Upgrade of the GERDA Experiment

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GERDA : The GERmanium Detector Array

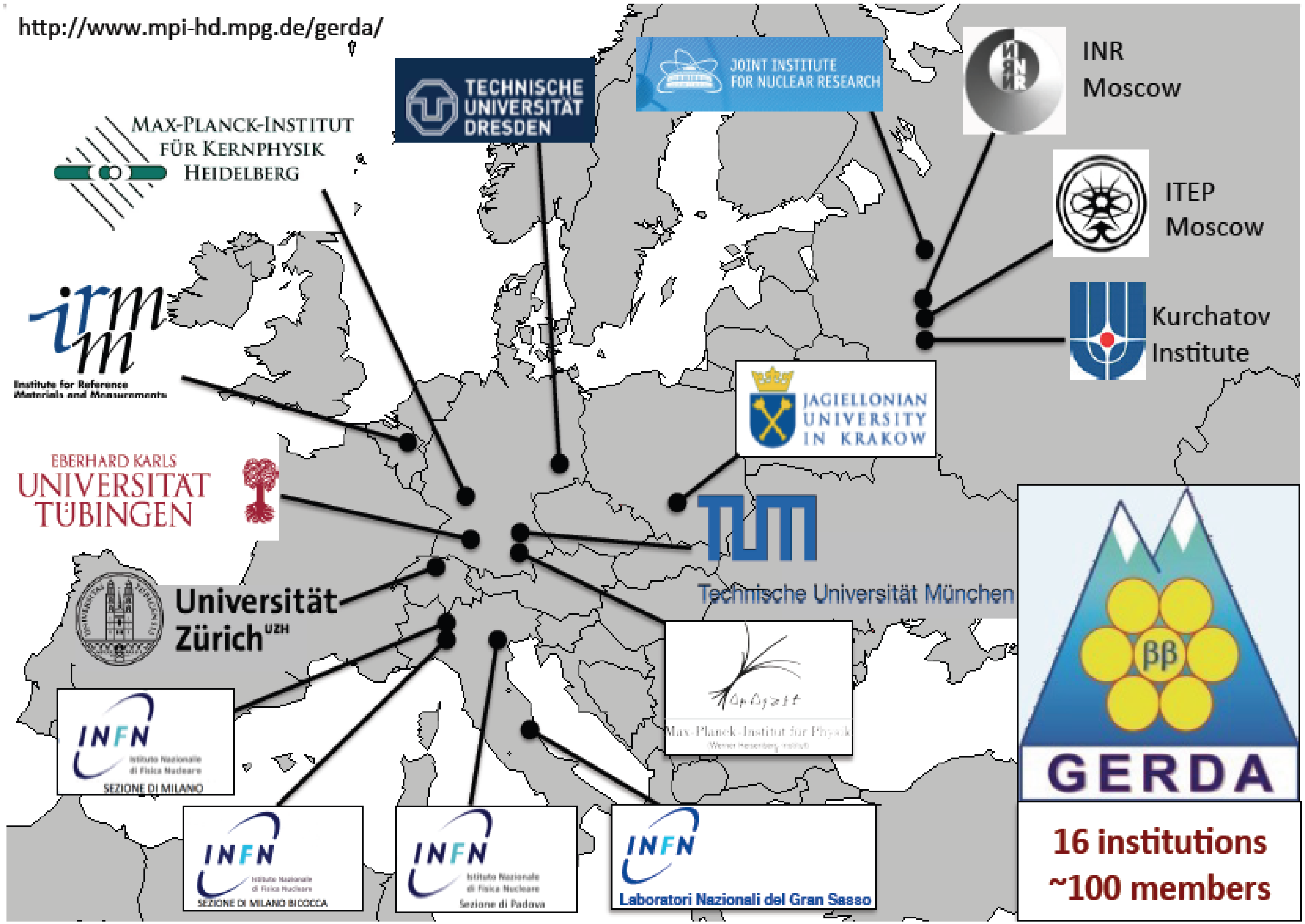
http://www.mpi-hd.mpg.de/gerda

searches for neutrinoless double beta decay of Ge-76 at the INFN deep-underground Laboratori Nazionali del Gran Sasso

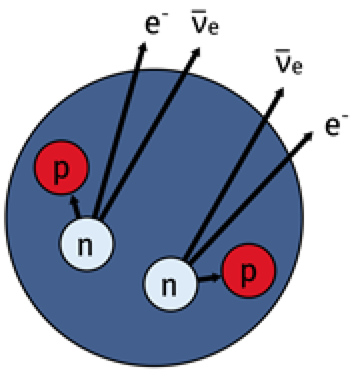
Upgrade to Phase II

- Introduction
- Upgrade measures
  - lock
  - detector mass & design
  - detector module design
  - LAr instrumentation for active veto
- Status
- Conclusion

GERDA collaboration



intro — double beta decay

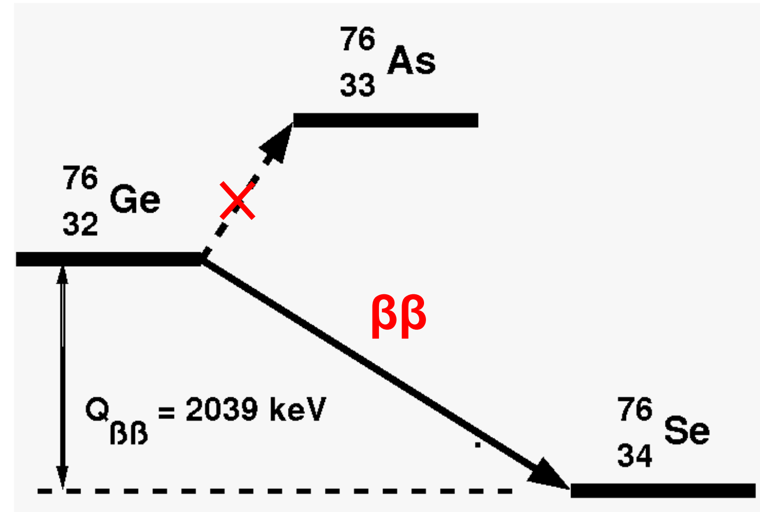


2νßß

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu$

conventional 2nd order process - observed in various nuclei

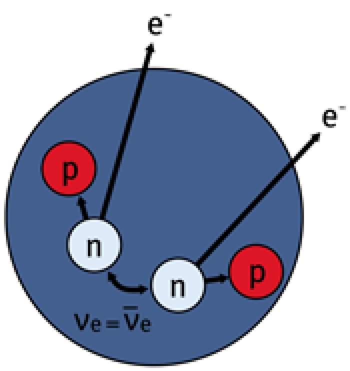
^{76}Ge : $T_{1/2} = 1.8 \cdot 10^{21}$ yr



$(A, Z) \rightarrow (A, Z+2) + 2e^-$

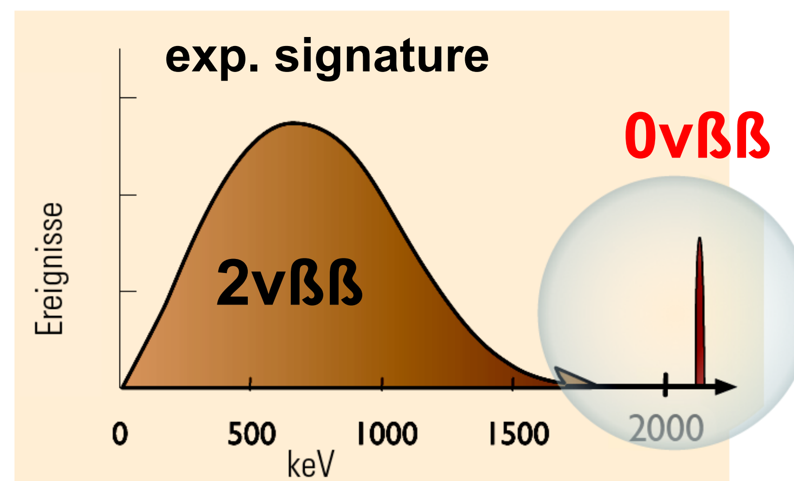
hypothetical process
$T_{1/2} > 10^{25}$ yr

- lepton number violation
- ν is Majorana fermion (i.e. its own anti-particle)
- access to ν mass scale (if light ν exchange)
- physics beyond SM

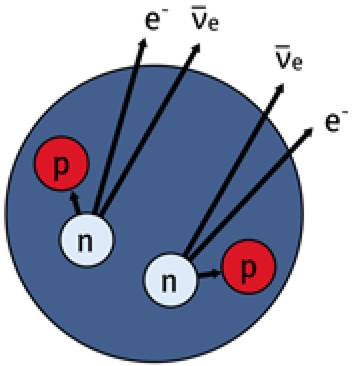


$\bar{\nu} = \nu$

0νßß



sum of kinetic energies

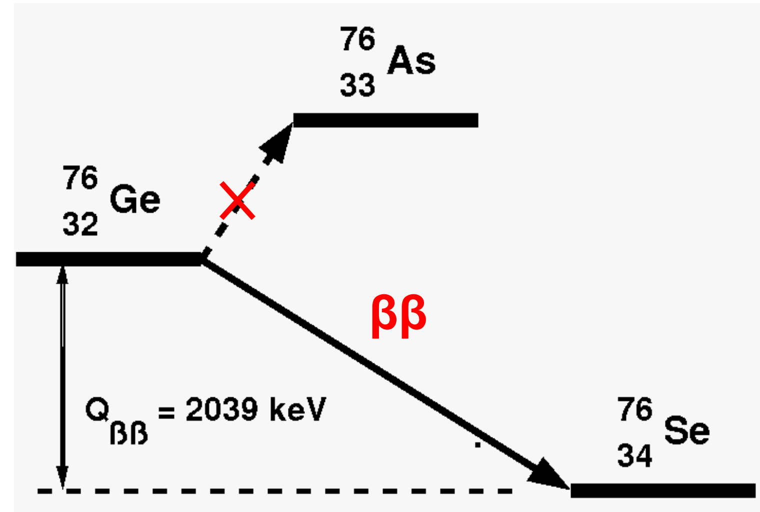


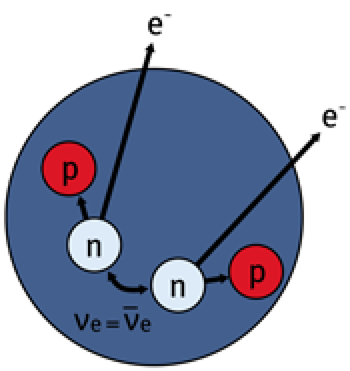
2vßß

(A,Z) → (A,Z+2) + 2e⁻ +2v

conventional 2nd order process - observed in various nuclei

^{76}Ge : $T_{1/2} = 1.8 \cdot 10^{21}$ yr





$\bar{\nu} = \nu$

0vßß

(A, Z) → (A, Z+2) + 2e⁻

hypothetical process
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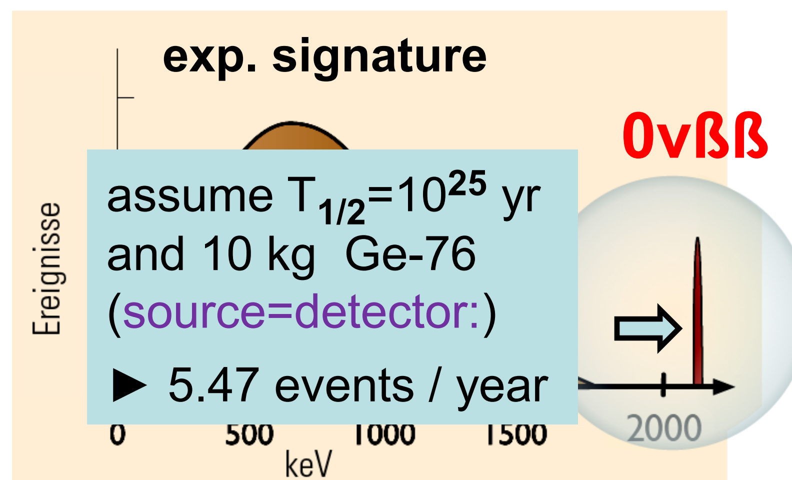
- physics beyond SM



assume $T_{1/2}=10^{25}$ yr and 10 kg Ge-76 (source=detector:)

