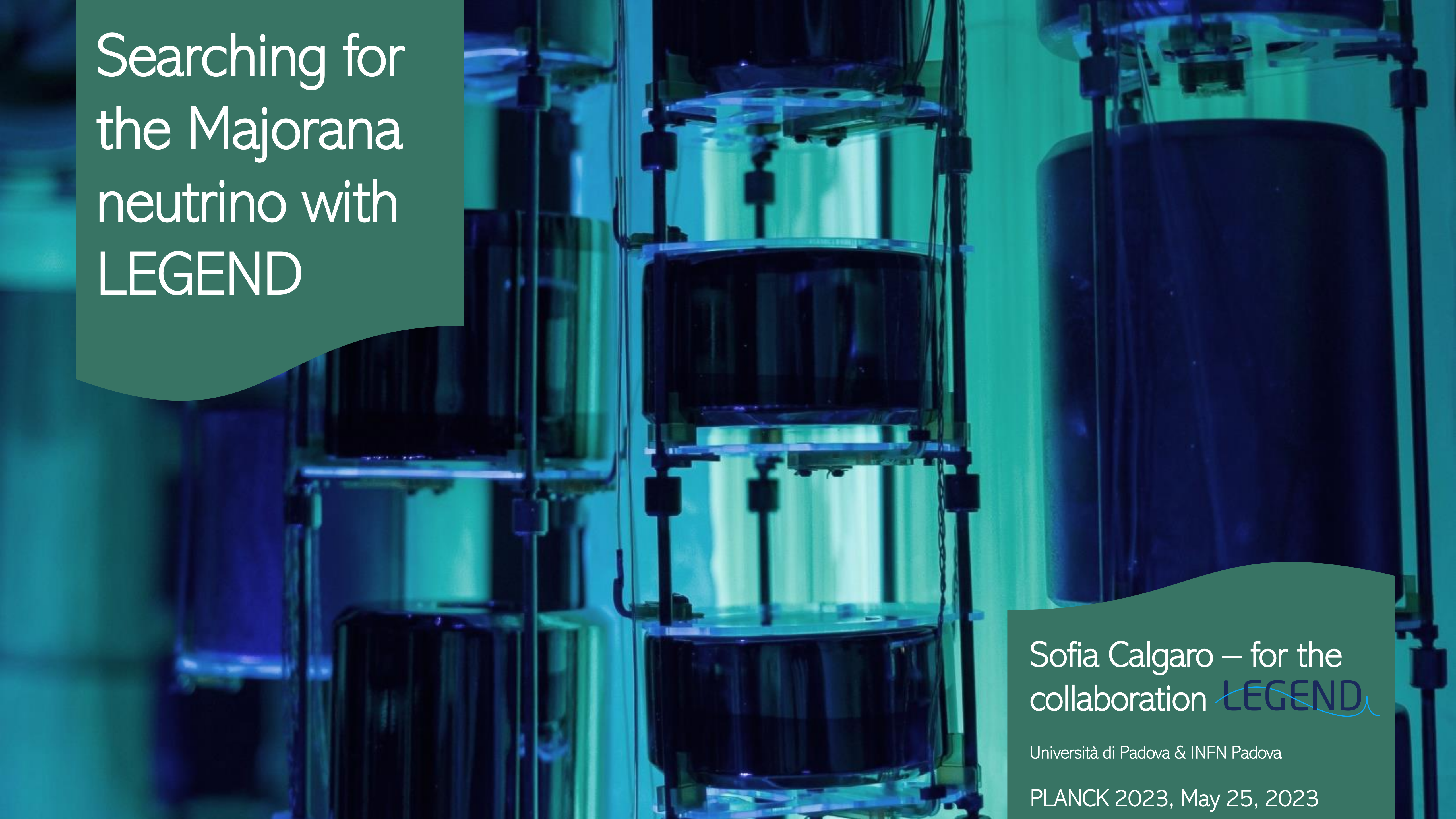


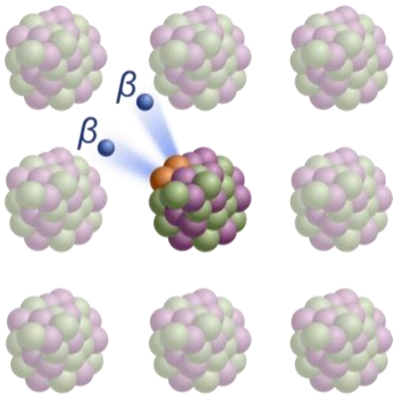
Searching for the Majorana neutrino with LEGEND

Sofia Calgaro – for the collaboration LEGEND

Università di Padova & INFN Padova

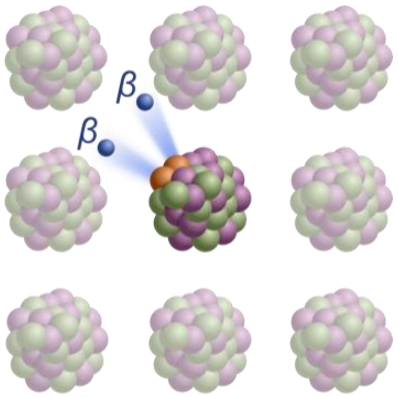
PLANCK 2023, May 25, 2023

The Nature of Neutrinos



- Neutrinoless double-beta **(0νββ) decay: the only known, feasible probe of the Majorana nature of neutrinos**

The Nature of Neutrinos



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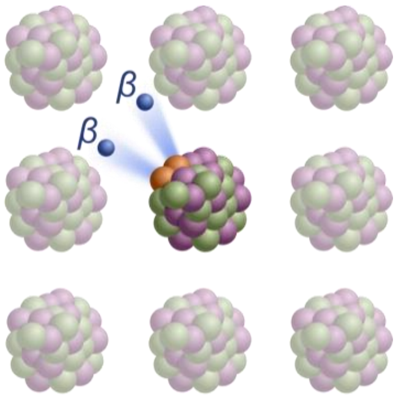

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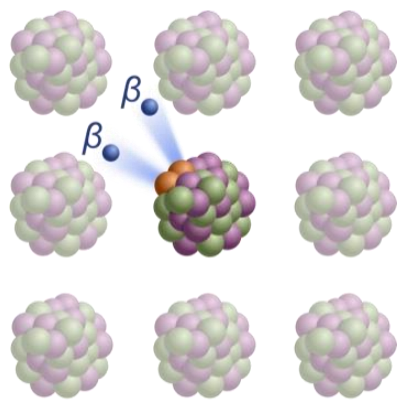

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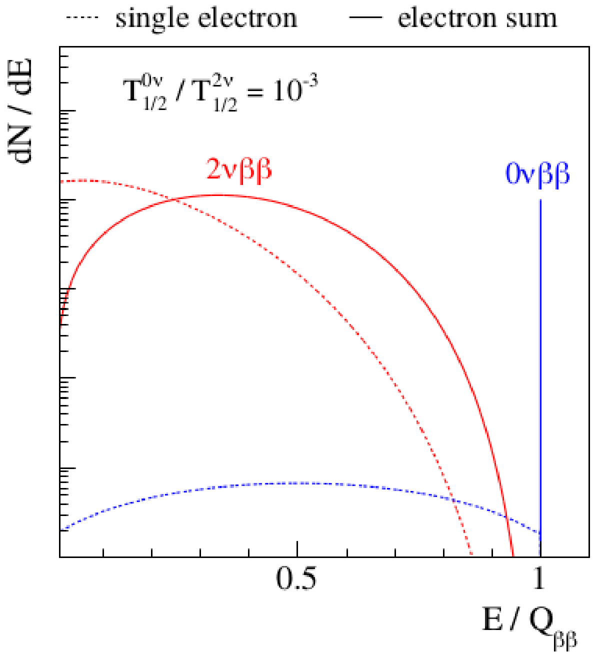
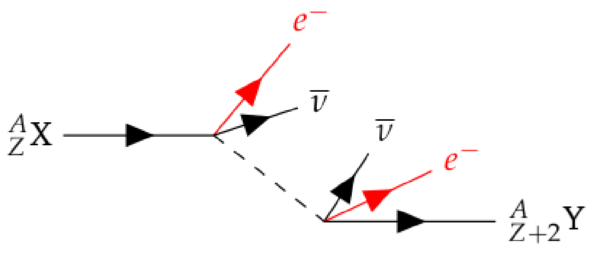
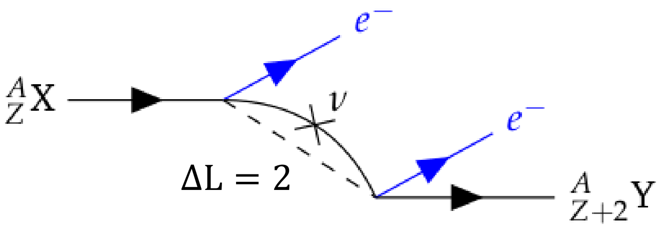


DOUBLE BETA DECAY



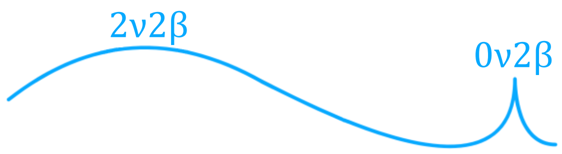
υ & $\bar{\upsilon}$ → we observe υ_L & $\bar{\upsilon}_R$

NEUTRINOLESS DOUBLE BETA DECAY



$\upsilon = \bar{\upsilon}$

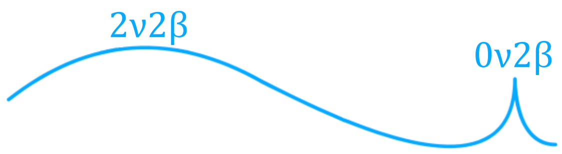
Neutrinoless ββ Decay



0ν2β signal

$$M_{iniz} - M_{fin} - 2m_e = Q_{\beta\beta}$$

Neutrinoless ββ Decay



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0ν2β half-life

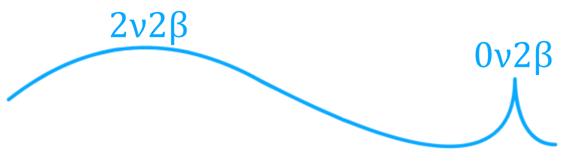
Phase-space integral, $2.36 \cdot 10^{-15}\ yr^{-1}$

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

$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$ → to compare results obtained with different isotopes

Effective Majorana neutrino Mass

Neutrinoless ββ Decay



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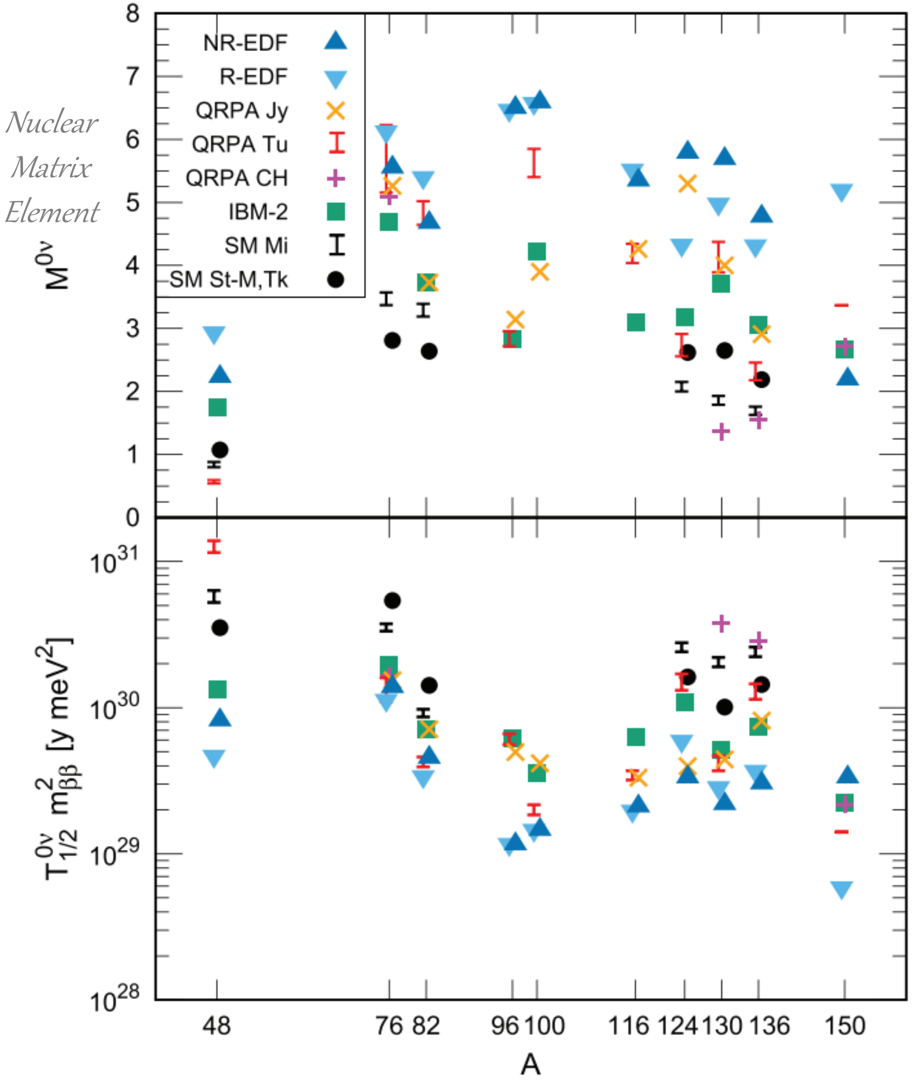
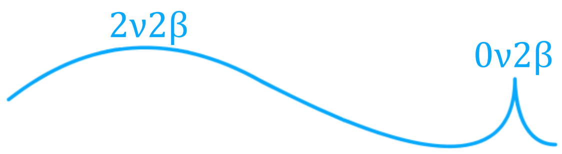
Effective Majorana neutrino Mass

J. Engel, J. Menéndez, "Status and Future of Nuclear Matrix Elements for Neutrinoless Double-Beta Decay: A Review", Rept. Prog. Phys. 80 (2017) 4, 046301.

Nuclear Matrix Element



Neutrinoless ββ Decay



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Effective Majorana neutrino Mass

0ν2β half-life sensitivity

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \varepsilon & \text{without bkg} \\ \epsilon \cdot f \cdot \sqrt{\frac{\varepsilon}{BI \cdot \Delta E}} & \text{with bkg} \end{cases}$$

ϵ: efficiency
f: isotopic fraction
$\varepsilon = M \cdot t$: exposure
ΔE: energetic resolution at $Q_{\beta\beta}$
BI: bkg level

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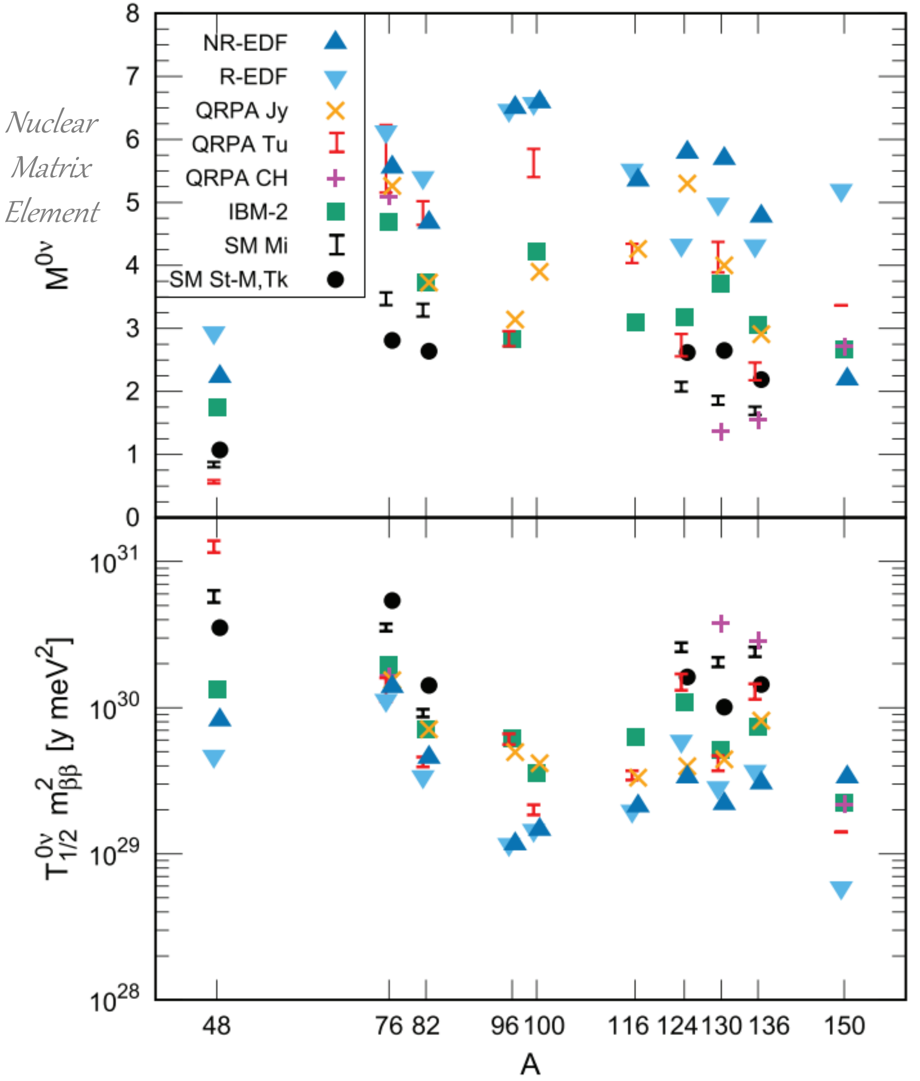


What is the best isotope to use?

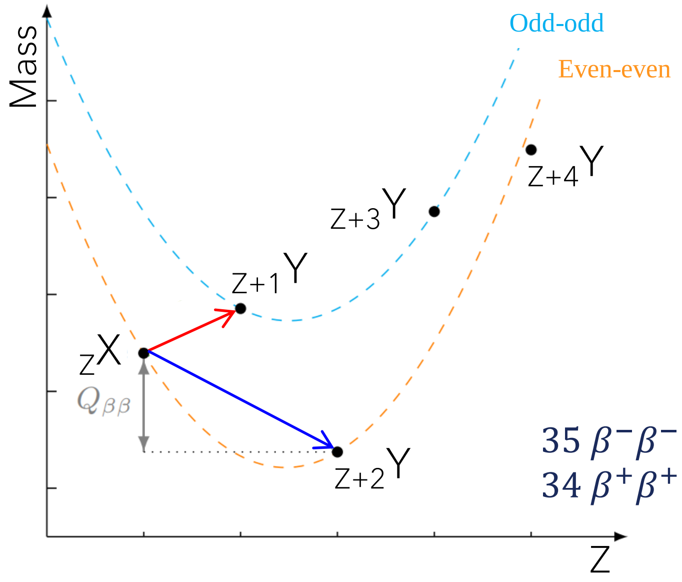
Searchig the 0ν2β

No theoretical preferences

- Large theoretical uncertainties
- $G^{0\nu}$ & NME are inversely correlated: tend to compensate

Experimental preferences

- Costs
- Energetic resolution
- Background level
- Scalability (liquids, gas, cristals)



Searchig the $0\nu2\beta$

No theoretical preferences

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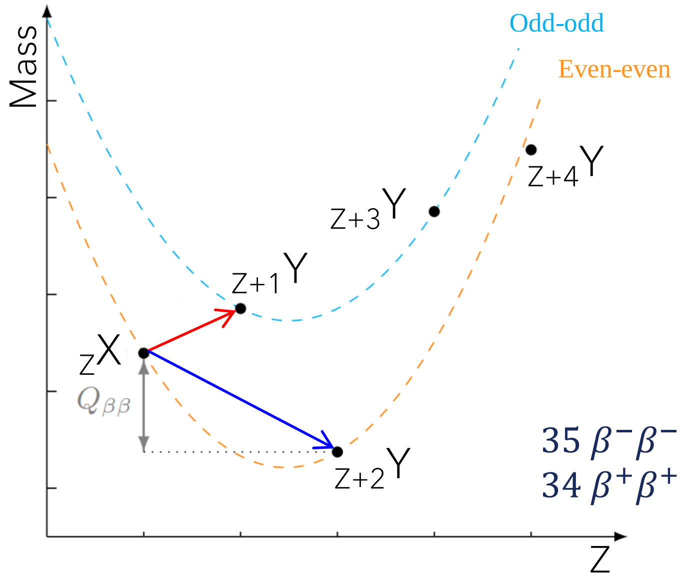
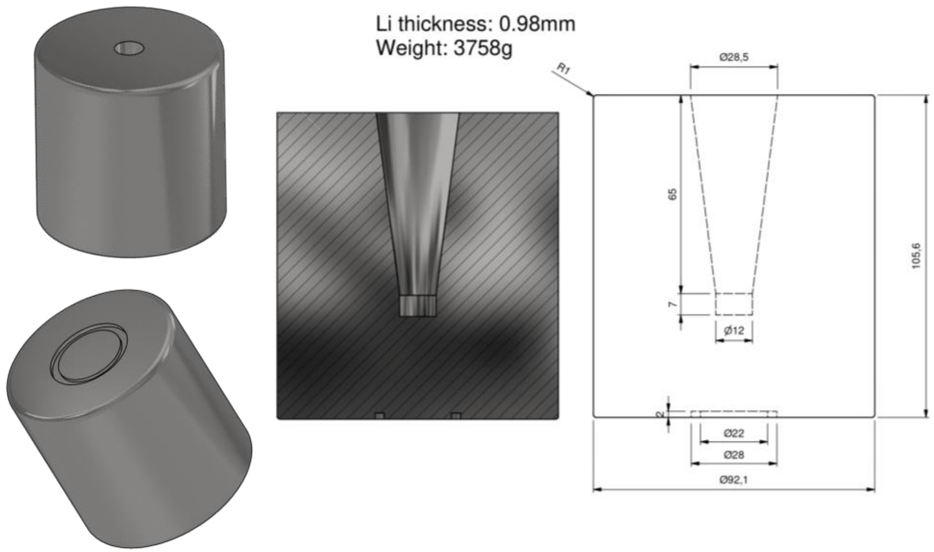


