neutrinoless double beta ($0\nu\beta\beta$) decay experiments

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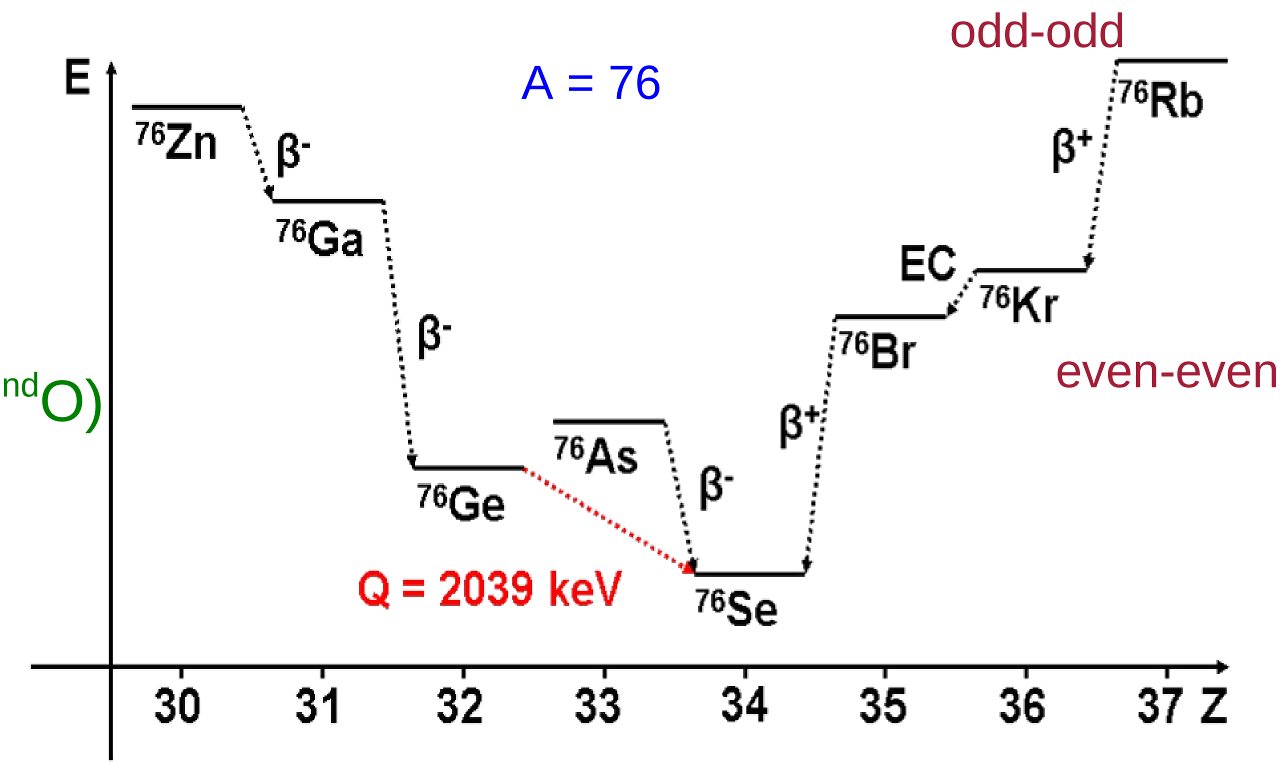
LAUNCH 17, Heidelberg, September 14, 2017

beta decay in isobars



single beta decay forbidden

double beta decay allowed (2^{nd}O)

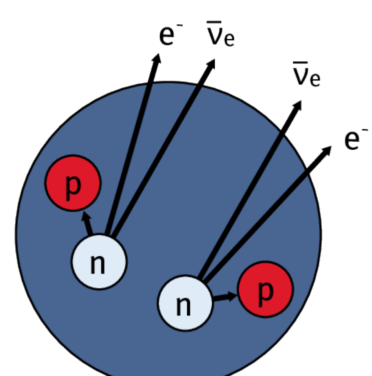
search in nuclear decay
for properties of ν !

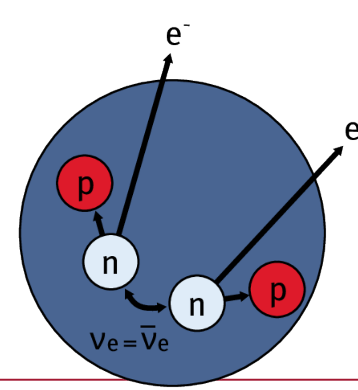
0νββ : violates lepton number ΔL=2

most interesting : is ν of Majorana type ?!

$\nu \equiv \bar{\nu}$

2νββ





0νββ

about  yr ago about  yr ago

about

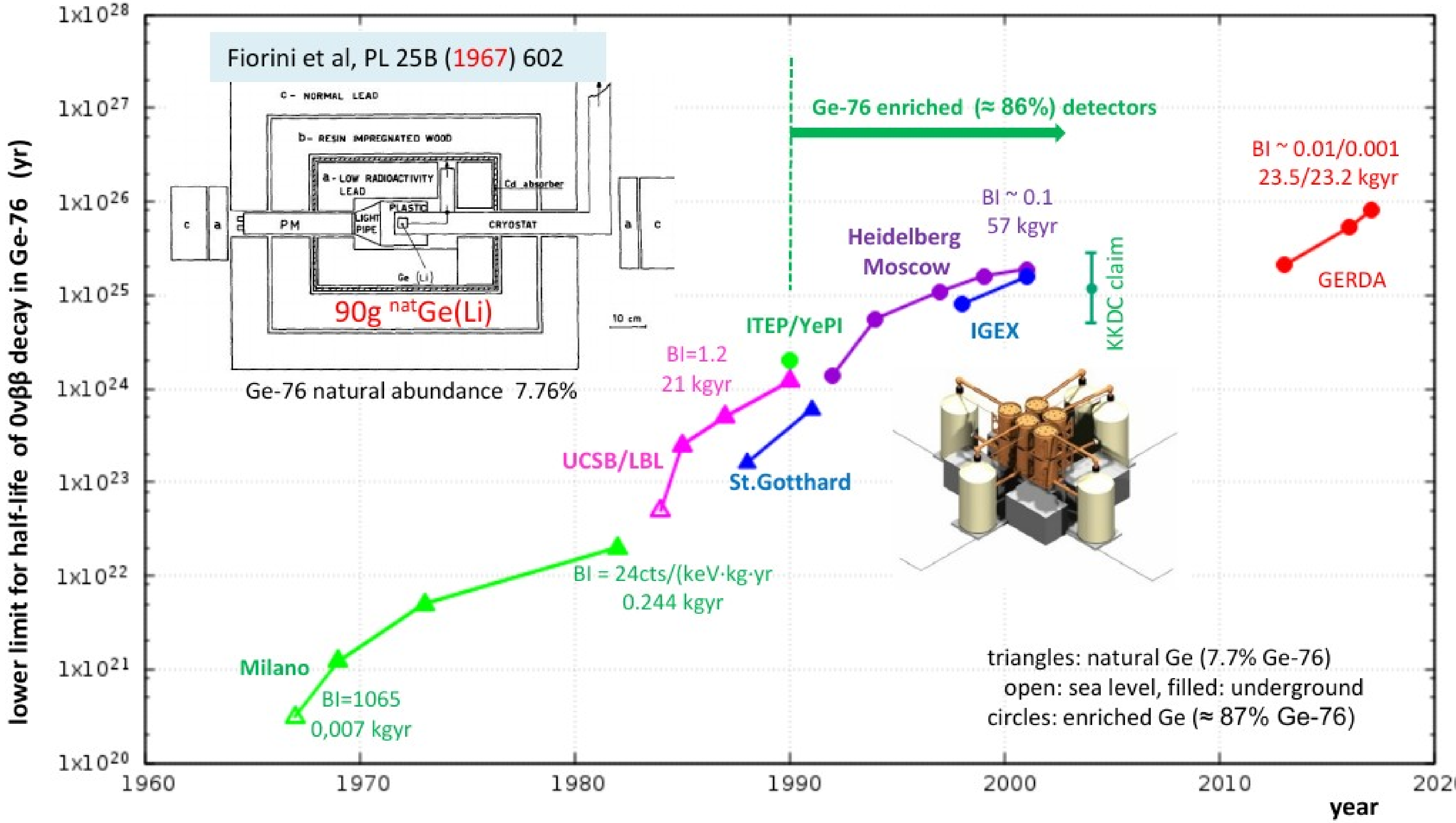
yr ago

double beta decay: M Göppert Mayer
J. Furry

many years of preparation

50 years of 0νββ decay search with Ge detectors

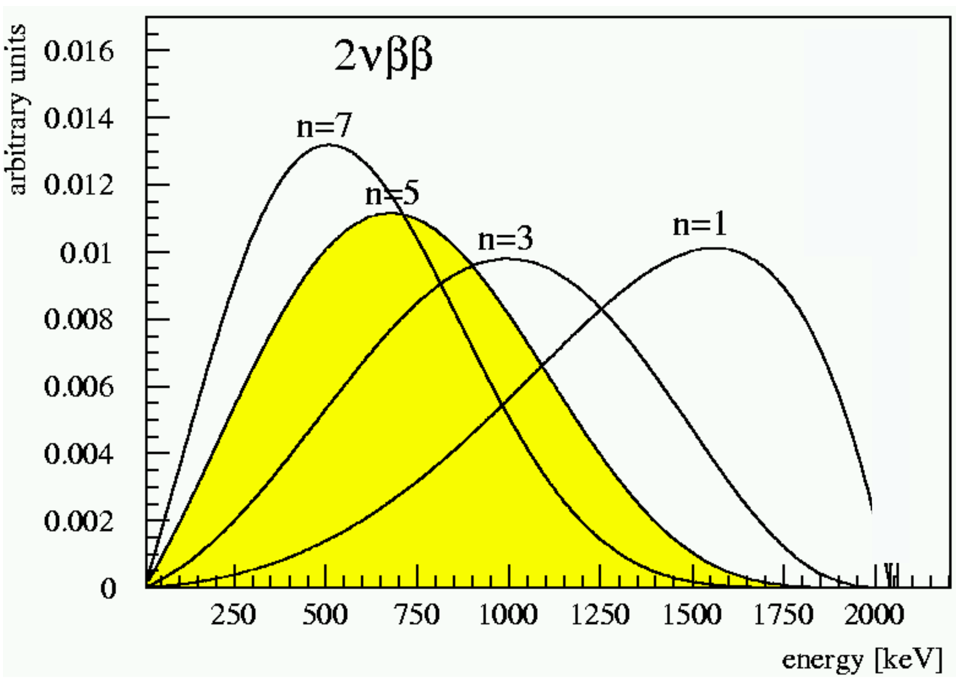
by KTK

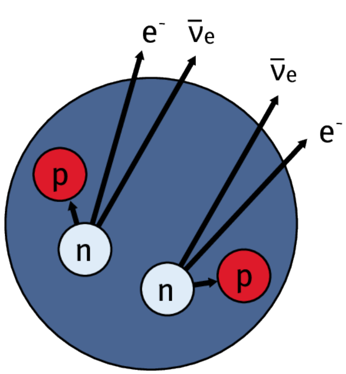


White Sands, NM, USA, 2015

spectrum: sum energy of both electrons

2νββ spectrum





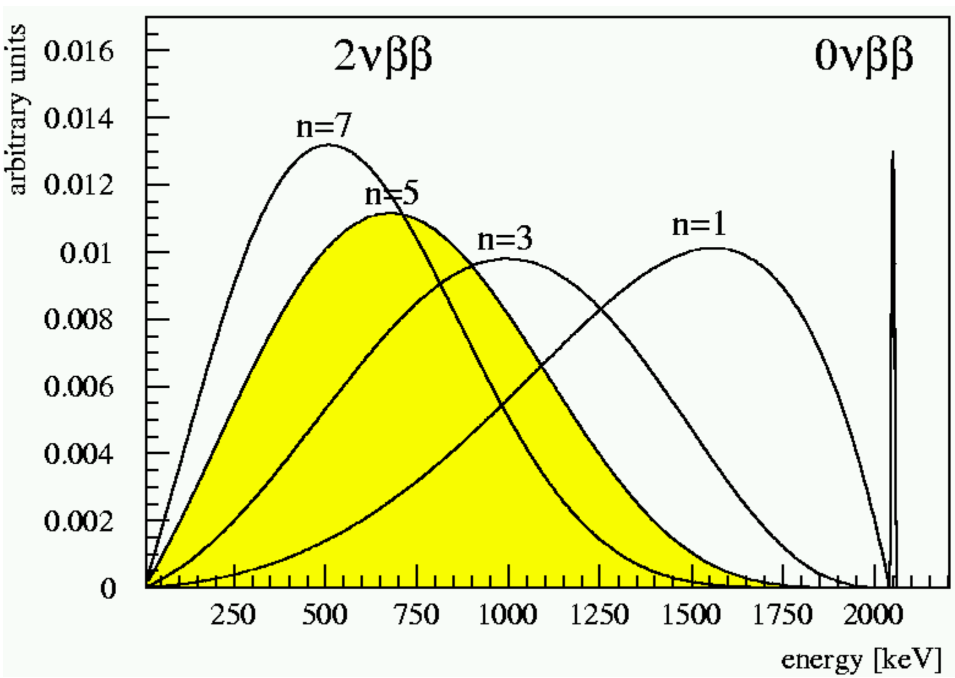
ν, Majoron,..

$2\nu\beta\beta$: $T_{1/2} \sim 10^{21}$ yr

$(10^{19} – 10^{24})$

spectrum: sum energy of both electrons

0νββ signal: peak at Q-value of reaction

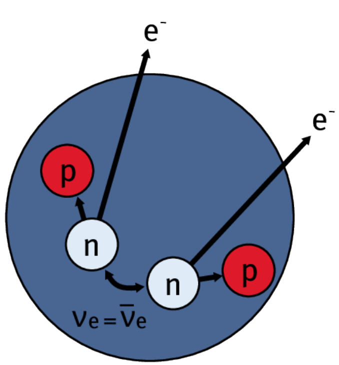


peak present ?

Majorana - nature

measuring: cts ⇒ half life

"Physics beyond SM"



ν, Majoron,..