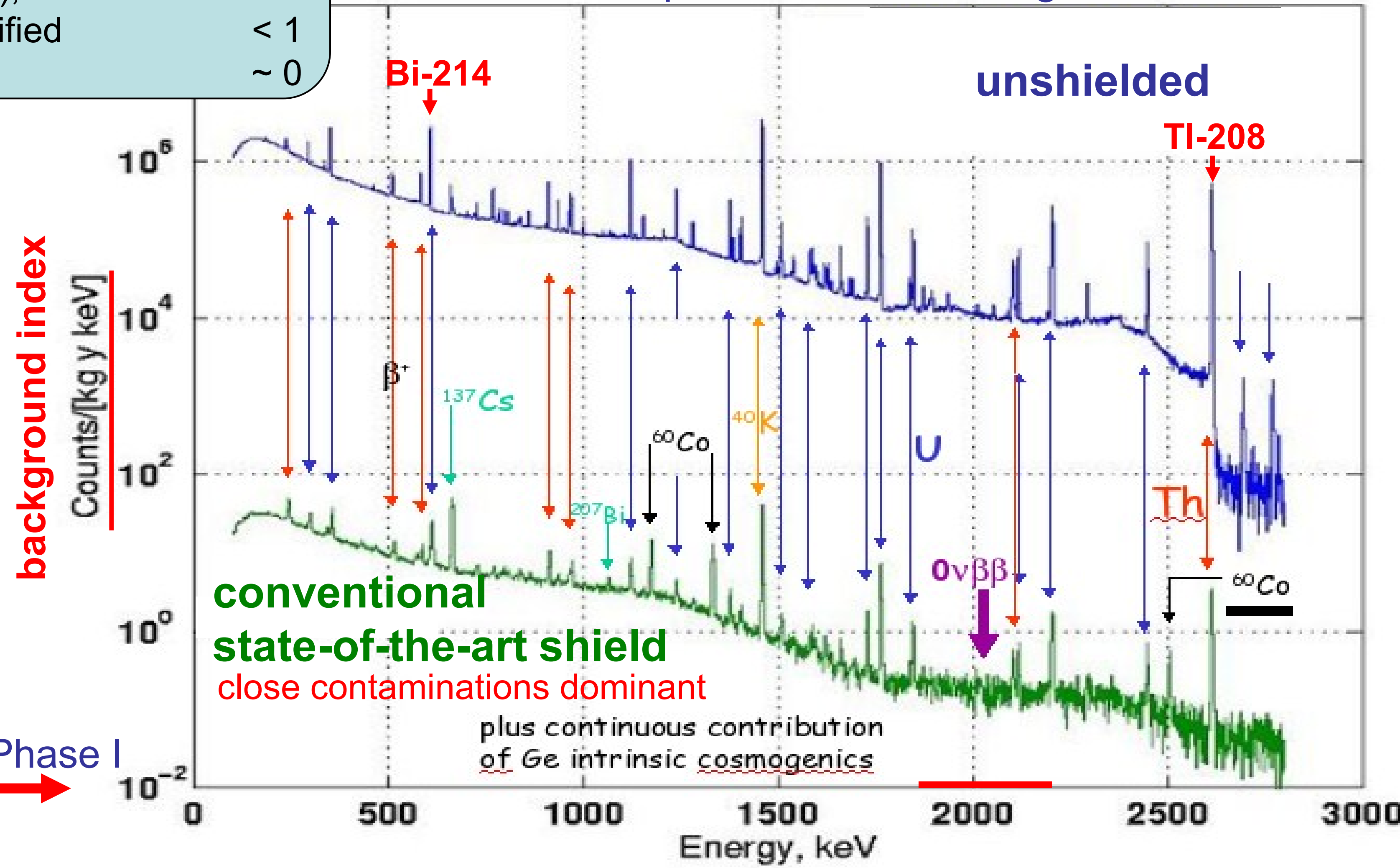
► 5.47 events / year

sum of kinetic energies

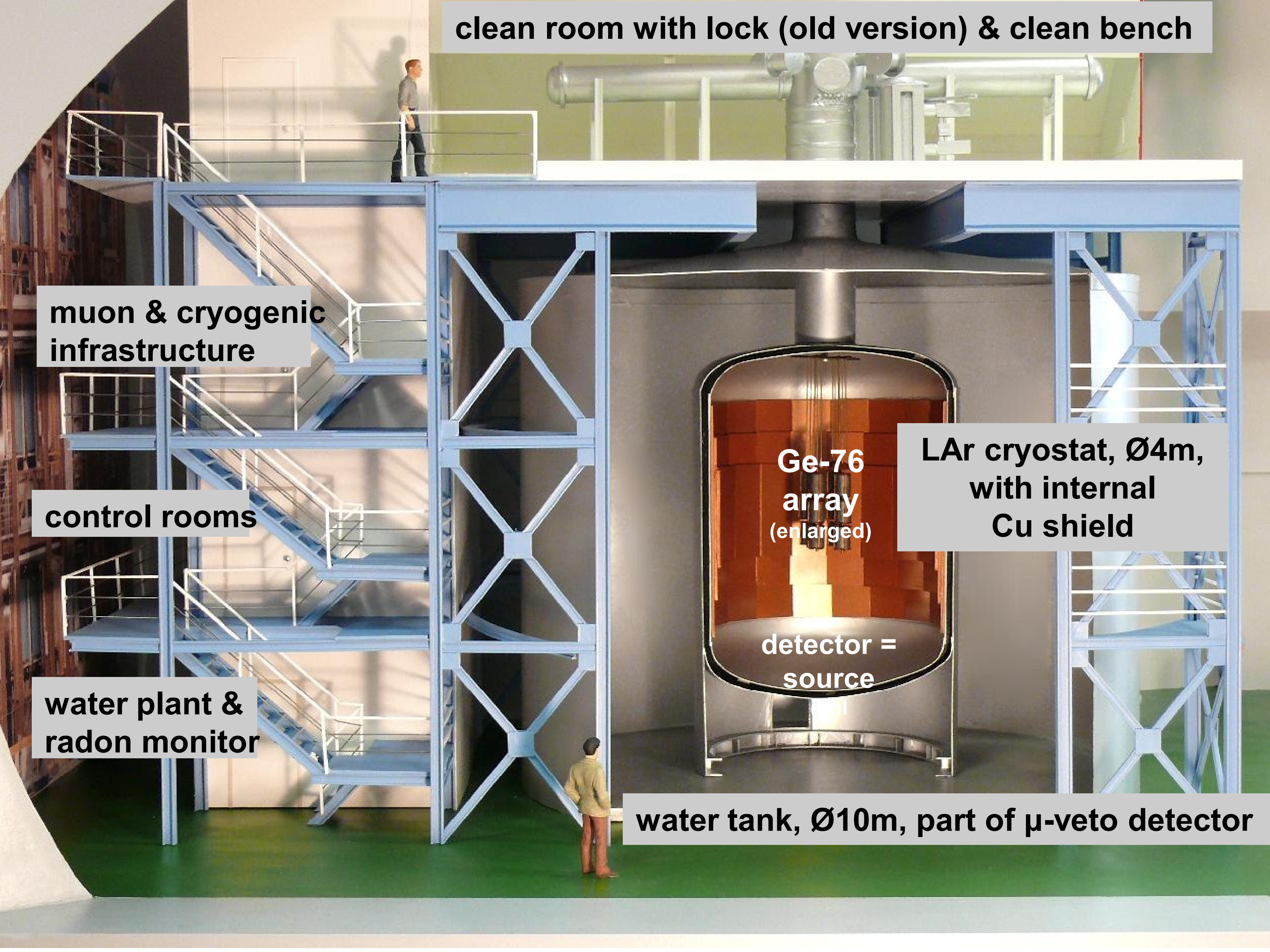
the challenge

Activity of Tl-208	(µBq/kg)
rock, concrete	3000000
stainless steel	~ 5000
Cu(NOSV), Pb	<20
water, purified	< 1
LN2, LAr	~ 0

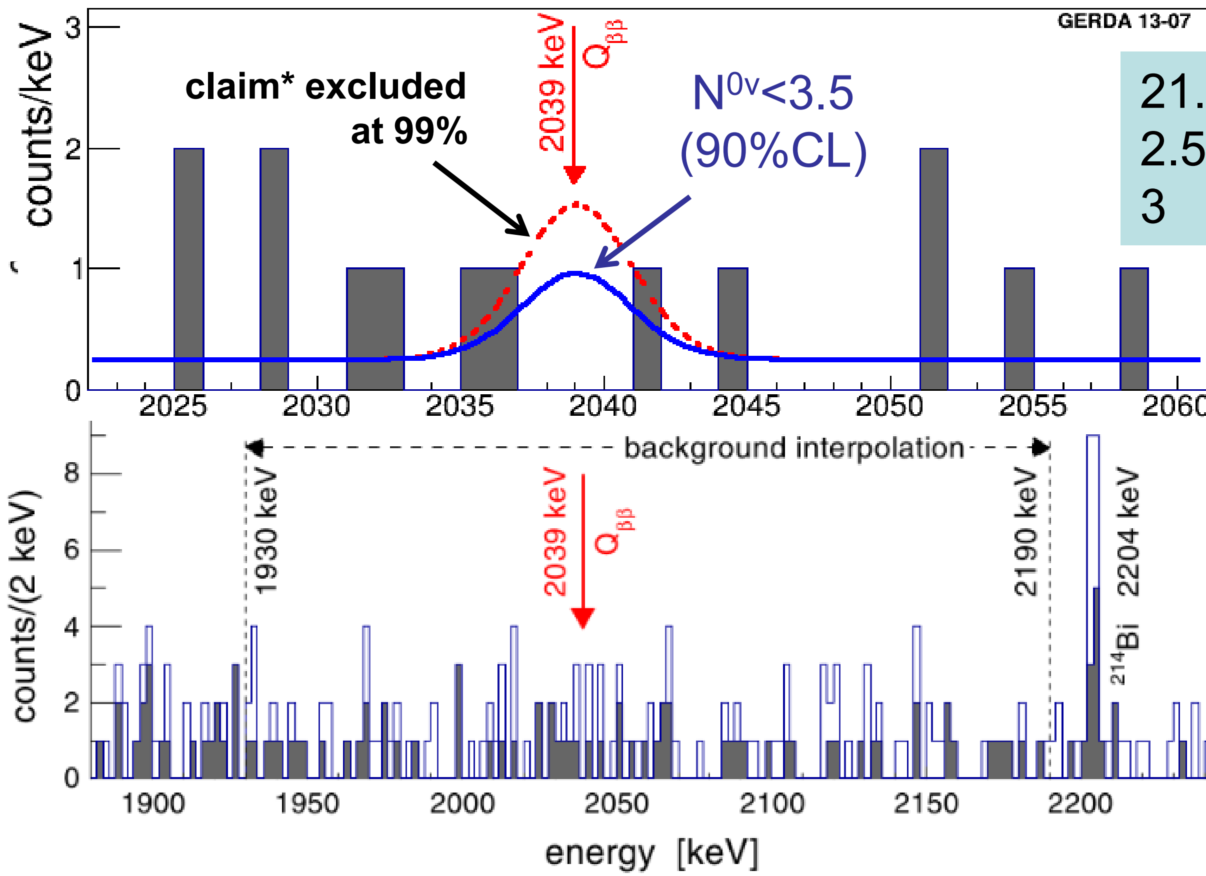
spectra taken underground at LNGS



GERDA Phase I


clean room with lock (old version) & clean bench
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
Ge-76 array
(enlarged)
LAr cryostat, Ø4m, with internal Cu shield
detector = source
water tank, Ø10m, part of μ-veto detector

GERDA Phase I result



21.6 kg· yr :
2.5 bgnd events expected
3 events observed

Frequentist: best fit $N^{0\nu} = 0$; $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) - sensitivity. : $2.4 \cdot 10^{25}$ yr

PRL 111 (2013) 122503

► The quest for 0νββ decay is open again!

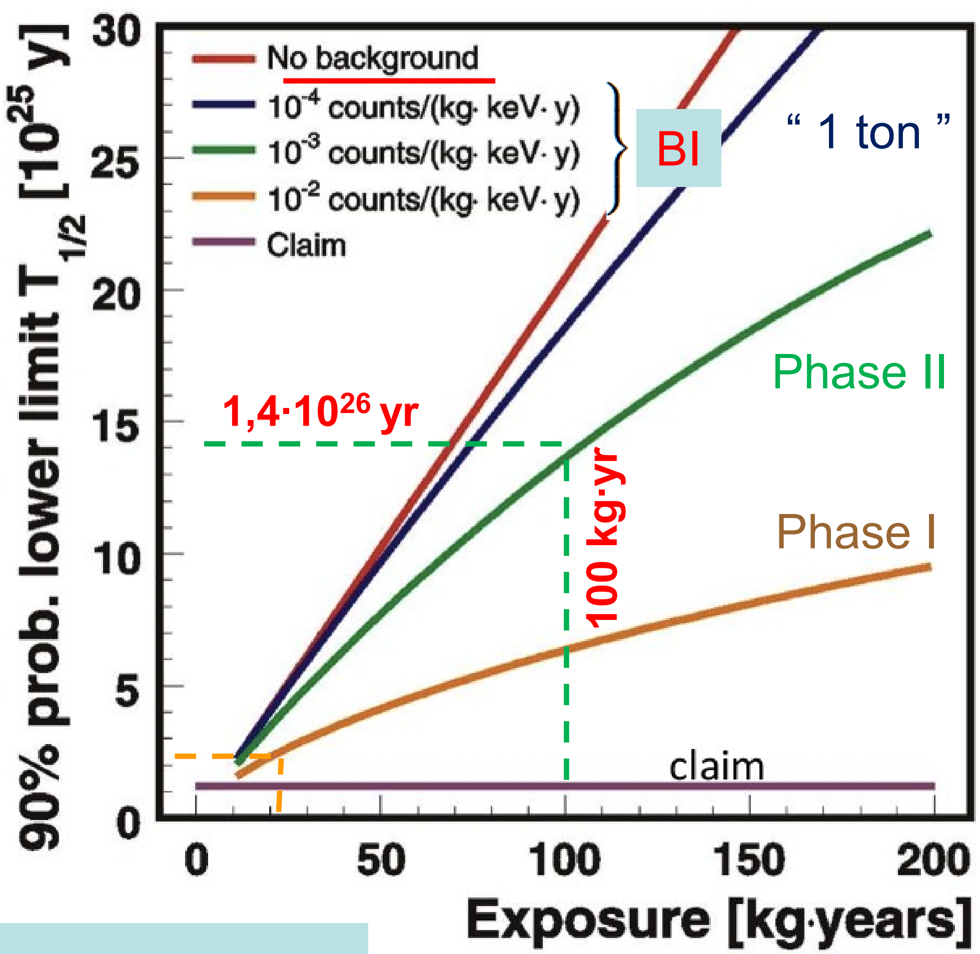
*claim: Klapdor-Kleingrothaus, PL B586 (2004) 198

Phase II goal

$$T_{1/2} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{if} \quad M \cdot t \cdot BI \cdot \Delta E \ll 1 \\ a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}} & \end{cases}$$

i.e. no background

a : enrichment
ε : efficiency
M: source mass
M·t : exposure
BI : background index
ΔE: e. resolution



Upgrade strategy:

Stay as long as possible in background-free regime.

