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)

IPA, September 2022

- Stems from previous achievements with Germanium (see D.Tedeschi and E.Bossio's talks) 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

Collab Meeting Seattle Dec 2019

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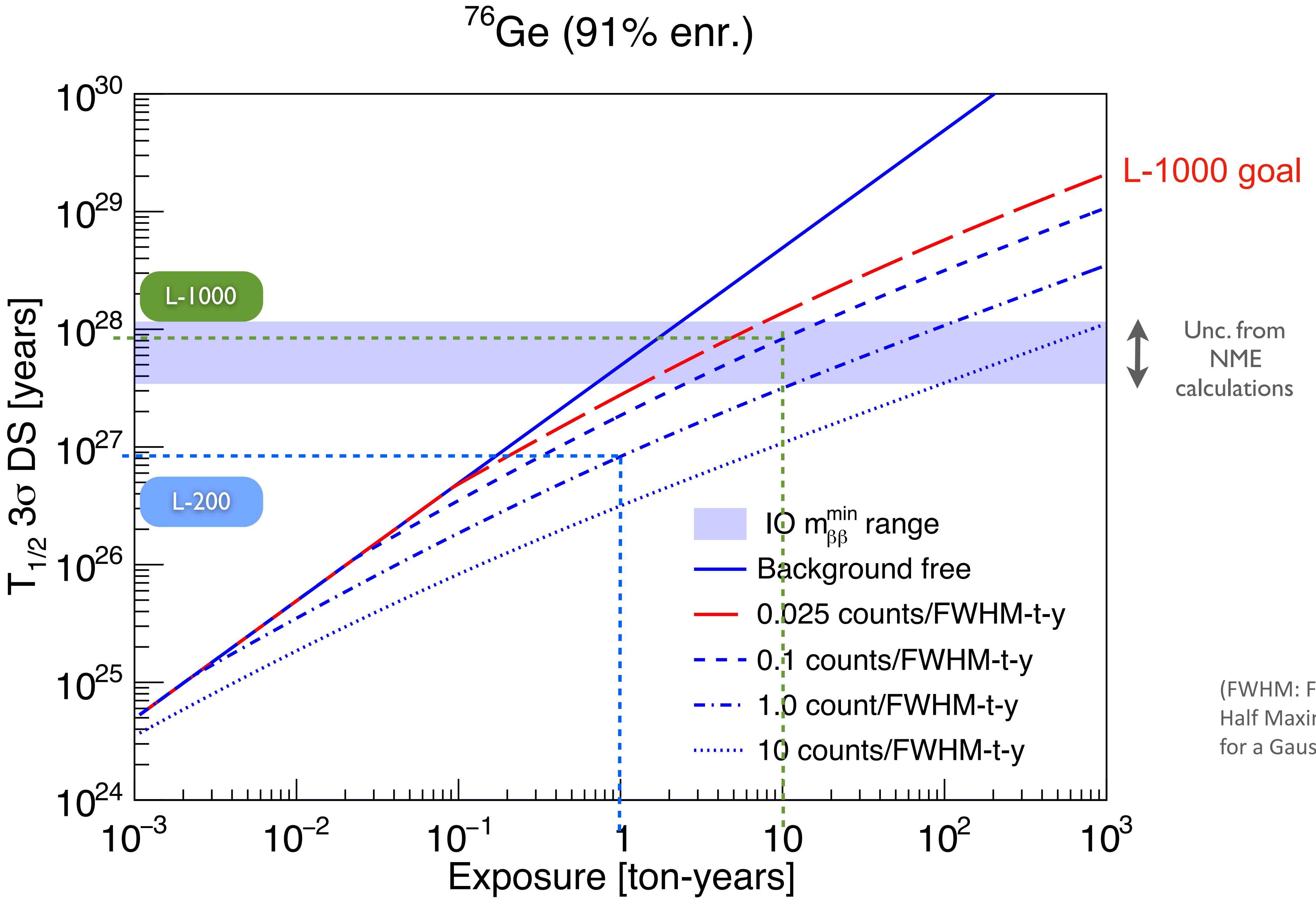
How far can we go?

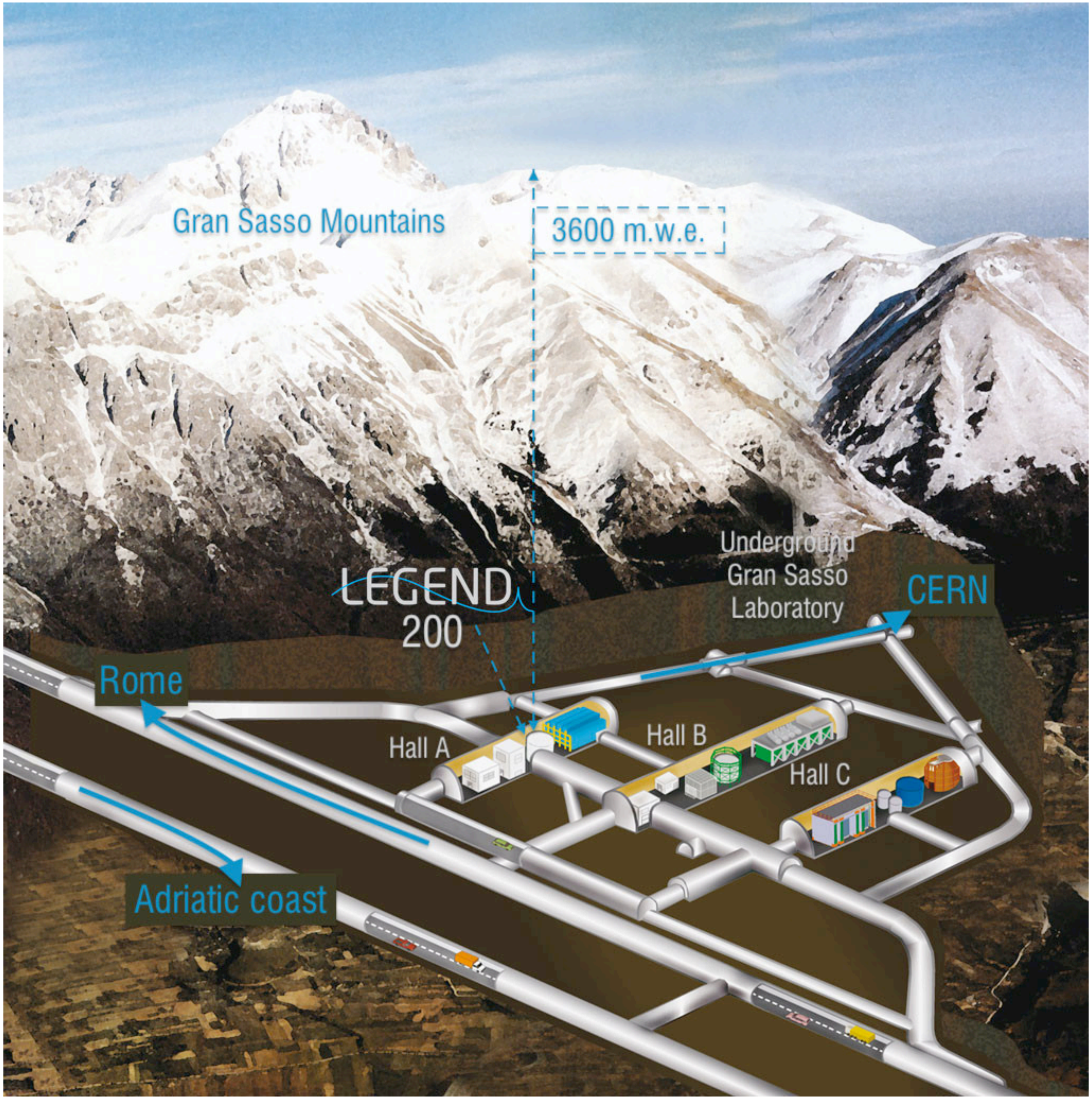


Unc. from
NME
calculations

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

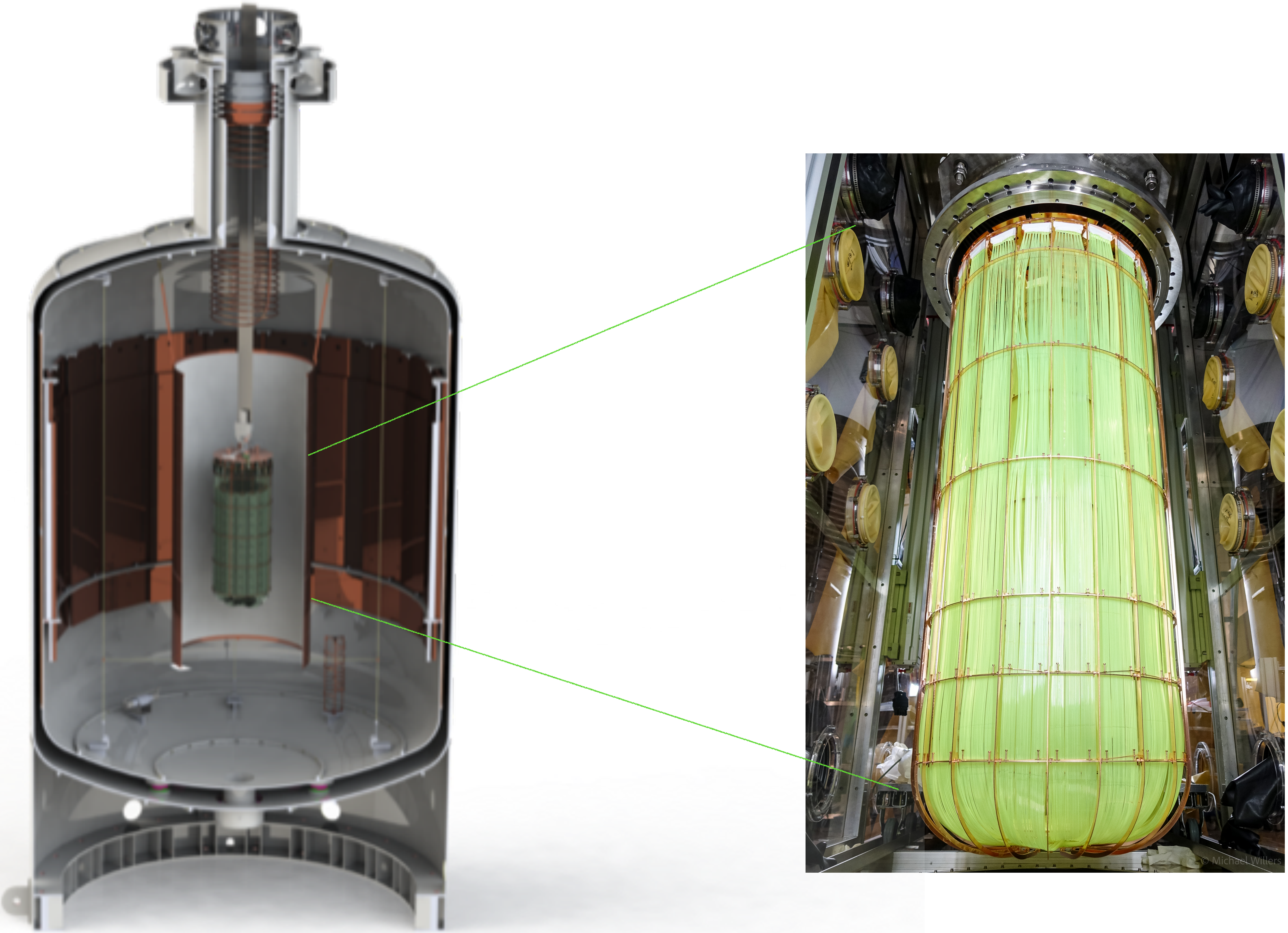
- Value of $T_{1/2}$ for which a ^{76}Ge-enriched experiment has a **50%** chance to observe a signal above background with **3σ** significance
- *Less than one background count* expected in a 4σ Region of Interest (ROI) with 10 t y exposure

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 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



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- 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)]

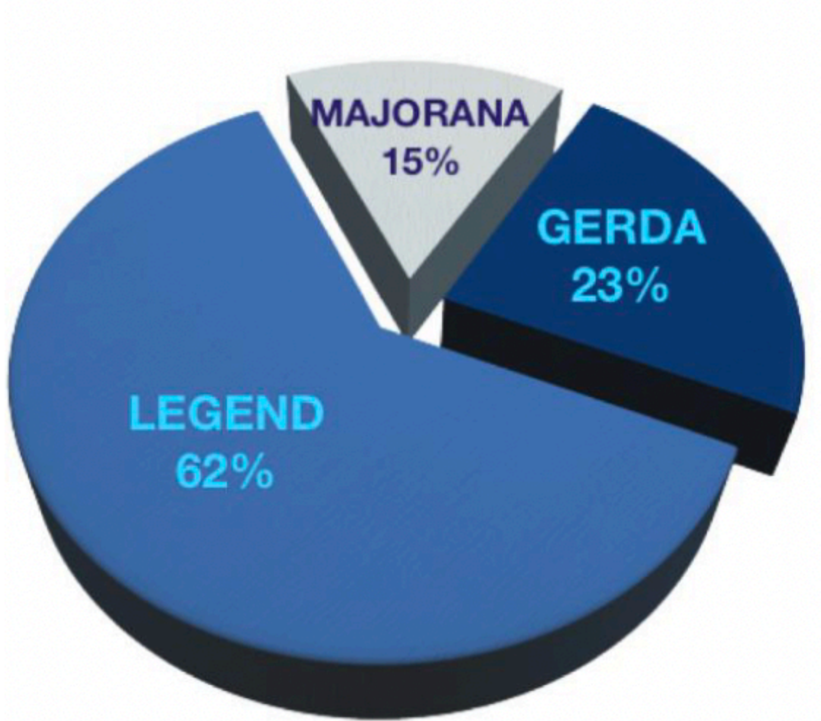
- ~60% of L-200 detectors are of this type
- Larger mass (1.5-2.0 kg, up to <2.5> kg for L-1000)
- but retaining **similar charge drift times across volume**

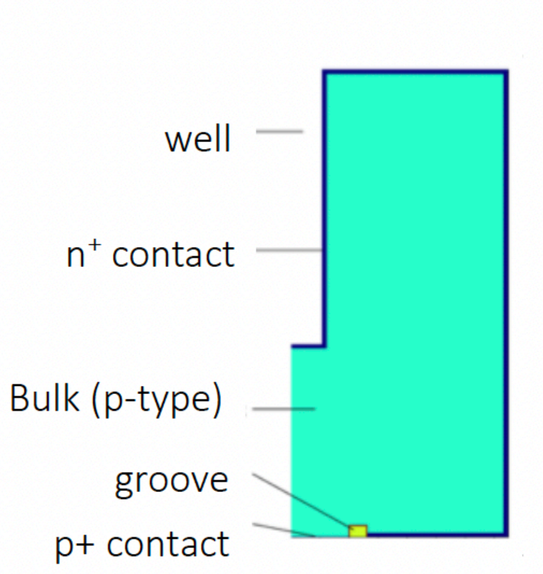
(important for Pulse Shape Discrimination, see later)

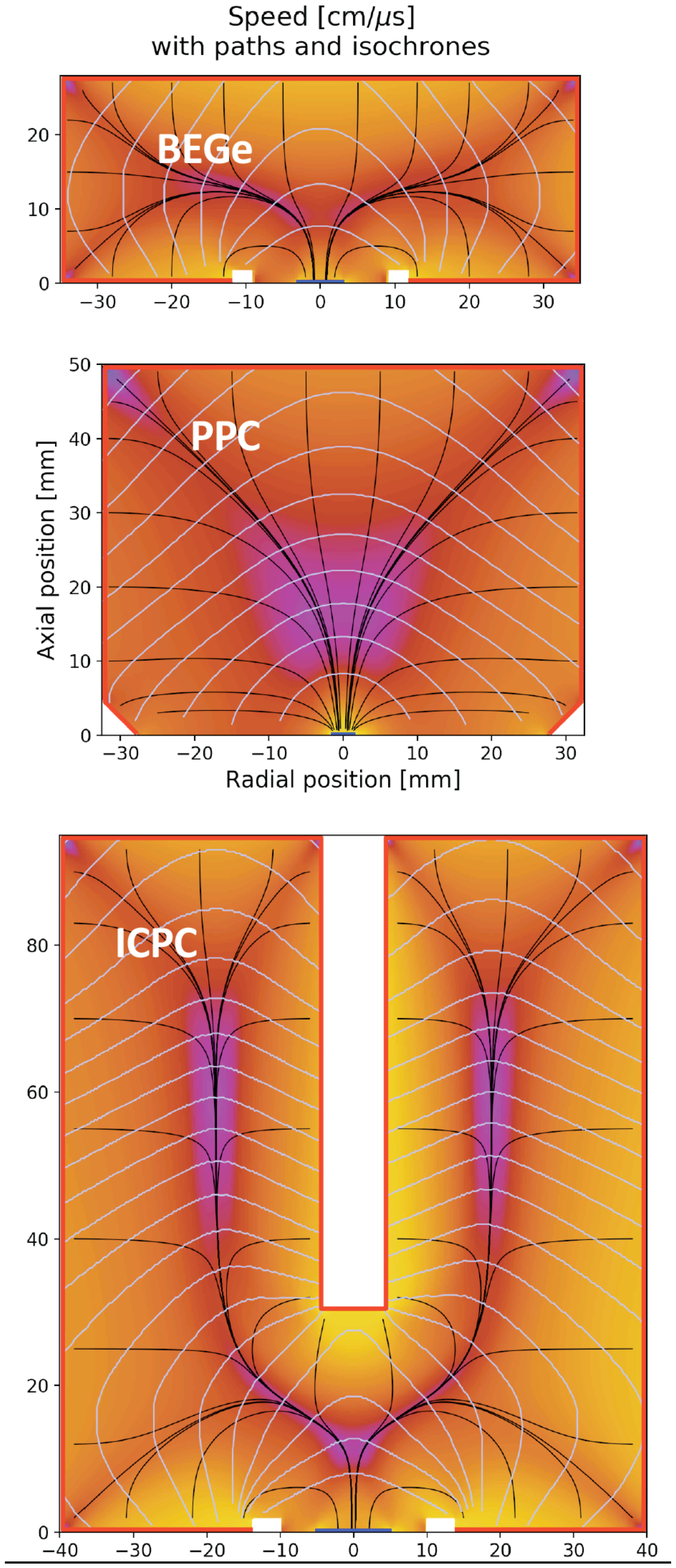
- Reduced surface-to-volume ratio (α and β): less dirty

cables, pre-amps

- Lower cost per kg, higher efficiency







Practice crystal for test of grinding, etching, etc.

