MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

GERDA

HPGe detector development for LEGEND

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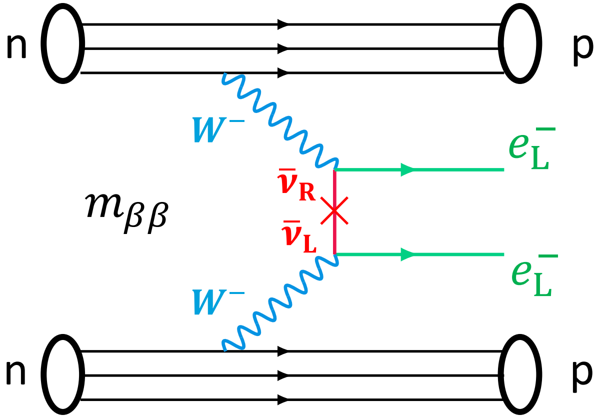
PSeGe workshop

Milan
September 2017

The physics case of LEGEND : $0\nu\beta\beta$ decay

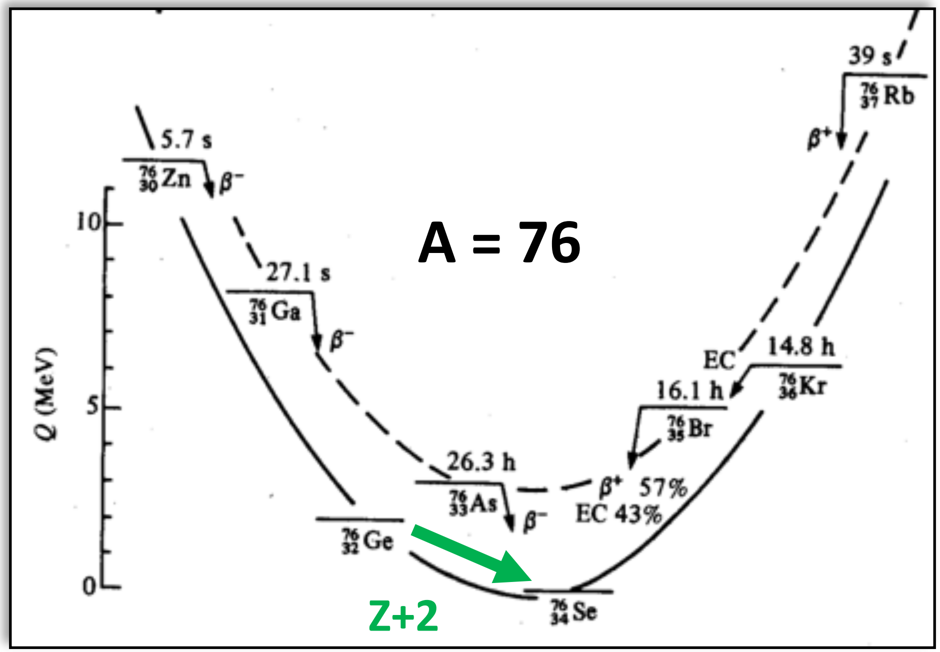
"Large Enriched Germanium Experiment for Neutrinoless ββ beta Decay"

- We look for neutrinoless double beta decays in ^{76}Ge

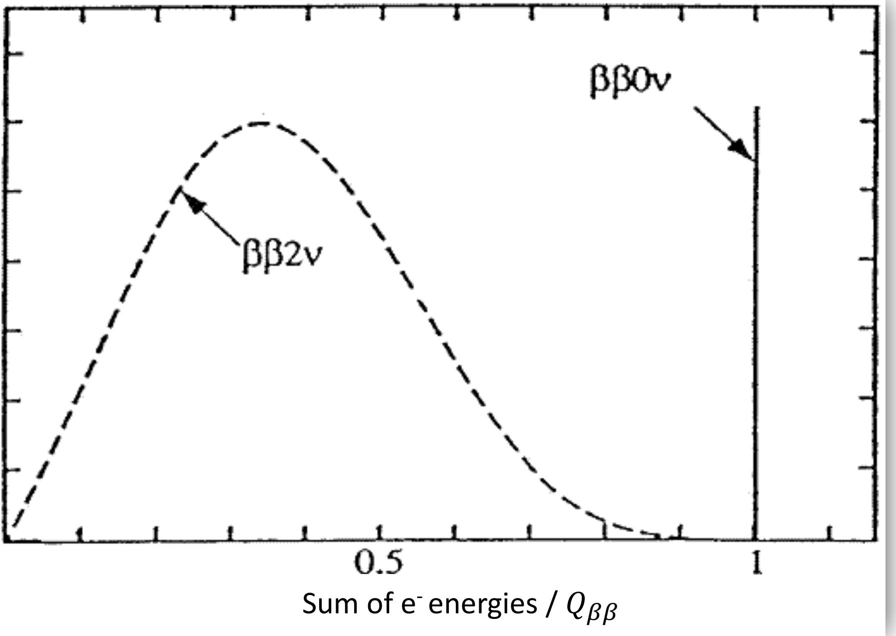


- Such process:
  - ✓ violates the Lepton Number by 2 units = New Physics!
  - ✓ determines the nature of neutrinos: Majorana particle $\boldsymbol{\nu} = \bar{\boldsymbol{\nu}}$
  - ✓ gives information on the $\boldsymbol{\nu}$ mass via $m_{\beta\beta}$

$0\nu\beta\beta$ decay experimental signature



$Q_{\beta\beta} = 2039$ keV

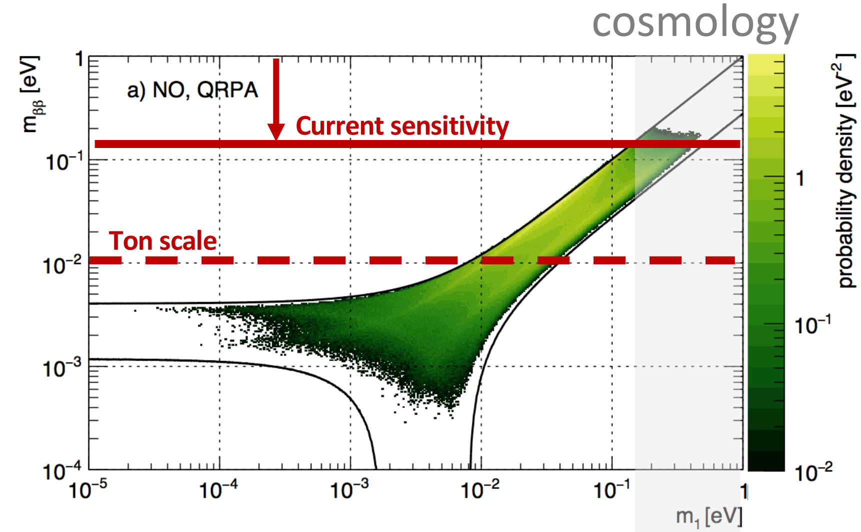


$$ {T^{0\nu}_{1/2}}^{-1} = g_A^4 \, G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} $$

