

# LEGEND-1000

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

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

**LEGEND-1000 Conceptual Design Report - CDR**  
CSN2-LEGEND1000-PM-220-CDR-1.0

30 June 2024

A fine giugno sottomesso il  
CDR di LEGEND-1000 alla  
CSN2

A luglio presentazione del  
CDR in CSN2

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

~270 members, 55 institutions, 12 countries  
from GERDA and MJD experiments + other groups  
Collaboration formed in October 2016



## LEGEND mission:

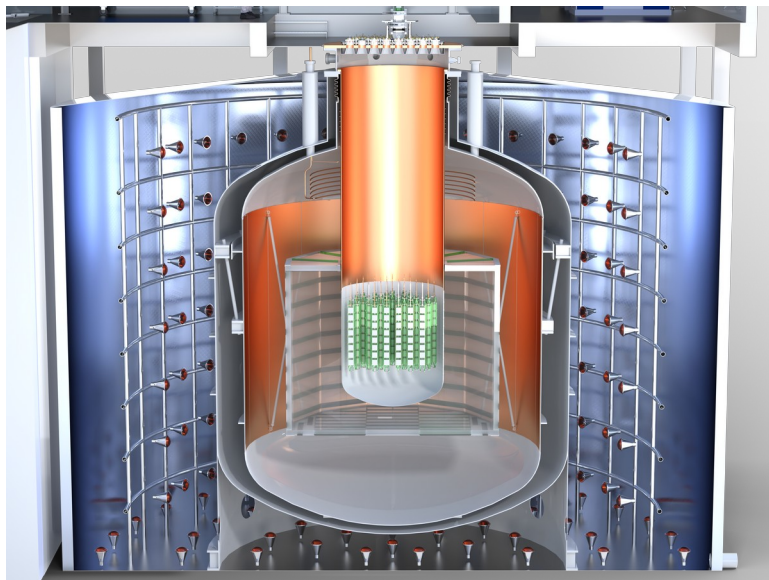
“The collaboration aims to develop a phased Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than  $10^{27}$  years, using existing resources as appropriate to expedite physics results”



# LEGEND: a staged approach

## First Stage (LEGEND-200):

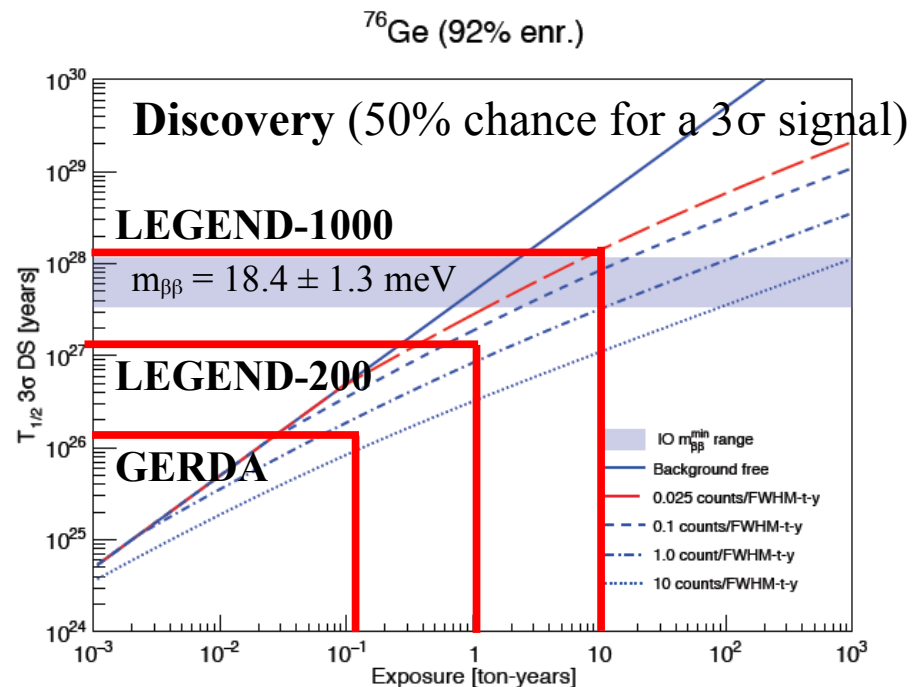
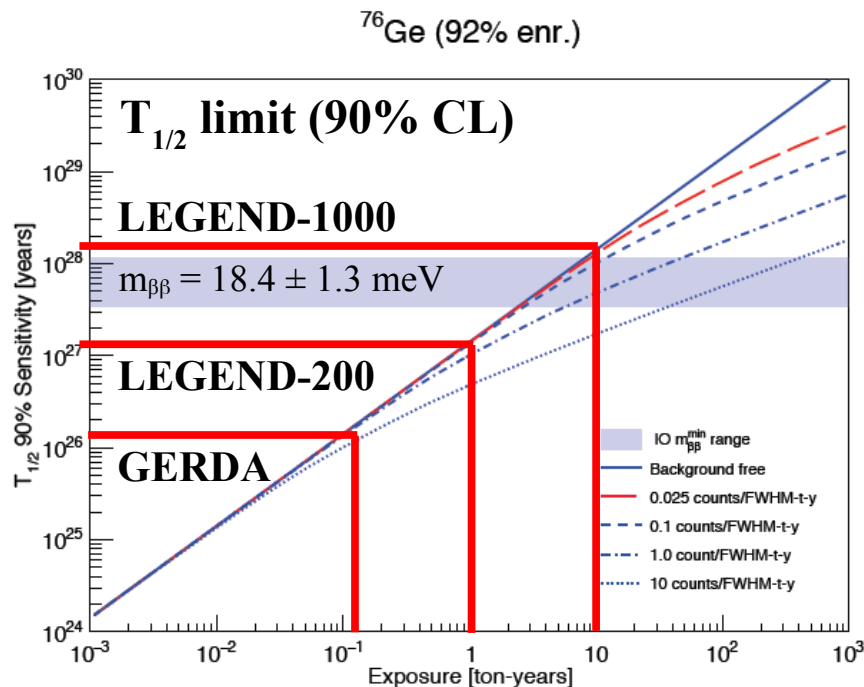
- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining 140 kg are new
- In data-taking from mid-March 2023



## Further Stages (LEGEND-1000):

- 1000 kg (staged)
- timeline and budget: highest priority from DOE after the Portfolio review (July 2021)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- LNGS is the preferred site, SNOLAB is the alternative

# sensitivity and discovery



## Plots details:

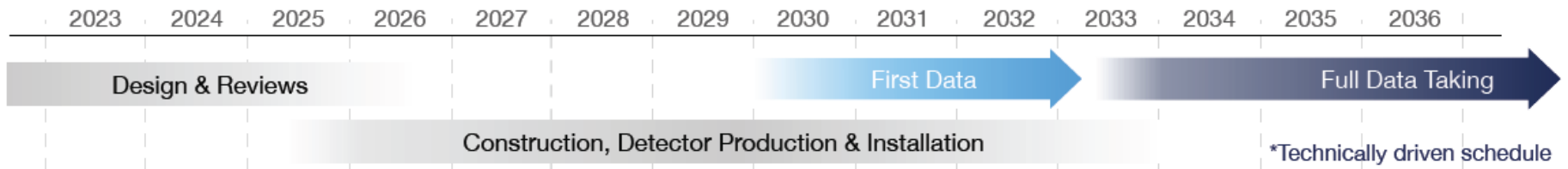
- ~69% efficiency (including: isotopic fraction, active volume fraction, analysis cuts)
- GERDA Phase II: 1.5 counts/(FWHM·ton·yr)
- LEGEND-200: 0.5 counts/(FWHM·ton·yr)
- LEGEND-1000: 0.025 counts/(FWHM·ton·yr)

➔ **N.B.: background-free<sup>(\*)</sup> condition is a prerequisite for a discovery**

