Review of DBD Experimental Results

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NNN 2016- Beijing 3th-7th November 2016

ββ decay

1. $(A,Z) \Longrightarrow (A,Z+2) + 2e^- + 2\overline{\nu}$

2. $(A,Z) \Longrightarrow (A,Z+2) + 2e^-$

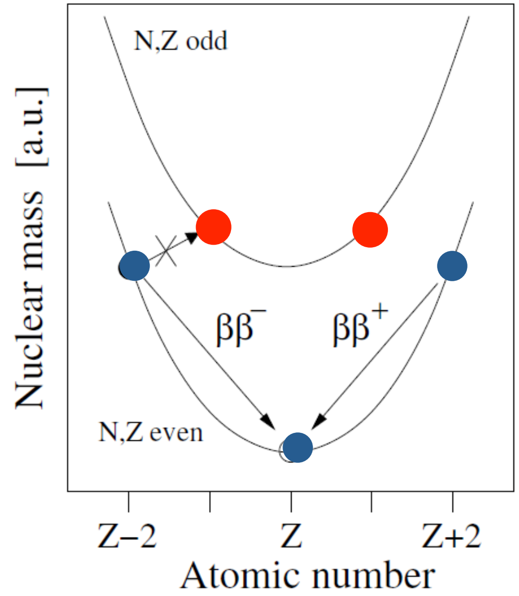
3. $(A,Z) \Longrightarrow (A,Z+2) + 2e^- + \chi$

2νββ; Allowed in SM; Observed in 12 Nuclei ; $T_{1/2}$ $10^{19} – 10^{21}$ yr

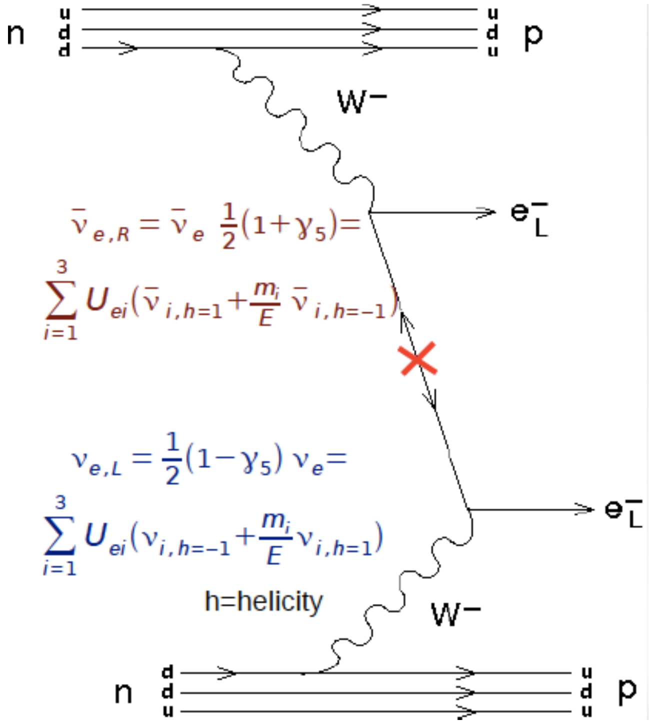
0νββ; NOT Allowed in SM; Not observed; $T_{1/2} > 10^{26}$ yr

ββ w. Majoron Emission; NOT foreseen in SM; NOT observed; $T_{1/2} > 10^{22}$ yr

- Processes 2 and 3 would imply new physics beyond SM
- 2 very sensitive to NP as Phase Space factor very favorab
- **2νββ** proposed by Goeppert-Meyer in 1935
- **0νββ** proposed by Furry (1935) and Racah (1937)
- First experiment looking for **0νββ** with Ge detectors in th '60s-'70s



$0\nu\beta\beta$: the mass mechanism



In most extensions of SM ⇨

- One $\bar{\nu}$ (L=1) is emitted at one vertex
- One ν (L= -1) is absorbed at second vertex

It is a forbidden process in SM and requires

- Lepton number violation by two units $\Delta L = 2$
- Majorana ν of finite mass $\nu_e = \bar{\nu}_e \; < m_\nu > \neq 0$

CAVEAT

DBD can address, although in a Nuclear Model Dependent way

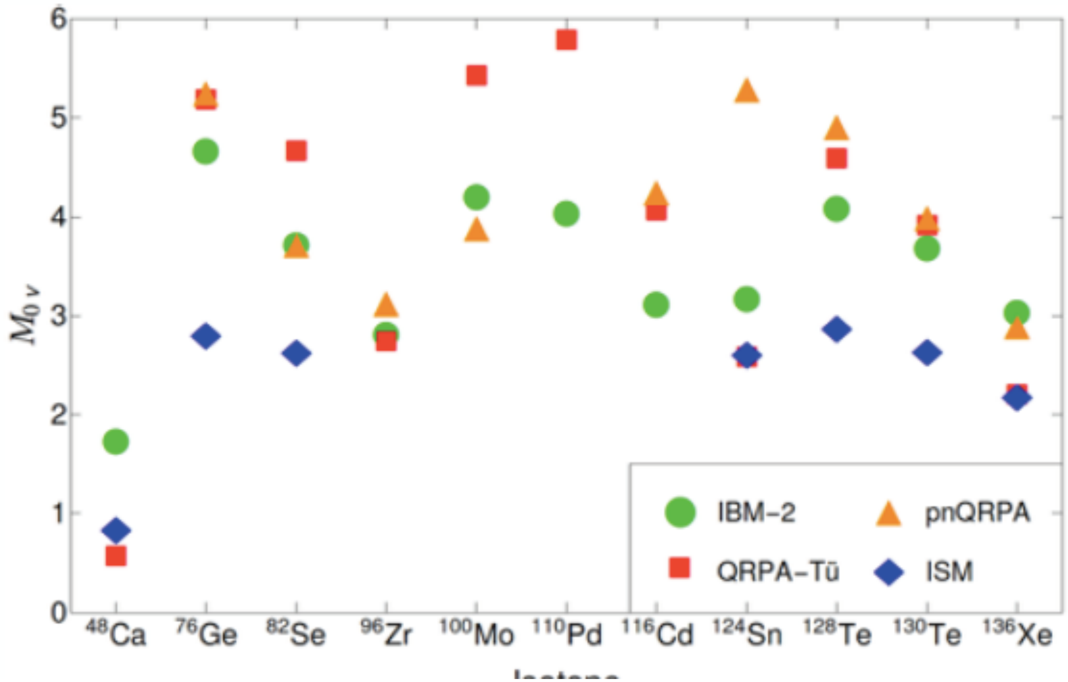
1. **Absolute mass scale: i.e. mass of the lightest ν**
2. **Hierarchy ($m_1 \ll m_2 < m_3$ or $m_3 \ll m_1 < m_2$) or degeneracy ($m_1 \approx m_2 \approx m_3$)**

$$0\nu bb \text{ rate} = (T_{1/2}{}^{0\nu})^{-1} \sim F_{0\nu}\,(Q,Z)\; |M_{0\nu}|^2 < m_{\beta\beta}>^2 / m_e^2$$

Phase space | **Nuclear Matrix Elements** | **Neutrino Mass Term**

The Nuclear Matrix Elements

IBM-2: J.Barea et al. Phys.Rev C 91 (2015) 034304
QRPA-Tu: F-Simkovic et al. Phys.Rev. C 87,(2013) 045501
pnQRPA: J. Hyvarinen et al. Phys.Rev. C 91(2015) 034304
ISM: J. Mendenez et al., Nucl.Phys. A 818,(2009) 139



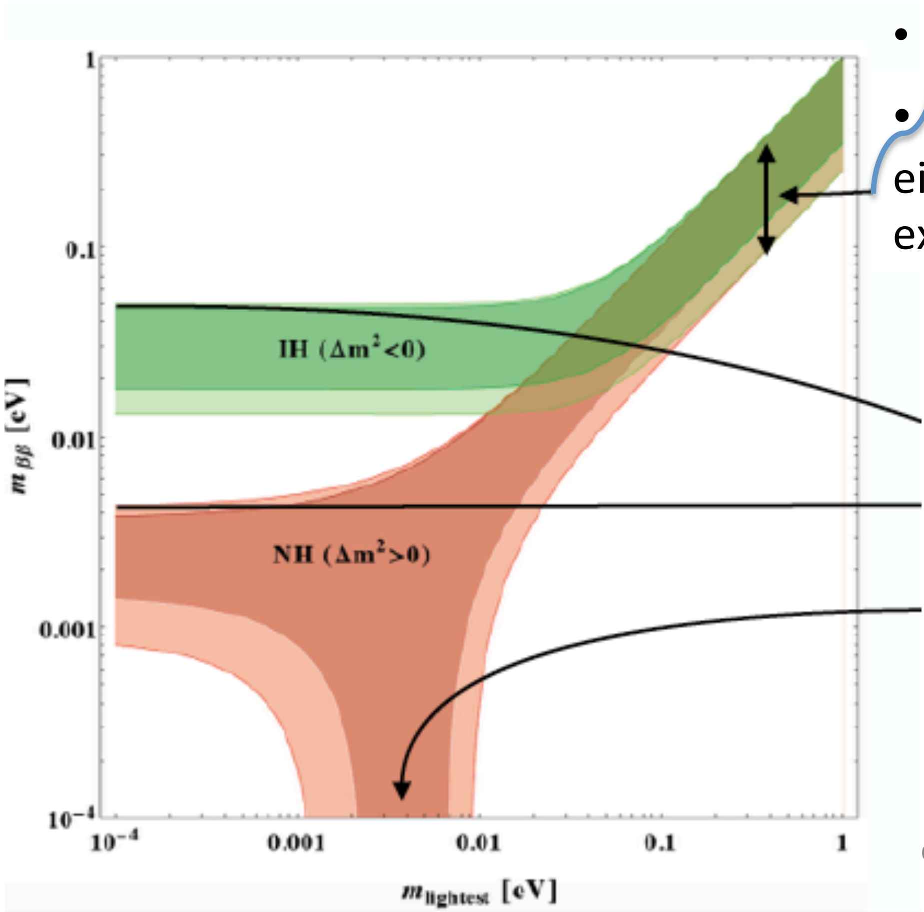
Conclusions:

- NME vary by factor 2-3 for a given nucleus depending on the model
- NME depends on g_A quenching value (1.269, 1.0, ….)
- Calculation discrepancies are one of the largest source of uncertainties in the $0\nu\beta\beta$ half-life computation
- No super element from NME

Light Neutrino Exchange

In the assumption of the exchange of a Majorana mass neutrino

$$< m_{ee} > = \left| \sum_k m_k \left| U_{ek}^2 \right| e^{i a_i} \right| = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$



- c_{ij}, s_{ij}: *PMNS elements*
- e^{ia}, e^{ib}: Majorana Phases totally unknown
- Plotting m_{ee} vs. the lightest neutrino eigenstates & constraining by oscillation experiments data, one gets 3 allowed bands

In the assumption $m_{lightest} << \delta m^2$

$$IH: \quad m_{\beta\beta} \le \sqrt{\Delta m^2}\left(|U_{e1}|^2 + |U_{e2}|^2\right) \approx 50 meV$$

$$NH: \quad m_{\beta\beta} \le \sqrt{\delta m^2}\,|U_{e2}|^2 + \sqrt{\Delta m^2}\,|U_3|^2) \approx few\ meV$$

Attention: $\boldsymbol{m_{\beta\beta}}$ could be < any m_i due to possible Majorana Phases cancellation !!

