Possible upgrade of GERDA

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Disclaimer
The GERDA collaboration is formed for Phases I and II.
Any extension requires a new collaboration with
new funding and LNGS approval

Motivation for $0\nu\beta\beta$

Baryon number (B) & Lepton number (L) are accidentally conserved in Standard Model

B is violated (baryogenesis) → expect L violation, mechanism unclear

Most SM extensions predict $\nu = \bar{\nu}$ →

neutrinoless double beta decay $0\nu\beta\beta$ should exist: (A,Z) → (A,Z+2) + 2e, $\Delta L=2$

other mechanisms (SUSY, W_R, ...) can cause $0\nu\beta\beta$ → L violation at LHC, ...

(W. Rodejohann, Nucl. Phys. Proc. Suppl. 229-232 (2012) 113)

from DOE Nuclear Science Advisory Committee report on $0\nu\beta\beta$ (24 April 2014)

It is the assessment of this Subcommittee that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery. Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in this next phase of discovery-caliber research.

if Majorana ν exchange dominates

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} \left| M'^{0\nu} \right|^2 \frac{\langle m_{ee} \rangle^2}{m_e^2}$$

g_A = axial coupling

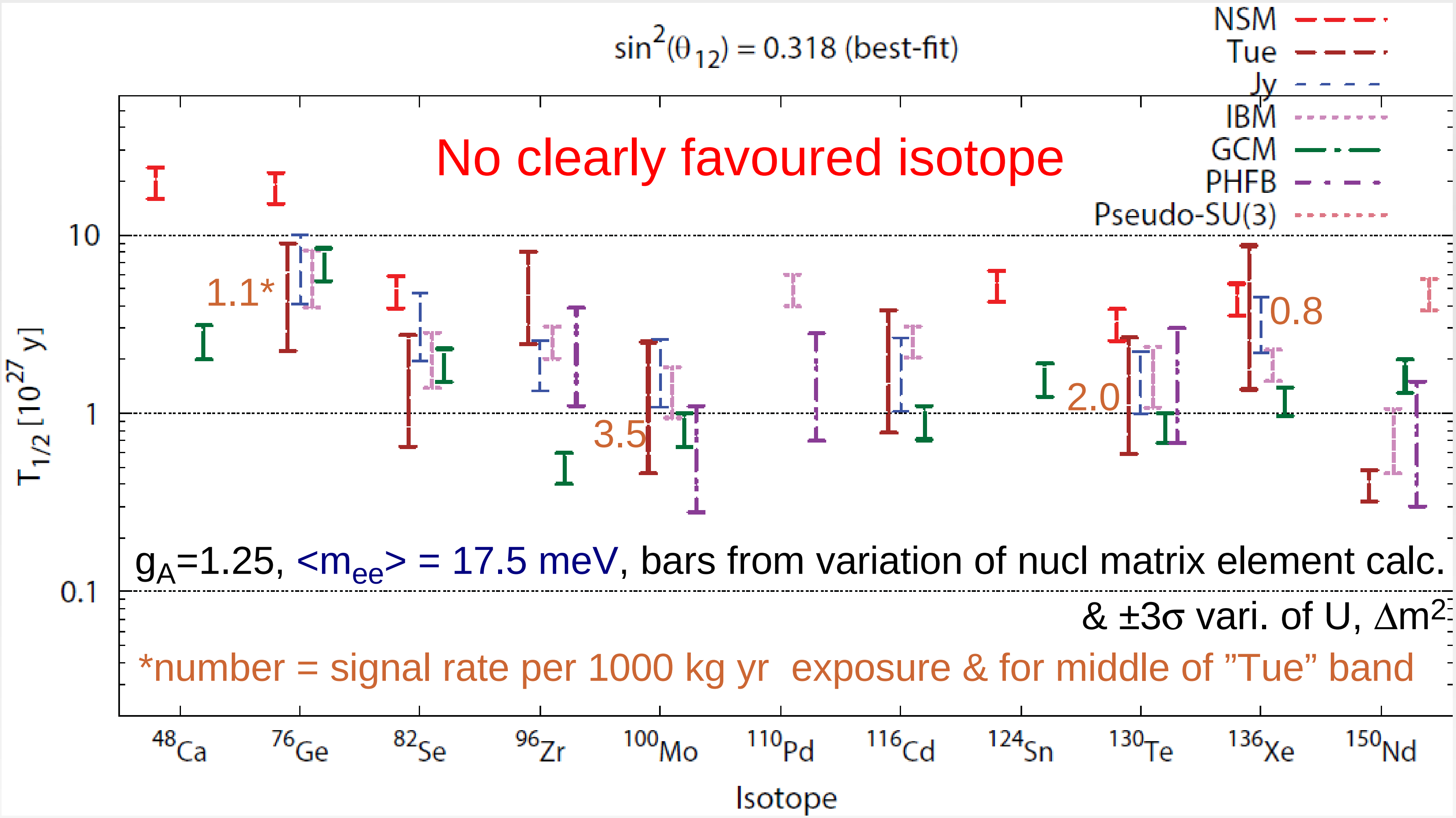
$G^{0\nu}$ = phase space factor

$M'^{0\nu}$ = nuclear matrix element

m_e = electron mass

for inverted mass hierarchy $\langle m_{ee} \rangle \gtrsim 17\ meV$

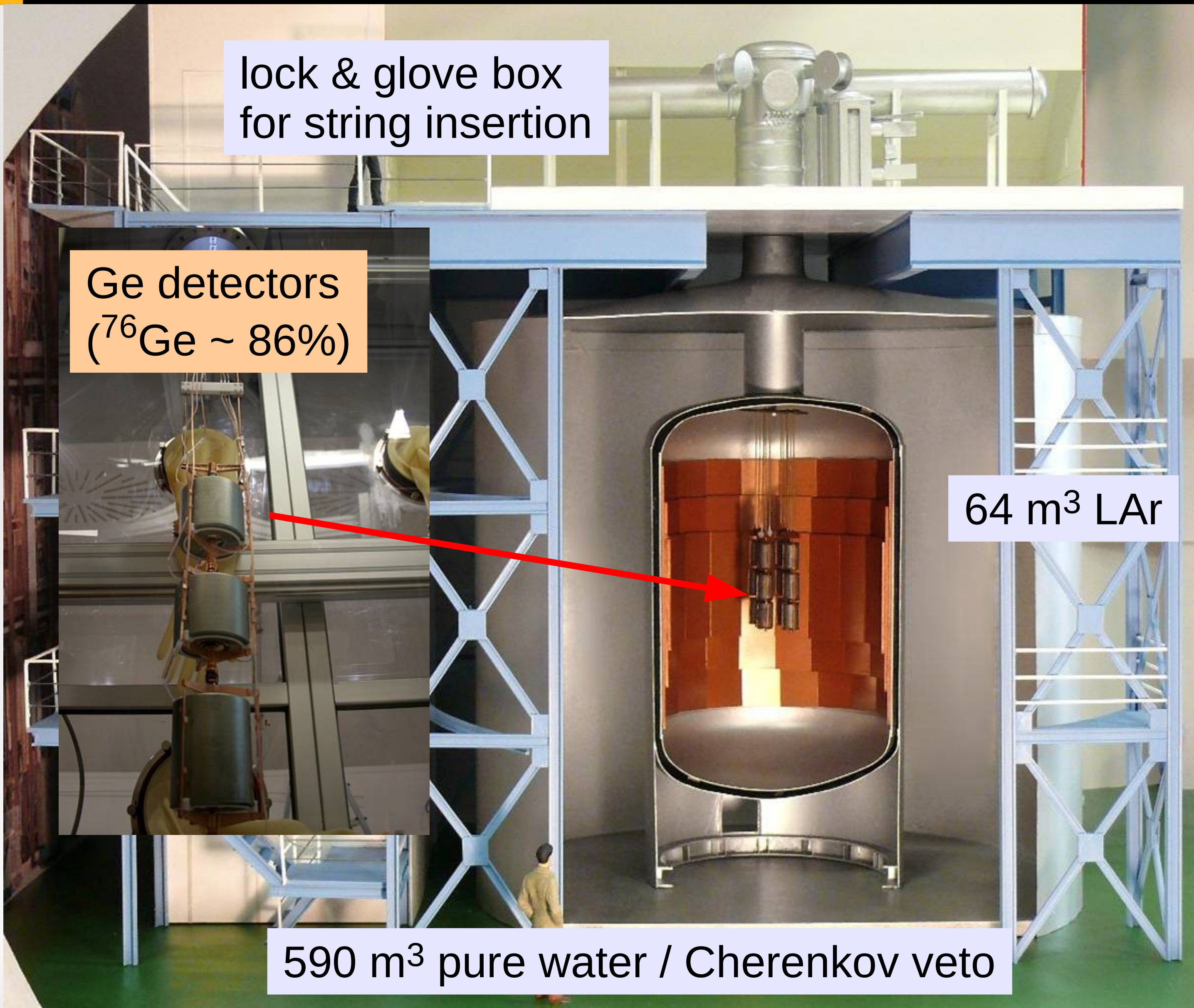
Expected $T_{1/2}$ for different matrix elements



taken from DOE Nuclear Science Advisory Committee report on 0νββ (24 April 2014)
