Neutrinoless Double Beta Experiments:

Majorana/GERDA and the Xenon challenge

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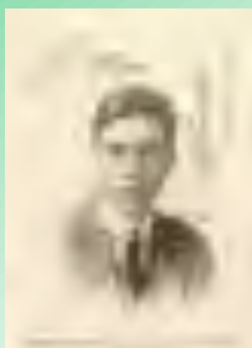
O U T L I N E



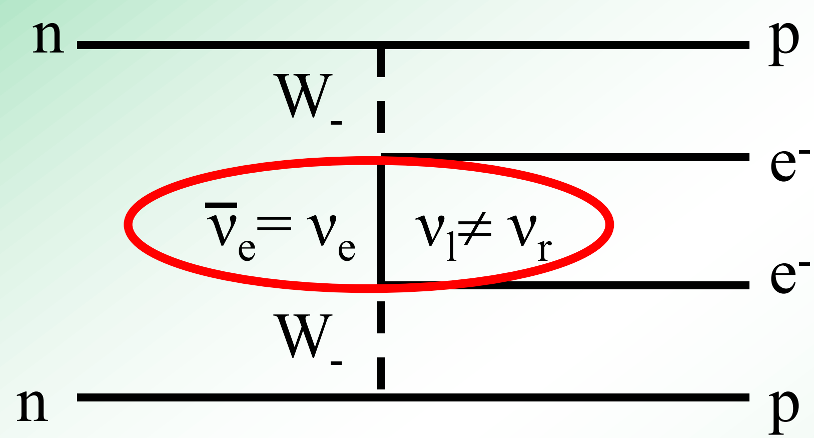
- Why is $0\nu\beta\beta$ decay so interesting?
- What determines the needed sensitivity to $0\nu\beta\beta$ decay?
- (Dis)Advantages of germanium and xenon
- HPGe experiments: HdM, IGEX, GERDA, Majorana
- Xenon experiments EXO and KAMLAND ZEN

Many thanks to:

John Wilkerson, Mike Marino and Jason Detweiler
for making available figures for Majorana, EXO200 and KAMLAND ZEN

Why is 0νββ decay so interesting?

0νββ-decay:



Neutrinoless mode of double beta-decay only possible if:

- **Neutrino has Majorana character**
- **Helicity flip can occur in the vertex**

Effective Majorana neutrino mass contributes to 0νββ-decay rate:

$$1/\tau = G(Q^5,Z)\ |M_{nucl}|^2\ \langle m_{ee}\rangle^2$$

0νββ decay-rate | **Phase space-factor** | **Matrix element** | **Effective Majorana Neutrino mass**

Why is 0νββ decay so interesting?

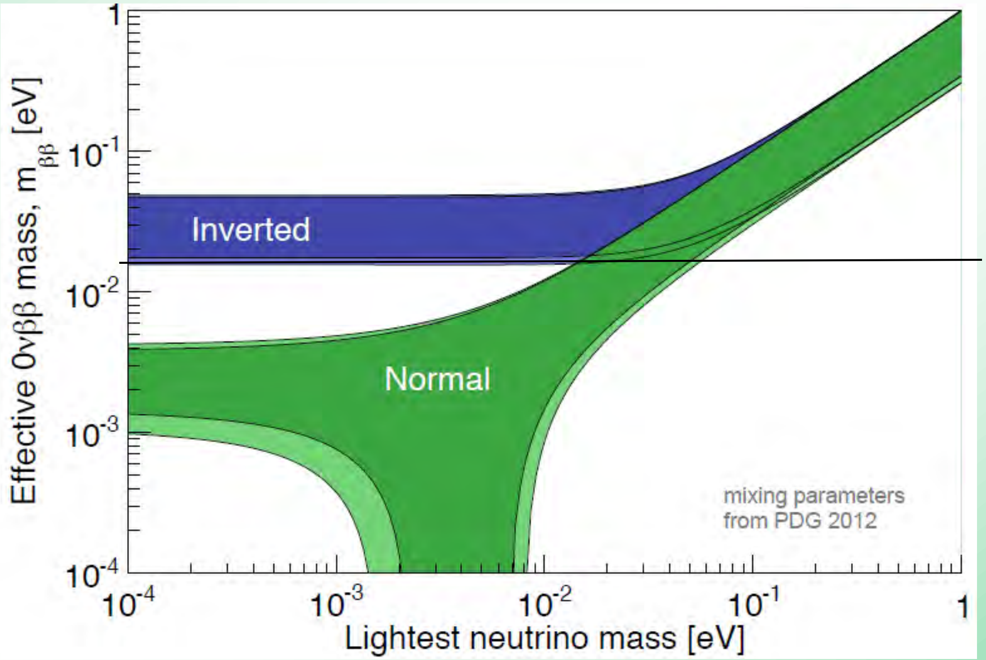
Observation of 0νββ decay:

- Lepton number violation!

- Neutrino must have Majorana nature!
- Determination of absolute mass scale?
- Mass hierarchy of Neutrinos?

- Information on CP violating phases?

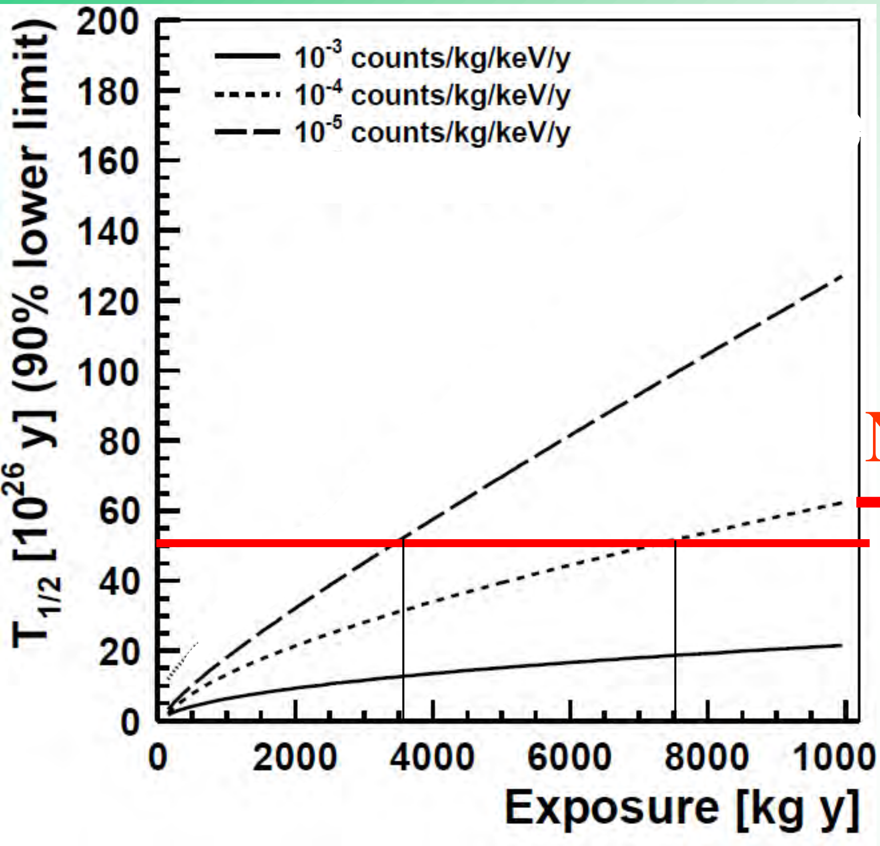
CP violating Majorana phases could be responsible for Baryogenesis via Leptogenesis



If – and only if - 0νββ decay mostly induced by light Majorana neutrino exchange

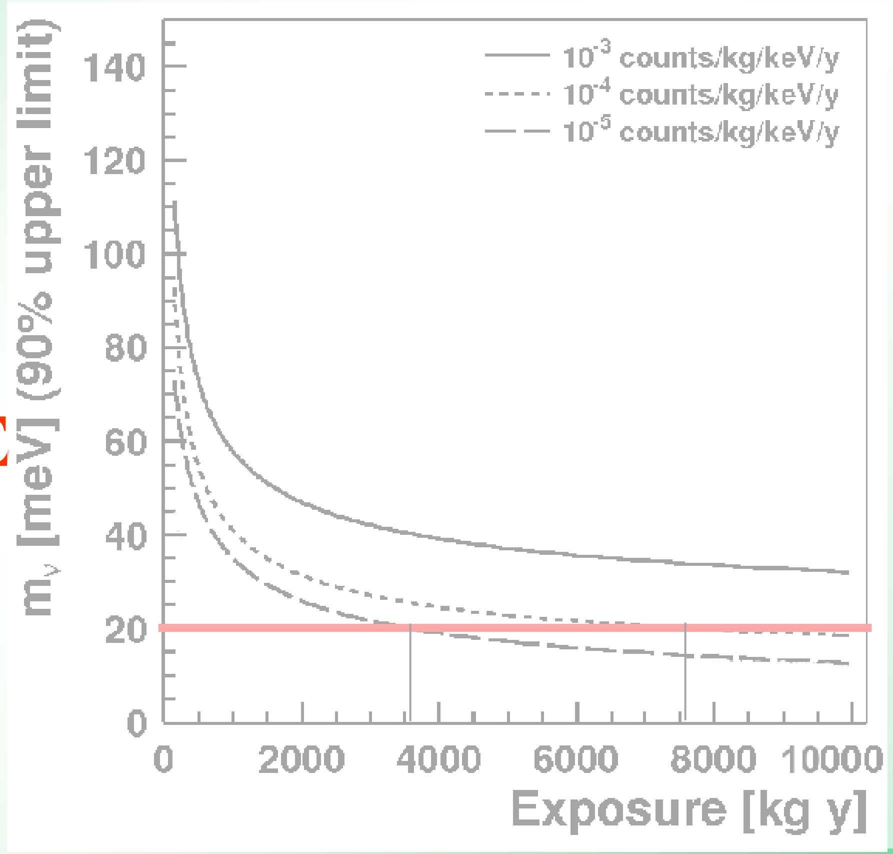
$m_{\beta\beta} \sim 20$ meV → ${}^{0\nu}T_{1/2} \sim 5 \cdot 10^{27}$ yr

The needed sensitivity to future 0νββ decay experiments?



NME

???



$m_{\beta\beta}$~20 meV → $^{0\nu}T_{1/2}$ ~ $5\cdot10^{27}$ yr

3500 kg yr exposure with BI = 10^{-5} cts/(kg yr keV)

or

7500 kg yr exposure with BI = 10^{-4} cts/(kg yr keV)

The needed sensitivity to 0νββ decay?

Figure of merit for half-life sensitivity:

b>0 : $S(T_{1/2}) \propto M_{nucl}^{2}\ a\ \varepsilon \sqrt{\frac{m\ t}{b\ \delta E}}$

b=0 : $S(T_{1/2}) \propto M_{nucl}^{2}\ a\ \varepsilon\ m\ t$

M_{nucl}	Nuclear matrix element	Chose isotope
b	Background rate of experiment	Minimize and select materials
a	Abundance of isotope	Use element with high natural abundance or enrich
M	Active detector mass	Increase target mass
ε	Detection efficiency (<1.0)	Source =! Detector
δE	Energy resolution	Use high resolution spectrometer
t	Measuring time (< 20yr)	Be patient

(Dis)Advantages of germanium

Very good energy resolution	Reduction of bkg in RoI: 2νββ-decay negligible, rest prop. RoI width (FWHM)
Source = Detector	High signal detection efficiency (95%)
Very high purity of detector material (zone refinement)	Very low intrinsic background
Segmentation and pulse shape extraction for event topologies	Build “intelligent detectors”
Considerable experience	Well known and reliable, improvements possible
Q-value not too high (phase space, background)	Reduce background
Natural abundance of ^{76}Ge 7,8%	Enrichment necessary

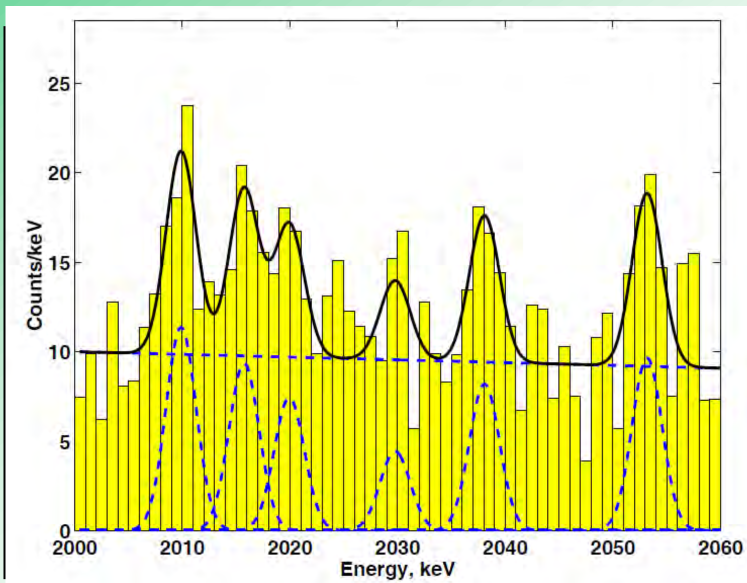
(Dis)Advantages of xenon

Source = Detector	High signal detection efficiency
Very high purity of detector source (fractional distillation)	Very low intrinsic background
Scintillation & detection of ions	“intelligent detectors” possible
No dangerous cosmogenic isotopes	Low cosmogenic contribution to background
“Easy” to scale $V \sim r^3$	Build ton scale
Q value at 2.46 MeV Above Comp. cont. of 2.6 MeV	Reduce background
Limited energy resolution	Reduce background Intrinsic limit on $0\nu\beta\beta$ decay
Natural abundance of ^{136}Xe 8,9%	Enrichment necessary $$ ^{136}Xe ~ 1/5 $$ ^{76}Ge

HPGe detectors for the search of 0νββ-decay

Most sensitive experiments so far :

Heidelberg-Moscow Experiment:



IGEX Experiment:

11.5 kg HP^{76} Ge Detectors 1990-2003
71.7 kg yr → 810 mol yr
0.16 Counts/(kg keV y) @ 2040 keV
→ $T_{1/2} \geq 1.9 * 10^{25}$ years (90% C.L.)

K-K et al. Eur. Phys. J.A 12 (2001)147.

Part of HdMo-collaboration:
Evidence: $T_{1/2} = 1.2 * 10^{25}$ years

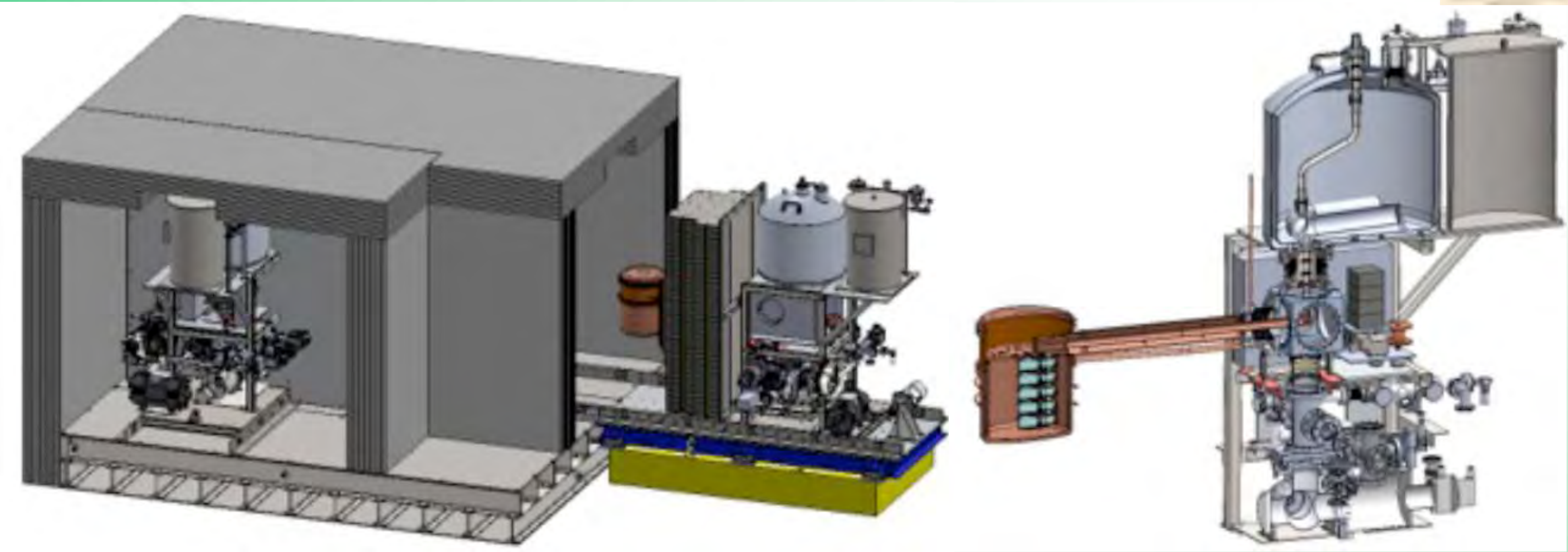
K-K et al., Phys Lett B 586(2004)198

6.8 kg HP^{76} Ge Detectors 1991-2000
8.9 kg yr → 101 mol yr
0.17 Counts/(kg keV y) @ 2040 keV
→ $T_{1/2} \geq 1.6 * 10^{25}$ years (90% C.L.)

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

The Majorana experiment

Operate HPGe detectors in ultra pure vacuum cryostat



Three Steps	Est. commissioning start dates
– Prototype Cryostat* (2 strings, natGe)	(Summer 2013)
– Cryostat 1 (3 strings enrGe & 4 strings natGe)	(Early 2014)
– Cryostat 2 (7 strings enrGe)	(Late 2014)

* Same design as Cryos 1 & 2, fabricated using OFHC Cu (non e-formed) components.

The Majorana experiment

Located underground at 4850' Sanford Underground Research Facility

Main MJD lab at 4850L Davis Campus, beneficial occupancy in May 2012.