2νββ: $T_{1/2}$ ~ 10^{21} yr

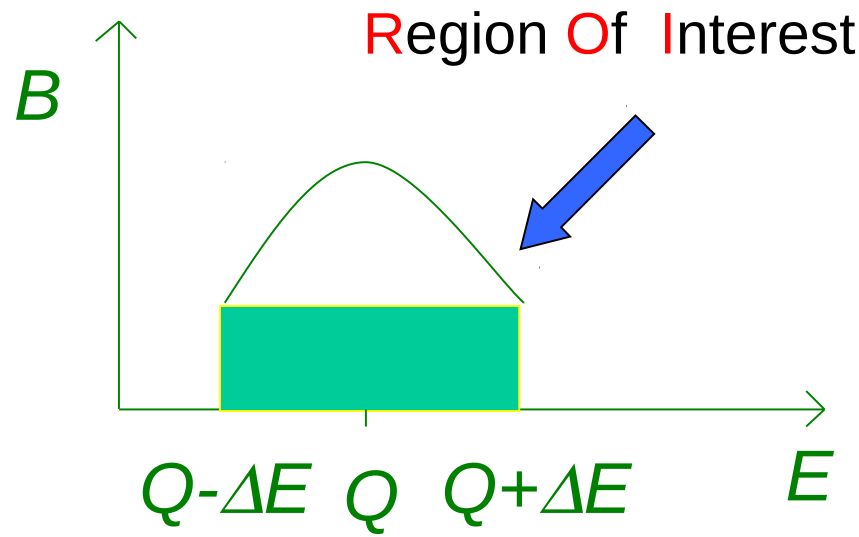
0νββ: $T_{1/2}$ > 10^{25} yr

extension of Standard Model

leptogenesis

sensitivity $S_{1/2}$ for $0\nu\beta\beta$

$$T_{1/2} = \ln 2 \bullet (N_A/A) \bullet M \bullet (N_{\beta\beta} / t)^{-1}$$



$N_{obs} \sim M * t$ für $b = 0$

$N_{BG} \sim M * t * \delta E * b$

sensitivity $\sim N_{obs} / \sqrt{N_{BG}}$

background ~ detector mass

$$S_{1/2} \propto a * \varepsilon * \sqrt{\frac{M * t}{\delta E * b}}$$

a : isotop. enrichment
ε : efficiency
M : mass
t : time of measurement
δE : energy resolution
b : background rate

relevant units for background index:
cts/(mol yr δE)

cts/(kg yr keV)

back of the envelope

assume background free; $T_{1/2} >> t$;

For half-lifes of $T_{1/2} = 10^{26}$ yr

$N_{\beta\beta} / t = 1$ event/yr

$$T_{1/2} = \ln 2 \cdot (N_A/A) \cdot M \cdot (N_{\beta\beta} / t)^{-1}$$

This is about 100 moles of isotope, implying ~kg

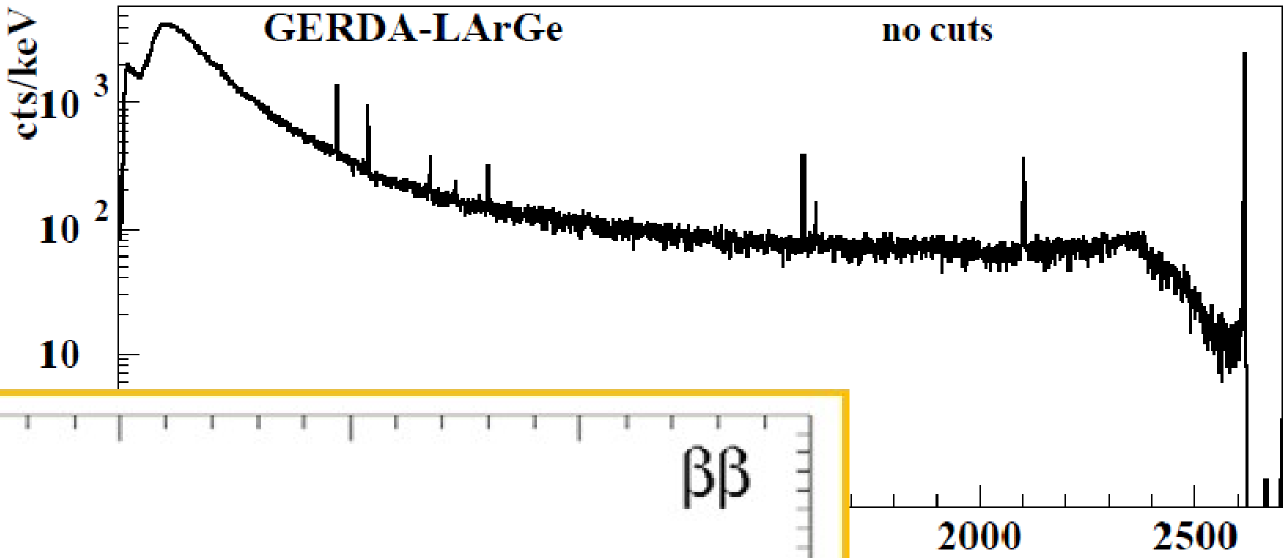
for ^{76}Ge : 21 kg @ 86% enriched

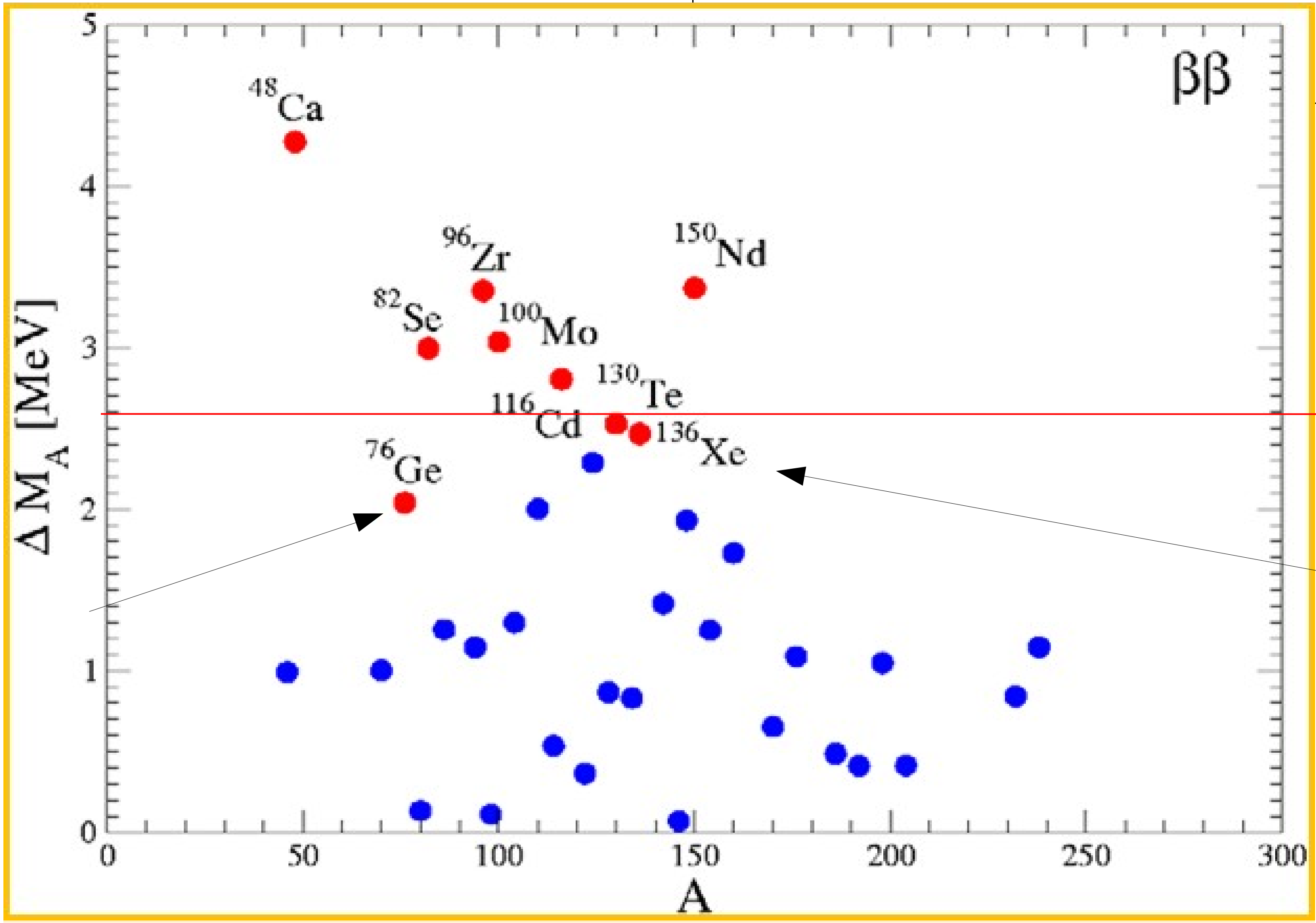
Now you only can loose:

nat. abundance a, efficiency ε, background B, ...

1g $^{76}GeO_2$ for 50 € (now 80-100€)

candidates





^{228}Th

2.615 keV

^{208}Tl

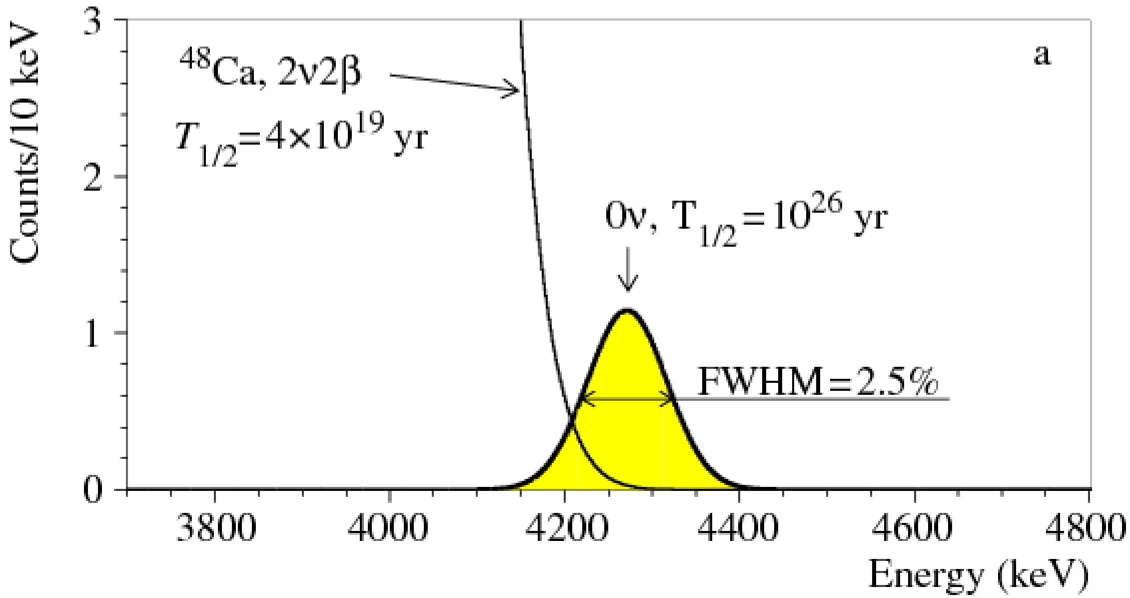
essentials for high sensitivity

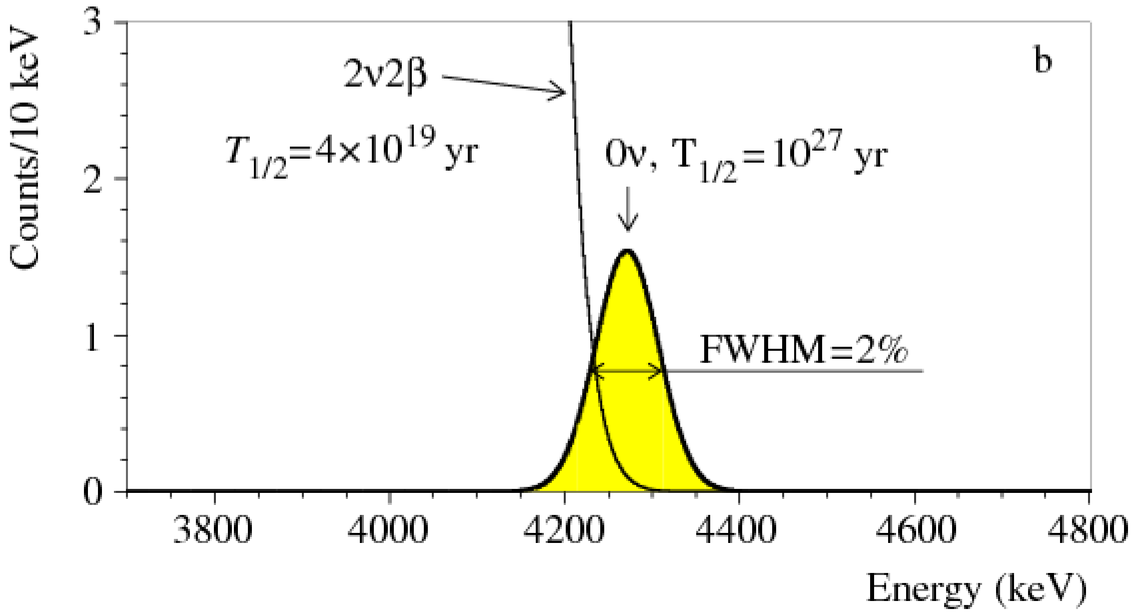
- large isotopic mass
- extended stable data taking
- high energy resolution

} exposure

resolution

^{48}Ca





ratio 2ν/0ν !!!

