Background-free search for $0\nu\beta\beta$ with GERDA and LEGEND

https://indico.lip.pt/event/696/

GERDA

Double Beta Decay: the road to normal hierarchy sensitivity

LEGEND

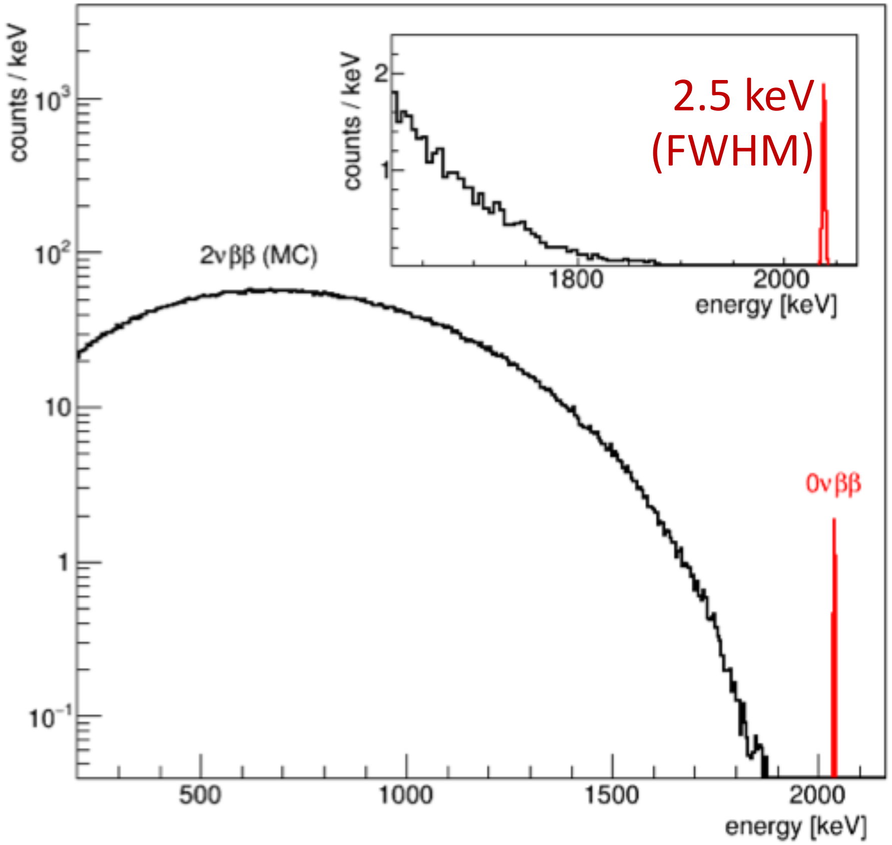
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Stefan Schönert | TU München
Onbehalf of the GERDA and LEGEND collaborations

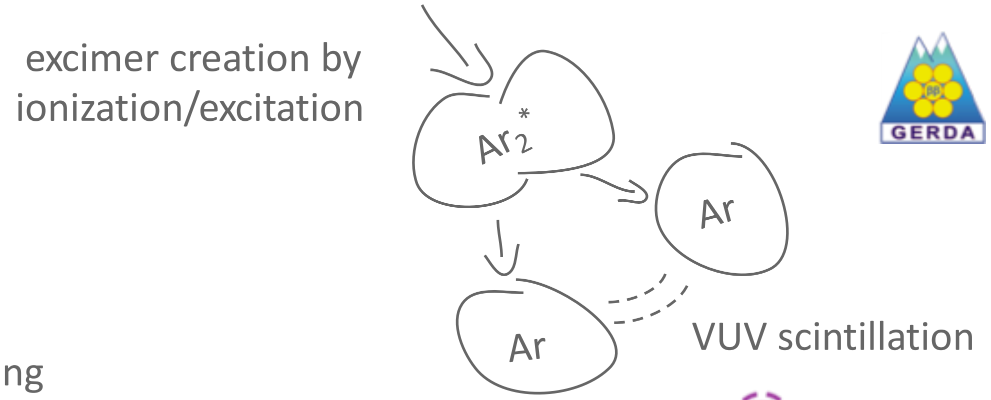
6. June 2022

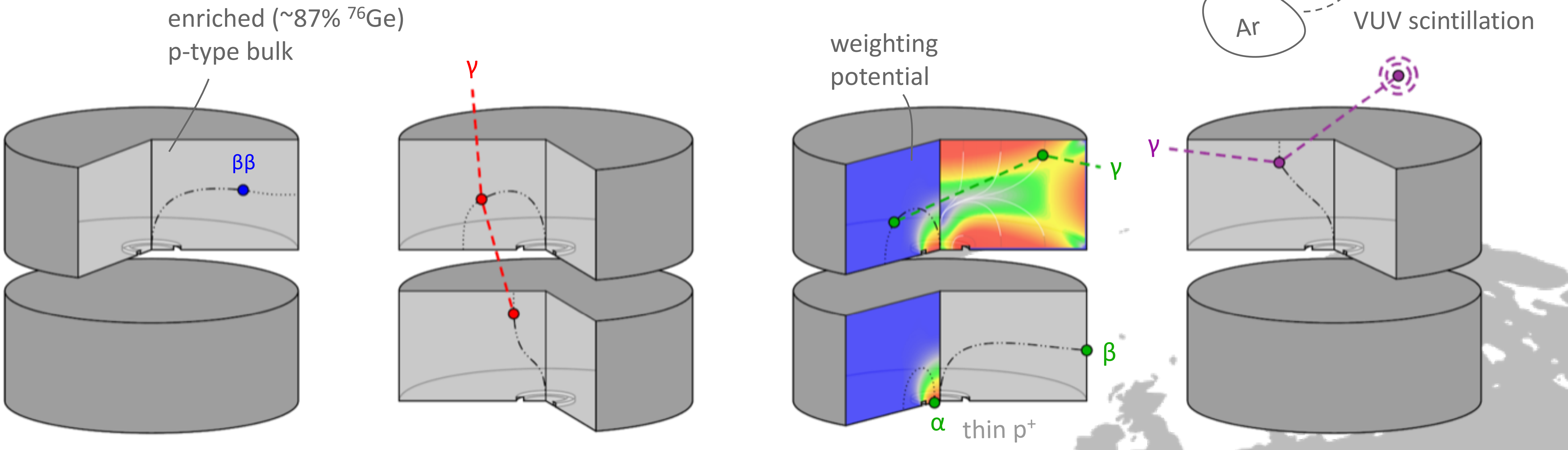
Key features of ^{76}Ge $0\nu\beta\beta$ searches

- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$
- Q-value of ^{76}Ge: $Q_{\beta\beta}$ = 2039 keV
- High purity Ge detectors (>87% ^{76}Ge)
  - source = detector => high detection efficiency
  - high purity => no intrinsic background
  - high density => $0\nu\beta\beta$ point like events
  - semiconductor => ΔE ~0.1% (FWHM) at $Q_{\beta\beta}$
- **$0\nu\beta\beta$ signature:**
  - Point-like energy deposition in detector bulk volume
  - Sharp energy peak at 2039 keV (FWHM ~ 2.5 keV)



Topology discrimination





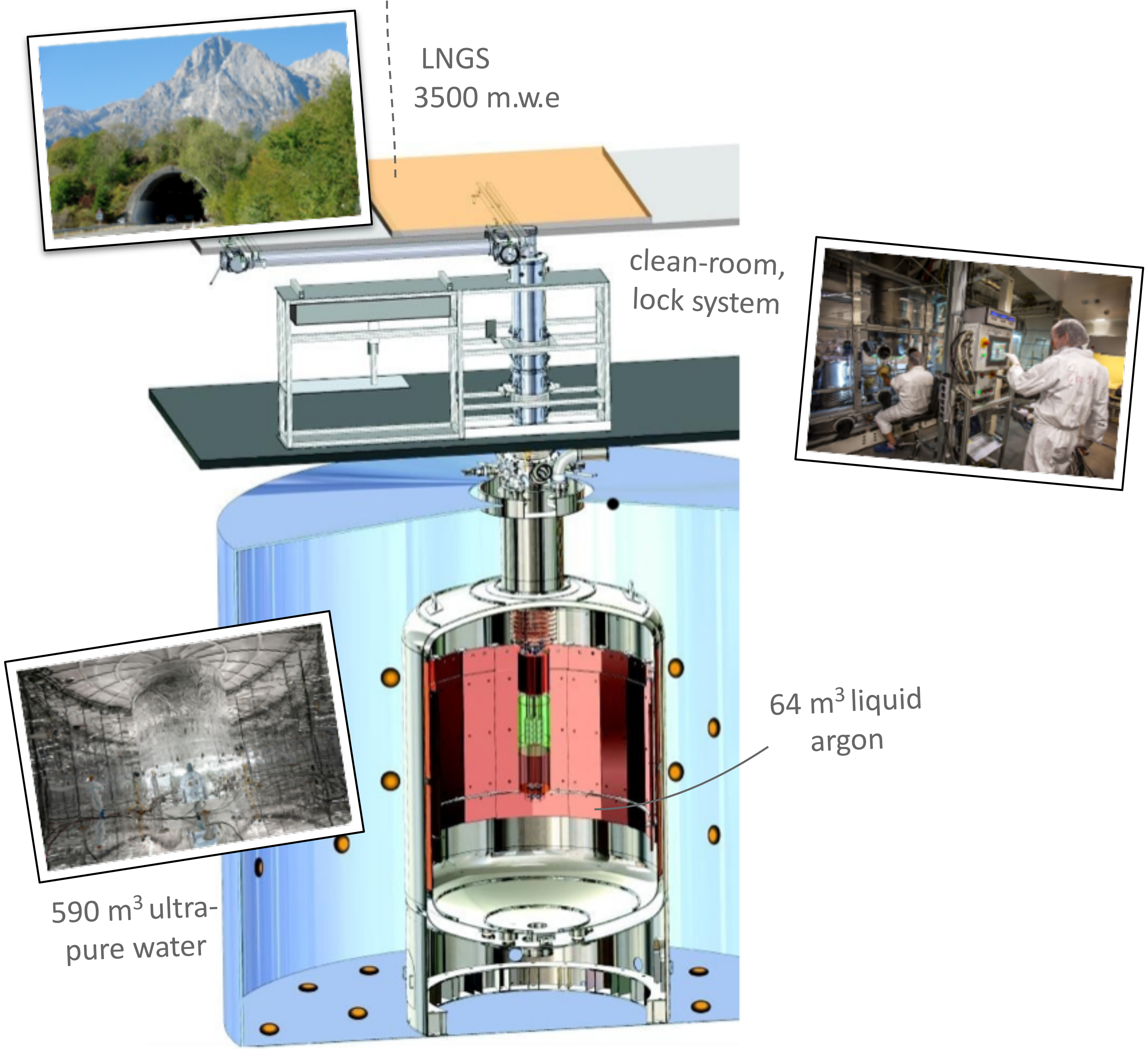
differentiate **point-like** *ββ* topology from:

multi-detector interactions

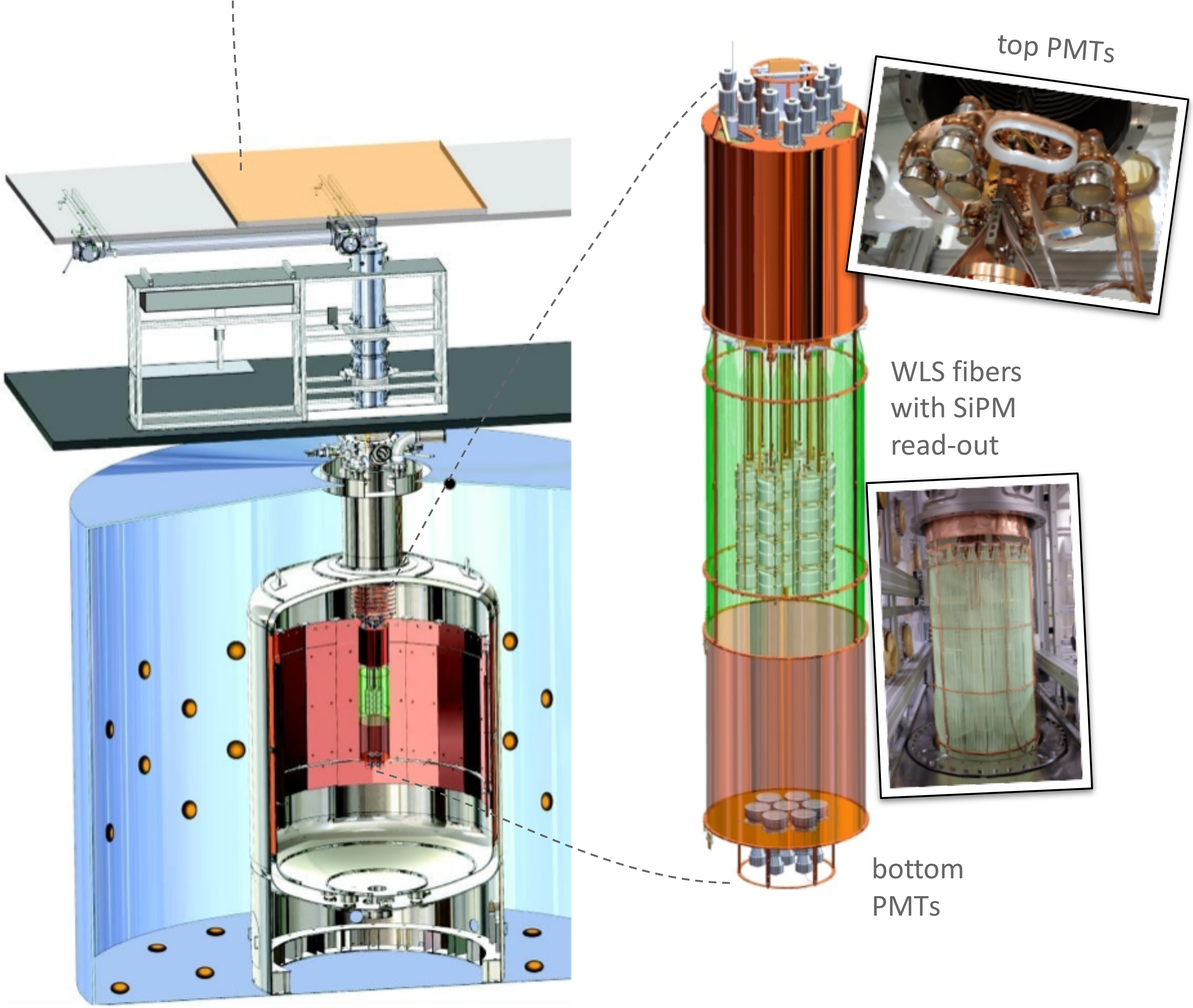
multi-site/surface interactions

interactions with **partial energy depositions**

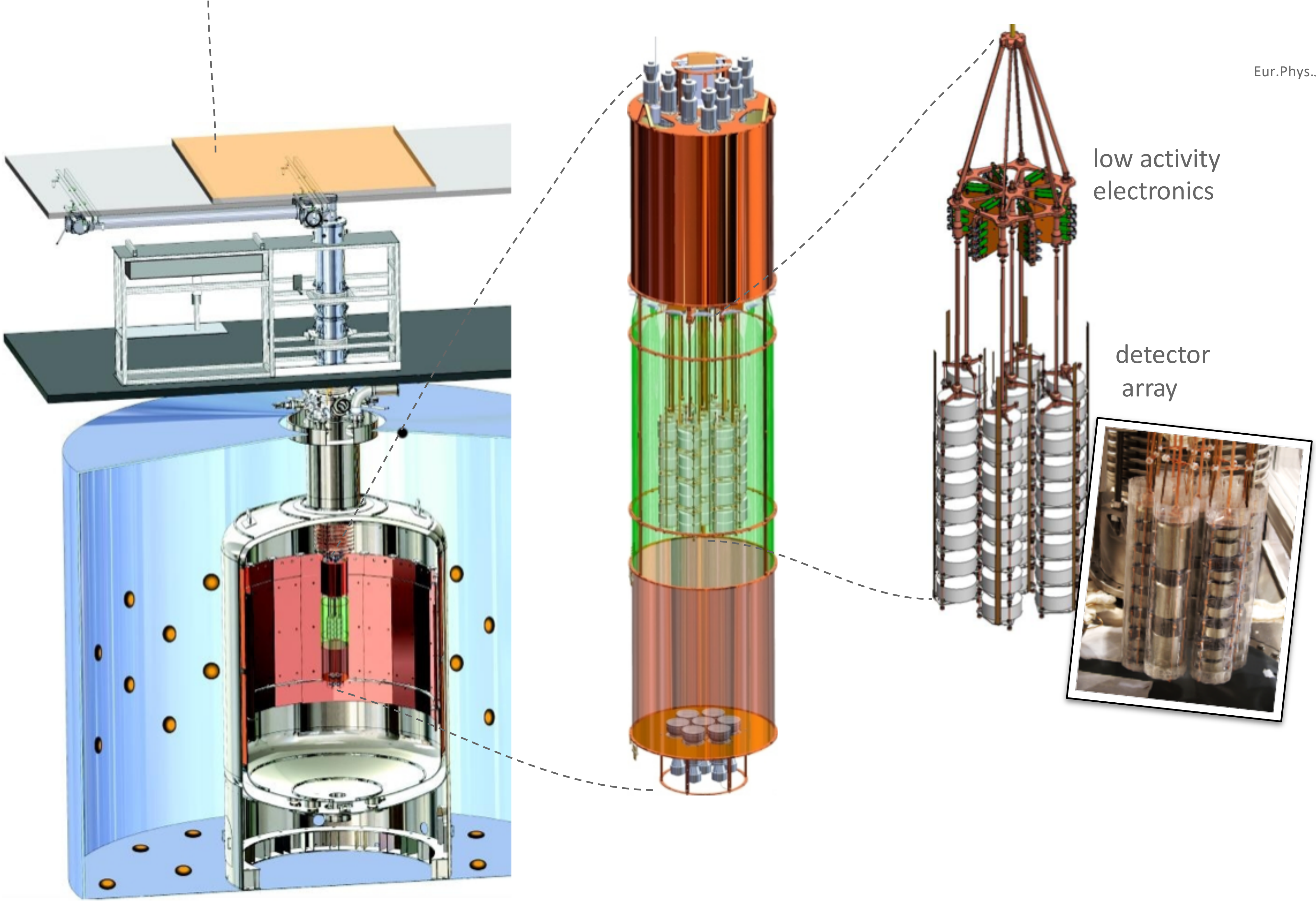
[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]



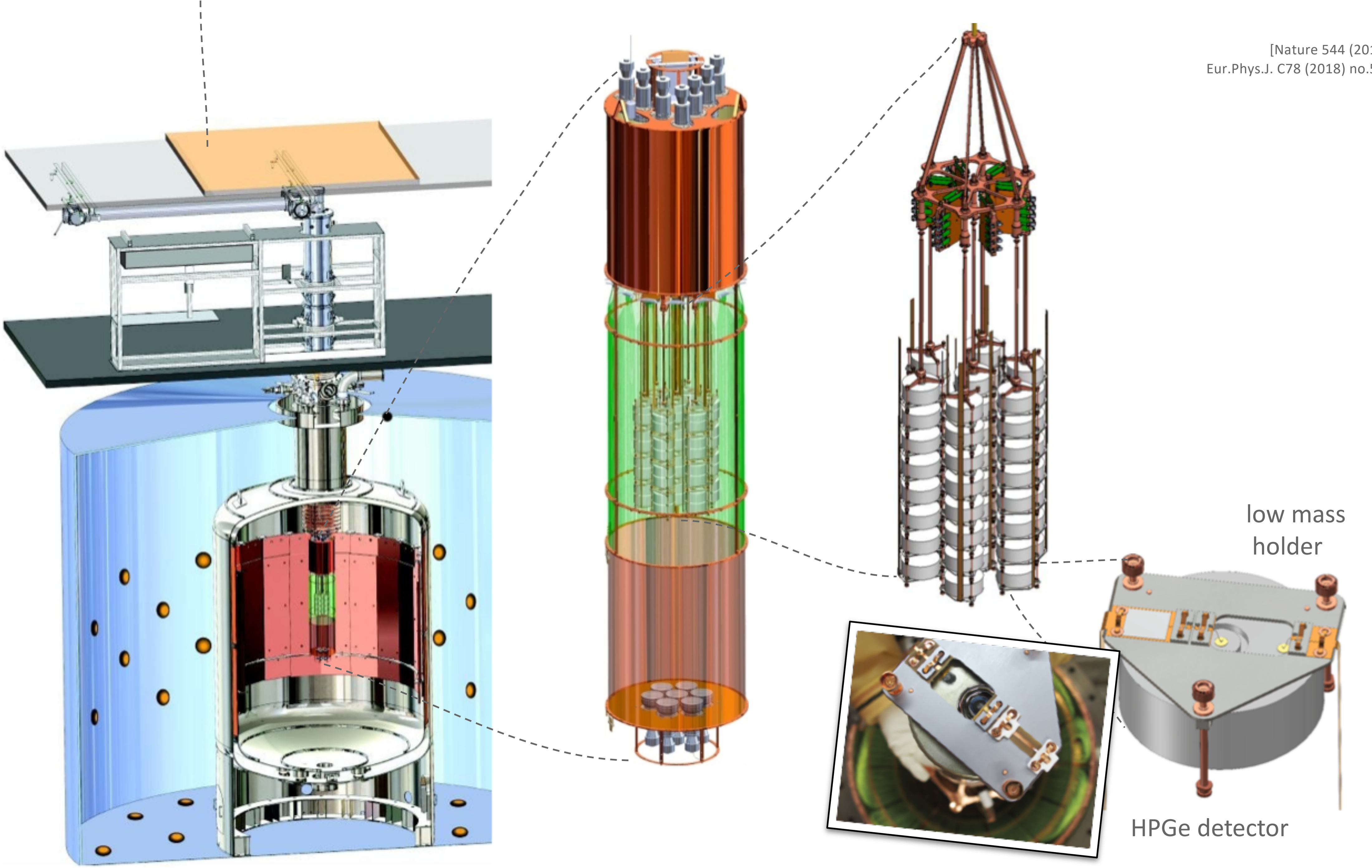
[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]



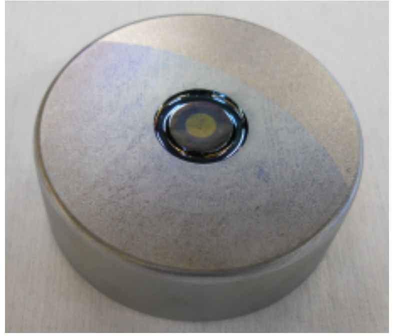
[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]



[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]

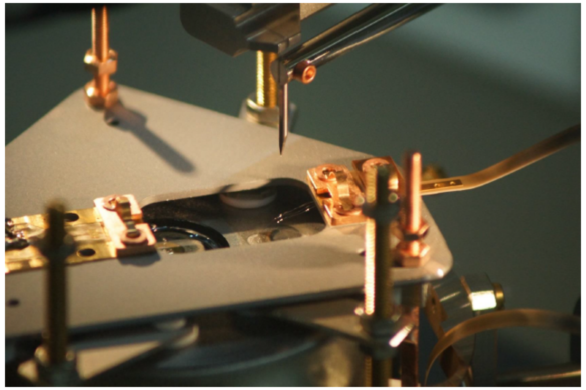


GERDA Phase II detector array

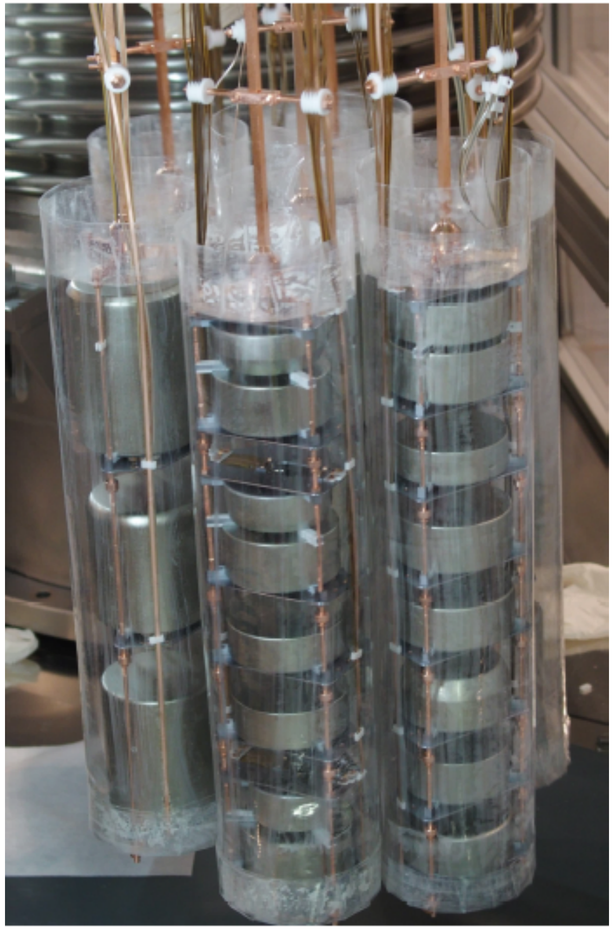


New thick-window BEGe detectors

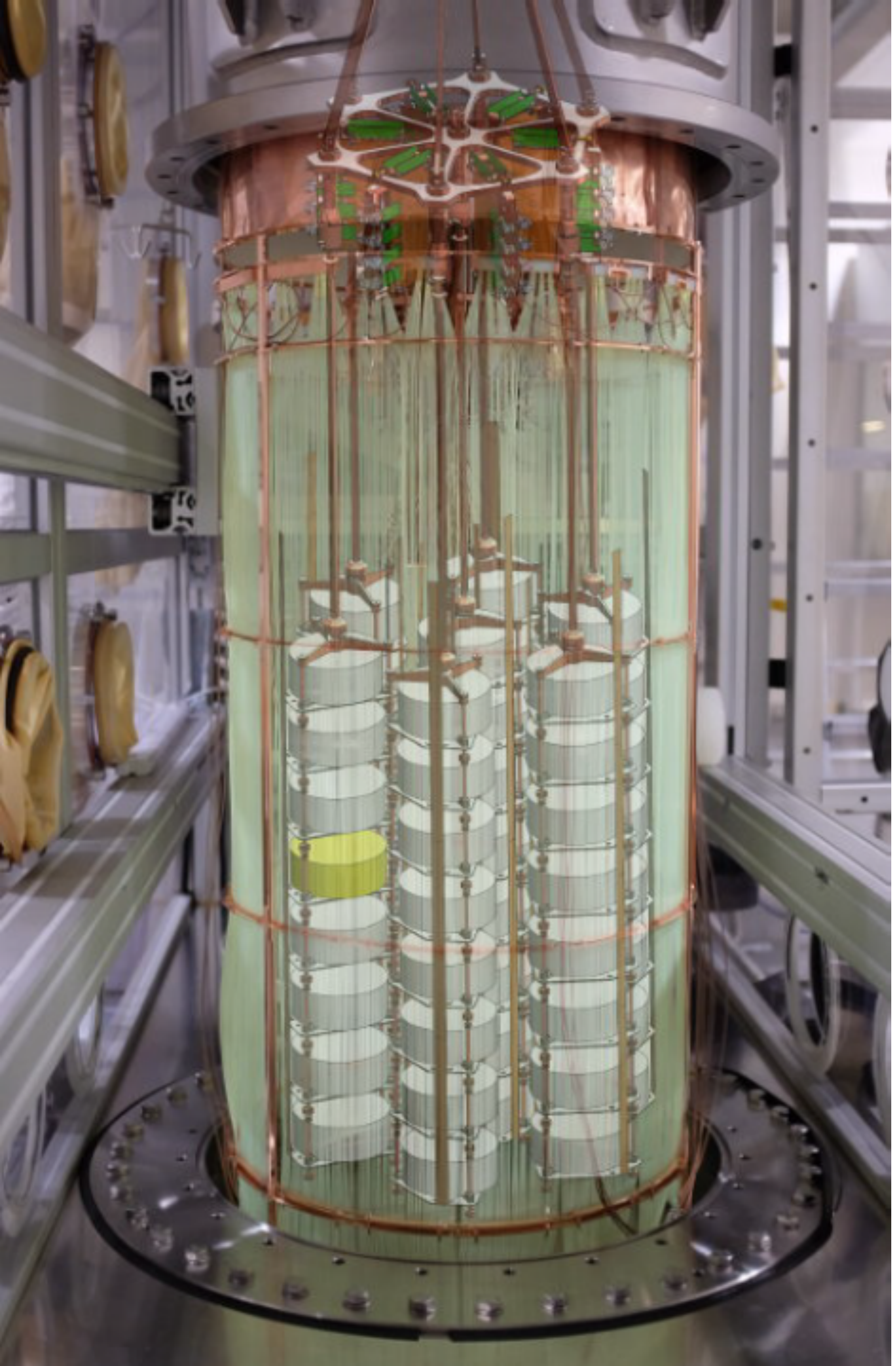
Low-mass detector holder (silicon, copper, PTFE)



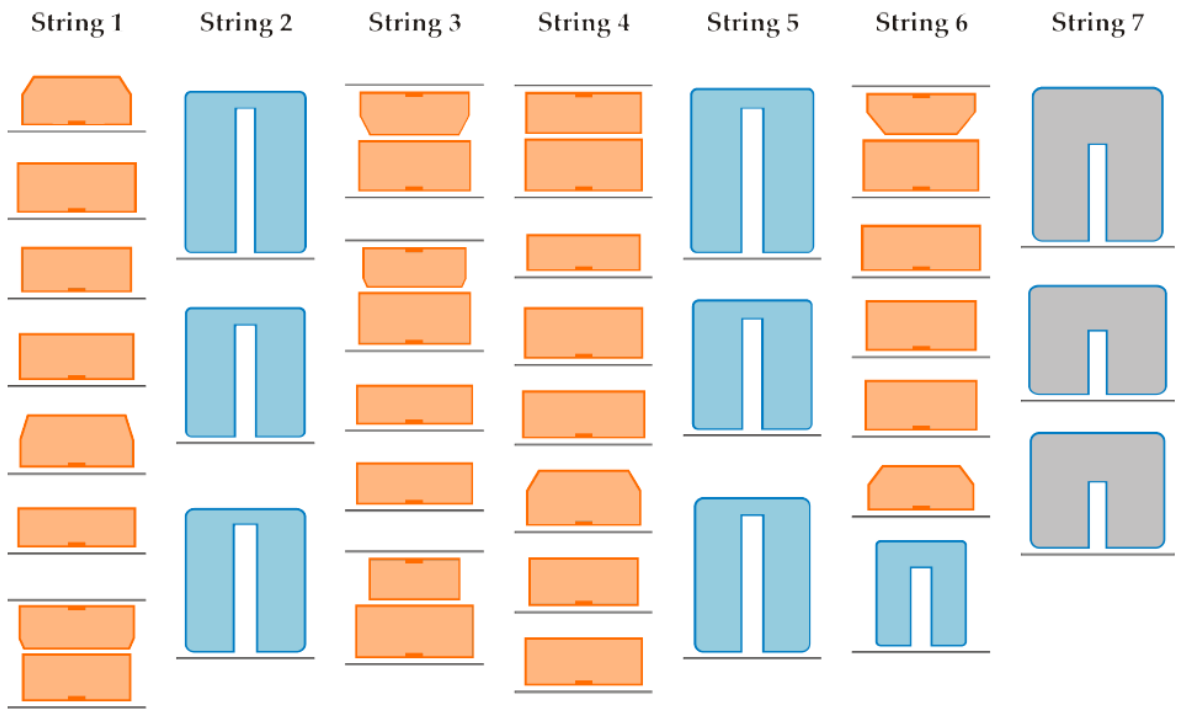
Signal and HV contacting by wire bonding
flat ribbon cables



TPB coated nylon mini-shrouds to reduce attraction K42 ions to n+ surface

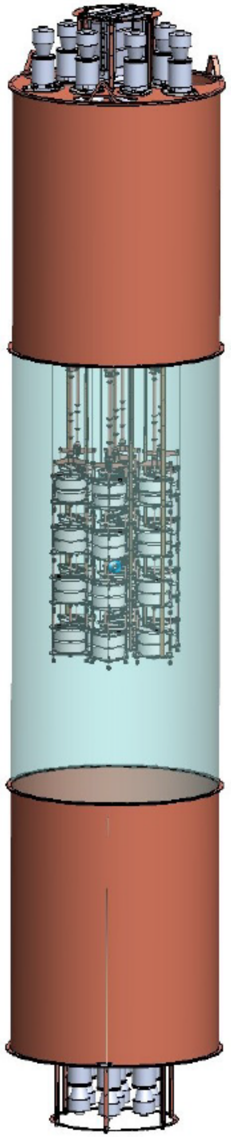


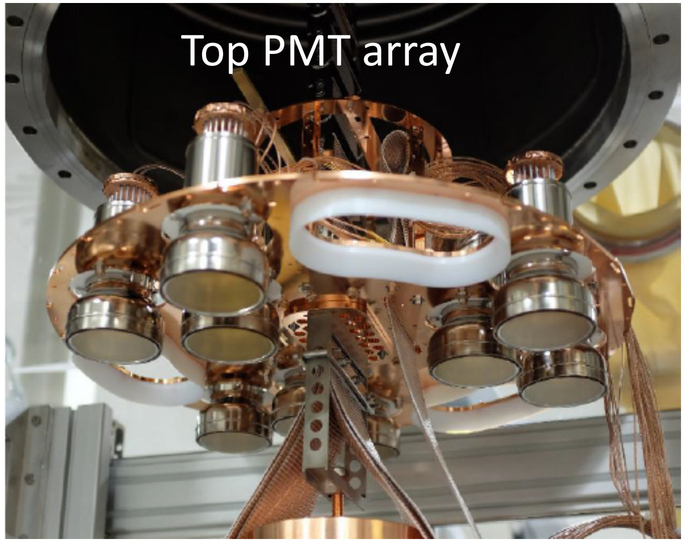
GERDA Phase II detector array

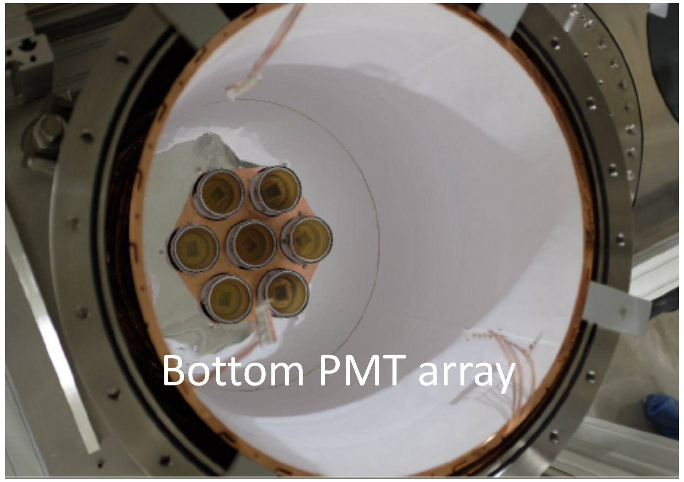


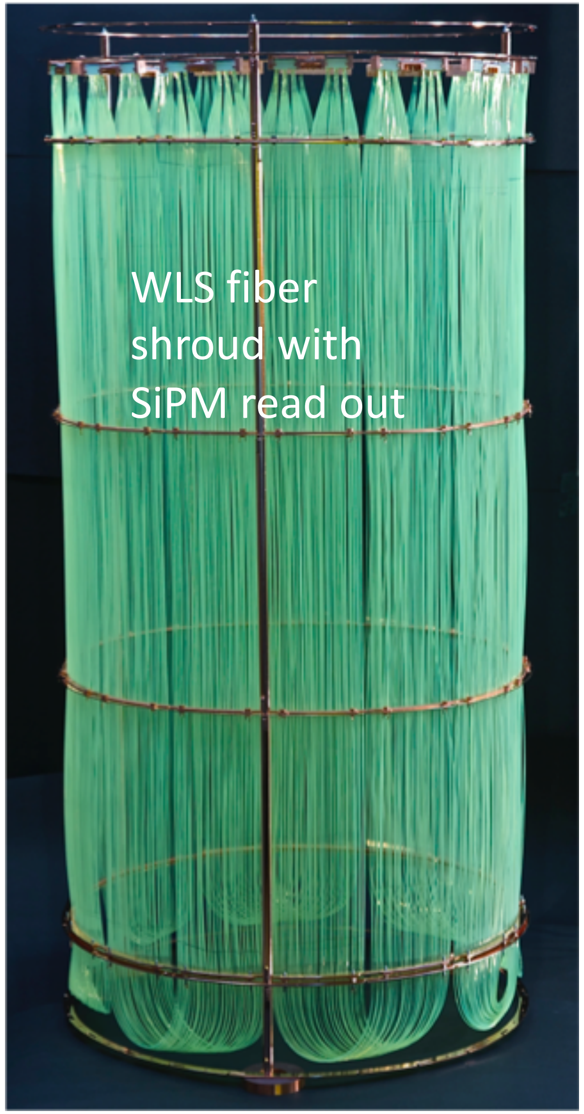
- 7 strings, 40 detectors in total
  - 7 enriched semi-coax (15.6 kg)
  - 30 enriched thick-window BEGe (20 kg)
  - 3 natural semi-coax (7.6 kg)
- HPGe array enclosed by liquid argon veto
- Phase II data started Dec. 2015