Operating Temporary Cleanroom Facility (TCR) at 4850L Ross Campus since Spring 2011

The Majorana experiment

Electroforming lab underground at Homestake mine

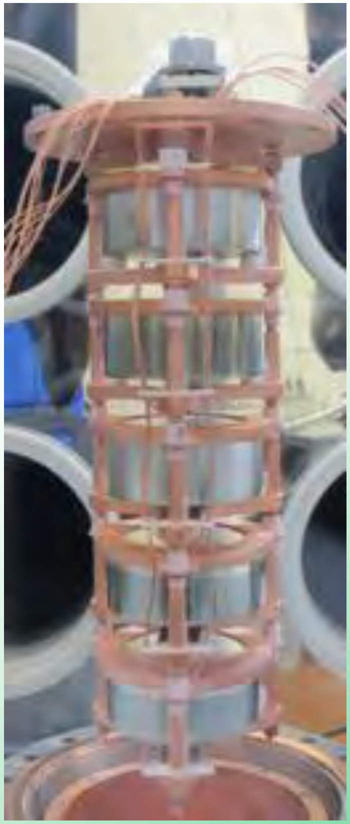
Electroformed Cu - over half of the electroformed copper is available: cryostat 1 material complete

Fabrication nearly complete, cleaning/etching going smoothly…

The Majorana experiment

Mounting of prototype cryostat and test string

prototype cryostat



MJD String ^{nat}Ge modified BEGes March 2013

The Majorana experiment

Enriched detectors status

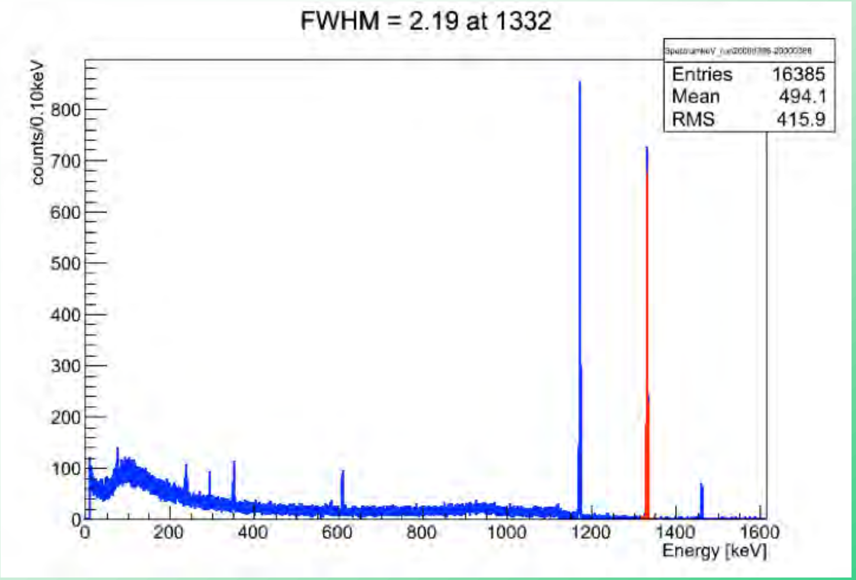
Enrichment:
ECP, Russia (42.5kg) ~ 87% ^{76}Ge

Reduction & Purification:
Electrochem Sys Inc.

Detector supplier:
Ametek/ORTEC

9 kg of ^{enr}BEGe detectors underground!

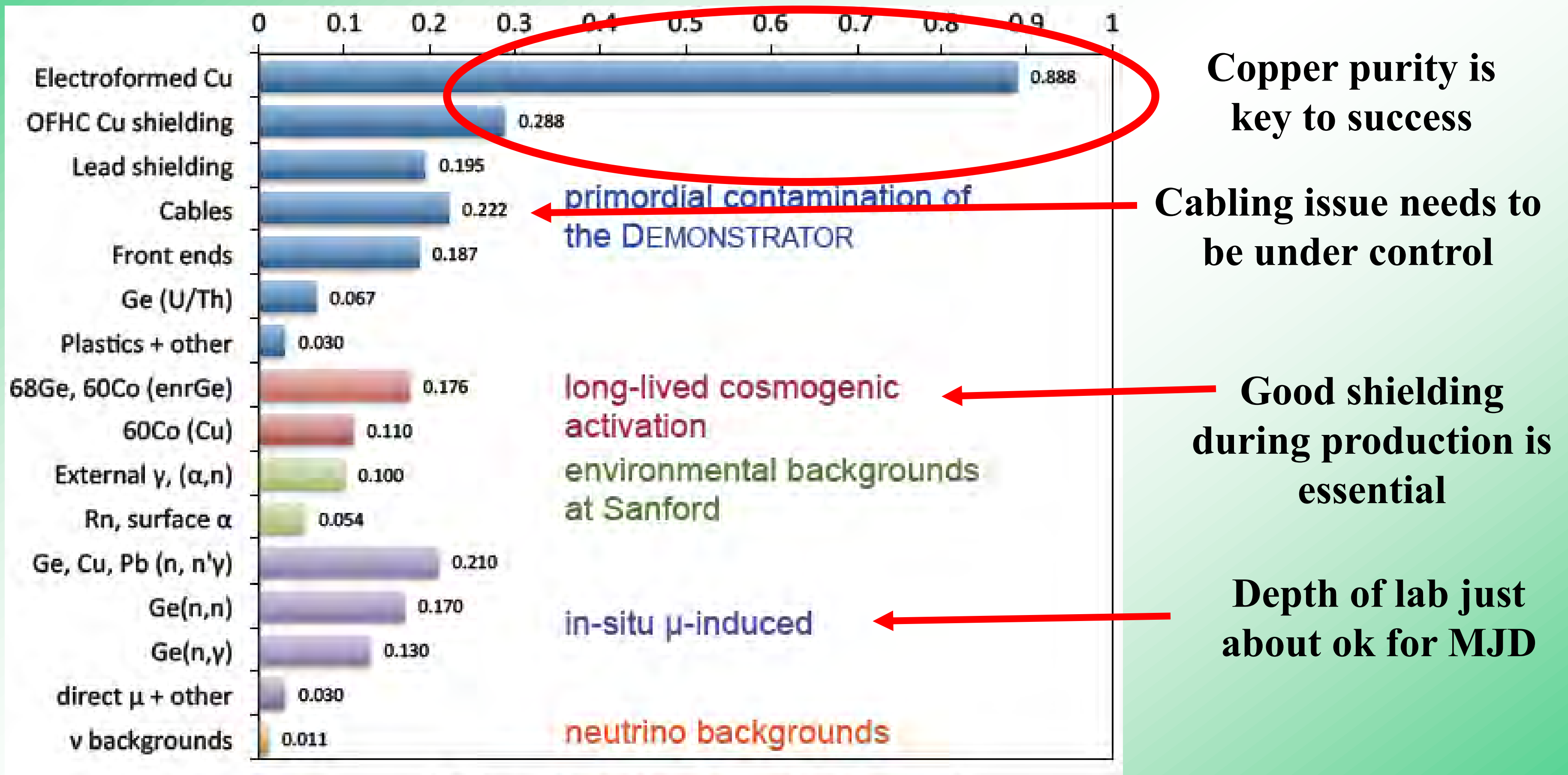
High yield expected: 65%-70%



April 4th: need somebody to get detectors running

The Majorana experiment

Screening and background prediction



J. Detwiler, MJ CD4 Background Criteria Report

2.9 counts/RoI/t/y → $7.25 \cdot 10^{-4}$ cts/(kg · yr · keV)

GERDA : Design and existing infrastructure

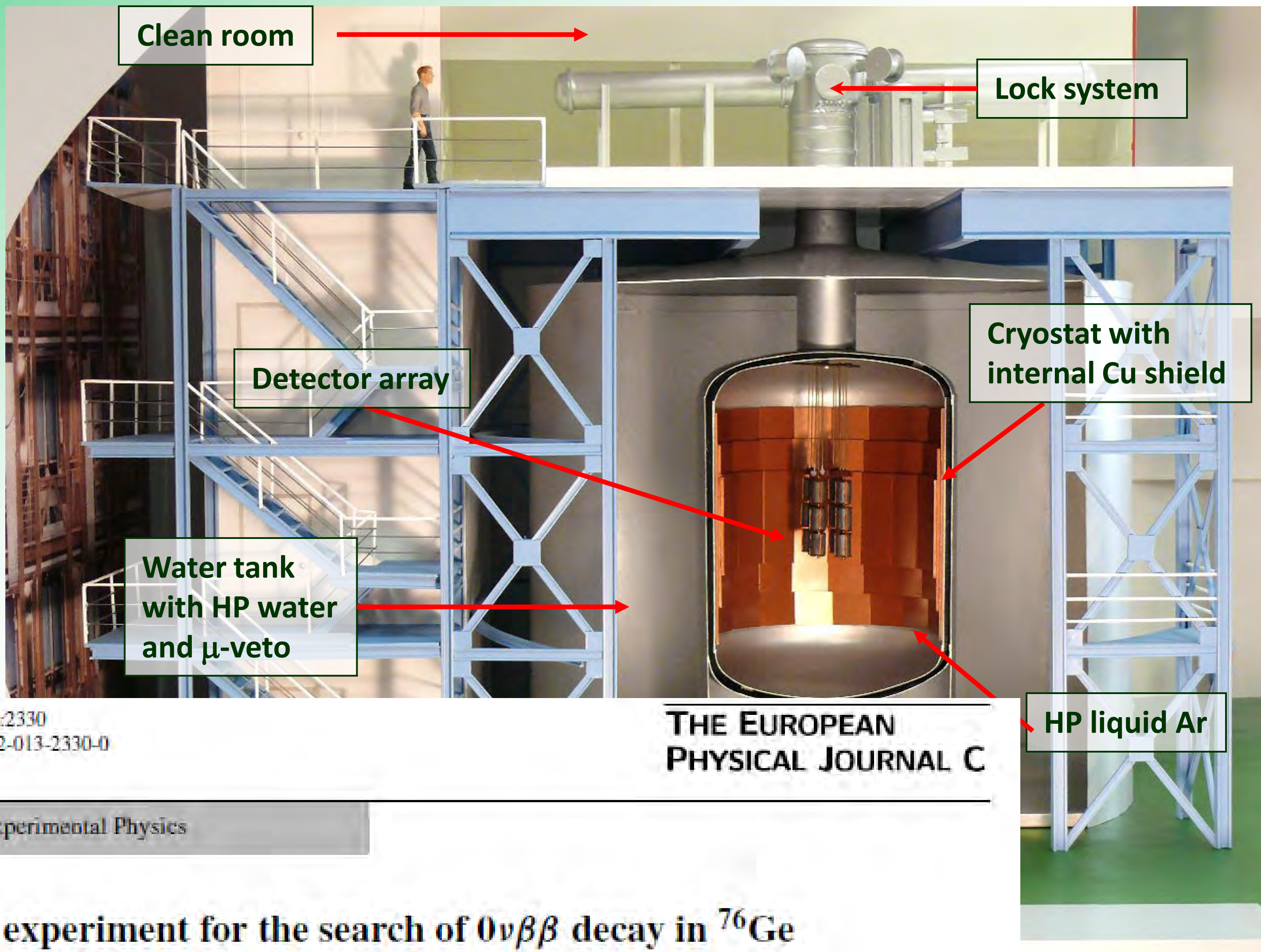
Location: Hall A of LNGS, Assergi, Italy
3500 mwe

Phase I: Use HdM and IGEX detectors

Phase II: Convert 37.5 kg of enriched germanium (87% ^{76}Ge) into HPGe detectors

GERDA : Design and existing infrastructure

Operate „naked“ HPGe detectors directly in ultra pure cryoliquid (G. Heusser, 1995)



Eur. Phys. J. C (2013) 73:2330
DOI 10.1140/epjc/s10052-013-2330-0

THE EUROPEAN PHYSICAL JOURNAL C

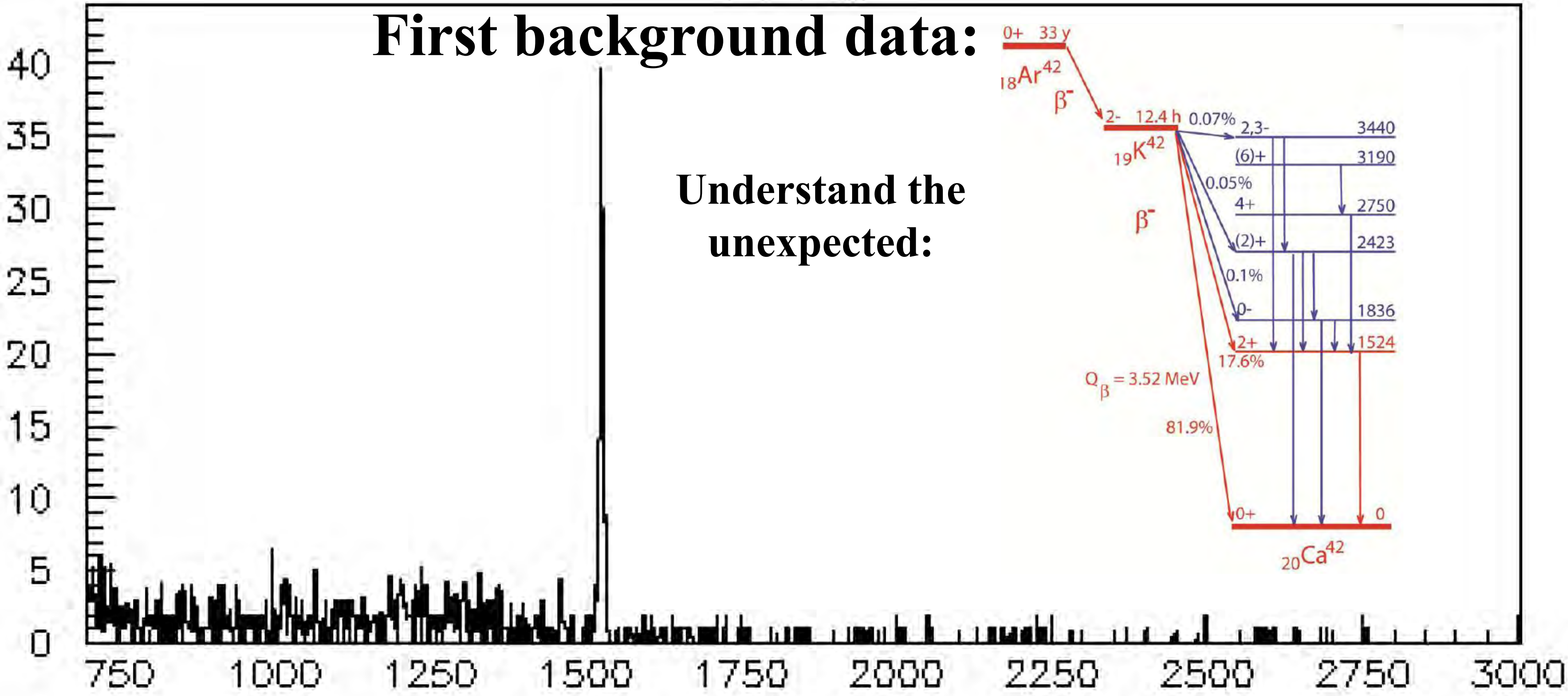
Regular Article - Experimental Physics

The GERDA experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge

GERDA : Results from commissioning

First background data:

Understand the unexpected:

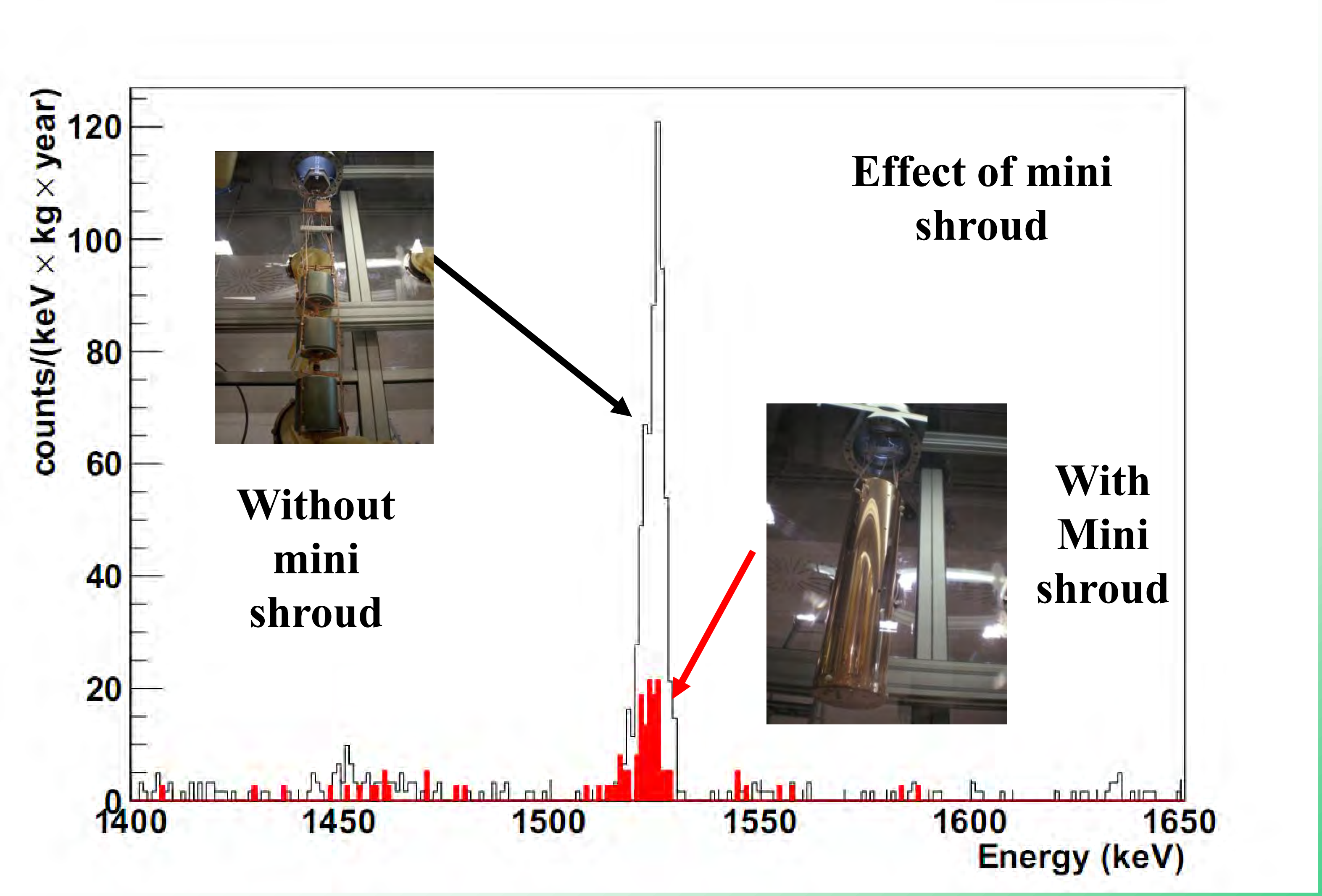


^{42}K ions have long life time in LAr (half life: 12.4 hours)
→ Drift in E-field
→ attracted to surfaces close to or on detector

^{42}Ar contamination in liquid Argon: A = (94.5±4.7±17.5) μBq/kg
Compare to previous upper limit Ashitkov et.al: A_{max}=41 μBq/kg