adopted from A. Dueck, W. Rodejohann and K. Zuber, Phys. Rev. D83 (2011) 113010

warning from theory colleague: unclear whether light Majorana neutrino exchange is dominating & other ν properties unknown → motivation to cover inverted mass hierarchy is artificial

GERDA concept: Ge in LAr



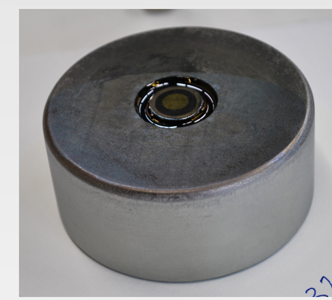
Phase I (2011-13):

$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

^{76}Ge $0\nu\beta\beta$ decay, PRL 111 122503

Phase II:

2x Ge mass (30 BEGe det.)



LAr scint. light readout

start in 2015

Why Ge?

disadvantages:

- small phase space factor $G^{0\nu}$
- more expensive (enrichment + diode production)
- scales not as easy as liquid/gas detectors

advantages:

- good energy resolution (currently best in the field)
  → small ROI & simple peak detection over smooth bkg
- lowest background if scaled by ROI
  → sensitivity comparable to experiments with much larger mass
- enrichment + diode production well established
  → no R&D needed
- effective use of expensive material (not used for self-shielding)
- large annual Ge production
- relative simple operation & background suppression

Why Ge?

Current experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/mol yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	$\langle m_{ee} \rangle$ limit [meV]	date
Gerda II	Ge	35/27	3	0.0004	15	80-190	-2019
MajoranaD	Ge	30/24	3	0.0004	15	80-190	-2019
EXO-200	Xe	170/80	88	0.03	6	80-220	-2019
Kamland-Zen	Xe	383/88 (600/?)	250	0.03	20	44-120	-2018
NEXT	Xe	100/80	17	0.0036	6	100-200	-2020
Cuore	Te	600/206	5	0.02	9	50-200	-2019
SNO+	Te	2340/160	270	0.02	9	50-200	-2020

