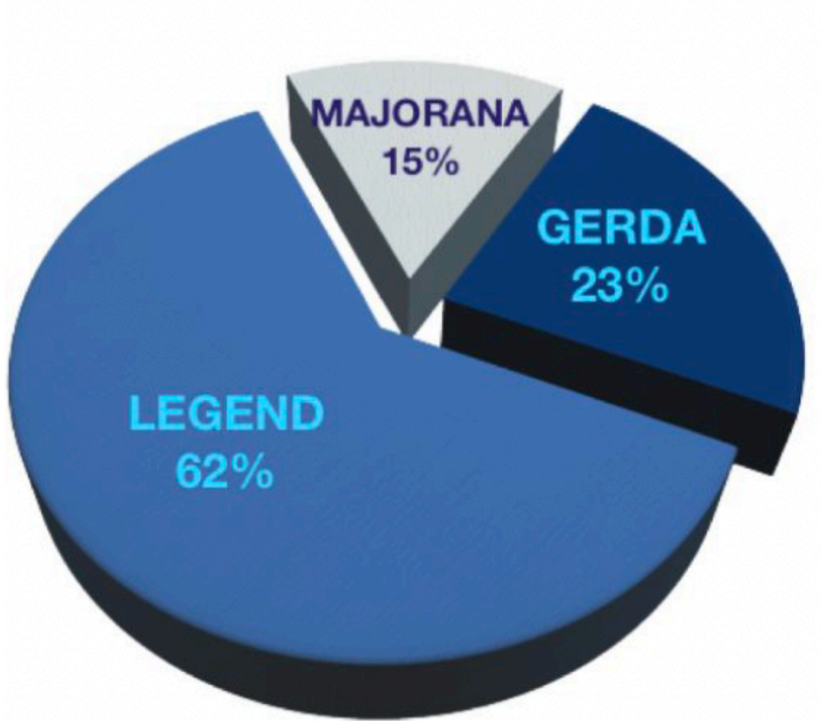
- ~60% of L-200 detectors are of this type
- Larger mass (1.5-2.0 kg, up to <2.5> kg for L-1000)
- but retaining **similar charge drift times across volume**

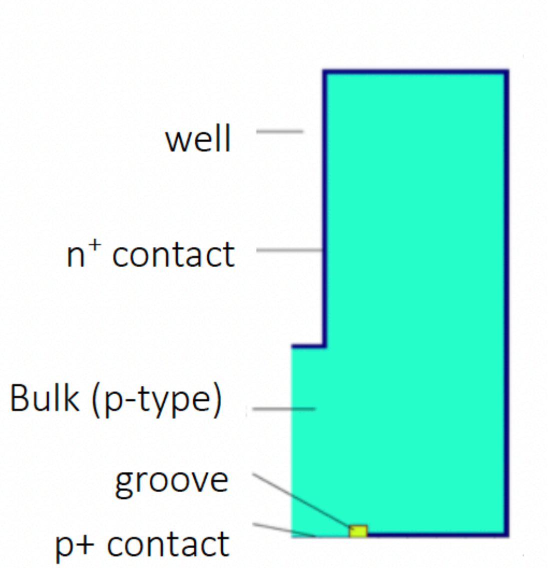
(important for Pulse Shape Discrimination, see later)

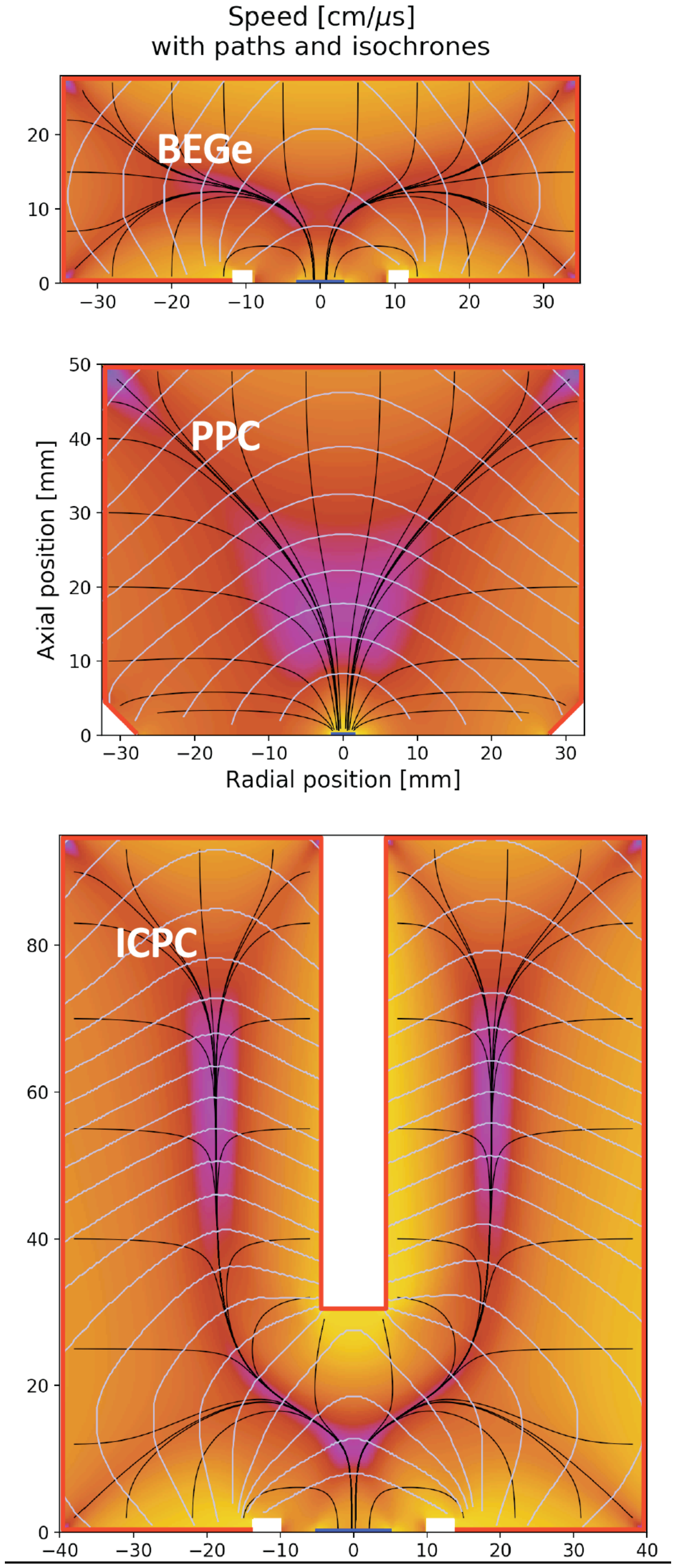
- Reduced surface-to-volume ratio (α and β): less dirty

cables, pre-amps

- Lower cost per kg, higher efficiency

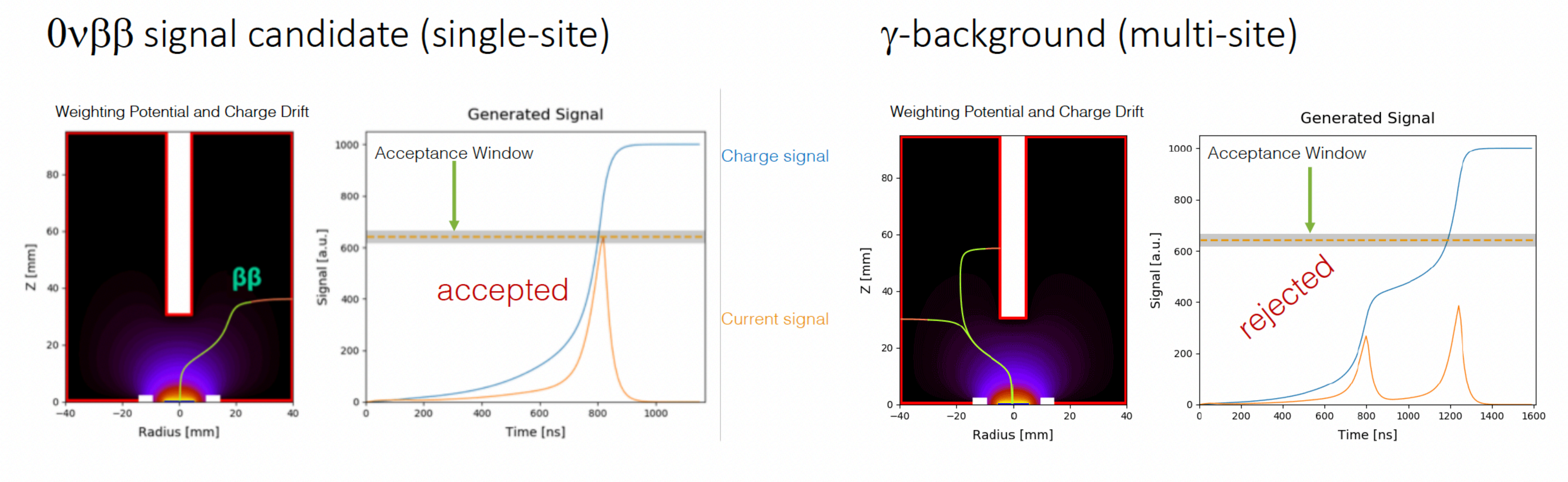






Origin of radioactive bkgs

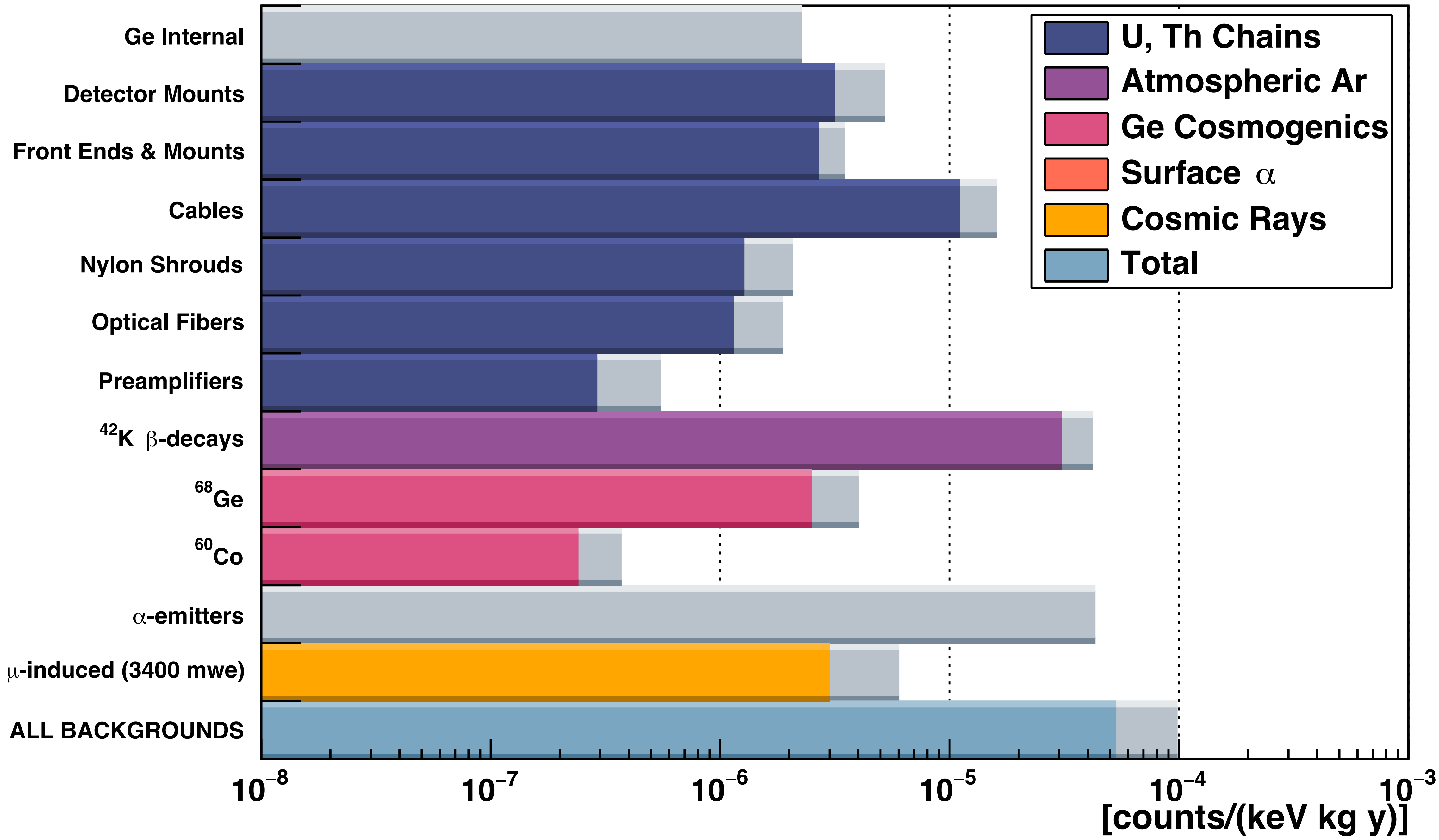
- α mainly from ^{210}Po (τ=138 days) coming from ^{238}U chain on diode surface and attracted to migrate towards p^+ electrode by its strong field
- γ comes from
  - various branches of U and Th chain on materials (FETs, cables, Cu mounts, plastics);
  - and from $^{40/42}$Ar → $^{40/42}$K → $^{40/42}$Ca* 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



0νββ signal candidate (single-site)

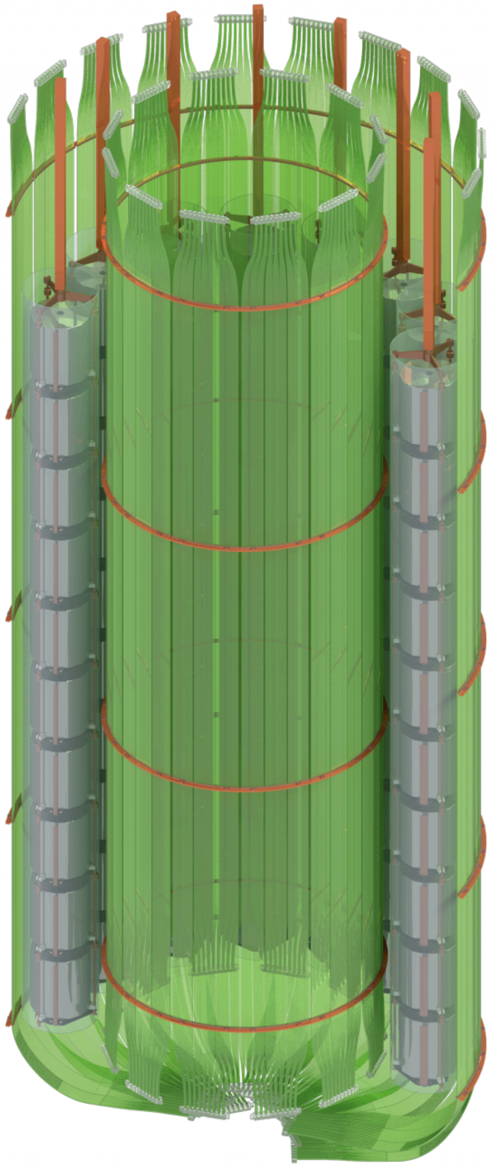
γ-background (multi-site)