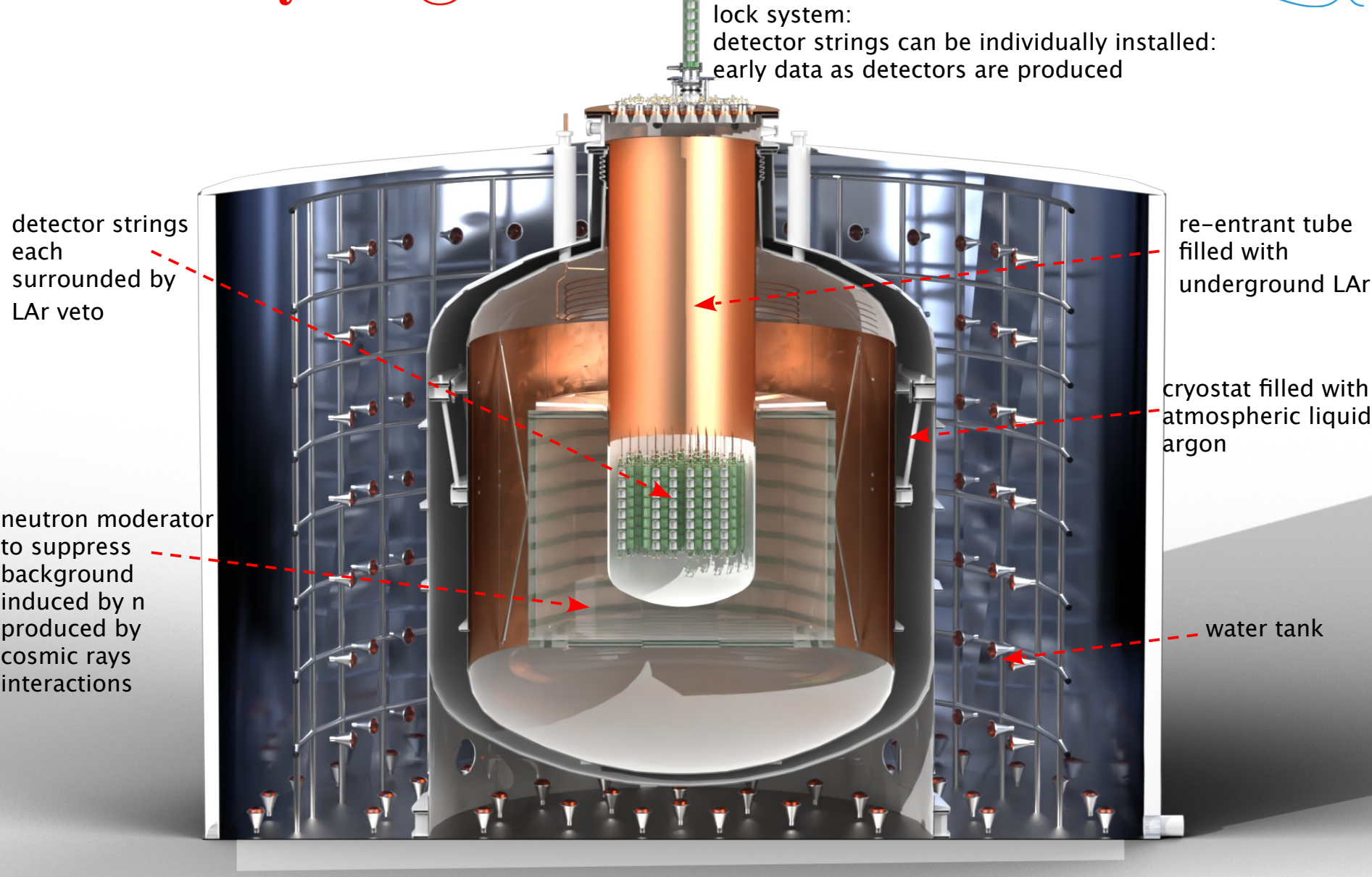
(\*) average expected bkg events < 1.0 in the ROI for the entire exposure

# performance parameters & timeline

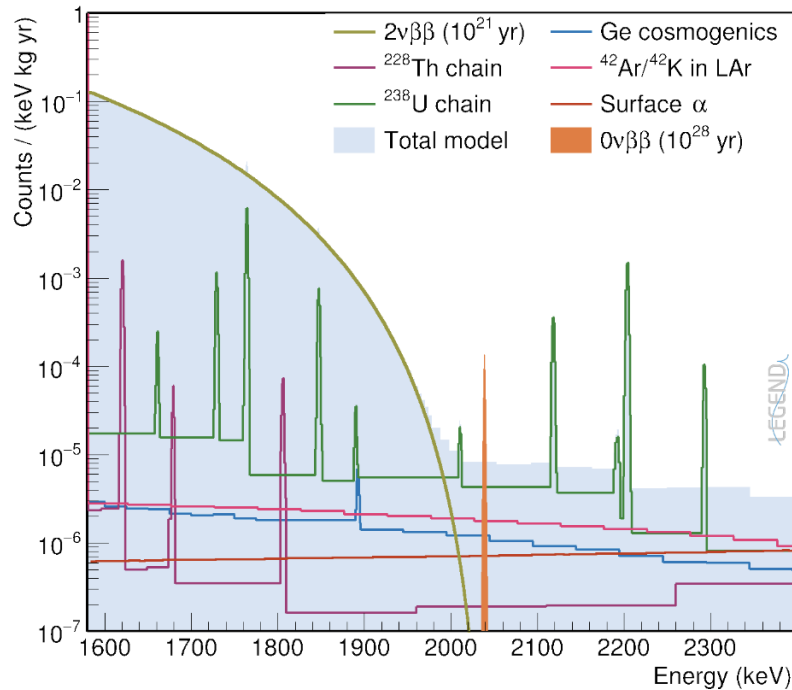
$0\nu\beta\beta$ decay isotope	$^{76}\text{Ge}$
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance	0.69
Total exposure	10 t·yr
Background goal	$< 10^{-5}$ cts/(keV·kg·yr) $< 0.025$ cts/(FWHM·t·yr)
$T_{1/2}^{0\nu}$	$1.3 \cdot 10^{28}$ yr (90% C.L. discovery) $1.8 \cdot 10^{28}$ yr (90% C.L. sensitivity)
$m_{\beta\beta}$	9.4 – 21.4 meV (99.7% C.L. discovery) 8.5 – 19.4 meV (90% C.L. sensitivity)



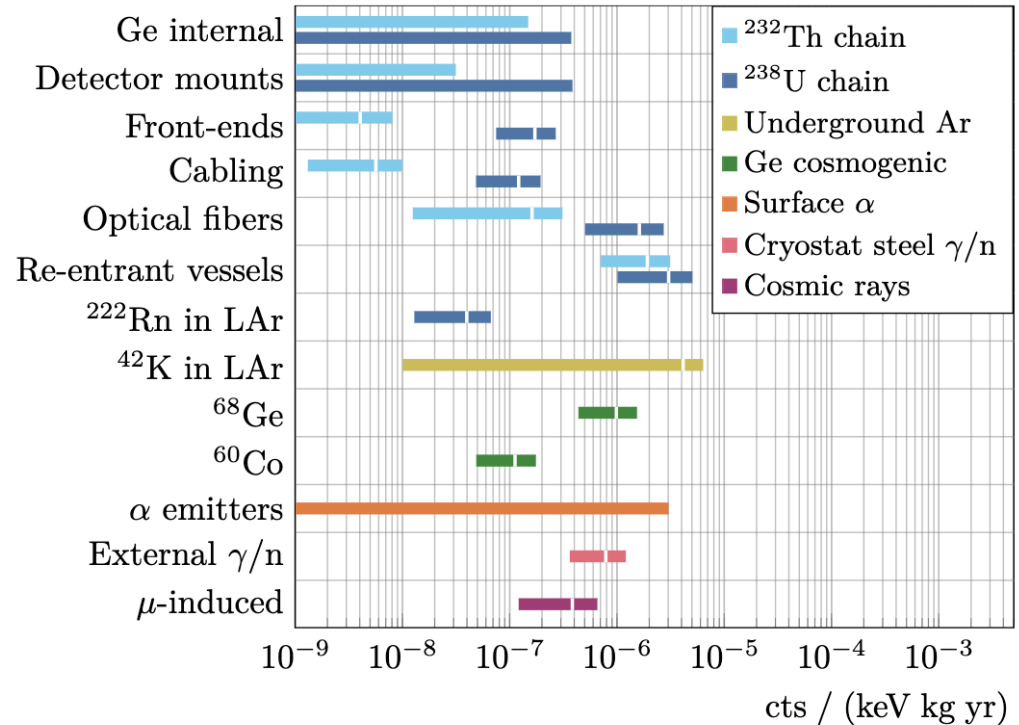
# General layout @ LNGS



# LEGEND-1000 background projections



Expected total spectrum from  $2\nu\beta\beta$  decay and from all background components after all cuts



Projected background index after all cuts:

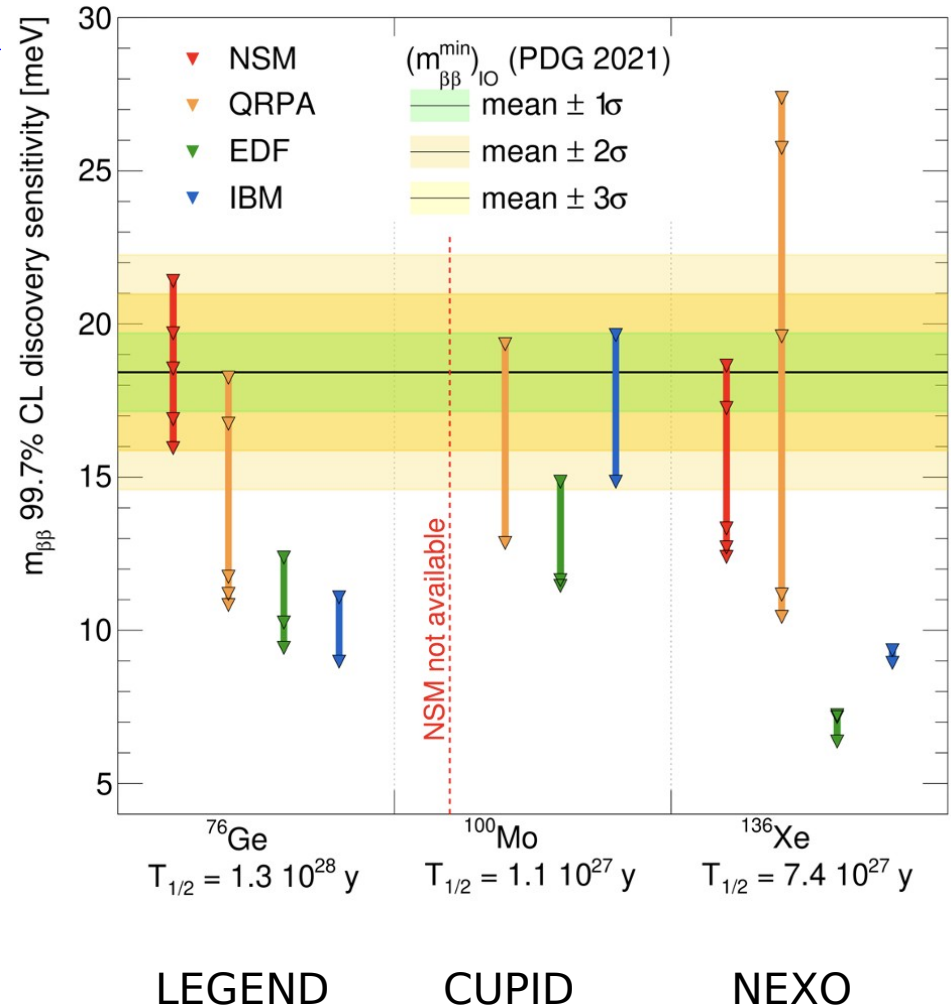
$$13.2^{+7.4}_{-8.4} \cdot 10^{-6} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$