FWHM = 2,**5** %

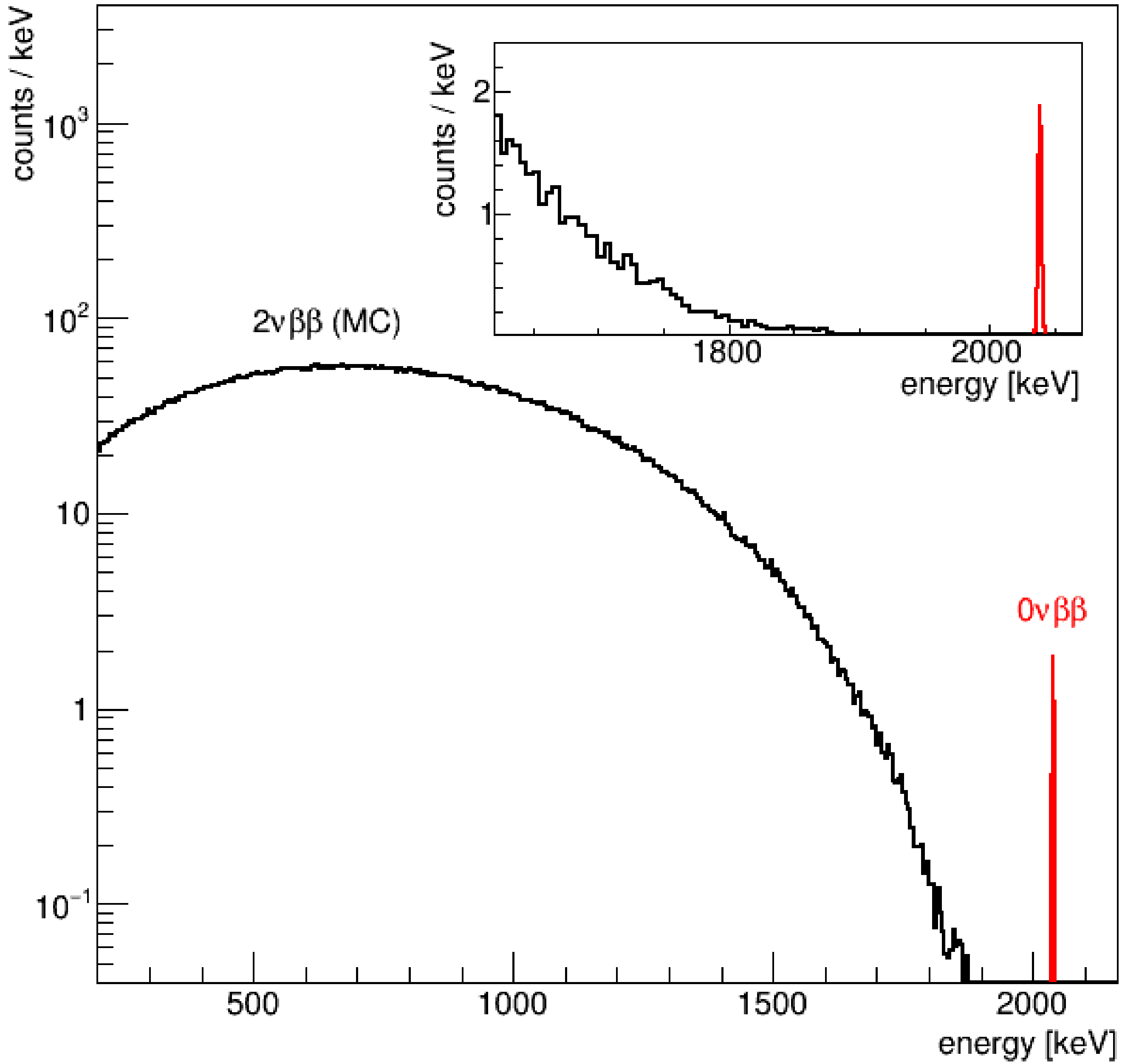
$T_{1/2} = 10^{26}$ yr

FWHM = 2,**0** %

$T_{1/2} = 10^{27}$ yr

⇒ **Ge dets: 0,2%**

resolution



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essentials for high sensitivity

- large isotopic mass
- extended stable data taking
  } exposure
- high energy resolution
- low background
  - radiopurity → special transports, UGL production
  - active and passive shielding → underground (reduced μ flux)

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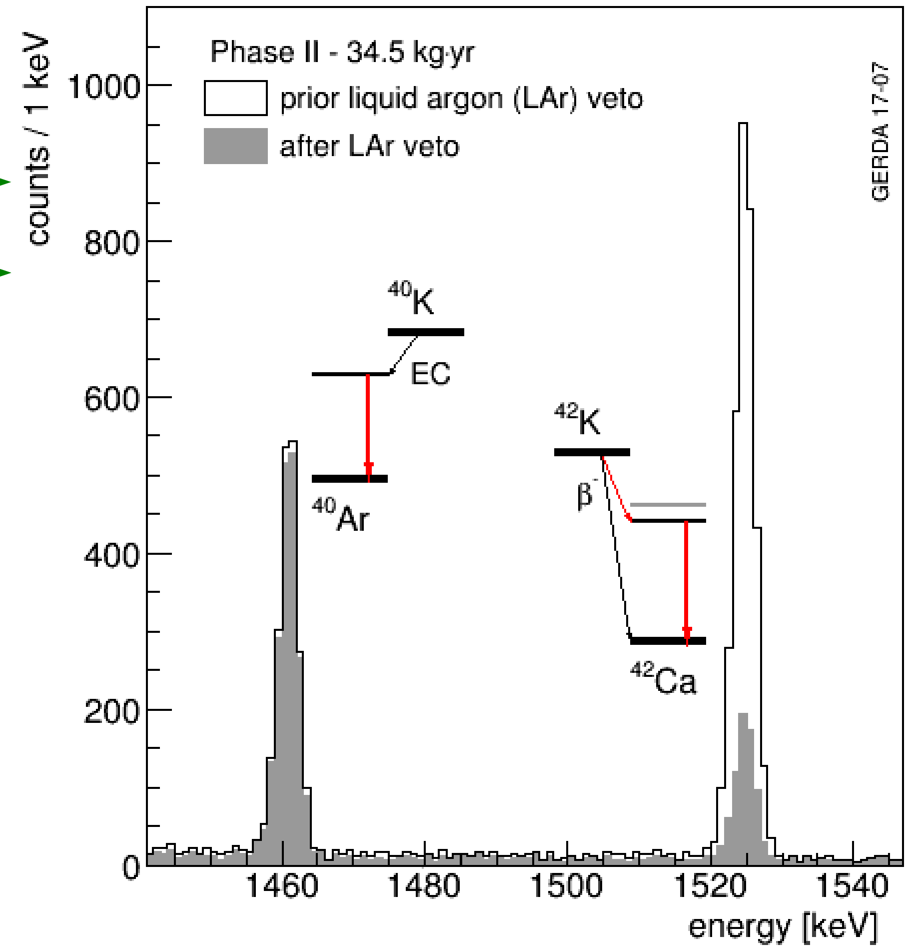

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- large isotopic mass
- extended stable data taking

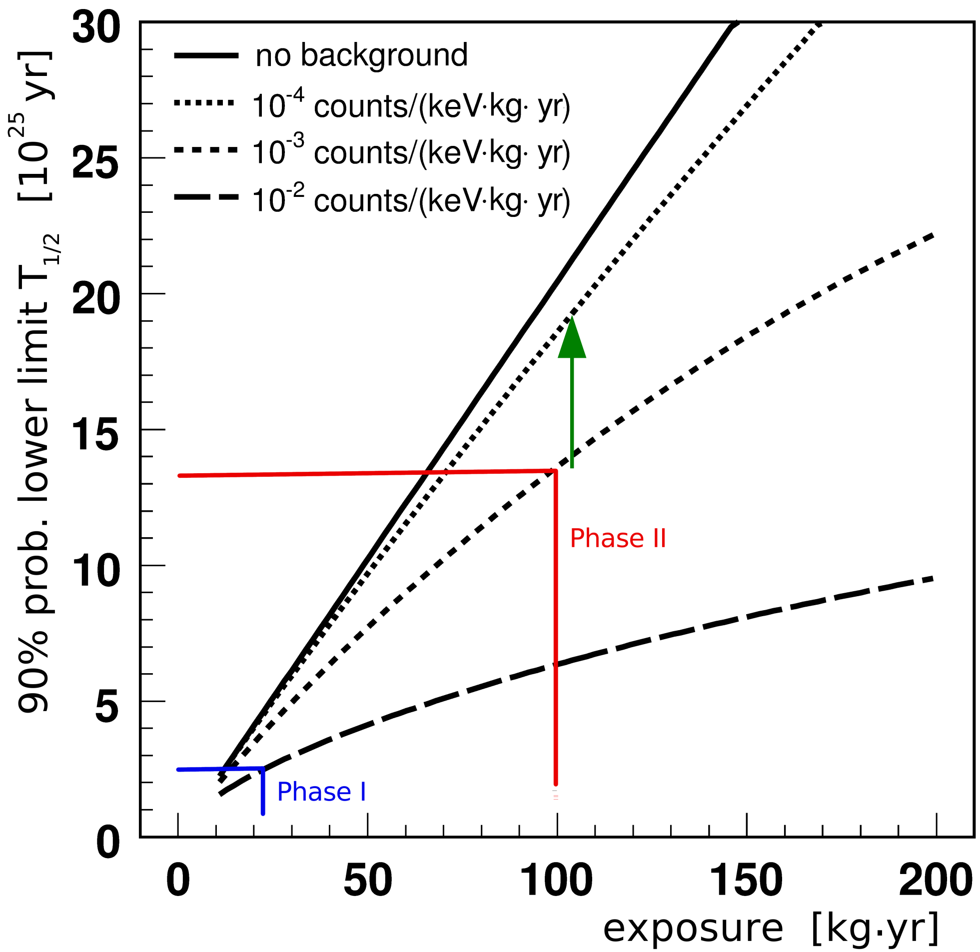
} exposure

- high energy resolution
- low background
  - radiopurity → special transports, UGL production
  - active and passive shielding → underground (reduced μ flux)
  - signal-sensitive analysis → PSD, Ba-tagging

essentials for high sensitivity

- large isotopic mass
- extended stable data taking
- high energy resolution
- low background
  - radiopurity
  - active and passive shielding
  - signal-sensitive analysis

} exposure

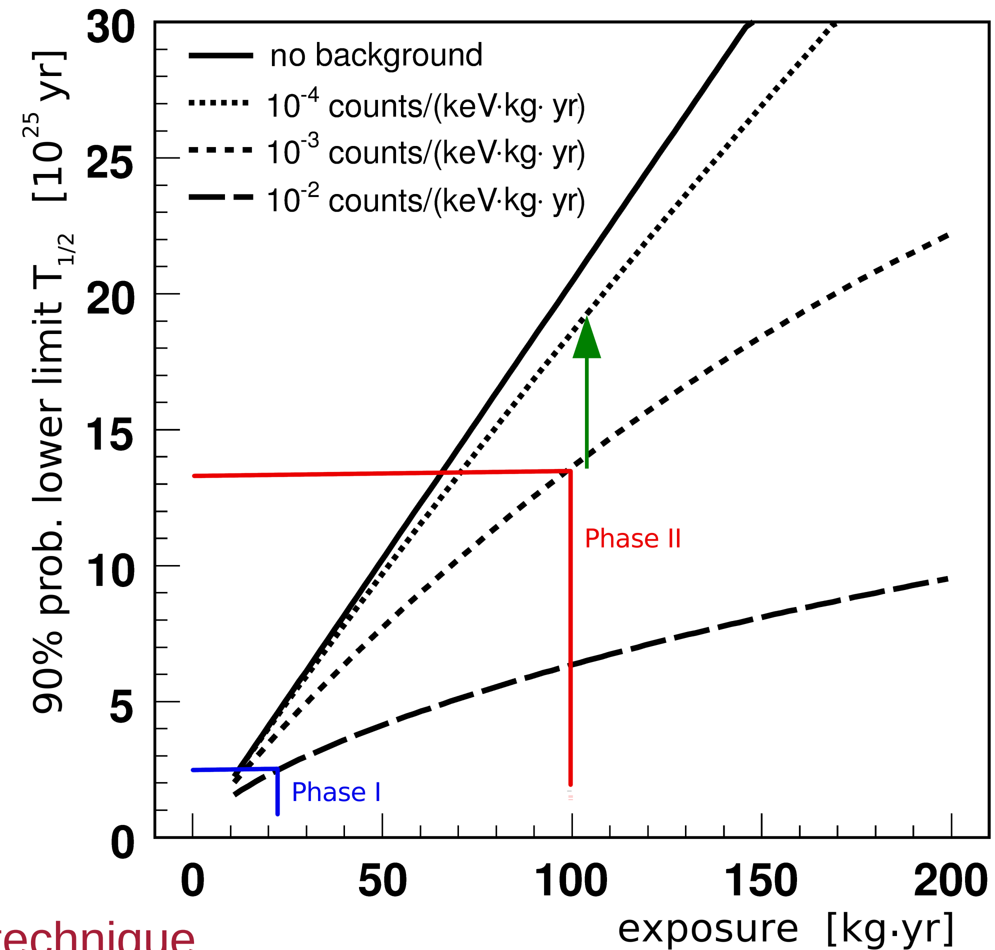


essentials for high sensitivity

- large isotopic mass
- extended stable data taking

} exposure

- high energy resolution
- low background
  - radiopurity
  - active and passive shielding
  - signal-sensitive analysis
- modelling of background (complete spectrum)
- statistical methods