Liquid argon instrumentation





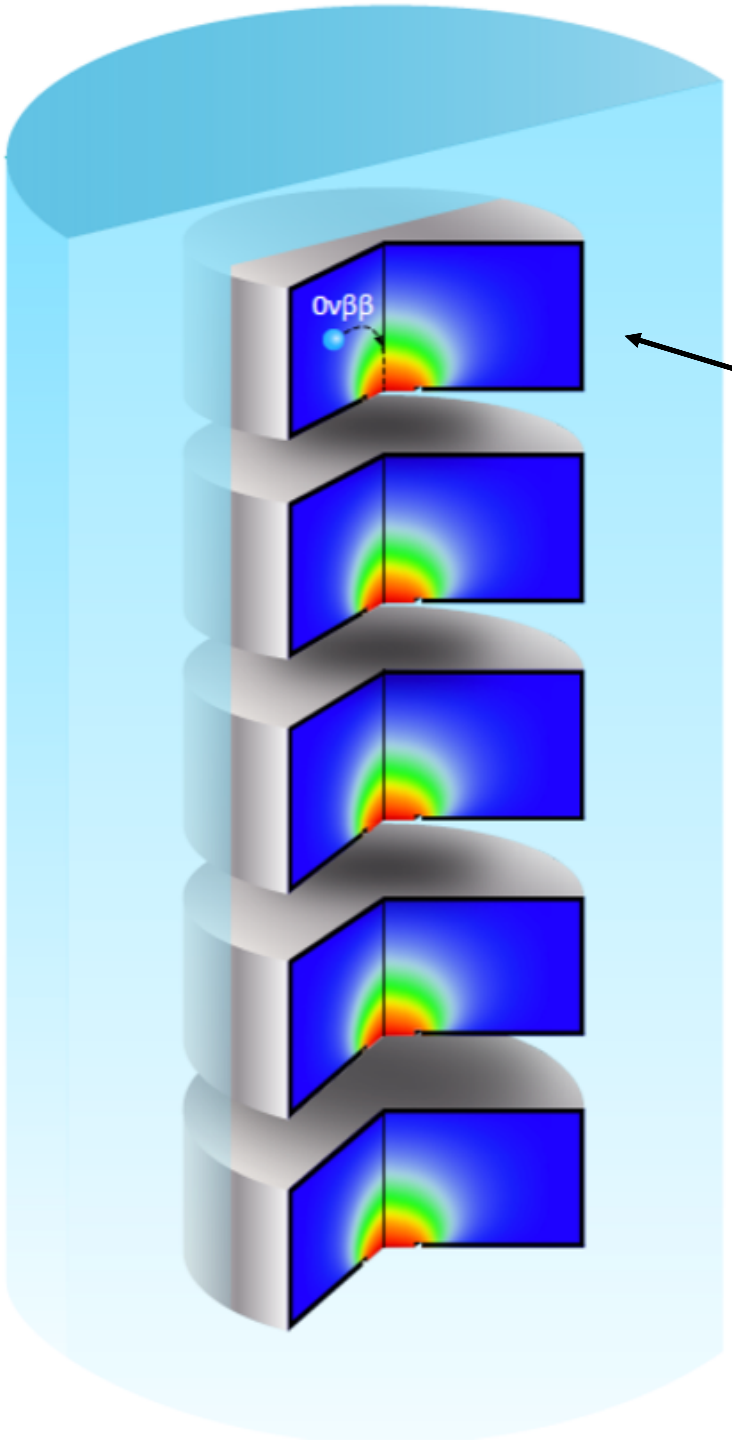


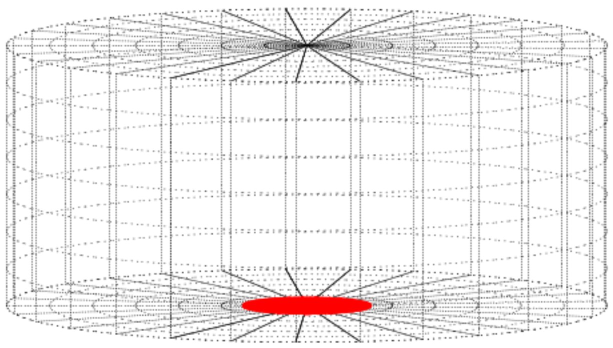


- Event rejection: >0.2-0.9 p.e. in any of SiPM or PMT channel (within 5μs of Ge trigger)
- Accidentals (dead time): 2.3±0.1% (Ar-39)

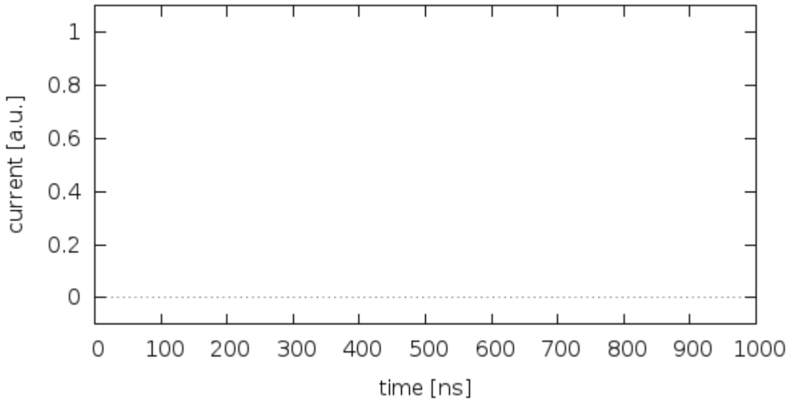
Pulse shape discrimination (BEGe)

Current pulse of signal-like event topology (SSE)



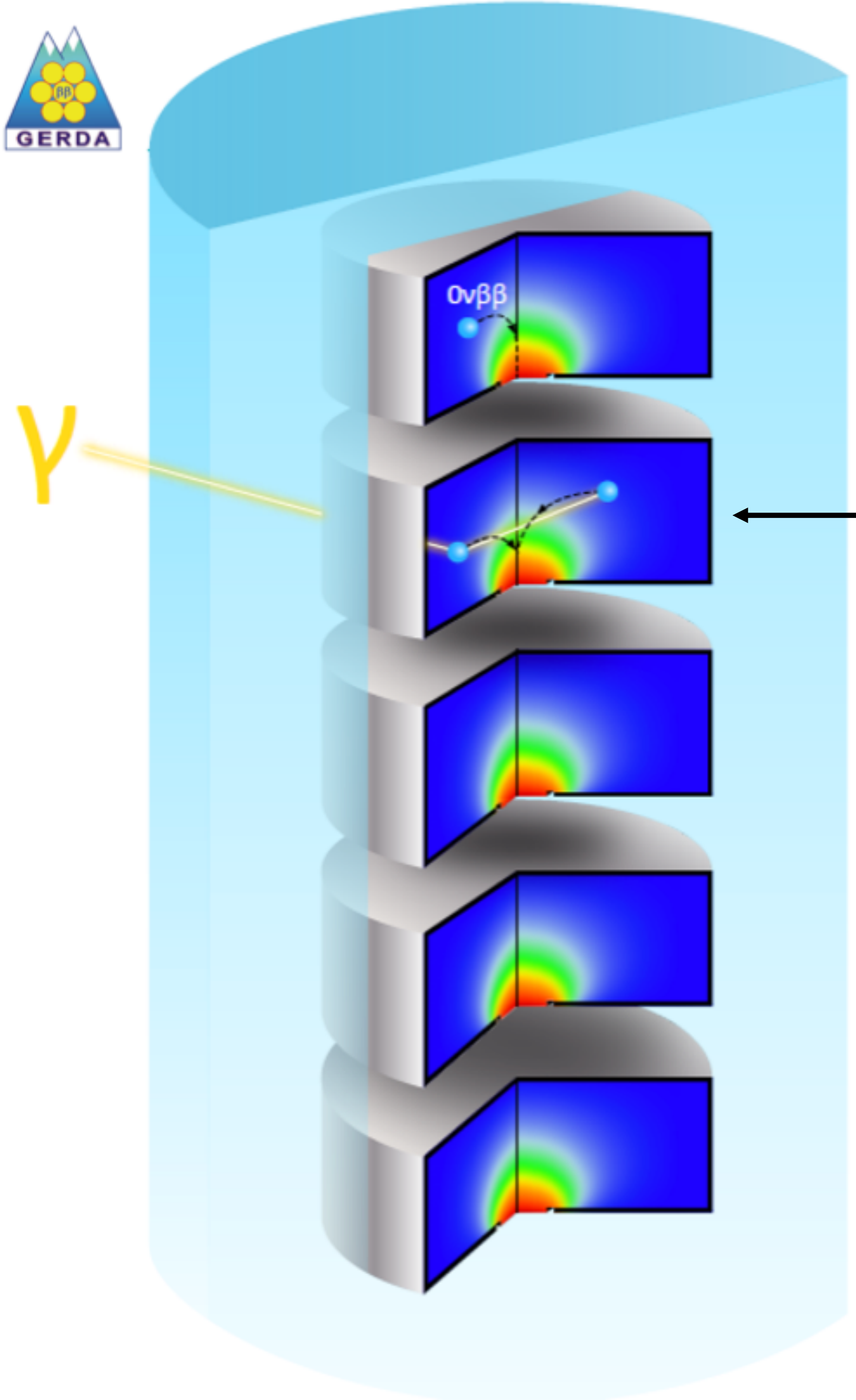


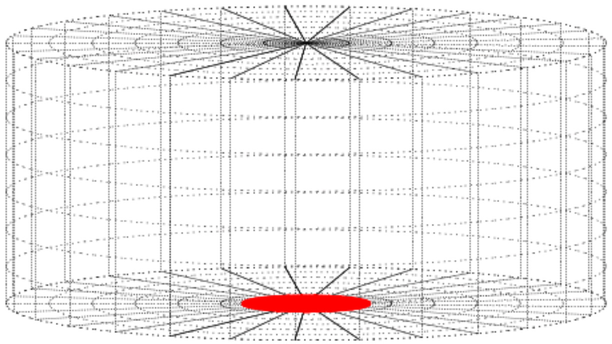
M. Agostini et al.
JINST 6 (2011) P03005



Pulse shape discrimination (BEGe)

Current pulse of background-like event topology (MSE)





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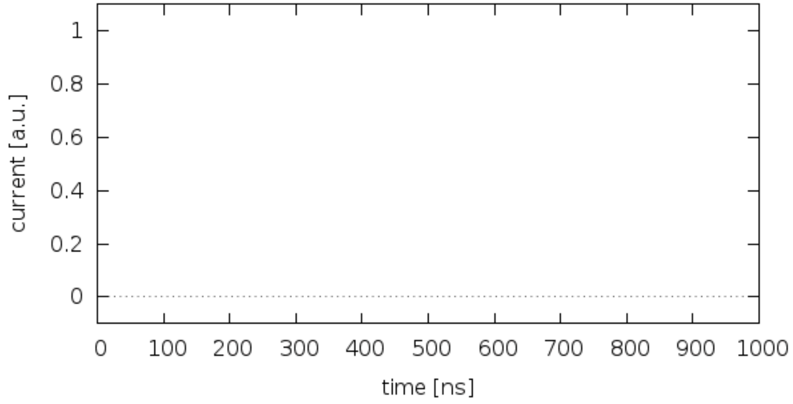
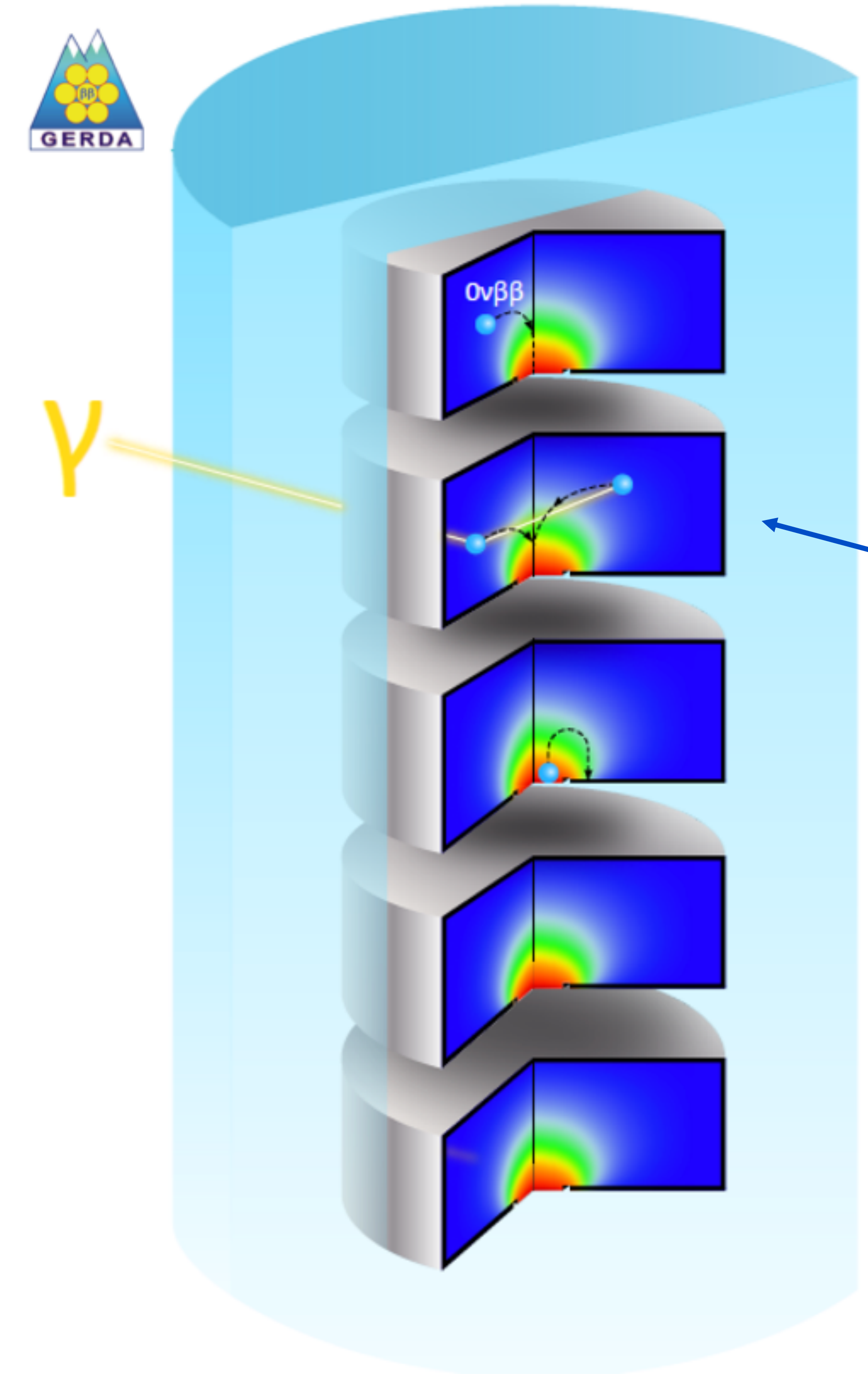
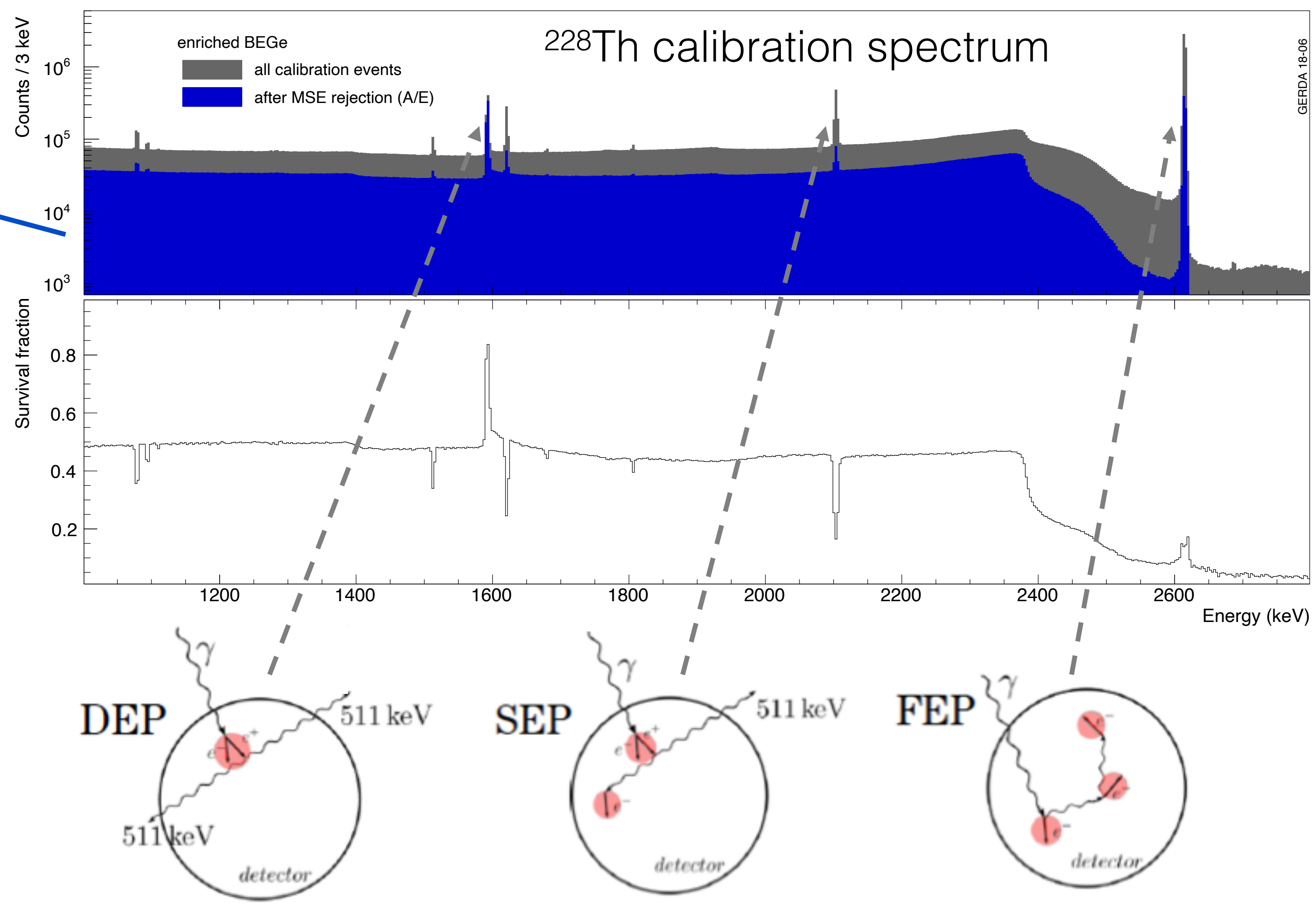


Pulse shape discrimination (BEGe)

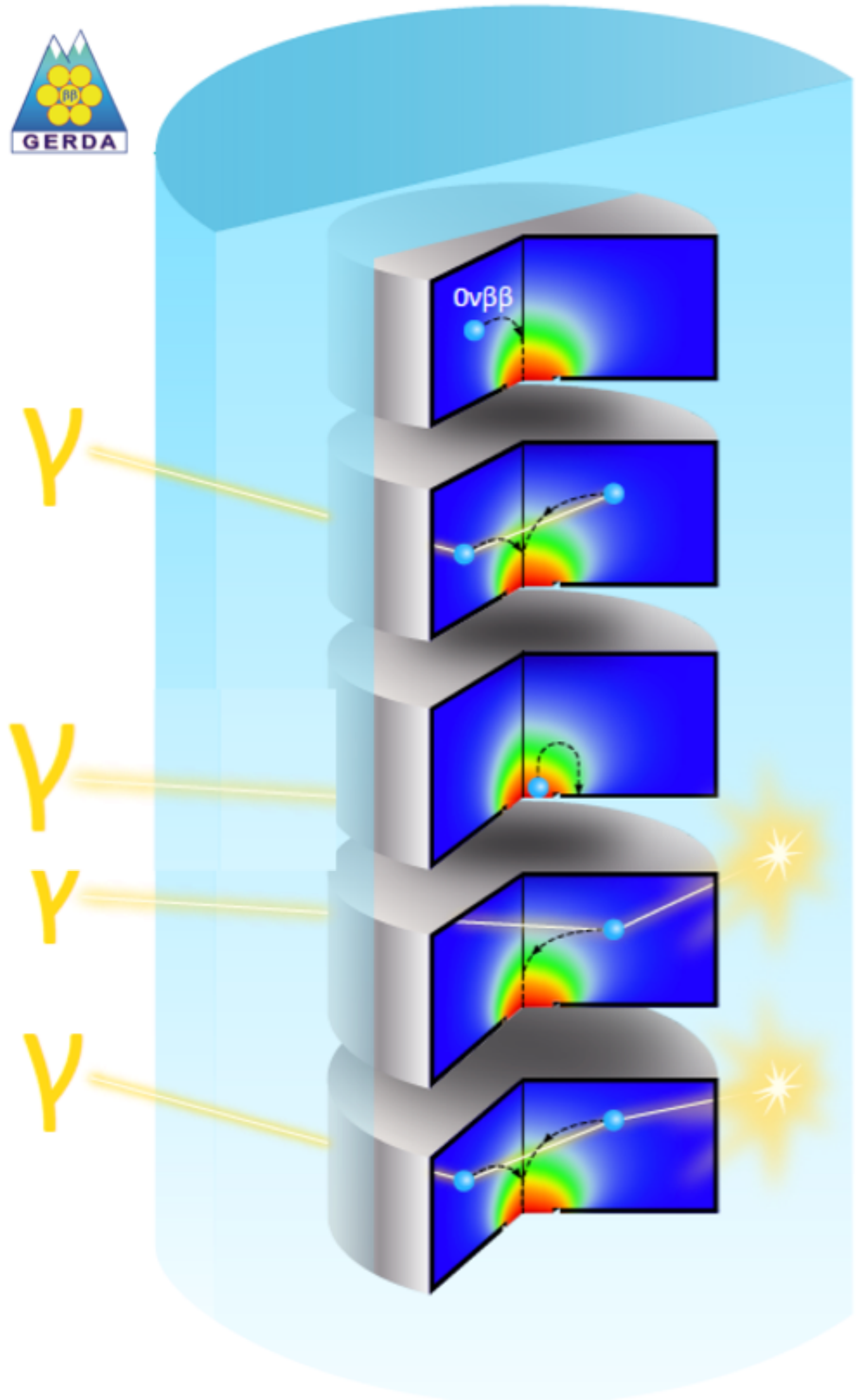
Current pulse of background-like event topology (MSE)