GERMANIUM, $^{76}_{32}\mathbf{Ge} \rightarrow {}^{76}_{34}\mathbf{Se} + \mathbf{2e^-}\ [+\mathbf{2\bar{\nu}_e}]$

$Q_{\beta\beta}(^{76}\mathrm{Ge}) = 2039.061 \pm 0.007$ keV

- Already established technology
- Source ≡ detector ⟹ high detection efficiency
- Ge: high purity ⟹ low intrinsic background
- Excellent energetic resolution ⟹ $\mathbf{FWHM \sim 0.1\%}$ @ $Q_{\beta\beta}$
- Low $\boldsymbol{Q_{\beta\beta}}$ ⟹ difficult to reach low bkg levels
- $\boldsymbol{f_{76}^{nat} \sim 8\%}$ ⟹ the enrichment in Ge-76 is necessary



Ge-76 Enriched Diodes

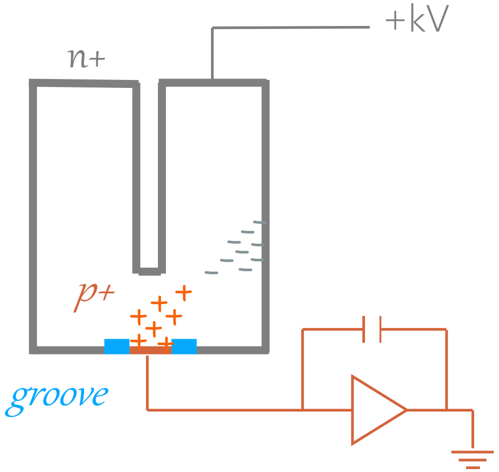
- p+ (implanted B) & n+ (diffused Li), passivated groove
- Full depleted crystals
- Different geometries: **BEGe, PPC, coaxials, IC**
- Mass: **~0.7-4 kg**

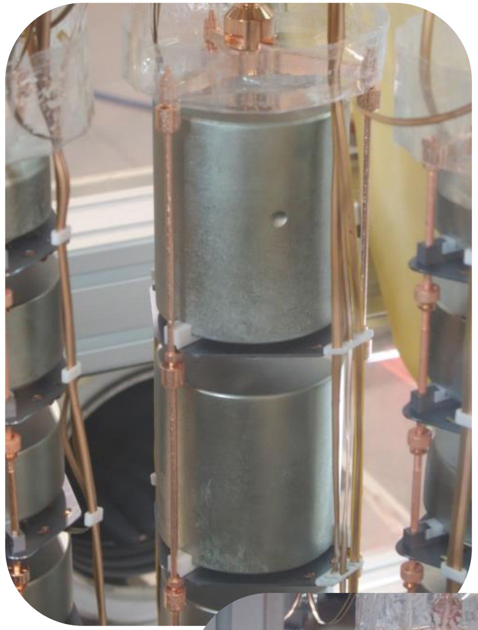

Broad Energy Germanium (BEGe)

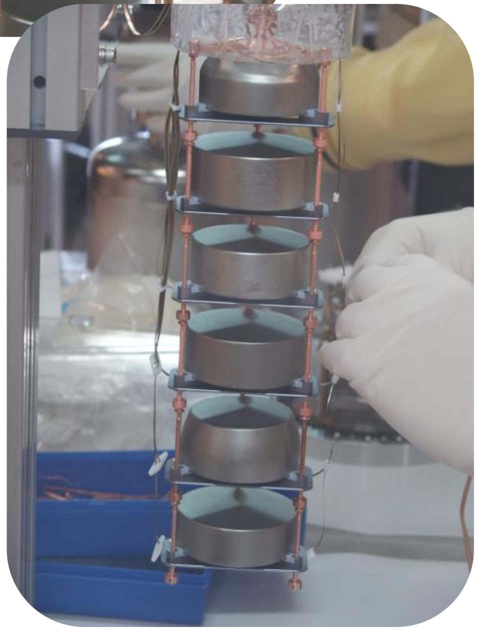

P-type Point-Contact (PPC)


Coaxial


Inverted Coaxial (IC)







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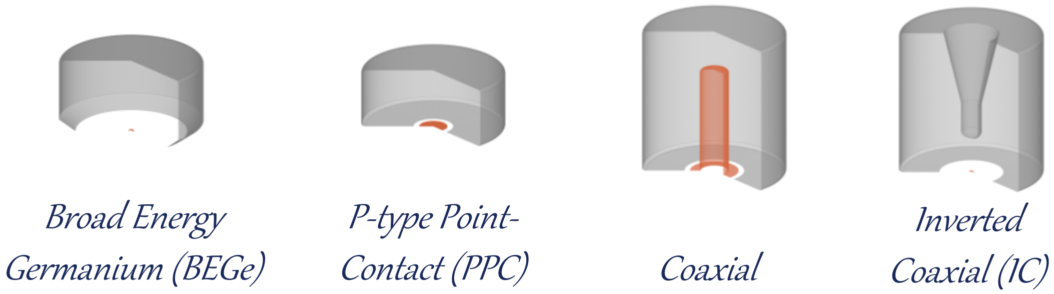
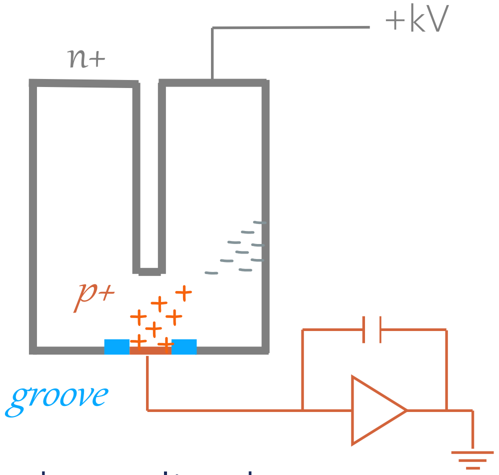
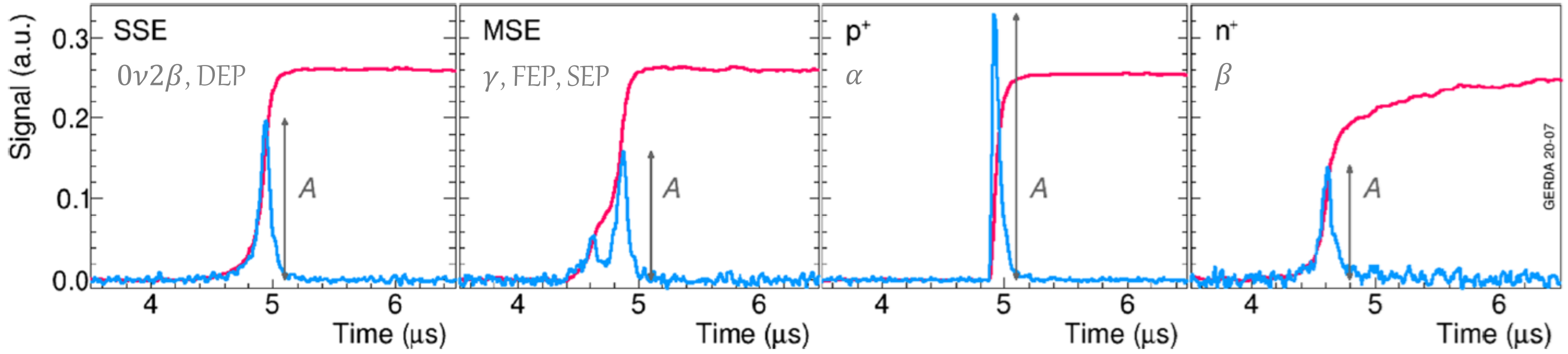




- Signal discrimination based on the signal risetime and amplitude
- Pulse shape discrimination (PSD) analysis



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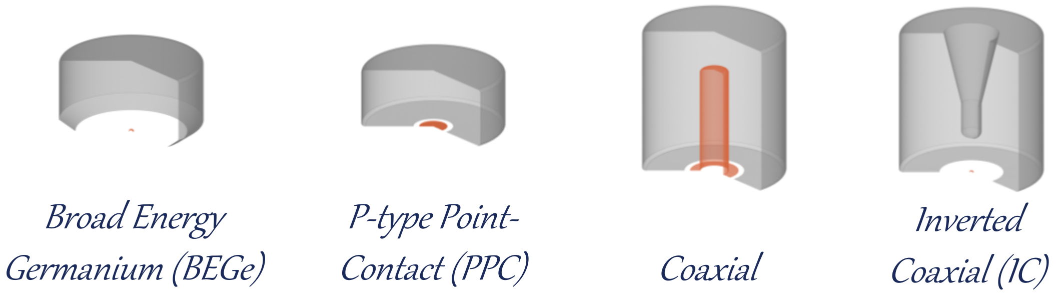

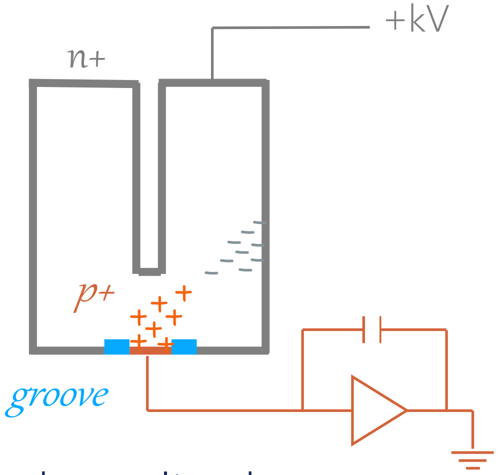

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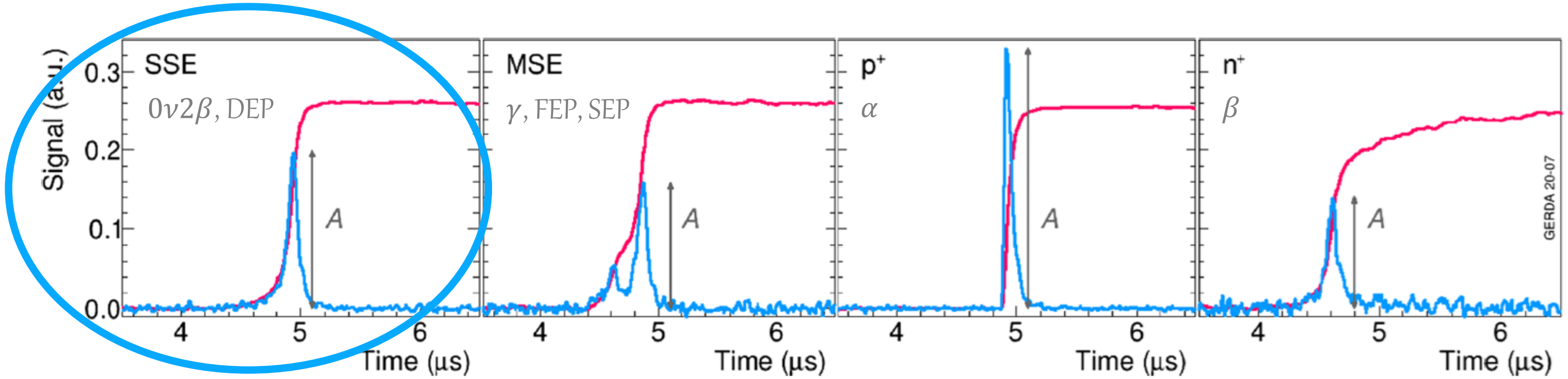
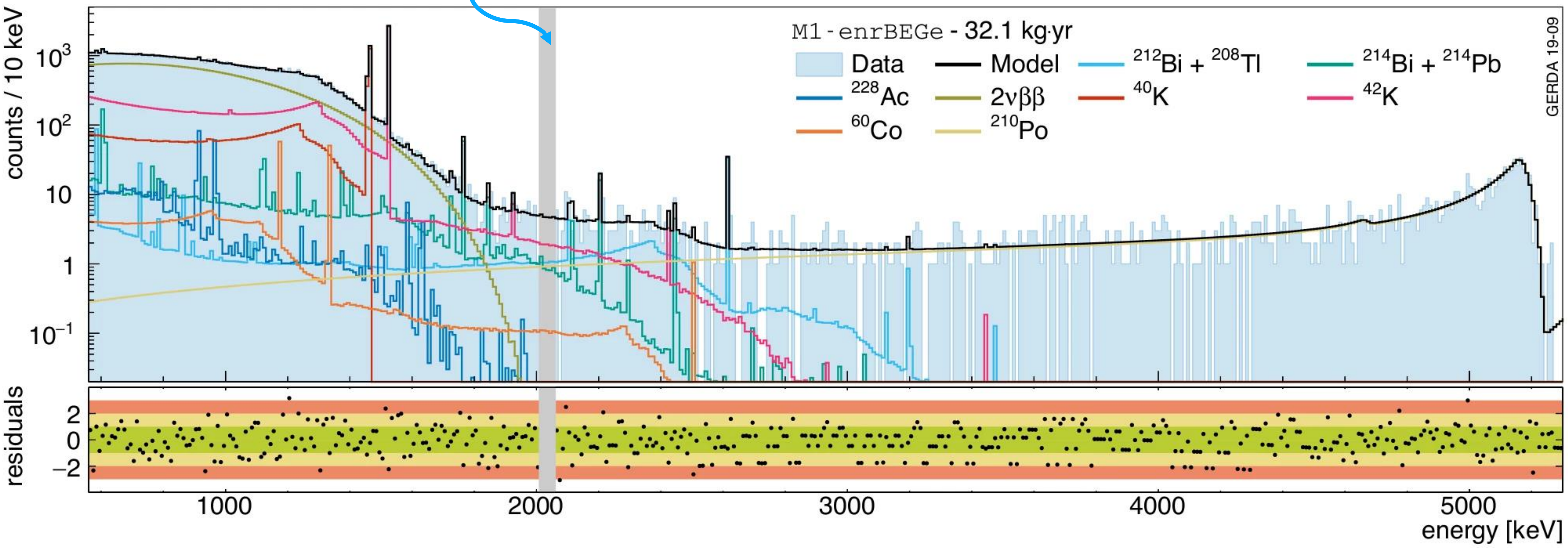


Energy Spectrum

$Q_{\beta\beta}(^{76}\mathrm{Ge}) = 2039.061 \pm 0.007\ \mathrm{keV}$



- Energy spectrum prior to the analysis cuts

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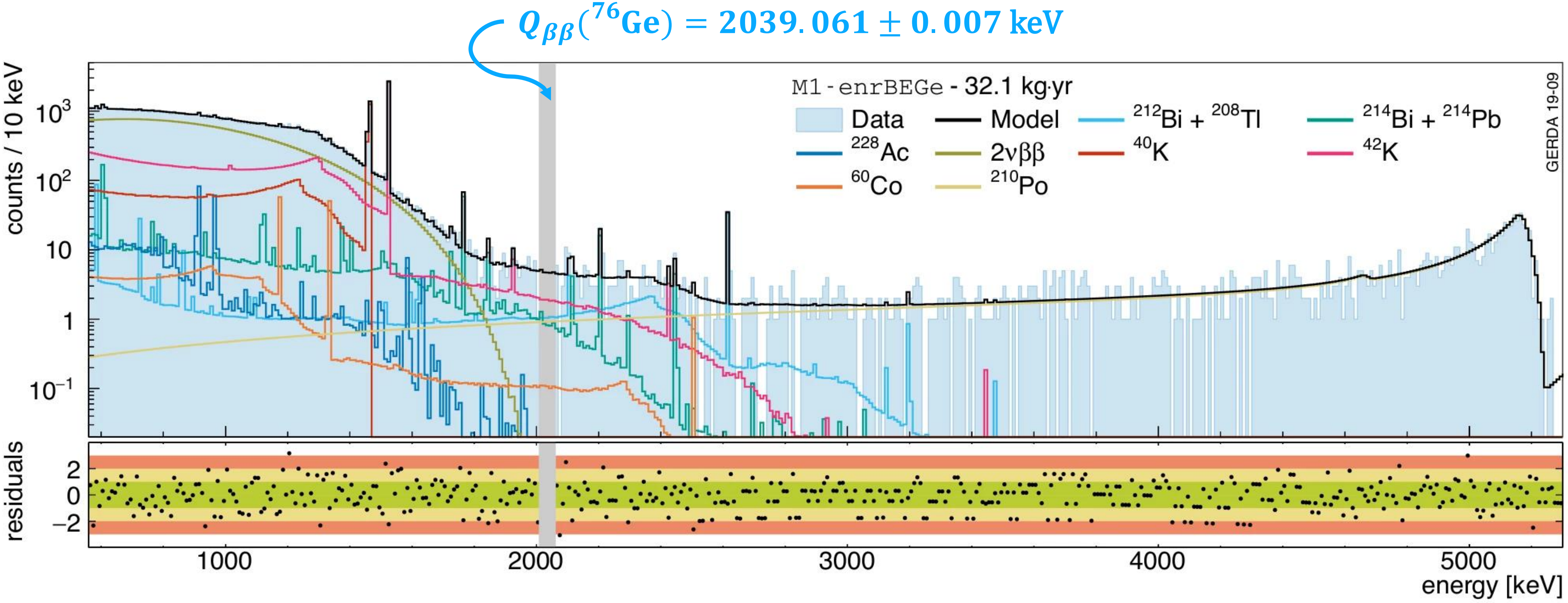

- Energy spectrum prior to the analysis cuts
- Blinded analysis in $Q_{\beta\beta} \pm 25$ keV

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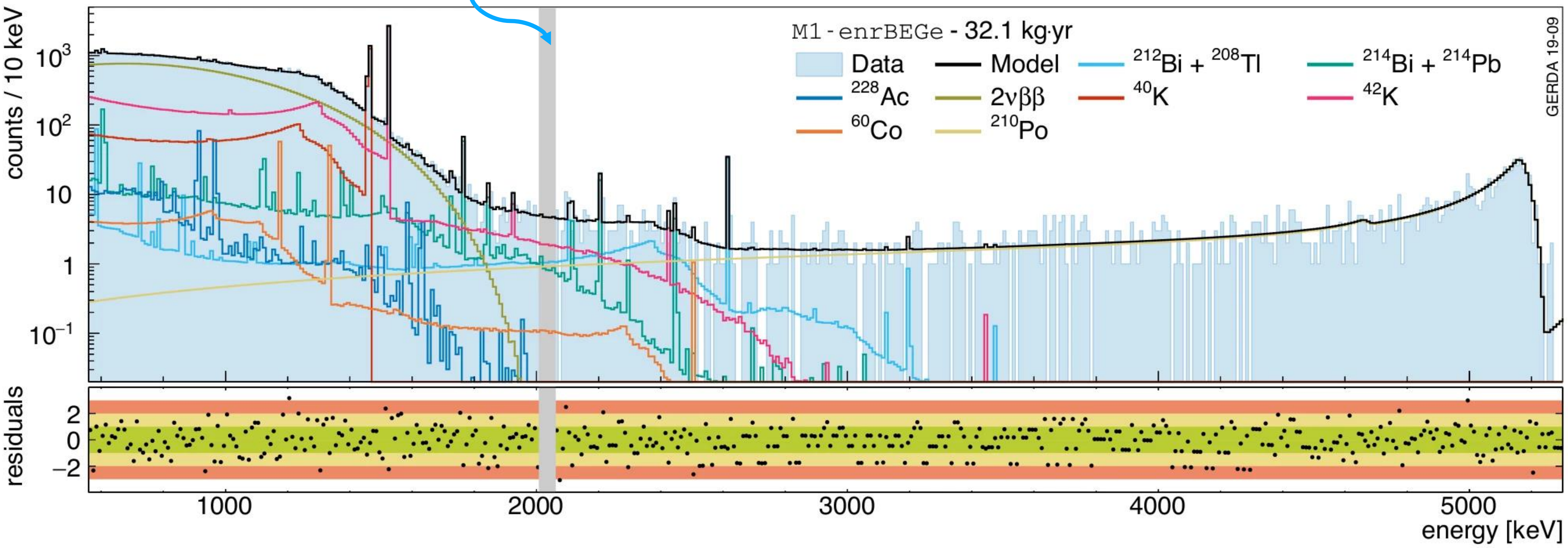

- Energy spectrum prior to the analysis cuts
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- The background index (BI) is evaluated starting from the study of the remnant spectrum

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \varepsilon & \text{with bkg} \\ \epsilon \cdot f \cdot \sqrt{\dfrac{\varepsilon}{BI \cdot \Delta E}} & \text{without bkg} \end{cases}$$

