Double Beta Decays

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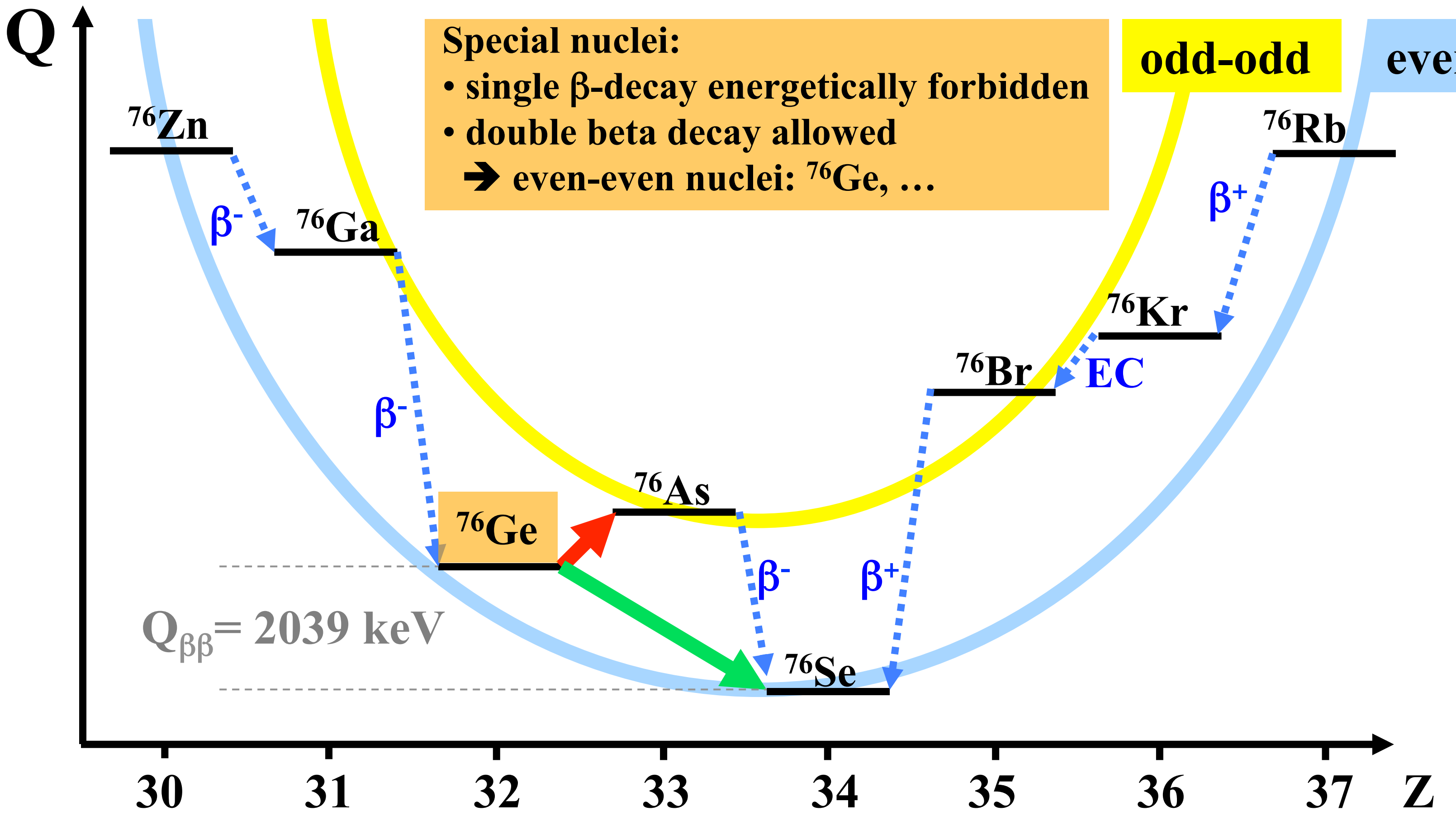
NNN13: International Workshop on Next generation Nucleon Decay and Neutrino Detectors

11-13 November 2013 *Kavli IPMU*

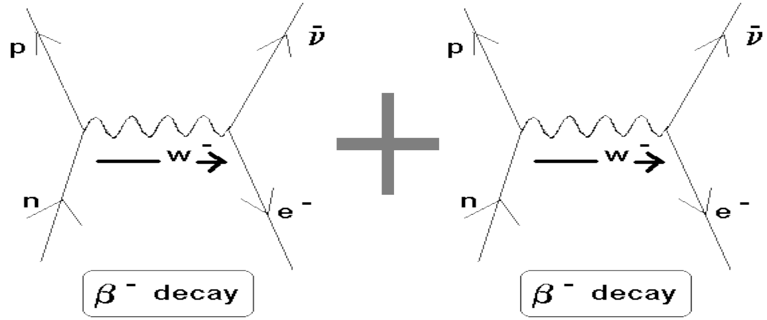
Double Beta Decay & Mass Parabolas



Double beta decay: $2n \rightarrow 2p + X$; $Q_x = -2$; energy $Q_{\beta\beta}$ goes $\simeq$ into X if $m_X \ll$ GeV

Double Beta Decay Processes

Standard Model:

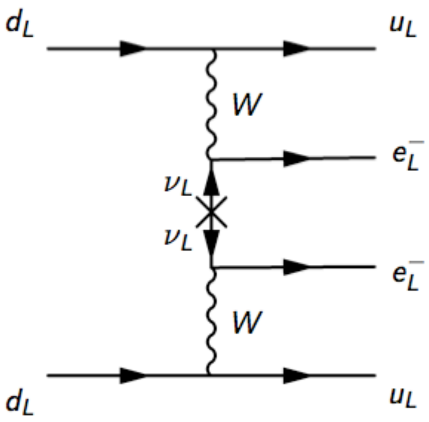


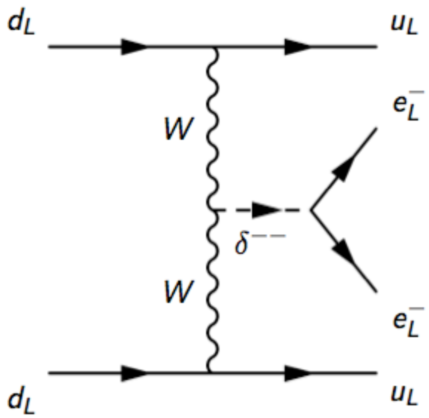
➔ 2 electrons + 2 neutrinos

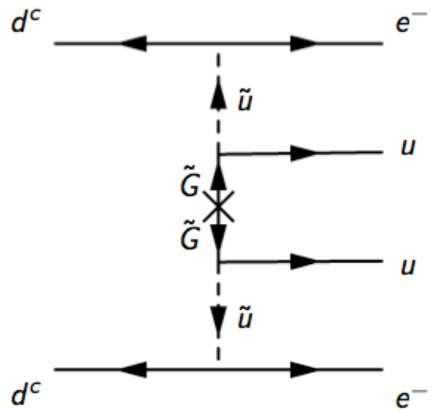
$2\nu\beta\beta$

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

$0\nu\beta\beta$







…

Majorana neutrino masses ←→ Dirac?

SM + Higgs triplet

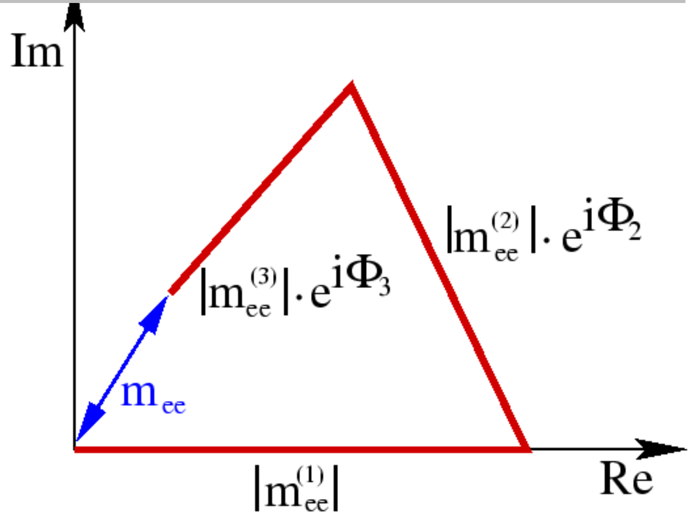
SUSY

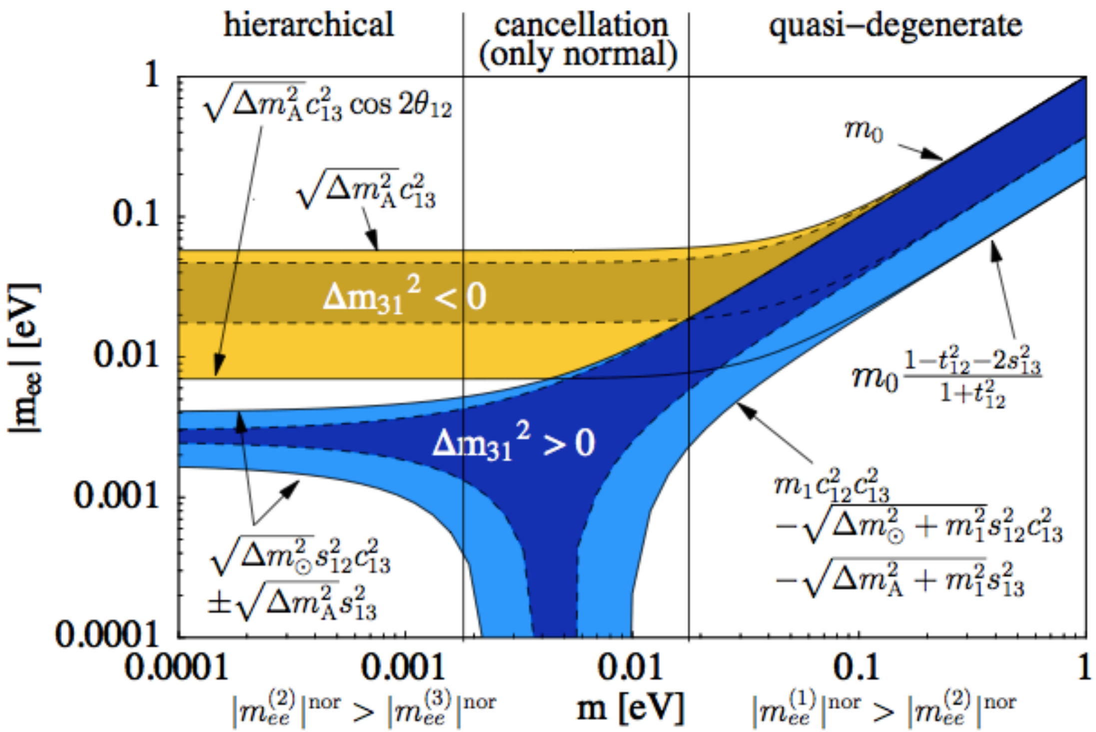
important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics

m_{ee}: The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$
$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$





Comments:

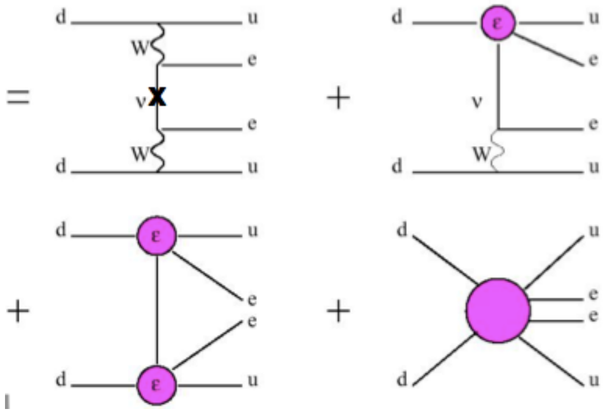
- **cosmology: further improvements? ←→ systematic errors**
- **NMEs➔ unavoidable theory errors**
- **assumption: no *other* ΔL=2 physics, no sterile neutrinos, ...**

Interference of ΔL=2 Operators

Usually $$\left(T^{0\nu}_{1/2}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}.$$

Dürr, ML, Neuenfeld

with interferences



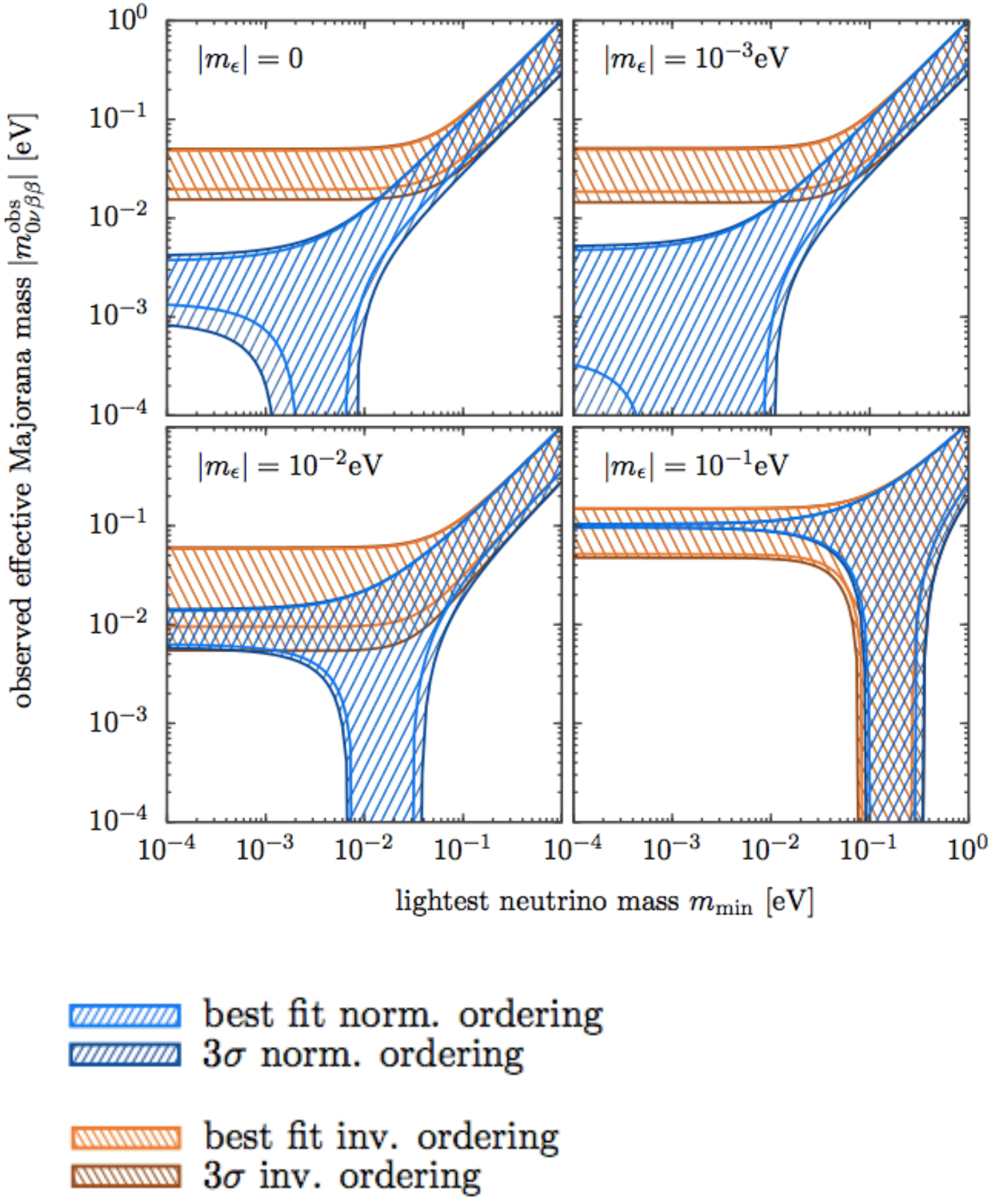
$$\begin{aligned}\left(T^{0\nu}_{1/2}\right)^{-1} &= |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^{\epsilon}|^2 \frac{G^{\text{int}}}{m_e^2} \\ &= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1})\mathcal{M}^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2} \\ &= |m^{\text{int}}_{0\nu\beta\beta}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2}\,,\end{aligned}$$

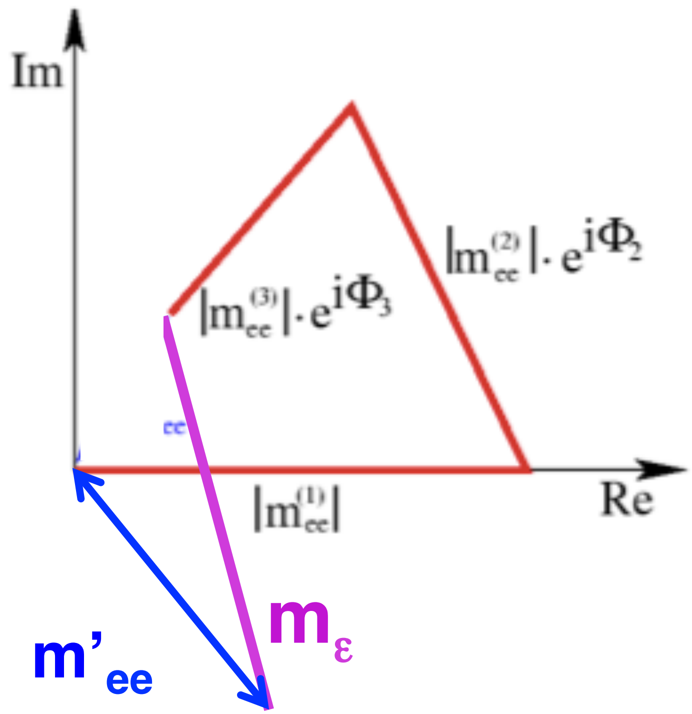
G^{int} = overall phase space factor

$\epsilon m_e \mathcal{M}^{\epsilon}$ ←→ determined by parameters of new physics

$$m^{\text{int}}_{0\nu\beta\beta} \equiv m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1} \equiv m_{0\nu\beta\beta} + m_{\epsilon}.$$

