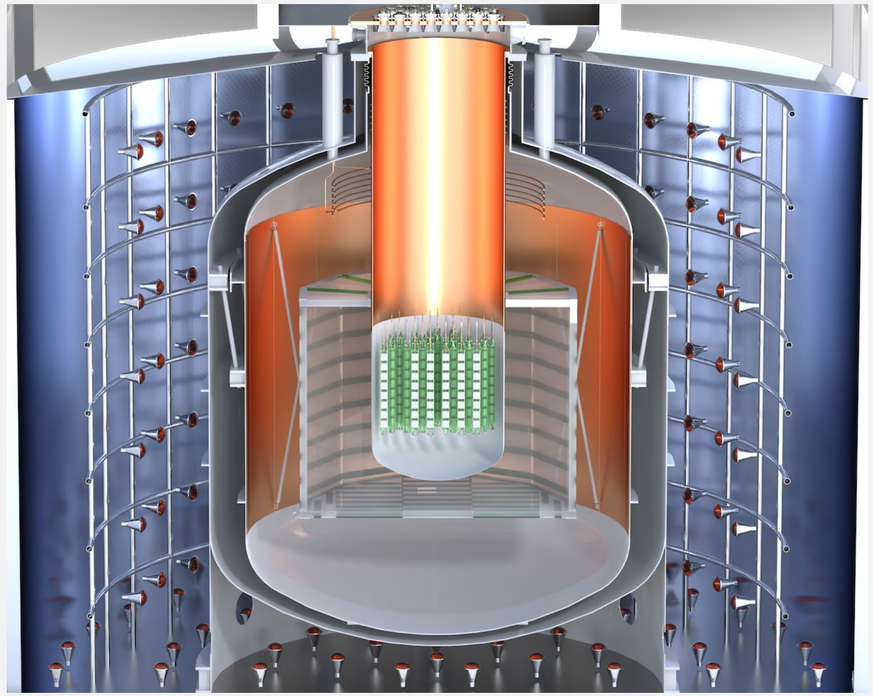
LEGEND:

Поиск двойного безнейтринного бета (0νββ) распада с германиевыми детекторами

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Konstantin Gusev
ЛЯП ОИЯИ

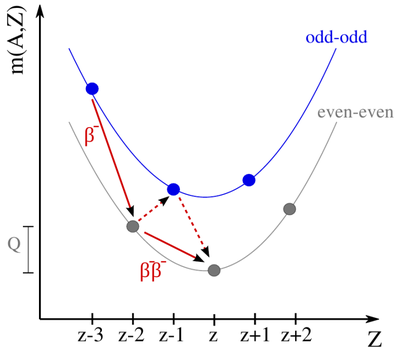
Общелабораторный семинар
15 января 2025

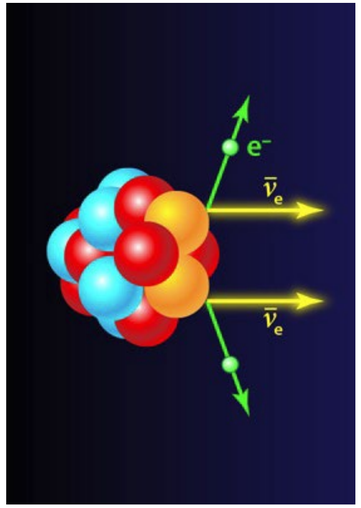
Vocabulary

- Experiments:
  - LEGEND – Large Enriched Germanium Experiment for Neutrinoless ββ Decay
  - GERDA – GERmanium Detector Array
  - MJD – Majorana Demonstrator
- HPGe detector types:
  - Coax – semi-coaxial
  - BEGe – Broad Energy Germanium
  - PPC – p-type Point Contact
  - IC or ICPC – Inverted Coaxial or Inverted Coaxial Point Contact
- LAr – Liquid Argon
- NMS – Nylon Mini-Shroud
- CC4 – low background cryogenic amplifier developed by GERDA
- LMFE – Low Mass Front End developed by MJD
- ASIC – Application Specific Integrated Circuit
- Sensitivity – expected number of signal events that an experiment has 50% chance of excluding at 90% CL
- Discovery sensitivity – expected number of signal events for which an experiment has 50% chance to observe an excess of events over the background at 99.73% CL

0νββ search: why?

Possible in 35 even-even nuclei
(β decay is energy/spin suppressed)





2νββ

- Rare process with half life is 10^{10} longer than the age of the universe, however already **observed** in 14 isotopes!
- Most precise measurement of 2νββ half-life in the world by **GERDA**:

$$T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = (2.043 \pm 0.033_{stat+sys}) \cdot 10^{21}\mathrm{yr}$$

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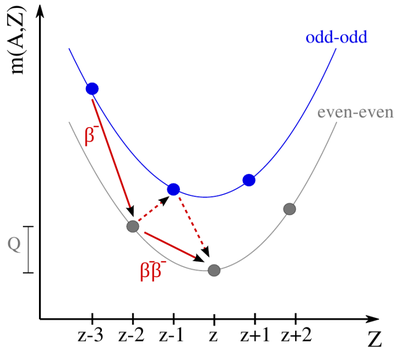

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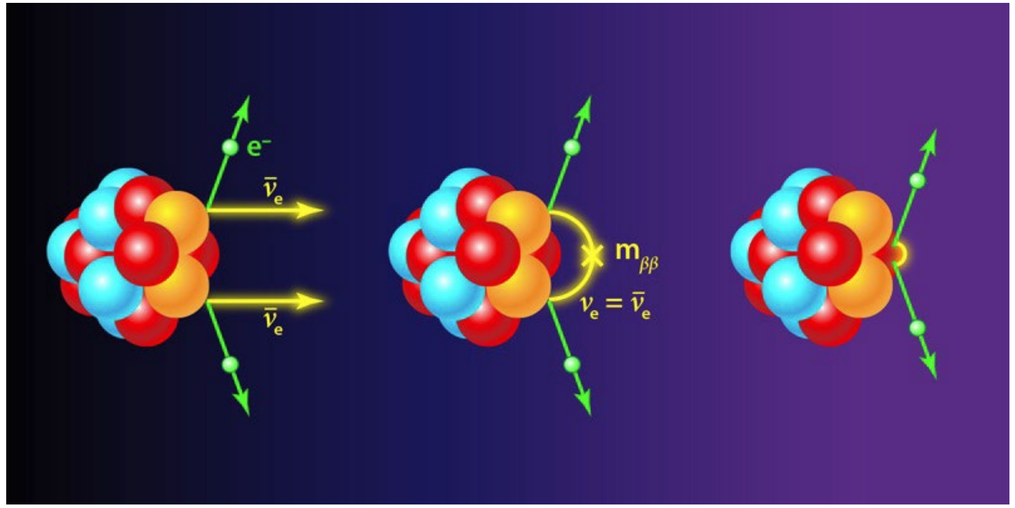


0νββ

- Violates lepton number
- Forbidden in Standard Model
  - New BSM physics
- Creates matter w/o antimatter
- Shows, that ν has Majorana mass component
- In case of light ν exchange
  - would give access to ν mass scale
  - would provide important input to cosmology

Link between 0νββ and ν-mass

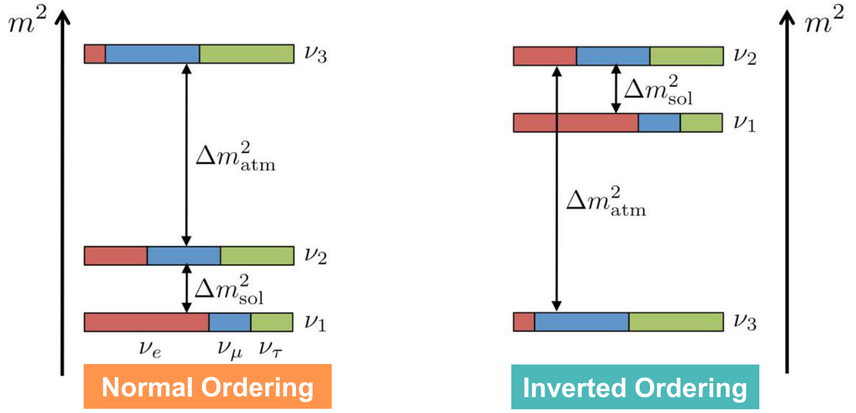
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\, g_A^4\, |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

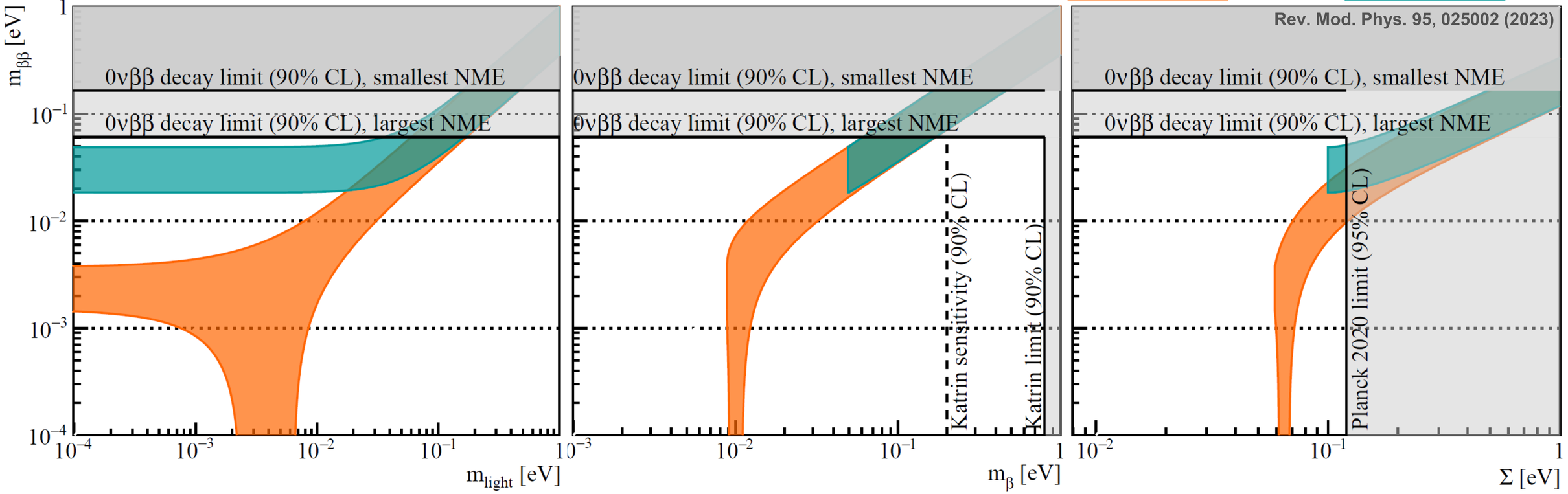
- $T^{0\nu}_{1/2}$: 0νββ decay rate
- $G^{0\nu}(Q,Z)$: Phase space factor
- $|M^{0\nu}|^2$: Nuclear Matrix Element
- $m_{\beta\beta}$: Effective Majorana neutrino mass

$$m_{\beta\beta} = |\sum U_{ei}^2 m_i|$$

$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

$$\Sigma \text{ or } m_{cosm} = \sum m_i$$



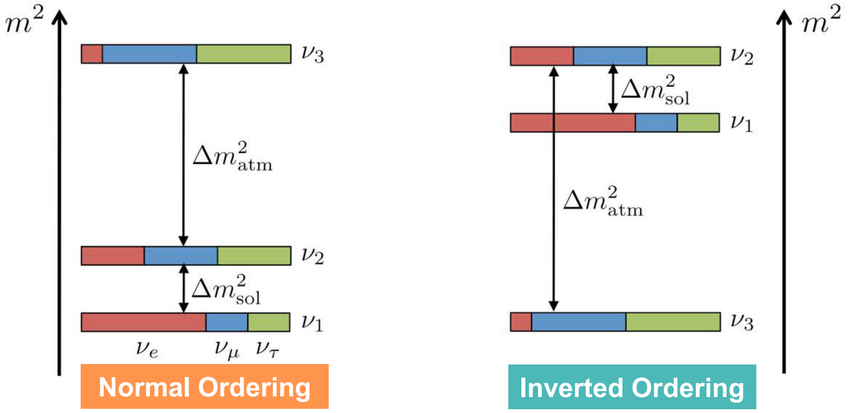


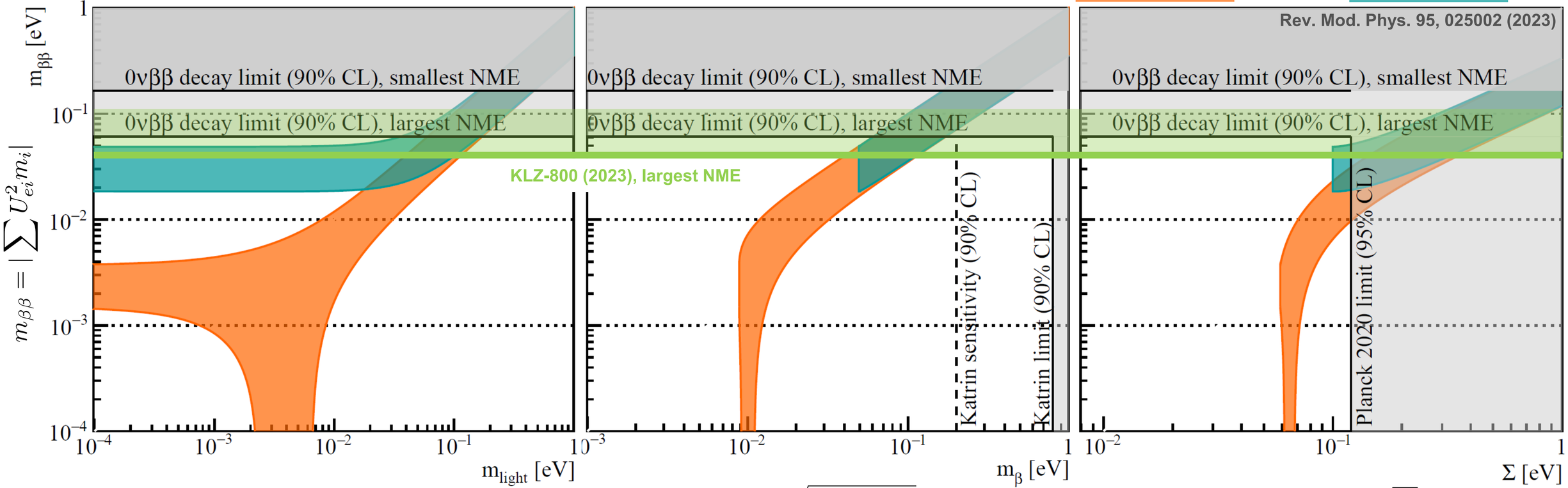
Link between 0νββ and ν-mass

Notes:

- **Recent KamLAND-Z 800** limit came to **IO** region

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)\, g_A^4 |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



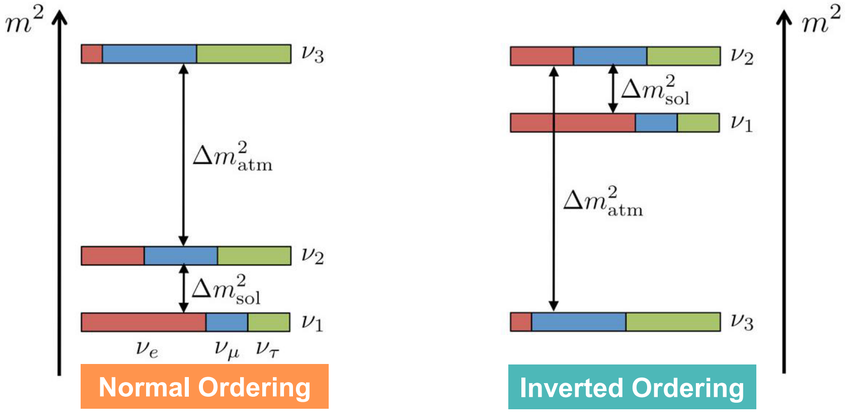


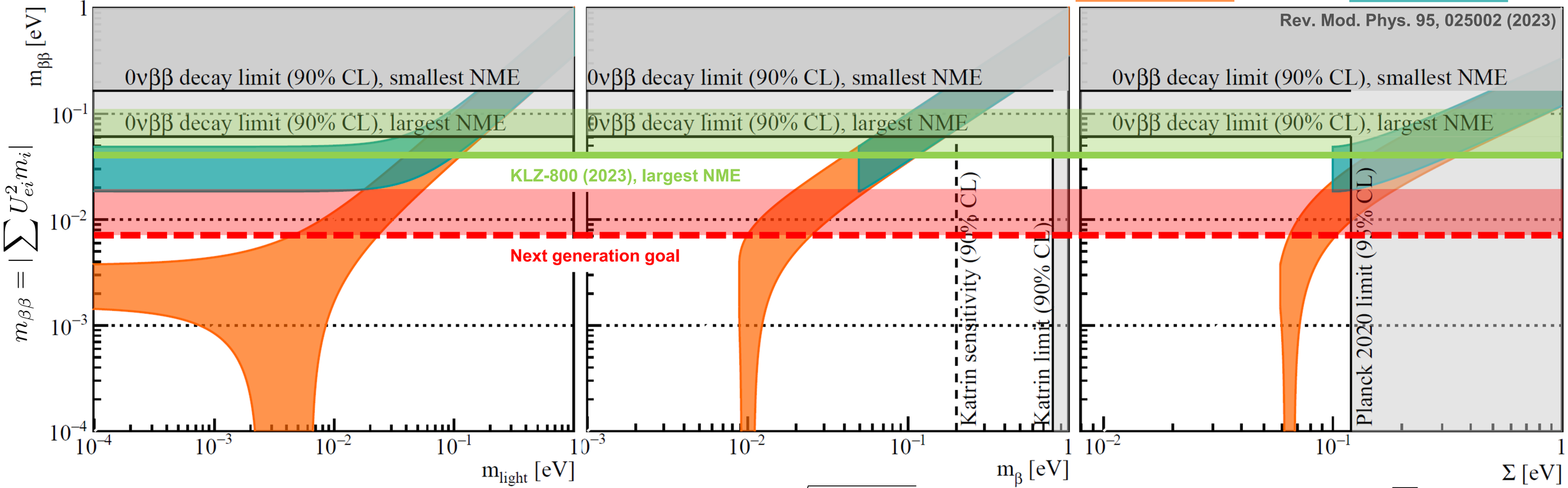
Link between 0νββ and ν-mass

Notes:

- **Recent KamLAND-Z 800** limit came to **IO** region
- Next generation projects fully cover **IO** and part of **NO**

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$





$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

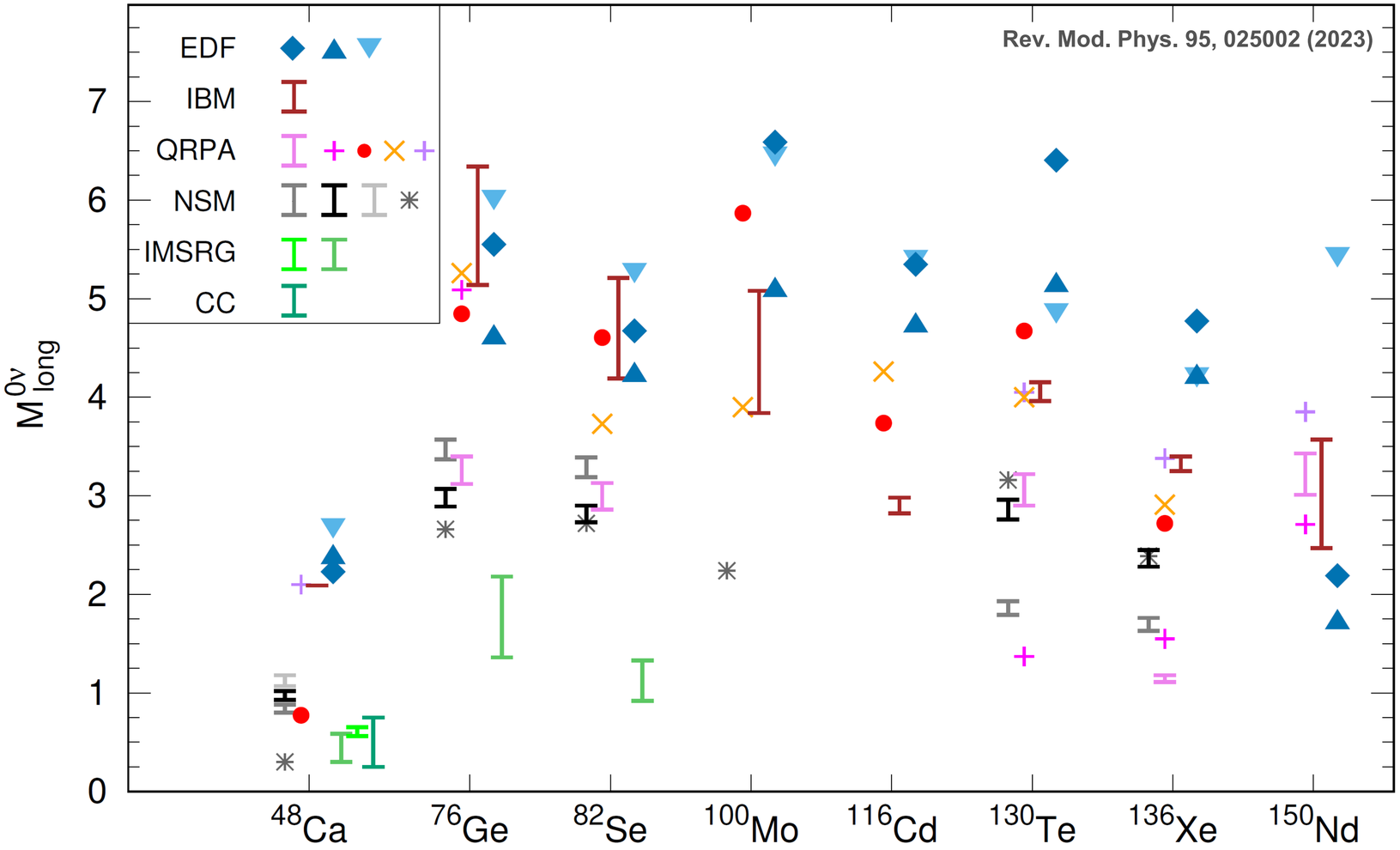
$$\Sigma \text{ or } m_{cosm} = \sum m_i$$

Nuclear Matrix Elements

Notes:

- Nuclear Matrix Element (NME) is a model dependent input to the result
- (NME) has large uncertainty depends on different models
- A lot of recent progress on the theoretical front to better constrain the value!
- No preferred isotope (?)

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



Phase Space, Q-value, Abundance

Phase space factor

- Higher – better

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Q-value

- Better > 2614.5 kev
- Above natural radioactivity

Natural abundance

- Enrichment is pretty expensive
- Influence the cost of an experiment

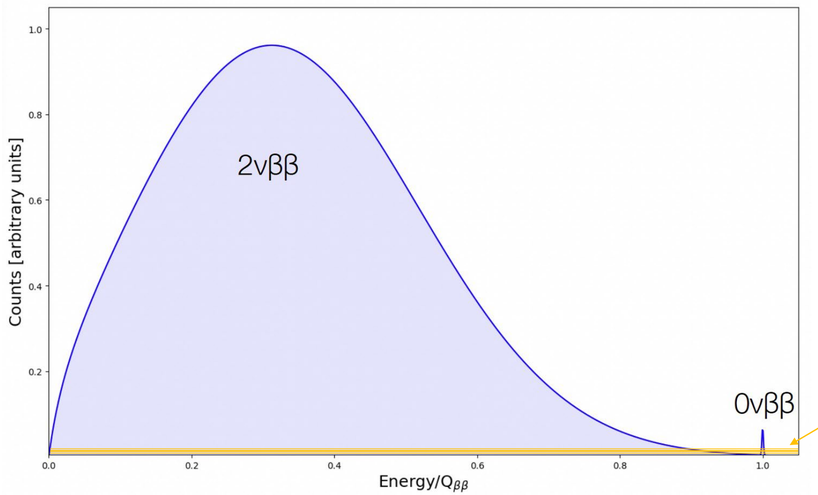
Isotope	$G^{0\nu}$ (10^{-14}yr)	Q(keV)	Nat. ab. (%)
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

*enrichment required except for ^{130}Te, not (yet) possible for all, costs differ

- No preferred isotope from G*M

Experimental design considerations

Signature: sharp peak at the end of 2νββ spectrum on some background

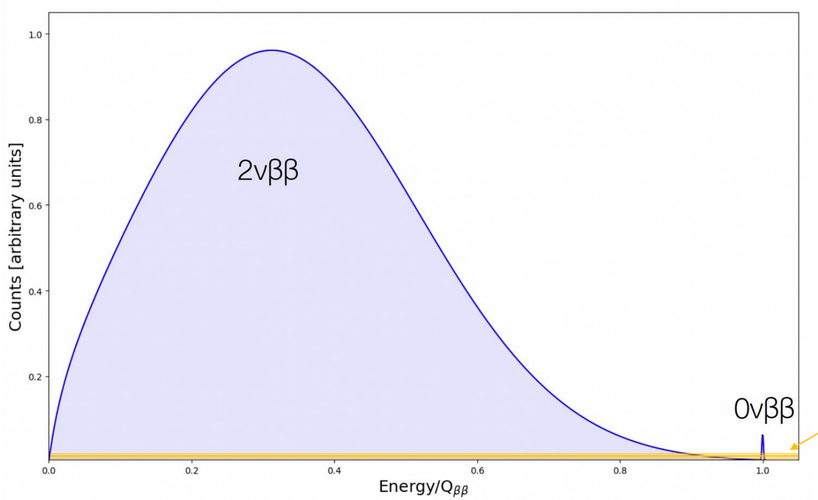


Exposure

$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{M\,t}{\Delta E\; BI}}$$

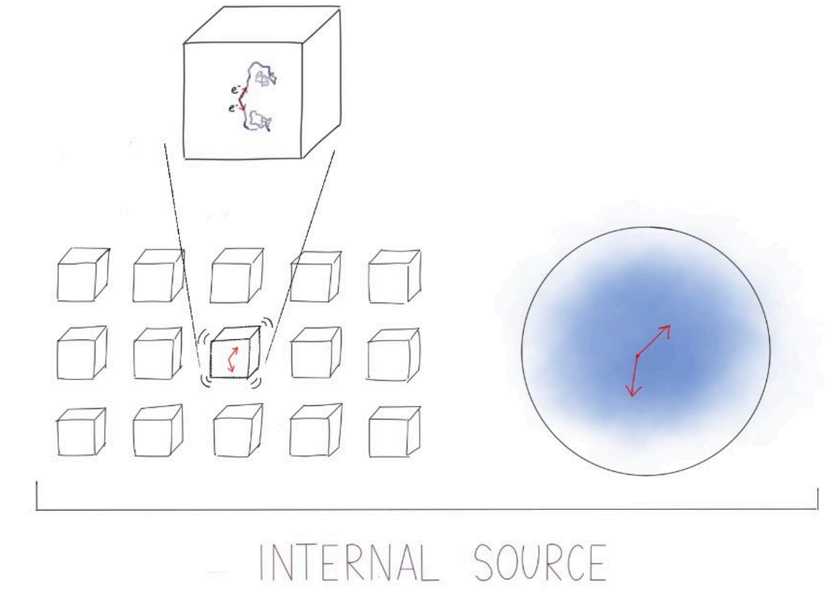
- Detector performance:
  - High mass and good long-term stability to increase exposure

Experimental design considerations

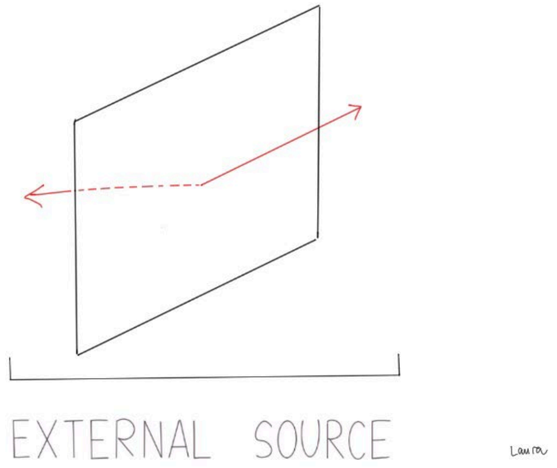


$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{M\,t}{\Delta E\;BI}}$$

Efficiency

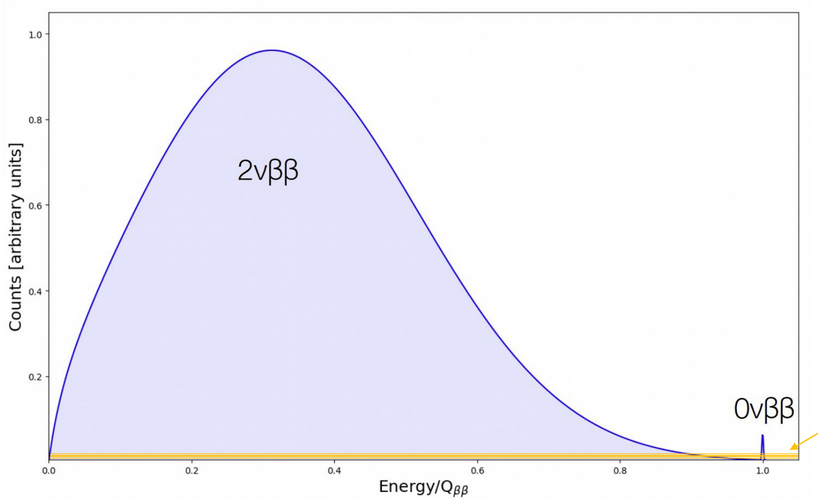


- Detector performance:
  - High mass and good long-term stability to increase exposure
  - High efficiency: source = detectors



Picture: Laura Manenti

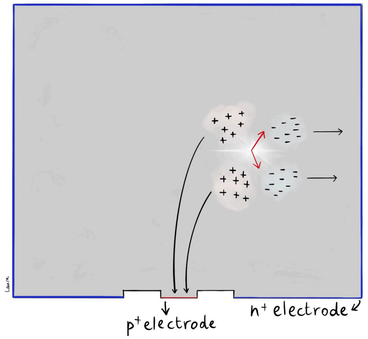
Experimental design considerations



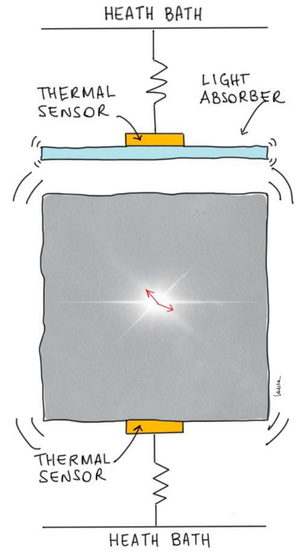
$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{M\,t}{\Delta E\,BI}}$$

Energy resolution

HPGe detector

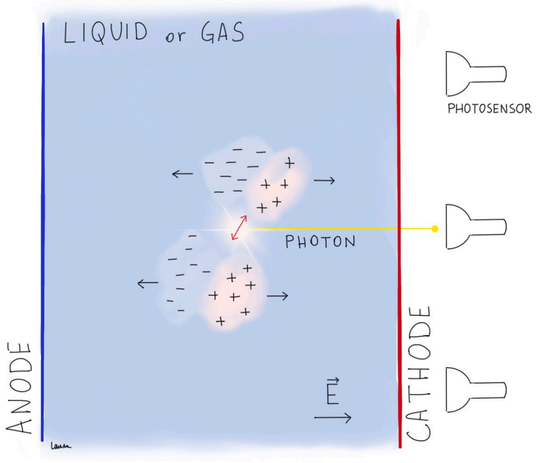


Bolometer

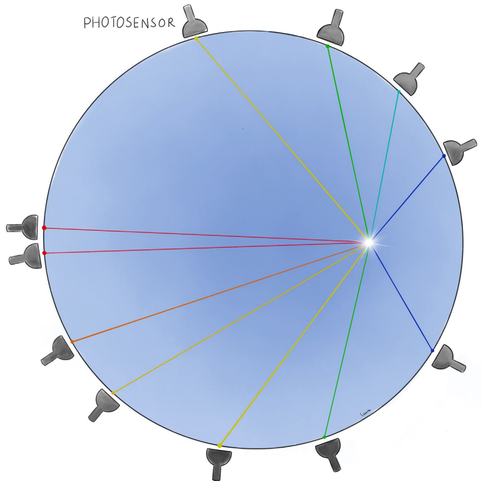


- Detector performance:
  - High mass and good long-term stability to increase exposure
  - High efficiency: source = detectors
  - Good energy resolution

TPC



Liquid scintillator



Pictures: Laura Manenti

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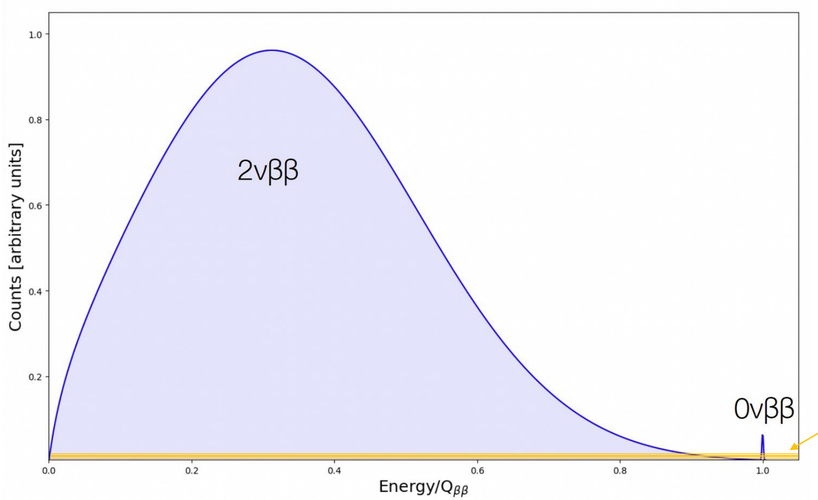

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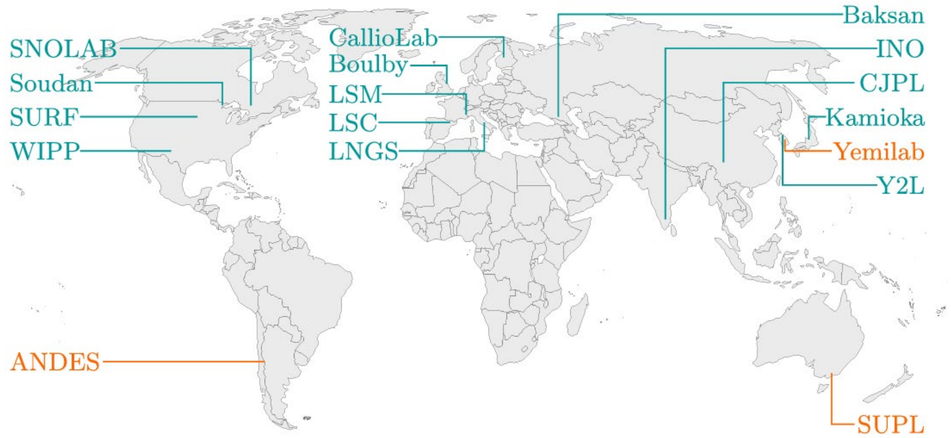
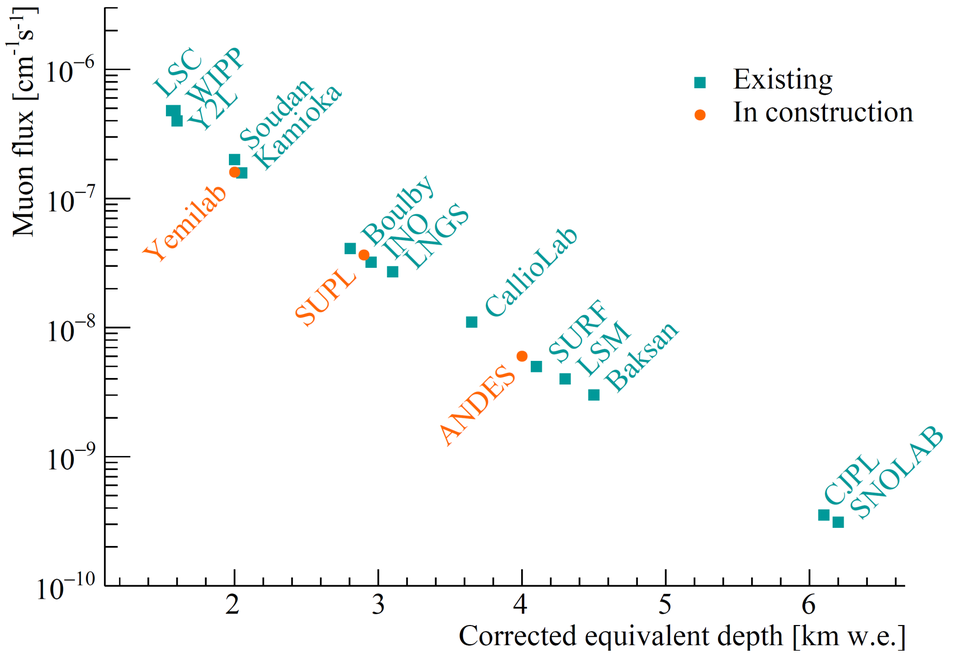
Background Index



- Detector performance:
  - High mass and good long-term stability to increase exposure
  - High efficiency: source = detectors
  - Good energy resolution
  - Small background:
    - Underground labs to reduce the cosmogenic
    - Materials handling and cleanliness
    - Strict radiopurity constraints
    - Passive and active (!) shielding
    - Signal discrimination technics



