Double Beta Decay
Status and Prospectives

Alberto Garfagnini

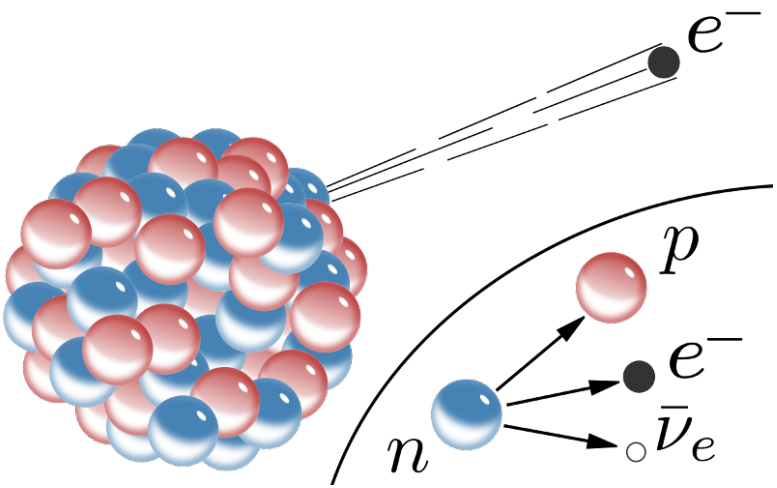
Physics in Collision, Tblisi, September 8 2022

Istituto Nazionale di Fisica Nucleare

Double beta decay

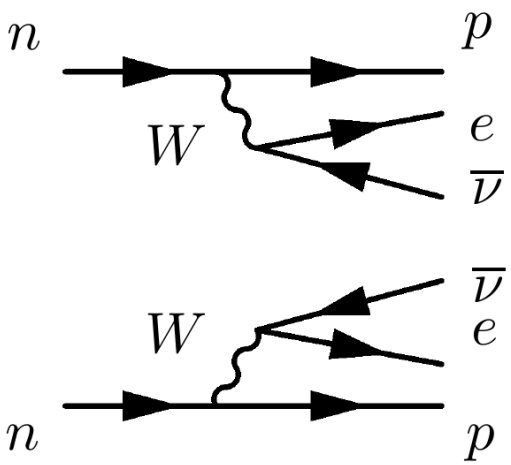
- it's a second order nuclear transition with two neutrons decaying into two protons:

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



2-neutrinos double-β decay ($2\nu\beta\beta$)

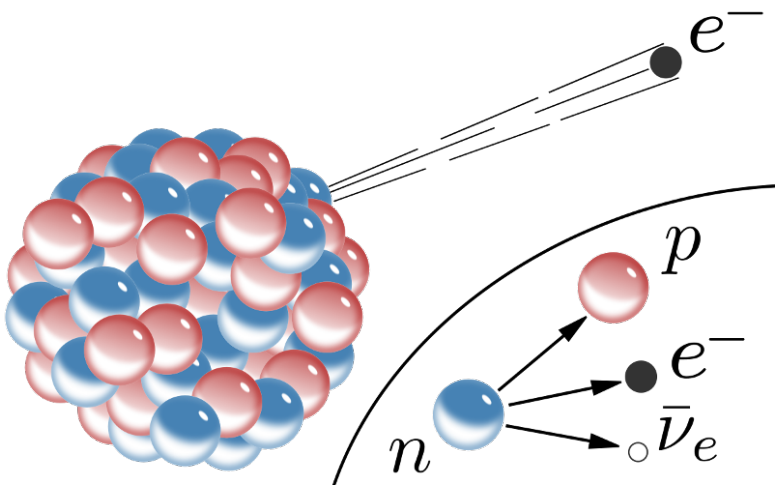
- it's a second order process, allowed in the Standard Model of Particle Physics
- first suggested by Goeppert-Mayer in 1935
  [M. Goeppert-Mayer, Phys. Rev., 48 (1935) 512]
- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- it has been measured in several isotopes
- $T^{2\nu}_{1/2}$ in the range $10^{19} - 10^{24}$ yr



Double beta decay

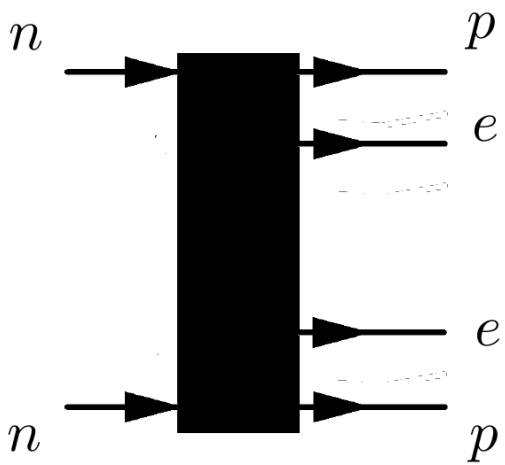
- it's a second order nuclear transition with two neutrons decaying into two protons:

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



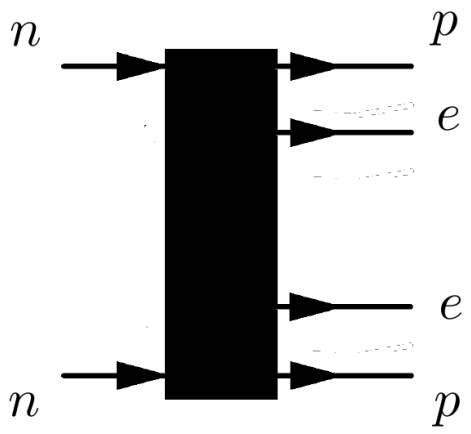
Neutrinoless double-β decay ($0\nu\beta\beta$)

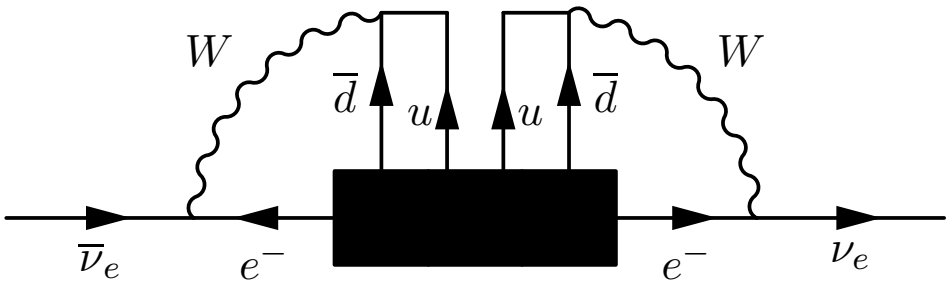
- foreseen by many extensions of the Standard Model of particle physics Particle Physics
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- never observed so far, but allowed in several isotopes
- $T^{0\nu}_{1/2} > 10^{26}$ yr



Why search for neutrinoless double-β decay ?

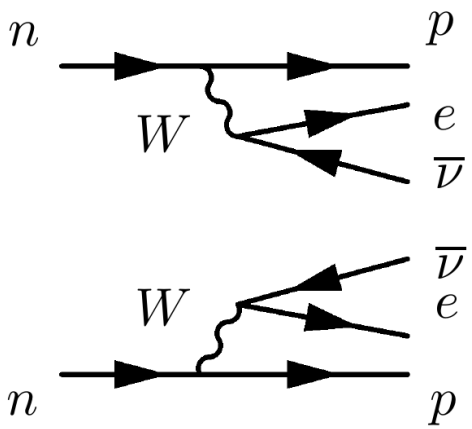
- if observed, would show a violation of the lepton number (ΔL = 2)
- it's the only known way to probe the Majorana neutrino nature

