Recent Progress in Double Beta Decay
&
Latest Results from GERDA

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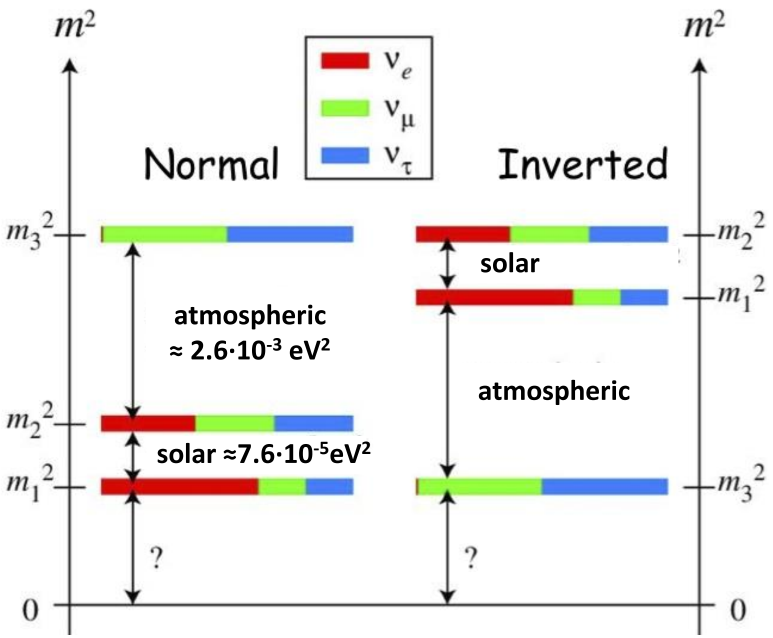
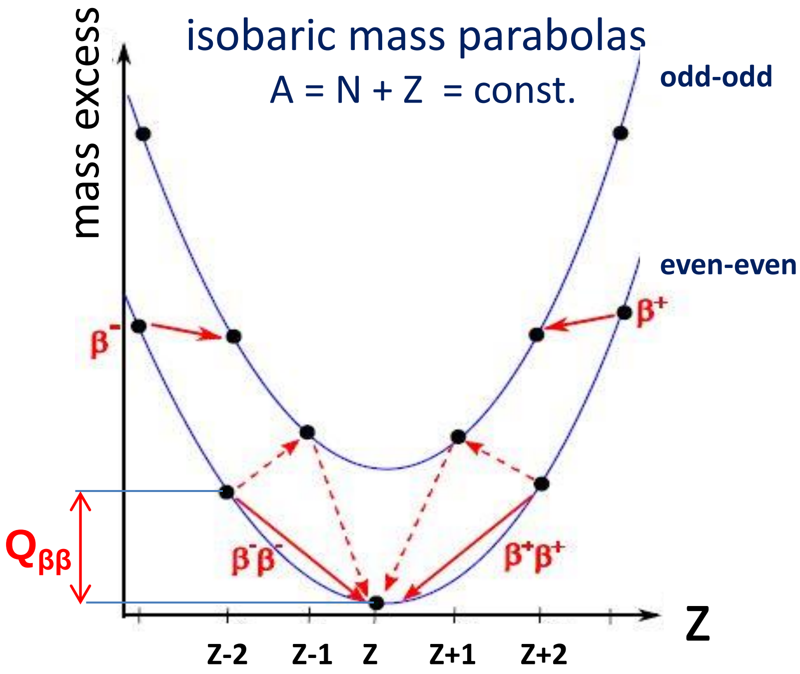
Thirteenth Conference on the Intersections of Particle and Nuclear Physics, CIPANP 2018
Palm Springs, May 29th – June 3rd, 2018

Outline

- Introduction to 2νββ and 0νββ decay
- Demonstration of recent progress
  - instrumentation
  - sensitivity / limits
- GERDA – latest results
- Summary and concluding remarks





known:
mass-squared splittings & mixing angles,
m_ν (heaviest) > 45 meV

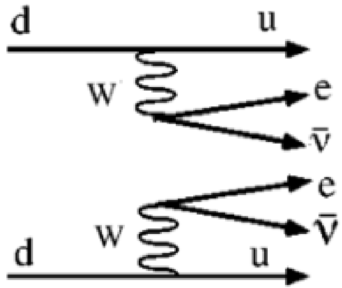
wanted:
mass ordering & absolute mass scale
CP phases
nature of neutrino:
Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$) fermion

M. Goeppert-Mayer (1935):
2 neutrino double beta (2νββ) decay
(A,Z) → (A,Z+2) + 2e$^-$ +2$\bar{\nu}$

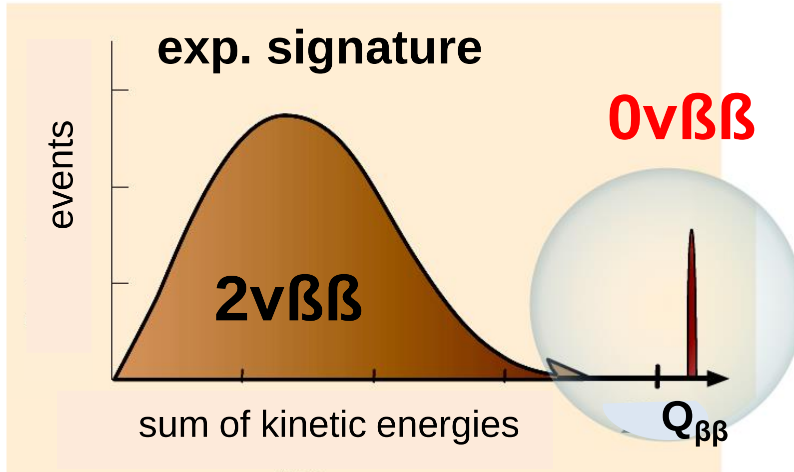
E. Majorana (1938):
neutrinoless double beta (0νββ) decay
(A,Z) → (A,Z+2) + 2e$^-$

ΔL = 2 lepton number violation
physics beyond the Standard Model

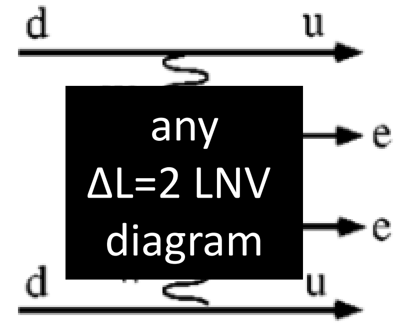
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



2vßß



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



0vßß

$\bar{\nu} = \nu$

conventional 2nd order process -
observed with remarkable precision

$$(T^{2\nu}_{1/2})^{-1} = (g_A^{eff})^4 \cdot G^{2\nu} \cdot |M^{2\nu}_{GT}|^2$$

isotope	2vββ half-life / yr	Experiment (year)
^{48}Ca	(6.4 ± 0.7 ± 1.1)· 10^{19}	NEMO-3 (2016)
^{76}Ge	(1.926 ±0.094)· 10^{21}	GERDA (2015)
^{82}Se	(9.2 ± 0.7) · 10^{19}	NEMO-3 (2015)
^{100}Mo	(6.92 ± 0.06 ± 0.36)· 10^{18}	LUMINEU (2018)
^{128}Te	2.84· 10^3 x $T_{1/2}$(^{130}Te)	*
^{130}Te	(8.2 ± 0.2 ± 0.6)· 10^{20}	CUORE-0 (2017)
^{136}Xe	(2.165 ±0.016 ± 0.059)· 10^{21}	EXO-200 (2014)
	(2.21 ± 0.02 ± 0.07) · 10^{21}	KamLAND-Zen (2016)
^{150}Nd	(9.34 ± 0.22 ± 0.61) · 10^{18}	NEMO-3 (2016)

see also A.S. Barabash NPA 935 (2015) 52

hypothetical $T_{1/2} > 10^{25}$ yr - if observed
neutrinos are Majorana fermions !

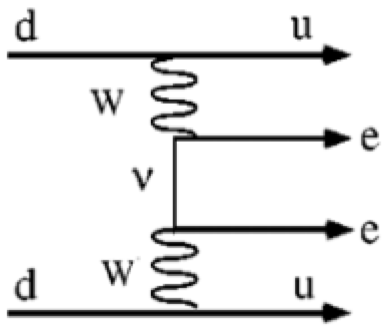
$$(T^{0\nu}_{1/2})^{-1} = g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\eta^{BSM}|^2$$

many decay mechanisms possible, e.g.:
- heavy neutrinos,
- right-handed currents,
- supersymmetric particles, ..

standard interpretation:

light Majorana-neutrino exchange

light Majorana-neutrino exchange



$$(T^{0\nu}_{1/2})^{-1} = g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \frac{< m_{\beta\beta} >^2}{m_e^2}$$

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

g_A : axial vector coupling (= 1.269)

$G^{0\nu}$: phase space factor ($\propto Q^5$)

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

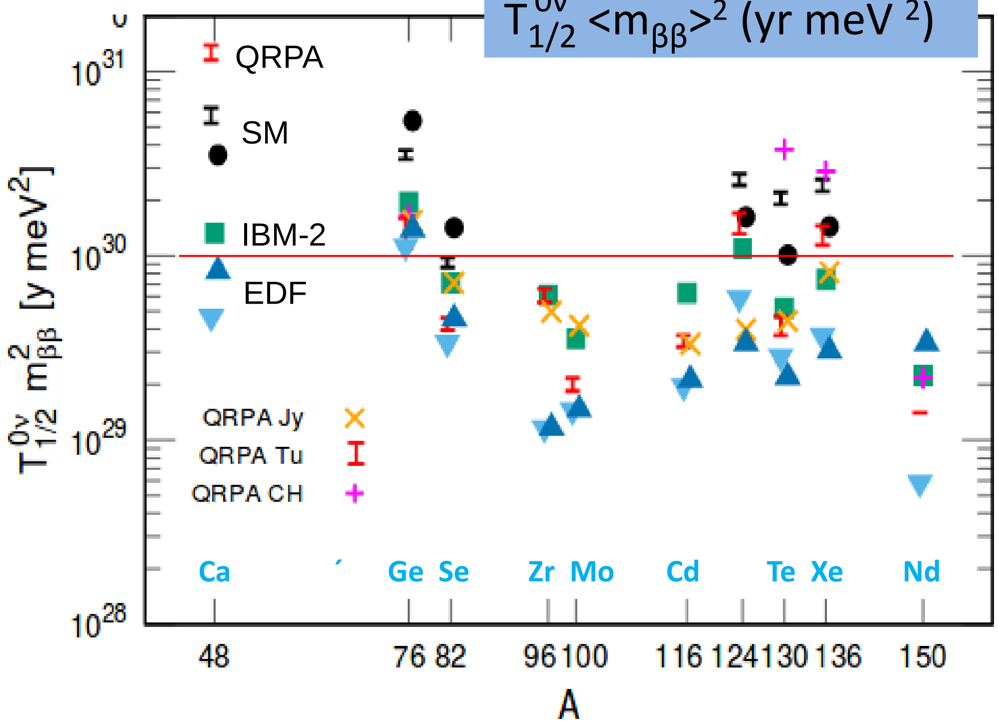
m_e : electron mass

$$< m_{\beta\beta} > = |\sum_i U_{ei}^2 \cdot m_i|$$

: effective Majorana-neutrino mass

U_{ei} : element of PMNS mixing matrix

$T^{0\nu}_{1/2} <m_{\beta\beta}>^2$ (yr meV ^{2})



Engel, Menéndez, arXiv:1610.06548

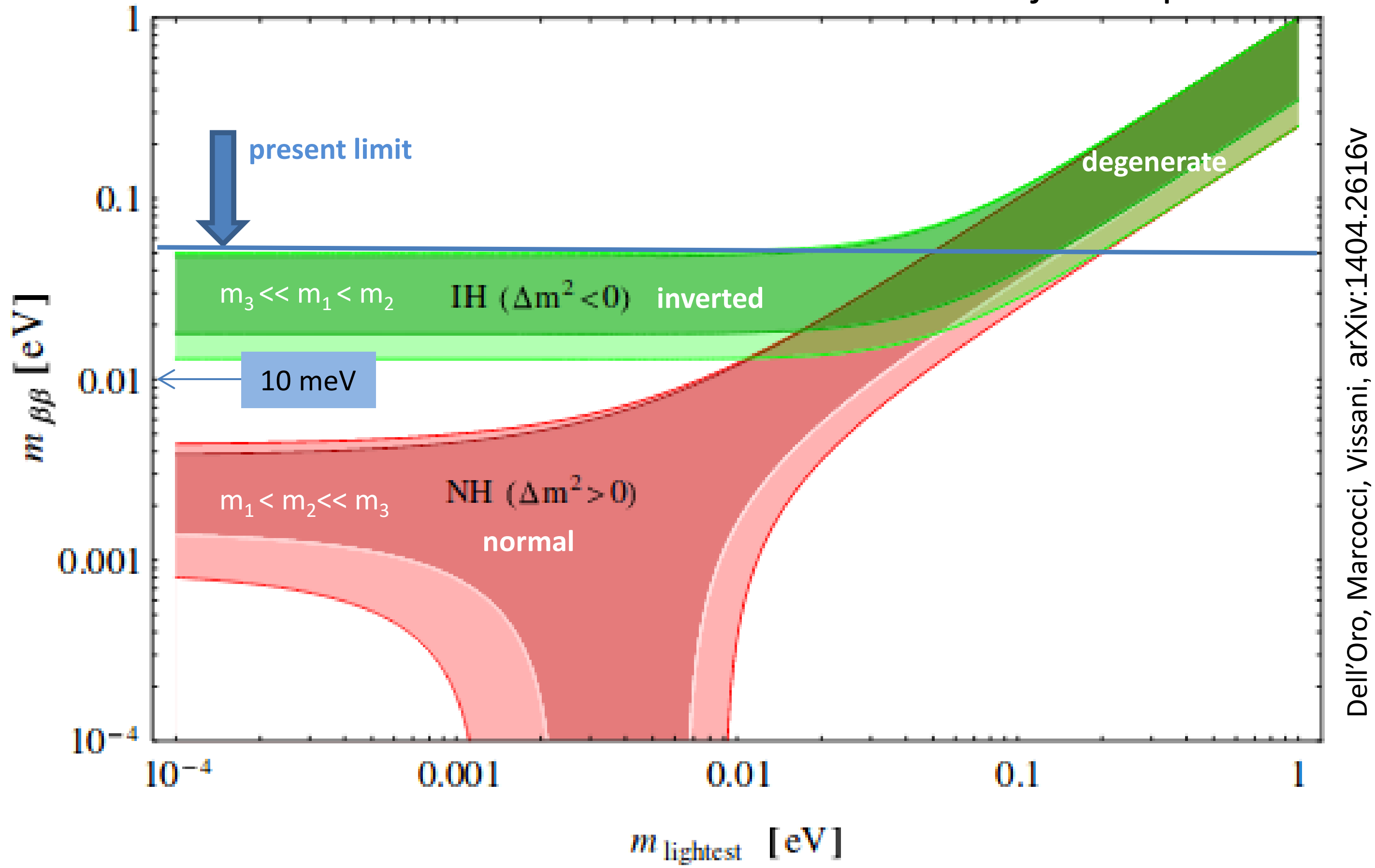
10 meV effective Majorana-neutrino mass

► half-life $T^{0\nu}_{1/2} \approx 10^{28}$ yr

assume $T_{1/2} = 10^{27}$ yr
and 100 kg Ge-76
(source=detector:)

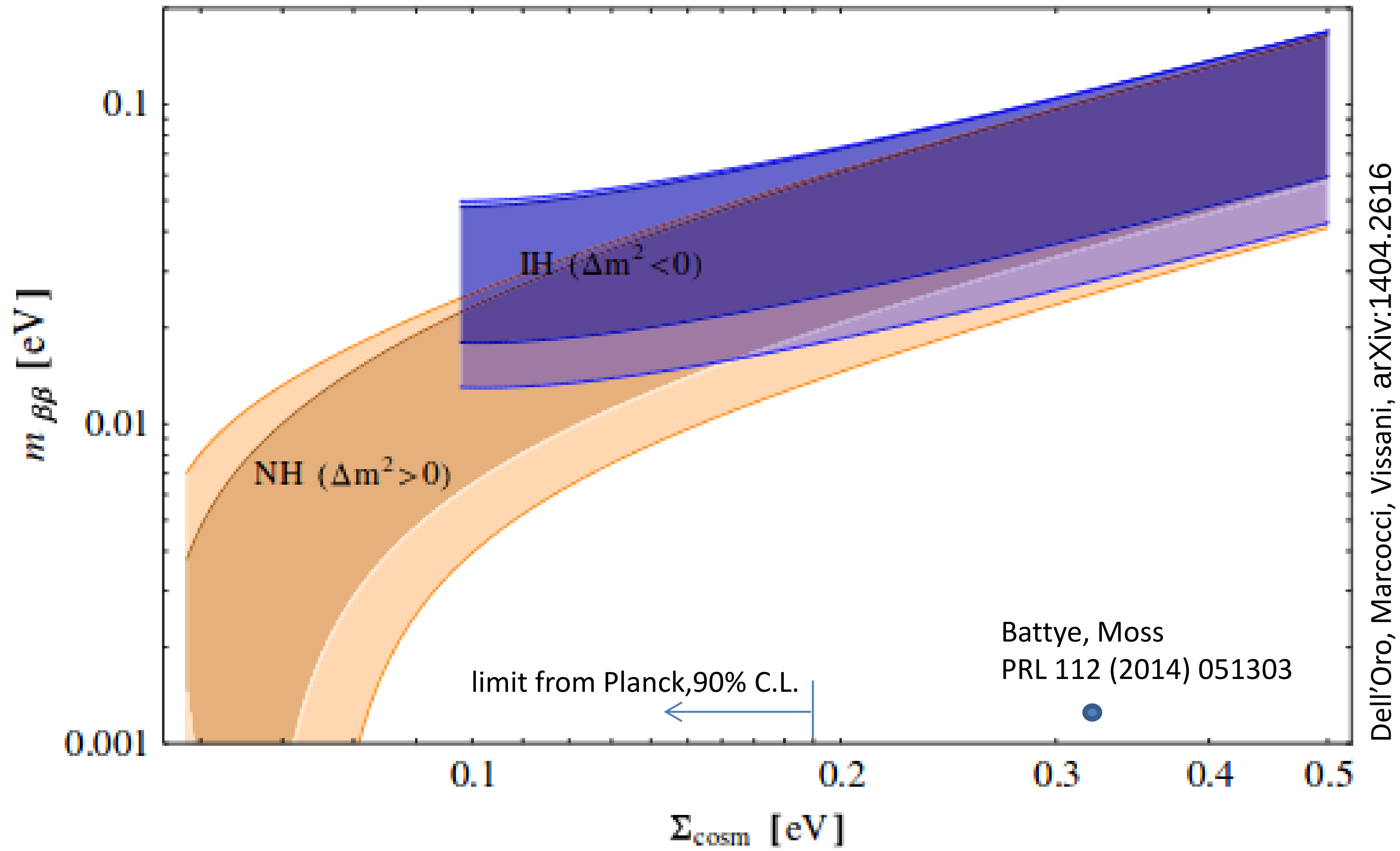
► ≈ 0.5 decays / year

deduced from oscillation data and scan of Majorana phases



Separation of inverted from normal hierarchy needs sensitivity of ≈10 meV, or $T^{0\nu}_{1/2} \approx 10^{28}$ years!

! Plot applies for 3 generations & light neutrinos.



Model-dependent limit from cosmology expected to improve soon.
(2019: SPT-3G + DES + BOSS expect $\sigma(\Sigma m_\nu) < 61$ meV)
Significant cross checks become possible.