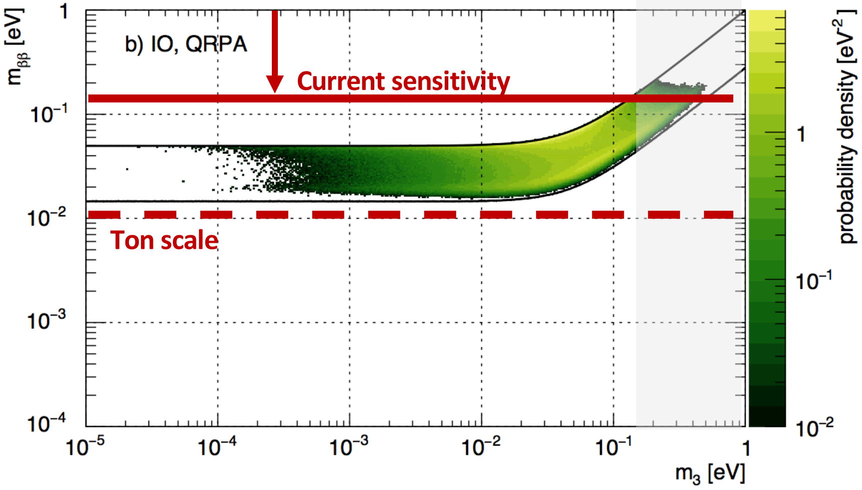
$T^{0\nu}_{1/2}$	**experimentally probed half-life**
g_A	**axial vector coupling cnst = 1.25**
$M^{0\nu}$	**nuclear matrix element**
$G^{0\nu}$	phase space factor
m_e	electron mass
$m_{\beta\beta}$	coupling strength (function of lightest ν mass)

Challenges

Physical interpretation



PRD 96, 053001 (2017)



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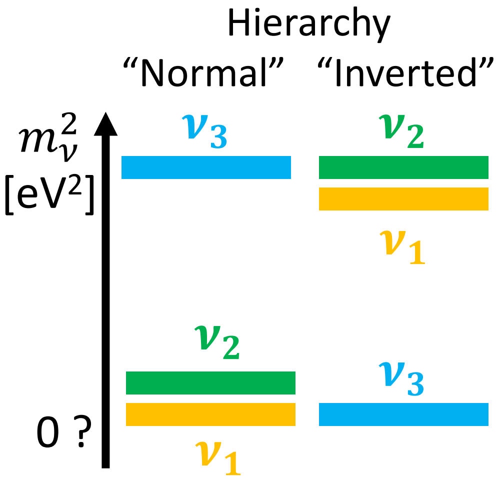


$$ m_{\beta\beta} = \sum_{i=1}^{3} m_i \, {U_{ei}}^2 $$

U = 3x3 PMNS matrix

Sensitivity and background expectation

- Experimental sensitivity:

$$T_{1/2}^{0\nu} \propto \begin{cases} M.t & \text{No bkg observed in the region of interest} \\ \sqrt{\dfrac{M.t}{B.\Delta E}} & \text{Large number of bkg events in the R.O.I} \end{cases}$$

- Background expectation:

$$N^{\mathrm{bkg}} = M.t.B.\Delta E$$

$M.t$	Exposure	[kg.yr]
ΔE	Energy resolution	[keV]
B	Background index	[cts/kev/kg/yr]

The ^{76}Ge as a good candidate

- Experimental sensitivity:

$$T^{0\nu}_{1/2} \propto \begin{cases} M.t & \text{No bkg observed in the region of interest} \\ \sqrt{\dfrac{M.t}{B.\Delta E}} & \text{Large number of bkg events in the R.O.I} \end{cases}$$

- Background expectation:

Ge based experiment

$$N^{\mathbf{bkg}} = M.t.B.\Delta E$$
$$\approx 0.05 \text{ cts}$$

$M.t$	Exposure	18.2 kg.yr
ΔE	Energy resolution	2.93 keV @ $Q_{\beta\beta}$
B	Background index	1 x 10^{-3} cts/kev/kg/yr

GERDA BEGe detectors
Nature 544 (2017) 47
+ TAUP17 data release

+ High detection efficiency : source = detector

Background suppression in GERDA

- Passive shielding :
  590 m^3 pure water tank

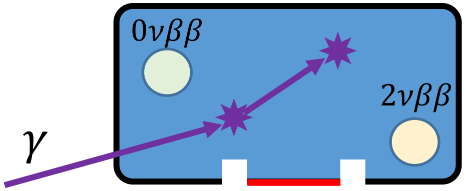
- Active shielding :
  muon + LAr veto
  - ➢Liquid Ar serves as a coolant

- **Analysis cuts :**
  Pulse shape discrimination

➢ Ge Detector Array:
10 coaxial + 30 BEGe

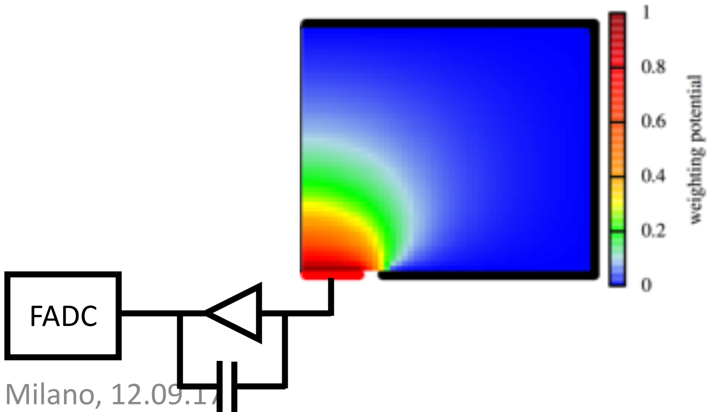
Pulse Shape Discrimination for BEGe

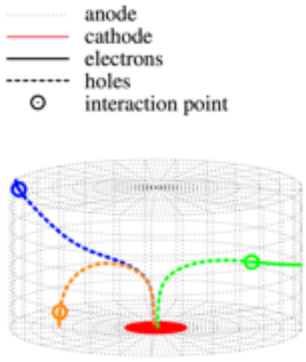
- $0\nu\beta\beta$ & $2\nu\beta\beta$ = "single site event" (SSE) i.e. localized energy deposition (~1 mm^3)
  Background = "multi site event" (MSE) mainly



- PSD goal: Discriminate between SSE and MSE

- PSD parameter: **A/E** for BEGe detectors
  - **E** → Energy deposited in the detector
  - **A** → Maximum of the current amplitude





