The GERDA Experiment and the Search for Neutrinoless Double Beta Decay

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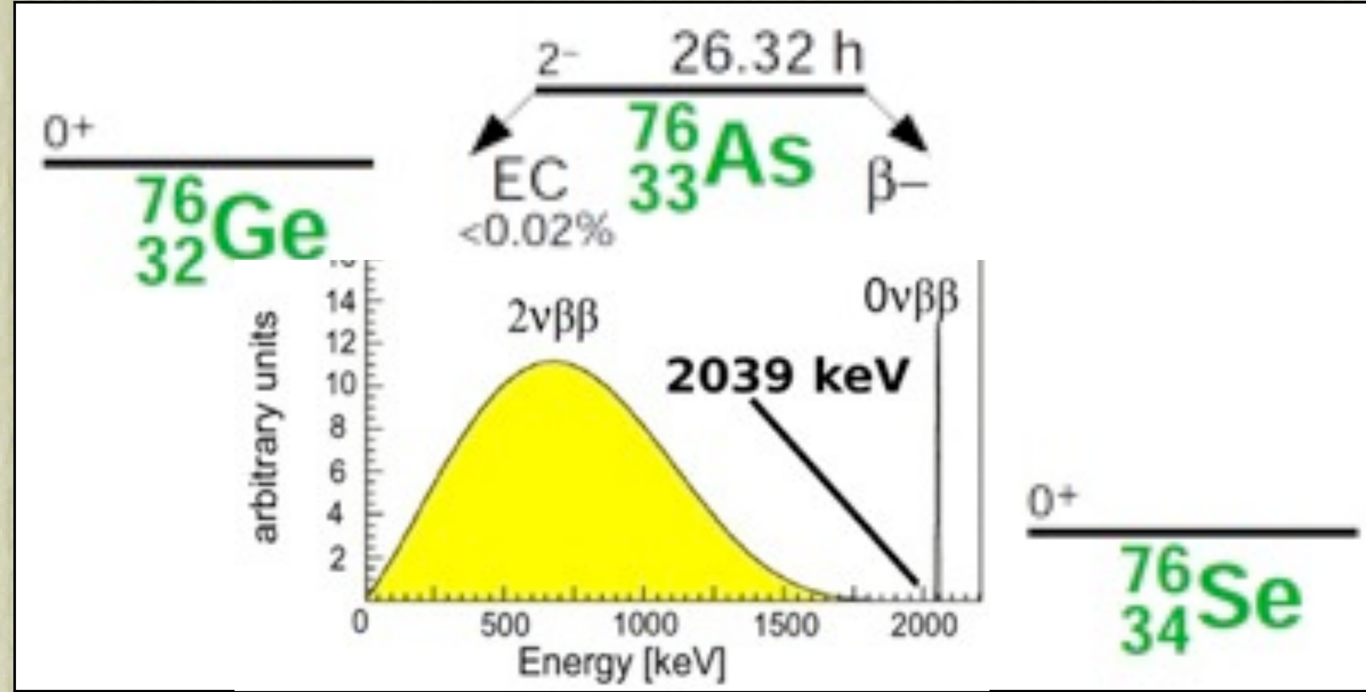
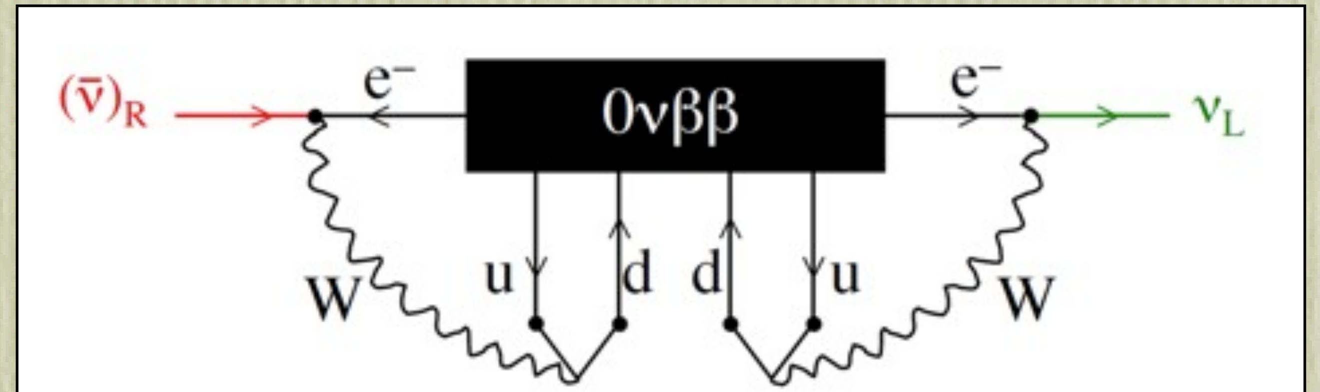
Double Beta Decay

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

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





B.Kayser ISAPP 11

Schechter-Valle theorem:

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

- Lepton number violation

Effective neutrino mass:

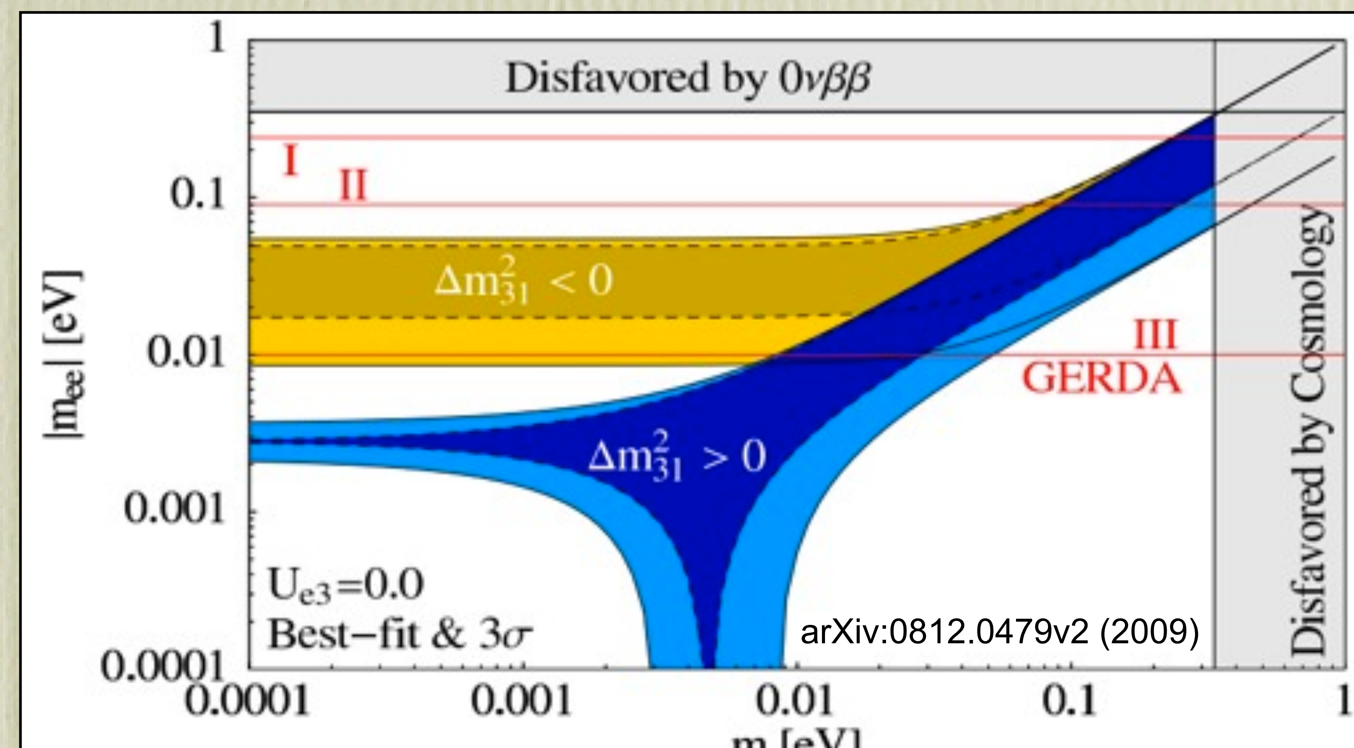
(only for dominant light Majorana neutrino exchange)

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

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

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

m_{ee} : effective neutrino mass



arXiv:0812.0479v2 (2009)