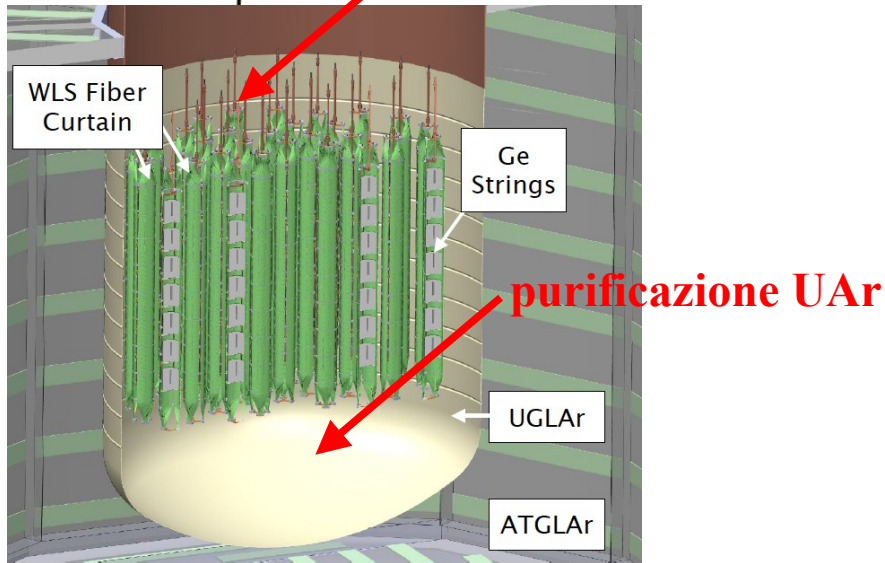
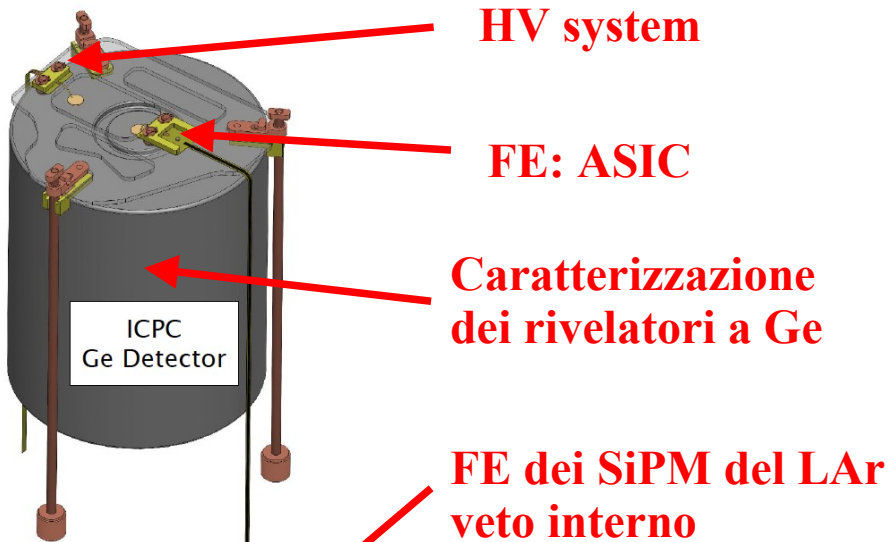
# LEGEND-1000 target sensitivities

- ◆  $m_{\beta\beta} = m_e / \sqrt{G g_A^4 M^2 T_{1/2}}$
- ◆ Inverted Ordering:  $m_{\beta\beta} > 18.4 \pm 1.3$  meV
- ◆ the discovery sensitivity required depends on the matrix element used
- ◆ the range of values given depends on the matrix elements that has been calculated for each isotope
- ◆ LEGEND-1000 will fully test inverted order and a large part of the normal ordering

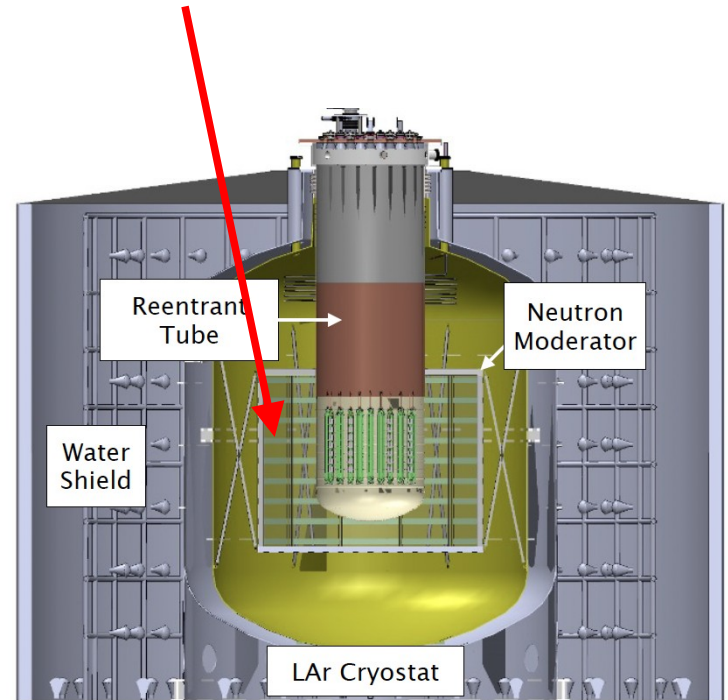
Agostini, Detwiler, Benato, Menendez, Vissani  
PRC, 104 (4) L042501 (2021)



