

L'esperimento LEGEND per la ricerca del neutrino di Majorana

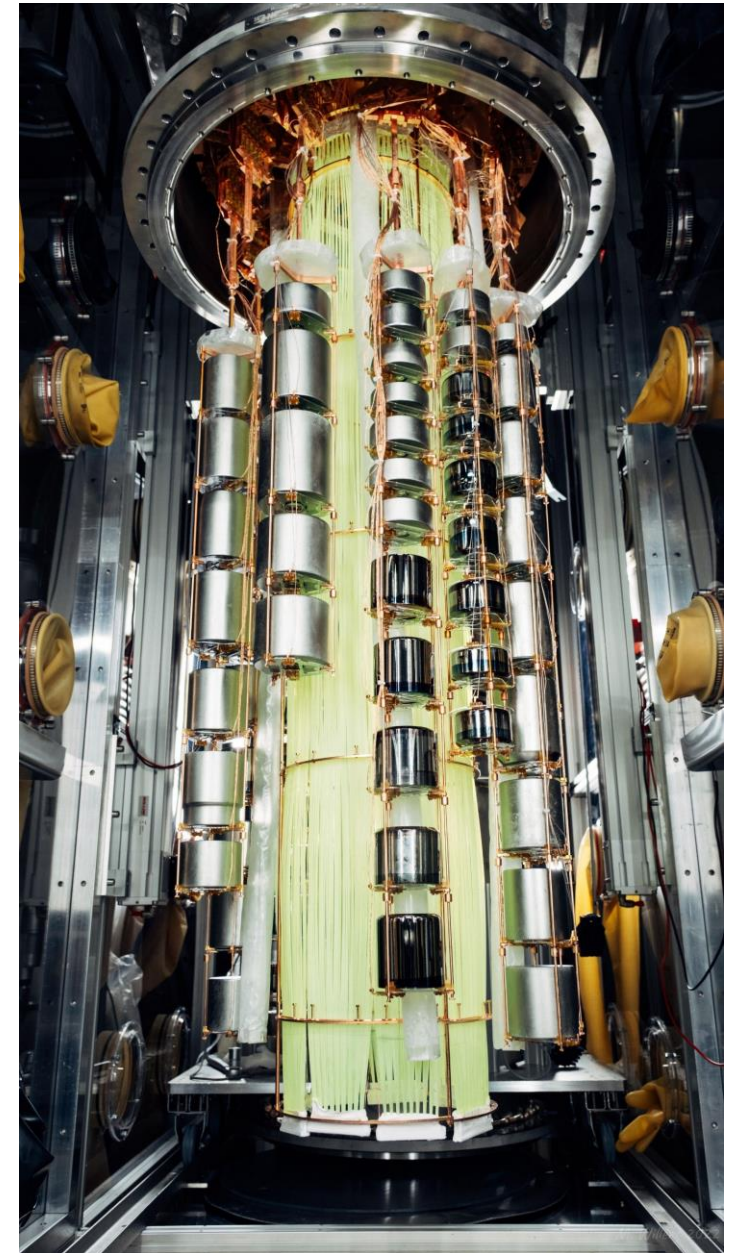
Sofia Calgaro - per la collaborazione **LEGEND**

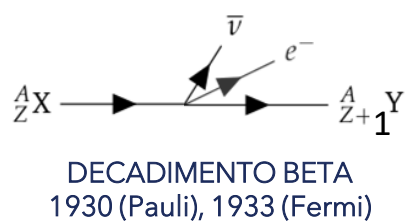
Università di Padova & INFN Padova
IFAE 2023, 12-14 aprile 2023



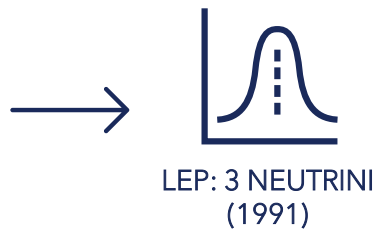
LEGEND = Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

- Doppio decadimento beta senza neutrini ($0\nu 2\beta$)
 - Processo oltre il modello Standard
 - Violazione del numero leptonico
 - No osservazioni sperimentali
- Esperimenti con germanio
 - Ottima risoluzione energetica
 - Discriminazione topologica degli eventi
 - Materiale principale per la ricerca di $0\nu 2\beta$
- LEGEND
 - Struttura dell'esperimento
 - Obiettivi e tappe futuri
 - Stato attuale e risultati preliminari





ν_e (1956)
 ν_μ (1962)



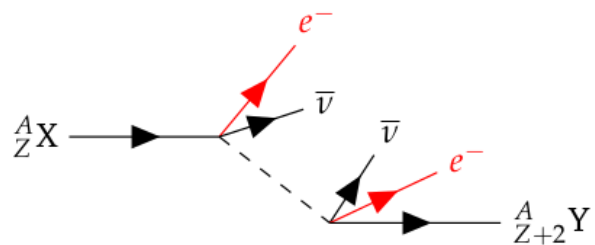
ν_τ (2000)



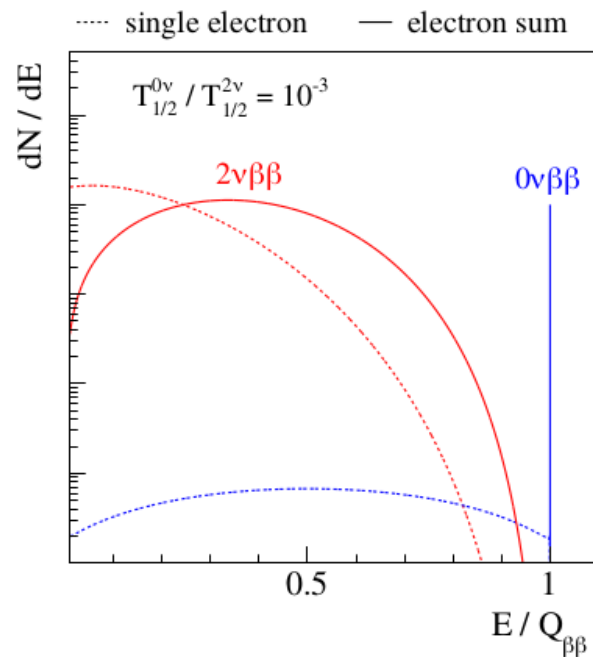
Particella di Dirac o di Majorana?



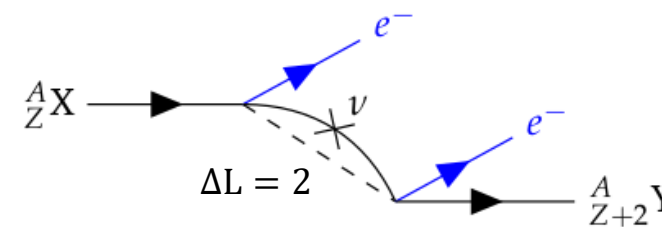
DOPPIO DECADIMENTO BETA



ν & $\bar{\nu}$ \rightarrow osserviamo solo ν_L e $\bar{\nu}_R$

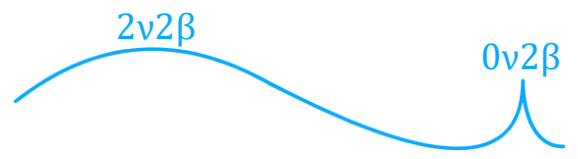


DOPPIO DECADIMENTO BETA SENZA NEUTRINI



ν \rightarrow osserviamo solo ν_L e ν_R

Doppio decadimento β senza neutrini



Segnale $\beta\beta$

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

Tempo di dimezzamento

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

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

Massa effettiva

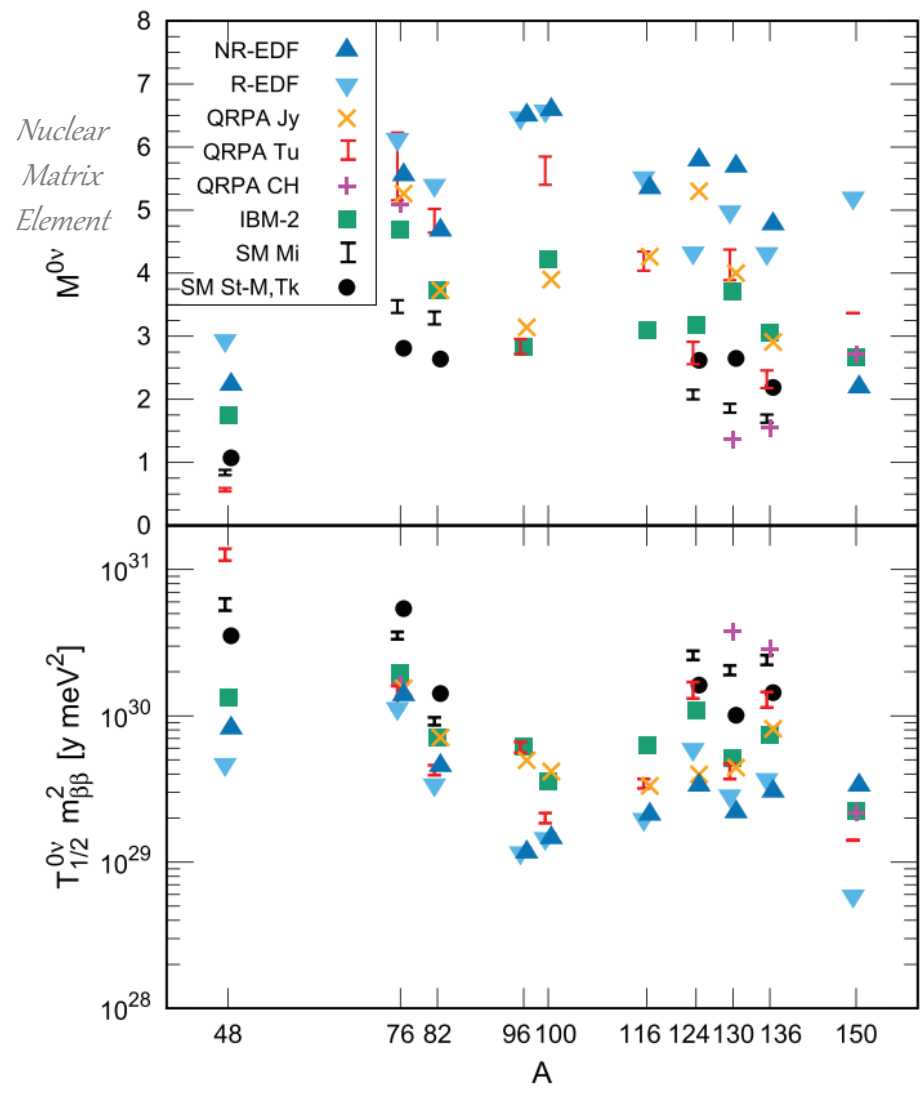
$$m_{ee} = |\sum_i U_{ei}^2 m_i| \rightarrow \text{per confrontare risultati di isotopi diversi}$$

Sensibilità tempo di dimezzamento $0\nu 2\beta$

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \varepsilon & \text{con fondo} \\ \epsilon \cdot f \cdot \sqrt{\frac{\varepsilon}{BI \cdot \Delta E}} & \text{senza fondo} \end{cases}$$

- ϵ : efficienza
- f : percentuale isotopa
- $\varepsilon = M \cdot t$: esposizione
- BI : livello di fondo
- ΔE : risoluzione energetica al $Q_{\beta\beta}$

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.



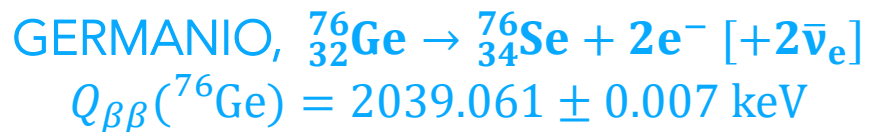
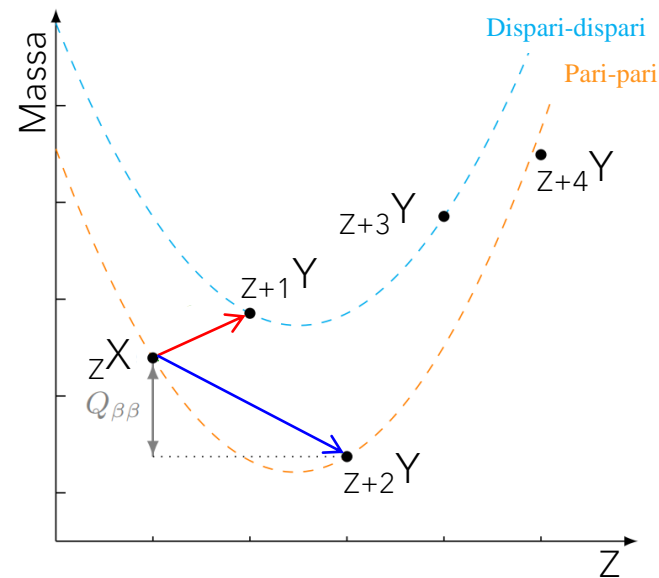
Dove cercare il $0\nu 2\beta$?

No preferenze teoriche

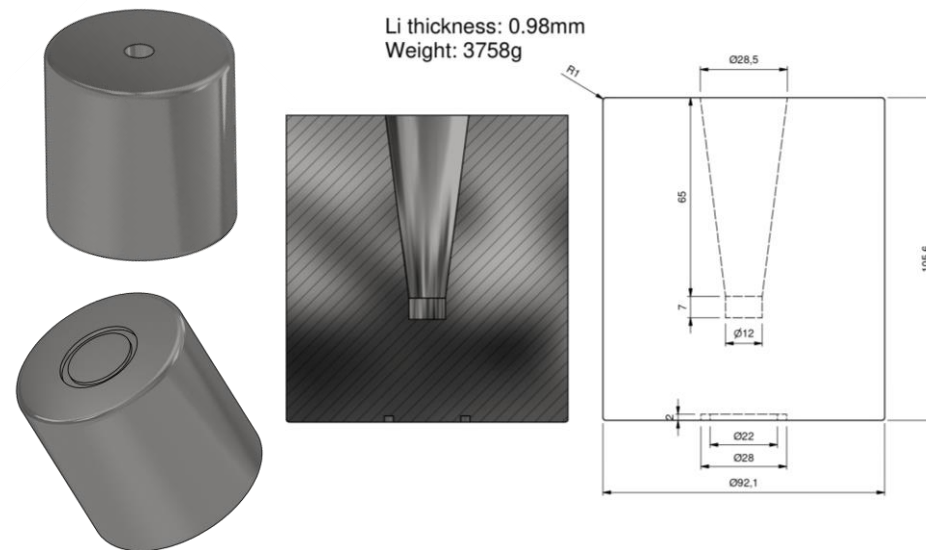
- Larghe incertezze teoriche
- $G^{0\nu}$ e NME sono inversamente correlate

Preferenze sperimentali

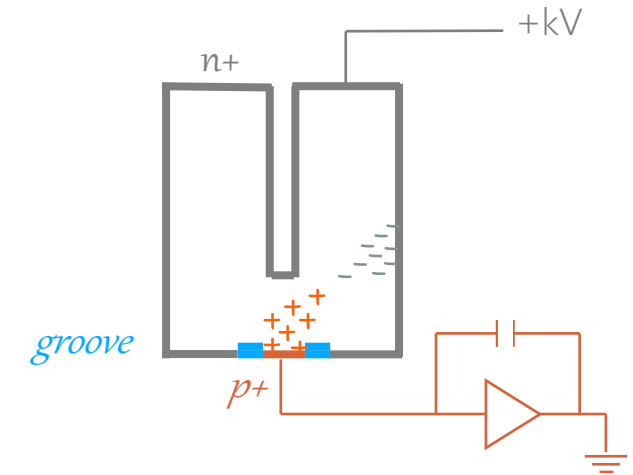
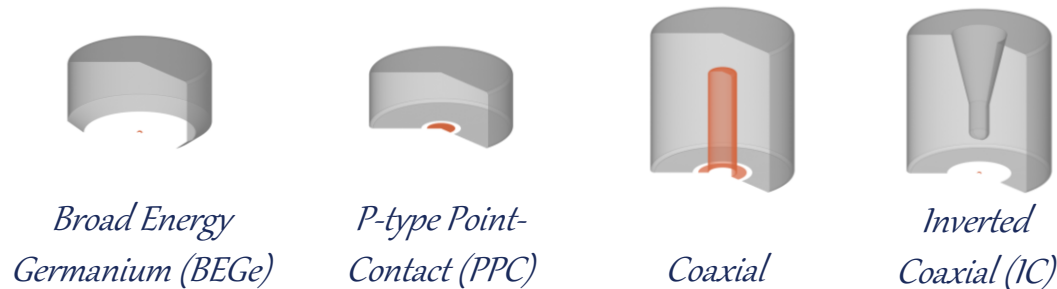
- \$\$\$
- Risoluzione energetica
- Livello di fondo
- Scalabilità (liquidi, gas, cristalli)