- physical & chemical properties decide on technique

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

$m_{\beta\beta} = 17.5$ meV

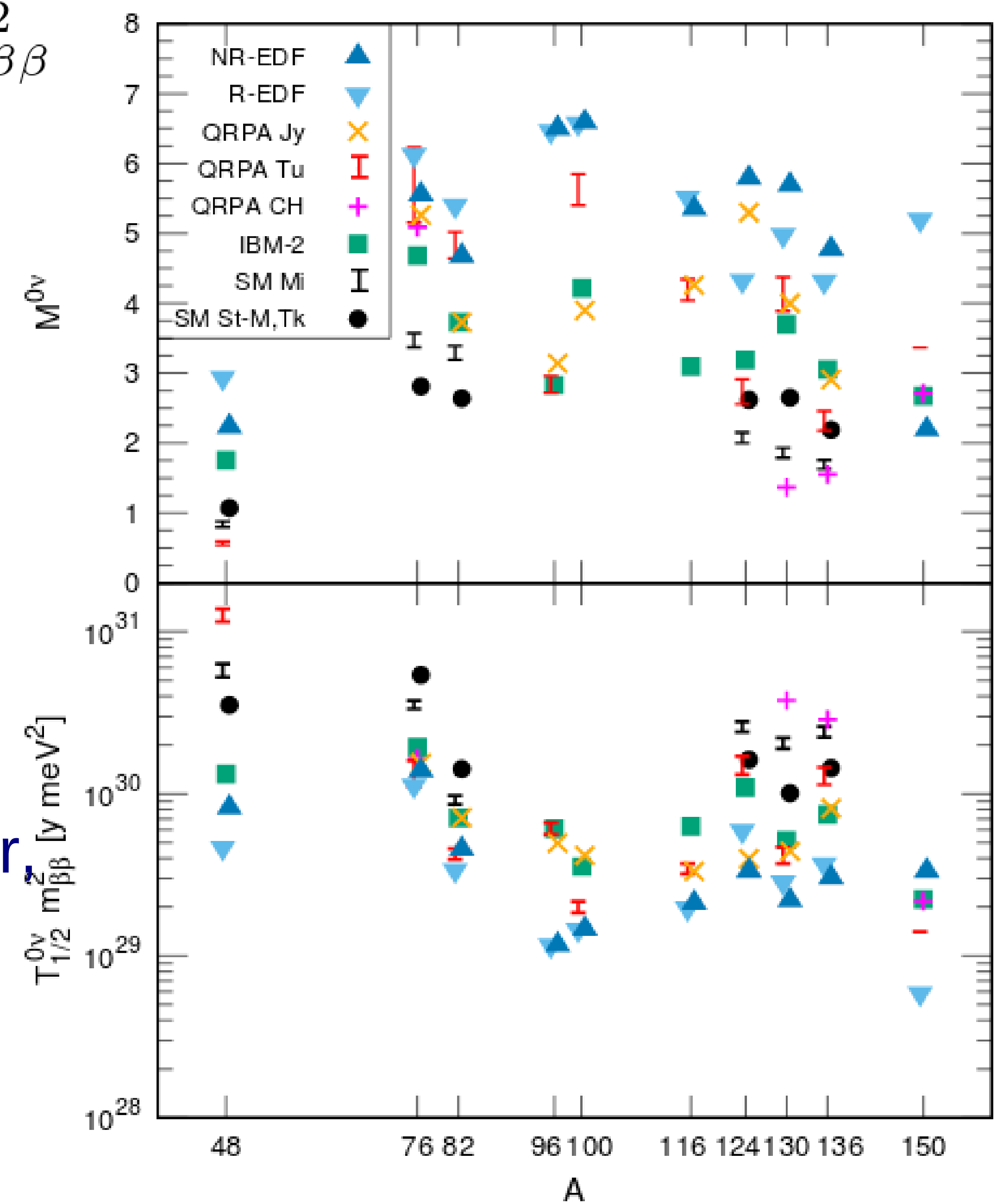
light neutrino exchange

main ('practical') isotopes

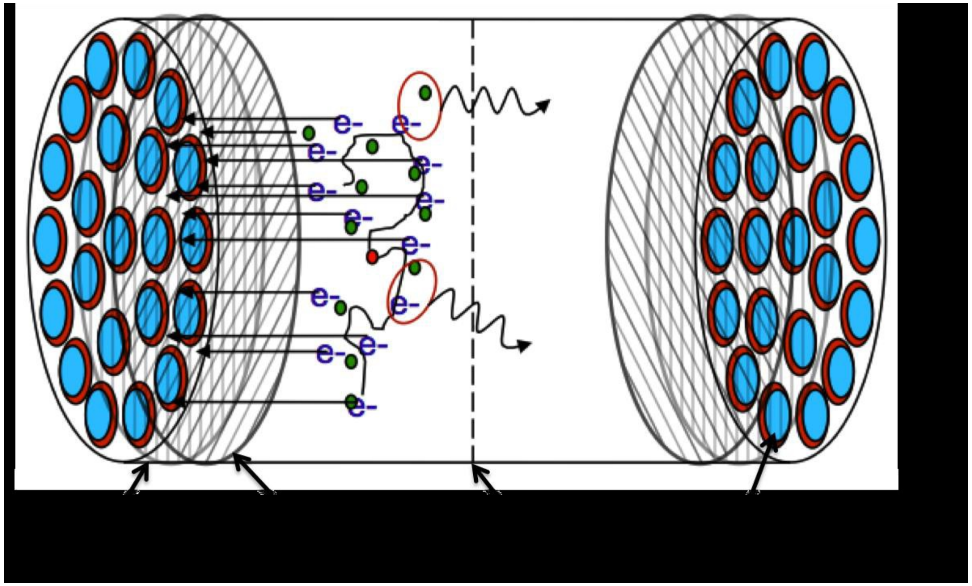
^{76}Ge, ^{130}Te, ^{136}Xe

techniques:
(liquid) scintillator, bolometer, TPC, calo-tracker, semiconductur,

Engel & Menendez 1610.06548



EXO

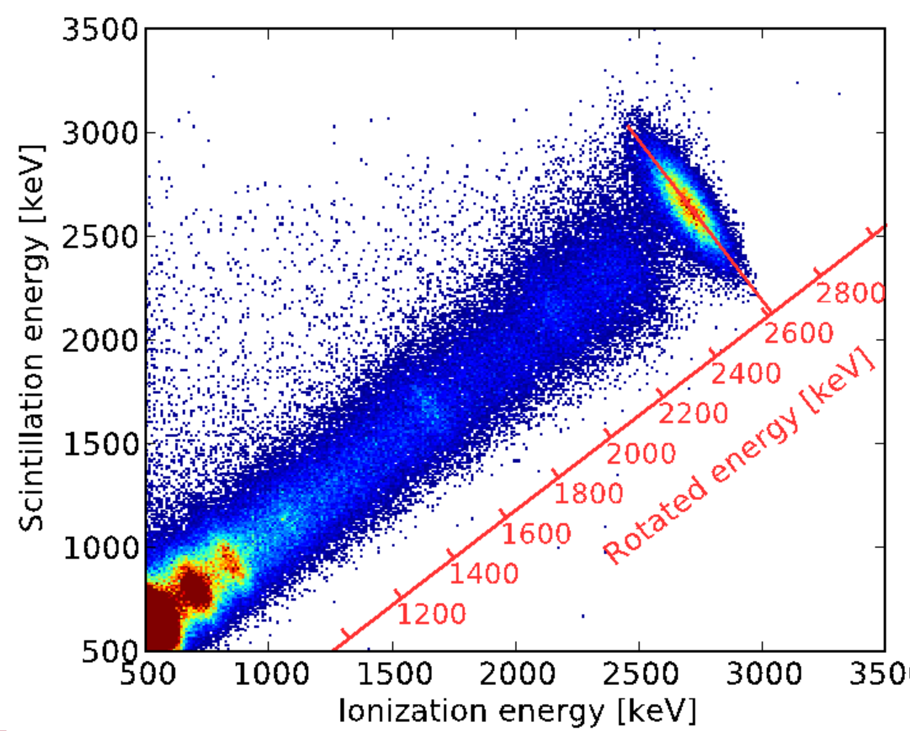


TPC

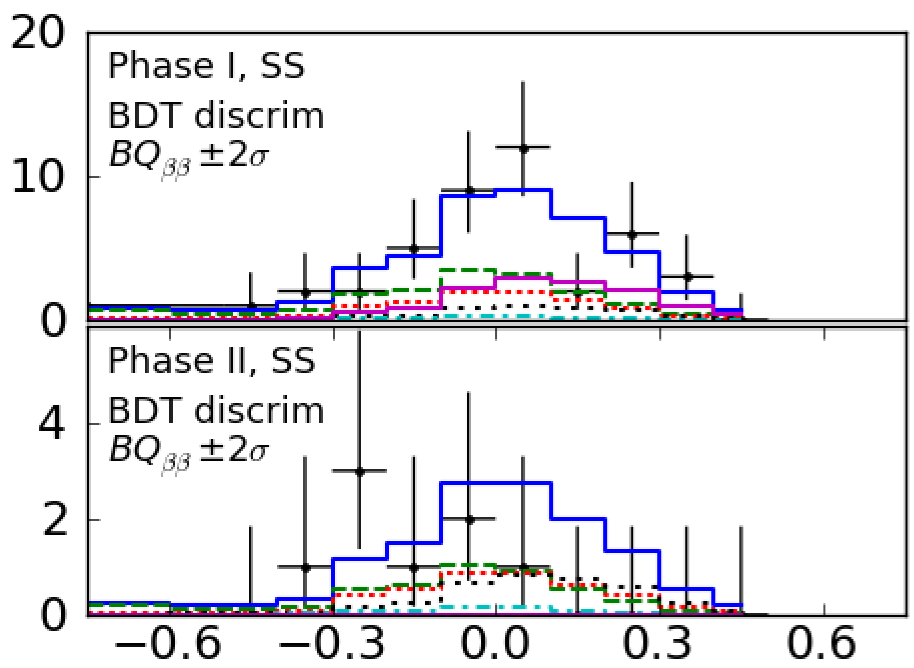
enriched Lxe

Q = 2458 keV

75 kg in FV



EXO

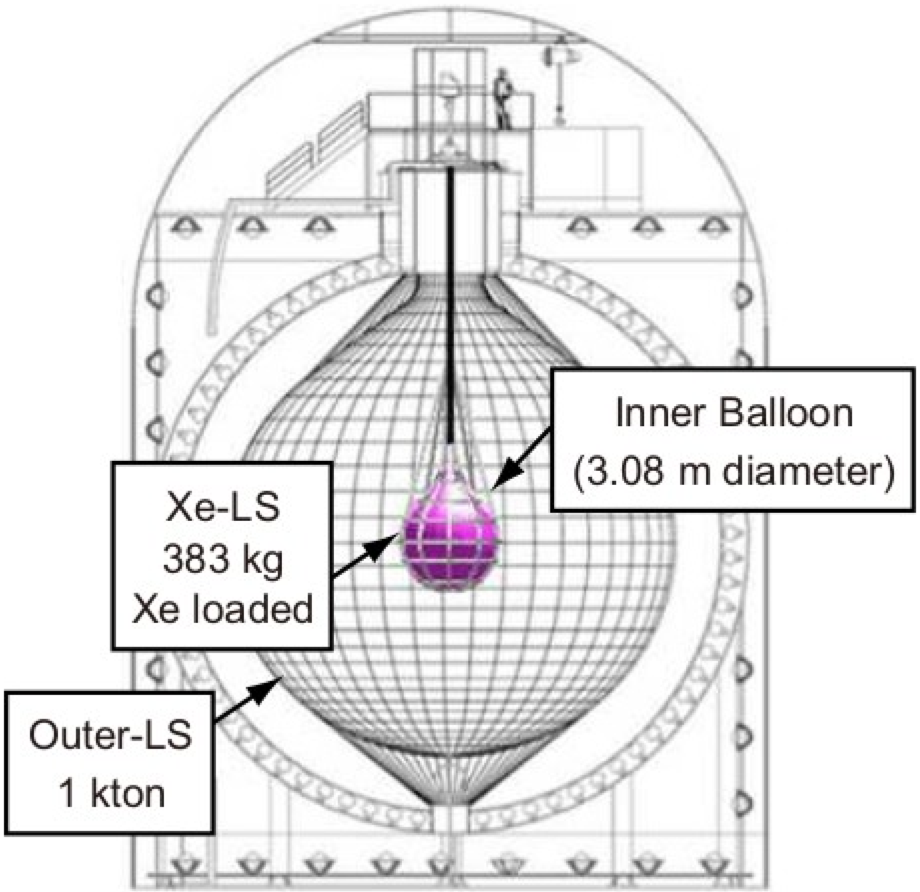


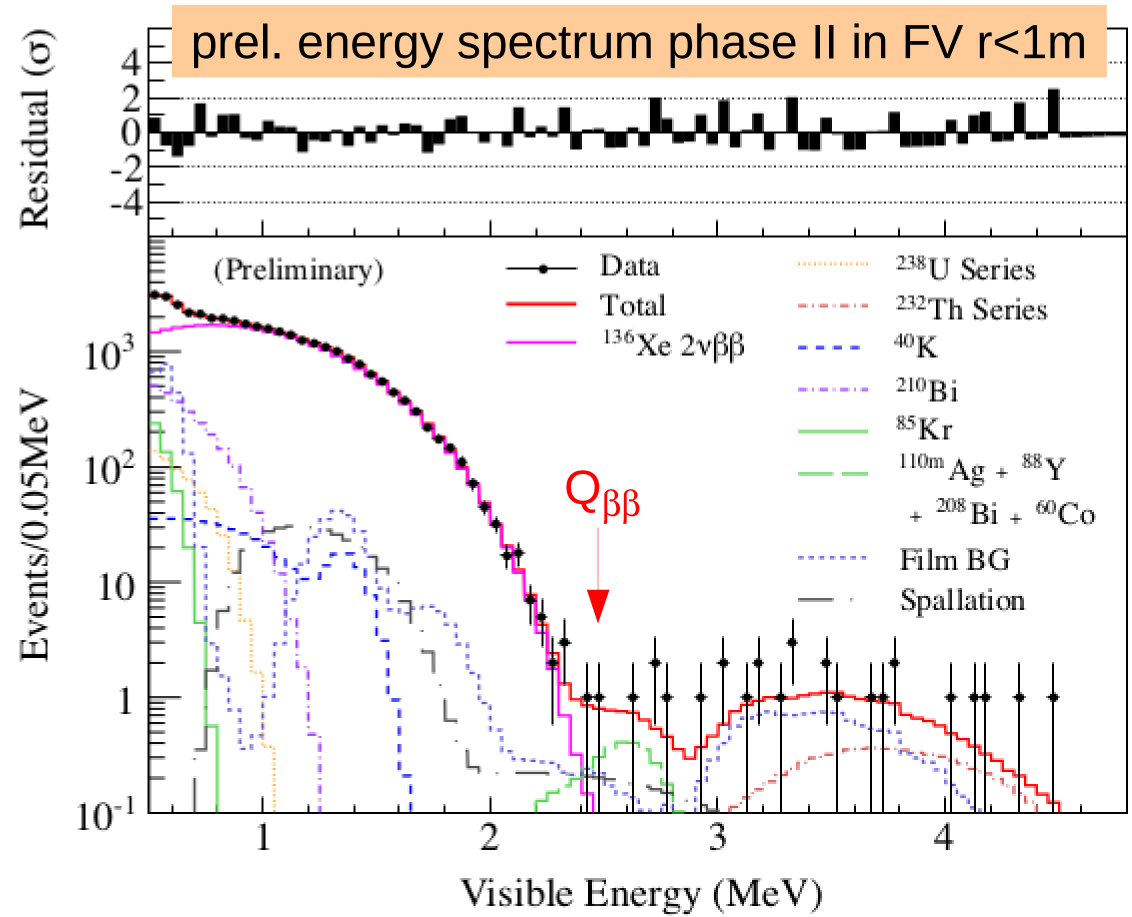
BI = 1.5 +/- 0.2 10^{-3} cts/(keV kg yr)

Sensitivity: 3.7×10^{25} yr (90% CL)

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

Kamland-Zen





start 2011 (phase I): fall out of ^{110m}Ag from Fukushima on inner balloon
2012-13: purifications of scintillator and Xe
Dec 2013 – Oct 2015: phase II → ^{110m}Ag bkg factor 10 reduced, Xe loading 2.44% --> 2.96%
now: larger & cleaner balloon, loading 380 kg → 750 kg, restart now, sensitivity $T_{1/2} > 2\ 10^{26}$ yr

current limit for 0νββ of ^{136}Xe: $T^{0\nu}_{1/2} > 2.6\cdot 10^{25}$ yr (90% C.L.)

