GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Raoul Cesarano
on behalf of the LEGEND collaboration

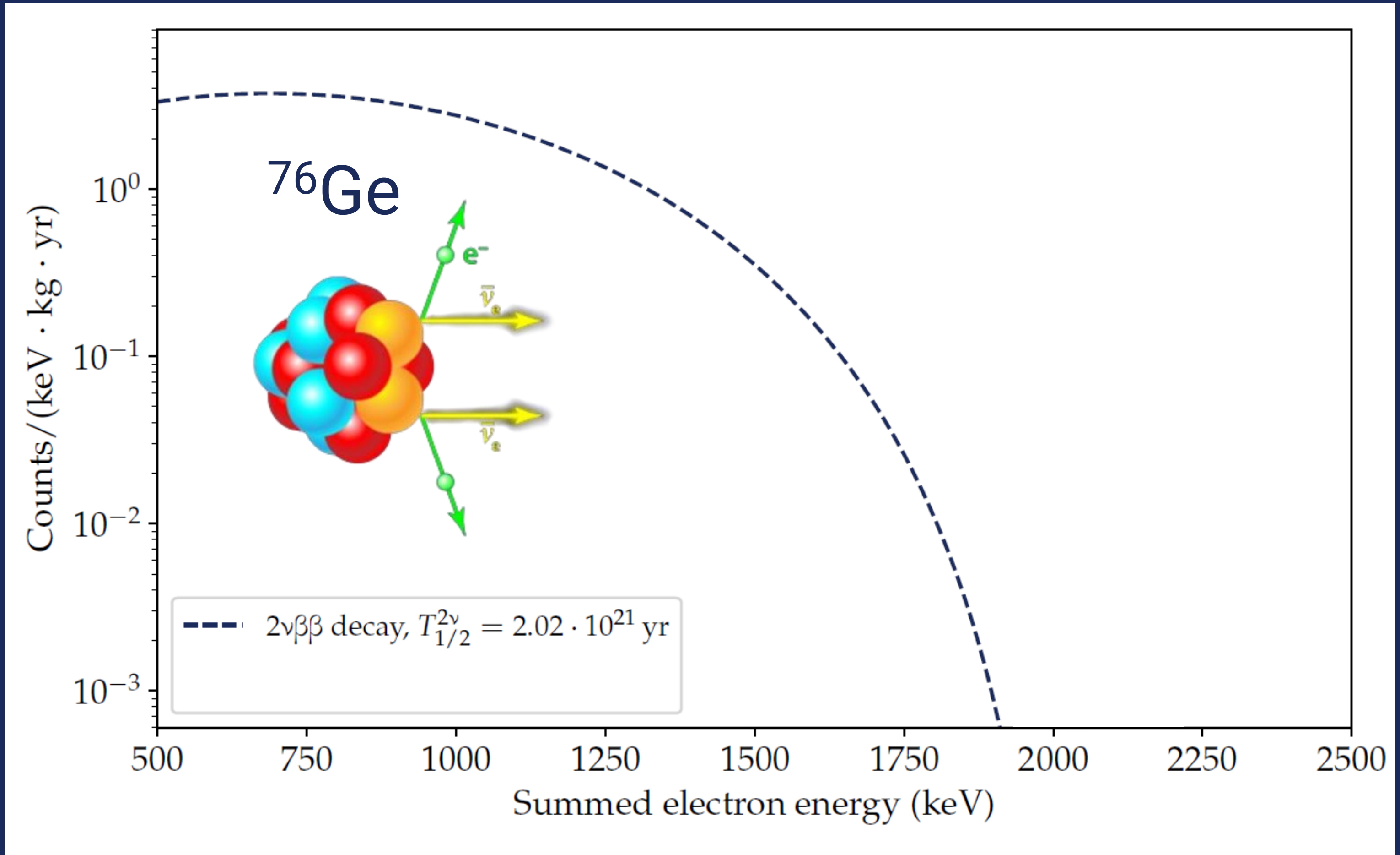
La Thuile 2024

How can we discover the neutrino's true nature?

Dirac

Majorana

What to search for



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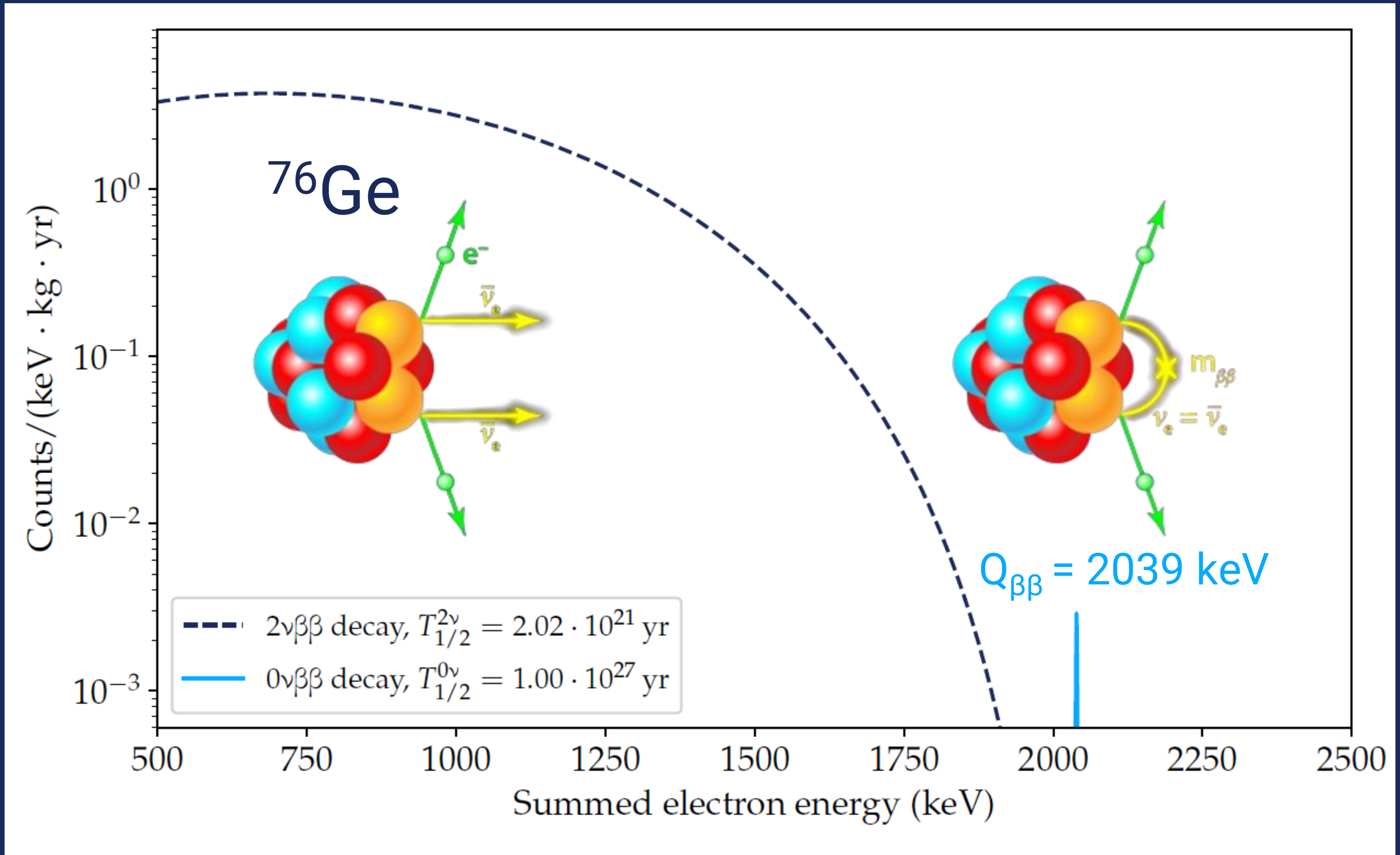

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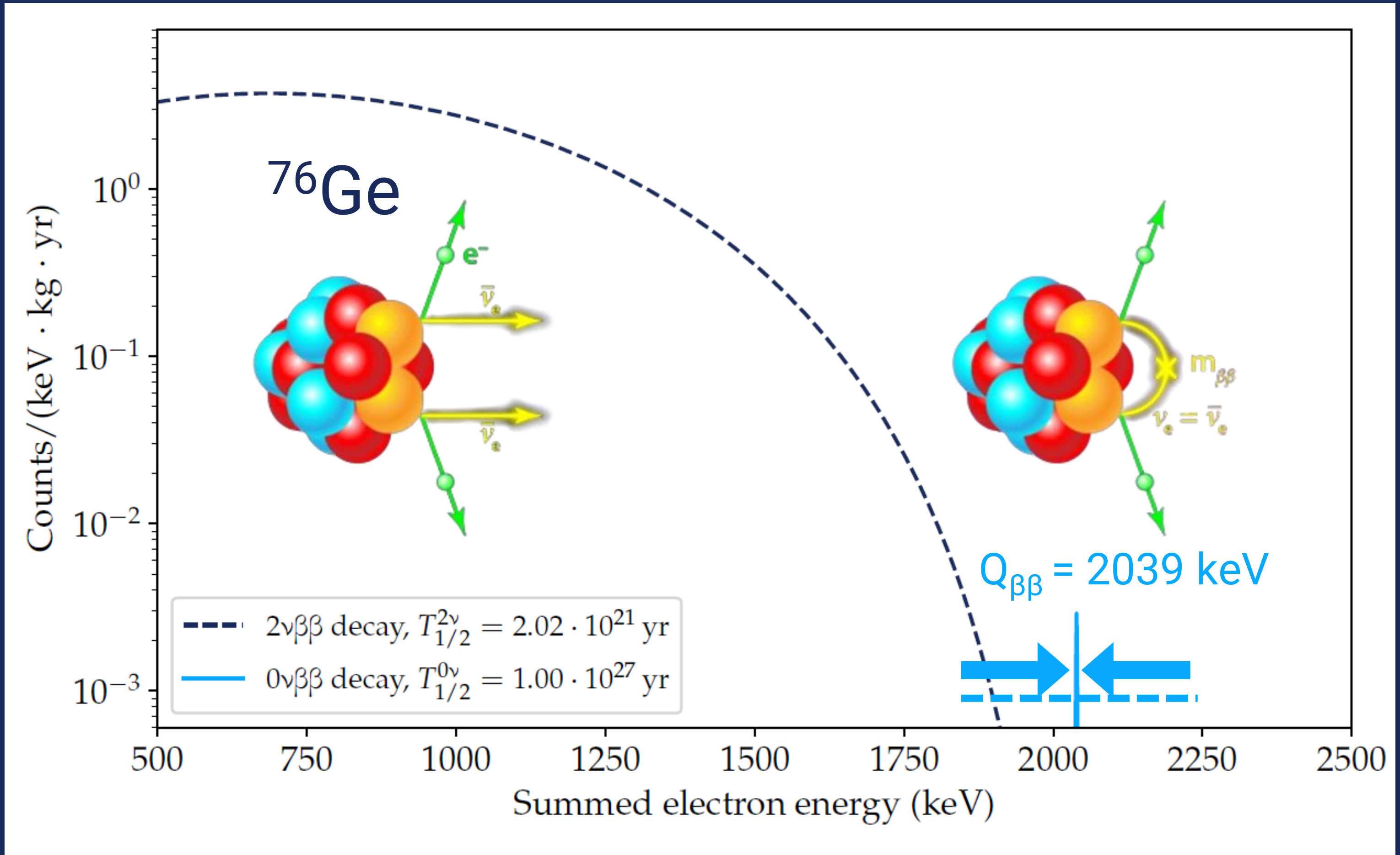


