Large Enriched Germanium Experiment for Neutrinoless ββ Decay

The CUPID and LEGEND double-beta decay experiments

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13th - 17th September 2021

Neutrinoless double beta decay

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^- + 2\,\bar{\nu}$

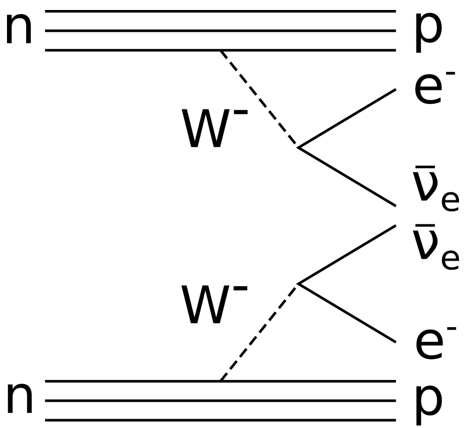
Double beta decay with neutrinos in the final state

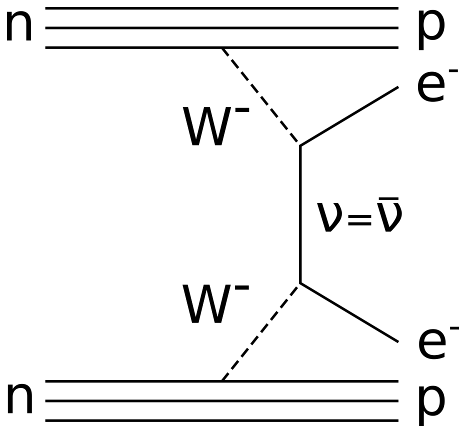
$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$ $\Delta L = 2 \longrightarrow$ beyond SM

Neutrinoless double beta decay

Standard Mechanism: light Majorana neutrino exchange

Non-standard mechanism: heavy neutrinos, RH currents, supersymmetric particle, etc.





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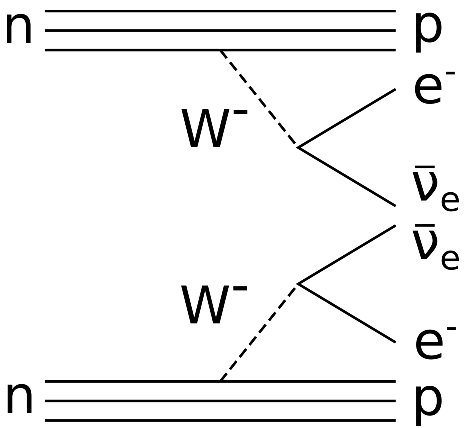

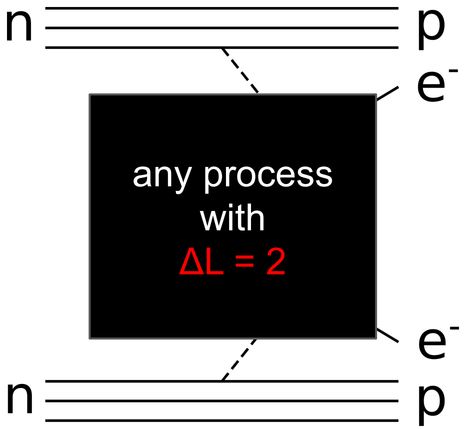

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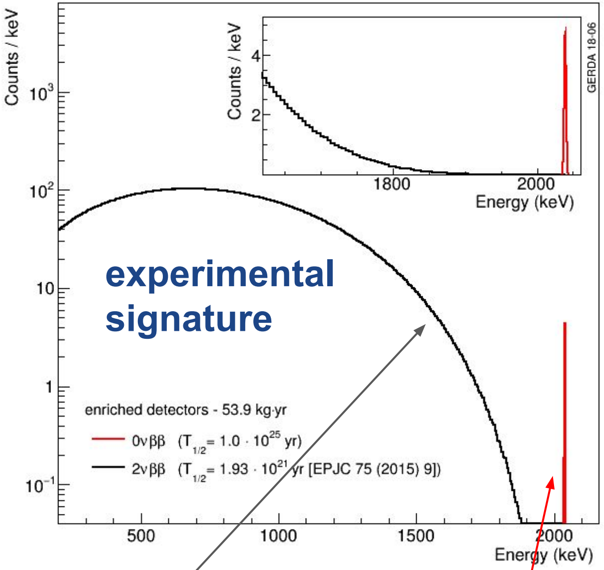


continuous spectrum of 2nbb

mono energetic line of 0nbb

Experimental challenges

Non-zero background

$$T^{0\nu}_{1/2} \propto \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

background index

energy resolution

Zero-background limit

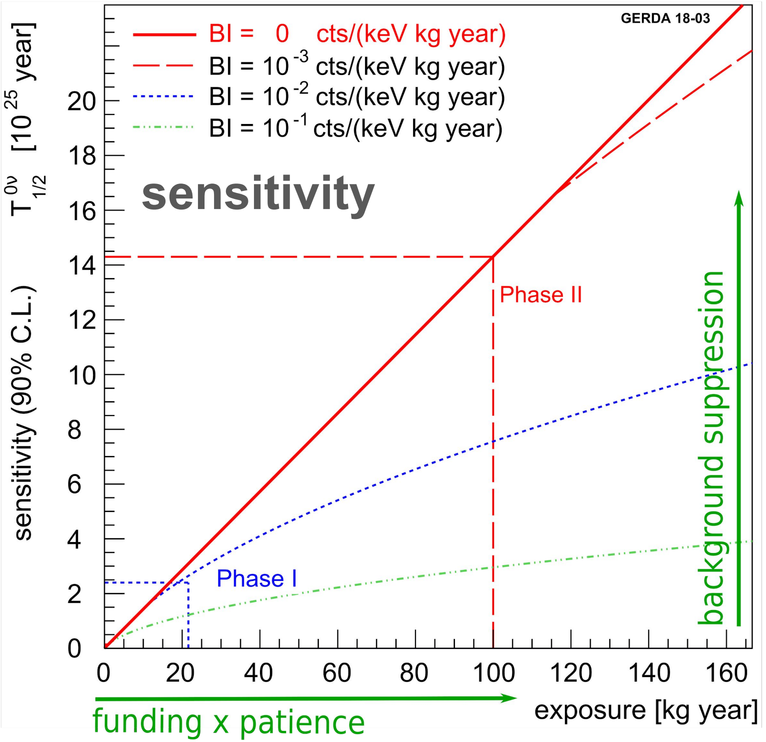
$$T^{0\nu}_{1/2} \propto \epsilon \cdot a \cdot M \cdot t$$