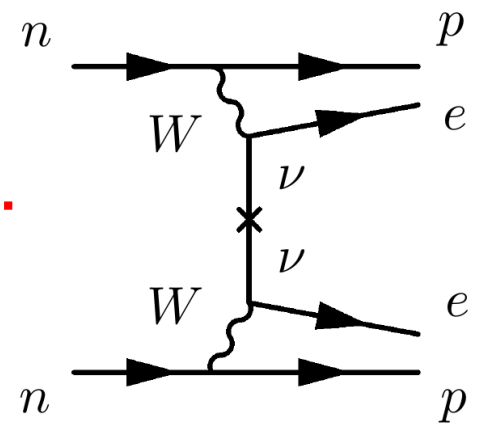


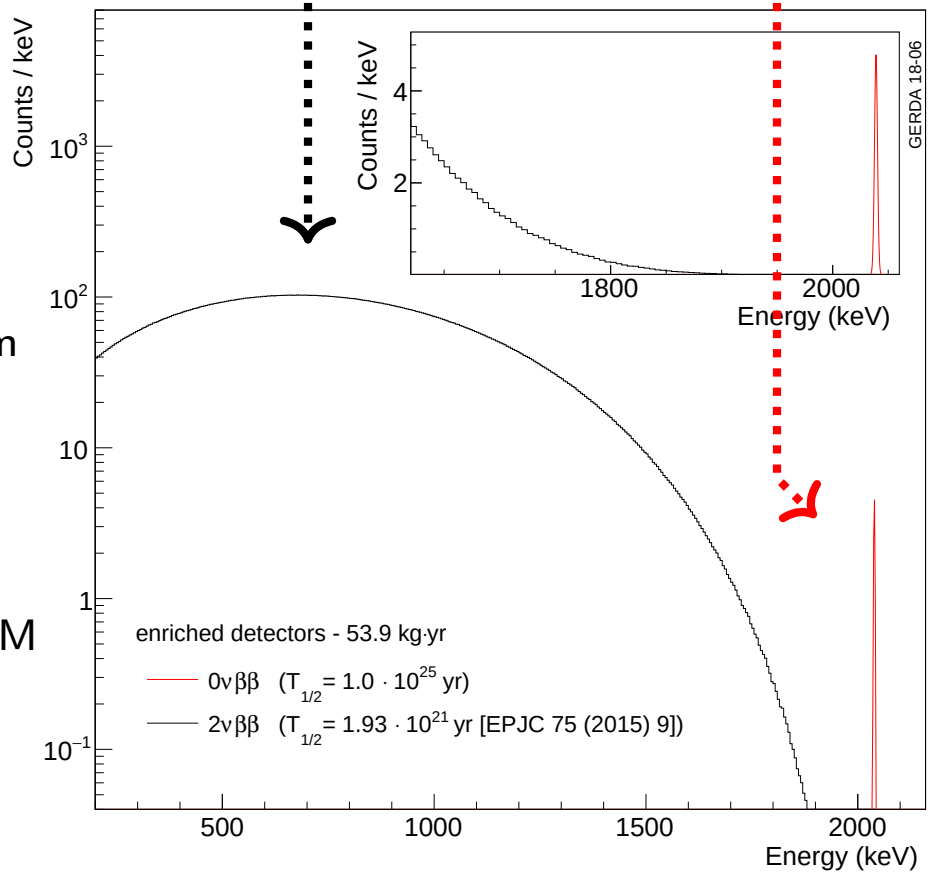


- Black Box theorem ([Schechter and Valle Phys.Rev.D25 (1982) 774]):
- non-null Majorana mass component
- bulk of neutrino mass not given by black-box operator ([Duerr et al., JHEP 1106 (2011) 091])

Double-β decay experimental signatures







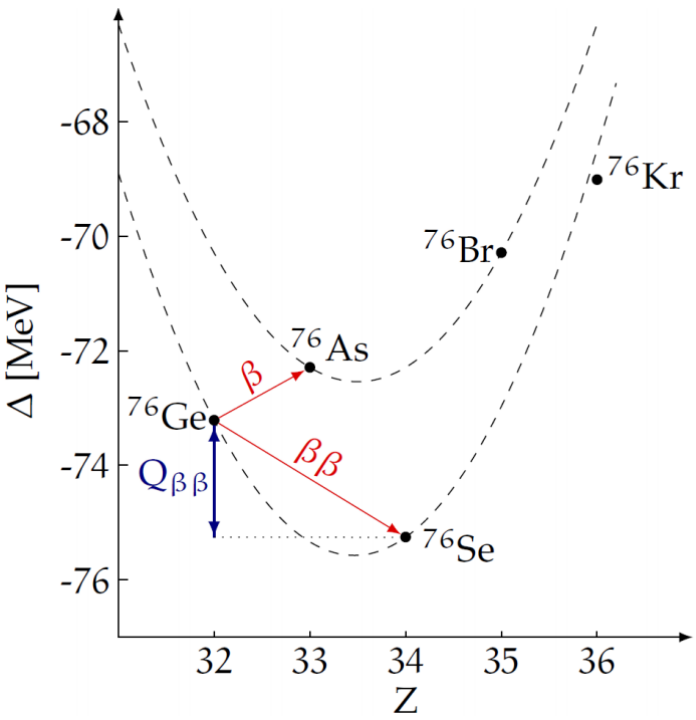
$2\nu\beta\beta$ decay

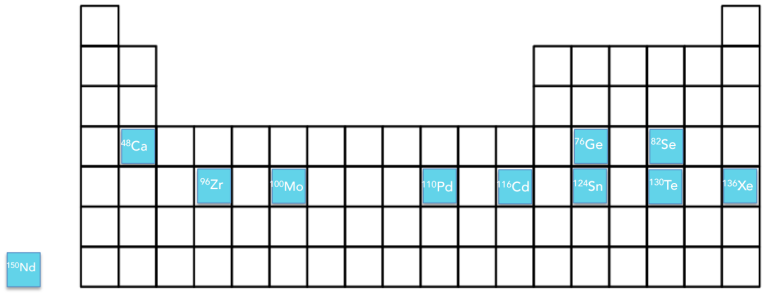
- energy continuum from 0 to $Q_{\beta\beta}$
- 2 electrons from vertex, 2 νs undetected
- foreseen in the SM

$0\nu\beta\beta$ decay

- peak at $Q_{\beta\beta}$
- 2 electrons from vertex
- lepton number violation $\Delta L = 2$

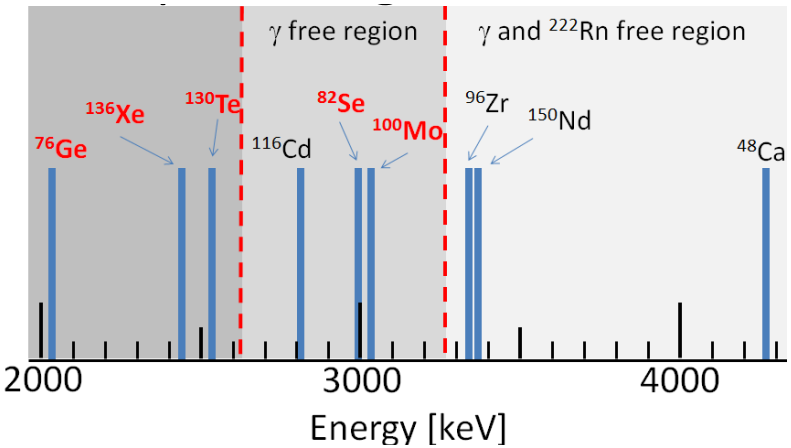
Double-β active isotopes





[from K. Schäffner]

- $\sim$ 35 isotopes available, 9 can be used for $0\nu\beta\beta$ searches
- to observe double β-decay, single β-decay must be forbidden due to energy conservation constraints

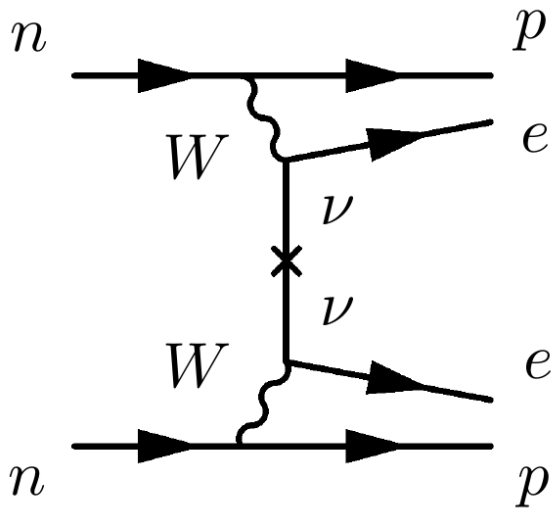


Isotope	Natural Abundance [%]	$Q_{\beta\beta}$ [keV]
^{48}Ca	0.19	4262.96(84)
^{76}Ge	7.6	2039.04(16)
^{82}Se	8.7	2997.9(3)
^{96}Zr	2.8	3356.097(86)
^{100}Mo	9.6	3034.40(17)
^{116}Cd	7.5	2813.50(13)
^{130}Te	34.5	2526.97(23)
^{136}Xe	8.9	2457.83(37)
^{150}Nd	5.6	3371.38(20)