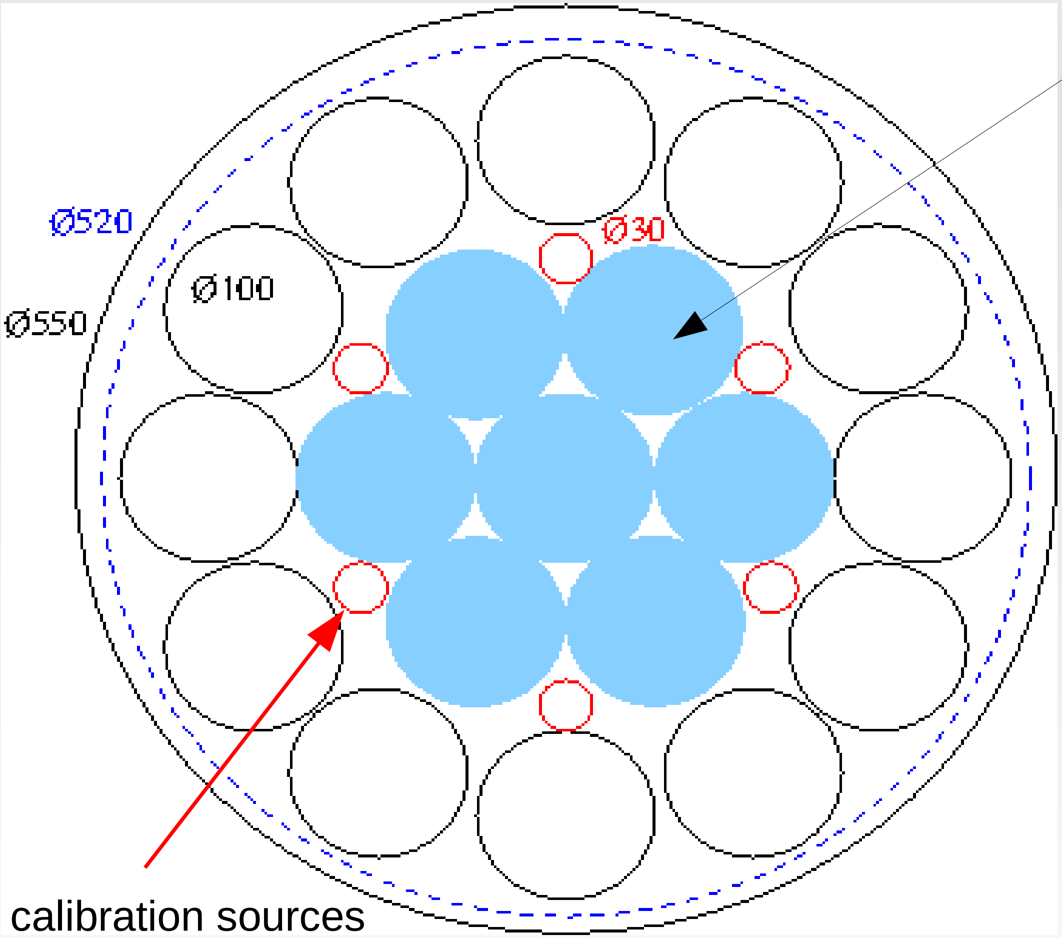
* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

[&] mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for EXO-200 and Kamland-Zen

Ge experiments have lowest background → similar sensitivity despite small mass

200 kg in GERDA cryostat



7 strings in Phase II

up 19 strings fit into Ø 500
usable Ø of cryostat ~550

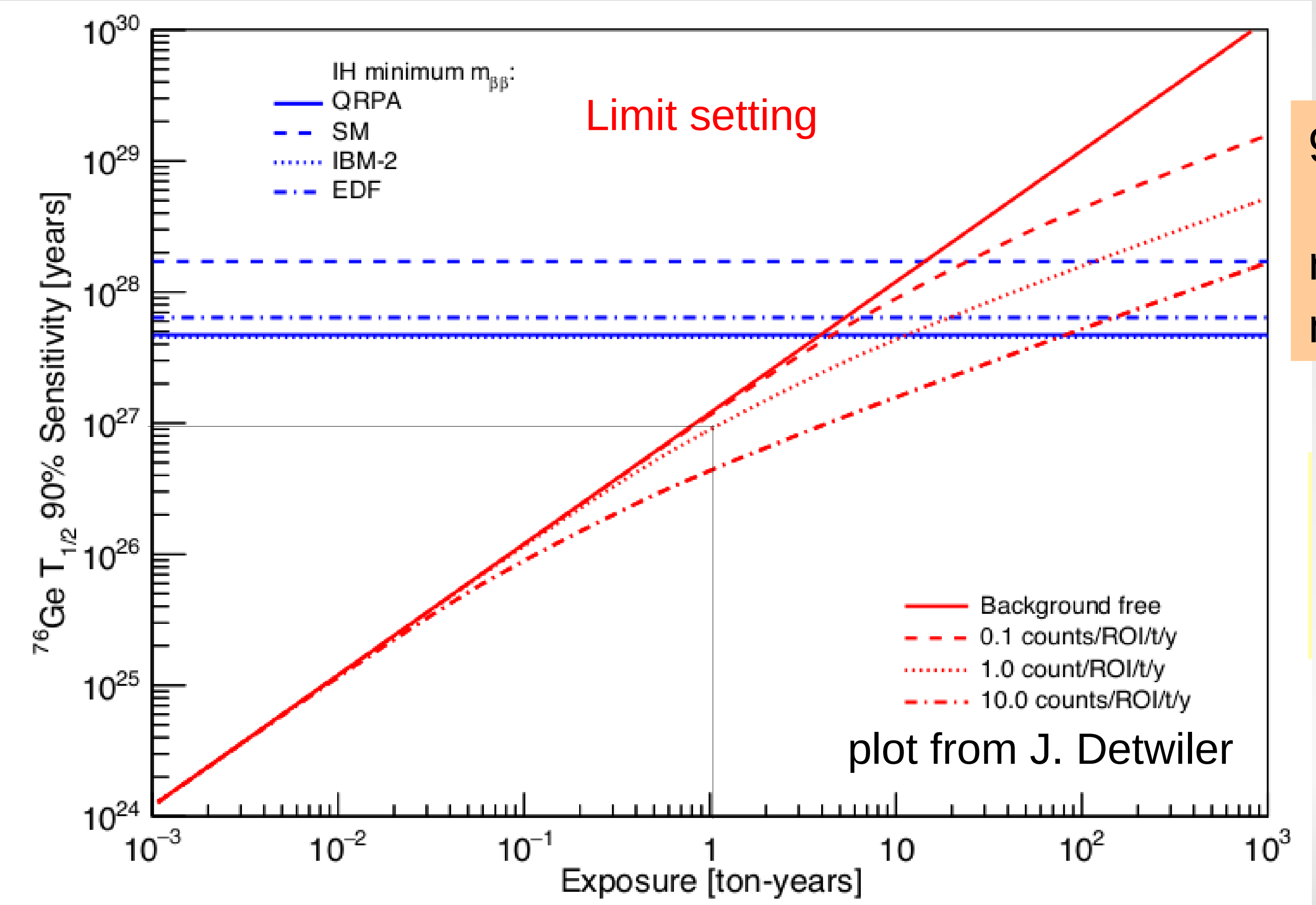
space for LAr veto Ø ~520?