efficiency

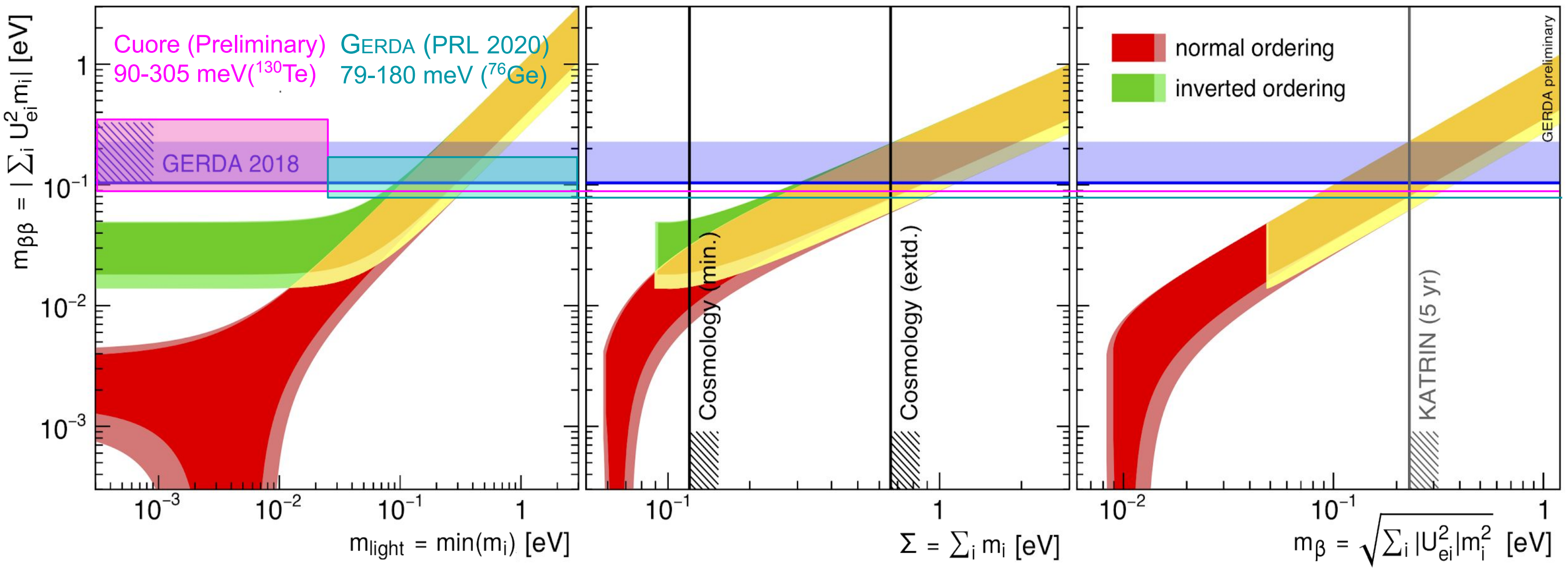
isotopic abundance

mass

measurement time



Parameter Space in the standard picture



three flavour oscillation parameters from [NuFit v4.1 (www.nu-fit.org)]

CUORE, arXiv: 2104:06906 GERDA, Phys. Rev. Lett. 125, 252502 (2020)

GERDA Phase II and MJD

LEGEND builds on the successful GERDA and MJD experiments

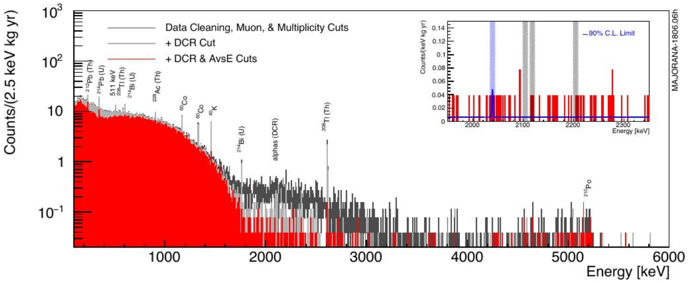
MJD - Majorana Demonstrator

- operation of Ge crystals in vacuum cryostat, ultra-clean underground electroformed copper
- SURF (South Dakota) until 2020
- ΔE: **2.53 keV** (FWHM at Q_{bb})
- BI: 4.7 x 10^{-3} cts / (kg keV yr)

GERDA - Germanium Detector Array

- operation of bare Ge crystals immersed in LAr, LAr scintillation for active veto
- LNGS (Italy) until Nov 2019
- ΔE: 2.6 keV (BEGe FWHM at Q_{bb})
- BI: **5.2 x 10^{-4} cts / (kg keV yr)**

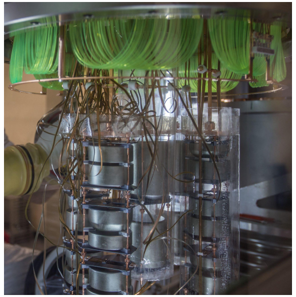
MJD

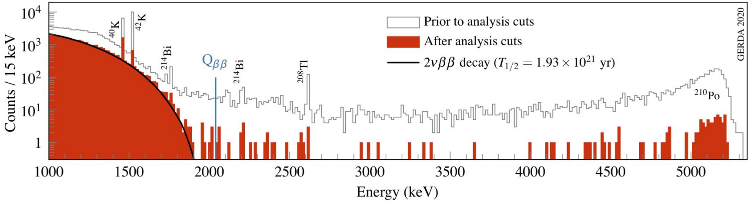


$T_{1/2}$ > 2.7 x 10^{25} yr (m_{bb} < 200-433 meV)

Phys. Rev. C 100, 025501 (2019)

GERDA





$T_{1/2}$ > 1.8 x 10^{26} yr (m_{bb} < 79-180 meV)

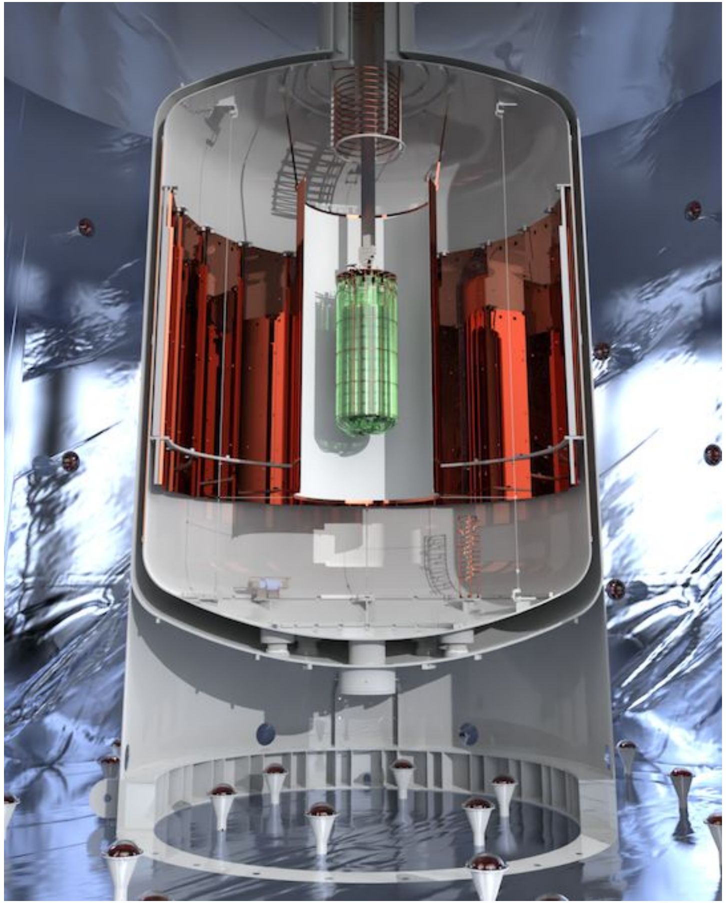
Phys. Rev. Lett. 125, 252502 (2020)

