Upgrades for GERDA Phase II

Mark Heisel
for the collaboration

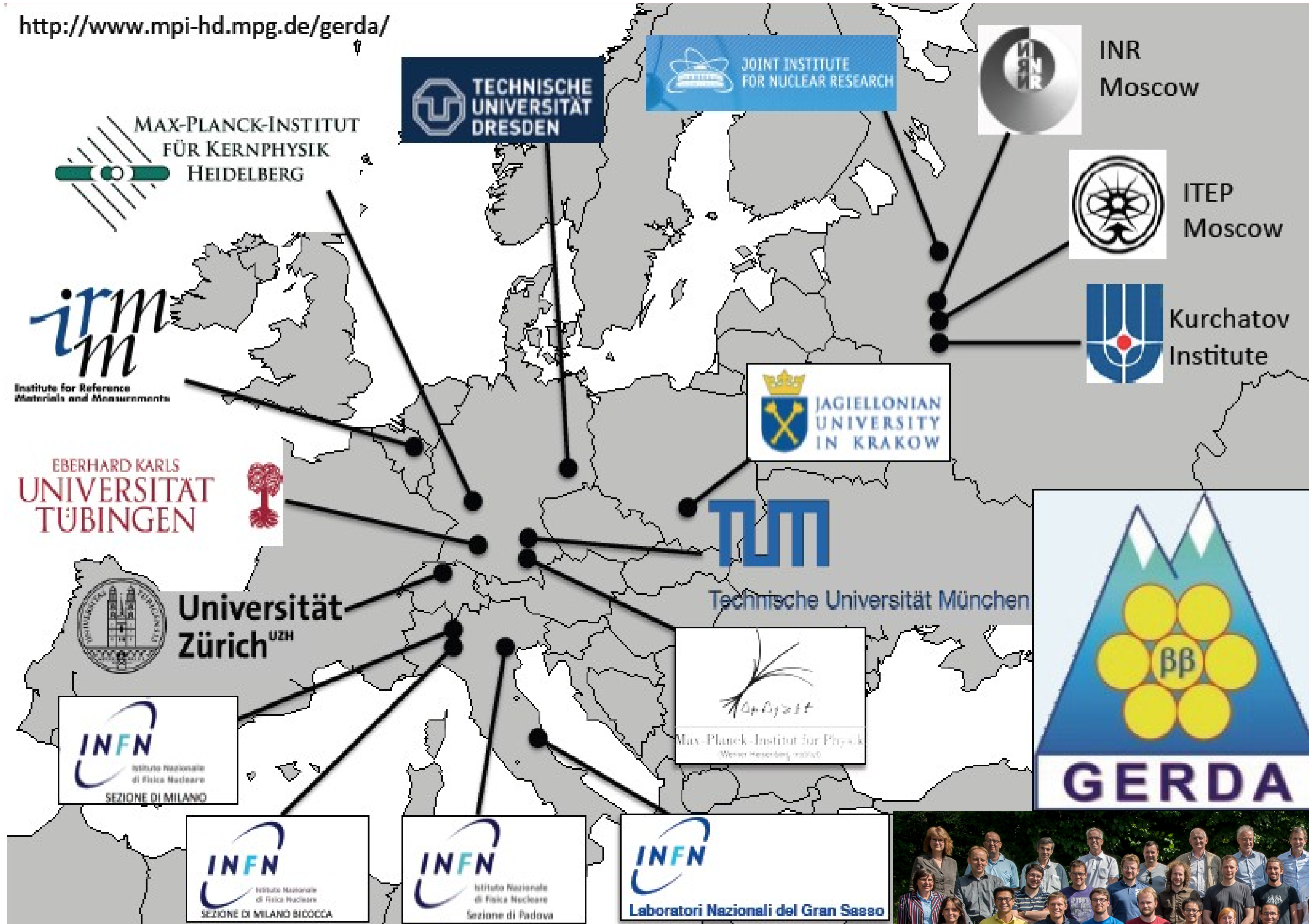
DBD2014
Hawaii2014

Hawaii, October 7, 2014

Max-Planck-Institut
für Kernphysik

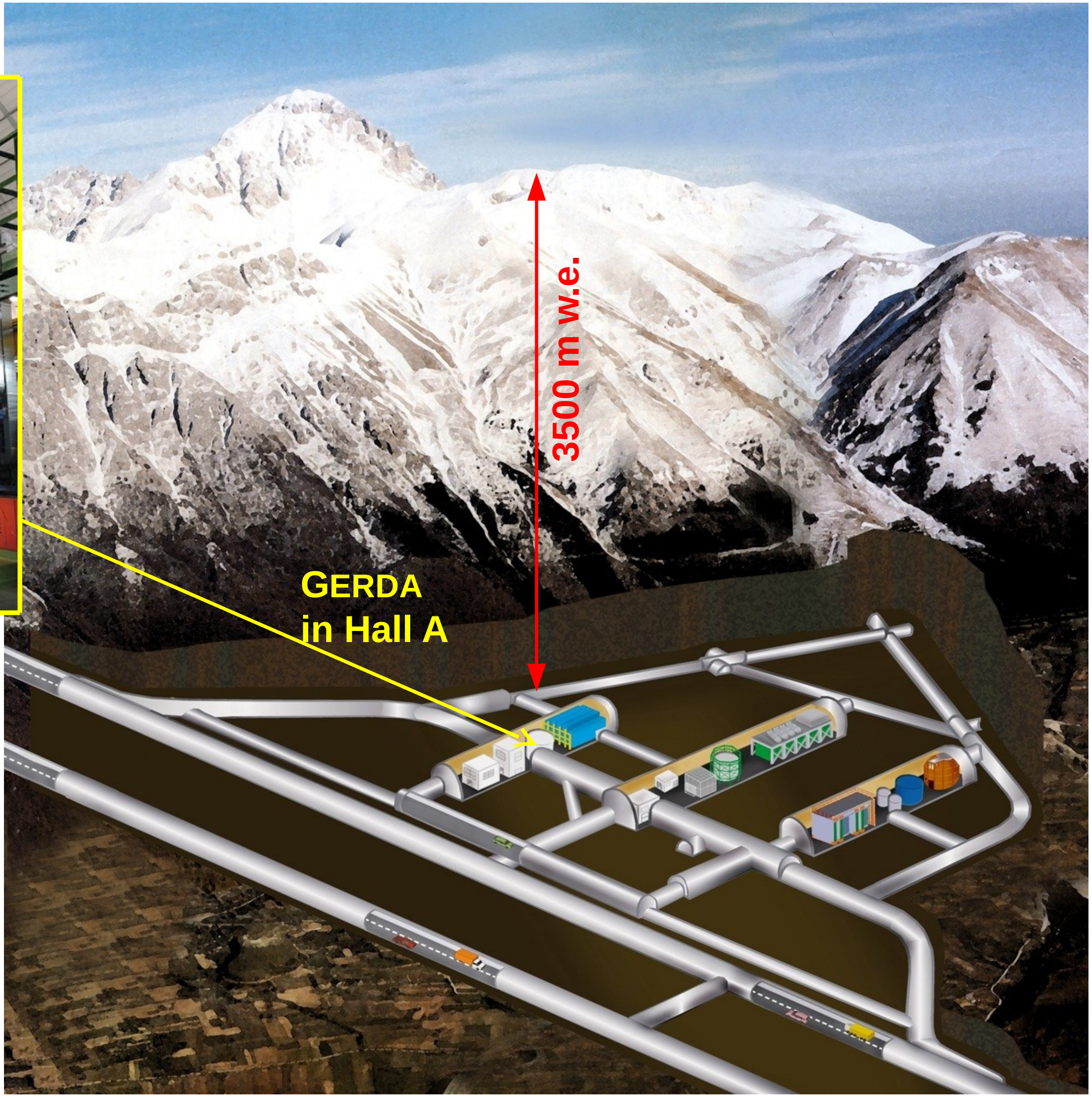
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

The collaboration



16 Institutions
~100 members

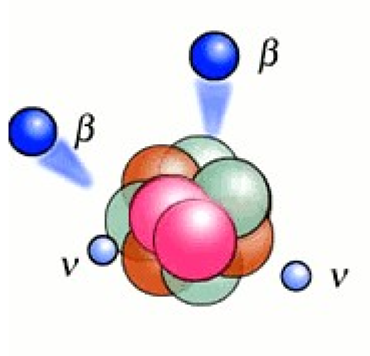
GERDA at Gran Sasso



Underground site to reduce cosmic muon flux by ~1,000,000

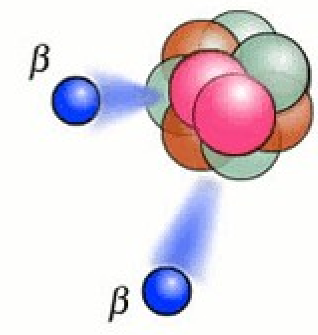
Motivation for 0νββ decay searches

2 neutrino
double beta decay



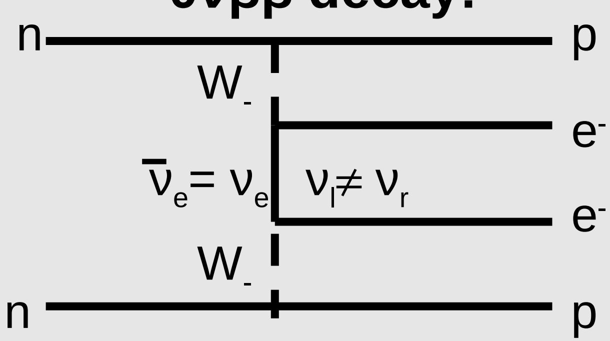
allowed by SM, $\Delta L = 0$

0 neutrino
double beta decay



forbidden in SM, $\Delta L = 2$

0νββ decay:

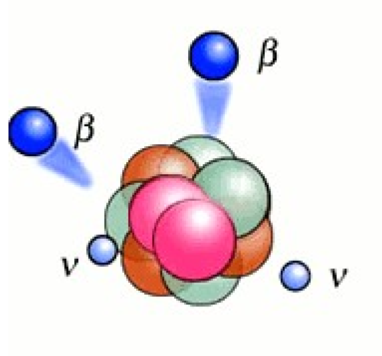


exchange of majorana neutrino

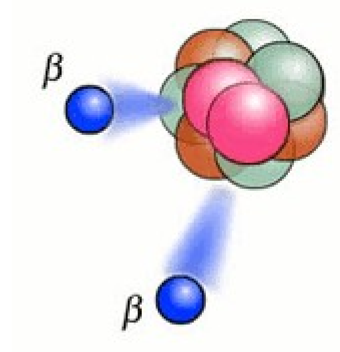
- ► Majorana nature of neutrino
- ► lepton number violation $\Delta L=2$!
- ► effective ν mass: $\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$
- ► access to ν mass hierachy

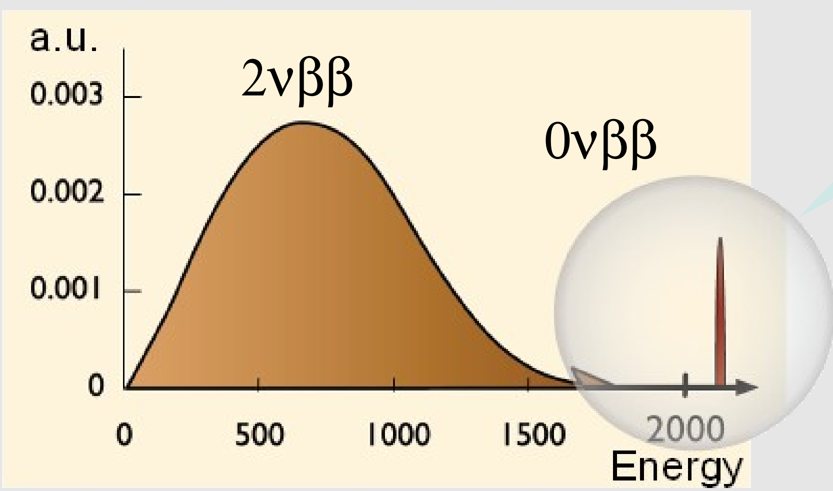
Double Beta Decay detection in ^{76}Ge

2 neutrino
double beta decay



0 neutrino
double beta decay





electron-energy spectrum

search for 0νββ peak at
$Q_{\beta\beta}$ = 2039 keV (^{76}Ge)

Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

half life — phase space integral — nuclear matrix element — effective ν mass

Double Beta Decay detection in GERDA

Sensitivity:

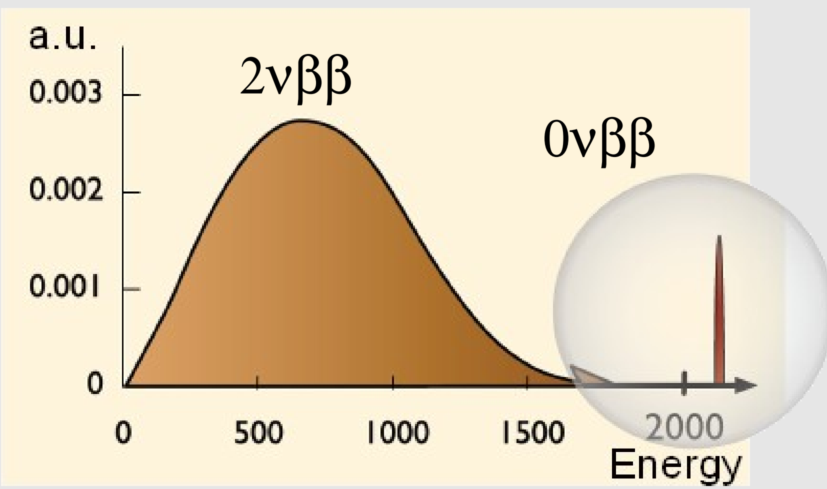
$$T_{1/2}^{0\nu} \sim \epsilon_{eff} \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

M·t = exposure

ε_{eff} = detection efficiency

ΔE = energy resolution

B = background index



electron-energy spectrum

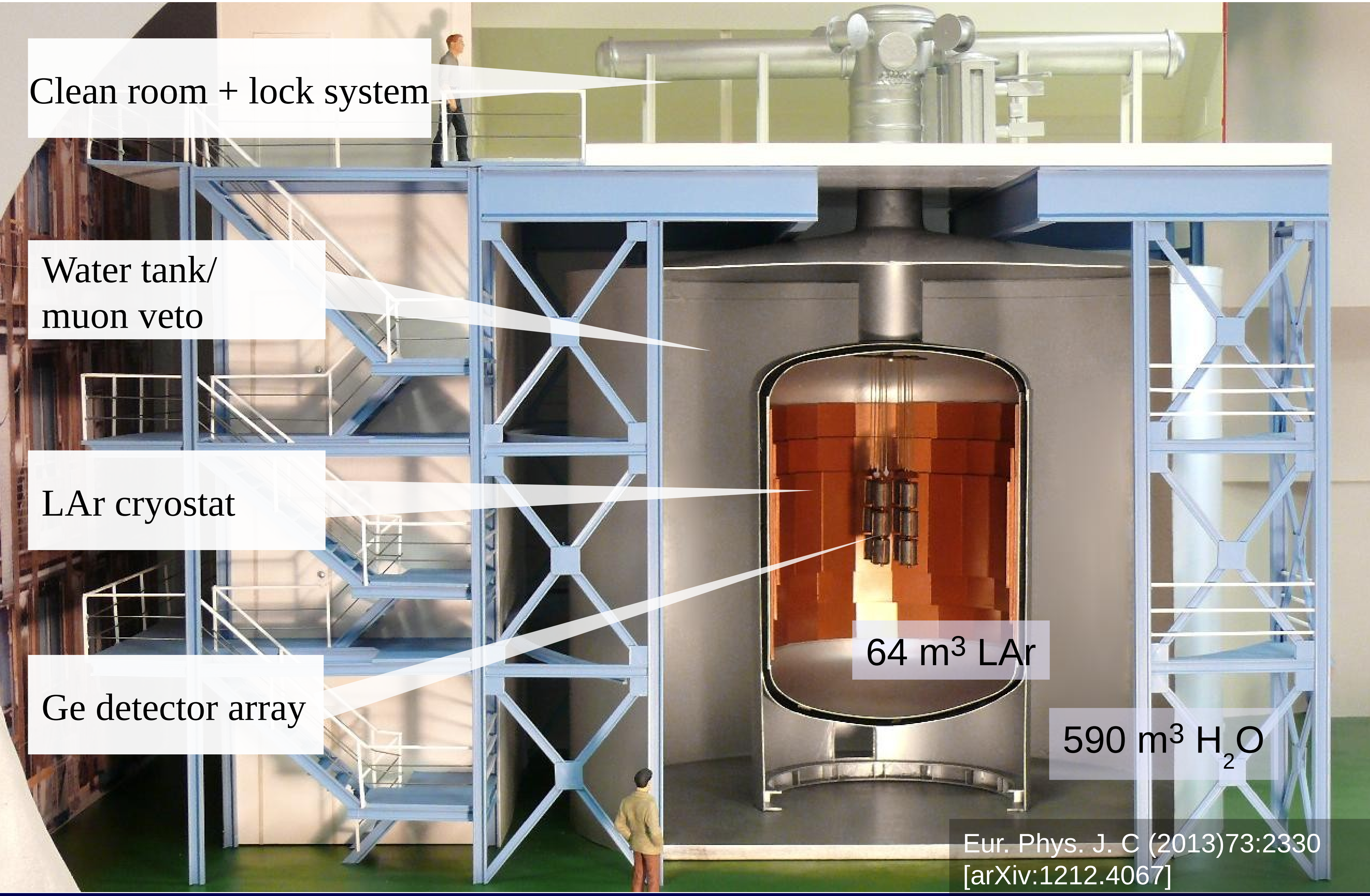
Detector = Source

detectors enriched to 86% ^{76}Ge

Phase	I	II
Exposure [kg ·yr]	15	100
Bg [counts/(keV·kg·yr)]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$ [eV]	0.23-0.39	0.09-0.15

A. Smolnikov, P. Grabmayr PRC 81 028502(2010)

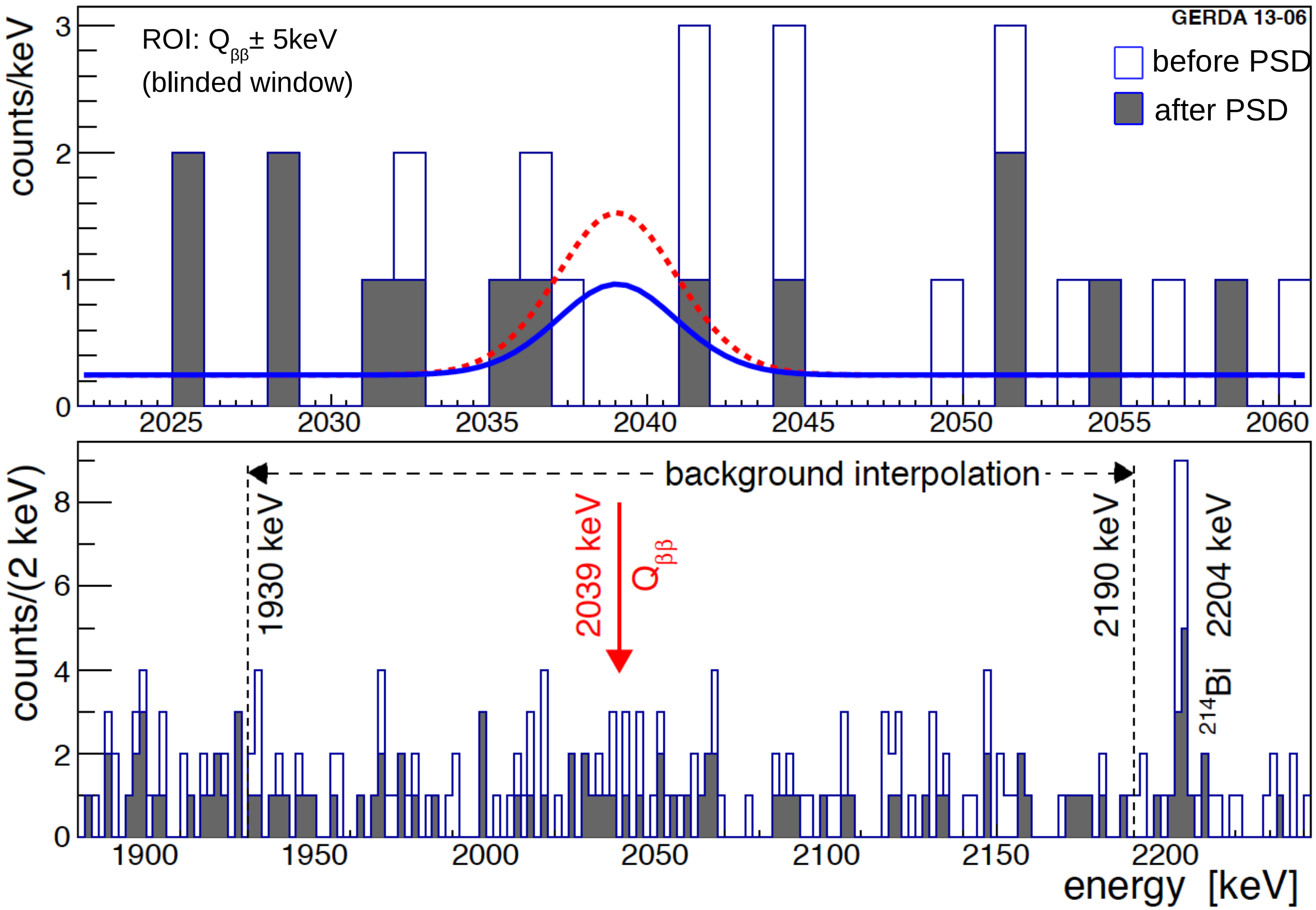
Germanium Detector Array



GERDA Phase I result ($0\nu\beta\beta$)

