Double Beta Decay Experiments

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Outline

part 1. Double Beta Decay

- intruduction
- DBD and neutrino mass
- NME
- decay signature
- detector choice
- experimental sensitivity
- background sources

part 2. DBD experiments:

- Ge experiments
- NEMO3
- Cuoricino

part 3. DBD experiments: the new generation

- on-going: GERDA – CUORE – EXO ...
- proposed ...
- conclusions

$0\nu\beta\beta$ present and new generation experiments

further explore "Klapdor claim"

NEMO3 still running (already discussed)

GERDA phase I (same nucleus: direct comparison)

CUORE-0

EXO-200

2nd generation - approach the IH region

CUORE GERDA II (approved, funded with R&D completed)

EXO-1ton (R&D status)

MAJORANA & GERDA III (to be funded)

3rd generation - full inspection of IH region

?????

$0\nu\beta\beta$ rate predicted for IH

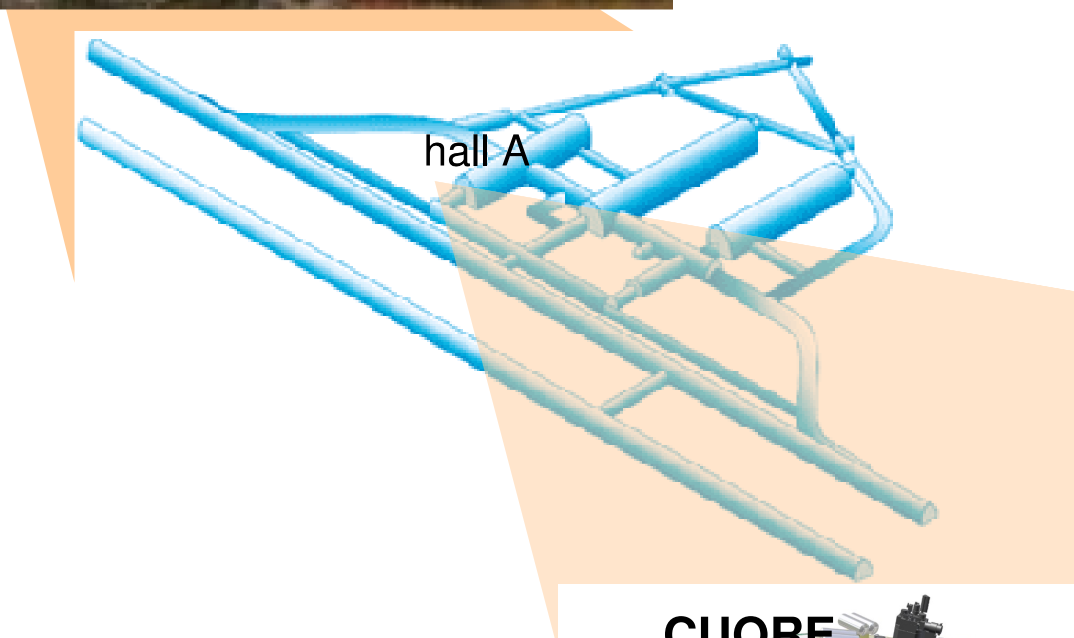
events/ton(of isotope)/year

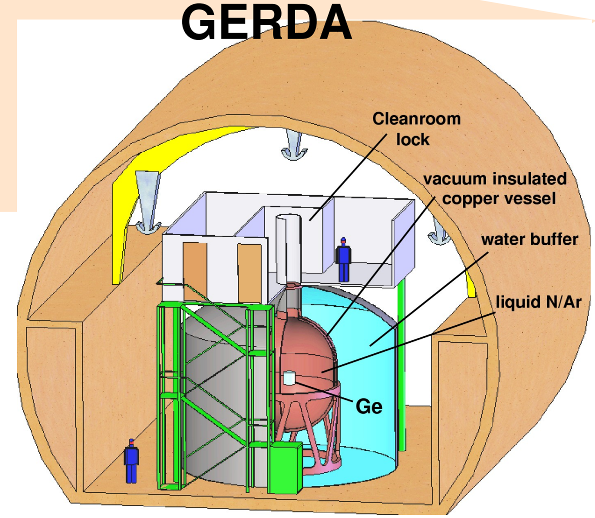
	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe	^{116}Cd
lower value	0.1	0.4	0.7	0.4	0.2	0.1
higher value	37.4	75.6	112.2	105.0	77.9	105.0

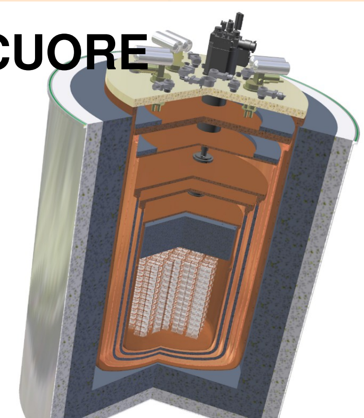
LNGS

Laboratori Nazionali del Gran Sasso

L'Aquila, ITALY







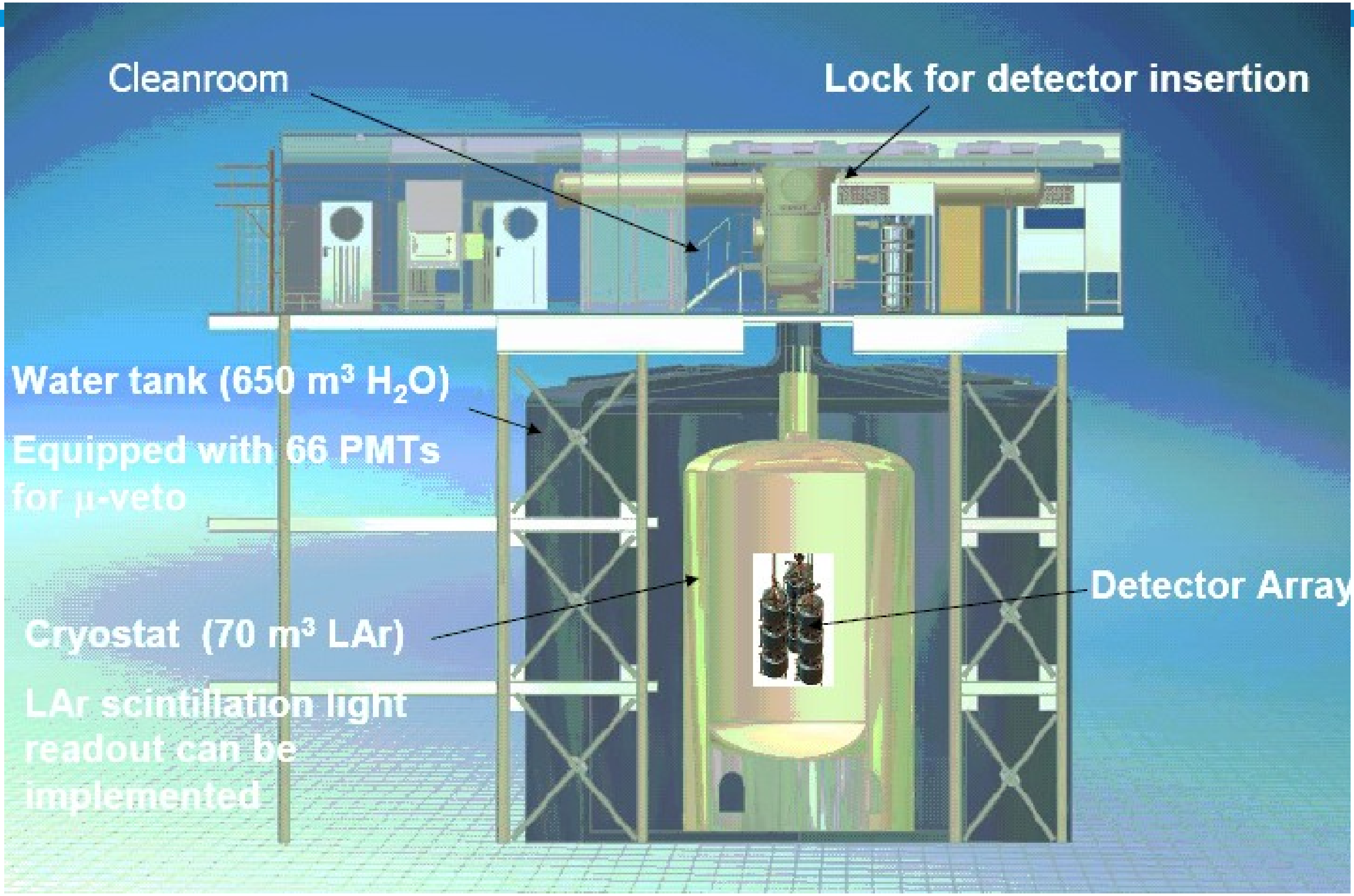
Cosmic Ray Shield

3200 m.w.e.

$\langle E_\mu \rangle$ ~270 GeV - $\text{Flux}_\mu \sim 1/m^2/h$

neutron flux ~ $3\ 10^{-6}$ $n/s/cm^2$

GERDA



- LAr provides a veto
- segmentation of diodes for a greater reduction of backgrounds
- operate with "naked" Ge diodes in LAr shielding

GERDA

Phase I ~ 15 kg ^{76}Ge

(crystals Heidelberg-Moscow + IGEX)

goal: in 1 y test with high statistic of the "Klapdor claim", confirm

Phase II ~ 30 kg ^{76}Ge

Segmented crystals -3 years of data-taking

goal: approach the IH region

Phase III ~ 1000 kg

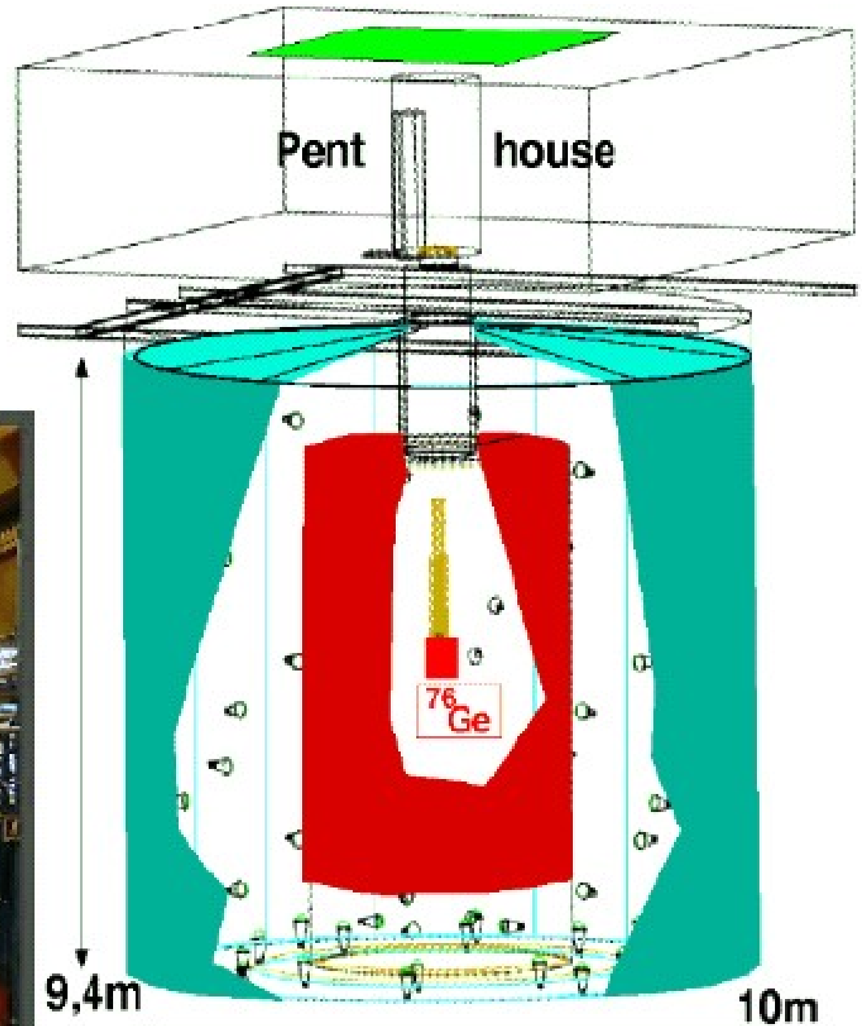
Segmented crystals Liquid Argon -10 years of data-taking

goal: completely explore the IH region

VERY EXPENSIVE in collaboration with MAJORANA !!!!

Water tank and muon veto

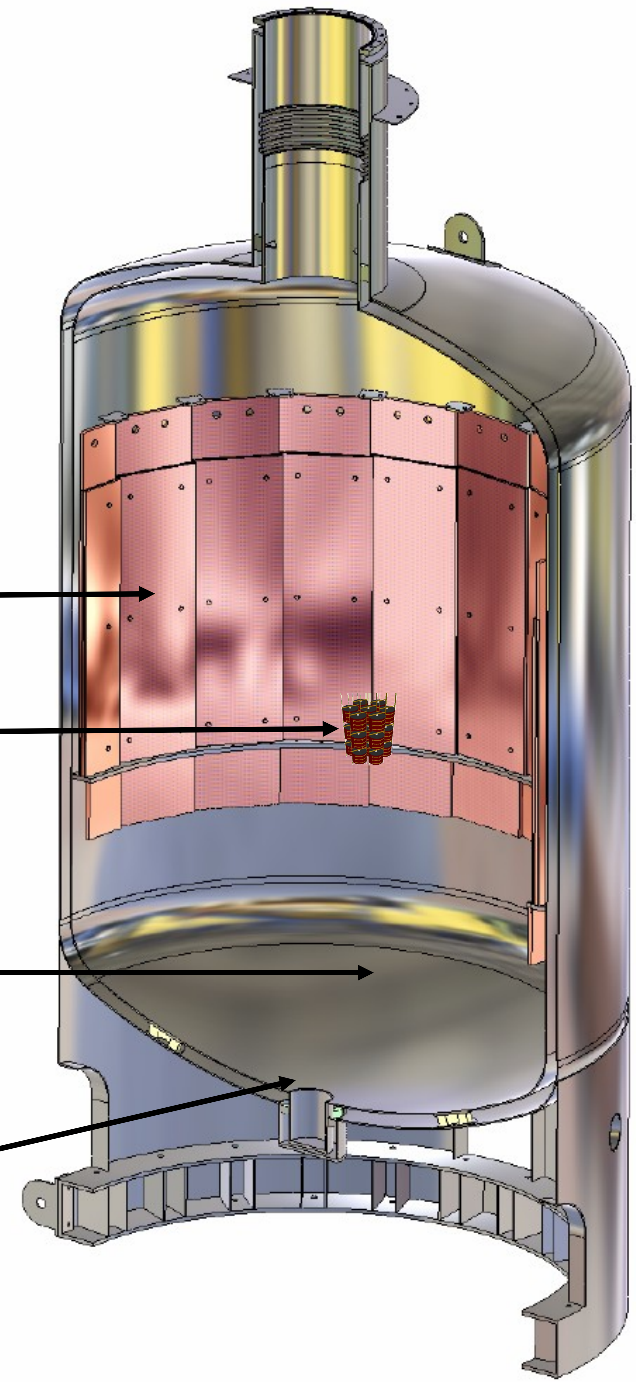
- Active shield
- Filled with ultra-pure water from Borexino plant
- 66 PMTs: Cherenkov detector
- Plastic scintillator on top of cleanroom



GERDA design

the Huge LAr shield substitutes the traditional Pb shield with the advantage of

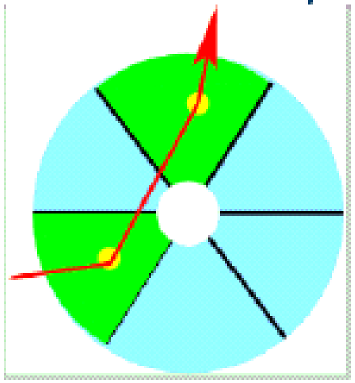
- higher radiopurity
- active shield feasible by scintillation read-out
- lower n and γ produced by μ interaction



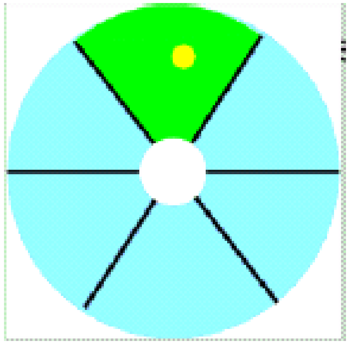
Phase II prototype crystals

Segmentation + Pulse Shape analysis for background reduction

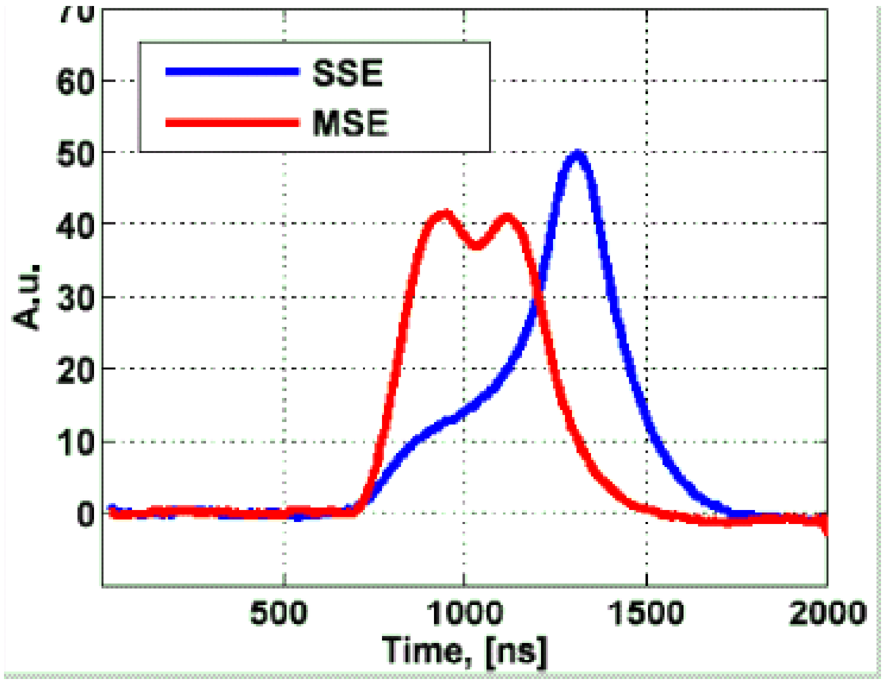
γ background typically Multi Segment Event



