Double Beta Decays

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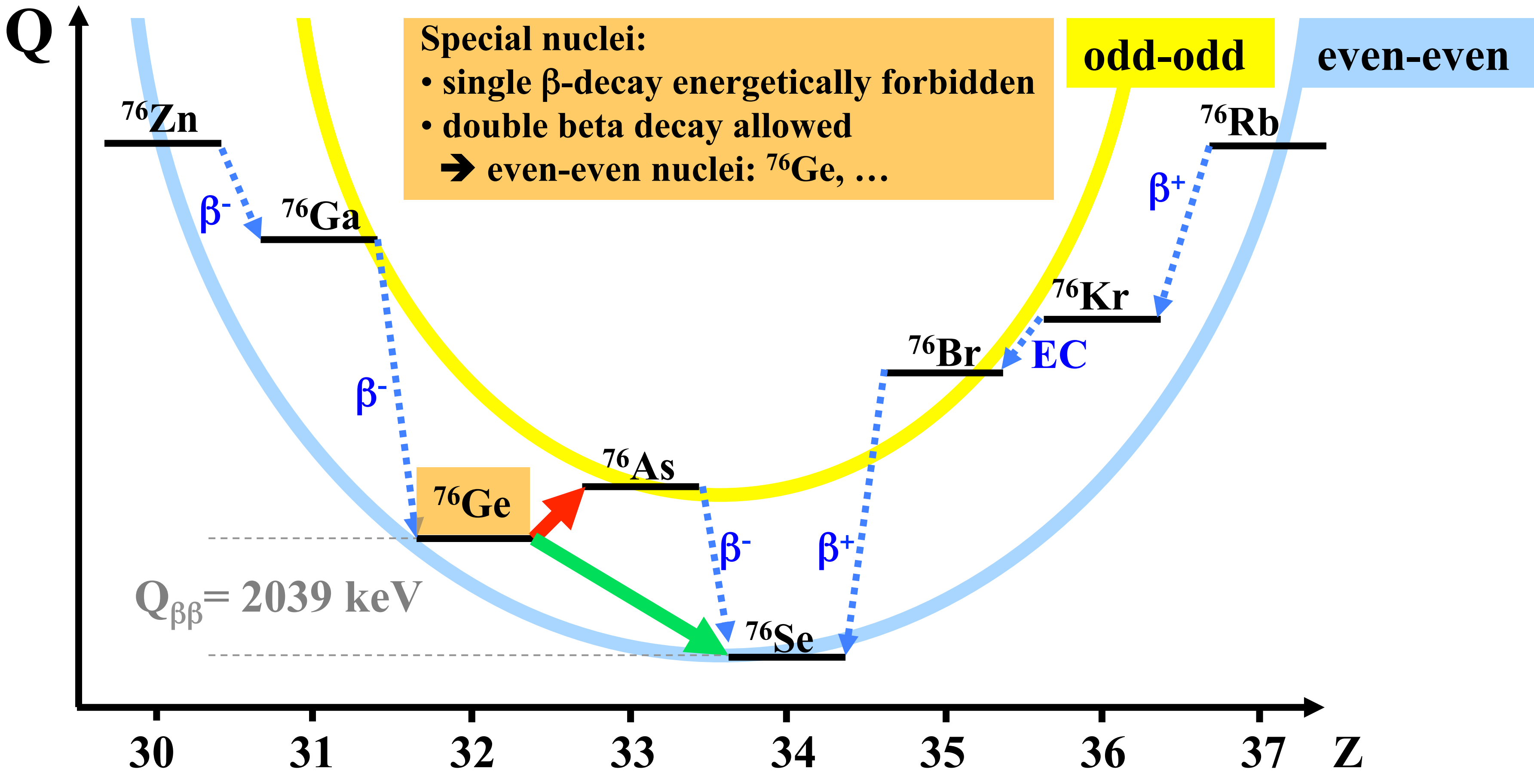
NNN13: International Workshop on Next generation Nucleon Decay and Neutrino Detectors

11-13 November 2013 *Kavli IPMU*

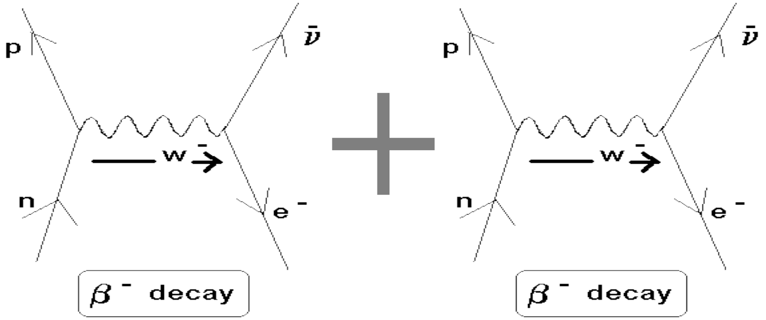
Double Beta Decay & Mass Parabolas



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

Double Beta Decay Processes

Standard Model:

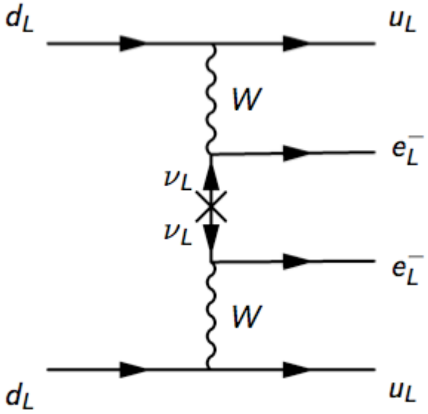


→ 2 electrons + 2 neutrinos

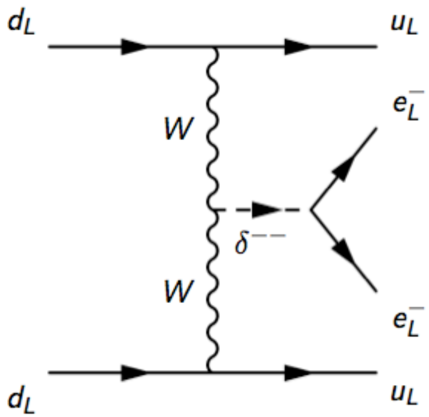
$2\nu\beta\beta$

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

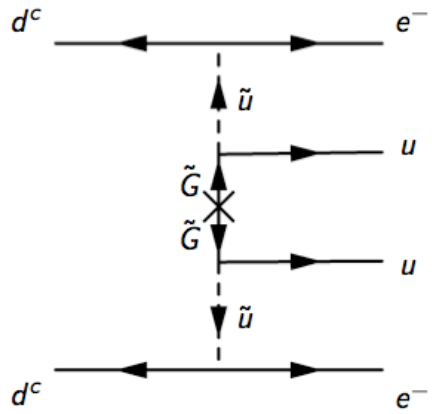
$0\nu\beta\beta$



Majorana
neutrino masses
←→ Dirac?



SM + Higgs triplet



SUSY

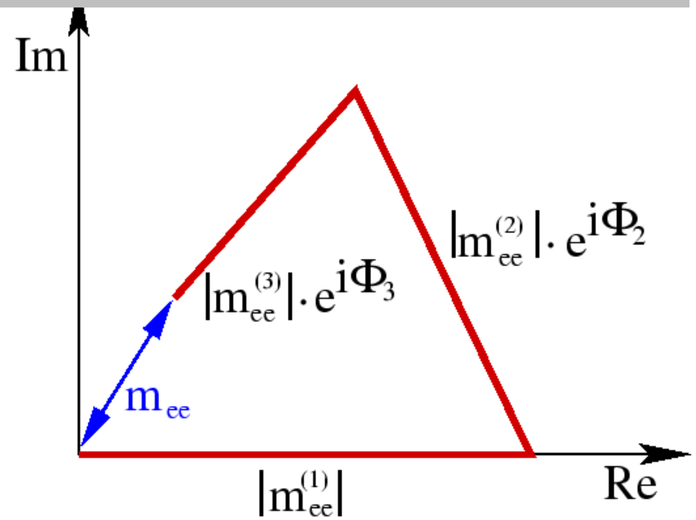
…

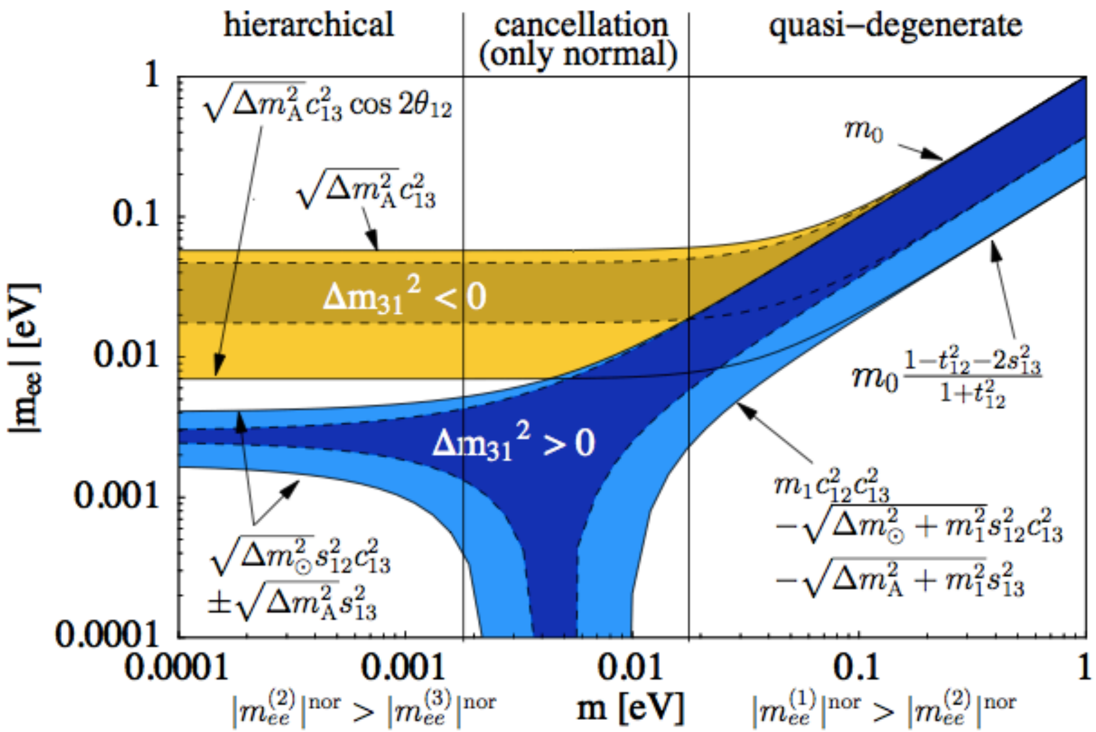
important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics

m_{ee}: The Effective Neutrino Mass

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

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





Comments:

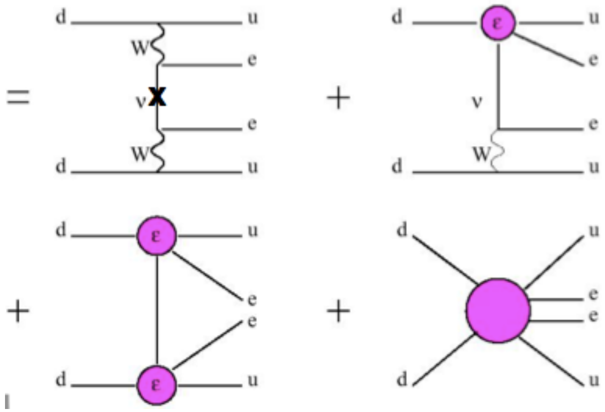
- **cosmology: further improvements?**
  ↔ systematic errors
- **NMEs→ unavoidable theory errors**
- **assumption: no *other* $\Delta L=2$ physics, no sterile neutrinos, ...**

Interference of ΔL=2 Operators

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

Dürr, ML, Neuenfeld

with interferences



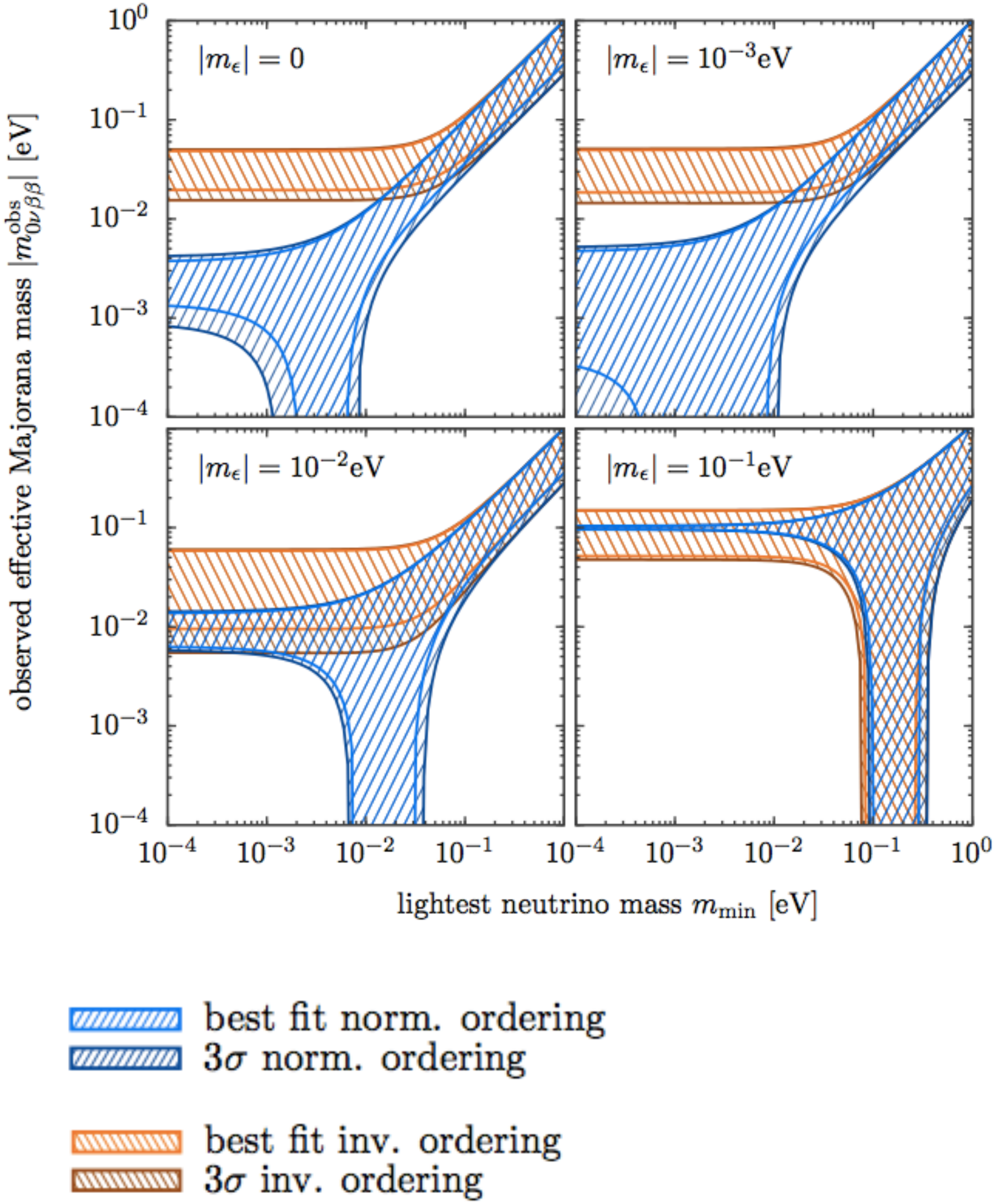
$$\left(T_{1/2}^{0\nu}\right)^{-1} = |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^{\epsilon}|^2 \frac{G^{\rm int}}{m_e^2}$$
$$= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1})\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2}$$
$$= |m_{0\nu\beta\beta}^{\rm int}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2},$$