$m_\varepsilon \simeq (\Lambda_{new})^{-5}$ **$m_{0\nu\beta\beta}$ = 1 eV ←→ $\Lambda_{new} \simeq$ TeV**





interferences

growing m_ε for fixed 0νββ

→ shifts of masses, mixings and CP phases

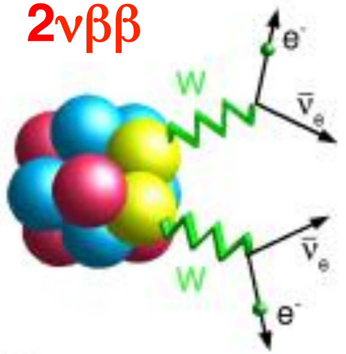
→ destroys ability to extract Majorana phases

→ sensitivity to TeV

Double Beta Decay Kinematics

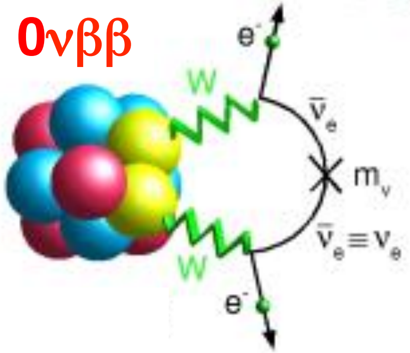
SM

2νββ

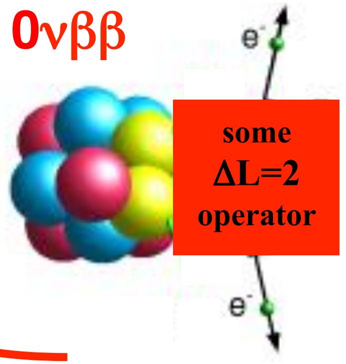


BSM

0νββ

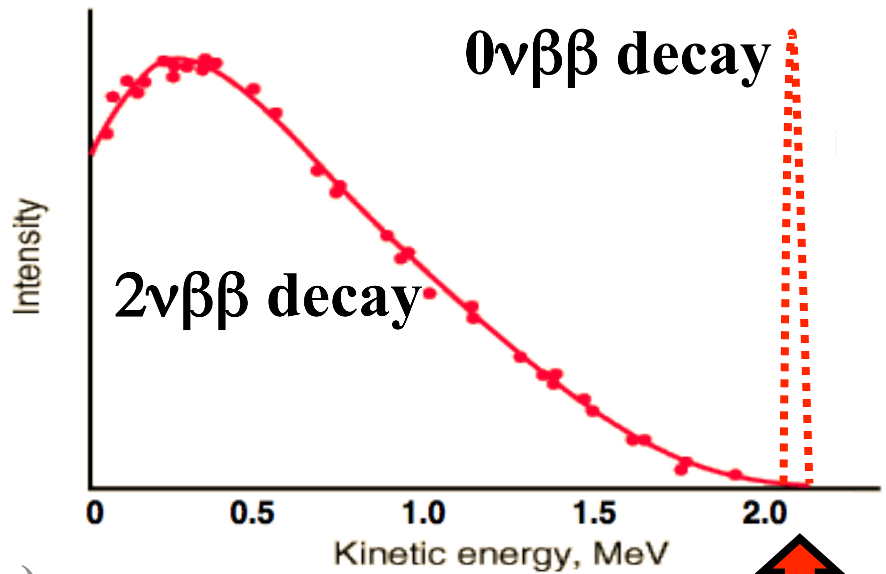


0νββ

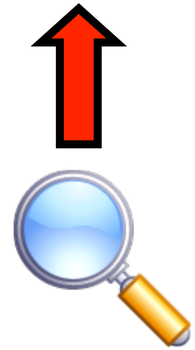


2νββ decay seen for diff. isotopes (Kirtsen,…)

$T^{1/2} = O(10^{18}\text{-}10^{21}$ years) ➔ up to $10^{11} \otimes T_{Universe}$

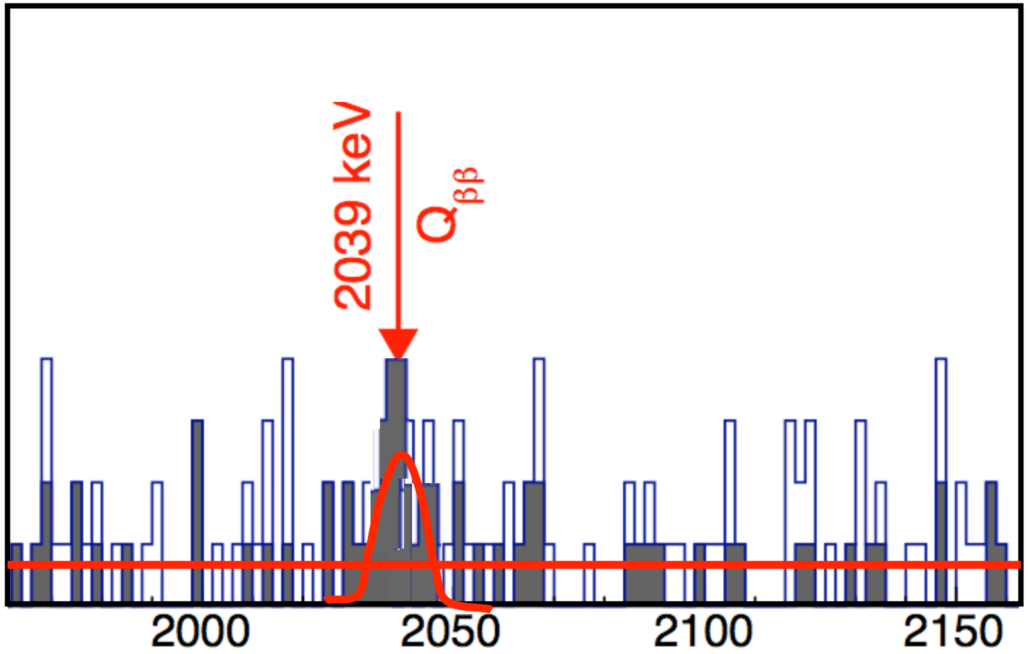


$T^{1/2} > O(10^{24}y)$



- 2νββ ➔ improvement
- search for 0νββ signal at $Q_{\beta\beta}$ = 2039 keV
- …backgrounds!

Experimental Challenges



- extremely rare process
  ➔ low statistics = few counts/bin
- known (unknown?) nuclear lines
- tail of $2\nu\beta\beta$ signal
- backgrounds
- signal at known $Q_{\beta\beta}$-value ?

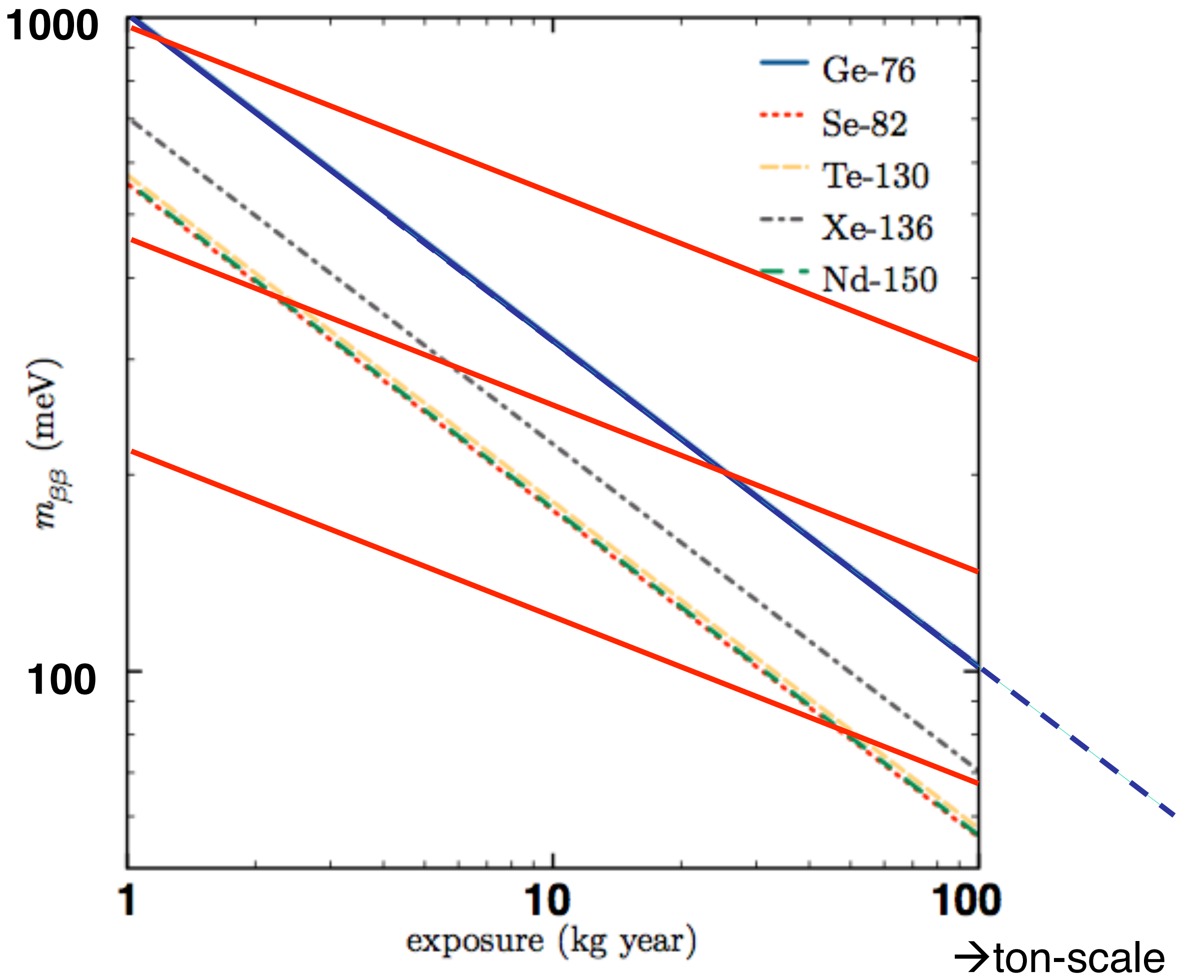
To best extract a $0\nu\beta\beta$ signal at $Q_{\beta\beta}$ and to avoid any misinterpretations:

- low background index (BI)
  ➔ careful material selection, screening, shielding, PSD (pulse shape disc.), …
- best possible energy resolution
  ➔ Germanium: source = detector (diode) ➔ few keV resolution
- if there is a signal
  ➔ different nuclei to exclude unknown nuclear physics

Sensitivity & Background (for a Majorana Mass)

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$

$$m_{\beta\beta} = \left|\sum_i U^2_{ei}\, m_i\right|$$



Without background:

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T^{0\nu}_{1/2}}$$

N_A = Avogadro's number
W = atomic weight of isotope
ε = signal detection efficiency
M = isotope mass
t = data taking time

→ $$m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}}$$

With background:

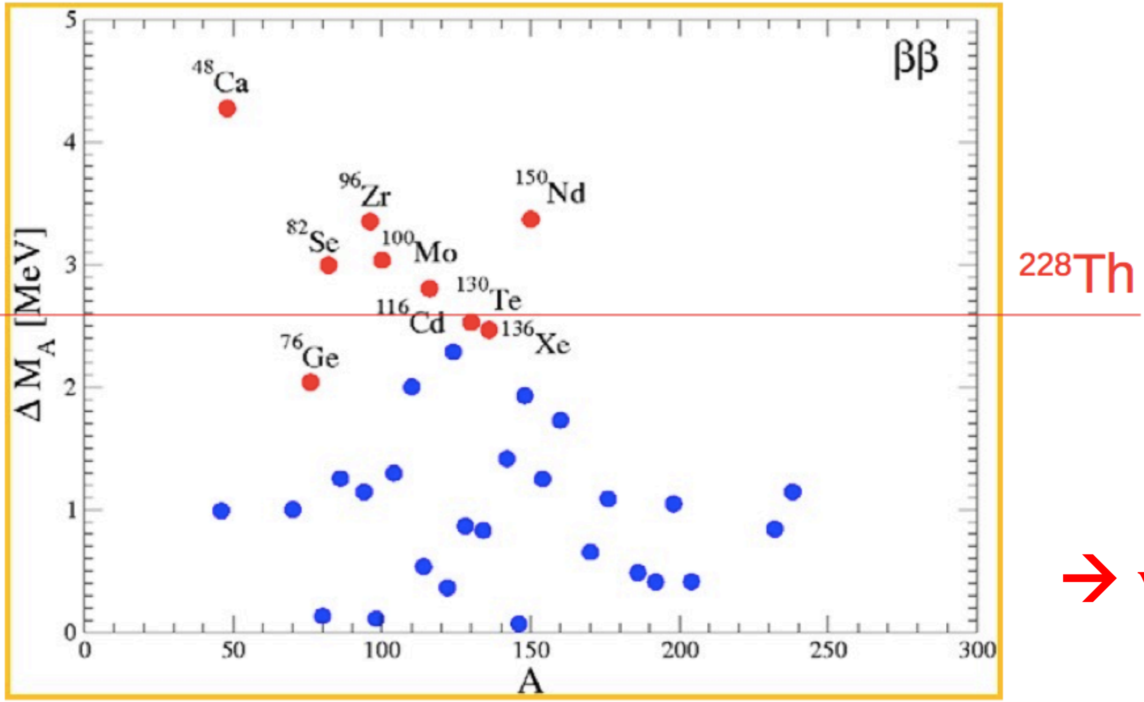
$$N' = N + N_{background}$$

→ $$m_{\beta\beta} = K_2 \sqrt{1/\varepsilon} \left(\frac{c\, \Delta E}{Mt}\right)^{1/4}$$

c = cts/keV kg yr ; ΔE = ROI

Which 0νββ Isotope?

- active mass ←→ isotopic abundance/enrichment ←→ cost, feasibility
- cleanliness (radiopurity) of 0νββ source and instrumentation
- high $Q_{\beta\beta}$ ←→ less nuclear backgrounds
- good energy resolution ←→ background rejection
- uncertainties in nuclear matrix elements
- …



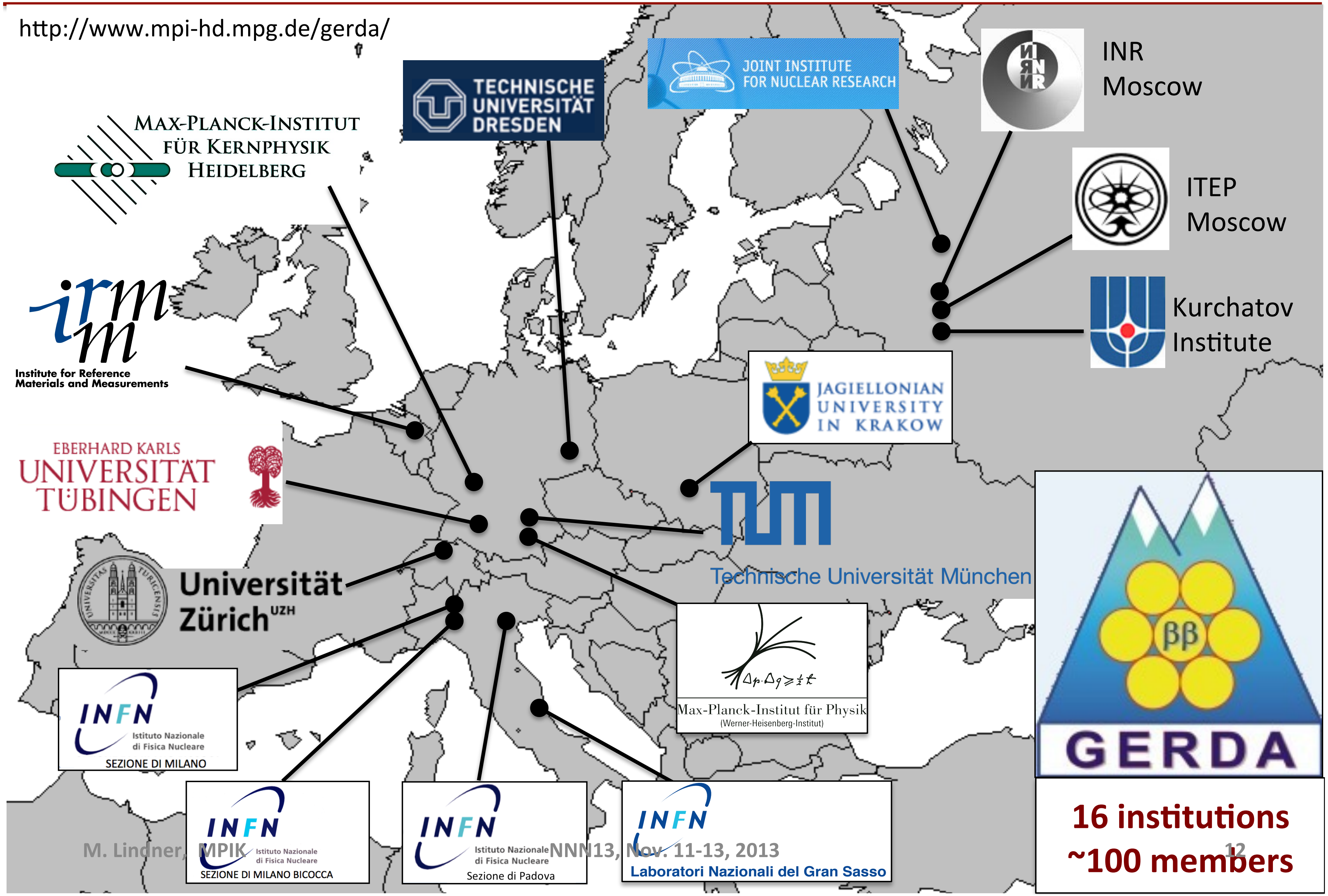
→ various promising options

List of Recent 0νββ Experiments / Projects

isotope	$G^{0\nu}$ $[\frac{10^{-14}}{yr}]$	$Q_{\beta\beta}$ [keV]	nat. ab. [%]	$T^{2\nu}_{1/2}$ [10^{20} y]	experiments
^{48}Ca	6.3	4273.7	0.187	0.44	CANDLES
^{76}Ge	0.63	2039.1	7.8	15	GERDA, Majorana Demonstr.
^{82}Se	2.7	2995.5	9.2	0.92	SuperNEMO, Lucifer
^{100}Mo	4.4	3035.0	9.6	0.07	MOON, AMoRe
^{116}Cd	4.6	2809.1	7.6	0.29	Cobra
^{130}Te	4.1	2530.3	34.5	9.1	CUORE
^{136}Xe	4.3	2457.8	8.9	21	EXO, Next, Kamland-Zen
^{150}Nd	19.2	3367.3	5.6	0.08	SNO+, DCBA/MTD