$$T_{1/2}^{0\nu\beta\beta} = ln2 \cdot \frac{N_A \cdot ia \cdot \epsilon}{n_\sigma \cdot m_A} \cdot \sqrt{\frac{M \cdot T}{B_i \cdot \Delta E}}$$

Isotopic abundance

Detector signal efficiency

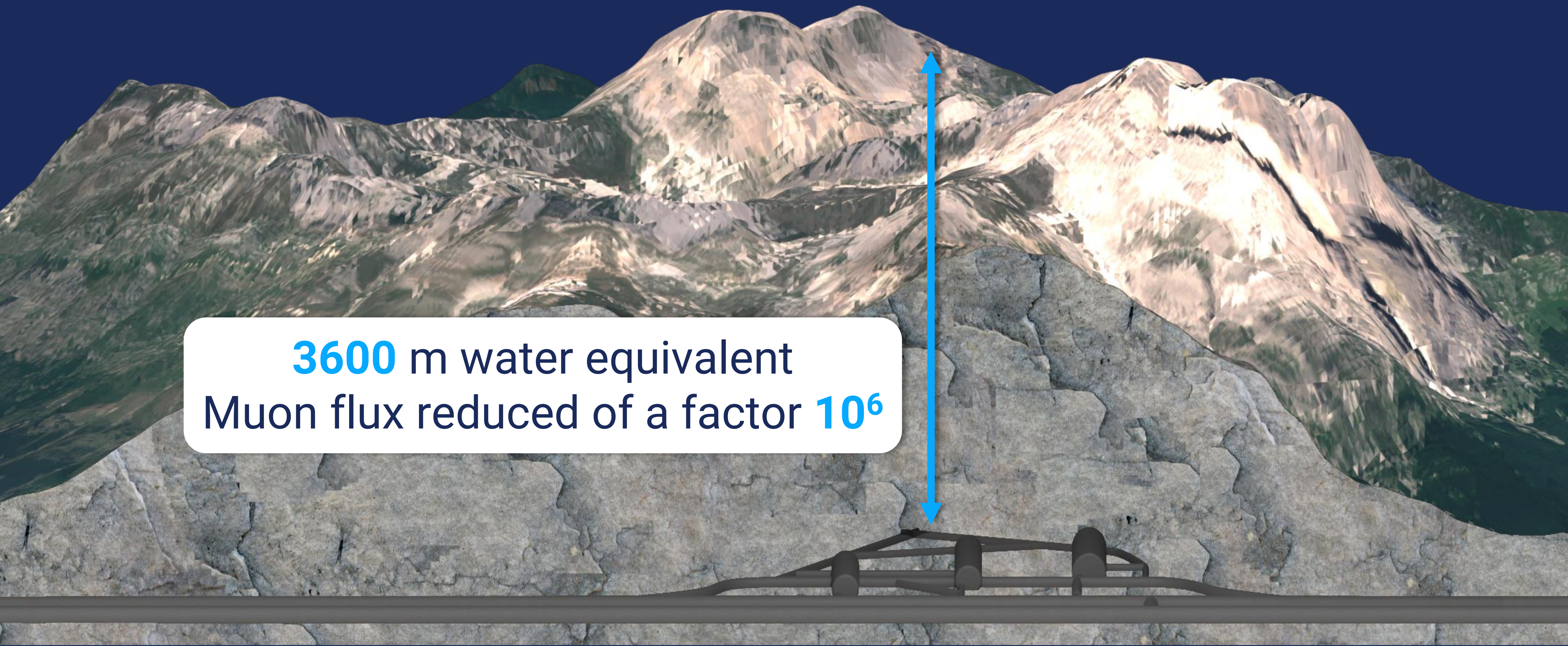
Exposure

Sensitivity

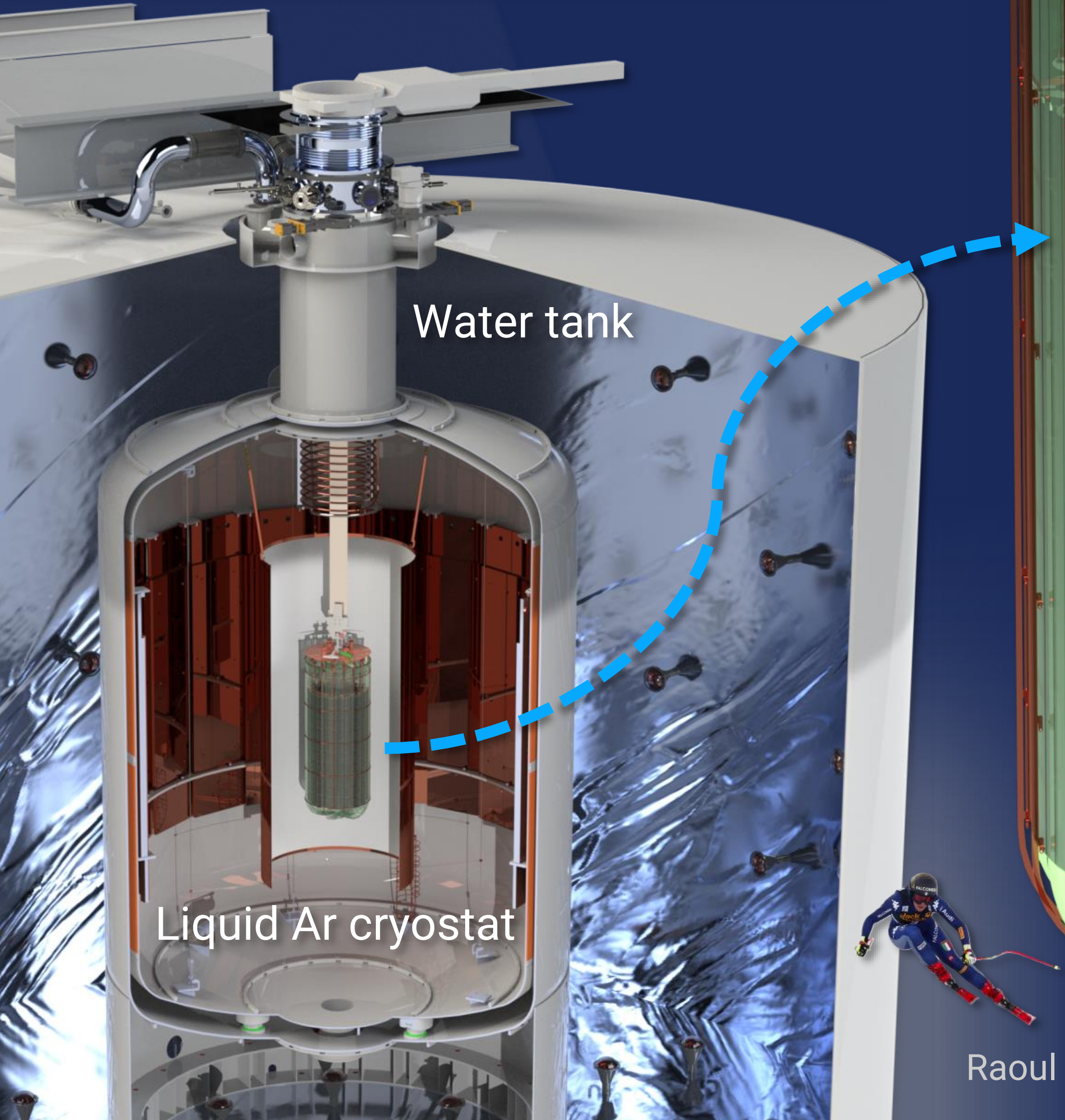
Background index

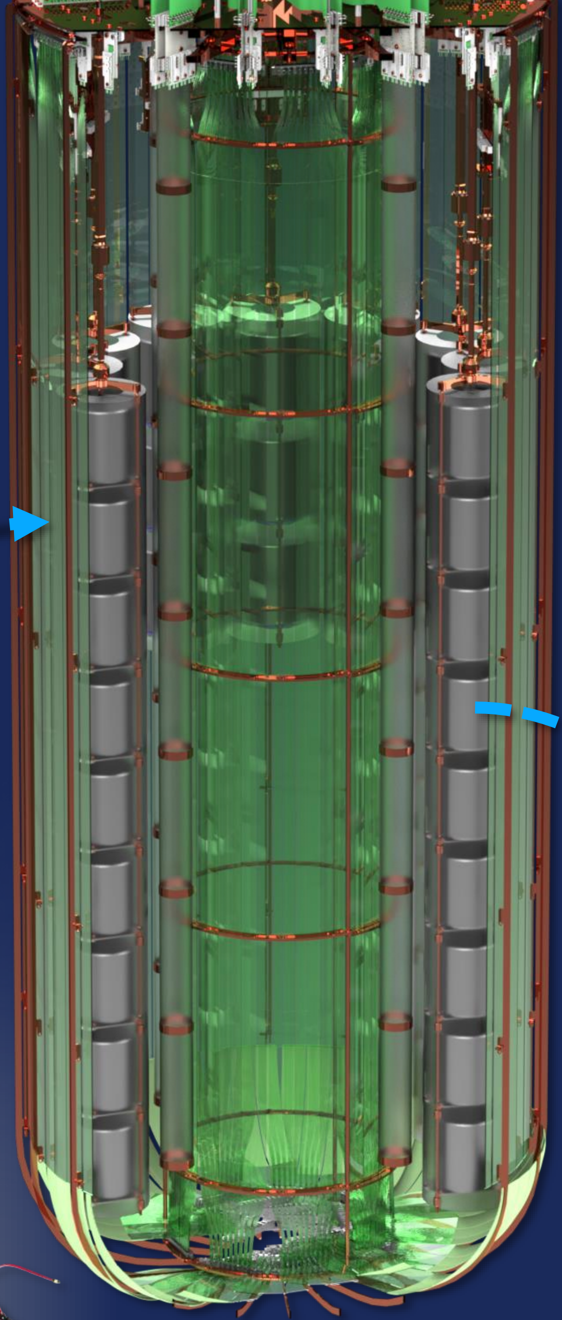