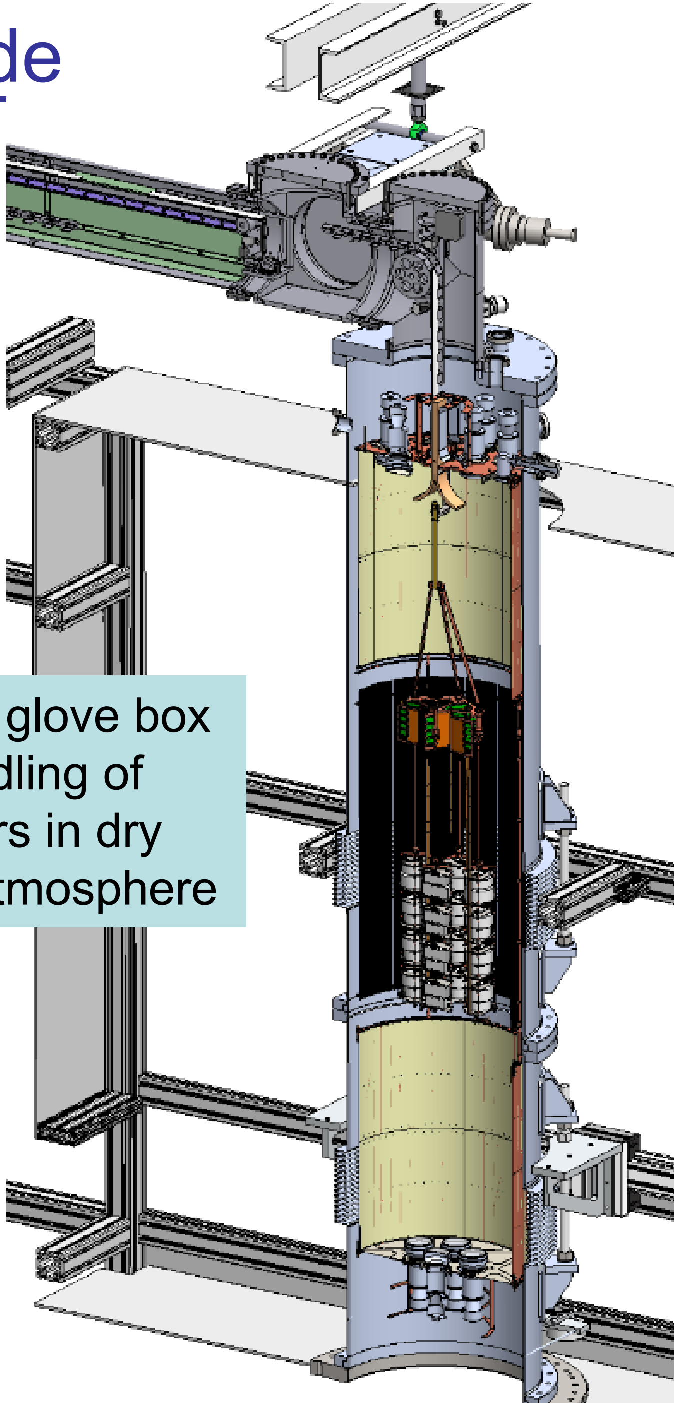
Increase mass / exposure and reduce BI and resolution.

upgrade

new lock

in cleanroom on top of cryostat:
replaces Phase I twin lock system

- larger: Ø 0.49 m, h = 2.8 m



lock within glove box for handling of detectors in dry nitrogen atmosphere

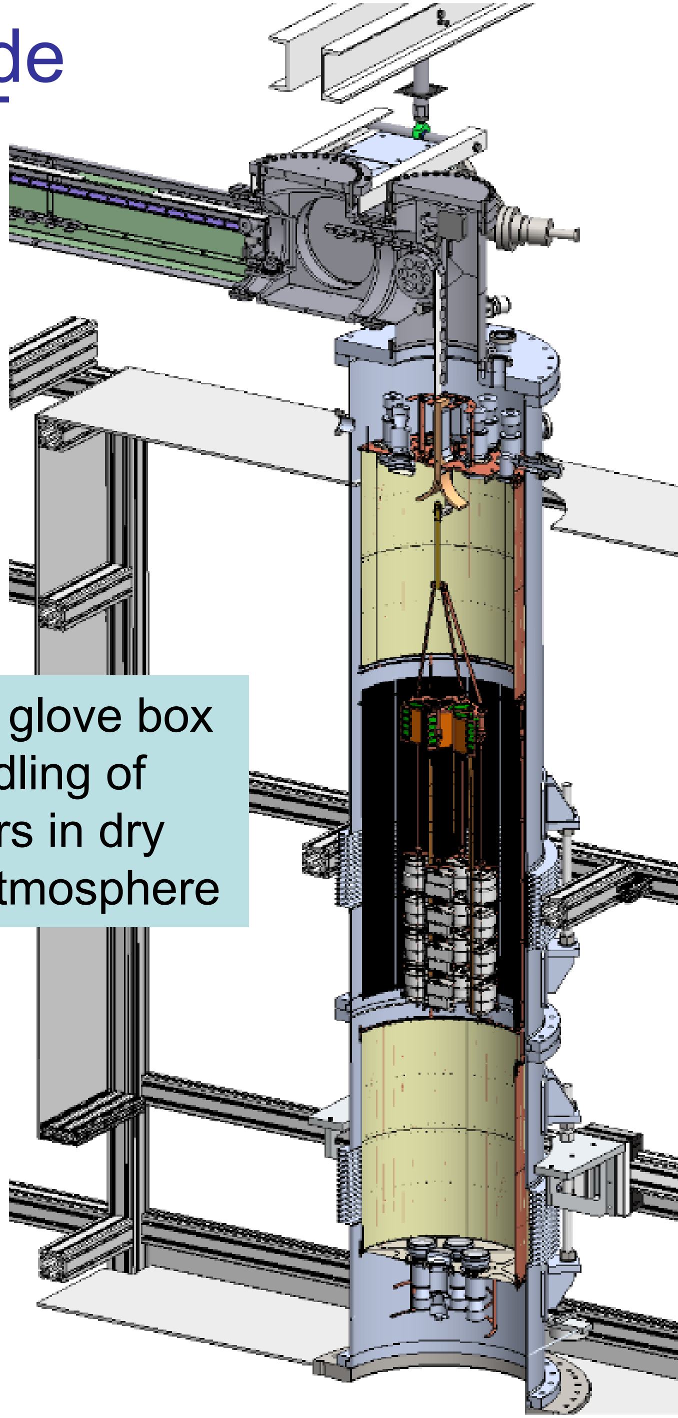
upgrade

new lock

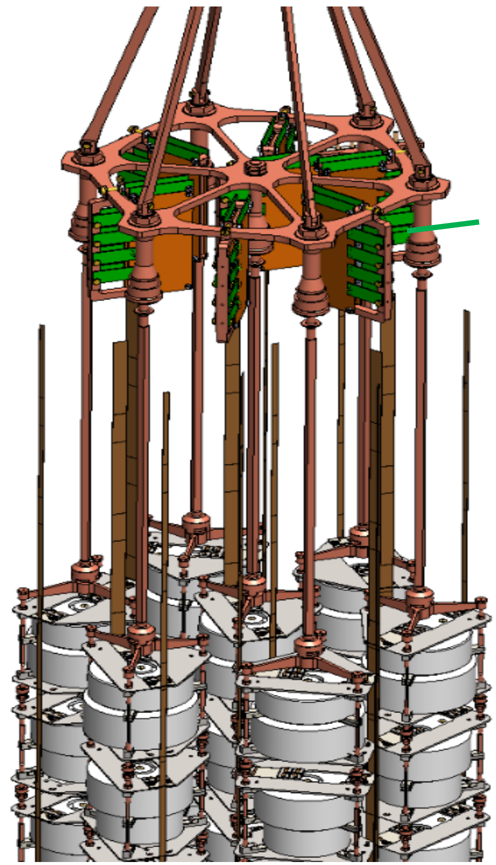
in cleanroom on top of cryostat:
replaces Phase I twin lock

- larger Ø 0.49 m, h = 2.8 m

► space for 7 string array



lock within glove box for handling of detectors in dry nitrogen atmosphere



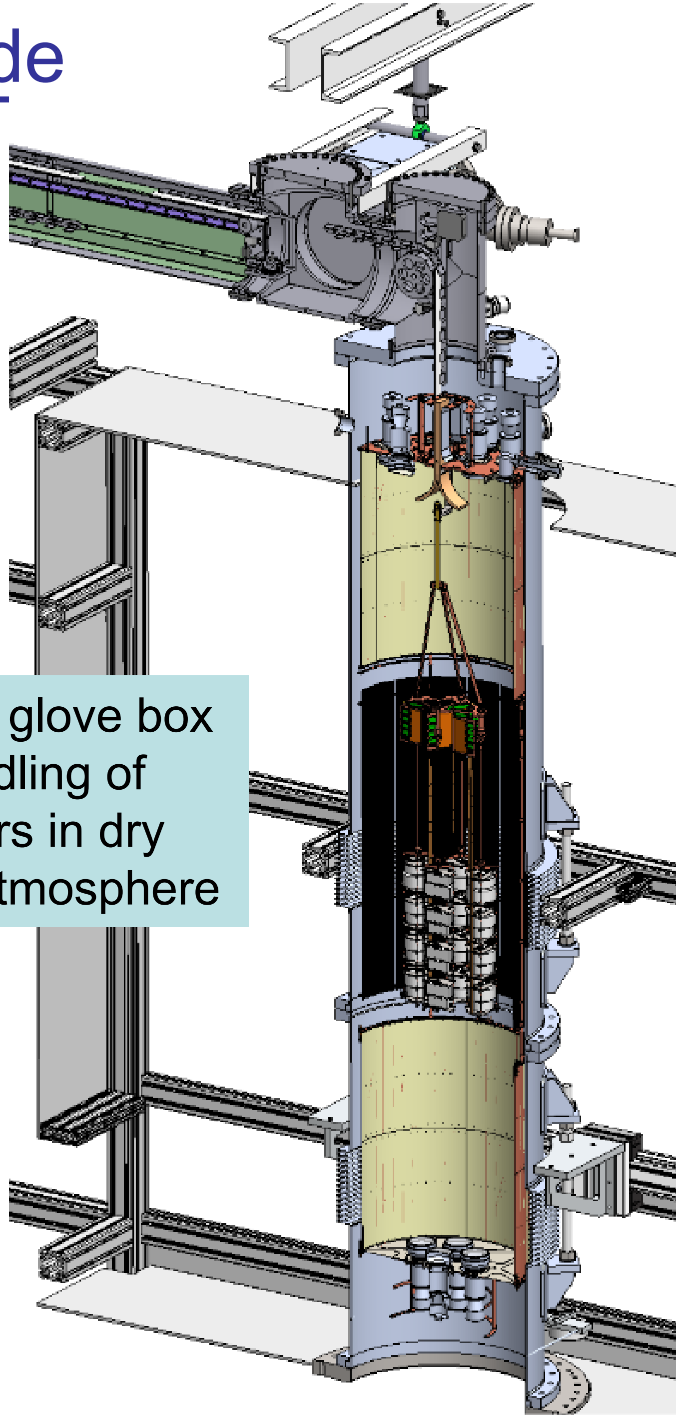
upgrade

new lock

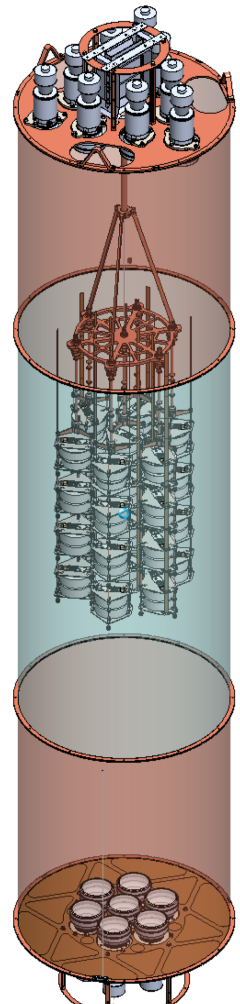
in cleanroom on top of cryostat: replaces Phase I twin lock

- larger Ø 0.49 m, h = 2.8 m

► space for 7 string array & surrounding LAr instrumentation for active veto



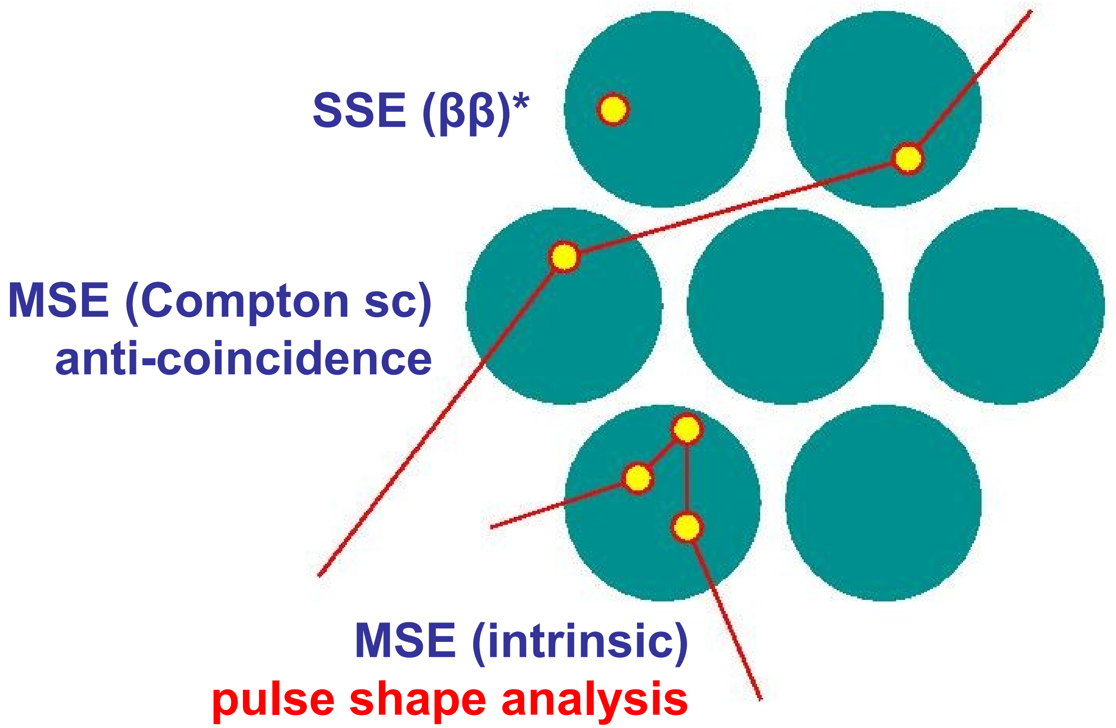
lock within glove box for handling of detectors in dry nitrogen atmosphere



Ge detector array and LAr veto simultaneously deployed in cryostat.

upgrade more & 'better' ^{enr}Ge diodes

wanted: discrimination of single (ββ signal) / multi site (background) events



* SSE: 1 MeV electron has 'range' of ~1 mm

upgrade more & 'better' ^{enr}Ge diodes

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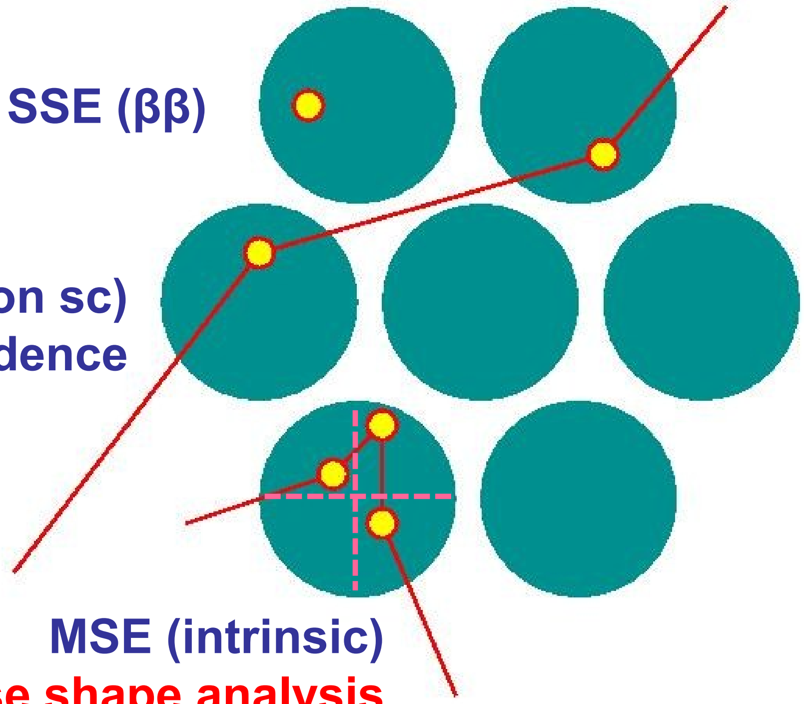


SSE (ββ)

MSE (Compton sc)
anti-coincidence

MSE (intrinsic)
pulse shape analysis
segmentation – anti-coincidence

Which detector design?