The Experimental Sensitivity

From the exponential decay law the **half-life** corresponding to the **minimum detectable n. of events ($N_{\beta\beta}$)** over **bkg** at a given CL

$$T_{1/2}^{0\nu} = \ln 2 \frac{\varepsilon \, N_{nuclei} \, T_{meas}}{N_{\beta\beta}}$$

$$N_{\beta\beta} \geq \sqrt{BI \cdot \Delta E \cdot M \cdot T_{meas}}$$

ε= detection efficiency

A= Atomic weight

i.a.= isotopic abundance

M = mass of detector [kg]

T = data taking time [y]

BI = background index [cts/(keV kg y)]

ΔE = FWHM @ $Q_{\beta\beta}$ [keV]

N_{bkg}>1

$$T_{1/2}^{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot T_{meas}}{BI \cdot \Delta E}}$$

Scale ~ Exposure

$$m_{ee} \propto \frac{1}{Q^{1/2} \cdot M_{0\nu}} \left(\frac{BI \cdot \Delta E}{M \cdot T_{meas}} \right)^{1/4}$$

Performances

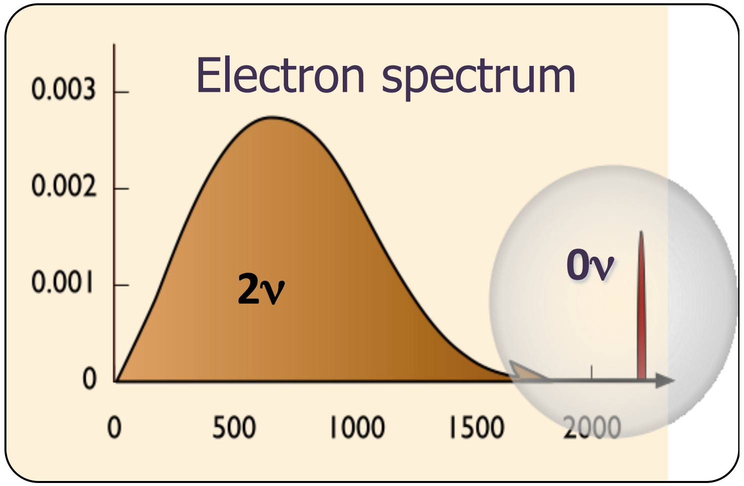
N_{bkg}< 1 → Bck free

$$T_{1/2}^{0\nu} \propto \varepsilon \frac{i.a.}{A} M \, T_{meas}$$

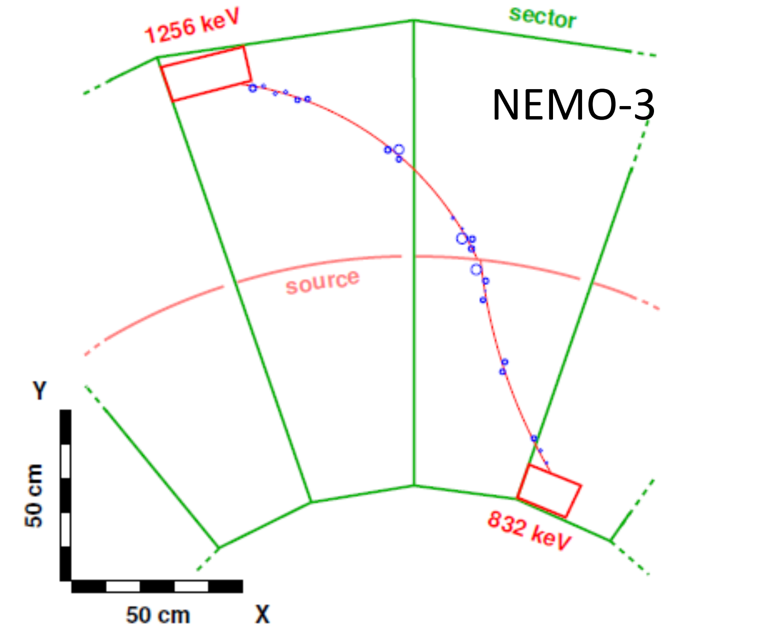
ββ: Experimental Signatures

- Minimal signature:

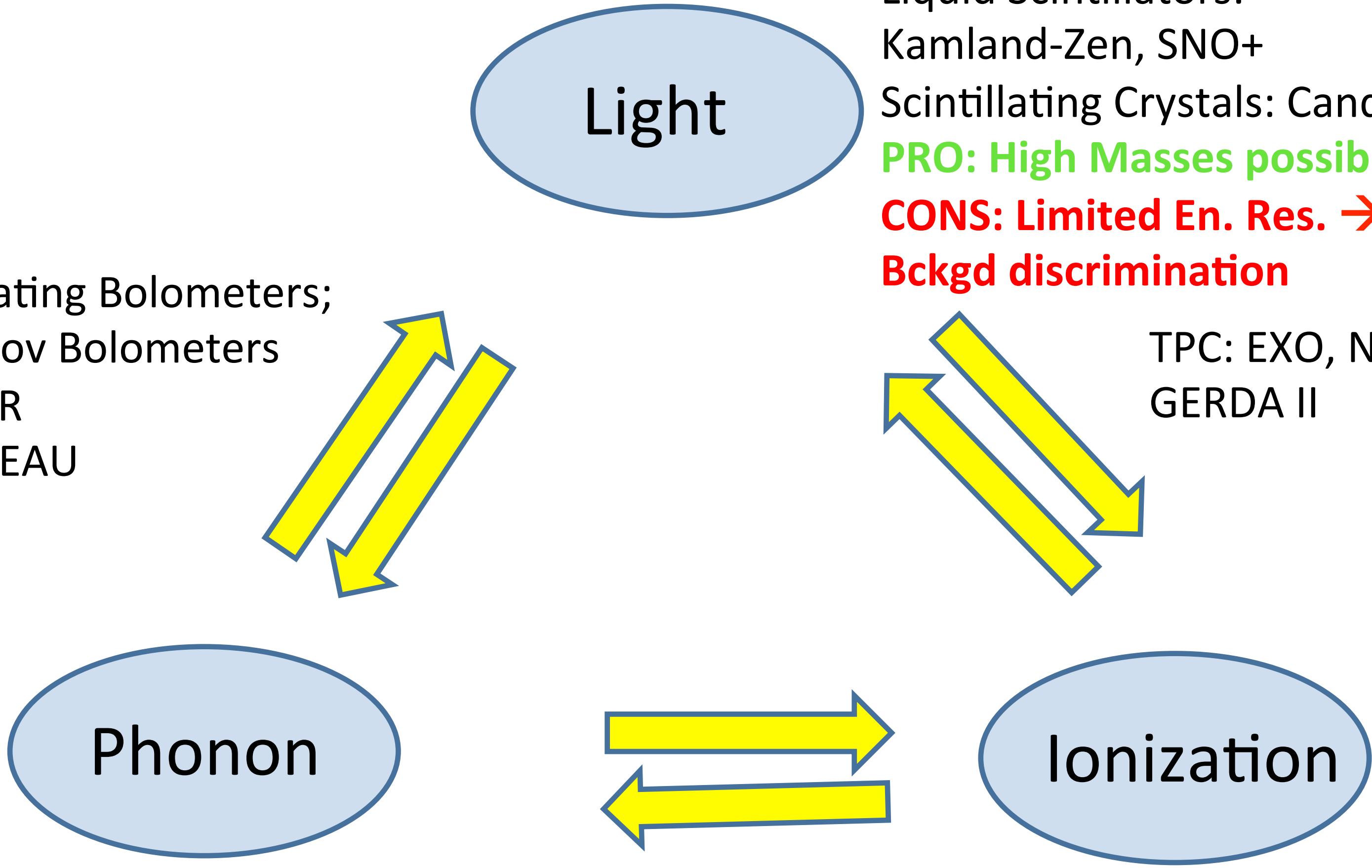
  Sum energy spectrum of the two e⁻
  - 0νββ exhibits a peak at $Q_{\beta\beta}$
  - 2νββ exhibit a continuum spectrum



- Additional signatures:
  - Single electron spectrum
  - Angular correlation between the two e⁻
  - Identification of Daughter nuclear species



Experimental Techniques: Better multiple event reconstruction



Liquid Scintillators:
Kamland-Zen, SNO+
Scintillating Crystals: Candles
PRO: High Masses possible
CONS: Limited En. Res. → Limited Bckgd discrimination

Scintillating Bolometers;
Cerenkov Bolometers
LUCIFER
LUMINEAU

TPC: EXO, NEXT
GERDA II

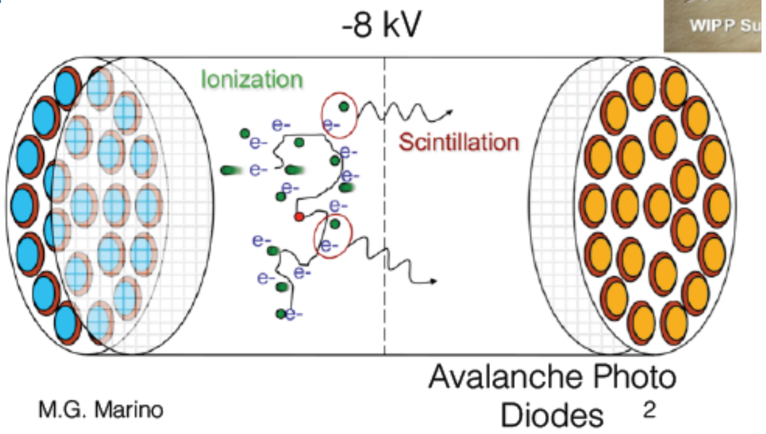
CUORE:
PRO: Good En. Res. → Good Bckgd discrimination
CONS: Difficult and Costly to scale up Masses

Semiconductor Calorimeters
GERDA; MAJORANA
Tracking Calorimeters
SuperNEMO; DCBA

EXO-200

Detector Type: Xe-TPC with double readout

- Active Traget ~ 110 kg
- σ_E/E ~ 1.25 % @ Q Value (~2.5 MeV)
- Background Mitigation: FV Cuts and Single Site vs multi-Site events→ 1.7 x 10^{-4} cts/(kev kg yr)



Physics results (Phase-I, 100 kg•yr)

$$T_{1/2}{}^{2\nu} = (2.165 \pm 0.016 \pm 0.059) \times 10^{21}\ \text{yr}$$

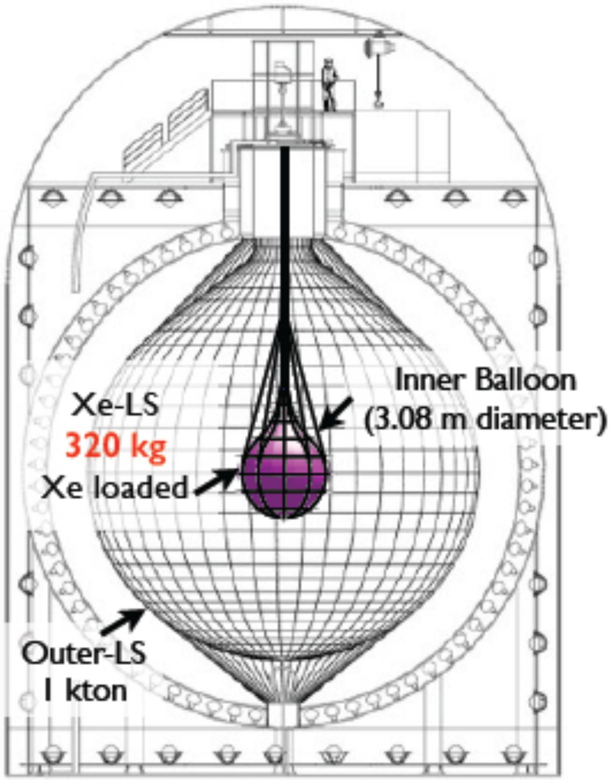
$$T_{1/2}{}^{0\nu} > 1.1 \times 10^{25}\ \text{yr @ 90\% C.L.}$$

Phys. Rev. C89 (2014) 015502
EXO-200 Collaboration, Nature 510, 229-234 (12-June 2014)

- After 2014 underground accident, EXO-200 started the data taking in April 2016 after upgrades (Energy Resolution, Radon mitigation) to imporve the sensitivity

