The GERDA Experiment and the Search for Neutrinoless Double Beta Decay

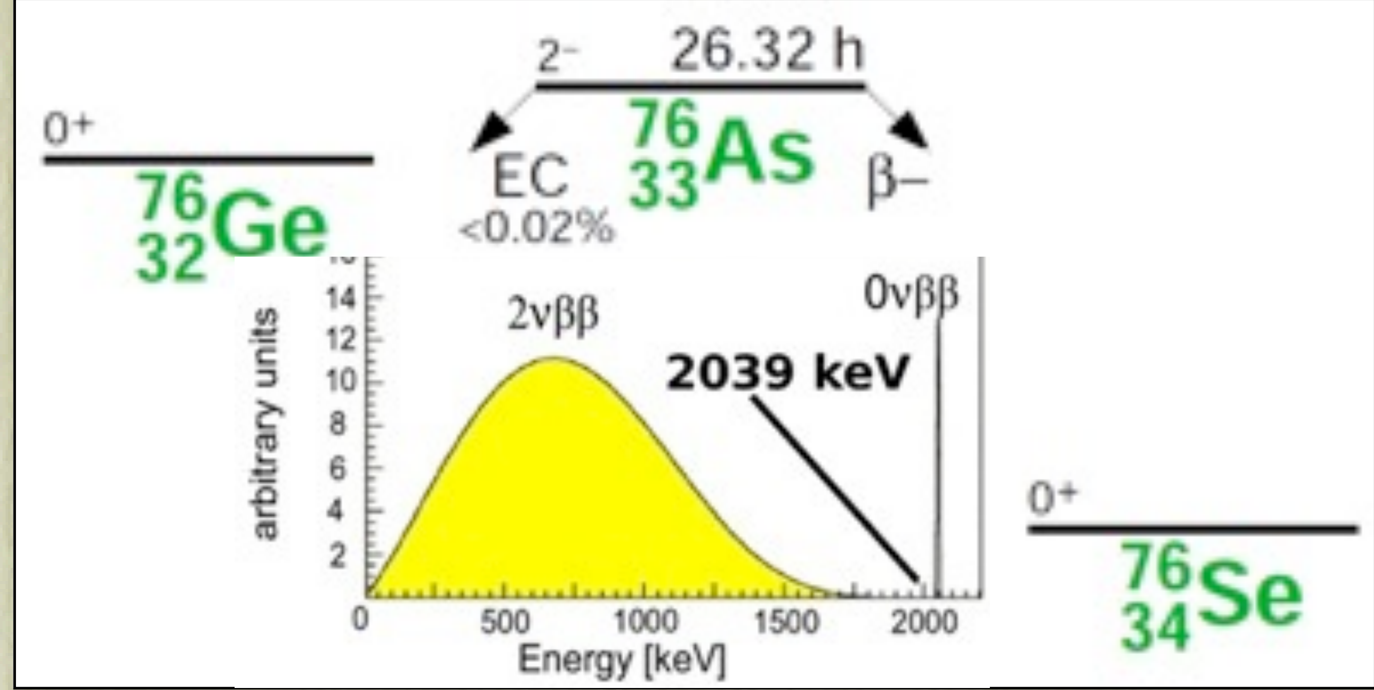
Björn Lehnert
(on behalf of the GERDA Collaboration)

Moriond, La Thuille,
17/03/2014

TECHNISCHE UNIVERSITÄT DRESDEN

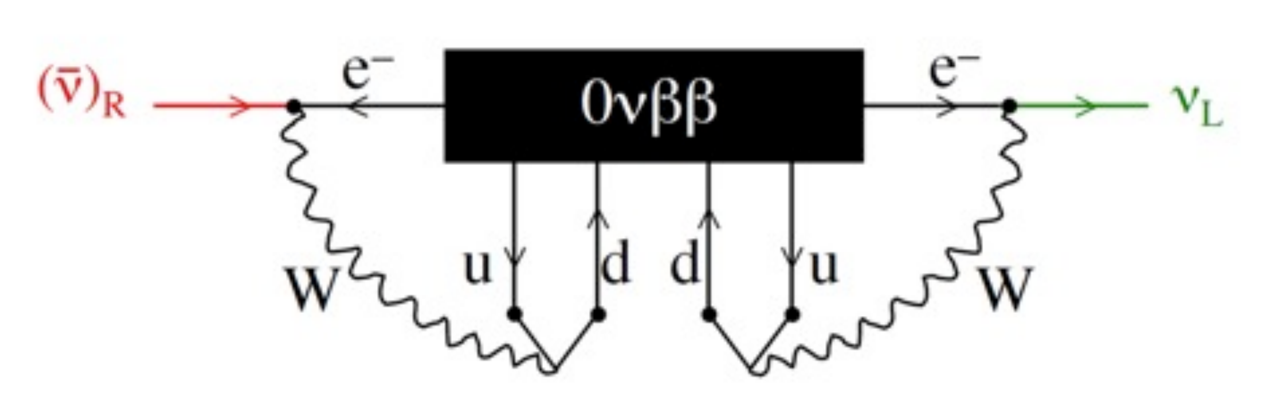
Institut für Kern- und Teilchenphysik

Double Beta Decay



$$2\nu\beta\beta : (Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$$

$$0\nu\beta\beta : (Z,A) \rightarrow (Z+2,A) + 2e^-$$



Schechter-Valle theorem:

If 0νββ exists, it can always be interpreted as a neutrino Majorana mass term

- Lepton number violation

Effective neutrino mass:

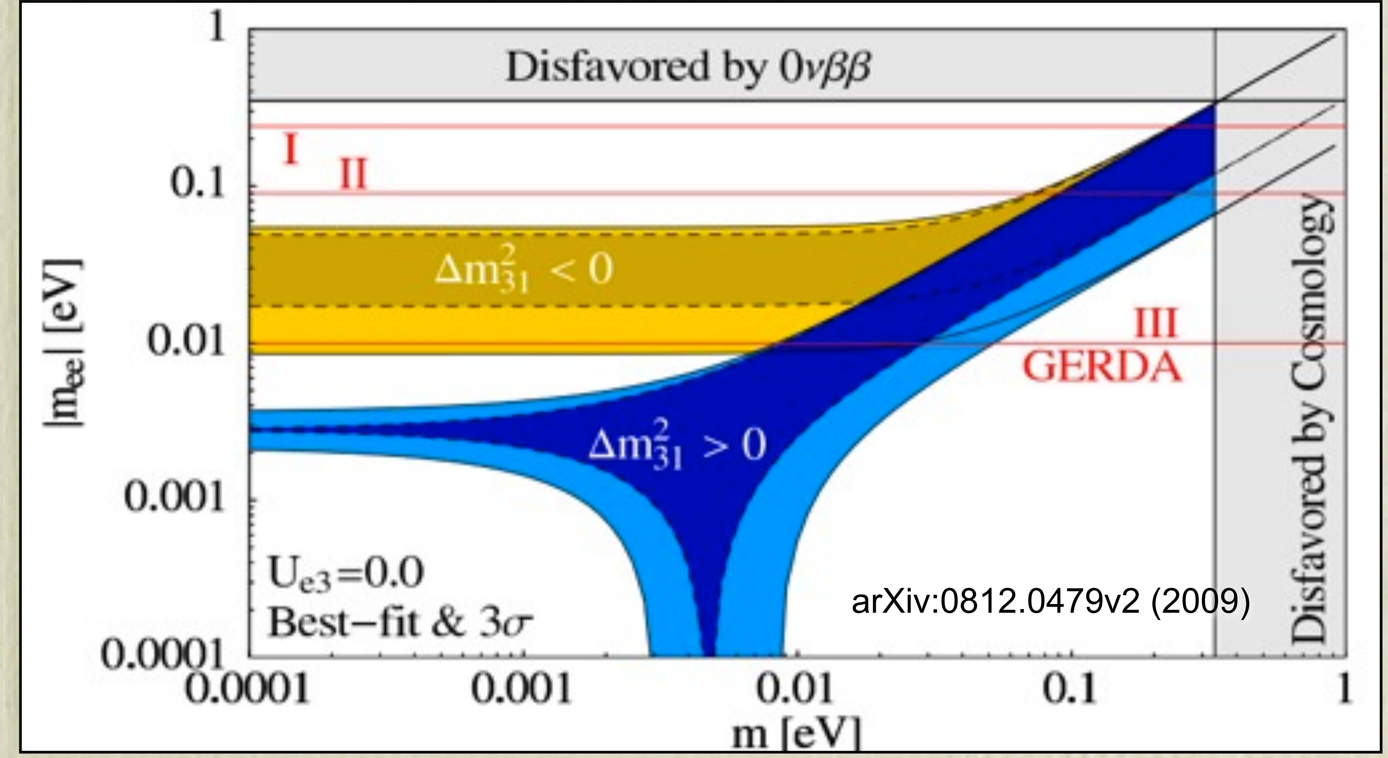
(only for dominant light Majorana neutrino exchange)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$

$F^{0\nu}$: phase space factor

$\mathcal{M}^{0\nu}$: nuclear matrix element

m_{ee} : effective neutrino mass



Double Beta Decay Experiments

Sensitivity: (for gaussian background)

$$T_{1/2}^{\text{limit}} \propto \alpha \cdot \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

α : isotopic abundance

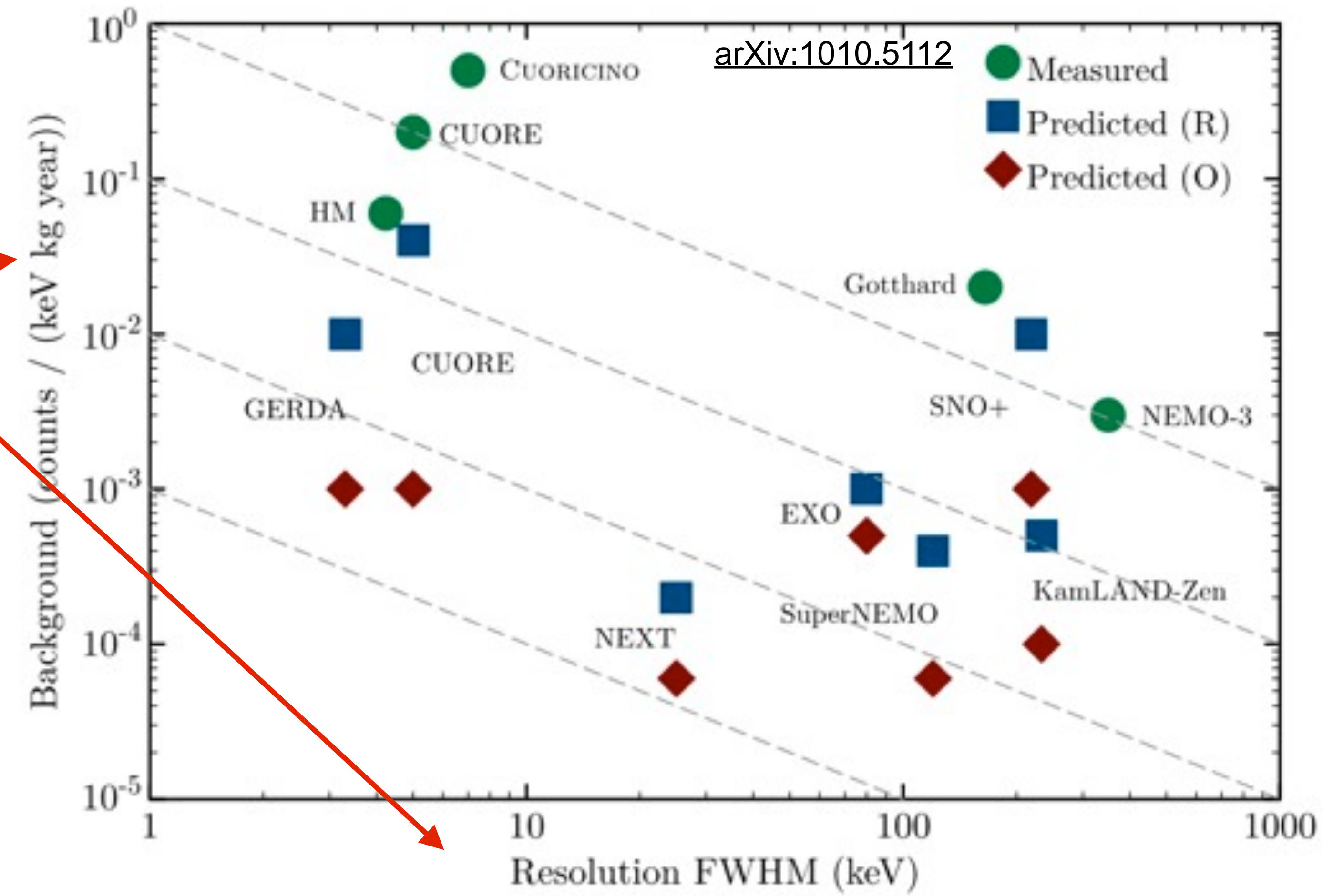
η : active volume fraction

ϵ : detection efficiency

$M \cdot T$: exposure

B : background index

ΔE : energy resolution



- Many DBD experiments using various nuclides and experimental techniques
- Recent results from EXO, KamLAND-ZEN and GERDA
- ^{136}Xe combined

$$T_{1/2}^{0\nu} > 3.4 \cdot 10^{25}\,\text{yr at 90\% C.L.}$$

- Claim of observation of 0νββ in ^{76}Ge by subgroup of Heidelberg-Moscow experiment

Phys. Lett. B 586 (2004)

$$T_{1/2}^{0\nu} = 1.19 \cdot 10^{25}\,\text{yr}$$

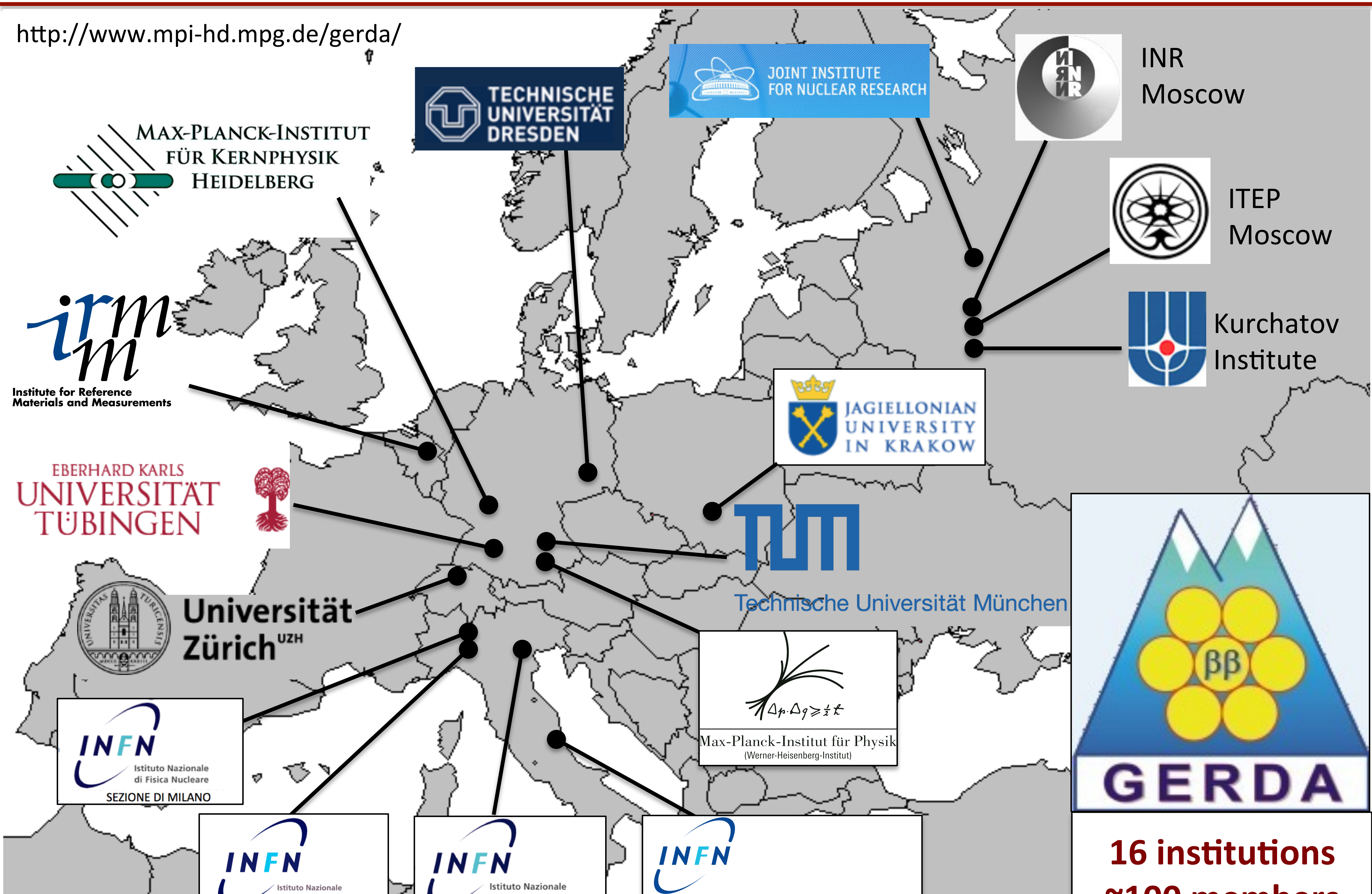
- Best previous ^{76}Ge limits:

$$\text{IGEX}: T_{1/2}^{0\nu} \geq 1.6 \cdot 10^{25}\,\text{yr (90\% C.L.)}$$

$$\text{HdM}: T_{1/2}^{0\nu} \geq 1.9 \cdot 10^{25}\,\text{yr (90\% C.L.)}$$

The GERDA Collaboration

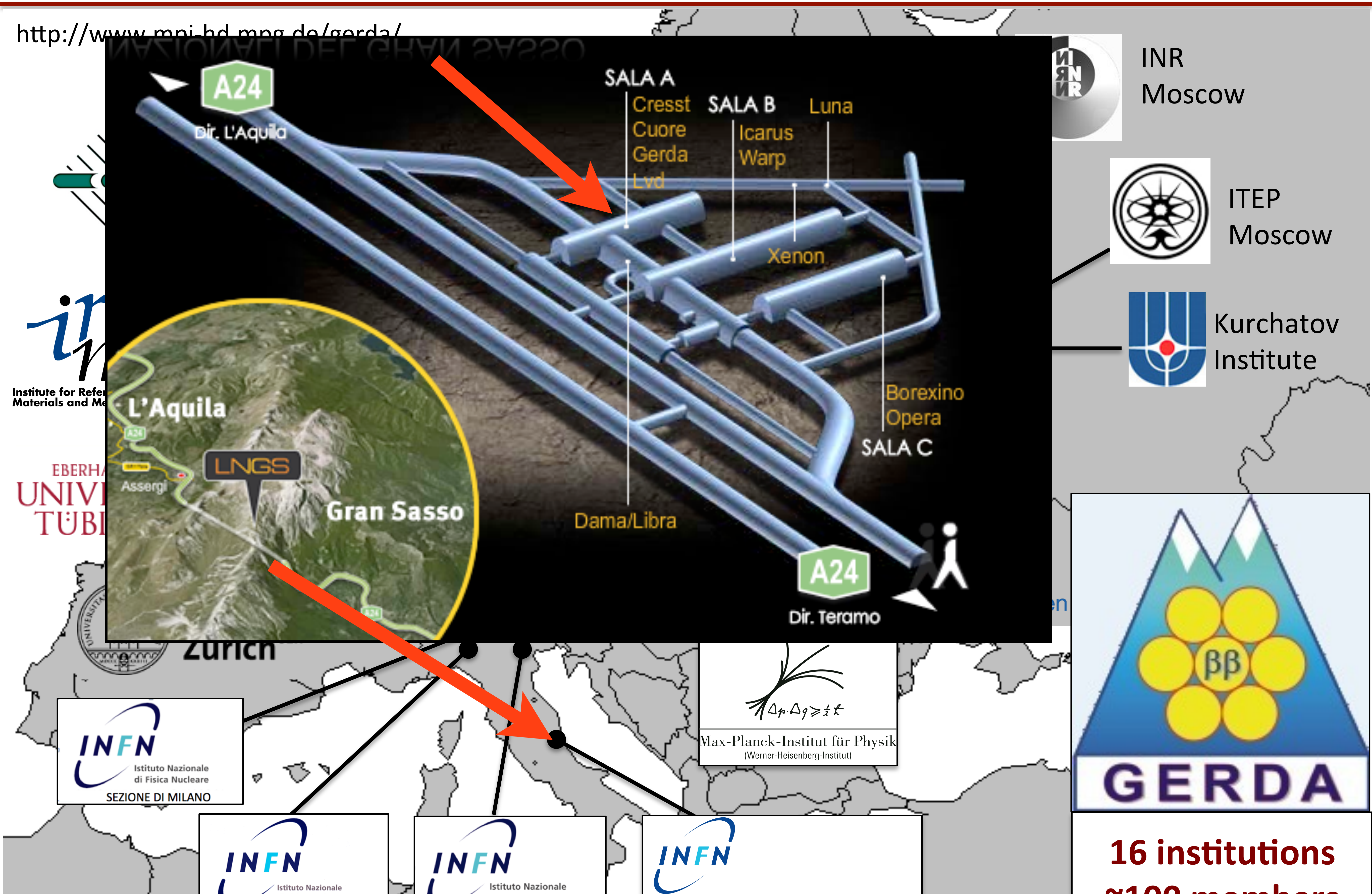
http://www.mpi-hd.mpg.de/gerda/



16 institutions
~100 members

The GERDA Collaboration

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

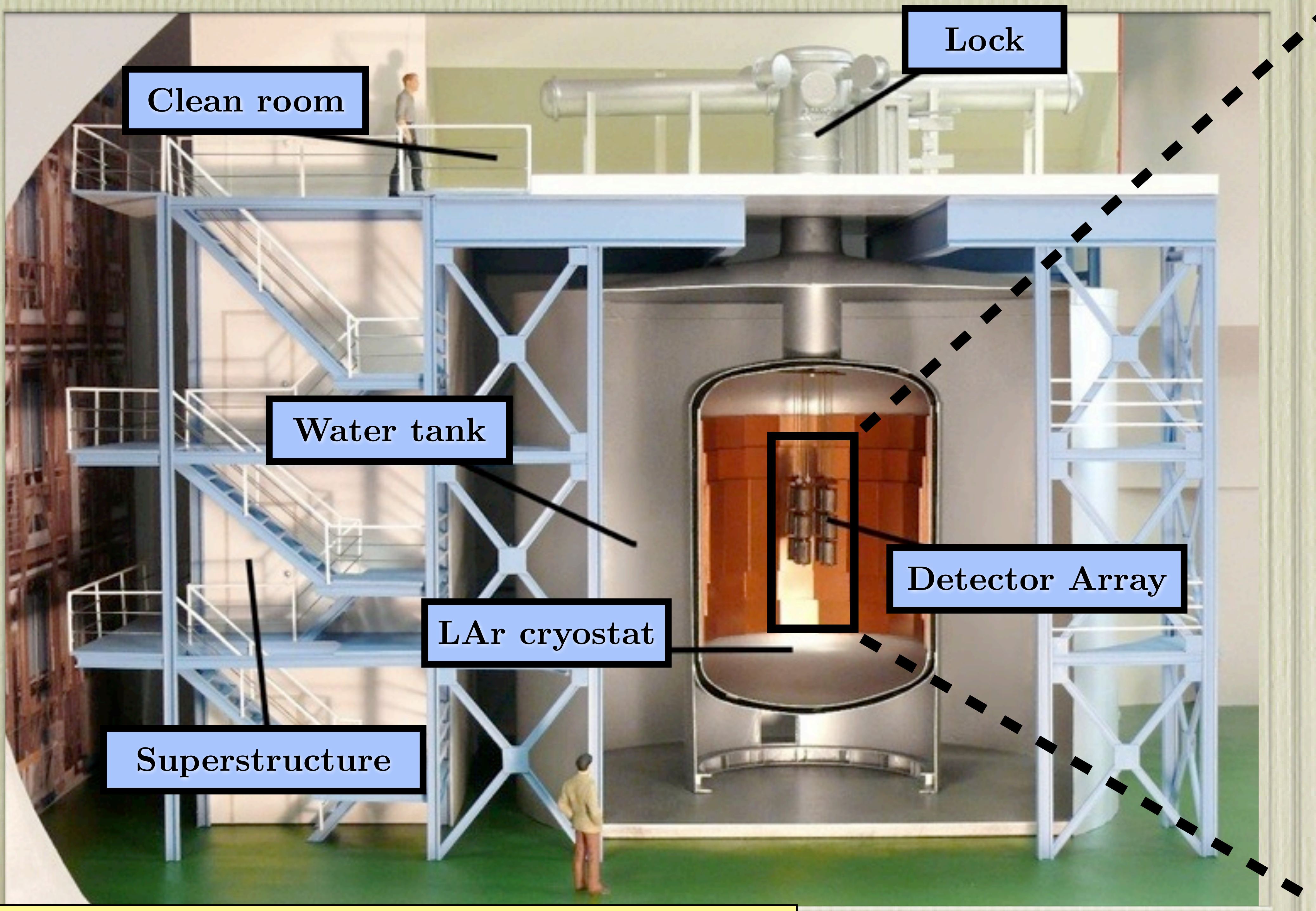


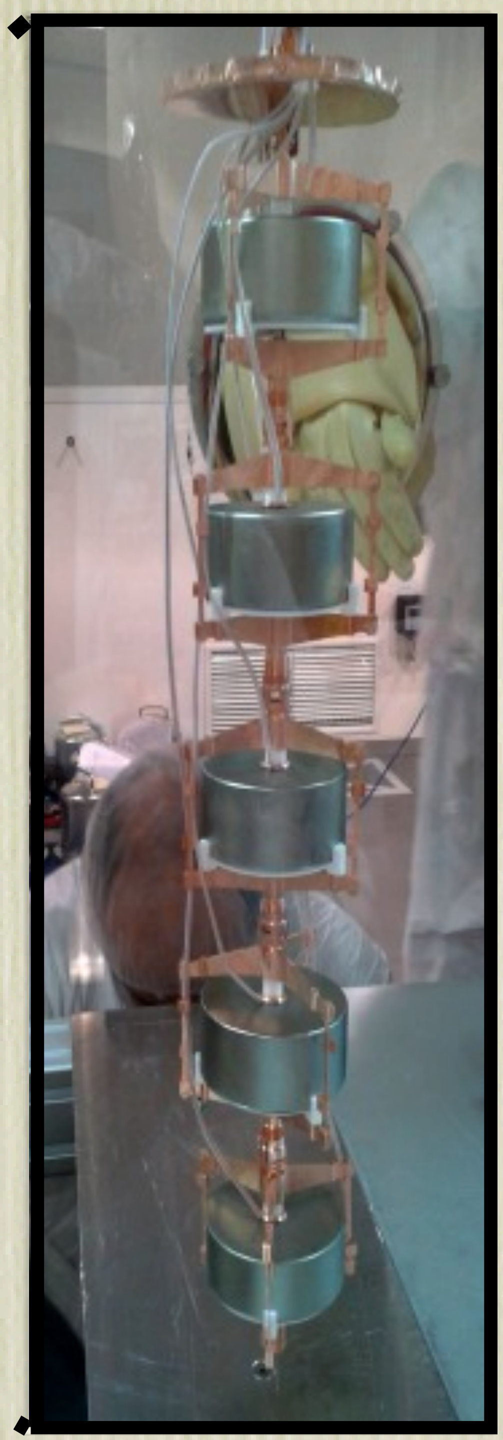
16 institutions
~100 members

GERDA: GERmanium Detector Array

Idea: Operate HPGe detectors naked in liquid argon (LAr)