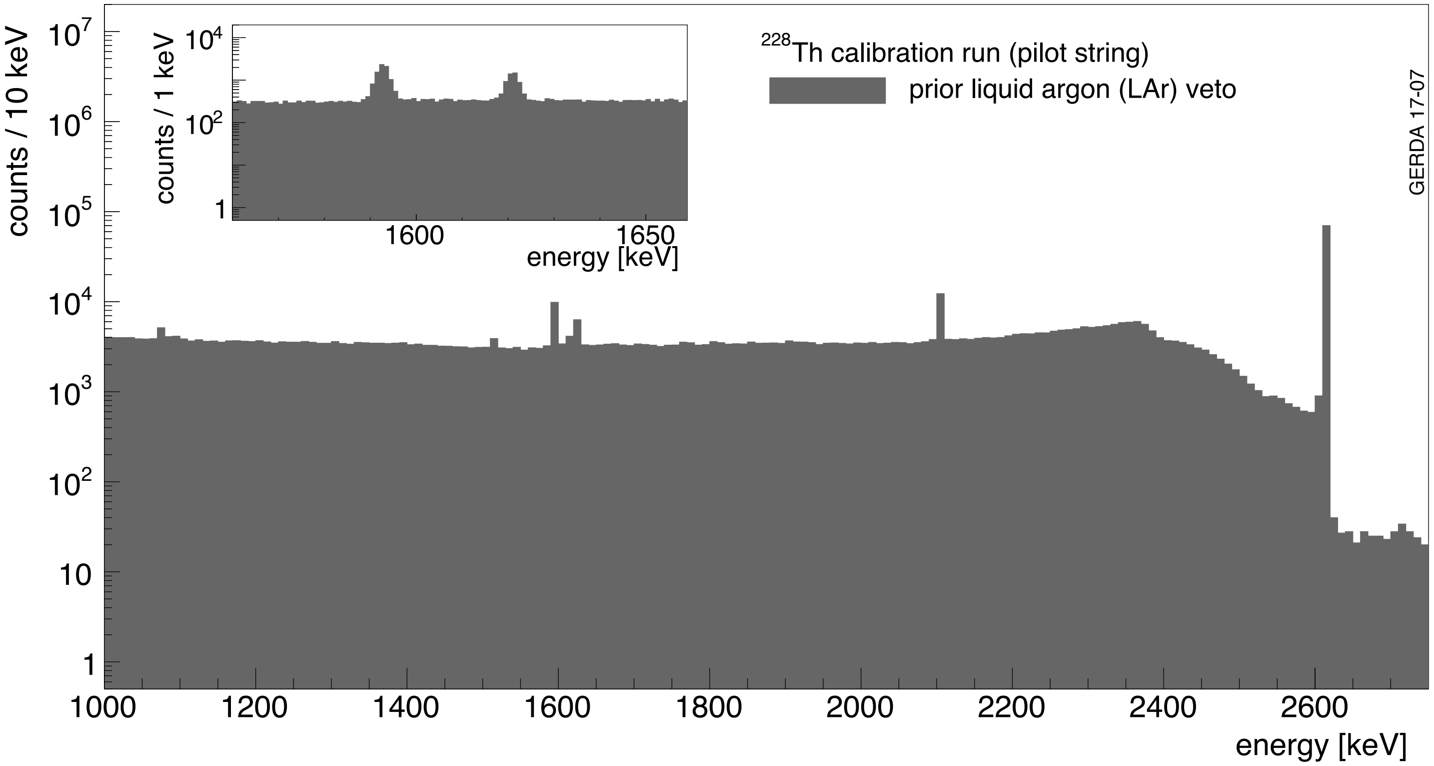




Interplay between PSD and LAr veto

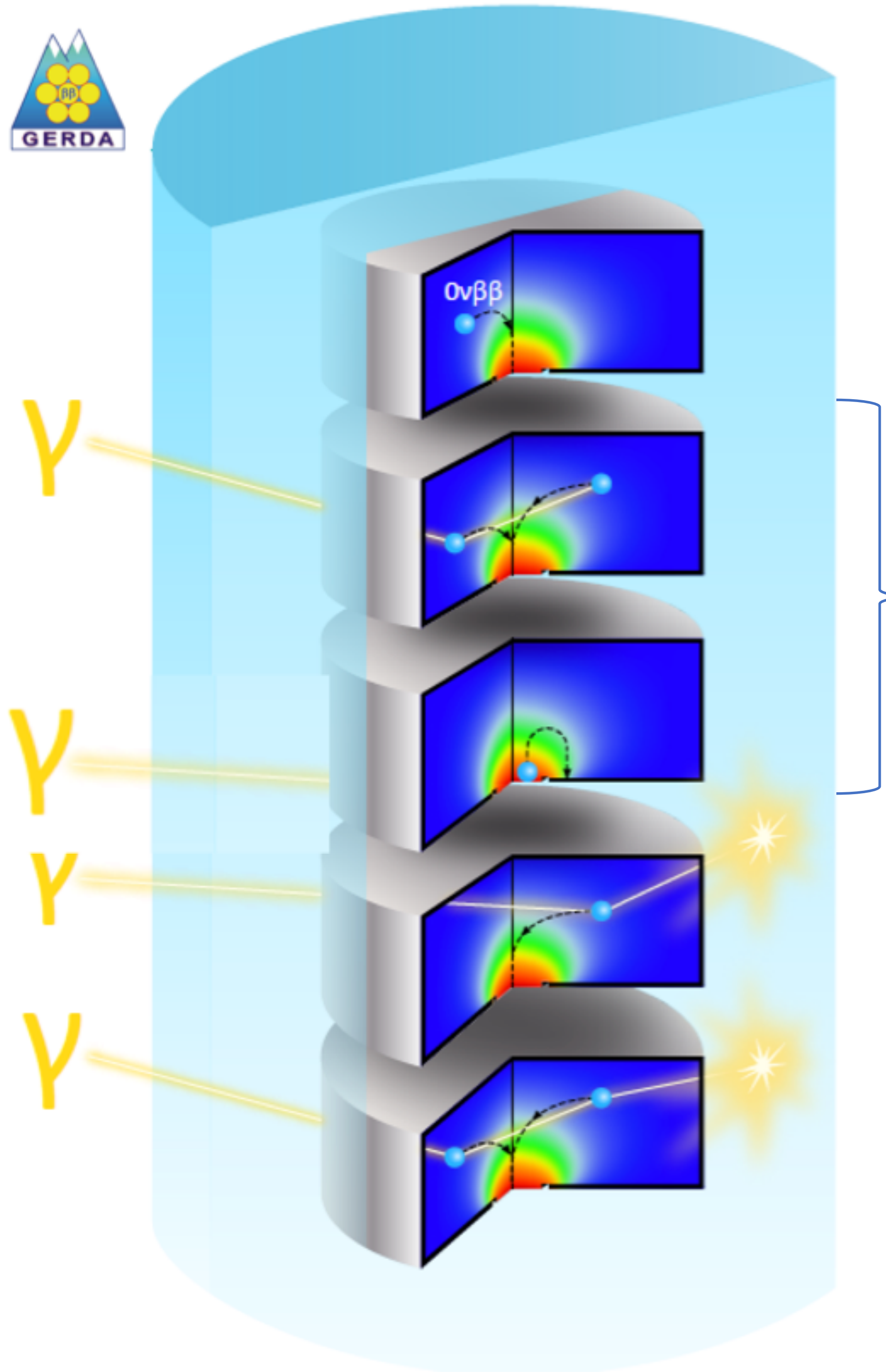
^{228}Th calibration source

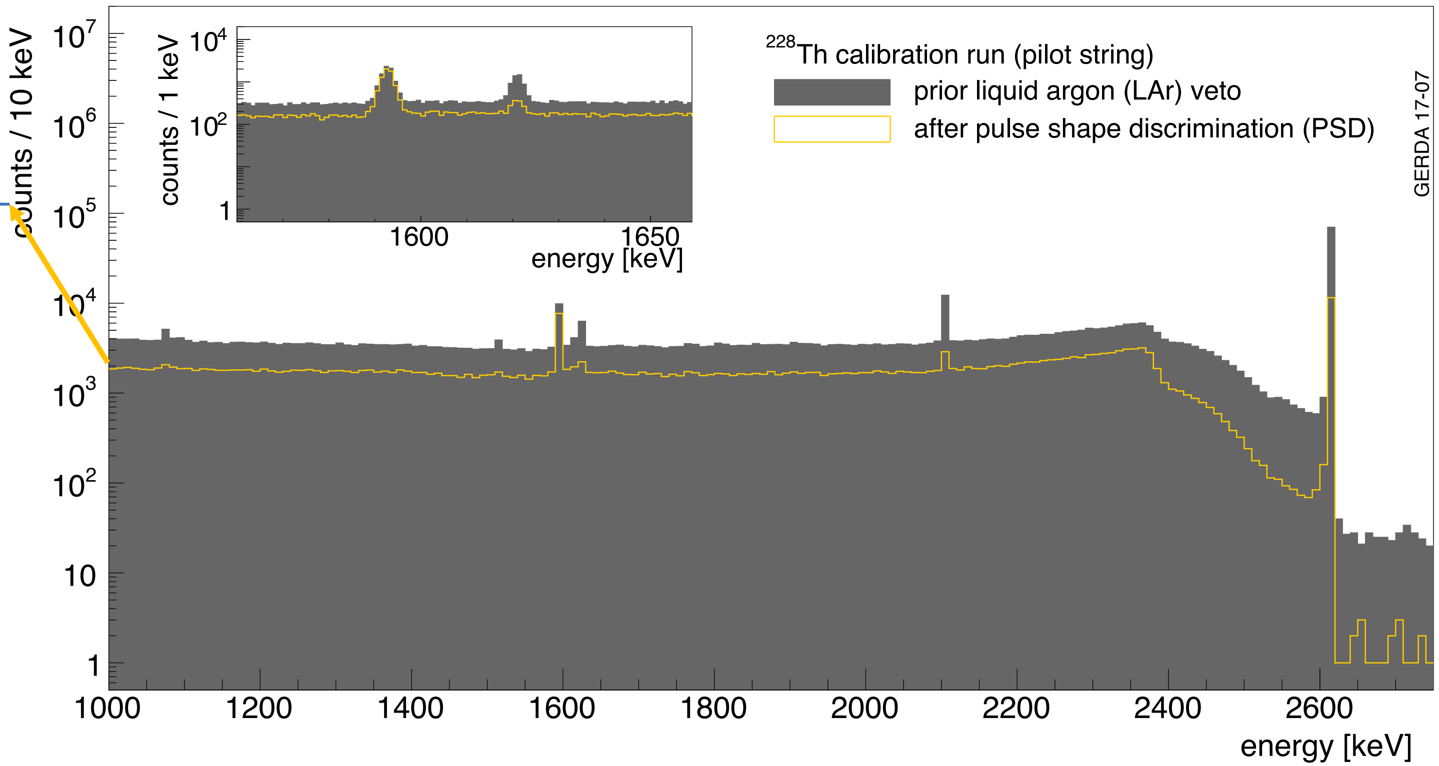




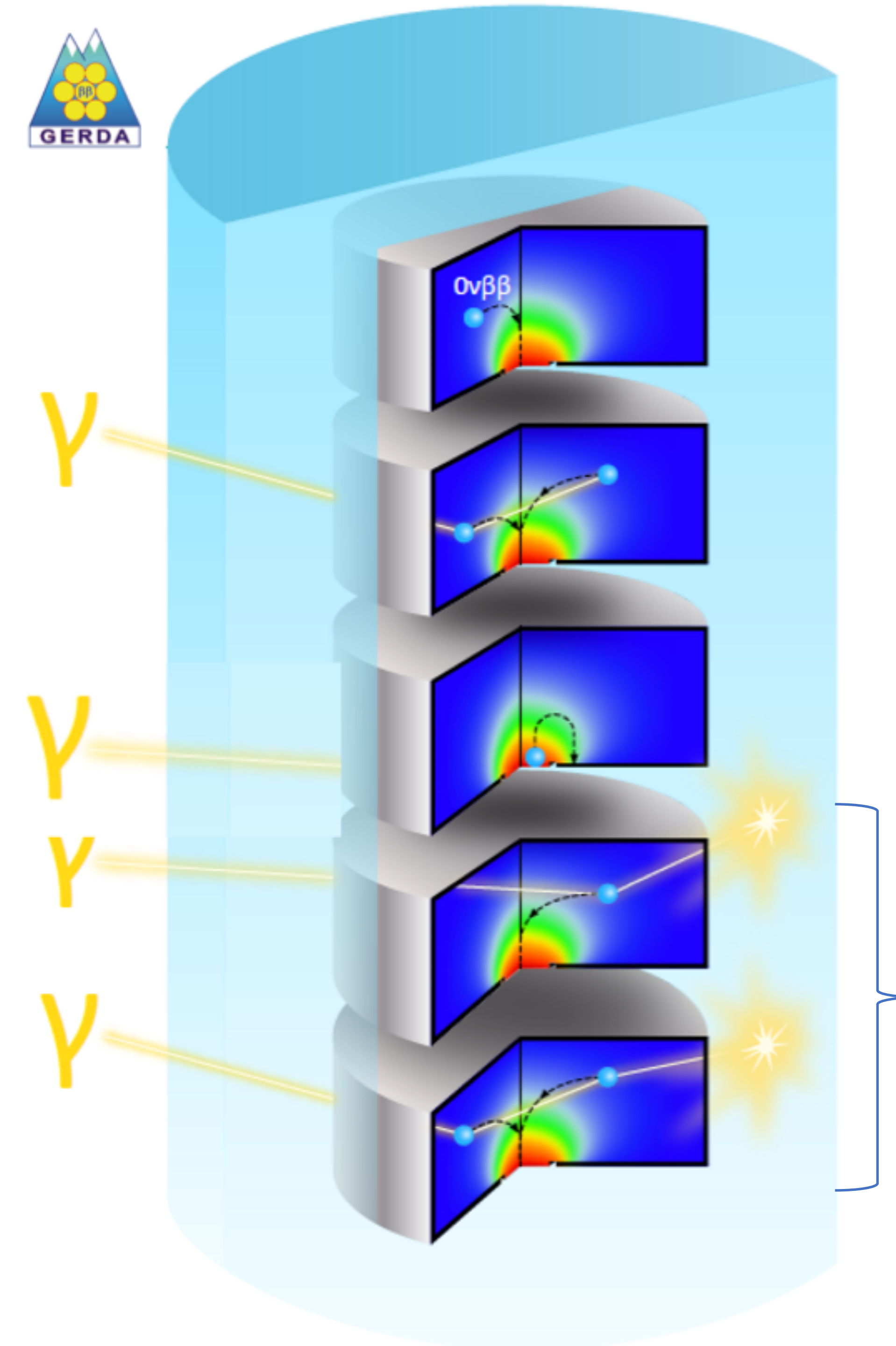
Interplay between PSD and LAr Veto

^{228}Th calibration source

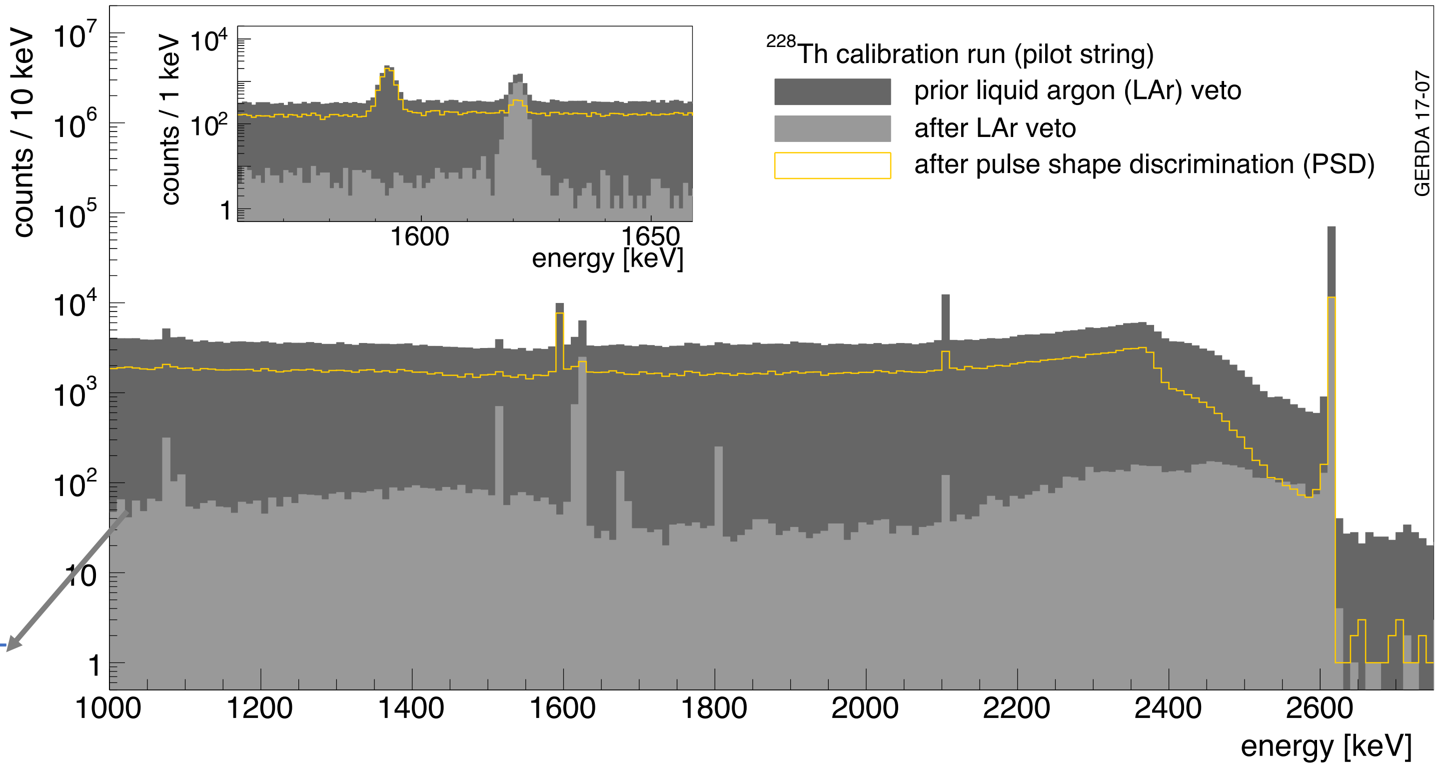




Interplay between PSD and LAr Veto

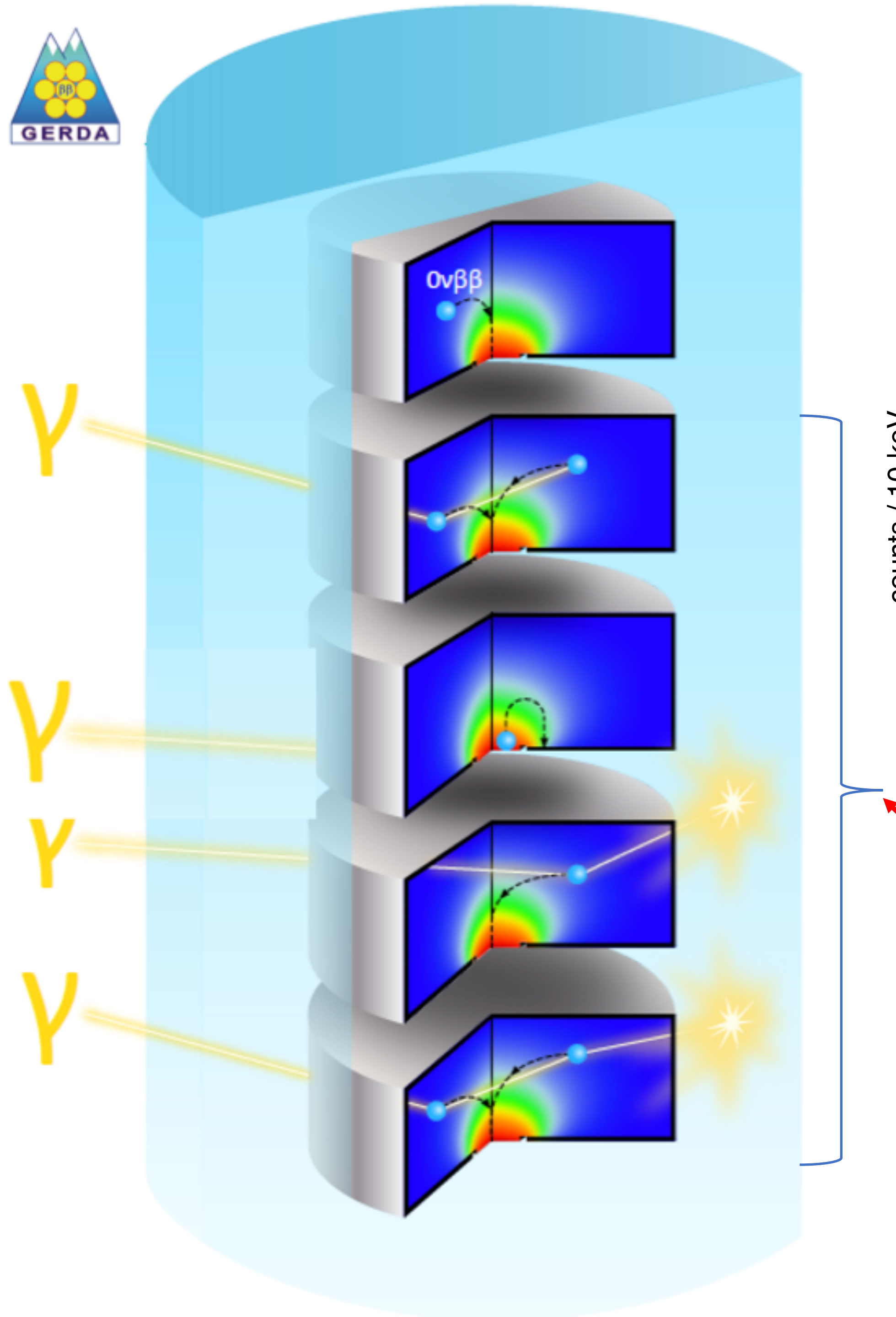


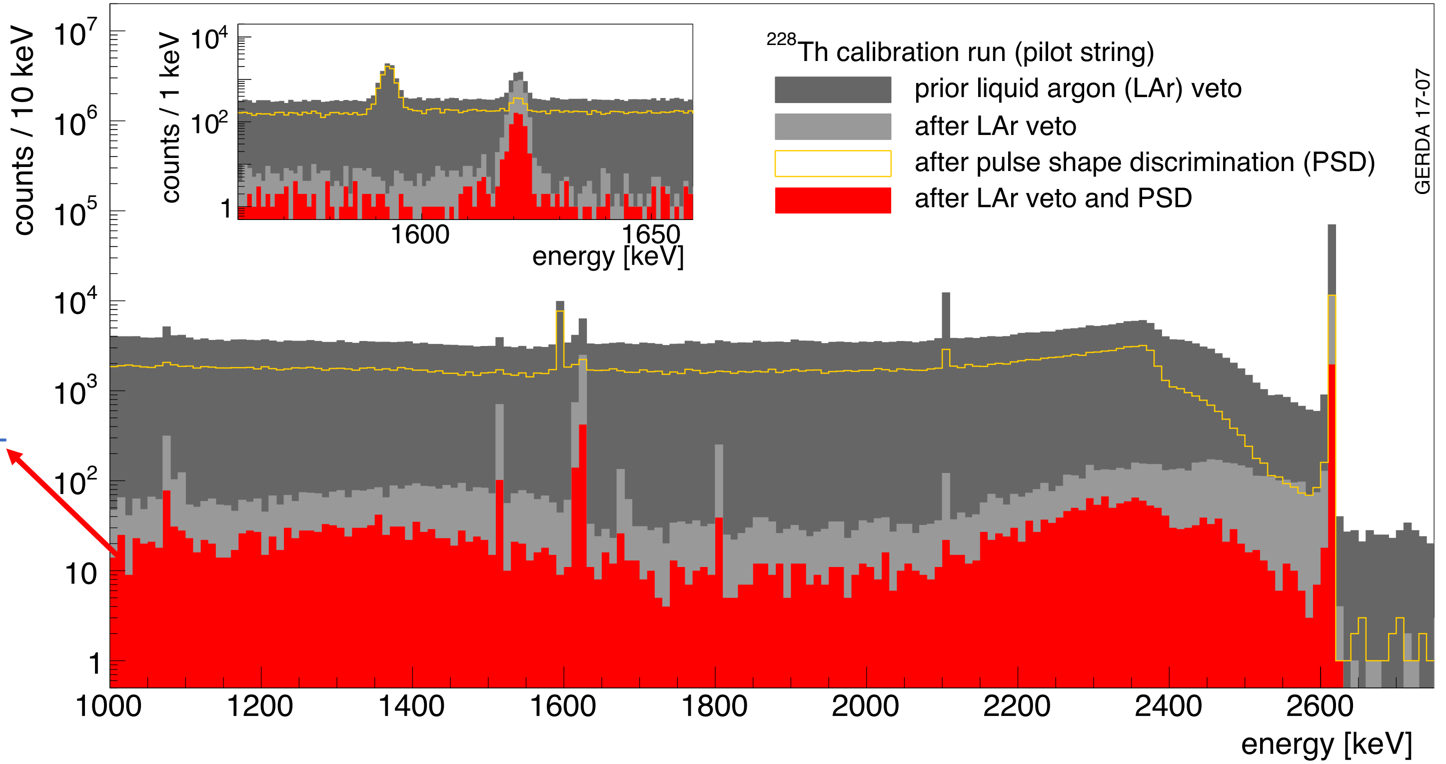
^{228}Th calibration source



Interplay between PSD and LAr Veto

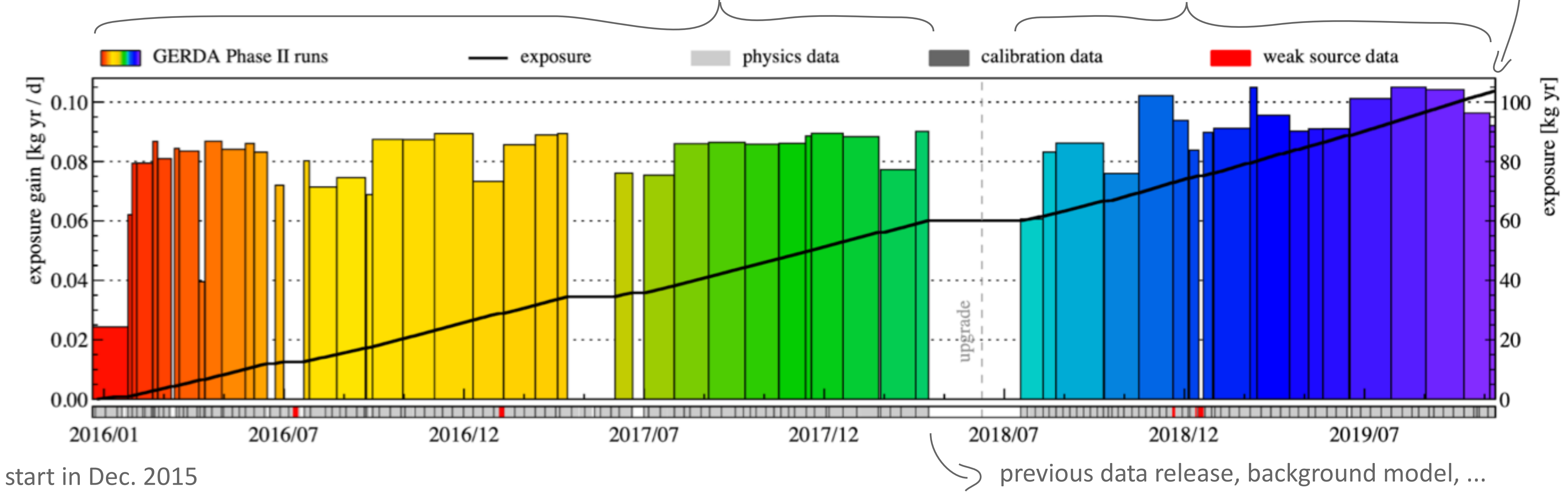
^{228}Th calibration source





Phase II data taking

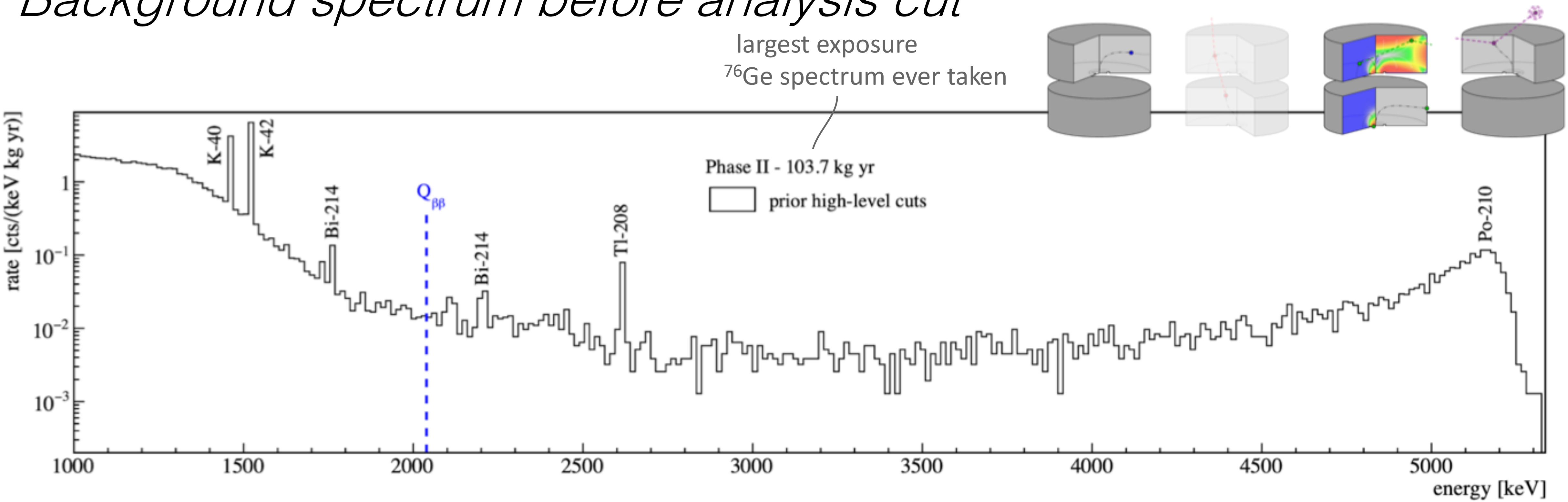
stop in Dec. 2019



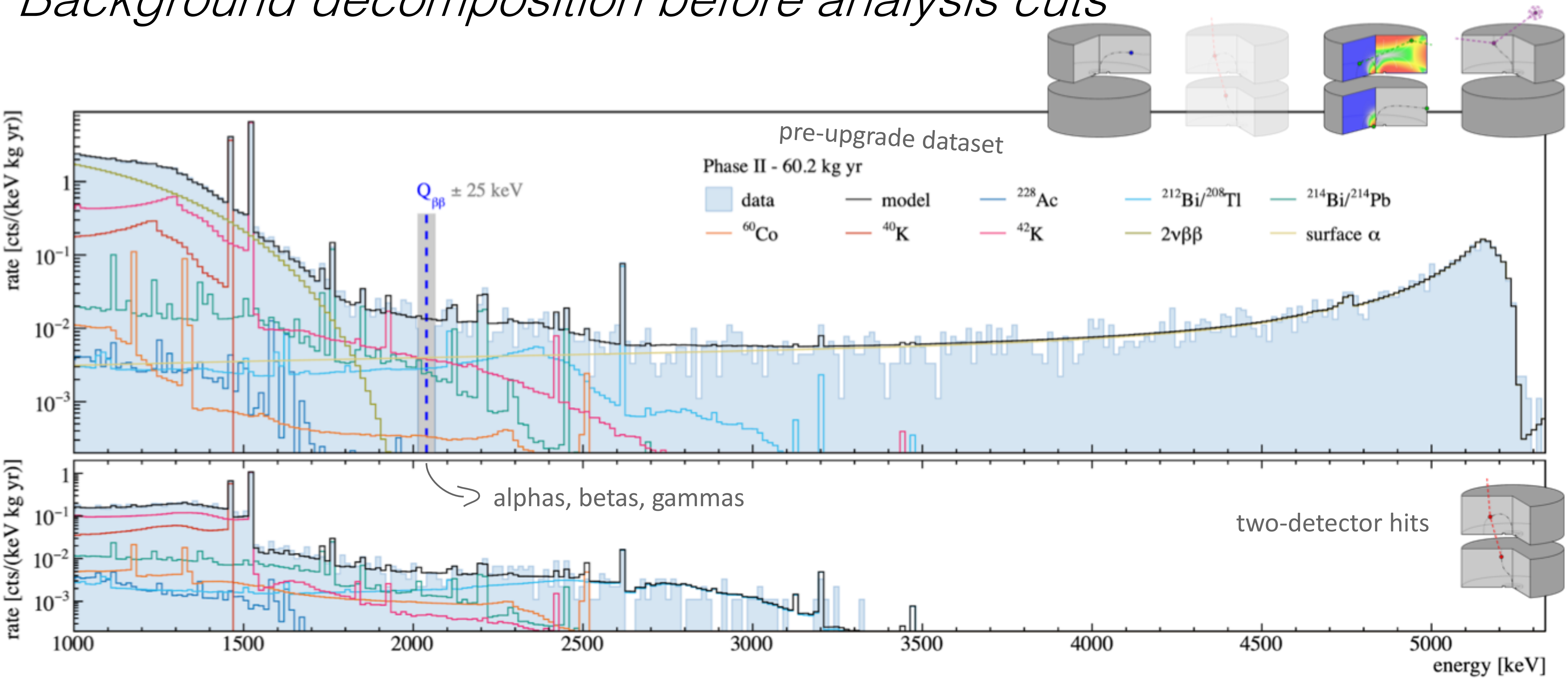
- pre-/post-upgrade data taking with **35.6 / 44.2 kg** of enriched HPGe detectors
- **4 yr** operation, with about **90%** duty cycle (incl. upgrade works), **103.7 kg yr** of data selected for analysis

Background spectrum before analysis cut

largest exposure
^{76}Ge spectrum ever taken



Background decomposition before analysis cuts

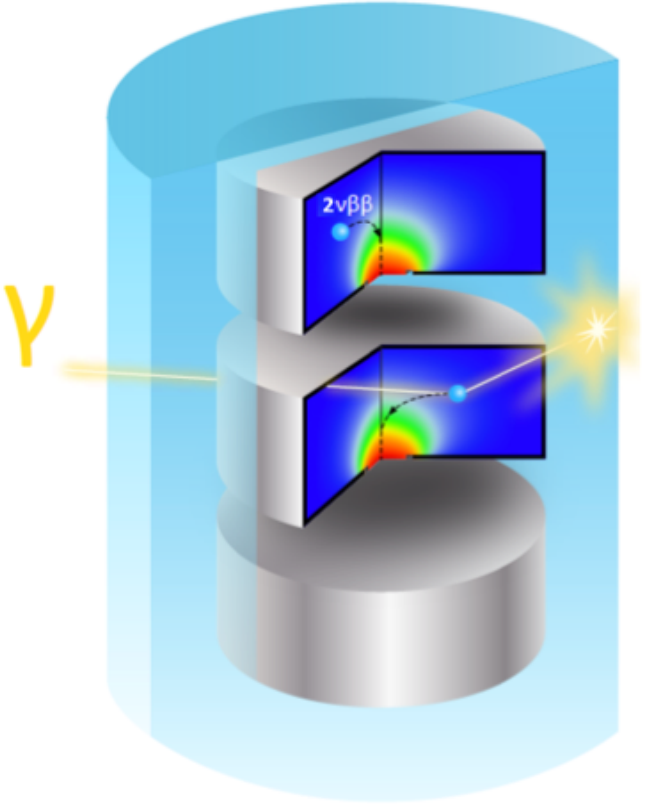


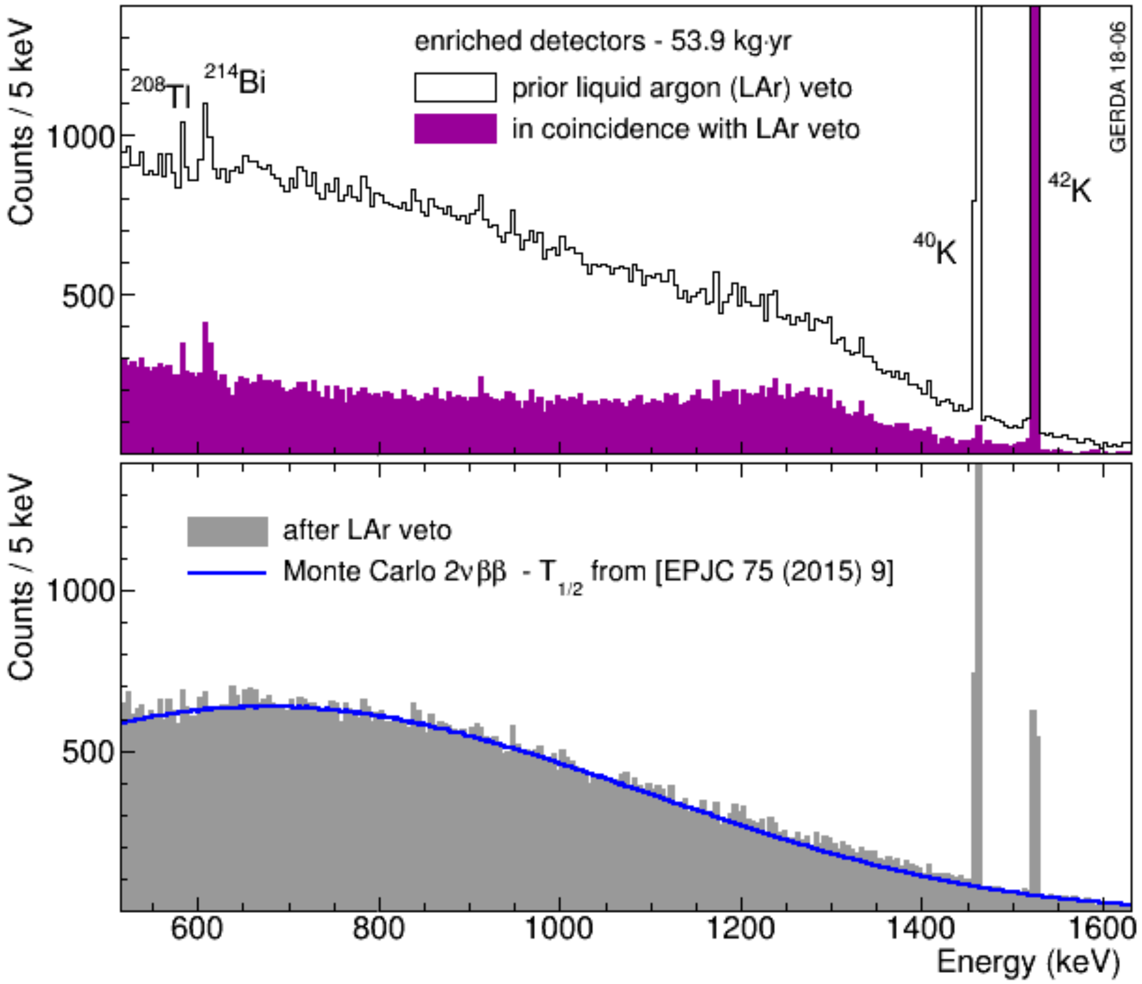
- combined Bayesian fit to multiple datasets with Monte Carlo *pdf*s for **nearby components**

[JHEP 03 (2020) 139]

screening measurements as priors

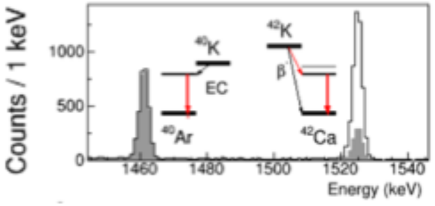
The 2nbb energy range: LAr instrumentation not only a 'veto'





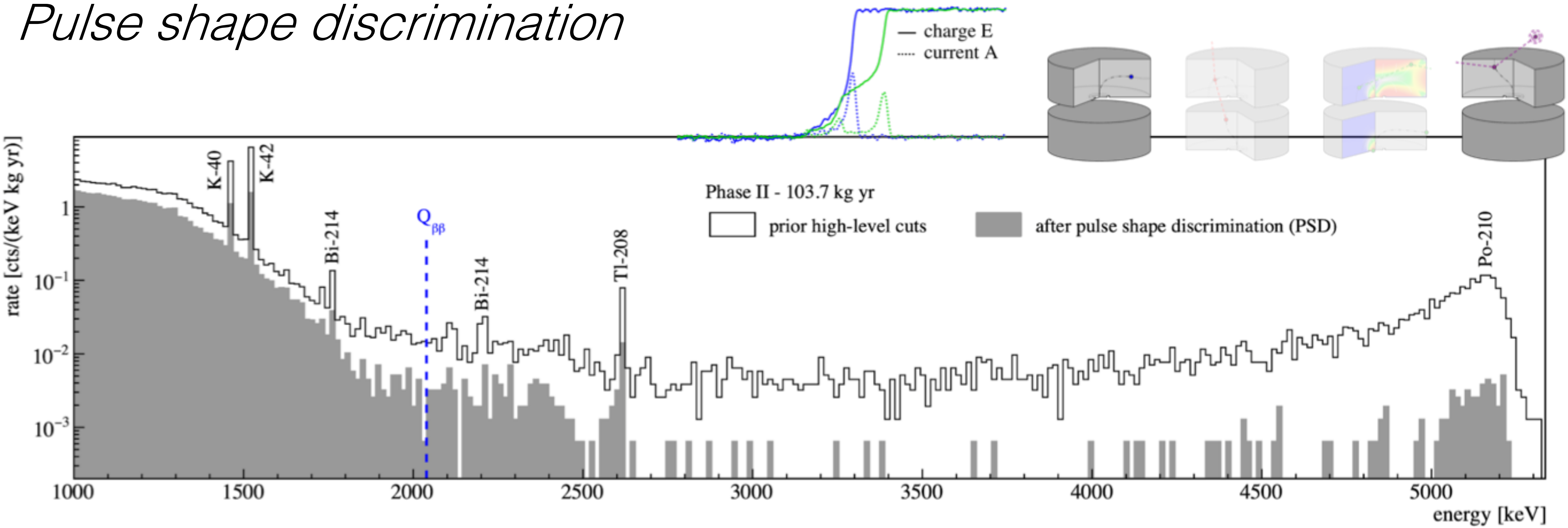
Signal acceptance of LAr veto: 97.7%

In coincidence: spectrum dominated by potassium



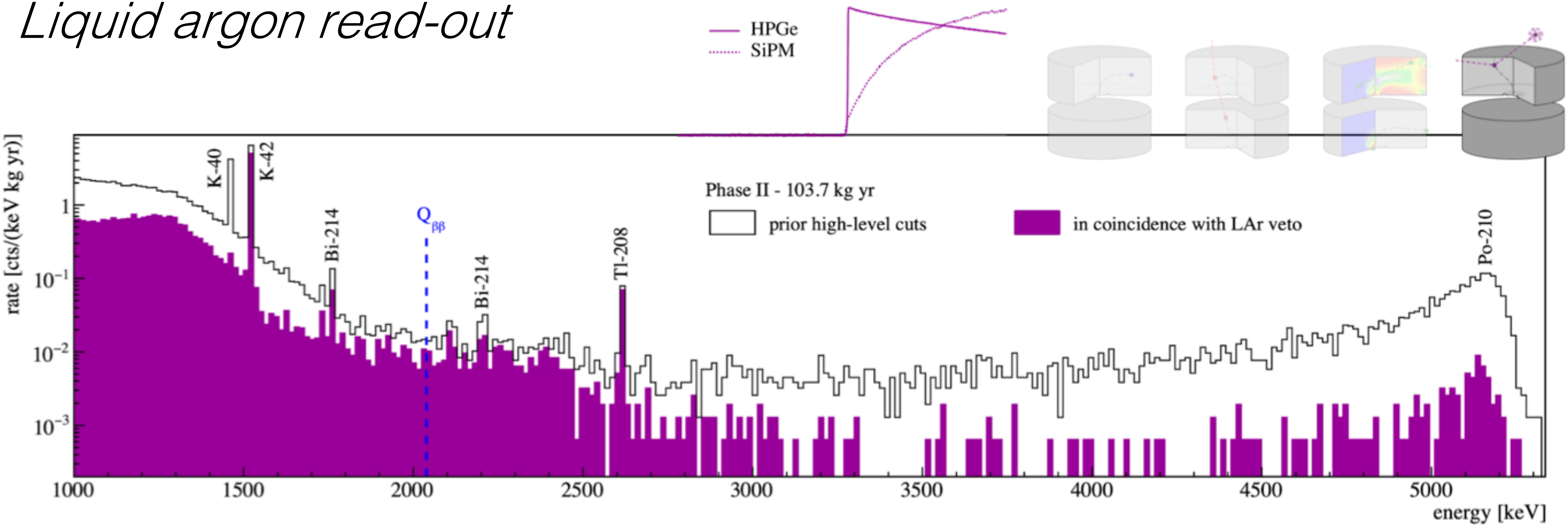
In anti-coincidence: **2νββ spectrum**

Pulse shape discrimination



- two-sided **mono-parametric** A/E cut for **BEGe / ICPC** detectors
  [Budjas et al., JINST 4 (2009) P10007]
- artificial neural network analysis plus consecutive risetime cut for coaxial detectors
  [Eur. Phys. J. C73 (2013) 2583]
- cut definition / training with ^{228}Th **calibration data** -> ^{208}Tl DEP as signal proxy
- $0\nu\beta\beta$ signal efficiency **~90%** (~70% for coaxials)