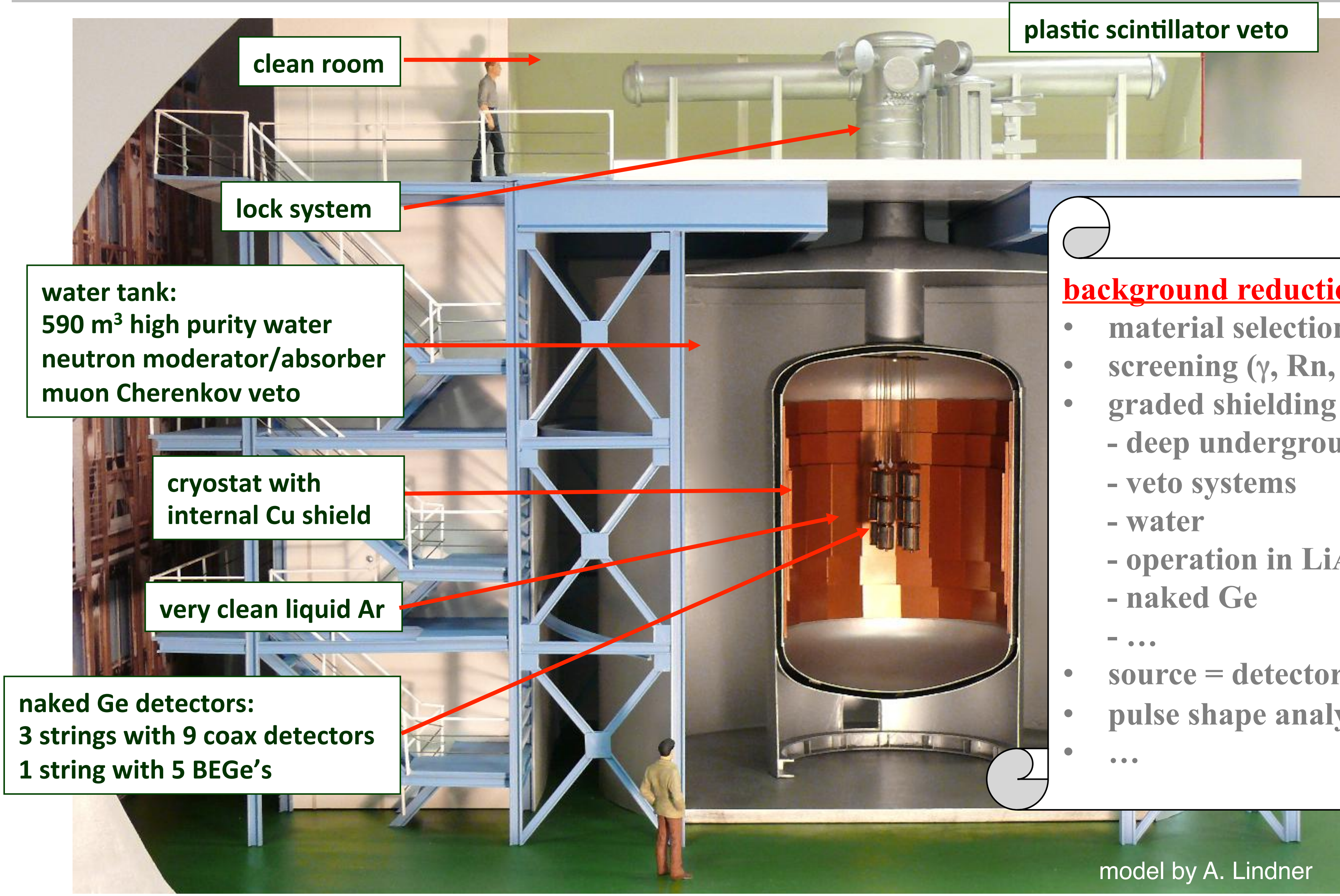
➔ **GERDA**
➔ **EXO, KamLAND-Zen**
➔ **future**

The GERDA Collaboration



16 institutions
~100 members

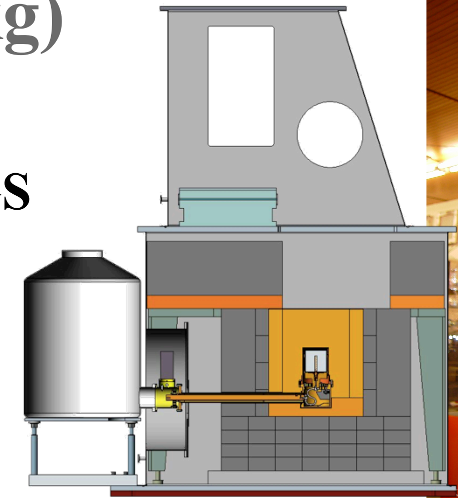
The GERDA Detector (original idea by G. Heusser, MPIK)



background reduction:
- material selection
- screening (γ, Rn, ...)
- graded shielding
  - deep underground
  - veto systems
  - water
  - operation in LiAr
  - naked Ge
  - ...
- source = detector
- pulse shape analysis
- ...

γ and Rn Screening Facilities

- γ-screening stations (1mBq/kg) **@MPIK underground lab**
- 4 GEMPIs (10μBq/kg) **@LNGS**
- New: GIOVE (50μBq/kg) **@MPIK**



➔ extensive task for GERDA and other experiments (XENON, …)

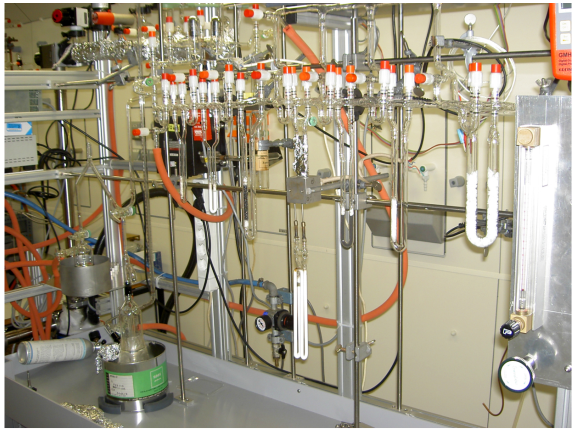
Rn Screening Facilities:

Gas counting systems (LNGS, MPIK)

^{222}Rn emanation technique

sensitivity = few atoms/probe

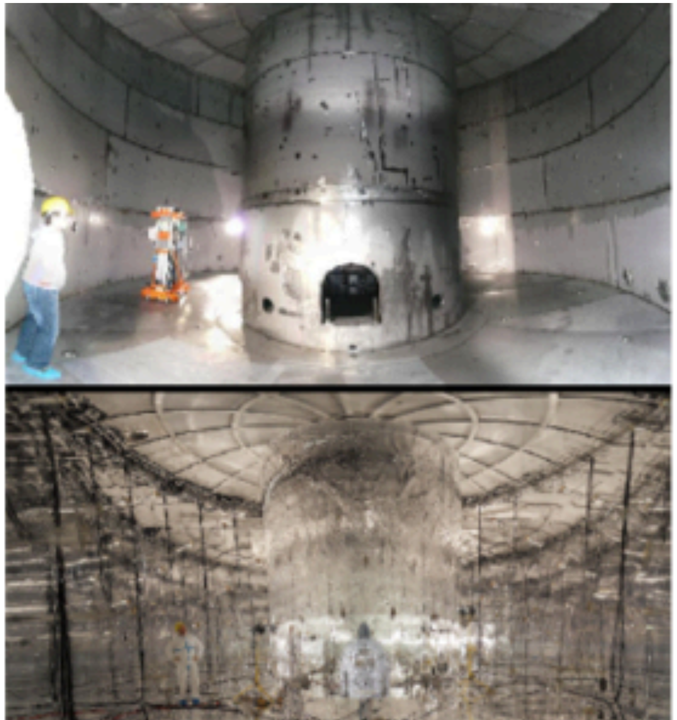
➔ typ. sensitivity: few μBq/m^2



ICPMS: …

Detector Construction @LNGS Hall A

- **2004: Letter of Intent**
- **R&D:** material selection and screening, tests of bare diodes in LAr
- **2008-2010: construction at LNGS (Gran Sasso, Italy)**
  - infrastructure & cryostat
  - water tank & muon veto
  - clean room, lock 6 clean benches
- **2010-2011:** comissioning
- **Nov. 2011:** start of phase I data taking



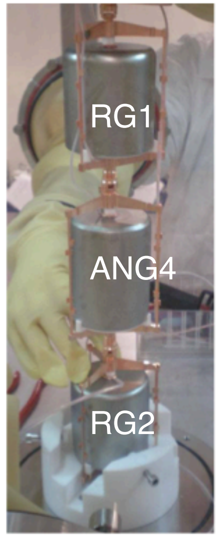
GERDA Phase I Detectors

Since Nov. 2011:
6 enriched (86% of ^{76}Ge)
ANG2, ANG3, ANG4, ANG5, RG1, RG2
→ 14.63 kg

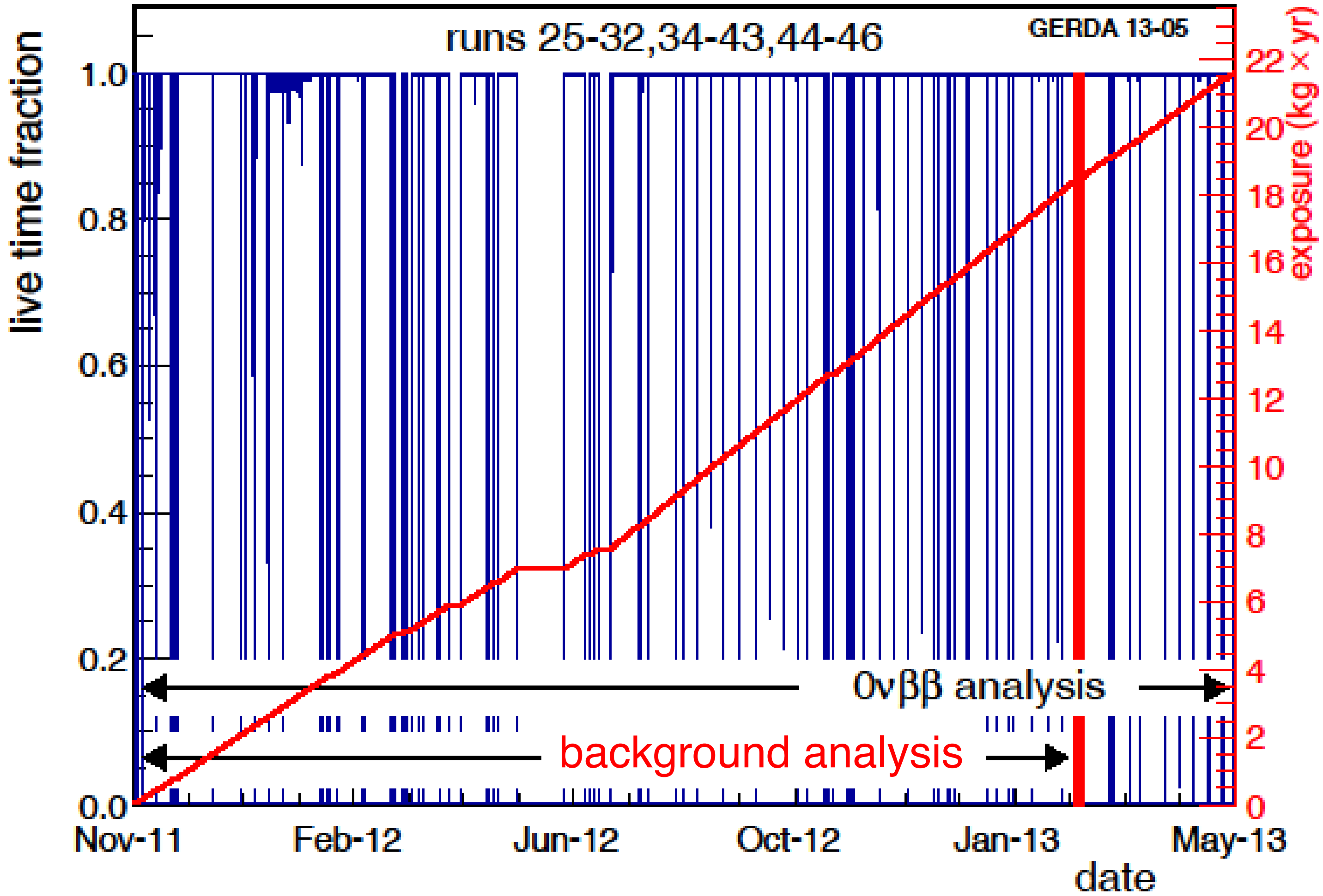
1 natural (7,83% of ^{76}Ge)
GTF112
→ 2.96 kg

Since July 2012:
4 BEGe (87% of ^{76}Ge)
GD32B-GD32D, GD35B
→ 3.00 kg

In addition: 2 coaxial and 1 BEGe unused due to high leakage currents



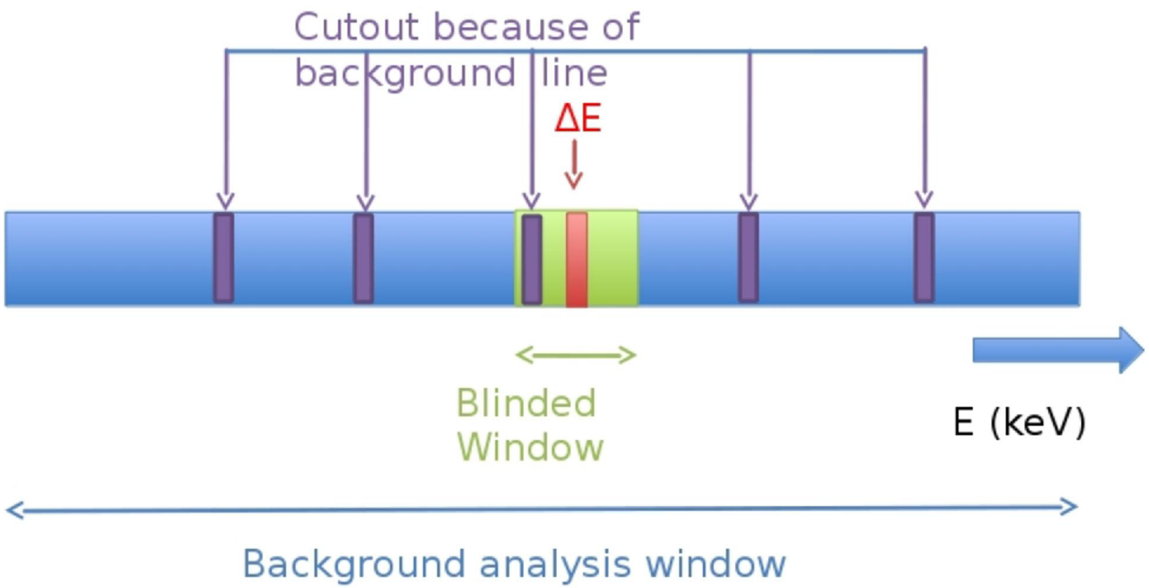
Data Taking



Stable data taking during most of the time (556 d, duty cycle 88%)