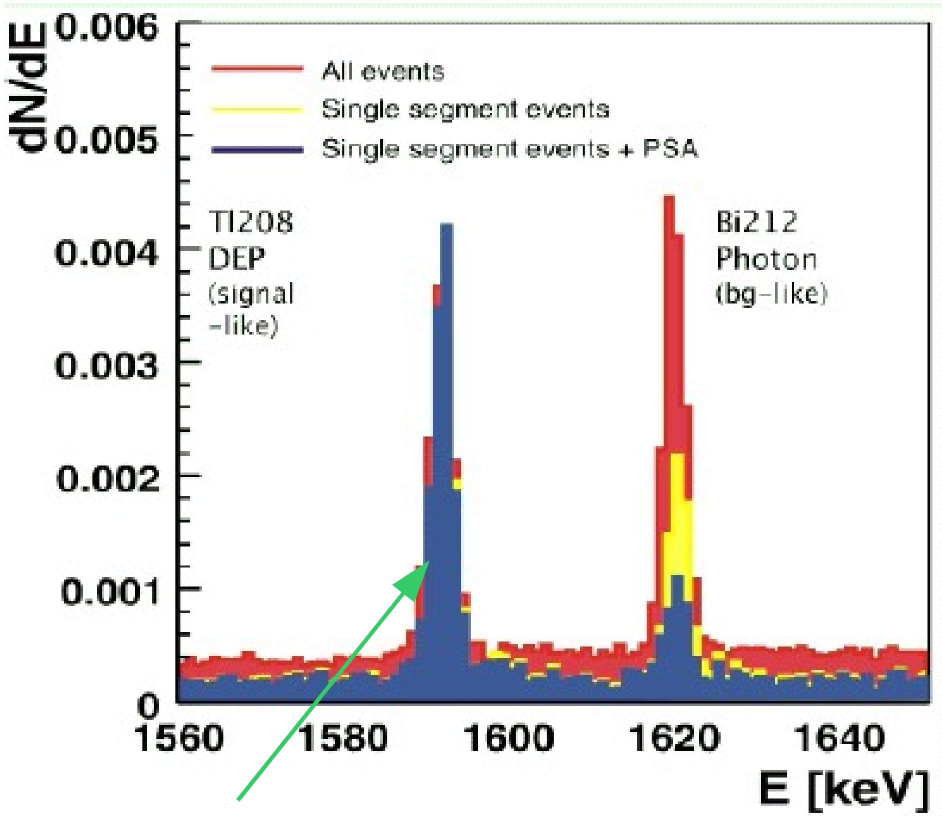
signal like event is always Single Segment Event



Pulse Shape Analysis can also distinguish SSE and MSE

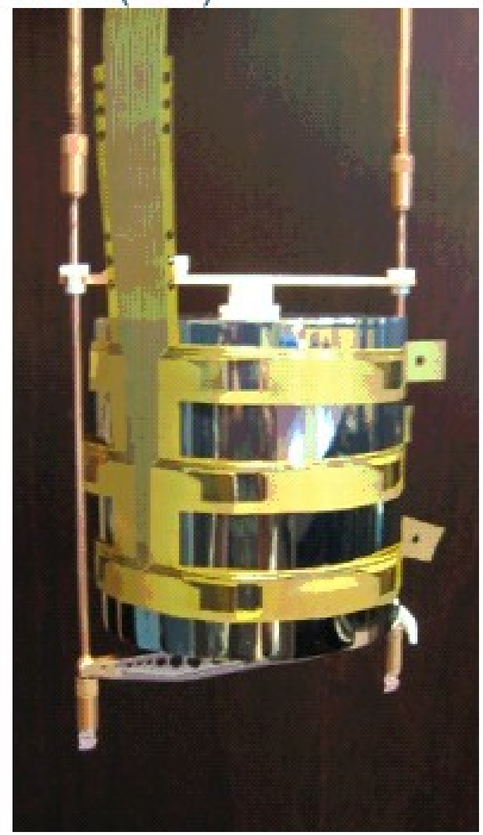


Applying PSA and Single Segment most of multisite events can be removed: NIM A 583 (2007) 332



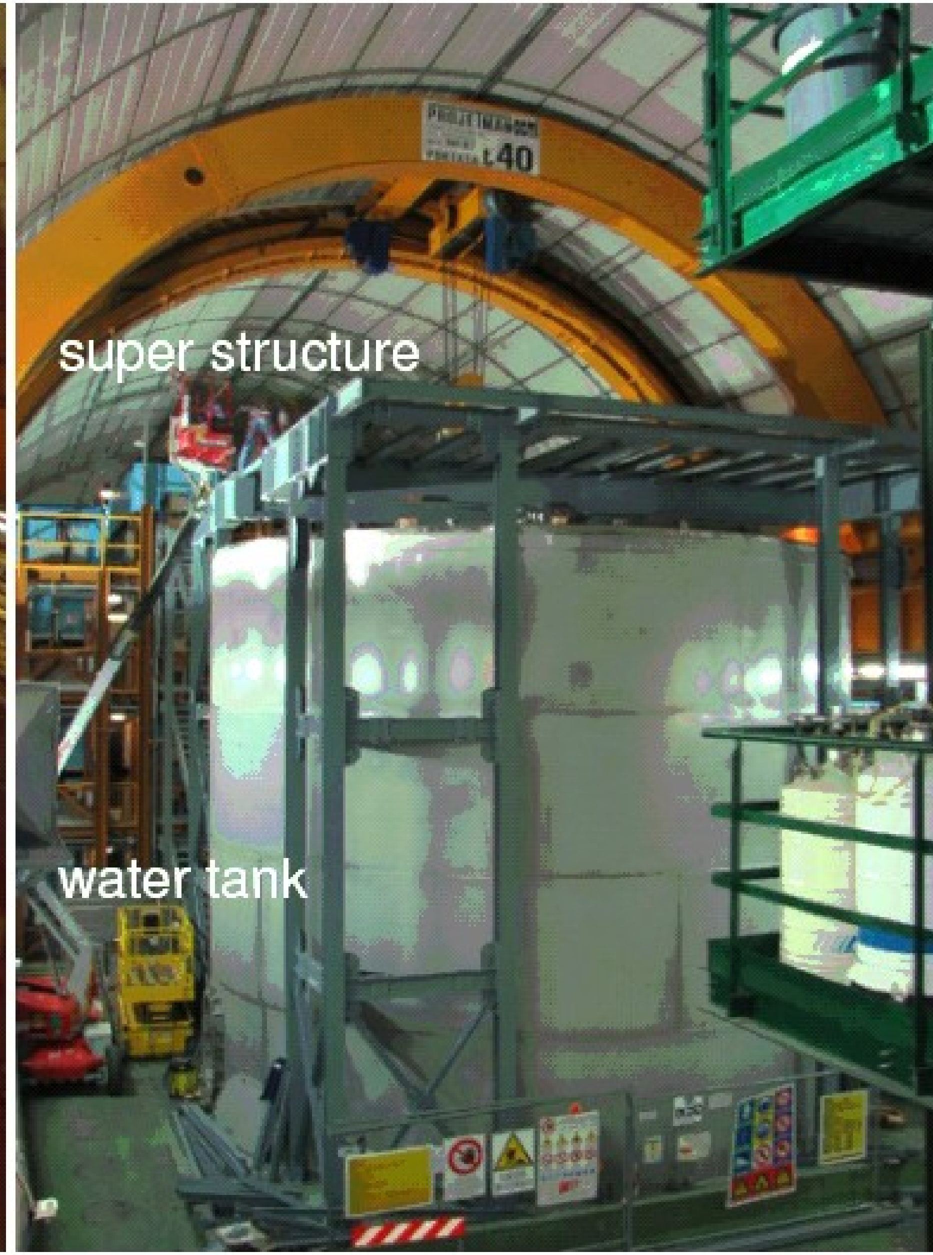
^{208}Tl double escape peak simulates a 0nbb event
(dep is due to the escape of two 511 keV γ due to annihilation)

By consequence we need segmented detector working in LAr (LN)



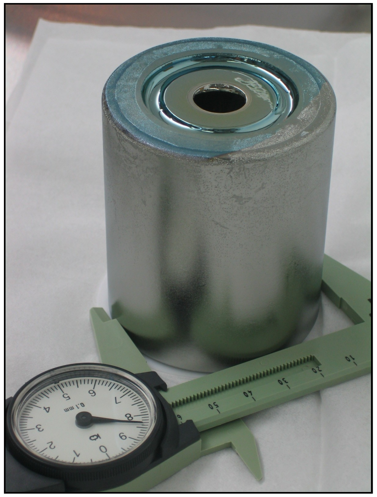
18 contacts, 18 diodes on one crystal

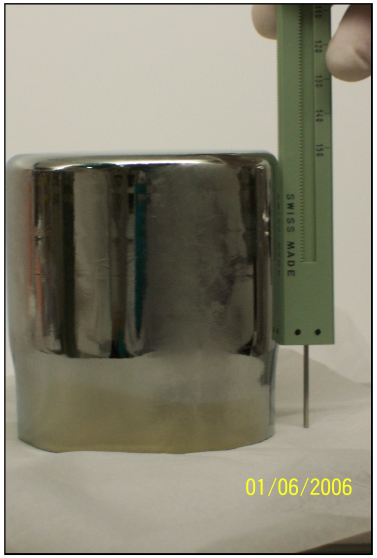
GERDA site at LNGS



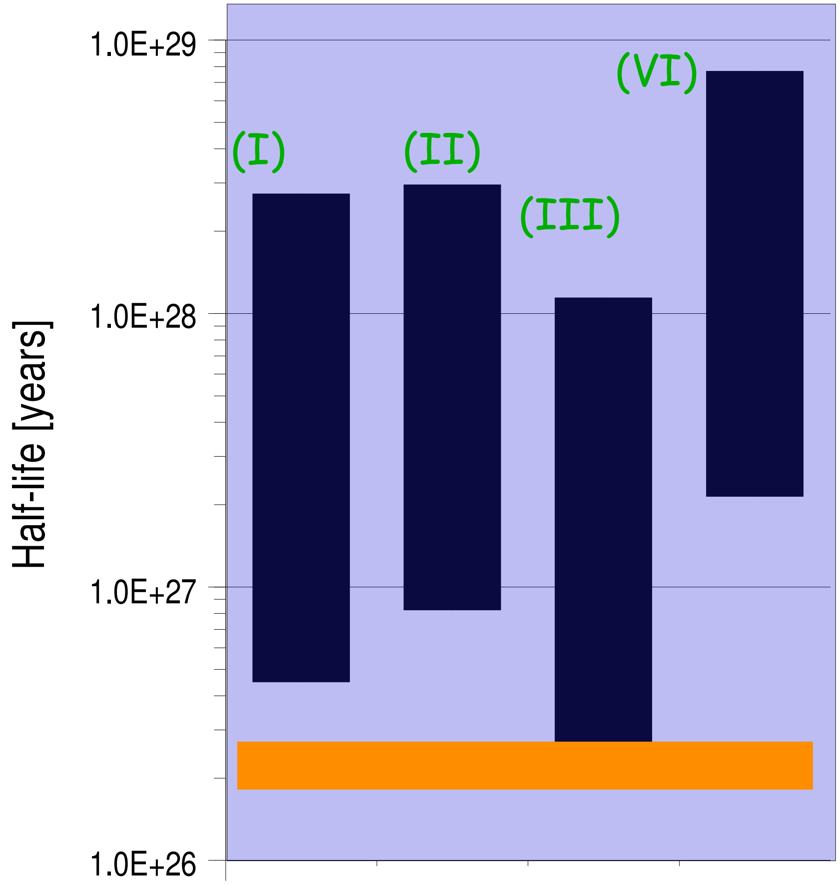
The GERDA detectors

- In 2006 3 IGEX diodes and 5 HM diodes were removed from their cryostats
- Dimensions were measured
- Construction of dedicated low-mass holder for each diode

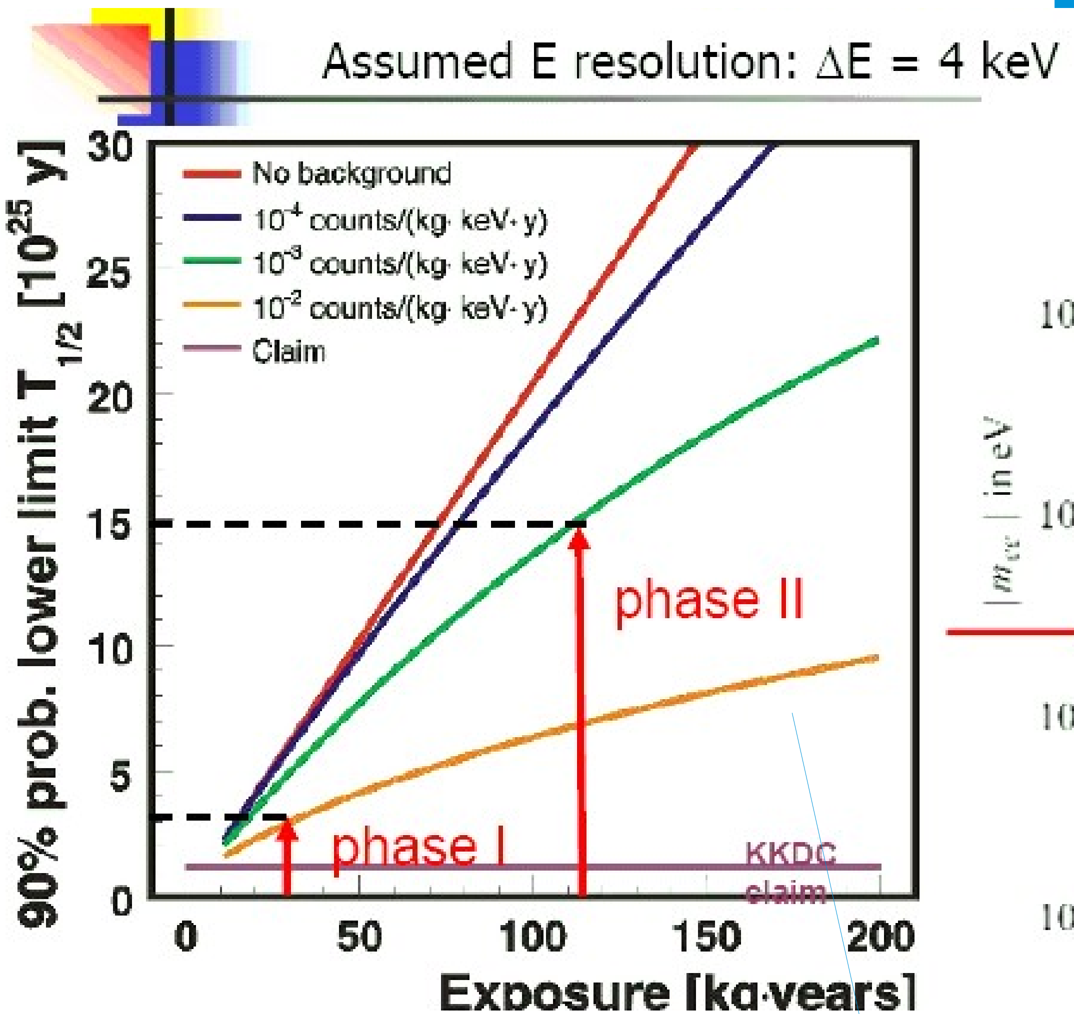




0νββ half-life predicted for IH according to different evaluation of the NME



GERDA II
exposure=30 kg * 4yr



(I) QRPA Rodin Faessler Simkovic Vogel: nucl-th:0706.4304v1

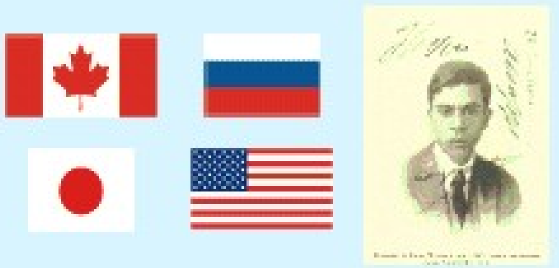
(II) QRPA Suhonen Civitarese: nucl-th/0208005

(III) QRPA Kortelainen Suhonen 2007

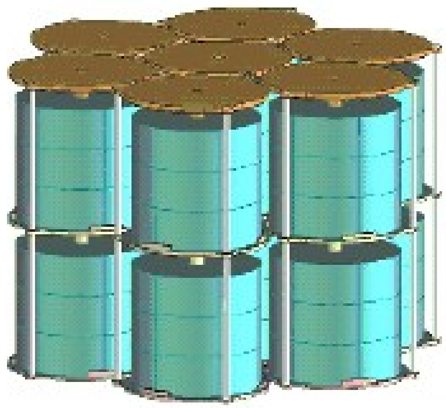
(IV) Shell Model Caurier et. al: nucl-th/0801.3760

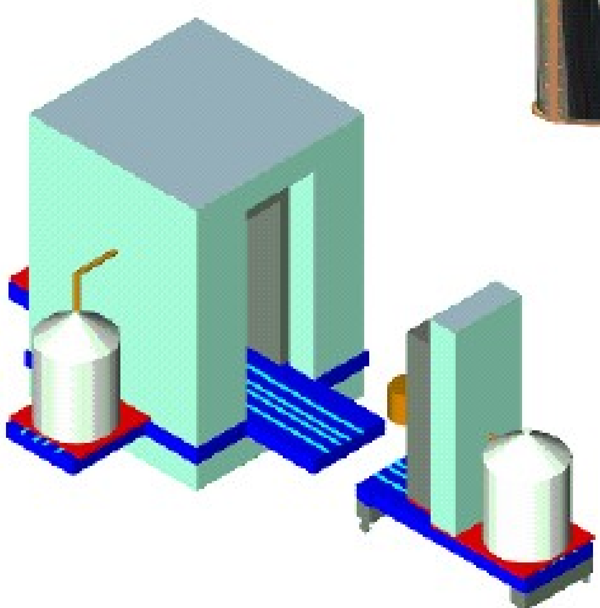
background rate in the HM experiment

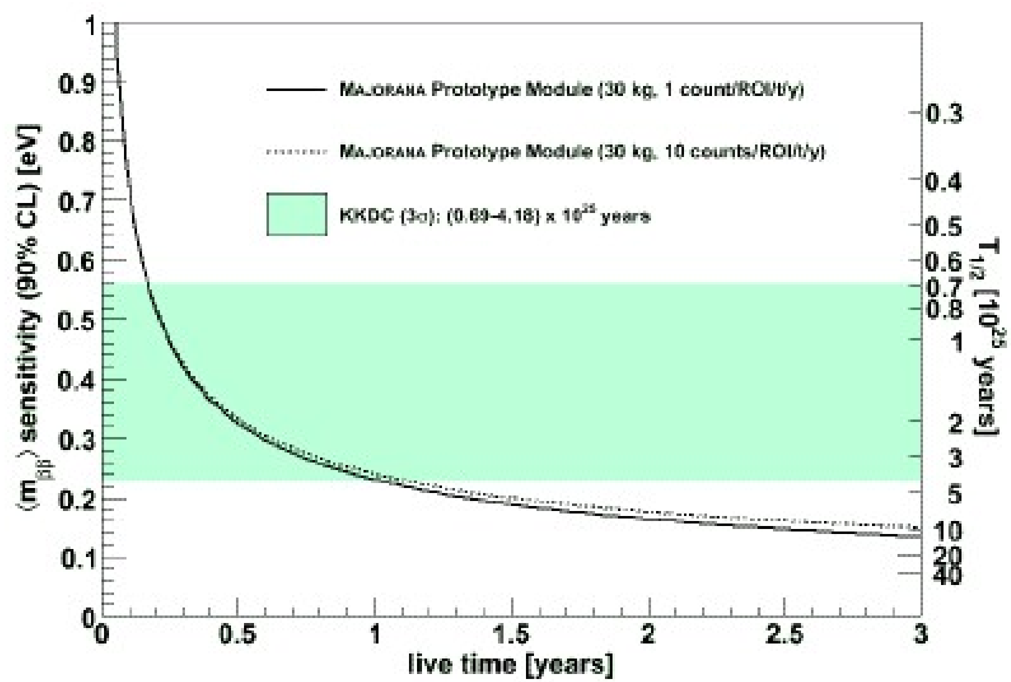
MAJORANA ^{76}Ge $0\nu\beta\beta$ -decay