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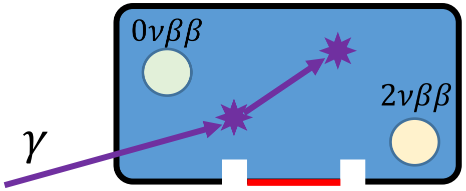

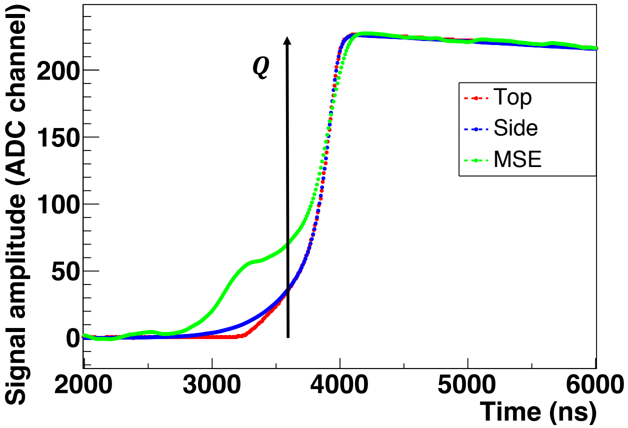

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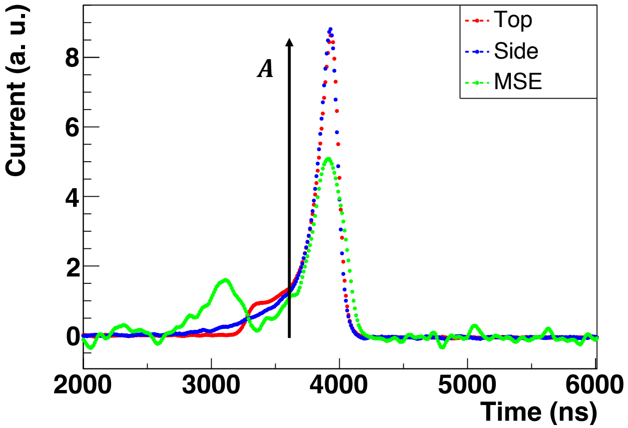
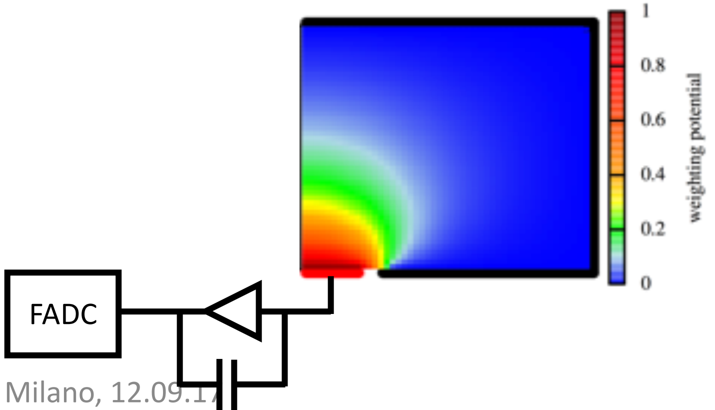
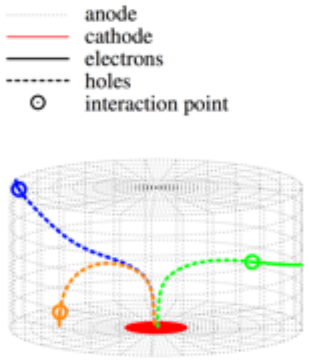
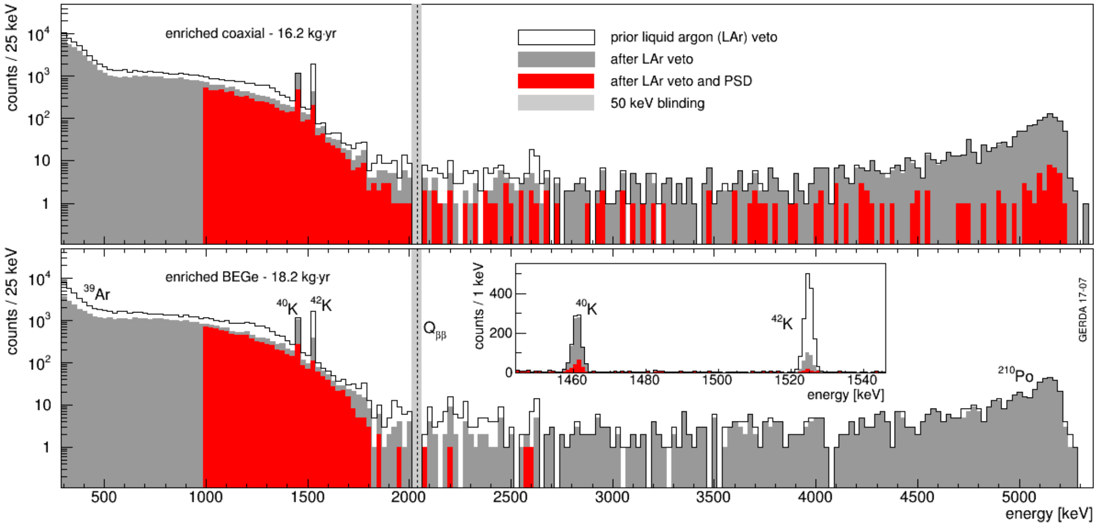
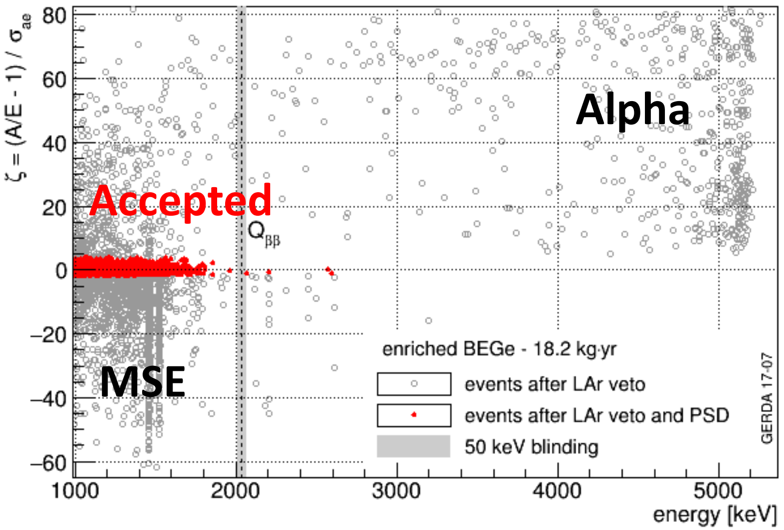






Current status of GERDA





No events at $Q_{\beta\beta} \pm \Delta E$
after all cut so far
in unblinded GERDA data

(see TAUP 2017 conference slides)