GERDA: 90% lower limit ($T^{0\nu}_{1/2}$) [Phys. Rev. Lett. 111 (2013) 122503]

Claim: $T^{0\nu}_{1/2} = 1.19\times10^{25}$ yr [Phys. Lett. B 586 198(2004)]



Exposure:
21.6 kg·yr

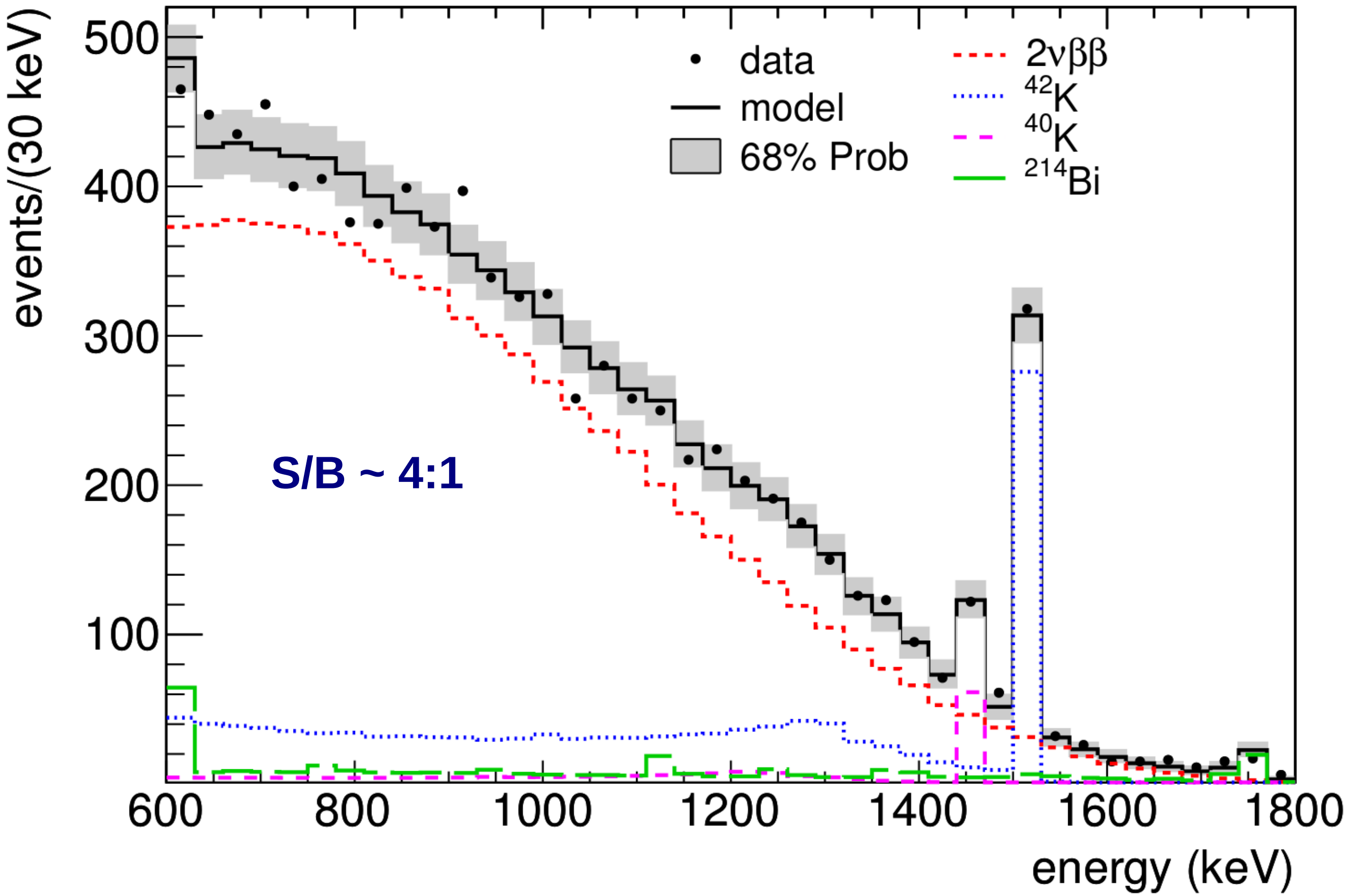
Background events (after PSD):
2.5 expected
3 observed

Expected signal Events (after PSD):
< 3 from our limit
5.9 ± 1.4 from claim

→ **claim is rejected with 99% prob.**

Frequentist: profile likelihood fit → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)

GERDA Phase I result (2νββ)



$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08\ \text{fit}}\ {}^{+0.11}_{-0.06\ \text{syst}}) \cdot 10^{21}\ \text{yr} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\ \text{yr}$$

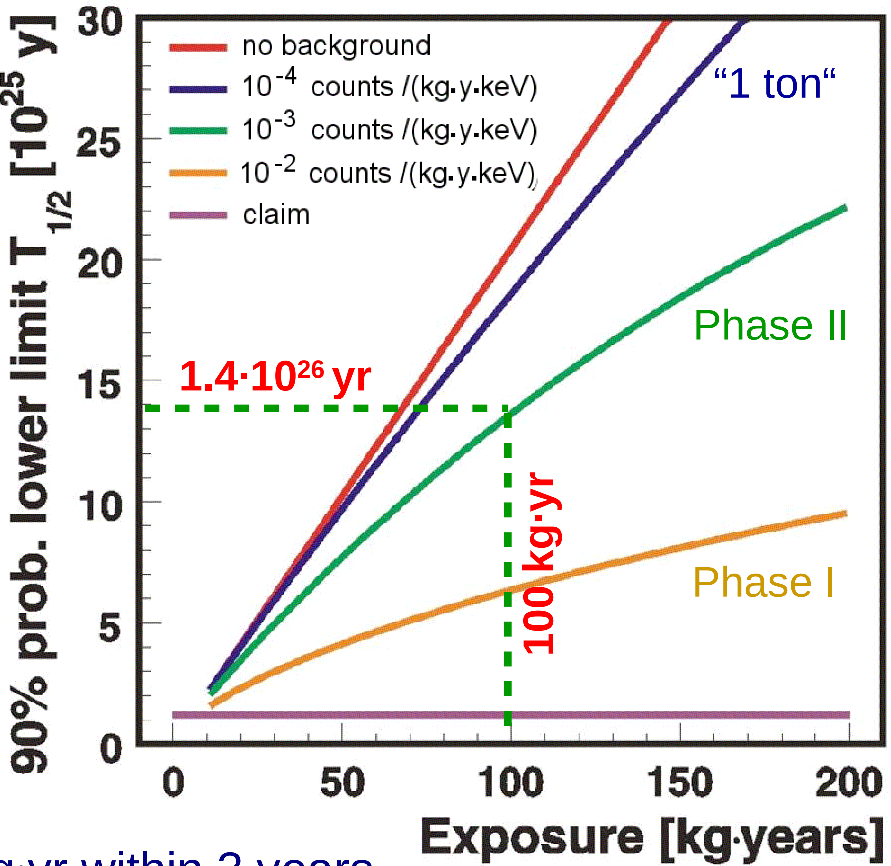
[J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110]

GERDA sensitivity

Sensitivity:

$$T_{1/2} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{if } \underbrace{M \cdot t \cdot BI \cdot \Delta E \ll 1}_{\text{i.e. "no background"}} \\ a \cdot \varepsilon \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} & \end{cases}$$

- a = enrichment fraction
- ε_{eff} = detection efficiency
- M·t = exposure
- ΔE = energy resolution
- BI = background index

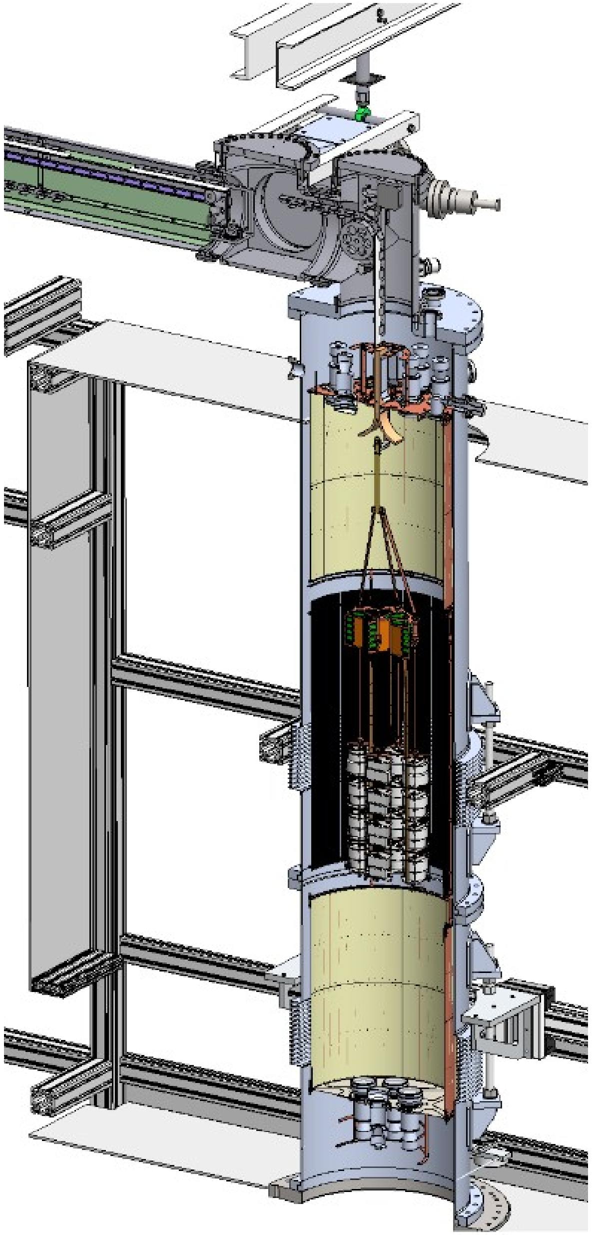


Phase II upgrade strategy:

► to collect total exposure: 100 kg·yr within 3 years
→ produce ~20 kg more detectors

► to reach background index: 1 x 10^{-3} cts/(keV·kg·yr)
→ use improved detector support & electronics
→ use active background suppression (PSD & LAr veto)

New lock

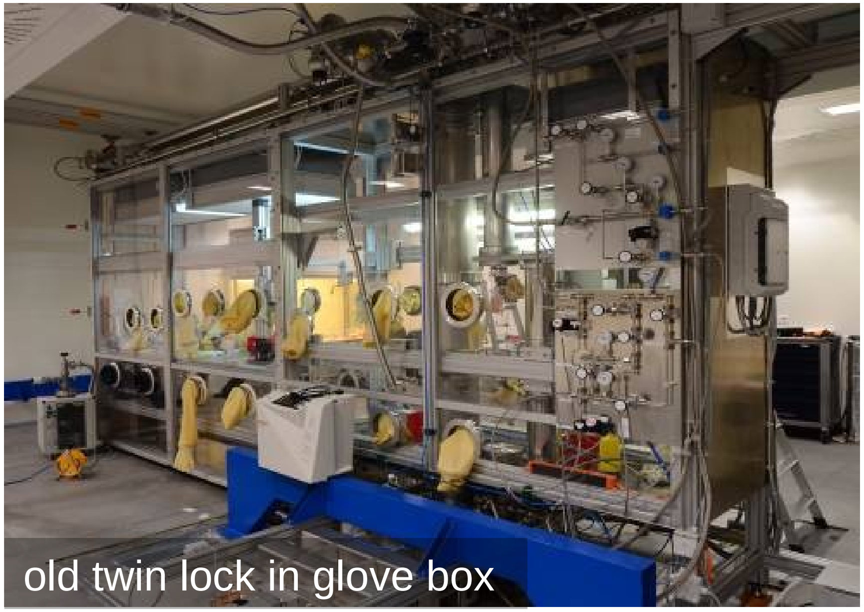


New lock for Phase II in GERDA cleanroom on top of cryostat:

► replaces Phase I twin lock

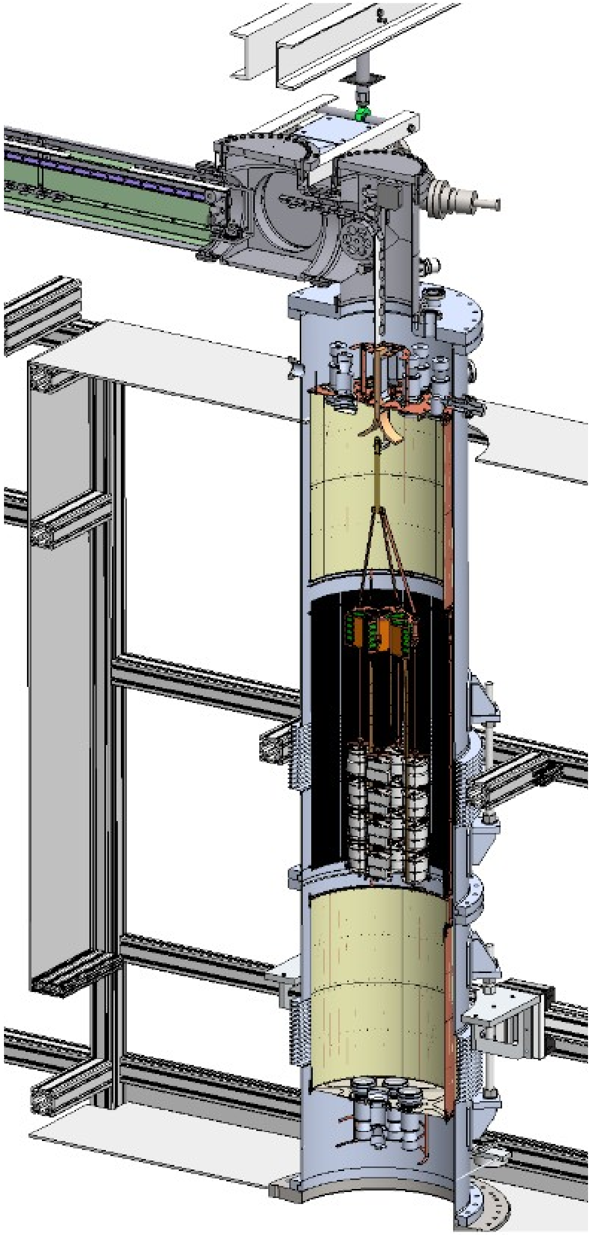
► larger Ø = 0.52 m, h = 2.8 m

► placed in glovebox to handle detectors in GN atmosphere



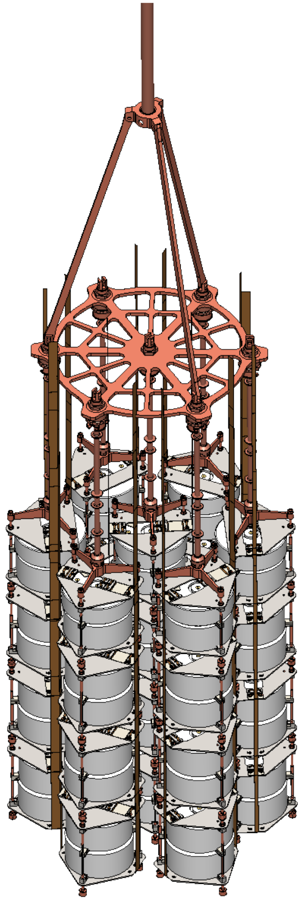
old twin lock in glove box

New lock

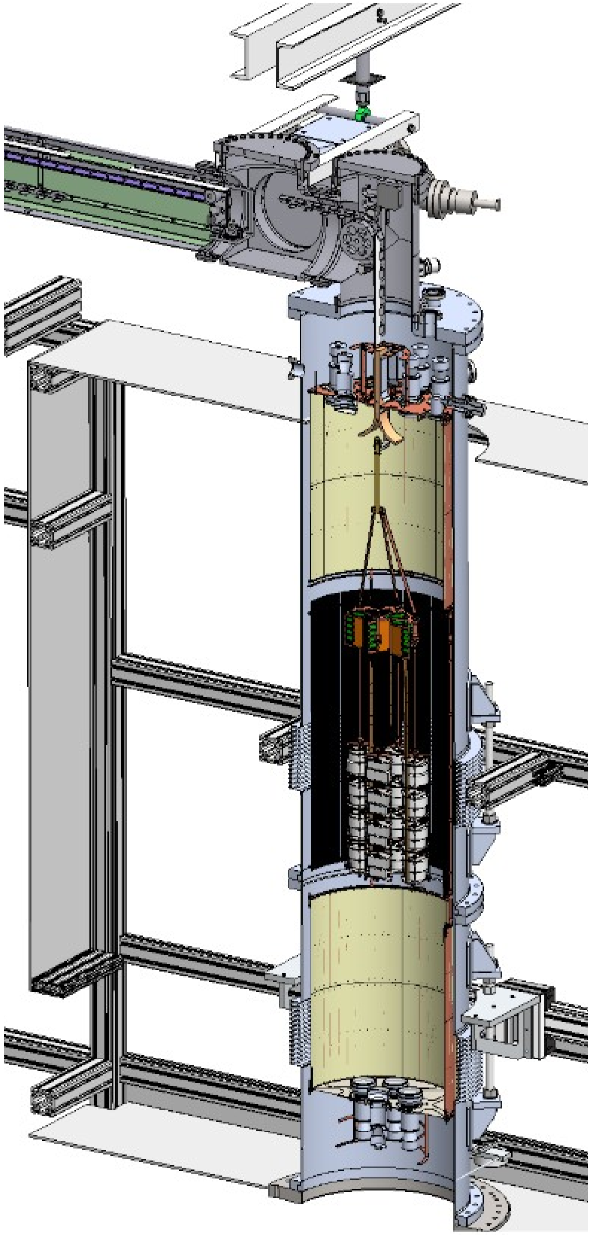


New lock for Phase II in GERDA cleanroom on top of cryostat:

- ► space to deploy 7 detector strings



New lock

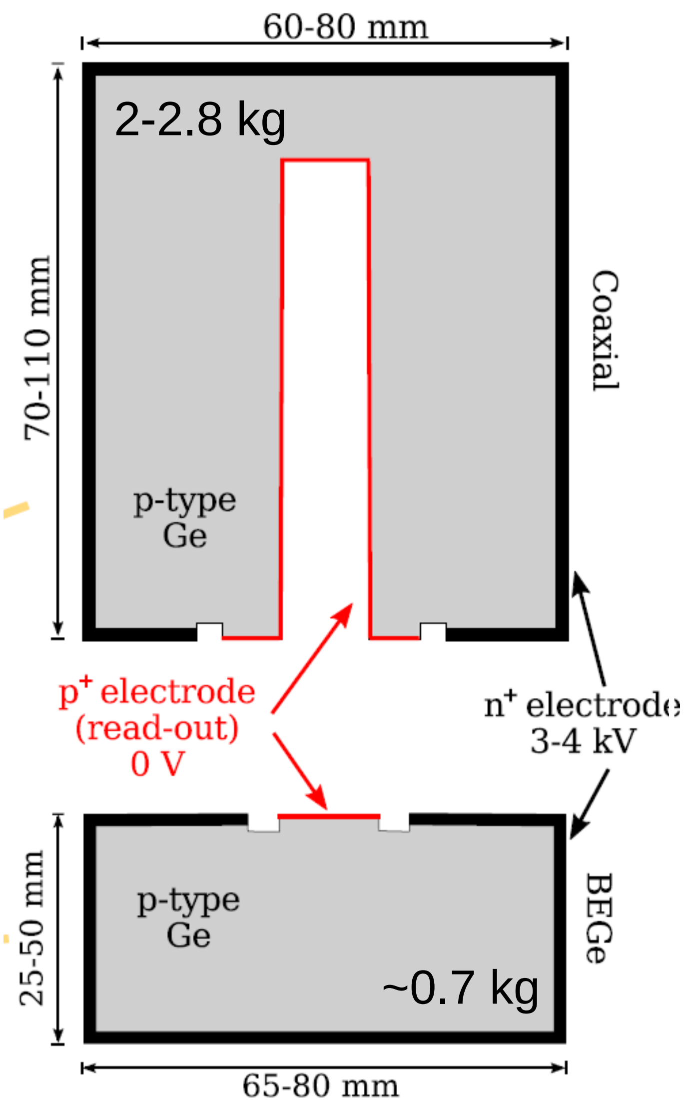


New lock for Phase II in GERDA cleanroom on top of cryostat:

► deploy retractable LAr light instrumentation for active veto

Ø = 0.49 m
h = 2.6 m

Detectors in Phase I & II



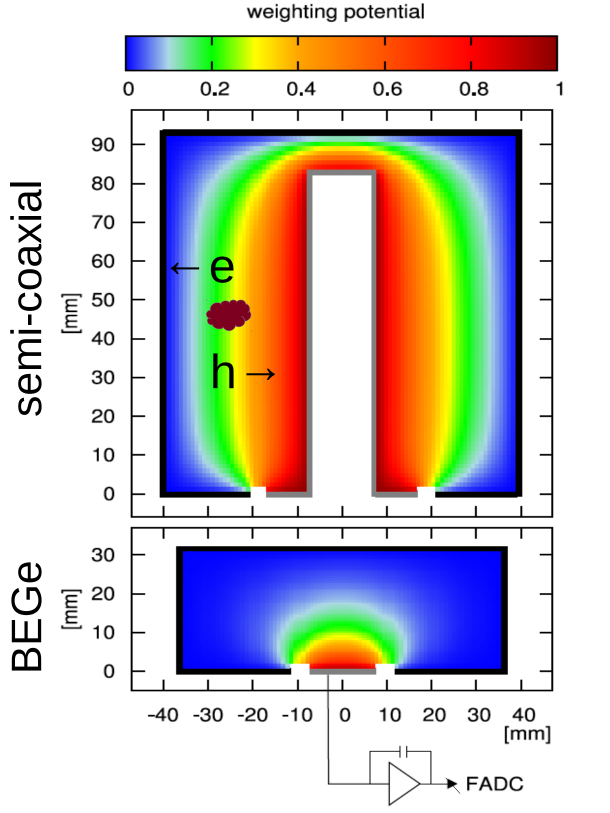
Phase I:

- use 8 refurbished semi-coaxial diodes from HdM & IGEX (total mass 17.67 kg)
- use pulse shape discrimination (PSD) based on artificial neural network
- also use 5 ^{enr}BEGe detectors (3.63 kg)

Phase II:

- use 30 ^{enr}BEGe detectors (20.5 kg) (in addition to semi-coaxial ones)
- small 'point-like' contact allows for superiour PSD & ΔE
- already tested in Phase I

Detectors in Phase I & II



$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

q= charge, v = velocity
(Shockley-Ramo theorem)

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Phase II:

- use 30 ^{enr}BEGe detectors (20.5 kg) (in addition to semi-coaxial ones)
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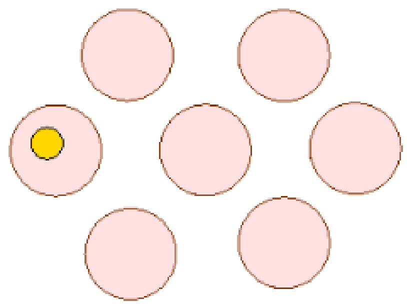
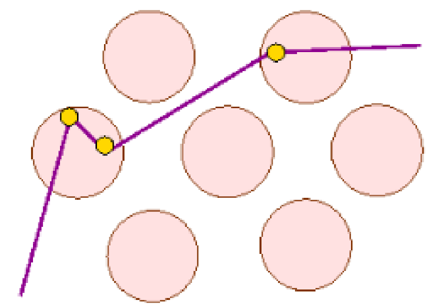
- already tested in Phase I

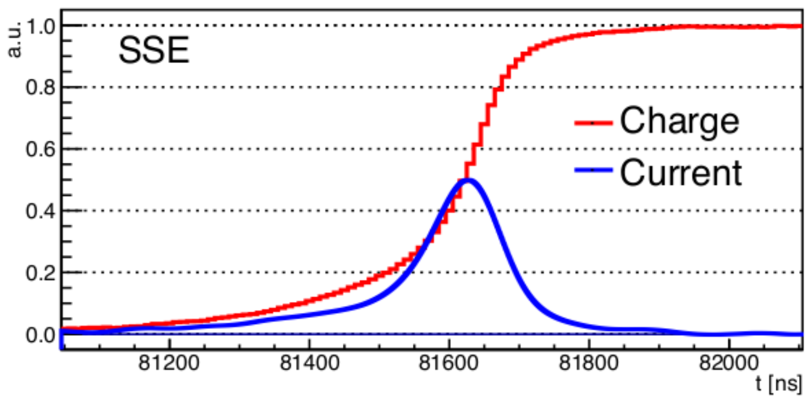
BEGe pulse shape discrimination

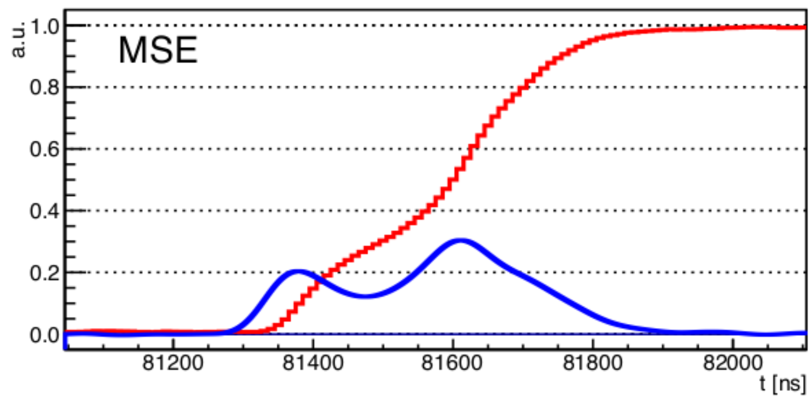
single site events: ββ, DEP
(signal like)



multi site events: Compton
(background like)





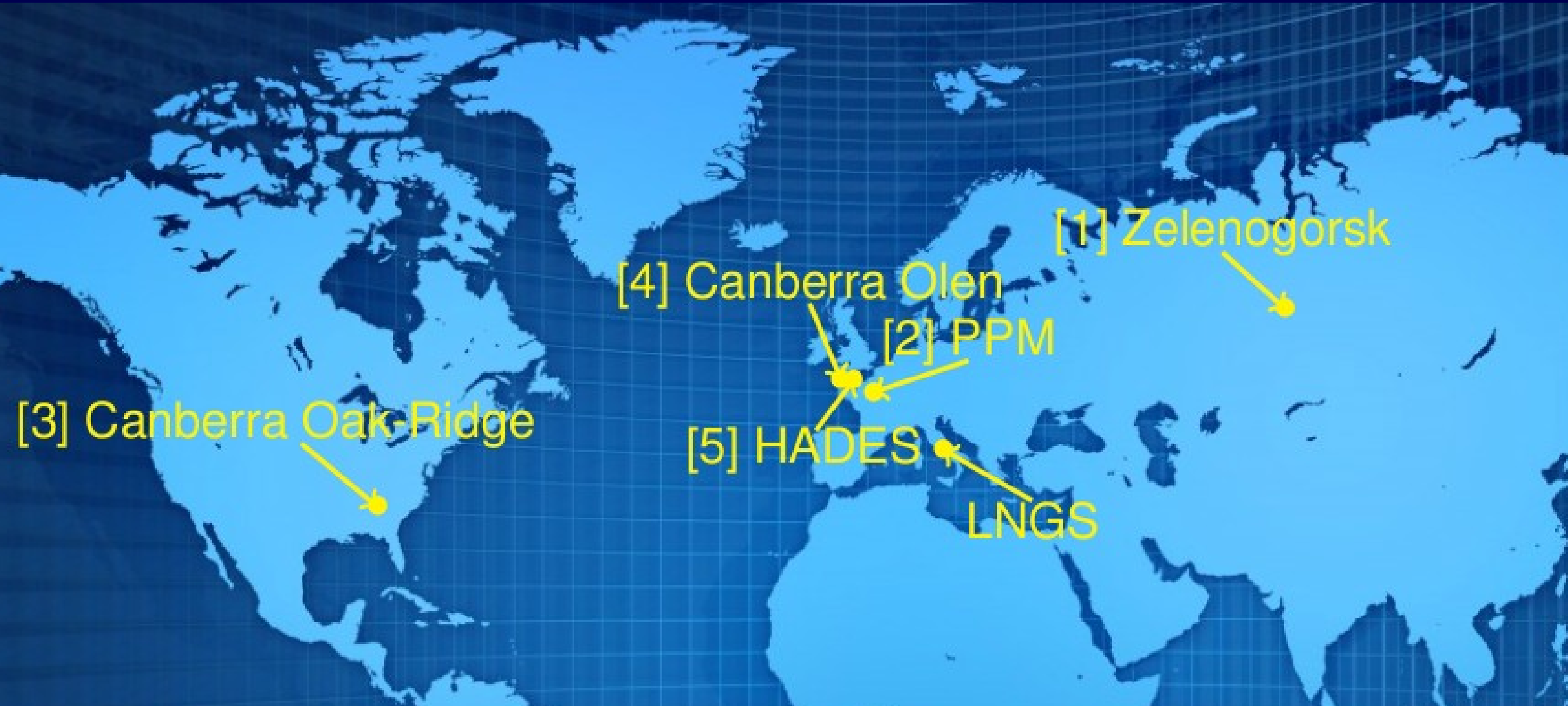


- well established cut parameter A/E = current pulse / charge pulse

- 0νββ efficiency = 92±2 % determined from DEP efficiency & simulation
- 2νββ efficiency = 91±5 % in good agreement to DEP efficiency
- reject > 80% of background events

[EPJ C73 (2013) 2583]

New detectors: from raw material to diode production

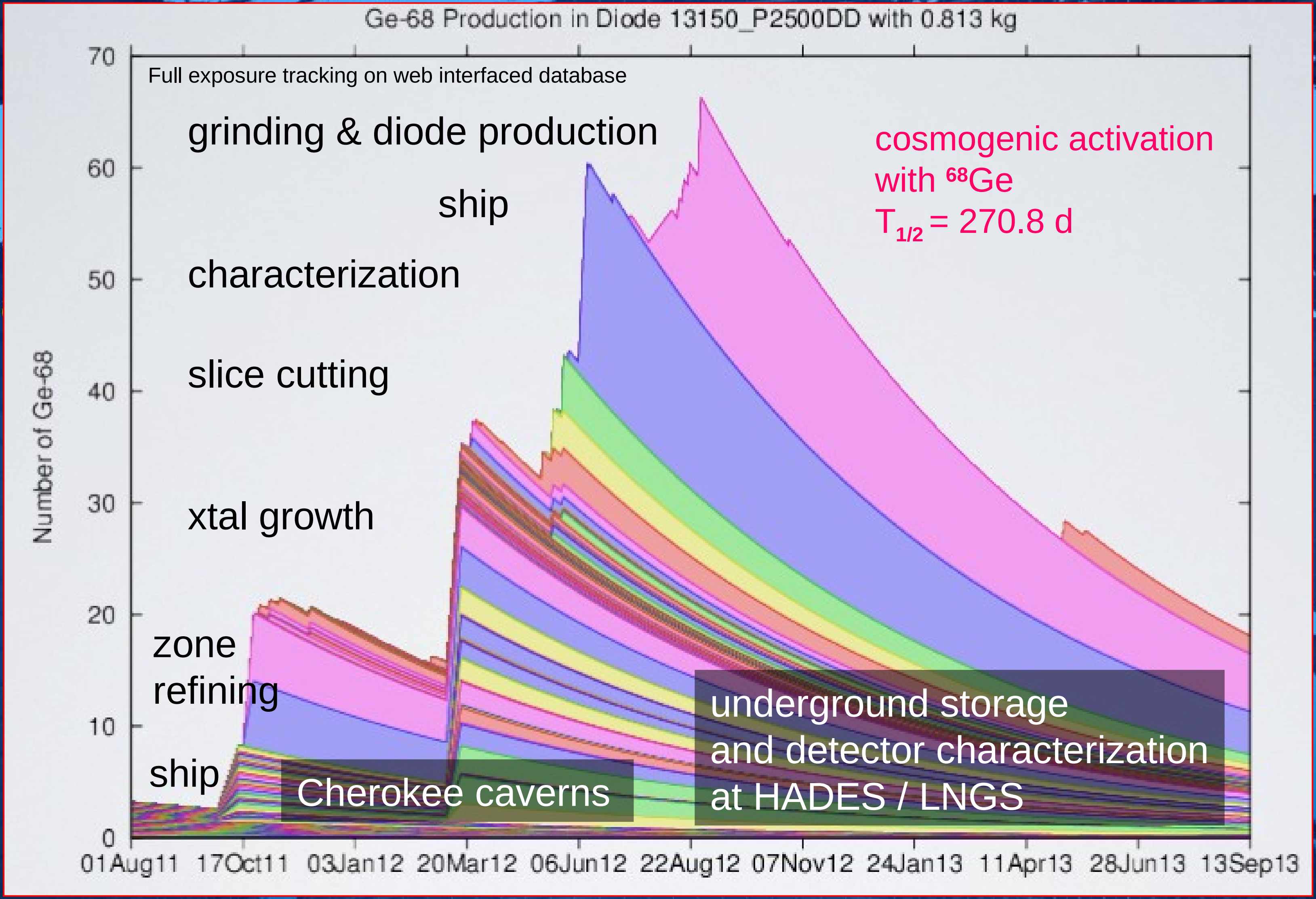


Ge crystal

- [1] Germanium enrichment, ECP, Zelenogorsk, Russia — 53.3 kg $^{enr}GeO_2$, 88% ^{76}Ge
- [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 (20.5 kg)
- [5] Diode storage and characterization, HADES, Mol, Belgium

New detectors: from raw material to diode production

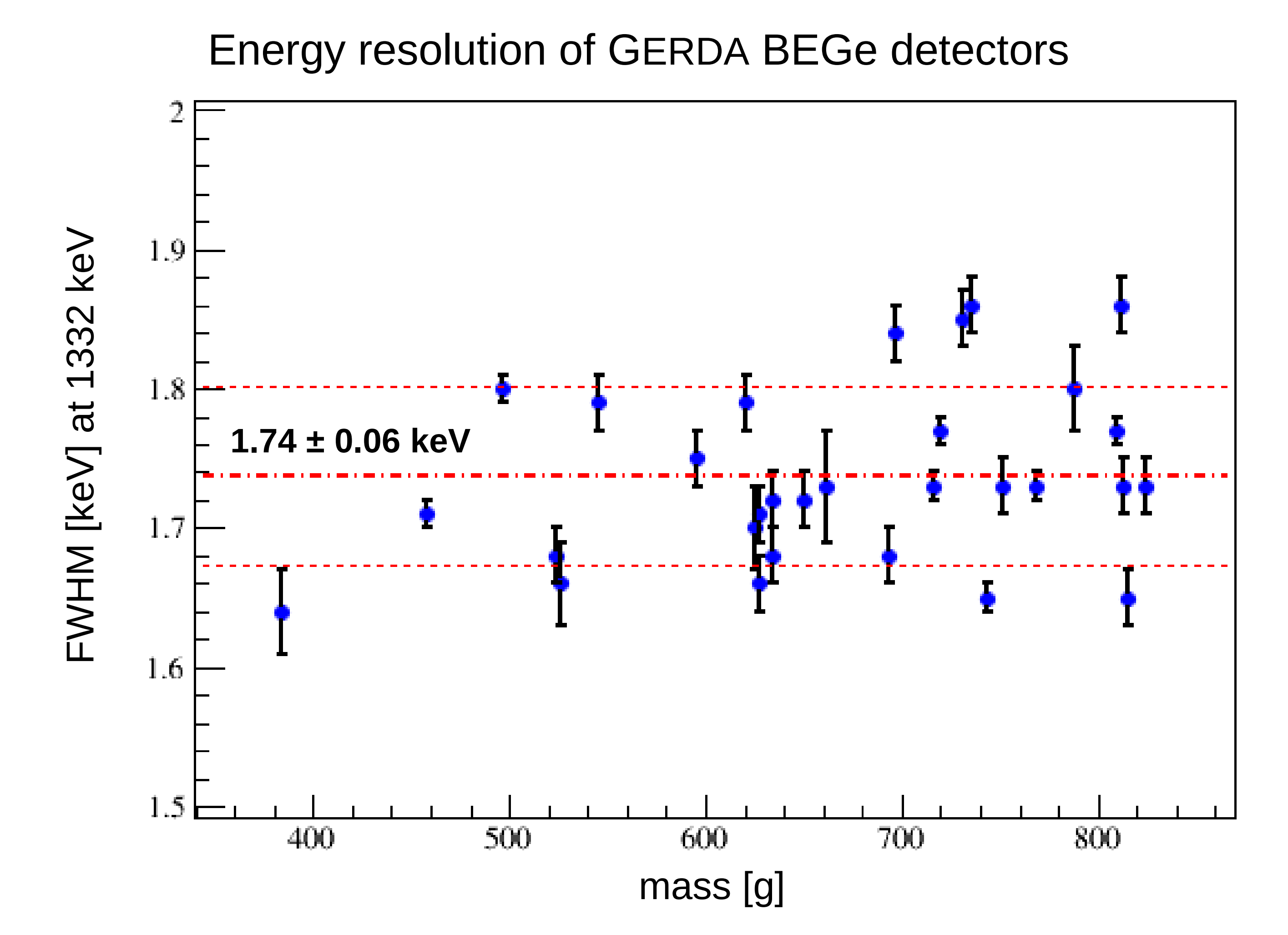
[3] C



New detectors: from raw material to diode production

[3] Canbe

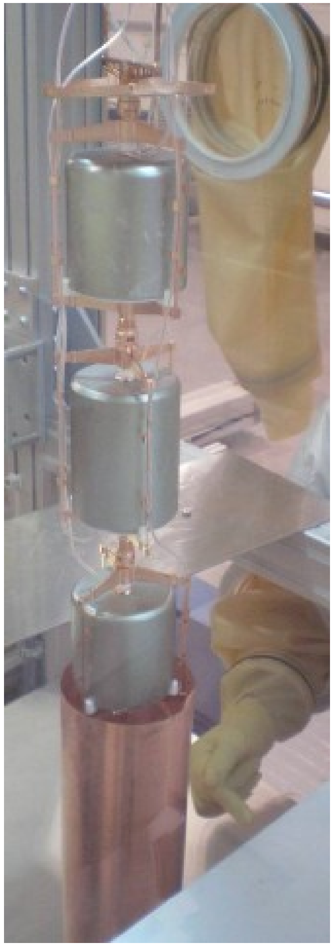
[1]
[2]
[3]
[4]
[5]



New detector strings

Phase I

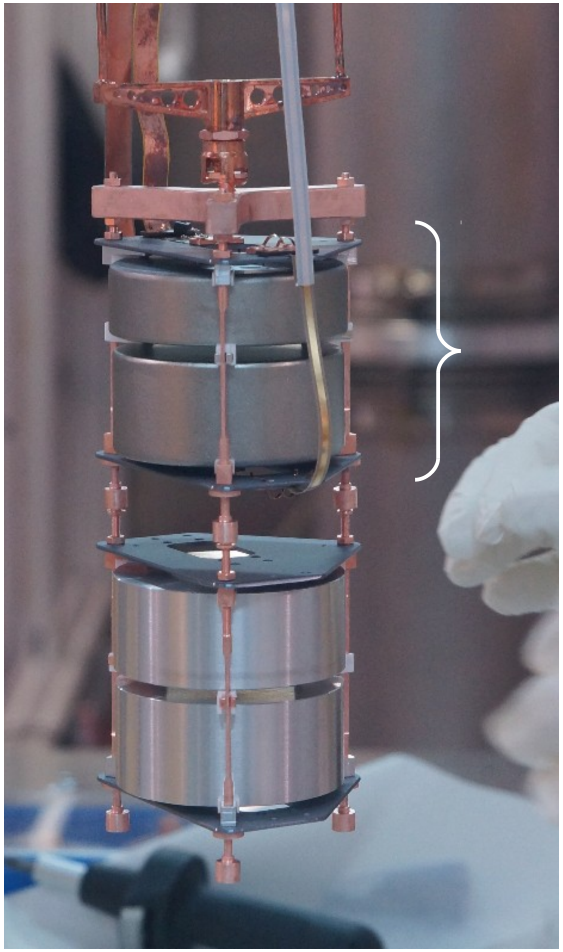
3 strings /w coaxial det



1 string /w BEGe det

Phase II

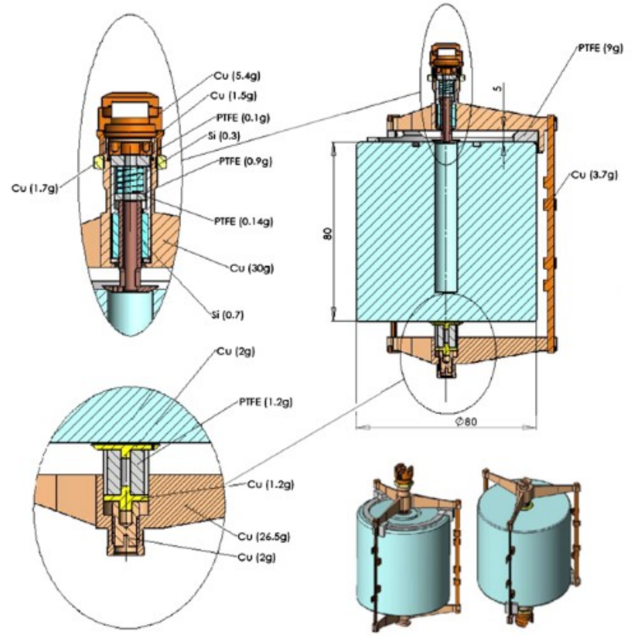
4 strings /w BEGe det
+3 strings coaxial det