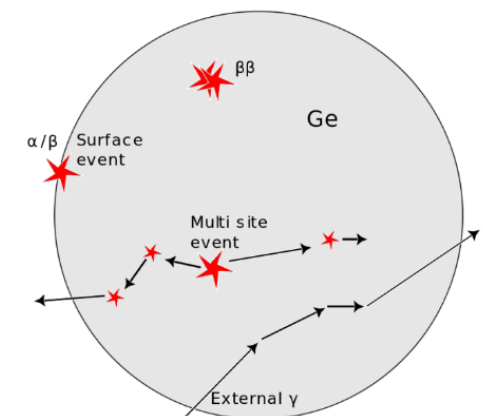
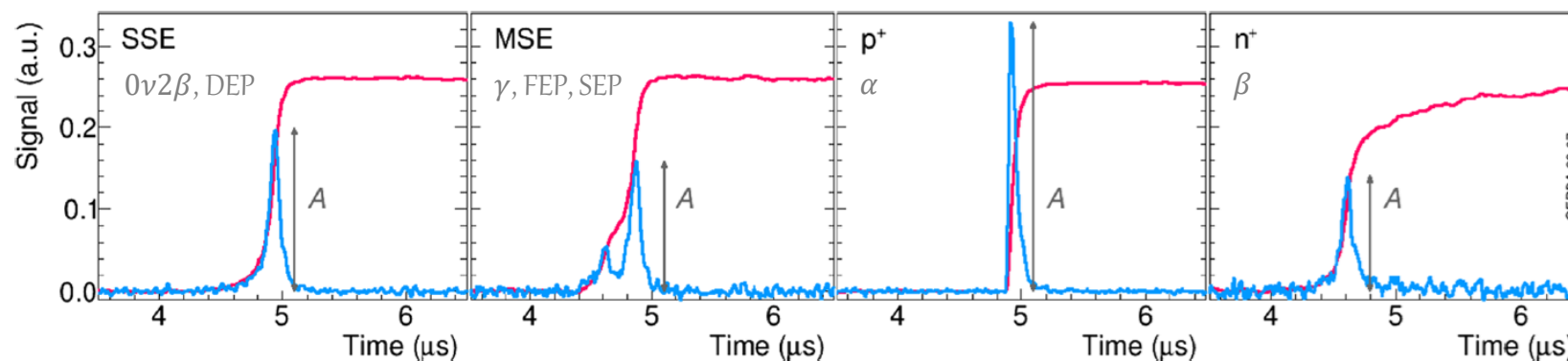
- Sorgente \equiv rivelatore \Rightarrow alta efficienza di rivelazione
- Ottima risoluzione energetica \Rightarrow **FWHM** \sim **0.1%** @ $Q_{\beta\beta}$
- Ge: alta purezza \Rightarrow basso fondo intrinseco
- Tecnologia già stabilita
- **Basso $Q_{\beta\beta}$** \Rightarrow complicato raggiungere bassi livelli di fondo
- **$f_{76}^{nat} \sim 8\%$** \Rightarrow necessario l'arricchimento in Ge-76

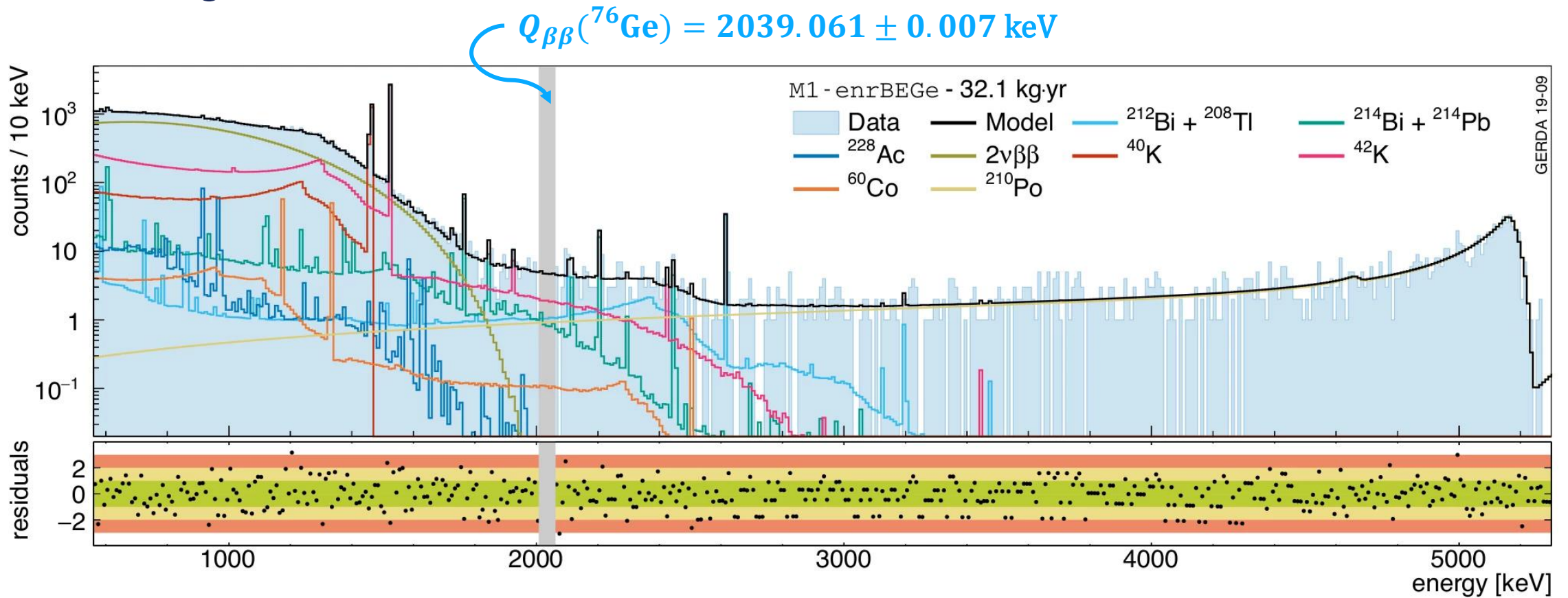


- Contatti p+ (boro impiantato) e n+ (litio diffuso), *groove* passivato
- Cristalli interamente *depleted*
- Diverse geometrie: BEGe, IC, PPC, coassiali
- Massa: ~0.7-4 kg



- Energia ricostruita basandosi sul *risettime* e ampiezza del segnale
- **Pulse shape discrimination (PSD)** per discriminare i singoli eventi



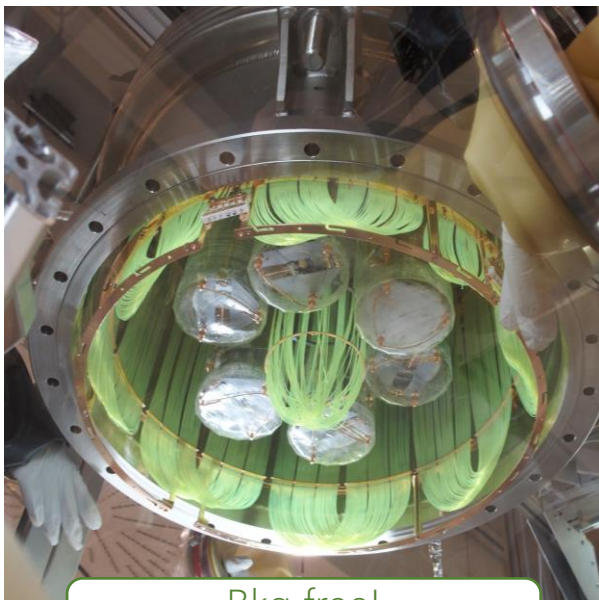


- Spettro prima dei tagli di analisi
- *Blinded analysis* nella finestra $Q_{\beta\beta} \pm 25 \text{ keV}$
- Il *background index* (BI) è valutato a partire dallo studio del restante spettro
- *Bkg-free regime*: <1 conteggio in $Q_{\beta\beta} \pm 0.5 \text{ FWHM}$

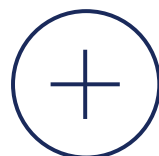
$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \epsilon & \text{con fondo} \\ \epsilon \cdot f \cdot \sqrt{\frac{\epsilon}{BI \cdot \Delta E}} & \text{senza fondo} \end{cases}$$

GERDA

GERmanium Detector Array



Bkg-free!
~0.3 eventi per 100 kg·yr



MAJORANA DEMONSTRATOR



LEGEND

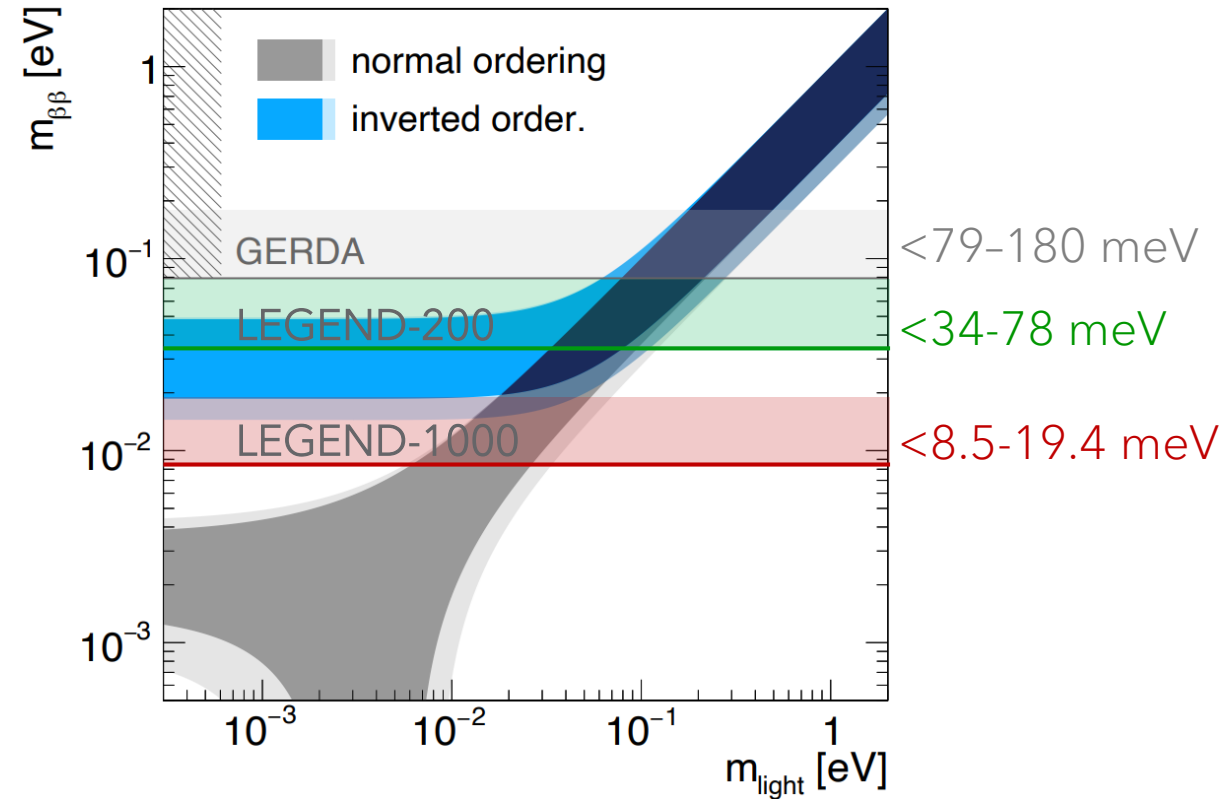
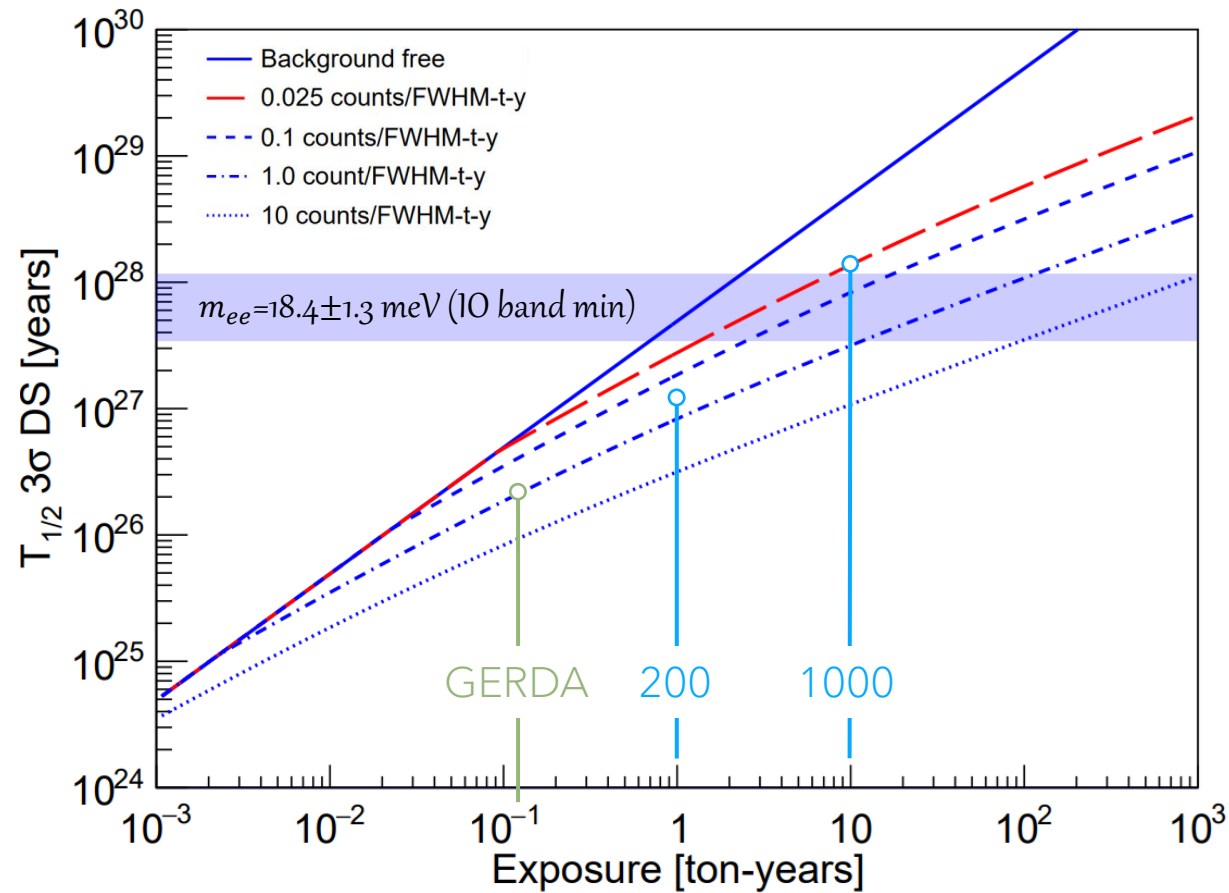
Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay



200

1000

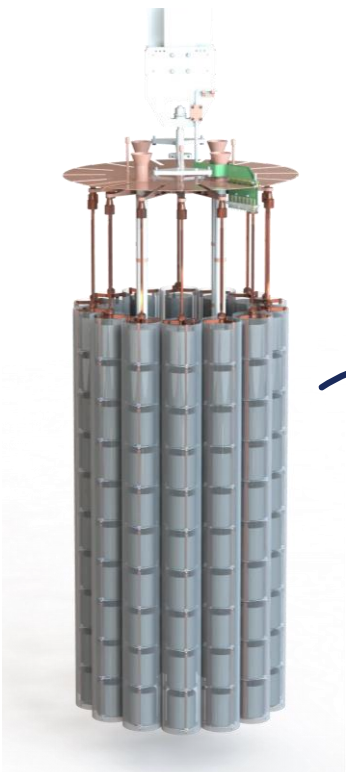
	GERDA	MAJORANA	LEGEND-200	LEGEND-1000
Massa [kg]	45	30	200	1'000
Esposizione [kg·yr]	100	26	1'000 >>> $\times 10$	10'000 >>> $\times 100$
BI [cts/(keV·kg·yr)]	$(5.2 \pm 1.6) \cdot 10^{-4}$	$(4.7 \pm 0.8) \cdot 10^{-3}$	$2 \cdot 10^{-4}$ <<< $\times 2.5$	10^{-5} <<< $\times 50$
Risoluzione [keV]	2.6 ± 0.2	2.53 ± 0.08	2.5	2.5