- Liquid argon serves as cooling, shielding and active veto

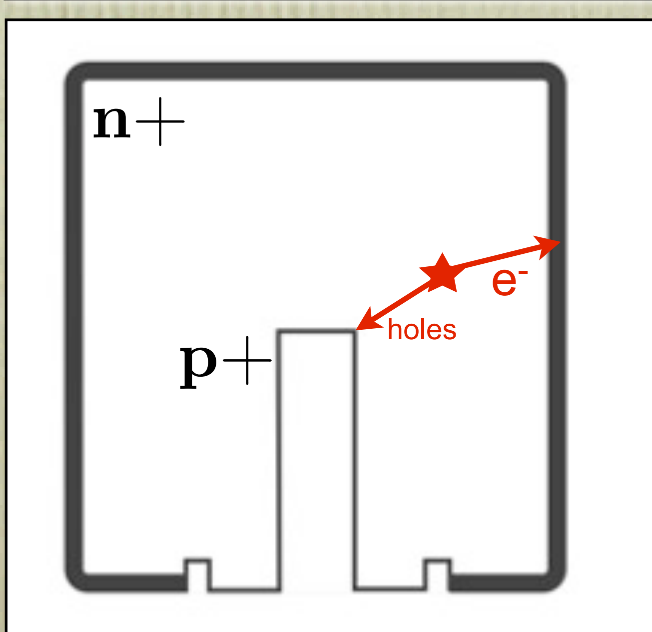




GERDA Physics Phases

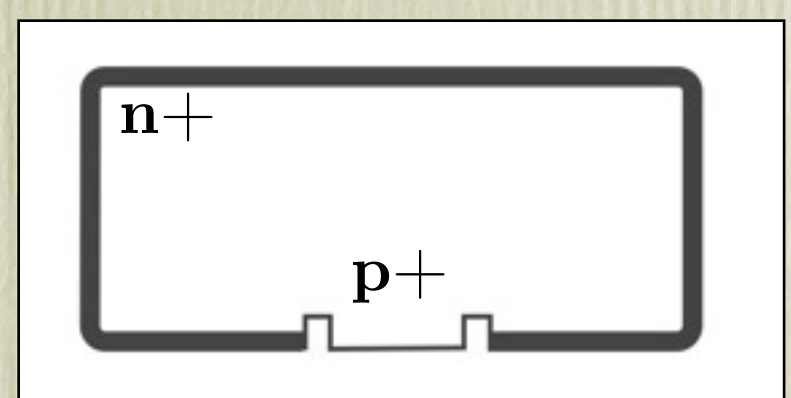
Phase I: Nov 12 - May 13

- 8 coaxial detectors from Heidelberg Moscow and IGEX
- ~18 kg enriched germanium (86%)
- ΔE ~4.5 keV @2.6 MeV
- 5 BEGe's deployed in Phase I since June 2012
- Exposure 21.6 kg yr
- Blind analysis



Phase II: Start during 2014

- 30 additional enriched BEGe Detectors
- Additional ~20 kg enriched germanium
- Enhanced pulse-shape properties and ΔE (FWHM ~3 keV @2.6 MeV)
- Background aim: 10^{-3} cts/(keV kg yr)
- Exposure aim >100 kg yr to explore 10^{26} yr range



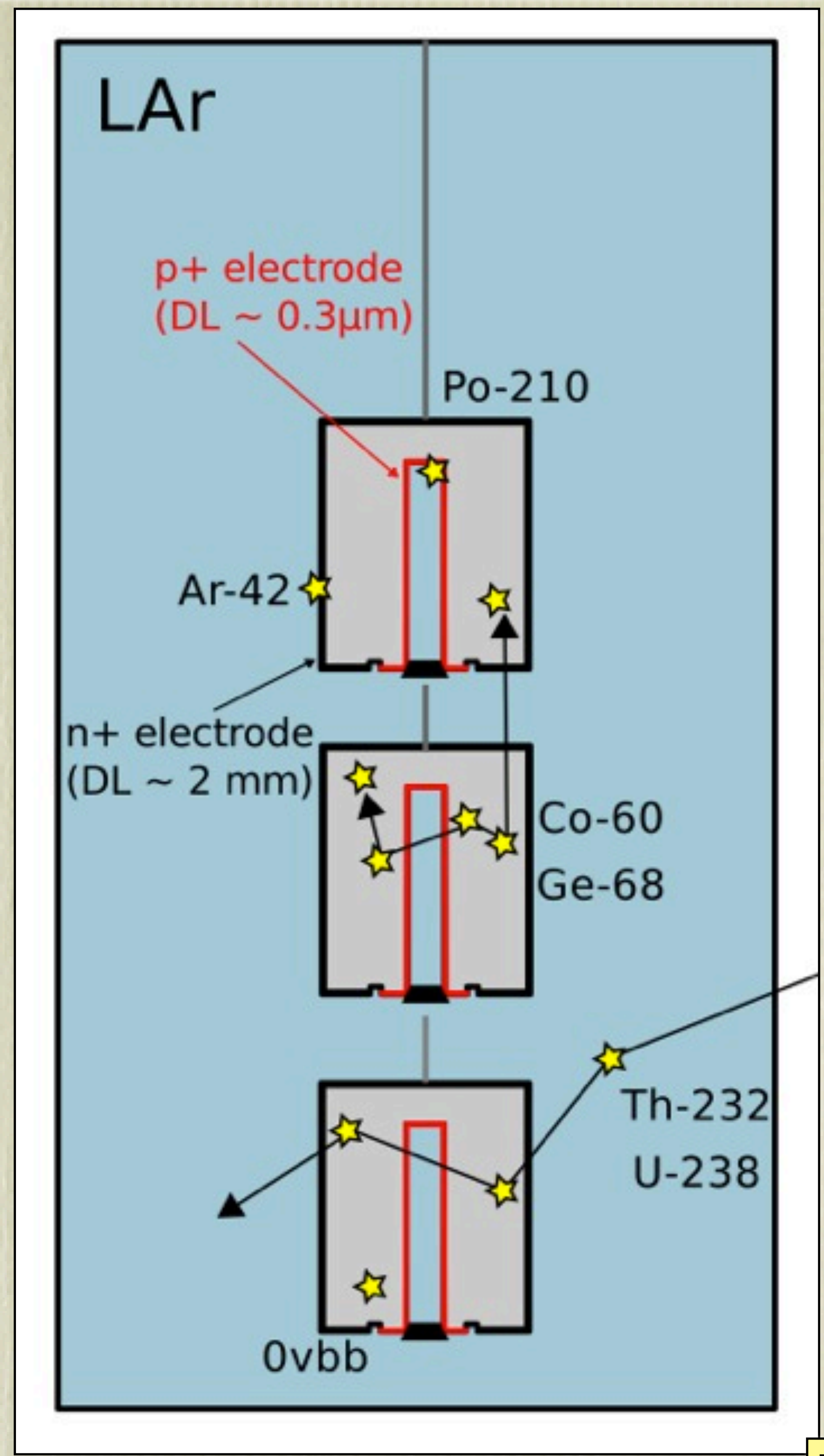
Backgrounds and Mitigation Strategies

Background sources

- Natural radioactivity (^{232}Th, ^{238}U chains)
  - ɣ-rays (e.g. ^{208}Tl, ^{214}Bi)
  - alpha-emitters on surface (^{210}Po, ^{222}Rn)
- Cosmogenic isotopes (^{68}Ge, ^{60}Co)
- Long-lived cosmogenic Ar isotopes (^{42}Ar, ^{39}Ar)

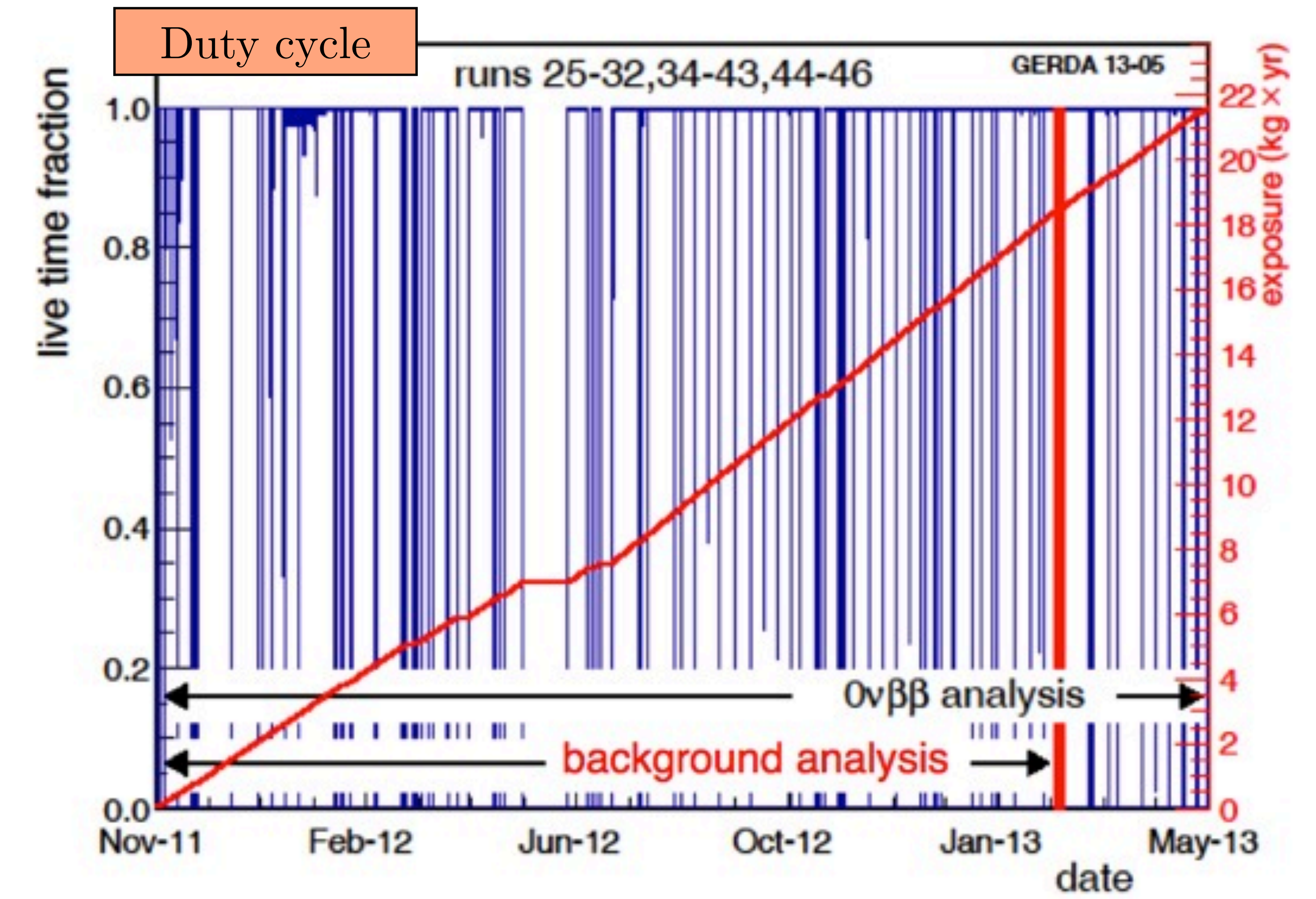
Mitigation strategies

- Underground location: muons, cosmogenic isotopes
- Water tank and Cherenkov-veto: neutrons, muons
- Detector anti-coincidence: ɣ-rays
- Time-coincidence: BiPo, ^{68}Ge
- Pulse-shape discrimination: surface events and ɣ-rays
- LAr scintillation veto [Phase II]

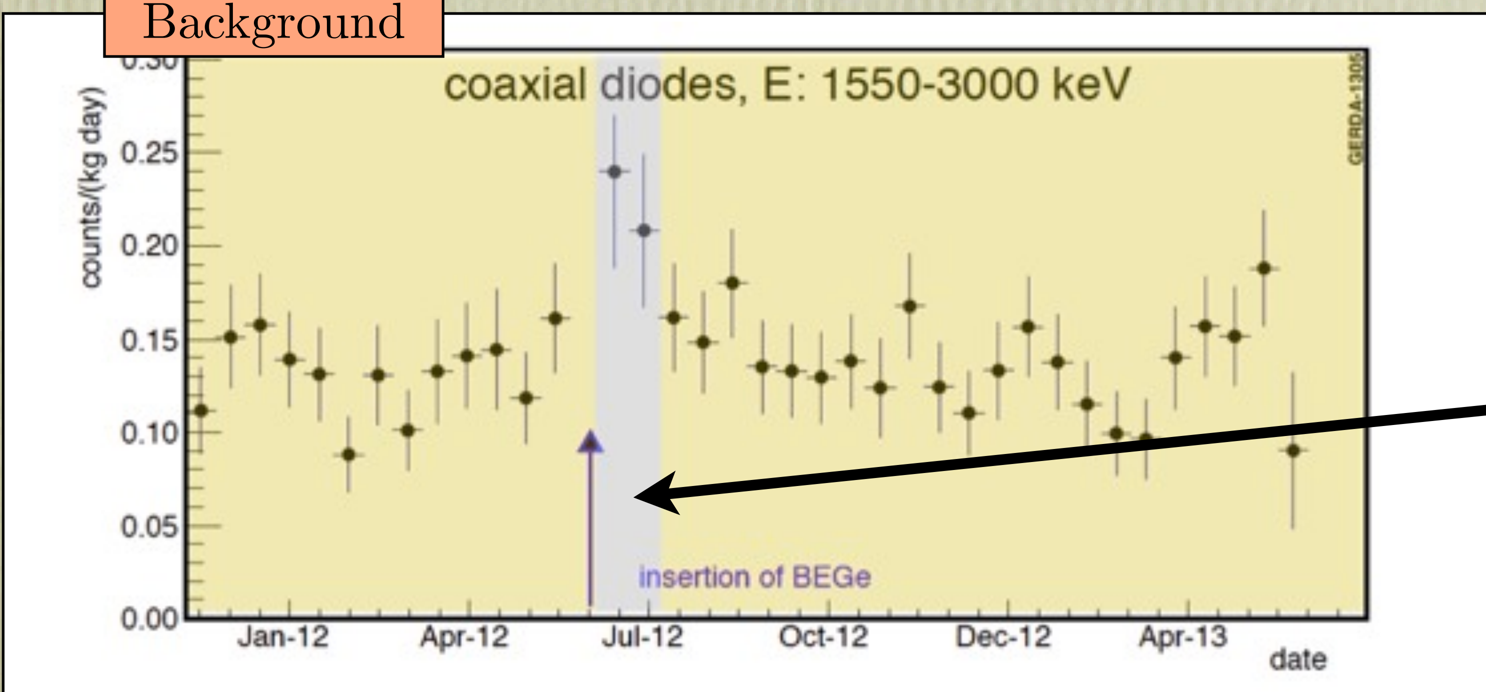


Duty Cycle and Data Sets for Phase I

Duty cycle



Background



Phase I data taking:

- Start: Nov 9 2011
- End: May 21 2013
- 556 calendar days
- Duty cycle: 88%

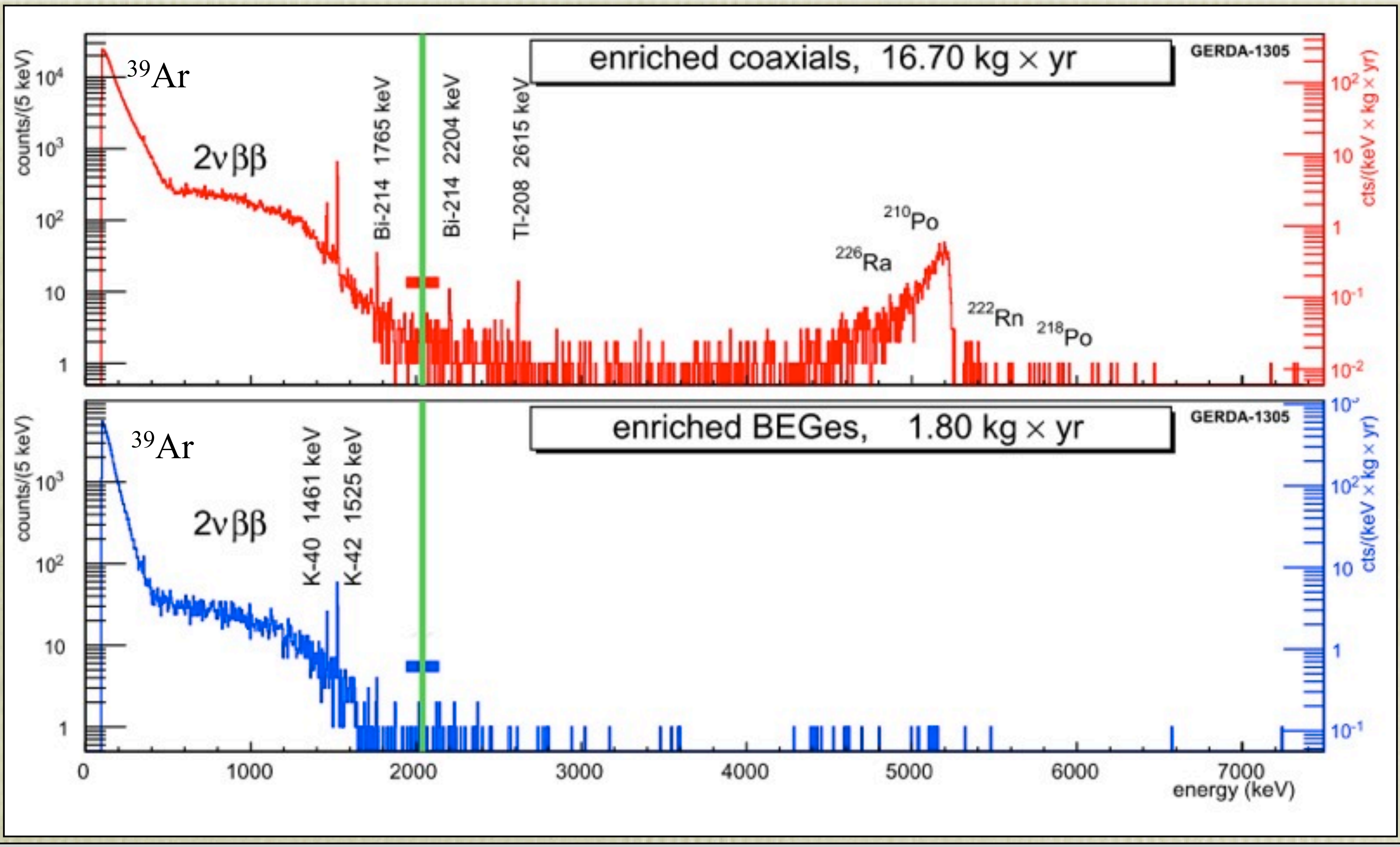
3 independent data sets:

splitting according to detectors class and run performance

Data set	Detectors	Exposure [kg yr]
Golden	Coaxial detectors	17.9
Silver	Coaxial det. in runs with large background	1.3
BEGe	BEGe detectors	2.4
Total		21.6

Phase I Spectrum and Background Model

arXiv:1306.5084



Main features:

- ^{39}Ar (565 keV β, 1 Bq/l LAr)
- 2νββ (GERDA measurement):

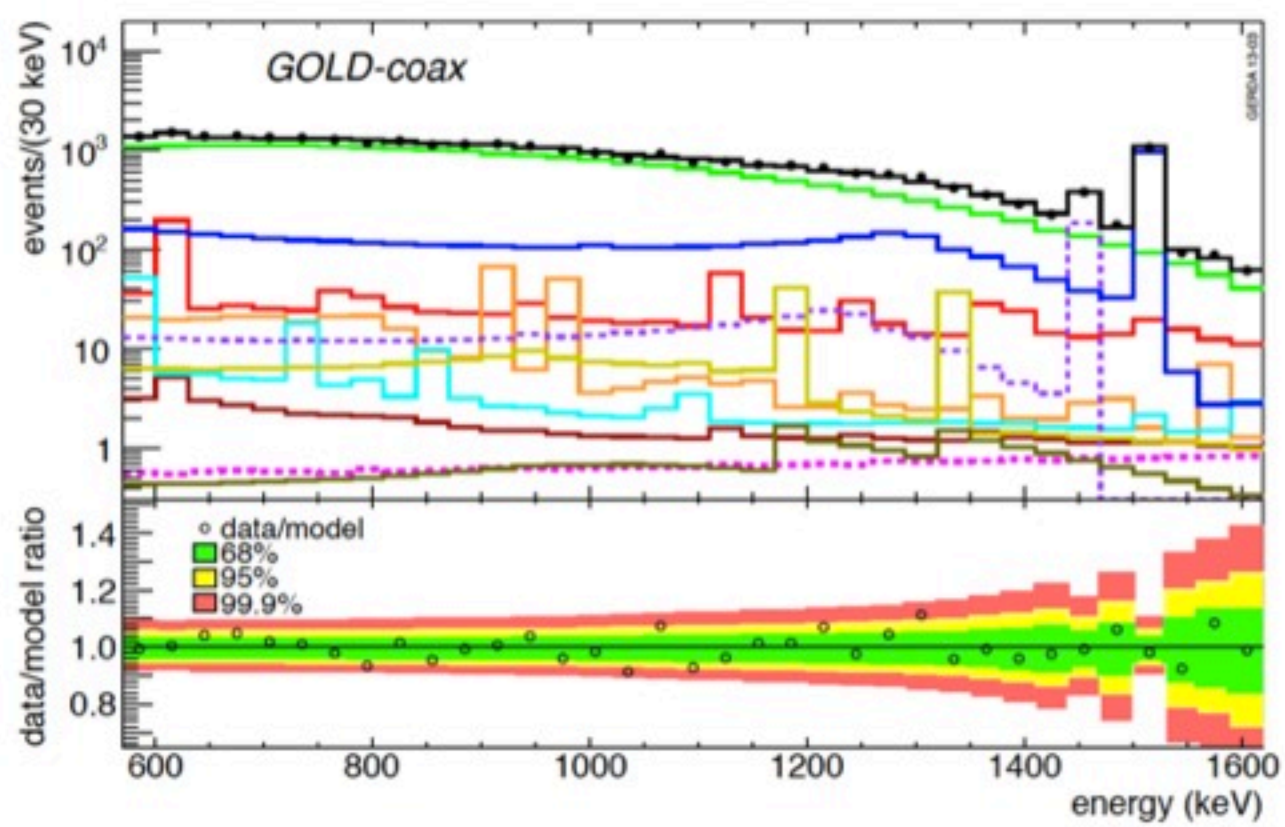
$$T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08}\,\mathrm{fit}\,^{+0.11}_{-0.06}\,\mathrm{syst}\right)\cdot 10^{21}\,\mathrm{yr}$$