LEGEND-200 status

- upgrade **existing infrastructure** at LNGS to **200 kg detector mass**
- under construction
  - ICPC detector production from enr. ^{76}Ge (92%)
  - LAr veto system improved
  - improved radio-purity: underground electroformed copper, Copper-Kapton laminated cables
  - optically active structural material
- start commissioning end of 2021

projected background **0.5 cts/(FWHM t yr)**
~1/3 wrt Gerda Phase II

5 yr sensitivity $T_{1/2} > 10^{27}$ yr (m_{bb} < 34-78 meV)



pCDR: arXiv:2107.11462

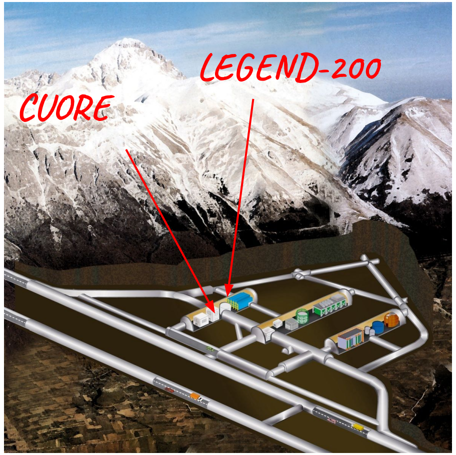
LEGEND background rejection

passive

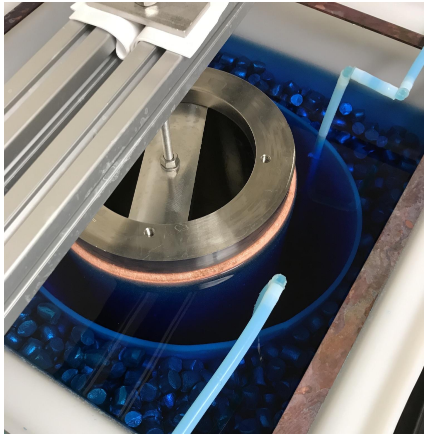
- underground lab
- shielding
- clean construction materials

LNGS

- 3800 mwe

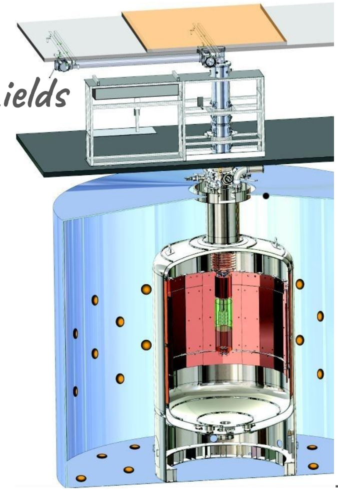


underground electroformed copper



passive shields

- water
- copper
- LAr



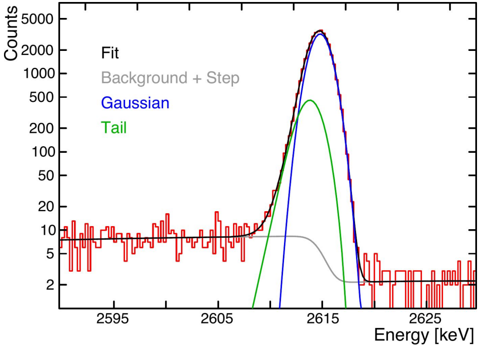
LEGEND background rejection

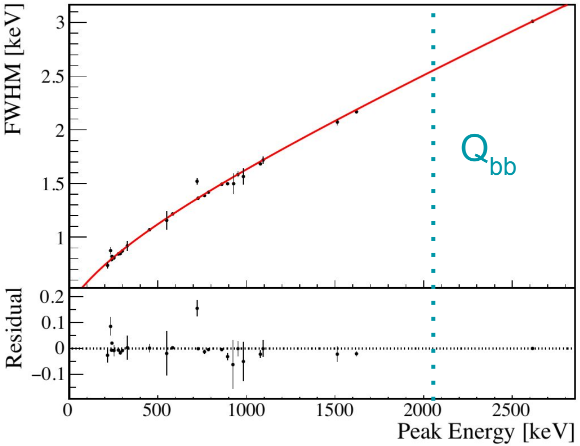
passive

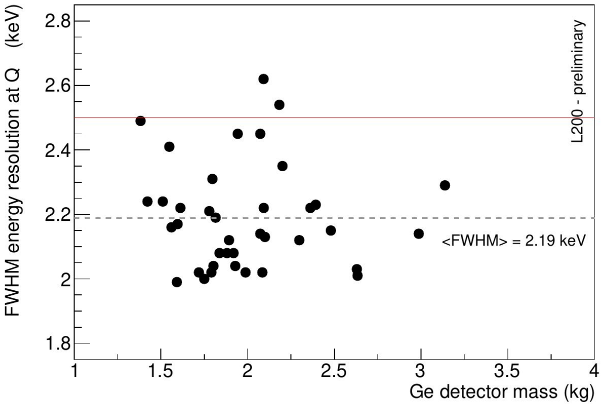
energy resolution

- energy resolution MJD
  2.53 keV @ Q_{bb}
- detector production
  Legend-200 mean vacuum
  2.19 keV <FWHM> @ Qbb
- 2nbb is not a background for LEGEND-200