16 BEGe / string
→ 300 detectors / 200 kg

goal

want < 1 bkg cnt in ROI (FWHM ~ 3 keV) after 5 yr running

→ background index < 3 x 10^{-4} cnt/(keV kg yr) = 1 cnt/(ROI t yr) (factor 3 lower than GERDA Phase II goal)

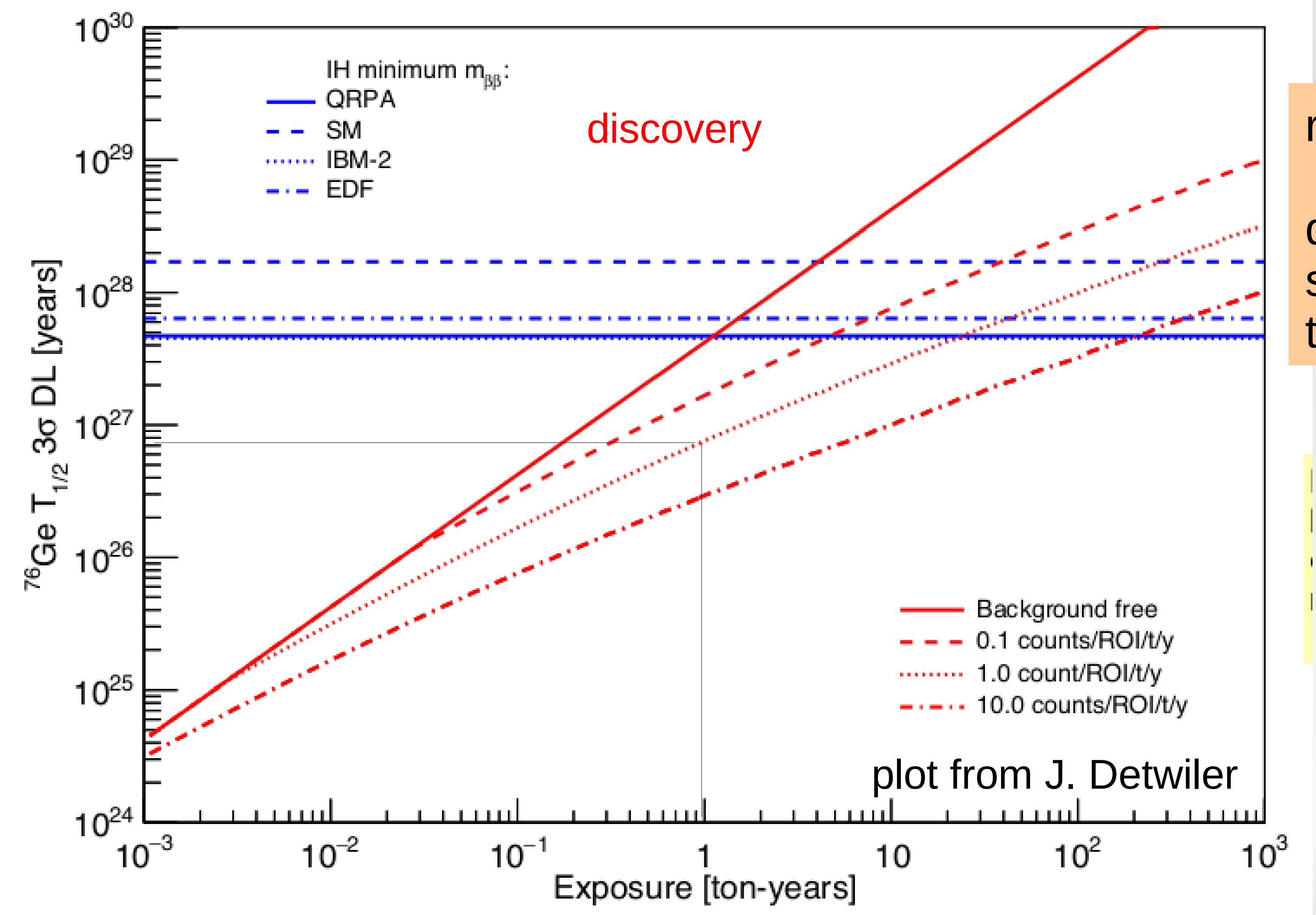


90% CL $T_{1/2}$ limit ~ 10^{27} yr

reminder: for 17 meV need about 10^{28} yr

goal

discovery limit: 50% chance for 3σ discovery



reach about 7×10^{26} yr

discovery depends stronger on bkg level than setting a limit

cost + time

Assumption: can pool all ^{76}Ge material from GERDA & Majorana
(~70 kg in Ge detectors + ~20 kg waste)
→ need about 140 kg additional ^{76}Ge

enrichment cost: 55 $/g (GERDA), 80 $/g (Majorana)
→ total = 7.7 – 11.2 M$ ~ 7.7 – 11.2 M€

diode production: extrapolate from GERDA / Majorana → 6 / 4 M€
factor 1.2 for logistics → 4.8 – 7.2 M€