How is $0\nu\beta\beta$ related to the neutrino mass

The simplest theory approach

- assume exchange of a light-Majorana ν
- possible in minimal extensions of the Standard Model (massive + Majorana ν)
- it is the dominant channel in most models

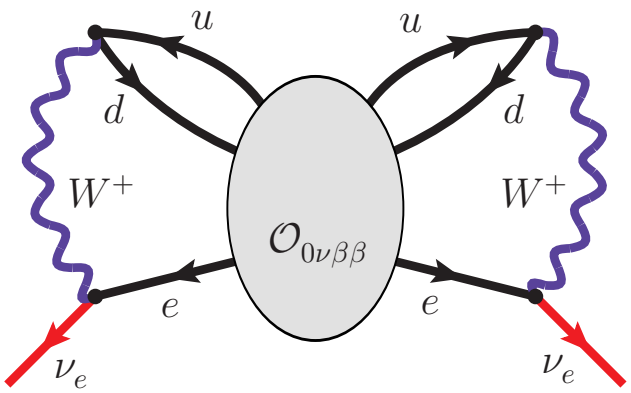


What we measure

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

- $G_{0\nu}$: phase space factor (calculable)
- $m_{ee} = \left|\sum_i U_{ei}^2 m_i\right|$
- U_{ei} : PNMS mixing matrix (complex) elements
- $\mathcal{M}_{0\nu}$: nuclear matrix element
- $|m_{ee}|$: effective Majorana mass

additional uncertainty from quenching of axial vector coupling (g_A)



[J. Liu et al., Phys. Lett. **B 760** (2016) 571, arXiv 1606.0488]

Two experimental approaches

Source = Detector

- the source sample is active and acts simultaneously as detector of the $\beta\beta$ decay
- Pros :

  high detection efficiency

  provides the highest tested masses and best sensitivity, so far

- Cons :

  serious limitations in the choice of the $0\nu\beta\beta$ isotope

  only few materials can satisfy the request to be at the same time the active material of a detector

- emblematic exceptions: ^{76}Ge (germanium diodes), ^{136}Xe (gas and liquid chambers) and ^{130}Te (bolometers)

Source $\neq$ Detector

- use an external-source (or in homogeneous, or passive source) :

  the electrons emitted by a very thin source sample ($\sim$ 60 mg/cm^2 in NEMO3) are observed by means of external detectors (tracker, calorimeter)

- Pros :
  - allow a full topological reconstruction of a $0\nu\beta\beta$ event
  - much easier access to other physics channels (i.e. Majoron)
  - in principle can deploy any $0\nu\beta\beta$ active isotope in the same detector
- Cons :
  - much lower masses available
  - very low detection efficiency

Experimental sensitivities

ROI background free

$$T^{0\nu}_{1/2} > \ln 2 \cdot \epsilon \cdot (mass \cdot time)$$

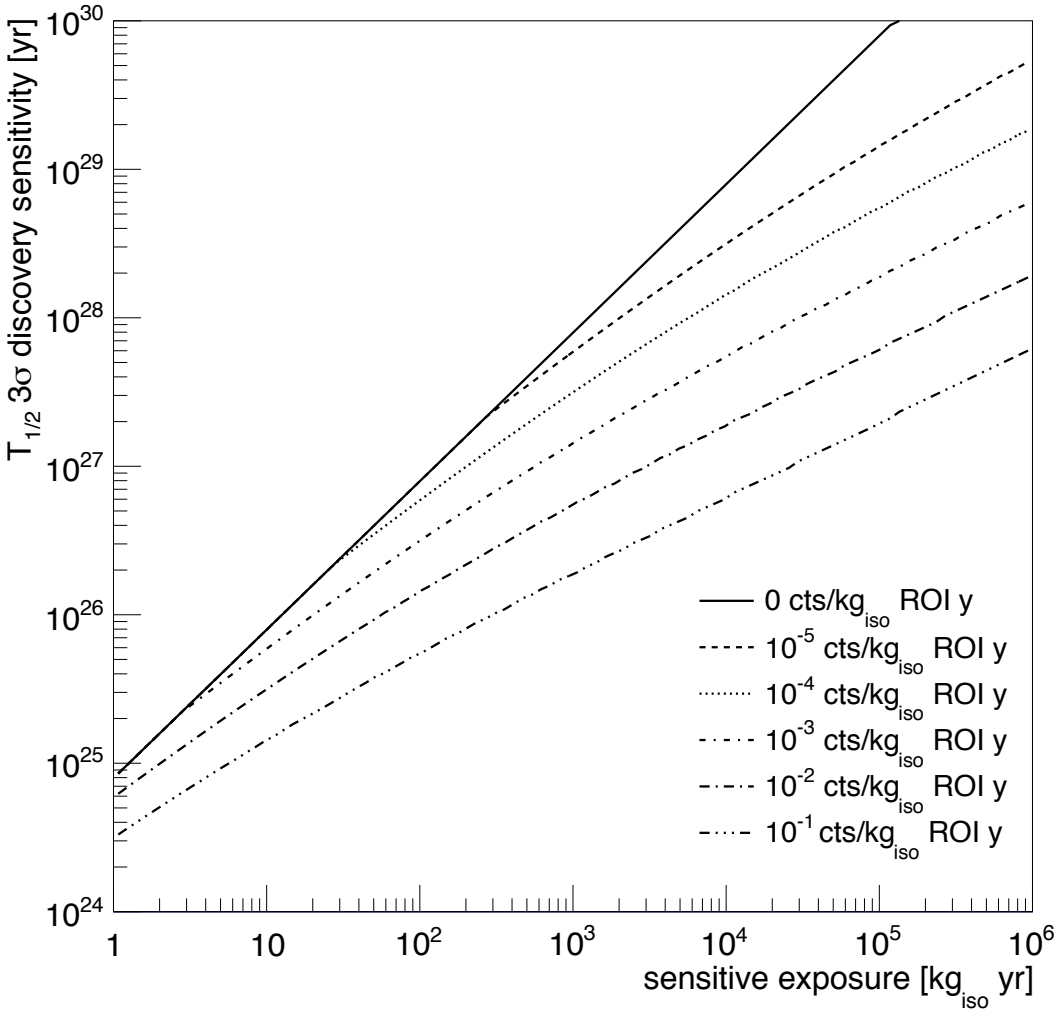
ROI background limited

$$T^{0\nu}_{1/2} > \ln 2 \cdot \epsilon \cdot \sqrt{\frac{mass \cdot time}{\Delta E \cdot BI}}$$