The big Germanium "mozzarella"

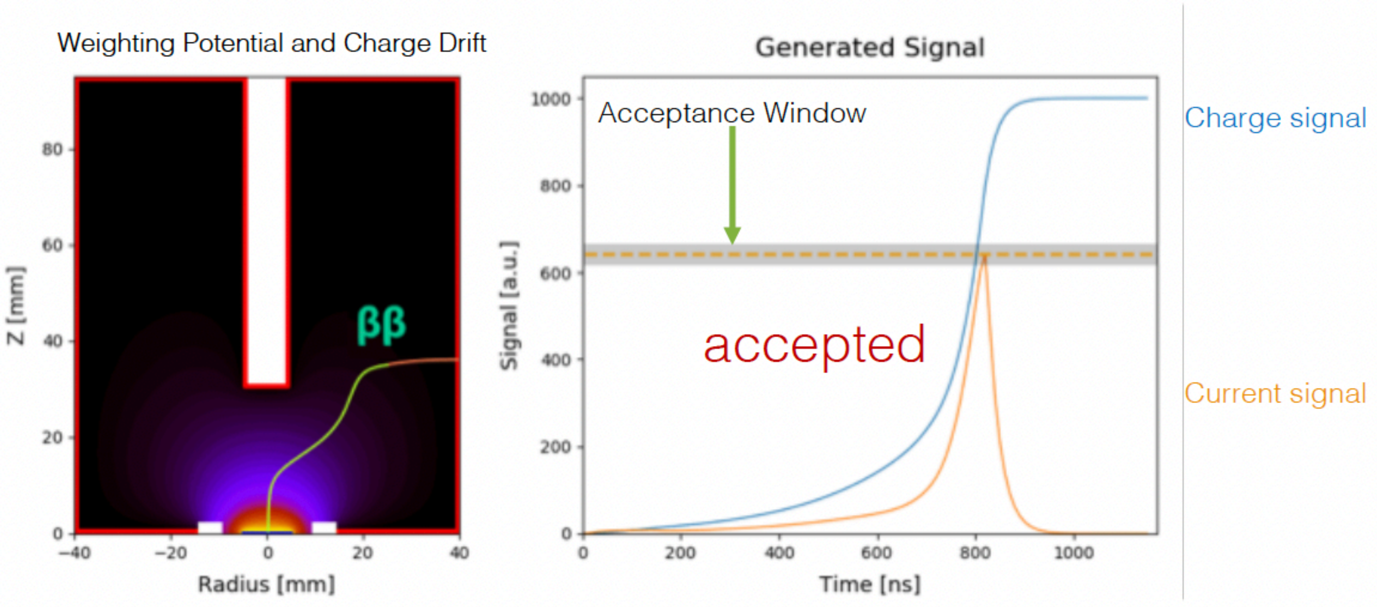
grown by PHDs Company, in Knoxville, Tennessee.

For more on bigger Ge diodes in view of L1000:
https://indico.phy.ornl.gov/event/128/contributions/541/

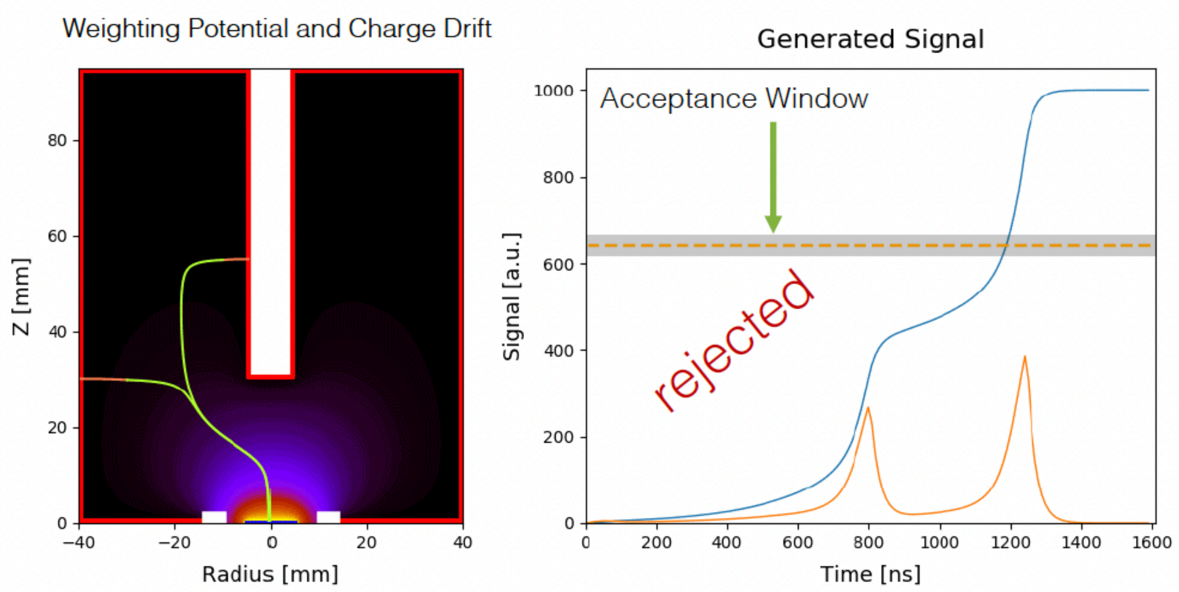
Origin of radioactive bkgs

- 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 $^{40/42}\mathrm{Ar} \rightarrow {}^{40/42}\mathrm{K} \rightarrow {}^{40/42}\mathrm{Ca}^*$ 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

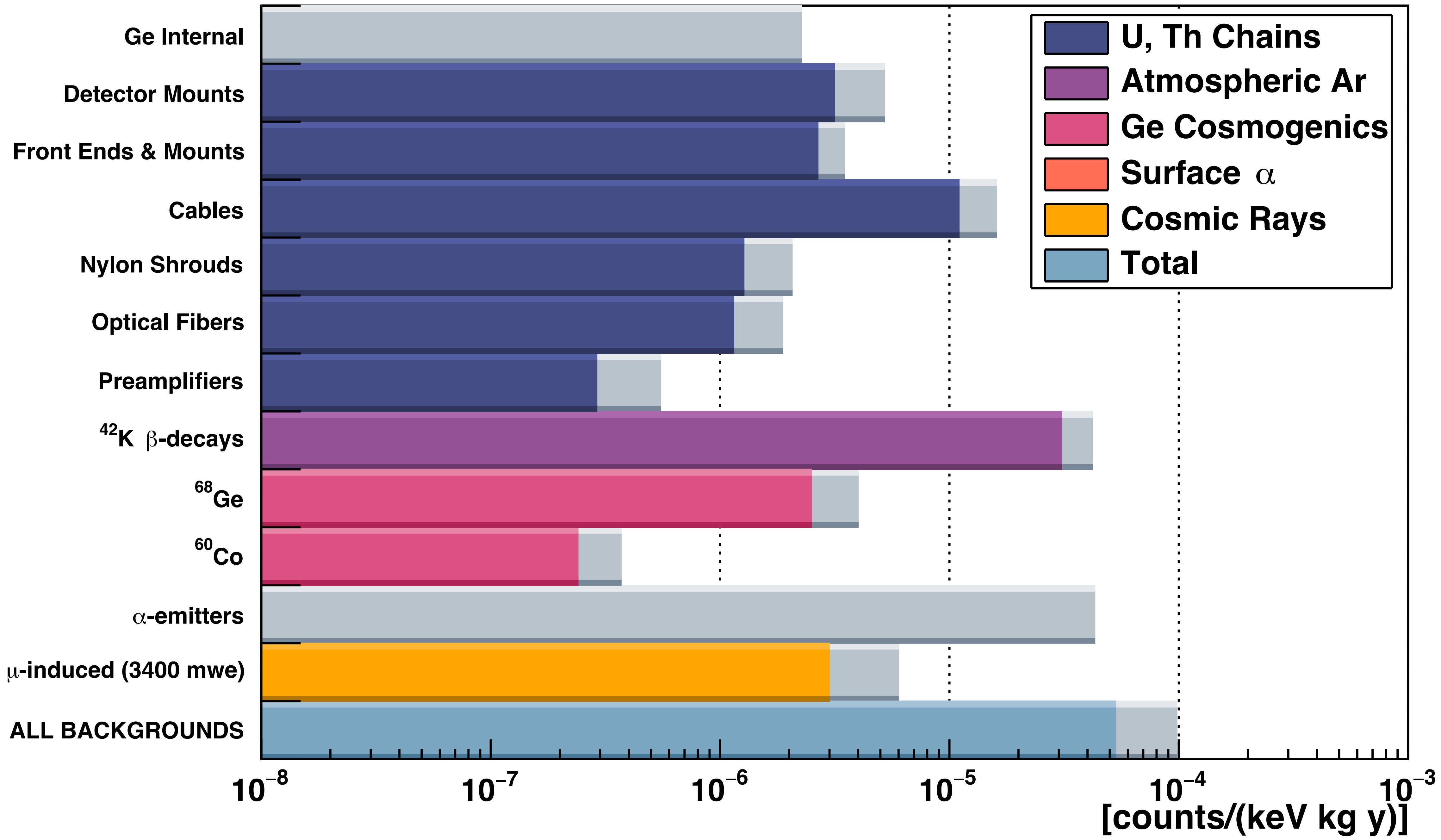
0νββ signal candidate (single-site)



γ-background (multi-site)



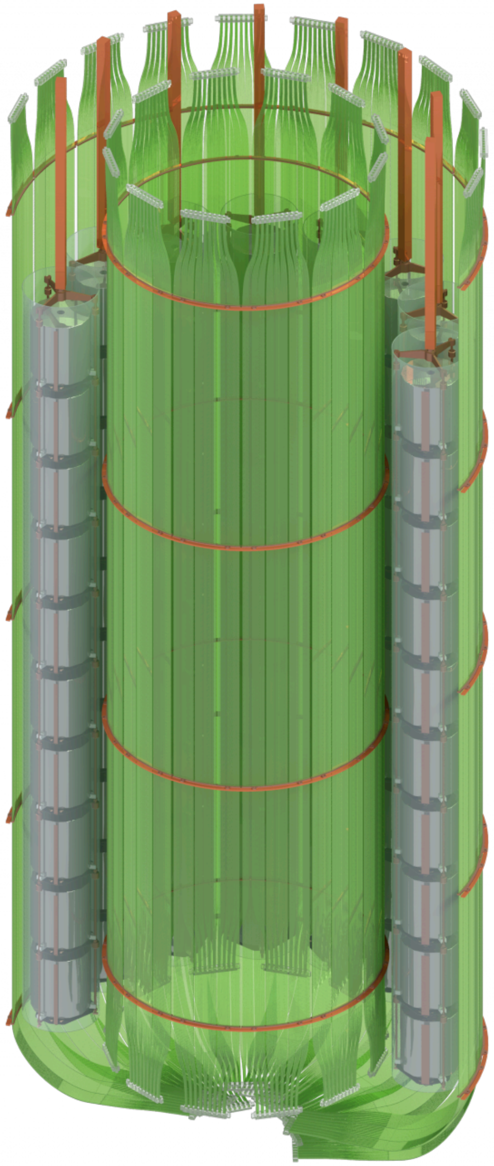
Expected bkg budget L-200

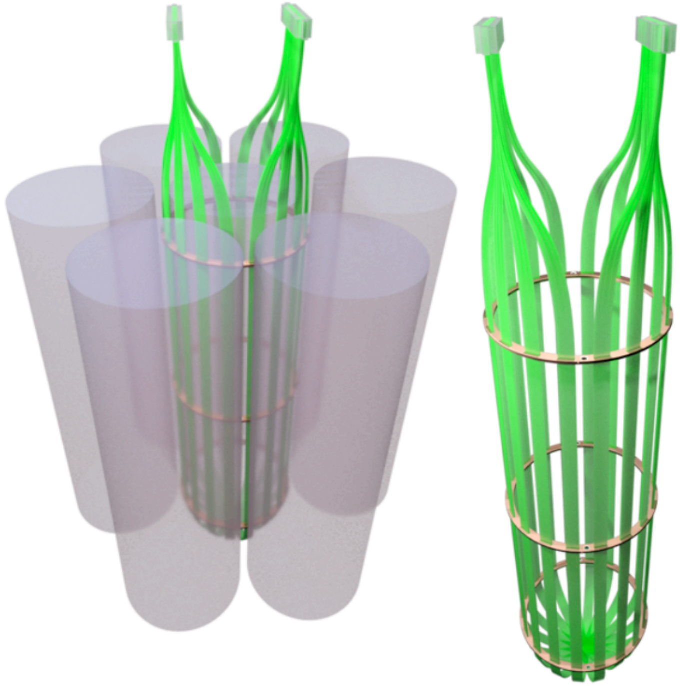


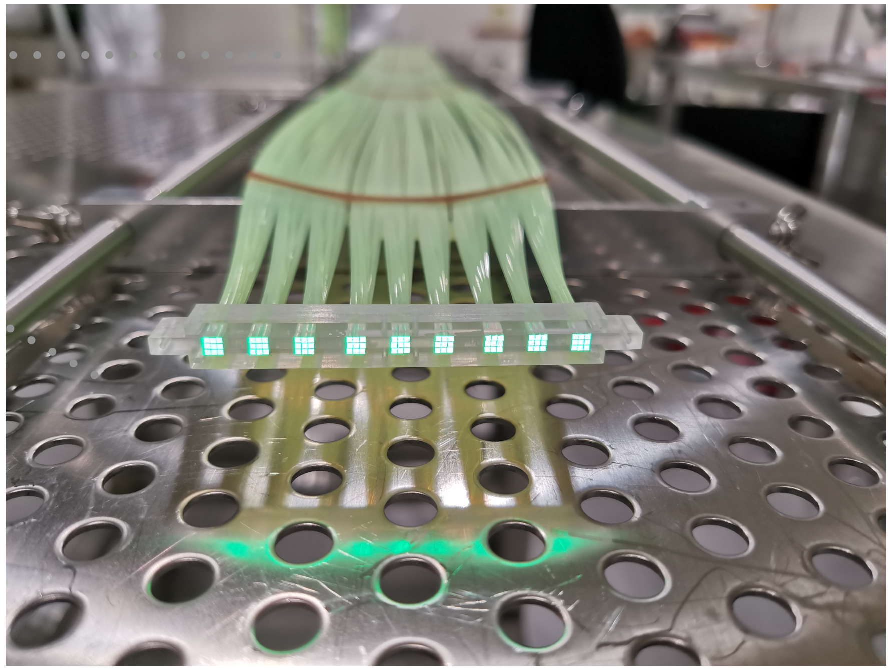
~ 2-3 times lower BI than GERDA

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 of fibers + high-activity β decays of sub-dominant isotope ^{39}Ar *[1.41 Bq/l (e.g. NIM A 574 83)]*

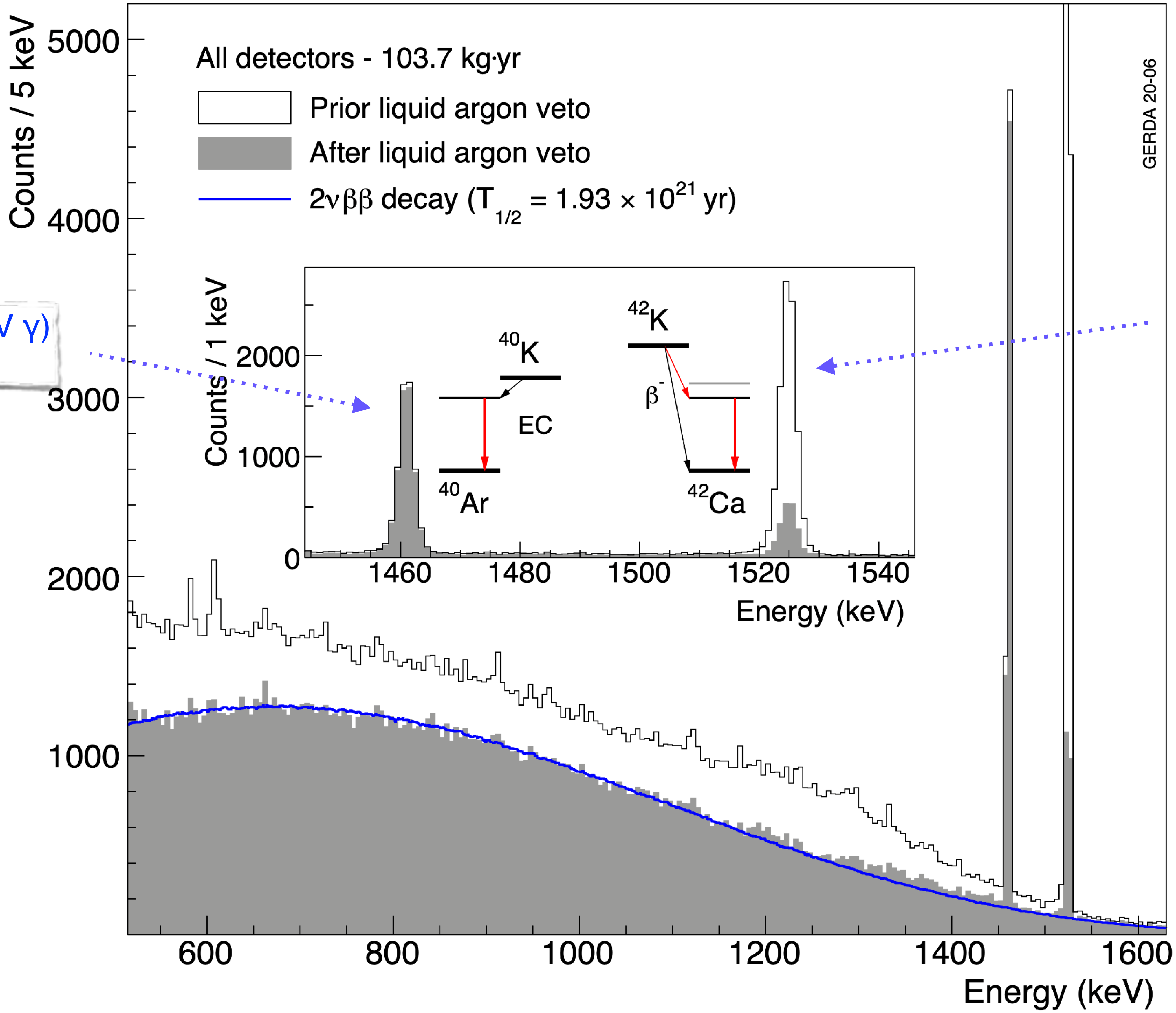






Benefit of active veto (lesson from **GERDA**)