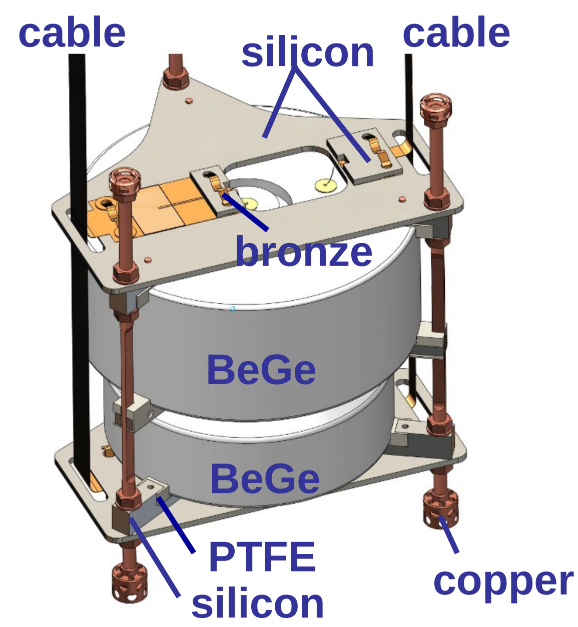
detector module /w BEGe pair

Detector holders

Phase I



Phase II

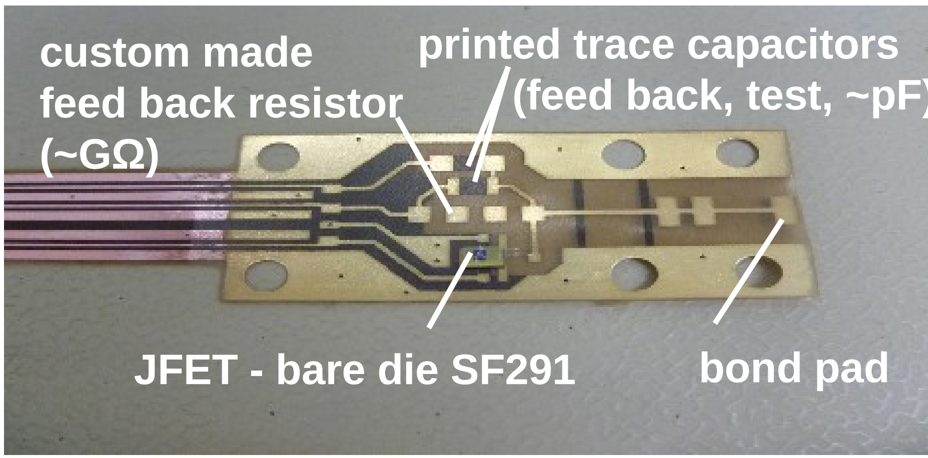


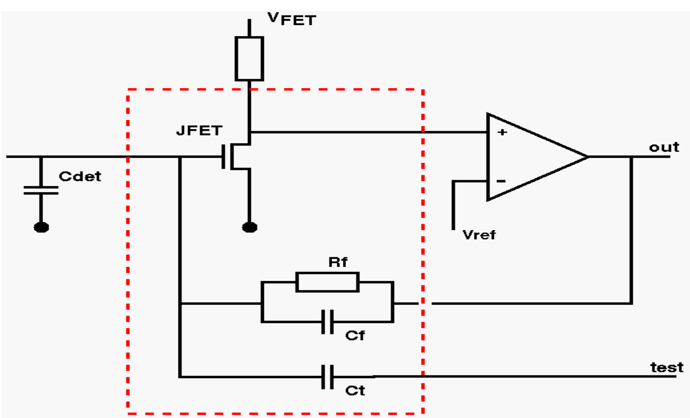
material	per 2.3 kg detector mass	per 1.3 kg detector mass
copper	81.4 g	25.8 g
PTFE	11.3 g	2.1 g
bronze	-	1.0 g
silicon	0.3 g	40.3 g

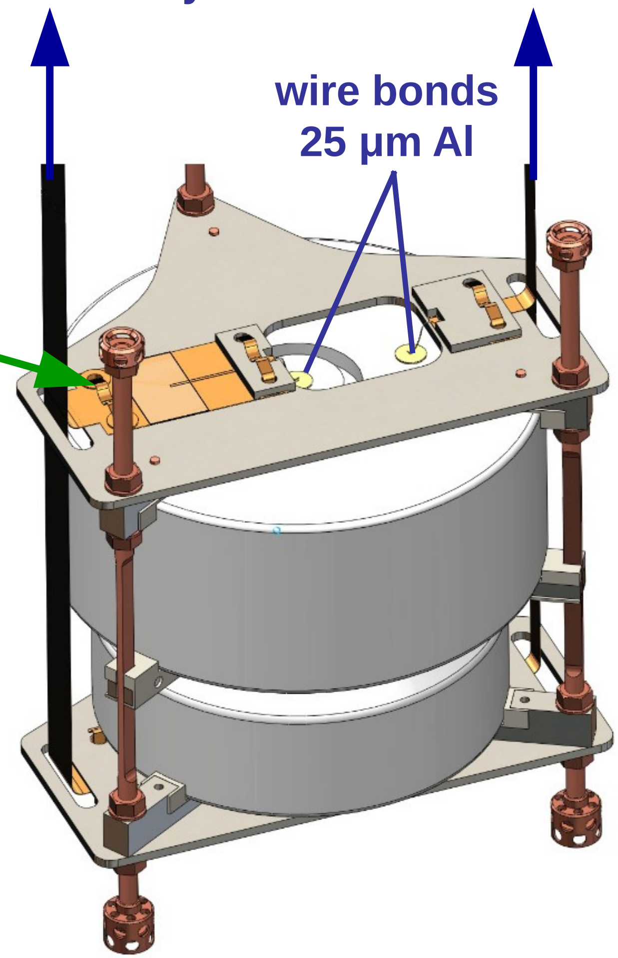
► significant amount of copper & PTFE replaced by intrinsically radio-pure silicon

Front end electronics

Phase II:	very front end electronics are very close to detector!
Phase I:	distance was > 30 cm





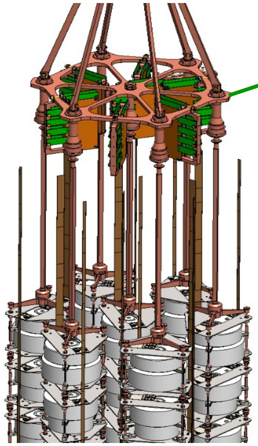


Front end electronics

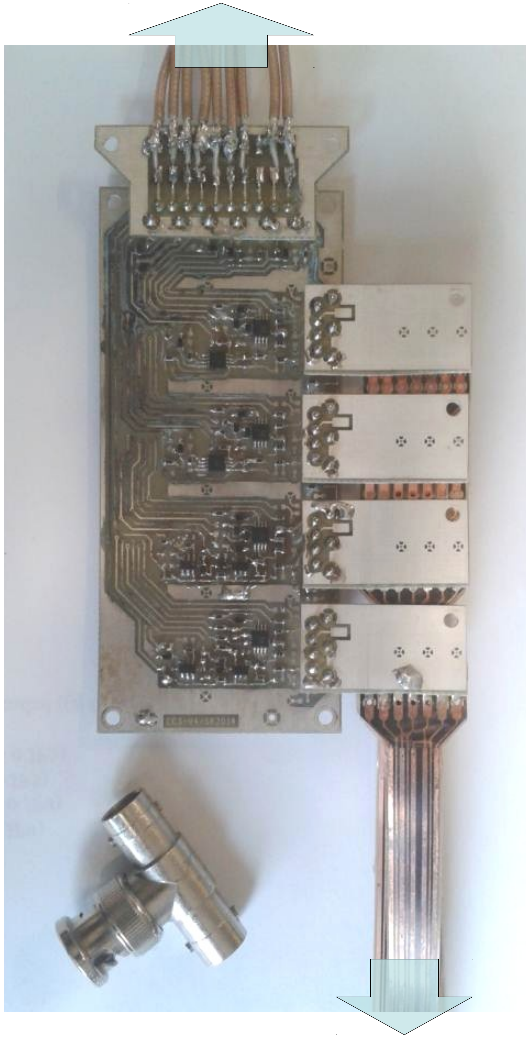
CC3: 4 Channel Charge Sensitive Preamplifier

→ upgrade of CC2 preamplifier of GERDA Phase I, based on commercially available op-amps

- **low-noise:**
  - → 0.7 keV FWHM pulser resolution
  - → 2.6 keV FWHM at 2.6 MeV with BEGe detector
  - → 20 MHz bandwidth allows PSD (A/E)
- **cryogenic:**
  - → suitable for operation in liquid Argon (50 mW/channel)
- **radio-pure electronics:**
  - → ≈ 50 µBq/channel (including pins) expected



10 m long coaxial cables to feedthrough flange

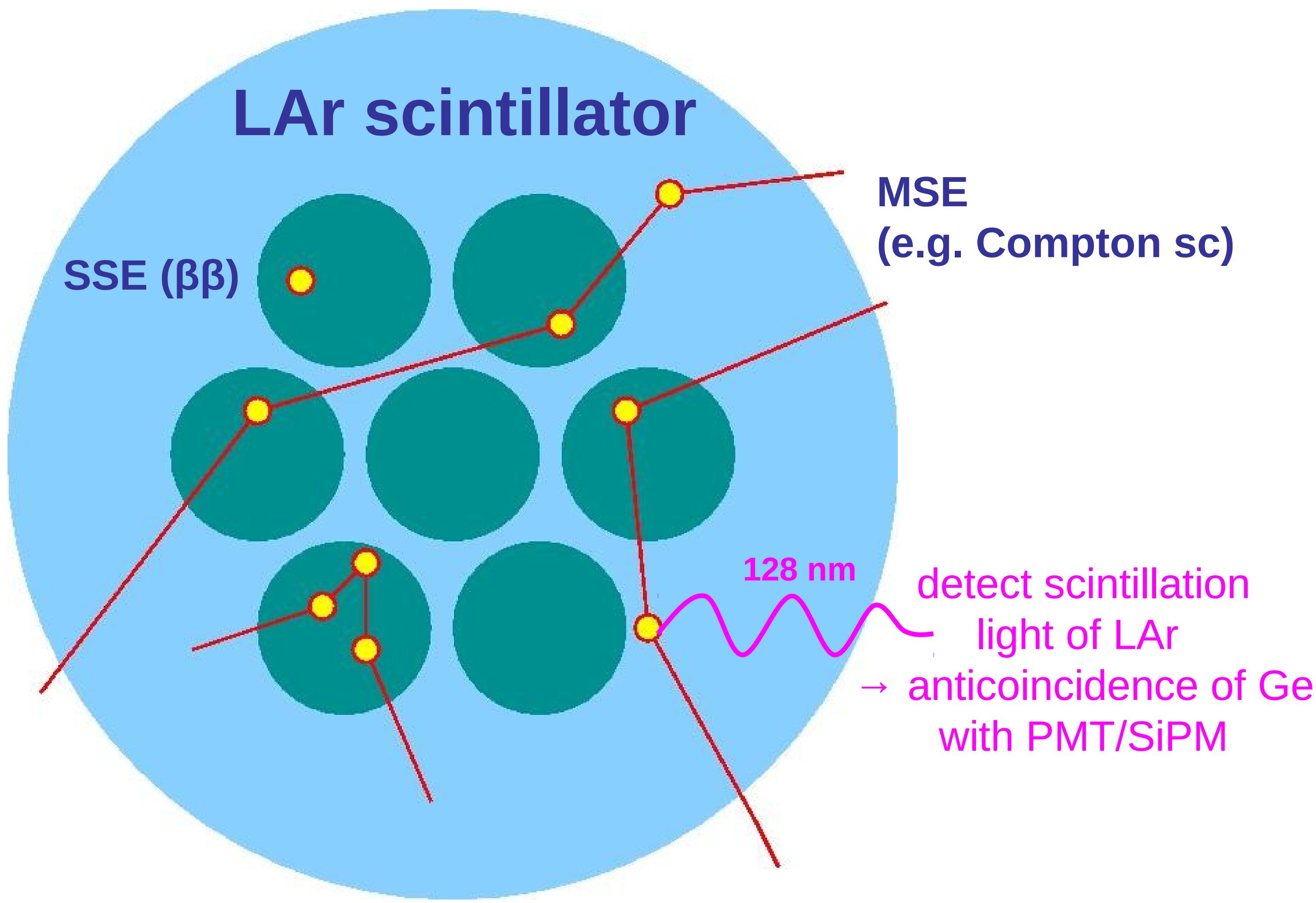


prototype version (FR4 laminate)

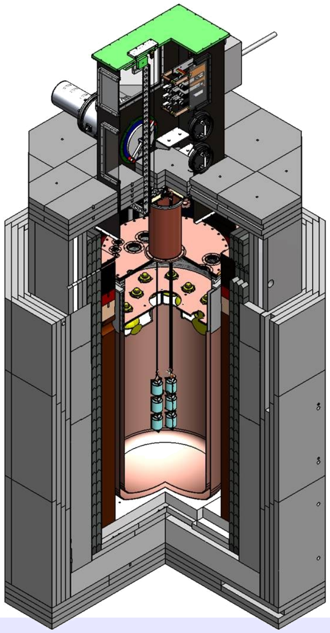
4x 0.5-1 m flex cables to VFE and detectors

Principle of liquid argon scintillation veto

Veto on events that deposit energy in liquid argon (40,000 γ/keV)

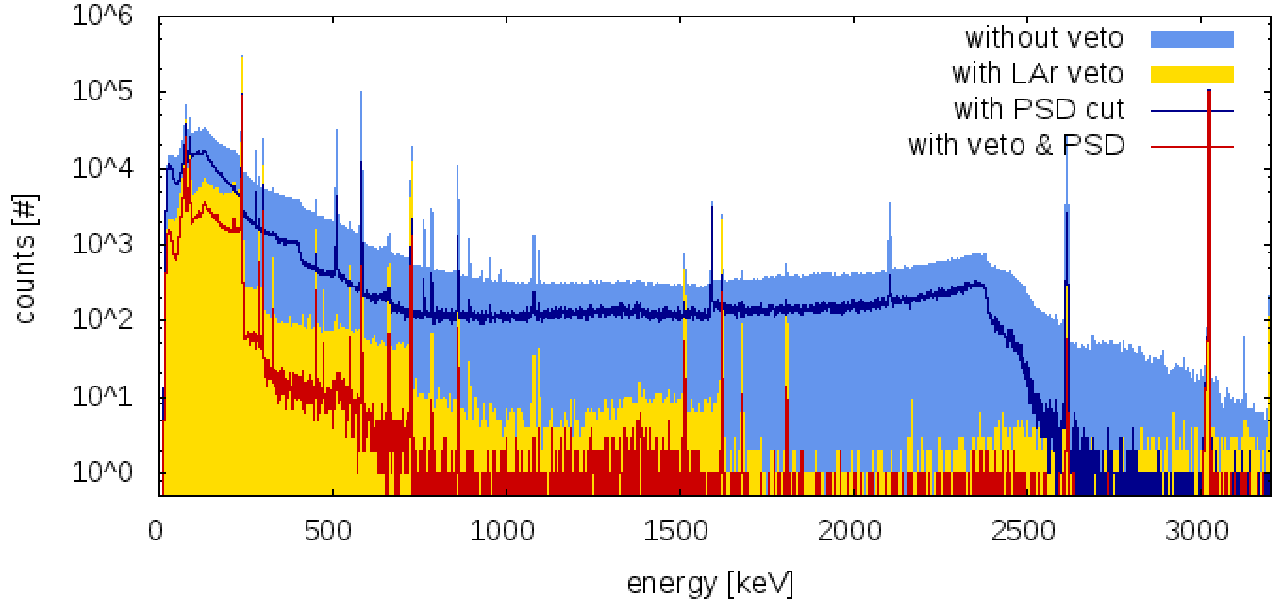


LArGe test bench



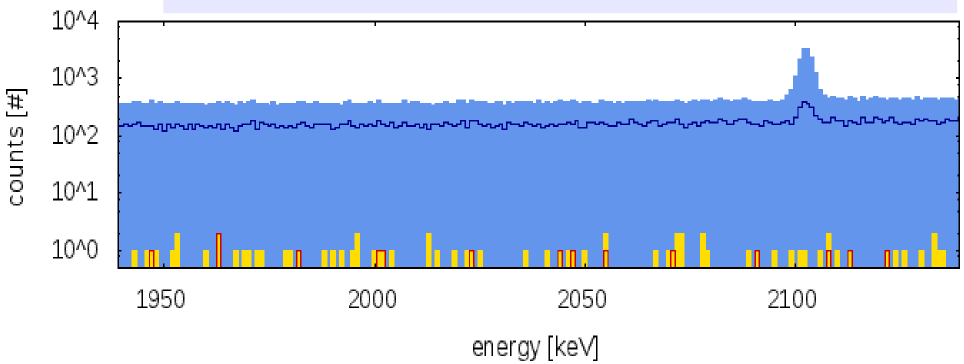
LArGe test bench
at Gran Sasso

e.g. close-by Th-228 source



source	position	suppression factor		
		LAr veto	PSD	total
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300
^{226}Ra	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3
	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5
^{228}Th	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15
	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300