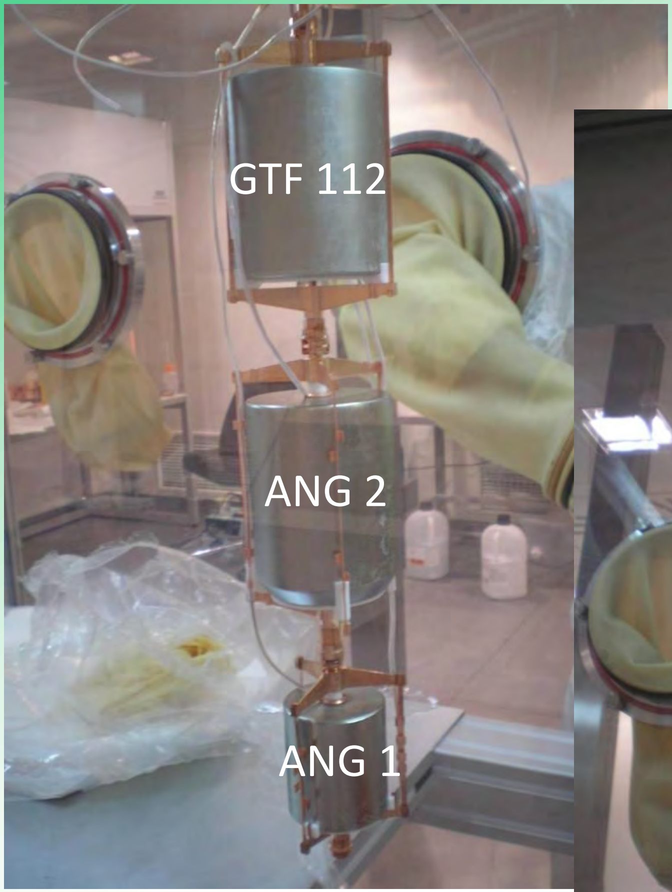
GERDA : Results from commissioning

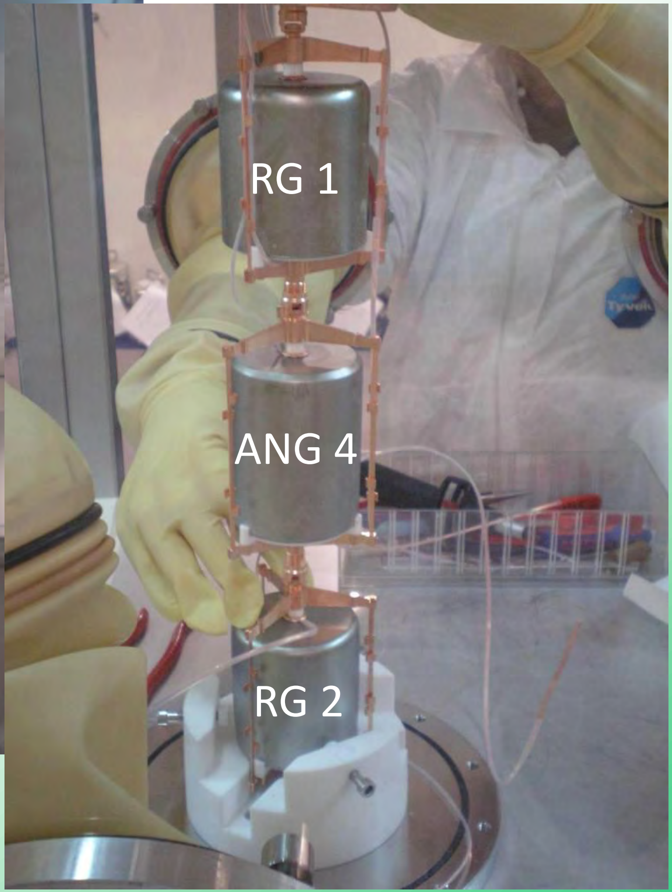
Background mitigation: control the unexpected



GERDA : Status of phase I

Installation of phase I detectors :

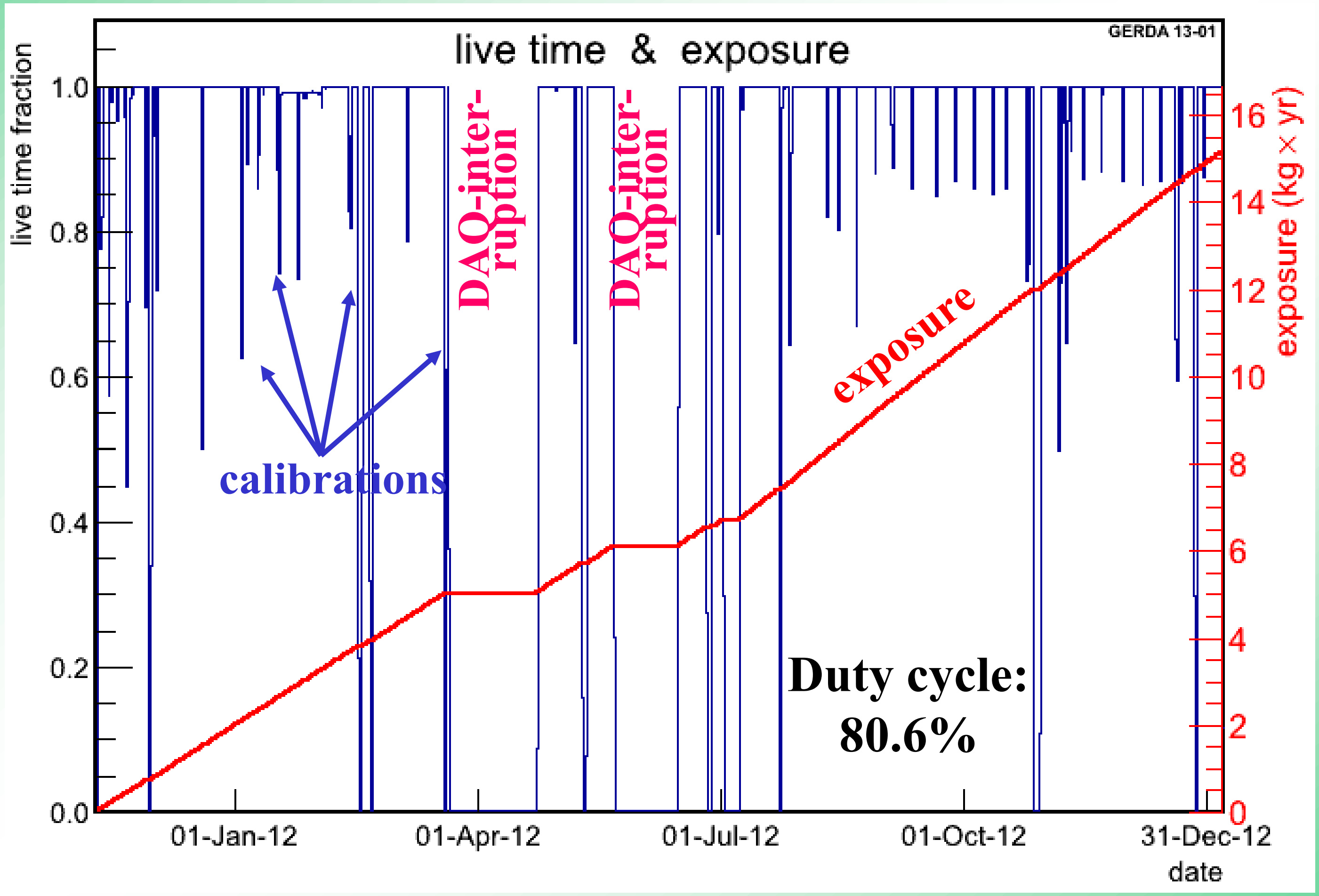




Deployed all phase I detectors in Nov. 2011 together with 1 natural HPGe detector

GERDA : Status of phase I

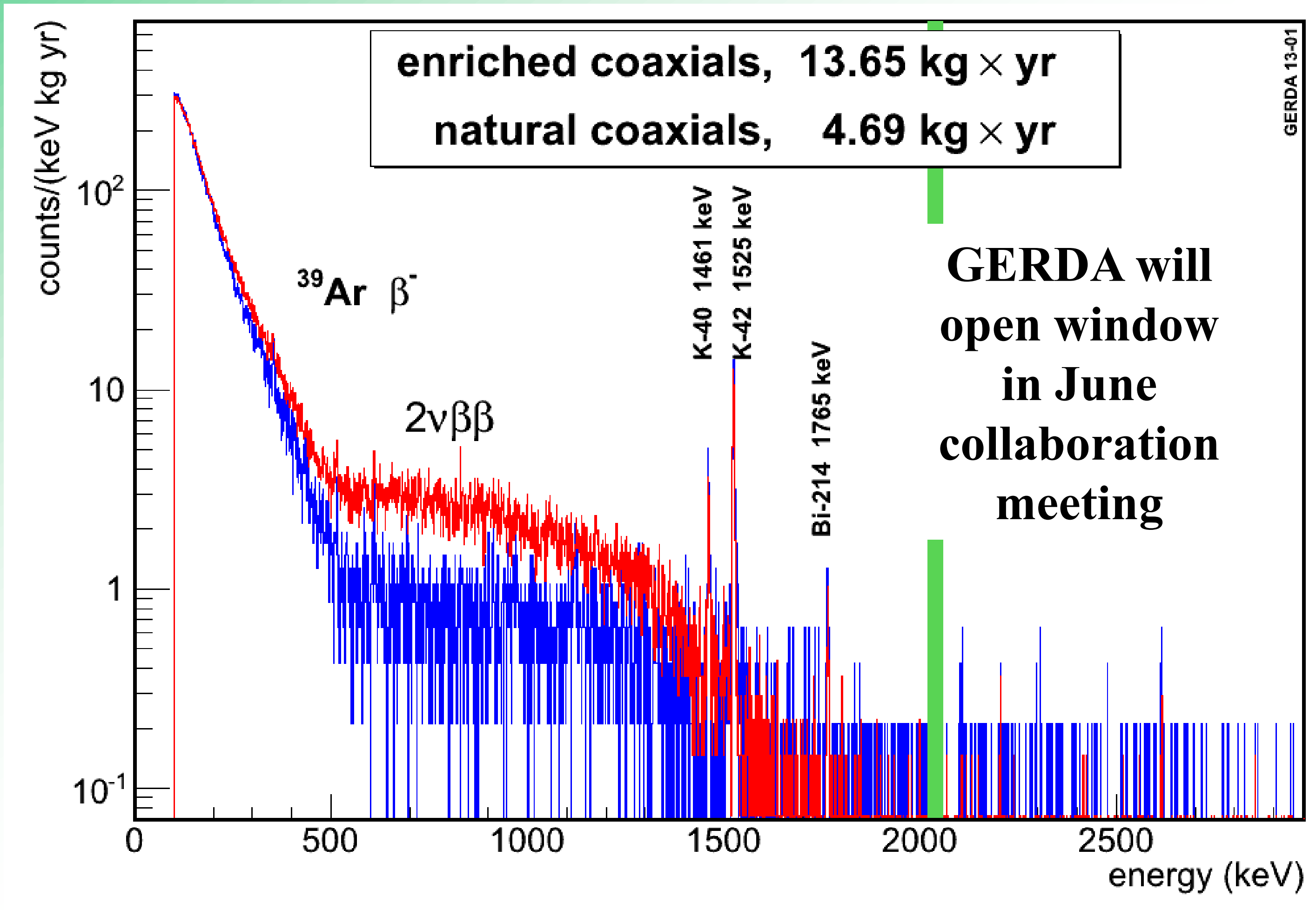
Start: 05 Jan 2013 19:13:40
Stop: 16 Feb 2012 08:24:13



Live time: 340.94 days = 0.934 yr
Exposure with Phase I detectors: 13.65 kg*yr

GERDA : Status of phase I

Natural vs. Enriched detectors:



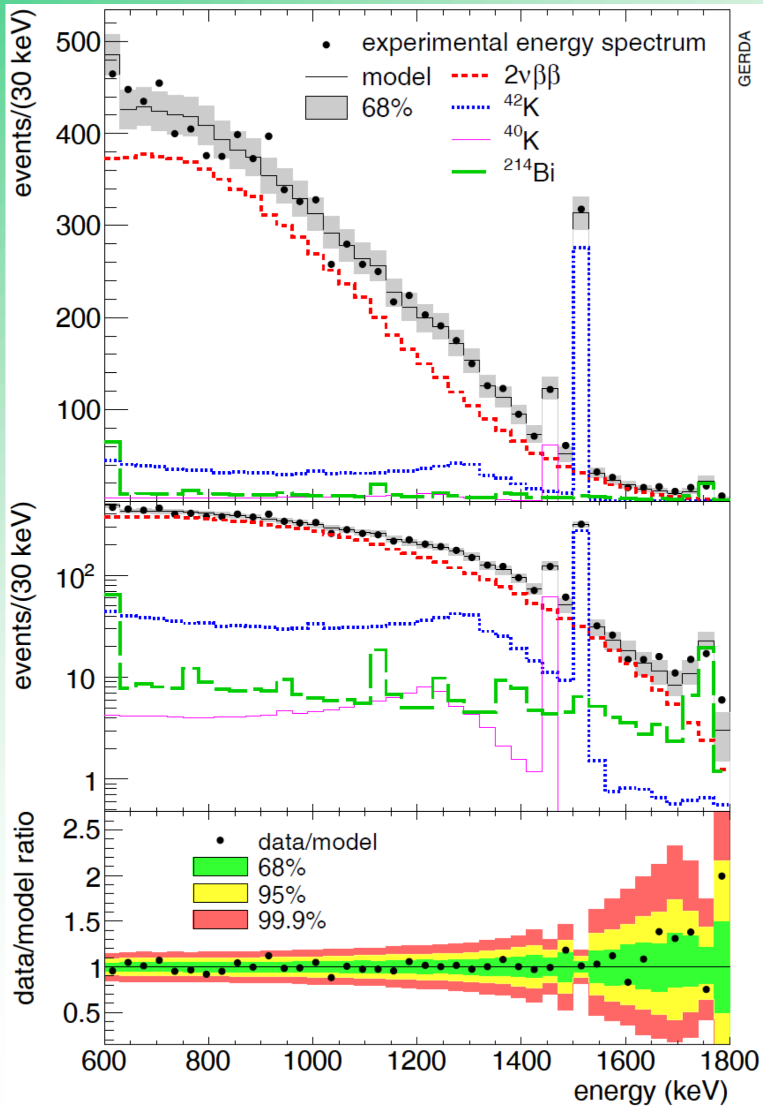
Coax all: $0.024^{+0.34}_{-0.31}$ cts/(kg y keV)

Coax LB: $0.017^{+0.34}_{-0.31}$ cts/(kg y keV)

(Remove 1 month data after array movement)

GERDA : Status of phase I

New measurement of $^{2\nu}T_{1/2}$ (^{76}Ge) published:

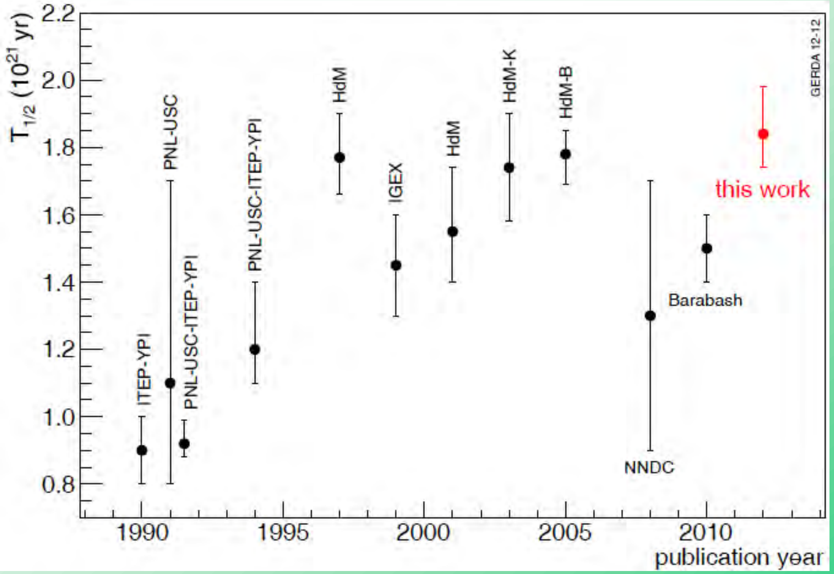


IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment

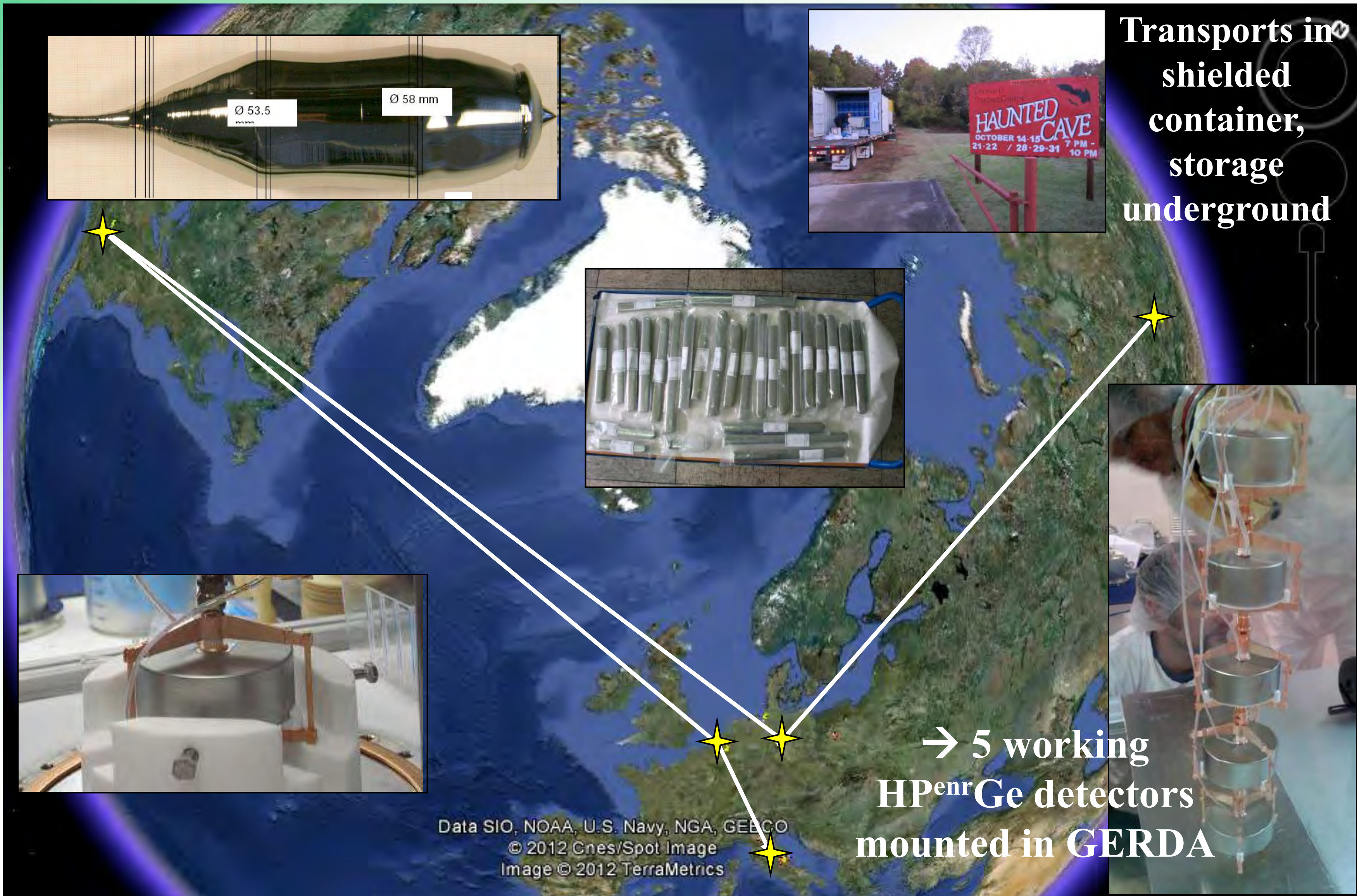
Signal to background ratio > 4 : 1

$$^{2\nu}T_{1/2}(^{76}\mathrm{Ge}) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\,\mathrm{yr}$$