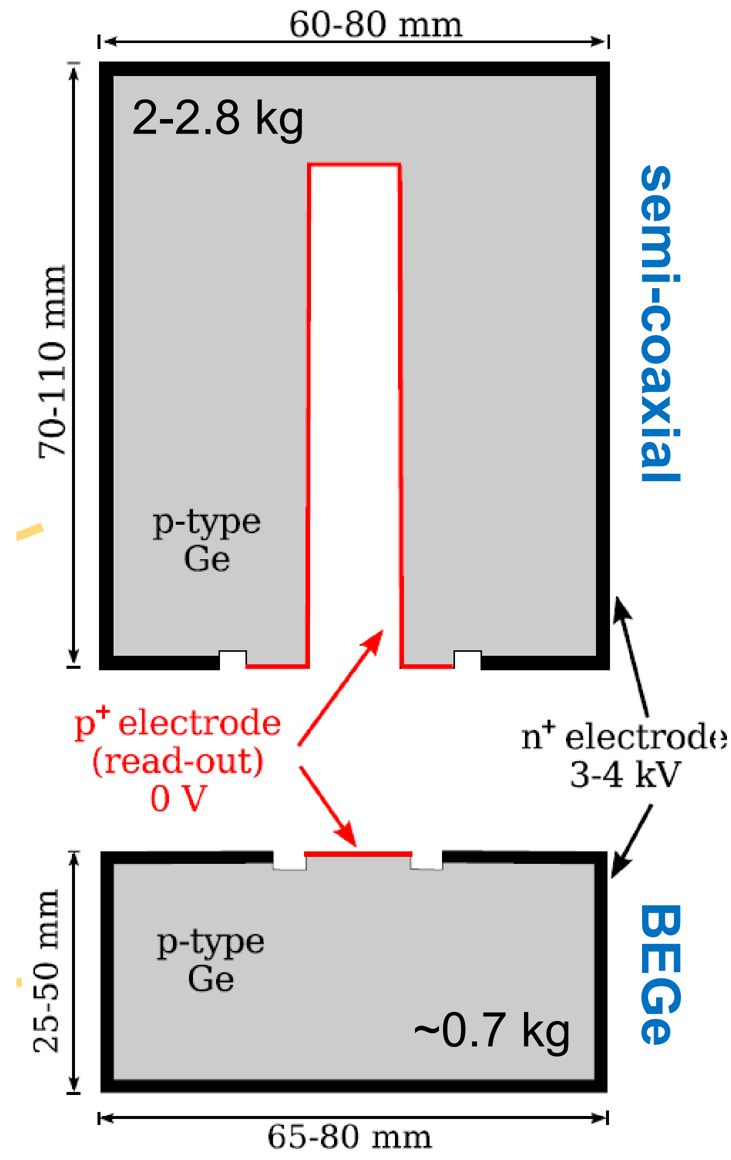
upgrade more & ‘better’ ^{enr}Ge diodes

Phase I:

Refurbished semi-coaxial detectors from HdM & IGEX experiments

n+ conductive Li layer, separated by a groove from the boron implanted p+ contact

Phase II detector type, already tested in Phase I:
BEGe – broad energy Ge detector



upgrade more & 'better' enrGe diodes

Phase I:

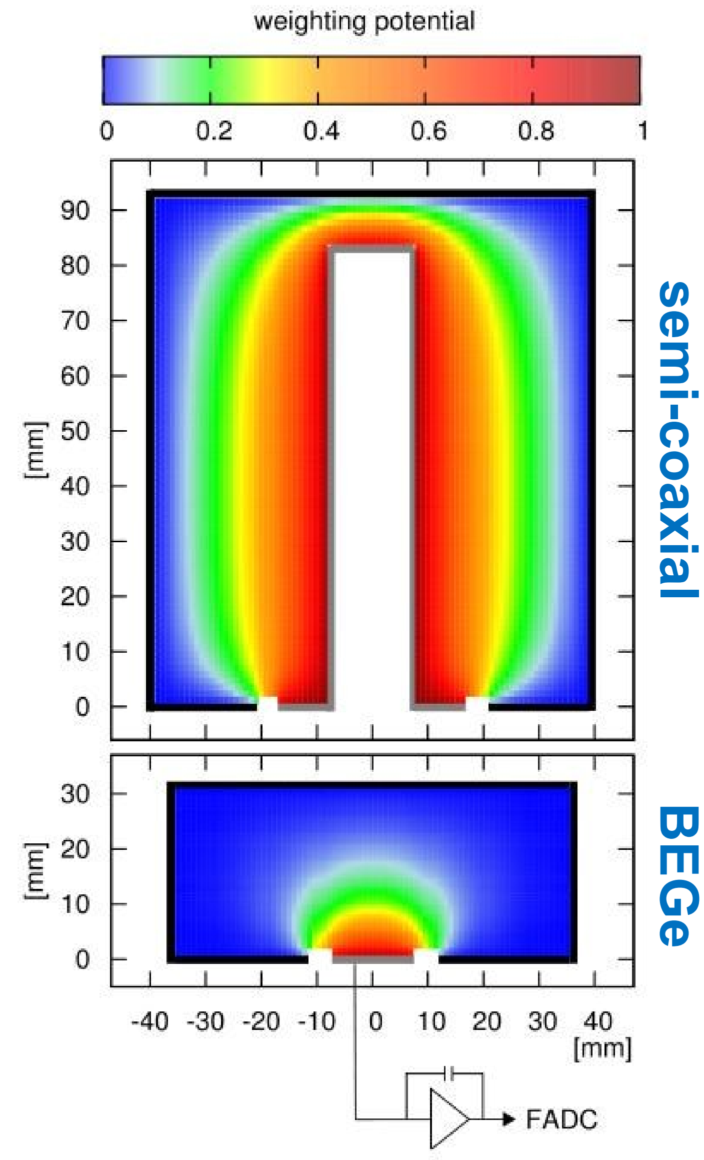
Refurbished semi-coaxial detectors from HdM & IGEX experiments

n+ conductive Li layer, separated by a groove from the boron implanted p+ contact

Phase II detector type, already tested in Phase I:

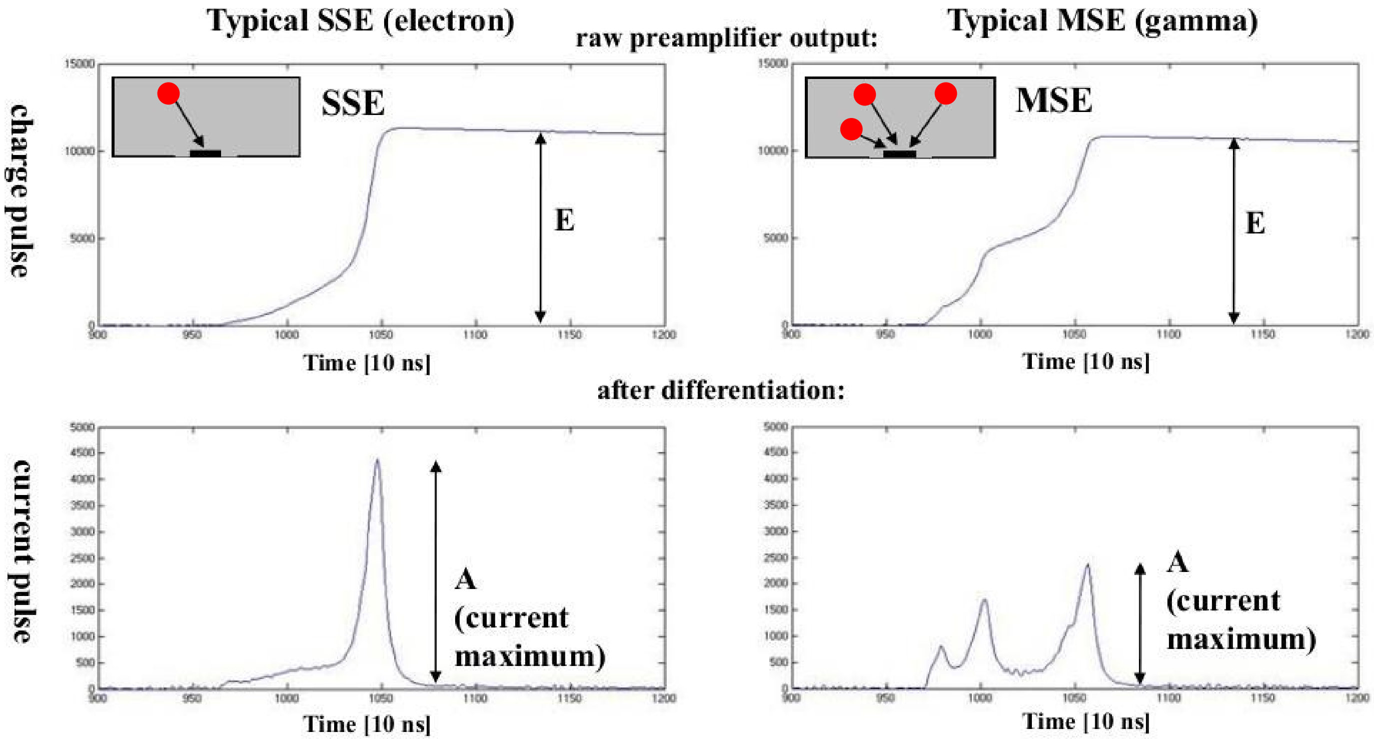
BEGe – broad energy Ge detector

‚point-contact' detector* with superior pulse shape discrimination (PSD) power and energy resolution



*Luke etal, IEEE TNS 36 (1989) 926

BEGe

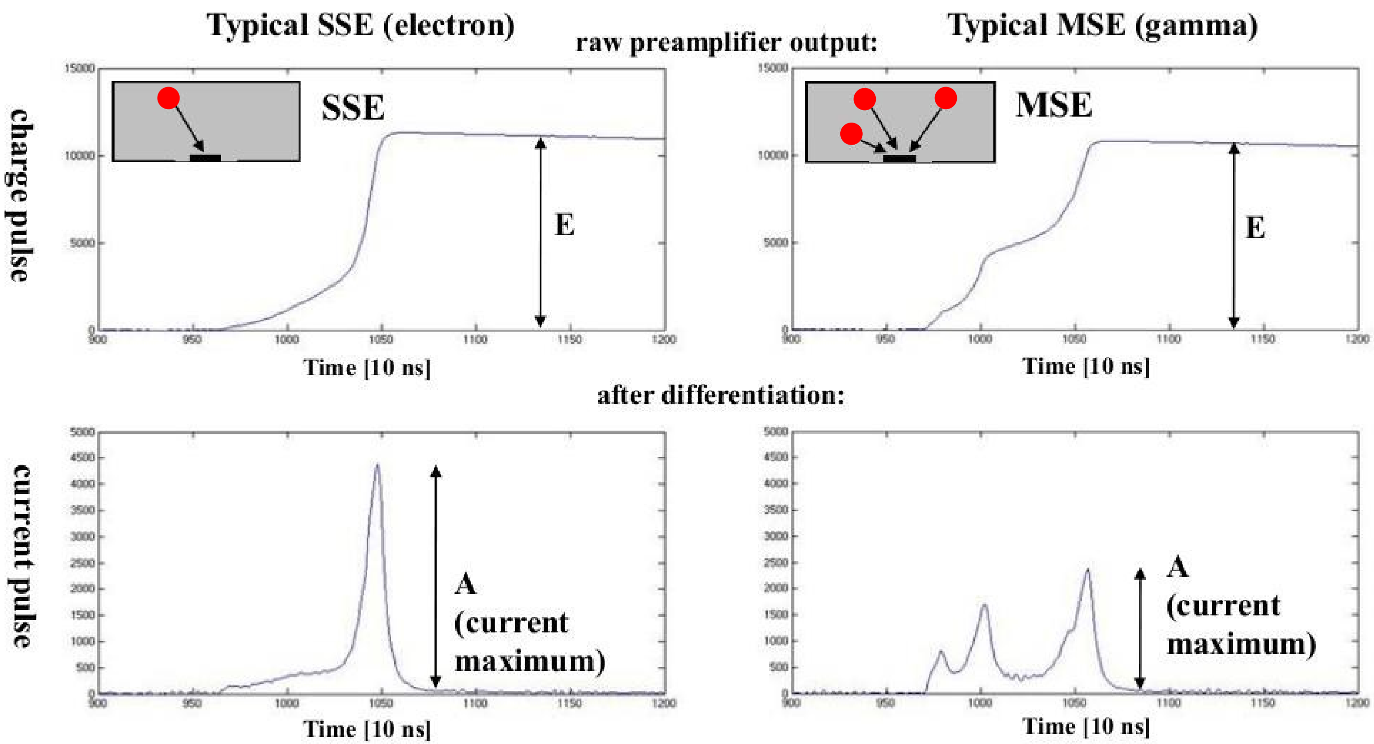


A/E ≡ 1

A/E < 1

A / E cut is robust, simple and well understood.