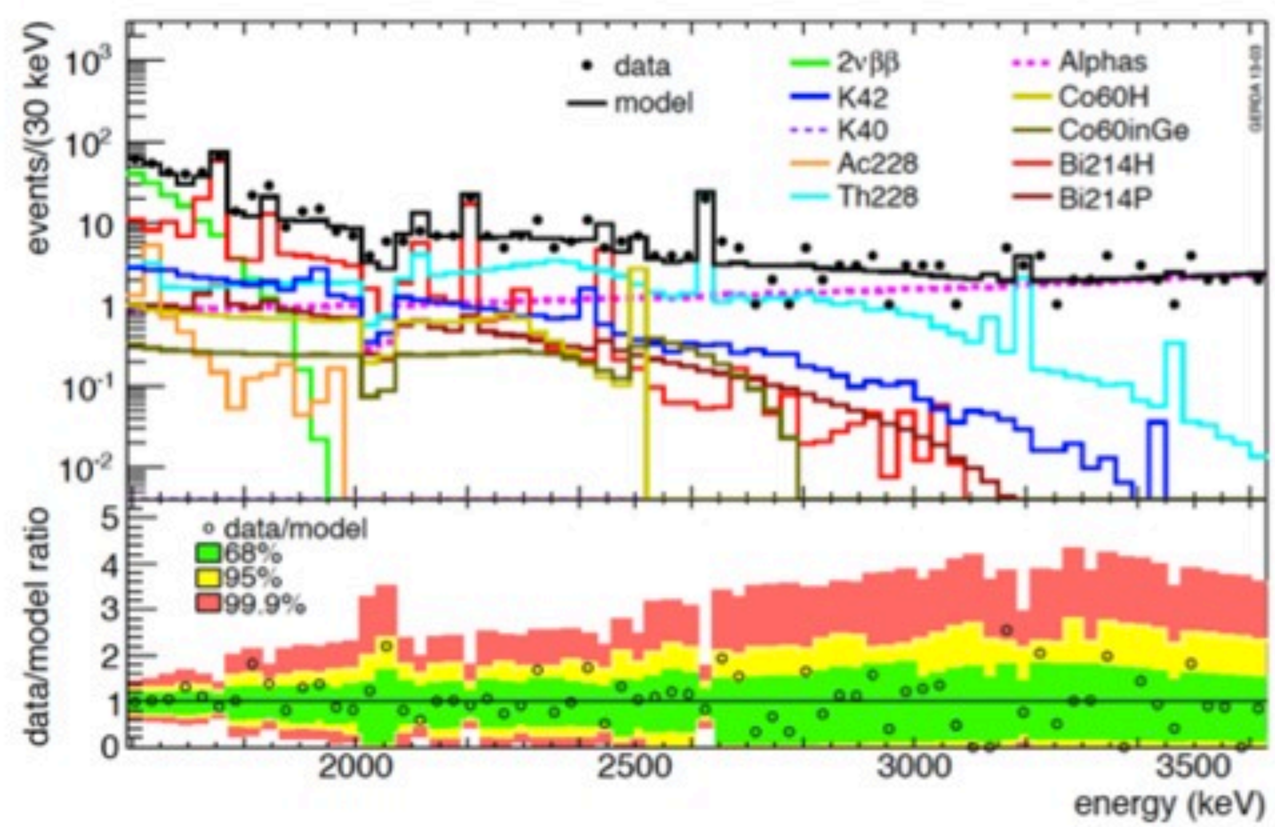
J.Phys.G 40 (2013) 035110

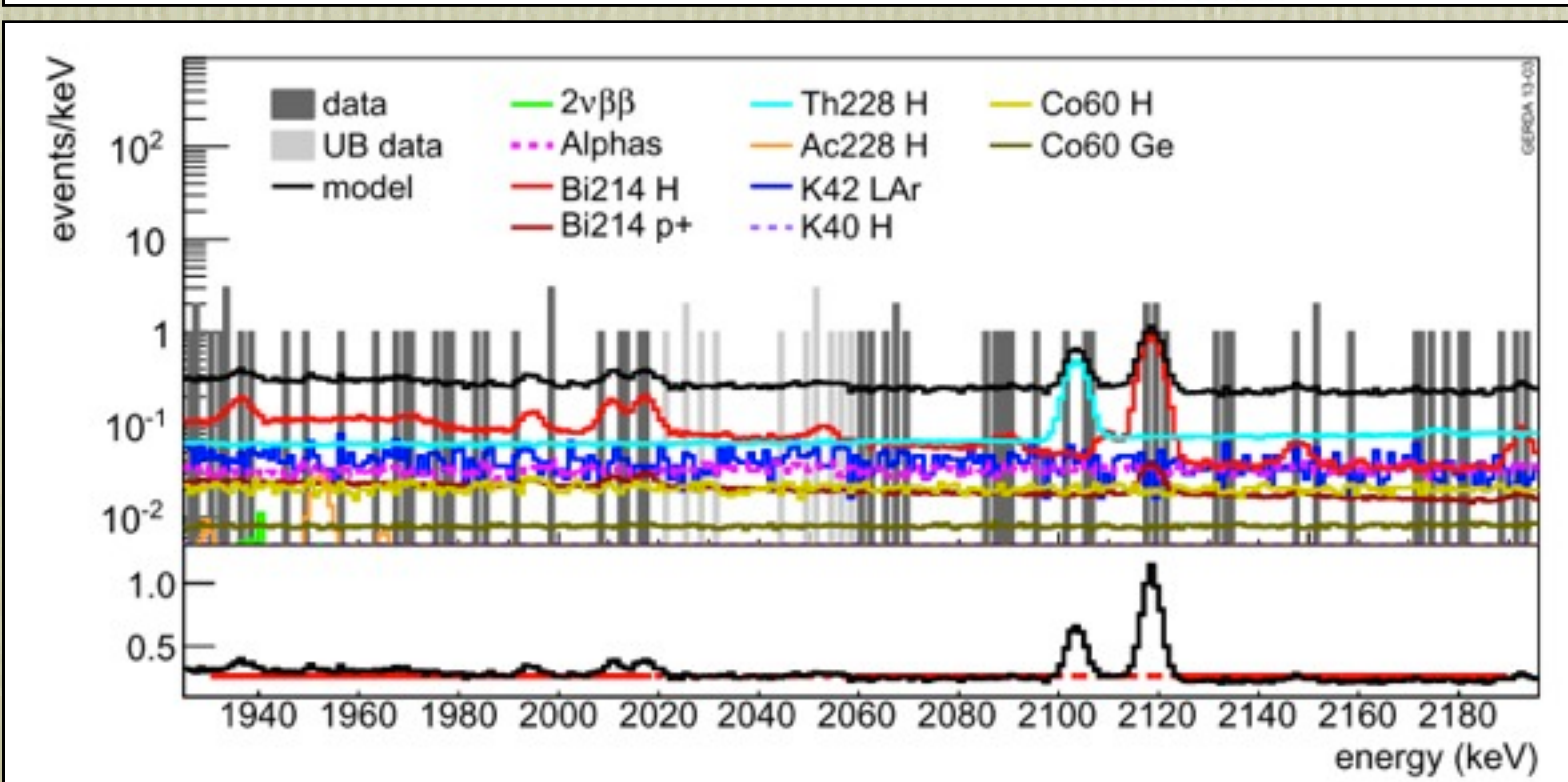
- ^{42}Ar, ^{42}K decay chain from inside LAr
- Alphas on surface of p^+ contact
- Decay chain γ-lines: reduced by factor 10 compared to Heidelberg-Moscow experiment

Phase I Spectrum and Background Model

arXiv:1306.5084





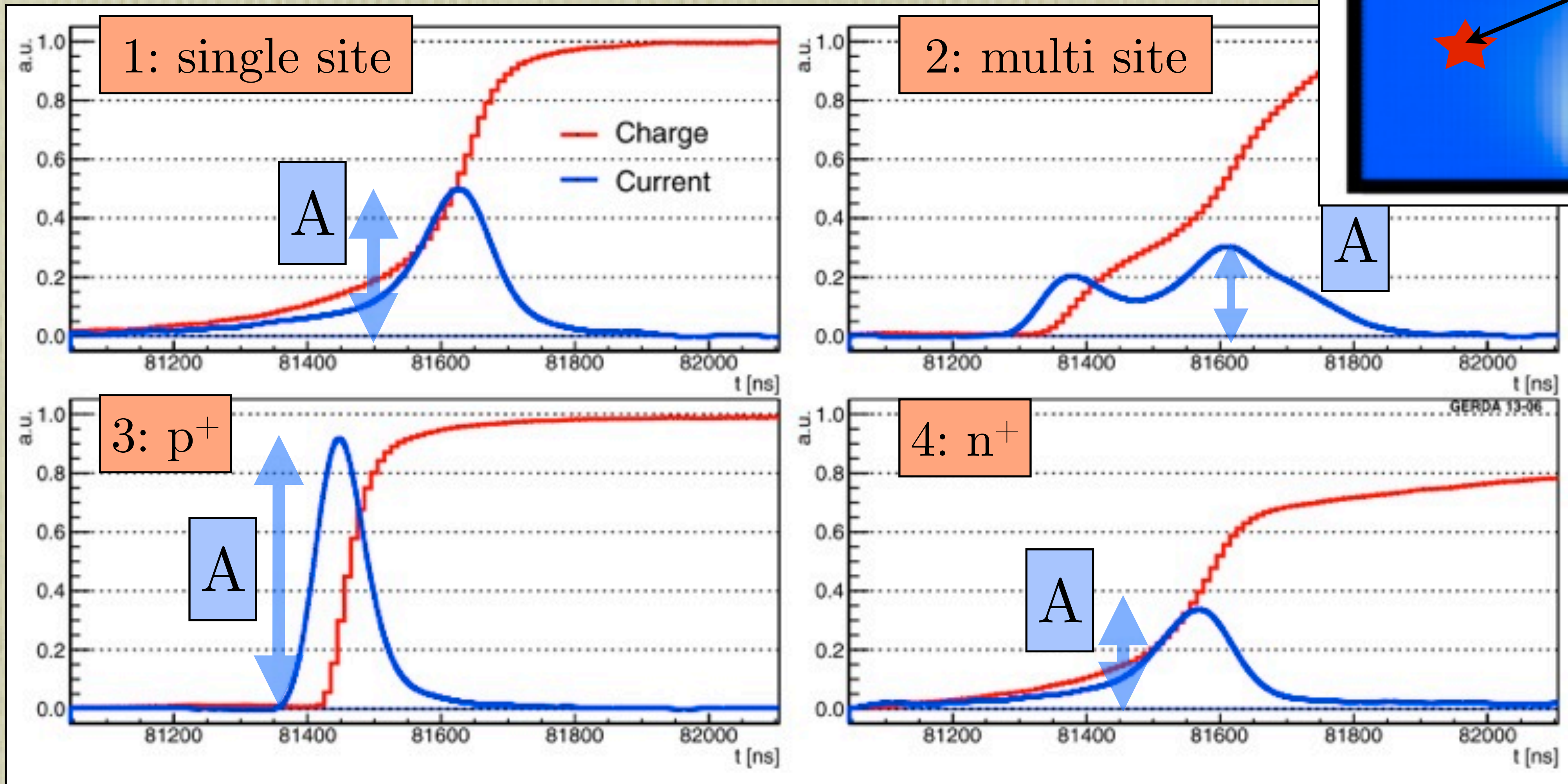


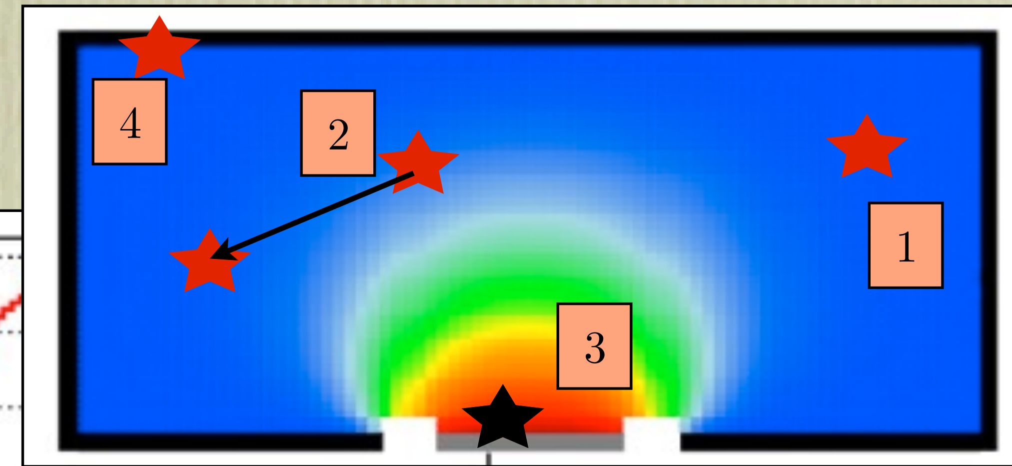
- MC of known (screening) and observed (gamma lines) background and fit to data 570 - 7500 keV
- Different combinations and positions tested
- Dominant: ^{214}Bi, ^{228}Th on detector holders, ^{42}K in LAr

Conclusion: No gamma lines in ROI; background flat between 1930 - 2190 keV

Pulse Shape Discrimination

Eur. Phys. J. C 73, 2583 (2013)

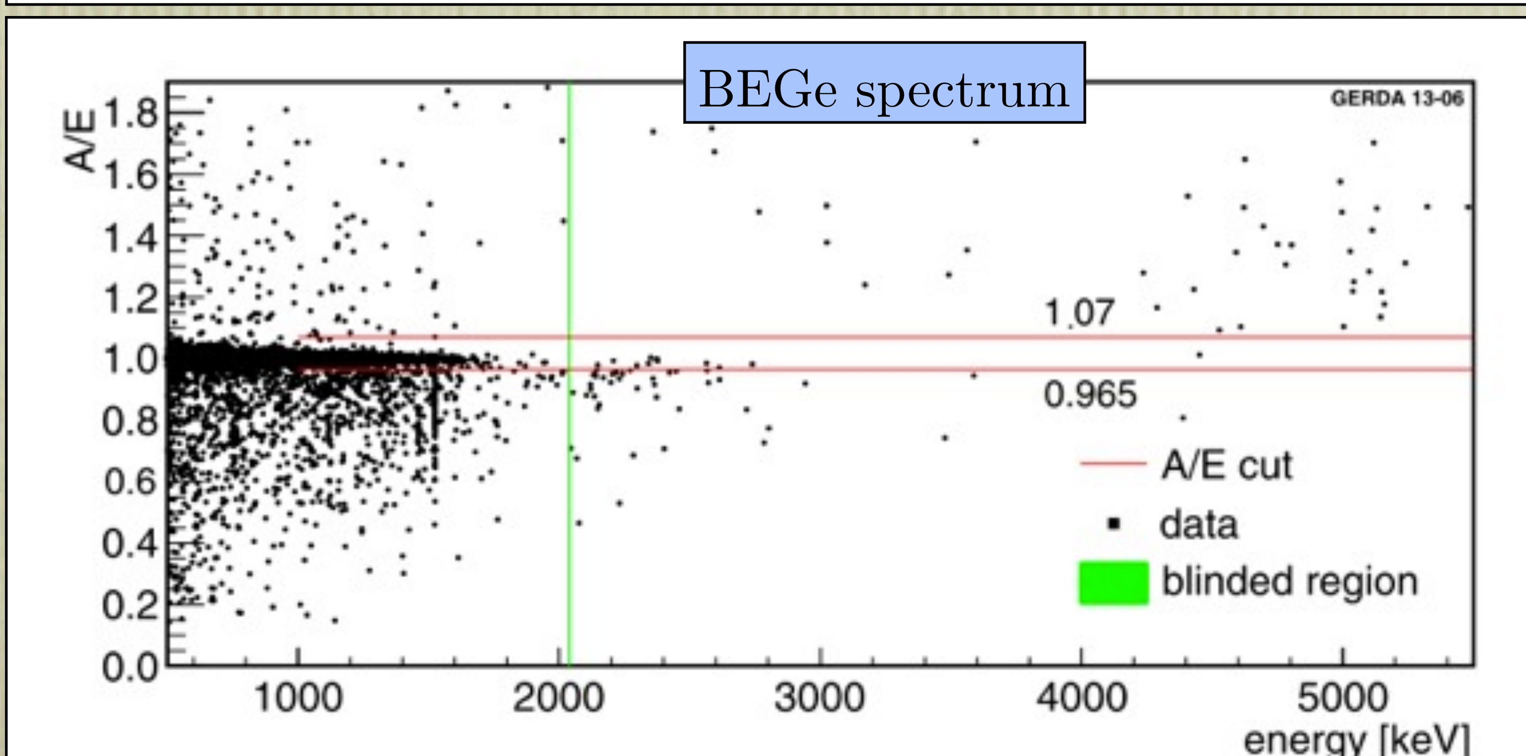




Pulse shape method:

BEGe detectors:
Amplitude / Energy

Coaxial detectors:
Neural network



BEGe:

Background Rejection: 80%

$0\nu\beta\beta$ efficiency: 92±2%

Coaxial detectors:

Background Rejection: 45%

$0\nu\beta\beta$ efficiency: 90^{+5}_{-9} %

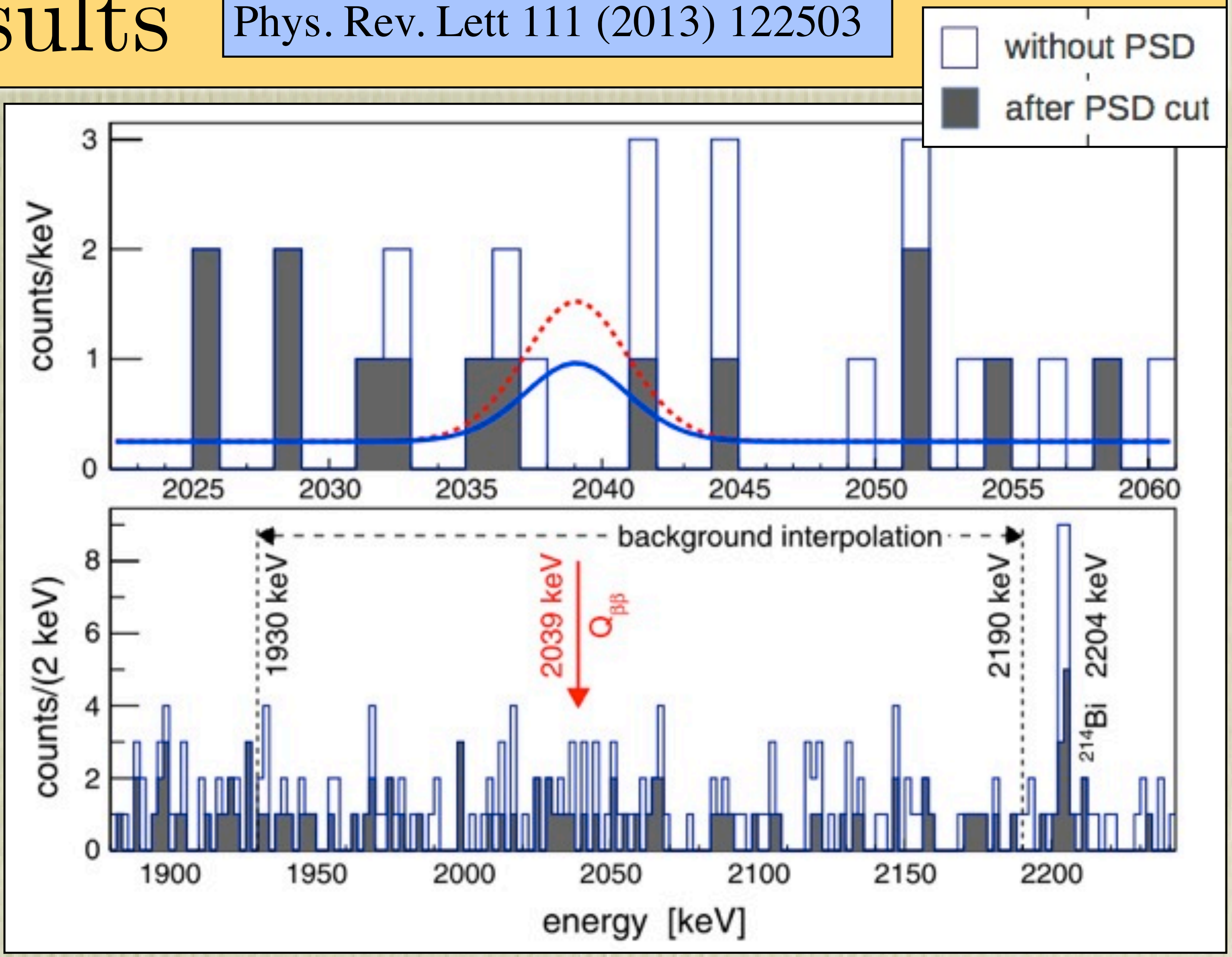
GERDA 0νββ Results

Phys. Rev. Lett 111 (2013) 122503

- Analysis cuts applied (Survival fraction around $Q_{\beta\beta}$)

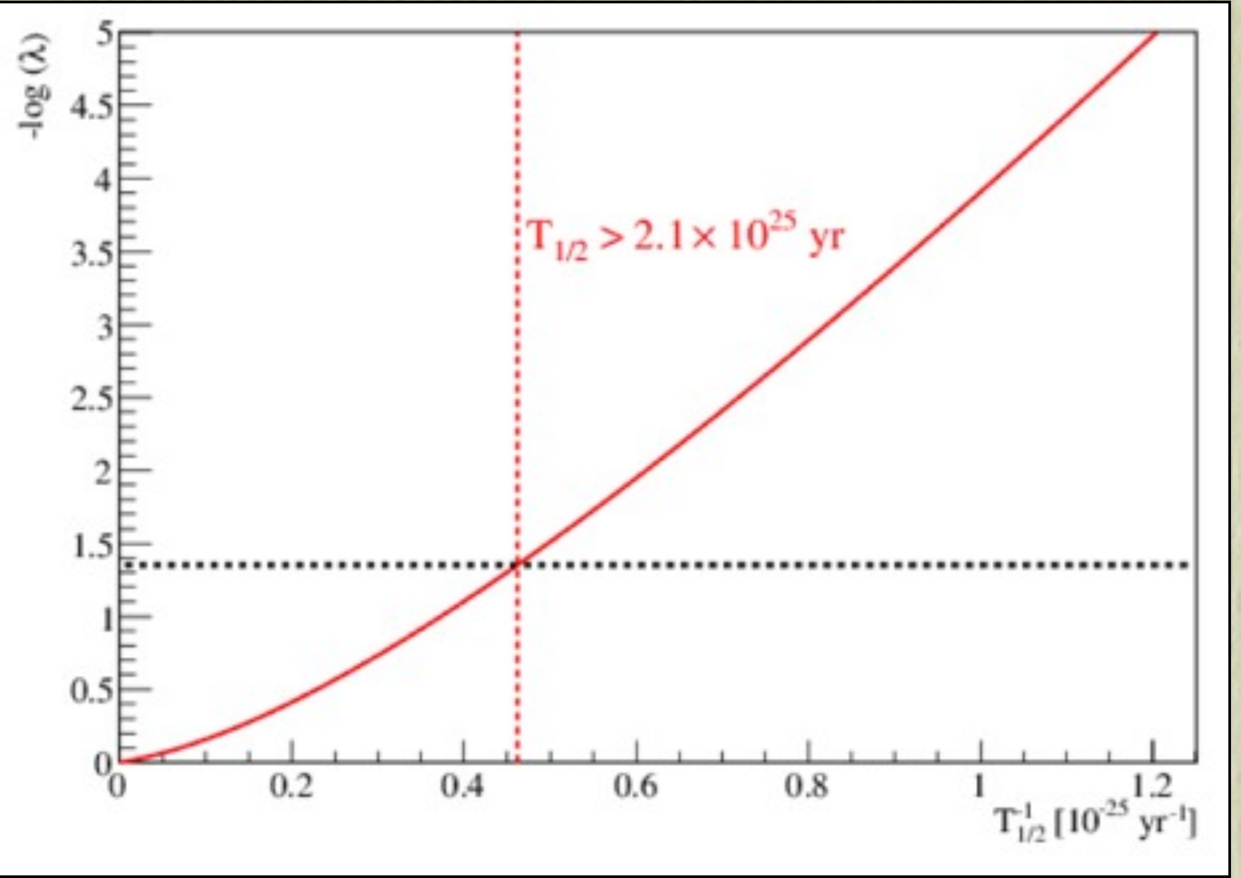
1. Quality cuts (≈ 99%)
2. Detector anti-coincidence (≈ ??%)
3. Muon-veto (≈ 60%)
4. Time coincidence (≈ 100%)
5. Pulse Shape cut (≈ 50%)

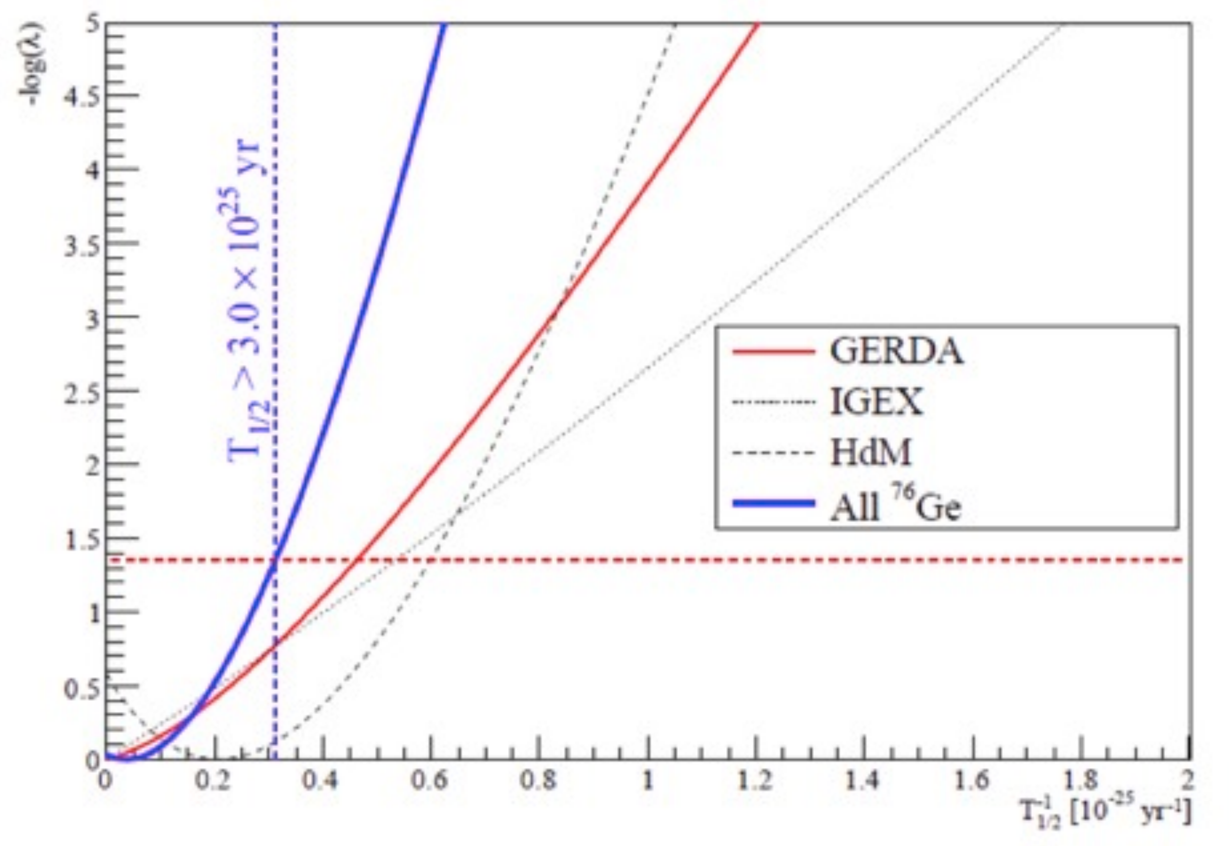
- **No peak in spectrum observed**
- **GERDA improves limit**



Data set	Exposure [kg yr]	background index [10^{-2} cts/(keV kg yr)]		expected counts ($Q_{\beta\beta}$ ± 5 keV)		observed counts ($Q_{\beta\beta}$ ± 5 keV)	
Golden	17.3	1.8	1.1	3.3	2.0	5	2
Silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	3.6	0.5	1.0	0.1	1	0
						w/o PSD	w PSD

GERDA 0νββ Results: Setting a Limit





Frequentist analysis (baseline result)

- Maximum likelihood spectral fit on 3 subsets with common $(T_{1/2})^{-1}$: Best fit n=0
- Median sensitivity:

$$T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}\,\text{yr at } 90\%\ \text{C.L.}$$

- **Profile likelihood result:**

$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\,\text{yr at } 90\%\ \text{C.L.}$$