KAMLAND-ZEN

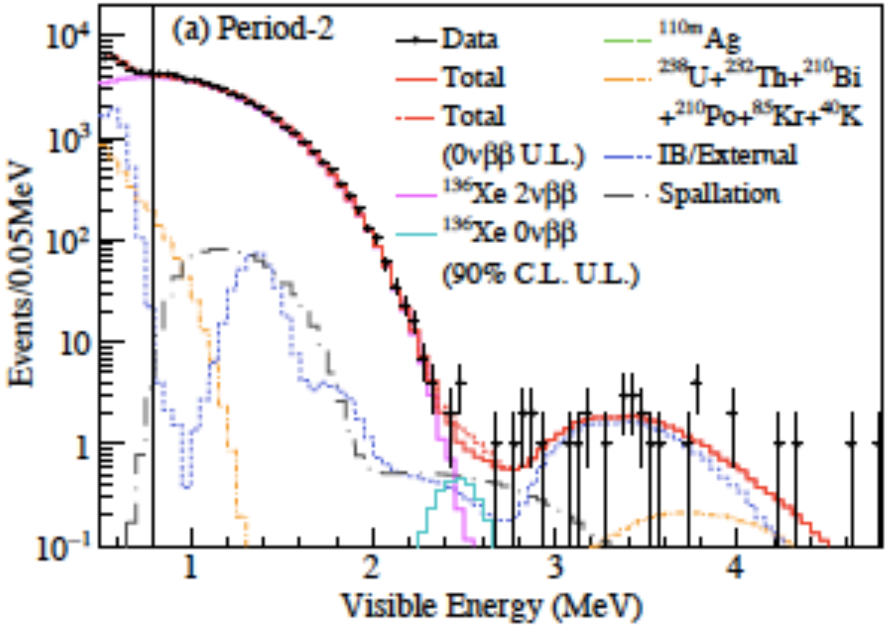
KamLAND-Zen Phase I



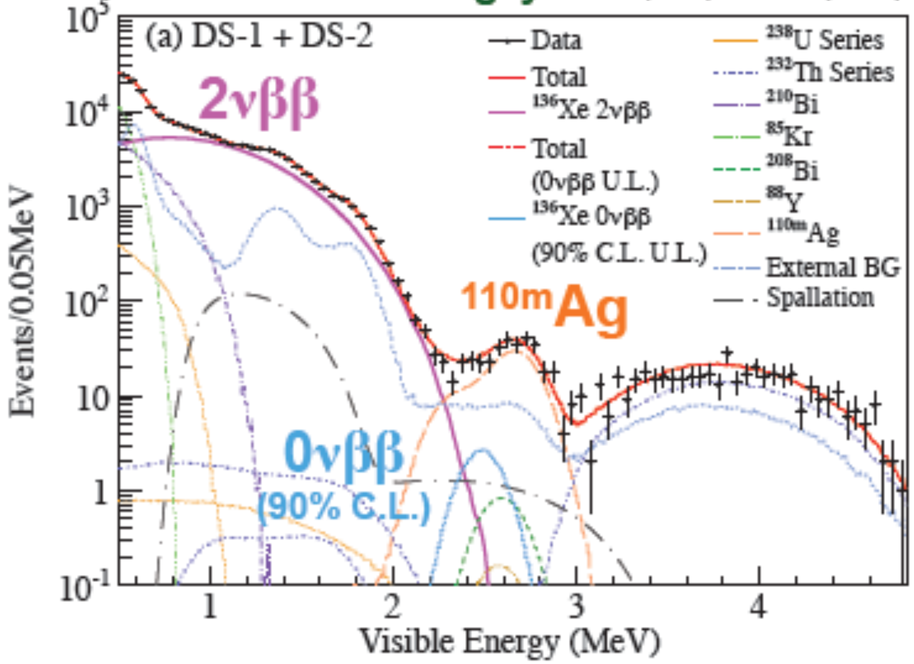
Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$\sigma_E(2.5\mathrm{MeV}) = 4\%$

Phase 2: $\sigma(E)/E$ (2.5 MeV) = 6 %



Phase 1 **89.5kg•yr** PRL, 110, 062502 (2013)



KZ-Phase II: (126 kg y) 2νββ

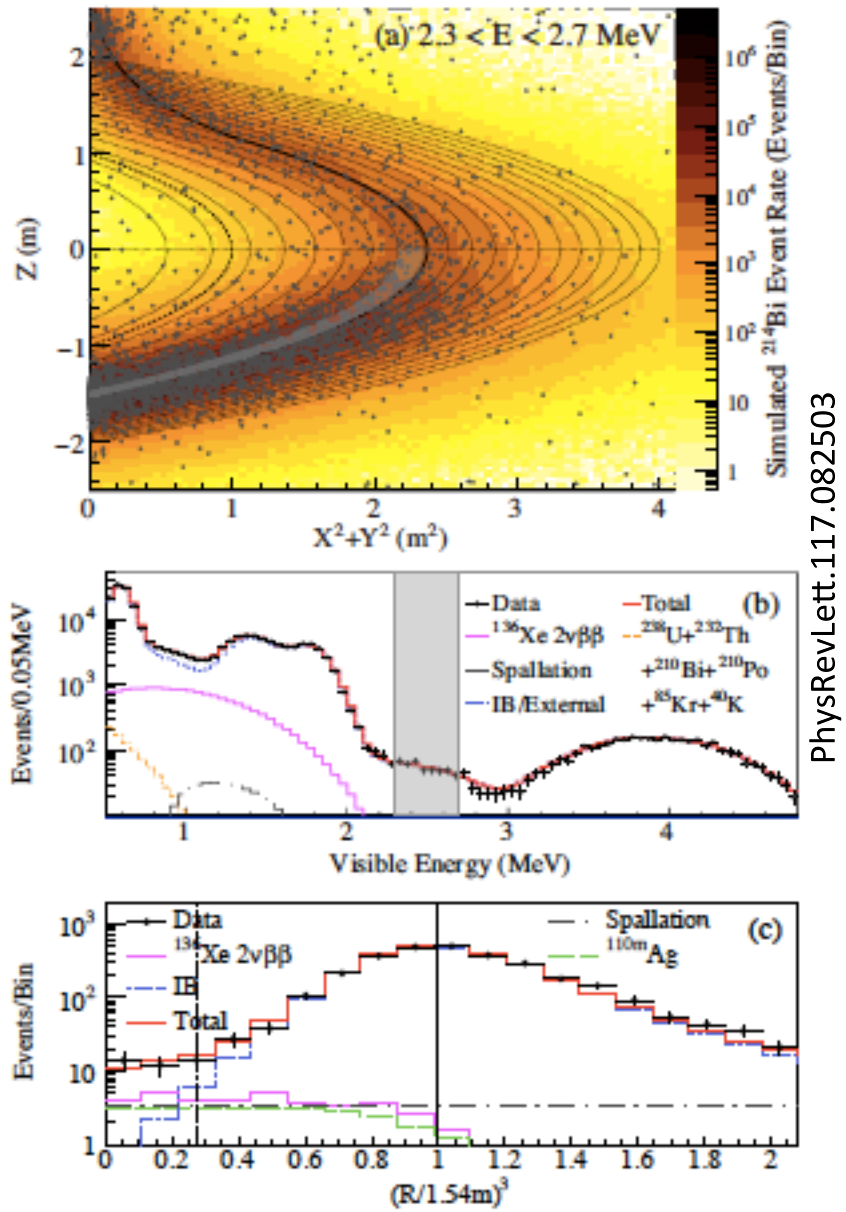
- Unexpected background consistent with ^{110m}A β^- decay (t=360 d, Q= 3.01 MeV) limited Phase I Sensitivity
- Divide PII data in two periods: (271 d & 264 d): observed the (presumed) ^{110m}Ag signal decaying *not* w. the proper lifetime
- Xe recovery & Purification campaign (18 months)
- Cut background by FV cuts
- Different background intensities (^{110m}Ag, ^{214}Bi) observed in top-bottom emispheres
- **$FV_{2\nu\beta\beta}$: 1 m** cut→ Exposure: 126 kg y
  - Major background sources: ^{85}Kr, ^{40}K, ^{210}Bi, ^{214}Bi, ^{228}Th- ^{208}Pb

$T_{1/2}^{\ 2\nu} = 2.21 \pm 0.02^{stat} \pm 0.07^{sist} \times 10^{21}$ yr

$N_{2\nu\beta\beta} = 100 \pm 1.5$ decay/(ton d)

- **Consistent with KZ-Phase I and EXO results**

Vertex Distribution of ^{214}Bi events



Kamland-Zen Phase II: 0νββ

PhysRevLett.117.082503

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.0	-	0.002
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.55	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.002	-	0.001
Spallation products				
^{10}C	2.7 ± 0.7	3.2	2.6 ± 0.7	2.7
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.9 ± 0.5	1.1	0.9 ± 0.5	0.8

- **$FV_{0\nu\beta\beta}$: 2 m** cut to use the full target mass→
- **Exposure = 504 kg•yr**

- z-profile of ^{214}Bi from IB folded in
- 3.5 m FV cut used to study spallation events dominated by ^{10}C. Eliminated by triple coincidence

- Period-2 (drastic ^{110m}Ag reduction) dominates the analysis
- ROI for background evaluation : 2.3-2.7 MeV

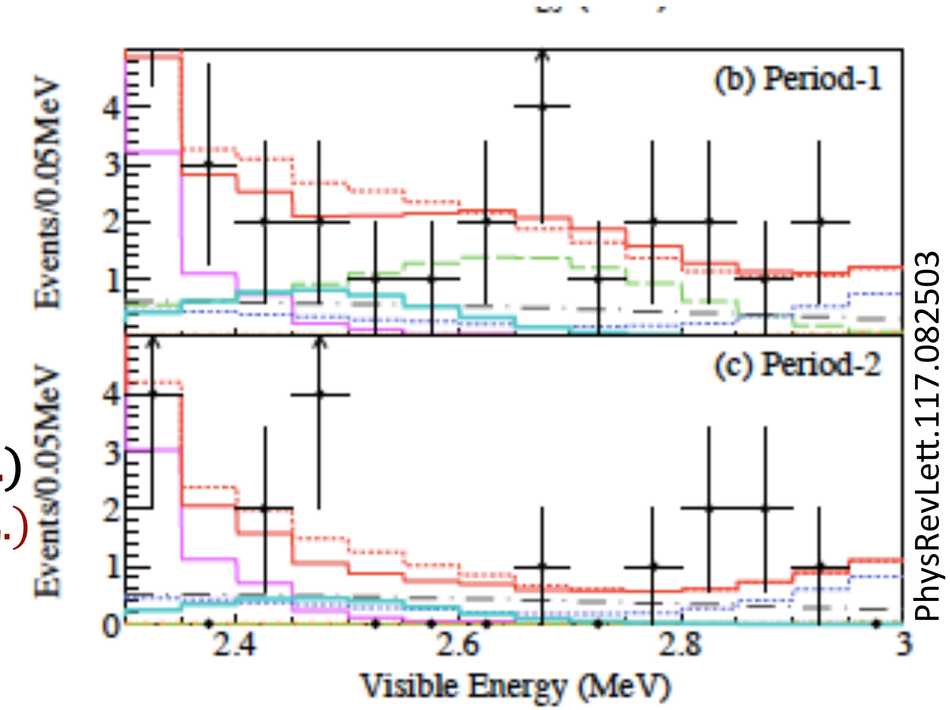
KZ Results: $0\nu\beta\beta$

- Results: Period I and Period II

  $N_{\beta\beta} < 22.4$ (kton d)$^{-1}$
  $T_{1/2}^{0\nu} > 9.6 \cdot 10^{25}$ y (90 % C.L.)

- **Sensitivity = $4.9 \cdot 10^{26}$ yr**

- Combining KZ-PII & KZ-PI
  - KZ-I: $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr (90 % C.L.)
  - KZ-II: $T_{1/2}^{0\nu} > 9.6 \cdot 10^{25}$ yr (90 % C.L.)



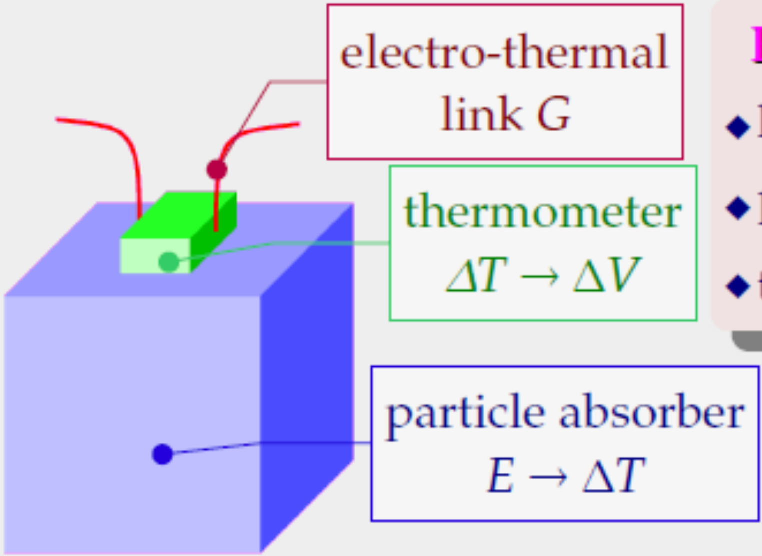
$T_{1/2}^{0\nu} > 1.6 \cdot 10^{26}$ yr (90 % C.L.)