Energy resolution

Gran Sasso National Laboratory (LNGS)



LEGEND - 200



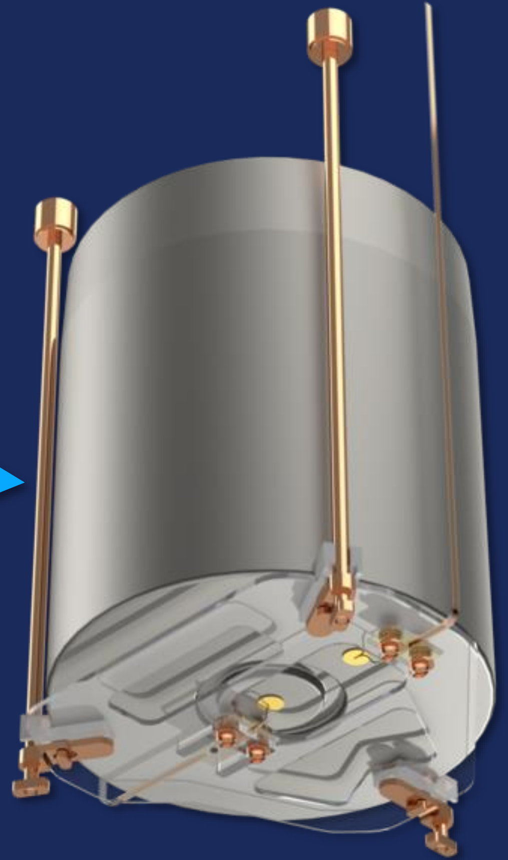


90 tons of liquid Ar

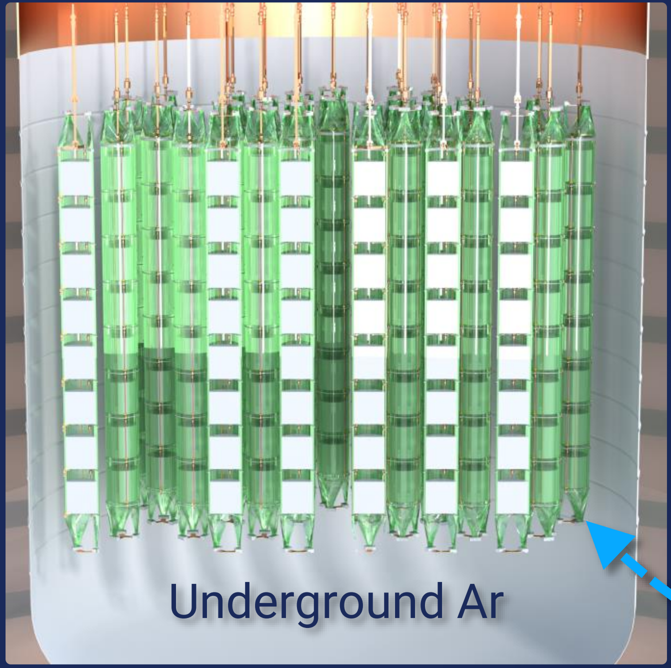
200 kg of enriched Ge

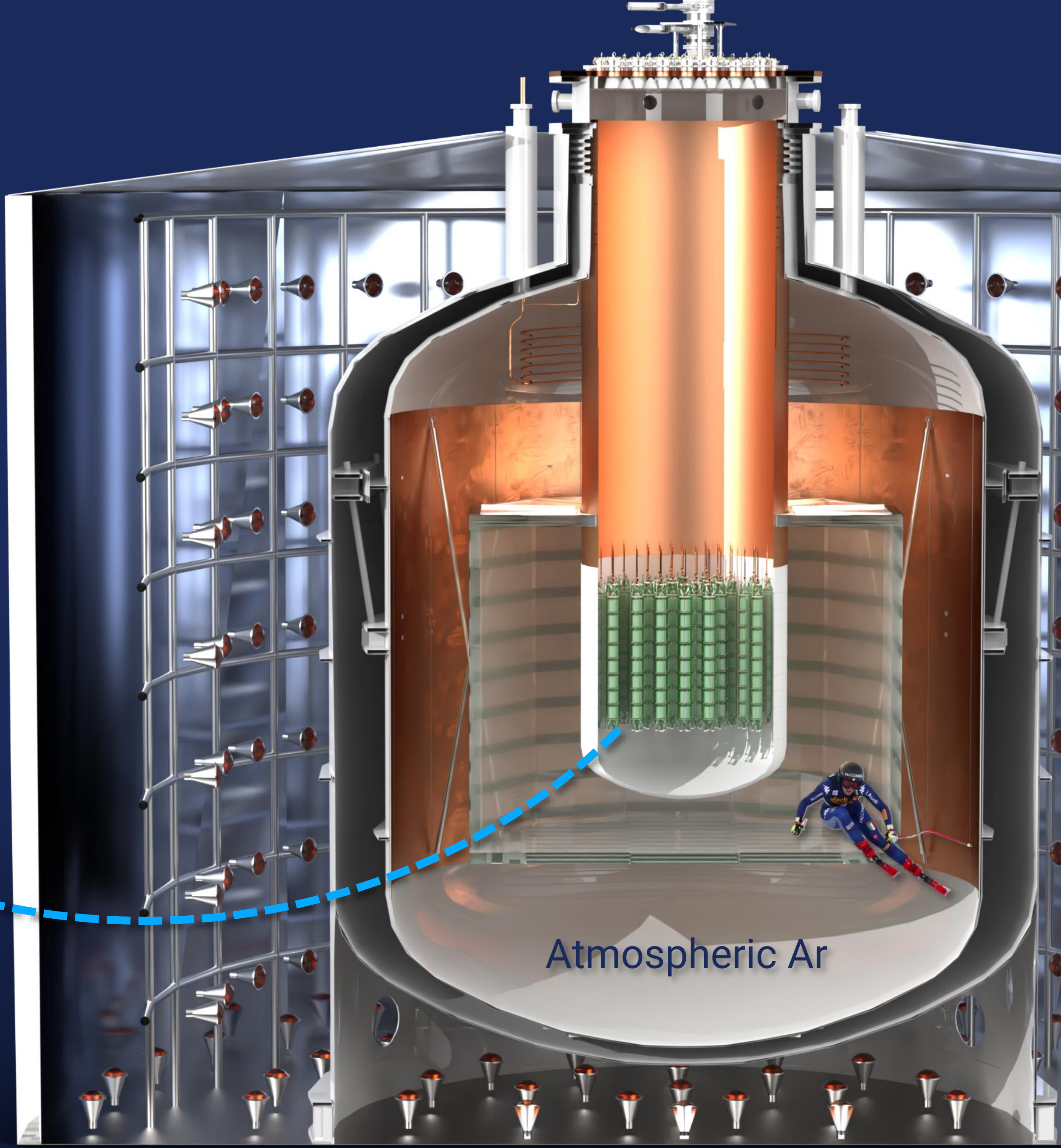
Stably taking data since 1 yr

$T_{1/2}^{0\nu\beta\beta}$ > 10^{27} yr @ 90% CL (5 yrs)



