Neutrino-less double beta decay experiments

Part II

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Table 3 Selection of $0\nu\beta\beta$ experiments.

experiment	isotope	mass [kg]	method	start / end	ref.
		past experiments			
Heidelberg-Moscow	^{76}Ge	11	ionization	-2003	[6]
Cuoricino	^{130}Te	11	bolometer	-2008	[40]
NEMO-3	^{100}Mo, ^{82}Se	7,1	track. +calorim.	-2011	[41]
		current experiments			
EXO-200	^{136}Xe	175	liquid TPC	2011-	[2]
Kamland-Zen	^{136}Xe	330	liquid scintil.	2011-	[3]
GERDA-I/ GERDA-II	^{76}Ge	15/35	ionization	2011-/ 2013-	[45]
CANDLES	^{48}Ca	0.35	scint. crystal	2011-	[46]
		funded experiments			
NEXT	^{136}Xe	100	gas TPC	2015	[47]
Cuore0/ Cuore	^{130}Te	10/200	bolometer	2012- 2015-	[48]
Majorana Demo.	^{76}Ge	30	ionization	2013	[49]
SuperNEMO demo./total	^{82}Se	7/100	track.+calorin	2014- /??	[50]
SNO+	^{150}Nd	44	liquid scint.	2013	[51]
		proposal, proto-typing			
Cobra	^{116}Cd		solid TPC		[52]
Lucifer	^{82}Se		bolom. +scint.		[53]
DCBA/MTD	^{150}Nd	32	tracking		[54]
MOON	^{82}Se, ^{100}Mo	30-480	track. +scint.		[55]
AMoRE	^{100}Mo	100	bolom. +scint.		[56]
Cd exp.	^{116}Cd		scint.		[57]

B. Schwingenheuer, Annalen der Physik, August 22, 2012

Plan for 2nd lecture

- Overview of experiments and R&D projects
- Discussion of
  - Nemo3/SuperNEMO
  - KamLAND-Zen
  - EXO
  - GERDA
  - Cuoricino/Cuore
  - Scintillating bolometers: Lucifer
- Outlook

Next generation experiments

Calorimeters

- **Ge diodes** — ε, ΔE, PID — ^{76}Ge → GERDA, Majorana
- **Bolometers** — ε, ΔE, (PID) — ^{130}Te, ^{82}Se, ^{100}Mo → Cuore, Lucifer, ZnMo4
- **Liquid Xe** — M, PID — ^{136}Xe → EXO
- **Scintillators** — M — ^{136}Xe, ^{150}Nd, ^{48}Ca, ^{100}Mo → KamLAND-zen, SNO+, Borexino, AMoRE

Electron tracking

- Tracko-calo Isotopes — ^{82}Se, (^{150}Nd, ^{48}Ca) → SuperNEMO
- Pixelized CdZnTe — ^{116}Cd → COBRA
- Gas TPC — ^{136}Xe → NEXT, EXO-gas

Next generation experiments

Calorimeters

Ge diodes
ε, ΔE, PID
^{76}Ge
→ GERDA, Majorana

Bolometers
ε, ΔE, (PID)
^{130}Te, ^{82}Se, ^{100}Mo
→ Cuore, Lucifer, ZnMo4

Liquid Xe
M, PID
^{136}Xe
→ EXO

Scintillators
M
^{136}Xe, ^{150}Nd, ^{48}Ca, ^{100}Mo
→ KamLAND-zen, SNO+, Borexino, AMoRE

Electron tracking

Tracko-calo
Isotopes
^{82}Se, (^{150}Nd, ^{48}Ca)
→ SuperNEMO

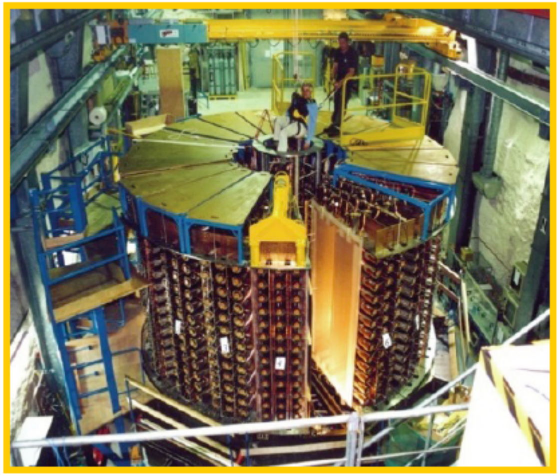
Pixelized CdZnTe
^{116}Cd
→ COBRA

Gas TPC
^{136}Xe
→ NEXT, EXO-gas

Experiments started operations in 2011

Adopted from F. Piquemal

NEMO 3



Tracking detector: drift chambers (6180 Geiger cells)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm (vertex)
Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification e^-, e^+, γ, α
Very high efficiency for background rejection

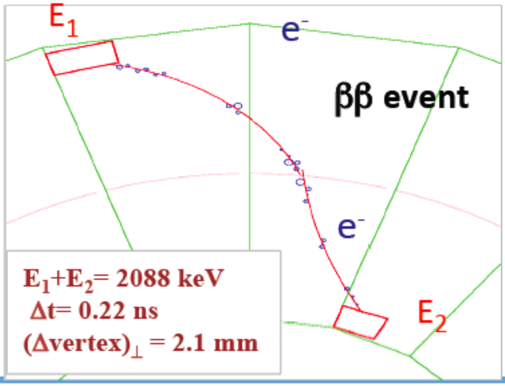
Background level @ $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : 1.2 10^{-3} cts/keV/kg/y

Multi-isotope (7 measured at the same time)

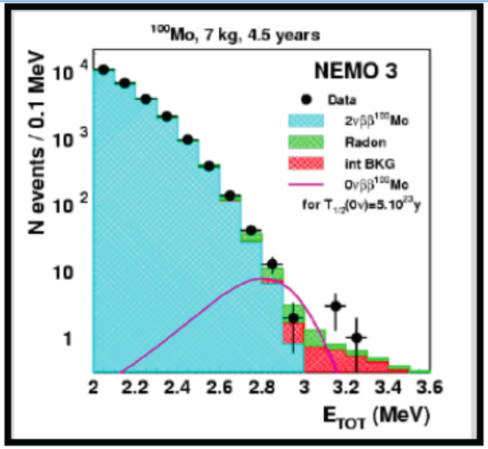
Running at Modane underground laboratory (2003 - 2011)

Unique feature

Measurement of all kinematic parameters: individual energies and angular distribution



Measurement of 7 isotopes $\beta\beta(2\nu)$ half-lifes
Excited states, Majoron limits for $\beta\beta(0\nu)$



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

^{100}Mo $T_{1/2}$ $(\beta\beta 0\nu) > 1.0\ 10^{24}$ y (90% C.L.)
$\langle m_\nu \rangle < 0.31 – 0.79$ eV

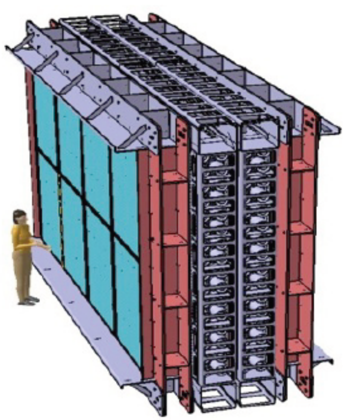
From F. Piquemal, Neutrino 2012

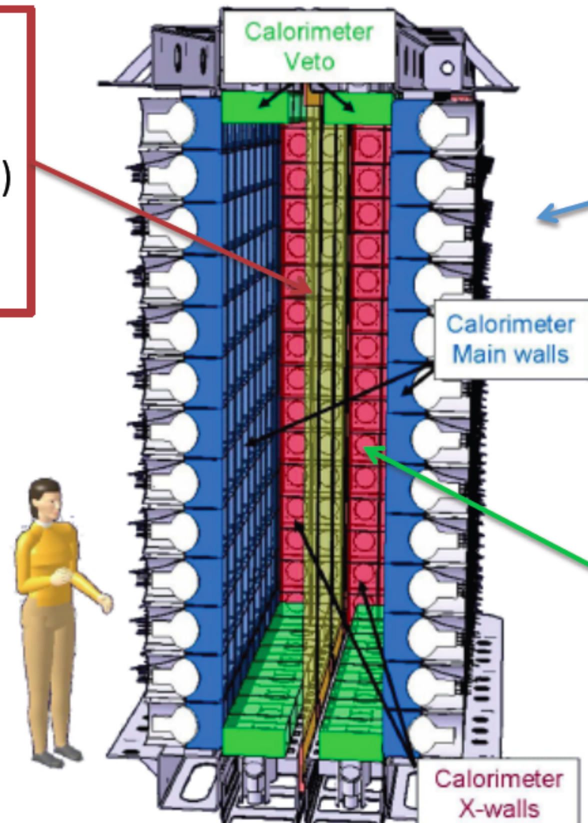
SuperNEMO Demonstrator

Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of ^{82}Se in 2 yr

Source

^{214}Bi < 10 μBq/kg
(NEMO3 100 μBq/kg)
208Tl < 2 μBq/kg
(NEMO3 100 μBq/k)





Calorimeter

ΔE/E < 4% @ 3 MeV
(NEMO3 8.6% at 3MeV)

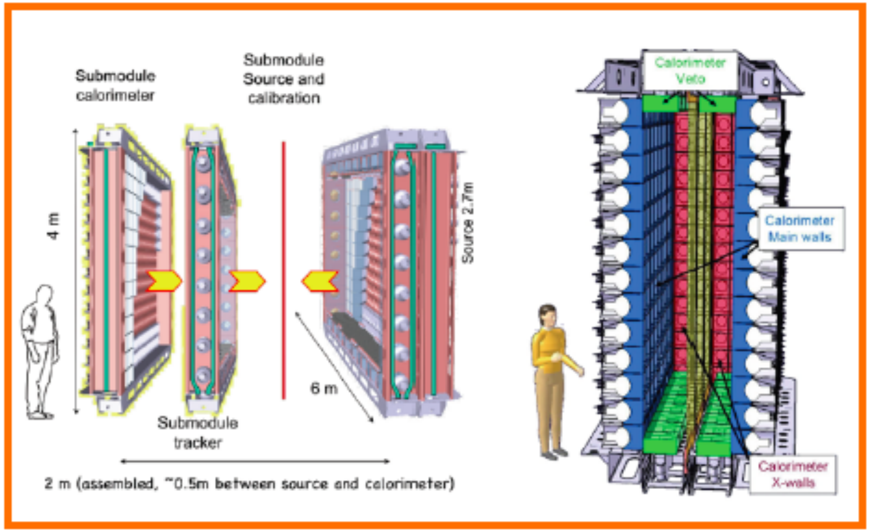
Tracker

3.7 m long (NEMO3 2.7 m)
σ_t = 5 mm, σ_z = 1 cm
Radon < 0.15 mBq/m^3
(NEMO3 5 mBq/m^3)
Wiring robot

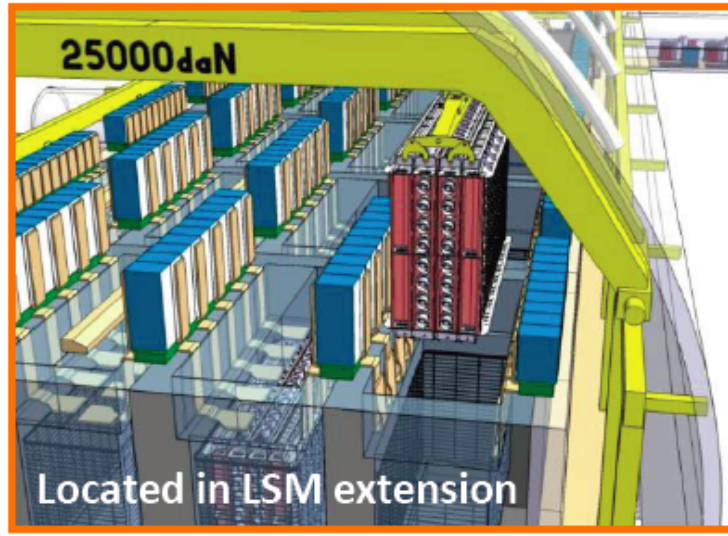
Global efficiency : 30 % (NEMO3 8%)

SuperNEMO

A module



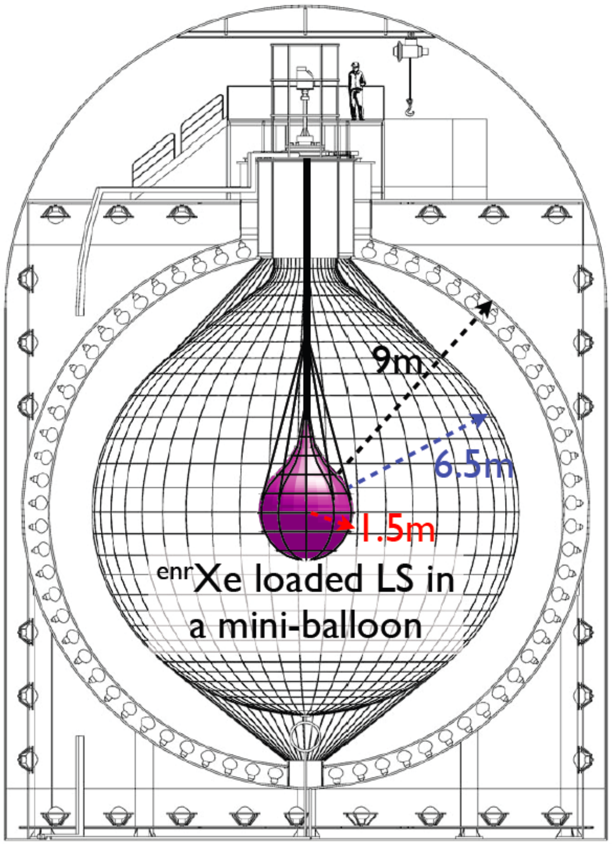
20 modules



	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$<m_\nu>$ sensitivity	200 – 400 meV	40 – 100 meV

KamLAND-Zen

Zero Neutrino
double beta decay search



idea to load Xe into LS is from Raju PRL72,1411(1994)

~320kg 90% enriched ^{136}Xe installed so far
total 600+ kg in the mine
production reaches 700kg in this year

From K. Inoue, Neutrino 2012

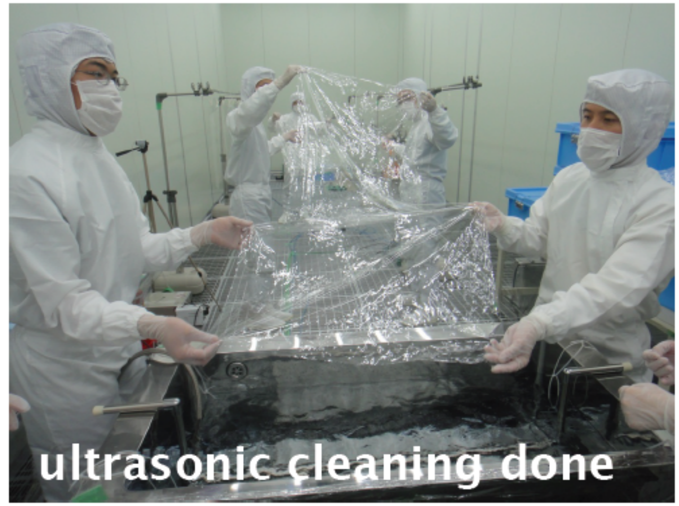
mini balloon fabrication

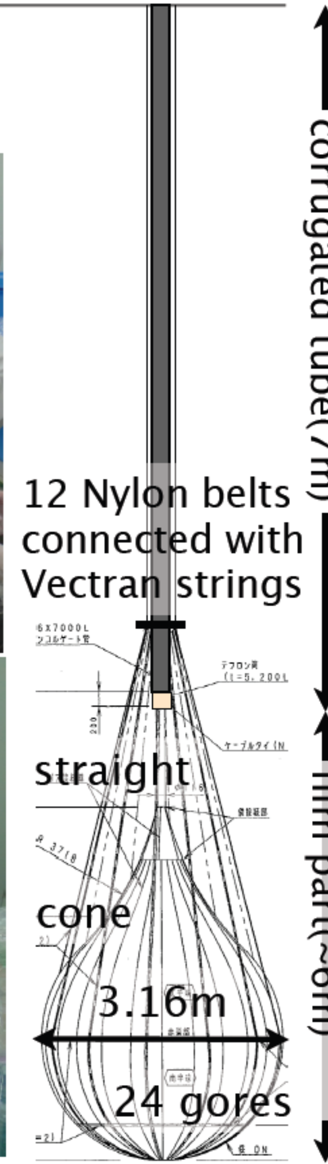
- produced in a class 1 super-clean-room
  (class 1 = less than 1 0.5-micron-particle in cubic feet)

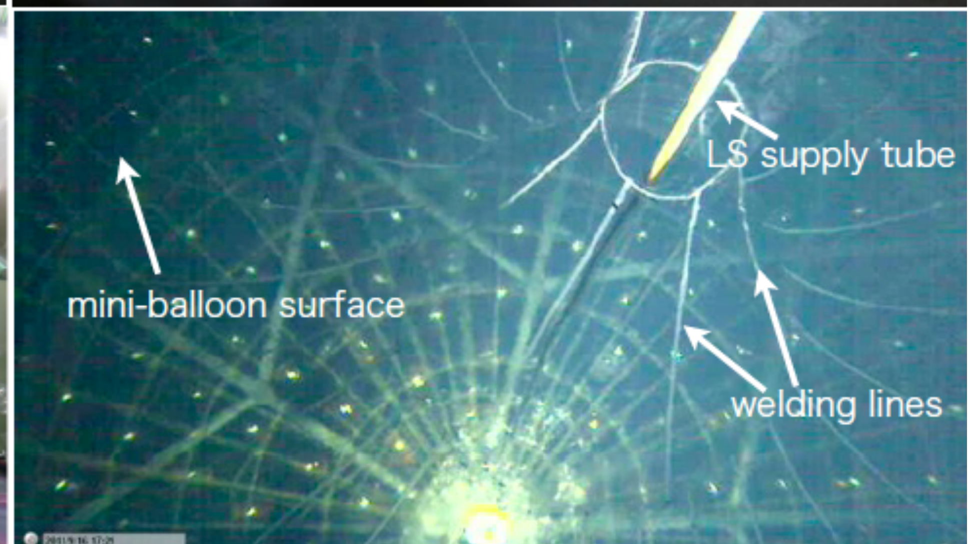
less material → 25 μm Nylon6
  transparency 99.4% @400nm
  strength 19.4 N/cm
  Xe barrier < 220 g/year

low radioactivity
  → specially made no filler film

U	:	150	→	2×10^{-12} g/g
Th	:	59	→	3×10^{-12} g/g
^{40}K	:	140	→	2×10^{-12} g/g

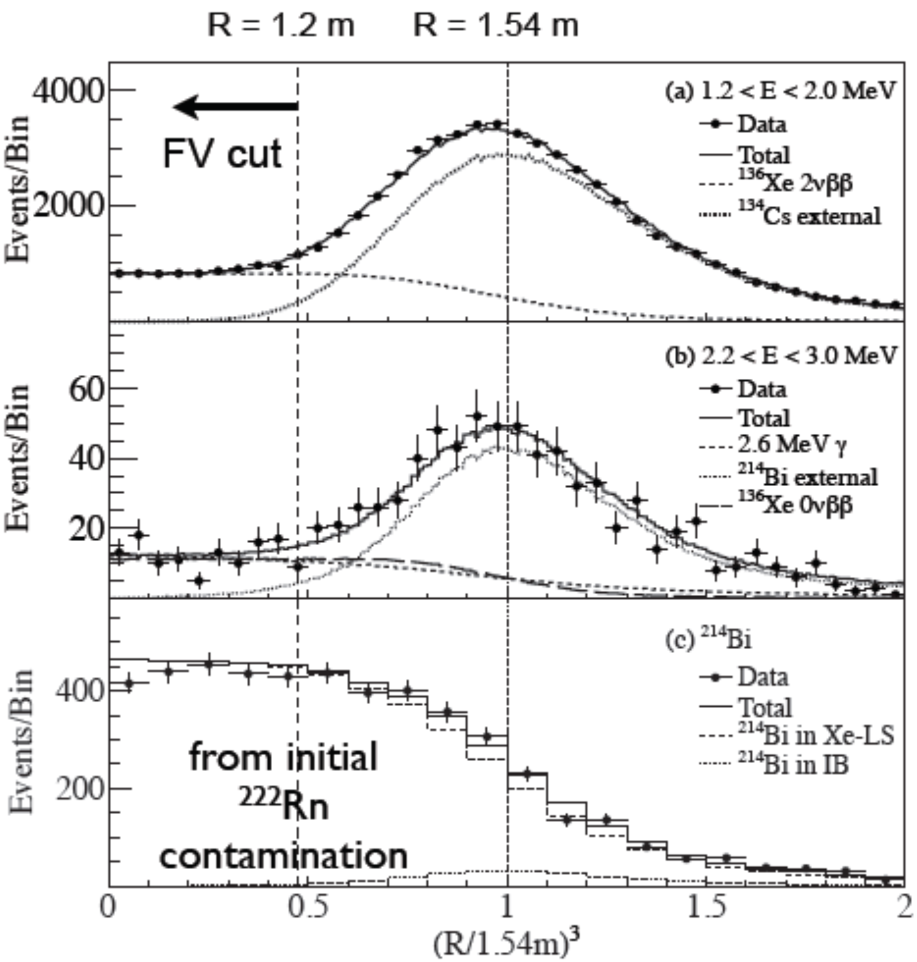






mini-balloon inflated with dummy LS and then replaced with Xe-loaded LS
density tuning finished and tubes to be extracted

R^3 vertex distribution



vertex resolution from balloon events

$\sim 15\text{cm}/\sqrt{E}$

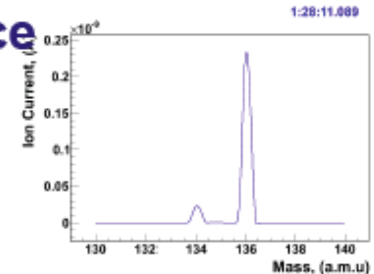
Fiducial volume of Xe-LS

R < 1.2 m V = 7.24 m^3

Xe isotopic abundance

^{136}Xe : 90.93%,

^{134}Xe : 8.89%



Xe amount by weight measurement

(supplied)-(returned)

- Xe concentration = (2.44 ± 0.01) wt%

consistent direct gas chromatography analysis

- Xe concentration = (2.52 ± 0.07) wt%

Uncertainty of the fiducial volume

^{214}Bi vertex uniformity check

$V_{1.2m} / V_{total} = 0.438 \pm 0.005$

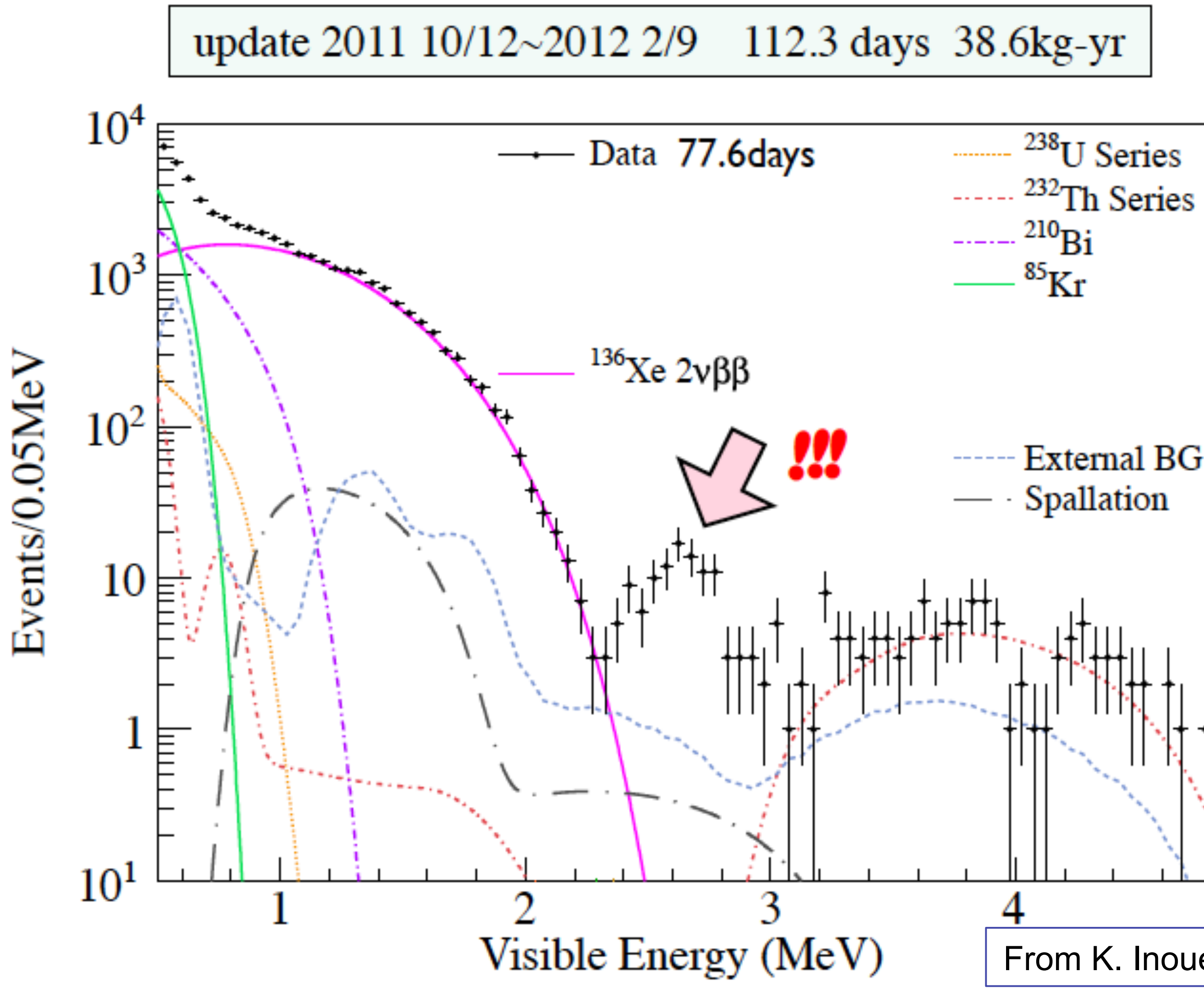
$N_{1.2m} / N_{total} = 0.423 \pm 0.007(\text{stat}) \pm 0.004(\text{syst})$

FV uncertainty ⟶ 5.2% dominant error

Xe amount in the fiducial volume

125±7 kg of ^{136}Xe in the FV

KamLAND-Zen: energy spectrum



From K. Inoue, Neutrino 2012

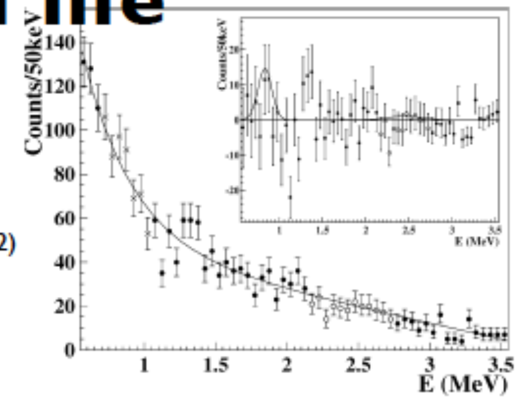
Measurement of the 2ν2β half life

DAMA (2002)

Liquid Xe scintillator

$T^{2\nu}_{1/2} > 1.0 \times 10^{22}$ years at 90% CL

Phys.Lett.B546,23(2002)



factor 5 contradiction

EXO-200 (2011)

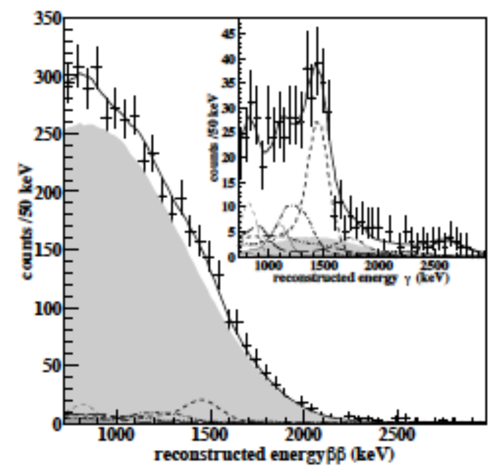
Liquid Xe TPC + scintillator

$T^{2\nu}_{1/2} = 2.11 \pm 0.04(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \times 10^{21}$ years

Phys.Rev.Lett.107,212501(2011)

update $T^{2\nu}_{1/2} = 2.23 \pm 0.017(\mathrm{stat}) \pm 0.22(\mathrm{syst}) \times 10^{21}$ years

arXiv:1205.5608



KamLAND-Zen (2012)

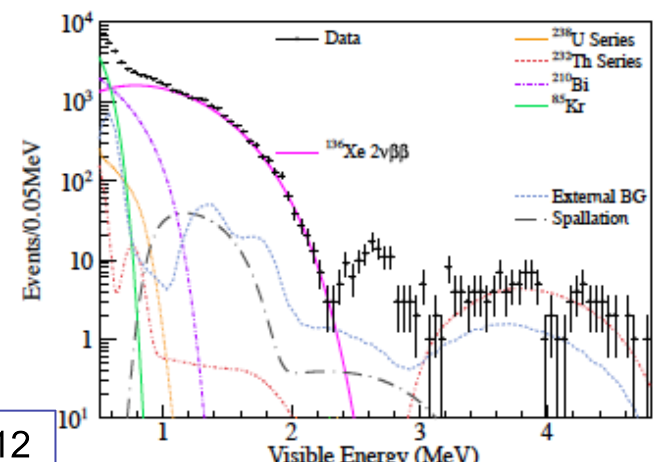
Xe loaded liquid scintillator

$T^{2\nu}_{1/2} = 2.38 \pm 0.02(\mathrm{stat}) \pm 0.14(\mathrm{syst}) \times 10^{21}$ years