The first limit in 10^{26} decade!!!!

KZ Perspectives

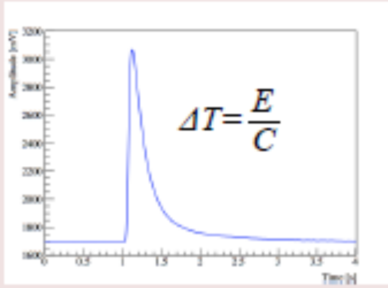
- Planned improvement with 800 kg ^{enr}Xe, reduced radioactivity IB.
- Requirements
  - significant improvement of the Energy Resolution because of $2\nu\beta\beta$ events leak
  - improved cuts on spallation events

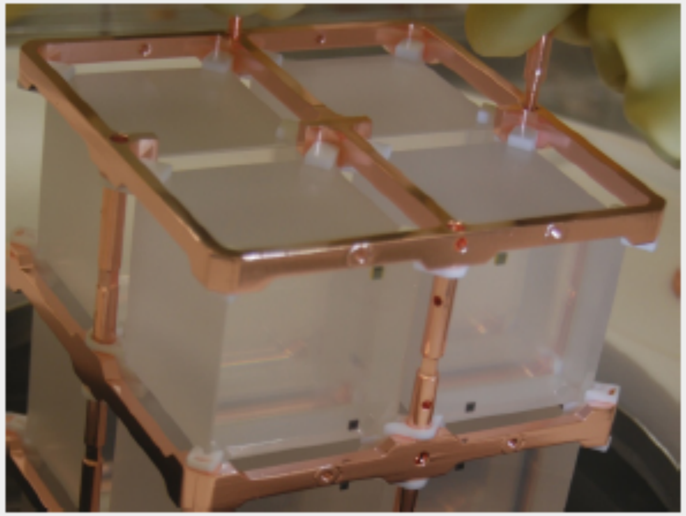
TeO_2 cryogenic detectors or bolometers



Properties of bolometers

- high energy resolution: $(k_B C T^2)^{1/2}$
- large choice of absorber materials
- true calorimeters





TeO_2 Absorbers

- low specific heat
- large crystals available
- radiopure
- $5\times5\times5$ cm^3 crystals have high detection efficiency for $\beta\beta0\nu$ events: ~87%

$T \sim 10$ mK
$\Delta T/\Delta E \sim 0.1$ mK/MeV
$\Delta V/\Delta E \sim 0.3$ mV/MeV
$\tau = C/G \sim 1$ s
$C \sim 2\times10^{-9}$ J/K

^{130}Te as $\beta\beta0\nu$ candidate

- high natural isotopic abundance: 34.2 %
- transition energy: Q = 2528 keV
- encouraging nuclear matrix element calculations

^{130}Te ββ0ν search with TeO_2 bolometers

MiDBD
1.8 kg ^{130}Te

1997-2001

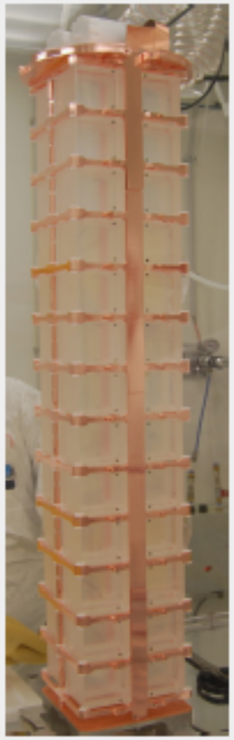
$\tau_{1/2}^{0\nu} > 2.1 \times 10^{23}$ y [1]
(90%C.L.)

Cuoricino
11.3 kg ^{130}Te

2003-2009

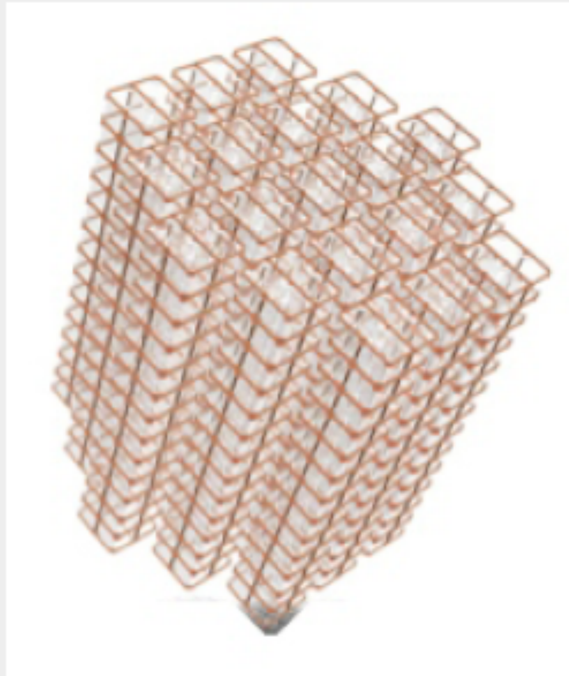
$\tau_{1/2}^{0\nu} > 2.8 \times 10^{24}$ y [2]
(90%C.L.)

CUORE-0
10.9 kg ^{130}Te



2013···2015

CUORE
~206 kg ^{130}Te



Start Commissioning
Expected early 2017

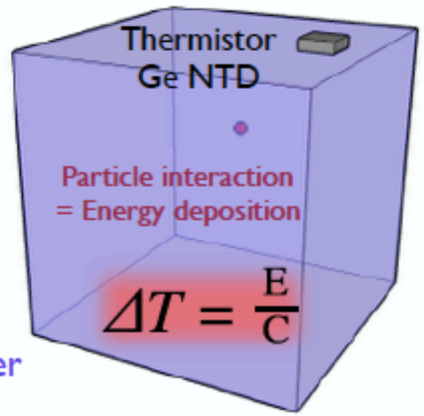
[1] C. Arnaboldi et al., Phys. Lett. B557 (2003) 167
[2] E. Andreotti at al., Astrop. Phys. 34 (2011) 822

CUORE-0

Detector Type: TeO_2 thermal detectors

- Active target: ~10 kg
- σ_E/E: ~0.2% @ Q value
- Coincidence veto for bkg reduction and modelling: 6×10^{-2} cnts/keV/kg/yr

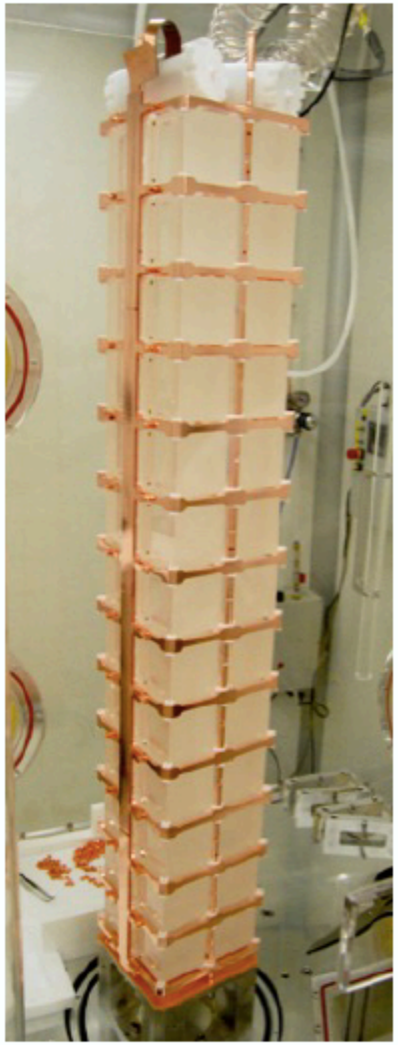
Energy release in crystals @ cryogenic temperature —> measurable T variation



Physics results (29.55 kg*y):

$$T^{2\nu}_{1/2} = (8.2 \pm 0.2^{\text{stat.}} \pm 0.6^{\text{sys.}}) \times 10^{20}\ \text{yr}$$

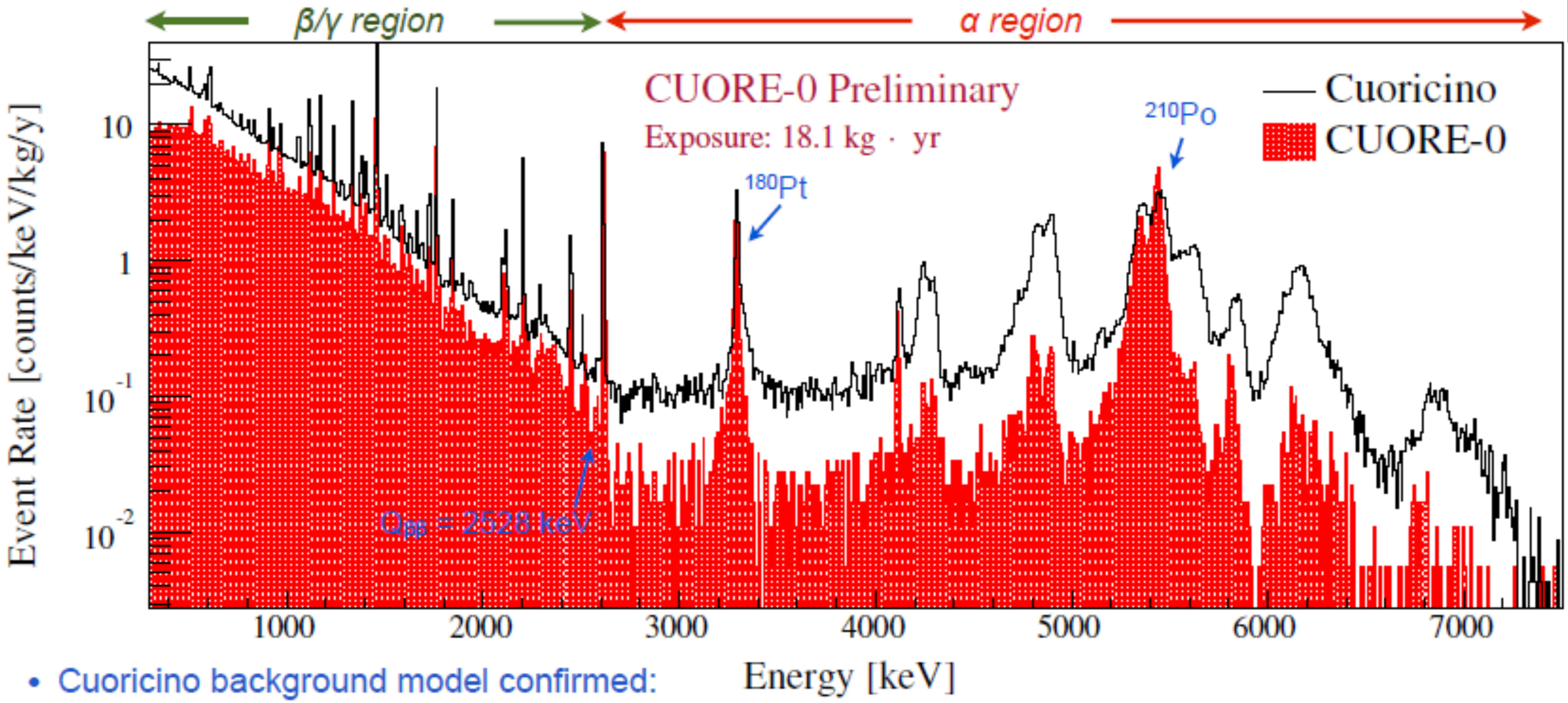
$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \text{yr @ 90\%C.L.}$$ (w/ Cuoricino)



Operated in former Cuoricino cryostat, with improved energy resolution, background level (materials selection, cleaning and handling), duty cycle and detector response model