… suppression at region of interest



Liquid argon light instrumentation

9x 3" PMT

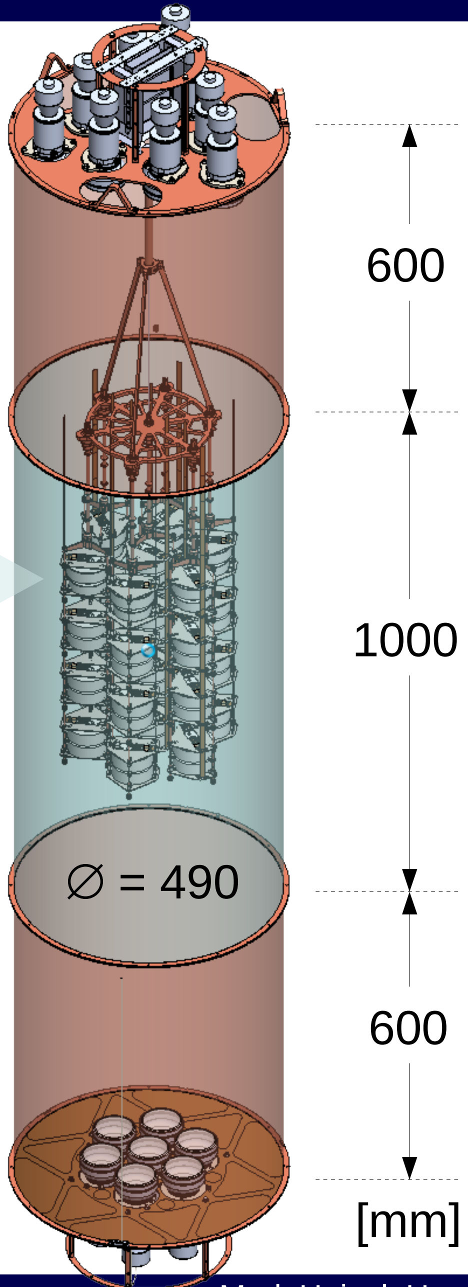
Cu shroud &
wavelength-shifter

Ge detectors

scintillating fibres
& SiPM read-out

Cu shroud &
wavelength-shifter

7x 3" PMT



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

Liquid argon light instrumentation

9x 3" PMT

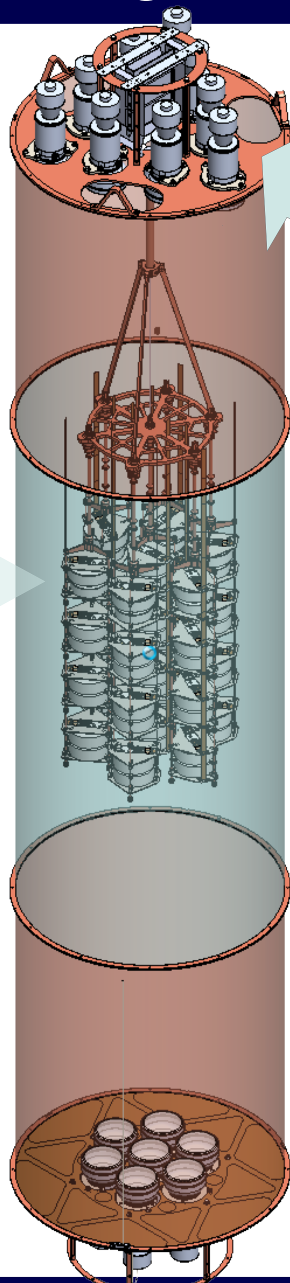
Cu shroud & wavelength-shifter

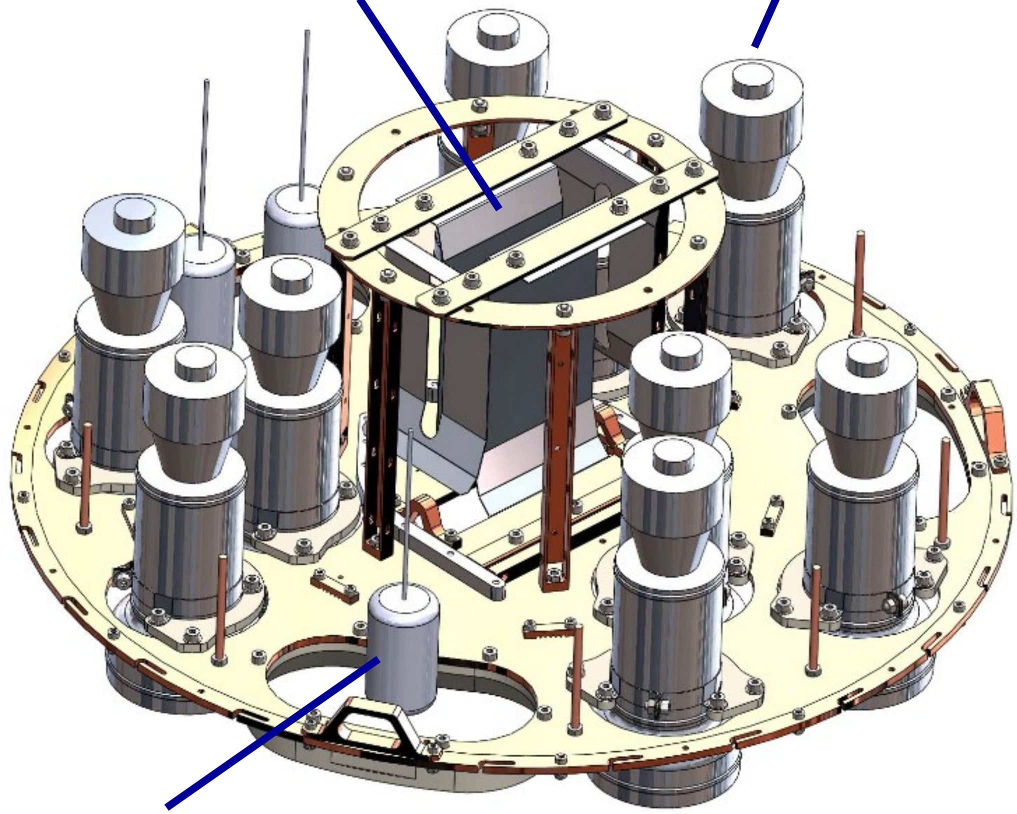
Ge detectors

scintillating fibres & SiPM read-out

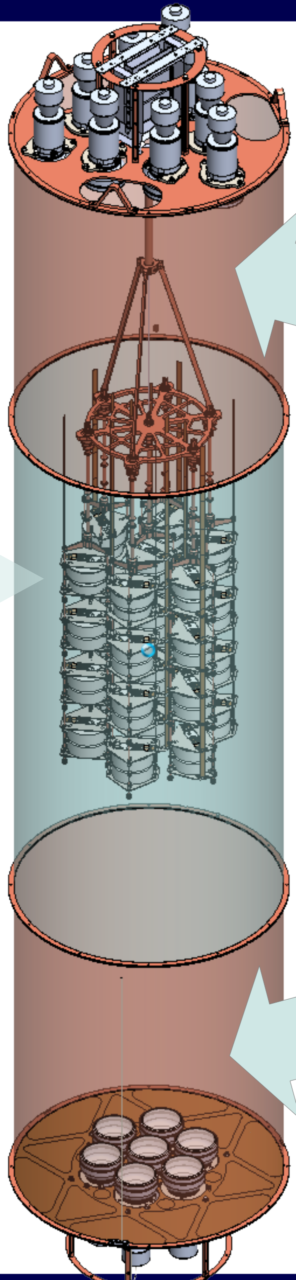
Cu shroud & wavelength-shifter

7x 3" PMT





Liquid argon light instrumentation



Cu shroud with Tetratex + WLS:

100 µm copper foil welded to 2 mm flanges

Liquid argon light instrumentation

9x 3“ PMT

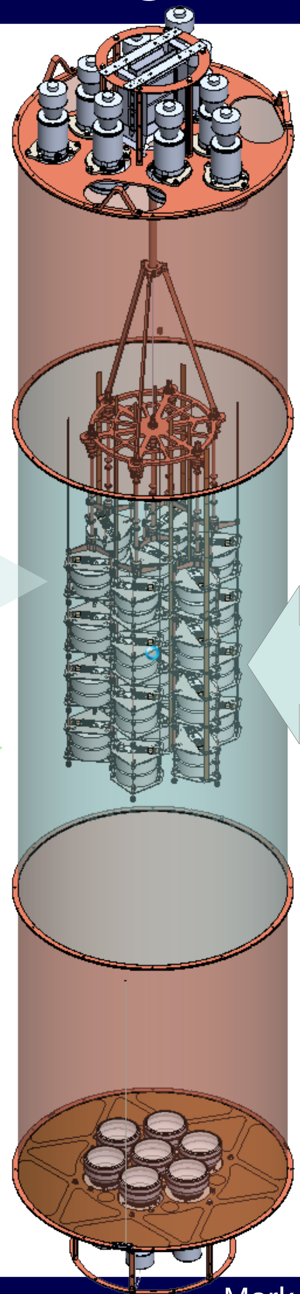
Cu shroud &
wavelength-shifter

Ge detectors

**scintillating fibres
& SiPM read-out**

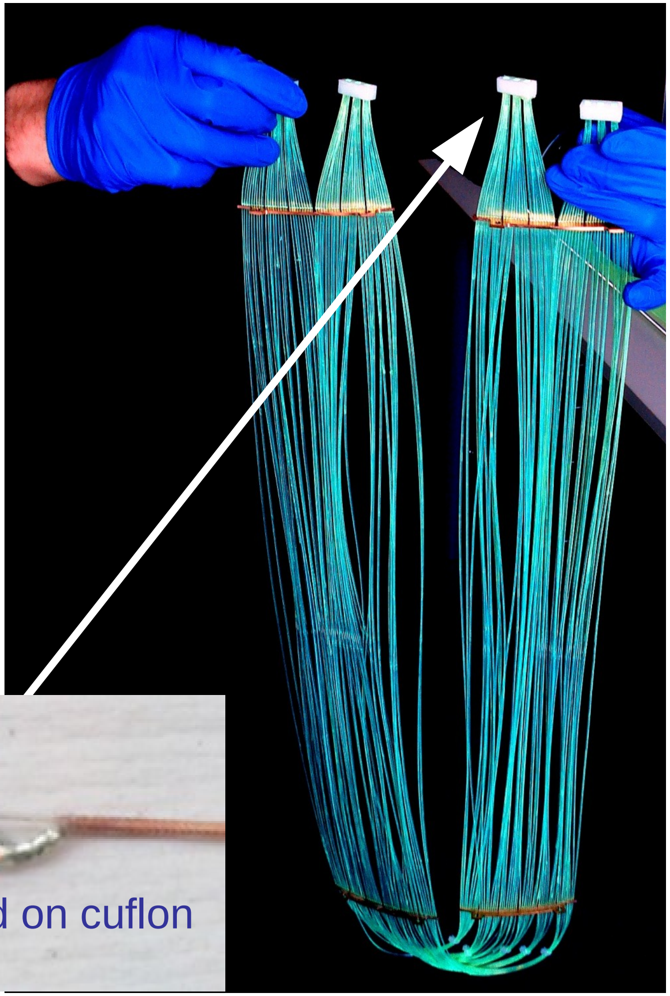
Cu shroud &
wavelength-shifter

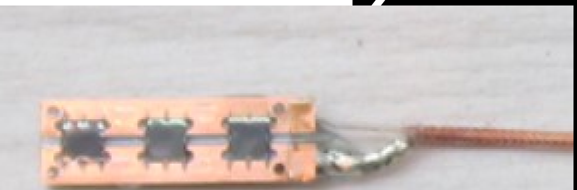
7x 3“ PMT



Scintillating fibres with KETEK SiPMs:

dense fibre curtain mounted on low mass copper support structure (not shown)





3 SiPMs mounted on cuflon for 3x9 fibres

Liquid argon light instrumentation

9x 3" PMT

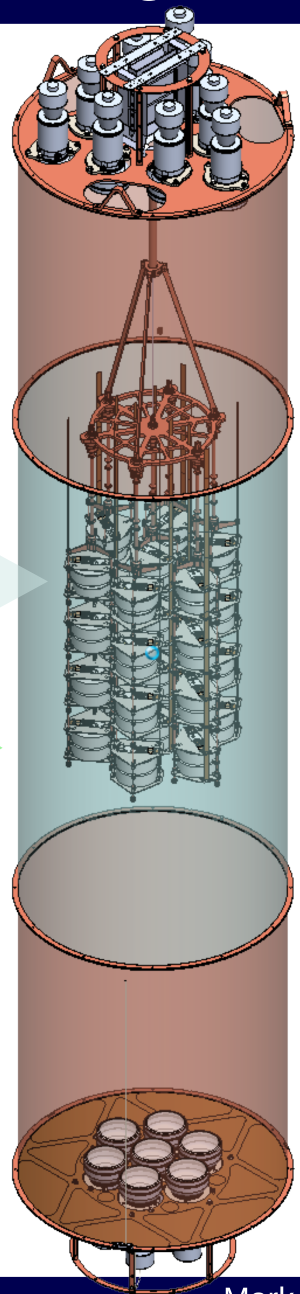
Cu shroud & wavelength-shifter

Ge detectors

scintillating fibres & SiPM read-out

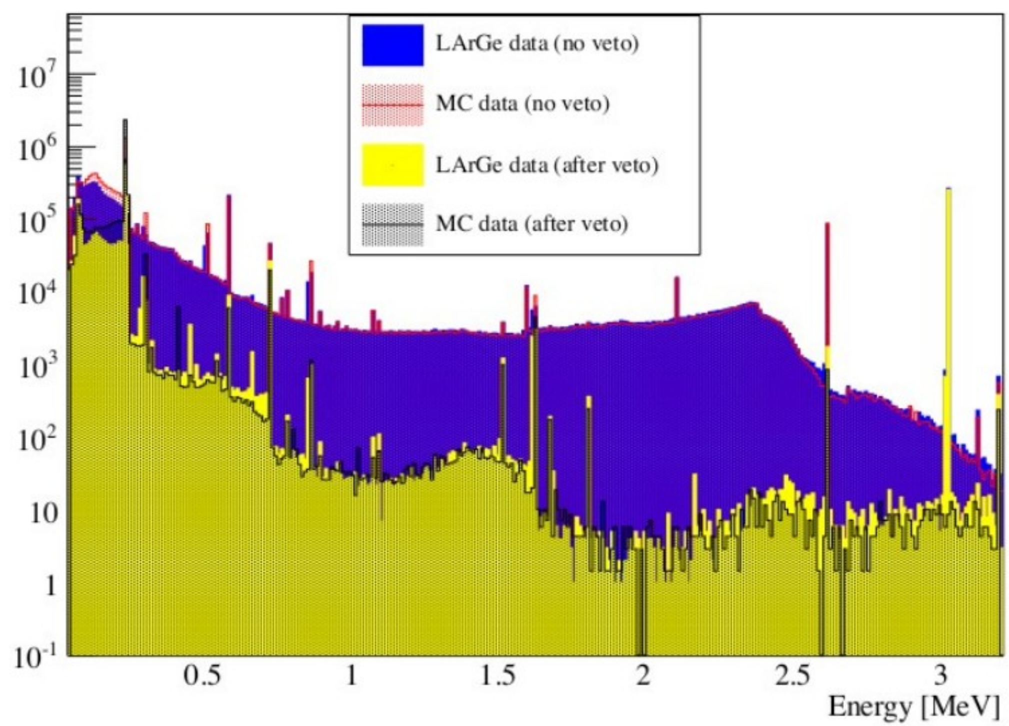
Cu shroud & wavelength-shifter

7x 3" PMT

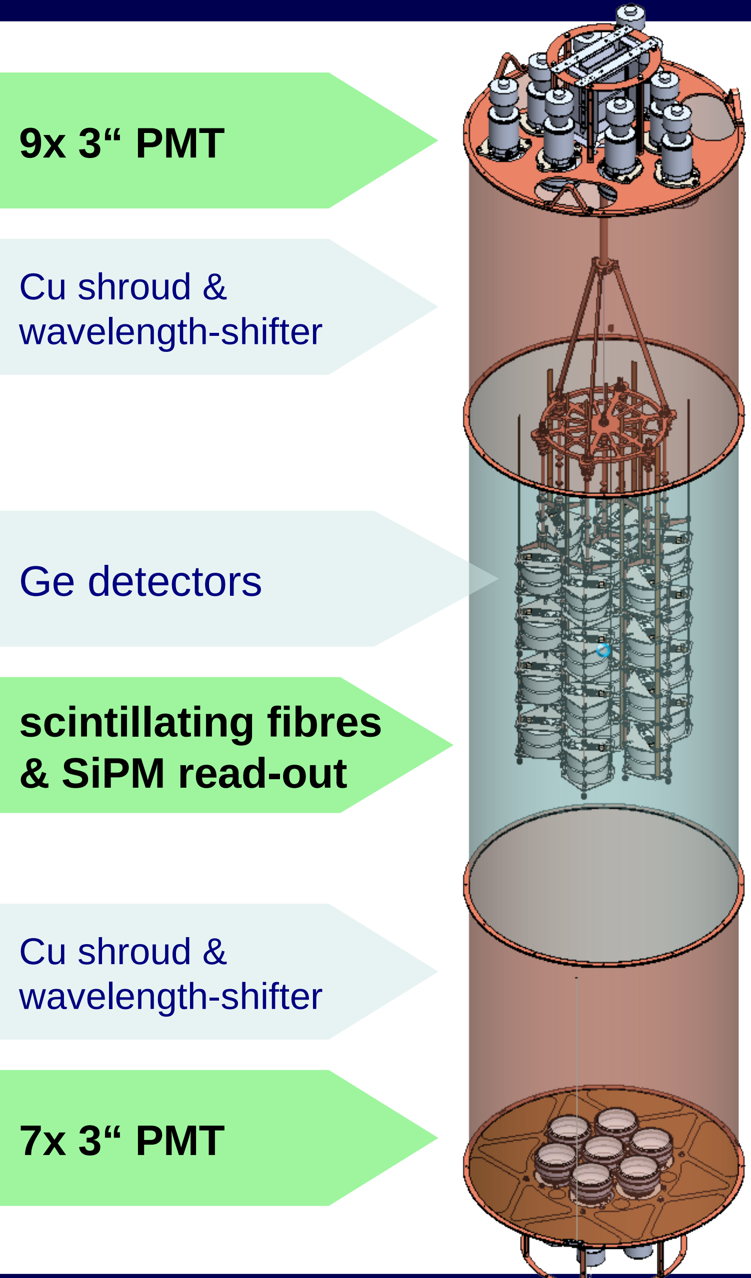


Monte Carlo (MC) campaign
to optimize veto geometry:

► good agreement between data & MC



Liquid argon light instrumentation



Monte Carlo (MC) campaign
to optimize veto geometry:

- ► good agreement between data & MC
- ► MC prediction around $Q_{\beta\beta}$ = 2039 keV:

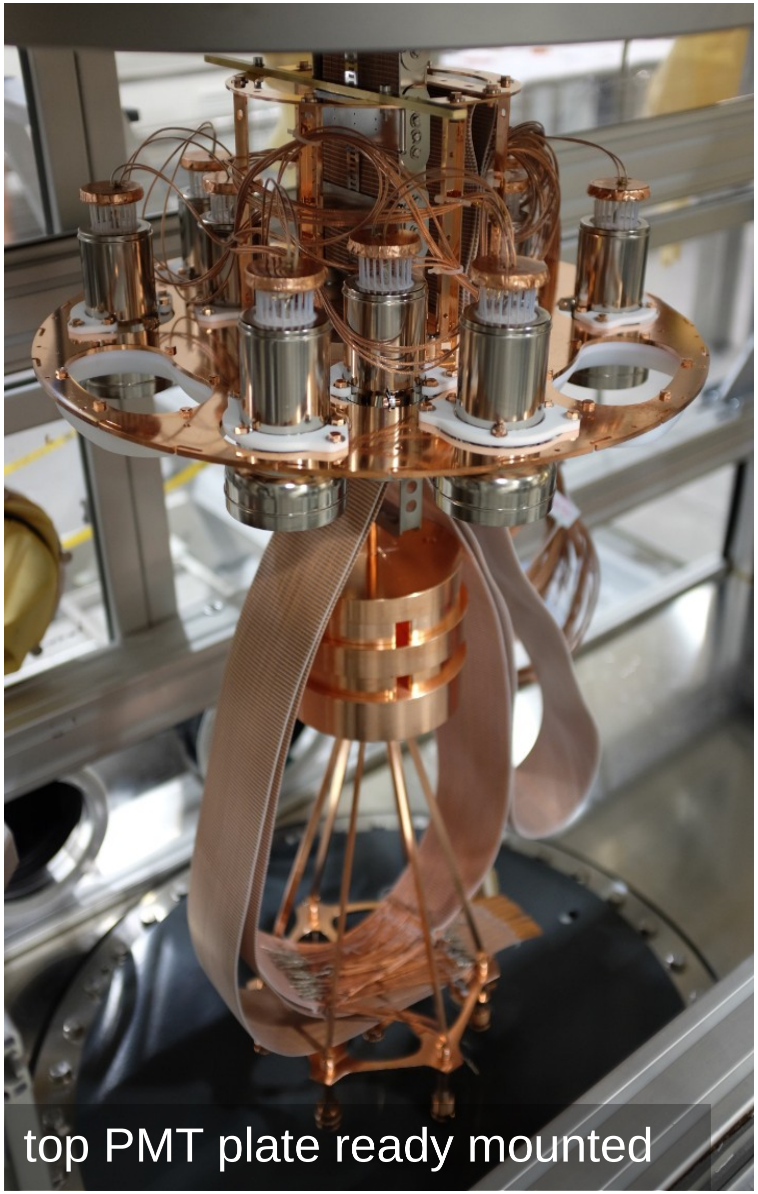
suppression factors:

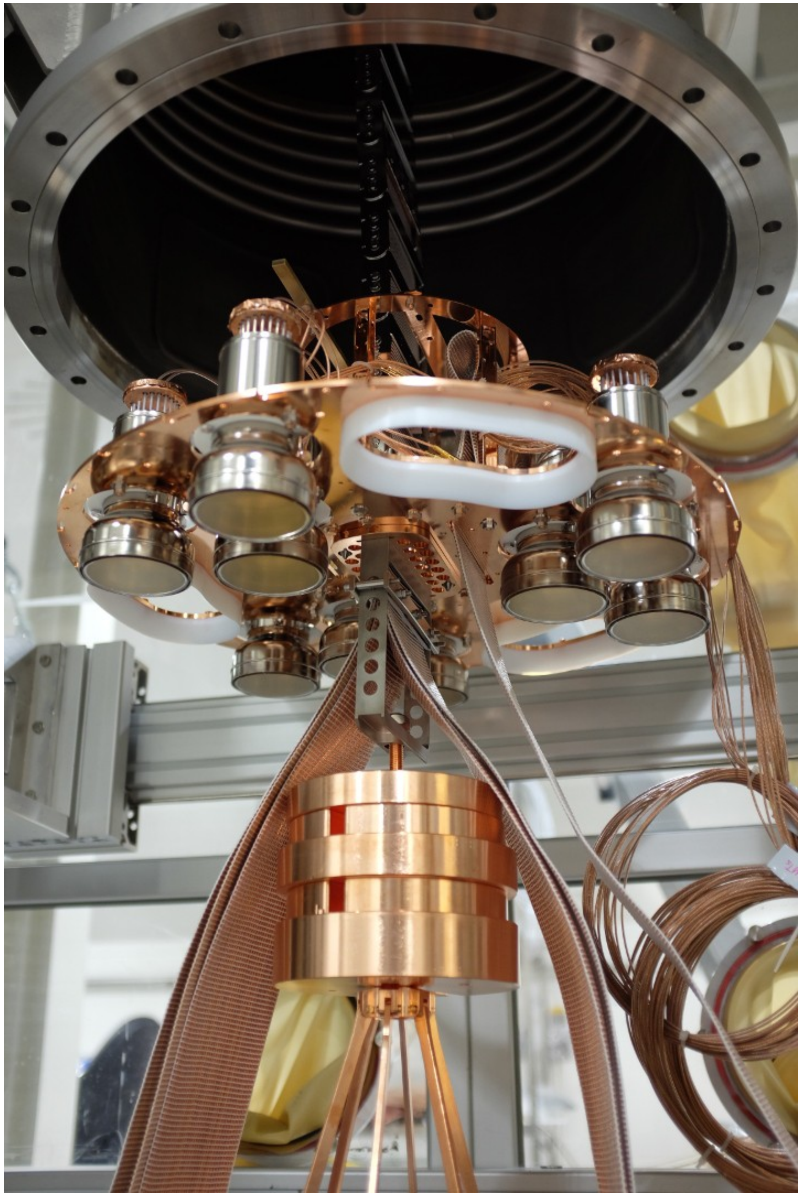
^{228}Th → up to ~370

^{214}Bi → up to ~10

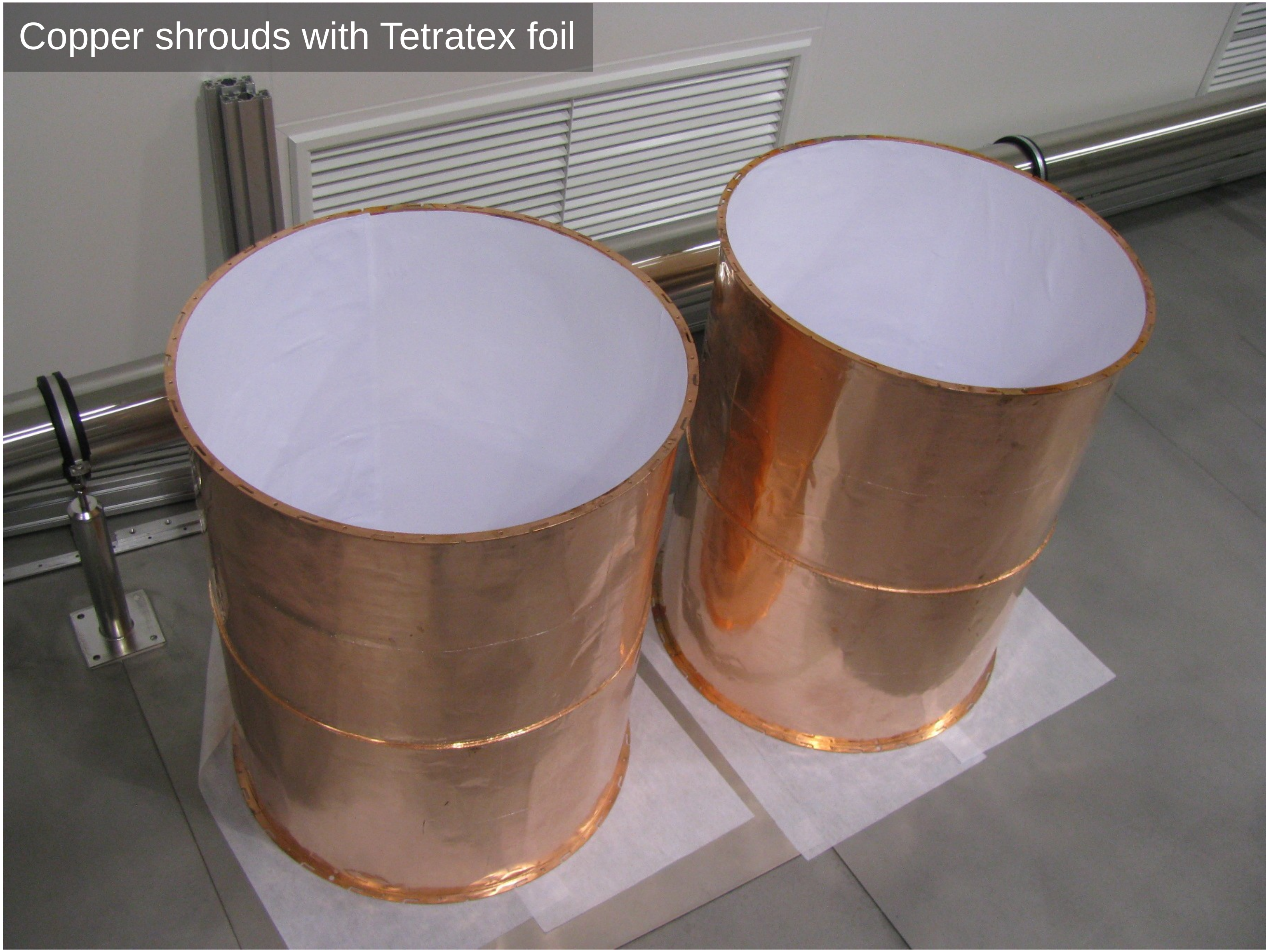
(depending on source location: e.g. detector holders, electronics …,→ the closer the better)

LAr veto installation

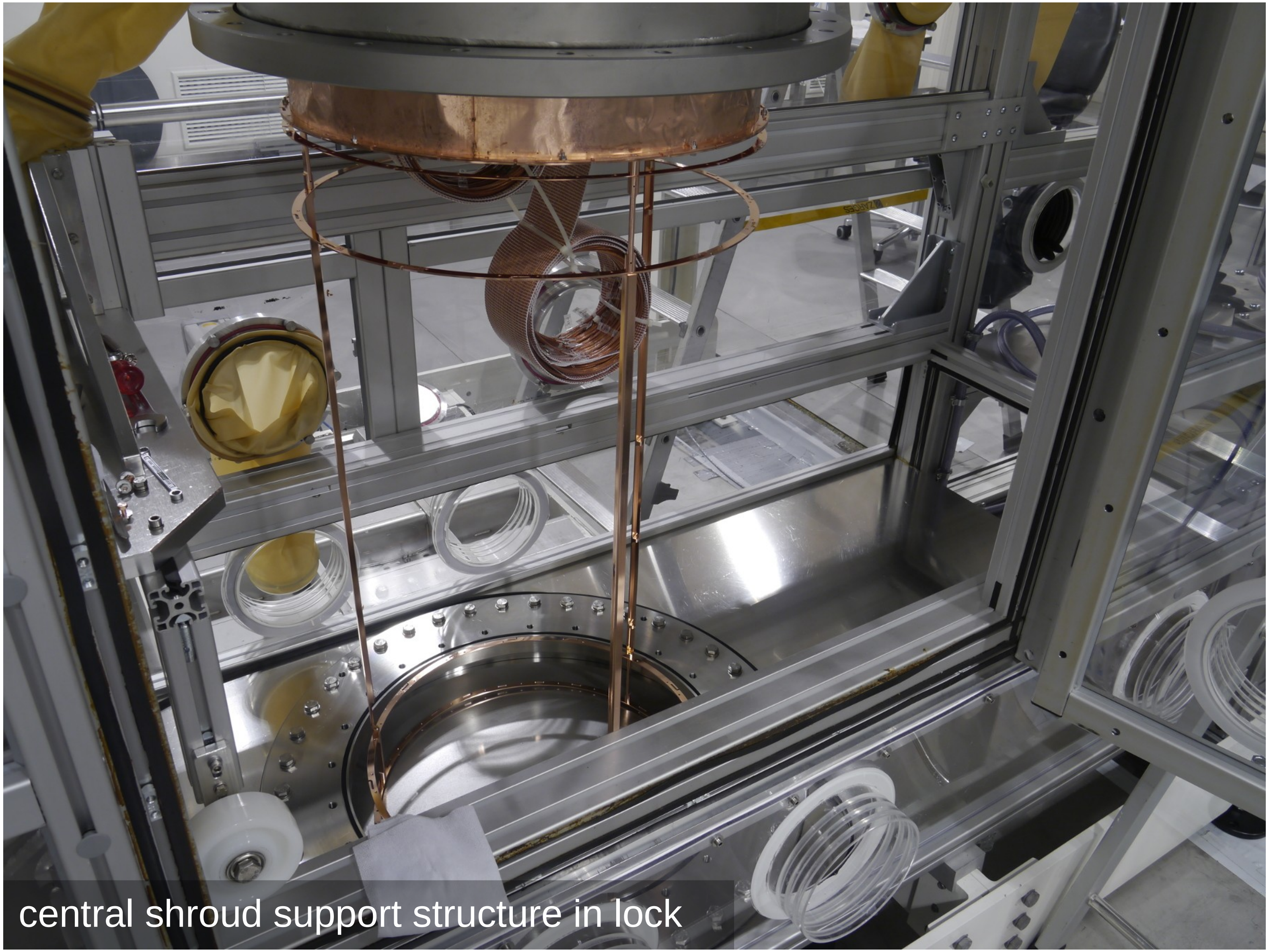




LAr veto installation

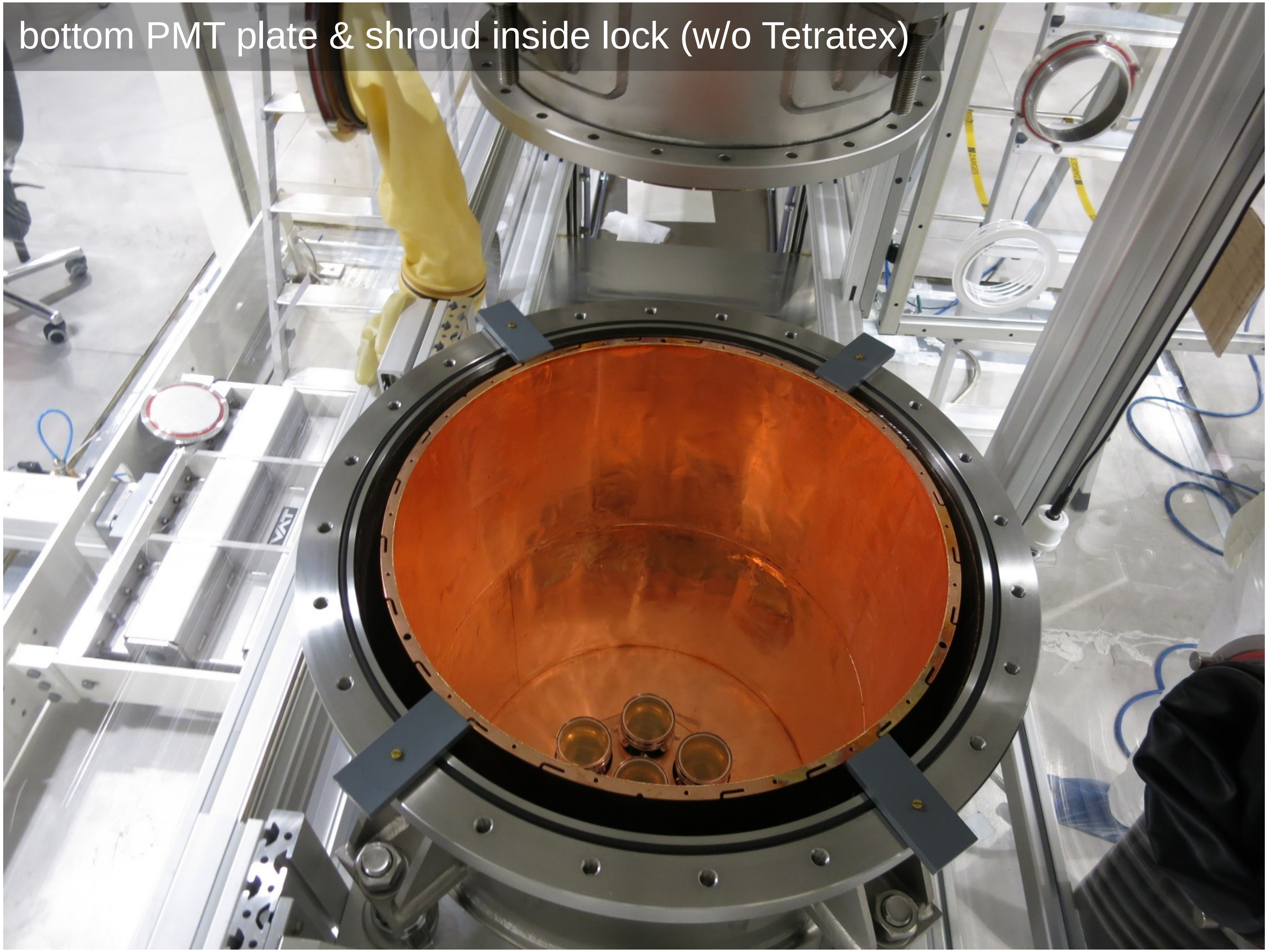


LAr veto installation



central shroud support structure in lock

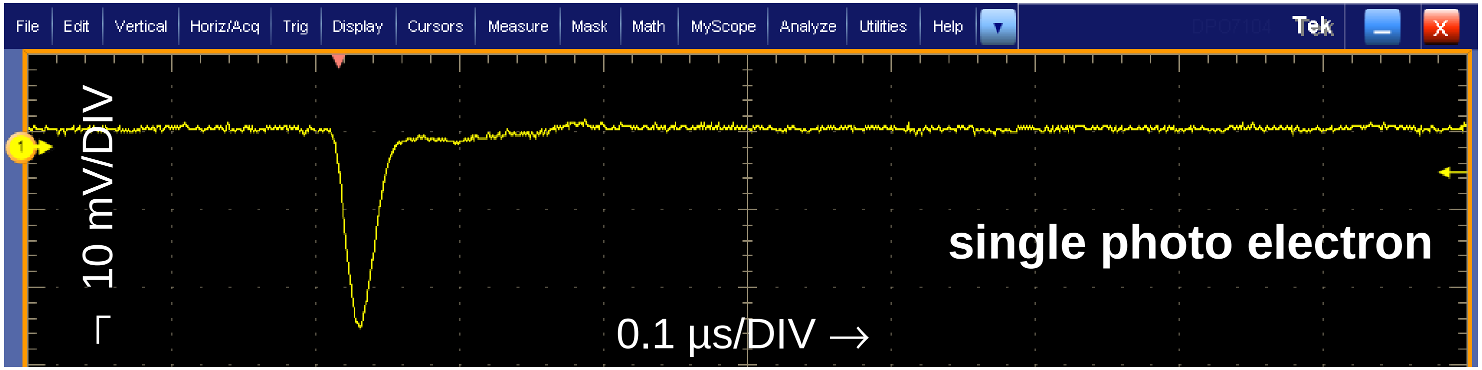
LAr veto installation

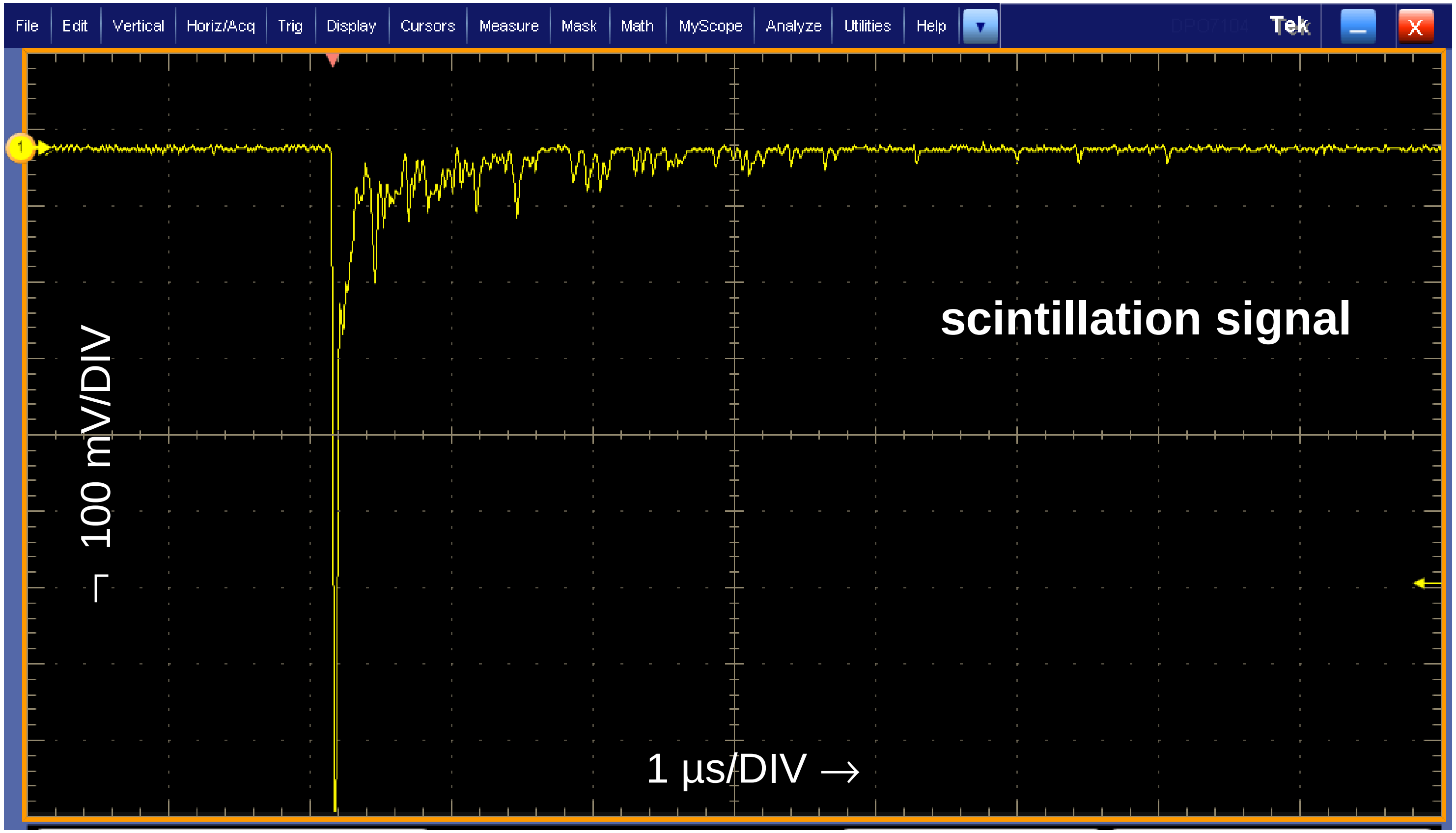


LAr veto installation

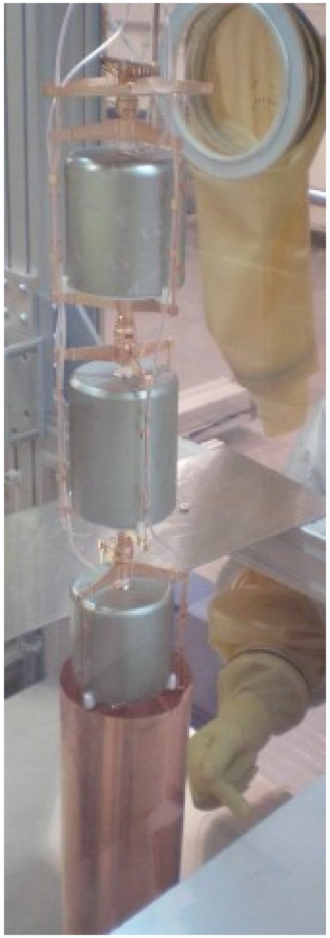
1st successful deployment of full LAr veto structure into GERDA cryostat (view from top through cryostat neck)

First PMT signals in cryostat





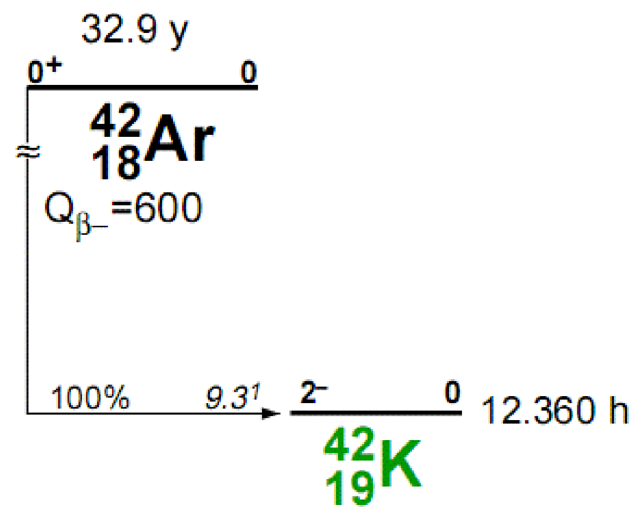
'Mini-shroud' against ^{42}K β-background



Phase I copper mini-shrouds

Phase I:

- copper mini-shrouds needed to prevent ^{42}K ions (progenies of ^{42}Ar) reach the detectors
  → shield E-field of detectors
  → shield against convection
- avoid crucial β-background ($E_\beta \leq$ 3.5 MeV) from ^{42}K