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

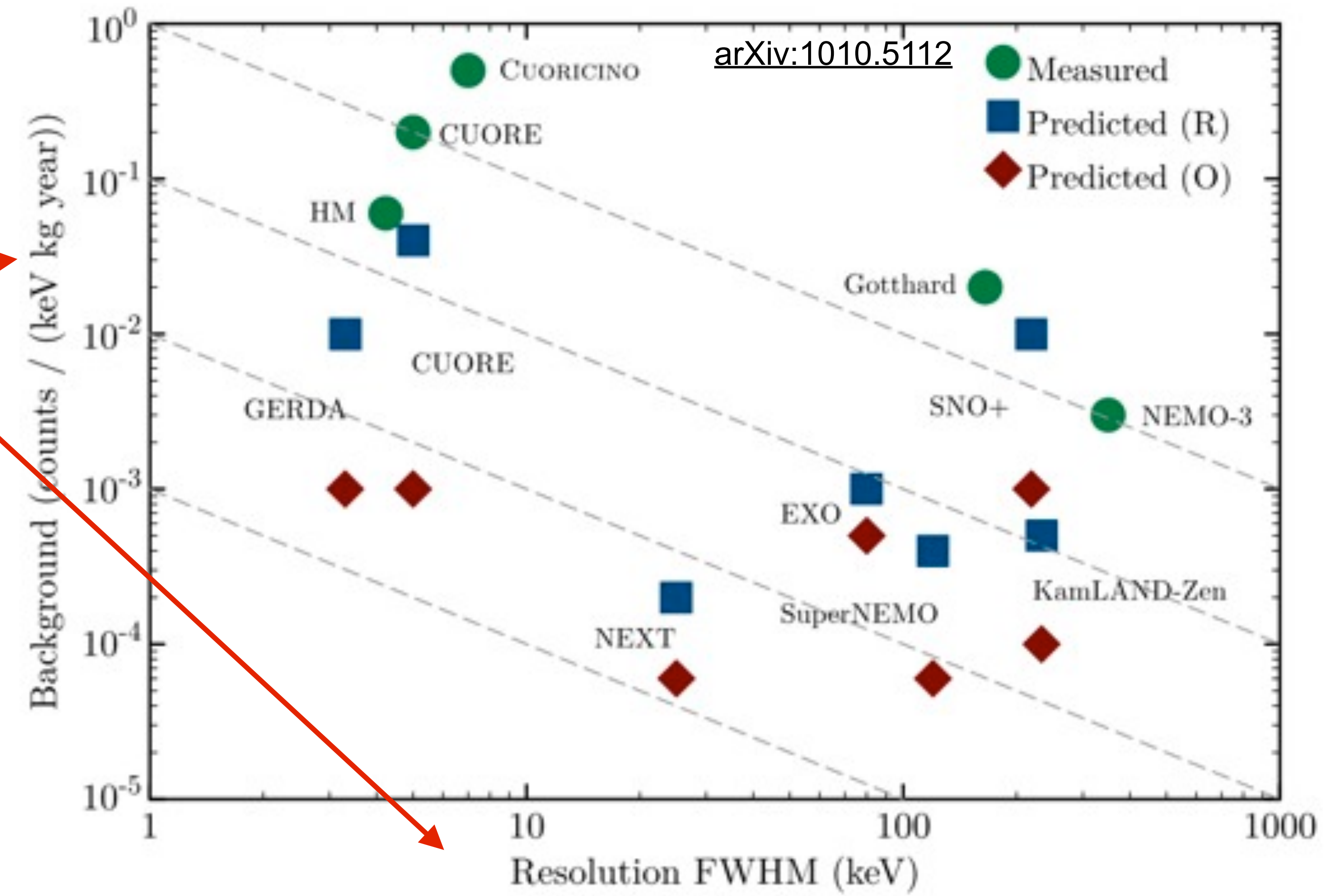
η : active volume fraction

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

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

- Best previous ^{76}Ge limits:

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

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

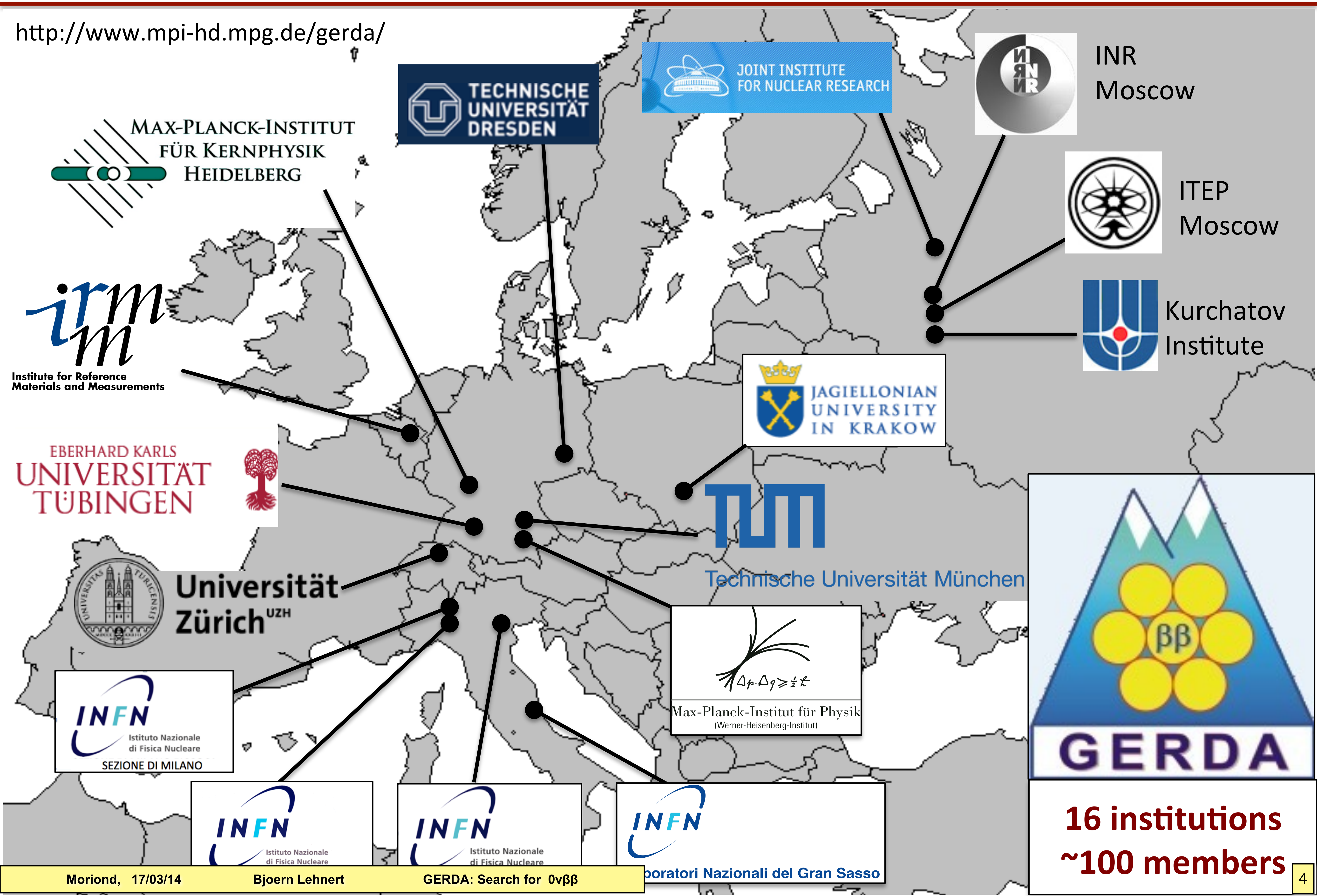
- Claim of observation of 0νββ in ^{76}Ge by subgroup of Heidelberg-Moscow experiment

Phys. Lett. B 586 (2004)