BEGe



A/E ≡ 1

A/E < 1

SSE accepted for 0.965 < A/E < 1.07:
0νββ efficiency = 92 ± 2 %
2νββ efficiency = 91 ± 5 %
80% of background events rejected

EPJ C73 (2013) 2583

upgrade segmented Ge detector ?

18-fold segmented
true coaxial n-type Ge detector

studied in great detail
worked as expected
Abt et al NIM A583 (2007) 332

abandoned for Phase II since

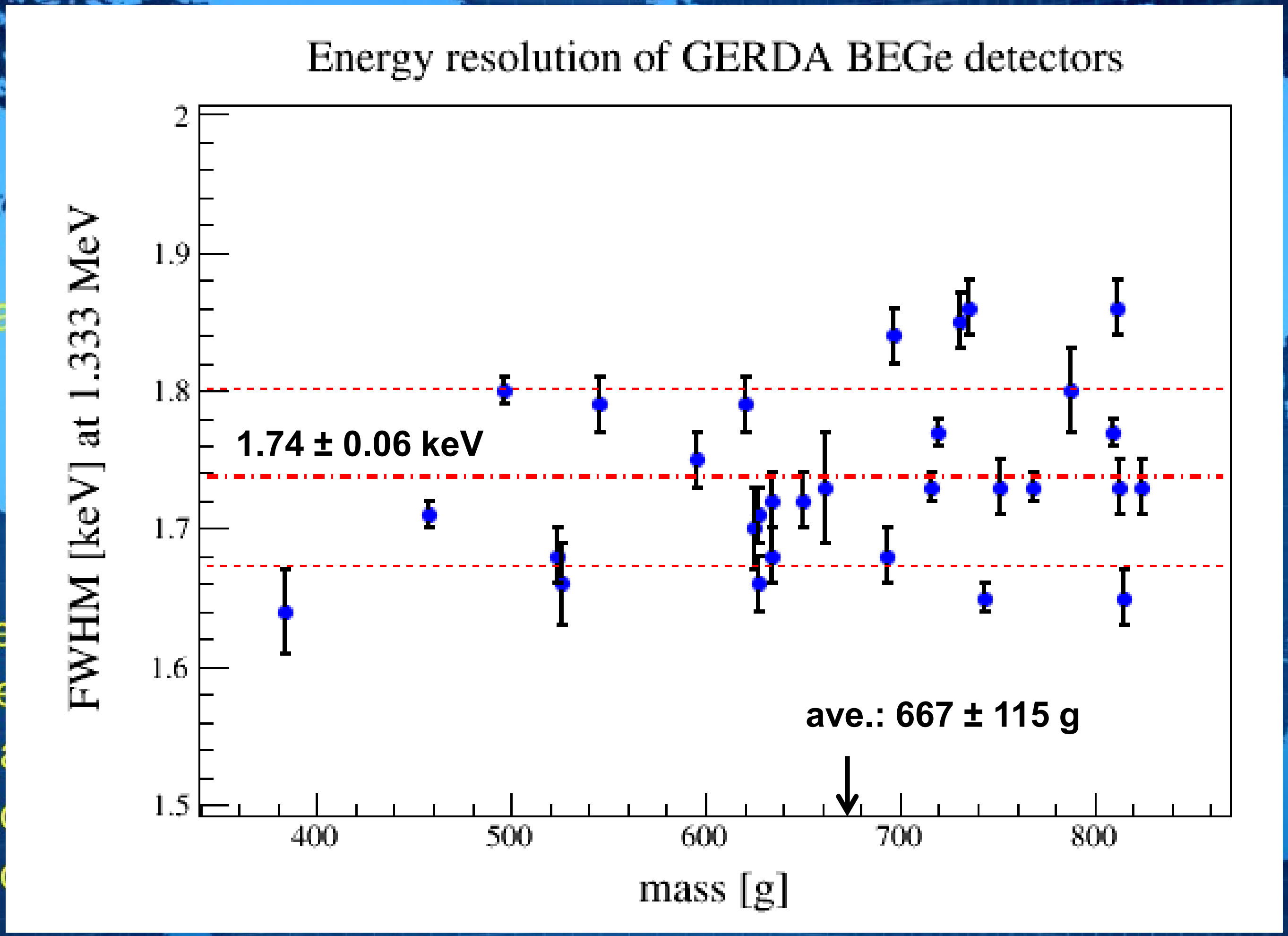
- difficult, expensive technology
- many contacts, many preamps
- lack of supplier for enriched Xtals
- …
- attractive alternative found

From raw germanium material to diode production

- [1] Germanium enrichment, ECP, Zelenogorsk, Russia — 53.3 kg $^{enr}GeO_2$, 88% Ge76
- [2] Metal reduction and purification, PPM, Langelsheim, Germany — 35.5 kg ^{enr}Ge, 6N
- [3] Xtal pulling/Zone refinement, Canberra, Oak Ridge, USA — 9 Xtals → 30 slices
- [4] Diode production, Canberra, Olen, Belgium — 30 ^{enr}Ge diodes (20kg)
- [5] Diode storage and characterization, HADES, Mol, Belgium

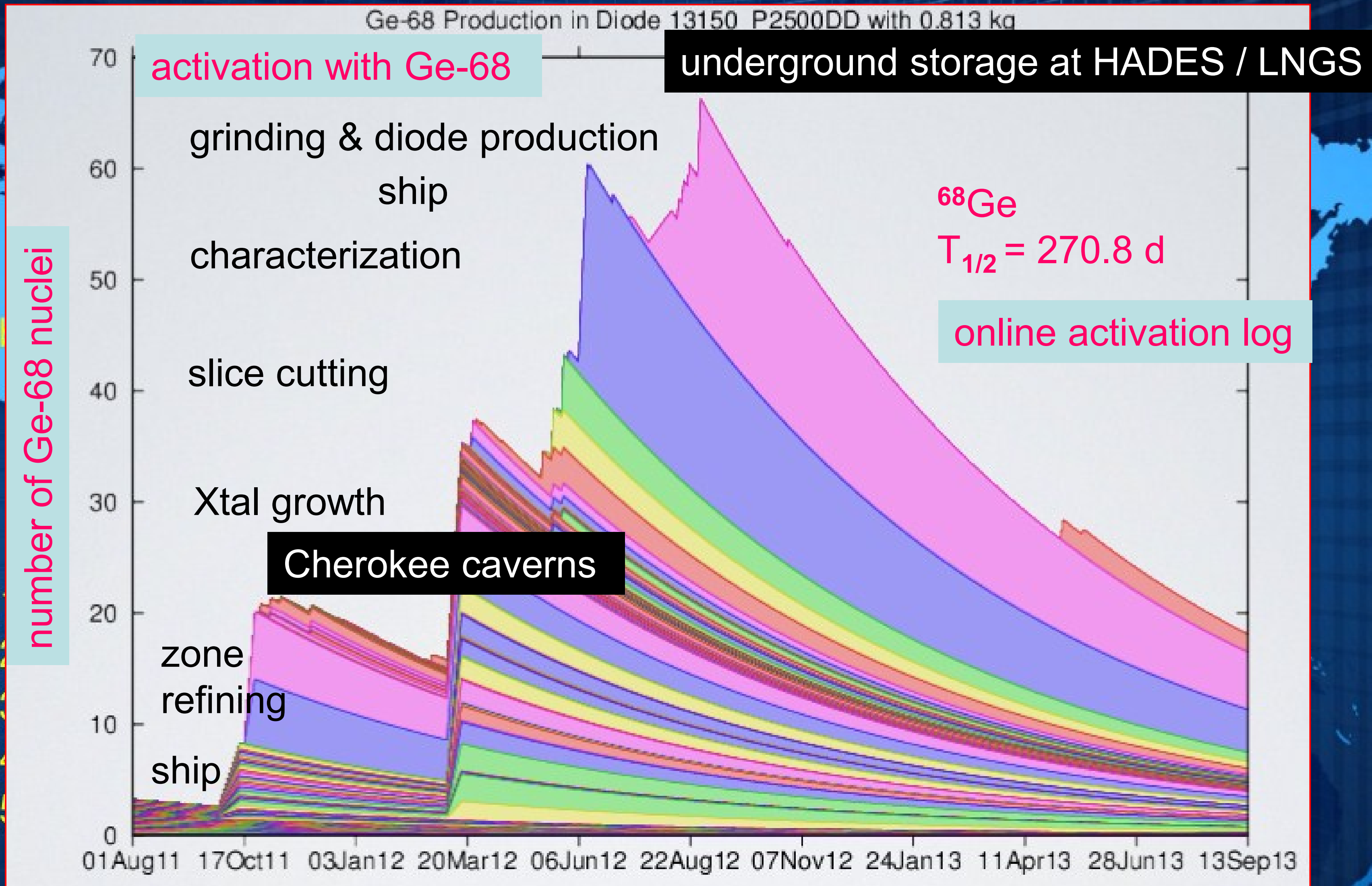
From raw germanium material to diode production

[3] Canberra



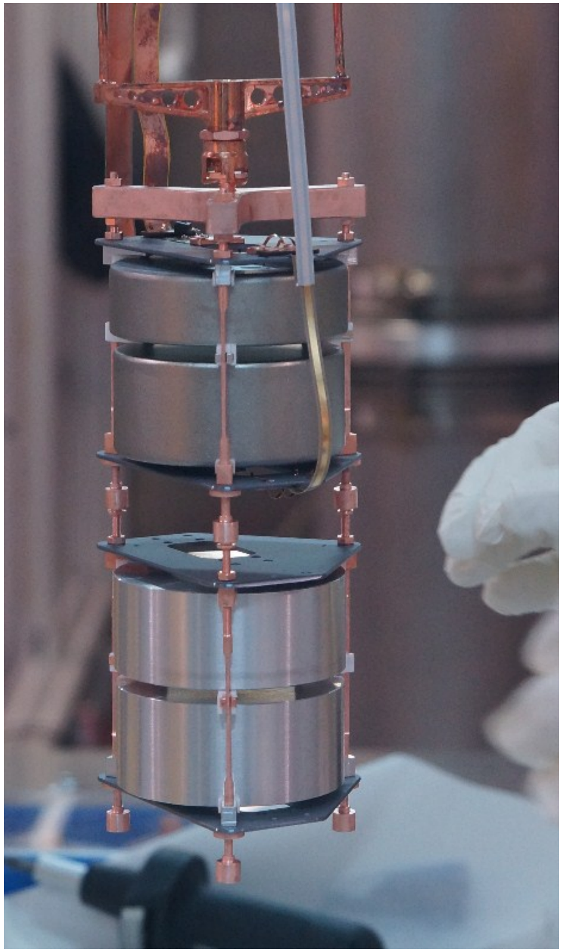
[1] Ge
[2] Me
[3] Xta
[4] Di
[5] Di

From raw germanium material to diode production



Phase I

Phase II

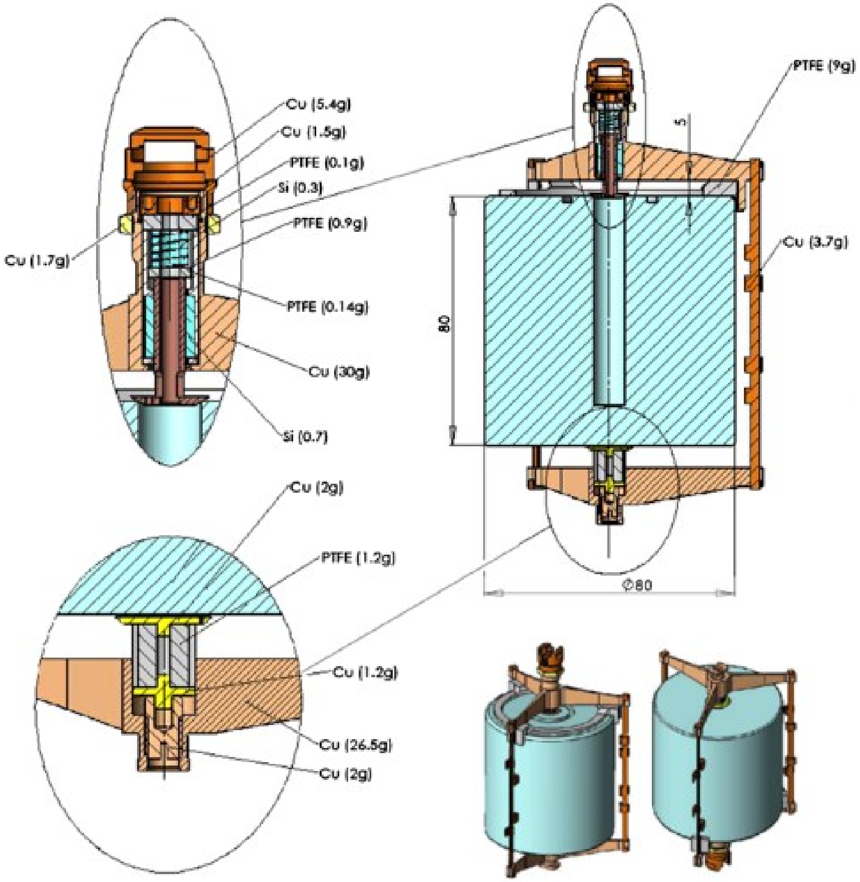


string en-closed by mini-shroud

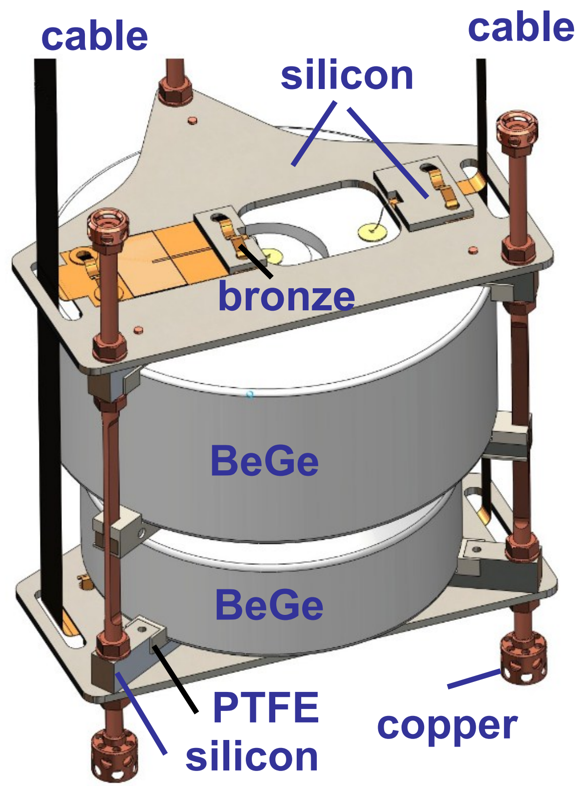
string assembled with individual detector modules