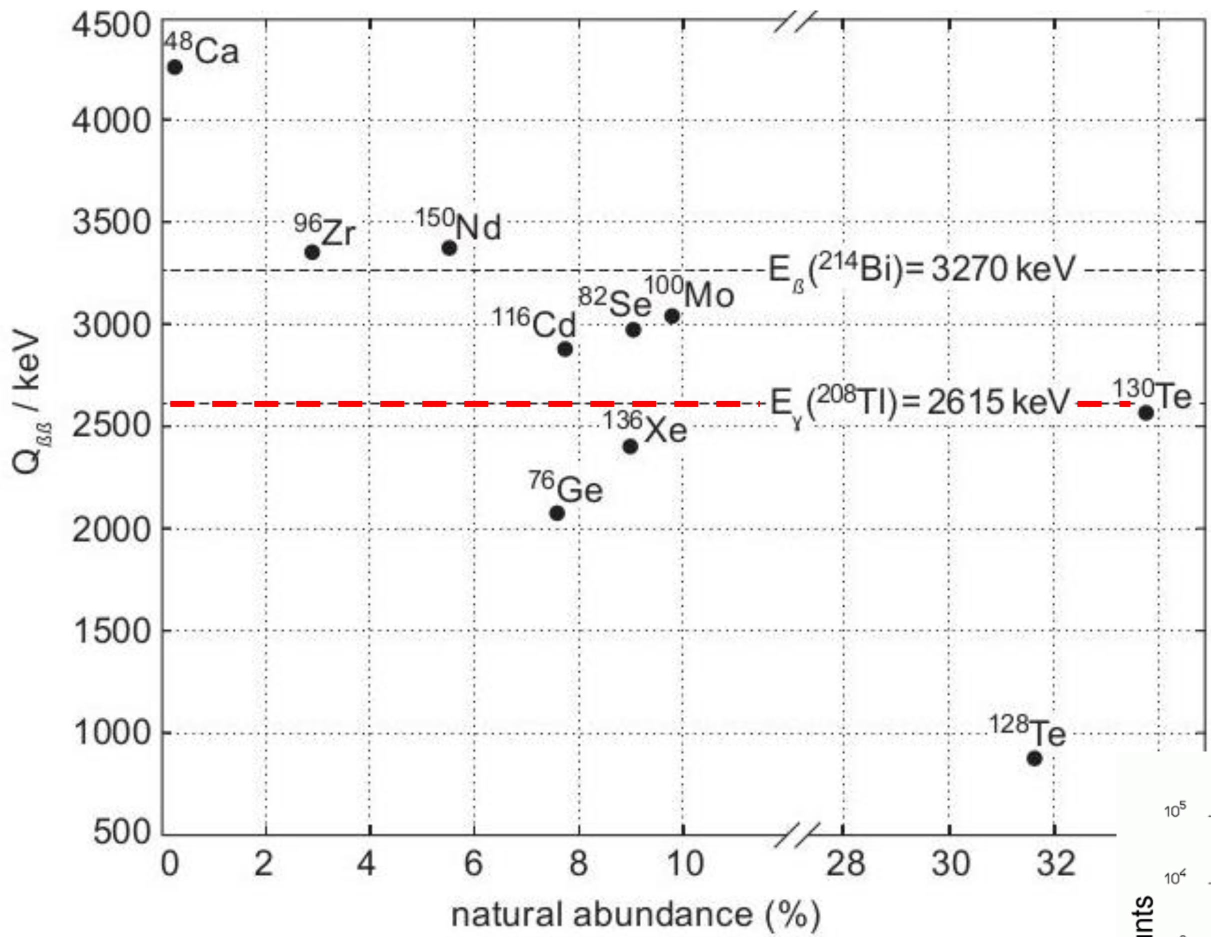
! Plot applies for 3 generations & light neutrinos.

Current Generation 0νββ Experiments

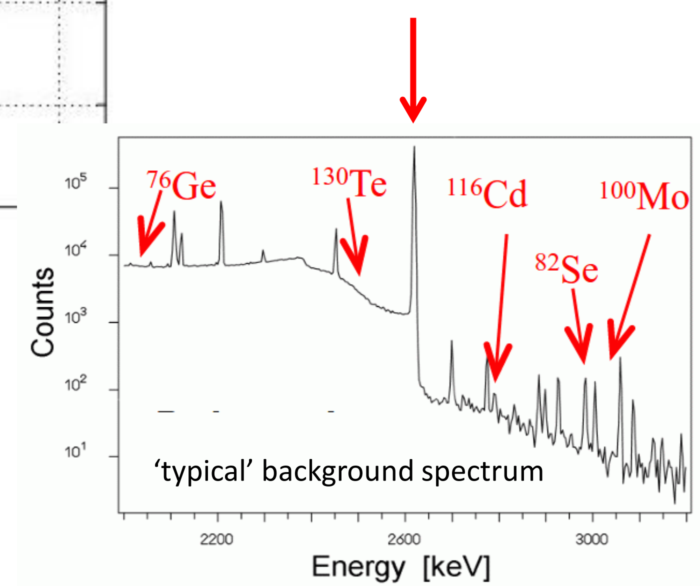
Experiment	Isotope	Technique (all calorimetric - but one)	Isotope Mass (kg)		Status
CANDLES	^{48}Ca	$^{nat}CaF_2$ scintillator, active veto	0.3		R&D
GERDA phase I	^{76}Ge	^{enr}Ge diodes in LAr	18		complete
GERDA phase II	^{76}Ge	^{enr}Ge diodes in LAr, active LAr veto	31		operating
Majorana Demo.	^{76}Ge	point contact ^{enr}Ge diodes in vacuo	26	•	operating
SuperNEMO	^{82}Se	foils with tracking	7		constr.
CUPID-0	^{82}Se	Zn^{enr}Se scintillating bolometer	5.2	•	operating
CUPID-0/Mo	^{100}Mo	$Li_2{}^{enr}MoO_4$ scintillating bolometer	5		start: 2018
AMoRE-I	^{100}Mo	$^{40}Ca^{enr}MoO_4$ scintillating bolometer	2.5		operating
CUORE	^{130}Te	$^{nat}TeO_2$ bolometer	210	•	operating
SNO+ phase I	^{130}Te	0.5% ^{nat}TeBD in liquid scintillator	1357	•	start: 2019
EXO-200	^{136}Xe	liquid ^{enr}Xe TPC	160	•	operating
KamLAND-Zen 400	^{136}Xe	2.7% ^{enr}Xe in liquid scintillator	380		complete
KamLAND-Zen 800	^{136}Xe	^{enr}Xe in liquid scintillator	750		start: 2018
NEXT-100	^{136}Xe	high pressure ^{enr}Xe TPC	91	•	start: 2019
LEGEND-200/1000	^{76}Ge	^{enr}Ge diodes in LAr, active LAr veto	175 / 873	•	
CUPID/Se/Mo/Te	tbd	enriched scintillating bolometer	300 - 500	•	
SNO+ phase II	^{130}Te	3% ^{nat}Te in liquid scintillator	7960	•	
nEXO	^{136}Xe	liquid ^{enr}Xe TPC	4500	•	
KamLAND2-Zen	^{136}Xe	^{enr}Xe in liquid scintillator	1000		

next generation

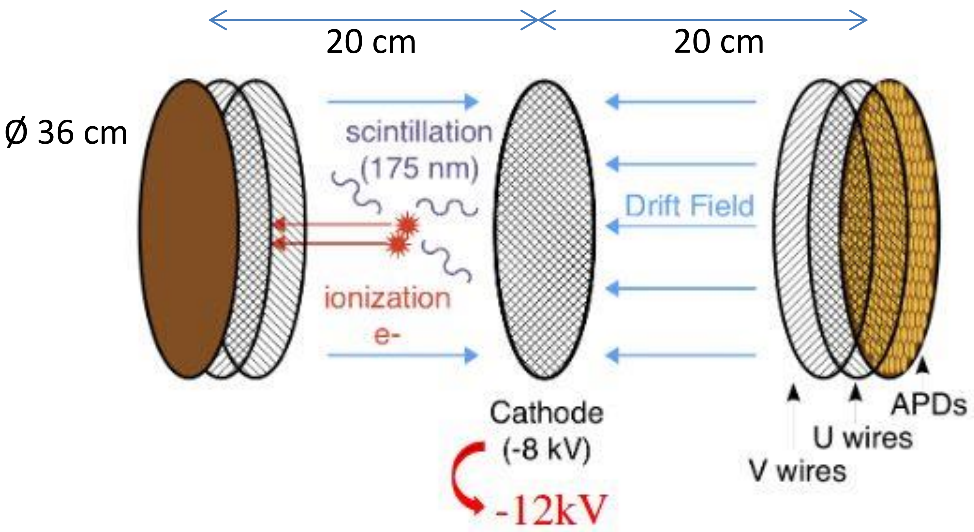
Double beta decay isotopes – $Q_{\beta\beta}$ and natural abundances



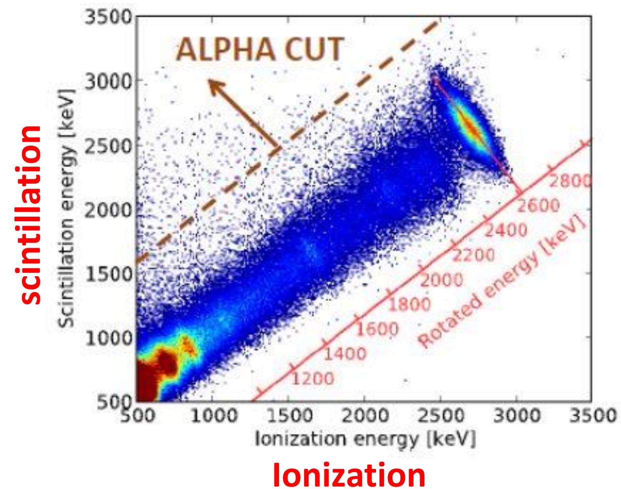
2615 keV γ line



WIPP, Carlsbad, NM 1624 m.w.e.



Scintillation vs. ionization, ^{228}Th calibration:



- cylindrical single phase TPC filled with ≈200 kg of liquid Xe enriched to 80.6% in ^{136}Xe
- fiducial volume 76.5 kg
- discrimination between single-site (signal-like) and multi-site (background) events
- 1st working hundred-kilogram-scale detector

anti-correlation between charge and scintillation response exploited for improved energy resolution

<u>Phase I:</u>

$T^{0\nu}_{1/2}$ sensitivity : $1.9 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $> 1.1 \cdot 10^{25}$ yr

* profile likelihood (90% CL)

Phase I 2011 exposure 10 kg·yr; break in 2014-2015 due to fire and radiation problems in WIPP; upgrade, restart 2016

Nature 510 (2014) 229

Upgrade for Phase II

Cathode voltage -8kV → -12kV
Radon suppression by factor of 10
Noise reduction, improved resolution

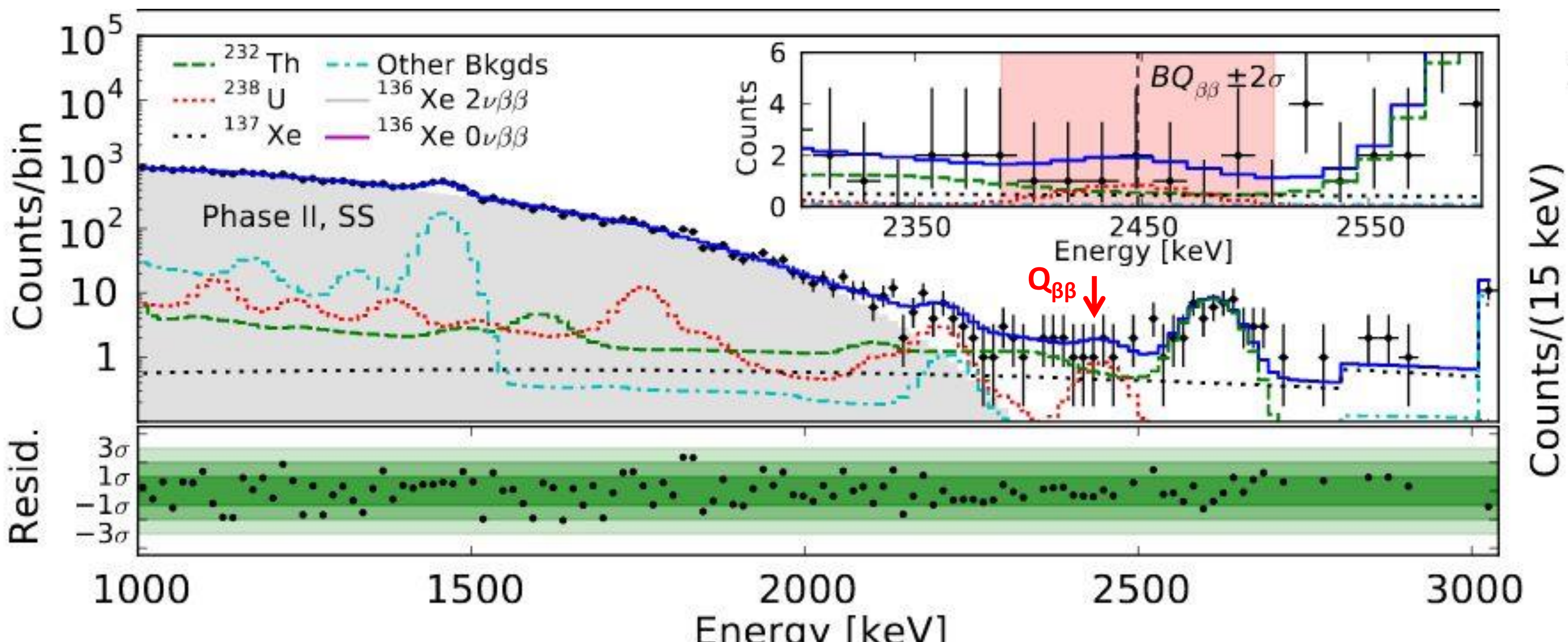
Will run up to $5 \cdot 10^{25}$ yr sensitivity

Phase I and II:

exposure = 177.6 kg·yr
FWHM@$Q_{\beta\beta}$ = 71 keV (2.9%)
BI = $(1.6 \pm 0.2) \cdot 10^{-3}$ cnts/(keV ·kg ·yr)

$T^{0\nu}_{1/2}$ sensitivity : $3.7 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $> 1.8 \cdot 10^{25}$ yr

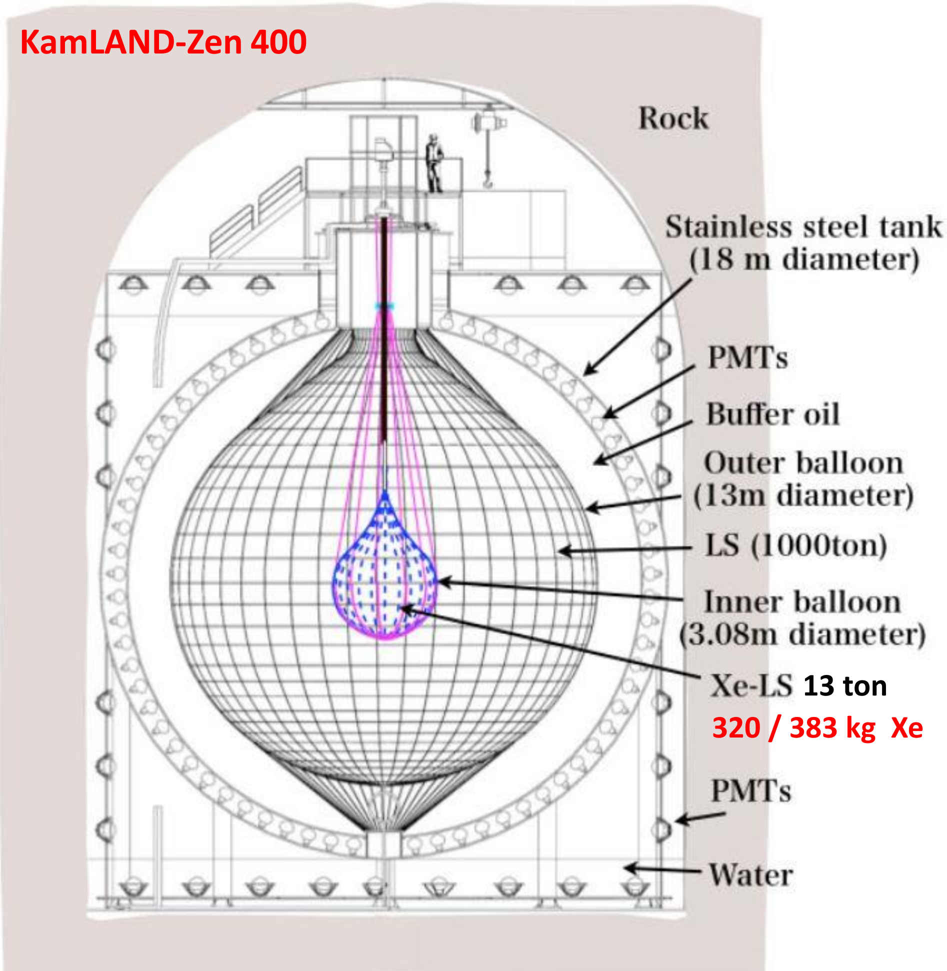
* profile likelihood (90% CL)



PRL 120, 072701 (2018)

KamLAND-Zen 400 / ^{136}Xe setup

Kamioka 2700 m.w.e.



^{136}Xe (≈ 3%) loaded liquid scintillator
(90% enrichment)

Phase I (2011-2012) 89.5 kg·yr

$T^{0\nu}_{1/2}$ sensitivity	:	$1.0 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit*	:	$> 1.9 \cdot 10^{25}$ yr

PRL , 062502 (2013)

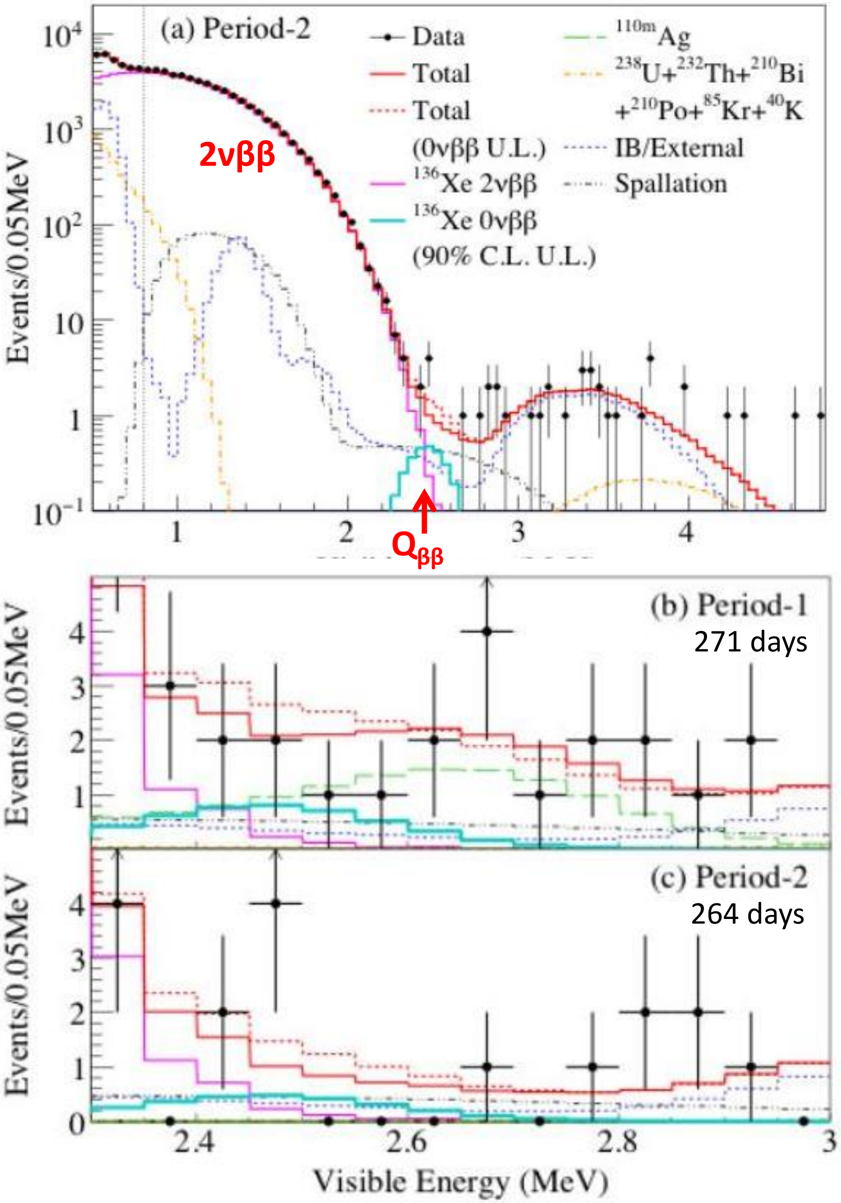
unexpected contamination in ROI
identified as ^{110m}Ag
from Fukushima accident or spallation