GERDA : Status and plans for phase II

The voyage of the enriched germanium



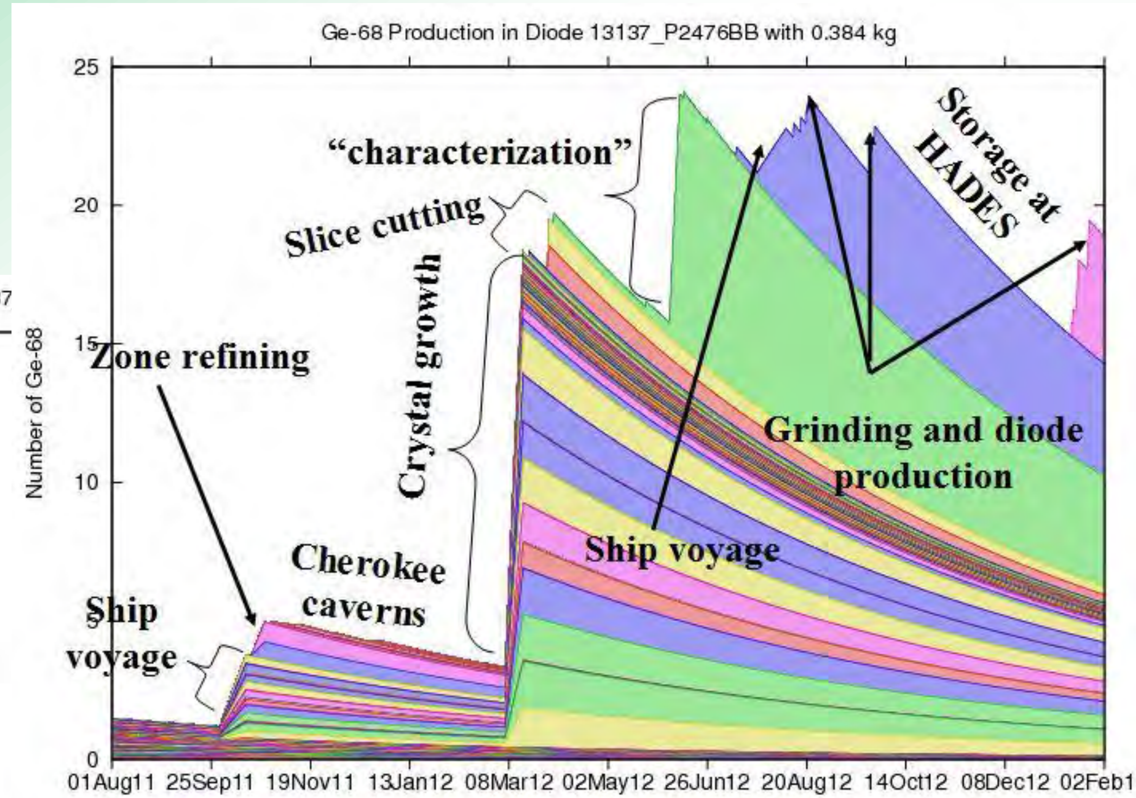
Transports in shielded container, storage underground

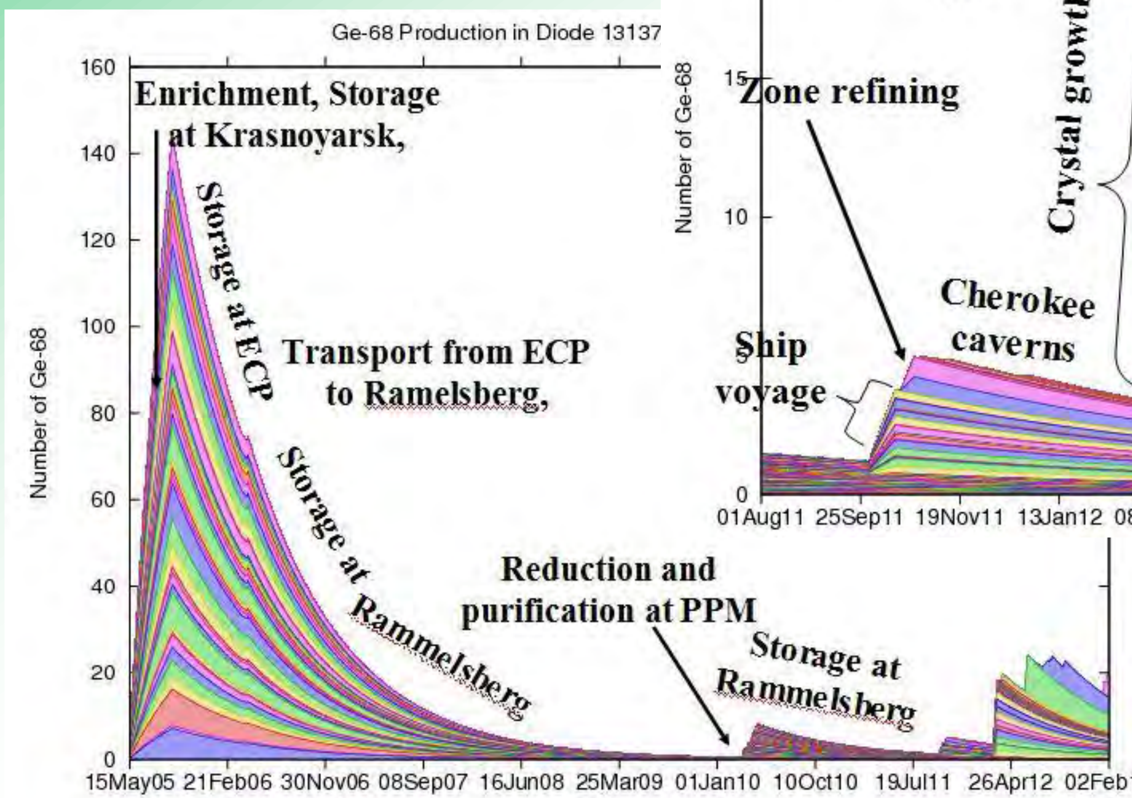
→ 5 working HP^{enr}Ge detectors mounted in GERDA

GERDA phase II plans and status

Monitoring of exposure to cosmic rays: Production history

Saturation actvity in ^{enr}Ge:
~1600 ^{68}Ge kg^{-1},
~10.000 ^{60}Co kg^{-1}

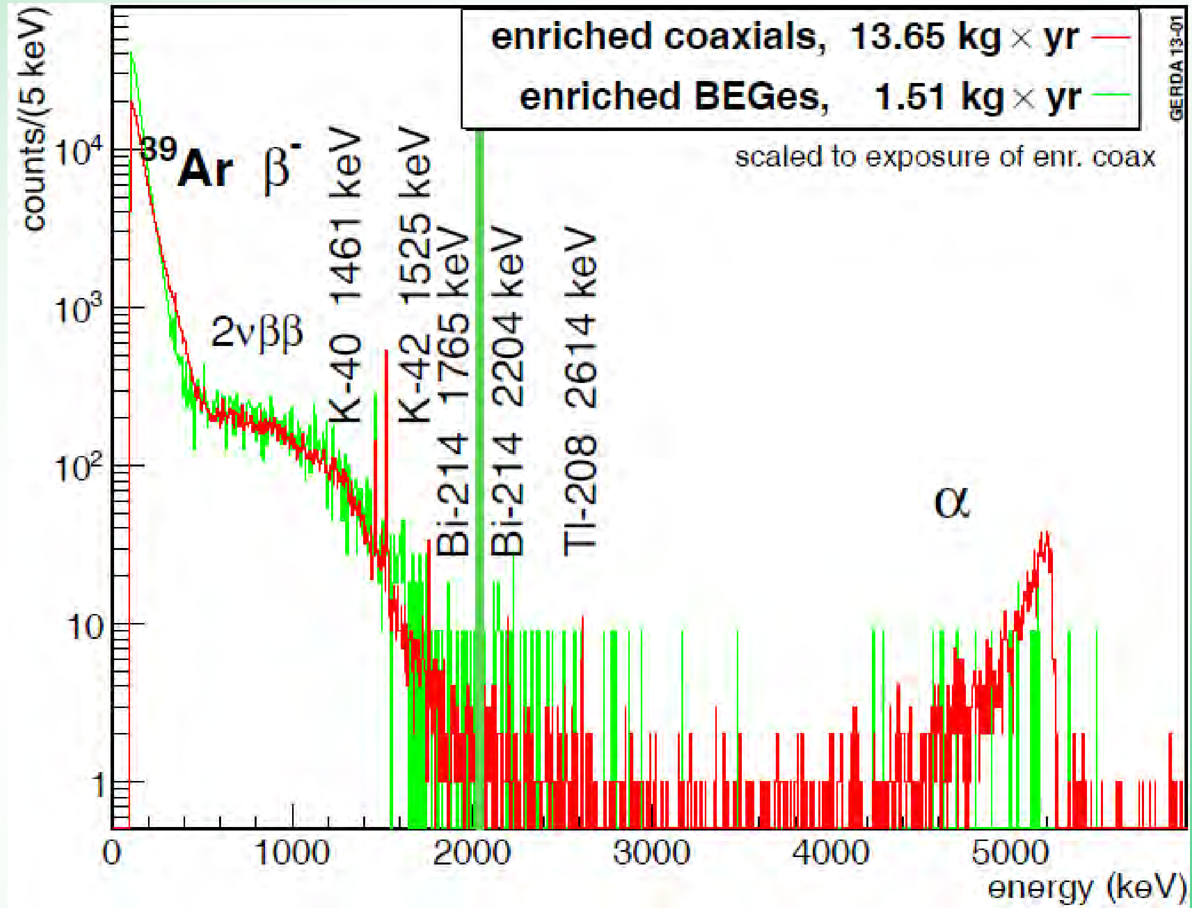




Expected:
^{68}Ge activity: 35.3 kg^{-1}
^{60}Co activity: 26.7 kg^{-1}

GERDA : Status of phase I

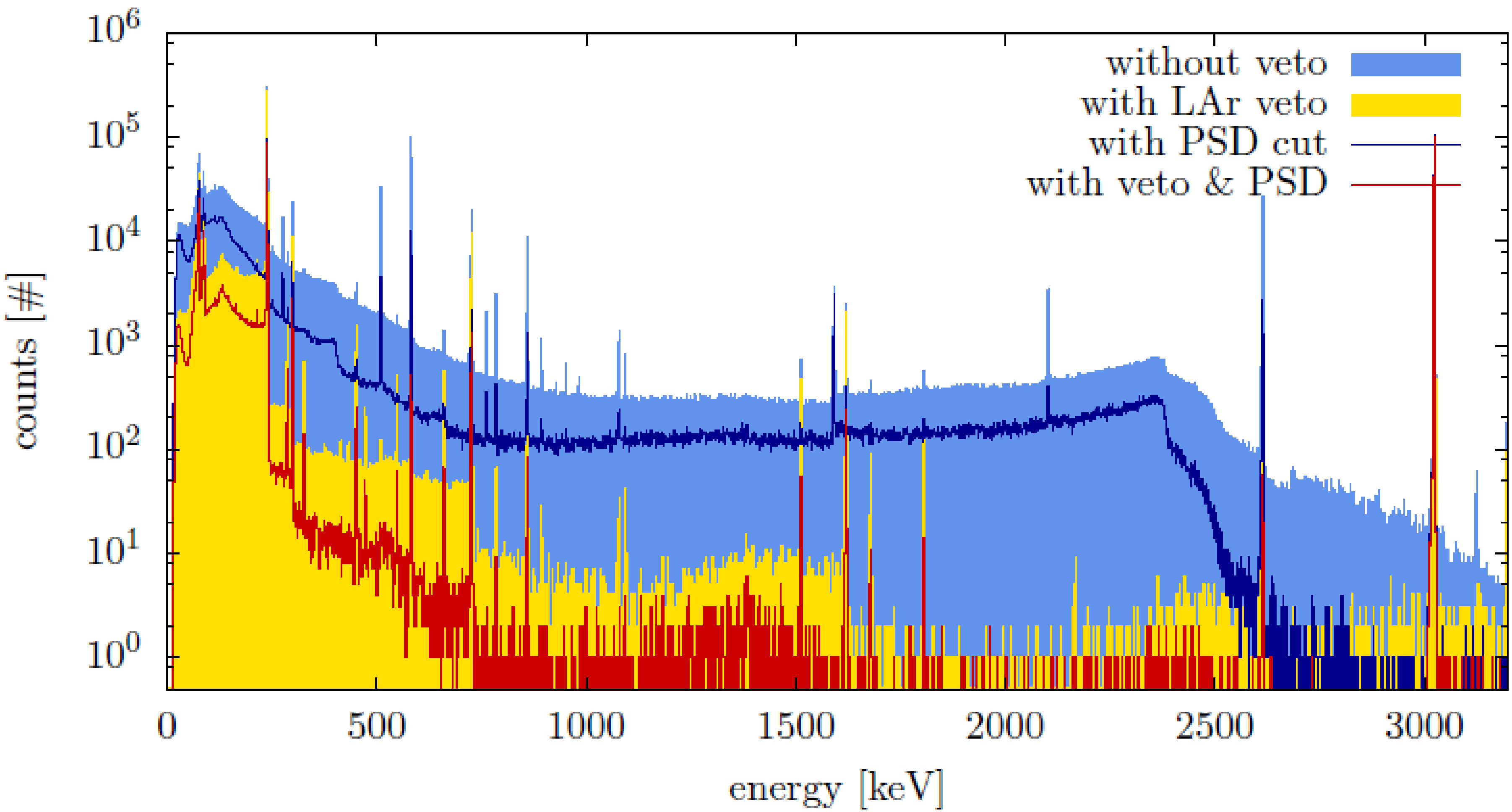
Background of enriched coax and BEGe detectors:



BEGe no PSA: $0.041^{+0.34}_{-0.31}$cts/(kg y keV)

GERDA phase II plans and status

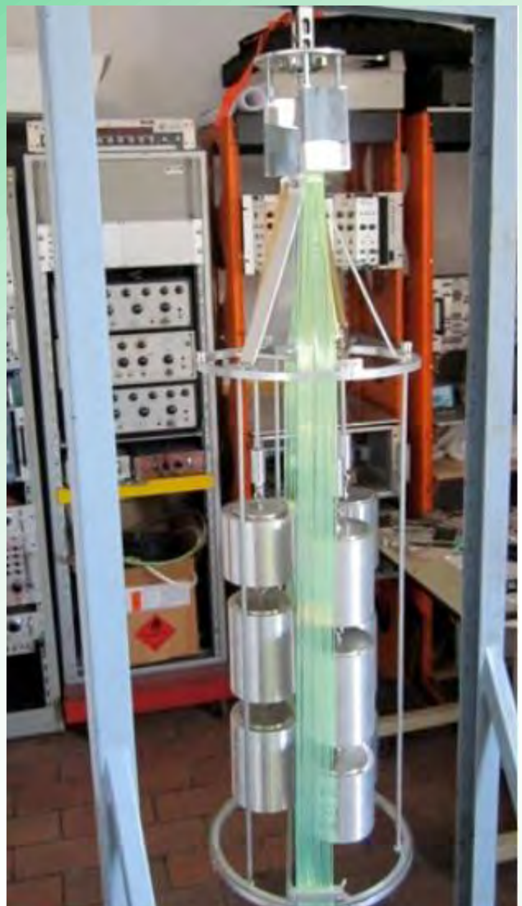
Background rejection by detection of LAr scintillation light



GERDA : Status and plans for phase II

Background rejection by detection of LAr scintillation light

Two solutions (supported by MC with light tracking):