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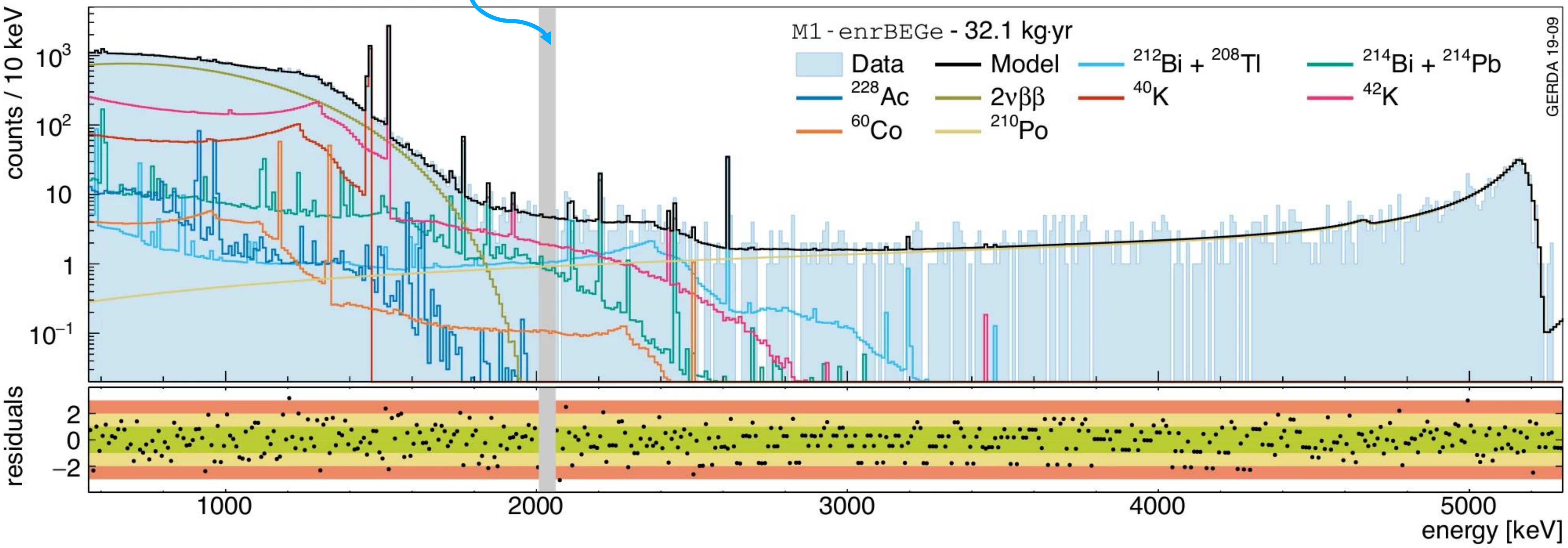

- Energy spectrum prior to the analysis cuts
- Blinded analysis in $Q_{\beta\beta} \pm 25$ keV
- The background index (BI) is evaluated starting from the study of the remnant spectrum
- **"Bkg-free regime": <1 count in $Q_{\beta\beta} \pm 0.5$ FWHM**

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \varepsilon & \text{without bkg} \\ \epsilon \cdot f \cdot \sqrt{\frac{\varepsilon}{BI \cdot \Delta E}} & \text{with bkg} \end{cases}$$

The LEGEND project

GERDA

GERmanium Detector Array

See Yannick Müller's talk (parallel 12)

Bkg-free!
~0.3 events for 100 kg yr

	GERDA
Mass [kg]	45
Exposure [kg·yr]	100
BI [cts/(keV·kg·yr)]	$(5.2\pm1.6)\cdot10^{-4}$
Resolution [keV]	2.6 ± 0.2

Ge-76 Experiments

GERDA

GERmanium Detector Array

See Yannick Müller's talk (parallel 12)

Bkg-free!
~0.3 events for 100 kg yr

MAJORANA DEMONSTRATOR

	GERDA	MAJORANA
Mass [kg]	45	30
Exposure [kg·yr]	100	26
BI [cts/(keV·kg·yr)]	$(5.2\pm1.6)\cdot10^{-4}$	$(4.7\pm0.8)\cdot10^{-3}$
Resolution [keV]	2.6 ± 0.2	2.52 ± 0.08

GERDA

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MAJORANA DEMONSTRATOR

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

200

1000

	GERDA	MAJORANA	LEGEND-200	LEGEND-1000
Mass [kg]	45	30	200	1'000
Exposure [kg·yr]	100	26	1'000	10'000
BI [cts/(keV·kg·yr)]	$(5.2\pm1.6)\cdot10^{-4}$	$(4.7\pm0.8)\cdot10^{-3}$	$2\cdot10^{-4}$	10^{-5}
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LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

200 **1000**

	GERDA	MAJORANA	LEGEND-200	LEGEND-1000
Mass [kg]	45	30	200	1'000
Exposure [kg·yr]	100	26	1'000 ››› ×10	10'000 ››› ×100
BI [cts/(keV·kg·yr)]	$(5.2\pm1.6)\cdot10^{-4}$	$(4.7\pm0.8)\cdot10^{-3}$	$2\cdot10^{-4}$	10^{-5}
Resolution [keV]	2.6 ± 0.2	2.52 ± 0.08	2.5	2.5

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GERmanium Detector Array

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Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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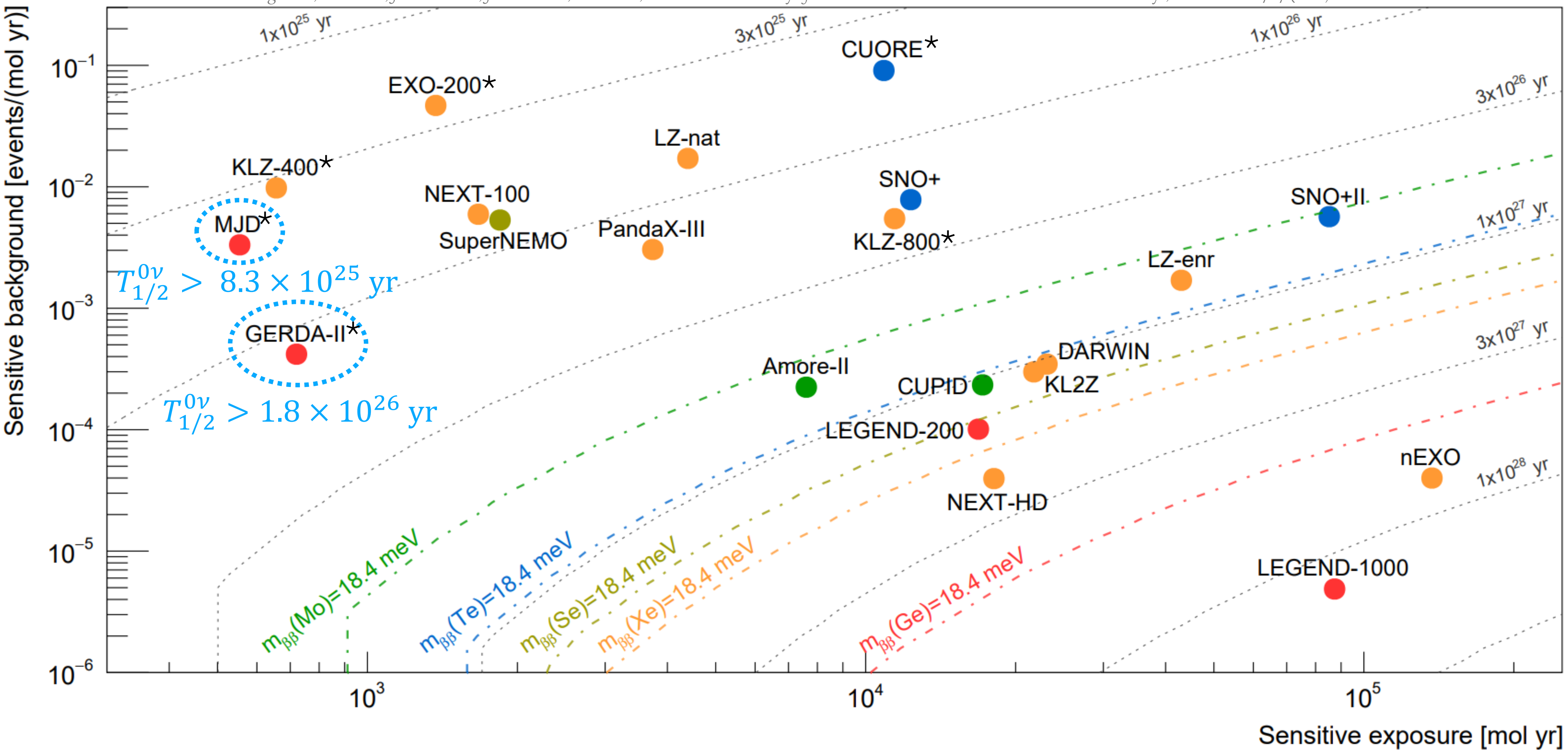
Resolution [keV]	2.6±0.2	2.52±0.08	2.5	2.5

$0\nu2\beta$ Experiments

M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani, "Toward the discovery of matter creation with neutrinoless double-beta decay", arXiv:2202.01787 (2022).



- Assumption: 10 yr of data acquisition for all experiments, but for those that already finished to operate (*)
- The colorful-dashed lines correspond to the half-life sensibility requested to test the inverted hierarchy with isotopes Mo-100, Te-130, Se-82, Xe-136, Ge-76

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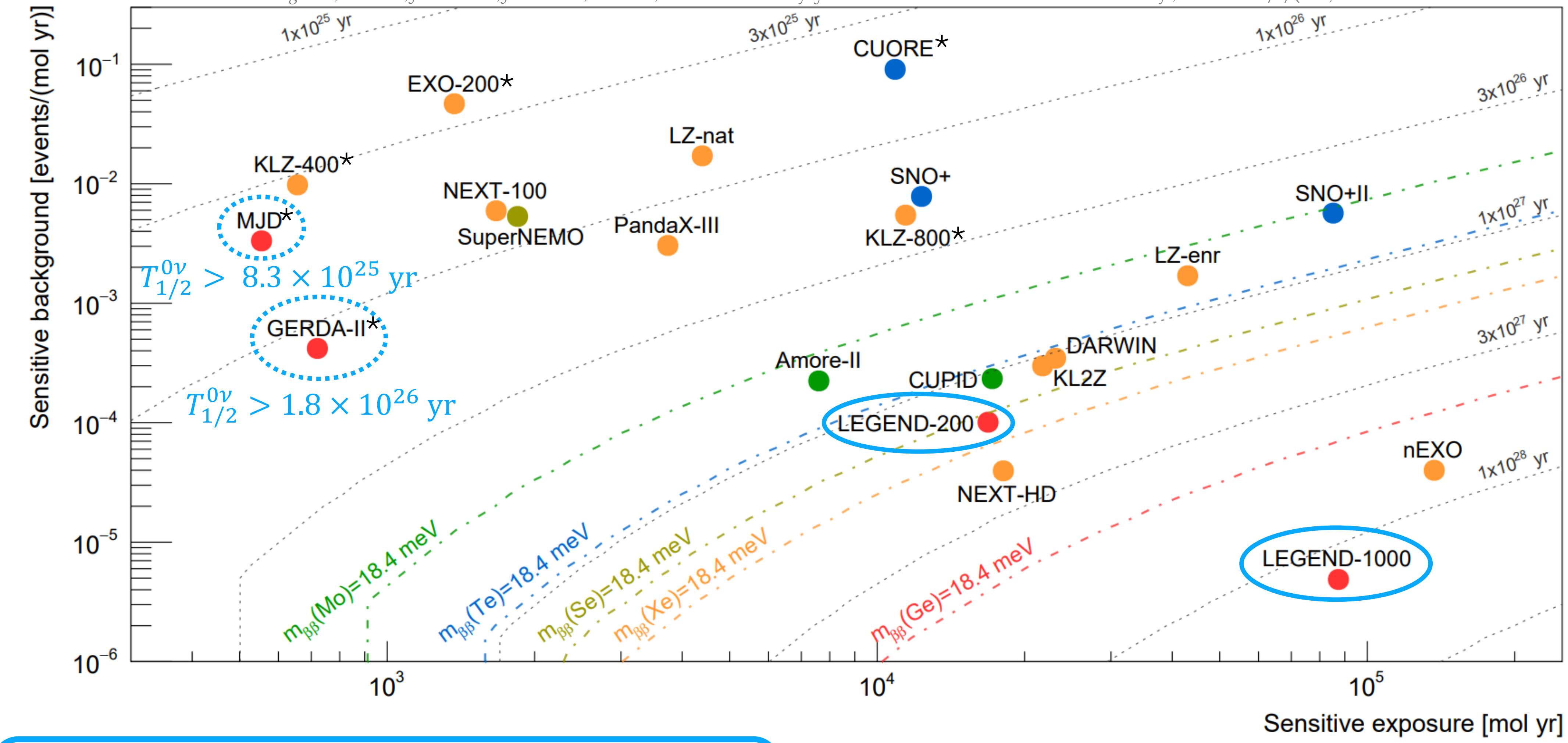

LEGEND-200: $T_{1/2}^{0\nu} > 10^{27}$ yr @ 90% CL

LEGEND-1000: $T_{1/2}^{0\nu} > 1.6 \cdot 10^{28}$ yr @ 90% CL

- Assumption: 10 yr of data acquisition for all experiments, but for those that already finished to operate (*)
- The colorful-dashed lines correspond to the half-life sensibility requested to test the inverted hierarchy with isotopes Mo-100, Te-130, Se-82, Xe-136, Ge-76

Inverse or Normal Hierarchy?

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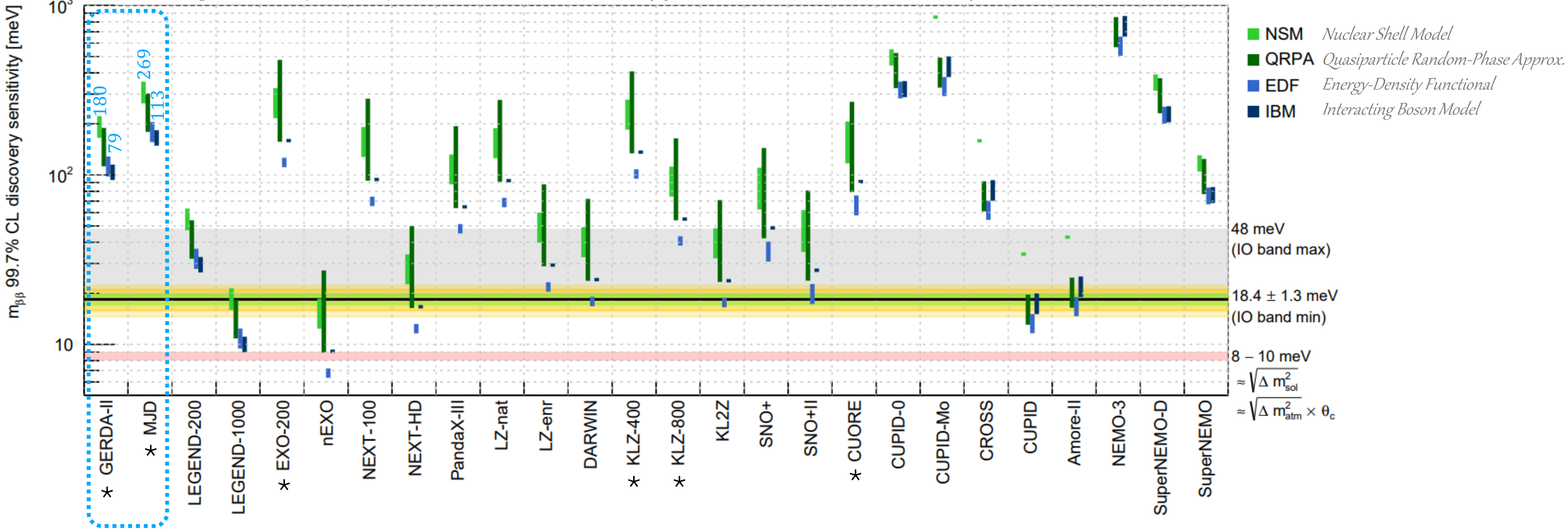

- Gray band: range of values $m_{\beta\beta}$ for the inverse hierarchy and $m_{light} \rightarrow 0$
- $m_{\beta\beta}$=18.4 meV: minimum allowed value for the IO
- 1σ, 2σ, 3σ uncertainty bands for $m_{\beta\beta}$=18.4 meV are shown in green, orange and yellow, respectively
- Red band at 8-10 meV: future aim for 0νββ next-generation experiments

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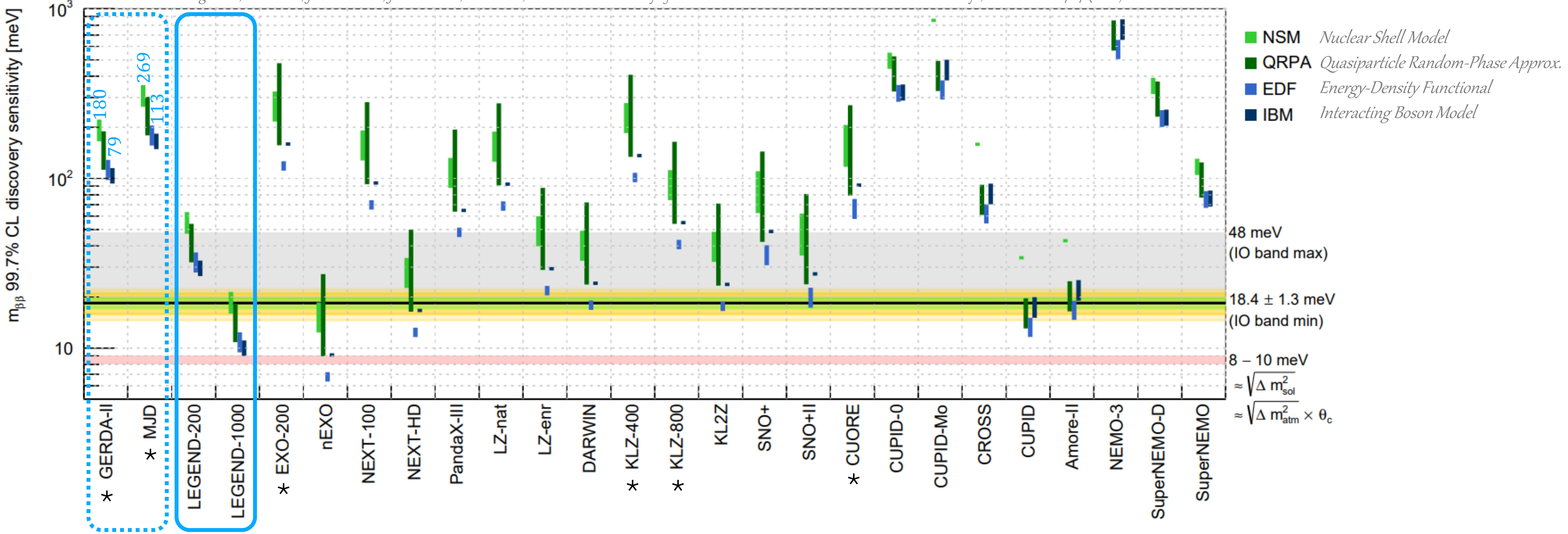
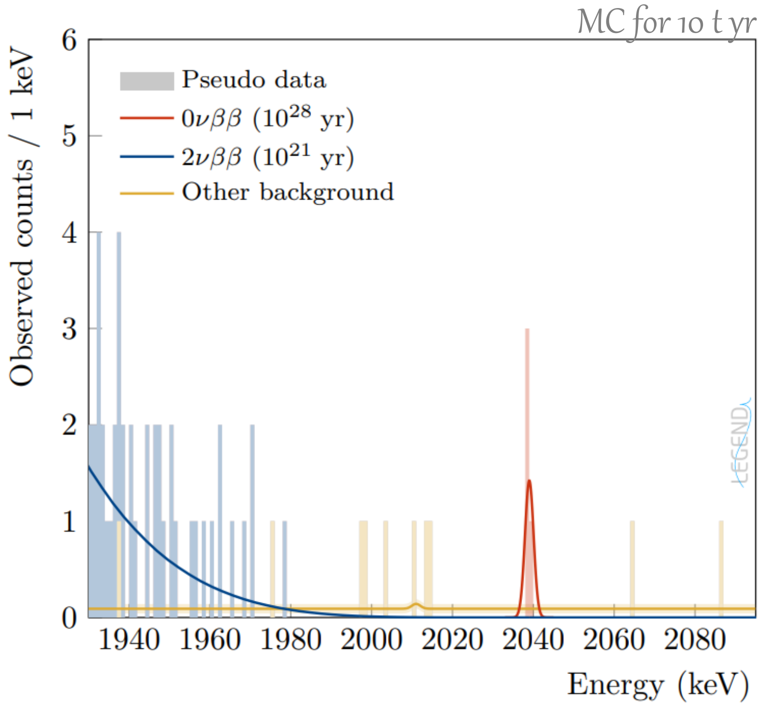


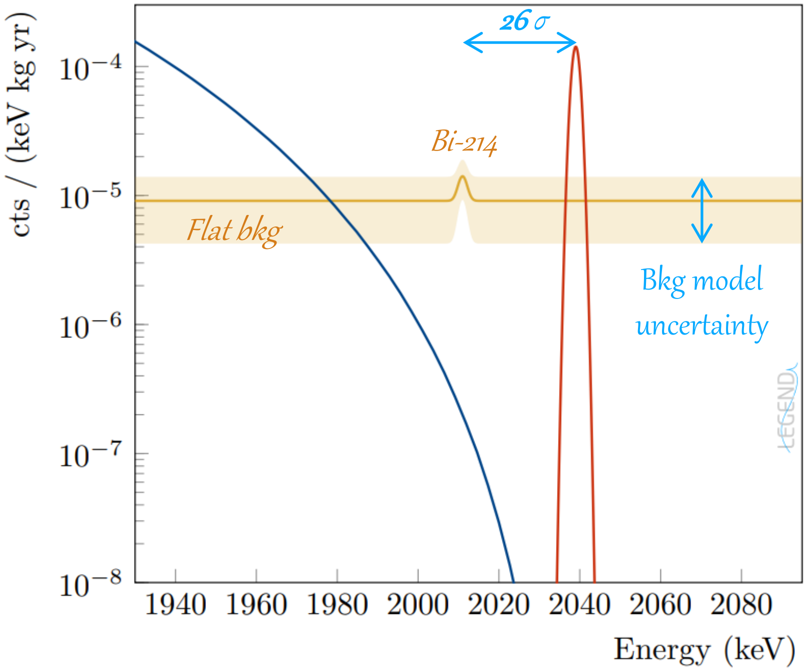
LEGEND-200: $m_{\beta\beta} < 34 - 78$ meV
LEGEND-1000: $m_{\beta\beta} < 8.5 - 19.4$ meV