Slides courtesy of dr. Steve Elliott



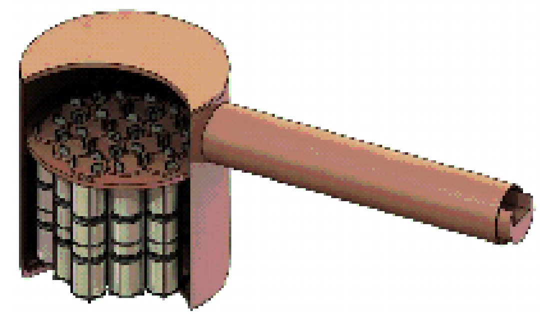


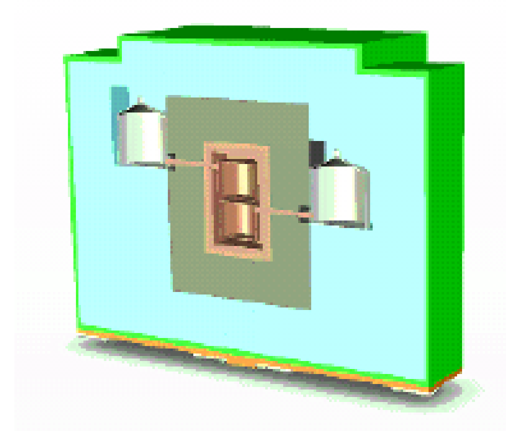


POSTER #56

The MAJORANA Demonstrator Module

Detectors are deployed in string and operated in an ultra-clean, electroformed Cu cryostat

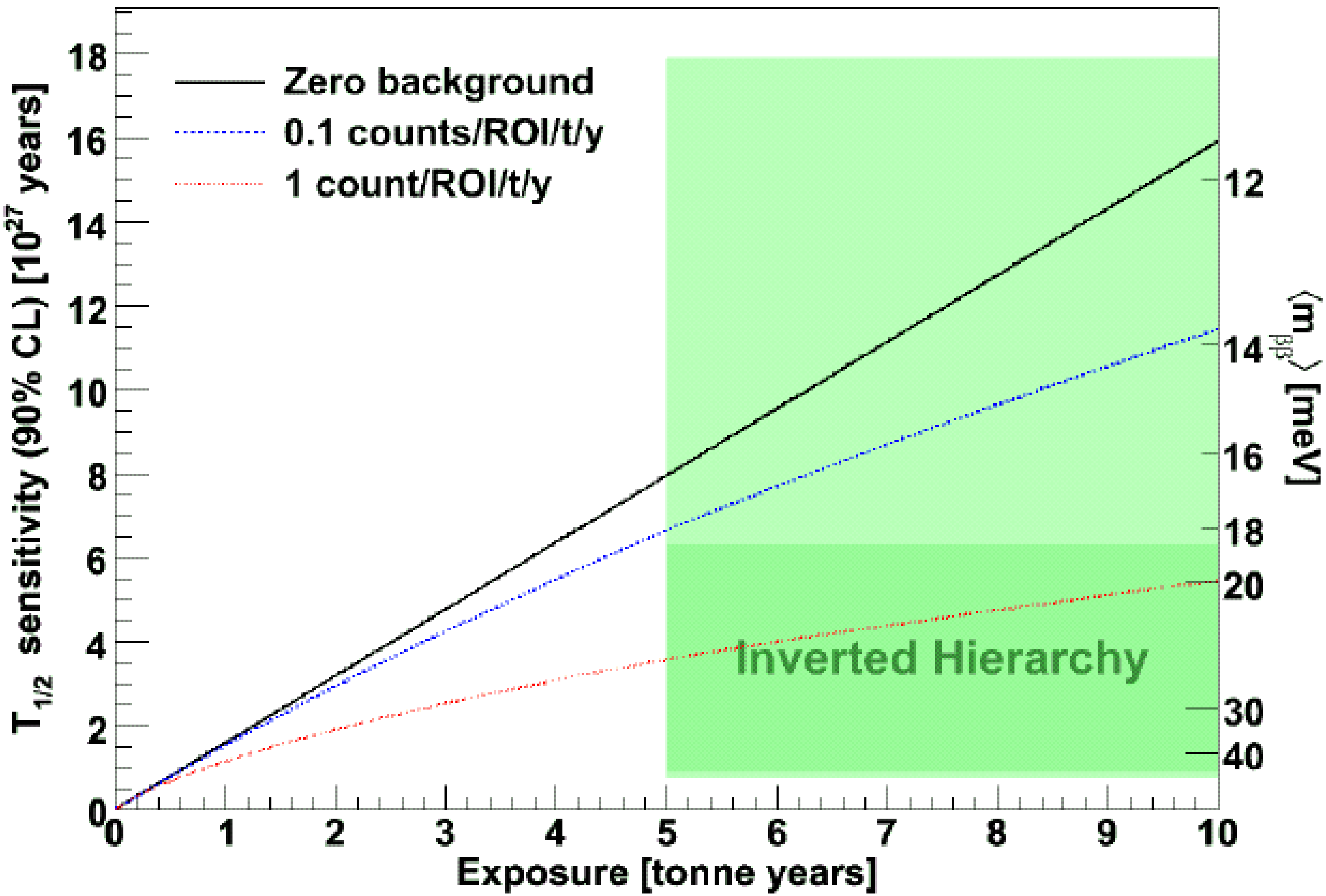




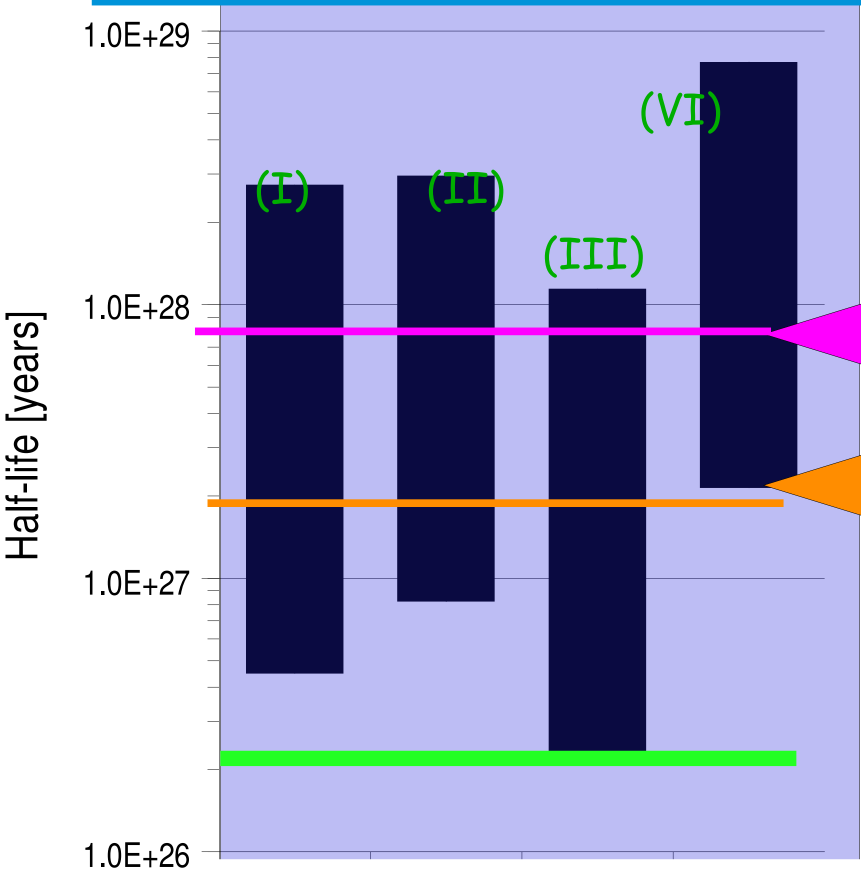
- 60-kg of Ge detectors
  - 30-kg of 86% enriched ^{76}Ge crystals required for science goal; 30-kg non enriched
  - Examine detector technology options p- and n-type, segmentation, point-contact.
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto
- Located underground 4850' level at SUSEL/DUSEL
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  - ~ **1 count/ROI/t-y** (after analysis cuts)

1-tonne Ge - Projected Sensitivity vs. Background

$T_{1/2}^{0\nu} = \ln(2) N \varepsilon t / UL(B)$



0νββ half-life predicted for IH according to different evaluation of the NME



MAJORANA 1 ton
0 counts in 5 y in the ROI
background < 10^{-5} c/keV/kg/y
exposure=1ton*5year

MAJORANA 1 ton
5 counts in 5 years in the ROI
background=1/ROI/t/Y ~ 2 10^{-4} c/keV/kg/y
exposure=1ton*5year

GERDA II
exposure=30 kg* 3yr

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(II) QRPA Suhonen Civitarese: nucl-th/0208005
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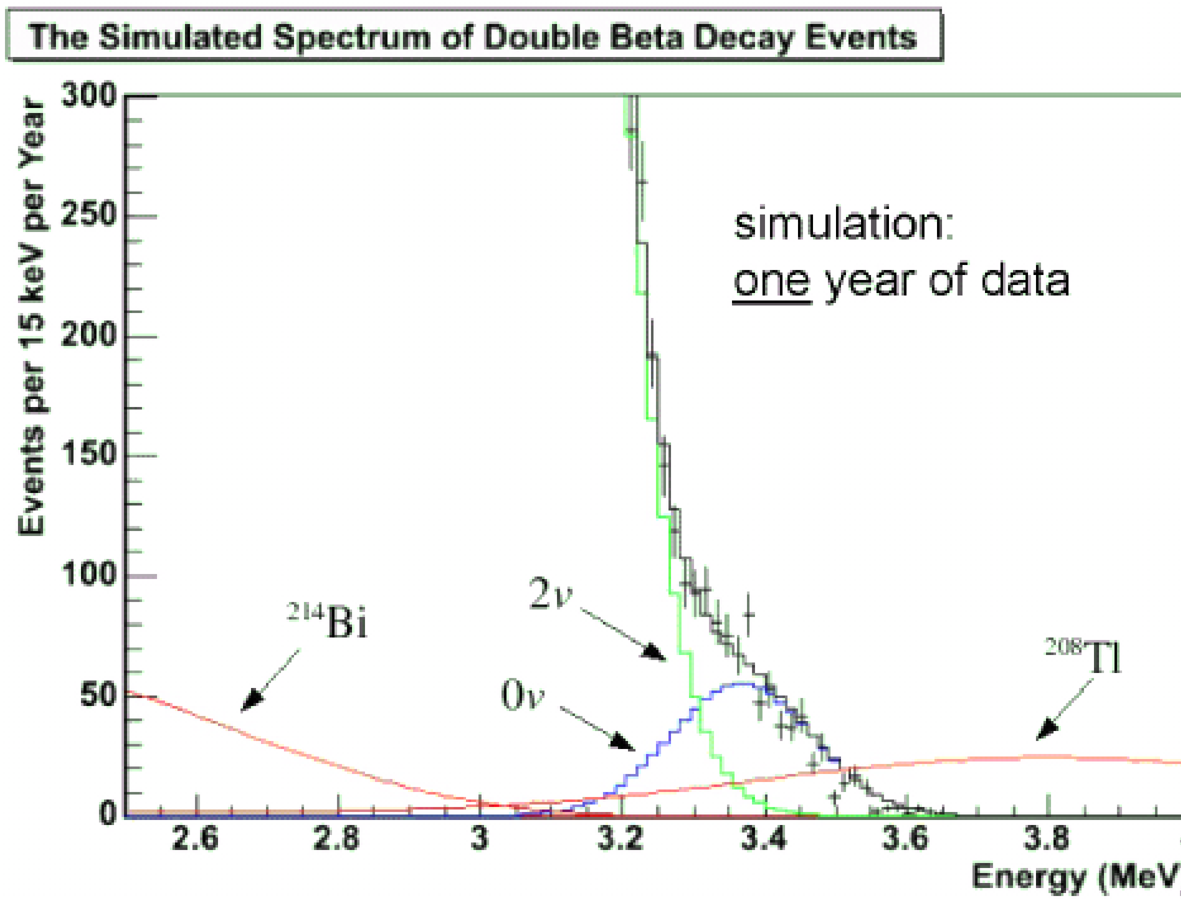
(IV) Shell Model Caurier et. al: nucl-th/0801.3760

Note this is a project !!
not jet funded
R&D status

- 1000 tons liquid scintillator in the SNO cavern
- 0.1% ^{nat}Nd dissolved in the scintillator containing 56 kg of ^{150}Nd isotope
- ^{150}Nd has a high (3.37MeV) endpoint
- Much of the infrastructure recycled from SNO (need to reverse the acrylic sphere tethering system and acquire LAB-based scintillator compatible with the Nd compound)
- Possibility to enrich Nd at AVLIS facility (France)



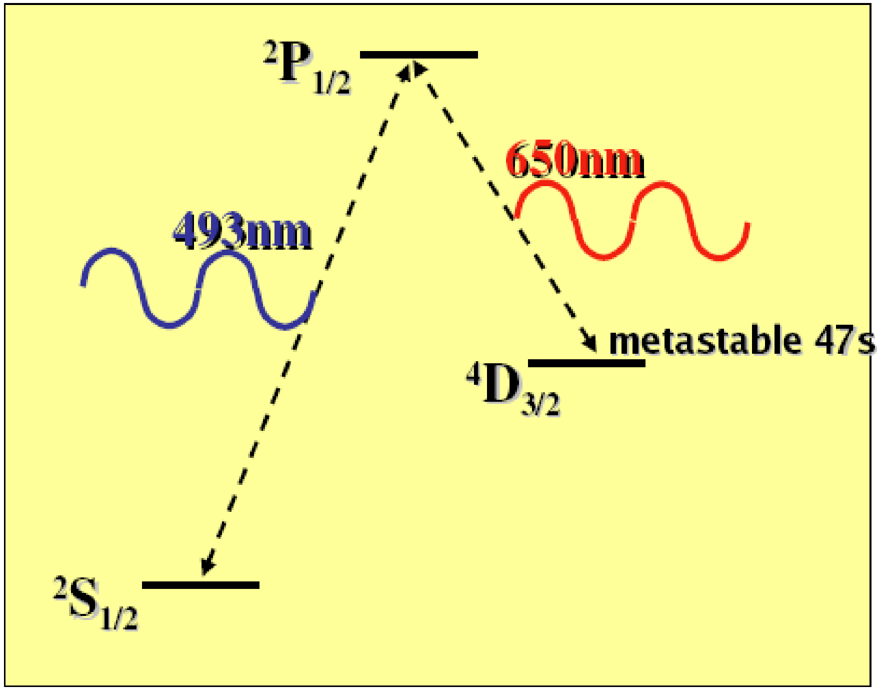
Background shape needs to be very well understood in order to extract meaningful results

EXO: a LXe TPC with ββ-tag

Identification of Ba ion :

$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$

by laser fluoresence



Xe offers a qualitatively new tool against background:

$^{136}Xe \rightarrow {}^{136}Ba^{++}$ e- e-

final state can be identified using optical spectroscopy *(M.Moe PRC44 (1991) 931)*

detector = TPC (energy, position)

read-out scintillation and ionization signal (improve energy resolution)

Xe nat. i.a. = 8.9% BUT ^{136}Xe enrichment easy and safe

EXO: a LXe TPC with ββ-tag

EXO-200:

200 kg of ^{136}Xe TPC with liquid Xe

detection of ionization + scintillation (FWHM ~ 2% @ 2.5 MeV)

no identification of the Ba^{+} ion

GOALS: test bkg achievement

measure $2\nu\beta\beta$ of ^{136}Xe

$0\nu\beta\beta$ of ^{136}Xe 2 y sensitivity ~ $6\ 10^{25}$ y

on-going

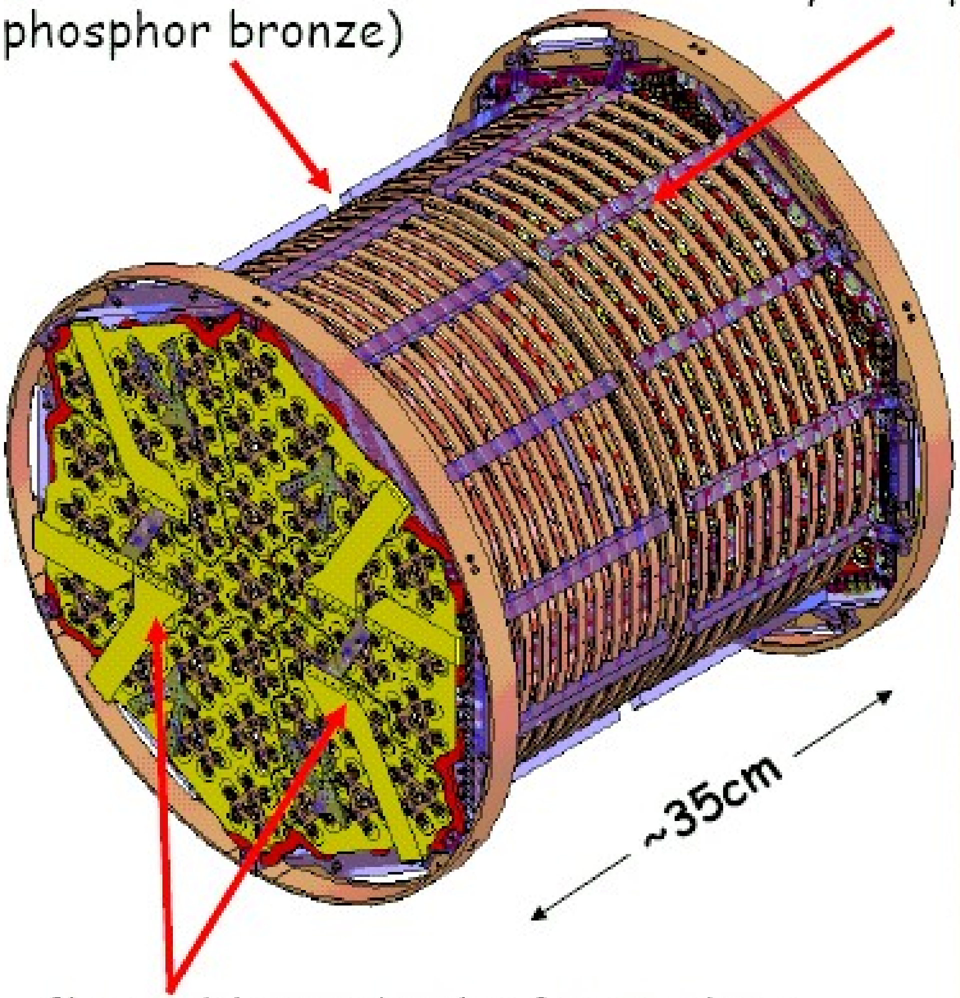
EXO-1 ton:

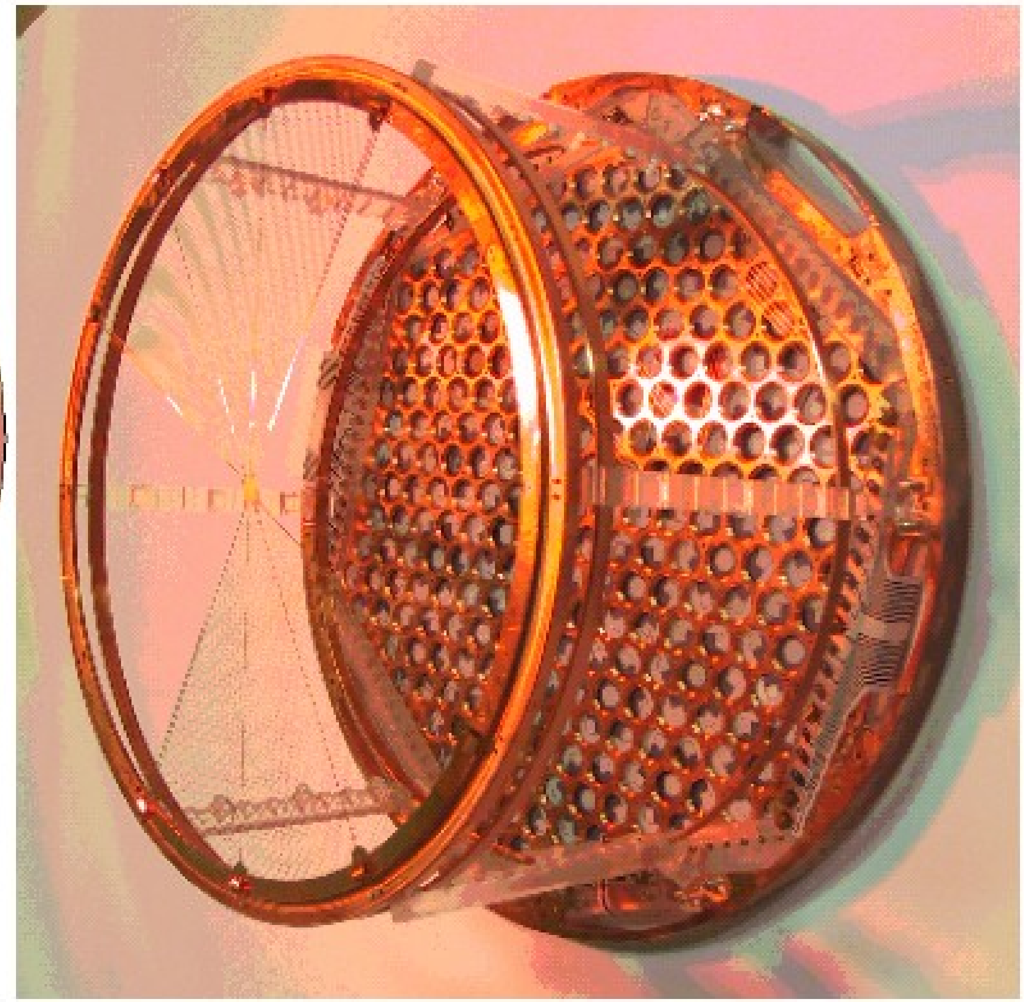
200 kg of ^{136}Xe TPC with liquid Xe (80% enrichment)

with identification of the Ba^{+} ion bkg < 0.0005 c/keV/kg/y

GOALS: $0\nu\beta\beta$ of ^{136}Xe 5 y sensitivity ~ $2\ 10^{27}$ y

EXO-200 LXe TPC field cage & readout planes





EXO-200kg Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2}>1\cdot 10^{22}$yr R.Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
EXO-200	0.2	70	2	1.6*	40	$6.4*10^{25}$	$0.133^{\dagger}$	0.186*

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5}\cdot 10^{25}$, ($\pm 3\sigma$)
(Phys. Lett. B 586 (2004) 198-212
consistently use Rodin's matrix elements for both Ge and Xe)

In 200kg EXO, 2yr:

• Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ

• Best case (NSM, lower limit) 162 events on top of 40 bkgd → 11σ

EXO neutrino effective mass sensitivity

Assumptions:

1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) Use for 2νββ $T_{1/2} > 1 \cdot 10^{22}$yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2 \cdot 10^{27}$	24	33
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1 \cdot 10^{28}$	5.3	7.3

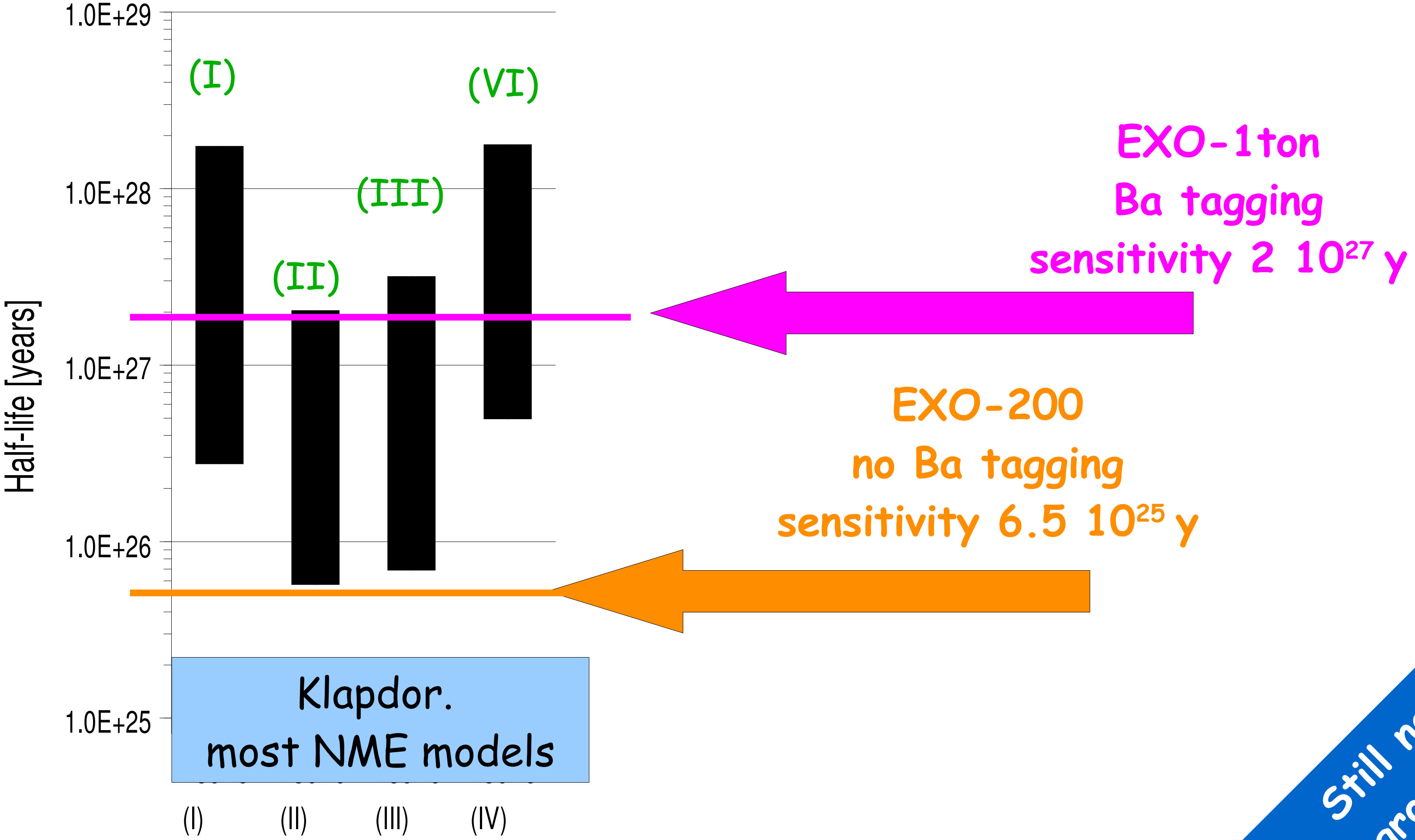
* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ Rodin, *et. al.*, Nucl. Phys. A 793 (2007) 213-215

\# Caurier, *et. al.*, arXiv:0709.2137v1

0νββ half-life predicted for IH according to different evaluation of the NME



Still no data.
Background evaluated
on the basis of MonteCarlo !!!

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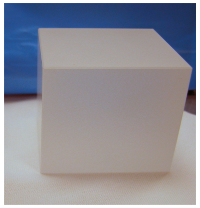
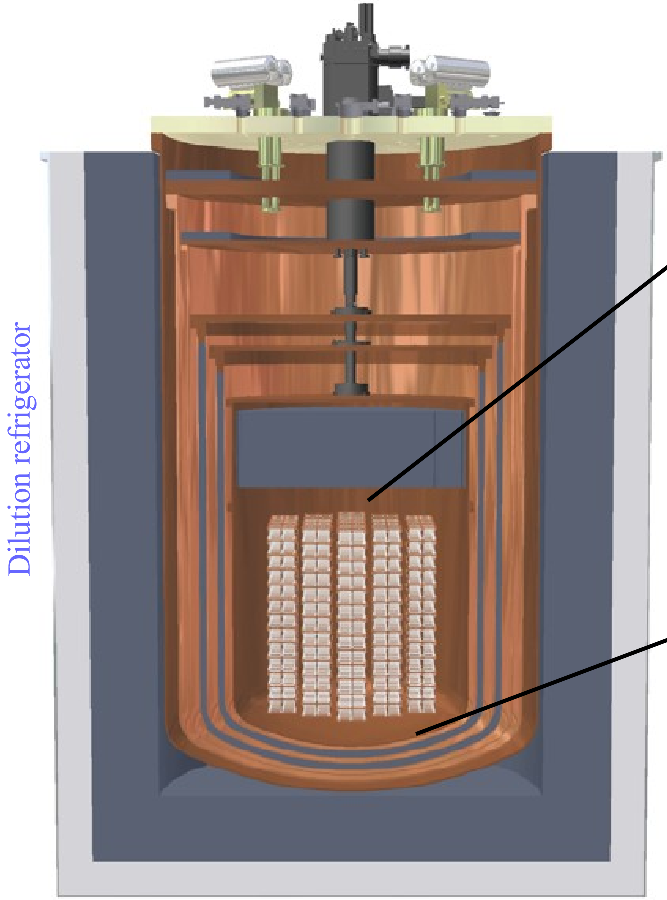
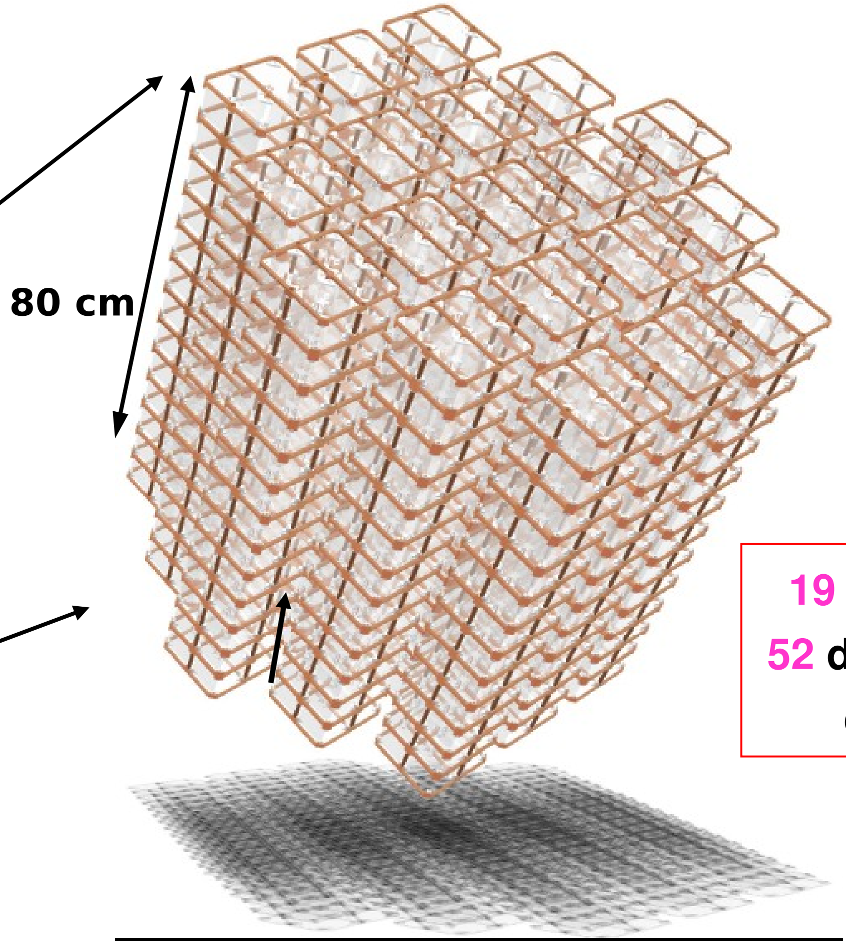
CUORE

750 g TeO_2  *x 988*

0.75 kg x 988 = **741 kg TeO_2**

~ 600 kg Te = **200 kg ^{130}Te**



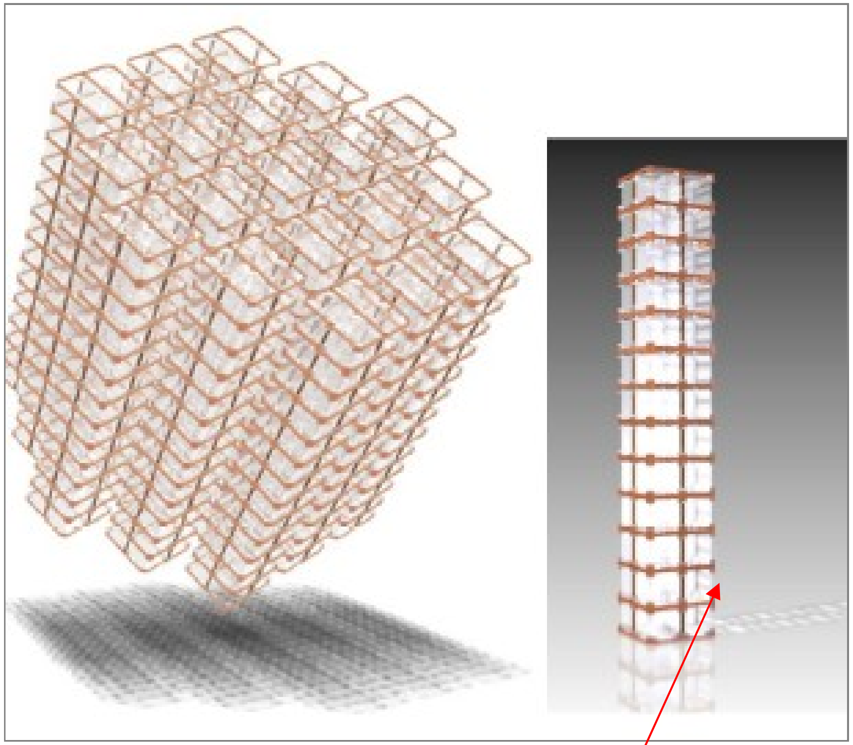


19 towers

52 detectors each

CUORE: background rejection

Compact structure, ideal for active shielding



Each tower is a CUORICINO-like detector

$0\nu\beta\beta$ is fully contained within 1 crystal

operating the crystals in anticoincidence
strong background reduction in the bb region

γ ray background	~3
n background	~100
muon background	~100

external shields + anticoincidence
reduce external background to negligible levels
FLUKA & GEANT4 simulations
muon veto probably not required

CUORE: material selection

severe selection of materials for their radioactive content

use internal roman lead (no ^{210}Pb)

measured contaminations (generally they are upper limits) used as input to MC GEANT4 simulation

Material and element		232Th [pg/g]	238U [pg/g]	40K [pg/g]	210Pb [Bq/kg]	60Co [uBq/kg]
TeO2 (RAD hall C + Cuoricino)	TeO2	0.2	0.1	< 1	< 0.00001	< 1
Cu (GeMPI – LNGS)	Cu	< 2.4	< 1.3	< 0.3	-	< 10
Roman Pb (GeMPI – LNGS)	Pb	< 18	< 4	< 2	< 0.004	< 10
Low Act Pb (1)	Pb	< 5.4	< 2.3	1.6	27	180
Low Act Pb (2)	Pb	< 7.6	< 3.7	1.7	23	< 11

CUORE

CUORE has a dedicated site in LNGS and the construction has started

The CUORE refrigerator is fully funded and has already been ordered

1000 crystals are funded by INFN and DoE and the delivery will start in Nov

The first CUORE tower (CUORE-0) will be assembled and operated in 2009

Schedule

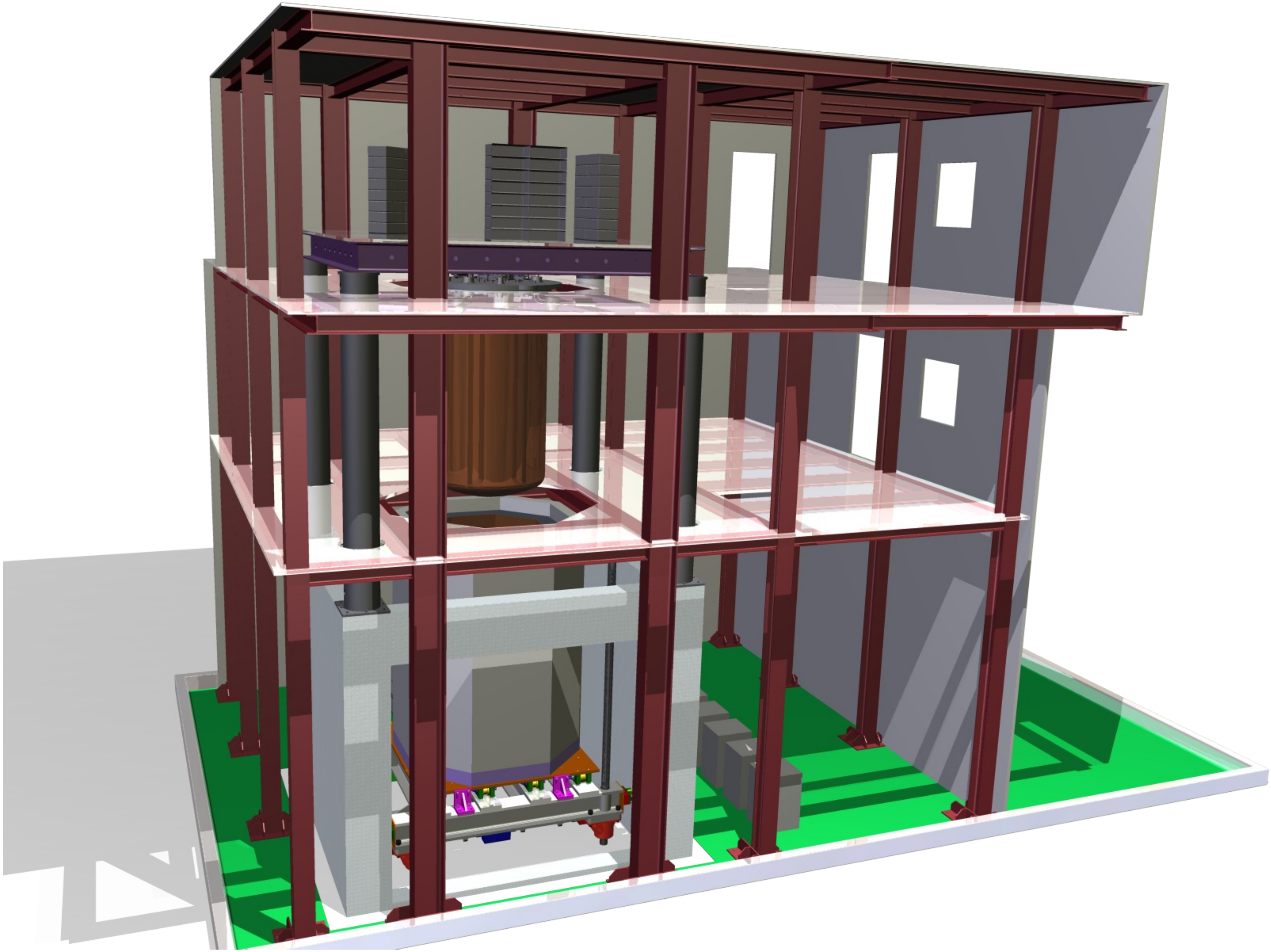
2008: Hut construction
Crystals production