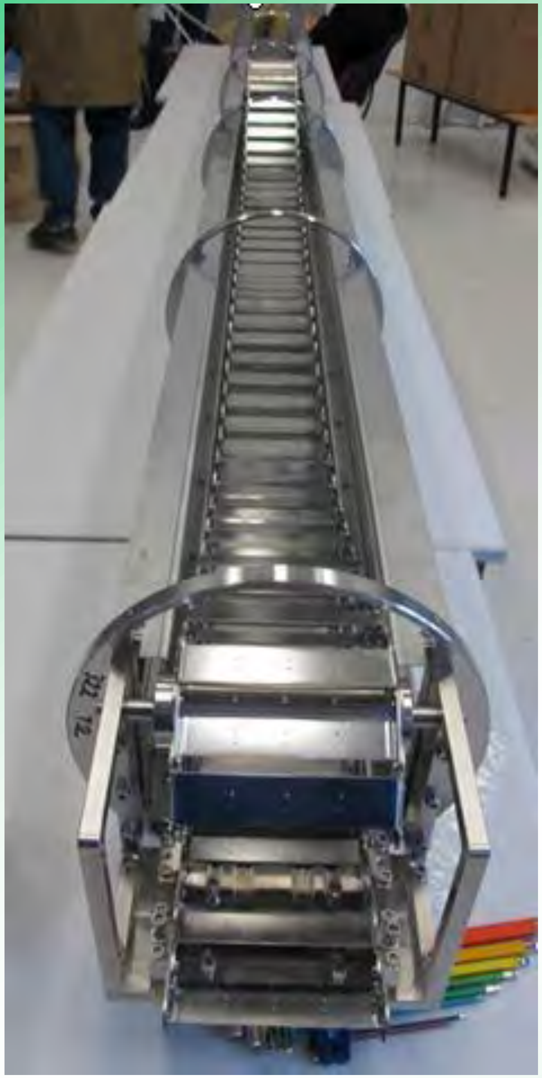


SiPMs connected to fibres

Low background PMTs

simulations show: reduction of background to 0.001 cts/(kg yr kev) realistic

GERDA phase II plans and status

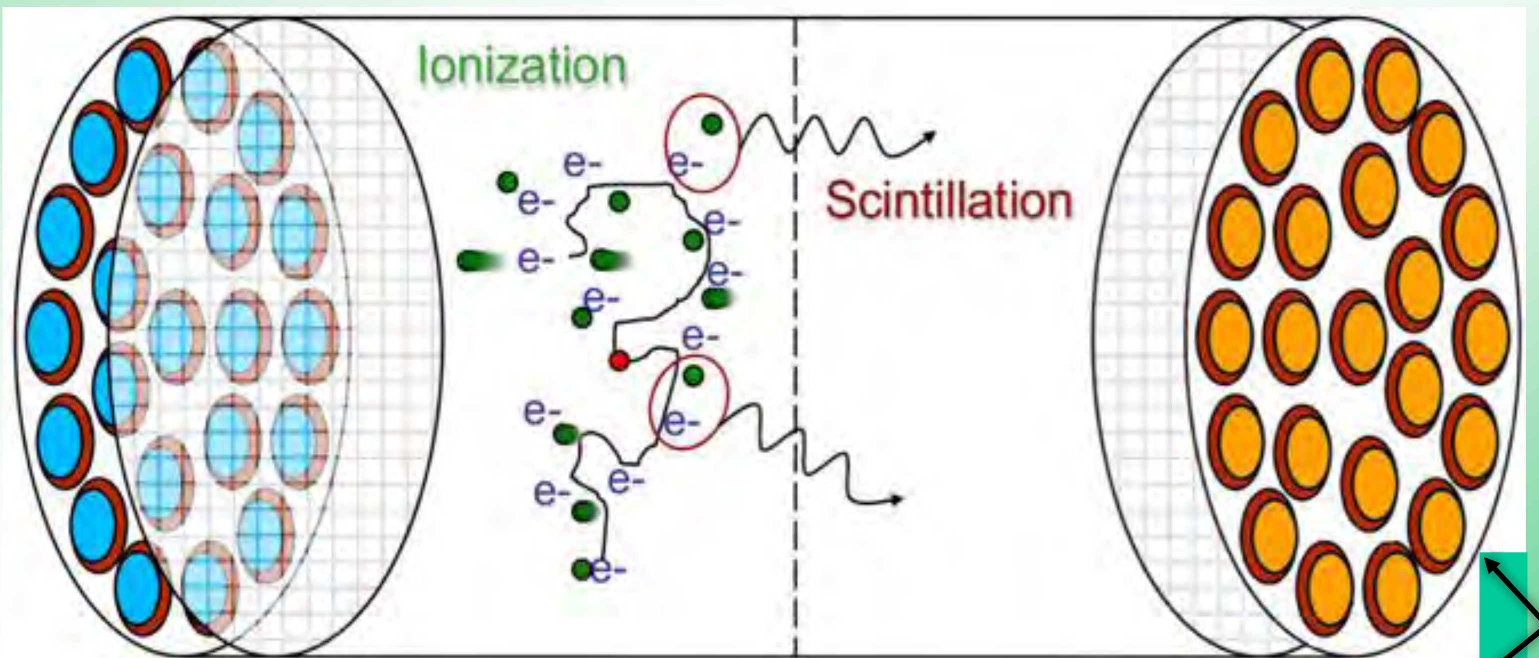


Mounting of new GERDA phase II infrastructure ongoing

Upgrade of GERDA infrastructure planned for summer 2013

XENON experiments: EXO 200

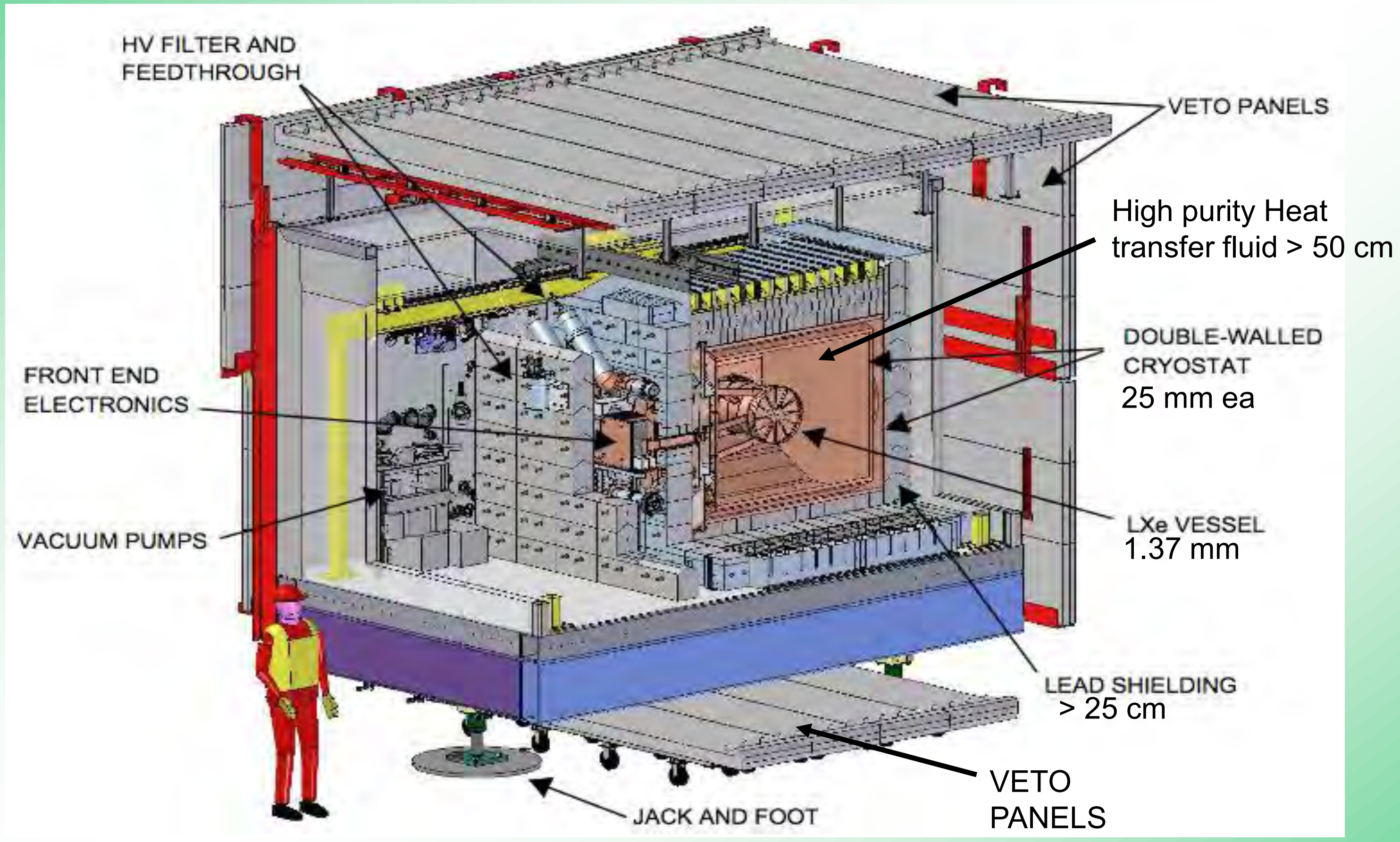
EXO Enriched Xenon Observatory



Avalanche Photo Diodes

XENON experiments: EXO 200

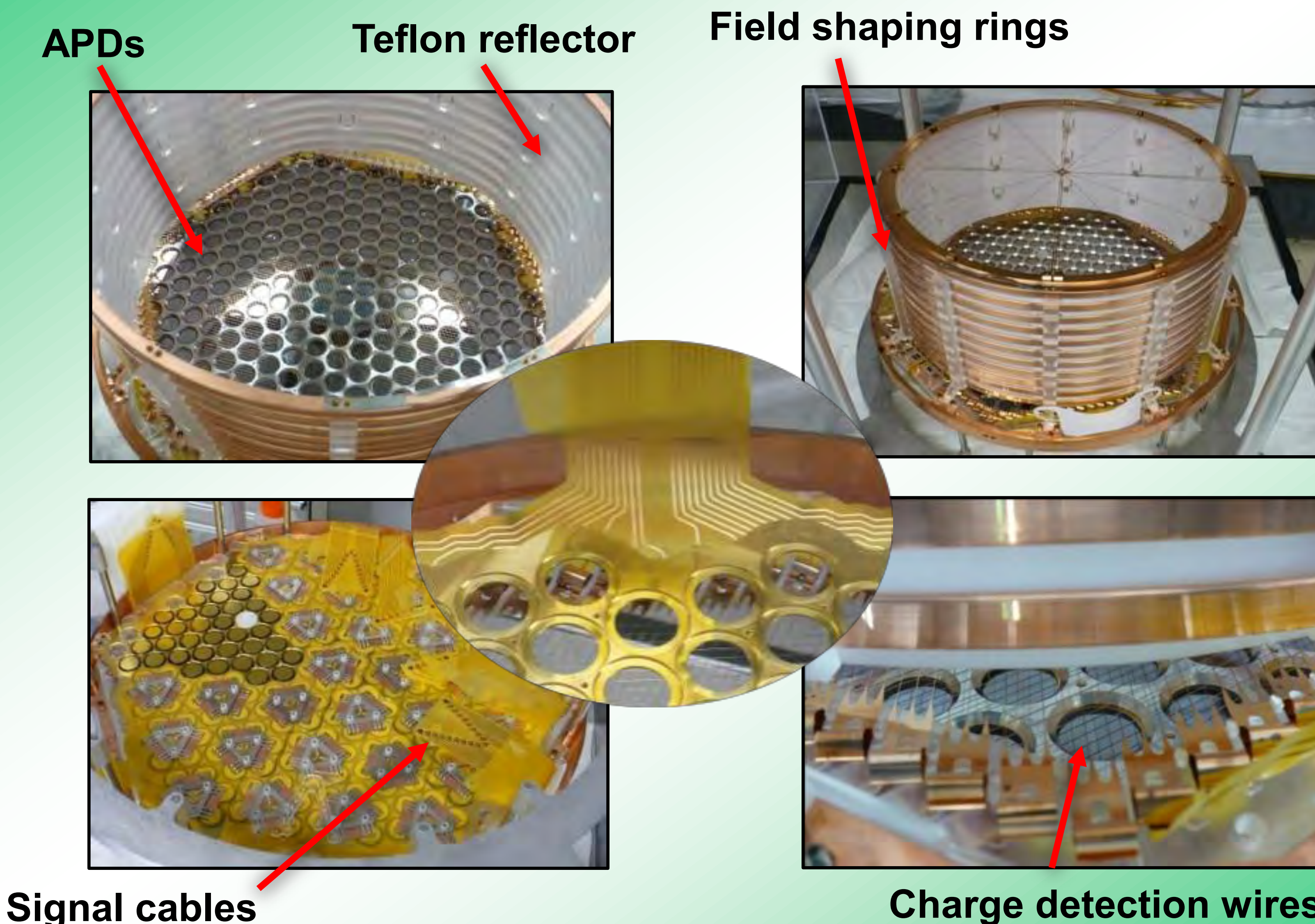
EXO 200 Design



175 kg LXe, 80.6% enr. in ^{136}Xe
Deployed at WIPP ~1600 mwe

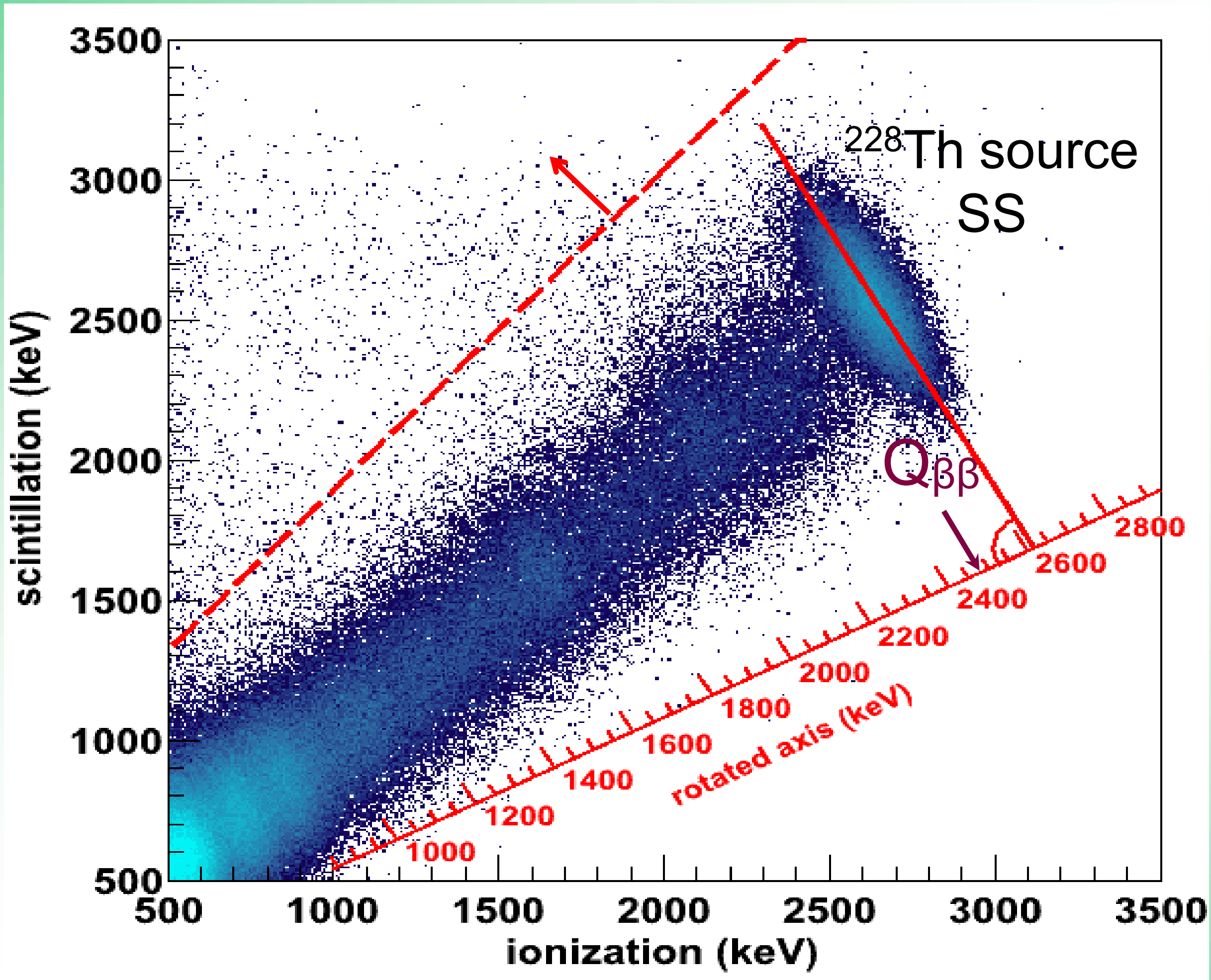
XENON experiments: EXO 200

Details of the TPC



XENON experiments: EXO 200

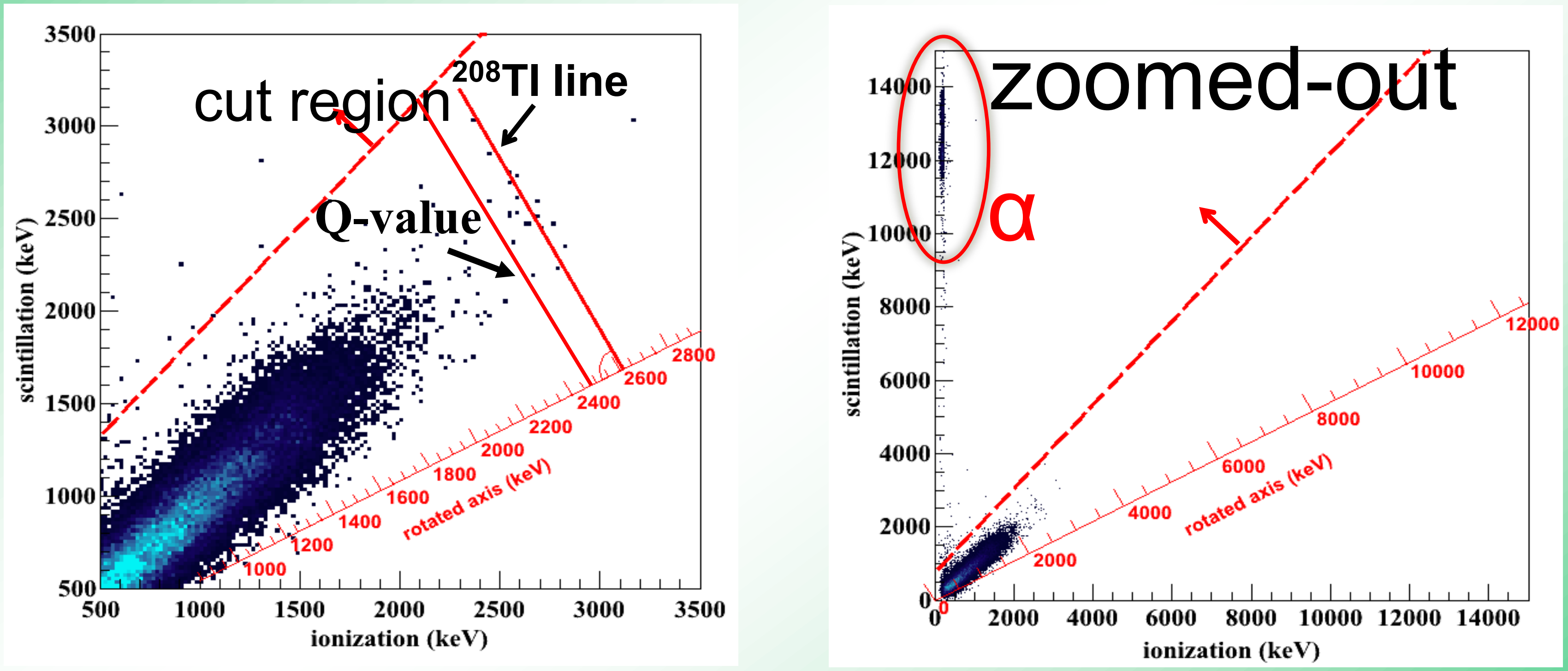
Calibration data



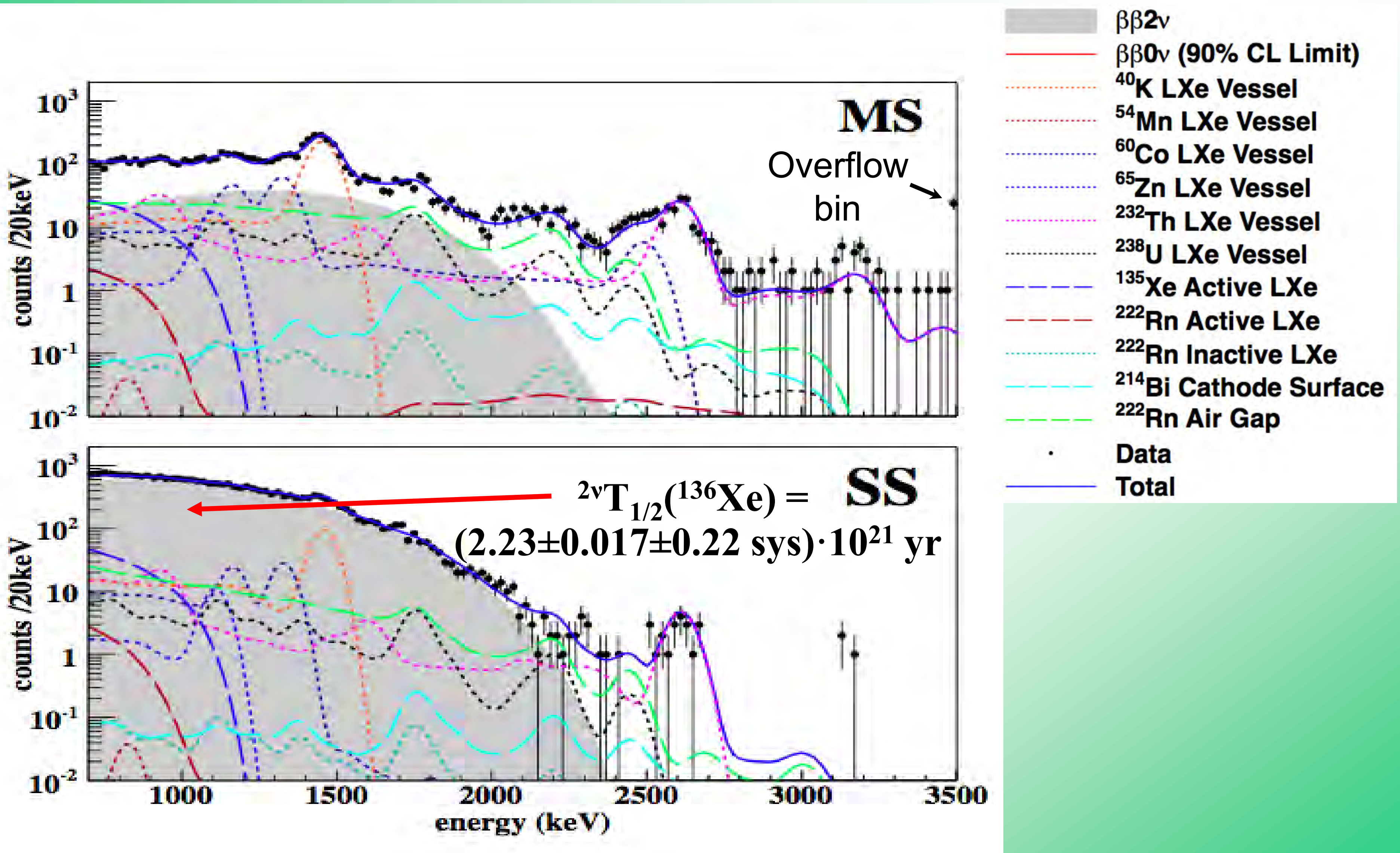
At $Q_{\beta\beta}$ (2458 keV):
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)