other hardware (cables, lock, LAr veto, …) about 2 M€

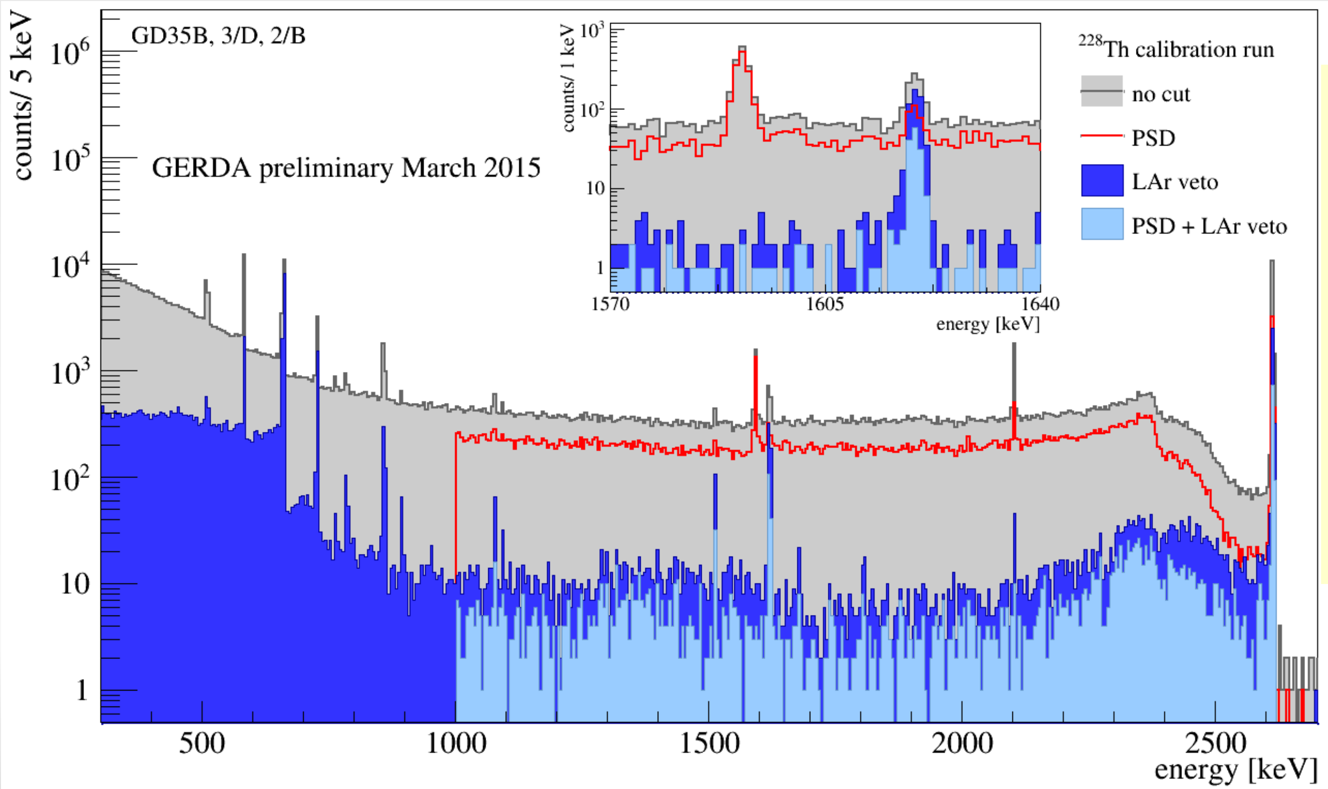
total cost for 200 kg in GERDA 15 – 20 M€ (European accounting)

time for enrichment & detector production ~ 3 yr + for mounting 1 yr

critical backgrounds: Th/U chains

^{232}Th bkg from far sources (stainless steel cryostat, rock) shielded by LAr/water
~ 0.3 cnt/(ROI t yr) before pulse shape & LAr veto (suppression factor >10)
^{226}Ra bkg factor ~5 less (NIM A606 (2009) 760, NIM A593 (2008) 448)

close sources = cables, detector support, nylon & electronics domintate ^{232}Th/^{226}Ra bkg
^{232}Th: LAr veto, anti-coincidence, pulse shape discrimination → suppression > 100x
^{226}Ra: same methods, but LAr veto less effective → suppression ~ 10x

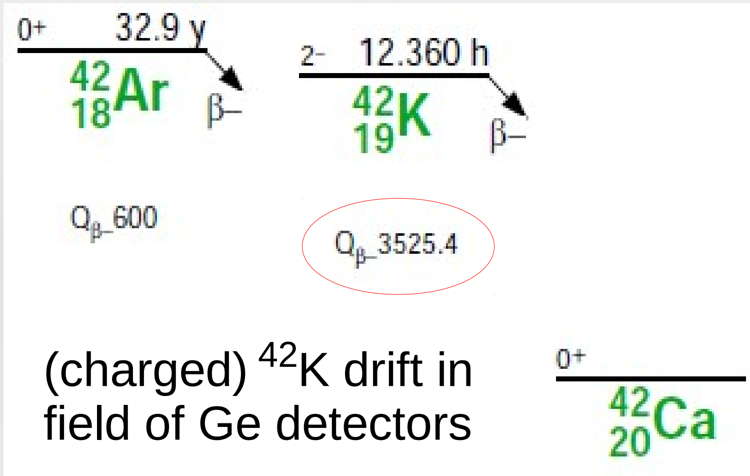


preliminary Phase II result
suppression > 90x for ^{228}Th

expect Phase II ~ 0.5 cnt/(ROI t yr)
dominated by ^{226}Ra contaminations
no special Cu, PTFE, … production

→ for 200 kg option need special production a la Majorana, EXO, ...