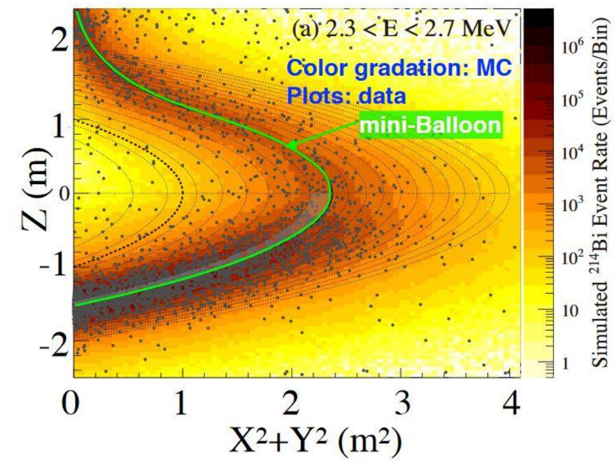
purification reduces ^{110m}Ag by factor of 10

Phase II (2013-2015) 504 kg·yr

KamLAND-Zen 400 / ^{136}Xe results

Phase II





Background dominated by ^{214}Bi decays at MIB

exposure = 593.5 kg·yr

FWHM@$Q_{\beta\beta}$ ≈ 270 keV (11%)

BI ≈ 0.4 · 10^{-3} cnts/(keV ·kg ·yr)

$T_{1/2}^{0\nu}$ sensitivity : 5.6 · 10^{25} yr

$T_{1/2}^{0\nu}$ limit* : > 9.2 · 10^{25} yr

$T_{1/2}^{0\nu}$ limit** : > 10.7· 10^{25} yr

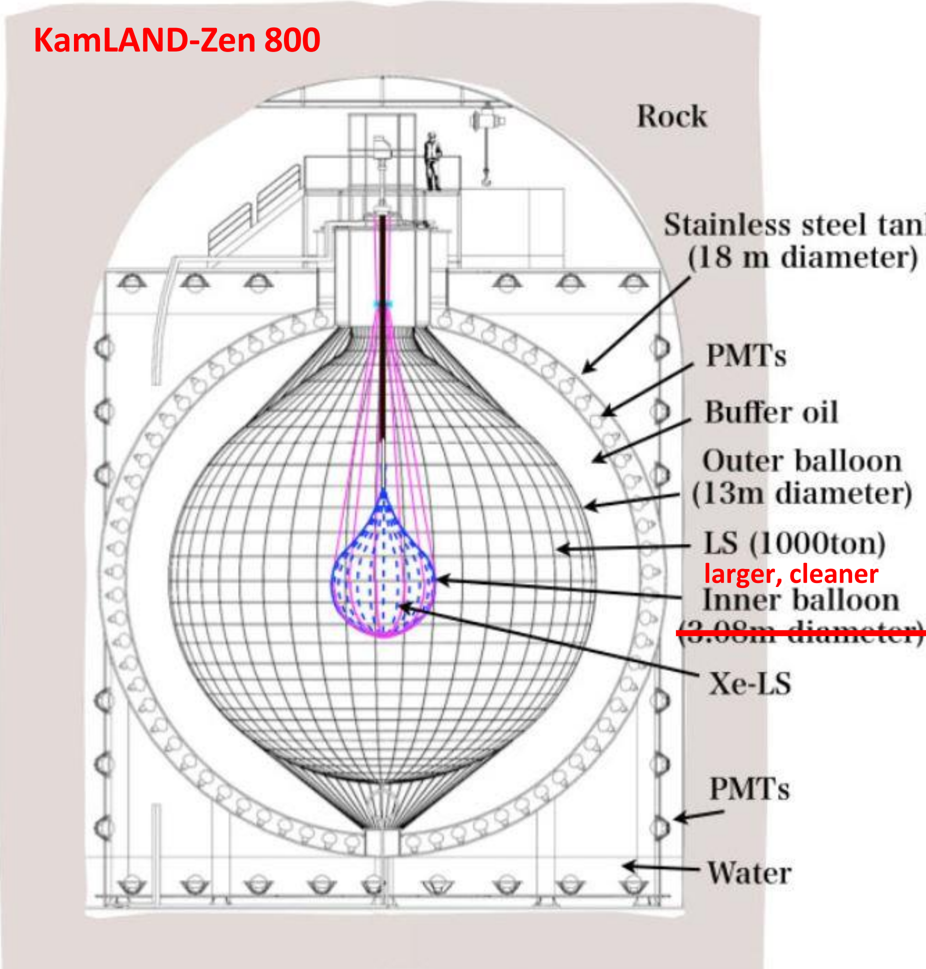
* profile likelihood (90% CL)

** Phase I + II combined

PRL , 082503 (2016)

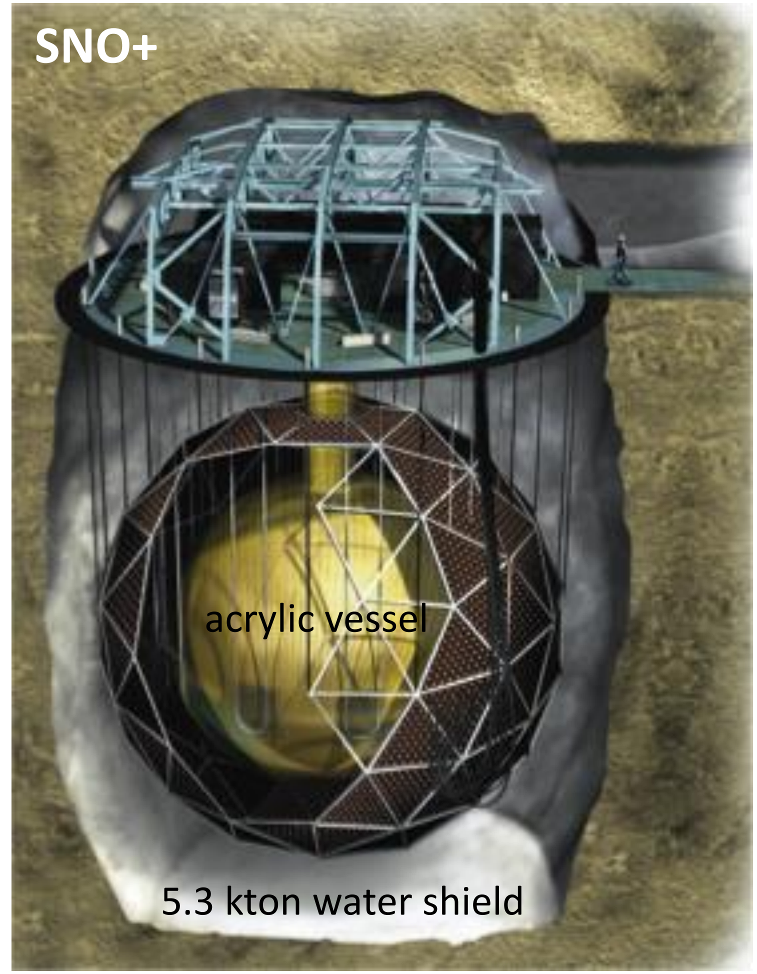
KamLAND-Zen 800 & SNO+ expected to start in 2018/19

Kamioka 2700 m.w.e.



≈750kg of ^{136}Xe in liquid scintillator (LS) (90% enrichment), new Inner Balloon

SNOLAB 6000 m.w.e.

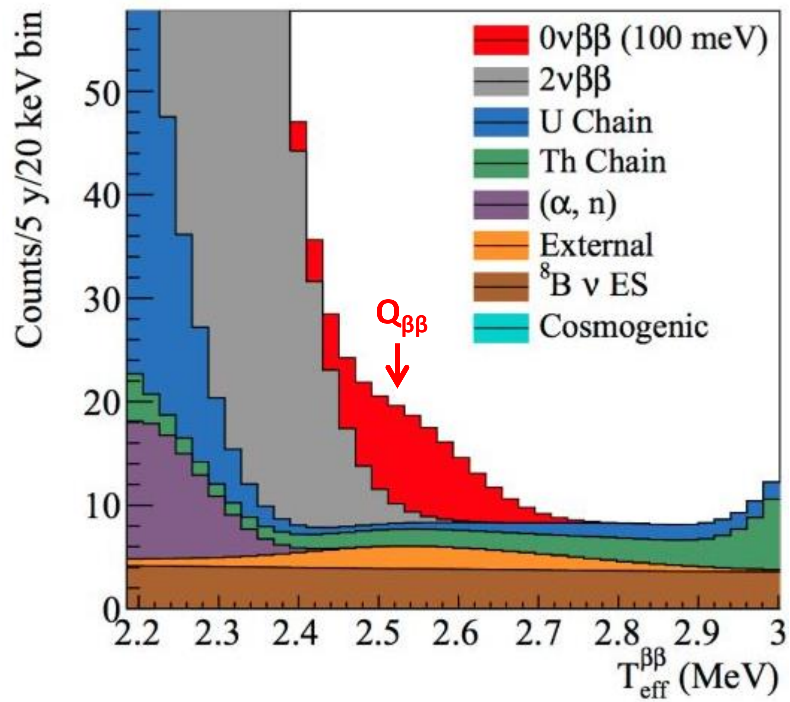


<u>Plan for Phase I</u>: 0.5% ^{nat}Te, i.e. 1.3 tons of ^{130}Te, in 780 tons of LS, - all contained in the Ø12m acrylic vessel

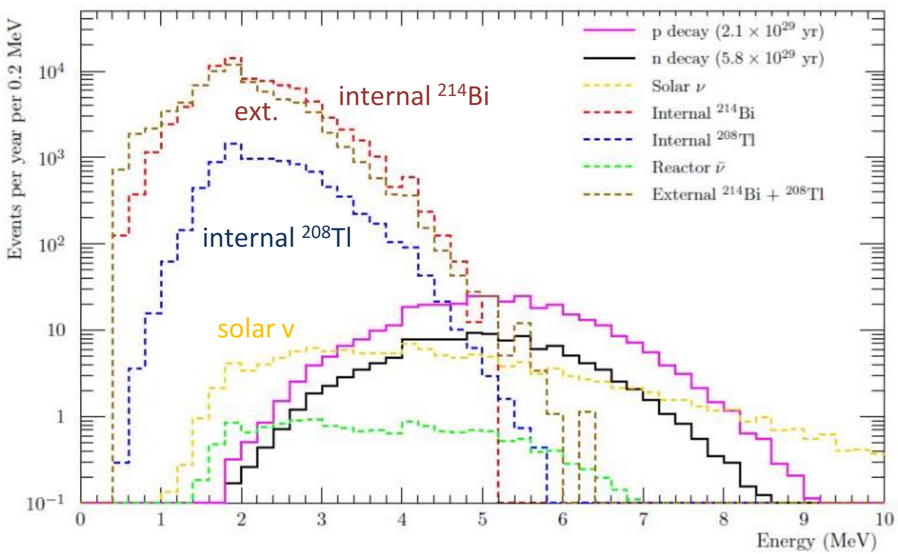
SNO+ / ^{130}Te expected performance

Status:

- Te acid underground since 2015
- Detector upgrade ready in April 2017
- Water-fill phase started in May 2017
- Currently taking physics data with water fill
- Scintillator process plant under commission
- Tellurium plant under construction
- Te loading in 2019

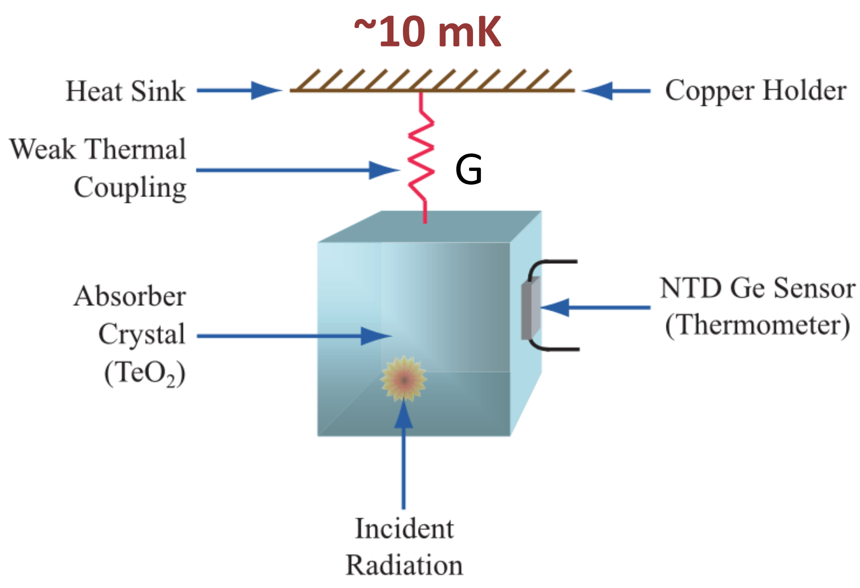


Expected spectrum for 5 years of SNO+ search for ^{130}Te 0vßß decay, sensitivity $2x10^{26}$ yr



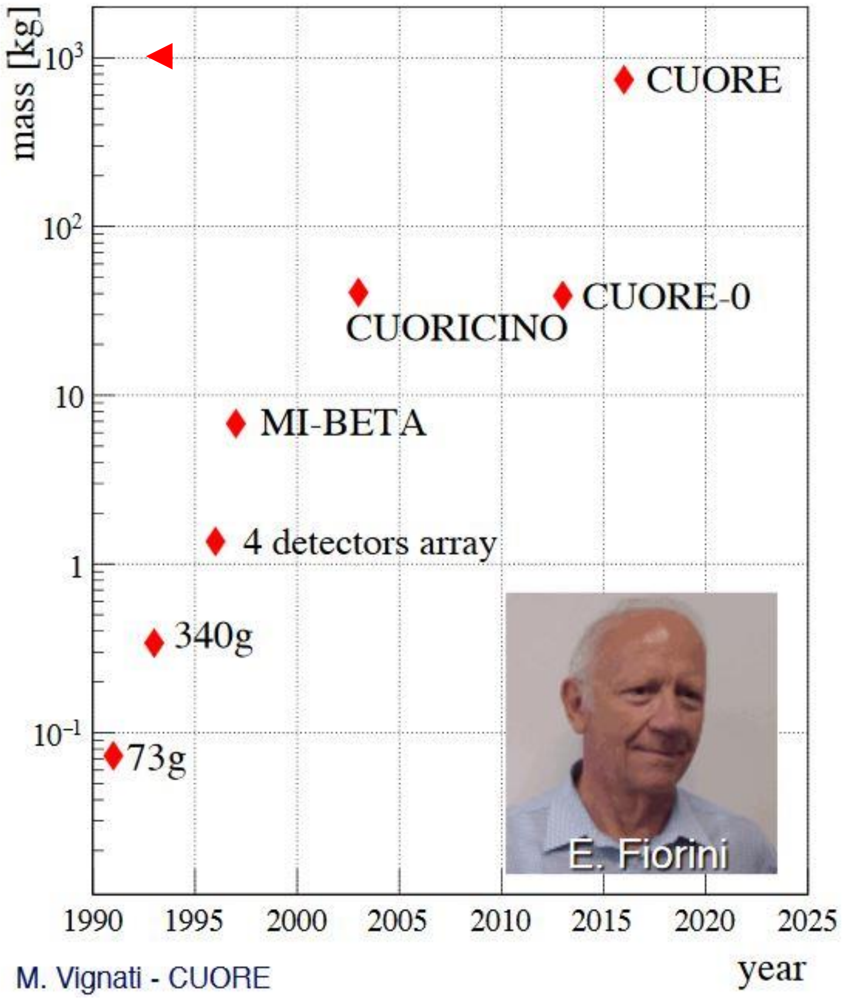
Expected spectrum for 6 months of SNO+ search for invisible nucleon decay, e.g. n→3v.

arXiv: 1711.11094



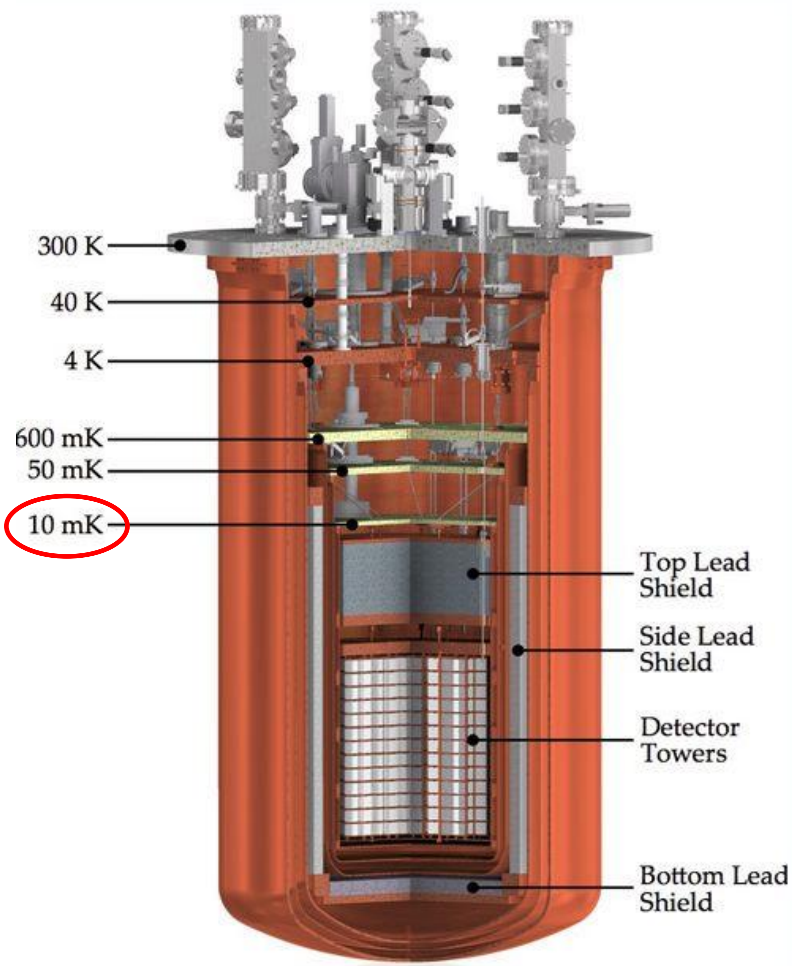
$m \approx 750$ g
$C \approx 2$ nJ / K
$\Delta T / \Delta E \approx 0.1$ mK /MeV
$\Delta V / \Delta E \approx 0.3$ mV /MeV
$G \approx 2$nW / K
$\tau \approx C / G \approx 1$s

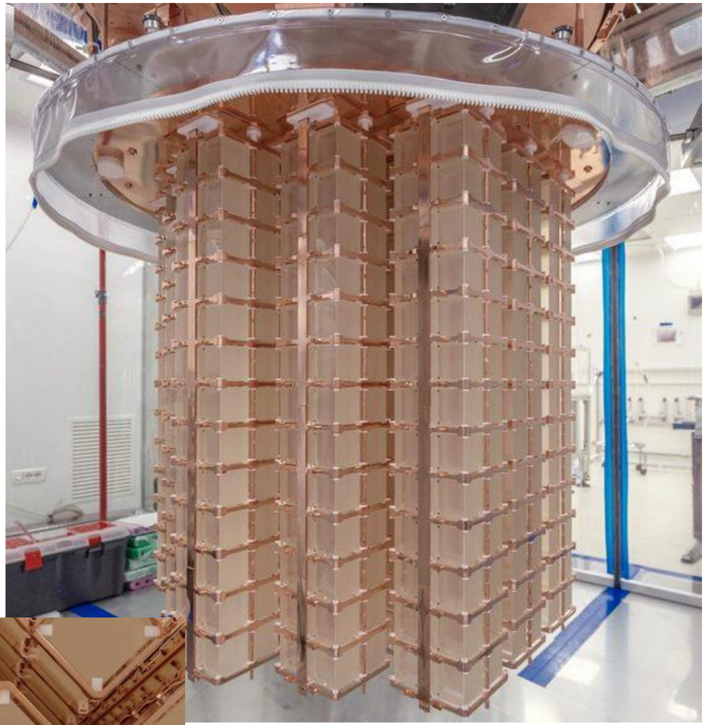
1st ton-scale cryogenic bolometer

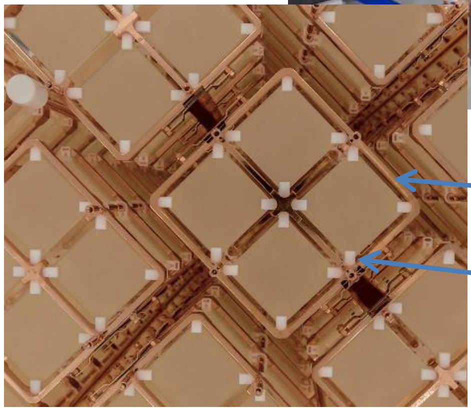


LNGS 3600 m.w.e.