XENON experiments: EXO 200

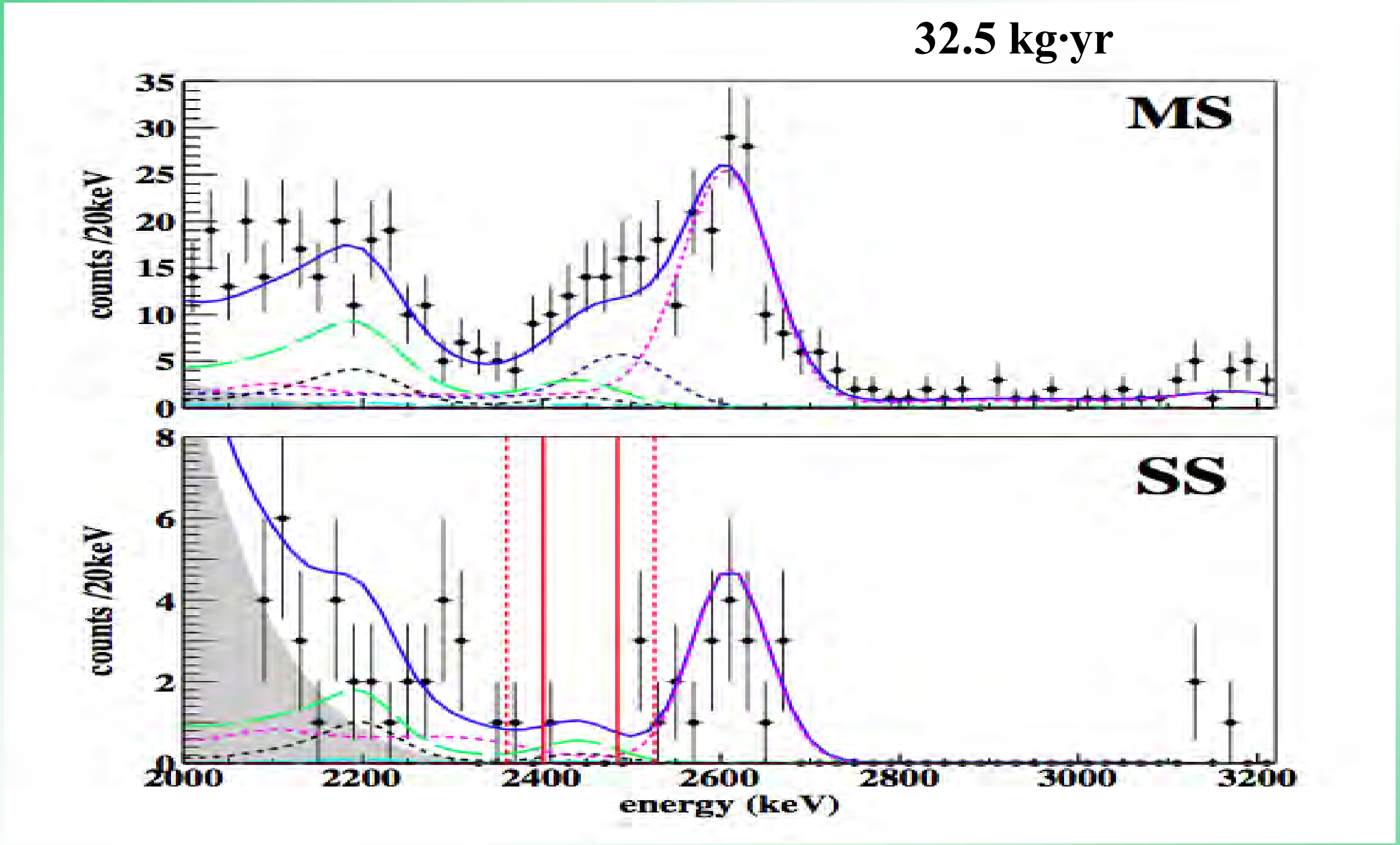
Low background data:



XENON experiments: EXO 200



XENON experiments: EXO 200



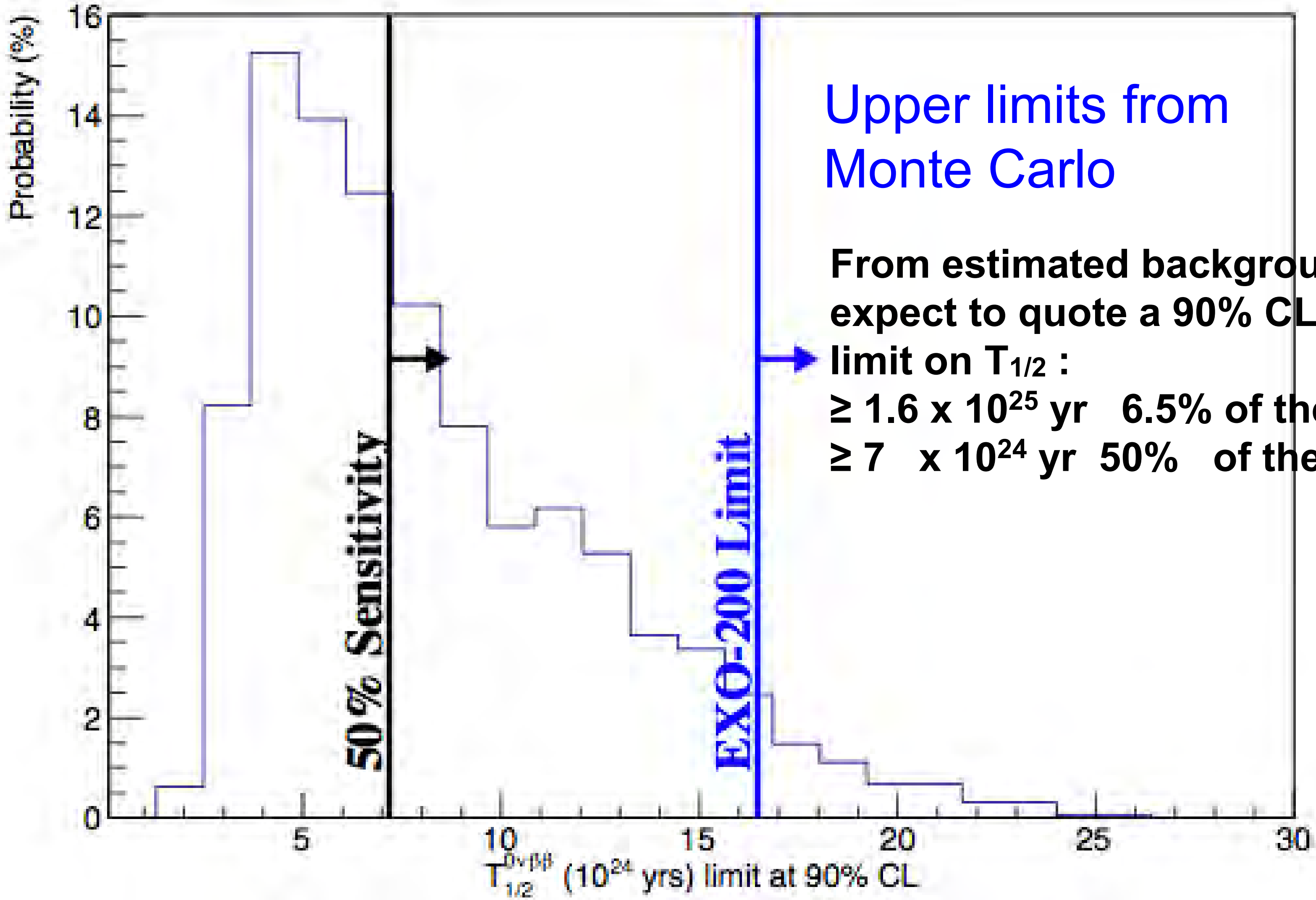
within ±1σ: (4.1±1) expected, 1 observed

within ±2σ: (7.5 ±0.5) expected, 5 observed

Limit on 0νββ-decay of ^{136}Xe: $^{0\nu}T_{1/2} > 1.6 \cdot 10^{25}$ yr

XENON experiments: EXO 200

Distribution of $0\nu\beta\beta$ $T_{1/2}$ 90% CL



Upper limits from Monte Carlo

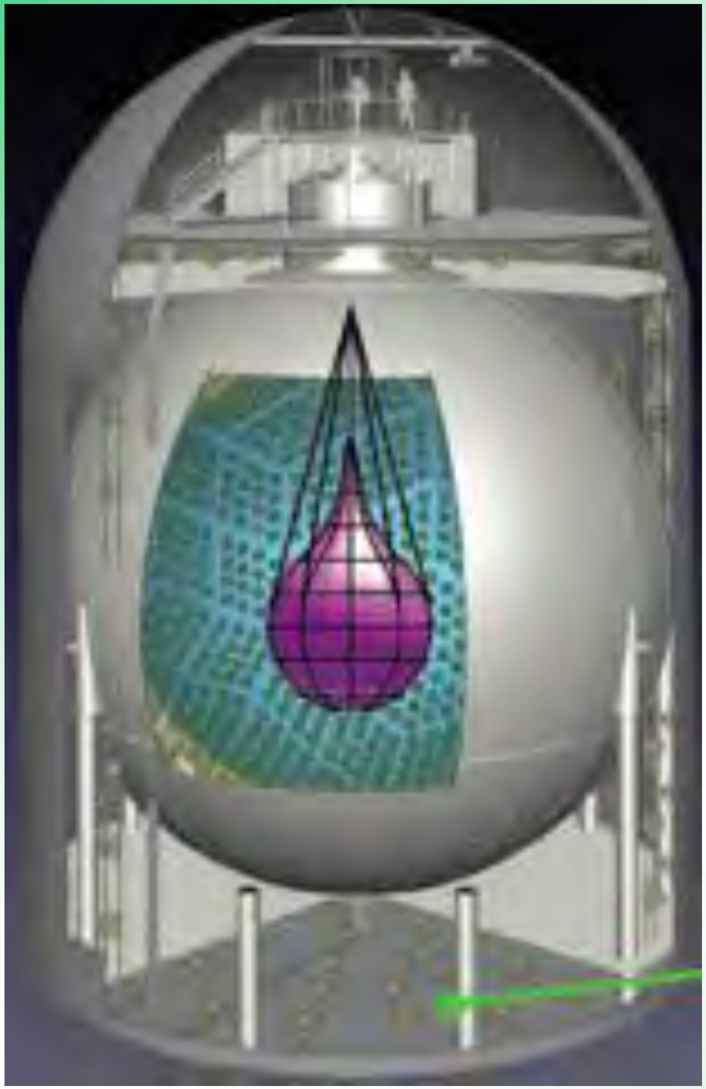
From estimated background, expect to quote a 90% CL upper limit on $T_{1/2}$:

≥ 1.6 x 10^{25} yr 6.5% of the time

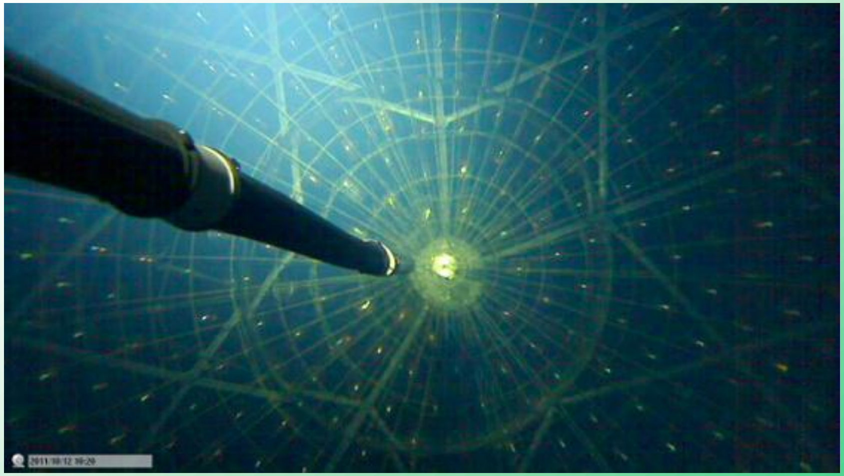
≥ 7 x 10^{24} yr 50% of the time

XENON experiments: KAMLAND ZEN

Use well known LS technology in existing KAMLAND tank:



- Utilizes substantial investment and expertise in KamLAND: 1200 m^3 LS
  ^{238}U: 3.5×10^{-18} g/g ^{232}Th: 5.2×10^{-17} g/g
- 300 kg of 91.7% ^{136}Xe (2.7% by wt. in liquid scintillator), 400 kg in hand.
  ^{238}U: 1.3×10^{-16} g/g ^{232}Th: 1.8×10^{-15} g/g
- σ_E=6.6%/sqrt(E), σ_P=15cm/sqrt(E)
- mini-ballon of R=1.7m, 25 microns thick



XENON experiments: KAMLAND ZEN

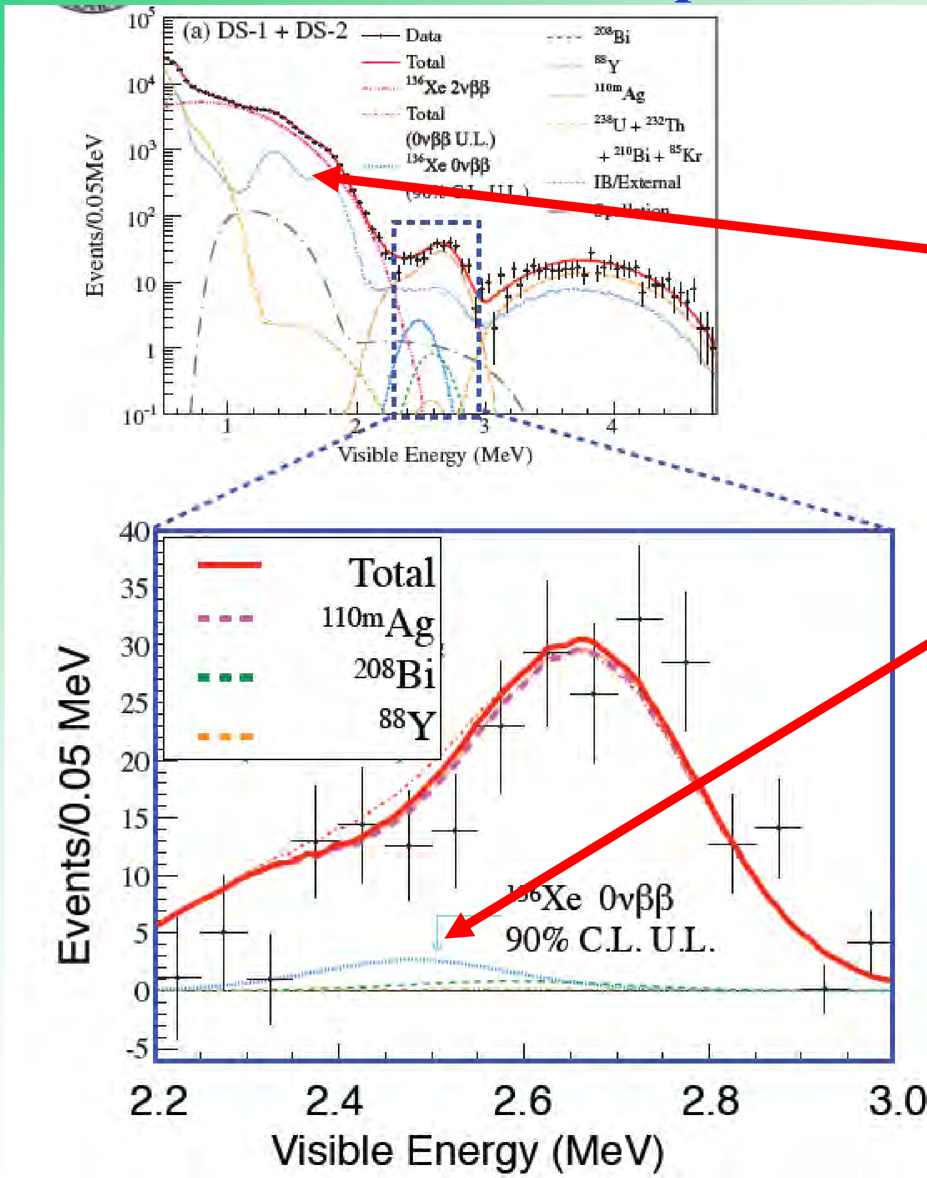
Transparency 99.4% @400nm

Xe barrier < 220 g/year

Spring and summer 2011: Installation of 25 µm Nylon6 foil:

- **Longer term plan upgrade to 700 kg ^{enr}Xe**

XENON experiments: KAMLAND ZEN

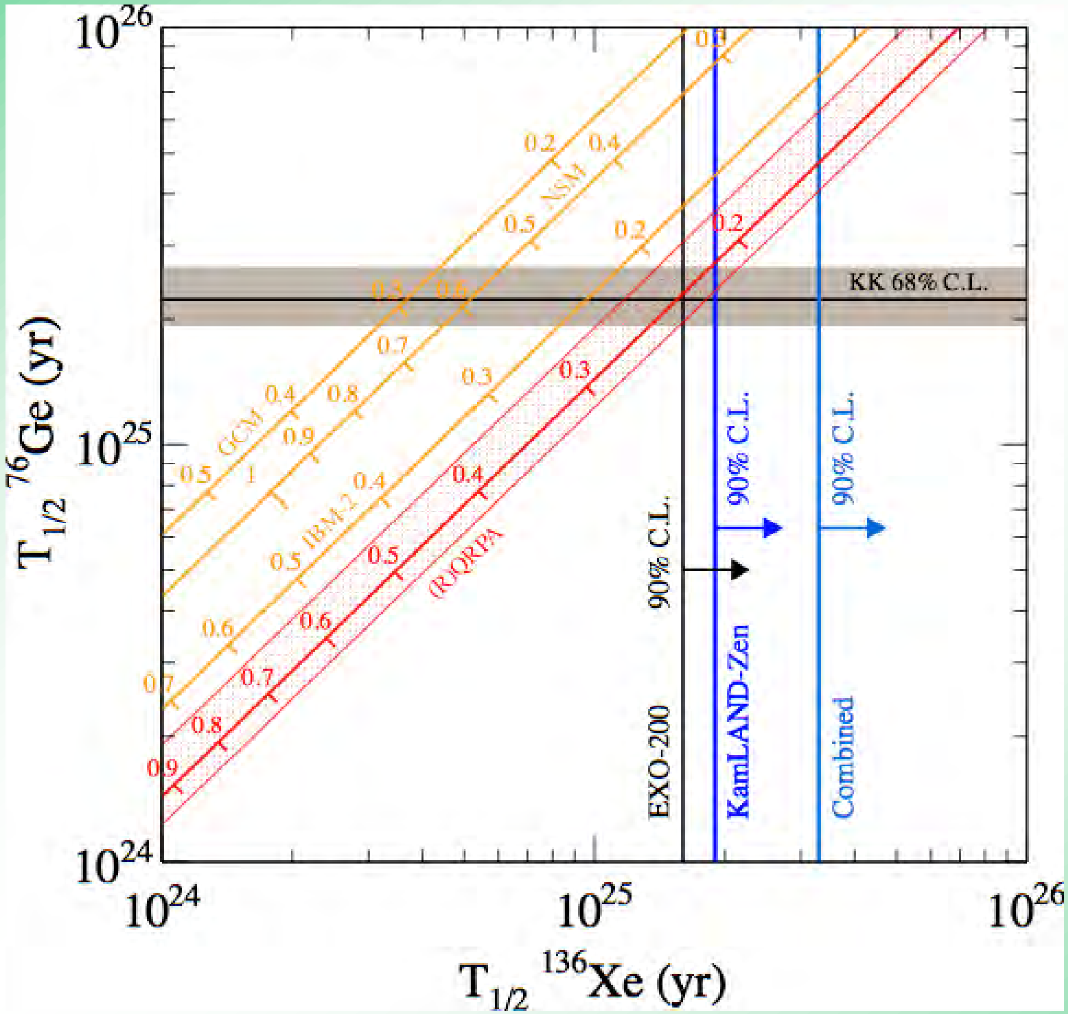


Measurement of 2νββ-decay of ^{136}Xe:
$^{2\nu}T_{1/2}$=(2.30±0.02±0.12)·10^{21} yr

Limit on 0νββ-decay of ^{136}Xe:
$^{2\nu}T_{1/2}$ > 1.9·10^{25} yr

Q-value: (2458.7±0.6) keV

XENON experiments vs. Klapdor



Is Klapdors result excluded?