K. Alfonso et al., Phys. Rev. Lett. 115, 102502 (2015)

CUORE-0 background

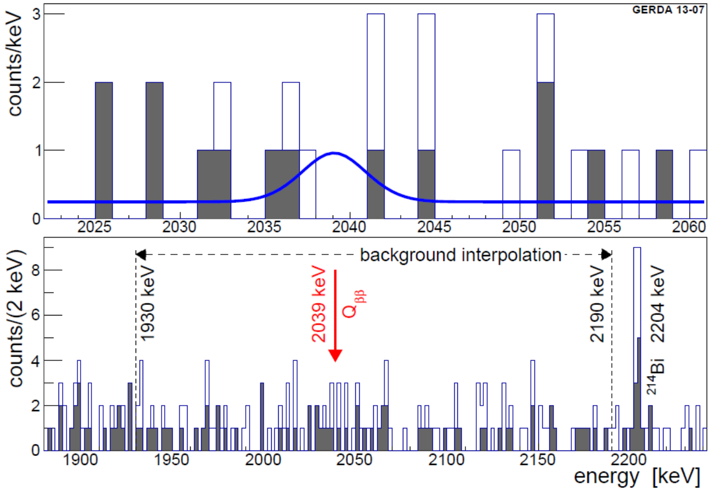


- Cuoricino background model confirmed:
  - environmental gamma's from material bulk contaminations
  - surface radioactive contaminations of close materials
- Evident reduction with respect to Cuoricino
  - factor of 6 for surface contaminations
  - factor ~2.5 in the ROI

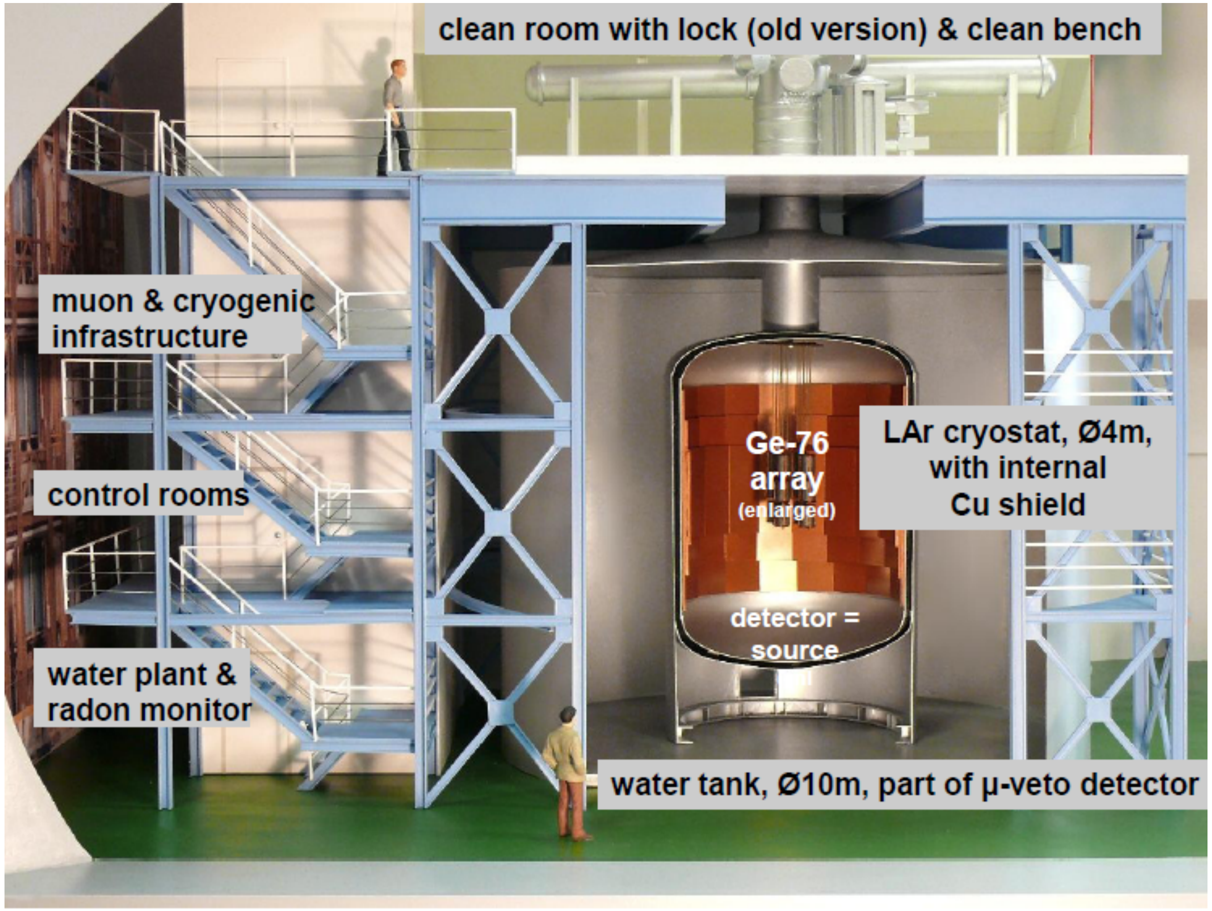
	0νββ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	**0.063 ± 0.006**	**0.020 ± 0.001**	78

GERDA

Phase I Data Taking: 2011-2013
Exposure: 21.6 kg•yr
Best fit: $N^{0\nu} = 0$
$N^{0\nu} < 3.5$ cts @ 90% C.L.
$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL
Median sensitivity:
$T_{1/2}^{0\nu} > 2.4 \times 10^{25}$ yr

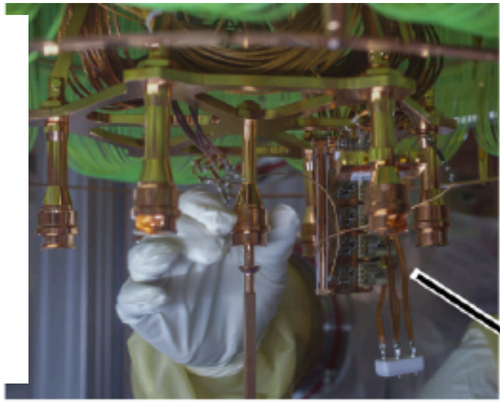


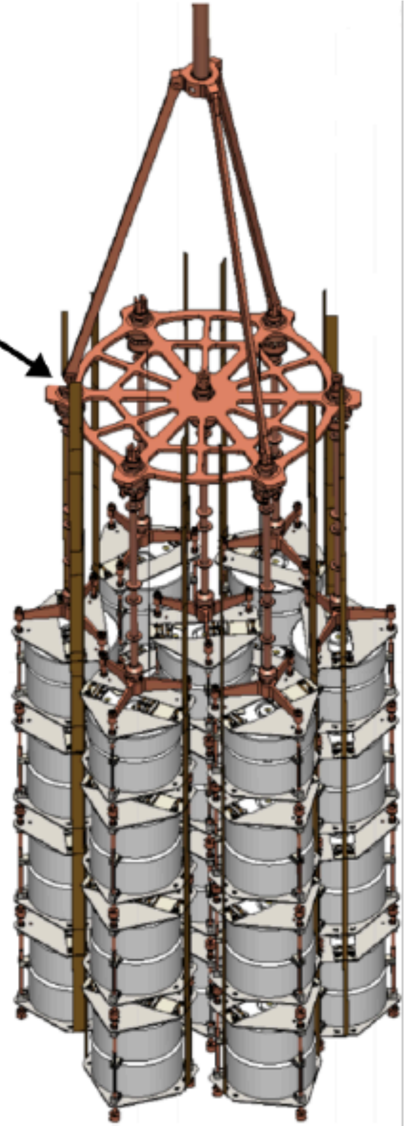
PRL 111 (2013) 122503



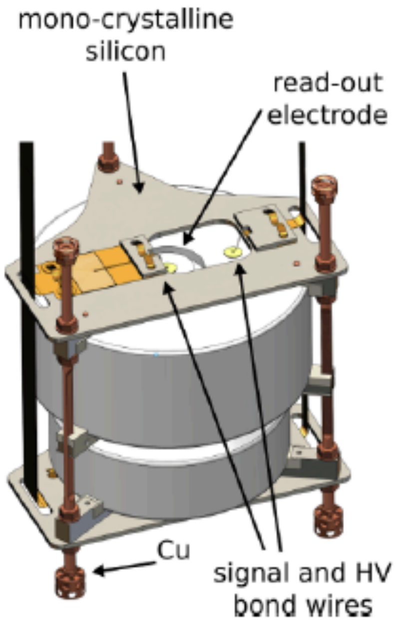
GERDA II Upgrade

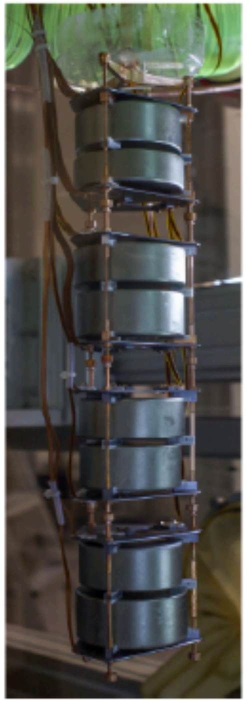
- 30 ^{enr}BEGe (20 kg) detectors produced at Canberra. 5 units already deployed in GERDA I[EPJC 75 (2015) 39]
- New lower mass holders
- Spring loaded contacts changed to wire bonded to improve contact quality





- New low-mass low-activity FE electronics low Rn emnation coax cables and detector-to-FE contacts



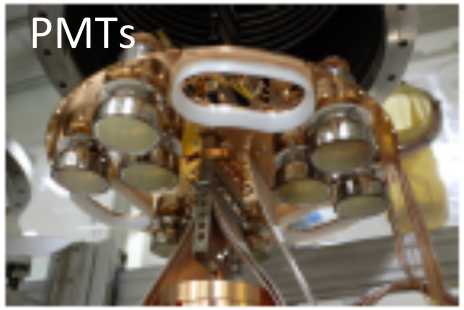


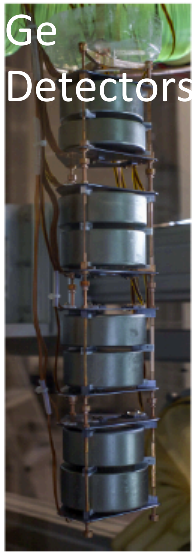
GERDA II: LAr Readout as Veto

LAr Scintillation Light readout to Veto radiation releasing energy both in LAr & in Ge.

Instrumentation:

- 16 PMT (9 top / 7 btm)
- 800 m fibers coated with WLS + 90 SiPMs)
- Nylon minishoud around each Ge string coated with WLS

