Application of noble gases in searches for neutrino-less double beta decay

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Outline

- Double beta decay
- Xe properties
- Xe-based $0\nu\beta\beta$ experiments
- LAr in $0\nu\beta\beta$ searches
- Summary

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Double Beta Decay

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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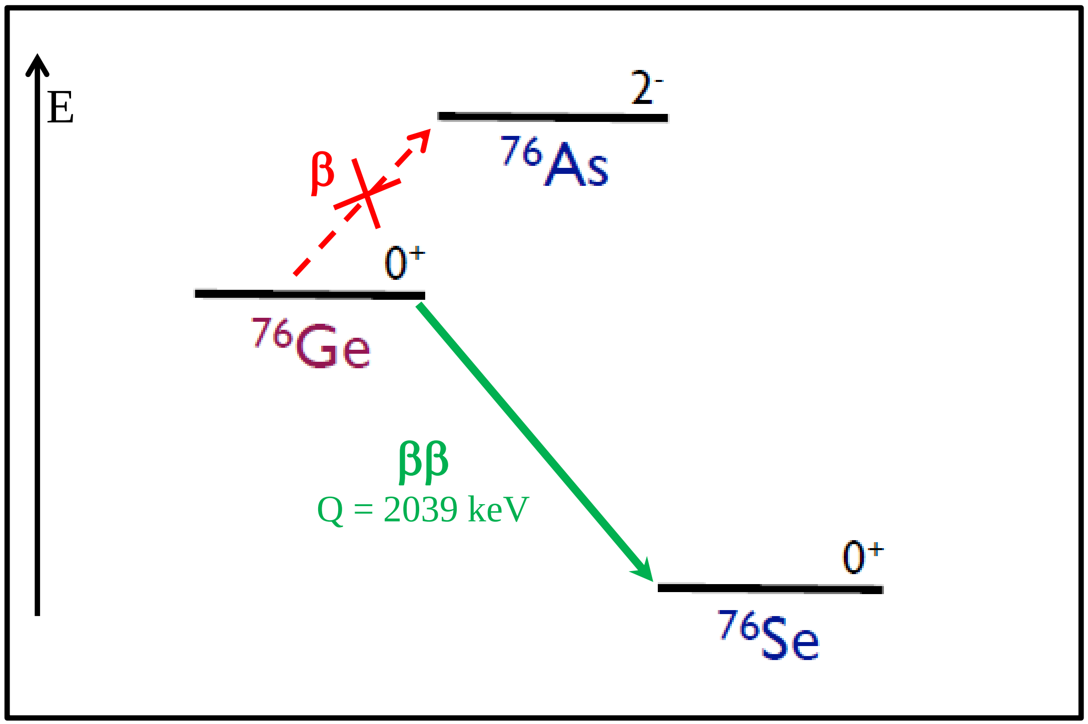
In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double Beta Decay Modes

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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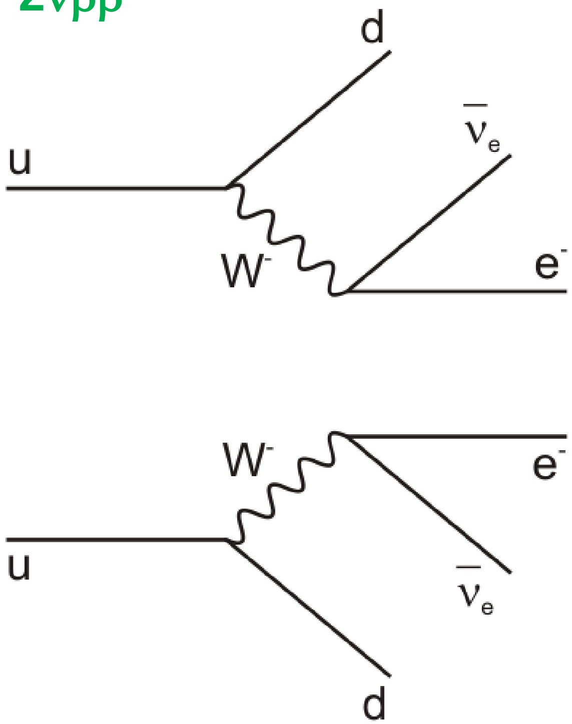
2νββ