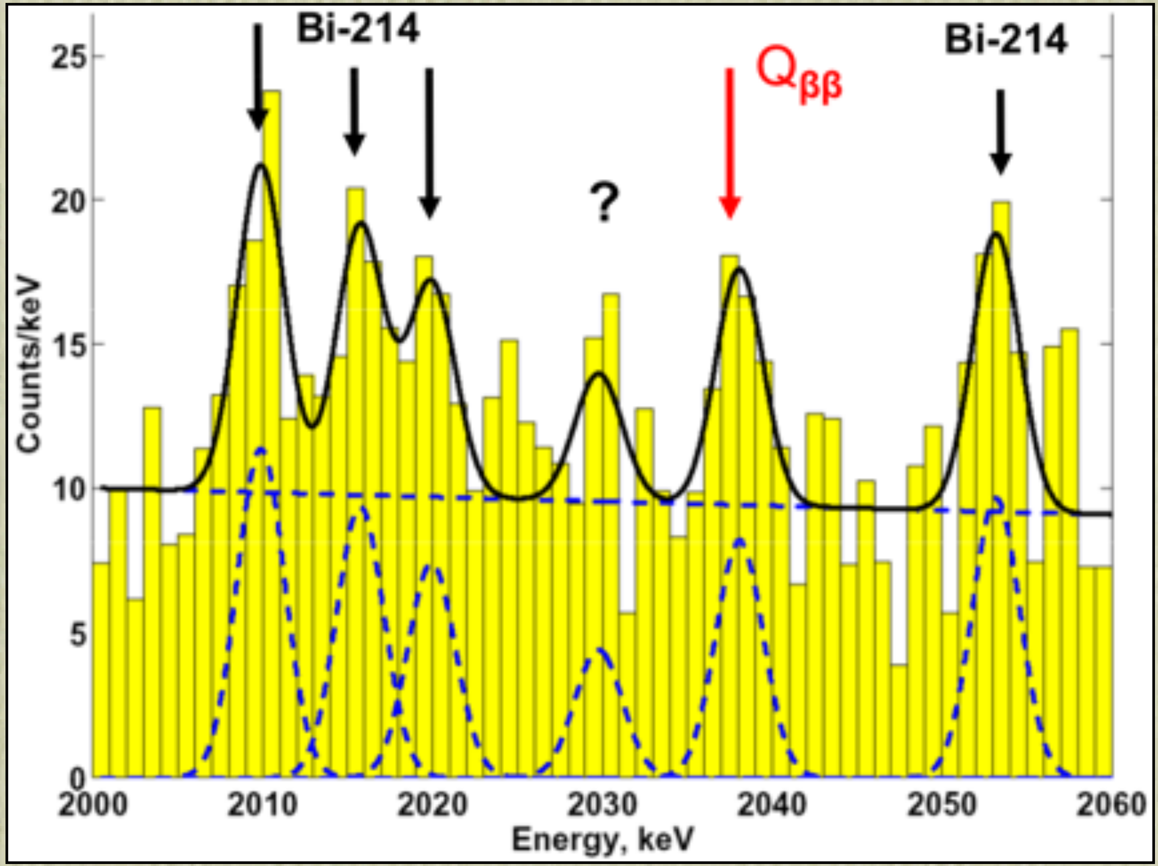
Combination ^{76}Ge:

(GERDA + HdM + IGEX)

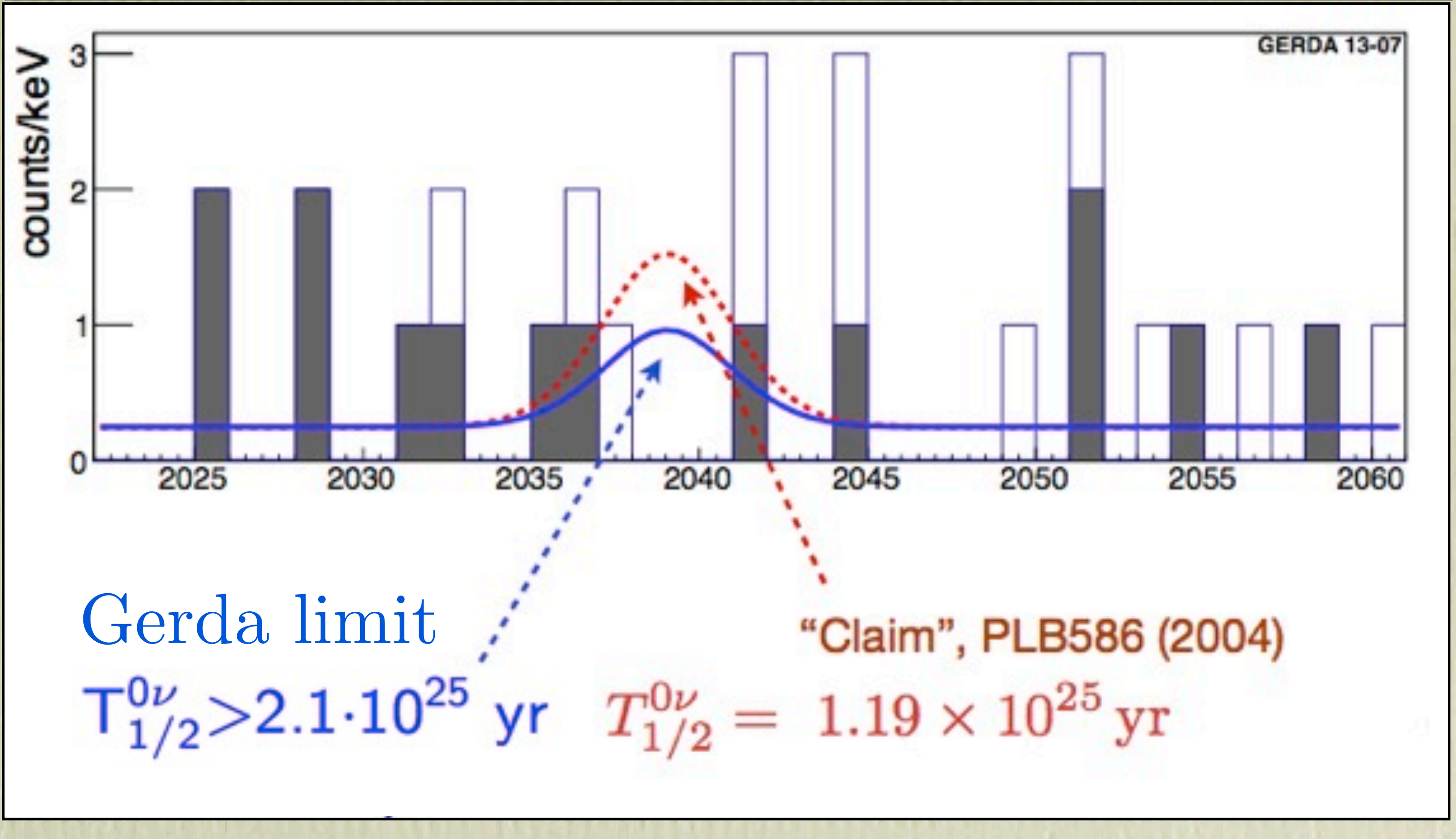
$$T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}\,\text{yr at } 90\%\ \text{C.L.}$$

GERDA 0νββ Results: Comparing with Claim

Heidelberg-Moscow: Phys. Lett. B 586 (2004)



GERDA: Phys. Rev. Lett 111 (2013) 122503



Comparing two hypotheses:

H_1: $T^{0\nu}_{1/2} = 1.19 \cdot 10^{25}$ yr

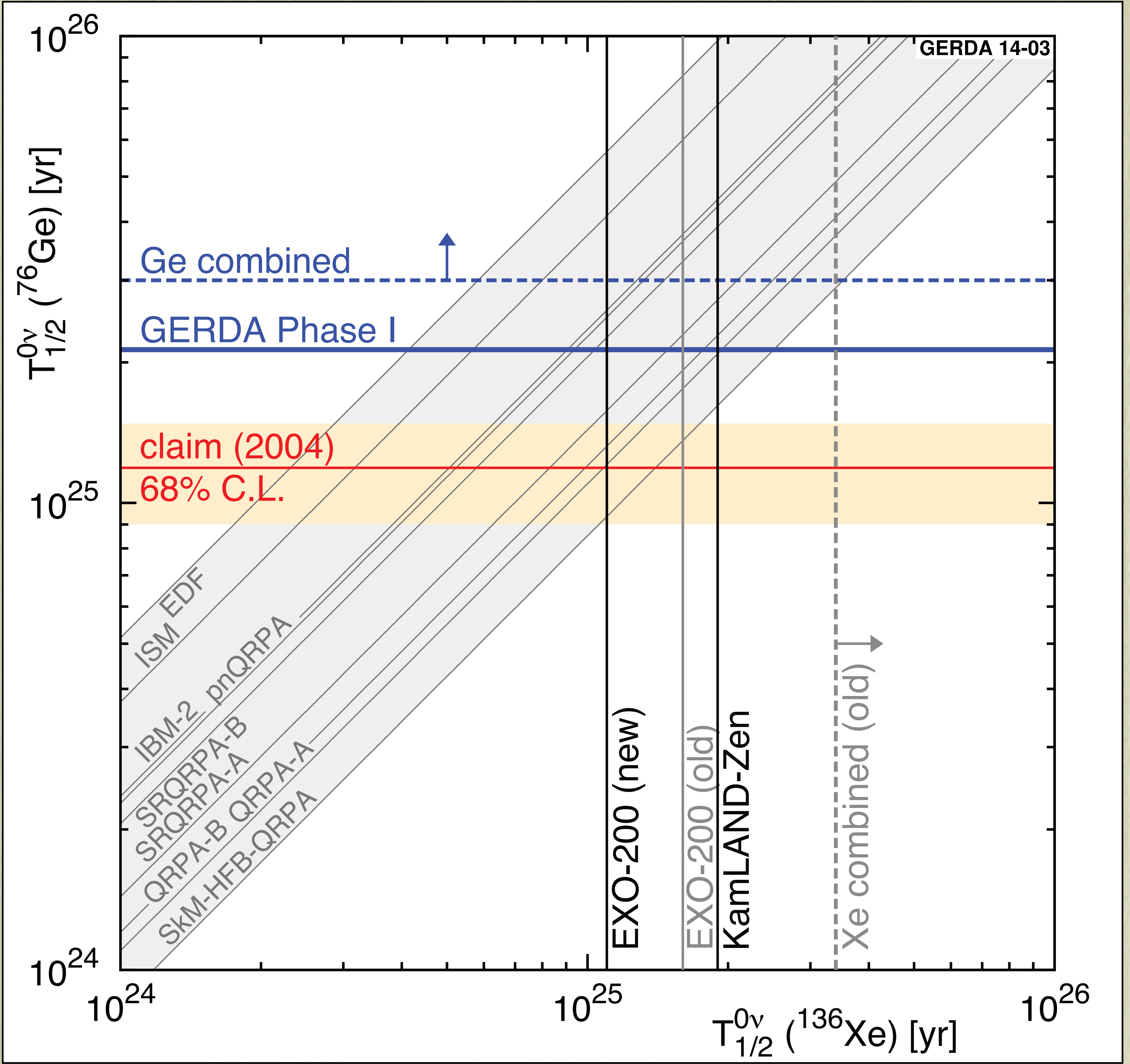
H_0: background only

GERDA only (best fit 0 events)

- $P(n=0|H_1) = 0.01$
- Bayes factor: $P(n=0|H_1)/P(n=0|H_0) = 0.024$
- 5.9 (+2.0) expected events in $\pm 2\ \sigma_E$ from claim (+background) after PSD. 3 observed

Not comparing to $T_{1/2}$ claim in Mod. Phys. Lett. 21 (2006) 157 because of inconsistencies in analysis (missing efficiencies) as pointed out in Ann. Phys. 525 (2013) 259

GERDA 0νββ Results: Comparing with Claim



Combined ^{76}Ge:

- Bayes factor:

$P(H_1)/P(H_0) = 2 \cdot 10^{-4}$

Combined ^{76}Ge + ^{136}Xe:

- Comparison via matrix elements
- Bayes factor (EXO old):

$P(H_1)/P(H_0) = 2.2 \cdot 10^{-3}$

Conclusion

- GERDA published Phase I results (21.6 kg yr and 0.01 cts/(keV kg yr))
  - GERDA Phase I: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
  - ^{76}Ge (+IGEX+HdM): $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr
  - $|m_{ee}| < 0.2$ - 0.4 eV (depending on matrix element)
  - Previous 0νββ claim only explained with 1% probability by GERDA in a model independent way
- Phase II transition ongoing. Main improvements:
  - Additional 20 kg BEGe detectors
  - Liquid argon scintillation veto

BACKUP

Light Majorana Neutrinos

Effective neutrino mass:

(only for dominant light Majorana neutrino exchange)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$

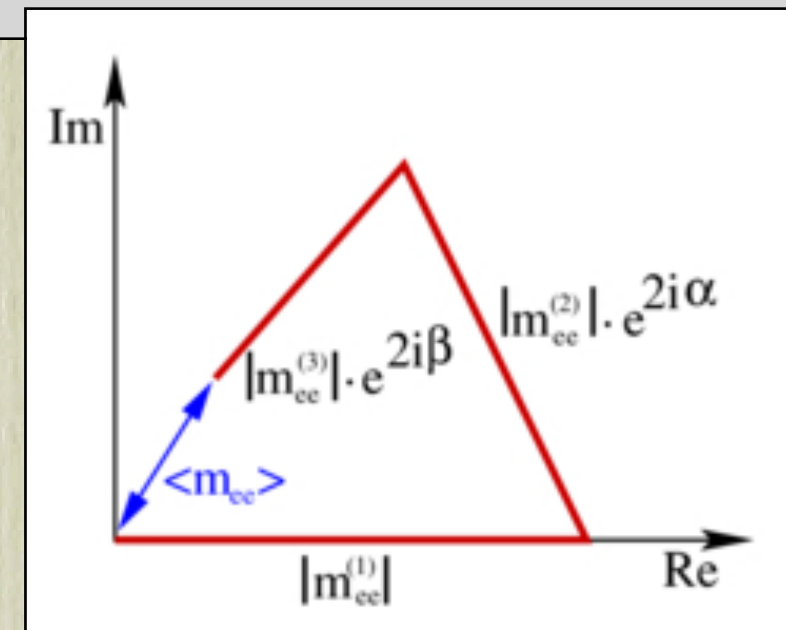
$F^{0\nu}$: phase space factor

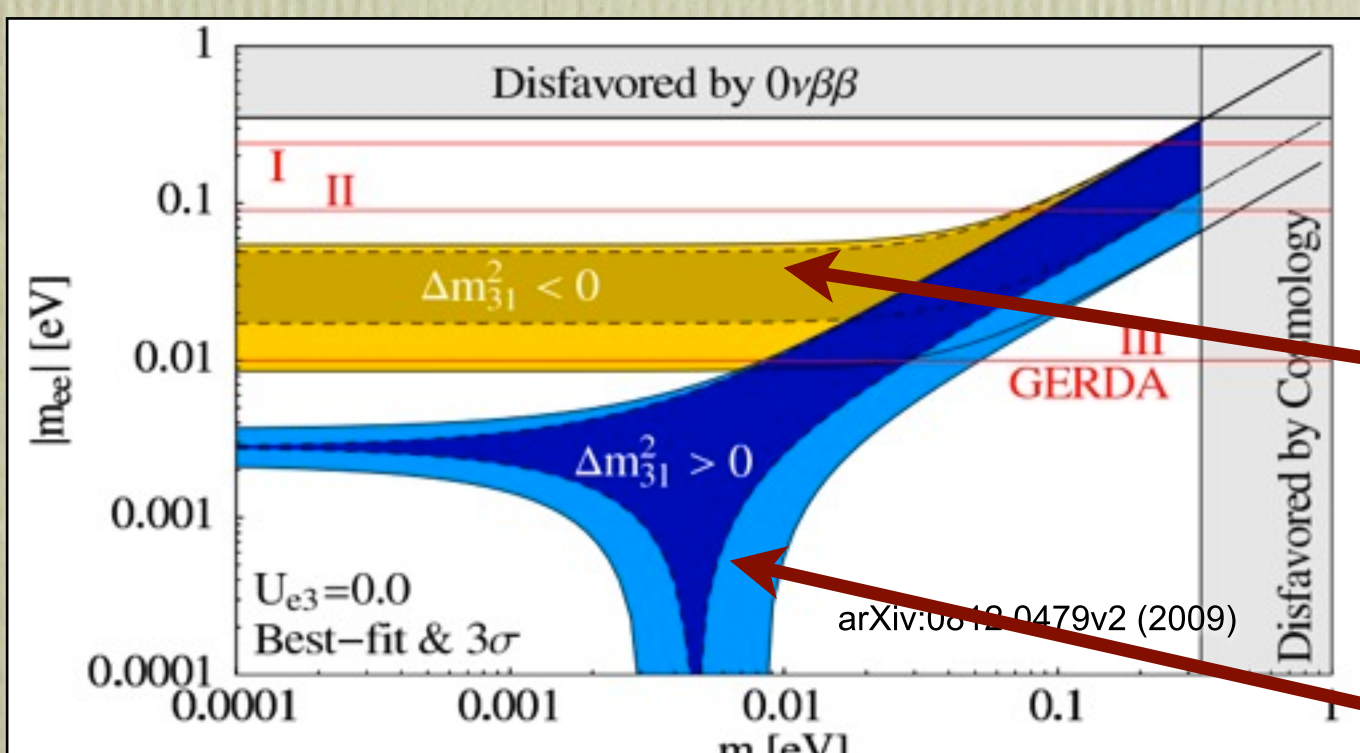
$\mathcal{M}^{0\nu}$: nuclear matrix element

m_{ee} : effective neutrino mass

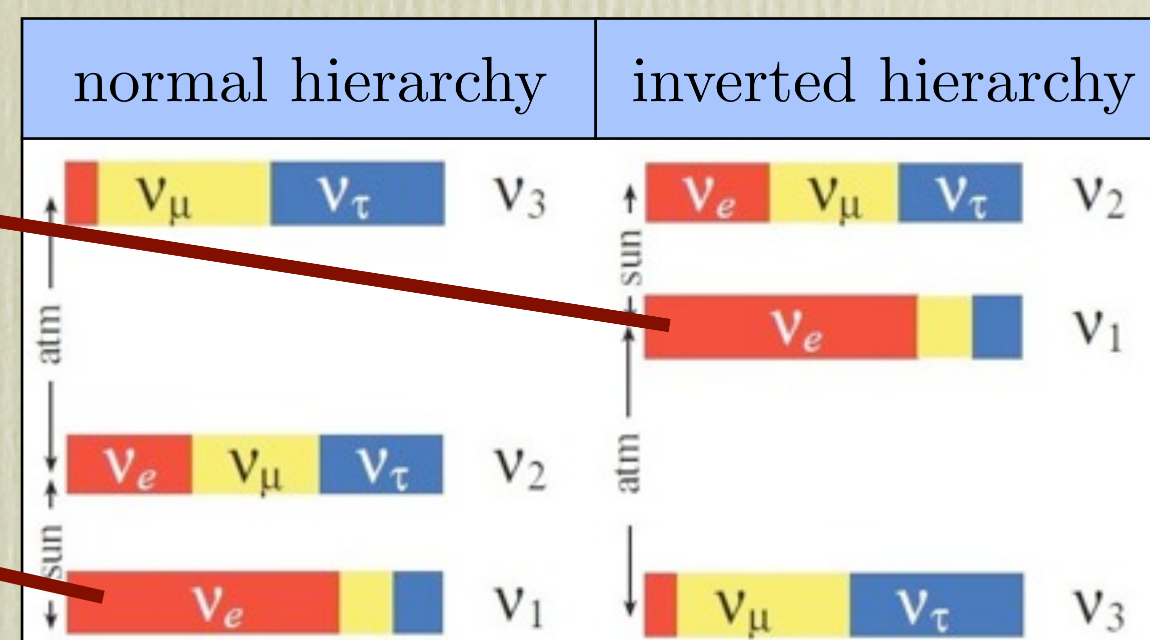
$$|m_{ee}| = \left|\sum_i m_i U_{ei}^2\right|$$

$$|m_{ee}| = \left|m_1 \left|U_{e1}^2\right| + m_2 \left|U_{e2}^2\right| \cdot e^{i(\alpha_2-\alpha_1)} + m_3 \left|U_{e3}^2\right| \cdot e^{-i(\alpha_1+2\delta)}\right|$$

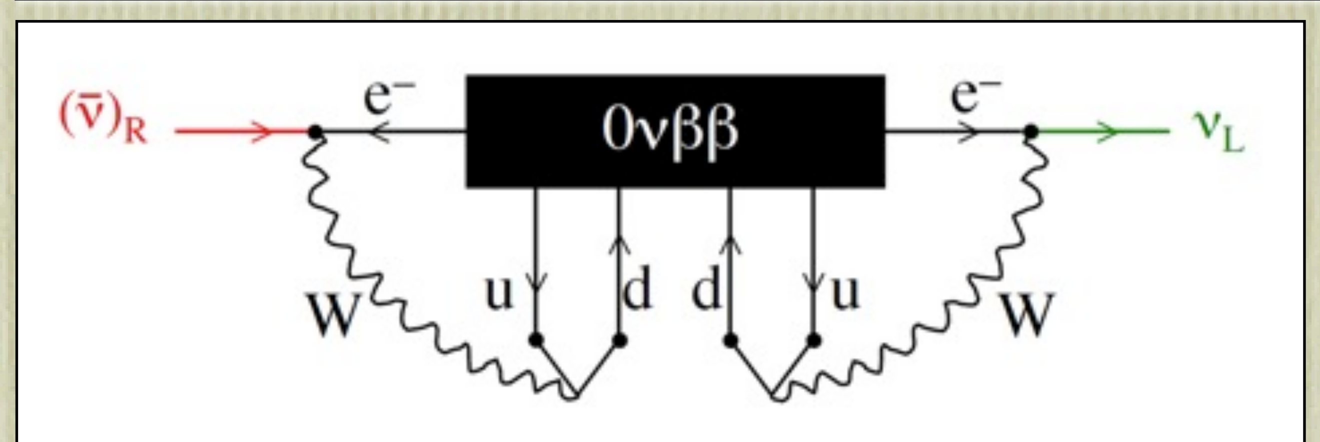




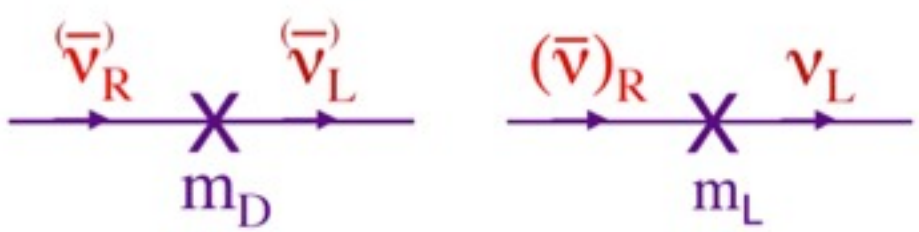
arXiv:0812.0479v2 (2009)



Other 0νββ Mechanisms



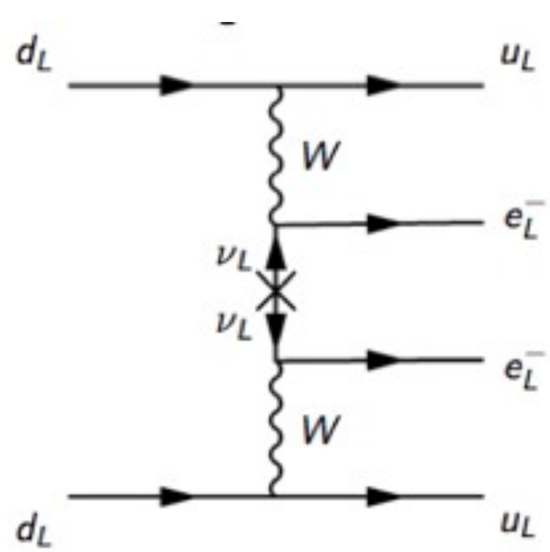
$$\mathcal{L} = m_D \bar{\nu}_R \nu_L + m_M \bar{\nu}_L \nu_L^c$$



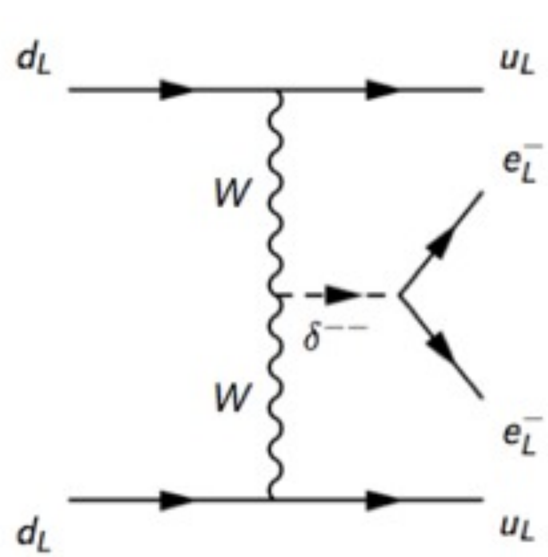
- Standard process: Light Majorana neutrino exchange
- There are also other lepton number violating processes that can trigger 0νββ
- **Schechter-Valle theorem:**

If 0νββ exists, it can always be interpreted as a neutrino Majorana mass term

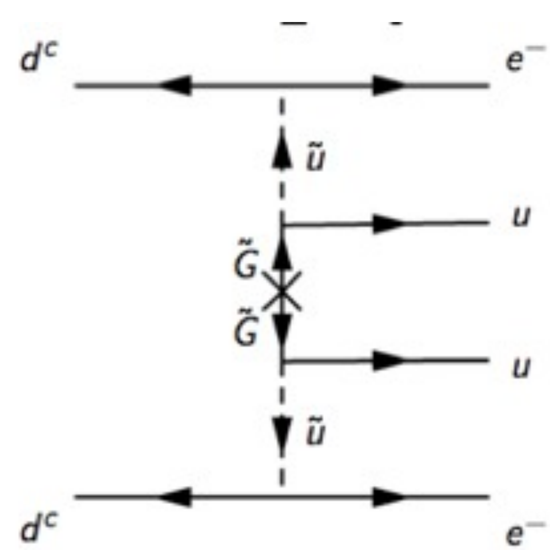
Possible processes (not exhaustive)



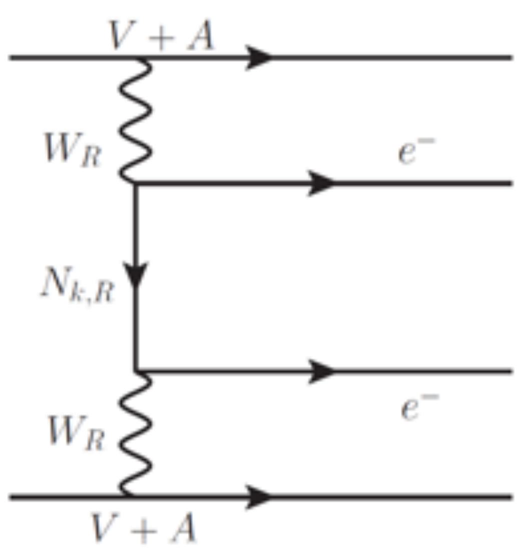
light Majorana



Higgs triplet



SUSY particle



right handed currents

Double Beta Decay Isotopes

Effective neutrino mass:

(only for dominant light Majorana neutrino exchange)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$