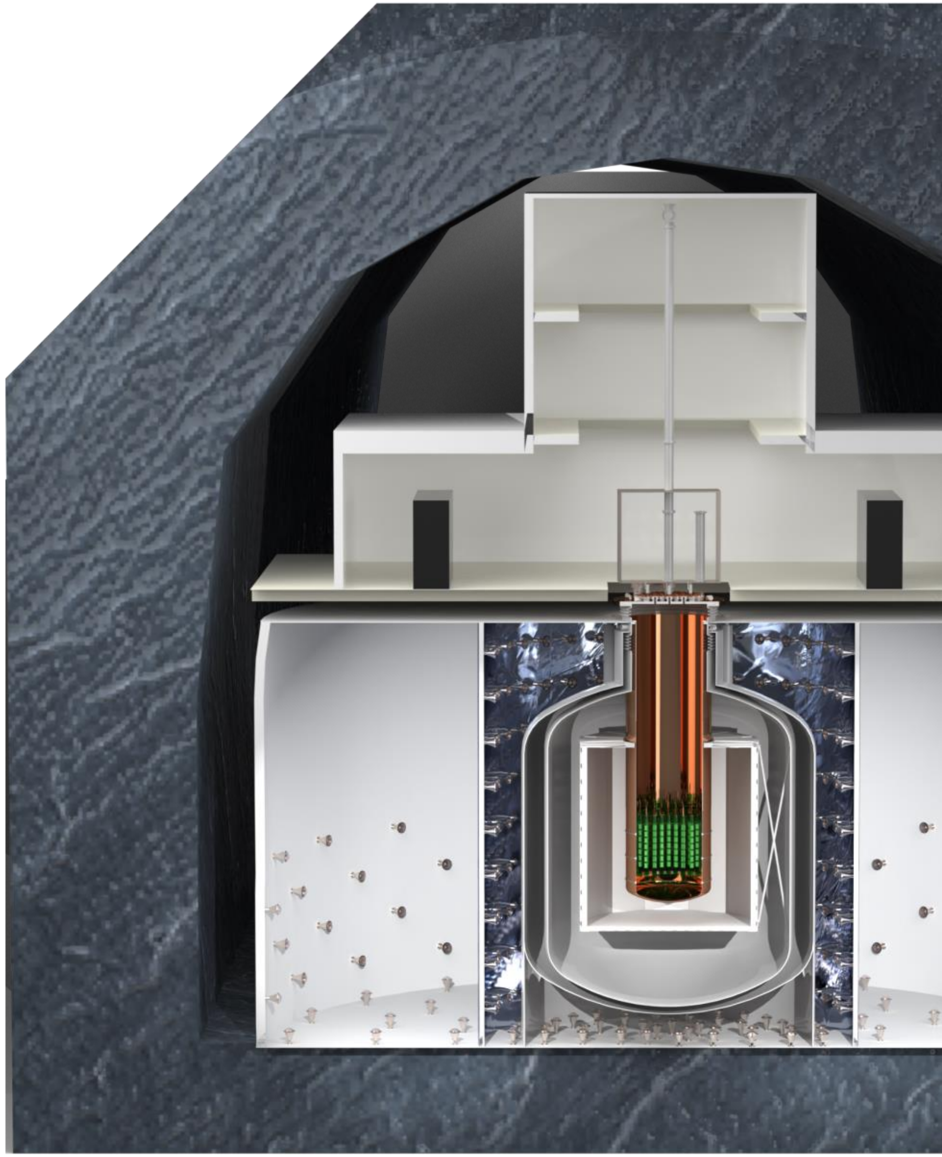
- Gray band: range of values $m_{\beta\beta}$ for the inverse hierarchy and $m_{light} \to 0$
- **$m_{\beta\beta}$=18.4 meV: minimum allowed value for the IO**
- 1σ, 2σ, 3σ uncertainty bands for $m_{\beta\beta}$=18.4 meV are shown in green, orange and yellow, respectively
- **Red band at 8-10 meV: future aim for 0νββ next-generation experiments**

The ultimate goal

LEGEND-1000



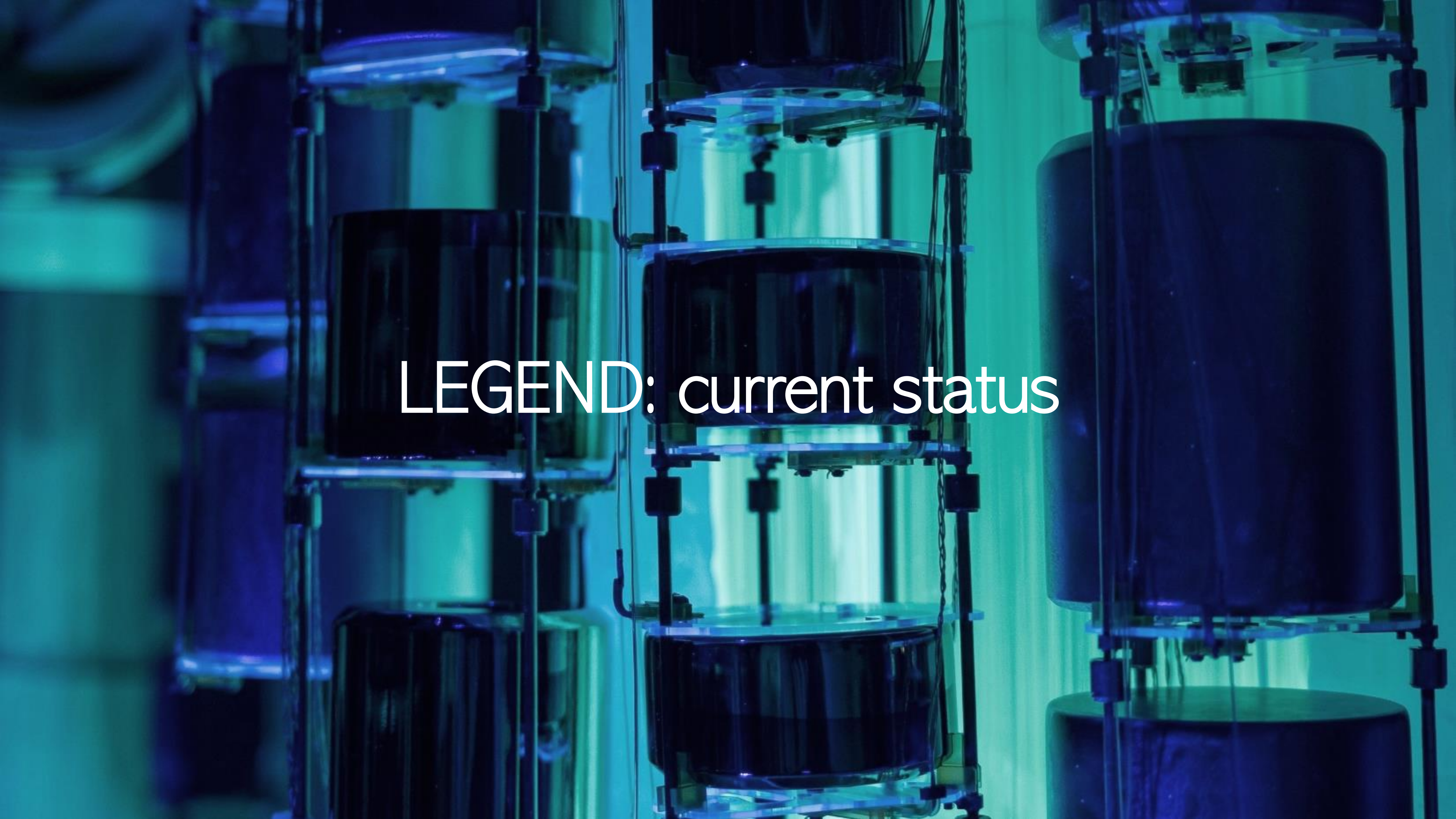




"By combining the lowest background levels and the best energy resolution in the field, ***LEGEND-1000*** *will perform a quasi-background-free search and* ***can make an unambiguous discovery of 0νββ decay*** *with just a handful of counts at the* $Q_{\beta\beta}$*"*

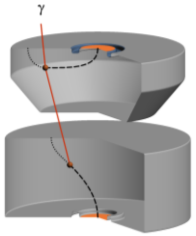
Pre-conceptual Design Report: https://inspirehep.net/literature/1892243

LEGEND: current status



LEGEND-200

Array
of germanium diodes



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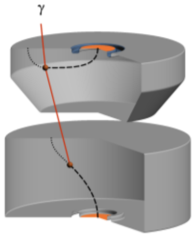
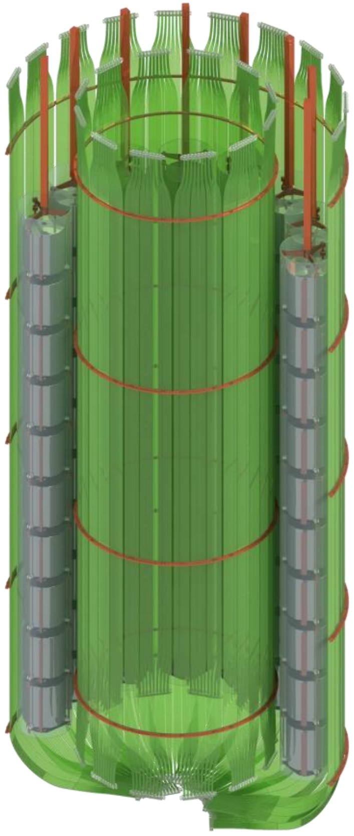
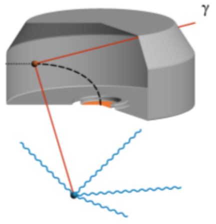


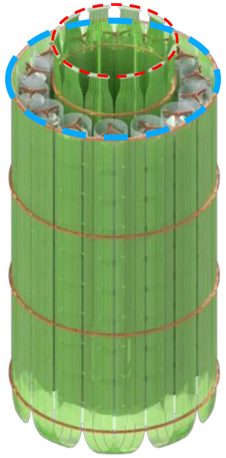
LAr veto

- 58 read-out modules of **SiPMs** coupled to WLS fibers





Outer Barrel (20+20)
Inner Barrel (9+9)



Criostat

- Ø 4m, H 5.88m
- LAr: 64 m^3

LEGEND-200

Array
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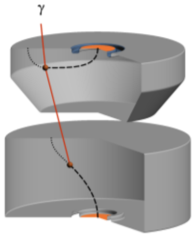

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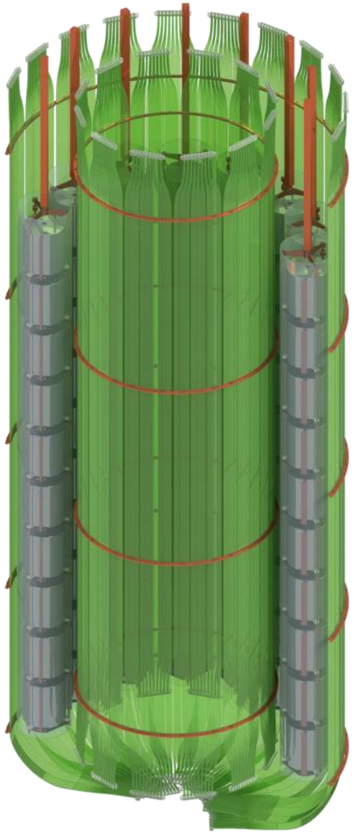
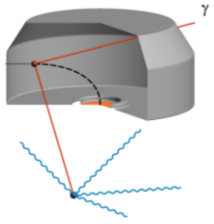
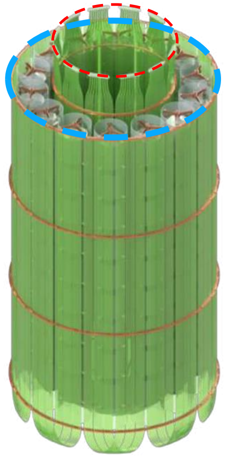




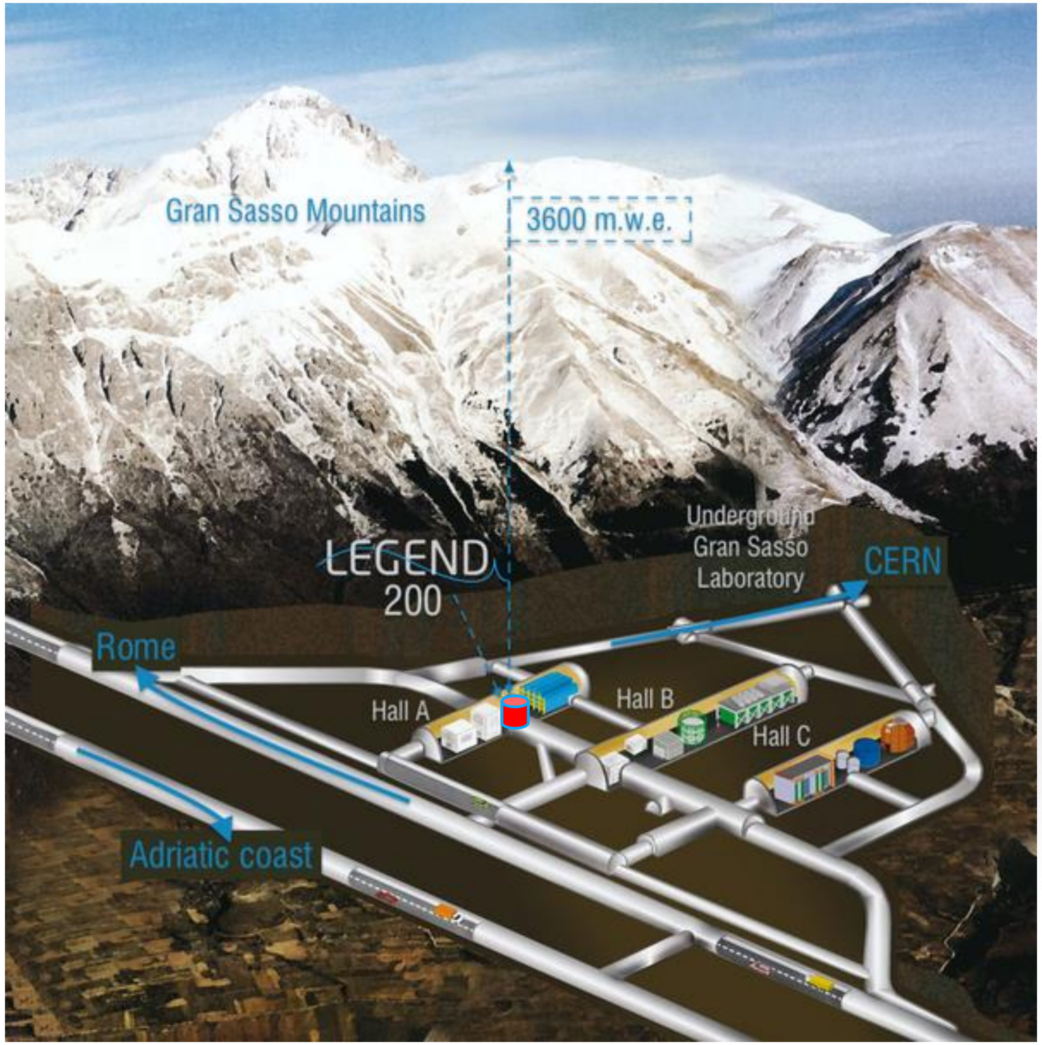


Criostat

- Ø 4m, H 5.88m
- LAr: 64 m^3

Ultrpure water tank

- Shields n, γ
- 66 PMTs (Cherenkov) + plastic scintillators for μ
- Ø 10m, H 8.5 m, V 590 m^3
- Clean room at 9.7 m



- LNGS-Hall A @ 3600 m w.e.
- Same infrastructure of GERDA
- Muon flux reduced to 1.25 / (m^2h) – factor $\mathcal{O}(10^6)$

LEGEND-200: first results

- **101 detectors** (10 strings): 6 coaxials, 26 PPC, 28 BEGe, 41 ICPCs
- **m_{tot}=142.4 kg** (122 kg for the anaysis)

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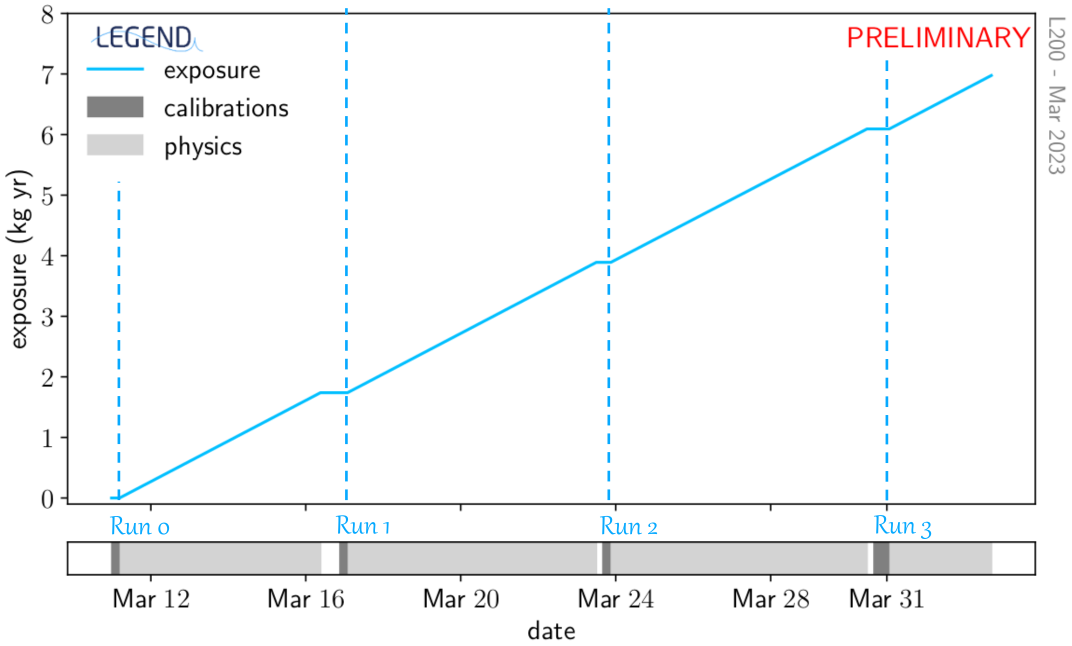
- Excluded unstable detectors (pulser, R=0.05 Hz)



Exposure: **~7 kg yr** (>2 kg yr / week)

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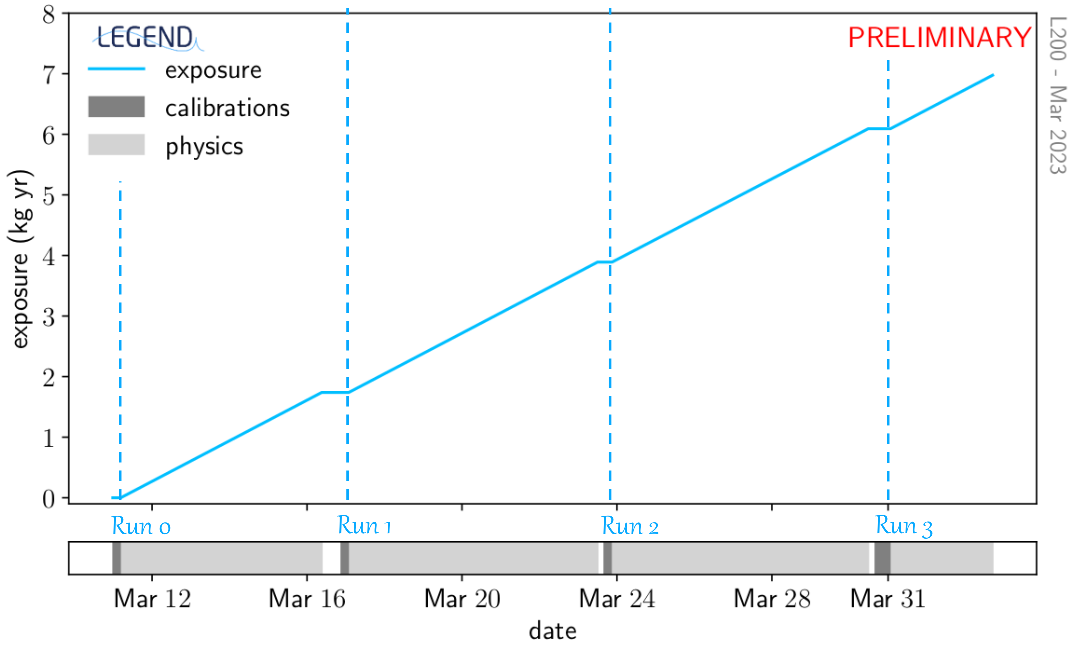

