GERDA: GERmanium Detector Array searching for $0\nu\beta\beta$ decay
GeDet: Germanium Detector R&D

Director: Allen Caldwell

Projector leaders: Béla Majorovits (GERDA), Iris Abt (GeDet)

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Group engineer: Franz Stelzer

Diplomand: Markus Kästle

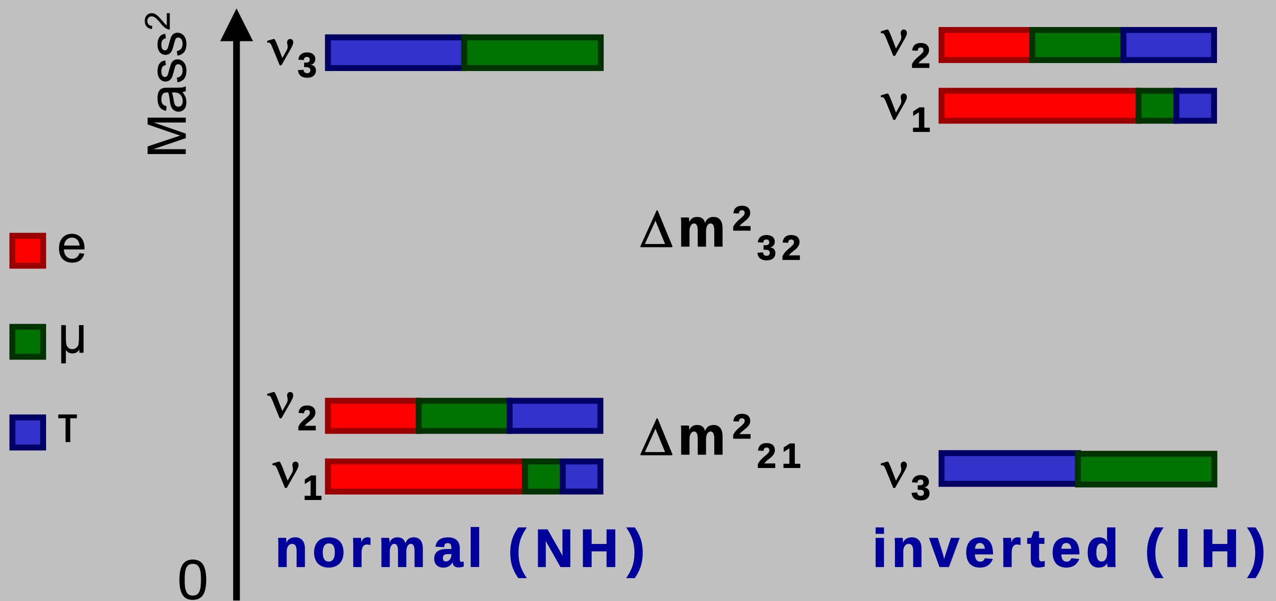
Werkstudenten/in: Golam Dastagir, Westa Domanova, Maximilian Empl, Daniel Greenwald, Andreas Kaiser

Construction: Karlheinz Ackermann, Stefan Mayer, Sven Voggt

Many thanks to colleagues from electronic & mechanic departments!

Project Review 17/12/2007

Neutrino masses & mixing parameters

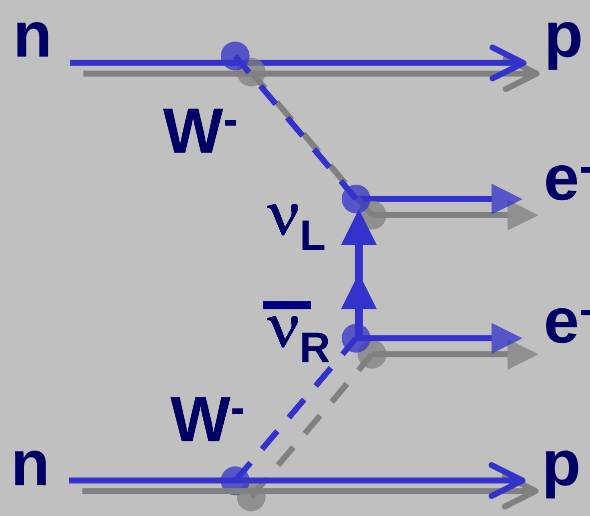


atmospheric accelerator → $\Delta m^2_{32} = 2.2 \cdot 10^{-3} eV^2$

solar reactor → $\Delta m^2_{21} = 8.1 \cdot 10^{-5} eV^2$

absolute mass ? NH or IH ? Dirac or Majorana($\nu = \bar{\nu}$) ?

$0\nu\beta\beta$ decay → effective Majorana neutrino mass $m_{\beta\beta}$



- $(A,Z) \rightarrow (A, Z+2) + 2e^-$
- $\Delta L \neq 0$
- happens, if $\nu = \bar{\nu}$ & $m_\nu > 0$

half life $$\left[T_{1/2}\right]^{-1} = G(^2Q,Z) \cdot \left| M^{GT} - \frac{g_V^2}{g_A^2} M^F \right| \cdot \left\langle m_{\beta\beta} \right\rangle^2$$

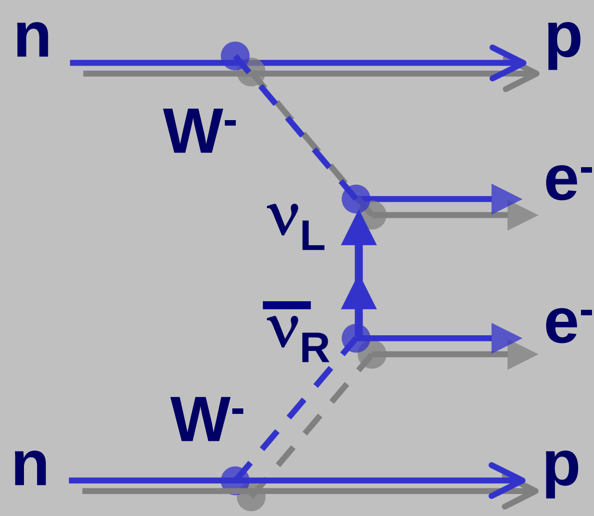
Phase space

nuclear matrix element

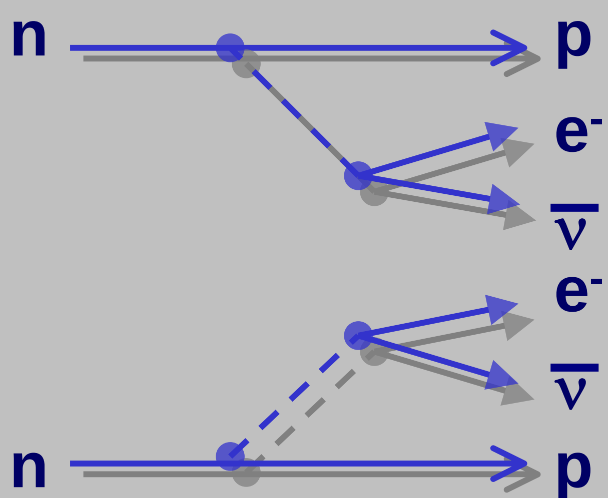
effective mass $m_{\beta\beta}$

$$\left\langle m_{\beta\beta} \right\rangle = \left| \sum_j m_j U_{ej}^2 \right| = \left| m_1 \cdot \left|U_{e1}\right|^2 + m_2 \cdot \left|U_{e2}\right|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 \cdot \left|U_{e3}\right|^2 e^{i(-\alpha_1 - 2\delta)} \right|$$

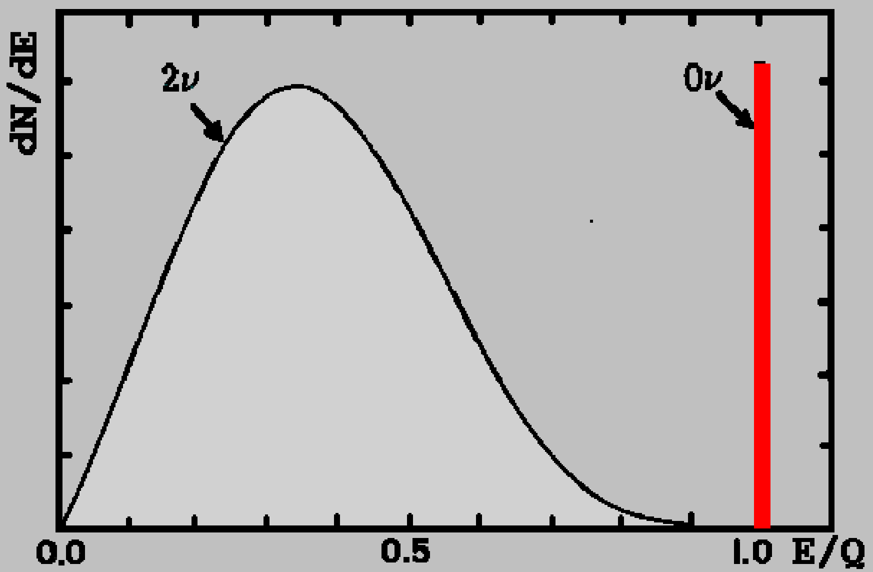
Measure $T_{1/2}$ of $0\nu\beta\beta$ decay



$0\nu\beta\beta$



$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



search for energy peak at Q value (Ge76: 2039keV)

$0\nu\beta\beta$ experiments

Experiment (selected)	Underground Laboratory	Isotope	$T_{1/2}$ [10^{21} y]	<m_{ee}> [*eV*]
Elegant VI	Oto (Japan)	^{48}Ca	> 95	< 7.2 - 44.7
Heidelberg-Moscow	Gran Sasso (Italy)	^{76}Ge	>19000 evidence: 11900	< 0.35 - 1.2 0.44
IGEX	Canfranc (Italy)	^{76}Ge	> 16000	< 0.3 - 1.5
NEMO-III	Frejus (France)	^{82}Se	> 140	< 1.7 - 4.9
NEMO-III		^{100}Mo	> 460	< 0.7 - 2.8
$CdWO_4$ scintillator	Solotvina (Ukrain)	^{116}Cd	> 170	< 1.5 - 1.7
Cuoricino	Gran Sasso	^{130}Te	> 1800	< 0.4 - 1.9
DAMA	Gran Sasso	^{136}Xe	> 1200	< 2.9

Why choose Ge76

sensitivity on $T_{1/2} \propto \varepsilon \bullet \sqrt{\frac{MT}{B}}$

$T_{1/2} \propto \varepsilon MT \text{ if } B = 0$

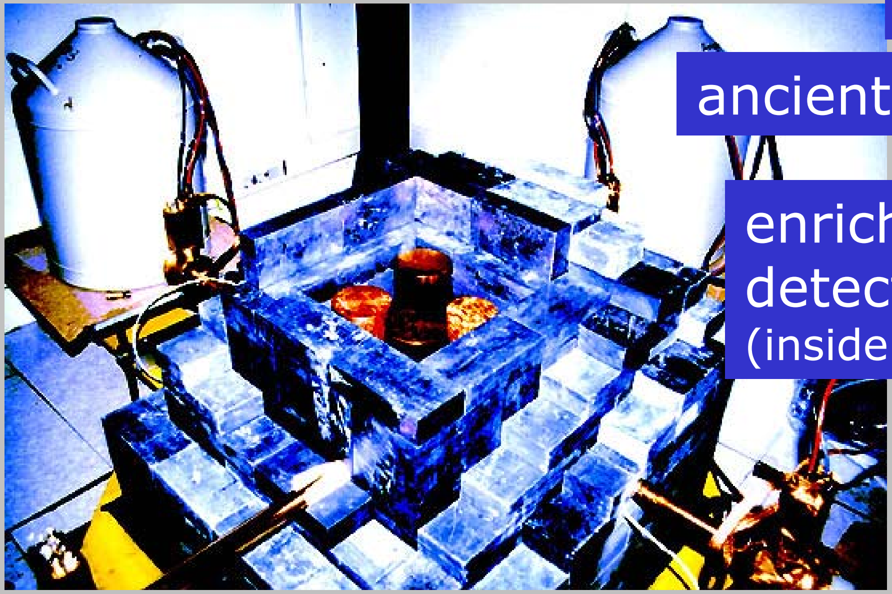
design focus	Ge76 advantage
high signal efficiency ε	source=detector, 85~95% ε
large target mass & long exposure **M·T**	existing IGEX & HdMo detectors
extremely low level Background B	ultrapure material (HPGe) excellent energy resolution →FWHM ~3keV at 2MeV, small search window →reduce background, including 2νββ new development →segmentation, new type of Ge detector etc…

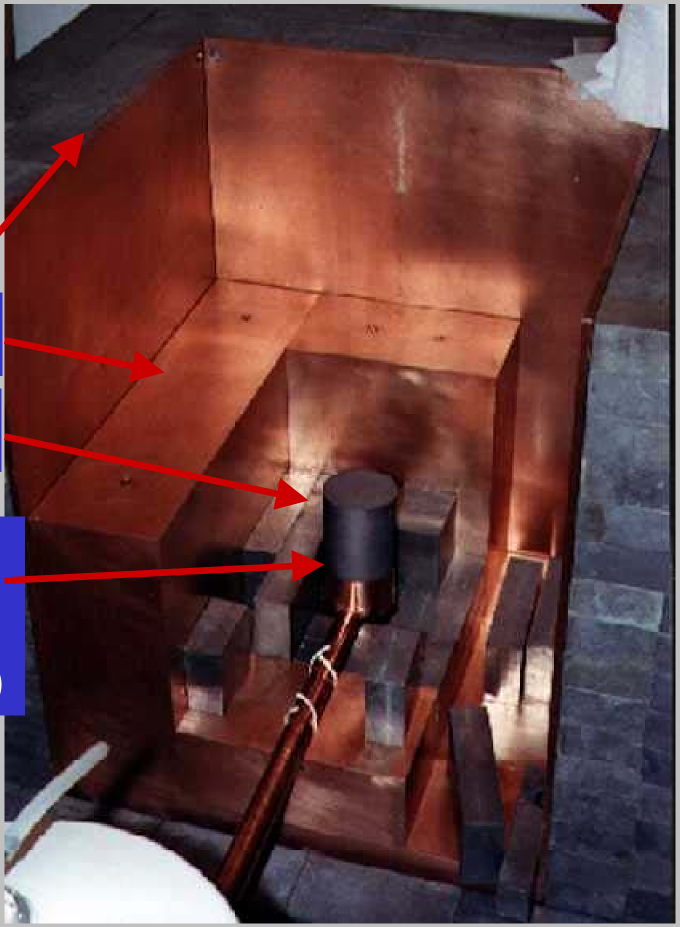
☹need enrichment (7.6% natural abundance, most bg scale with target mass)