$F^{0\nu}$: phase space factor

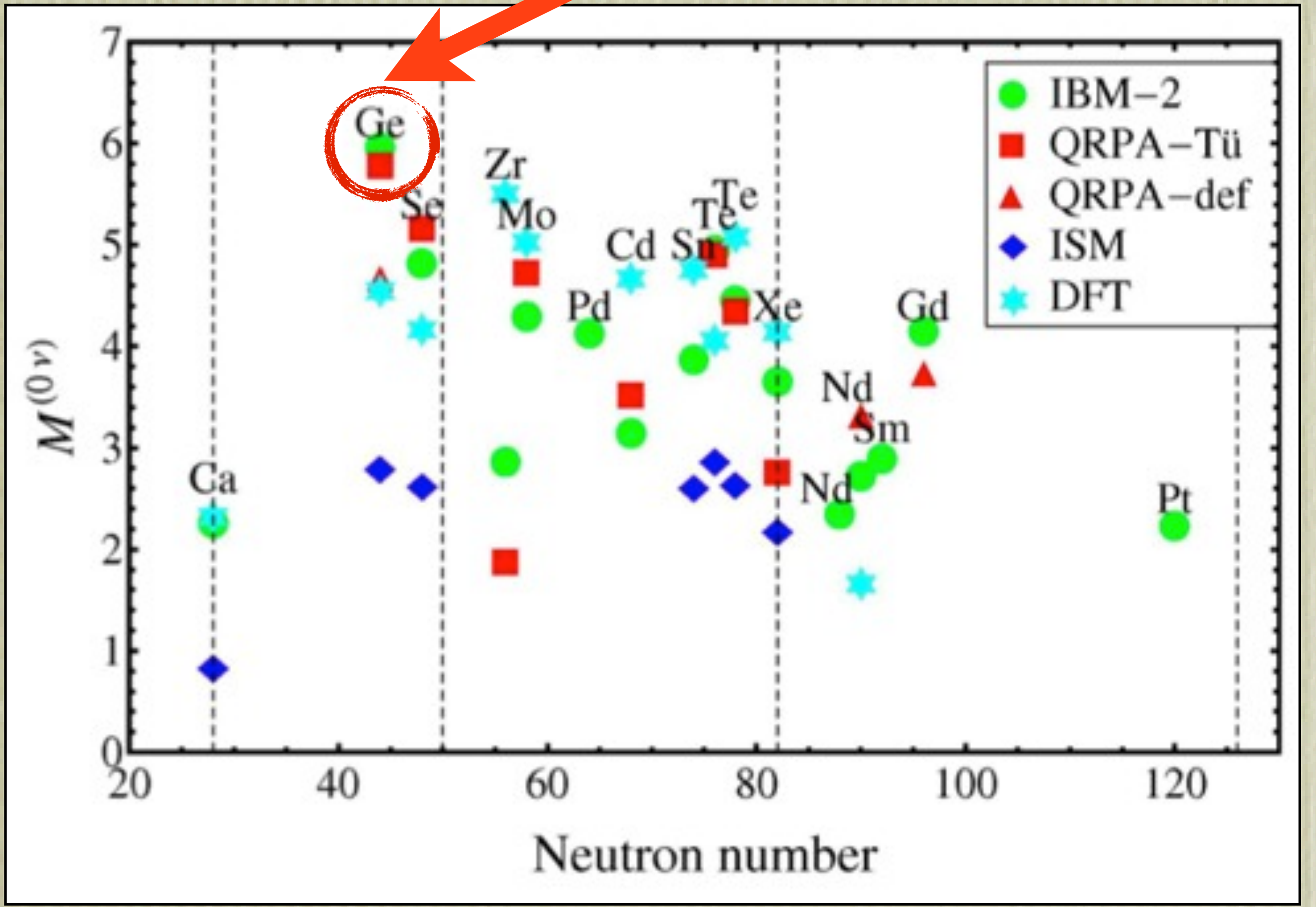
$\mathcal{M}^{0\nu}$: nuclear matrix element

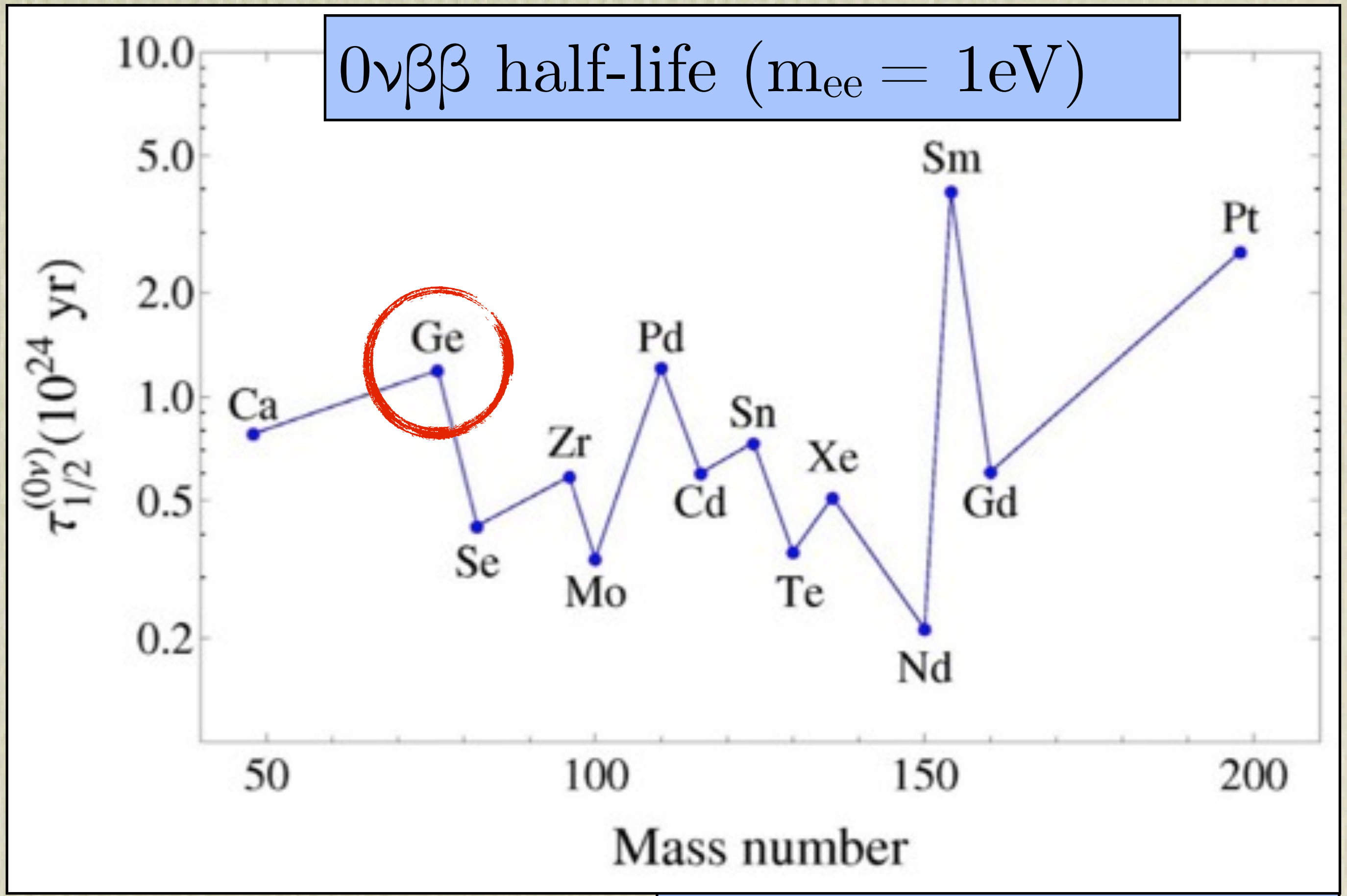
m_{ee} : effective neutrino mass

phase space factor (atomic physics)

matrix element (nuclear physics)

Beyond SM process (particle physics)





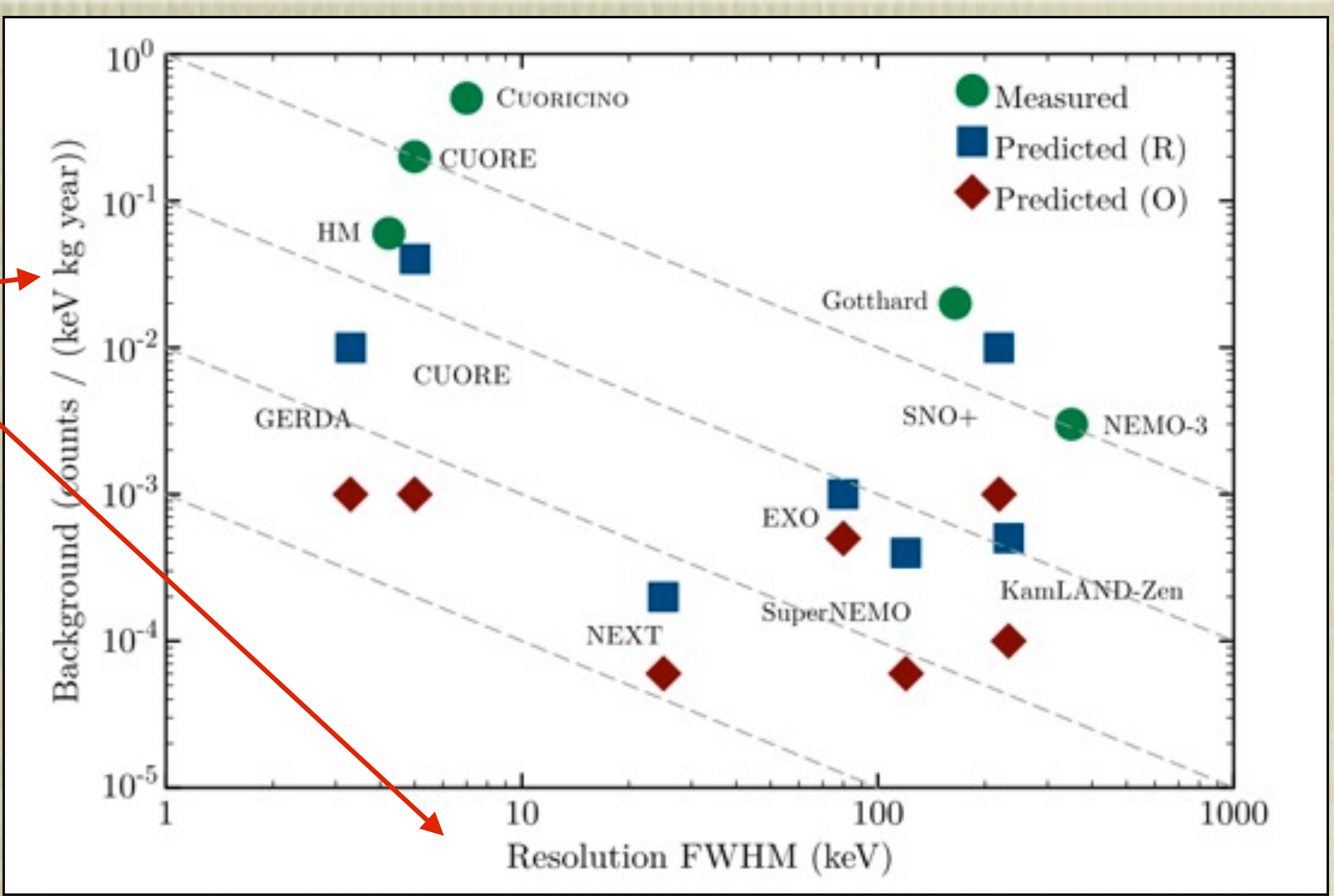
F. Iachello LNGS seminar (2013)

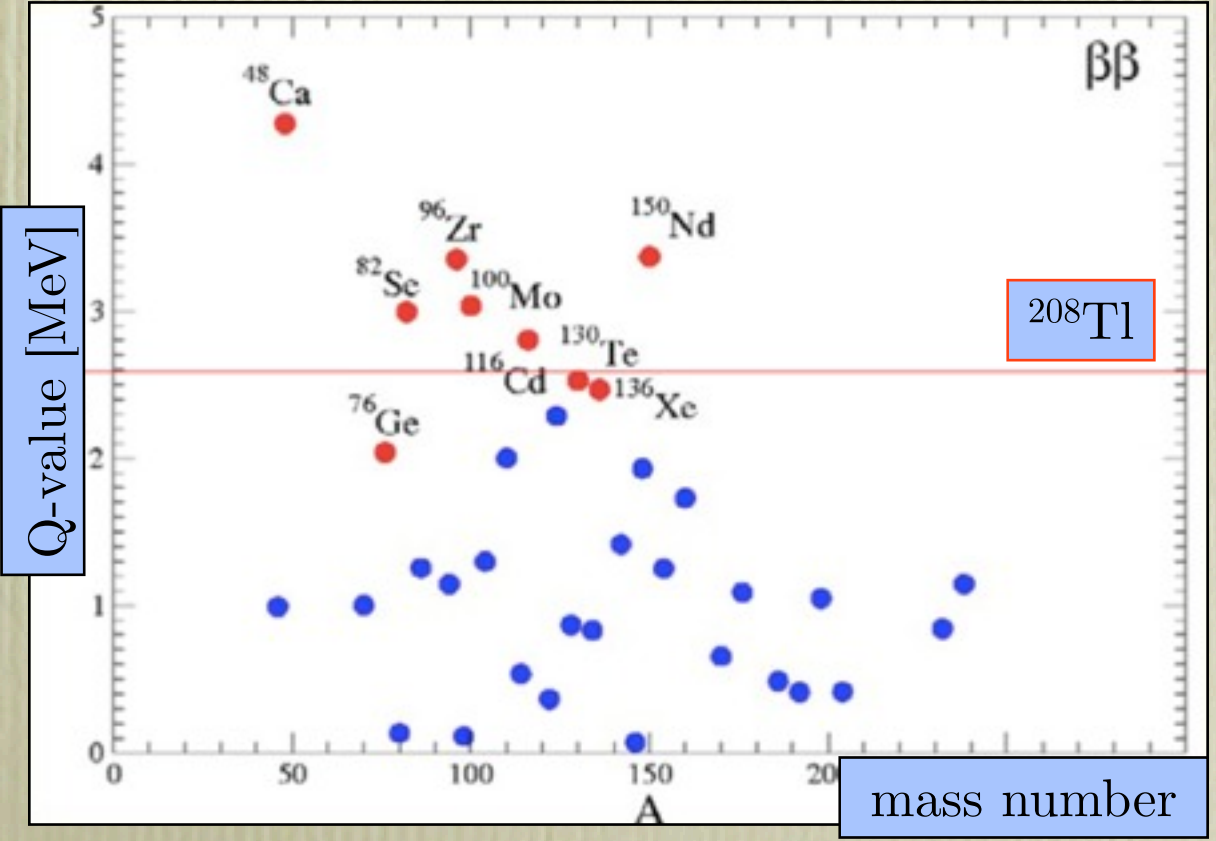
Double Beta Decay Experiments

Sensitivity: (for Gaussian background)

$$T_{1/2}^{\mathrm{limit}} \propto \alpha \cdot \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

α : isotopic abundance
η : active volume fraction
ϵ : detection efficiency
$M \cdot T$: exposure
B : background index
ΔE : energy resolution





Advantage ^{76}Ge:

- Excellent energy resolution O(0.1%)
- Good detection efficiency O(80%)
- Intrinsic low background (Semiconductor)

Disadvantages ^{76}Ge:

- Expensive enrichment
- Q-value < 2614 keV

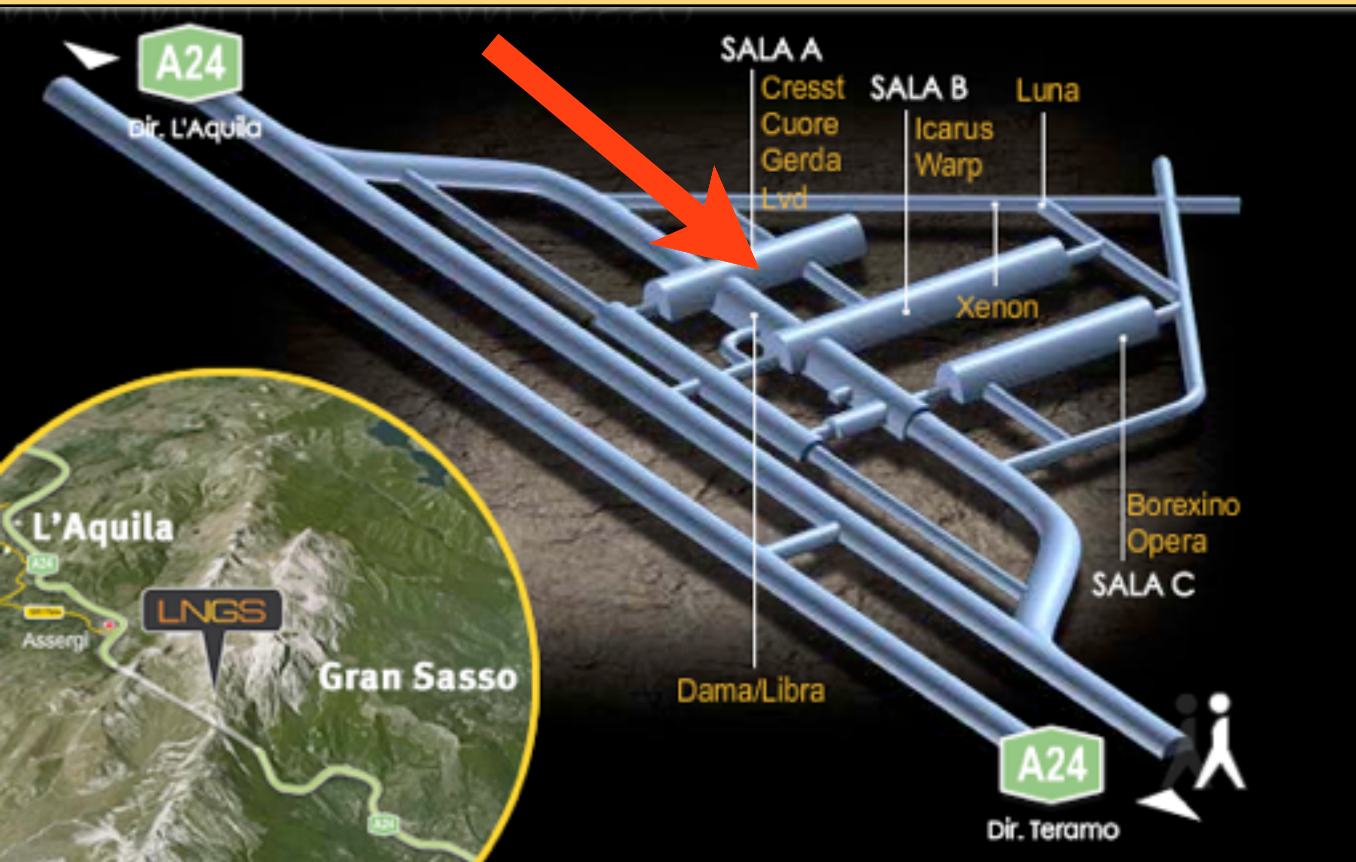
DBD Isotopes

Isotope	Q (MeV)	Percent natural abund.	Element cost [5] ($/kg)	$G^{0\nu}$ $(10^{-14}/\text{yr})$ [6]	$M^{0\nu}$ (avg) [7]	Annual world production [5] (tons)	$0\nu/2\nu$ rate [2,8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.4×10^8	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	118	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	2000	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	1.4×10^6	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	2.5×10^5	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	207	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	2.2×10^4	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	2.5×10^5	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	$\sim$150	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	50	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	$\sim 10^4$	0.024

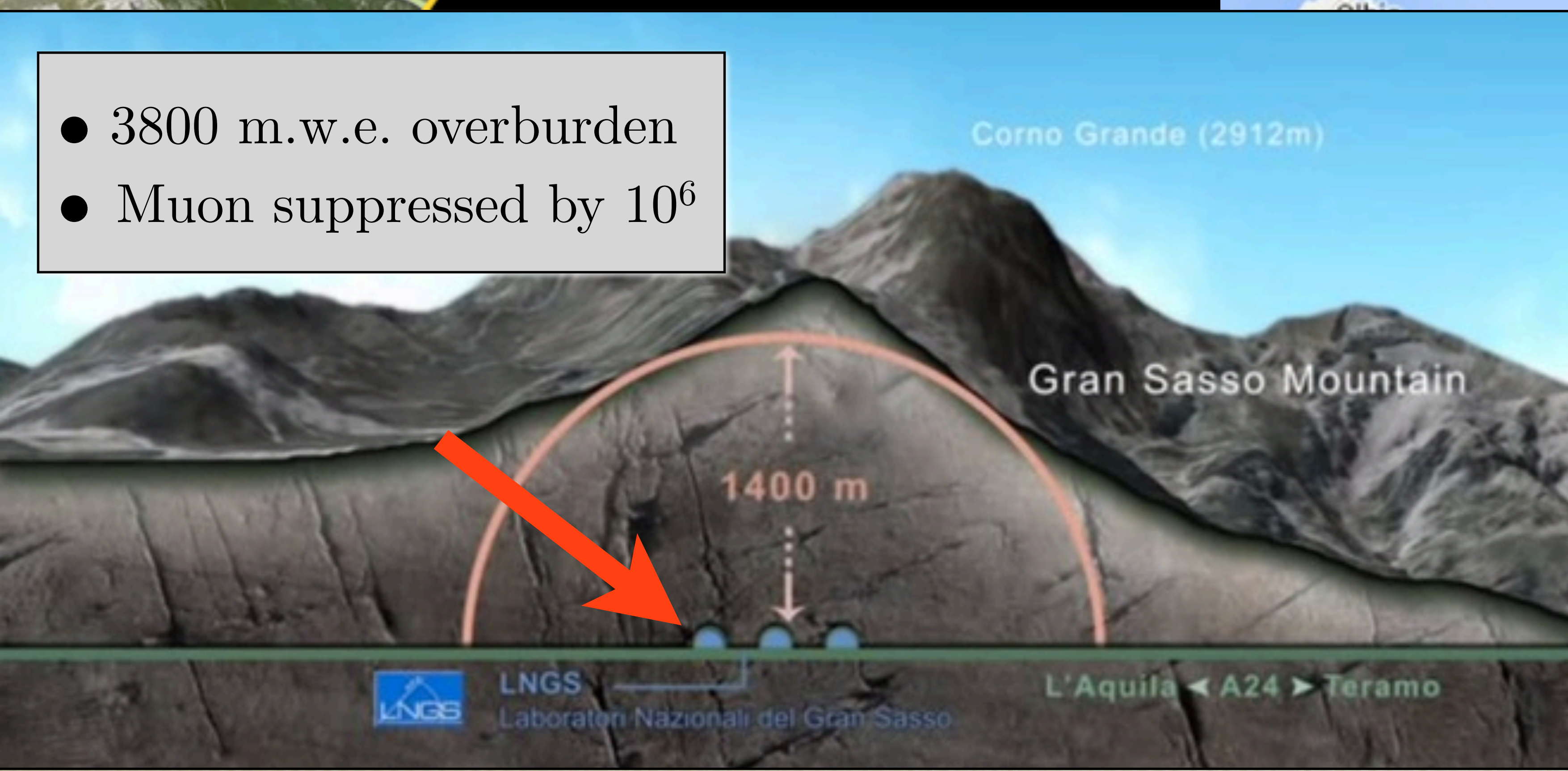
PHYSICAL REVIEW D 87, 071301(R) (2013)

@ LNGS, L'Aquila, Italy

Laboratori Nazionali del Gran Sasso



- 3800 m.w.e. overburden
- Muon suppressed by 10^6



History

LOW-RADIOACTIVITY
BACKGROUND TECHNIQUES

G. Heusser

Max-Planck-Institut für Kernphysik, P.O. Box 103 980, D-69029 Heidelberg, Germany