Liquid argon read-out



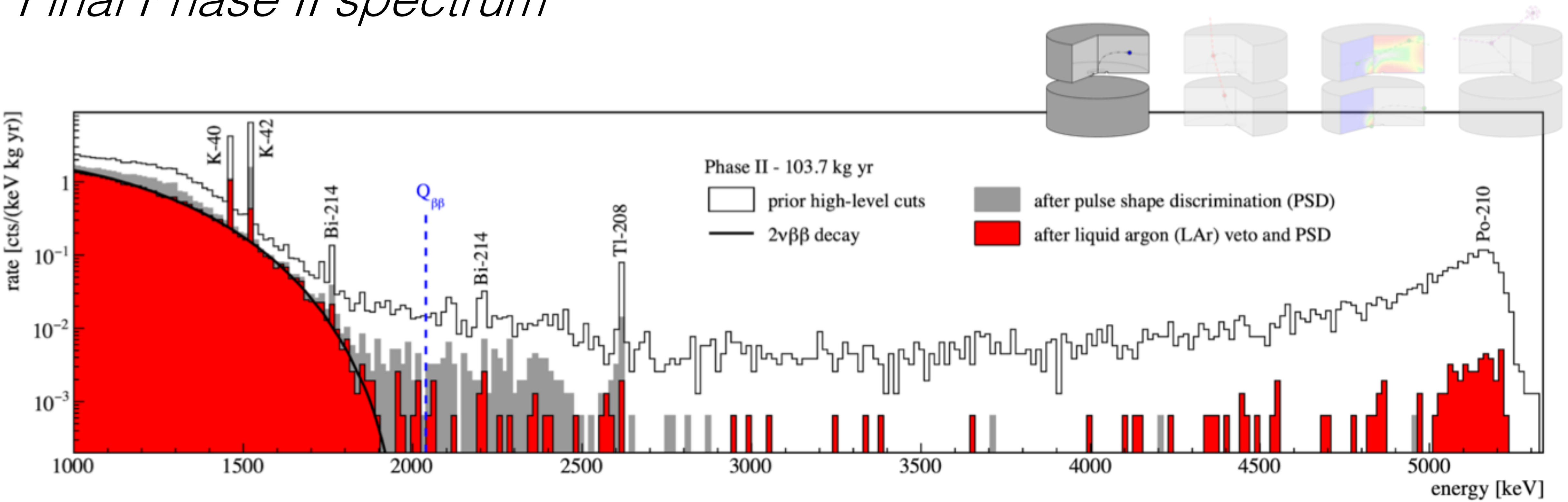
- channel-wise **(anti-)coincidence condition** (PMTs/SiPMs)
- **sub-PE threshold**, contains characteristic scintillation **timing** (triplet emission)
- $0\nu\beta\beta$ signal efficiency (1 - random coincidence rate) **> 97%**

^{39}Ar, dark rate

lifetime ~1 µs

GERDA

Final Phase II spectrum



- "clean" **2νββ continuum**

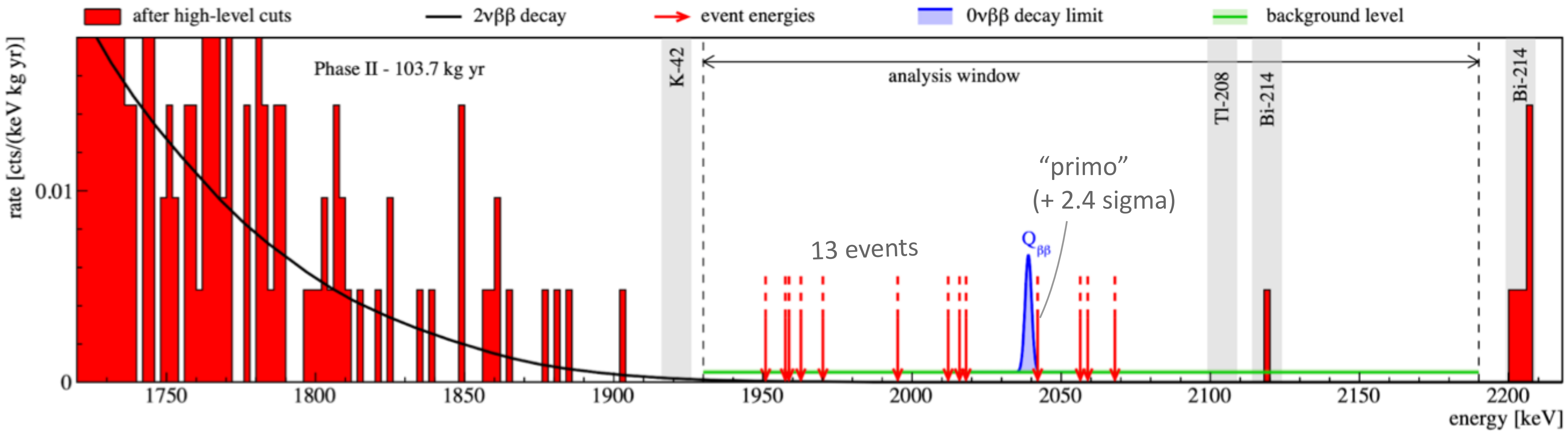
shape analysis in preparation

- sparse **single counts at > $Q_{\beta\beta}$**

no alphas in BEGe / ICPC

Final GERDA result

< 1 cts in 100 kg yr and 5 keV



- background index **$5.2^{+1.6}_{-1.3}\cdot 10^{-4}$ cts/(keV kg yr)**, energy resolution **~3 keV** (FWHM)

  resolution tracked per detector/period

- combined (data partitions, Phase I) **unbinned maximum likelihood fit**
  [Nature 544 (2017) 47]

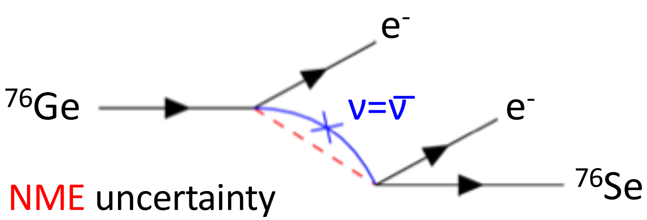
  Gaussian signal on flat background

- **Frequentist**: $N^{0\nu} = 0$ best fit, $\boldsymbol{T_{1/2} > 1.8\cdot 10^{26}}$ **yr** (median sensitivity -”-) at 90% C.L.,
  Bayesian: flat prior on rate, $T_{1/2} > 1.4\cdot 10^{26}$ yr at 90% C.I.

  > $2.3\cdot 10^{26}$ yr for flat prior on m_{bb}

GERDA

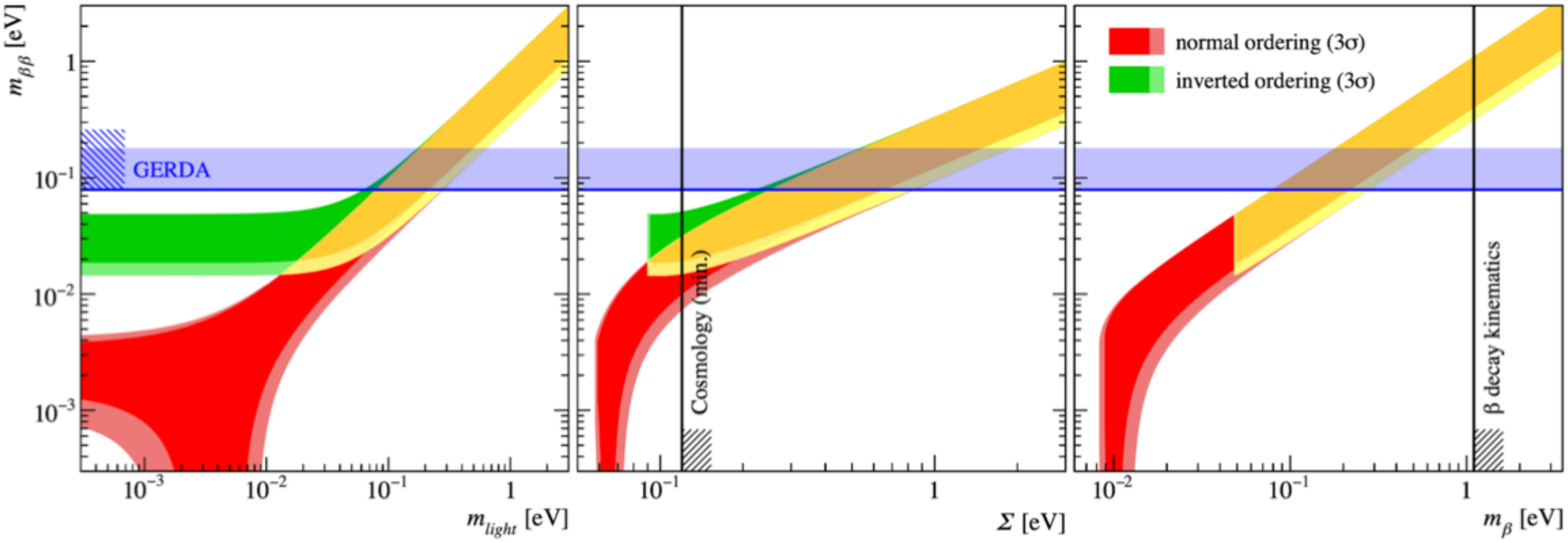
Mass observables



NME uncertainty

[Engel, Menéndez, Rept.Prog.Phys. 80 (2017) no.4, 046301]

three flavour oscillation parameters from [Esteban et al., JHEP 09 (2020) 178]



C. Wiesinger, Dissertation 2020 (TUM)

$\boldsymbol{m_{\beta\beta}}$ **< [0.08,0.18] eV**

others:

KamLAND-Zen:
< [0.05,0.23] eV

CUORE:
< [0.07,0.34] eV

-> Planck+BAO: $\boldsymbol{\Sigma}$ **< 0.12 eV**

[Aghanim et al., arXiv:1807.06209]

-> KATRIN: $\boldsymbol{m_\beta}$ **< 1.1 eV**

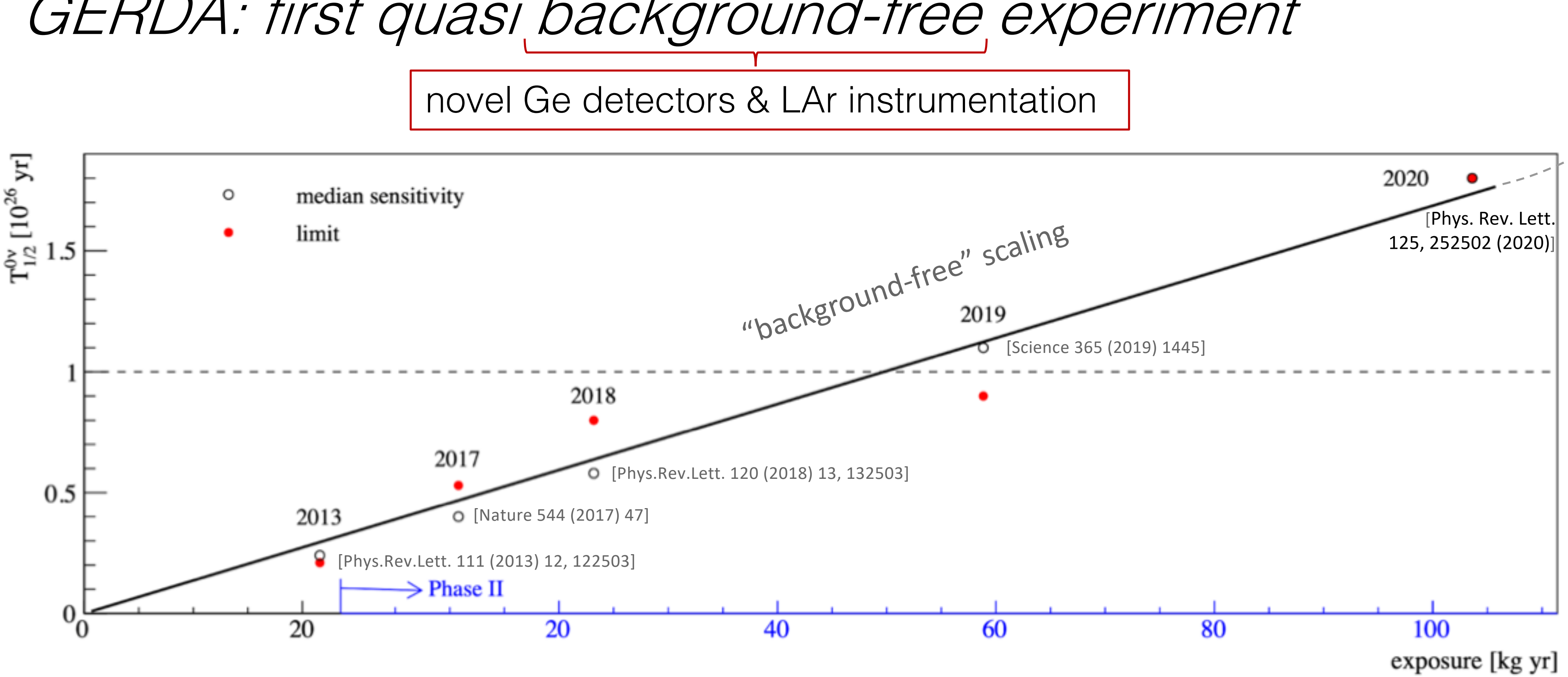
[Aker et al., Phys.Rev.Lett. 123 (2019) no.22, 221802]

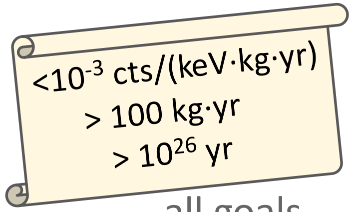
- given "standard" assumptions 0νββ decay searches constrain **neutrino mass**
- **interplay** with cosmology / direct mass measurements -> m_{light} < [0.1,0.5] eV, sum < [0.2,1.5] eV, m_b < [0.1,0.5] eV

[Science 365 (2019) 1445]

GERDA: first quasi background-free experiment

novel Ge detectors & LAr instrumentation





all goals surpassed

- GERDA has finished successfully

first experiment with sensitivity beyond 10^{26} yr

- **no signal found** -> "no neutrinos not found"
- further results (2νββ decay, BSM physics) to come

Recent publications:
Final Results of GERDA on the Search for Neutrinoless Double-β Decay, **Phys. Rev. Lett.** 125, 252502 (2020)
The first search for bosonic super-WIMPs with masses up to 1 MeV/c2 with GERDA , **Phys. Rev. Lett**. 125 (2020) 011801
Modeling of GERDA Phase II data , **J .High Energ. Phys**. 2020, 139 (2020)
Probing Majorana neutrinos with double-β decay, **Science 365**, 1445 (2019);
Improved Limit on Neutrinoless Double-β Decay of 76Ge from GERDA Phase II, **Phys. Rev. Lett.** 120 (2018) 132503
Background-free search for neutrinoless double-β decay of 76Ge with GERDA, **Nature** 544 (2017)
More at https://www.mpi-hd.mpg.de/gerda/public/index-pubgall.html

Combine the best from two worlds

Majorana Demonstrator

29.7 kg of enriched p+ point contact (PPC) detectors with **low noise electronics** in compact shield from u**nderground electroformed copper**

background:	$(6.2 \pm 0.6)\cdot10^{-3}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>8.3\cdot10^{25}$ yr (90% C.L.) [J. Gruzko, Nu2022]
where:	SURF (SD)
when:	completed

GERDA Phase II

44.2 kg of enriched BEGe/coaxial/ICPC detectors operated in low A **active LAr shield**

background:	$5.2^{+1.6}_{-1.3}\cdot10^{-4}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>1.8\cdot10^{26}$ yr (90% C.L.) [accepted by Phys.Rev.Lett.]
where:	LNGS (IT)
when:	**completed**

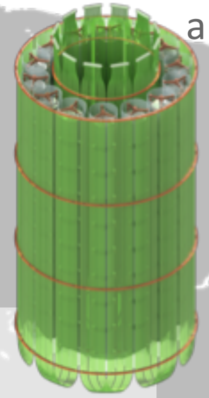
Combine the best from two worlds

LEGEND

*"... develop a **phased**, **^{76}Ge** based double-beta decay experimental program with **discovery potential** at a half-life **beyond 10^{28} years**, using **existing resources** as appropriate to expedite physics results."*

? SNOLAB

? LNGS



LEGEND-200

up to **200 kg** of enriched ICPC(/BEGe/PPC) detectors in GERDA infrastructure

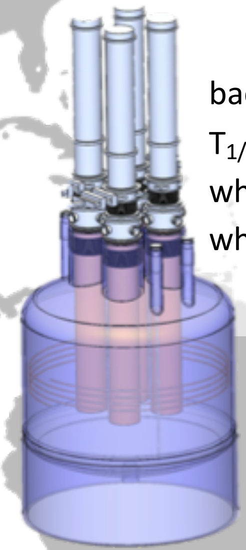
background:	< $2\cdot10^{-4}$ cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	>10^{27} yr
where:	LNGS (IT)
when:	**2021**

1/3 of
GERDA

LEGEND-1000

1000 kg, staged via individual payloads

background:	10^{-5} cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	>10^{28} yr
where:	**to be selected**
when:	contingent on funding decisions



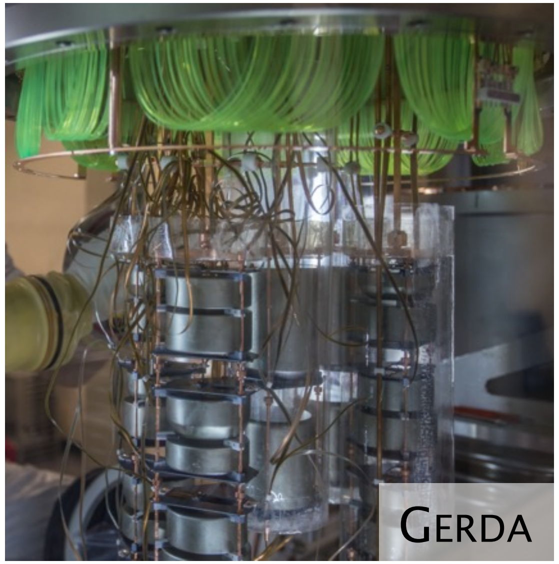
4 payloads in
UAr

The LEGEND Collaboration

- The goal of the LEGEND Collaboration is to design, construct, and field LEGEND-1000, a ton-scale experiment
  - *"The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."*

- The LEGEND collaboration was formed in 2016 through a merger of the MAJORANA and GERDA collaborations, along with several new institutions
- It includes 266 members, 48 institutions, 11 countries

MAJORANA



GERDA

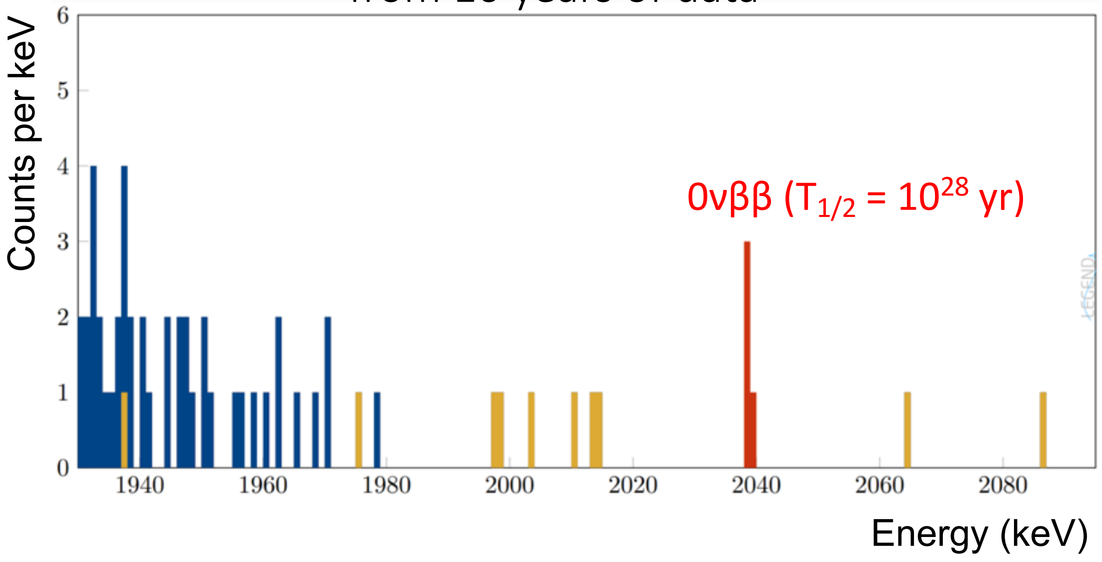
The LEGEND Collaboration

The LEGEND-1000 Discovery Sensitivity

“The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years...”

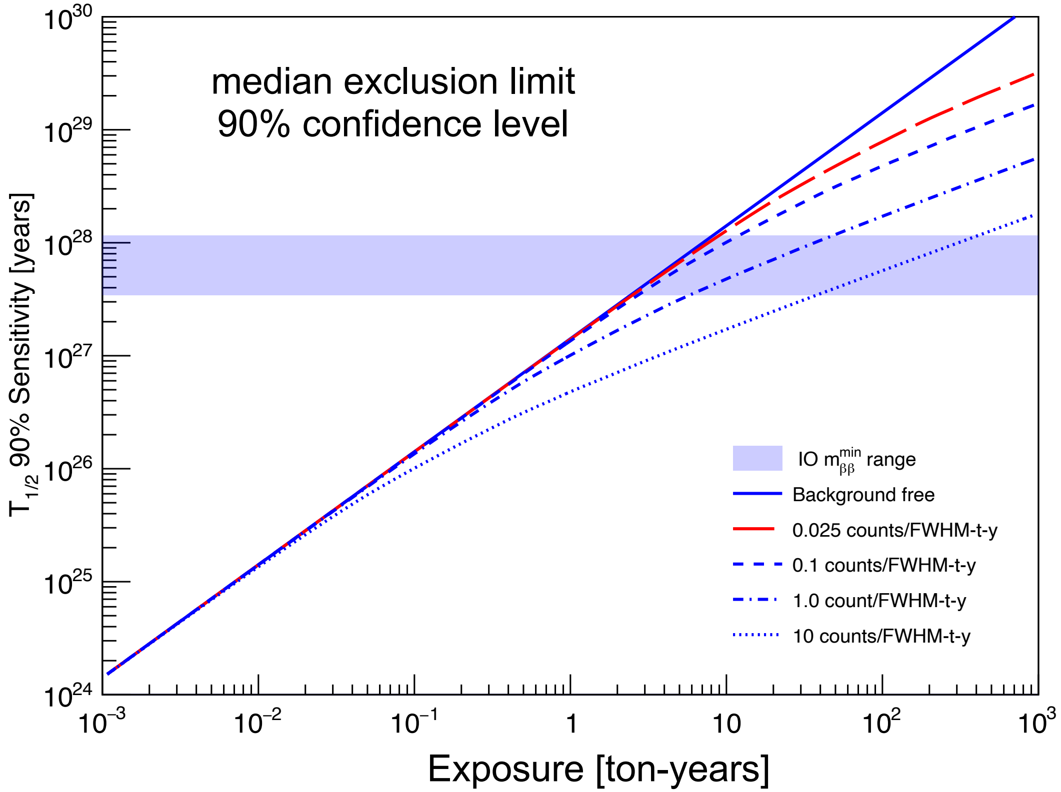
- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event rate**
    - The best possible **energy resolution**

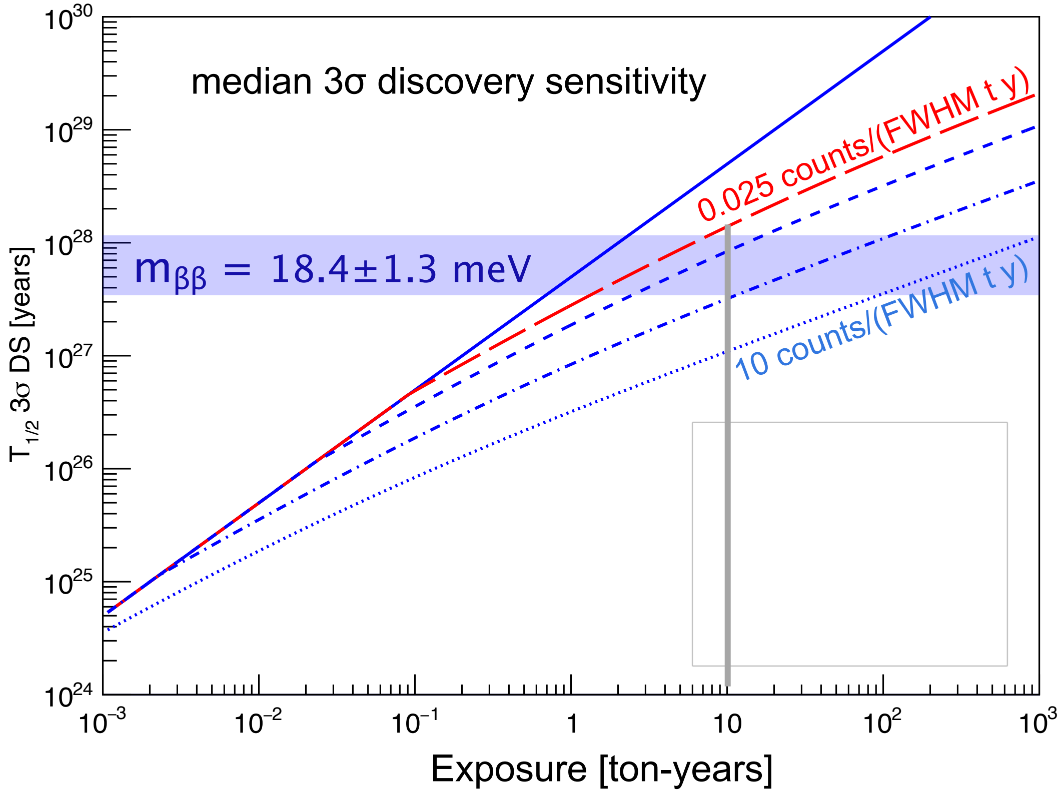
Simulated example spectrum, after cuts, from 10 years of data



The Effect of Background

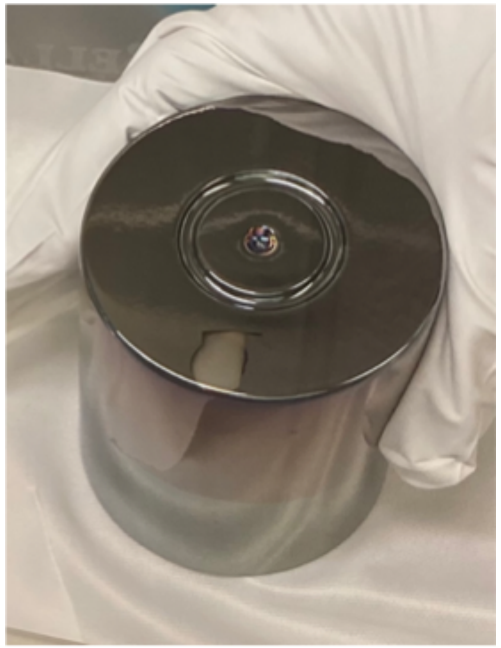
- Background-free: Sensitivity rises linearly with exposure
  Background-limited: Sensitivity rises as the square root of exposure
- Our background goal is the red line, 0.025 counts/(FWHM t y), “quasi-background-free”
  - *Less than one background count* expected in a 4σ Region of Interest (ROI) with 10 t y exposure
    (FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)





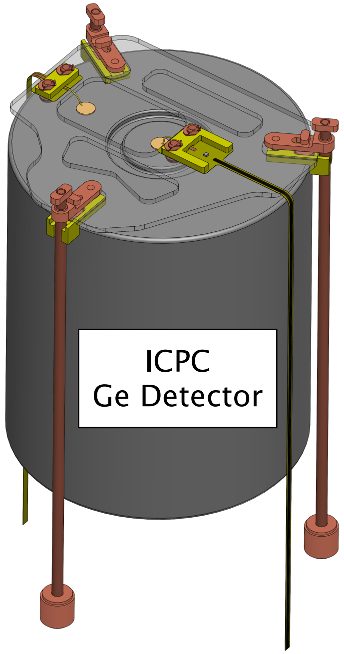
Why Germanium?

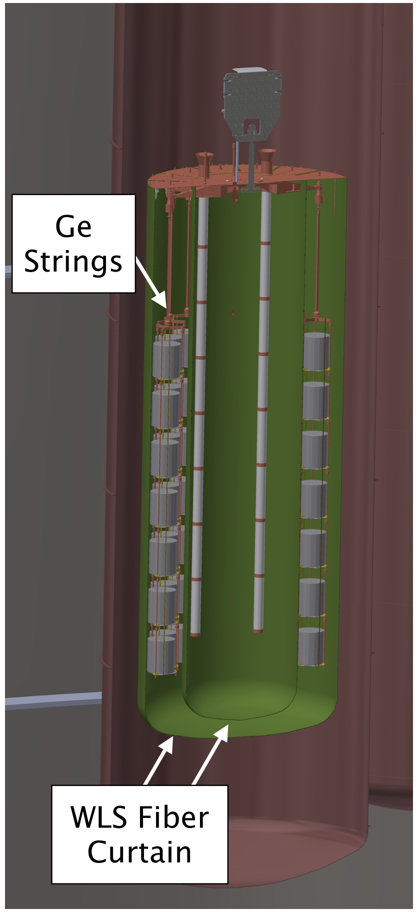
- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
  - Therefore, no background peaks anywhere near the energy of interest
  - Background is flat and well understood
  - Background will be measured, with no reliance on background modeling
  - All this leads to an excellent likelihood that an observed signal will be ***convincing***
- Low risk, high impact
  - Demonstrated performance of the entire technology chain
  - GERDA has produced the lowest background per FWHM of any experiment
  - MAJORANA has produced the best resolution
  - Requires no extrapolation from current detector performance
  - Proven track record, with history of leading limits
  - The team is experienced and ready to transition from LEGEND-200 construction to LEGEND-1000
  - A stable cost estimate, with appropriate contingency

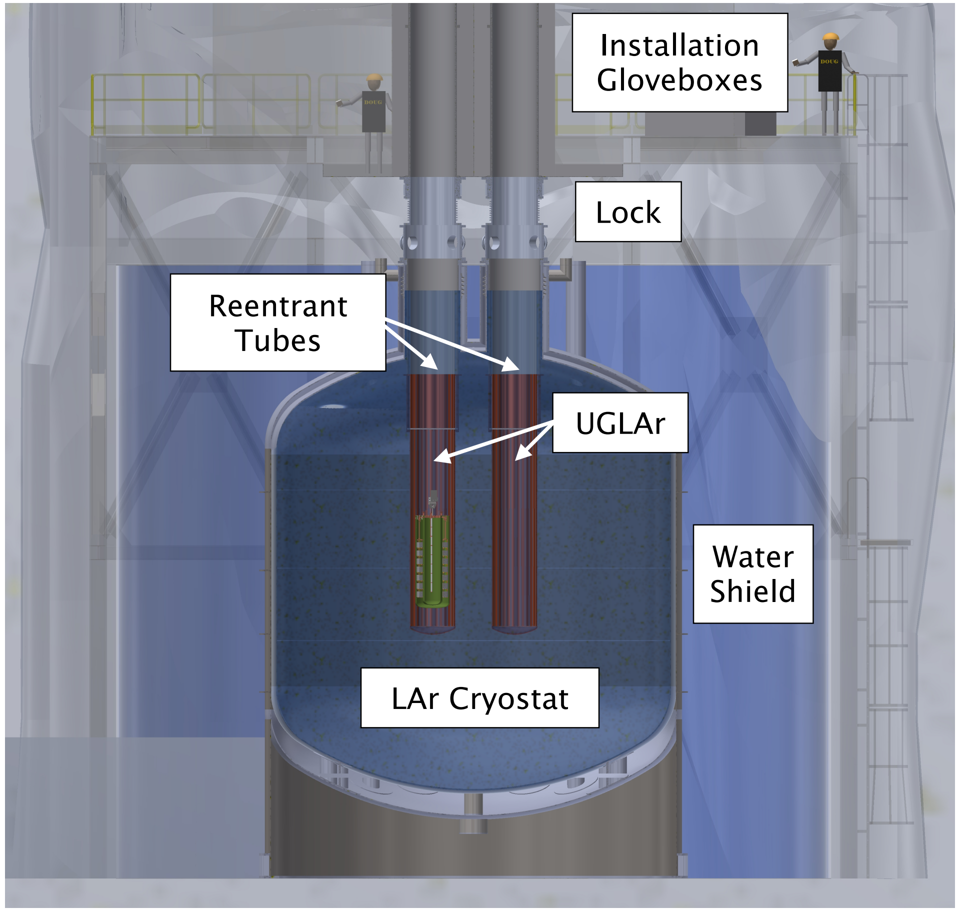


LEGEND-1000: A discovery experiment for 0νββ of ^{76}Ge

Quasi-background-free search for 0νββ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV







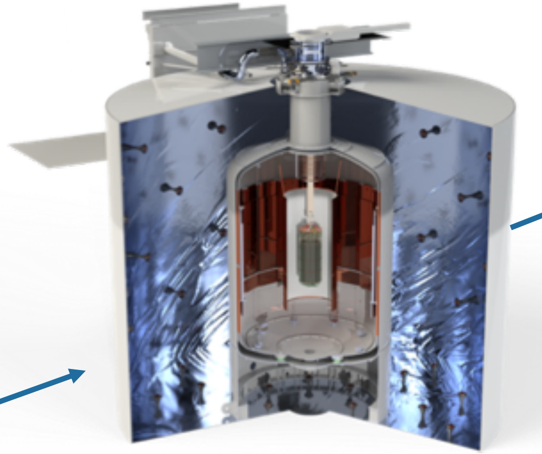
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