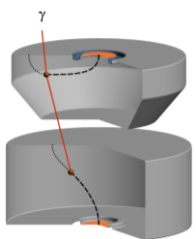
LEGEND-200: $T_{1/2}^{0\nu} > 10^{27}$ yr @ 90% CL
 LEGEND-1000: $T_{1/2}^{0\nu} > 1.6 \cdot 10^{28}$ yr @ 90% CL



- LNGS-Hall A @ 3600 m w.e.
- Riutilizza l'infrastruttura di GERDA
- Flusso di muoni ridotto a $1.25 / (m^2h)$

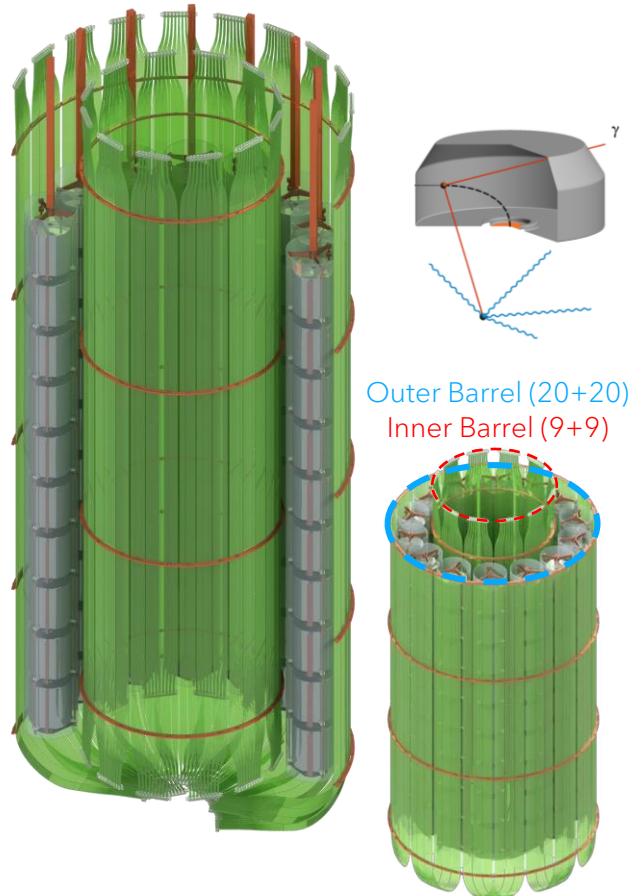


Array di rivelatori al germanio



LAr veto

- 58 moduli di read-out tramite SiPMs accoppiati con fibre WLS
- 9 (top) + 7 (bottom) PMTs



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

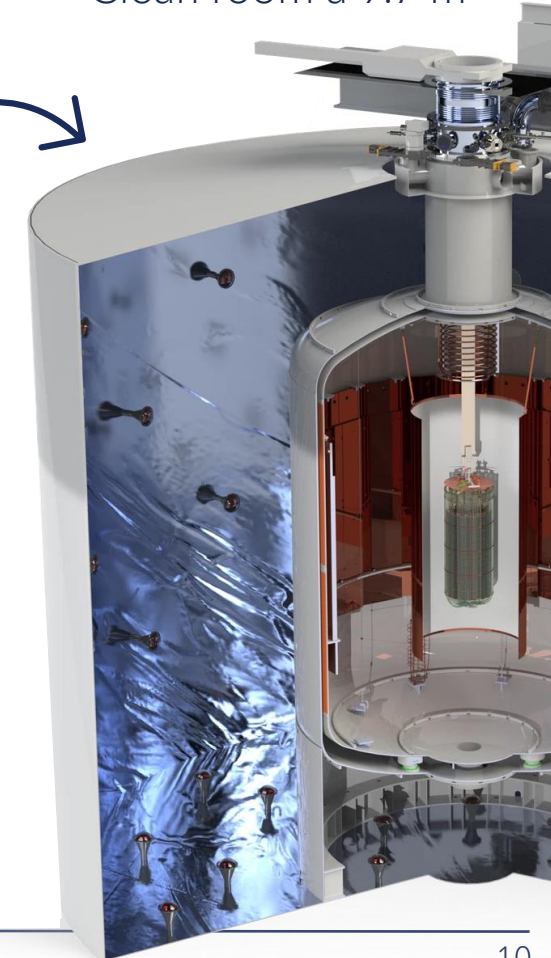


Criostato

- Ø 4m, H 5.88m
- LAr: 64 m³

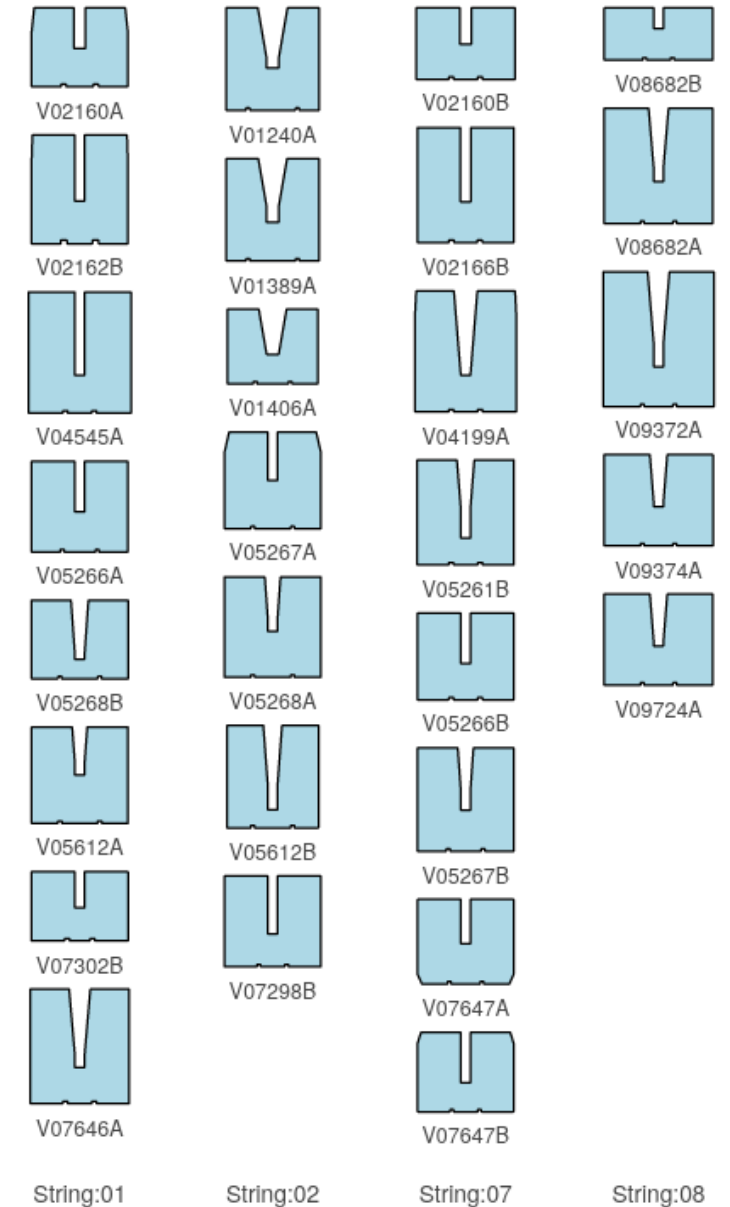
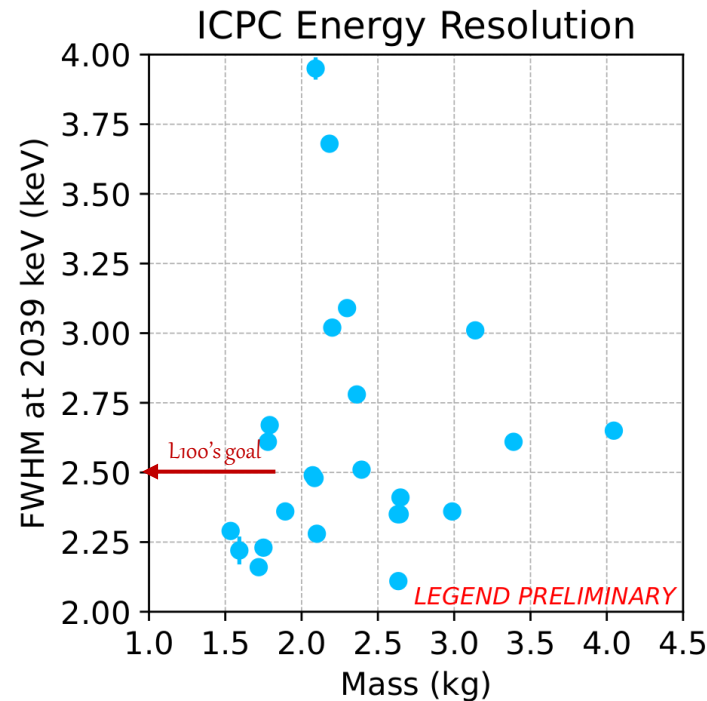
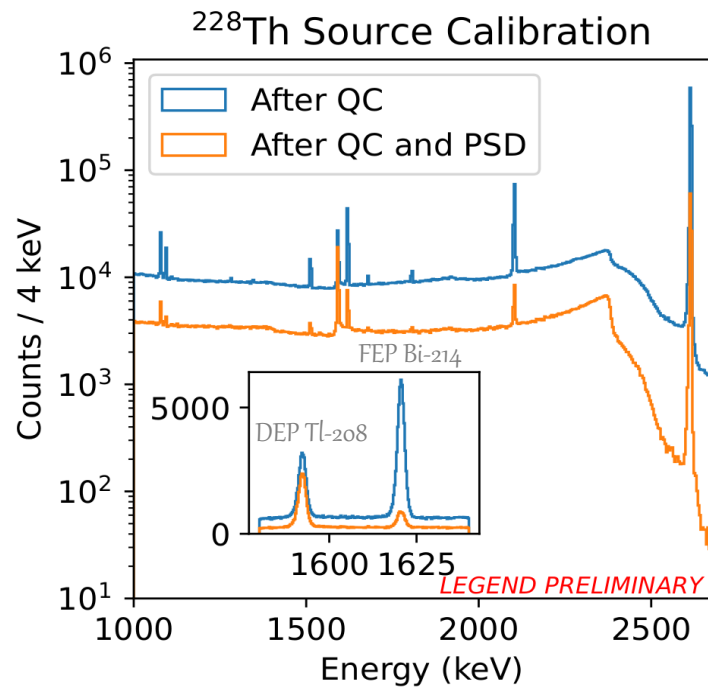
Tanica di acqua ultrapura

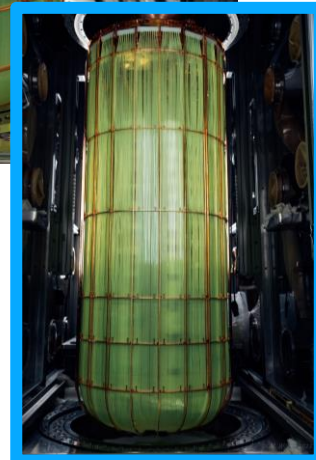
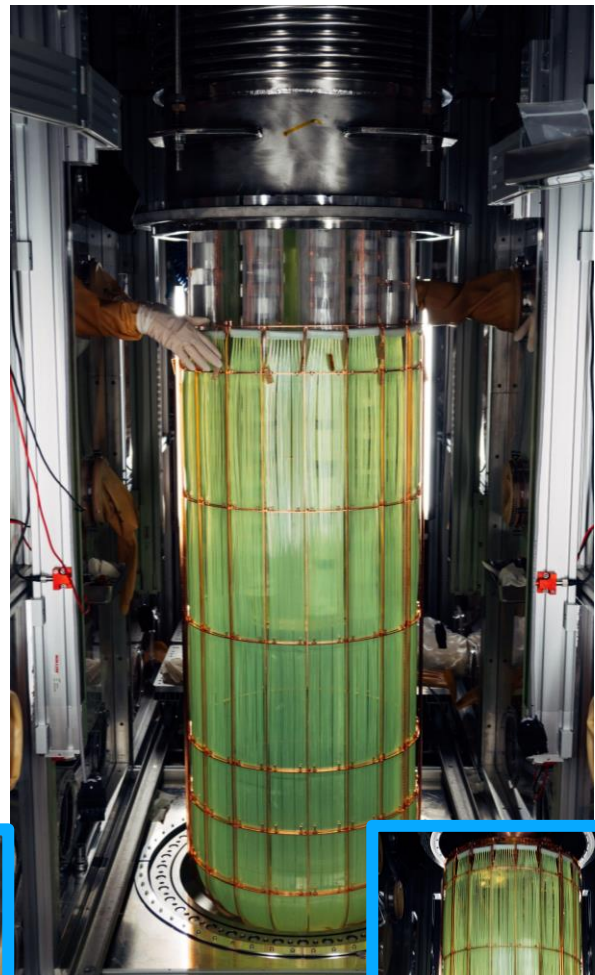
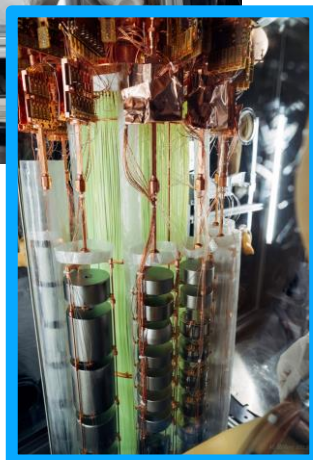
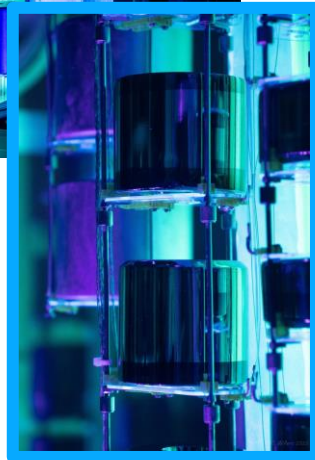
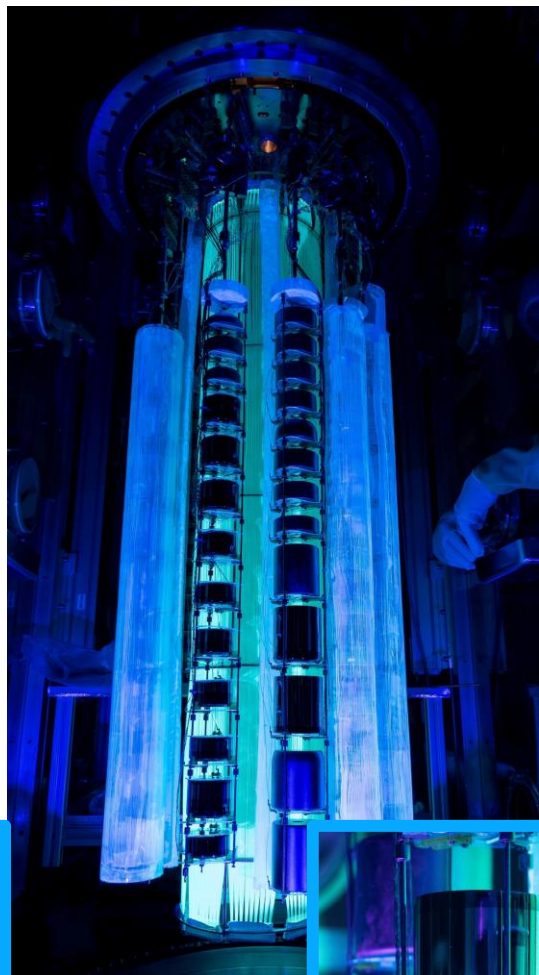
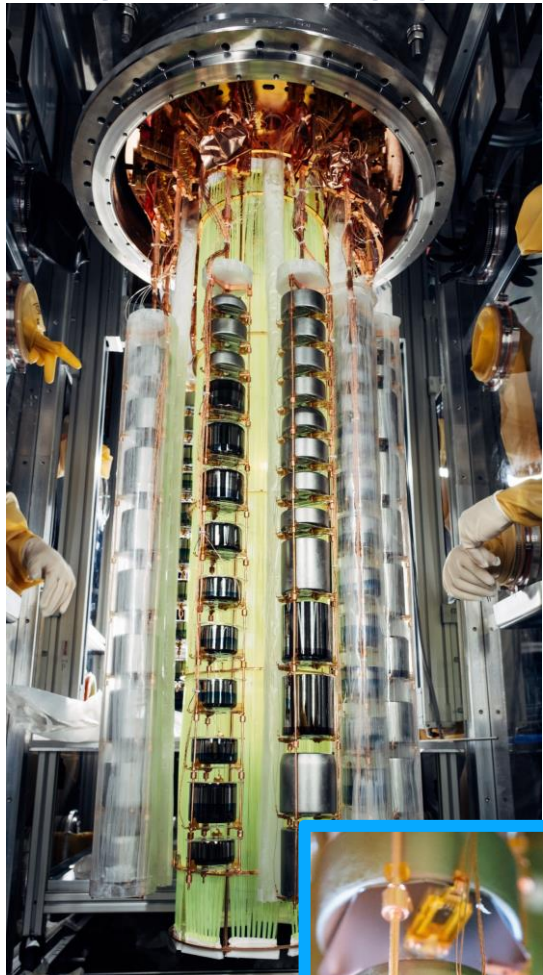
- Scherma n, γ
- 66 PMTs (Cherenkov) + scintillatori plastici per μ
- Ø 10m, H 8.5 m, V 590 m³
- Clean room a 9.7 m