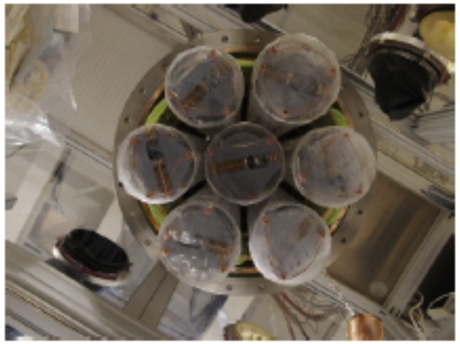


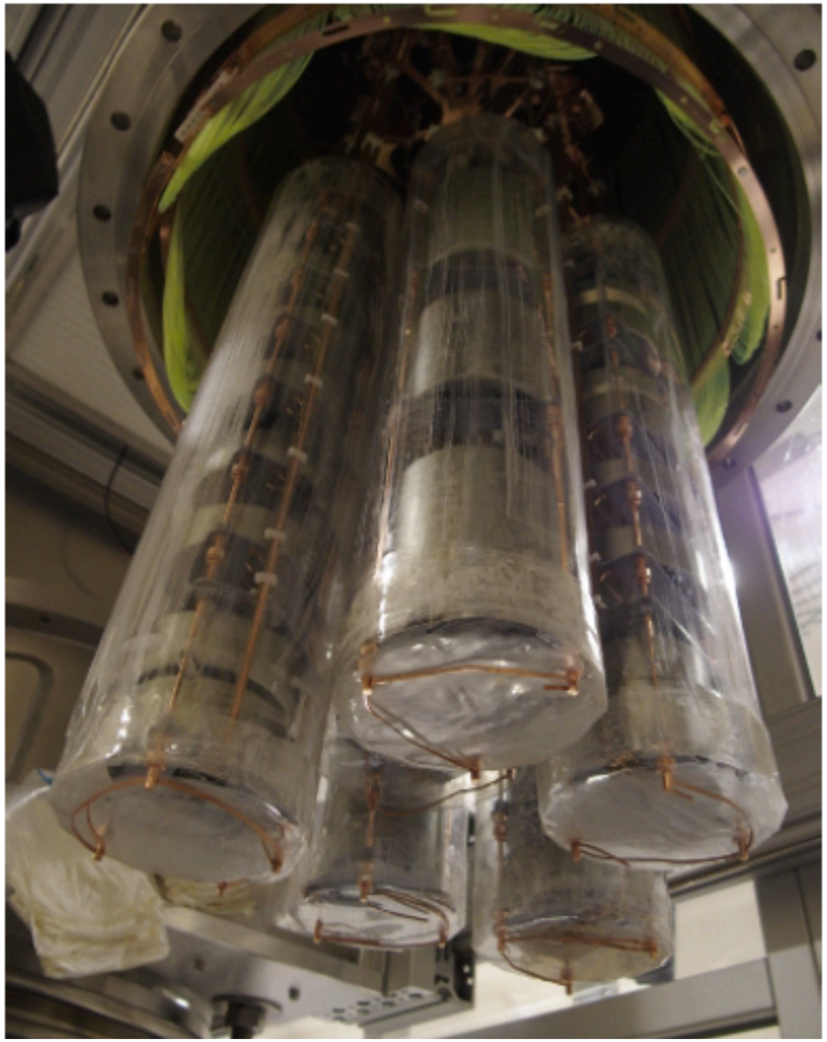


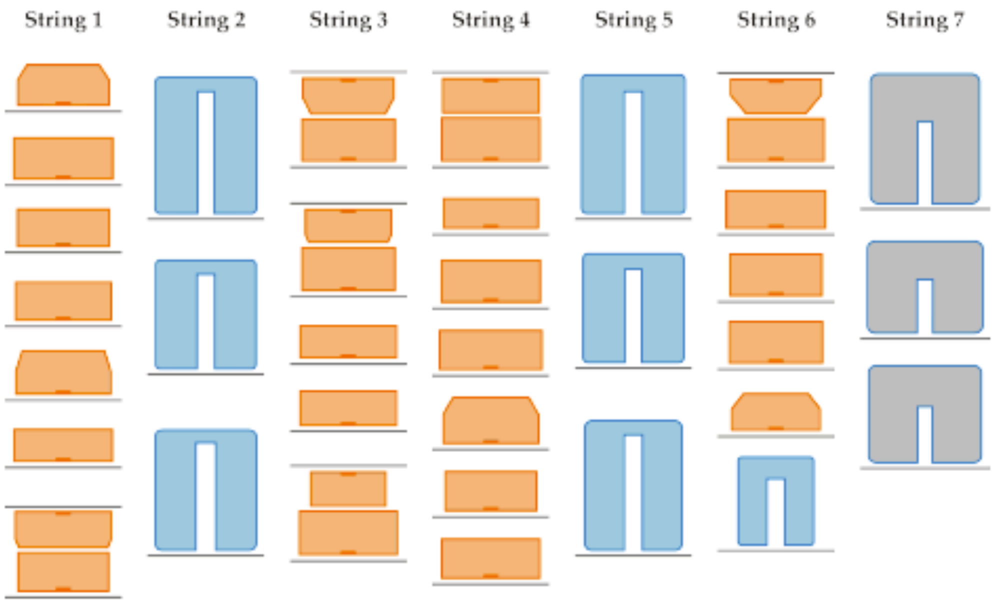
GERDA II: Final configuration

- Deployed in Dec 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

⇒ 35.8 kg of enr detectors

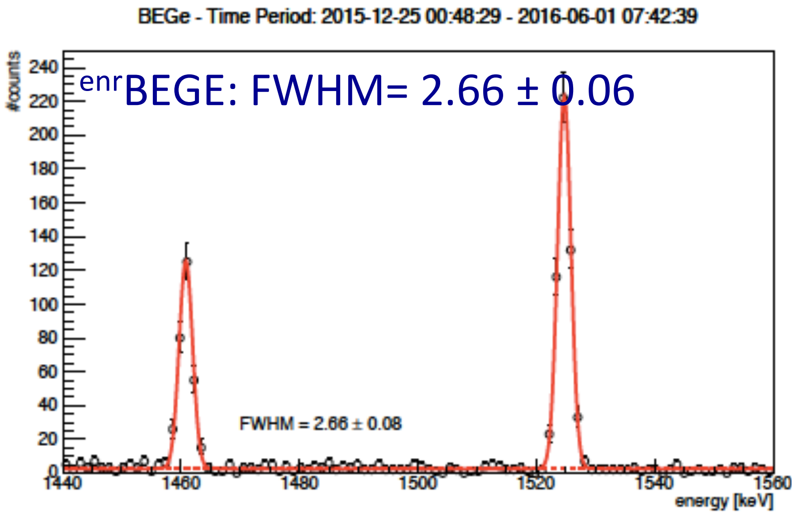




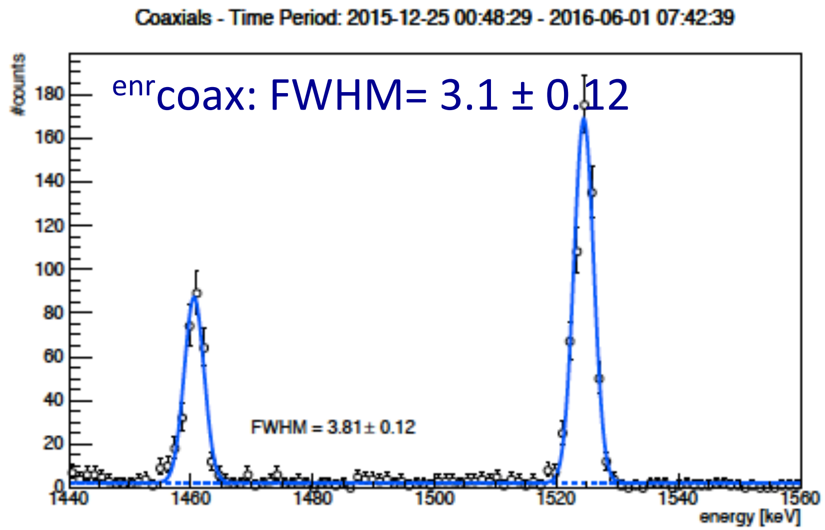


- **All Working**
- **Few show reverse current after months of operation in LAr. Some detectors show instabilities-> not used for analysis**

GERDA: Superior En Resolution of PHY-DATA

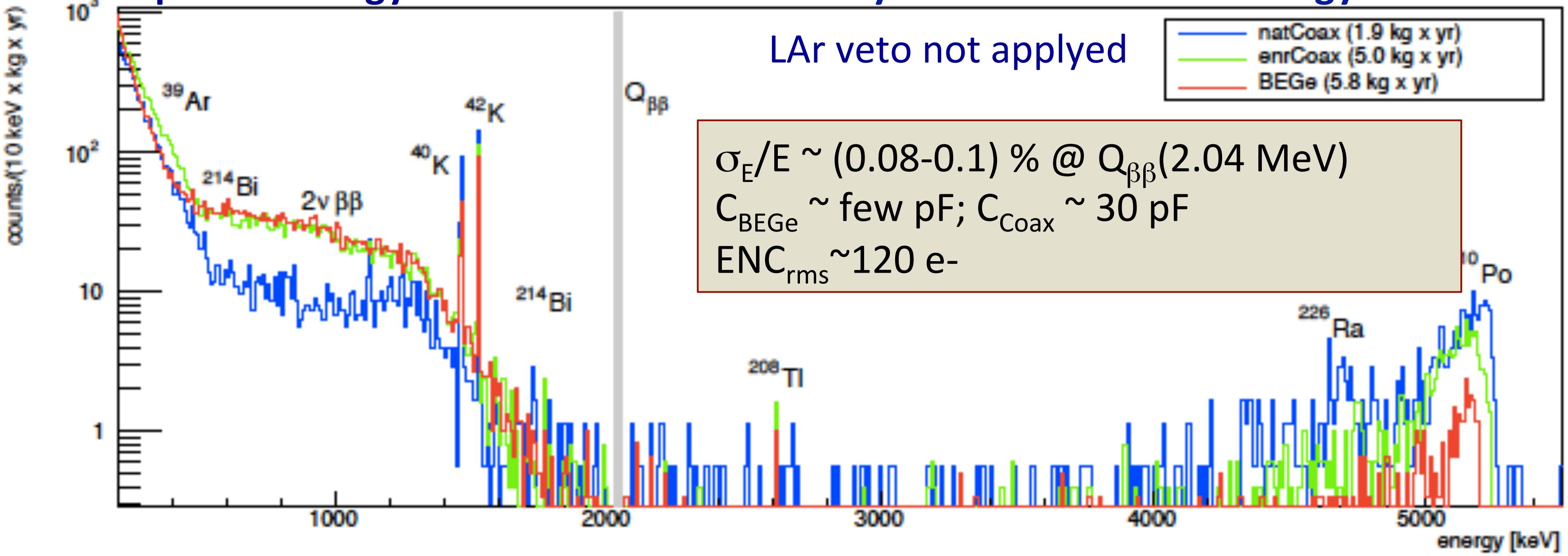


^{enr}BEGE: FWHM= 2.66 ± 0.06



^{enr}coax: FWHM= 3.1 ± 0.12

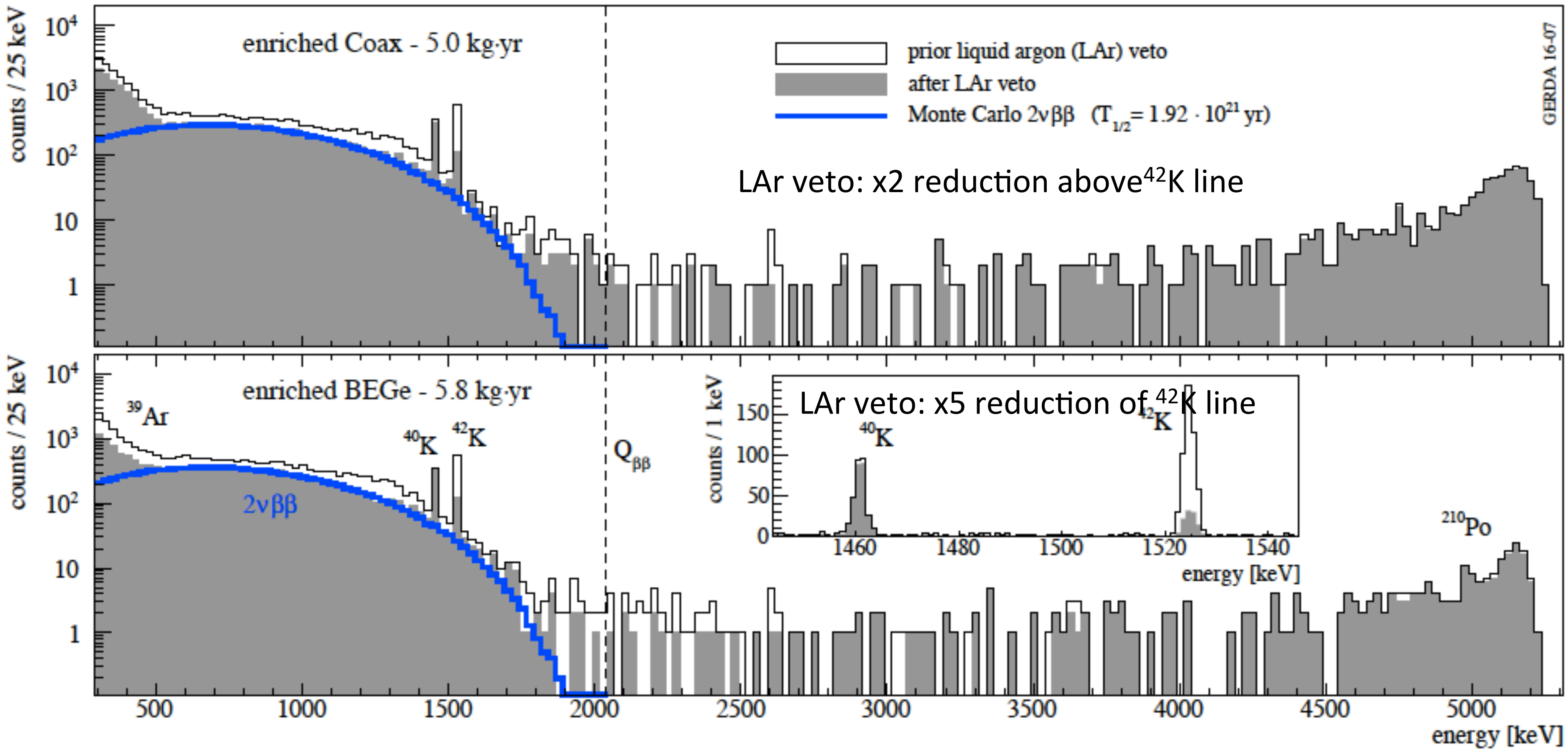
Superior Energy Resolution ←→ Stability of the Calibrated Energy Scale