Innovation toward LEGEND-1000

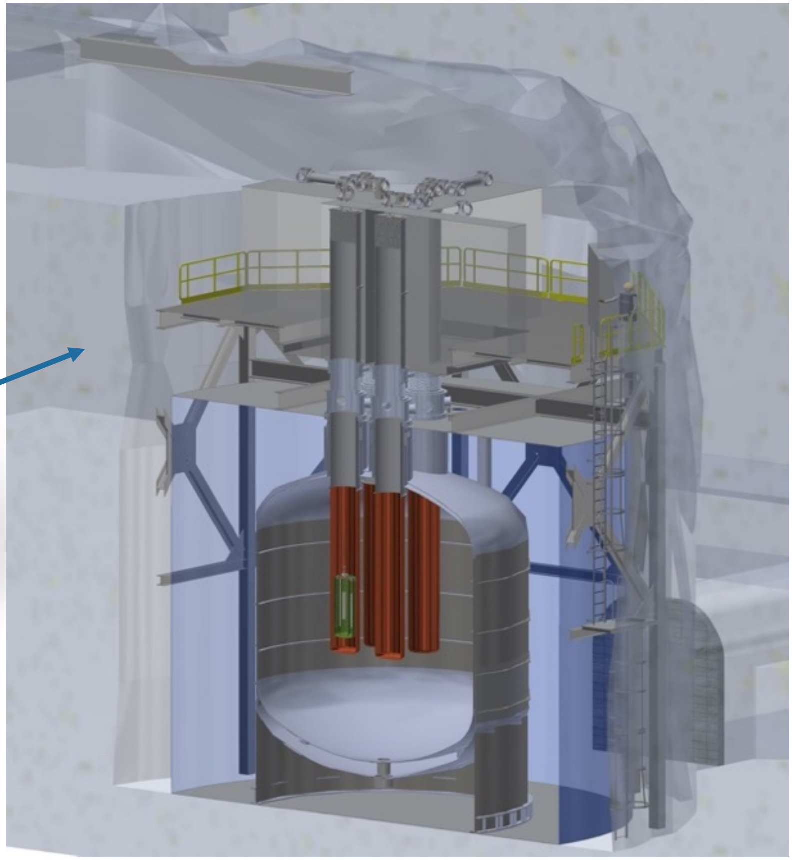
The LEGEND-1000 design builds on a track record of breakthrough developments

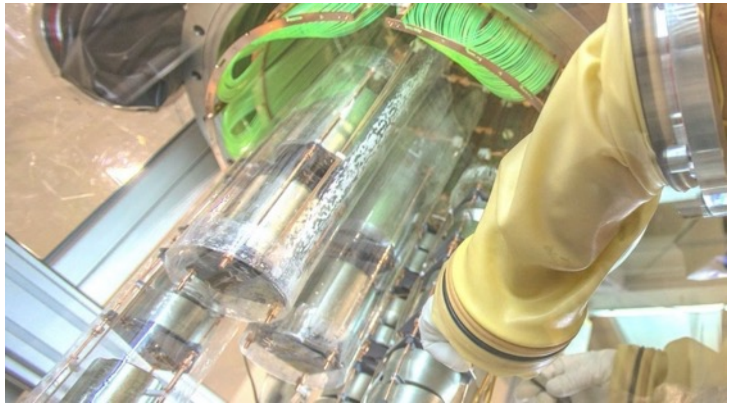
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (commissioning 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

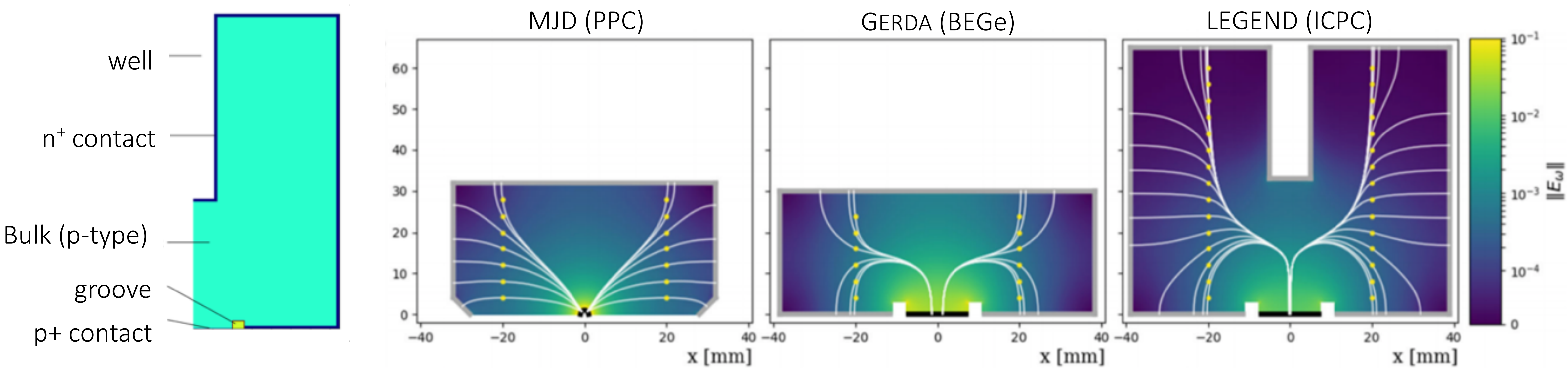
MJD

PPC: p-type Point Contact Ge detectors

BEGe: (modified) Broad Energy Ge detectors

EFCu: Electroformed copper

Innovation toward LEGEND-1000: ^{enr}Ge Detectors

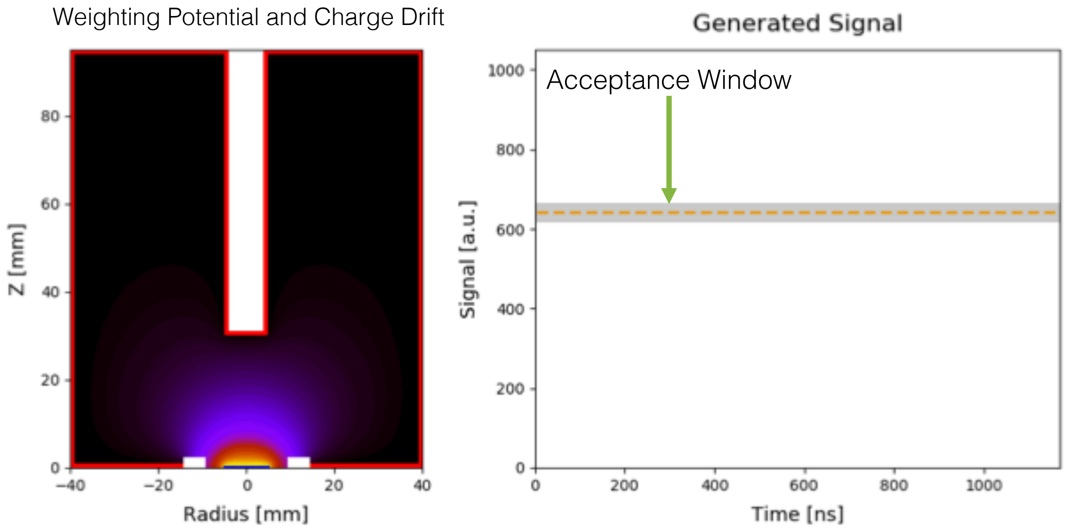


- P-type detectors: Insensitive to alphas on n$^+$ contact
- Small p$^+$ contact: Event topology discrimination
- Large-mass ICPC detectors: About 4 times lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



Charge signal

Current signal

Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

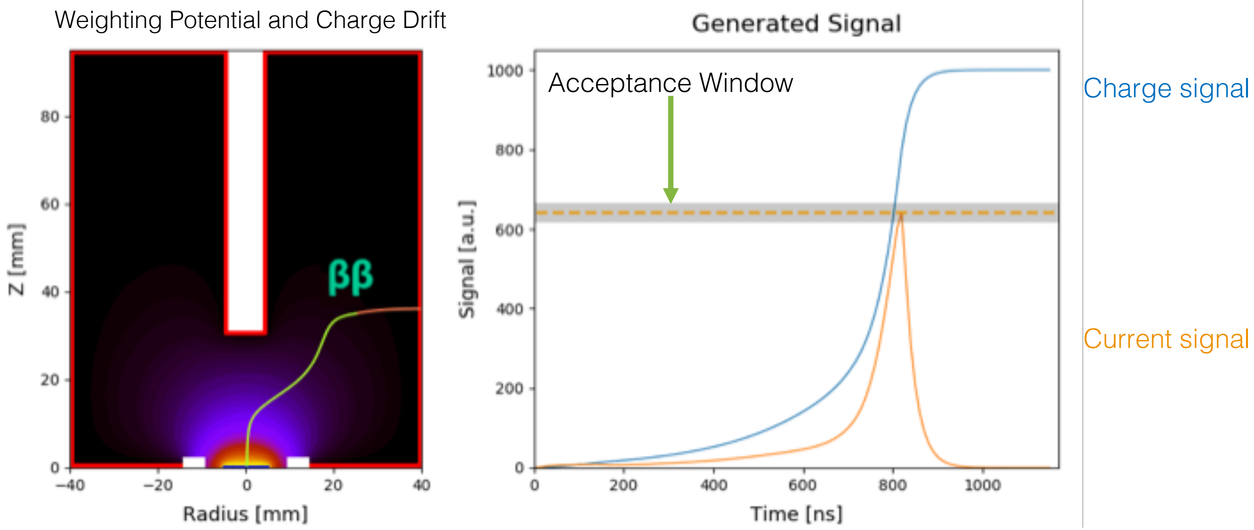
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



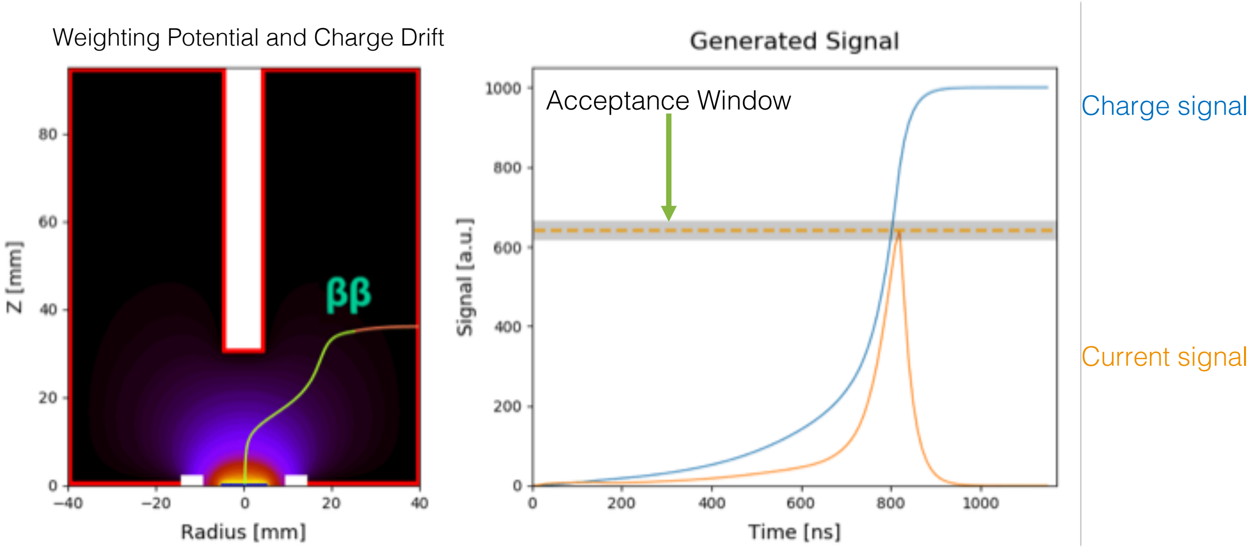
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

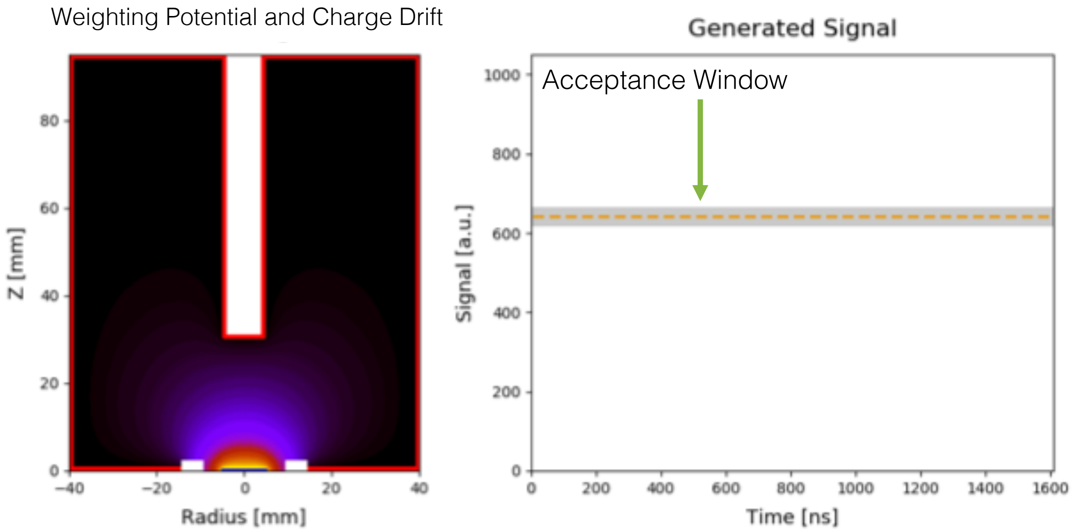
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



γ-background (multi-site)



Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

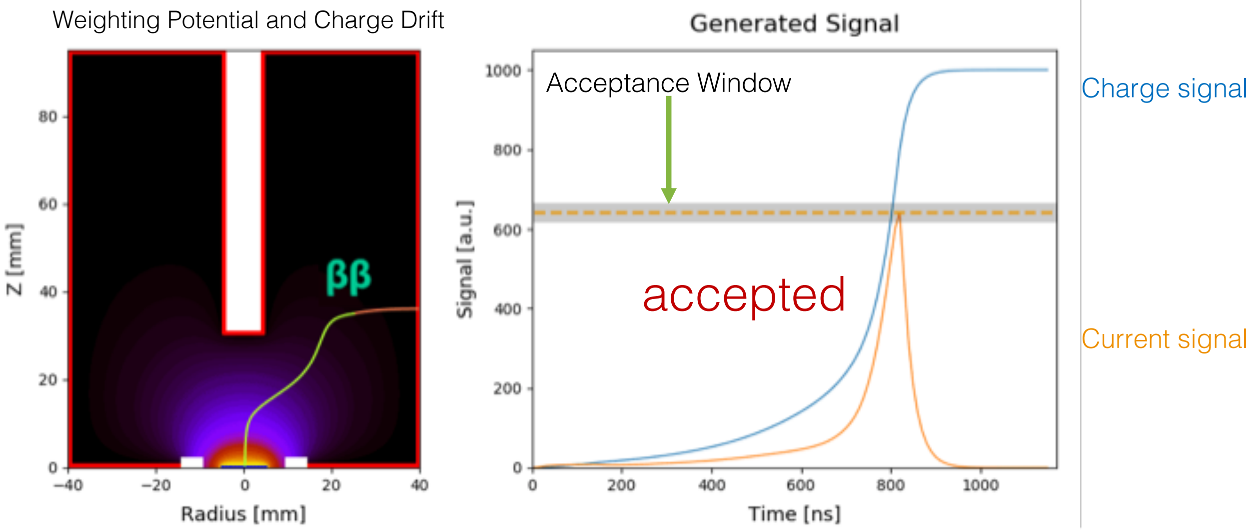
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

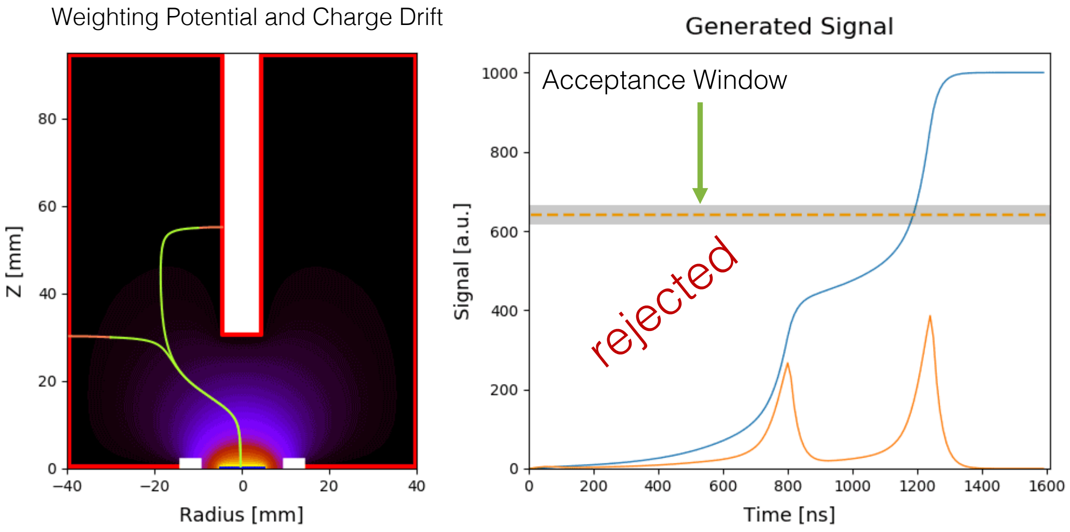
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



γ-background (multi-site)



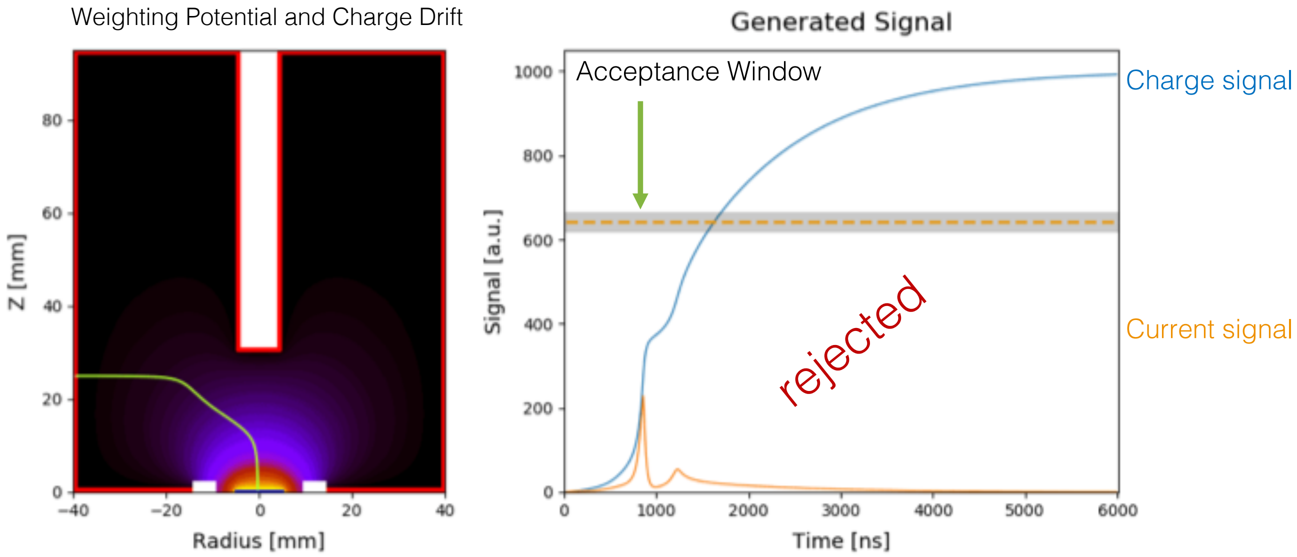
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

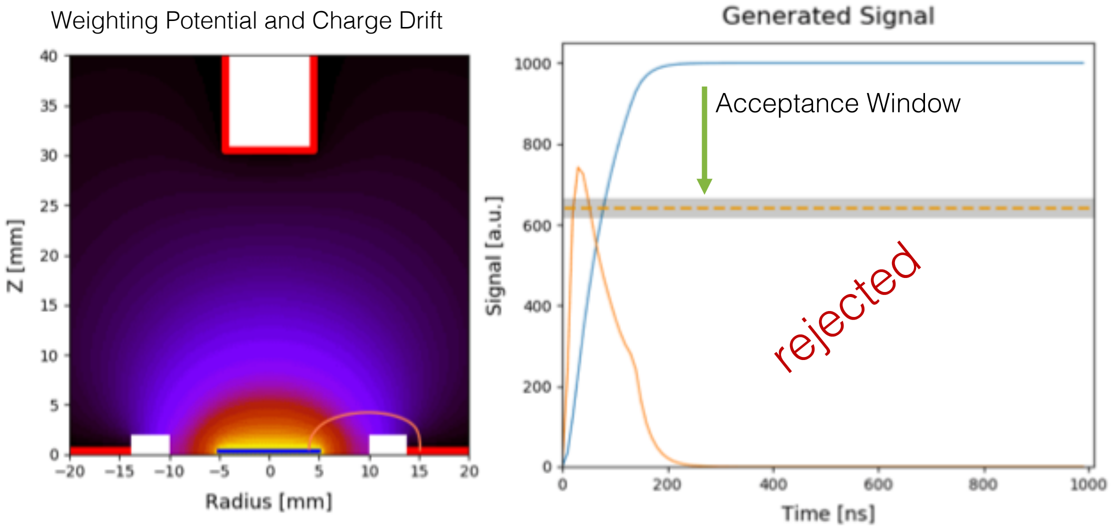
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

Surface-β-background ^{42}K (^{42}Ar) on n+ contact



α-background on p+ contact



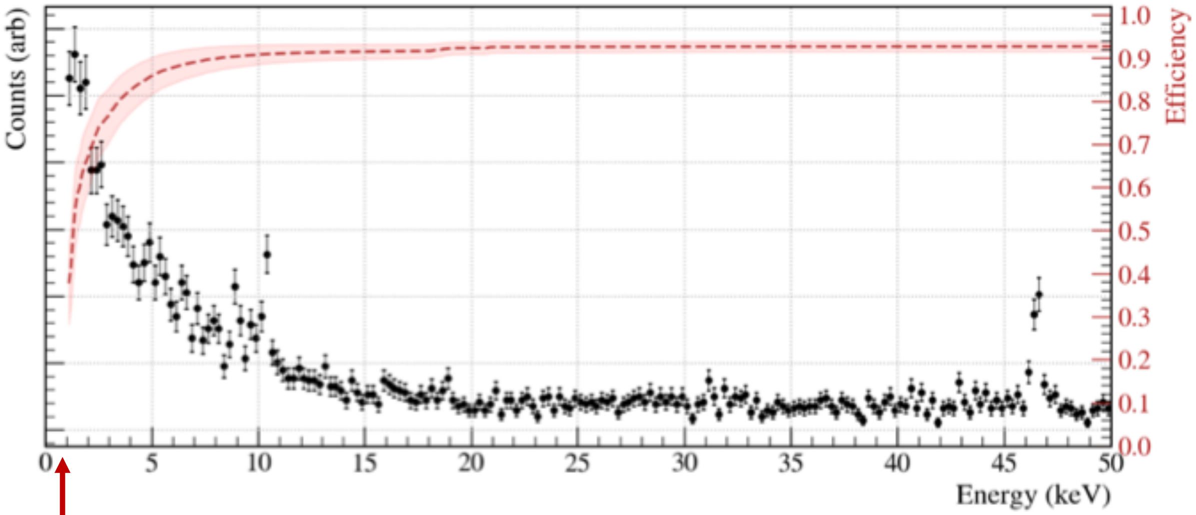
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

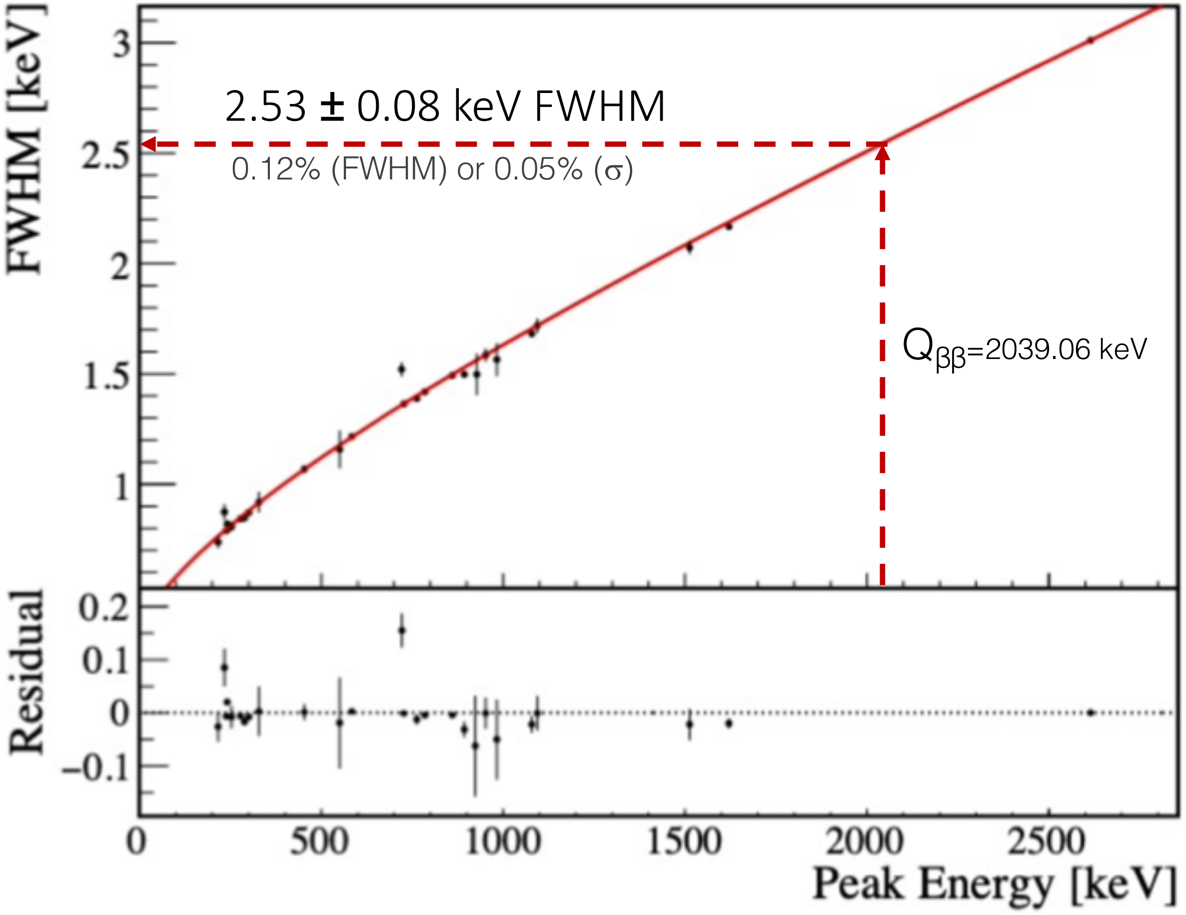
Innovation toward LEGEND-1000: Electronics & Materials

MJD: Low noise front-end electronics required for

- excellent energy resolution
- optimal pulse shape analysis
- low-energy threshold



~1 keV energy threshold



MJD: APS April Meeting D19.00007 (2021)

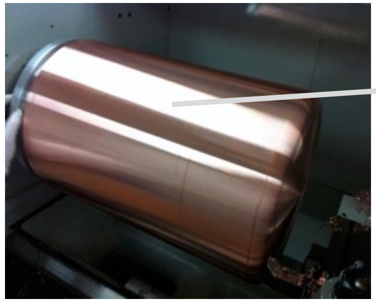
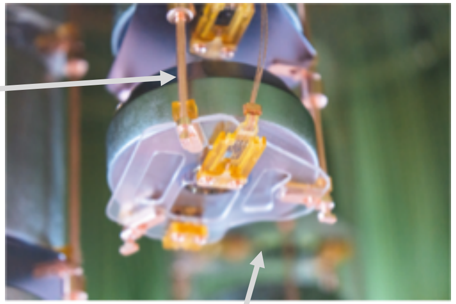
Innovation toward LEGEND-1000: Electronics & Materials

- **Minimize** materials close to Ge detectors and use of **highest purities**:
  - Underground electroformed copper (EFCu) reduces U, Th, and cosmogenic activation

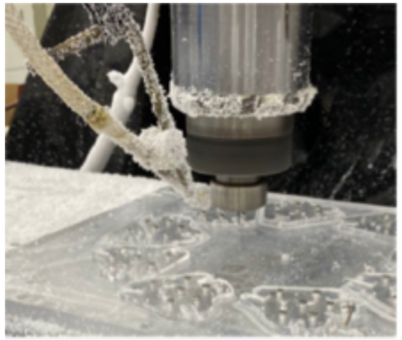
    $< 0.017 \pm 0.03$ pg/g ^{238}U

    $< 0.011 \pm 0.05$ pg/g ^{232}Th
  - Copper-Kapton laminated cables
- **Optically active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures

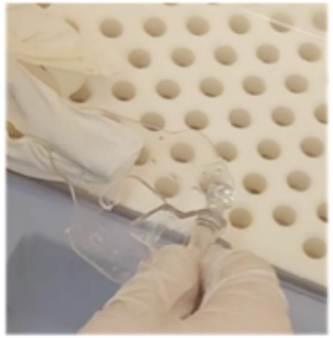
EFCu for holders and reentrant tube

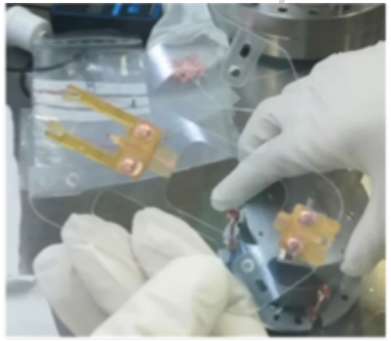
PEN: scintillating (self-vetoing) high-purity detector support



Machining



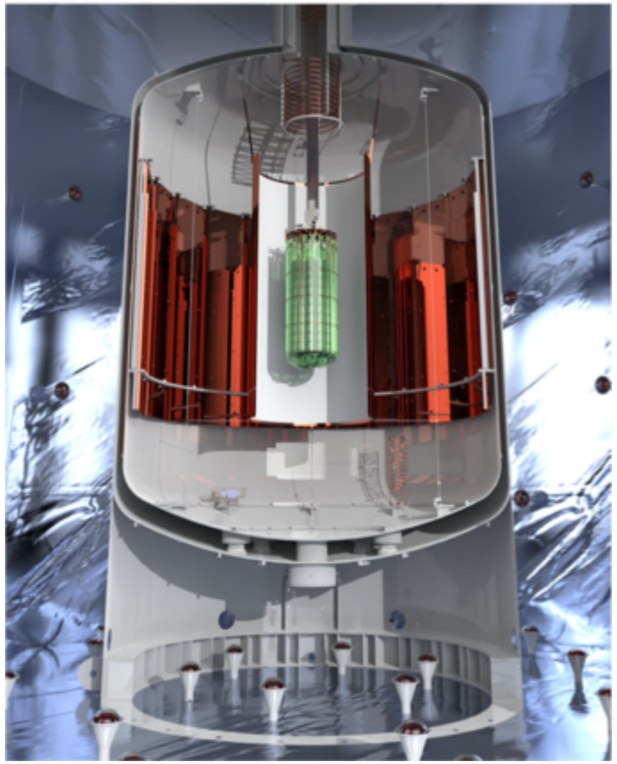
Cleaning

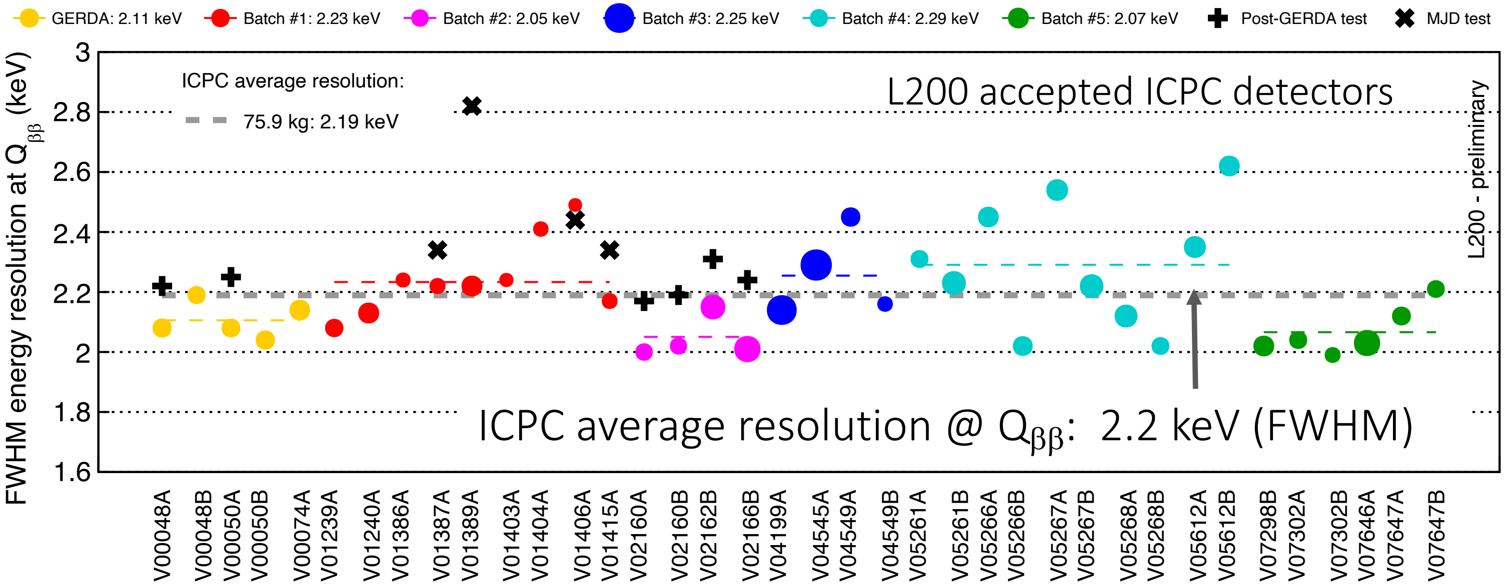


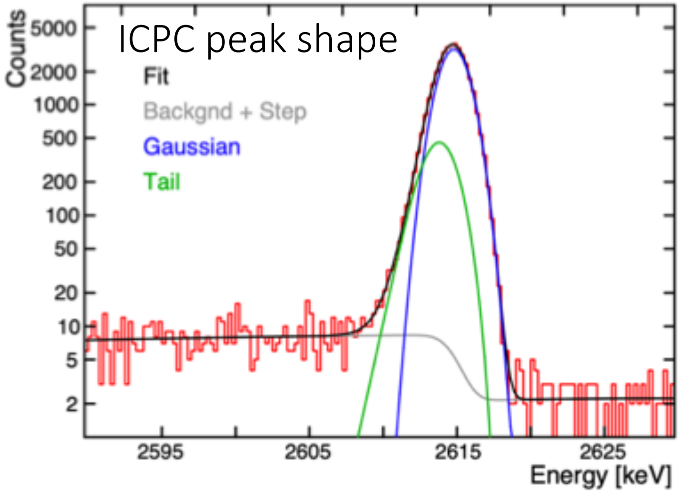
PEN plate

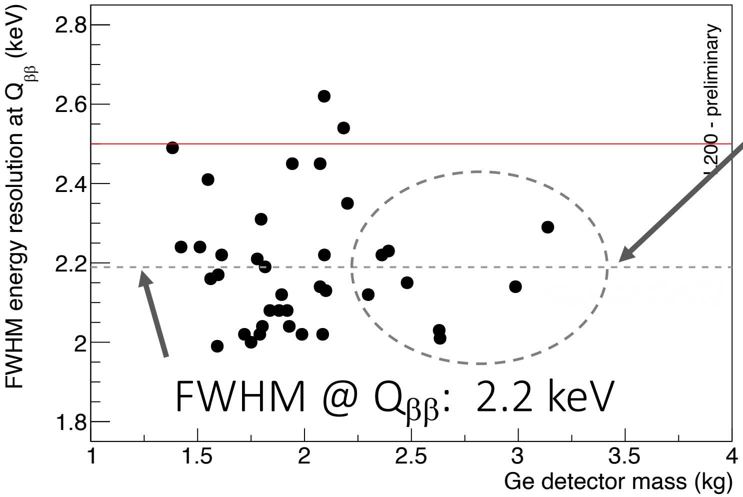
Innovation toward LEGEND-1000: LEGEND-200