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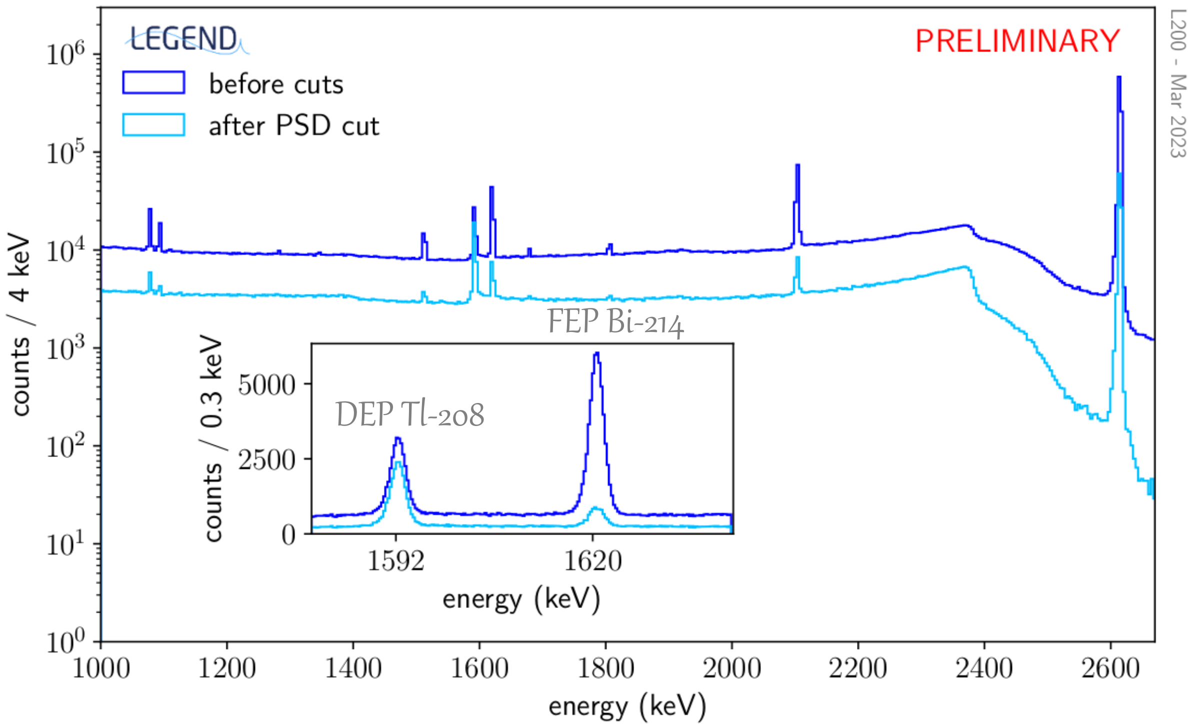
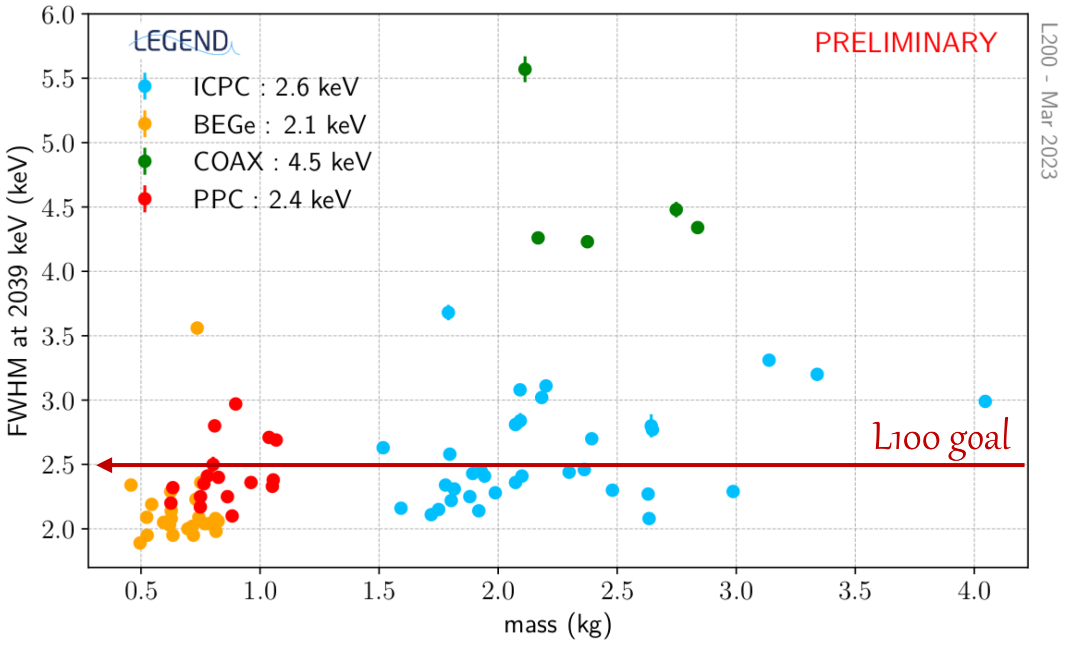


PSD tested with **13 sources of Th-228:**
multi-site events (FEP Bi-214): **~10% s.f.**
single-site events (DEP Tl-208): **~90% s.f.**

LEGEND-200: performance at $Q_{\beta\beta}$



Energy resolution:
FWHM ~ 2.4 keV @ $Q_{\beta\beta}$
(4.5 keV for coaxials)

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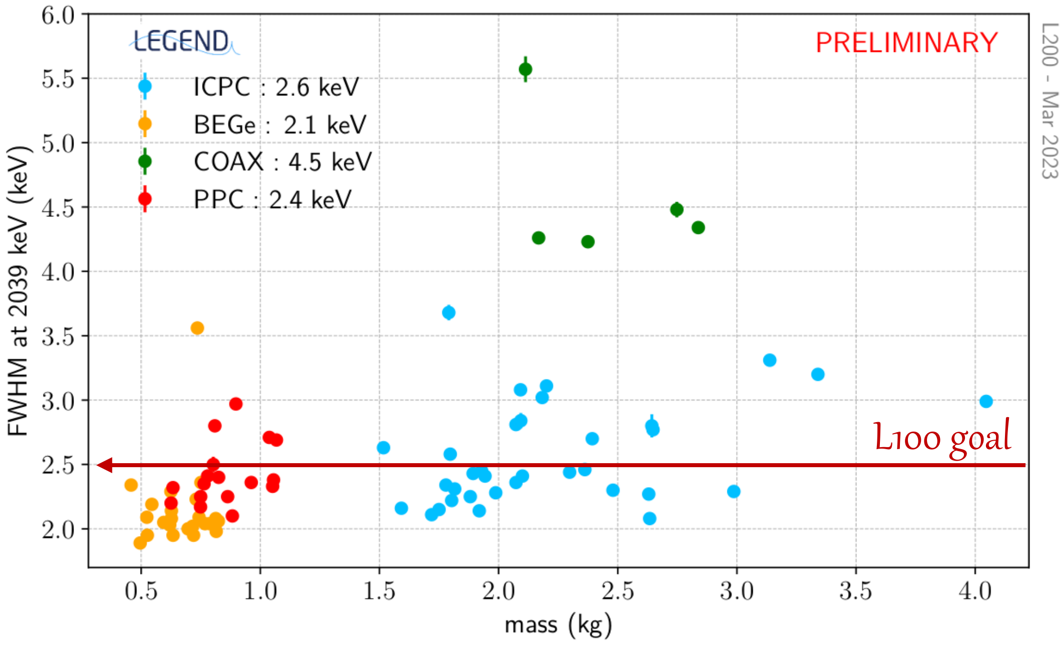

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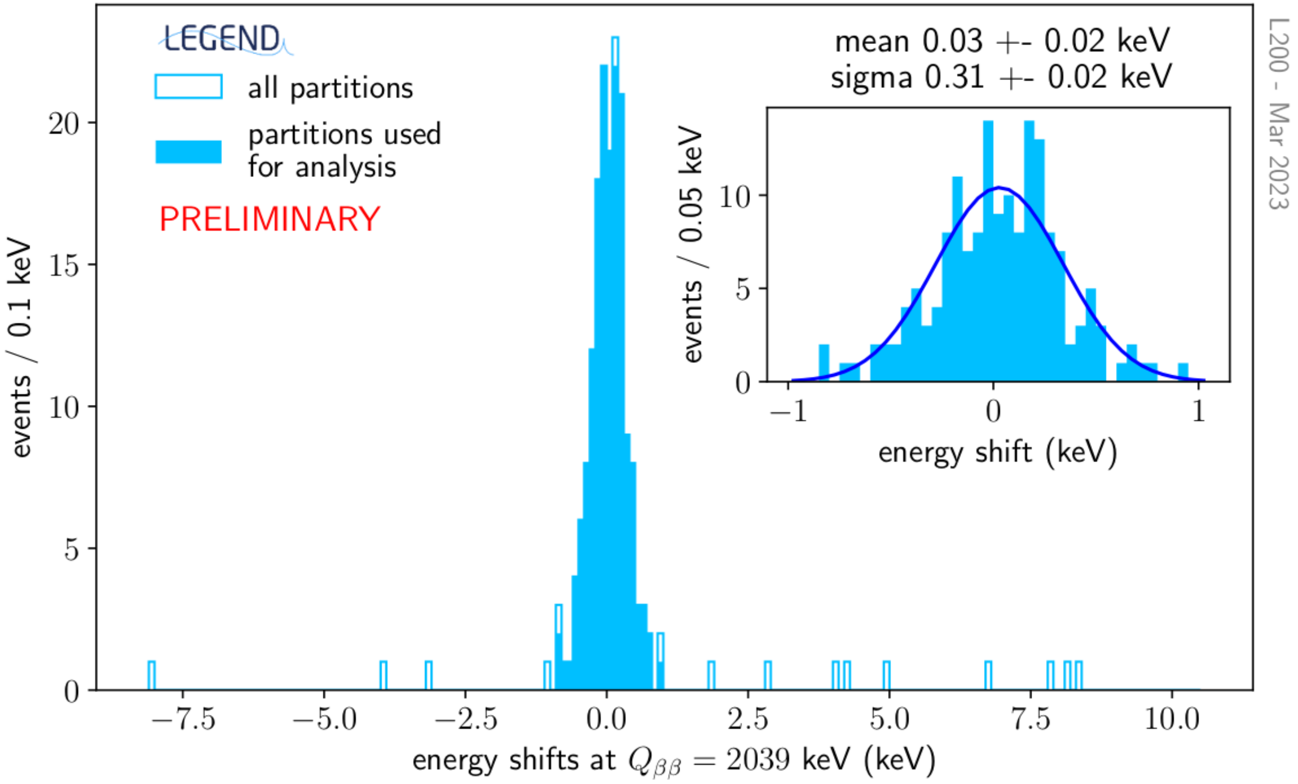
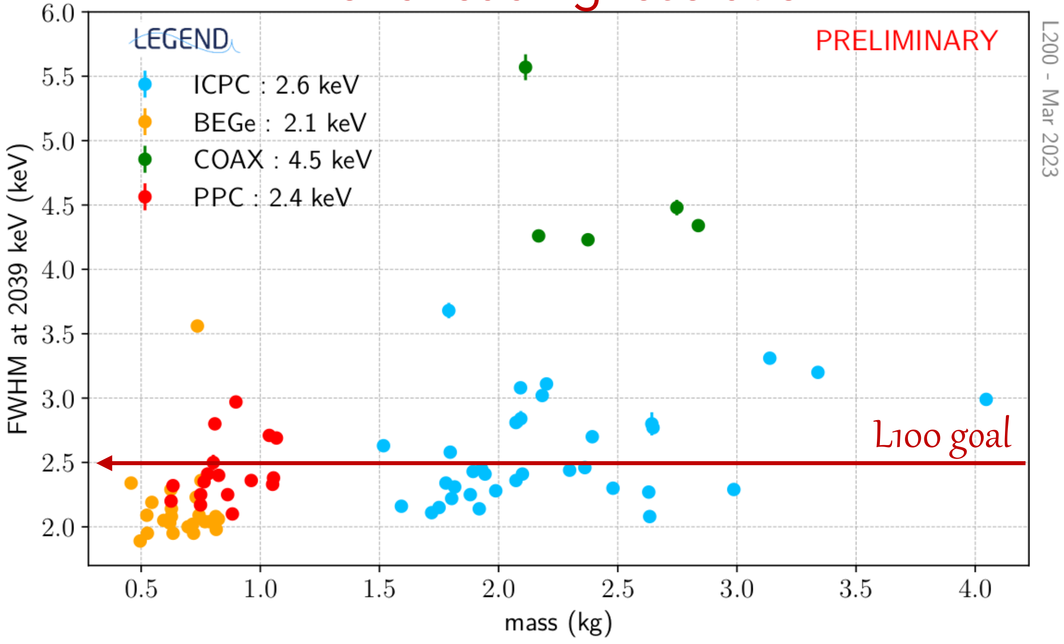


Energy shifts
between subsequent calibrations

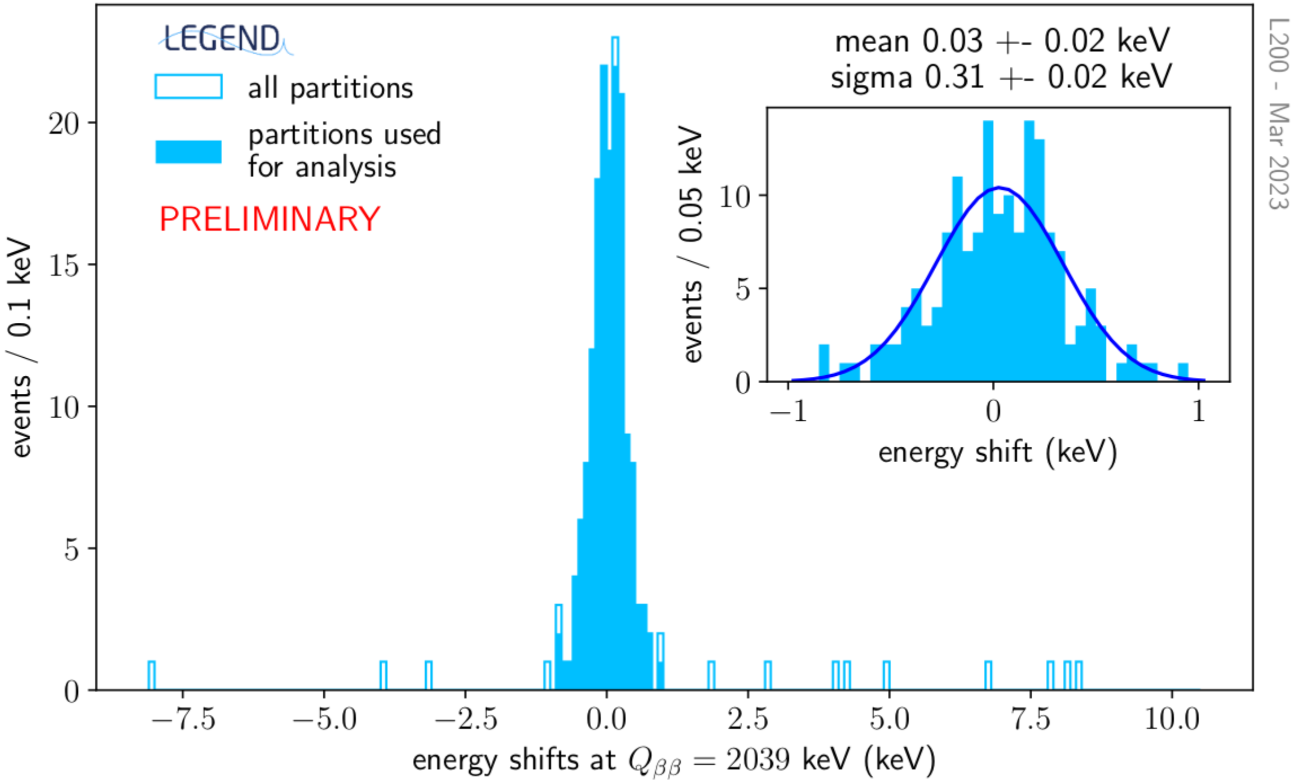
LEGEND-200: performance at $Q_{\beta\beta}$

World-leading resolution



Energy resolution:
FWHM ~ 2.4 keV @ $Q_{\beta\beta}$
(4.5 keV for coaxials)

Extremely stable for >120 kg of detectors



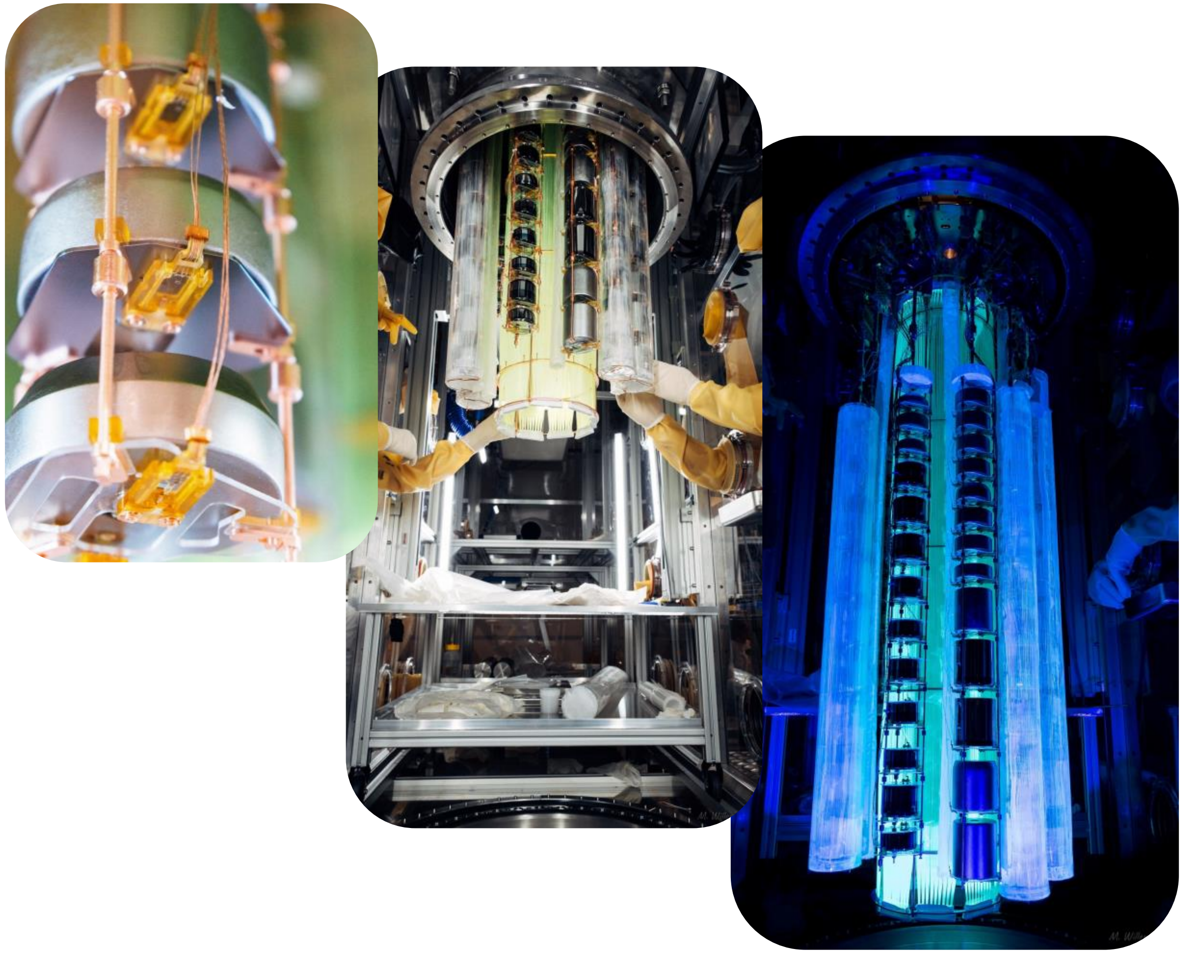
Energy shifts
between subsequent calibrations

Conclusions

Looking for 0νββ…

LEGEND = Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- Neutrinoless Double Beta ($0\nu2\beta$) Decay
  - Requires the construction of large experiments
- Germanium Experiments
  - GERDA and MJD demonstrated the advantages of using the germanium detector technology
- LEGEND
  - Optimized for the search for the $0\nu2\beta$ decay
  - ICPC detectors already satisfy L1000 requirements
  - PSD cuts consisten with expectations
  - ~50 kg of detectors in hand/production
  - BI in late summer, first $0\nu2\beta$ decay results in 2024

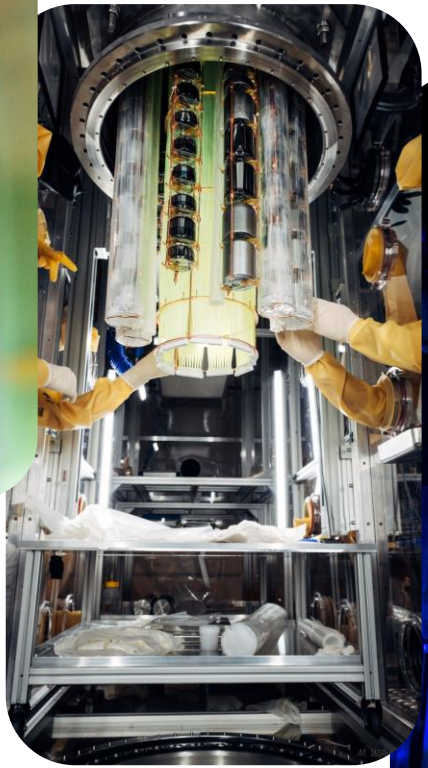
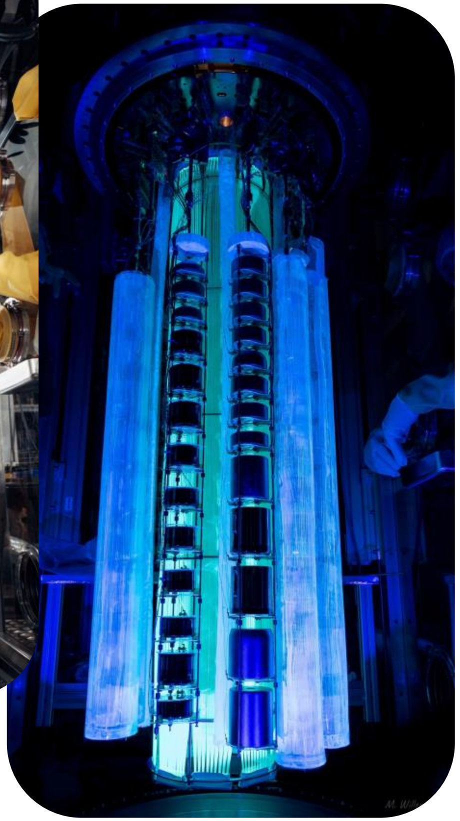


LEGEND = Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Physics	Signature	Energy Range
Bosonic dark matter	Peak at DM mass	< 1 MeV
Electron decay	Peak at 11.8 keV	~ 10 keV
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV
Solar axions	Peaked spectra, daily modulation	$2 - 10$ keV
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$
WIMP and related searches	Exponential excess, annual modulation	< 10 keV
Baryon decay	Timing coincidence	> 10 MeV
Fractionally charged cosmic-rays	Straight tracks	few keV
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV
Inelastic boosted dark matter	Positron production	$<$ few MeV
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar

...and many more!