LEGEND - 1000





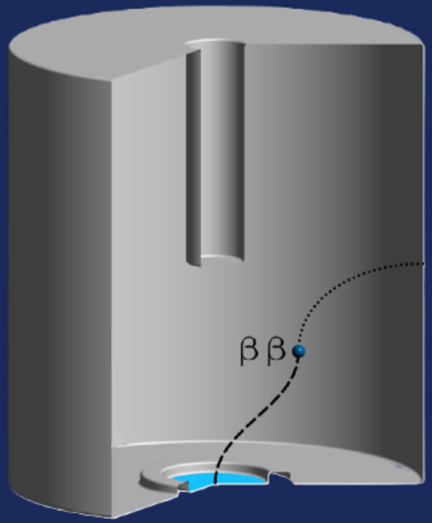
336 detectors of **3 kg avg. mass**

1000 kg of Ge detectors

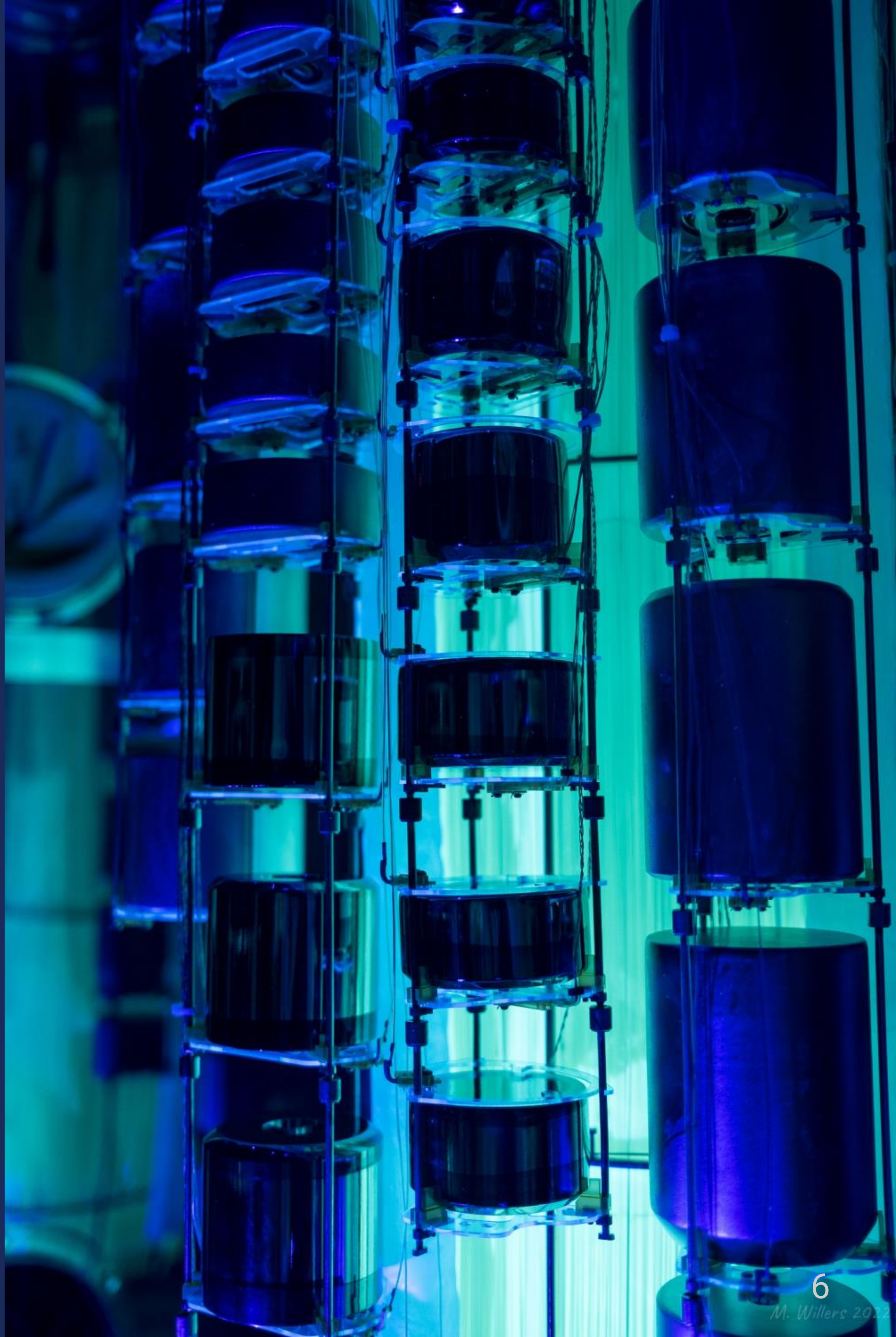
First data in 2030

$T_{1/2}^{0\nu\beta\beta} > 1.4 \cdot 10^{28}$ yr @ 90% CL (10 yrs)

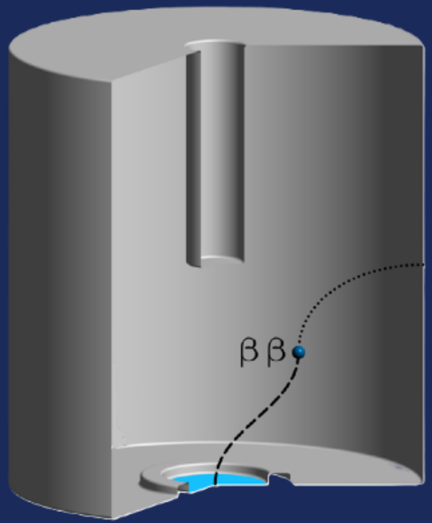
Event topology



Single Site Event (SSE)



Event topology



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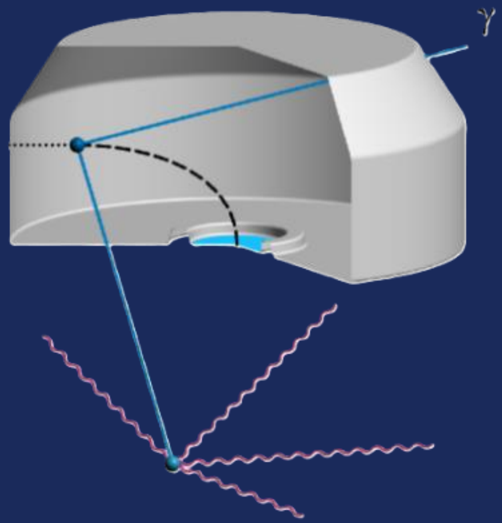
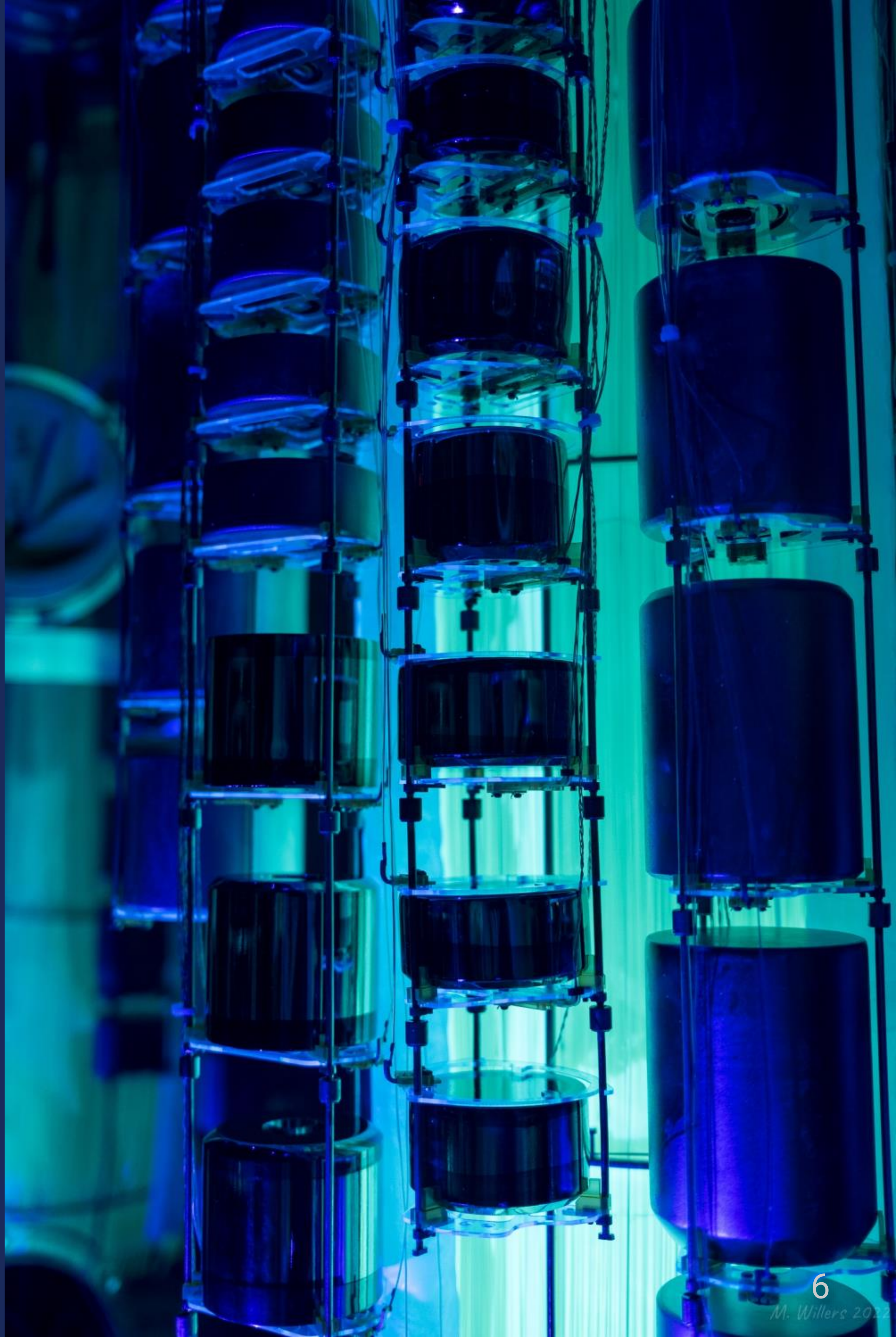


Liquid Ar coincidence



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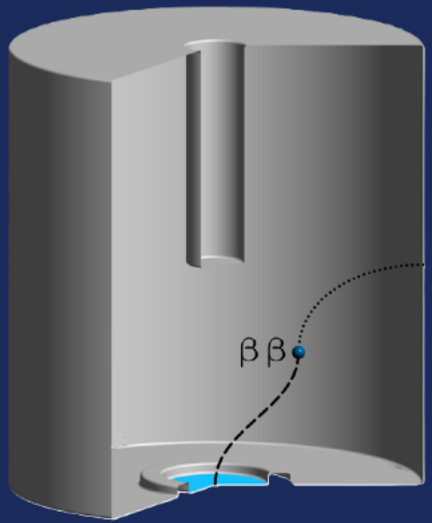