Expected bkg budget L-200

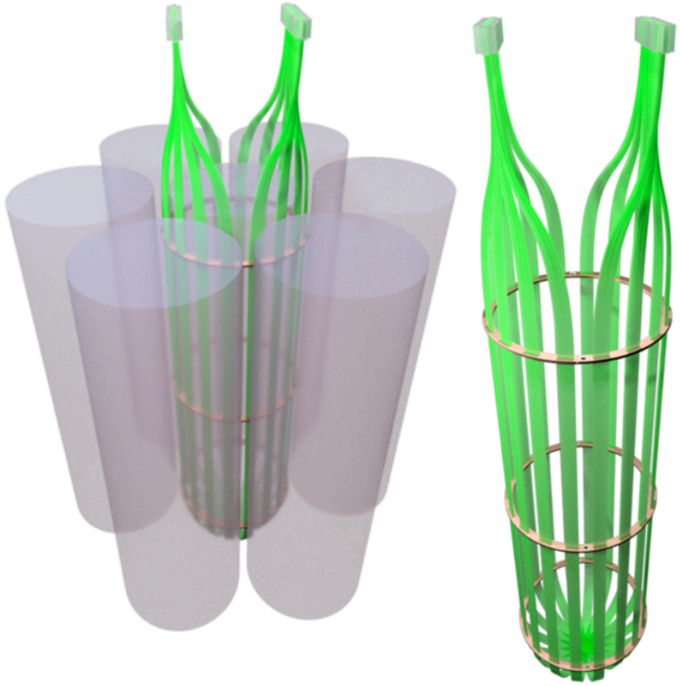


~ 2-3 times lower BI than GERDA

LAr active detector

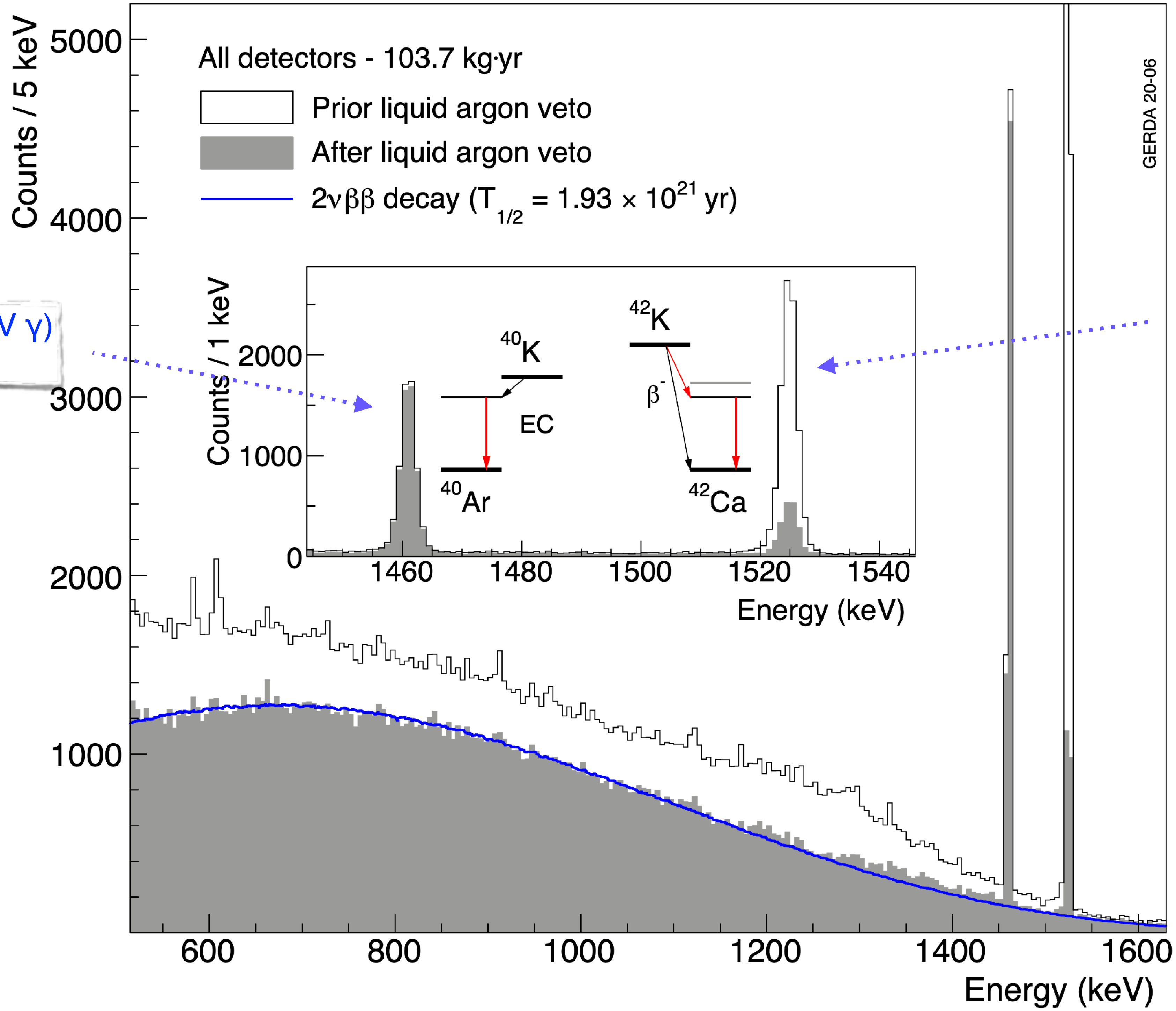


- Retain a crucial element of **GERDA**: instrument LAr volume to read out light from scintillation
    - 2 shrouds of optical fibers for enhanced coverage coated in TBP as WLS + SiPM with new FE electronics
    - Reflective foil around outer shroud to increase light collection
- Veto radiogenic backgrounds but can also measure energies and identify processes (*see later*)
- Self-vetoeing from:
    - radioactivity from fibers
    - high-activity β decays of sub-dominant isotope ^{39}Ar *[1.41 Bq/l (e.g. NIM A 574 83)]*



Benefit of active veto (lesson from **GERDA**)

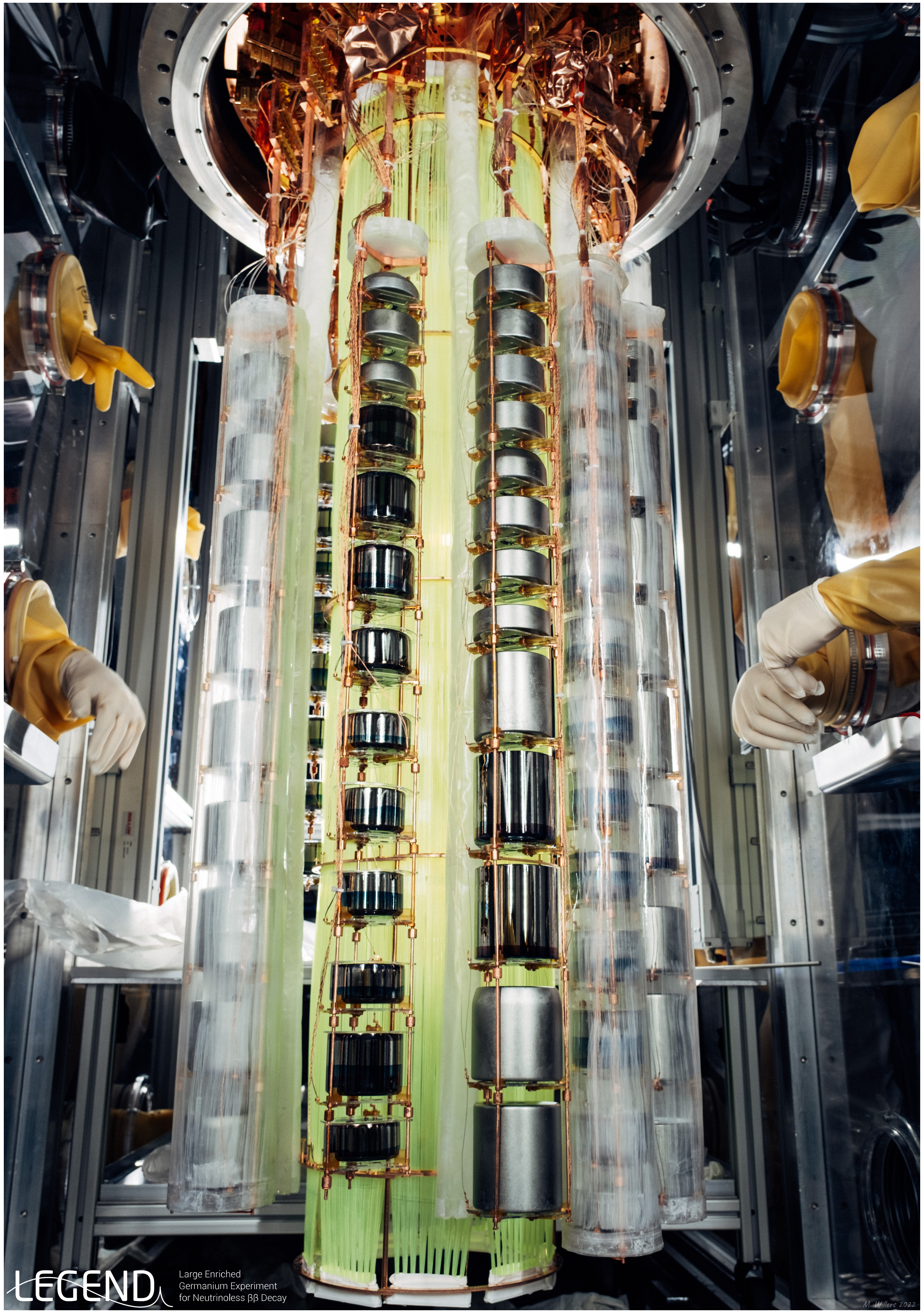
^{40}K(EC, 1460 keV γ)
no energy in LAr



^{42}K($β^-$)
$β^-$ energy in LAr suppresses ^{42}Ca γ line (E=1524 keV) by factor ~5

Eur. Phys. J. C (2018) **78**: 388

- 0ν2β decay signal efficiency: ε_{LAr} = (98.2 ± 0.1)% after upgrade
- Accidental coincidences give 1.8% dead time after upgrade
- **Factor 6 bkg reduction in the ROI** (1930 keV to 2190 keV) **on top of PSD**



Current status…

☑ **140 kg taking data since June**

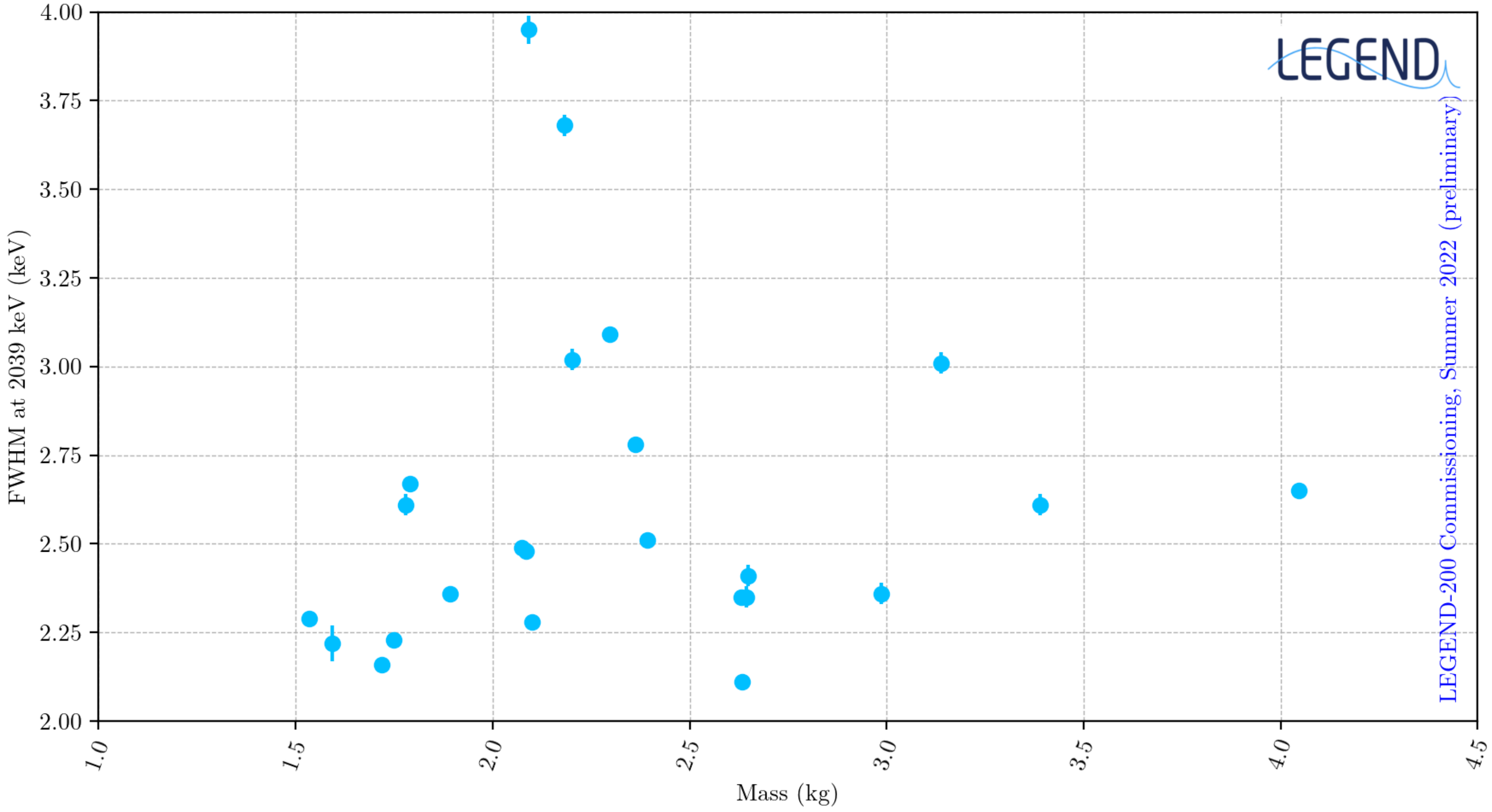
- Taking regular physics and calibration data with various trigger streams
- Reach 200 kg by the end of the year

- Goal (5 yr runtime):
  - Discovery sensitivity T1/2 > 1027 yr (99.7% C.L.)
  - m(ββ) < 33 – 71 meV

☑ **First 60 kg: taken data over summer**

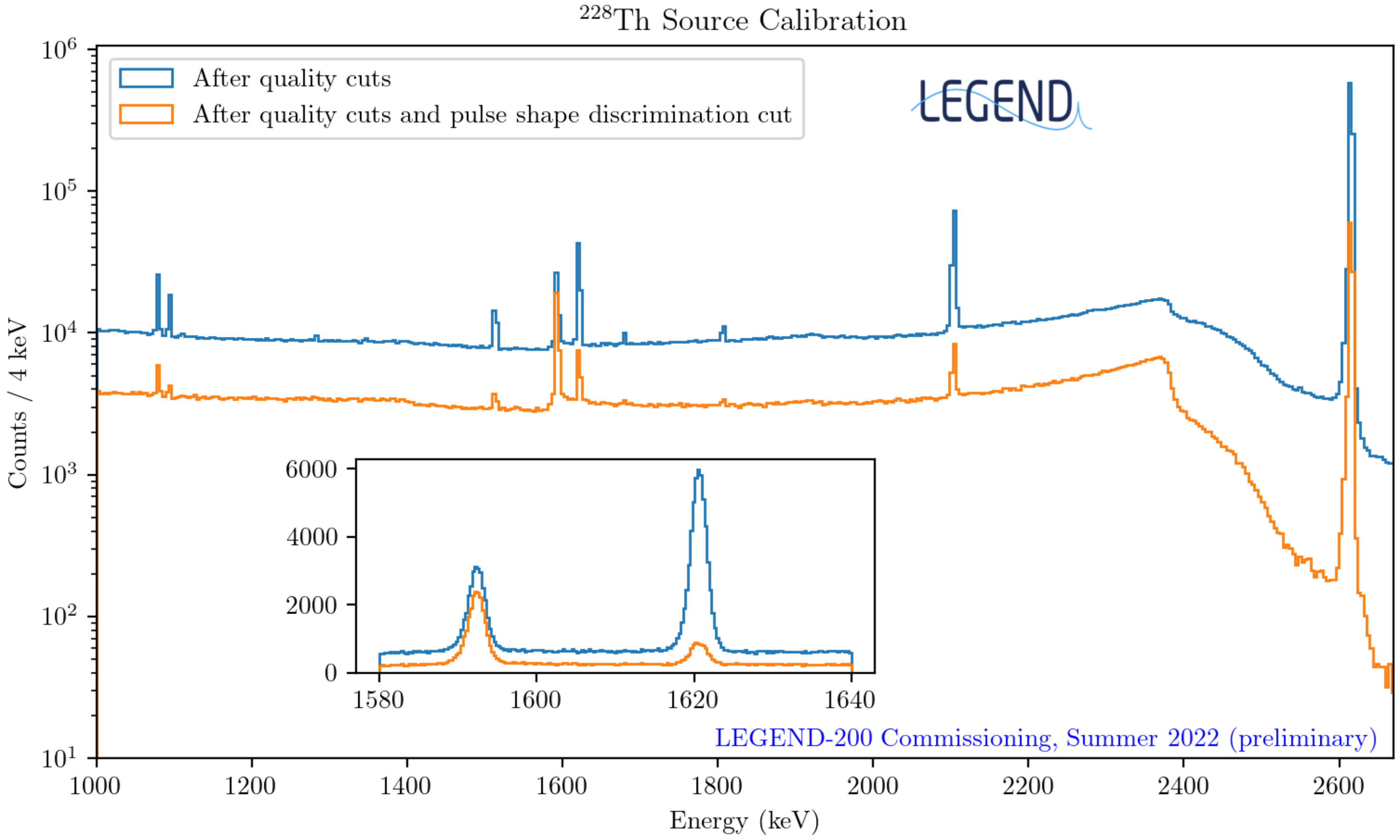
- commissioning and performance evaluation