NMEs? Mechanism? Understanding of background?

Instead of conclusions: what did we learn?

GERDA

- Argon → $^{39}Ar + ^{42}Ar$
- Discharges in gas

→ CEDEX like

→How easy to scale to ton scale?

Majorana:

- Copper/lead shield

→ μ-induced neutrons

→ Need deep enough UGL

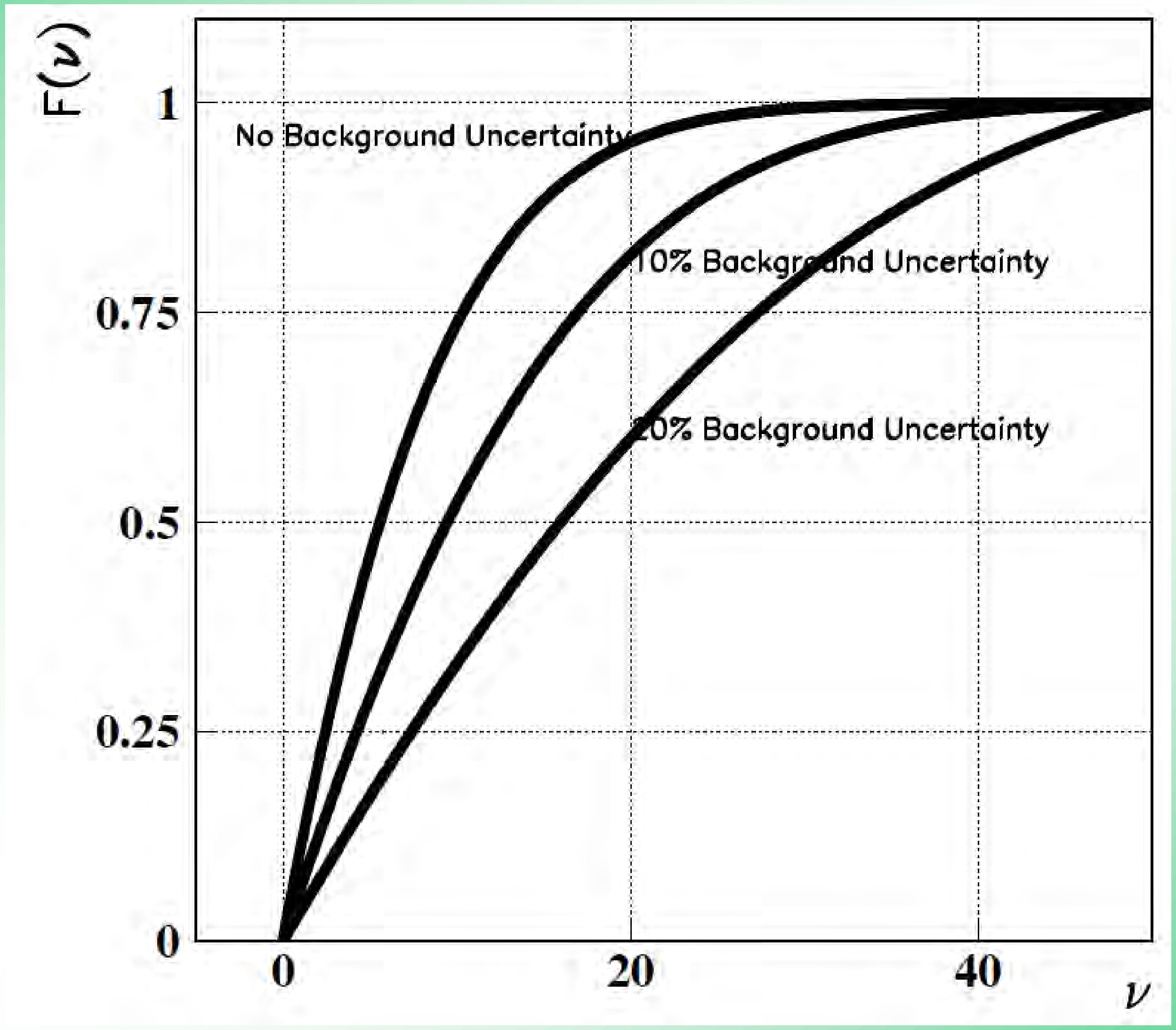
XENON:

- Can be scaled. But what is the max. limit? Systematics?
- Resolution??? Can there ever be a discovery with ^{136}Xe?
- Gas? Liquid? Tagging?

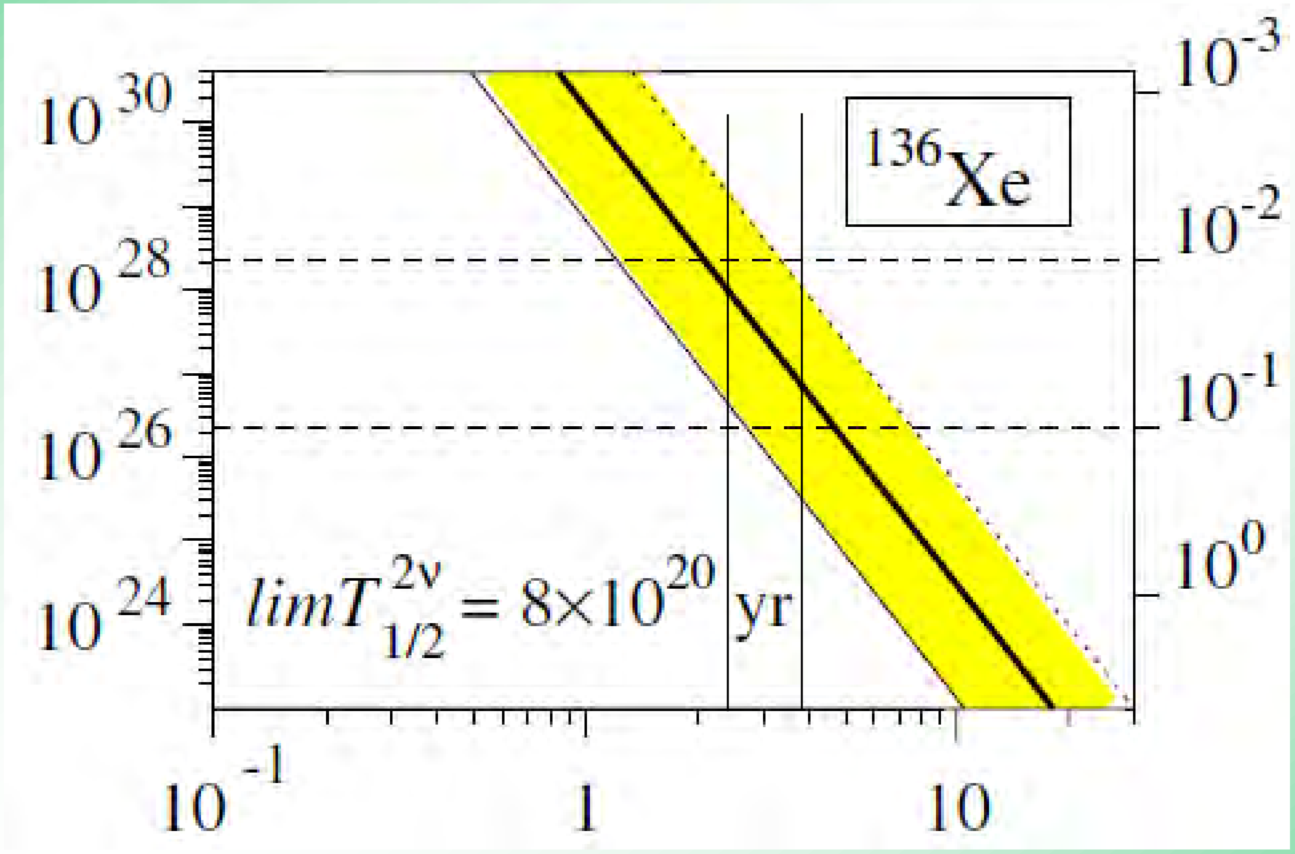
→Why not to combine xenon, germanium, 0νββ and DM?

(DM & ^{76}Ge: 2νββ background...???)

XENON experiments vs. Klapdor



1.6%sigma

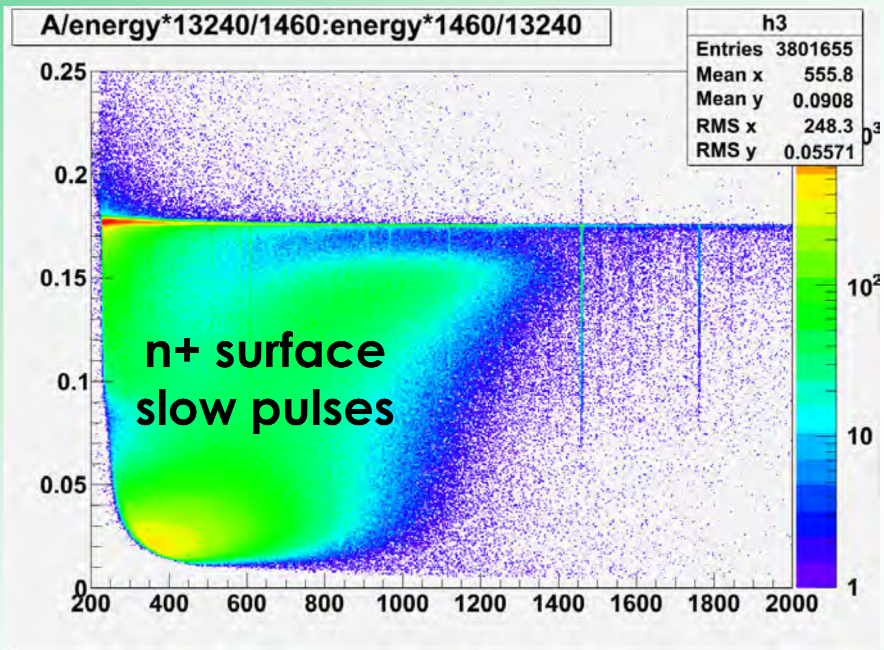

10^{30}
10^{28}
10^{26}
10^{24}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{-1}
1
10
^{136}Xe
$limT^{2\nu}_{1/2} = 8\times10^{20}$ yr

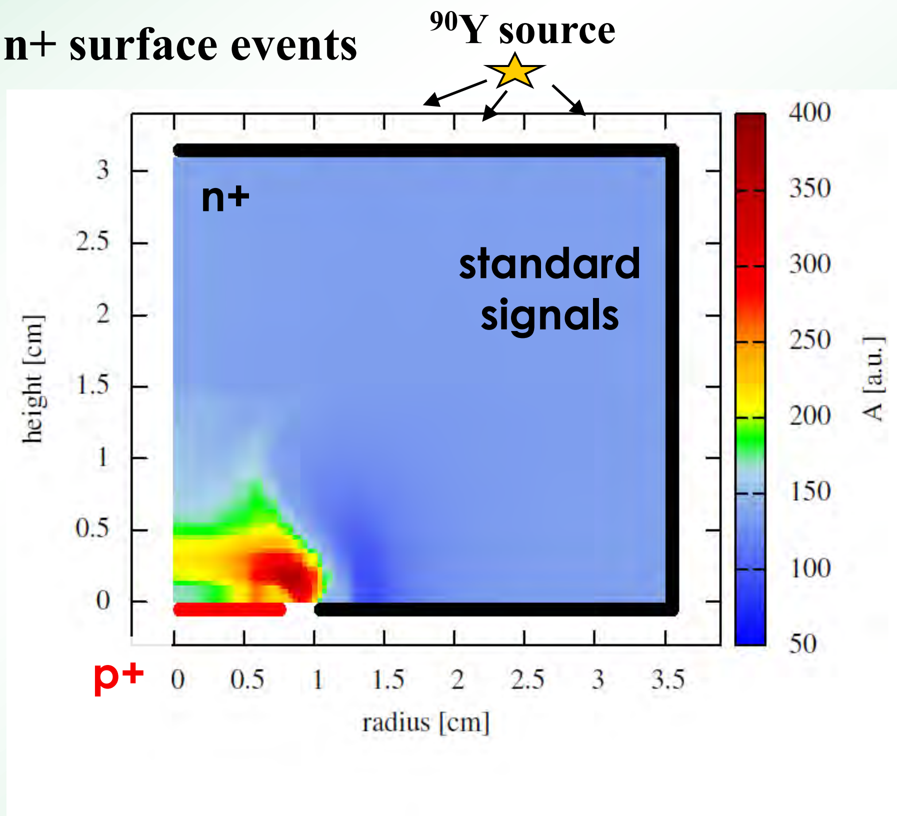
Plans for phase II: new detectors

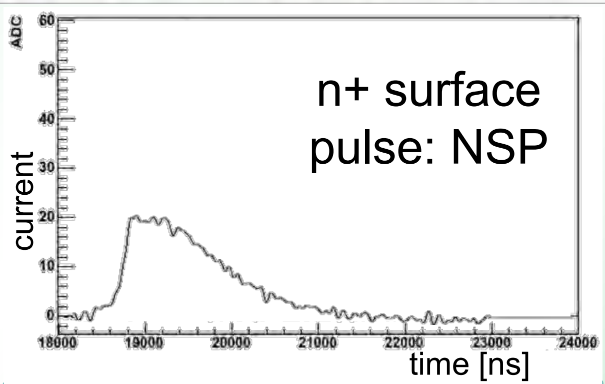
Background recognition powers of BEGes

Identify surface events:

Data taken with ^{90}Y β-source → n+ surface events







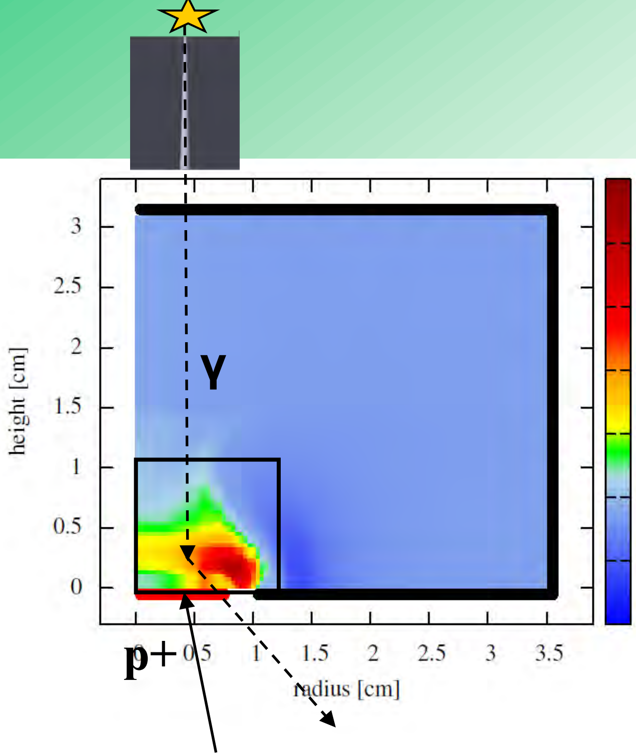
→**Low E-fields in "partially" dead layer**