energy resolution MJD







detector production
LEGEND-200
vacuum energy
resolution at Q_{bb}

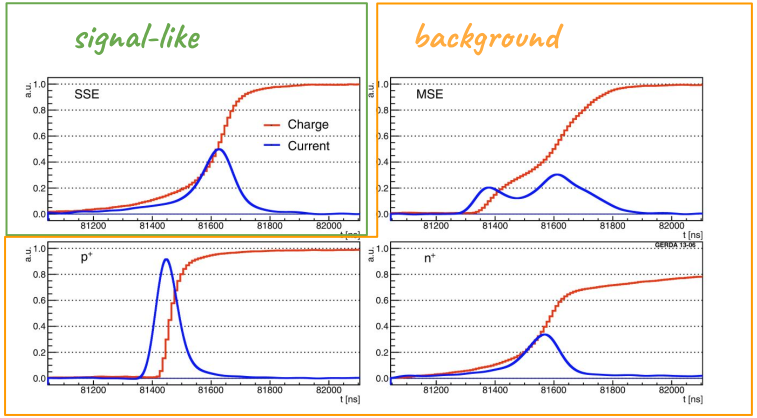
LEGEND background rejection

passive

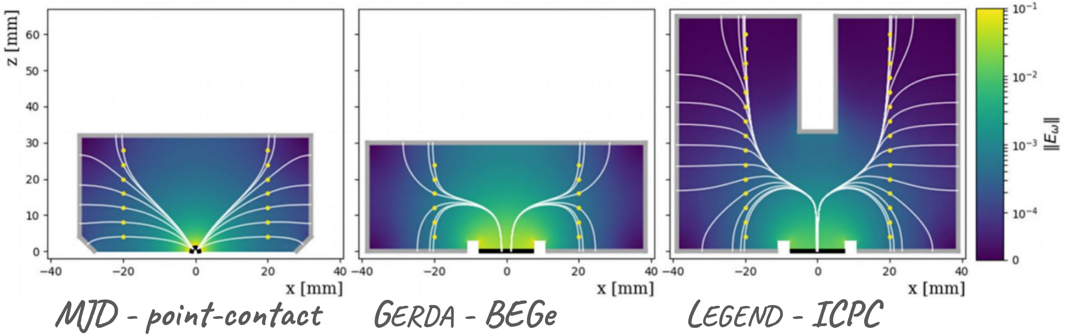
energy resolution

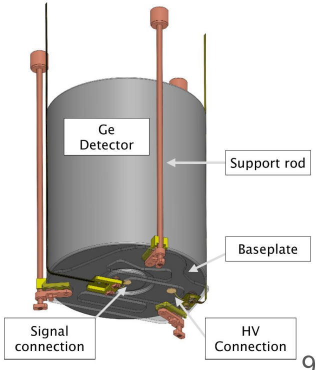
pulse shape discrimination

- reject γ- and α-backgrounds



weighting potential





LEGEND background rejection

passive

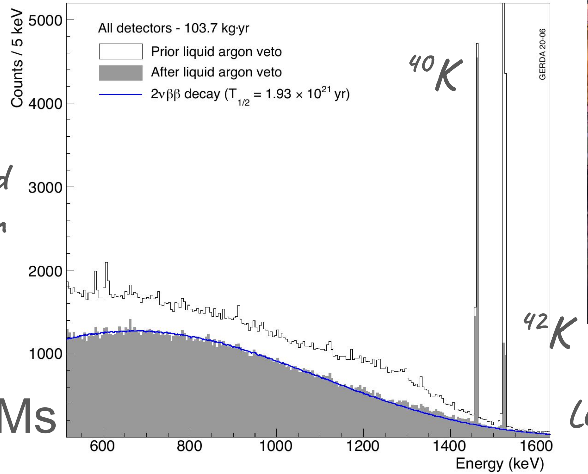
energy resolution

pulse shape discrimination

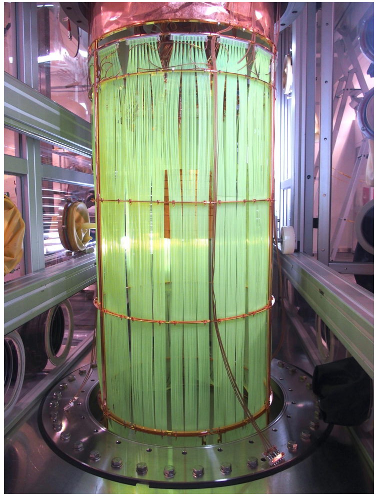
Liquid Argon (LAr) veto

- light-guiding fibers coupled to SiPMs
- LAr 128 nm scintillation light
- optically active polyethylene naphthalate (PEN) holder plates: shifts 128 nm to ~440 nm and scintillates
- teflon reflector for better light collection
- LAr quality monitoring & purification NEW

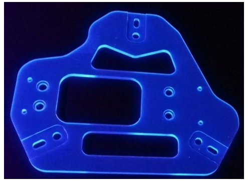
LAr veto background suppression



GERDA implementation

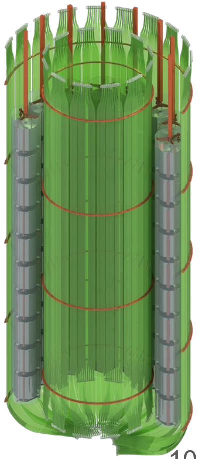


NEW



PEN

LEGEND design



NEW

teflon reflector

Going tonne scale LEGEND-1000

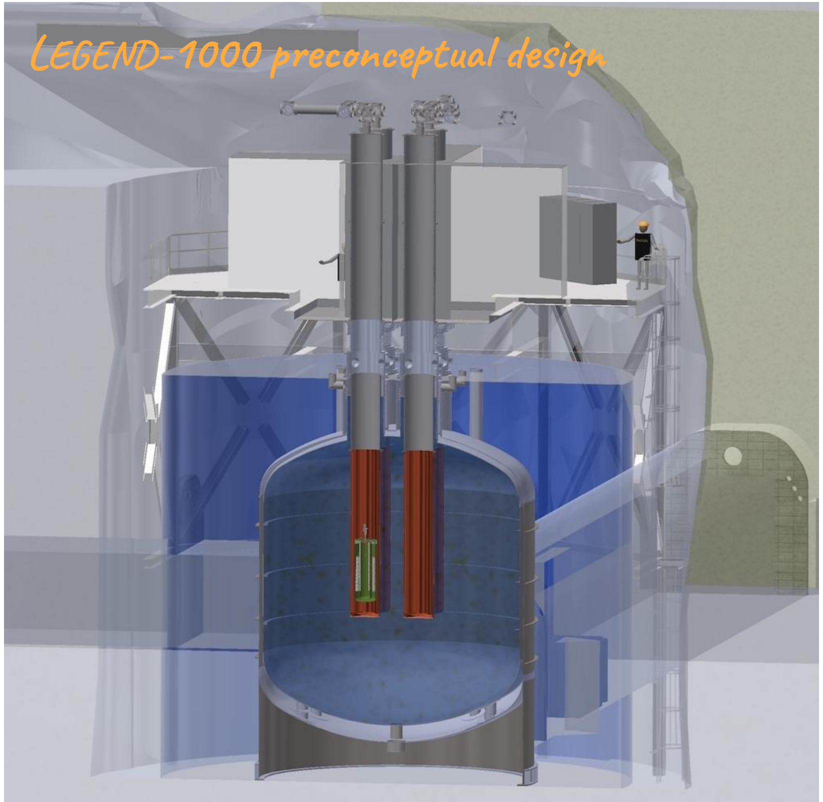
- LEGEND-1000 is designed with 4x LEGEND-200 reentrant tubes
- UgLAr inside reentrant tubes
- all LAr volumes instrumented with veto system
- baseline laboratory SNOLAB
- possibility to build LEGEND-1000 at LNGS is investigated

EPJC volume 78, 597 (2018)

"Virtual depth by active background suppression: revisiting the cosmic muon induced background of GERDA PhaseII"

10 yr target sensitivity

$T_{1/2} > 1.6 \times 10^{28}$ yr ($m_{bb} < 9\text{-}19$ meV)



pCDR: arXiv:2107.11462

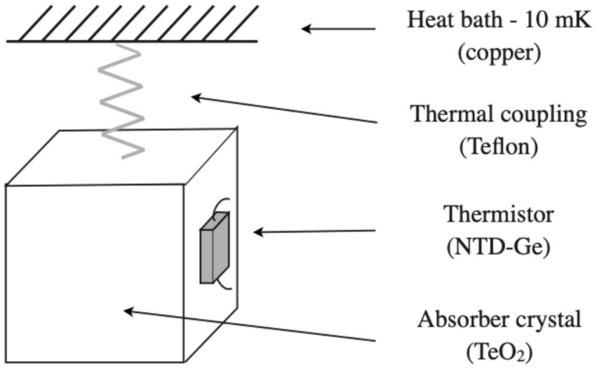
Bolometric technique

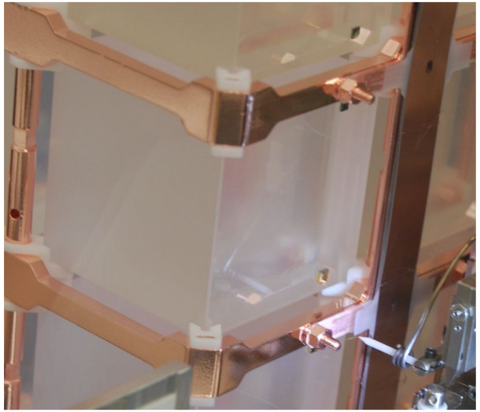
Cryogenic detectors ~ 10 mK operating temperature