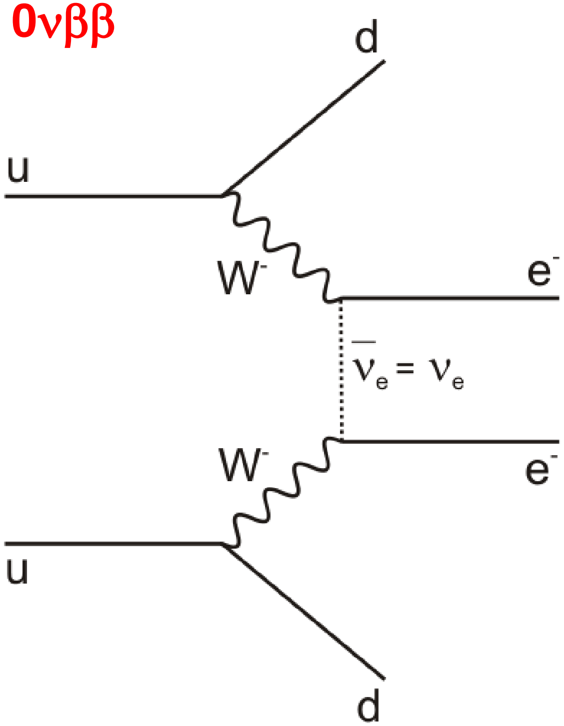


$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\Delta L = 0$

$T_{1/2} \sim 10^{18} - 10^{24}$ yr

0νββ

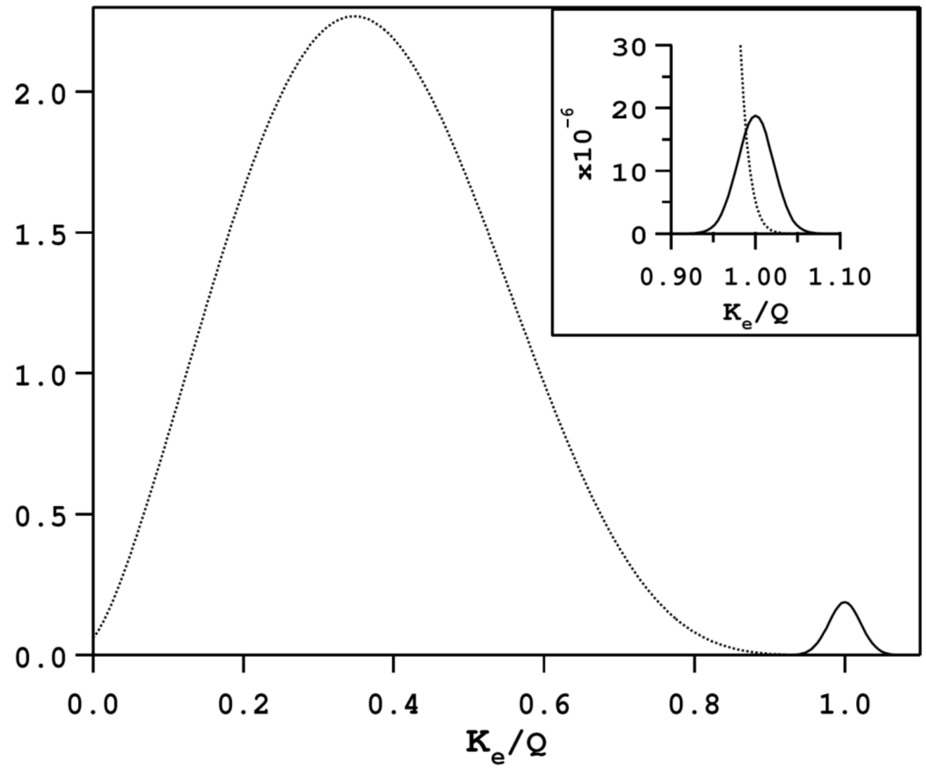


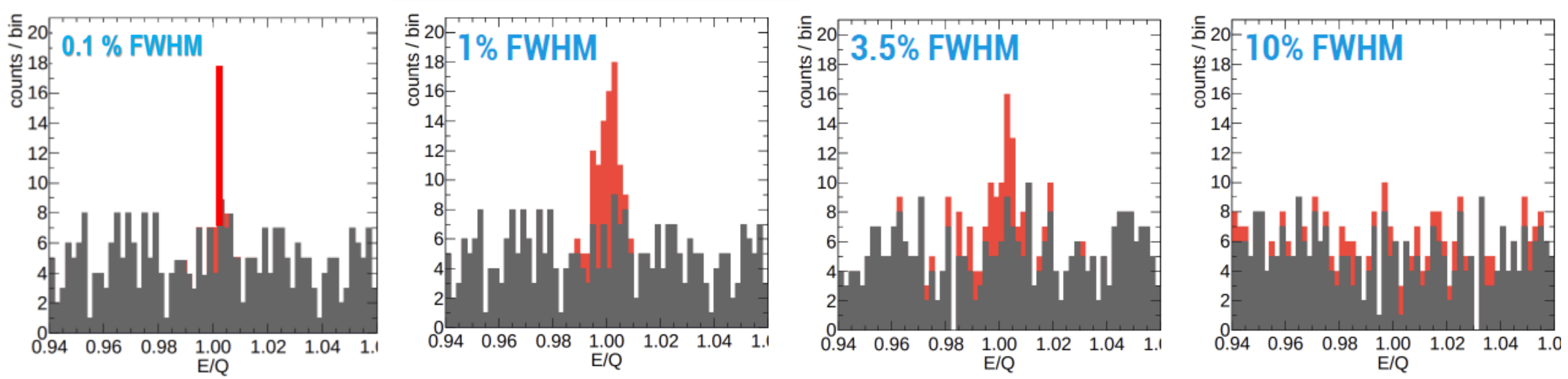
$(A,Z) \rightarrow (A, Z+2) + 2e^-$

$\Delta L = 2$

$T_{1/2}^{exp} > 2.3\times10^{26}$ yr

Double Beta Decay Modes





A. Simon

Neutrinoless ββ Decay

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

ε – detection efficiency

A – isotope molar mass

a – isotope mass fraction

M – active mass

T – measurement time

B – background rate

ΔE – energy resolution

M·T – exposure

Neutrinoless ββ Decay

ββ decay
Xe properties
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$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{T_{1/2}} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < m_{ee} >^2$$

Space phase factor ($\sim Q_{bb}^5$)

Nuclear matrix element

Effective neutrino mass

$$< m_{ee} > = |\sum_j m_j U_{ej}^2|$$

ββ decay
GERDA design
Bkg reduction
GD final result
LEGEND
Summary

Background Issue

No background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

Background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{T_{1/2}} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < m_{ee} >^2$$

$$\boldsymbol{< m_{ee} > \sim \frac{1}{\sqrt{T_{1/2}}} \sim \sqrt[4]{\frac{B \cdot \Delta E}{M \cdot T}}}$$

$$(\boldsymbol{M} \cdot \boldsymbol{T})\uparrow \times \mathbf{100} \rightarrow \boldsymbol{T_{1/2}} \uparrow \mathbf{10} \rightarrow \boldsymbol{< m_{ee} >} \downarrow \times \sim\mathbf{3}$$

$0\nu\beta\beta$ Decay Expected Rate

ββ decay

Xe properties

Xe based $0\nu\beta\beta$ experiments

LAr in $0\nu\beta\beta$ decay searches

Summary

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Zero-background case back on an envelope

$$T_{1/2} = \frac{ln2}{N_{\beta\beta}} \frac{N_A}{A} M \cdot T$$

If one wants to measure **$T_{1/2} \sim 10^{27}$ yr ($m_{ee} \sim 50$ meV)**

Then **1 event/y** requires about **10^{27} source atoms**

It means about **1000 moles** of isotope is needed

implying mass of **~100 kg**

And now one can only loose because of:

abundance, detection efficiency, background, energy resolution

Next Generation Experiments

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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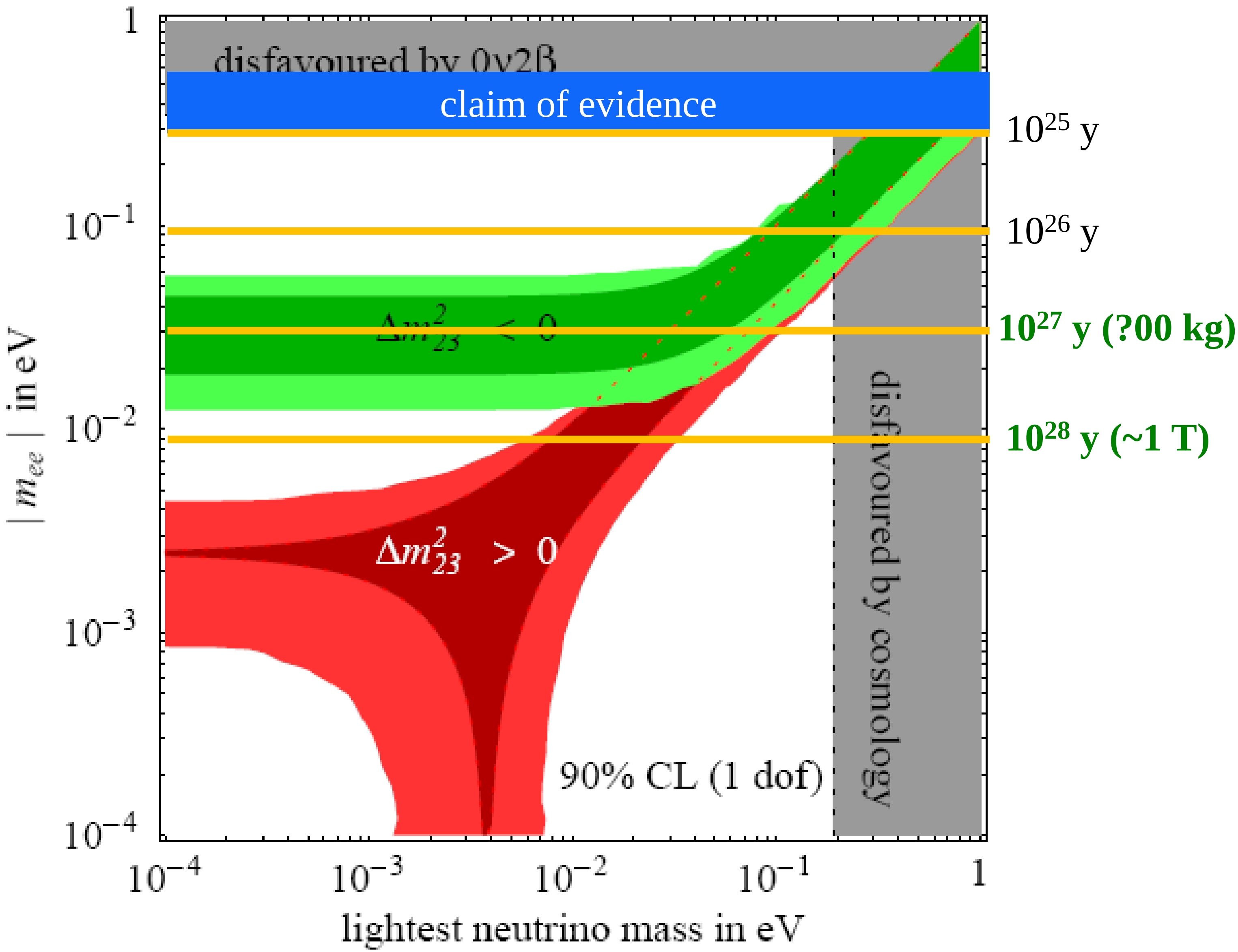