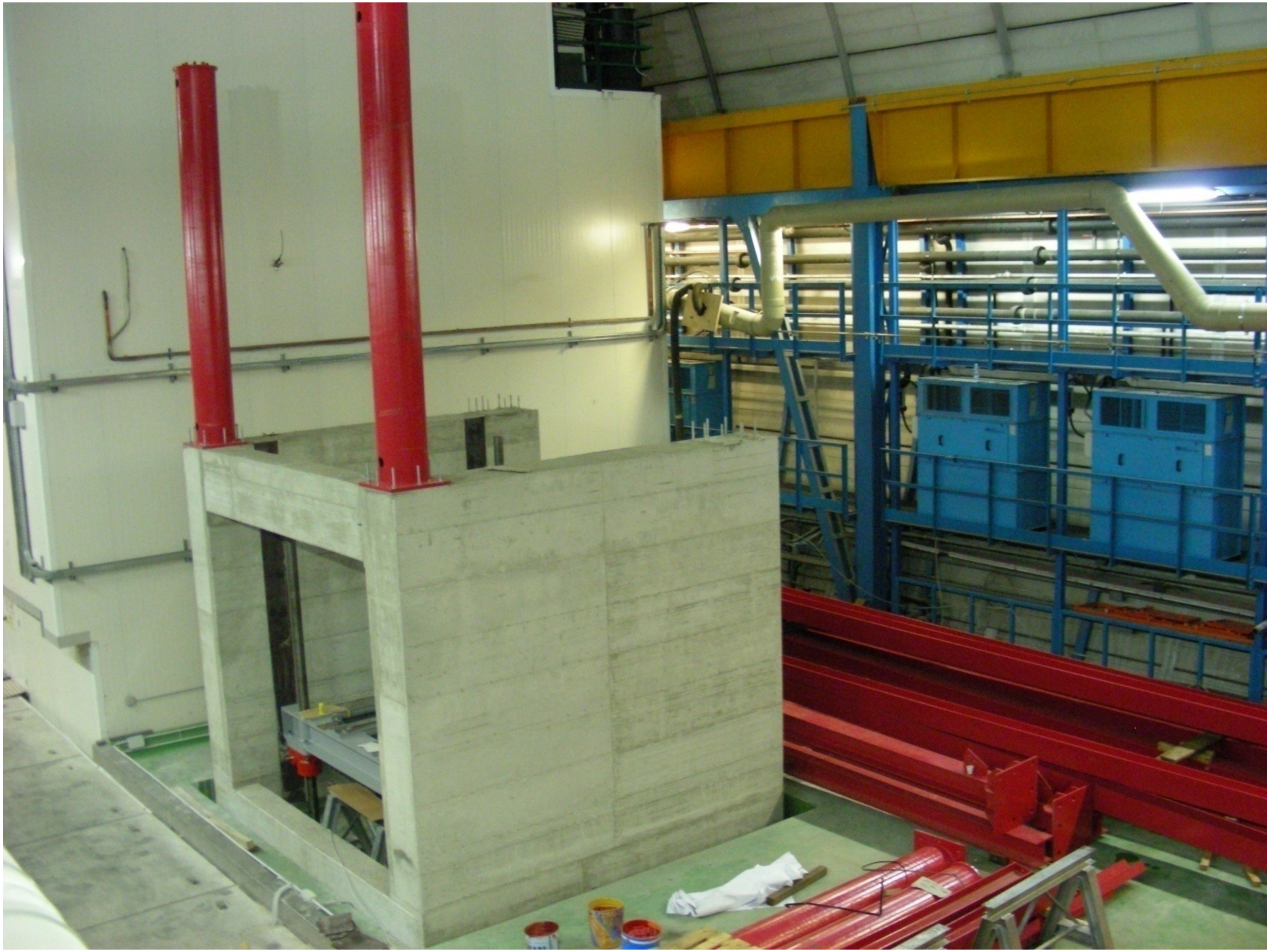
2009: Utilities
Clean room
External Shielding
Cryostat Installation and commissioning

2010-11:
Detector assembly
Faraday Cage
Front-end & DAQ

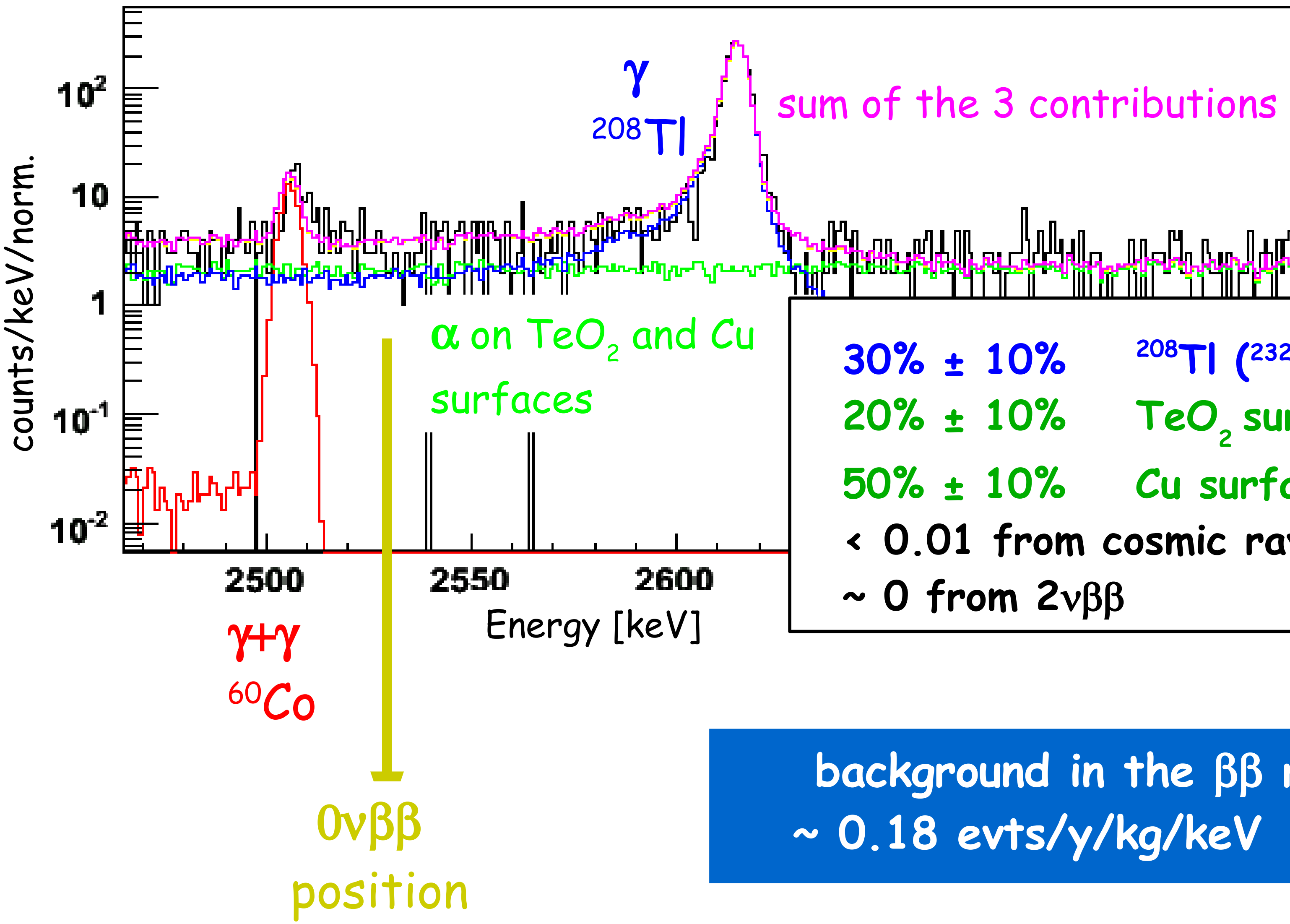
2012: Data taking

CUORE hut





From Cuoricino to CUORE



30% ± 10%	^{208}Tl (^{232}Th cryostat)
20% ± 10%	TeO_2 surfaces (α ^{232}Th or ^{238}U)
50% ± 10%	Cu surfaces (α ^{232}Th or ^{238}U)

< 0.01 from cosmic rays (n and μ)

~ 0 from 2νββ

background in the ββ region
~ 0.18 evts/y/kg/keV at $Q_{\beta\beta}$

Cuoricino background sources in the $0\nu\beta\beta$ region

1) 30% ± 10% ^{208}Tl (^{232}Th cryostat)

2) 20% ± 10% TeO_2 surfaces (α ^{232}Th or ^{238}U)

3) 50% ± 10% Cu surfaces (α ^{232}Th or ^{238}U)

Source 1 = Tl 2615 keV line -> just a problem of shielding

CUORE Tl line bkg = **< 10^{-3} c/keV/kg/y**

Source 2 = Crystal surface contamination the contamination can be controlled with proper surface treatments (including chemical etching and polishing with "clean" powders). A recent test on 8 crystals (CUORE-like) proved that the new surface treatment studied in LNGS reduces the contamination by a factor ~ 4

Hall C measured contamination **< 3 10^{-3} c/keV/kg/y**

Source 3 = Unknown source candidates are surface contamination of inert part of the detector

Hall C measured contamination projected in CUORE **~ 2/4 10^{-2} c/keV/kg/y**

a dedicated array of 8 5x5x5 cm^3 crystals operated in Hall C
ICMPS bulk and surface measurement
low bkg Ge spectroscopy
some more investigation on neutrons contribution

Measured contamination projected (MonteCarlo) on CUORE

	Background 10-3 c/keV/kg/y	
External gamma	< 1	MEASURED
Exp. Apparatus	< 1	MEASURED
Detector structure bulk	< 1	MEASURED
Crystal bulk	< 0.1	MEASURED
Detector structure surfa	~ 20-40	Extrapolated from our bkg model
Crystal surfaces	< 3	MEASURED
Neutrons	< 0.1	MC simulation (validated with a n source exp
Muons	0.4+/-0.1	MC simulation without veto

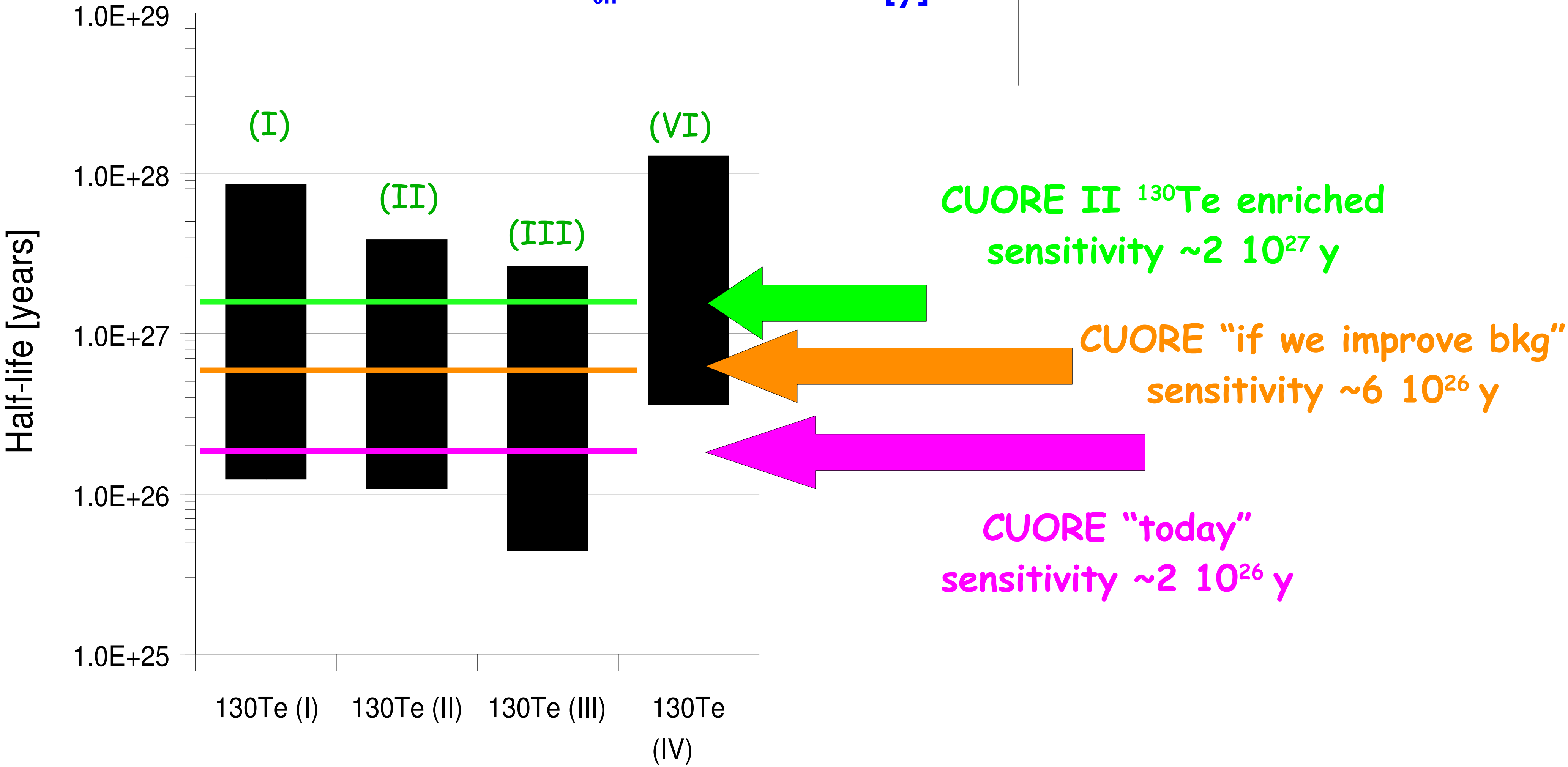
Limiting factor to 0.01 c/keV/kg (red)

Limiting factor to 0.001 c/keV/kg (yellow)

MEASURED = experimentally measured contamination extrapolated to CUORE through MC simulation

CUORE sensitivity:

Bkg	[c/keV/kg/y]	0.01	0.001
FWHM	[keV]	5	5
S_{0n} – 5 years	[y]	2.1 10^{26}	6.6 10^{26}



CUORE-0

will be the first CUORE tower to be installed in the dilution refrigerator in hall A of LNGS, presently housing Cuoricino

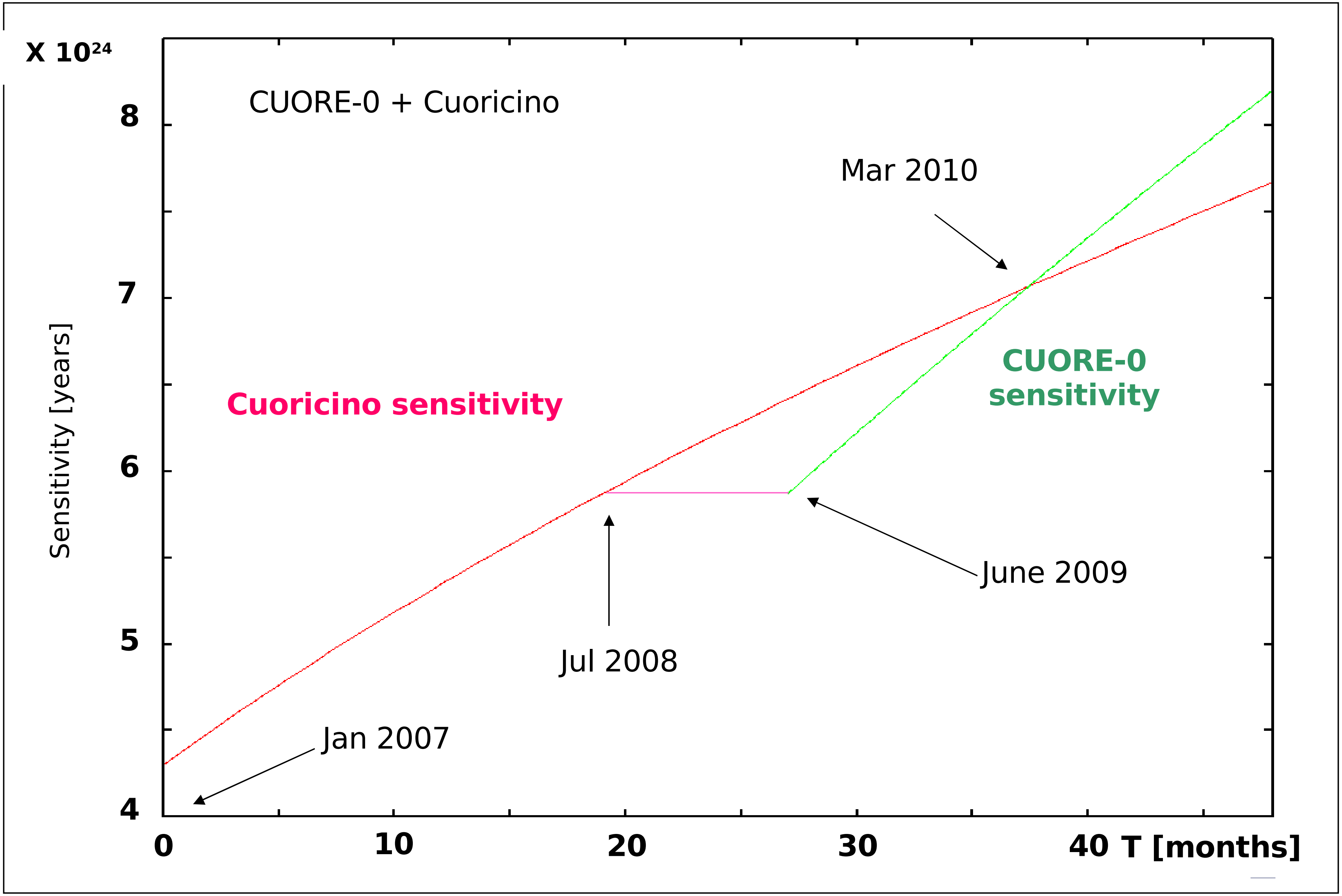
Motivations of CUORE-0

- Test the many improvements done on several technical aspects of the assembly procedure:
  - gluing
  - holder
  - zero-contact approach
  - wires
  - ...