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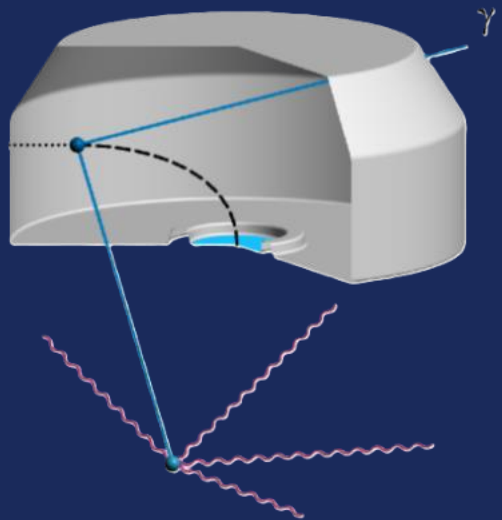

Liquid Ar coincidence

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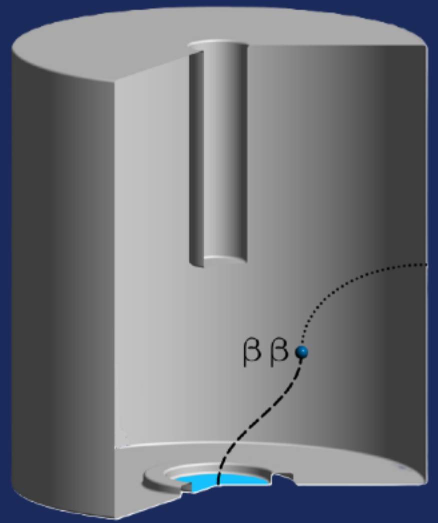

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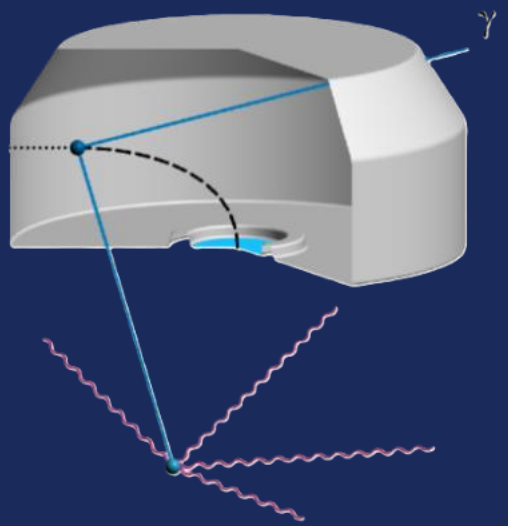

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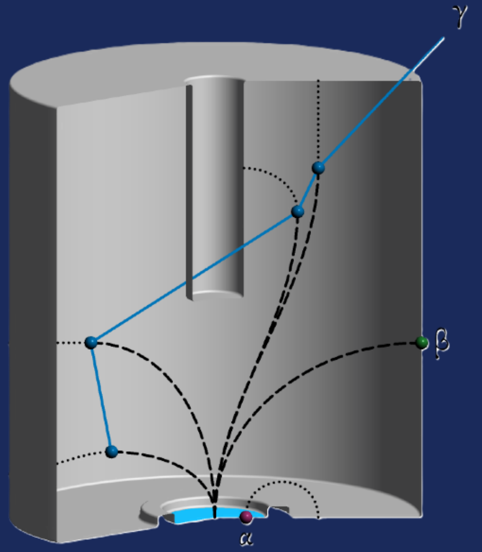
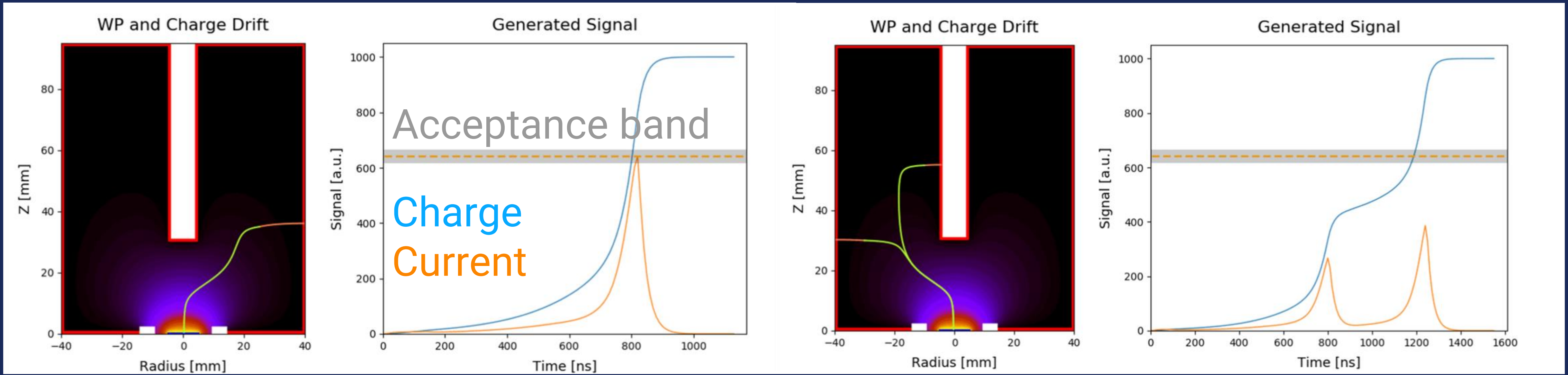
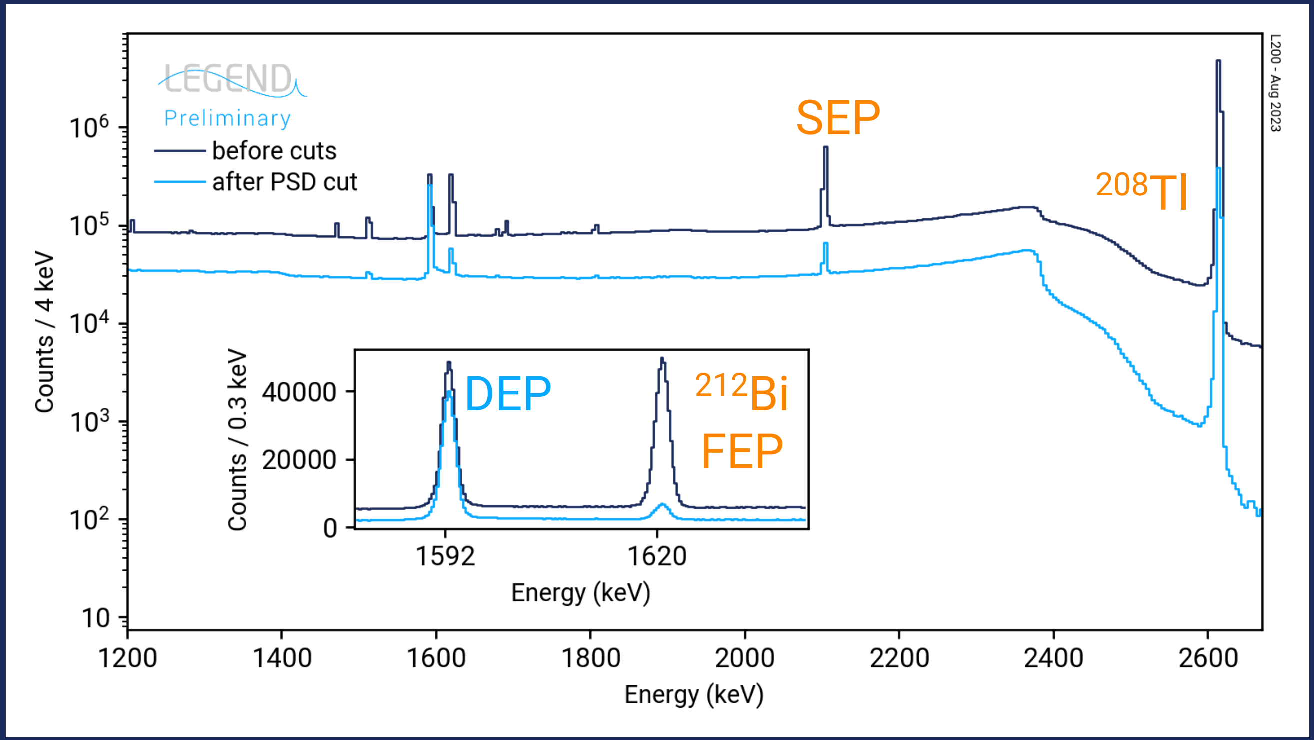