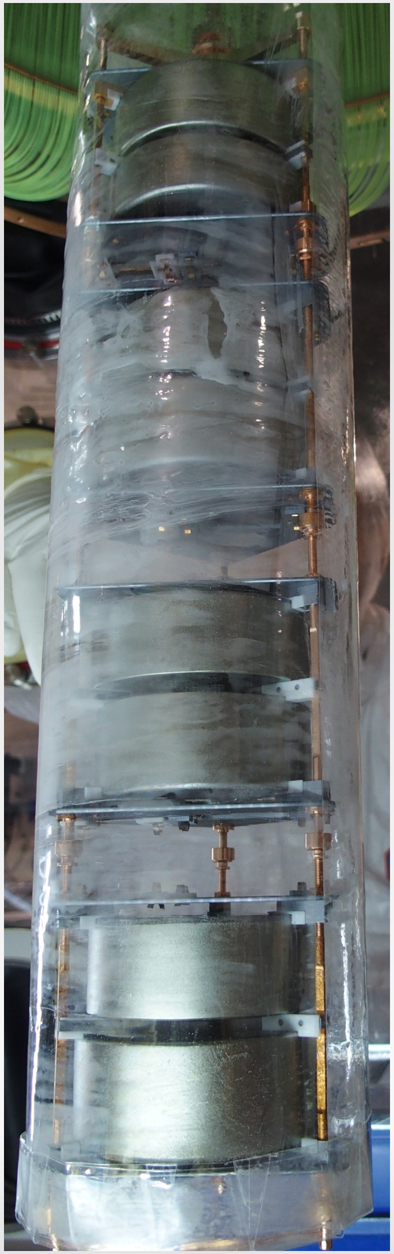
critical backgrounds: ^{42}Ar



Phase I: initially dominant background
→ add copper foil around det. string

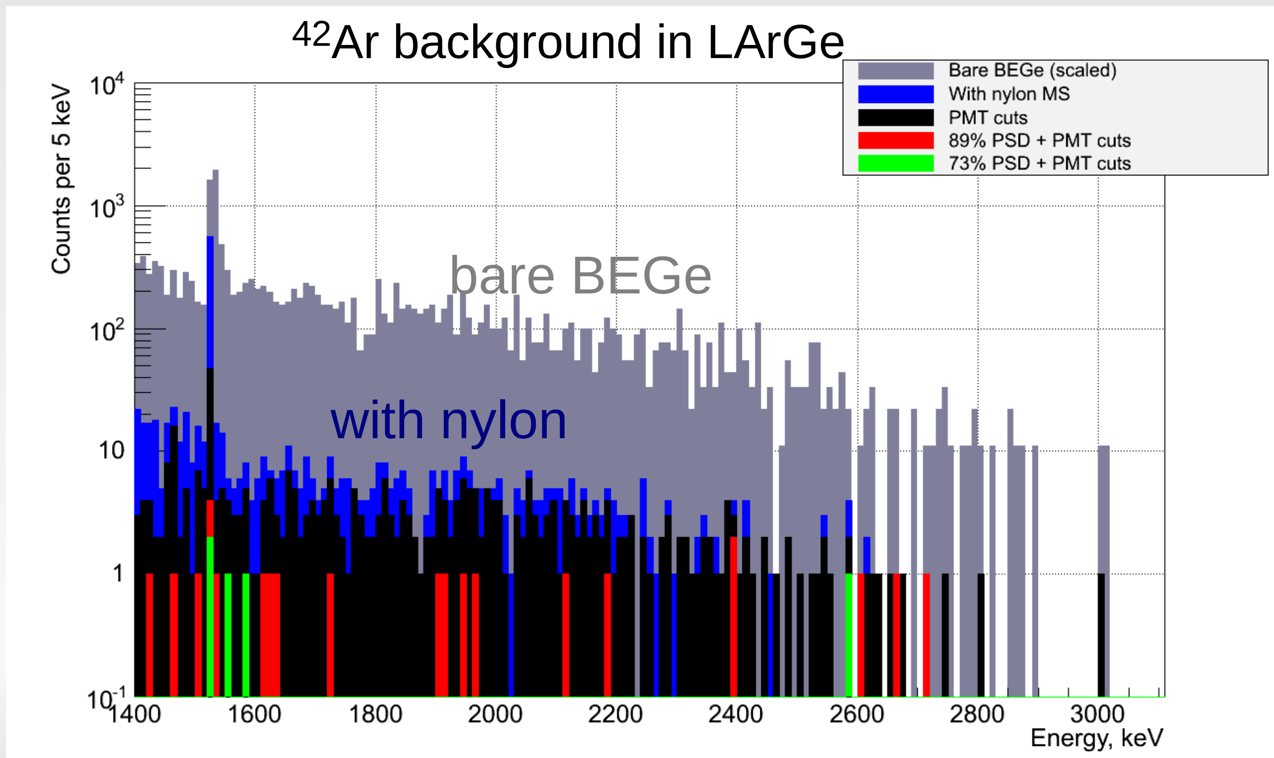
Phase II: nylon foil around string
(covered with wavelength shifter)

critical backgrounds: ^{42}Ar



LArGe test stand result

1 ton LAr doped with ^{42}Ar, ~1000x concentration of natural Ar
BEGe det. in nylon cylinder, LAr veto with PMTs
→ background suppression factor SF = 15 from nylon
→ LAr veto + Ge det. pulse shape SF = 70
→ expect in GERDA 0.6-2 cnt/(ROI t yr) for 1.0-0.6 mm n$^+$ dead layer
need for "200 kg" add. SF by software or hardware (e.g. thicker n+)



critical backgrounds: muons

"direct" muons: not a problem due to muon veto (efficiency ~ 99%), anti-coincidence cuts, pulse shape discr., LAr veto

delayed background: production of isotopes by muon induced n, p,γ

MUSUN + Geant4 simulation results for muon induced isotopes (for Phase II)