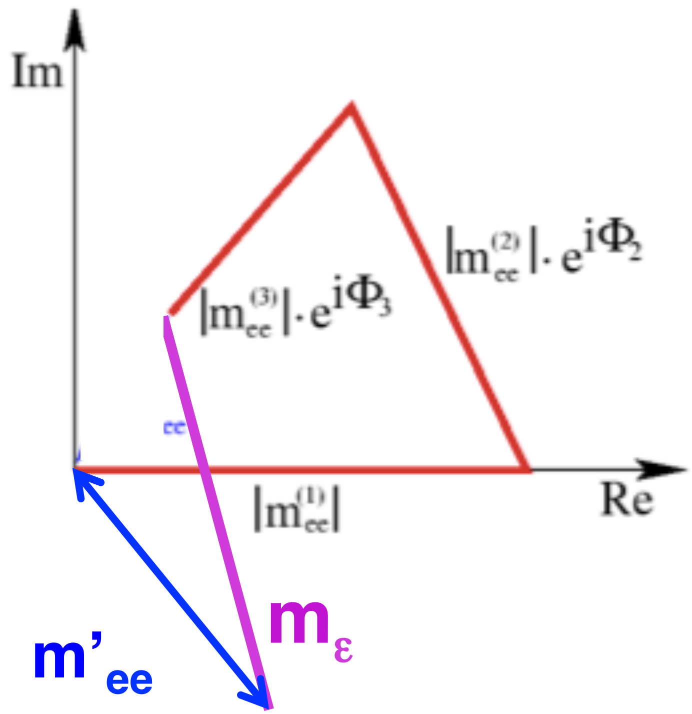
$G^{\rm int}$ = overall phase space factor

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

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

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





interferences

growing m_ε for fixed $0\nu\beta\beta$

→ shifts of masses, mixings and CP phases

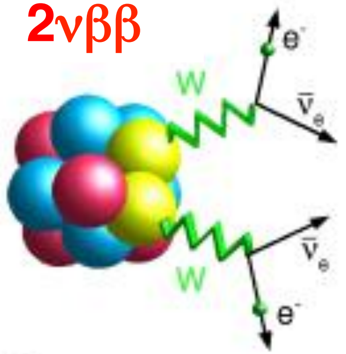
→ destroys ability to extract Majorana phases

→ sensitivity to TeV

Double Beta Decay Kinematics

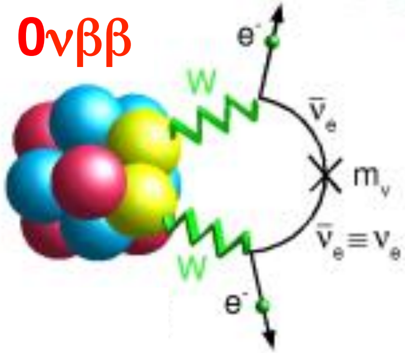
SM

$2\nu\beta\beta$

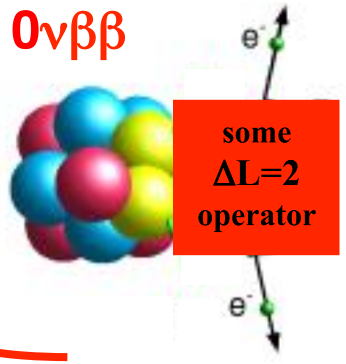


BSM

$0\nu\beta\beta$

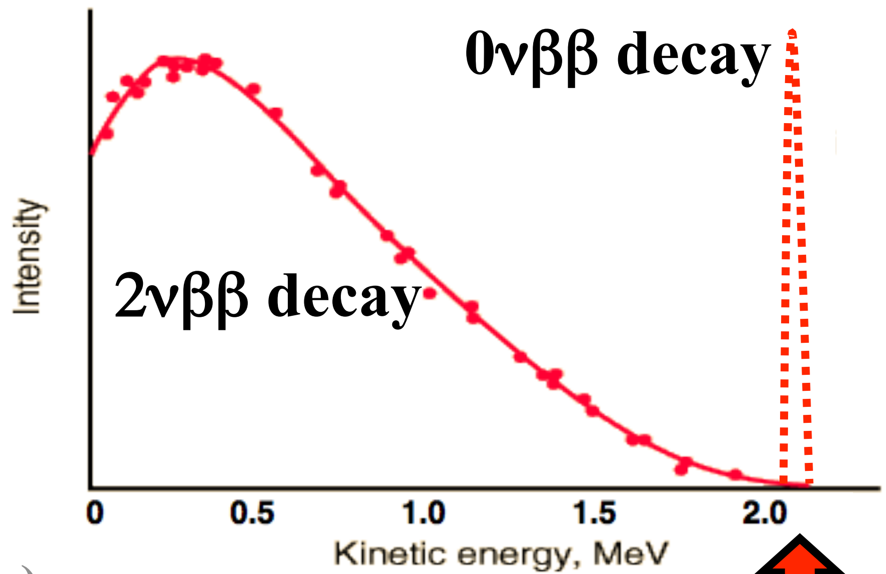


$0\nu\beta\beta$

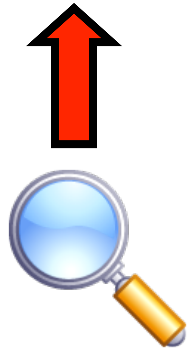


$2\nu\beta\beta$ decay seen for diff. isotopes (Kirtsen,…)

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

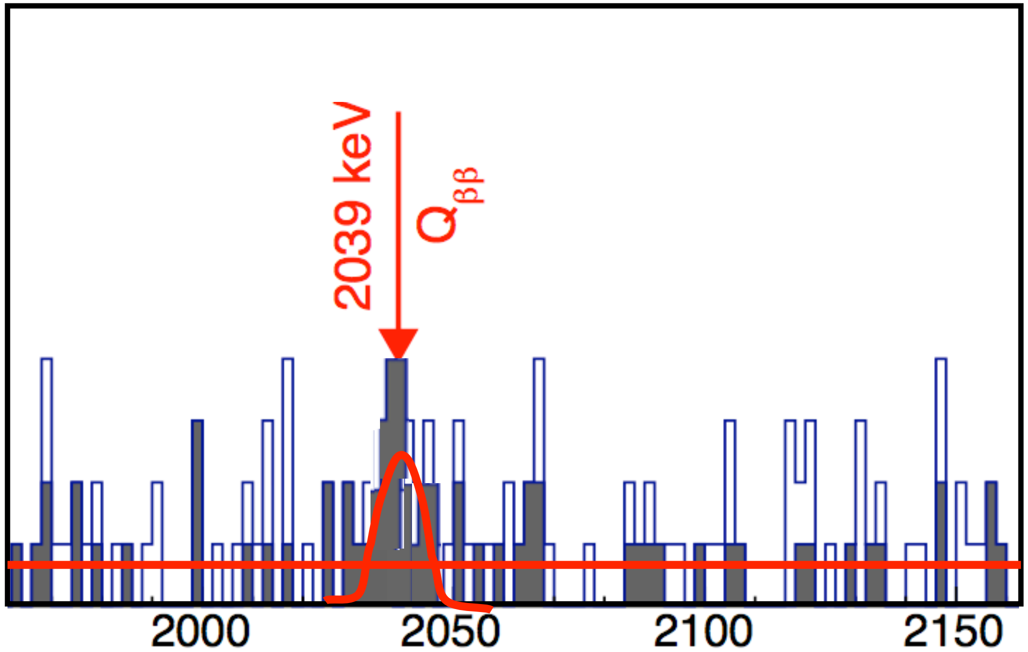


$T^{1/2} > O(10^{24}y)$



- $2\nu\beta\beta$ → improvement
- search for $0\nu\beta\beta$ 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 ?

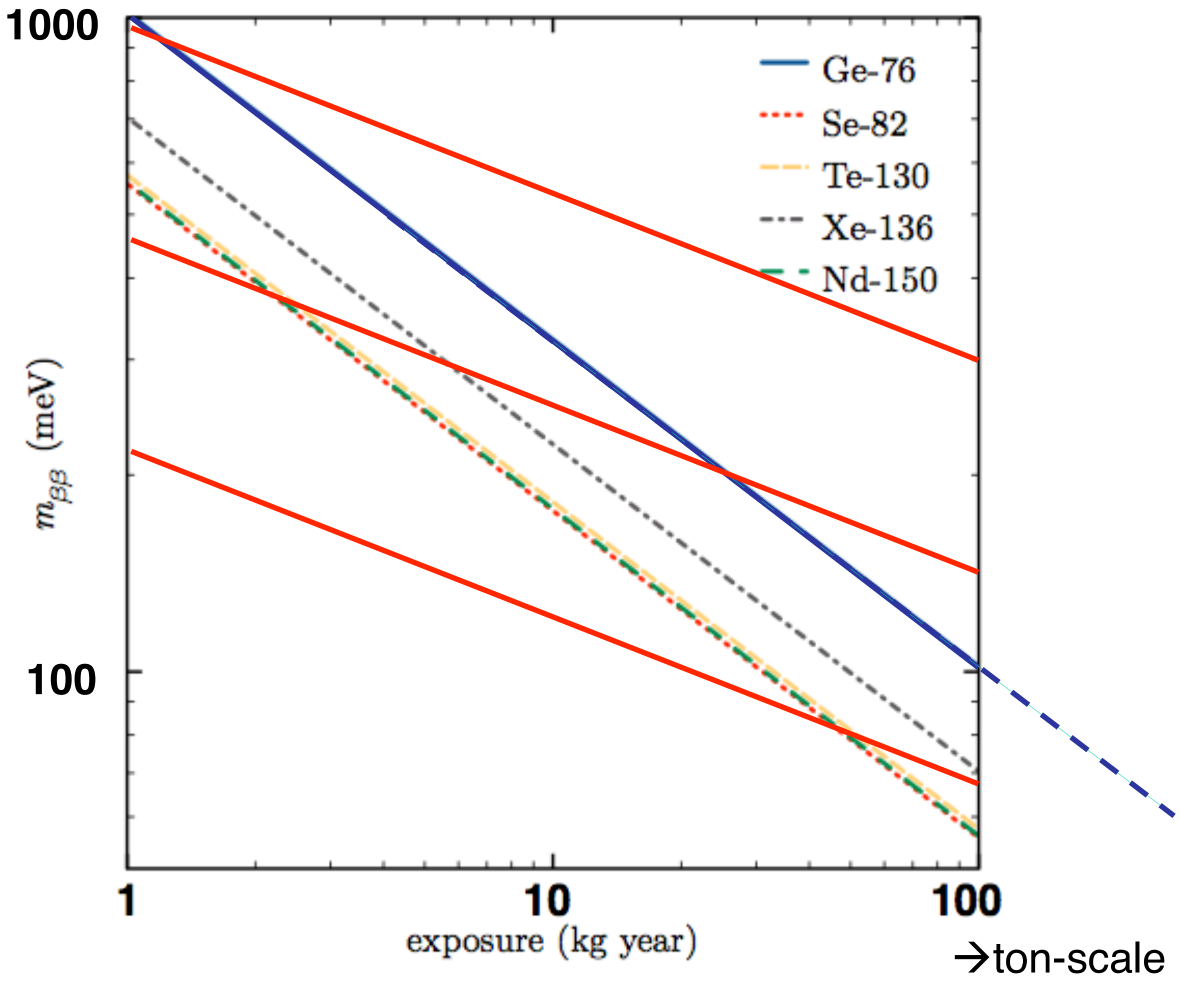
To best extract a $0\nu\beta\beta$ signal at $Q_{\beta\beta}$ and to avoid any misinterpretations:

- 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:

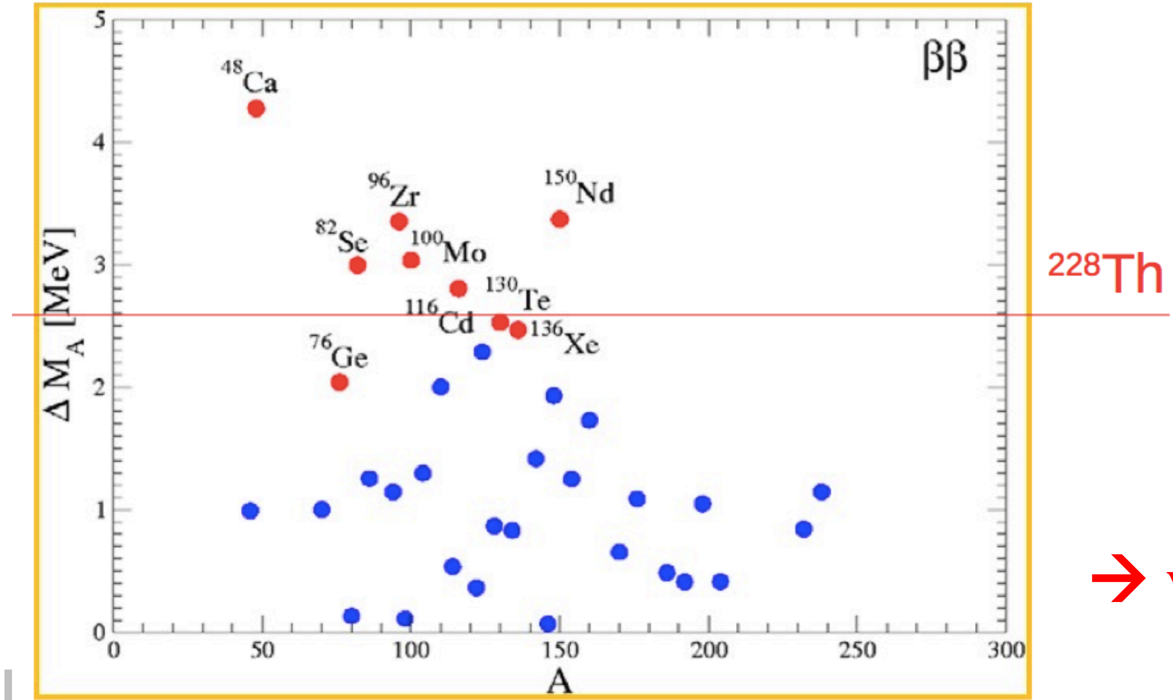
$$N' = N + N_{background}$$

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

c = cts/keV kg yr ; ΔE = ROI

Which $0\nu\beta\beta$ Isotope?

- active mass ←→ isotopic abundance/enrichment ←→ cost, feasibility
- cleanliness (radiopurity) of $0\nu\beta\beta$ 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	$G^{0\nu}$ $[\frac{10^{-14}}{\text{yr}}]$	$Q_{\beta\beta}$ [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