the idea '95

Hall A before construction

Water tank construction

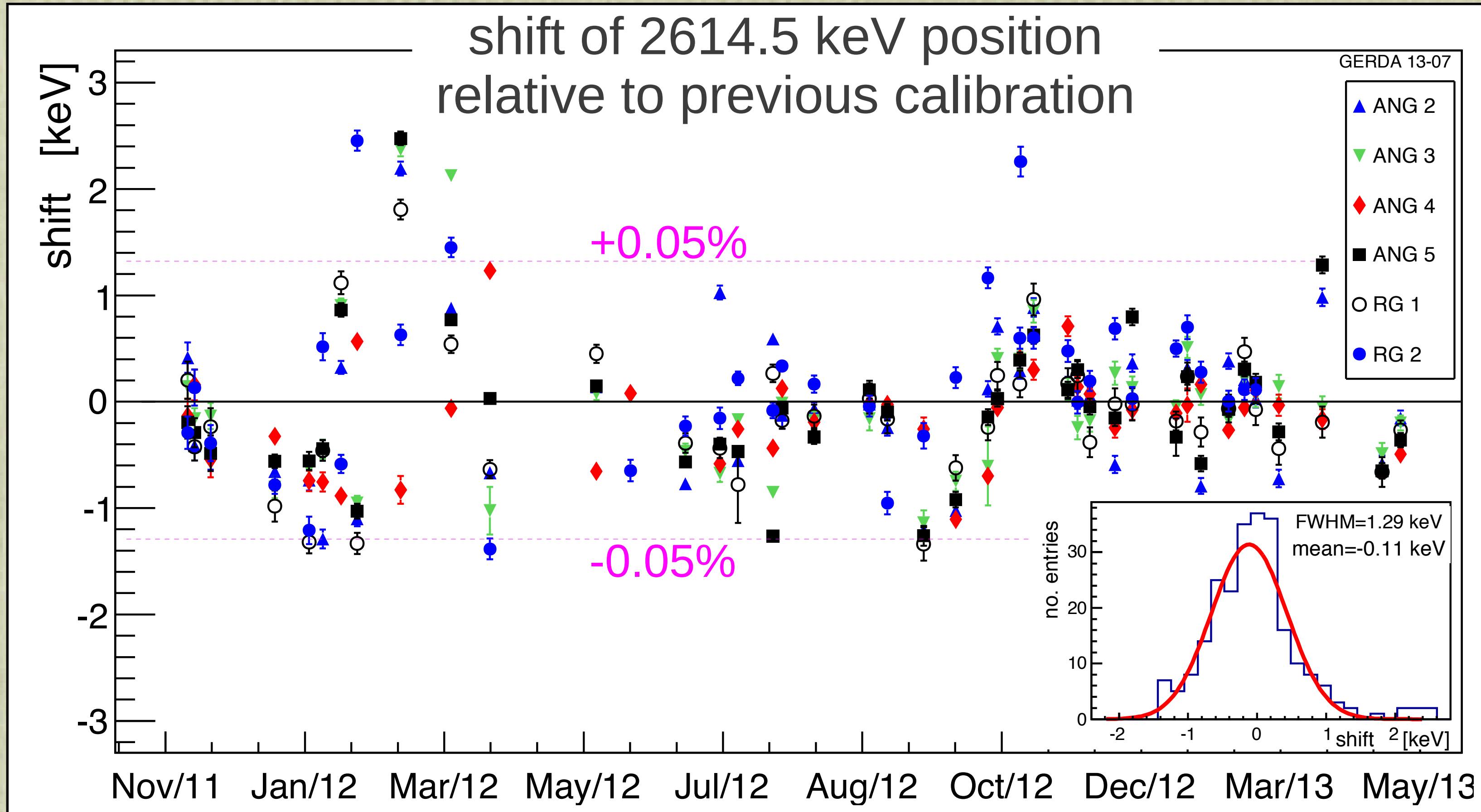
Hall A today

The cryostat

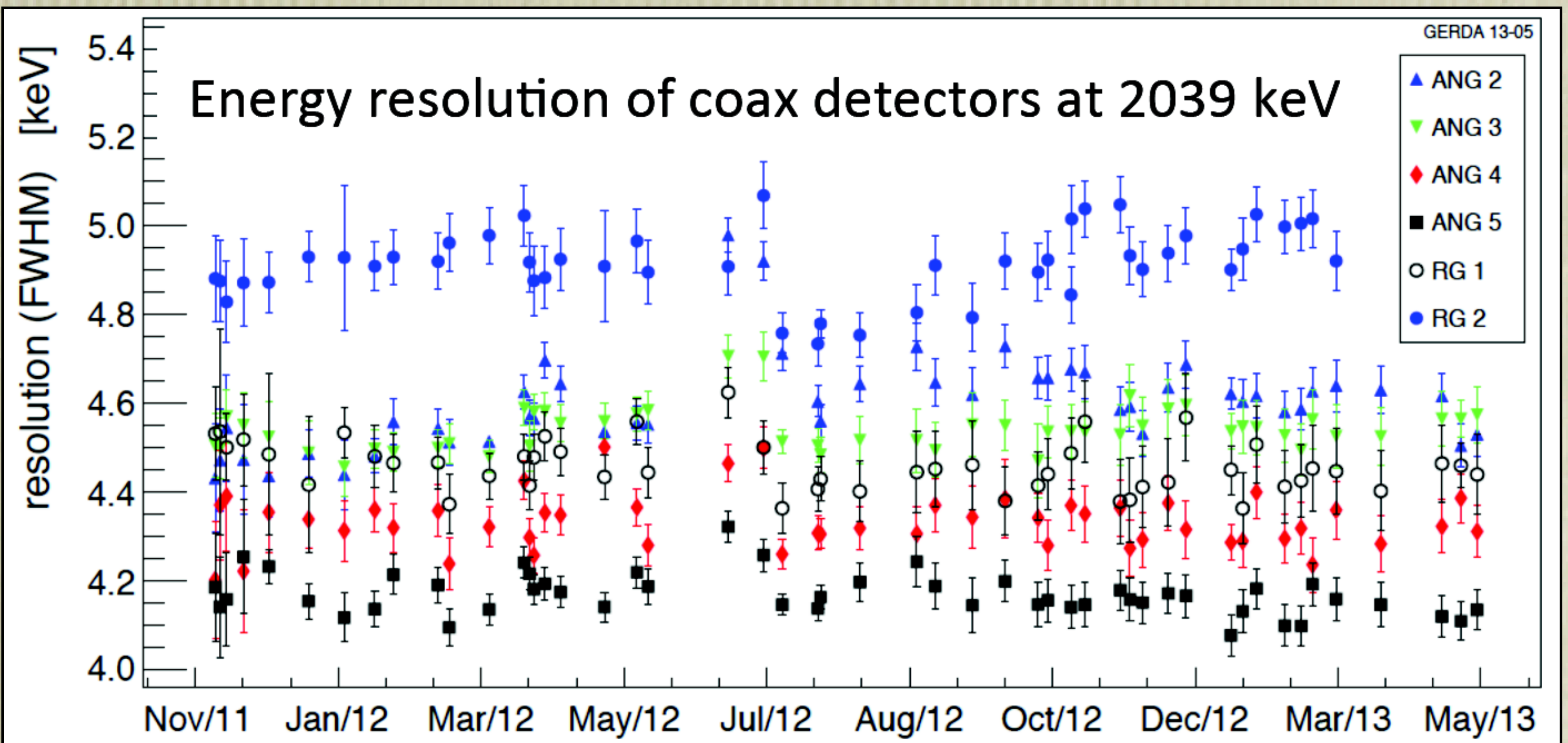
The muon veto

Official inauguration

Run Calibration and Stability



Shifts are small compared to FWHM at Q_{bb}



Detector calibration with

- 3 ^{228}Th sources 1h per week
- 0.05 Hz pulser

- Energy shift usually <1 keV between calibrations
- Energy resolution stable

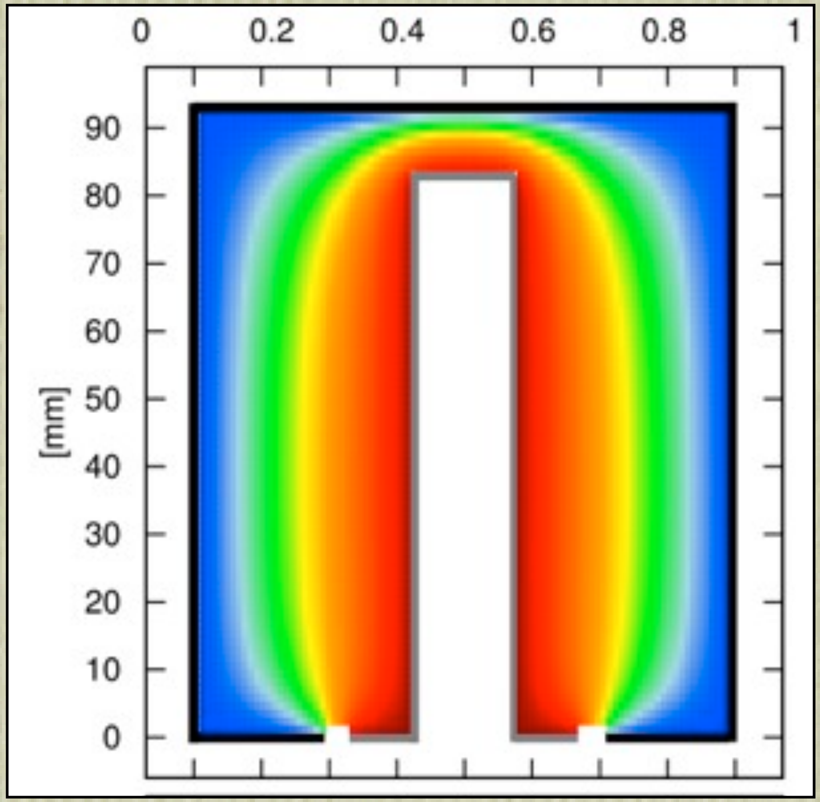
FWHM @ Q_{bb} (2039 keV):

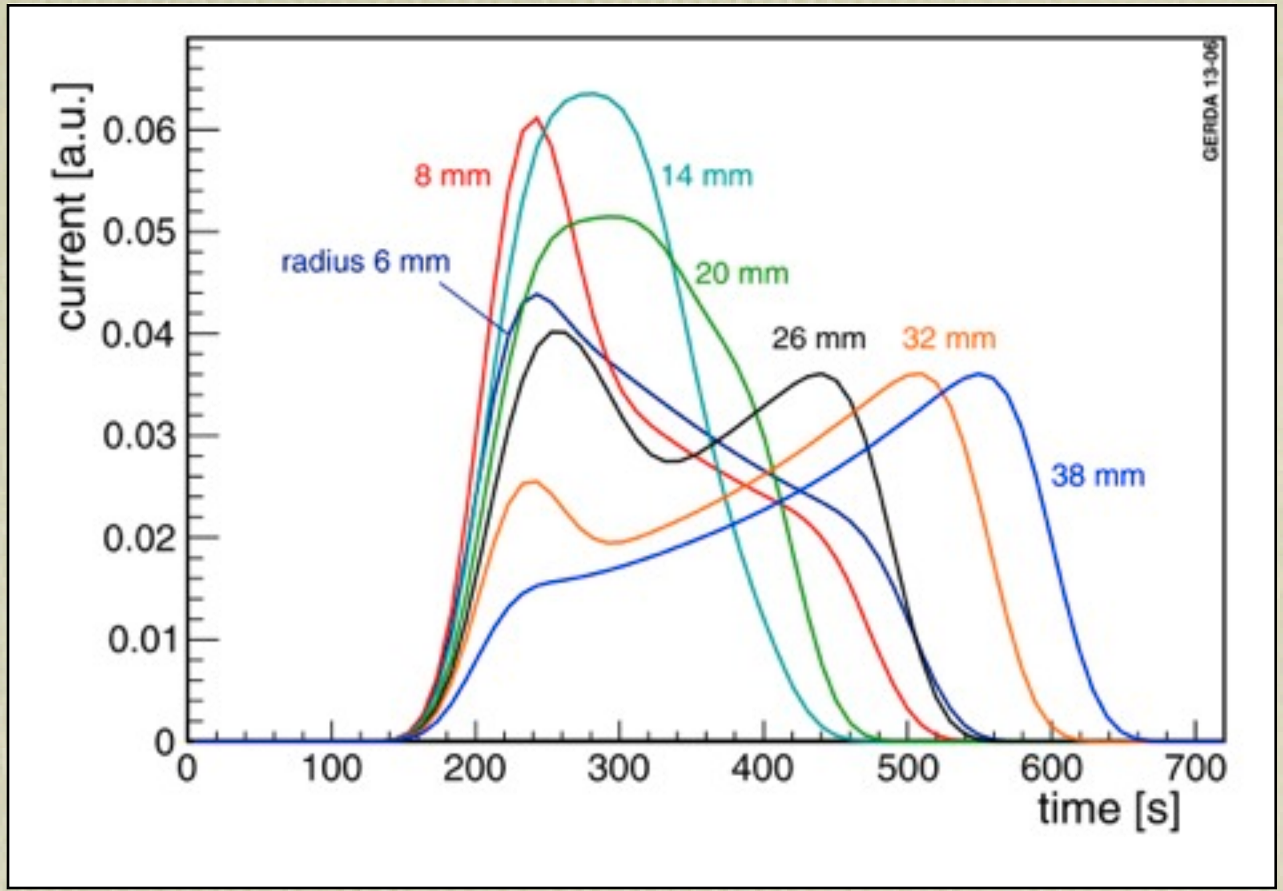
(exposure weighted average)

Coaxial: 4.8±0.2 keV (0.23 %)

BEGe: 3.2±0.2 keV (0.16 %)

Pulse Shape Discrimination: Coaxial Detectors



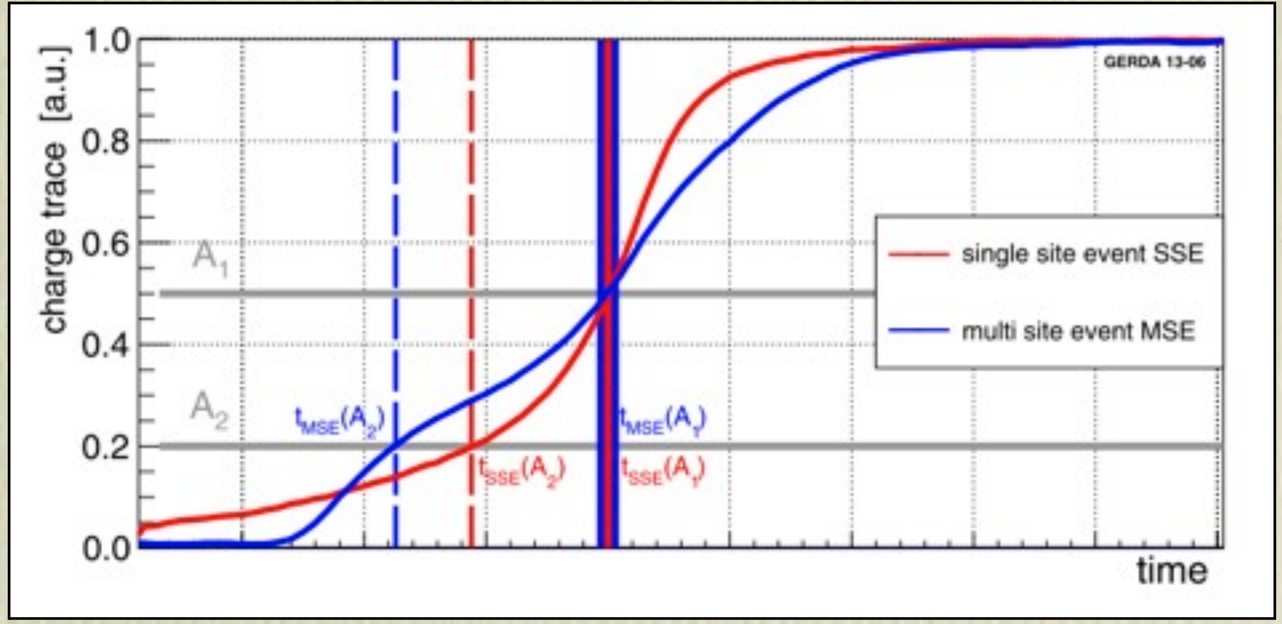


Pulse-shapes more complex in coaxial detectors. Three approaches:

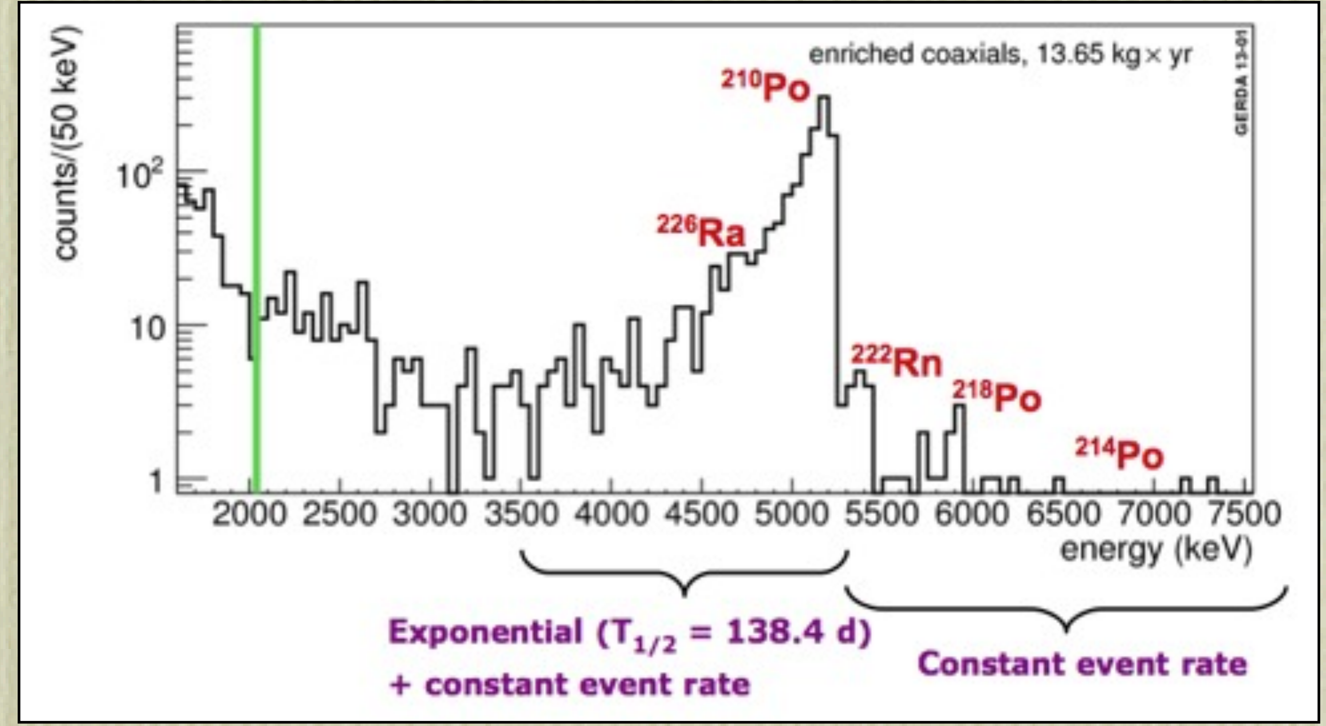
1. Artificial Neural Network (baseline method)

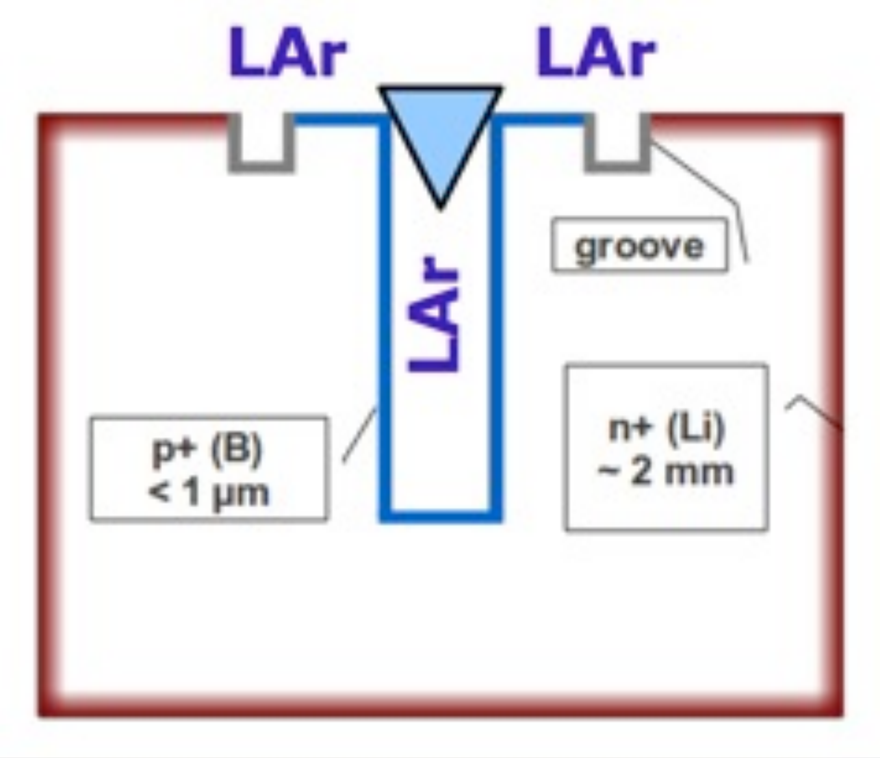
2. Likelihood analysis

3. Pulse asymmetry

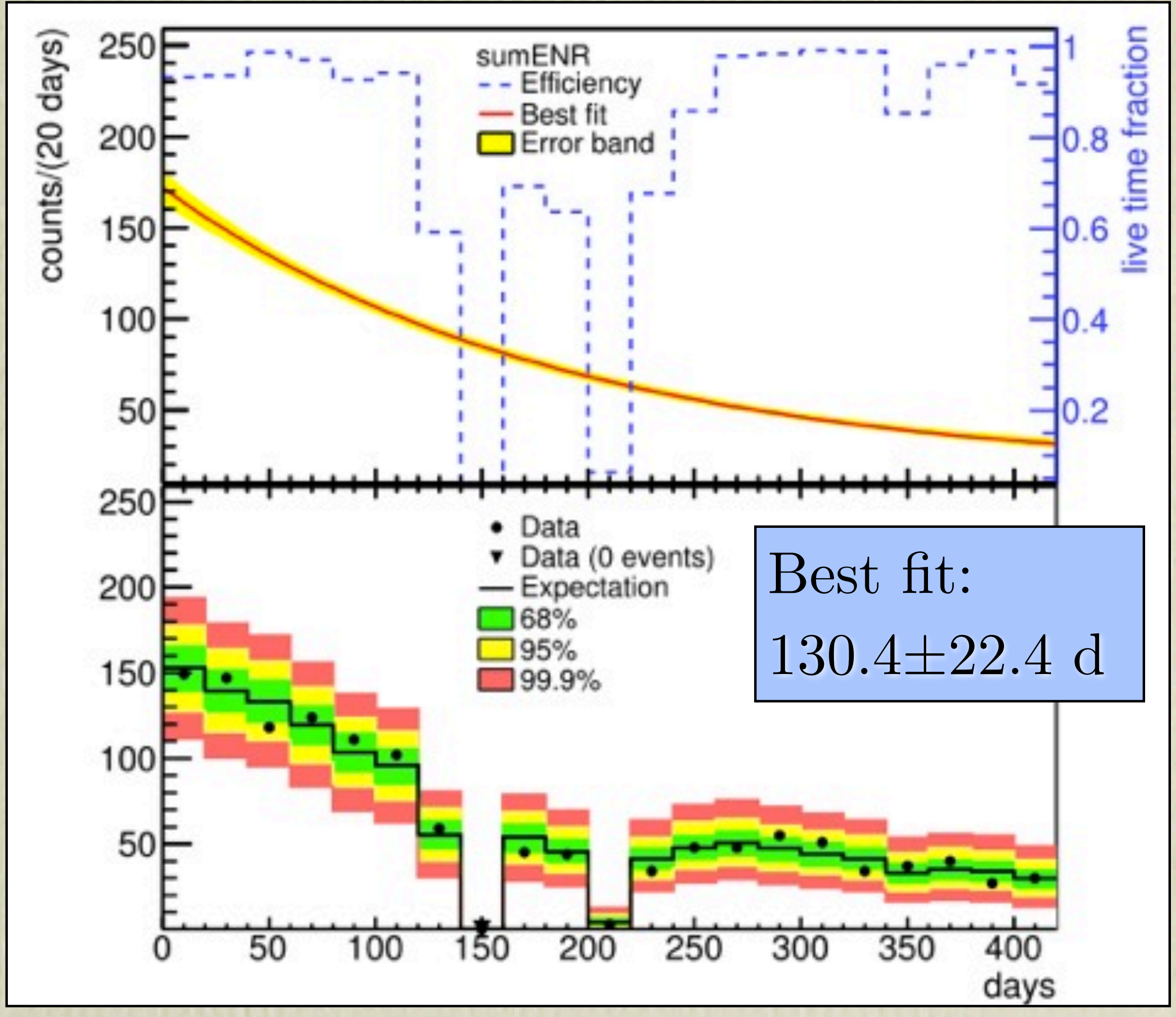


Alpha Background





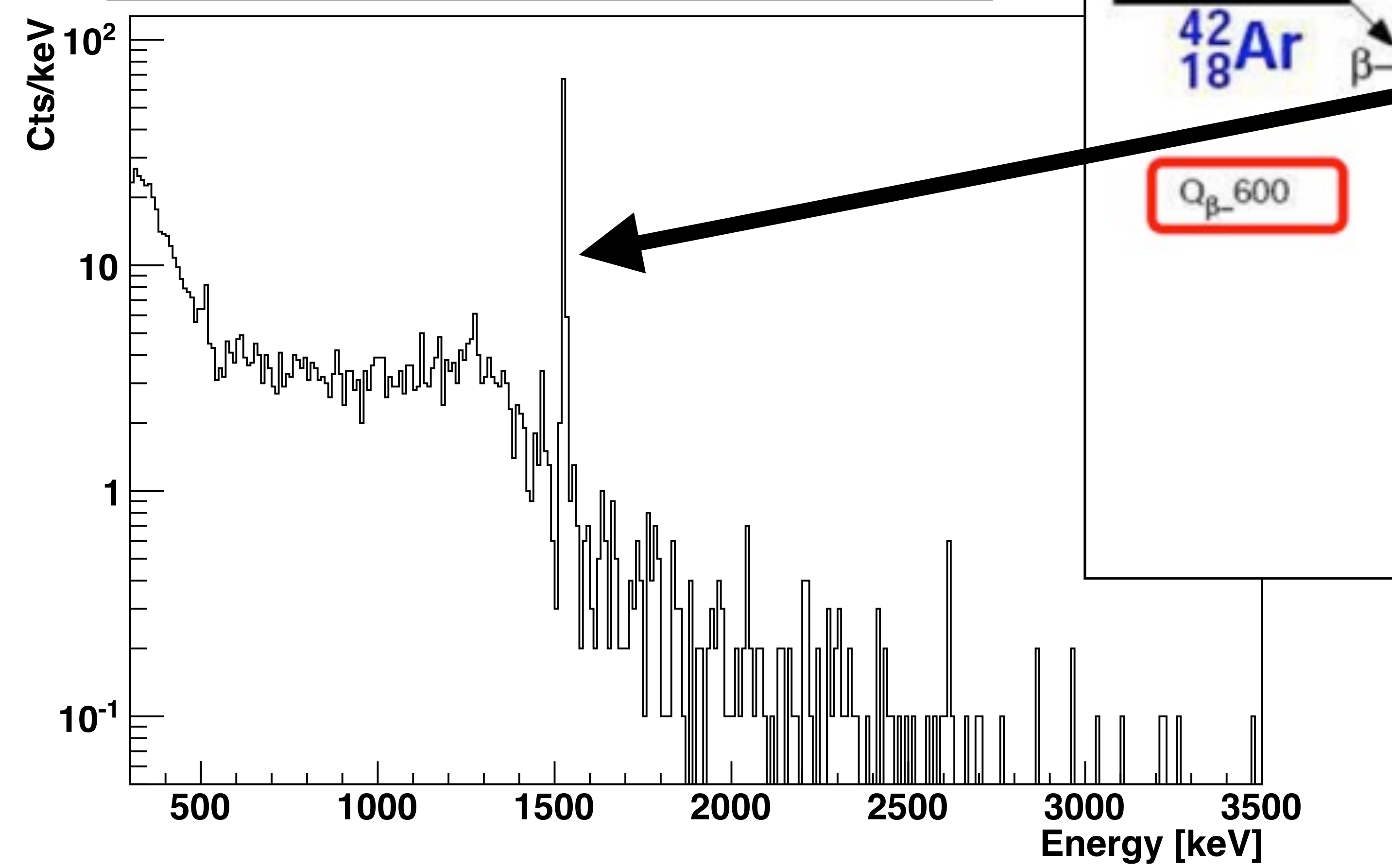
- Alpha decays close to thin p+ dead layer
- Low energy tail contributes to background in Q_{bb}
- Rate decays in agreement with ^{210}Po $T_{1/2}$ (138.4 d)