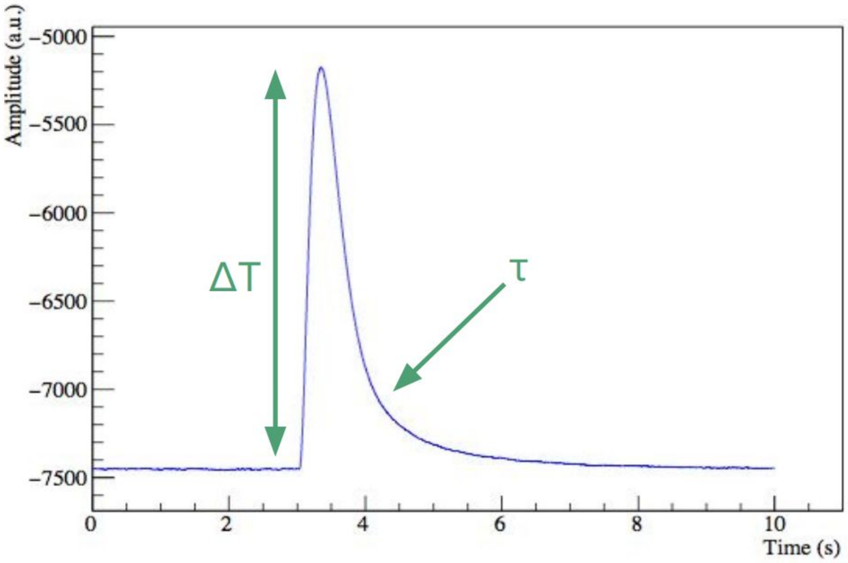
Low heat capacity → very temperature sensitive
ΔT ~ E/C

Neutron Transmutation Doped Ge thermistor (NTD) → resistance depends on temperature

Good energy resolution (~0.2% FWHM)

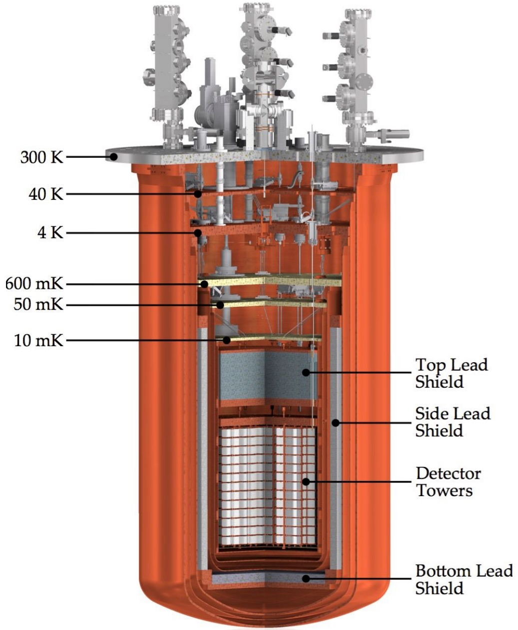


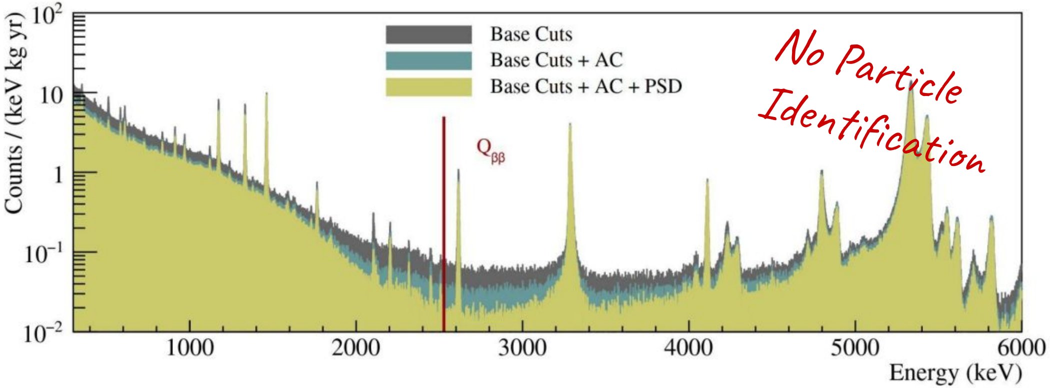


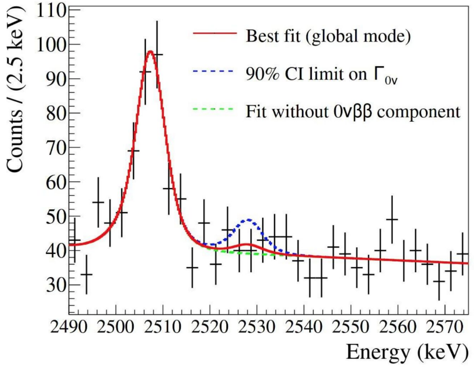


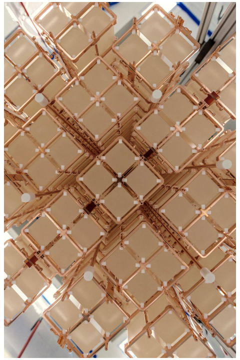
CUORE experience

Custom dry dilution refrigerator
988 $^{nat}TeO_2$ crystals @ ~10mK
34% isotopic abundance (206 kg ^{130}Te)
Outer + inner roman lead shielding
Background index @ $Q_{\beta\beta}$ ~ 1.49 10^{-2} cts/(keV kg yr)
Running since 2017, collected > 1 tonne.yr exposure
$T_{1/2}$ (^{130}Te) > 2.2x10^{25} yr ($m_{\beta\beta}$ < 90-305 meV)





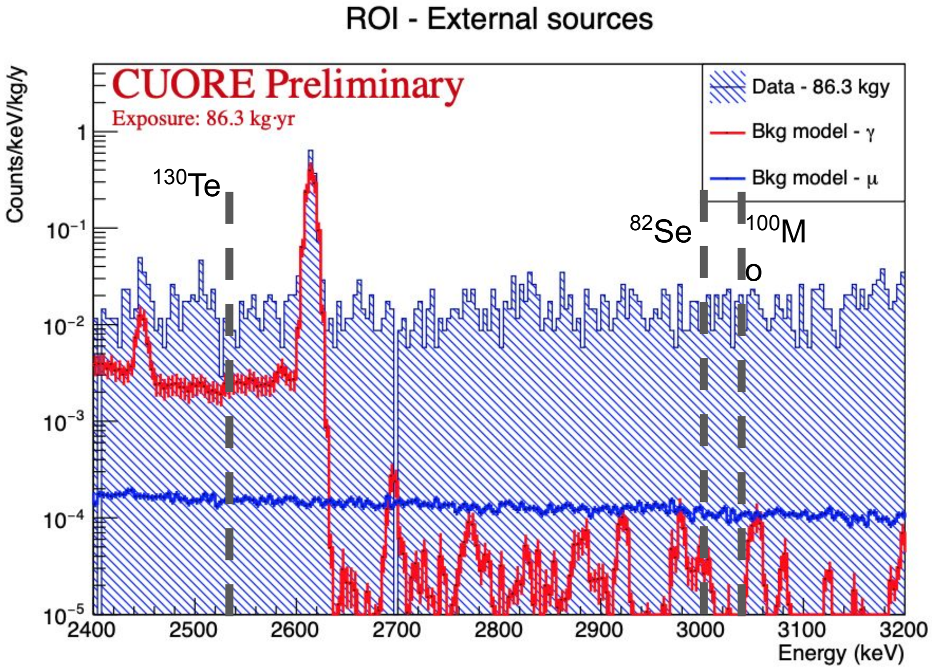




[CUORE, PRL 126 (2021) 17, 171801](#) [CUORE, arXiv: 2104:06906](#)