# Attività INFN



Neutron Moderator: sia parte passiva che attiva



+ screening dei materiali

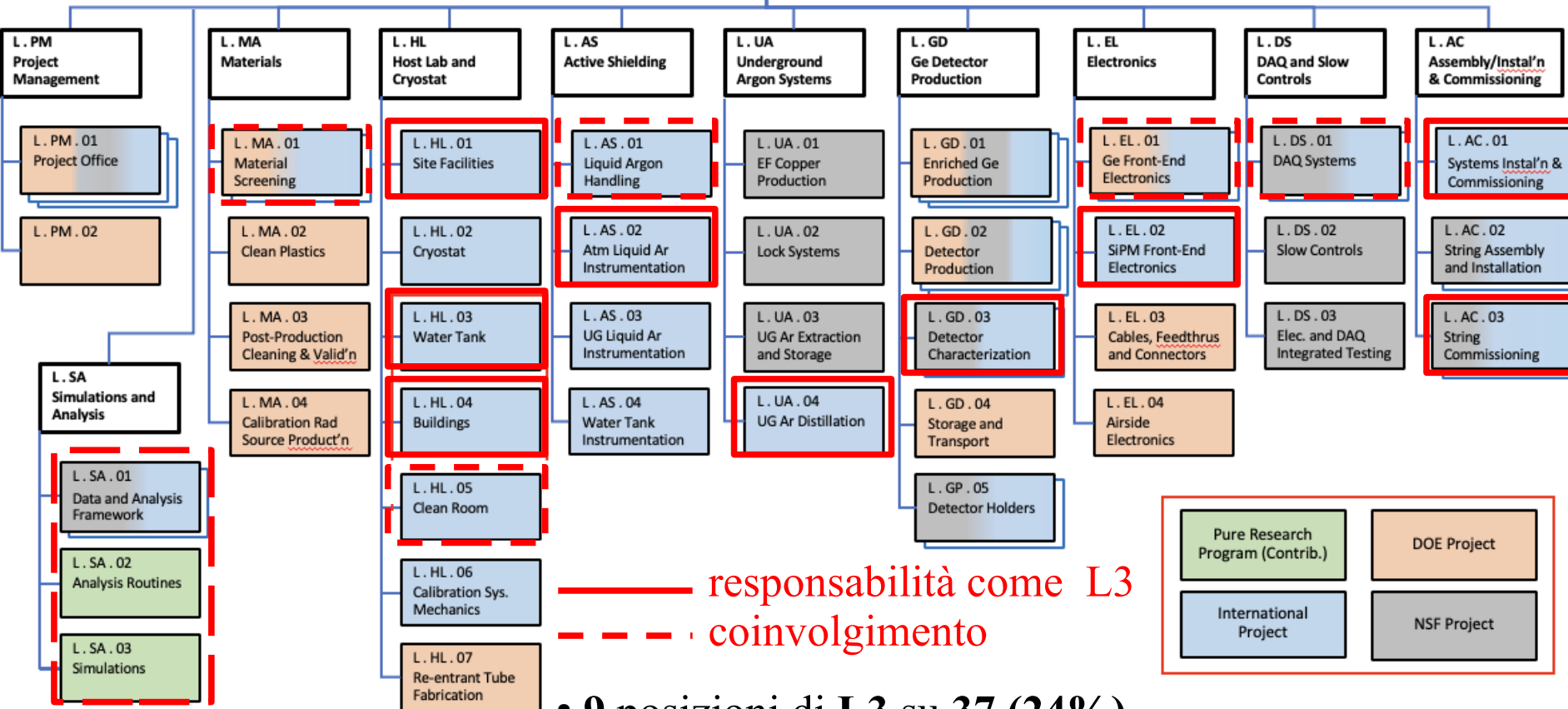


**+ integrazione della criogenia, water filling, water purification, scarichi, rete dati, rete elettrica, allarmi ...**

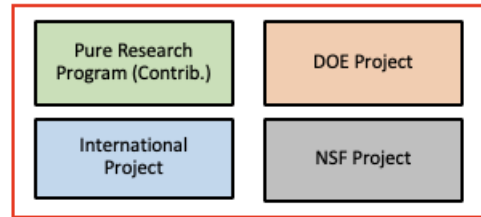
# LEGEND-1000: WBS



## LEGEND 1000

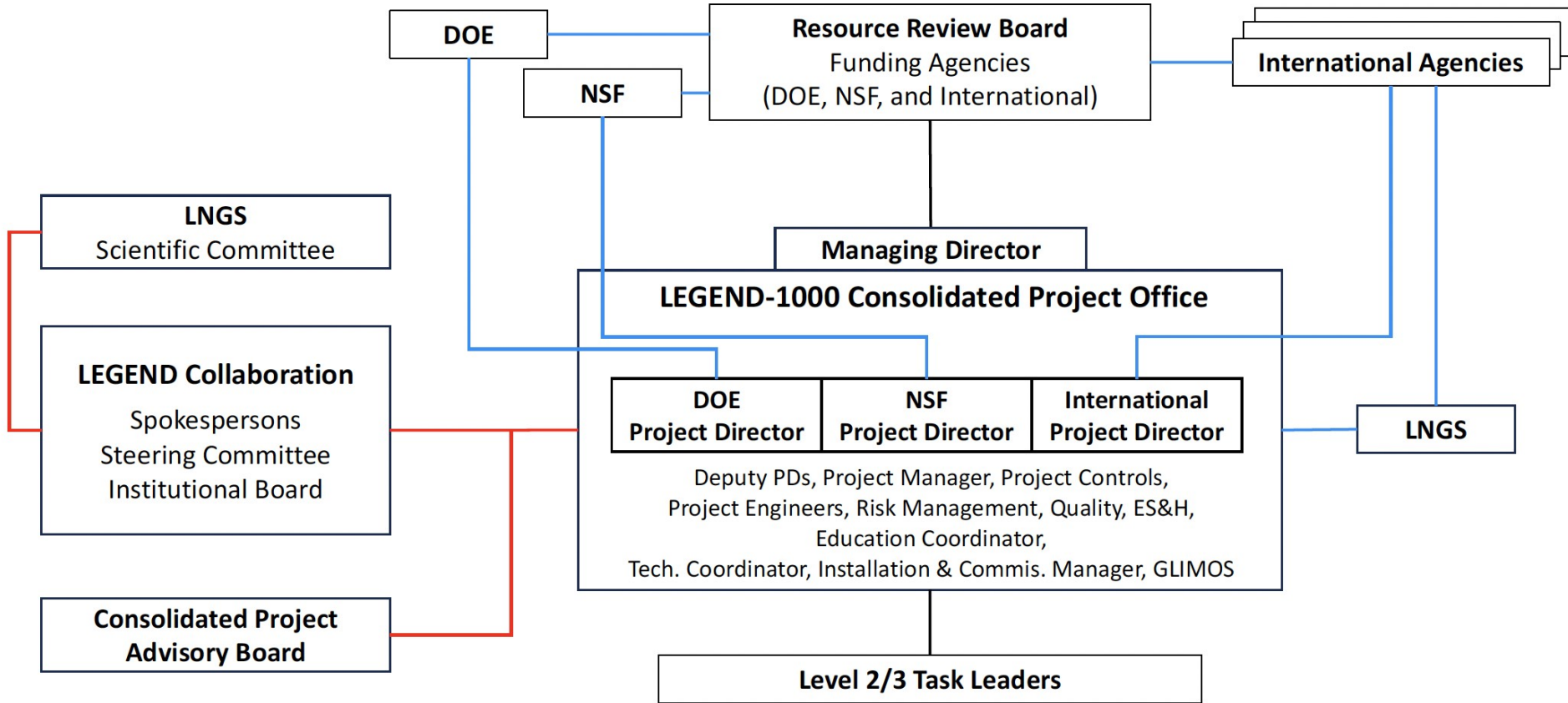


  ————— responsabilità come L3  
  - - - - - coinvolgimento

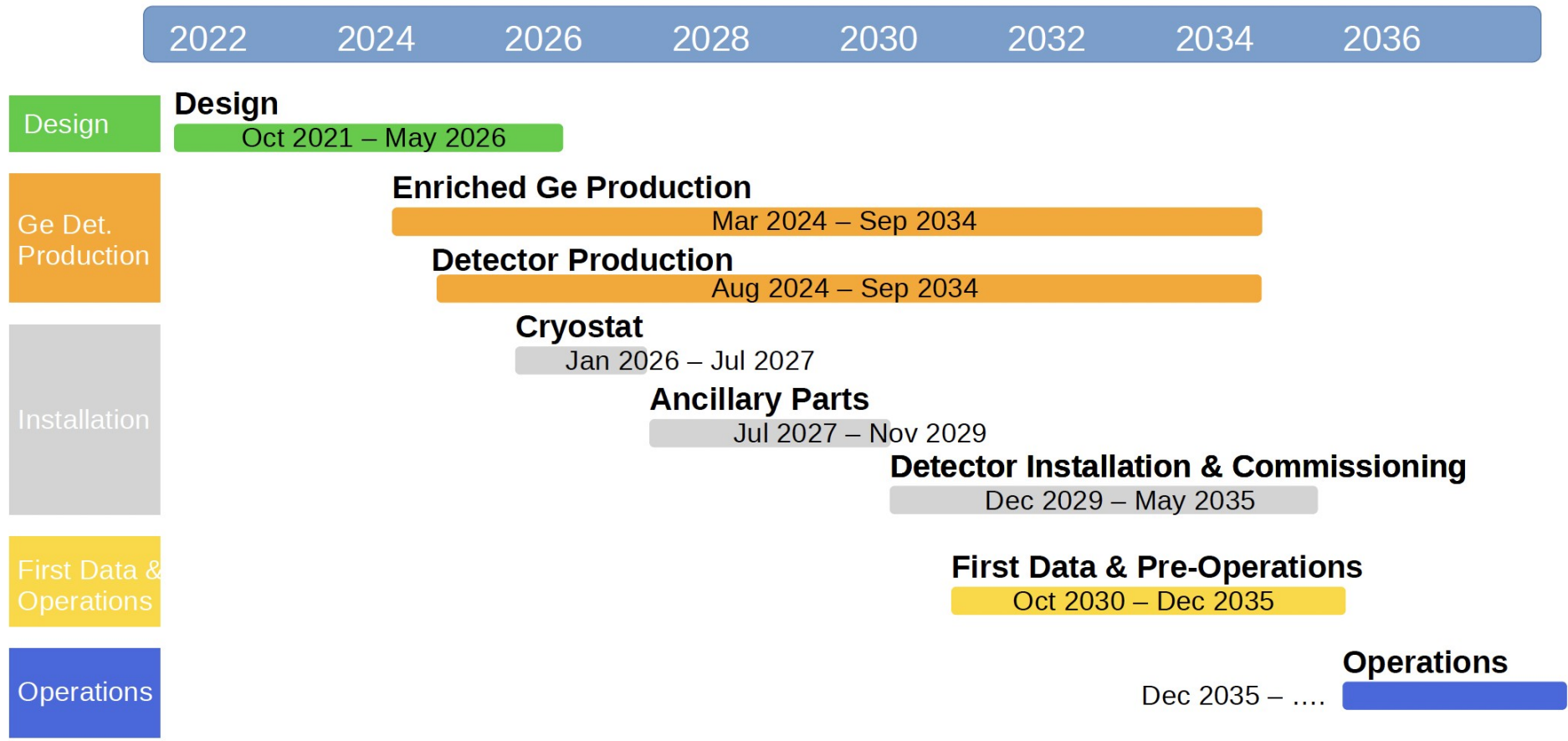


- 9 posizioni di L3 su 37 (24%)
- 9 posizioni di L3 su 23 International Project (39%)
- coinvolgimento generale in 17 WG su 37 (46%)
- posizioni L2 non ancora assegnate

# LEGEND-1000: Governance



# LEGEND-1000: cronoprogramma(\*)



(\*) assumendo un profilo di finanziamento ottimale

# LEGEND-1000: budget

- suddivisione prevista del budget: 53% DOE; 12% NSF; 35% agenzie europee
- DOE:
  - superato nel luglio del 2021 il CD-0 (Portfolio Review)
  - in novembre 2024 CD-1
- NSF:
  - Site Visit Review in aprile 2024; Reverse Site Review (9-10 luglio 2024)
  - se superati, il finanziamento (~90 M\$) parte da aprile 2025
- INFN: CDR sottomesso a fine giugno
- BMF (Germania): partecipazione ad una call (50-100 M€) entro quest'anno
- MPIK (Germania): già finanziato il criostato (5.5 M€), poi verrà altro
- Polonia: già finanziato il sistema di purificazione del LAr (~2 M€)
- Svizzera: richiesto finanziamento per sistema di calibrazione + rivelatori (~2 M€)
- UK: da sottomettere un proposal (~16 M£)

# Richieste finanziarie all'INFN da parte dei gruppi INFN

Items	Costs (k€)
HV of the Ge detectors	420
Ge characterization	360
FE of all the SiPMs	520
Outer Liquid Argon instrumentation	2800
UAr purification and transportation	150
DAQ	1200
Water Tank	900
Central Building	735
Clean Rooms	200
Ancillary Equipment	800
Total	8085