$mass \cdot time = exposure$

ΔE : energy resolution

BI : background level at $Q_{\beta\beta}$

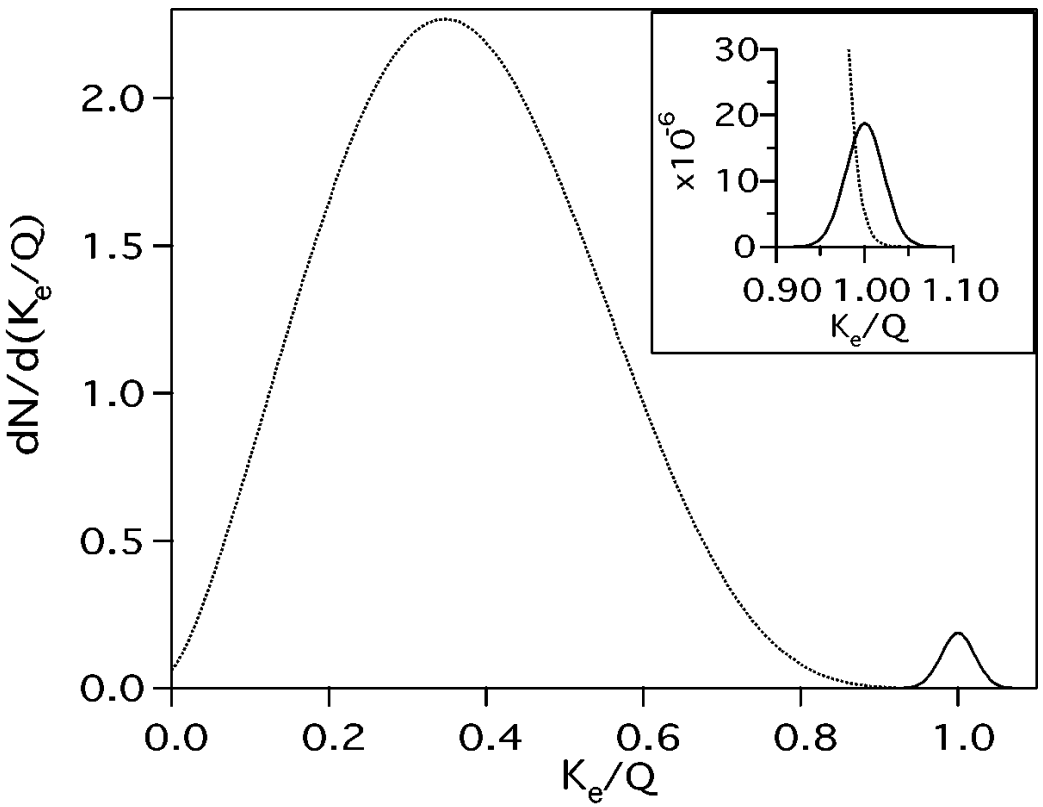


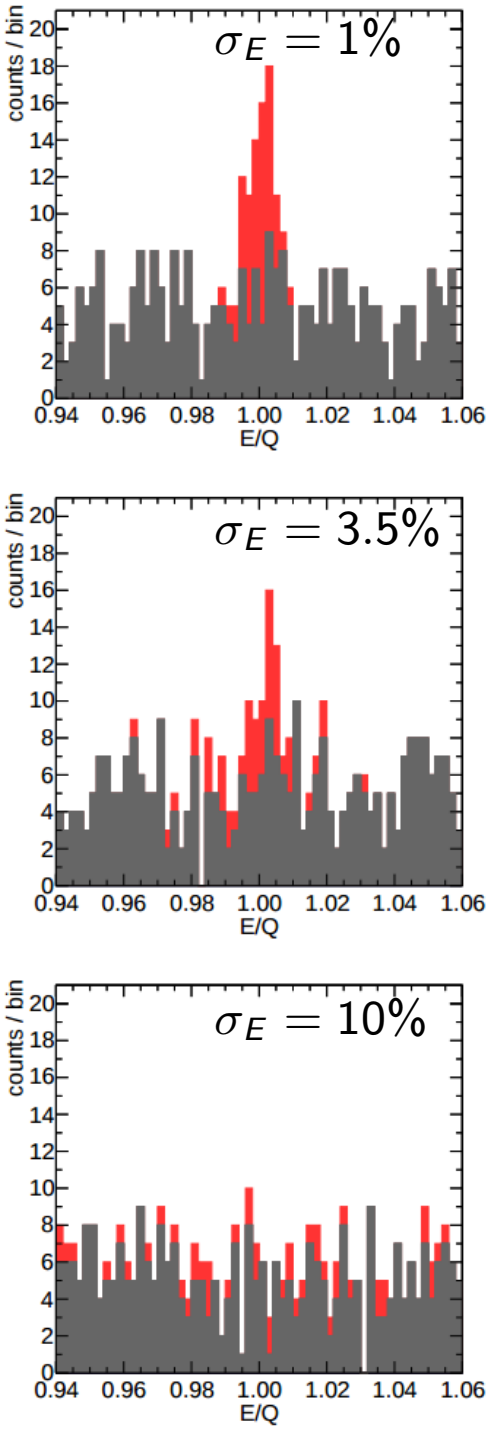
[Agostini, Benato, Detwiler, PRD96 (2017) 053001]

Mass, ΔE and BI at $Q_{\beta\beta}$ are crucial parameters for designing a $0\nu\beta\beta$ experiment

Energy resolution

- maybe the most relevant feature to identify the sharp $0\nu\beta\beta$ peak over an almost flat background
- very useful also to keep under control the background induced by the unavoidable tail of the $2\nu\beta\beta$ spectrum
- it represents a limiting factor in low resolving detectors





[J.J. Gomez-Cadenas and J. Martin-Albo, PoS(GSSI14) 004]

Isotopic Abundance

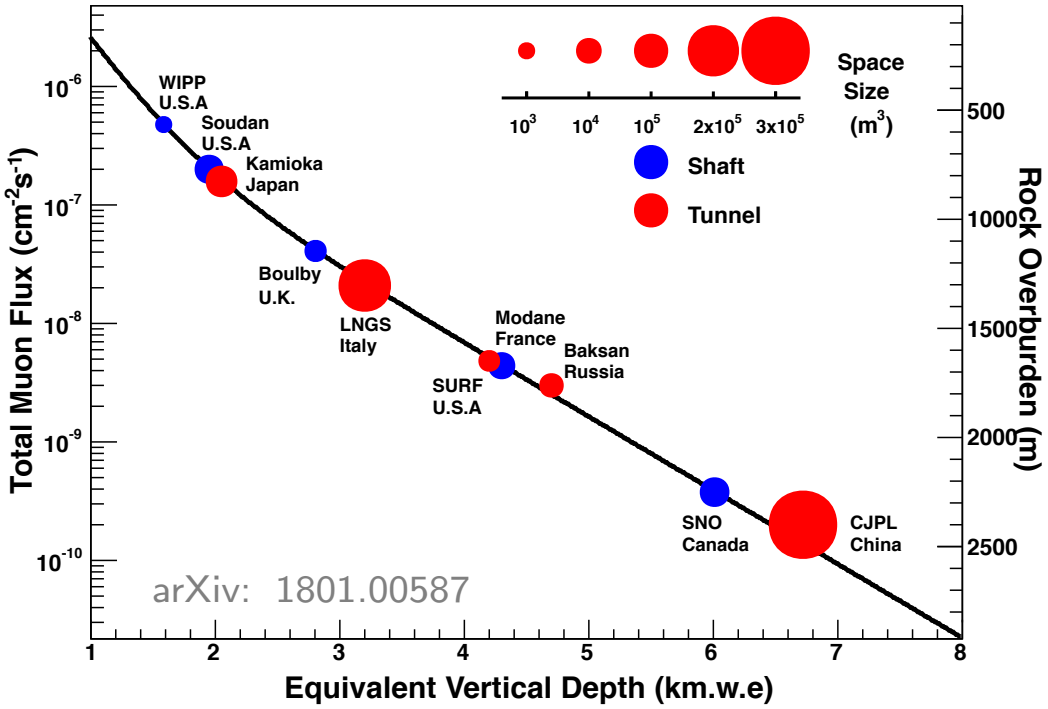
- another key ingredient in the choice of the $0\nu\beta\beta$ isotope
- in most of the cases, the values are in the few % range
- two significant extreme exceptions: ^{130}Te and ^{48}Ca
  - ^{130}Te is the only case in which a high sensitivity is possible even with natural samples
  - ^{48}Ca natural abundance is well below 1% ➜ isotopic enrichment is indispensable
- to limit the detector size and since the background level scales roughly with the total mass of the detector, isotopic enrichment is a necessity for almost all next generation experiments

[O. Cremonesi and M. Pavan, Adv.High Energy Phys. 2014 (2014) 951432, arXiv: 1310.4692]

Isotope	$Q_{\beta\beta}$ (keV)	I.A.(%)	$G^{0\nu}$	$H^{0\nu}$
^{48}Ca	4272	0.187	24.81	826.2
^{76}Ge	2039	7.8	2.36	49.6
^{82}Se	2995	8.73	10.16	198.1
^{96}Zr	3350	2.8	20.58	342.7
^{100}Mo	3034	9.63	15.92	254.5
^{110}Pd	2018	11.72	4.82	70.0
^{116}Cd	2814	7.49	16.70	230.1
^{124}Sn	2287	5.79	9.04	116.5
^{128}Te	866	31.69	0.59	7.4
^{130}Te	2527	33.8	14.22	174.8
^{136}Xe	2458	8.9	14.58	171.4
^{148}Nd	1929	5.76	10.10	109.1
^{150}Nd	3371	5.64	63.03	671.7
^{154}Sm	1215	22.7	3.02	31.3
^{160}Gd	1730	21.86	9.56	95.5
^{198}Pt	1047	7.2	7.56	61.0

The Background Index (BI)

- another fundamental ingredient
- the possibility to reach the zero-background region, i.e. linear dependence on $m_{\beta\beta}$ and $T_{1/2}^{0\nu\beta\beta}$ is particularly appealing
- natural radioactivity of detector components (bulk or surface) is often the main background source
- external backgrounds originated outside the detector have also to be taken into account
- underground location is the usual and fundamental recipe to get rid of cosmic rays induced background (i.e. cosmogenic activations, neutrons, ...)
- a well designed effective shields may compensate the benefits of a very deep laboratory