Next Gen. Experiment - requirements

ββ decay
Xe properties
Xe based 0νββ experiments
LAr in 0νββ decay searches
Summary

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- Large detector masses → tones to reach 10^{28} yr
  - scalability / modularity
  - moderate costs
- High isotopic abundance → enrichment
- High detection efficiency → target = detector
- Ultra-low background → bcg-free operation
  - Intrinsic (target) and external
  - Particle identification
  - Event topology
  - PSD
- Very good energy resolution → discovery
- Stable operation over many years → proven technology

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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0νββ Decay Isotopes

35 isotopes can undergo 0νββ decay

only ~1/3 is experimentally relevant

Isotope	$Q_{\beta\beta}$ [keV]	A [%]	$G_{0\nu}$ [10^{-15} y]	$M_{0\nu}$	Experiments
$^{48}Ca \rightarrow ^{48}Ti$	4271	0.19	24.8	0.7 – 3.0	CANDLESS
$^{76}Ge \rightarrow ^{76}Se$	2039	7.8	2.36	2.2 – 6.2	GERDA, MAJORANA, LEGEND
$^{82}Se \rightarrow ^{82}Kr$	2995	9.2	10.2	2.2 – 5.6	CUPID-0
$^{96}Zr \rightarrow ^{96}Mo$	3350	2.8	20.6	2.8 – 6.6	ZICOS
$^{100}Mo \rightarrow ^{100}Ru$	3034	9.6	15.9	3.8 – 6.8	CUPID, AMORE, NEMO-III
$^{110}Pd \rightarrow ^{110}Cd$	2013	11.8	4.8	4.0 – 6.6	ISOLDE
$^{116}Cd \rightarrow ^{116}Sn$	2802	7.5	16.7	3.0 – 5.6	Aurora
$^{124}Sn \rightarrow ^{124}Te$	2228	5.6	9.0	2.0 – 5.8	TIN.TIN
$^{130}Te \rightarrow ^{130}Xe$	2530	34.5	14.2	1.2 – 6.6	CUORE, SNO+
$^{136}Xe \rightarrow ^{136}Ba$	2458	8.9	14.6	1.4 – 4.8	EXO, NEXT, PANDA, KamLAND-Zen
$^{150}Nd \rightarrow ^{150}Sm$	3367	5.6	63.0	2.0 – 5.2	NEMO-III

$0\nu\beta\beta$ Decay Isotopes

- $\beta\beta$ decay
- Xe properties
- Xe based $0\nu\beta\beta$ experiments
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35 isotopes can undergo $0\nu\beta\beta$ decay

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0νββ Decay Experiments

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Ionization

Tracking
(Super)NEMO

Crystals
GERDA
LEGEND
MAJORANA
COBRA

Ionization + Scintillation: TPC
(n)EXO, PANDA, DARWIN (LXe)
NEXT (GXe)

Scintillation

LS
KAMLAND-Zen
SNO+

Crystals
CANDLES

Scintillating Bolometers
CUPID, AMoRE

Heat

Bolometers
CUORE

0νββ Decay Experiments

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Ionization

Tracking

(Super)NEMO

Crystals

GERDA

LEGEND

MAJORANA

COBRA

^{136}Xe in Xe

Ionization + Scintillation: TPC

(n)EXO, PANDA, DARWIN (LXe)

NEXT (Gxe, tracking)

Scintillation

LS

KAMLAND-Zen

SNO+

Crystals

CANDLES

^{136}Xe in LS

Scintillating Bolometers

CUPID, AMoRE

Heat

Bolometers

CUORE

0νββ Decay Experiments

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Ionization

Tracking
(Super)NEMO

Crystals
GERDA
LEGEND
MAJORANA
COBRA

LAr / UGLAr used as LS for bcg reduction

^{136}Xe in Xe

Ionization + Scintillation: TPC
(n)EXO, PANDA, DARWIN (LXe)
NEXT (Gxe, tracking)

Scintillation

LS
KAMLAND-Zen
SNO+

Crystals
CANDLES

^{136}Xe in LS

Scintillating Bolometers
CUPID, AMoRE

Heat

Bolometers
CUORE

Advantages of Xe

ββ decay
Xe properties
Xe based 0νββ experiments
LAr in 0νββ decay searches
Summary

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- Scintillation: high light yield, transparent to own light
- Ionization: high yield, low electron affinity, signal amplification possible
- Relatively high $G_{0\nu}$
- Xe ca be used „directly" as gas or liquid, no further processing of the material needed
- Easy to handle/transport in pressure cylinders
- Scaling (up to several tones) possible (no radio-isotopes)
- Xe as a gas can be purified
- High-Z material, good self-shielding properties
- Ba tagging might become possible to further reduce backgrounds
- Relatively low cost of ^{enr}Xe
- FWHM good enough to handle 2νββ background (~1%)
- LXe: degassing and Rn emanation strongly suppressed
- In GXe possible tracking

Disadvantages of Xe

- Light emitted at 178 nm
- Relatively low $M_{0\nu}$
- $Q_{\beta\beta}$ below 2.6 MeV ^{208}Tl gamma line
- $Q_{\beta\beta}$ = 2458 keV, close to a ^{214}Bi gamma line
- Xe is volatile – risk of loss
- Modest global production compared to enrichment requirements
- Scaling possible but requires upgrade of cryogenic infrastructure
- Lots of material used for self-shielding
- Continuous purification with purity monitoring needed for long-term stable operation
- HHV required for TPC operation
- Relatively poor FWHM (compared e.g. to solid state detectors)
- PSD not applicable
- In GXe (room temperature) ^{222}Rn emanation may dominate the background

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Purification of Xe

- ββ decay
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- Due to degassing of detector components and Rn emanation Xe must be continuously purified to maintain required electron lifetimes (some ms) and to keep the background low
- To remove electro-negative impurities hot getters are used (gas phase purification)
- The bigger the detector is the faster Xe must be circulated and purified
- Removal of Rn is not trivial:
  – low-temperature adsorption methods are not effective,
  – application of more complicated distillation may be necessary. The turn-over time is defined by the ^{222}Rn half-life (3.8 d). In case of several tons of LXe to be purified → application of several (smaller) distillation columns
  – identification of all major sources necessary – screening
- The size of the detector may be limited by the ability to purify Xe