Phys.Rev.C85,045504(2012)

update $T^{2\nu}_{1/2} = 2.30 \pm 0.02(\mathrm{stat}) \pm 0.12(\mathrm{syst}) \times 10^{21}$ years

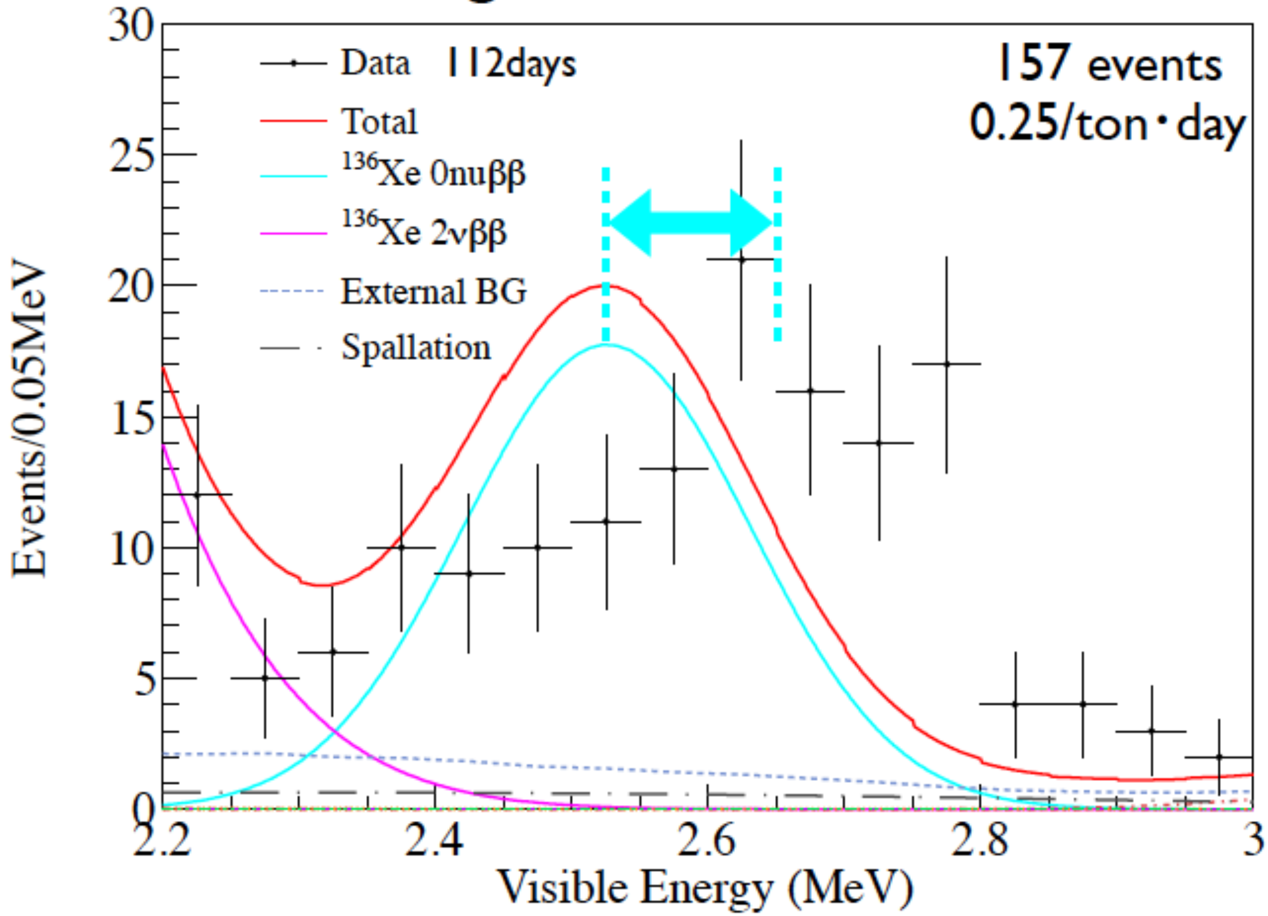
arXiv:1205.6372



From K. Inoue, Neutrino 2012

Background situation

Peak fit with 0ν signal

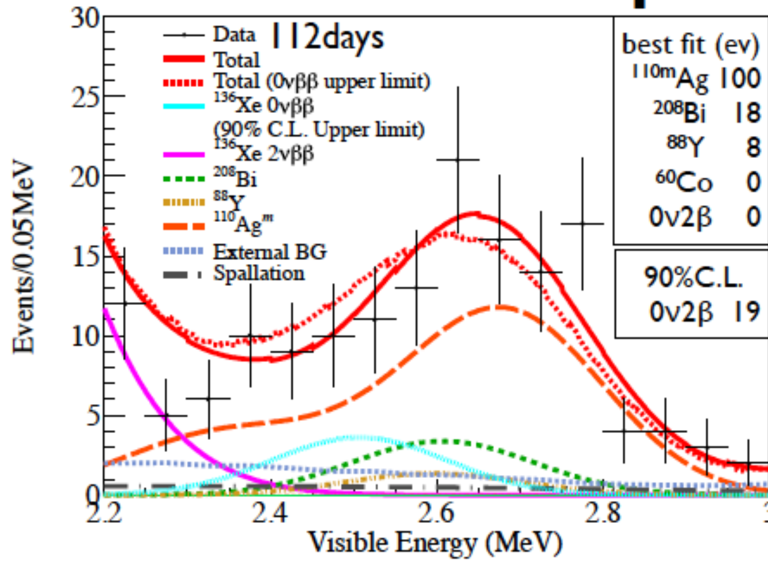


Peak position is different from that of expected 0ν.

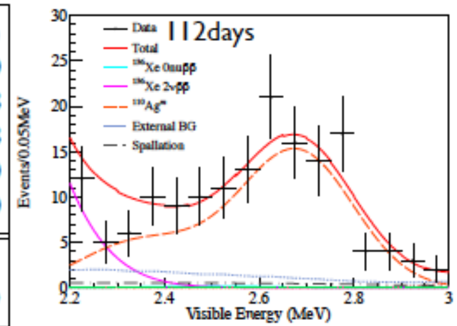
0ν only is rejected at more than 8σ level.

From K. Inoue, Neutrino 2012

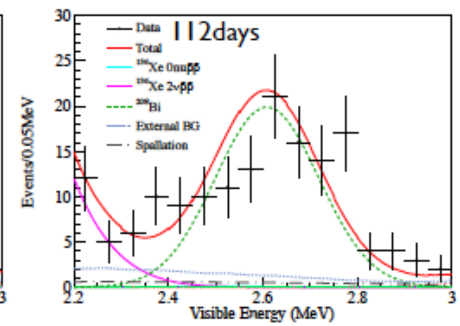
Limit on the 0ν2β half life



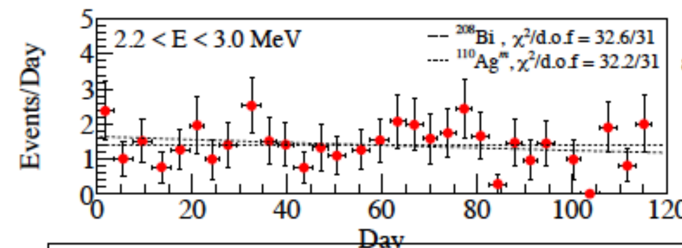
simultaneous fit and 90% CL upper limit for 0ν2β



^{110m}Ag fits well



^{208}Bi doesn't fit well



^{88}Y 36.0

stable in time, but no strong discrimination yet

(χ^2 at 2.2~3.0MeV)

	χ^2 112days	
simul. fit	11.6	
0ν+^{110m}Ag	13.1	
0ν+^{208}Bi	22.7	△
0ν+^{88}Y	22.2	△
0ν+^{60}Co	82.9	✕
0ν only	85.0	✕

BG is likely to be ^{110m}Ag

$T^{0\nu}_{1/2} > 5.7\times10^{24}$ years at 90% C.L. (78days)

factor 5 improvement from DAMA

$T^{0\nu}_{1/2} > 6.2\times10^{24}$ years (KL-Zen 112days)

(ref. current best is 16×10^{24} years from EXO-200)

(R)QRPA (CCM SRC)
Phys.Rev.C79,055501(2009)

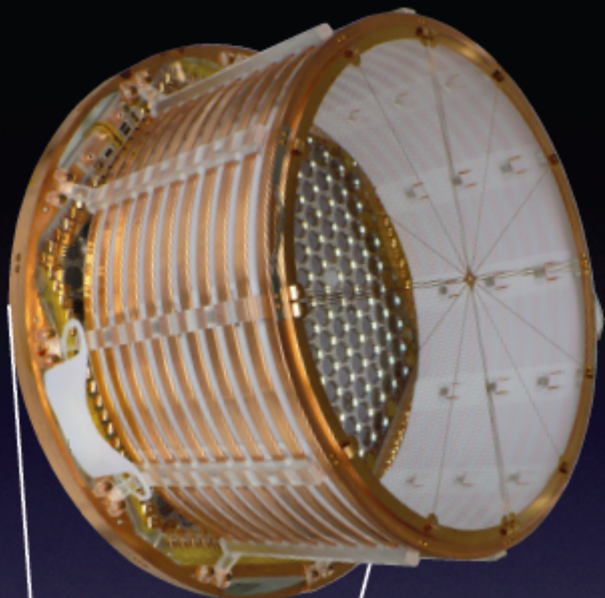
$\langle m_{\beta\beta}\rangle$ <0.26~0.54 eV @90% C.L.

15

From K. Inoue, Neutrino 2012

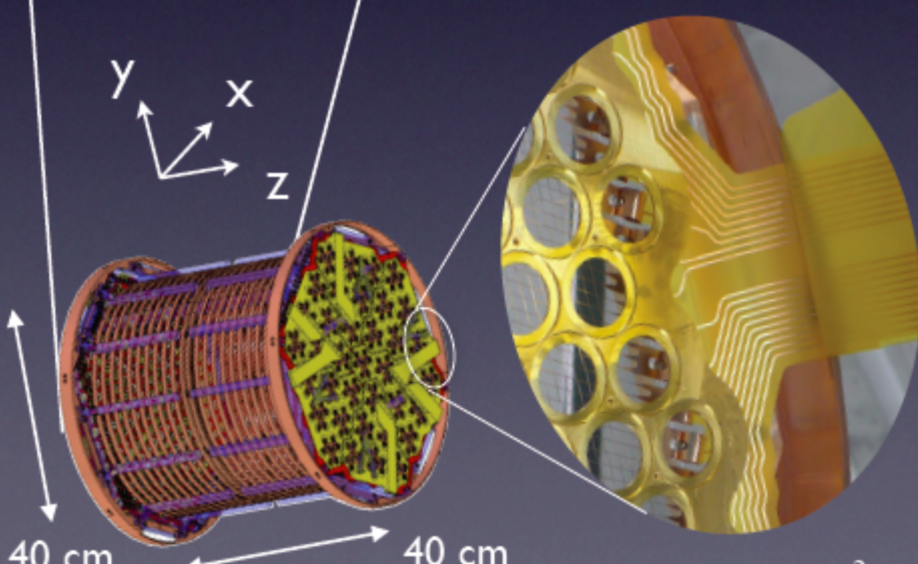
N.B.: limit depends on correctness of background model

The EXO-200 TPC



Two almost identical halves reading **ionization** and 178 nm **scintillation**, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60° (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 376 V/cm



- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue

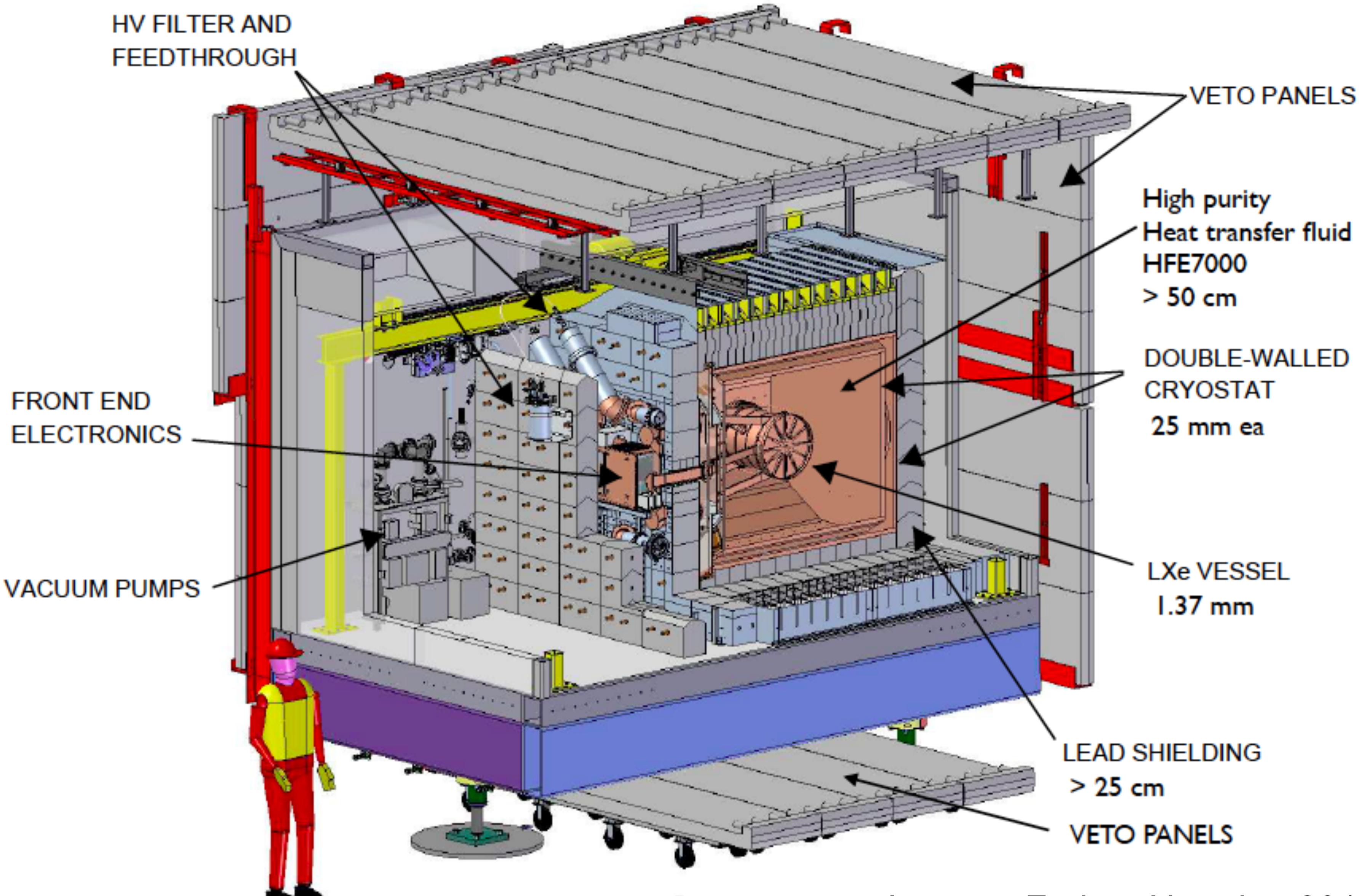
Comprehensive material screening program

Goal: 40 cnts/2y in $0\nu\beta\beta$ ±2σ ROI, 140 kg LXe

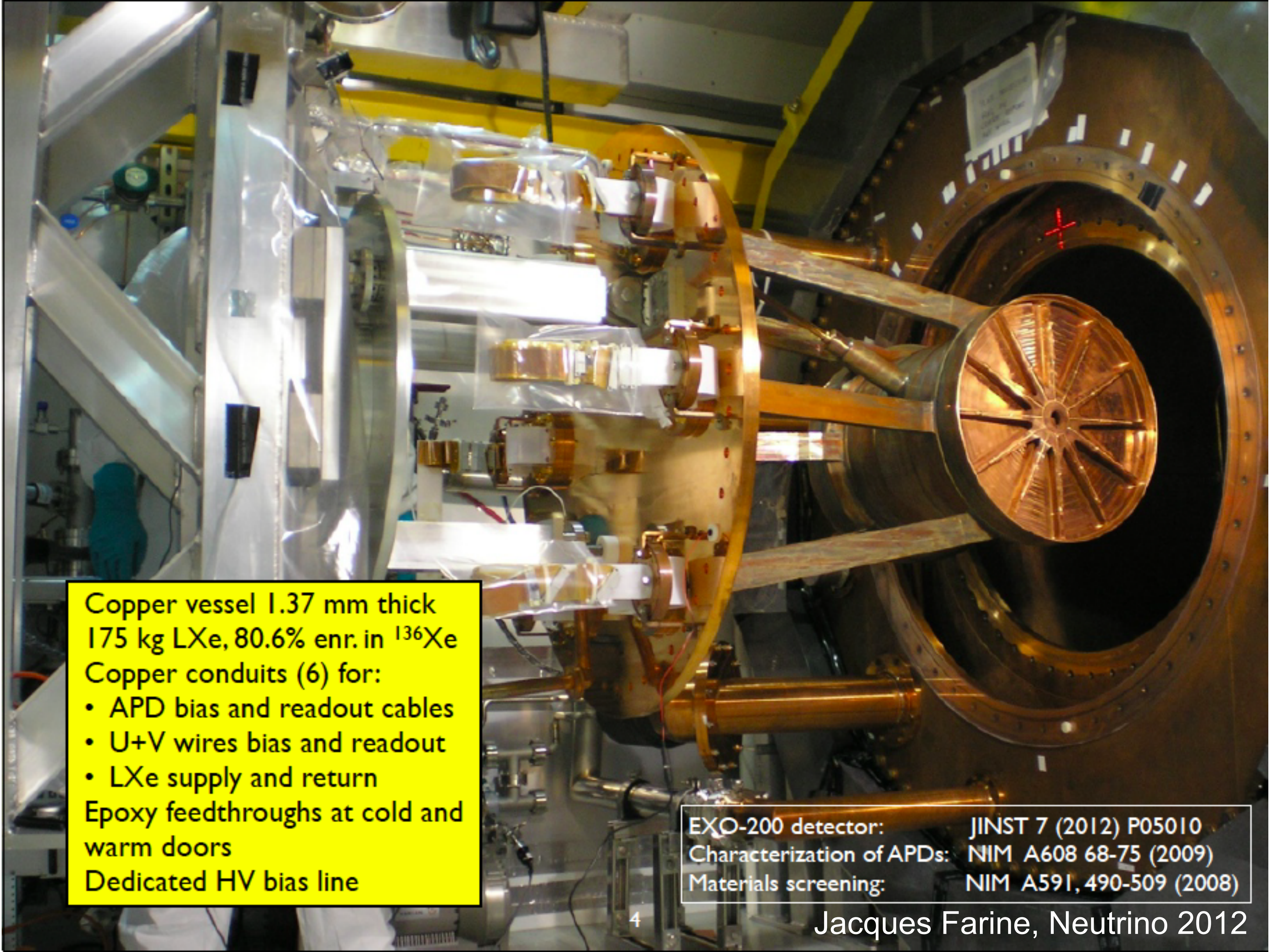
3

Jacques Farine, Neutrino 2012

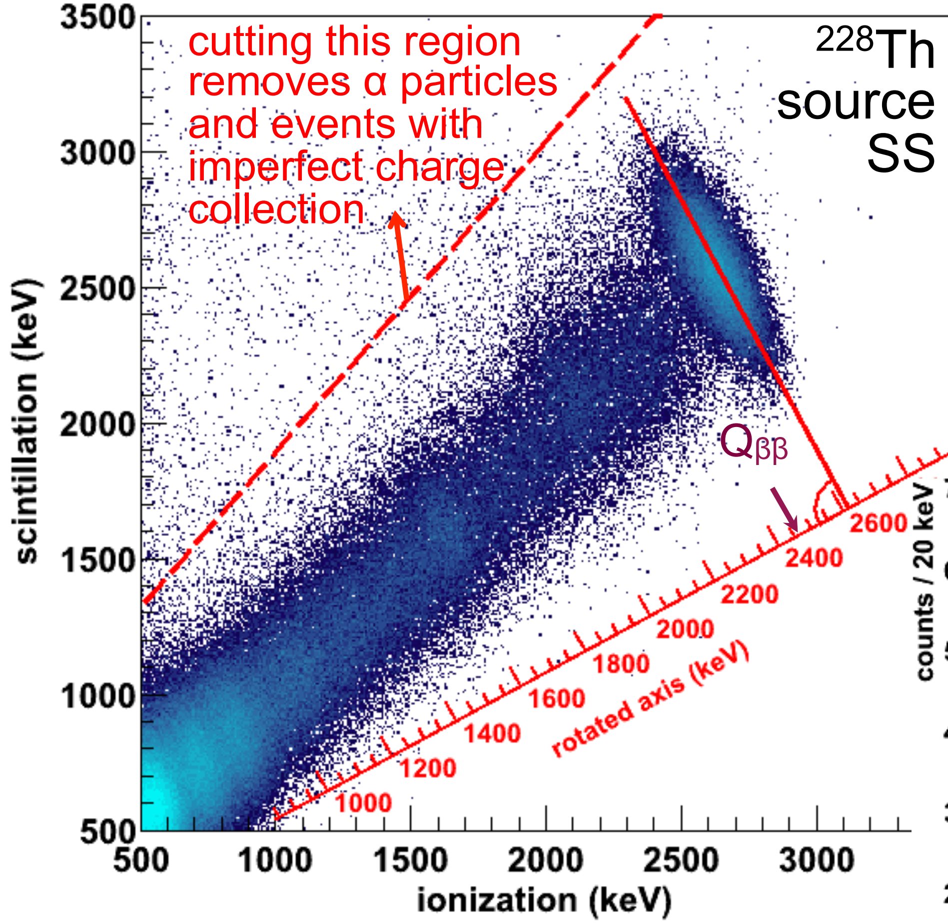
The EXO-200 Detector



Jacques Farine, Neutrino 2012


Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in 136Xe
Copper conduits (6) for:
• APD bias and readout cables
• U+V wires bias and readout
• LXe supply and return
Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)
4
Jacques Farine, Neutrino 2012

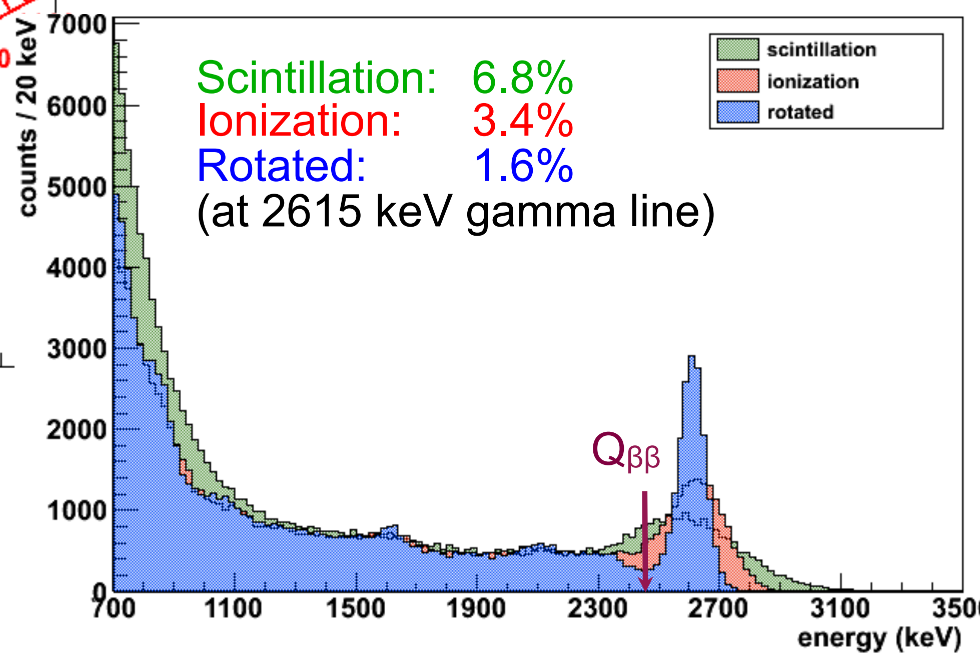
Combining Ionization and Scintillation



Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

E. Conti et al. Phys. Rev. B 68 (2003) 054201

Use projection onto a rotated axis to determine event energy

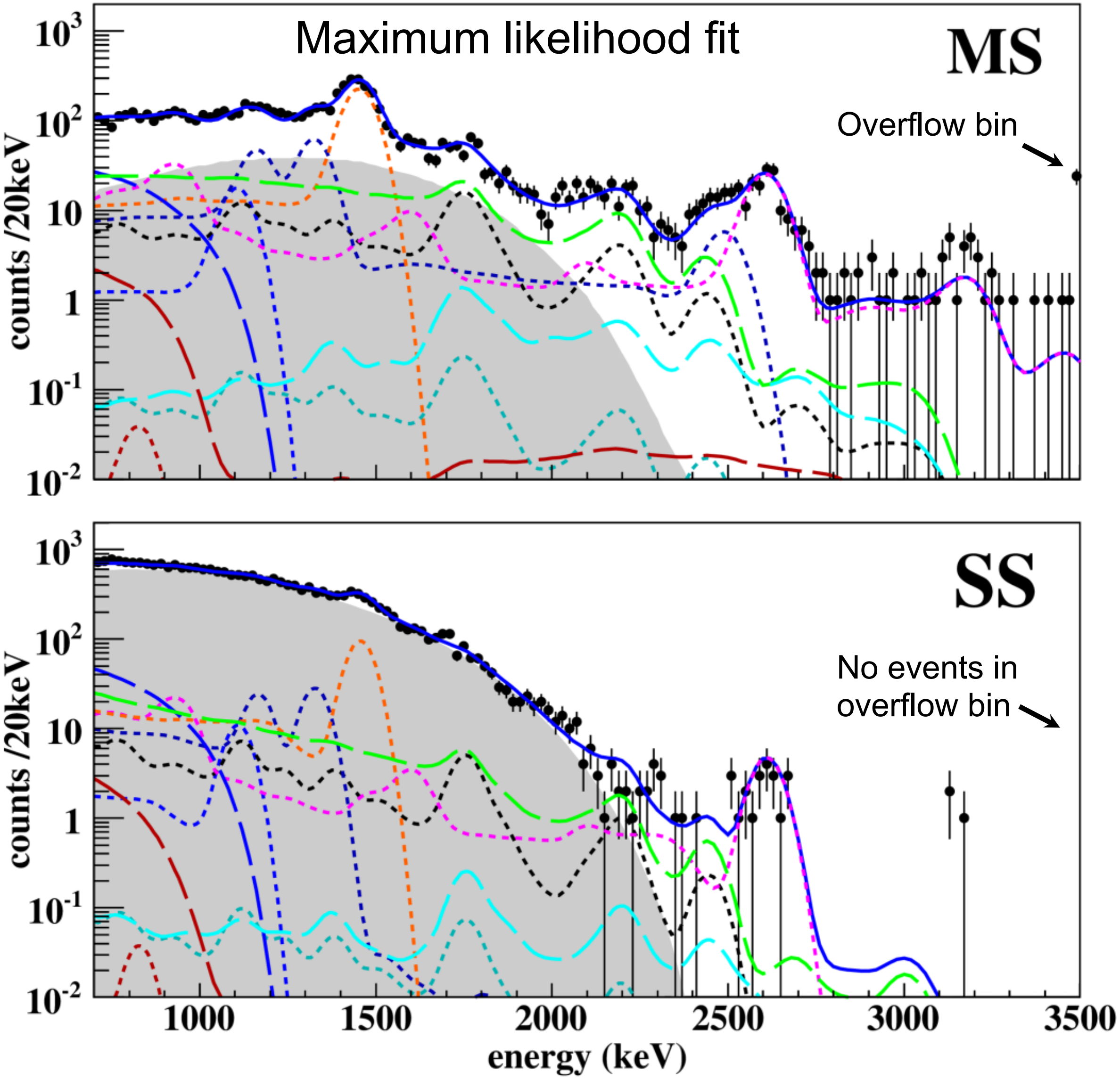


Rotation angle chosen to optimize energy resolution at 2615 keV

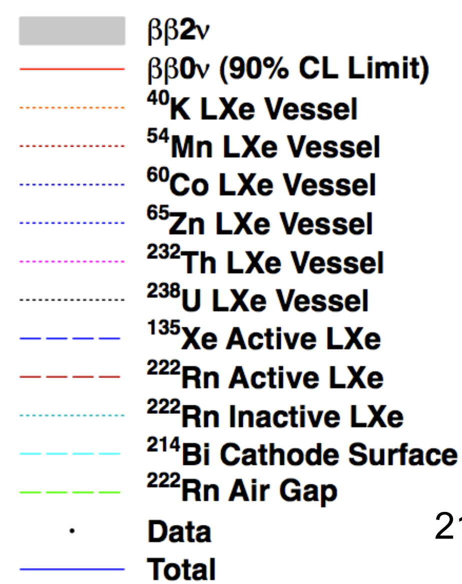
Jacques Farine, Neutrino 2012

From J. Farine, Neutrino 2012

Low Background Spectrum



- Trigger fully efficient above 700 keV
- Low background run livetime: **120.7 days**
- Active mass: **98.5 kg LXe (79.4 kg ^{136}LXe)**
- Exposure: **32.5 kg·yr**
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with 2νββ and 0νββ PDFs