^{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

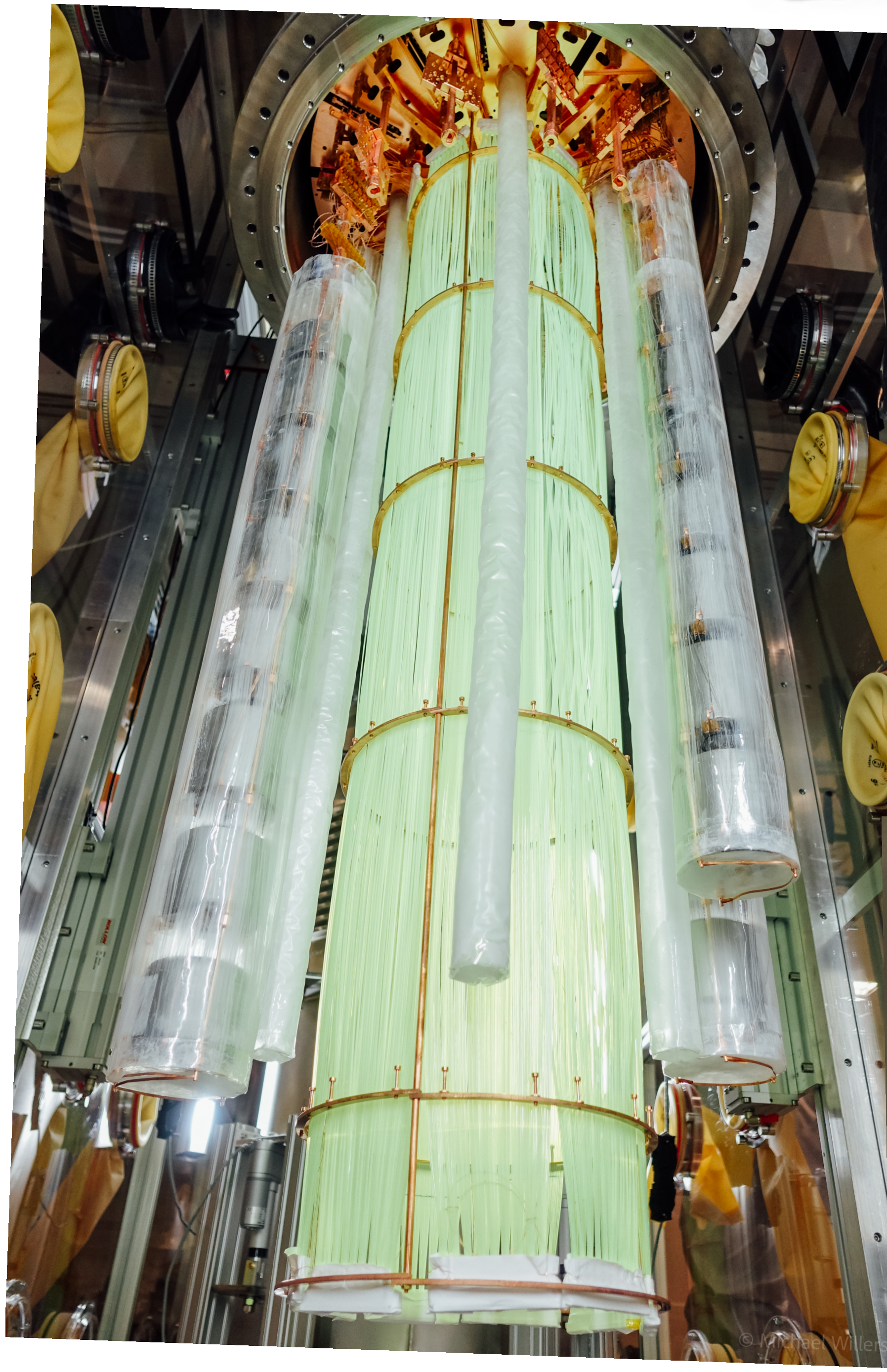
Eur. Phys. J. C (2018) **78**: 388

- 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

At present…

☑ **60 kg taking data since June**

- Taking data during summer for commissioning and performance evaluation
- Rest to be assembled in autumn to reach 200 kg
- Then start physics data taking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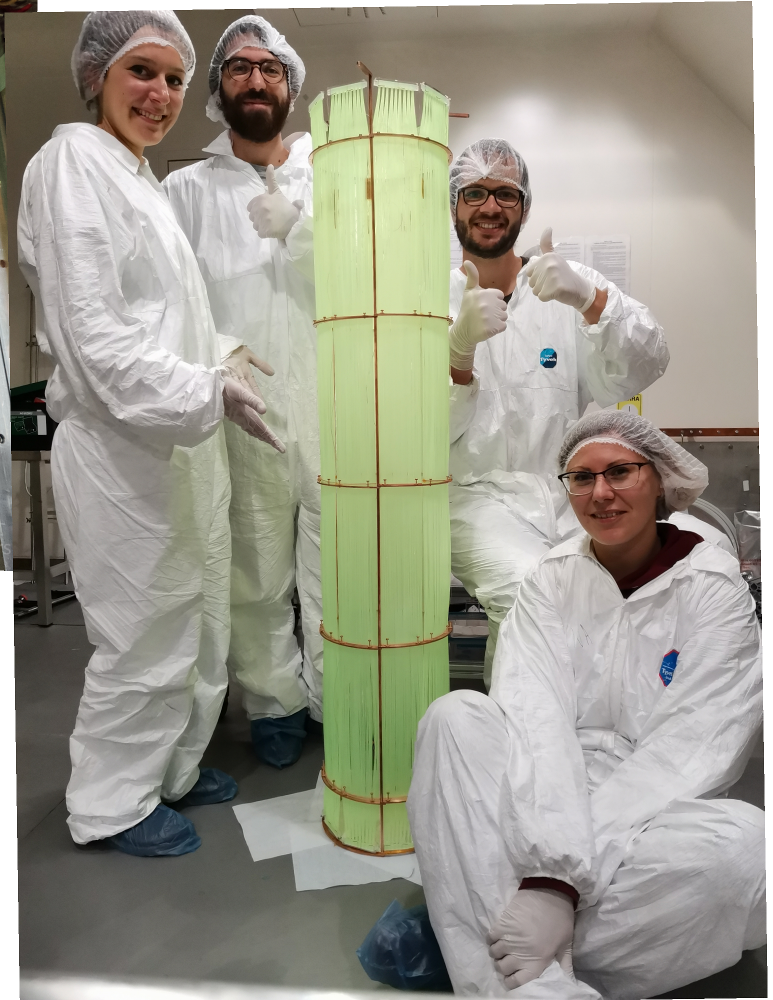
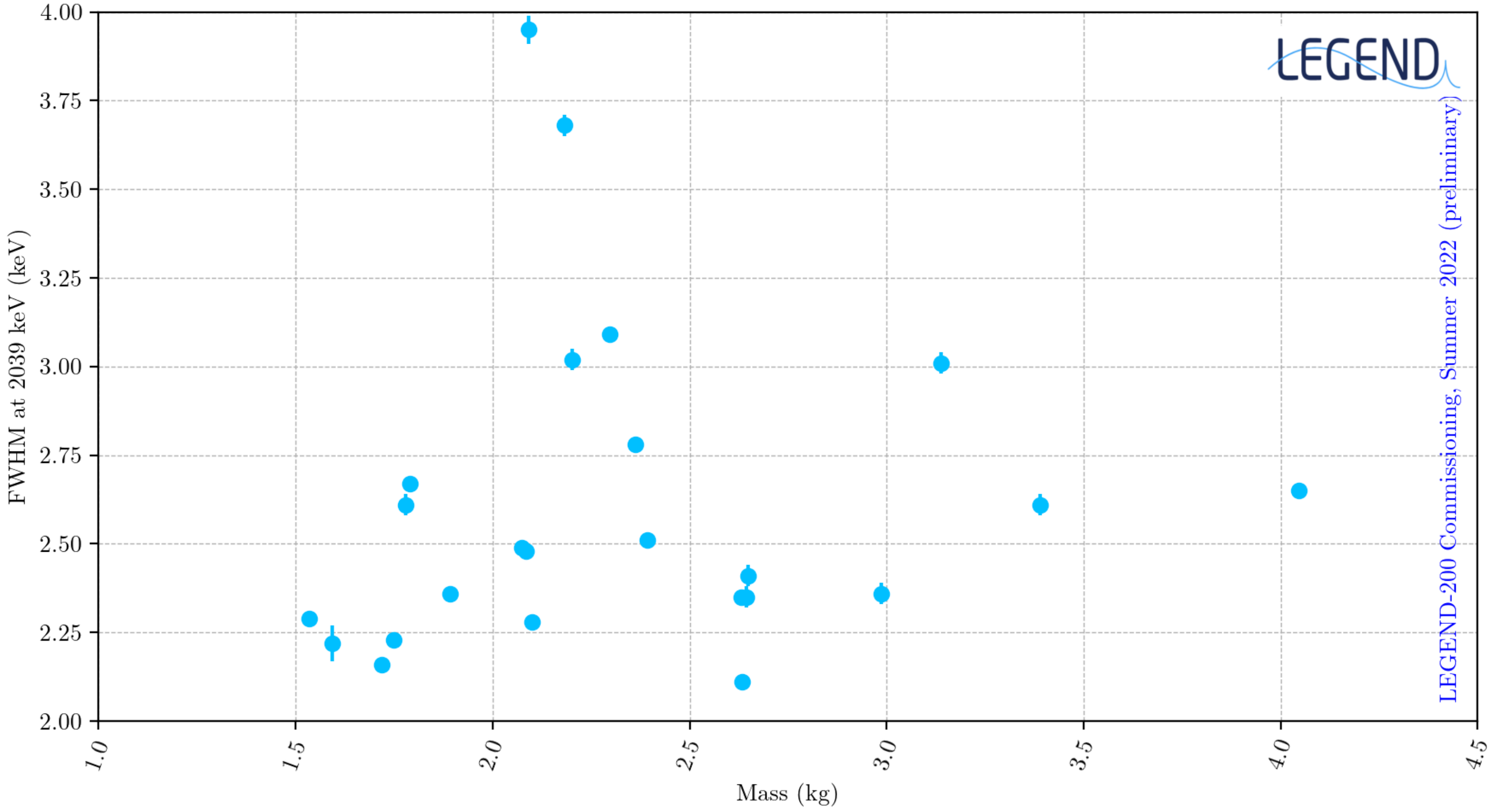
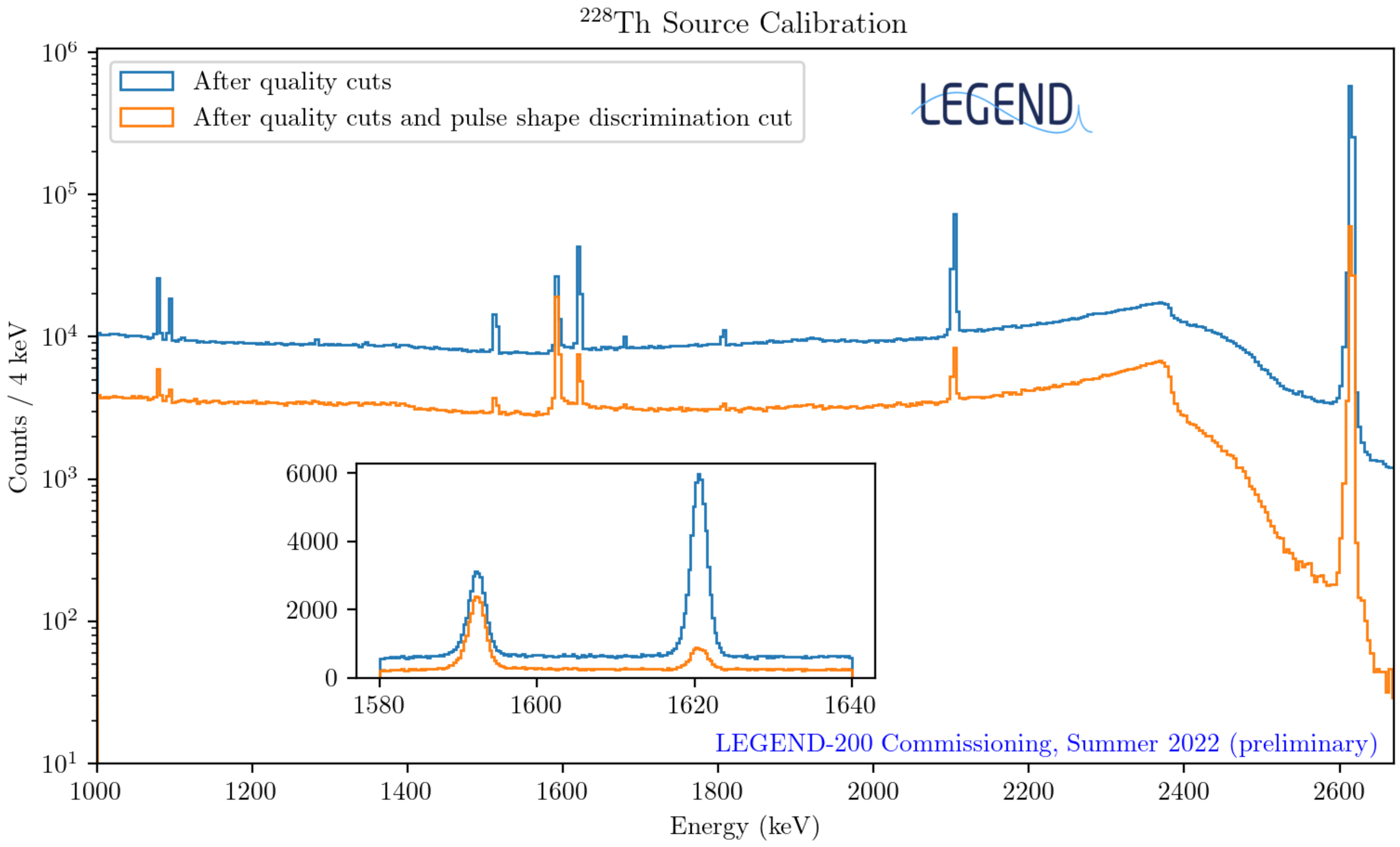


Fresh! Initial commissioning performance

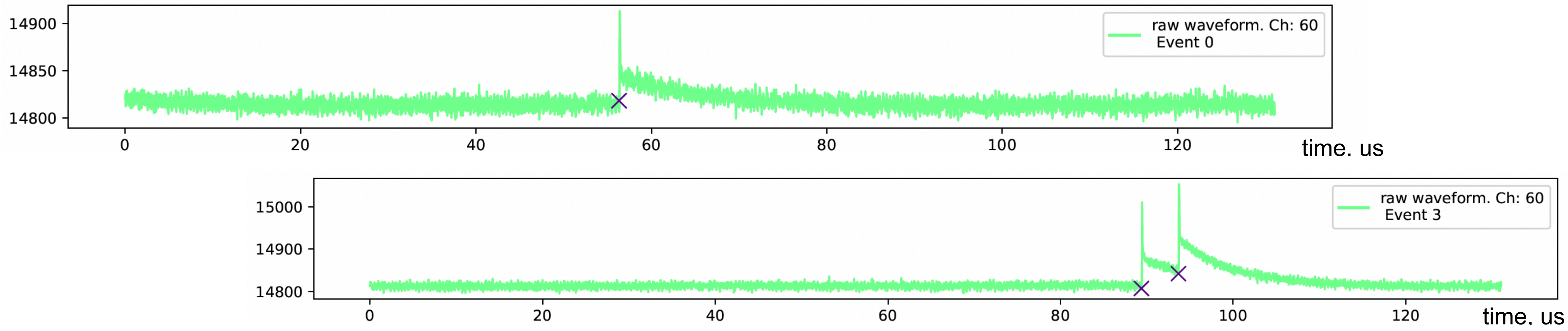


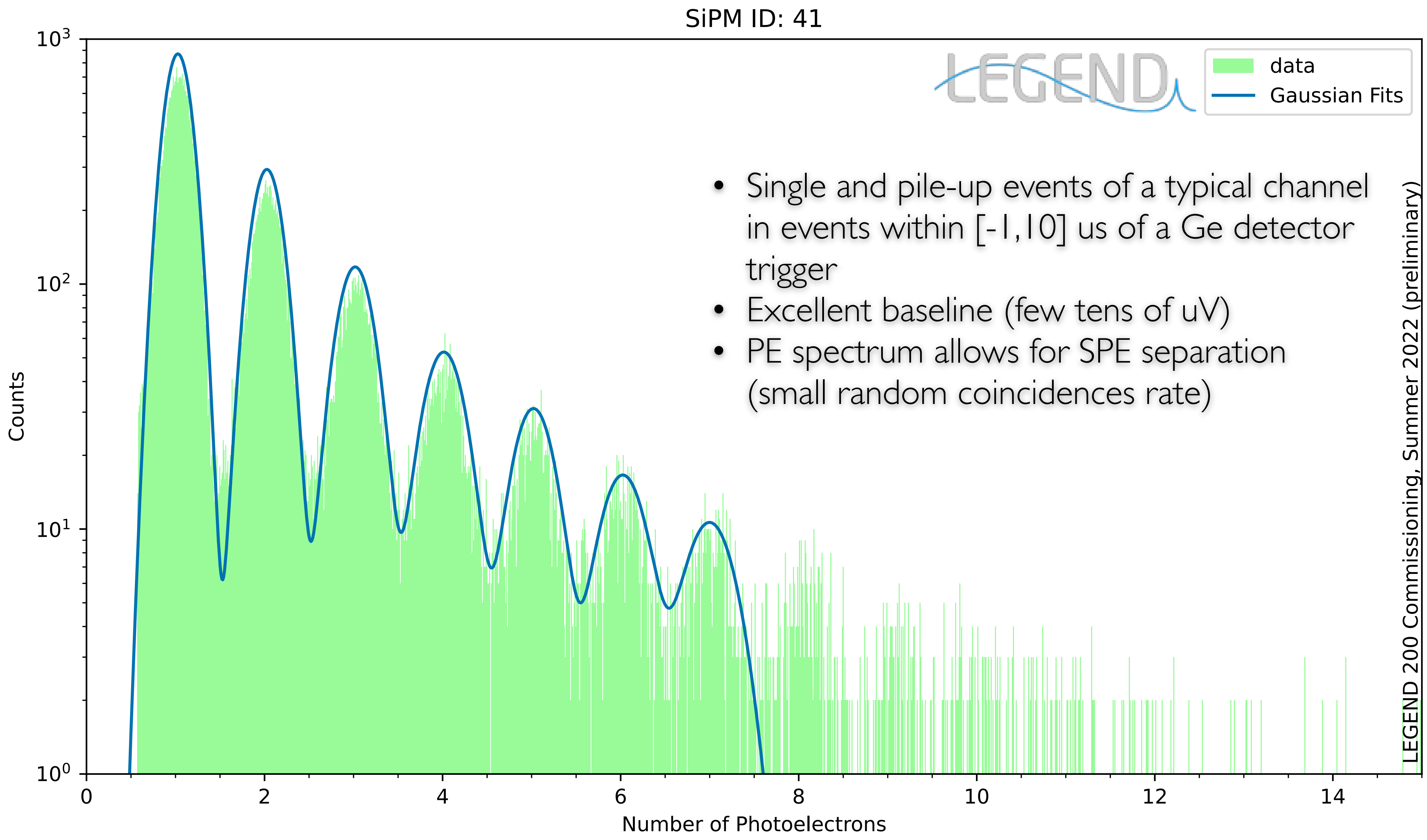
- Preliminary energy resolution from August commissioning runs of 60 kg in full set-up
- Resolution does not depend on detector mass, heavier detectors sport excellent reso
- Work on-going on read-out/noise to improve reso on some channels