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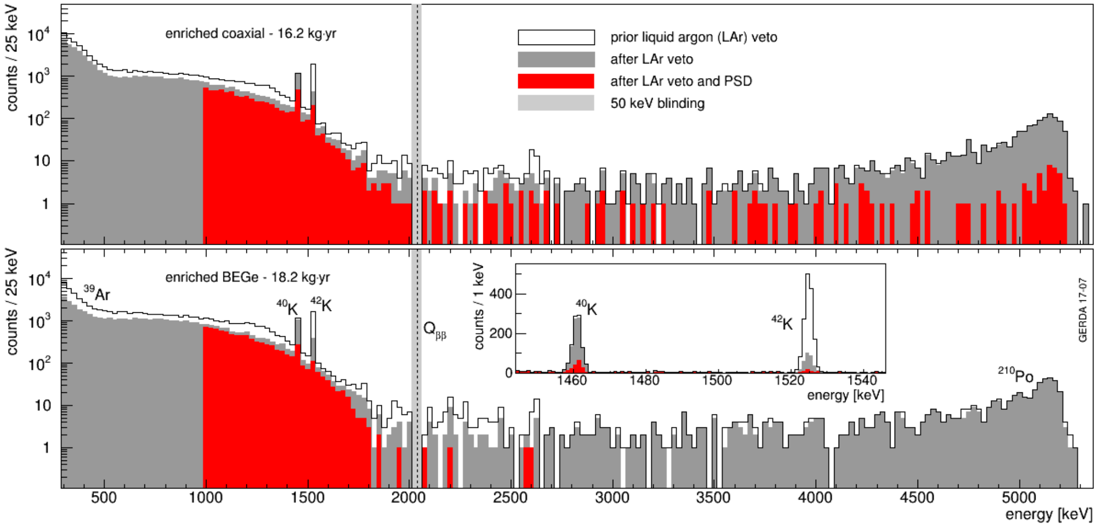

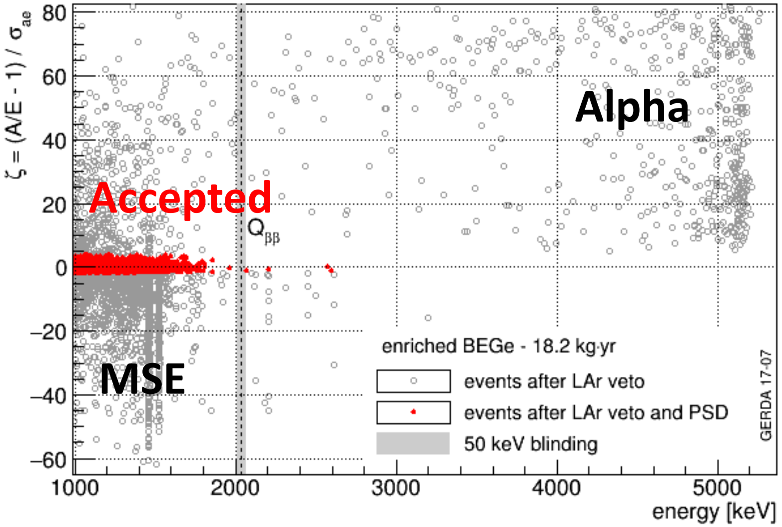

	GERDA (^{76}Ge)	KamLAND – Zen (^{136}Xe)
Median sensitivity	**5.8×10^{25} yr**	5.6×10^{25} yr
90% CL limit	8.0×10^{25} yr	**10.7×10^{25} yr**
Exposure	470 mol.yr	**3700 mol.yr**
Background	**5-20 cts/(ton.ROI.yr)**	60-100 cts/(ton.ROI.yr)

No events at $Q_{\beta\beta} \pm \Delta E$
after all cut so far
in unblinded GERDA data

(see TAUP 2017 conference slides)

Next generation Ge based experiment well motivated by the GERDA/MAJORANA Demonstrator experiences in reducing the background

A 50 years story…

Year of last publication	Collaboration	Mass	Ge type	Detector type
1967	Fiorini & al	1.2 kg	Natural	Coaxial
2002	IGEX	6.4 kg	Enriched	Coaxial
2003	HDM	11 kg	“	Coaxial
2013	GERDA ph I	16 kg	“	6 x Coaxial + 5 x BEGe
2017	GERDA ph II	36 + 8 kg	Enr. + Nat.	10 x Coaxial + 30 BEGe
2017	MAJORANA Demonstrator	30 + 14 kg	Enr. + Nat.	35 x P-PC + 33 BEGe

Completed

On going

A 50 years story… which continues!

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…	LEGEND	200 / 1000 kg	Enriched	P-PC / BEGe / **Inverted Coax**

Completed

On going

Future

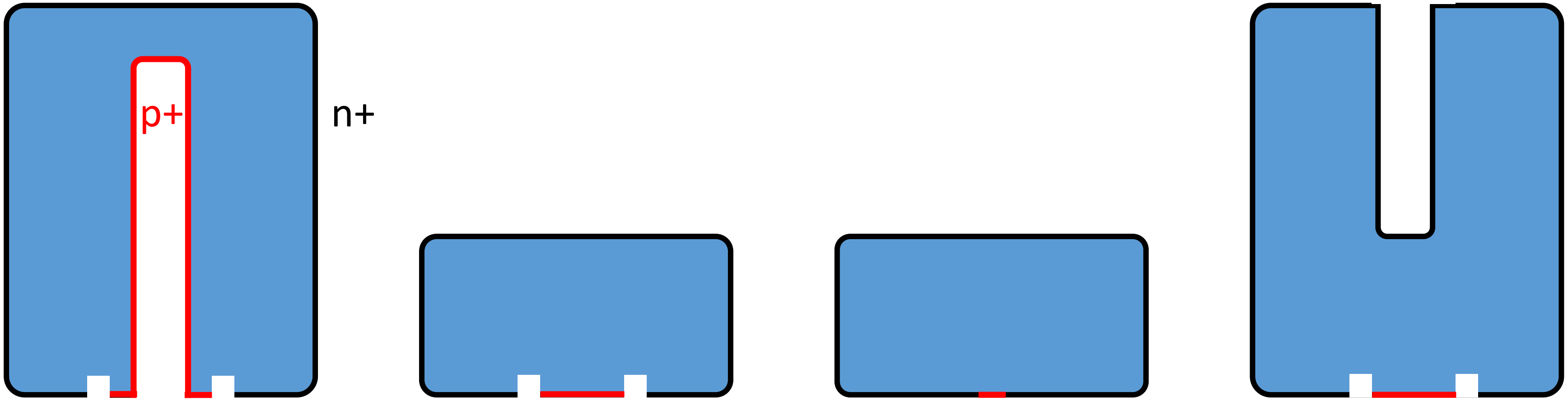
GERDA infrastructure
@ LNGS - Italy

(D. Radford – NIMA 665, 2011)