- CUORE-0 background should be around 1/3 of Cuoricino background in the DBD energy region and close to the CUORE target in energy degraded alpha region

- CUORE-0 will be a powerful experiment that will overtake soon Cuoricino sensitivity

CUORE-0 vs Cuoricino



Cuoricino result vs. HM claim of evidence:

HM claim of evidence:

$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) × 10^{25} (3σ range)

$T_{1/2}^{-1} = F(Q_{\beta\beta},Z)\ |M|^2\ \langle m_\nu \rangle^2$

^{130}Te predicted

$T_{1/2}^{0\nu}$ (y) range

CUORE0

6×10^{24} y

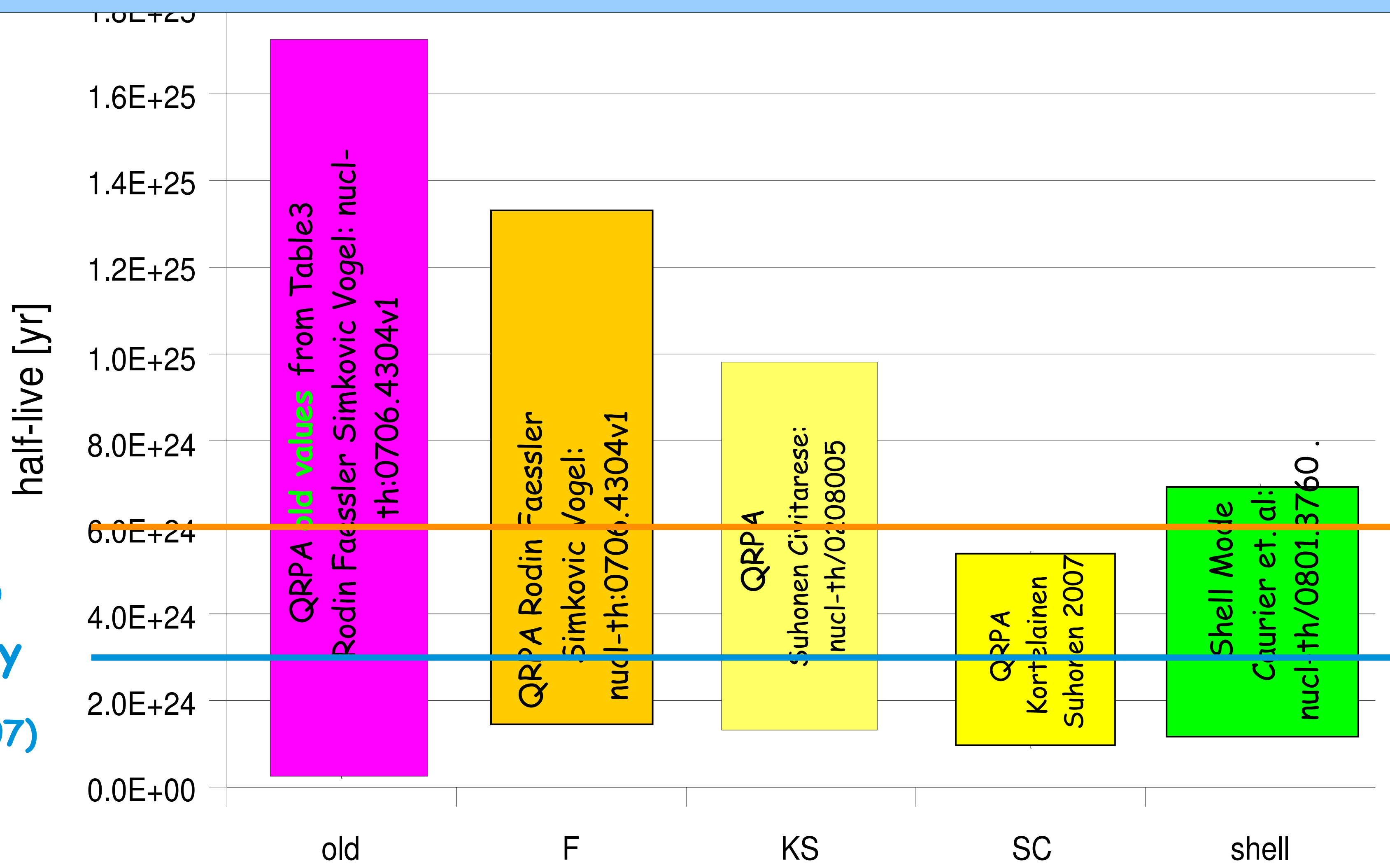
@90%

(2010)

Cuoricino

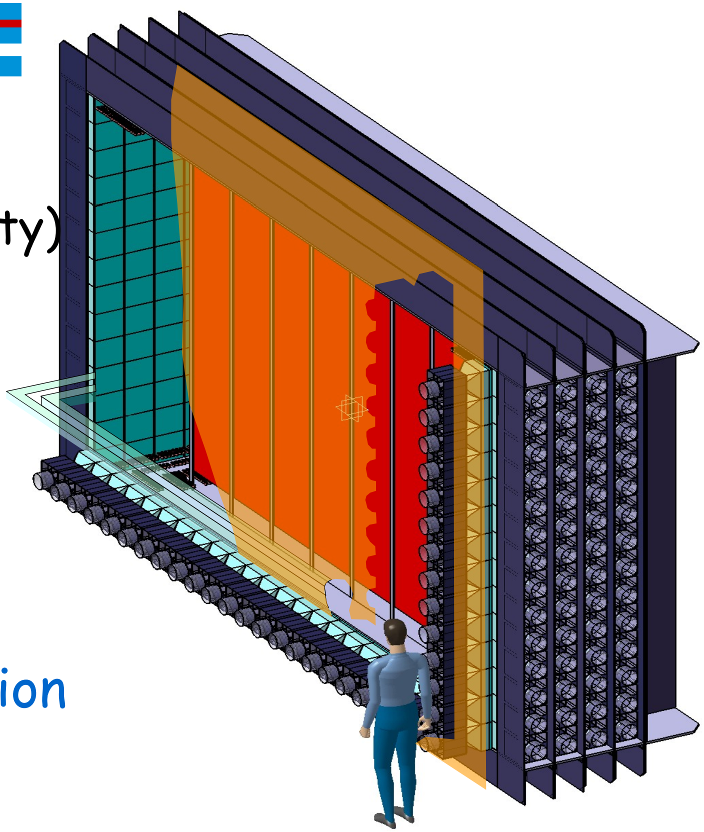
3.1×10^{24} y

(summer 2007)



SuperNEMO:

(France, UK, Russia, Spain, USA, Japan, Czech Republic,Ukraine, Finland)



Tracko-calo with 100 kg of ^{82}Se or ^{150}Nd
(possibility to produce ^{150}Nd with the French AVLIS facility)

$T_{1/2} > 2.\ 10^{26}$ yr $\langle m_\nu \rangle < 0.05 - 0.09$ eV

Modules based on the NEMO3 principle
Measurements of energy sum, angular distribution and individual electron energy

3 years R&D program: improvement of energy resolution
Increase of efficiency
Background reduction
....

100 kg →20 modules

R&D funded by France, UK and Spain

2009: TDR
2011: commissioning and data taking of first modules in Canfranc (Spain)
2013: Full detector running

next future

between 2010 and 2011 full test of "Klapdor claim"

- NEMO3 + CUORE0 indirect test (and partial, i.e not covering all NME)
- GERDA I direct test of the signal
- EXO indirect test (if bkg good will cover almost all the NME)

after 201?

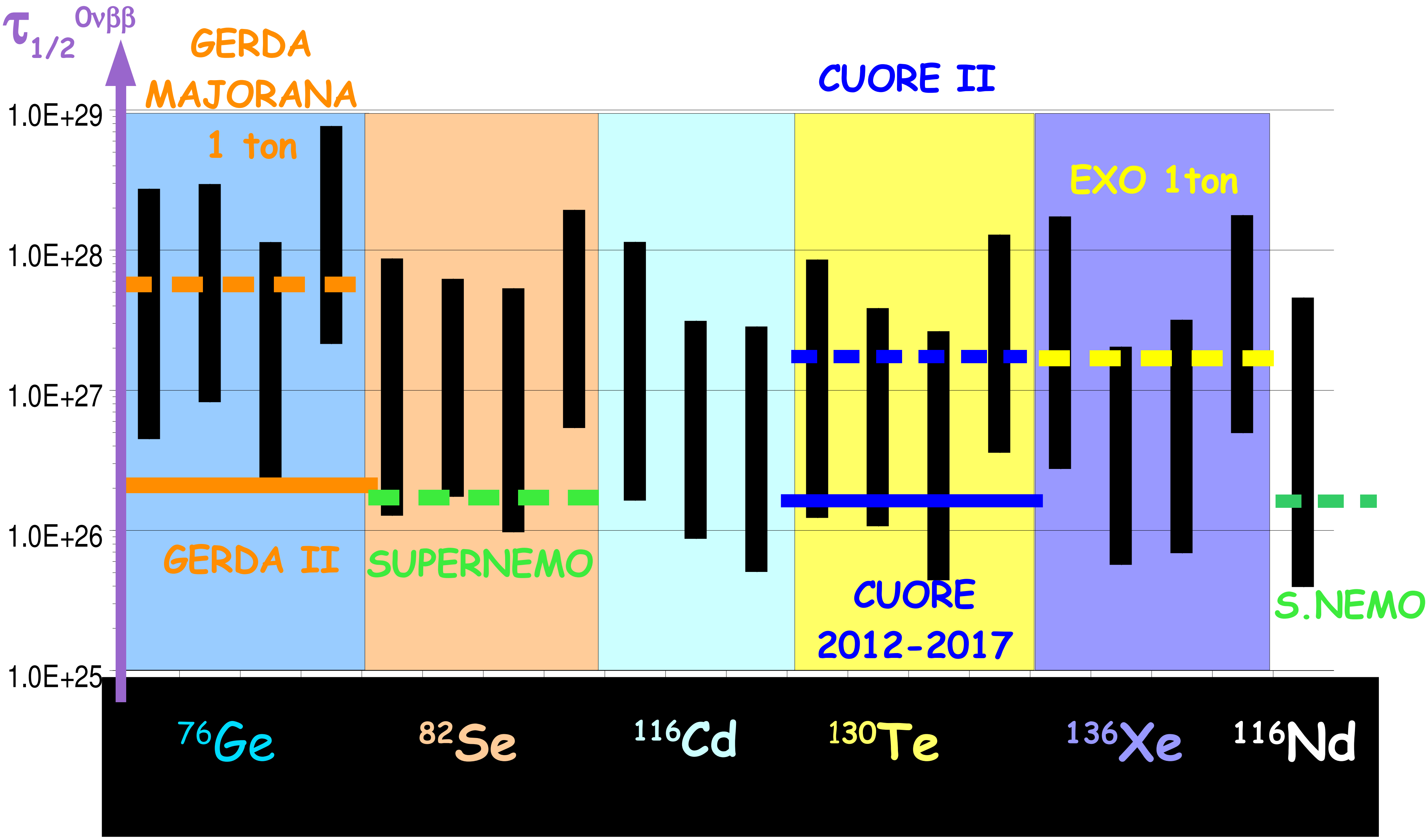
- CUORE will start in 2012
- GERDA II will start in (?)
- NEMO3 (?)
- EXO-1ton (?)
- MAJORANA+GERDA III (?)

IF they fulfill the background requirements
IF no news in the panorama of NME
they will enter IH
BUT
they will never be able to exclude it

... MANY OTHER projects not discussed

what for the 3rd generation?

approaching the IH



3rd generation

1st option

improve background

increase the mass

2^{nd} option

0 background experiment

EXO 1 ton with Ba tag

feasibility have to be still proved

Majorana+Gerda 1 ton

feasibility is almost proved

it is only a combination of shields, material selection, special production of detectors ...

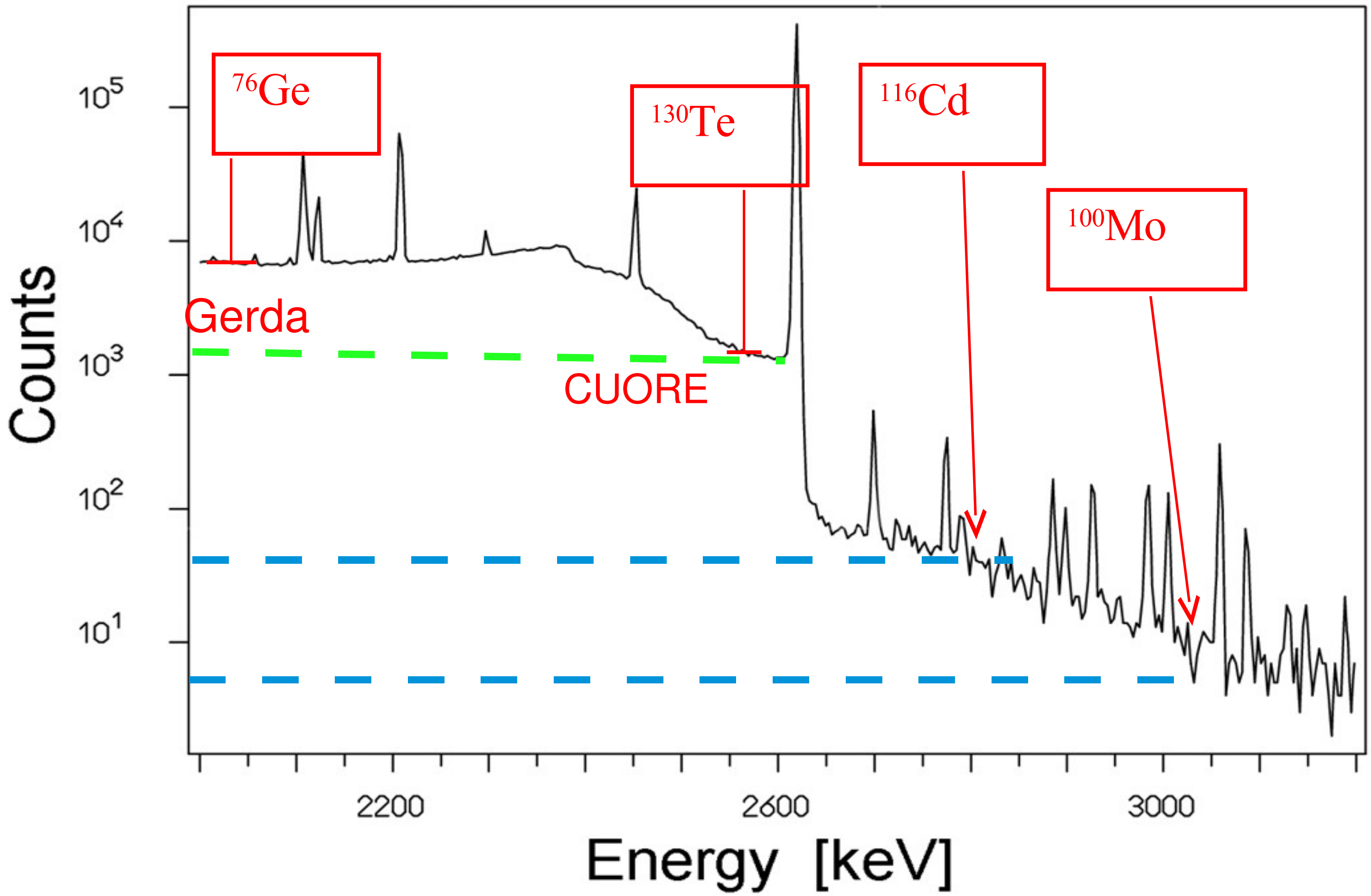
MONEY

3^{rd} option

new detectors

BOLUX: The (far) Future

A STRAIGHTFORWARD GAIN IN BACKGROUND:
ISOTOPES WITH HIGHER Q-value



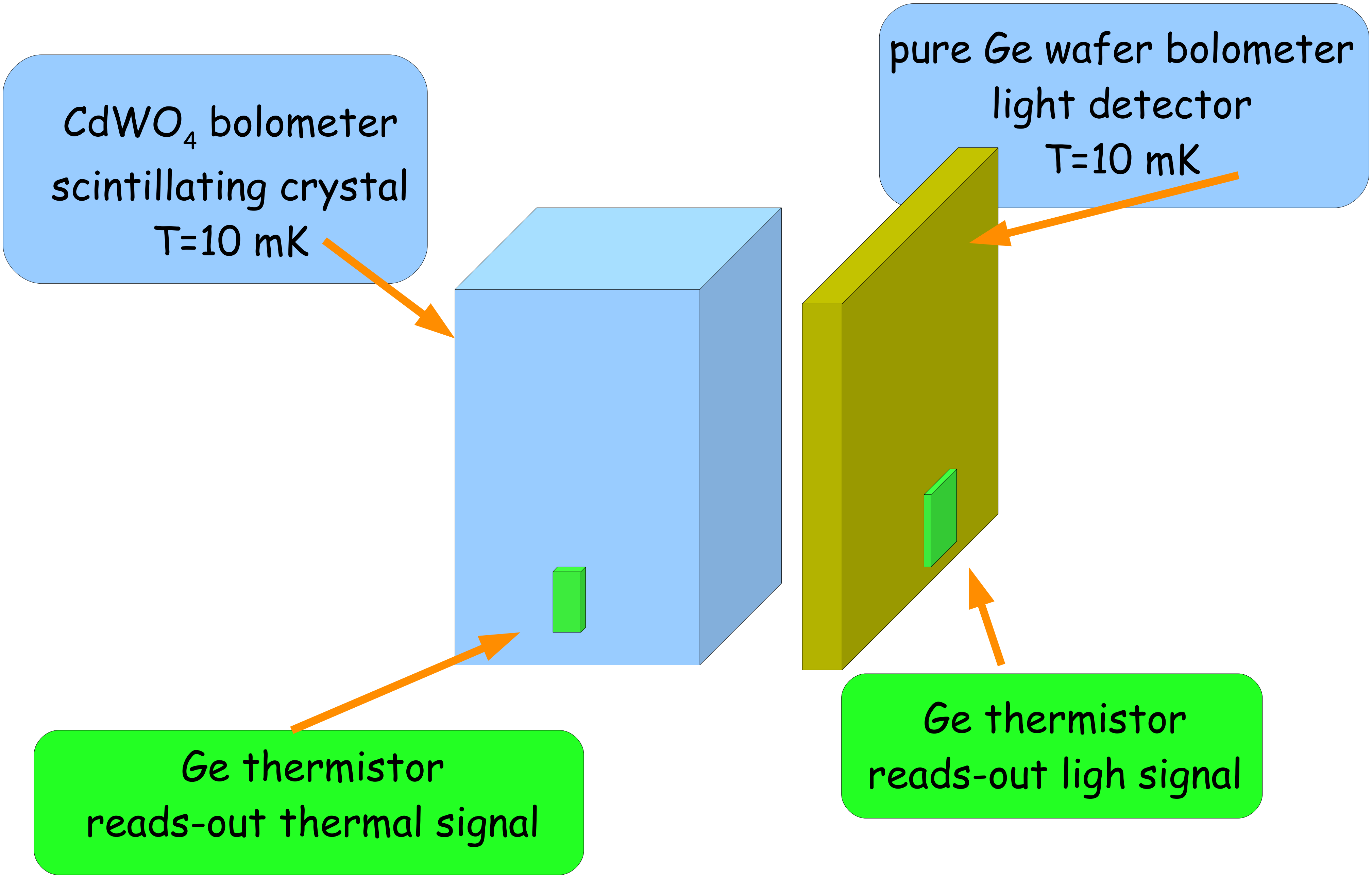
above 2.6 MeV the γ rate is 1-2 order of magnitude lower