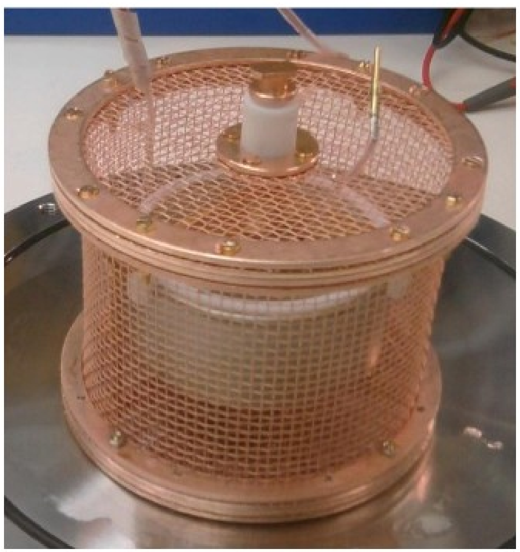


'Mini-shroud' against ^{42}K β-background

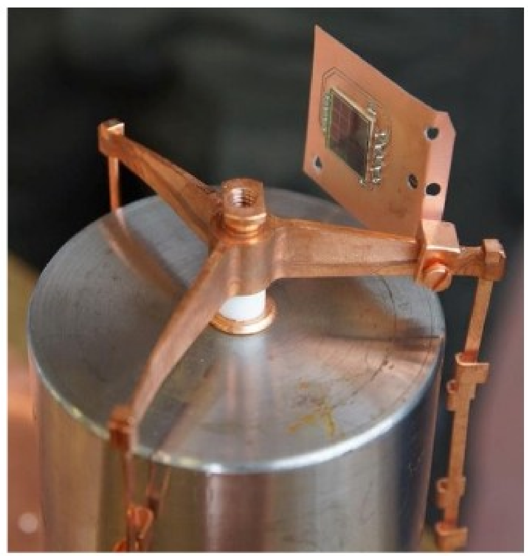
Phase II:

► need transparent or optically active mini-shroud to detect scintillation emitted close-by detectors

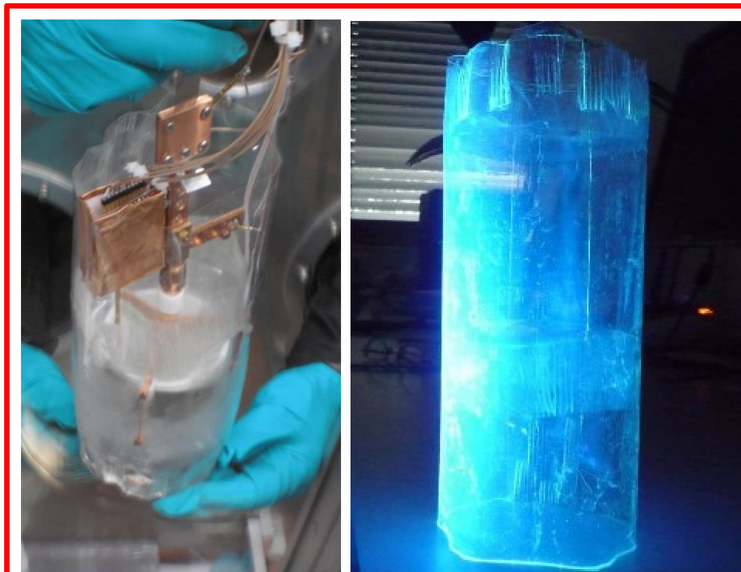
Several options were tested:



copper mesh on HV



SiPM
in non-transparent shroud

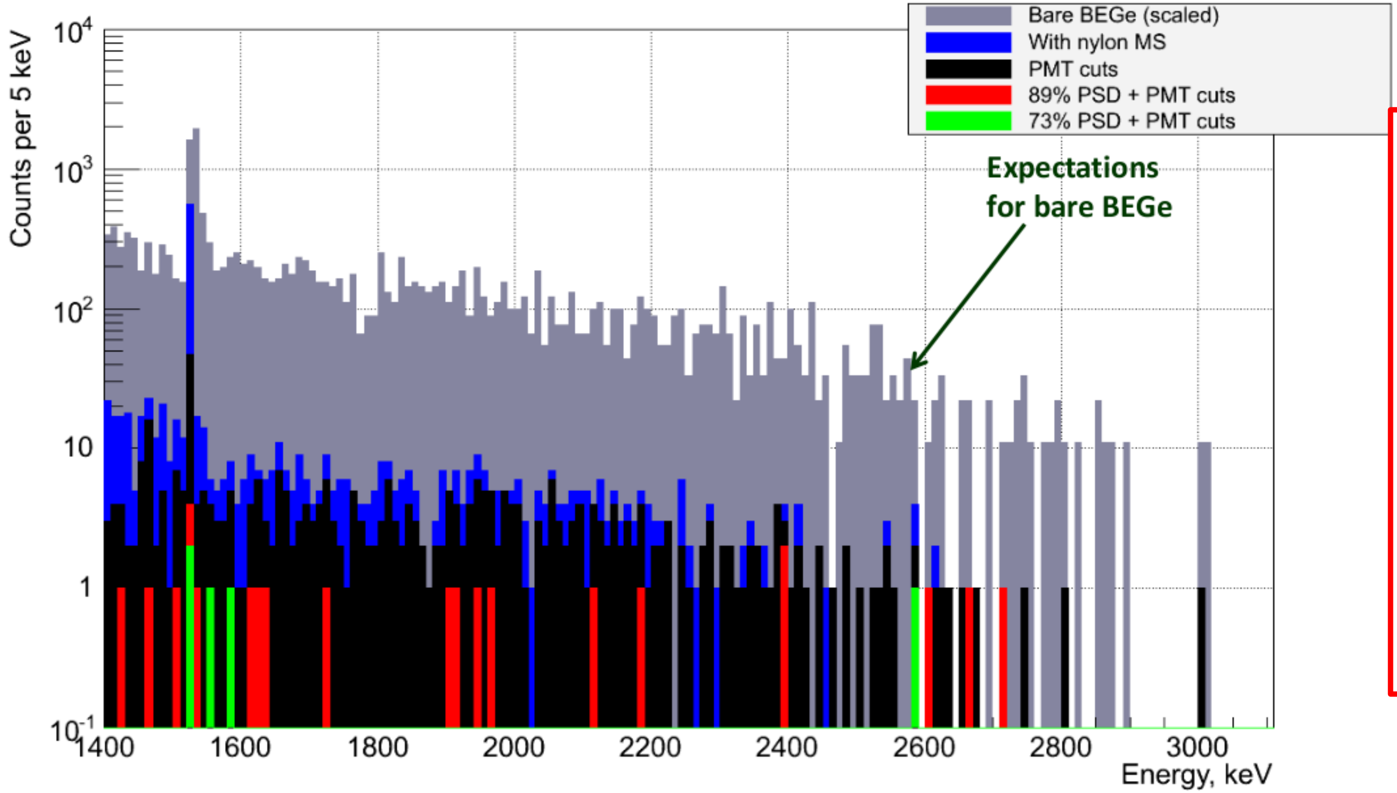


nylon shroud coated with TPB/PS

'Mini-shroud' against ^{42}K β-background

Phase II:

suppression of ^{42}K background by three orders of magnitude at $Q_{\beta\beta}$ using LAr veto /w nylon mini-shroud and PSD:



nylon mini-shroud coated with TPB/PS

measurement in LArGe test bench spiked with ^{42}Ar statistics corresponding to ~17 kg×yr in natural argon.

Conclusion

Phase II goals:

- exposure: 100 kg·yr within 3 years
- background index: 1×10^{-3} cts/(keV·kg·yr)

$\Rightarrow$ **$T^{0\nu}_{1/2} > 1.4 \times 10^{26}$ yr**

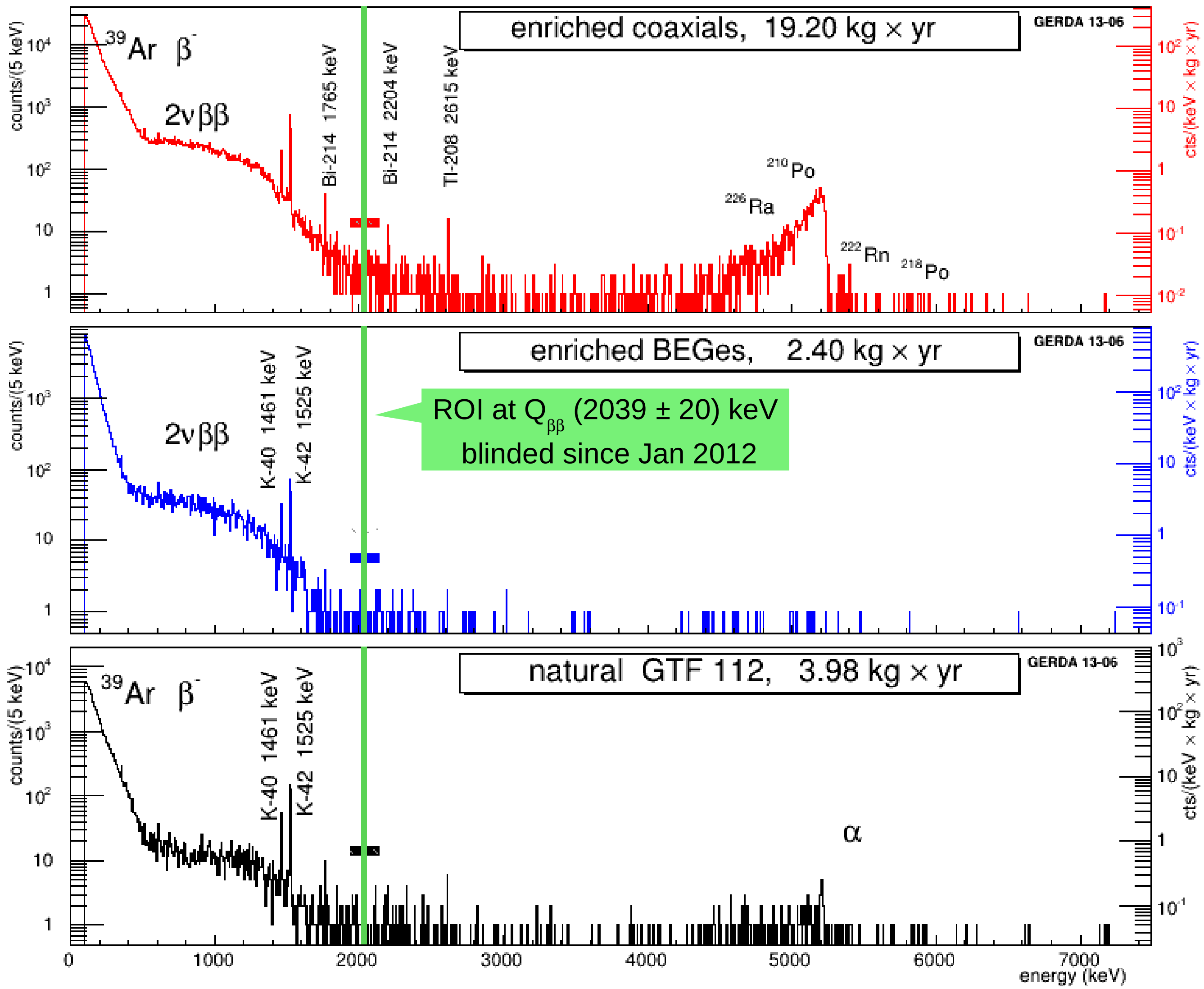
- successfully deploy new detectors & use LAr veto

Phase II upgrade status:

- new lock installed and ready to use
- 20.5 kg of new ^{enr}BEGe detectors procured, tested & stored at LNGS
- new detector holders & front end electronics available
- LAr instrumentation beeing installed in GERDA
- test of first BEGe string with LAr veto starting this month!

Backup

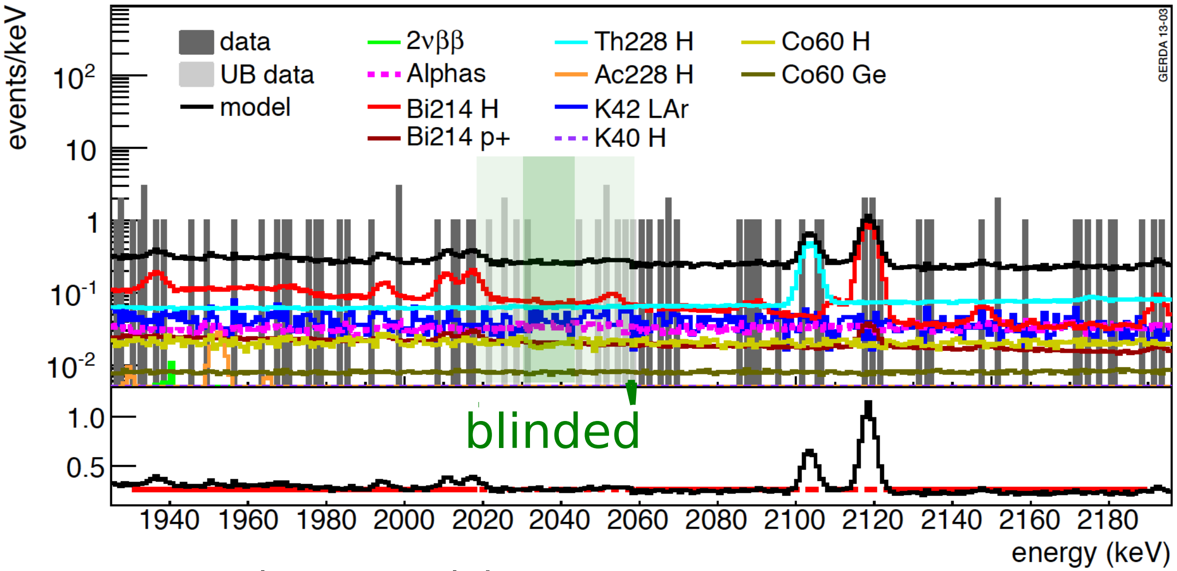
GERDA Phase I full energy spectrum



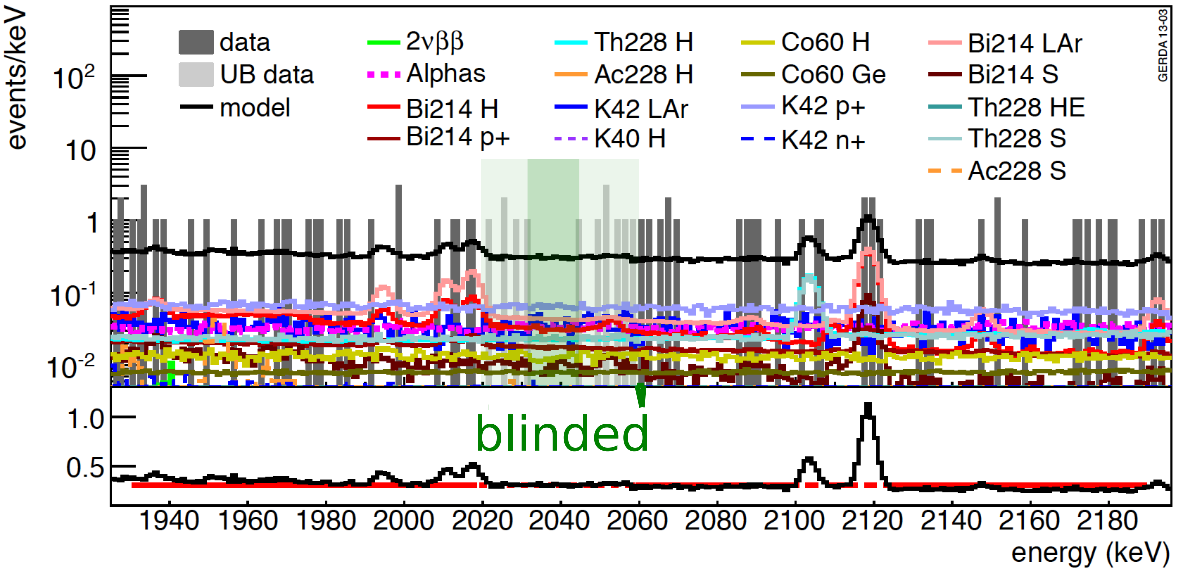
<u>Dominant background sources:</u> ^{42}Ar, ^{228}Th & ^{226}Ra in holder, α on detector surface

Background model at $Q_{\beta\beta}$

Minimal model



Maximum model



- **no background peak at $Q_{\beta\beta}$**
- **background is flat** in 1930-2190 keV
  - → excluding known peaks at 2104 and 2119 keV
  - → expect <<1 event in other weak ^{214}Bi lines (e.g. 2017, 2053 keV)
- **partial unblinding** after fixing calibration & background model

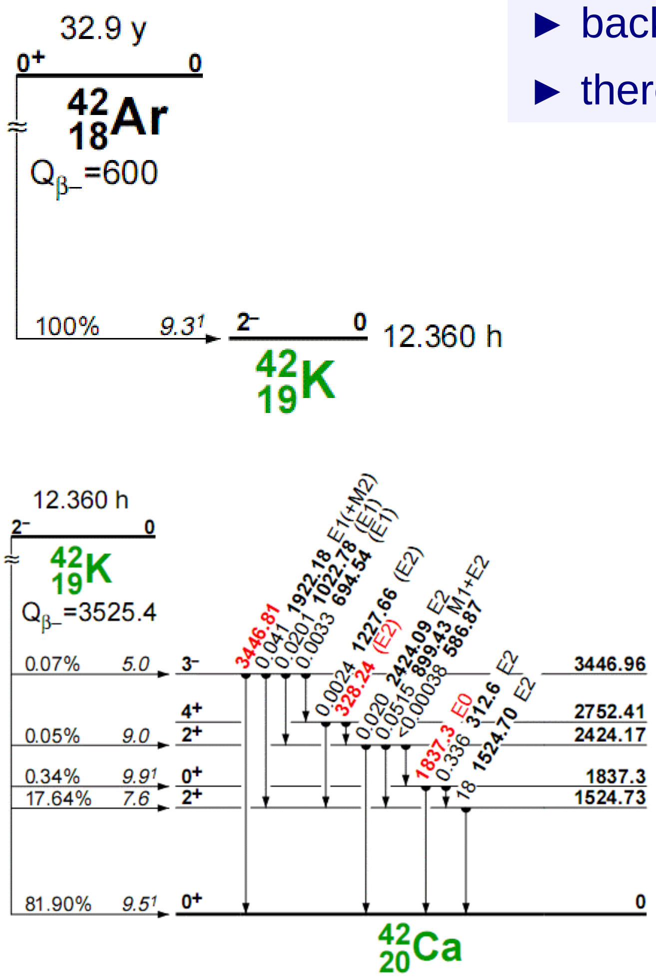
Background index:

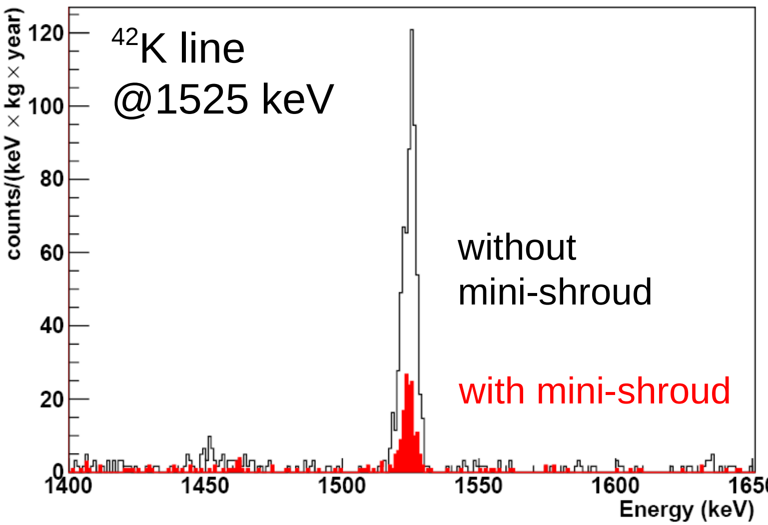
Golden coax:
$$BI = 1.75^{+0.26}_{-0.24} \cdot 10^{-2} \text{ cts/(keV kg yr)}$$
BEGe:
$$BI = 3.6^{+1.3}_{-1.0} \cdot 10^{-2} \text{ cts/(keV kg yr)}$$