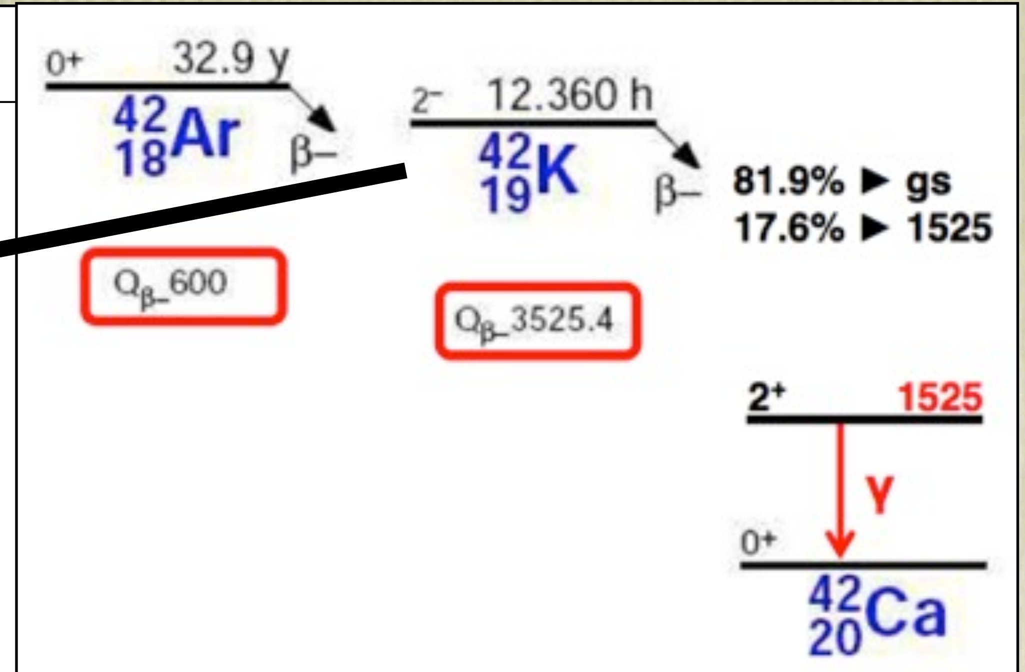


Best fit:
130.4±22.4 d

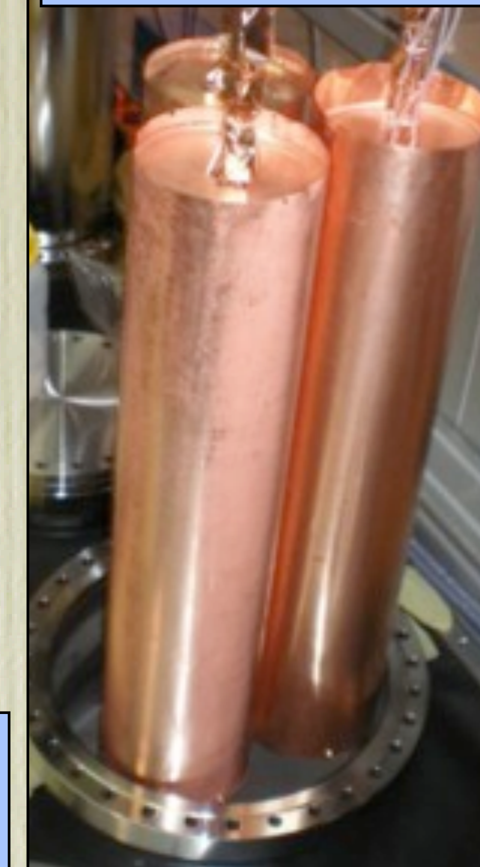
Commissioning: First Data (16/07/2010)

very early GERDA spectrum



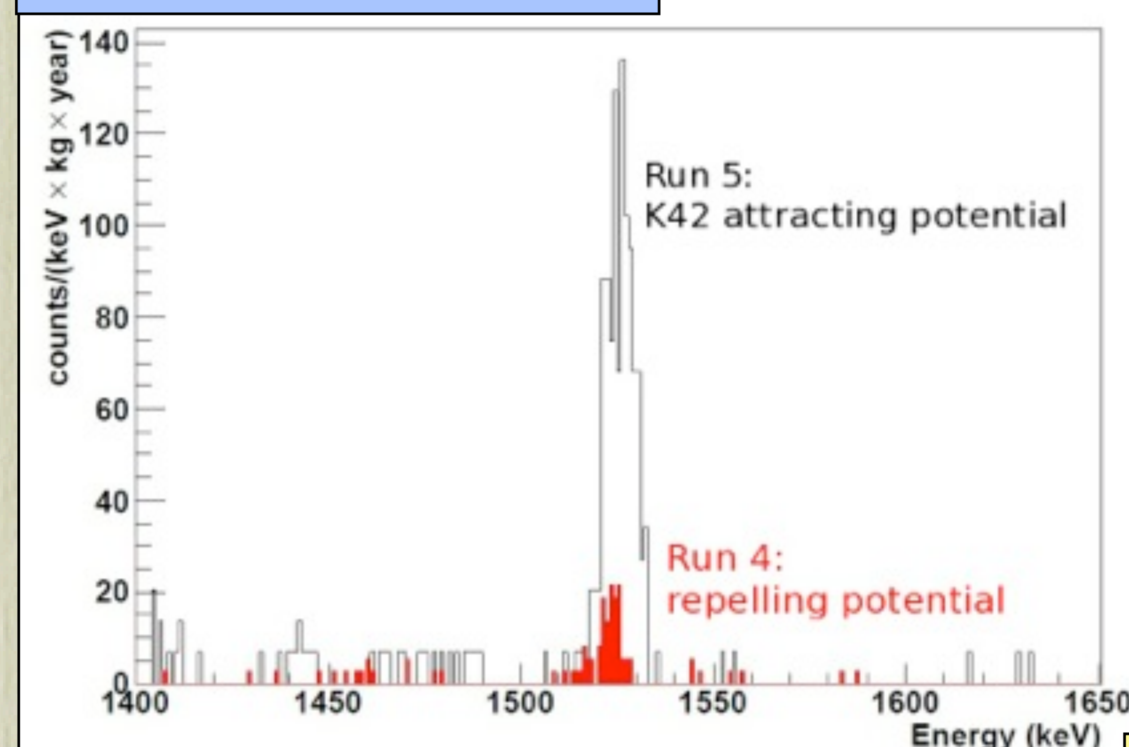


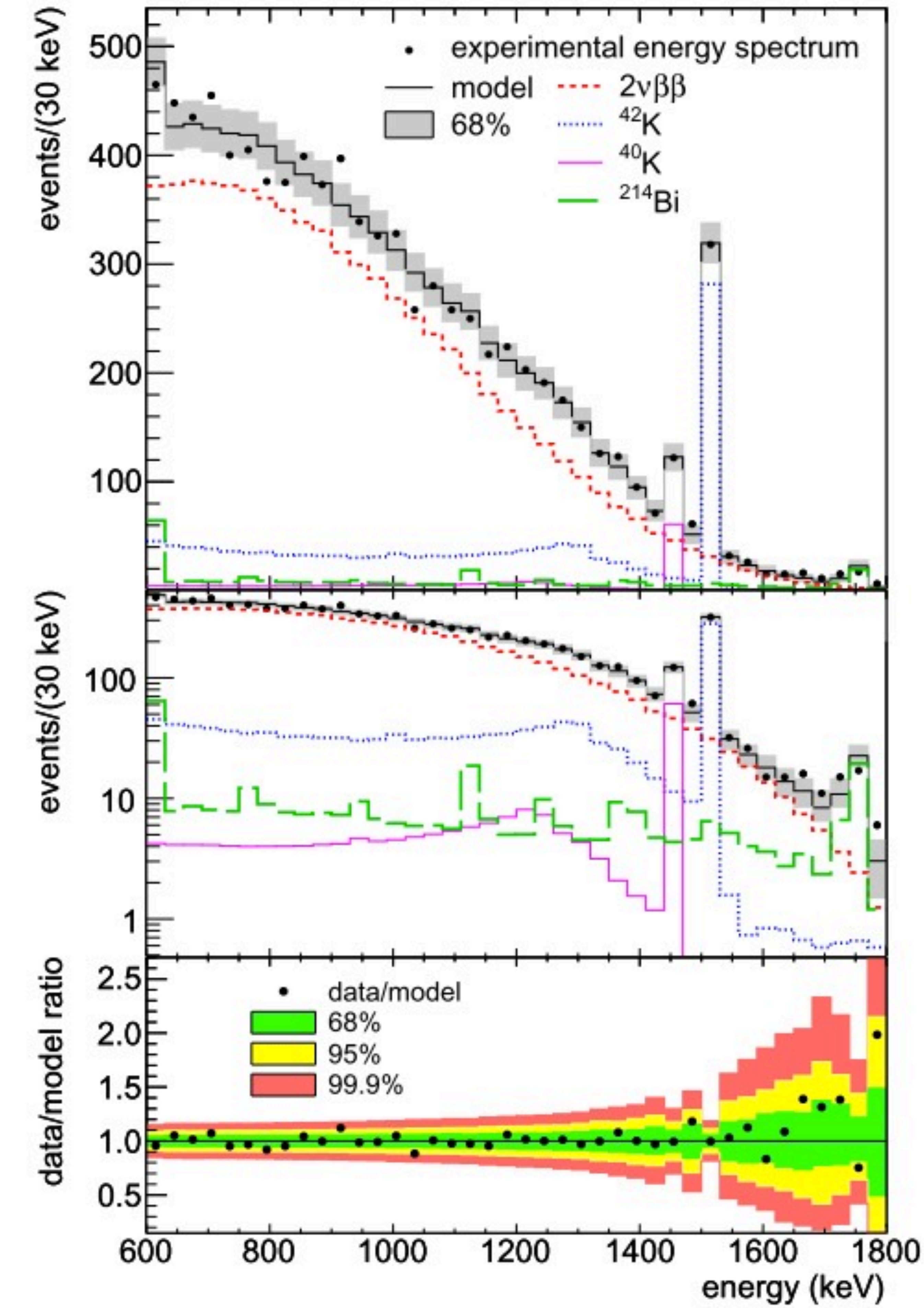
Mini-shrouds (MS)



- Larger ^{42}Ar contribution than expected
- 1.5 years of commissioning to understand and mitigate ^{42}K background
- Conclusion:
  - ^{42}K is charged and attracted by HV
  - Installation of mini-shroud in Phase I

Test with HV potentials on MS





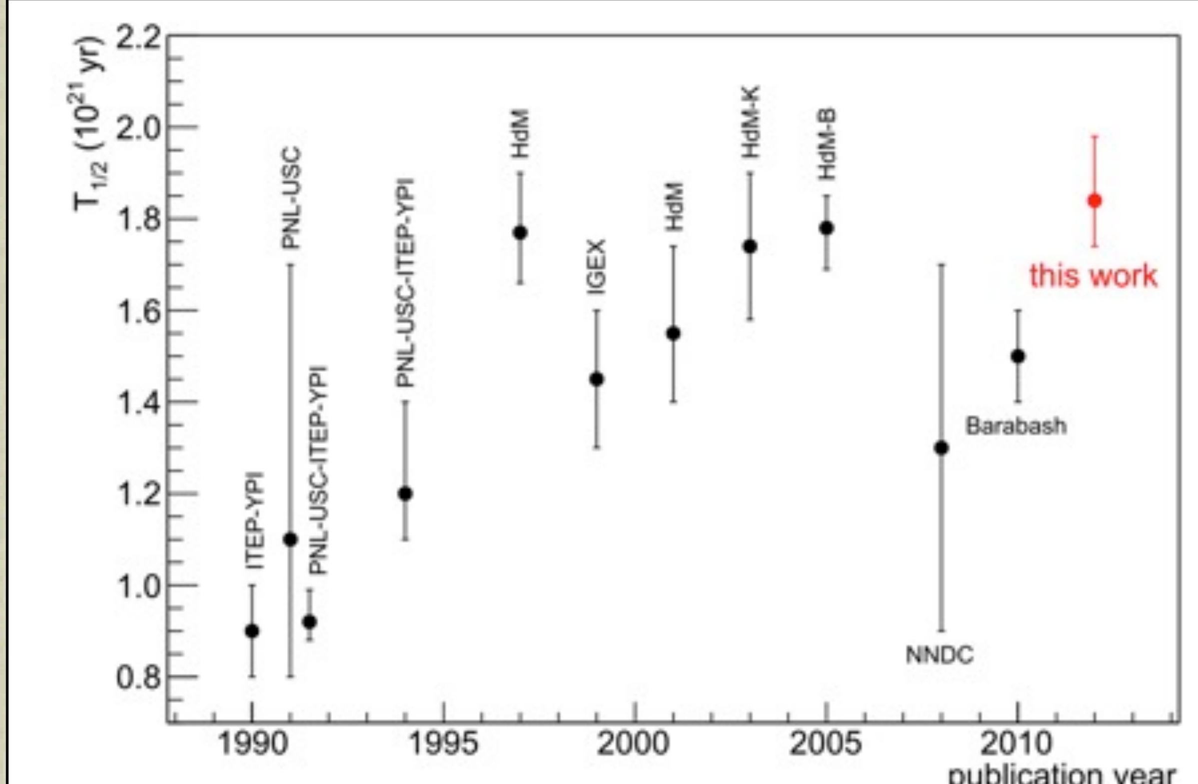
2νββ Measurement

J.Phys.G 40 (2013) 035110

- Binned ML fit with 32 parameters (Bayesian analysis)
- 5.04 kg yr exposure: 7030 2νββ events
- Larger than previous S/B ratio: 4:1

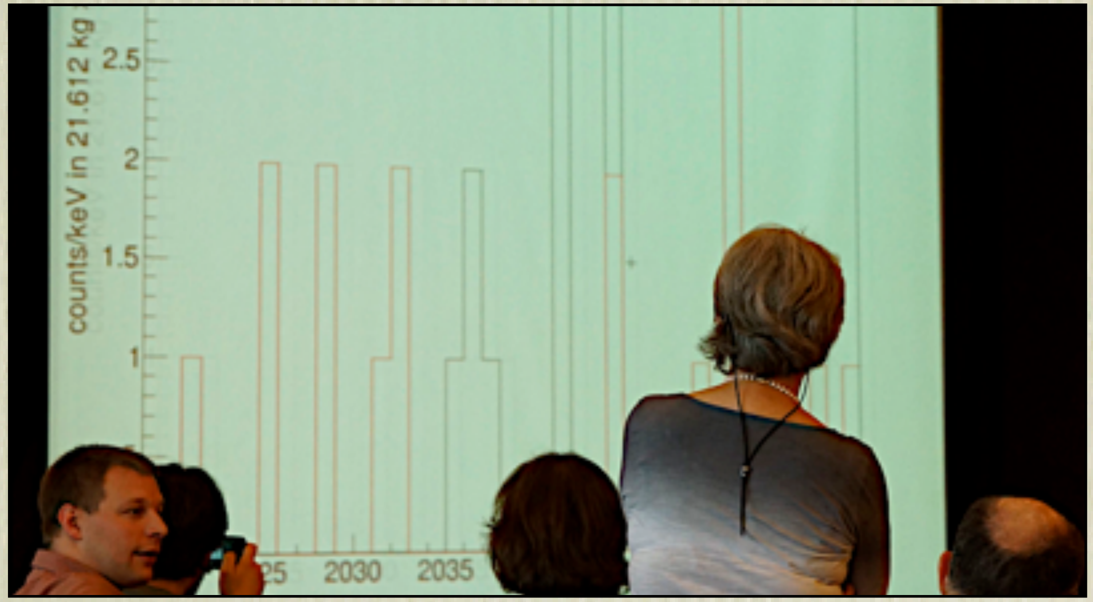
GERDA Result

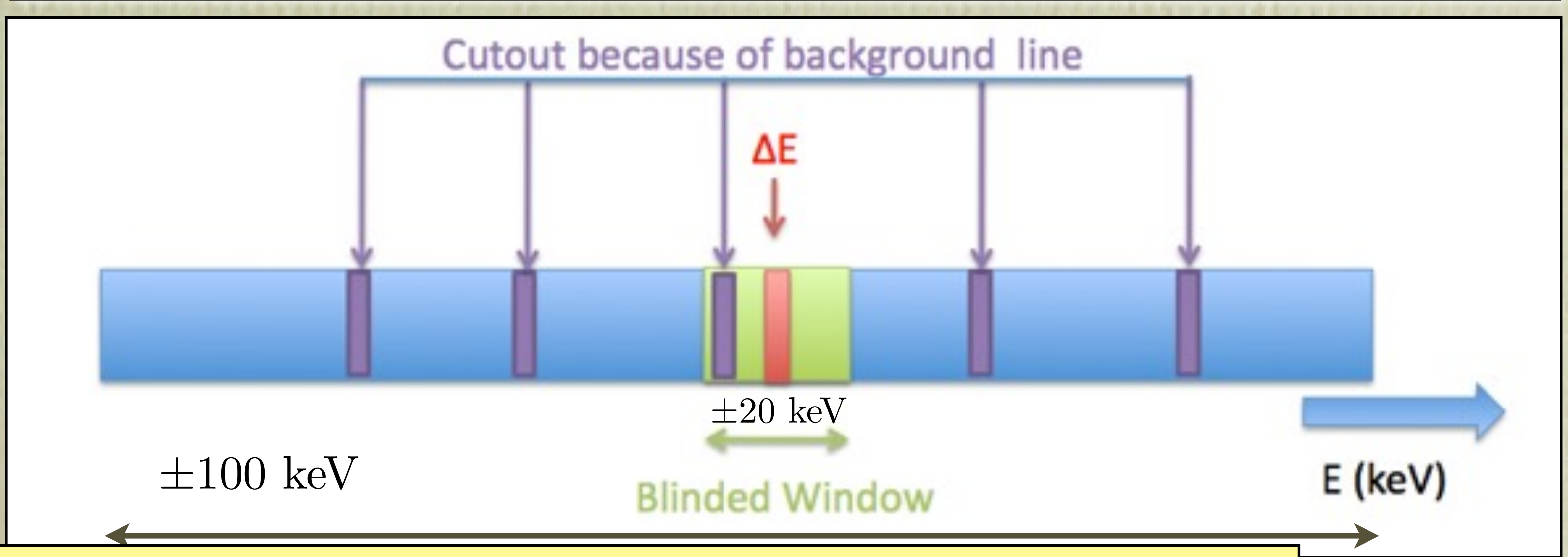
$$T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08}\,\mathrm{fit}\ {}^{+0.11}_{-0.06}\,\mathrm{syst}\right) \cdot 10^{21}\,\mathrm{yr}$$



Phase I: $0\nu\beta\beta$ Blind Analysis

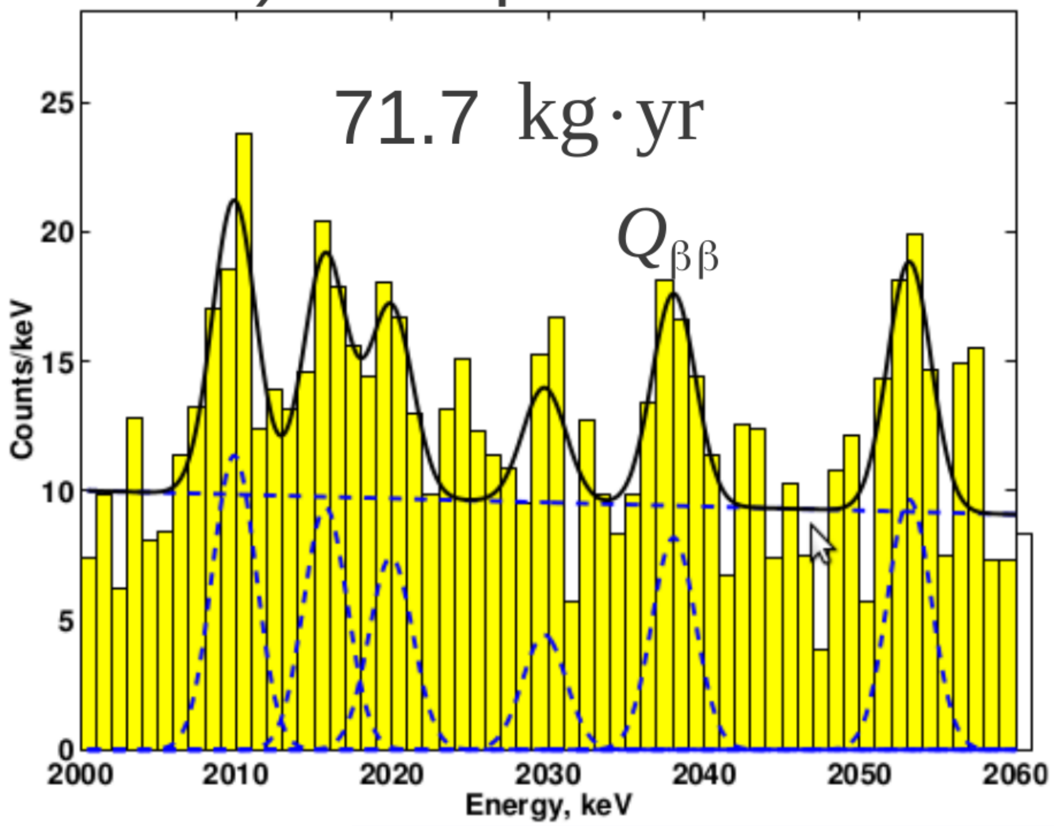
1. Data after Jan 2012 was blinded in ±20 keV around $Q_{\beta\beta}$
   - Avoid tuning the analysis towards signal or no-signal outcome
2. All data processing, quality cuts and statistical analysis methods were fixed
   - Paper with background model, pulse shape methods (including all analysis parameters) fixed prior to final unblinding
3. Final unblinding at GERDA Collaboration meeting June 2013 in Dubna





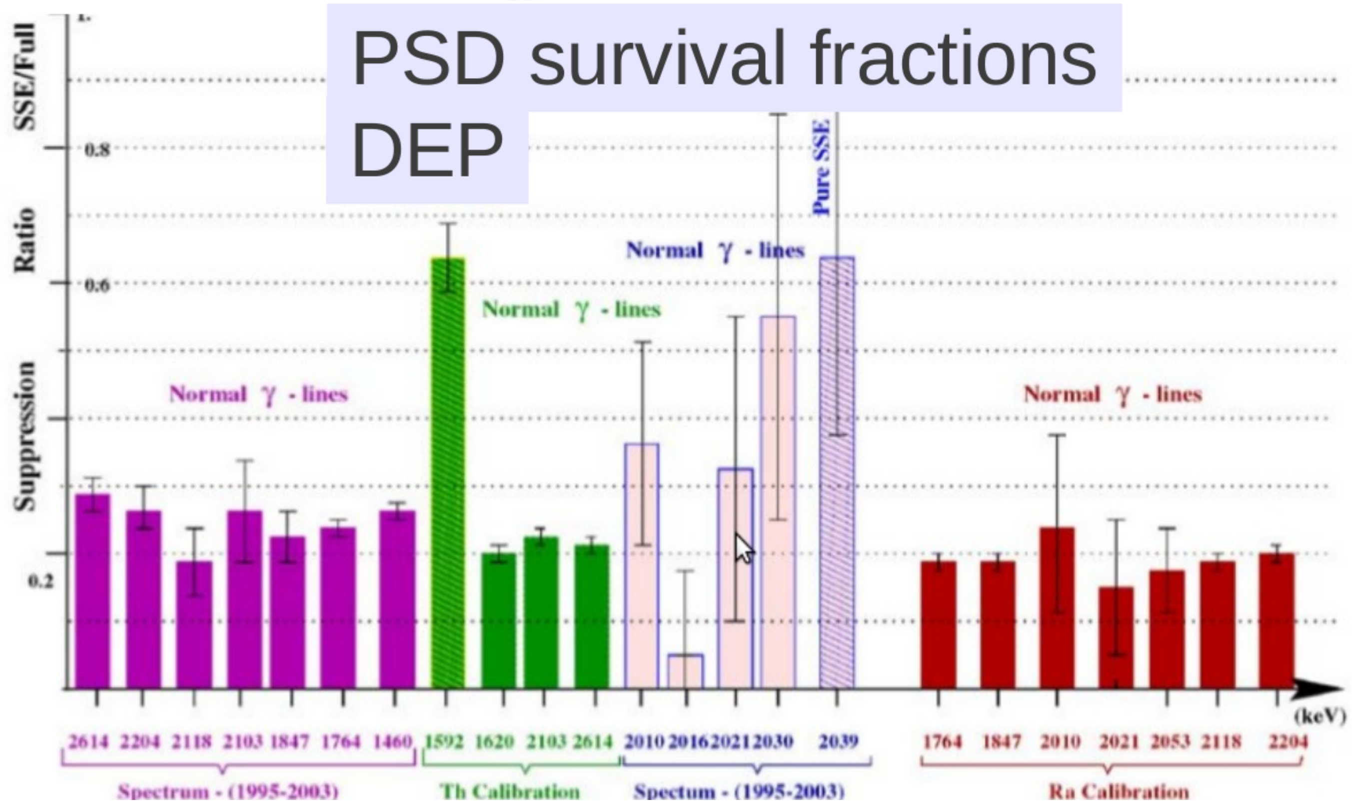
Why not compare to Klapdor 2006 Claim?

a) 2004 publications: NIM A522 371 & PL B586 198



entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events
$$T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right)\cdot 10^{25}\,\mathrm{yr}$$

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events
$$T^{0\nu}_{1/2} = \left(1.25^{+0.49}_{-0.27}\right)\cdot 10^{25}\,\mathrm{yr}$$



PSD survival fractions
DEP

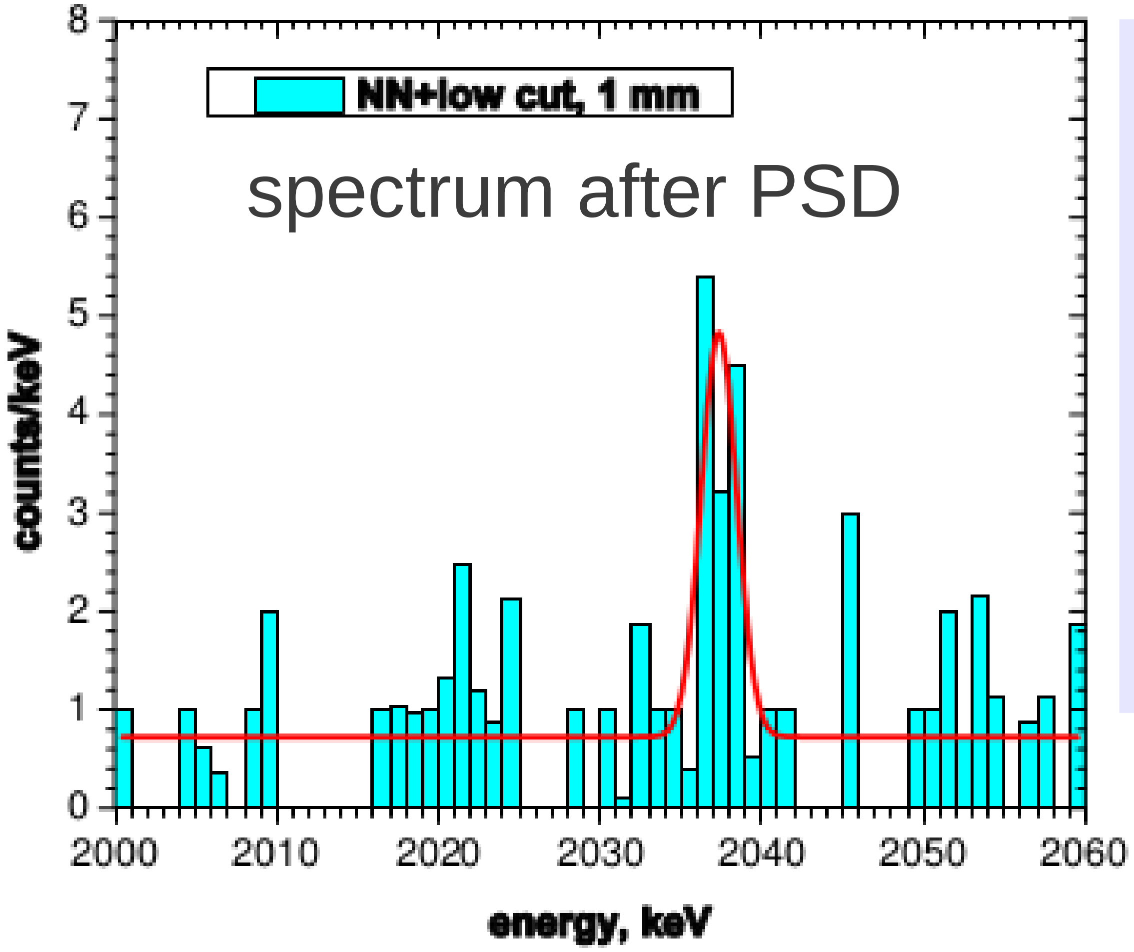
with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%
$\rightarrow \quad T^{0\nu}_{1/2} = 1.23\cdot 10^{25}\,\mathrm{yr}$

Without efficiency correction:
$$T^{0\nu}_{1/2} = 1.98\cdot 10^{25}\,\mathrm{yr}$$

No efficiency correction is applied in any publication!