$$T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}\,\text{yr}$$

The GERDA Collaboration

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



16 institutions
~100 members

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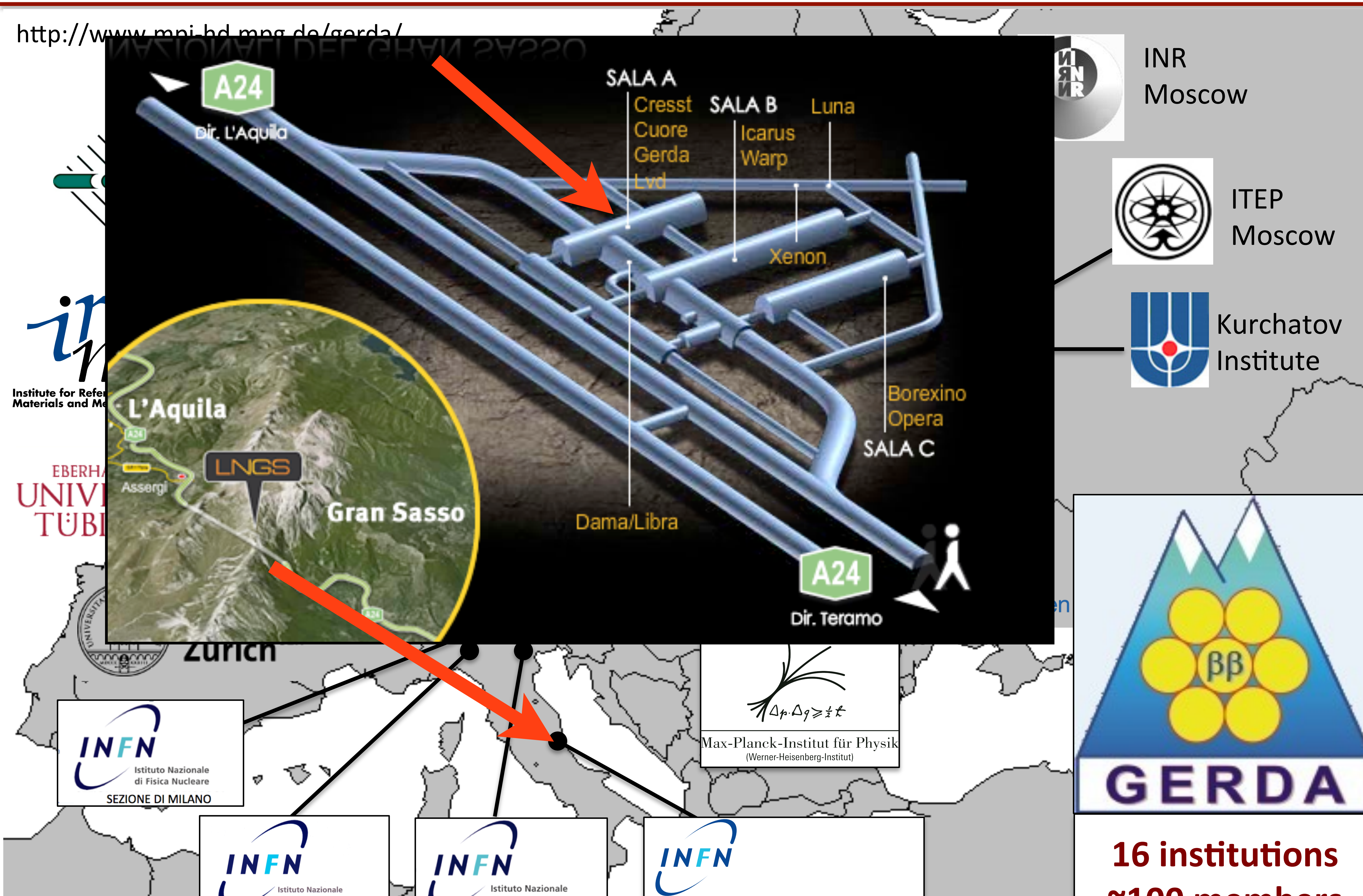

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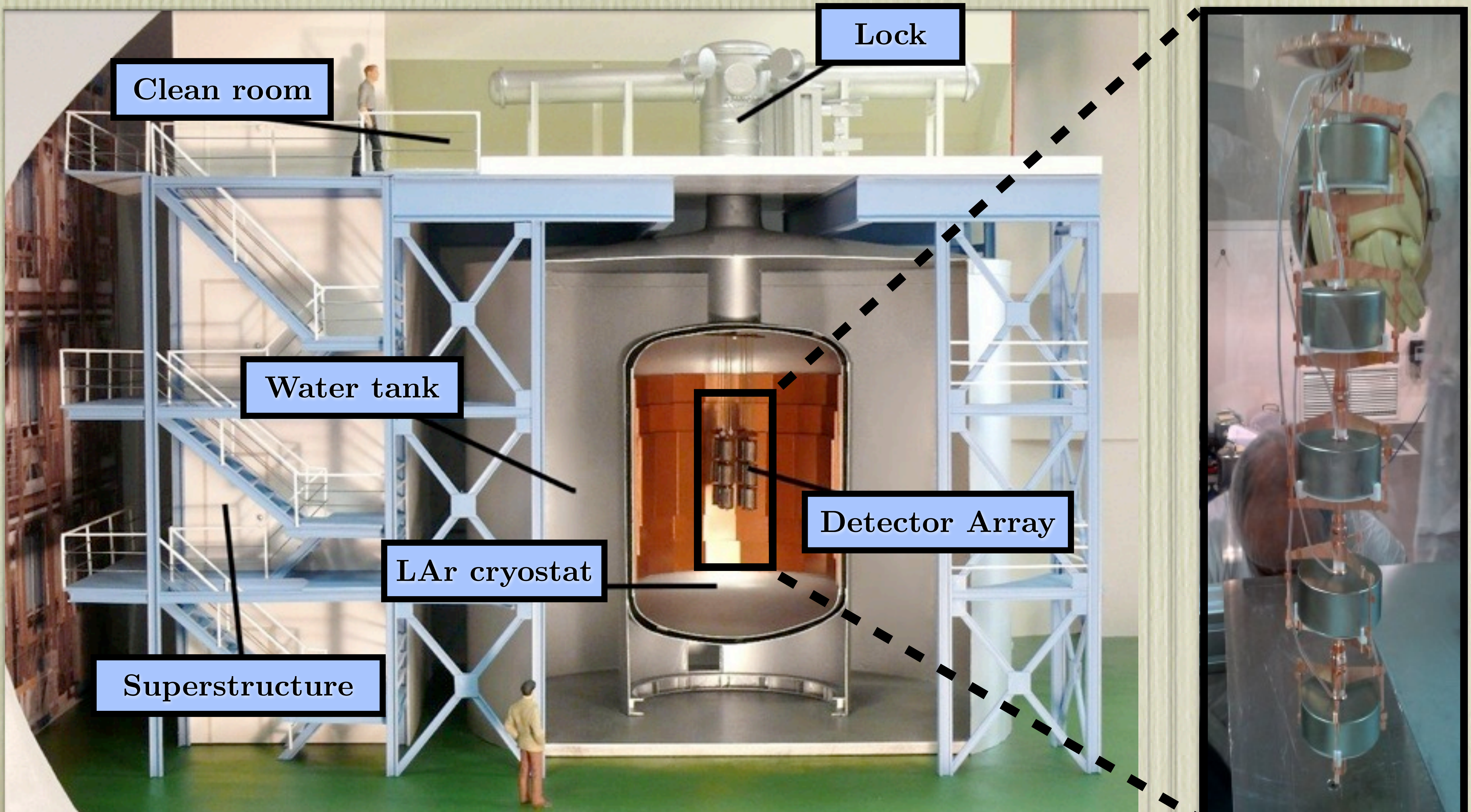
GERDA: GERmanium Detector Array

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

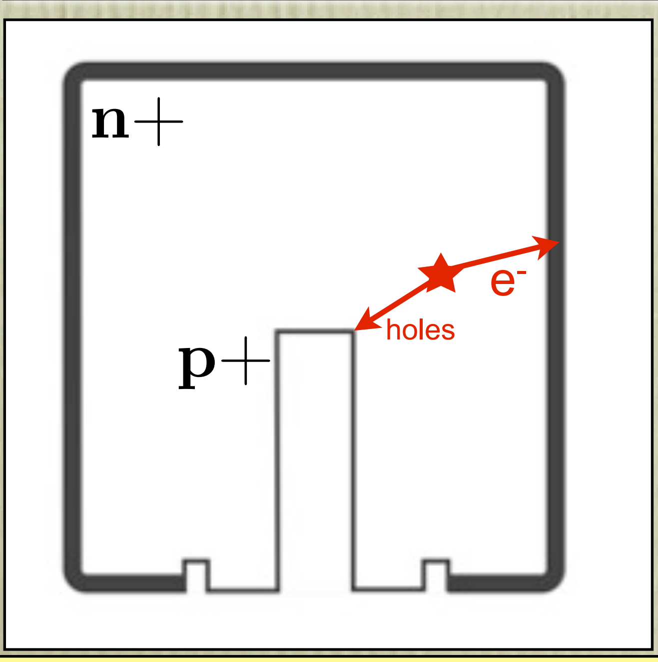
- Liquid argon serves as cooling, shielding and active veto



GERDA Physics Phases

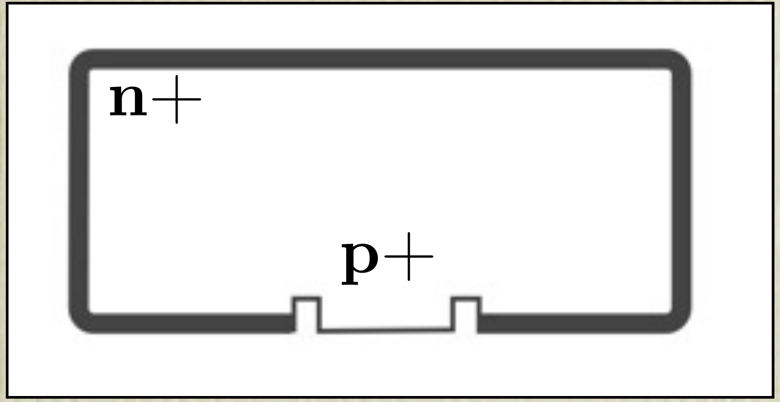
Phase I: Nov 12 - May 13

- 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
- Background: 10^{-2} cts/(keV kg yr)
- 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