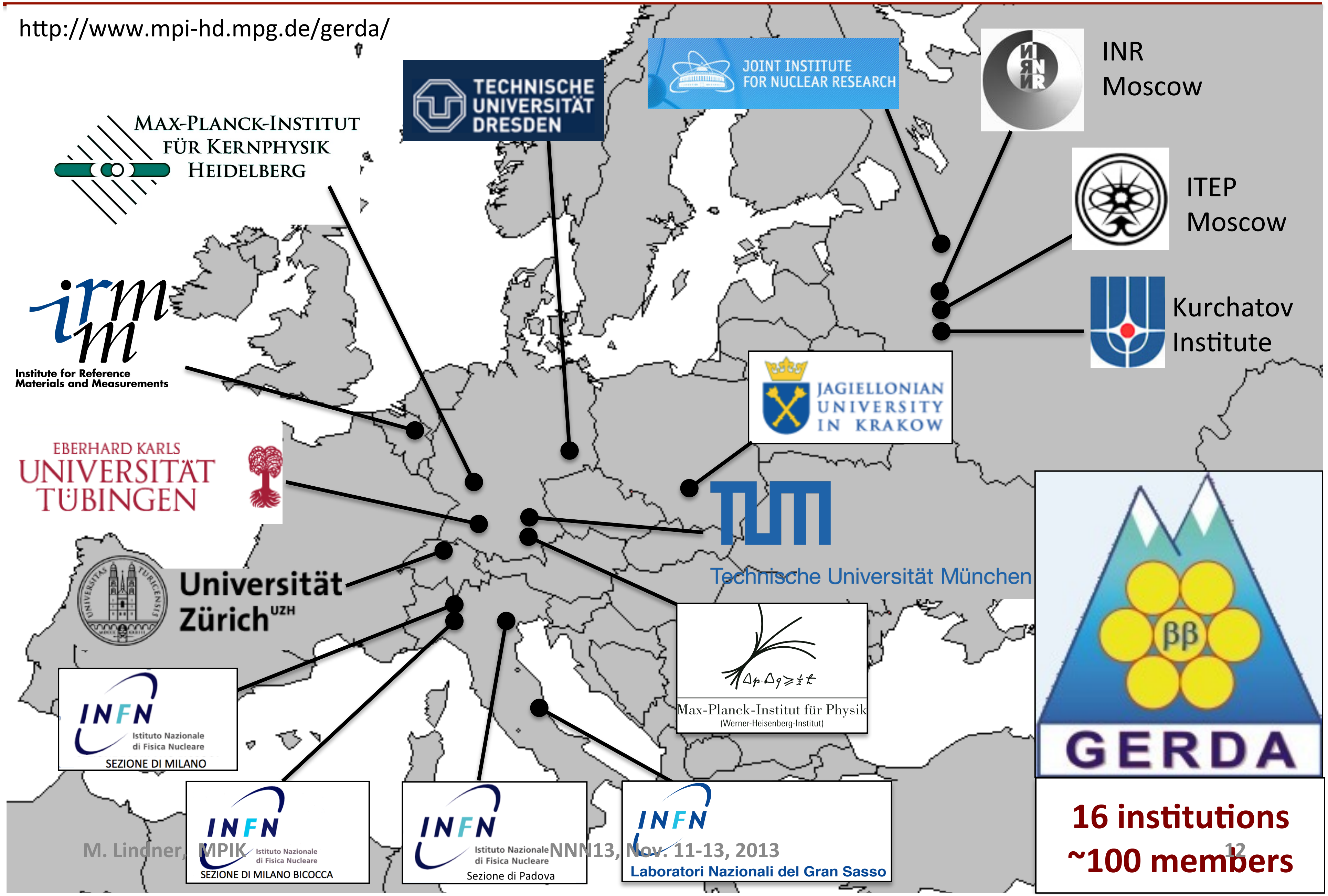
➔ **GERDA**

➔ **EXO, KamLAND-Zen**

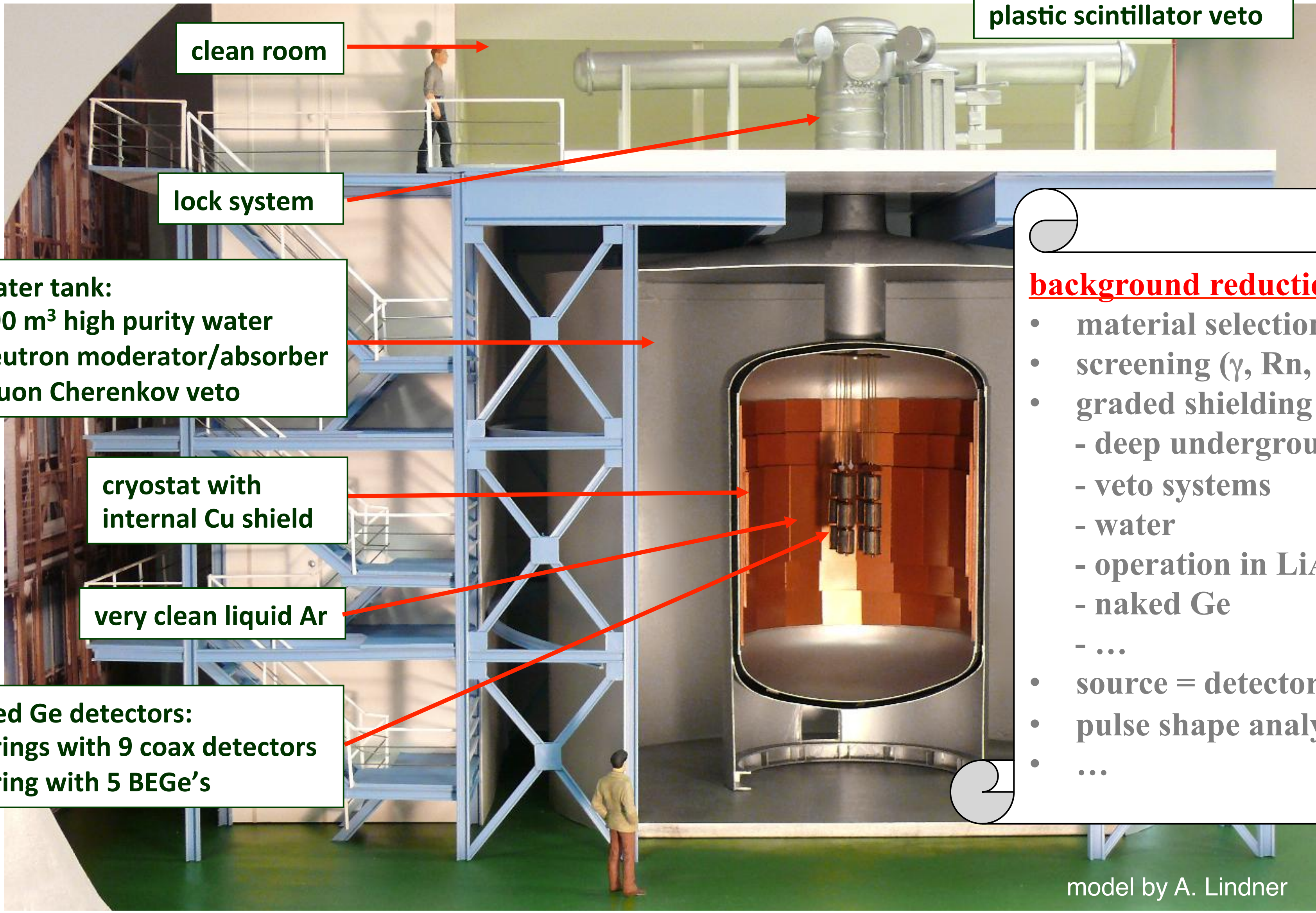
➔ **future**

The GERDA Collaboration

http://www.mpi-hd.mpg.de/gerda/



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

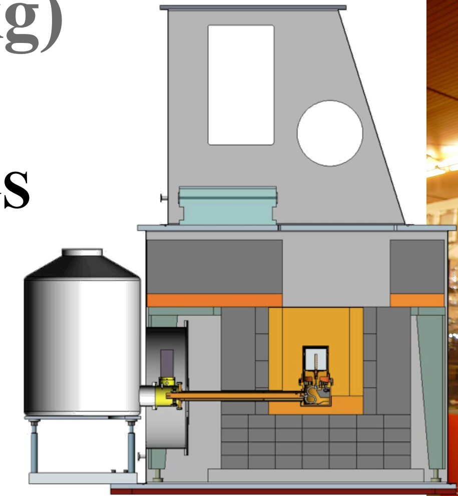


background reduction:

- 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, …)

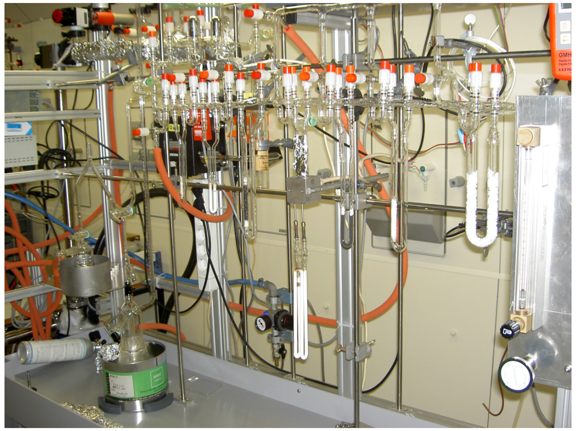
<u>Rn Screening Facilities:</u>

Gas counting systems (LNGS, MPIK)

^{222}Rn emanation technique

sensitivity = few atoms/probe

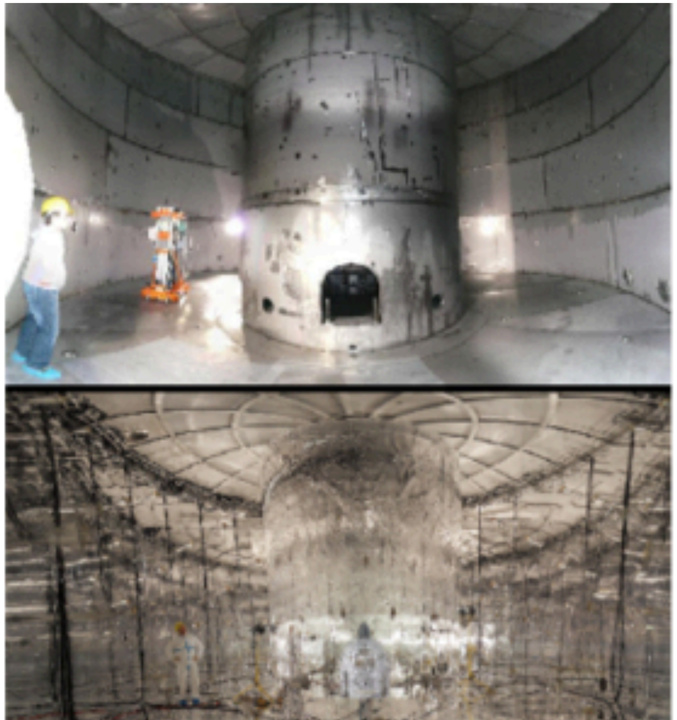
➔ typ. sensitivity: few $\mu Bq/m^2$



<u>ICPMS: …</u>

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



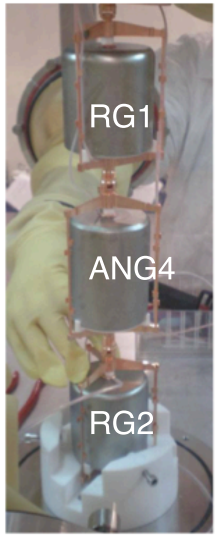
GERDA Phase I Detectors

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

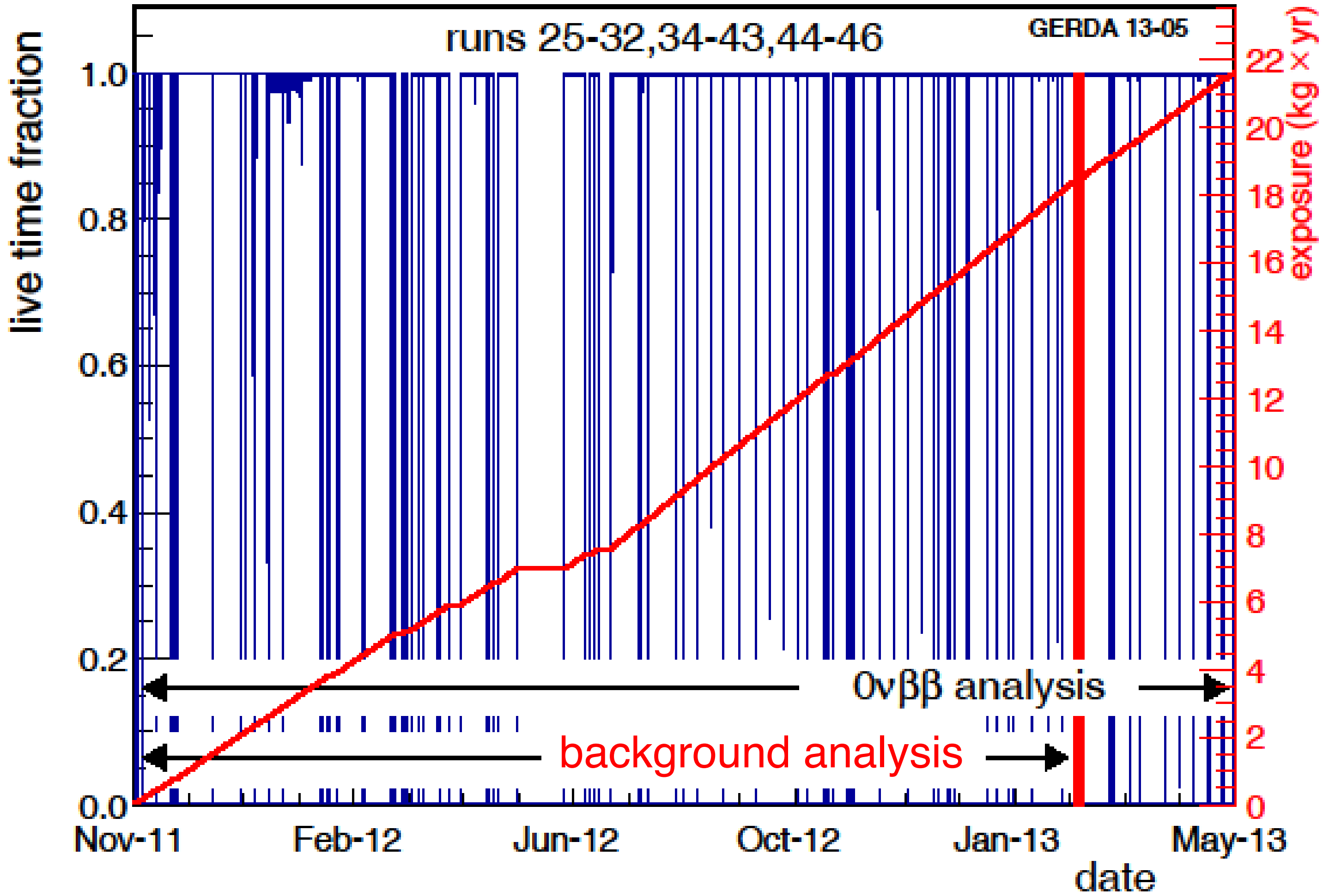
1 natural (7,83% of ^{76}Ge)
GTF112
→ 2.96 kg

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

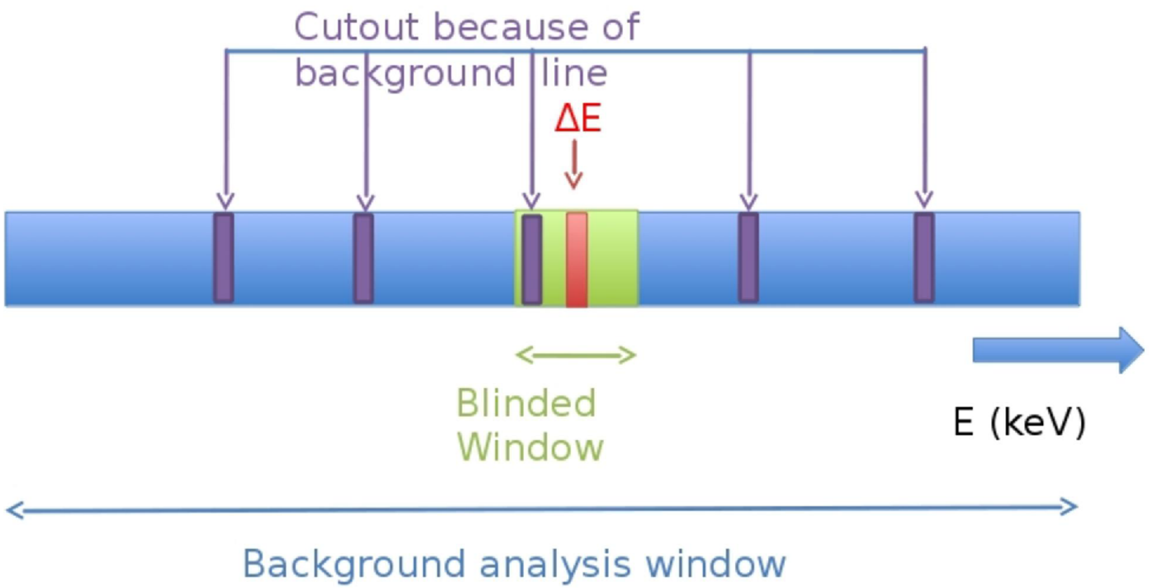


Data Taking



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

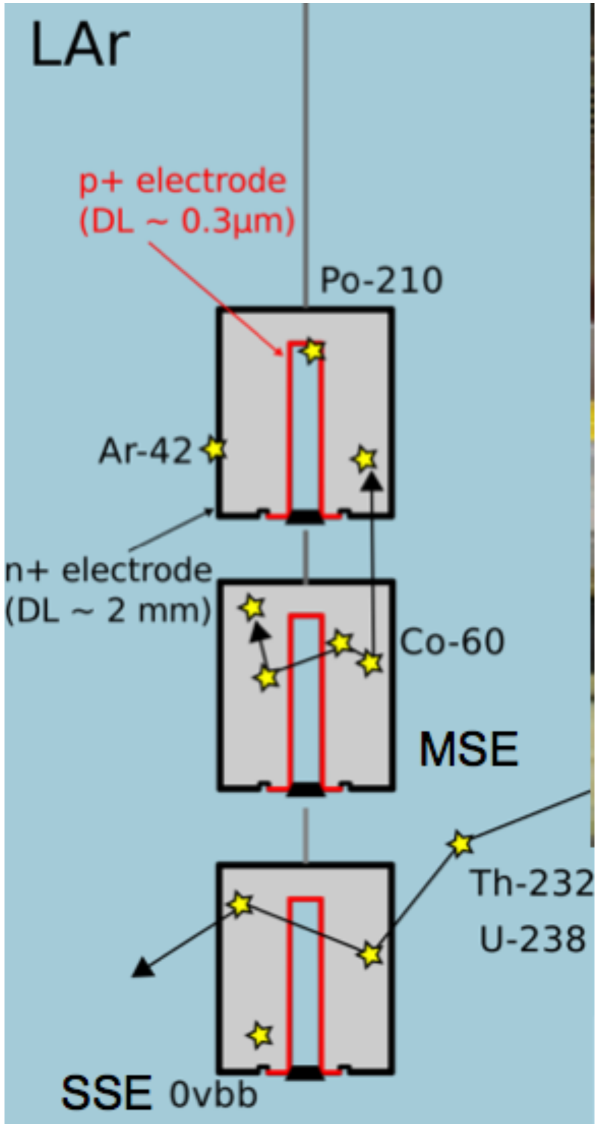
The outer dead layer of the detectors is not active