^{42}K background

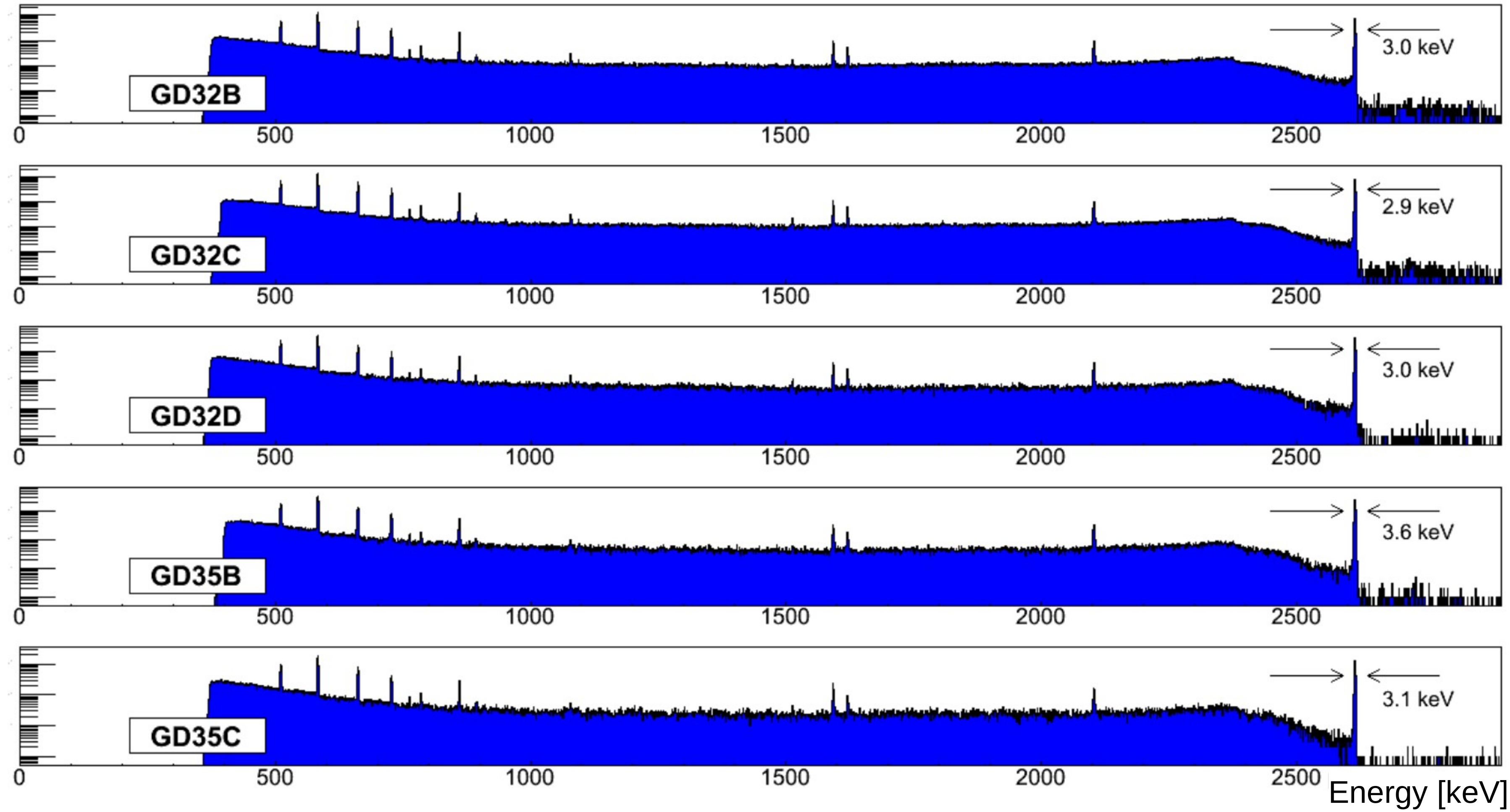
^{42}Ar activity used for proposal:	<41 µBq/kg @90% CL	[Barabash et al.,2002]
measured in GERDA:	(93.0 ± 6.4) µBq/kg	(preliminary result)

- ► background enhanced by collection of ^{42}K ions via E-field
- ► therefore: E-field & convection free configuration in 'mini-shroud'



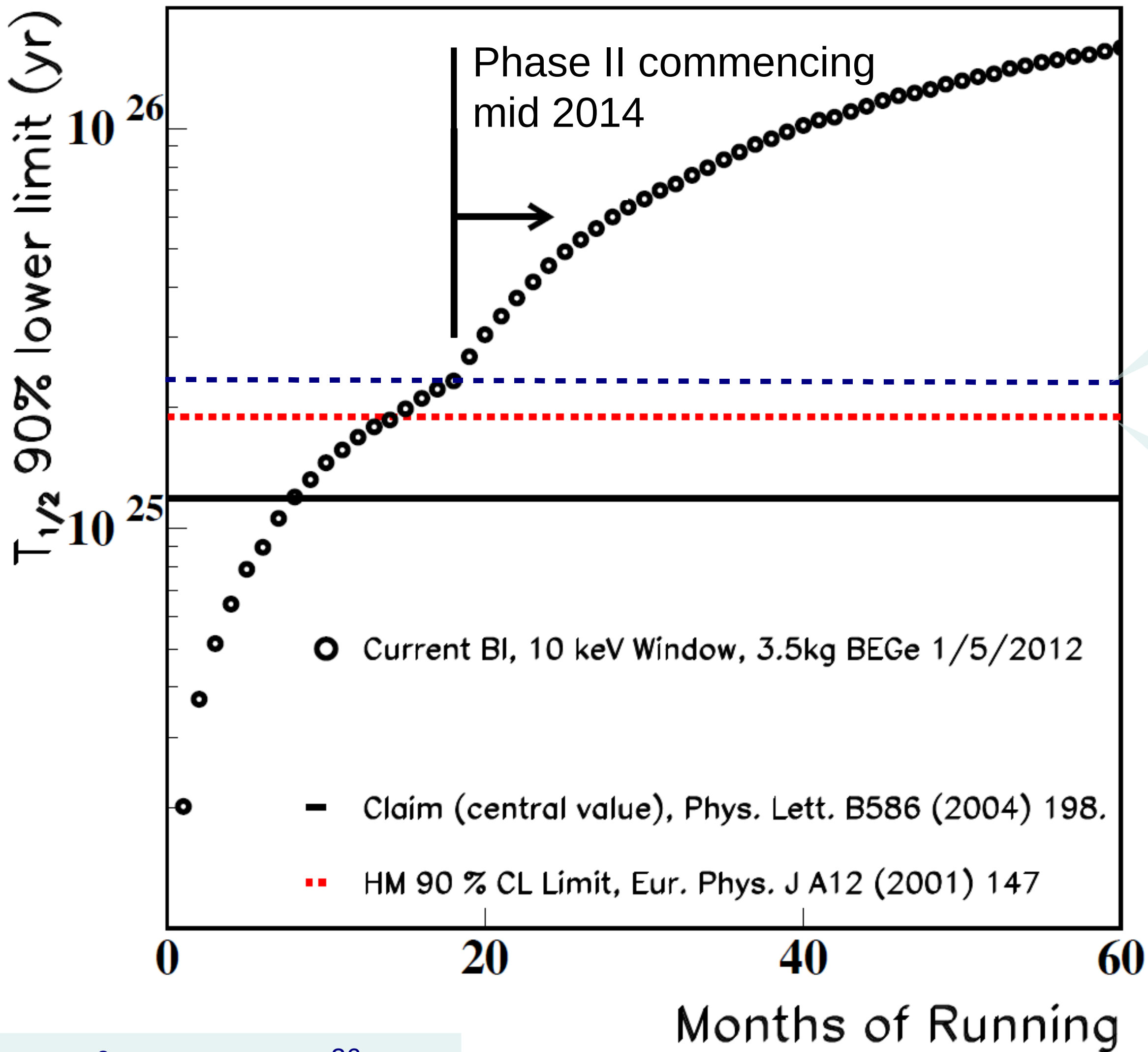


July 2012: 5 ^{enr}BEGe's deployed in GERDA



total mass: 3.6 kg

GERDA 0νββ sensitivity projection

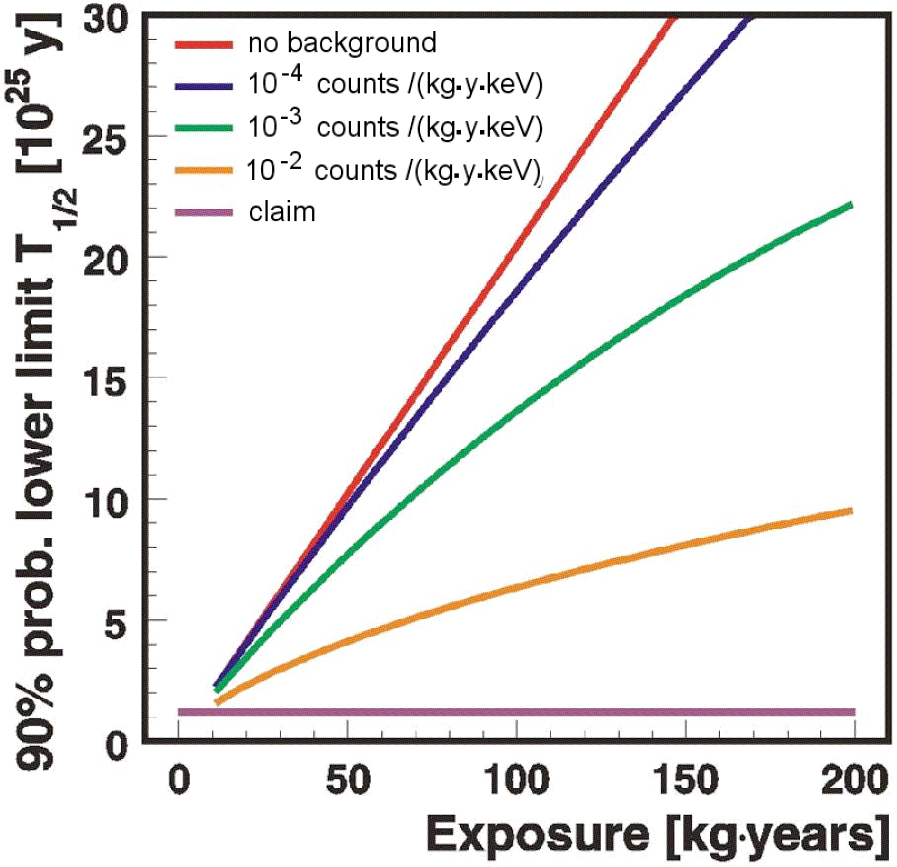


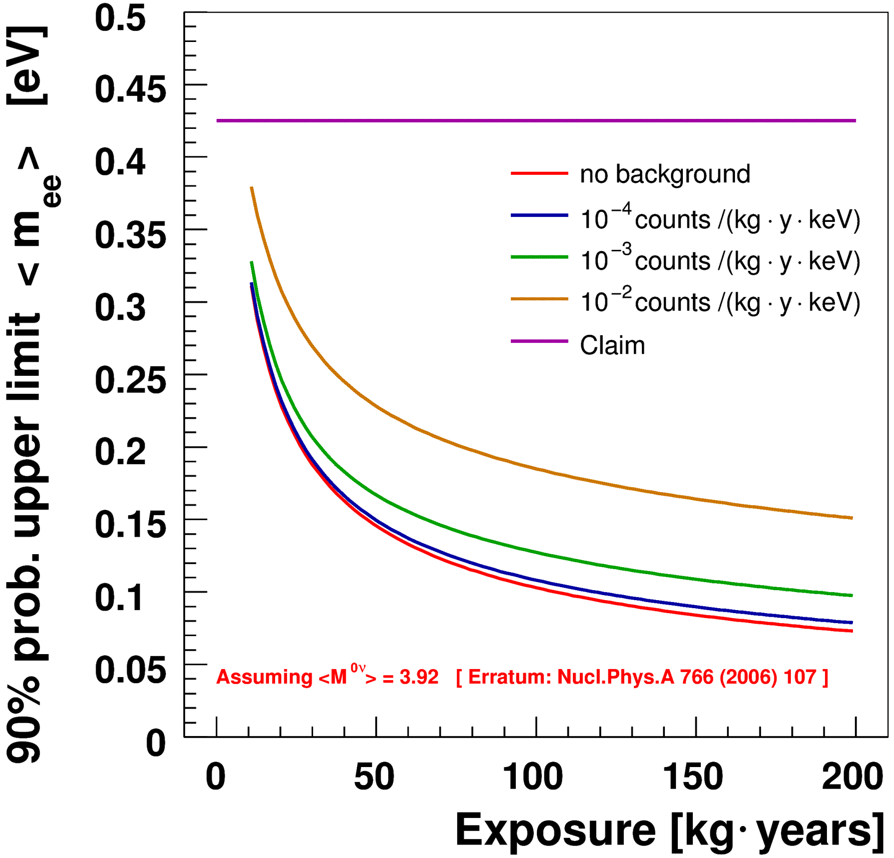
GERDA Phase I limit (90% C.L.)

Heidelberg-Moscow claim (2004)

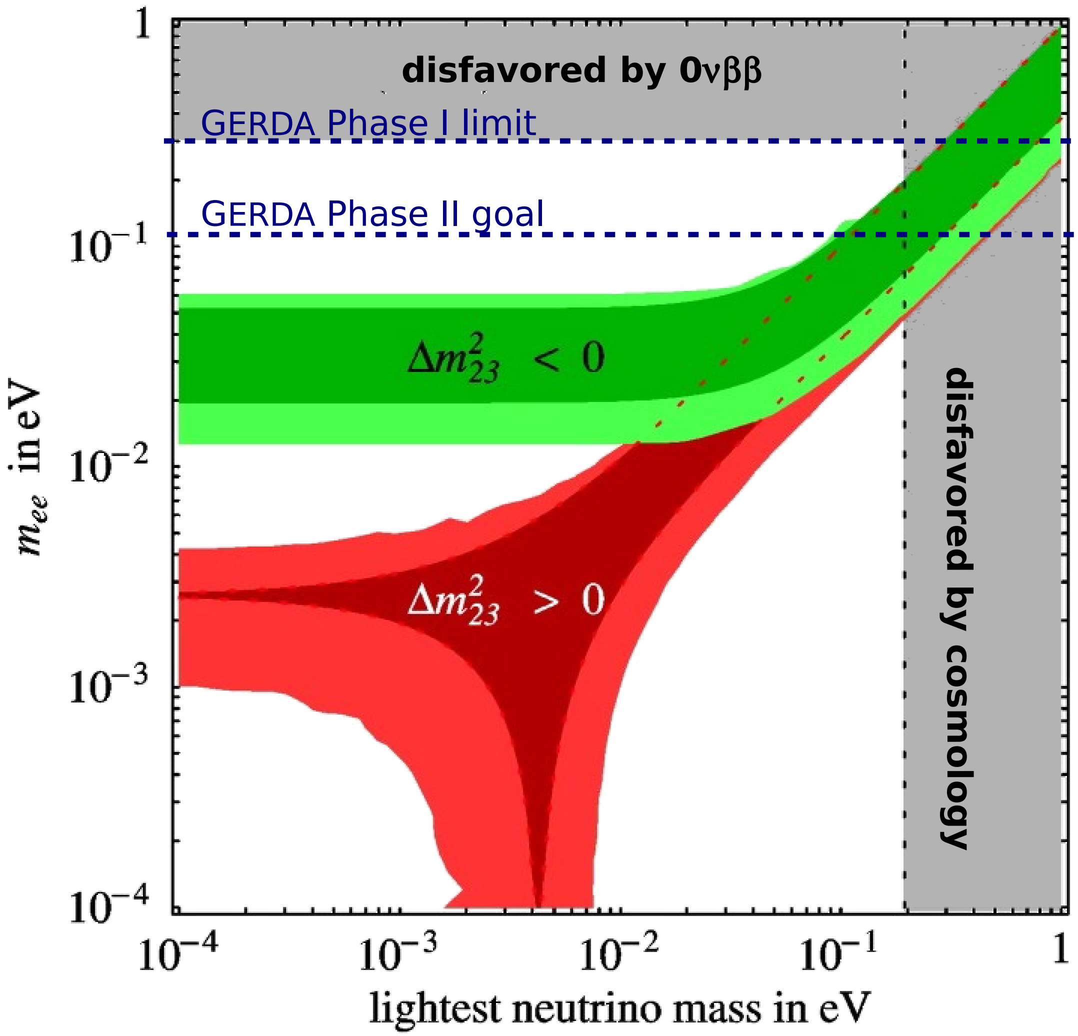
Phase II goal: $T^{0\nu}_{1/2}$ > 1.5 x10^{26} yr

GERDA 0νββ sensitivity projection





Neutrino hierarchy? Neutrino mass scale?



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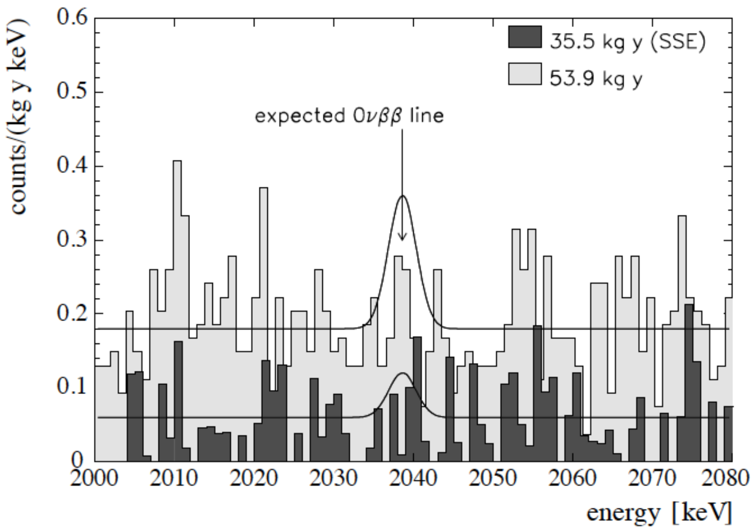
effective electron neutrino mass:

$$|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|$$

m_i=masses of n mass eigenstates, U_{ei}=elements of neutrino mixing matrix, $e^{2i\alpha,\beta}$ = Majorana CP phases

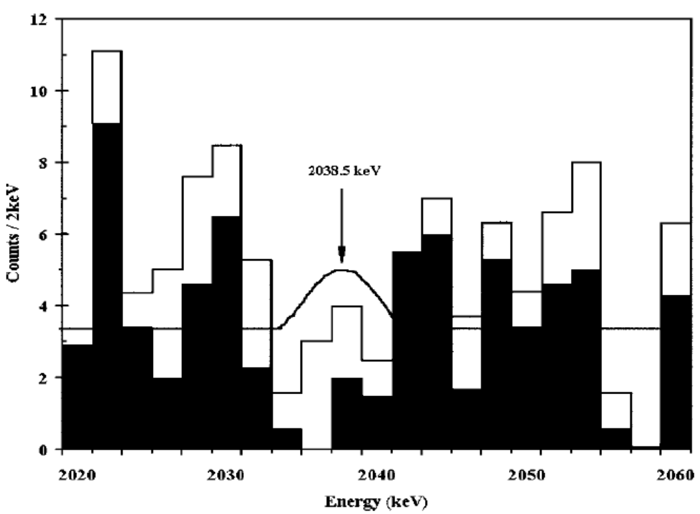
^{76}Ge 0νββ search before GERDA



Heidelberg-Moscow

[H.V. Klapdor-Kleingrothaus et al.,
(Eur. Phys. J. A 12, 147-154 (2001)]

Exposure	Result $T^{0\nu}_{1/2}$	
53.9 kg·yr	> 1.3×10^{25} yr	(no PSD)
35.5 kg·yr	> 1.9×10^{25} yr	(with PSD)
		(90% C.L.)

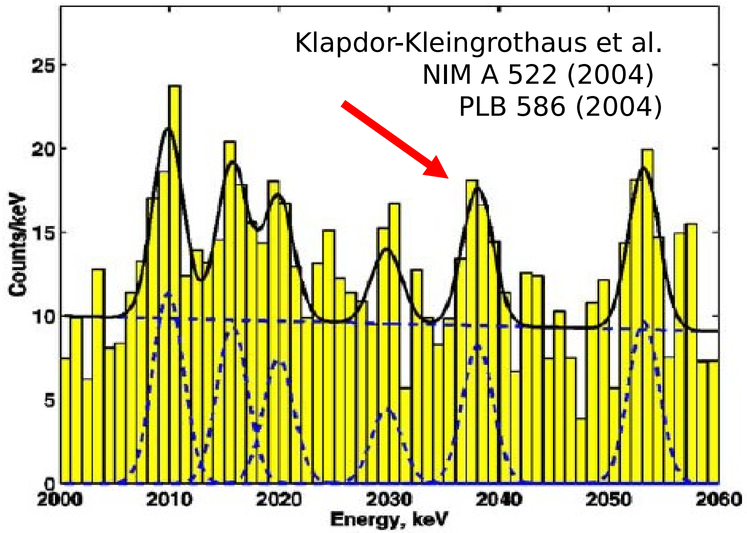


IGEX

[Aalseth et al.,
Phys. Rev. D 65 (2002) 092007]

Exposure	Result $T^{0\nu}_{1/2}$
8.8 kg·yr:	> 1.6×10^{25} yr
	(90%C.L.)

^{76}Ge $0\nu\beta\beta$: the claim



Klapdor-Kleingrothaus et al. (2004)
[NIM A 522 371 (2004), PLB 586 198 (2004)]

- Claim: 4.2σ evidence for $0\nu\beta\beta$
  $T_{1/2}$ = 1.19 x 10^{25} yr
- Exposure: 71.7 kg·yr,
  Background: 0.17 / (kg·yr·keV)
- Events: 28.75 ± 6.87 (bgd: ~60)

Klapdor-Kleingrothaus et al. (2006)
[Mod. Phys. Lett. A 21, 1547 (2006)]

- Claim: $T_{1/2}$ = 2.23 x 10^{25} yr (~6σ)
- not considered by us, because:
  (1) reported half-life can be reconstructed* only with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
  (2) ε_{fep} = 1 (also used in result from 2004), GERDA value for same detectors is ε_{fep} = 0.9

* B. Schwingenheuer in Ann. Phys. 525, 269 (2013)