Kamland-ZEN phase II

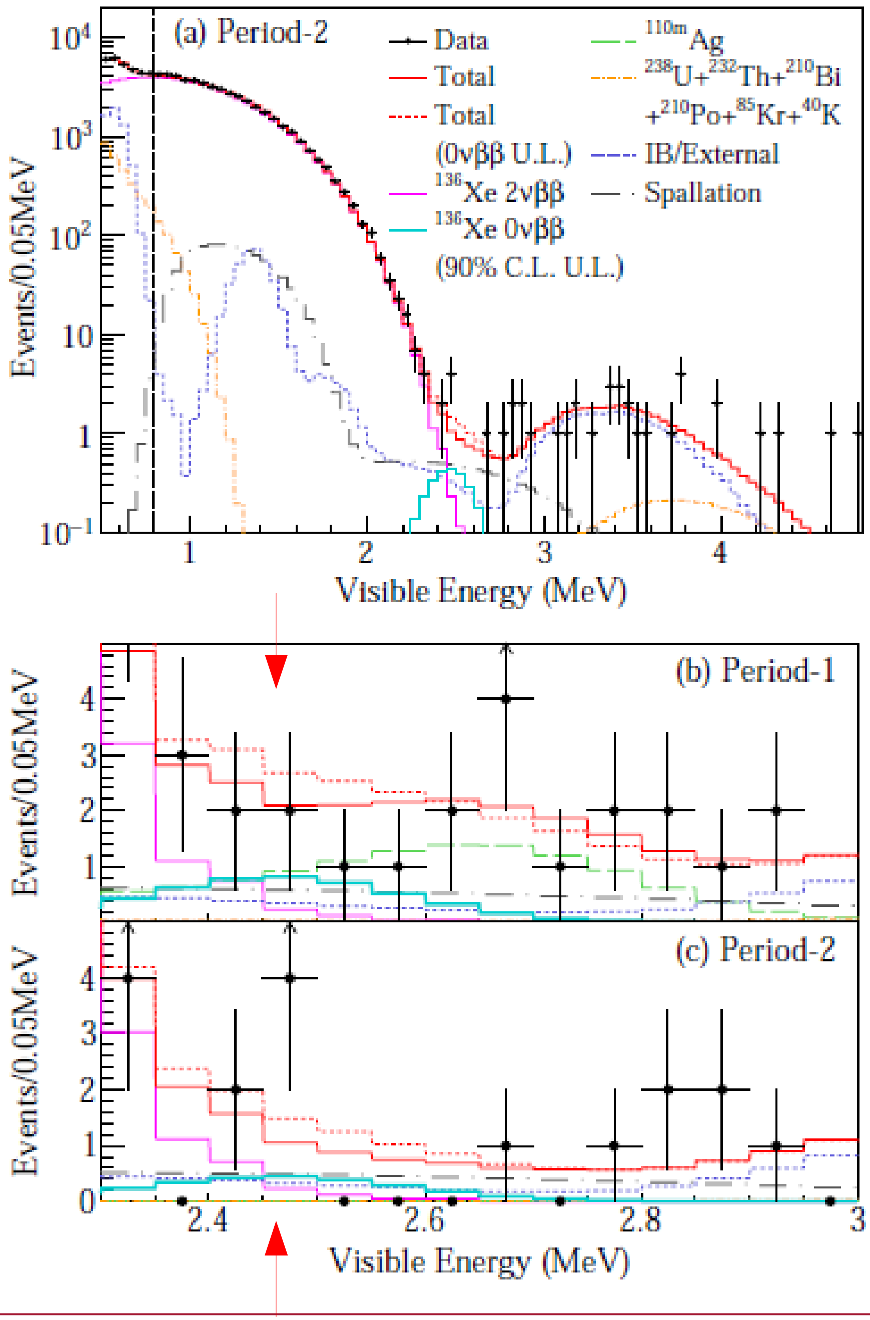
$Q_{\beta\beta}$ = 2458 keV

σ = 110 keV $\sim 7.3\% / \sqrt{E(\mathrm{MeV})}$

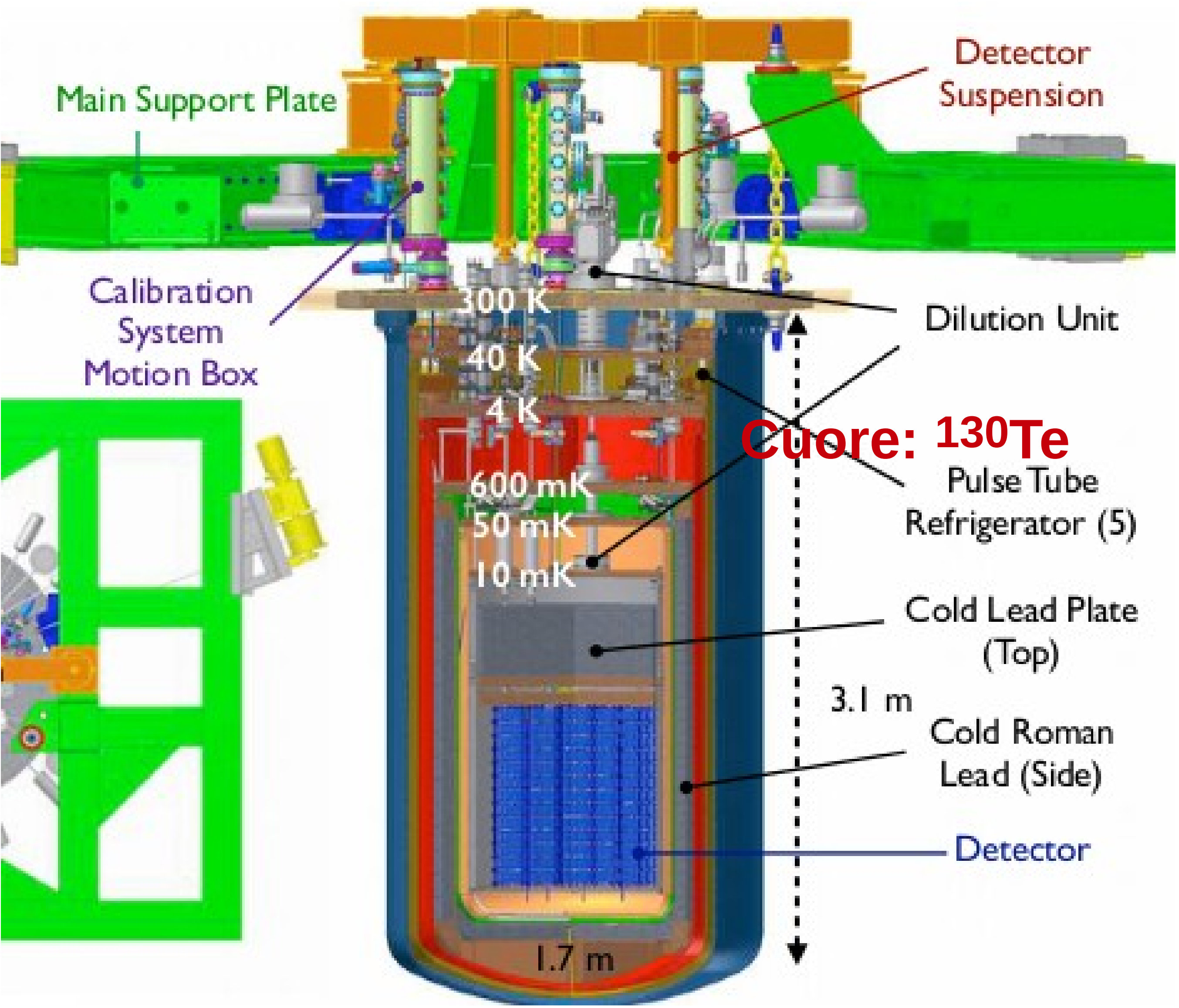
$T^{2\nu}_{1/2} = 2.21 \pm 0.02(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \times 10^{21}$ yr.

$T^{0\nu}_{1/2} > 1.1 \times 10^{26}$ yr (90% C.L.)

1605.02889



Cuore: ^{130}Te



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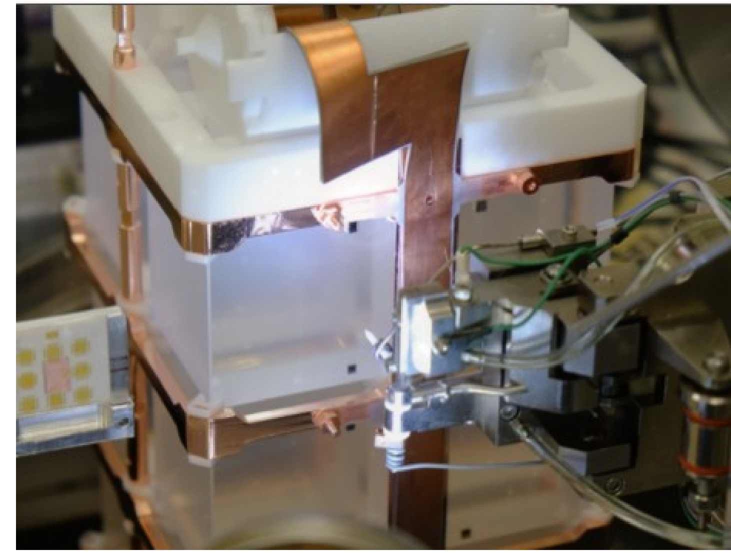


988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

calorimeter with Ge NTD readout,
$\Delta T \sim 0.1$ mK / MeV
~ 5 keV FWHM

all towers are assembled!
test cool down of cryostat ok,
next: step mount towers + commissioning
physics run start end 2016,
sensitivity 90% limit ~ 1 10^{26} yr

CUORE

CUORE
(Cryogenic Underground Observatory for Rare Events)

Primary goal: search for $0\nu\beta\beta$ decay in ^{130}Te

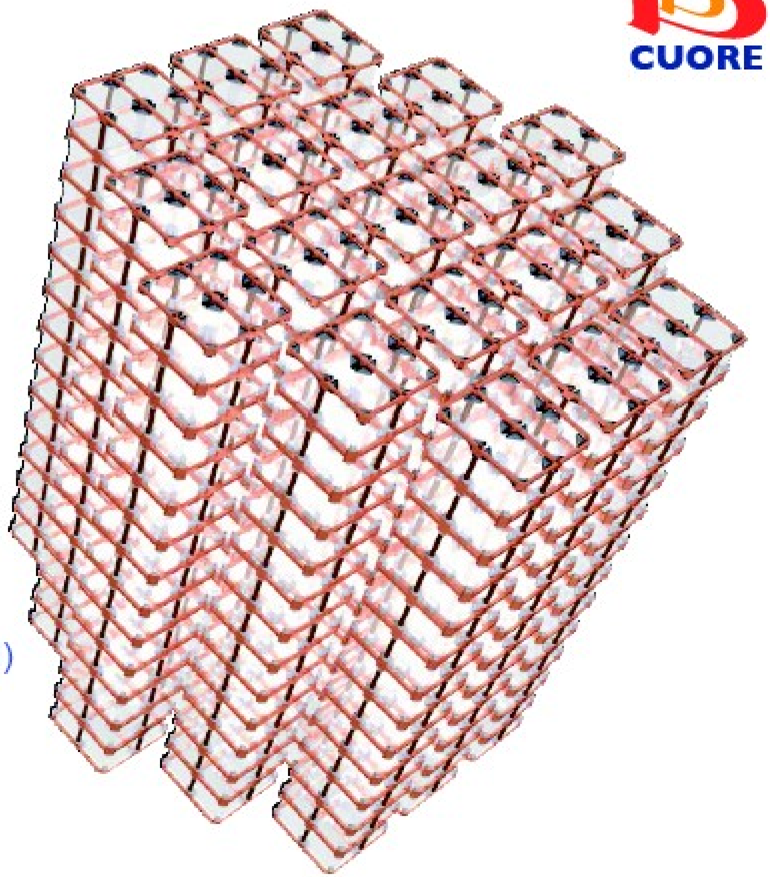
Closely packed array of 988 TeO_2 crystals arranged in 19 towers

^{130}Te:
- large transition energy: $Q_{\beta\beta}$ (^{130}Te) 2527.5 keV
- highest natural isotopic abundance (33.8%)

CUORE design parameters:
- mass of TeO_2: **742 kg** (206 kg of ^{130}Te)
- low background aim: **10^{-2} c/(keV·kg·yr)**
- energy resolution: **5 keV** FWHM in the Region Of Interest (ROI)
- high granularity
- deep underground location
- strict radio-purity controls on materials and assembly