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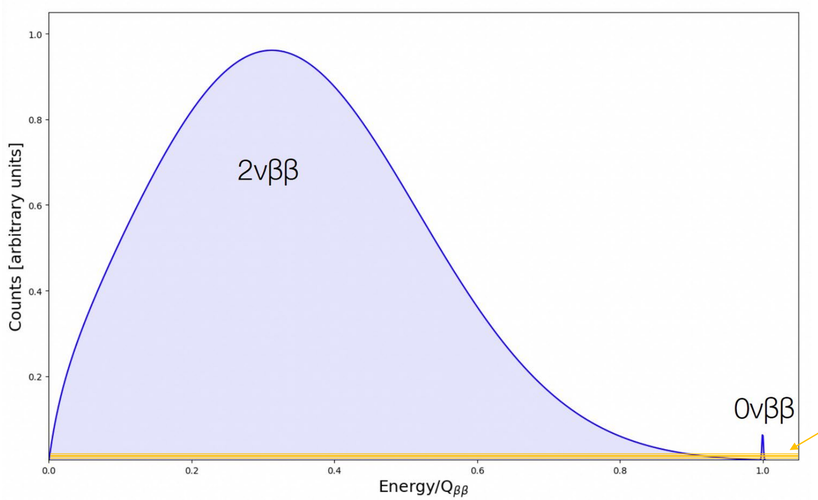

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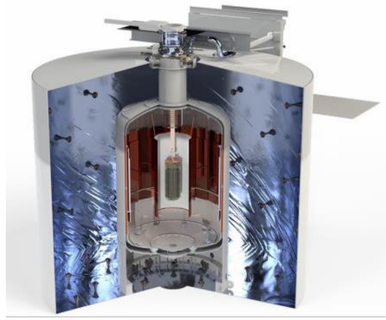
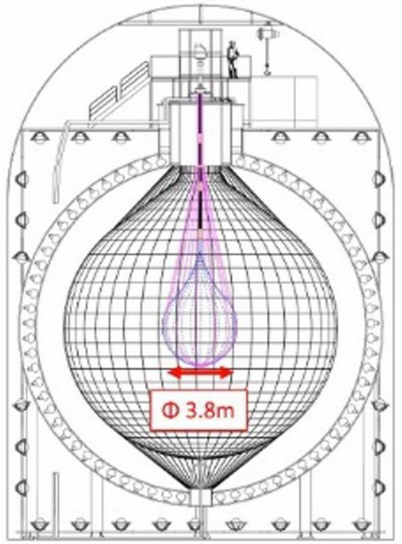


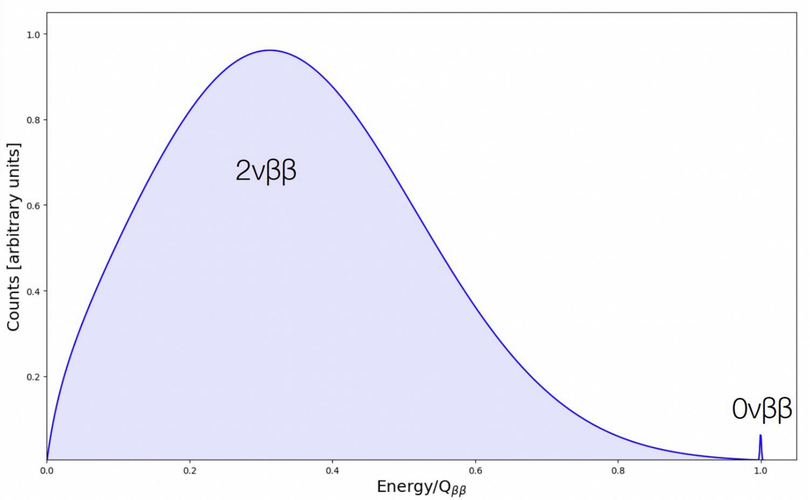
LAr (high Z, active)

Pb (high Z)



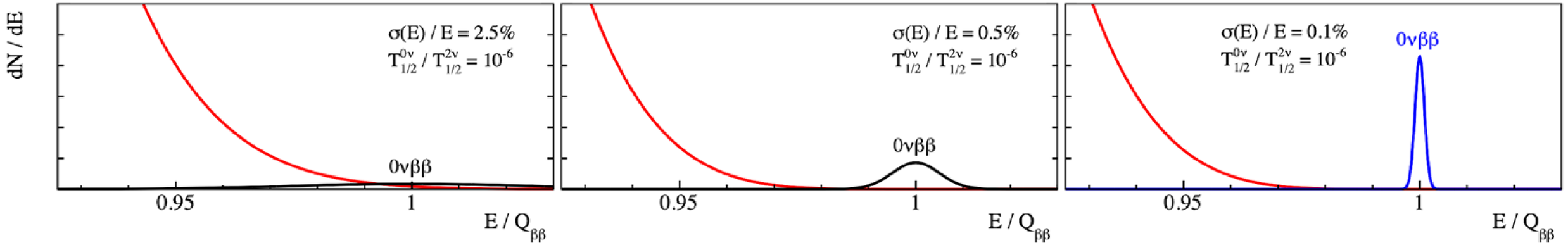
Fiducialization

“Background free” experiment



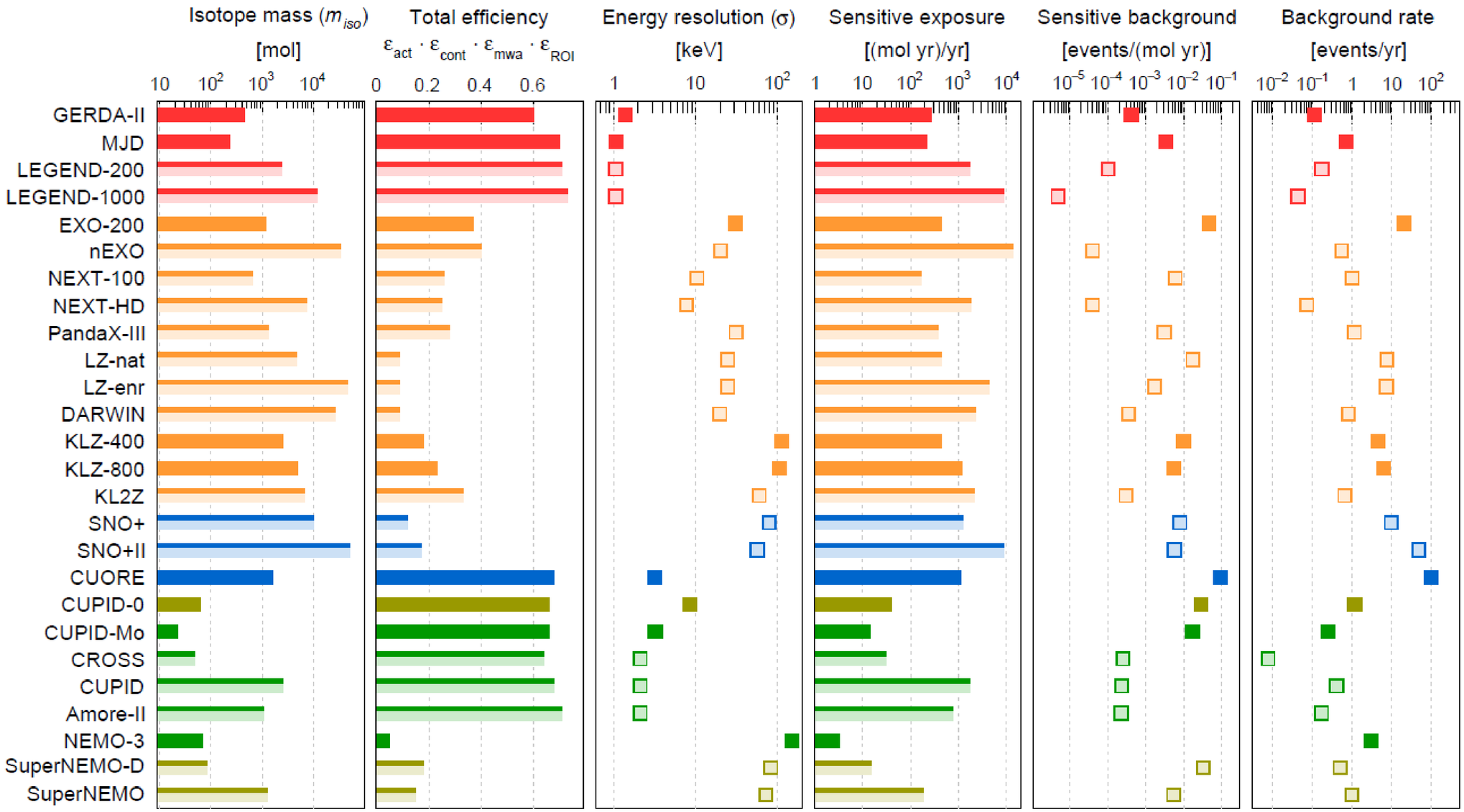
$$T_{1/2}^{0\nu} \propto \epsilon\, M\, t$$

- But energy resolution still essential!



Experimental landscape

- ^{76}Ge
- ^{136}Xe
- ^{130}Te
- ^{100}Mo
- ^{82}Se



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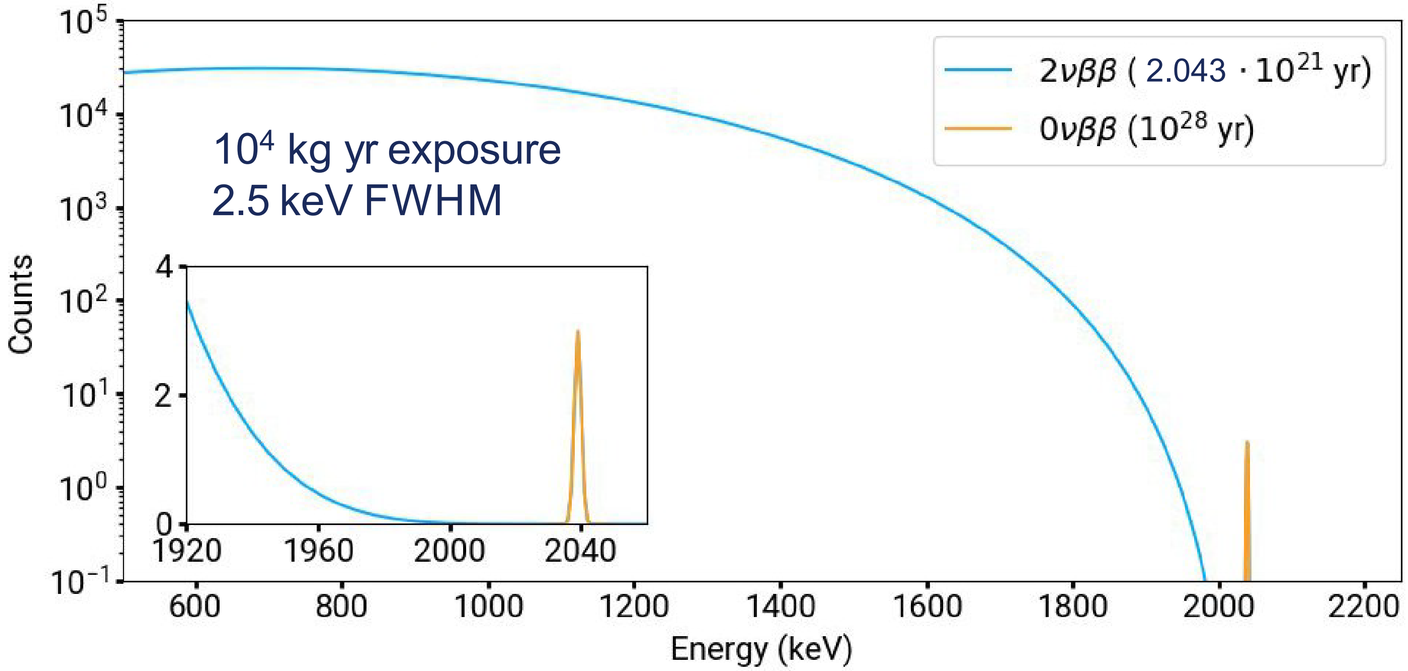
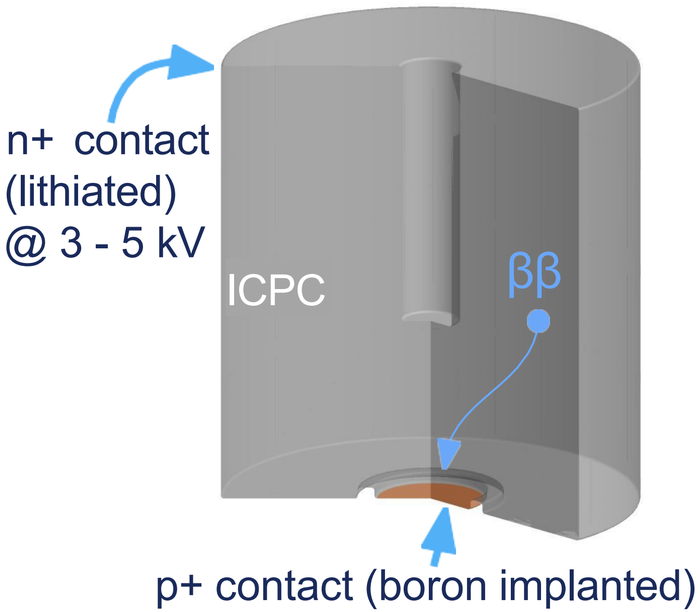
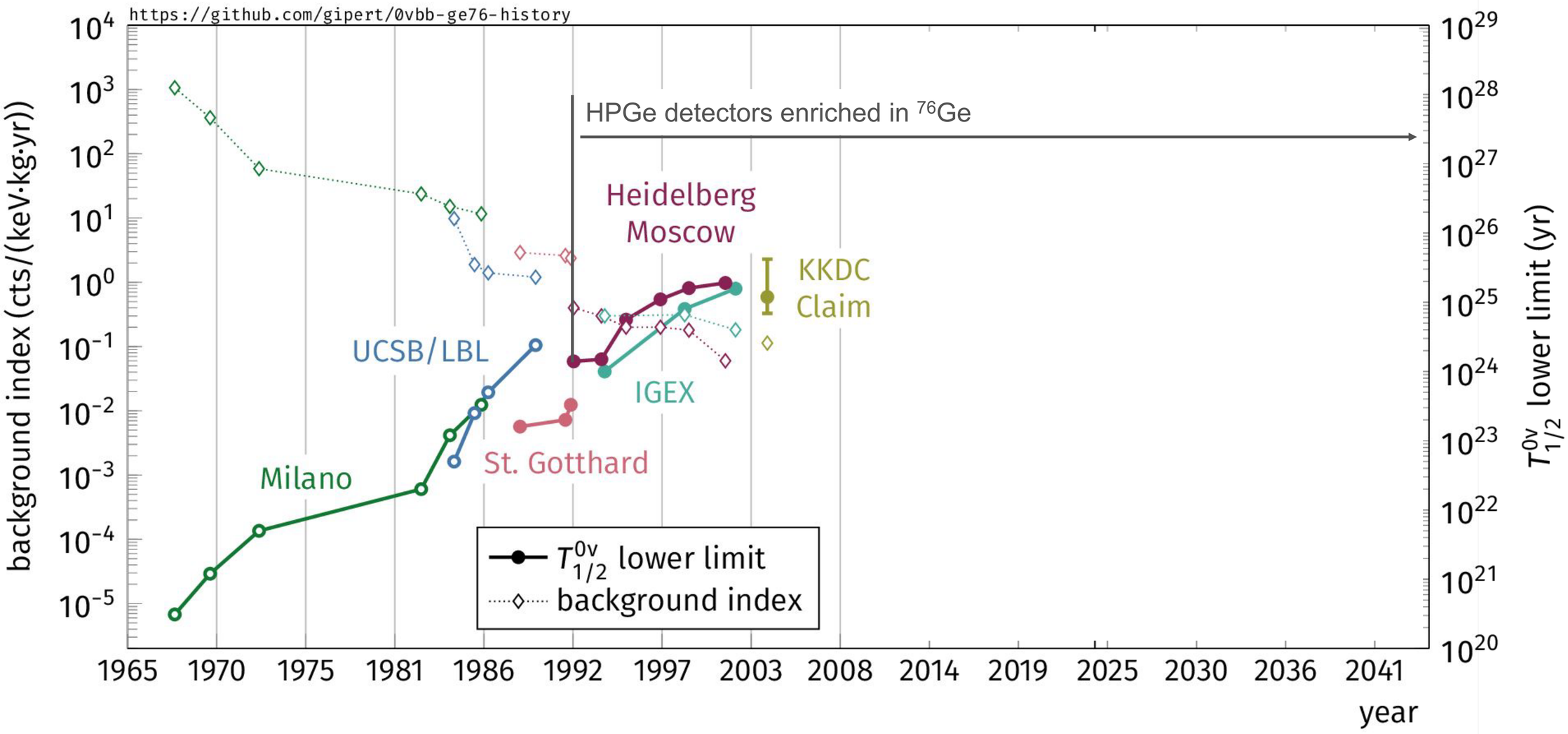
0νββ search with HPGe detectors enriched in ^{76}Ge





- High-Purity Germanium detectors enriched in ^{76}Ge
  - ββ source = detector → high efficiency
  - high purity → low intrinsic background
  - isotope enrichment → ≳ 90 % ^{76}Ge
  - excellent energy resolution → ~ 0.1 % FWHM @ $Q_{\beta\beta}$
  - topological discrimination → pulse shape discrimination (PSD)

History of 0νββ search with HPGe detectors



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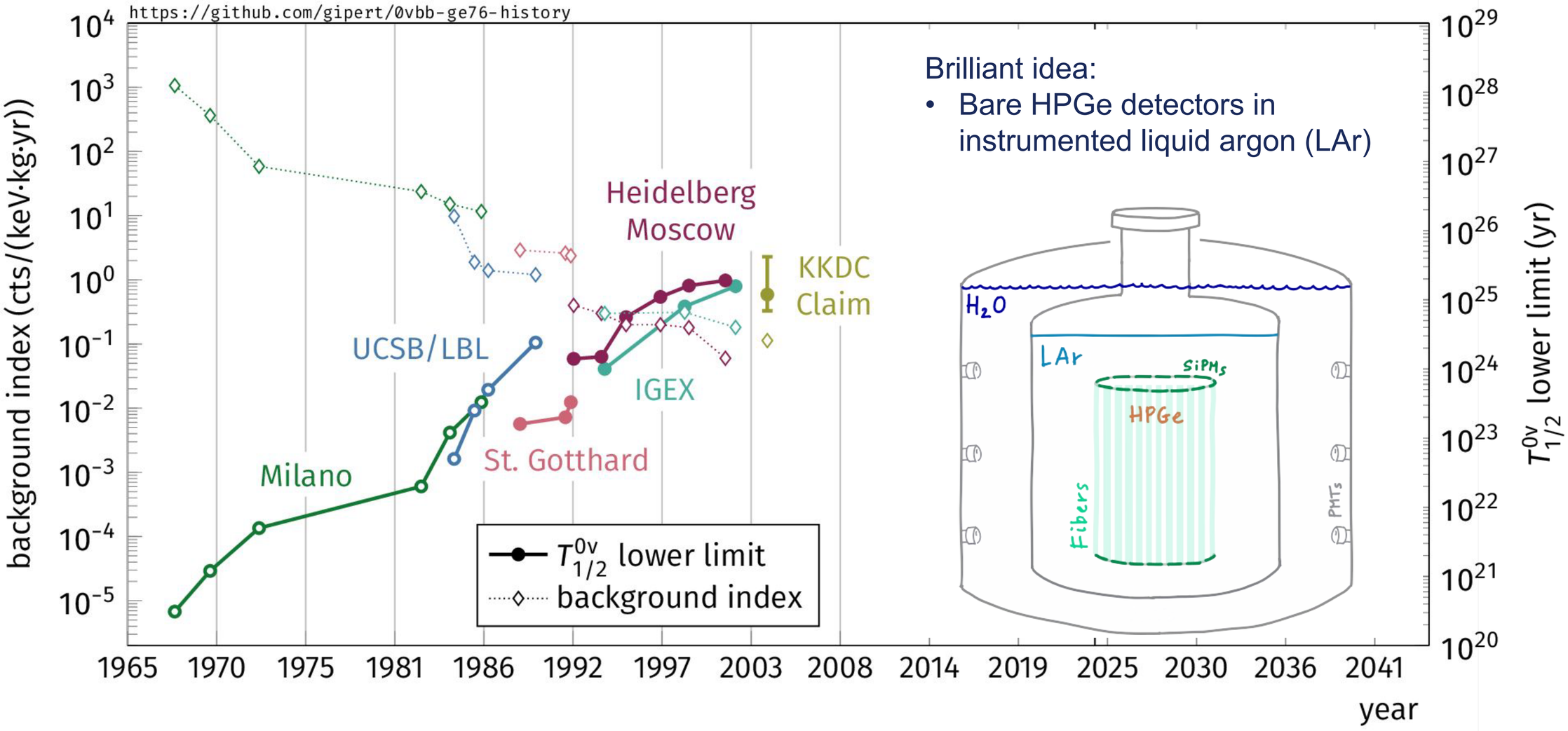

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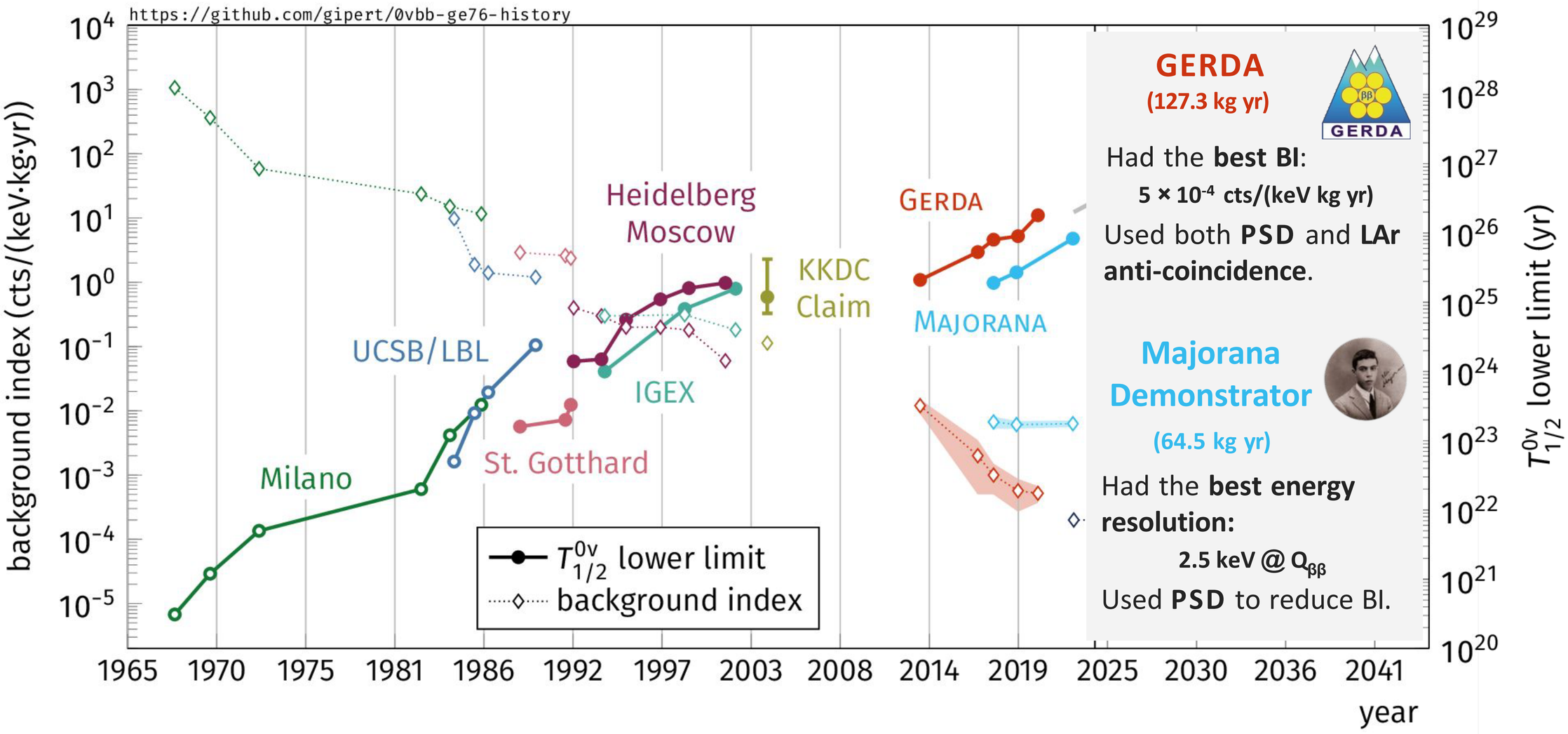

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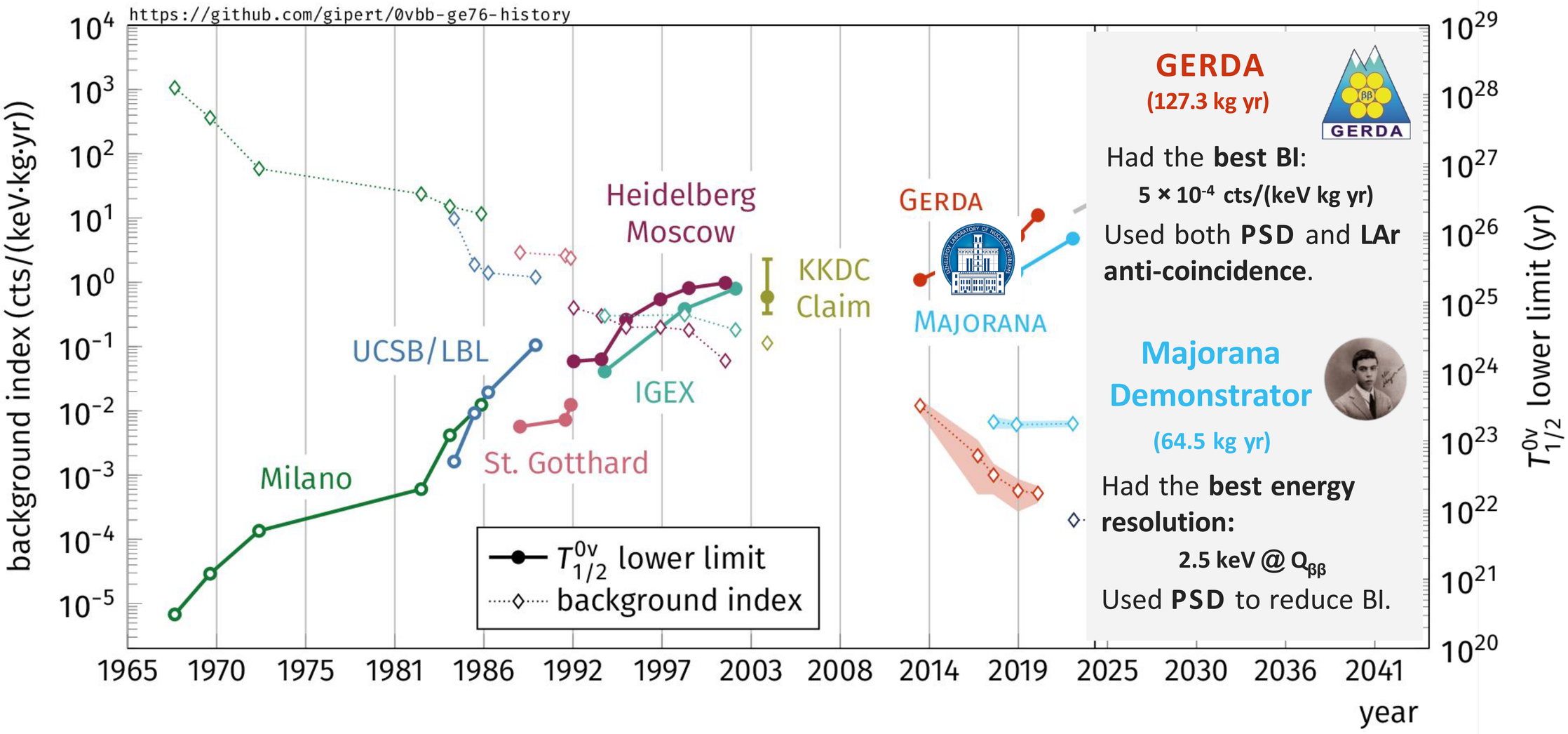
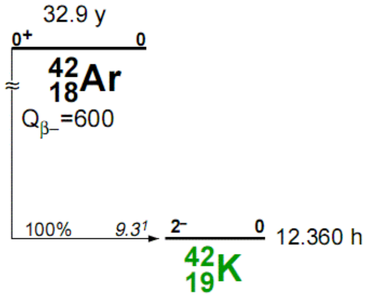
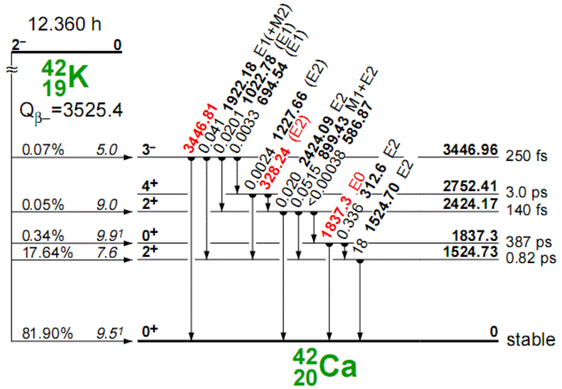


^{42}Ar problem

- In the first phase of GERDA elevated background from ^{42}K was found; ^{42}K (daughter of ^{42}Ar) – beta decay isotope with end point of 3.5 МэВ. Estimated activity in LAr ~ **(40-90) uBq/kg.**
- **Very dangerous background!**





^{42}Ar problem and solution

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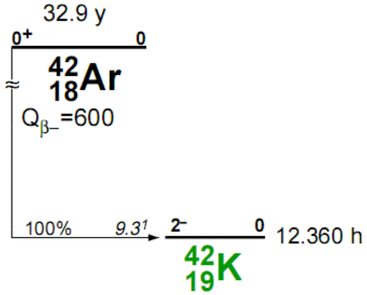

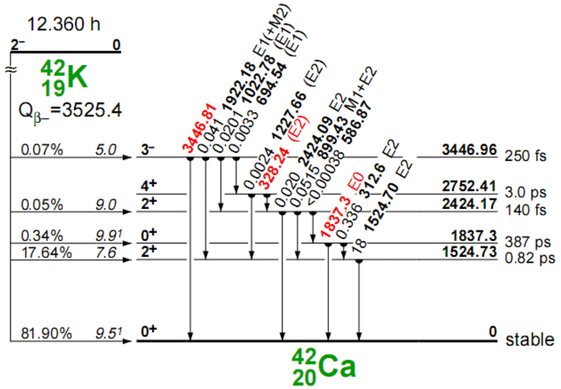

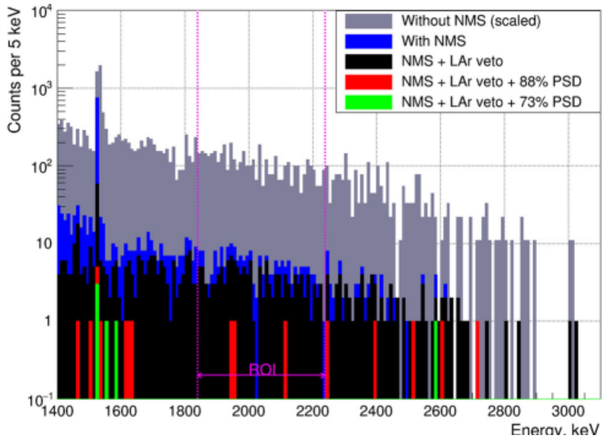

- Widely investigated
- Solution for GERDA Phase II found: nylon mini-shroud!

- Used in LEGEND-200 as well!

^{42}Ar problem and solution

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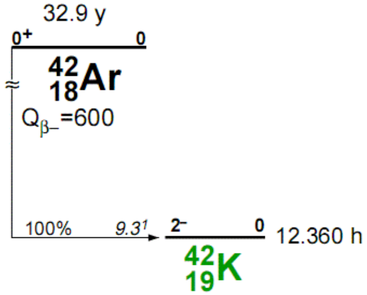
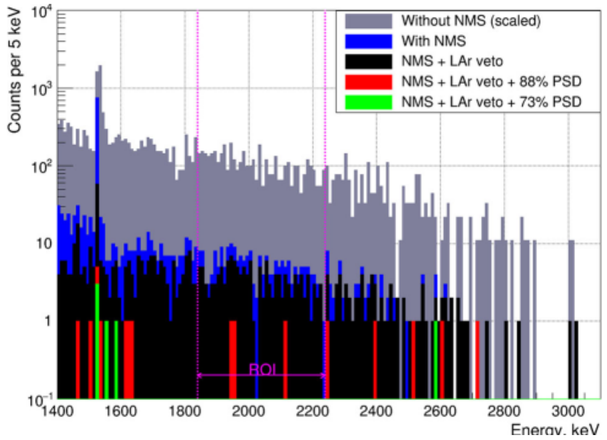
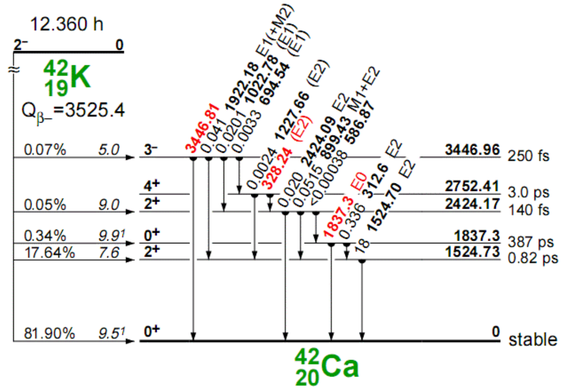


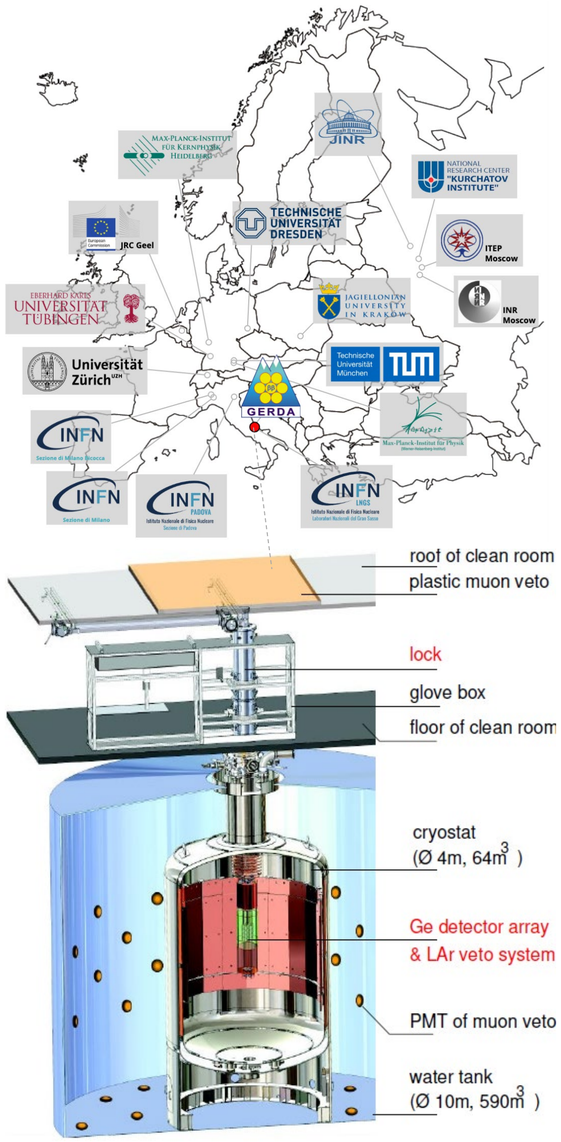




- Widely investigated
- Solution for GERDA Phase II found: nylon mini-shroud!

- Used in LEGEND-200 as well!