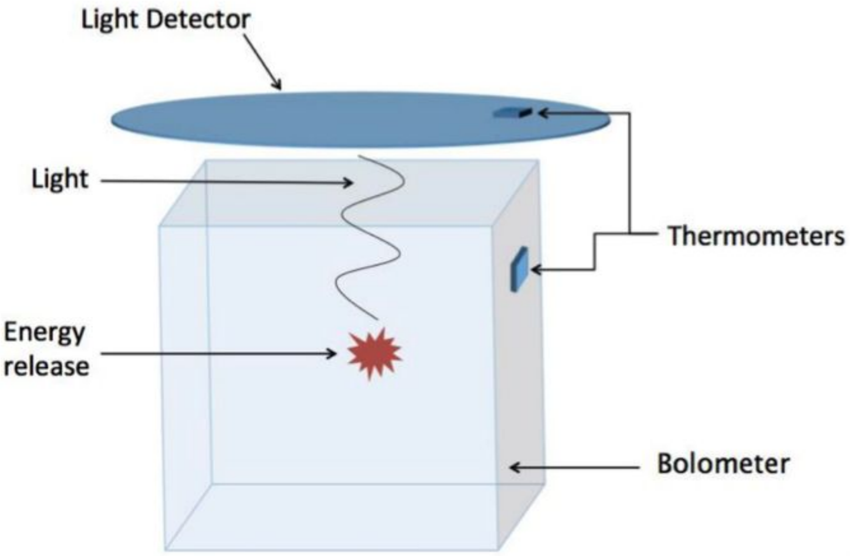
Particle identification is needed

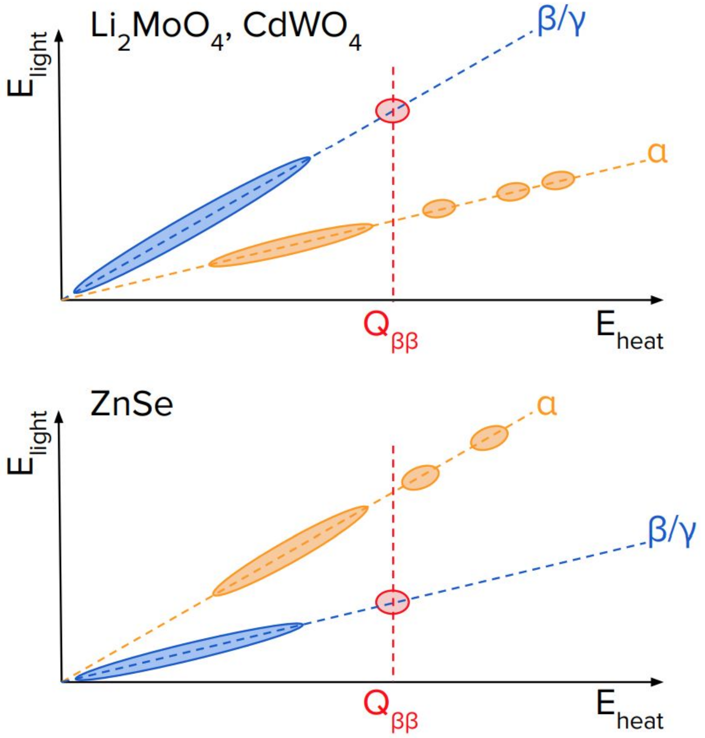
- Most of the background comes from partly-contained α particles from U/Th chains
- Q-value > 2.6 MeV (^{82}Se / ^{100}Mo) reduces β/γ background by ~2 orders of magnitude
- Remaining dominant contribution: muons (active veto)



CUPID, pre-CDR arXiv: 1907.09376

Particle IDentification (PID): dual readout

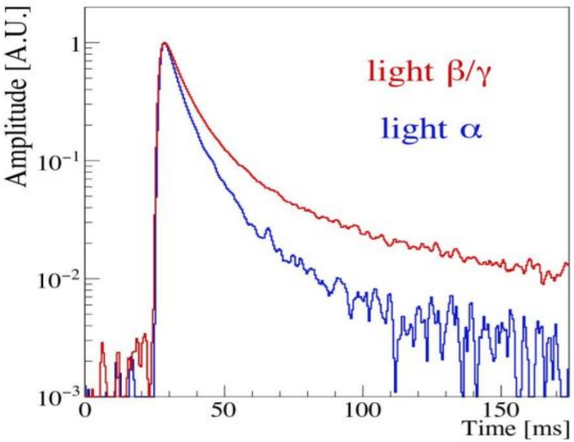


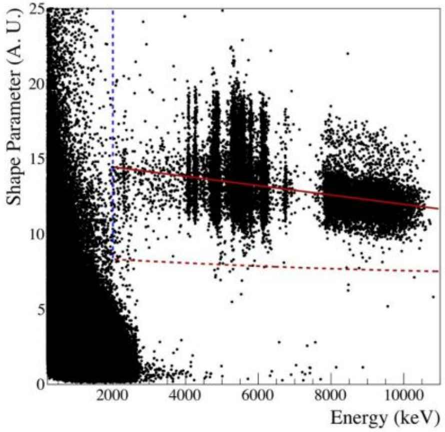


CUPID-0 (^{82}Se)

- 26 ZnSe crystals
  (24 enriched 95% in ^{82}Se)
- CUORICINO cryostat @ LNGS
- PID via pulse shape
- 16.59 kg yr exposure (phase I + II)
- ~ 20 keV resolution
- Background
  Phase I ~ 3.5 10^{-3} cts/(keV kg yr)
  Phase II ~ 5.5 10^{-3} cts/(keV kg yr)
- $T_{1/2}$ (^{82}Se) > 4.7 10^{24} yr
  ($m_{\beta\beta}$ < 276-570 meV)

Preliminary
(TAUP21)





[CUPID-0, PRL 123 (2019) 032501](#)

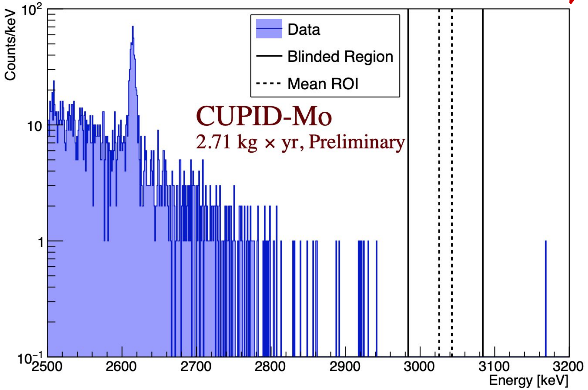
[CUPID-0, NIM, A 958 (2020) 162441](#)

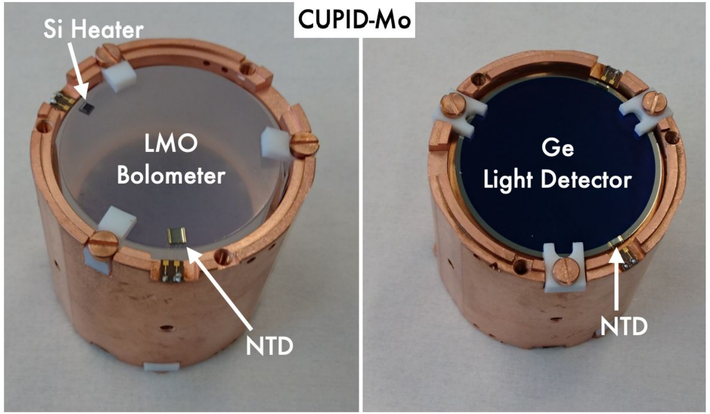
[CUPID-0, PRL 123 (2019) 262501](#)