→ 20 kg*y in April 2013 **➔ final exposure 21.6 kg * yr**

The Blinding Procedure



After Jan. 2012:
blinding of $Q_{\beta\beta}$±20keV
←→ avoid biases

Data processing details fixed before unblinding
- quality cuts
- pulse shape discrimination parameters
- analysis method → three data sets

golden	= 17.9 kg*yr
silver	= 1.3 kg*yr
BEGe	= 2.4 kg*yr

unblinding
in June 2013

Backgrounds

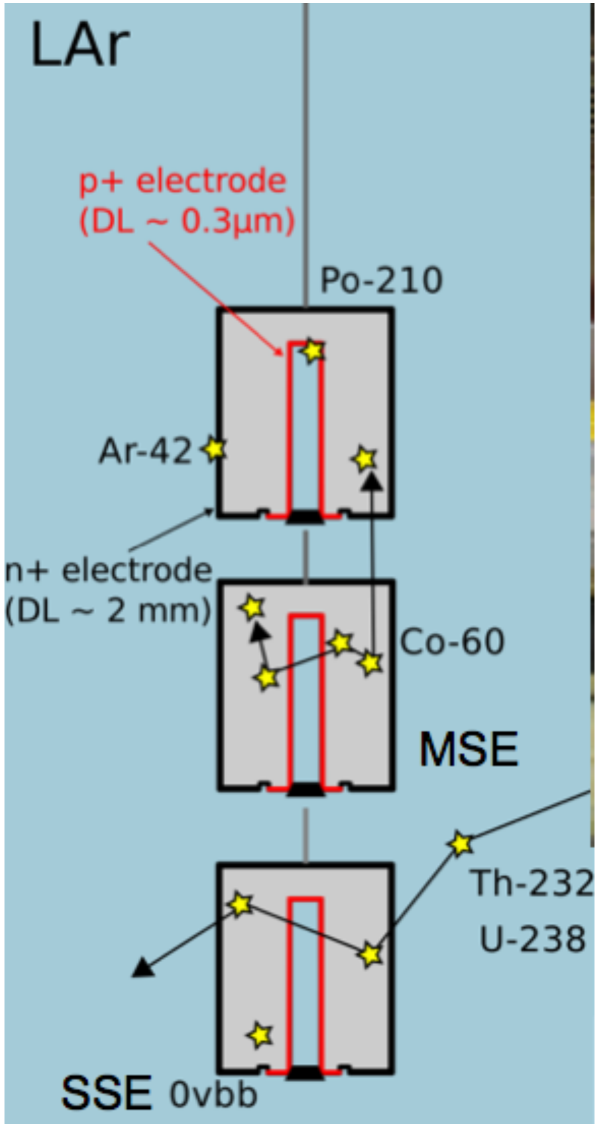
The outer dead layer of the detectors is not active

Background sources:

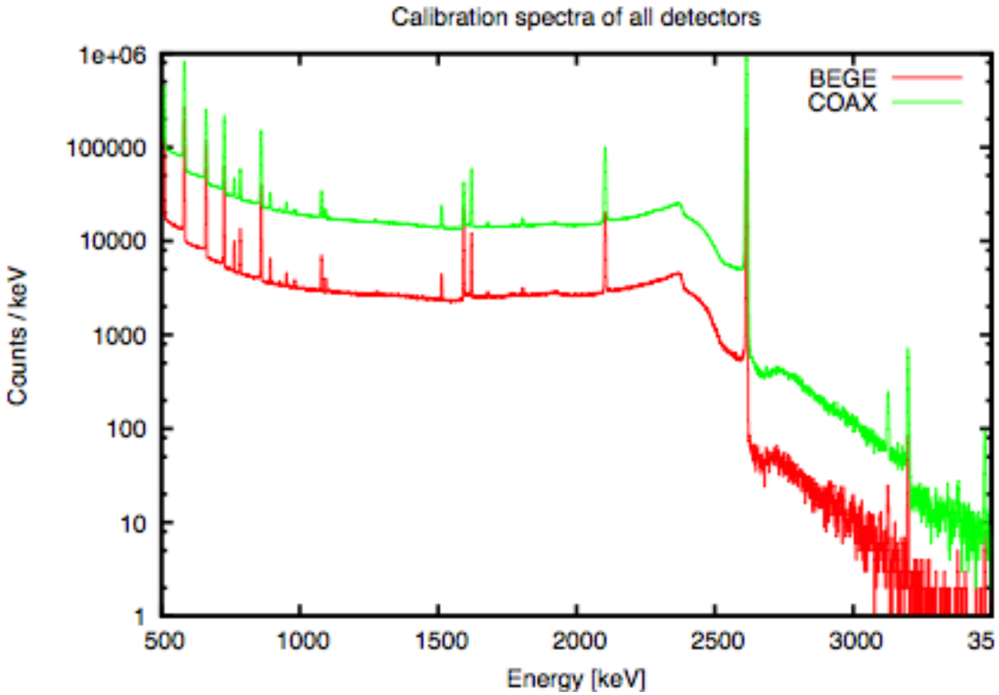
- α decays on the p^+ surface
- β decay of ^{42}K on the surface or close to the detector from ^{42}Ar (10x more than expected)
- β decay of ^{60}Co inside detectors
- γ from ^{208}Tl, ^{214}Bi and from various set-up components

Generic phase I background reduction

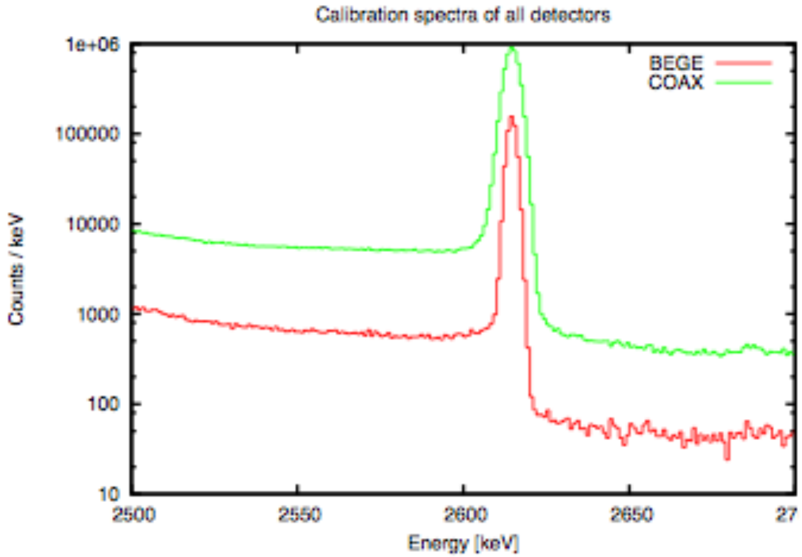
- use cleanest possible materials
- cut detector coincidences
- prevent ^{42}K ions from drifting to detectors using mini-shrouds



Detector Performance



from ^{208}Tl

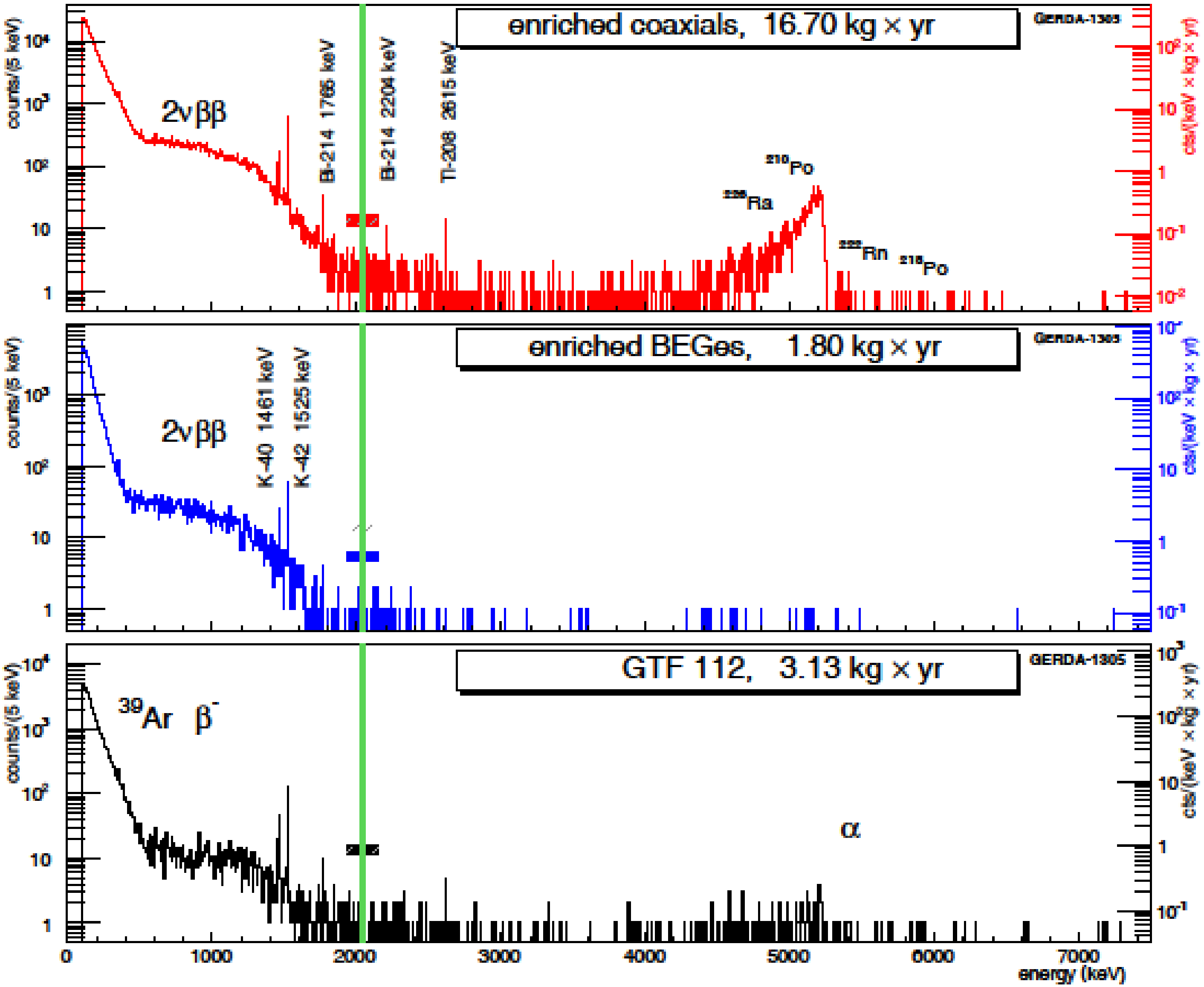


Energy resolution:

coaxial at $Q_{\beta\beta}$:	(4.8 $\pm$ 0.2) keV	at 2614.5 keV (4.2 - 5.8) keV
BEGe	(3.2 $\pm$ 0.2) keV	(2.6 - 4.0) keV

- stable energy resolution
- no energy drift between consecutive calibrations (<0.05%)
- leakage currents stable (except RG2)

The Background Spectrum



green = blinded

2νββ result
arXiv:1212.3210
J.Phys.G: Nucl. Part. Phys. 40(2013) 035110

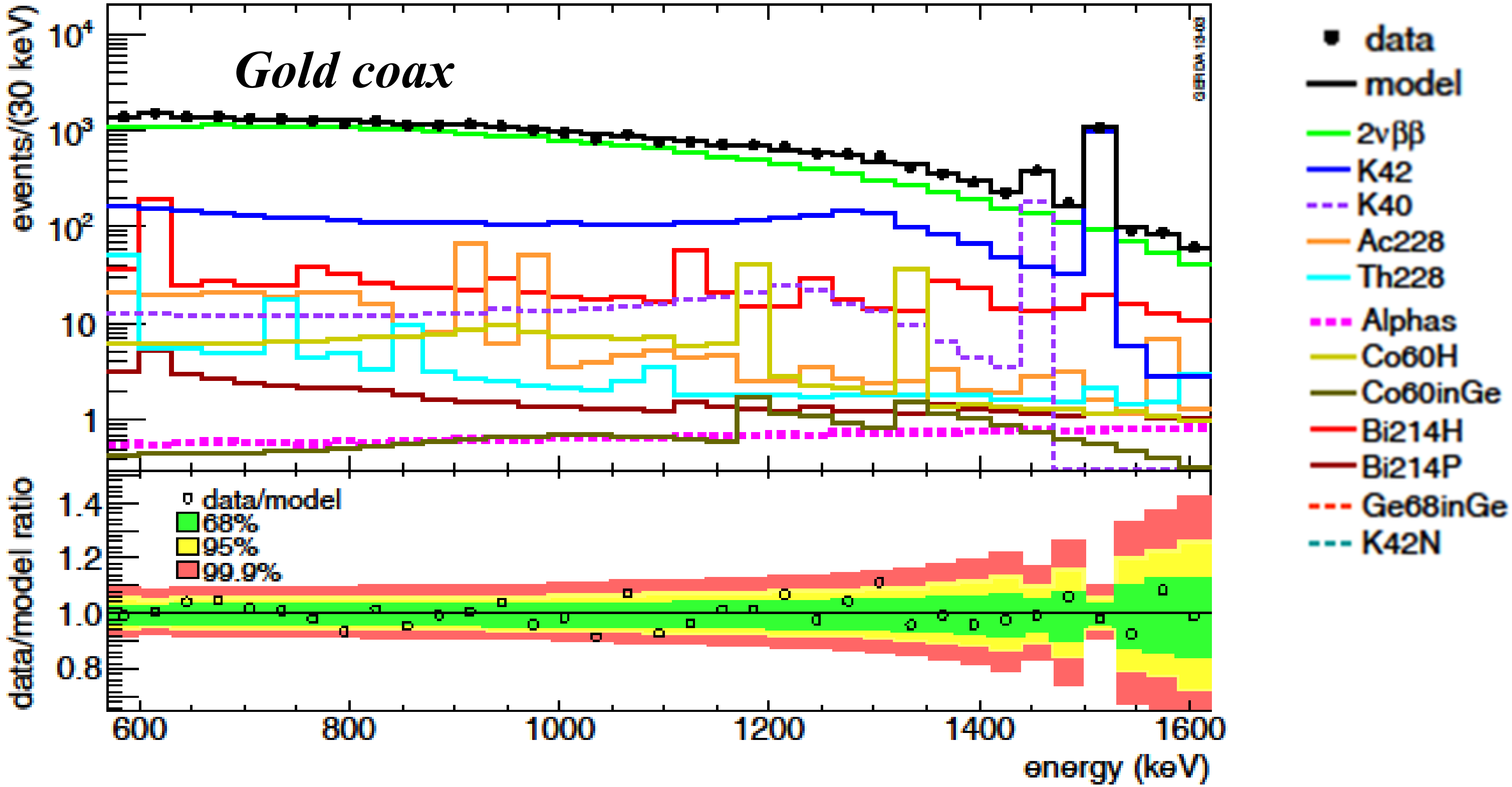
$$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.08})\ 10^{21}\ \text{yr}$$

backgrd. paper
arXiv:1306.5084
to appear in EPJ C

The Background Model

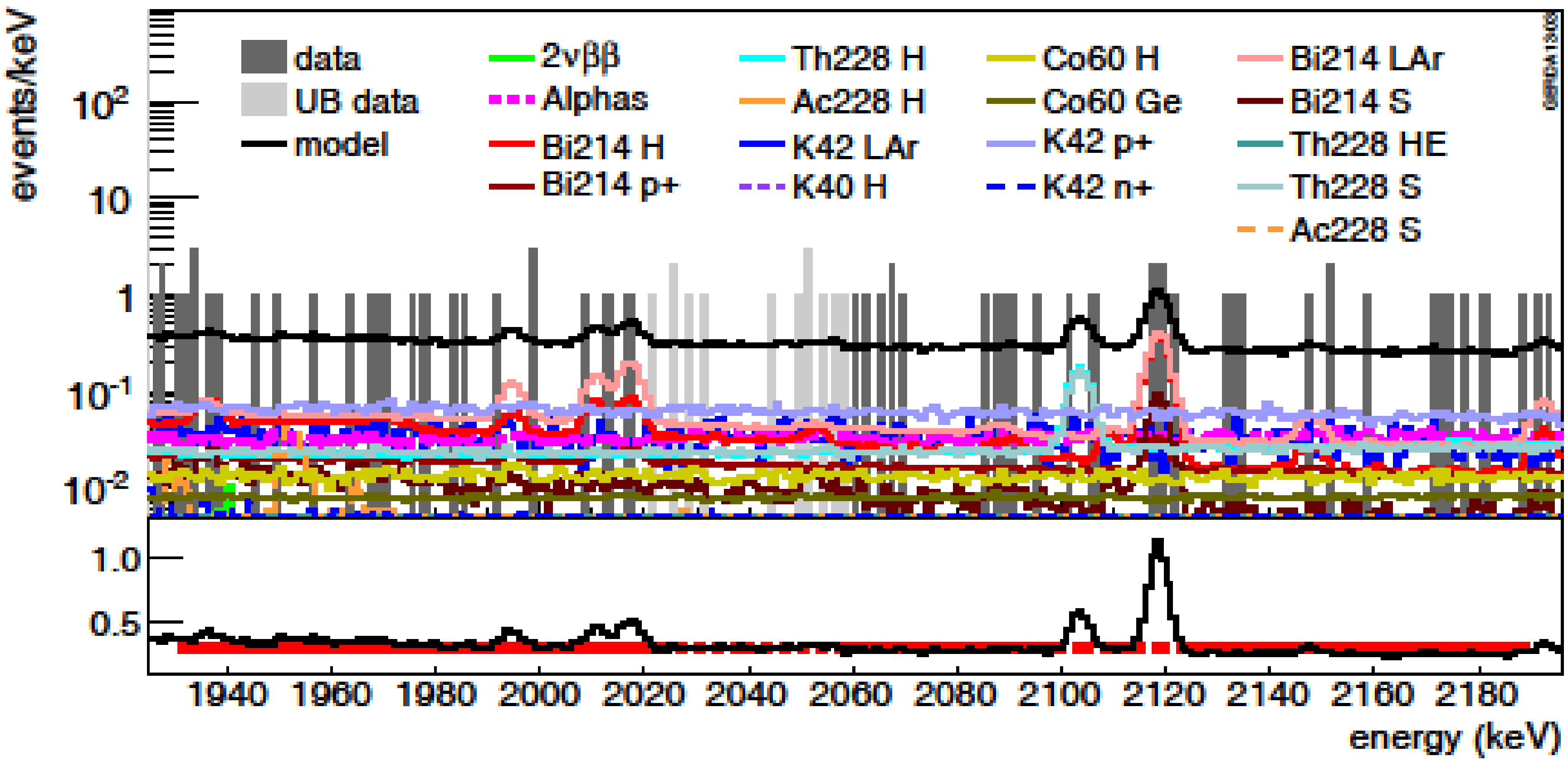
Background decomposition with all simulated components; fit window 570-7500 keV