GERDA – first “background free” 0νββ search



- ✓ GERDA successfully finished data taking in Dec 2019
- ✓ Full data set analyzed in 2020

- ✓ **103.7 kg yr** of ^{76}Ge exposure collected in **Phase II** (**127.3** kg yr with Phase I)

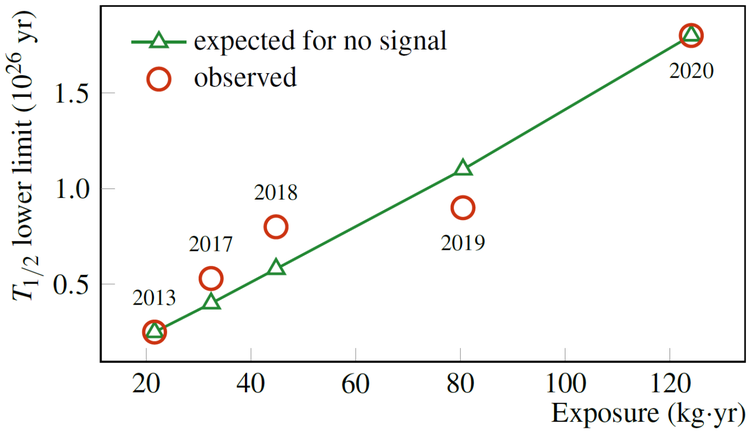
- ✓ All design goals **surpassed!**

GERDA Phase II	goals	achievements
background	~ 10^{-3} cts/(keV kg yr)	$\mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}}$ cts/(keV kg yr)
exposure	≥ 100 kg yr	**103.7** kg yr
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	$\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

- ✓ GERDA achieved world best half-life limit!

$$T^{0\nu}_{1/2} > 1.8 \times 10^{26} \text{ yr (90\% CL)}$$

- ✓ Linear increase of sensitivity vs exposure is proven!
- ✓ Opened bright future for the next step:



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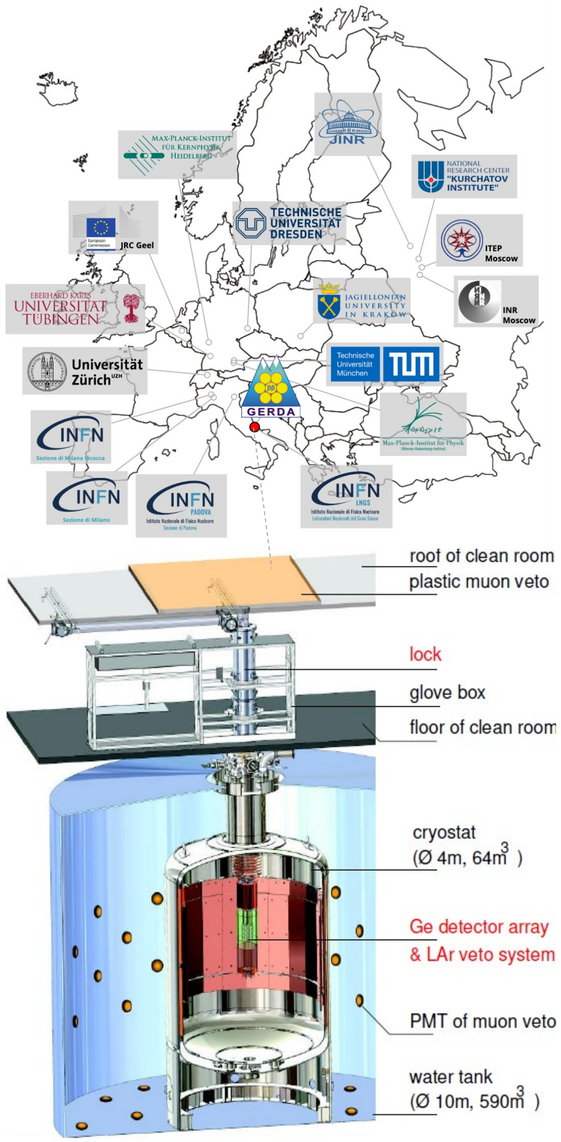

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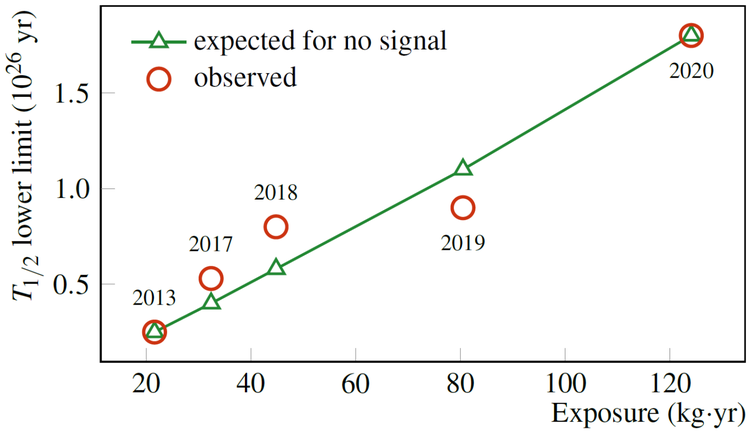
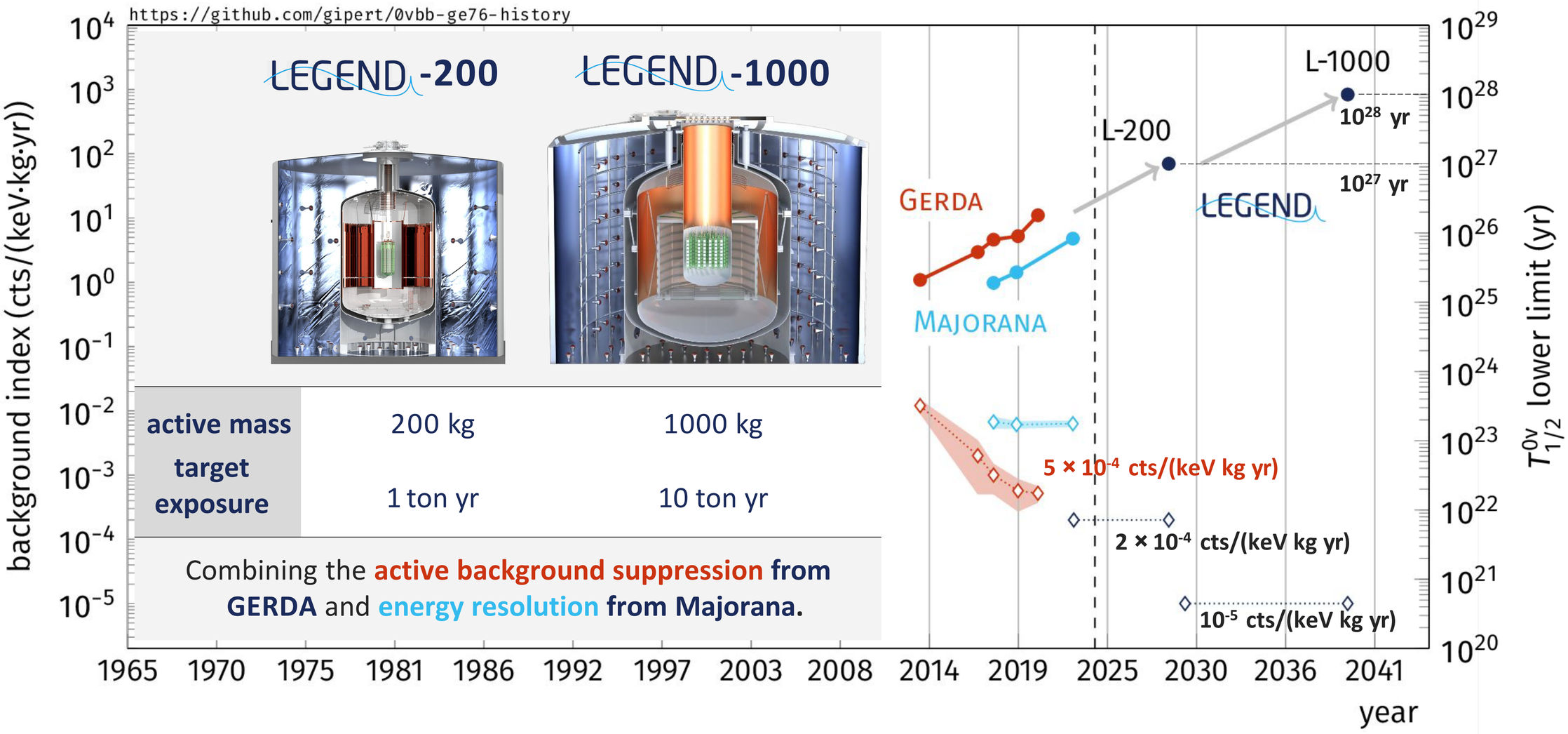
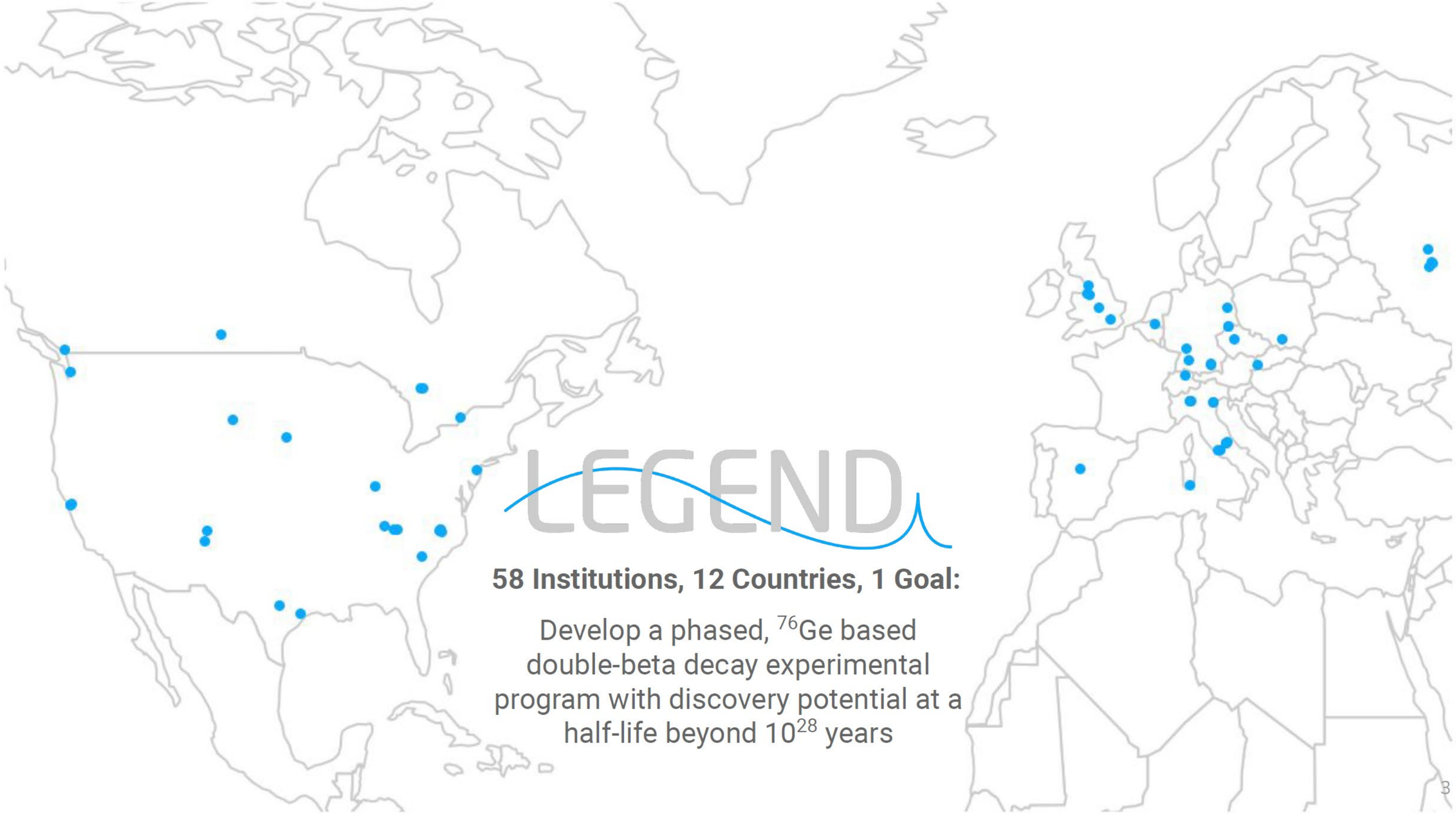


New history of 0νββ search with HPGe detectors



LEGEND Collaboration



58 Institutions, 12 Countries, 1 Goal:

Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years

LEGEND Collaboration

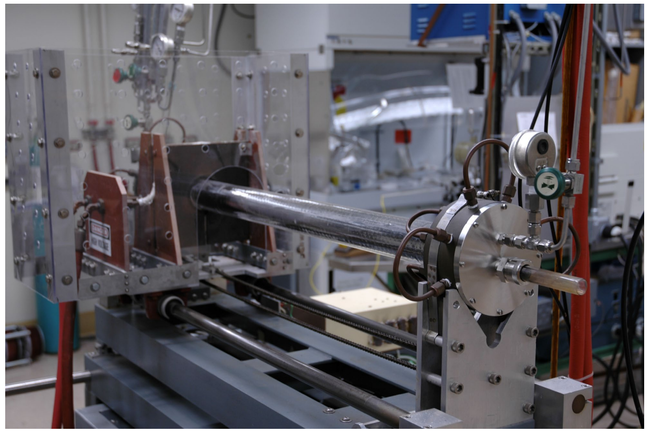
^{76}Ge Enrichment and Detector Production

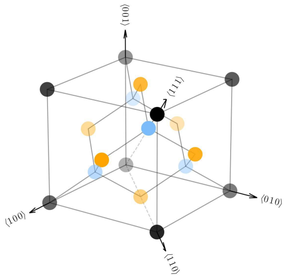
Commercial Enrichment

Germanium Oxide

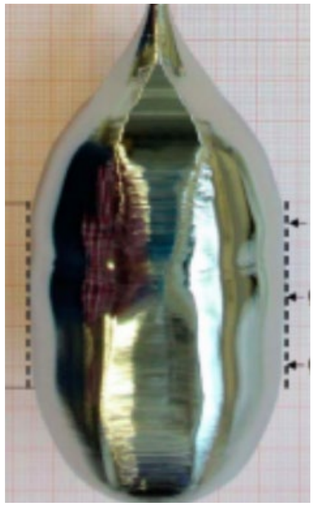
Germanium Metal

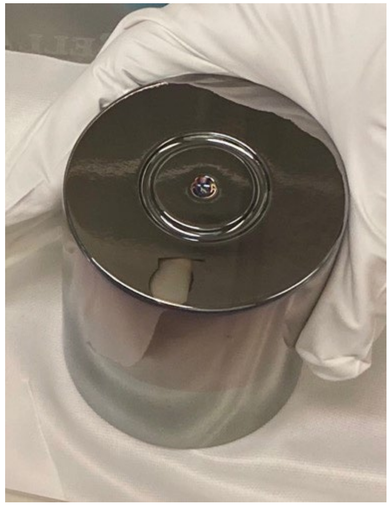
Zone Refining





Crystal Growth

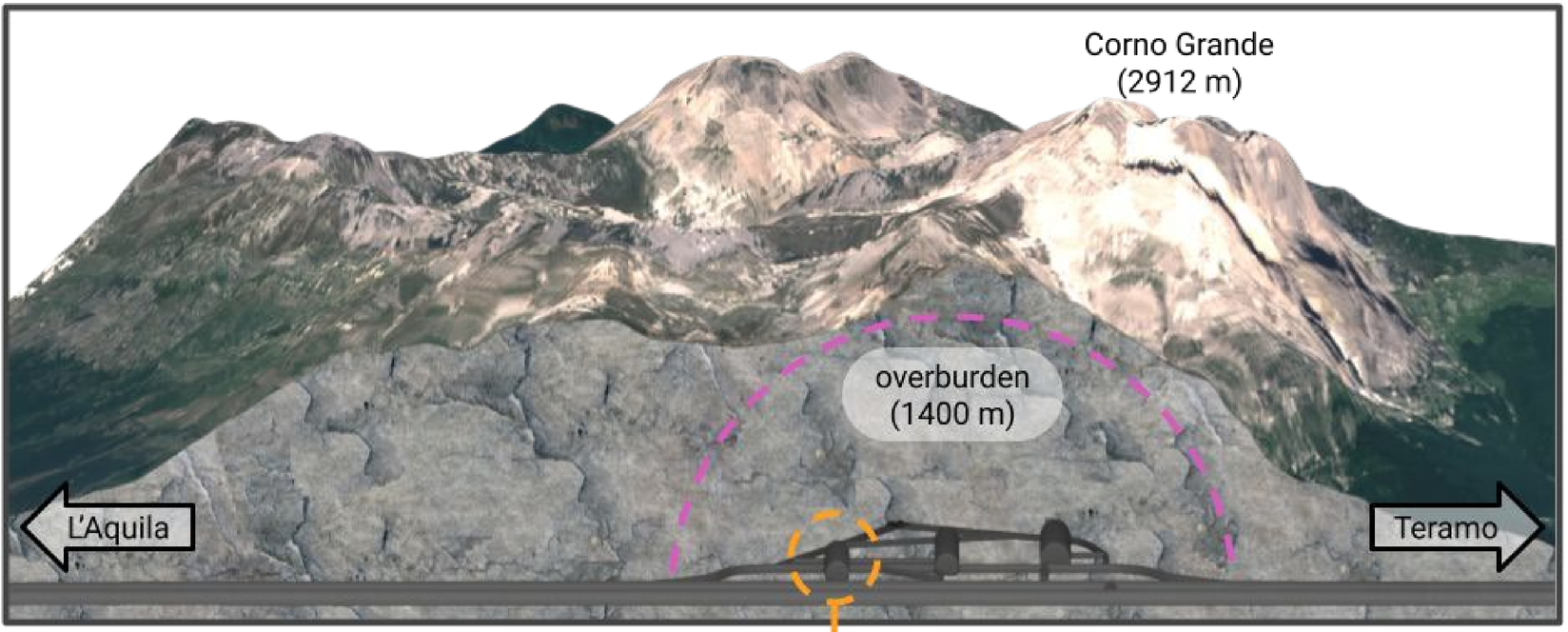


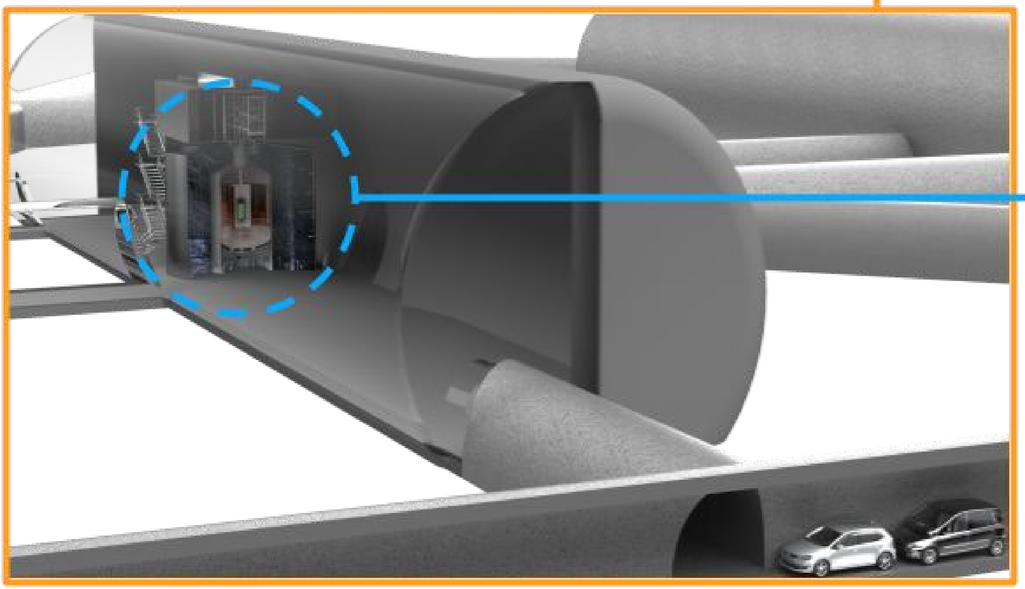


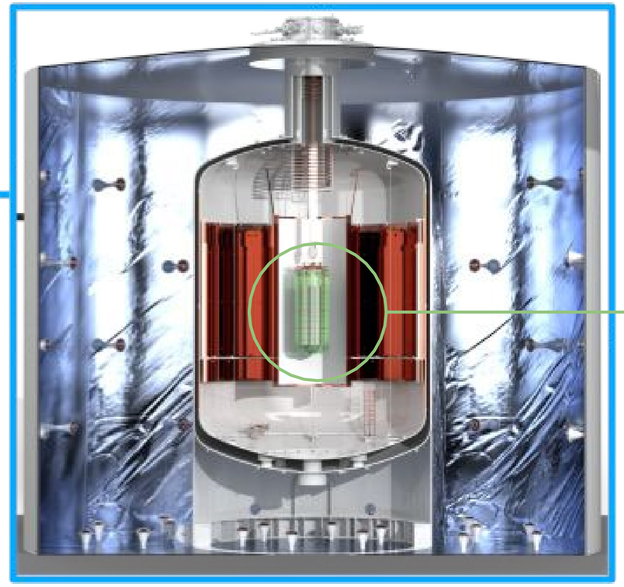
Detector Fabrication

Acceptance Testing

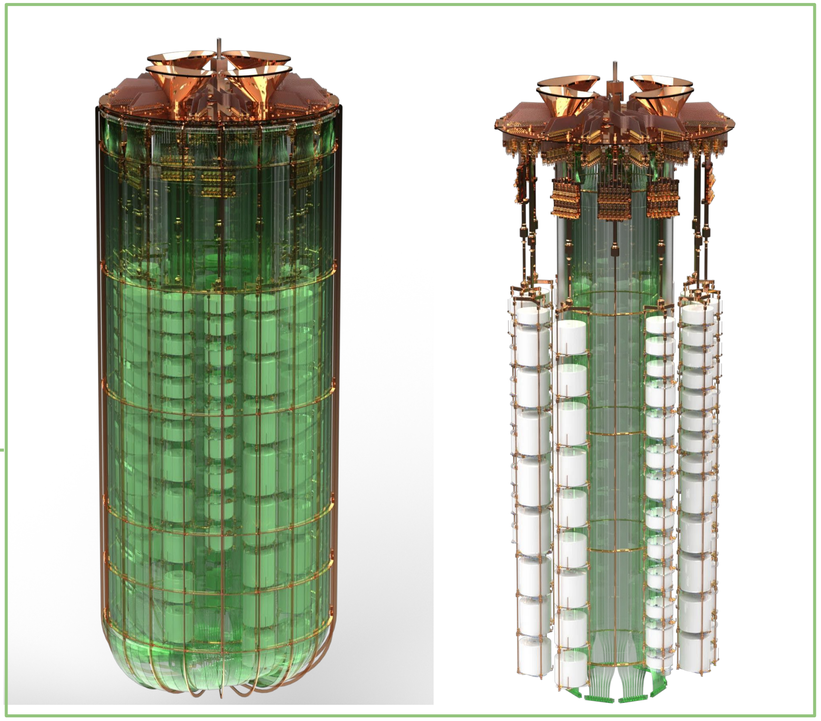
LEGEND-200: Location (LNGS Hall A) and design





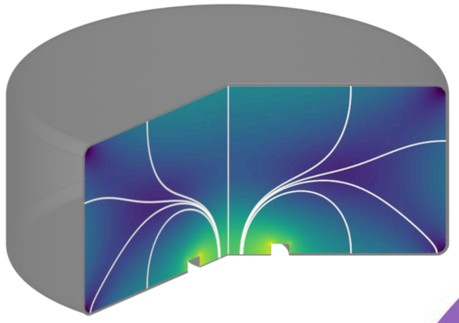


- 200 kg HPGe Detectors
- LAr instrumentation (two fiber shrouds)
- Infrastructure of GERDA
- $T > 10^{27}$ yr
- $< 2 \cdot 10^{-4}$ cts/(keV kg yr)

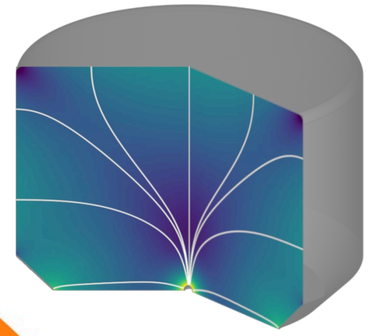


LEGEND-200: detectors

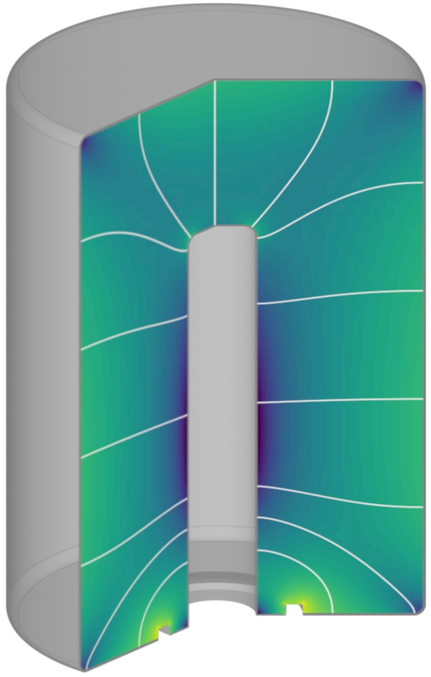
BEGe

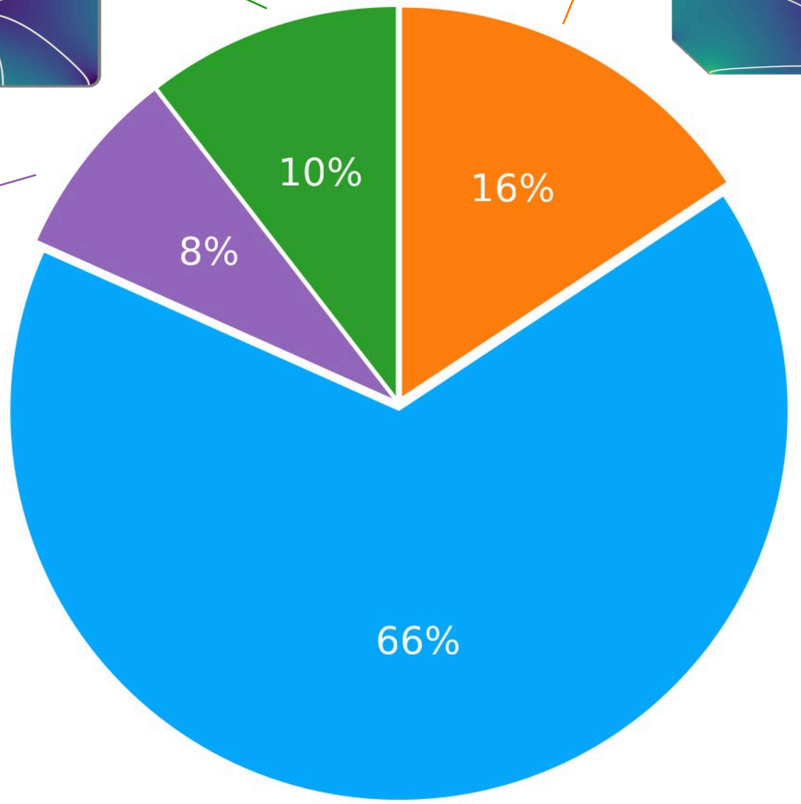


PPC

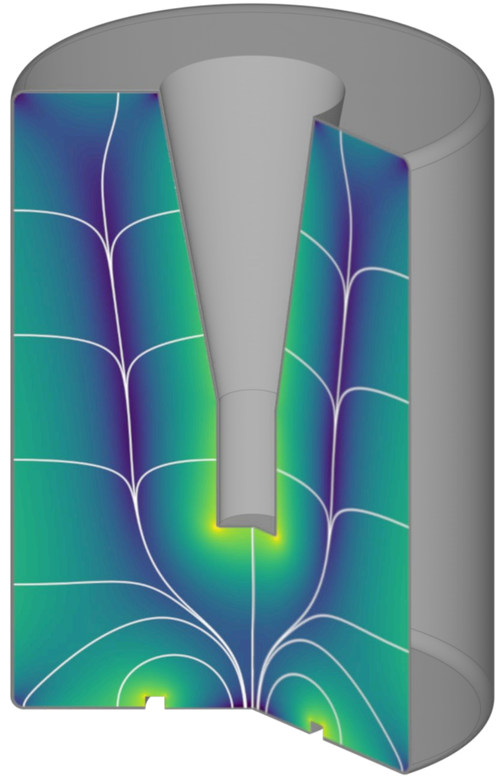


Coax

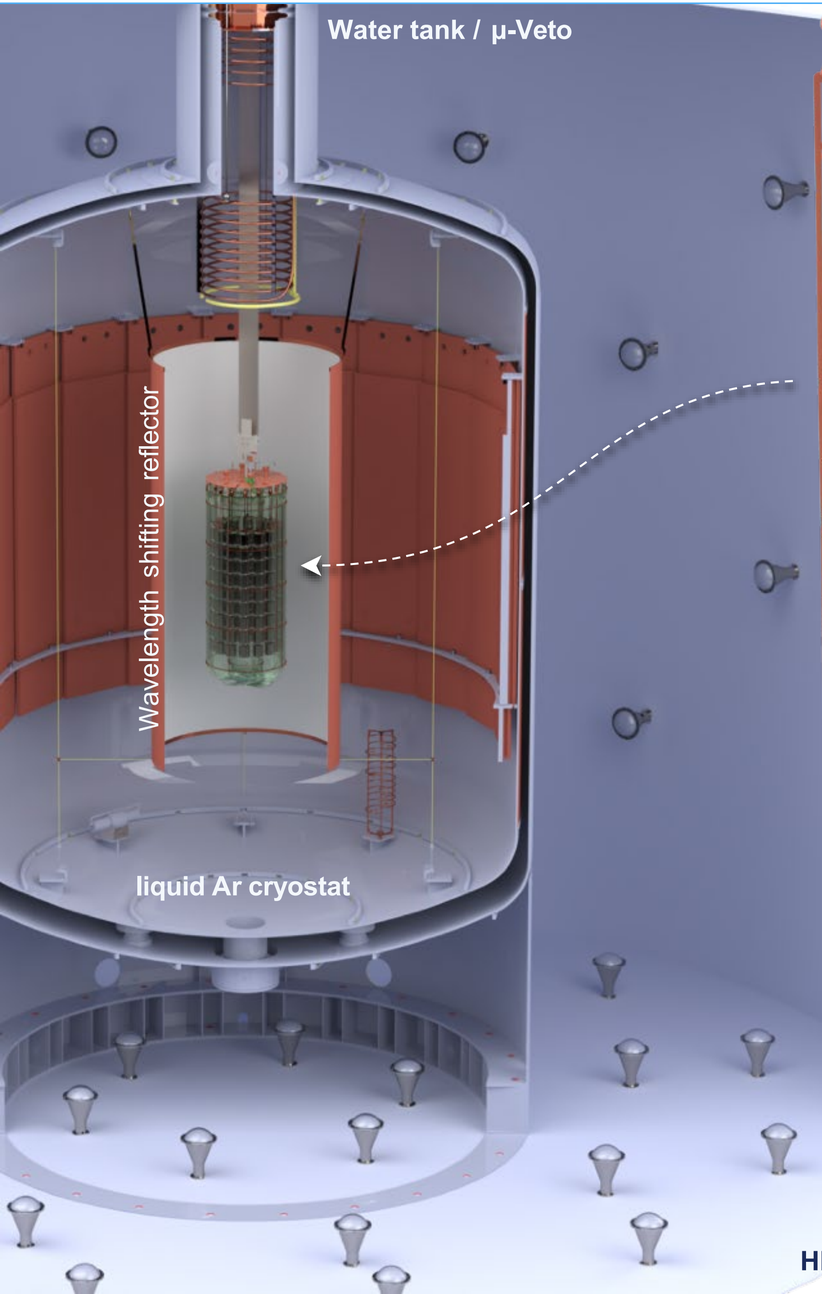


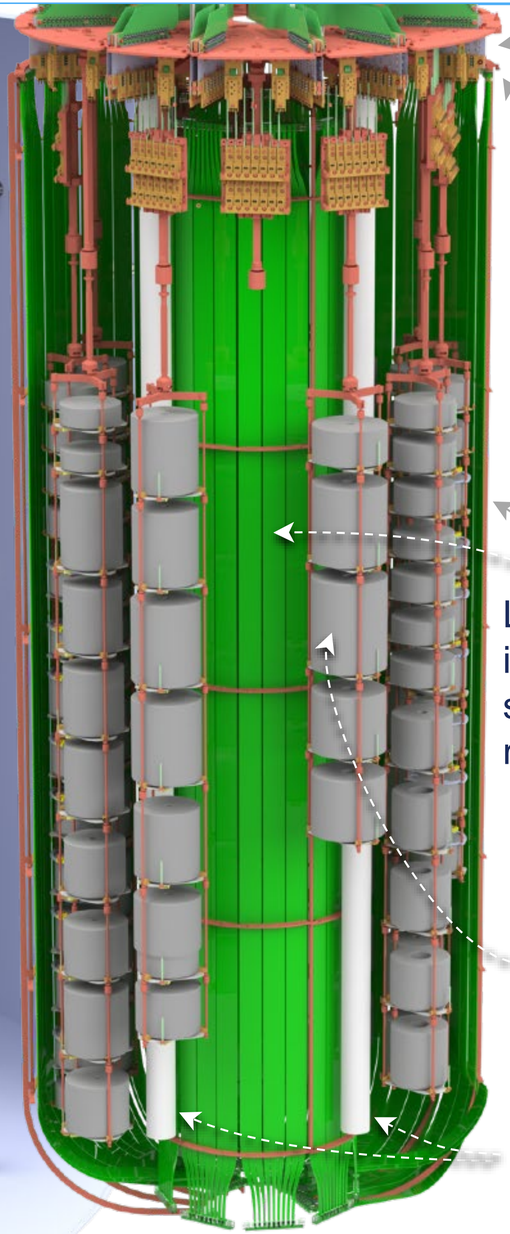


LEGEND IC



LEGEND-200: the best from GERDA and Majorana





HPGe Detector array & LAr Instrumentation

HPGe readout electronics
based on MJD Low Mass Front-End
and GERDA charge sensitive amplifier (CC4)

Detector mount: underground copper,
optically active PEN plates & radiopure plastics

Liquid Argon instrumentation:
inner & outer fiber barrels with
silicon photomultiplier (SiPM)
readout at top & bottom

Larger mass (inverted coaxial)
HPGe detectors with up to 4 kg

Source funnels for
^{228}Th calibration sources

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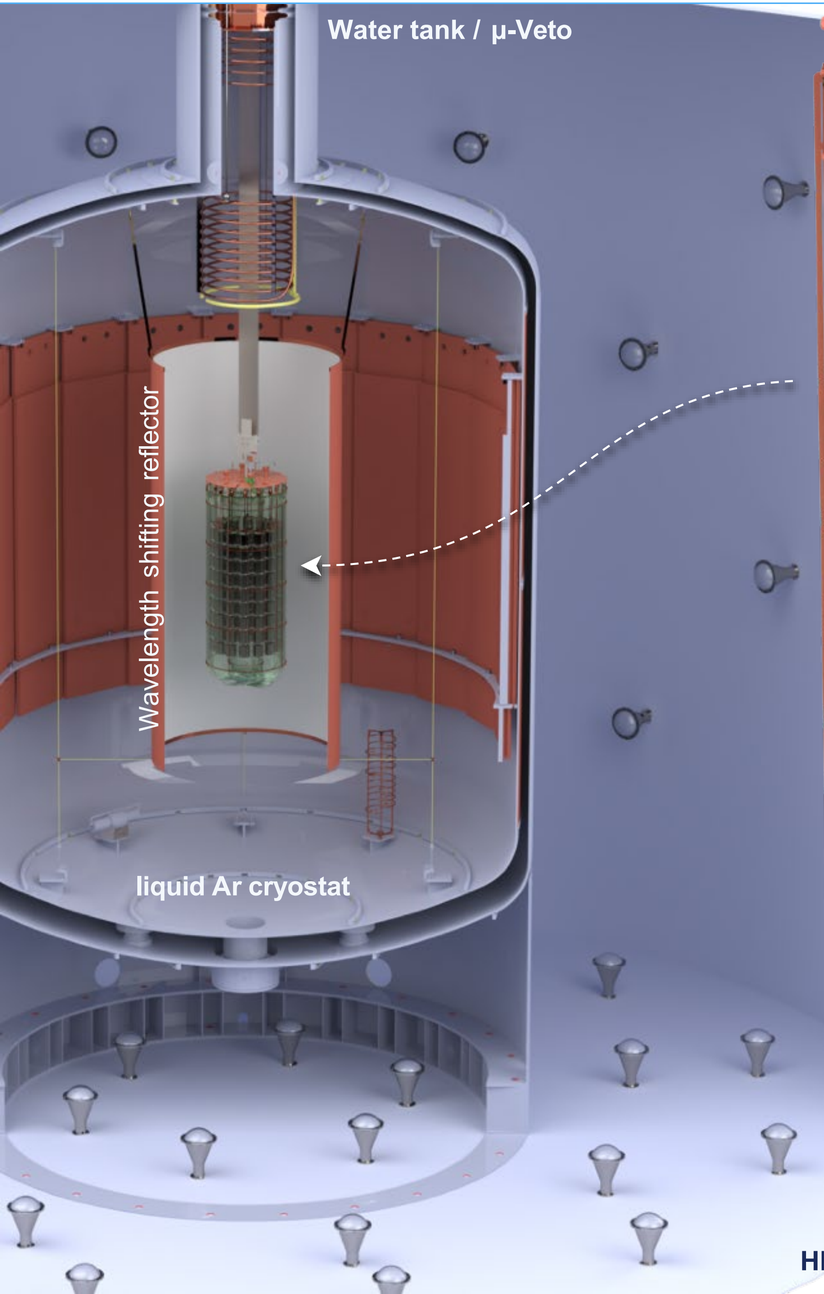

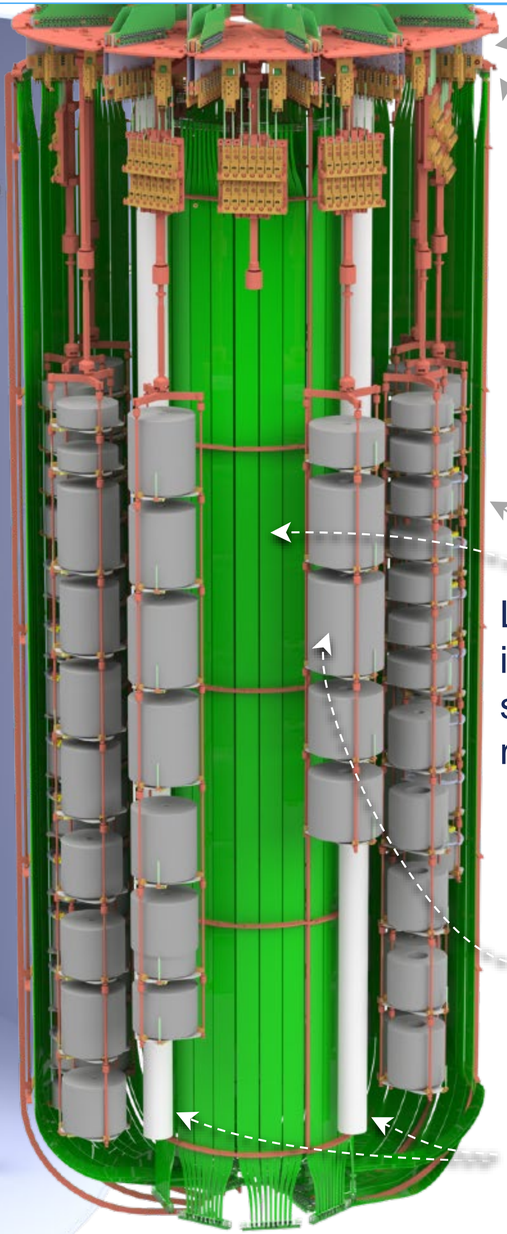

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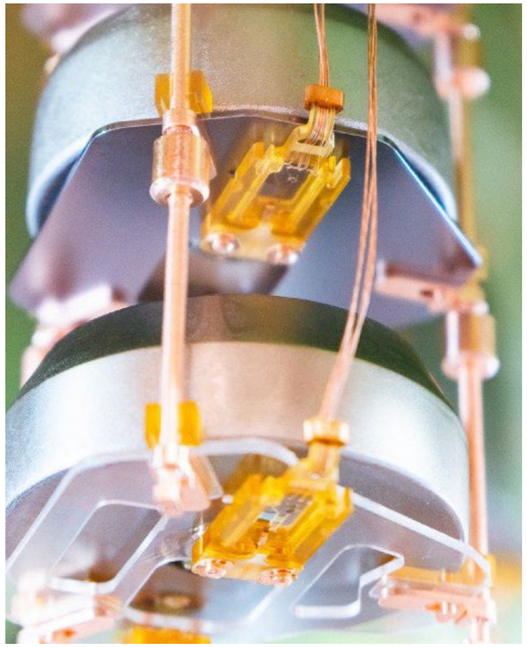
LEGEND-200: Integration and commissioning