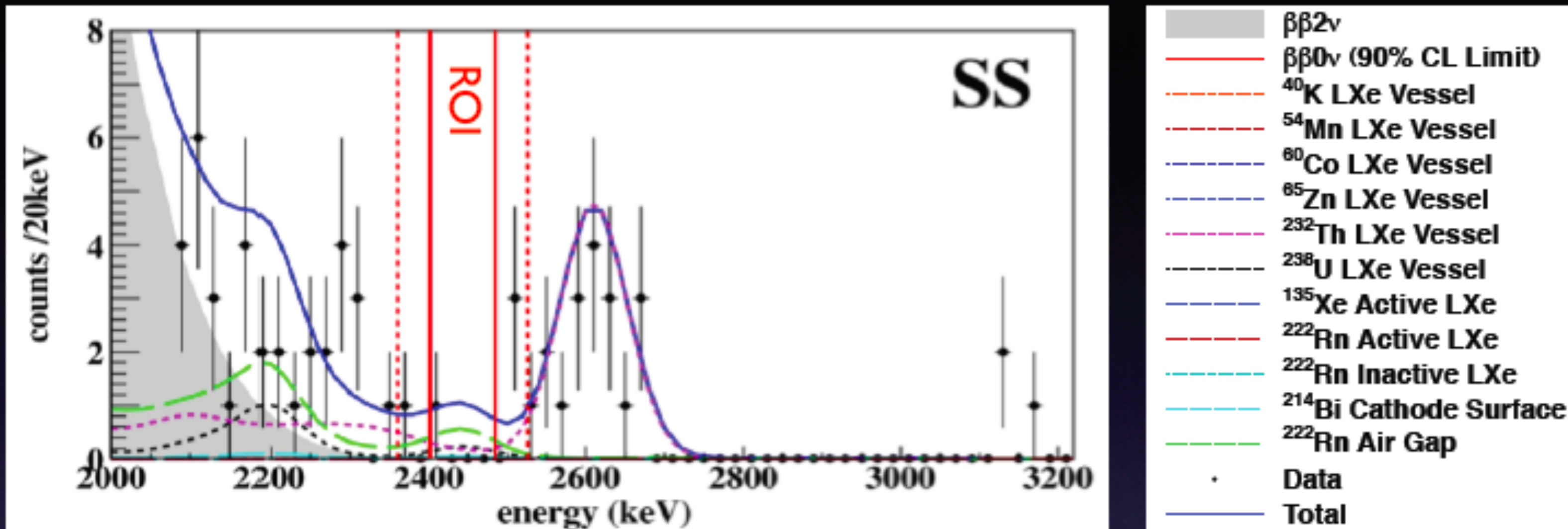


$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

(In agreement with previously reported measurements)

From J. Farine, Neutrino 2012

Background counts in ±1,2 σ ROI



	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

EXO-200 goal (slide 3):

40 cnts/2y in ±2σ ROI, 140 kg LXe

In this data 120 days, 98.5 kg, this would be: 4.6

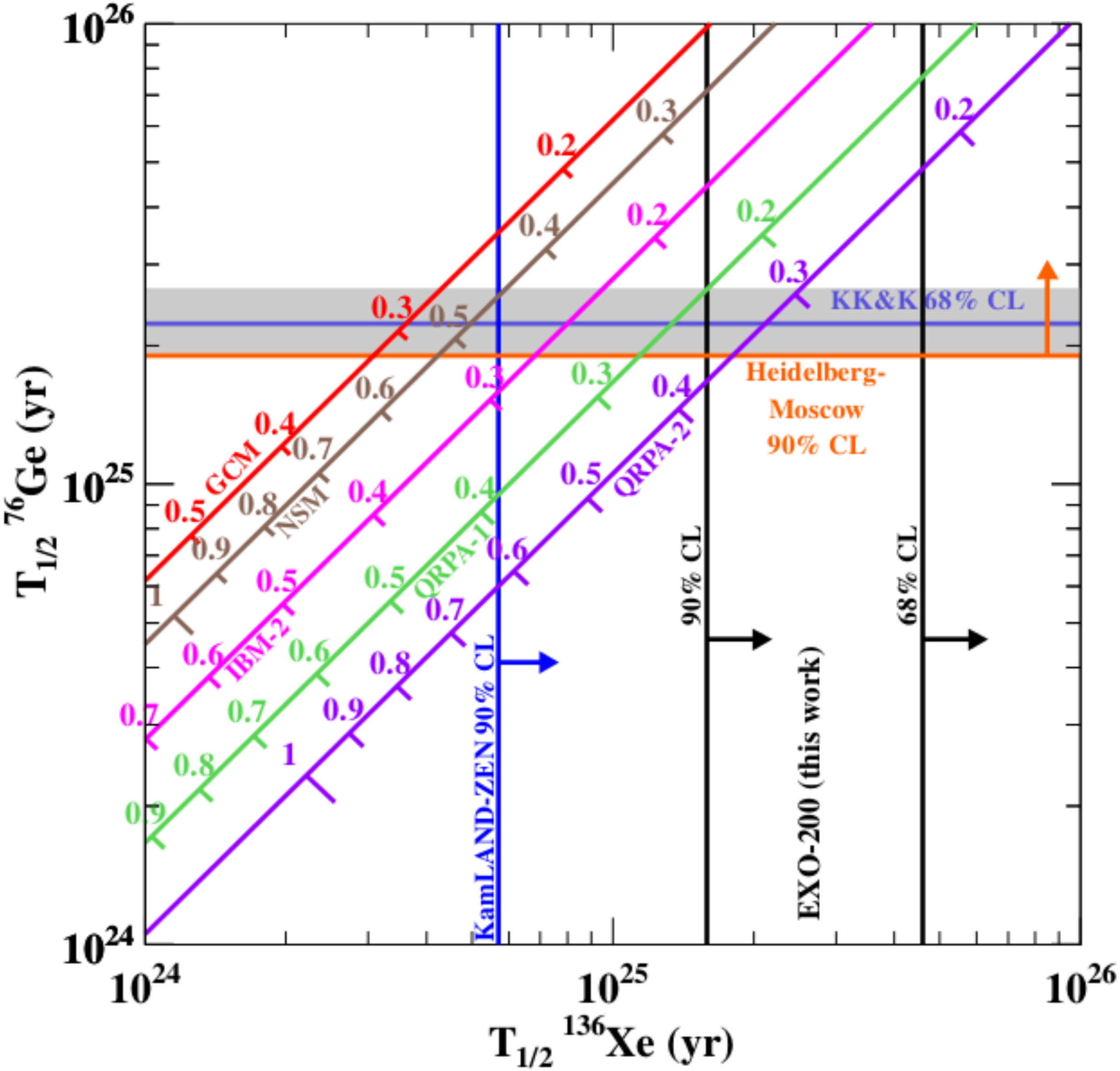
Expected from the fit: 7.5

Observed: 5

Background within expectation

From J. Farine, Neutrino 2012

Limits on $T_{½}^{0\nu\beta\beta}$ and $<m_{\beta\beta}>$



90% C.L. limit compared with Recent ^{136}Xe constraints (KamLAND-ZEN) >2.5 factor improvement.

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

$<m_{\beta\beta}> < 140 – 380$ mV

(90% C.L.)

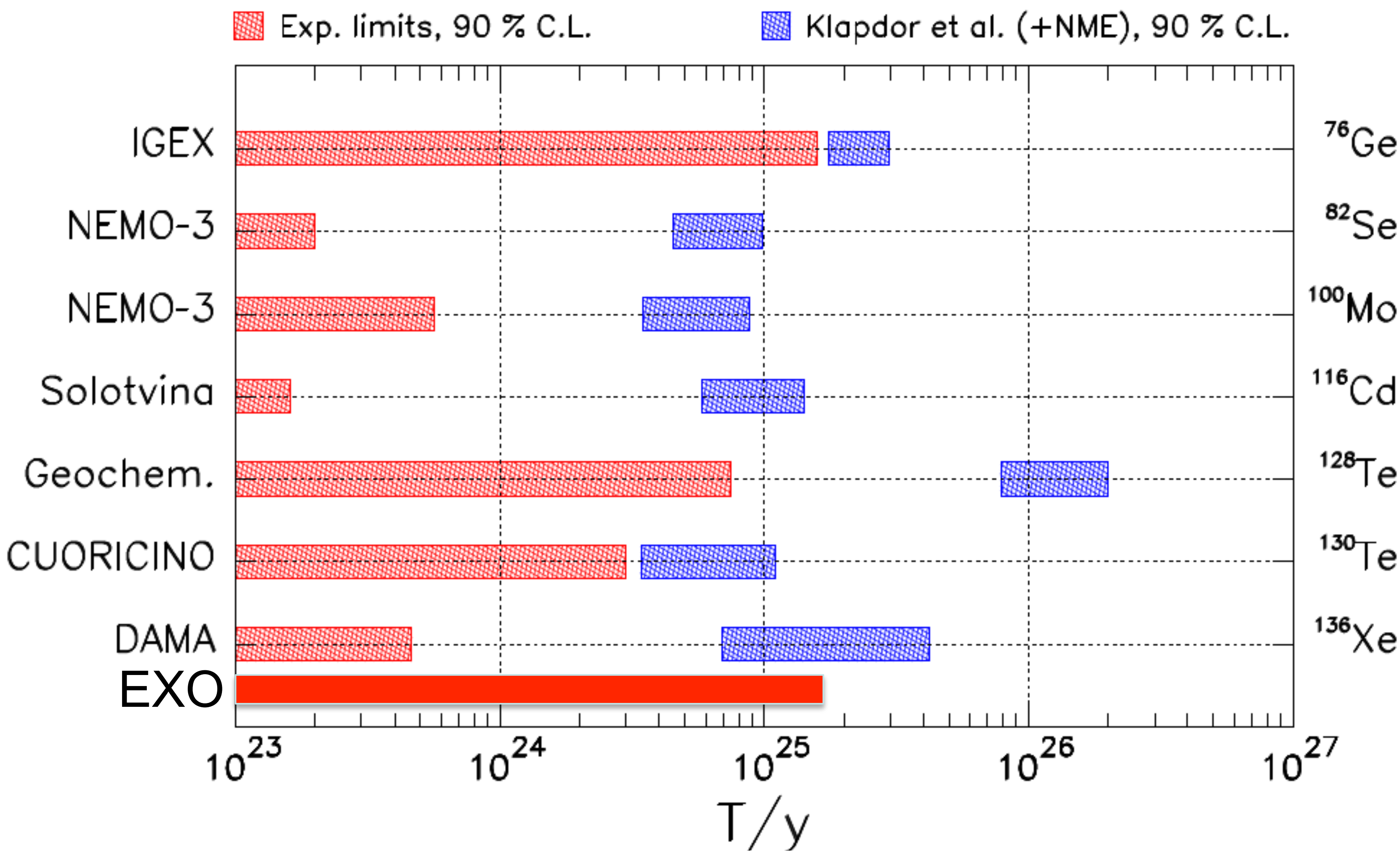
[arXiv:1205.5608]

Tension with discovery claim in Ge.

KamLAND-Zen Collaboration
Phys. Rev. C 85 (2012) 045504]
[H.V. Klapdor-Kleingrothaus et al.
Eur. Phys. J. A12 (2001) 147]
[H.V. Klapdor-Kleingrothaus and I.V. Krivosheina
Mod. Phys. Lett., A21 (2006) 1547]

Comparison of upper limits (90 % C.L.) with claim [16] for QRPA NME

A.Faessler, G.L. Fogli, E. Lisi, V. Rodin, A.M. Rotunno, F. Simkovic, PhysRevD.79.053001 arXiv: 0810.5733v2 (EXO result included by 'hand')



[16] H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, "The Evidence For The Observation Of $0\nu\beta\beta$ Decay: The Identification Of $0\nu\beta\beta$ Events From The Full Spectra," Mod. Phys. Lett. A **21**, 1547 (2006).

Table 2 Bayesian posterior probabilities $p(\bar{H})$ using EXO-200 data for the hypothesis that the $0\nu\beta\beta$ signal of Heidelberg-Moscow is correct. Probabilities are given for different matrix element calculations and for the $\pm1\sigma$ and $\pm2\sigma$ energy windows.

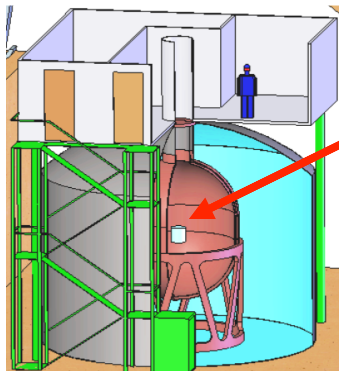
method	expected signal events	$p(\bar{H})$ in %	expected signal events	$p(\bar{H})$ in %
	in $\pm1\sigma$ window		in $\pm2\sigma$ window	
QRPA max	4.4 ± 1.1	4	6.1 ± 1.5	6
QRPA min	2.8 ± 0.7	11	3.9 ± 0.9	16
ISM	10.6 ± 2.5	0.1	14.8 ± 3.5	0.2
GCM	14.3 ± 3.4	0.03	19.9 ± 4.8	0.05
pnQRPA	6.3 ± 1.5	1	8.8 ± 2.1	2
IBM	6.1 ± 1.5	1	8.6 ± 2.1	2

N.B. comparison with HdM claim (28±6.86) cts in 71.7 kg yr

B. Schwingenheuer, Annalen der Physik, August 22, 2012

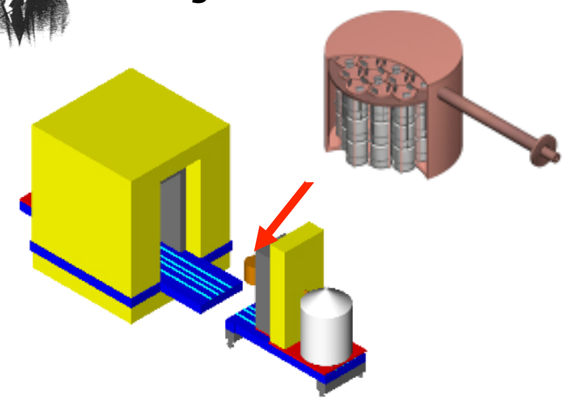
Two ^{76}Ge projects:

GERDA



- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. detectors; total ~40 kg

Majorana

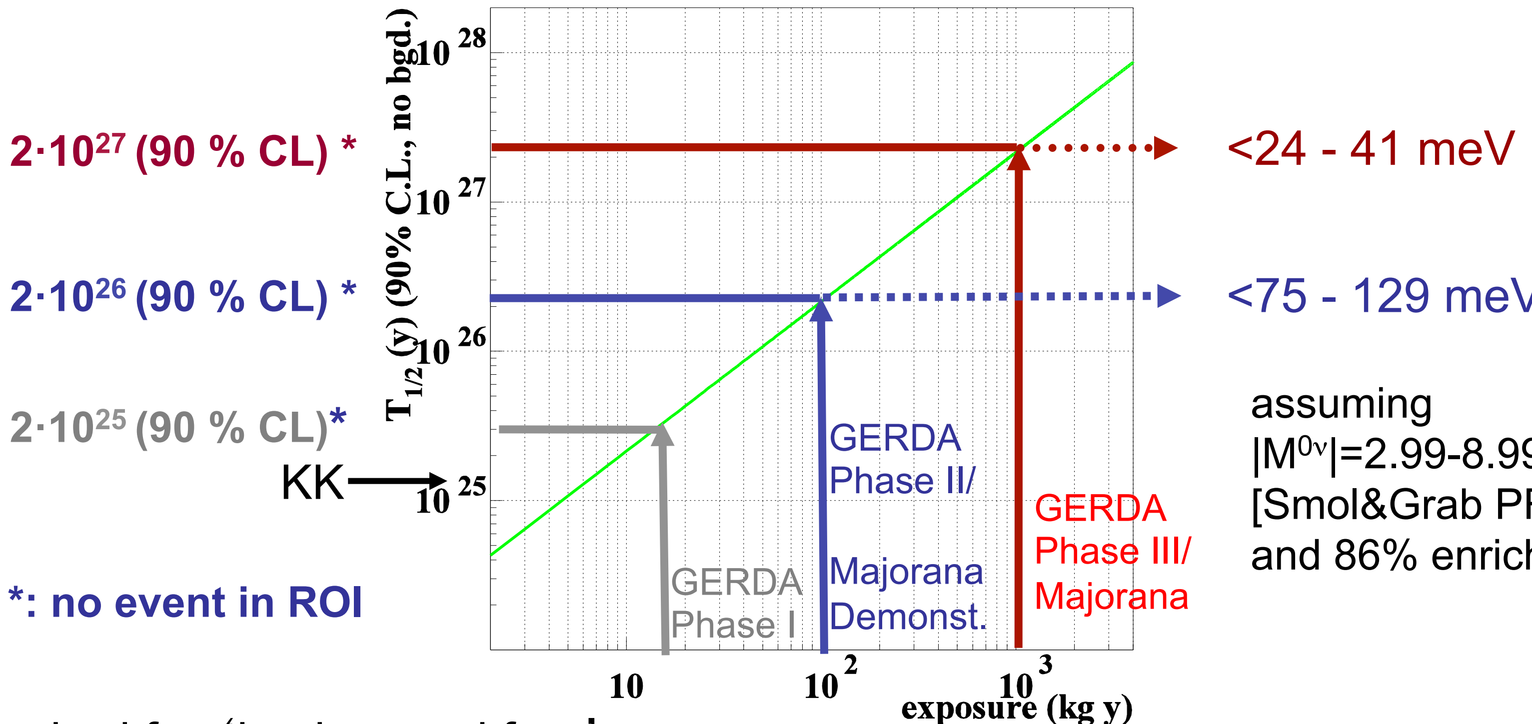


- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana

Phases and physics reach



assuming $|M^{0\nu}|$=2.99-8.99 [Smol&Grab PRC' 10] and 86% enrichment

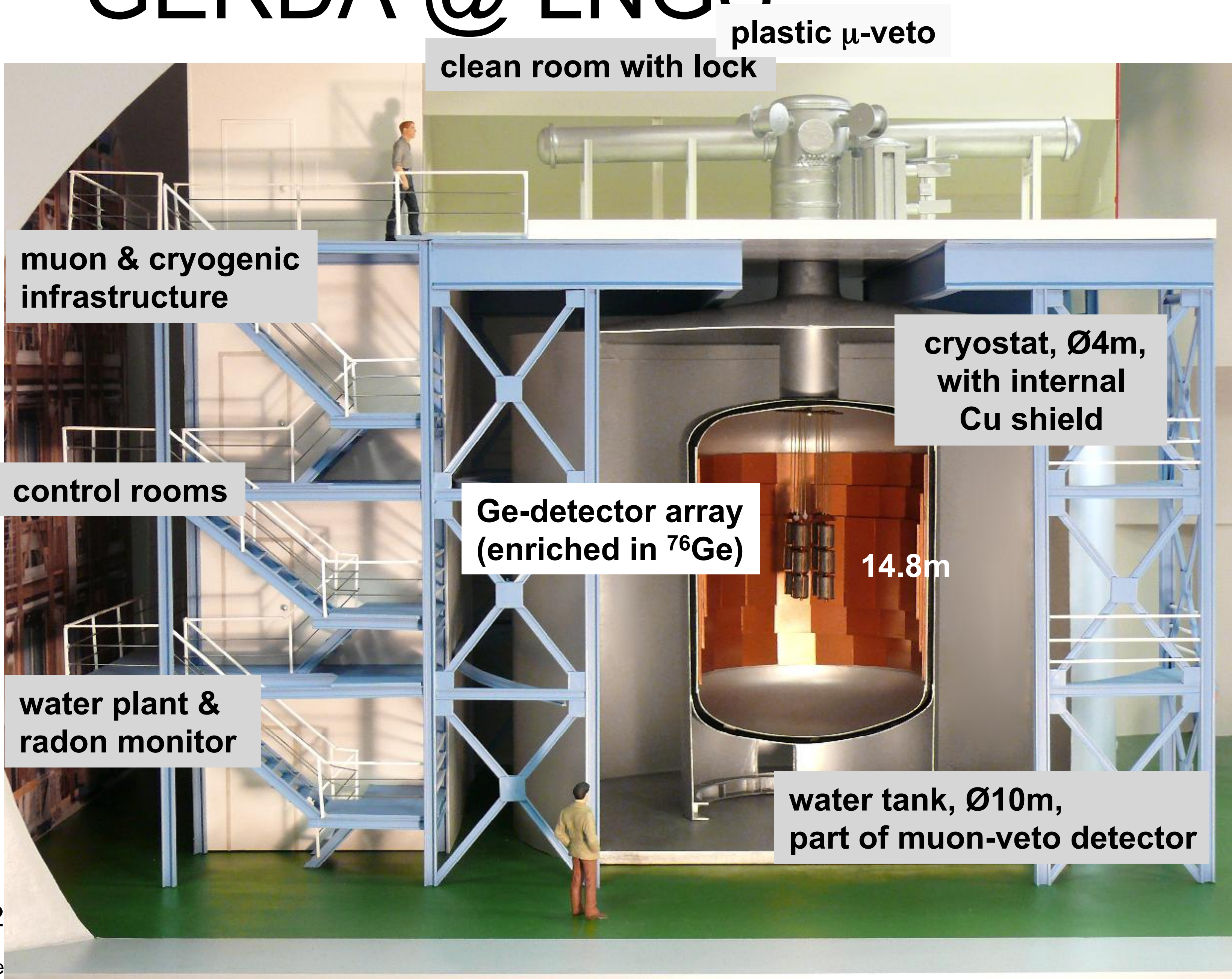
required for 'background free' exp. with ΔE~3.3 keV (FWHM): **O(10^{-3})** **O(10^{-4})** counts/(kg·y·keV)

Background requirement for GERDA/Majorana:

⇒Background reduction by factor **10^2 - 10^3** required w.r.t. to precursor exps.

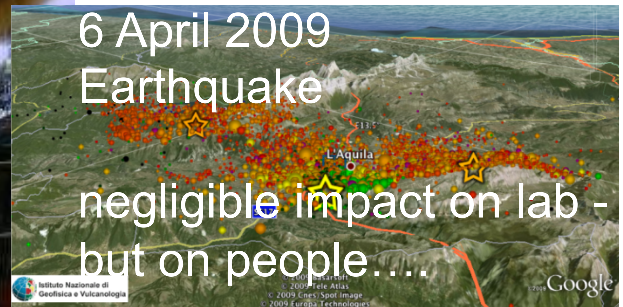
⇒Degenerate mass scale **O(10^2 kg·y)** ⇒ Inverted mass scale **O(10^3 kg·y)**

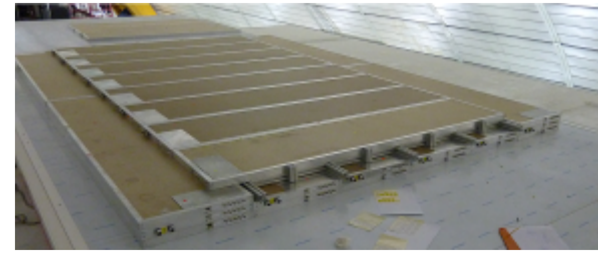
GERDA @ LNGS



plastic μ-veto
clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat, Ø4m, with internal Cu shield
Ge-detector array (enriched in 76Ge)
14.8m
water tank, Ø10m, part of muon-veto detector

GERDA construction: 2008-2010

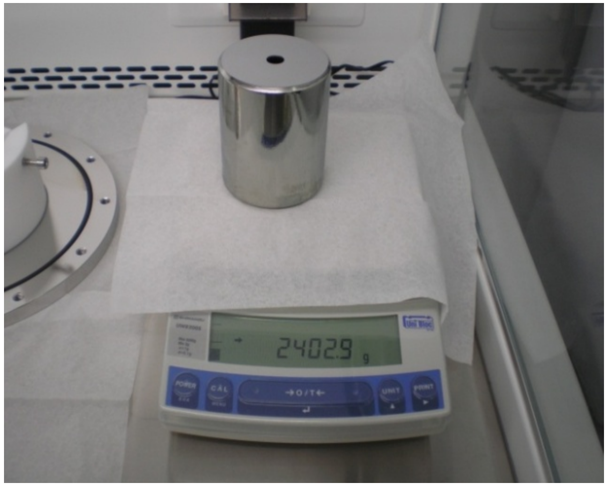




© Jan Hattenbach

GERDA Inauguration @ LNGS: Nov 2010

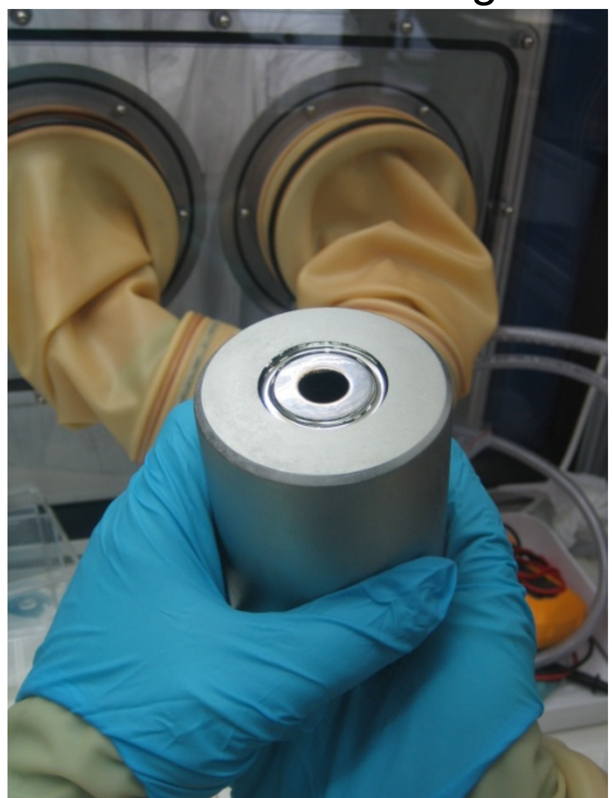
Phase I detectors



- All diodes reprocessed and optimized for LAr
- Well tested procedure for detector handling
- Long term stability in LAr established
- Energy resolution in LAr: ~2.5 keV (FWHM) @1.3 MeV

<u>8 diodes (from HdM, IGEX):</u>

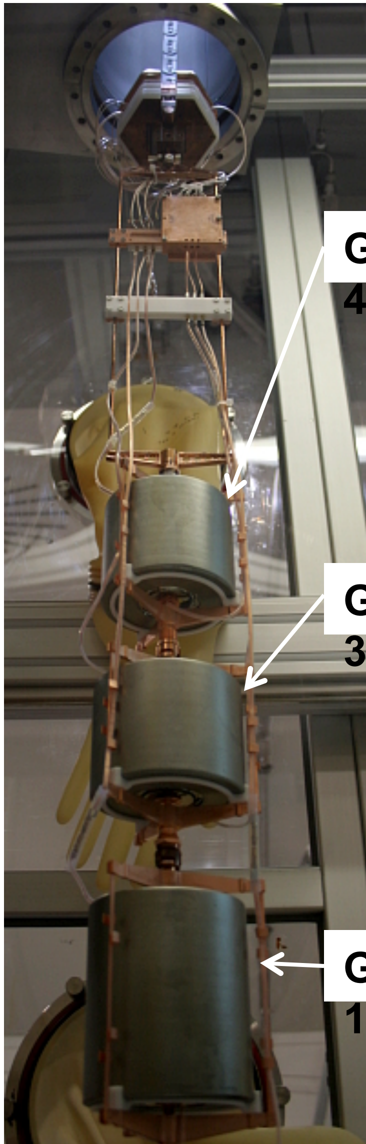
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



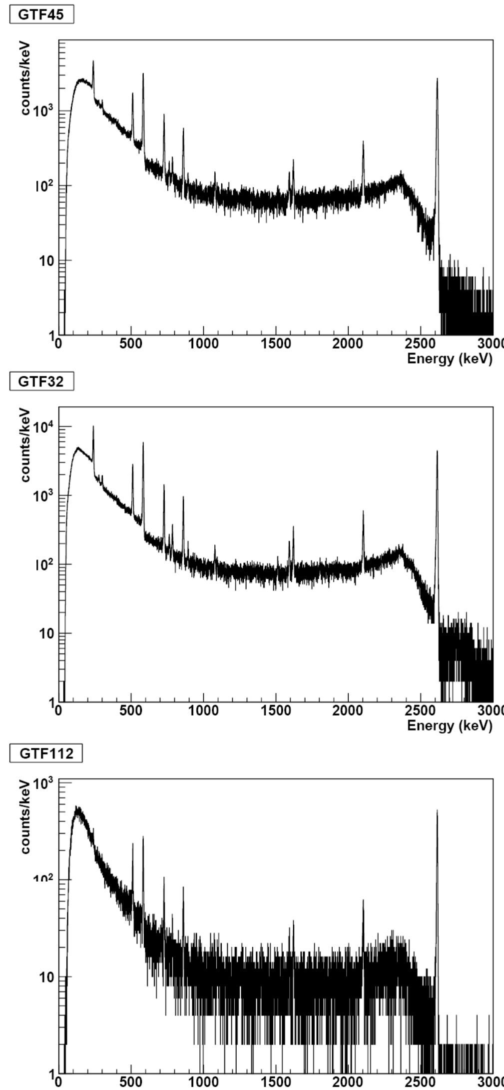
<u>6 diodes from Genius-TF:</u>

- ^{nat}Ge
- Total mass: 15.60 kg

Commissioning runs (with non-enriched detectors)