BUT

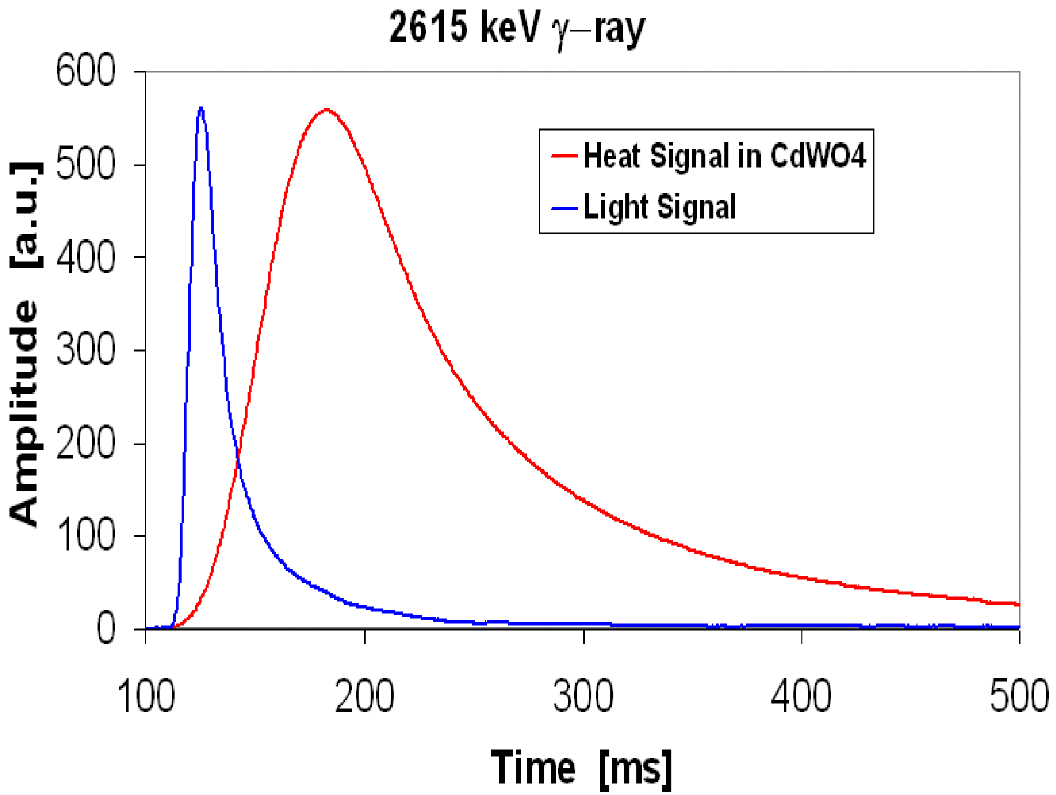
there is α background potentially dangerous

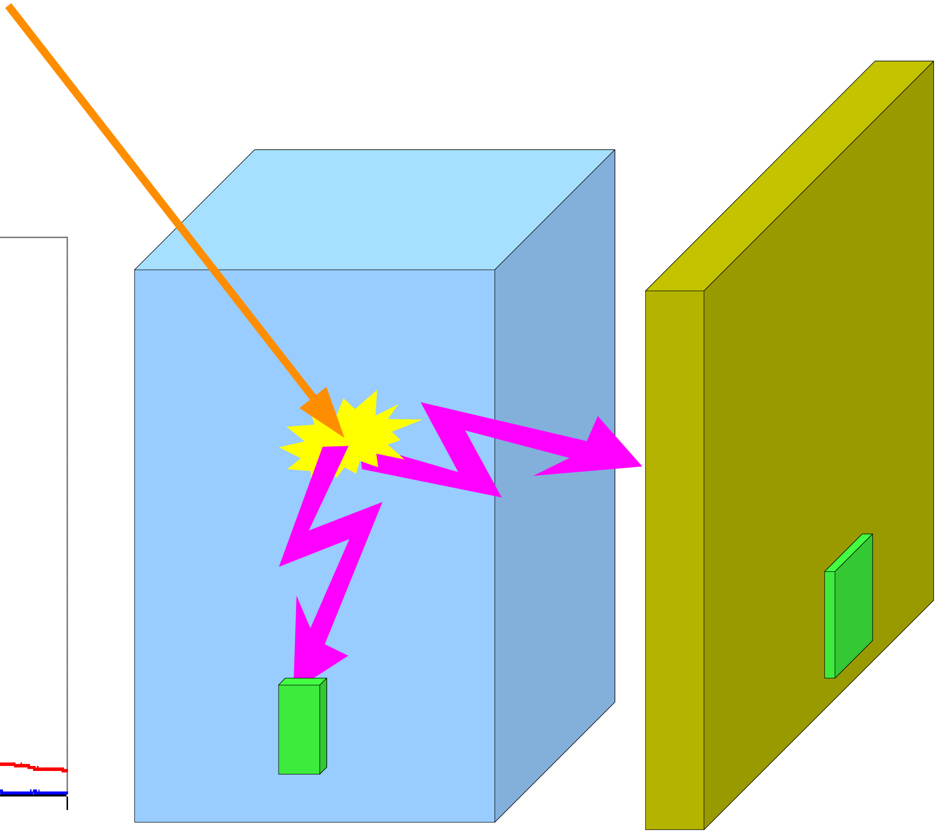
Environmental *underground* background:
^{238}U and ^{232}Th trace contaminations

BOLUX: The (far) Future



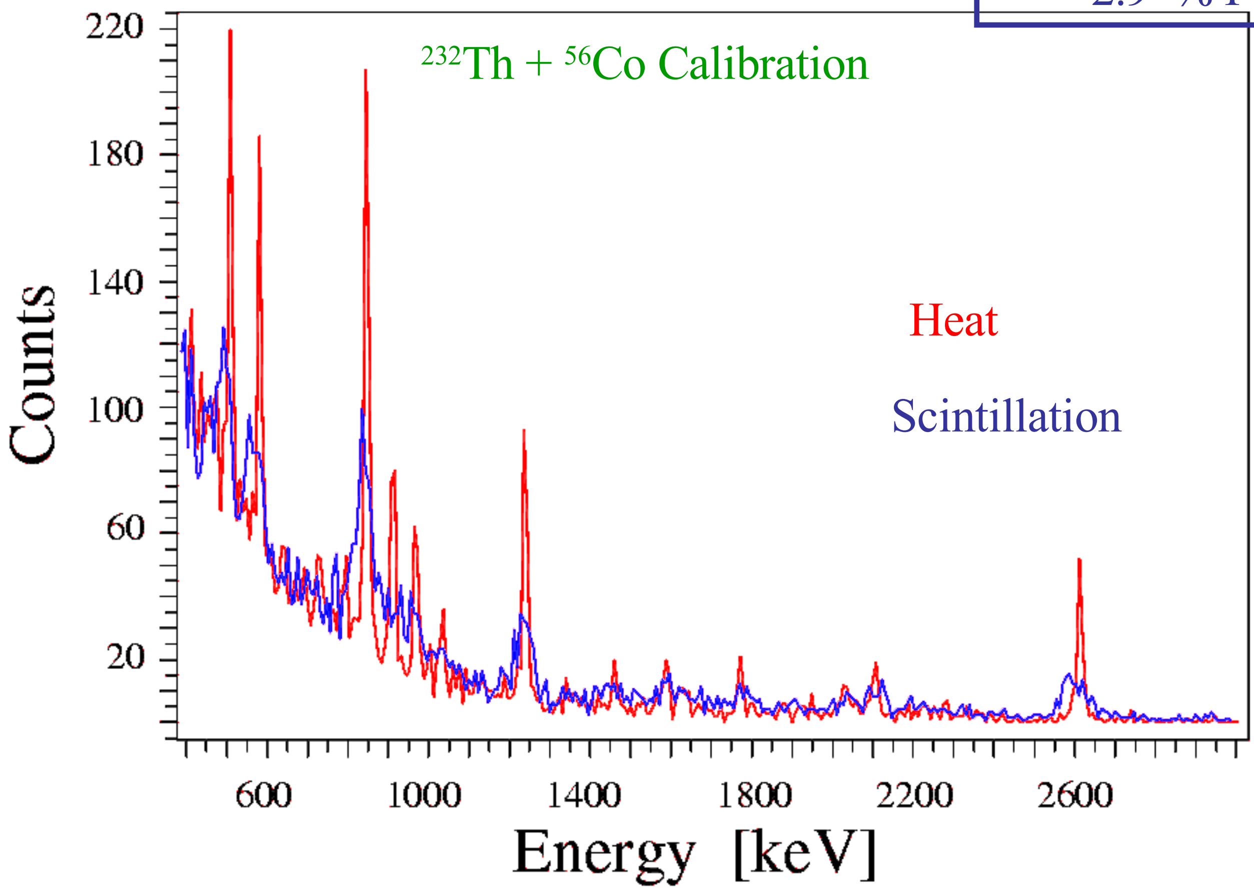
BOLUX: The (far) Future





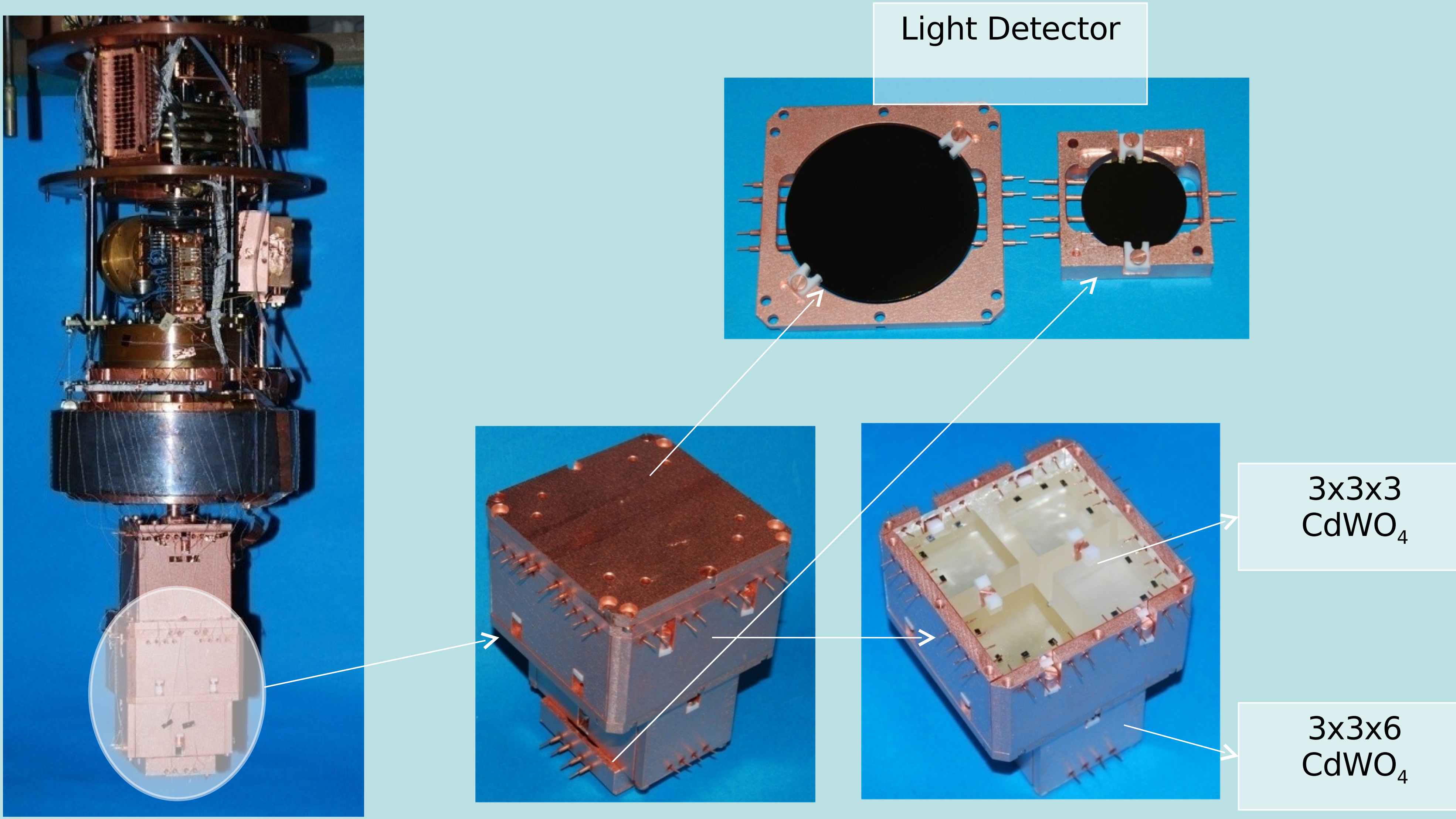
Heat
0.2% FWHM @ 2615 keV

Scintillation
2.9 % FWHM @ 2615 keV

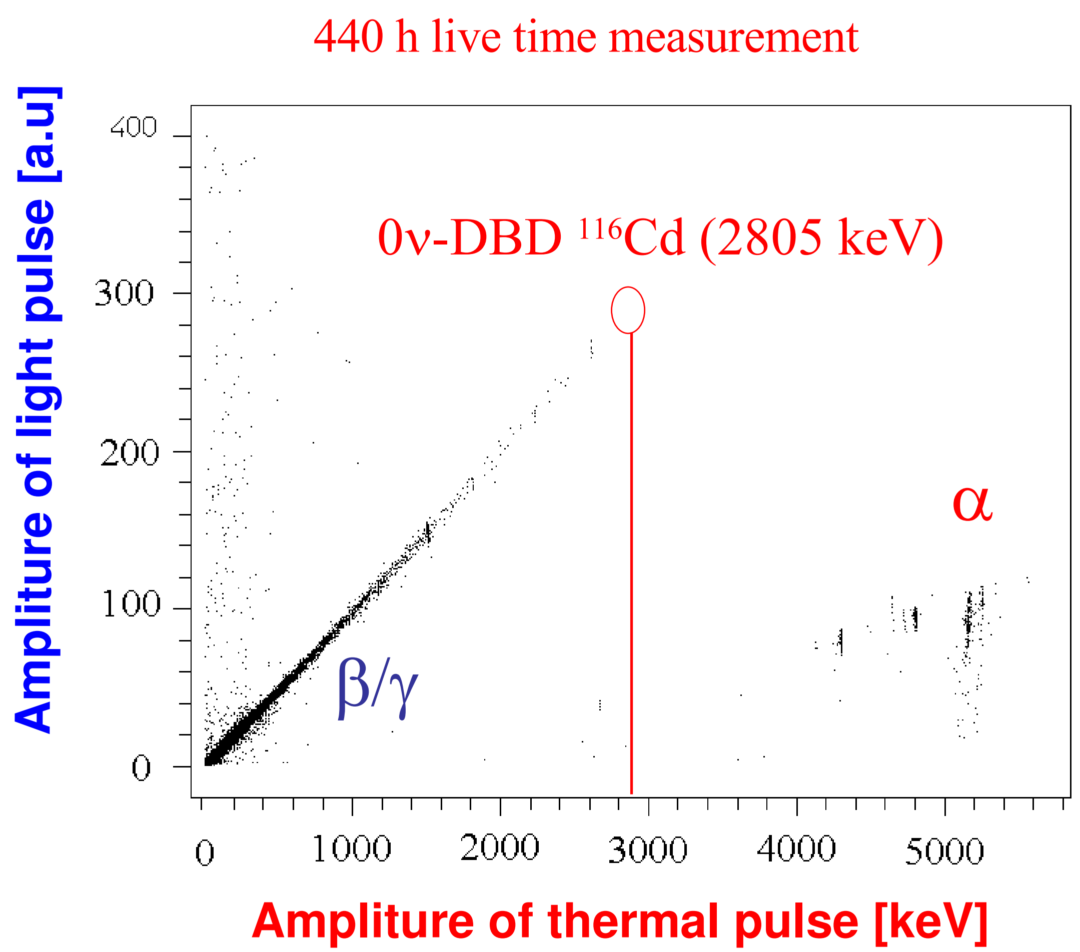


2.9% FWHM is the best result ever achieved with $CdWO_4$ as scintillator

BOLUX: The (far) Future



BOLUX: The (far) Future

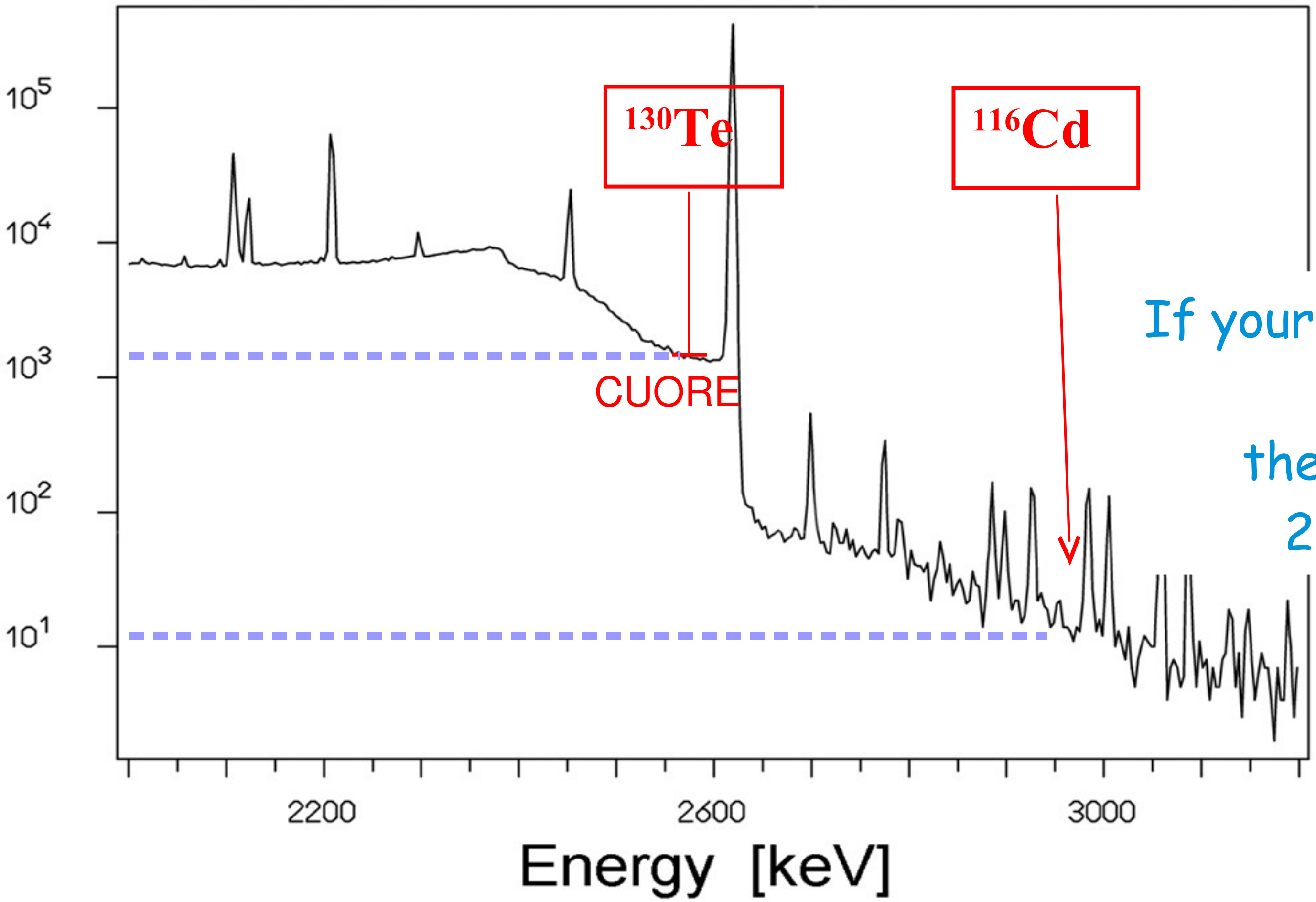


β/γ and α are clearly separated

α background can be rejected with high efficiency

BOLUX: The (far) Future

calibration spectrum of a Ge detectors
here a contribution is negligible



If your exp. region is above 2.6 MeV
and you reject alphas
the gain could be as high as
2 orders of magnitude !!!