Previous Ge76 experiment: Heidelberg-Moscow

5 p-type Ge76-enriched detectors

- operated in Vacuum
- shielded with Pb & Cu
- underground (LNGS)





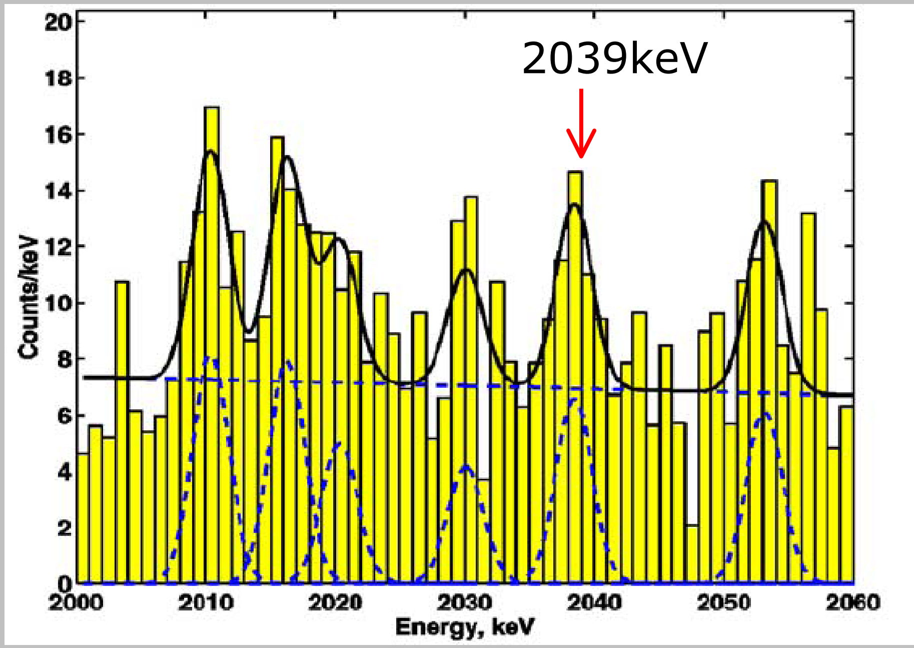
Previous Ge76 experiments

	HdMo	IGEX
exposure[kg·y]	71.1	8.87
B [counts/kg·keV·y]	0.11	0.2
$T_{1/2}$ limit (90%CL)[y]	$1.9 \cdot 10^{25}$	$1.6 \cdot 10^{25}$

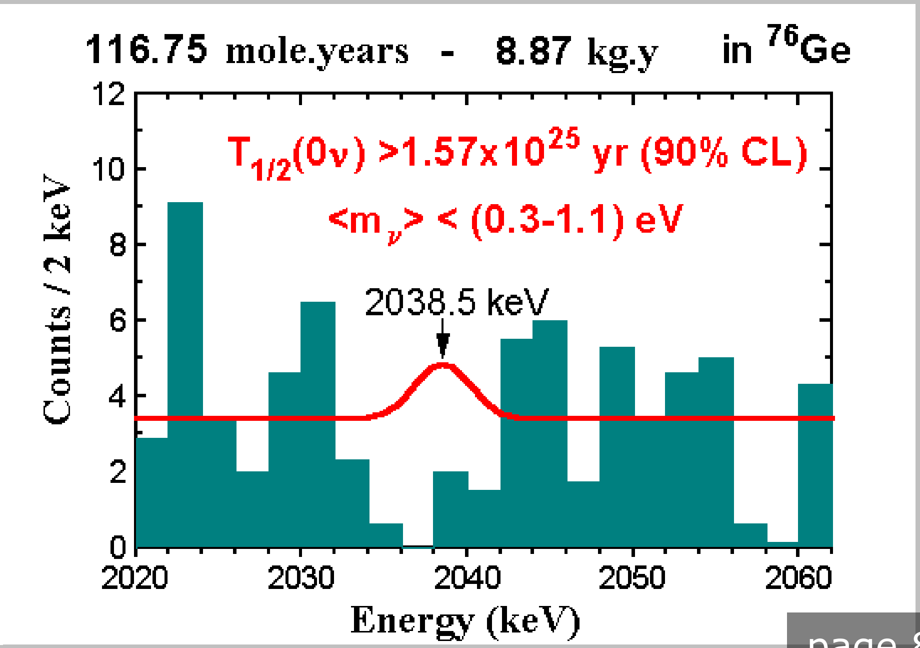
"Evidence for $0\nu\beta\beta$" $1.2 \cdot 10^{25}$
H.V.Klapdor-Kleingrothaus, etc., (0.69-4.18 3σ)
Phys. Lett. B 586 (2004) 198-212

Background index B:
counts/kg·keV·y
kg: Ge mass
keV: energy window
year: exposure time

HdMo



IGEX



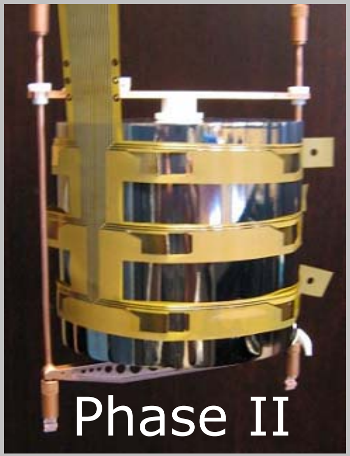
GERDA concept

Ge detectors directly submerged in LAr

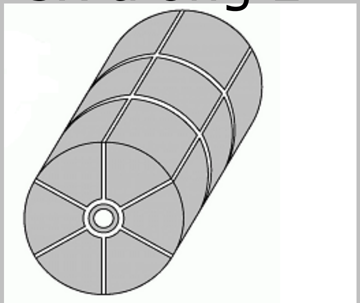
✓LAr purer than conventional Pb & Cu
✓easy for large volume