L1000 BSM paper on the way

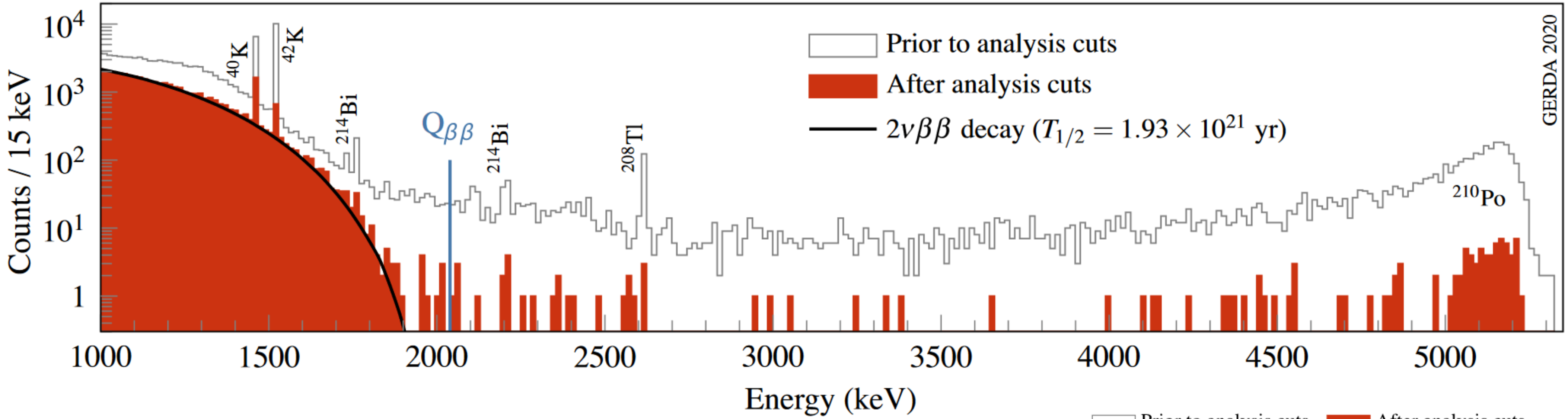




THANK YOU FOR YOUR ATTENTION


Backup slides

GERDA Results

GERDA collaboration, "Final Results of GERDA on the Search for Neutrinoless Double-β Decay", PRL 125, 252502 (2020)



- **November 2011 – September 2013 (Phase I)**
- **December 2015 – November 2019 (Phase II)**
- Analysis performed over *k* partitions:

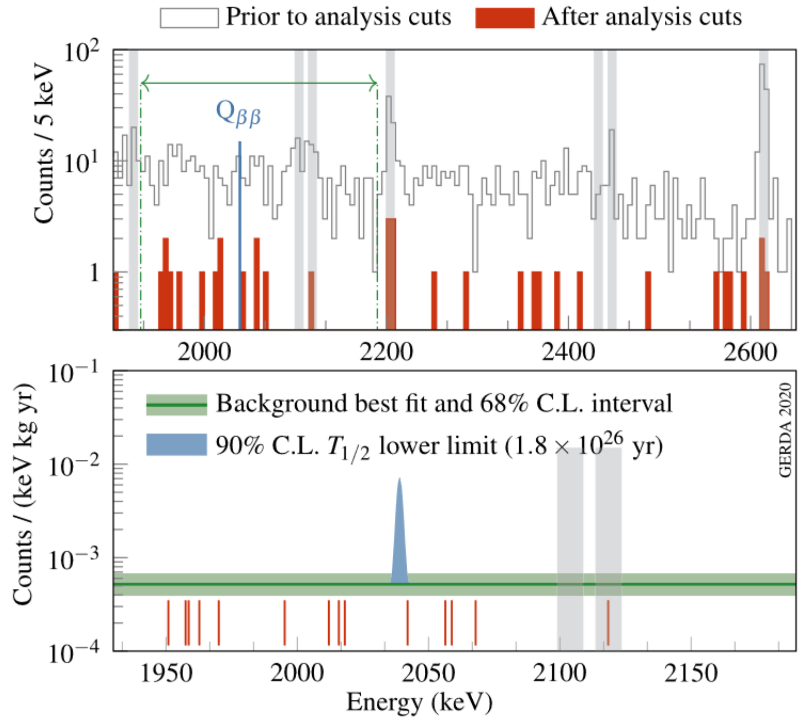
$$\mathcal{L} = \prod_k \left[\frac{(\mu_{s,k} + \mu_{b,k})^{N_k} e^{-(\mu_{s,k}+\mu_{b,k})}}{N_k!} \times \prod_{i=1}^{N_k} \frac{1}{\mu_{s,k} + \mu_{b,k}} \times \left(\frac{\mu_{b,k}}{\Delta E} + \frac{\mu_{s,k}}{\sqrt{2\pi}\sigma_k} e^{-\frac{(E_i - Q_{\beta\beta})^2}{2\sigma_k^2}} \right) \right]$$

- Best limit (and sensitivity assuming no signal) in the world:

$$T_{1/2}^{0\nu} > 1.8 \cdot 10^{26} \text{ yr @ 90\% CL}$$

- Best BI in the *Region Of Interest* (ROI):

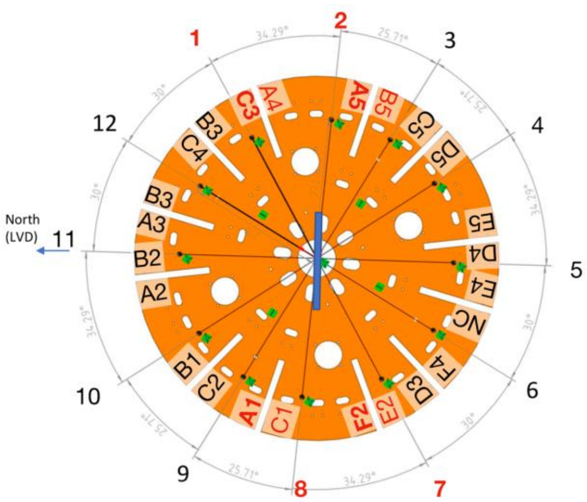
$$BI = 5.2^{+1.6}_{-1.3} \cdot 10^{-4} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)}$$



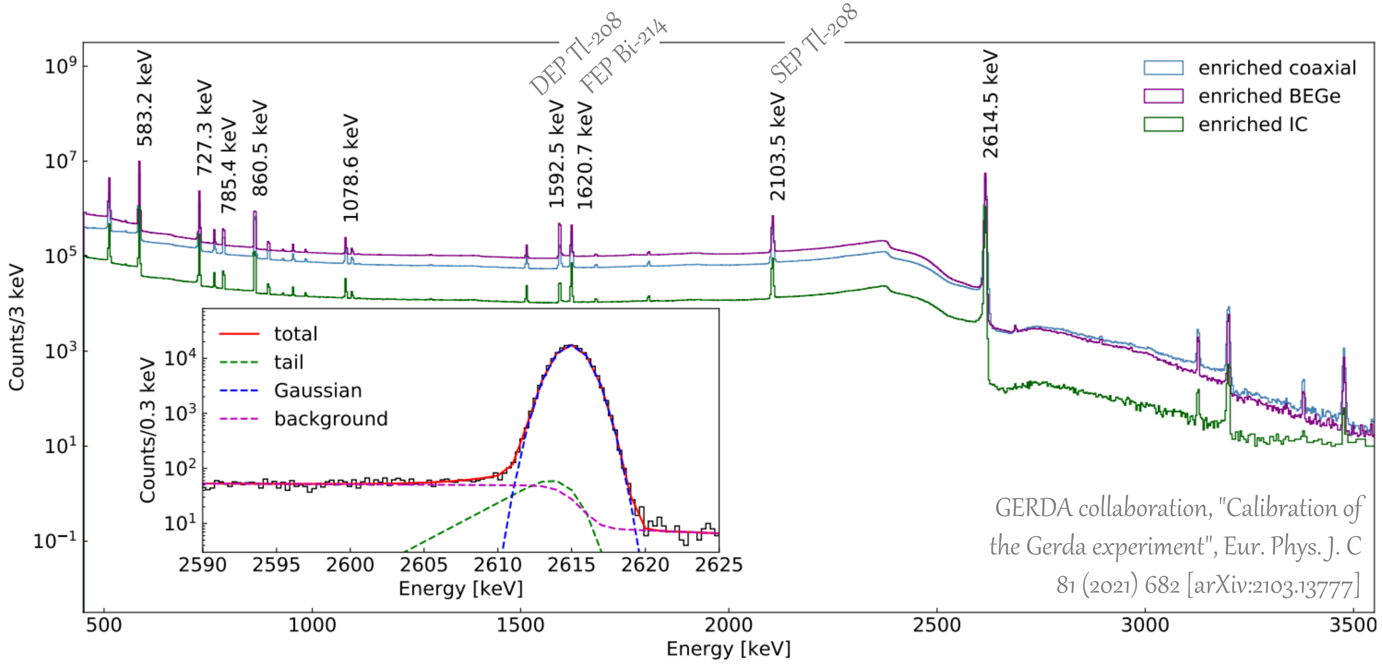
Calibration Procedure

- 4 (+1) *Source Insertion Systems* (SIS), 16 **Th-228** sources
- Use γ lines of known energies to pass from ADC to keV (physical unit)
- Peak fitting algorithm to extract each detector's resolution
- 3 terms:
  - Signal = gaussian
  - Bkg #1= linear + step (flat bkg below/above the peak derived from multiple Compton scatterings)
  - Bkg #2 = tail at low energies (due to incomplete charge collection effects + pile-up events residuals)

View from the top (array)

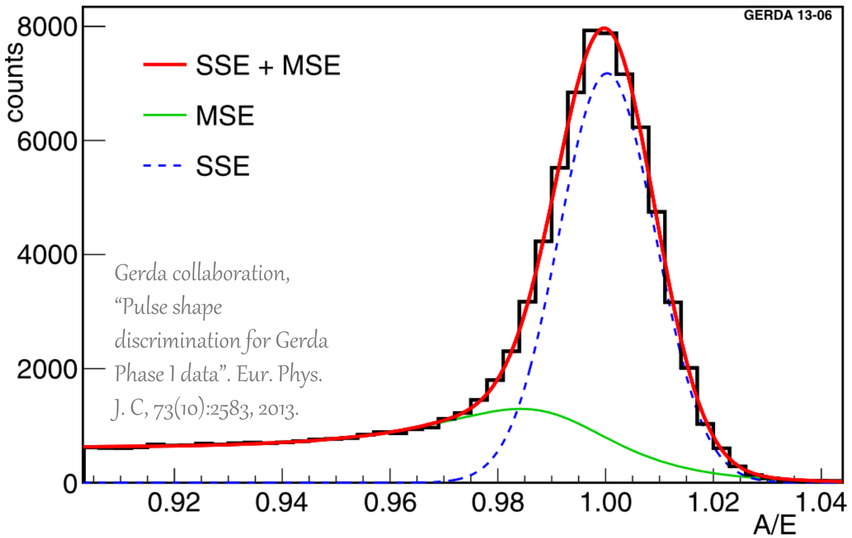


View from the top (funnels)

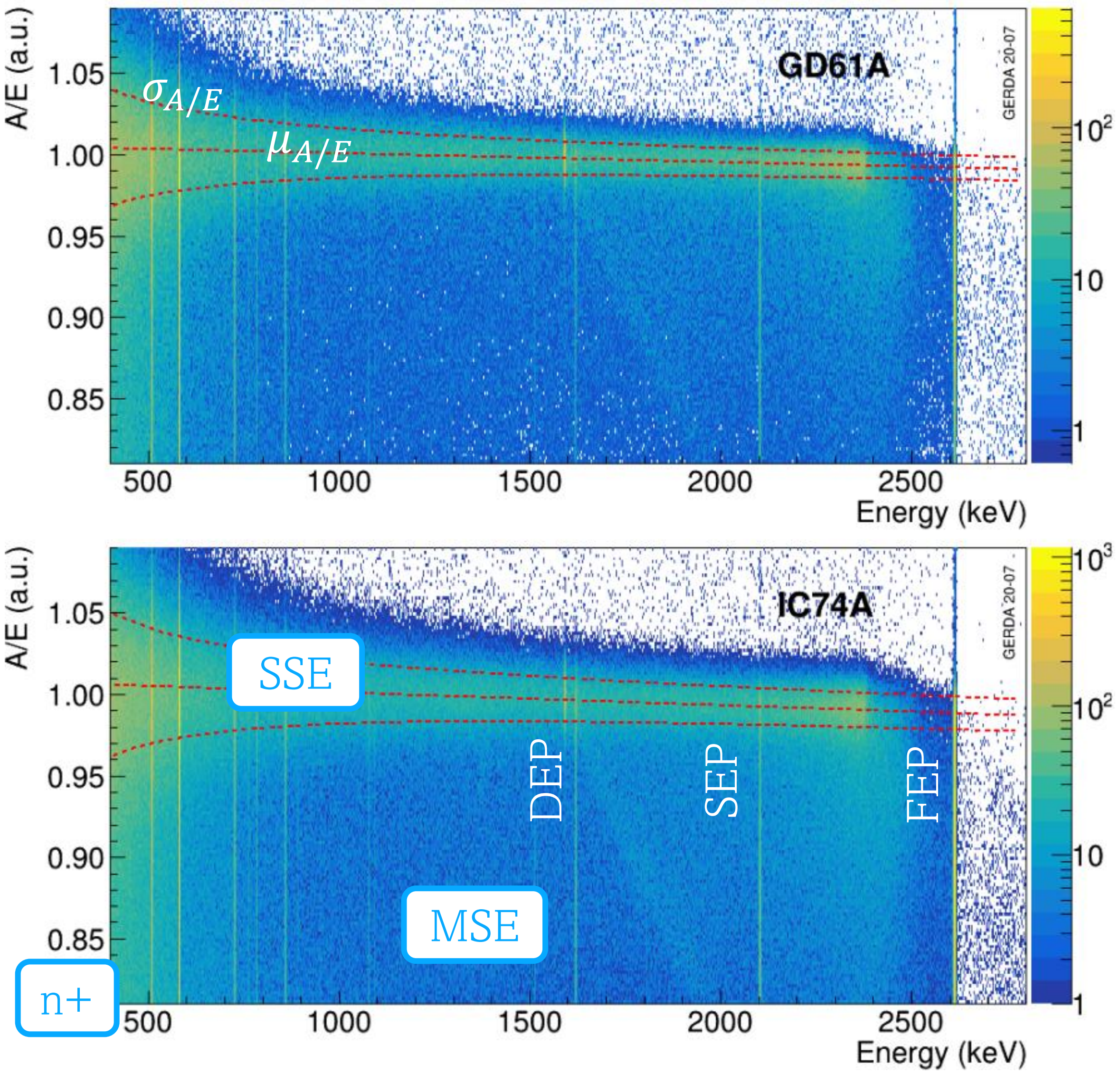


GERDA collaboration, "Calibration of the Gerda experiment", Eur. Phys. J. C 81 (2021) 682 [arXiv:2103.13777]

Pulse Shape Discrimination (PSD) Analysis



GERDA collaboration, "Pulse shape analysis in Gerda Phase II", arXiv:2202.13355 (2022)



- A/E: gaussian (SSE) + tail at low energies (MSE):

$$f(x = A/E) = \frac{n}{\sigma_{A/E} \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu_{A/E})^2}{2\sigma^2_{A/E}}} + m \cdot \frac{e^{f\cdot(x-l)} + d}{e^{(x-l)/t} + l}$$

- Cuts over A/E are performed for each detector separately
- "A/E classifier": energy independent,

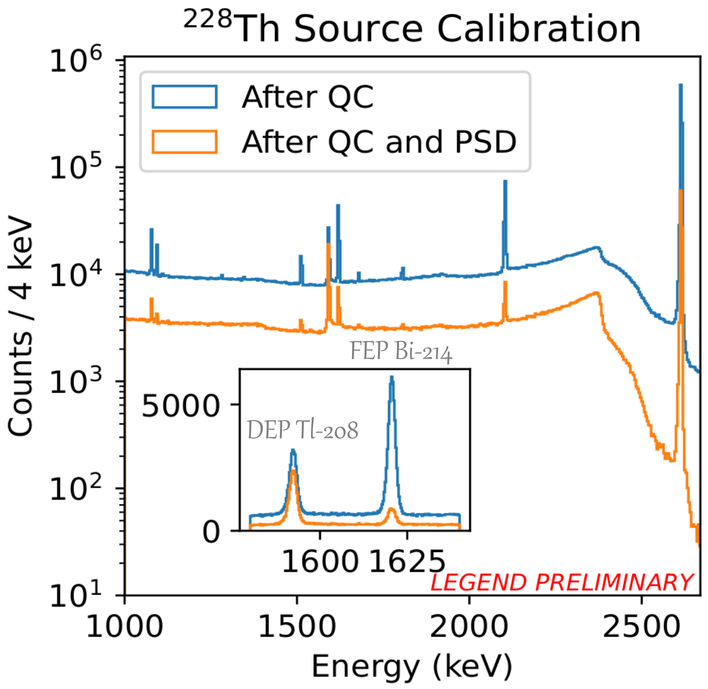
$$\zeta = ([A/E] / \mu_{A/E}(E) - 1) / \sigma_{A/E}$$

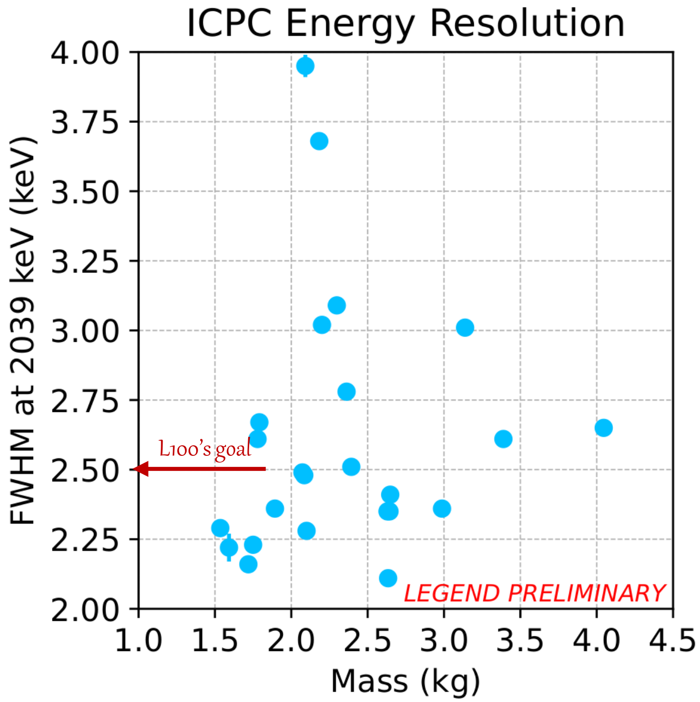
- ζ distribuited around 0, with std=1 for SSEs