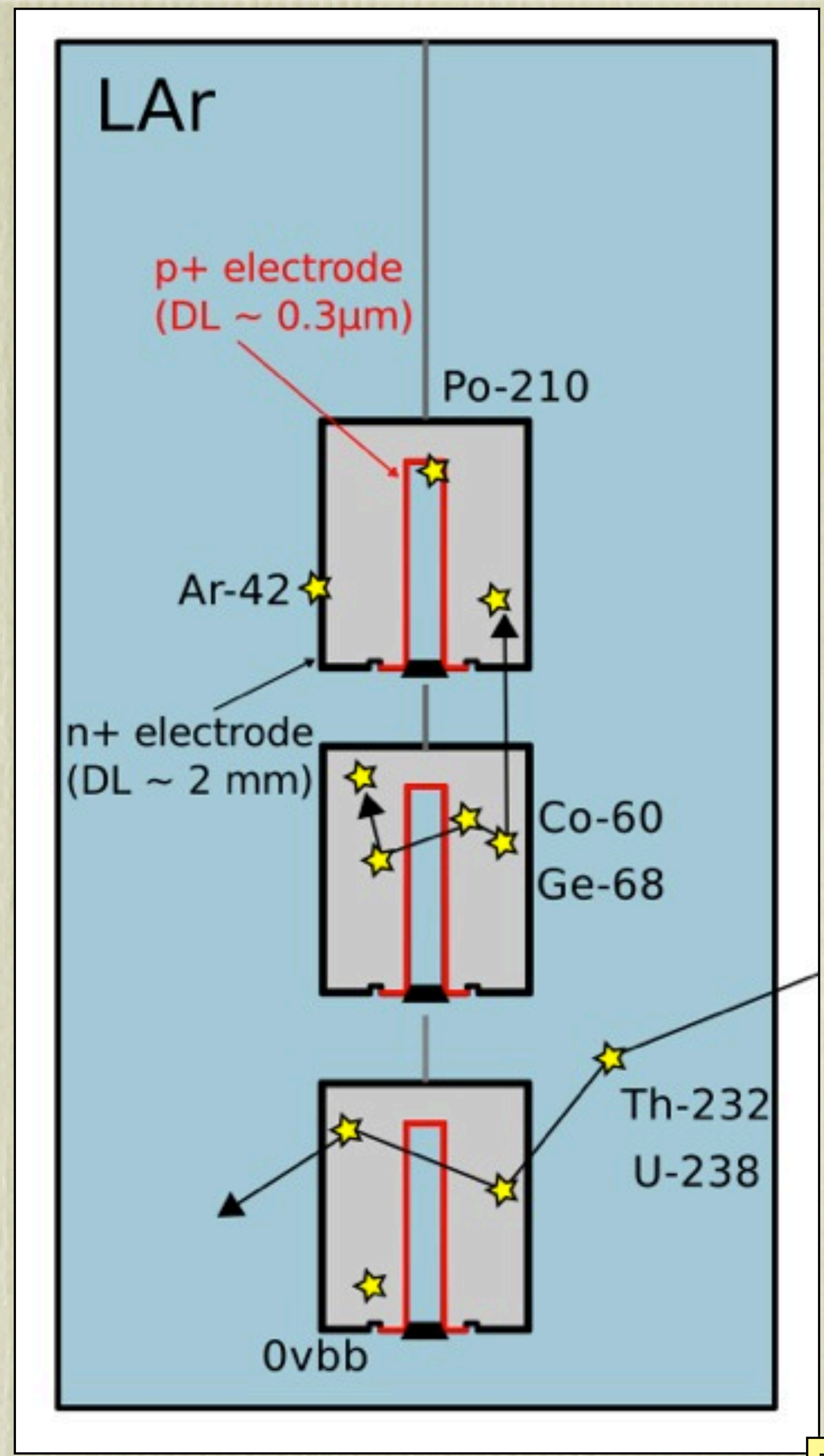
Backgrounds and Mitigation Strategies

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)