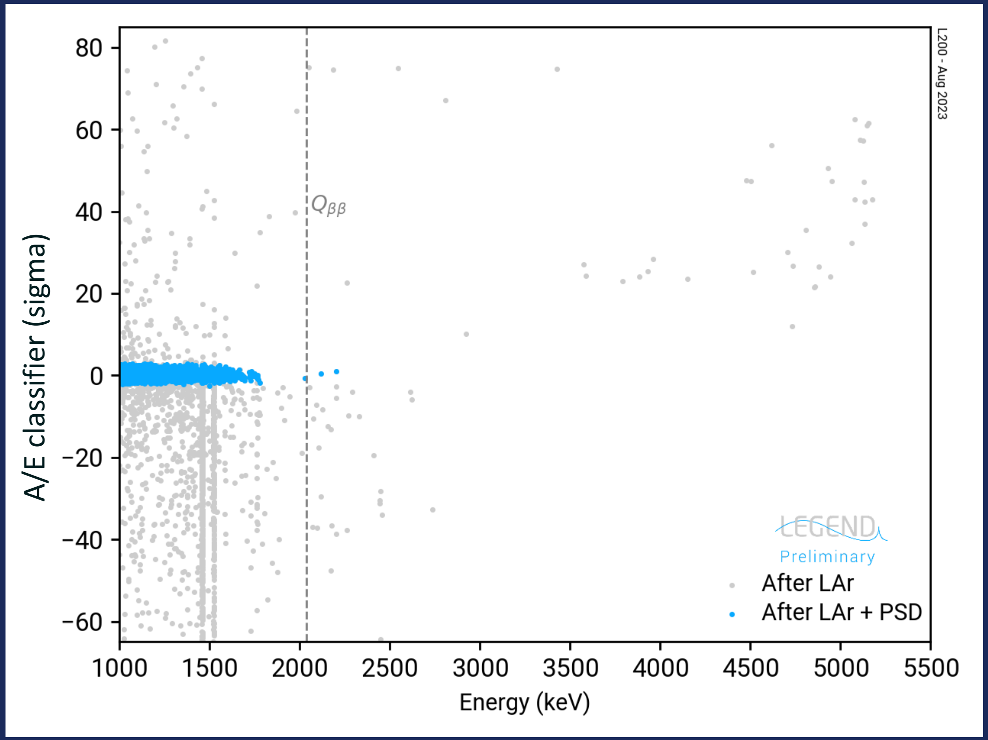
Multi Site Event (MSE)

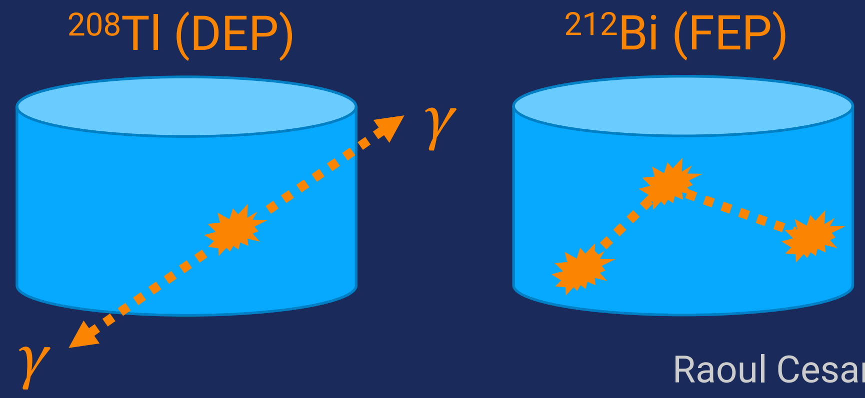
How signals generate in Germanium detectors



PSD preliminary performance

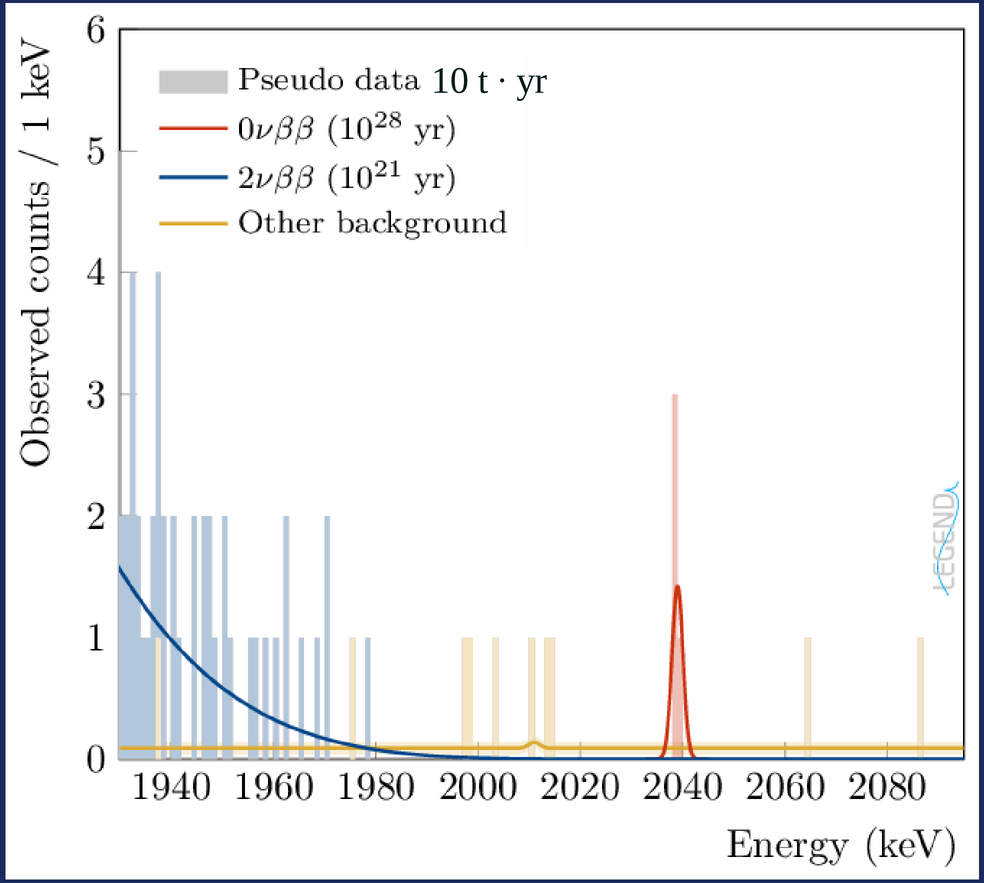


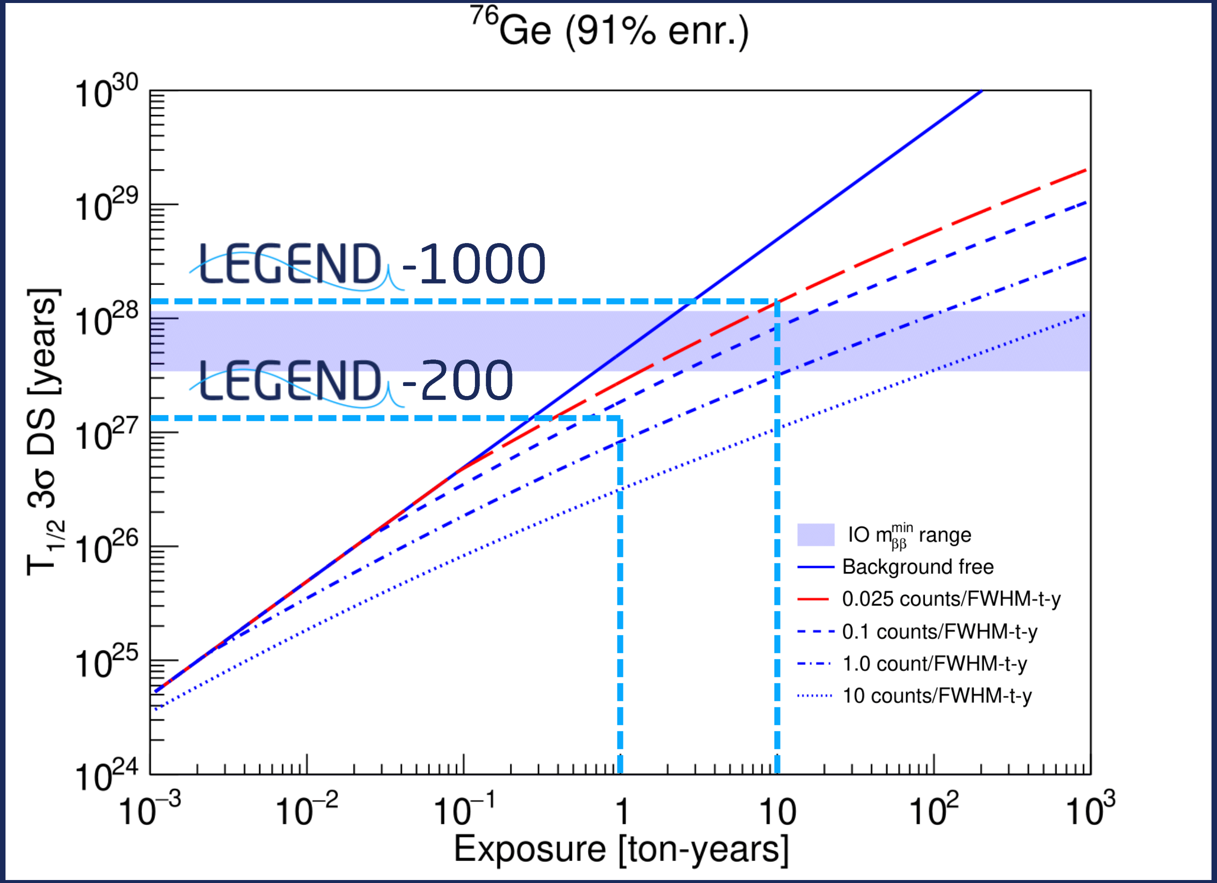




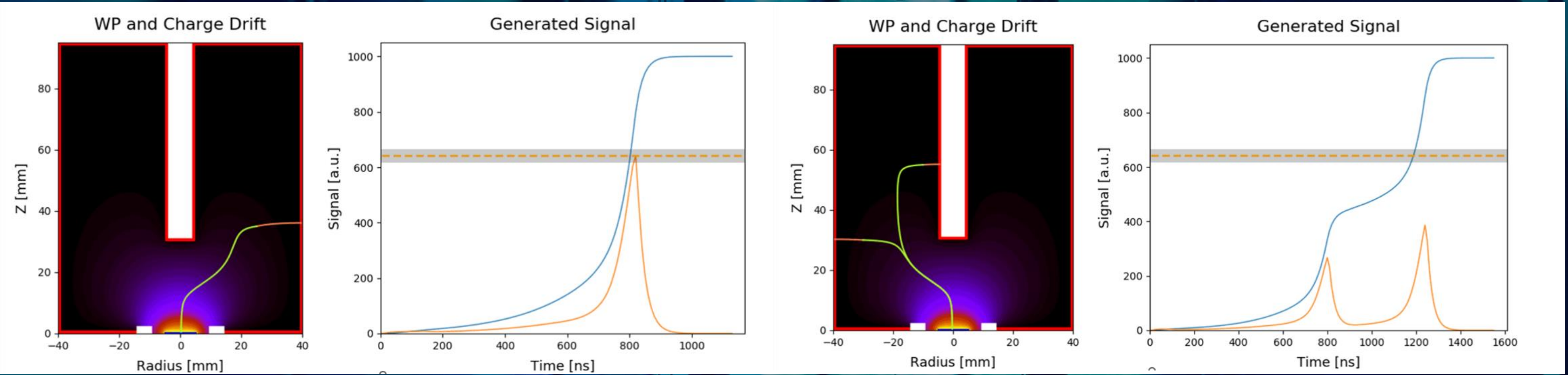
- DEP are used as proxy for SSE
- FEP and SEP for MSE
- PSD tuned to 90% survival at ^{208}Tl DEP