Minimum model: minimum set of background components



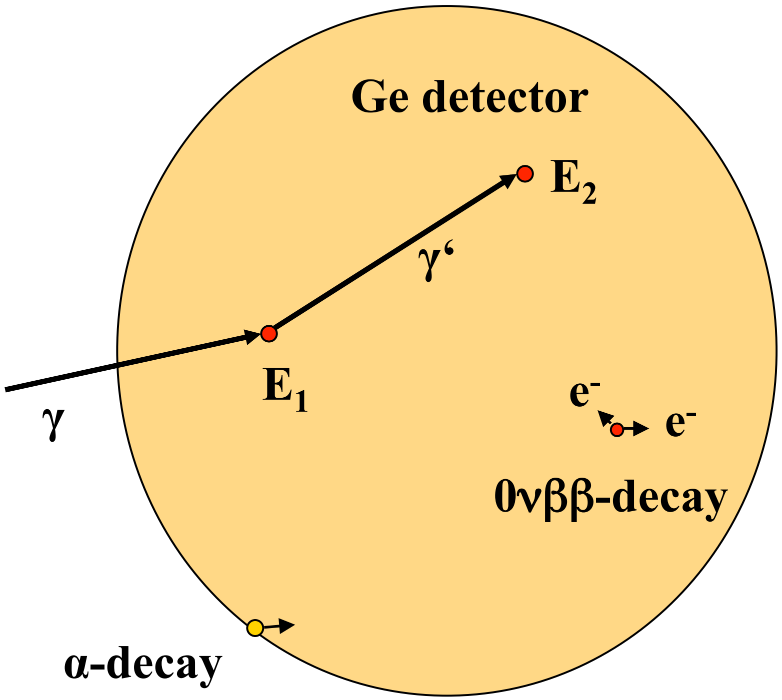
Background Composition: Maximum Model

total set of known background components leading to distinguishable spectra ➔

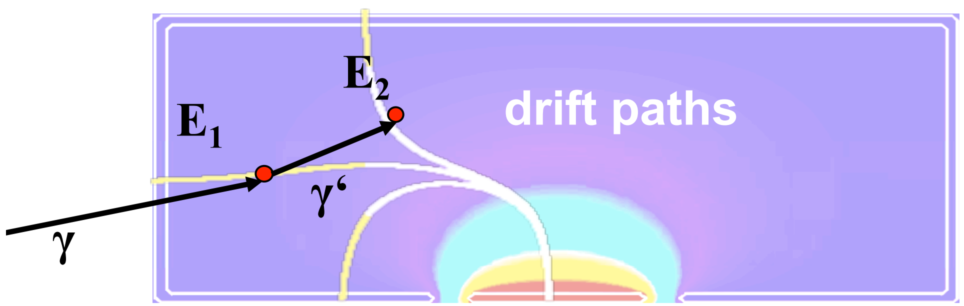


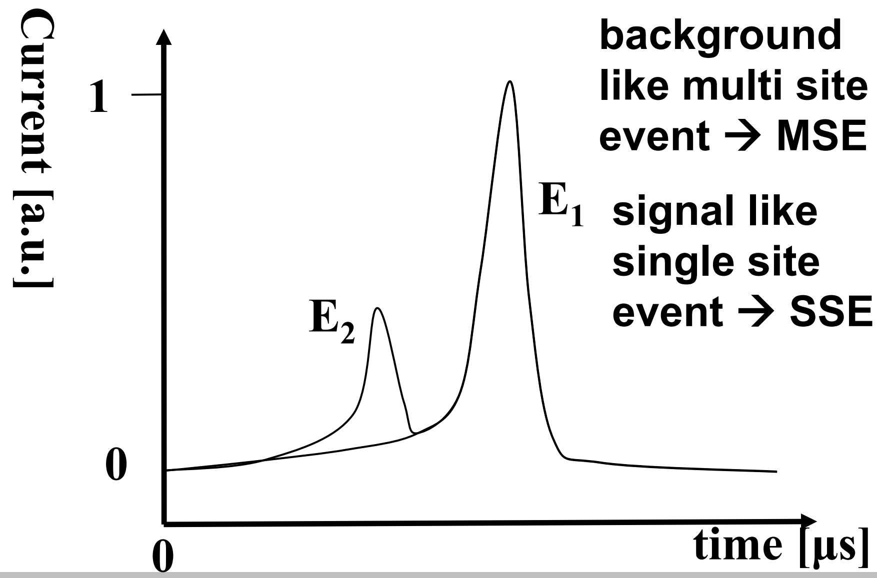
Pulse Shape Discrimination

- Single Site Events (SSE)
- Multi Site Events (MSE)



- 0νββ-decays → localized energy deposition→ SSE
- Compton scattering evt. → background like MSE
- surface events→ SSE @ surface
- SSE by γ's look like events (cannot be rejected)
- β particles enter via n^+ surface → slow pulses
- α's @ p^+ contact → comparatively high signal





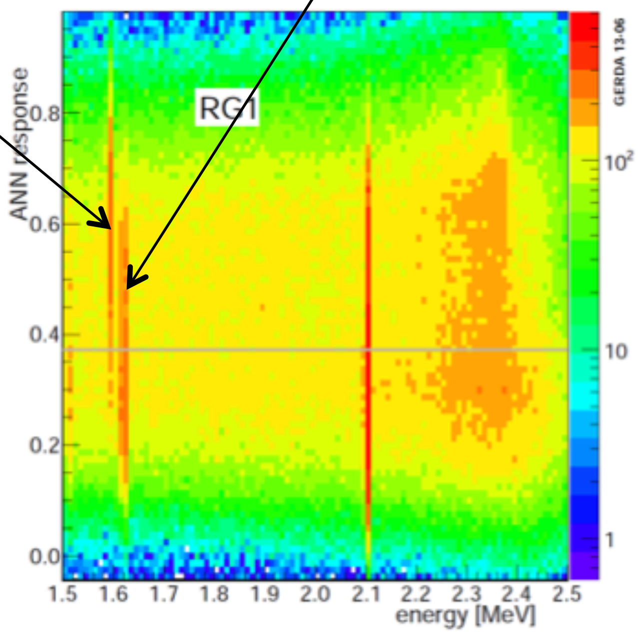
Pulse Shape Discrimination: Coaxial

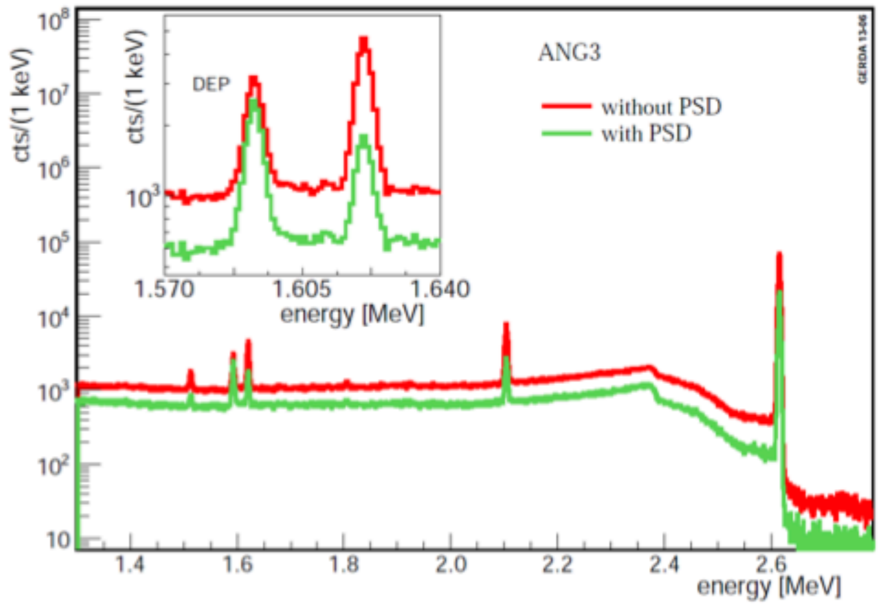
3 independent PSD methods:

- likelihood classification
- PSD selection based on pulse asymmetry
- neural network analysis (ANN)
  ➔ training with calibration data

SSE library: DEP peak of ^{208}Tl → gamma at 1592 ± 1 keV

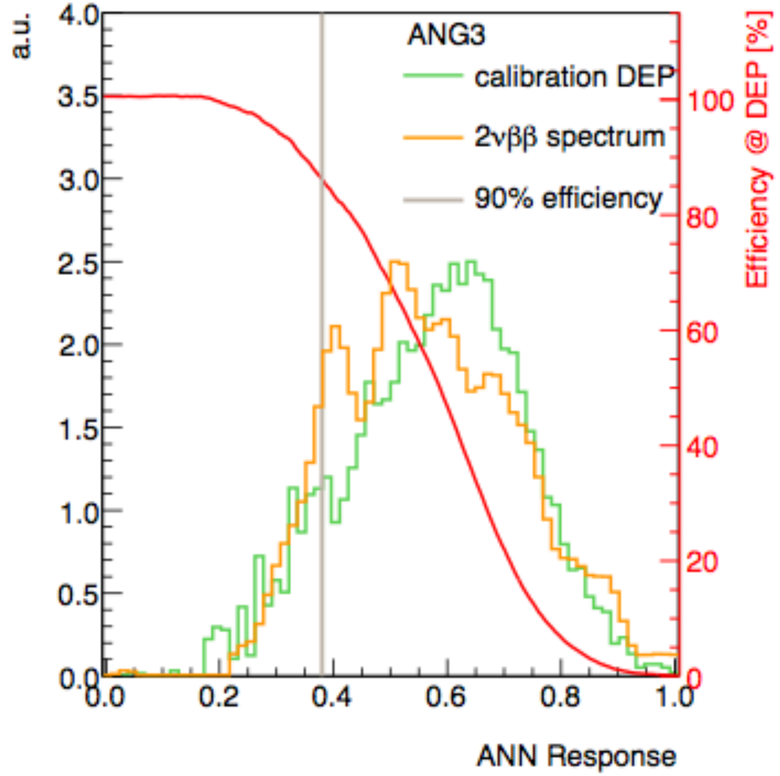
MSE library: FAP (Full Absorption Peak) of ^{212}Bi at 1620 keV

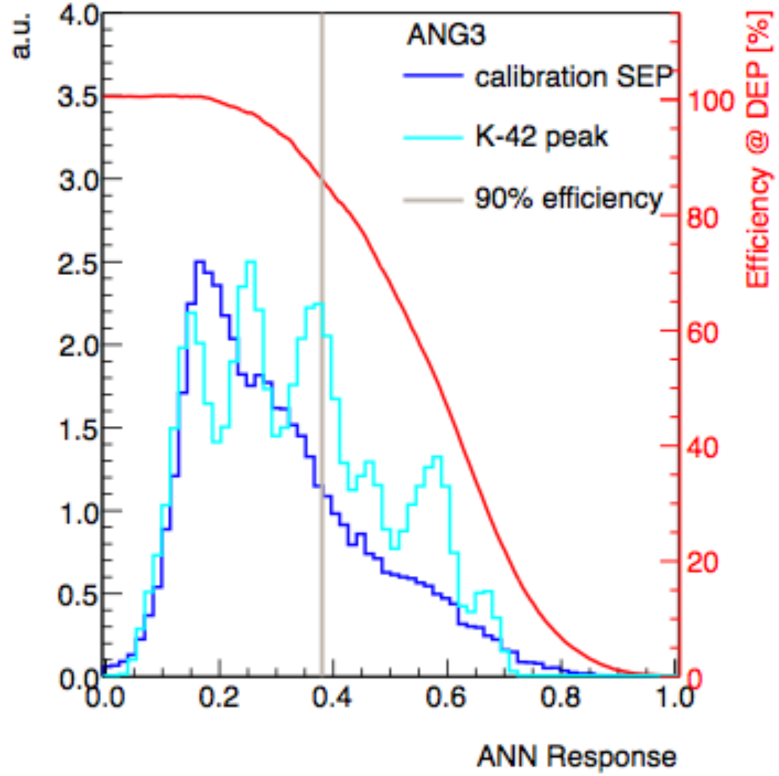




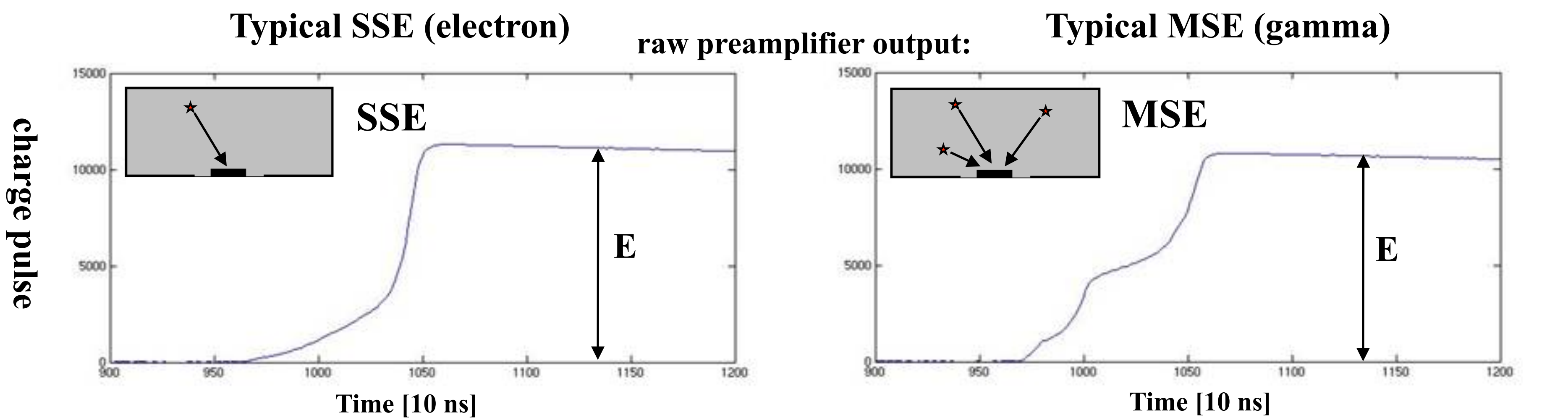
Neural Network Training with Calibration Data

- DEP events in the interval $1592\,\mathrm{keV} \pm 1\,FWHM$ serve as proxy for SSE
- Full energy line of ^{212}Bi in the equivalent interval around $1620\,\mathrm{keV}$ are dominantly MSE, taken as background events

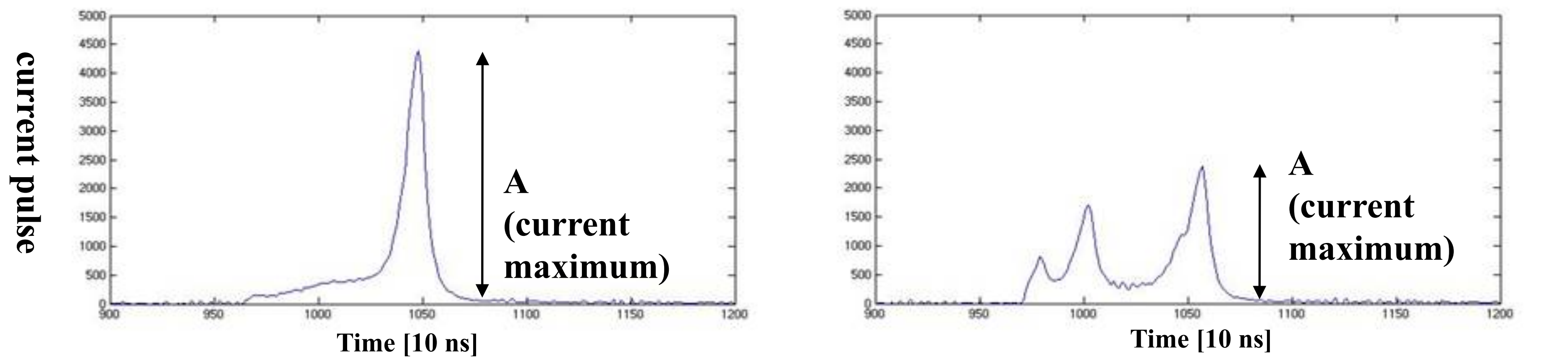




Pulse Shape Discrimination: BEGe A/E Cuts



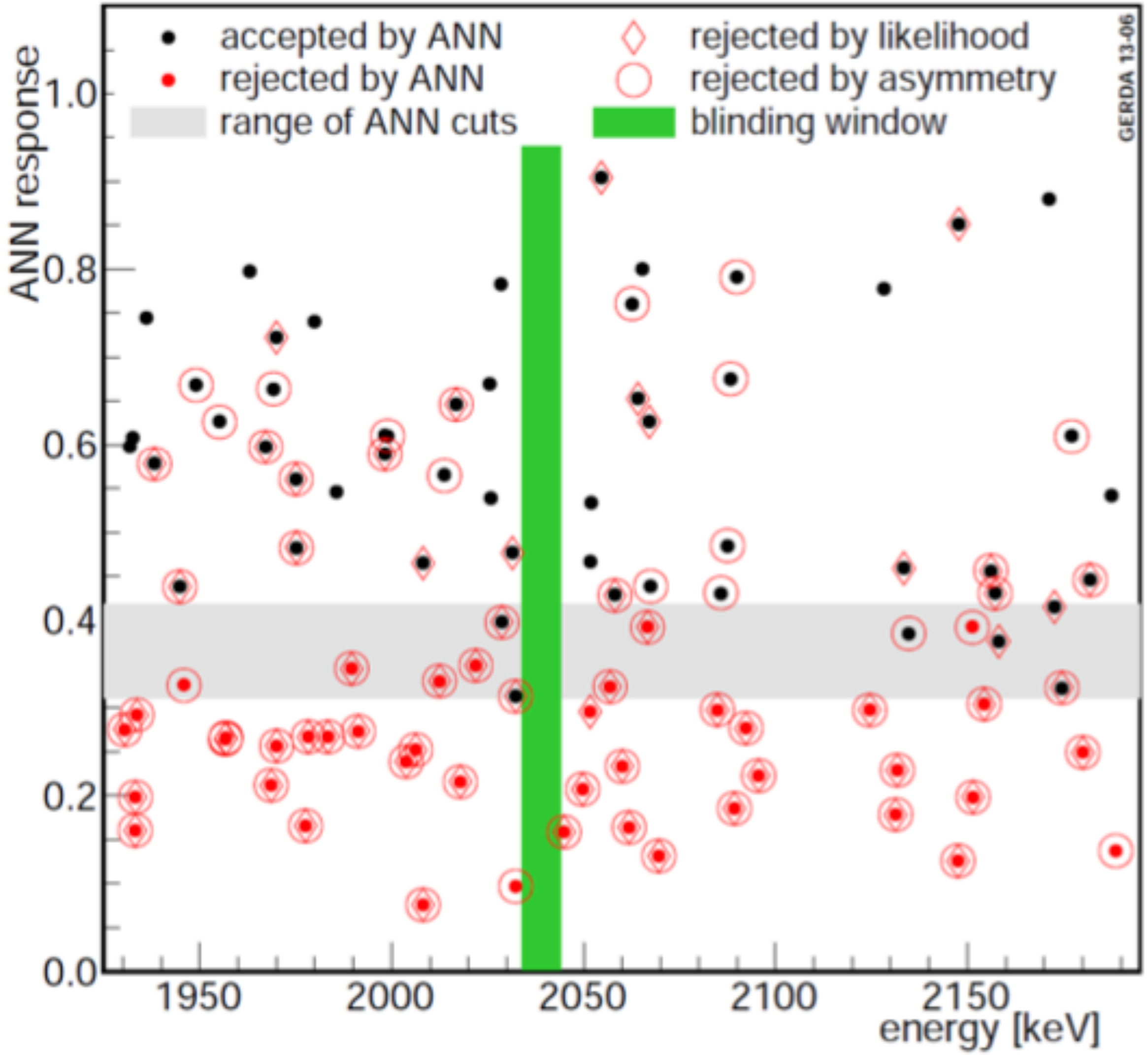
after differentiation:



➔ **Cutting in A/E ➔ rejects background like MSEs**

➔ **ε_{PSD} = 0.92 ± 0.02 ➔ ca. 85% of background events at $Q_{\beta\beta}$ rejected**

Application of PSD to Phase I Data

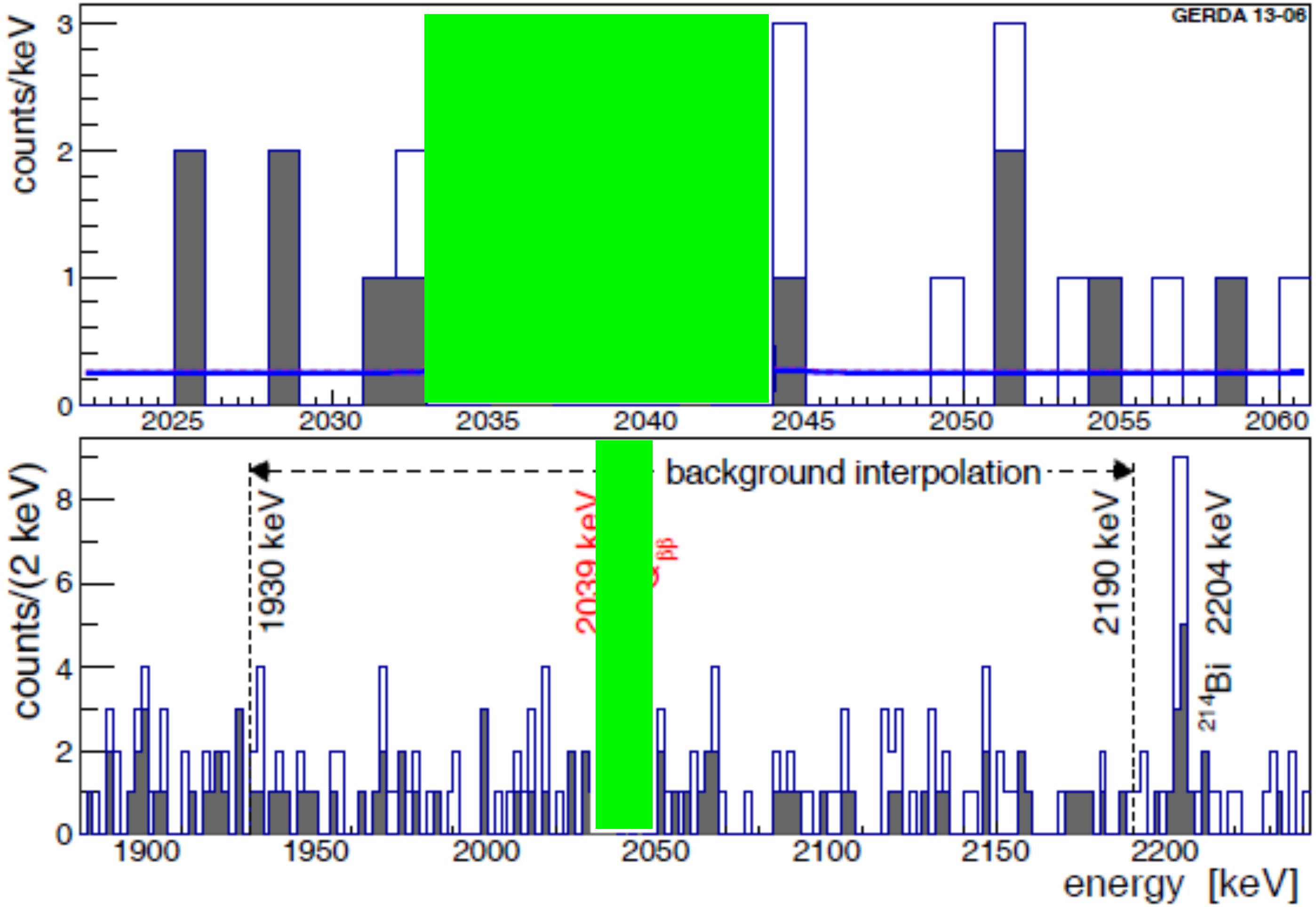


- all events removed by ANN are removed by at least one other method
- events discarded by ANN are in 90% of the cases discarded by all 3 methods
- in a larger energy window about 3% are only rejected by ANN

⇒ About 45% of events are rejected

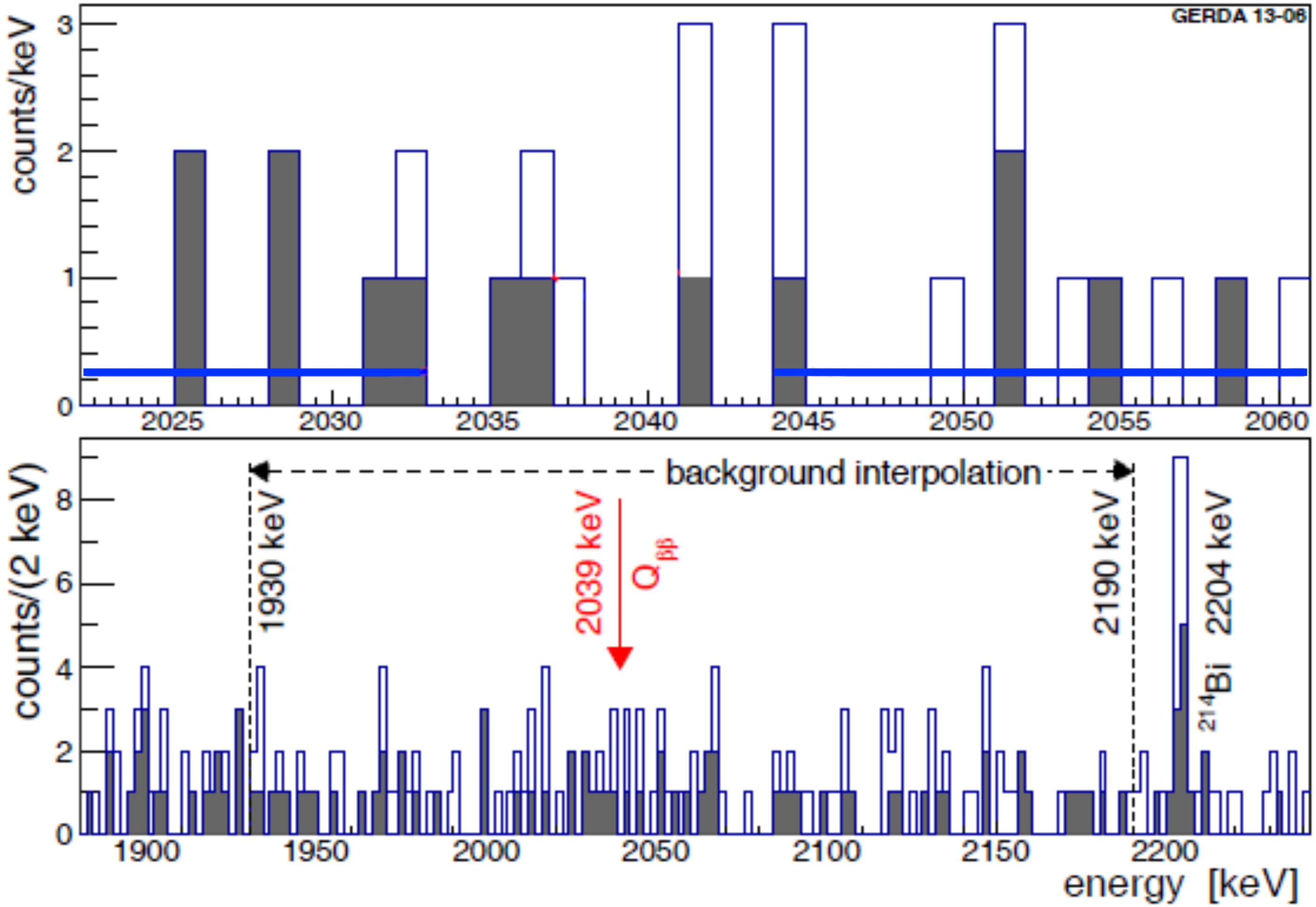
Efficiency: $\epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09}$

The Region of Interest



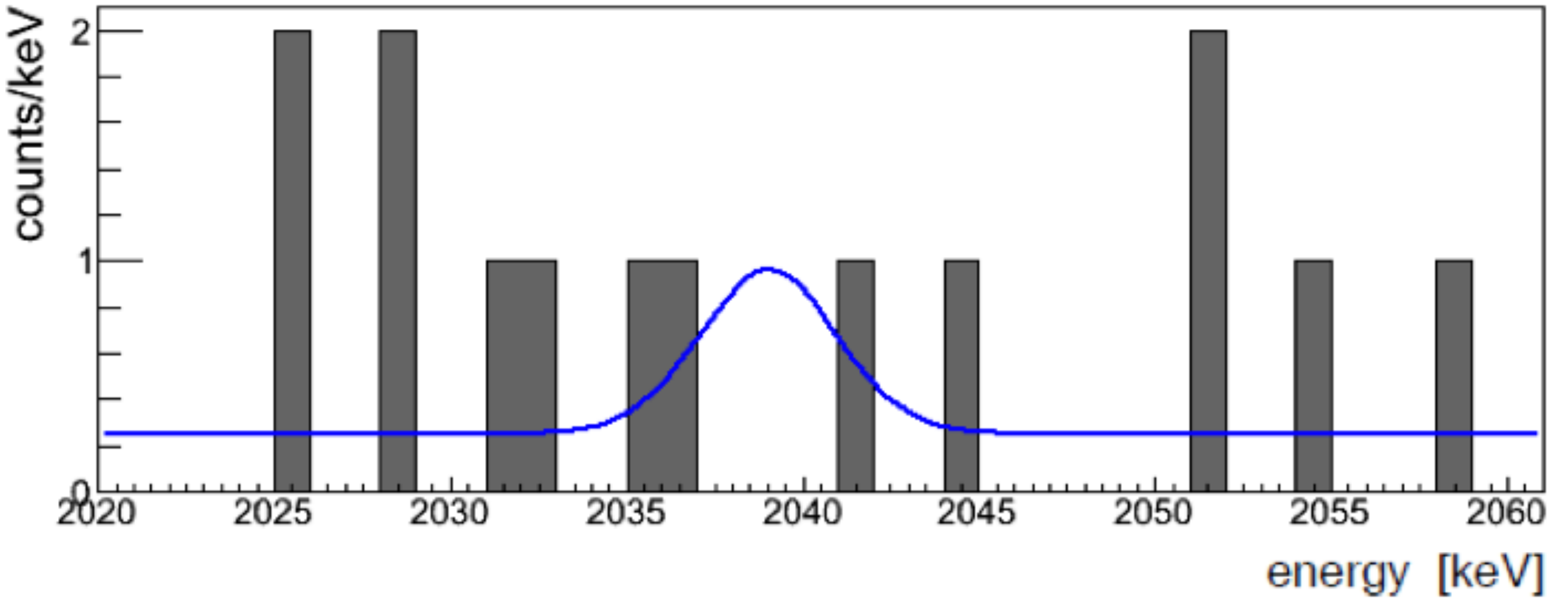
expected bg from interpolation: 5.1 events w/o PSD
2.5 events with PSD

The Region of Interest



expected bg from interpolation:	5.1 events w/o PSD 2.5 events with PSD	observed	➔ 7 events w/o PSD ➔ 3 events with PSD

Profile Likelihood Fit to PSD Spectrum



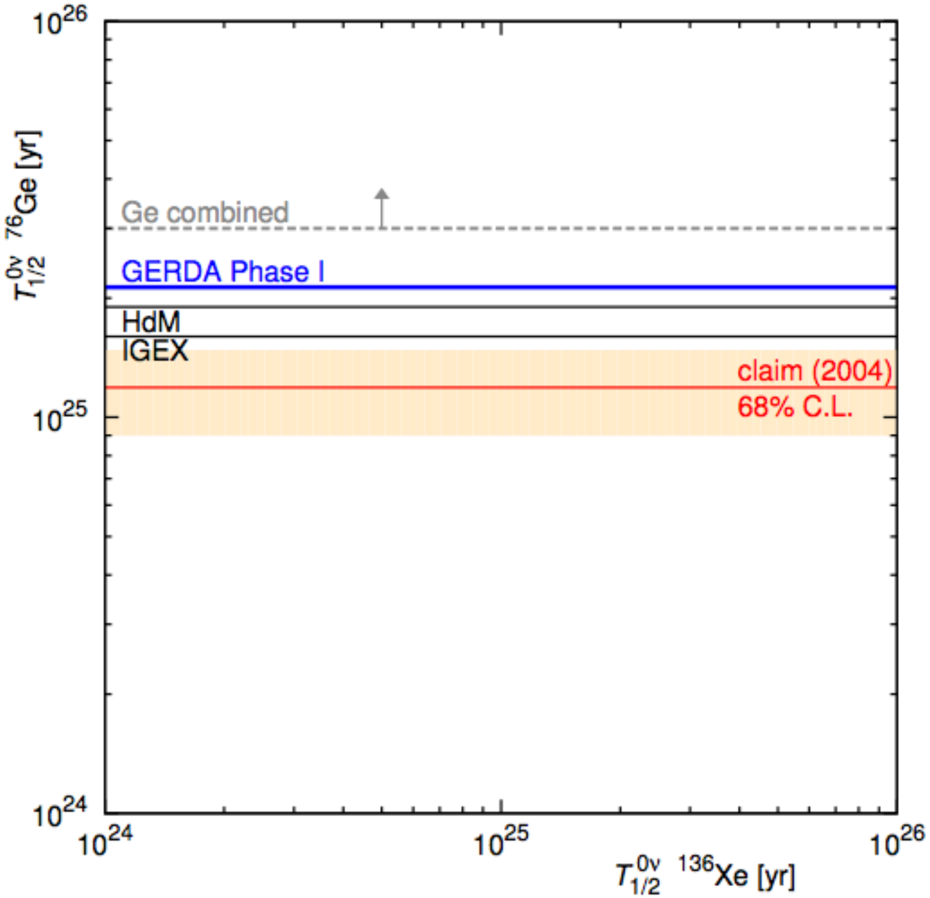
profile likelihood (PL) fit:

signal = a*flat background + b*line

➔ best fit: $N^{0\nu} = 0$; upper limit: $N^{0\nu} < 3.5$ (90%CL)

➔ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 * 10^{25}$ yr (90% C.L.)