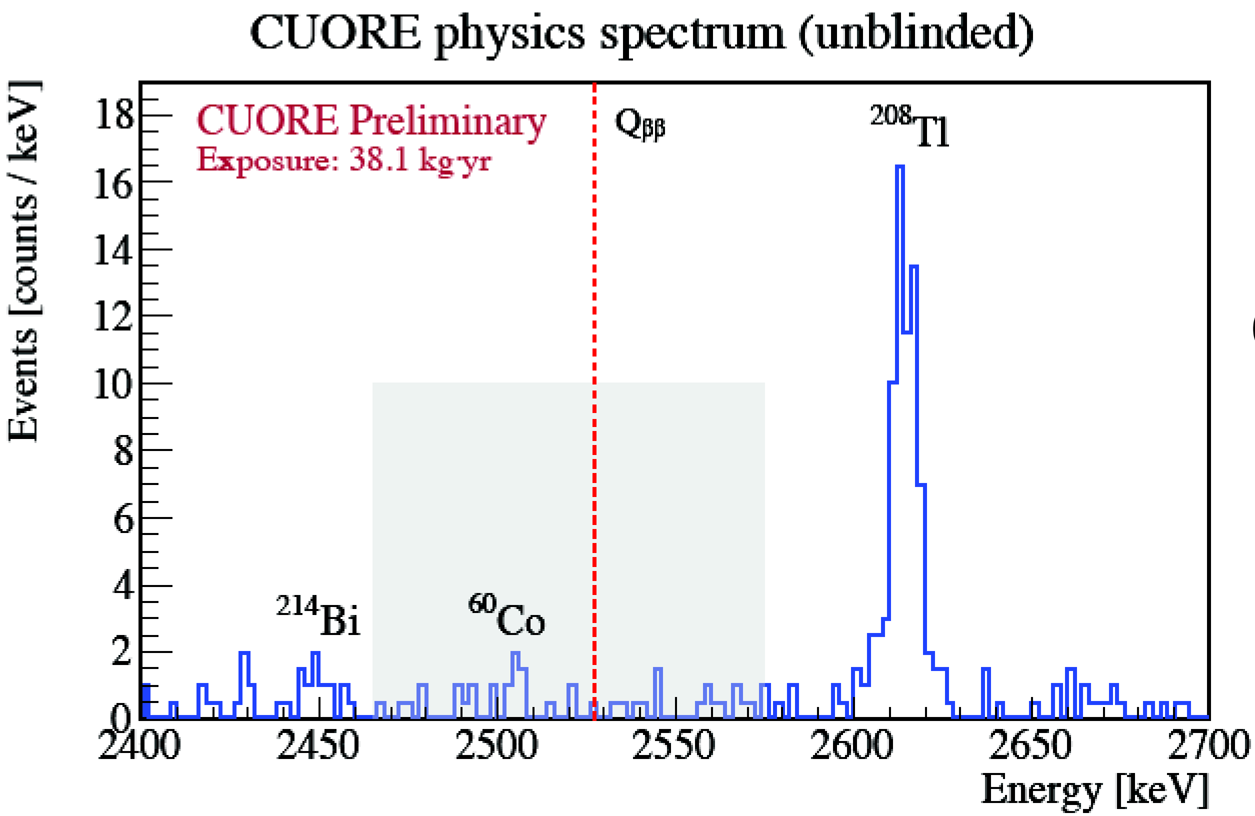
CUORE projected sensitivity (5 years, 90% C.L.):

$T_{1/2} > 9 \times 10^{25}$ yr



CUORE

CUORE

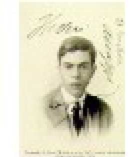


$\Delta E \sim$ 10 keV

BI =
(9.8 –1.5+1.7) × 10^{-3} cts/(keV·kg·yr)

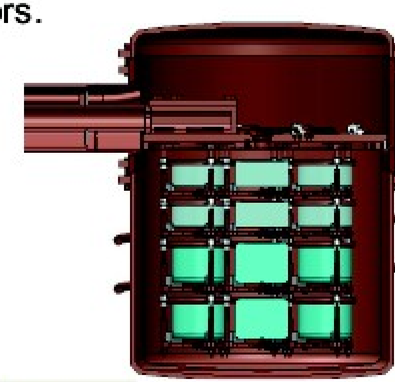
- Best fit decay rate: **$(-0.03_{-0.04}^{+0.07}$ (stat.) ± 0.01 (syst.))×10^{-24} / yr**
- Decay rate limit (90% CL, including systematics): **0.15×10^{-24} / yr**
- Half-life limit (90% CL, including systematics): **4.5×10^{24} yr**
- Median expected sensitivity: **3.6×10^{24} yr (arXiv:1705.10816)**

The MAJORANA DEMONSTRATOR

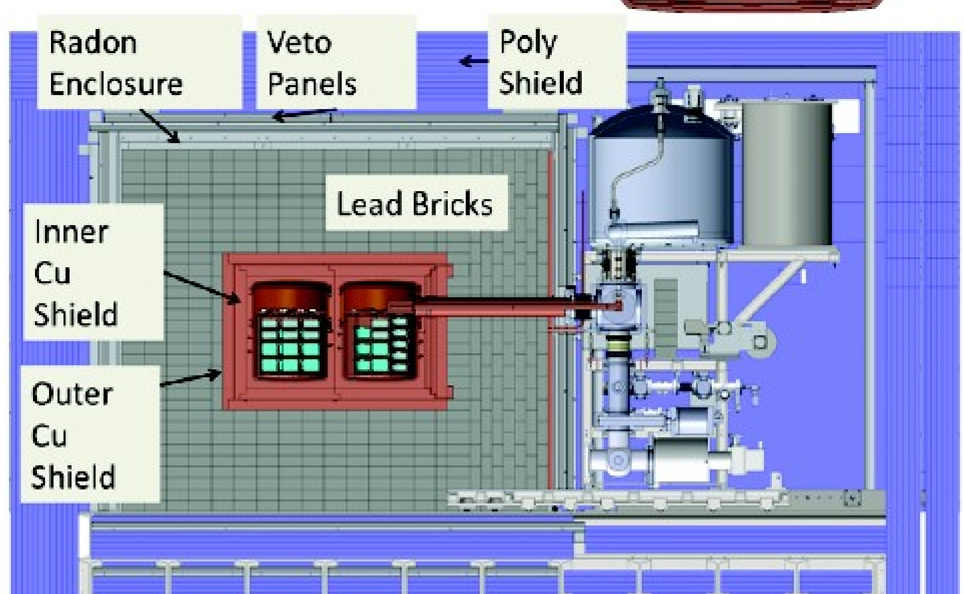


Operating underground at 4850' Sanford Underground Research Facility with the best energy resolution (2.4 keV FWHM @ 2039 keV) of any ββ-decay experiment.

Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



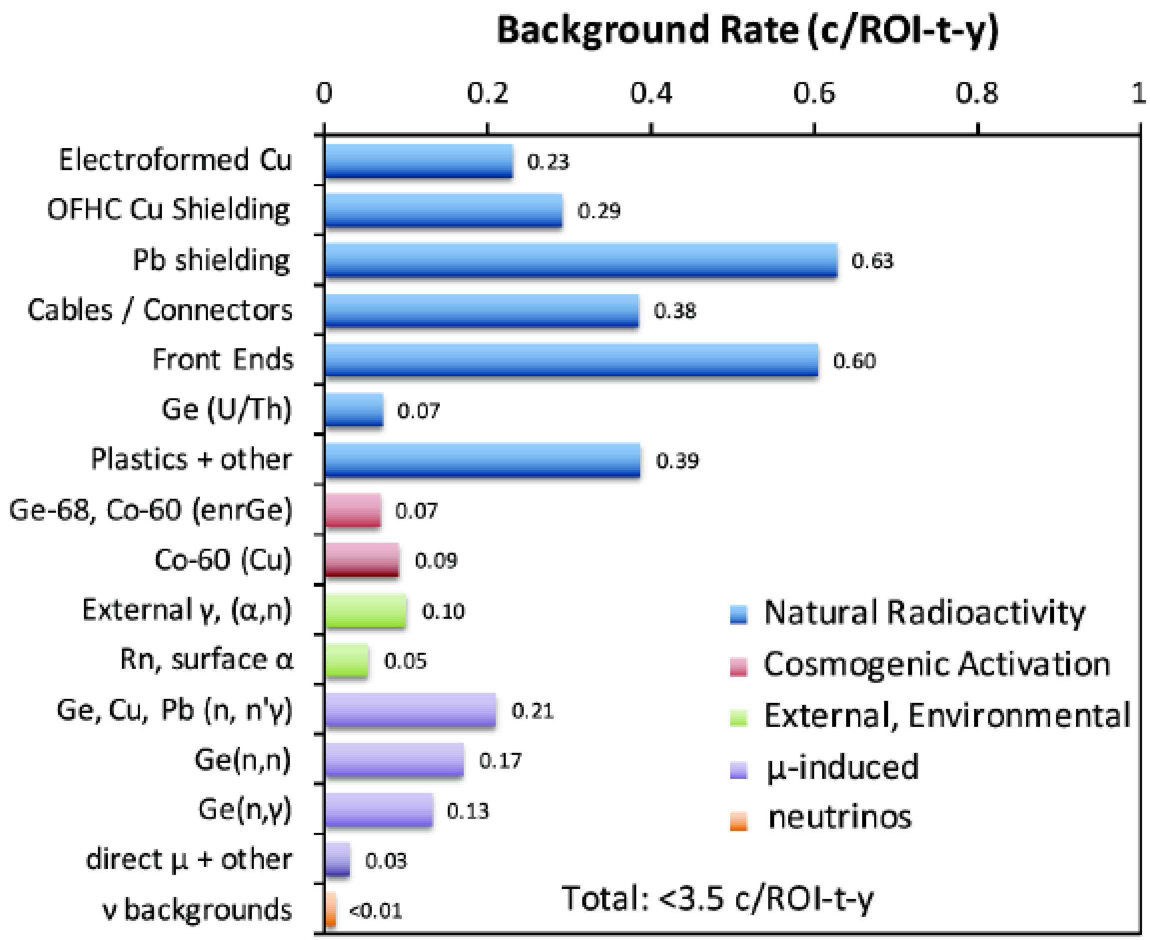
- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
  - 3 counts/ROI/t/y (after analysis cuts) Assay U.L. Currently ≤ 3.5
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013) arXiv:1308.1633

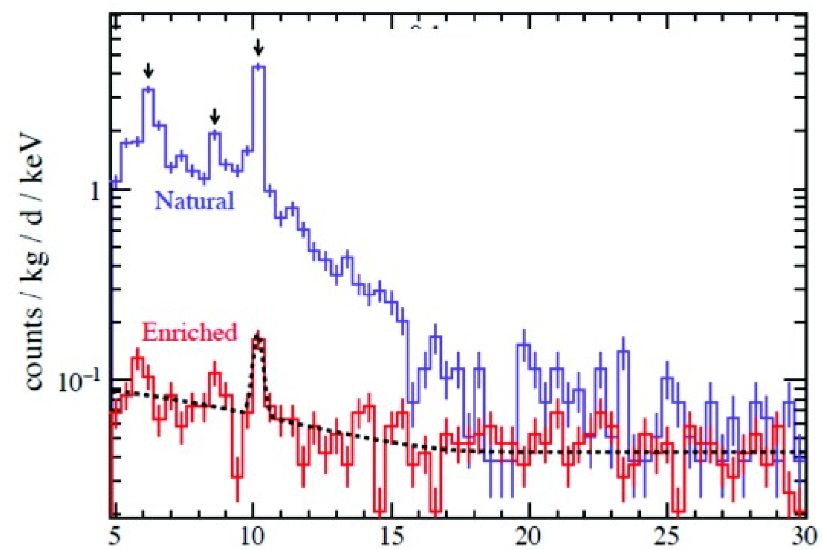
Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