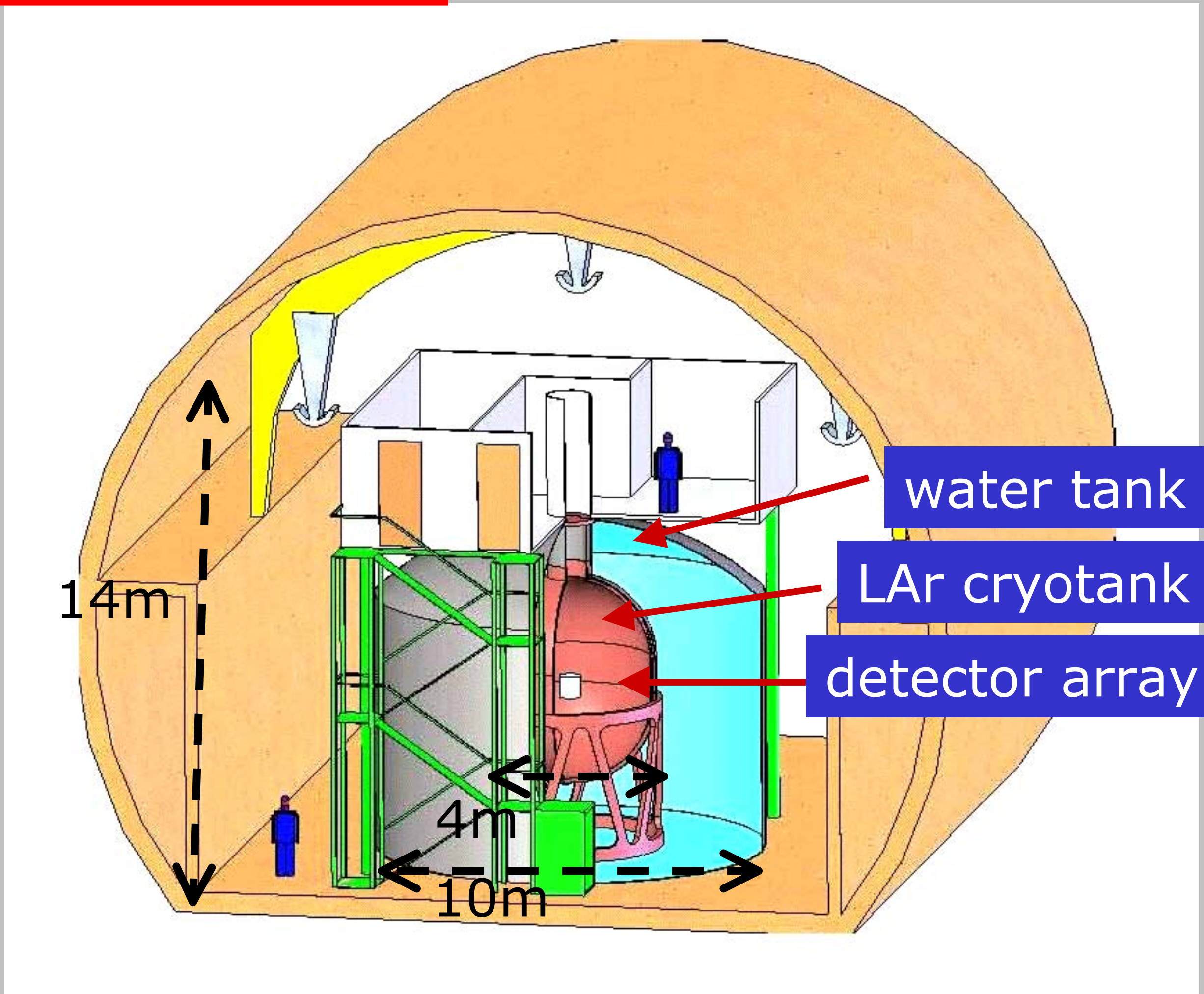
new detectors segmented

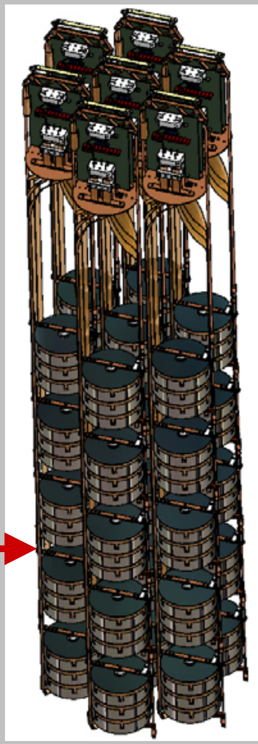
✓further reducing background



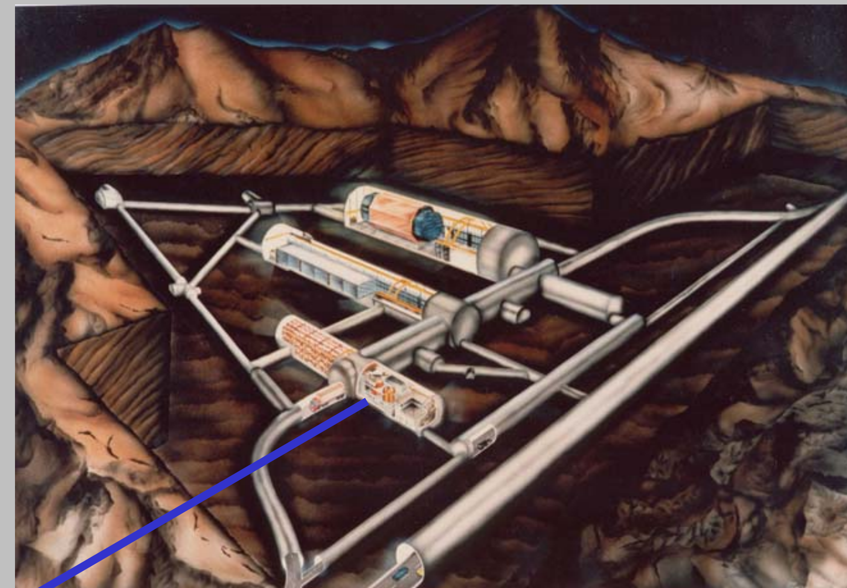
18 segments
6x along ϕ
3x along z

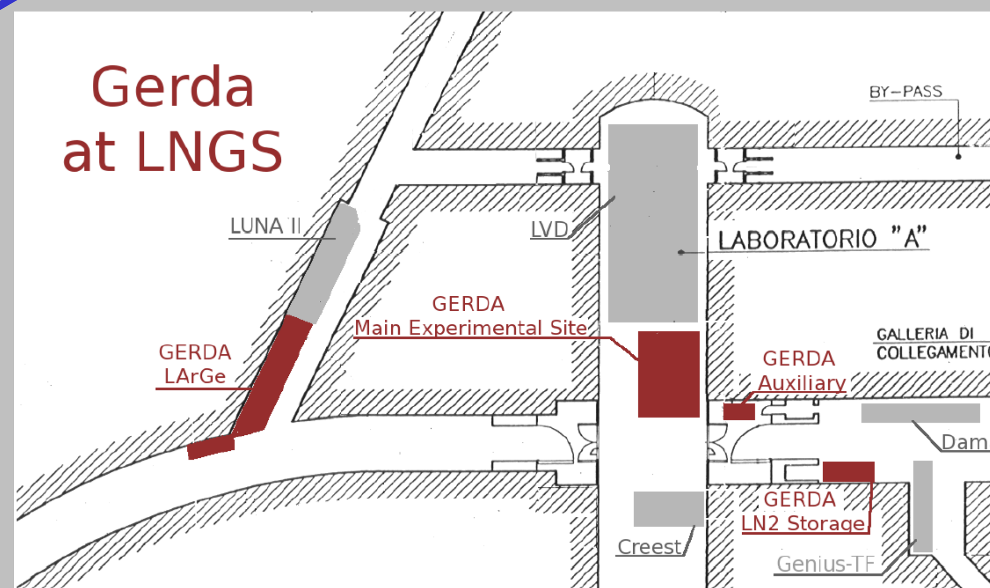




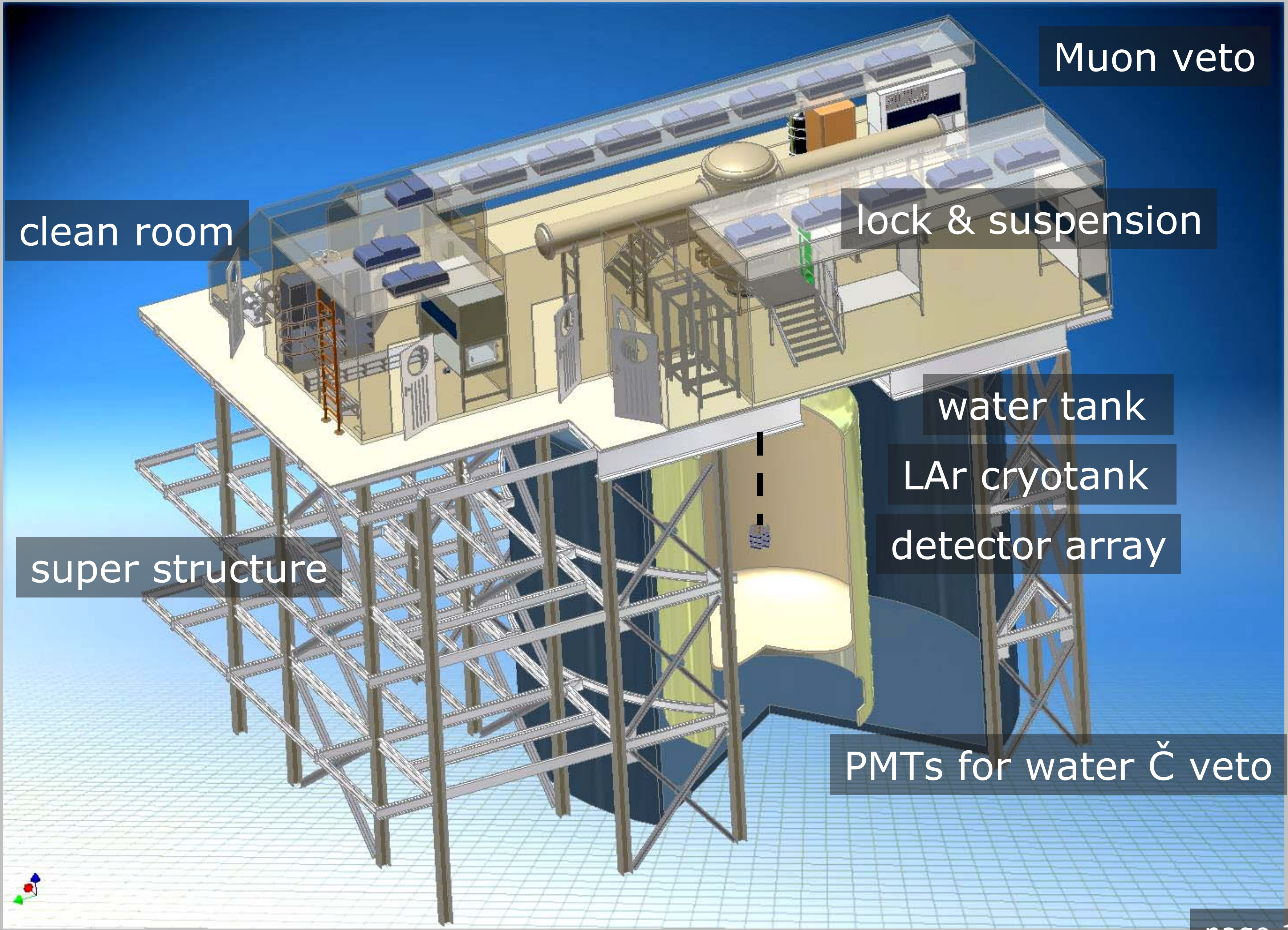


GERDA experiment at LNGS



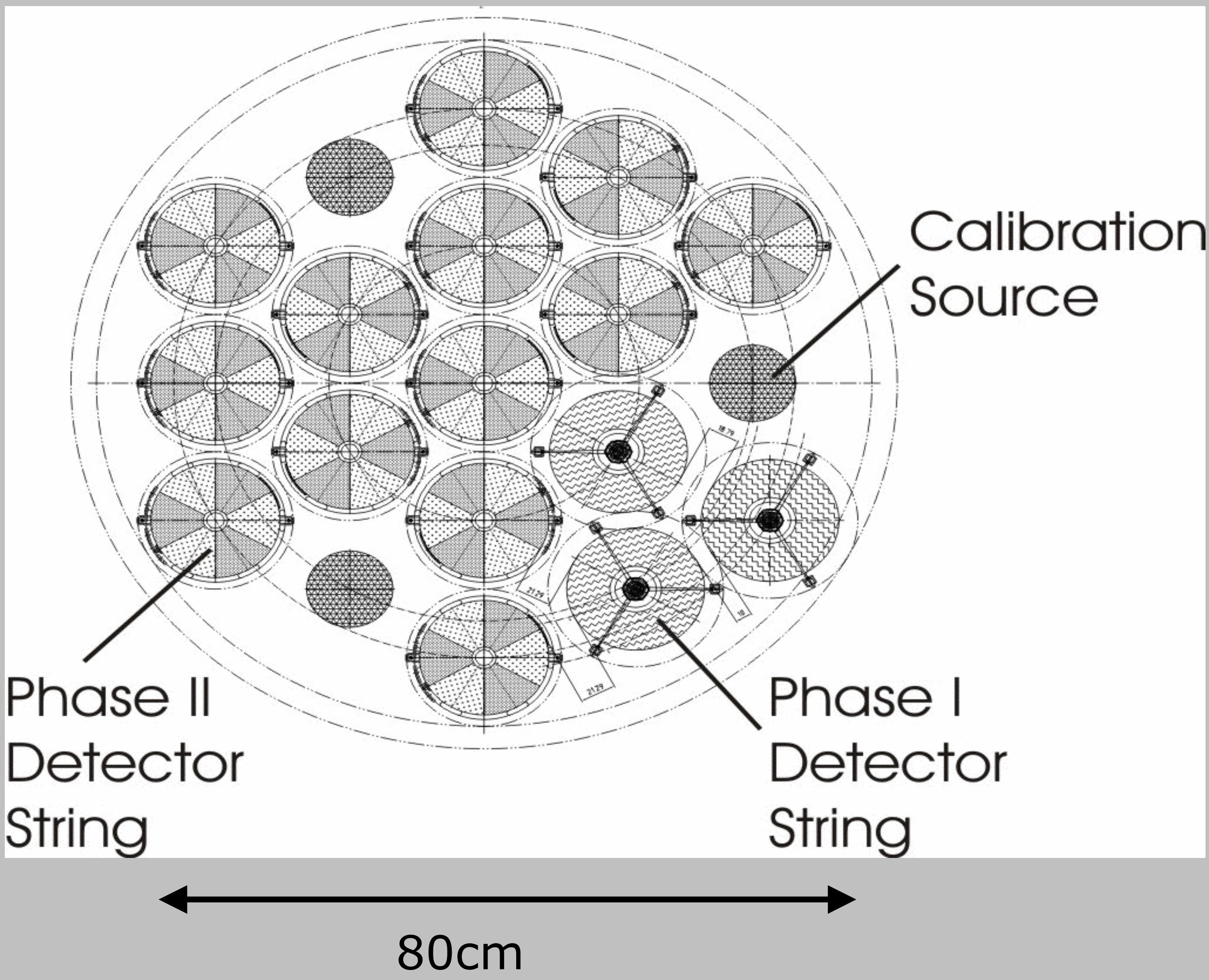


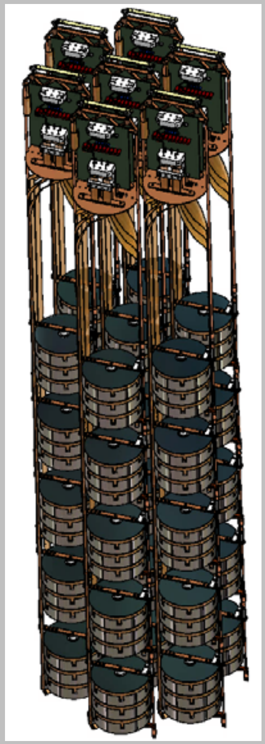
GERDA design



GERDA detector array

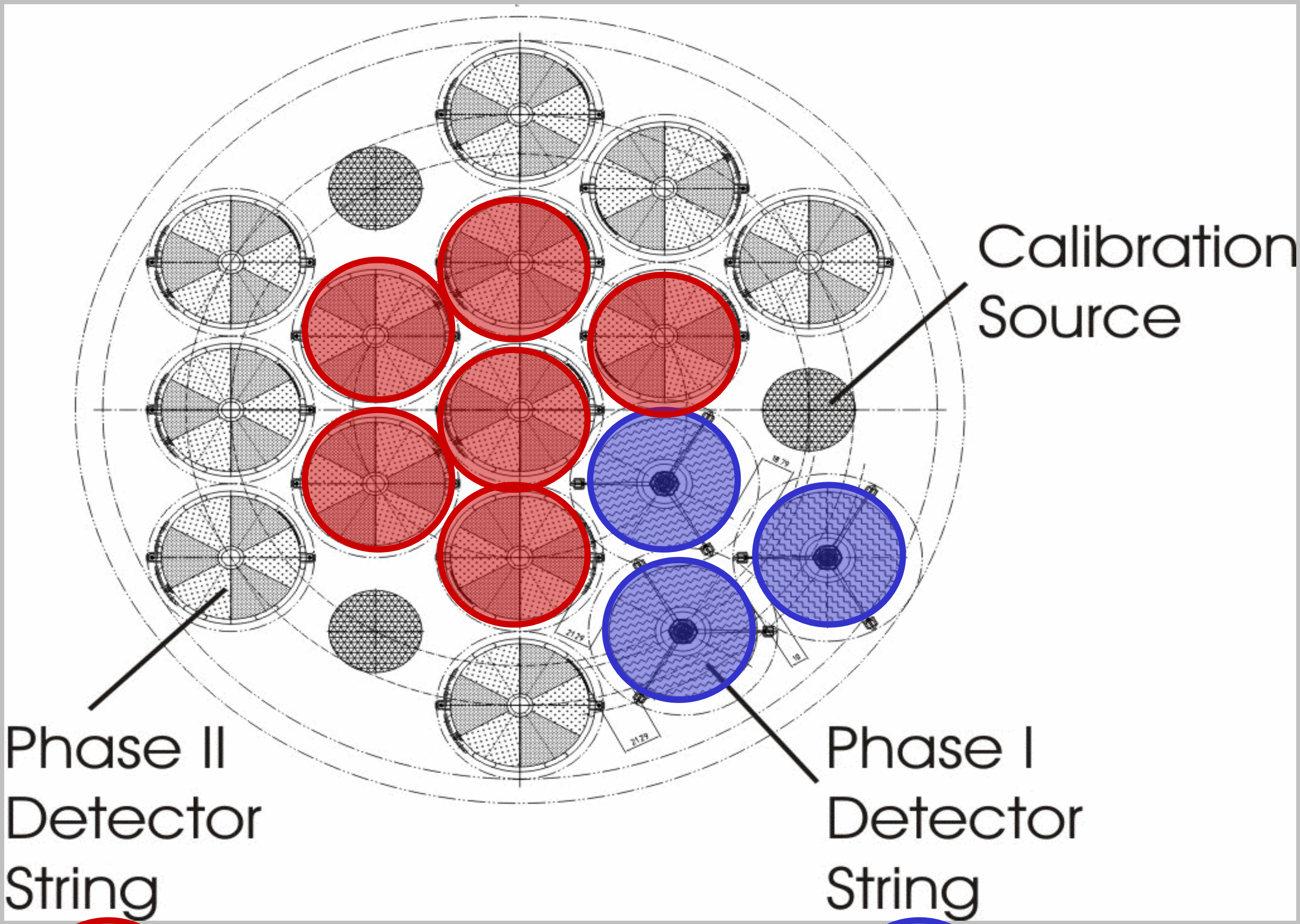
top view:

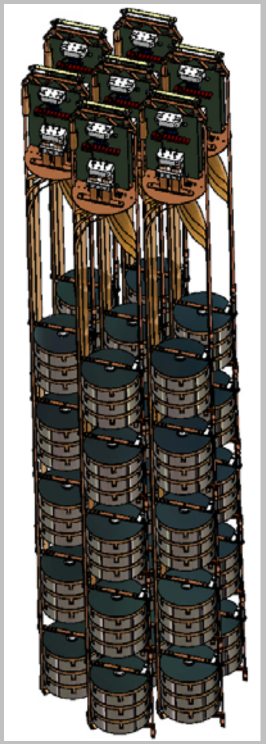




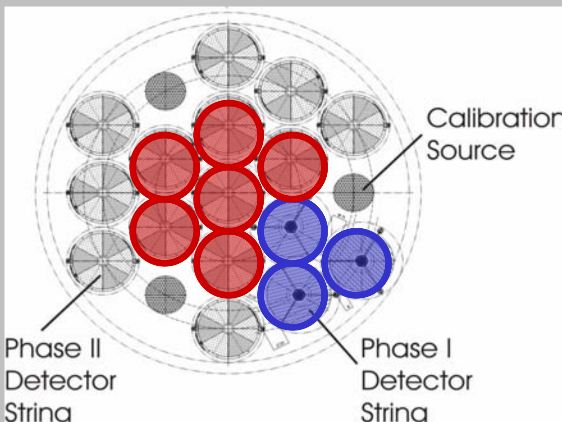
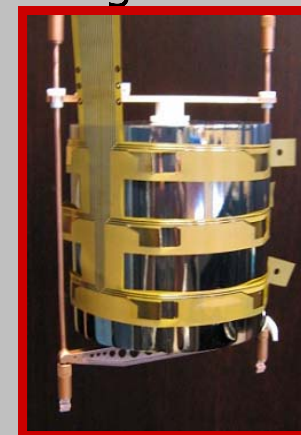
GERDA detector array

top view:





GERDA phase approach

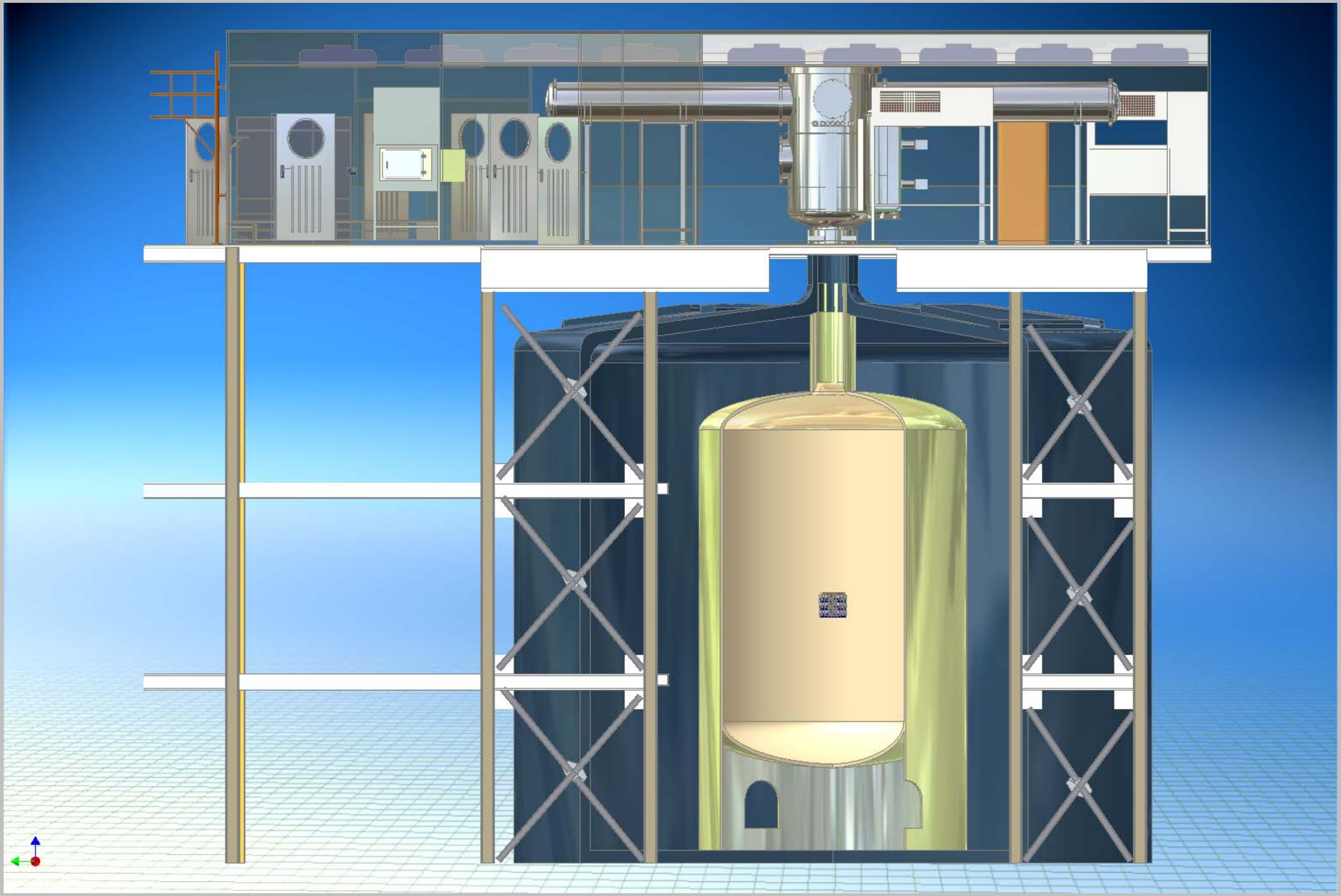
phase	I	II	III
detectors 	5 Hd-Mo & 3 IGEX detectors, 17.9 kg 	18-fold seg., ~25kg 	1ton scale
exposure[kg·y]	30	100	>10000
bg [counts/kg·keV·y]	10E-2	10E-3	<10E-4
limit on $T_{1/2}$ [10E25 y]	verify/veto KK-claim	15	>1000
limit on $m_{\beta\beta}$ [eV]	0.27	0.13	~0.02

If Klapdor-Kleingrothaus claim is true, phase-I expect ~13 signal events, and 3 bg. events in 10keV window at Q

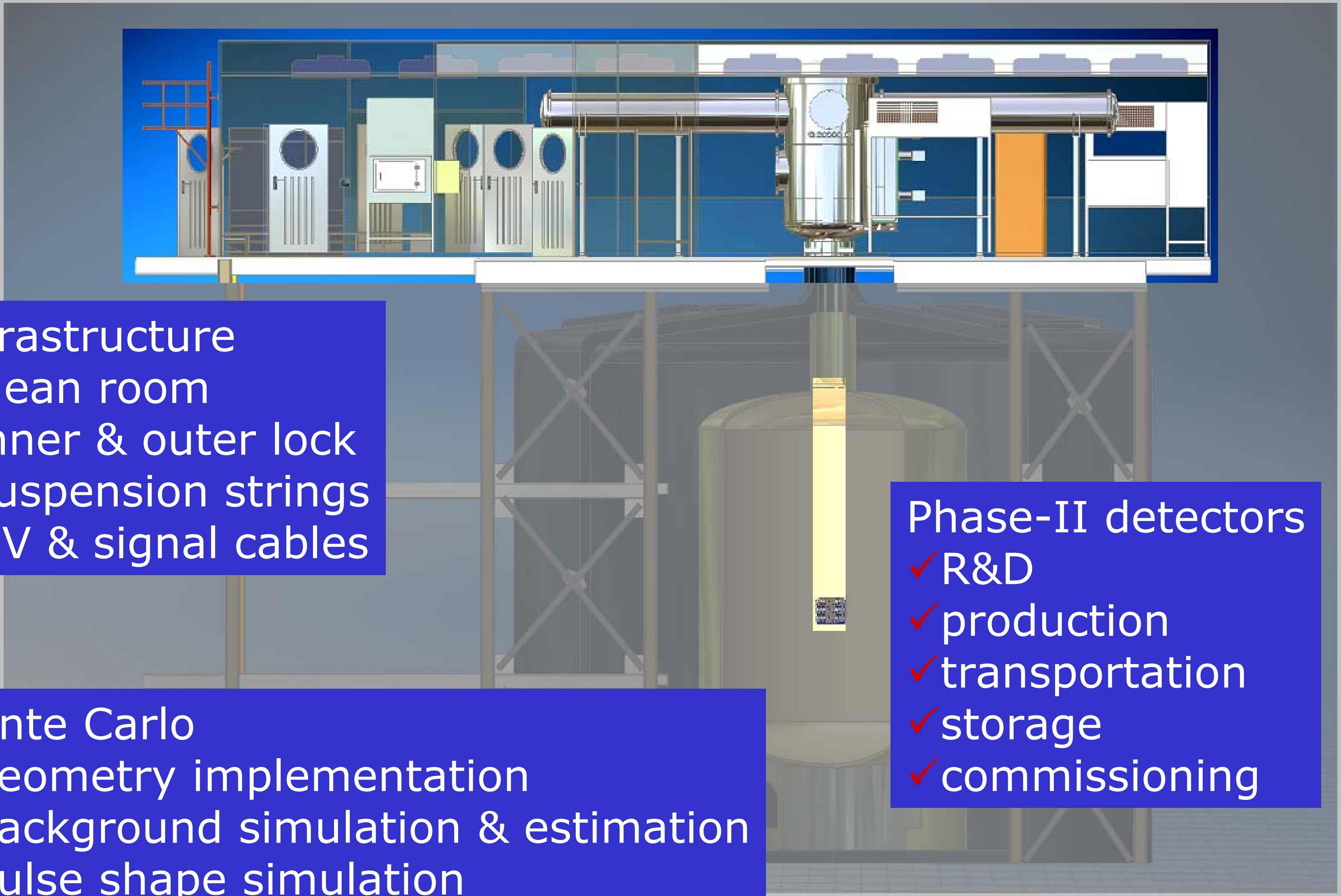
GERDA collaboration

Institute for Reference Materials and Measurements, Geel, Belgium
Institut für Kernphysik, Universität Köln, Germany
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Insititut), München, Germany
Physikalisches Institut, Universität Tübingen, Germany
Dipartimento di Fisica dell'Univeristá; di Padova e INFN Padova, Padova, Italy
INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
Universitá; di Milano Bicocca e INFN Milano, Milano, Italy
Jagiellonian University, Cracow, Poland
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia
Russian Research Center Kurchatov Institute, Moscow, Russia
University Zurich, Switzerland

Our institute responsibilities



Our institute responsibilities



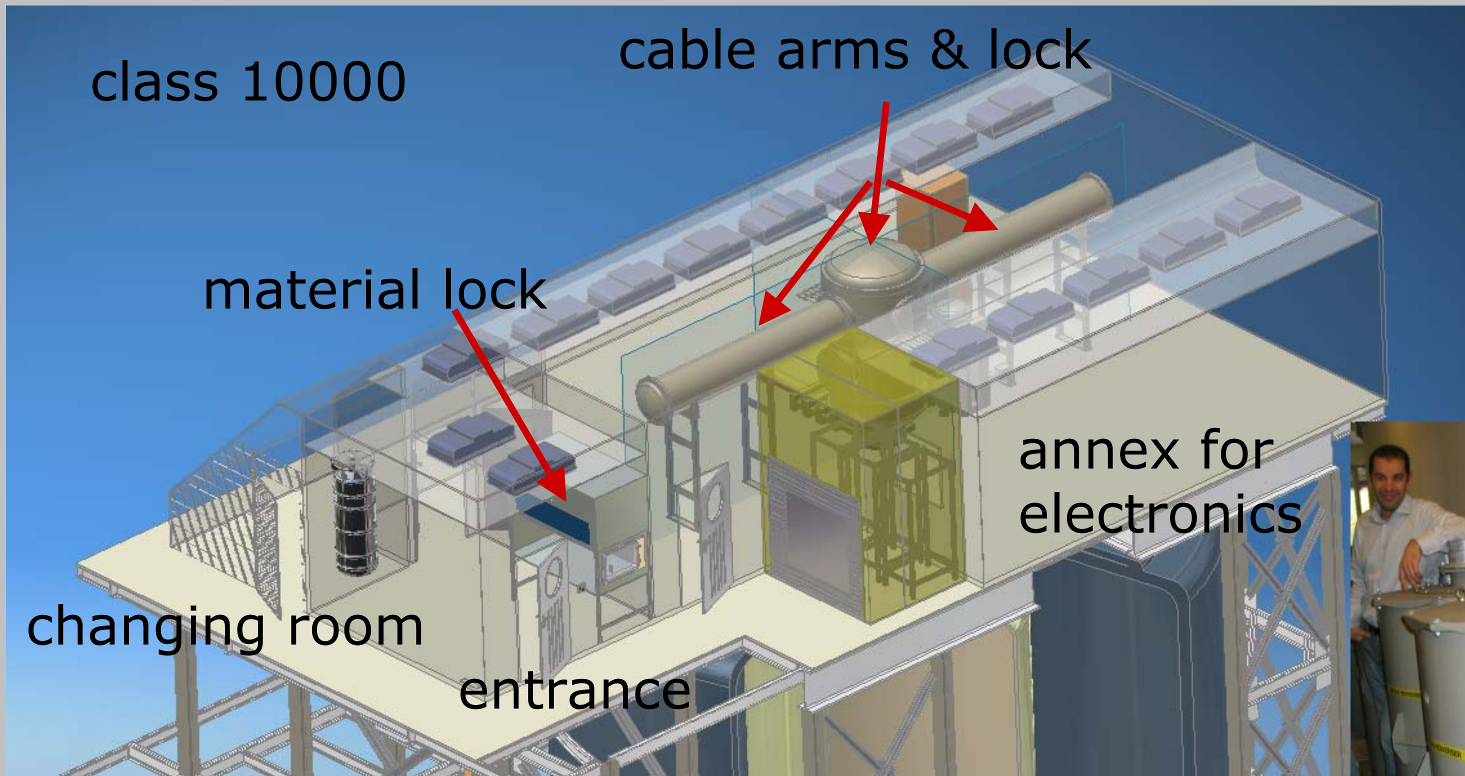
Infrastructure
- ✓clean room
- ✓inner & outer lock
- ✓suspension strings
- ✓HV & signal cables

Phase-II detectors
- ✓R&D
- ✓production
- ✓transportation
- ✓storage
- ✓commissioning

Monte Carlo
- ✓geometry implementation
- ✓background simulation & estimation
- ✓pulse shape simulation