28 rivelatori ICPC, 4 stringhe

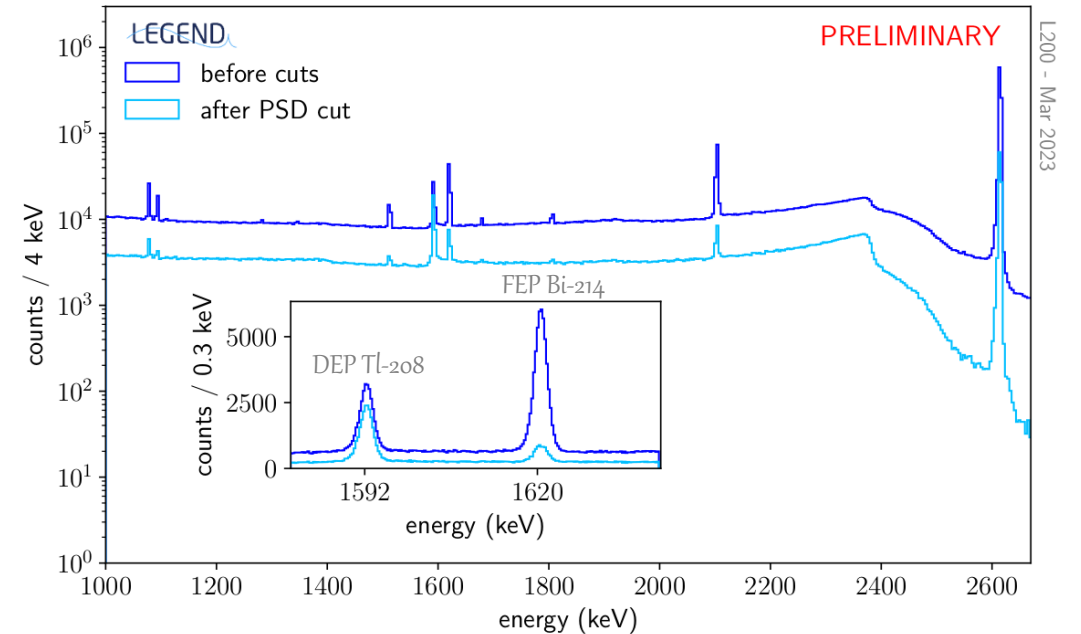
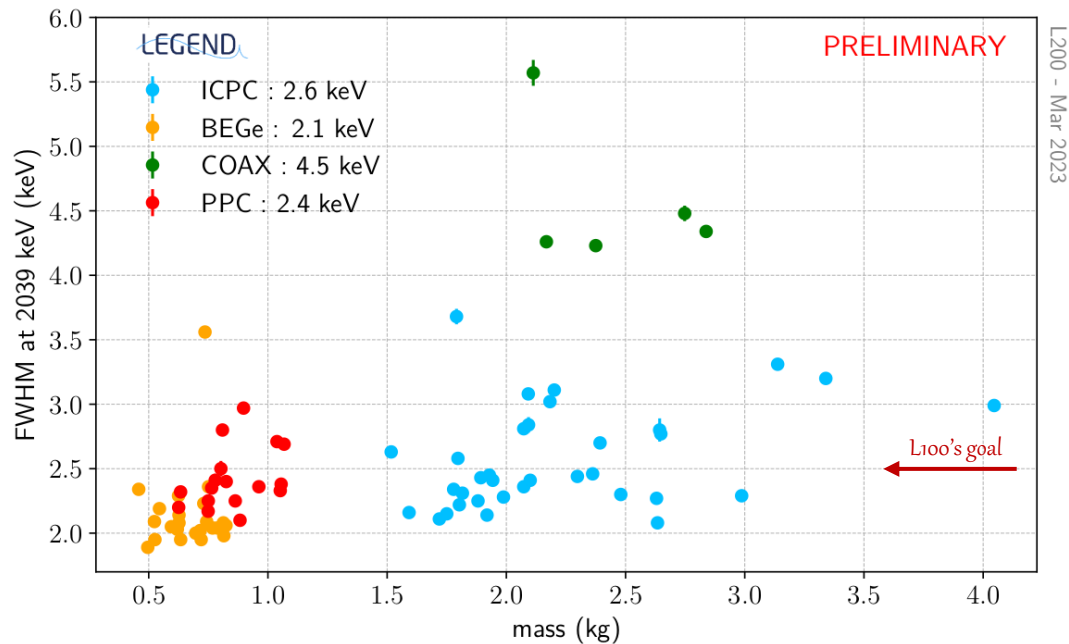
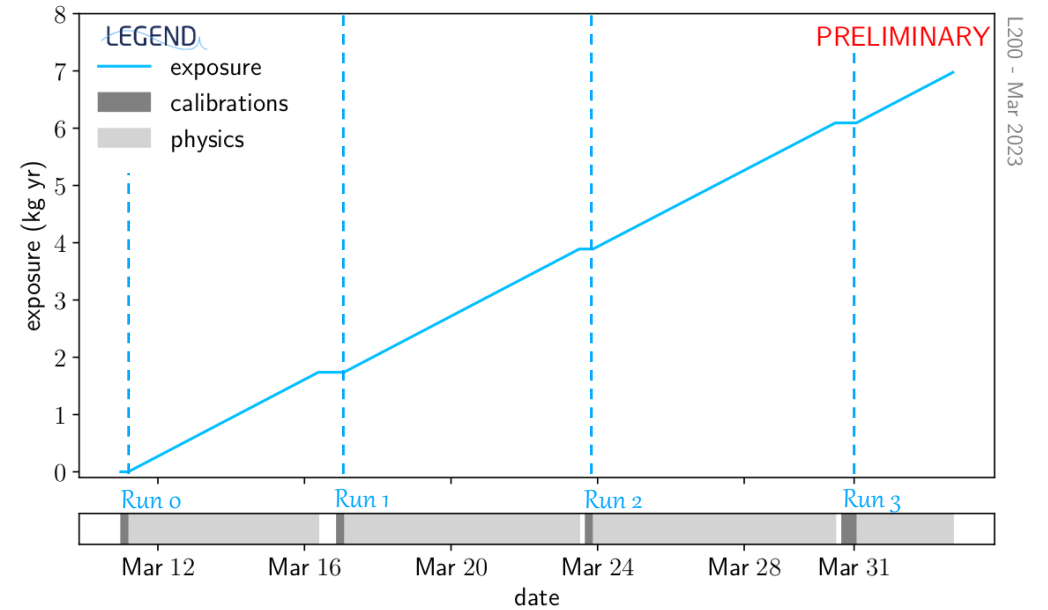
- $m_{\text{tot}} = 63.905 \text{ kg}$
- Periodo di presa dati: **Giugno - Dicembre 2022**
- Esclusi rivelatori instabili (pulser, $R=0.05 \text{ Hz}$)
- PSD testata tramite **13 sorgenti di Th-228** (3 calibrazioni)
 - Eventi *multi-site* (FEP Bi-214): $\sim 10\%$
 - Eventi *single-site* (DEP Tl-208): $\sim 90\%$
- Esposizione finale: **2.248 kg yr**



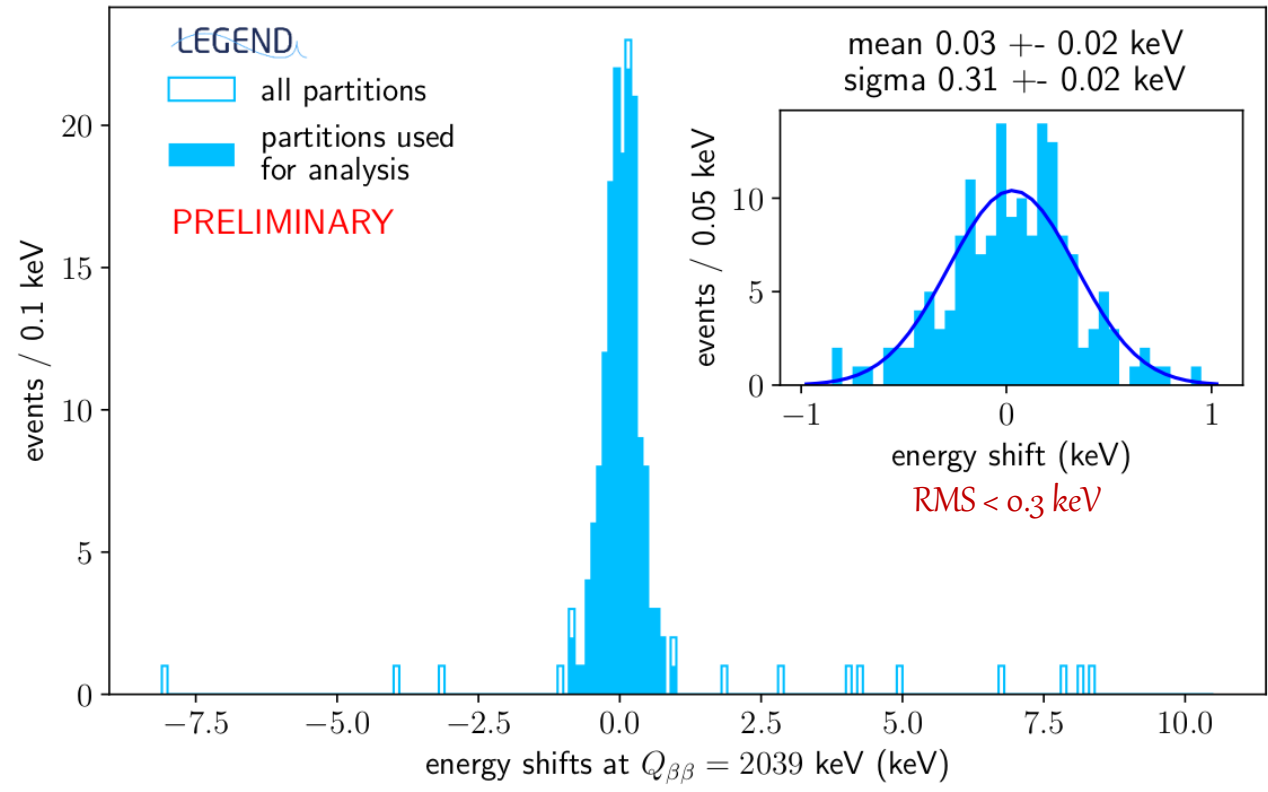


101 rivelatori, 11 stringhe
 6 coassiali + 26 PPCs
 28 BEGe + 41 ICPCs

- $m_{\text{tot}} = 142.4 \text{ kg}$ (122 kg utilizzabili per l'analisi)
- Presa dati stabile iniziata il **12 Marzo 2023**
- Esposizione: $\sim 7 \text{ kg yr}$ ($> 2 \text{ kg yr / week}$)
- FWHM $\sim 2.4 \text{ keV @ } Q_{\beta\beta}$ (4.5 keV per coax)

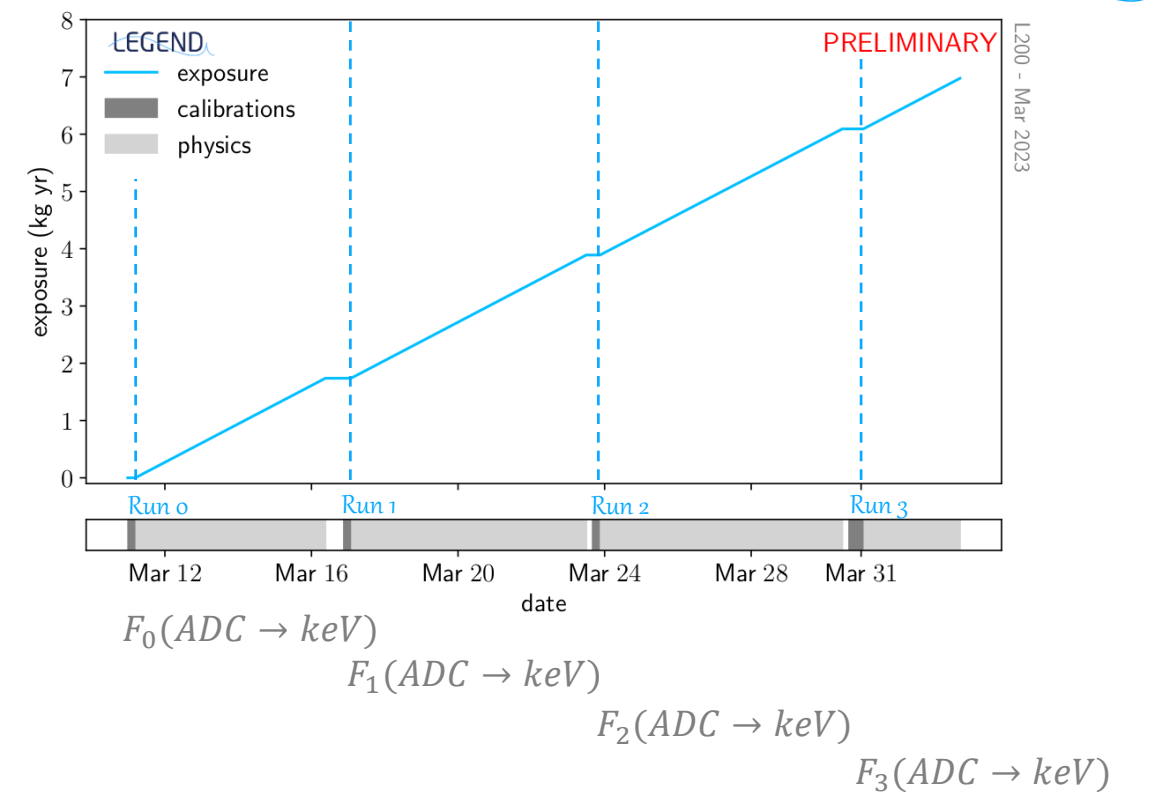


Performance al $Q_{\beta\beta}$



L200 - Mar 2023

Shift dell'energia e studio della stabilità nel tempo tra calibrazioni successive



1. Calcolo di F_i^{-1} (keV \rightarrow ADC) al $Q_{\beta\beta}$
2. Studio dello shift in ADC tra calibrazioni successive,
$$\Delta G_{i,i-1} = F_i^{-1}(Q_{\beta\beta}) - F_{i-1}^{-1}(Q_{\beta\beta})$$
3. Conversione dello shift $\Delta G_{i,i-1}$ usando la prima calibrazione ("run 0"), $F_0(ADC \rightarrow keV)$

LEGEND = Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

- Doppio decadimento beta senza neutrini ($0\nu 2\beta$)
 - Richiede la costruzione di esperimenti su larga scala
- Esperimenti con germanio
 - GERDA e MJD hanno dimostrato i vantaggi derivanti dall'uso della tecnologia dei rivelatori al germanio
- **LEGEND**
 - Ottimizzato per la ricerca del $0\nu 2\beta$
 - Detector ICPC soddisfanno già le richieste per L1000
 - PSD cut soddisfacenti per L200 e L1000
 - ~50 kg di rivelatori in mano/produzione
 - BI in estate, primi risultati $0\nu 2\beta$ nel 2024

<https://legend-exp.org/>

LEGEND Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

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Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay - LEGEND

The LEGEND collaboration is comprised of over 250 researchers from about 50 institutions from around the world, working together to develop the largest ^{76}Ge neutrinoless double-beta decay experiment in history. By combining the technological expertise and experience from the GERDA experiment and MAJORANA DEMONSTRATOR, LEGEND is expected to reach a design sensitivity two orders of magnitude greater than its predecessors.