Background sources:

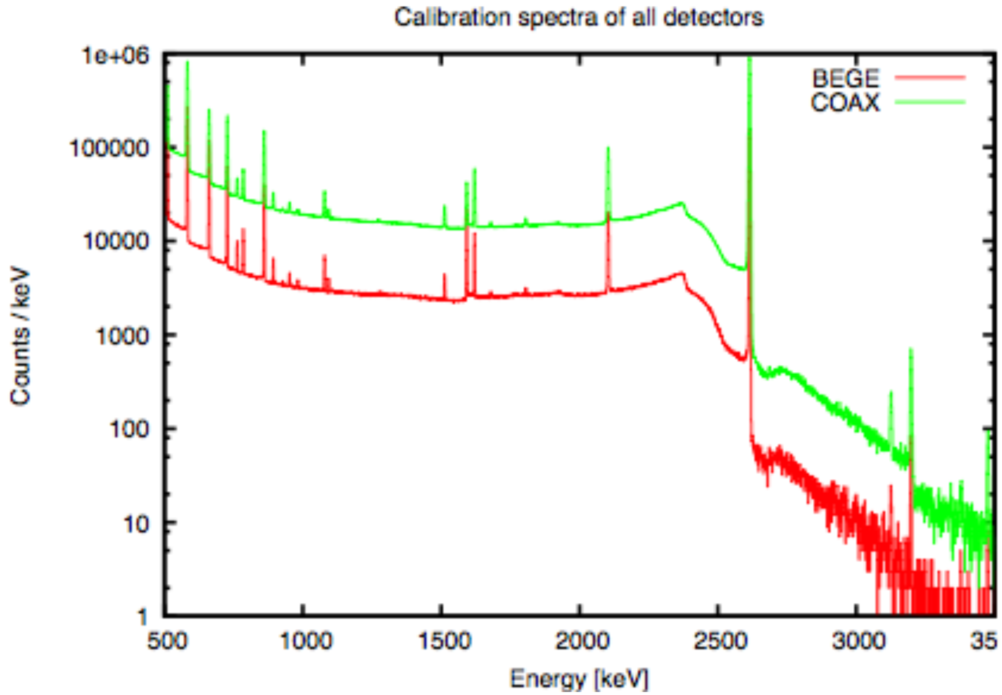
- α decays on the p^+ surface
- β decay of ^{42}K on the surface or close to the detector from ^{42}Ar (10x more than expected)
- β decay of ^{60}Co inside detectors
- γ from ^{208}Tl, ^{214}Bi and from various set-up components

Generic phase I background reduction

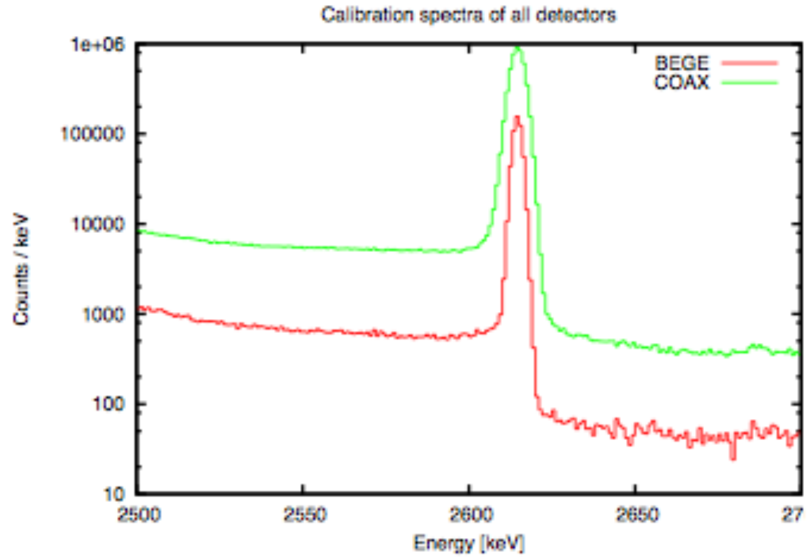
- use cleanest possible materials
- cut detector coincidences
- prevent ^{42}K ions from drifting to detectors using mini-shrouds



Detector Performance



from ^{208}Tl

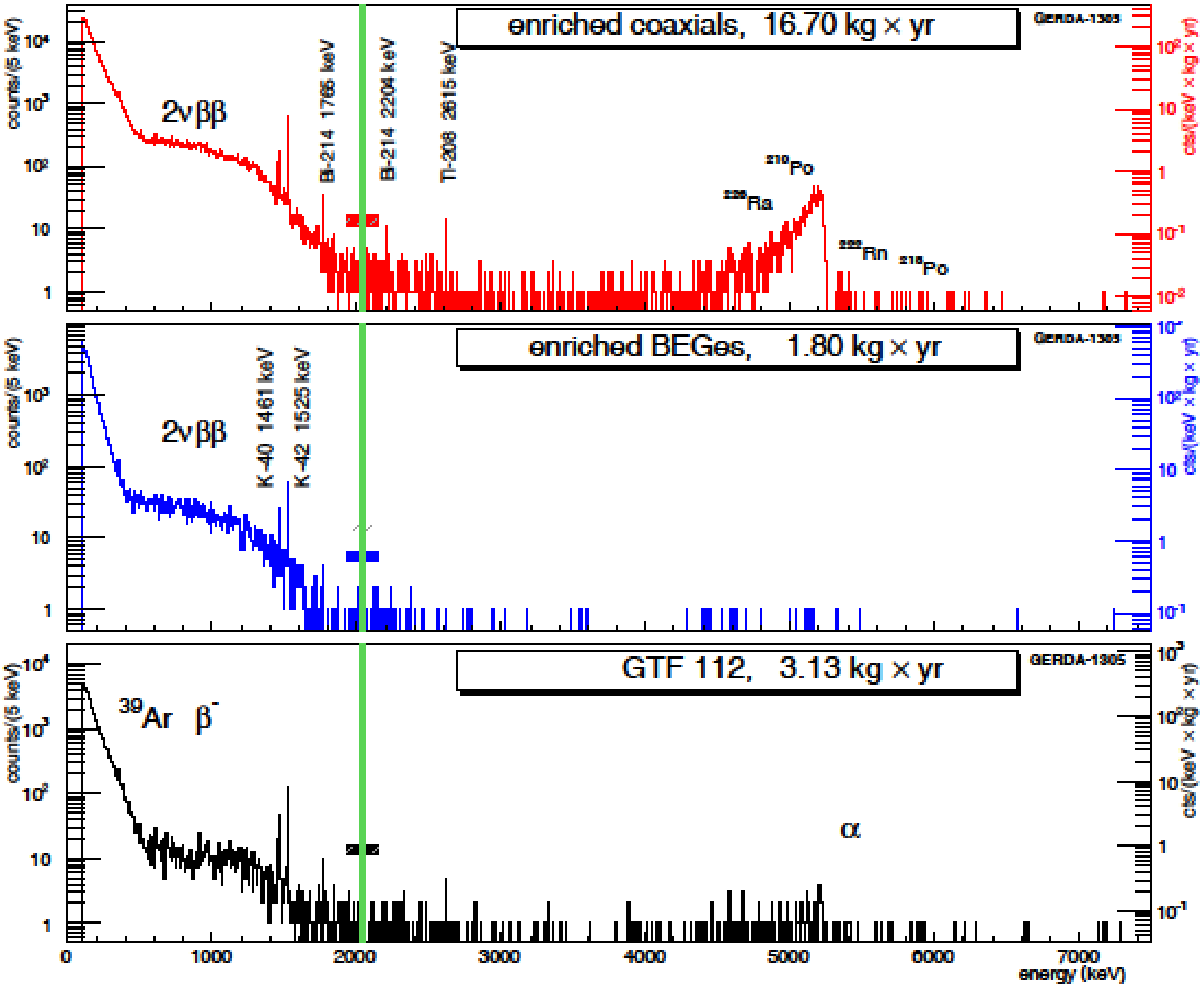


Energy resolution:

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

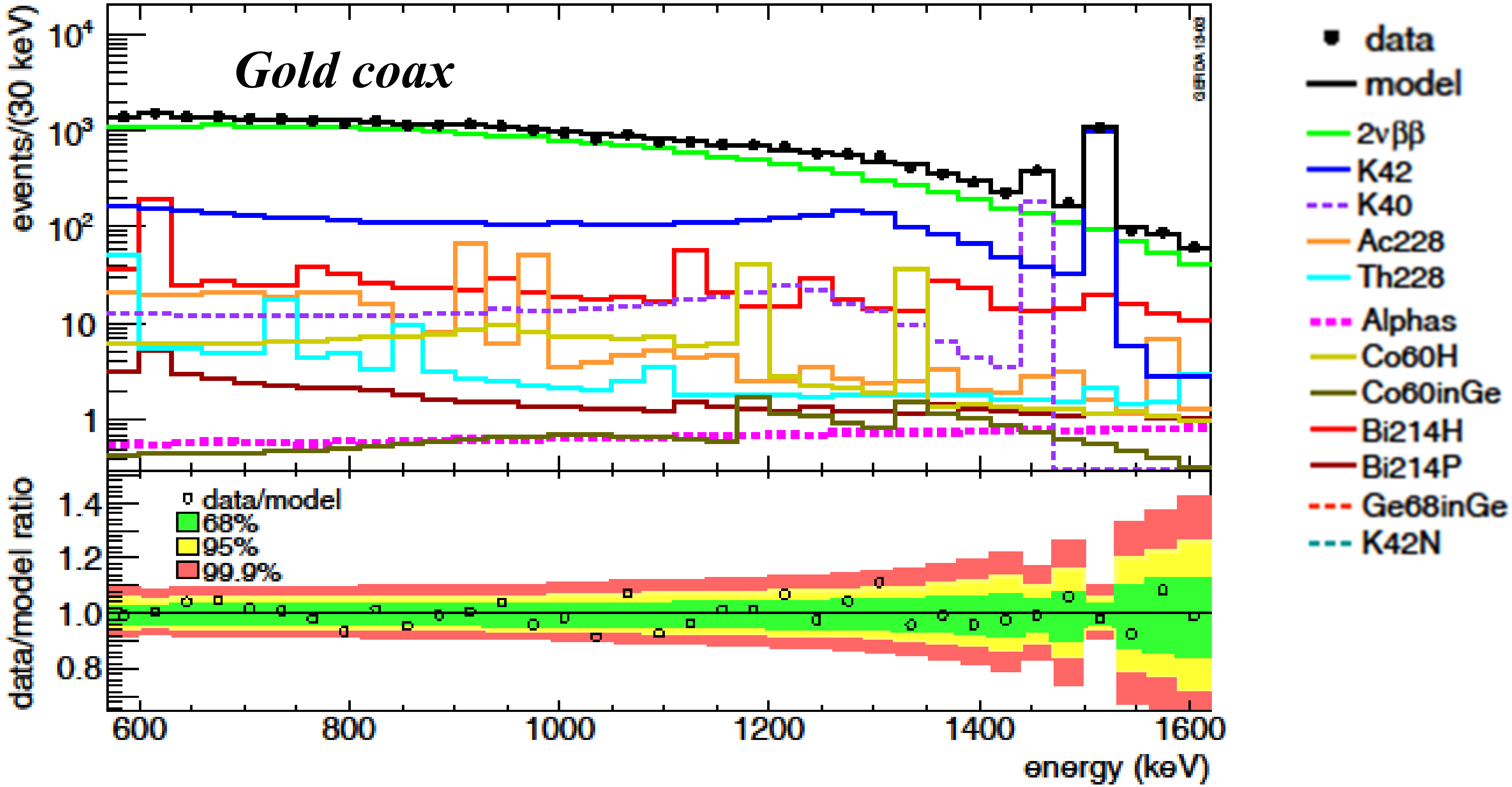
$$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.08})\ 10^{21}\ \text{yr}$$

backgrd. paper
arXiv:1306.5084
to appear in EPJ C

The Background Model

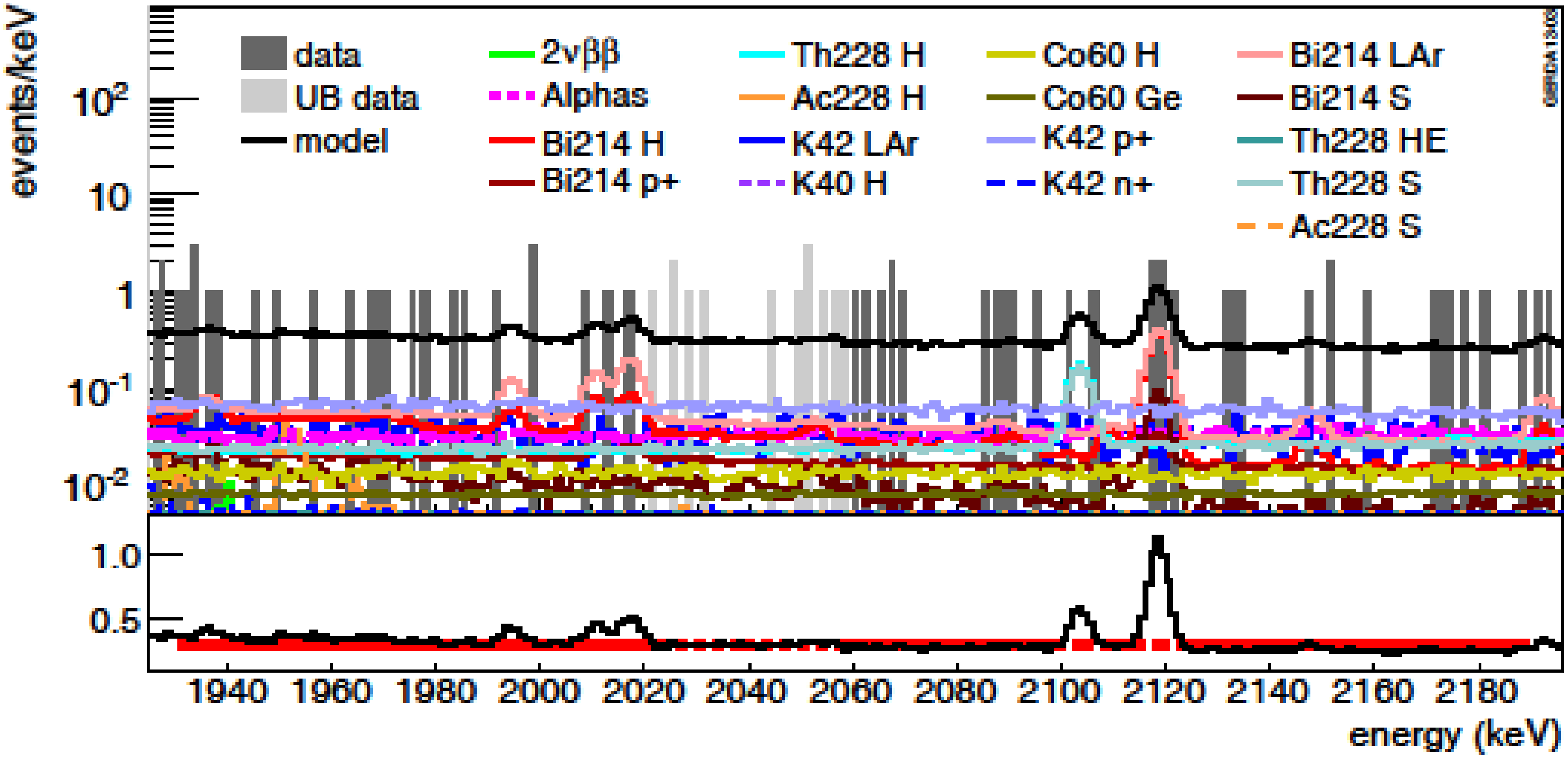
Background decomposition with all simulated components; fit window 570-7500 keV