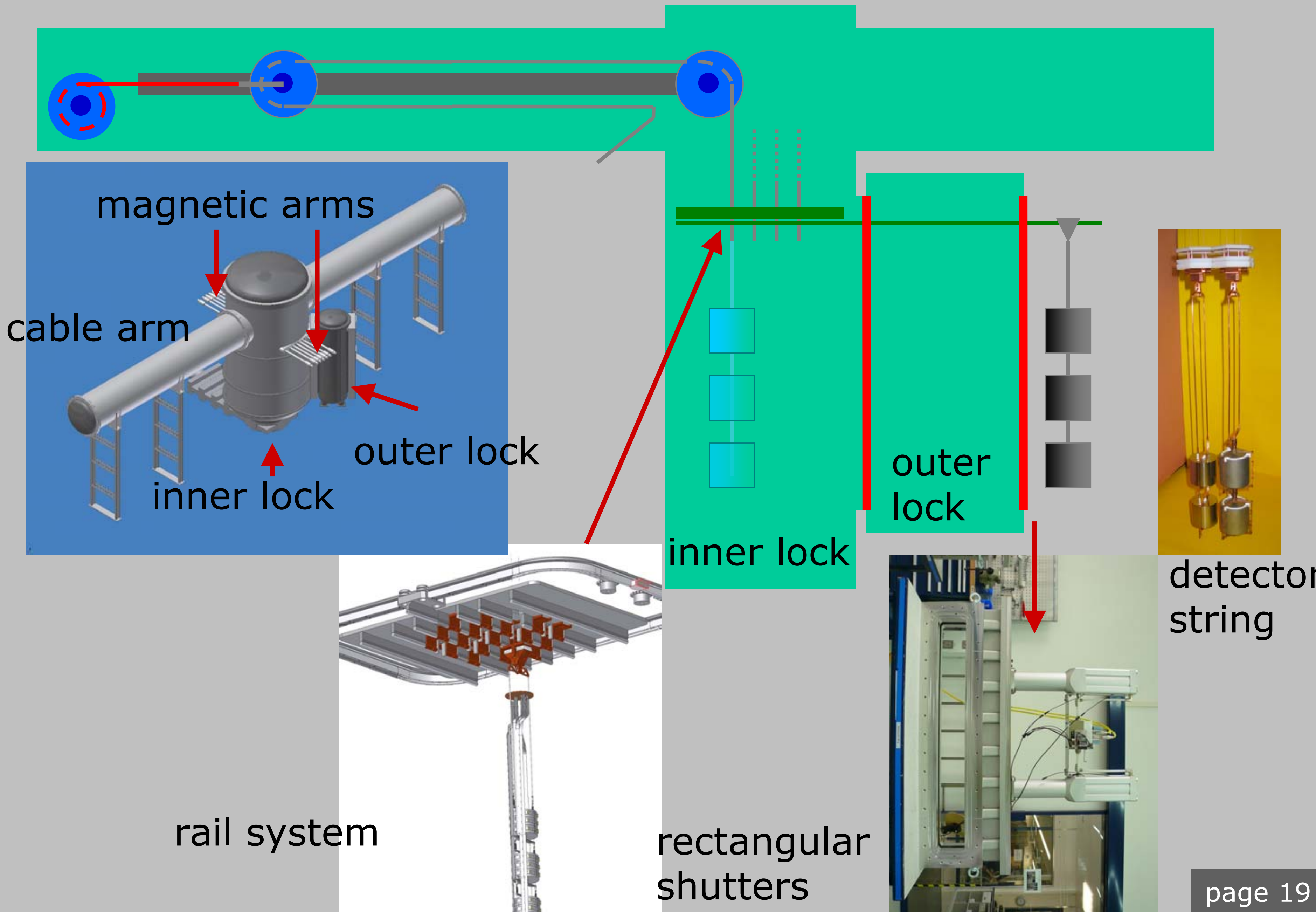
Analysis

Infrastructure: clean room

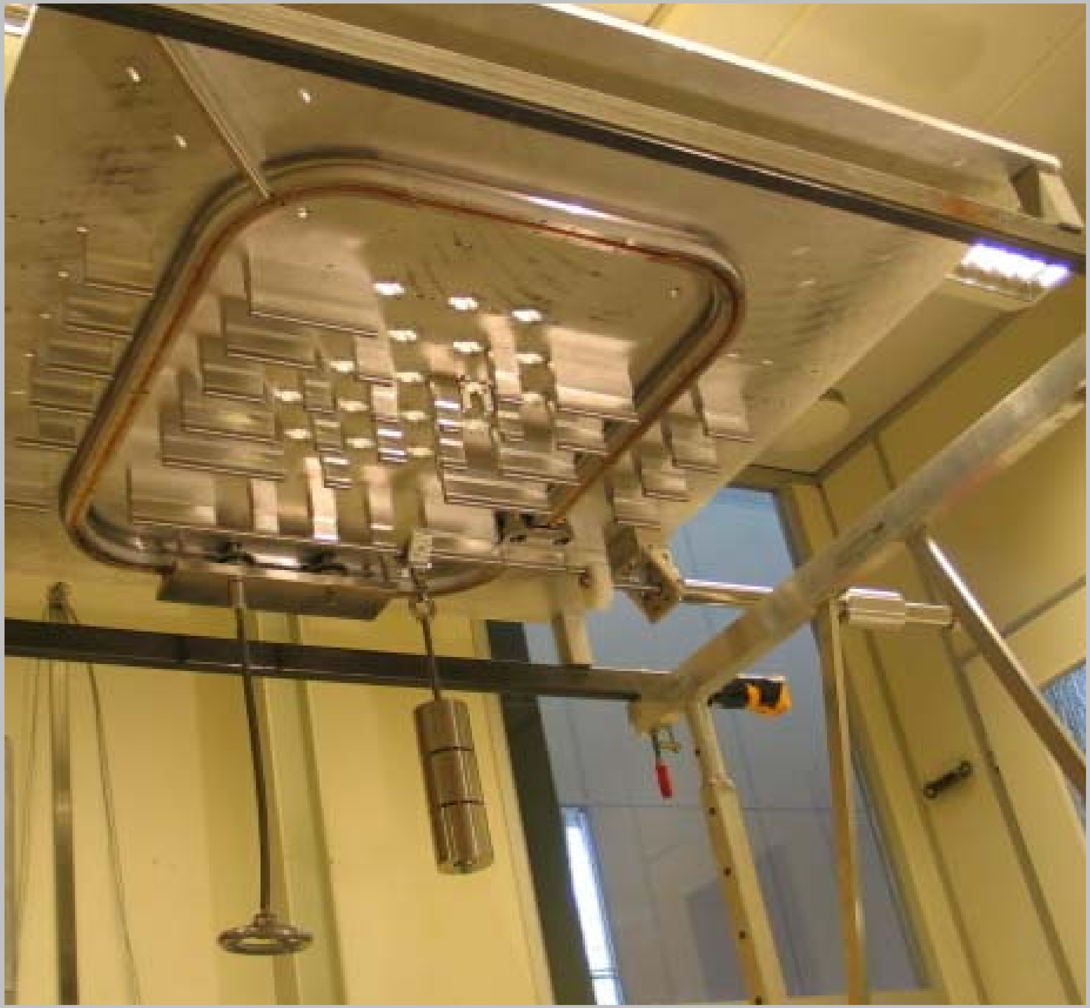


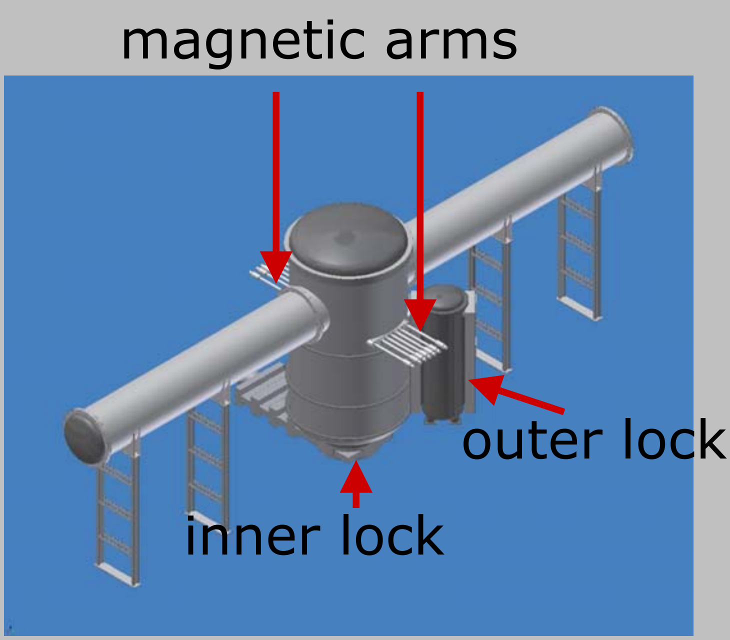
- provide Radon-reduced air in crystal enviroment
  8 active Chaco filter (total 1.25ton) from
  ICDO, International Civil Defence Organization, Geneva
- tender for participation competition closed

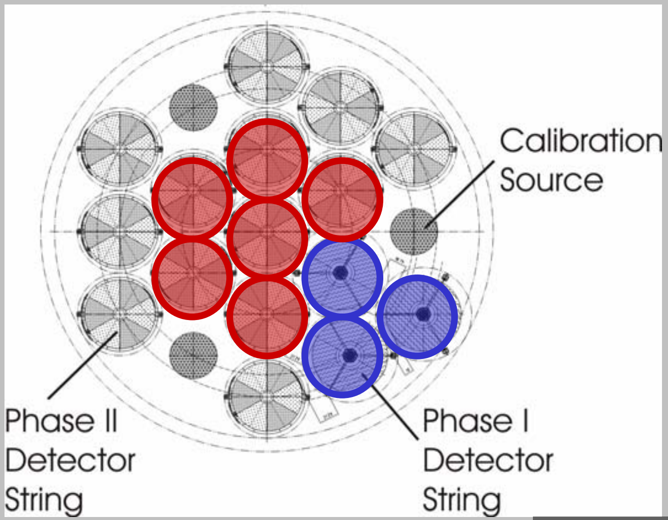
Infrastructure: inner, outer locks & cable arms