988 $^{nat}TeO_2$ bolometers 984 working
active mass: 742 kg
isotope mass: 206 kg ^{130}Te

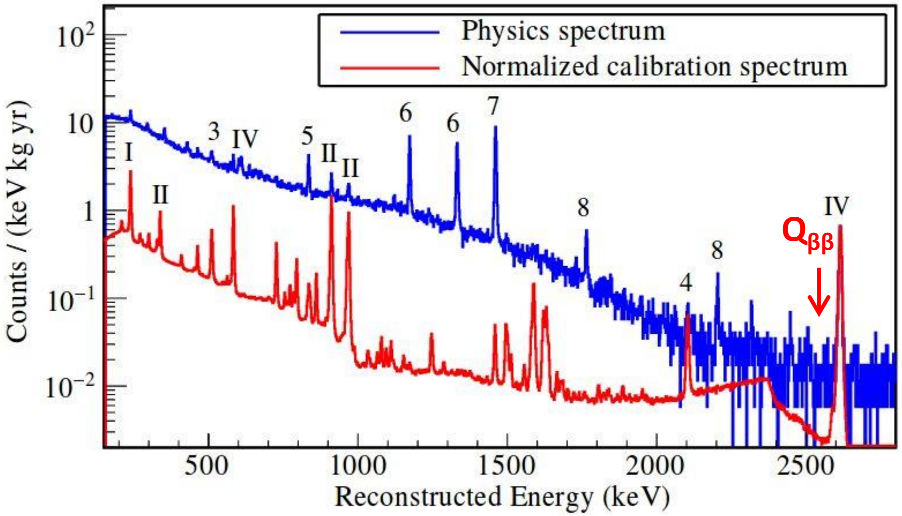




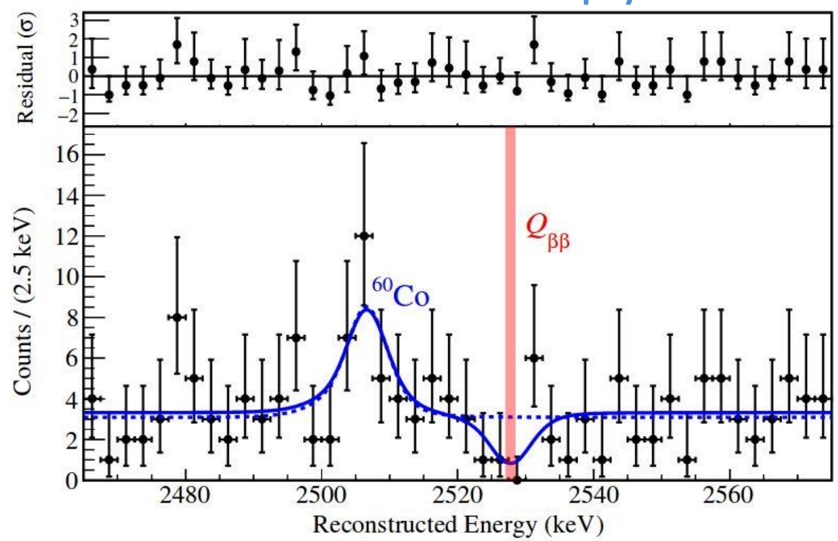


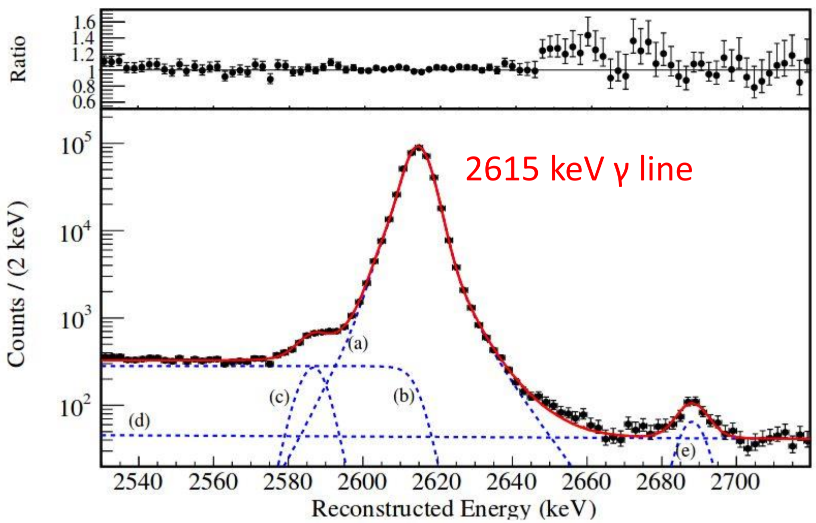
copper frame – heat sink

PTFE supports – thermal impedance



physics data ROI





complex line shape

TeO_2 exposure = 86.3 kg·yr

FWHM@$Q_{\beta\beta}$ = 7.7 ± 0.5 keV (0.3%)

BI = (14 ± 2)· 10^{-3} cnts/(keV ·kg ·yr)

Background in ROI mostly α particles!

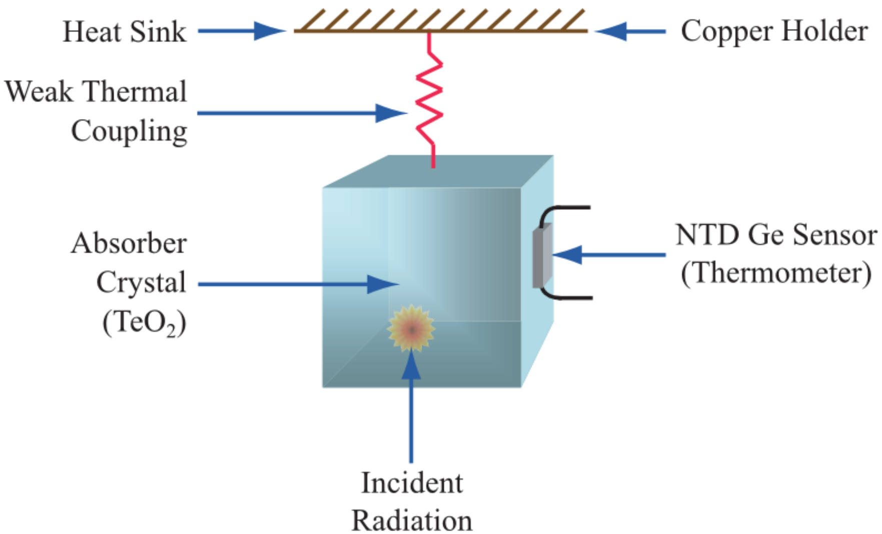
$T^{0\nu}_{1/2}$ sensitivity	:	0.7· 10^{25} yr
$T^{0\nu}_{1/2}$ limit*	:	>1.5 · 10^{25} yr

* profile likelihood (90% CL)

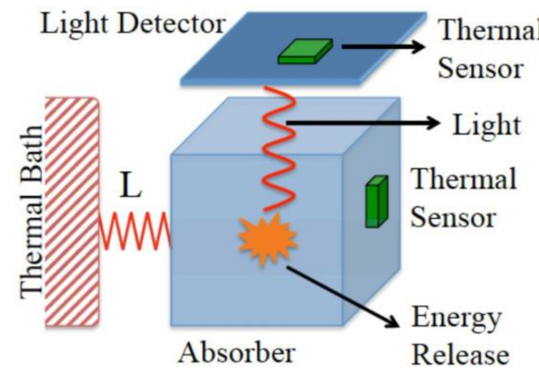
PRL 120, 132501 (2018)

CUORE with Particle ID = CUPID

CUORE dominant BGND: surface α particles



CUPID rejection of α particles by detecting both heat and light



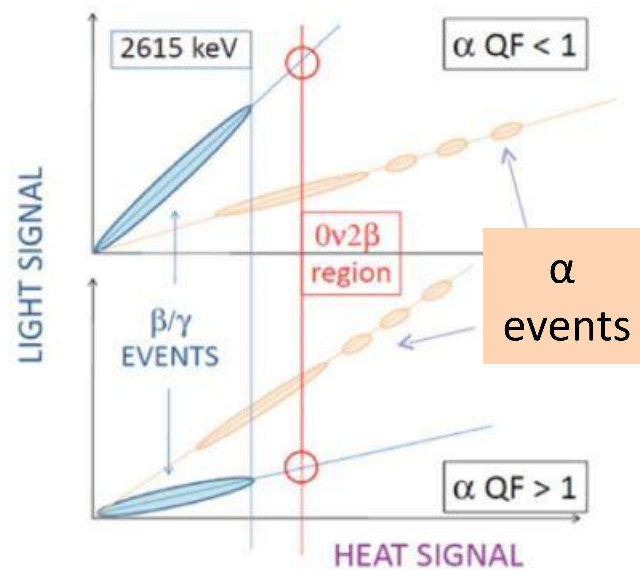
scintillating crystal

or Cherenkov light in TeO_2

R&D for highly radiopure scintillating crystals

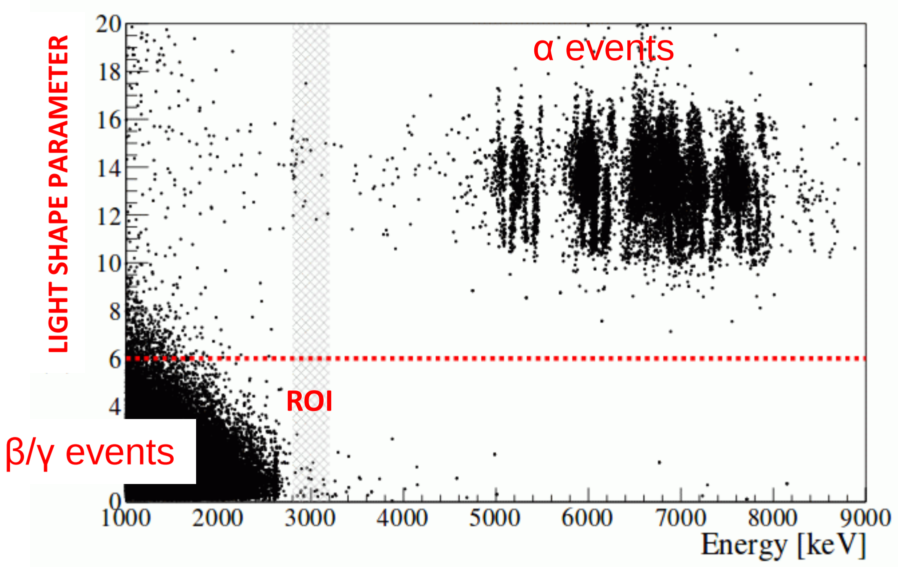
- $Zn^{82}Se$ CUPID-0
- $Zn^{100}MoO_4$................ LUCIFER, LUMINEU
- $Li_2{}^{100}MoO_4$..................dto
- $^{40}Ca^{100}MoO_4$...............AMoRE
- $^{116}Cd^{100}MoO_4$............ KINR-ITEP-DAMA

Poda, Giuliani, arXiv:1711.01075



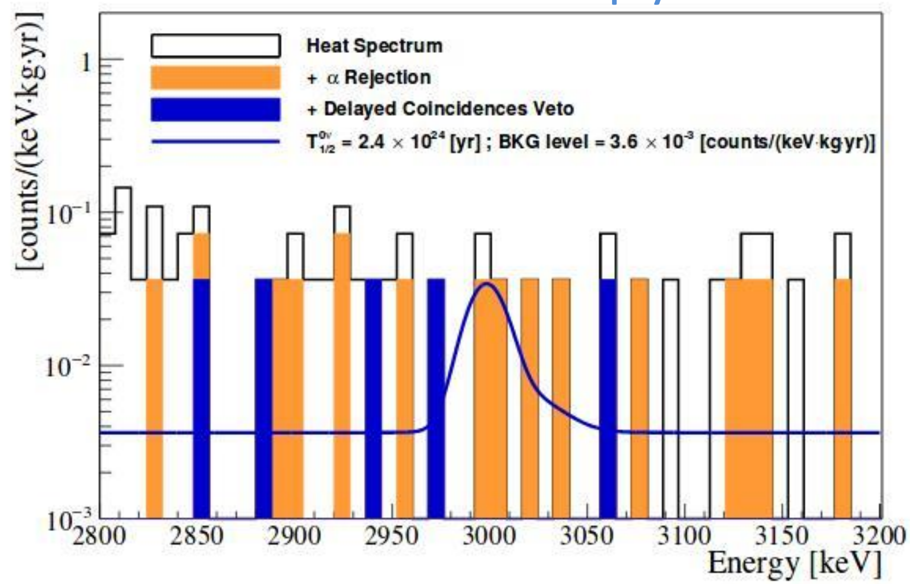
CUPID-0 / ^{82}Se results

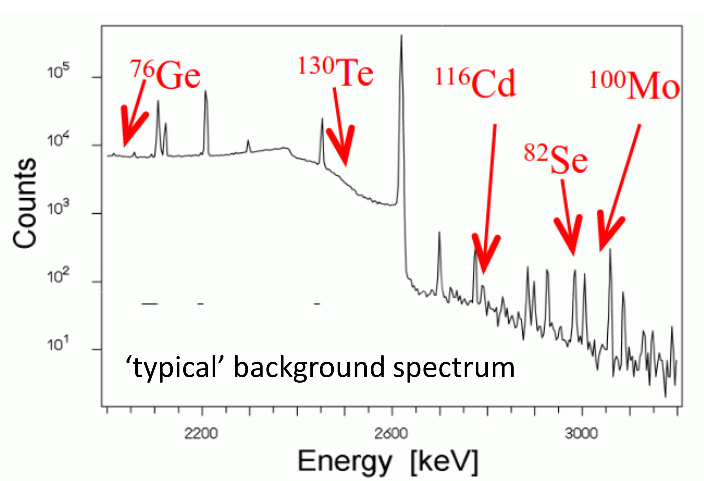
LNGS 3600 m.w.e.



Lowest BGND level ever in bolometric experiment!

physics data ROI





^{82}Se exposure = 1.83 kg·yr

FWHM@$Q_{\beta\beta}$ = 23 ± 0.6 keV (0.9%)

BI = (3.6 ± ≈2)· 10^{-3} cnts/(keV·kg·yr)

$T^{0\nu}_{1/2}$ sensitivity : $2.3 \cdot 10^{24}$ yr

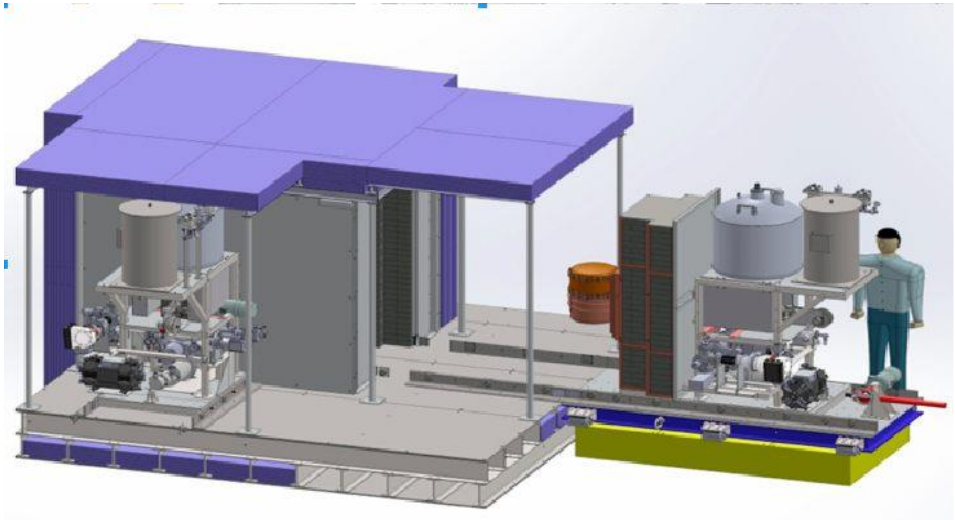
$T^{0\nu}_{1/2}$ limit* : > $2.4 \cdot 10^{24}$ yr

* Bayes (90% CI)

PRL accept. May 08 (2018)

SURF 4300 m.w.e.

Ge diodes in vacuo,
electro-formed copper & lead shield



≈ 44 kg Ge, 29.7 kg thereof enriched,
p-type point contact HPGe detectors

LNGS 3600 m.w.e.

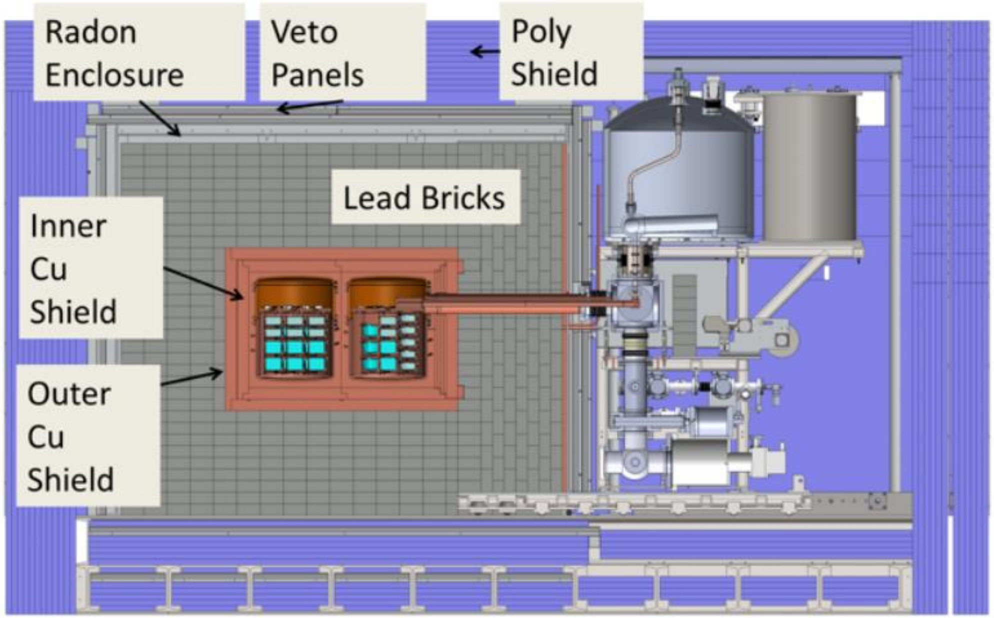
Ge diodes in active LAr shield,
low-mass holders, water shield

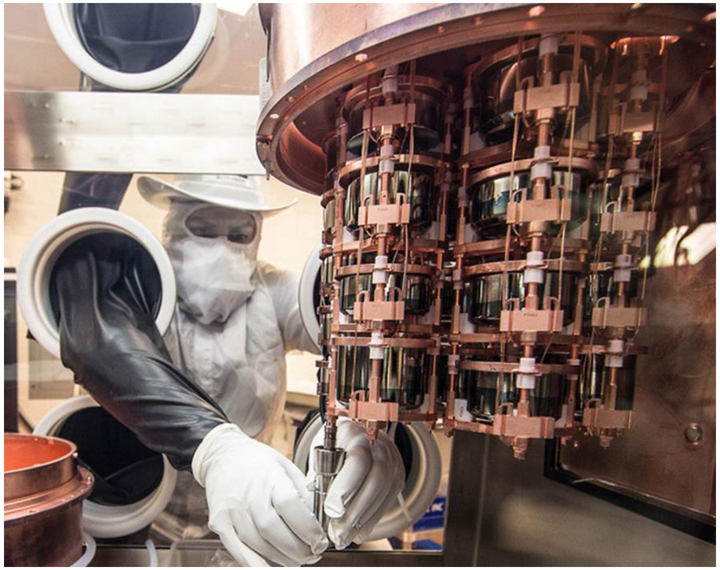
≈ 43 kg Ge, 35.8 kg thereof enriched,
semicoaxial and BEGe HPGe detectors