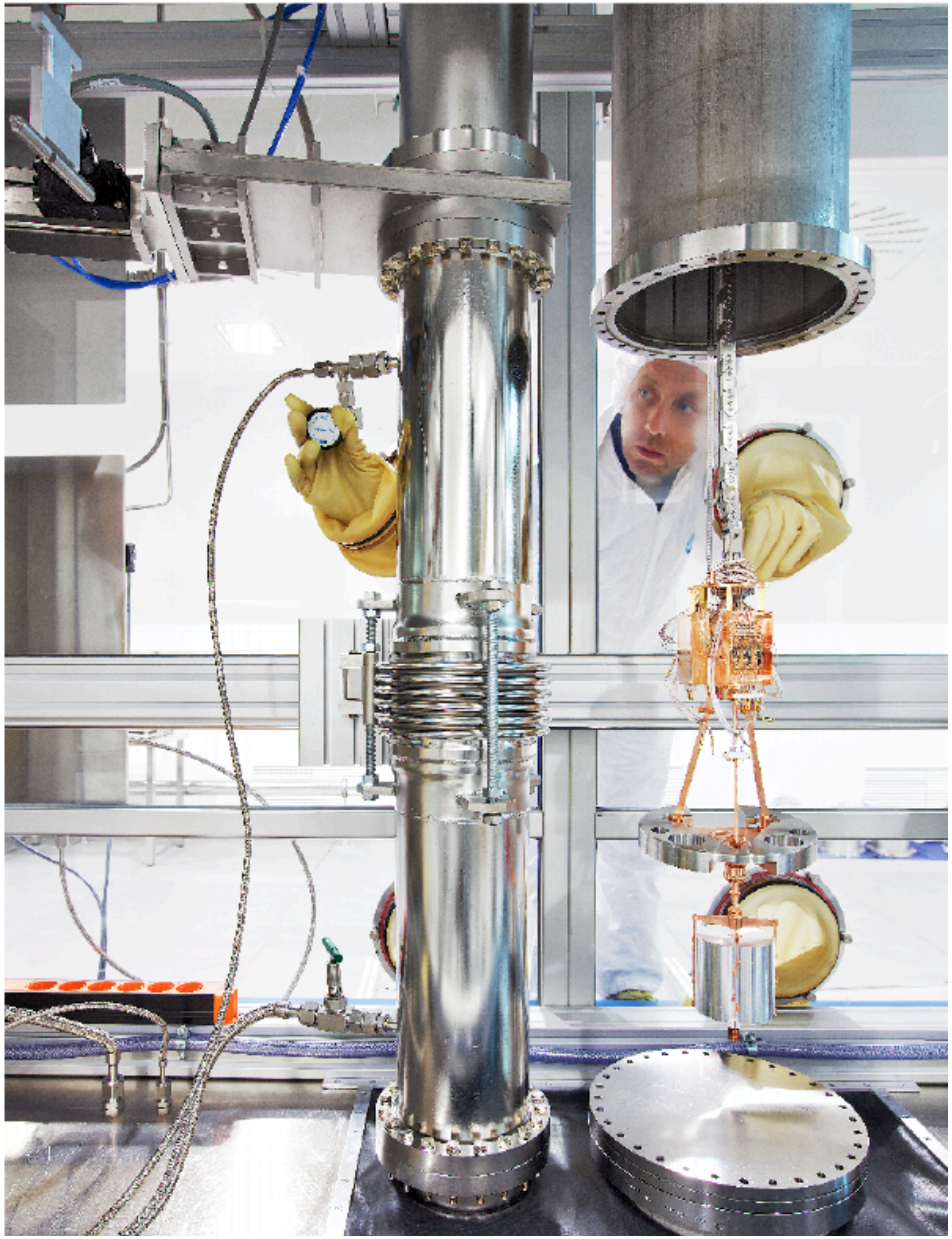
Calibration with ^{228}Th:



Commissioning runs with **non-enriched low-background detectors** to study performance and backgrounds (June 2010 – Mai 2011)

Energy resolutions during commissioning:
dependent on chosen detector configuration:

- Coaxial (Phase I): 4-5 keV (*FWHM*) @ 2.6 MeV
- BEGe (Phase II): 2.8 keV (*FWHM*) @ 2.6 MeV



detector mock-up and lock-system

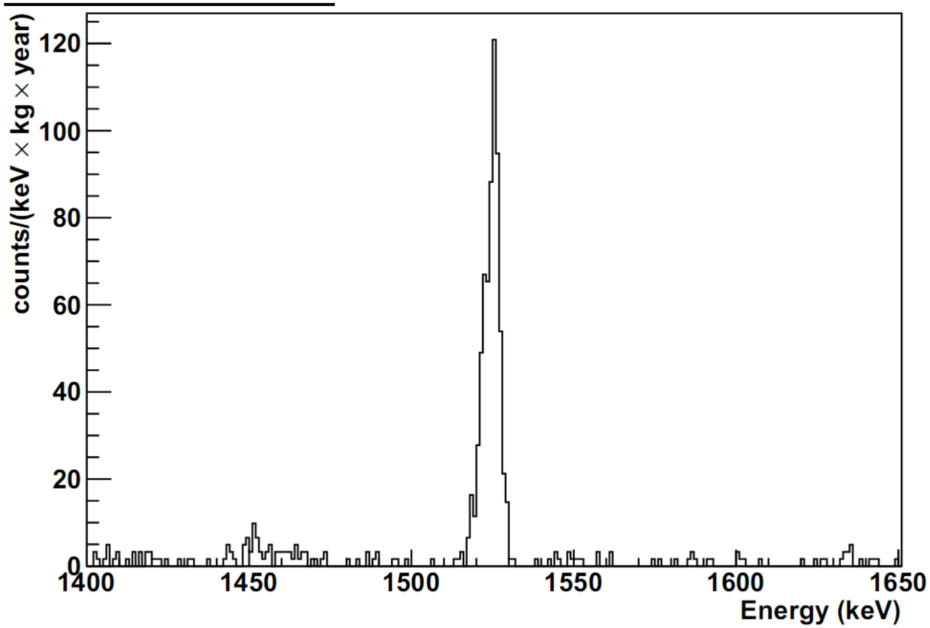
Commissioning runs:

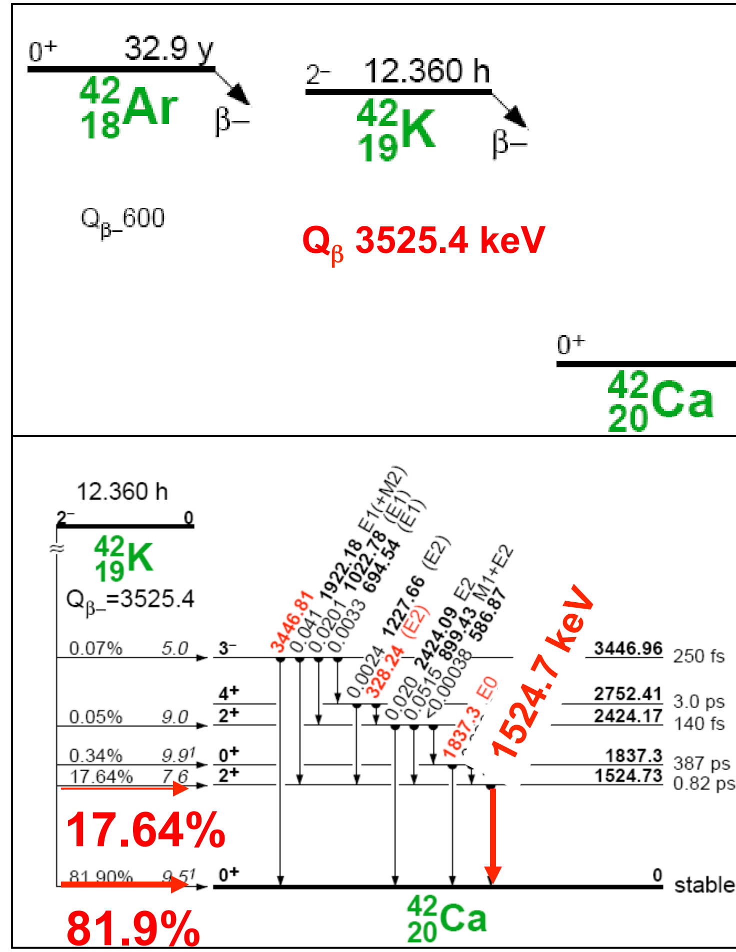
The unexpected ^{42}Ar (^{42}K) signal

GERDA proposal: $^{42}Ar/^{nat}Ar < 3\cdot10^{-21}$

[Barabash et al. 2002,
Final publication: $2.3\ 10^{-21}$]

GERDA measurement:

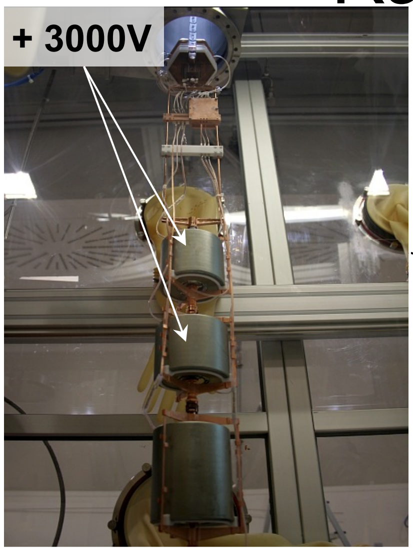


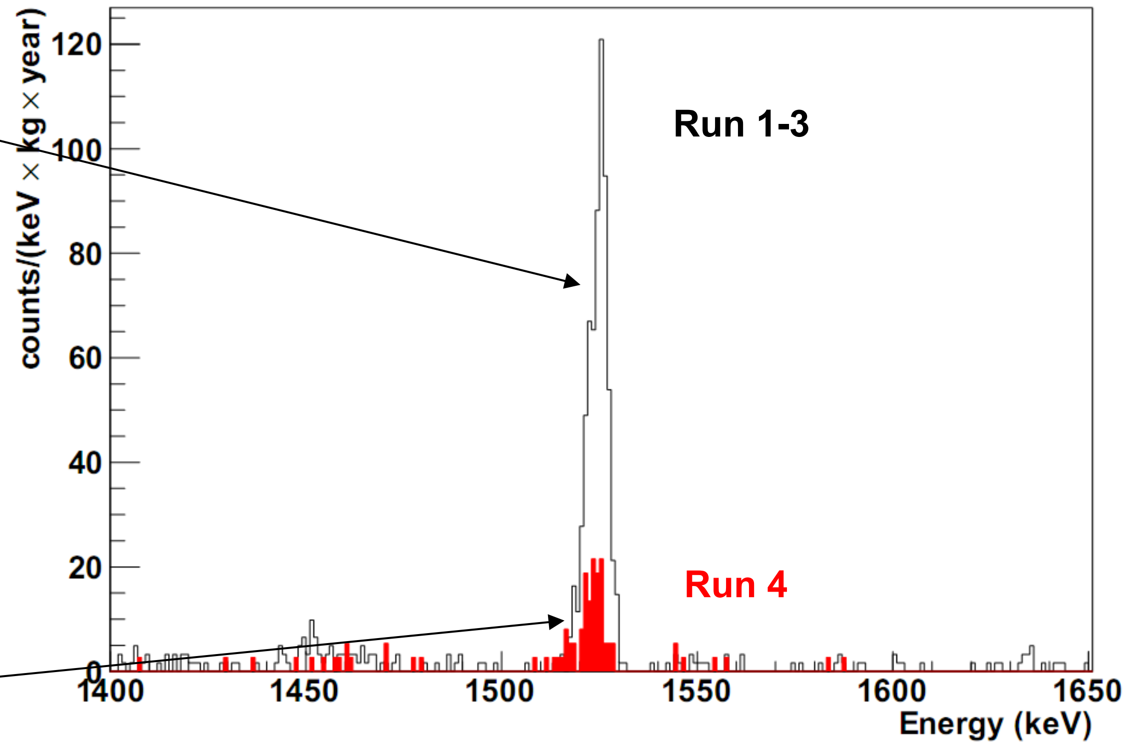


- measurement in apparent contradiction with limit from literature
- lower enhancement of count rate by collection of ^{42}K ions by E-field of diodes

Commissioning runs:

Rate of $^{42}K(^{42}Ar)$: 1525 keV peak

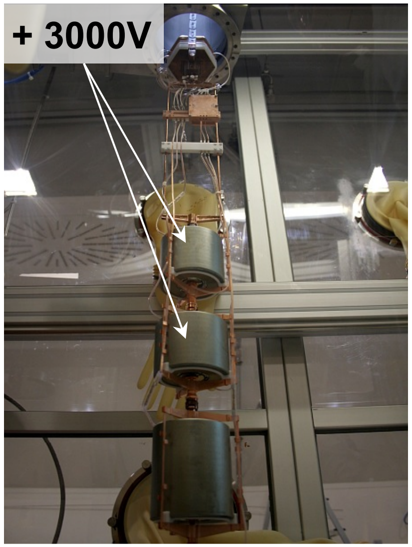


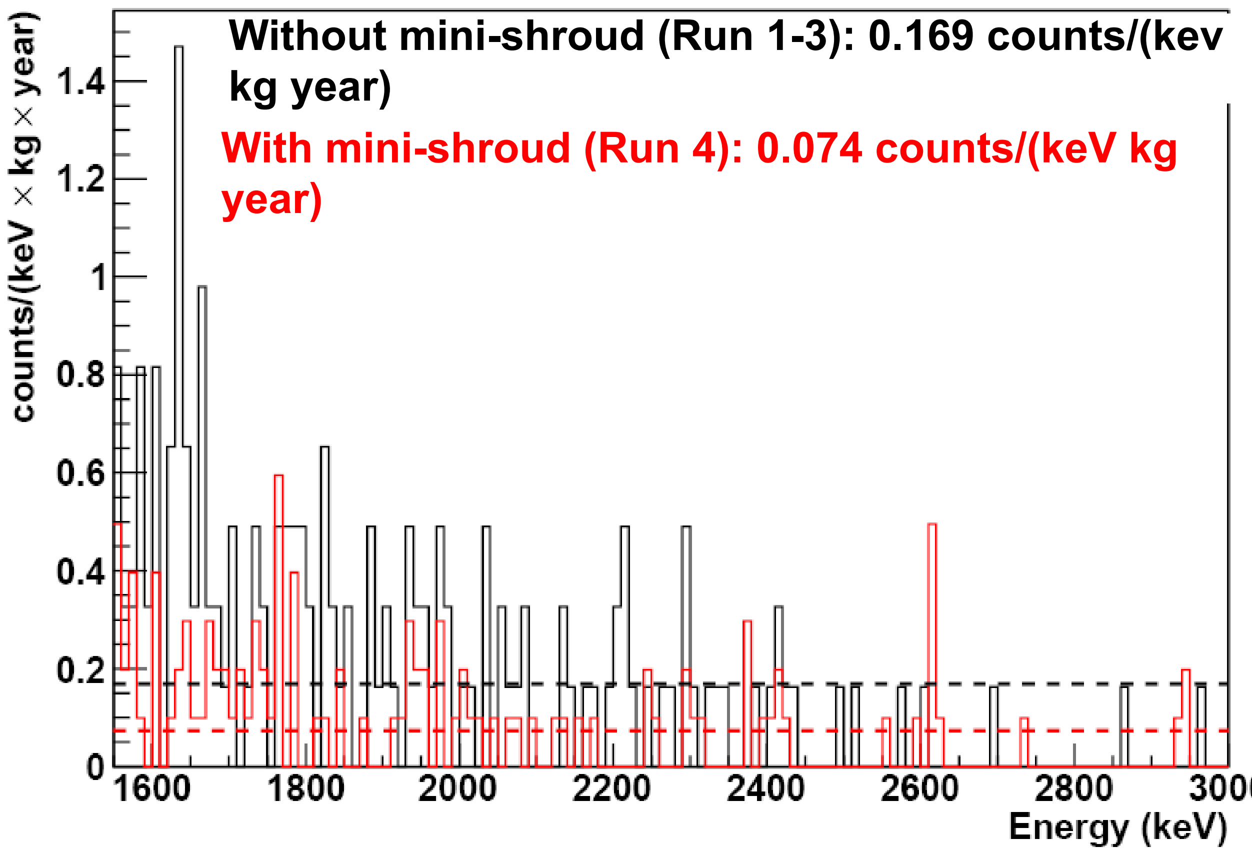


Two spectra normalized to the same exposure

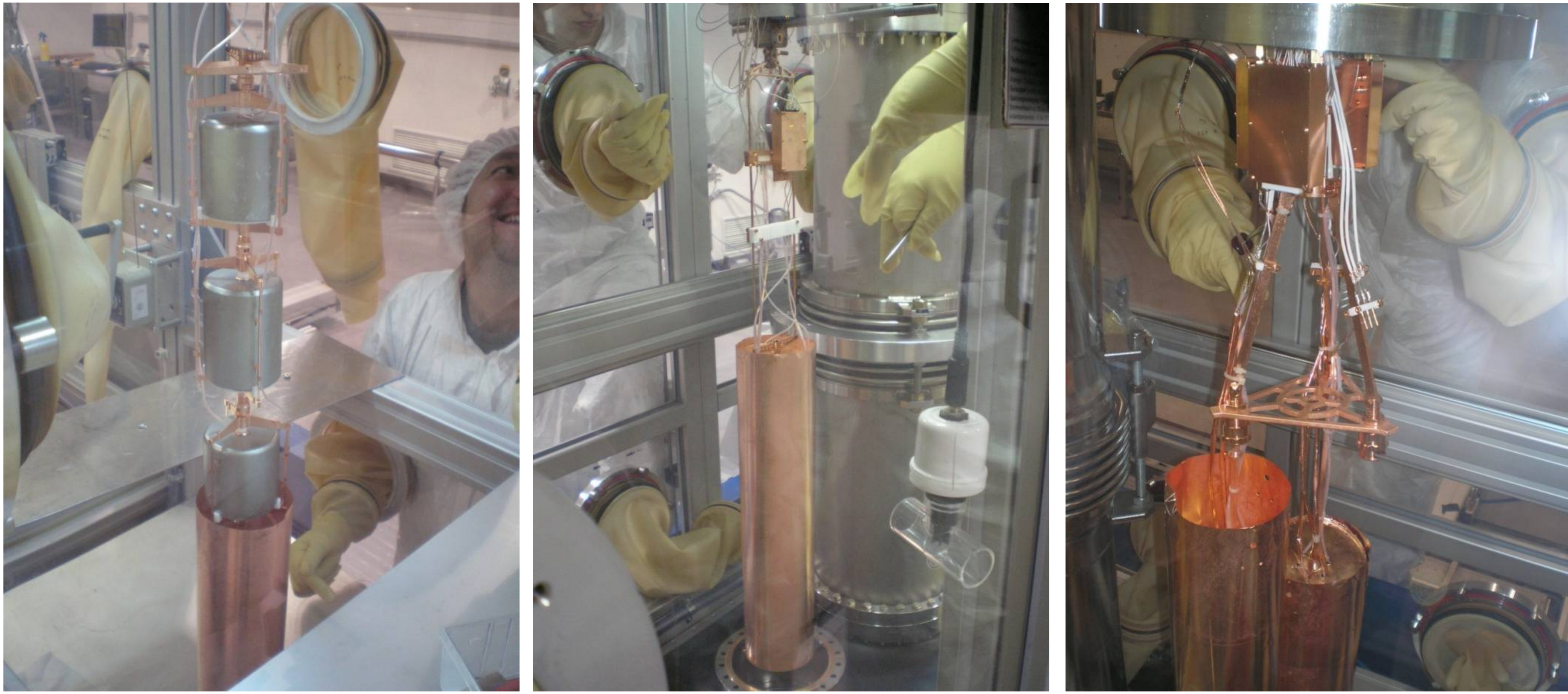
Commissioning runs:

Rate of ^{42}K: high-energy region



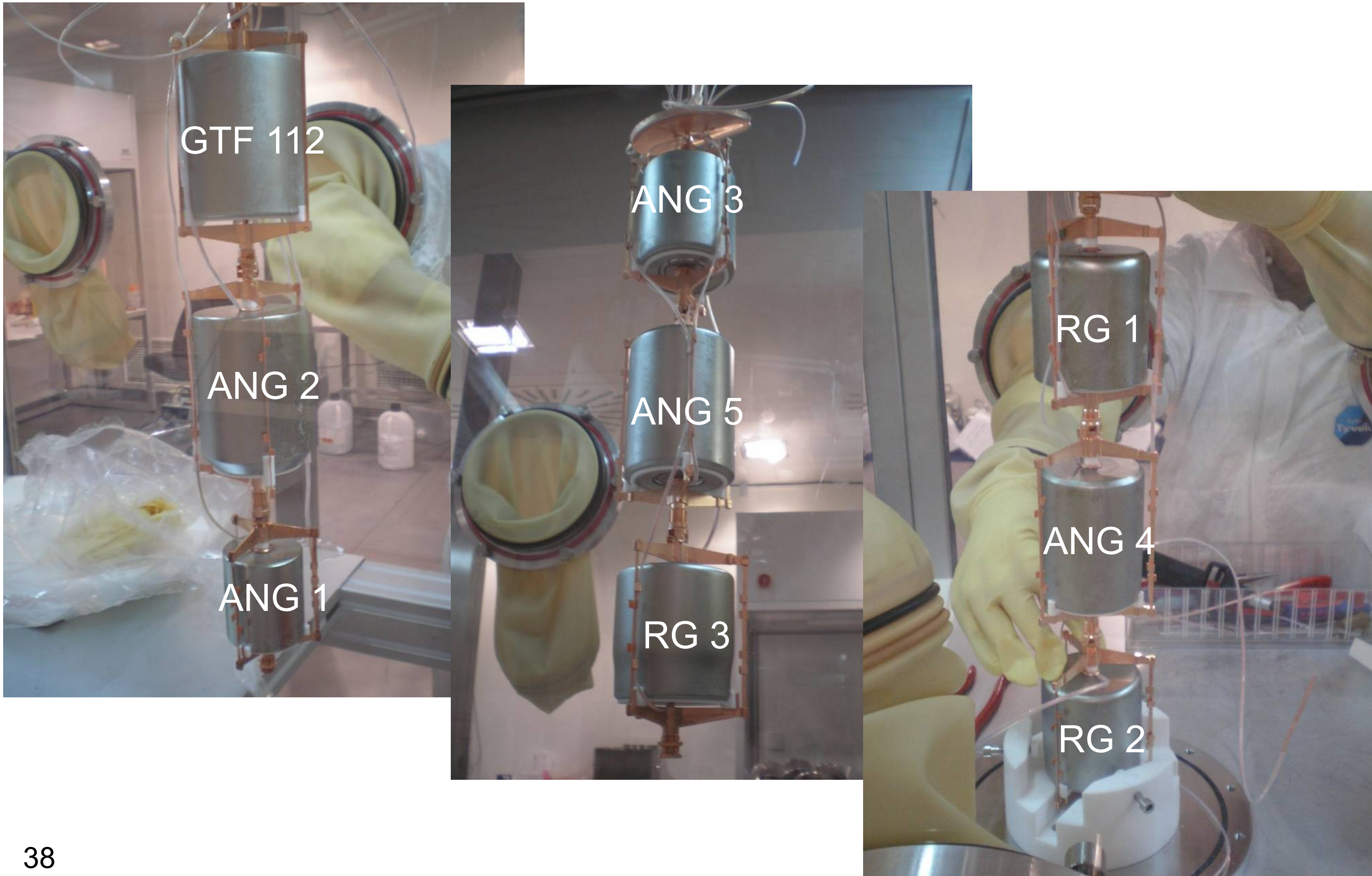


Last commissioning runs (June – September 2011):
3 enriched + 5 non-enriched detectors

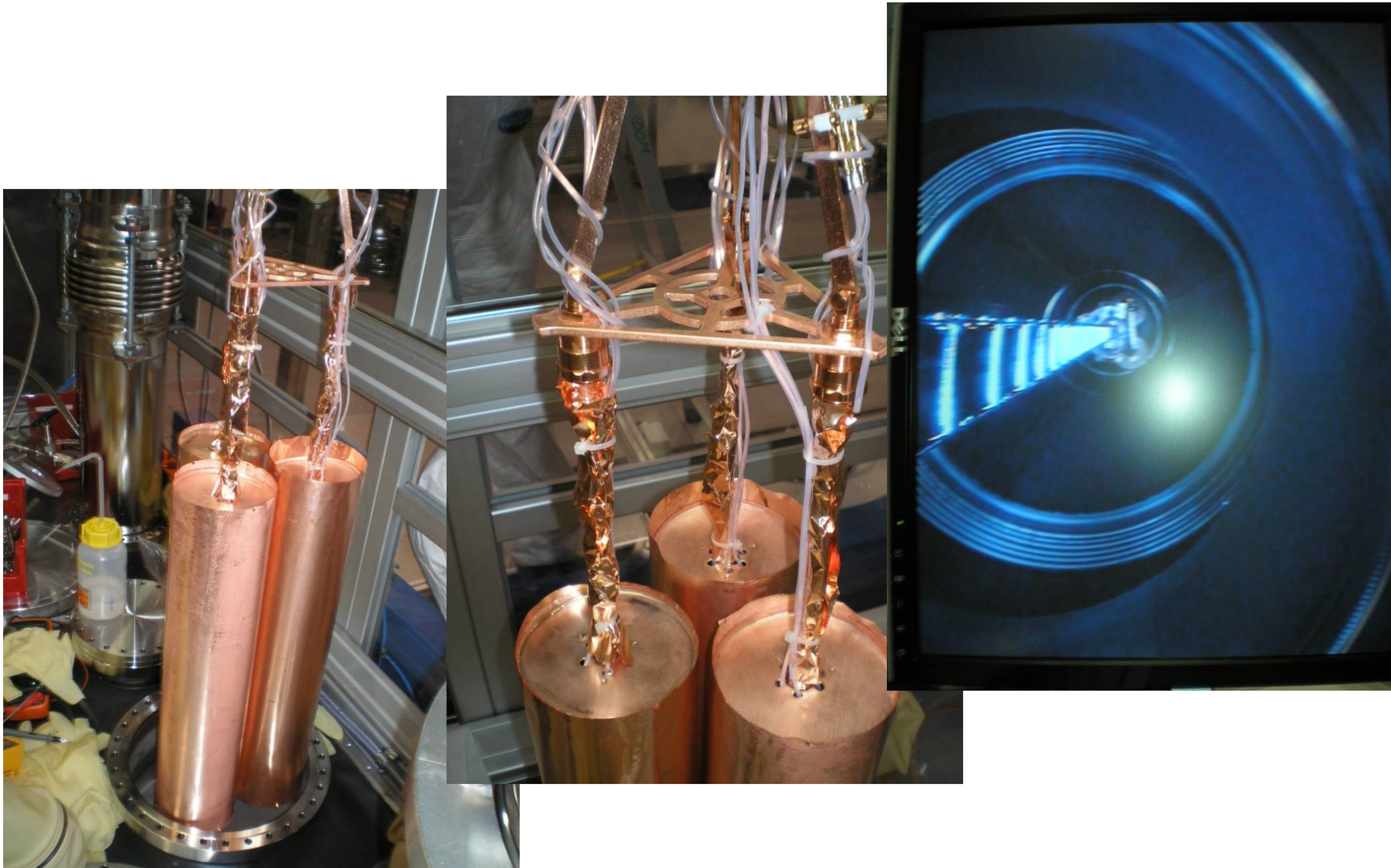


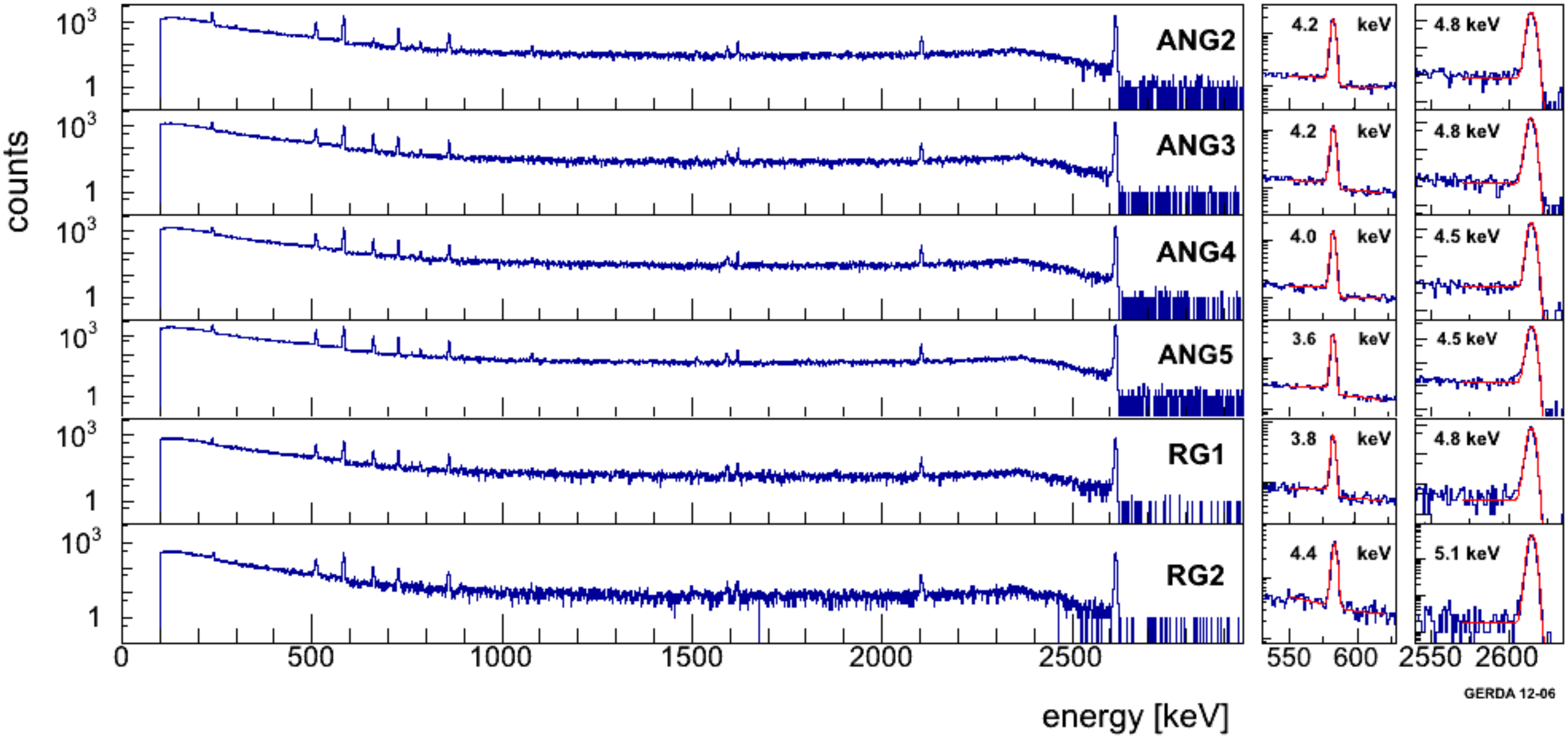
- All detectors installed inside new mini-shrouds
- First GERDA 2νββ spectrum measured!
- Ready to deploy all enriched detectors

Commissioning phase completed:
8 enriched detectors deployed in GERDA in October 2011!