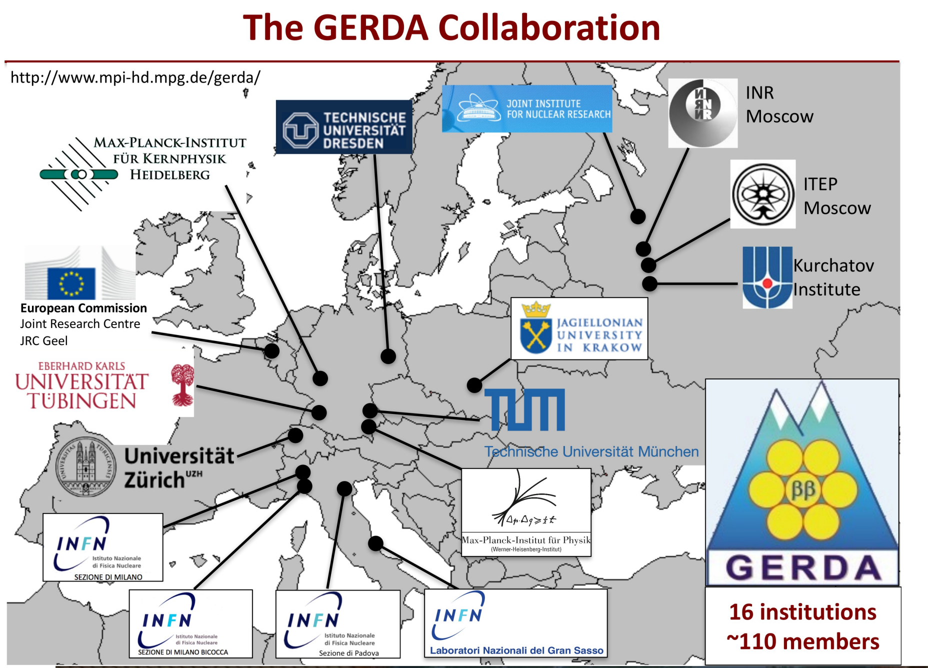
Majorana



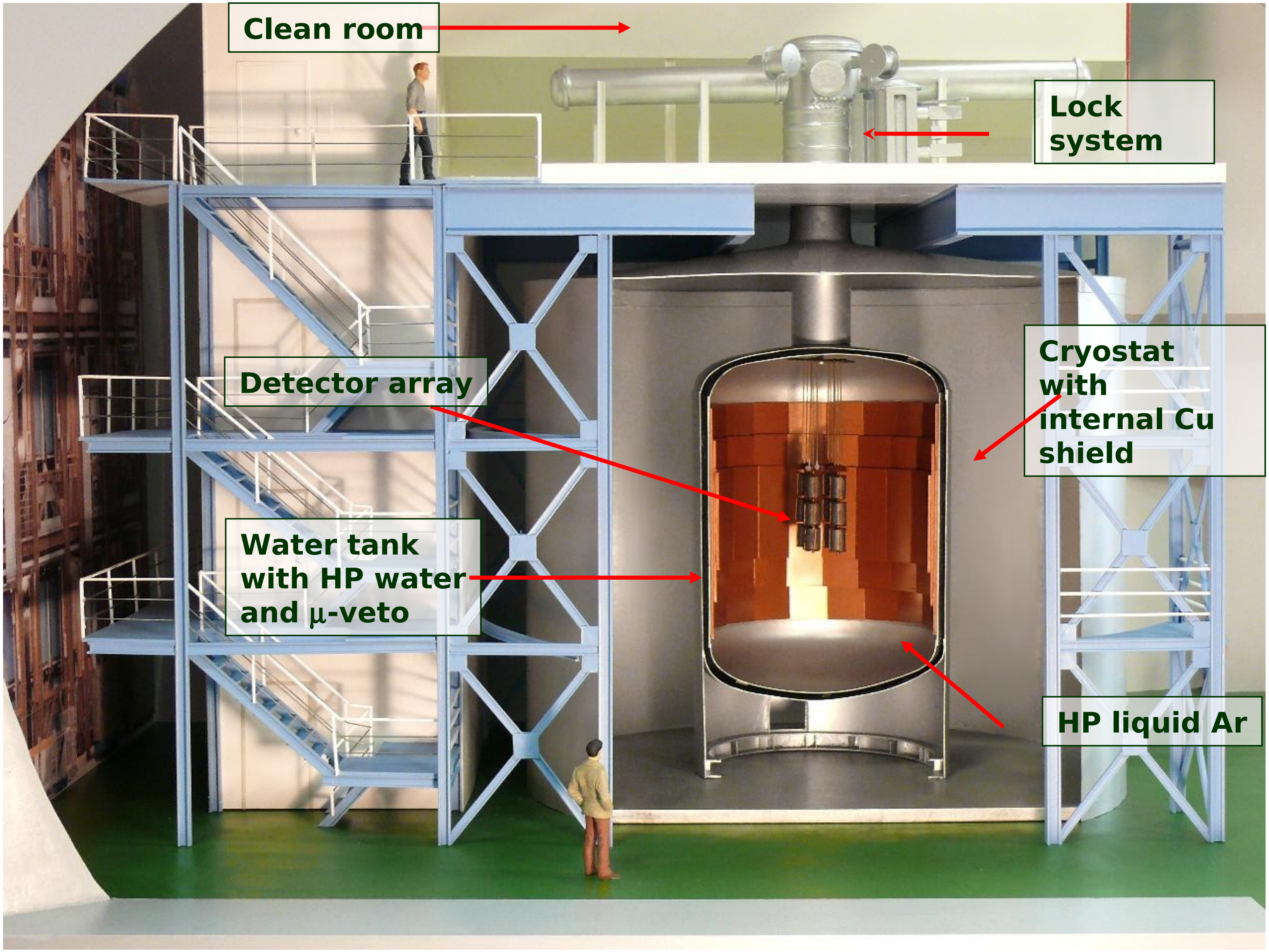
ΔE ~ 2.4 keV

physics at low energies





Cracow, June 2017



Phase II

40 detectors in 7 strings

3 nat. 7.6kg (7.8%)