upgrade detector module

Phase I



Phase II

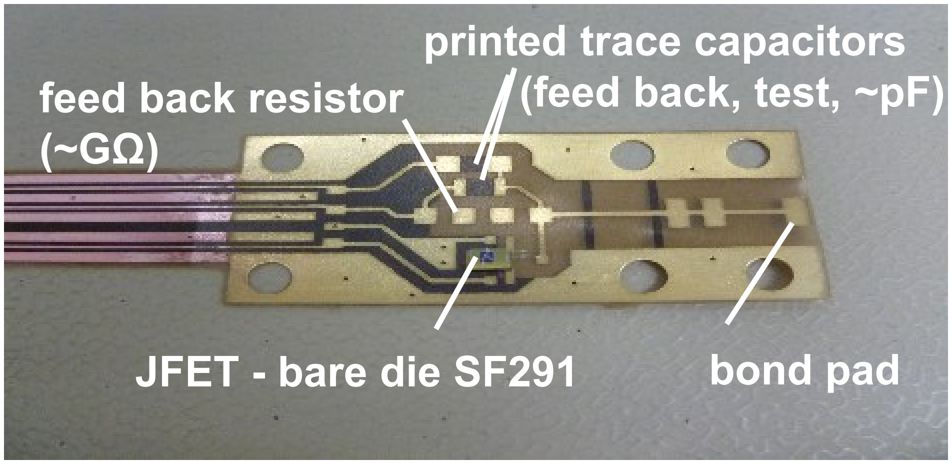


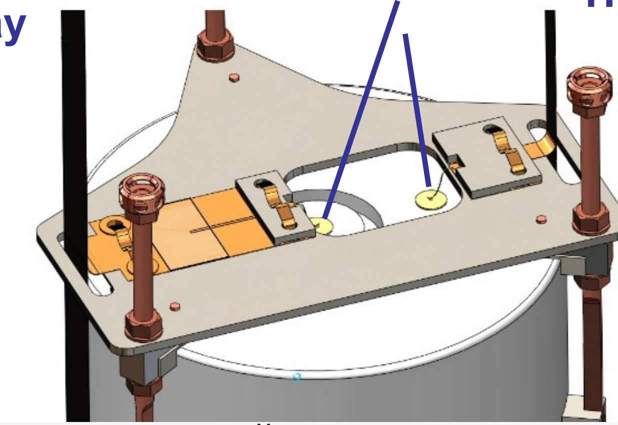
	Phase I	Phase II
copper	81.4 g / 2.3 kg	25.8 g / 1.3 kg detector mass
PTFE	11.3 g	2.1 g
bronze	-	1.0 g
silicon	0.3 g	40.3 g

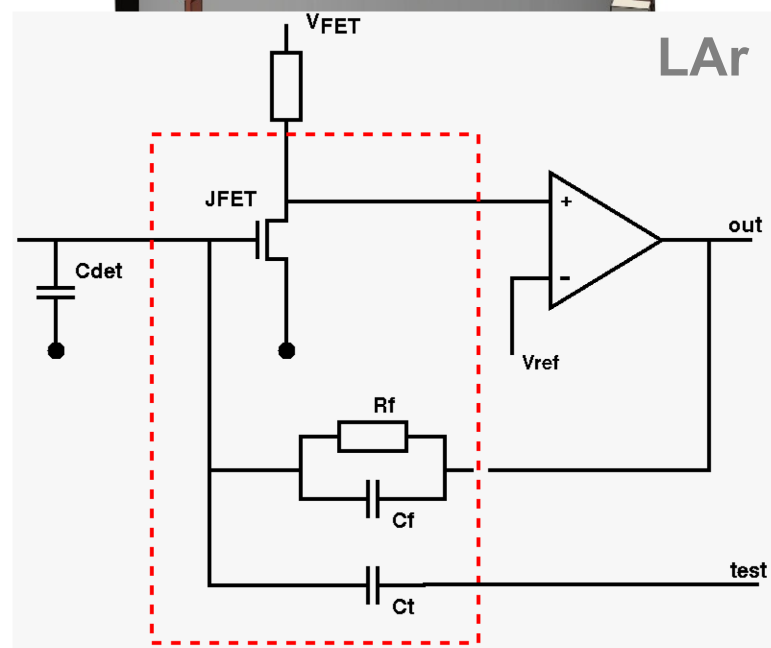
► Significant amount of copper & PTFE replaced by intrinsically radio-pure silicon!

upgrade front end electronics

very front end electronics in Phase II close to detector - distance >30cm in Phase I







Options for custom-made feed back resistor (commercial chips: not radio-pure enough, or too large parasitic elements vs conductive substrate):

- amorphous Ge
- TiN
- W all on quartz substrate

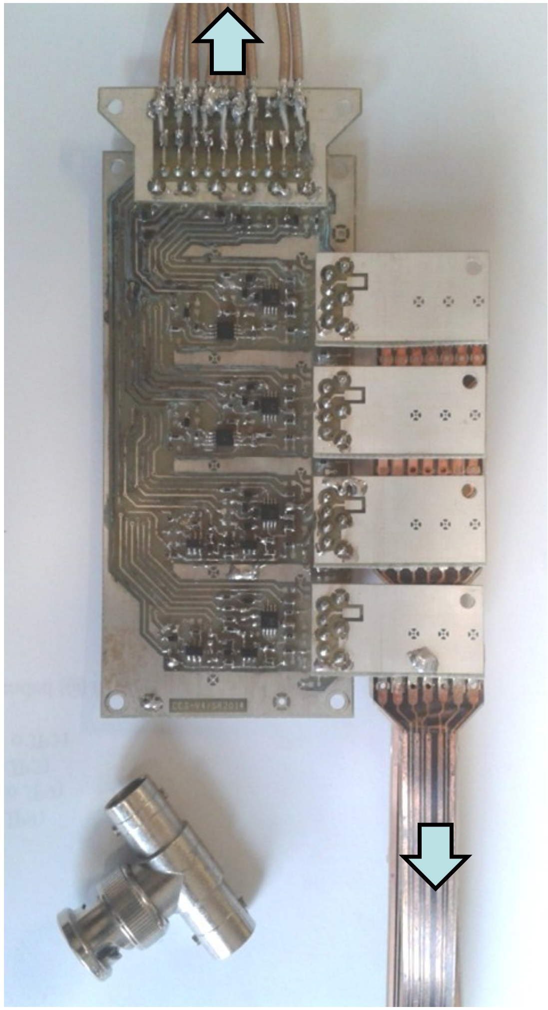
→ stability problems to be solved

front end electronics

CC3: 4 Channel Charge Sensitive Preamplifier

- upgrade of CC2 preamplifiers of GERDA Phase I
- based on commercially available opamps
- low-noise, cryogenic and radio-pure electronics
  - 0.7 keV FWHM pulser resolution
  - 2.6 keV FWHM at 2.6 MeV with BEGe detector
  - 20 MHz bandwidth allows PSD (A/E)
  - suitable for operation in liquid Argon (50 mW/channel)
  - ≈ 50 μBq / channel (including pins) expected
  - additional line driver available

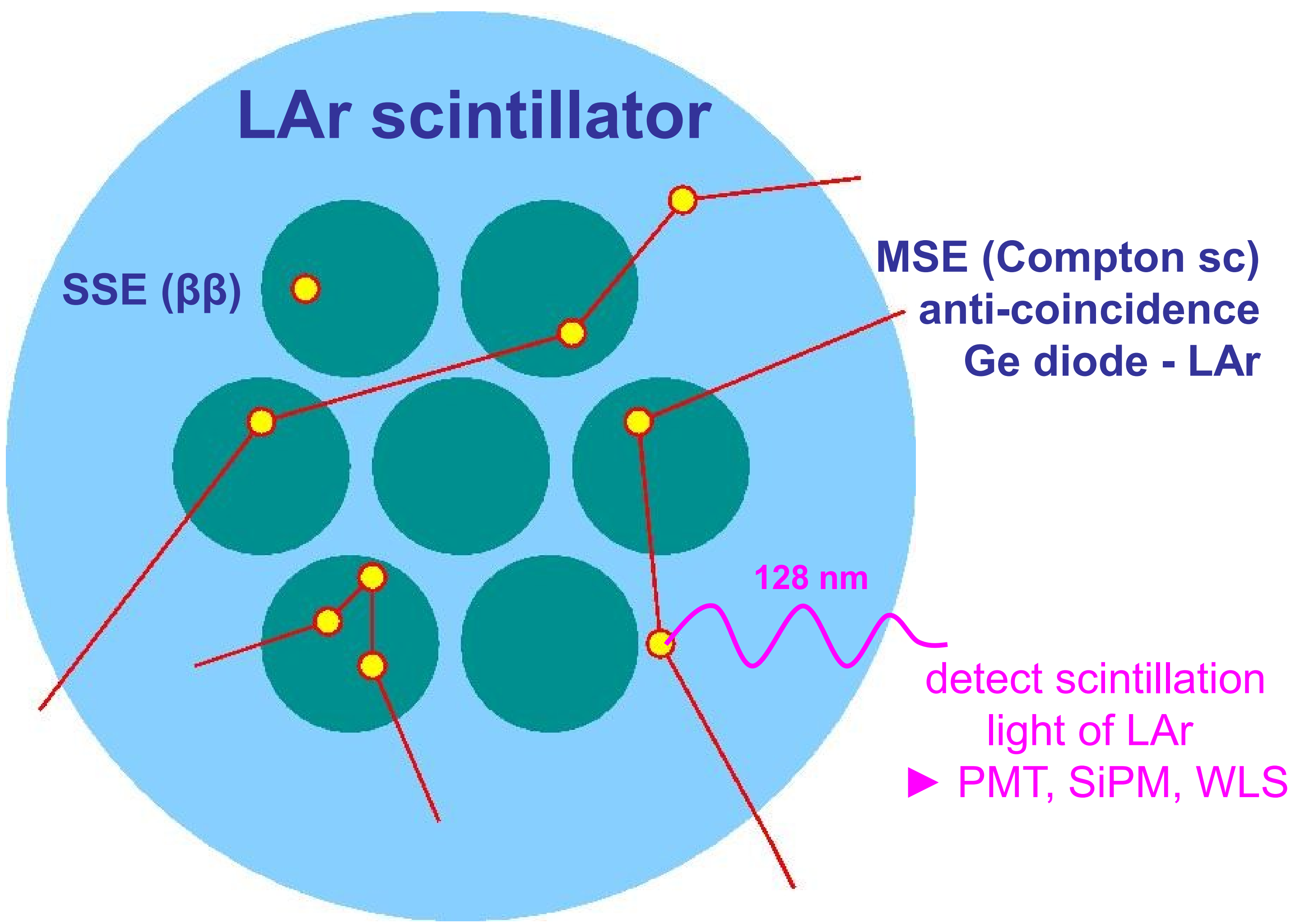
10 m long coaxial cables to the feedthru flange



prototype version (FR4 laminate)