Goal: prove design for ton scale w.r.t. background & modular construction

'Traditional' setup: vacuum cryostats in passive copper/lead shield with ultraclean materials

custom point contact detectors to reject surface & multi-site events



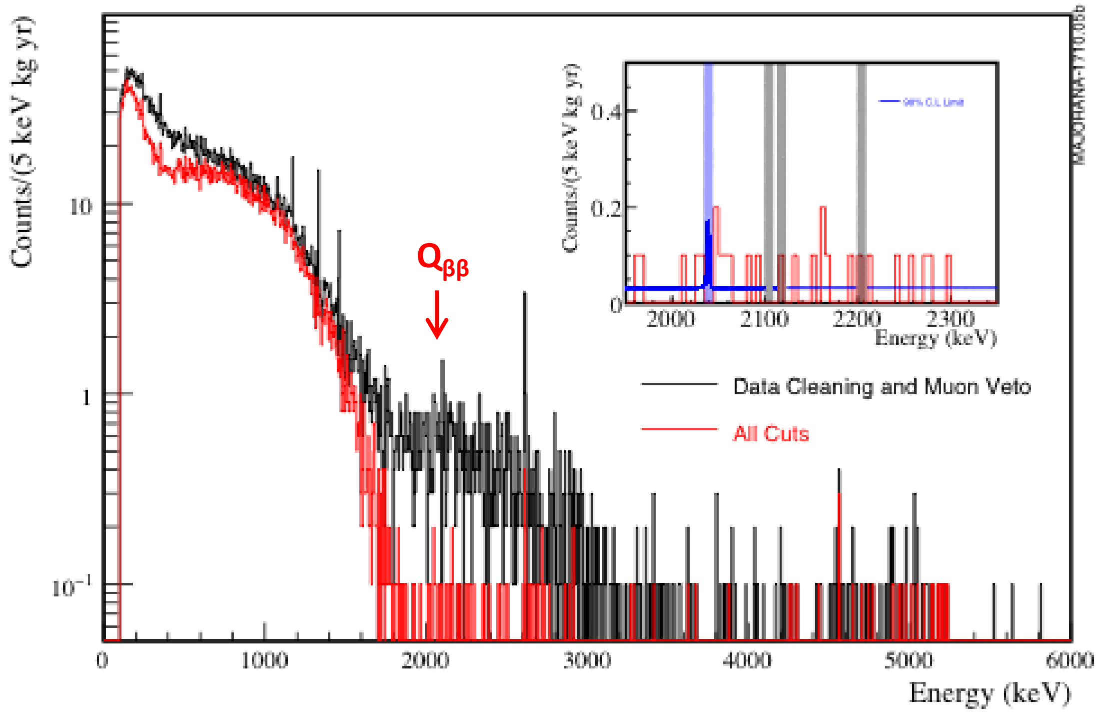


Prototyping: 2014-2015, 10 detectors

Module 1 : Dec 2015 final installation

Module 2: July 2016 finished

1st data release



- Best resolution of any ββ experiment to date: 2.52 keV at $Q_{\beta\beta}$
- Projected background rate 4 c/(FWHM·t·yr)
- Analysis of ≈ 26 kg·yr data in progress, expected sensitivity $5 \cdot 10^{25}$ yr

^{76}Ge exposure = 9.95 kg·yr

FWHM@$Q_{\beta\beta}$ = 2.52 ± 0.08 keV (0.12%)

BI = (6.7 ± 1.4)· 10^{-3} cnts/(keV·kg·yr) (total)

= (1.6 ± 1.1)· 10^{-3} cnts/(keV·kg·yr) (best)

$T^{0\nu}_{1/2}$ sensitivity : $2.1 \cdot 10^{25}$ yr

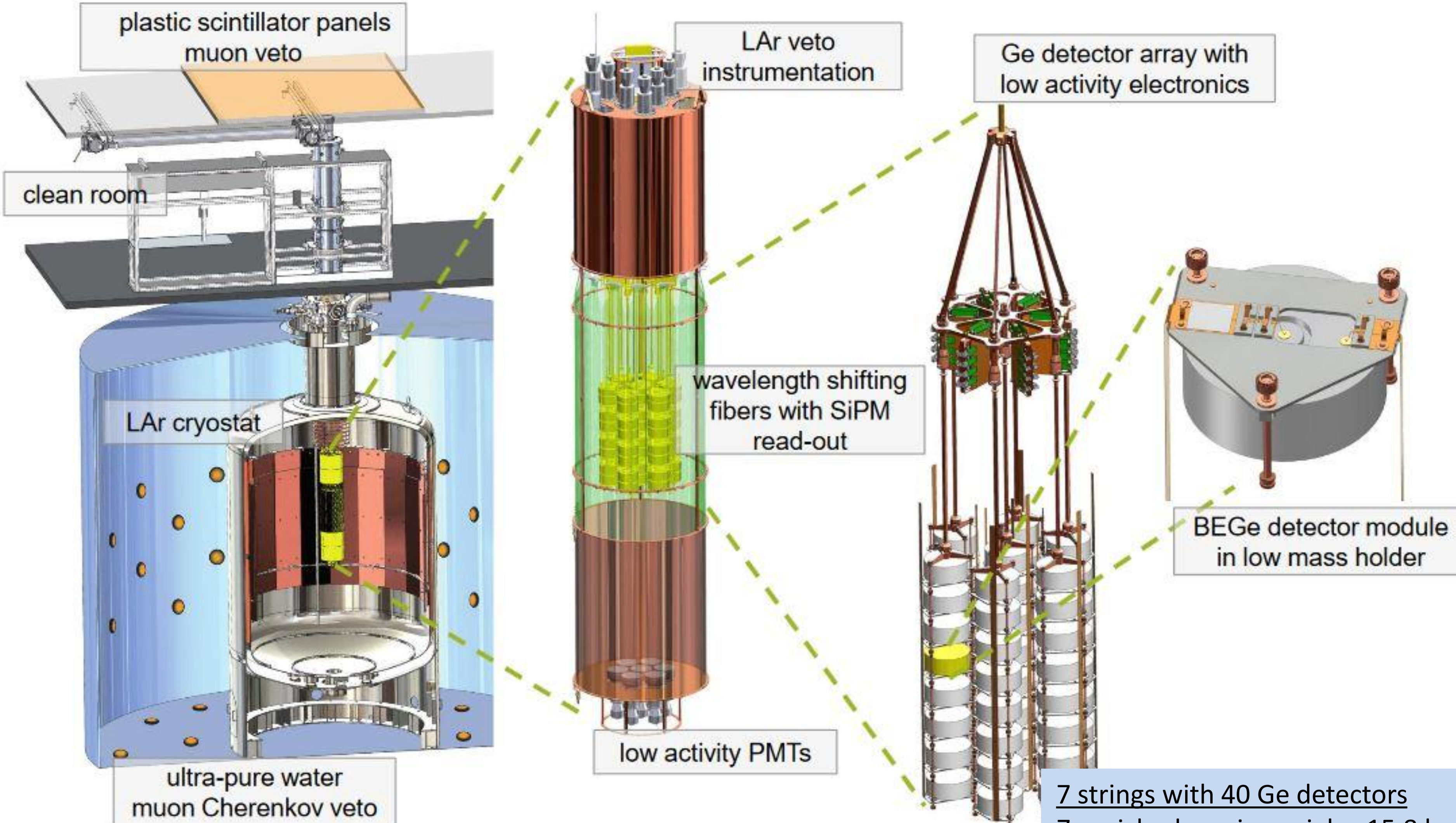
$T^{0\nu}_{1/2}$ limit* : $>1.9 \cdot 10^{25}$ yr

* profile likelihood (90% CL)

PRL 120, 132502 (2018)

LNGS 3600 m w.e.

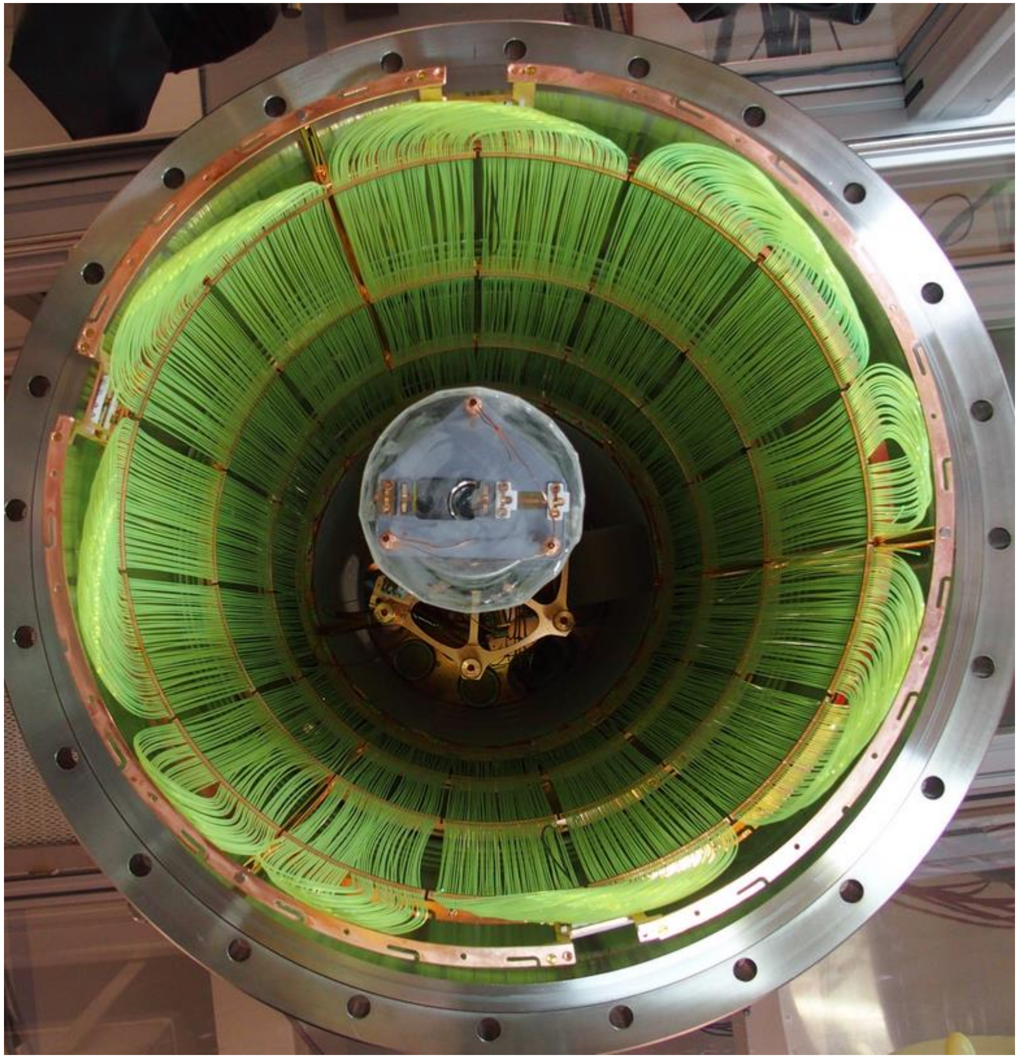
Phase I from Nov 2011 to May 2013
21 kg yr



<u>7 strings with 40 Ge detectors</u>
7 enriched semi-coaxials - 15.8 kg
30 enriched BEGe 20 kg
3 natural semi-coaxials

EPJC 78 (2018) 388

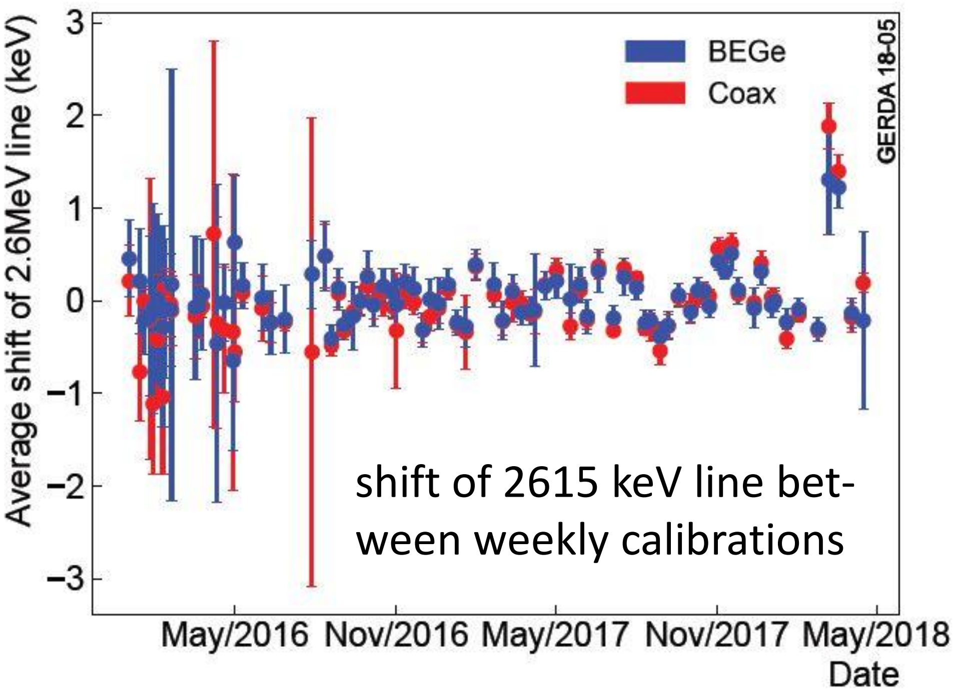
photos from commissioning



view from bottom: pilot string and
part of LAr veto in open lock

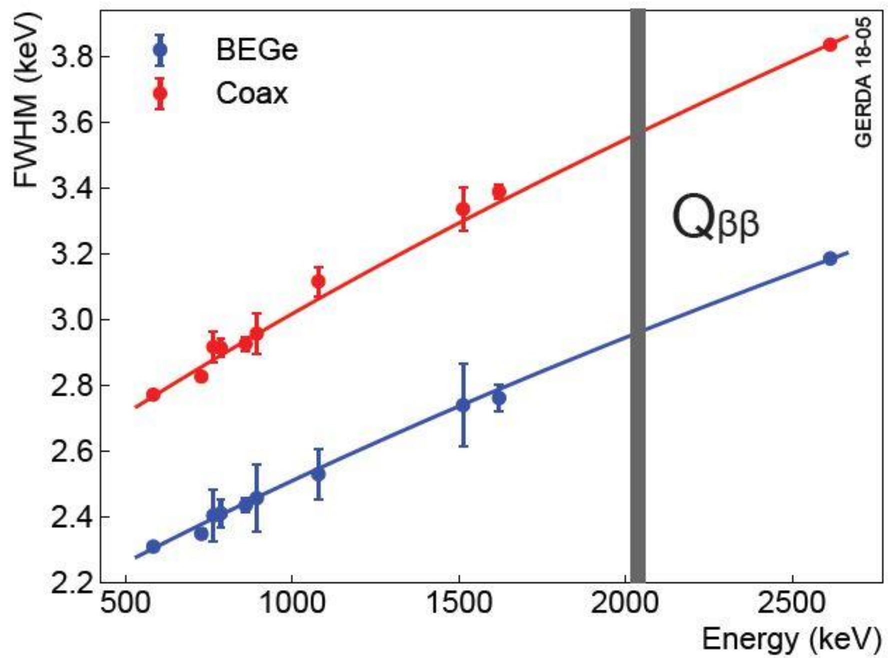
assembly of detector array

Time stability of energy scale



Most data points within ±1σ
data discarded if shift >2 keV

Average energy resolutions at $Q_{\beta\beta}$

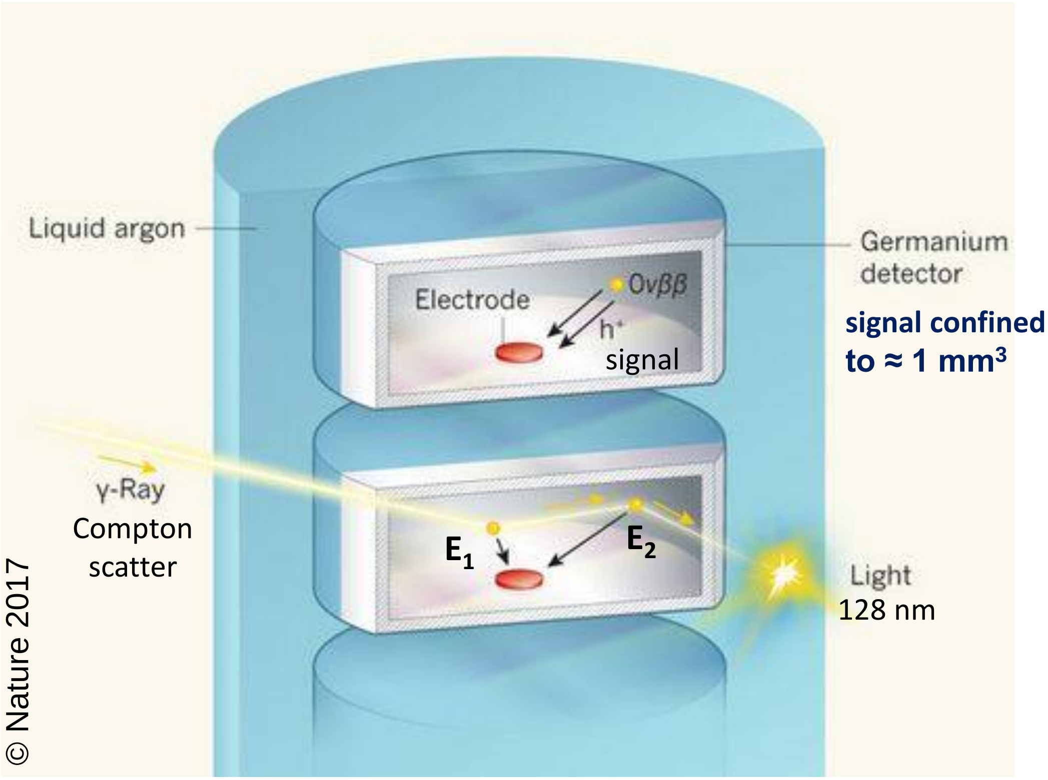


FWHM at $Q_{\beta\beta}$:

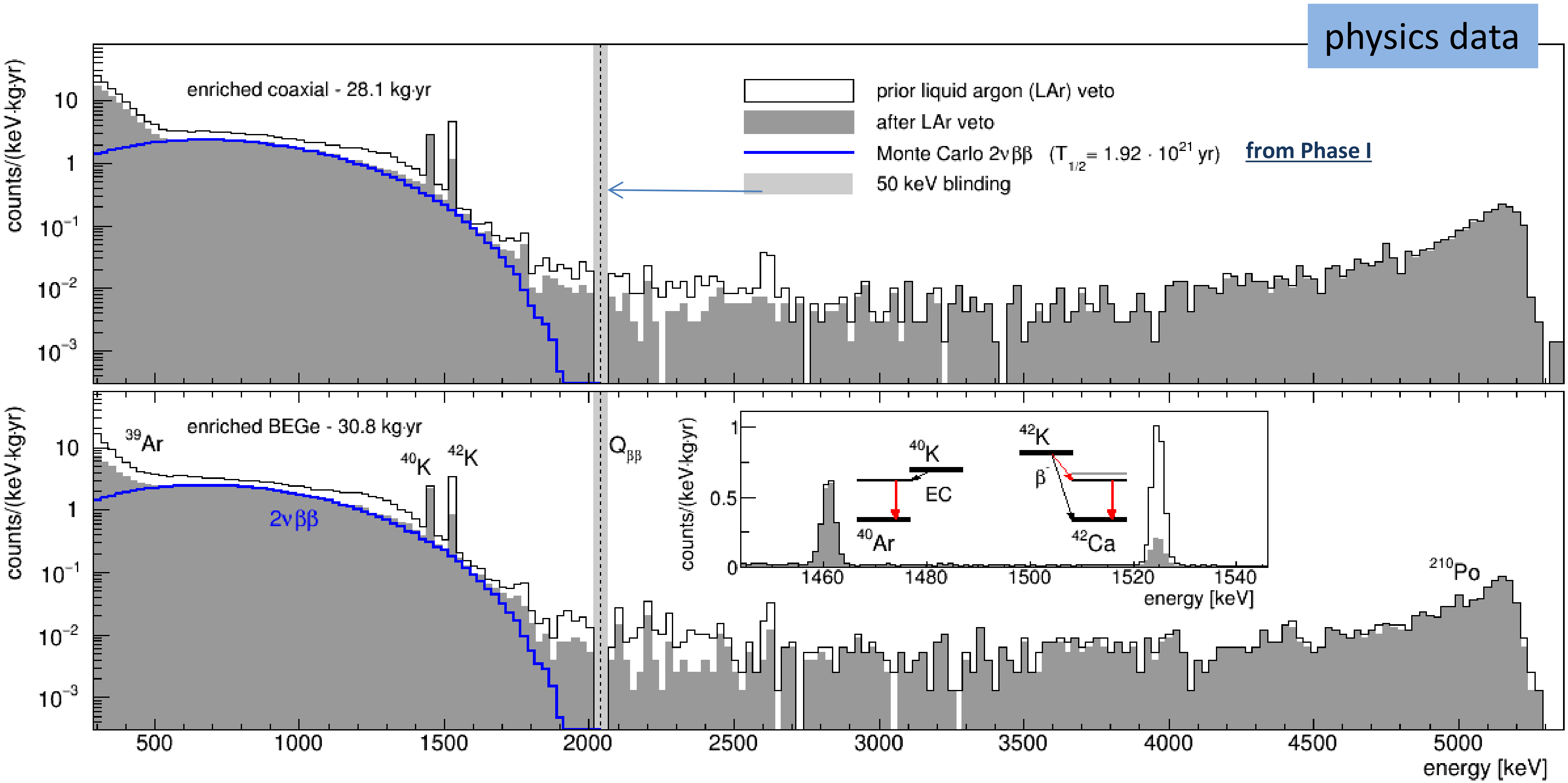
semi-coaxials : 3.57 ± 0.01 keV

BEGe detectors: 2.96 ± 0.01 keV

Discrimination of **signal-like single site-events** and **multiple interactions** & surface events

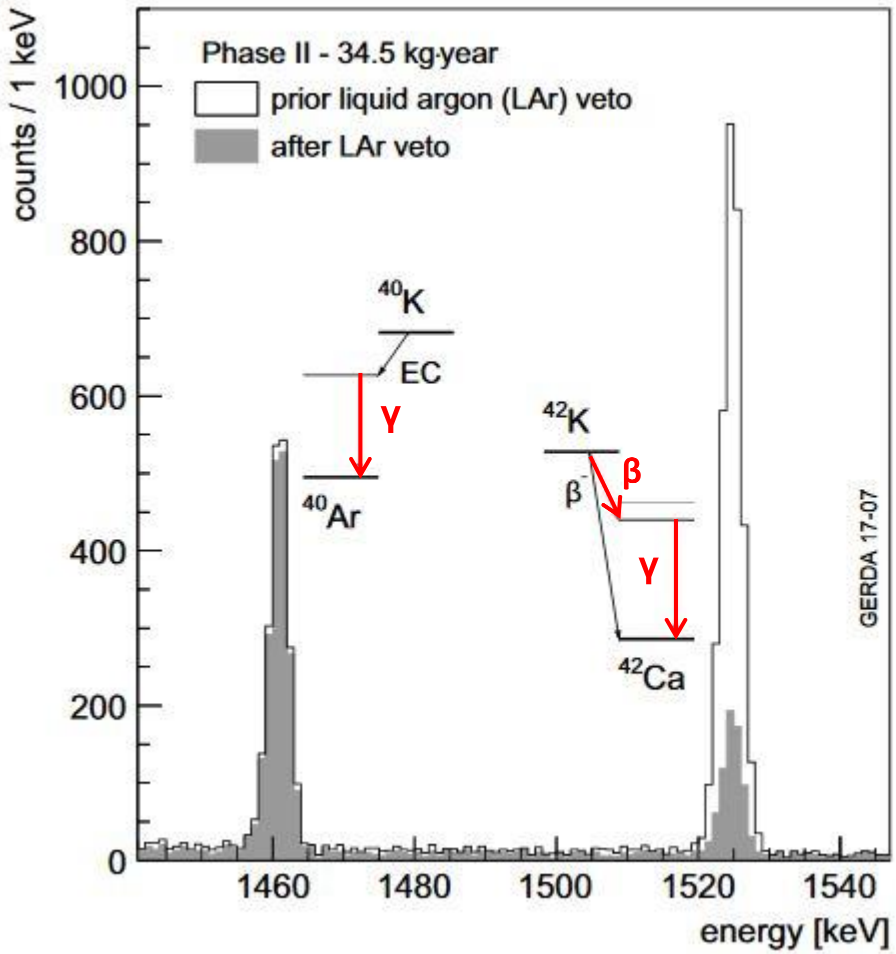


- Anticoincidence with muon veto system
- anti-coincidences within detector array
- ► anti-coincidence with active LAr shield

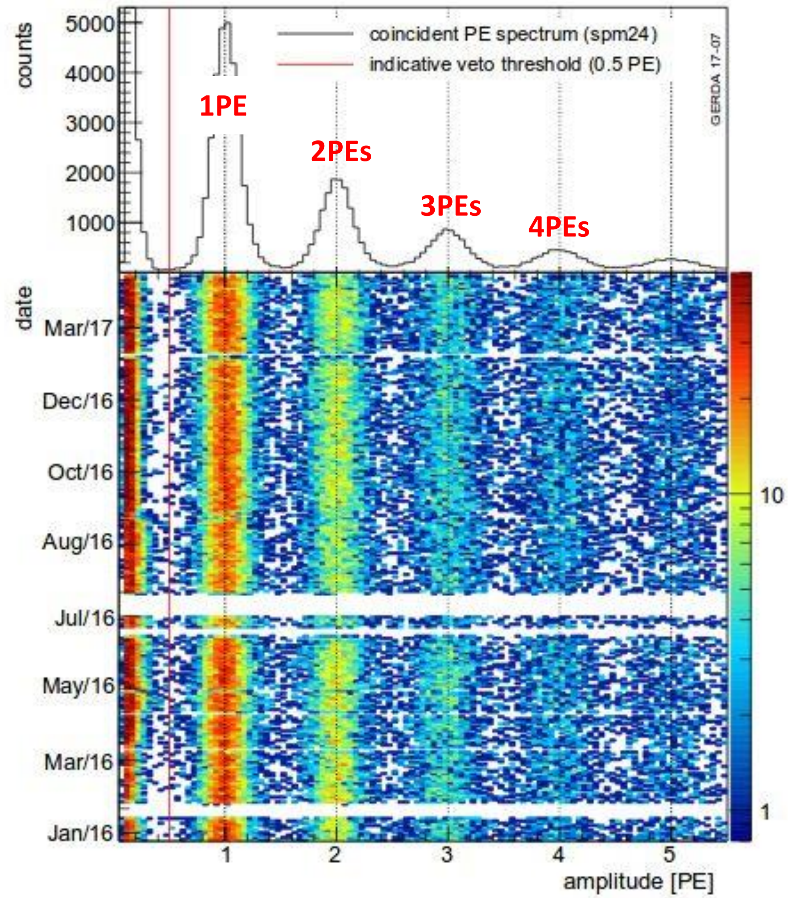


Most prominent features: ^{39}Ar (<500 keV), 2νββ continuum , ^{40}K and ^{42}K γ lines, α particles

- Compton continuum of ^{40,42}K γ lines strongly suppressed
- ^{40,42}K γ lines useful to monitor LAr veto performance with physics data

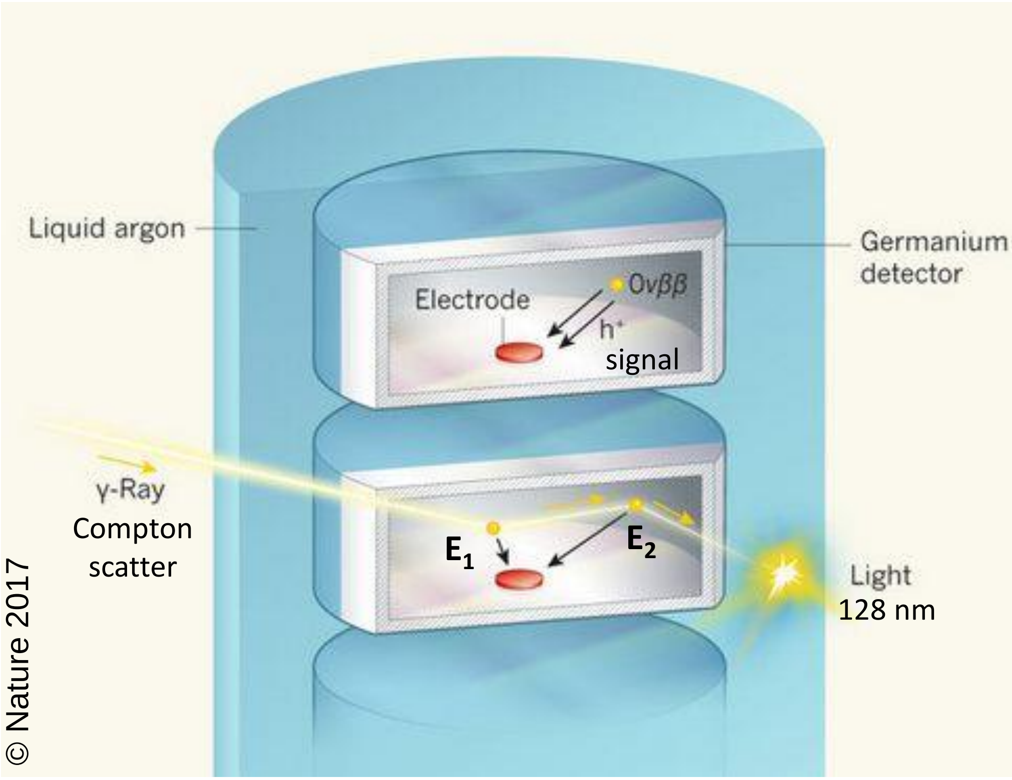


LAr veto acceptance 97.7(7) %

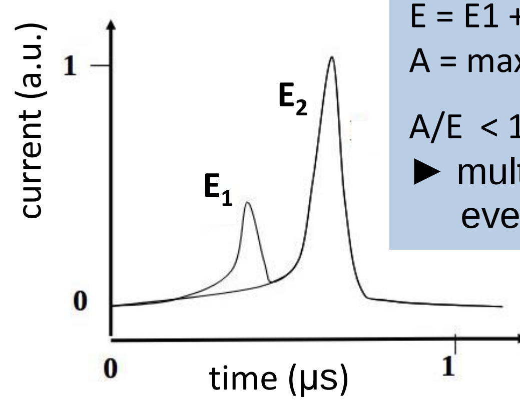


LAr time stability

Discrimination of **signal-like single site-events** and **multiple interactions** & surface events



BEGe (point contact) detector
time profile of current pulse

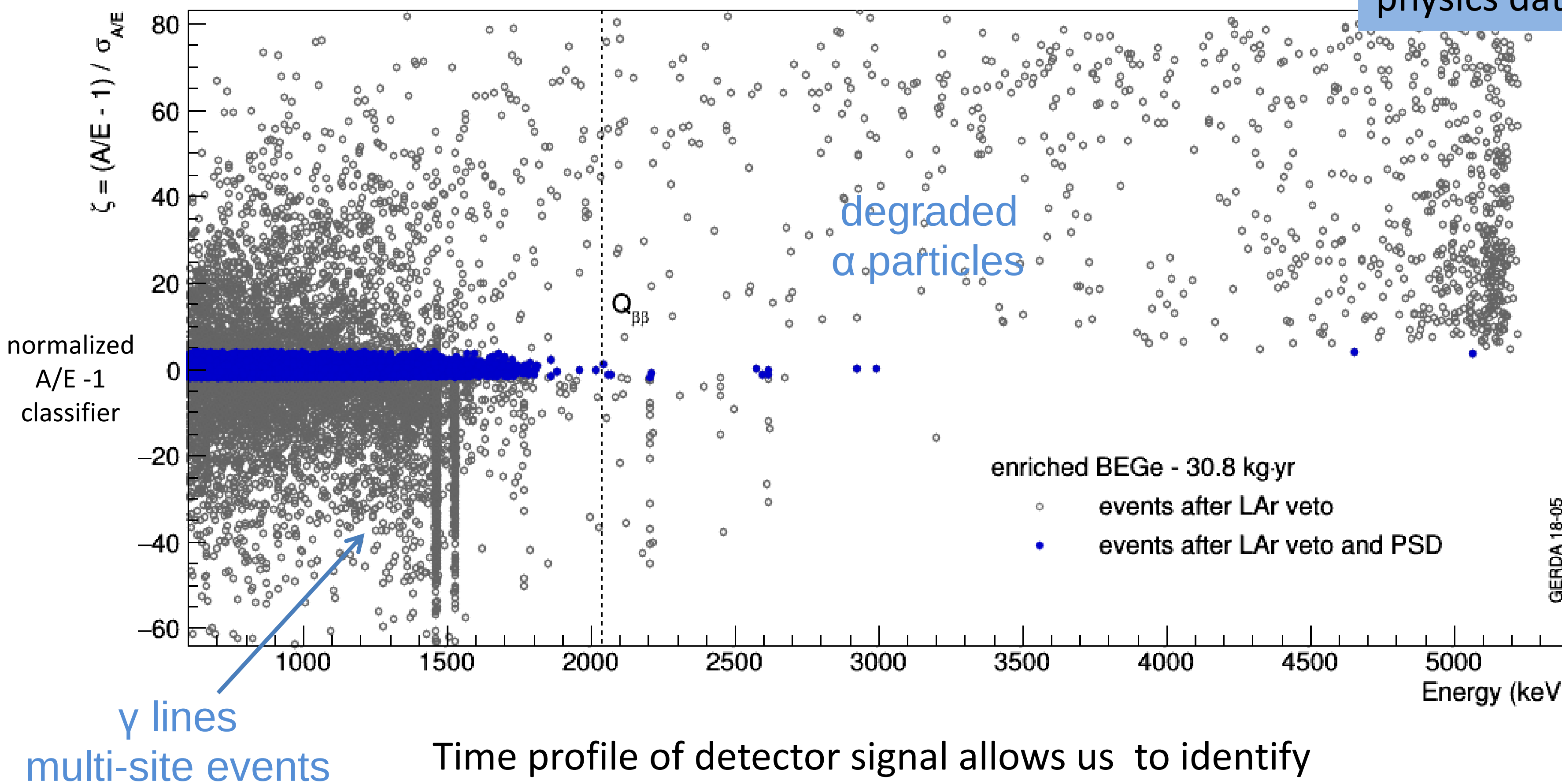


E = E1 +E2
A = max (E1,E2)

A/E < 1
► multi-site event

- anti-coincidences within detector array
- anti-coincidence with active LAr shield
- ► pulse shape discrimination (PSD)
- future?!: anti-coincidence with active construction materials

physics data

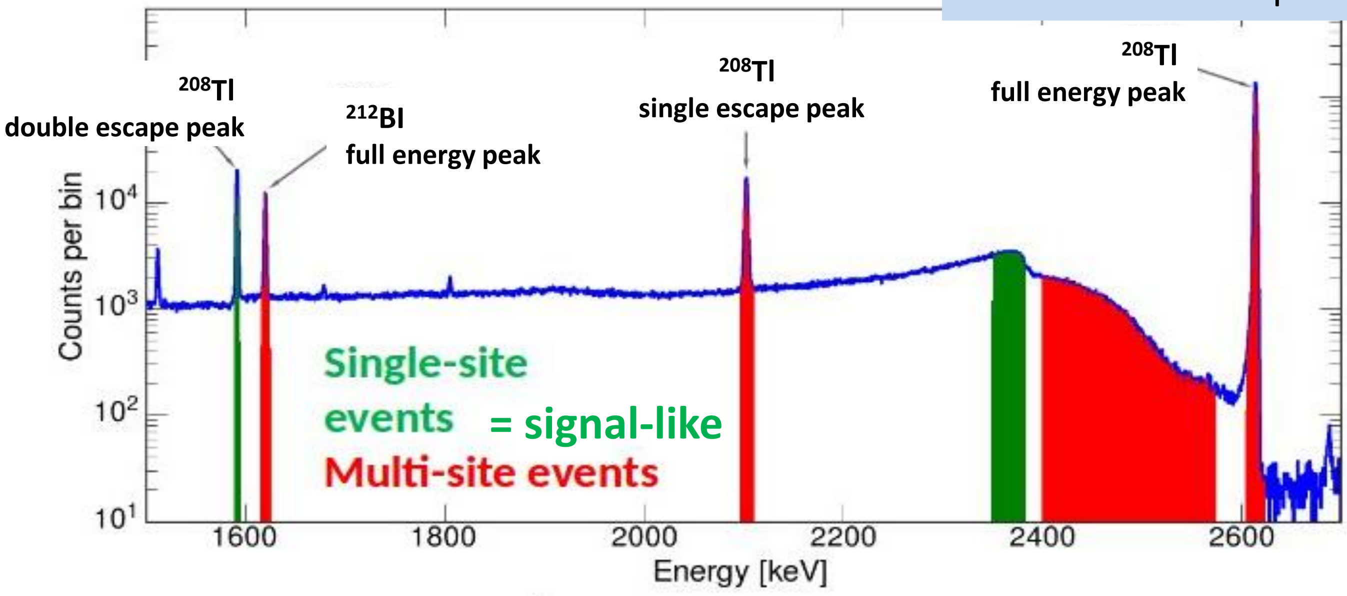


Time profile of detector signal allows us to identify signal-like events with simple A/E cut

most α (surface) events removed
γ lines suppressed by factor of ≈6

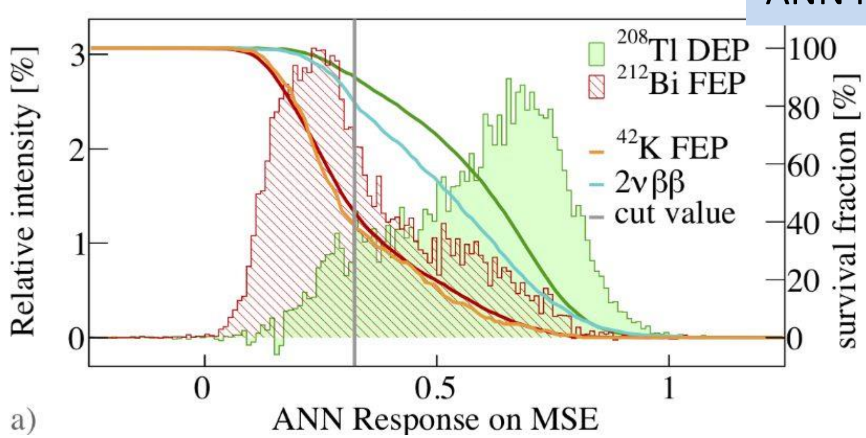
efficiency for 0νββ events: (88 ± 3)%

^{228}Th calibration spectrum



calibration data used for training of artificial neural network* (ANN)
to distinguish single-site and multi-site events