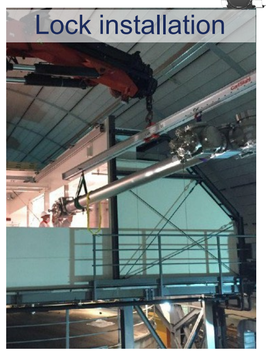
- water tank & cryostat from GERDA re-used

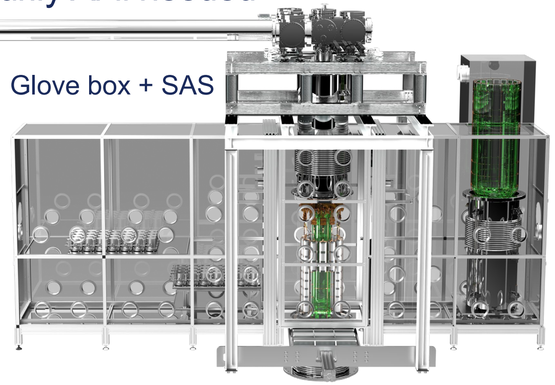


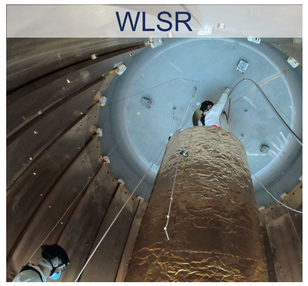
Post-GERDA Test:
First test of new technologies (HPGe electronics, PEN plates) & detectors in GERDA infrastructure

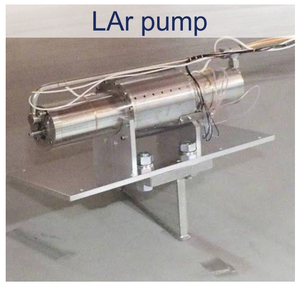
Cryostat infrastructure – completely new:

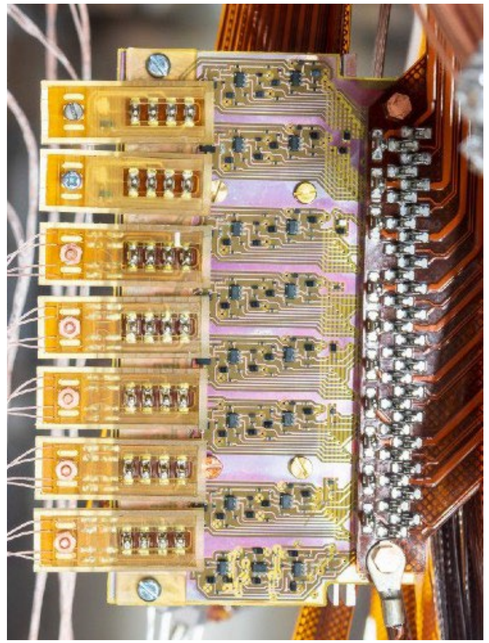
- Lock
- Mechanics
- Wiring
- Glovebox + string assembly system
- WLSR – to improve LAr veto efficiency
- LLAMA – to constantly check LAr quality
- LAr pump – to purify Ar if needed



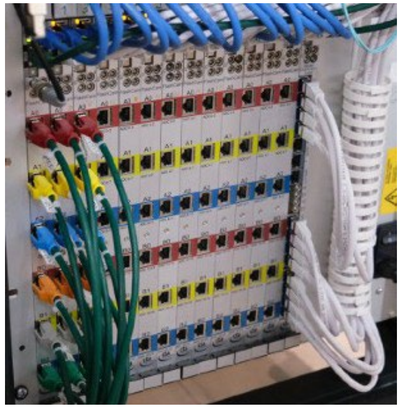








Electronics & DAQ tests:



Electronics & DAQ tests
Mechanics & glovebox installation

Post-GERDA Test

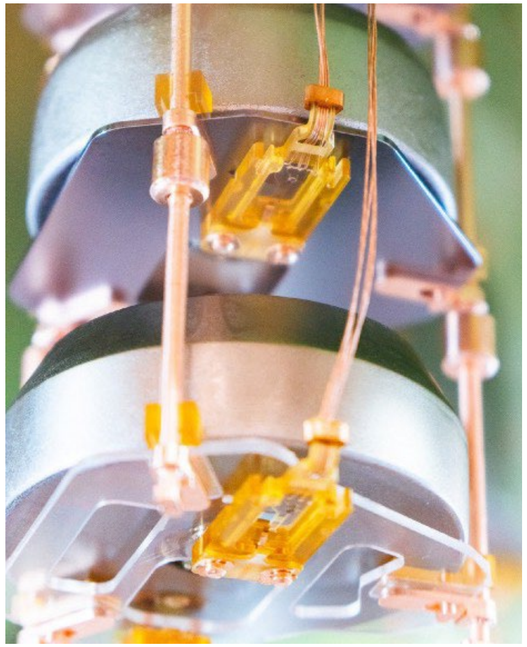
Upgrade of cryostat infrastructure

2020

2021

LEGEND-200: Integration and commissioning

- ✓ water tank & cryostat from GERDA re-used



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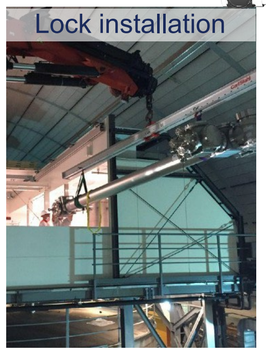
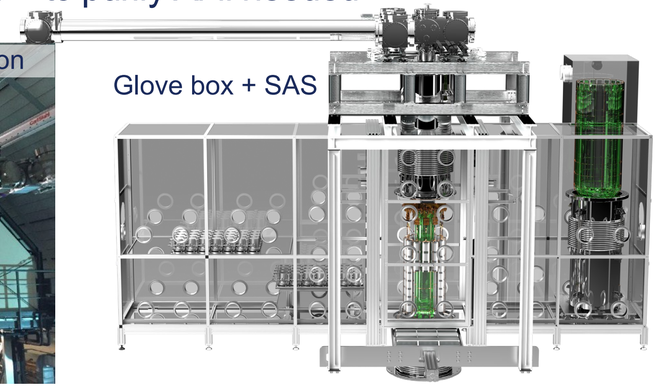
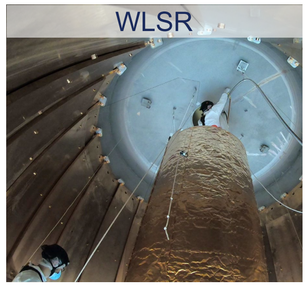
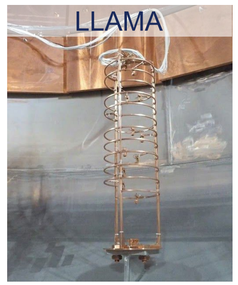
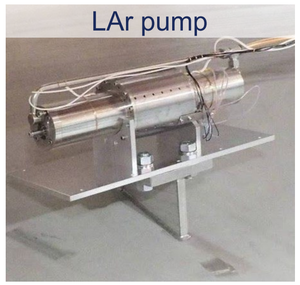
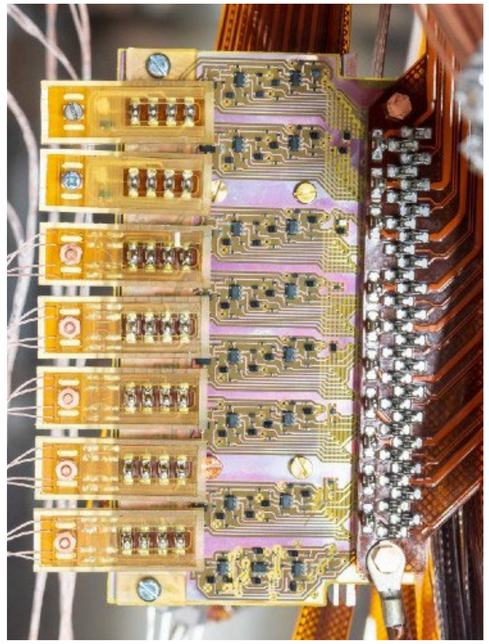




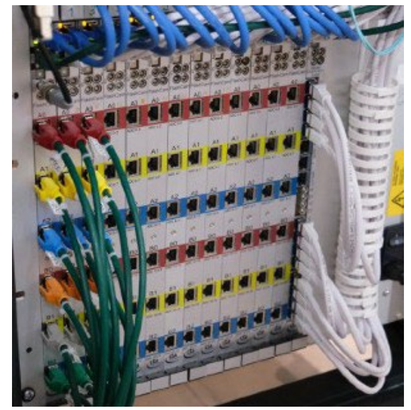








Electronics & DAQ tests:



Electronics & DAQ tests
Mechanics & glovebox installation

Post-GERDA Test

Upgrade of cryostat infrastructure

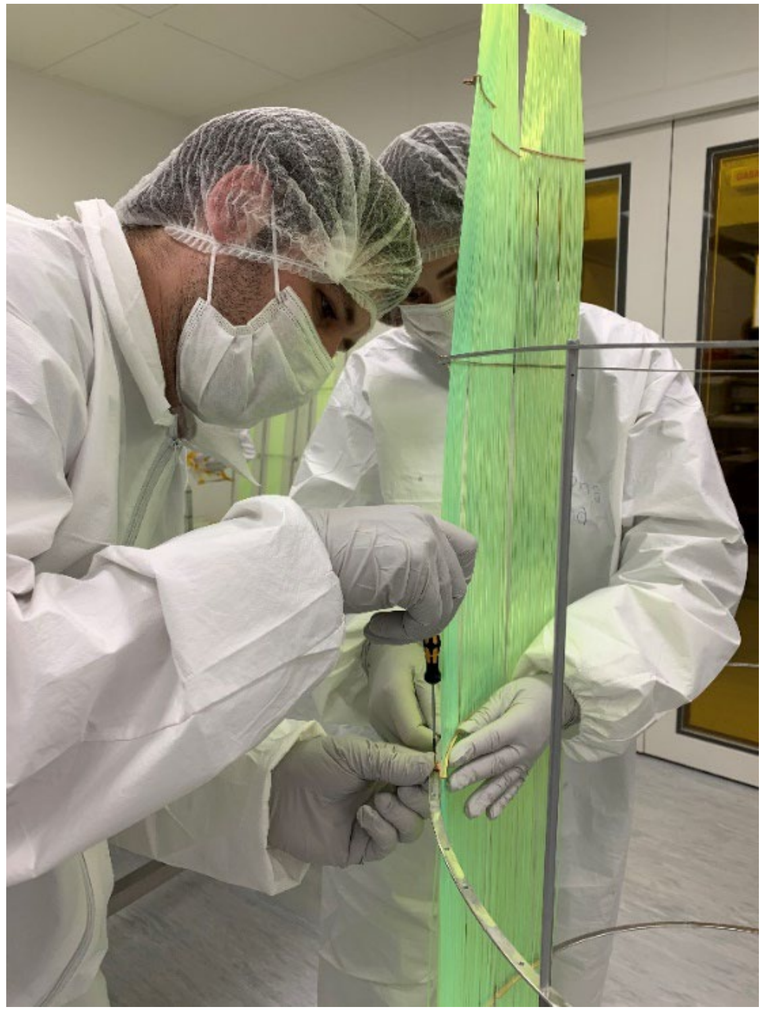
2020

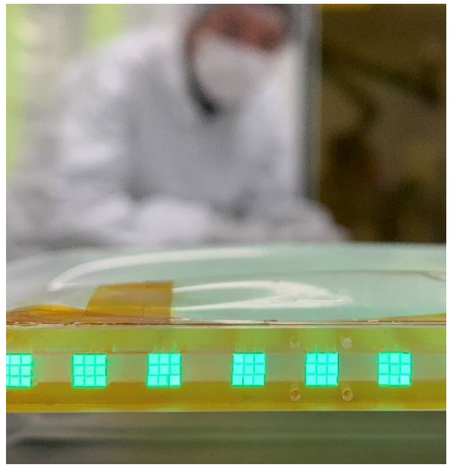
2021

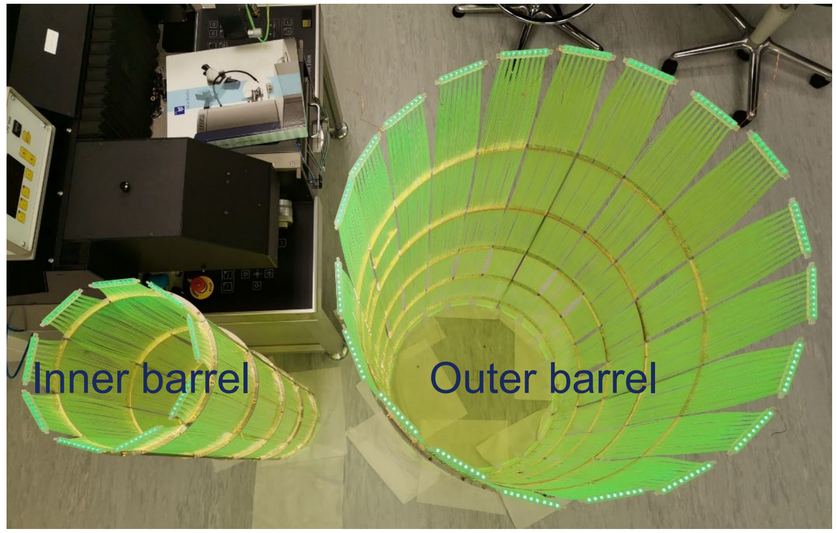
LEGEND-200: Integration and commissioning

LAr instrumentation production

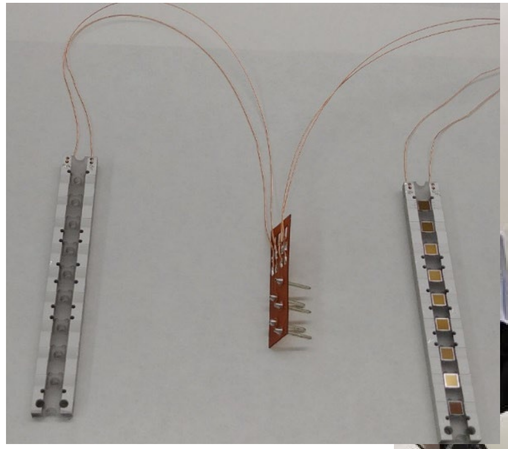
Production of LAr instrumentation modules







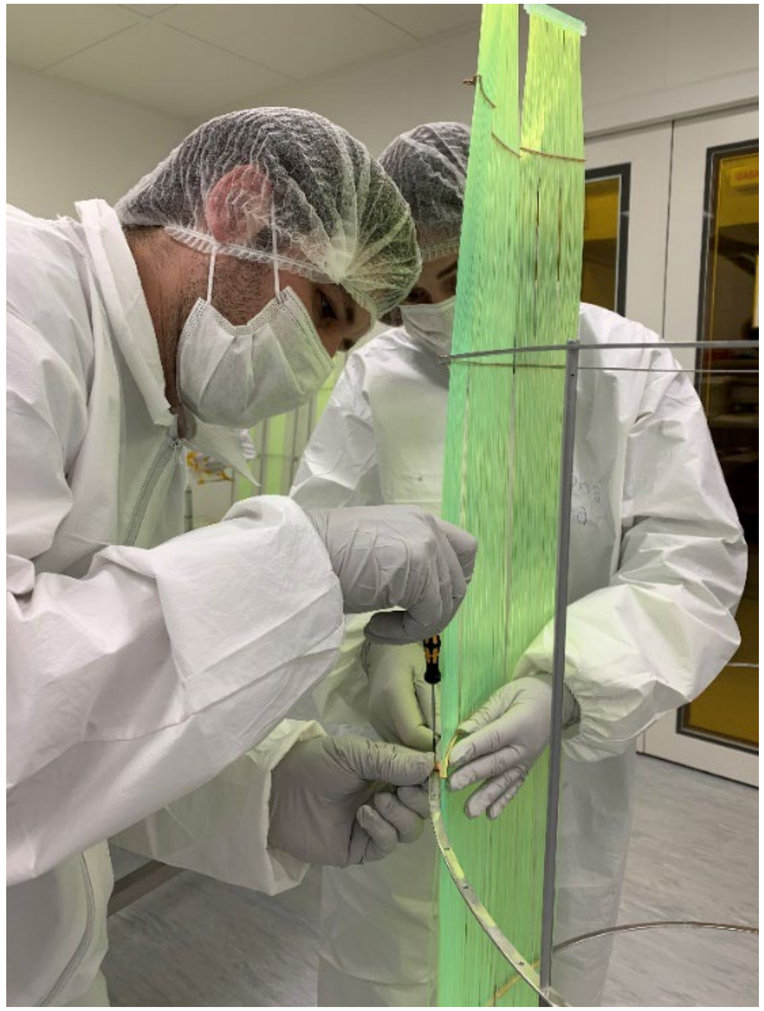
Bonding of SiPM arrays

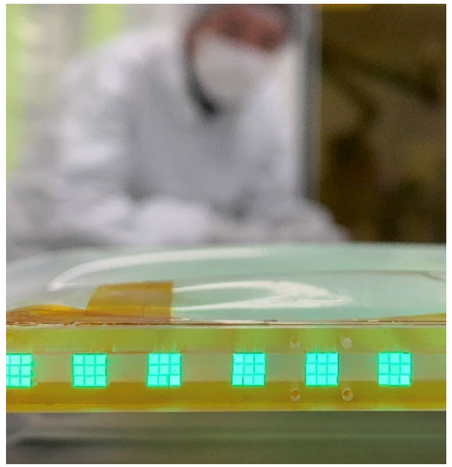


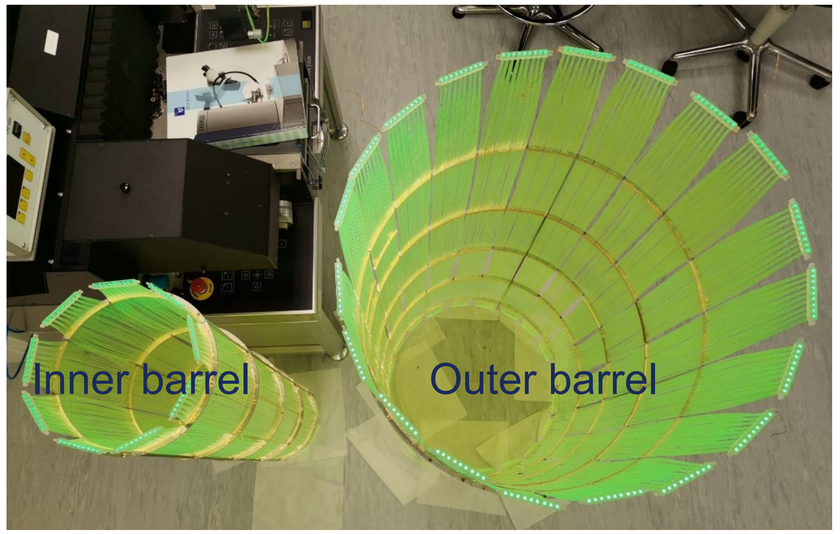
LEGEND-200: Integration and commissioning

LAr instrumentation production

Production of LAr instrumentation modules







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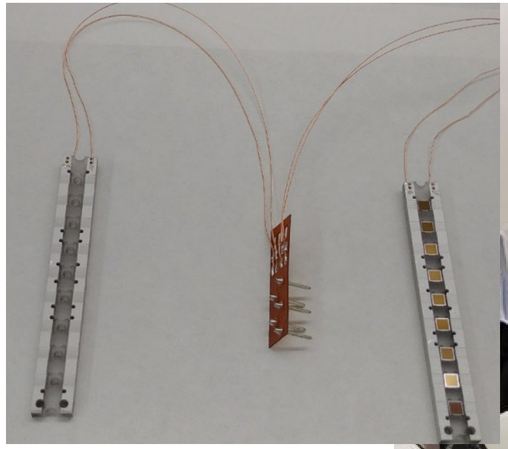
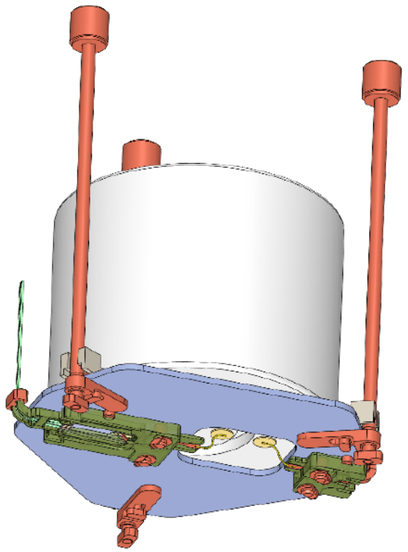
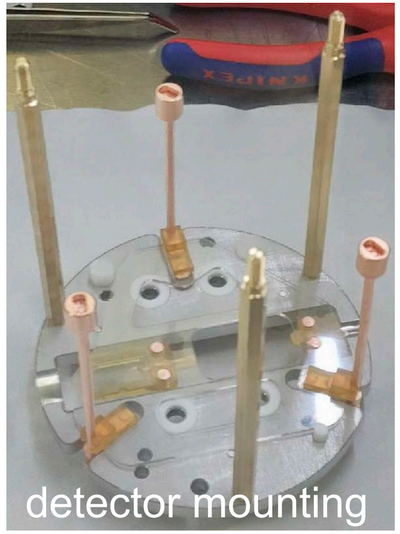


LEGEND-200: Integration and commissioning

HPGe detectors mounting and bonding and string assembly

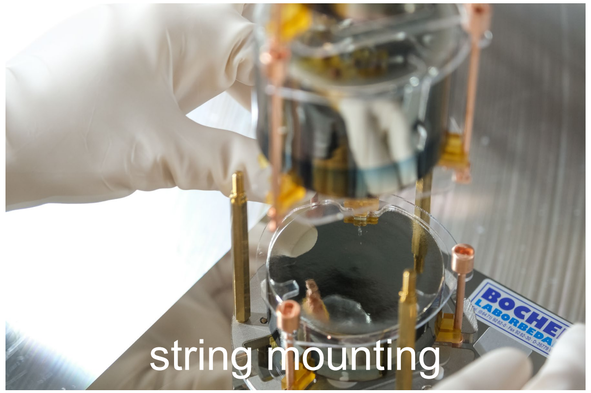


layout of bonded HV
and signal contacts

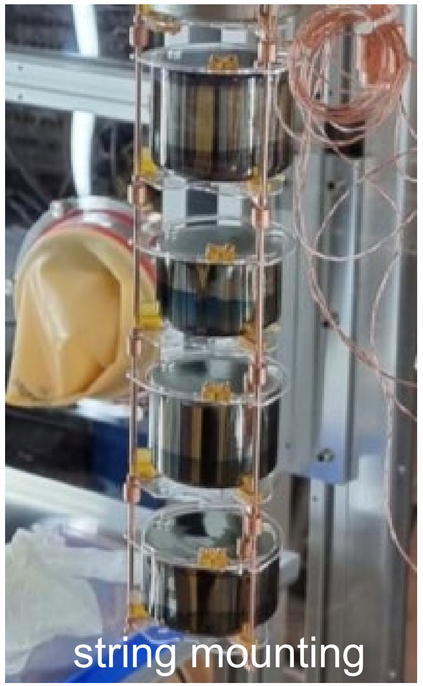


detector mounting

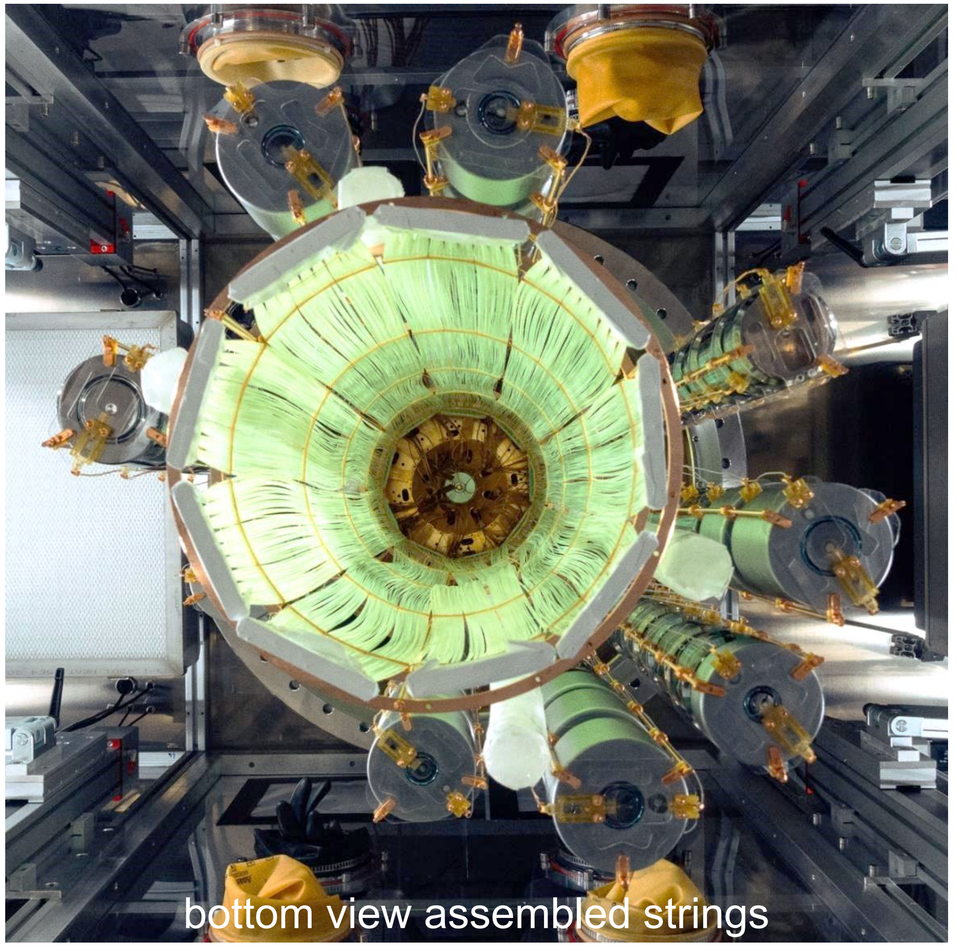
detector mounting



string mounting



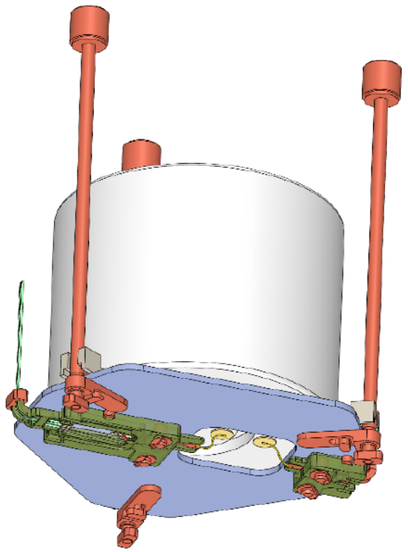
string mounting



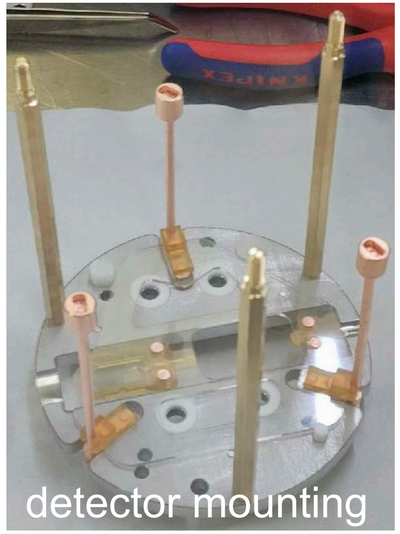
bottom view assembled strings

LEGEND-200: Integration and commissioning

HPGe detectors mounting and bonding and string assembly

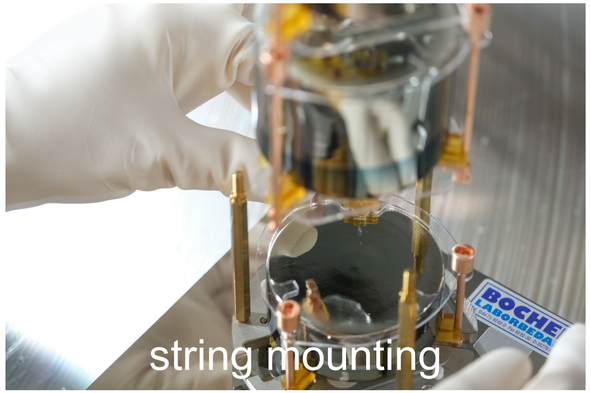


layout of bonded HV and signal contacts

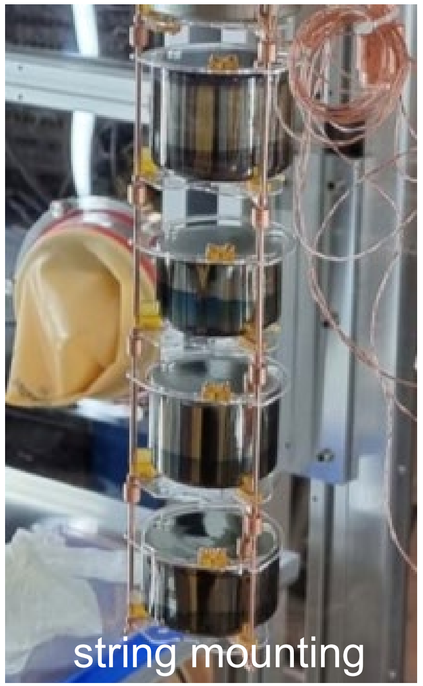


detector mounting

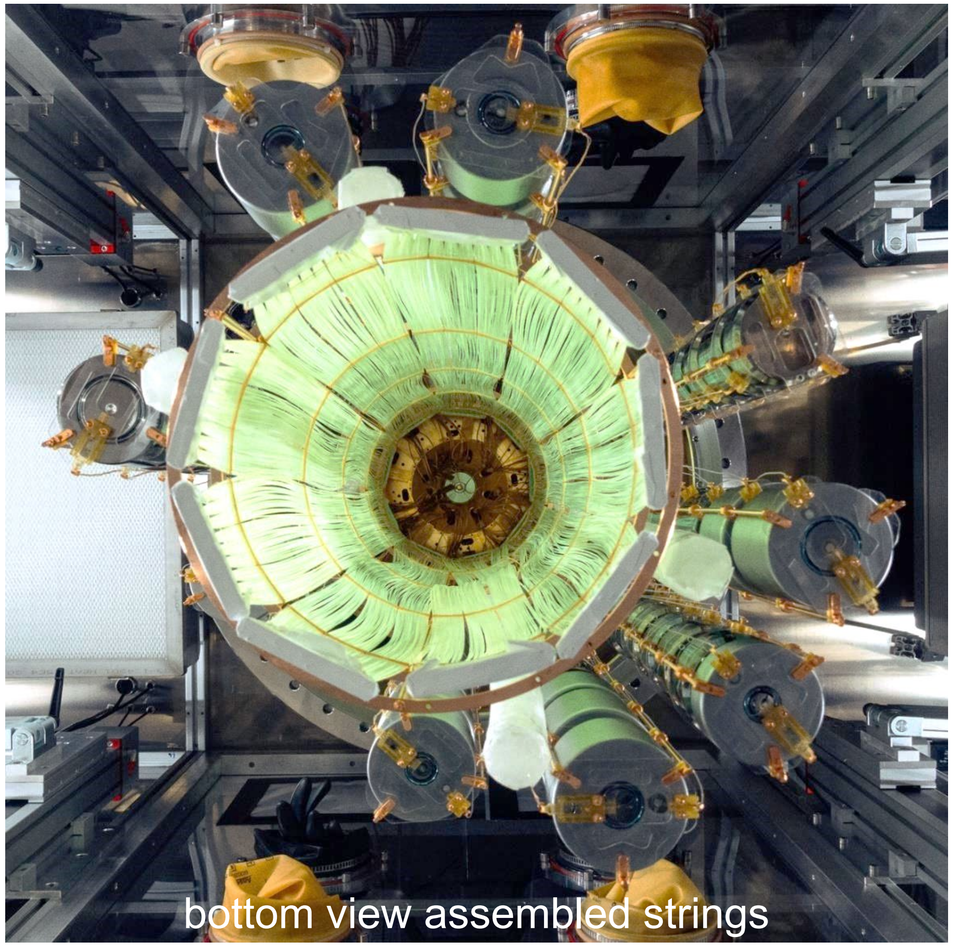
detector mounting



string mounting



string mounting



bottom view assembled strings

LEGEND-200: Integration and commissioning

HPGe detector strings assembly

Video

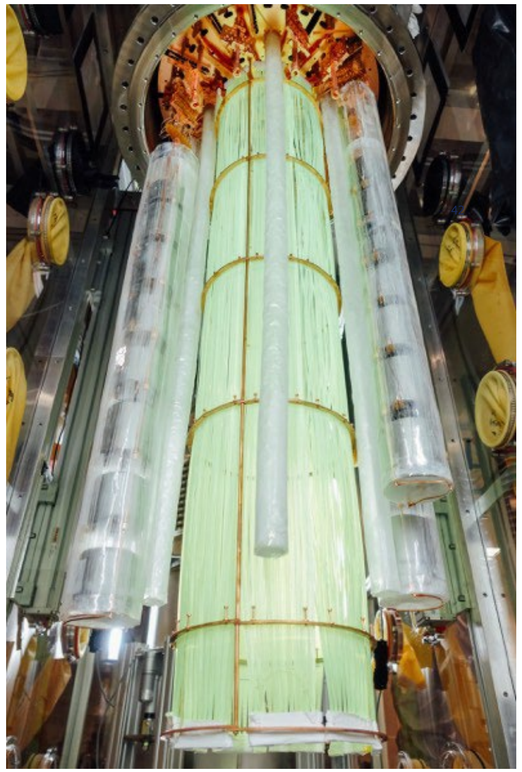
LEGEND-200: Integration and commissioning

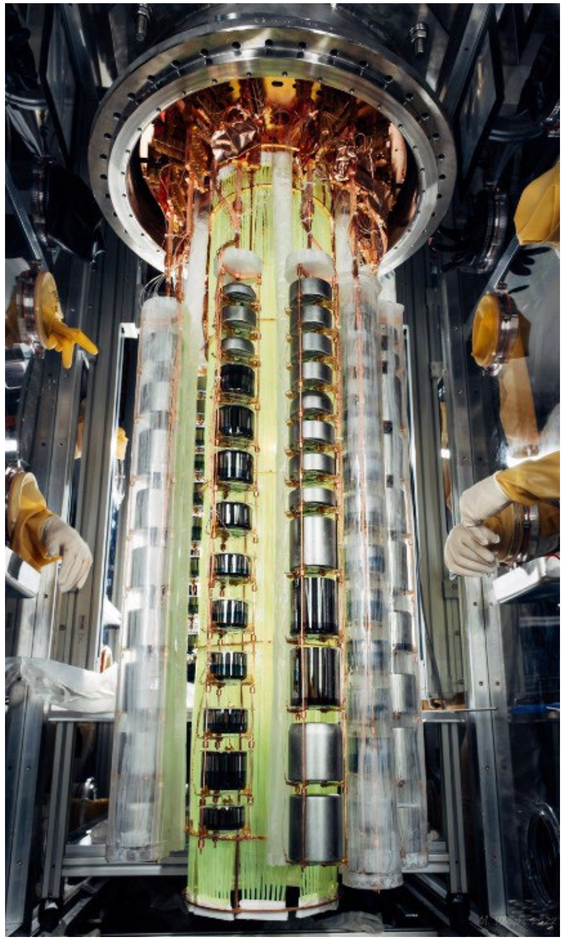

E. Sacchetti

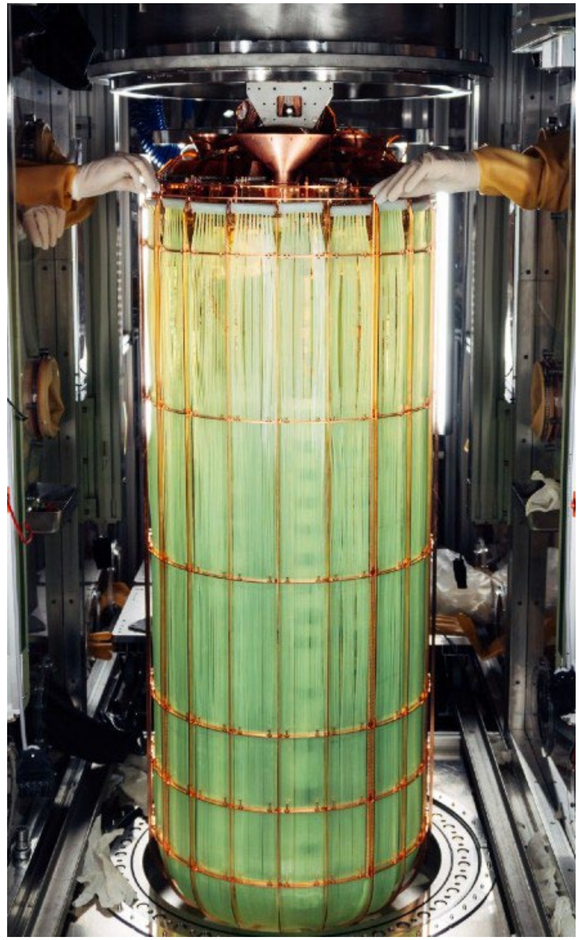
Photo: E. Sacchetti

LAr instrumentation:
Commissioning of LAr instr. hardware & readout electronics.