# Attività a Padova

# Meccanica del neutron moderator

Very-very-very preliminary study for mass esteem

Diameter 4.08 m

Height 3 m

~ 5.6 m<sup>3</sup> of PMMA , ~ 6.6 tons if density  $\rho \sim 1.19$

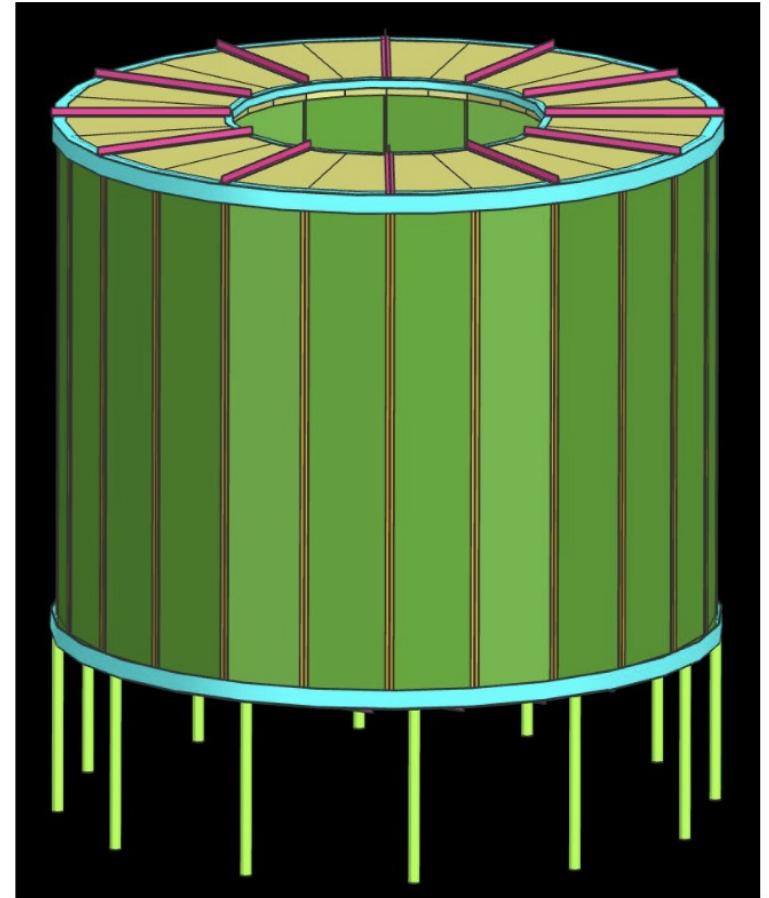
PMMA slabs 480 to 520 mm wide, may be increased to ~ 550 mm to reduce number of vertical struts of the frame

Vertical and radial T profiles 50x50 mm, 5 mm thick (3 mm maybe possible)

L and C "circular" frames 80x120 mm (X-section reduction maybe possible), 3 mm thick

Feet O.D. 70 mm, 3mm thick (Dia reduction maybe possible)

Prima punto da verificare è il background budget generato dalla struttura metallica (assumendo 3 mBq/kg di Th)

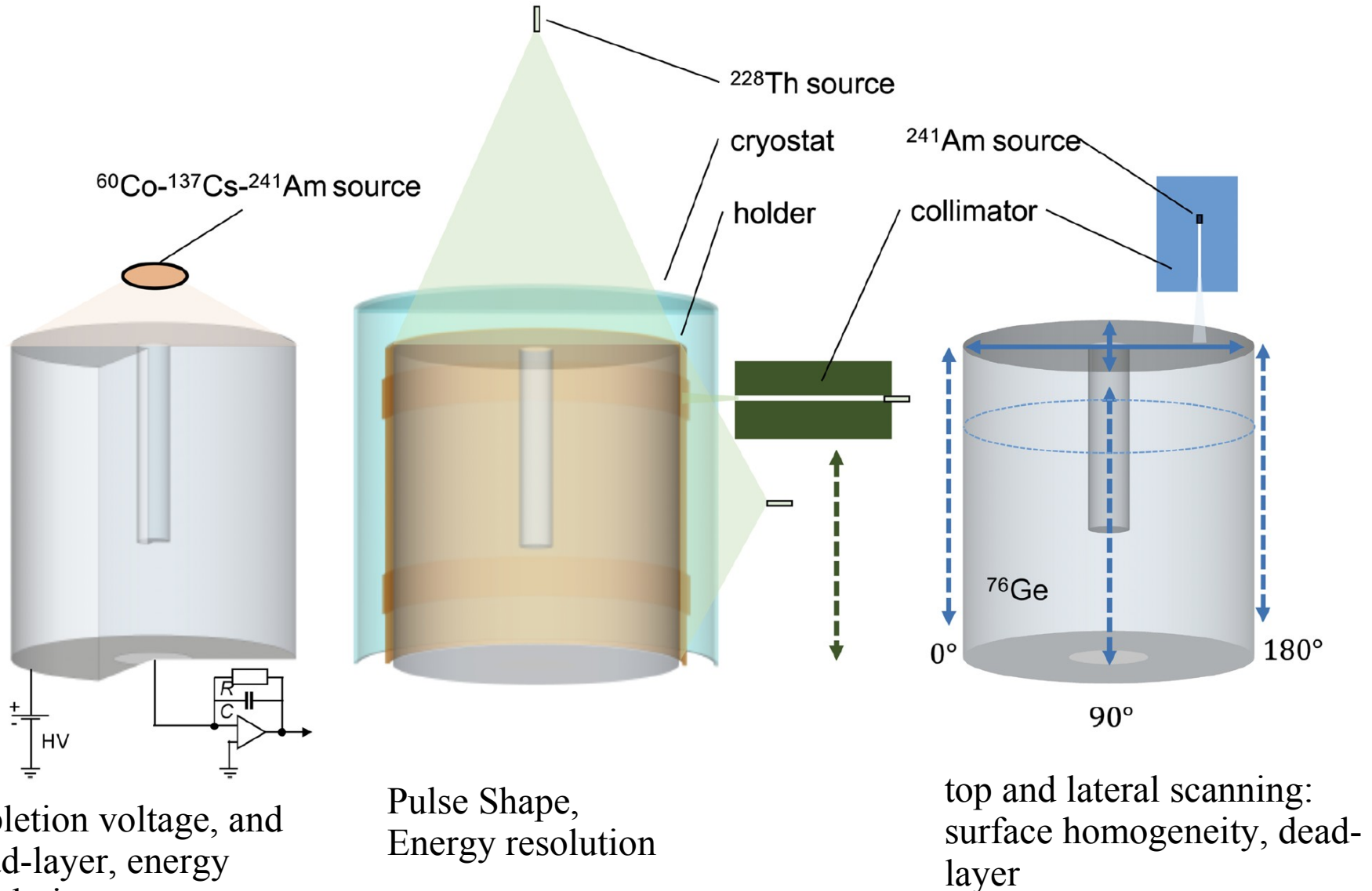


M. Benettoni, M. Zago

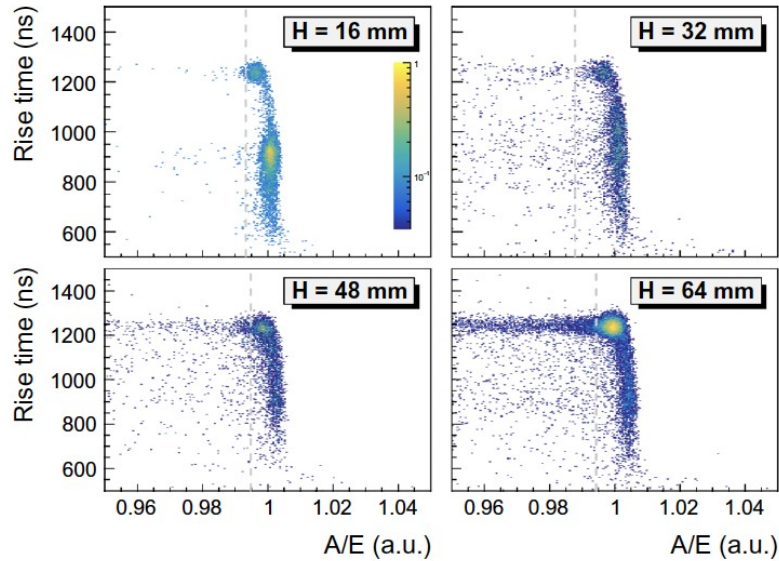
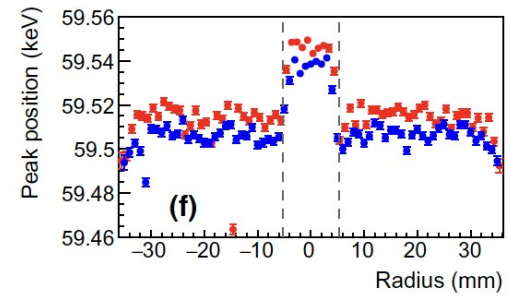
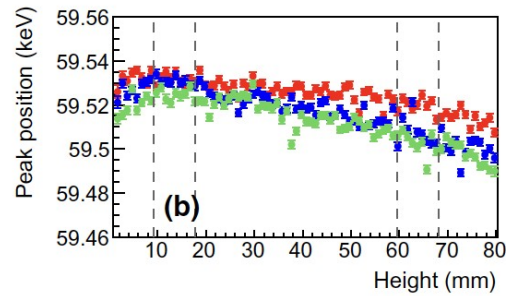
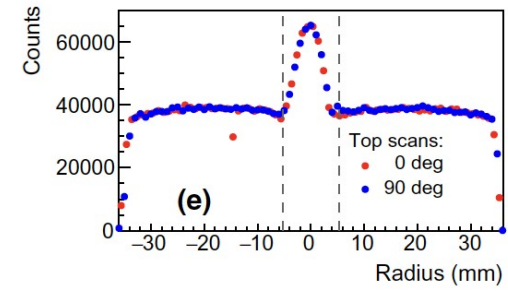
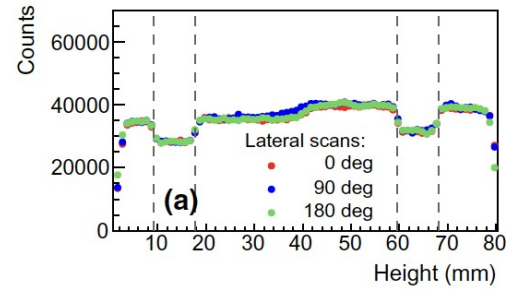
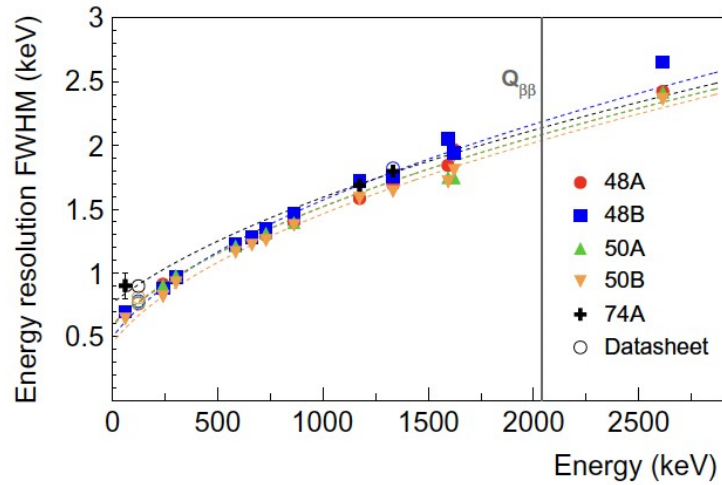
# Altre attività connesse con il neutron moderator