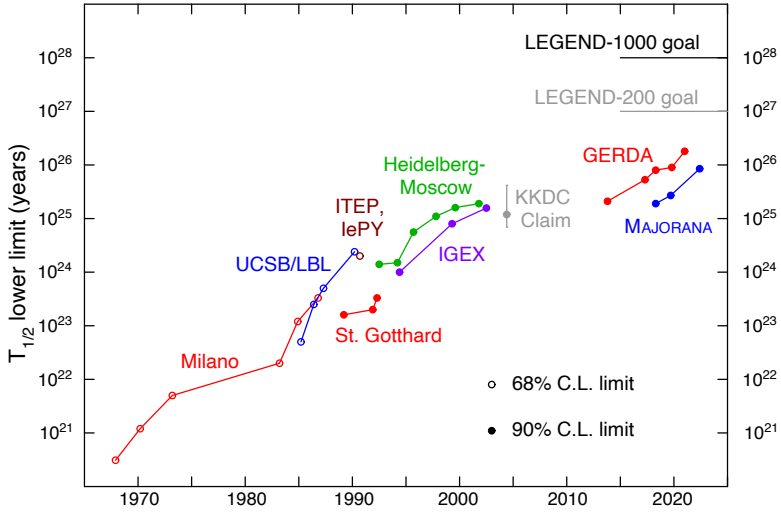


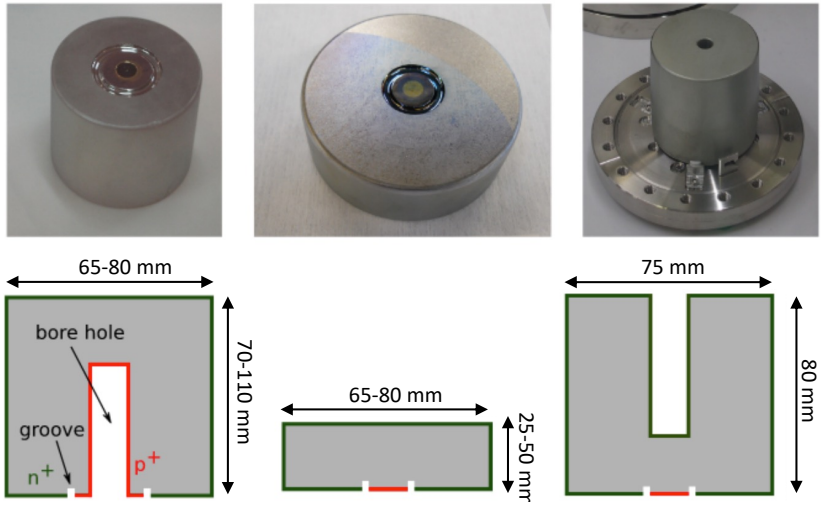
Double Beta Decay Experiments around the World

GERDA and Majorana

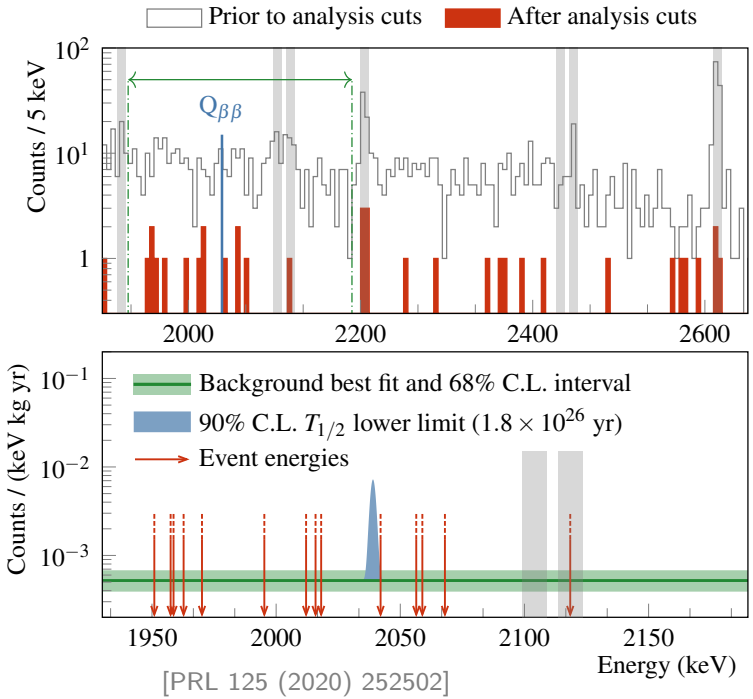
^{76}Ge

- ^{76}Ge has a long history in the search for $0\nu\beta\beta$
- low isotopic abundance ➜ need enrichment
- detector production is industrial standard
- superb energy resolution
- best result available from the GERDA experiment: GERDA is the first background-free experiment in $0\nu\beta\beta$ searches
  - lowest background ever: $5.2 \cdot 10^{-4}$ counts/(keV kg yr)
  - exposure: 127.2 kg yr ; $T_{1/2} > 1.8 \cdot 10^{26}$ yr
- the MAJORANA demonstrator experiment achieves a similar result:
  - background index: $6.2 \cdot 10^{-3}$ counts/(keV kg yr)
  - exposure: 65.5 kg yr; $T_{1/2} > 8.3 \cdot 10^{25}$ yr





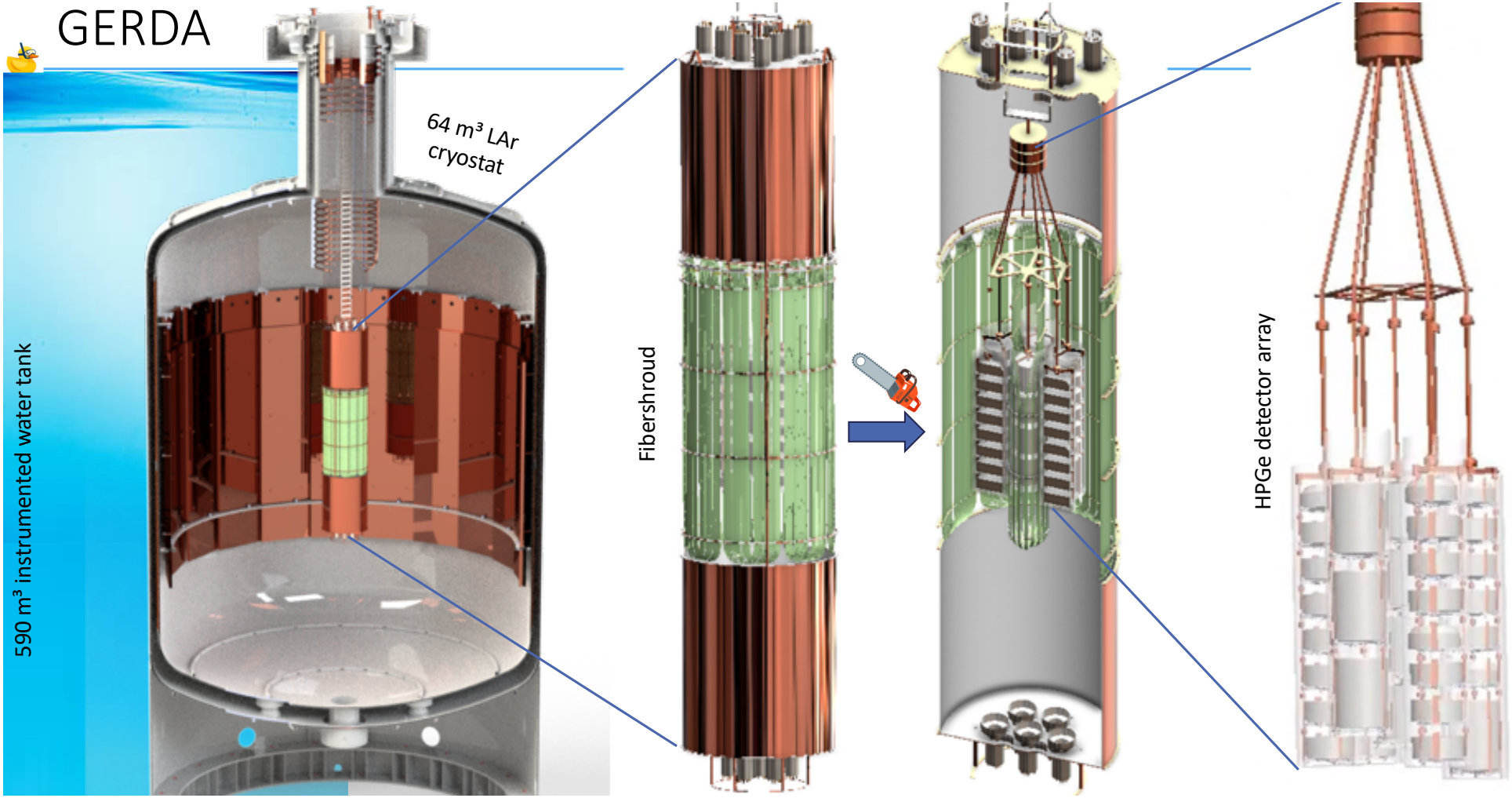
[EPJC 79 (2019) 11 / EPJC 81 (2021) 505]