Initial commissioning performance

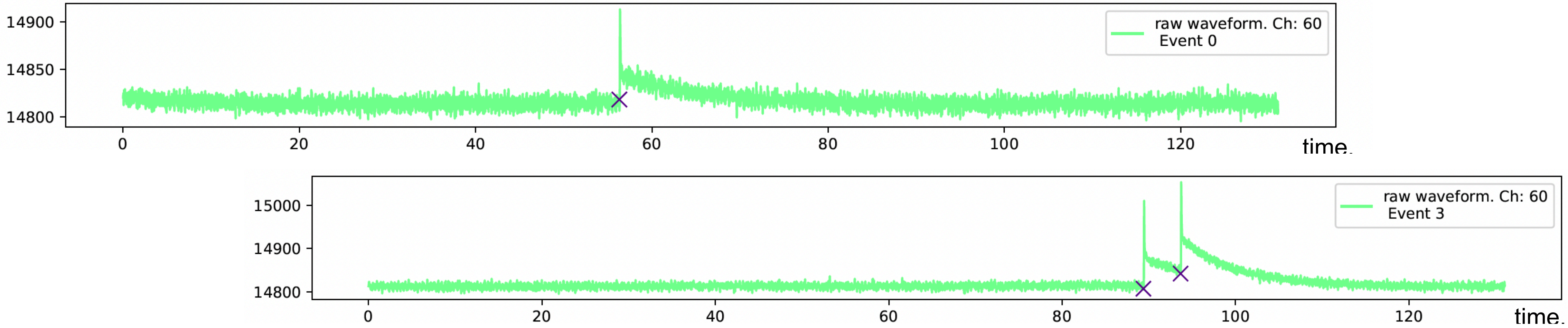


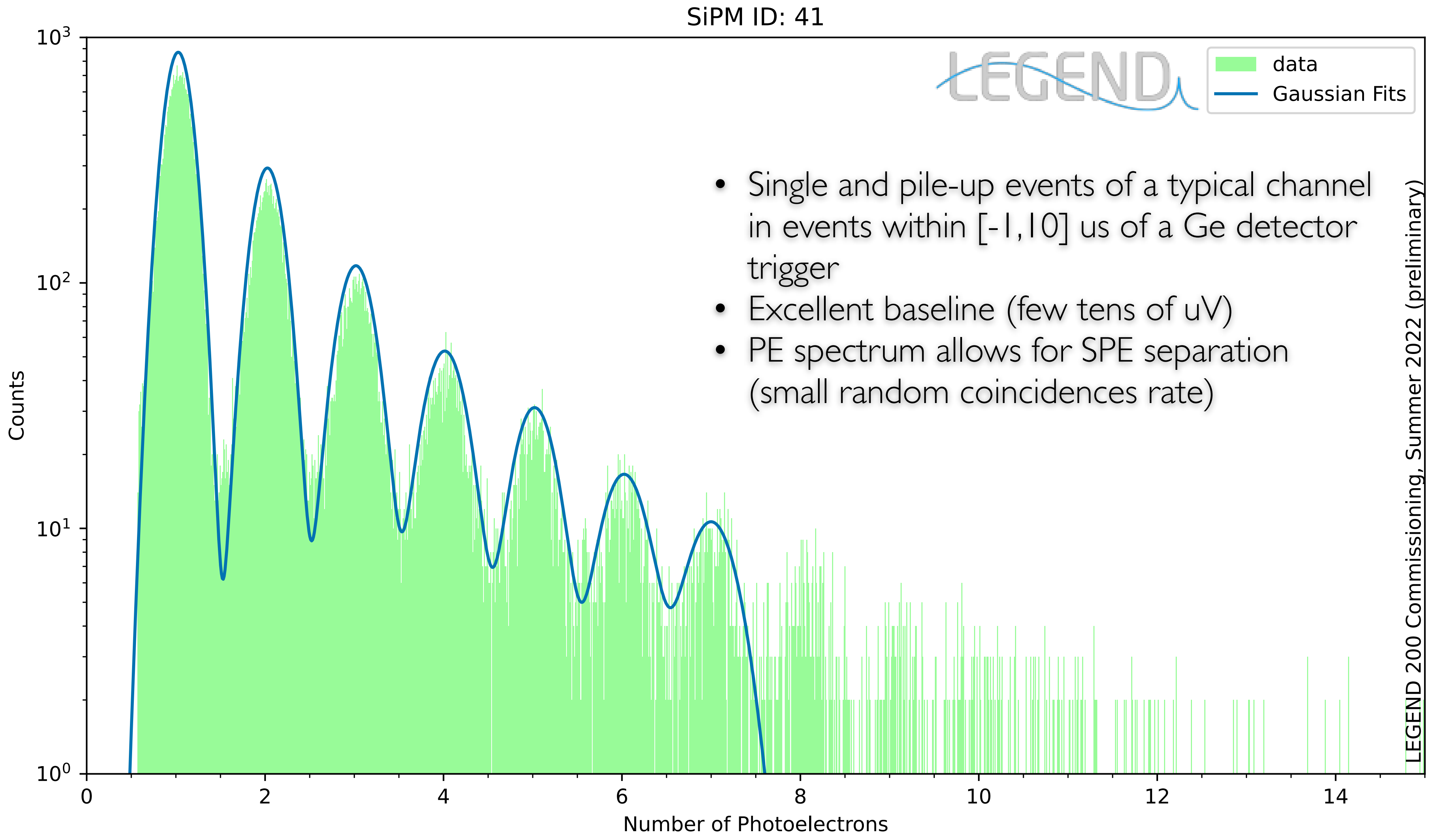
- Preliminary energy resolution from August commissioning runs of 60 kg in full set-up
- ***FWHM ~ 2.8 keV at Q(ββ)***
- Resolution does not depend on detector mass, heavier detectors also show excellent reso
  - Optimisation work being finalised on read-out/noise on some channels

- ^{228}Th sources ($T_{1/2}$=1.9 yr, A~5 kBq/source)
- Response checked at various energies about once a week
- Used for resolution and to extract benchmark performance of PSD on radiogenic backgrounds



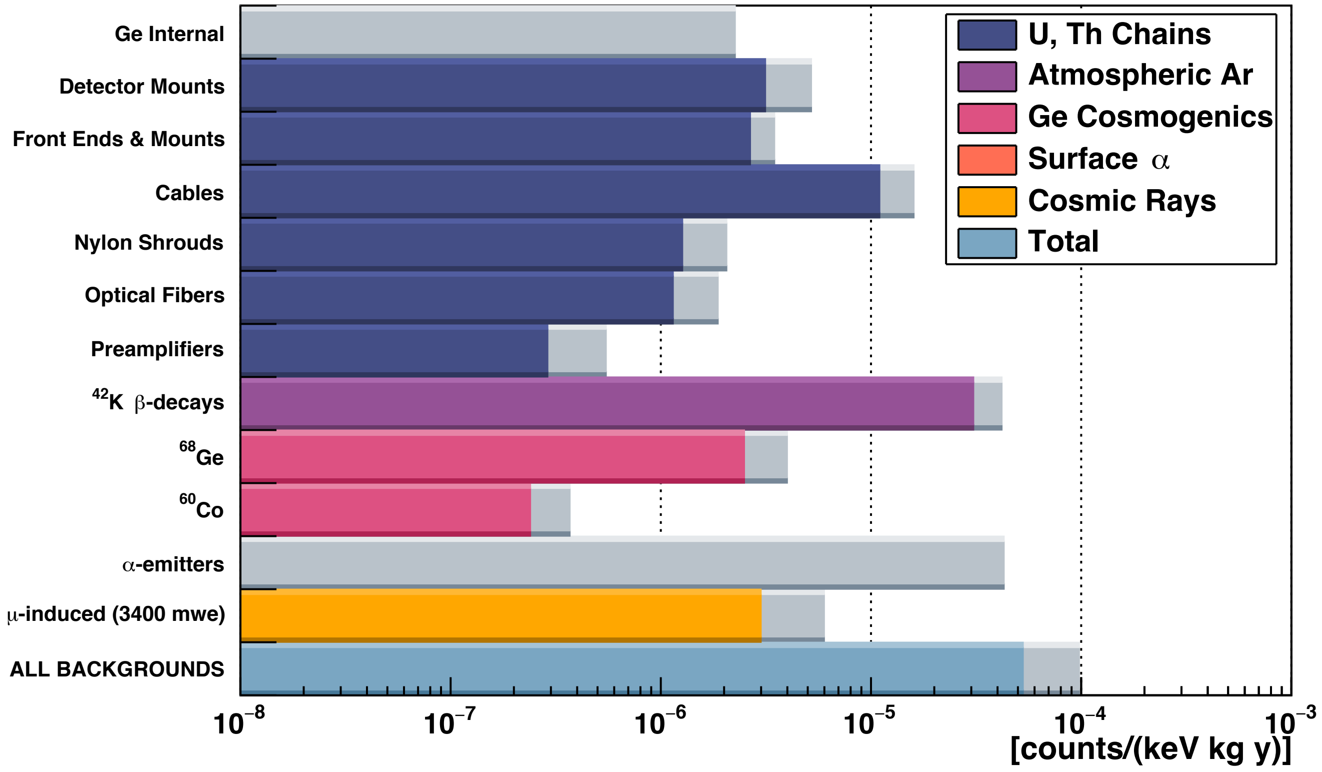
Preliminary SiPM perfo in 60 kg runs

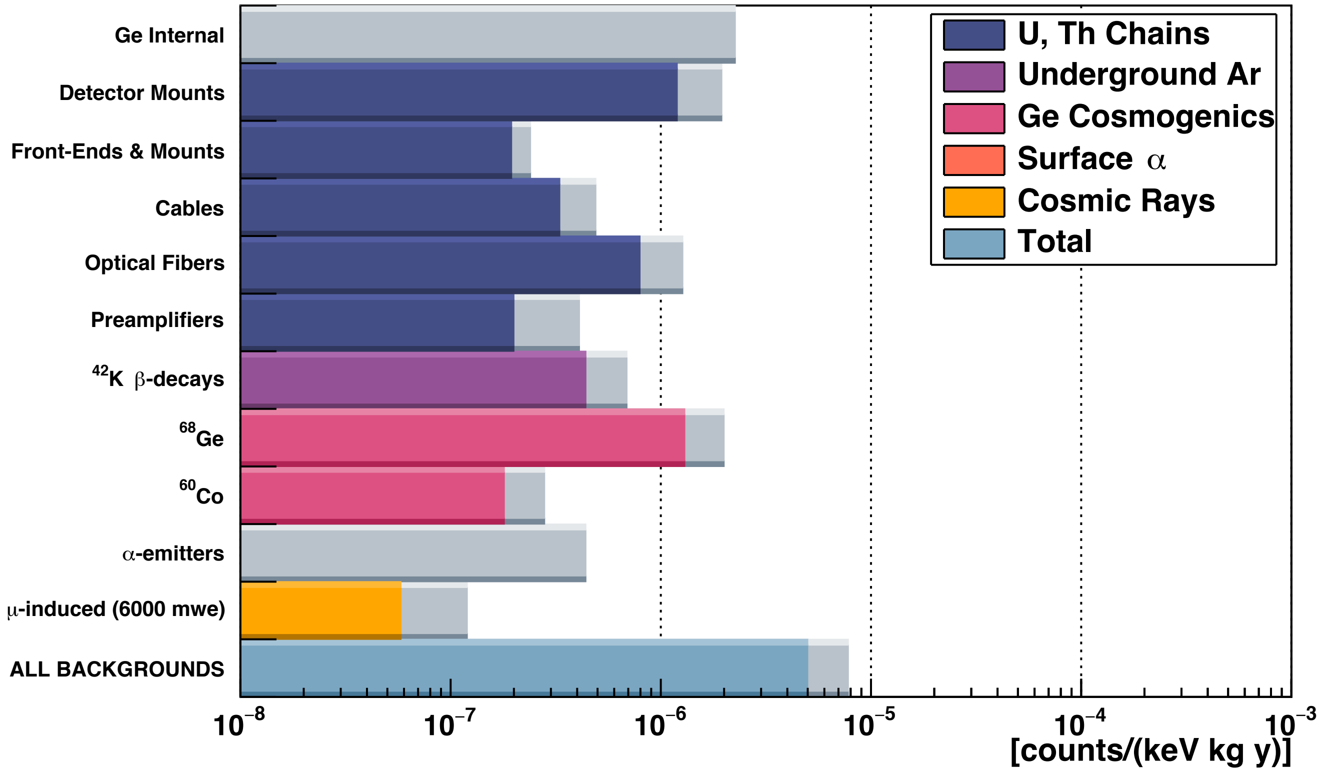




- Single and pile-up events of a typical channel in events within [-1,10] us of a Ge detector trigger
- Excellent baseline (few tens of uV)
- PE spectrum allows for SPE separation (small random coincidences rate)

L-200 → L-1000

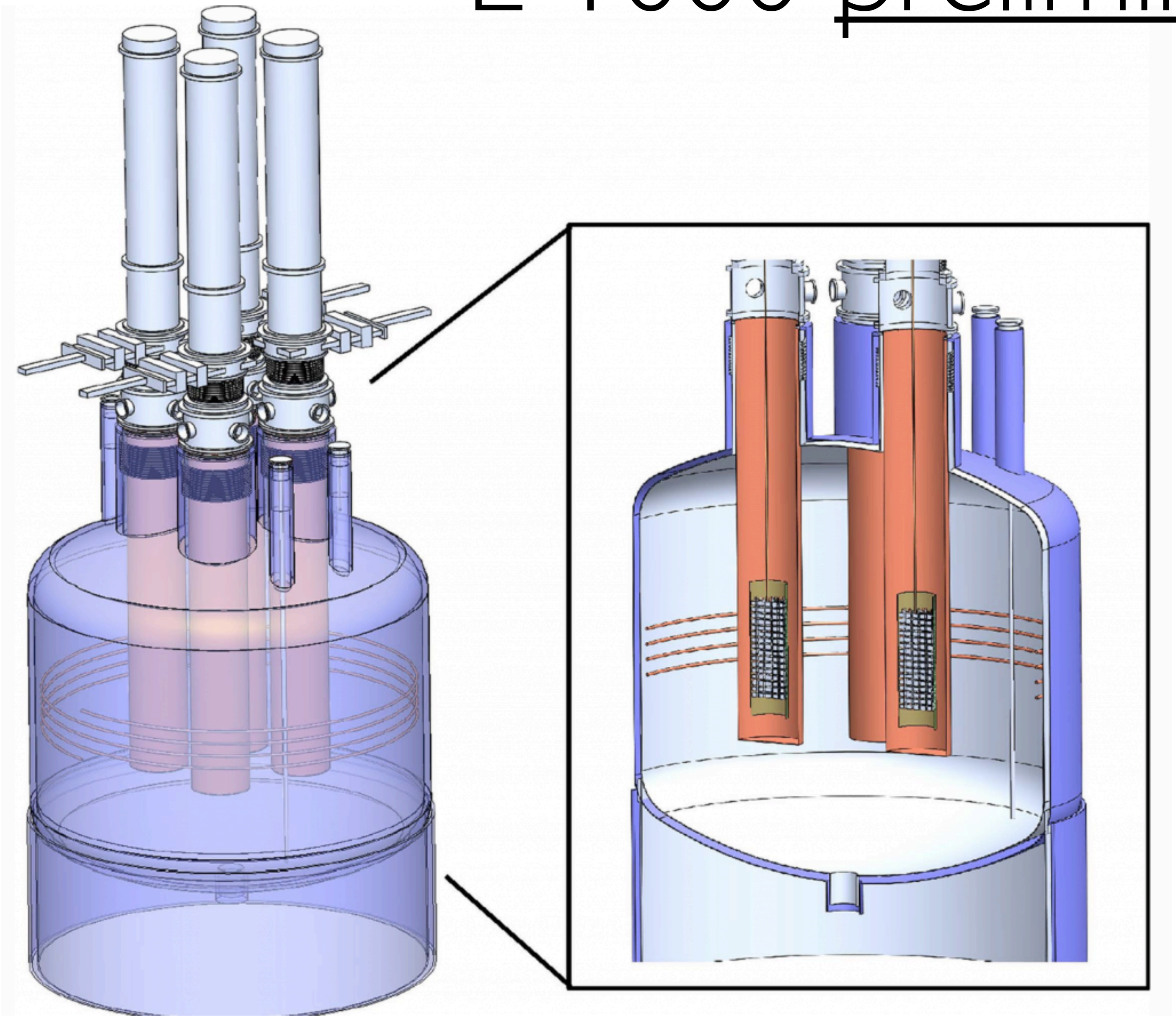




- Largest reductions are on ^{42}K, α, μ
- + "trimming" here and there on radio-purity of materials, esp. cables
- Need specialised work to stop cosmogenic bkg, esp. if at LNGS

~ 50 times lower BI than GERDA

L-1000 preliminary design



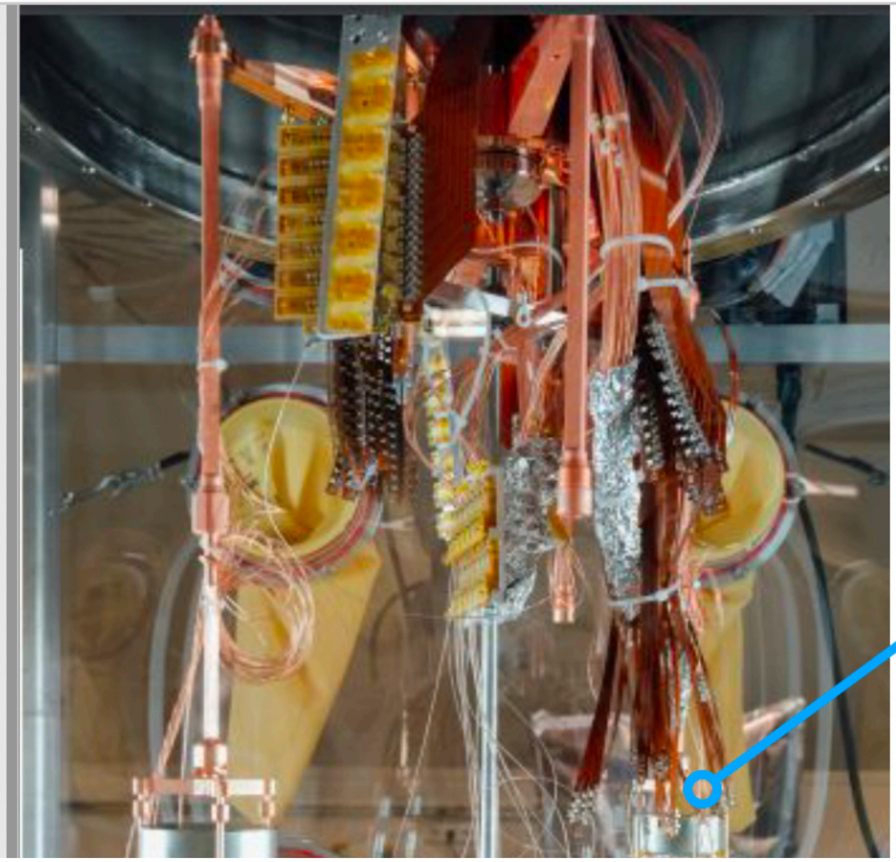
- String concept replicated in 4 payloads, in total ~400 detectors
- Dedicated Underground Ar cryostat, ~3m^3 in volume
- Modest-sized LAr cryostat in "water tank" (6 m Ø LAr, 2-2.5 m layer of water) or large LAr cryostat w/o water (9 m Ø)
  - Other options still remain under investigation in order to achieve max bkg reduction (esp. cosmogenic)

- Site yet TBD (LNGS? SNO?): both 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: larger ICPC, electronics, neutron veto, use of UG Ar, radio-cleaner fibers