87 % enriched

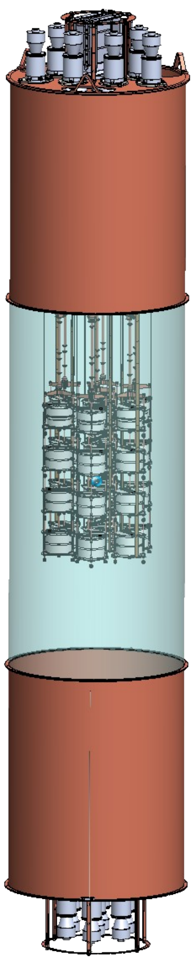
7 coax 15.8kg
30 BeGe 20.0kg

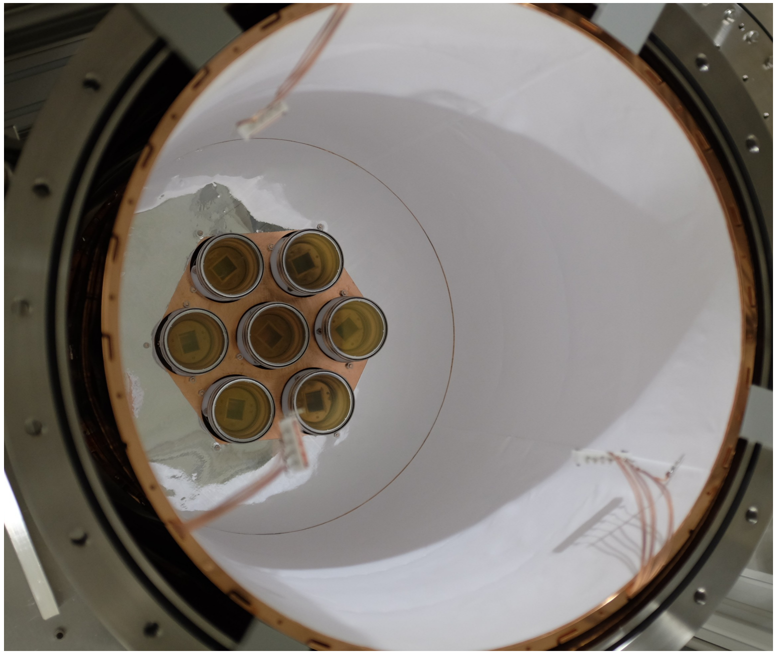
Eur. Phys. J. C 73 (2013) 2330

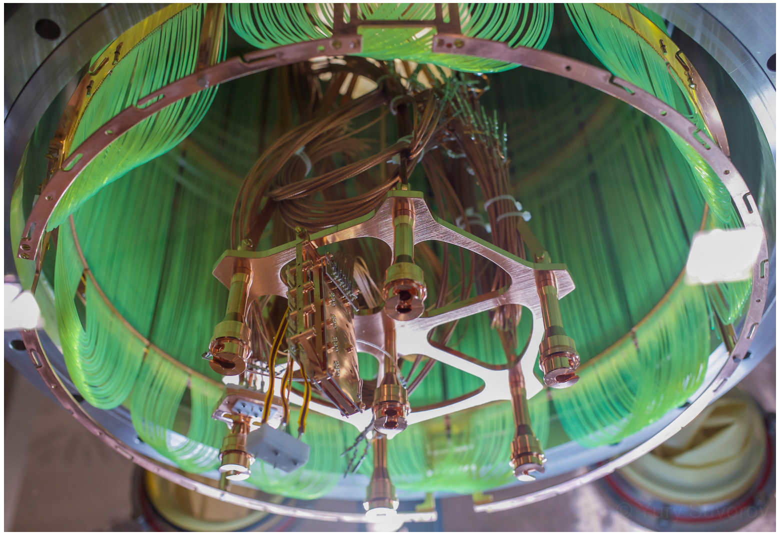
GERDA : design and construction

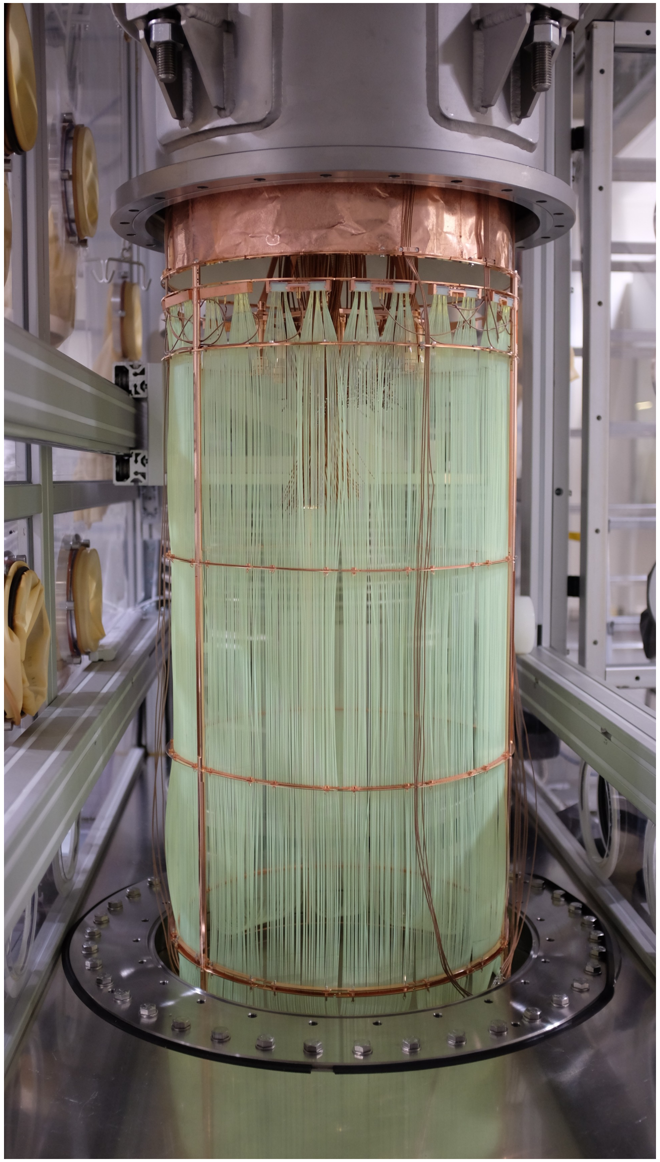
proposal 2004

LNGS, Hall A





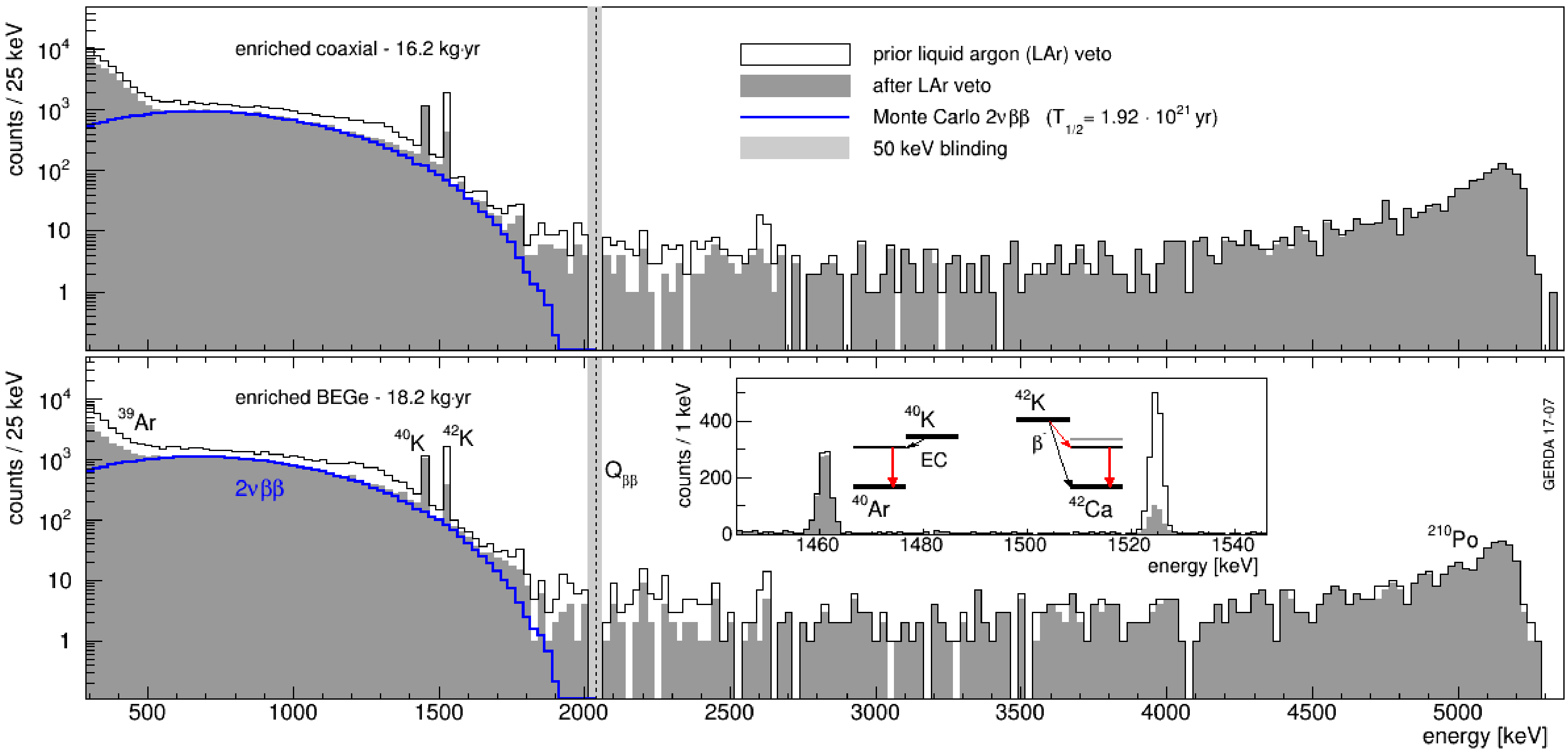




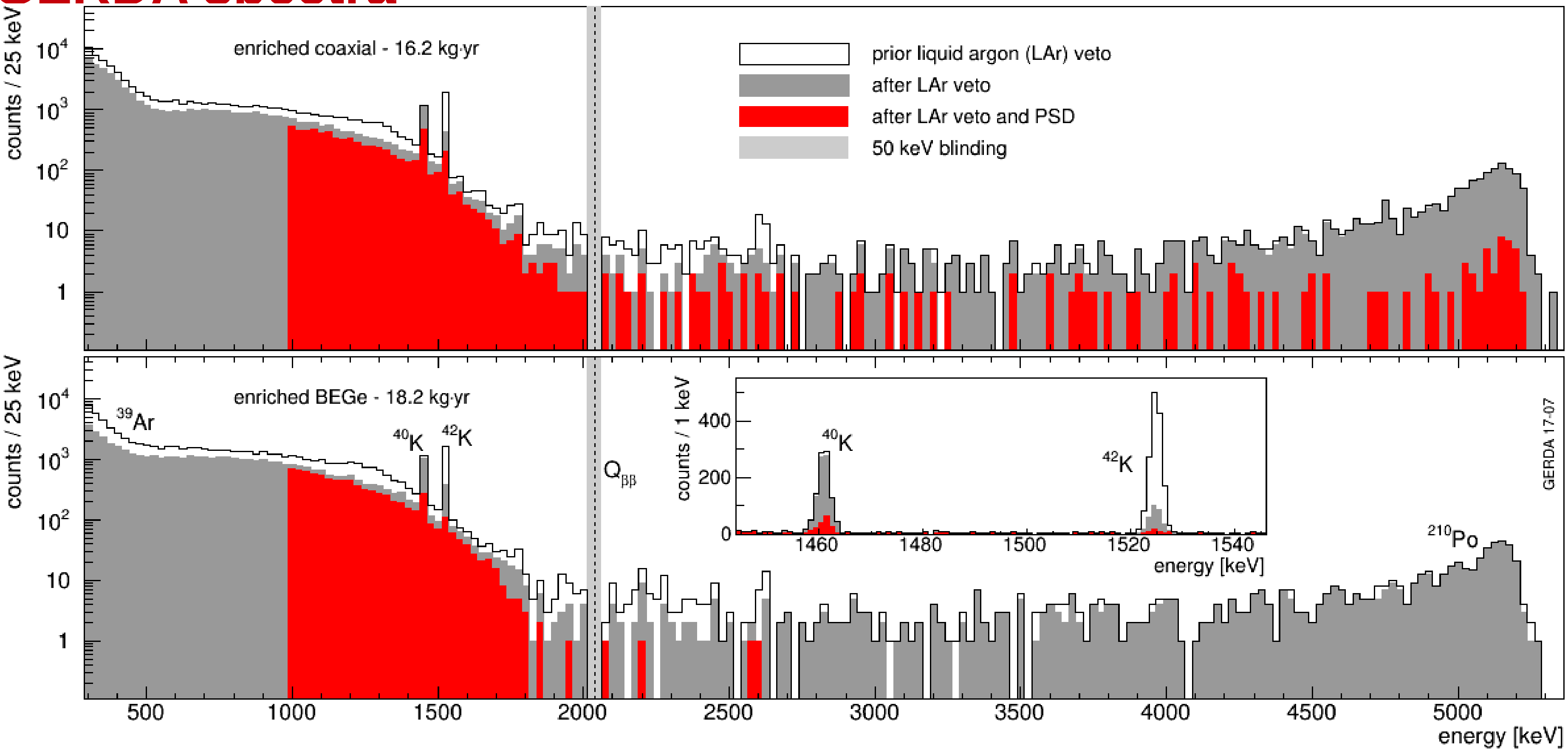
liquid-Argon-Instrumentation

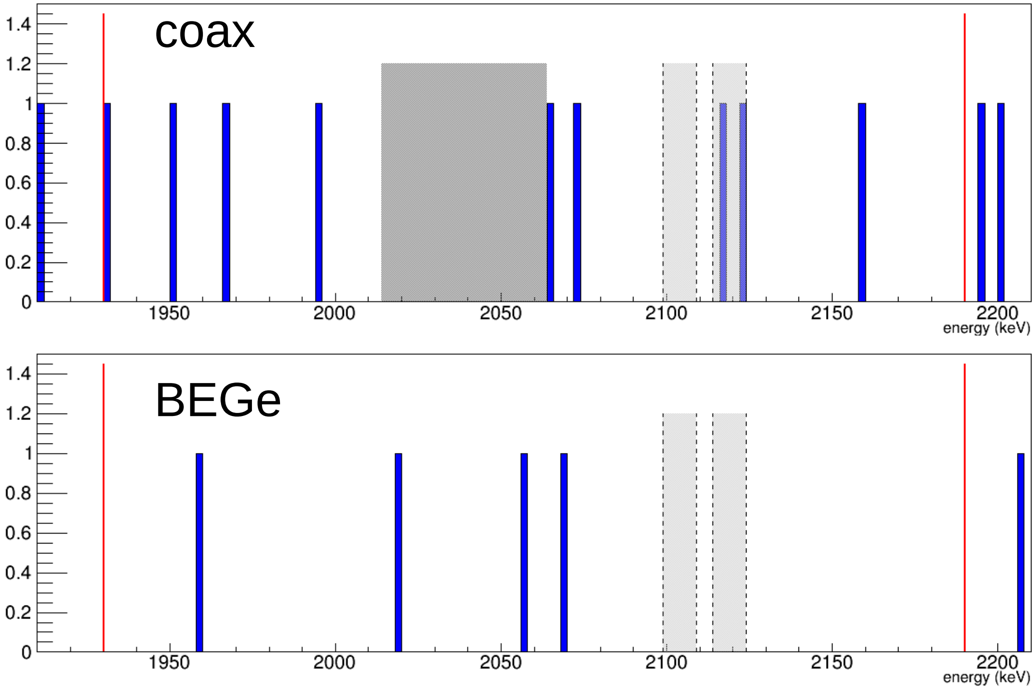
surface contaminations & Compton scattering produce scintillation light (128nm) in LAr

GERDA spectra



GERDA spectra

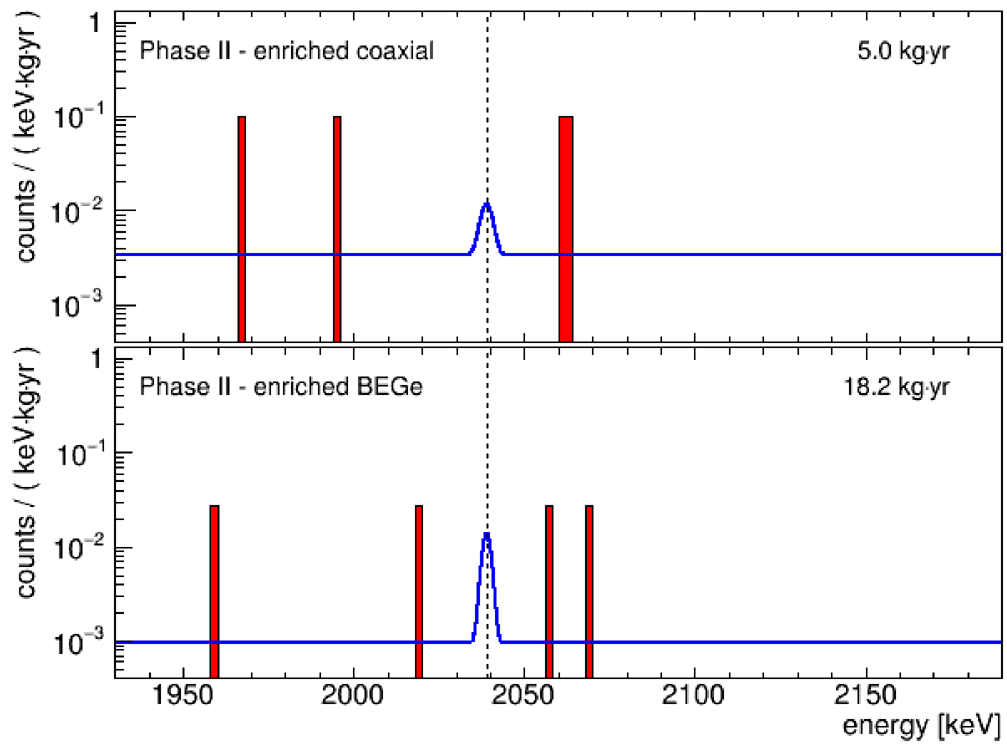




background index

$\mathbf{2.7\ +1.0\ -0.8\ \ 10^{-3}}$ cts/(keV kg yr)

$\mathbf{1.0\ +0.6\ -0.4\ \ 10^{-3}}$ cts/(keV kg yr)



comparison of experiments / designs

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cts/ t yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	m_{ee} limit [meV]
Gerda II	Ge	35/27	3	5	15	80-190
Majorana D	Ge	30/24	3	5	15	80-190
EXO-200	Xe	170/80	88	220	6	80-220
Kamland-Z	Xe	383/88 750/??	250	40 ?	20	44-120
Cuore	Te	600/206	5	300	9	50-200
NEXT-100	Xe	100/80	17	30	6	80-220
SNO+	Te	2340/260	190	60	17	36-150
nEXO	Xe	5000/4300	58	5	600	8-22
Ge-200	Ge	200/155	3	1	100	35-75
Ge-1000	Ge	1000/780	3	0.2	1000	10-23

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)
[&] mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency
note: values are design numbers except for GERDA; EXO-200 and Kamland-Zen

Why ^{76}Ge? (there are other isotopes)

disadvantages:

- small phase space factor $G^{0\nu}$
- expensive (enrichment + diode production)
- scales not as easy as liquid/gas detectors

advantages:

- good energy resolution (currently best in the field)
  → small ROI & simple peak detection over smooth bkg
- lowest background if scaled by ROI
  → sensitivity comparable to experiments with much larger mass
- enrichment + diode production well established
  → no (little) R&D needed
- effective use of expensive material (not used for self-shielding)
- large annual Ge production
- 'relative' simple operation & background suppression

background free: sensitivity prop. to exposure [not sqrt(exposure)]

summary

new experiments on $0\nu\beta\beta$ decay

if found, then leads to physics beyond SM !

Cuore, Kamland-Zen, EXO, GERDA, Majorana

^{130}Te, ^{136}Xe, ^{76}Ge

GERDA: high resolution & background free

exposure $\mathcal{E} =$ 46.7 kg yr

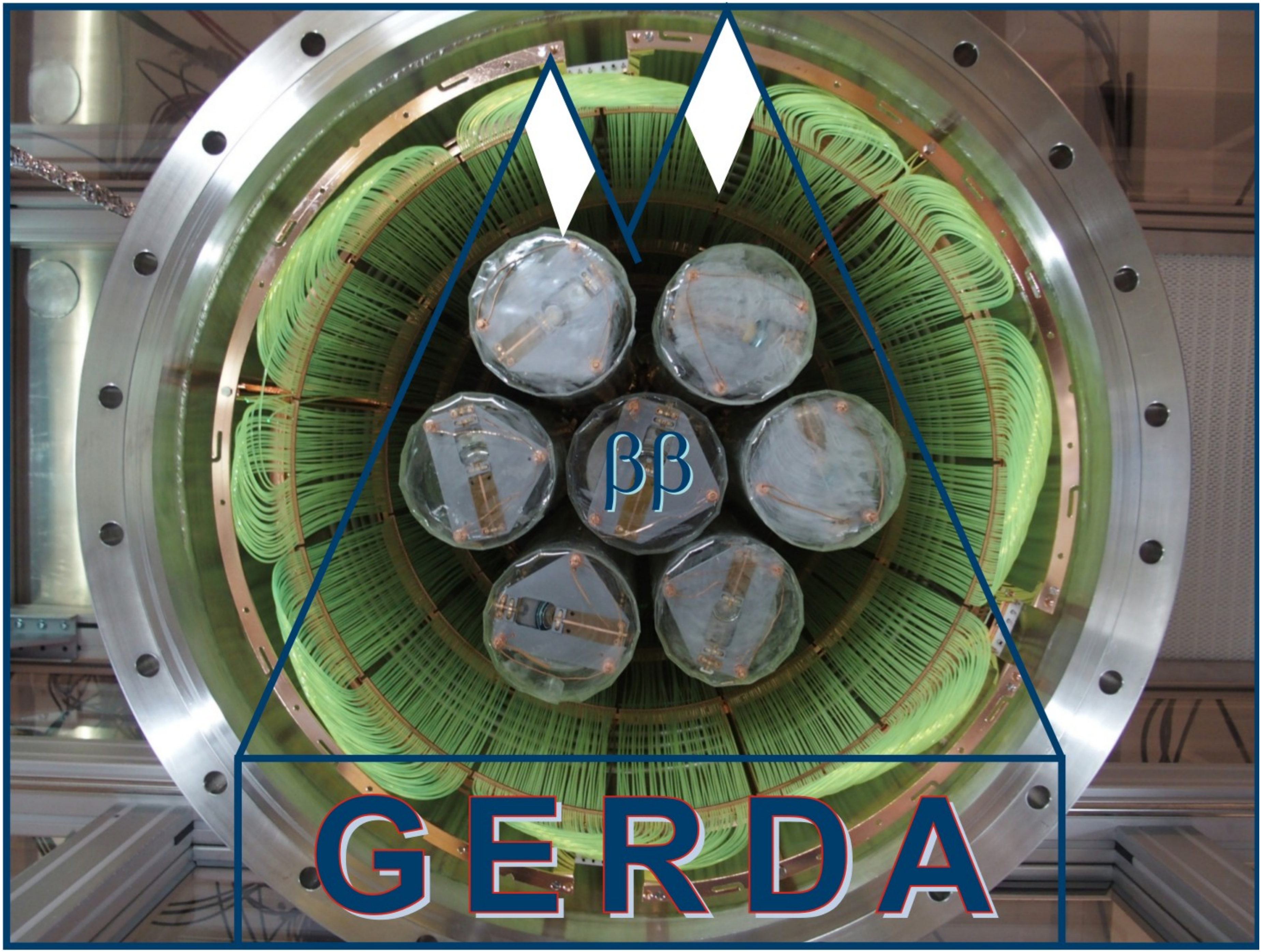
new limit

$T_{1/2}^{0\nu} > 8.0 \cdot 10^{25}$ yr (90% C.L. frequentist)

sensitivity

$T_{1/2}^{0\nu} > 5.8 \cdot 10^{25}$ yr (90% C.L.)

data taking of Phase II is continued (running stably)


ββ
GERDA