Combination / Comparison of Ge Results



Combine: **GERDA phase I + HdM + IGEX**

➔ PL fit to combined data

➔ backgrounds = free paramaters

➔ Best fit for $N^{0\nu} = 0$

➔ **$T_{1/2}(0\nu\beta\beta)$> 3.0*10^{25} yr(90% CL)**

KK-claim: $T_{1/2}(0\nu\beta\beta) = 1.19 * 10^{25}$ yr

Stronger 2006 claim has known error: 100% PSD efficiency assumed
➔ realistic efficiency = no improvement

GERDA:

- **much lower BI**
- **no unknown nuclear lines**
- **flat background in ROI**

GERDA upper limit from PL fit:
< 3.5 events (90%CL)
KK claim strongly disfavoured
(Bayes factor $2*10^{-4}$)

KK claim → GERDA should see (2σ):
5.9 $\pm$ 1.4 signal counts
2.0 $\pm$ 0.3 background counts
→ probability for a fluctuation 1%

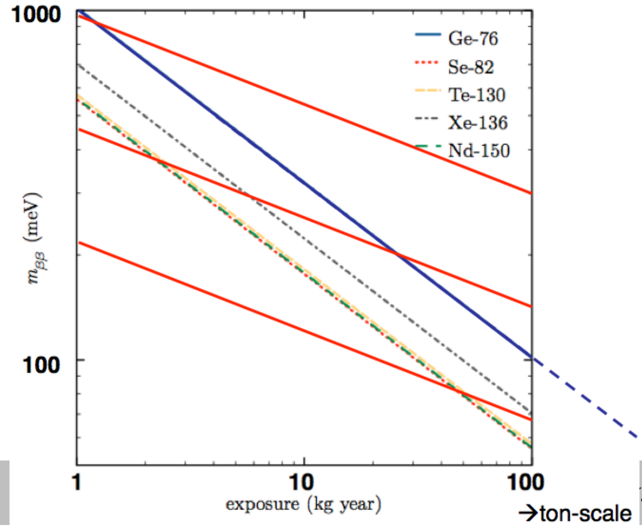
GERDA Outlook

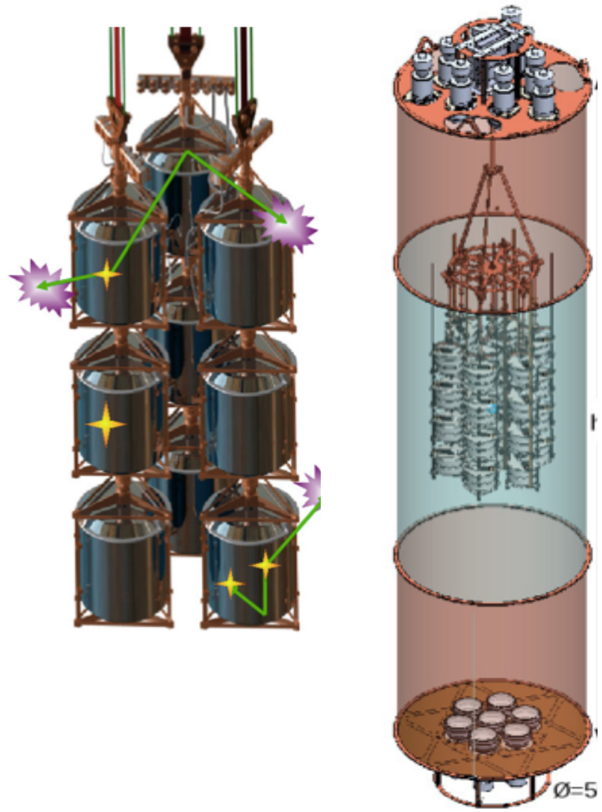
Transition to phase II:

✓ drainage, inspection & refilling of WT

- Installation of more new BEGe detectors
  ➔ ~factor 2 in ^{76}Ge mass
- Installation of light instrumentation
  ➔ fibers and PMTs = anti-Compton veto
  ➔ further reduction of background index
- **Continue data taking with more mass, less BI, longer time, …**

➔





The EXO Collaboration

Enriched Xenon Observatory
EXO
for double beta decay

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University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, F. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith

Duke University, Durham NC, USA – P.S. Barbeau

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ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, A. Pocar, D. Shy, J.D. Wright

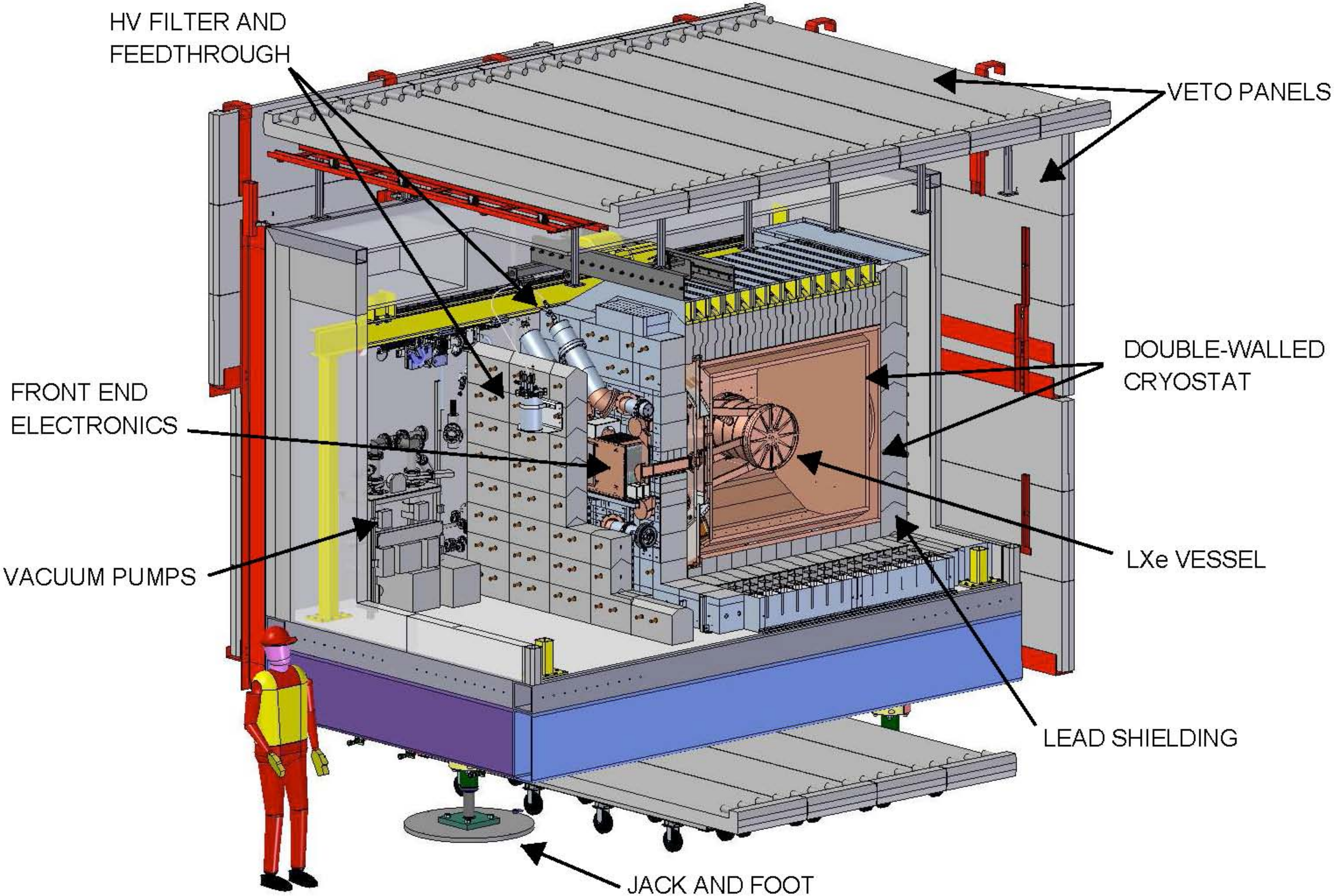
University of Seoul, South Korea - D.S. Leonard

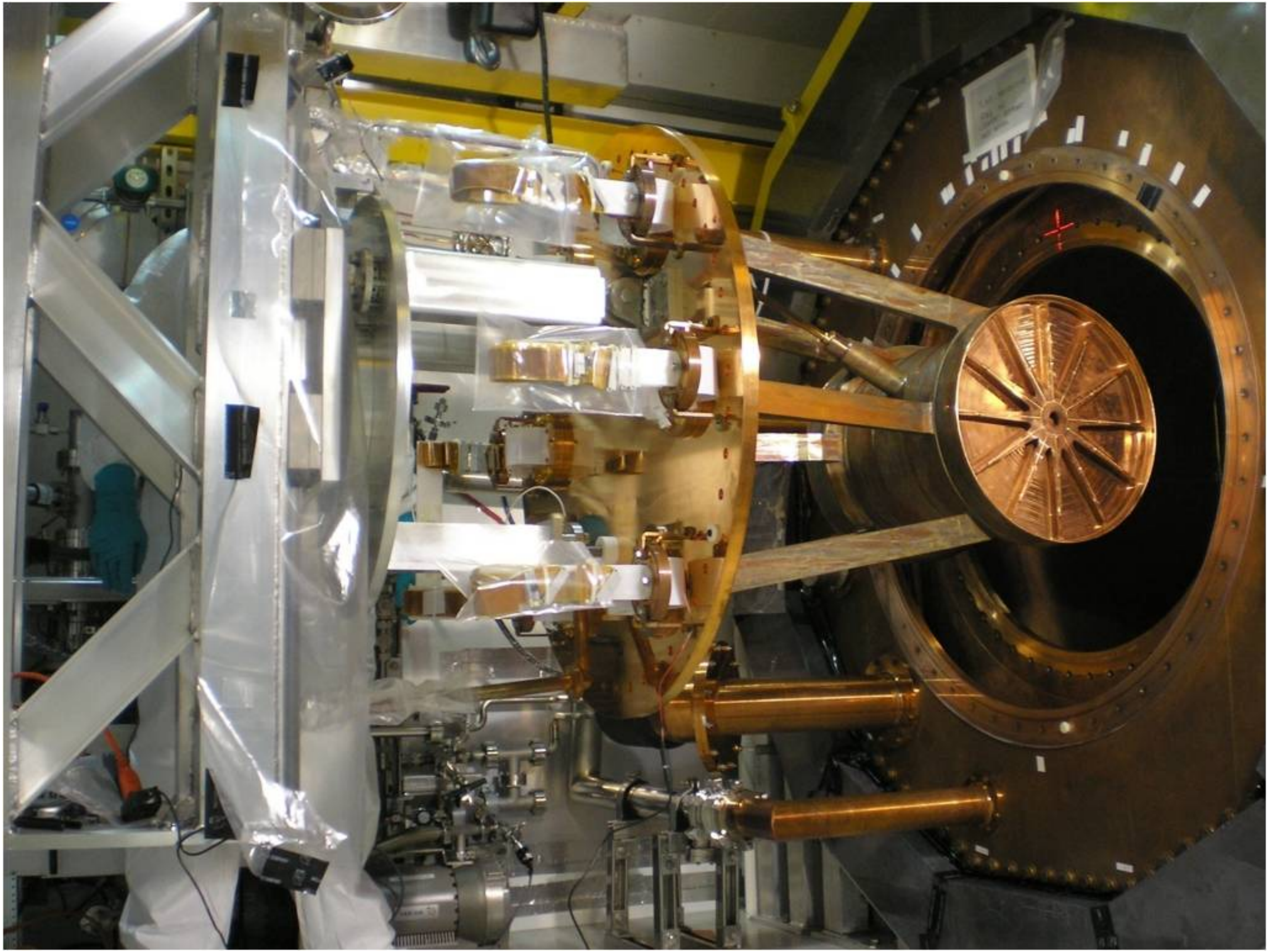
SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, A. Dragone, K. Fouts, R. Herbst, S. Herrin, A. Johnson, R. MacLellan, K. Nishimura, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, M. Weber, L. Wen

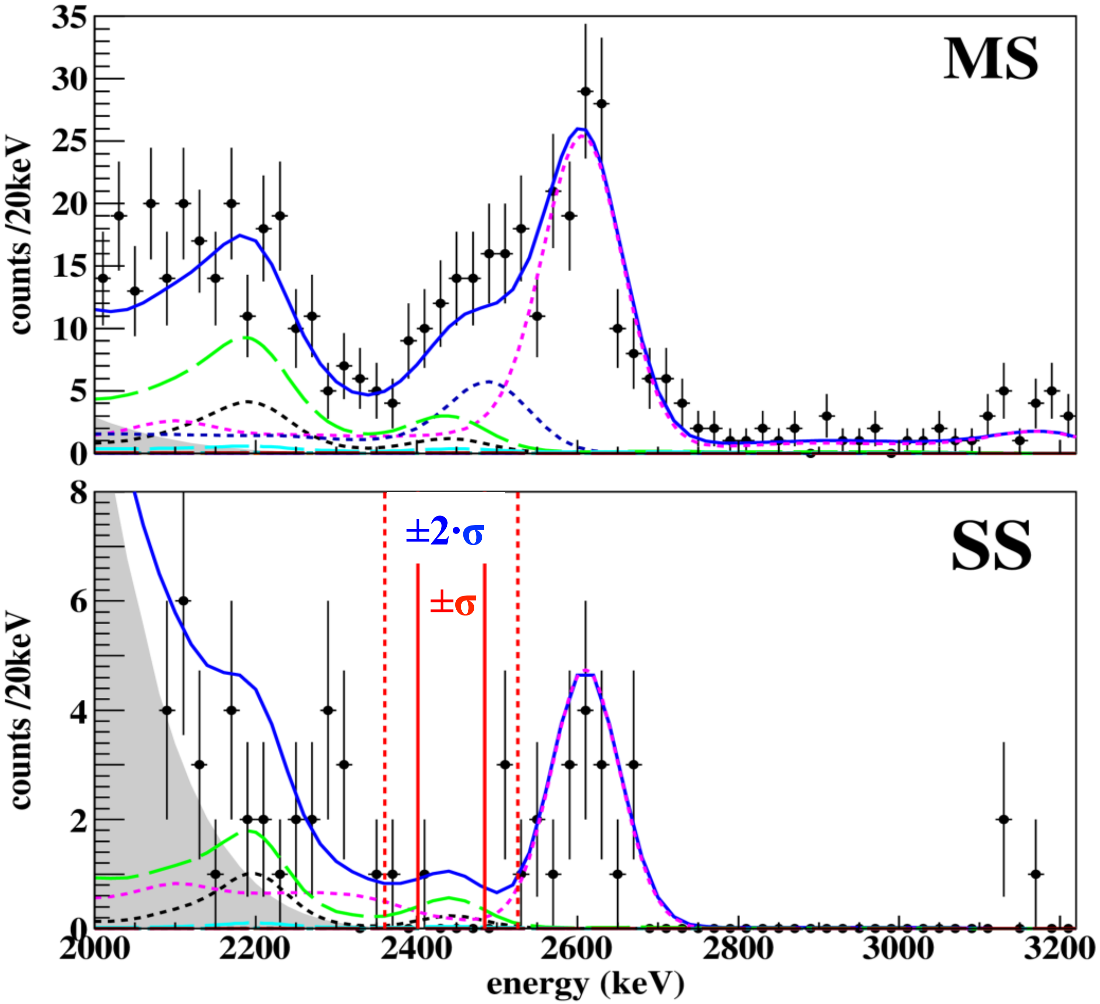
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – P.A. Amaudrux, D. Bishop, J. Dilling, P. Gumplinger, R. Krucken, C. Lim, F. Retière, V. Strickland


HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
LXe VESSEL
VACUUM PUMPS
LEAD SHIELDING
JACK AND FOOT



EXO-200 0νββ-data (32.6 kg·yr)



No peak observed at $Q_{\beta\beta}$.

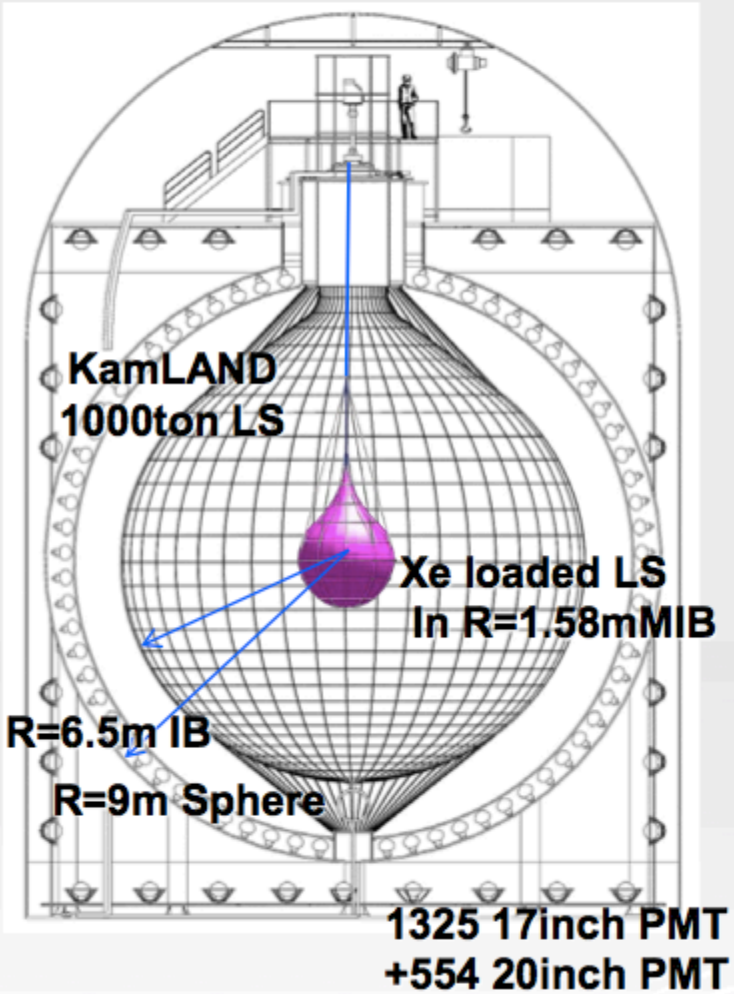
MC background model:
$1.5 \cdot 10^{-3}$ cnts/(keV·yr·kg)

Measured background:
153±69 cnts/(±2·σ·ton·yr)
31±31 cnts/(±σ·ton·yr)

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ yr$$ **(90% CL)**

$\langle m \rangle_{\beta\beta} < 140 - 380$ meV

KamLAND-Zen



KamLAND-Zen collaboration

- Tohoku University
- Kavli IPMU Tokyo University
- Osaka University
- University of California Berkeley
- LBNL
- Colorado State University
- University of Tennessee
- TUNL
- University of Washington
- NIKHEF and University of Amsterdam

1st phase

^{136}Xe ~320kg (91% enriched)