BOLUX: The (far) Future

If your exp. region is above 2.6 Me and you reject alphas
the gain could be as high as 2 orders of magnitude !!!

excluding α contribution CUORE would have a background of 0.001 c/keV/kg/y with scintillating bolometers
a bkg of 10^{-5} c/keV/kg/y is feasible

CUORE is designed in order allow the replacement of TeO_2 crystals with other bolometers

Assume we use CUORE refrigerator
1 ton $CdWO_4$ ~ 300 kg of natural Cd
natural i.a. ^{116}Cd = 7.6% assume enriched to 30%
~100 kg of ^{116}Cd
background = 1/100 CUORE best background
= 10^{-5} counts/kg/keV/y

sensitivity of ~ 10^{28} y !!!!

still R&D
problem of enrichment
crystal contamination
engeneering of the detector ....

The (far) Future

we fight with mass and background

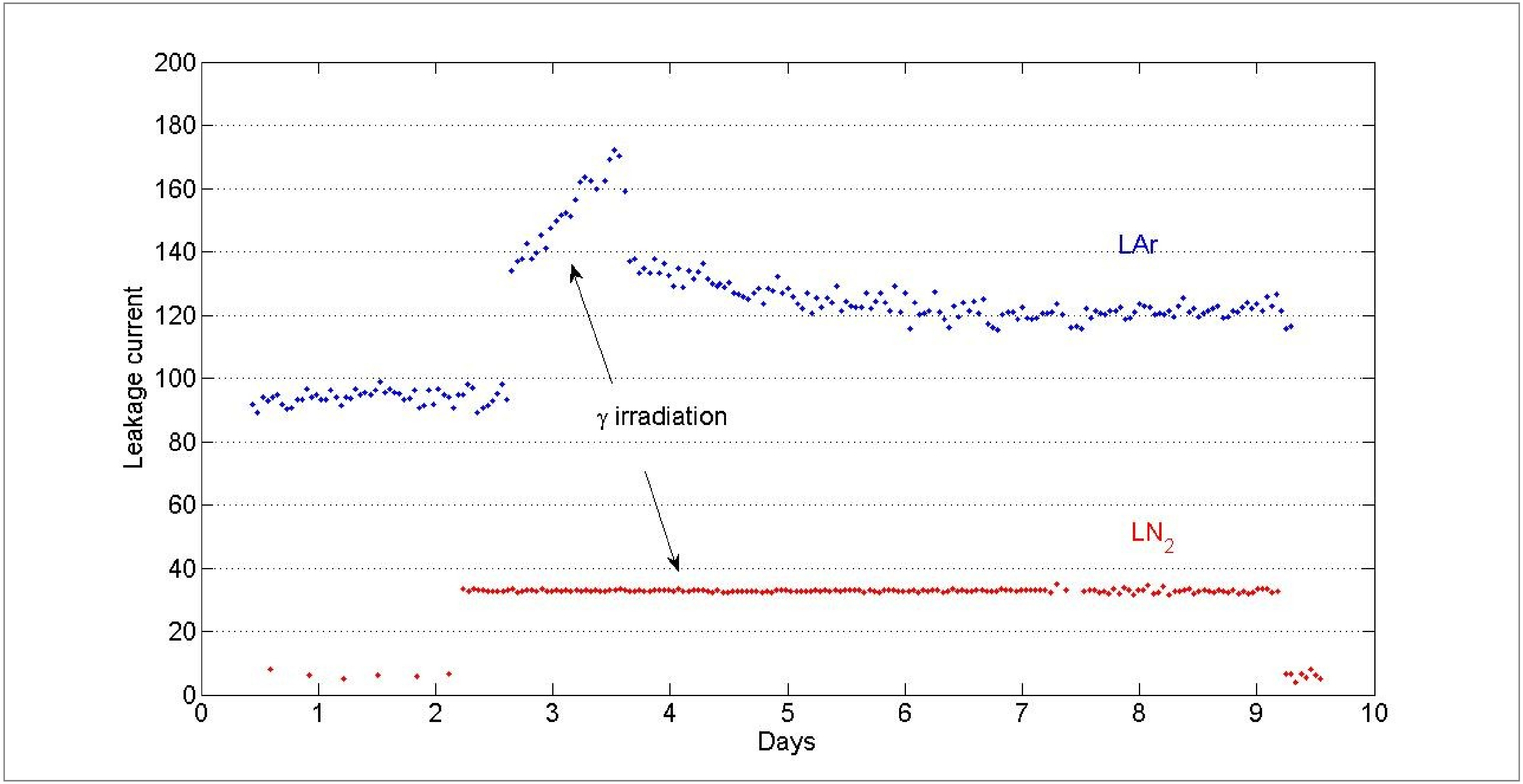
is there any other possible approach?

The (far) Future

a useful tool

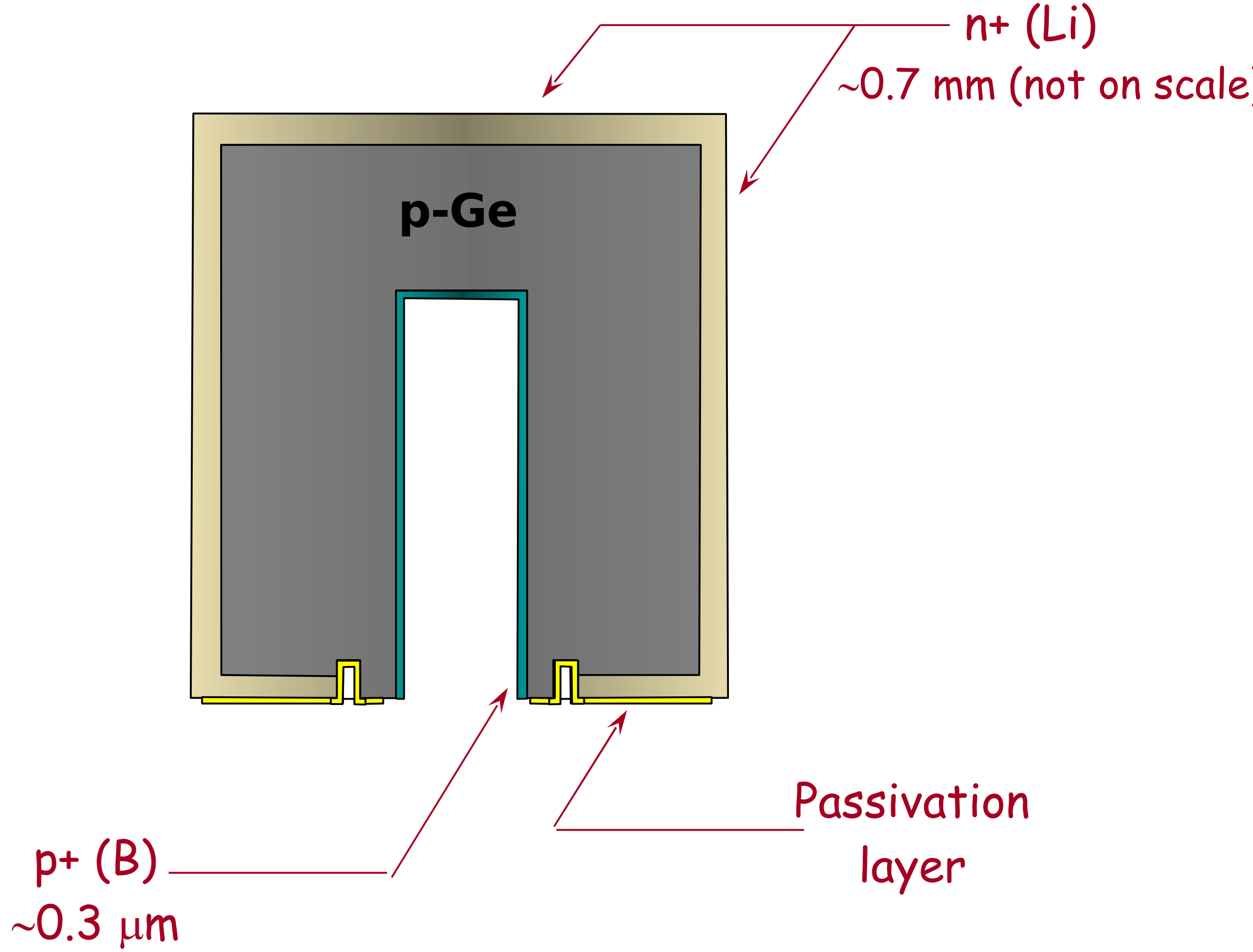
spares

Issue of the radiation-induced leakage current



Problem much more serious if irradiation of the bottom part

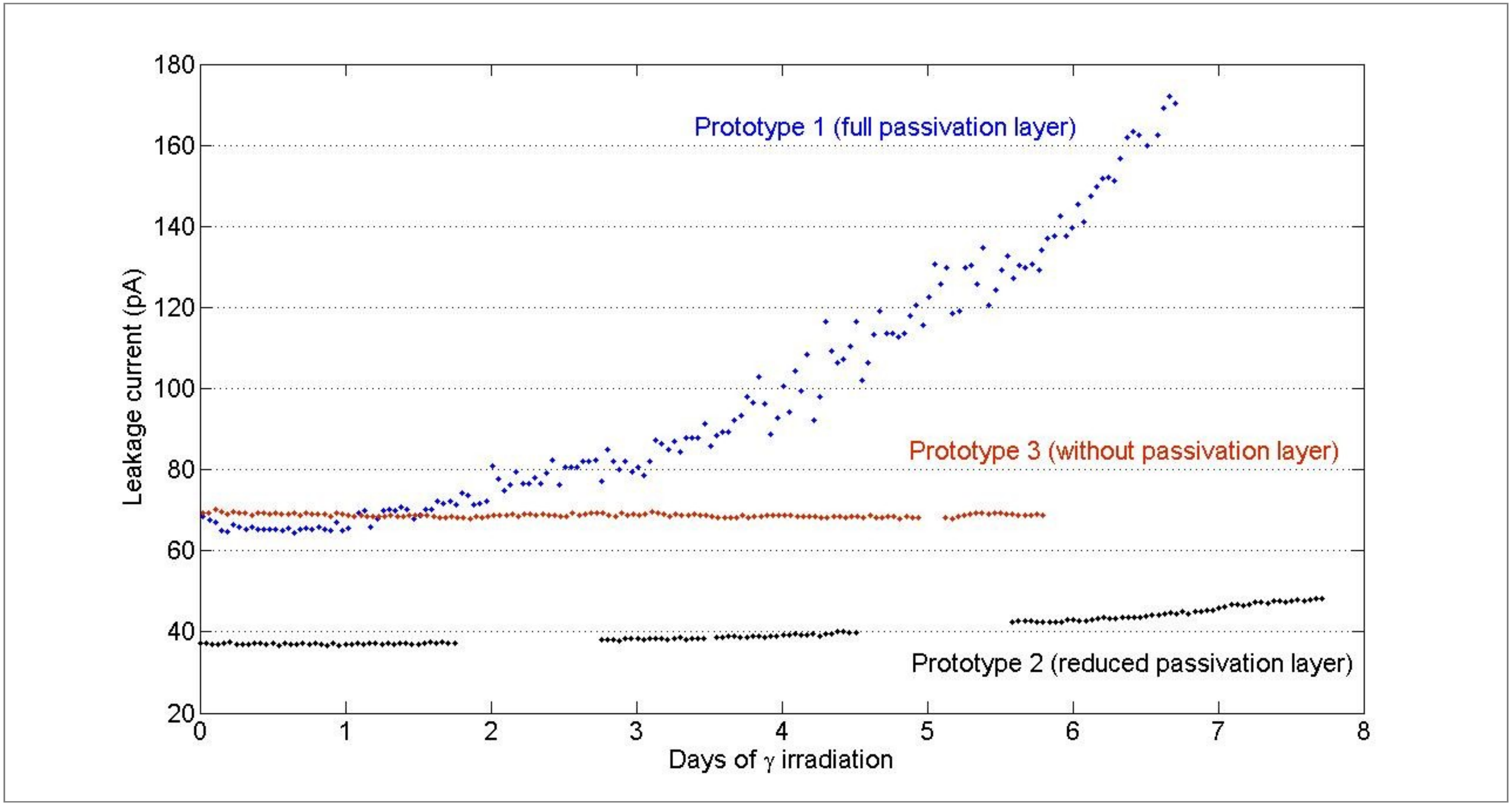
Origin of the problem: the passivation layer



Solution

Calibration 1 week → negligible increase of LC during live-time of GERDA (<10 pA)

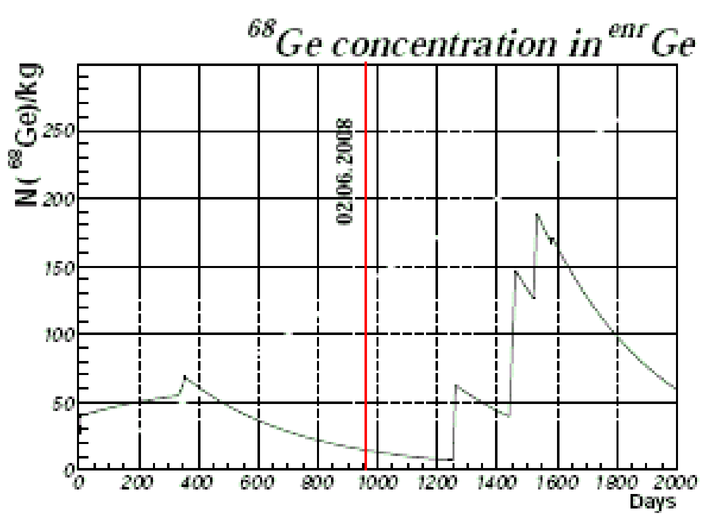
(Note: ΔLC ~ 1 nA → 1.6 keV deterioration)

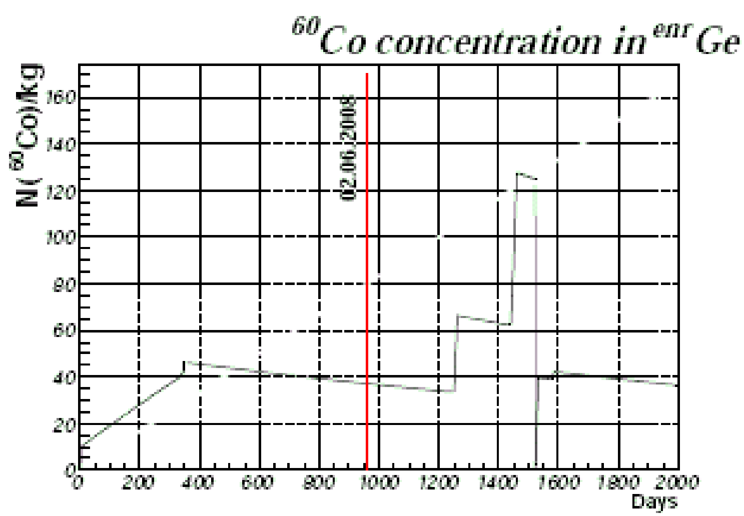


Procurement of Ge

- Natural Ge contains about 7% of ^{76}Ge. Enriched to 87% in Krasnoyarsk (Russia)
- 37.5 kg enriched Ge delivered to Munich in 2006, now stored underground.
- Also delivered 50 kg depleted Ge (leftover of the enrichment) used for purification and crystal pulling tests.

- Estimated background index for Phase I (HM, IGEX) crystals is only 10^{-2} cts/(keV kg y) mainly because of the cosmogenicaly produced ^{60}Co
- For the production of Phase II crystals we need to reduce exposure.
- With underground storage of the material between each step of processing the projected background contribution of ^{68}Ge is about $\sim 10^{-3}$cts/(keV kg y) and $\sim 10^{-5}$cts/(keV kg y) for ^{60}Co





GERDA: Background evaluation and reduction

Source	Actions
γ's from external environment ^{208}Tl and ^{214}Bi	▪Shield with hyperpure liquids (H_2O 3 m+LAr 2 m) $\Rightarrow 3\times10^{-5}$ kg^{-1}y^{-1}keV^{-1}
^{228}Th (<10 mBq/kg) in Cryostat (SS)	▪HP Cu shield (25 µBq/kg; 10-15 cm thick)+LAr
μ induced prompt signals	▪~1400 m rock overburden ▪Anticoincidence between crystals(&segments) ▪μ-vetoes: top (plastic scint.) +Water Cherenkov $\Rightarrow 10^{-4}$ kg^{-1}y^{-1}keV^{-1}
μ induced delayed signals n+^{76}Ge$\rightarrow$^{77m}Ge$\Rightarrow$^{77}As ($t_{1/2}$= 53 s)	▪Low-Z shields ▪Delayed concid. Tag decay chain $\Rightarrow 10^{-4}$ kg^{-1}y^{-1}keV^{-1}
Internal to crystals Cosmogenic ^{60}Co ($t_{1/2}$= 5.27 y) (crystal production)	▪Minimize time above ground after crystal growing ▪Diode & segments antic., PSA $\Rightarrow 3.5\times10^{-5}$ kg^{-1}y^{-1}keV^{-1}
Internal to crystals Cosmogenic ^{68}Ge ($t_{1/2}$= 270 d) (crystal and detector productions)	▪Minimize time above ground after enrichment; shielded transport container After two years underground $\Rightarrow 5\times10^{-4}$ kg^{-1}y^{-1}keV^{-1} Reduce by segmentation and PSA
Front-end electronics, cables, support	▪Materials minimisation (grams) & selection. Still under R&D $\Rightarrow \approx5\times10^{-4}$ kg^{-1}y^{-1}keV^{-1}

Conclusion - Summary

- GERDA is under construction
- Construction of Phase I expected to be finished soon, start of datataking expected in 2009
- Development of Phase II detectors is on the way
- Detector grade Ge crystals (Ph. II) expected in 2009
- 18 fold segmented prototypes are working in vacuum and in LN
- Many other R&D projects with possible application in Ph.II are running in parallel: point contact detectors, scintillation light detection in LAr etc.

Strategies for the control of the surface background from inert materials

(A) Passive methods ⇒ surface cleaning

Mechanical action

Chemical etching / electrolitical processes

Passivation

→ ① "Legnaro" method

→ ② "Gran Sasso" method

(B) Active methods ("reserve weapons") ⇒ events ID

→ ① surface sensitive bolometers (Como)

→ a. scintillating bolometers able to separate α from elettrons / γ (LNGS / Roma)

The diagnostic problem

It is difficult and quite demanding in terms of time and money to verify the effectiveness of a method to reduce the surface radioactiviy

Two methods:

Assuming CUORICINO background

(A) Direct counting

$$A^{sup}_{3-4\ MeV} \approx 1.7\ counts / cm^2\ y$$

runs in hall C

(B) Concentration measurements

contamination in U – Th of the order of ng/g

Not appliable at all for ^{210}**Pb** or ^{226}**Ra**

ICPMS analysis