[PRL 125 (2020) 252502]

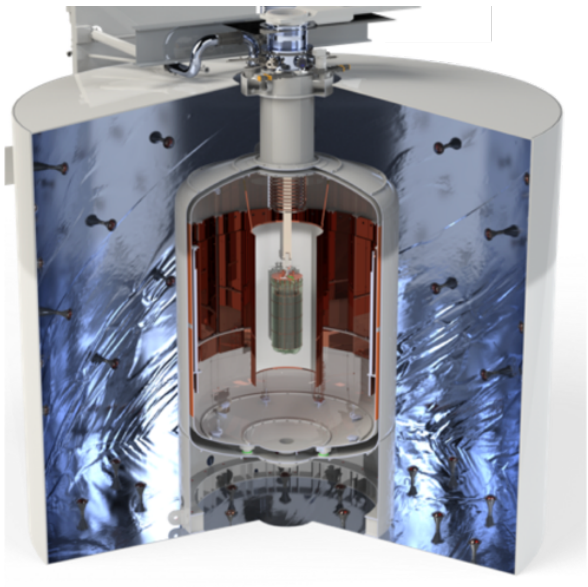
GERDA Cryostat and Active Veto

^{76}Ge



LEGEND: a staged approach

^{76}Ge

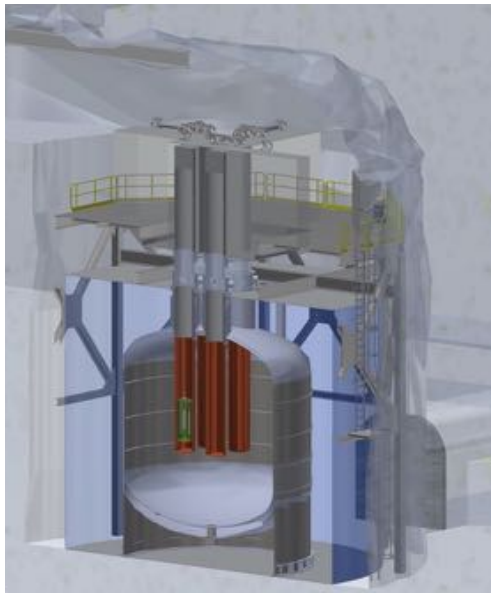


LEGEND-200:

- 200 kg, upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal

  < 0.6 cts/(FWHM t yr)

  < 2×10^{-4} cts/(keV kg yr)
- Now in commissioning, physics data starting in 2022

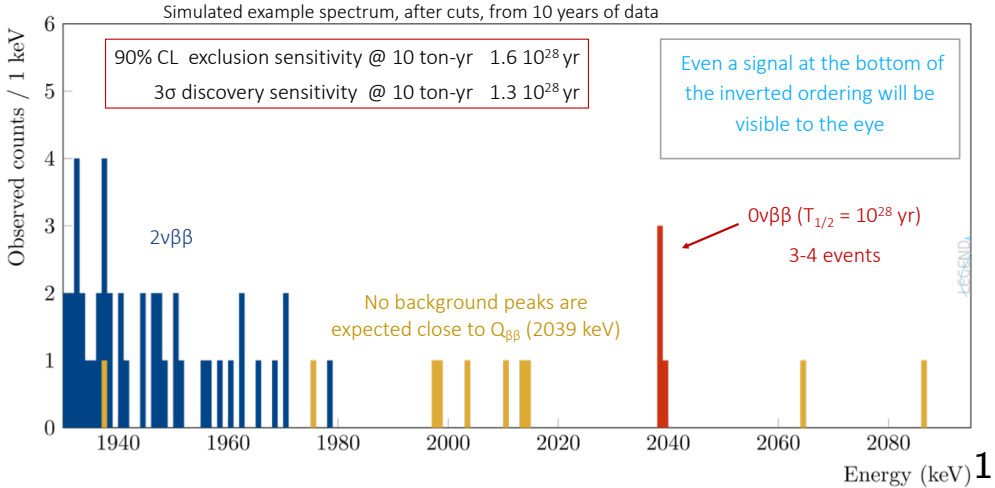


LEGEND-1000:

- 1000 kg, staged via individual payloads (~400 detectors)
- Timeline connected to review process
- Background goal <0.025 cts/(FWHM t yr),<1×10^{-5} cts/(keV kg yr)
- Location to be selected

arXiv: 2107.11462

LEGEND-200 (1 ton-yr)
90% CL exclusion sensitivity : $1 \cdot 10^{27}$ yr
3σ discovery sensitivity : $1 \cdot 10^{27}$ yr
LEGEND-1000 (10 ton-yr)
90% CL exclusion sensitivity : $1.6 \cdot 10^{28}$ yr
3σ discovery sensitivity : $1.3 \cdot 10^{28}$ yr