R=1.58m balloon

V=16.5m^3

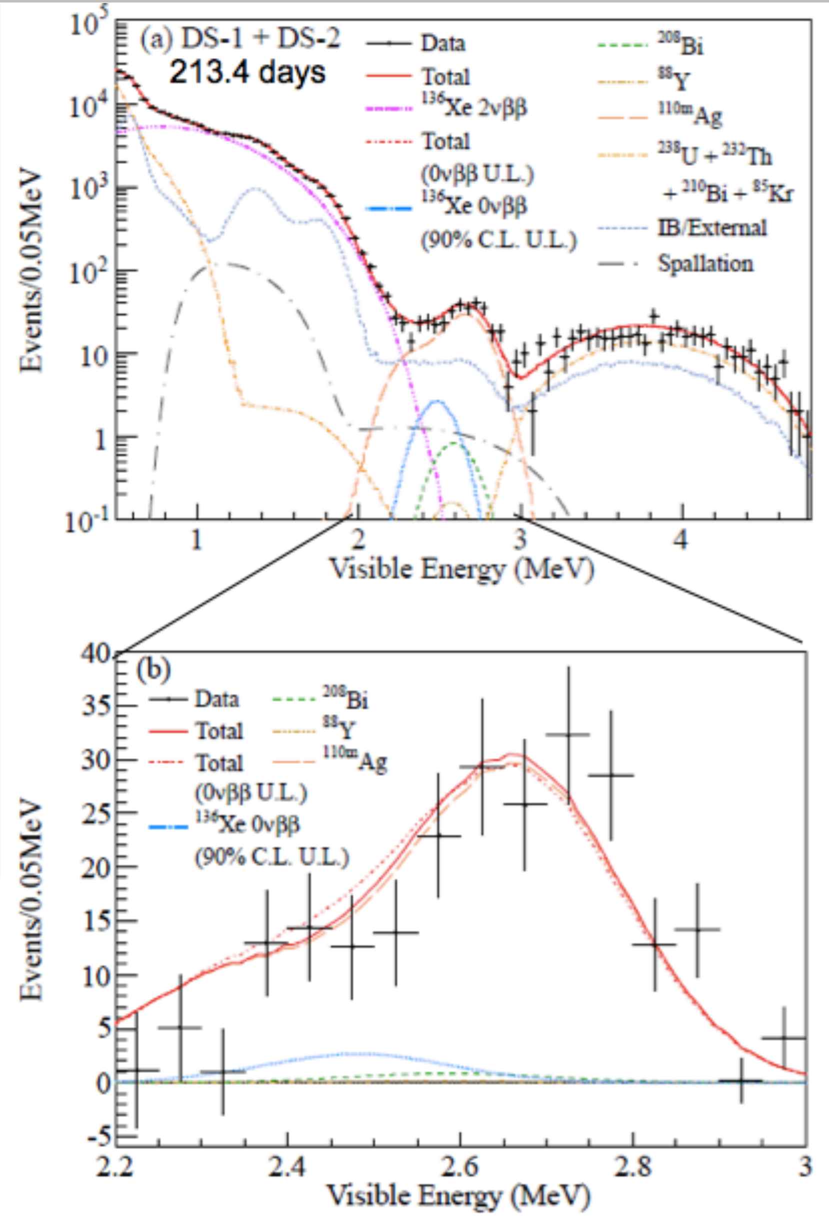
LS : C10H22(81.8%) + PC(18%) + PPO + Xe(~3wt%)

ρLS: 0.78kg/ℓ

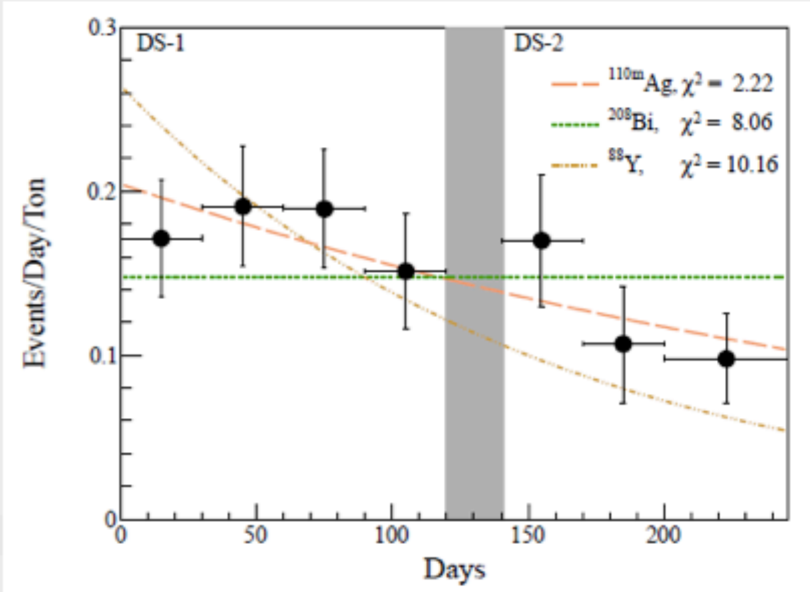
target : ~60meV / 2years for 0νββ

courtesy M. Koga

KamLAND-Zen Phase I Results



2.2MeV < E < 3.0MeV

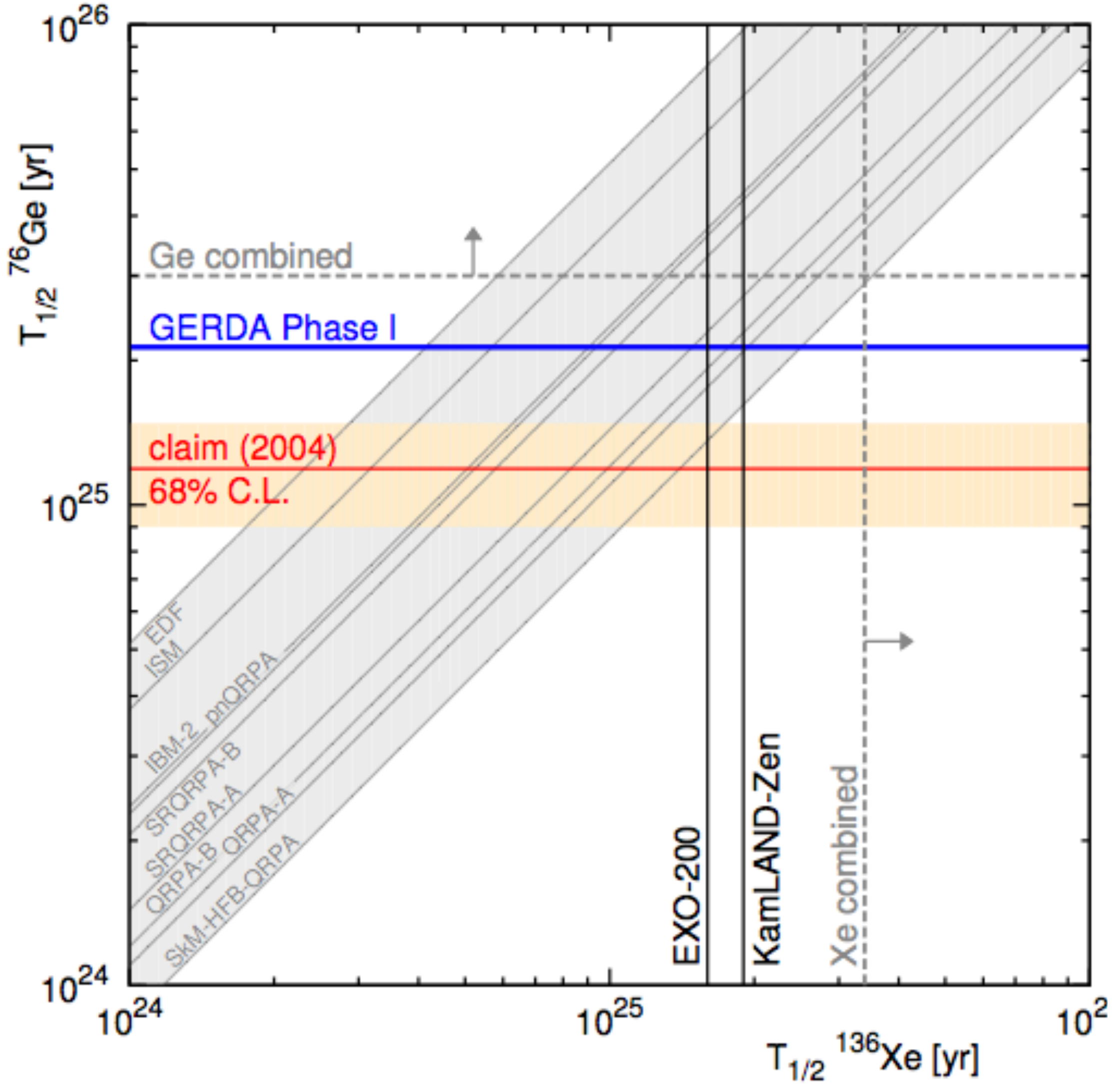


KamLAND-Zen

$T^{0\nu}_{1/2}$ > 2.1x10^{-25} yr @90%CL

Phys.Rev.Lett.110:062502,2013.

Comparison of Ge and Xe Results



Assumptions:

- exchange of Majorana neutrinos

- NME ratios better known

→ NME ratio has spread !

→ at best one is right

→ model dependence

Bayes factors:

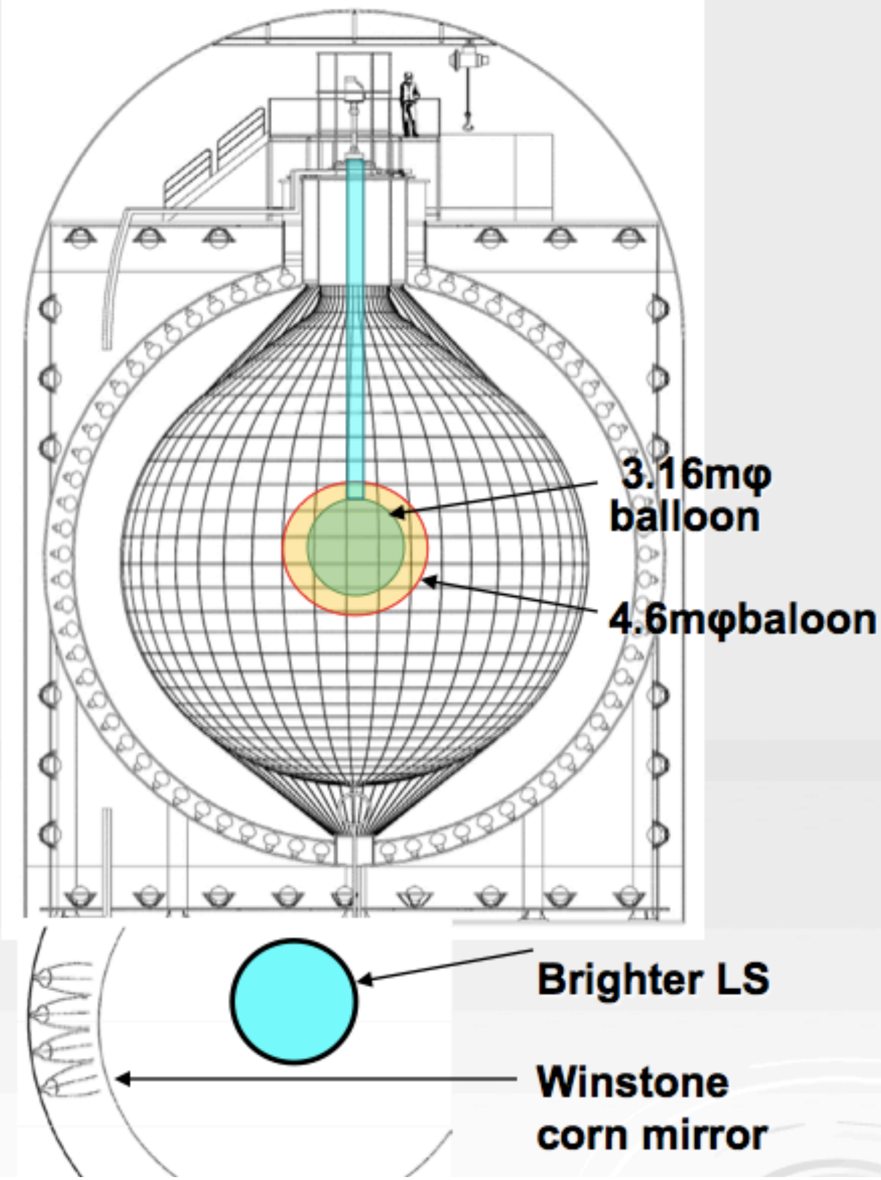
EXO: 0.23

KamLAND-Zen: 0.40

All with GERDA: 0.0022

➔ KK claim even more disfavoured

Future Plans of KamLAND-Zen



re-start (from Nov. 2013?)

KamLAND-Zen2

- we will purchase 700~800kg enrich ^{136}Xe to the end of 2013
- make bigger balloon
- same component XeLS (~3wt%)
- main tank inspection & OD repair (beginning of 2015?)

↓ tank opening (201?)

KamLAND2-Zen ^{136}Xe 800~1000kg

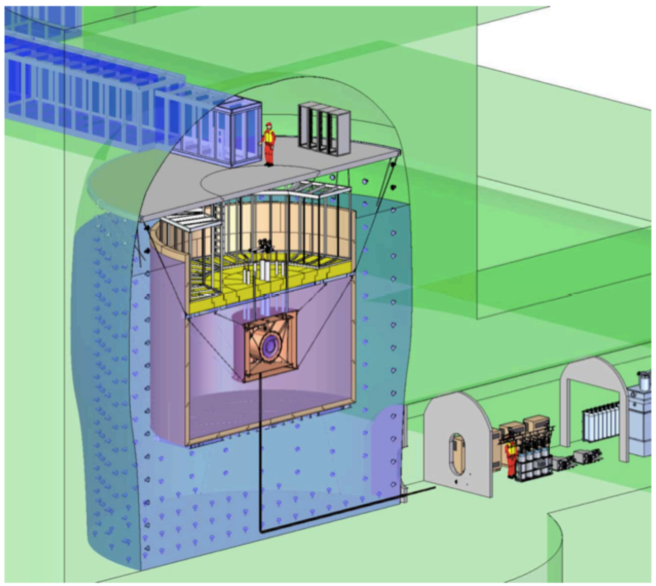
- R=2.3m balloon, $V=51.3m^3$,$S=66.7m^2$
- Detector upgrade
  improvement of energy resolution
  (brighter LS, higher light concentrator)
  ~25meV with 5 years

Future Plans of EXO: → nEXO

- **EXO has 3.6 times more data → should be published soon…**
- **EXO started to study the case for a 5 ton (~4.5 ton fiducial) Xe experiment, *initially* without Ba-tagging. Tagging should remain an option, you could consider it a (backgd.) risk mitigation tool**
  - 4.5 tons of active ^{enr}Xe (80% or higher)
  - 1.5% (σ) energy resolution
  - Background from Monte Carlo **using normalizations derived from EXO-200 data and materials assa**
  - **3 times finer wire pitch than EXO-200, lower energy threshold → 2 times better e-γ discrimination than EXO-200**

Goals: probe and possibly fully cover the inverted hierarchy neutrino mass range. In case Ba detection is added test part of the normal hierarchy

Sketch of nEXO in the SNOlab Cryopit

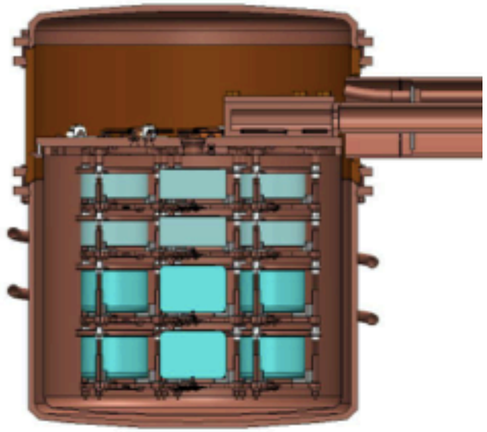


Future of Ge-Experiments

GERDA: on-going modifications for phase II → data taking

MAJORANA demonstrator:
under construction → data taking

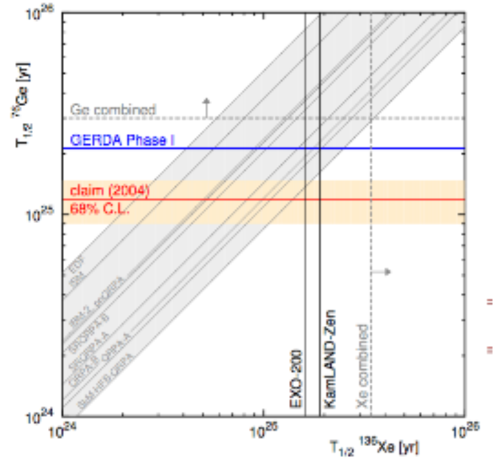
- ~ 30 kg ^{enr}Ge + ~ 10 kg ^{nat}Ge detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015



GERDA + MAJORANA cooperation agreement:
- open exchange of knowledge & technologies (e.g. MaGe, R&D)
- intention to merge for ton-scale experiment
→ best techniques developed & tested in GERDA and MAJORANA

Conclusions

- GERDA phase I finished data taking with unprecedented BI
- The background is understood very well: flat in ROI
- 3 independent pulse shape discrimination techniques efficiently reduces background
- Half life limit for 0νββ-decay of ^{76}Ge:
  2.1·10^{25} yr (90% C.L.)
  GERDA+HdM+ IGEX: 3.0·10^{25} yr (90% C.L.)



- Similar limits from EXO and KamLAND-Zen
  Xe→Ge translation depends on matrix element ratios...
- Ge+Xe combined: HdM claim very strongly disfavored!

- New result from EXO expected soon
- Very promising upgrades / plans for the future!