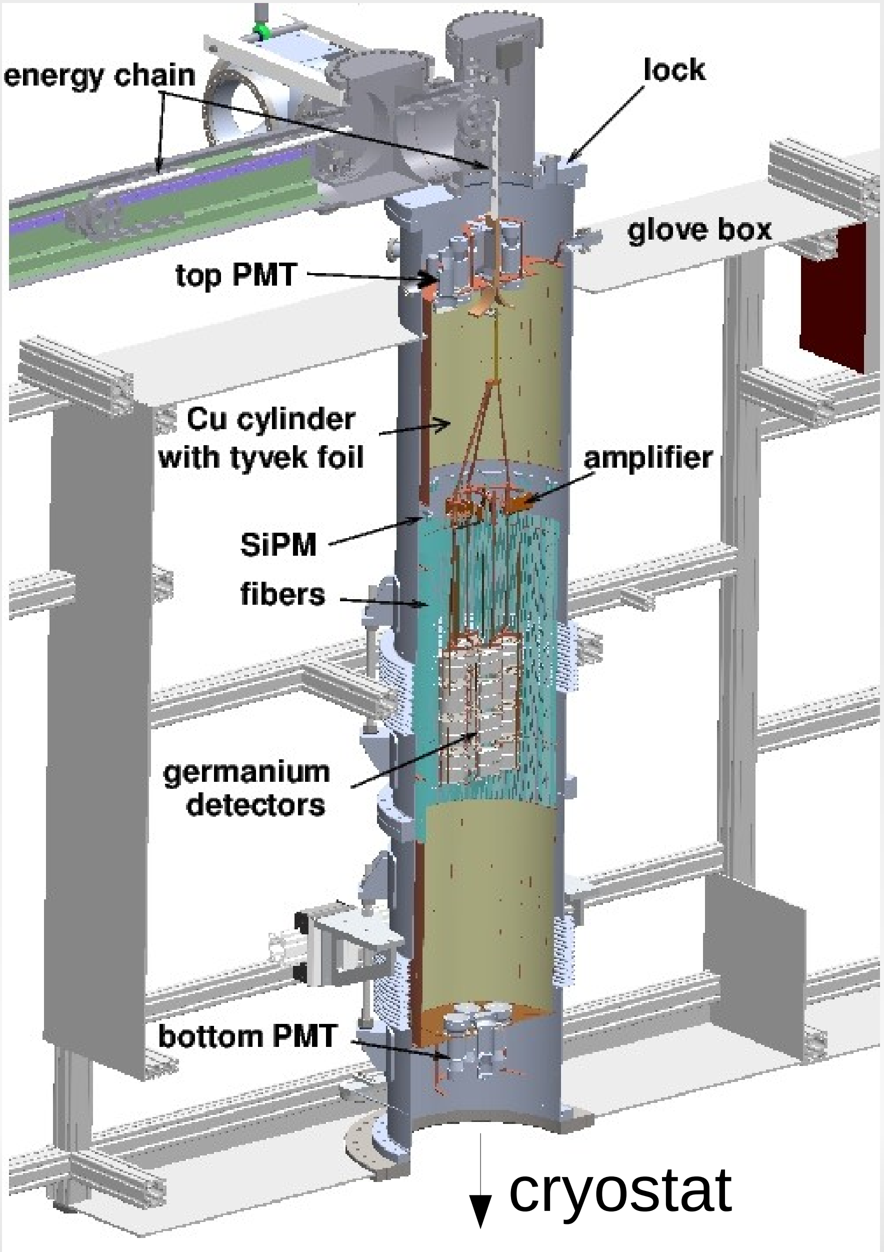
reminder:
$Q_{\beta\beta}$ = 2039 keV

Isotope	$T_{1/2}$	decay	Q value [keV]	background [cnt/(ROI t yr]
^{74}Ga	8.1 m	β^-	5368	0.01
^{75}Ga	126 s	β^-	3392	0.01
^{76}Ga	33 s	β^-	7010	0.01
^{77}Ge	11.3 h	β^-	2702	0.1
^{77m}Ge	53 s	β^-	2861	0.1
^{38}Cl	37 m	β^-	4916	0.003
^{40}Cl	1.4 m	β^-	7482	0.003

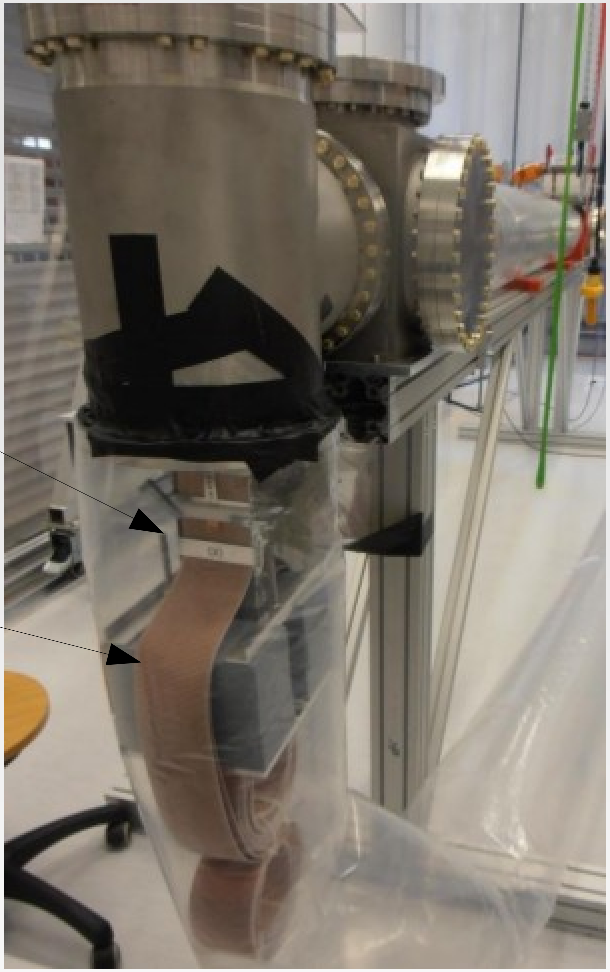
^{77m}Ge decays w/o γ → most dangerous bkg