- ^{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



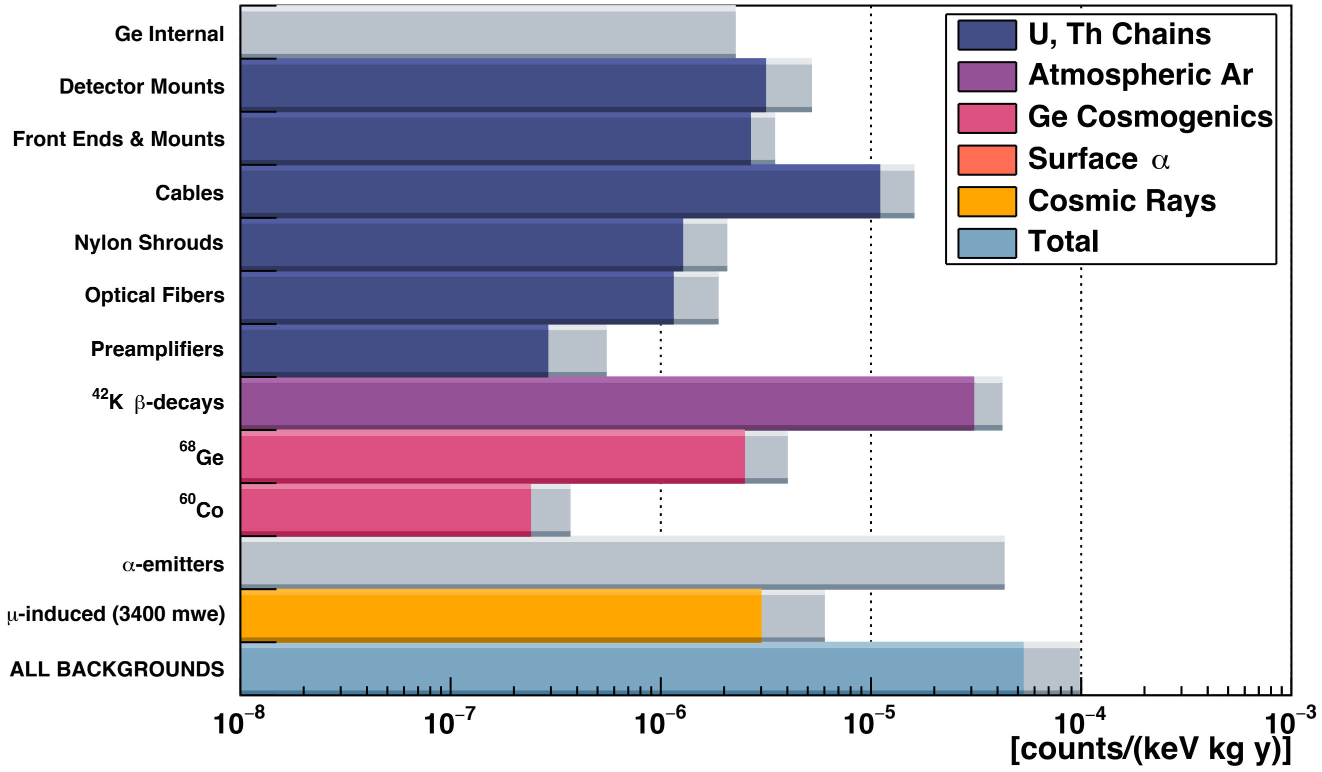
Preliminary SiPM perfo in 60 kg runs

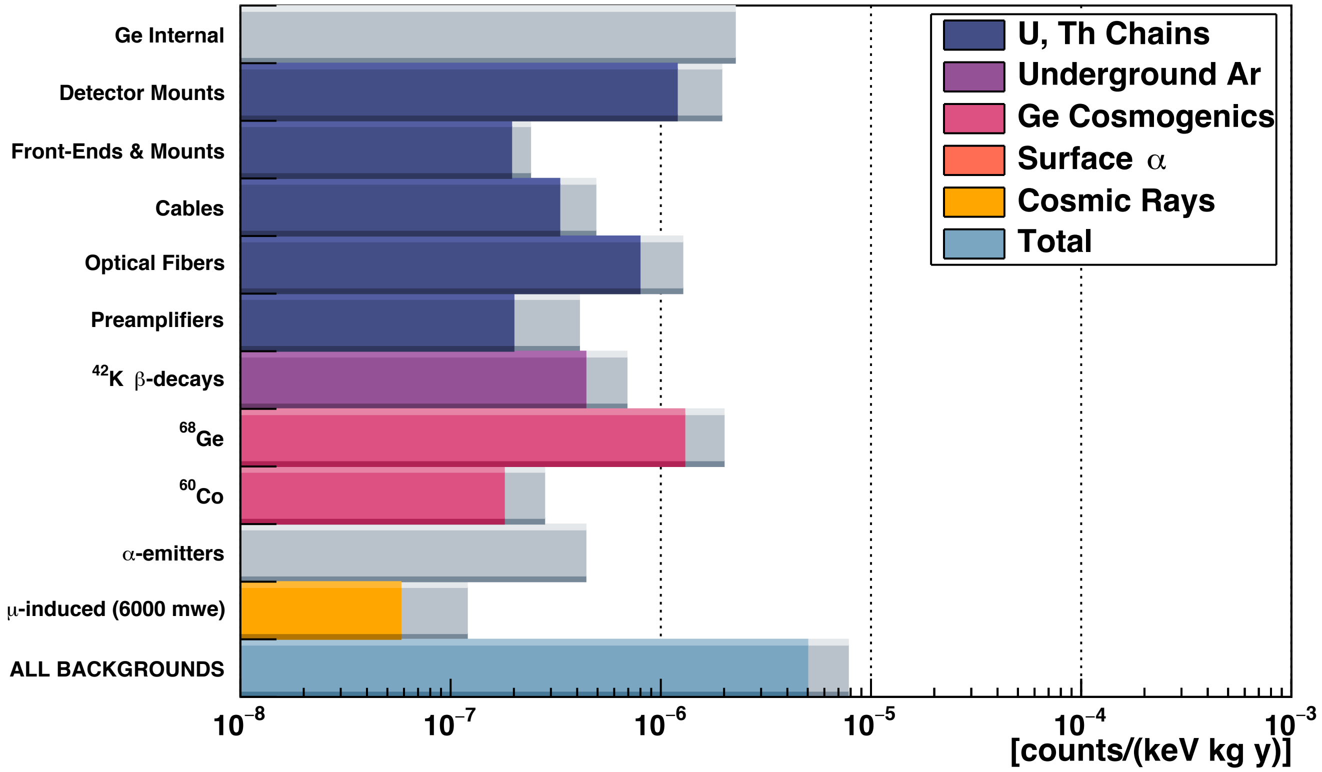




- Single and pile-up events of a typical channel in events within [-1,10] us of a Ge detector trigger
- Excellent baseline (few tens of uV)
- PE spectrum allows for SPE separation (small random coincidences rate)

L-200 → L-1000



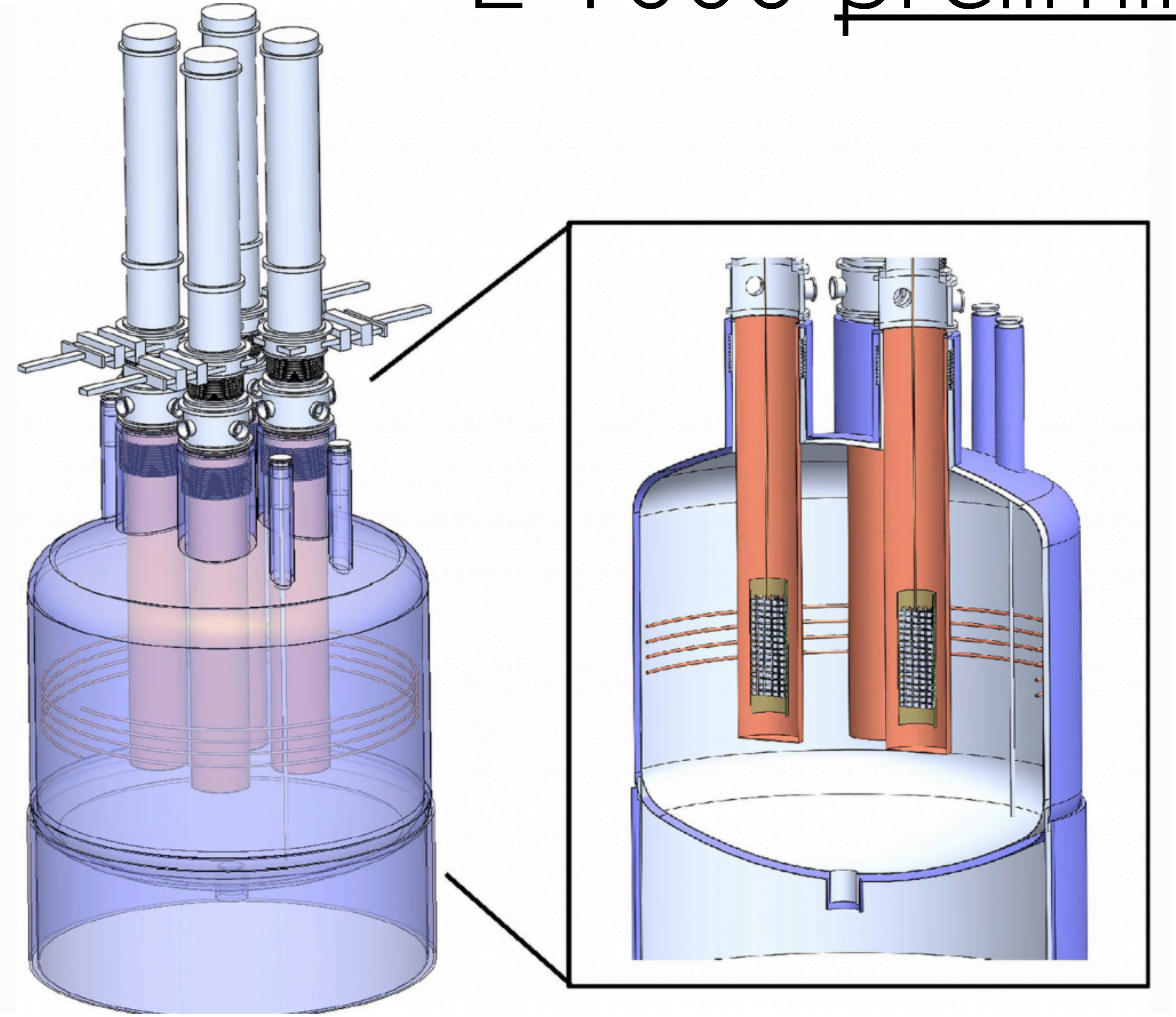


- Largest reductions are on ^{42}K, α, μ
- Need specialised work to “kill” cosmogenic bkg, esp. if at LNGS
- + “trimming” here and there on radio-purity of materials, esp. cables

~ 50 times lower BI than GERDA

L-1000 preliminary design

https://arxiv.org/abs/2107.11462
pre-CDR soon to be published



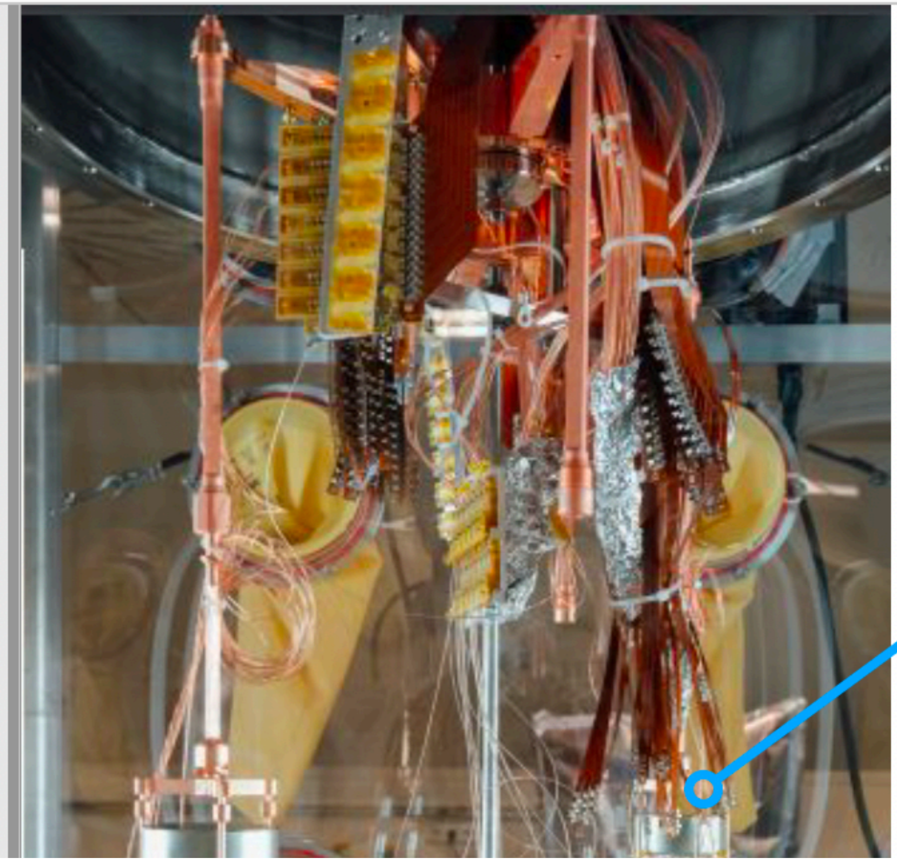
- String concept replicated in 4 payloads, in total ~400 detectors
- Dedicated Underground Ar cryostat, ~3m^3 in volume
- Modest-sized LAr cryostat in “water tank” (6 m Ø LAr, 2-2.5 m layer of water) or large LAr cryostat w/o water (9 m Ø)
  - Other options still remain under investigation in order to 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, UGEF Cu, PEN, neutron veto, use of UG Ar, radio-cleaner fibers

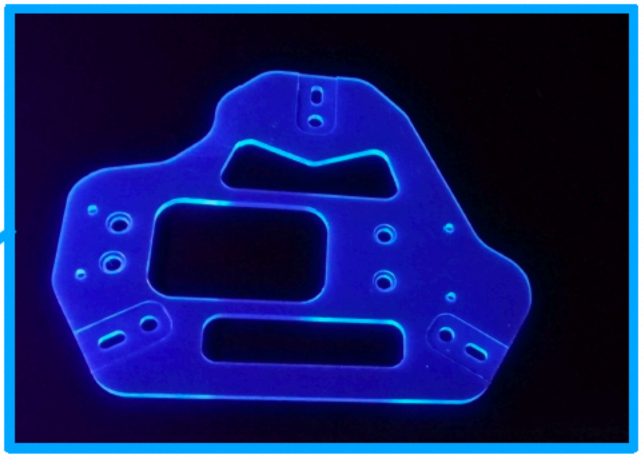
2 examples of remedies against bkg

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

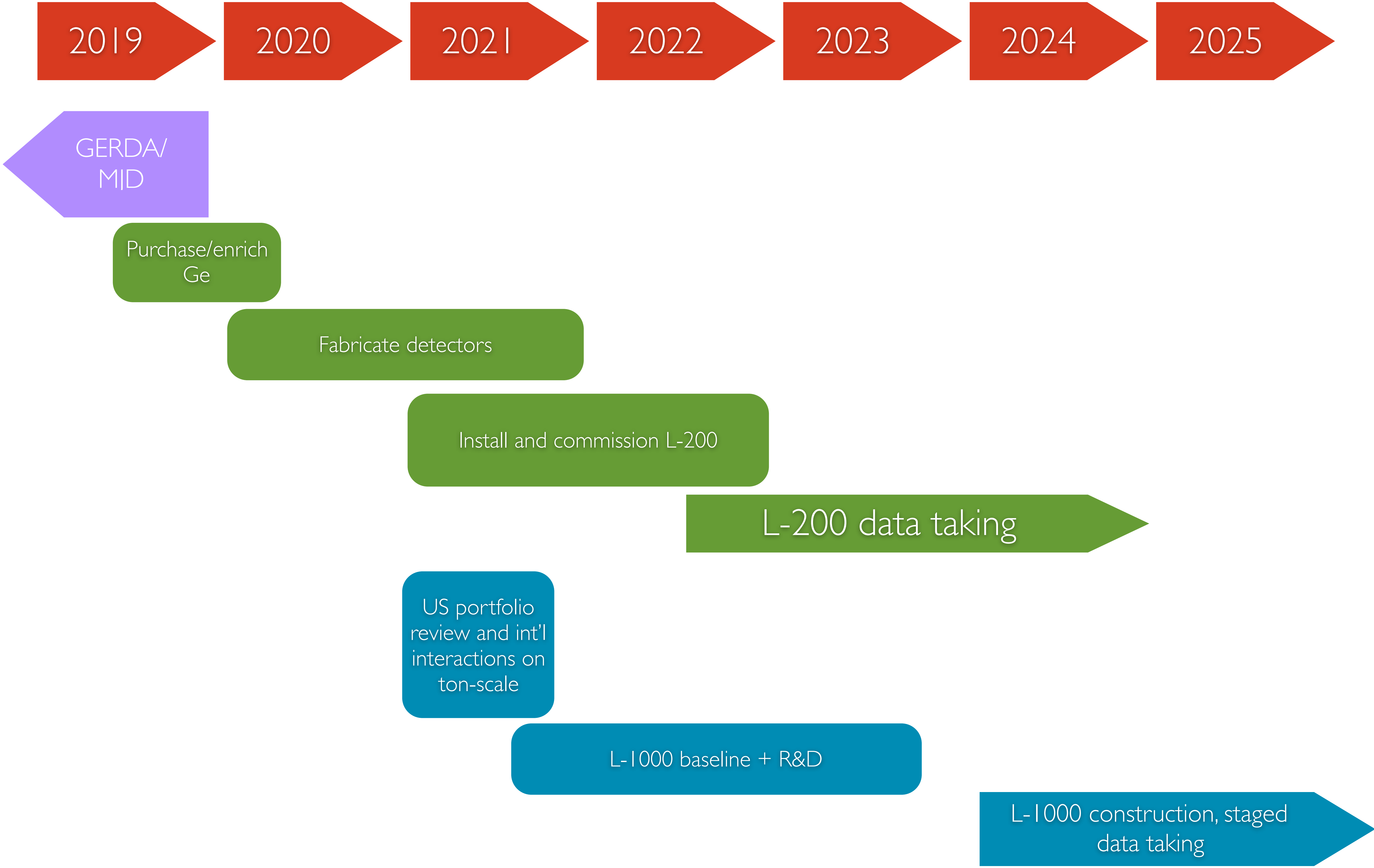
- PEN — Poly(ethylene 2,6-naphthalate) is a scintillating plastic (1/3 LY of conventional plastic scintillators)
- Meets radio-purity req. ≤ 1 μBq/piece for Ra/Th, it's self-vetoing