The physics case Majorana neutrinos

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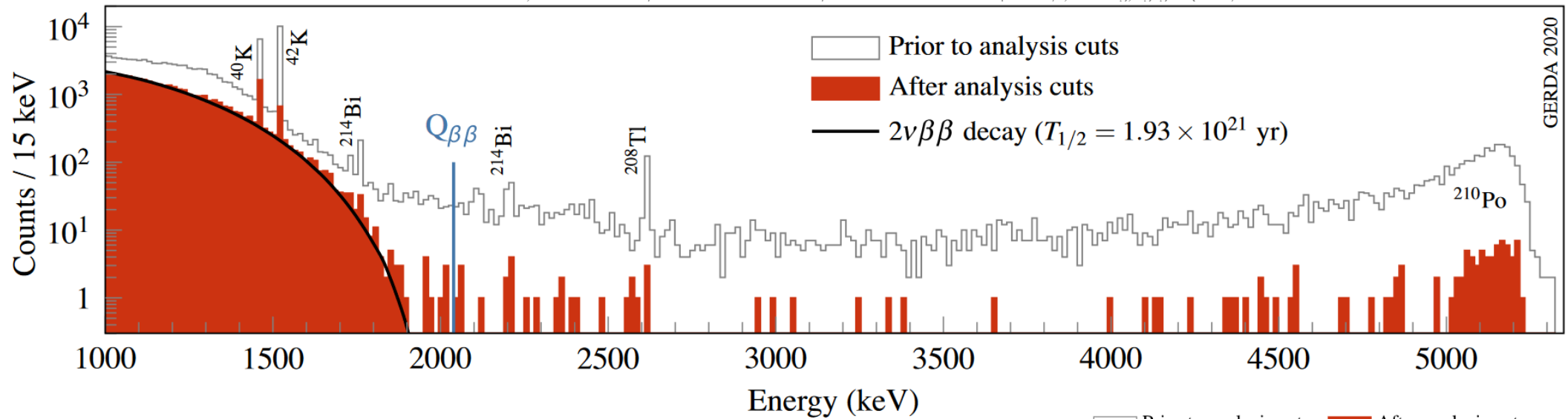
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GRAZIE PER L'ATTENZIONE



BACKUP



- Novembre 2011 – Settembre 2013 (Fase I)
- Dicembre 2015 – Novembre 2019 (Fase II)
- Analisi basata su k partizioni:

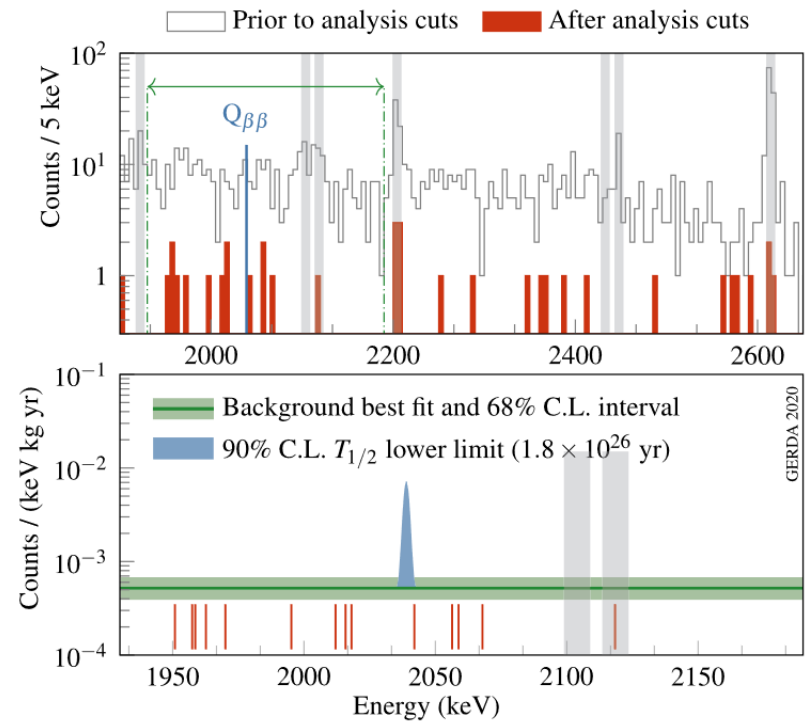
$$\mathcal{L} = \prod_k \left[\frac{(\mu_{s,k} + \mu_{b,k})^{N_k} e^{-(\mu_{s,k} + \mu_{b,k})}}{N_k!} \times \prod_{i=1}^{N_k} \frac{1}{\mu_{s,k} + \mu_{b,k}} \times \left(\frac{\mu_{b,k}}{\Delta E} + \frac{\mu_{s,k}}{\sqrt{2\pi}\sigma_k} e^{-\frac{(E_i - Q_{\beta\beta})^2}{2\sigma_k^2}} \right) \right]$$

- Migliore limite (e sensibilità in assenza di segnale) al mondo:

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

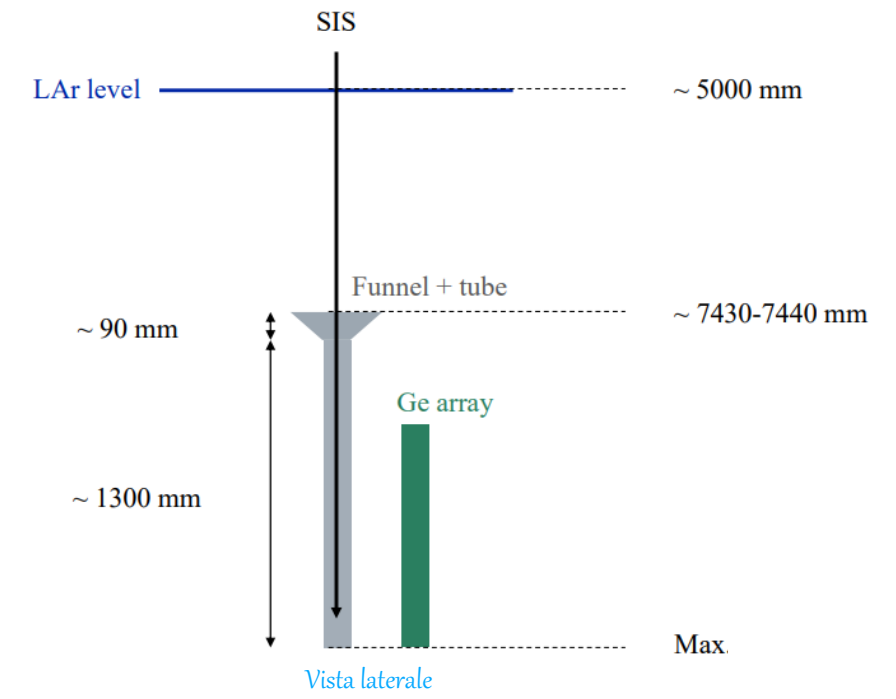
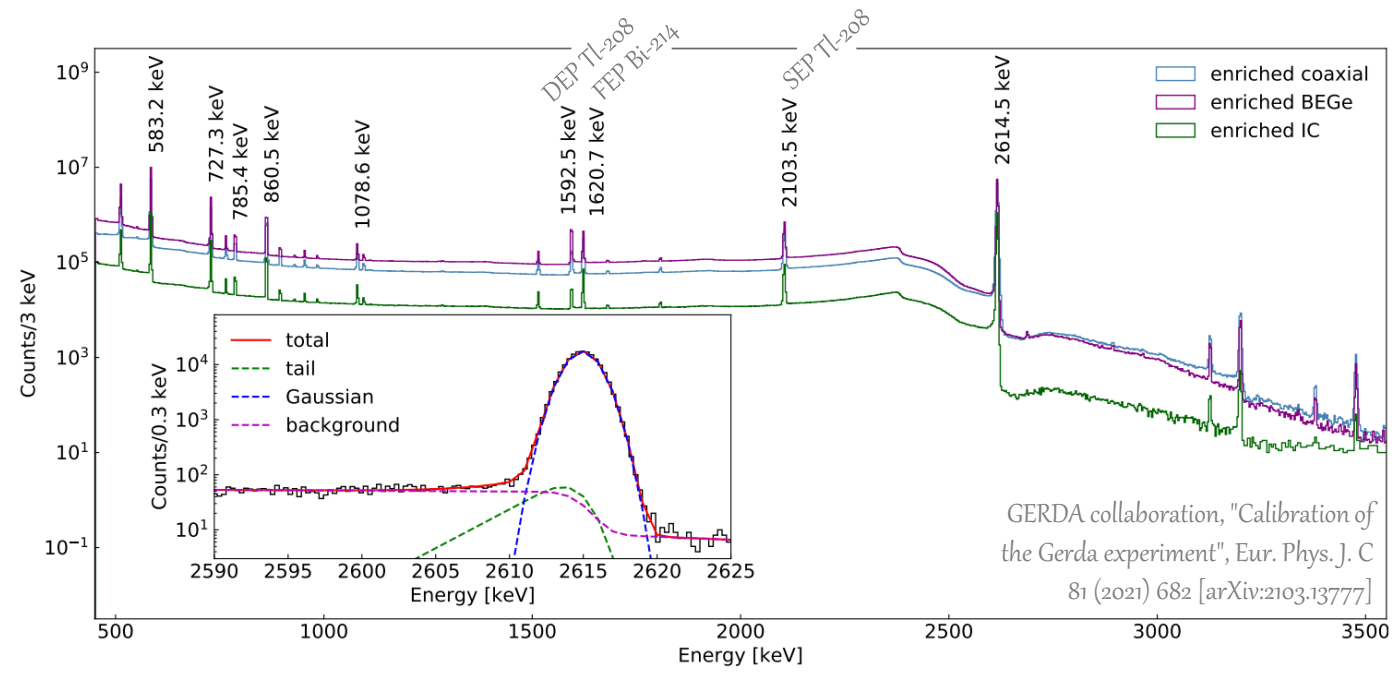
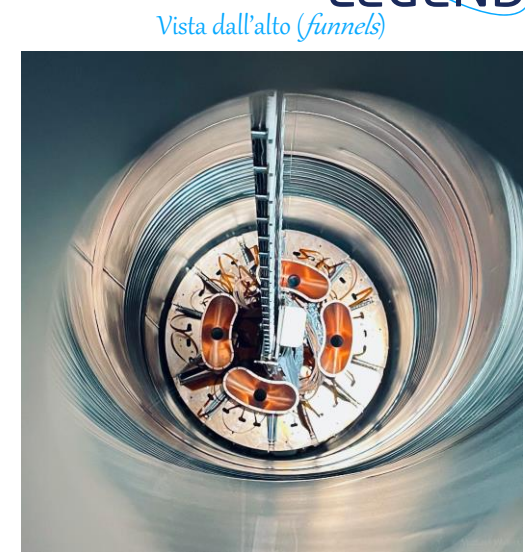
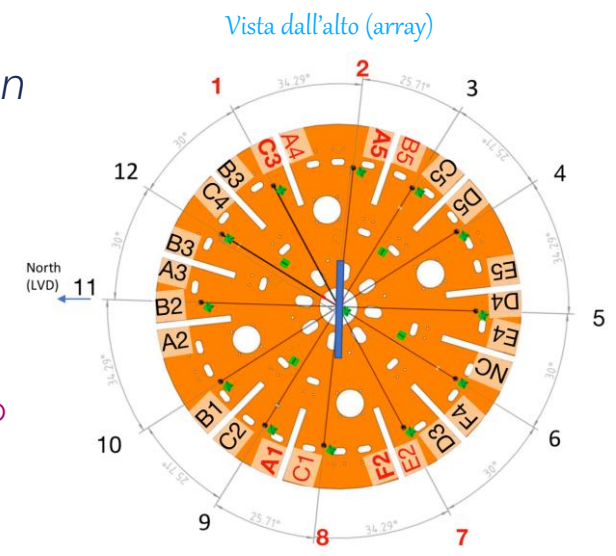
- Migliore BI nella *Region Of Interest* (ROI):

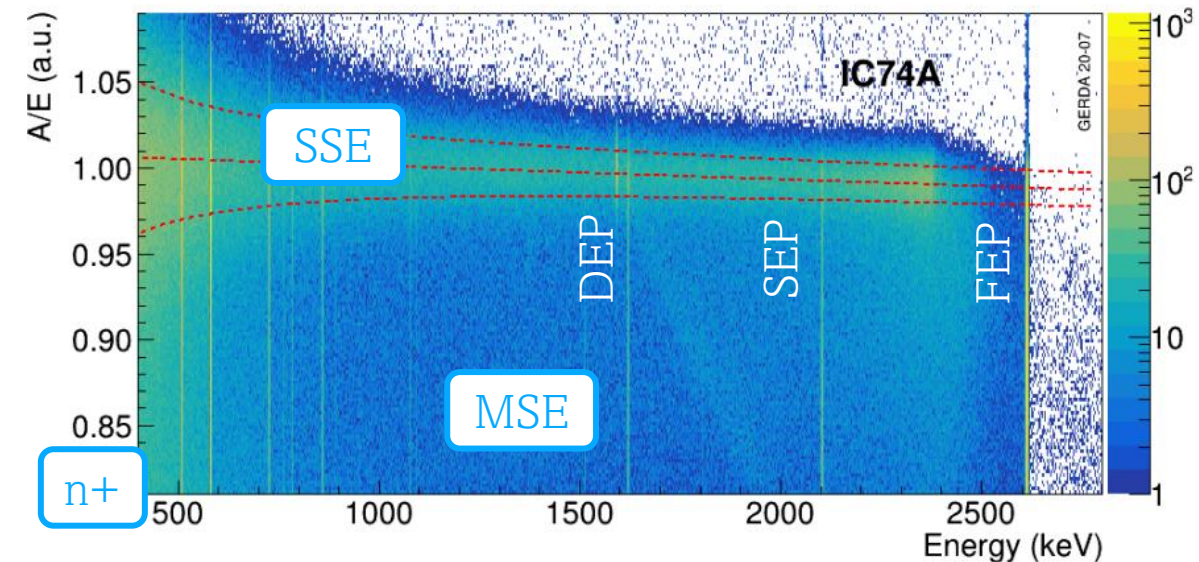
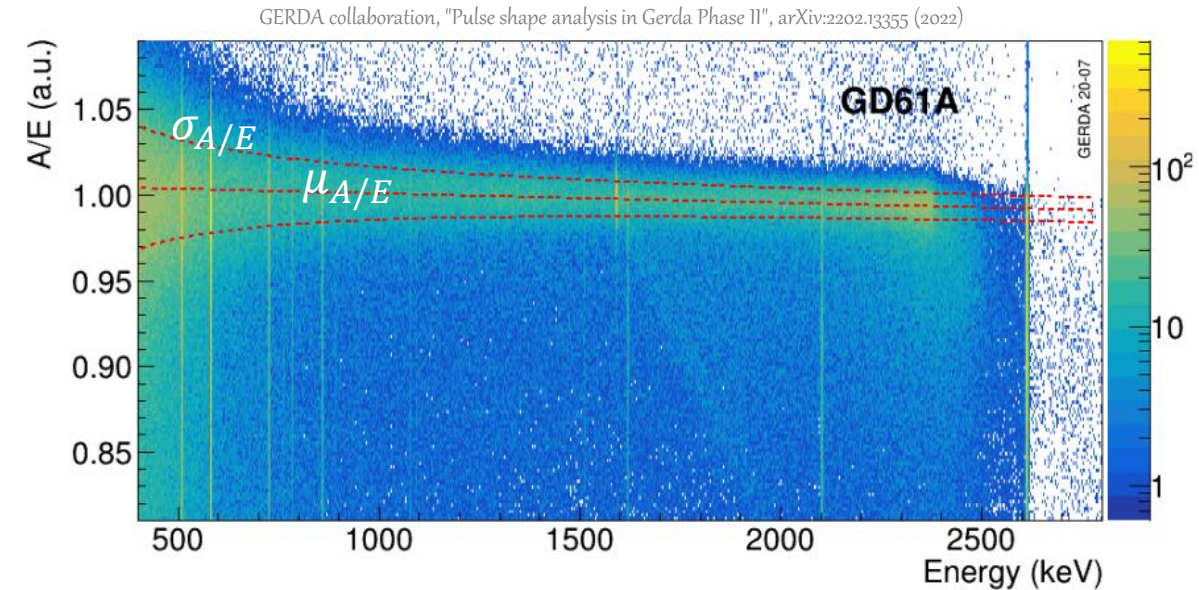
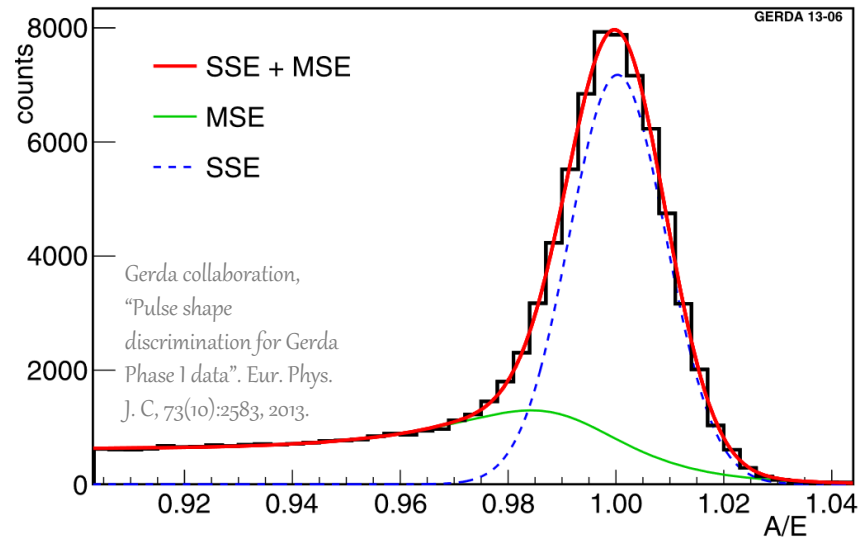
$$BI = 5.2_{-1.3}^{+1.6} \cdot 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$