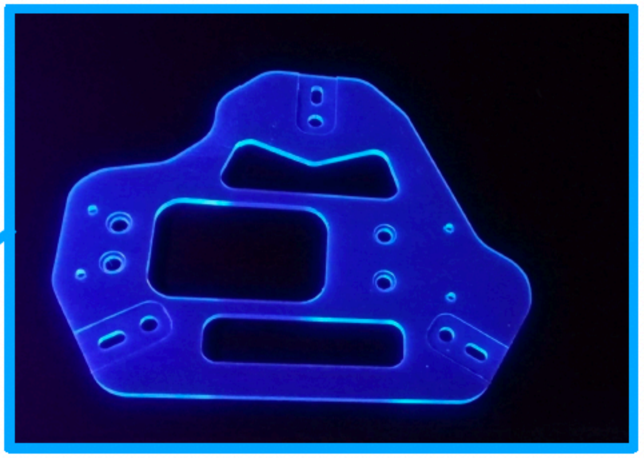
2 examples of remedies against bkg

- UGEFCu used in L200 b/c of its high radio-purity (<u>≤ 0.1 μBq/kg</u> Th/U chains, very low in cosmogenic ^{60}Co)
- Advancements in the understanding of post machining contamination of plastics and metals for L-1000

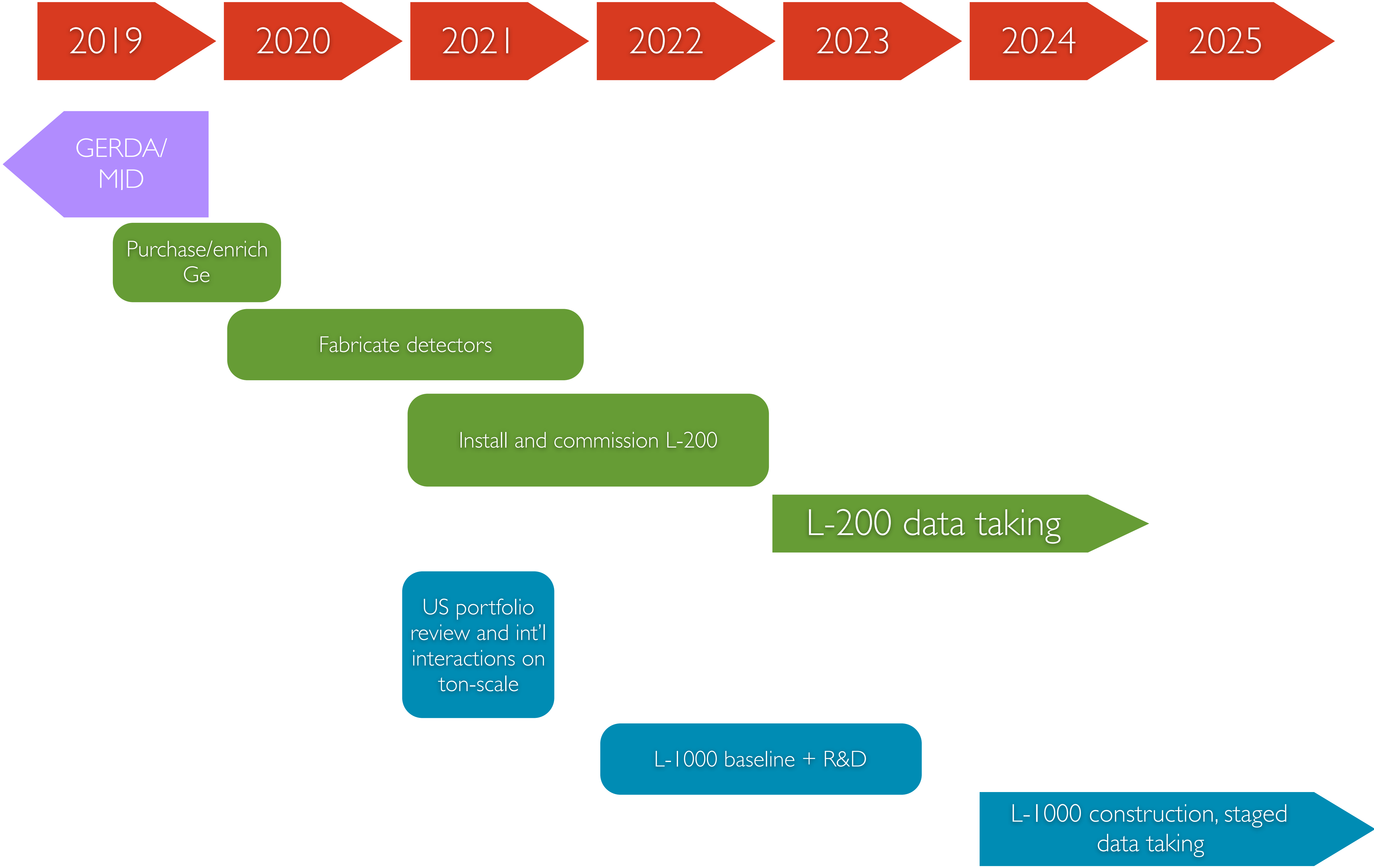
- PEN — Poly(ethylene 2,6-naphthalate) is a scintillating plastic (1/3 LY of conventional plastic scintillators)
- Meets radio-purity req. <u>≤ 1 μBq/piece</u> for Ra/Th, it's self-vetoing



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



(Approx) timeline



2019

2020

2021

2022

2023

2024

2025

GERDA/
MJD

Purchase/enrich Ge

Fabricate detectors

Install and commission L-200

L-200 data taking

US portfolio review and int'l interactions on ton-scale

L-1000 baseline + R&D

L-1000 construction, staged data taking

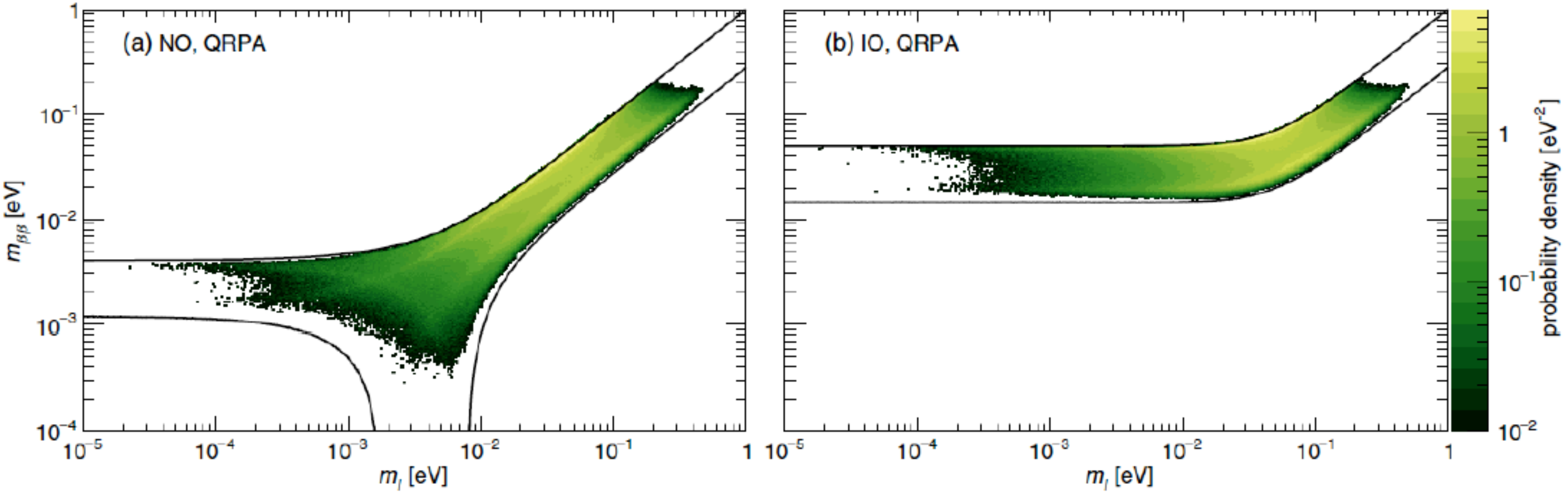
Back-up

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

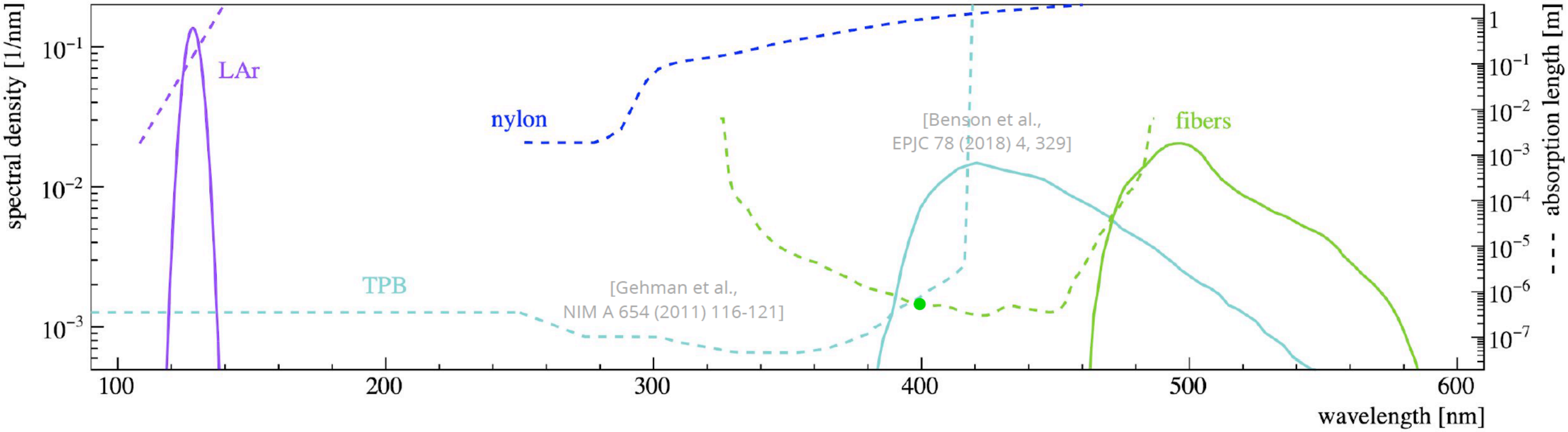


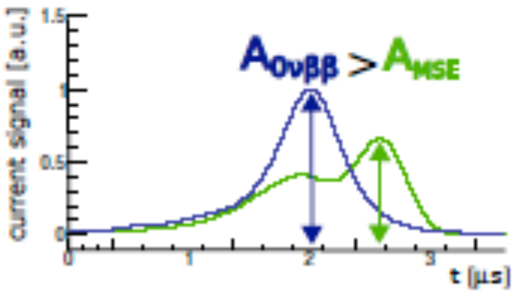
TABLE XV. The relevant properties of PEN.

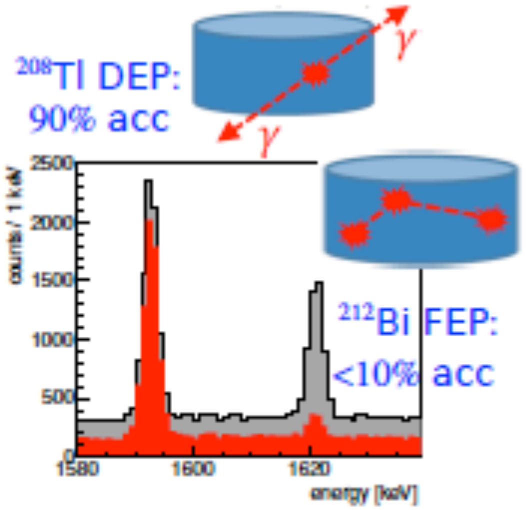
Property	**Value**	
Atomic composition	$[C_{14}H_{10}O_4]_n$	
Density: δ	$1.35\,g/cm^3$	
Melting point	270°C	
Peak emission λ	445±5 nm	
Light yield	≈ 4000 photons/MeV	
Decay constant	34.91 ns	
Attenuation length	≈ 5 cm	
Young's modulus: E [GPa]	1.855±0.011 (296 K)	3.708±0.084 (77 K)
Yield strength: σ_{el}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

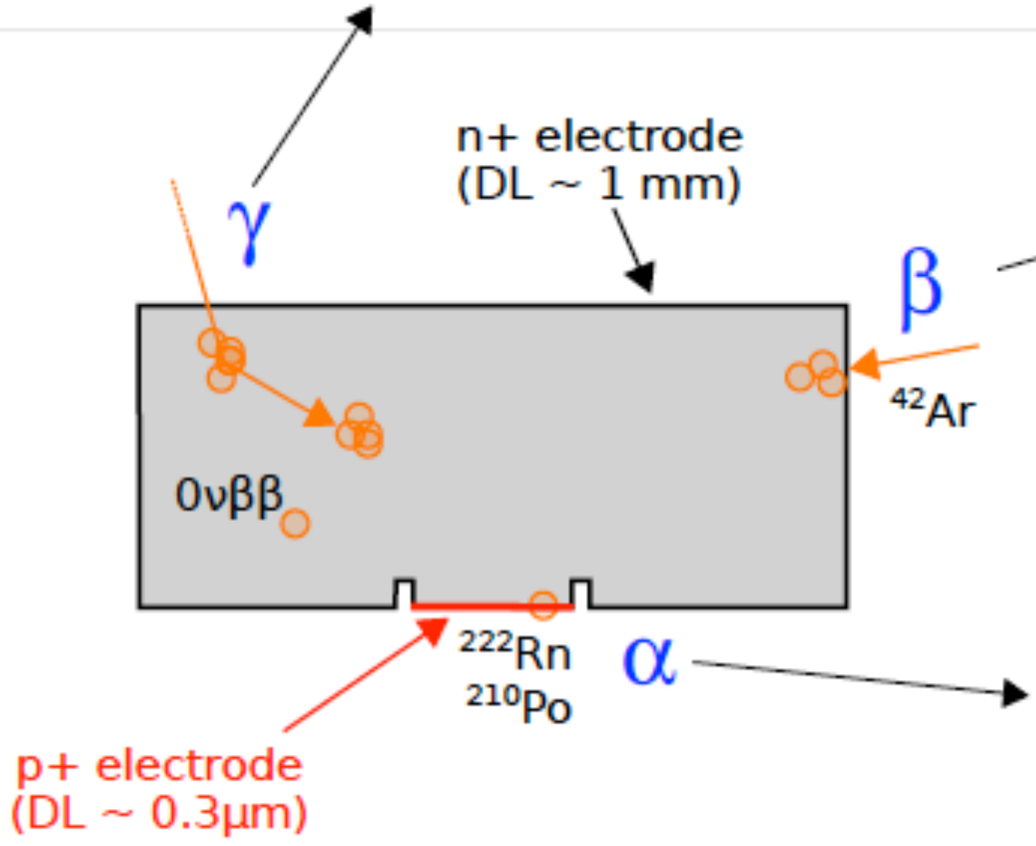
Phase II upgrade: BEGe detectors

Broad Energy Germanium

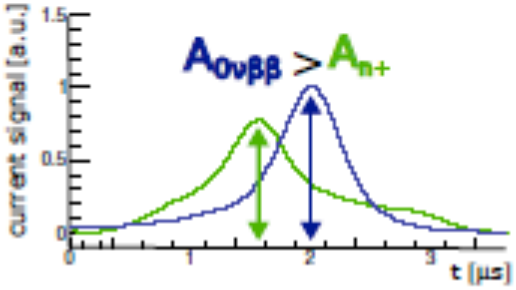
γ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for 0νββ events

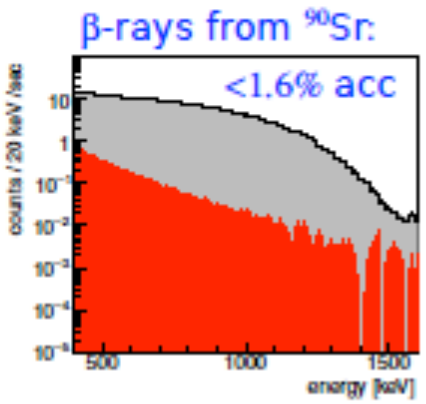




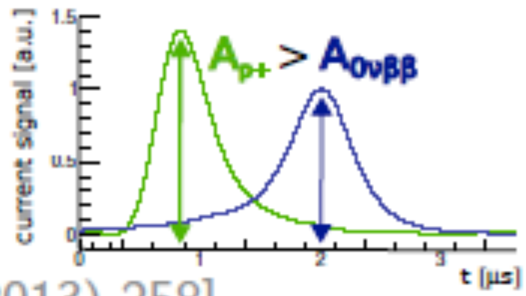


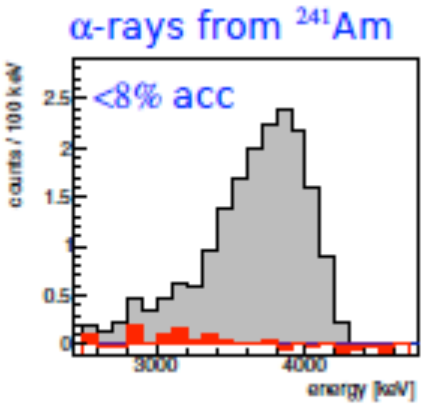
events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal





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

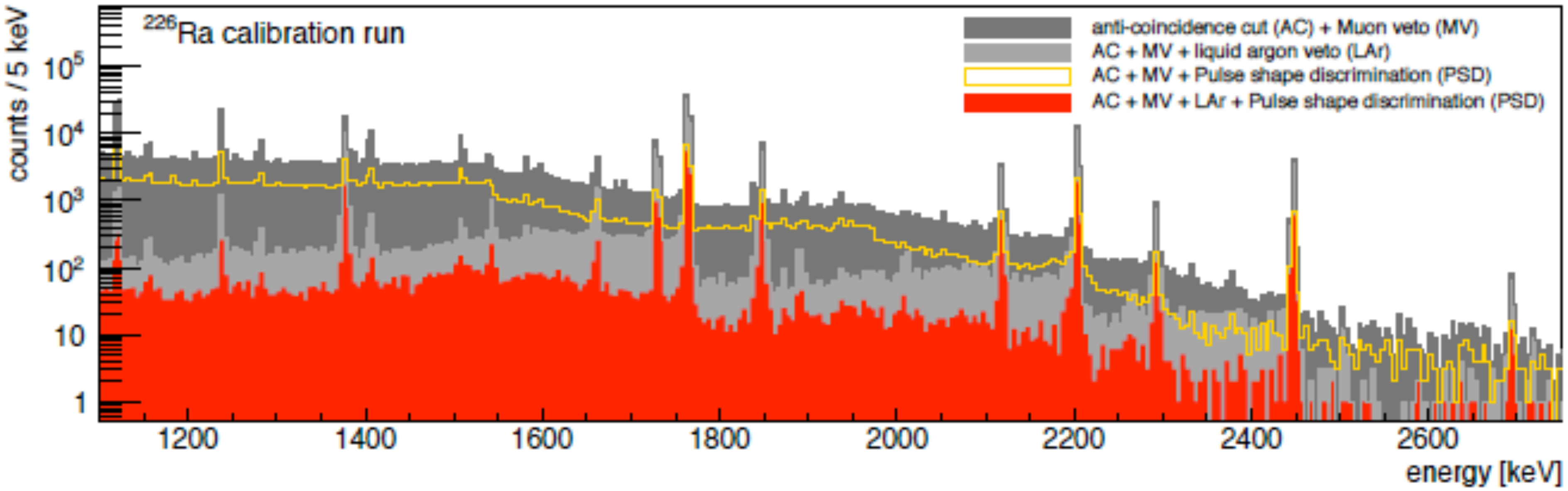


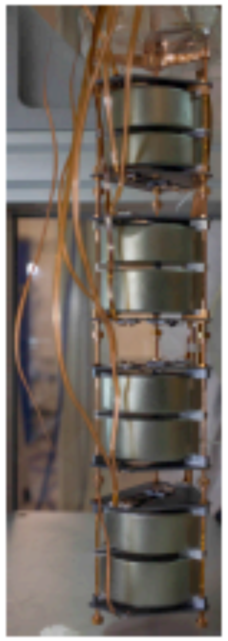


[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

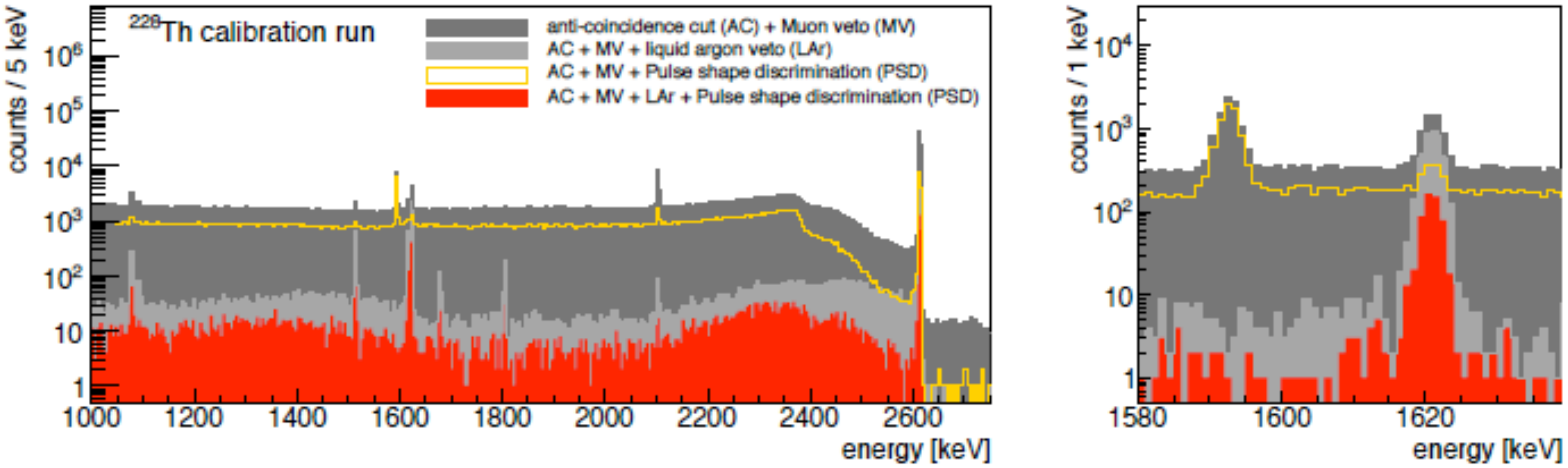
PSD and LAr veto during Phase II commissioning

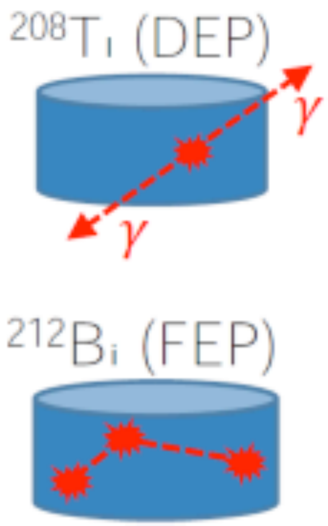
^{226}Ra calibration run (single BEGe string in GERDA):





^{228}Th calibration run:





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

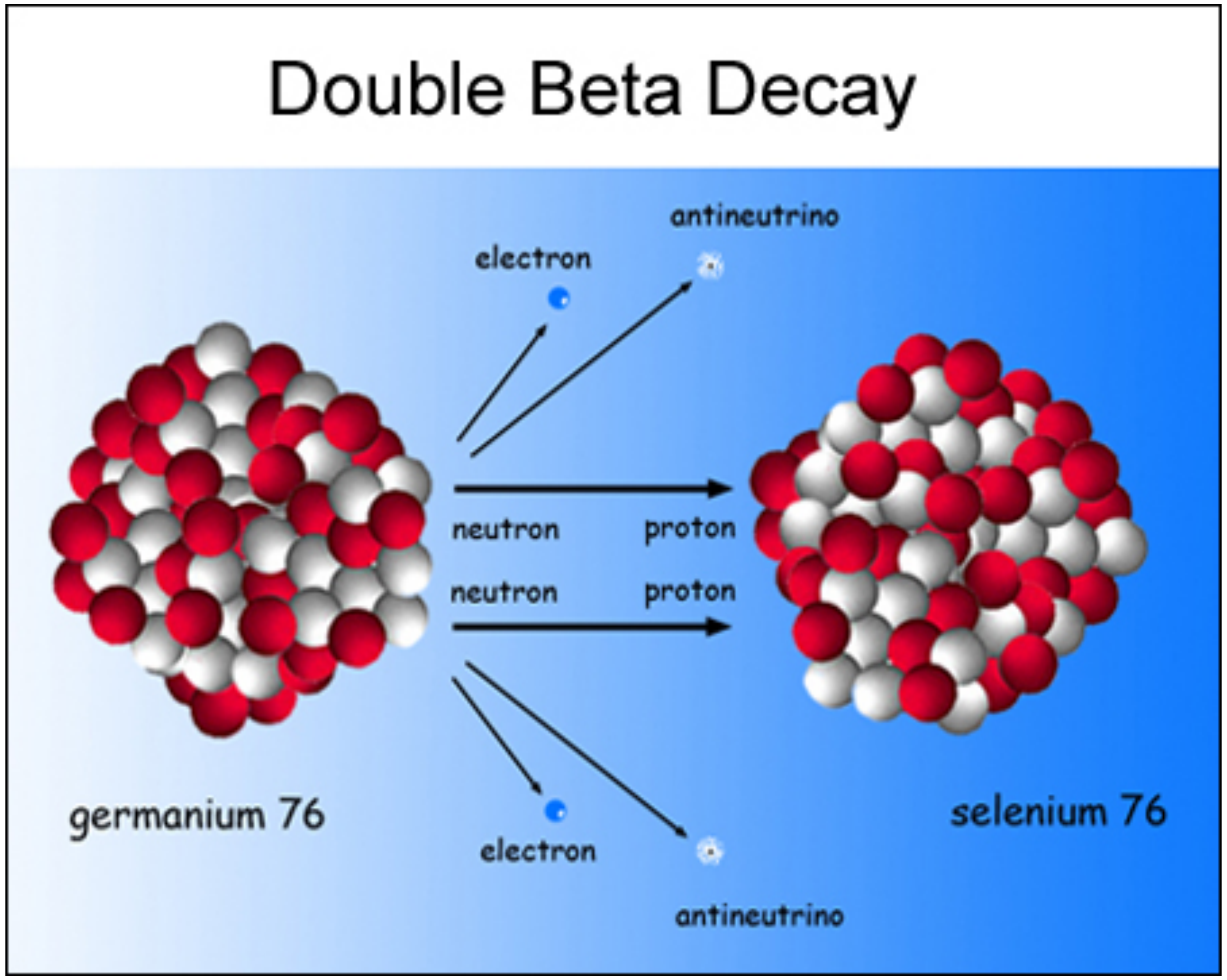
Suppression depends on isotope, location and detector configuration

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

Gerda

0ν2β decays

ΔL=0



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

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

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

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

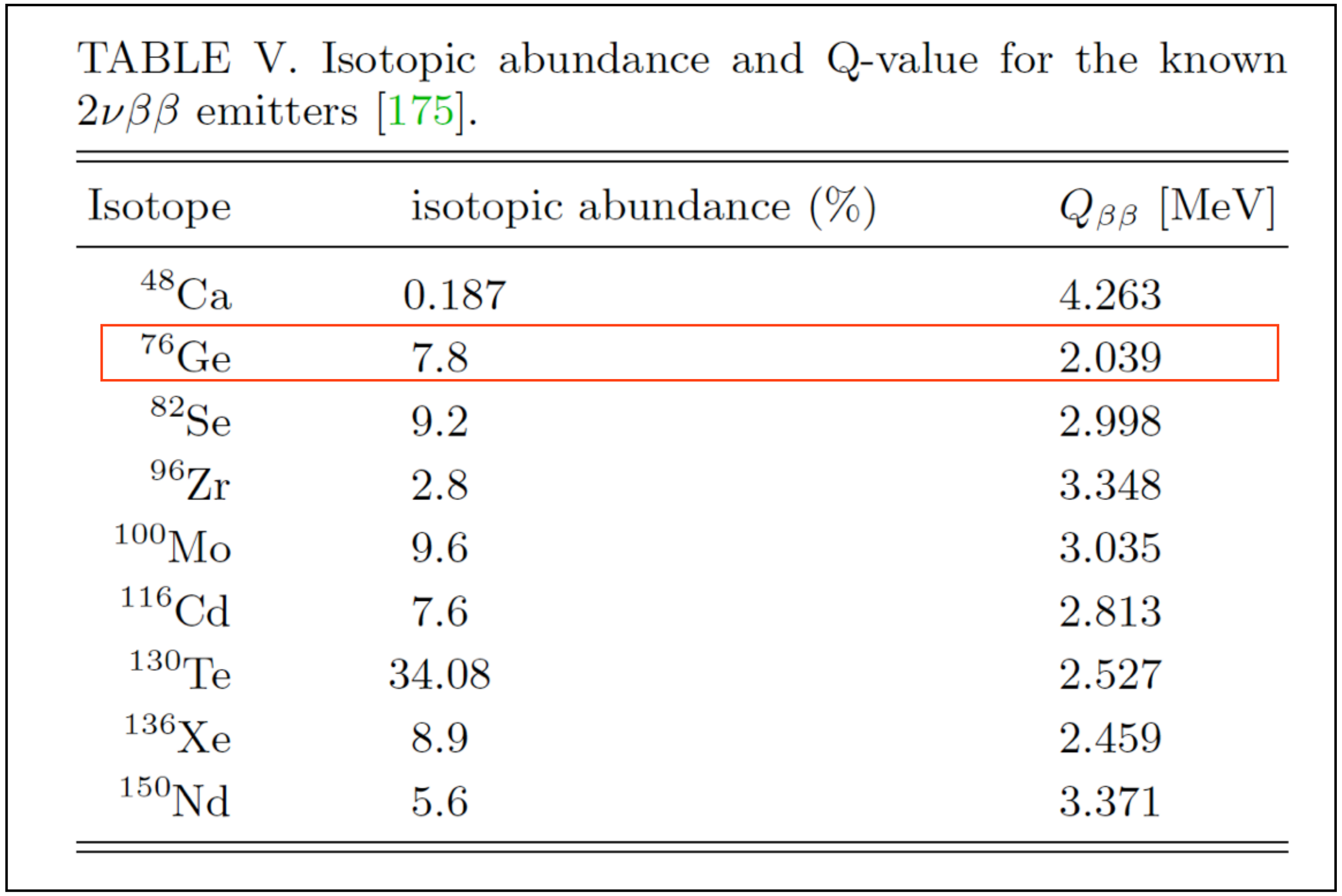
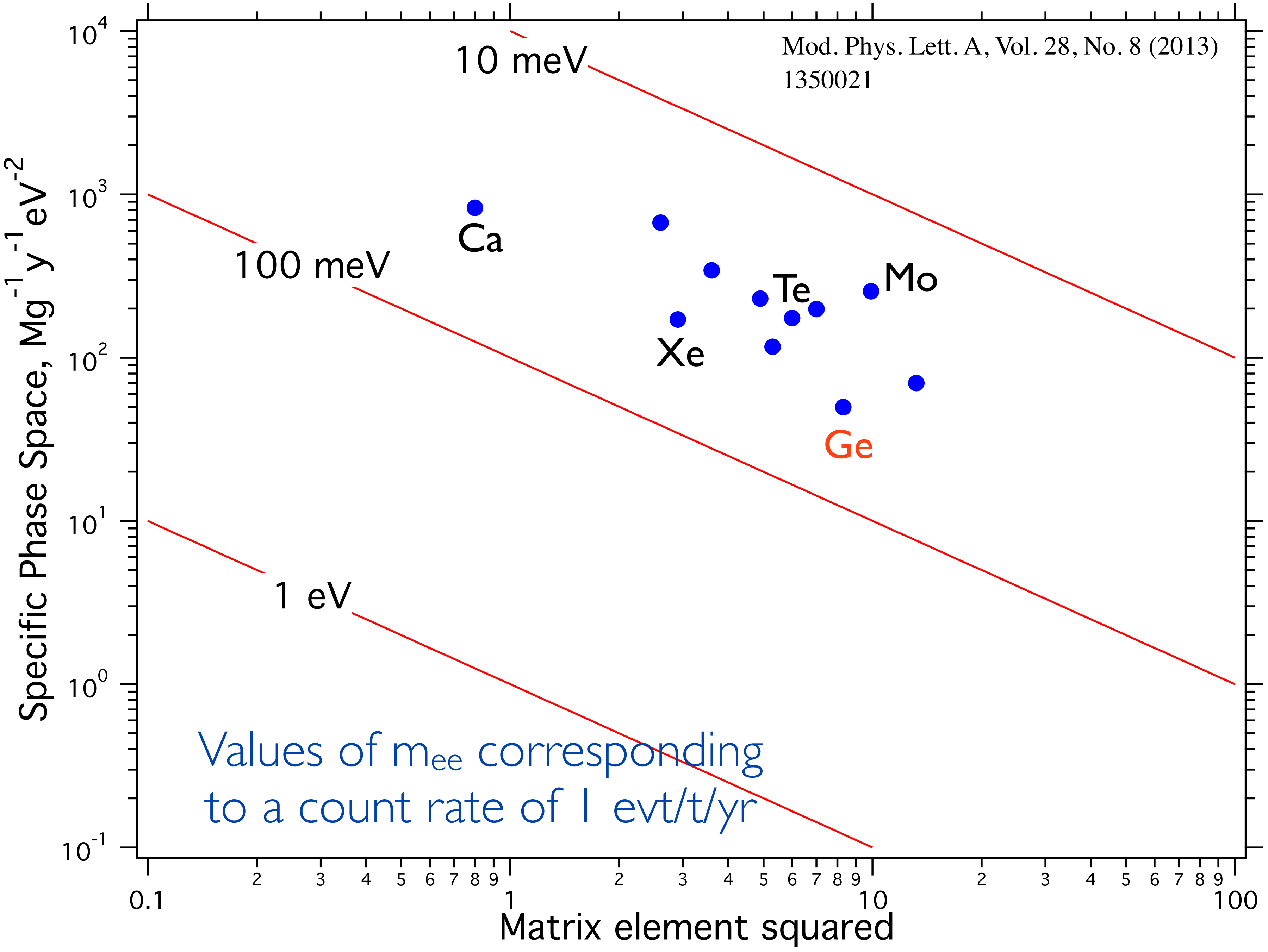


TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

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

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

Comparing different isotopes



Mod. Phys. Lett. A, Vol. 28, No. 8 (2013) 1350021

Values of m_{ee} corresponding to a count rate of 1 evt/t/yr

- 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

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

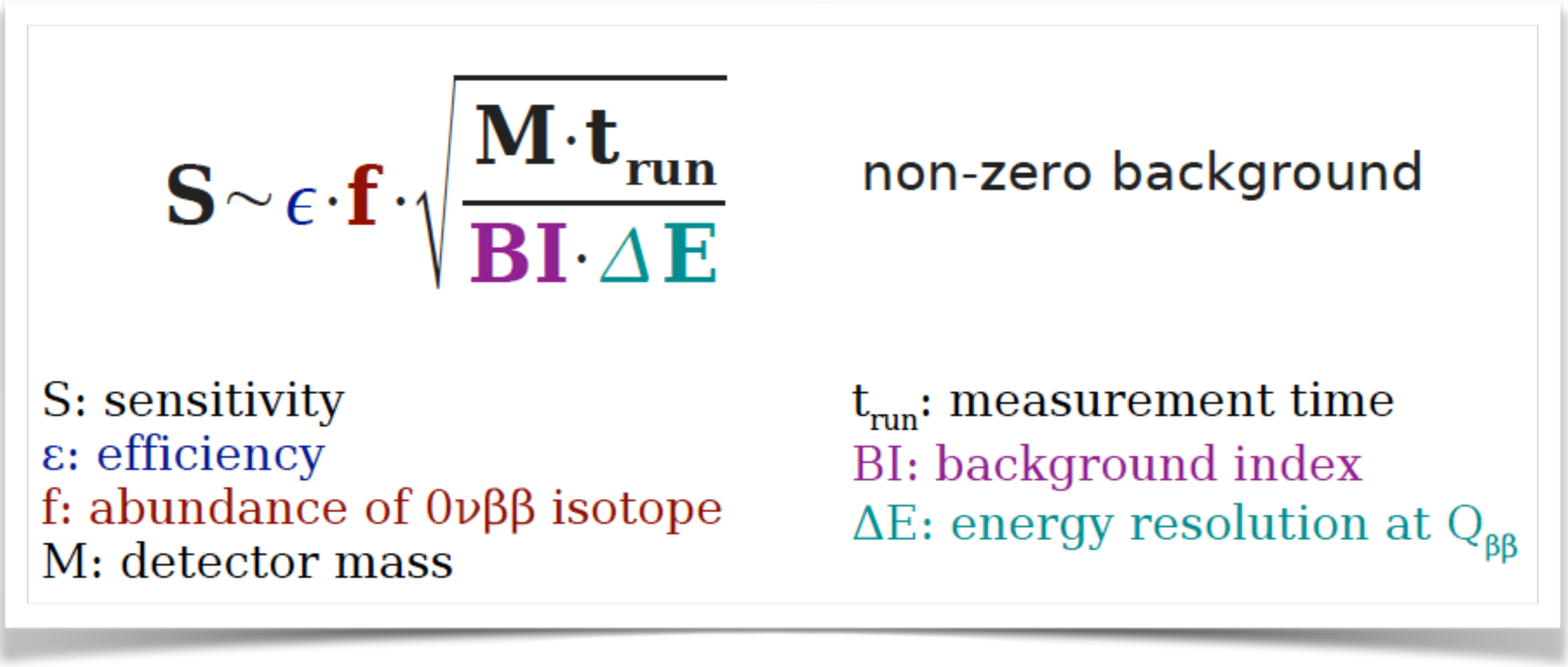
nuclear matrix element

phase space factor

effective Majorana neutrino mass

Experimental sensitivity

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



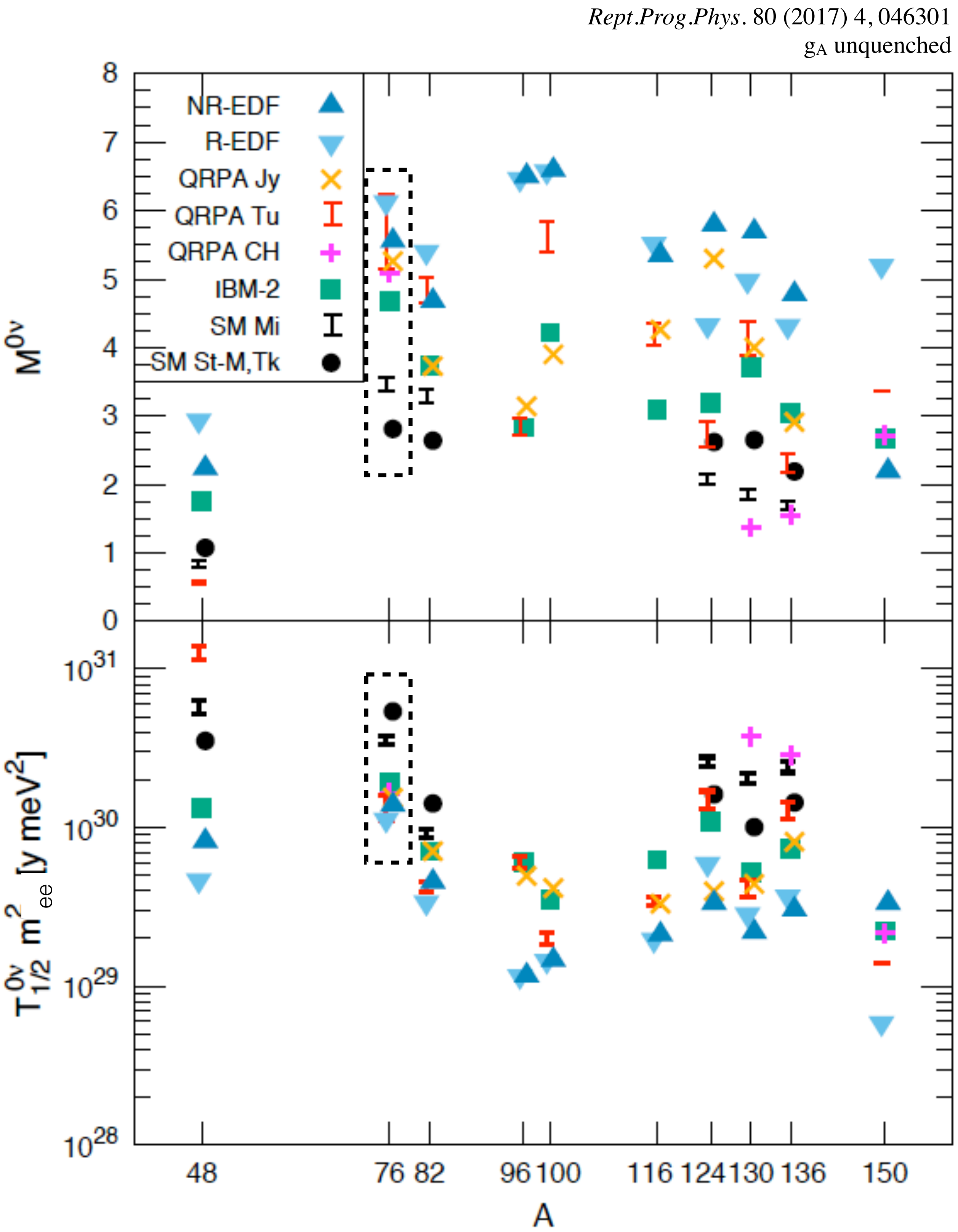
$$\mathbf{S} \sim \epsilon \cdot \mathbf{f} \cdot \sqrt{\frac{\mathbf{M} \cdot \mathbf{t}_{\mathbf{run}}}{\mathbf{BI} \cdot \Delta \mathbf{E}}}$$

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 $Q_{\beta\beta}$

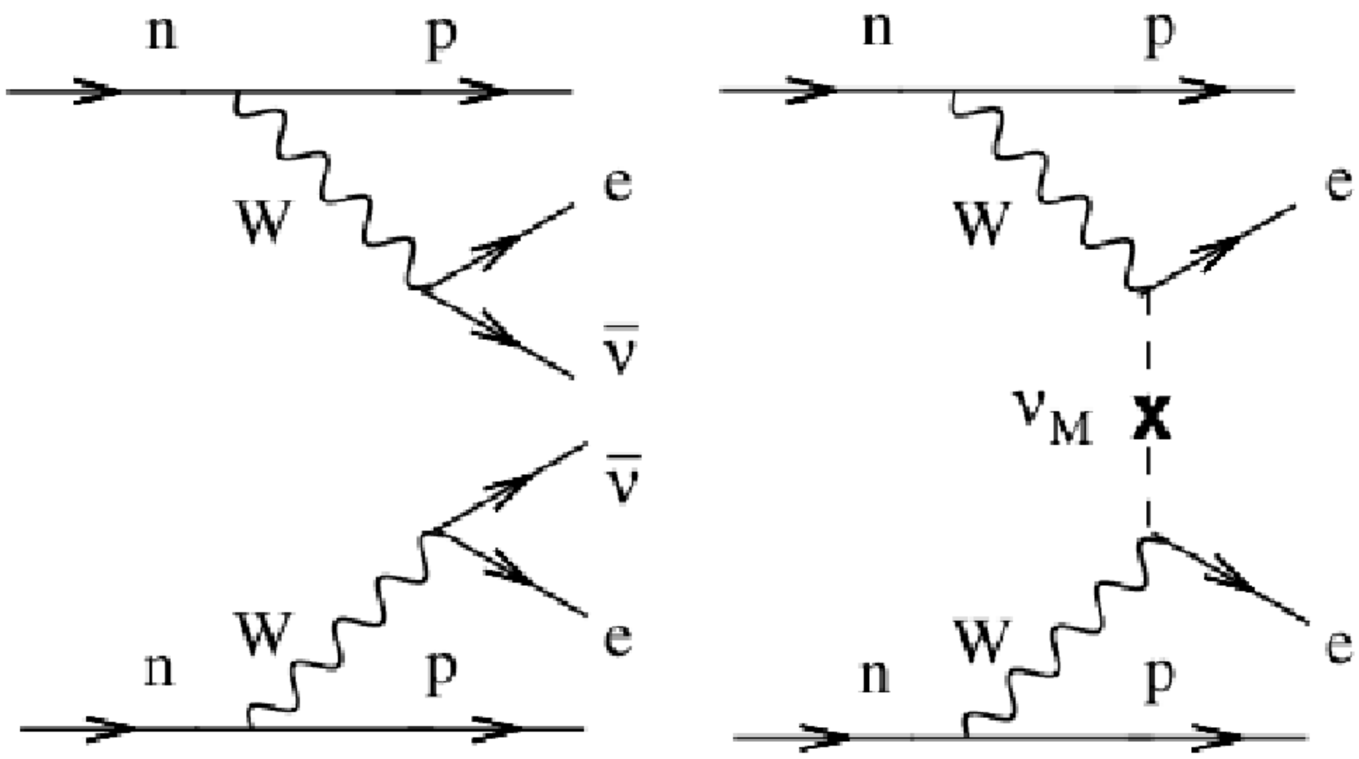
Nuclear Matrix Element values from various nuclear models



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

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)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

nuclear matrix element

phase space factor

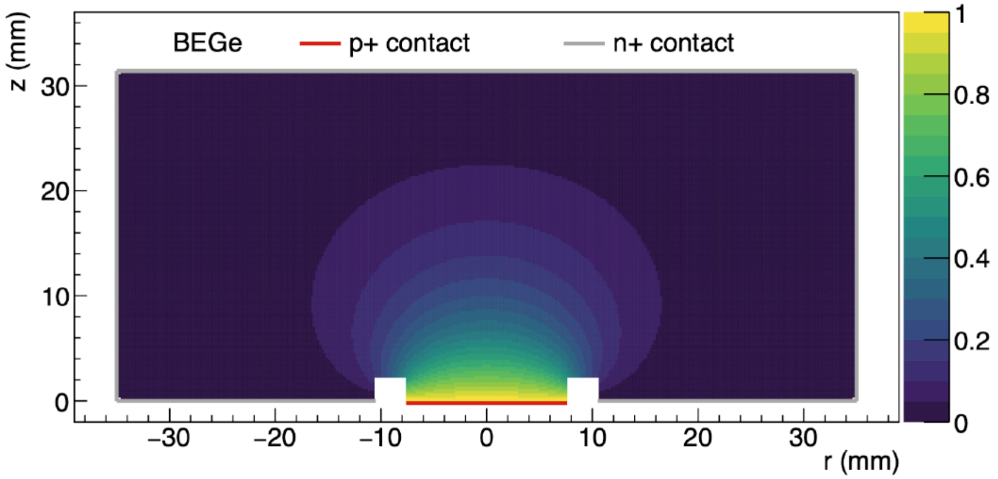
$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