^{222}Rn in XENON1T

ββ decay

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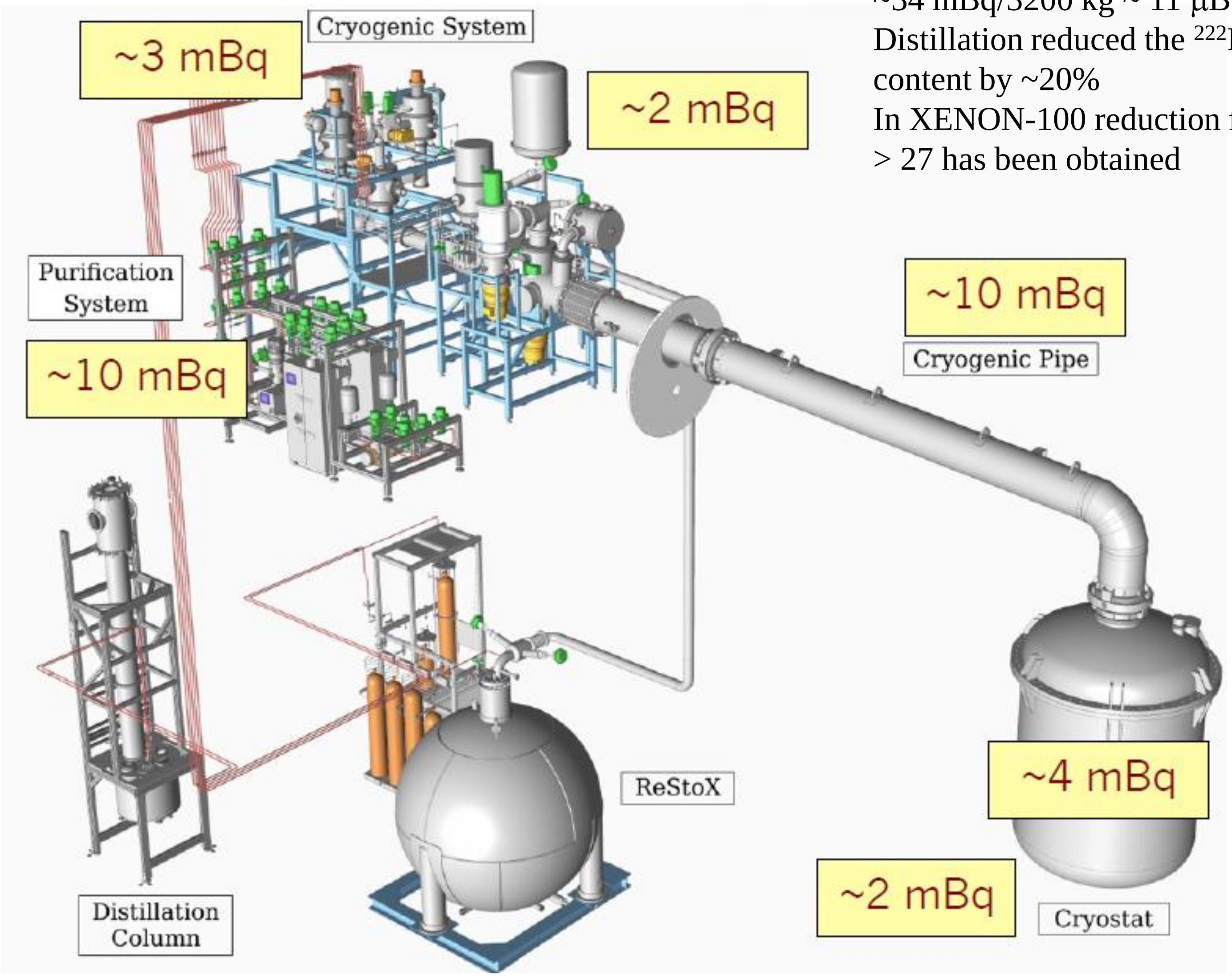
~34 mBq/3200 kg ~ 11 μBq/kg
Distillation reduced the ^{222}Rn content by ~20%
In XENON-100 reduction factor > 27 has been obtained



H. Simgen, LRT2019

EXO-200

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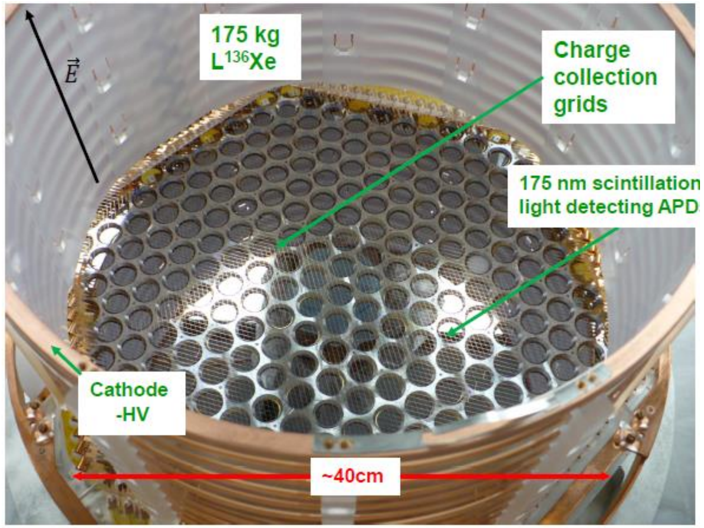
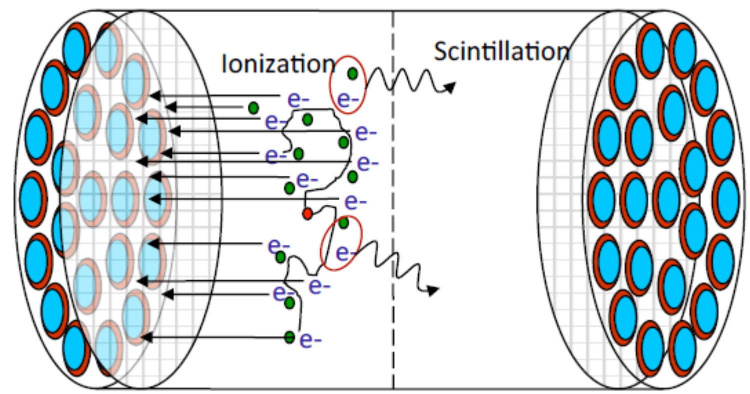
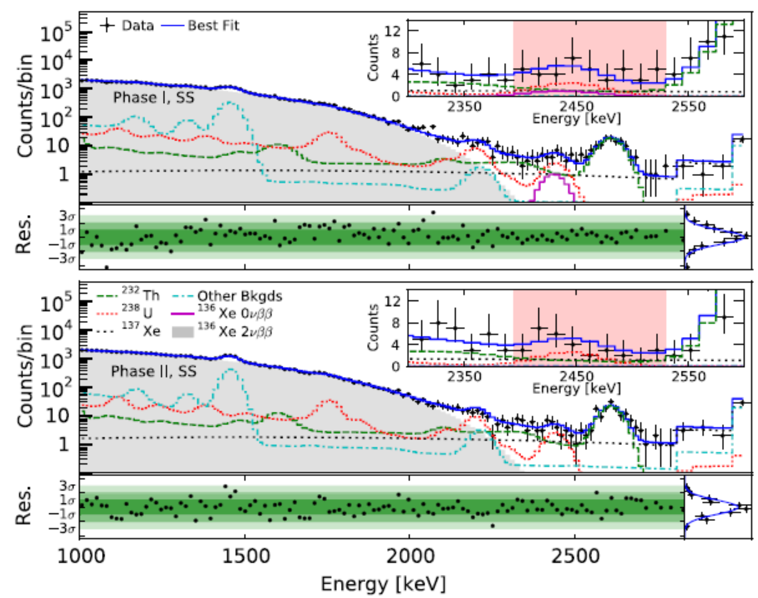