New detector type envisioned

- A ton scale project implies
  large detectors: m > 1.5 kg (2-3 kg x 300-500)

- Background level reduction requires
  high Pulse Shape Discrimination (PSD) performance
  reduced amount of surrounding materials (cable, holders, …)



coaxial	BEGe	P-PC	**Inverted coaxial**
Large mass	**Small mass**	**Small mass**	**Large mass**
Low PSD perf.	**High PSD perf.**	**High PSD perf.**	**High PSD perf.**

Detector configuration requirements

- R&D focused on p-type inverted coaxial detector with $m = [1.5 - 3]$ kg

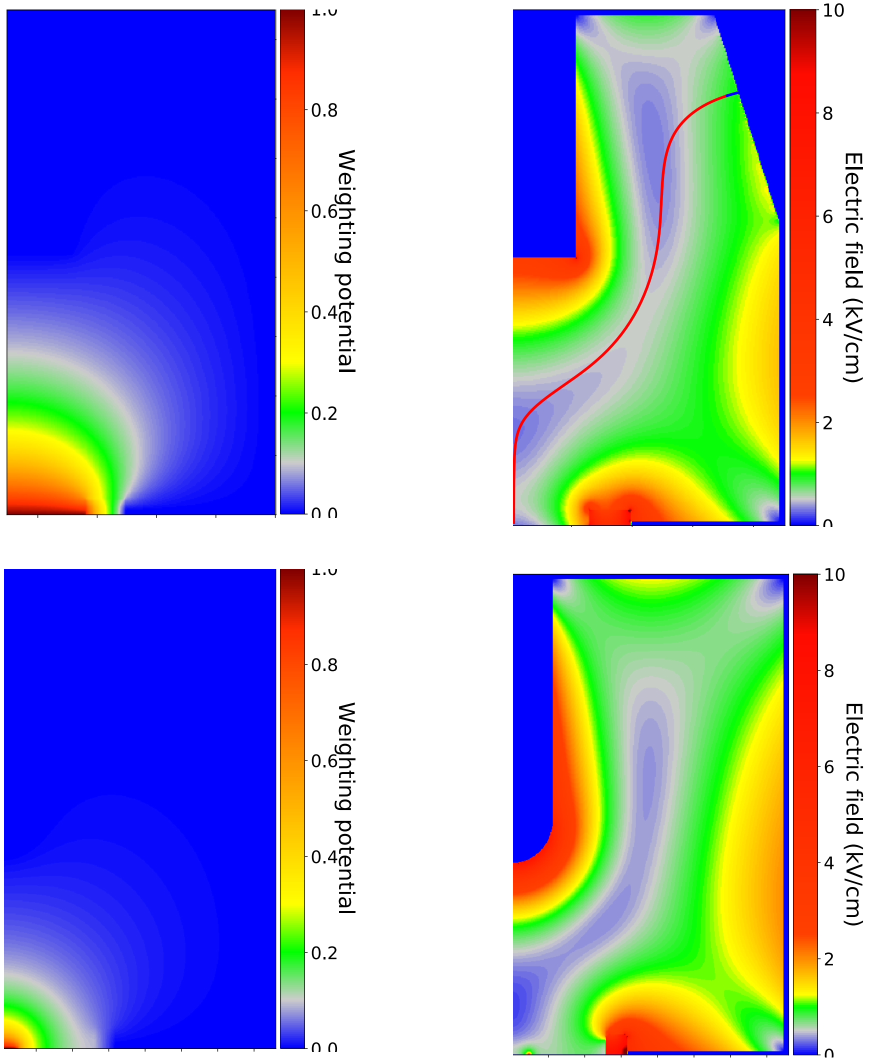
- Bias voltage < 4000 V
  to keep LC at the 10 pA level

- Passivation layer thickness: 0.7 – 1.5 mm
  to remove alpha

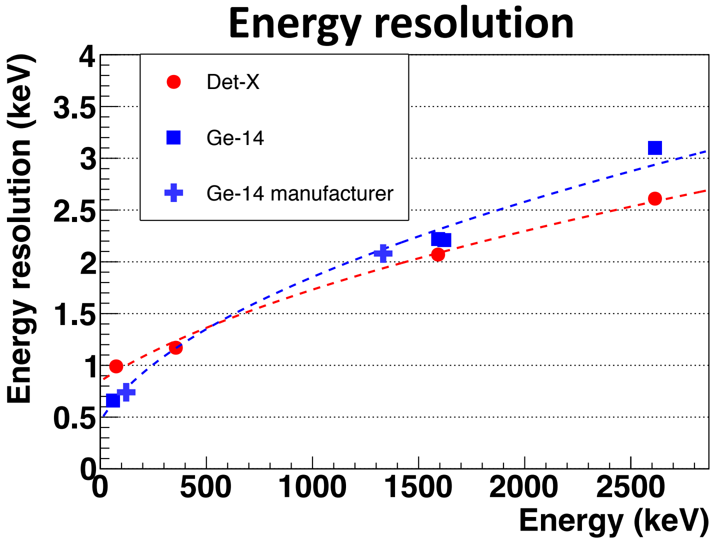
- E-field configuration such that $E_{\text{min}} > 100 - 200$ V/cm
  - Impurity concentration ~ 10^{10}/cm^3
  - Gradient ~ $1{\times}10^{10}$/cm^3

- Benefit from the "funnel effect" to keep high PSD performance
  -> BEGe-like p-contact

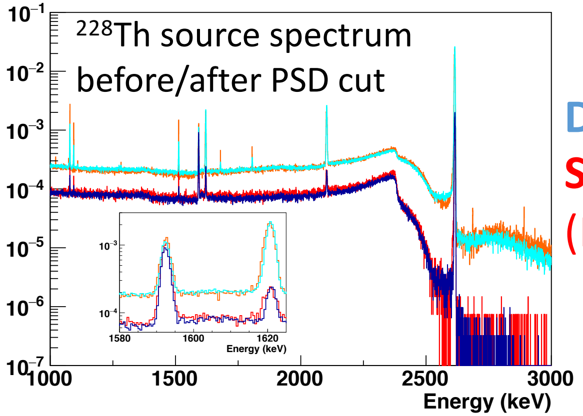
ADL simulation (upgraded AGATA software)



$0\nu\beta\beta$ decay experiment compatibility


Energy resolution

Two natural Ge inverted coaxial detectors characterized so far in vacuum cryostat (1.5 kg and 2.7 kg) in Mol (Be) and Dresden (Ge)