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

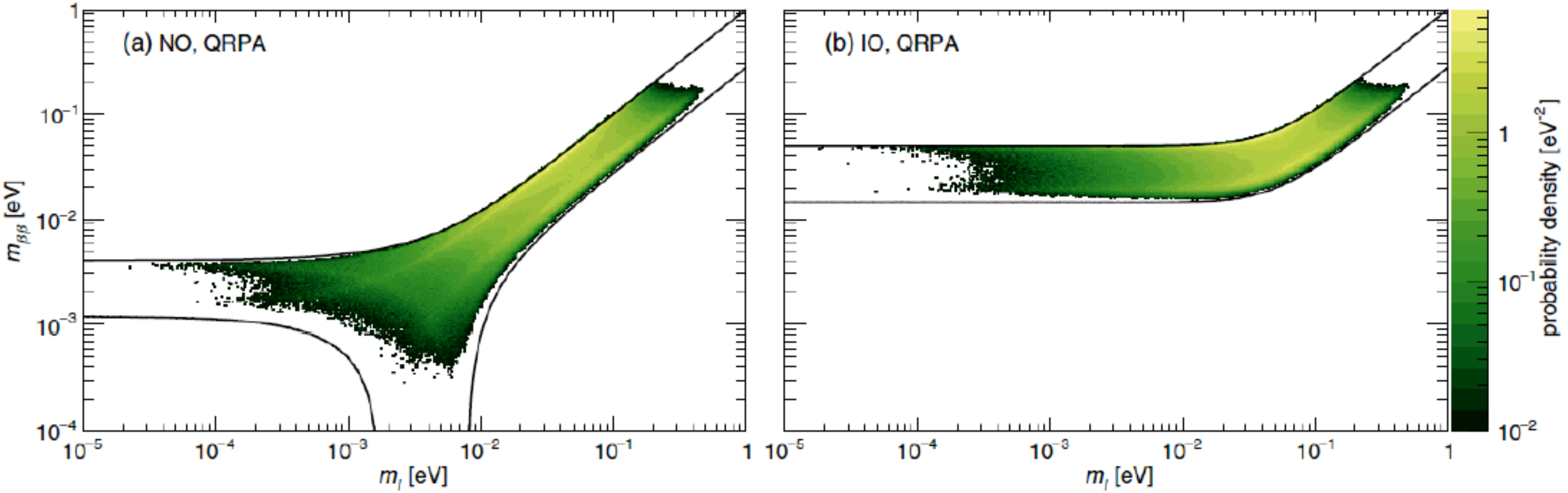
Back-up

MO separation

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

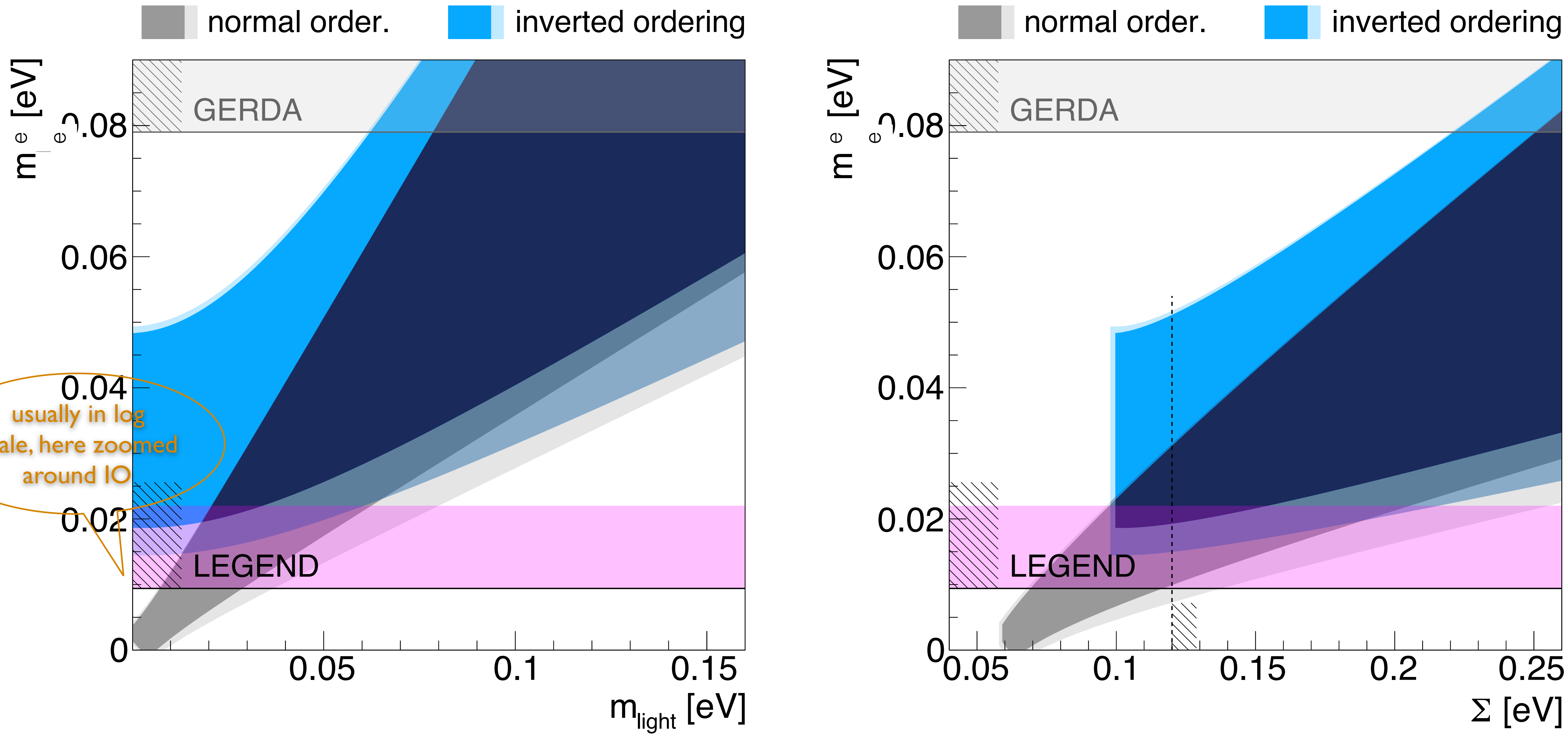
$$= \left|m_0 c_{12}^2 c_{13}^2 + \sqrt{m_0^2 + \delta m_{\rm sol}^2}\, s_{12}^2 c_{13}^2 e^{2i(\alpha_2-\alpha_1)} + \sqrt{m_0^2 + \delta m_{\rm sol}^2 + \delta m_{\rm atm}^2}\, s_{13}^2 e^{-2i(\delta_{\rm CP}+\alpha_1)}\right| \quad \text{NO}$$

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



Phys. Rev. D 96, 053001

Connection with mass ordering

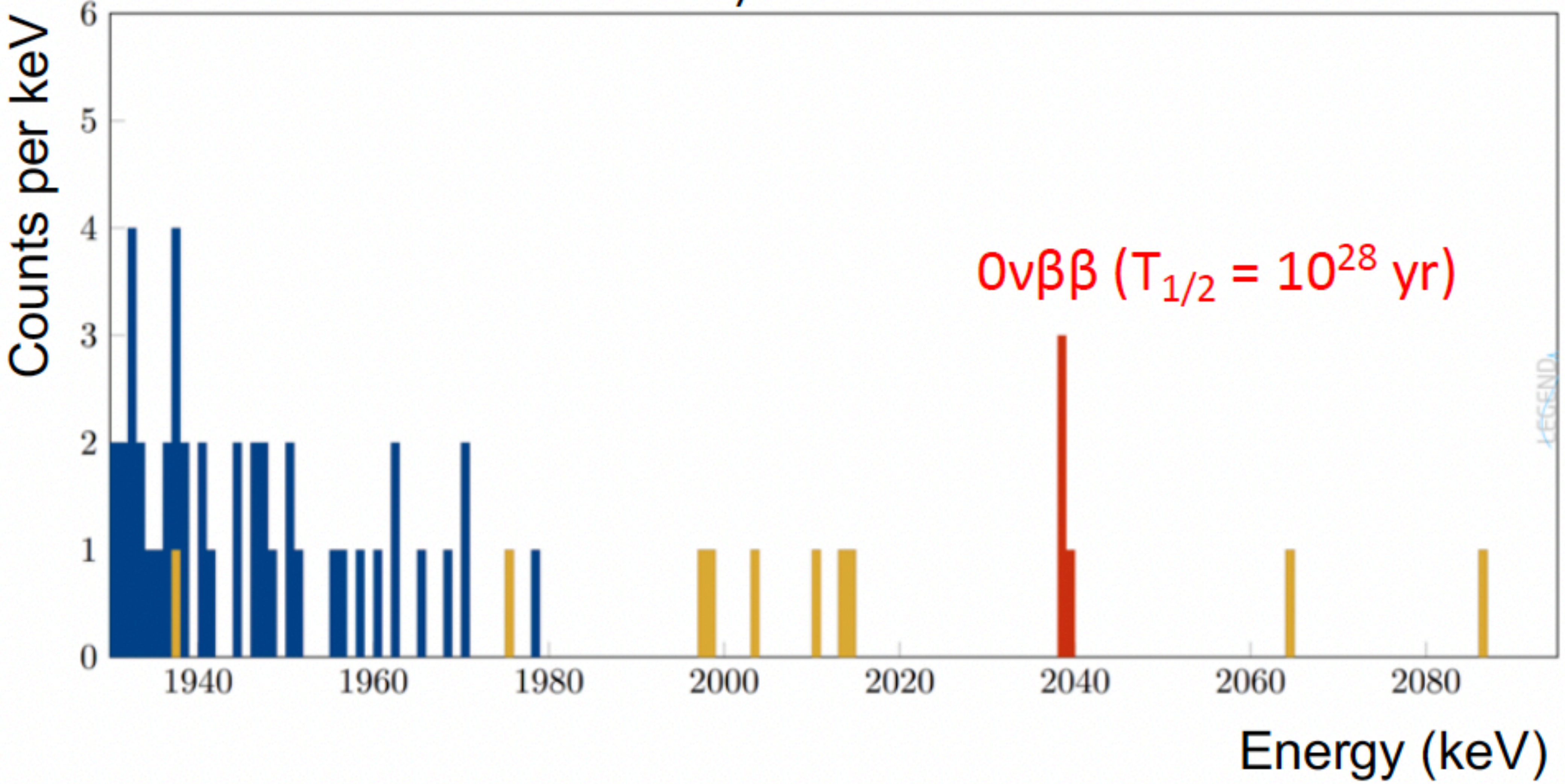


usually in log scale, here zoomed around IO

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

- 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)

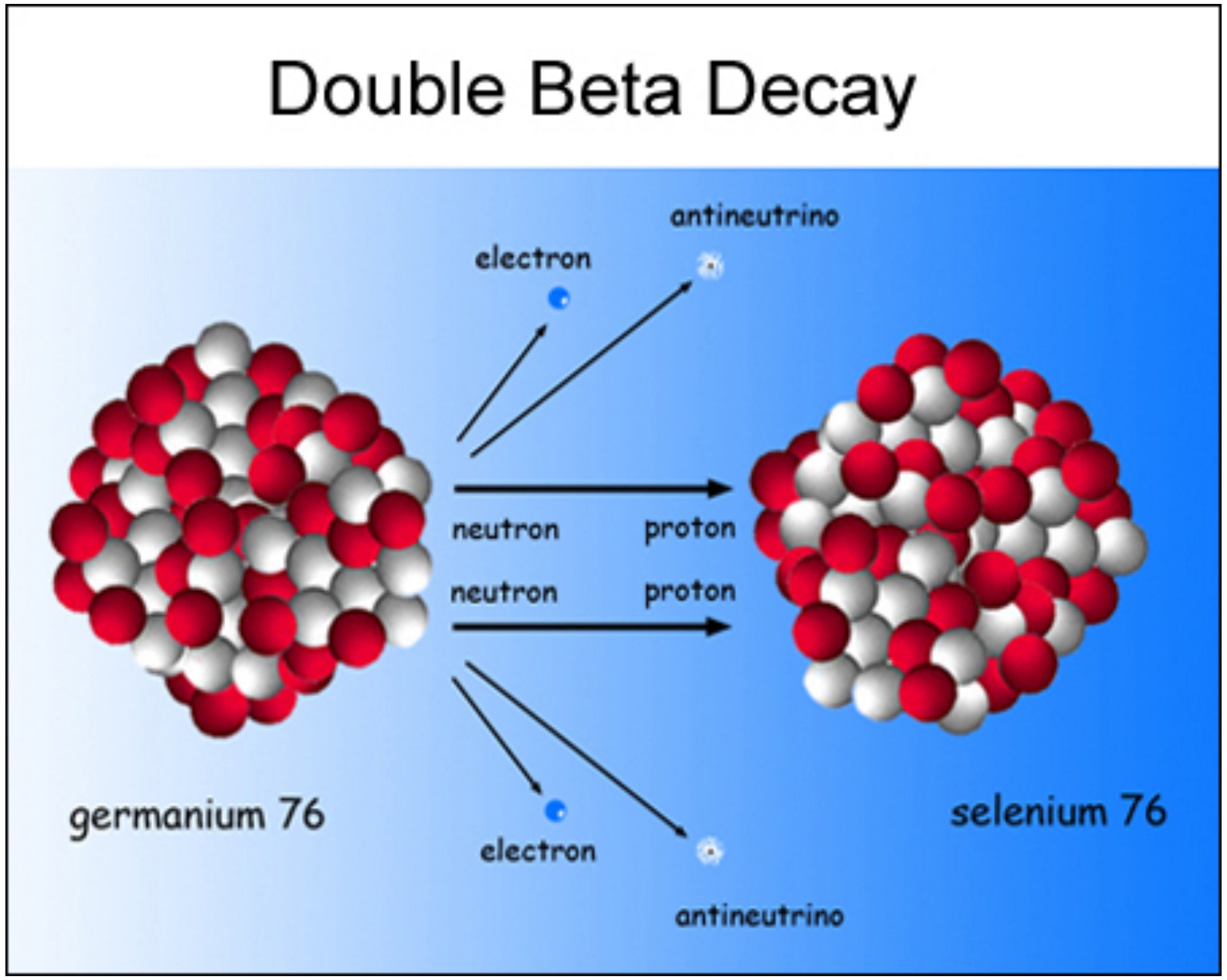
Simulated example spectrum, after cuts, from 10 years of data



0νββ ($T_{1/2} = 10^{28}$ yr)

0ν2β decays

ΔL=0



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

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

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

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

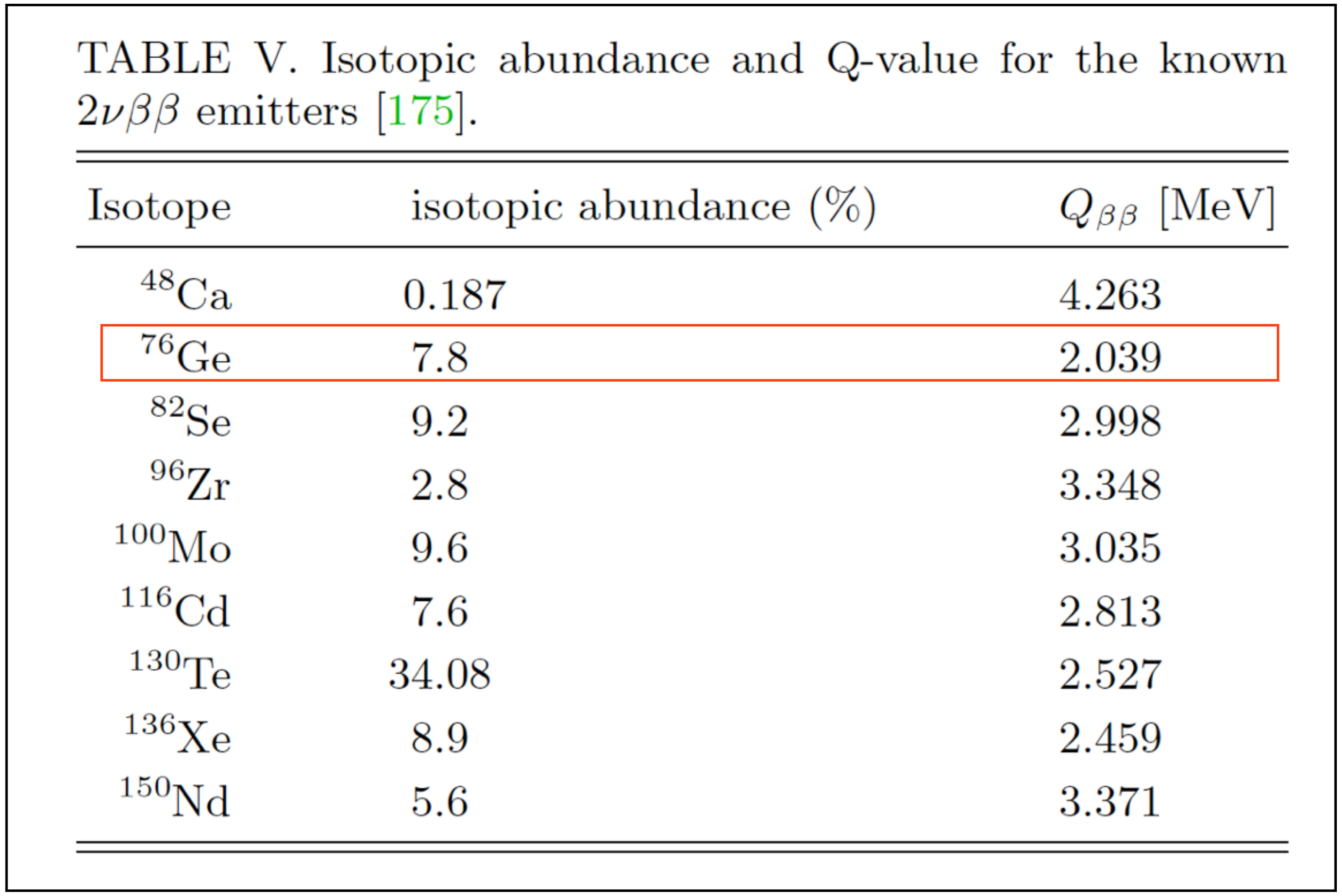


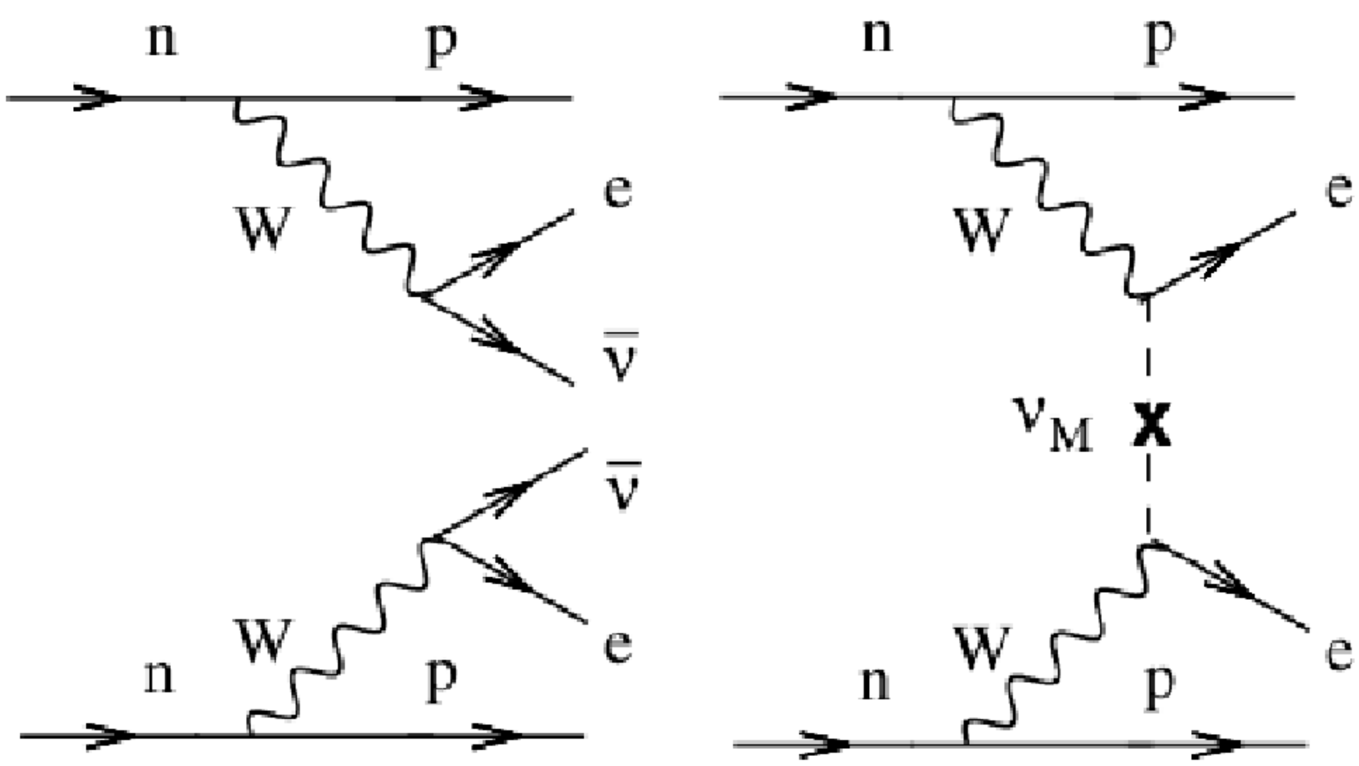
TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