EXO-200 final result:

- M $L^{136}Xe$ = 175 kg
- M×T = 234.1 kg×yr
- BI: $(1.8 \pm 0.2)\times10^{-3}$ cts/(kg×yr×keV)
- $T_{1/2}$ ($0\nu\beta\beta$) > 3.5×10^{25} yr (90% C.L.)
- $m_{\beta\beta} \leq$ (93 – 286) meV



KamLAND-Zen

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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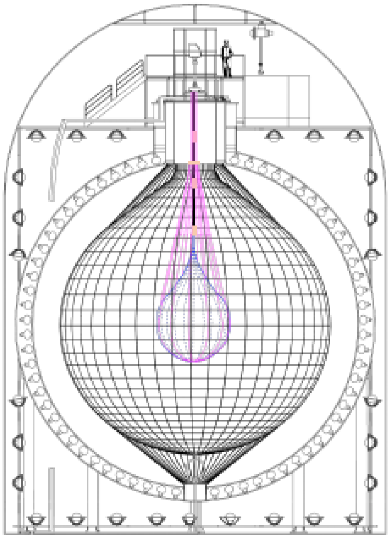
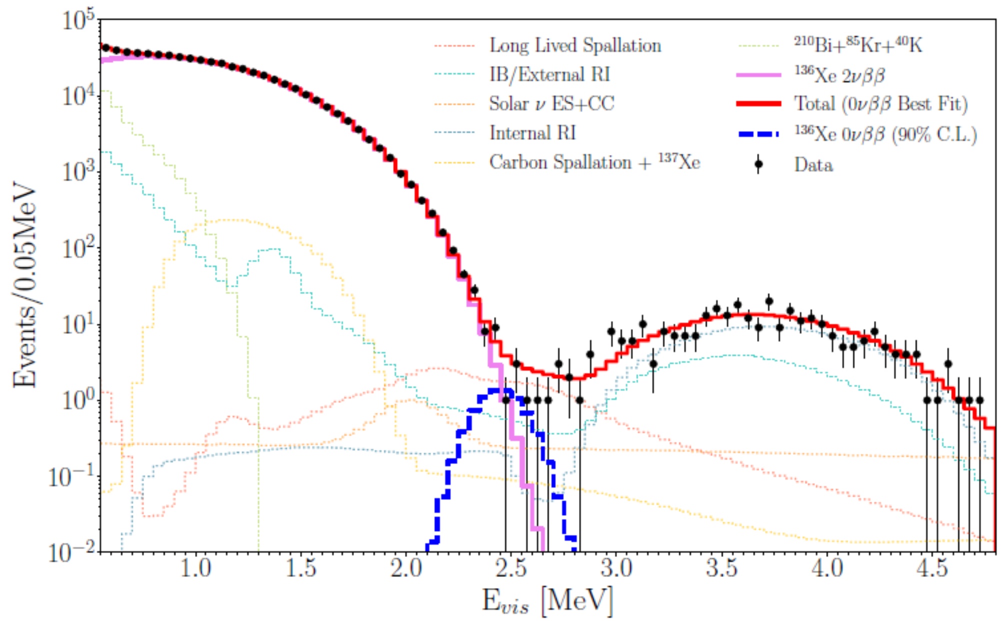


KamLAND-Zen 800:

- Mini-balloon Radius = 1.90 m
- Xenon mass = 745±3 kg
- Data taking started Jan. 2019



KamLAND-Zen 800 latest result:

– M L^{136}Xe = 745 kg
– M×T = 970 kg×yr
– BI: ~10^{-4} cts/(kg×yr×keV)
– $T_{1/2}$ (0νββ) > 2.3×10^{26} yr (90% C.L.)
– $m_{\beta\beta} \leq$ (36 – 156) meV

Background	Best-fit Frequentist	Best-fit Bayesian
^{136}Xe 2νββ	11.98	11.95
Residual radioactivity in Xe-LS		
^{238}U series	0.14	0.09
^{232}Th series	0.84	0.87
External (Radioactivity in IB)		
^{238}U series	3.05	3.46
^{232}Th series	0.01	0.01
Neutrino interactions		
^{8}B solar ν e^- ES	1.65	1.65
Spallation products		
Long-lived	12.52	11.80
^{10}C	0.00	0.00
^{6}He	0.22	0.21
^{137}Xe	0.34	0.34

Xe vs. Ge

- $\beta\beta$ decay
- Xe properties
- Xe based $0\nu\beta\beta$ experiments
- LAr in $0\nu\beta\beta$ decay searches
- Summary

Parameter	EXO-200	KamLAND -Zen 800	NEXT-White	GERDA
M [kg]	175	745	4.3	44.2
M×T [kg×yr]	234.1	970	2.8	127.2
FWHM at $Q_{\beta\beta}$ [keV]	25	100	22	3
BI [cts/(kg×keV×yr)]	1.8×10^{-3}	$\sim10^{-4}$		5.2×10^{-4}
Bcg-free operation [Y/N]	N (~20)	N (~30)	N	Y (<1)
$T_{1/2}^{0\nu}$ [10^{26} yr]	0.35	2.3		1.8

- Presently the best limit on $T_{1/2}^{0\nu}$ comes form Xe
- Good energy resolution and low background are key factors for discovery
- Costs: experiment specific

Argon

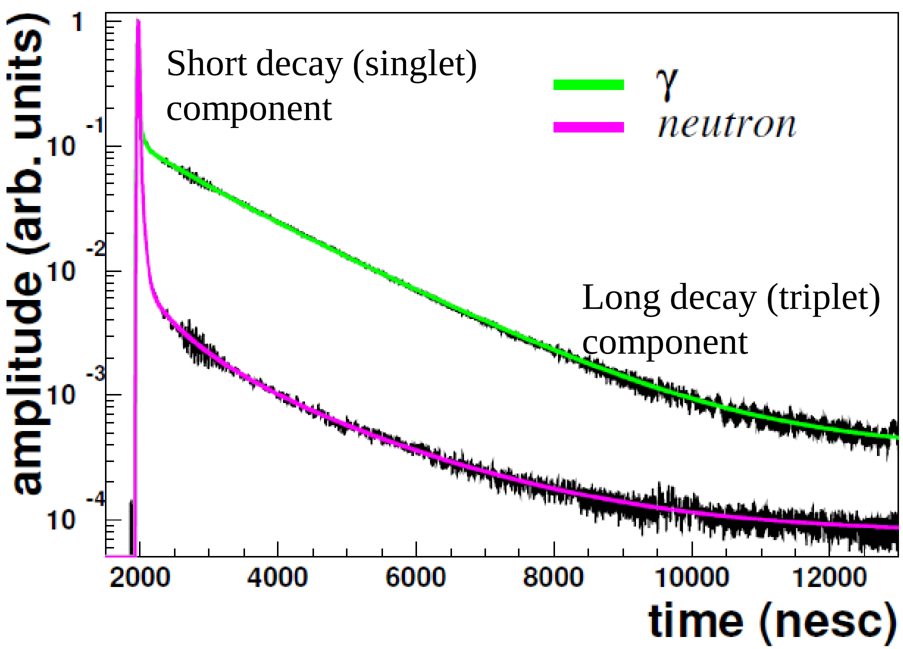
- Ar / LAr not used as a target in the 0νββ decay searches
- In GERDA LAr used as cooling medium for HP^{enr}Ge detectors and as a passive and active shield (main background reduction tool in Phase II)