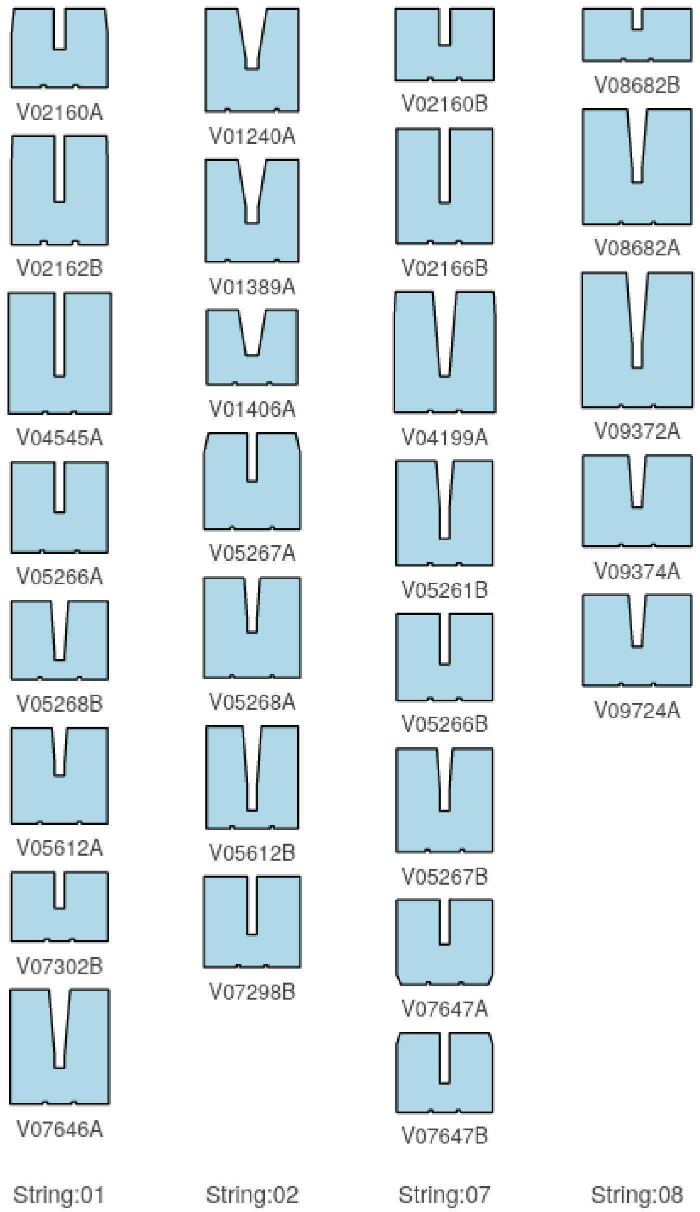
LEGEND-60

28 ICPC detectors, 4 strings

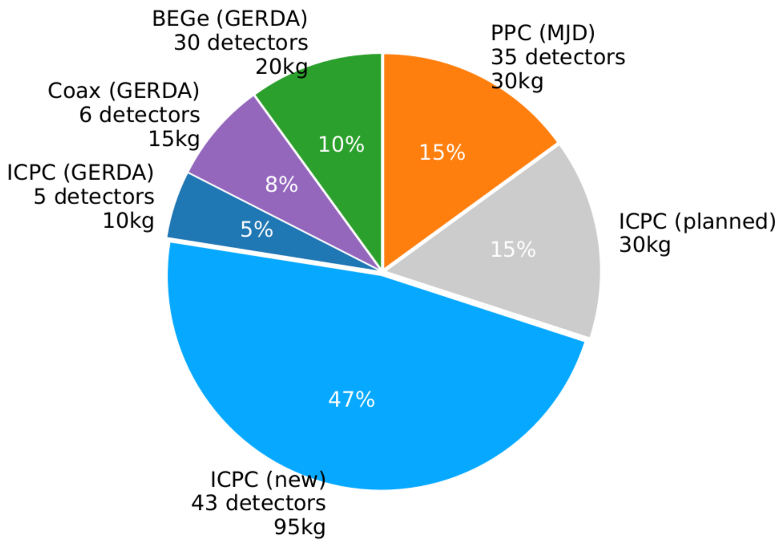
- m_{tot}=63.905 kg
- Data taking period: **June – December 2022**
- Excluded unstable detectors (pulser, R=0.05 Hz)
- Exposure: **2.248 kg yr**

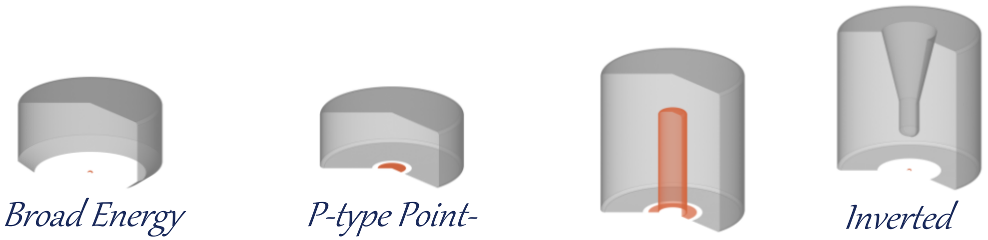




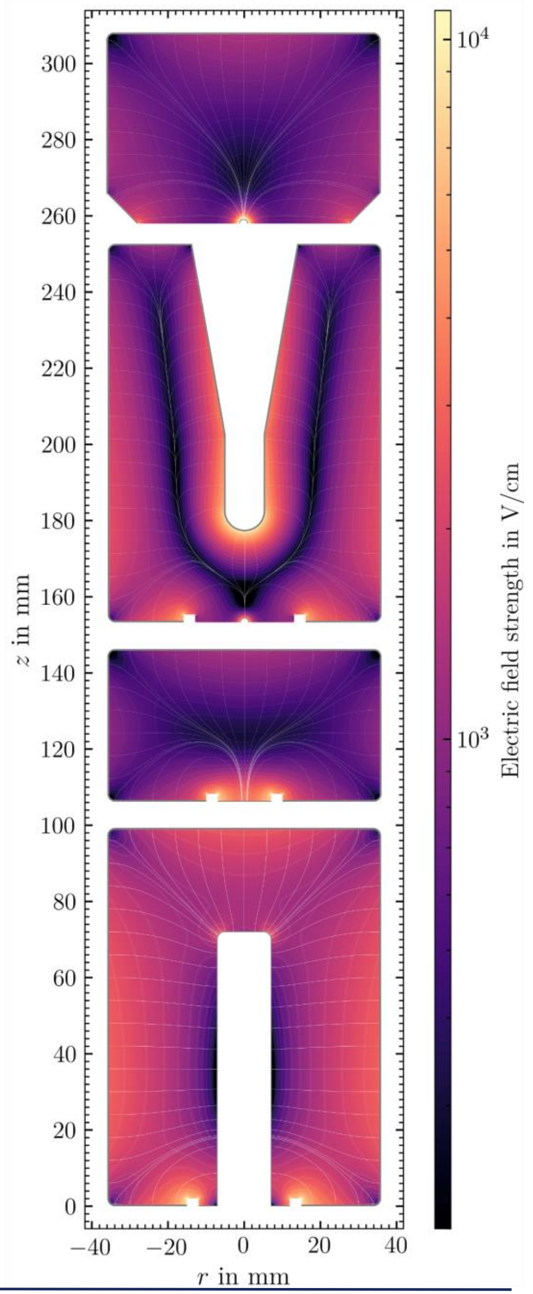


LEGEND-200 Ge Diodes

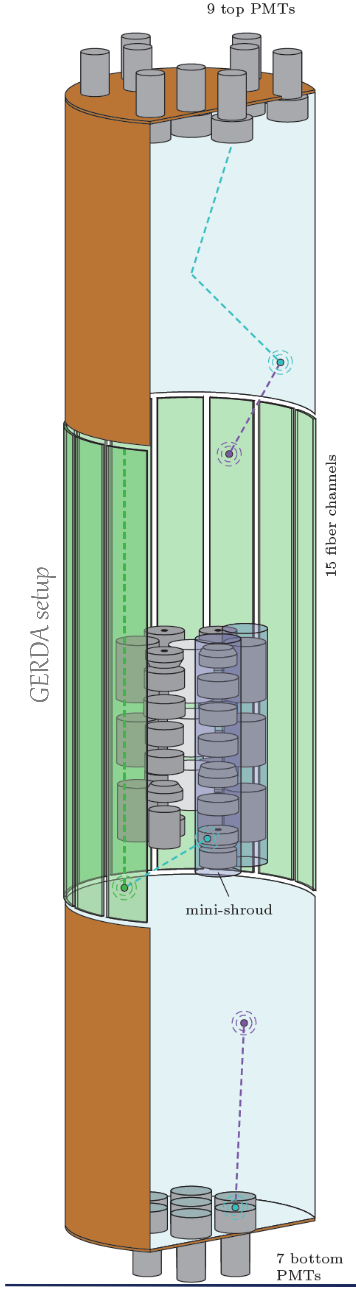




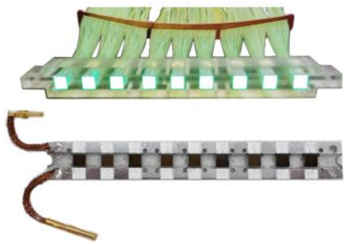
Broad Energy Germanium (BEGe) *P-type Point-Contact (PPC)* *Coaxial* *Inverted Coaxial (IC)*



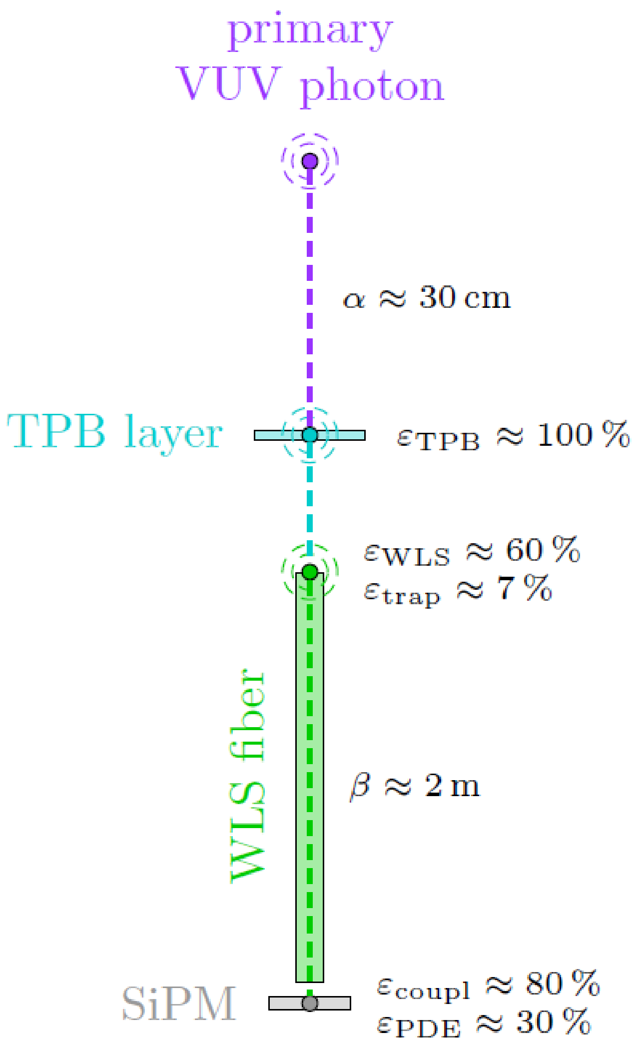
LAr Instrumentation



- Two barrels in LAr @ ~ 84K
  - Ø 590 mm, H 1500 mm
  - *Inner Barrel*, IB: 9 fibres modules = 18 SiPM channels
  - *Outer Barrel*, OB: 20 fibres modules = 40 SiPM channels
- Array of 9 SiPMs read in parallel
  - Ketek PM33100T 3x3 mm
  - 81 WaveLength Shifting (WLS) fibers

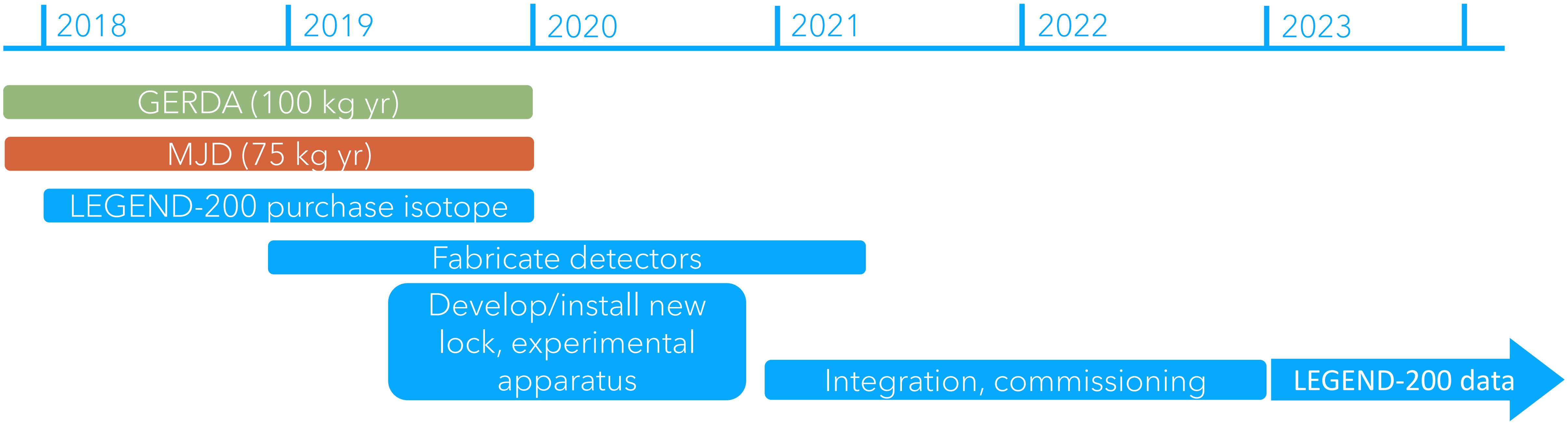


- Nylon Mini-shrouds (MS)
  - Suppressiond of K-42 ions background
  - Transparent to LAr scintillation light (covered with TetraPhenyl Butadiene, TPB)
  - Nylon: low-background material
- Fiber shroud cylinder
  - Ø 1375 mm, H 3000 mm
  - Reflected photons reach fibers without any LAr attenuation
  - Help to detect photons produced outside the barrels

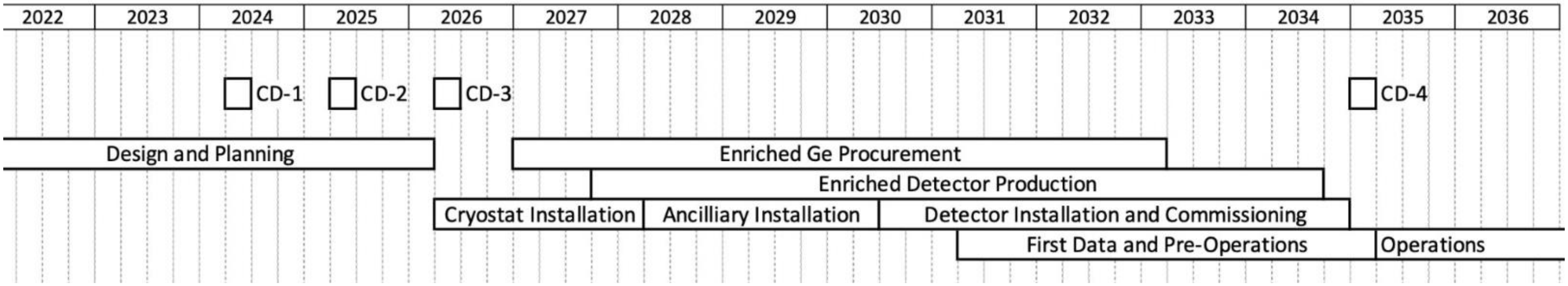


GERDA collaboration, "Liquid argon light collection and veto modeling in GERDA Phase II", arXiv:2212.02856 (2022)

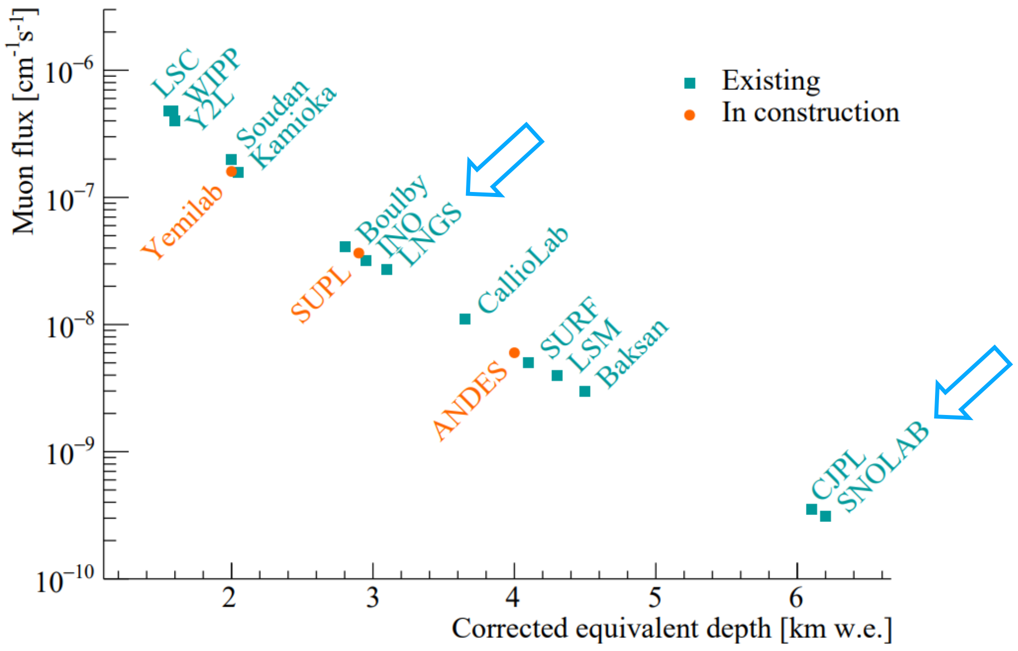
Timeline

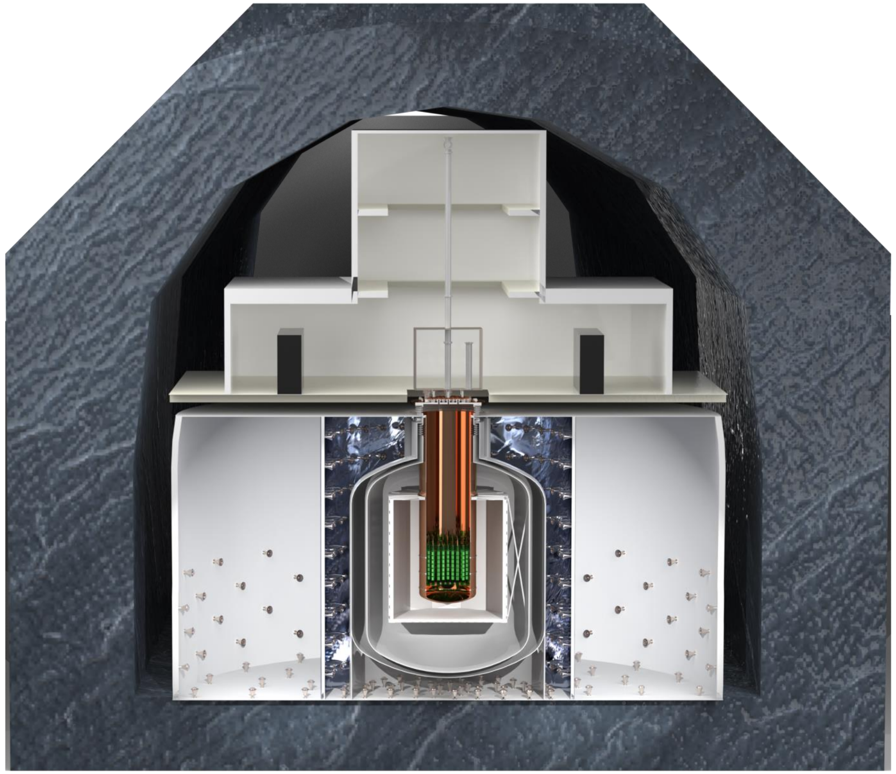


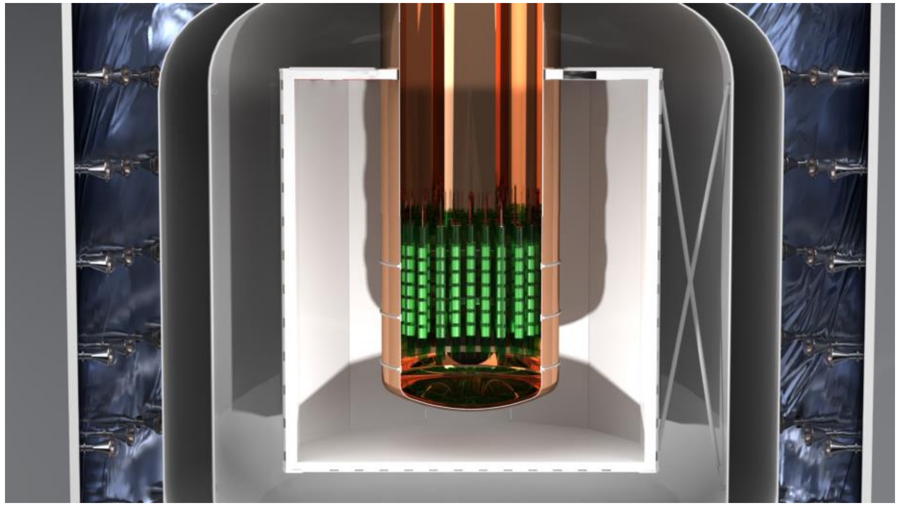
LEGEND-1000



LEGEND-1000



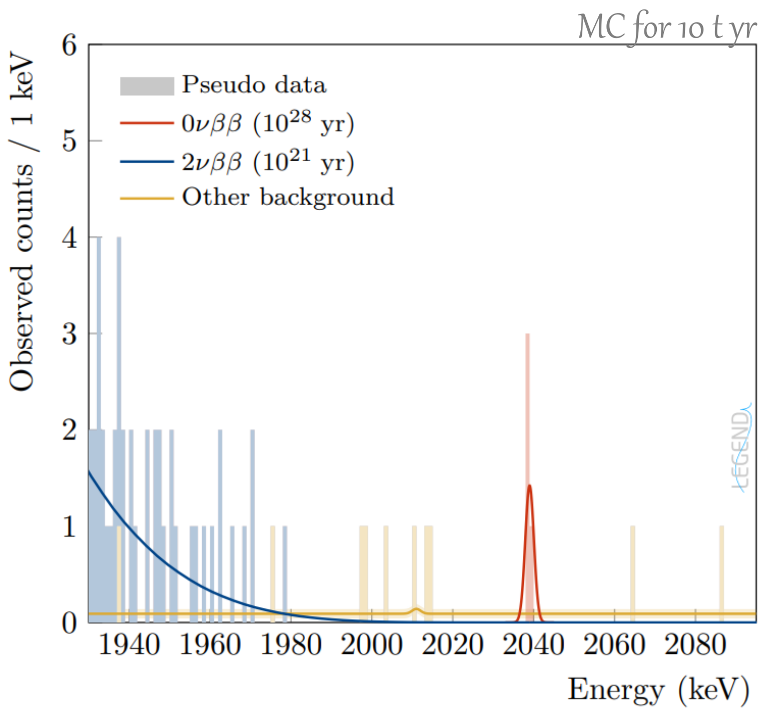


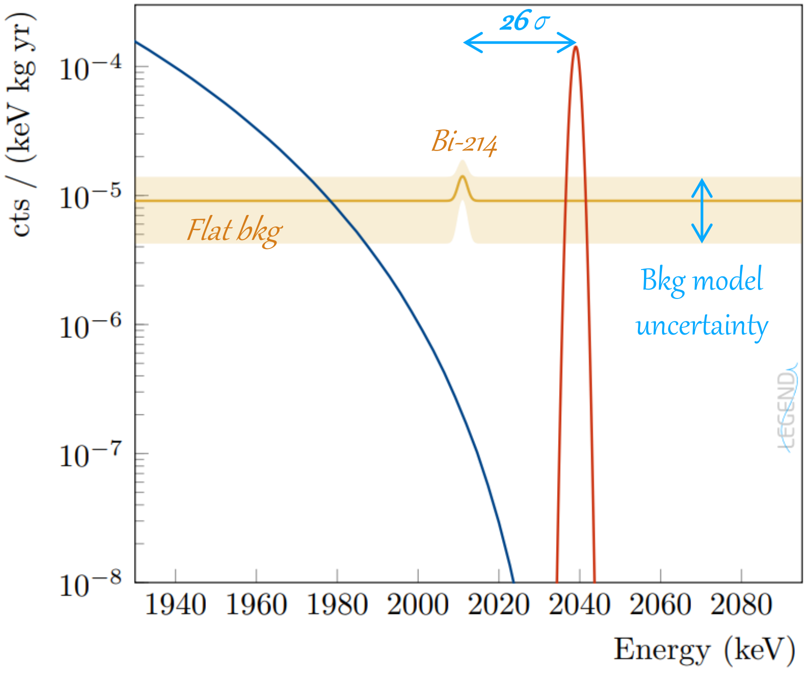


- Baseline design: **1000 kg** of germanium in **4** ***re-entrant tubes*** containing **LAr underground** (reduces ^{42}K produced from ^{42}Ar)
- Background level reduced by a factor 20 wrt LEGEND-200
- **SNOLAB** (6010 m w.e.) **or LNGS** (3600 m w.e.) – DOE, ~July '23
- CD-0 approved by the United States Department of Energy (DOE)