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

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

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)

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

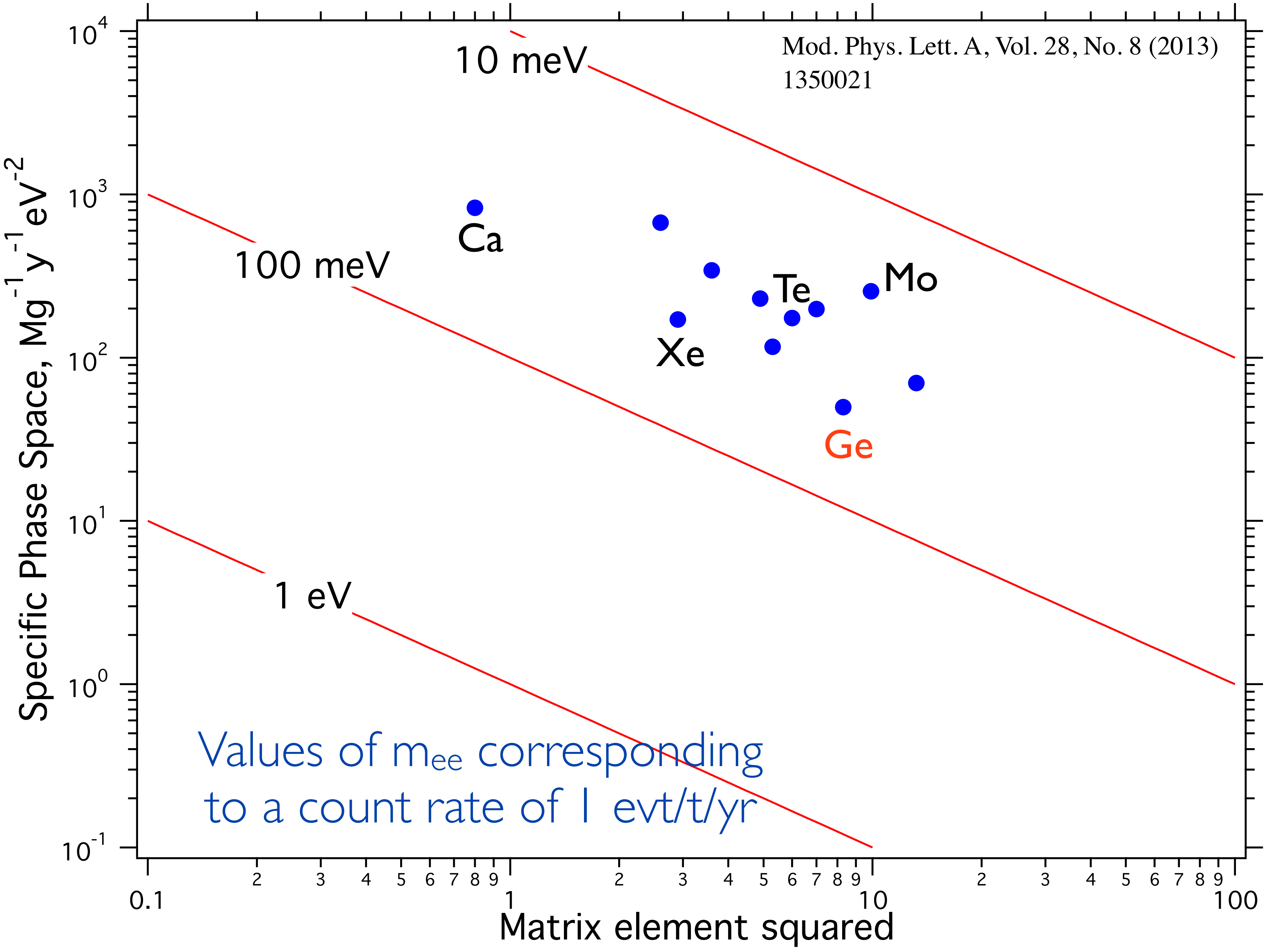
nuclear matrix element

phase space factor

effective Majorana neutrino mass

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

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

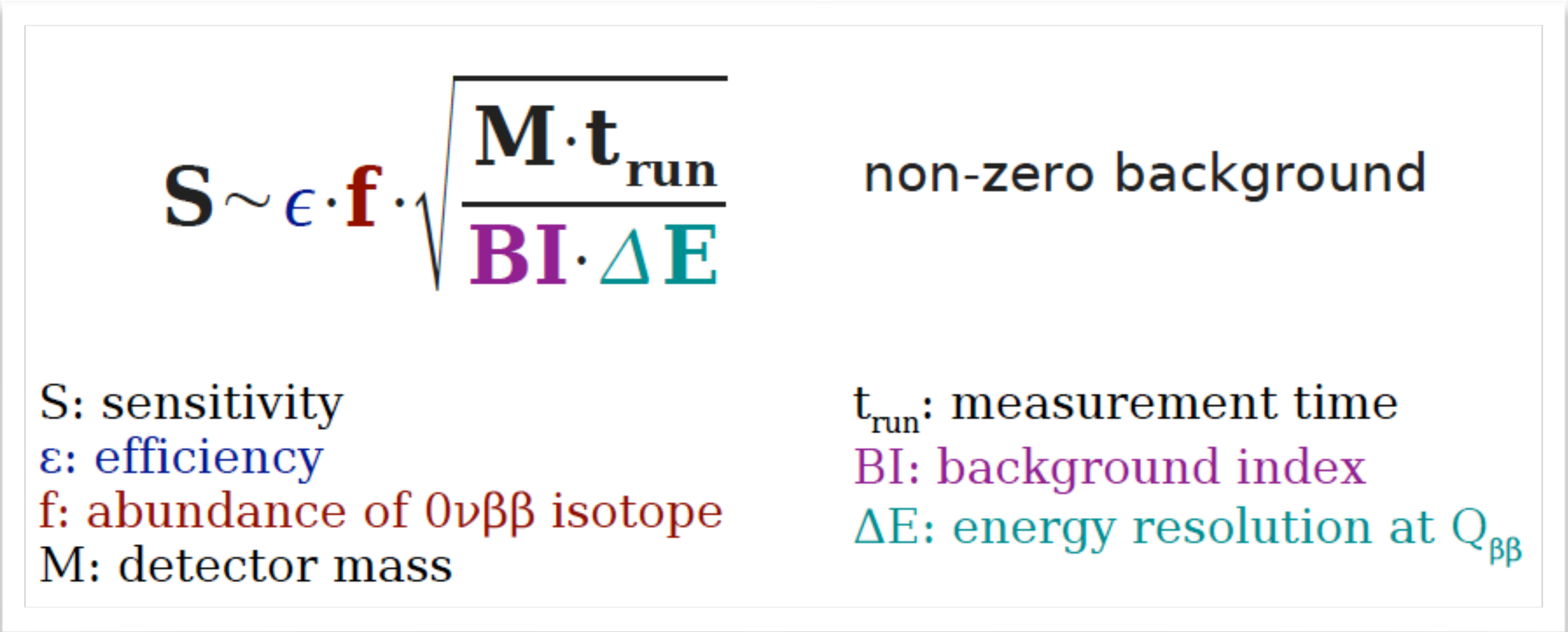
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \underset{\substack{\uparrow \\ \textit{phase space factor}}}{G^{0\nu}}(Q_{\beta\beta}, Z)\ \underset{\substack{\uparrow \\ \textit{nuclear matrix element}}}{\left|M^{0\nu}\right|^2} \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

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

effective Majorana neutrino mass

Experimental sensitivity

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



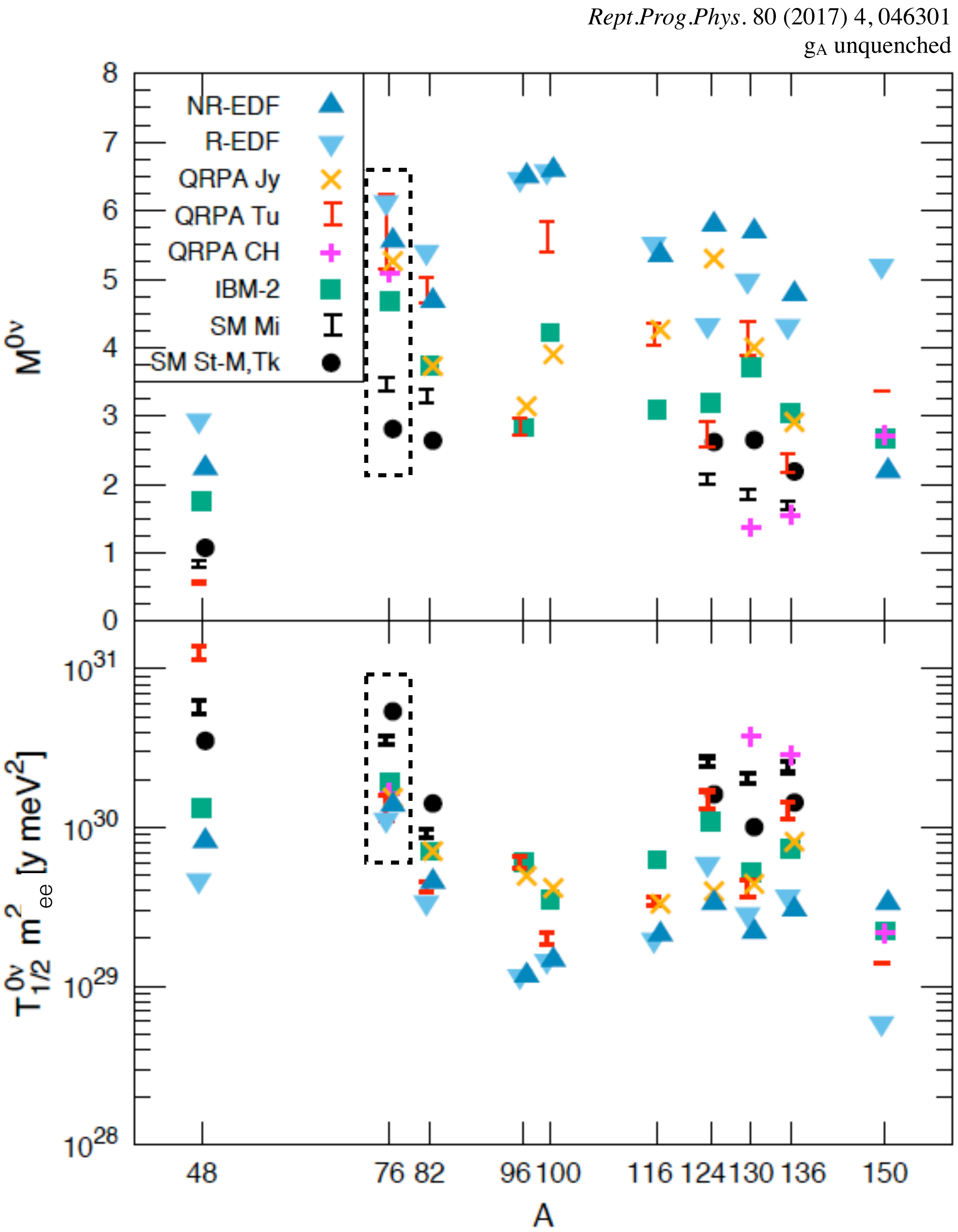
$$S \sim \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t_{run}}{BI \cdot \Delta E}}$$

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 $Q_{\beta\beta}$

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}

Other BSM physics opportunities

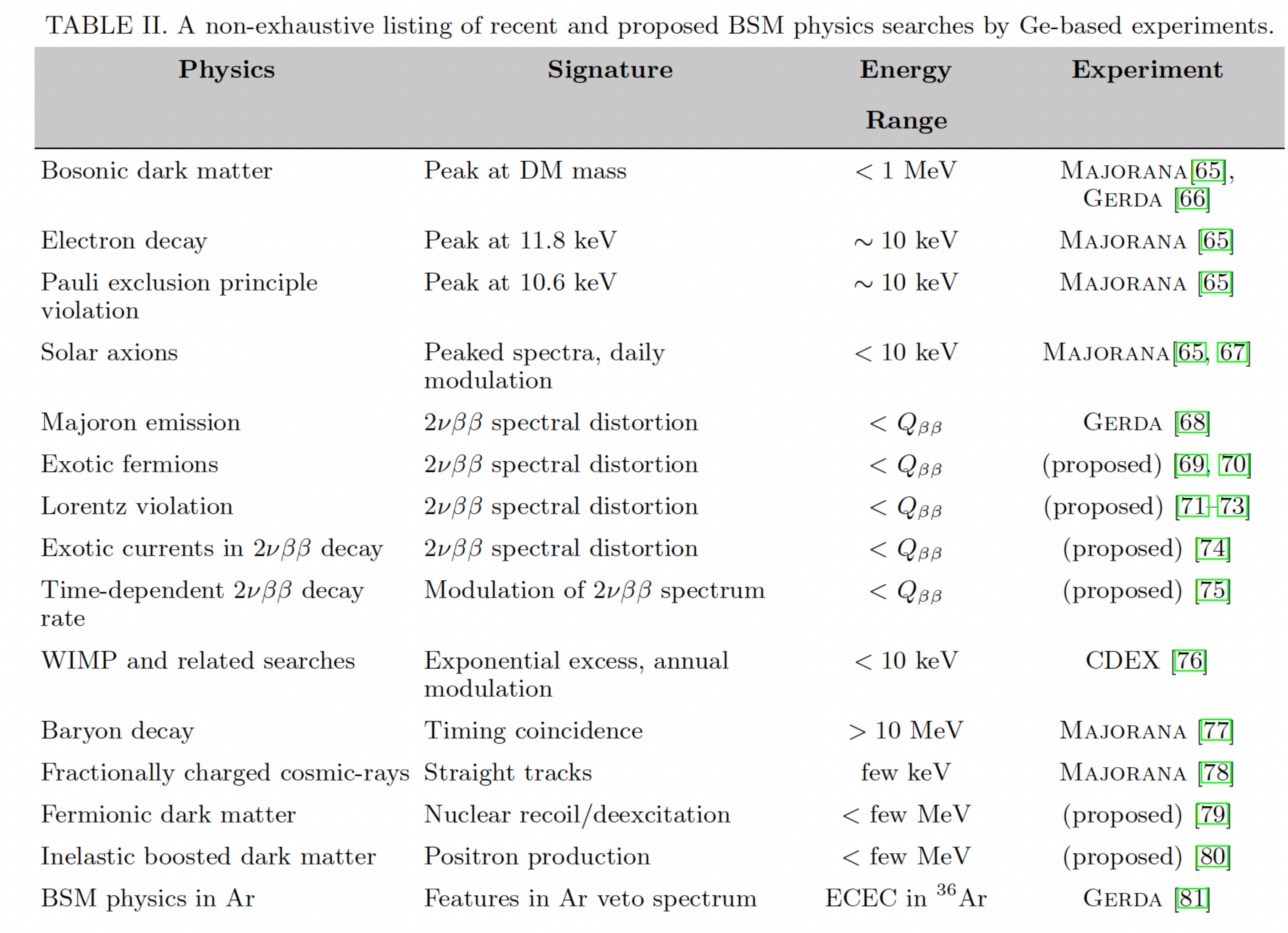


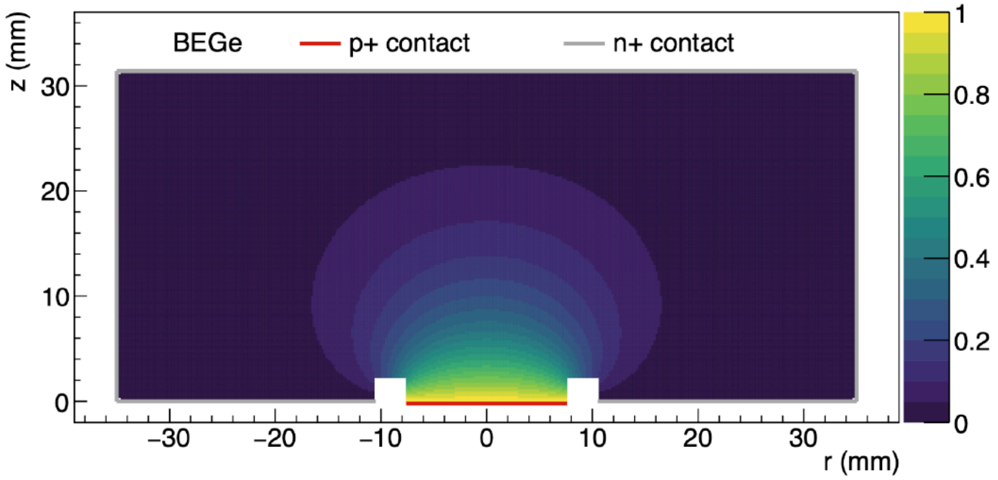
TABLE II. A non-exhaustive listing of recent and proposed BSM physics searches by Ge-based experiments.