- simulazione dell'apparato
- partecipazione ai tests delle guide di luce
- partecipazione alla caratterizzazione e tests dei SiPMs
- partecipazione al disegno, costruzione commissioning di due test stands ai LNGS (LEGENDArYno, LEGENDARy)

# Ge detector characterization



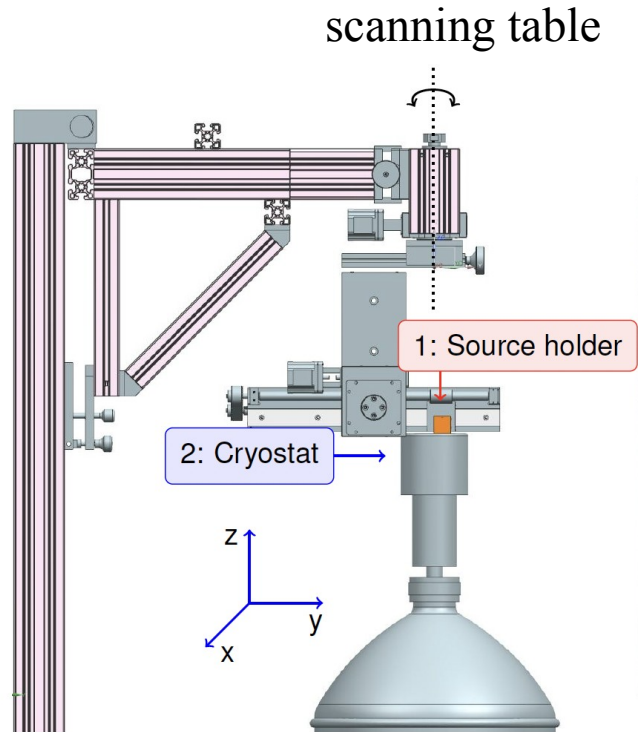
# Ge detector characterization



# Ge detector characterization



static table



scanning table



# Attività di Padova



## GERDA

- analisi dati (studio contaminazione di  $^{85}\text{Kr}$ )
- vari duties all'interno della Collaborazione

## LEGEND-200

- coordinazione e lavori sul DAQ, slow control
- coordinamento e partecipazione ai tests sui nuovi rivelatori (Inverted Coaxial) ad HADES (Belgio) con relativa analisi dei dati
- creazione dei tools di data quality dell'esperimento
- modellizzazione mediante MC della risposta del FE e della pulse shape discrimination
- partecipazione al data-taking del rivelatore (shifts)
- vari duties all'interno della Collaborazione

## LEGEND-1000

- vari duties all'interno della Collaborazione
- coordinazione dei gruppi italiani coinvolti in LEGEND-1000
- partecipazione allo sviluppo del neutron-moderator
- caratterizzazione dei rivelatori a Ge



# Richieste finanziarie

Missioni	36.0 keuro
Consumo	7.0 keuro
Inventario	19.0 keuro
Apparati	---

# Richieste ai Servizi della Sezione

Officina Meccanica	2.0 m.u.
Progettazione Mecc.	6.0 m.u.
Elettronica	1.0 m.u.
Calcolo e reti	0.5 m.u.

# Anagrafica

Bettini A.	PO	0%
Brugnera R.	PA	70%
Calgaro S.	dottoranda	100%
Garfagnini A.	PA	30%
Lippi I.	INFN	60%
Pertoldi L.	ric. estero	100%
Sada C.	PO	60%
Saleh G.	dottoranda	100%
Serafini A.	RtdA	60%
Stroili R.	PA	20%
Taffarello L.	INFN	30%



**backup slides**

- L-200 uses the GERDA infrastructure (cryostat, clean room, water plan, ...) at LNGS
- new elements: part of the enriched Ge detectors, cables, LAr veto, FE electronics, DAQ
- **February 2020**: L-200 took over the GERDA infrastructure
- **November 2021**: start commissioning
- **March 2023**: start of the physics run with ~140 kg of enriched detectors

➤ **L-200 Background Index goal at  $Q_{\beta\beta}$ :**

$$2 \cdot 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$

➤ **L-200 Sensitivity goal:**

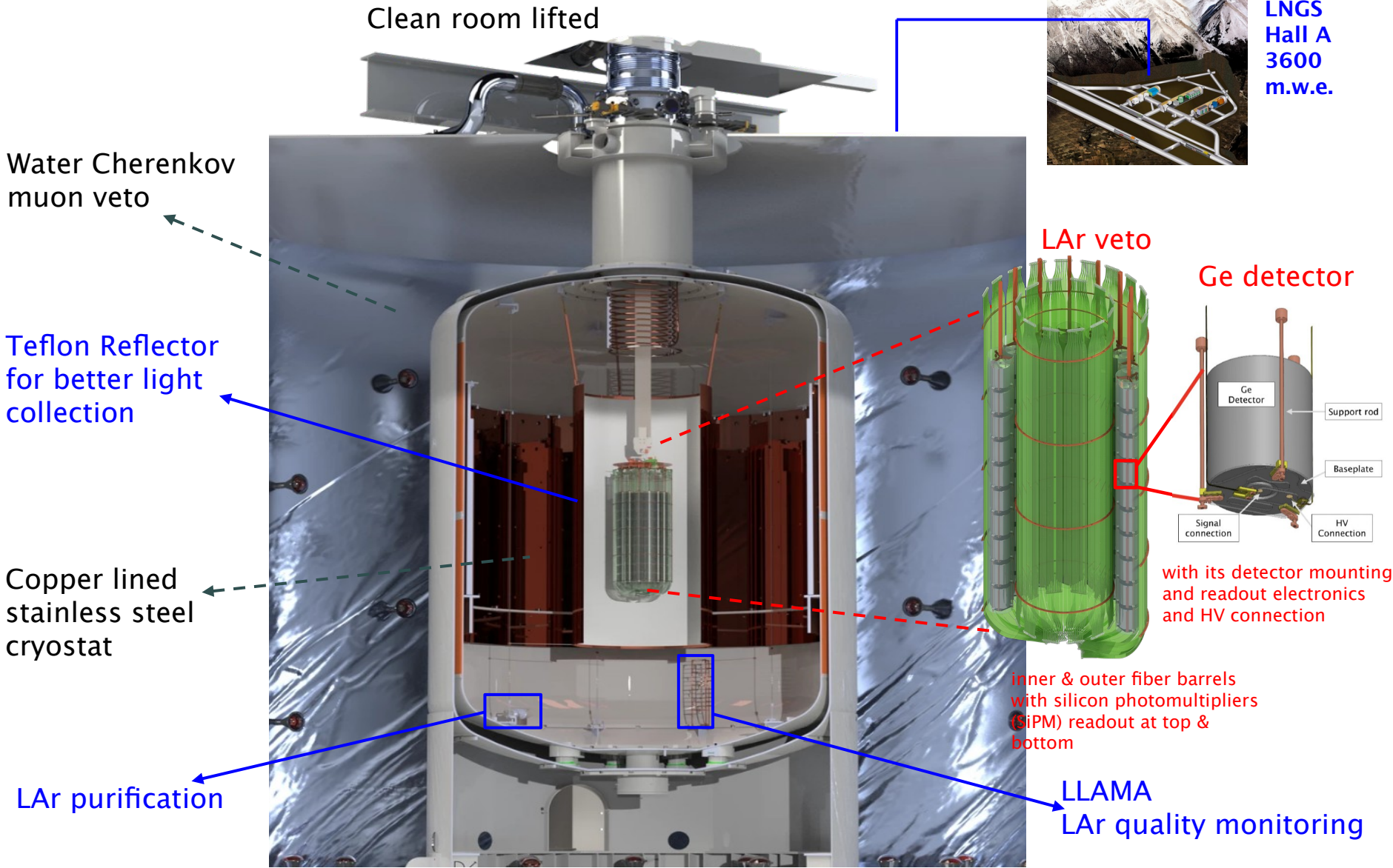
$$T_{1/2} > 1.5 \cdot 10^{27} \text{ years (90\% CL exclusion)}$$

after **1 ton·yr** of exposure

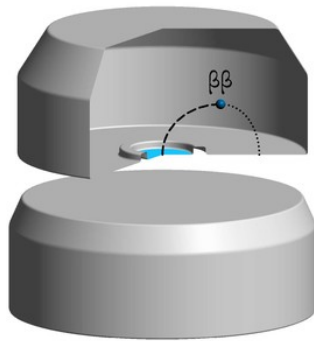
$$m_{\beta\beta} < 27 - 64 \text{ meV (90\% CL exclusion)}$$