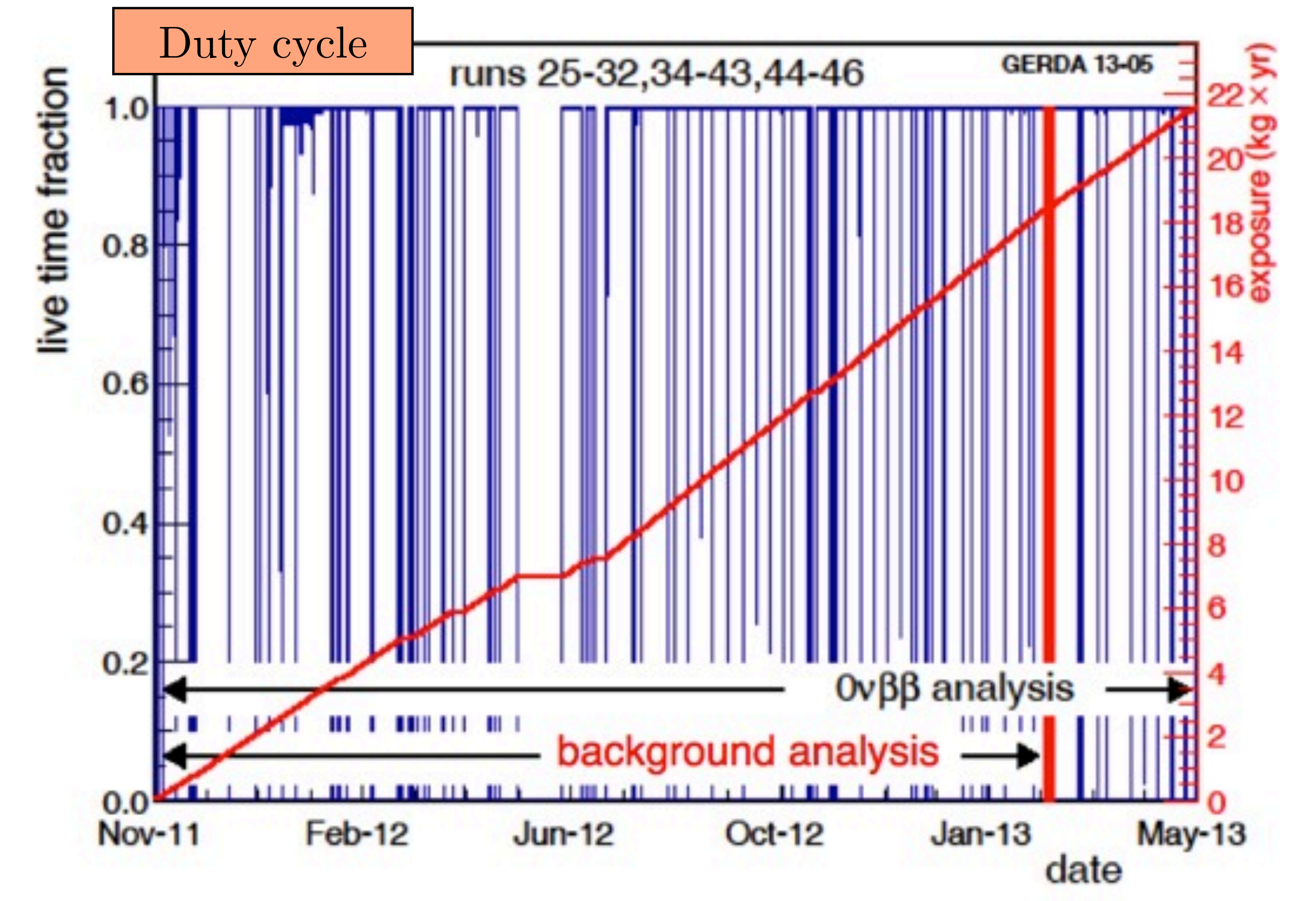
Mitigation strategies

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

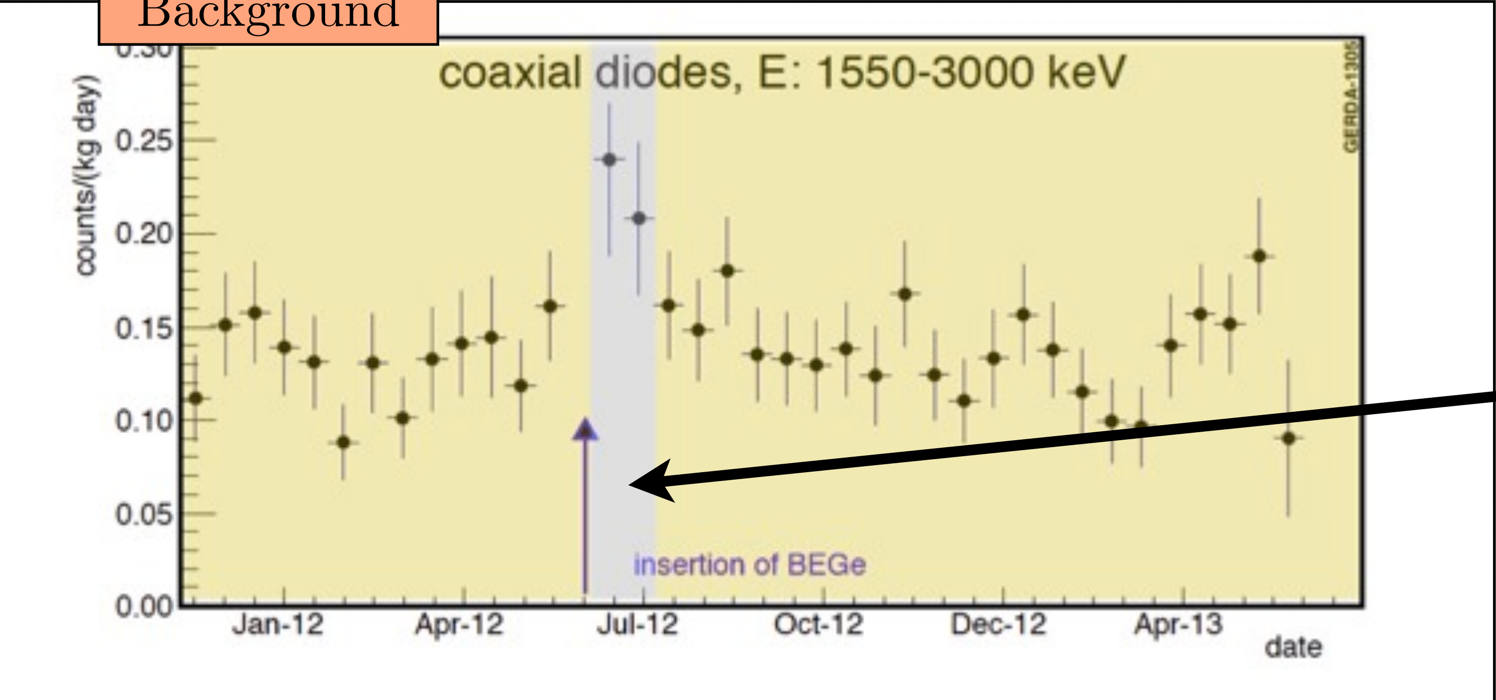


Duty Cycle and Data Sets for Phase I

Duty cycle



Background



Phase I data taking:

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

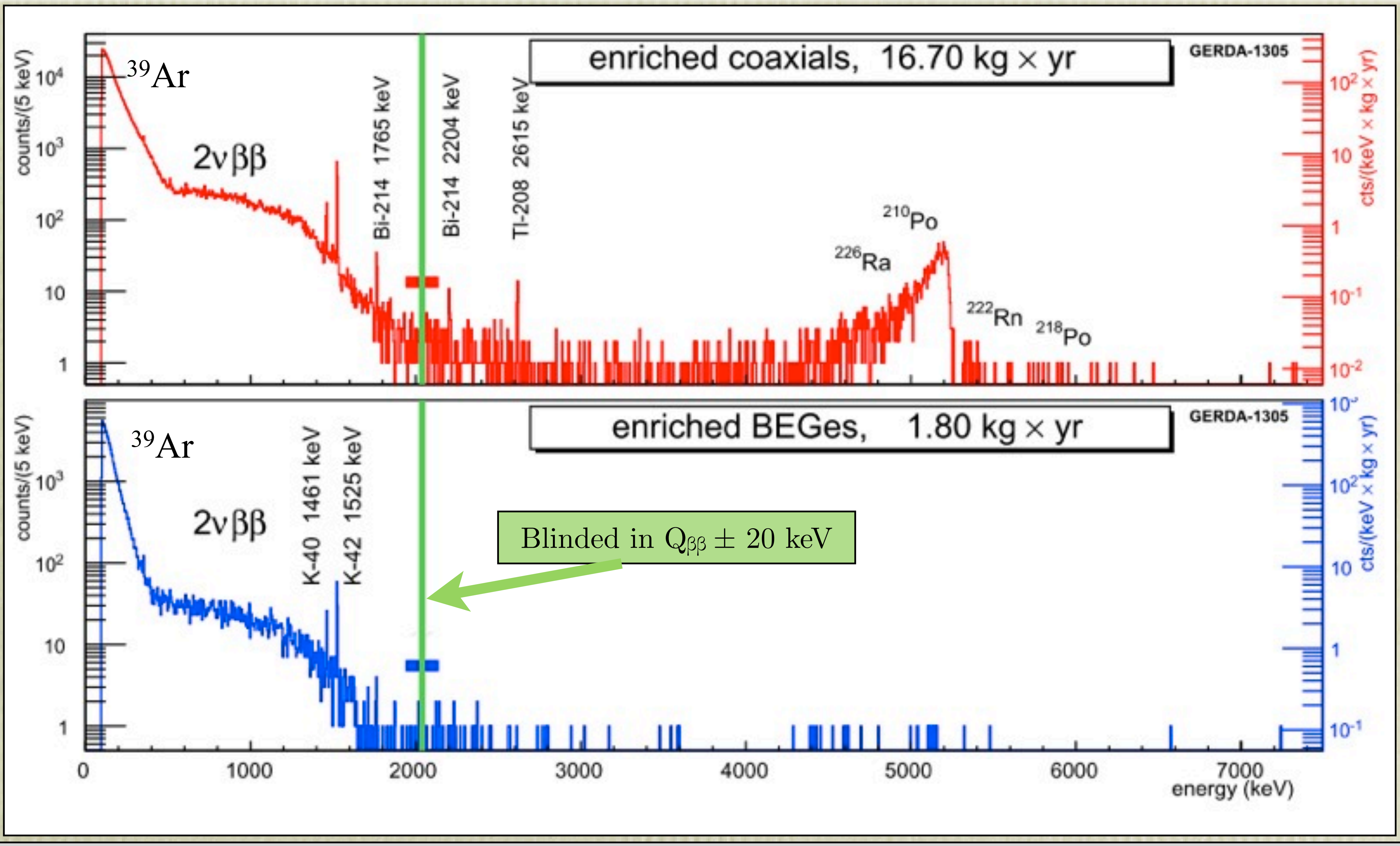
3 independent data sets:

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
doi:10.1140/epjc/s10052-014-2764-z



Main features:

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

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

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

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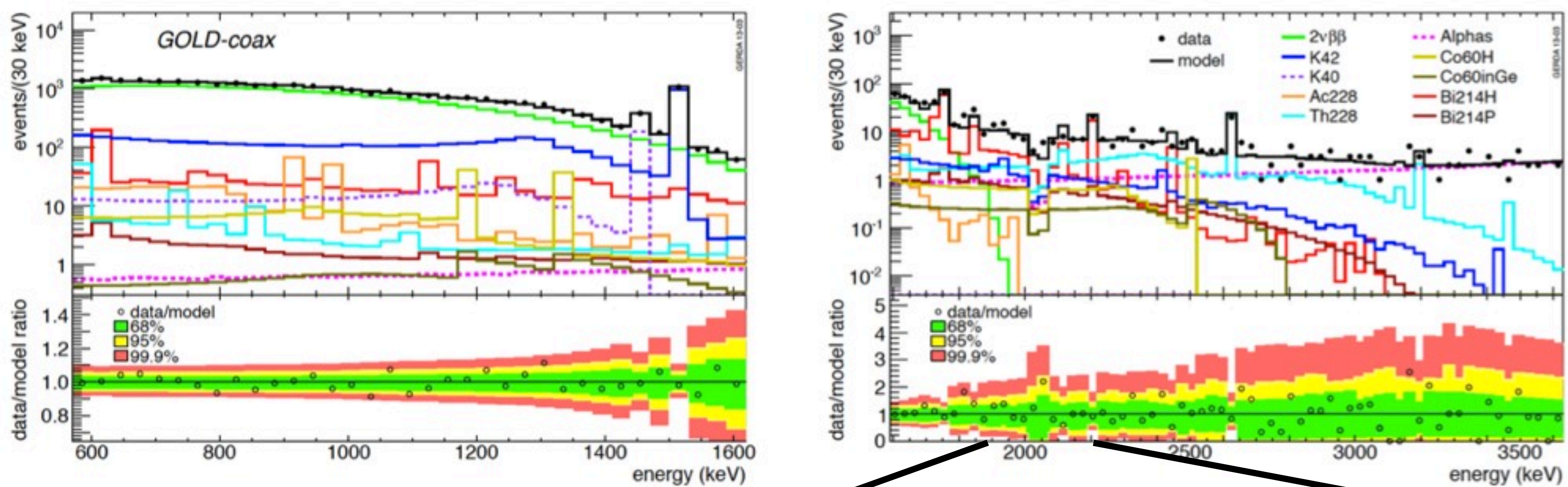
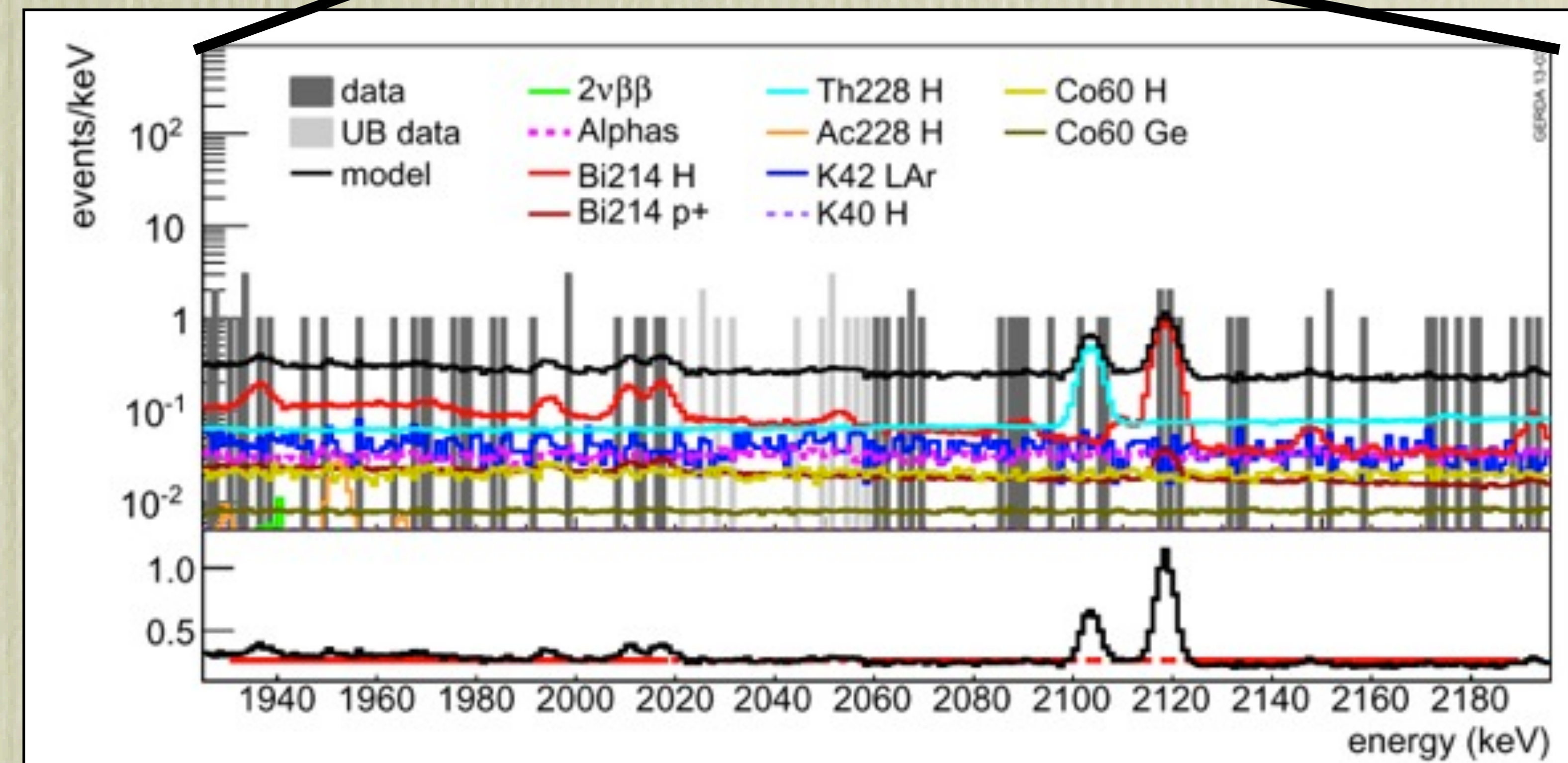




- MC of known (screening) and observed (gamma lines) background and fit to data 570 - 7500 keV
- Different combinations and positions tested
- Dominant: ^{214}Bi, ^{208}Tl on detector holders, ^{42}K in LAr, alphas

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

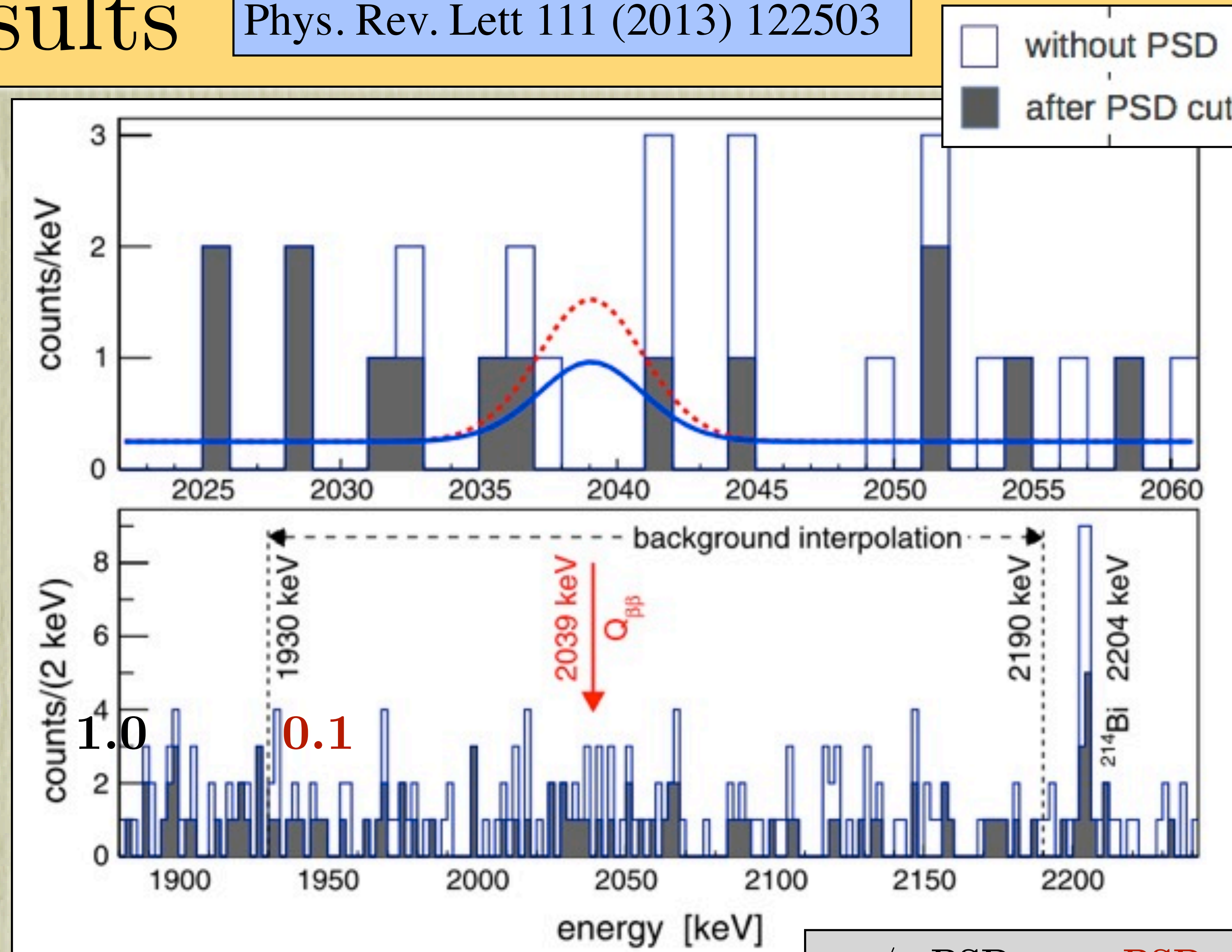
GERDA 0νββ Results

Phys. Rev. Lett 111 (2013) 122503

- Unblinding of data after all analysis parameters and methods were fixed
- Analysis cuts applied (Survival fraction around $Q_{\beta\beta}$)