60 kg campaign:
First operation of 60 kg of HPGe detectors and full LAr instr.
Final hardware optimisations
Special calibration runs







142 kg installation:
Installation of all available HPGe detectors as well as full LAr installation, DAQ, readout electronics

Electronics & LAr instrumentation commissioning | 60 kg campaign + special calibration | 142 kg installation & commissioning | **Physics data taking**

2022 — 2023

LEGEND-200: Integration and commissioning


E. Sacchetti

Photo: E. Sacchetti

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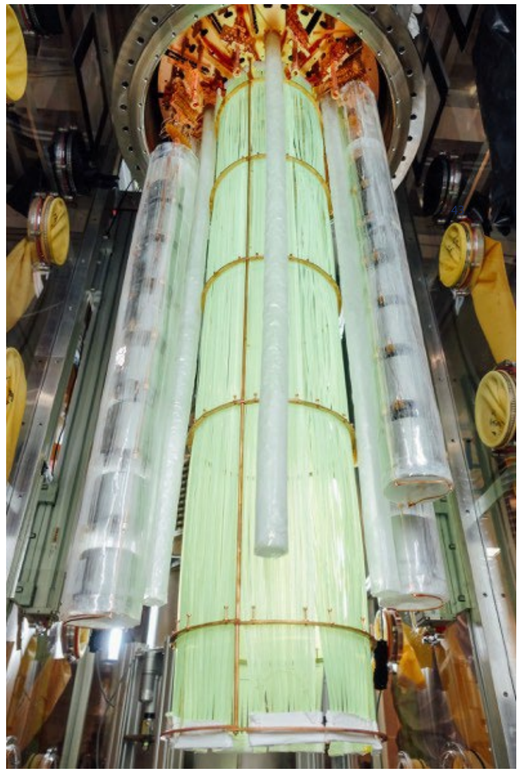

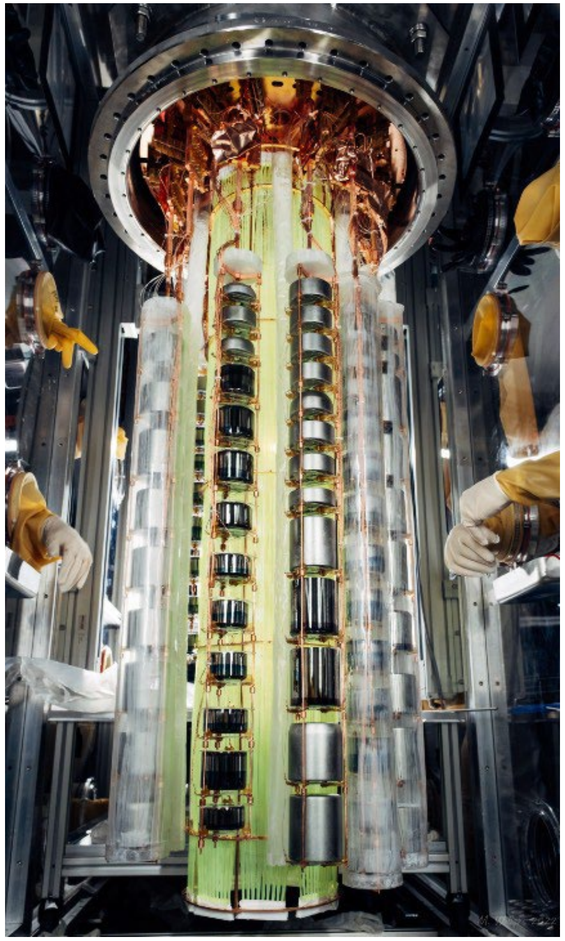

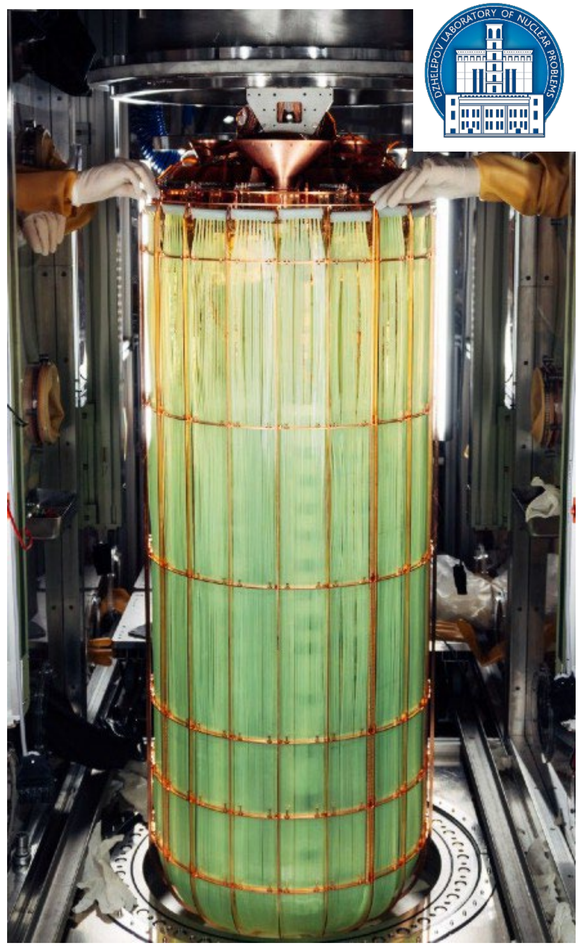

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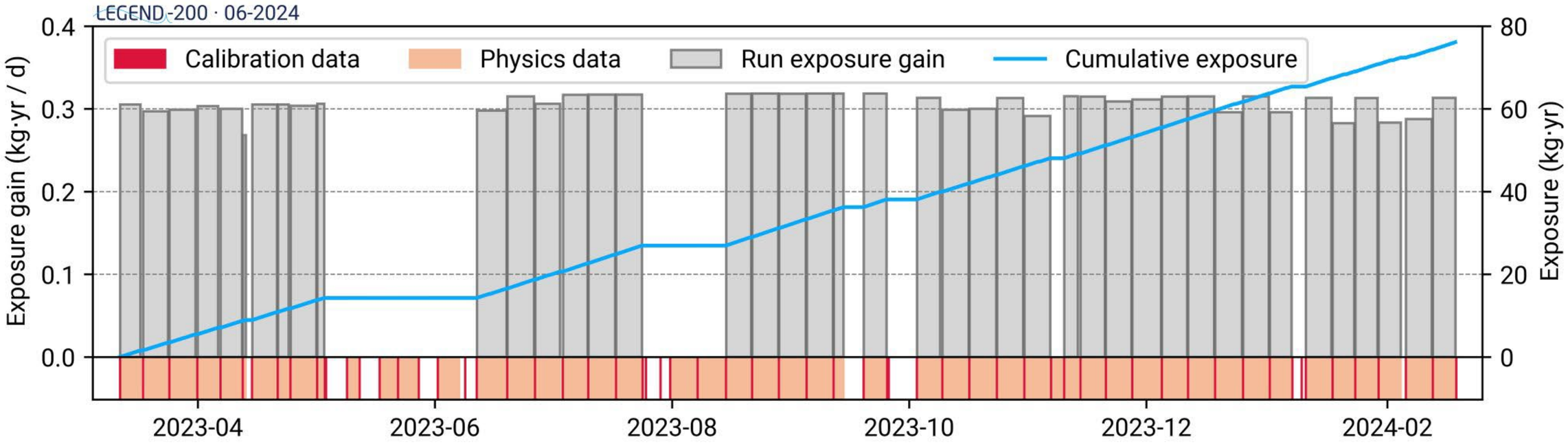
Electronics & LAr instrumentation commissioning — 60 kg campaign + special calibration — 142 kg installation & commissioning — **Physics data taking**

2022 — 2023

LEGEND-200: First Physics Data

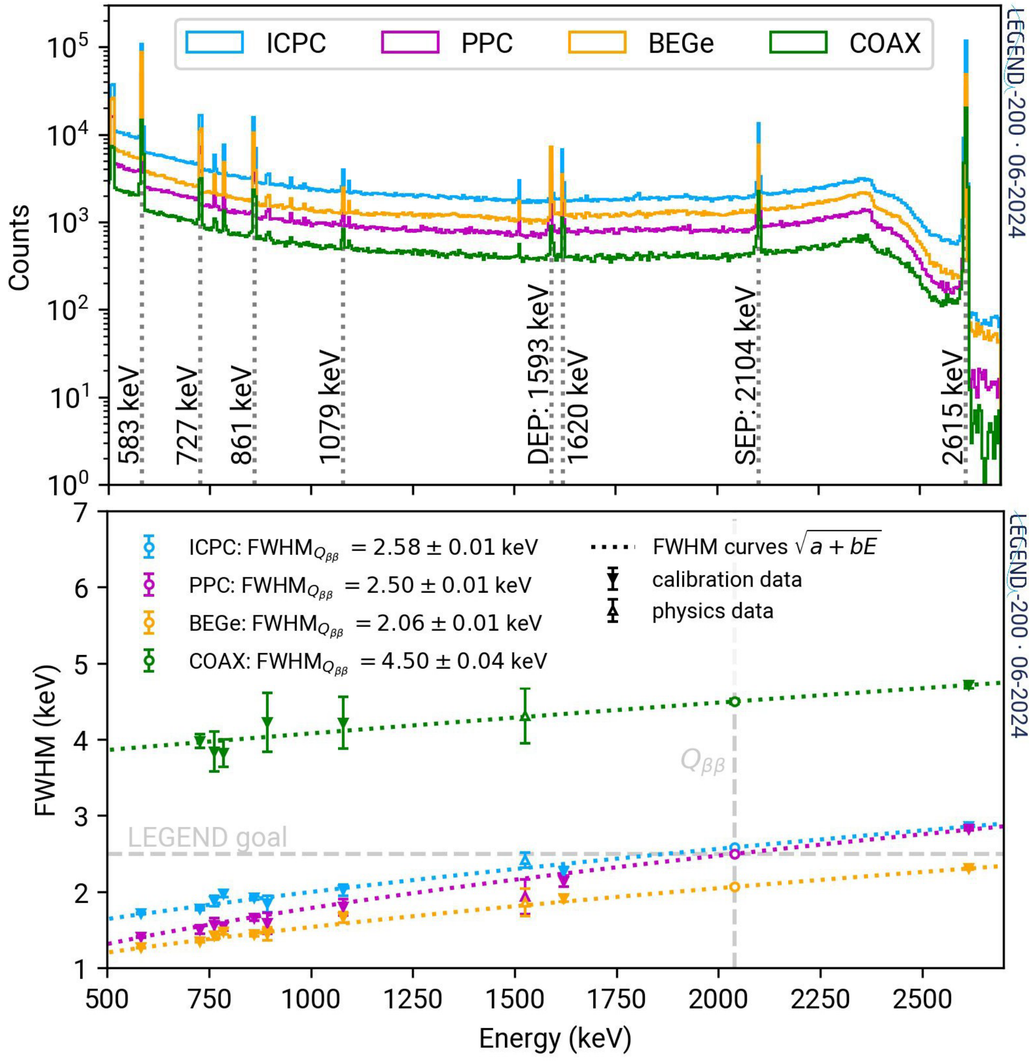
About 1 yr of physics data exposure captured:

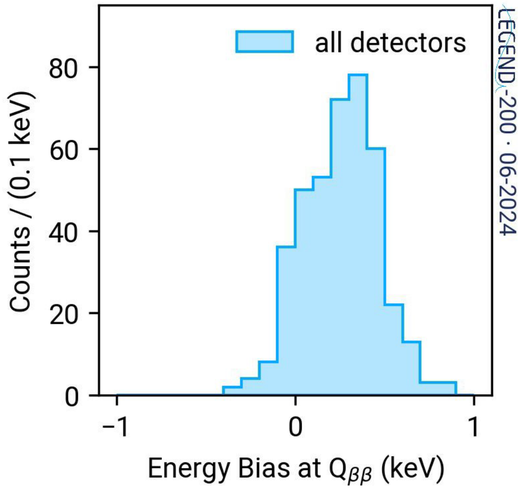


- Total physics data: 76.2 kg yr
- $0\nu\beta\beta$ data set: 48.3 kg yr

only data with fully vetted Pulse Shape Discrimination (PSD) parameters, i.e. w/o Coax detectors

LEGEND-200: Energy Scale and Resolution





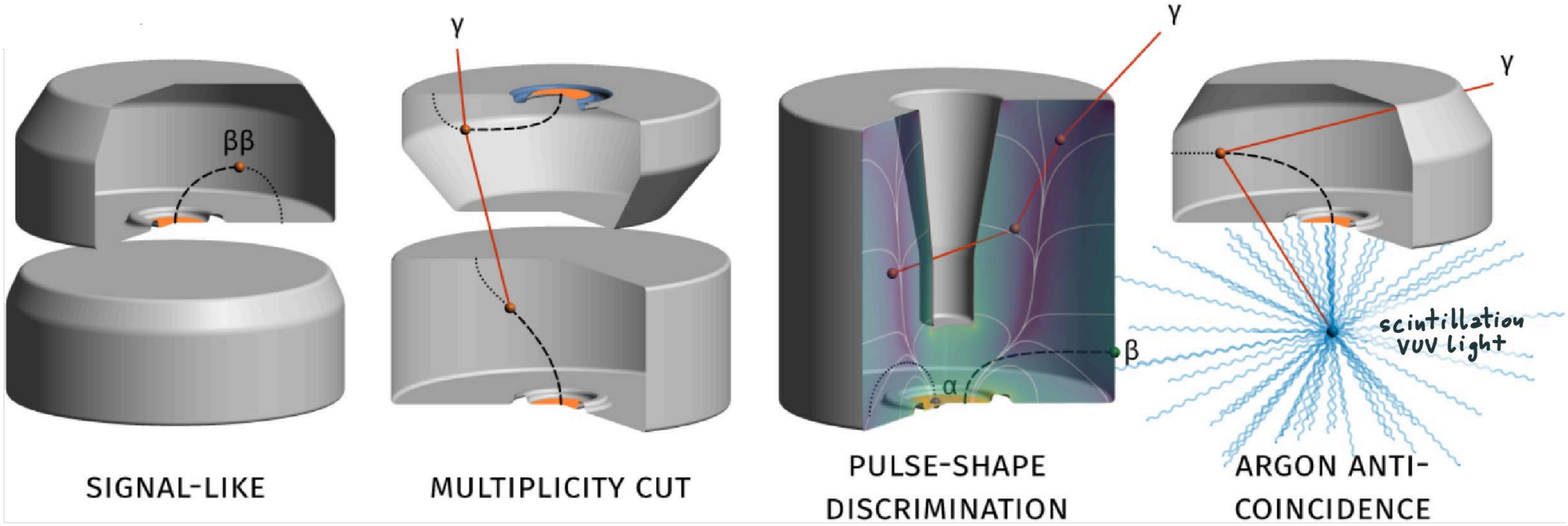
Stable energy observables

- weekly ^{228}Th calibrations

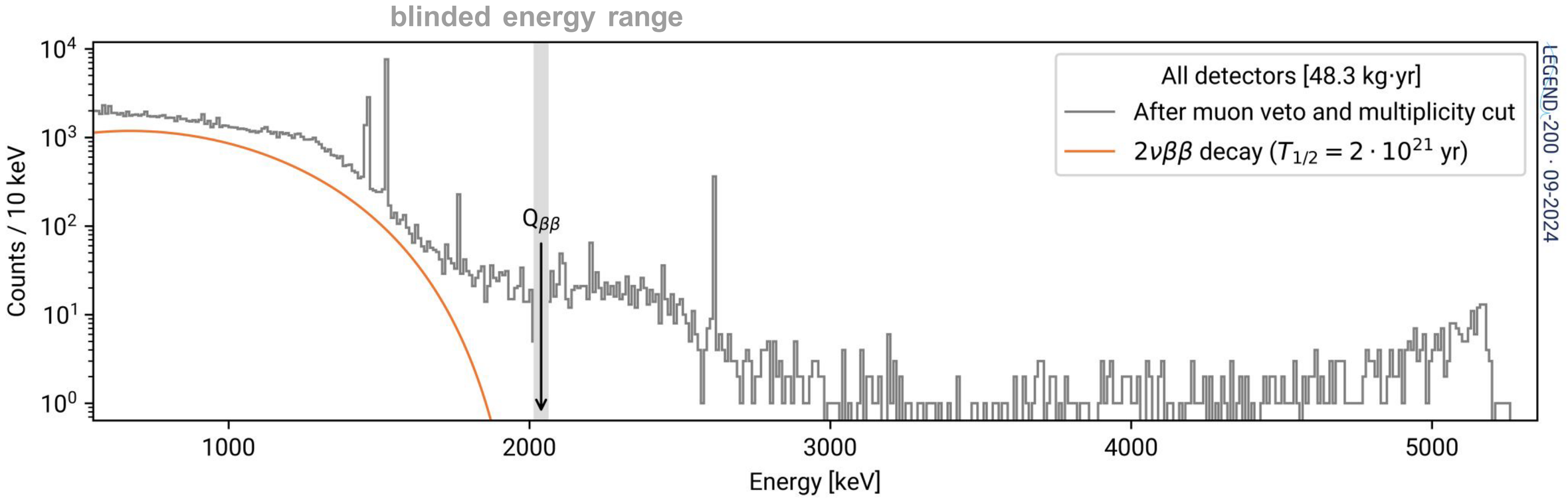
~0.1% FWHM at $Q_{\beta\beta}$

- including large inverted-coaxial detectors

LEGEND-200: Signal and background discrimination



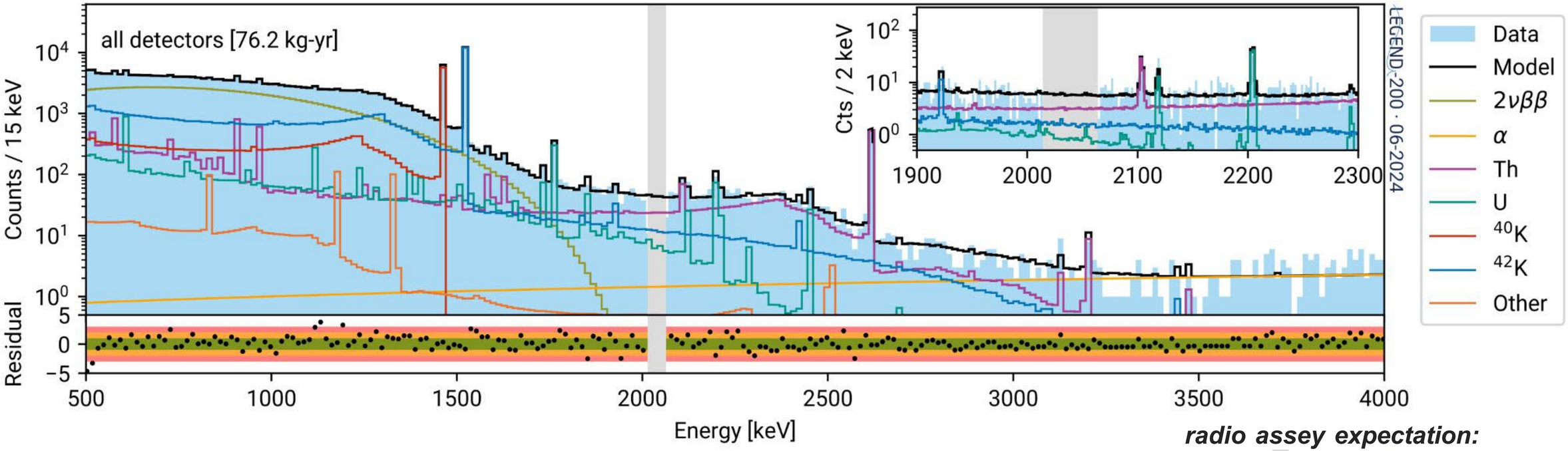
LEGEND-200: Quality, Muon Veto and Multiplicity



- **Blinding** applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- 26% of events rejected by multiplicity cut near $Q_{\beta\beta}$

LEGEND-200: Modeling before Analysis Cuts

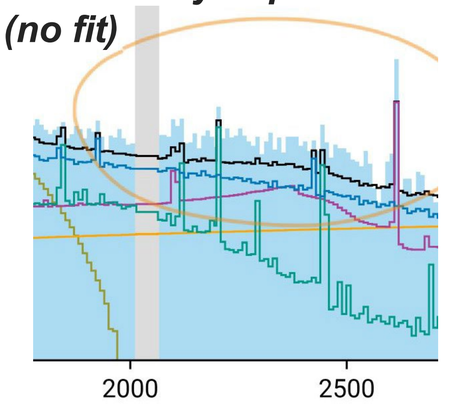
fit:



Bayesian background model using data before analysis cuts

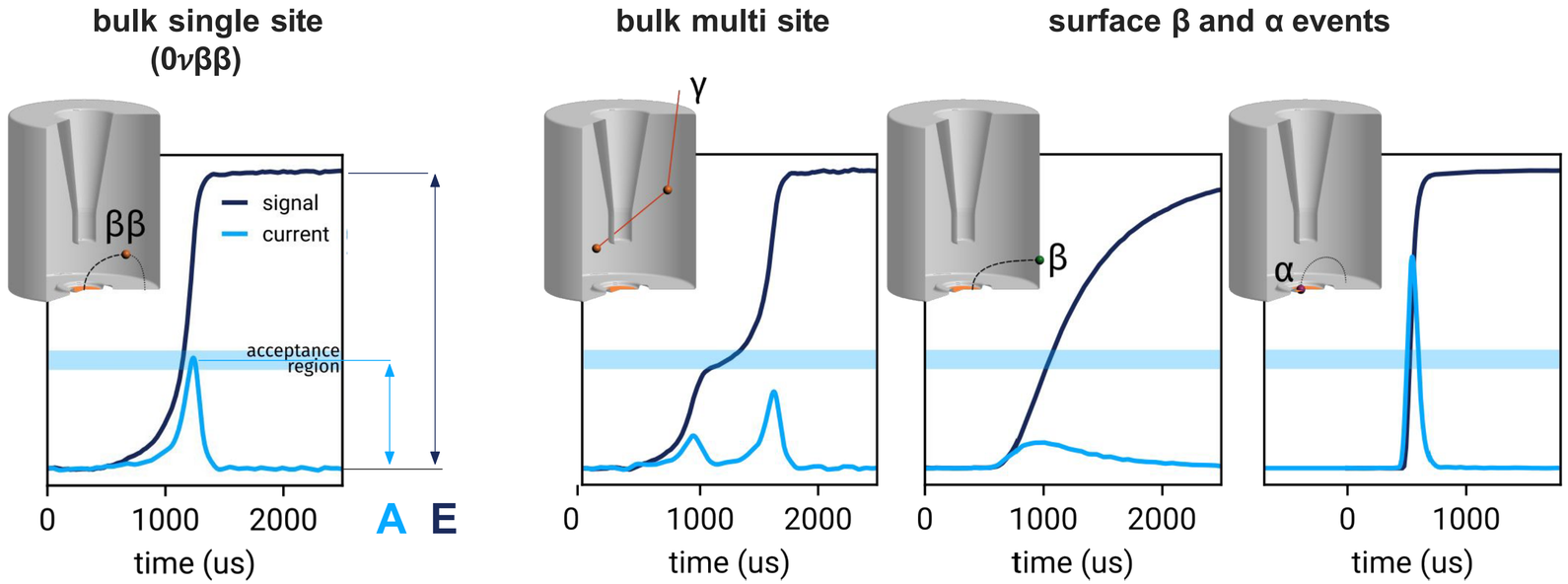
- fit reproduced data well
- estimates 2-3x higher ^{208}Tl / ^{214}Bi compared to radio assey expectation
- comprehensive screening campaign currently ongoing

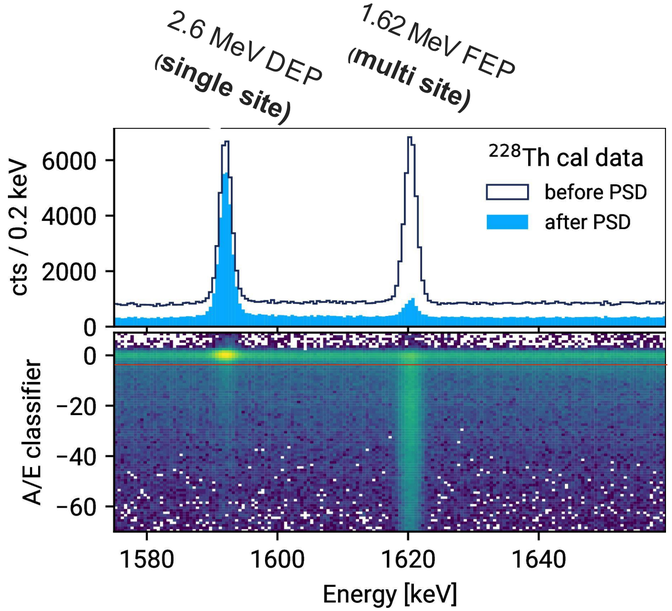
radio assey expectation:
(no fit)



LEGEND-200: HPGe Pulse Shape Discrimination

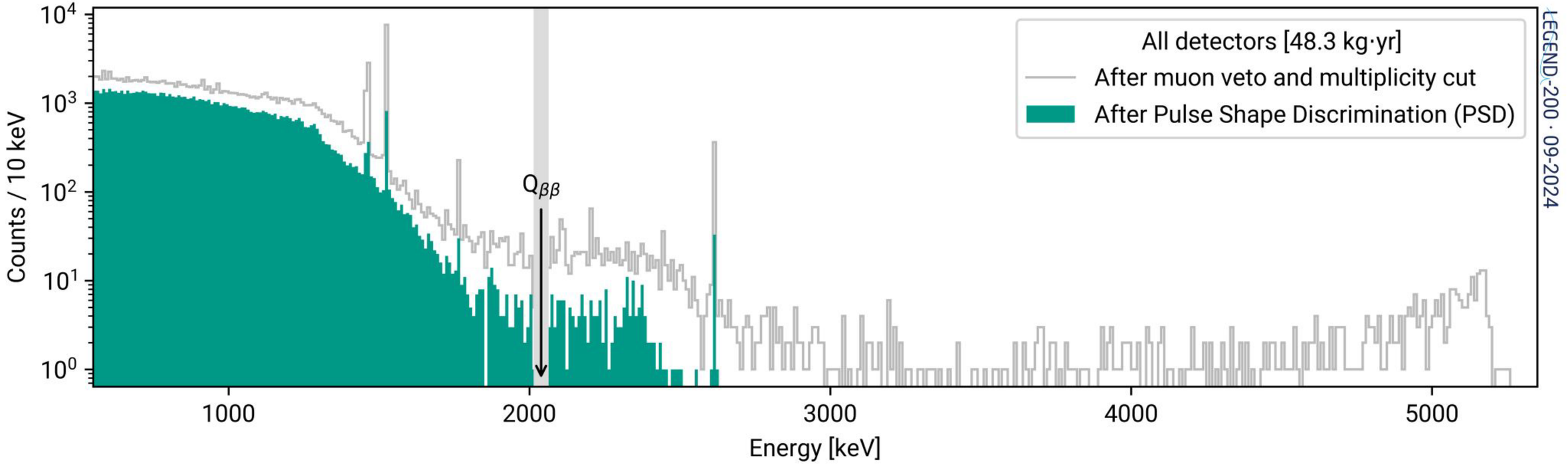
- **Pulse shape classifier: A/E = max(current) / energy**





- PSD methods for Coaxial detectors under development
- 0νββ survival fraction of ~(85±4)%

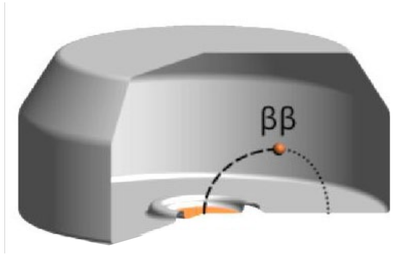
LEGEND-200: After PSD



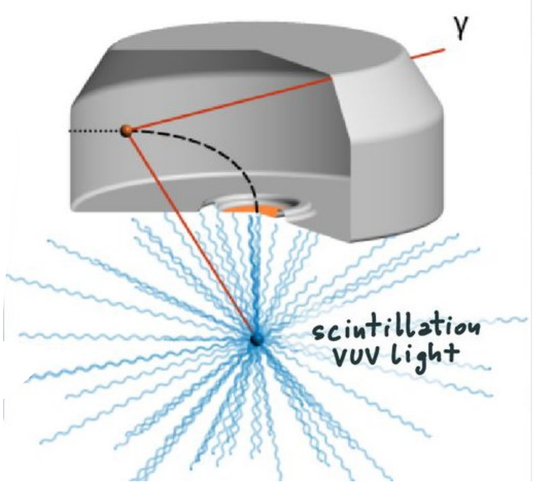
- Strong suppression of surface α and β (^{42}K) events
- ~40% of Compton are single-site events at $Q_{\beta\beta}$

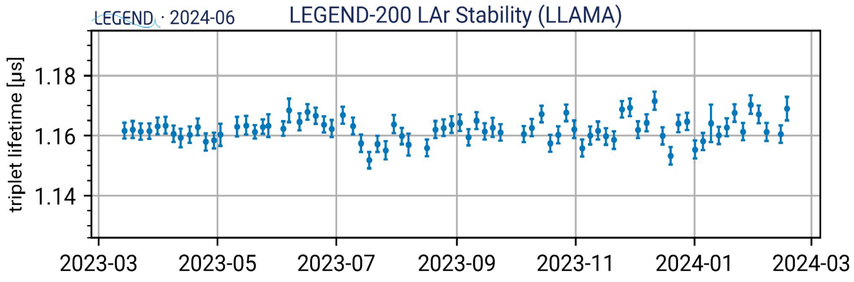
LEGEND-200: Argon anti-coincidence

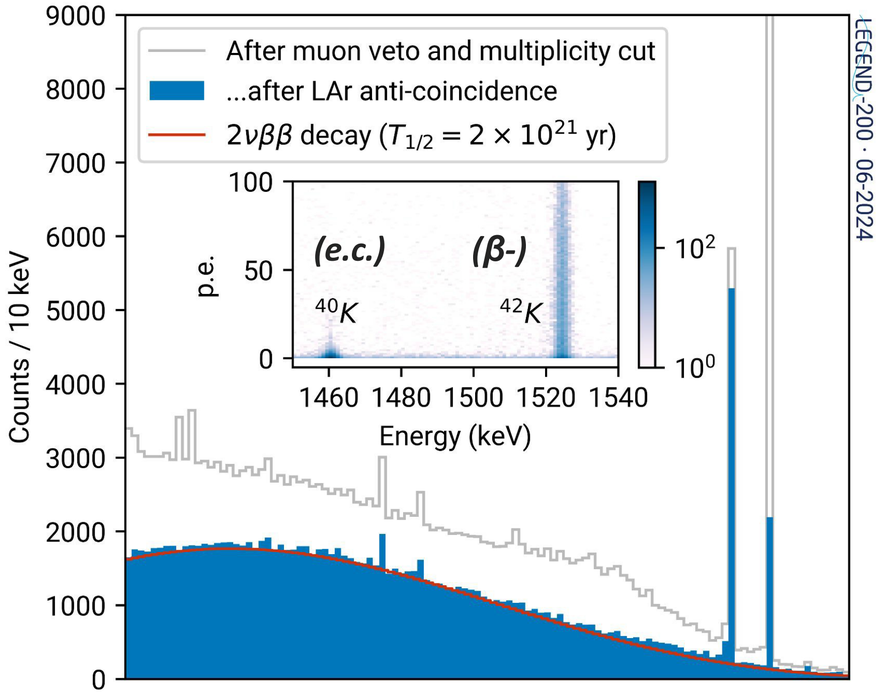
Signal
w/o scintillation light



Background
w/ scintillation light

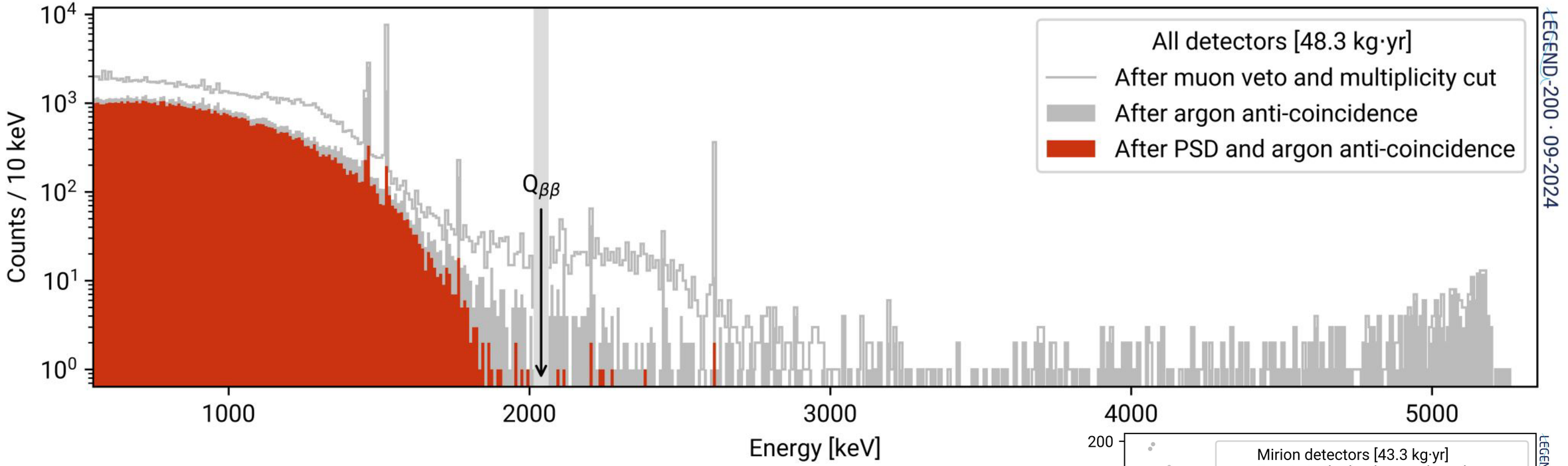




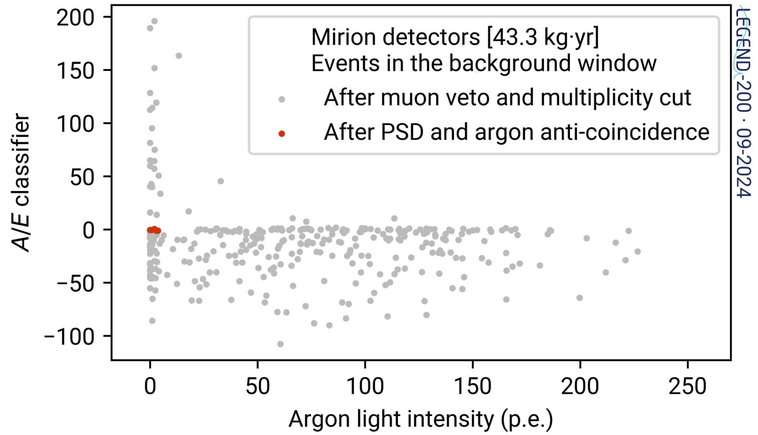


- Strong suppression of background above 2νββ
- ββ decay signal acceptance of ~93%