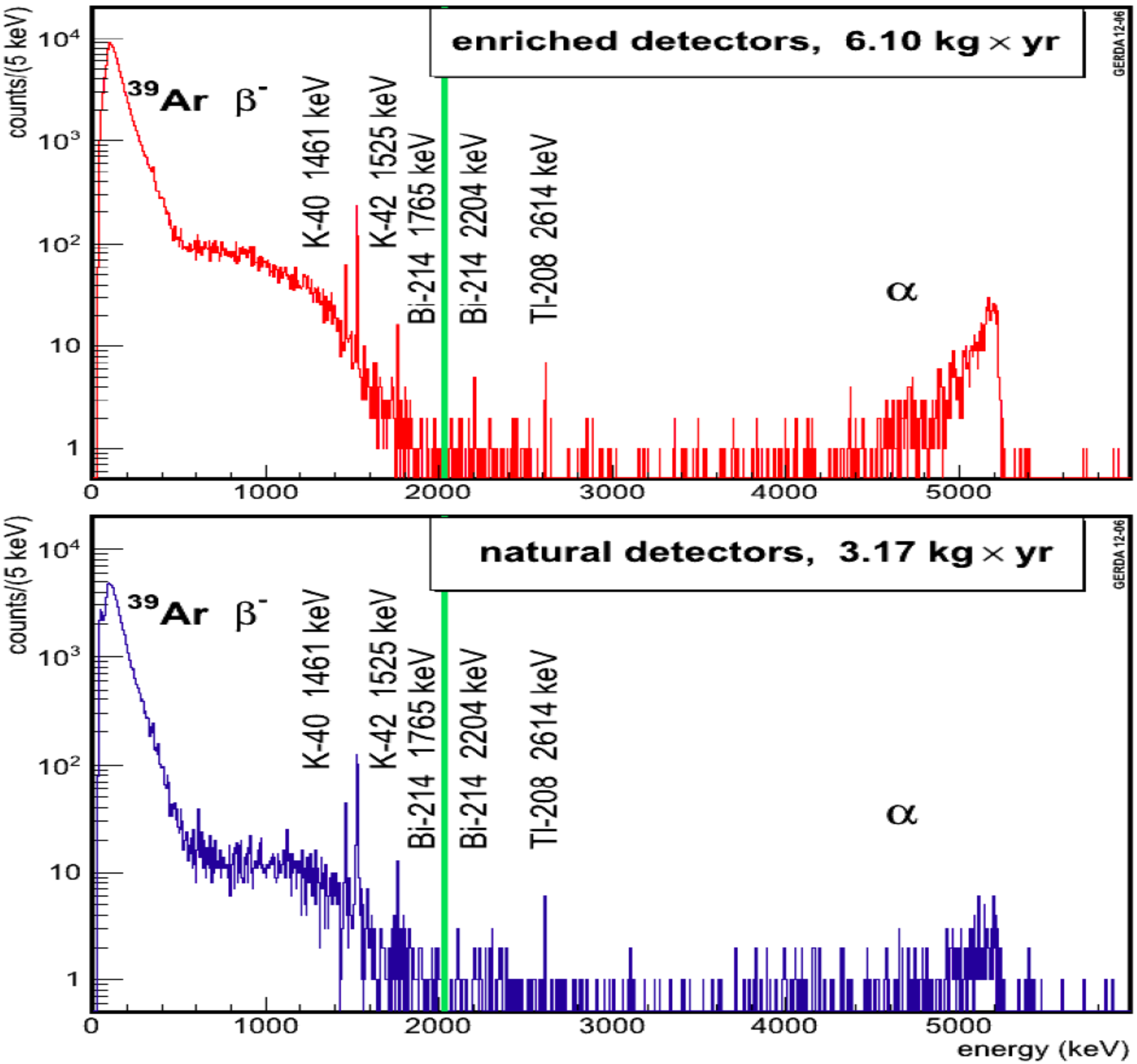


Commissioning phase completed: all enriched detectors in GERDA in October 2011!





Th-228 calibration spectra taken regularly 1 per 7-14 days



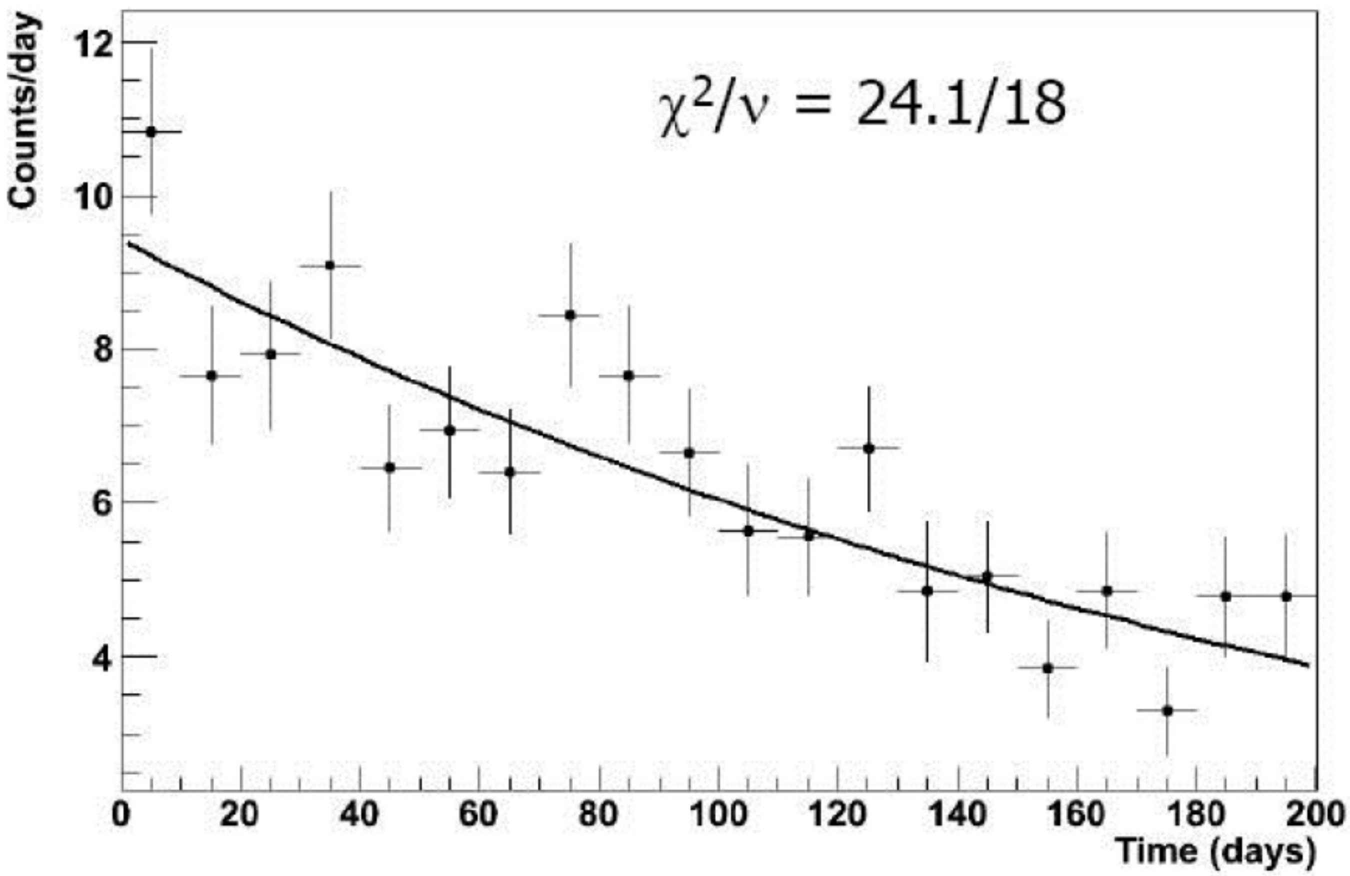
Cuts applied:

- Data quality (noise)
- Muon-veto
- Ge-Ge anti-coincidenc

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

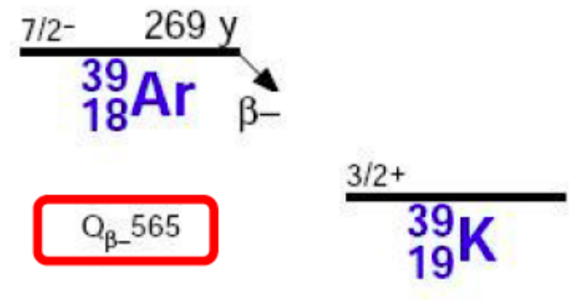
Visible backgrounds:

- Ar-39
- Alphas
- Indicated isotopes
- 2νββ decay of Ge-76

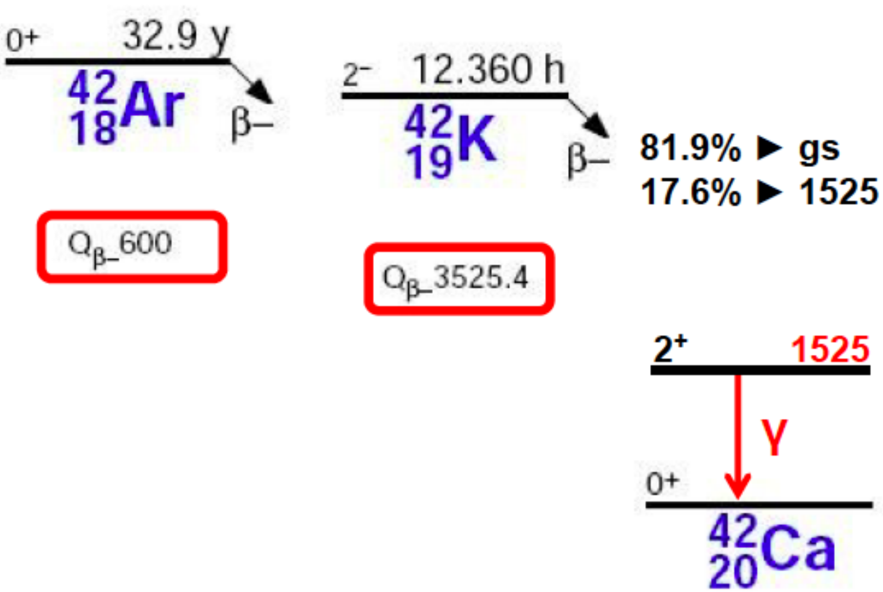


Tentative fit yields τ = (225±30) d; consistent with Po-210 (200 d), dto. Energy
Some indication that Po-210 was introduced in one refurbishing period

preliminary results: background: unstable Ar isotopes



Published activity of (1.01±0.08) Bq/kg (Benetti et al., NIM A574 (2007) 83) fully compatible with our data

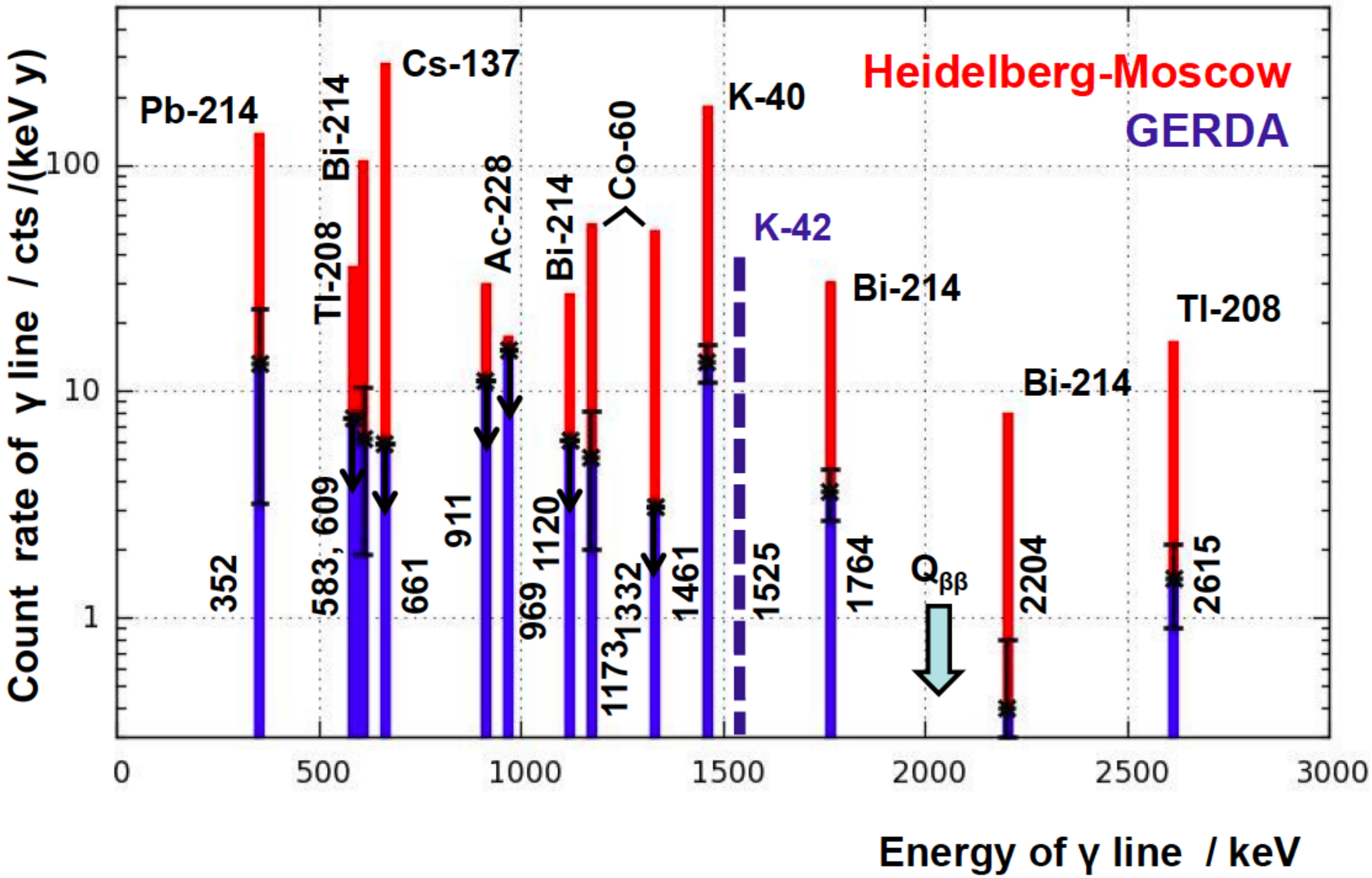


Limit <41 μBq/kg (90% CL) (Ashtikov et al., arXiv:nucl-ex/0309001) NOT compatible with our data

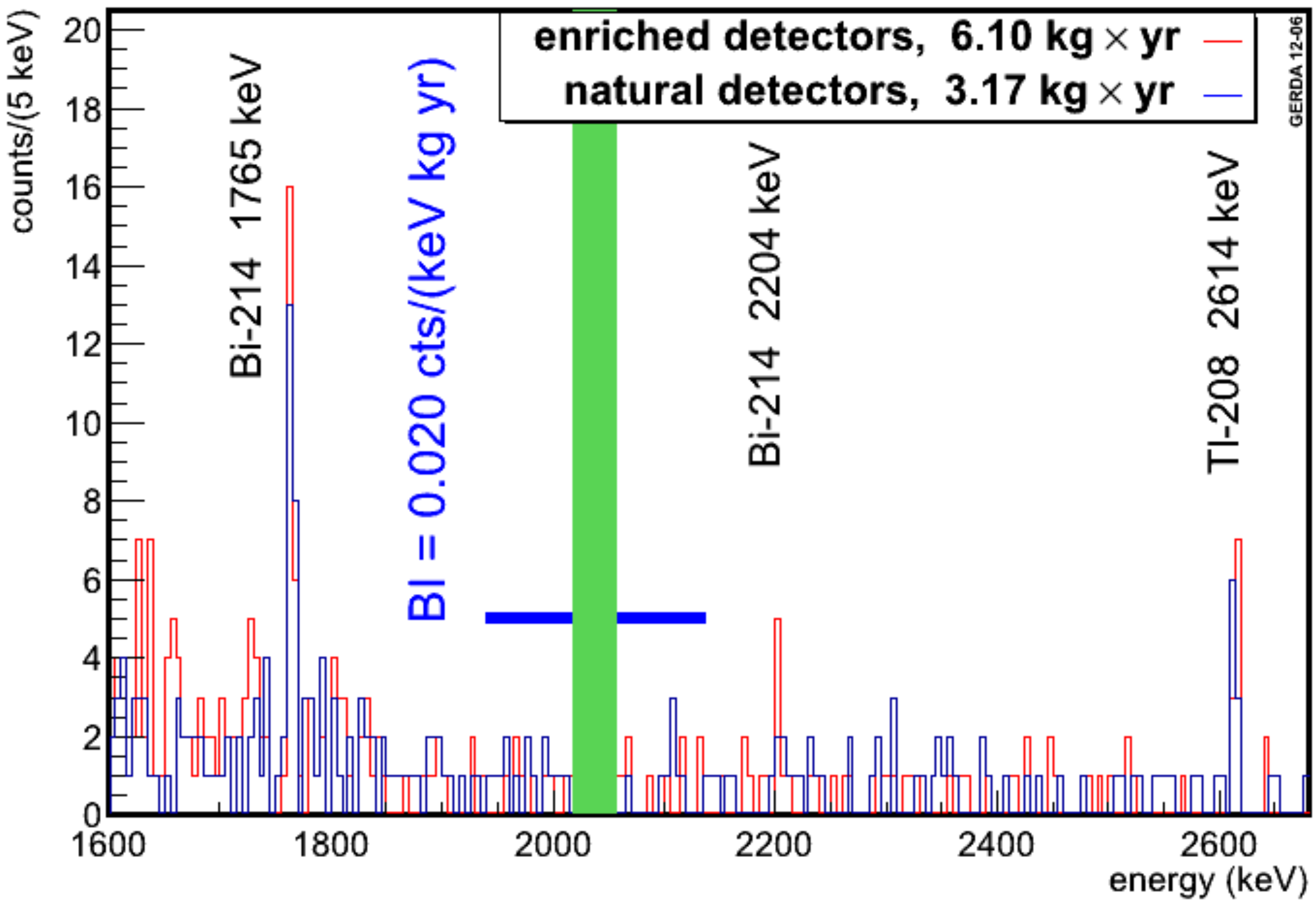
Intensity of 1525 keV line in E-field free setup indicates Ar-42 activity to be more than twice the value of avove limit

Evidence that charge K-42 ions drift in electic field of Ge-diodes.
Minishroud as shield against E-field

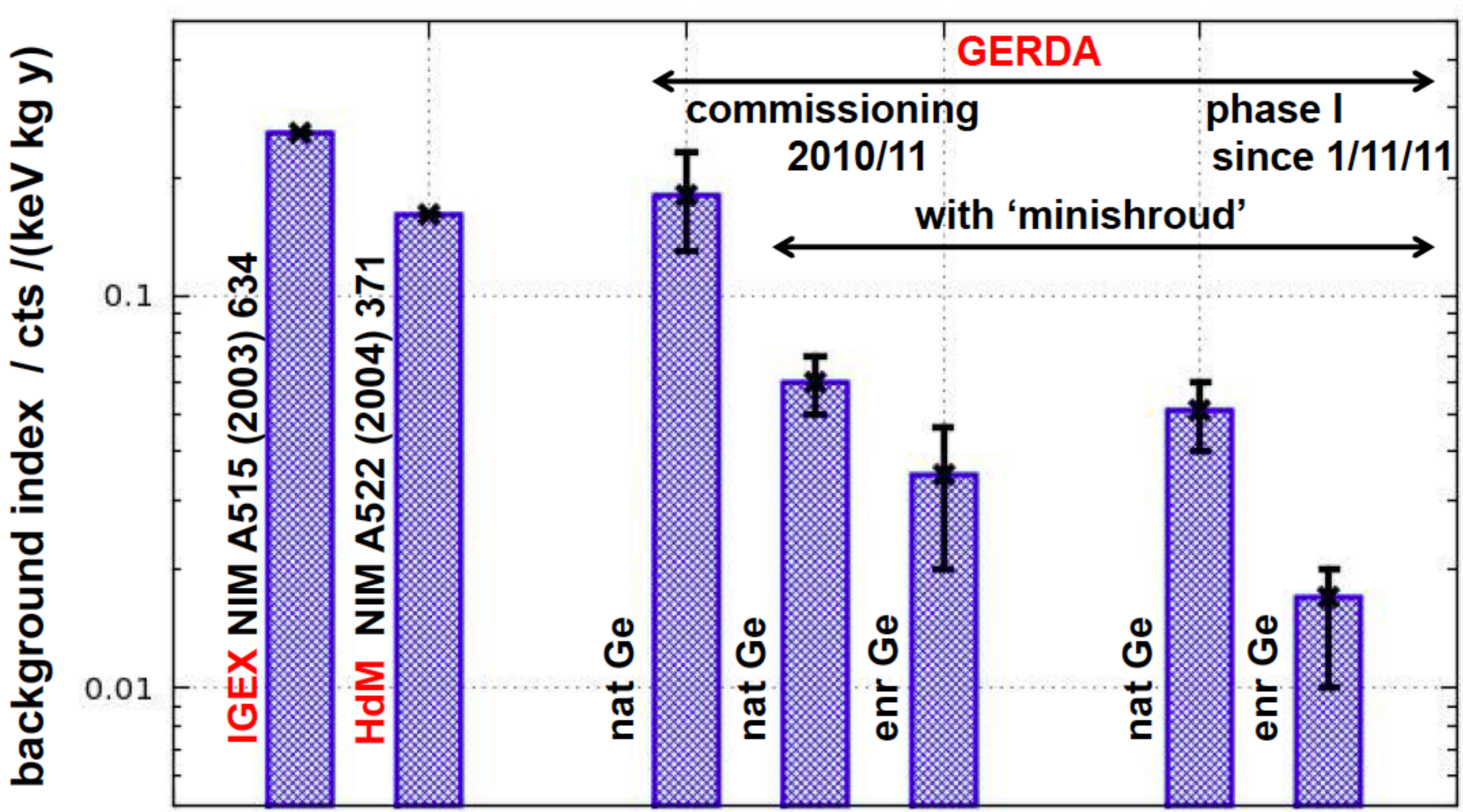
preliminary results: comparison with precursor experiments



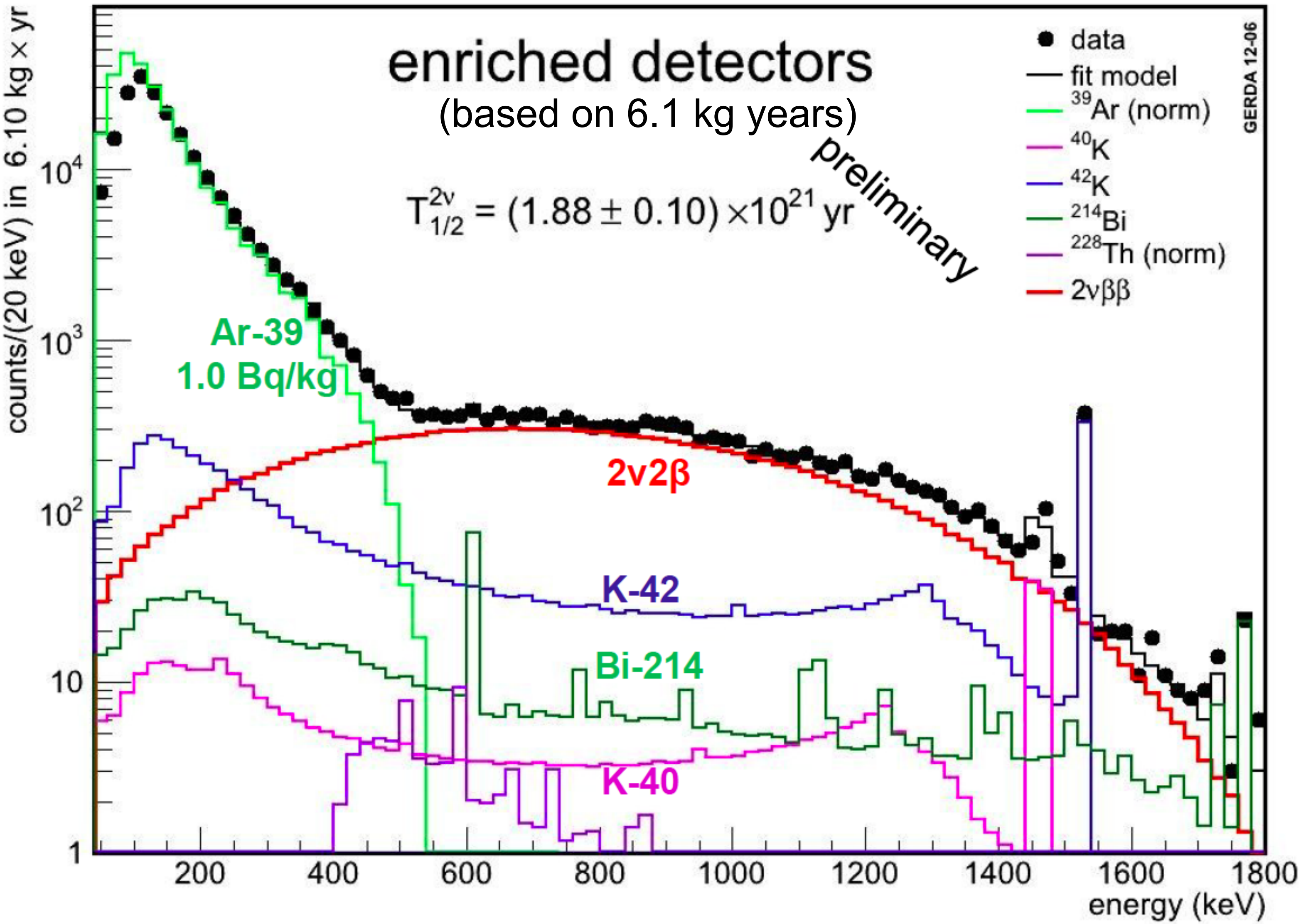
GERDA /HdM intensity ratio typically 1/10



Background index usually evaluated in ($Q_{\beta\beta}$± 100) keV
(excluding blinded region of ($Q_{\beta\beta}$±20) keV)

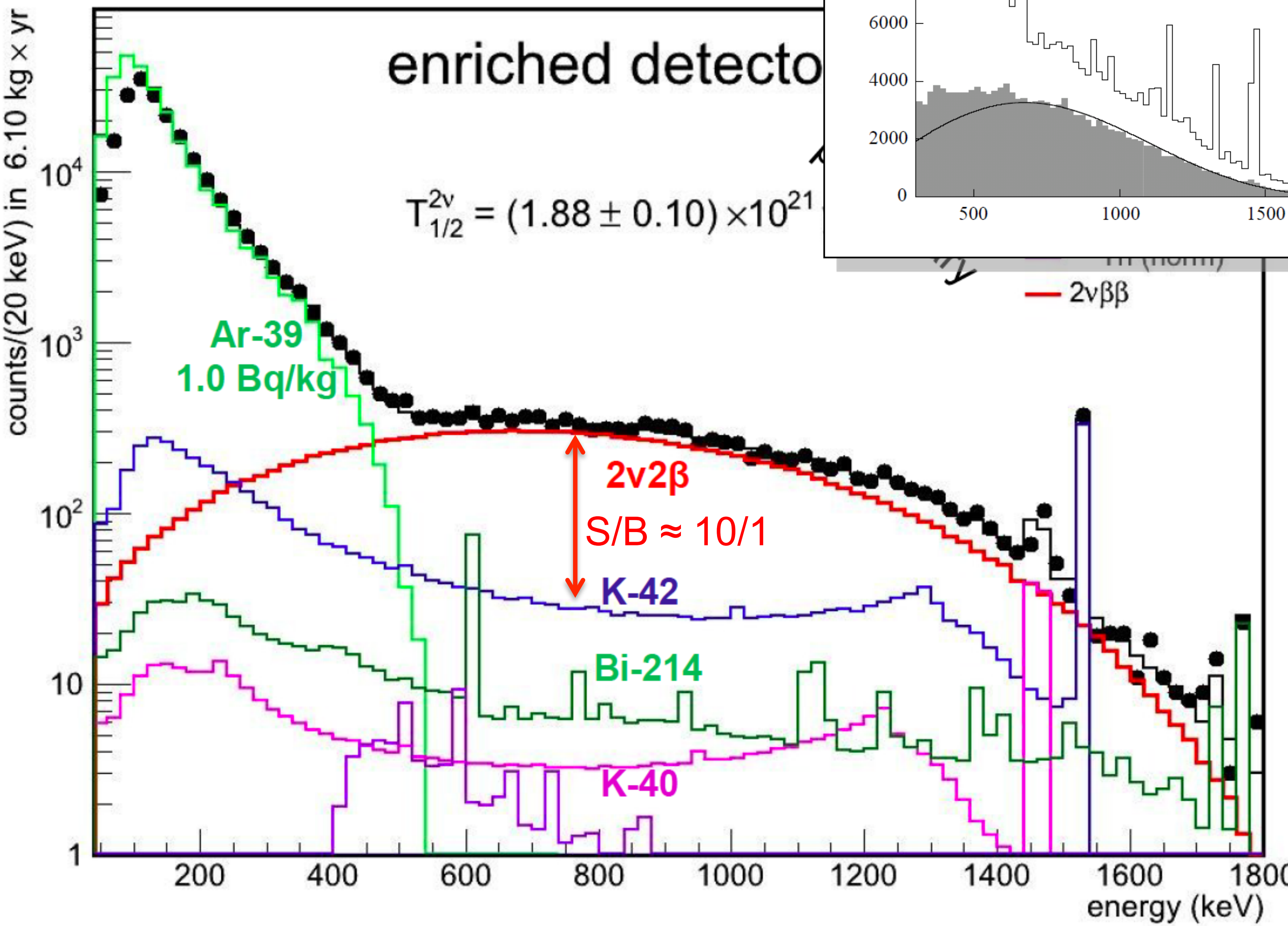


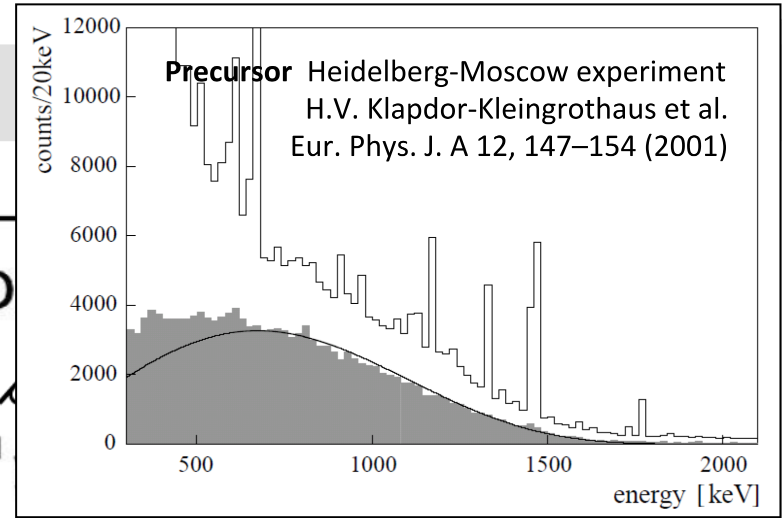
GERDA / HdM BI ratio almost 1/10



enriched detectors
(based on 6.1 kg years)
preliminary
T^{2ν}_{1/2} = (1.88 ± 0.10) ×10^{21} yr
data
fit model
39Ar (norm)
40K
42K
214Bi
228Th (norm)
2νββ
GERDA 12-06
Ar-39
1.0 Bq/kg
2ν2β
K-42
Bi-214
K-40
counts/(20 keV) in 6.10 kg × yr
energy (keV)