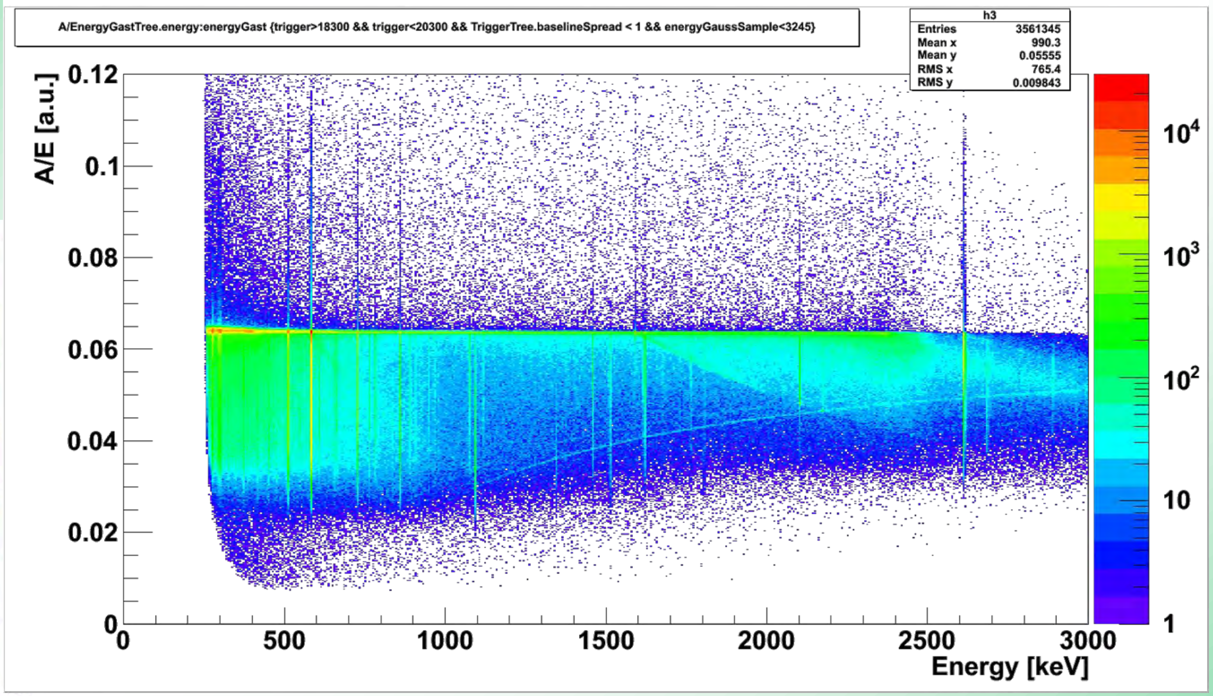
→**Slow pulses**

→**Decrease A/E parameter**

Plans for phase II: new detectors

Background recognition powers of BEGes

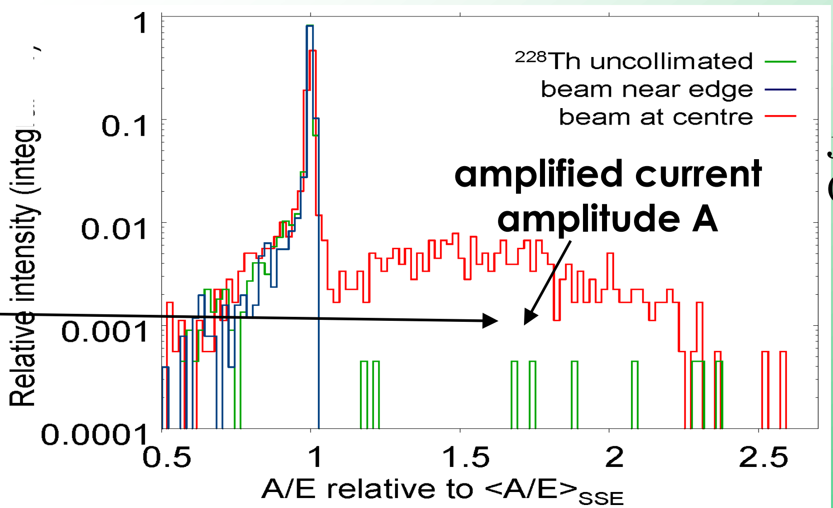




At p+ contact also e^- are "visible"

→ A_{max}/E is increased

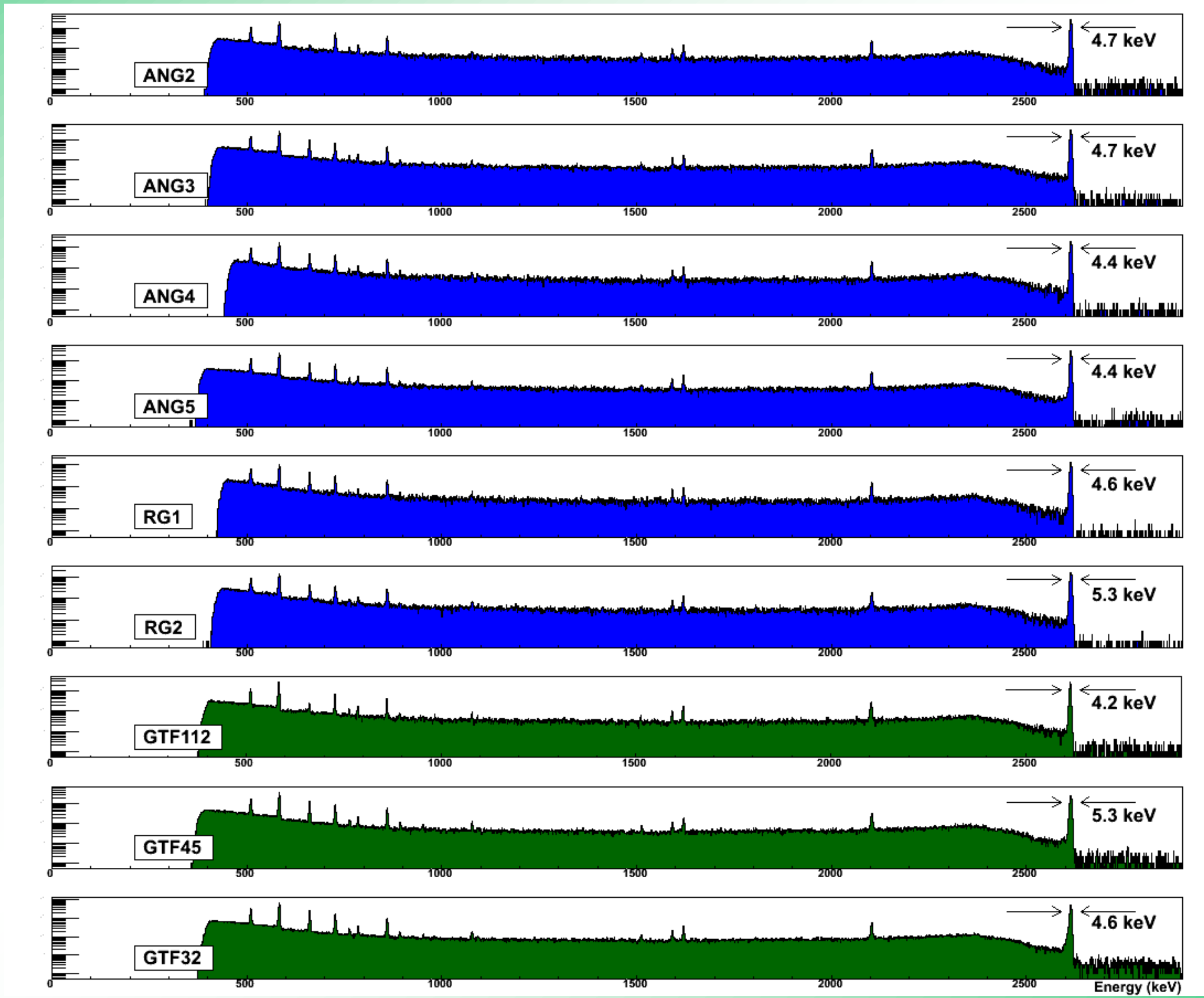
M. Agostini et al., JINST 6 P03005 (2011)



D. Budjas et al., JINST 4 P10007 (2009)

GERDA : Status of phase I

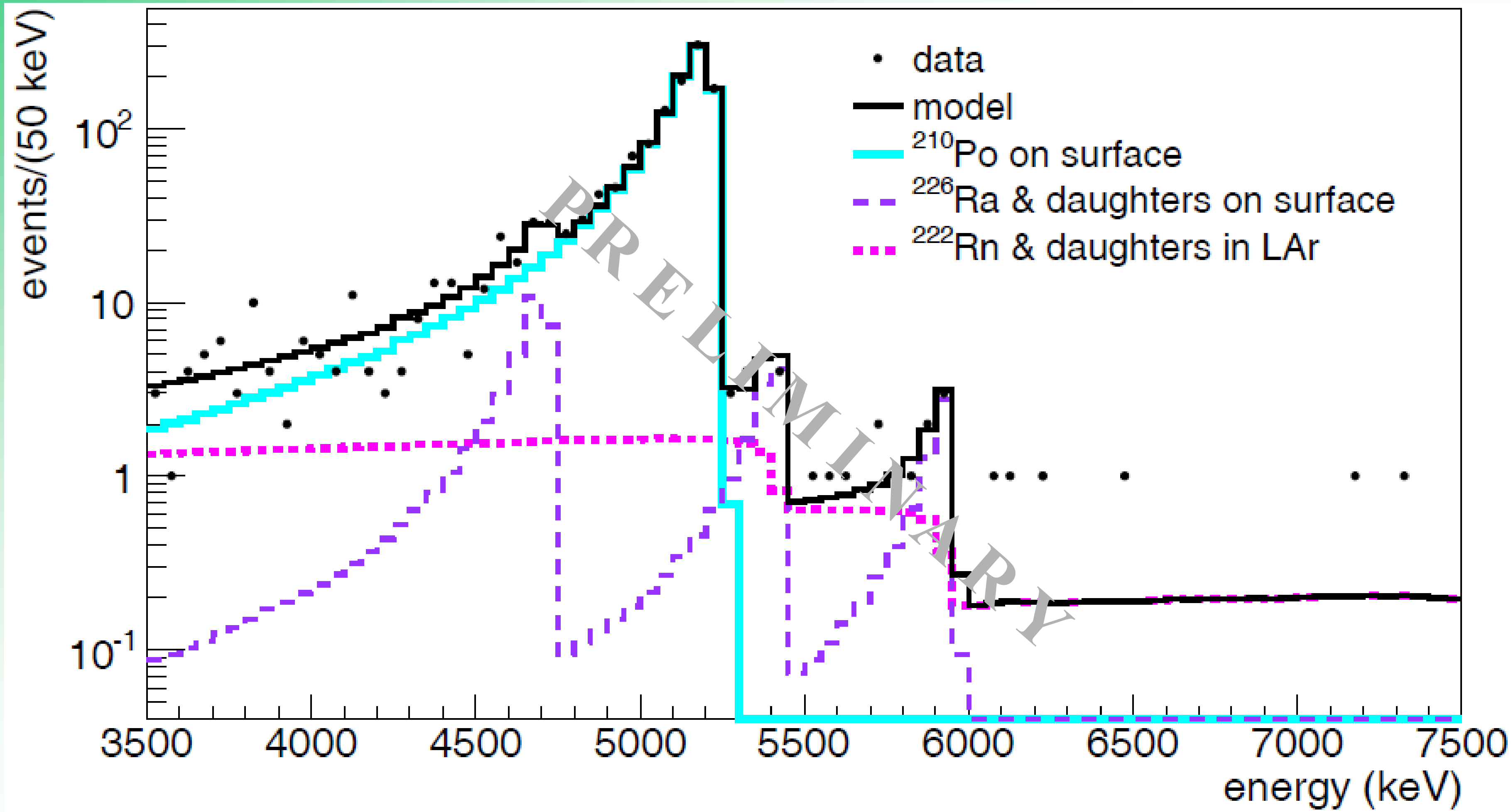
Energy calibration of all detectors:



ANG1 and RG3 are NOT included

GERDA : Status of phase I

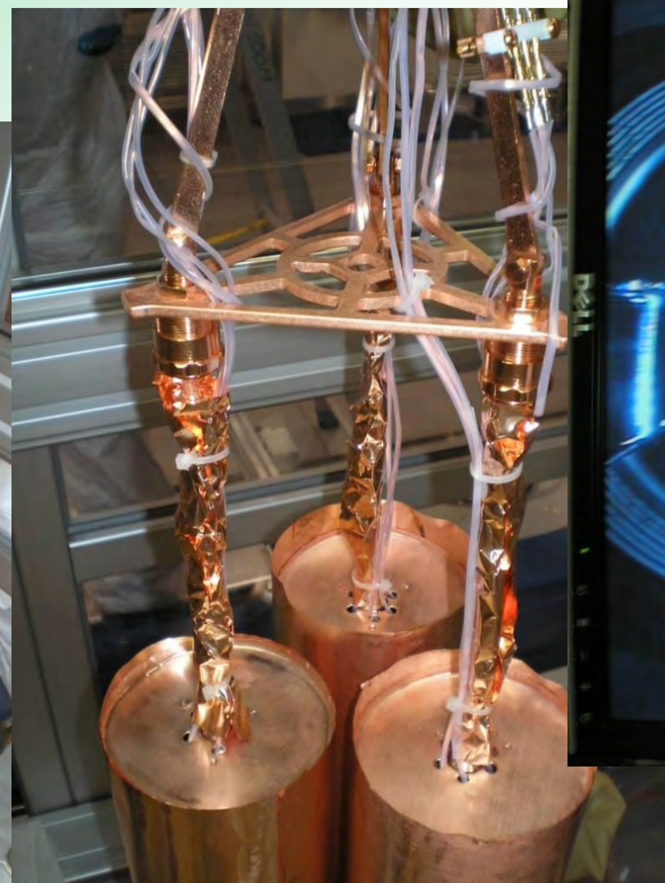
Background decomposition:



α-peaks are crucial for understanding background in RoI (contributions from ^{226}Ra decay chain)

GERDA : Status of phase I

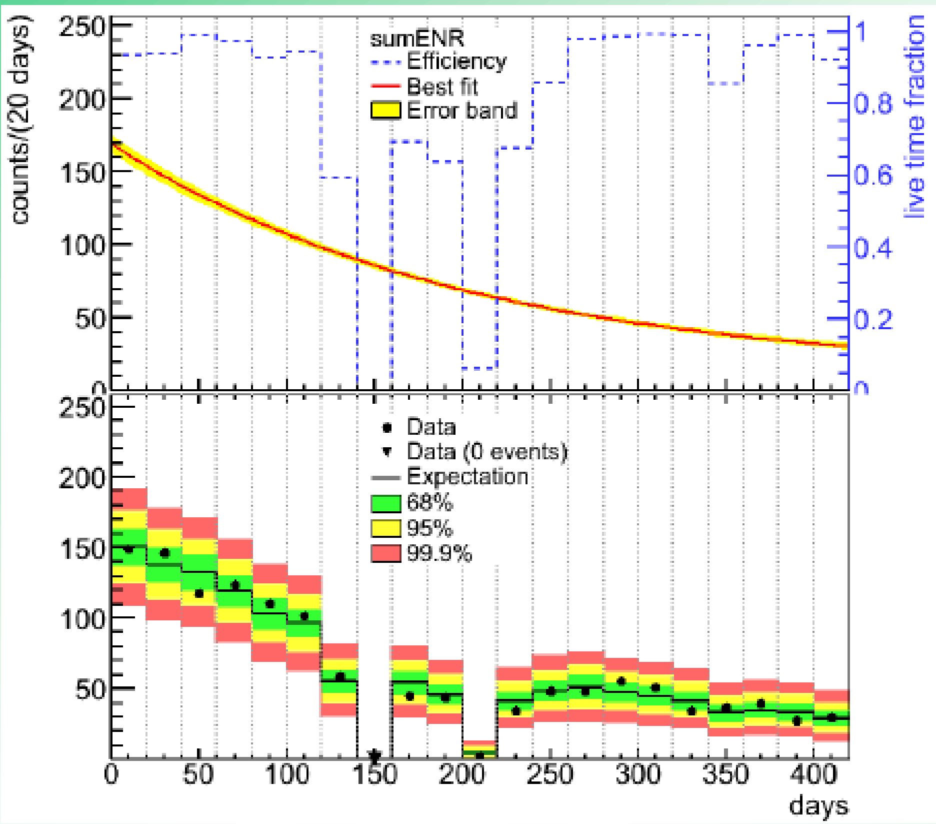
Installation of phase I detectors :

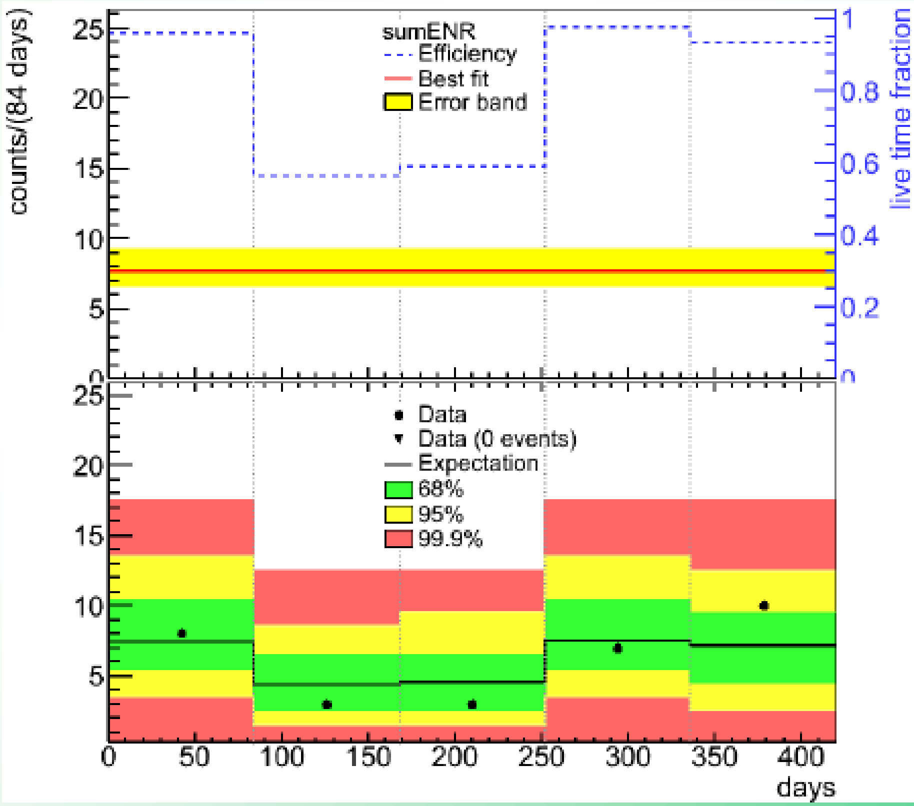


Physics runs started 9th of Nov. 2011. Data in Energy RoI is blinded since 9th of Jan. 2012

GERDA : Status of phase I

Count rate in 5.3 MeV peak and E>5.3 MeV as fct. of time:





→ ^{210}Po contamination of p+ surface ($T_{1/2}$ = 138 days)

→ ^{226}Ra contamination on and close to p+ surface

GERDA : Status of phase I

Comparison of backgrounds lines in HdMo and GERDA experiments

isotope	energy [keV]	^{nat}Ge (3.17 kg yr)		^{enr}Ge (6.10 kg yr)		HDM (71.7 kg yr)
		tot/bck [cts]	rate [cts/(kg yr)]	tot/bck [cts]	rate [cts/(kg yr)]	rate [cts/(kg yr)]
^{40}K	1460.8	85/15	$21.7^{+3.4}_{-3.0}$	125/42	$13.5^{+2.2}_{-2.1}$	181 ± 2
^{60}Co	1173.2	43/38	<5.8	182/152	$4.8^{+2.8}_{-2.8}$	55 ± 1
	1332.3	31/33	<3.8	93/101	<3.1	51 ± 1
^{137}Cs	661.6	46/62	<3.2	335/348	<5.9	282 ± 2
^{228}Ac	910.8	54/38	$5.1^{+2.8}_{-2.9}$	294/303	<5.8	29.8 ± 1.6
	968.9	64/42	$6.9^{+3.2}_{-3.2}$	247/230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1
^{208}Tl	583.2	56/51	<6.5	333/327	<7.6	36 ± 3
	2614.5	9/2	$2.1^{+1.1}_{-1.1}$	10/0	$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5
^{214}Pb	352	740/630	$34.1^{+12.4}_{-11.0}$	1770/1688	$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8
^{214}Bi	609.3	99/51	$15.1^{+3.9}_{-3.9}$	351/311	$6.8^{+3.7}_{-4.1}$	105 ± 1
	1120.3	71/44	$8.4^{+3.5}_{-3.3}$	194/186	<6.1	26.9 ± 1.2
	1764.5	23/5	$5.4^{+1.9}_{-1.5}$	24/1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7
	2204.2	5/2	$0.8^{+0.8}_{-0.7}$	6/3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5

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