0.5-1 m (4x) flex cables to VFE and detectors

wanted: discrimination of single (ββ signal) / multi site (background) events



hybrid LAr veto system

PMTs and SIPMs & fibers are deployed together with detector array through Phase II lock w/o LAr drainage

top plate with
9 PMTs

Cu shroud 1, h~ 60 cm

flange

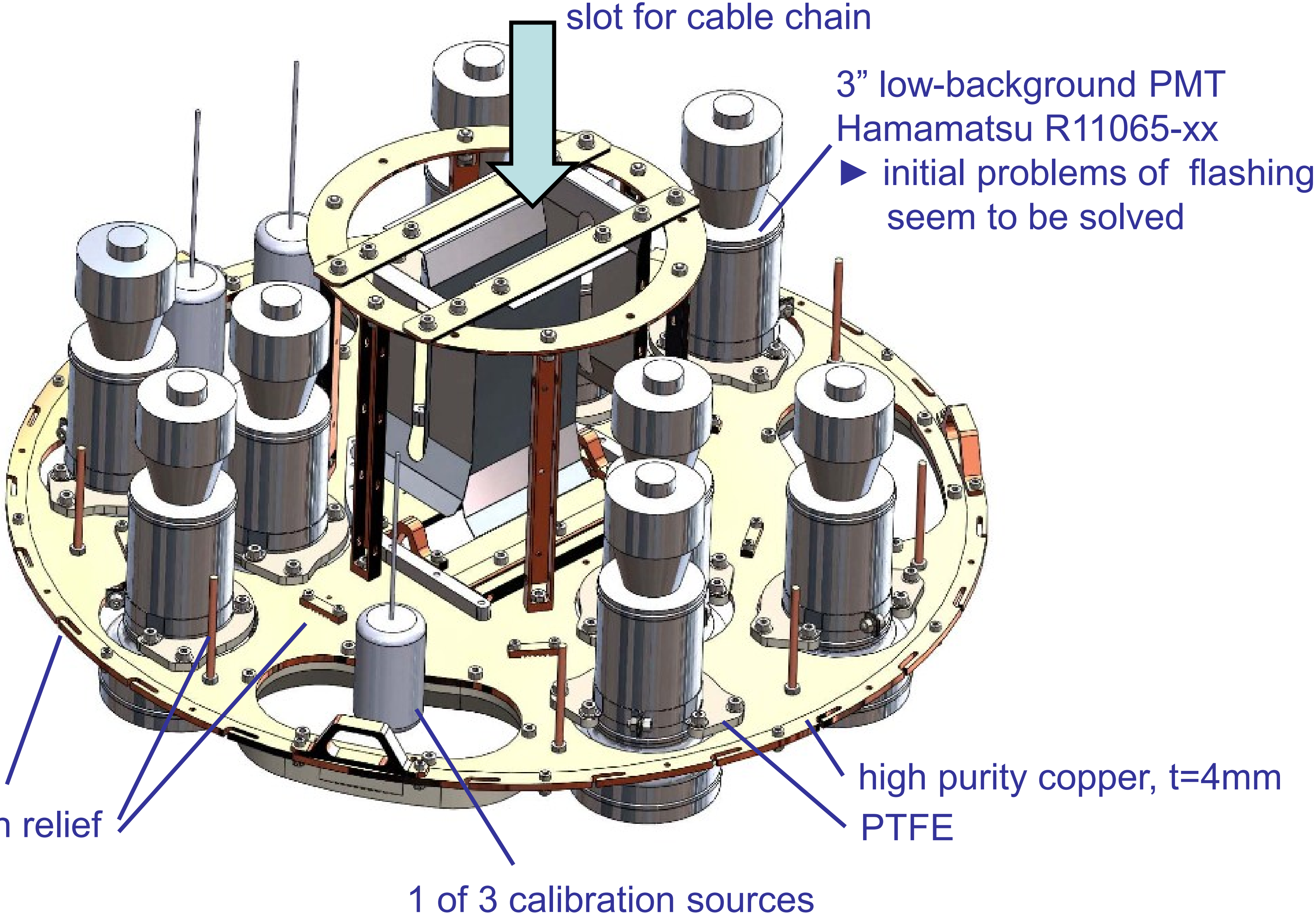
Ø49 cm central window, h~100 cm,
covered by dense curtain of 1x1 mm^2
scintillating fibers on radius of 23.25 cm;
readout by KETEK SIPMs 3x3 arrays

flange

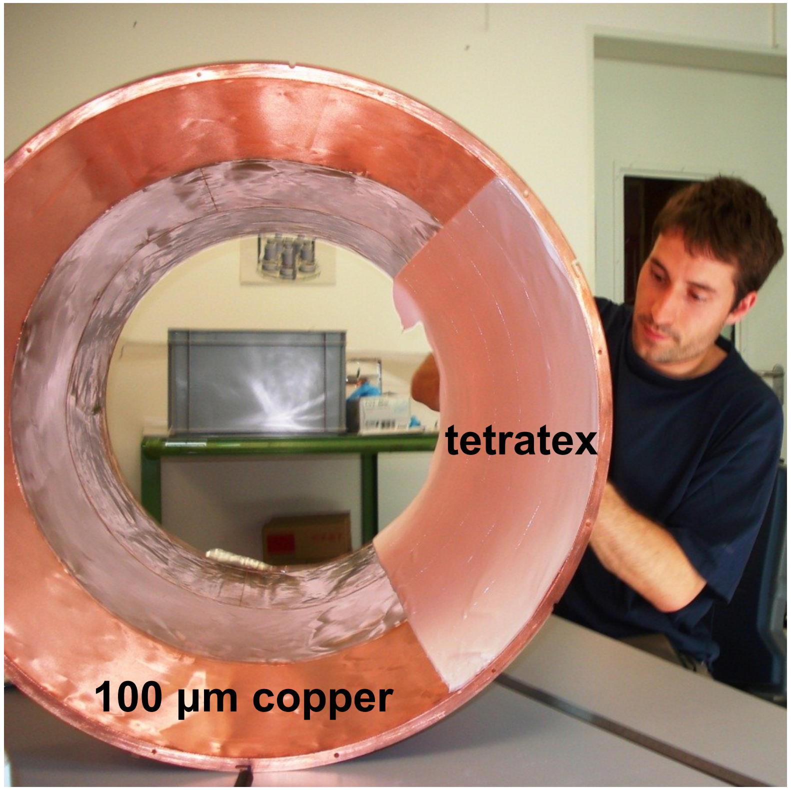
Cu shroud 2 Ø49 cm, h~60cm, t=0.1mm
coated with tetratex & WLS (TPB)

bottom plate with 7 PMTs

LAr veto   top PMT support plate



LAr veto — copper shroud lined with WLS

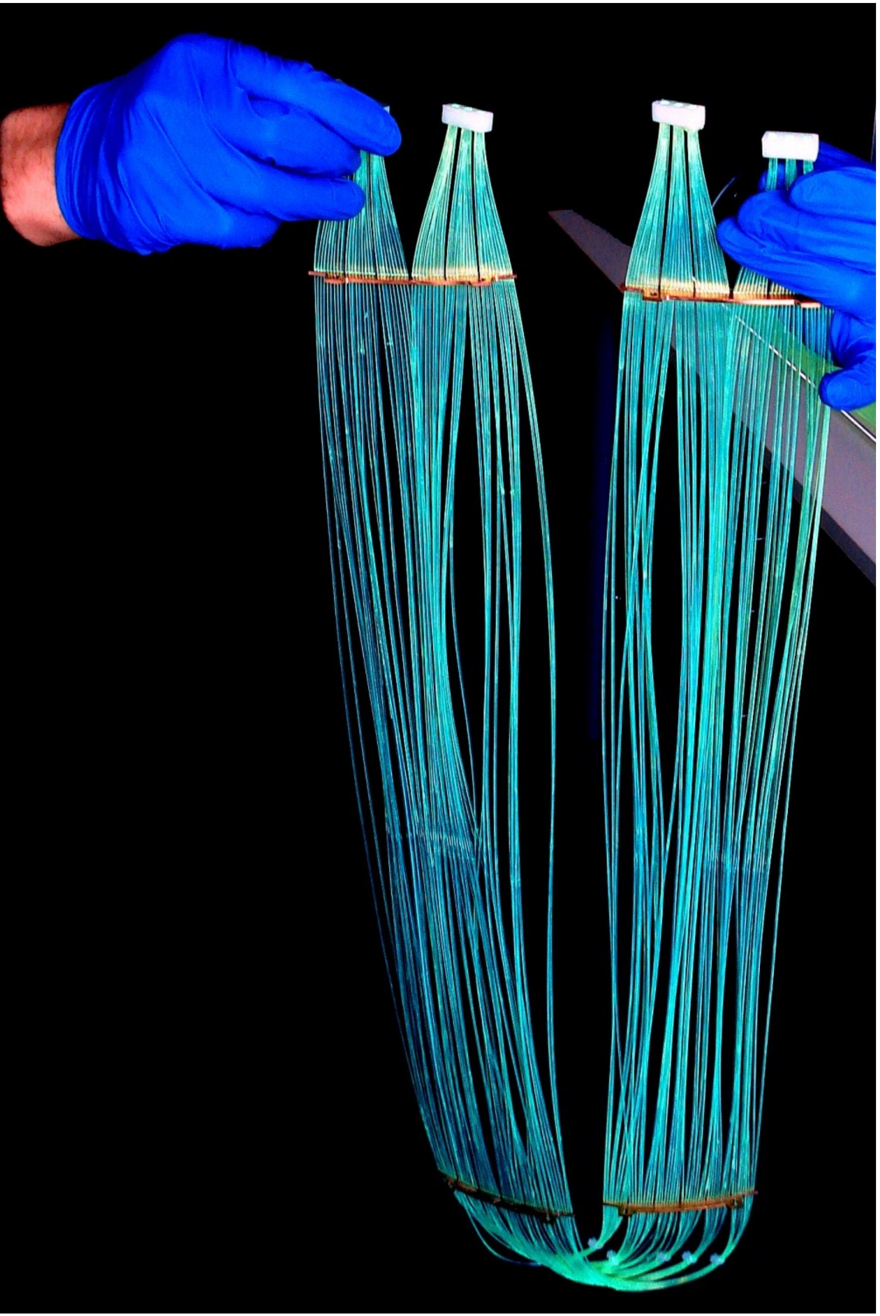


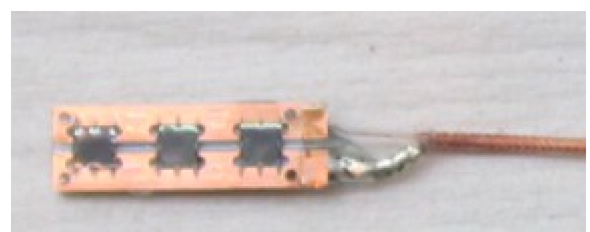
coated Tetratex being stitched
with 100 µm nylon wire

Ø 49 cm - h = 60 cm
t = 100 µm copper foil
t = 2 mm cooper flanges, laser welded

LAr veto

fiber curtain



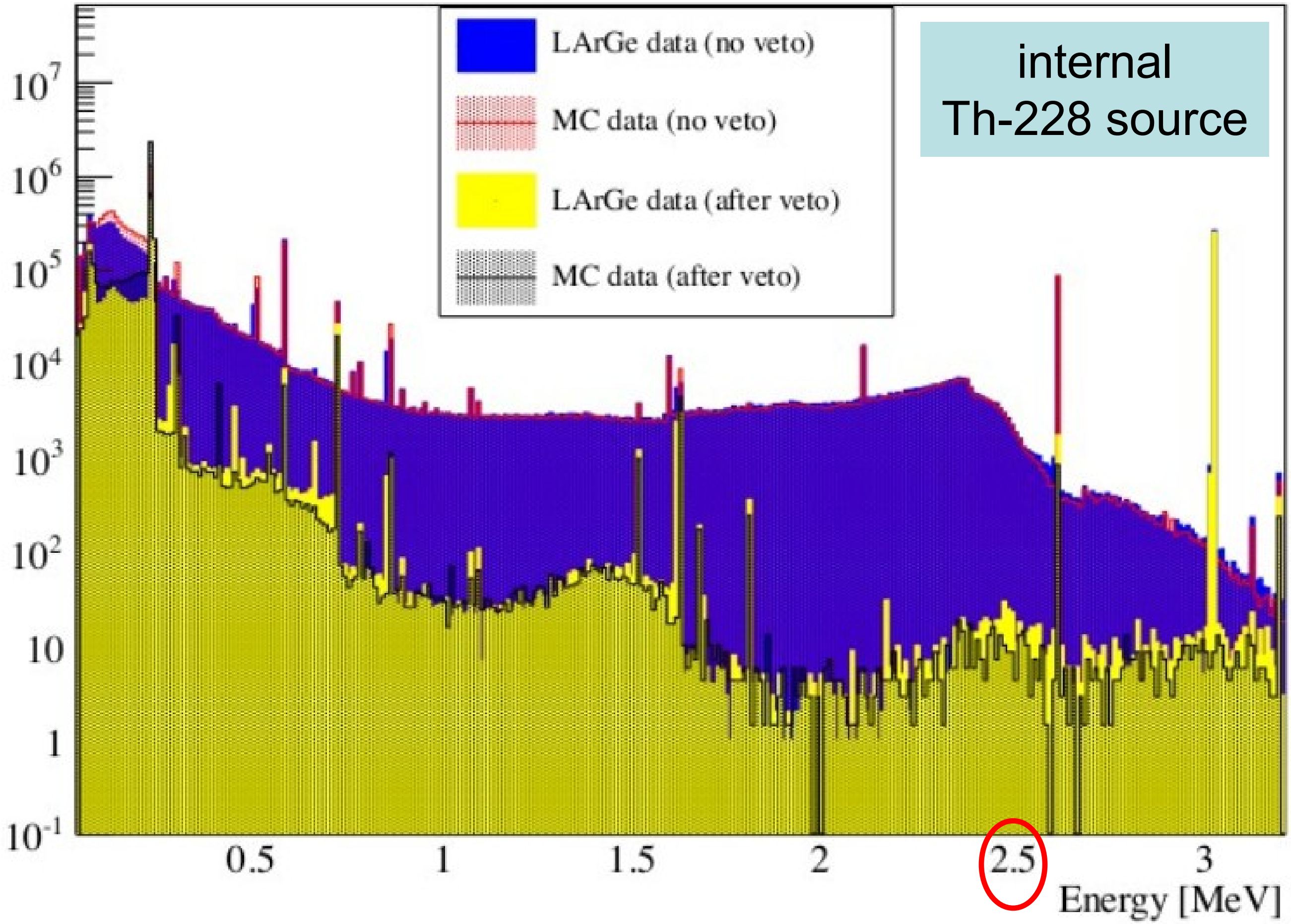


3 SiPMs mounted on cuflon

LAr veto performance

MC: XUV & optical photons tracked
XUV attenuation 60 cm
reflectivity measured

data vs Monte Carlo – good agreement



internal
Th-228 source

background suppression factors :

3 – 10 for Bi-214 depending on location
60-300 for Tl-208 if close to detector

LAr veto — transparent mini-shroud

Phase I:
Cu mini-shrouds

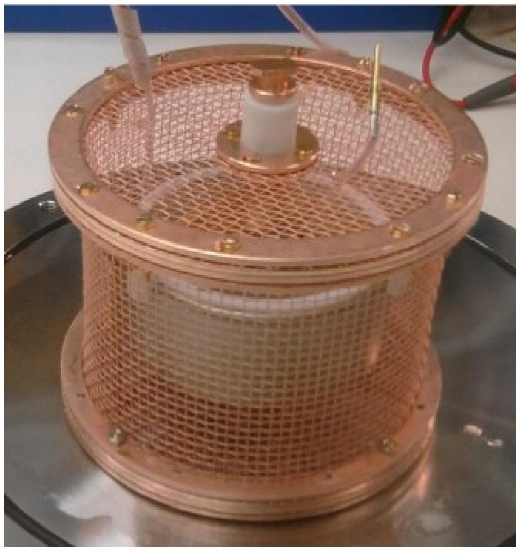
- shielding E-Field of detectors
- shielding against convection
- essential for reaching BI = 0.01