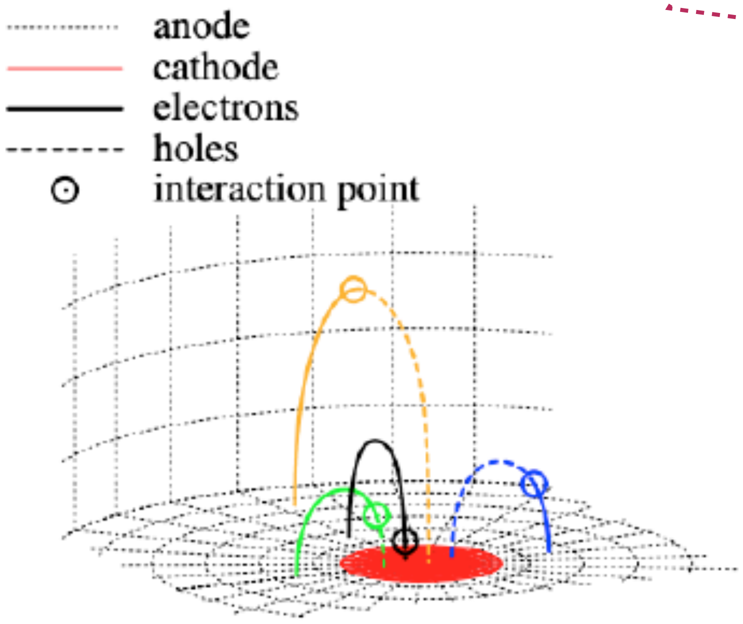
effective Majorana neutrino mass

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

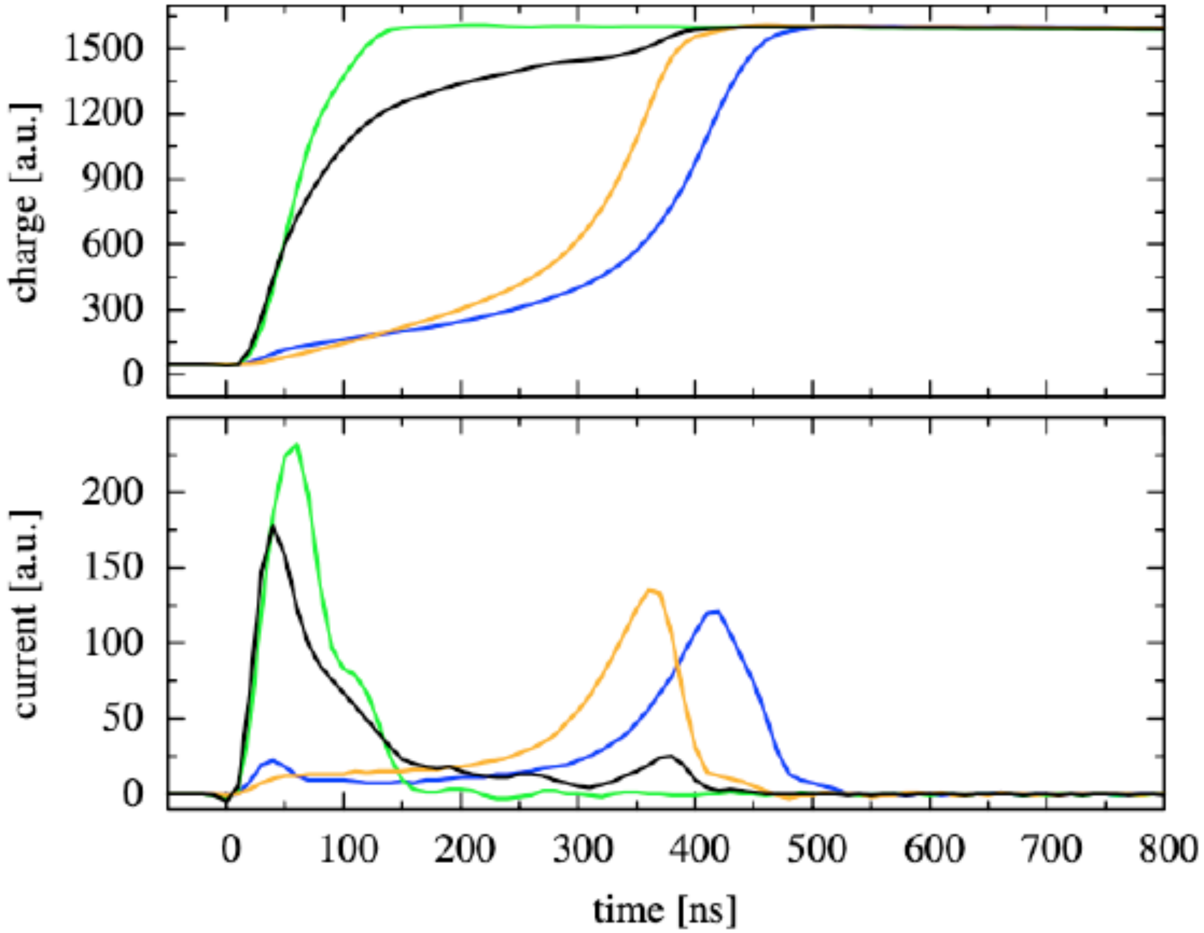
PSD in Ge: concept

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





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

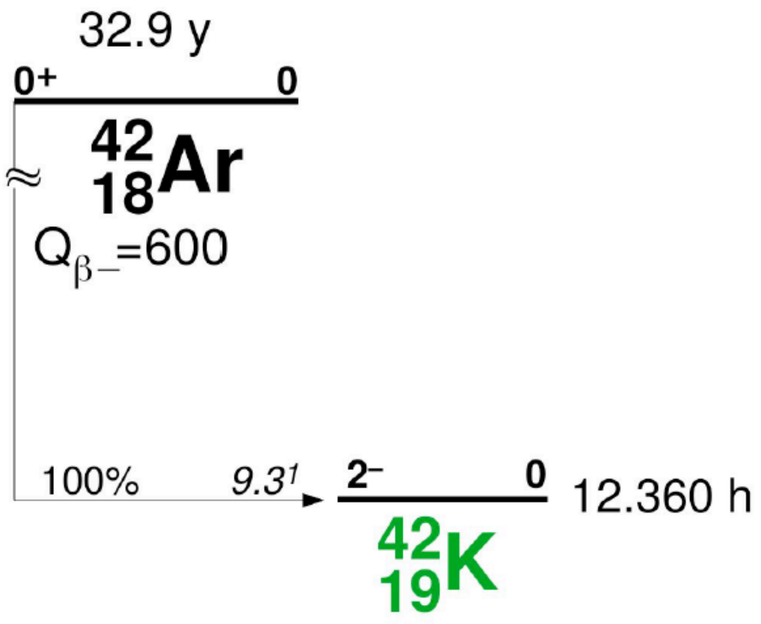


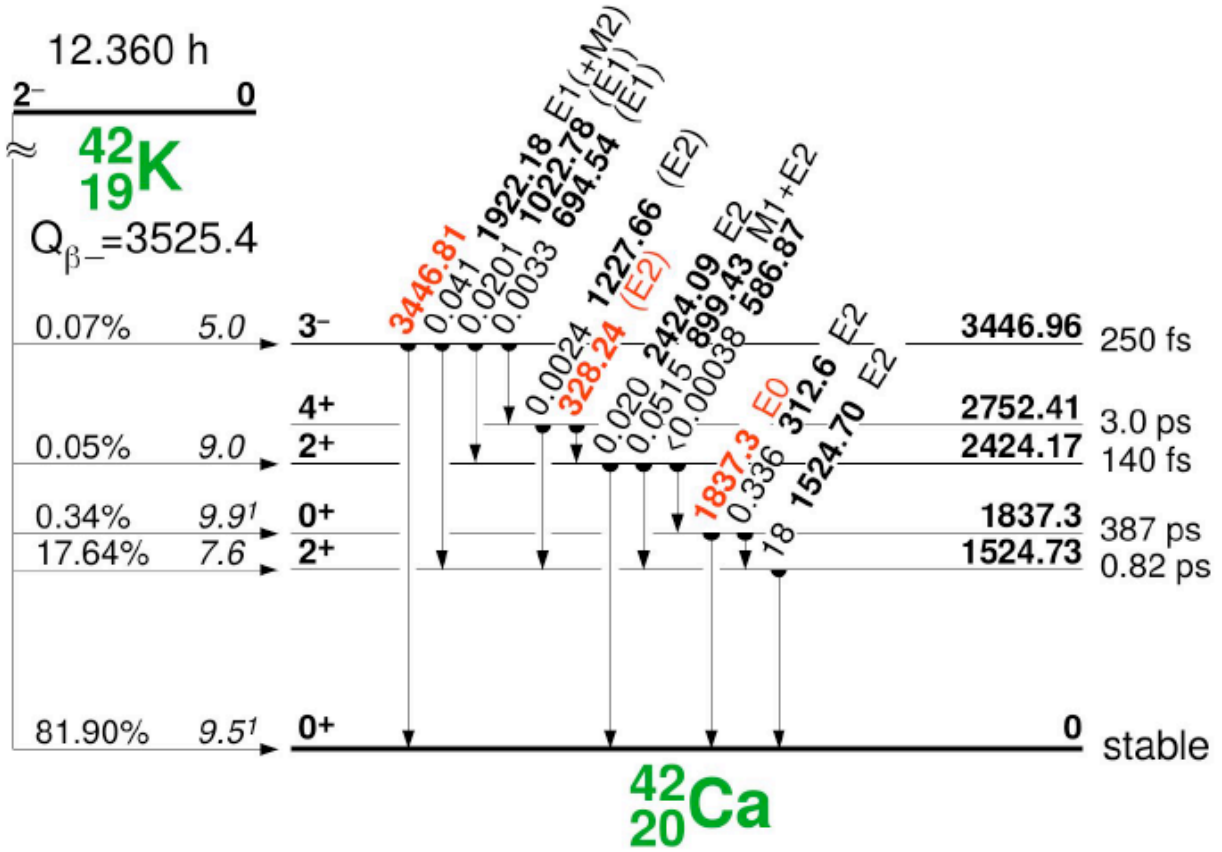
- Uniform configuration of weighting potential in PC enhances (>90%) "**yellow**" type wrt others

- 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

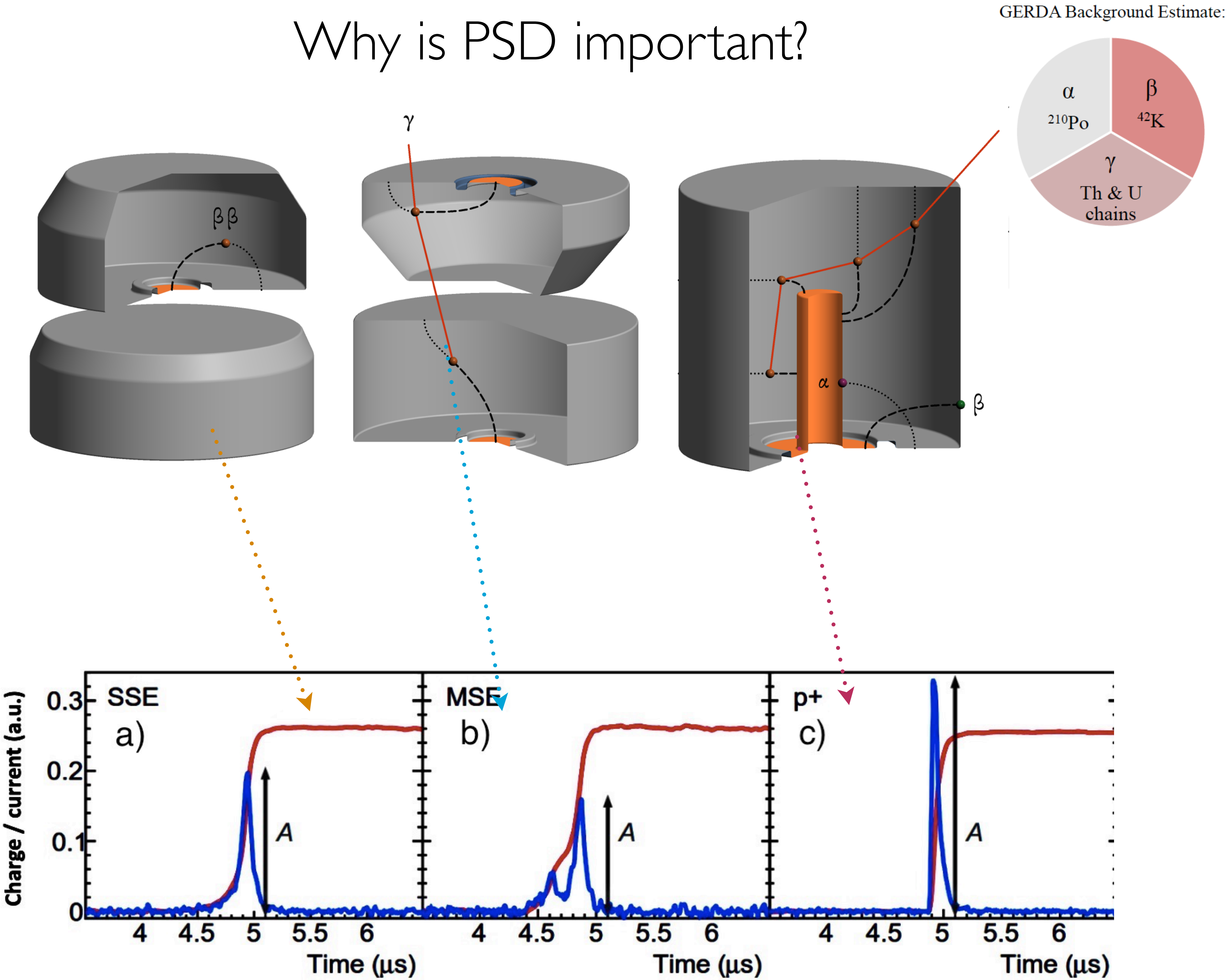
Origin of radioactive bkgs

- α mainly 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, plastics);
  - and from $^{40/42}$Ar → $^{40/42}$K → $^{40/42}$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



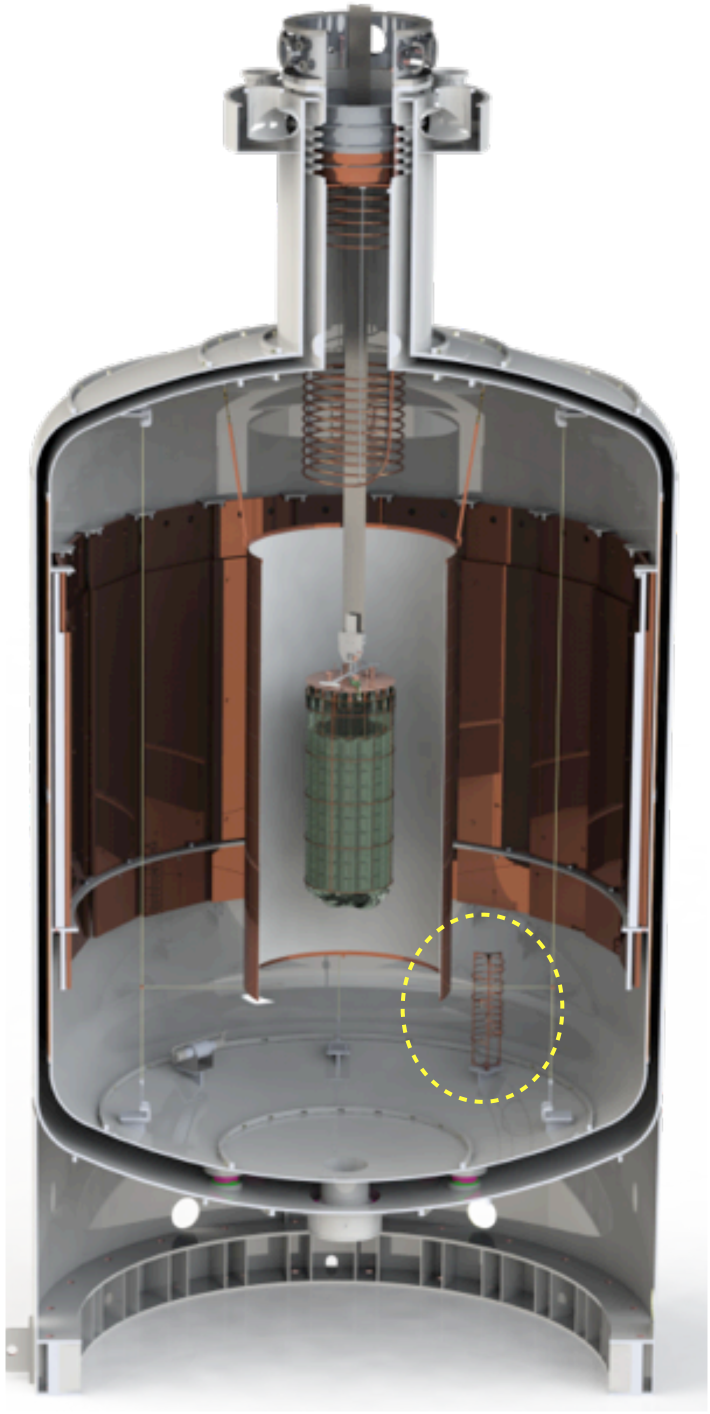


Why is PSD important?



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

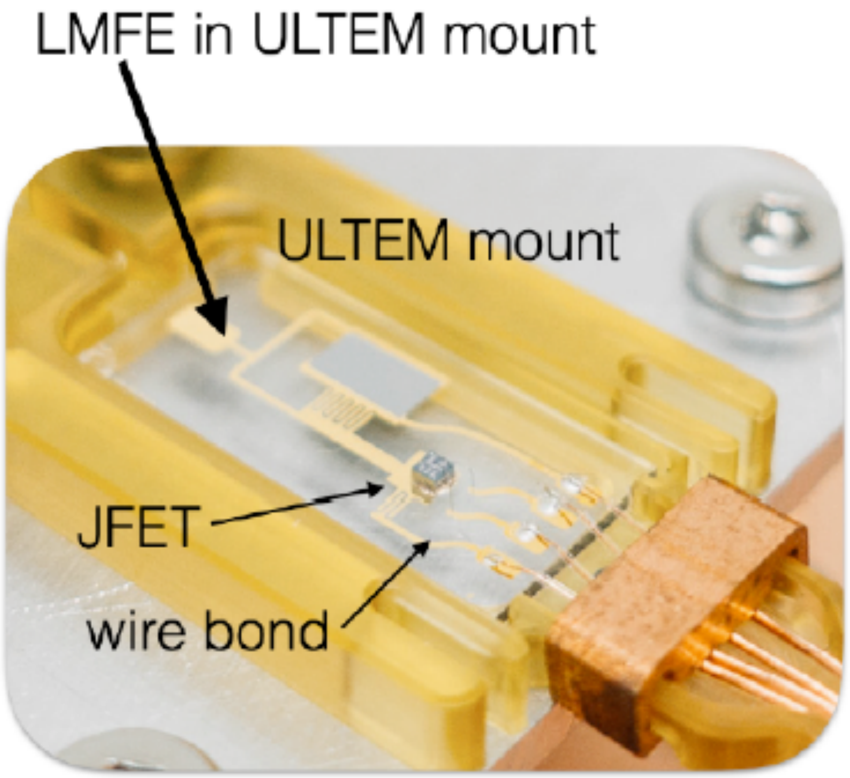


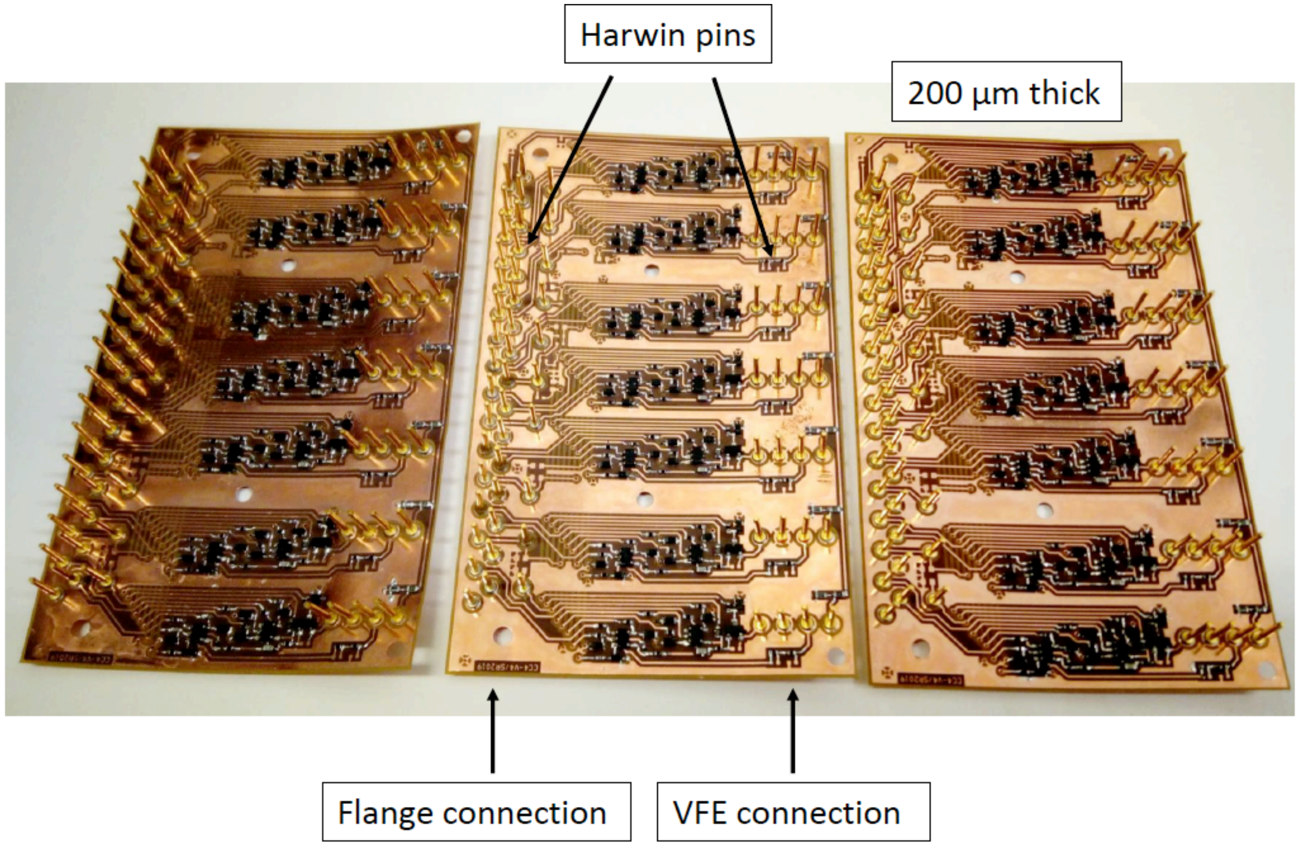
- triplet attenuation highly depends on recombination with impurities (N, O, Xe ppm-to-ppb) sneaking at Ar distillation
- "class 5.5" LAr from plant + in place at LNGS ad-hoc system to purify LAr as it flows between tank and cryostat
- Expected to result in $\lambda_{att} \lesssim$ 1m, small wrt cryostat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

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

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

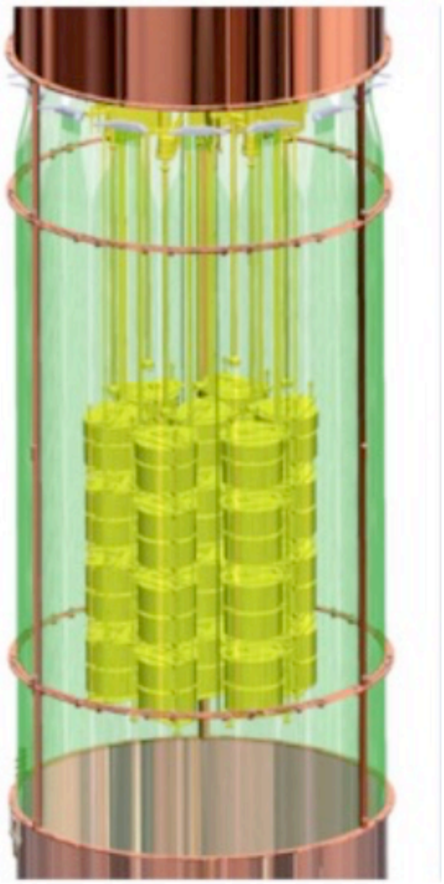




UG electro-formed copper

- Applies experience of MJD, which used 1.2 tons of UGEFCu because of its radio-purity (≤ 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