Minimum model: minimum set of background components

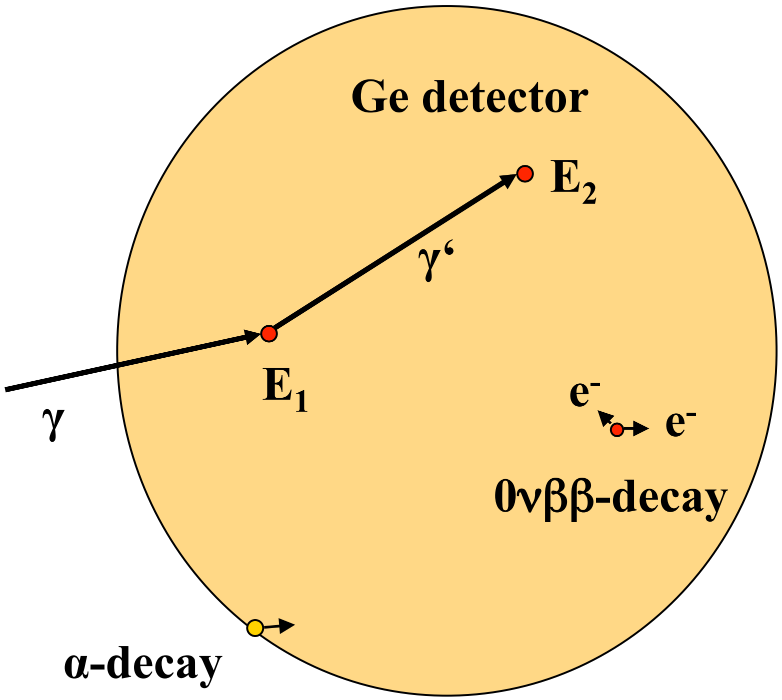


Background Composition: Maximum Model

total set of known background components leading to distinguishable spectra ➔

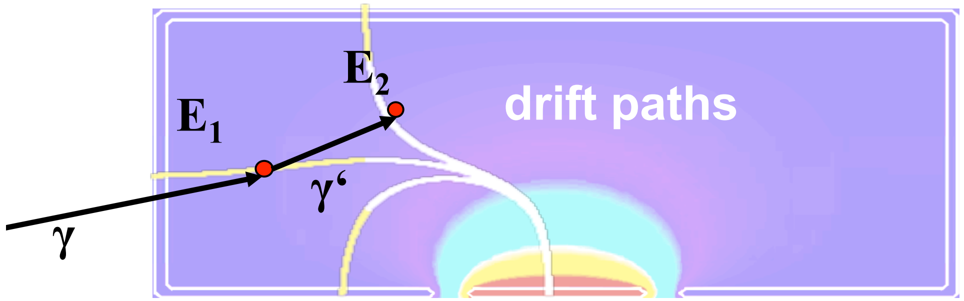


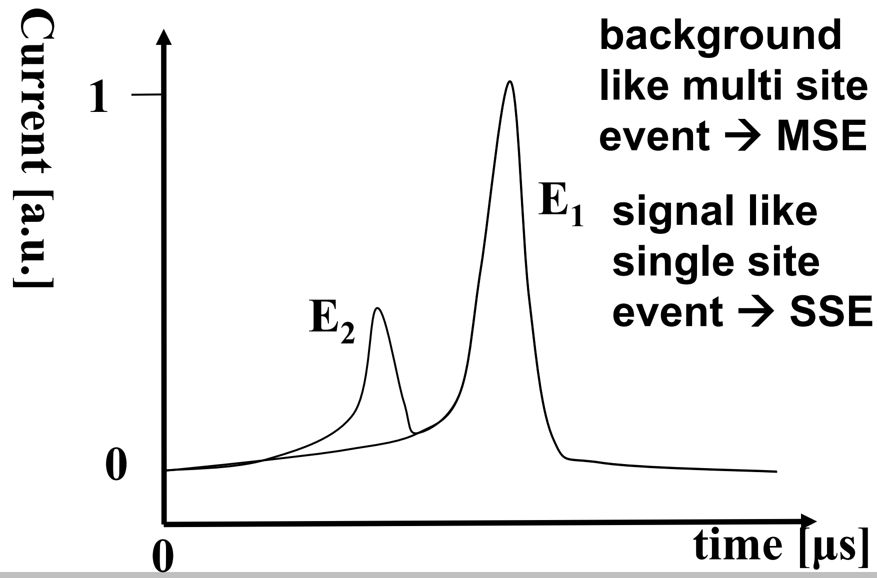
Pulse Shape Discrimination



- **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





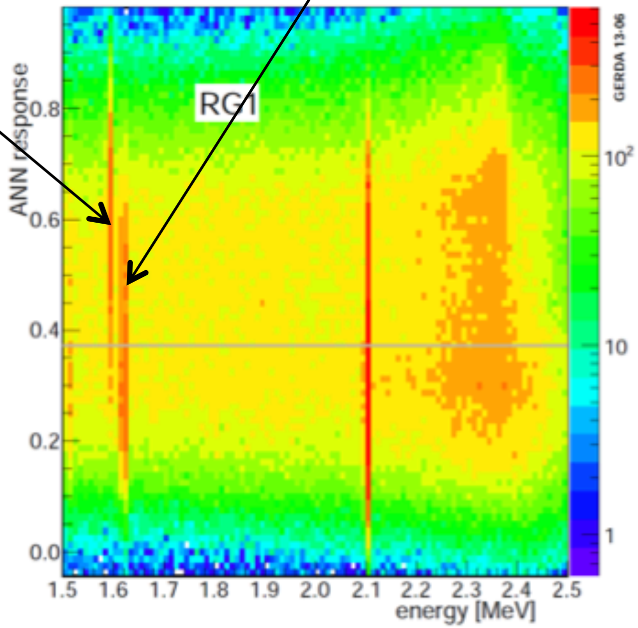
Pulse Shape Discrimination: Coaxial

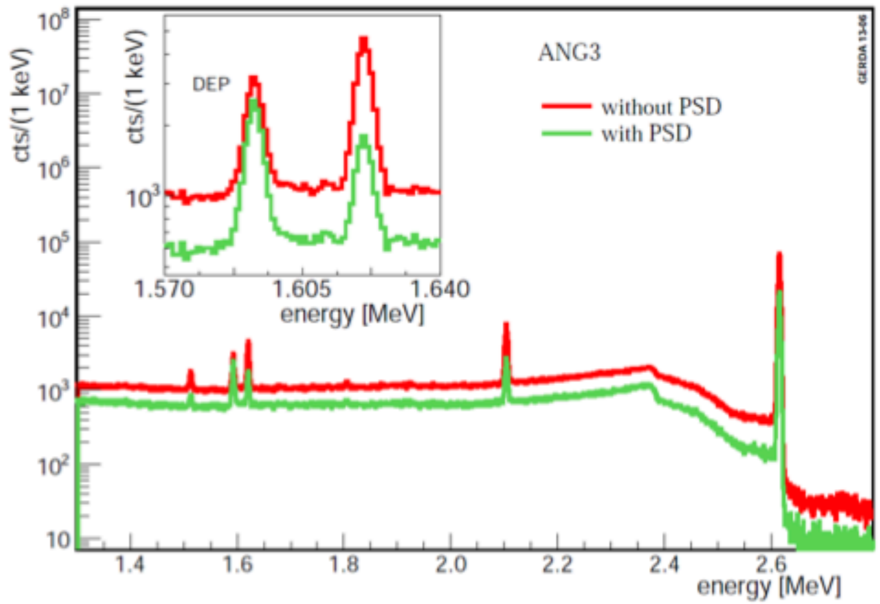
3 independent PSD methods:

- 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

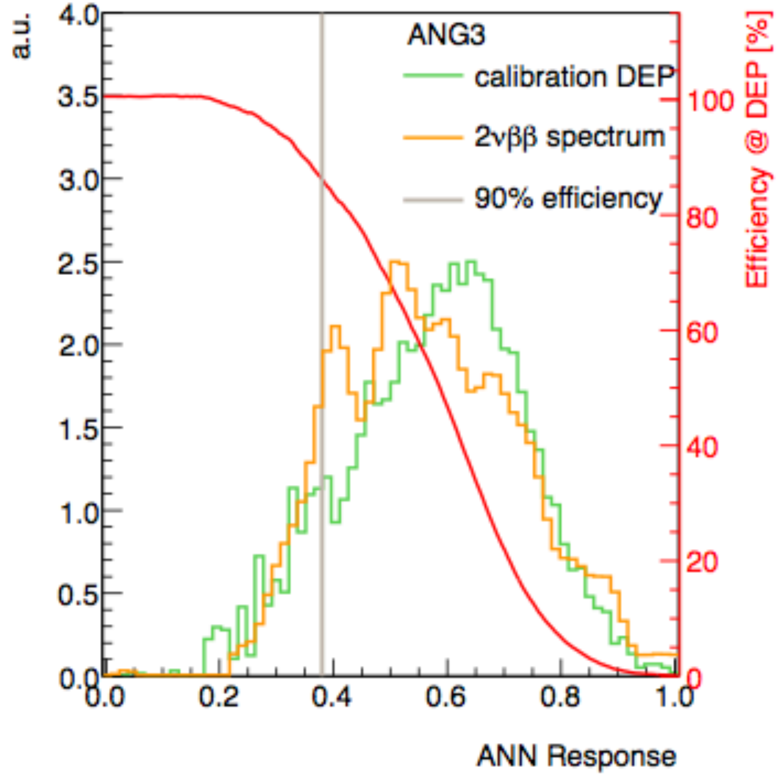
MSE library: FAP (Full Absorption Peak) of ^{212}Bi at 1620 keV

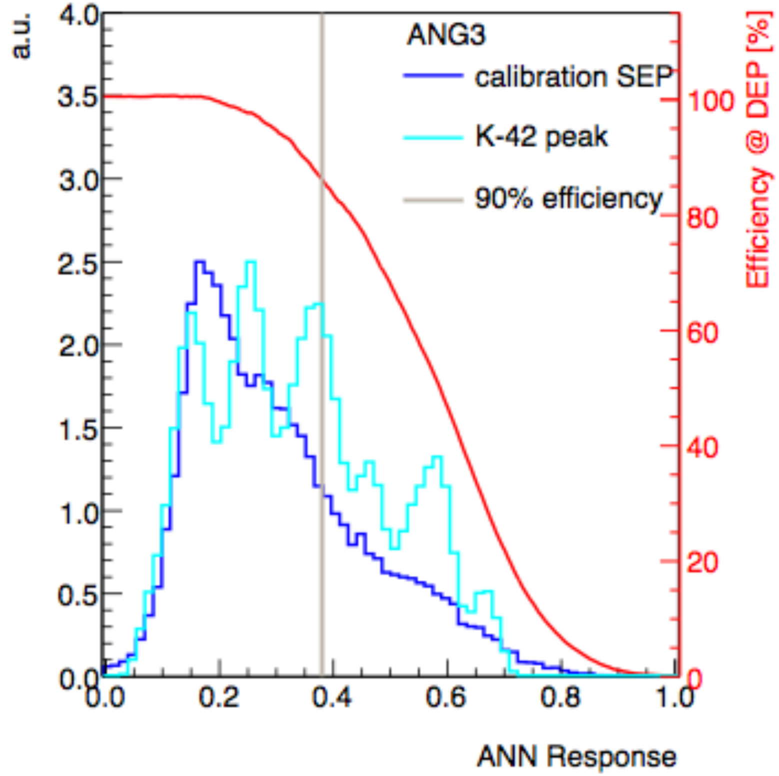




Neural Network Training with Calibration Data

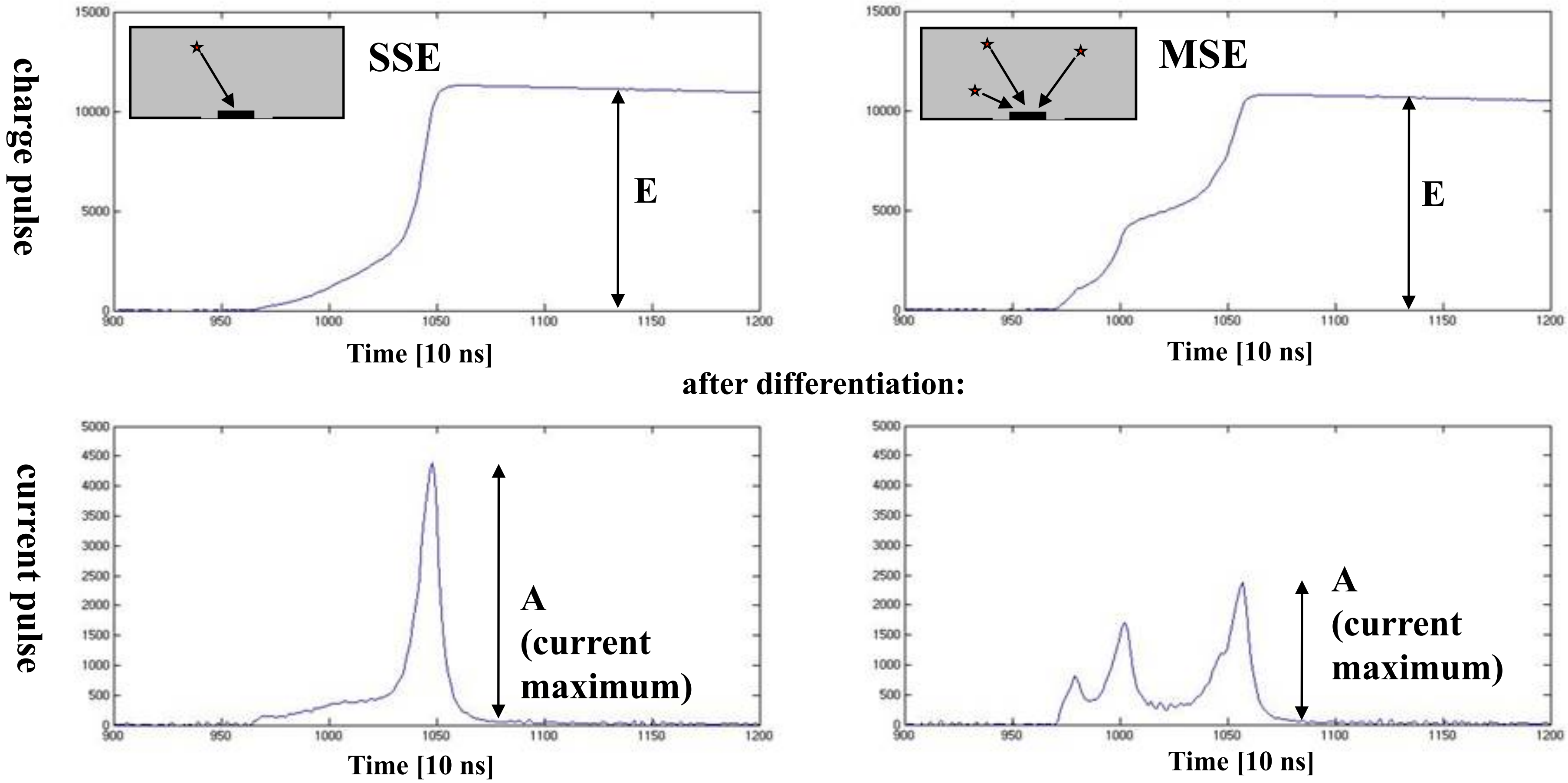
- DEP events in the interval 1592 keV $\pm\, 1\, FWHM$ serve as proxy for SSE
- Full energy line of ^{212}Bi in the equivalent interval around 1620 keV are dominantly MSE, taken as background events