background seems to be low enough but large uncertainties in MC

modifications needed: lock

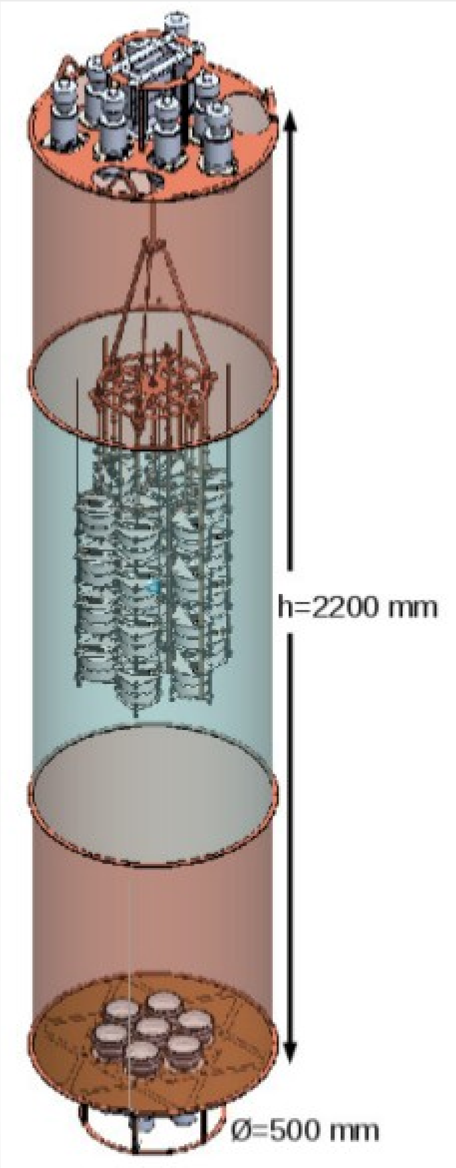


Ge strings + LAr veto suspended by energy chain

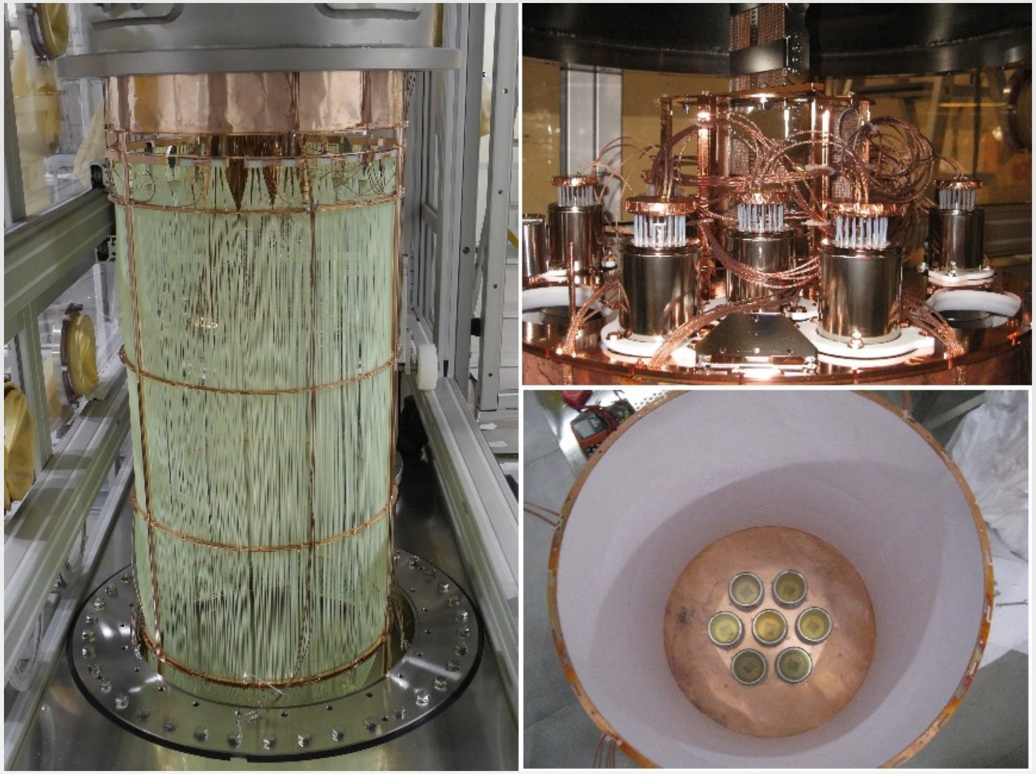


needs new concept for cabling and string assembly + operation

modifications needed: LAr veto



hybrid design: PMTs + fibers with SiPM readout



lowered with the Ge detectors into the cryostat,
200 kg option: - enough radial space for same concept?
alternative: mount fixed in cryostat
→ redesign of infrastructure inside cryostat ...
- PMTs too radioactive?

Why Ge?

from DOE Nuclear Science Advisory Committee report on 0nbb (24 April 2014):
list of highly desirable design features of any next-generation double beta decay search

- Very low, and preferably flat, background within the spectral region of interest, relative to the signal size anticipated at the half-life sensitivity goal; YES

- Good energy resolution with excellent energy calibration, to enhance a potential signal signal above backgrounds & to minimize the 2νββ tail underneath the 0νββ peak; YES

- Ability to scale the experimental approach to larger masses at realizable cost, as needed to maximize the discovery potential within the inverted hierarchy region; YES

- Tracking capability to enhance identification of 0νββ decay event topology; "yes"

- A favorable 0νββ Q-value to enhance the phase space factor and provide a region of interest above many of the gamma ray lines from U- and Th-chain contaminants; no
  but low A compensates (more mole/kg, larger matrix elements, smaller g_A quenching, ...)

- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal. YES

Summary

prejudice: 0νββ exists, ΔL=2 process → new physics beyond SM
$T_{1/2}$ unkown, discovery can be around the corner

^{76}Ge detector features:

- known technology (enrichment + diode production)
- best energy resolution
- lowest bkg in ROI
- flat background at Q value

  → important features for discovery

GERDA Phase II & Majorana Demonstrator start data taking soon,
if experiments meet specifications
→ next step can be combined collaboration for ”200 kg” and beyond

GERDA can host ~200 kg of Ge detectors:
- cost ~ 15-20 M€,
- construction 3-4 yr + 1 yr mounting,
- background reduction x3 relative to Phase II goal needed to be ”background free”
- $T_{1/2}$ sensitivity for 90% CL limit ~ 10^{27} yr