- Procurement of ^{76}Ge (92% enr.)
- Novel ICPC detectors
- Improved LAr system
- Low-background materials
- Commissioning 2021



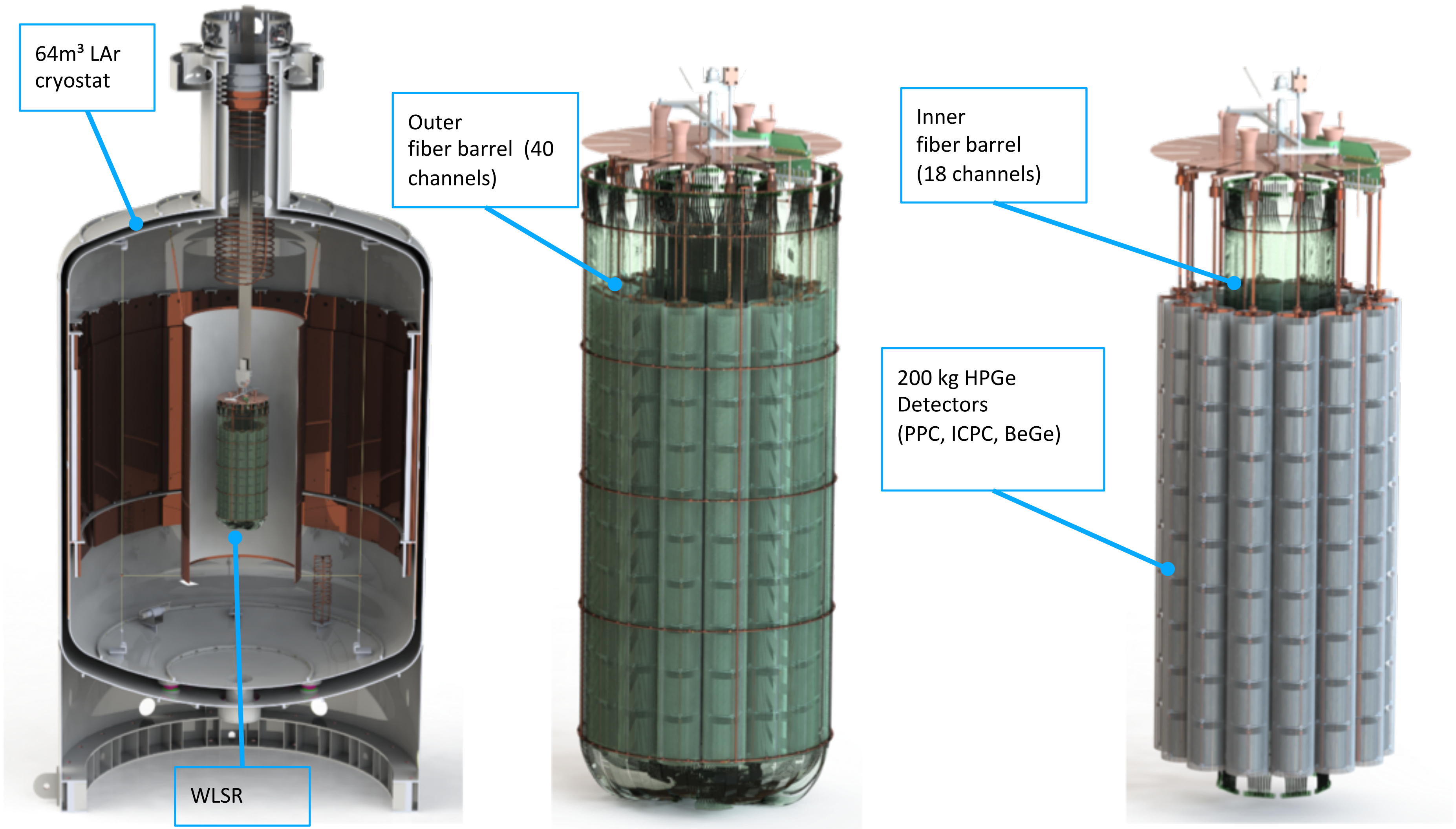






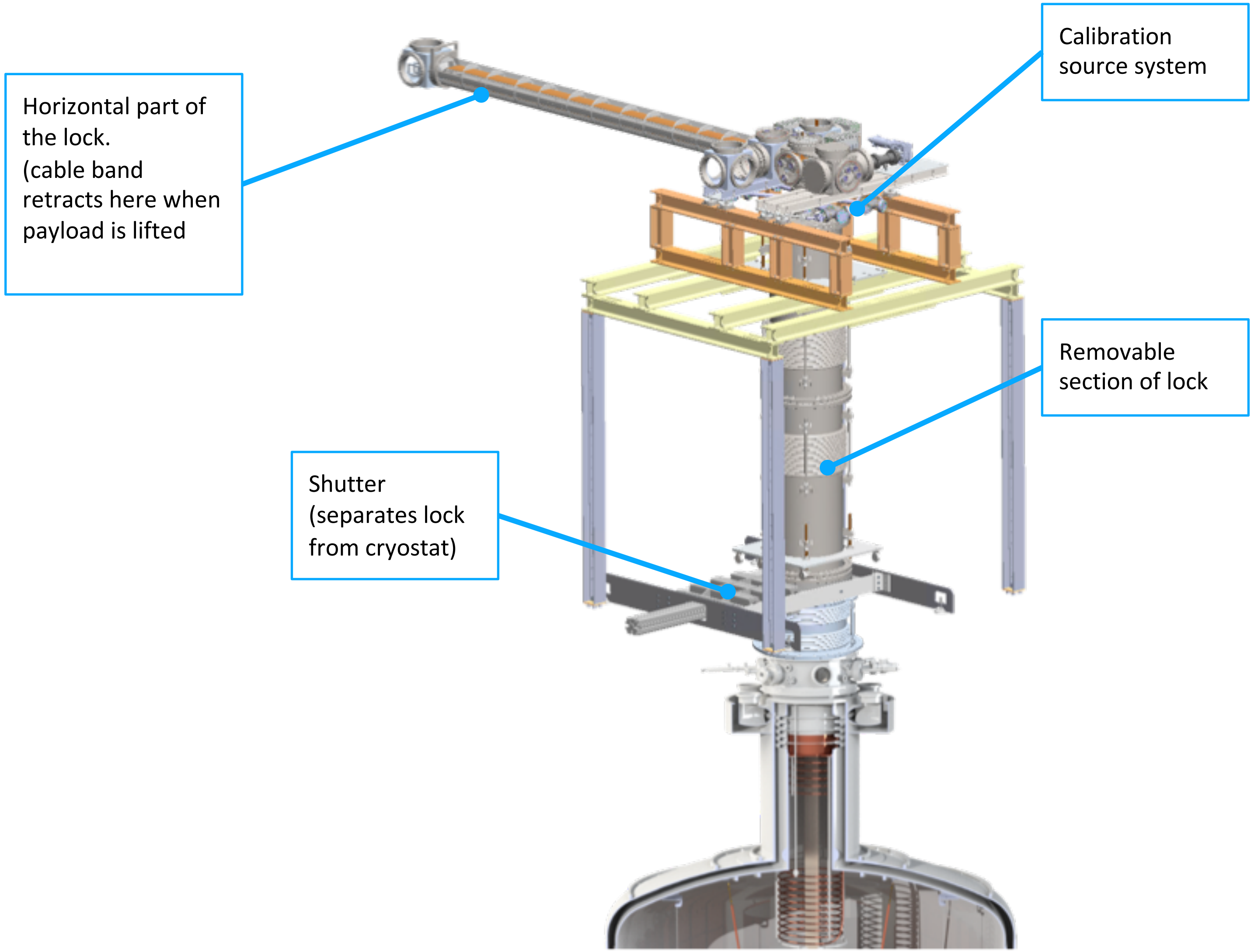
Large mass detectors show excellent energy resolution

LEGEND-200



64m³ LAr
cryostat
Outer
fiber barrel (40
channels)
Inner
fiber barrel
(18 channels)
200 kg HPGe
Detectors
(PPC, ICPC, BeGe)
WLSR

LEGEND-200: Lock System

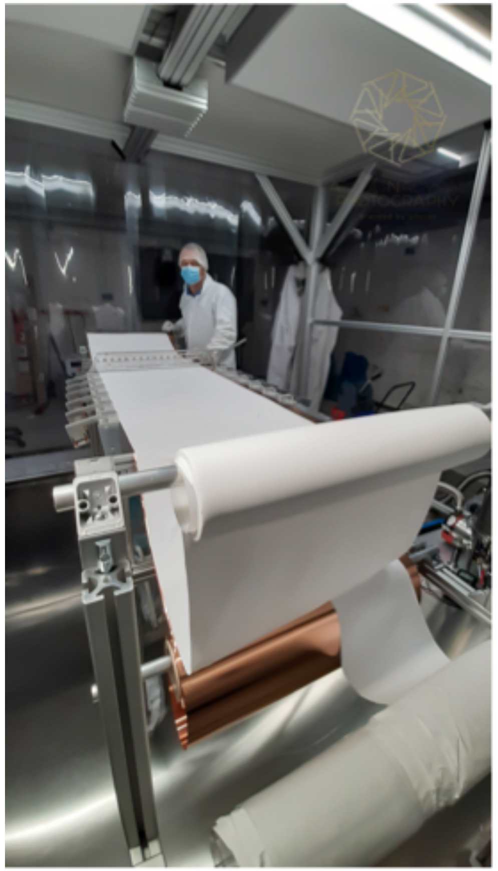


LEGEND-200: the lock system

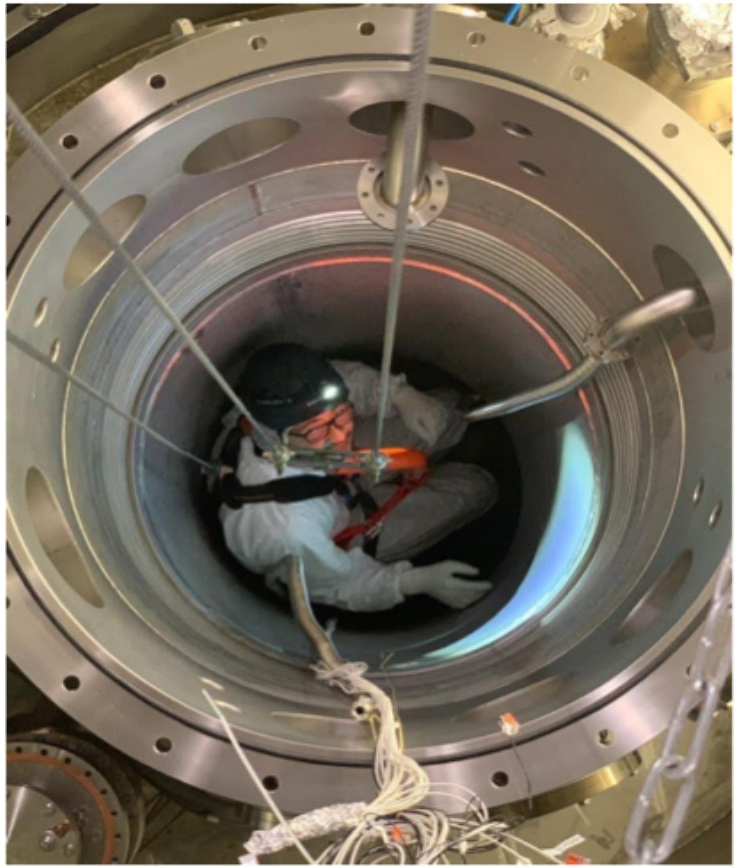
Cleanroom roof is opened and the components for the lock system are lifted into the cleanroom.

As soon as the roof is closed again & everything is cleaned the lock components are aligned with the cryostat.

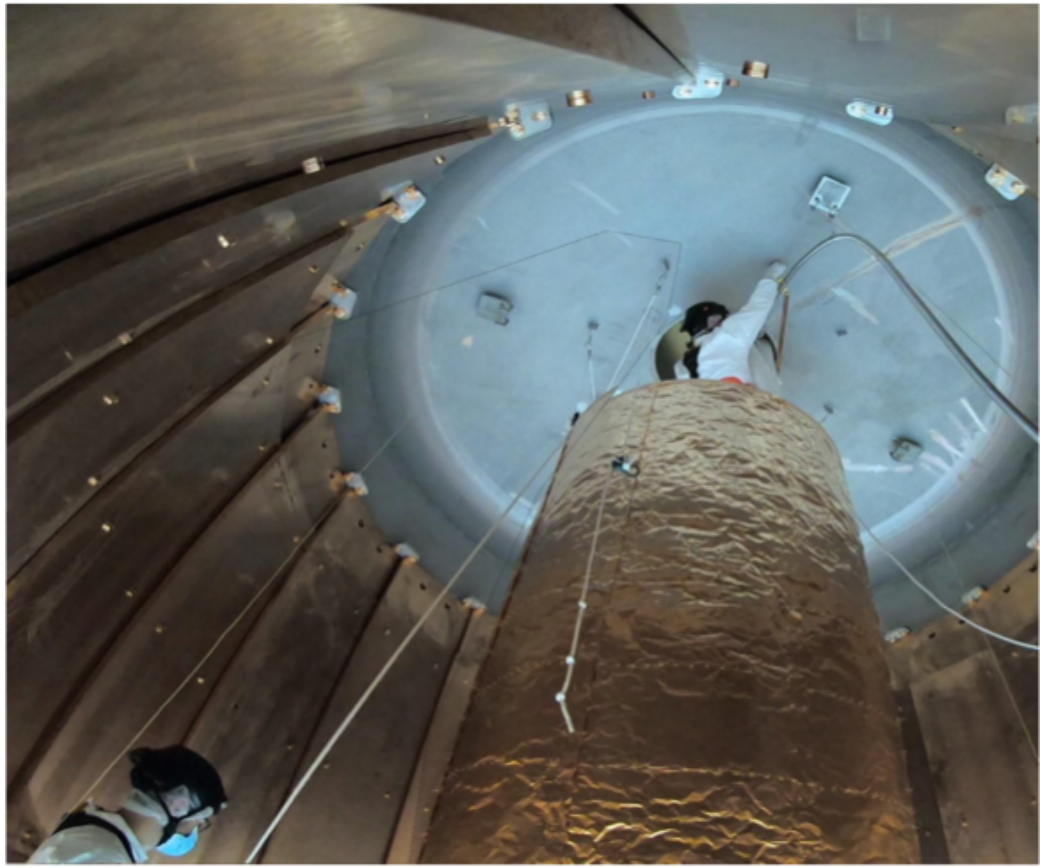
LEGEND-200: Installations inside of the cryostat



Wavelength Shifting Reflector (WLSR)

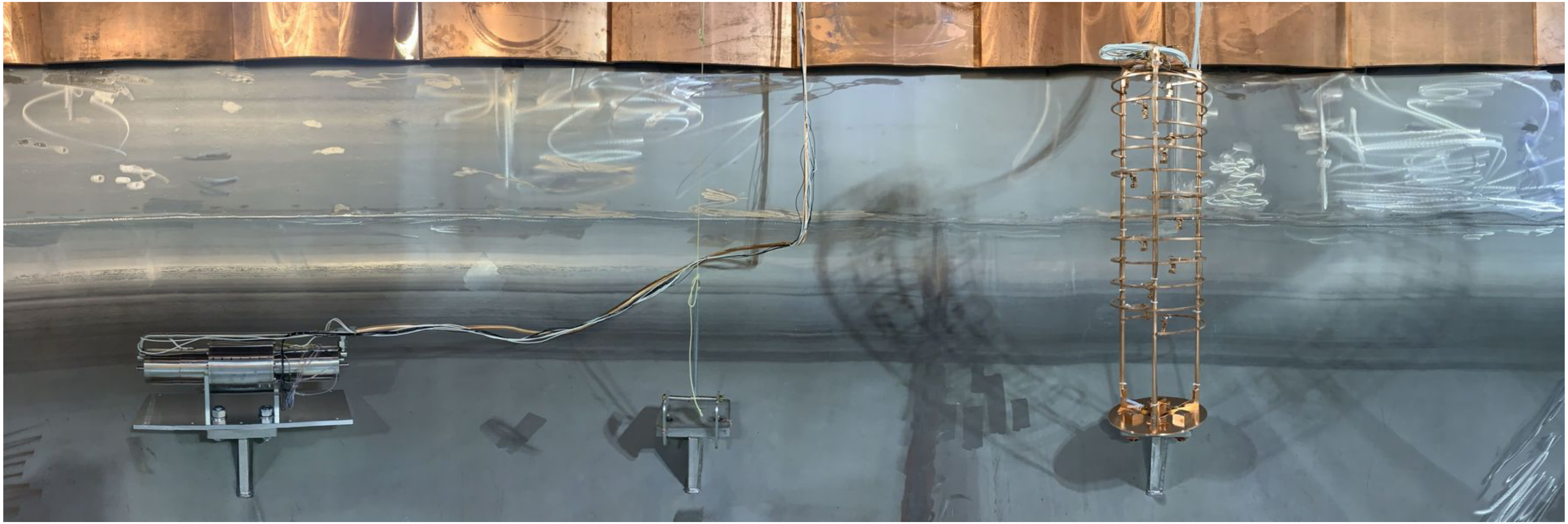


Liquid Argon is evaporated GERDA Lock is removed. Enter the cryostat



Wavelength Shifting Reflector (WLSR) is installed. It restricts the LAr volume around the detectors. Also shifts scintillation light to blue and reflects it back towards the LAr instrumentation

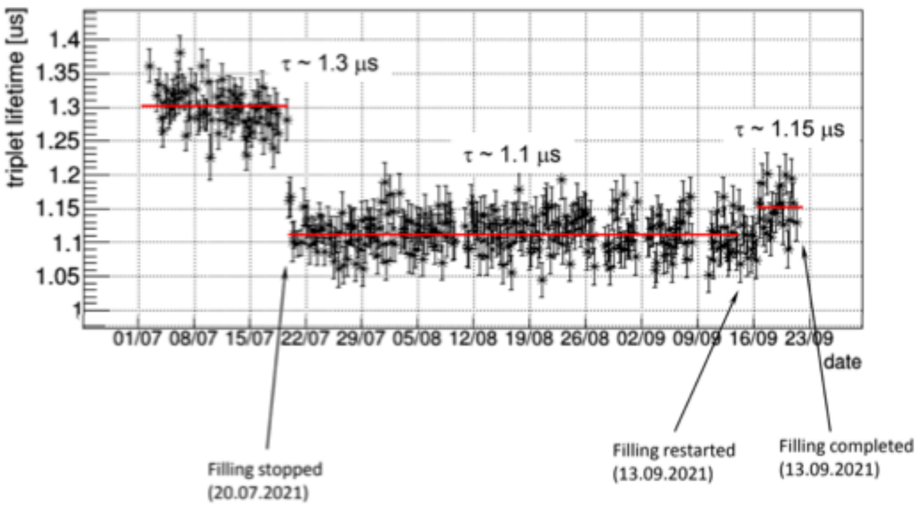
LEGEND-200: Installations inside of the cryostat

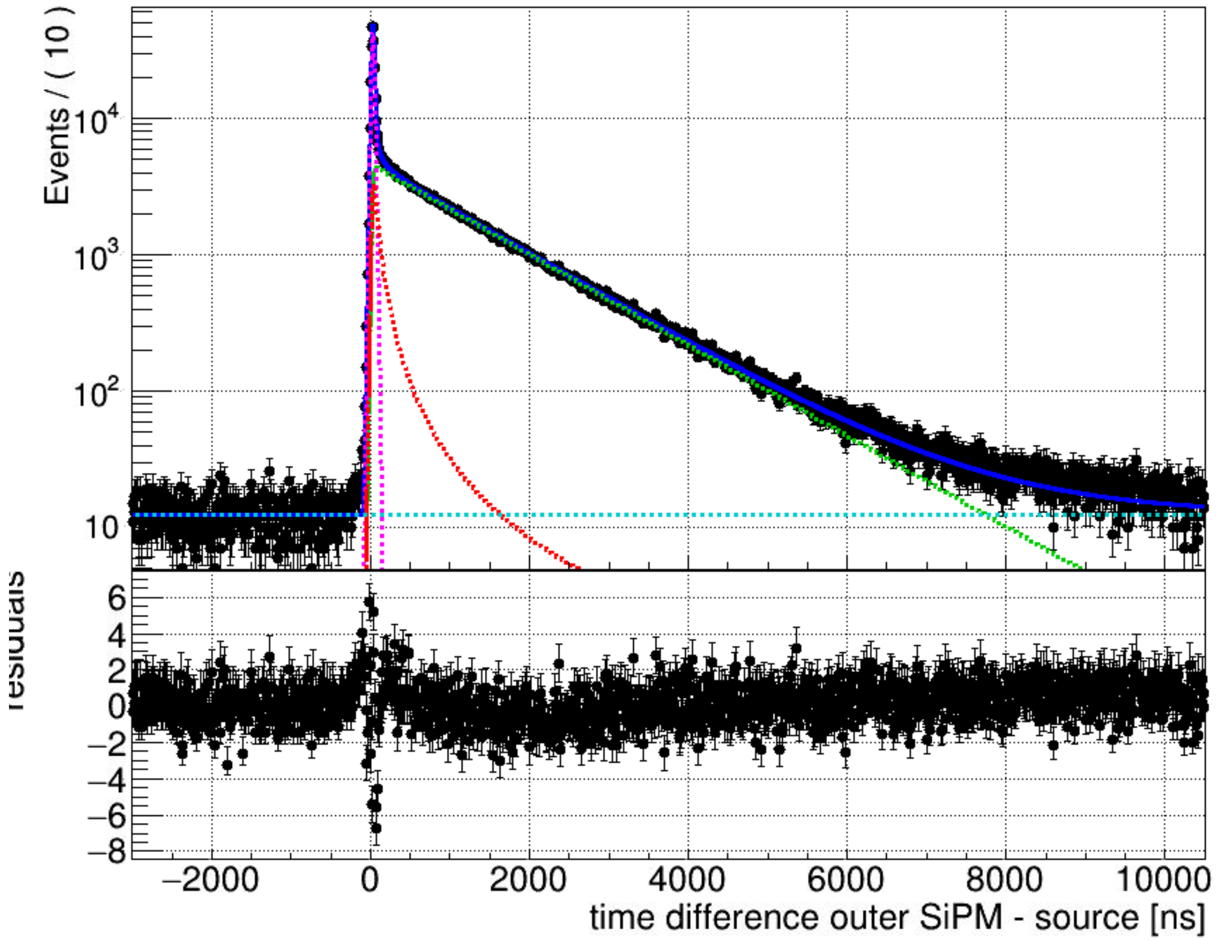


Liquid Argon pump allows if needed to pump LAr out of the cryostat for a liquid phase purification cycle

LEGEND **L**iquid **A**rgon **M**onitoring **A**pparatus (**LLAMA**): Continuously monitors Triplet lifetime and light yield of the LAr scintillation light

LEGEND-200: liquid argon purification and filling

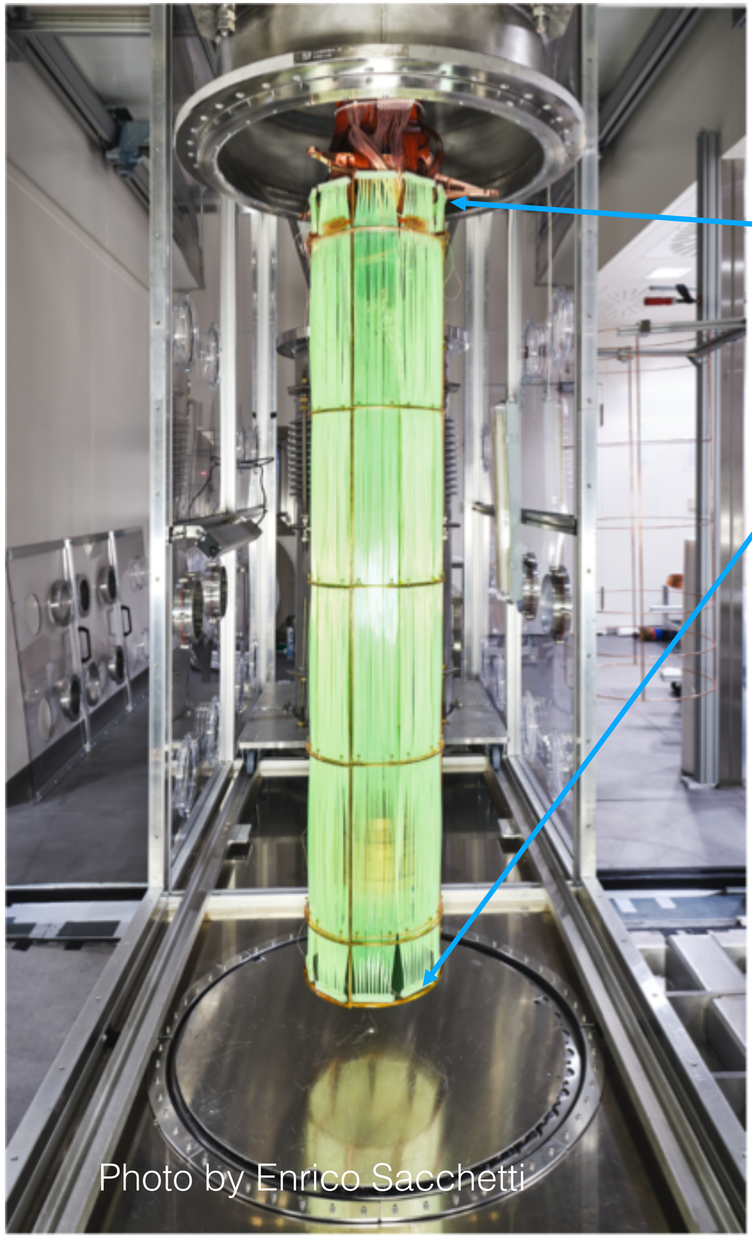


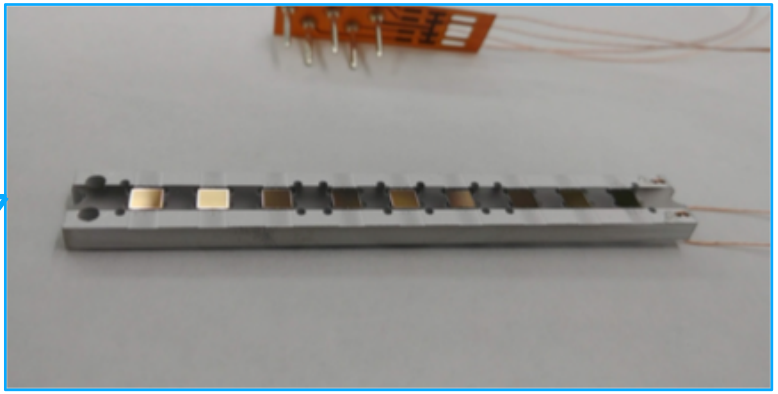


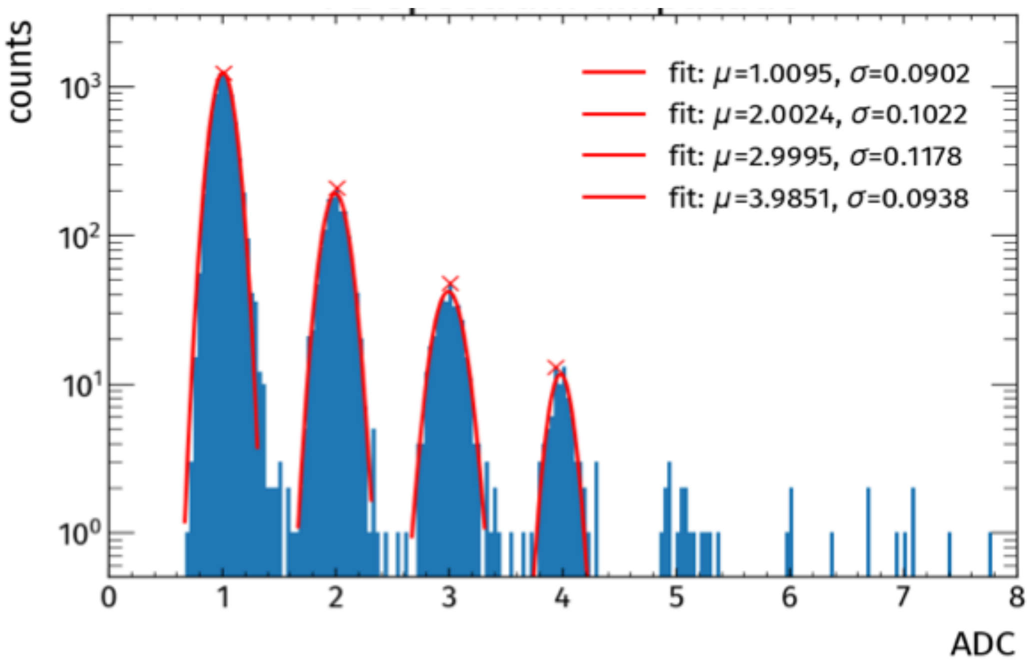
LEGEND-200: glove box and lock system

Photos by Enrico Sacchetti

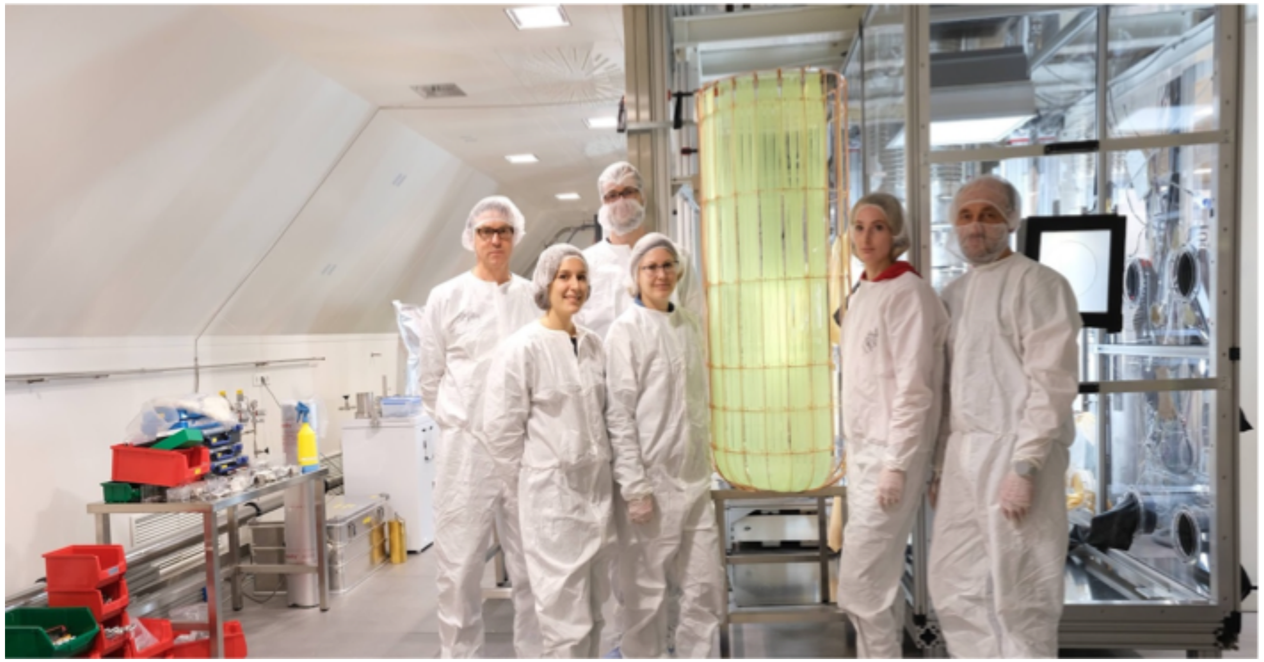
LEGEND-200: Commissioning of LAr Inner Barrel