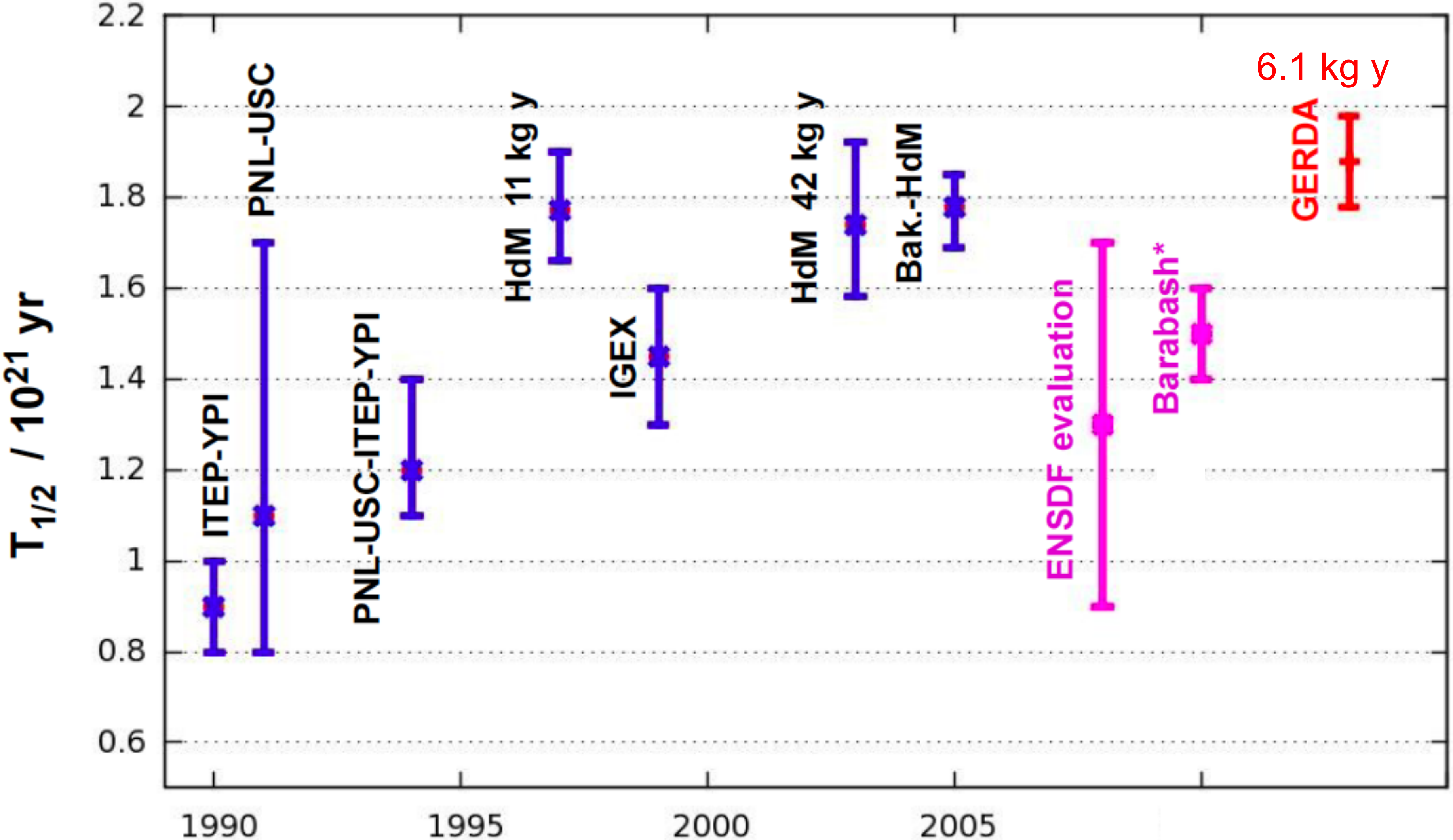
preliminary results: 2νββ spectrum





Significant improvement of S/B ➔ less systematic uncertainties

preliminary results: 2νββ half-live



* Evaluation by Barabash PR C81 (2010) 035501

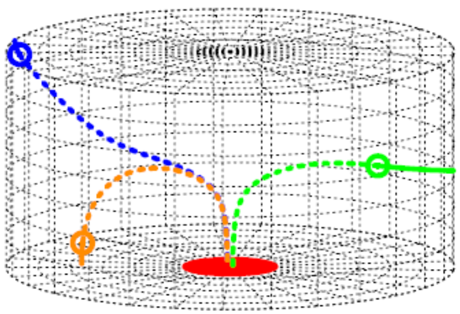
GERDA Phase I expected completion in spring 2013:

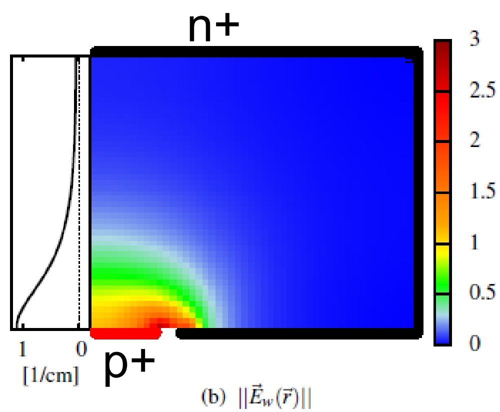
- Unblinding & physics analysis

Subsequently start of GERDA Phase II:

- Goal: reduce background by factor 10 w.r. to Phase I
- Up to additional 30 enriched BEGe detectors (20 kg)
- Liquid argon veto instrumentation

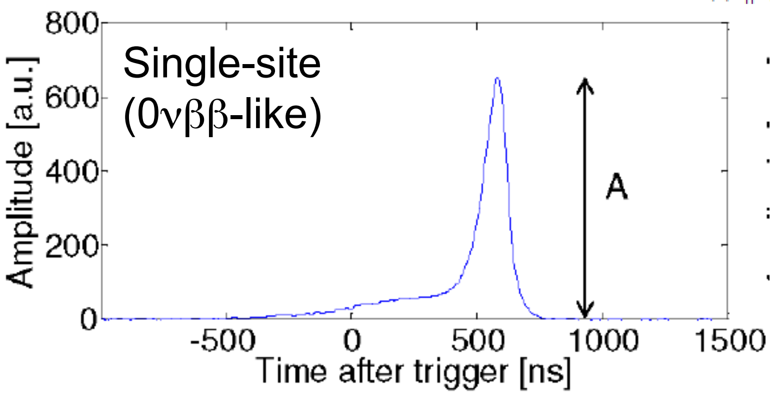
Phase II detectors: novel thick window BEGe detectors with advanced pulse shape performance

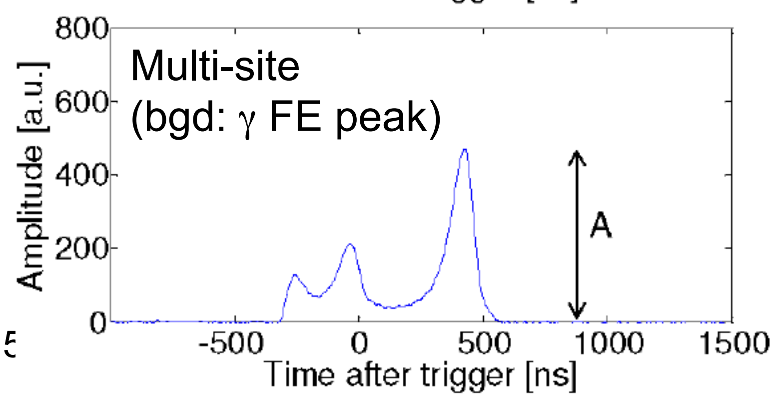


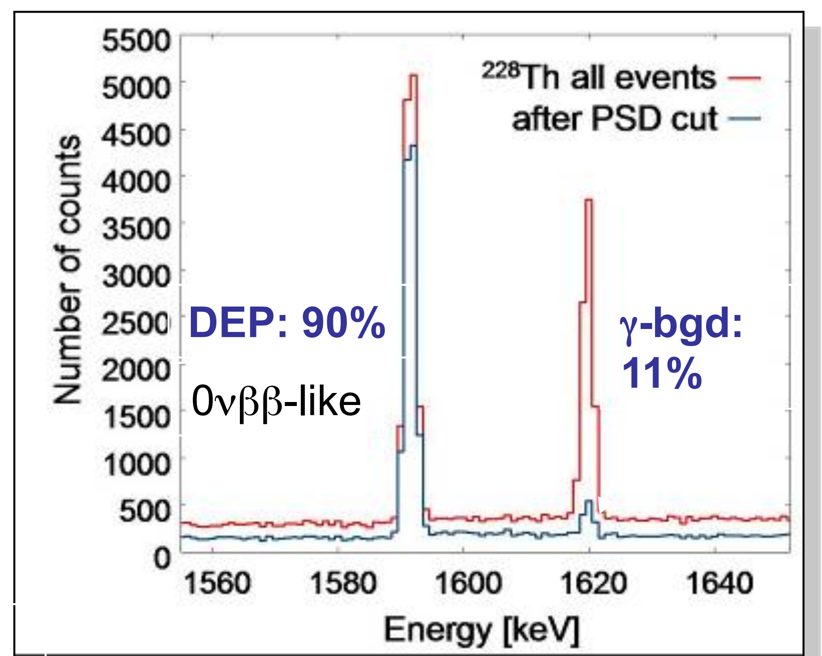


Signal shape provides clear topology for event-by-event signal ID / bgd discrimination:

- **SSE/MSE** discrimination
- **Surface** events:
  - n+ slow pulses
  - p+: 'amplified' current pulses

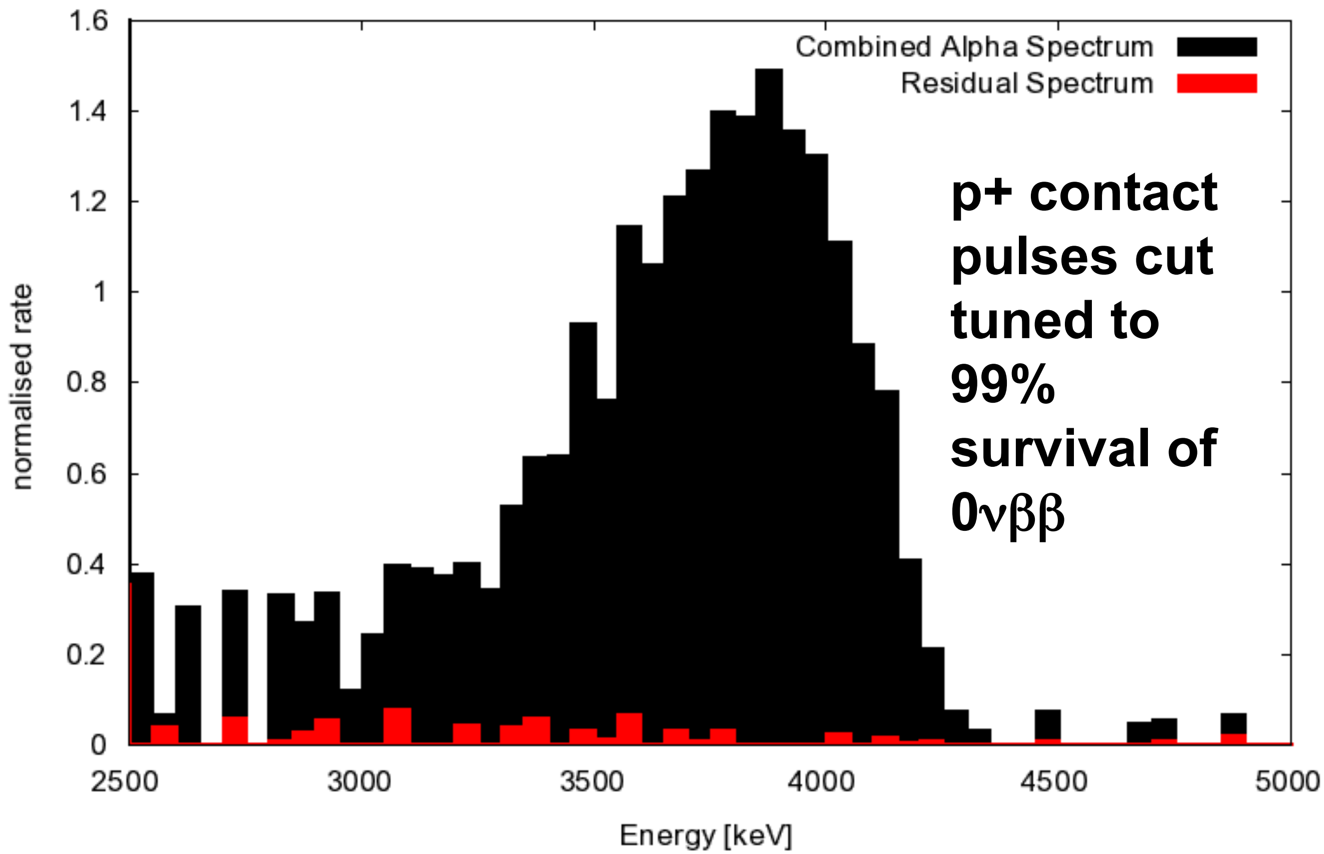






Budjas et al., JINST 4 P10007 (2009)
M. Agostini et al., JINST 6P03005 (2011)

Suppression of p+ contact pulses via PSD measured using Am-241 alpha source

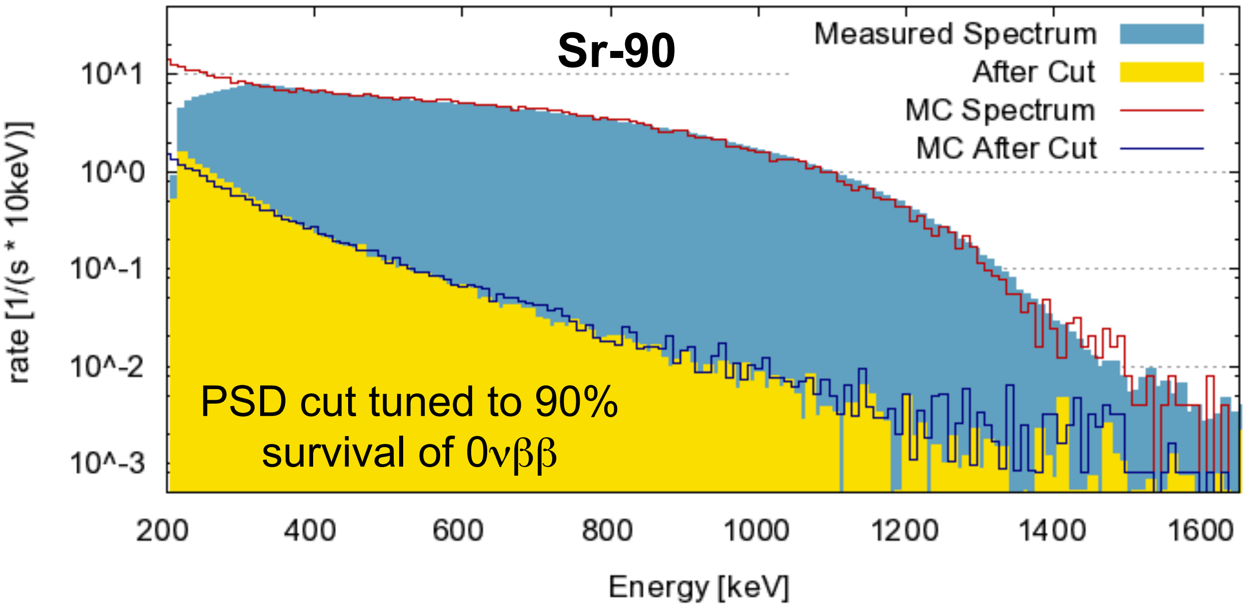


surface	p+ contact	groove inner	groove bottom	groove outer
event survival fraction *	< 0.011	< 0.12	< 0.009	< 0.011

* 90% confidence upper limits

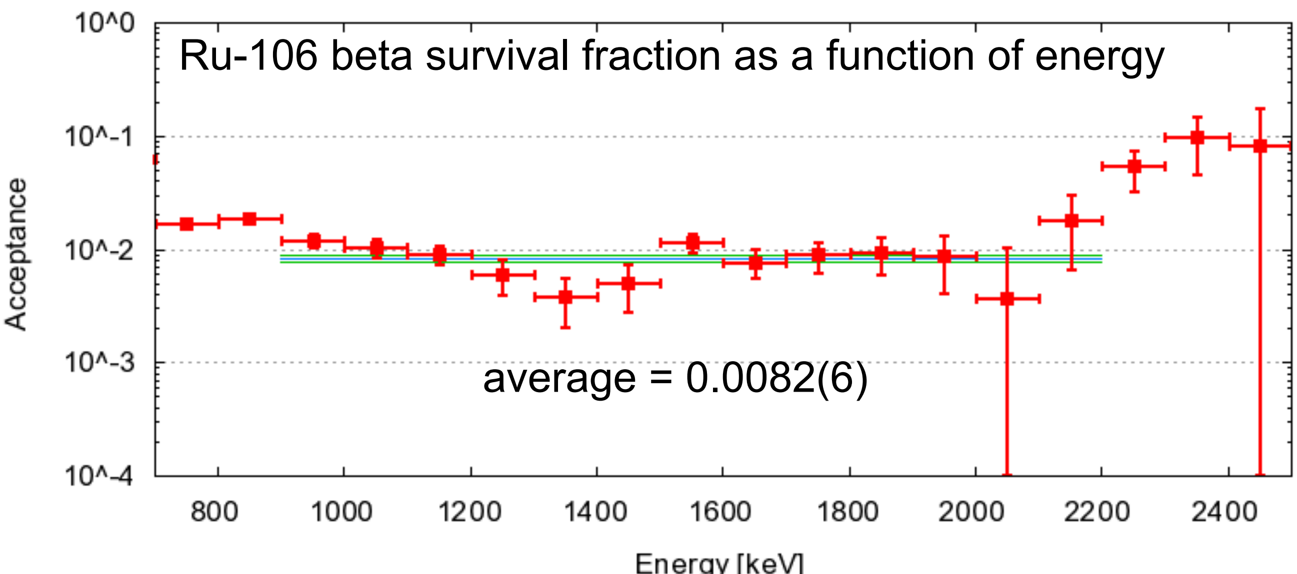
results limited by background in test setup; improved measurement analysis under way

Suppression of n+ surface events via PSD measured using Sr-90 and Ru-106 beta sources



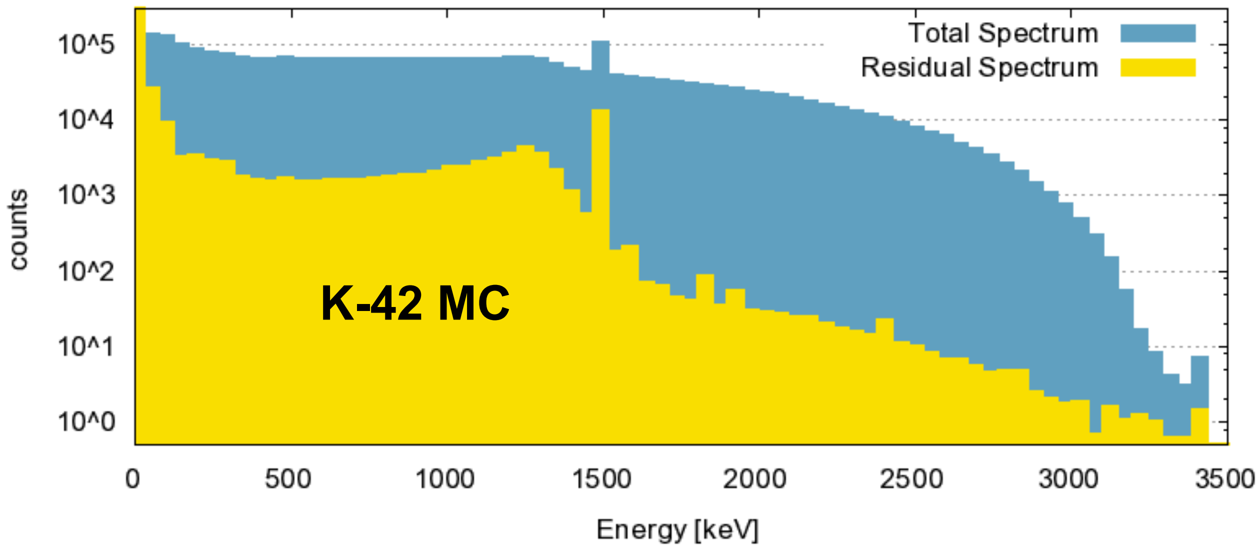
MC cut set to 20% survival of gamma-like events and 0.1% survival of beta-like events

good quantitative agreement of simulated suppression with measurement



beta n+ surface event PSD rejection power demonstrated stable in region 1 - 2 MeV

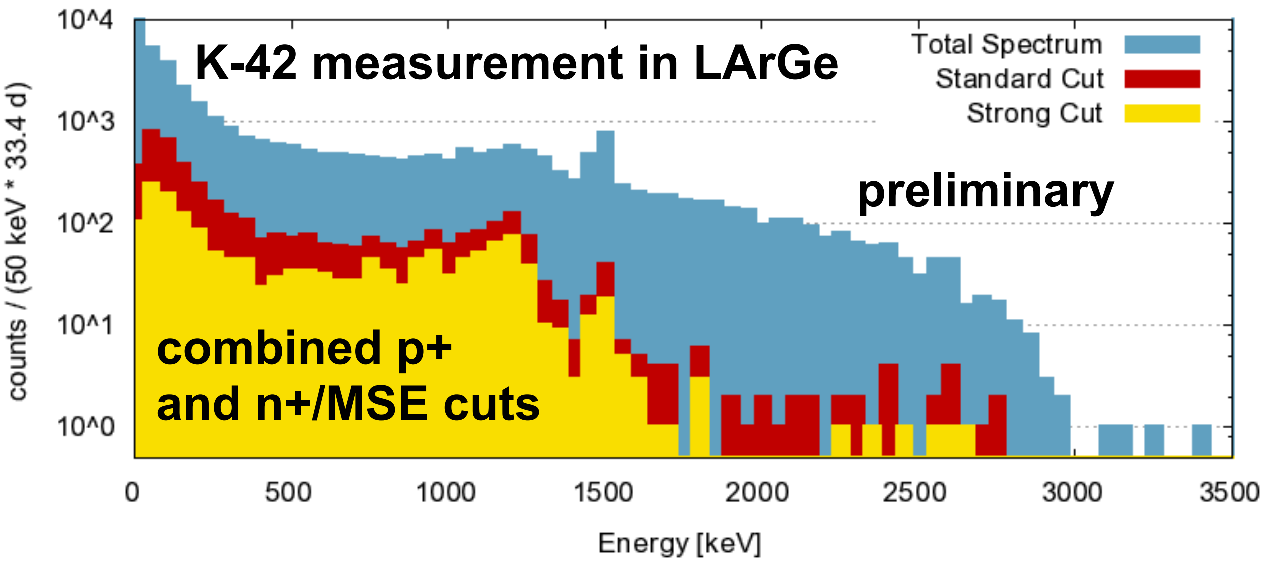
Suppression of K-42 n+ and p+ events via PSD measured with BEGe detector in LArGe with spiked ^{42}Ar



MC cut set to 20% survival of gamma-like events and 0.1% survival of beta-like events

expected surviving fraction at $Q_{\beta\beta}$: 0.13%

exp. suppression factor: 800



"Standard cut":
$0\nu\beta\beta$ survival: 89%
K-42 survival at $Q_{\beta\beta}$: 0.4% - 2%
suppression factor: 50 - 250

"Strong cut":
$0\nu\beta\beta$ survival: 65%
K-42 survival at $Q_{\beta\beta}$: < 0.23%
suppression factor: > 430 (90% C.L.)