LAr veto not applied

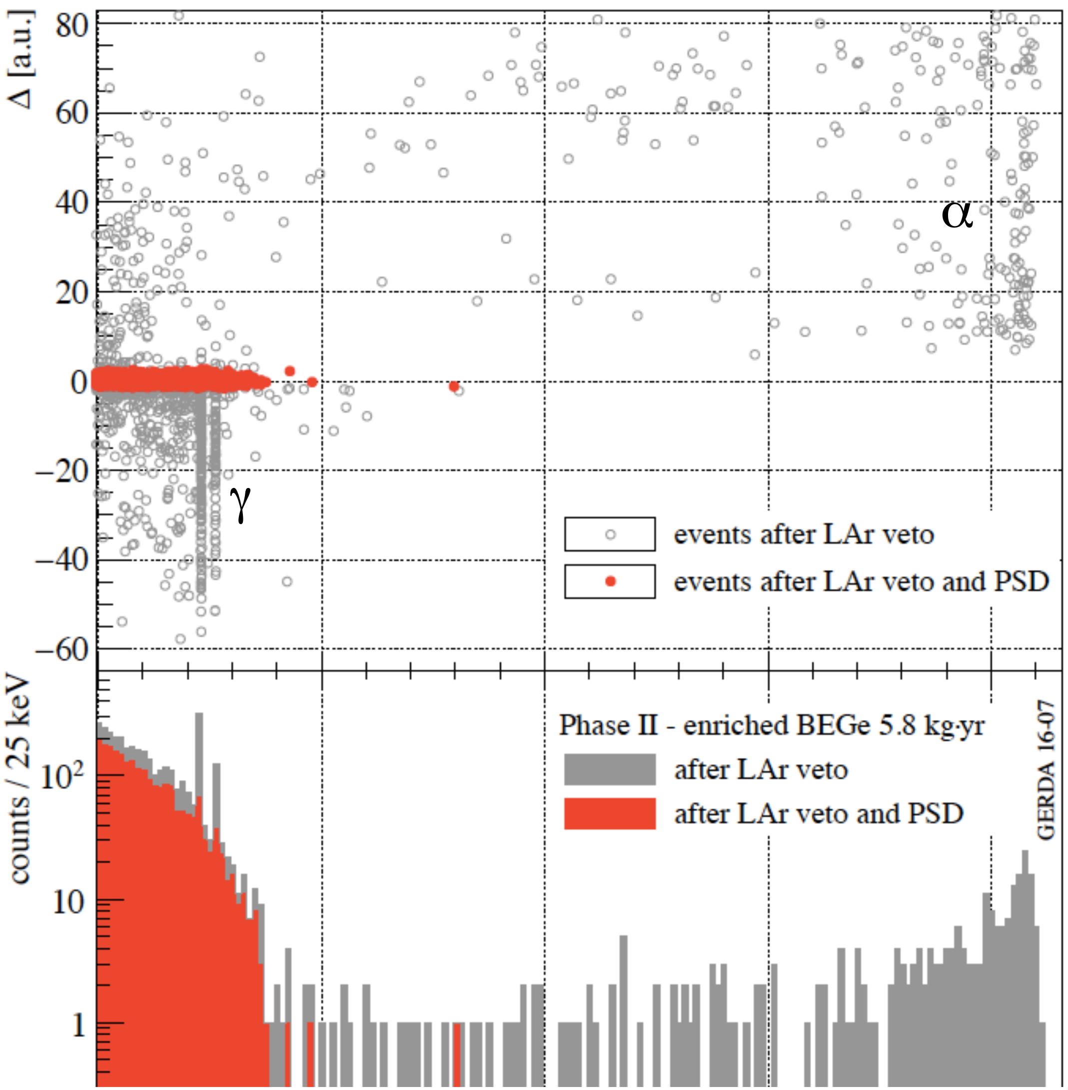
σ_E/E ~ (0.08-0.1) % @ $Q_{\beta\beta}$(2.04 MeV)
C_{BEGe} ~ few pF; C_{Coax} ~ 30 pF
ENC_{rms}~120 e-

GERDA II: COAX and BEGE – 10.8 kg yr



Data Blinded in an ROI +/- 20 keV around $Q_{\beta\beta}$=2039 keV

GERDA: The Pulse Shape Discrimination



The *current* (dq/dt) waveform time profile is used to discriminate:

- Particle position
  - surface vs bulk,
  - at readout electrode vs bias electrode
- Particle type (α,γ)
- Method is calibrated with point-like event proxies as double escape peak (DEP) of 2.6 MeV calibration γ-line, Compton Edges

Efficiency

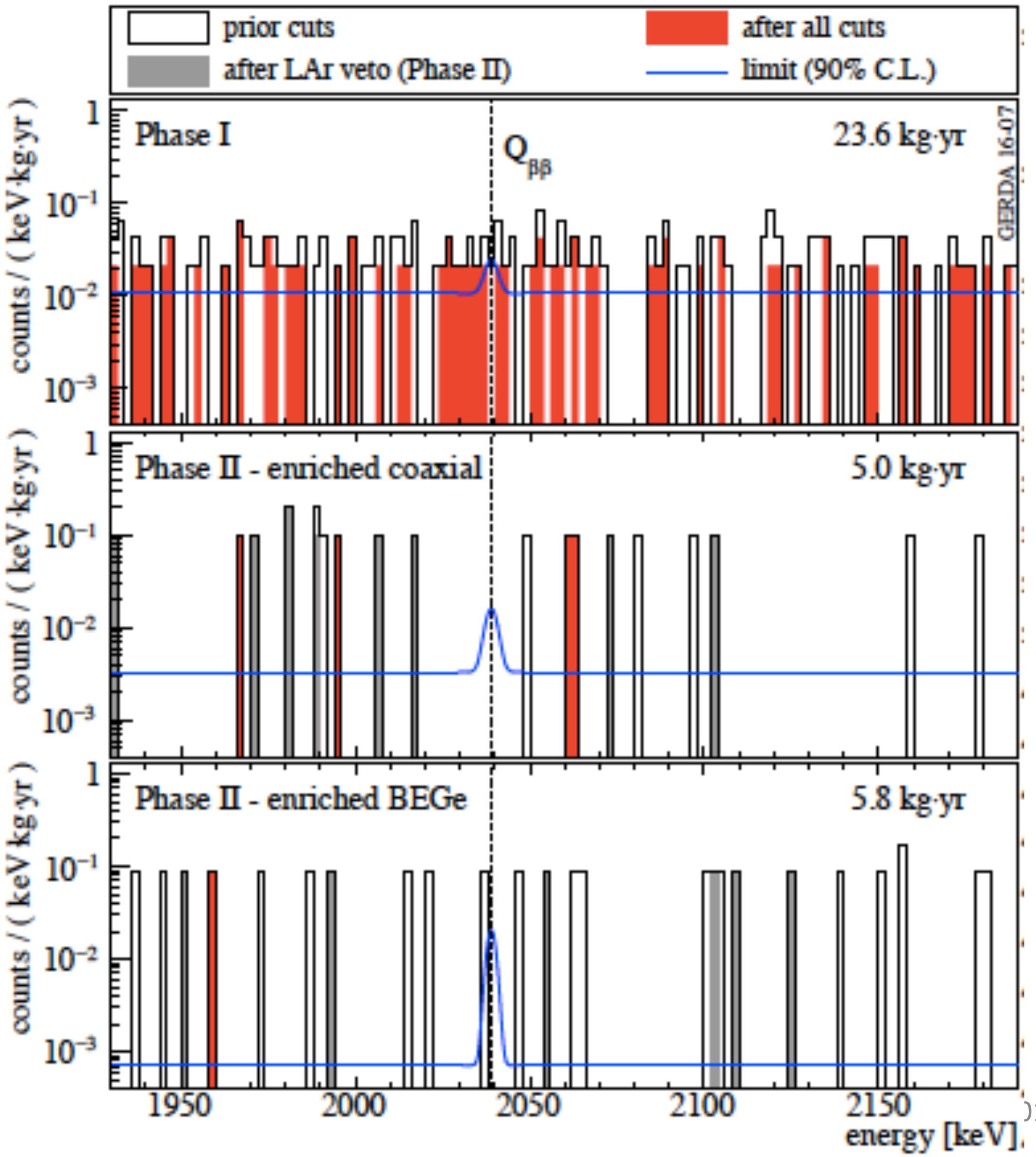
- DEP=(87.3 ± 0.2 ± 0.8)%
- 2νββ=(85.4 ± 0.8 ± 1.7)%

In the full fit window 1930-2190 keV only 1 evt remain

$BI_{BEGE}= 0.7^{+1.2}_{-0.5} \times 10^{-3}$ cts/kev•kg•yr

Quasi-Zero-Bckgrd Experiment !!

Recent Results



Fit Window : 260 keV
Performed Profile Likelihood fit of the 3 data sets

- B (constant) + Signal (Gaus($Q_{\beta\beta}$,σ_E))
- 4 free parameters in the fit B_{PI}, B_{PII}^{coax} , B_{PII}^{BEGe}, $1/T_{1/2}^{0\nu}$
- Systematics folded in

$T_{1/2}^{0\nu}$ > 5.2 x 10^{25} yr @ 90% CL

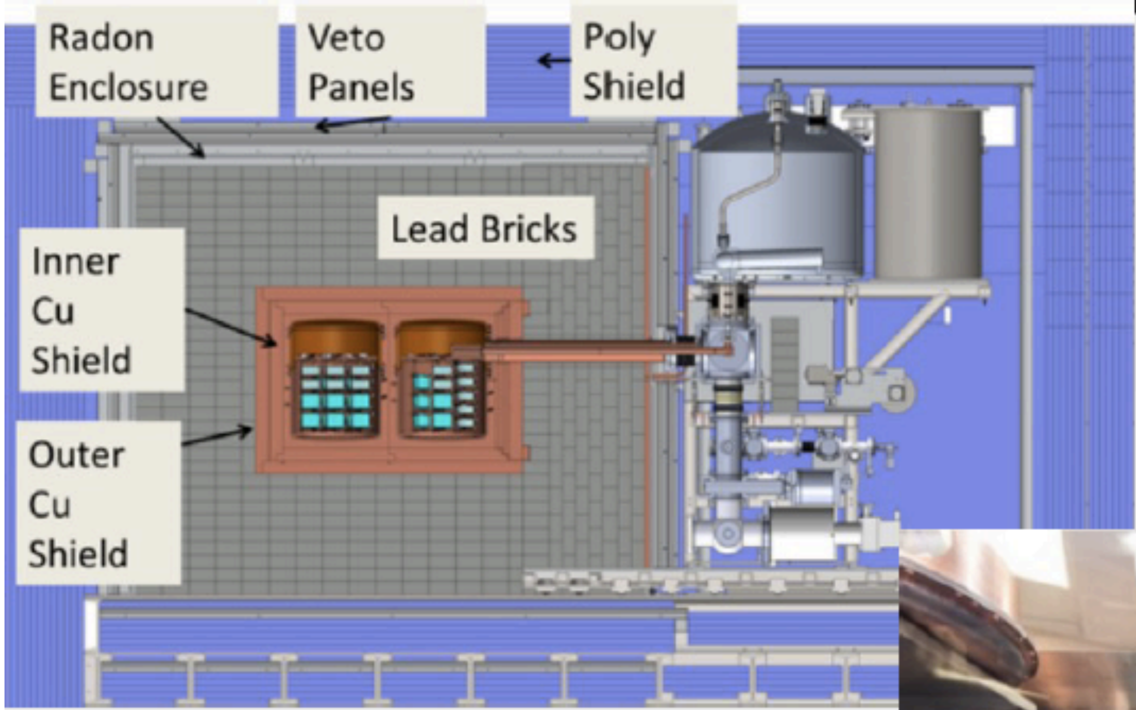
Simulated Median sensitivity:
$T_{1/2}^{0\nu}$ > 2.4 x 10^{25} yr

Eventually $T_{1/2}^{0\nu}$ > 1.0 x 10^{26} yr

Experiment w. lowest bckgrd and higher En. Res.