Pulse Shape Discrimination: BEGe A/E Cuts

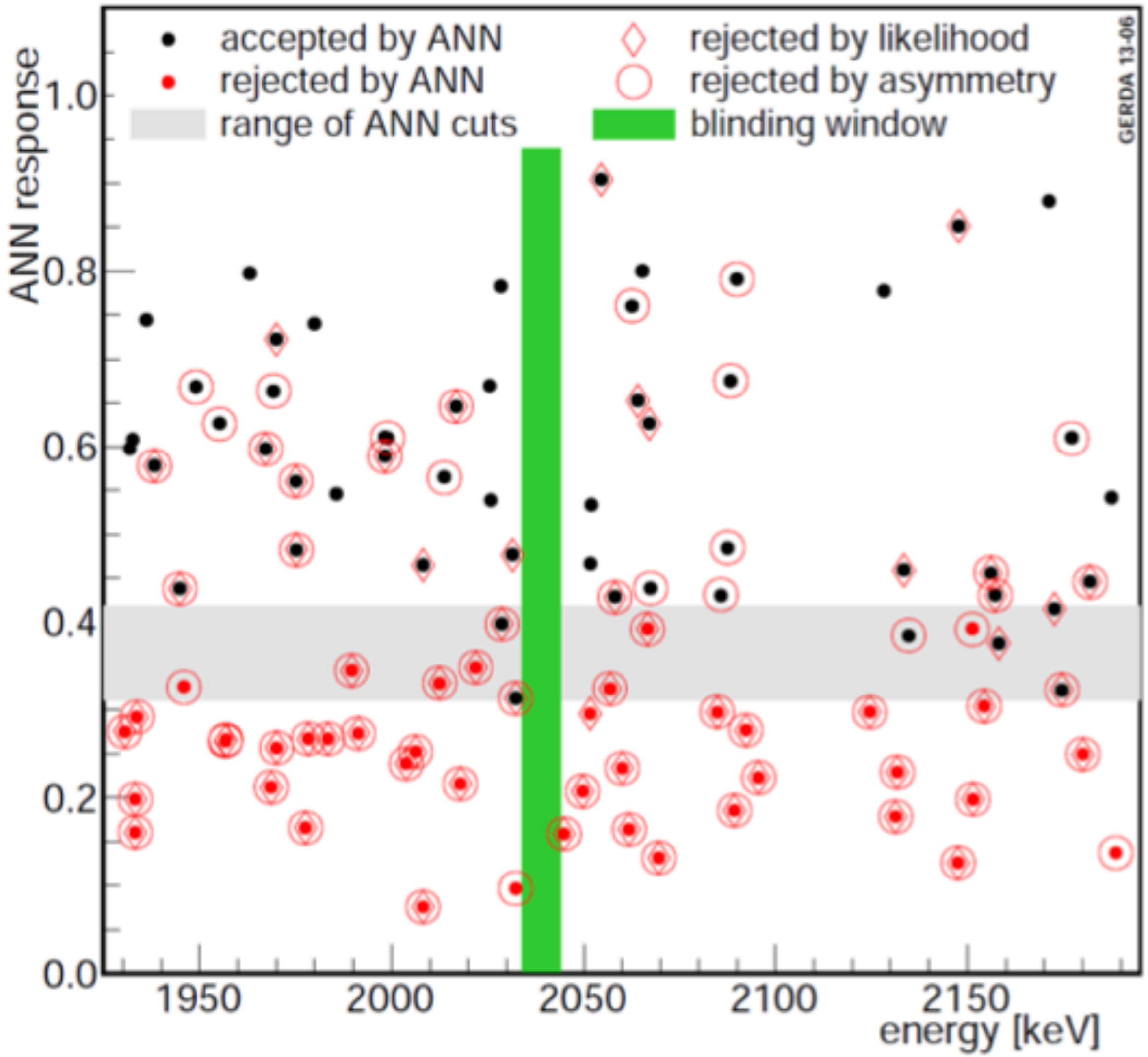
Typical SSE (electron) | **raw preamplifier output:** | **Typical MSE (gamma)**



➔ Cutting in A/E ➔ rejects background like MSEs

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

Application of PSD to Phase I Data

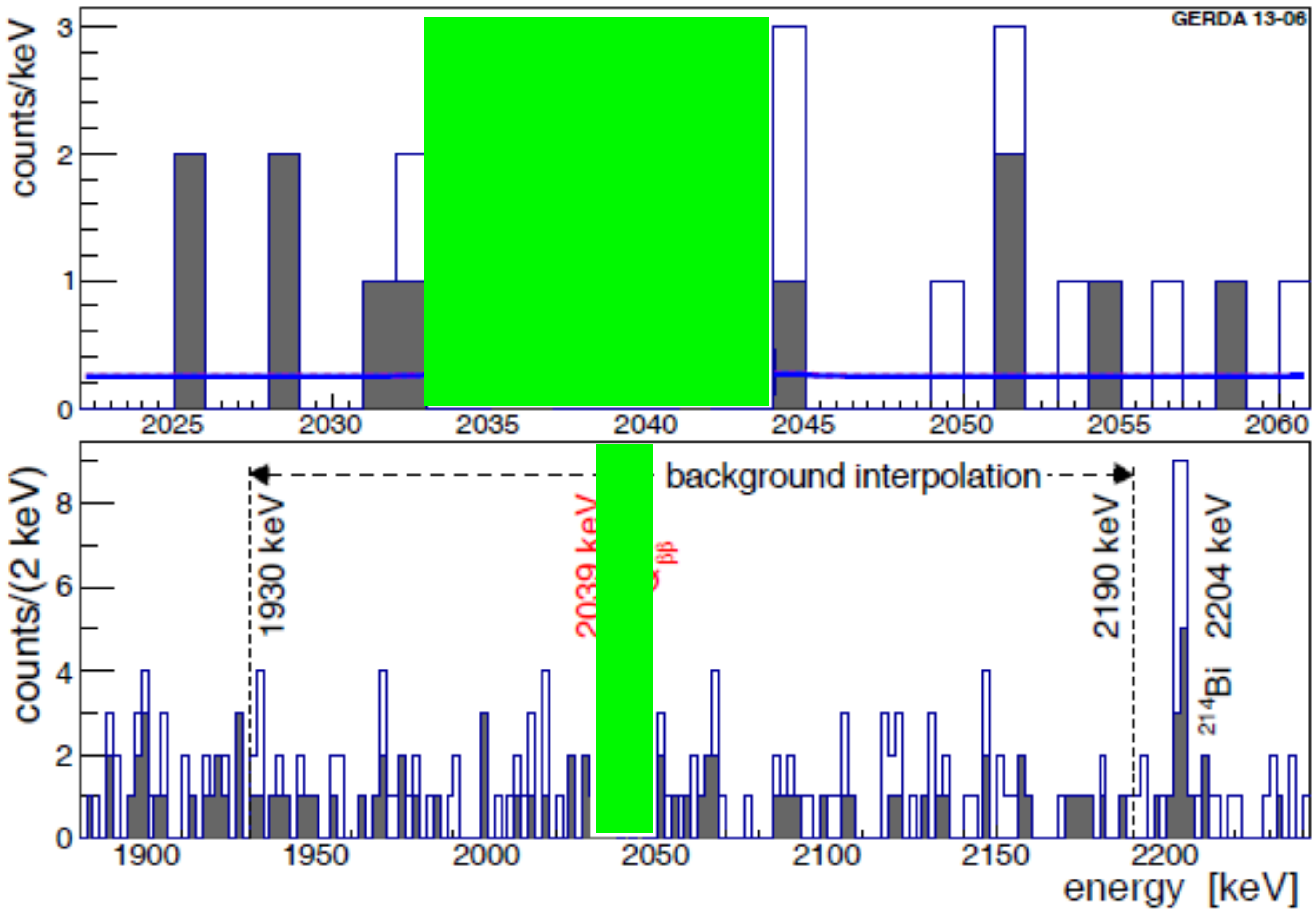


- all events removed by ANN are removed by at least one other method
- events discarded by ANN are in 90% of the cases discarded by all 3 methods
- in a larger energy window about 3% are only rejected by ANN

⇒ About 45% of events are rejected

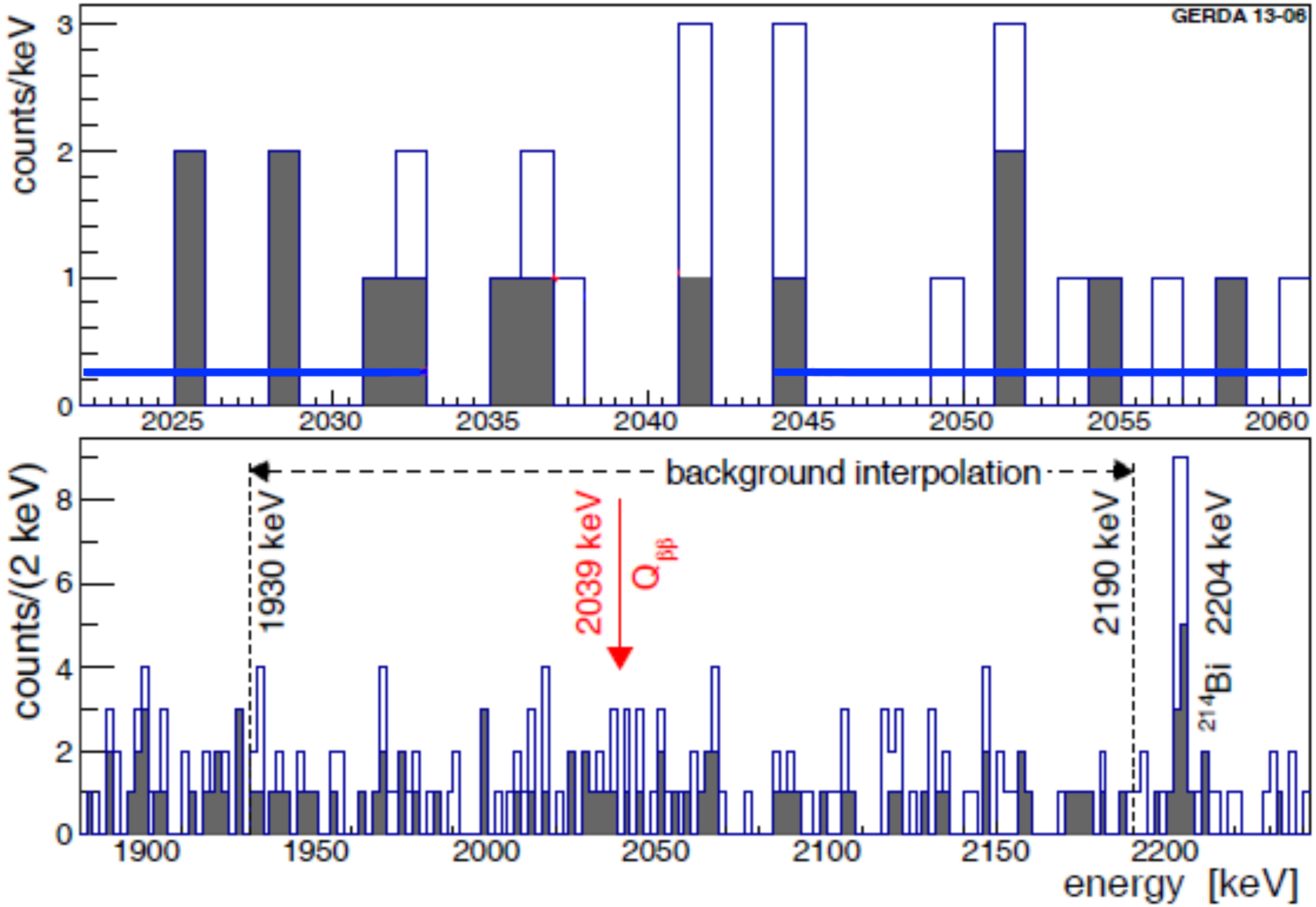
Efficiency: $\epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09}$

The Region of Interest



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

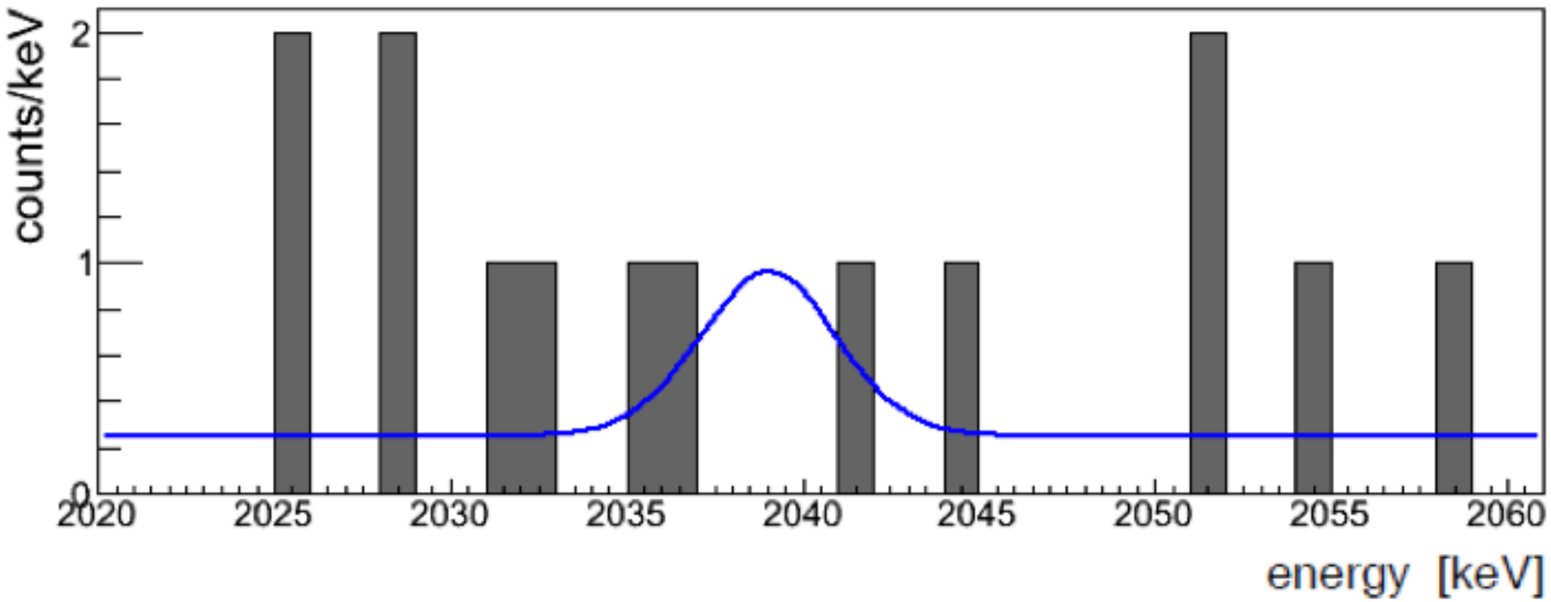
The Region of Interest



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



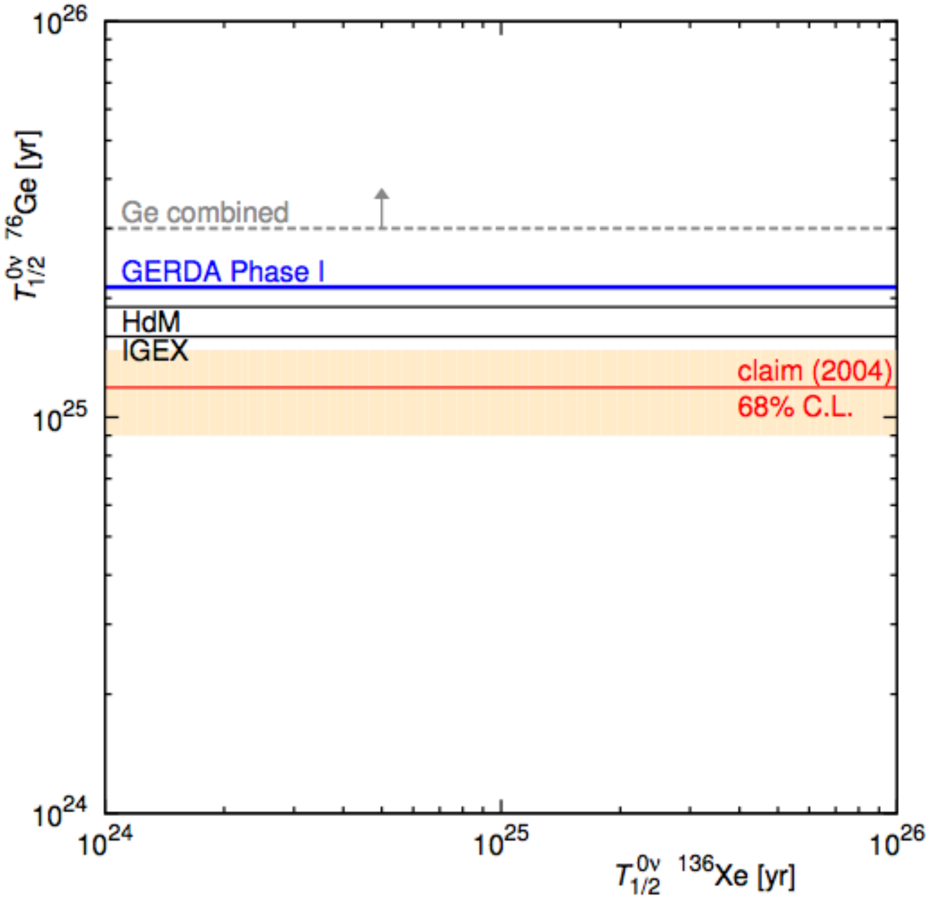
profile likelihood (PL) fit:

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

KK-claim: $T_{1/2}(0\nu\beta\beta) = 1.19 \times 10^{25}$ 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 ± 1.4 signal counts
2.0 ± 0.3 background counts
→ probability for a fluctuation 1%

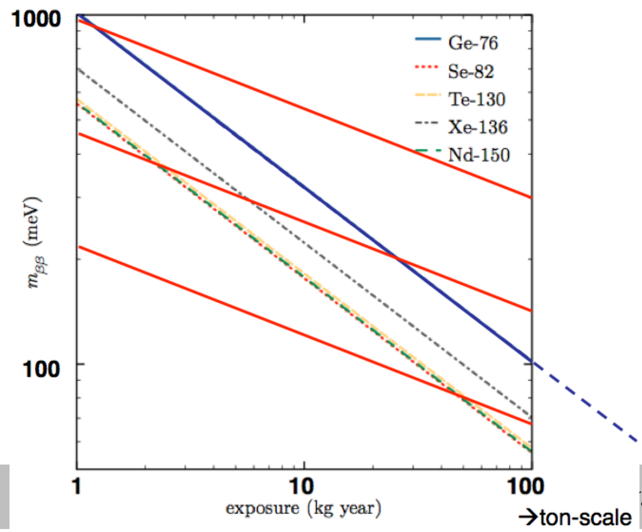
GERDA Outlook

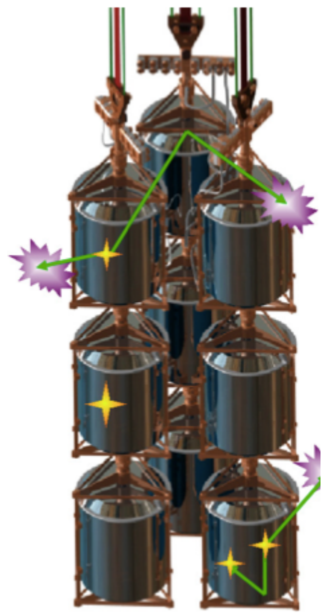
Transition to phase II:

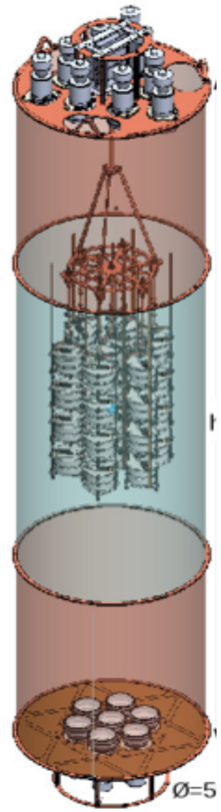
✓ drainage, inspection & refilling of WT

- 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

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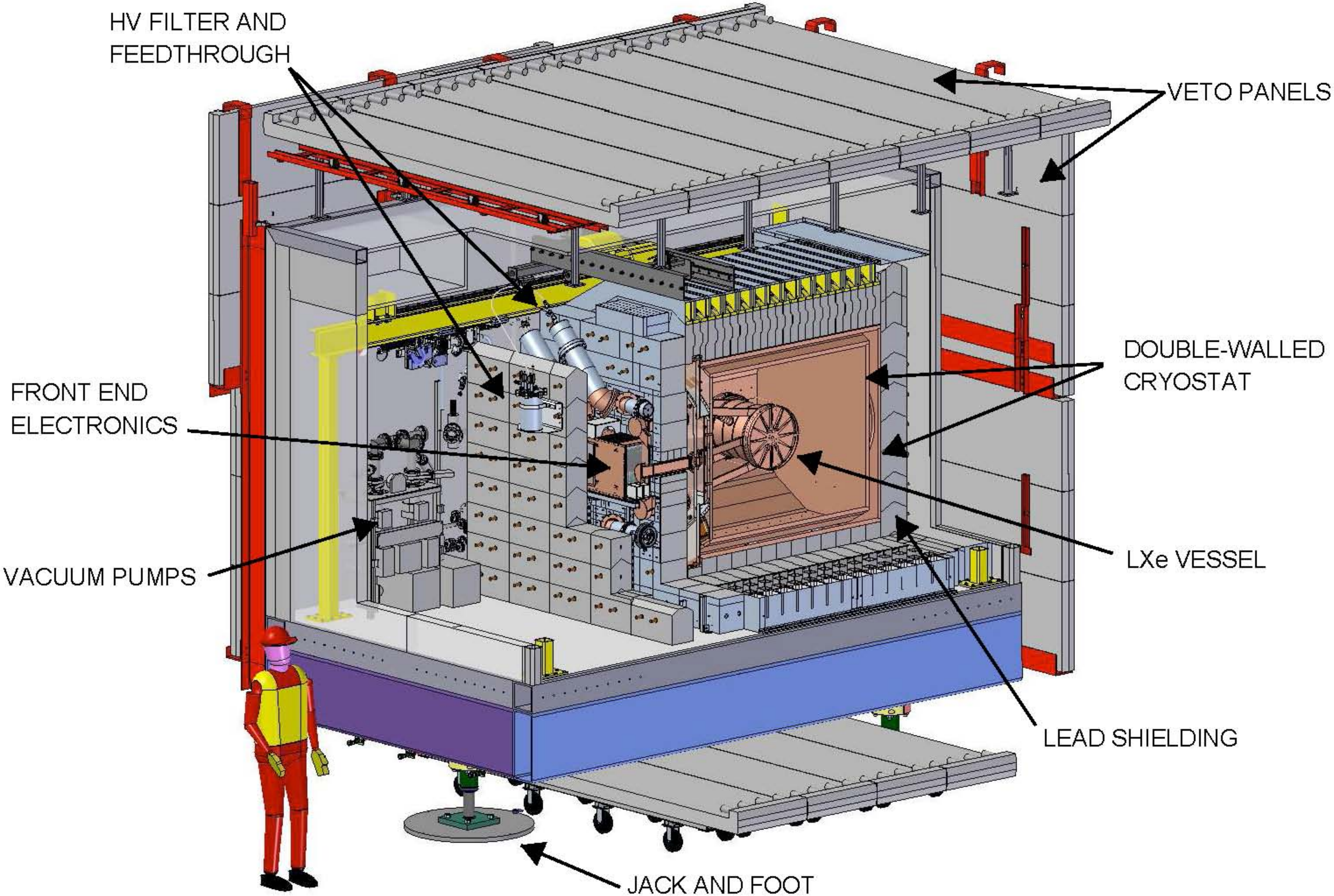
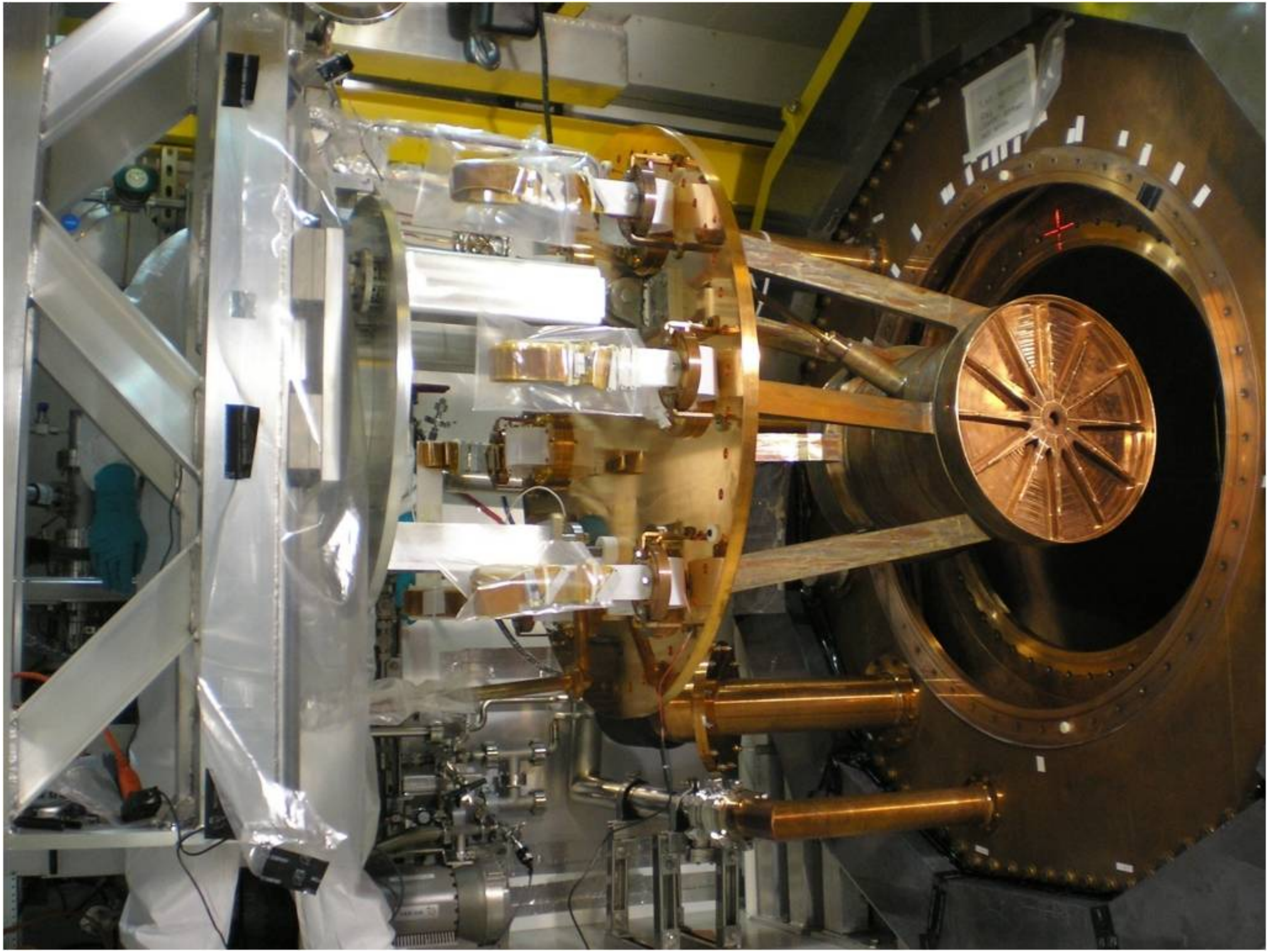
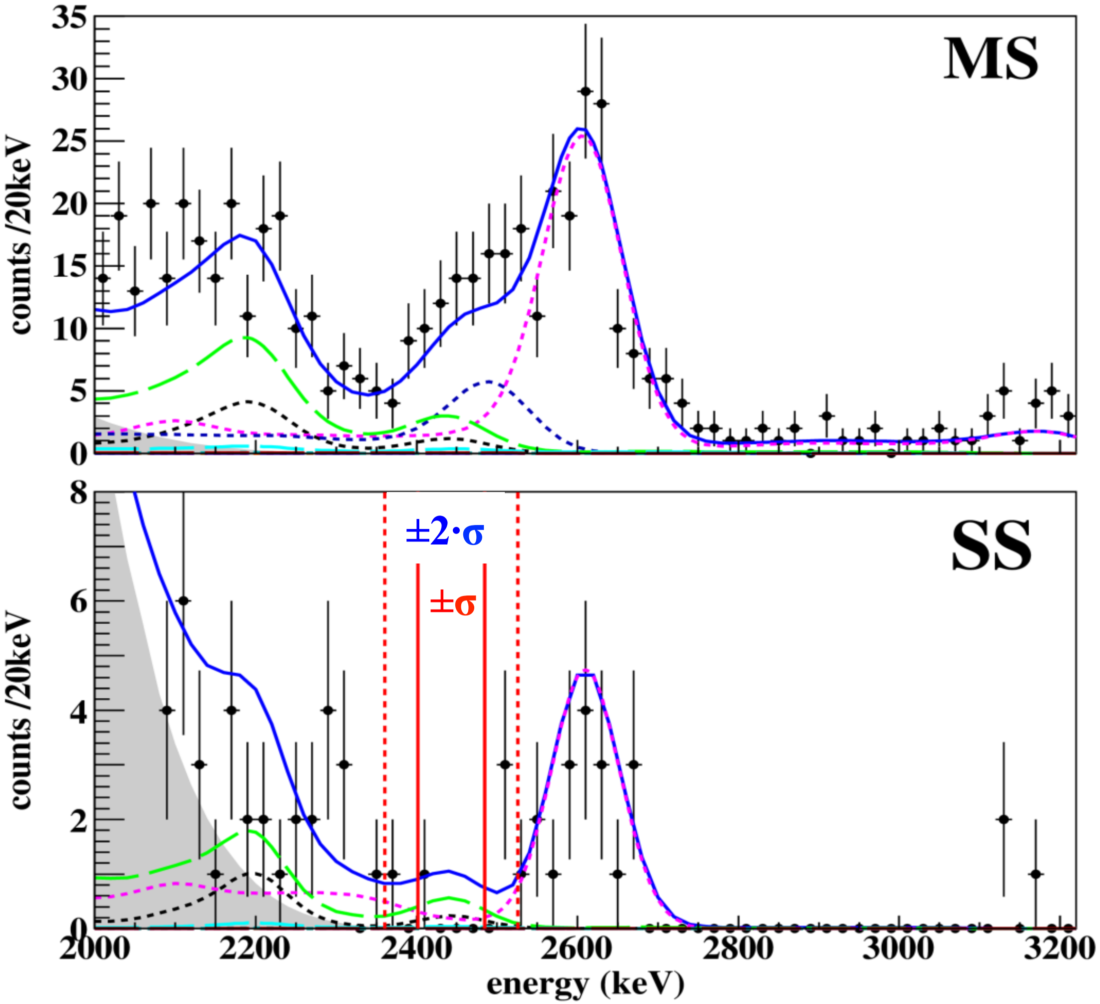
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

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
FRONT END
ELECTRONICS
DOUBLE-WALLED
CRYOSTAT
VACUUM PUMPS
LXe VESSEL
LEAD SHIELDING
JACK AND FOOT



EXO-200 0νββ-data (32.6 kg·yr)