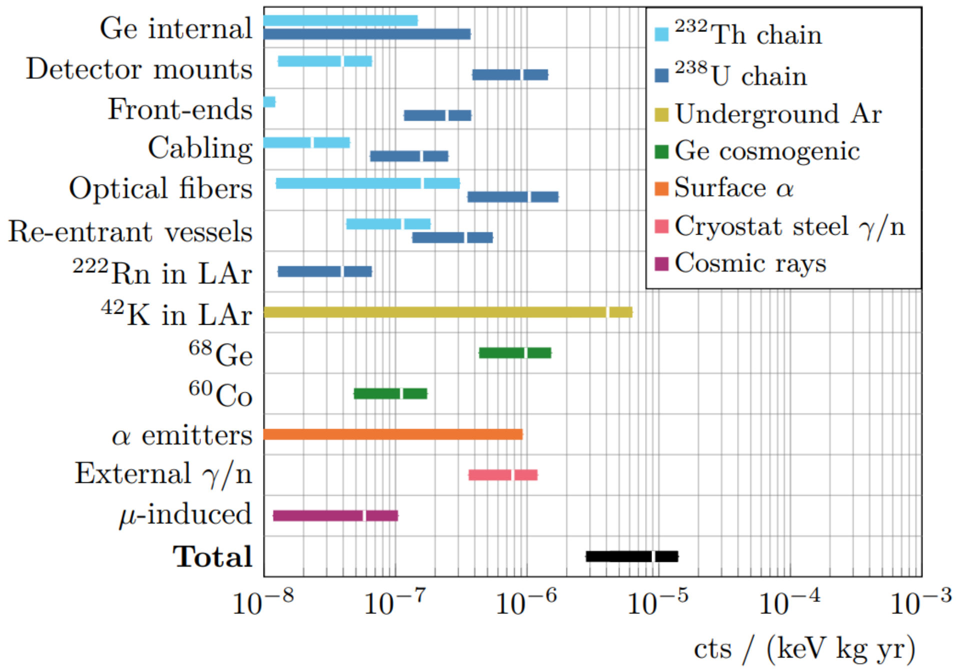
Pre-conceptual Design Report: https://inspirehep.net/literature/1892243

The Ultimate Goal





1σ bands (or 90% CL upper limits) for the significant background contributions



- Background contributions derived from the **background model of LEGEND-1000** (calibrated over data collected by GERDA & MJD)
- Less than 1 background event expected around the $Q_{\beta\beta}$ peak
- No **2ν2β** in proximity of $Q_{\beta\beta}$
- **3-4 signal events**, visible by eye

Pre-conceptual Design Report: https://inspirehep.net/literature/1892243

0ν2β Experiments

LEGEND

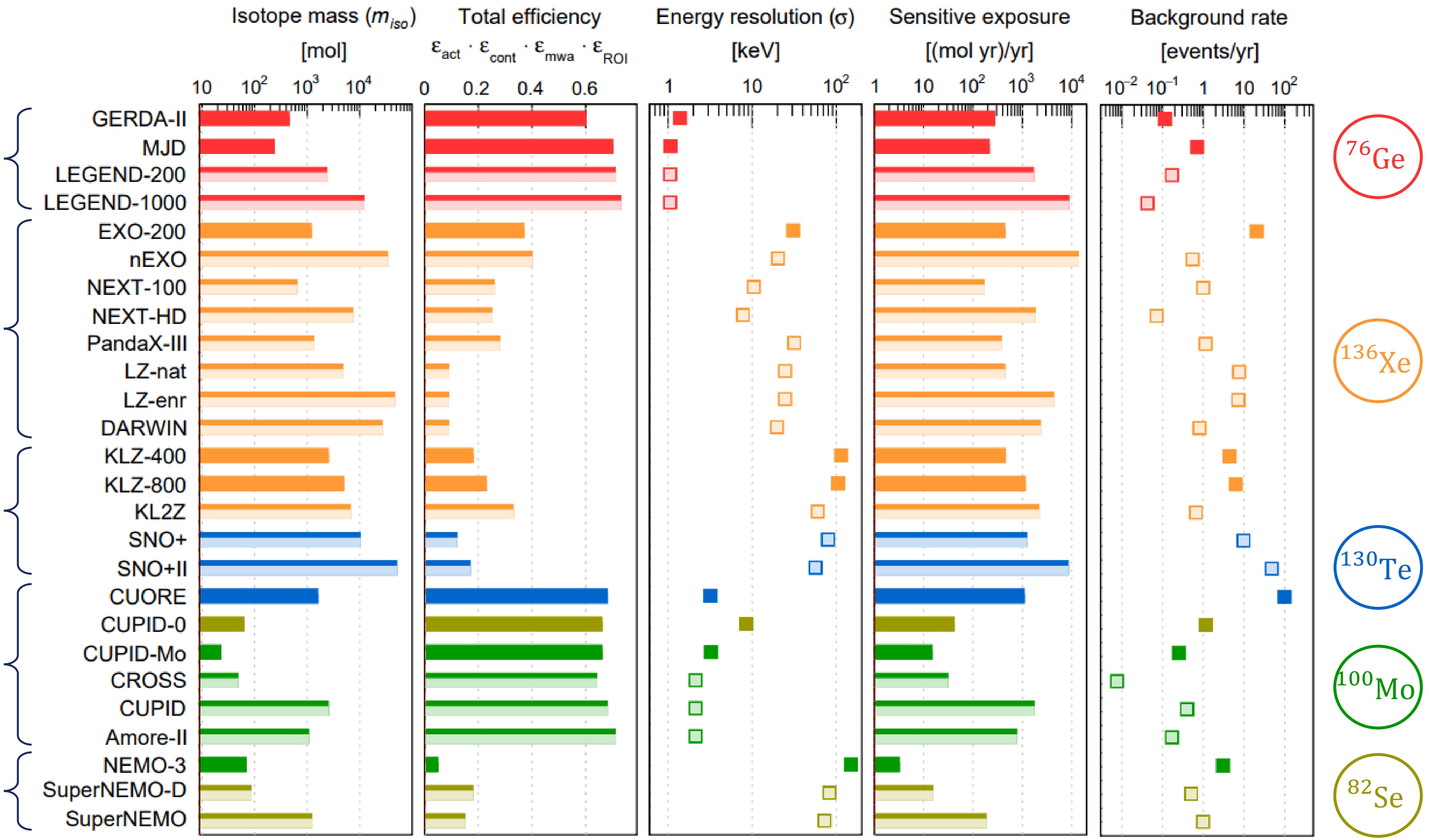
HPGe Diodes
Excellent resolution and efficiency, low bkg level

Xenon *Time Projection Chambers*
High m_{iso}, tracking of particles

Liquid Scintillators
High m_{iso}

Cryogenic Calorimeters
Excellent resolution and efficiency, high granularity

Tracking Calorimeters
Tracking of particles, decay kinematics



M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani, "Toward the discovery of matter creation with neutrinoless double-beta decay", arXiv:2202.01787 (2022).

$0\nu2\beta$ Experiments

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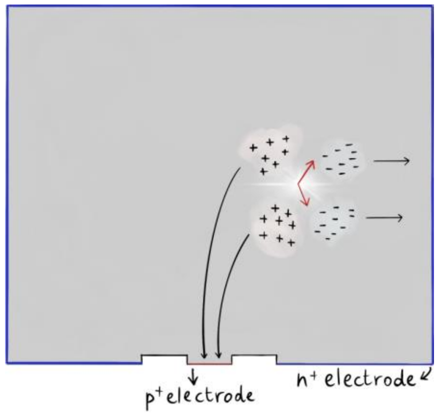
Experiment	Isotope	Status	Lab	m_{iso} [mol]	ε_{act} [%]	ε_{cont} [%]	ε_{mva} [%]	σ [keV]	ROI [σ]	ε_{ROI} [%]	$\mathcal{E}$ $\left[\frac{mol\cdot yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{events}{mol\cdot yr}\right]$	λ_b $\left[\frac{events}{yr}\right]$	$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	completed	LNGS	$4.5\cdot10^{2}$	88	91	79	1.4	-2,2	95	273	$4.2\cdot10^{-4}$	$1.1\cdot10^{-1}$	$1.2\cdot10^{26}$	93-222
MJD	^{76}Ge	completed	SURF	$3.1\cdot10^{2}$	91	91	86	1.1	-2,2	95	212	$3.3\cdot10^{-3}$	$7.1\cdot10^{-1}$	$4.7\cdot10^{25}$	149-355
LEGEND-200	^{76}Ge	construction	LNGS	$2.4\cdot10^{3}$	91	91	90	1.1	-2,2	95	1 684	$1.0\cdot10^{-4}$	$1.7\cdot10^{-1}$	$1.5\cdot10^{27}$	27-63
LEGEND-1000	^{76}Ge	proposed		$1.2\cdot10^{4}$	92	92	90	1.1	-2,2	95	8 736	$4.9\cdot10^{-6}$	$4.3\cdot10^{-2}$	$1.3\cdot10^{28}$	9-21
Xenon time projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	completed	WIPP	$1.2\cdot10^{3}$	46	100	84	31	-2,2	95	438	$4.7\cdot10^{-2}$	$2.1\cdot10^{+1}$	$2.4\cdot10^{25}$	111-477
nEXO	^{136}Xe	proposed	SNOLAB	$3.4\cdot10^{4}$	64	100	66	20	-2,2	95	13 700	$4.0\cdot10^{-5}$	$5.5\cdot10^{-1}$	$7.4\cdot10^{27}$	6-27
NEXT-100	^{136}Xe	construction	LSC	$6.4\cdot10^{2}$	88	76	49	10	-1.0,1.8	80	167	$5.9\cdot10^{-3}$	$9.9\cdot10^{-1}$	$7.0\cdot10^{25}$	66-281
NEXT-HD	^{136}Xe	proposed		$7.4\cdot10^{3}$	95	89	44	7.7	-0.5,1.7	65	1 809	$4.0\cdot10^{-5}$	$7.2\cdot10^{-2}$	$2.2\cdot10^{27}$	12-50
PandaX-III-200	^{136}Xe	construction	CJPL	$1.3\cdot10^{3}$	77	74	65	31	-1.2,1.2	76	374	$3.0\cdot10^{-3}$	$1.1\cdot10^{+0}$	$1.5\cdot10^{26}$	45-194
LZ-nat	^{136}Xe	construction	SURF	$4.7\cdot10^{3}$	14	100	80	25	-1.4,1.4	84	440	$1.7\cdot10^{-2}$	$7.5\cdot10^{+0}$	$7.2\cdot10^{25}$	64-277
LZ-enr	^{136}Xe	proposed	SURF	$4.6\cdot10^{4}$	14	100	80	25	-1.4,1.4	84	4302	$1.7\cdot10^{-3}$	$7.3\cdot10^{+0}$	$7.1\cdot10^{26}$	20-87
Darwin	^{136}Xe	proposed		$2.7\cdot10^{4}$	13	100	90	20	-1.2,1.2	76	2 312	$3.5\cdot10^{-4}$	$8.0\cdot10^{-1}$	$1.1\cdot10^{27}$	17-72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	completed	Kamioka	$2.5\cdot10^{3}$	44	100	97	114	0,1.4	42	450	$9.8\cdot10^{-3}$	$4.4\cdot10^{+0}$	$3.3\cdot10^{25}$	95-408
KLZ-800	^{136}Xe	taking data	Kamioka	$5.0\cdot10^{3}$	55	100	100	105	0,1.4	42	1 143	$5.5\cdot10^{-3}$	$6.2\cdot10^{+0}$	$2.0\cdot10^{26}$	38-164
KL2Z	^{136}Xe	proposed	Kamioka	$6.7\cdot10^{3}$	80	100	97	60	0,1.4	42	2 176	$3.0\cdot10^{-4}$	$6.5\cdot10^{-1}$	$1.1\cdot10^{27}$	17-71
SNO+I	^{130}Te	construction	SNOLAB	$1.0\cdot10^{4}$	20	100	97	80	-0.5,1.5	62	1 232	$7.8\cdot10^{-3}$	$9.7\cdot10^{+0}$	$1.8\cdot10^{26}$	31-144
SNO+II	^{130}Te	proposed	SNOLAB	$5.1\cdot10^{4}$	27	100	97	57	-0.5,1.5	62	8 521	$5.7\cdot10^{-3}$	$4.8\cdot10^{+1}$	$5.7\cdot10^{26}$	17-81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	taking data	LNGS	$1.6\cdot10^{3}$	100	88	92	3.2	-1.4,1.4	84	1 088	$9.1\cdot10^{-2}$	$9.9\cdot10^{+1}$	$5.1\cdot10^{25}$	58-270
CUPID-0	^{82}Se	completed	LNGS	$6.2\cdot10^{1}$	100	81	86	8.5	-2,2	95	41	$2.8\cdot10^{-2}$	$1.2\cdot10^{+0}$	$4.4\cdot10^{24}$	283-551
CUPID-Mo	^{100}Mo	completed	LSM	$2.3\cdot10^{1}$	100	76	91	3.2	-2,2	95	15	$1.7\cdot10^{-2}$	$2.5\cdot10^{-1}$	$1.7\cdot10^{24}$	293-858
CROSS	^{100}Mo	construction	LSC	$4.8\cdot10^{1}$	100	75	90	2.1	-2,2	95	31	$2.5\cdot10^{-4}$	$7.6\cdot10^{-3}$	$4.9\cdot10^{25}$	54-160
CUPID	^{100}Mo	proposed	LNGS	$2.5\cdot10^{3}$	100	79	90	2.1	-2,2	95	1 717	$2.3\cdot10^{-4}$	$4.0\cdot10^{-1}$	$1.1\cdot10^{27}$	12-34
AMoRE-II	^{100}Mo	proposed	Yemilab	$1.1\cdot10^{3}$	100	82	91	2.1	-2,2	95	760	$2.2\cdot10^{-4}$	$1.7\cdot10^{-1}$	$6.7\cdot10^{26}$	15-43
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	completed	LSM	$6.9\cdot10^{1}$	100	100	11	148	-1.6,1.1	42	3	$9.4\cdot10^{-1}$	$3.0\cdot10^{+0}$	$5.6\cdot10^{23}$	505-1485
SuperNEMO-D	^{82}Se	construction	LSM	$8.5\cdot10^{1}$	100	100	28	83	-4.2,2.4	64	15	$3.3\cdot10^{-2}$	$5.0\cdot10^{-1}$	$8.6\cdot10^{24}$	201-391
SuperNEMO	^{82}Se	proposed	LSM	$1.2\cdot10^{3}$	100	100	28	72	-4.1,2.8	54	185	$5.3\cdot10^{-3}$	$9.8\cdot10^{-1}$	$7.8\cdot10^{25}$	67-131

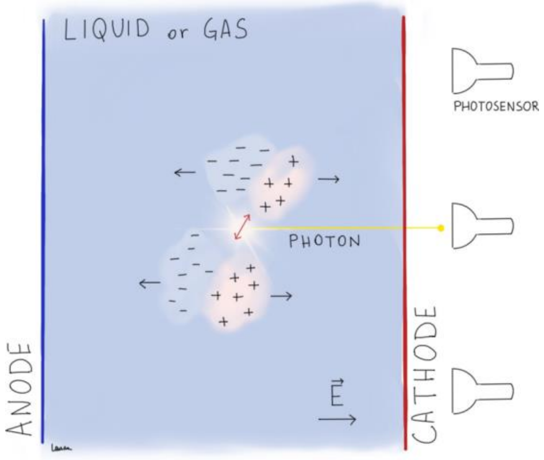
$0\nu2\beta$ Detecting Techniques

LEGEND



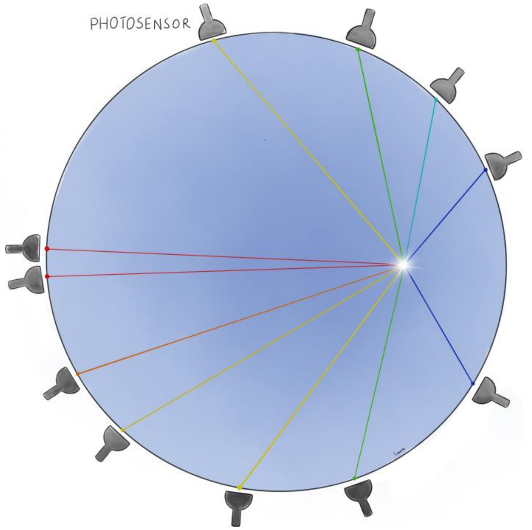
High-purity Ge (HPGe) detector

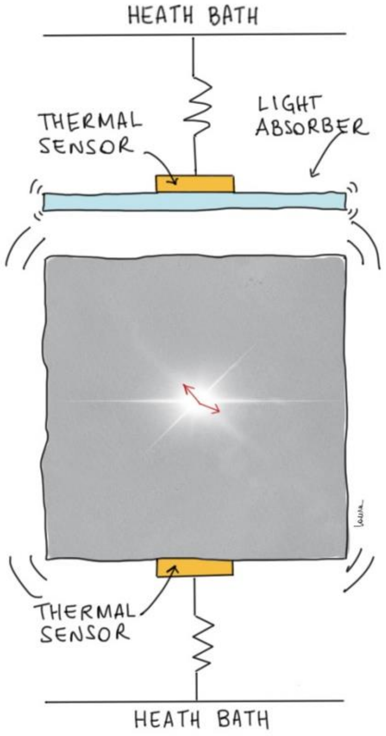
$e^- - h$ clusters created by ionization are collected to the electrodes by an electric field



Xe Time Projection Chambers

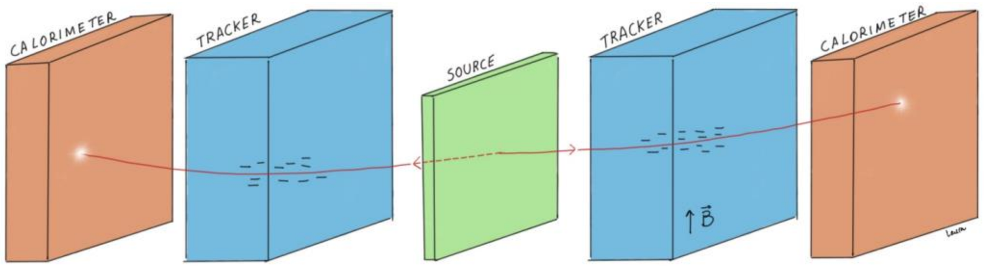
$e^- - h$ clusters created by ionization are collected to the electrodes by an electric field. In addition, scintillation light is detected by light sensors, providing the timing of the event





Cryogenic Calorimeters

Phonon and scintillation light signals are read-out through superconductive thermal sensors



Tracking Calorimeters

The charge, momentum, and energy of the particles ejected by the source is measured yhtouugh a combination of magnetic-field trackrs and calorimeters

Liquid Scintillators

The position of an event can be reconstructed through he time of flight of the scintillation photons

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The Collaboration

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