  → high purity

  → relatively high density

  → High scintillation (ionization) yield

  → Scintillation at 128 nm (WLS needed)



PRD 103, 043001 (2021)

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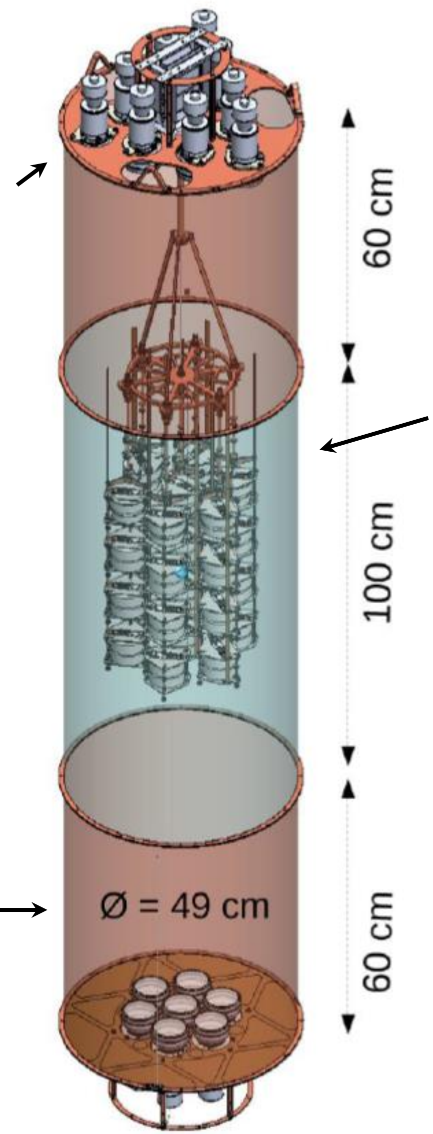
GERDA LAr veto

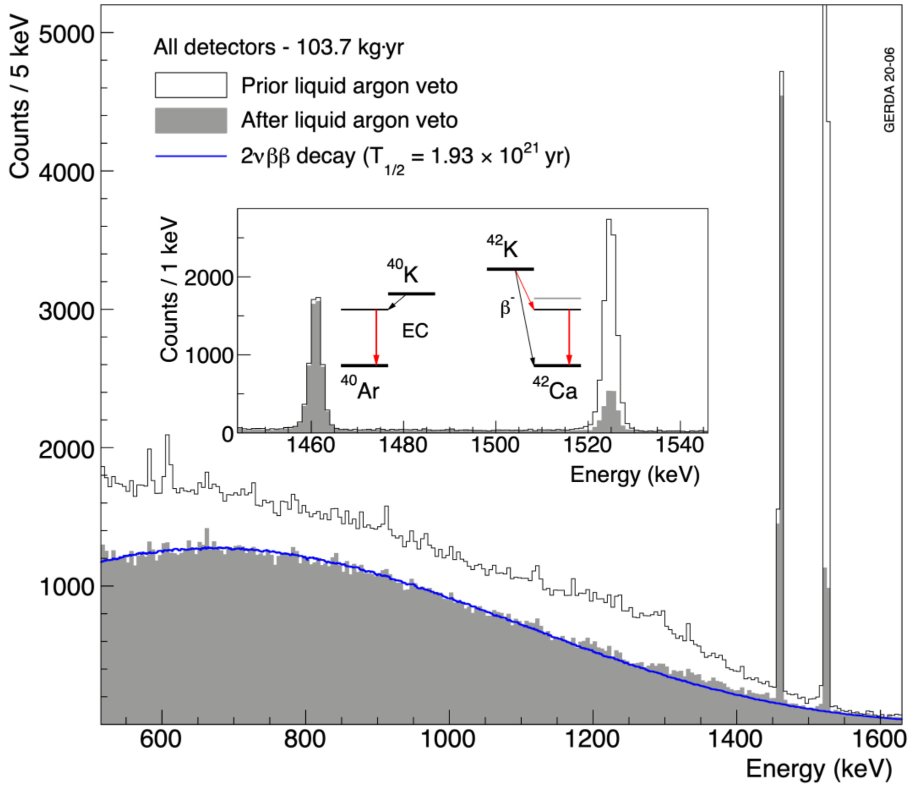
16 3” PMTs
Cylinder with WLS
(TETRATEX foil)



810 wavelength
shifting fibers
coupled to 90 SiPMs

GERDA LAr veto performance

- Channel-wise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~ 0.5 P.E.
- Acceptance determined from random triggers: (97.9 ± 0.1) %
- $^{40}K/^{42}K$ Compton continua completely suppressed
- γ-rays survival fractions: ^{40}K (EC) = ~100 %, ^{42}K (β^-) ~20 %
- Almost pure 2νββ spectrum after LAr veto cut (600 – 1300 keV)
- **Background suppression in ROI (2039 ± 2σ): × 6**



- ββ decay
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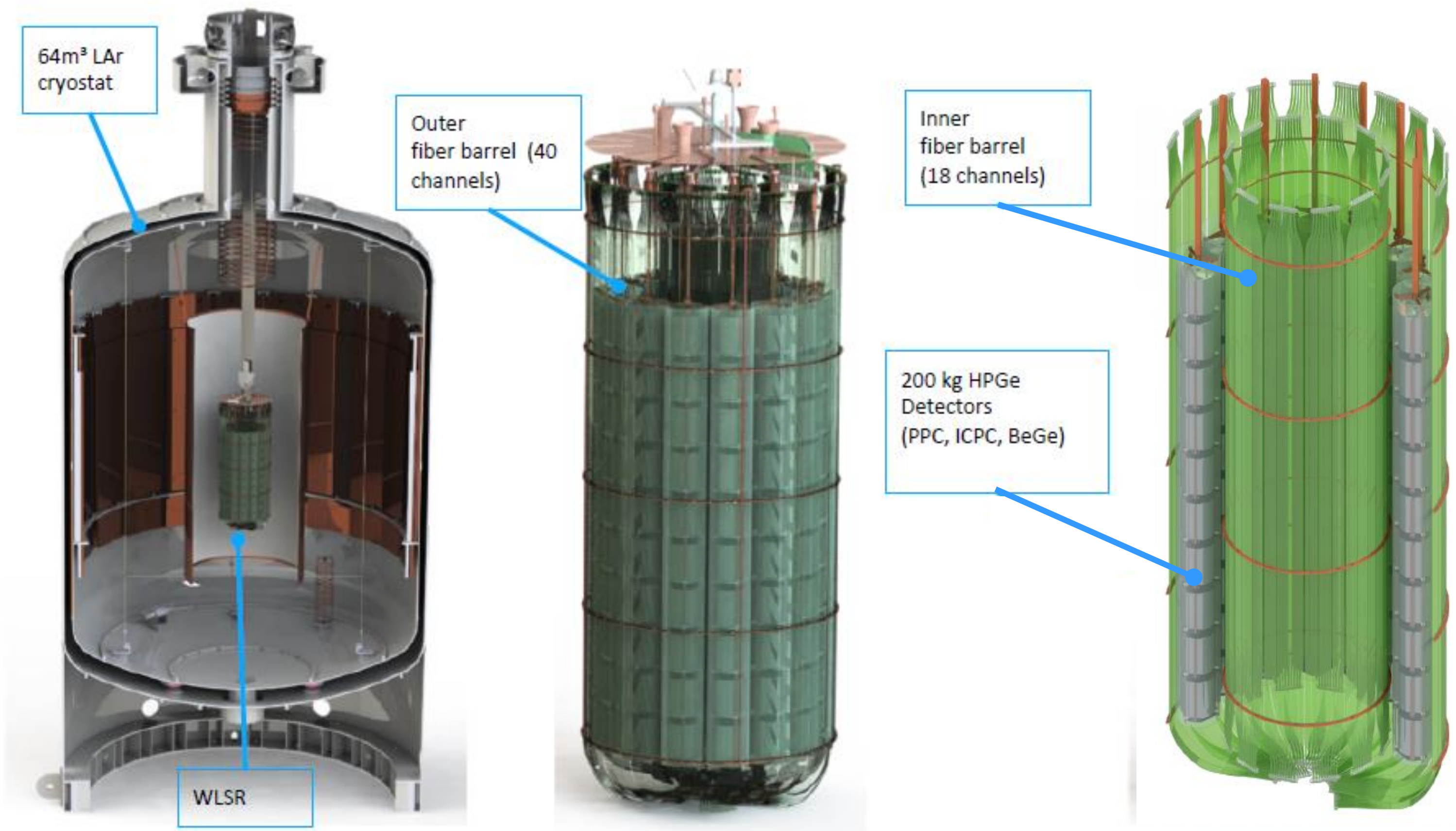
LEGEND-200 LAr veto