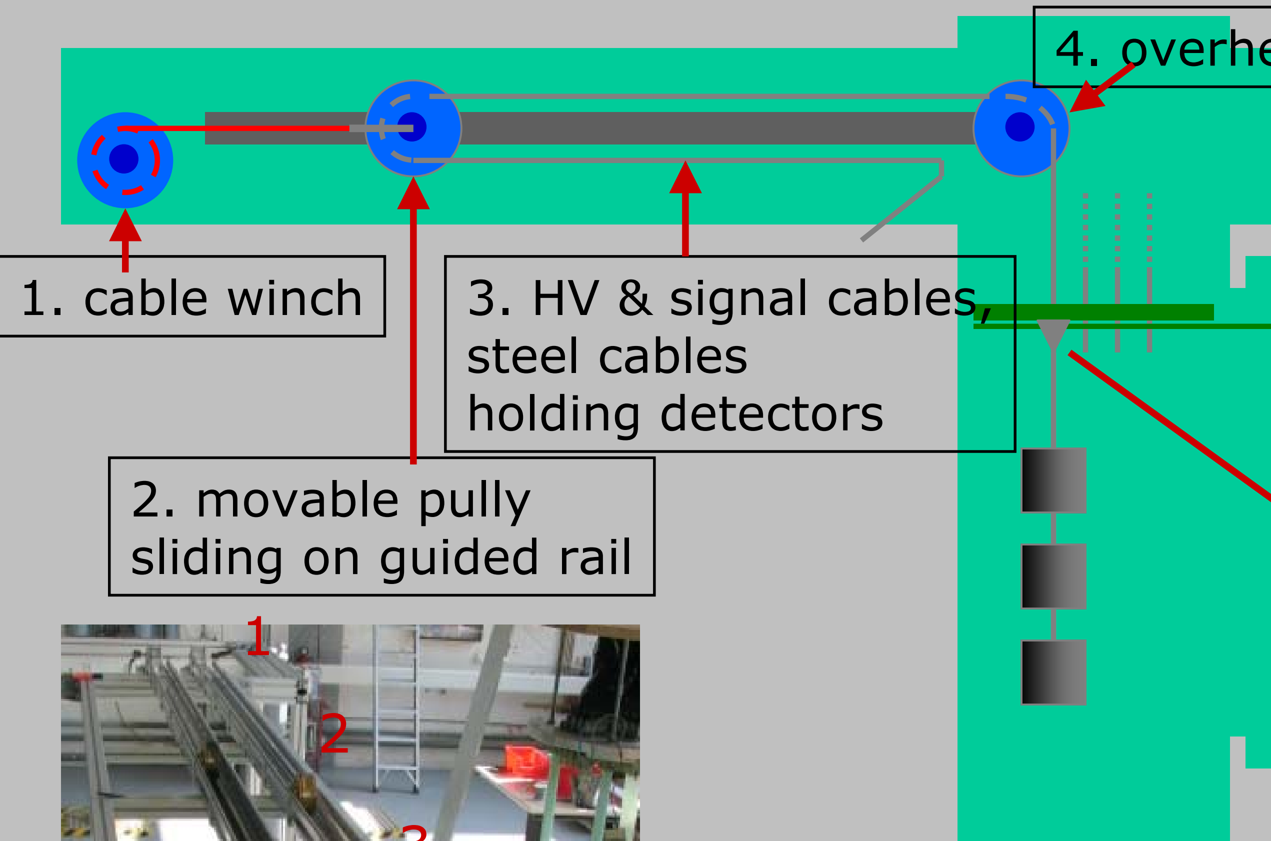
Infrastructure: rail system

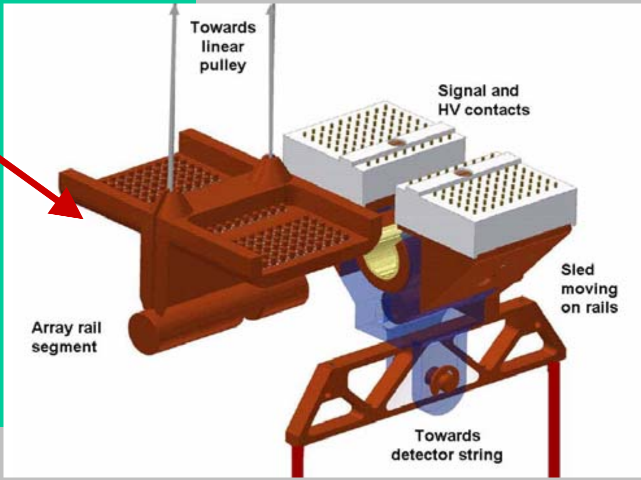


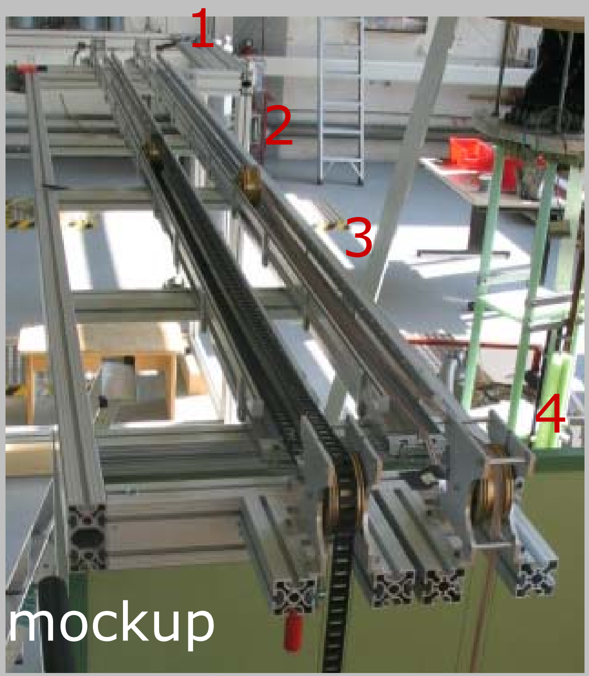




Infrastructure: lowering detector string into LAr

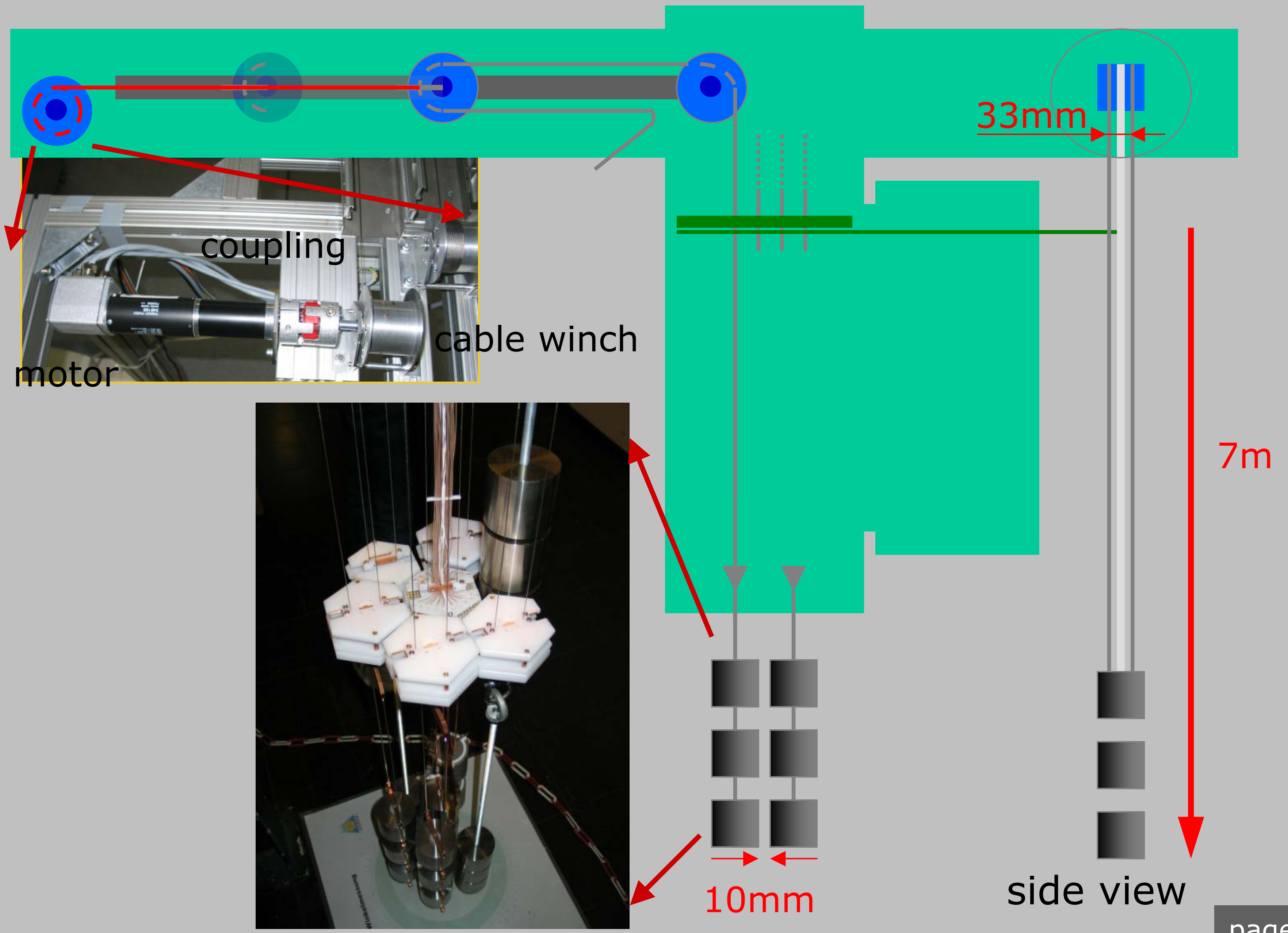




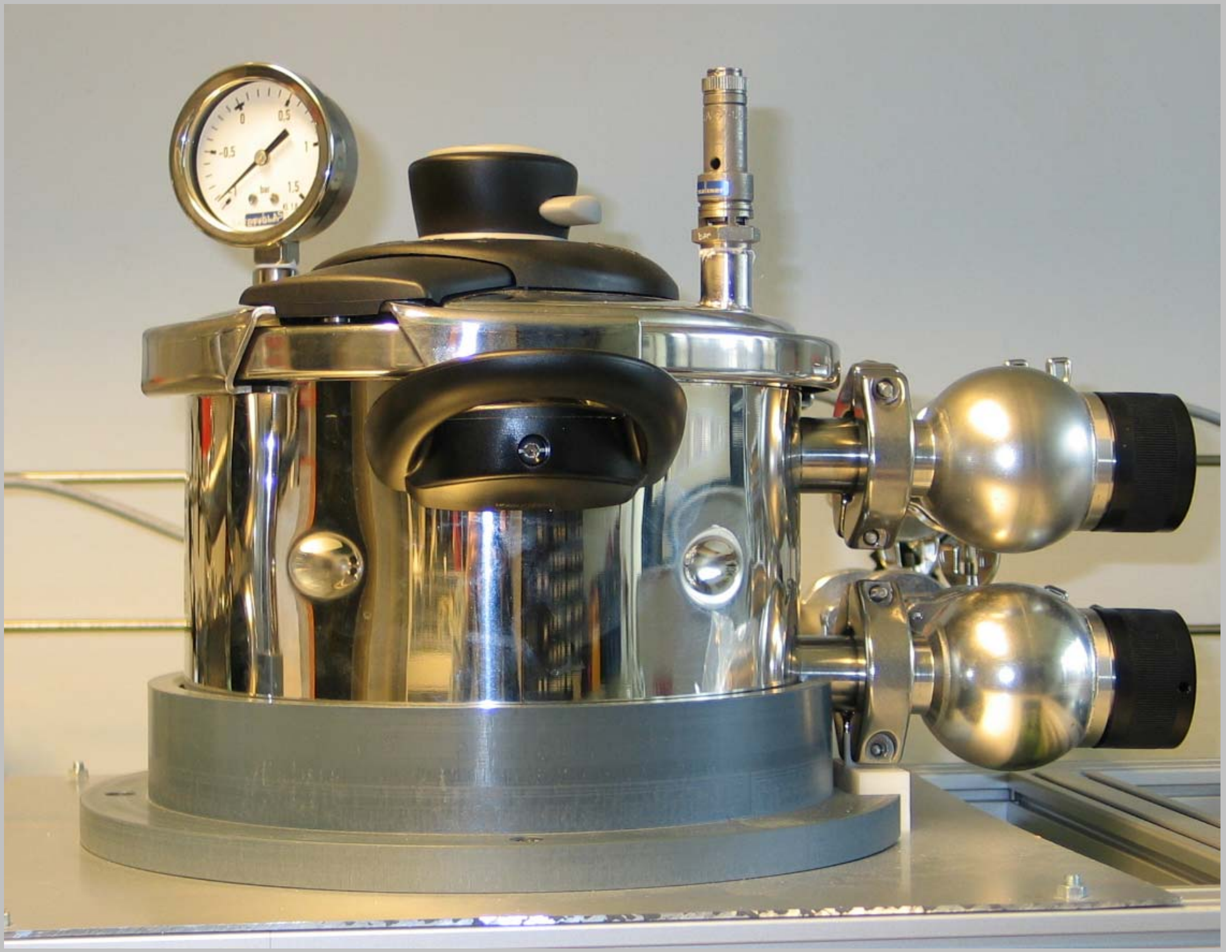


signal & HV cable
contact matrix

Infrastructure: lowering detector string into LAr



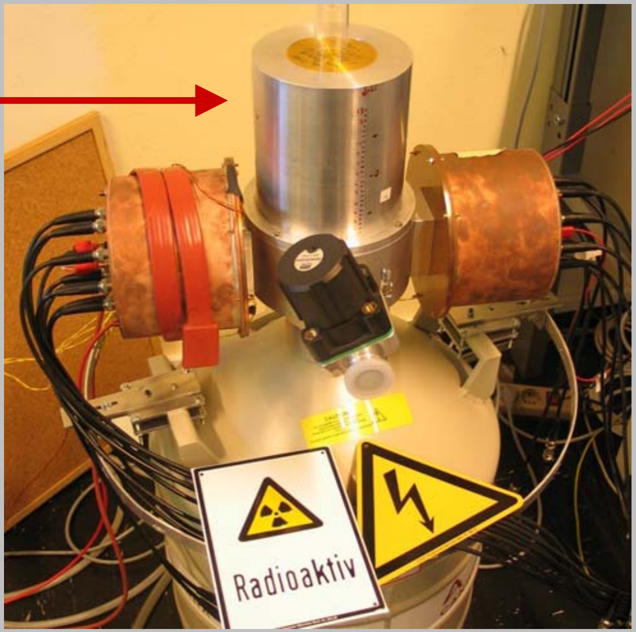
Infrastructure: detector transportation & on-site storage



Detectors can be stored in Vacuum or gas N2/Ar environment.

Phase-II prototype detector R&D

One 18-fold segmented n-type detector exposed to γ and n sources
→ confirmed segmentation technique & MC simulation



„Characterization of the detector“ I. Abt *et al.* NIM A **577** (2007) 574

„Identification of photon events... “ I. Abt *et al.* NIM A **583** (2007) 332-340

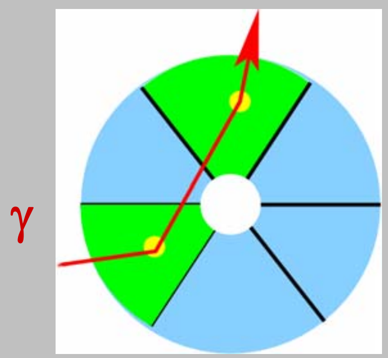
„Pulse shape analysis... “ I. Abt *et al.* EPJC accepted

„Test of PSA...“ I. Abt *et al.* Submitted to EPJC

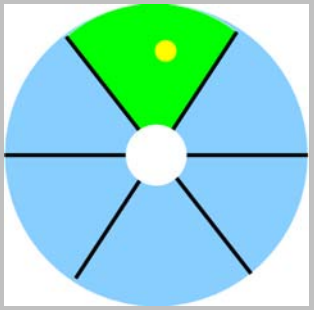
„Neutron interaction...“ I. Abt *et al.* Submitted to EPJA

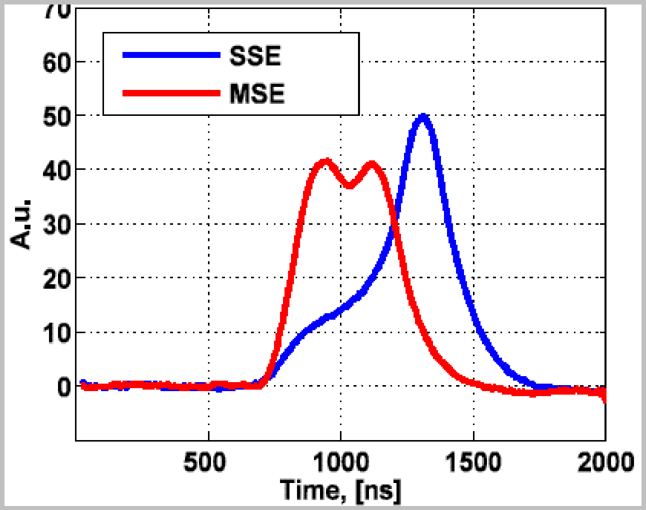
Phase-II prototype detector R&D: remove γ background

γ background
multi-site event



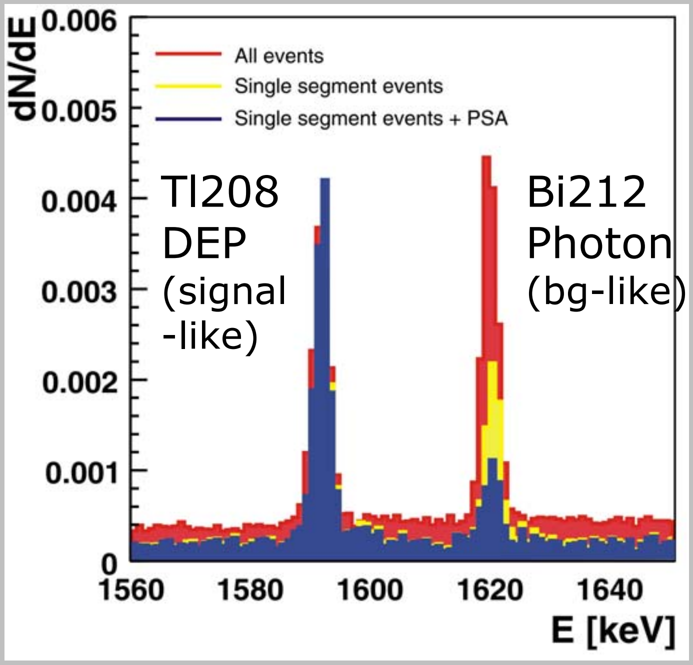
singal: 2 electrons
single-site event





step 1: single-segment (crystal)