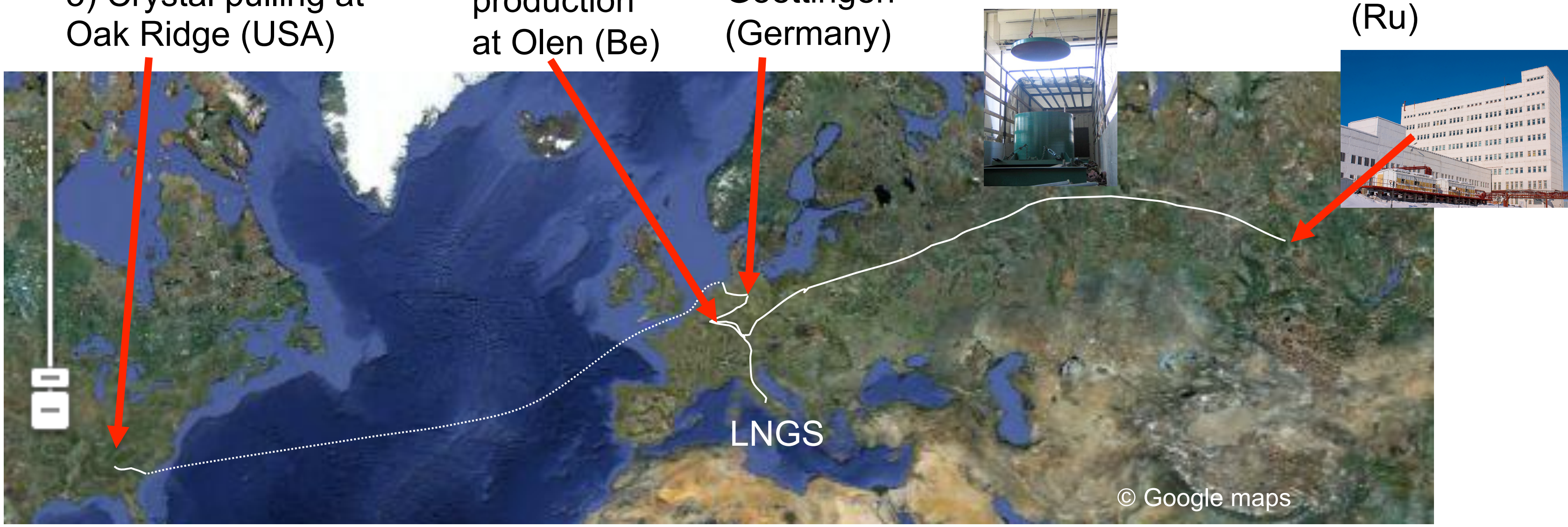
Path of new 37.5 kg of ^{enr}Ge (87% enrichment in ^{76}Ge): from isotope separation to final Phase II detectors

3) Crystal pulling at Oak Ridge (USA)

4) Detector production at Olen (Be)

2) Reduction and zone refinment at Goettingen (Germany)

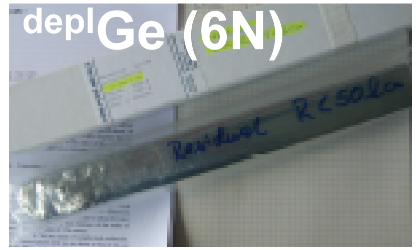
1) Isotope enrichement at ECP, Svetlana (Ru)



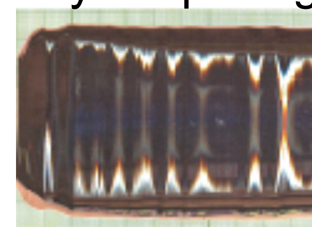
To minimize activation by cosmic ray:

- Transportation by truck or ship in shielded containers
- deep underground storage

Production test of BEGe detectors from depleted Ge for GERDA Phase II

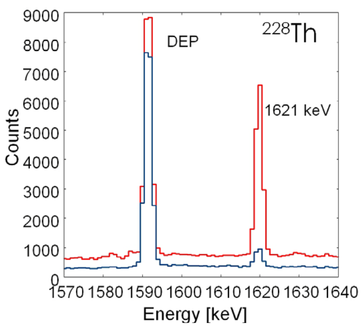


Crystal pulling



crystal slice

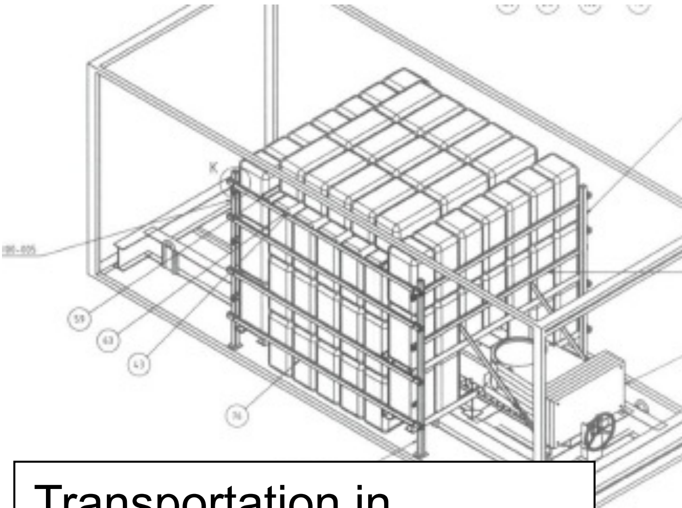
Full production chain tested with isotopic depleted germanium



After successful test of production production chain with ^{depl}Ge:

- **37.5 kg of 86% ^{enr}Ge** (in form of GeO2) purified to **35.4 kg (94%) of 6N** (+ 1.1 kg tail = 97%);

Production of enriched Ge crystals at Oak Ridge (USA) started October 17, 2011

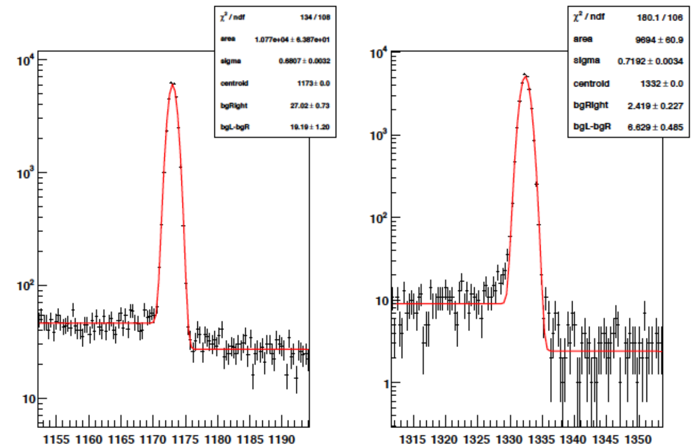


Transportation in shielded container to minimize cosmic ray activation

Ge stored underground storage when not processed

- Crystal production started on 17th of October
- Completion planned for June
- Production of first detectors: Jan/Feb 2012
- End of 2012: all Phase II detectors available

Acceptance test of enriched BEGe detectors underground at HADES facility (vicinity of Canberra, Olen, Be)



Complete detector characterization including energy resolution, dead layer, active volume, PSA, precision surface scan

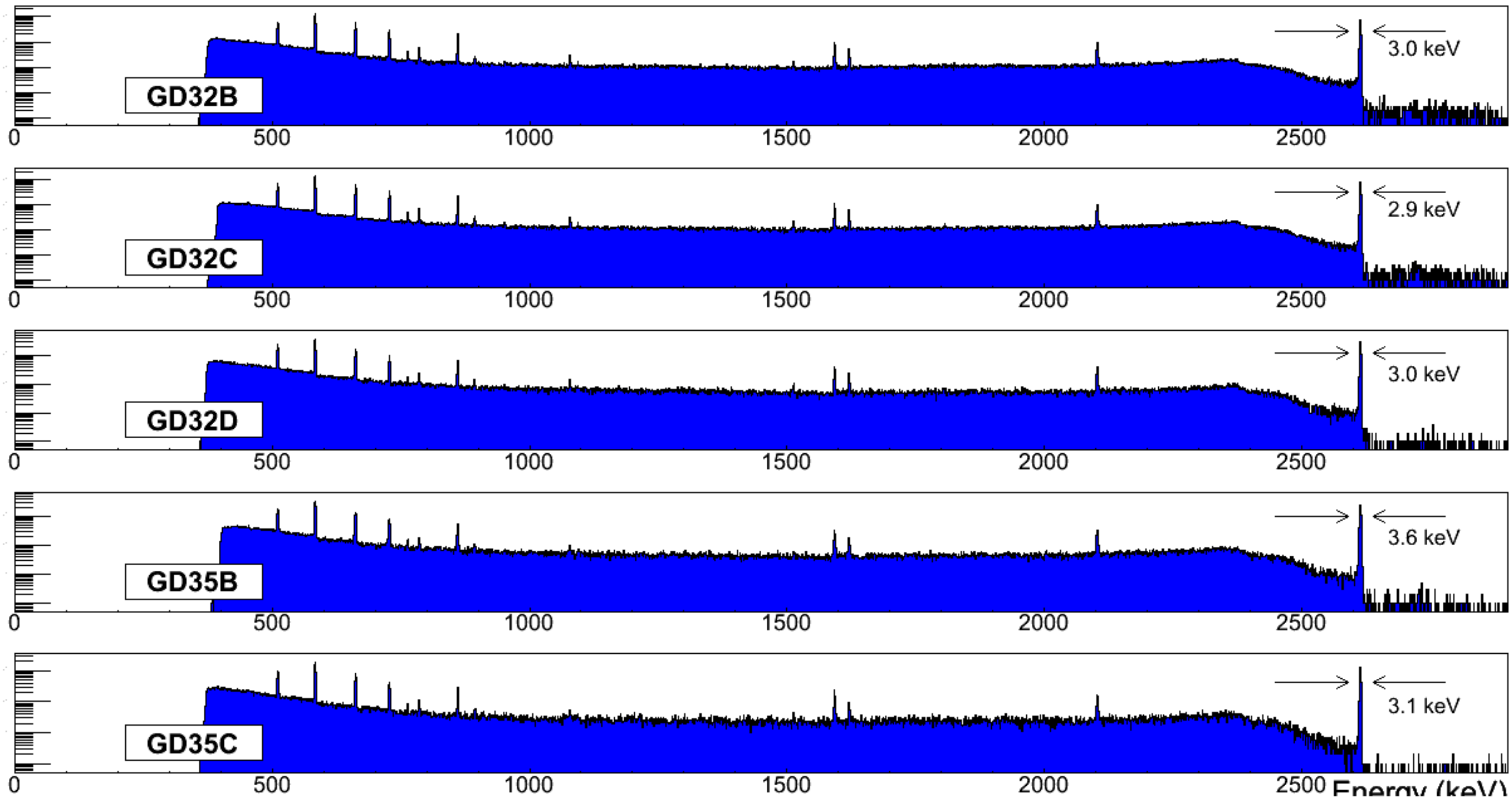
Diode	Crystal	Mass (kg)	Resolution (keV) ^{60}Co (1173 keV)	Average Dead layer (mm) ^{133}Ba
ARCHIMEDES	#2432AA	0.5	1.62 ± 0.02	0.8
AGAMENNONE	#2432BB	0.7	1.64 ± 0.01	0.8
ANDROMEDA	#2432CC	0.7	1.59 ± 0.01	0.8
ANUBIS	#2432DD	0.7	1.59 ± 0.01	0.8
ARGO	#2435AA	0.8	1.60 ± 0.01	0.7
ACHILLES	#2435BB	0.8	1.65 ± 0.01	0.8
ARISTOTELES	#2435CC	0.6	1.62 ± 0.02	-

Table 2: First results of the first ^{enr}BEGe prototypes. The diodes have been produced from different slices (AA-DD and AA-CC) from two grown crystals (#2432 and #2435).

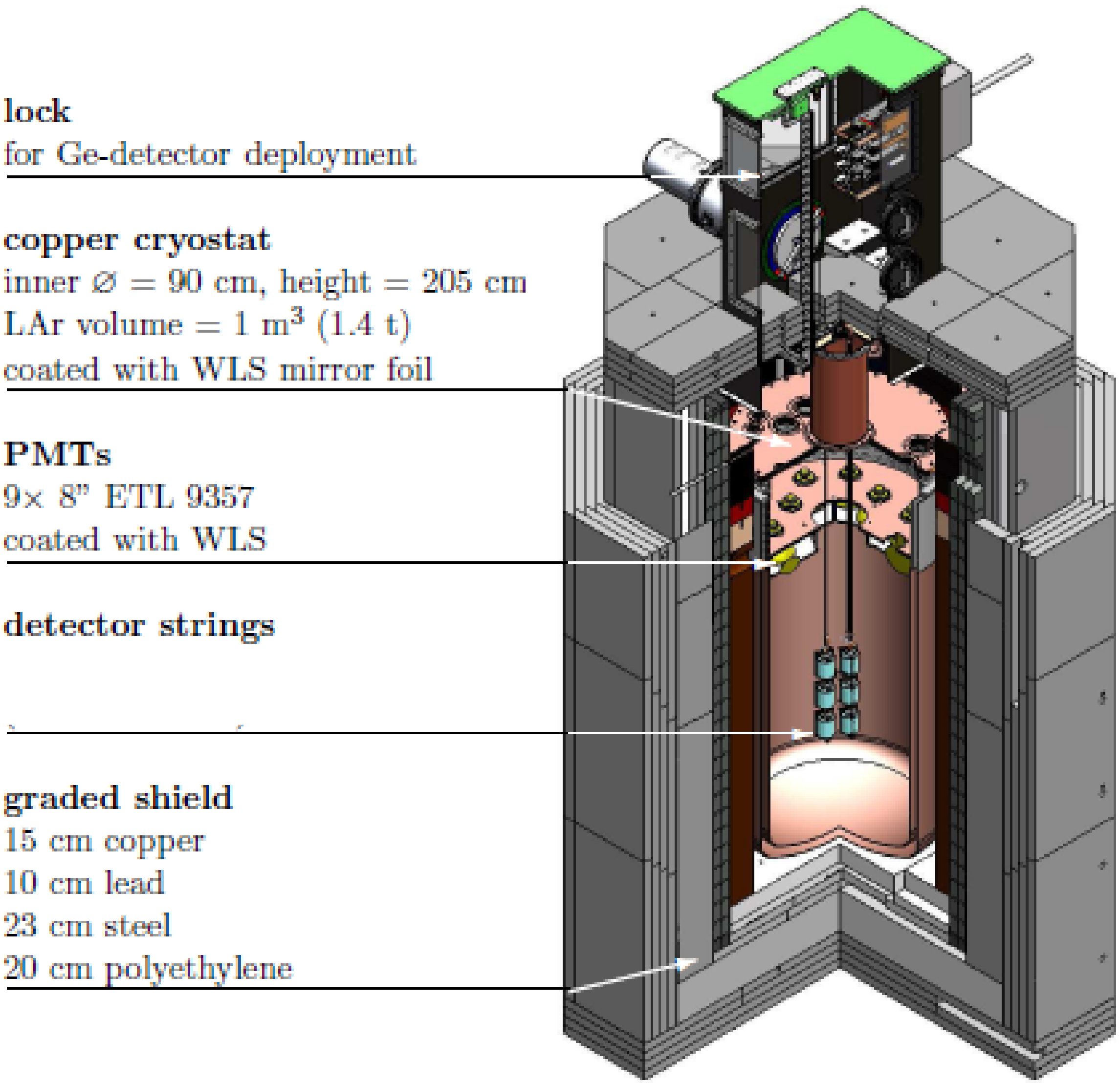
production of 7 crystal slices and detector tests completed:

- All detectors have excellent energy res.: 1.7 keV (FWHM) @1.3 MeV

First 5 Phase II enriched BEGe detectors deployed in GERDA

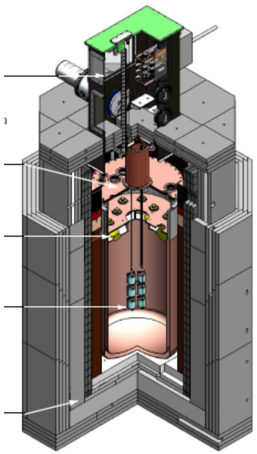


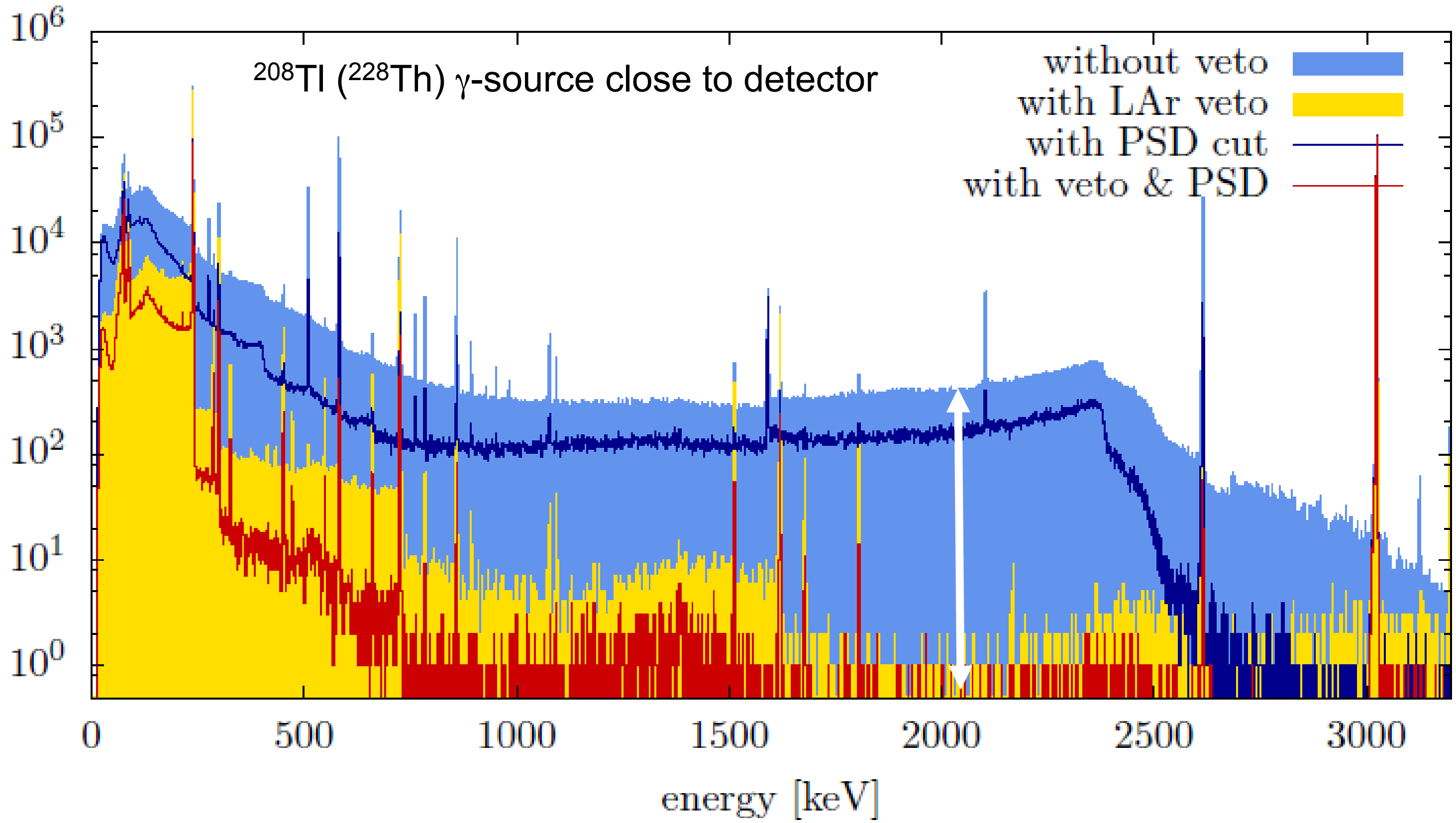
R&D: liquid argon instrumentation for Phase II



Low background **GERDA-LArGe test facility @ LNGS**: Detection of coincident liquid argon scintillation light to discriminate background

R&D liquid argon instrumentation



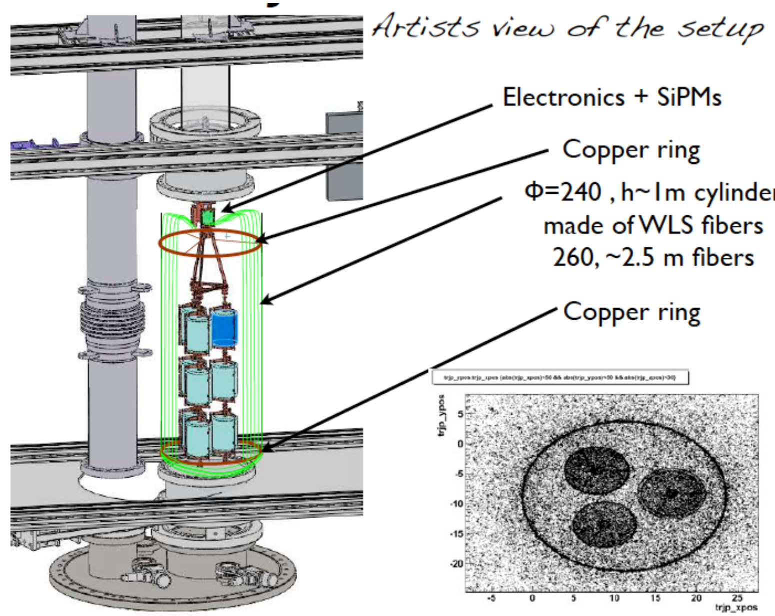


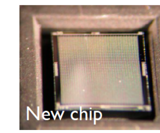
Operation of Phase II detector prototype in LArGe:
Measured suppression factor at $Q_{\beta\beta}$: **~0.5·10^4** for a ^{228}Th calibration source
Also: successful read out scintillation light with fibers coupled to SiPMs

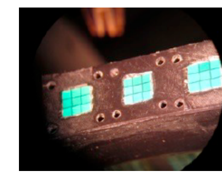
LAr instrumentation for Phase II

PMT option (Ø500)

SiPM & scintillating fiber option (Ø250)

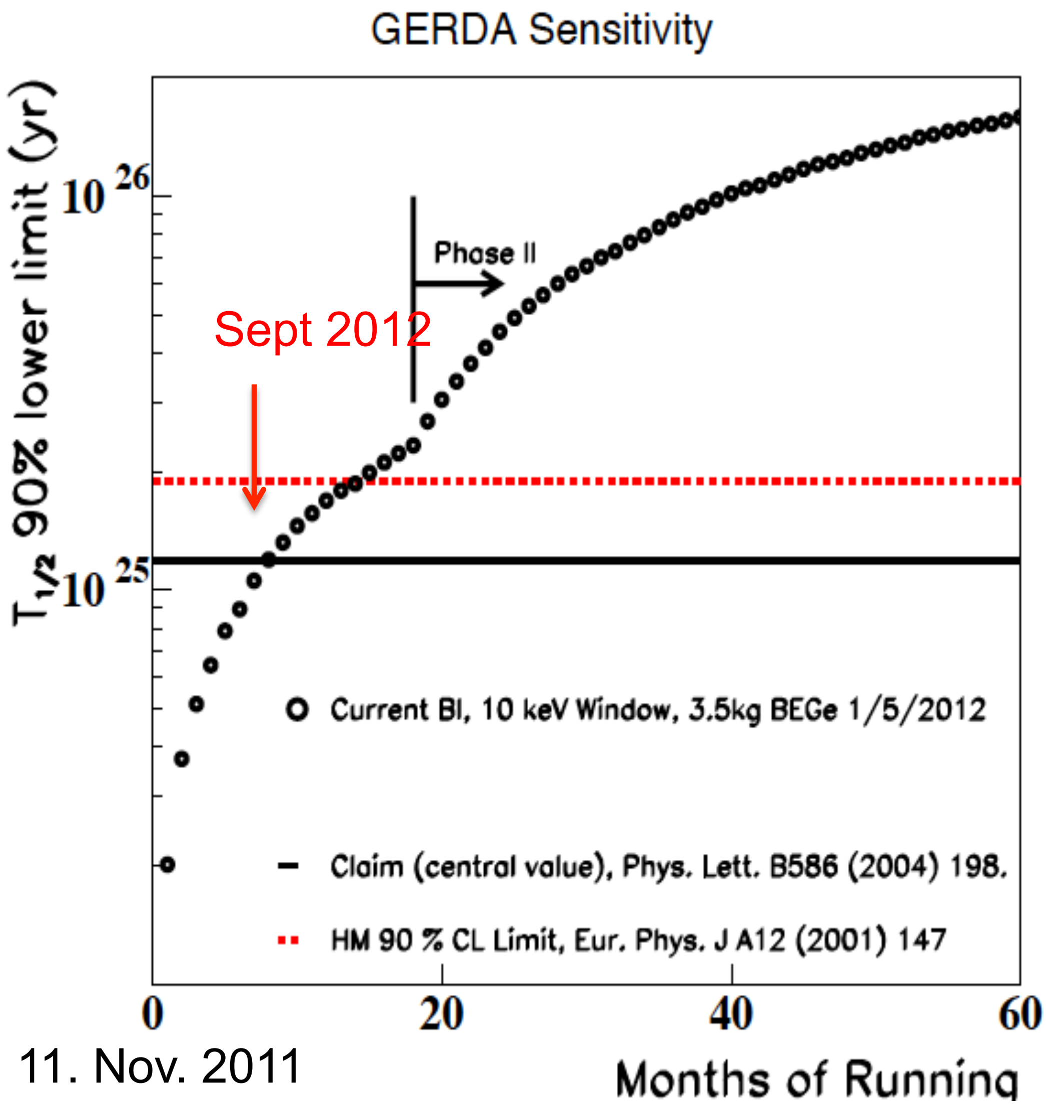






- 3^{rd} option: R&D on large area avalanche photodiodes or UV sensitive SiPMs on custom low activity substrates has started
- MC campaign to compare competing options ongoing
- Hardware for PMT and fiber options available & prototype/test setup construction started

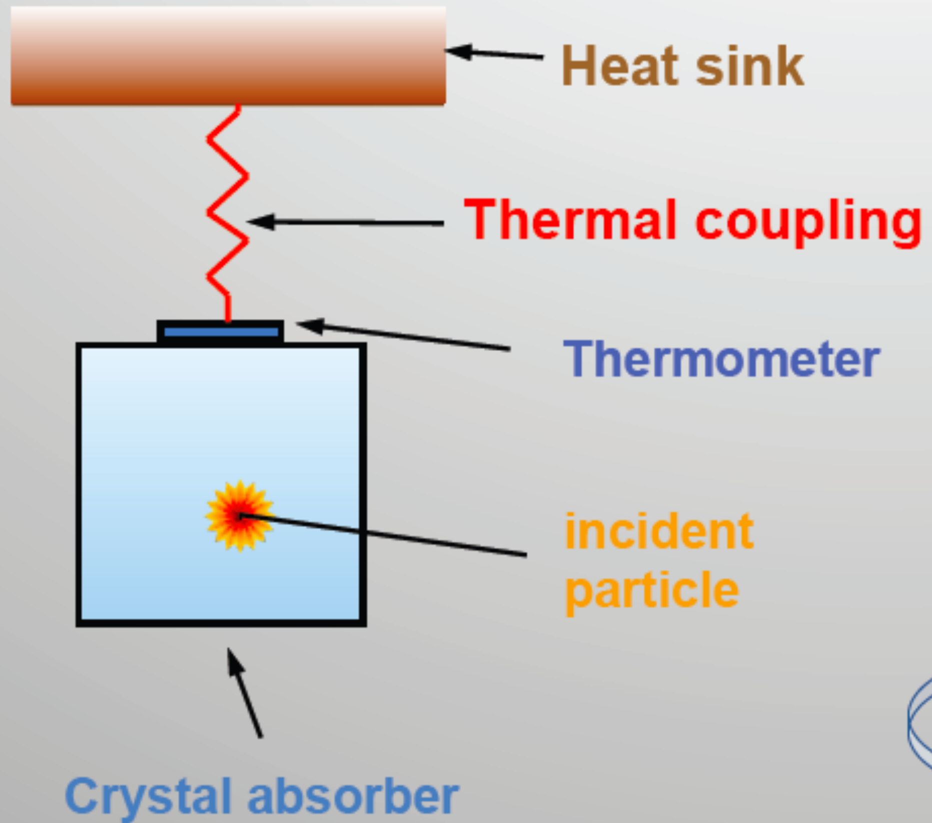
GERDA Phase I/II sensitivity



11. Nov. 2011

Bolometric technique

The working principle is very simple:



This technique measures **all** the energy deposited by a particle in form of increase of temperature in the absorber

↓

Absorber ≡ DBD source

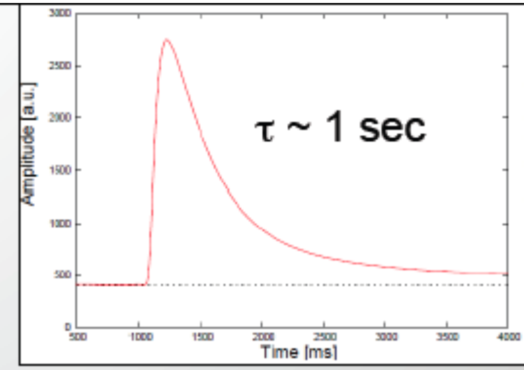
Signal: $\Delta T = E/C$

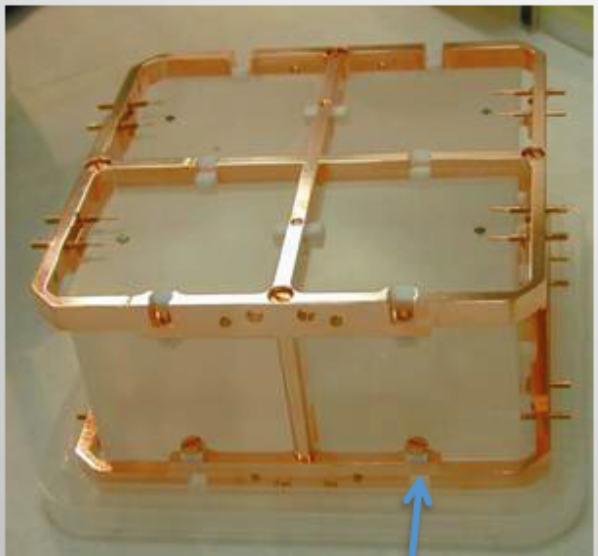
Time constant $= C/G$

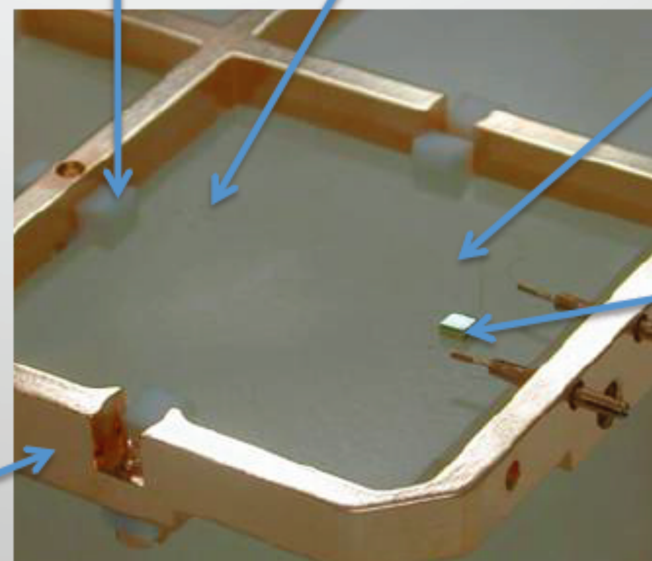
Low heat capacity
- Low temperatures (~10mK)
- Dielectric diamagnetic materials

From M. Pedretti, Neutrino 2012

TeO_2 Bolometers







PTFE pieces

TeO_2 crystal

25 μm gold wire connection

Neutron Transmutation Doped Ge sensor

Copper holder

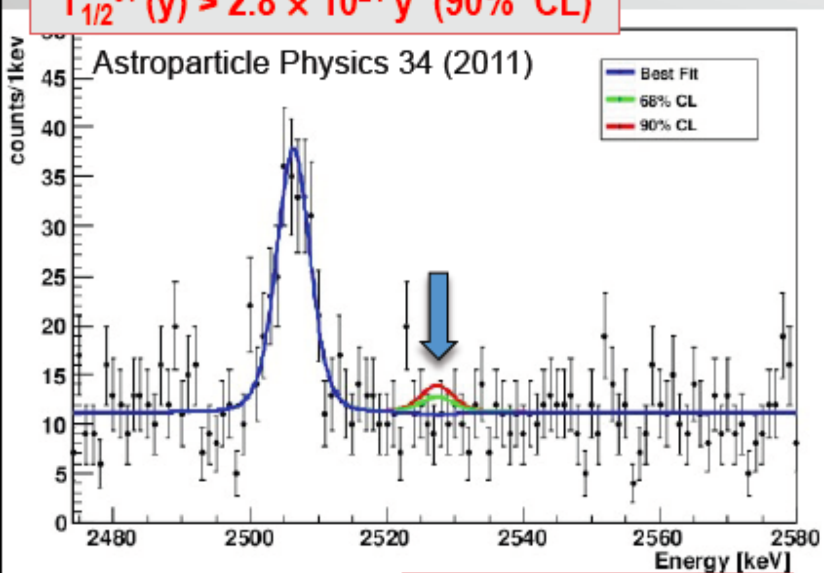
From M. Pedretti, Neutrino 2012

Bolometric 0νDBD experiment evolution

$\Delta E = 6.2 \pm 2.5$ keV (~0.3% FWHM)