- Geometry optimized to minimize dead volumes
- LAr purified during cryostat filling (τ = 1.15 μs) – see G. Haranczyl talk

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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^{42}Ar problem

ββ decay

Xe properties

Xe based 0νββ experiments

LAr in 0νββ decay searches

Summary

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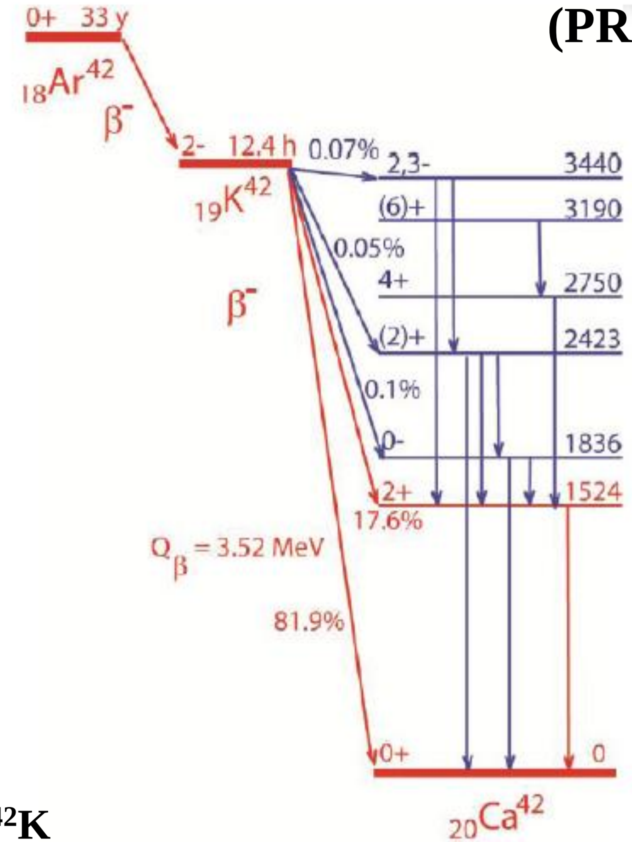
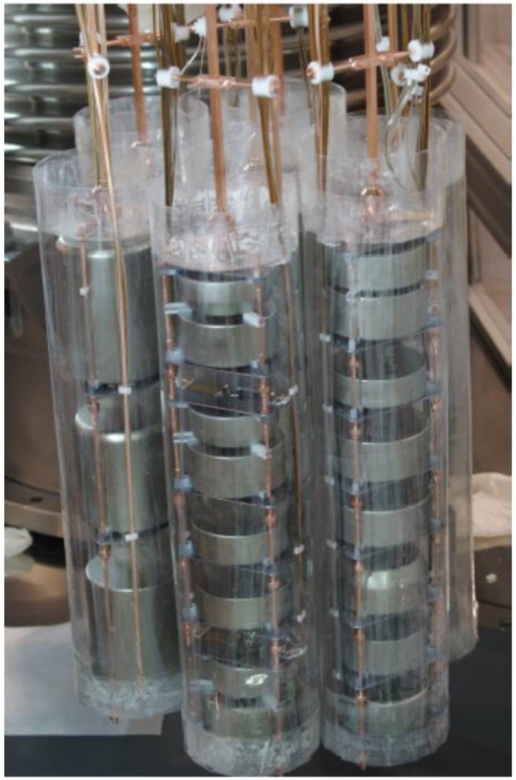
^{42}Ar activity concentration in LAr: 40 μBq/kg (PRD 100 (2019) 072009)





^{42}K

- Charged after creation
- $T_{1/2}$ = 12.36 h
- Q = 3525.4 keV
- Mostly a pure β emitter
- Most intense γ ray at 1525.7 keV (18 %)

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

- β decay
- Bremsstrahlung from β
- 2424 keV γ ray

LEGEND background budget

ββ decay

Xe properties

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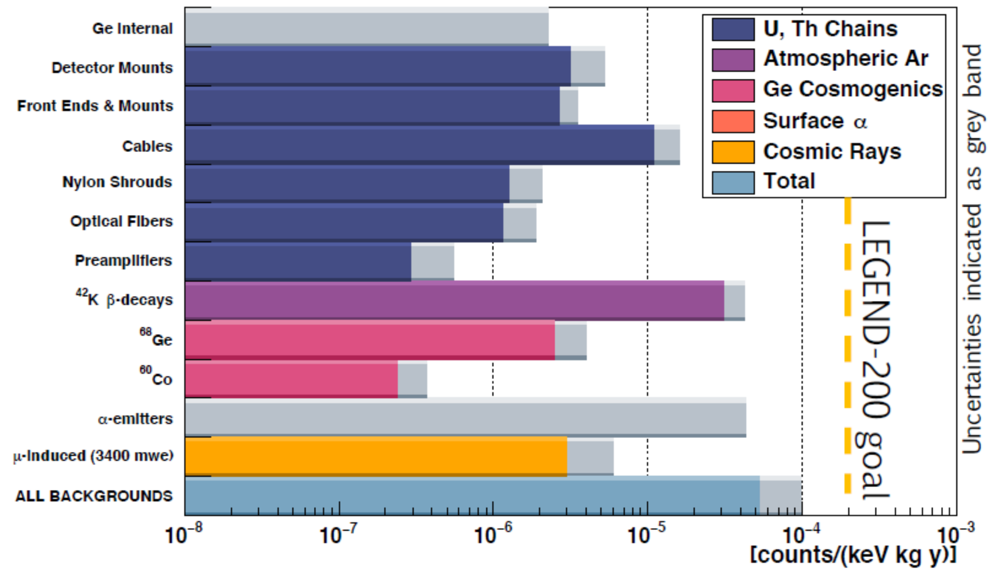
LAr in 0νββ decay searches