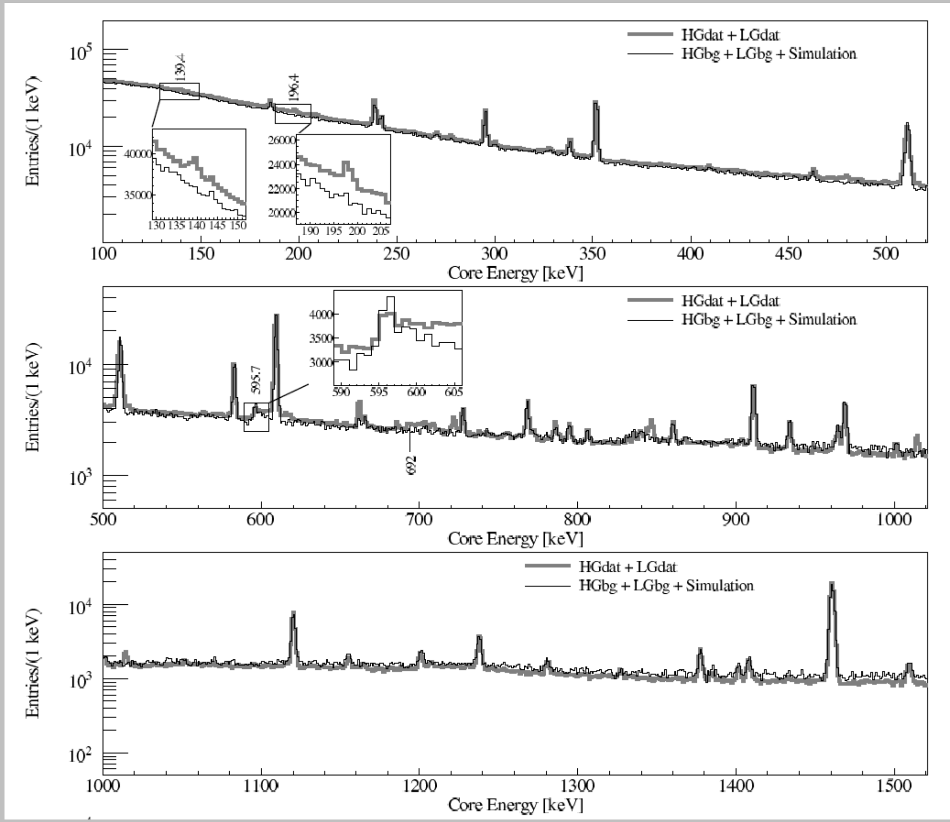
step 2: pulse shape analysis

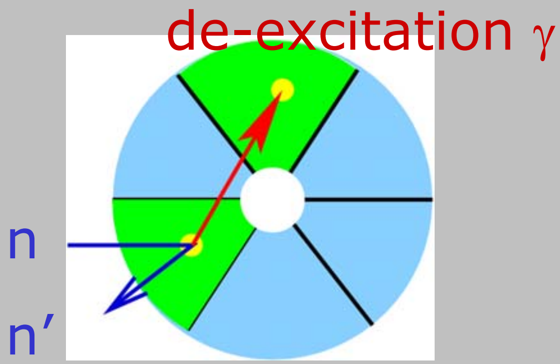


Phase-II prototype detector R&D: neutron interactions

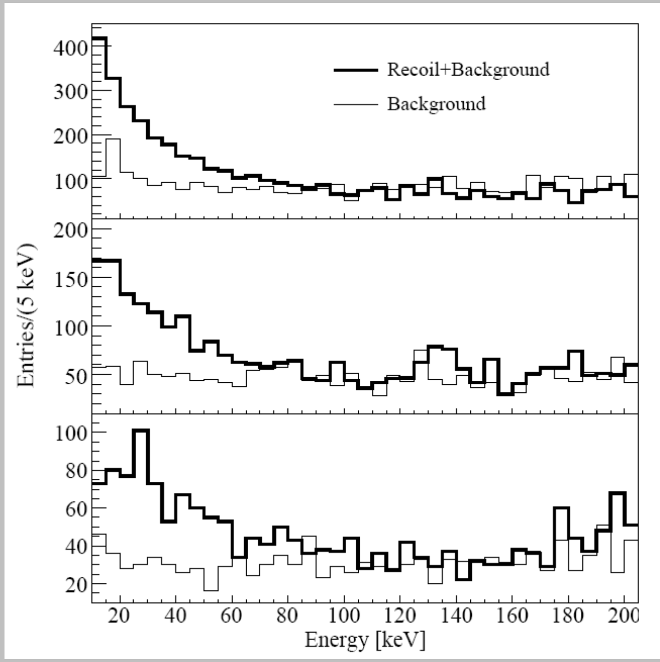
- study neutron interaction with Ge
- check Geant4 MC simulation

energy spectrum from AmBe source





inelastic scattering (n, n′γ)



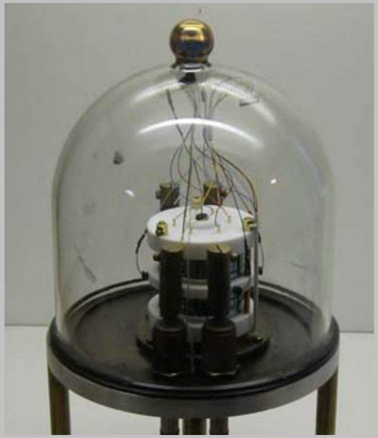
recoil energy spectra

New test stand for phase-II prototype detectors under construction

Gerdalinchen-II with up to
3 detectors directly in LN2/LAr.

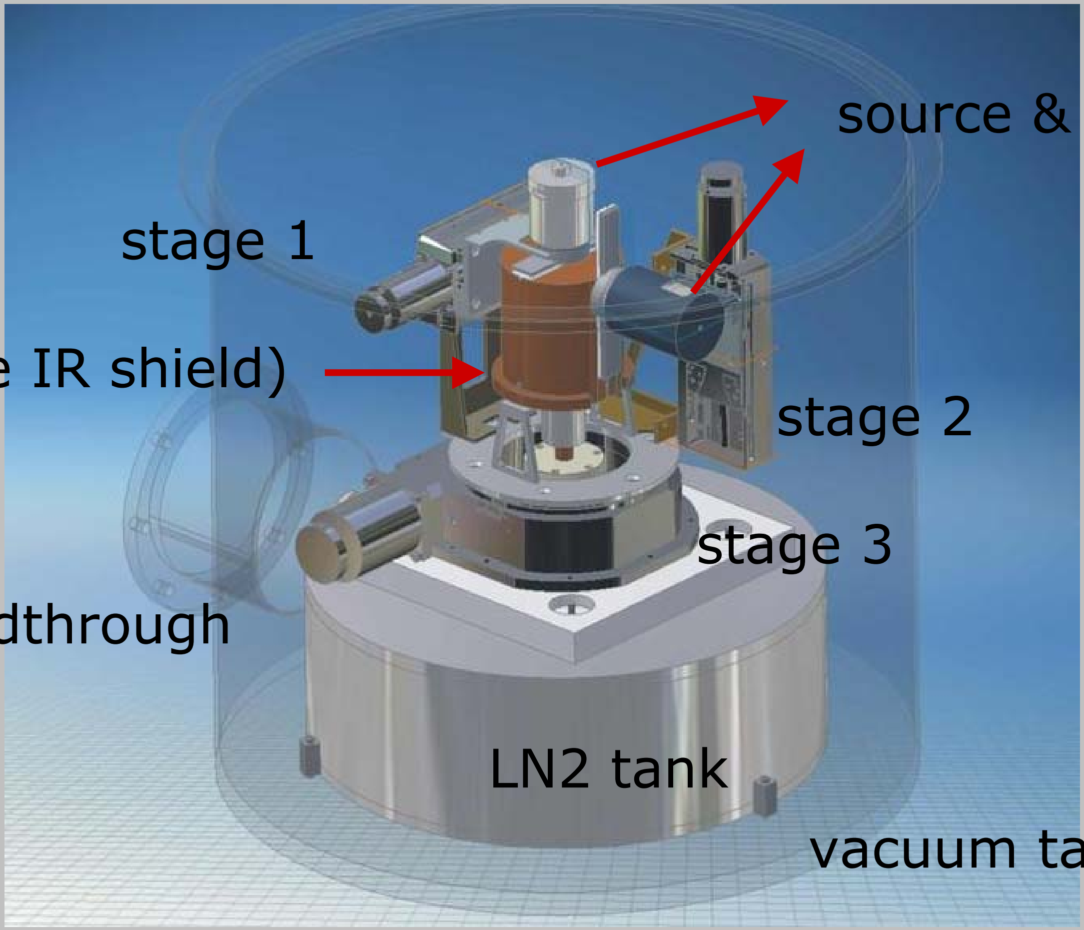
2 18-fold n-type &
1 18-fold p-type detectors

Program:
- detector performance
- segment & crystal anti-coincidence cut
- pulse shape



18-fold p-type

GeDet: new test stand for general purpose



3D scan of Ge detector surfaces with γ, α sources & laser.
study segment boundary,
pulse shape,
crystal axis....

Phase-II detector delivery status

Ge76 enrichment — 37.5 GeO2, 87% enriched in Ge76, delivered 06 ✓

↓

Ge76 metal

measure dilution: mass spectrometer
measure impurity: MS, resistivity, Hall-effect, PTIS(Photo-thermal ionization spectroscopy)

↓ impurity? dilution?

zone-refinement

↓ impurity? dilution?

PPM Pure Metals, Langelsheim

- 50kg depleted GeO2 bought for test.
- first ZR → <6N purity & 77% yield.
- more tests on going → expect >80%.

Czochralski puller

crystal pulling

↓ impurity? (→ zone-refinement)

Institut für Kristalzüchtung, Berlin

- R&D contract.
- growed crystal with materials from PPM.
- will measure impurity using Hall-effect & PTIS.
- help from Berkeley.

detector production — Canberra France delivered 2 prototypes 06/07 ✓

Phase-II detector delivery status

fraction of Ge isotopes

(Institute of Microelectronics Technology & High Purity Materials, Chernogolovka, Moscow)

	Ge1a	Ge1b	Ge2b	Ge3b	Ge4b	Ge_i1	Ge_i3	Ge_i4	Ge n
70	22.8	22.7	22.8	22.8	22.8	22.74	22.75	22.70	21.2
72	30.1	30.0	30.00	30.00	30.00	30.07	30.05	30.08	27.8
73	8.32	8.30	8.33	8.33	8.32	8.32	8.30	8.29	7.75
74	38.2	38.4	38.3	38.3	38.3	38.27	38.30	38.34	35.9
76	0.59	0.60	0.59	0.59	0.60	0.60	0.60	0.59	7.35

depleted GeO2 | metal Ge | Ge after ZR | natural

No dilution of natural Ge

ICPMS on metal Ge

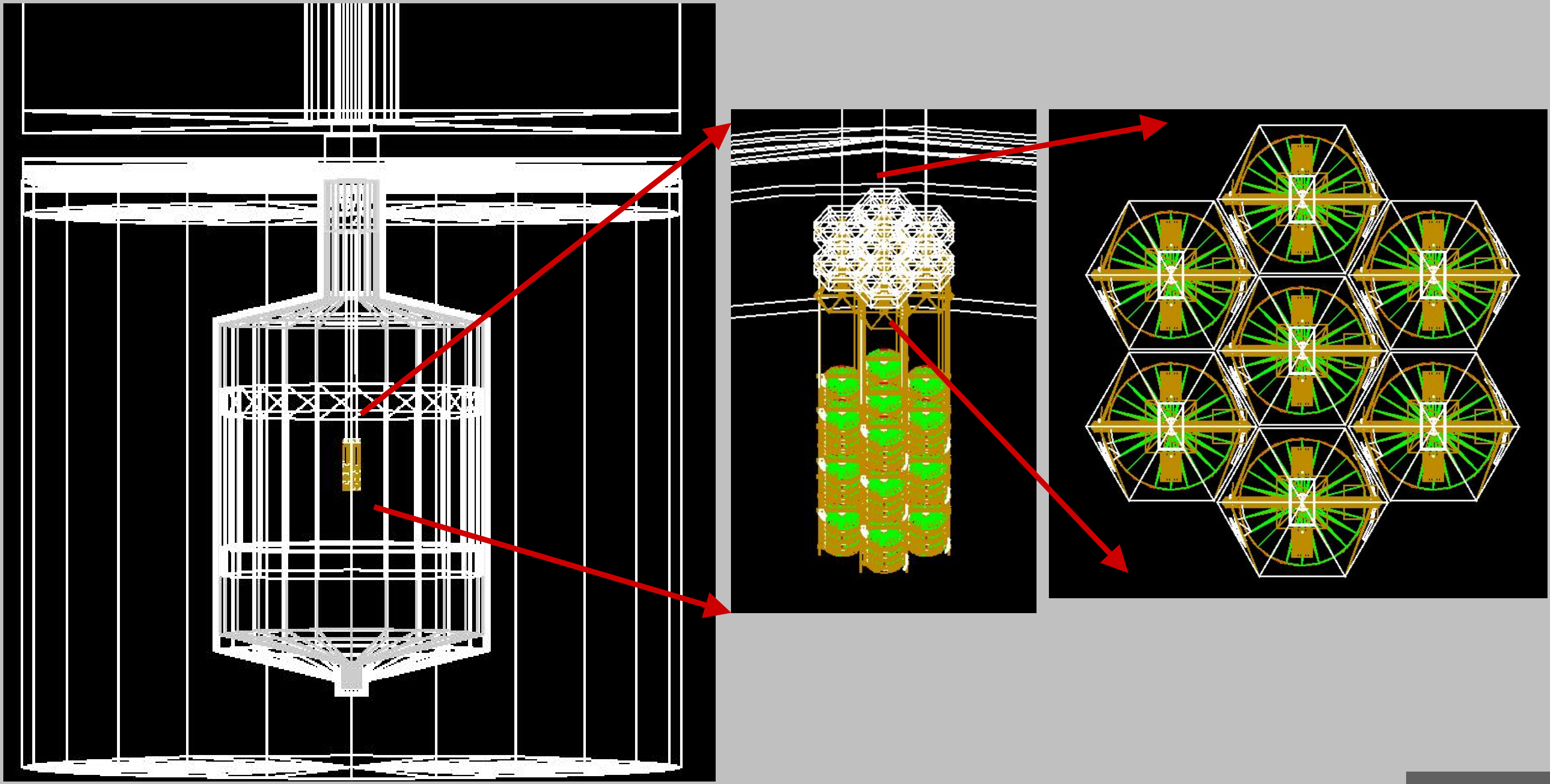
(inductively coupled plasma MS)