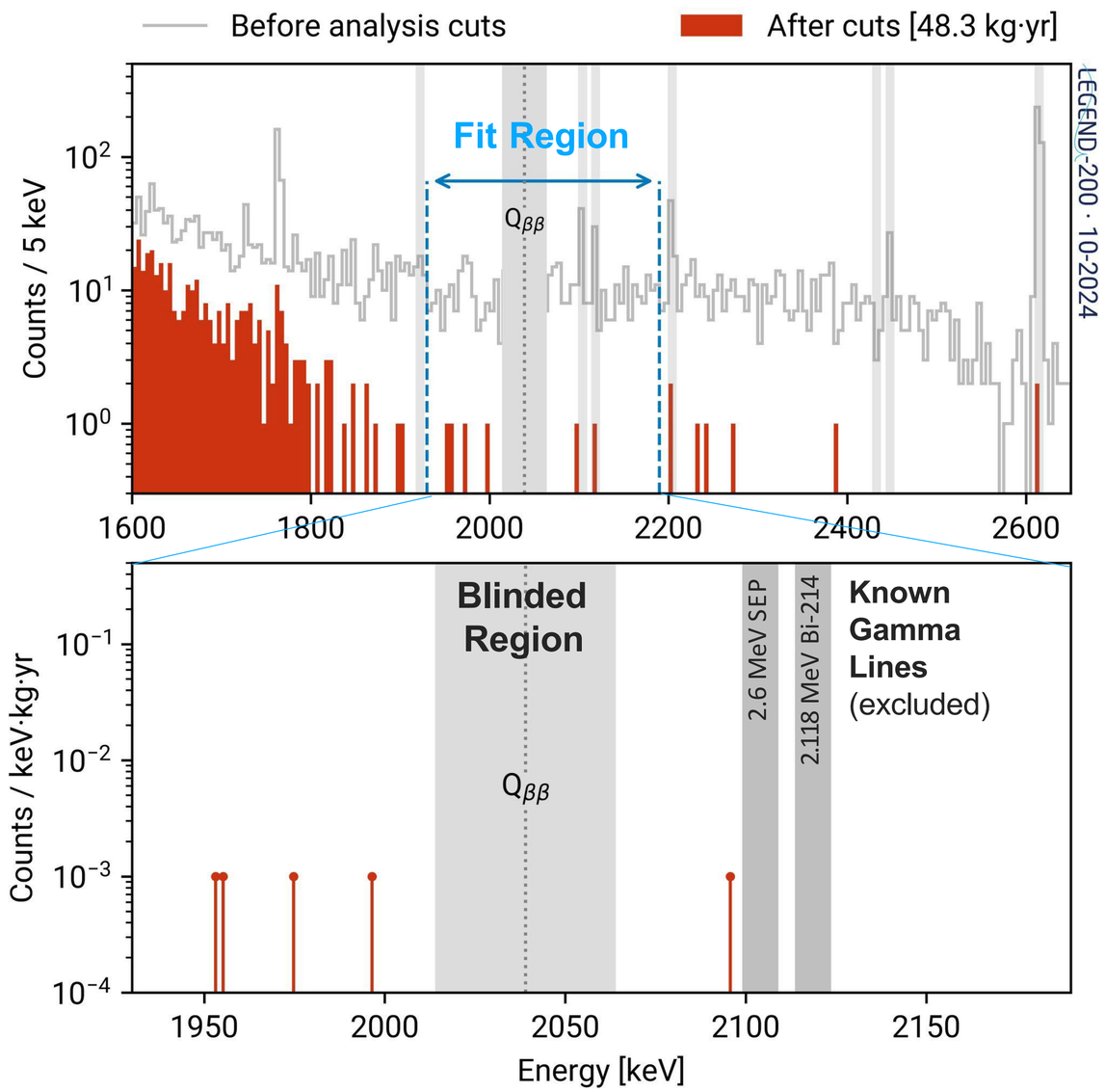
LEGEND-200: After PSD and LAr anti-coincidence



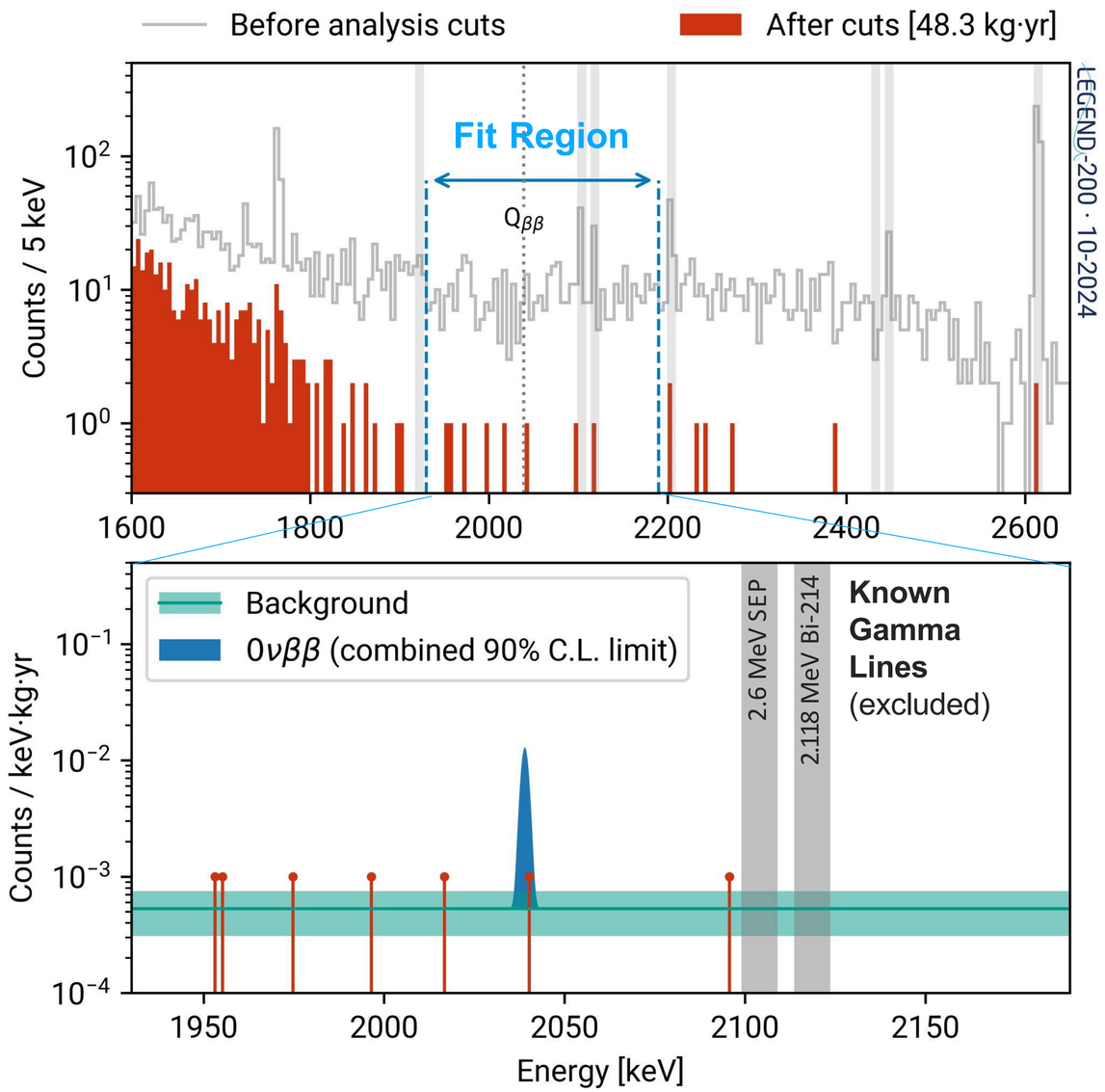
- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%



LEGEND-200: Data in the ROI



LEGEND-200: Data in the ROI – after Unblinding



7 events surviving. Background index:

$$BI = (5.3 \pm 2.2) \times 10^{-4} \text{ cts / (keV kg yr)}$$

GERDA, MAJORANA and LEGEND combined fit:

- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

Sensitivity	Observed
2.8×10^{26} yr	$> 1.9 \times 10^{26}$ yr

LEGEND-200 contribution

- event at 1.4σ from $Q_{\beta\beta}$ weakens combined limit

LEGEND-200: Status and Plans

- Currently in “background characterization” phase
  - measurements with special setup configurations to test background hypotheses completed
  - radioassay campaign to re-measure the radiopurity is ongoing

- New deployment soon
  - repair of HPGe and SiPM channels completed
  - preparing to install additional ~35 kg of HPGe detectors (in 2 steps)

- Restart data taking in February 2025

LEGEND-200 is a versatile, “quick turnaround” experimental instrument. Enabling prompt investigation of issues and a swift return to data taking.

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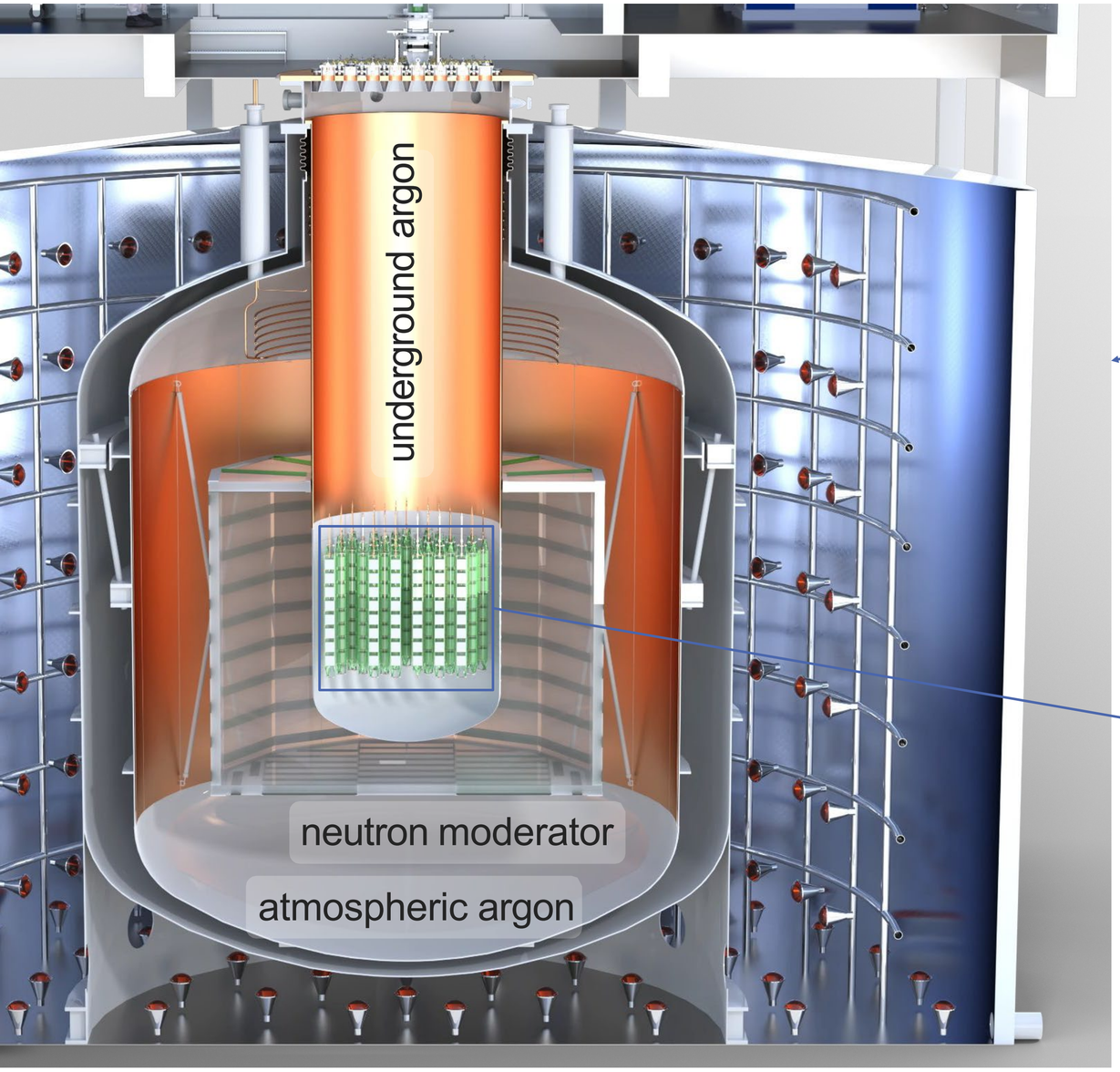
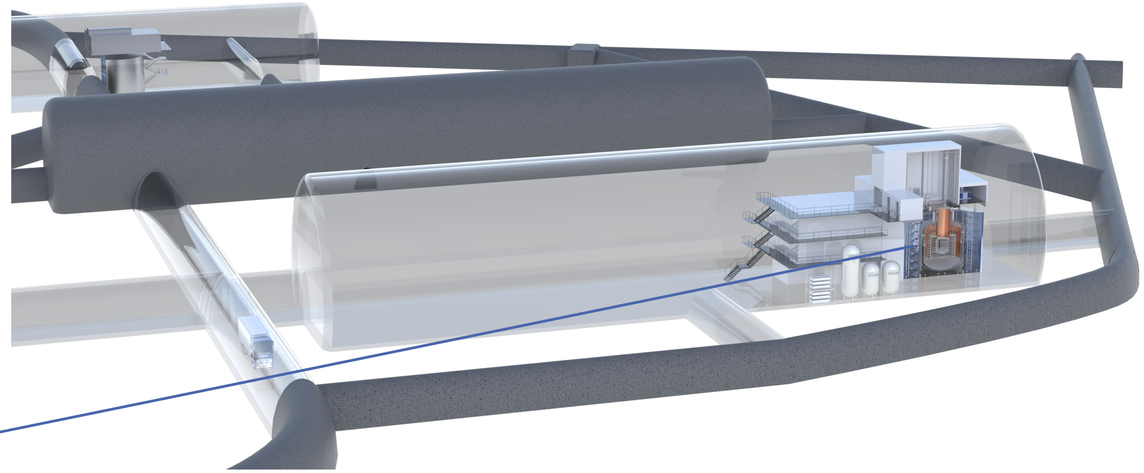
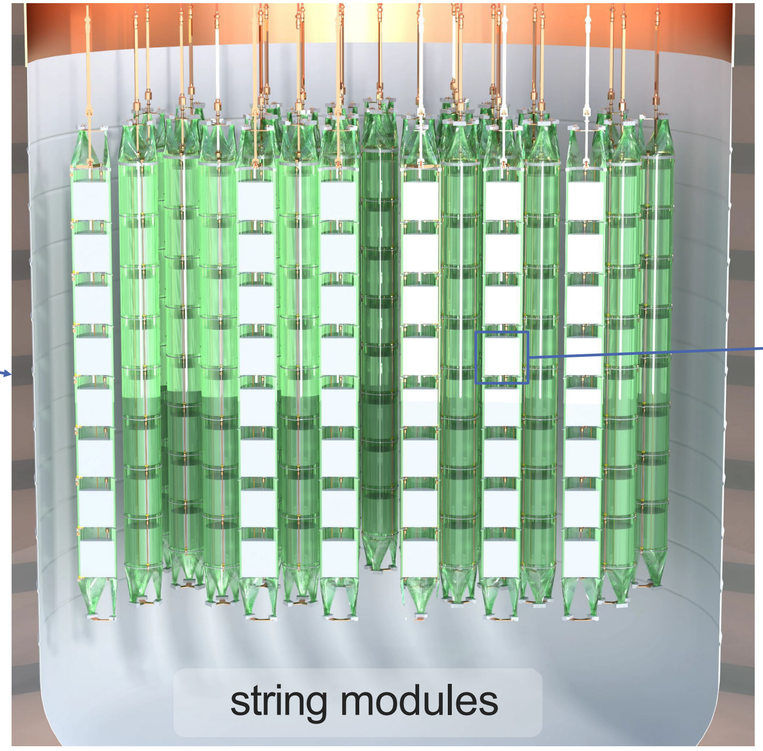
LEGEND. Episode 1000: A new hope

LEGEND-1000 @ LNGS Hall C

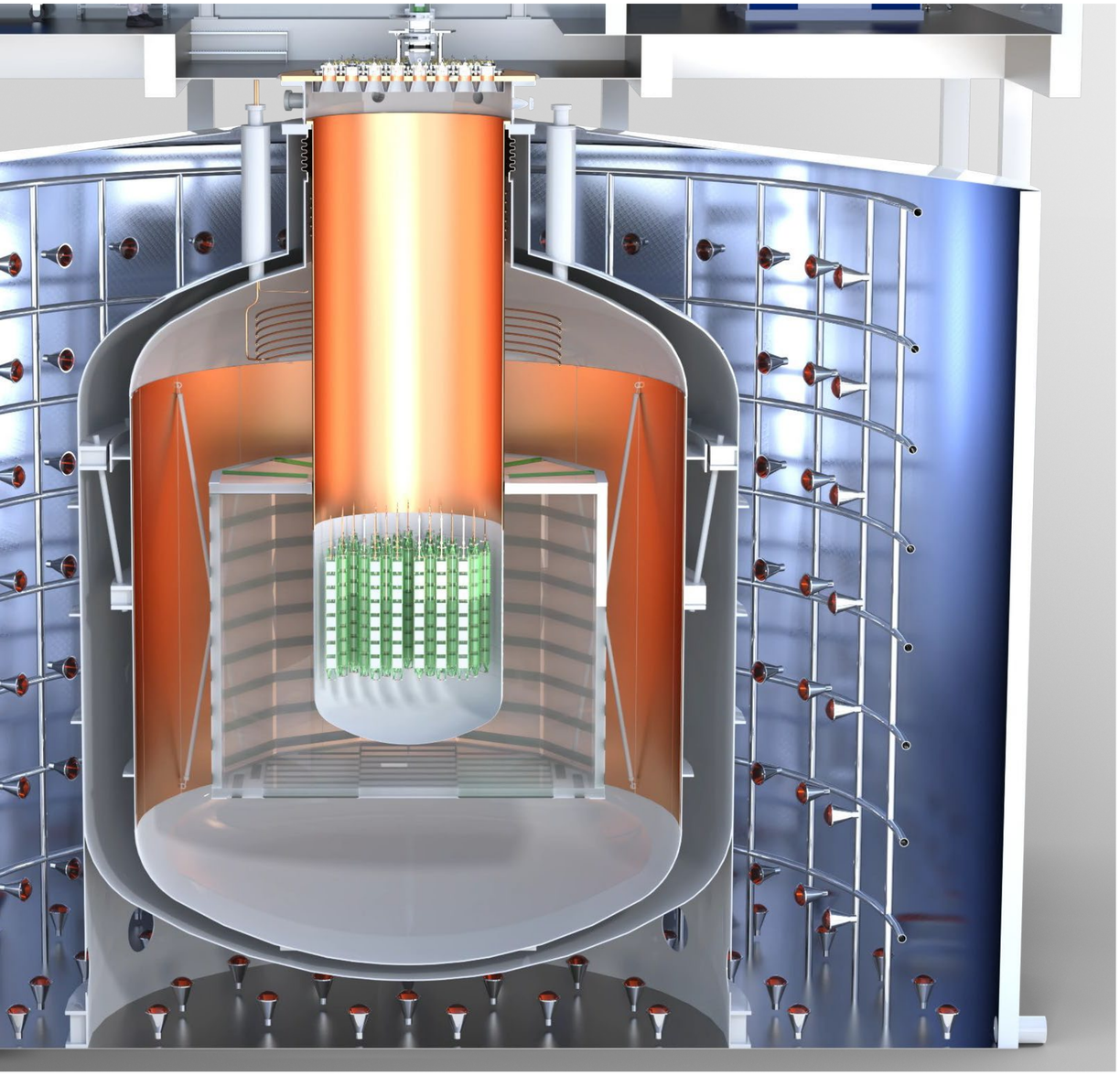






336 IC detectors
3 kg avg. mass

LEGEND-100: Designed for an Unambiguous Discovery

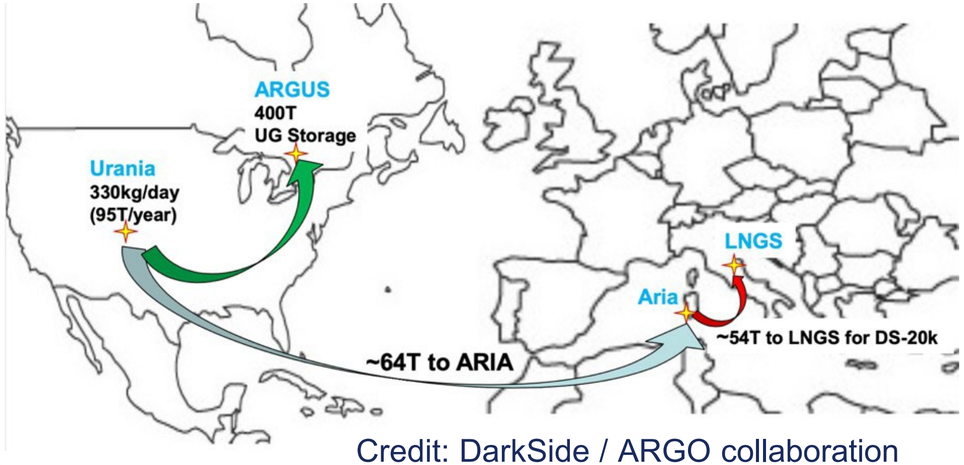


- 1000 kg HPGe Inverted Coaxial Detectors
- New cryostat
- Large-mass IC detectors:
  - Excellent FWHM
  - Great PSD
  - Less cables and holder materials
- Underground LAr reentrant tube in an atmospheric LAr cryostat
- Single string design, modular approach
- Radiopure components
- $T^{0\nu}_{1/2} > 1 \cdot 10^{28}$ yr
- Background: $<1 \times 10^{-5}$ cts/(keV kg yr)

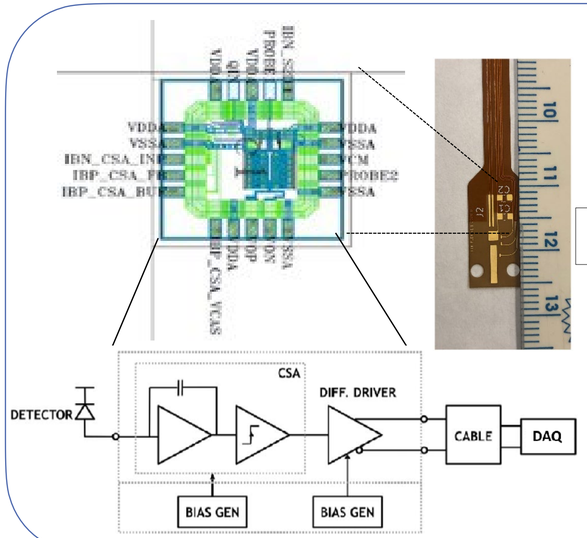
LEGEND-1000
Pre-Conceptual Design Report
arXiv:2107.11462

LEGEND-1000: Radiopure Components

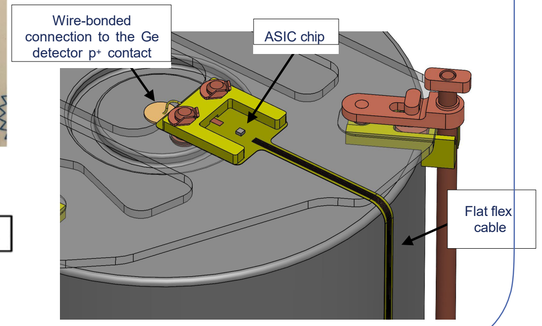
20-25 t of **underground-sourced LAr** reduced in ^{42}Ar
Acquisition builds on pioneering work of DarkSide collaboration



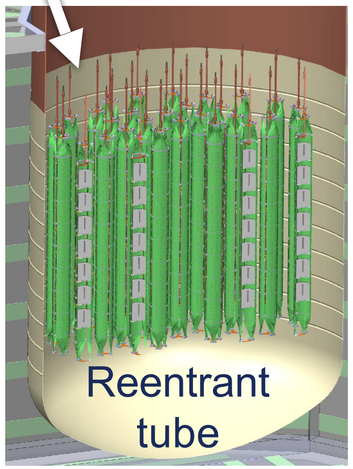
Credit: DarkSide / ARGO collaboration



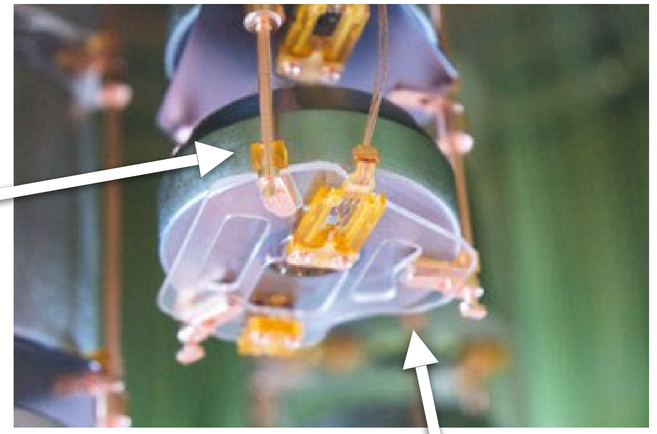
ASIC Front-End
Low noise / low threshold

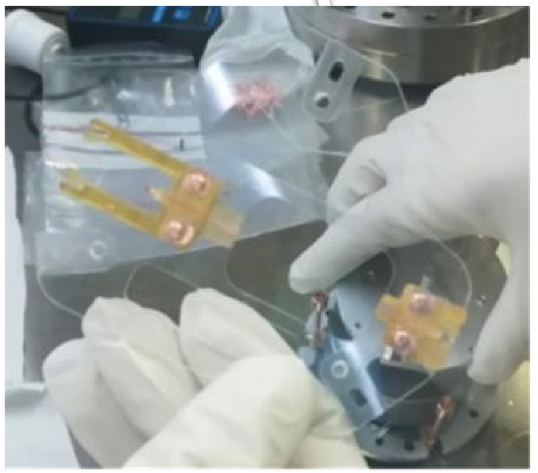


Underground electroformed Cu for detector holders and reentrant tube



Example LEGEND-200 Detector holder

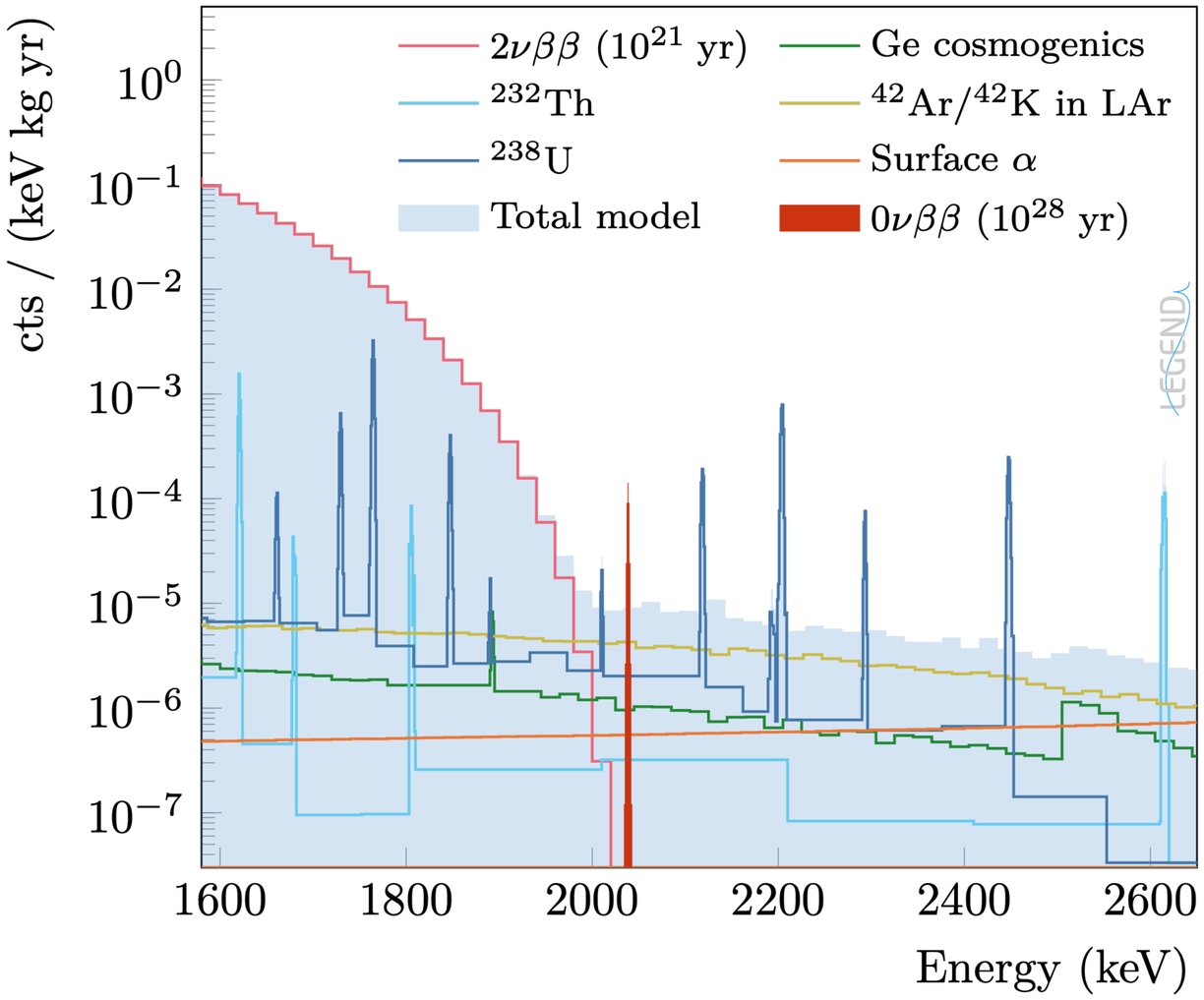




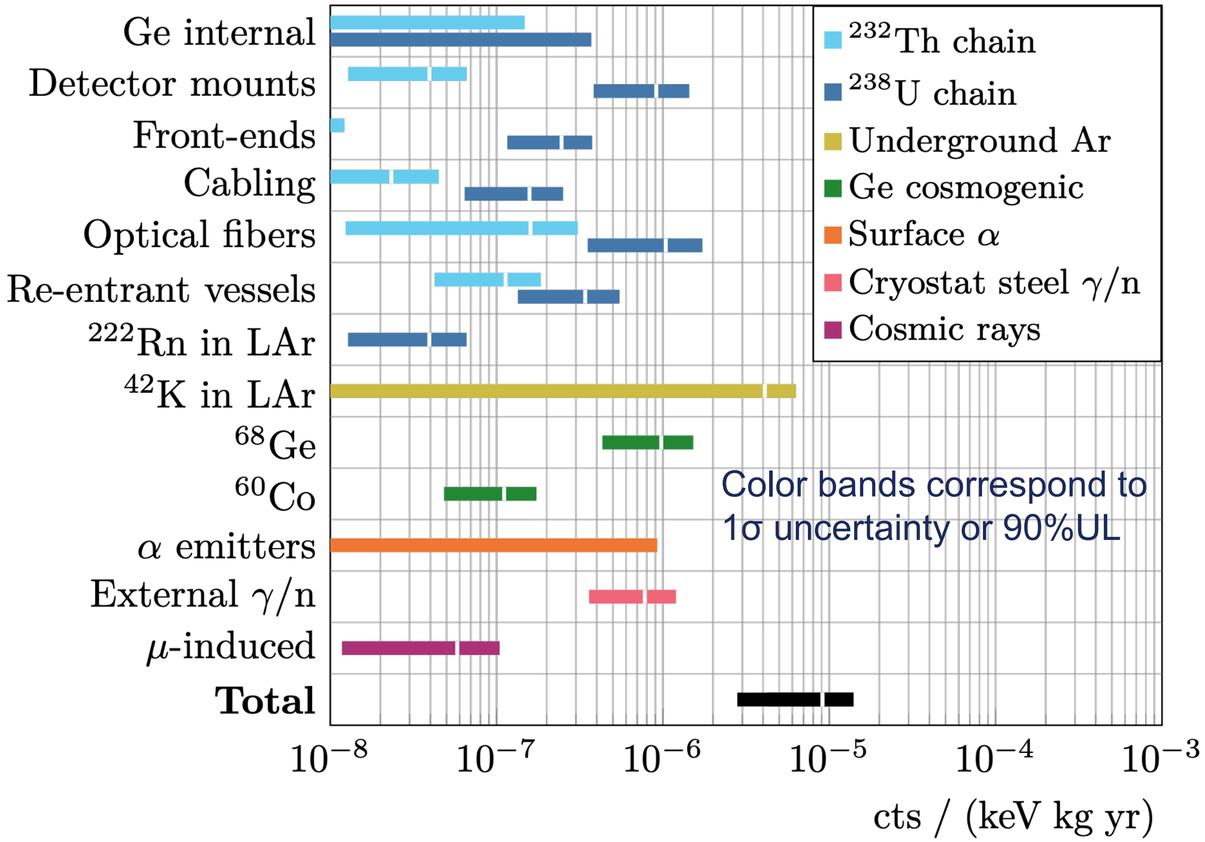
PEN: scintillating (self-vetoing) high-purity detector support

LEGEND-1000: Background Model

Simulated total background spectrum after cuts

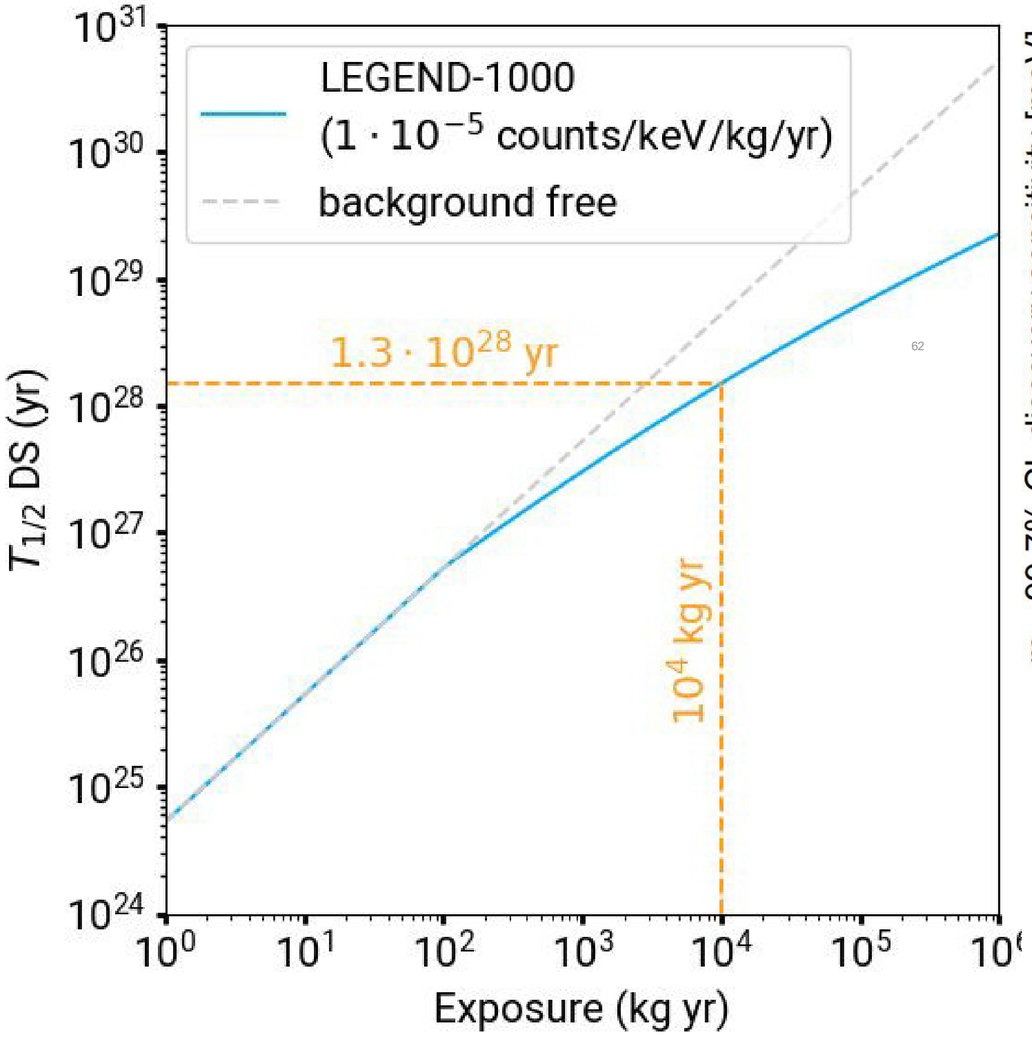


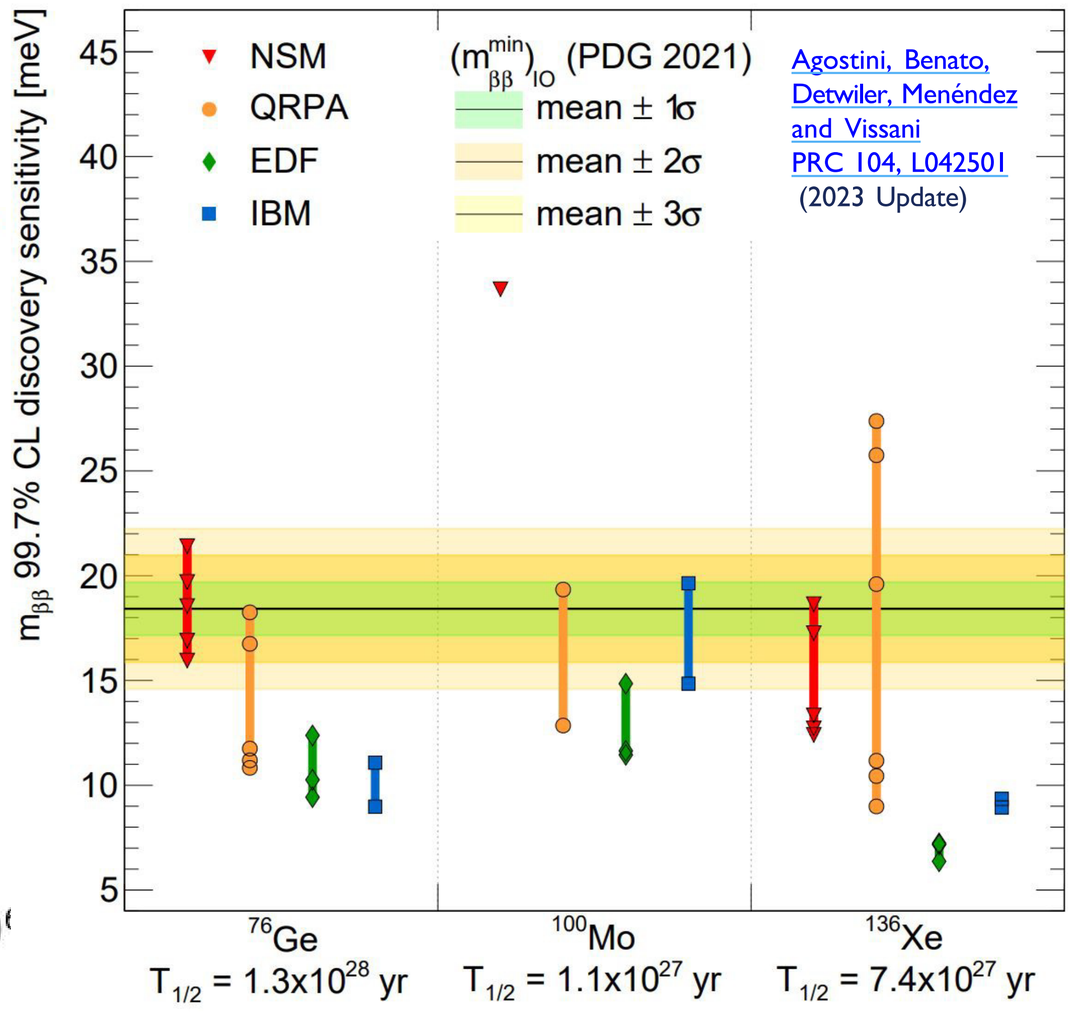
Expected background contributions (preliminary)