# LEGEND-200: the experiment

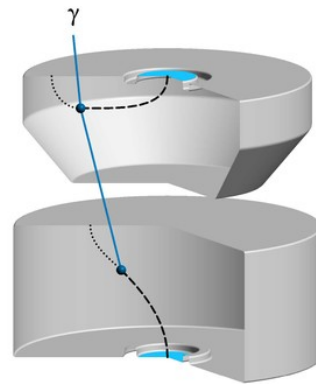


# active background reduction tools



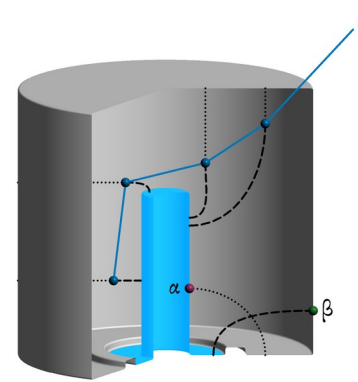
Single-site event topology (SSE)

- $2\nu\beta\beta$
- $0\nu\beta\beta$



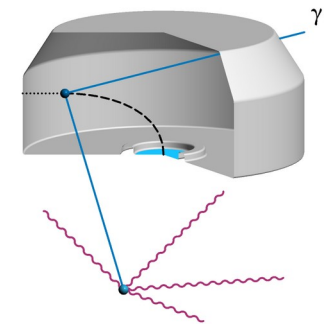
Detector multiplicity

- scattered events



Pulse Shape Discrimination (PSD)

- scattered multi-site events (MSE)
- surface events



LAr-anti coincidence

- intrinsic backgrounds
- Ge cosmogenics

Water Cherenkov anti-coincidence

- muons

# efficiencies

Efficiencies	MJD/GERDA Achieved	LEGEND-1000 Projected
Active volume fraction	88.5%	92.0%*
Containment efficiency	89.0%	92.0%*
Fraction of isotopic mass	87.5%	91.0%
Analysis cuts	90.0%	90.0%
Total (w/o ROI)	62.0%	<b>69.3%</b>
Events in ROI	95.0%	95.0%
Total (w/ ROI)	58.9%	<b>65.9%</b>

\*Improvement due to larger-mass ICPC detectors

# clean materials

## ◆ Underground electroformed copper

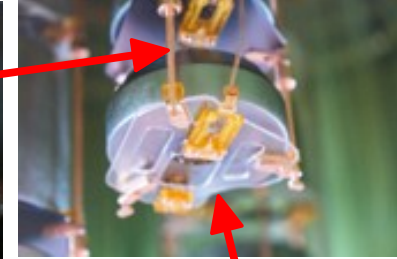
reduces U/Th cosmogenic activation of  $^{60}\text{Co}$  in Cu

$< 0.017 \pm 0.03 \text{ pg}(^{238}\text{U})/\text{g}$

$< 0.011 \pm 0.05 \text{ pg}(^{232}\text{Th})/\text{g}$



## Underground electroformed copper



## ◆ Polyethylene naphthalene (PEN)

replaces optically inactive structural materials

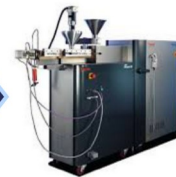
◆ Shift 128 nm LAr scintillation light to  $\sim 440 \text{ nm}$

◆ Yield strength higher than copper at cryogenic temperatures

◆ Evaluated in L-200



Polymer synthesis



Pelletization



Injection molding



CNC machining

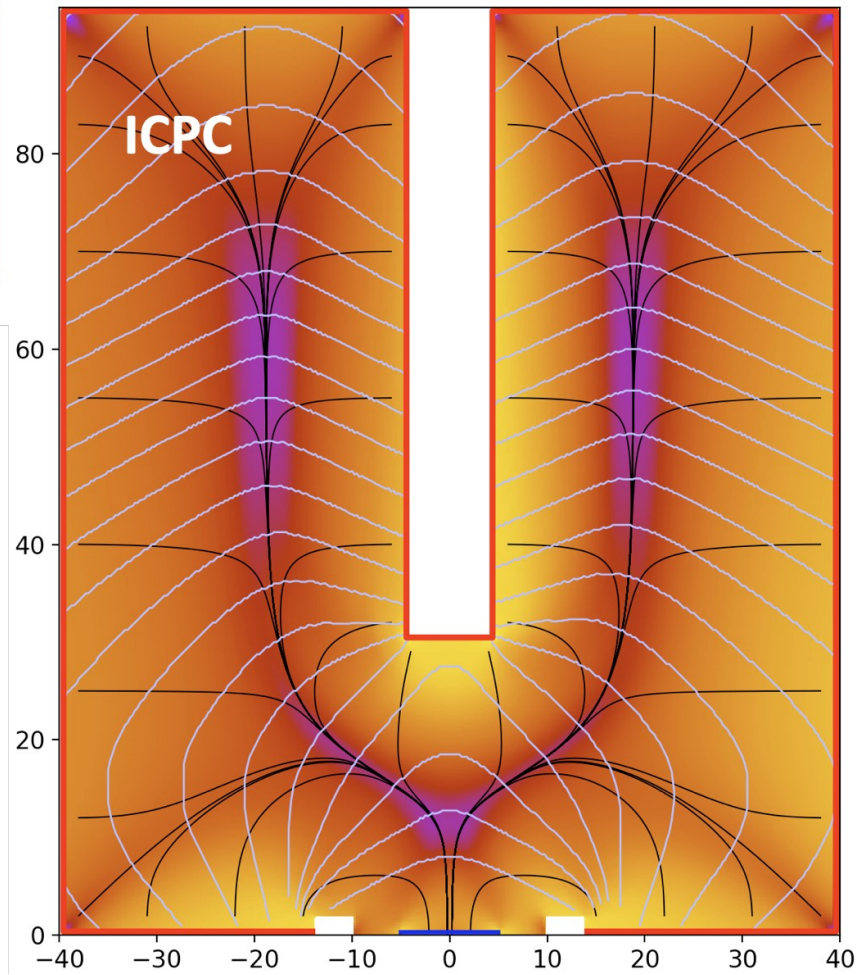
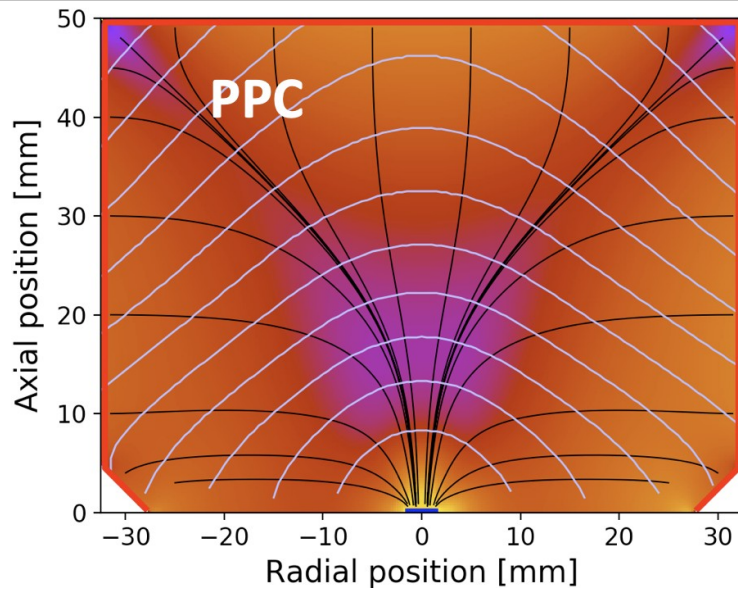
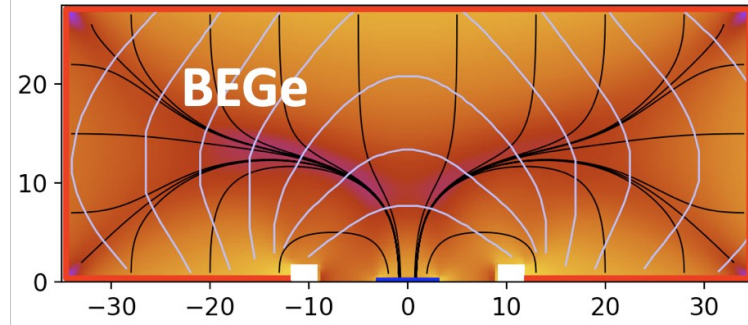


Final component

**PEN: scintillating high purity detector support**

# Ge Detectors

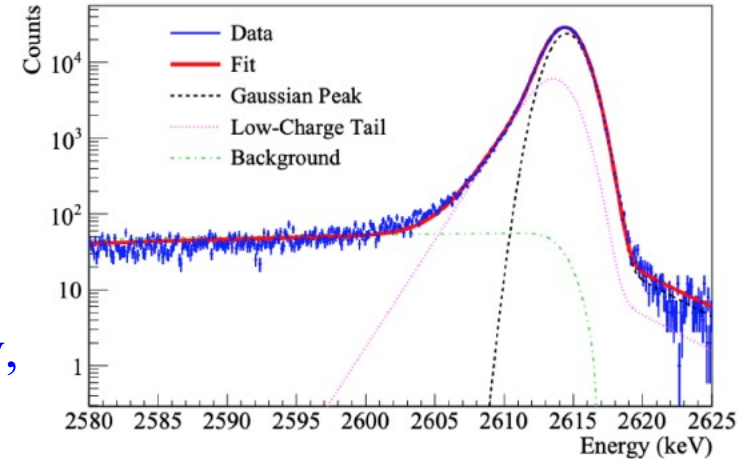
Speed [cm/ $\mu$ s]  
with paths and isochrones