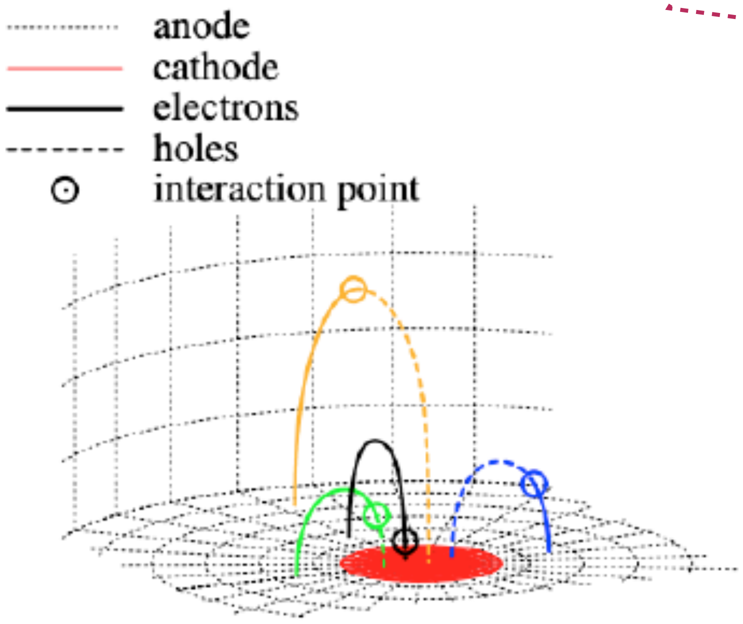
Physics	Signature	Energy Range	Experiment
Bosonic dark matter	Peak at DM mass	< 1 MeV	Majorana[65], Gerda [66]
Electron decay	Peak at 11.8 keV	~ 10 keV	Majorana [65]
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV	Majorana [65]
Solar axions	Peaked spectra, daily modulation	< 10 keV	Majorana[65, 67]
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	Gerda [68]
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [69, 70]
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [71–73]
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [74]
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$	(proposed) [75]
WIMP and related searches	Exponential excess, annual modulation	< 10 keV	CDEX [76]
Baryon decay	Timing coincidence	> 10 MeV	Majorana [77]
Fractionally charged cosmic-rays	Straight tracks	few keV	Majorana [78]
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV	(proposed) [79]
Inelastic boosted dark matter	Positron production	$<$ few MeV	(proposed) [80]
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar	Gerda [81]

https://arxiv.org/pdf/2107.11462.pdf

PSD in Ge: concept

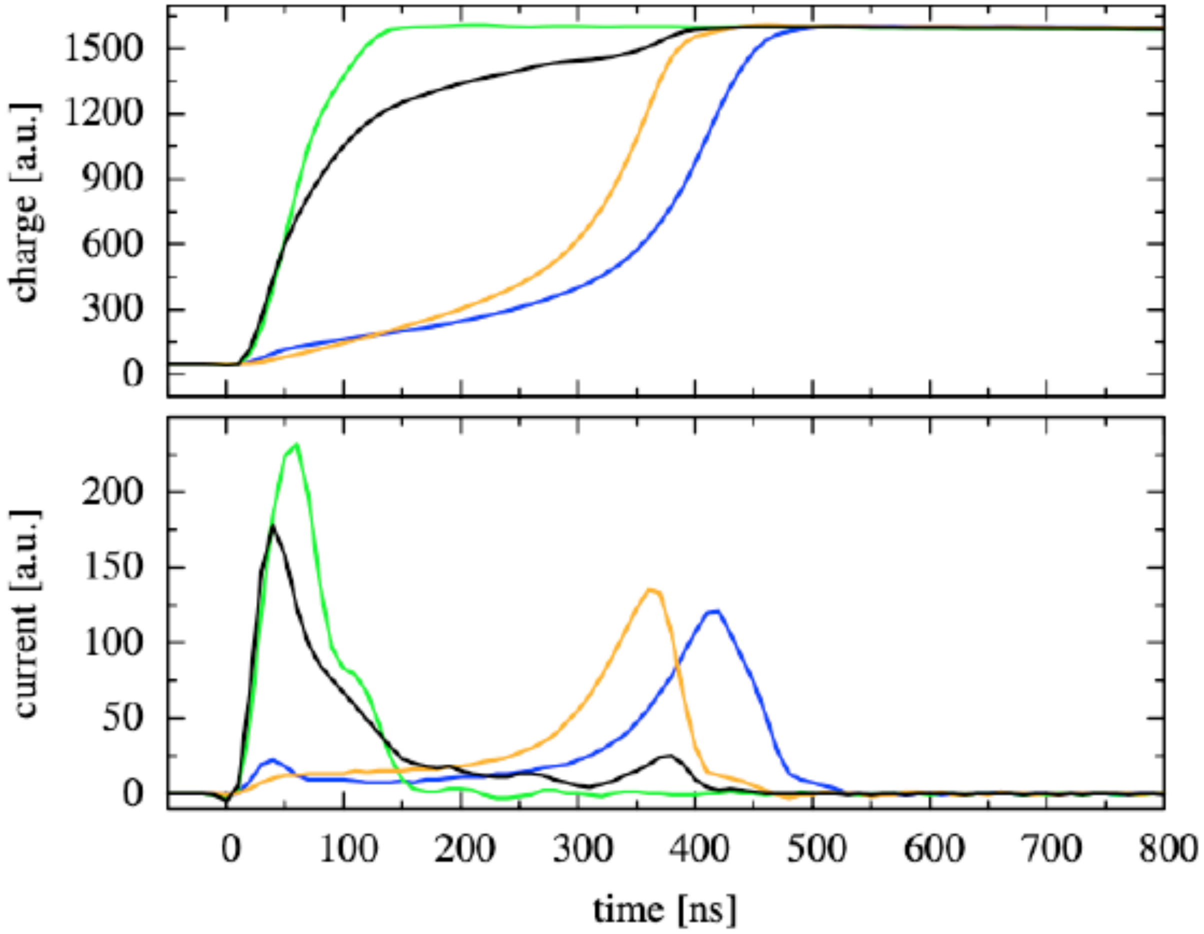
See also: Nucl.Instrum.Meth.A 891 (2018) 106-110





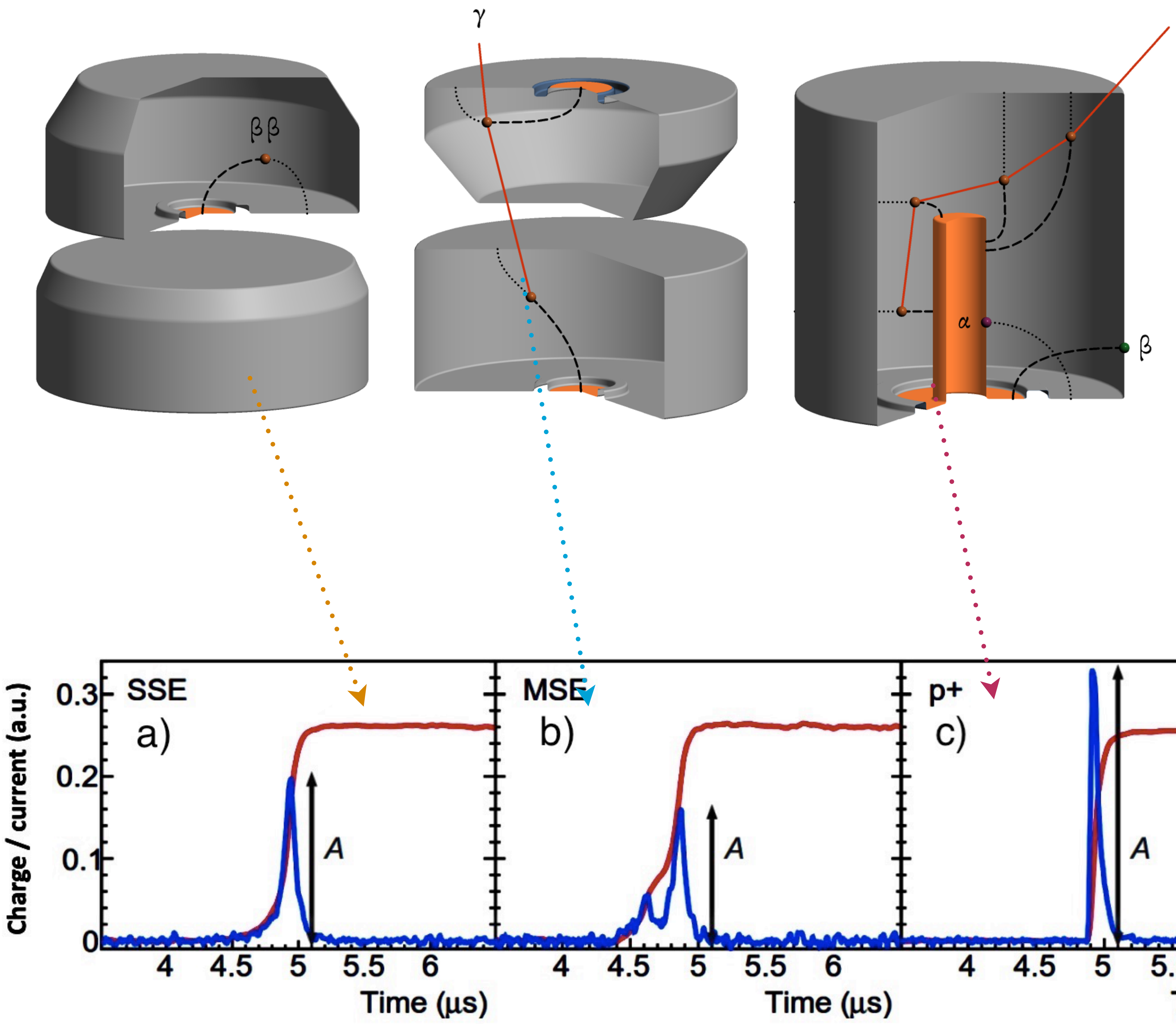
- Uniform configuration of weighting potential in PC enhances (>90%) "**yellow**" type wrt others

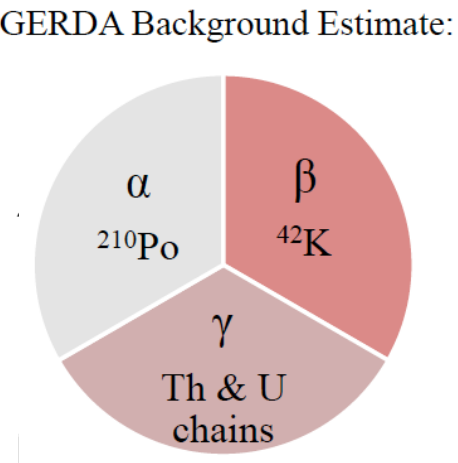
- Markedly different Q and A spectra according to where energy deposition occurs in crystal



- 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

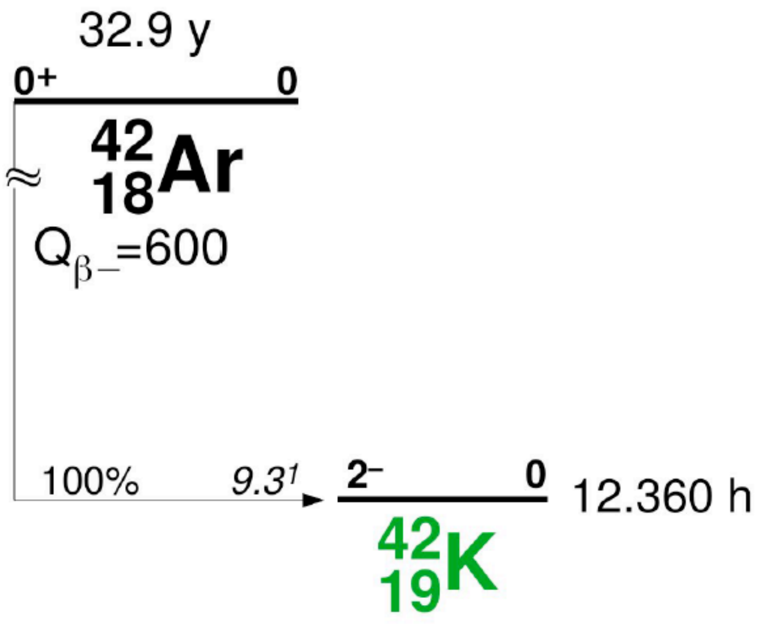
Why is PSD important?

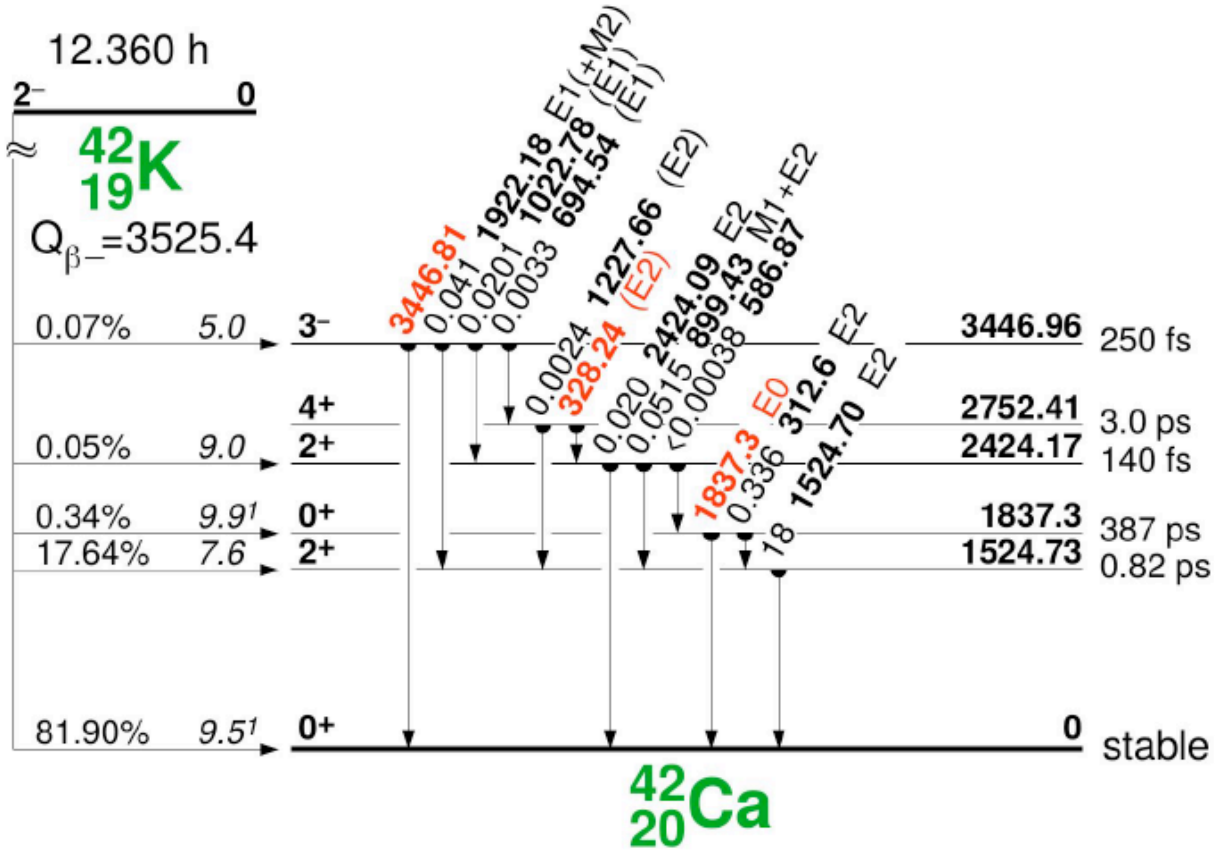



GERDA Background Estimate:

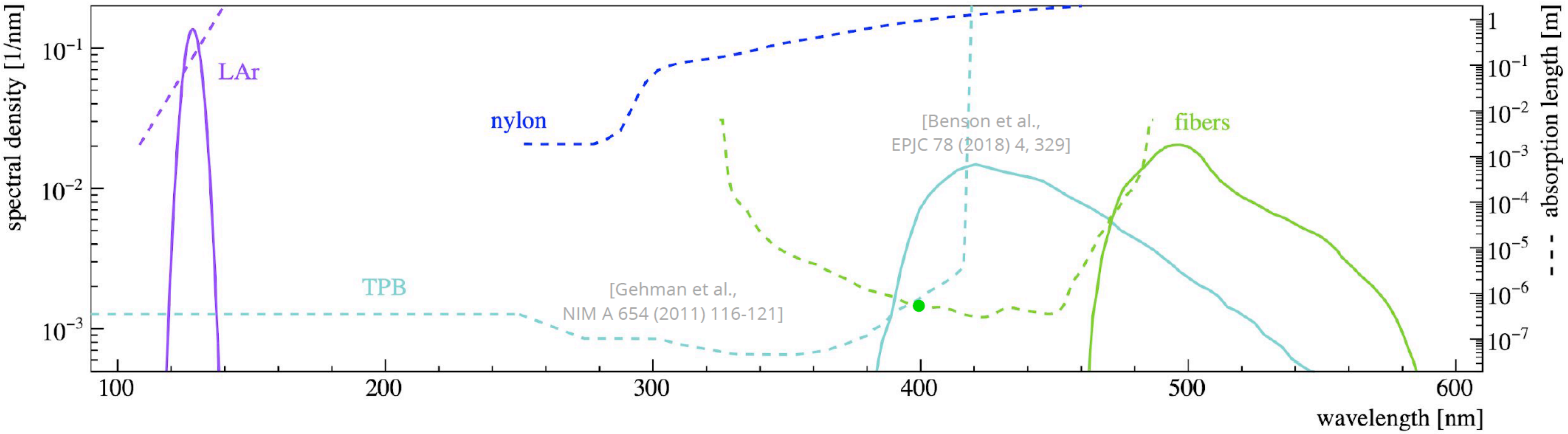
Origin of radioactive bkgs

- 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





Active veto optical parameters



[Gehman et al., NIM A 654 (2011) 116-121]

[Benson et al., EPJC 78 (2018) 4, 329]