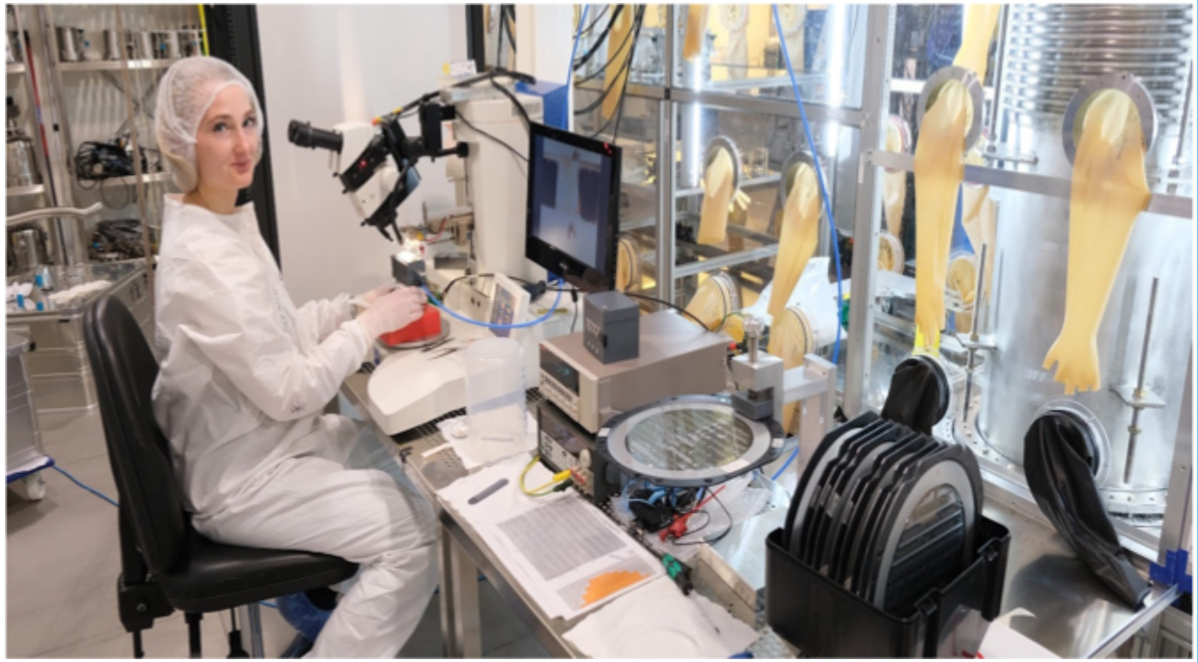




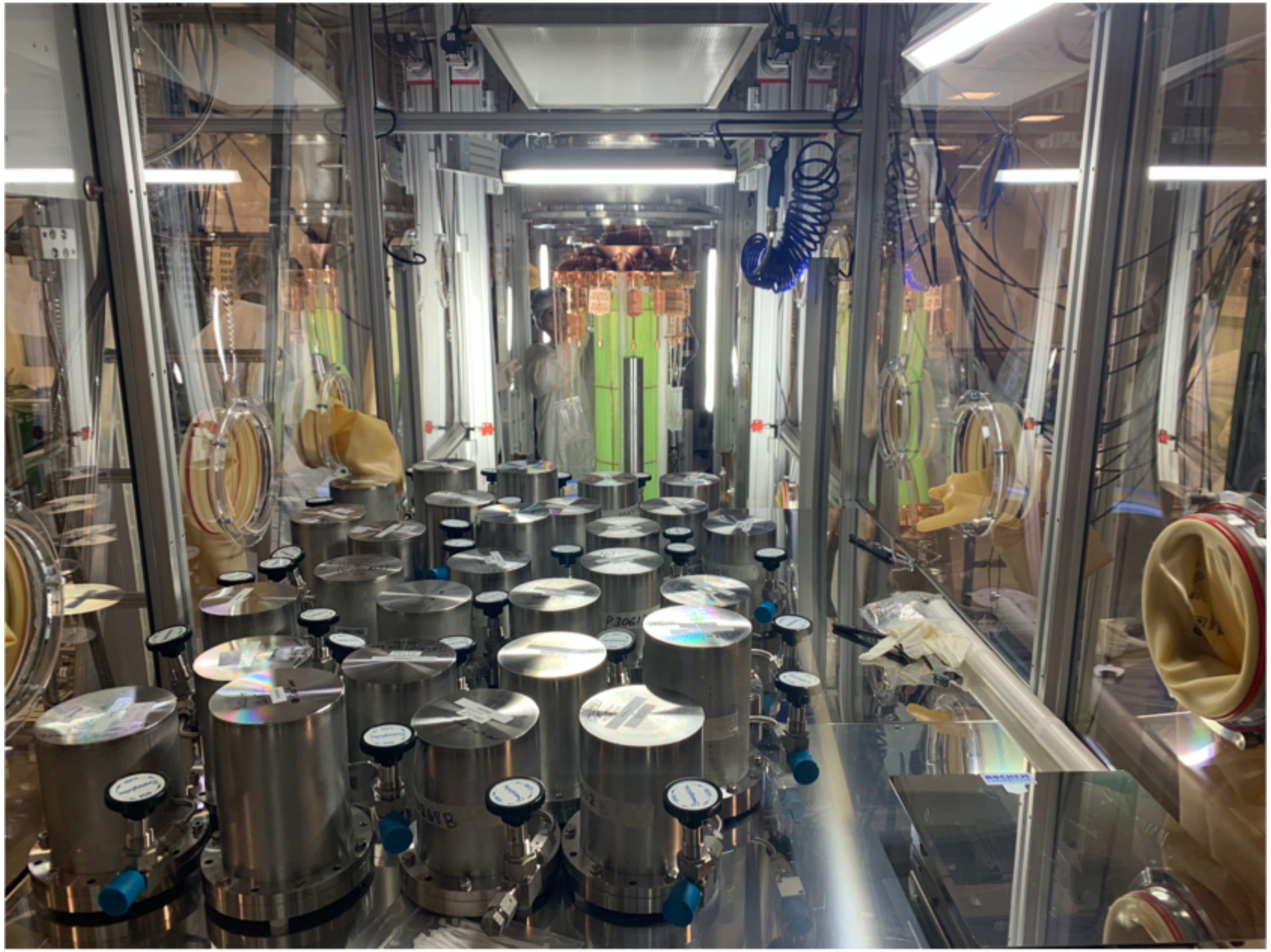


LEGEND-200: commissioning of LAr Outer Barrel

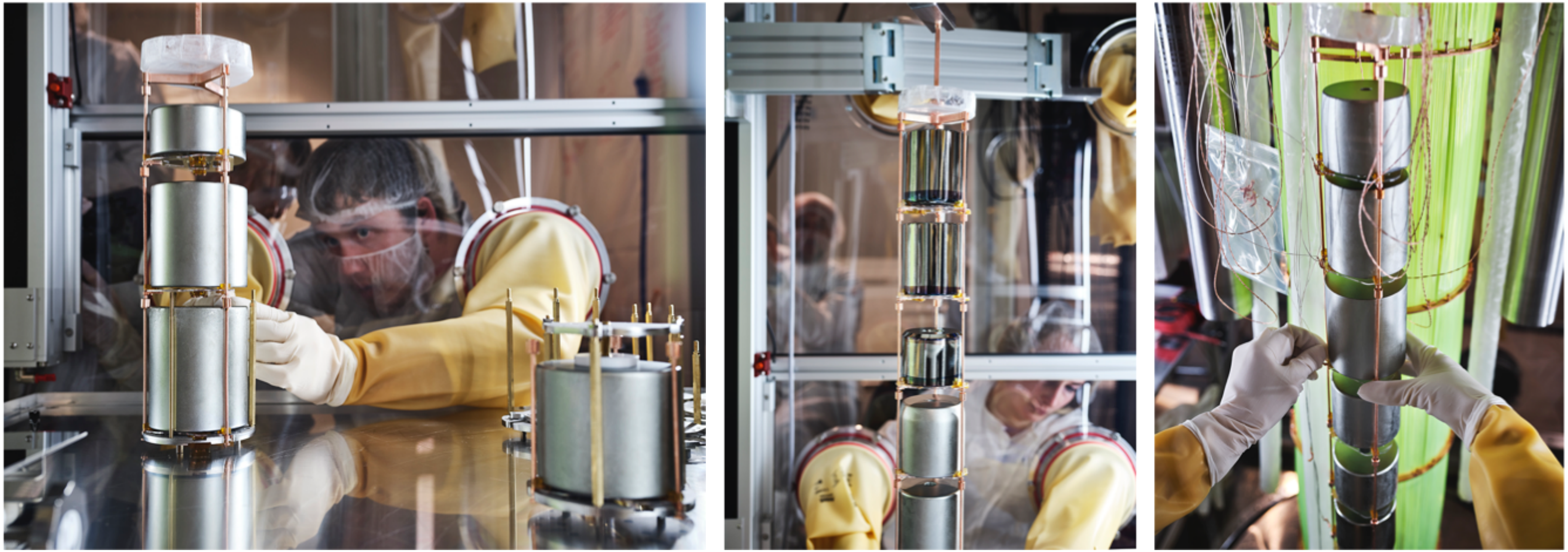




LEGEND-200: Commissioning with 60 kg of HP-^{enr}Ge

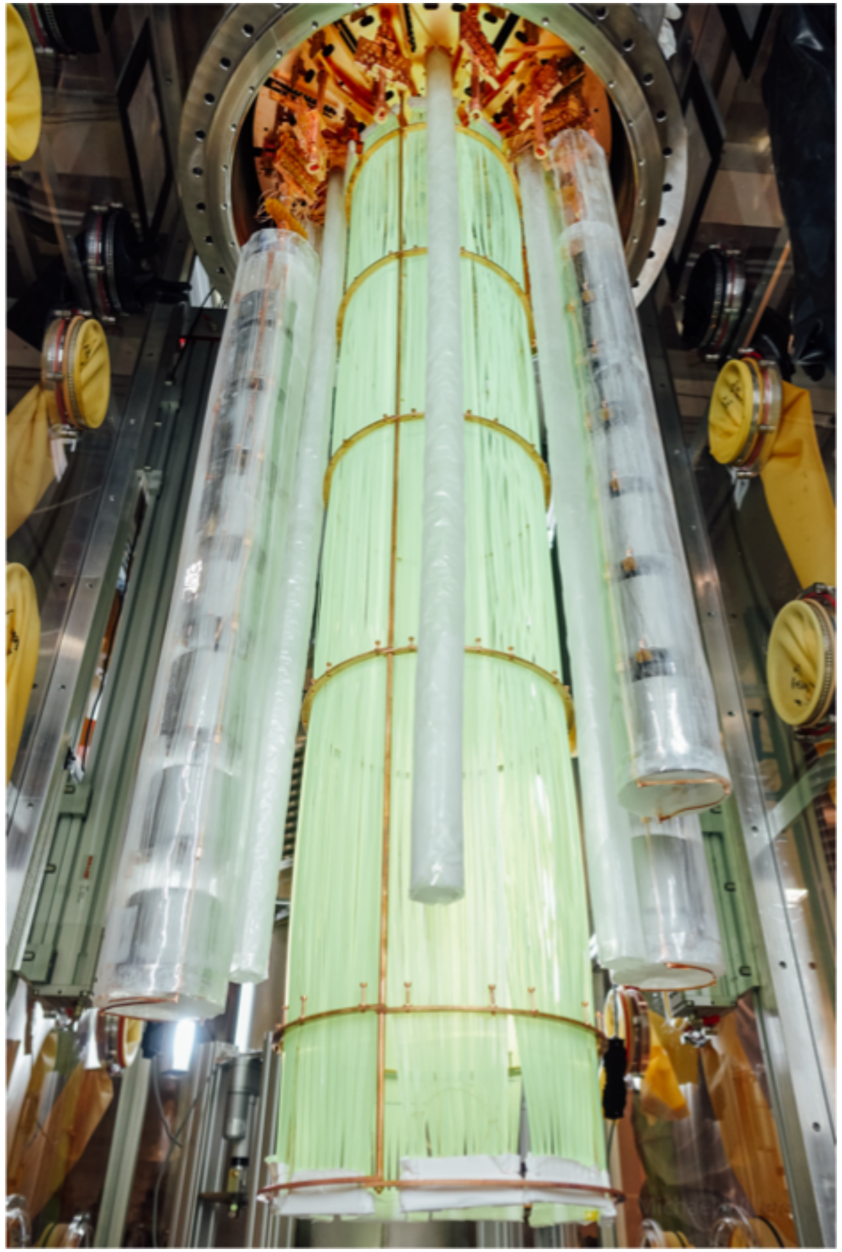


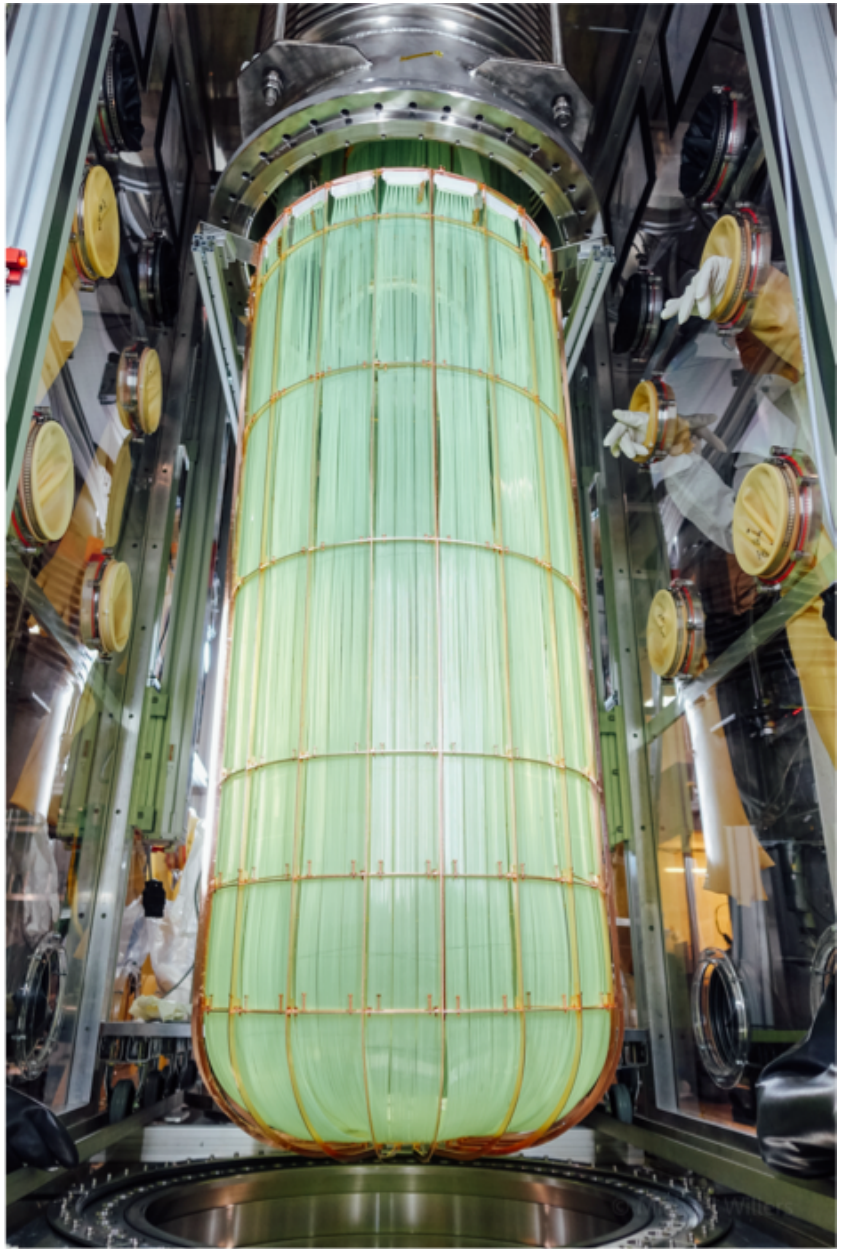
LEGEND-200: Assembly of detector strings



Photos by Enrico Sacchetti

LEGEND-200: Commissioning with 60 kg of HP-^{enr}Ge





Photos by M. Willers

LEGEND-200: Commissioning with 60 kg of HP-^{enr}Ge

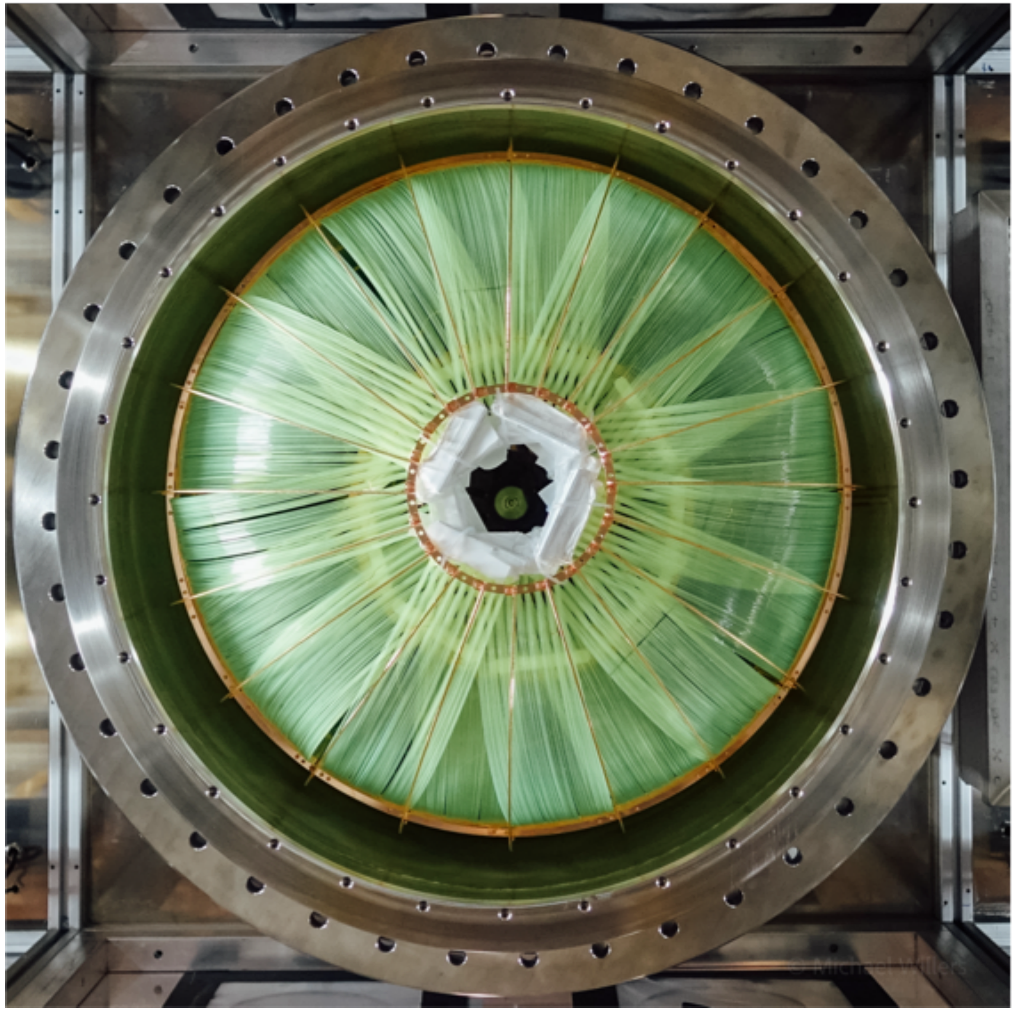
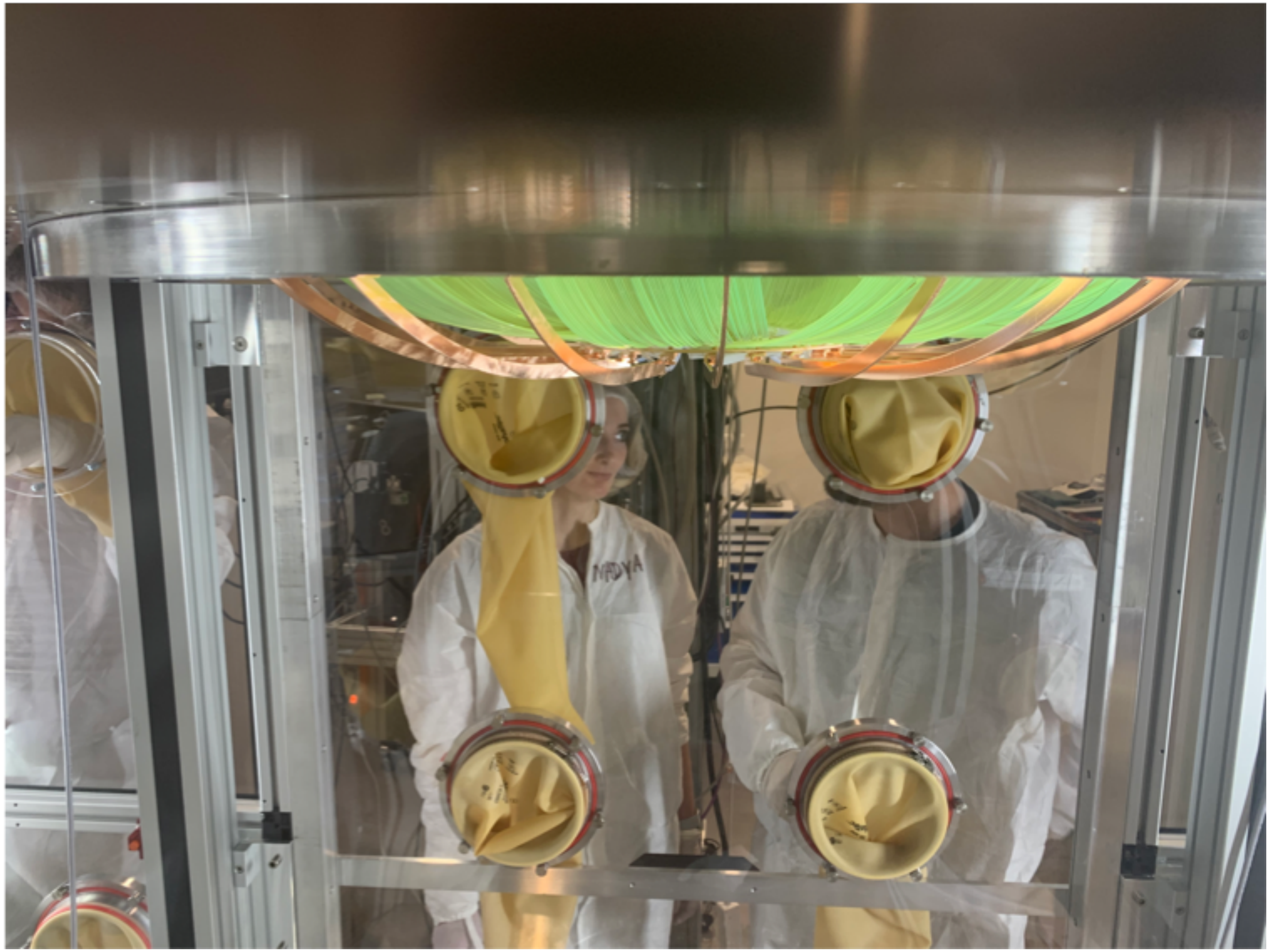
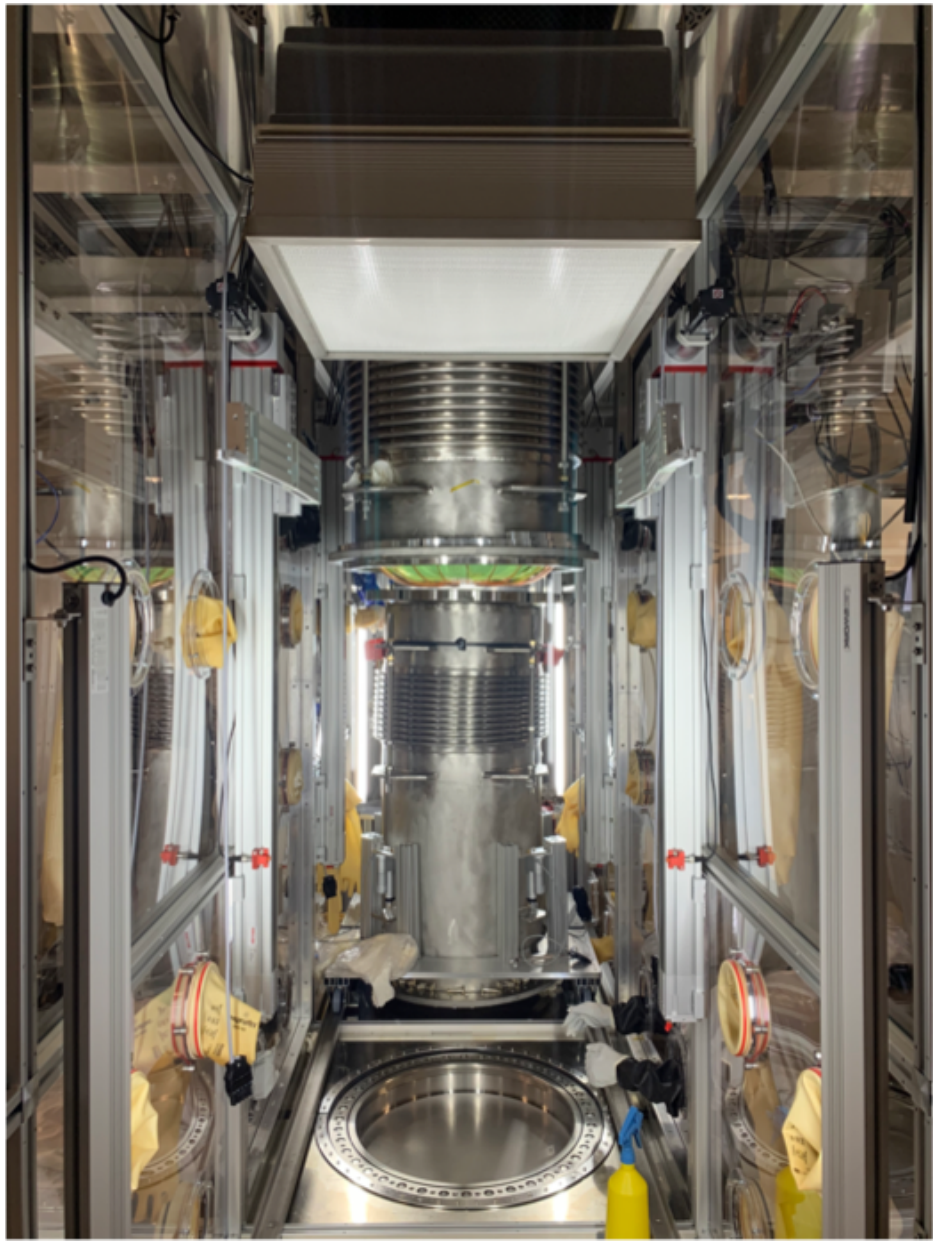
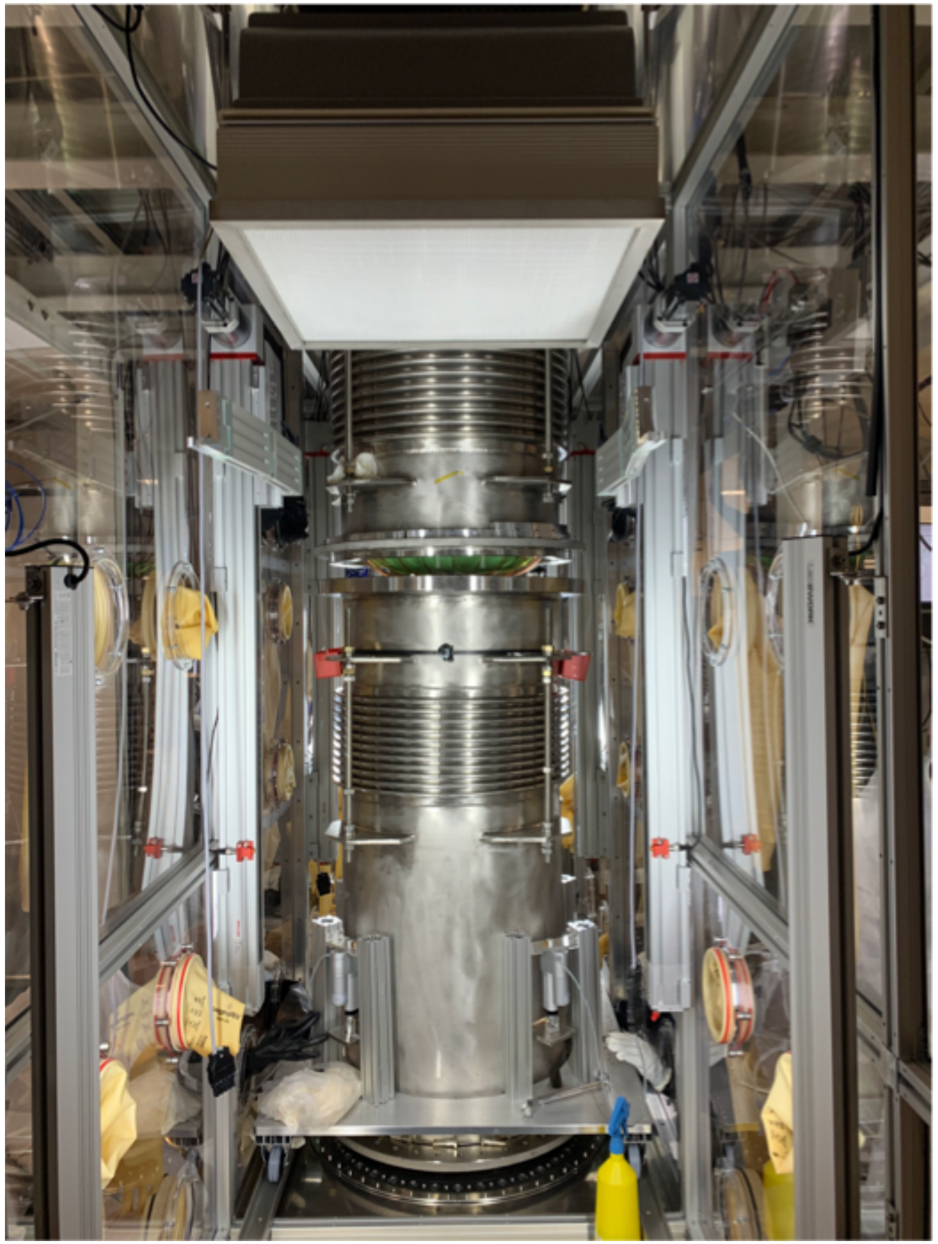


Photo by M. Willers



LEGEND-200: Closing the lock & commissioning with 60 kg HPGe

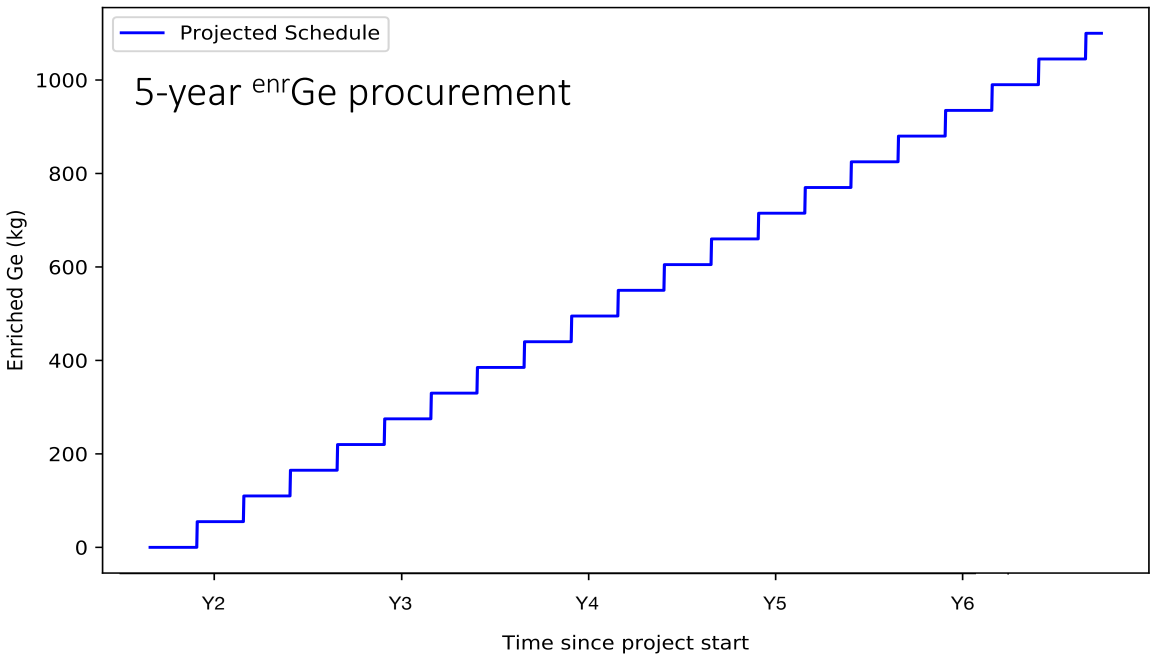


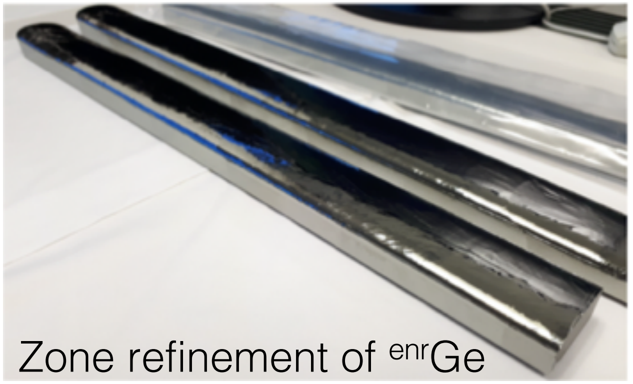


The Baseline Design: Ge-76 Acquisition & Processing

1000 kg of enriched Ge detectors:

- Fabricate 870 kg of new detectors; use 130 kg from LEGEND-200; recycle 50 kg of small detectors
- Procure 1100 kg of enriched Ge (92% ^{76}Ge)
- 220 kg/y for 5 years through ECP(JSC) & Urenco
- No interference of world annual production (130 t/y)
- ^{enr}Ge metal production (50 Ω-cm) and chemical recycling at VPMS[1,2]
- LEGEND-200 experience:
  - Reliable production of 185 kg enriched isotope from ECP(JSC) and Urenco
  - Zone refinement at VPMS (and IKZ[1])
  - Chemical purification and recovery at VPMS & LNGS[1]



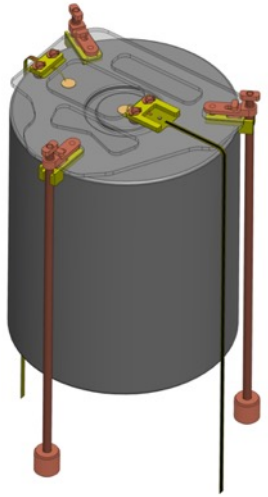


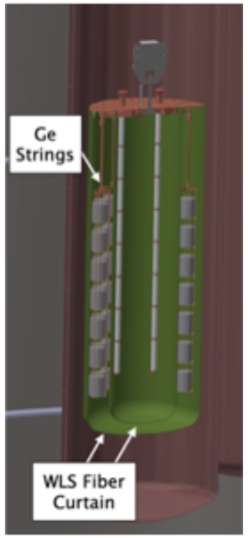
Zone refinement of ^{enr}Ge

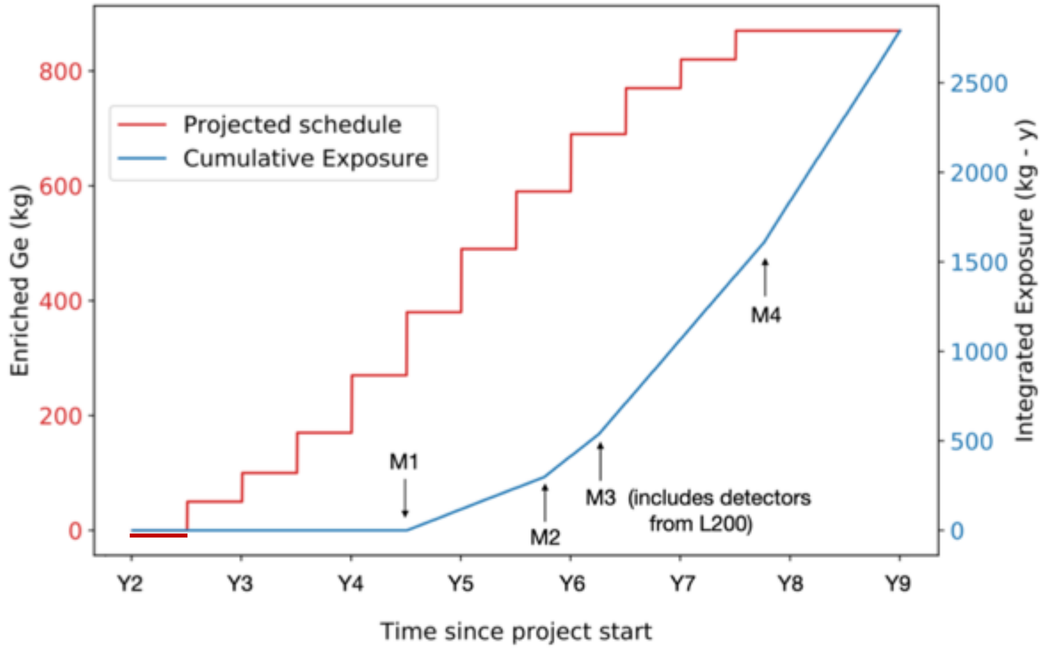
Chem. recycling

[1] Technology expertise also internal to LEGEND: IKZ, INR, USD, USC
[2] Purification system at VPMS owned by UNC

The Baseline Design: Detector Arrays







ICPC detector assembly:

- 2.6 kg average mass
- EFCu
- PEN
- ASIC front end
- Flat flex cables

Detector arrays:

- 4 arrays
- 100 ICPCs / array
- 1000 kg total mass
- 0.12% FWHM (0.05% σ) at $Q_{\beta\beta}$
- Double-barrel LAr instrumentation
- Underground argon
- Reentrant tubes

ICPC detector production:

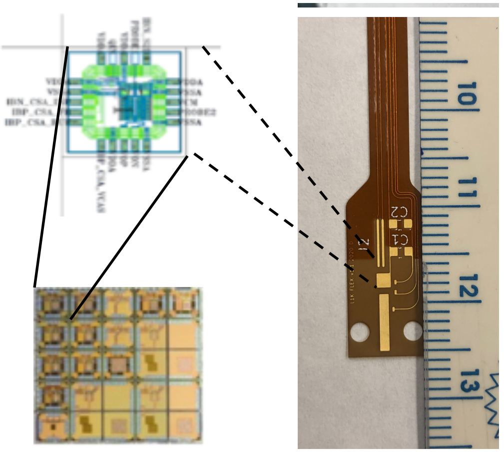
- Two established vendors plus 2 additional vendors
- 1st year: 50 detectors / y
- Subsequent years: 110 / y
- LEGEND-1000 staged approach: Detectors for first module are ready 2.5 years after start of production

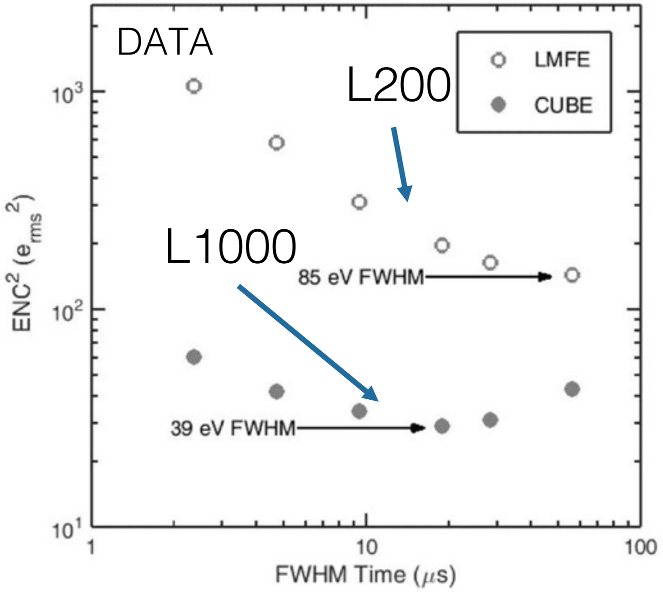
The Baseline Design: Front-End Electronics & DAQ

Front-end CSA ASIC:

- Low noise / threshold: <1 keV
- Large dynamic range: 10 MeV
- Sufficient bandwidth: 50 MHz
- Detector capacitance: 5 pF

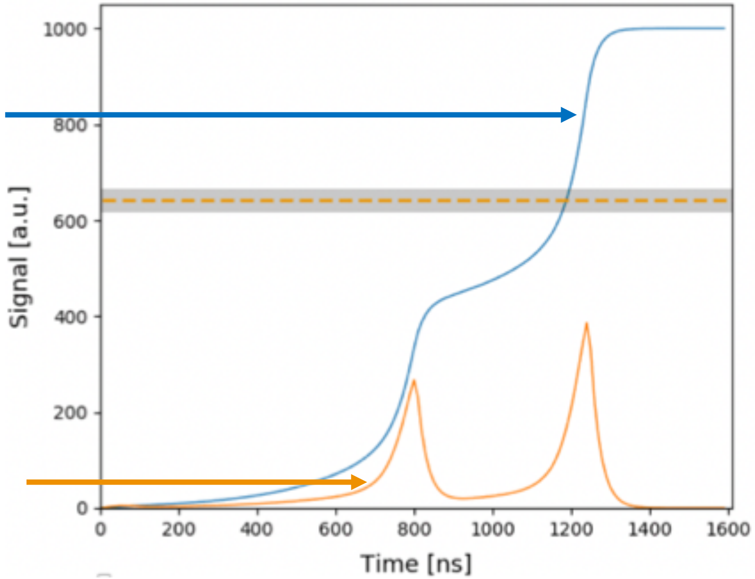
LEGEND-1000 prototype





Data Acquisition:

- Full digitization of Ge, LAr system, water Cherenkov systems
- Off-line filtering

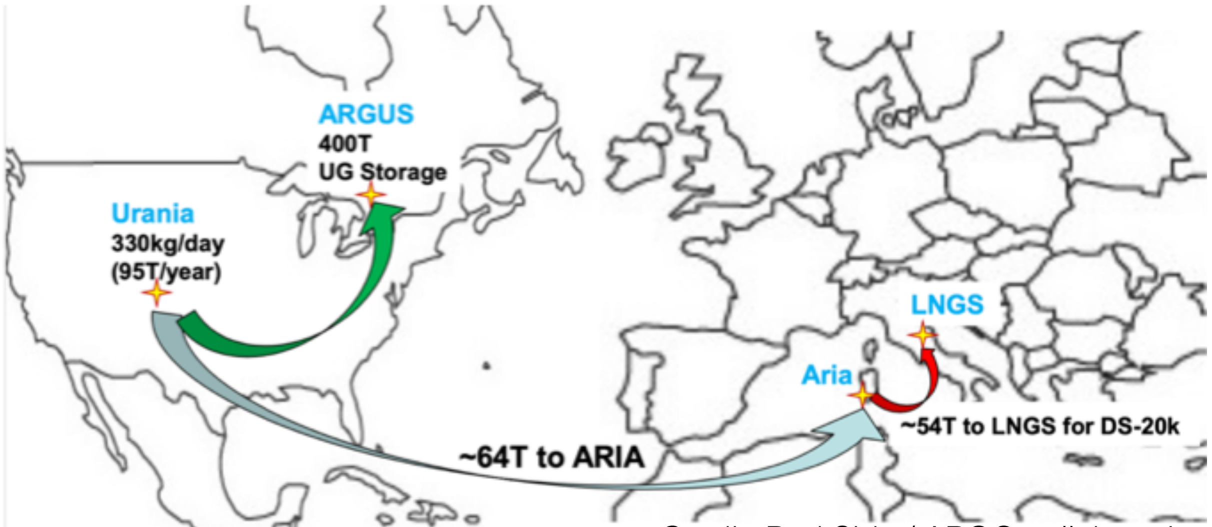


- LEGEND-1000 DAQ built on LEGEND-200 design; successfully operated during Post-GERDA Test (PGT)

The Baseline Design: Underground Liquid Argon

LEGEND

- 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)



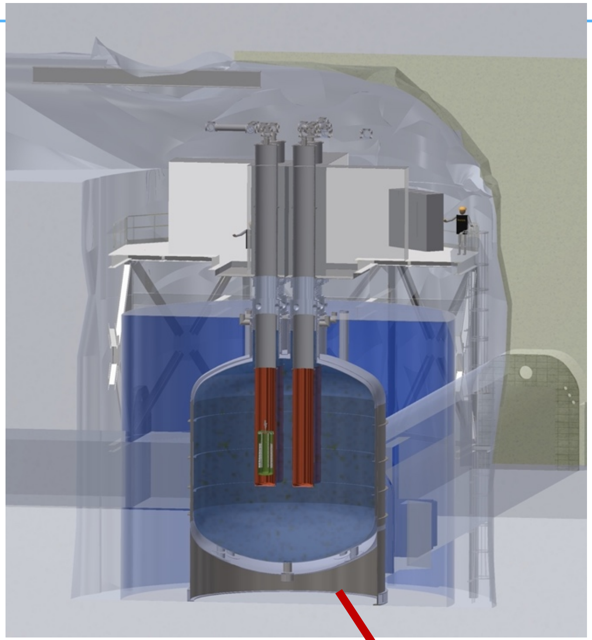
Credit: DarkSide / ARGO collaboration

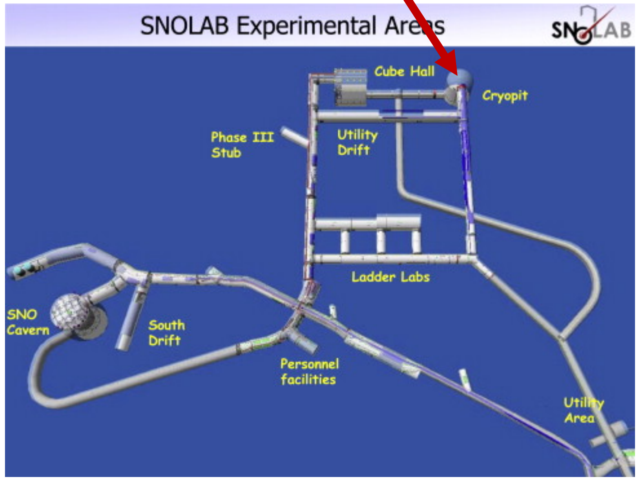
UGAr is depleted in ^{42}Ar (^{39}Ar)

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~~

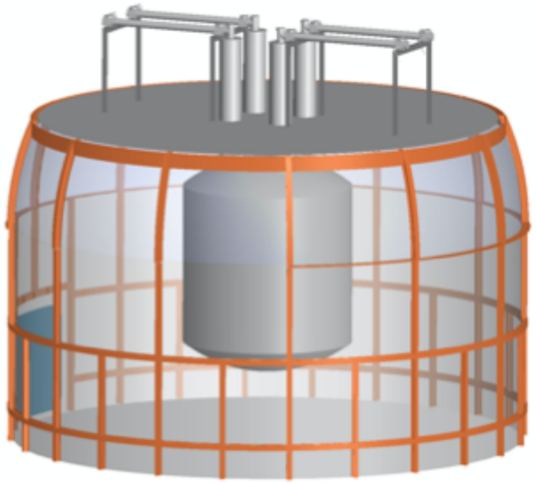
[1] " …we are confident that the production of the required UAr can be completed in a time scale useful for the accomplishment of the LEGEND-1000 experiment.. The present statement is an expression of interest and availability from INFN…"

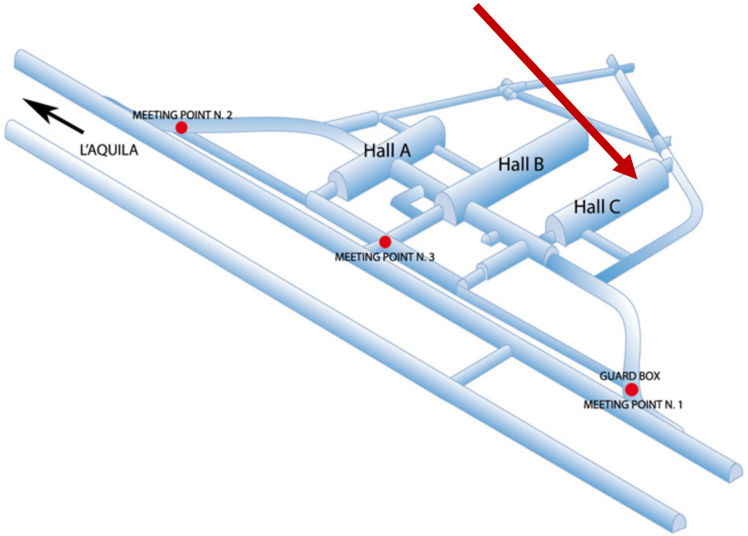
LEGEND-1000 underground sites





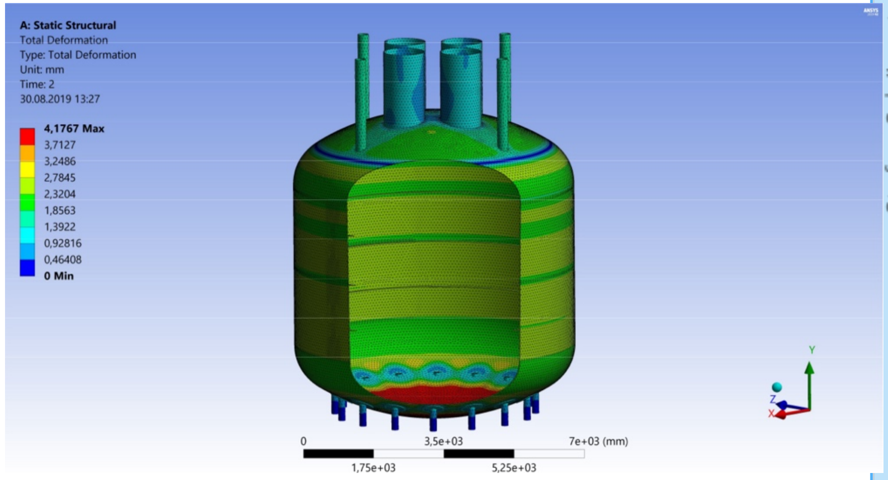
SNOLAB: New underground tank infrastructures required





LNGS: Re-purpose BOREXINO tank and infrastructures; Also under consideration: LVD space with 3 cryostats

- SNOLAB **deeper** than LNGS; LNGS **depth sufficient** with tagging in-situ produced cosmogenic isotopes
- Repurposing of **BOREXINO** tank and infrastructures for LEGEND-1000



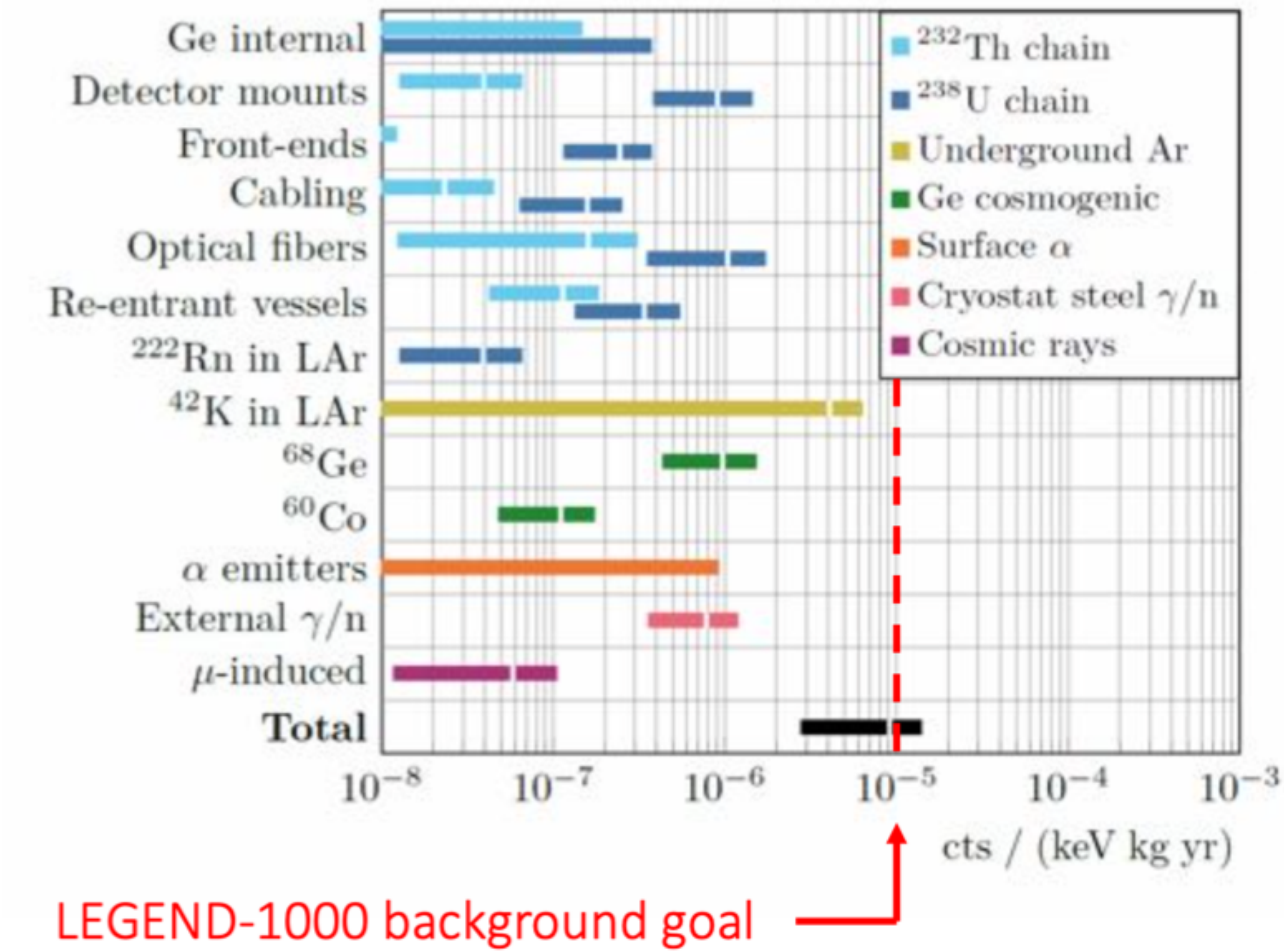
Deformation of cryostat for seismic event at LNGS

Muon-induced background estimates ($^{77(m)}Ge$)

- At **SNOLAB depth :**
  - 5.8 x 10^{-8} cts /(keV kg yr)
  - 0.6% of the background budget; even assuming a large uncertainty, the in-situ background contribution remains small.
- At **LNGS depth**
  - **Including a minimal implementation of delayed coincidence suppression, but no further measures,**
    - 5.4 x 10^{-6} cts /(keV kg yr) (7-m baseline detector layout),
      2.0 x 10^{-6} cts /(keV kg yr) (4 x 4-m cryostats).
    - 20-50% of the total background budget
  - Adding neutron moderating materials in the LAr, tagging sibling neutrons in the LAr and in the Gd-loaded water shield, and using topology information
    - <1 x 10^{-6} cts /(keV kg yr) (7-m baseline detector layout)
    - This is < 10 % of the total background budget

LEGEND-1000 Background projections

Background index at $Q_{\beta\beta}$ after all cuts



Improvements from LEGEND-200:

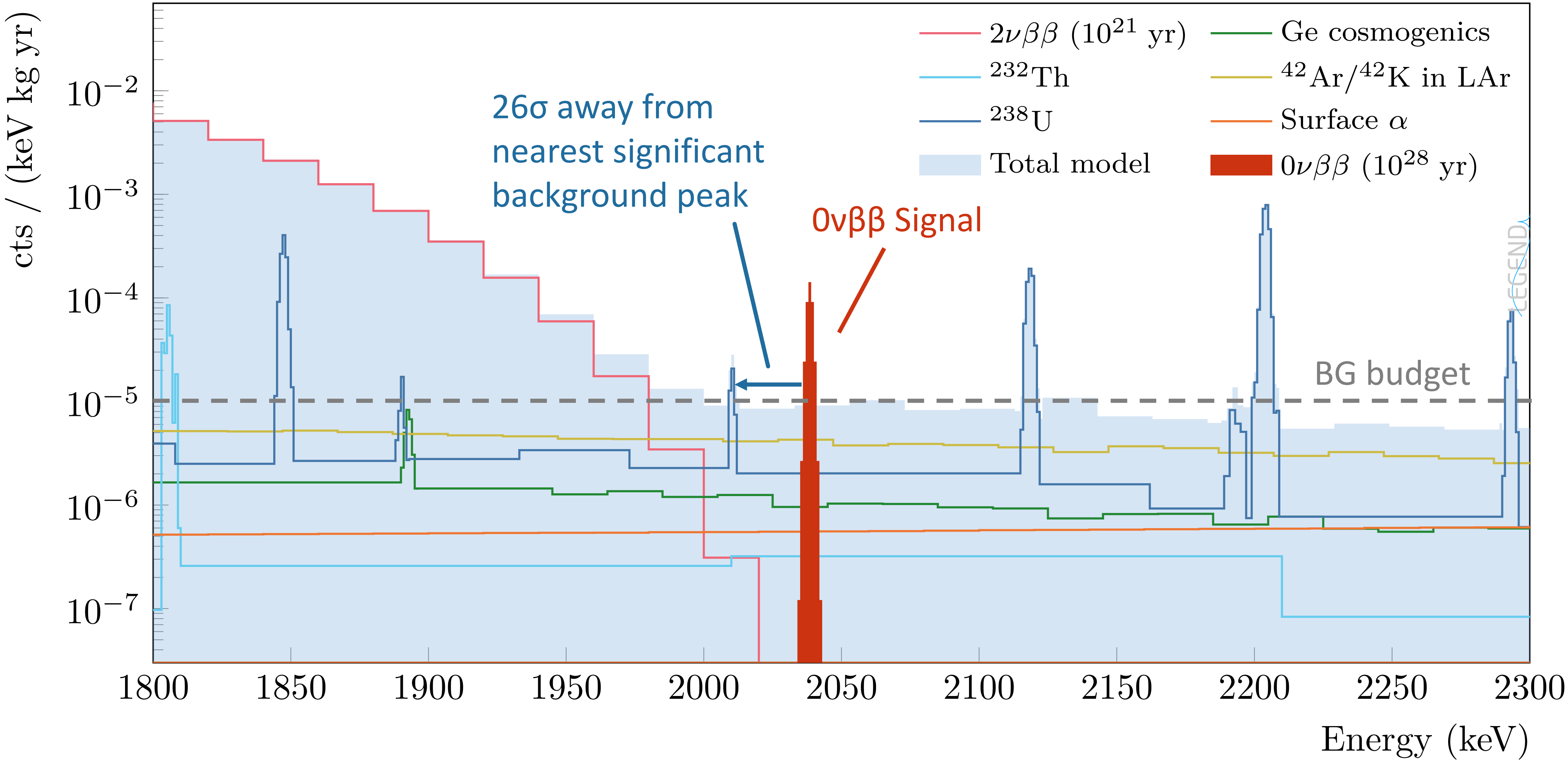
- Larger detectors (2.6 kg avg)
- New cables and ASIC read-out
- Underground Ar surrounding detectors
- Optimized array spacing and LAr instrumentation
- Deeper underground site or additional neutron shielding & tagging: SNOLAB and LNGS options

Projected background index after all cuts:

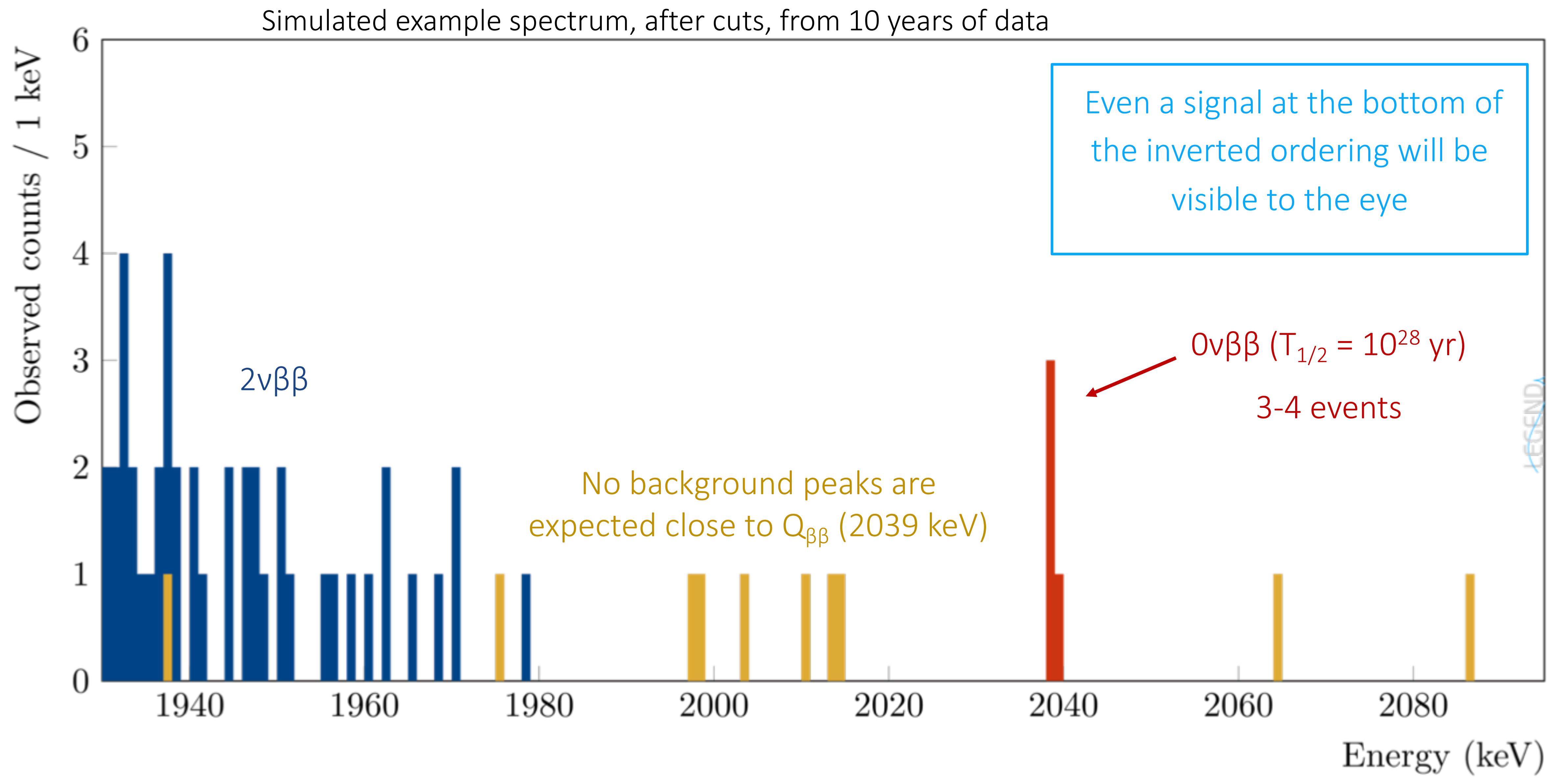
$$9.4^{+4.9}_{-6.3} \times 10^{-6}\ \text{counts/(keV kg yr)}$$

Quasi-background free operation up to 10 ton-year exposure, for unambiguous discovery beyond 10^{28} years

The LEGEND-1000 Background Model



Designed for an Unambiguous Discovery



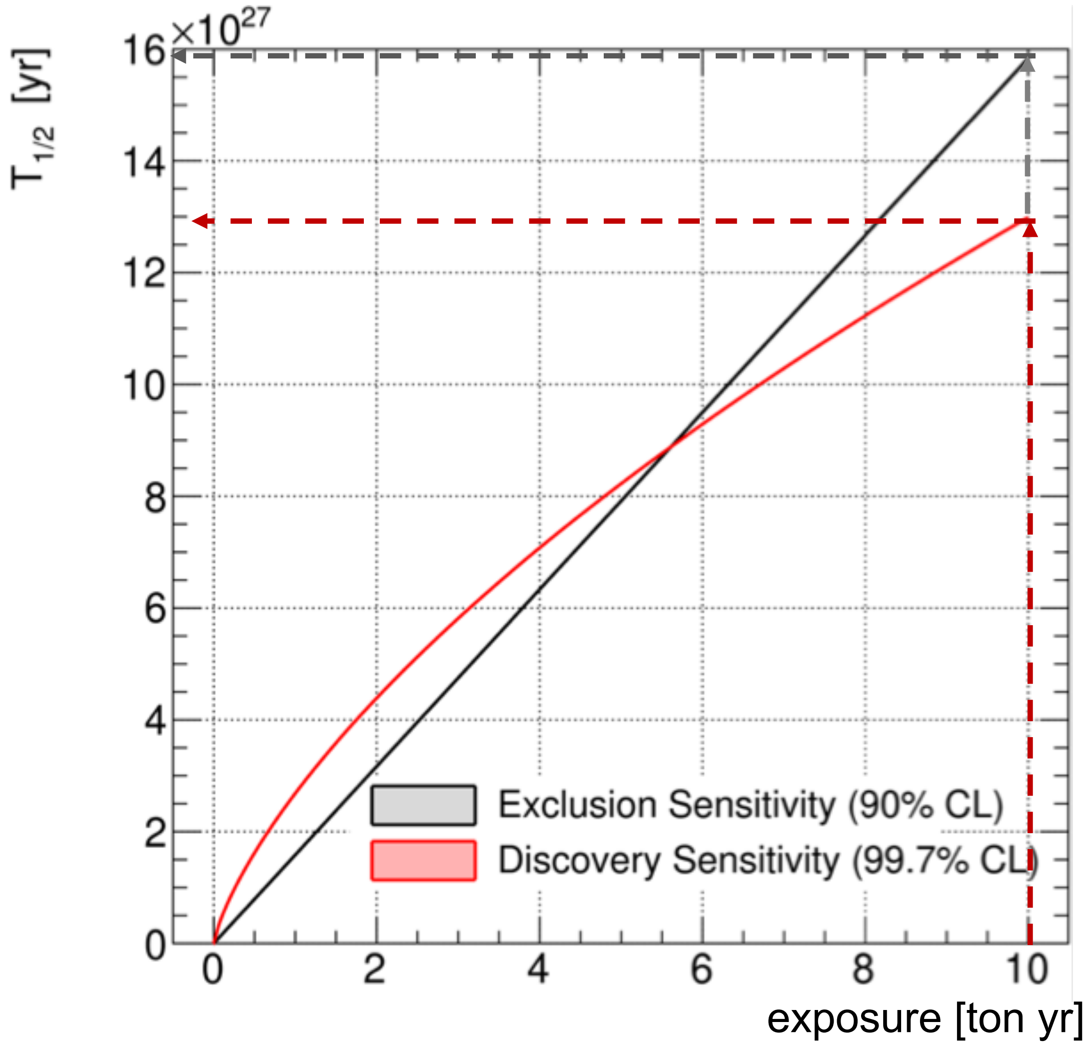
Sensitivity $T_{1/2}$

90% CL exclusion sensitivity @ 10 ton-yr	1.6 10^{28} yr
3σ discovery sensitivity @ 10 ton-yr	1.3 10^{28} yr

- $T_{1/2} \propto \mathcal{E}/N_{0\nu\beta\beta}$
- Background free ➜ linear sensitivity growth
- 10^{28} yr in discovery mode (x100 better than GERDA & MAJORANA)

LEGEND will explore uncharted territory and open new energy frontiers

New physics can manifest at any $T_{1/2}$ value!



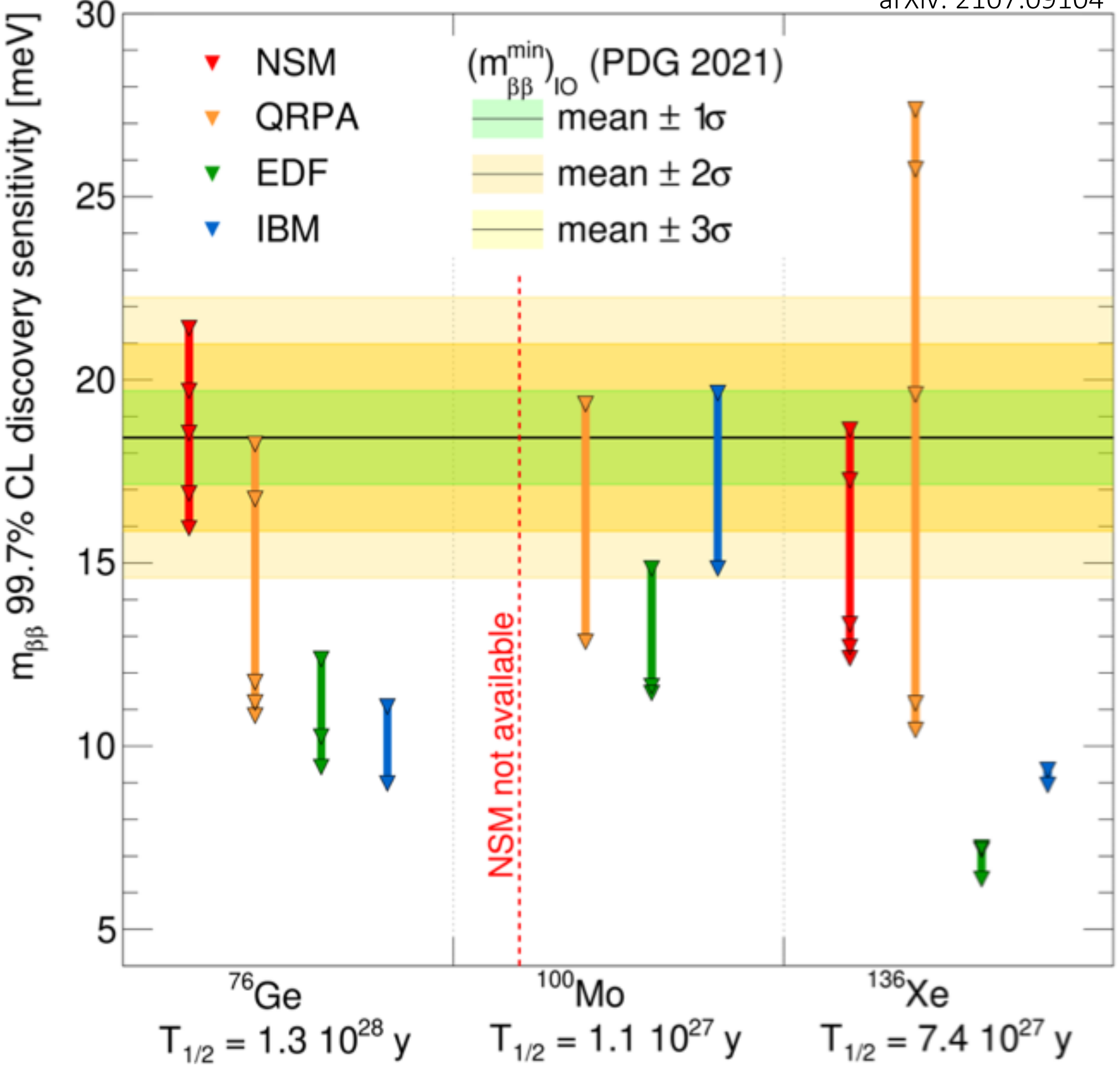
Sensitivity $m_{\beta\beta}$

- $m_{\beta\beta} = m_e / \sqrt{G\ g_A^4\ M^2\ T_{1/2}}$
- Inverted ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- *M* ➜ 4 many-body methods, each with specific systematics (soon also ab initio)
- Multiple, different set of calculations for each many-body method and isotope

LEGEND will fully test inverted ordering and a large part of the normal ordering space

Discovery sensitivity <18.4 meV for 3/4 many-body methods & 12/15 calculations

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
arXiv: 2107.09104



Conclusion

- LEGEND-1000 is optimized for a quasi-background-free $0\nu\beta\beta$ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - Our background model is based on the demonstrated success of MAJORANA and GERDA, detailed simulations, and well-understood improvements
  - LEGEND has a low-risk path to meeting its background goal of 10^{-5} counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and topology discrimination allow for an unambiguous discovery of $0\nu\beta\beta$ decay at $T_{1/2} = 10^{28}$ years
- The reference design plans for the instrument to be sited in the SNOLAB Cryopit (baseline site)
- Alternatively, the instrument can be sited at LNGS (Hall C) (alternative site)
- LEGEND-1000 International Project Organization established with ORNL as US DOE leadlab
- We have a strong, experienced, international collaboration that "aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."

LEGEND-1000 Preconceptual Design Report: https://arxiv.org/pdf/2107.11462.pdf