BI_{BEGE}= 7 $^{+1.2}_{-0.5}$ x 10^{-4} cts/kev•kg•yr
BI_{COAX}= 35^{+21}_{-15} x10^{-4} cts/kev•kg•yr

Majorana Demonstrator @ SURF



29 kg ^{76}Ge detectors (87% enr) in conventional copper/lead shield (+15 kg ^{nat}Ge detectors)

point-contact detectors →
  rejection surface evt + multiple int.

ultra-clean copper ("home made")
+ cables + …

goal: prove design for ton scale

proto-type module:
  10 detectors, 2014-2015

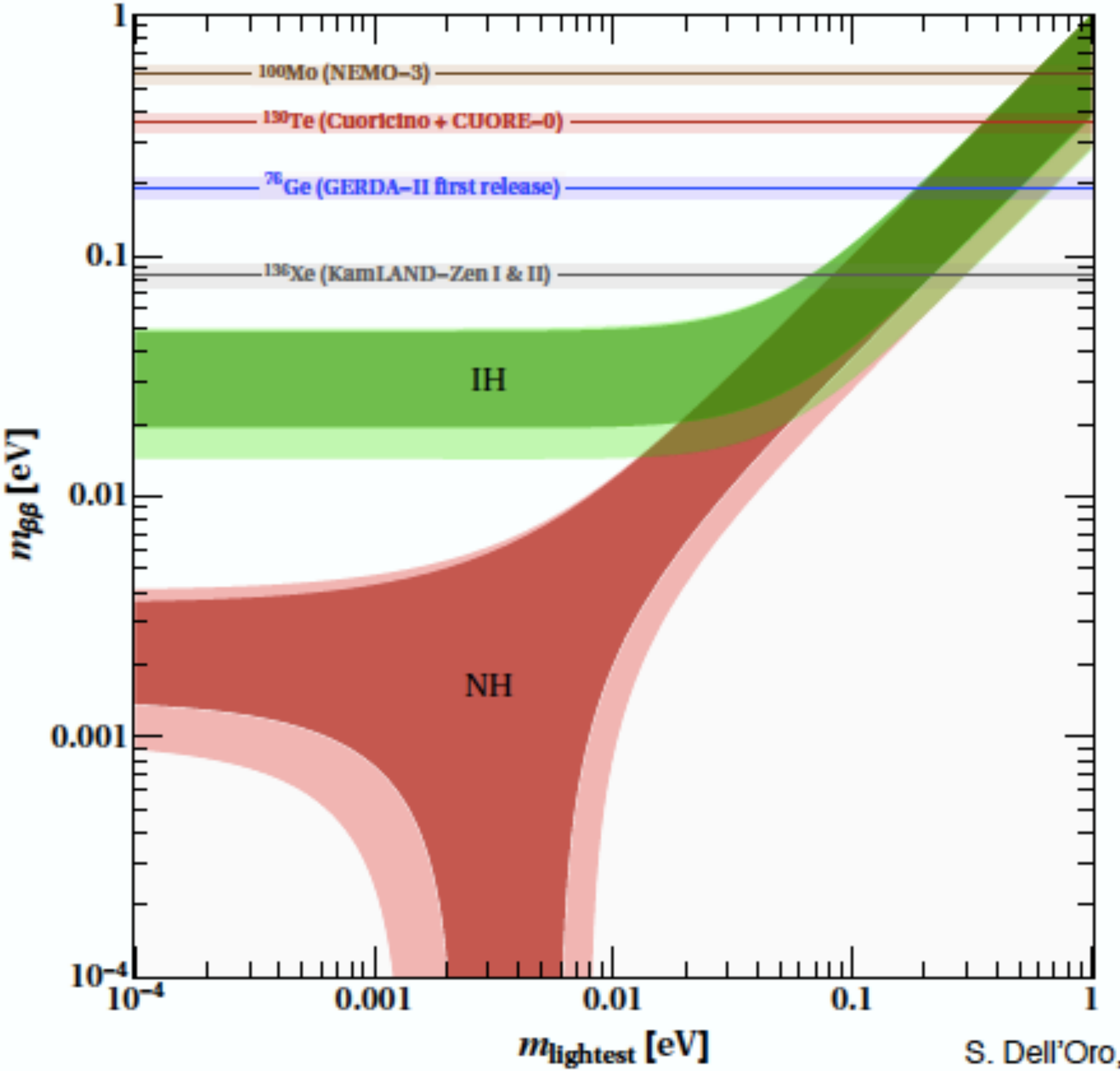
Module 1
  29 detectors, 2015 first installation
  running since Jan 2016

Module 2:
  29 detectors, taking data since Aug

Next Generation-Germanium

- After several years of regular contacts and information exchange between the two Collaborations, last week in Atlanta (US) a new Collaboration NG-Ge has formed
- Bulk of Collaboration: GERDA + Majorana open to new collaborators
- Goal:
  - Realize a new $0\nu\beta\beta$ ^{76}Ge project to go ahead GERDA and Majorana Demonstrator scales
  - Active Ge Mass: 150-200 kg depending on funds
  - Achieve BI ~ 10^{-4} cts /(kev•kg•yr)
- Site: LNGS
- LOI: Expected Beginning 2017

Experimentl results: The Slow approach to the IH



S. Dell'Oro, Presentation at NuFact 2016

Comparison of Ge vs Xe & Te projects

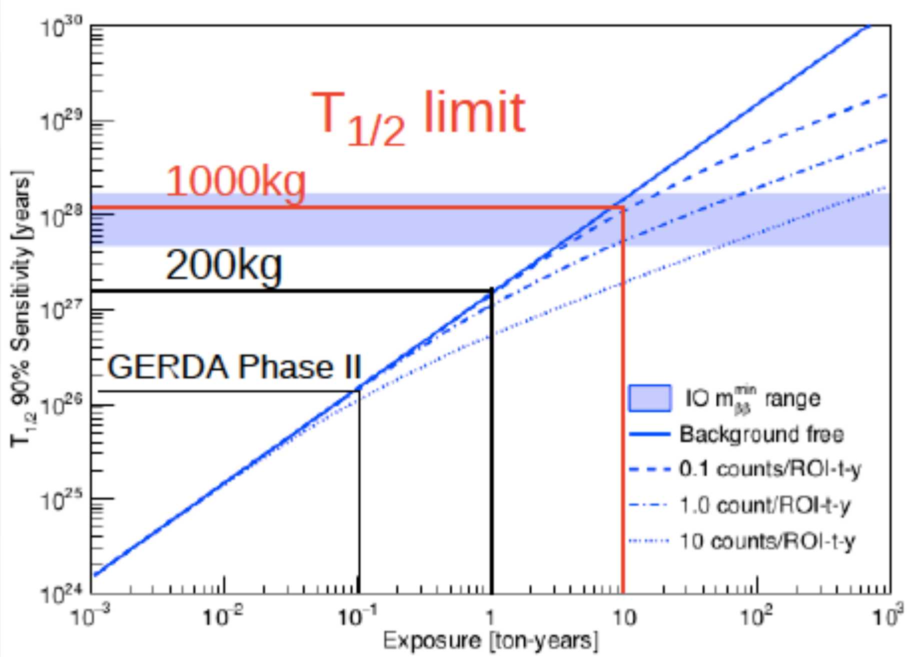
Achieved in blue

	Total Mass of isotope [kg]	Expected/ Achieved BI [cts/keV·kg·y]	Expected/ Achieved FWHM [keV]	Exposure [kg·y]	$T_{1/2}$ Sensitivity (90%CL) [y]	m_{ee} Sensitivity (90%CL) [meV]
Gerda II	31	10^{-3}	< 4	~100	$> 10^{26}$	90-150
Gerda II	31	$<=10^{-3}$	3.0-4.0	10.8	$5.2 \cdot 10^{25}$	160-260
GERDA I	16	$\sim 10^{-2}$	3.2-4.8	21.6	$2.1 \cdot 10^{25}$	200-400
Majorana	30	$<10^{-3}$	< 4		$> 10^{26}$	
Cuore	206	10^{-2}	5	1000	$9.5 \cdot 10^{25}$	51-133
Cuore 0	10.9	$0.6 \cdot 10^{-2}$	5.1	9.8	$2.7 \cdot 10^{24}$	0.3 – 0.7
Cuoricino	11.6	$15.3 \cdot 10^{-2}$	6.3	20	$2.8 \cdot 10^{24}$	0.3 – 0.7
n-EXO	5000					down to 8
EXO 200 ult.			73			50
EXO 200	200	$1.7 \cdot 10^{-3}$	112	100	$1.1 \cdot 10^{25}$	190-450
KZ ultimate	600-800					20
KZ comb.				130	$1.1 \cdot 10^{26}$	60 -160
Kam-Zen II	348	$3.0 \cdot 10^{-4}$ (1m FV)	350	504	$9.6 \cdot 10^{25}$	
Kam-Zen I	320		285	89.5	$1.9 \cdot 10^{25}$	

Conclusions

- $0\nu\beta\beta$ is actively searched since 60 yrs.
- This year attained by KZ the 10^{26} yr lower limit on $T^{1/2}_{0\nu}$ of ^{136}Xe by KamlandZEN
- ^{76}Ge experiment showed to have superior Energy Resolution (important handle vs bckgrd) and to have reached the background free regime where $T^{1/2}_{0\nu}$ ~ *Exposure*
- Top of IH region not yet attained: the next generation 200 kg-Ge project, KZ-800,CUPID, n-EXO aims to reach it *($T^{1/2}_{0\nu} \sim 10^{27}$).*
- Ton-scale experiments will reach the $T^{1/2}_{0\nu} \sim 10^{28}$ *yr*
- Other NSM Mechanism than Majorana Mass could contribute to $0\nu\beta\beta$: LRSM (so far not confirmed at LHC) should find $\Delta L=2$ and W_R

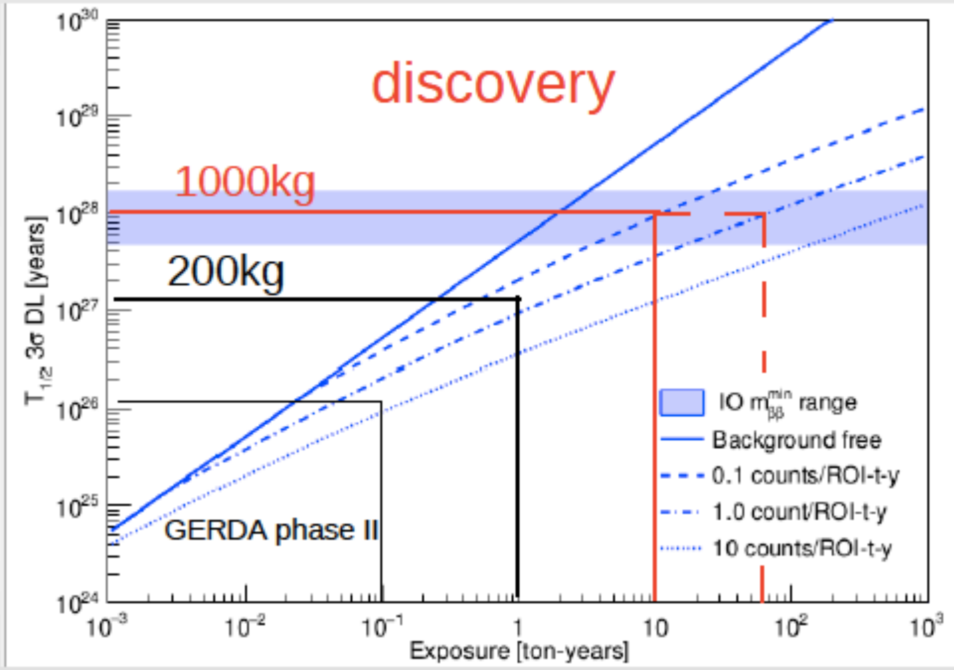
^{76}Ge sensitivity limit + discovery



plots by Jason Detwiler based on
m_{ee} = 18 meV, current matrix element calc.
GERDA numbers for efficiency & enrichment

GERDA Phase I ~ 30 cnt/(ROI t yr) - achieved
Phase II ~ 3 cnt/(ROI t yr) - achieved
future "200 kg" ~ 0.5 cnt/(ROI t yr)
"1000 kg" ~ 0.1 cnt/(ROI t yr)

discovery: 50% chance for a 3σ signal discovery



for discovery:
factor 10 worse in background
→ need factor ~6 in exposure

"background free" very important
(for all isotopes)