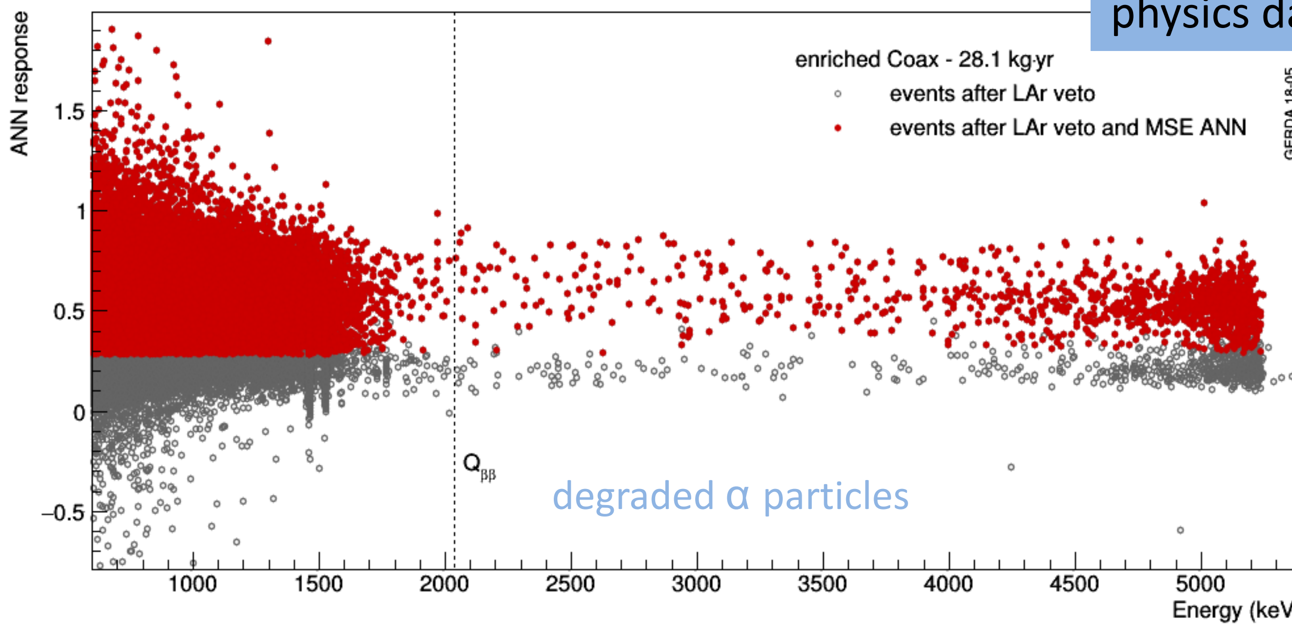
ANN reponse



* TVMA toolkit

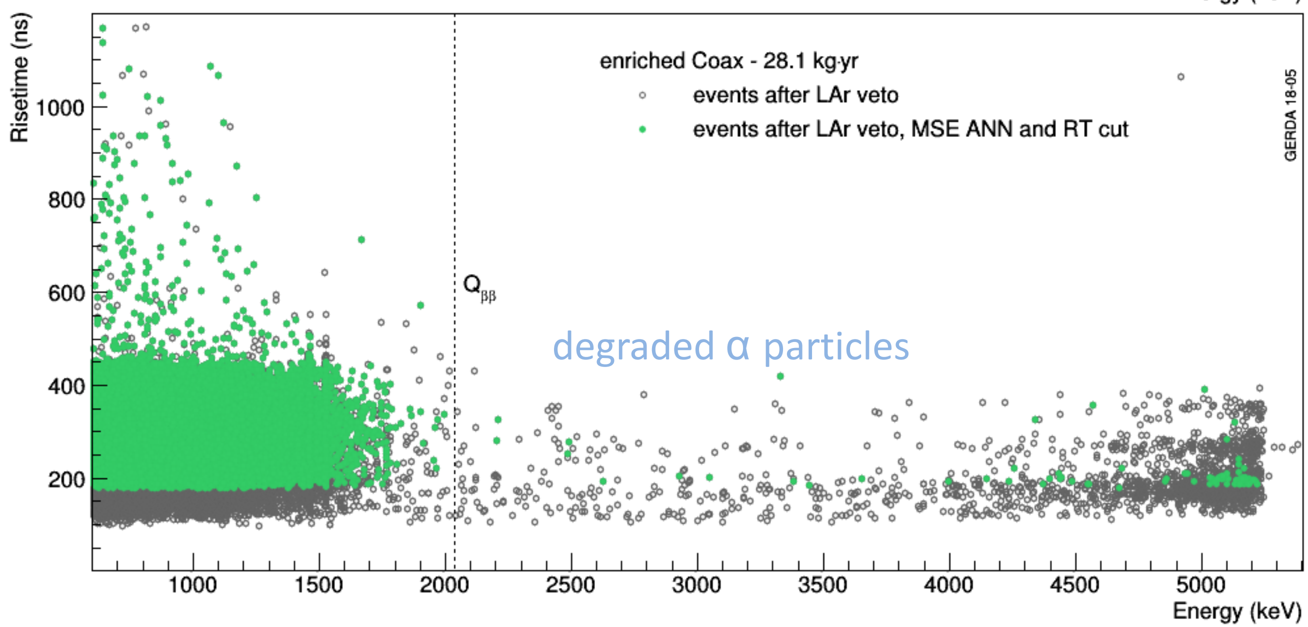
physics data

1st cut on ANN response



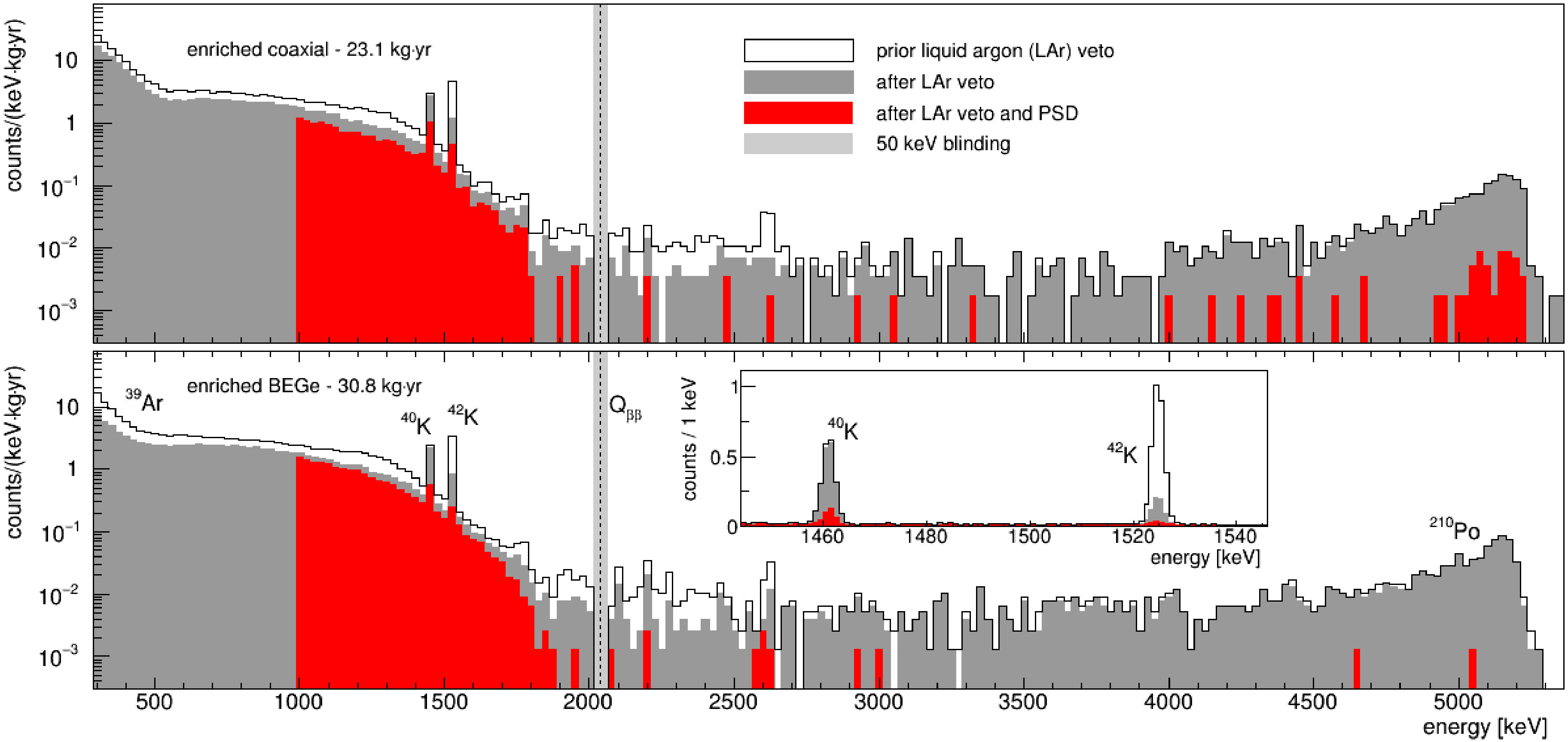
efficiency for $0\nu\beta\beta$ events: (84 ± 5)%

new: 2nd cut on risetime



efficiency for $0\nu\beta\beta$ events: (84 ± 0.4)%

GERDA results after all cuts



highly efficient LAr and PSD cuts

Background index at $Q_{\beta\beta}$:

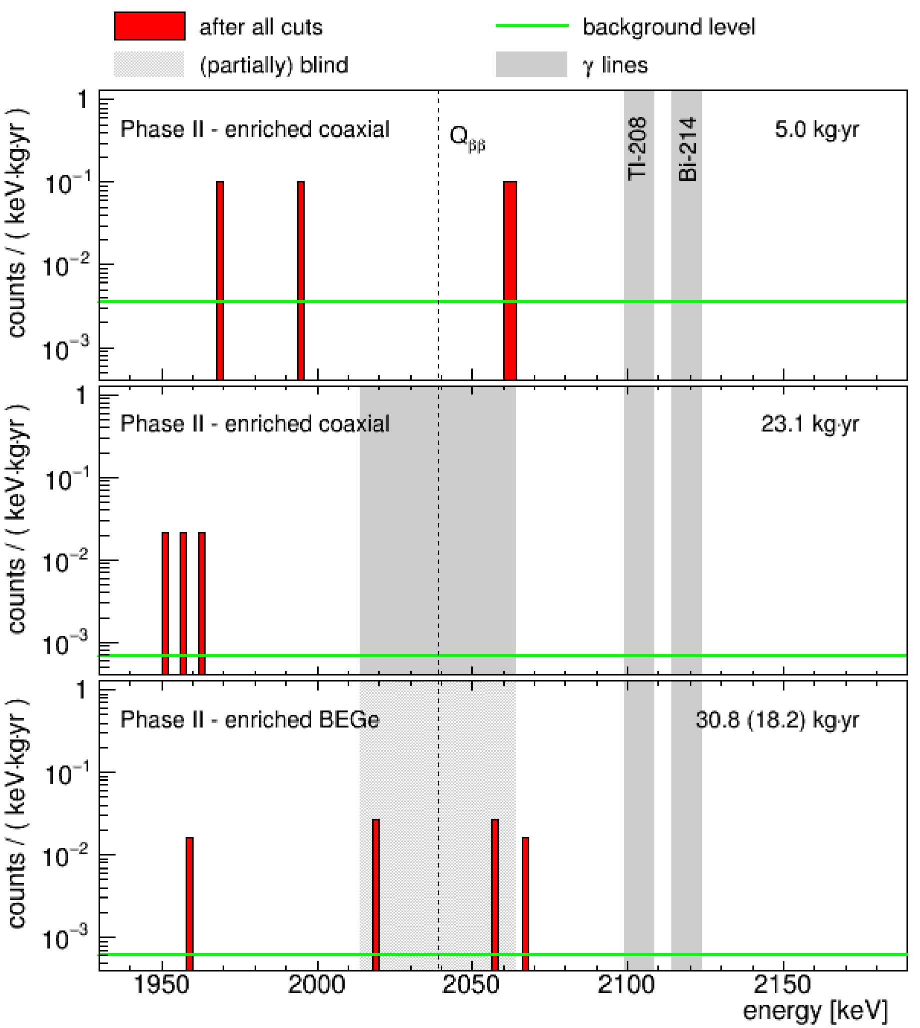
coaxials & BEGe: $(0.6^{+0.4}_{-0.3}) \cdot 10^{-3}$ cts / (kev kg yr)

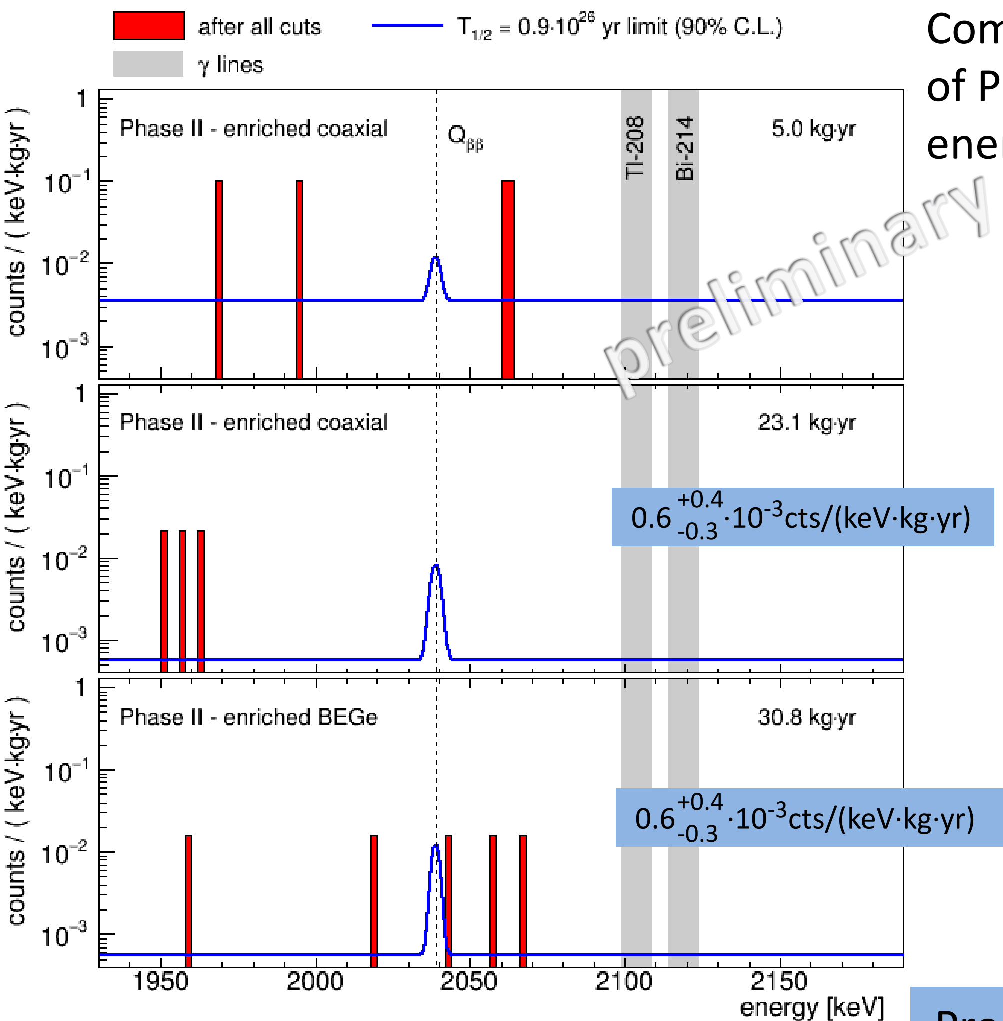
	dataset	exposure (kg·yr)	FWHM (keV)	efficiency	BI 10^{-3}cts/(keV·kg·yr)	
1	PI golden	17.9	4.3(1)	0.57(3)	11±2	
2	PI silver	1.3	4.3(1)	0.57(3)	30 ±10	
3	PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}	unblinded 13.06.2013 - ref.1)
4	PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}	
	PI total	23.5				
	PII coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$	
	PII BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$	unblinded 17.06.2016 - ref.2)
	PII coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$	
	PII BEGE	5.8				
	PII BEGe	12.4	2.9(1)	0.60(2)	$1.0^{+0.6}_{-0.4}$	unblinded 30.06.2017 - ref.3)
5	PII coaxial	5.0	3.57(1)	0.52(4)	$3.5^{+2.1}_{-1.5}$	
6	PII coaxial	▶ 23.1	3.57(1)	0.48(4)	$0.6^{+0.5}_{-0.3}$	unblinded 03.05.2018
7	PII BEGE	5.8				
		12.4				
		▶ 12.6	2.96(1)	0.60(2)	$0.6^{+0.4}_{-0.3}$	unblinded 03.05.2018
	PII total	58.9				

1) PRL 111 (2013) 122503 - $T^{0\nu}_{\beta\beta} > 2.1 \cdot 10^{25}$yr (90%C.L.), sensitivity $2.4{\cdot}10^{25}$yr
2) Nature 544 (2017) 47 - $T^{0\nu}_{\beta\beta} > 5.3 \cdot 10^{25}$yr (90%C.L.), sensitivity $4.0{\cdot}10^{25}$yr
3) PRL 120 (2018) 132503 - $T^{0\nu}_{\beta\beta} > 8.0 \cdot 10^{25}$yr (90%C.L.), sensitivity $5.8{\cdot}10^{25}$yr

preliminary

GERDA results in ROI after all cuts before unblinding





Combined unbinned maximum likelihood fit of Phase I and II data sets in (1930-2190) keV energy interval with Gauss at $Q_{\beta\beta}$ + const. BGND

Frequentist analysis (preliminary):

best fit $N^{0\nu} = 0$

$T^{0\nu}_{1/2} > 9.1 \cdot 10^{25}$ yr at 90% C.L.

median sensitivity (no signal):

$T^{0\nu}_{1/2} > 11 \cdot 10^{25}$ yr at 90% C.L. !!!

Bayesian analysis (preliminary):

$T^{0\nu}_{1/2} > 7.6 \cdot 10^{25}$ yr at 90% C.I.

median sensitivity:

$T^{0\nu}_{1/2} > 8.2 \cdot 10^{25}$ yr at 90% C.I.

Probability of stronger limit: 59% - Bayes factor P(signal+bgnd) / P(background only) = 0.054

like in Phase I:

- analysis window (1930-2190 keV, excl. ±5 keV around 2 known γ lines (2104, &2119 keV)
- flat background acc. to background model (EPJ C74 (2074) 2764)

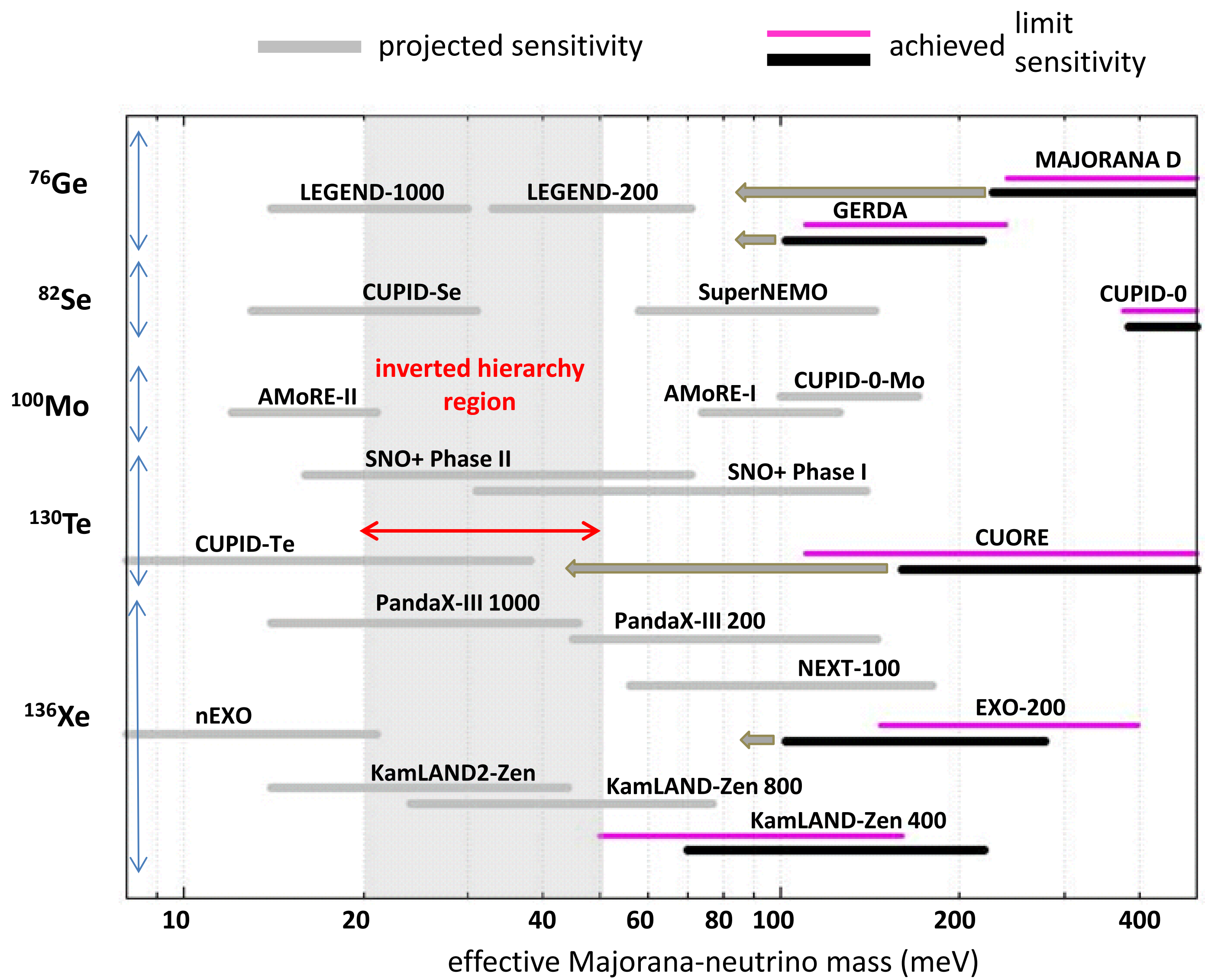
Experiment	Isotope	Exposure kg x yr	Sensitivity 10^{25} yr	T Limit 10^{25} yr	Reference
GERDA	^{76}Ge	46.7	5.8	8.0	PRL 120, 132503 (2018)
GERDA	^{76}Ge	► 71.8	► 11	9.5	latest - PRELIM.
Majorana Demo.	^{76}Ge	10	2.1	1.9	PRL 120, 132502 (2018)
CUPID-0	^{82}Se	1.83	0.23	0.24	PRL acc. May 08 (2018)
NEMO-3	^{100}Mo	34.3		0.11	PR D92, 072011 (2015)
CUPID-0/Mo	^{100}Mo	0.1		0.06	AIP 1894, 020017 (2017)
CUORE	^{130}Te	86.3	0.7	1.5	PRL 120, 132501 (2018)
EXO-200	^{136}Xe	177.6	3.7	1.8	PRL 120, 072701 (2018)
KamLAND-Zen 400	^{136}Xe	► 594	5.6	► 10.7	PRL 117, 082503 (2016)

► <u>'Background-free' regime:</u>

If M·t·BI·FWHM < 1, sensitivity scales with exposure M·t, with sqrt(M·t / BI·FWHM) if background-limited!