Designed for an unambiguous discovery





Thank you for your attention

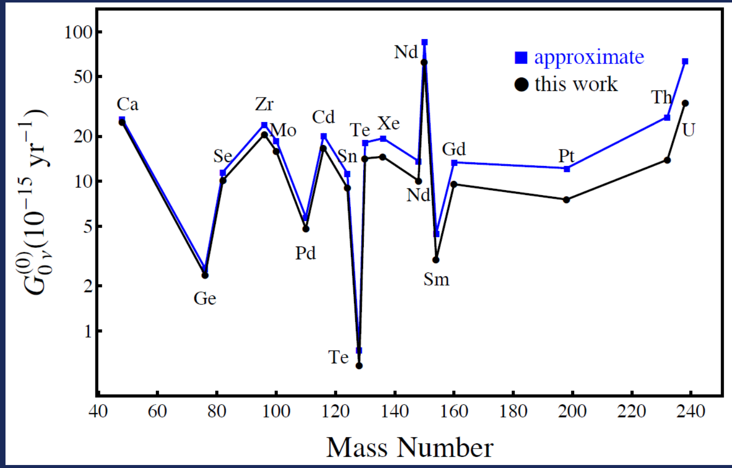


BACKUP SLIDES

0νββ half life

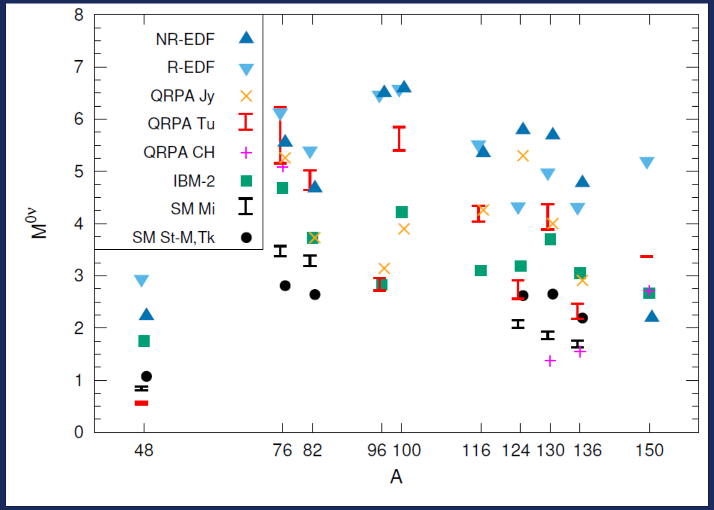
$$\Gamma^{0\nu} = \left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \quad |M_{0\nu}|^2 \quad \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Phase space factor
Atomic physics



https://doi.org/10.1103/PhysRevC.85.034316

Nuclear matrix element
Nuclear physics



https://doi.org/10.48550/arXiv.1610.06548

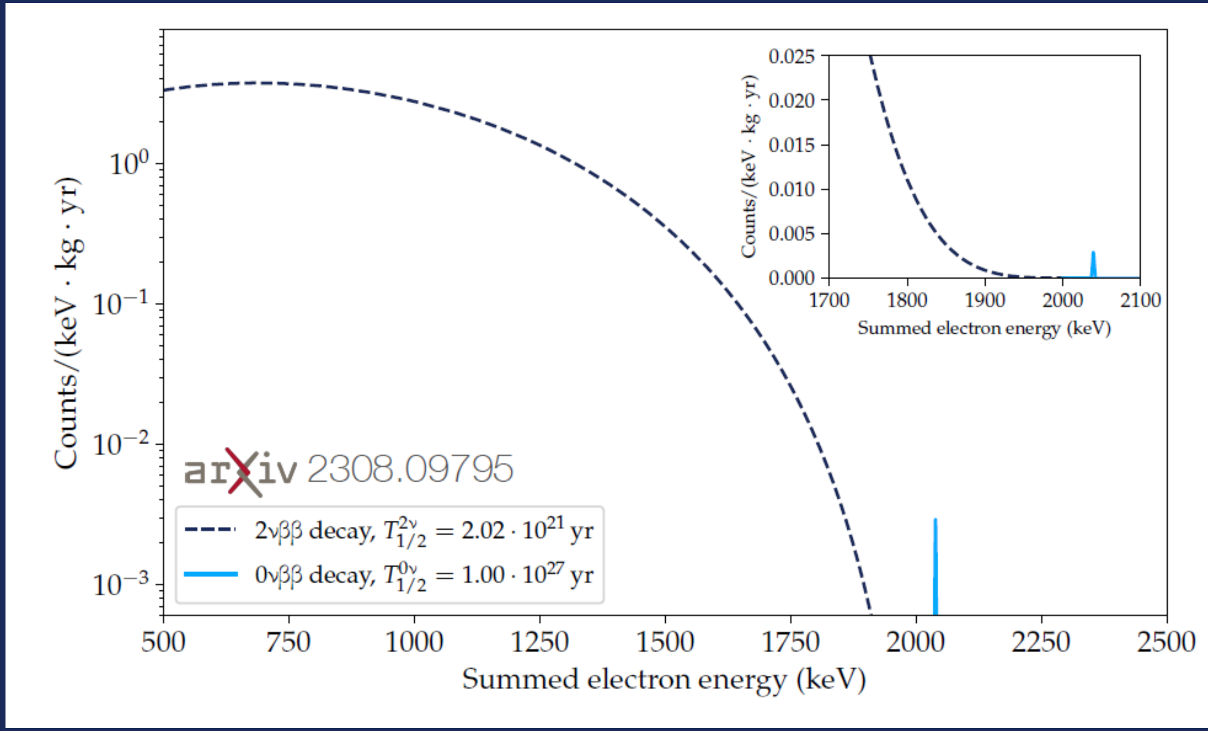
Effective Majorana mass
Particle physics

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu 1} + s_{12}^2 c_{13}^2 m_{\nu 2} e^{i\phi_{12}} + s_{13}^2 m_{\nu 3} e^{i\phi_{13}}$$

$\phi \rightarrow$ *Majorana phases*

Ge advantages

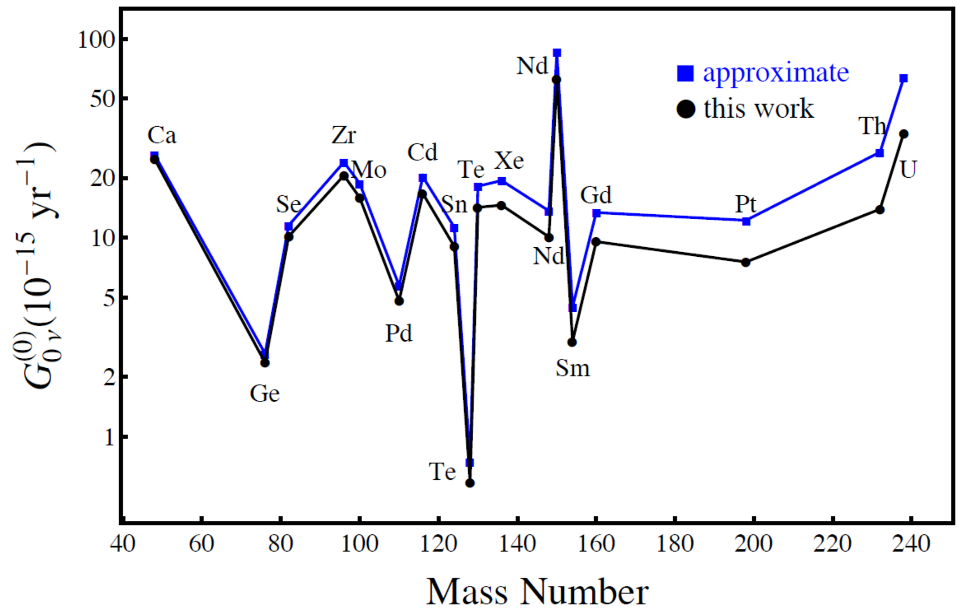
- The source is embedded in the detector, providing high efficiency
- Best energy resolution, FWHM better than 0.1% at $Q_{\beta\beta}$ = 2039 keV
- Highly radio-pure
- High density
- PSD capabilities
- Enrichment up to 88% in ^{76}Ge



Ge disadvantages

- Low $Q_{\beta\beta}$, below the ^{208}Tl line of 2615 keV
- Rather expensive enrichment process
- Low value of the phase space factor respect to other isotopes. This implies the need to reach a longer $T^{0\nu}_{1/2}$ to probe a given $m_{\beta\beta}$ value