Why not compare to Klapdor 2006 Claim?

b) 2006 publication: Mod Phys Lett A21 p. 1547-1566



fit gives 11.32±1.75 signal events

$\rightarrow T_{1/2}^{0\nu} = \left(2.23^{+0.44}_{-0.31}\right) \cdot 10^{25}$ yr

error on signal count not correct since smaller than Poisson error

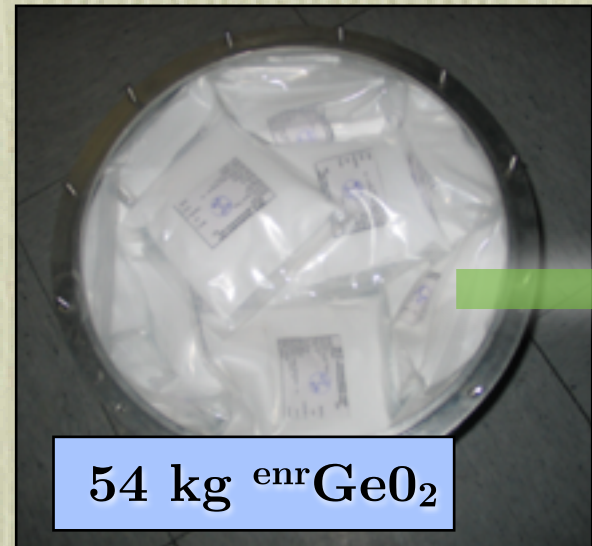
PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses:
Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks

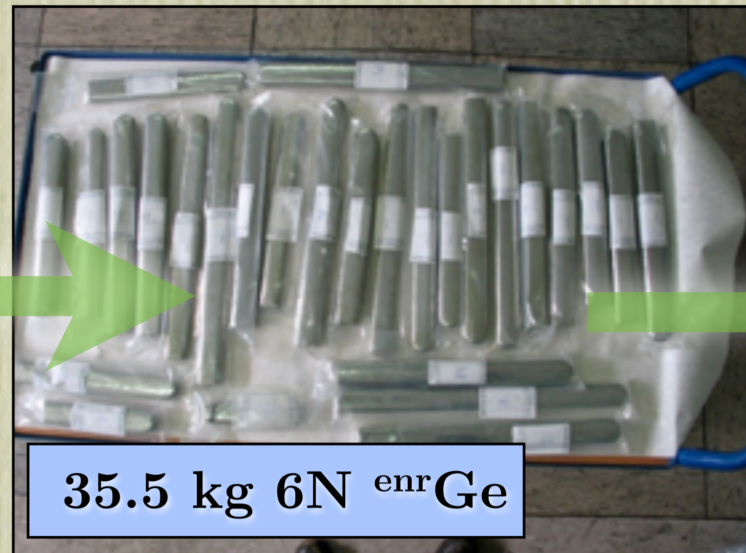
NO event overlap between the 2 sets!?

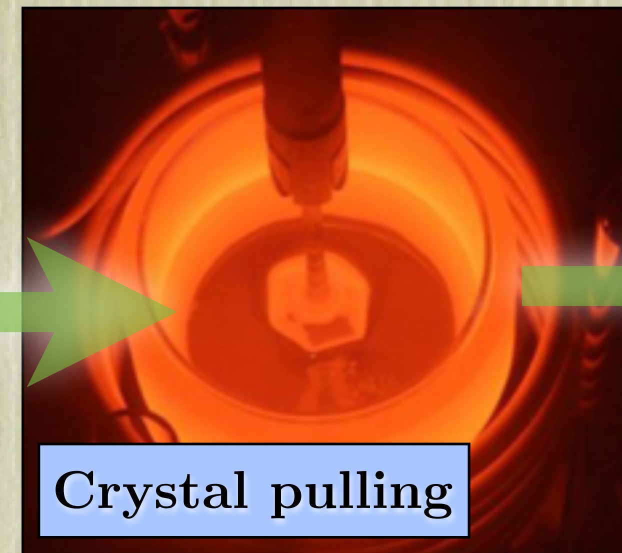
statement of publication:
- "multi site events are suppressed by 100%",
– $0\nu\beta\beta$ efficiency = 1 used for $T_{1/2}^{0\nu}$

efficiency factor not considered
→ calculation of $T_{1/2}^{0\nu}$ not correct
→ GERDA does not use this result

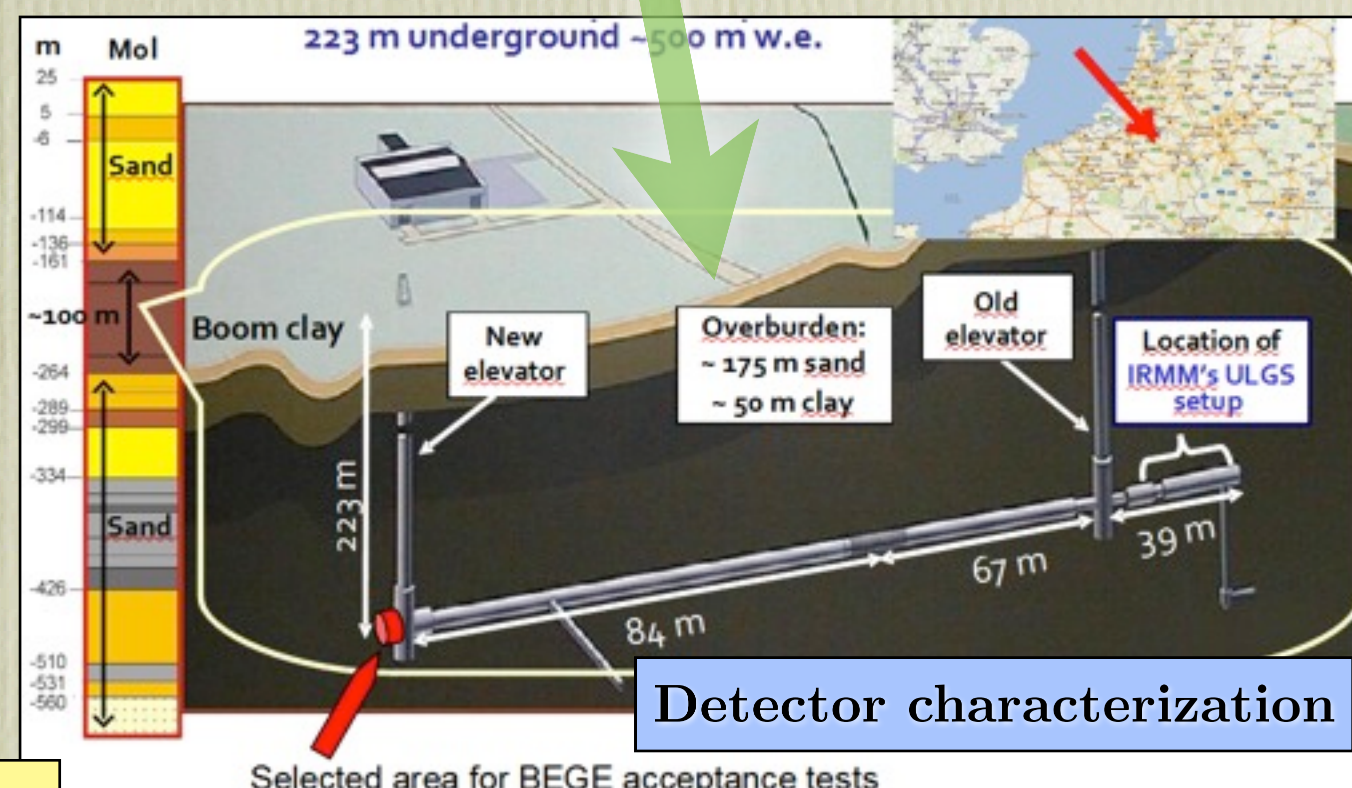
Phase II: BEGe Detectors







- Whole production chain from $^{enr}GeO_2$ to BEGe diode organized by GERDA and tested with ^{dep}Ge (JINST 8 P04018 2013)
- Total gain 30 BEGes with 20.5 kg (58 % yield)
- Detector characterization in HADES underground facility, Belgium
- Exposure to cosmic rays reduced as much as possible:
  - Transport in shielded container
  - Storage and testing underground

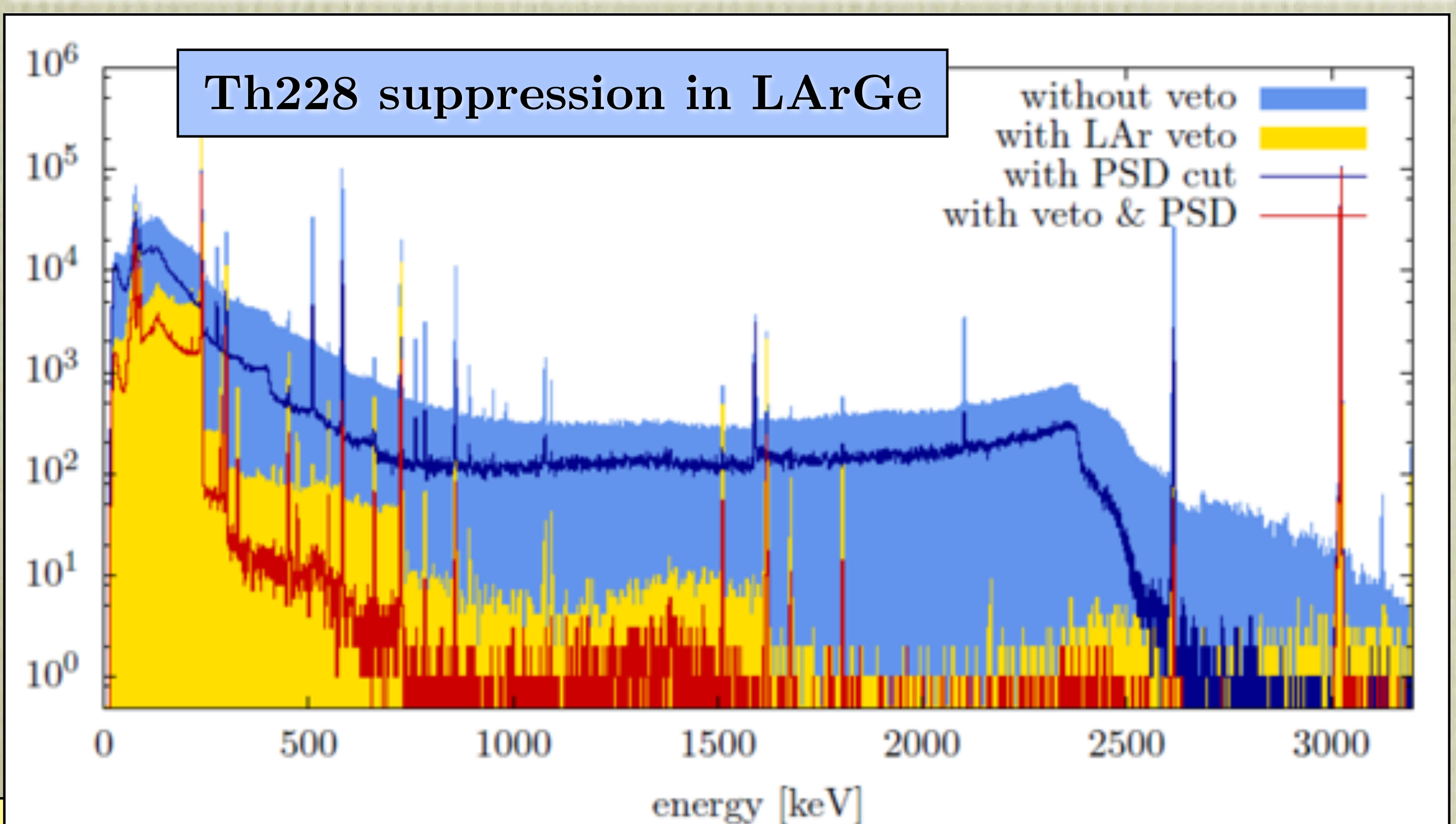


Phase II: BEGe Detector Transport

- Minimization of cosmic ray exposure
- Transport in 26t container shielded with steel and water
- Storage and testing underground

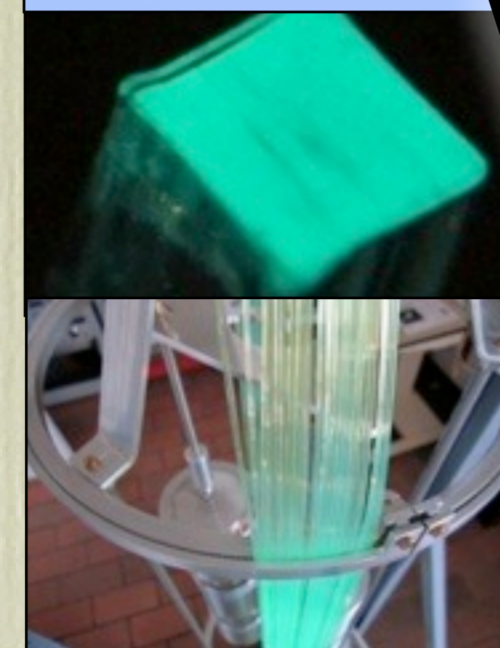
Phase II: LAr Scintillation Veto

- Experimental proof of principle in R&D facility LArGe (LNGS)
- Investigation of different design principles for GERDA with tuned MC simulations:
  - **PMT arrays** on top and bottom
  - **Fiber shroud** with SiPM readout
  - **SiPMs** inside mini shroud (if deployed)
- Combination of designs is favored

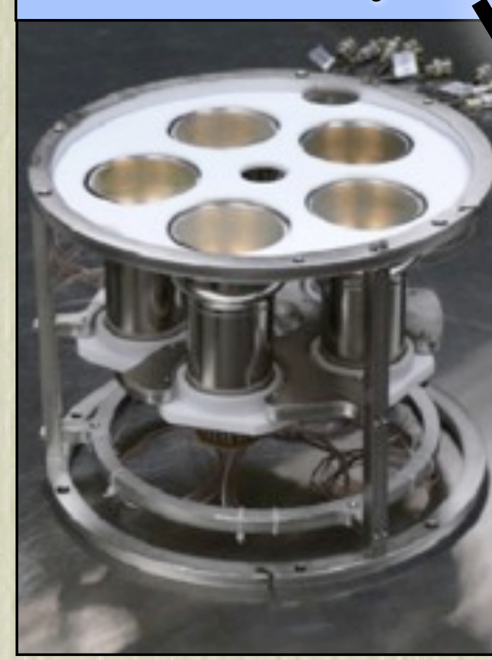


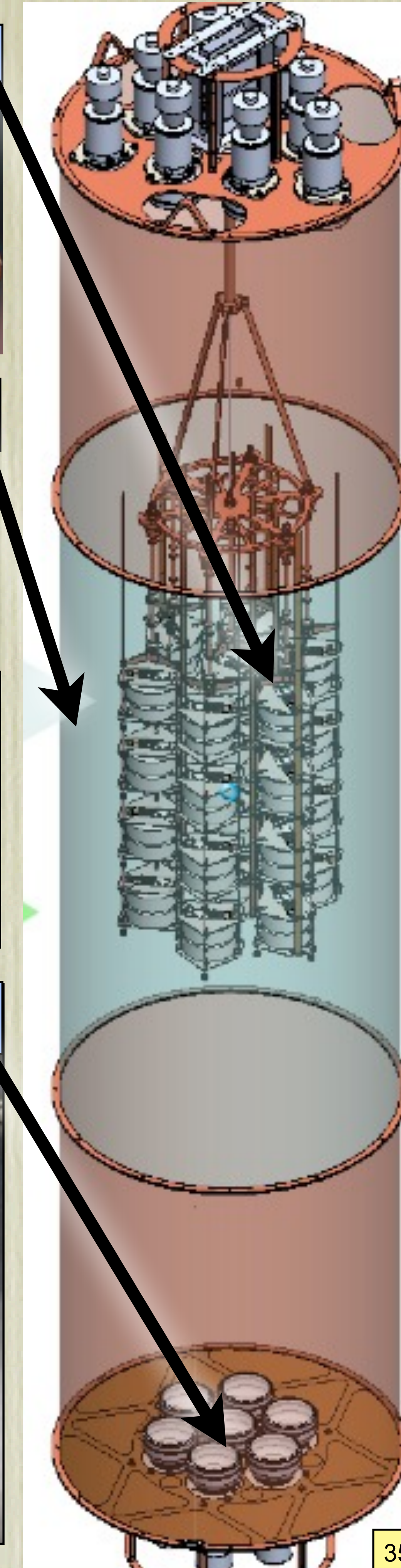
SiPMs

Optical fibers

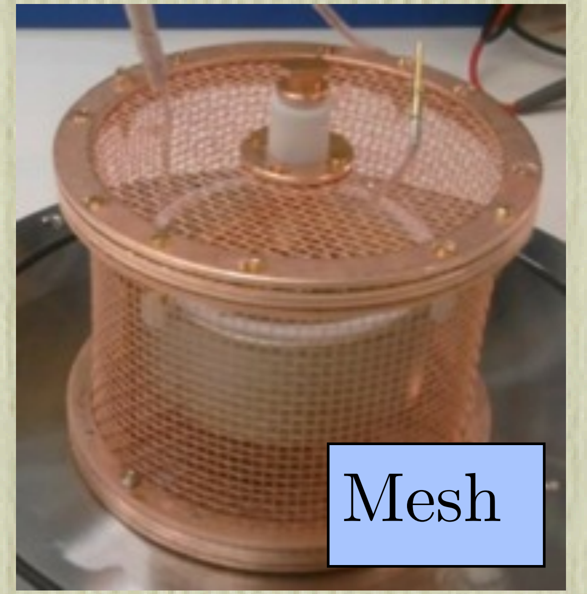


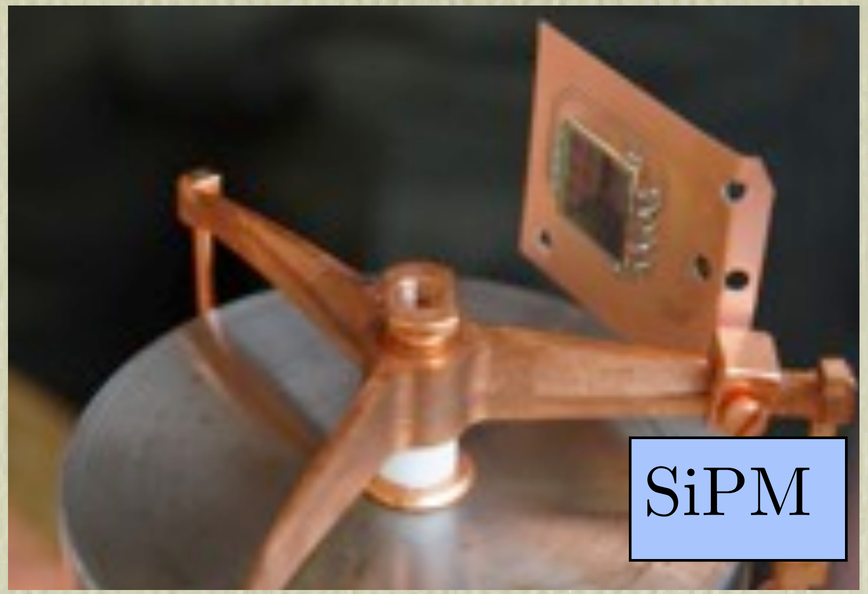
PMT arrays

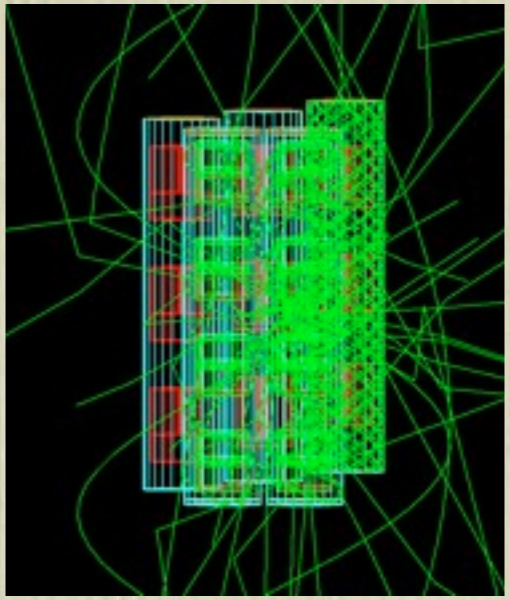




Mini Shroud (MS) Options for Phase II







Mini shroud advantages:

- Metal: Electric field
- Transparent: Improved LAr veto
- Hermetic: Limits ^{42}K convection

Suppression factors from MC for nylon MS:

- >100 (^{208}Th Holders)
- ≈30 (^{241}Bi LAr), ≈10 (^{241}Bi Holders)
- ≈10 (^{42}K LAr), ≈1 (^{42}K Surface)

Investigated options

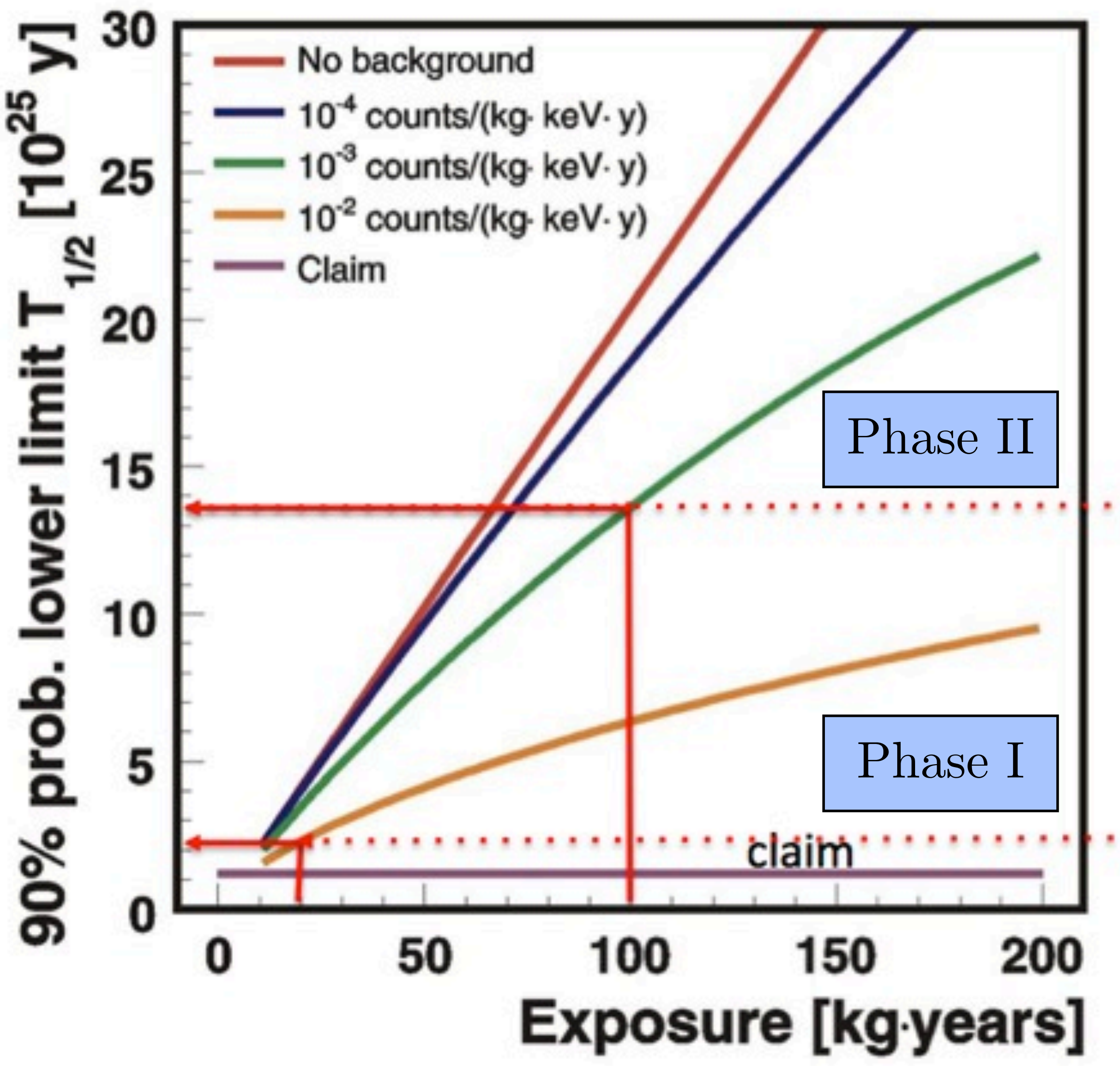
- Mesh MS
- Copper MS with SiPMs inside
- **Nylon MS**
- PE MS
- Mesh MS with readout

Outlook

Background expectations for Phase II

Background	without cuts (10^{-3} cts/(keV·kg·yr)	after PSD + Veto (10^{-3} cts/(keV·kg·yr)
^{228}Th (near)	≤ 5	≤ 0.01
^{228}Th (1m away)	<3	<0.01
^{228}Th (distant)	<3	<0.1
^{214}Bi (holder/MS)	≤ 5	≤ 0.13
^{214}Bi (near p^+)	<6	<0.03
^{214}Bi (n^+)	<7	<0.15
^{214}Bi (1m away)	<3	<0.08
^{60}Co (near)	1	0.001
^{60}Co (in Ge)	≤ 0.3	≤ 0.0004
^{68}Ga (in Ge)	≤ 2.3	≤ 0.04
^{226}Ra (α near p^+)	1.5	<0.03
^{42}K (β on n^+)	~ 20	<0.86
unknown (n?)	?	?

Sensitivity



- PSD in BEGe + LAr instrumentation
- Background estimation from Phase I
- PSD suppression can be optimized with $0\nu\beta\beta$ efficiency