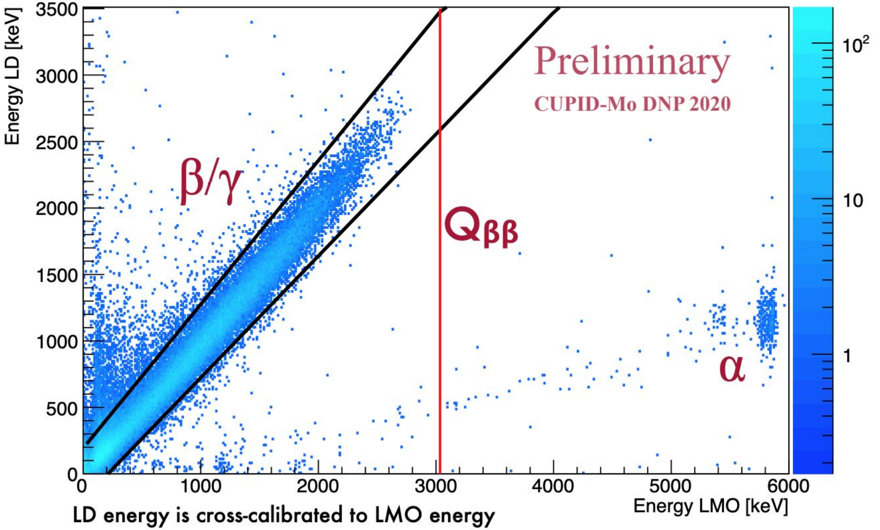
CUPID-Mo (^{100}Mo)

- 20 cylindrical Li_2MO_4 crystals
- 20 Ge wafers as light detectors
- > 95% enrichment, ~2.6 kg (^{100}Mo)
- EDELWEISS cryostat (~21 mK)
- Laboratoire Souterrain de Modane (LSM)
- Resolution @ $Q_{\beta\beta}$ ~ 7.4 keV FWHM
- Background $O(10^{-3})$ cts/(keV kg yr)
- $T_{1/2}$ (^{100}Mo) > 1.8 10^{24} yr ($m_{\beta\beta}$ < 280-490 meV)

Preliminary (TAUP21)





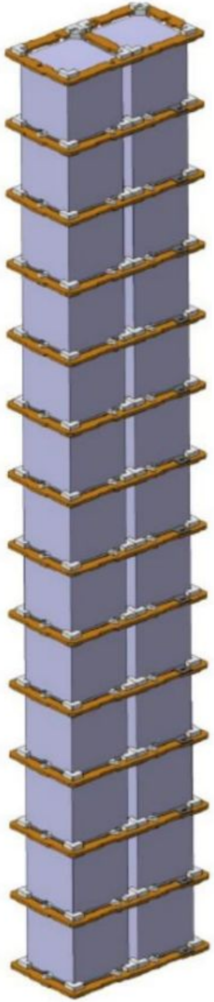


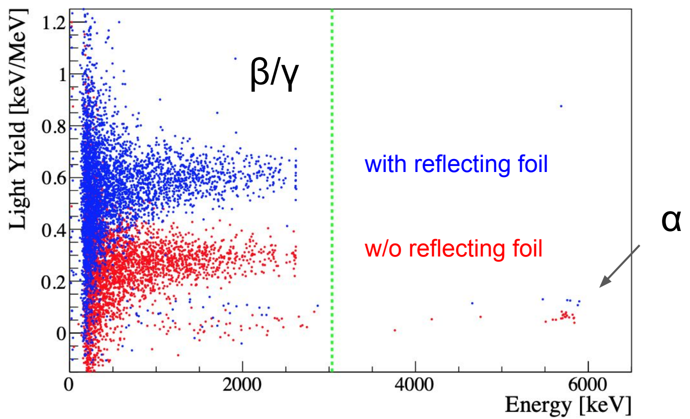
CUPID-Mo PRL 126 (2021) 18, 181802

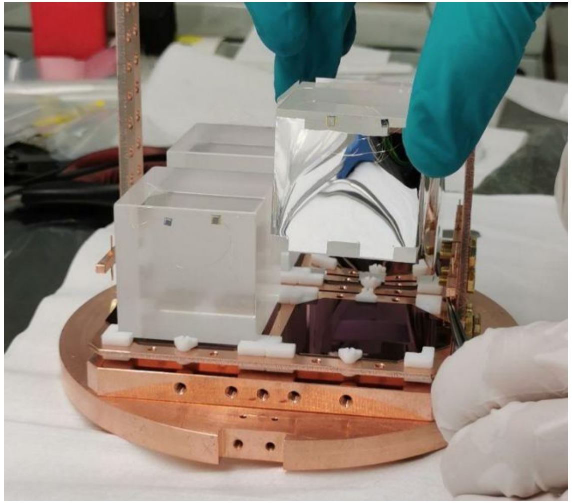
CUPID

- 1500 Li_2MO_4 45x45x45 mm^3 crystals
- > 95% enrichment → ~ 250 kg (^{100}Mo)
- CUORE cryogenic infrastructure
- simpler tower structure (test in progress)
- Dual readout (particle identification)
- Target resolution: 5 keV FWHM
- Target background: 10^{-4} cts/ (keV kg yr)
- Target sensitivity > 10^{27} yr ($m_{\beta\beta}$~ 12-20 meV)

[CUPID, arXiv:1907.09376]
[CUPID, EPJ C 81 (2021) 2, 104]
[CUPID, arXiv:2011.11726]
[CUPID, JINST 16 (2021) 02, P02037]







Conclusion

Next 0nbb experiments at LNGS

Legend-200 will start commissioning end of 2021

5 yr exclusion sensitivity
$T_{1/2} > 10^{27}$ yr (m_{bb} < 34-78 meV)

possibility for **Legend-1000** at LNGS under study (ongoing DoE review process)

10 yr discovery sensitivity
$T_{1/2} > 1.3 \times 10^{28}$ yr (m_{bb} < 9-21 meV)

CUPID under DoE review process

10 yr discovery sensitivity
$T_{1/2} > 1.1 \times 10^{27}$ yr (m_{bb} < 12-20 meV)

minimum of m_{bb} roughly between 14 meV and 22 meV for inverted hierarchy

Thanks for your attention!

Experimental challenges

- 2nbb is rare decay with longest half lives ever measured 10^{18}-10^{24} yr
- 0nbb even worse > 10^{26} yr

age of the universe 10^9 yr this is an awfully long time

Let's look at some formulas

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

phase space

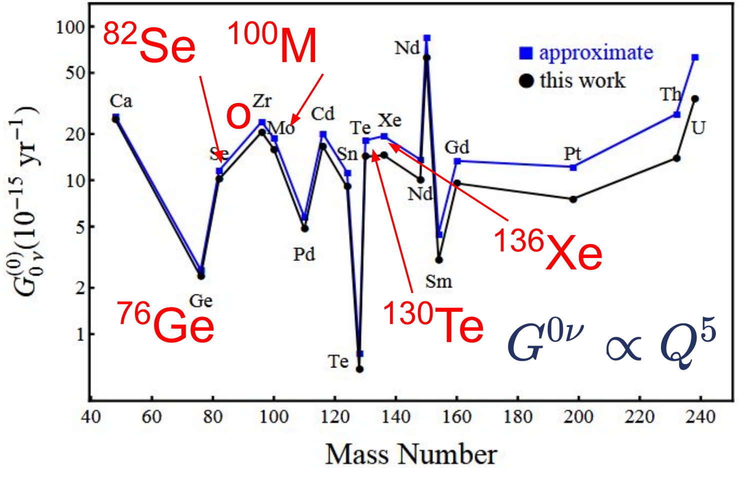
nuclear matrix element

majorana mass (standard interpretation)