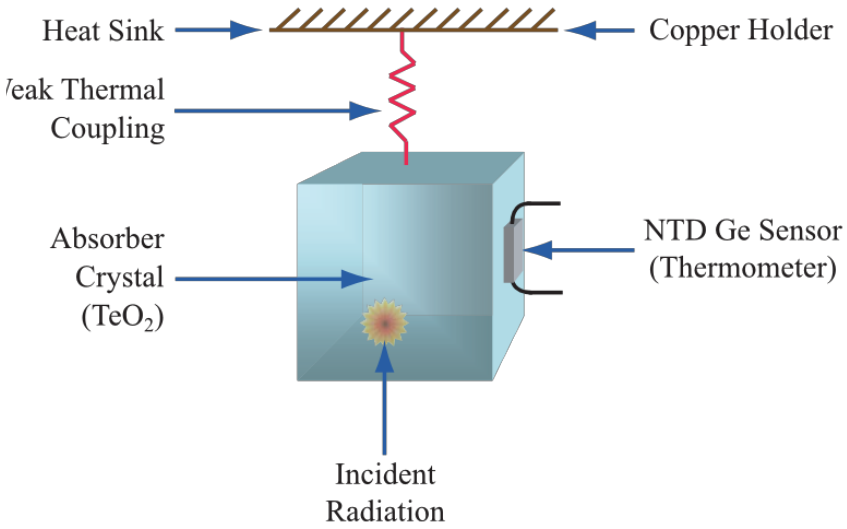


CUORE / CUPID bolometers

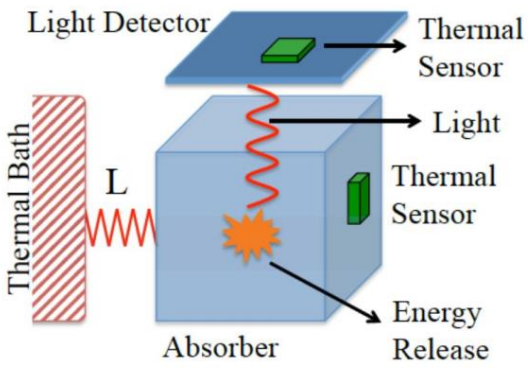
^{130}Te

CUORE with Particle ID = CUPID

CUORE dominant BGND: surface α particles

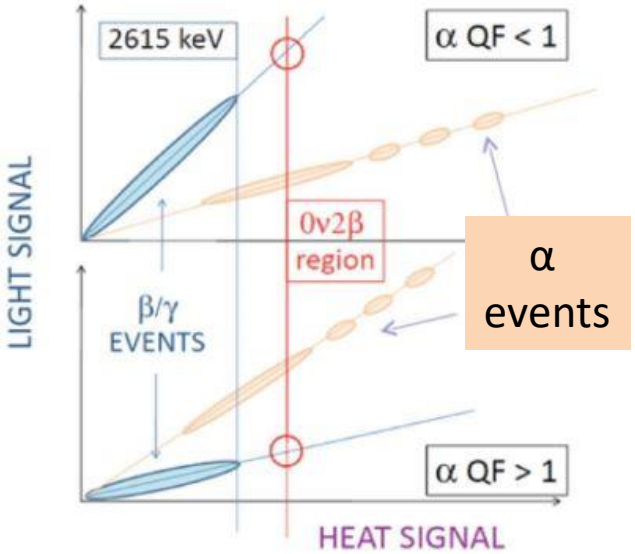


CUPID rejection of α particles by detecting both heat and light



scintillating crystal

or Cherenkov light in TeO_2



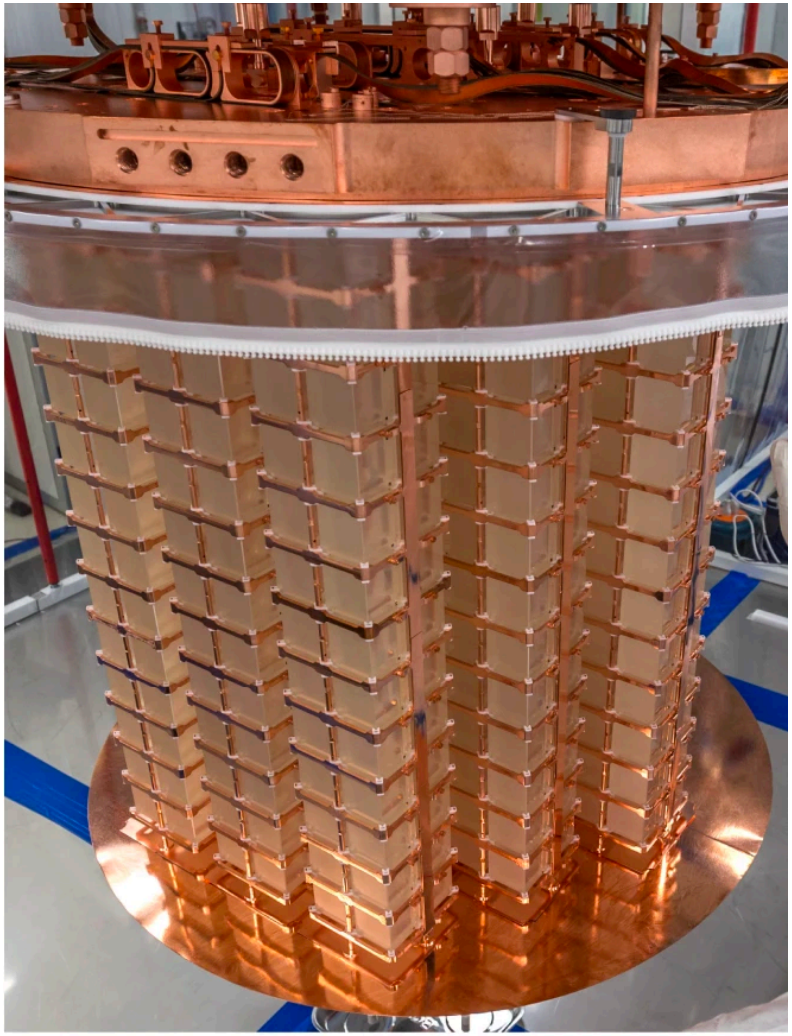
<u>R&D for highly radiopure scintillating crystals</u>

- $Zn^{82}Se$ 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

CUORE

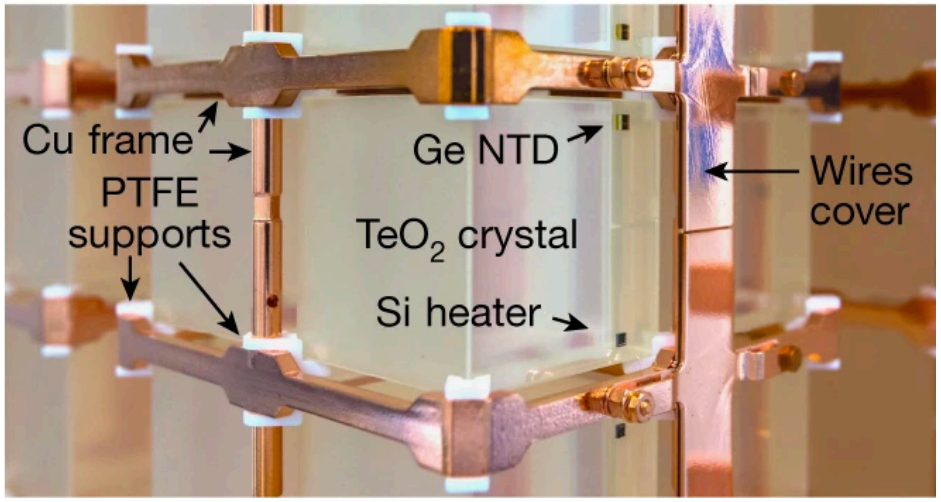
^{130}Te



Array of closely packed **988 TeO_2 crystals arranged in 19 towers**

High Mass of TeO_2: **742 kg**

206 kg of ^{130}Te, 188 kg of ^{128}Te, 0.5 kg of ^{120}Te



@10 mK

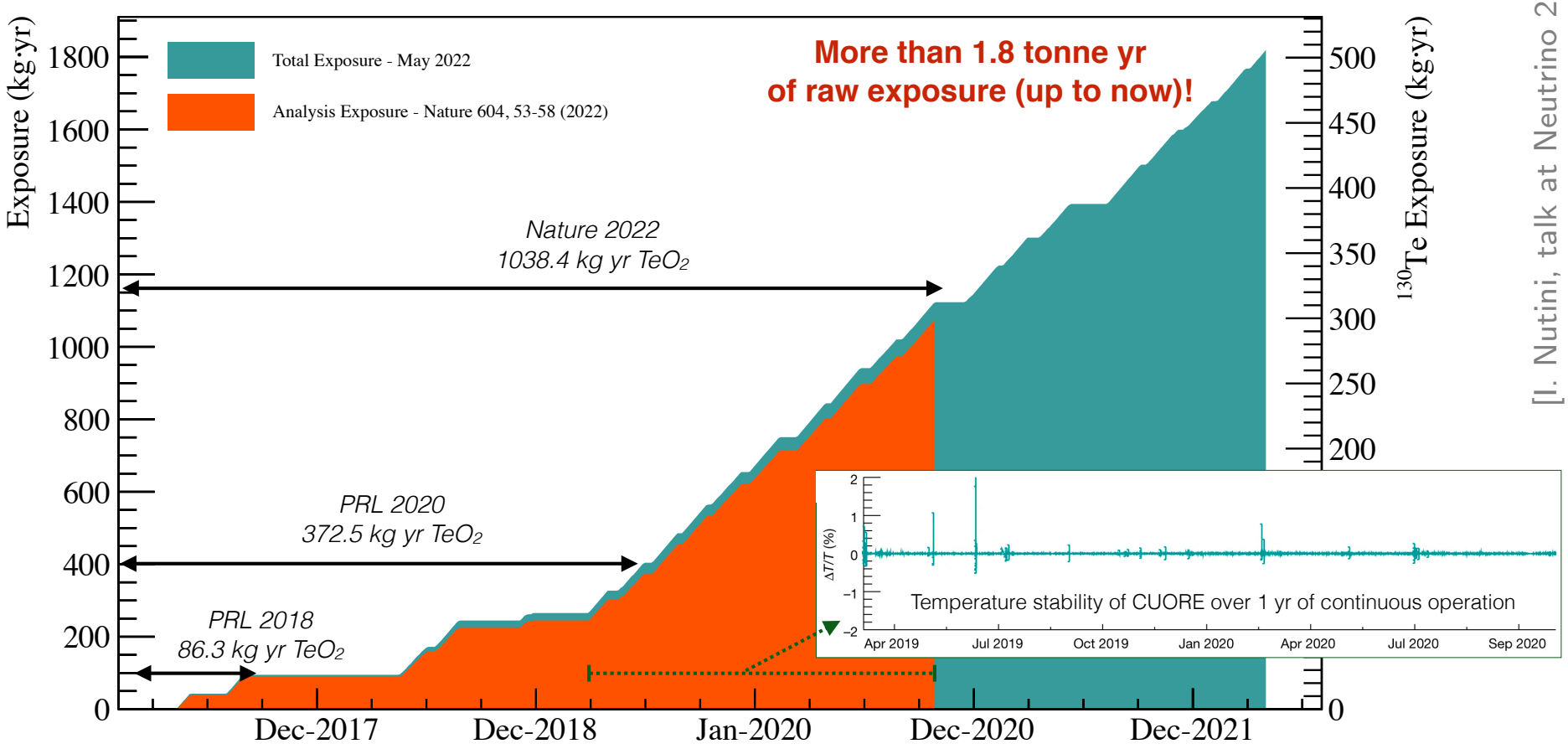
$\Delta T_{crystal}$ ~ 100 μK/MeV ; ΔV_{NTD} ~ 400 μV/MeV