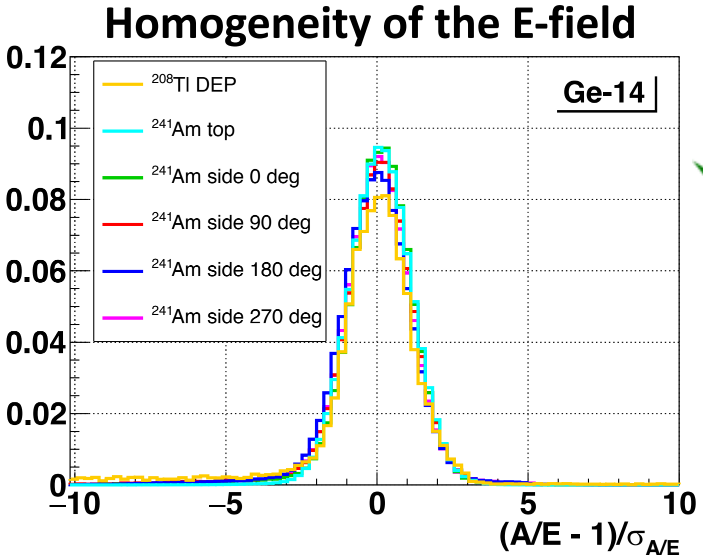


^{228}Th source spectrum before/after PSD cut

Data

Simulation

(MaGe + ADL)


Homogeneity of the E-field

Survival fraction after PSD

(%)	HADES	Dredsen	GERDA BEGe
^{208}Tl DEP	90.6	90.2	90
^{212}Bi FEP	10.3	8.4	9.4
^{208}Tl SEP	6.1	5.5	6.0
^{208}Tl FEP	9.2	8.0	7.7
$Q_{\beta\beta}$	33	35.6	33.5

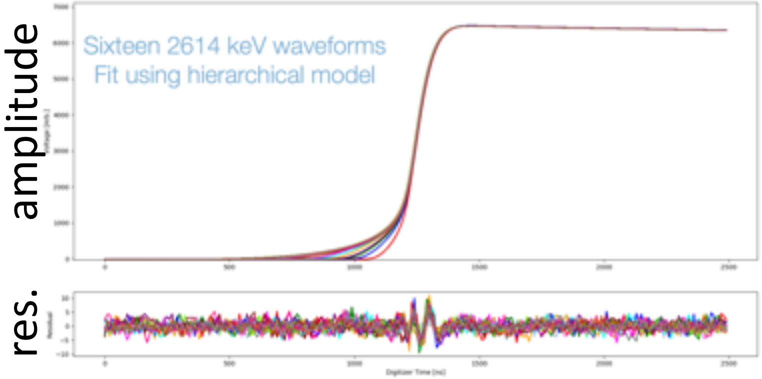
A word about simulation

- Two software currently used for field and trace calculations: **ADL** (AGATA) & **SigGen** (D. Radford)

- Limiting factors:
  - impurity concentration (linear gradient assumed)
  - electronic response (from pulser data or RC circuit model)

- Some activities apart from new detector design studies:

MAJORANA:
Fit of individual waveform from data with an accuracy at the 1/1000 level
-> Position sensitivity !



GERDA:
Current effort put on the full detector array energy spectrum simulation after LAr/PSD cuts for ^{228}Th calibration/$0\nu\beta\beta$/$2\nu\beta\beta$/Bkg spectrum.

- ➢ Monte-Carlo simulation for energy deposition
- ➢ ADL simulation to produce waveforms which are used in the PSD analysis

- ➢ Goal: Obtain $0\nu\beta\beta$ signal efficiency after cuts

Summary

- $\mathbf{0\nu\beta\beta}$ has far reaching consequences for Particle Physics
- Current experiments sensitivity cannot discriminate the mass hierarchy
  - ➢ Need to build a ton scale experiment
  - ➢ Further reduce the background index
- GERDA and MAJORANA Demonstrator have demonstrated the pertinence of a future ton-scale Germanium based project
- LEGEND collaboration has been formed in 2016
  - ➢ Ge detector R&D effort focused on inverted coaxial technology
  - ➢ Proof of compatibility achieved with 2 detectors
  - ➢ Significant effort put in detector response simulation (ADL & SigGen)

LEGEND : 47 Institutions, 219 Scientists

- Univ. New Mexico
- L'Aquila Univ. and INFN
- Gran Sasso Science Inst.
- Lab. Naz. Gran Sasso
- Univ. Texas
- Tsinghua Univ.
- Lawrence Berkeley Natl. Lab.
- Leibniz Inst. Crystal Growth
- Comenius Univ.
- Lab. Naz. Sud
- Univ. of North Carolina
- Sichuan Univ.
- Univ. of South Carolina
- Jagiellonian Univ.
- Banaras Hindu Univ.
- Univ. of Dortmund
- Tech. Univ. – Dresden
- Joint Inst. Nucl. Res. Inst.

- Nucl. Res. Russian Acad. Sci.
- Joint Res. Centre, Geel
- Chalmers Univ. Tech.
- Max Planck Inst., Heidelberg
- Dokuz Eylul Univ.

- Queens Univ.
- Univ. Tennessee
- Argonne Natl. lab.
- Univ. Liverpool
- Univ. College London

- Los Alamos Natl. Lab.
- Lund Univ.
- INFN Milano Bicocca
- Milano Univ. and Milano INFN
- Natl. Res. Center Kurchatov Inst.
- Lab. for Exper. Nucl. Phy. MEPhI
- Max Planck Inst., Munich
- Tech. Univ. Munich
- Oak Ridge Natl. Lab.
- Padova Univ. and Padova INFN
- Czech Tech. Univ. Prague
- Princeton Univ.
- North Carolina State Univ.
- South Dakota School Mines Tech.
- Univ. Washington
- Academia Sinica
- Univ. Tuebingen
- Univ. South Dakota
- Univ. Zurich

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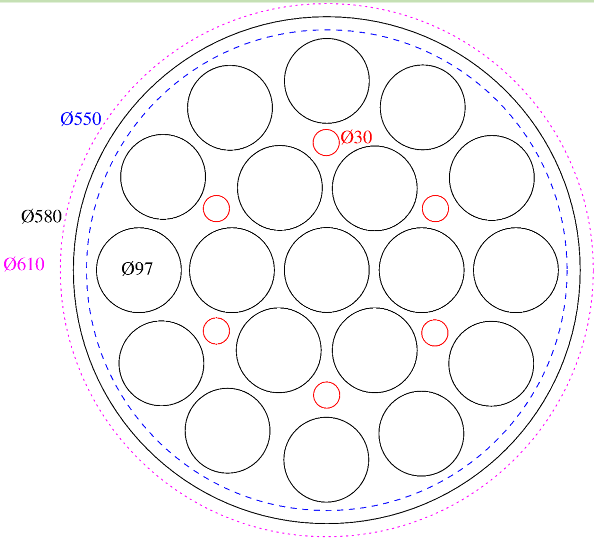
LEGEND 200 – 1st step