Calibrazione

- 4 (+1) sistemi di inserimento delle sorgenti (*Source Insertion Systems, SIS*)
- 16 sorgenti di Th-228 (attività ~ kBq)
- 2h @ 8300 mm, 8990 mm (~k eventi al picco a 2.6 MeV)
- 3 contributi:
 - segnale = gaussiana
 - fondo 1 = lineare + step (fondo piatto al di sopra o al di sotto del picco derivante da Compton scattering multipli)
 - fondo 2 = coda a bassa energia (effetti di collezione incompleta della carica + residui di pile-up)

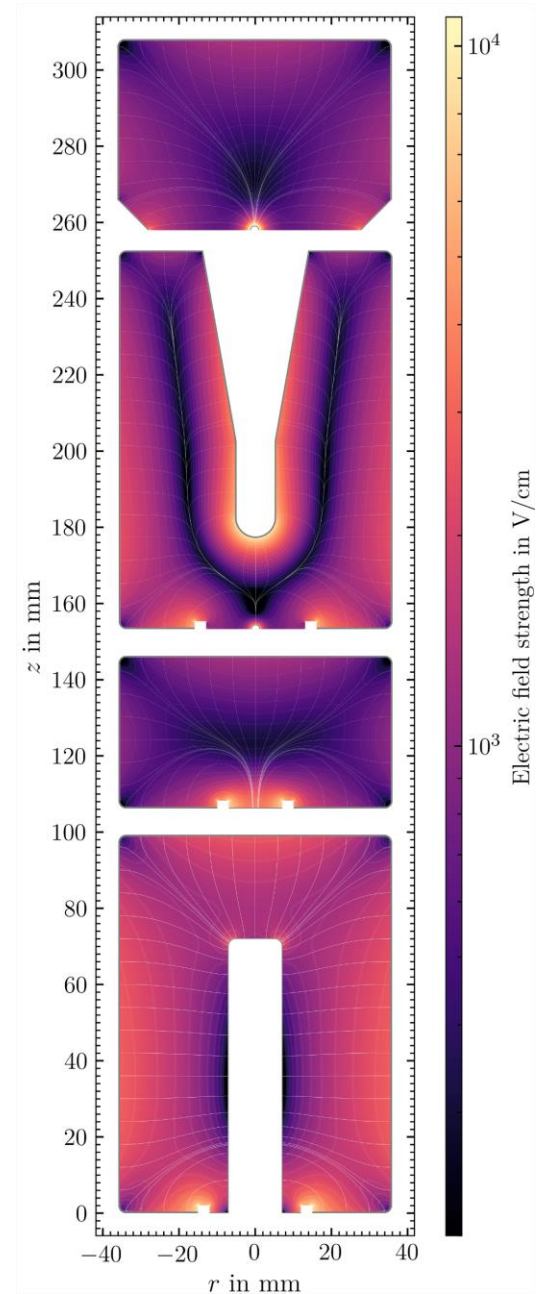
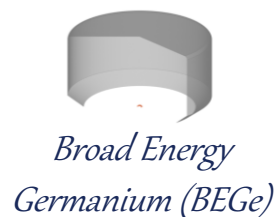
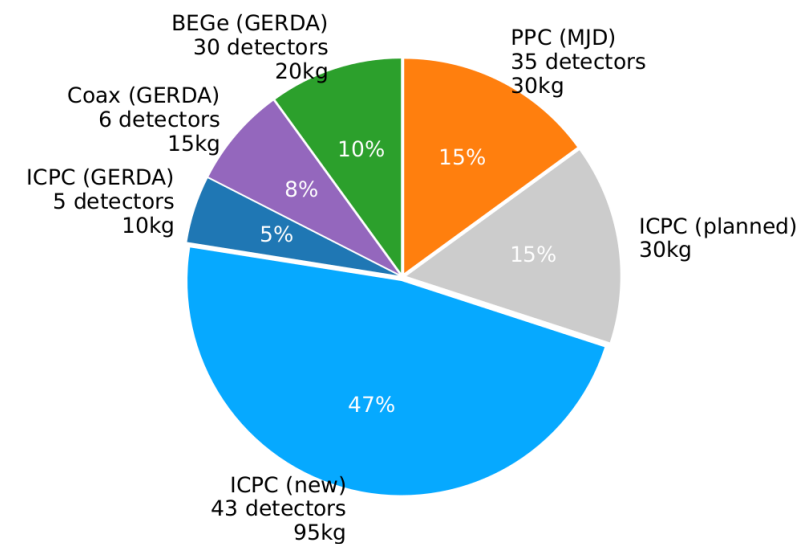




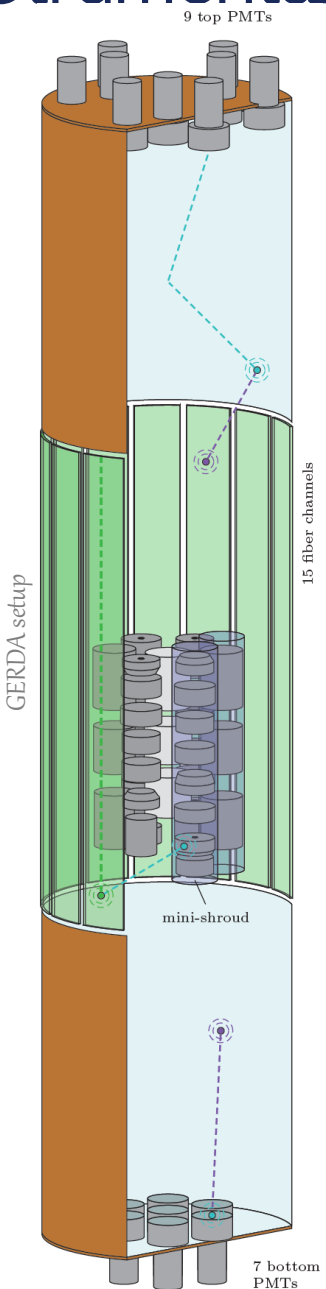
- A/E: gaussiana (SSE) + coda a bassi valori (MSE):

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

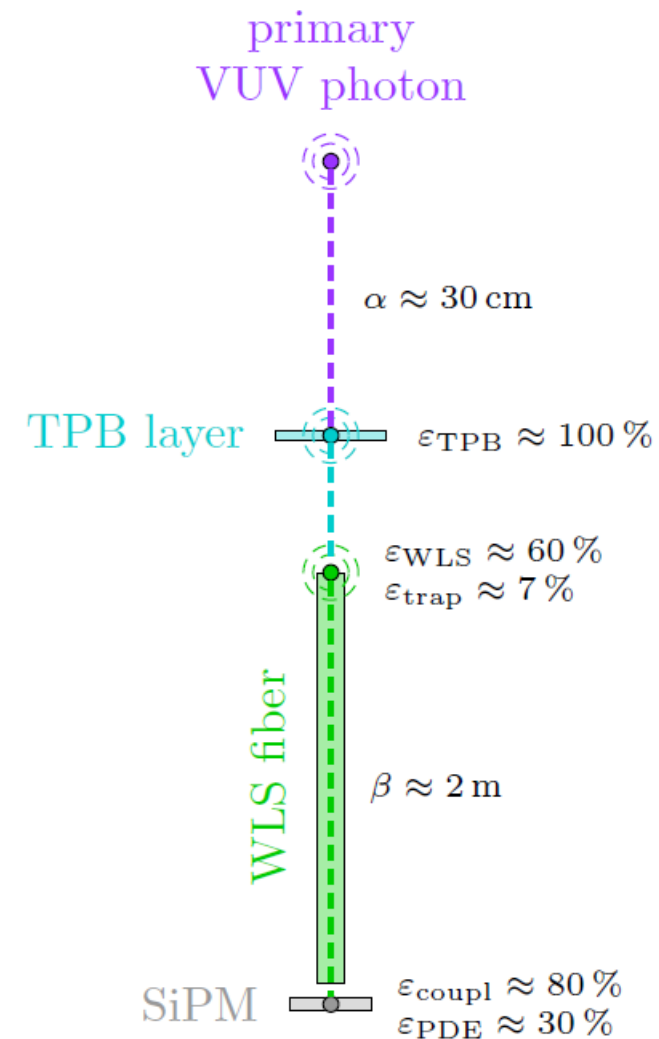
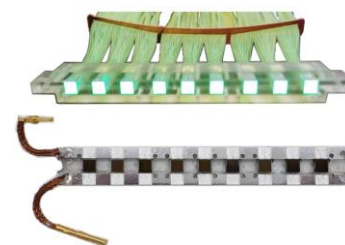
- I cut su A/E sono eseguiti per ciascun rivelatore
- "A/E classifier": indipendente dall'energia
- $\zeta = ([A/E] / \mu_{A/E}(E) - 1) / \sigma_{A/E}$
- ζ distribuito attorno allo 0, con dev std pari a 1 per SSEs



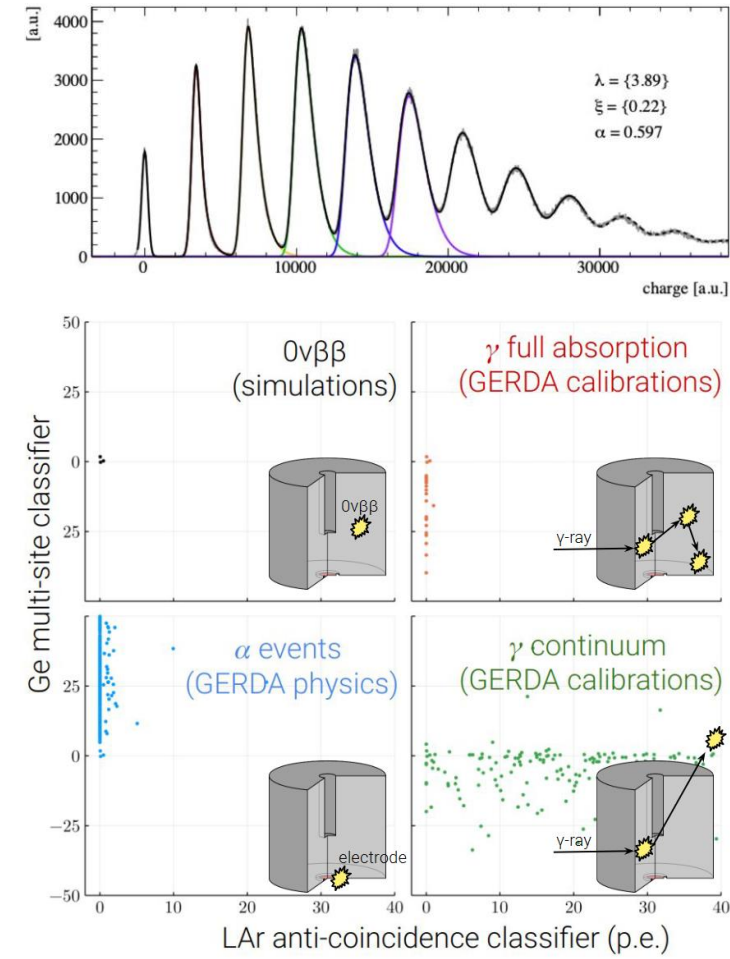
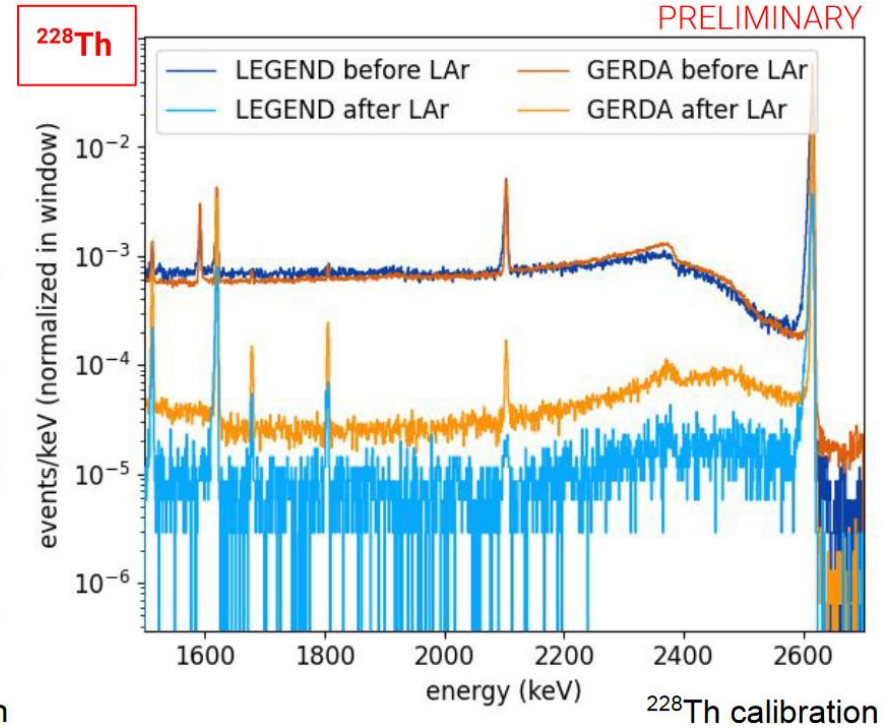
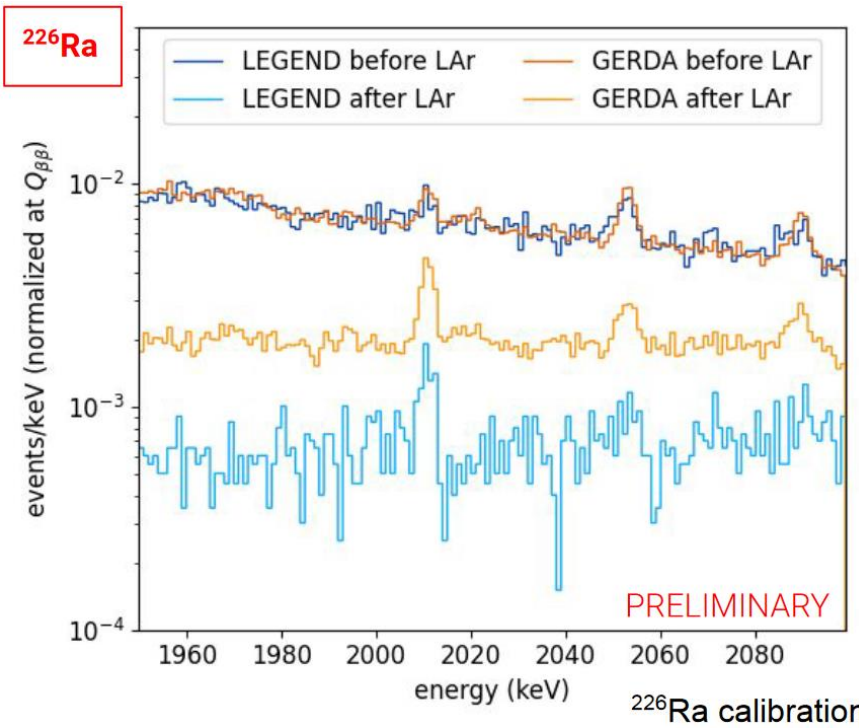
Strumentazione del LAr