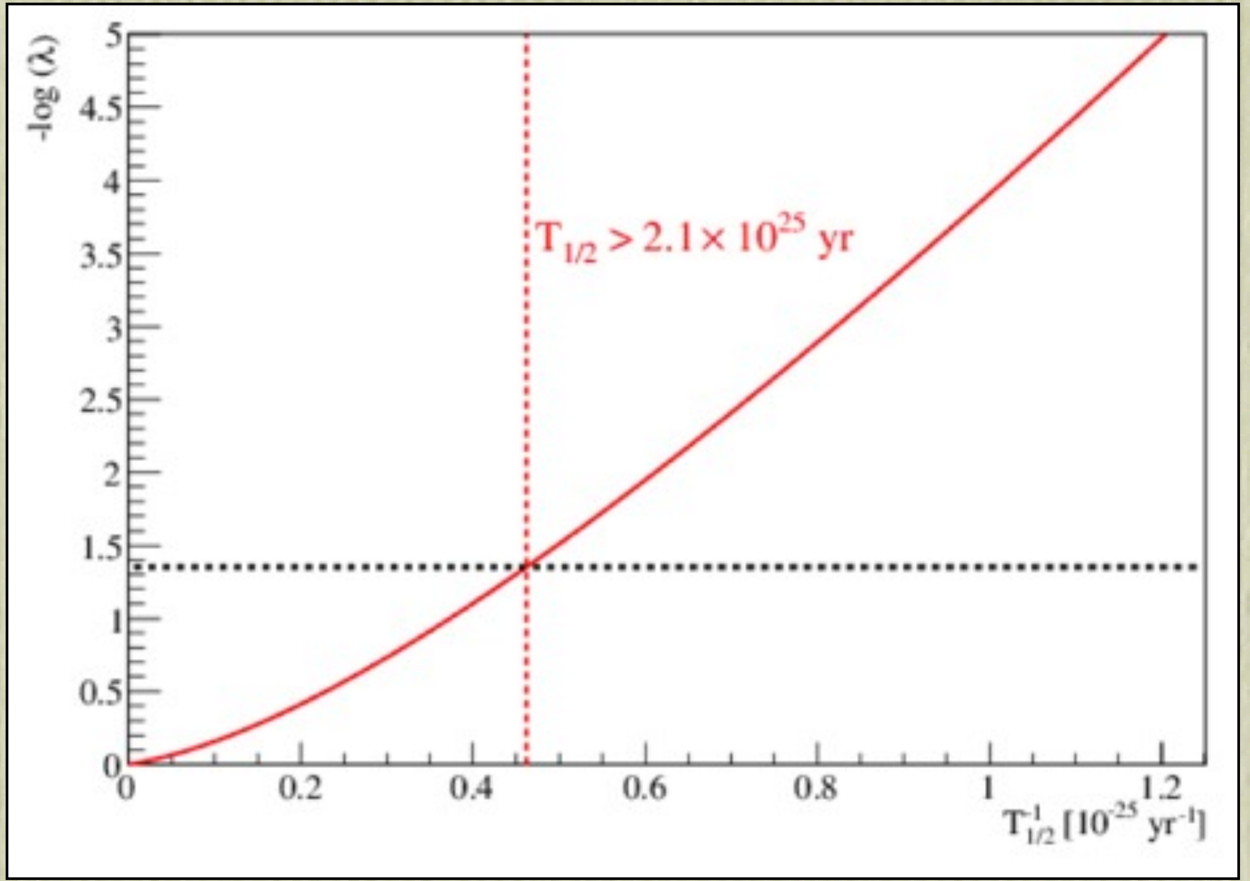
1. Quality cuts (> 99%)
2. Detector anti-coincidence (≈ 65%)
3. Muon-veto (≈ 95%)
4. Time coincidence (≈ 100%)
5. Pulse Shape cut (≈ 50%)

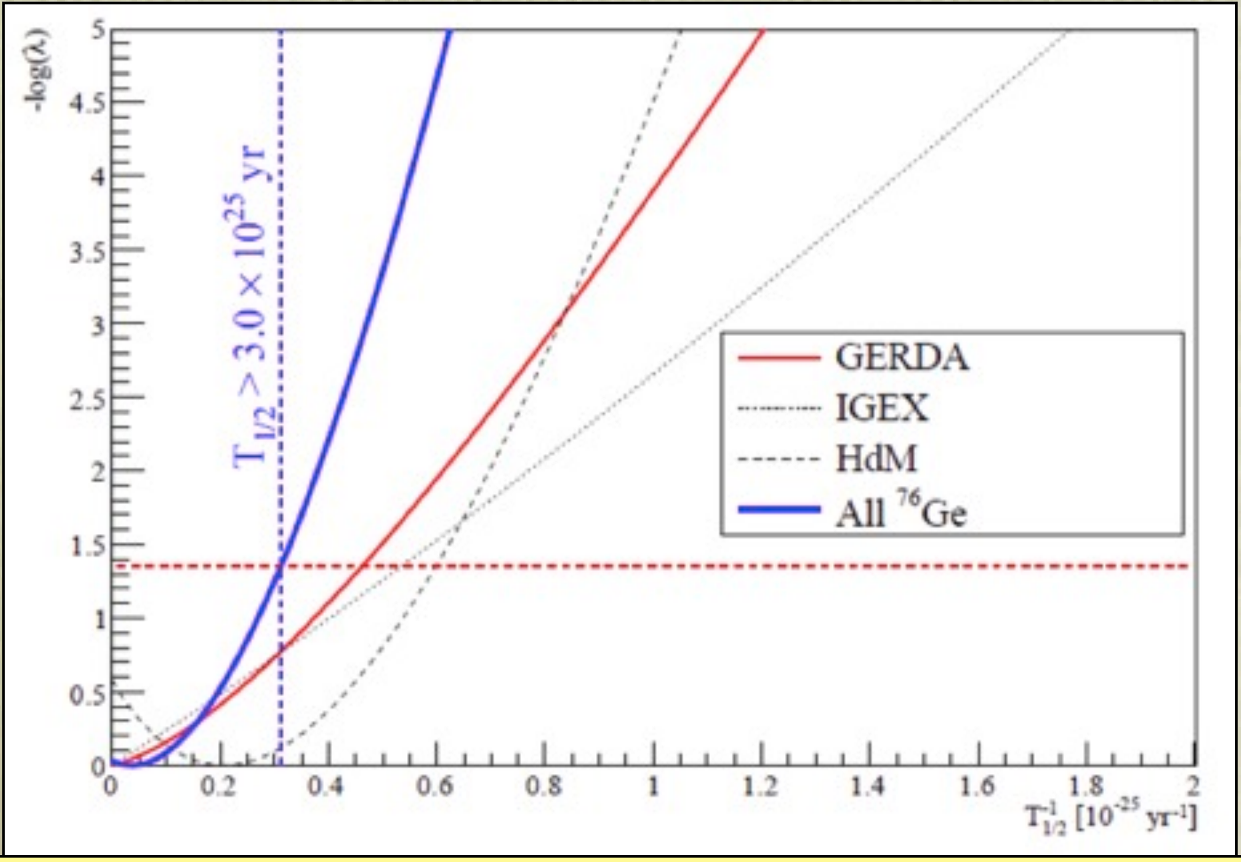
- **No peak in spectrum observed**
- **GERDA improves limit**



Data set	Exposure [kg yr]	background index [10^{-2} cts/(keV kg yr)] w/o PSD	background index w PSD	expected counts ($Q_{\beta\beta}$ ± 5 keV) w/o PSD	expected counts w PSD	observed counts ($Q_{\beta\beta}$ ± 5 keV) w/o PSD	observed counts w PSD
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
				5.1	2.5	7	3

GERDA $0\nu\beta\beta$ 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
- **Profile likelihood result:**

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

- Median sensitivity:

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

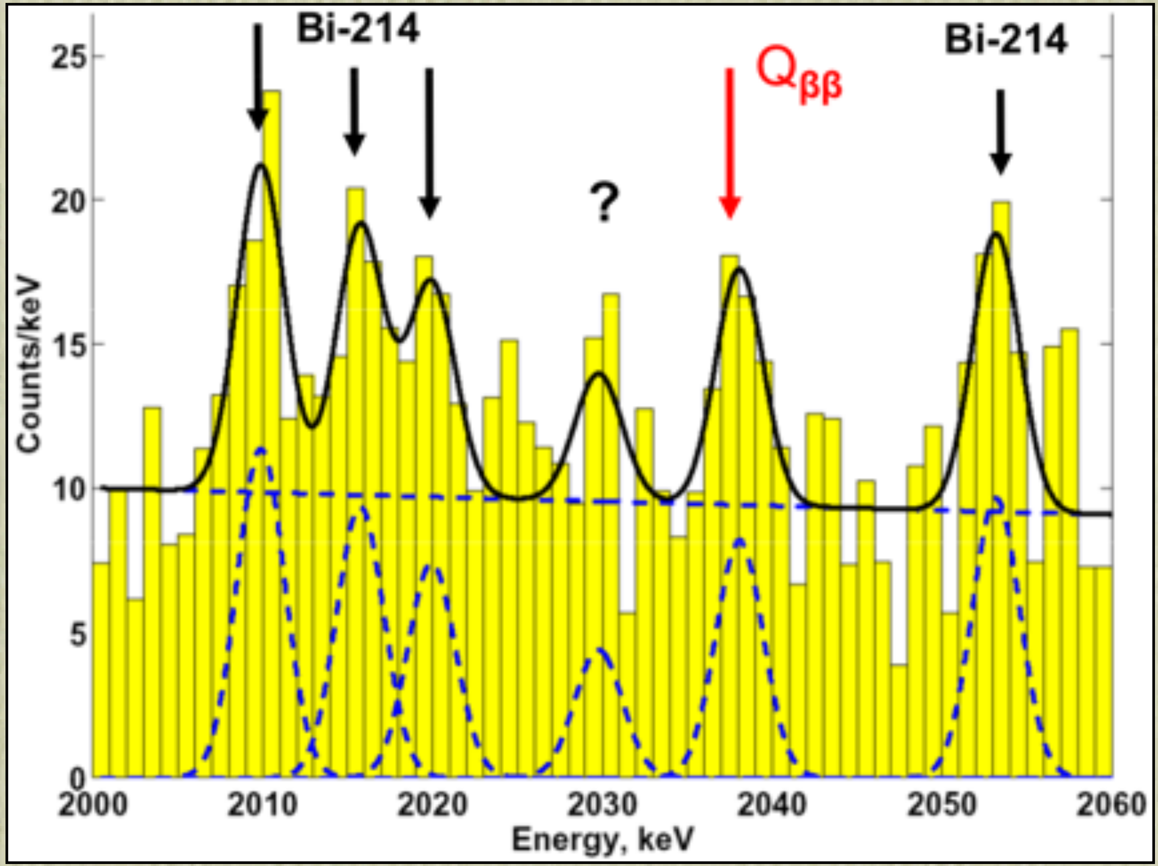
Combination ^{76}Ge:

(GERDA + HdM + IGEX)

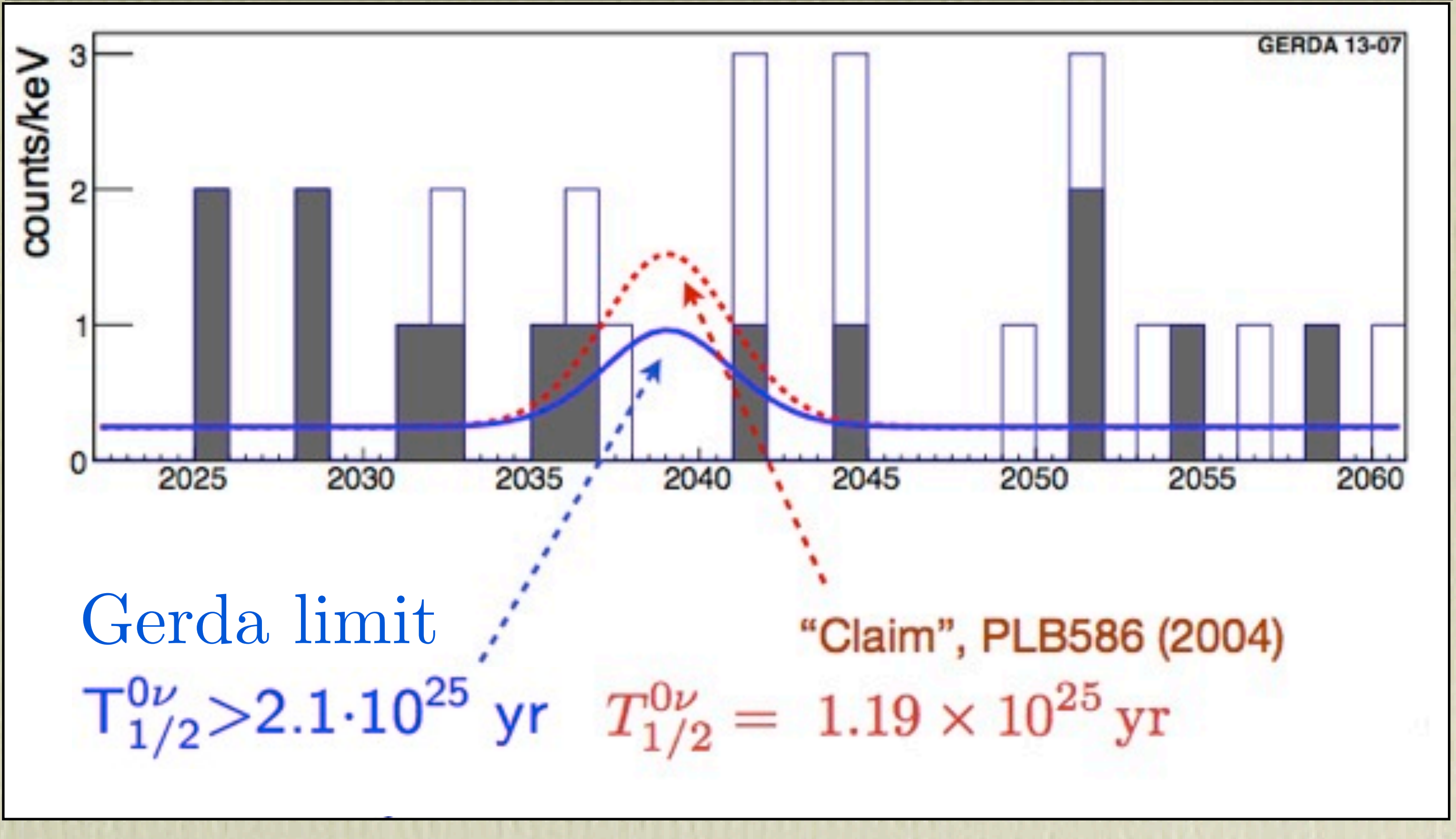
$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}\,\text{yr at } 90\%\text{ C.L.}$$

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: $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ 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) 269

GERDA 0νββ Results: Comparing with Claim

Combined ^{76}Ge:

- Bayes factor:

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

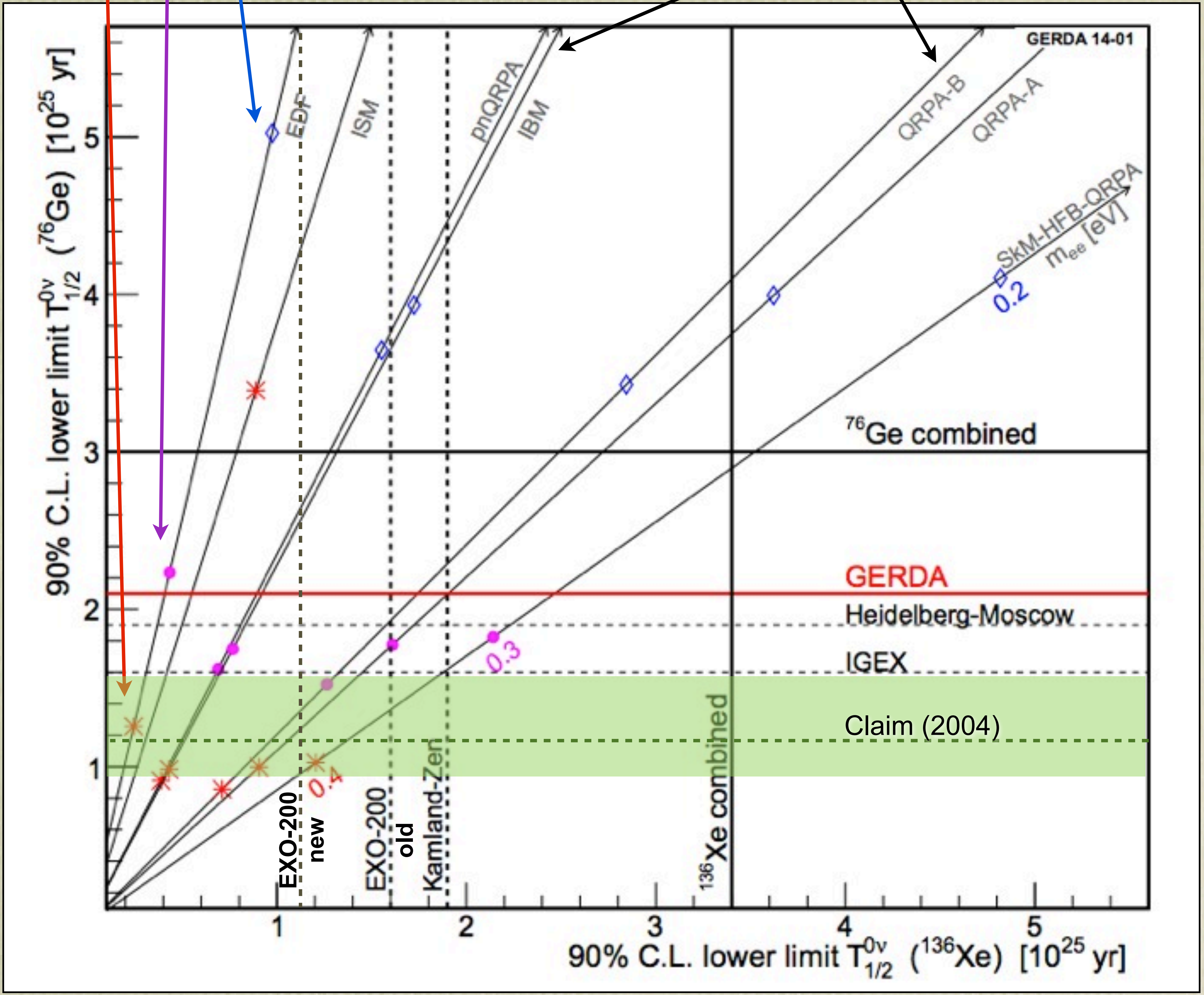
Combined ^{76}Ge+^{136}Xe:

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

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

Fixed neutrino mass at 0.4, 0.3, 0.2 eV

Different NME calculations for light Majorana neutrino dominance



Conclusion

- GERDA published Phase I results of blind analysis

  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 at 90% C.L.
  - $|m_{ee}| < 0.2$ - 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