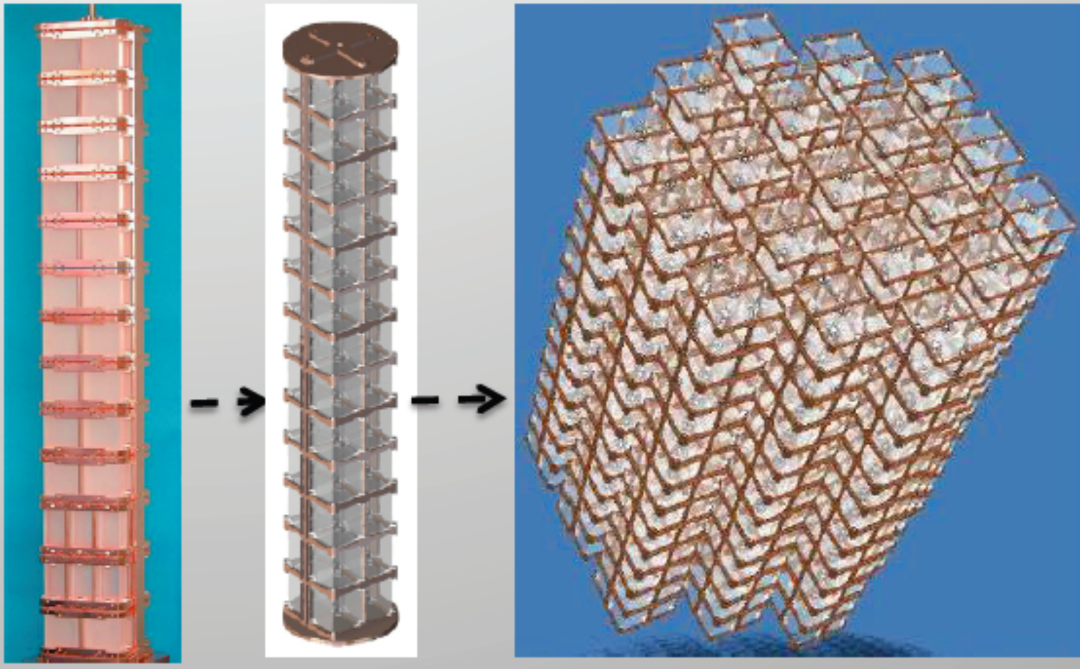
Bkg = 0.169±0.006 c/keV/kg/y

$T_{1/2}^{0\nu}$ (y) > 2.8×10^{24} y (90% CL)



$\langle M_{bb} \rangle < 0.3 - 0.7$ eV

CUORICINO	CUORE-0	CUORE
40 kg	(2012)	1 ton
(2003-2008)		(~2014)

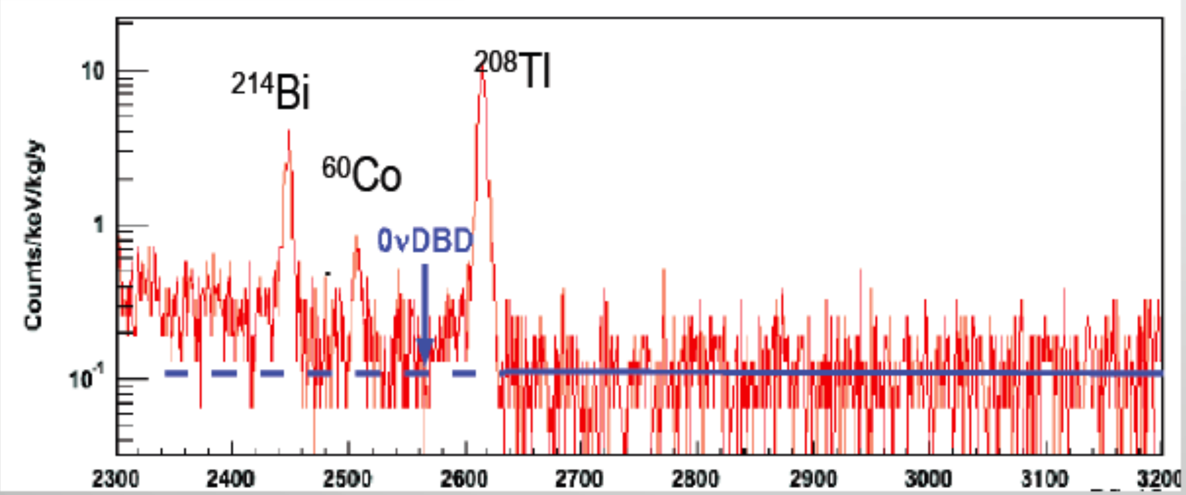


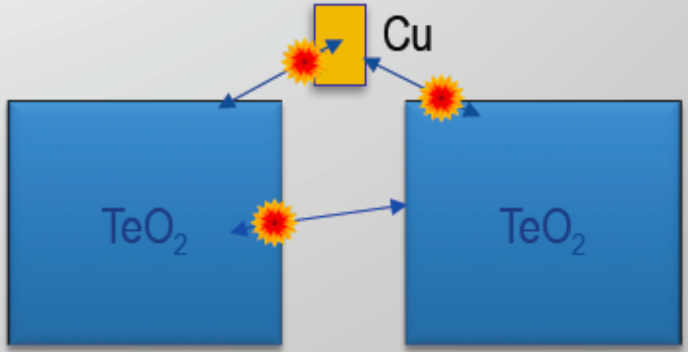
From M. Pedretti, Neutrino 2012

CUORICINO lesson: background

Sensitivity of current generation bolometric DBD experiment is limited by bkg.

MC: the background in CUORICINO is due to degraded alpha particles which release only part of their energy in the detector (surface contamination)





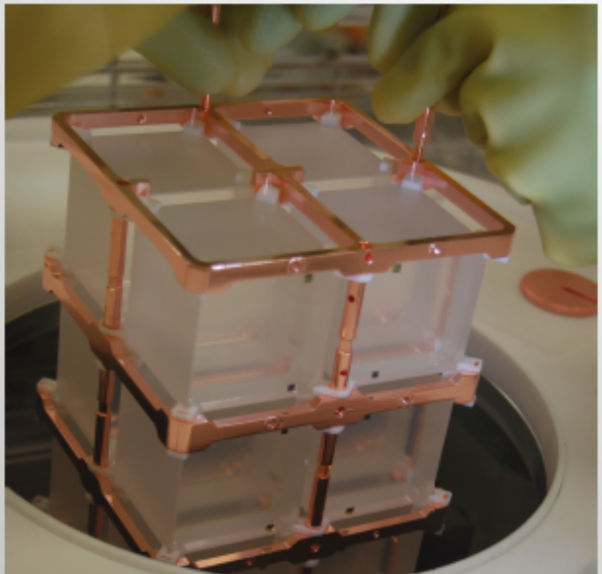
$b_{CUORICINO}$ = 0.169 c/keV/kg/y due to:

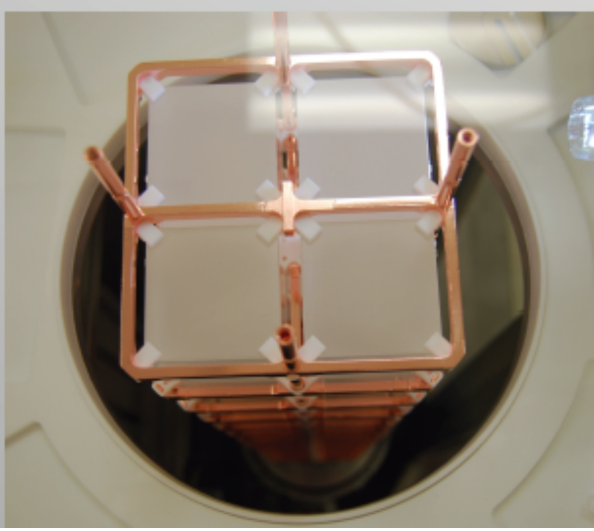
- ^{232}Th in cryostat (30 ± 10%) → γ
- TeO_2 surfaces (10 ± 5%)
- Surfaces facing detectors (50 ± 20%)

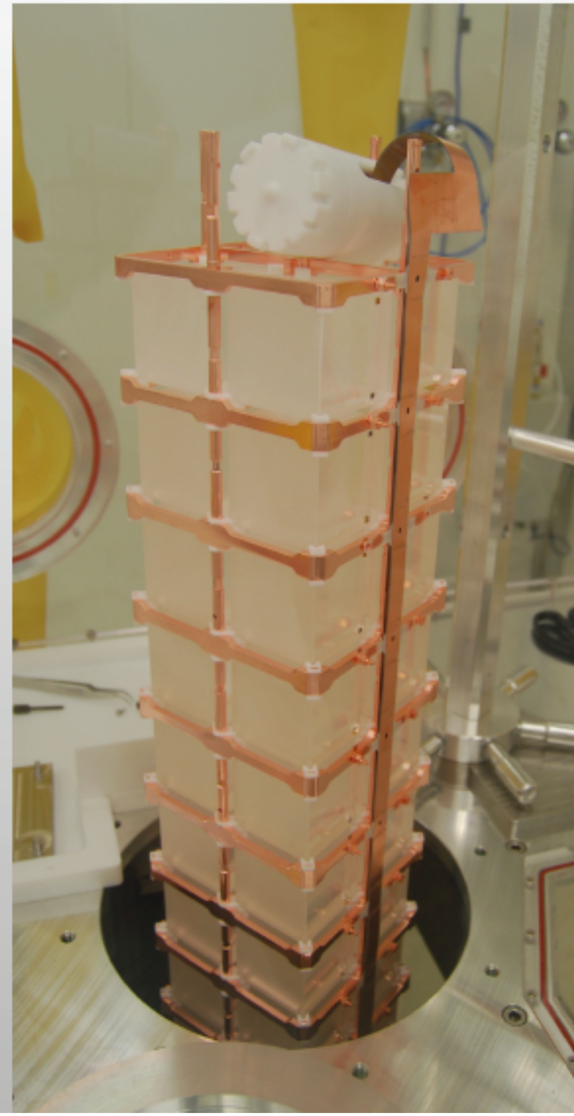
} degraded α particles

From M. Pedretti, Neutrino 2012

CUORE-0: tower assembly

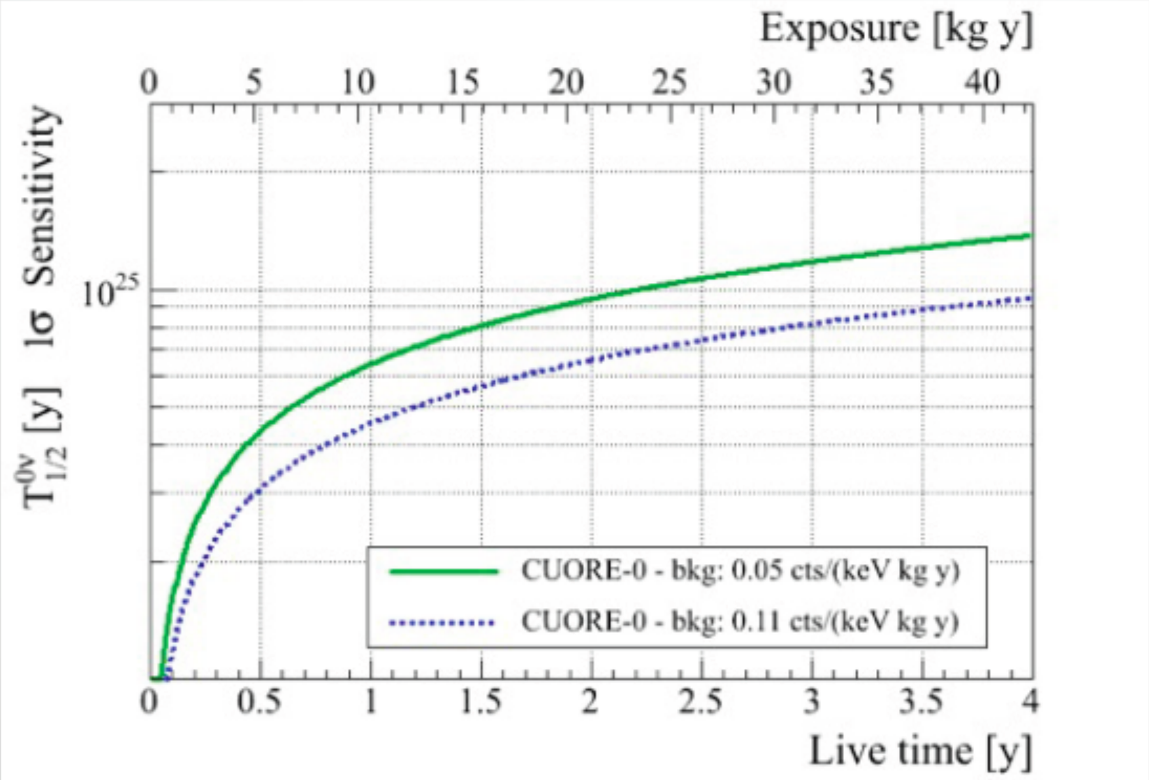






From M. Pedretti, Neutrino 2012

CUORE-0: sensitivity



Limited by the cryostat contamination bkg

Background: 0.05-0.11 c/keV/kg/y range

If 0.05 c/(keV kg y), expected 2-year sensitivity is

$T_{1/2}$ = 5.9 x 10^{24} y @ 90% CL

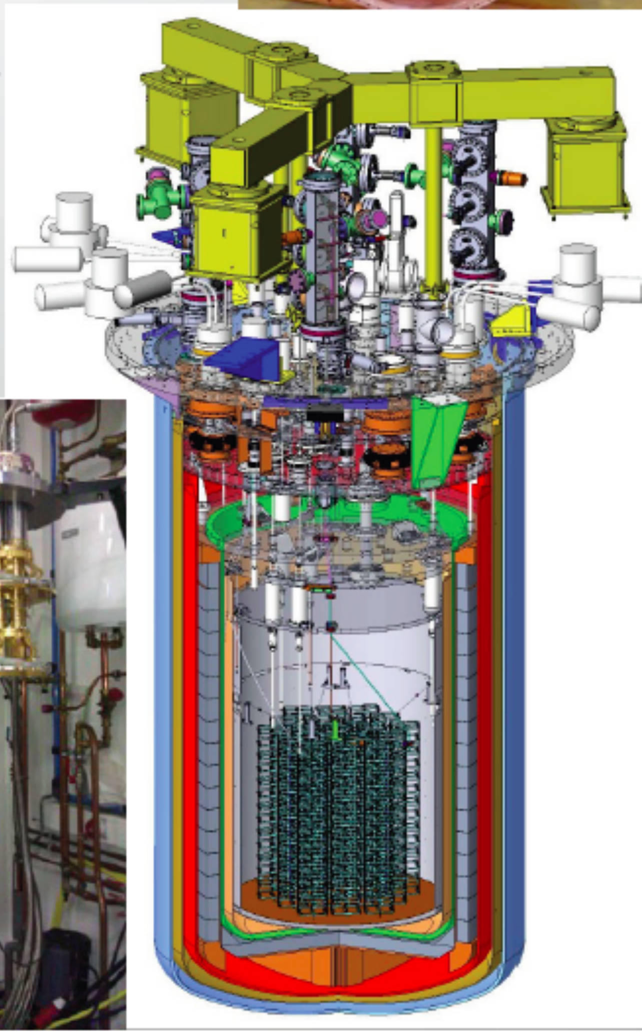
(CUORICINO: $T_{0\nu} > 2.8\times10^{24}$ y)

$m_{\beta\beta}$ = 170 - 390 meV

From M. Pedretti, Neutrino 2012

CUORE status

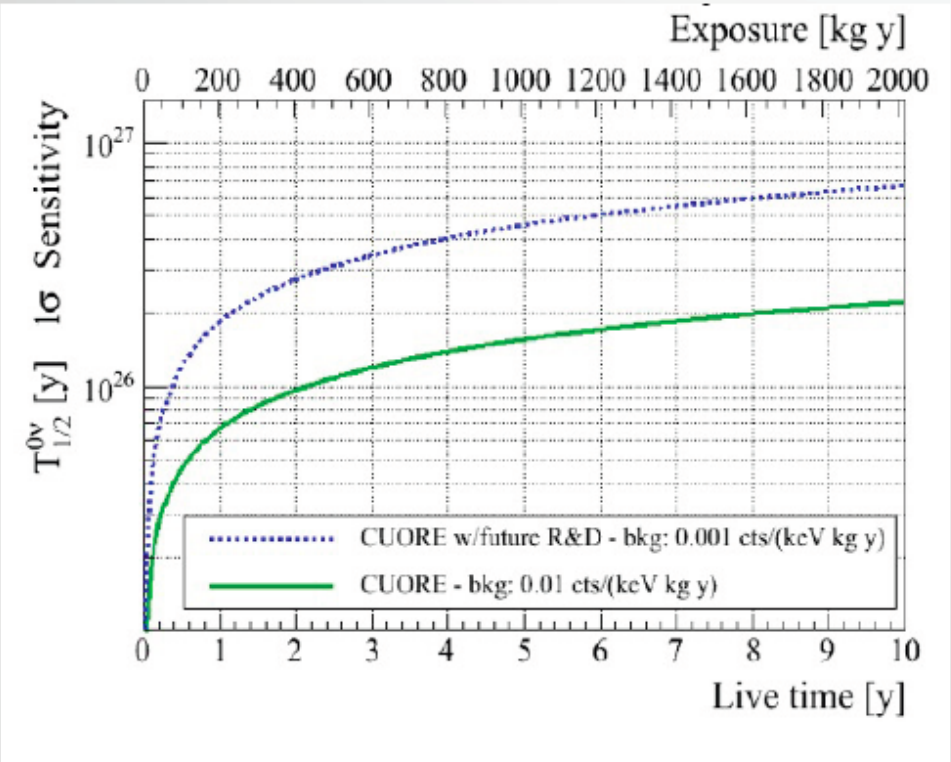
- Crystals, almost all arrived (all at LNGS by the end of 2012)
- Copper parts are being machined and cleaned
- Dilution unit delivered to LNGS (though some repairs needed)
- CUORE Hut, and most of all the infrastructures, ready
- Detector assembly line, ready (small modifications)
- Radon abatement system installed
- 3 (of 6) cryostat vessels delivered soon at LNGS
- Commissioning of the cryostat second half of 2012



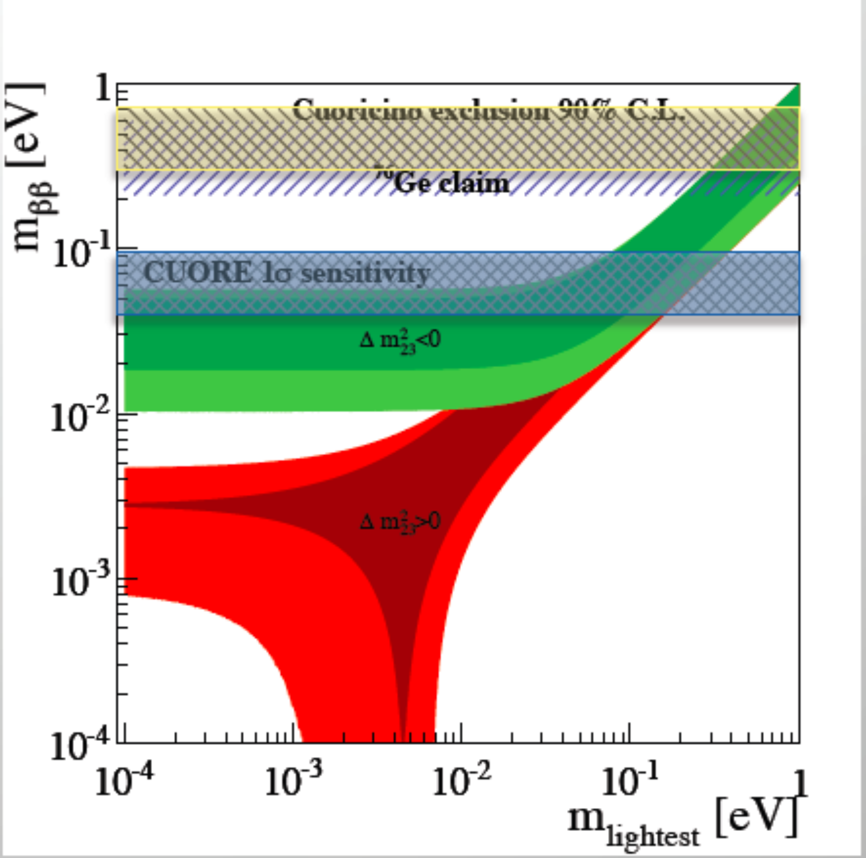
Crystals	12/12
Thermistors	13/03
Cleaned Cu parts	13/12
Cryogenic	13/12
Tower Assembly	14/04
Detector insertion	14/07
Cool Down	14/11

From M. Pedretti, Neutrino 2012

CUORE sensitivity



F. Alessandria et al. [CUORE coll.]
http://arxiv.org/abs/1109.0494v1



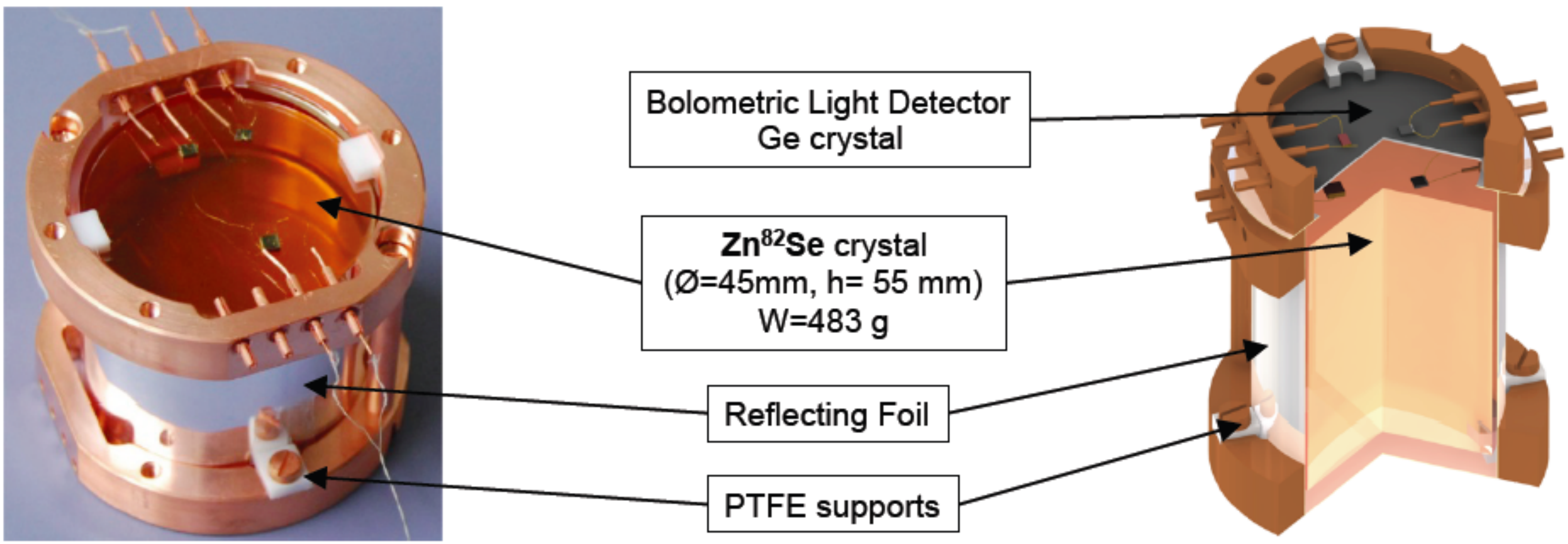
$T_{1/2}^{0\nu}$ (^{130}Te) > 1.6 x 10^{26} y (1σ)
$m_{\beta\beta}$ < 40 - 90 meV

From M. Pedretti, Neutrino 2012

Scintillating bolometers: Lucifer

R&D funded (3.3 M€) by ERC, in the form of an advanced GRANT (03/2010→03/2015)

Scintillating bolometers to recognize the α-induced background thanks to the readout of the scintillation light



Array of 36÷44 enriched (95%) $Zn^{82}Se$ crystals.

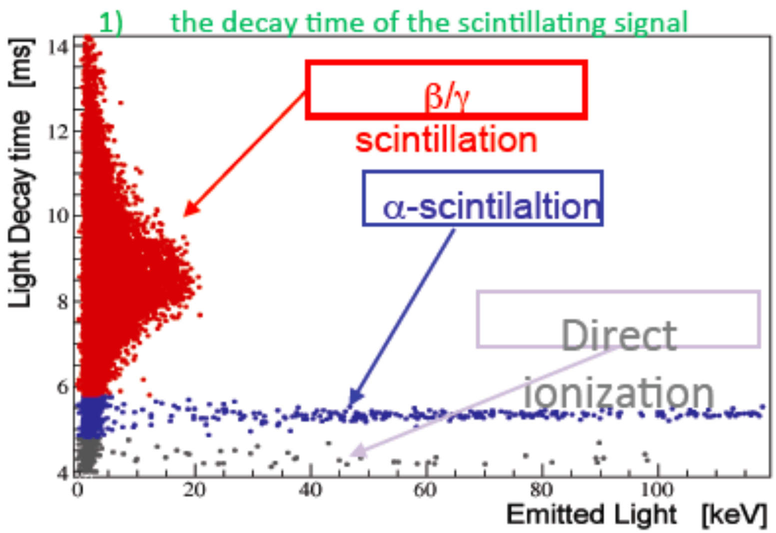
Expected background in the ROI (2995 keV) is ~ 3÷6 10^{-3} c/keV/kg/y

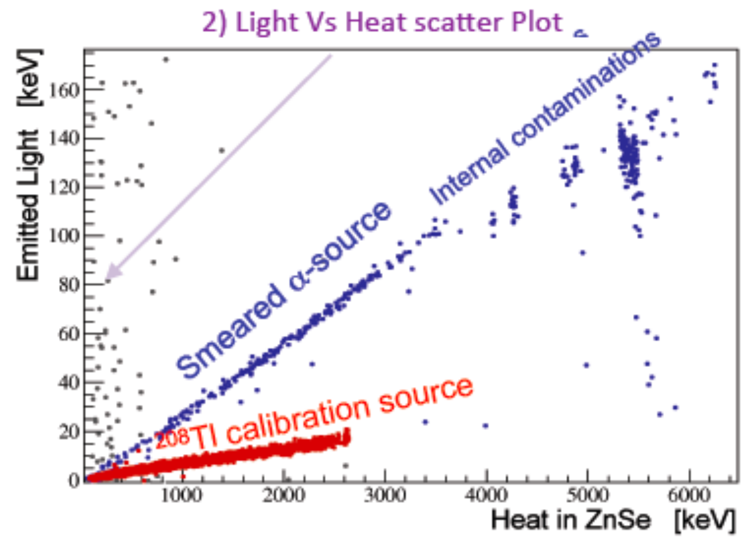
Energy resolution ~10 keV FWHM

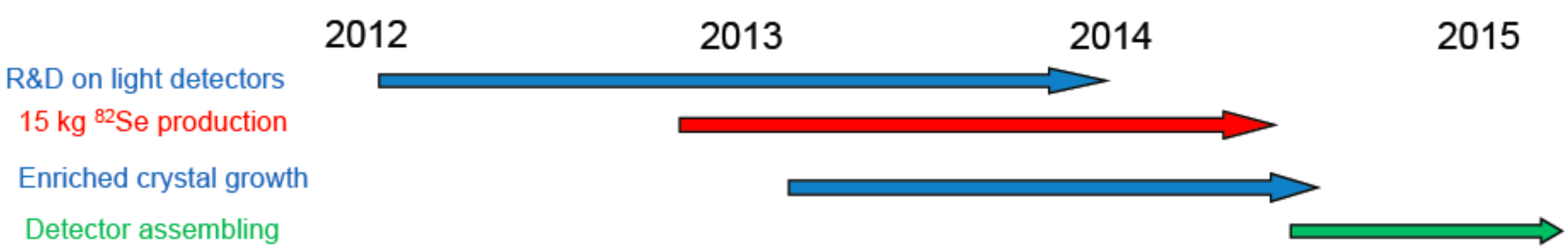
The α-induced background is recognized:

1) the decay time of the scintillating signal

2) the different scintillation yield between α and γ/β particles (the "usual" light Vs Heat scatter plot)







LUCIFER will be located in CUORICINO (now CUORE-0) cryostat, once CUORE-0 will finish his data taking (2015)

Summary / Conclusion

- Central quest: are neutrinos Majorana particles?
- DBD only practical approach to give answer
- Difficult and costly experiments
- Phased approach in DBD
  - carefully monitor whether promised detector performance are reached during upcoming years
  - degenerate mass scale (test KDKC claim) by GERDA, EXO and KamLAND-zen: complementarity of DBD and Katrin (Dirac vs. Majorana)
  - inverted mass scale can be scrutinized within next 5-10 years
- DBD community "opinion":
  - 3 different isotopes (or more) (NME!) for inv.-hierarchy study
  - Traco-calo needed, in particular when signal seen in calorimeter found to study angular distribution etc. (leading term?)

Summary & Outlook

0νββ experimental strategy during the next decade