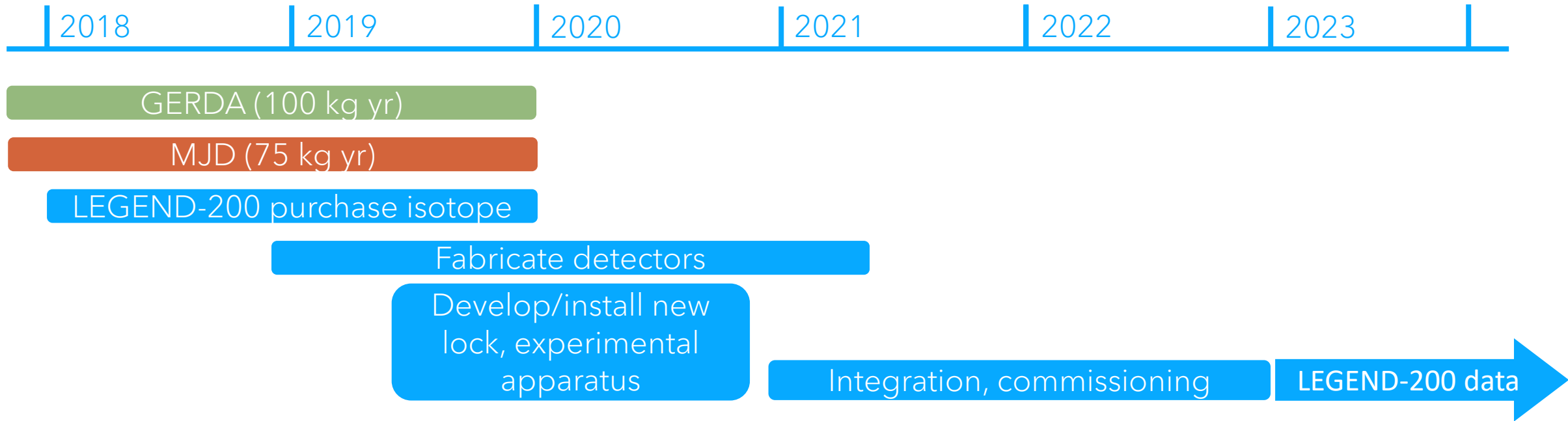
- Due *barrels* immerse in LAr @ ~ 84K
 - \varnothing 590 mm, H 1500 mm
 - *Inner Barrel, IB*: 9 moduli di fibre = 18 canali SiPM
 - *Outer Barrel, OB*: 20 moduli di fibre = 40 canali SiPM
- Array di 9 SiPM letti in parallelo
 - Ketek PM33100T 3x3 mm
 - 81 fibre *WaveLength Shifting* (WLS)
- Nylon *Mini-shrouds* (MS)
 - Soppressione del fondo di ioni K-42
 - Trasparente alla luce di scintillazione del LAr (rivestimento con *TetraPhenyl Butadiene*, TPB)
 - Nylon: materiale con fondo molto basso
- Cilindro WLS-riflettore
 - \varnothing 1375 mm, H 3000 mm
 - Foglio di rame ricoperto con TPB
 - I fotoni riflessi raggiungono le fibre senza alcuna attenuazione nel LAr
 - Aiuta a rivelare fotoni prodotti all'esterno delle *barrels*



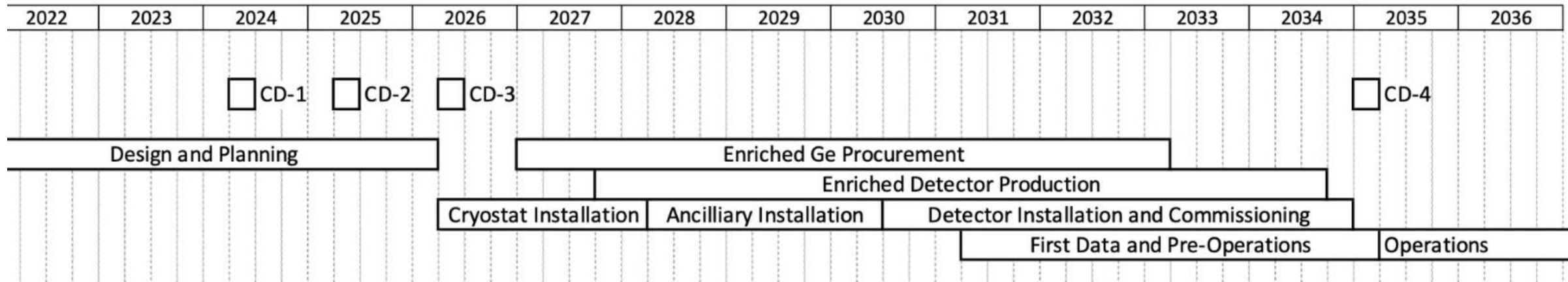
GERDA collaboration, "Liquid argon light collection and veto modeling in GERDA Phase II", [arXiv:2212.02856](https://arxiv.org/abs/2212.02856) (2022)

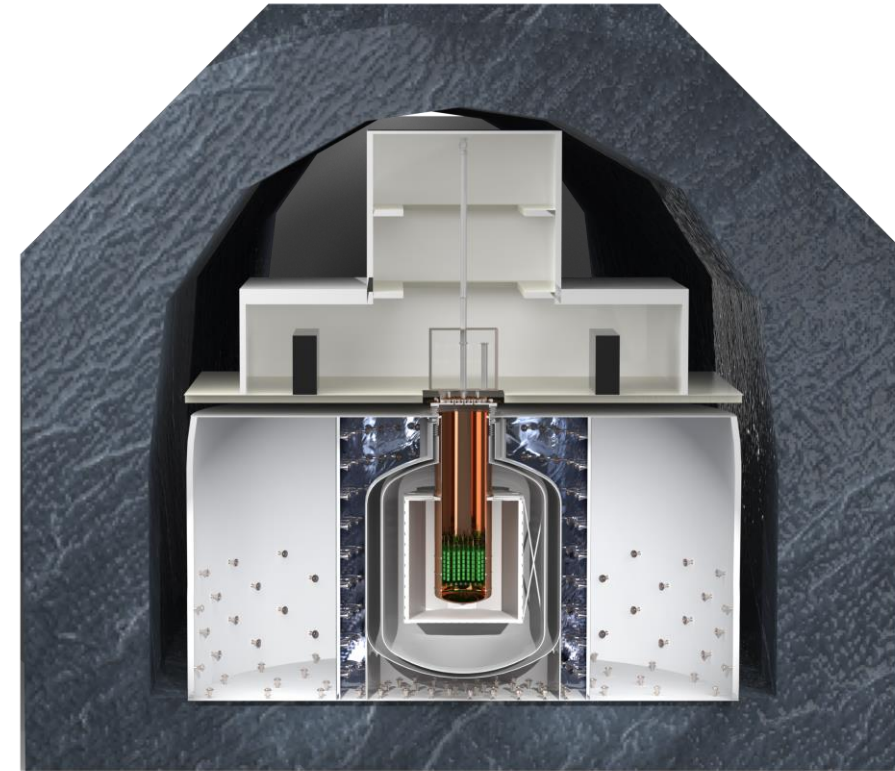
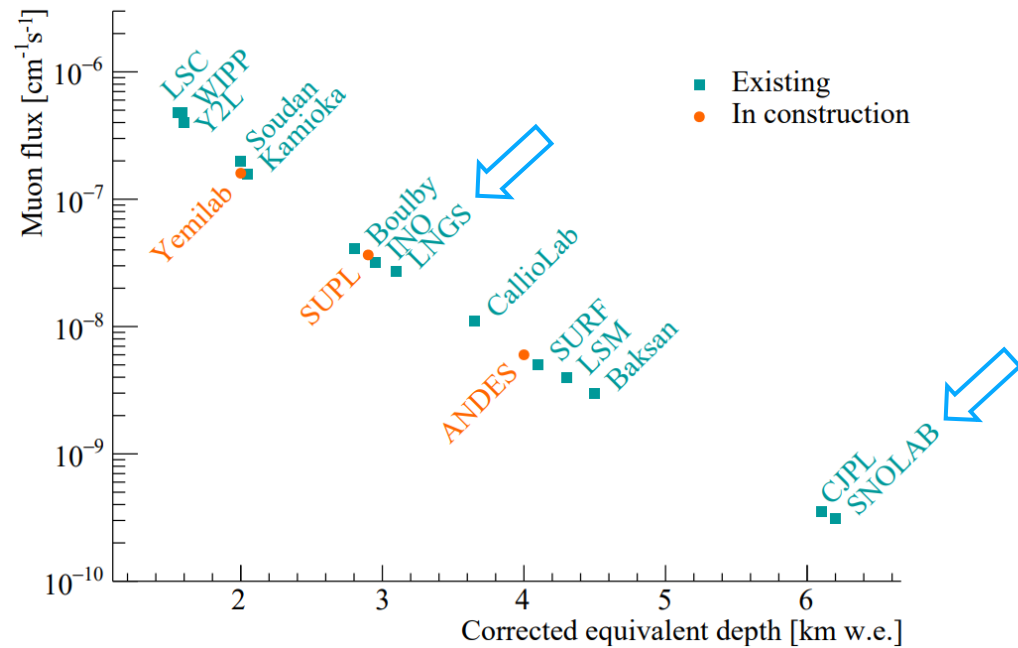


- Rendimento testato durante la fase di commissioning
- Miglioramento di un **fattore 3** nella riduzione del fondo rispetto a GERDA



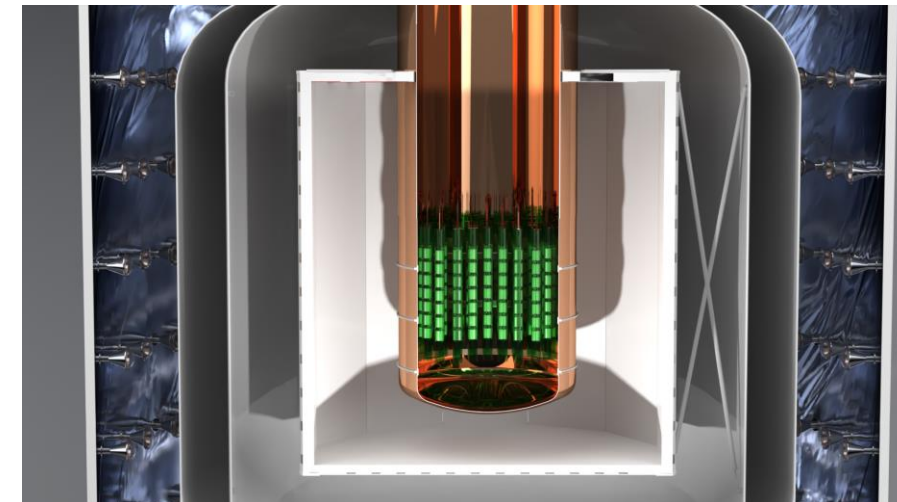
LEGEND-1000

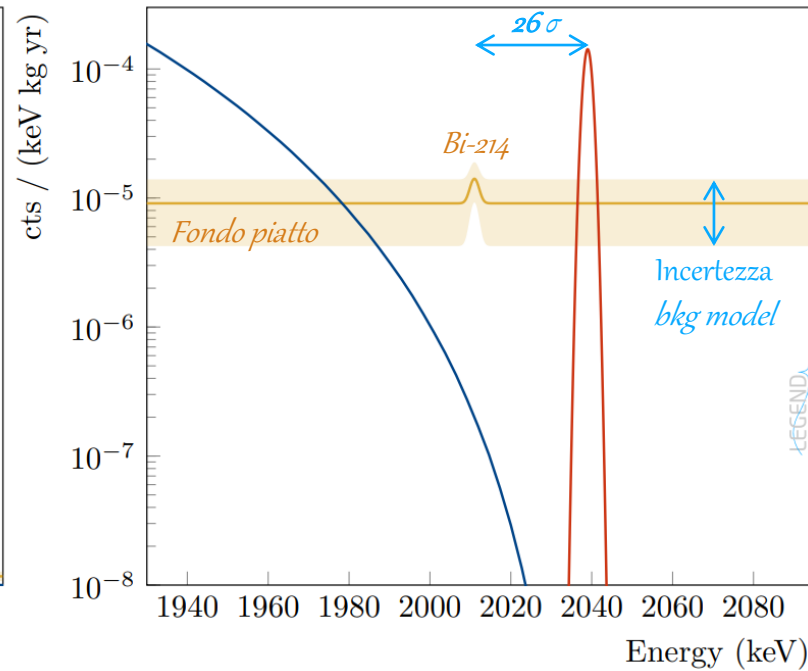
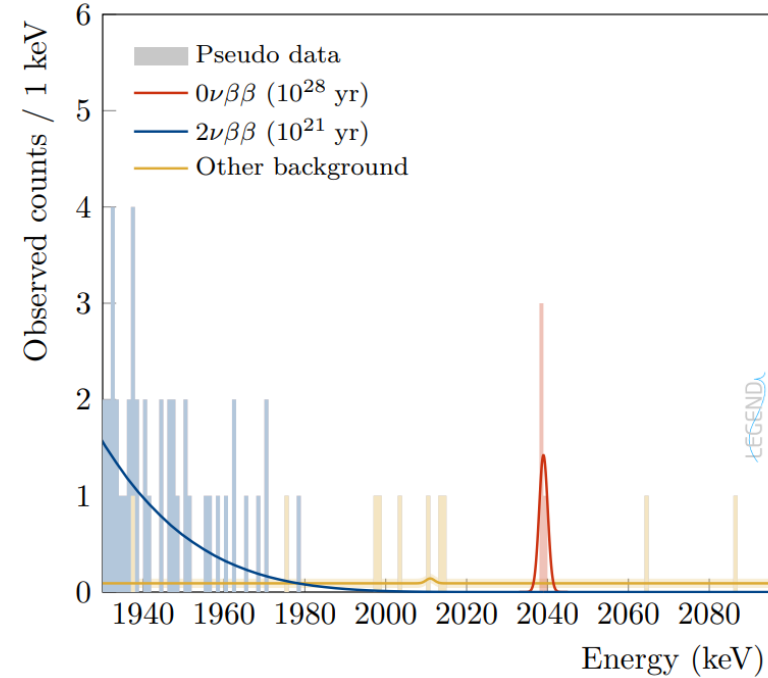




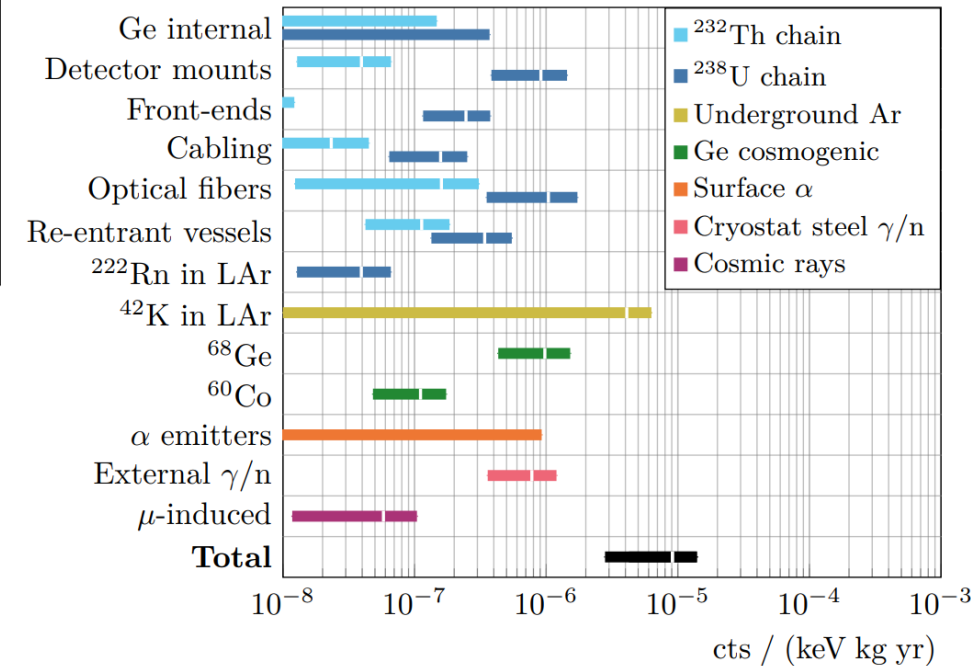
- Baseline design: 1000 kg di germanio in 4 *re-entrant tubes* contenenti LAr underground (riduce ^{42}K prodotto da ^{42}Ar)
- Livello di fondo ridotto di un fattore 20 rispetto LEGEND-200
- SNOLAB (6010 m w.e.) o LNGS (3600 m w.e.) - DOE, ~luglio '23
- CD-0 approvato dal Dipartimento dell'Energia (DOE) degli Stati Uniti d'America