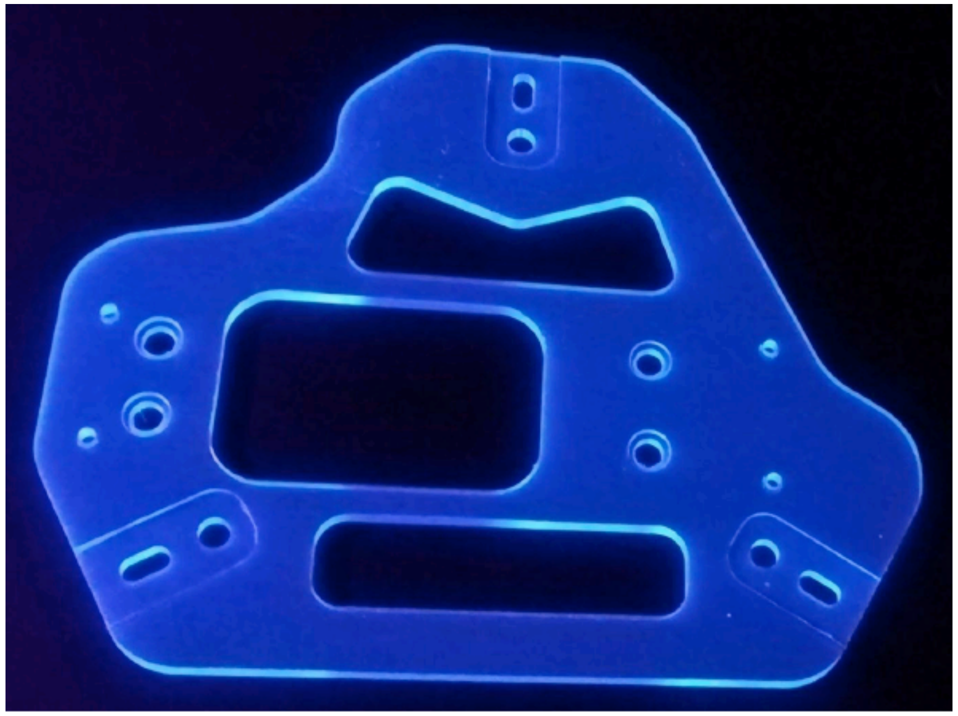


EFCu can be placed next to detectors, in LAr: improves signal/noise and, consequently, PSD

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

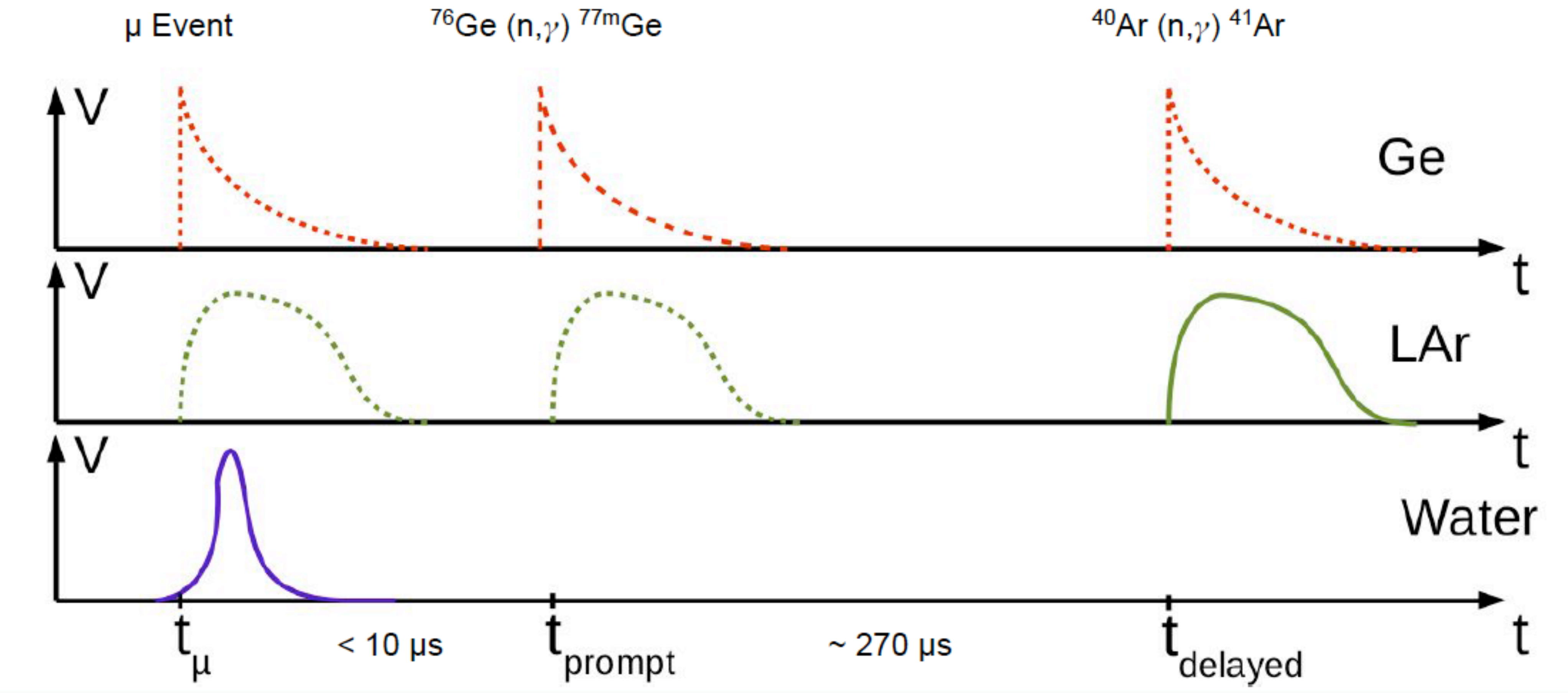
Plates fitting read-out electronics

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



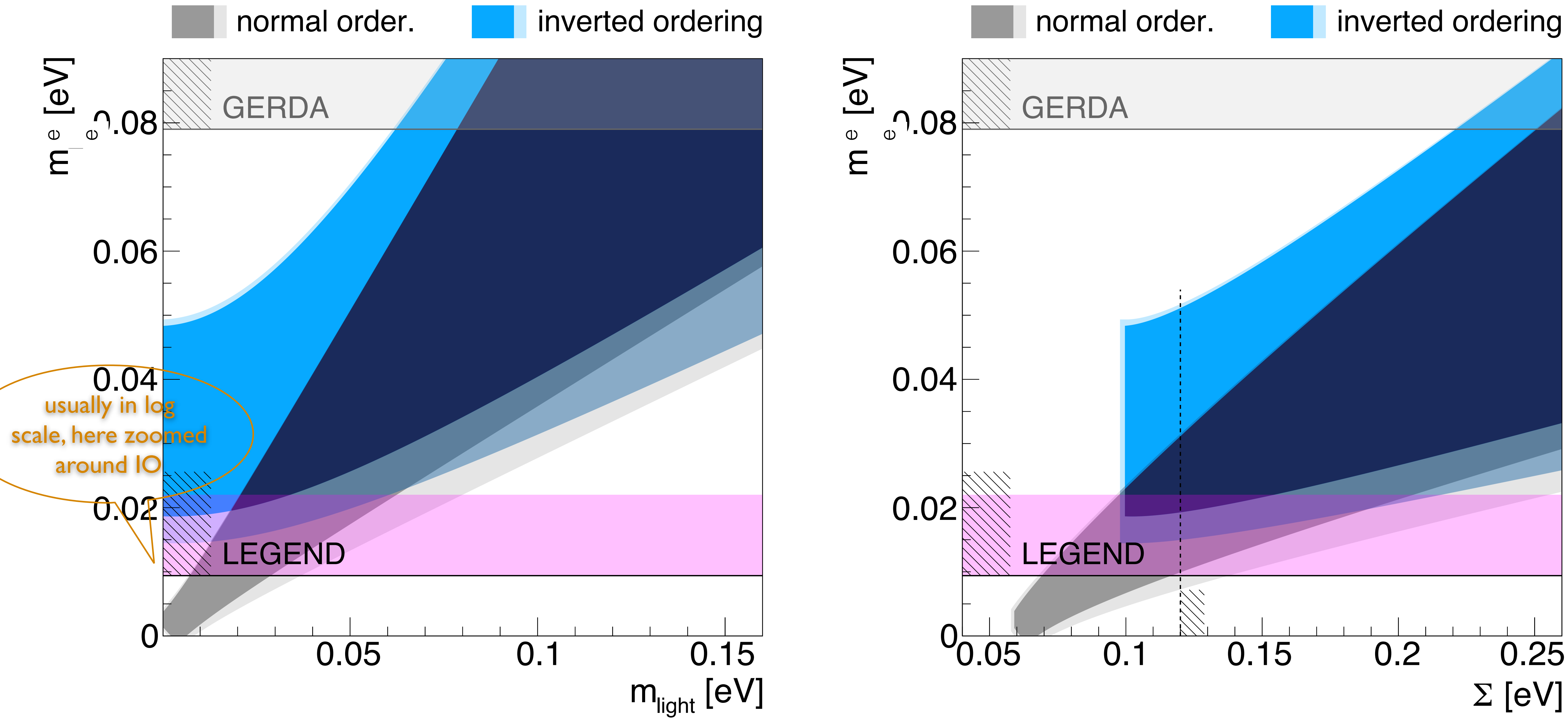
Alpha

- 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

Connection with mass ordering

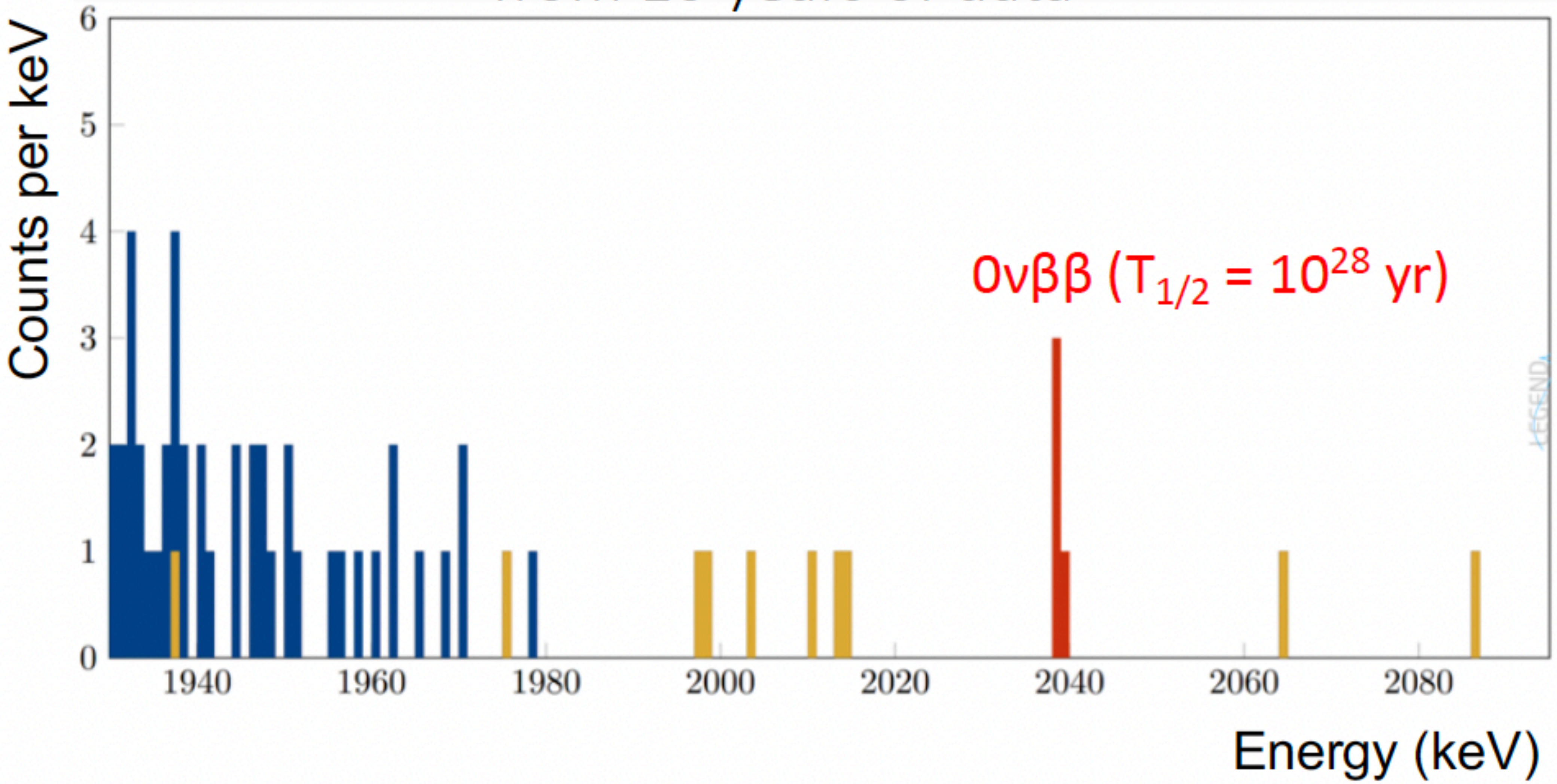


usually in log scale, here zoomed around IO

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

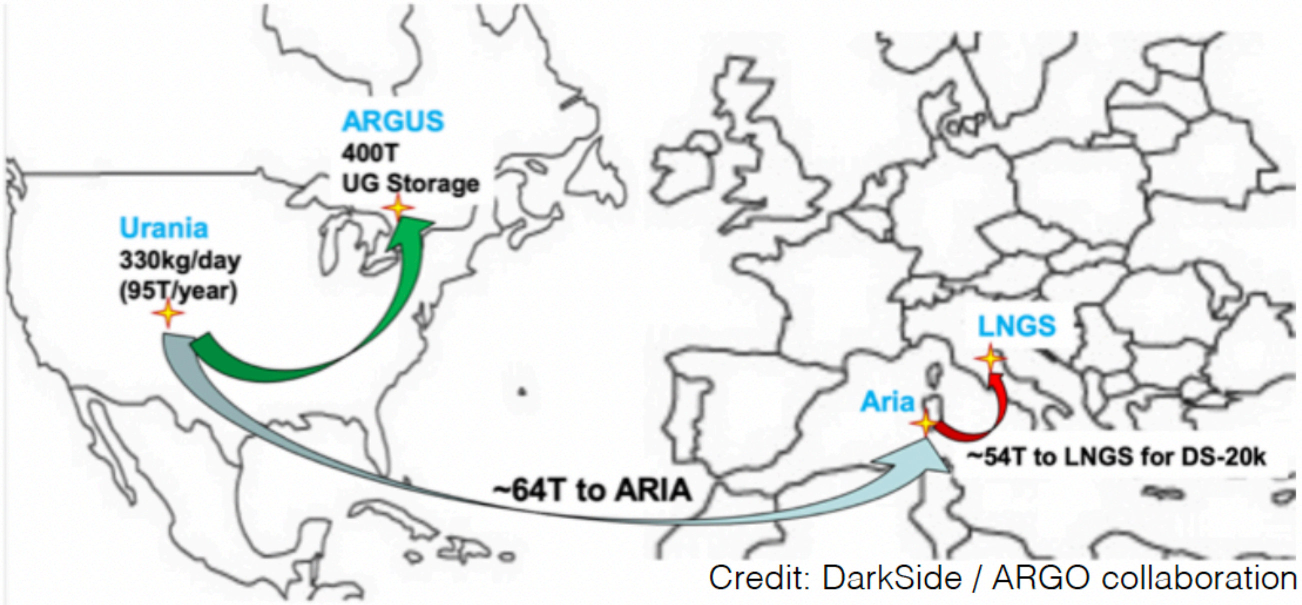
- Limits on m_{ee} from above, can try to rule out IH
  - electron flavour: mix of mass eigenstates, entering $<m_{ee}>$ differently for the two MO
  - <u>nuclear matrix element uncertainties</u>: biggest spoiler in the conversion (shaded area)

Simulated example spectrum, after cuts, from 10 years of data



The Baseline Design: Underground Liquid Argon

- L1000 needs 20-25 t of UGLAr
- Builds on pioneering work of DarkSide collaboration
- UGAr will be mined at Urania facility (U.S.) 95 t/y
- Logistics and storage technology under development by DarkSide/ARGO collaboration for LNGS and SNOLAB
- Expression of interest from INFN president[1] and DarkSide leadership
- UGAr production for LEGEND-1000 in 2023 (after DS-20k)



Credit: DarkSide / ARGO collaboration

UGAr is depleted in ^{42}Ar (^{39}Ar)

Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ε	^{37}Cl
^{38}Ar	0.063%	stable		
~~^{39}Ar~~	~~trace~~	~~269 y~~	~~β⁻~~	~~^{39}K~~
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β⁻	^{41}K
~~^{42}Ar~~	~~syn~~	~~32.9 y~~	~~β⁻~~	~~^{42}K~~

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[1] " …we are confident that the production of the required UAr can be completed in a time scale useful for the accomplishment of the LEGEND-1000 experiment.. The present statement is an expression of interest and availability from INFN…"