Projected background index ~ 10^{-5} cts/(keV kg yr)

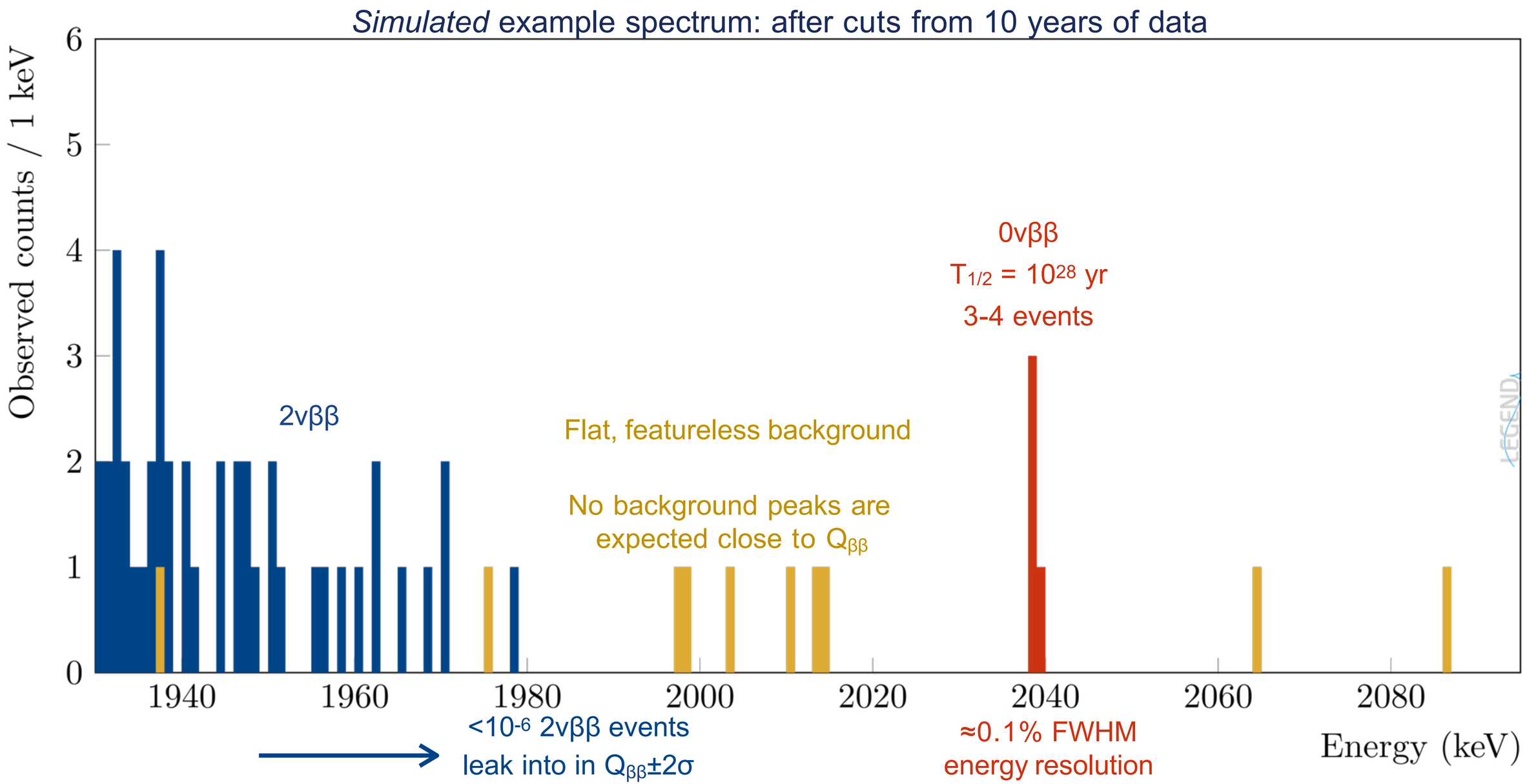
LEGEND-1000: Sensitivity



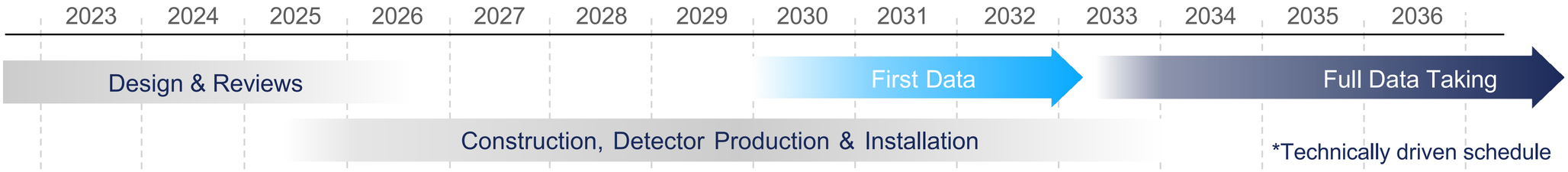


- LEGEND will span the inverted ordering and a large part of the normal ordering space
- Discovery sensitivity <18.4 meV for 12/15 calculations

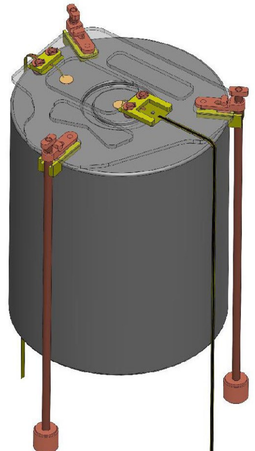
LEGEND-100: Designed for an Unambiguous Discovery



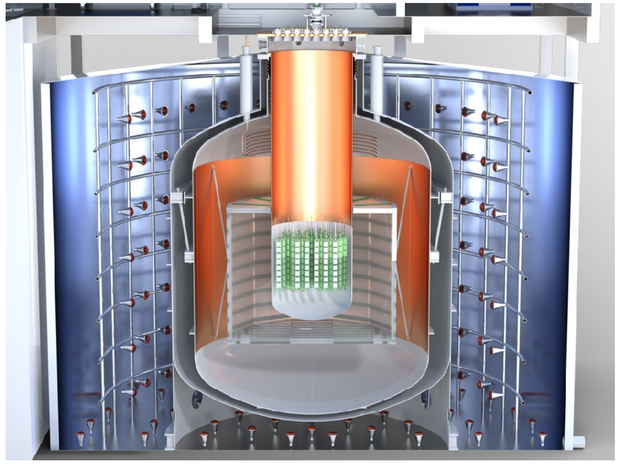
LEGEND-1000: Timeline & Outlook



- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - LEGEND has a low-risk path to meeting its background goal of 10^{-5} counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of 0νββ decay at $T_{1/2} = 10^{28}$ years
- The reference design accommodates siting in SNOLAB Cryopit or LNGS Hall C



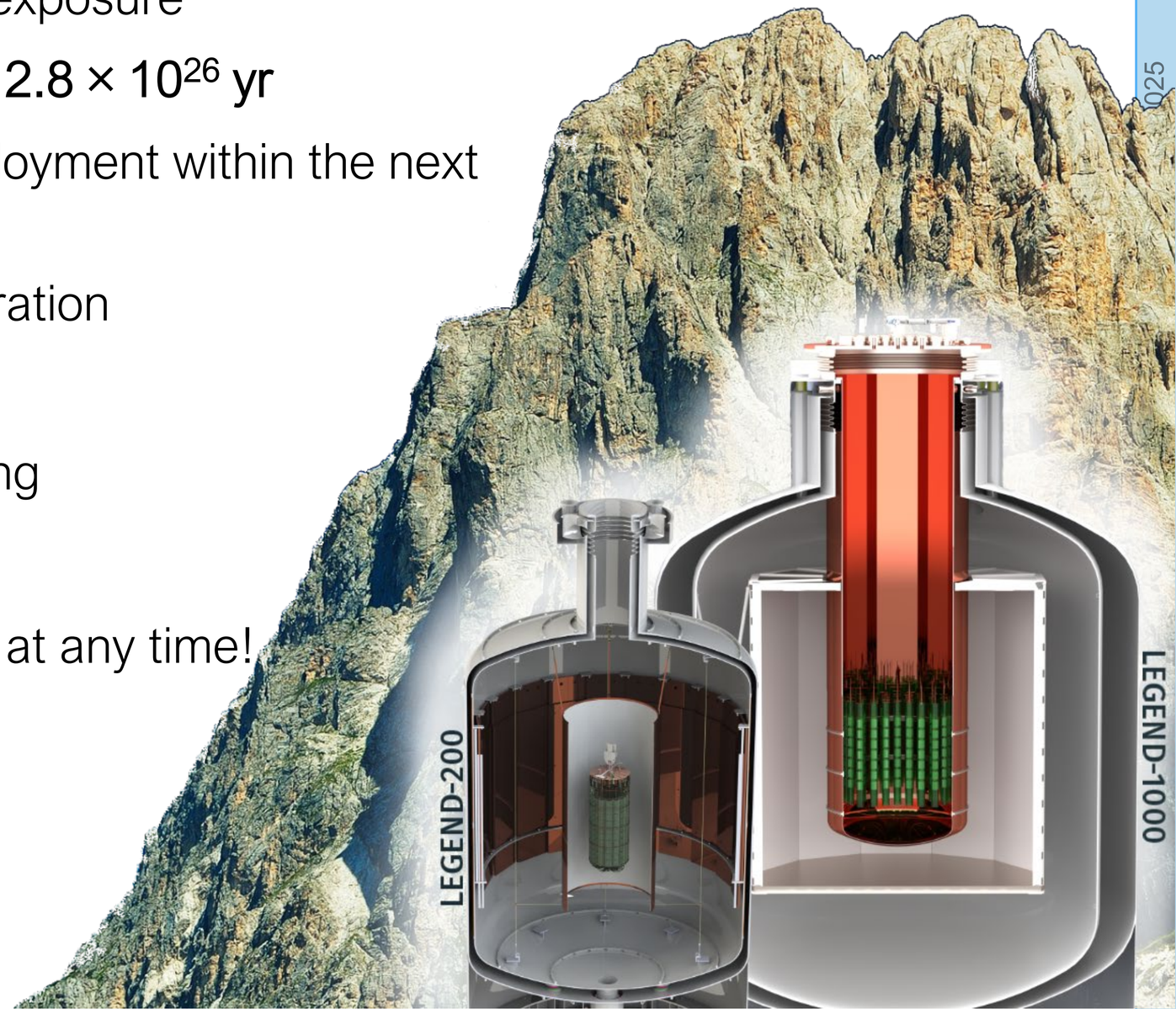
LEGEND Website
https://legend-exp.org/



- **LEGEND-200** has collected over a year of exposure
  - first unblinding with combined sensitivity: **2.8×10^{26} yr**
  - reassembly and additional detectors deployment within the next months
  - instrumental and analysis paper in preparation

- **LEGEND-1000** preparation at LNGS ongoing

- "…an era in which a discovery could come at any time!"



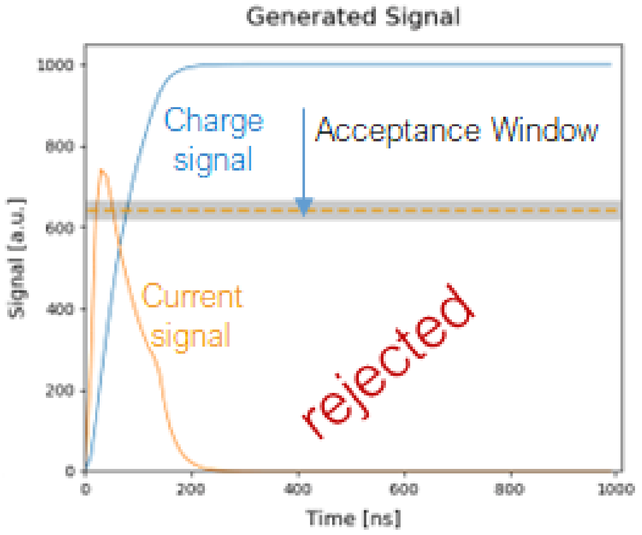
Backup slides

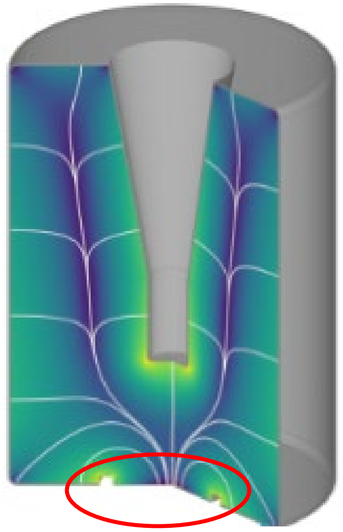
Event @ 2040 keV

- Passivated surfaces separating n-type and p-type anodes can degrade energy of alpha events into region near Q-value

Mirion Detectors:

- Ditch near point-contact
- Events near ditches + PC have high current amplitude
- Use events with high A/E values to identify

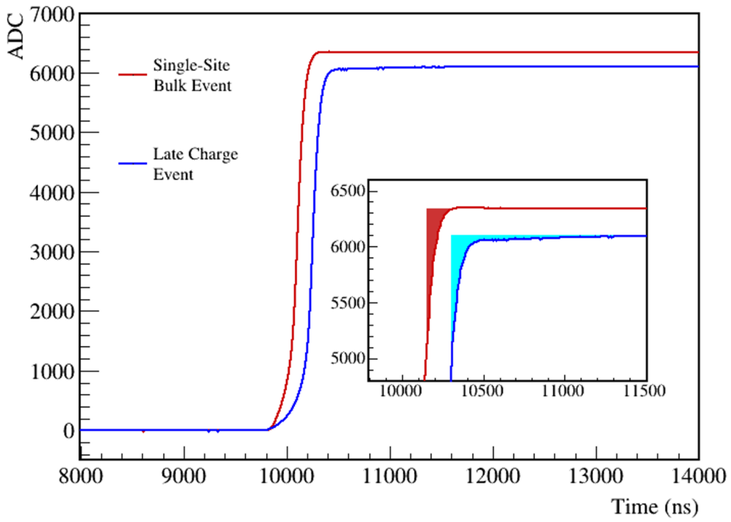


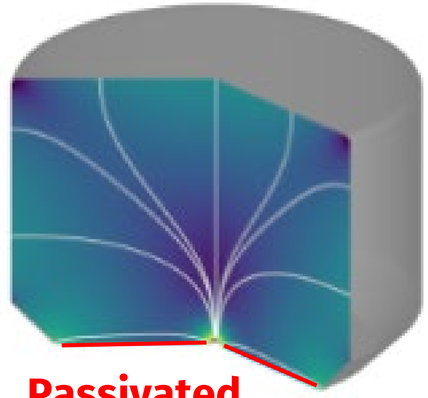


High A/E region

Ortec Detectors:

- Large thin passivated surface
- Events on passivated surface have slow charge collection component
- “Late charge” (LQ) cut identifies presence of slow component

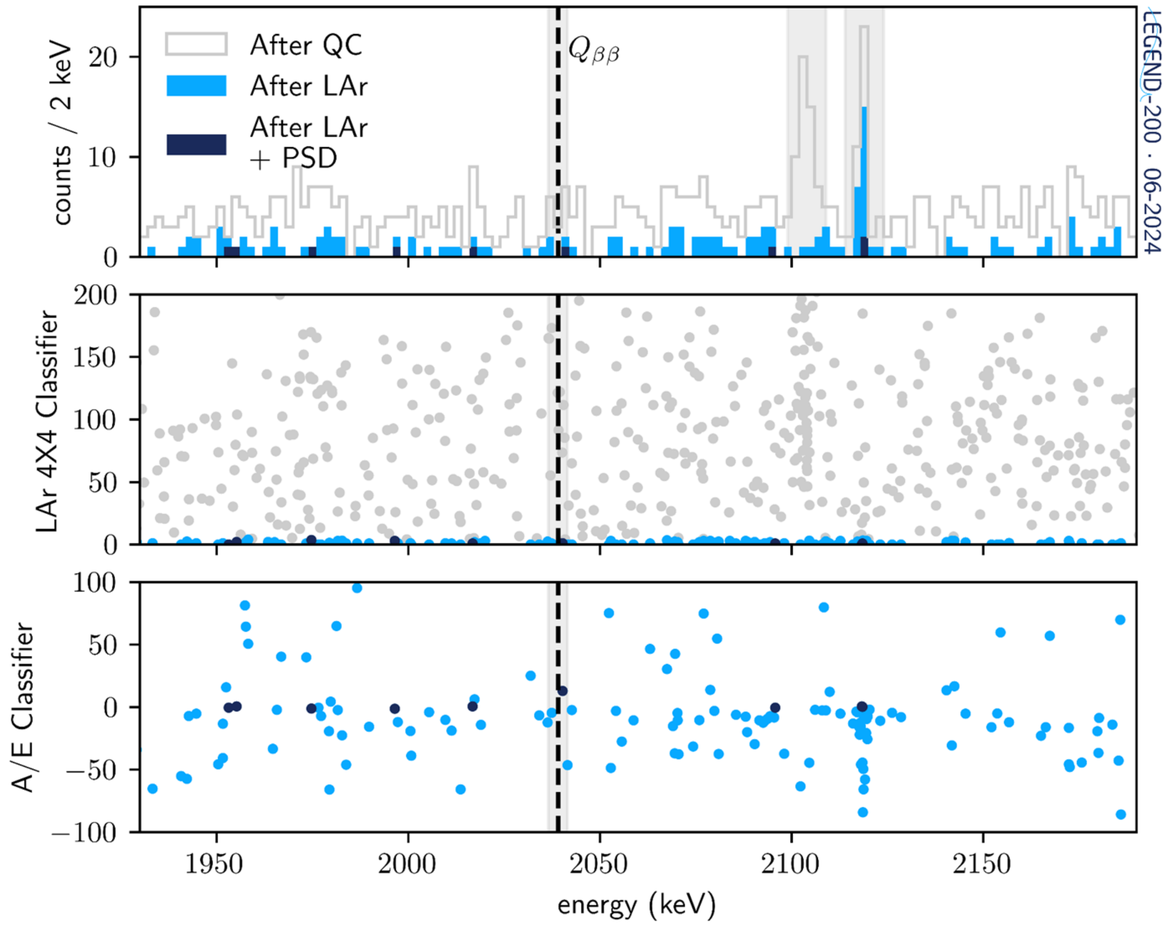




Passivated surface (high LQ)

Event @ 2040 keV

- Low drift time -> event close to p+ contact
- High A/E outside acceptance band if used
- PPC detectors known to be susceptible to background surface events due to passivated surface
- Statistical study performed result was that at level of statistics high A/E not needed
- Understudied parameter space -> Need higher statistics to investigate
- Recent background runs without the “nylon mini-shroud” will help in this regard
- Special measurement of this PPC performed



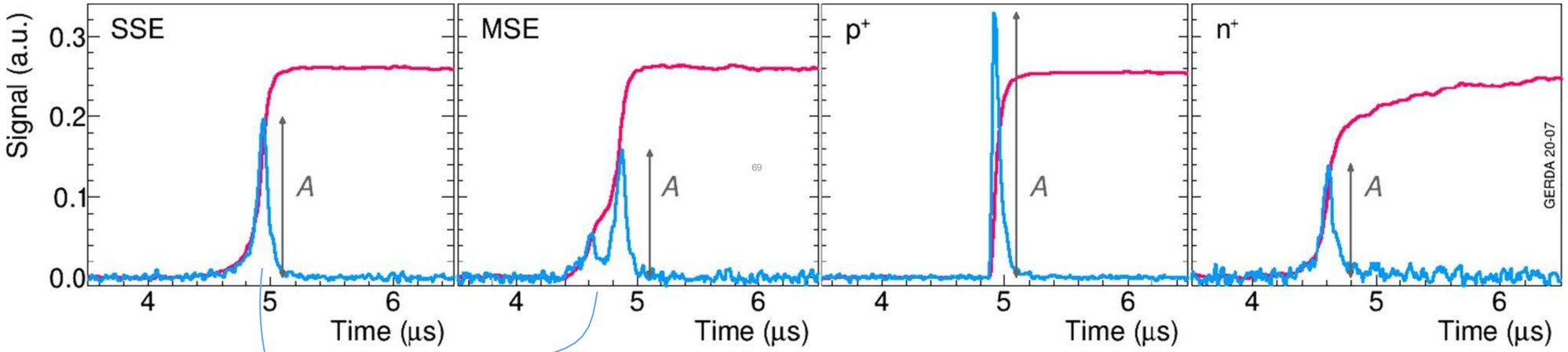
PSD in details

Single site event (e.g. ^{208}Tl DEP, ββ)

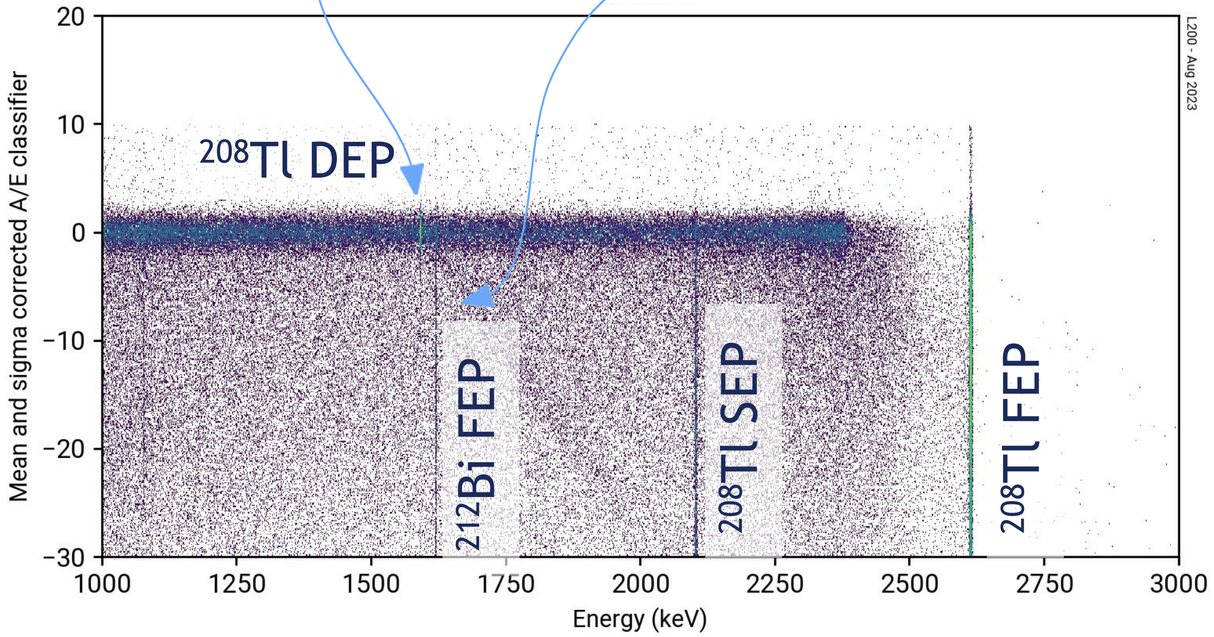
Multi site event (e.g. ^{212}Bi FEP)

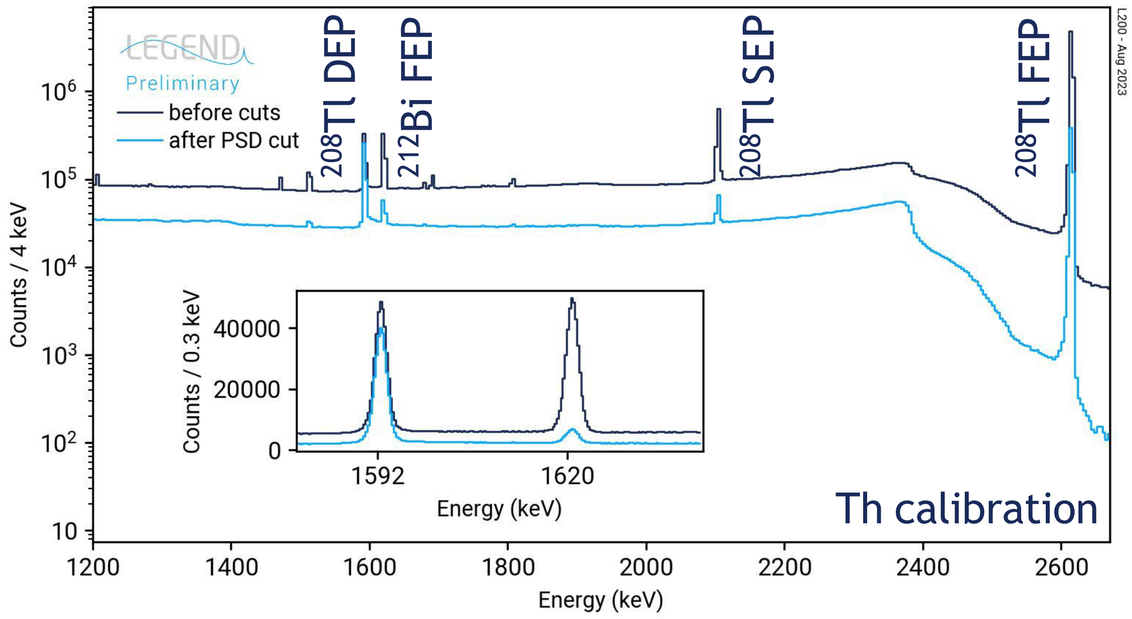
p$^+$ surface event

n$^+$ surface event (e.g. incomplete charge collection)

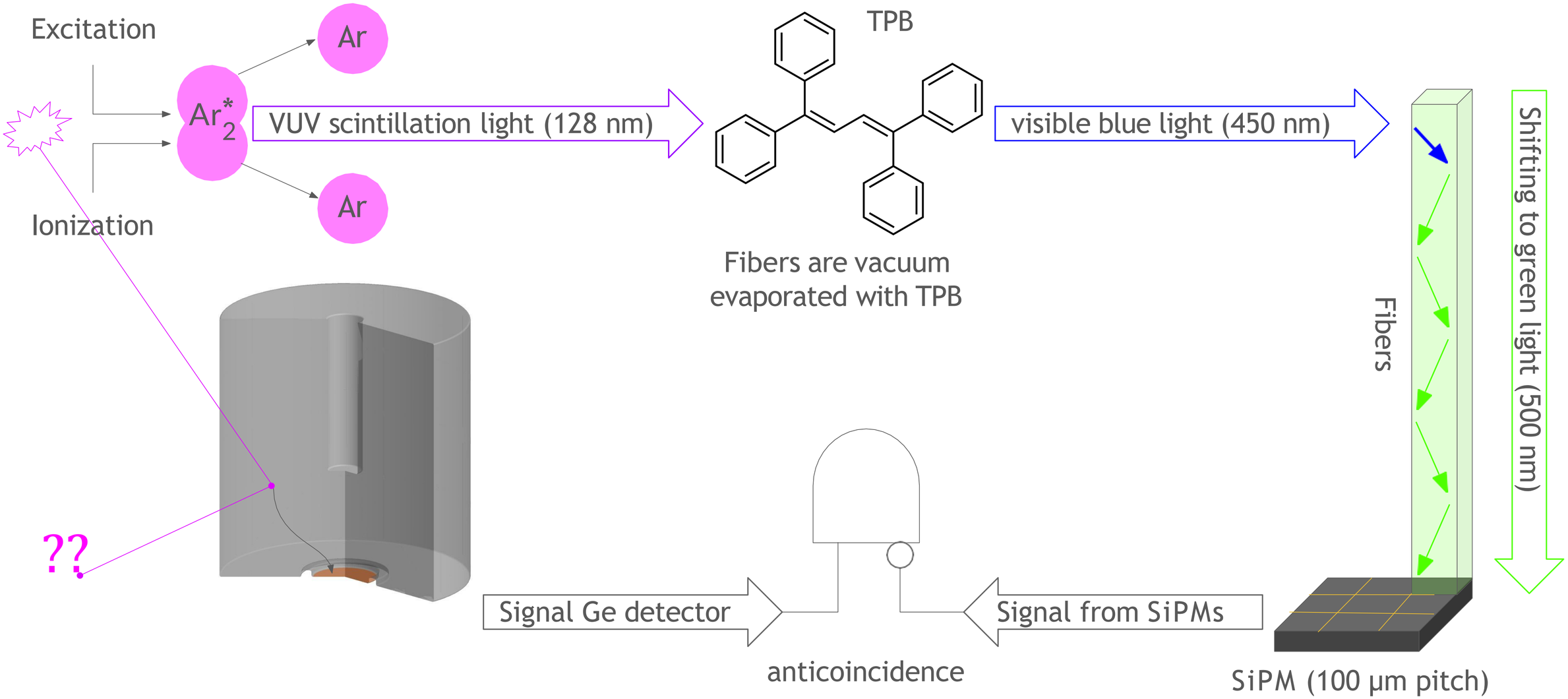


- Need to accept SSE (e.g. ββ)
- Reject the rest
- Optimize with calibration

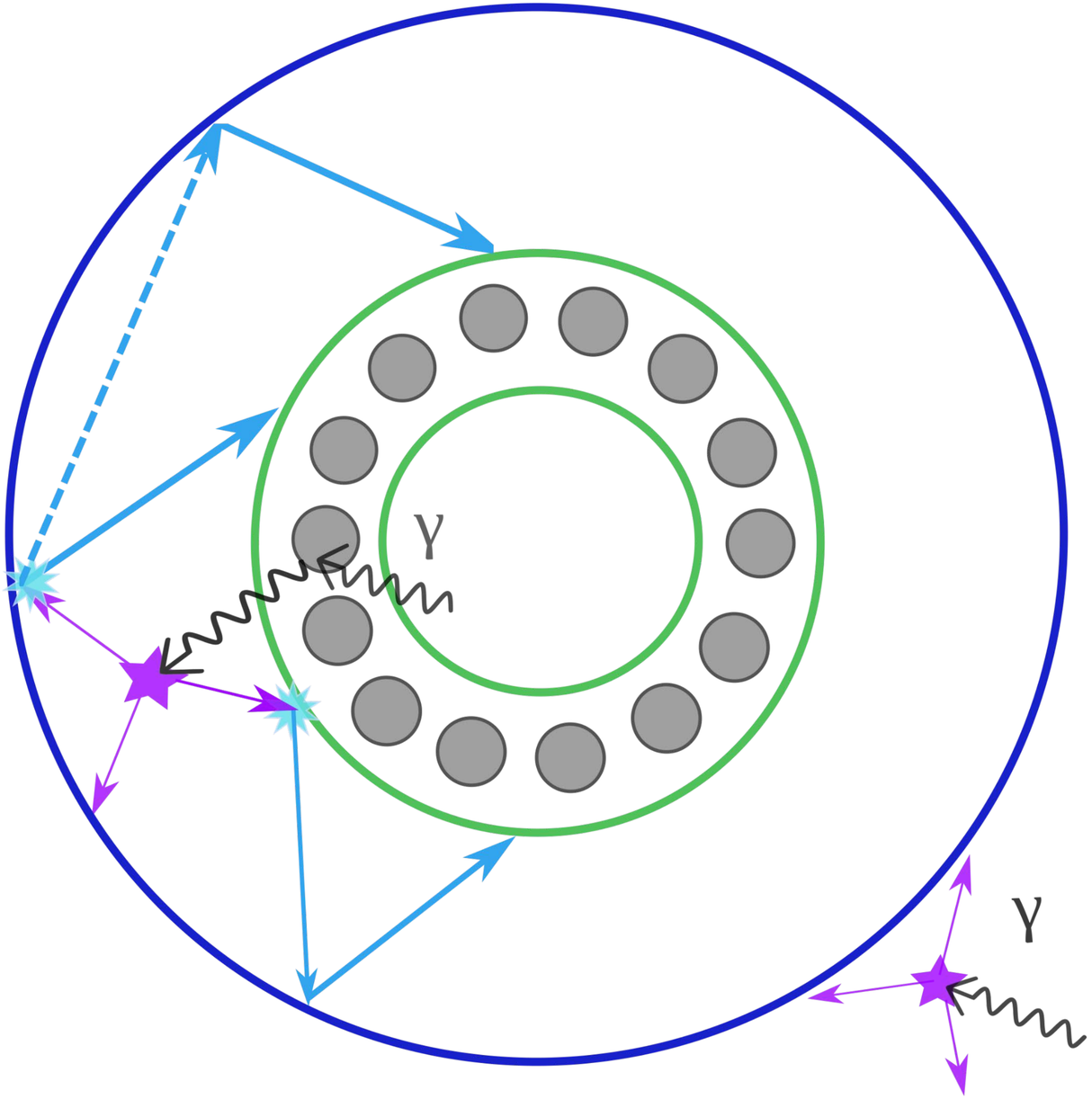




LAr scintillation principle



Wavelength Shifting Reflector

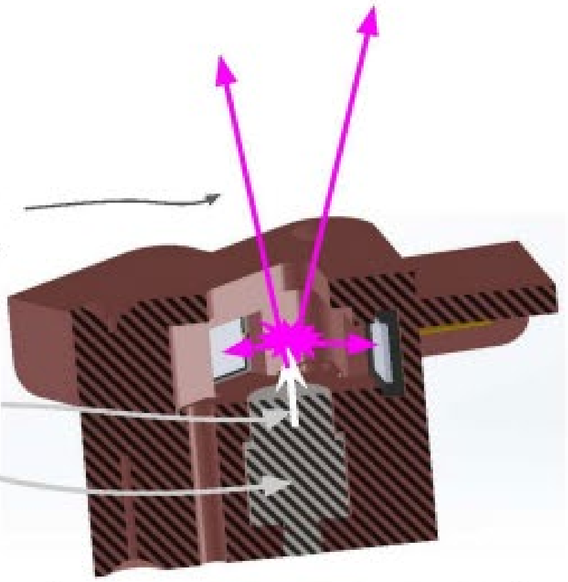


It restricts the LAr volume around the detectors.