► prevent K-42 ions ($E_\beta \leq 3.5$ MeV), progenies of Ar-42, to reach detectors

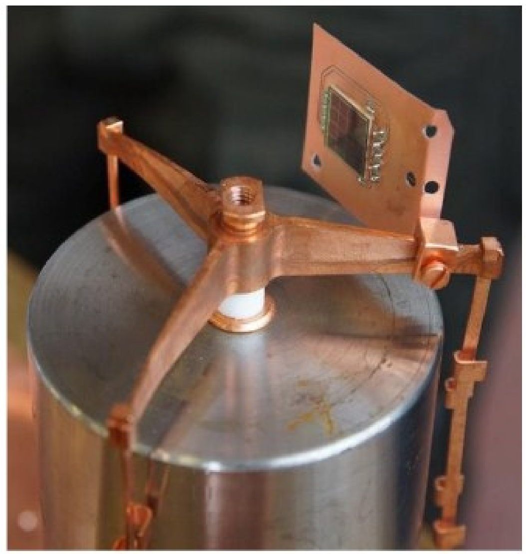
Phase II:
Transparent or optically active mini-shroud needed to detect scintillation light emitted close to detectors

LAr veto transparent mini-shroud

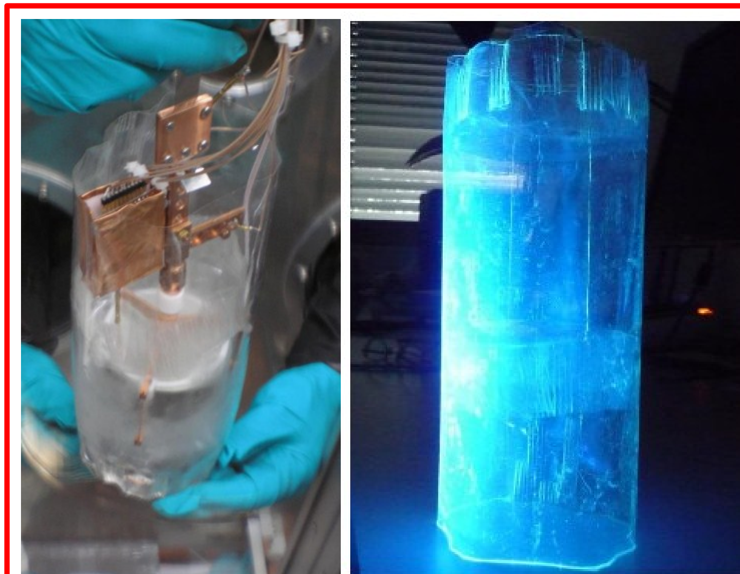
various options tested



copper mesh on HV



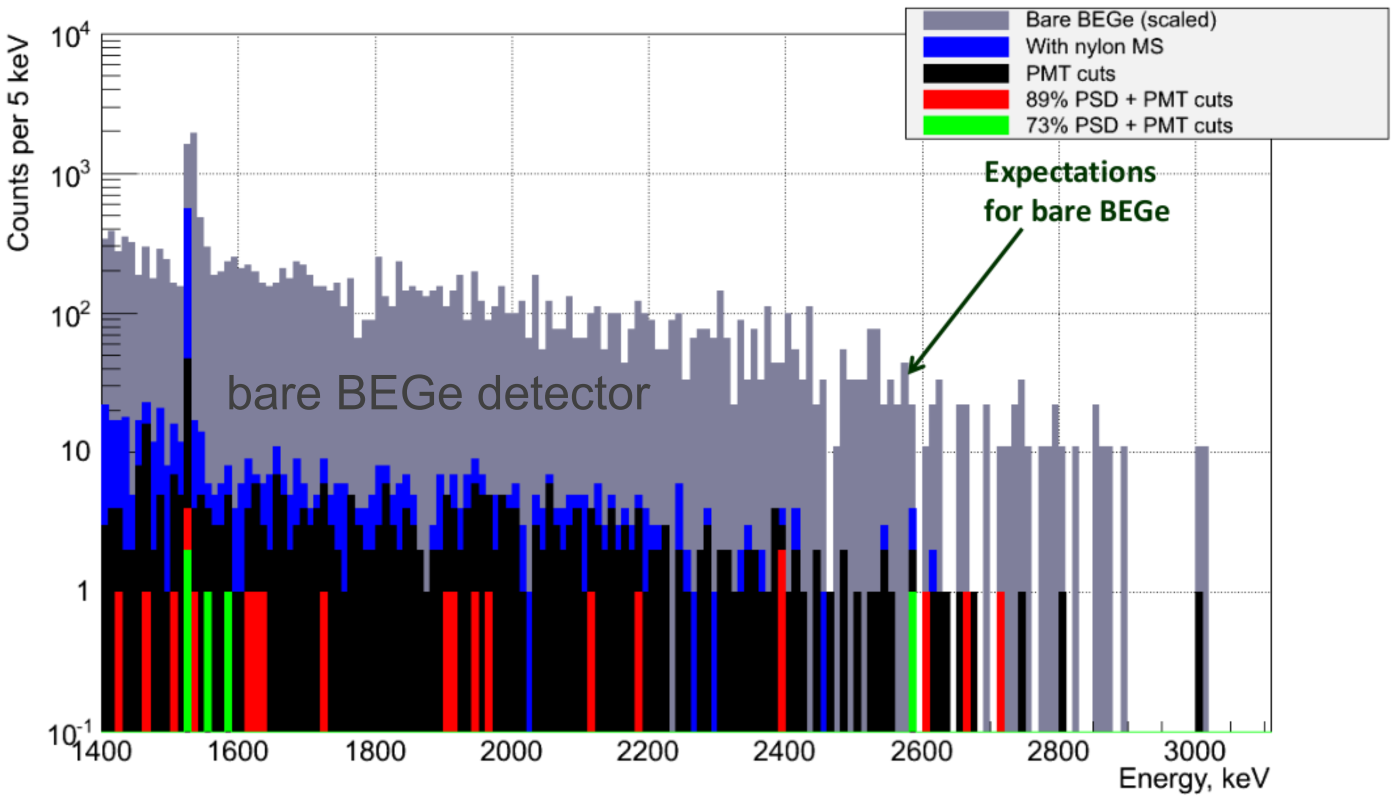
SiPM
in non-transparent shroud



nylon shroud coated with TPB/PS

LAr veto transparent mini-shroud

suppression of K-42 events



nylon mini-shroud coated with TPB/PS

measurement in LArGe test stand spiked with Ar-42 - statistics corresponding to ~ 17 kg yr in natural argon.

status

GERDA Phase I concluded in September 2013

- Water tank drained (and refilled)
- Inspection of cryostat and water tank by certified body
  - ► no indication of corrosion after 3 years of operation
  - ► system safety of pressure equipment certified
- Replacement of 2 of 3 broken PMTs of Cherenkov system
- Rescue of calibration source from bottom of filled cryostat (dropped by accident during Phase I)

June 2014

- All BEGe detectors for Phase II stored at LNGS
- Glove box modified for new lock
- Phase II lock installed

Next steps

- Measurement of (i) Rn emanation in lock (ii) Ar triplet lifetime in gas and LAr (iii) attenuation length of scintillation light in GERDA
- ► ready for start of commissioning, deployment of first Phase II string

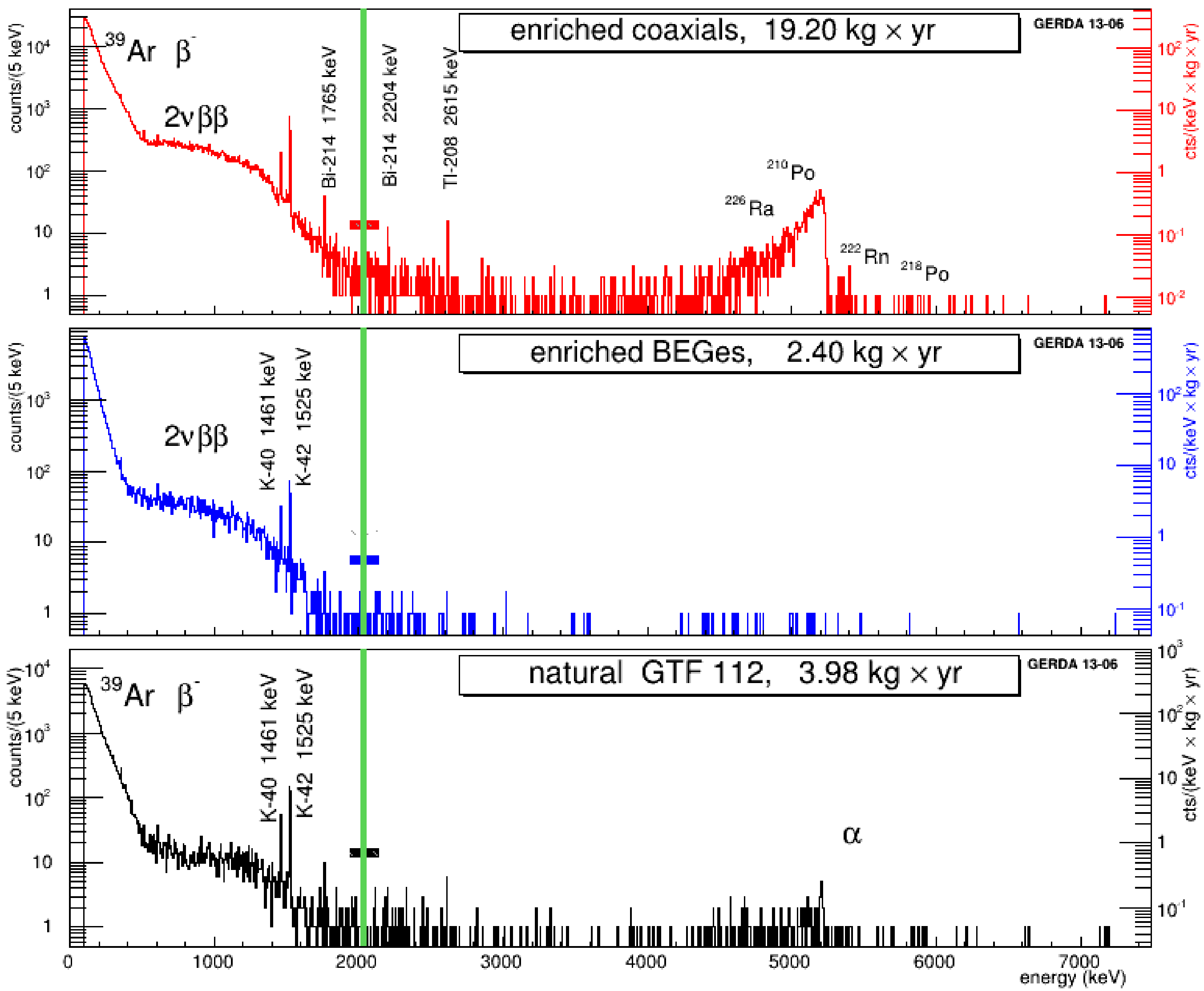
Phase II goal: sensitivity $T^{0\nu}_{1/2}$(Ge-76) ~ 1.4 ·10^{26} yr at 100 kg·yr

- BI to be reduced by another order of magnitude to 0.001 cts/ (keV kg yr)
  - more BEGe detectors with better PSD (& resolution)
  - instrumentation of LAr to veto specific backgrounds
  - less & cleaner material in detector holders, cables, ..
- get exposure of ~100 kg·yr within 3 years
  - double detector mass (15 kg semi-coaxial + 20 kg BEGe)
- Phase II commissioning to start by the summer of this year

	Phase I	Phase II
a : enrichment	0.86	0.88
ε : efficiency	0.72	0.72
M: source mass / kg	15	~35
M·t : exposure / (kg yr)	21.6	100
BI : background index	0.01	0.001
ΔE: e. resolution / keV	4.5	<3

End / Backup

Phase I measured spectra



muon veto & Ge-Ge anti-coincidences applied

Blinded region of ($Q_{\beta\beta}$ ± 20) keV

Visible backgrounds:
- **Ar-39**
- **Alphas**
- **Indicated isotopes**
  - ► **K-42 at 1525 keV**
- **2ν2β decay of Ge-76**

GERDA background model

source	location	units	*GOLD-coax* minimum	*GOLD-coax* maximum	*GOLD-nat* minimum
^{40}K c)	det. assembly	µBq/det.	152[136,174]	151[136,174]	218[188,259]
^{42}K c)	LAr	µBq/kg	106[103,111]	91[72,99]	98.3[92,108]
^{42}K c)	p^{+} surface	µBq		11.6[3.1,18,3]	
^{42}K c)	n^{+} surface	µBq		4.1[1,2,8.5]	
^{60}Co c)	det. assembly	µBq/det.	4.9[3.1,7.3]	3.2[1.6,5.6]	2.6[0,6.0]
^{60}Co c)	germanium	µBq	>0.4 †)	>0.2 †)	6[3.0,8.4]
^{214}Bi c)	det. assembly	µBq/det.	35[31,39]	15[3.7,21.1]	34.1[27.3,42.1]
^{214}Bi c)	LAr close to p^{+}	µBq/kg		<299.5	
^{214}Bi m)	radon shroud	mBq		<49.9	
^{214}Bi c)	p^{+} surface	µBq	2.9[2.3,3.9] †)	3.0[2.1,4.0] †)	1.6[1.2,2.1] †)
^{228}Th c)	det. assembly	µBq/det.	15.1[12.7,18.3]	5.5[1.8,8.8]	15.7[10.0,25.0]
^{228}Ac c)	det. assembly	µBq/det.	17.8[10.0,26.8]	<15.7	25.9[16.7,36.7]
^{228}Th m)	radon shroud	mBq		<10.1	
^{228}Ac m)	radon shroud	mBq		91.5[27,97]	
^{228}Th f)	heat exchanger	Bq		<4.1	

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Phase I

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficieny for 0νββ
ε_{psd}: signal acceptance

Data set	Exposure (kg yr)
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$\langle f_{76} \rangle$	$\langle f_{av} \rangle$	$\langle \varepsilon_{fep} \rangle$	$\langle \varepsilon_{psd} \rangle$	$\langle \varepsilon \rangle$
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ±0.02	0.663 ±0.022