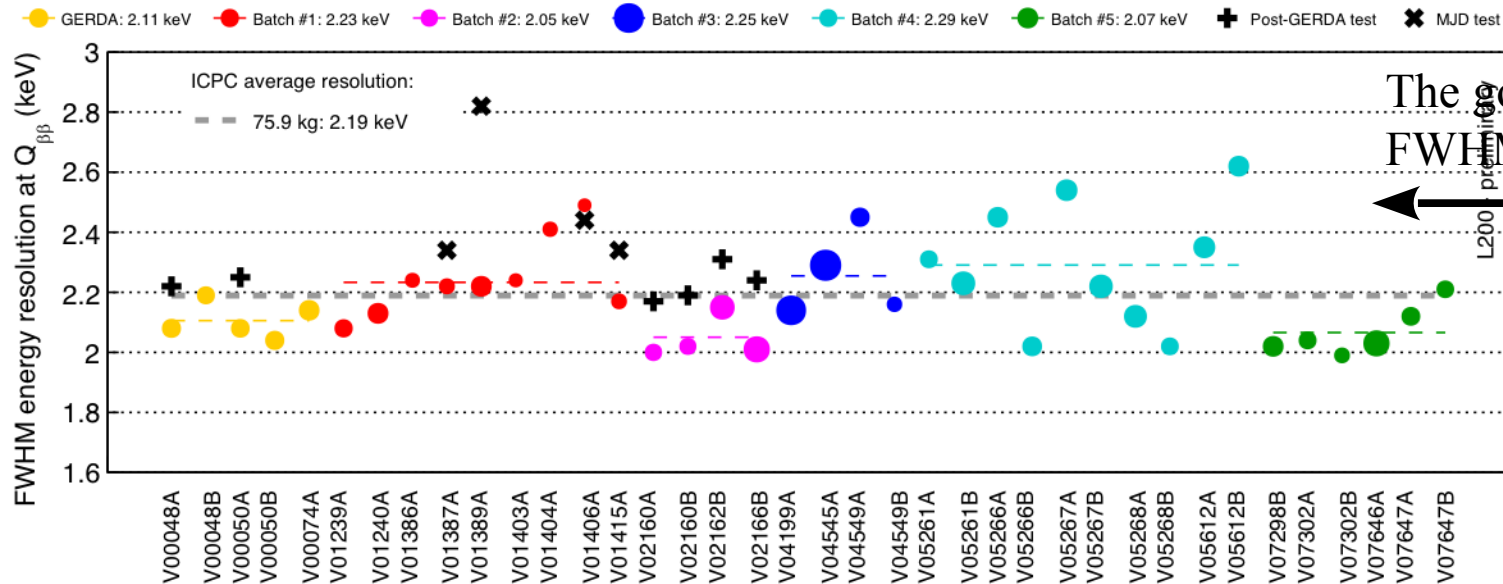
In LEGEND-200 four different types of enriched Ge detectors will be used:  
BEGe (GERDA), PPC (Majorana), ICPC (GERDA, L-200) and semicoax (GERDA)

# ICPC: energy resolution

- ◆ Excellent energy resolution leads to lower backgrounds and higher discovery potential
- ◆ No resolution degradation seen in higher-mass ICPCs
- ◆ Well-understood peak shape, energy scale stability, and linearity (better than 0.1%) lead to improved confidence in results



Energy resolution of ICPCs from characterization tests and calibration runs in GERDA and MJD

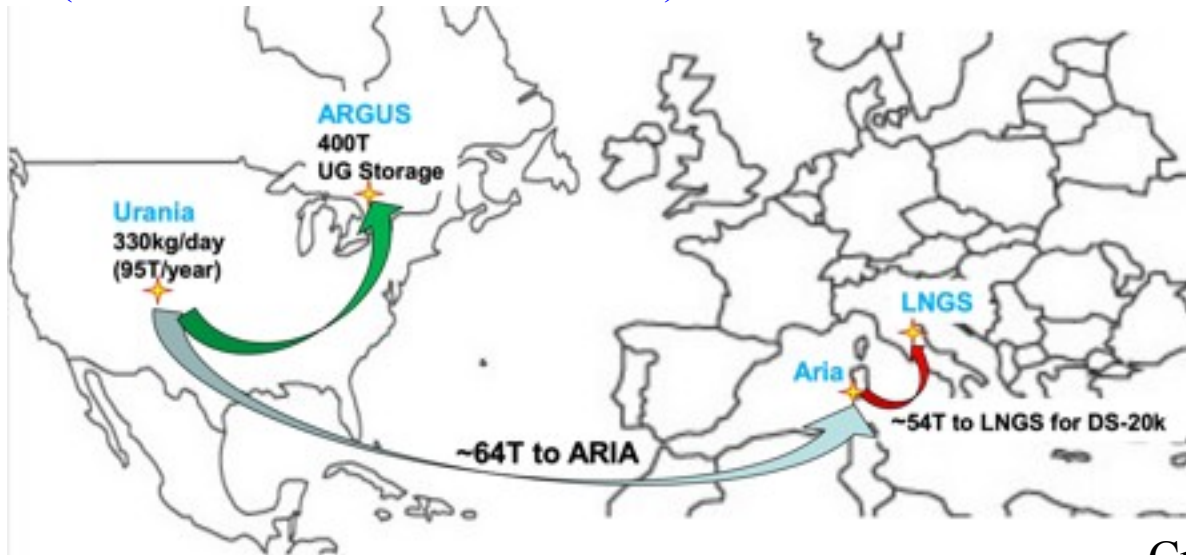


The goal is to reach a FWHM @  $Q_{\beta\beta} = 2.5$  keV



# Underground Liquid Argon

- ◆ one of the most important background:  $^{42}\text{K}$  from  $^{42}\text{Ar}$  (produced in atmosphere by cosmic rays)
- ◆ in GERDA and in LEGEND-200 under control thanks to nylon minishrouds and PSD
- ◆ in LEGEND-1000 we think to use underground Ar ( $\sim 18.5$  t in the 4 re-entrant tubes)
- ◆ technology developed by the DarkSide collaboration
- ◆ expected a reduction factor of  $\sim 1400$  in  $^{42}\text{Ar}$  respect to the  $^{42}\text{Ar}$  content in atmospheric Ar (similar to the reduction of  $^{39}\text{Ar}$ )



Credit: DarkSide/Argo collaboration

# DATA IN THE REGION OF INTEREST — AFTER UNBLINDING LAST WEEK!



- 7 events surviving. Background index  
 $BI = 5.3 \pm 2.2 \cdot 10^{-4}$  cts / (keV kg yr)

**PRELIMINARY!**

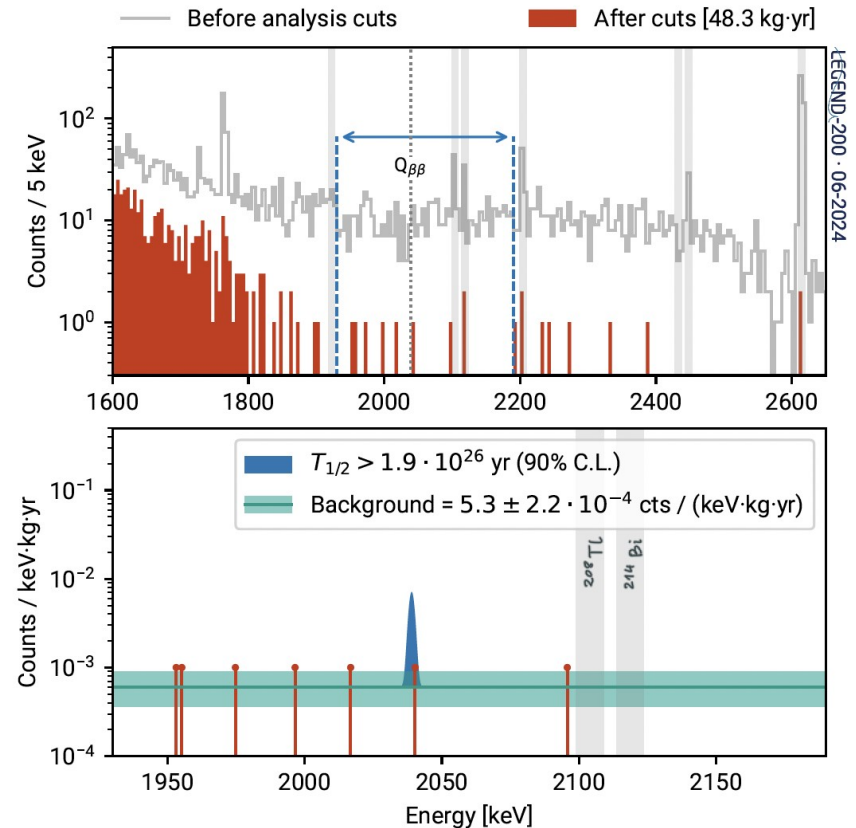
## GERDA, MAJORANA and LEGEND combined fit

- $p$ -value of background-only = 26%
- $T_{1/2}^{0\nu}$  lower limits (90% frequentist C.L.)

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

## LEGEND-200 contribution

- +30% of limit median expectation
- event at  $1.4 \sigma$  from  $Q_{\beta\beta}$  weakens combined limit



LEGEND-200 · 06-2024