Also shifts scintillation light to blue and reflects it back towards the LAr instrumentation

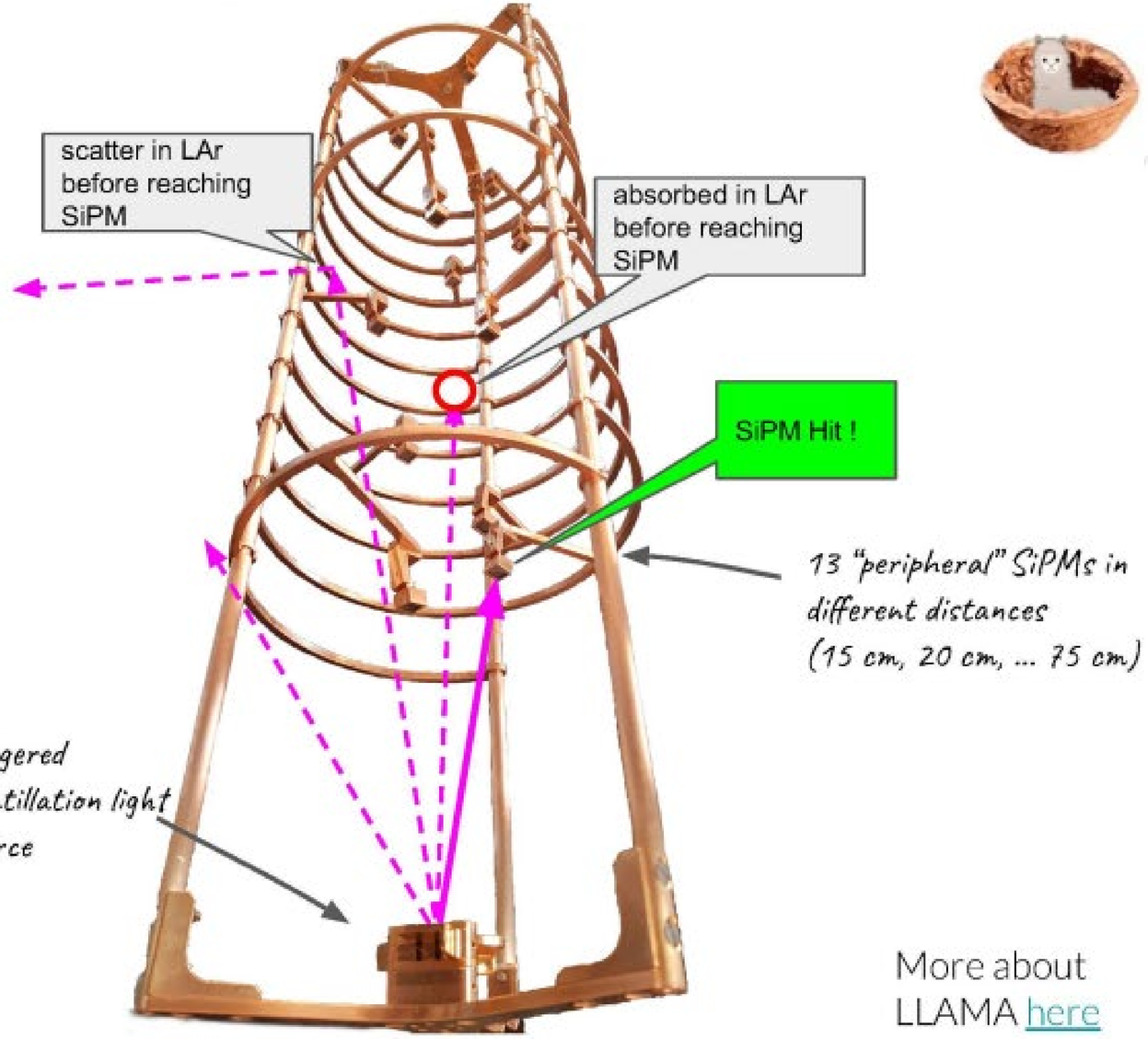
LEGEND LAr monitoring Apparatus

LLAMA in a nutshell



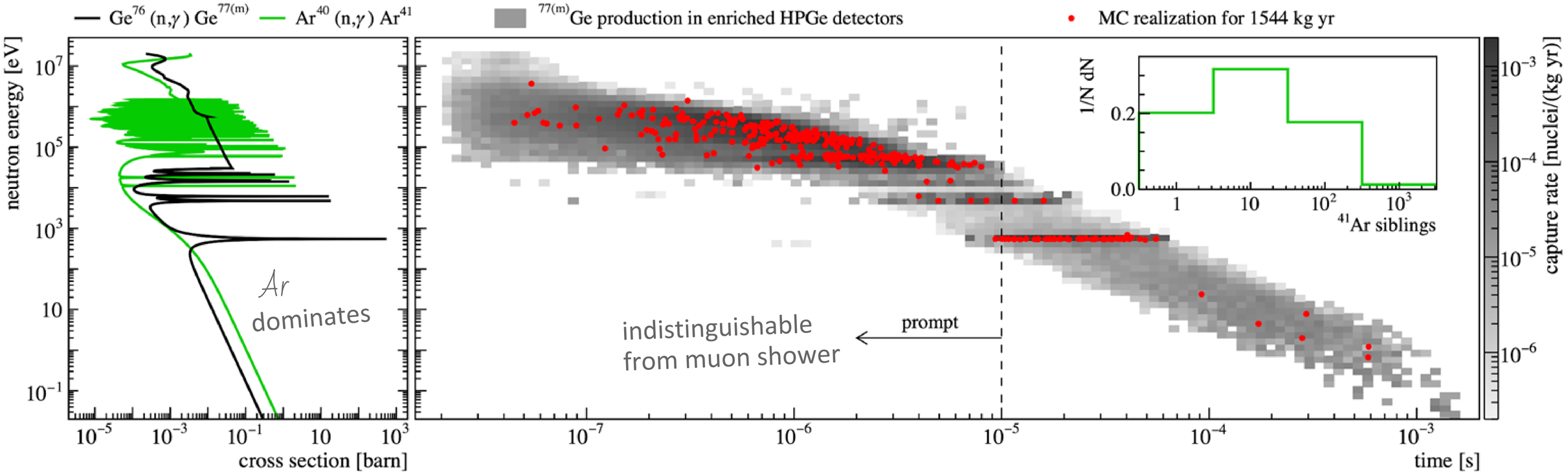
green LED -> calibration

triggered scintillation light source



More about LLAMA here

Virtual depth by active background rejection



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- **depth-dependent** in-situ production of **$^{77(m)}$Ge** by muon-induced neutron capture, **(0.21+-0.01) nuclei/(kg yr)** in GERDA at LNGS
- single-beta **^{77m}Ge** background can be reduced by **delayed tagging cuts**, active reduction cuts place LNGS at **~5000 m.w.e virtual overburden**

Other BSM Physics with LEGEND-1000

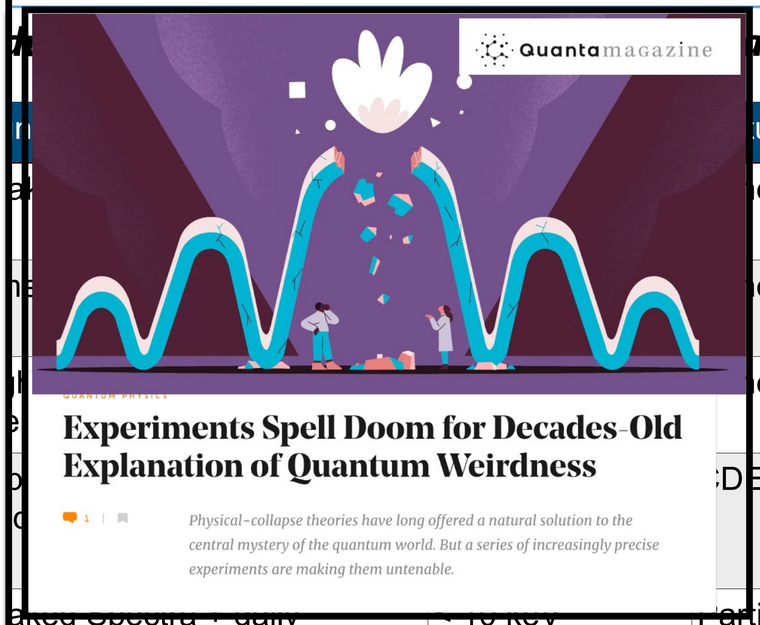
^{39}Ar reduction due to the use of underground-sourced argon enables a suite of BSM physics searches

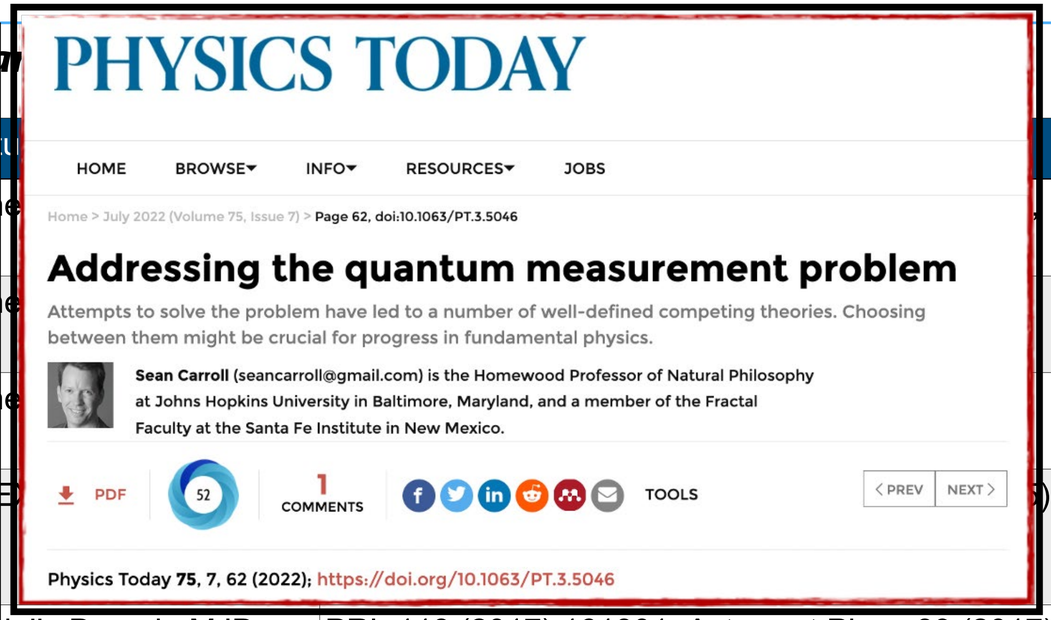
Mechanism	Signature	Energy range	Status	*Recent* Germanium References
Bosonic Dark Matter	Peak at m_b	5 — 100keV	Done in MJD, GERDA	PRL 118 (2017) 161801, PRL 125 (2020) 011801, PRL 132 (2024) 041001, EPJ C84 (2024) 940
Baryon Decay	Time Correlation, High Energy	0-10 MeV	Done in MJD	PRD 99 (2019) 072004 EPJ C83 (2023) 778
Fractionally Charged Cosmic rays	High Multiplicity-coincidence events	Few keV	Done in MJD	PRL 120 (2018) 211804
WIMP searches	Exponential Excess + Annual Modulation. Migdal Effect	< 10 keV	CDEX/MALBEK/CoGeNT	PRL 120 (2018) 241301, Phys. Procedia 61 (2015) 77
Solar axions	Peaked Spectra + daily modulation	< 10 keV	Partially Done in MJD	PRL 118 (2017) 161801; Astropart.Phys. 89 (2017) 39, Wiseman PhD Thesis
Majoron Emission	2νββ spectral distortion	$Q_{\beta\beta}$	Done in GERDA	EPJ. C75 (2015) 416
Lorentz Violation	2νββ spectral distortion	$Q_{\beta\beta}$		PRD 88 (2013) 071902
Electron Decay	Peak at 11.8 keV	~10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078, EPJ C84 (2024) 940
Pauli Exclusion Principle Violation	Peak at 10.6 keV	~ 10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078
BSM physics in Ar	Features in Ar Veto spectrum		ECEC in Ar36 (GERDA)	EPJ C75 (2015) 416

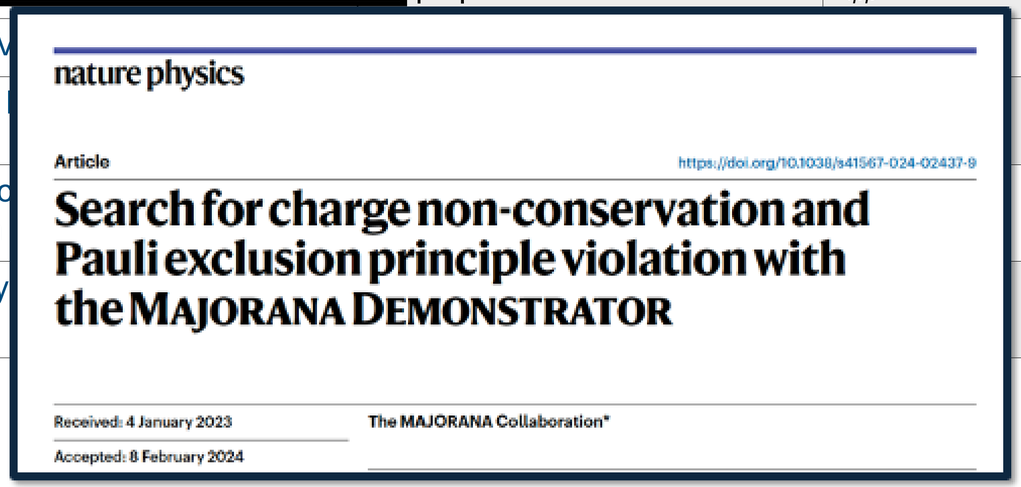
+ Prompt Supernova Neutrinos, SuperWIMPS, Solar Neutrinos, QM Wavefunction Collapse…

Other BSM Physics with LEGEND-1000

https://journals.aps.org/prl/issues/129/8



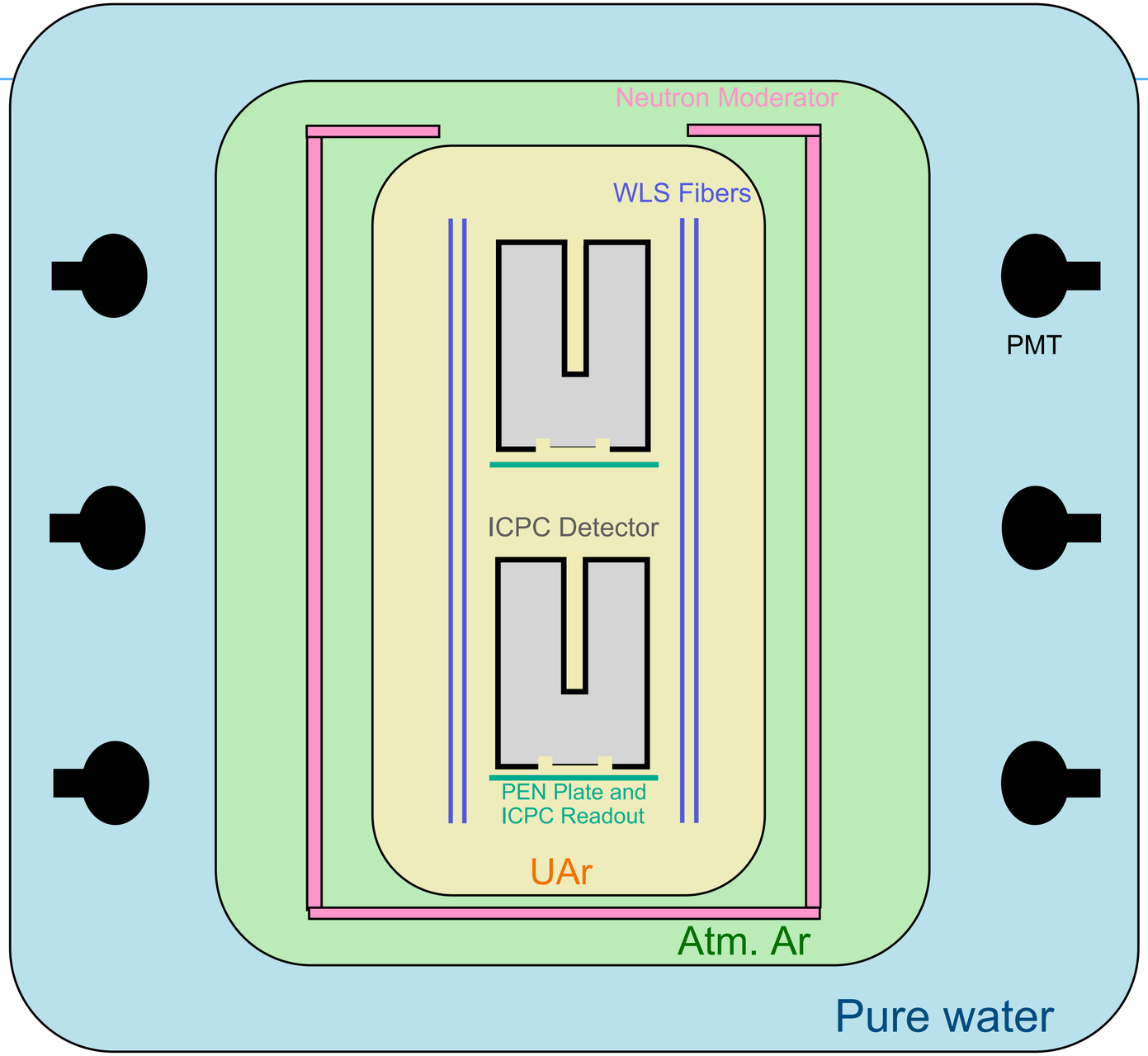




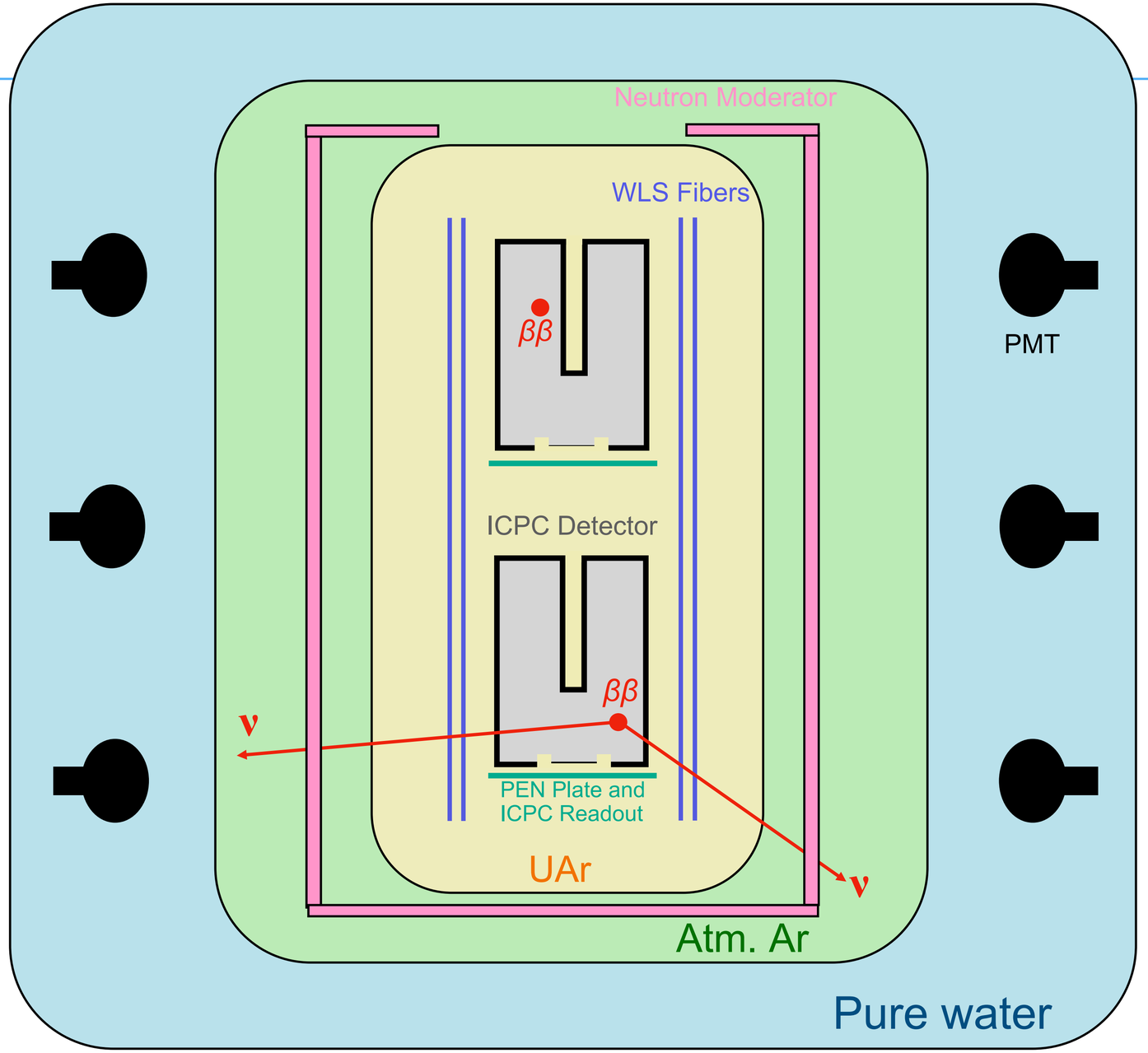
	dulation		Partially Done in MJD	PRL 118 (2017) 161801; Astropart.Phys. 89 (2017)
	ββ spectral distortion	$Q_{\beta\beta}$		
Lorentz V				
Electron				20 (2024)
Pauli Exc Violation				20 (2024) 1078
BSM phy			ECEC	

+ Prompt Supernova Neutrinos, SuperWIMP

L1000: Idea


Neutron Moderator
WLS Fibers
PMT
ICPC Detector
PEN Plate and
ICPC Readout
UAr
Atm. Ar
Pure water

L1000: Idea



0νββ: single energy deposit (*E*) in ~1 mm^3 volume

E = *Q*-value

2νββ: single energy deposit in ~1 mm^3 volume

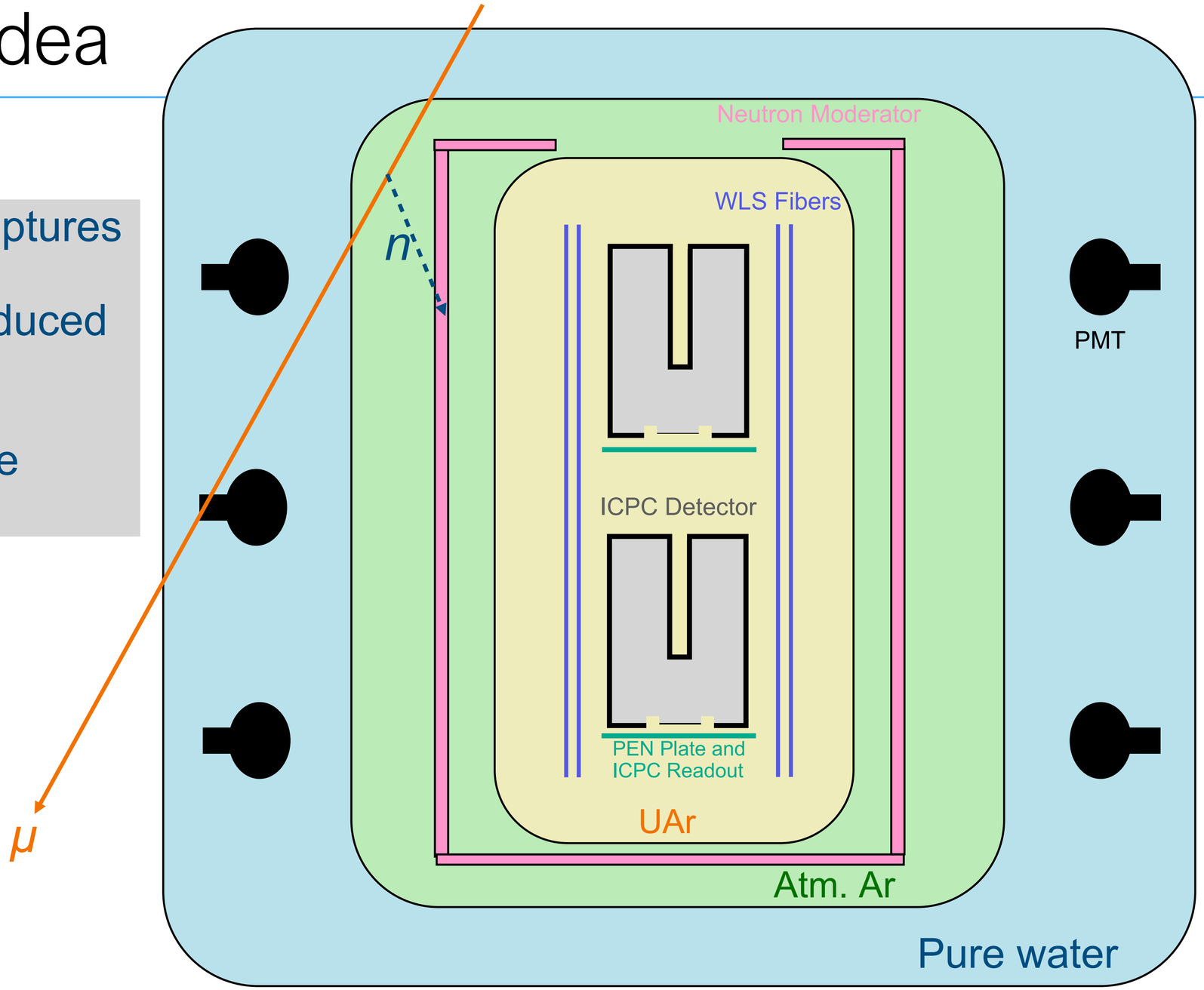
Anti-neutrinos undetected

E < *Q*-value

L1000: Idea

Moderator captures cosmogenic neutrons produced in LAr

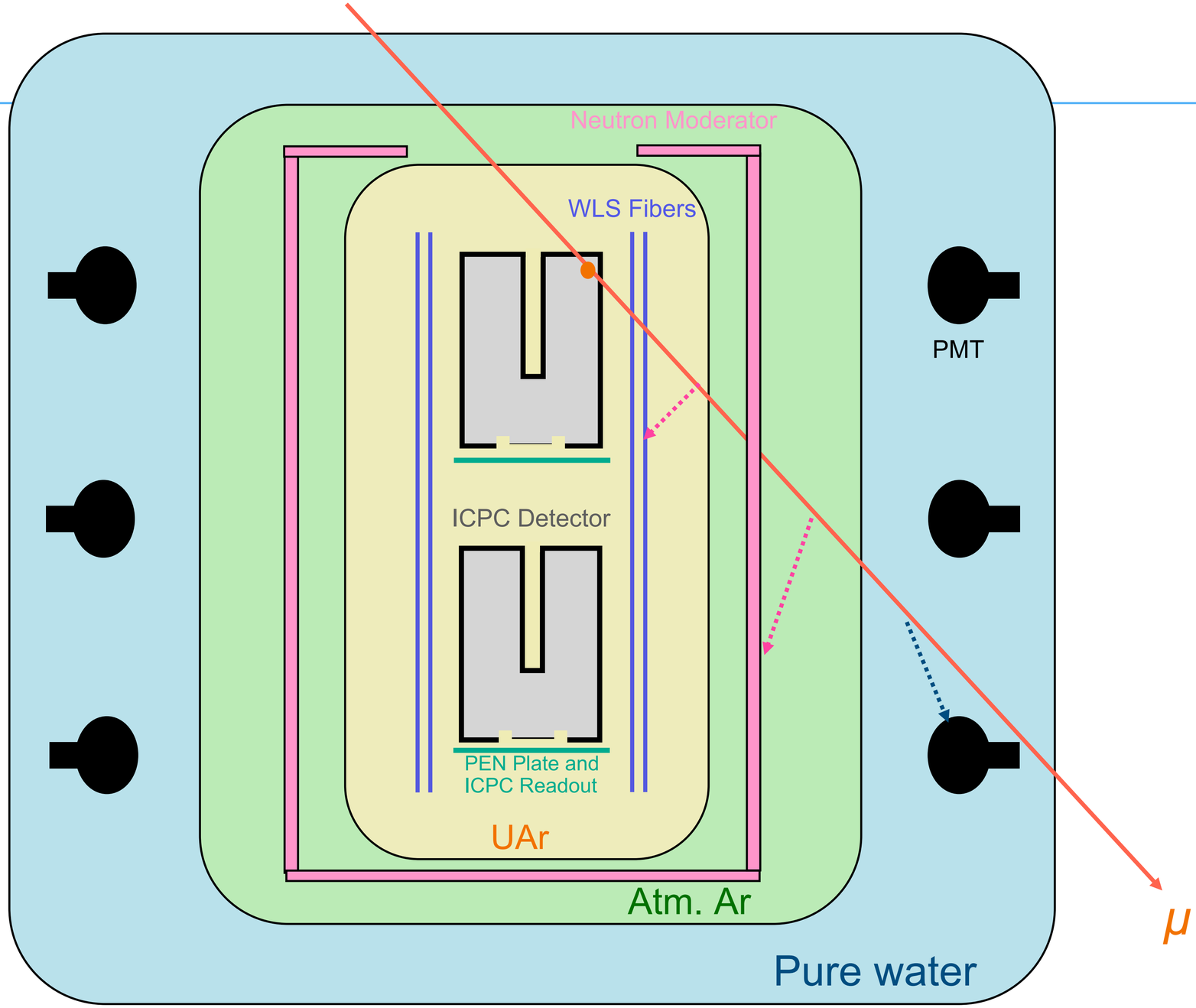
Reduces ^{77}Ge production



L1000: Idea

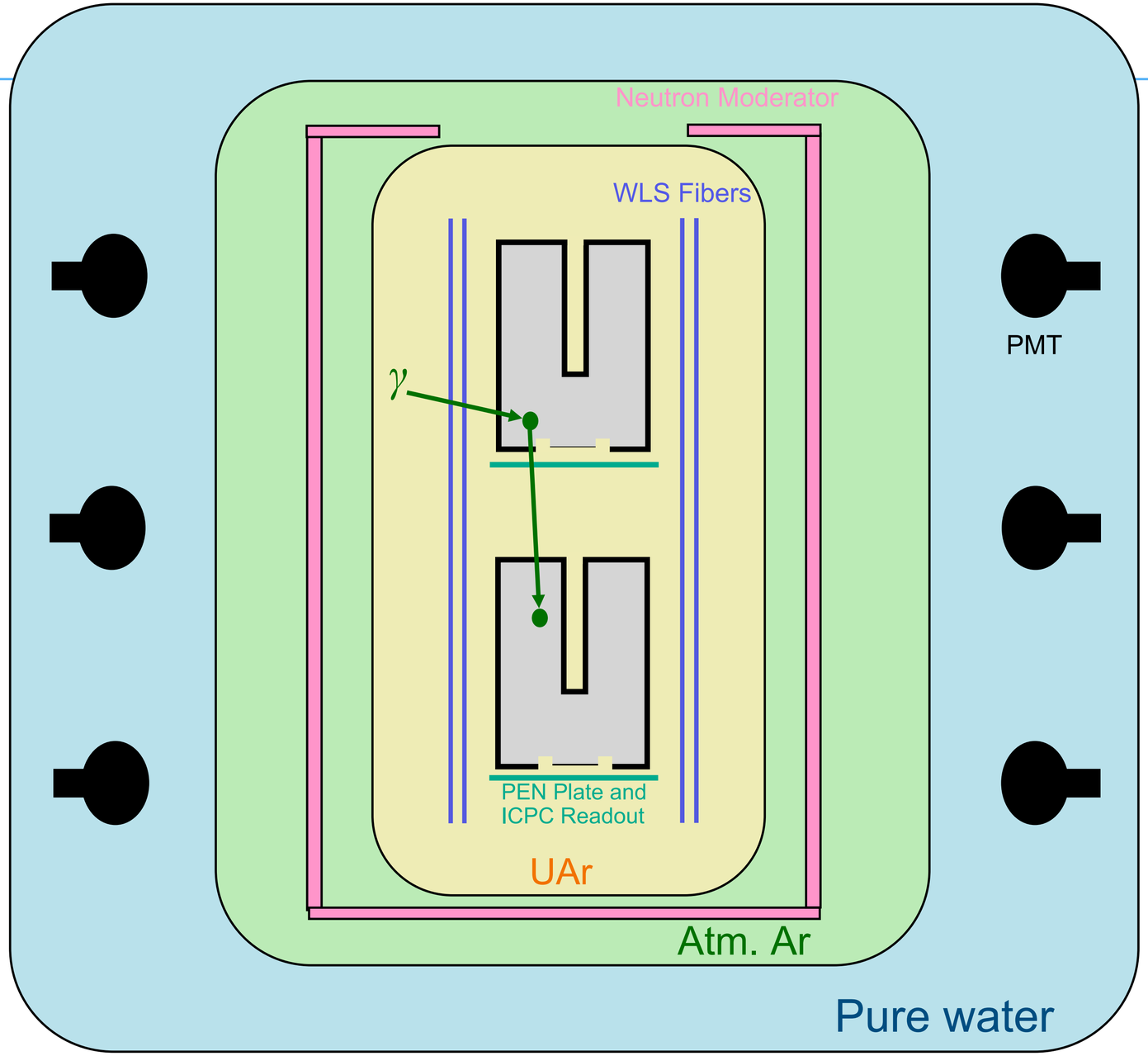
Muon veto uses Cerenkov light and LAr scintillation

WLS and light guides installed on moderator



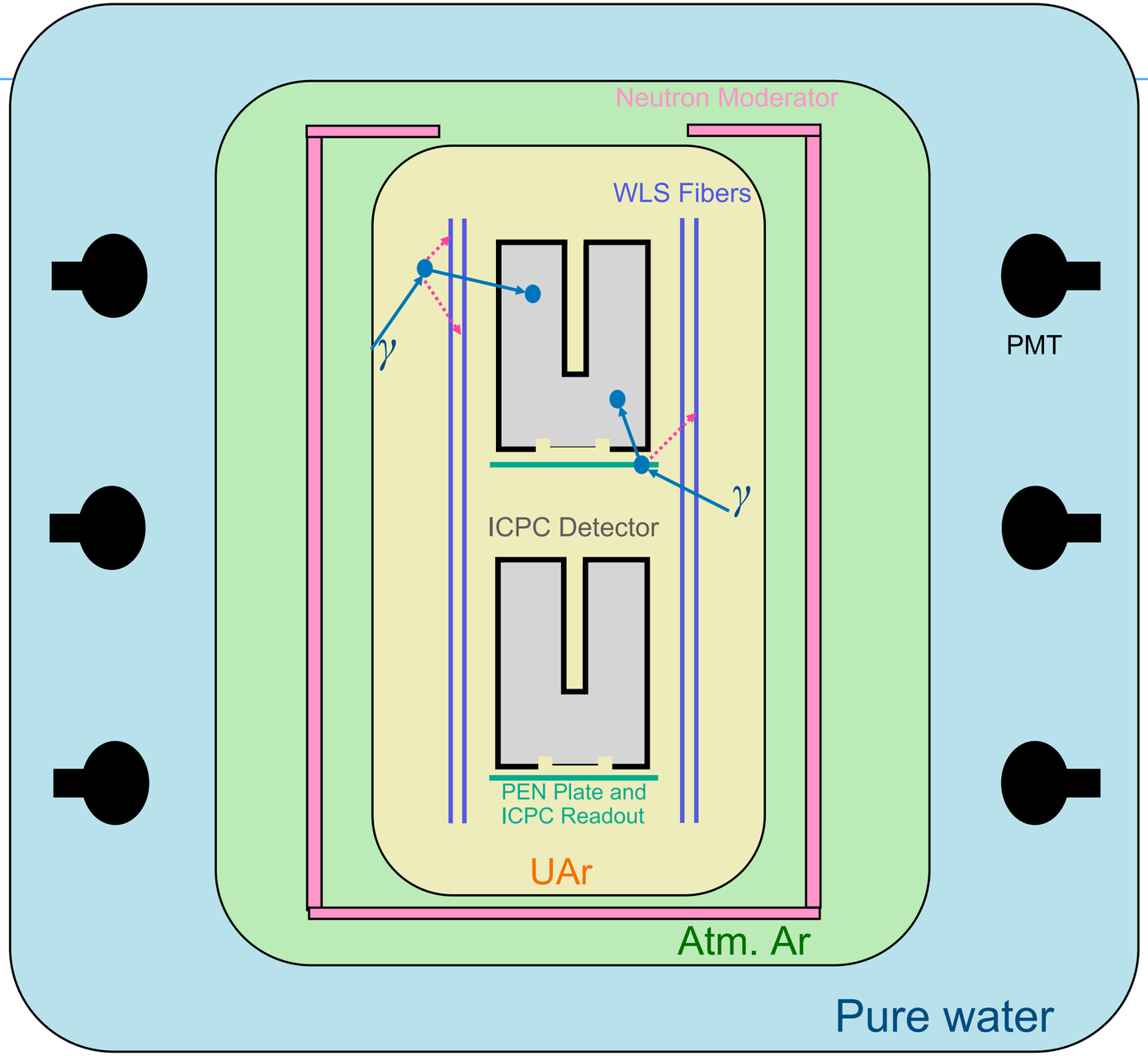
L1000: Idea

Detector coincidence tags gammas

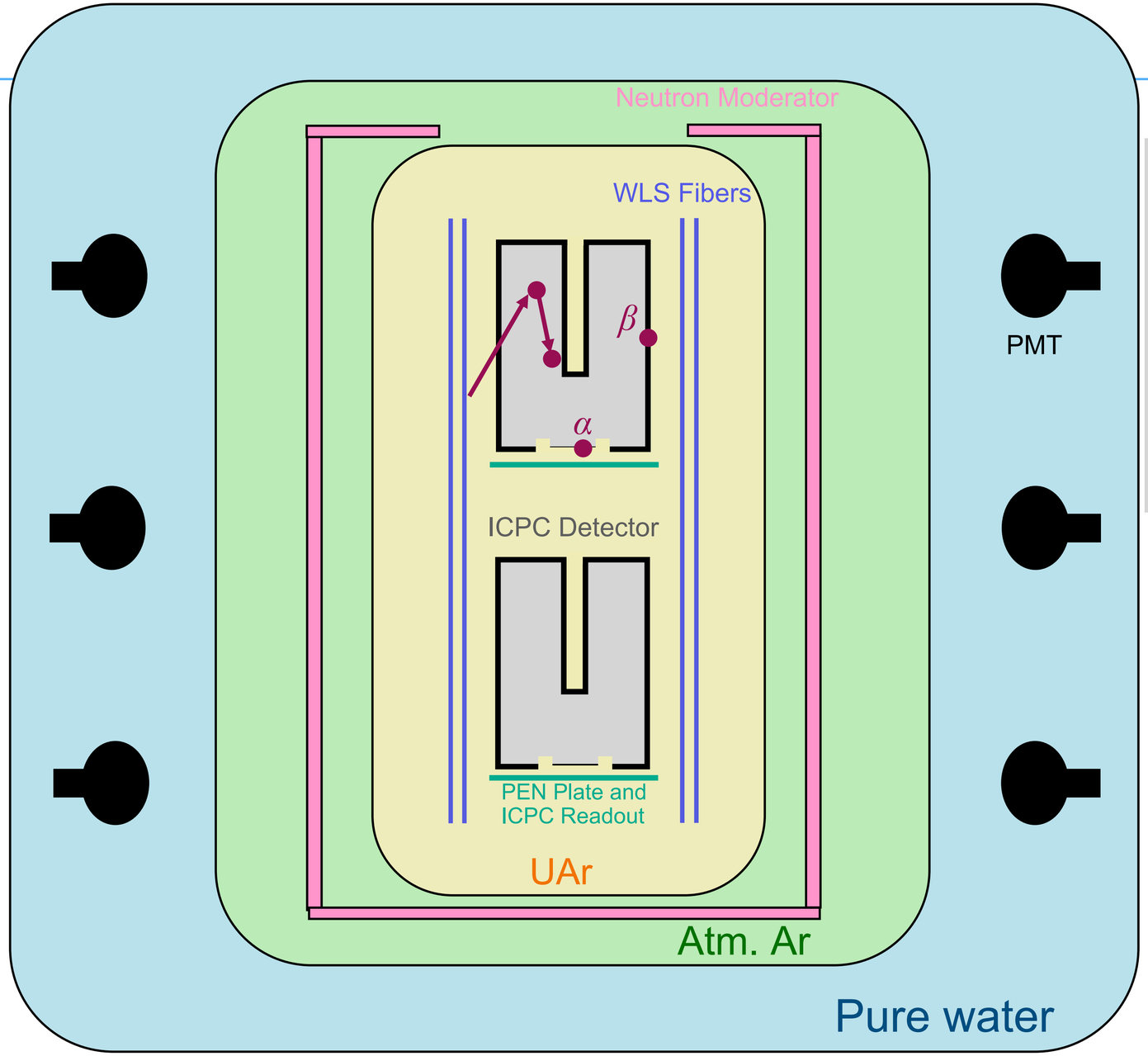


L1000: Idea

LAr Veto and scintillating PEN plates tag gammas



L1000: Idea



Pulse shape discrimination (PSD) removes multi-site and surface events

See: J02.00002, J02.00004