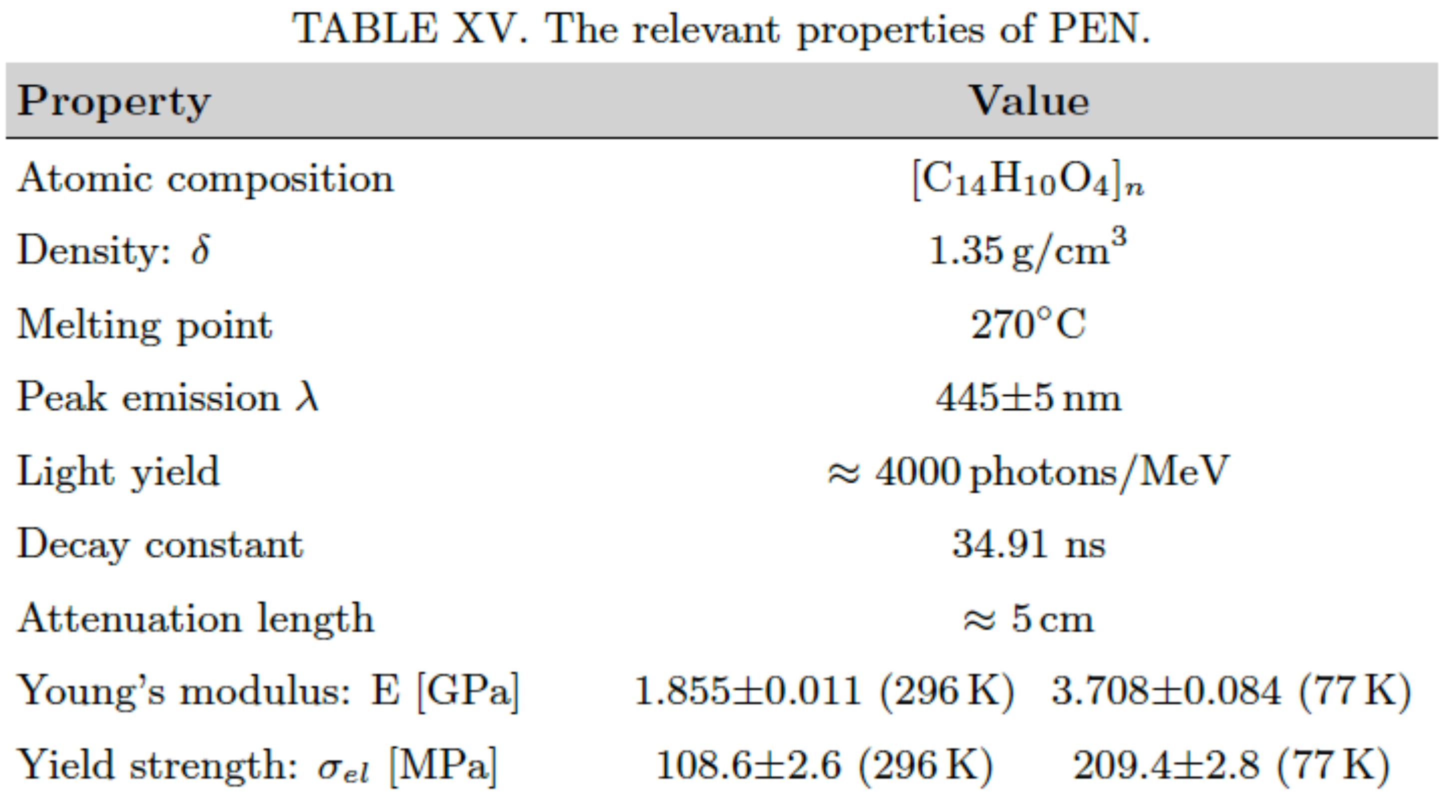


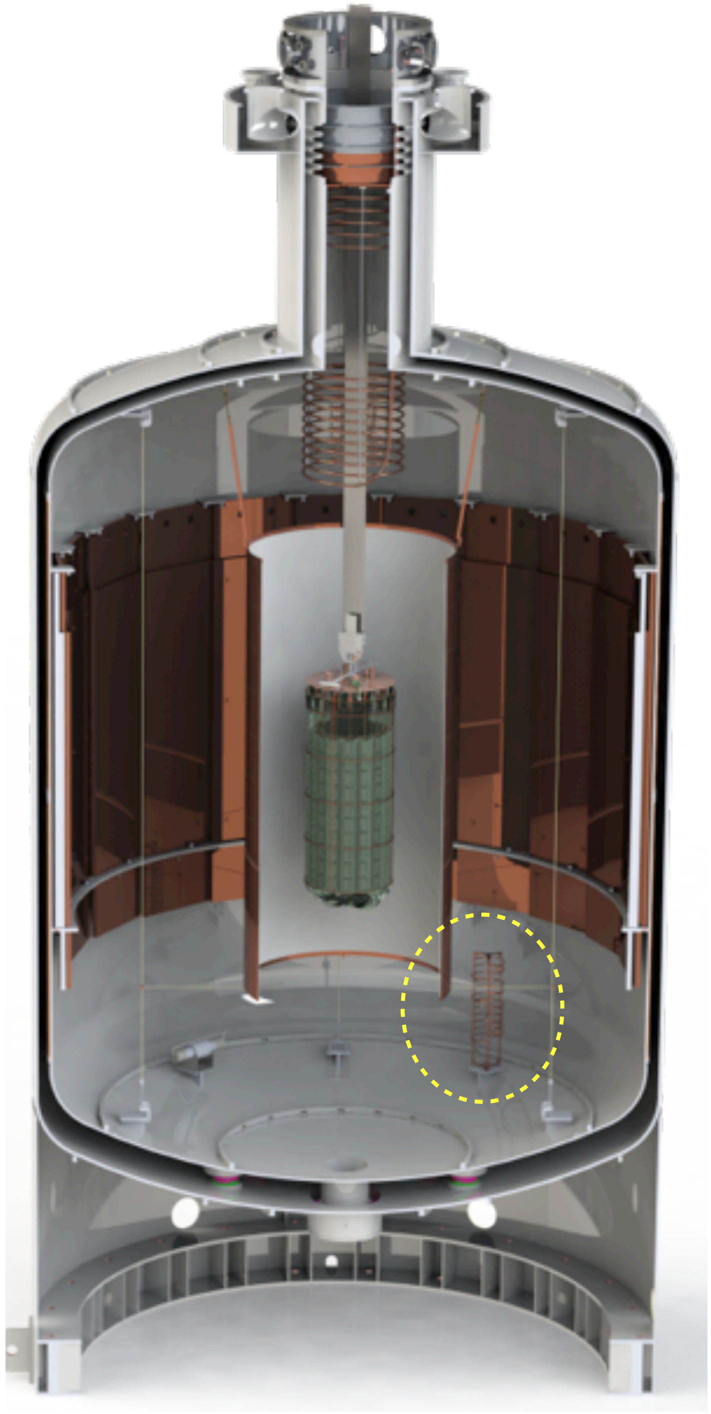
TABLE XV. The relevant properties of PEN.

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	$\approx$ 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)

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

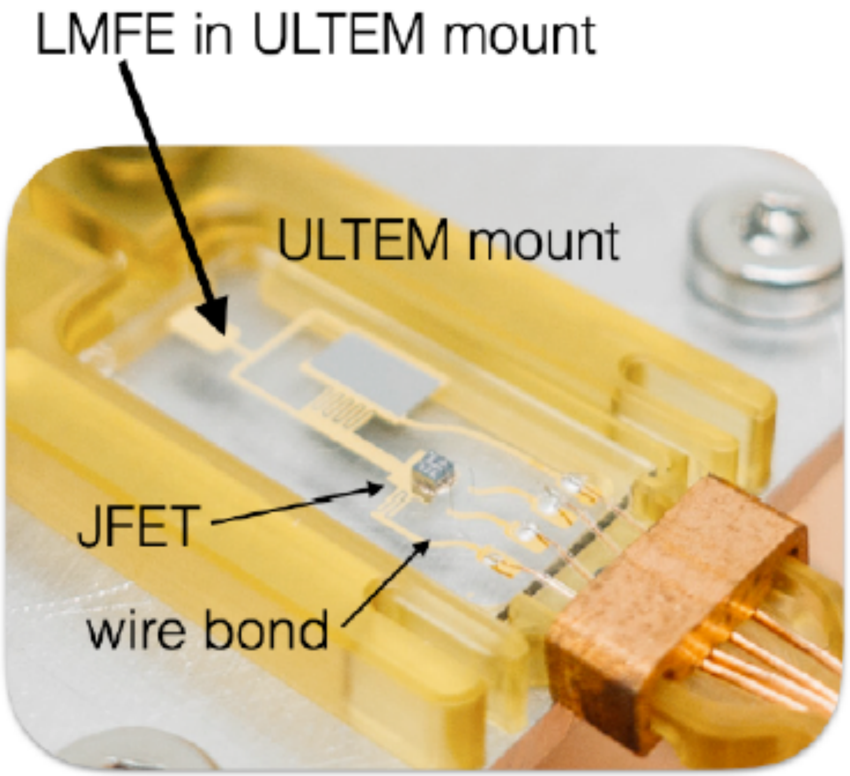
- triplet attenuation highly depends on recombination with impurities (N, O, Xe ppm-to-ppb) sneaking at Ar distillation
- "class 5.5" LAr from plant + in place at LNGS ad-hoc system to purify LAr as it flows between tank and cryostat
- Expected to result in $\lambda_{att} \lesssim 1$m, small wrt cryostat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

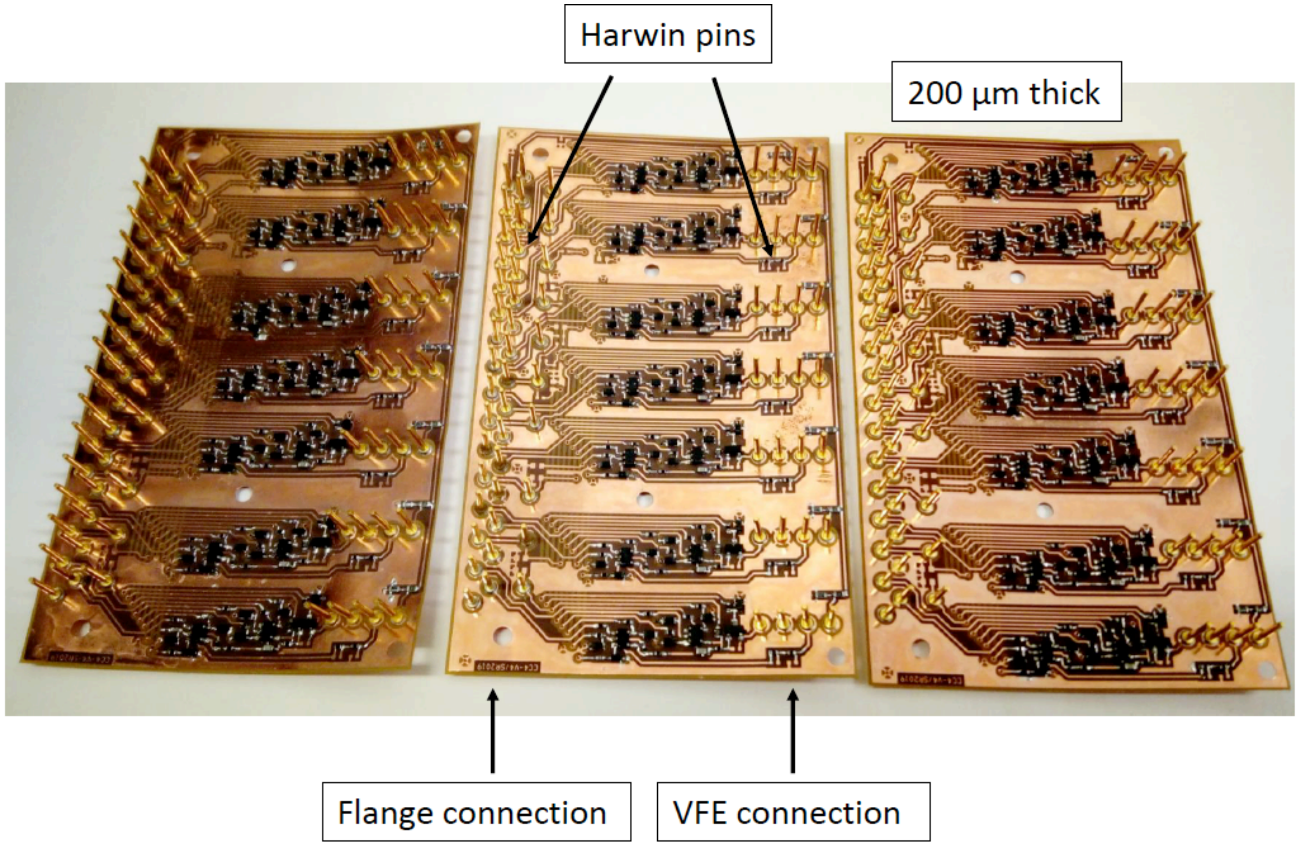


LLAMA device in LAr will monitor in time attenuation and triplet lifetime

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

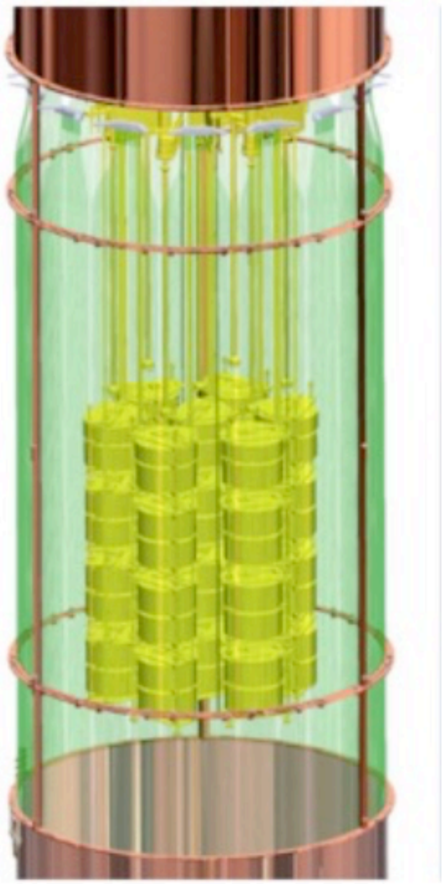




UG electro-formed copper

- 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

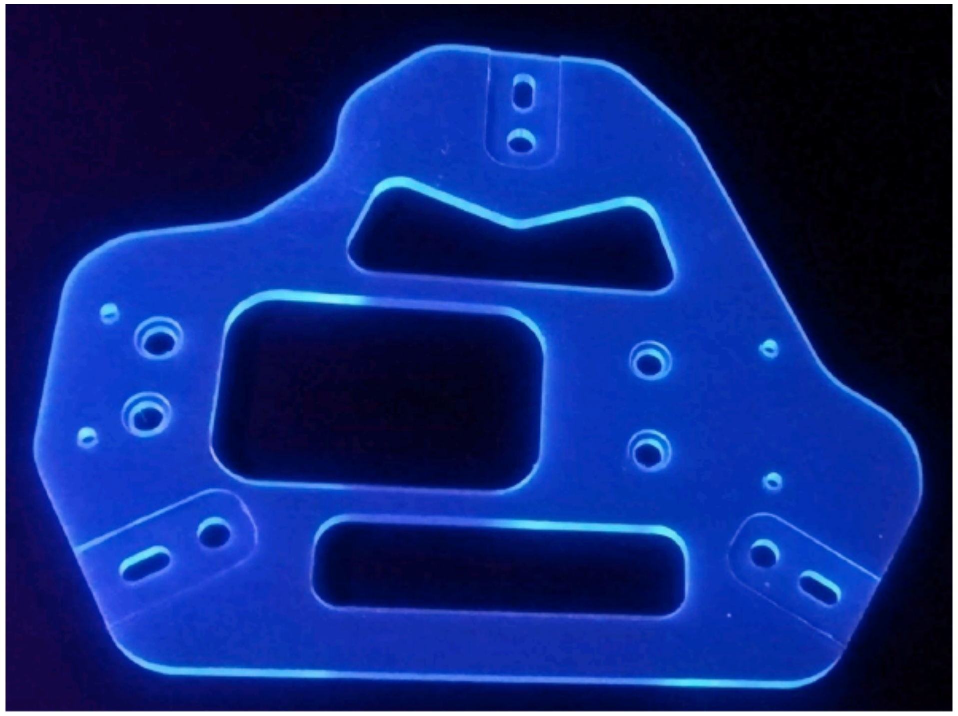


EFCu can be placed next to detectors, in LAr: improves signal/noise and, consequently, PSD

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

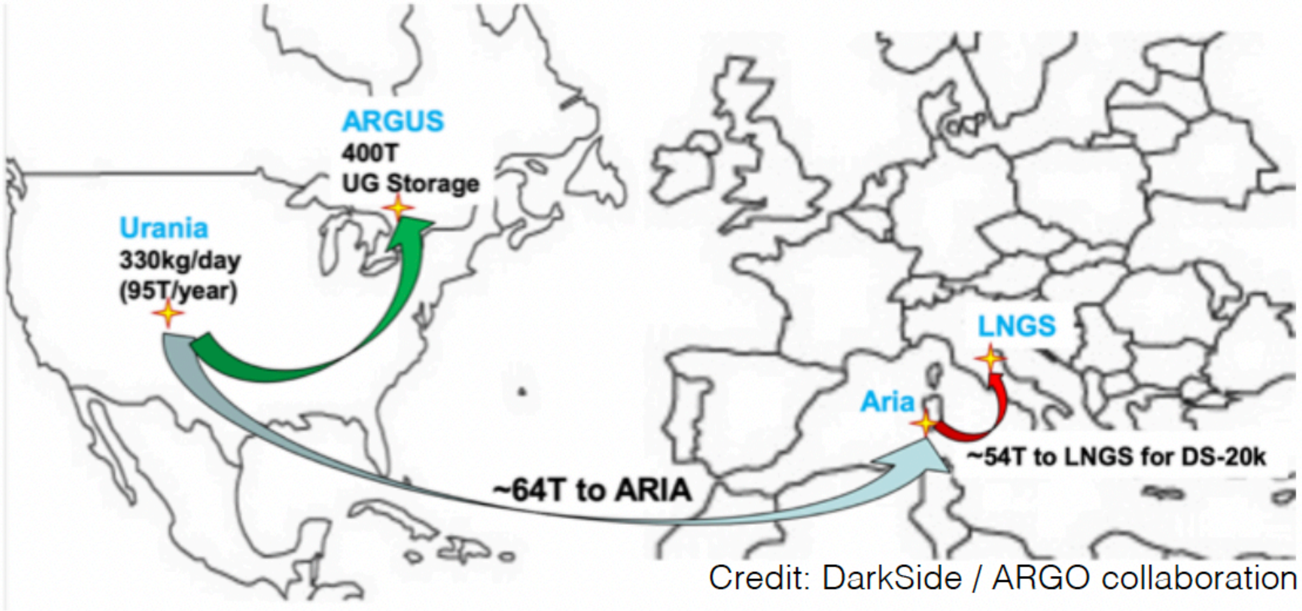
Plates fitting read-out electronics

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?

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)

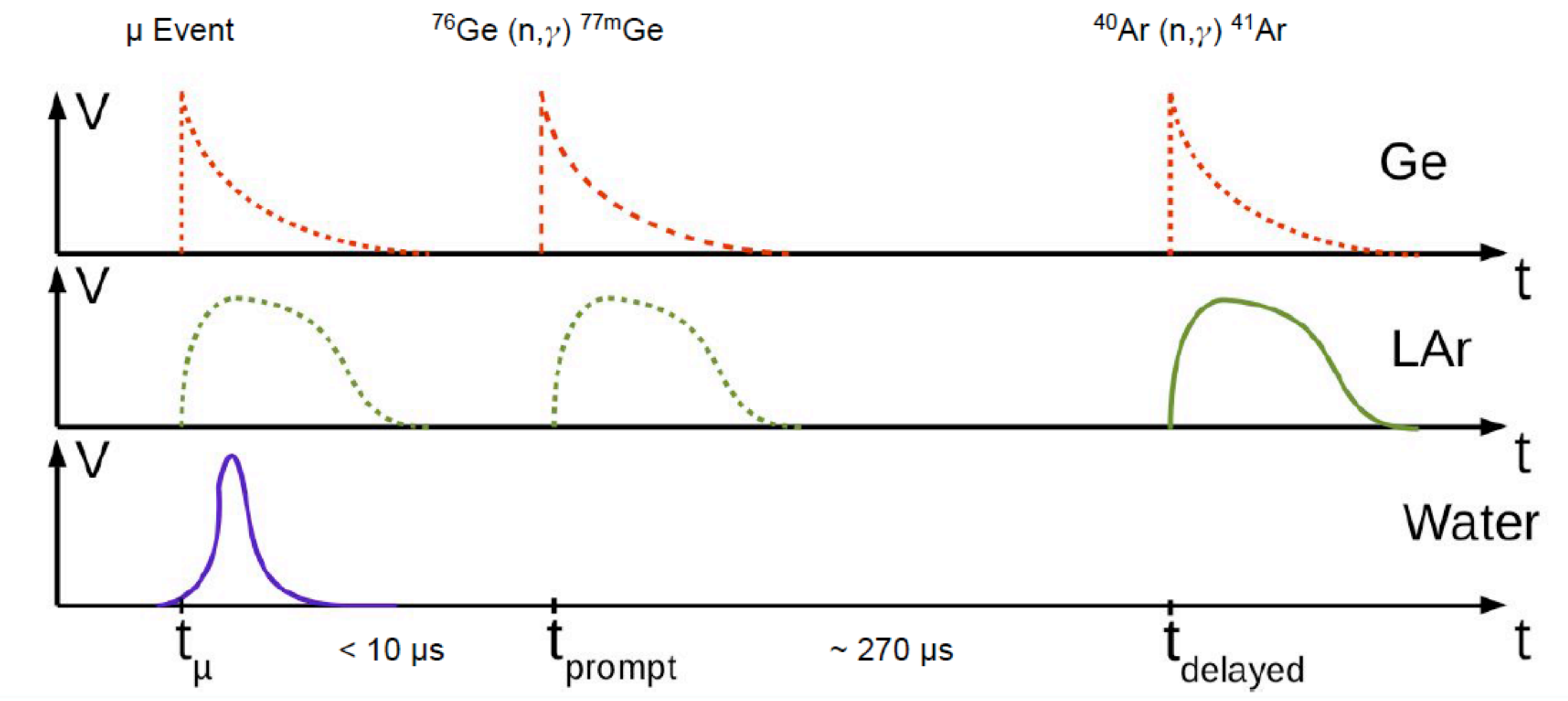
Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ε	^{37}Cl
^{38}Ar	0.063%	stable		
~~^{39}Ar~~	~~trace~~	~~269 y~~	~~β^-~~	~~^{39}K~~
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β^-	^{41}K
~~^{42}Ar~~	~~syn~~	~~32.9 y~~	~~β^-~~	~~^{42}K~~

---

[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...”

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 n^+, too-thick for α
- Hard to estimate rate 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

Preliminary SiPM perfo in 60 kg runs