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

Experimental challenges

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

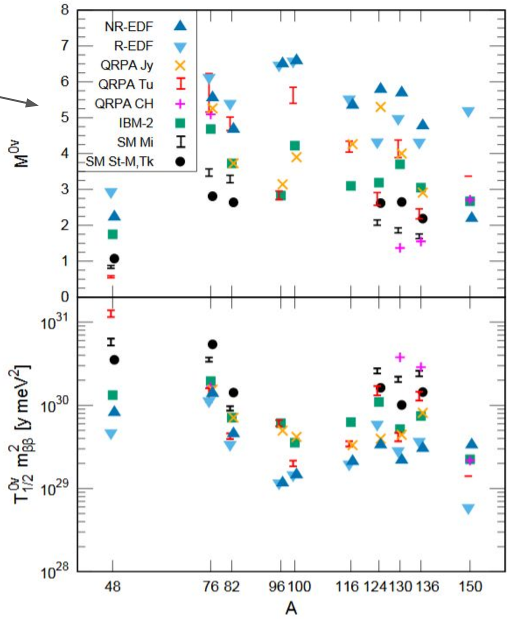


Phase Space

Nuclear Matrix Elements

factor 2-3 between predictions

all candidate isotopes quite similar



Experimental challenges

Isotopic abundance

- enrichment
- isotope selection

Energy resolution

- development
- not much that can be done

Efficiency

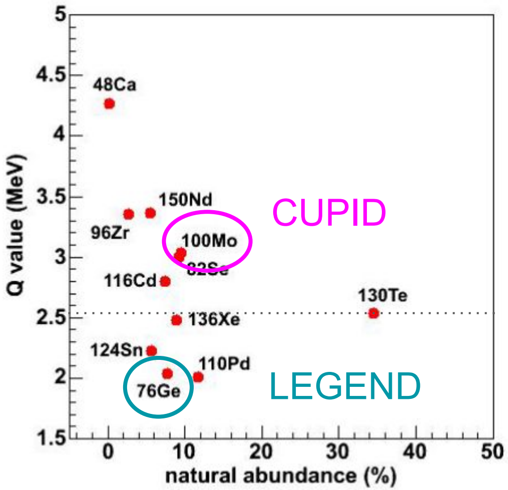
- preferred:
  source = detector

Time

- be patient

Mass

- spend more money
  -> go tonne scale



Background sources

Natural radioactivity

- clean and sparse construction
- shielding
- isotope selection for high Q-value (above 2.6 MeV)

Cosmic muons

- Underground laboratories

Neutrons

- specific shielding (water, PE)

Long lived cosmogenic isotopes

- store detectors (and construction materials) underground

LEGEND Numbers

TABLE IV. Experimental parameters in the LEGEND-1000 discovery potential and background projections.

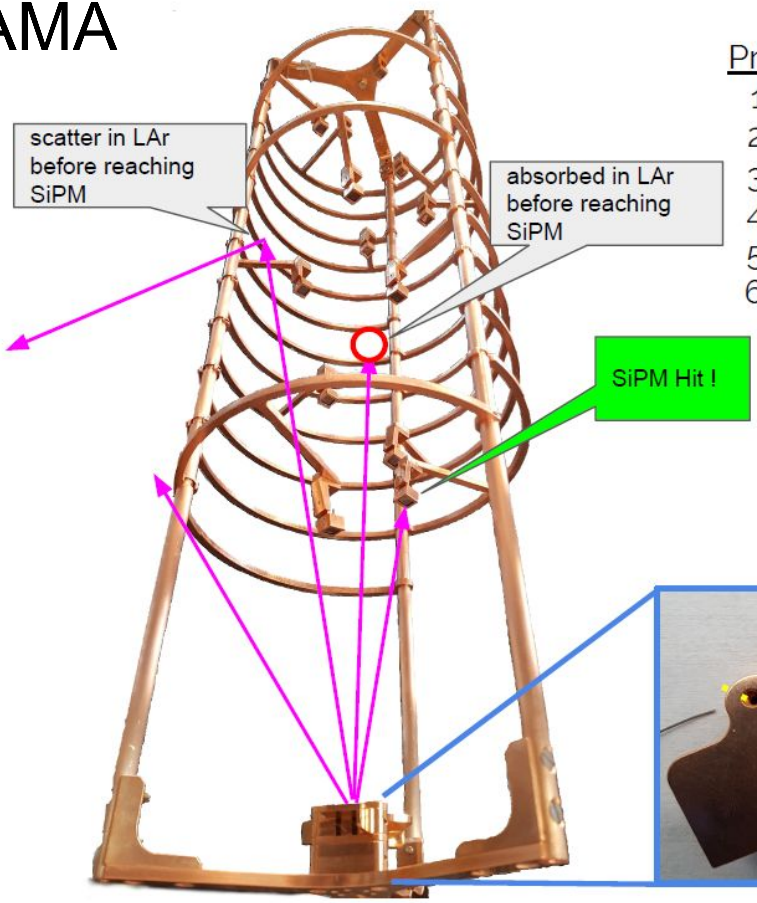
Parameter	**Value**
Performance Parameters	
$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance[a]	0.69
Live time goal	10 yr
Total exposure goal	10 t yr
Background goal	$< 1 \times 10^{-5}$ cts/(keV kg yr)
	< 0.025 cts/(FWHM t yr)
$T^{0\nu}_{1/2}$	1.3×10^{28} yr (99.7% CL discovery)
	1.6×10^{28} yr (90% CL sensitivity)
$m_{\beta\beta}$	9.4–21.4 meV (99.7% CL discovery)
	8.5–19.4 meV (90% CL sensitivity)
Physics Parameters	
$M_{0\nu}$	2.66–6.04 [28, 37]
$G_{0\nu}$	2.363×10^{-15} /yr [22]
g_A	1.2724

CUPID Numbers

Table 10: Parameters of the CUPID detector in the baseline scenario, in the optimistic background scenario, and for a large bolometric detector with 1 metric ton of ^{100}Mo isotope.

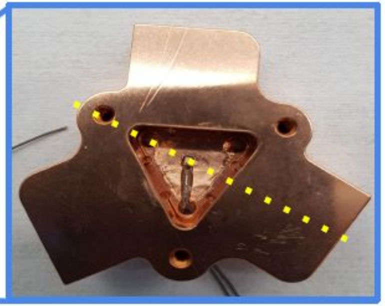
Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

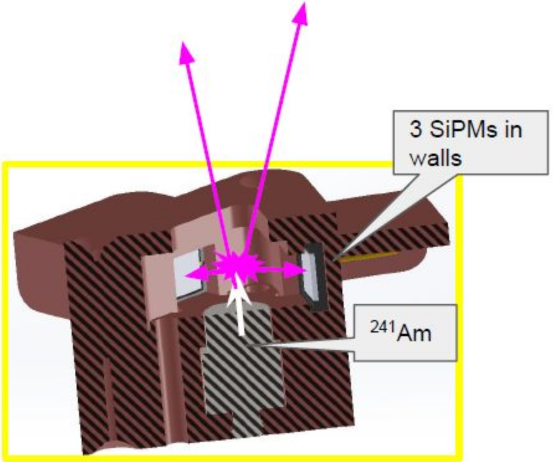
LLAMA



Principle of scintillation run:

1. ^{241}Am emits 60 keV gamma
2. gamma creates scintillation light in LAr
3. 3 source SiPMs detect light → trigger FADC
4. some photons exit source & travel upwards
5. hit on peripheral SiPM creates signal
6. counting Nr of peripheral SiPM hits and dividing by Nr of total gamma/scintillation events → PPT (pulse per trigger) value





Teflon Reflector