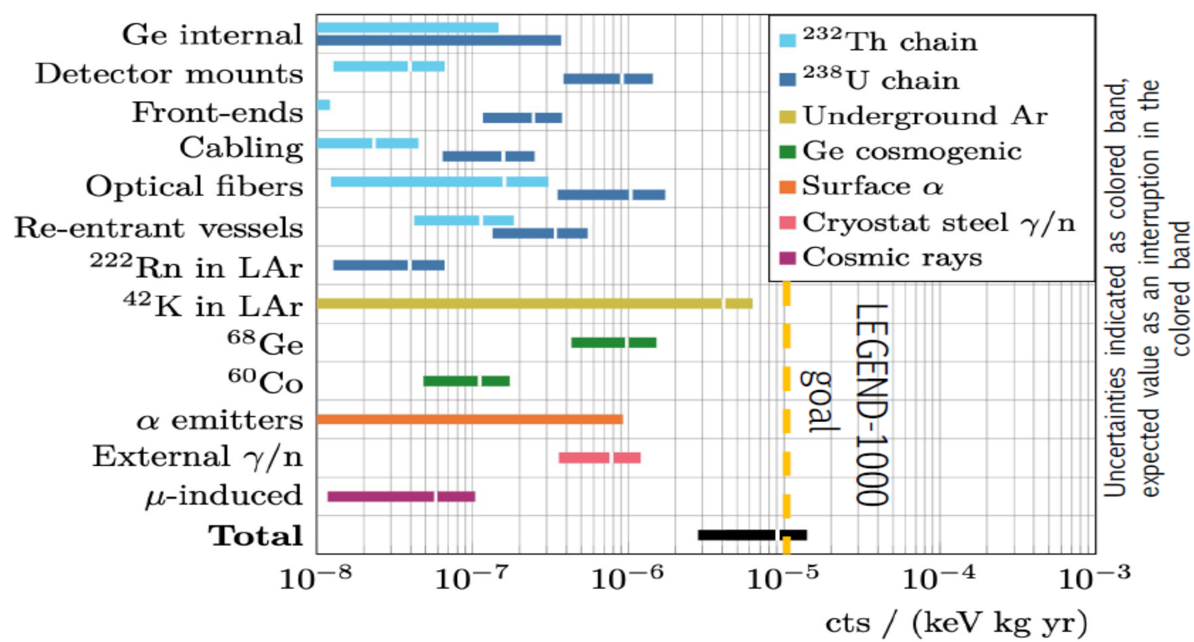
Summary

L-200
ALAr used
$C_{Ar\text{-}42}$ = 40 μBq/kg



L-100 UGLAr (DARKSIDE) used

^{42}Ar activity concentration lower by 1500 w.r.t ALAr



LEGEND-1000 conceptual design

ββ decay

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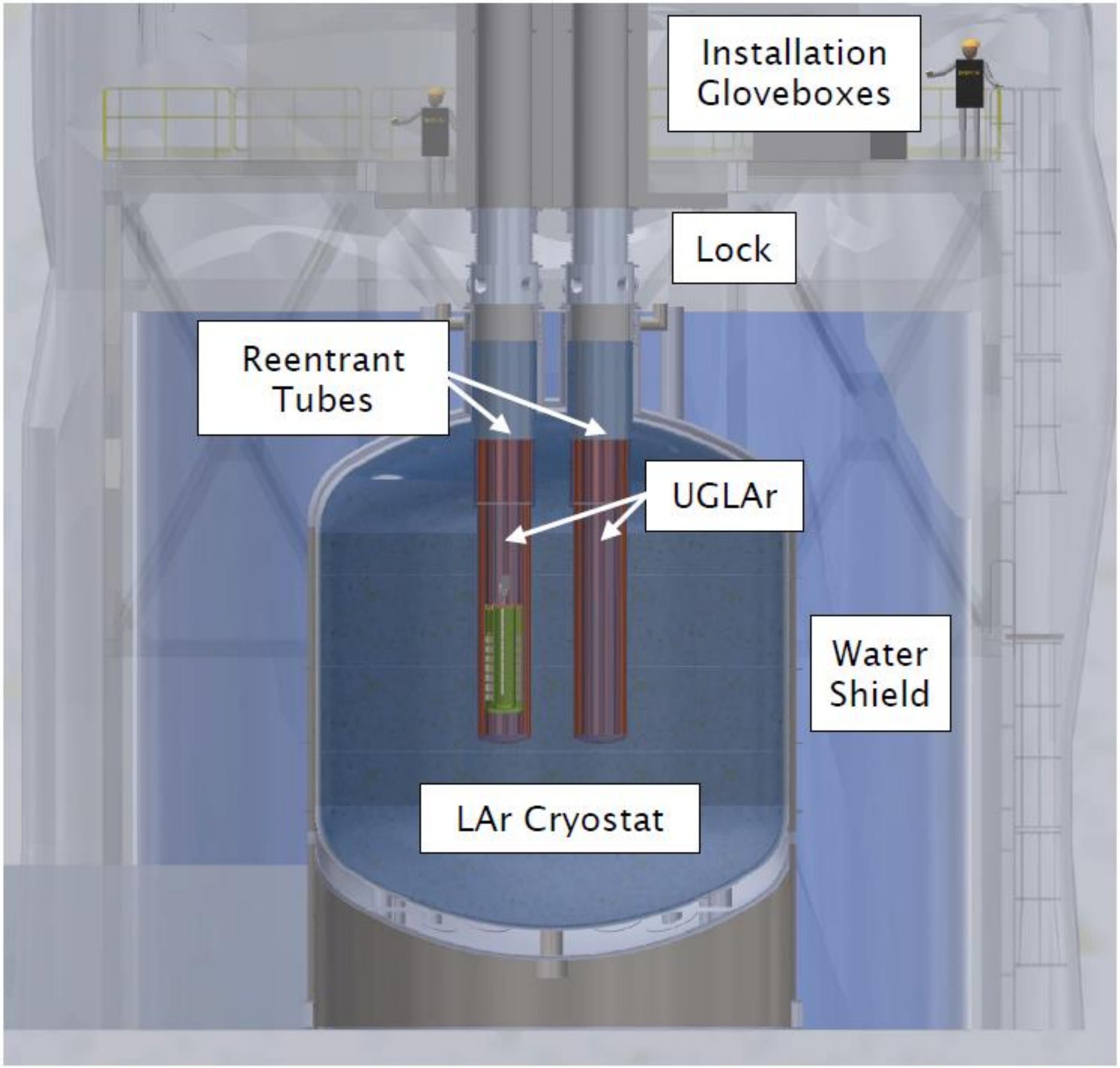

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Summary

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- Neutrino-less double beta decay plays an important role in particle and astro-particle physics
- Several experimental efforts exploring different techniques are implemented
- Nex generation experiments needs to probe $T_{1/2}^{0\nu}$ at the level of $10^{27} – 10^{28}$ yr to explore IH
- Noble gases paly an important role in neutrino-less double beta decay searches
- Efforts to improve the detector parameters
- Presently the best limit for $T_{1/2}^{0\nu}$ comes form Xe-based experiment
- Energy resolution and background are key parameters for discovery potential