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371



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HPGe detectors geometries

M= 2,5 kg

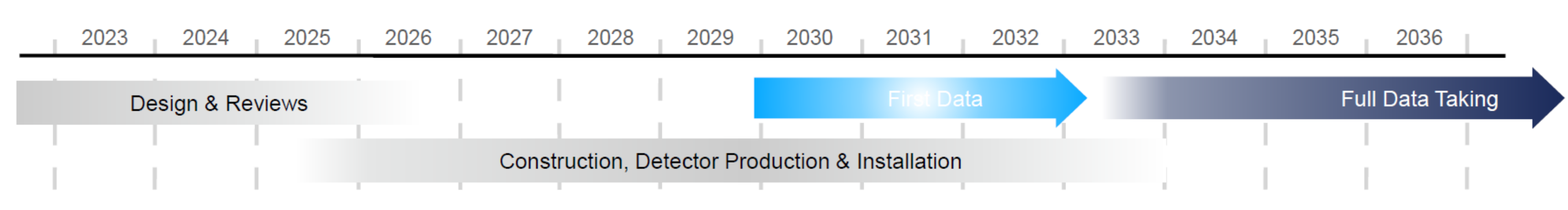
Bore hole → depletion of a larger volume → large mass detector

D=8 cm, H = 3 cm, M= 0,8 Kg
Mass limited down to 1 kg
Smaller p+ area
Lower noise
Better ΔE
Better PSD

The *well* allows depleting the detector at the usual operational voltage of about 4000 V with a mass above 3 kg

Good PSD capabilities

LEGEND timeline

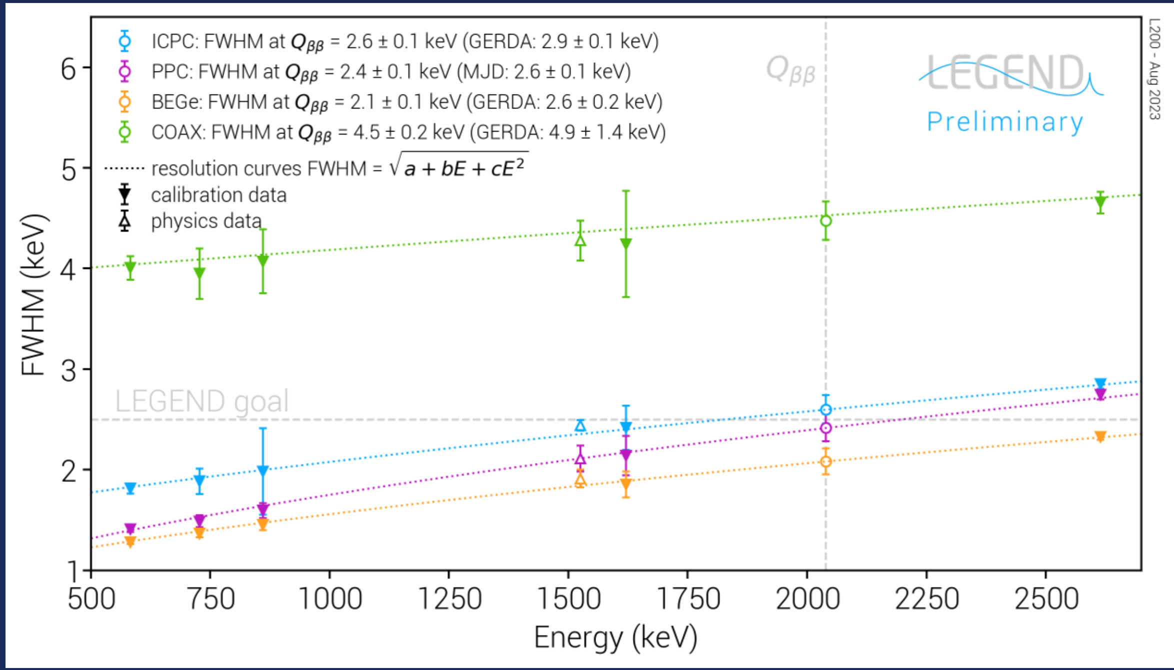


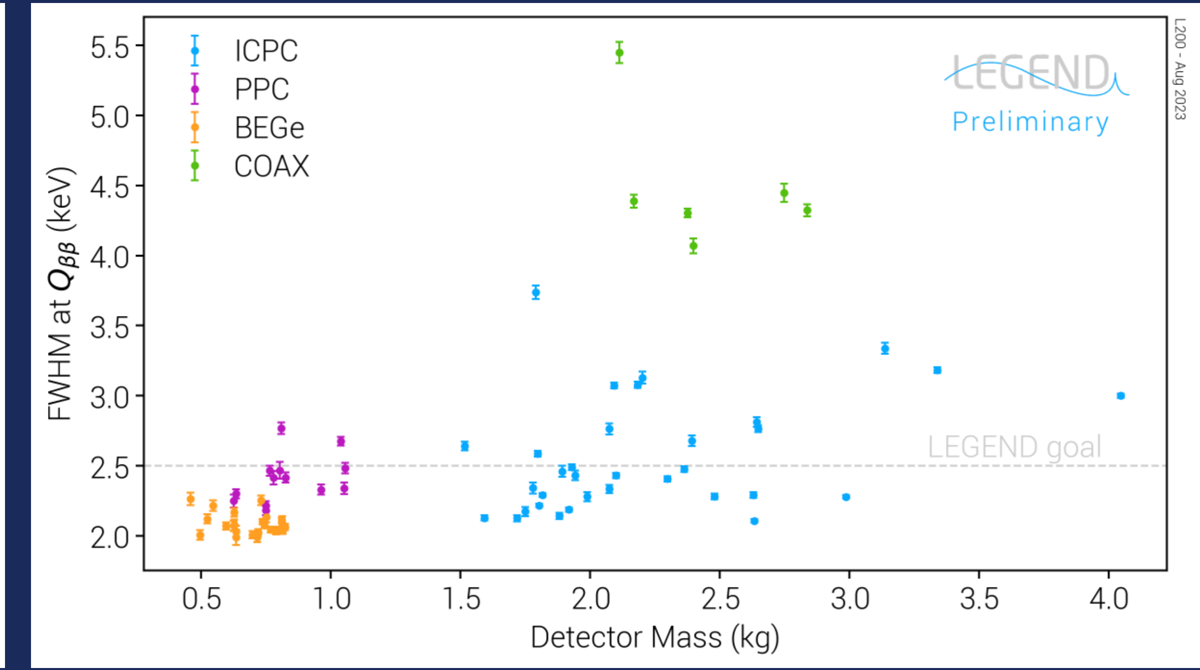
Lowest BI → GERDA

Best energy resolution → MAJORANA

	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)]	$(5.2 \pm 1.6) \cdot 10^{-4}$	$(4.7 \pm 0.8) \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Resolution [KeV]	2.6±0.2	2.52±0.08	2.5	2.5

Energy resolution preliminary performance

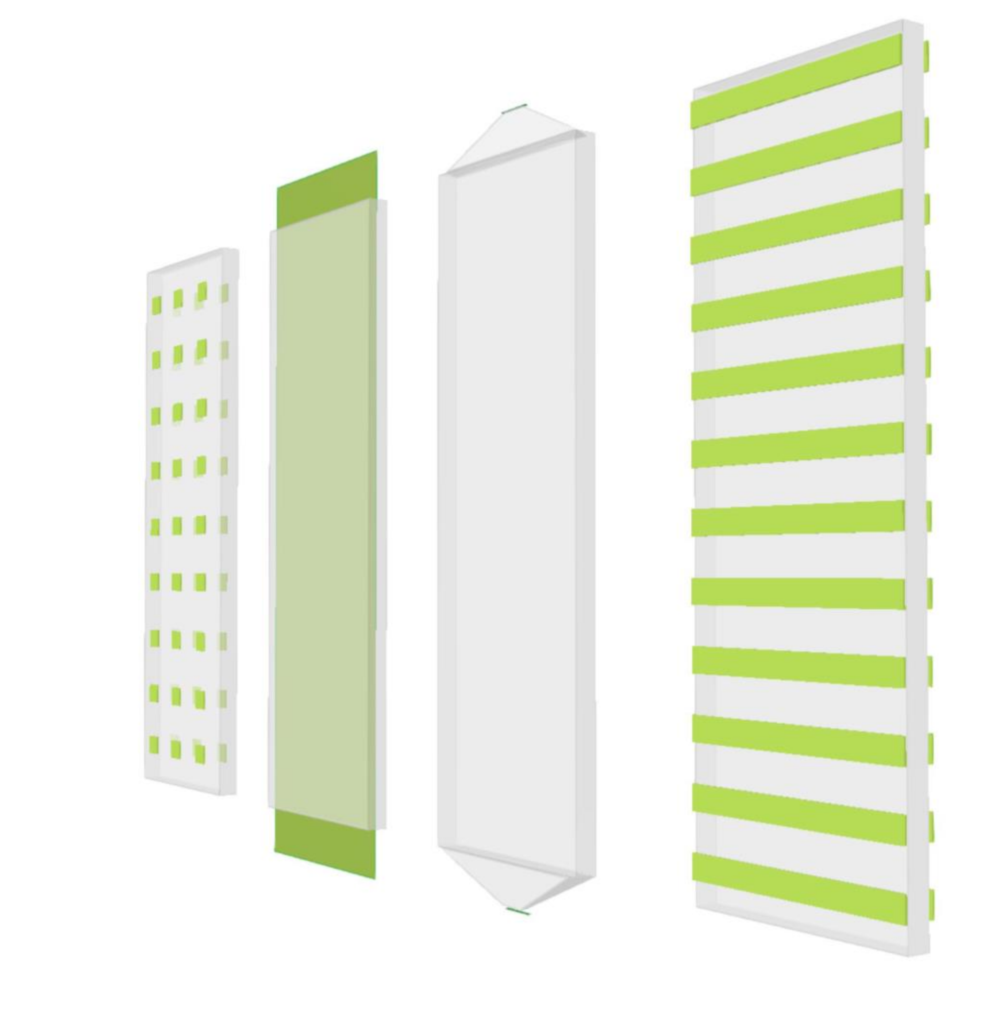




Overall improvement in energy resolution @$Q_{\beta\beta}$

Energy scale very stable between calibrations

Neutron moderator



0νββ experiments comparison