- Reuse existing GERDA infrastructure at LNGS.
- Modifications of internal cryostat piping so can accommodate up to 200 kg of detectors.
- Improvements
  - use some larger Ge detectors (1.5 - 2.0 kg)
  - improve LAr scintillator light collection (2x in test stand)
  - lower mass, cleaner cables
  - lower noise electronics
- Estimate background improvement by ~ x5 over GERDA/MAJORANA (Goal 0.6 c /(FWMH t y))
  - intrinsic : including ^{68}Ge/^{60}Co all OK
  - external Th/U: cleaner materials based on those used in MJD
  - surface events : alpha & β rejection via PSD
  - ^{42}Ar : better suppression & mitigation
  - muon induced : OK
- Contingent upon funding, data taking by 2021

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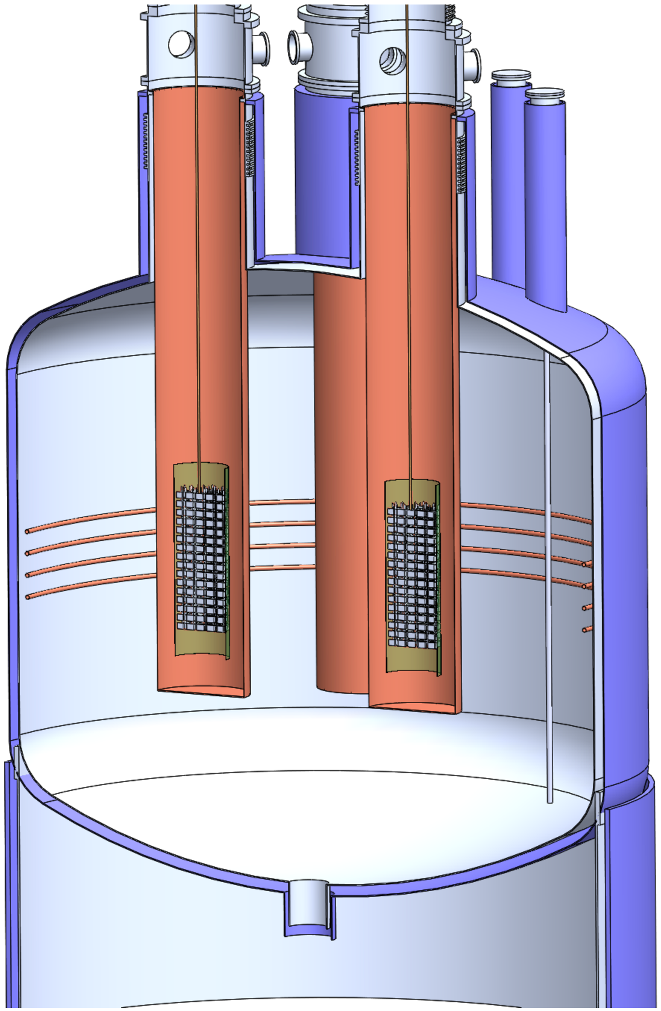
LEGEND 1000 – “Baseline” design



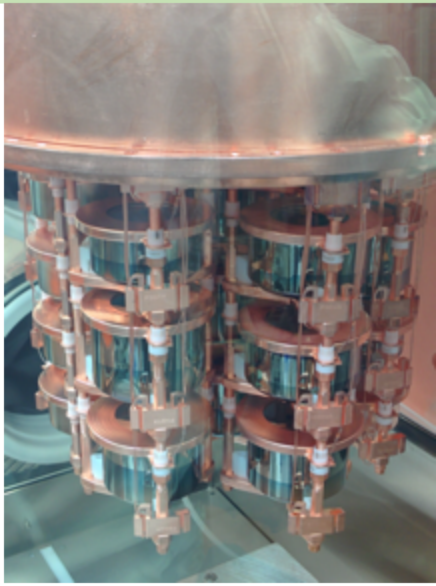
- 1000 kg
- BG goal (x30 lower) : 0.1 c /(FWHM t y)
- 4-5 payloads in LAr cryostat in separate 3 m^3 volumes, payload 200/250 kg, with ~100+ detectors.
- Every payload “independent” with individual lock
- LAr detector volume separated by thin (electro-formed) Cu from main cryostat volume.
- Use depleted LAr in inner detector volumes
- Modest sized LAr cryostat in “water tank” (6 m ¯ LAr, 2-2.5 m layer of water)

or

large LAr cryostat w/o water (9 m ¯) with separate neutron moderator

Slide: J.F. Wilkerson – TAUP 2017

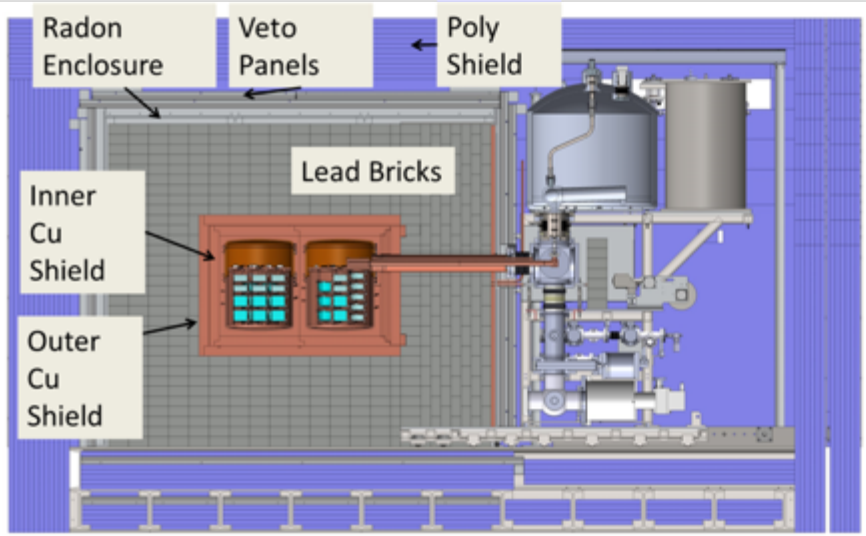
The MAJORANA Demonstrator



Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale expt.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

Operating underground at 4850’ Sanford Underground Research Facility

- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
  3 counts/(ROI t y) (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/(ROI t y) for a tonne experiment
- **44.1-kg of Ge detectors**
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- **Ultra low-activity components and construction**
- **Compact Shield**
  - low-background passive Cu and Pb
  - shield with active muon veto