Element	DL ppm	GeO_2	1/4	2/4	3/4	Element	DL ppm	GeO_2	1/4	2/4	3/4
Li	0,006	<DL	<**0.01**	<DL	<DL	Sb	0,03	<DL	<DL	<DL	<DL
Be	0,0005	<DL	<DL	<DL	<DL	Te	0,006	<**0.02**	<DL	<DL	<DL
B	0,1	<DL	<DL	<DL	<DL	Cs	0,001	<DL	<DL	<DL	<DL
Na	20	<DL	<DL	<DL	<DL	Ba	0,5	<DL	<**7**	<**1.8**	<DL
Mg	1	<DL	<DL	<DL	<DL	La	0,003	<DL	<DL	<DL	<DL
Al	2	<DL	<DL	<DL	<DL	Ce	0,01	<DL	<DL	<DL	<DL
K	6	<DL	<DL	<DL	<DL	Pr	0,001	<DL	<DL	<DL	<DL
Ca	7	<**10**	<DL	<DL	<DL	Nd	0,002	<DL	<DL	<DL	<DL
Sc	0,02	<DL	<DL	<DL	<DL	Sm	0,0003	<DL	<DL	<DL	<DL
Ti	0,4	<DL	<DL	<DL	<DL	Eu	0,0002	<DL	<DL	<DL	<DL
V	0,5	<DL	<DL	<DL	<DL	Gd	0,0009	<DL	<DL	<DL	<DL
Cr	2	<DL	<DL	<DL	<DL	Tb	0,0001	<DL	<DL	<DL	<DL
Mn	0,2	<DL	<DL	<DL	<DL	Dy	0,0003	<DL	<DL	<DL	<DL
Fe	5	<DL	<DL	<DL	<DL	Ho	0,0001	<DL	<DL	<DL	<DL
Co	0,02	<DL	<DL	<DL	<DL	Er	0,0001	<DL	<DL	<DL	<DL
Ni	[illegible]	<DL	[illegible]	<DL	<DL	Tm	0,0001	<DL	[illegible]	<DL	<DL
Cu	[illegible]	<DL	[illegible]	[illegible]	[illegible]	Yb	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Zn	2	<DL	<DL	<DL	<DL	Lu	[illegible]	<DL	<DL	<DL	<DL
Ga	0,1	<DL	<DL	<DL	<DL	Hf	0,01	<DL	<DL	<DL	<DL
As	0,2	<DL	<DL	<DL	<DL	Ta	0,01	<DL	<DL	<DL	<DL
Se	0,3	<DL	<DL	<DL	<DL	W	83	<DL	<DL	<DL	<DL
Rb	0,009	<DL	<DL	<DL	<DL	Re	0,003	<DL	<DL	<DL	<DL
Sr	0,04	<DL	<DL	<DL	<DL	Ir	0,0004	<DL	<DL	<DL	<DL
Y	0,001	<DL	<DL	<DL	<DL	Pt	0,06	<DL	<DL	<DL	<DL
Zr	0,02	<DL	<DL	<DL	<DL	Au	0,01	<DL	<DL	<DL	<DL
Nb	0,02	<DL	<DL	<DL	<DL	Hg	0,6	<DL	<DL	<DL	<DL
Mo	0,07	<DL	<DL	<DL	<DL	Tl	0,0002	<DL	<DL	<DL	<DL
Rh	0,01	<DL	<DL	<DL	<DL	Pb	0,2	<DL	<DL	<DL	<DL
Pd	0,04	<**0.35**	<DL	<DL	<DL	Bi	0,002	<DL	<DL	<DL	<DL
Ag	0,04	<DL	<DL	<DL	<DL	Th	0,0006	<DL	<DL	<DL	<DL
Cd	0,004	<DL	<DL	<DL	<DL	U	0,0002	<DL	<DL	<DL	<DL

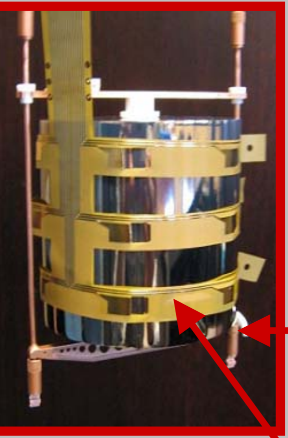
<DL: impurity below detection limit

Monte Carlo package MaGe (Majorana-Gerda)

- Geant4-based, developed together with Majorana.
- object-oriented framework allows parallel developing
  → same physics, different geometries.
- optimized for low energy & low bg.
- code sharing & physics verification.



MC simulation of background (phase II)



Part		Background contribution [10^{-4} counts/(kg·keV·y)]
Detector	**^{68}Ge**	**4.3** → after 2 years
	^{60}Co	0.3
	Bulk	3.0
	Surf.	**3.5** → further reduction expected from PSA
Holder	Cu	1.4
	Teflon	0.3
Cabling	Kapton	1.5
Electronics		**3.5**
LAr		1.0
Infrastructure		0.2
Muons and neutrons		2.0
Total		21.0

Summary

Open questions in ν : absolute mass? hierarchy? Majorana or Dirac?
→ GERDA (searching $0\nu\beta\beta$ in Ge76) might address all.

- Infrastructure mock up built at institute.
- Various tests show smooth detector handling.
  (shutter, rail, suspension, electronic contacts, lowering…)

- Phase-II detector & GeDet R&D: rich physics program.
- Enriched material delivered.
- Tests with purification & crystal pulling ongoing, promising.

- MC campaign (all contamination, all components) ongoing.
- Learn from GeDet R&D test stands.

GERDA construction started

cryotank top
(inner)

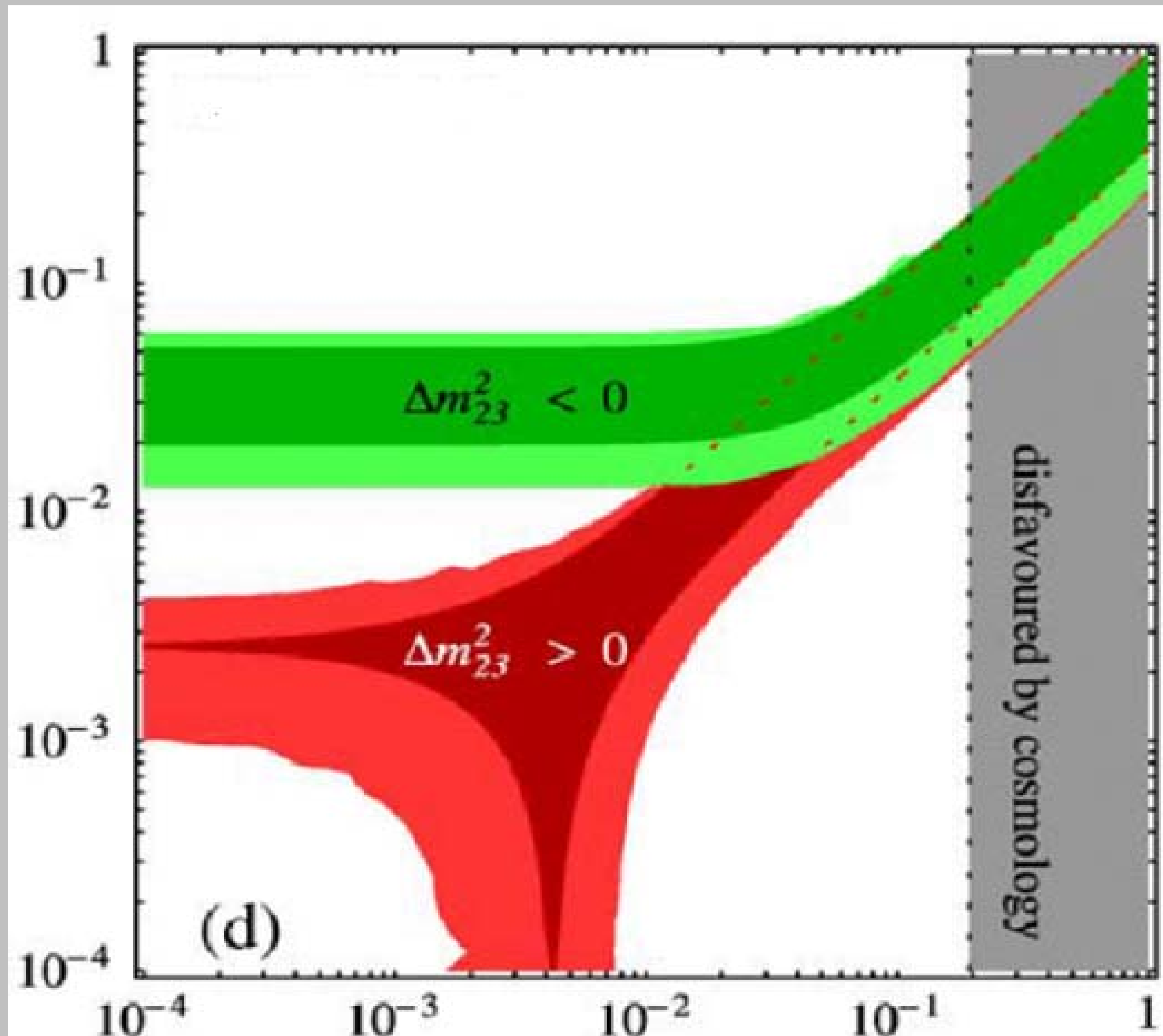
ground level for water tank

cryotank top
(outer)

backup

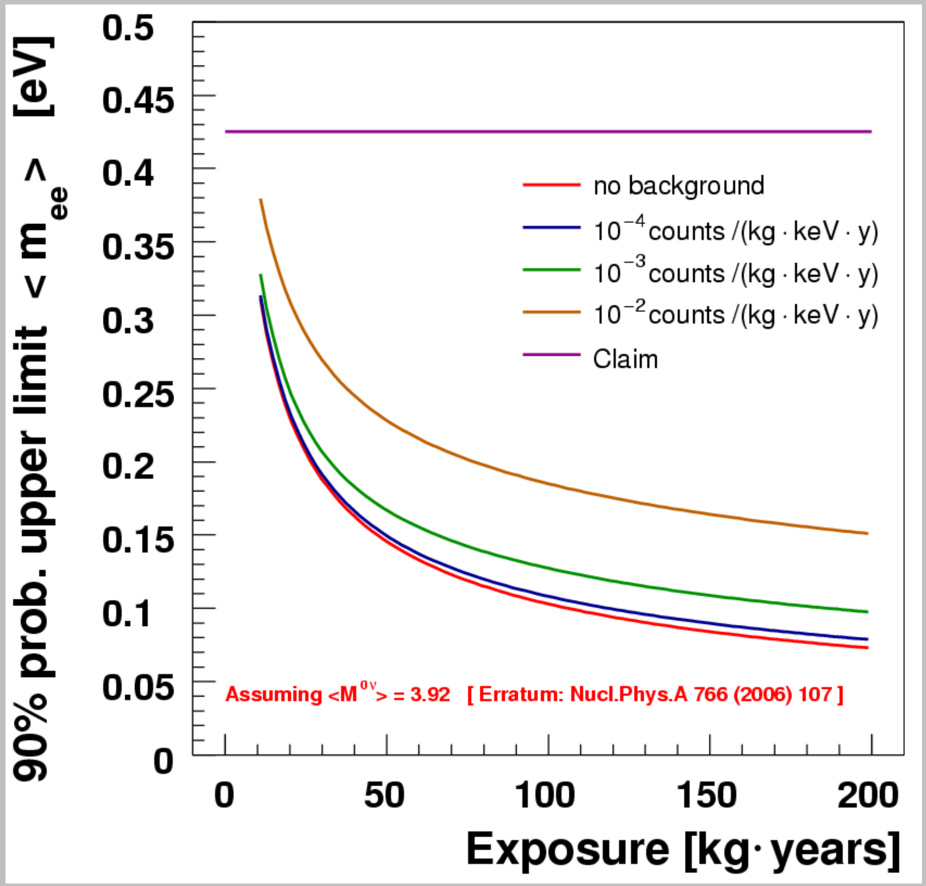
Effective Majorana neutrino mass vs. neutrino mass

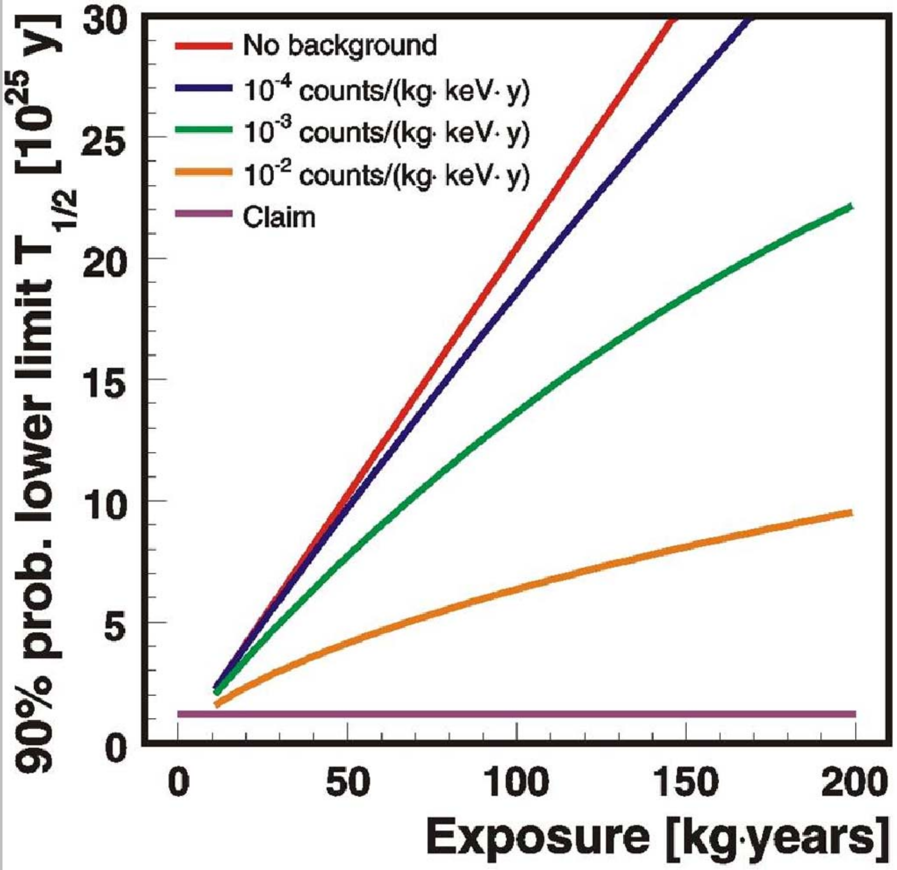
$m_{\beta\beta}$ (eV)



Lightest neutrino mass (eV)

Sensitivity on effective Majorana neutrino mass





Infrastructure: test, test, test……

Lock: Radon tight? Vacuum tight?

Detector inserting & lowering:

- suspension cables clean? hold in LAr?
- rail system smooth & precise?
- lowering procedure (how much time, wait..)?
- lowering without disturbance from LAr boiling?
- detectors angle and position well-defined afterwards?
- …

HV and signal cables and contacts:

- impedance? Bandwidth? Cross talk? Hold in LAr? Clean?
- HV feedthrough in gas Ar?
- …

Detector storage: Radon tight? Vacuum tight?

……