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

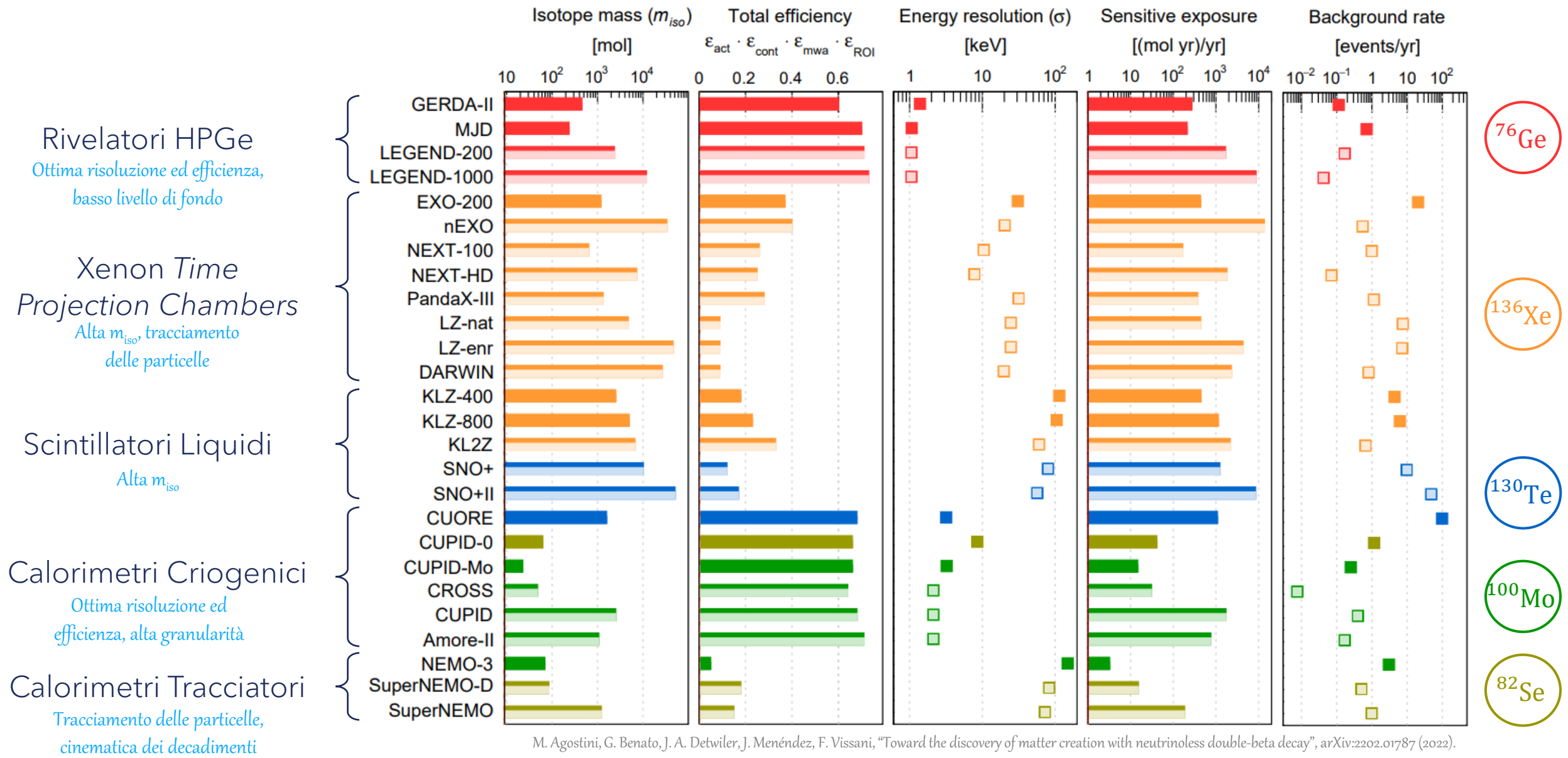




Bande 1σ (o limiti superiori al 90% CL) per i contributi di fondo significanti



- Toy Monte Carlo per un'esposizione di 10 t yr
- Contributi di fondo derivati dal *background model* di LEGEND-1000 (tarato sui dati di GERDA e MJD)
- Meno di un evento di fondo atteso intorno al picco $Q_{\beta\beta}$
- No $2\nu 2\beta$ in prossimità del $Q_{\beta\beta}$
- 3-4 eventi di segnale, visibili ad occhio nudo

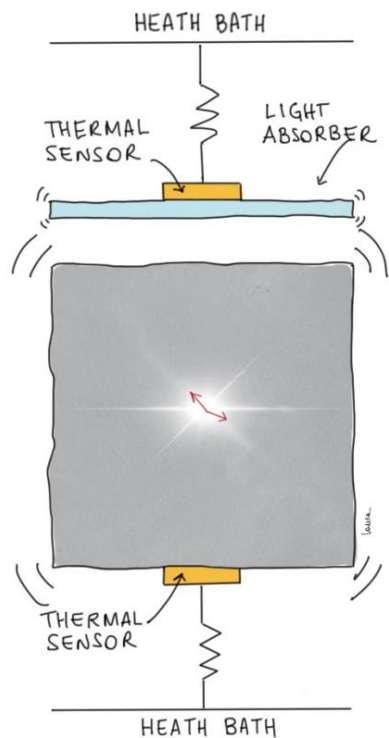
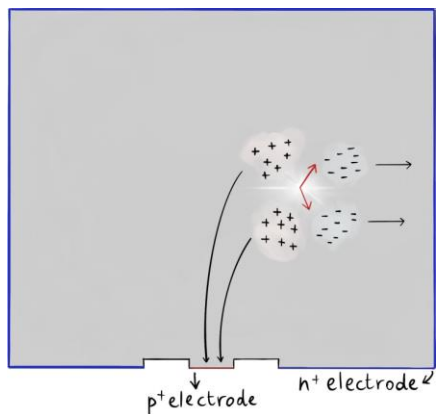


M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani, "Toward the discovery of matter creation with neutrinoless double-beta decay", arXiv:2202.01787 (2022).

Esperimenti 0ν2β

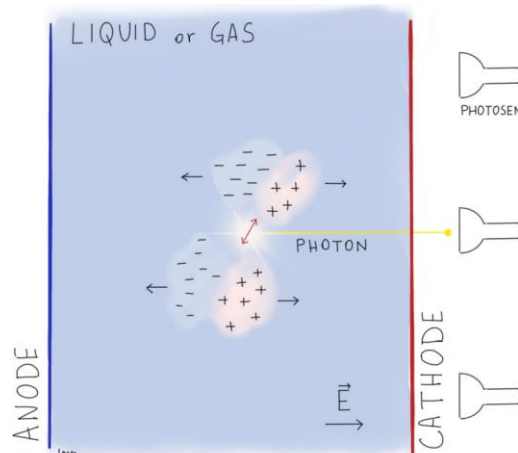
High-purity Ge (HPGe) detector

Coppie $e^- - h$ create per ionizzazione vengono collezionate dagli elettrodi per via di un campo \vec{E} applicato



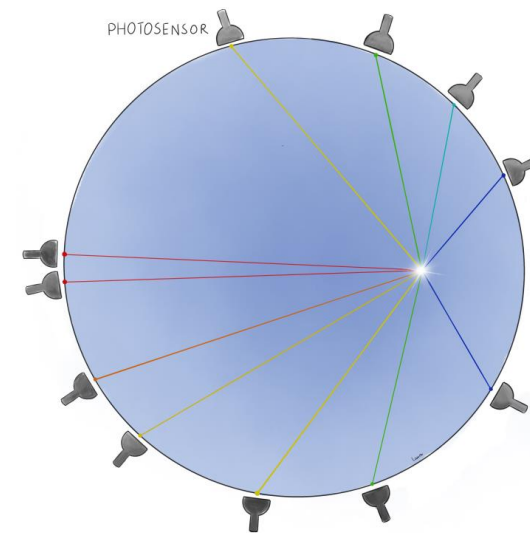
Calorimetri Criogenici

I segnali dei fononi e fotoni vengono letti attraverso sensori termici superconduttivi



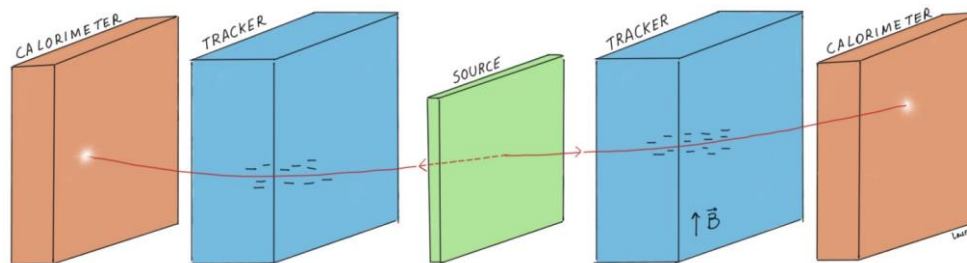
Xe Time Projection Chambers

Oltre a coppie $e^- - h$, viene rivelata luce di scintillazione tramite appositi sensori, fornendo così un'informazione temporale



Scintillatori Liquidi

La posizione di un evento viene ricostruita attraverso il tempo di volo dei fotoni di scintillazione

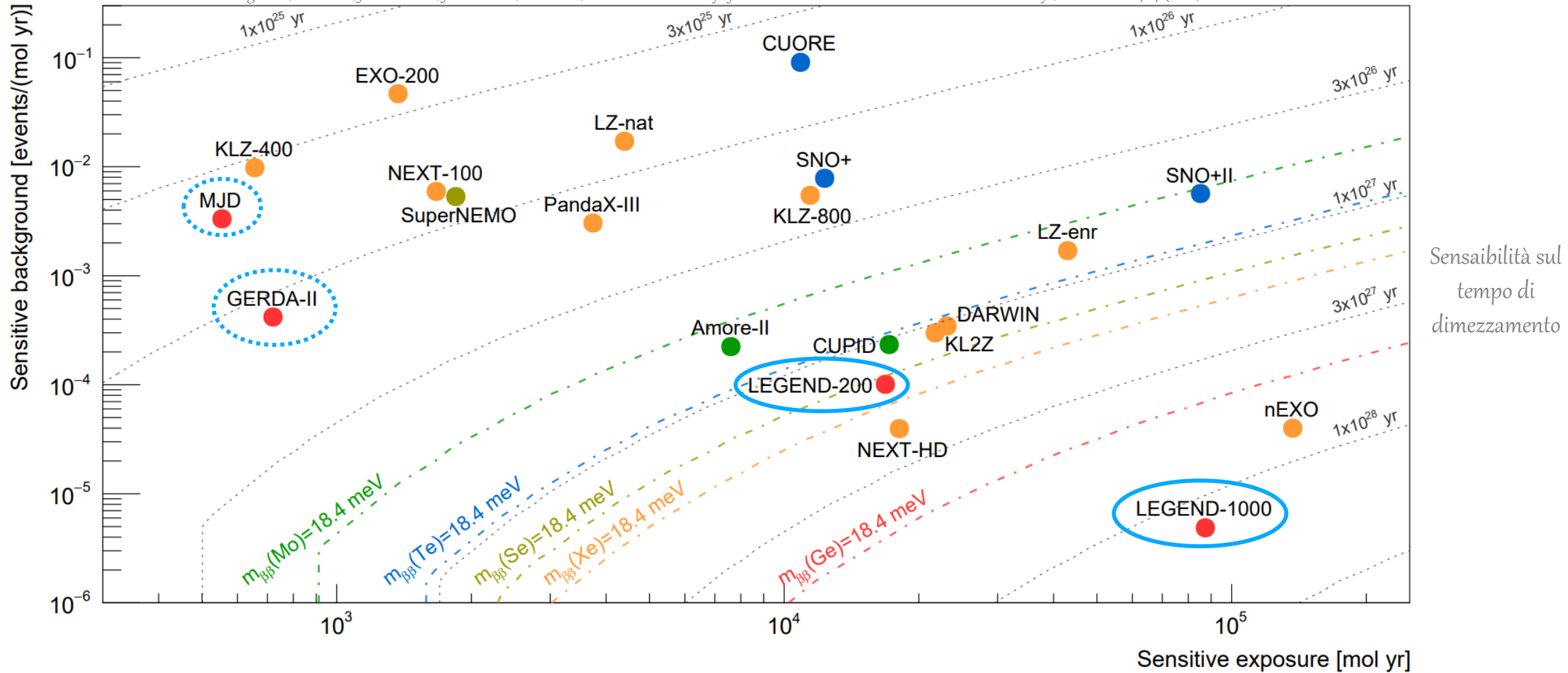


Calorimetri Tracciatori

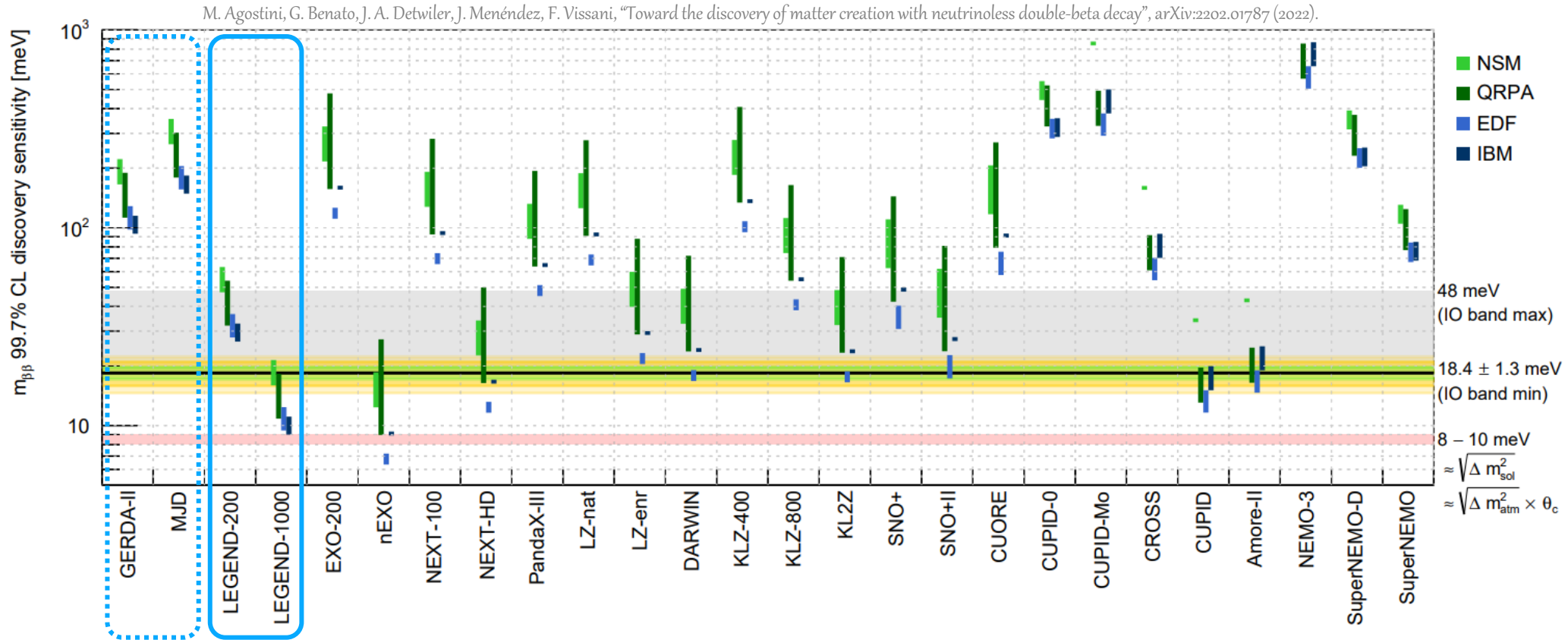
La carica, il momento, e l'energia delle particelle emesse dalla sorgente vengono misurate tramite una combinazione di tracciatori con campo \vec{B} e calorimetri

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).

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).



- Un tempo di acquisizione dati pari a 10 anni è stato assunto per tutti gli esperimenti, a meno di quelli già completati
- Le linee colorate e tratteggiate corrispondono alla sensibilità sul tempo di dimezzamento richiesta per testare lo scenario di gerarchia inversa con gli isotopi Mo-100, Te-130, Se-82, Xe-136, Ge-76



- Banda grigia: range di valori $m_{\beta\beta}$ per gerarchia inversa (*Inverted Order, IO*) e $m_{light} \rightarrow 0$
- Linea nera: valore minimo di $m_{\beta\beta}$ per IO
- Le bande di incertezza 1σ , 2σ , 3σ per $m_{\beta\beta} = 18.4$ meV sono rappresentate in verde, arancione e giallo, rispettivamente
- Banda rossa a 8-10 meV: obiettivo futuro per esperimenti $0\nu\beta\beta$
- NSM (*Nuclear Shell Model*), QRPA (*Quasiparticle Random-Phase Approximation*), EDF (*Energy-Density Functional*), IBM (*Interacting Boson Model*): diversi modelli e teorie nucleari usati nel calcolo dei *Nuclear Matrix Elements* (NMEs)



- 51 istituzioni
- 11 nazioni – Belgio, Canada, Repubblica Ceca, Germania, Italia, Polonia, Russia, Slovacchia, Svizzera, UK, USA
- ~270 membri

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