N. Abgrall et al., Adv. High Ener. Phys. 2014, 365432 (2013); arXiv:1308.1633

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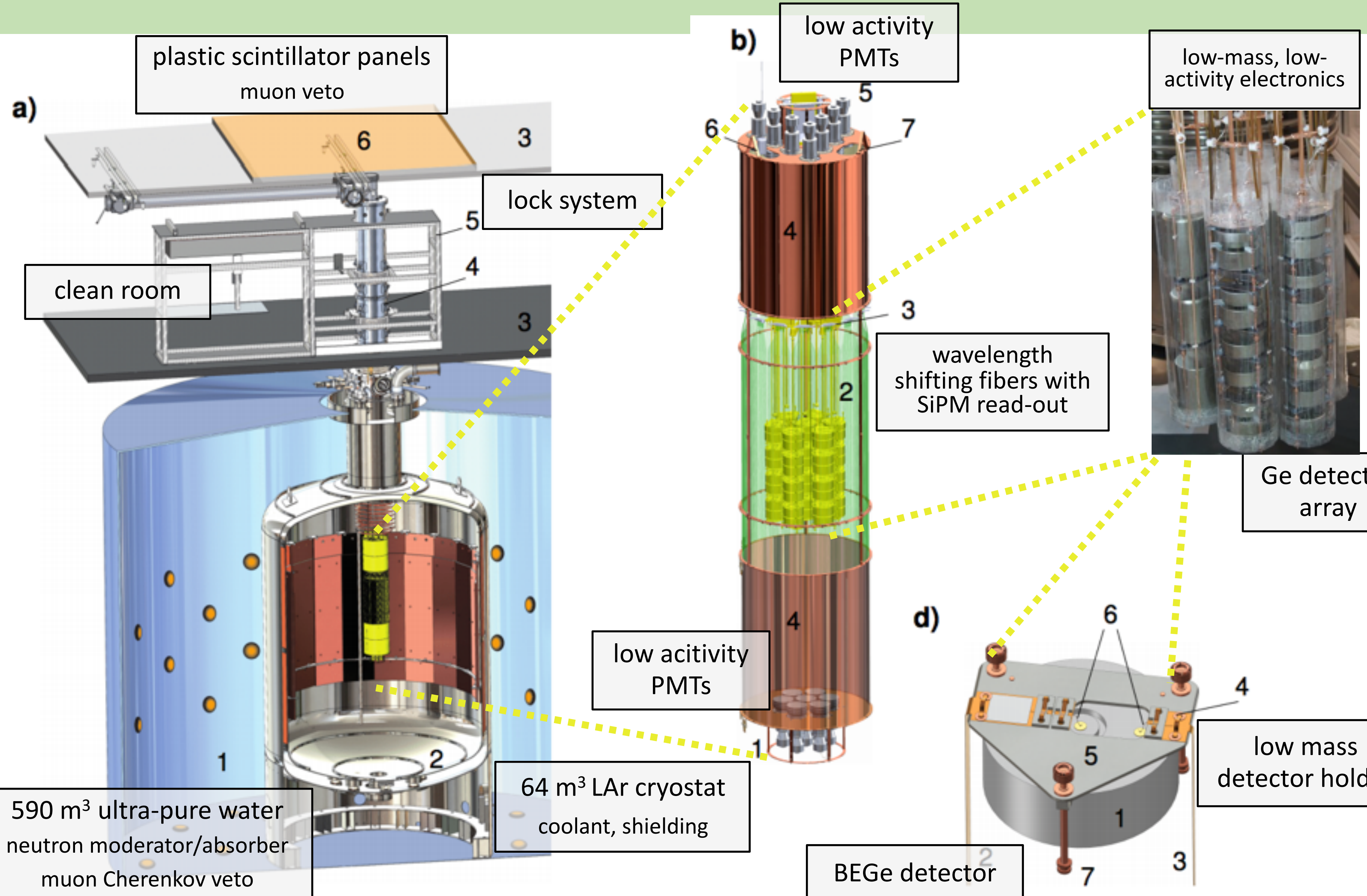
The Germanium Detector Array



plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra-pure water
neutron moderator/absorber
muon Cherenkov veto

64 m³ LAr cryostat
coolant, shielding

low activity
PMTs

wavelength
shifting fibers with
SiPM read-out

low acitivity
PMTs

low-mass, low-
activity electronics

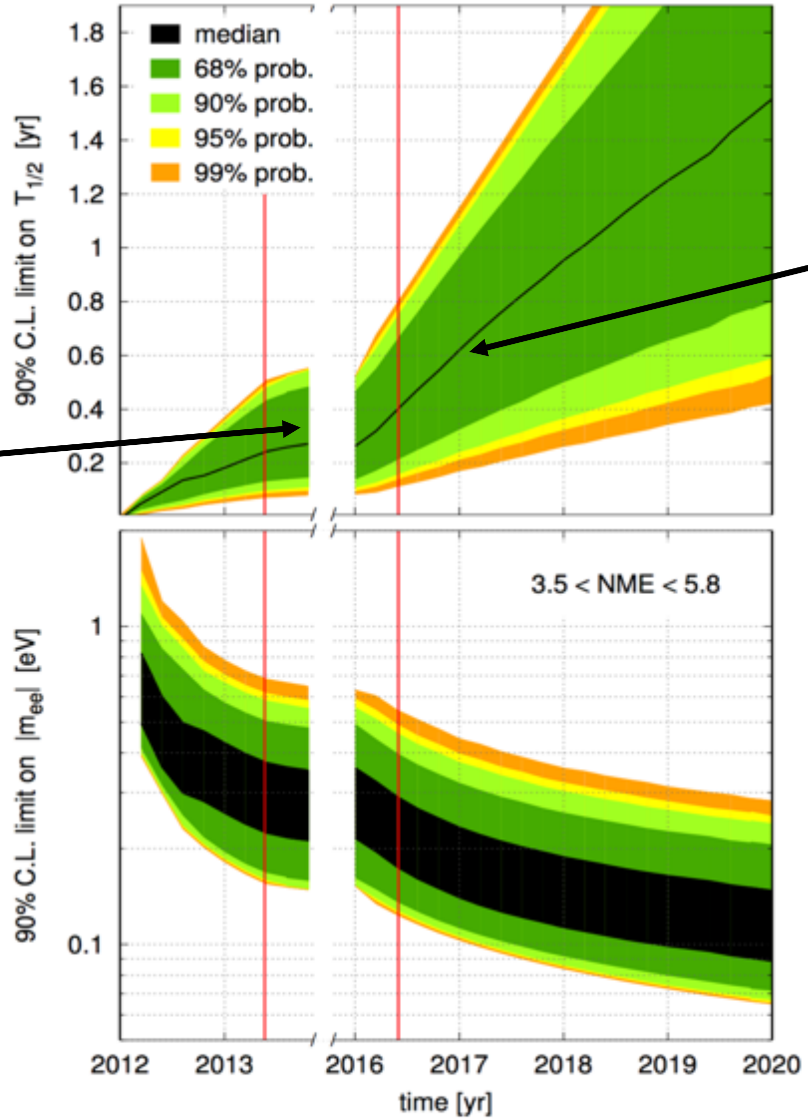
Ge detector
array

low mass
detector holder

BEGe detector

Slide: L. Pandola – TAUP 2017

Projected limits for GERDA



Current status

Phase I