GERDA will be 'background-free' up to design exposure of 100 kg·yr.

Summary achieved $<m_{\beta\beta}>$ upper limits & sensitivities, projected sensitivities



Concluding remarks

The search for $0\nu2\beta$ decay is a worldwide effort. Its observation would establish the violation of lepton number and the neutrino to be a Majorana fermion.

No signal observed yet – but major experimental progress achieved including

- the successful operation of a ton-scale bolometer at 10mK
- the demonstration of scintillating bolometers for significant background reduction
- the feasibility of 'background-free' experiments up to the design exposure
- the reach of $T_{1/2}^{0\nu}$ sensitivities beyond 10^{26} yr

This progress justifies a next generation of experiments designed for sensitivities of 10^{27} – 10^{28} yr covering the inverted hierarchy region.

^{76}Ge experiments have demonstrated the highest resolution and the lowest background of any isotope for $0\nu\beta\beta$ decay searches. This motivated in 2016 the formation of the LEGEND Collaboration for a ton-scale ^{76}Ge experiment which will combine the best features of MAJORANA and GERDA.
The preparations for a first stage with 200 kg that will use the modified GERDA infrastructure are in full progress.

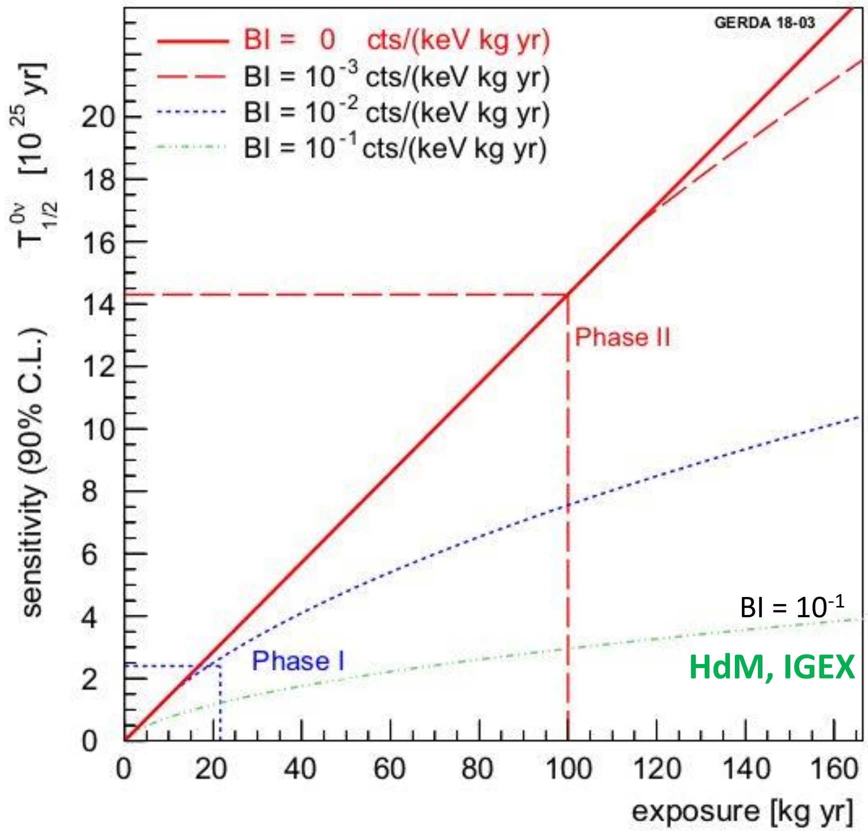
Back-up slides

N.B. sensitivity vs background index BI

'background-free'

$$T_{1/2} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{if} \quad M \cdot t \cdot BI \cdot \Delta E < 1 \\ a \cdot \varepsilon \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} \end{cases}$$

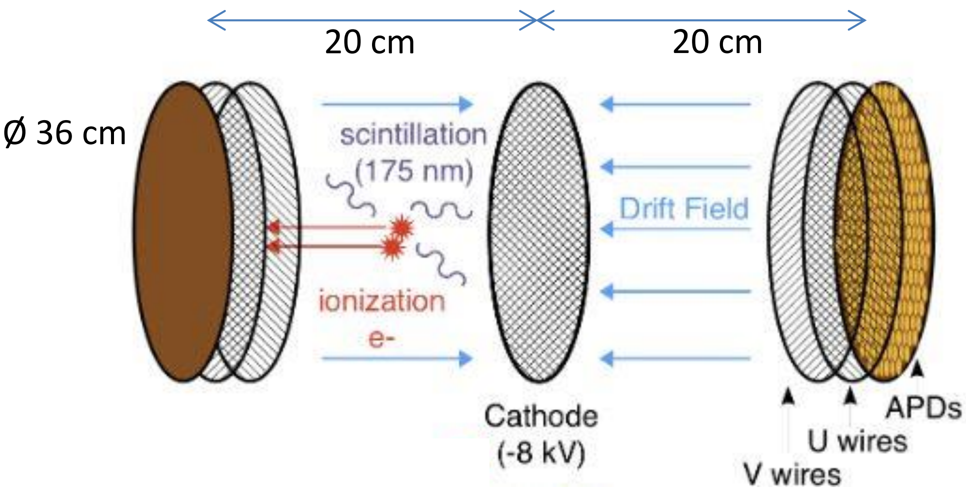
a : enrichment
ε : detection efficiency
M: source mass
M·t : exposure
BI : background index at $Q_{\beta\beta}$
ΔE: energy resolution = ROI



GERDA Phase II is expected to stay background-free up to the design exposure of 100 kg•yr
most efficient use of enriched isotope!

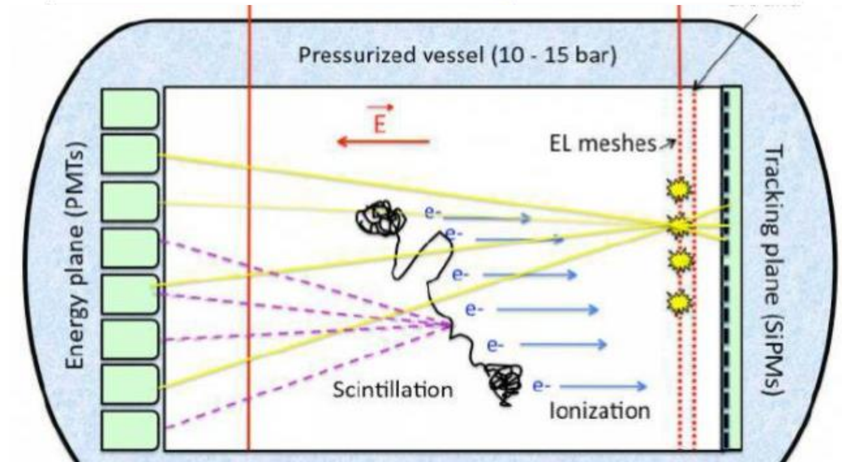
EXO-200 - NEXT-100

liquid Xe TPC



FWHM@$Q_{\beta\beta} \approx 2 - 3$ %

high pressure gaseous Xe TPC Ø 53cm, L= 135cm



1.15 m^3 -100 kg ^{136}Xe gas

Electroluminescent detection of the ionization

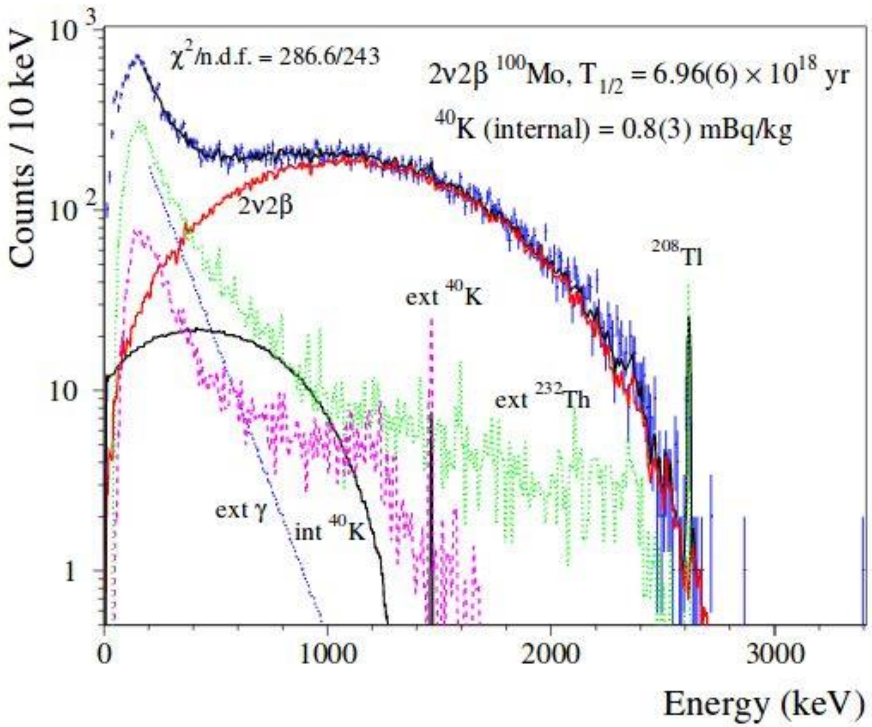
- very good energy resolution FWHM@$Q_{\beta\beta} \approx 0.5 - 0.7\%$
- 3D track reconstruction for background rejection

New promising approach for tagging final ^{136}Ba nucleus using single-molecular fluorescence imaging

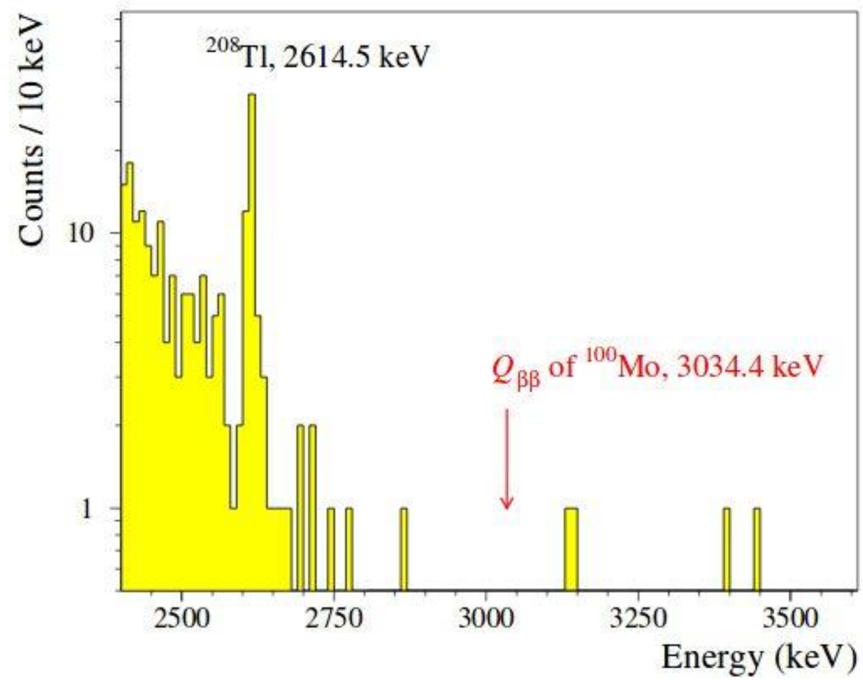
PRL 120 (2018) 132504

LUMINEU / EDELWEISS / CUPID-0/Mo results

LSM Modane   4800 m w.e.



physics data ROI



$T_{1/2}^{2\nu2\beta}$ (10^{18} yr)	S/B	Experiment	$\beta\beta$ Source	^{100}Mo exposure
7.11±0.02(stat)±0.54(syst)	40	NEMO-3	^{100}Mo foils	7.37 kg×yr
6.92±0.06(stat)±0.36(syst)	10	LUMINEU	$Li_2{}^{100}MoO_4$ bol.	0.04 kg×yr

exposure = 0.1 kg·yr

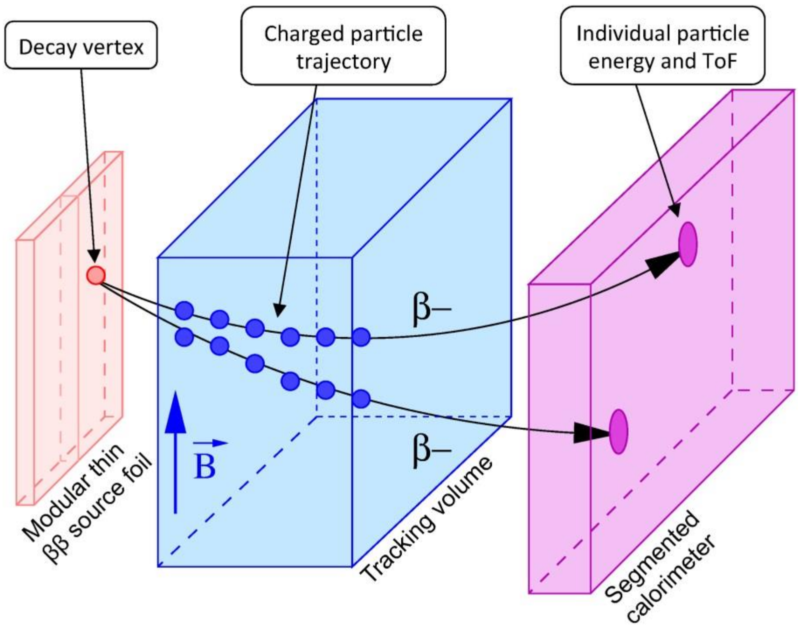
FWHM@$Q_{\beta\beta}$ = 5-6 keV (0.2%)

BI ≈ 60 · 10^{-3} cnts/(keV·kg·yr)*

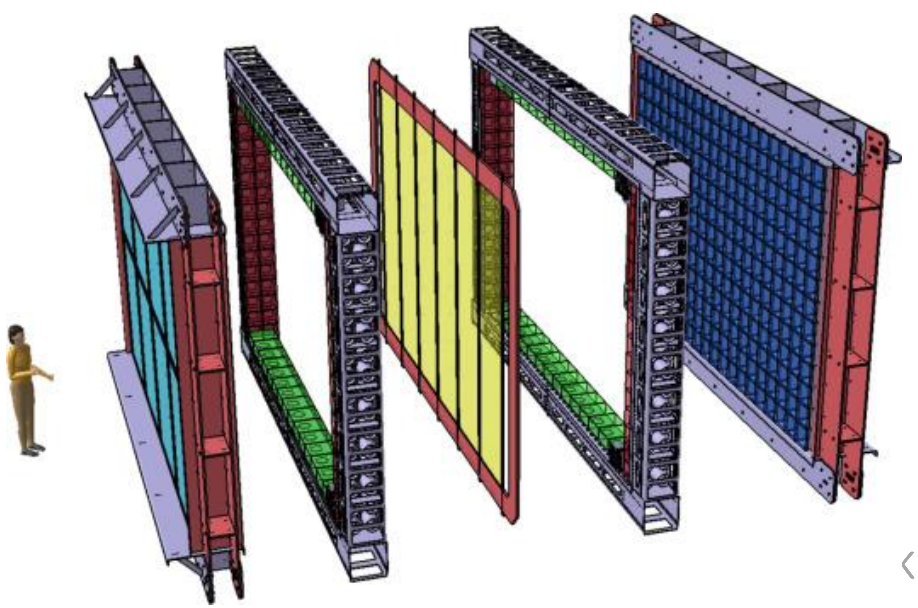
* No muon veto, no pile-up rejection

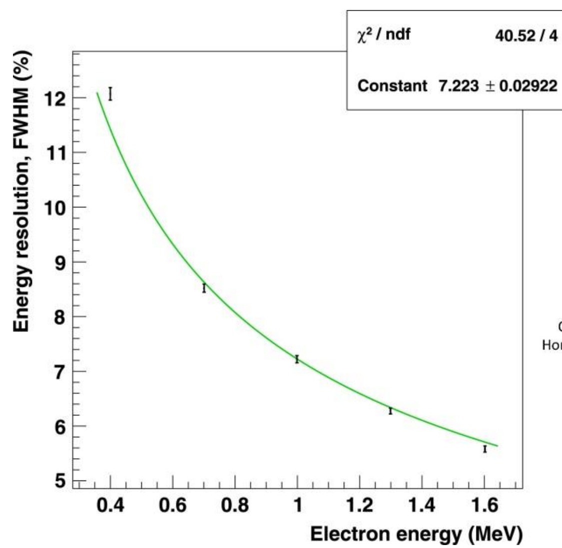
arXiv:1709.07846

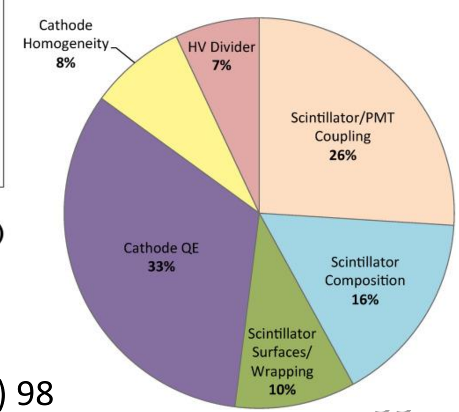
SuperNEMO



	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	7.2×10^{18}	9.9×10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg
Level of radon A(^{222}Rn)	~ 5.0 mBq/m^3	< 0.15 mBq/m^3
Sensitivity after 5 y of data taking	$T^{0\nu}_{1/2} > 10^{24}$ y	$T^{0\nu}_{1/2} > 6 \times 10^{24}$ y







NIM 868 (2017) 98

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay

Mission: ‘The **LEGEND collaboration*** aims to develop a phased, Ge-76-based double-beta decay experiment program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.’

First phase: up to 200 kg of Ge-76
modification of existing GERDA infrastructure
BG goal x5 lower than GERDA, 0.6 c / (FWHM ton year)
R&D underway, start could be by 2021

Subsequent stages: 1000 kg (staged)
BG goal x30 lower, 0.1 c / (FWHM ton year)
location: tbd - required depth (Ge-77m) under investigation
timeline connected to U.S. DOE down select process

*legend-exp.org , 47 institutions, 219 scientists