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

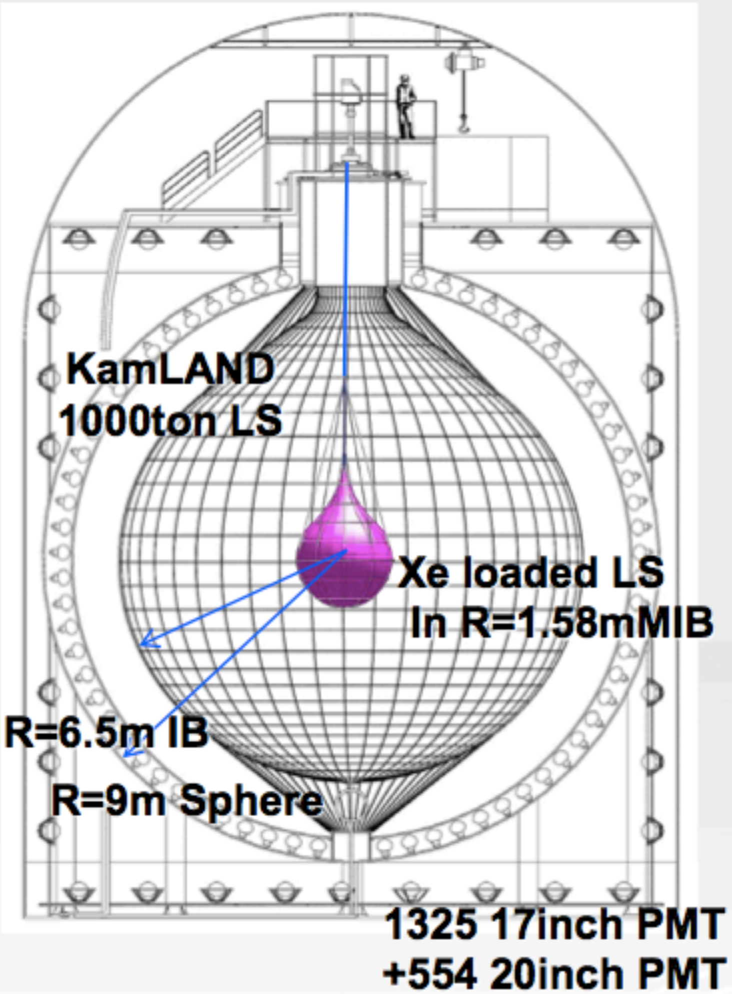
MC background model:
$1.5 \cdot 10^{-3}$ cnts/(keV·yr·kg)

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

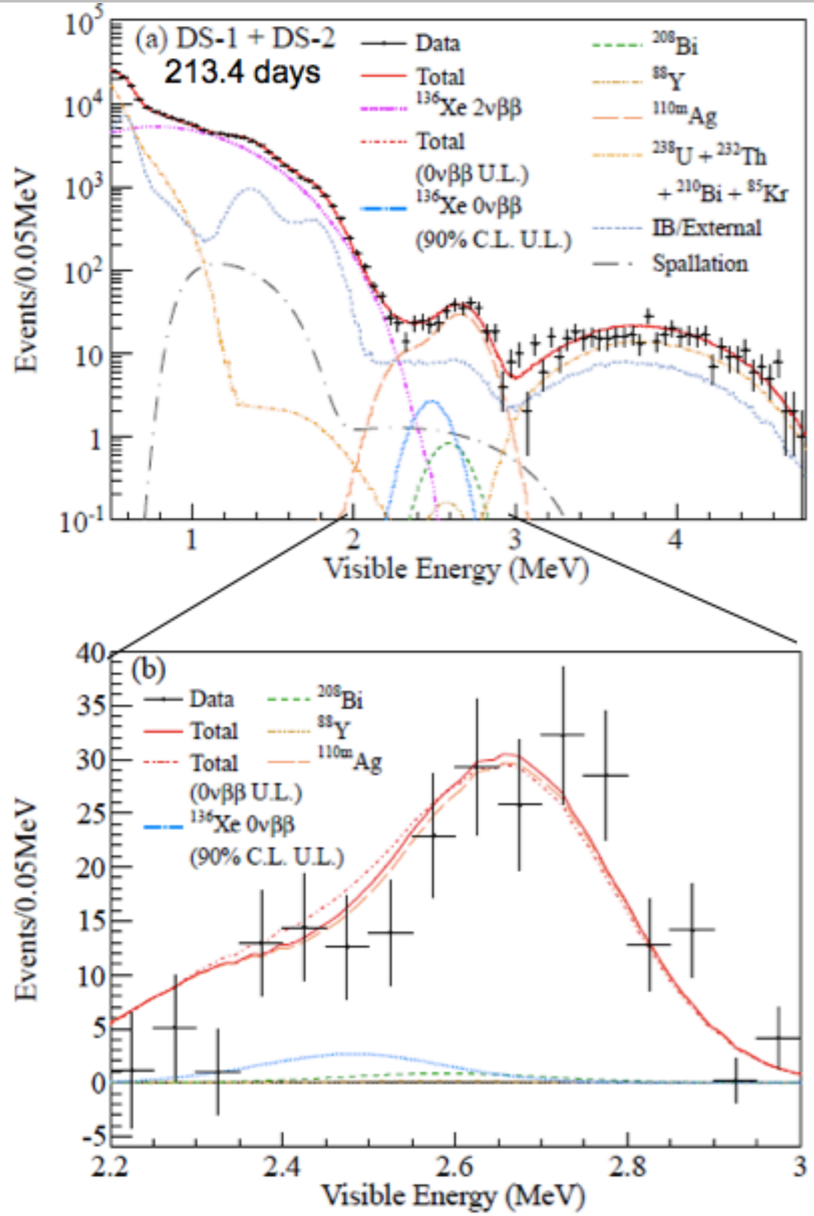
LS : C10H22(81.8%) + PC(18%) + PPO + Xe(~3wt%)

ρLS: 0.78kg/ℓ

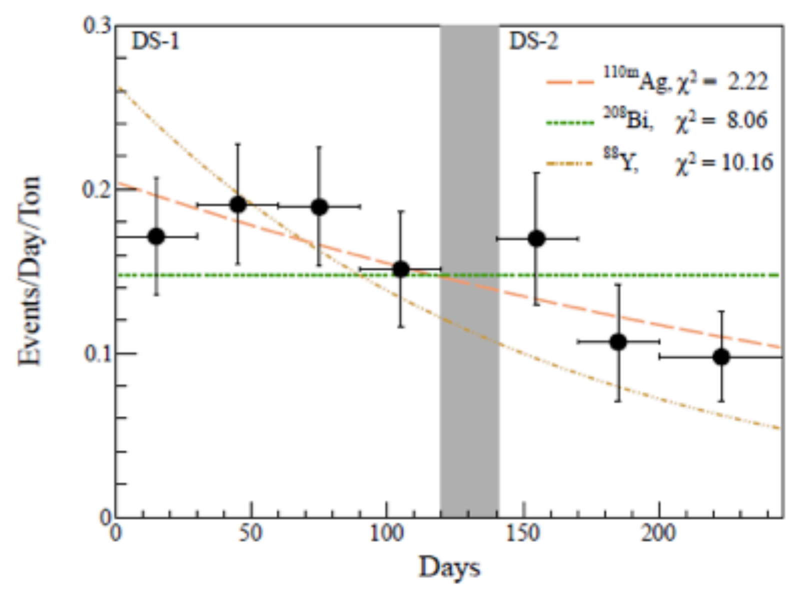
target : ~60meV / 2years for 0νββ

courtesy M. Koga

KamLAND-Zen Phase I Results



2.2MeV < E < 3.0MeV

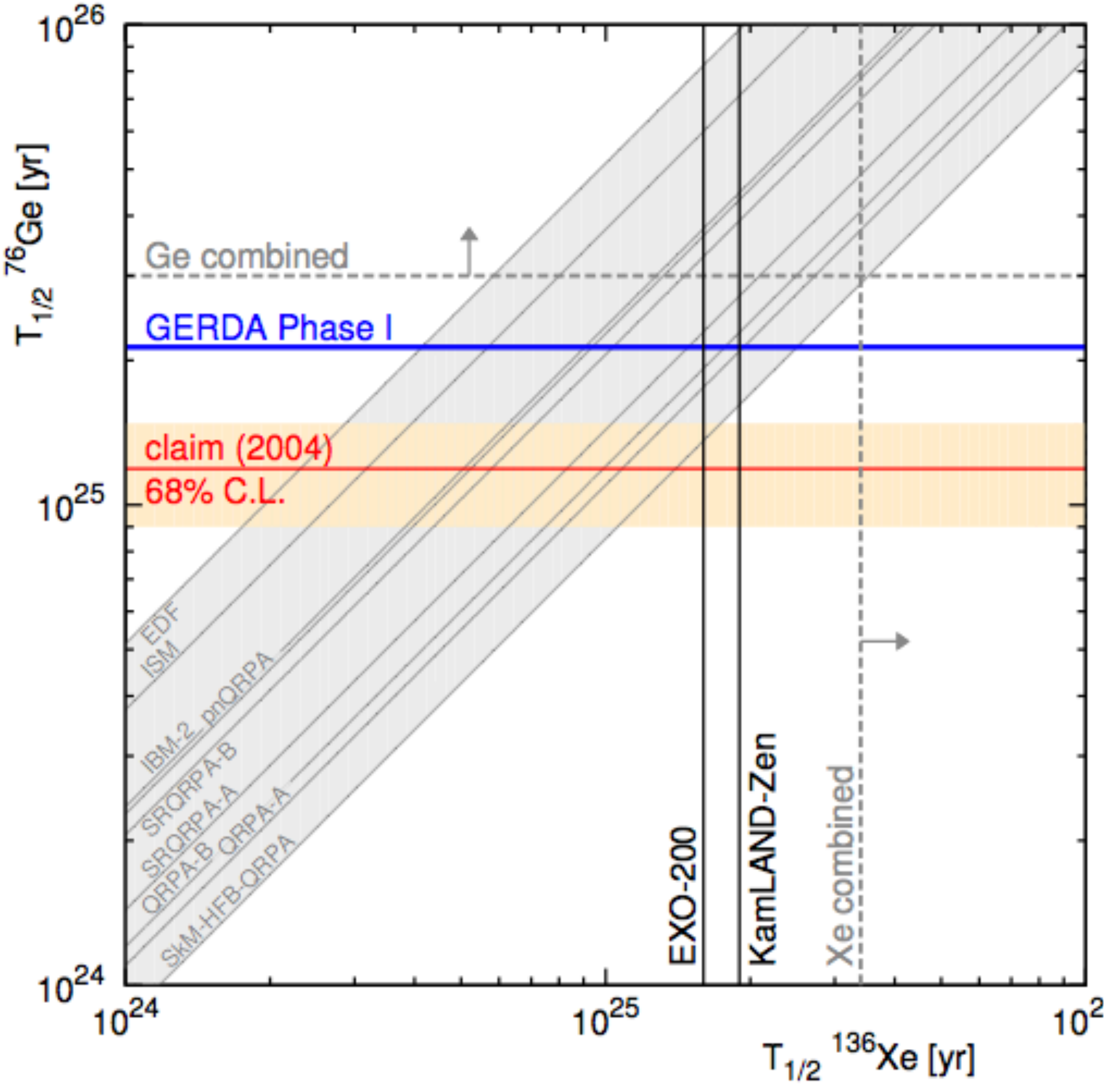


KamLAND-Zen

$T^{0\nu}_{1/2}$ > 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

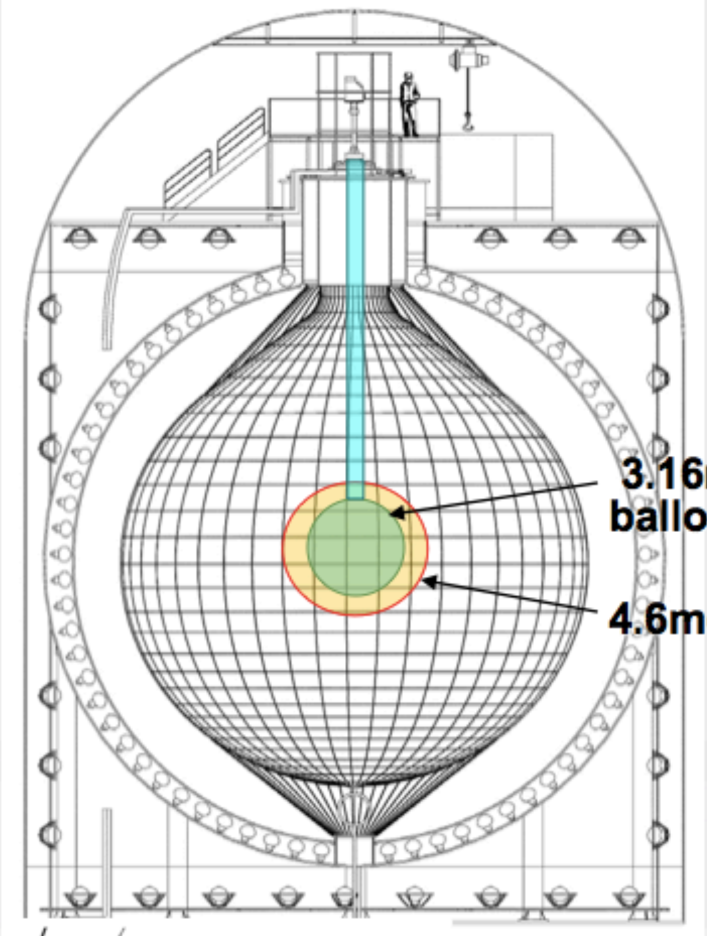
→ NME ratio has spread !
→ at best one is right
→ model dependence

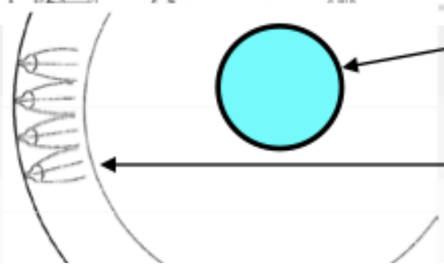
Bayes factors:
EXO: 0.23
KamLAND-Zen: 0.40

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?)

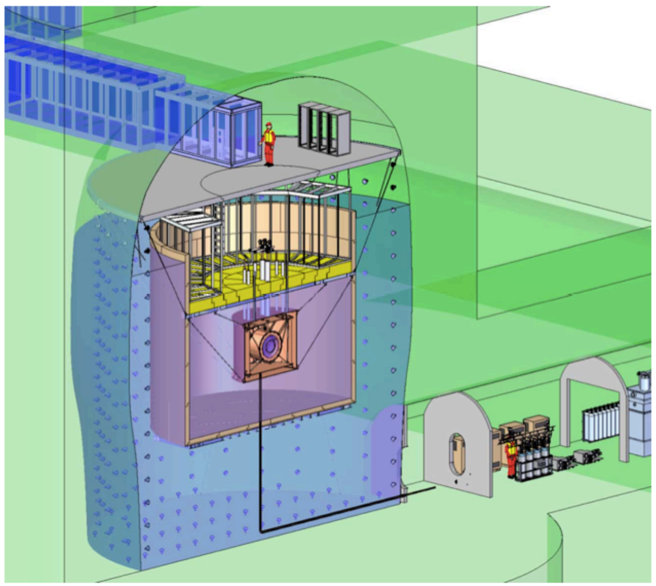
tank opening (201?)

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**

Sketch of nEXO in the SNOlab Cryopit



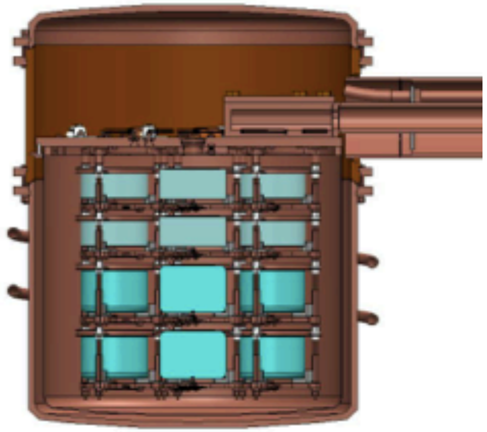
Goals: probe and possibly fully cover the inverted hierarchy neutrino mass range. In case Ba detection is added test part of the normal hierarchy

Future of Ge-Experiments

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

MAJORANA demonstrator:
under construction → data taking

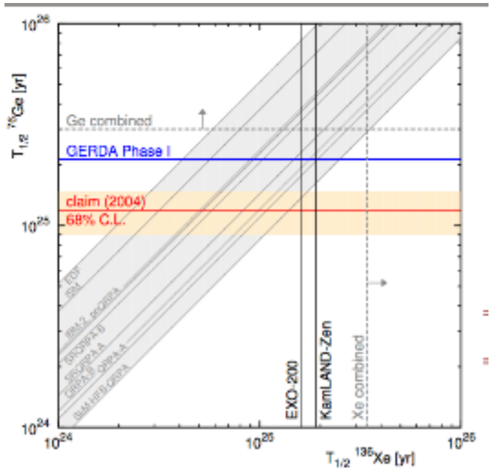
- ~ 30 kg ^{enr}Ge + ~ 10 kg ^{nat}Ge detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015



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:**
  $2.1 \cdot 10^{25}$ yr (90% C.L.)
  GERDA+HdM+ IGEX: $3.0 \cdot 10^{25}$ 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!**