[I. Nutini, talk at Neutrino 2022]

CUORE

^{130}Te

- Data taking started in Spring 2017: detector commissioning and optimisation
- Physics data taking since early 2019, at operating temperature 11-15 mK. **Uptime ~90%**. Data taking rate ~50 kg/month



[I. Nutini, talk at Neutrino 2022]

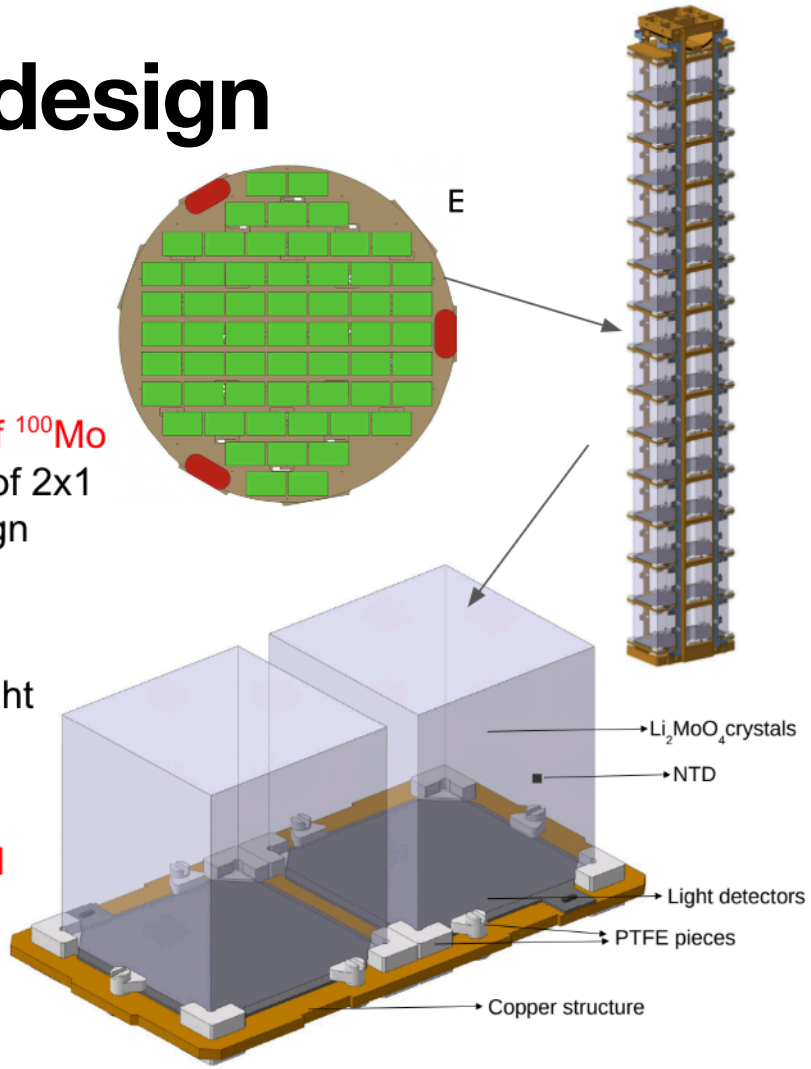
CUPID baseline design

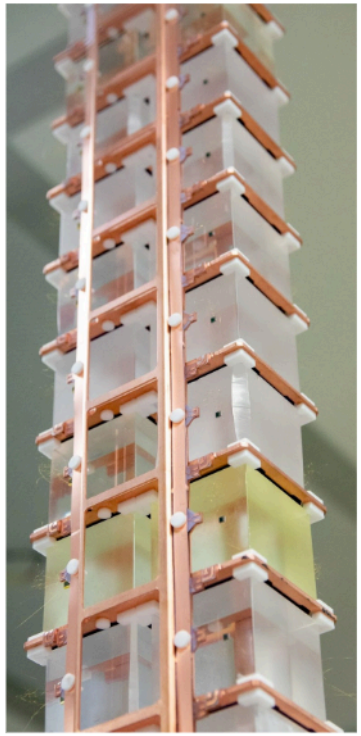
45 x 45 x 45 mm^3 $Li_2{}^{100}MoO_4$ crystals
- Crystal mass: 280 g

1596 total crystals
- 450 kg of $Li_2{}^{100}MoO_4$
- 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design

Ge light detectors with SiO anti-reflective coating
- Each crystal has top and bottom light detectors
- No reflective foils

Muon veto for muon-induced background suppression





[G. Fantini, talk at ICHEP 2022]

CUPID goals (10 ton yr):
Background goal $< 10^{-4}$counts/(keV·kg·yr) in the ROI
90% CL exclusion sensitivity: $9.1 \cdot 10^{27}$ yr
3σ discovery sensitivity: $8 \cdot 10^{27}$ yr

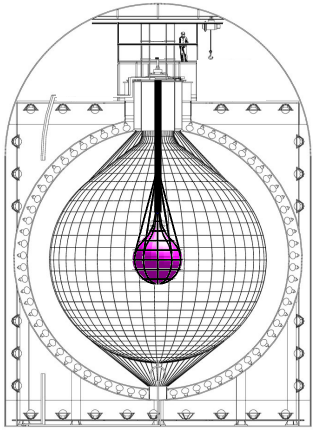
KamLAND-Zen

^{136}Xe

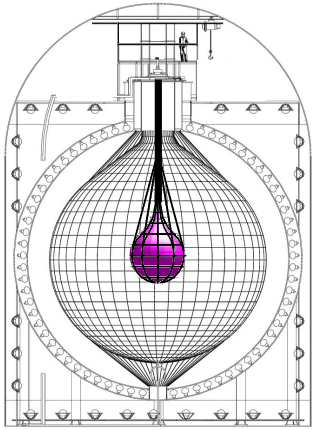
- KamLAND, in operation at Kamioka mine (Japan) since 2002
- 1-kton high purity LS in a 6.5 m radius balloon

- search for $0\nu\beta\beta$ in ^{136}Xe : Q-value 2.458 MeV
- ballon at the centre of the detector with ^{136}Xe loaded LS
- enrichment: 90%, dissolved at 3% in weight

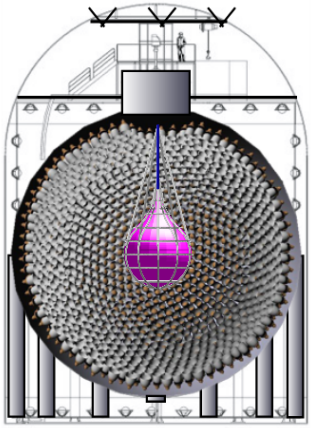
Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015



Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019



Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution



Reanalysis $\xrightarrow{\text{combined}}$ **1st result** arXiv:2203.02139v1 [hep-ex]
& Long paper in preparation

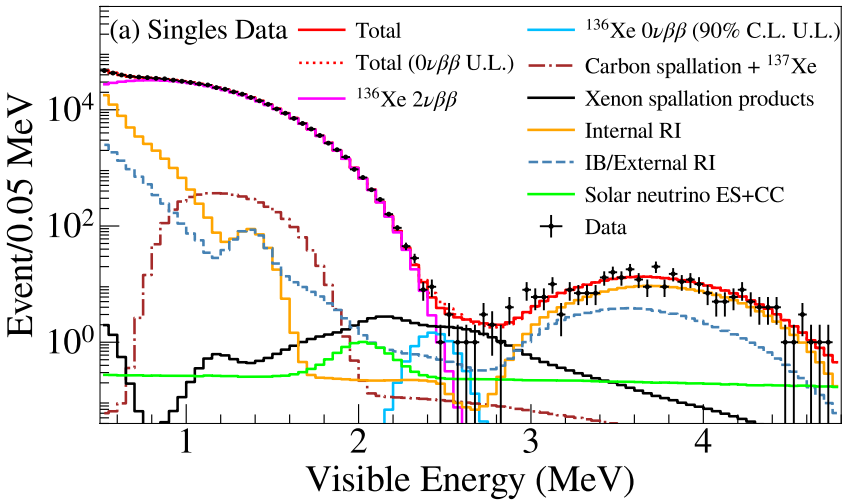
KamLAND-Zen 800 results

^{136}Xe

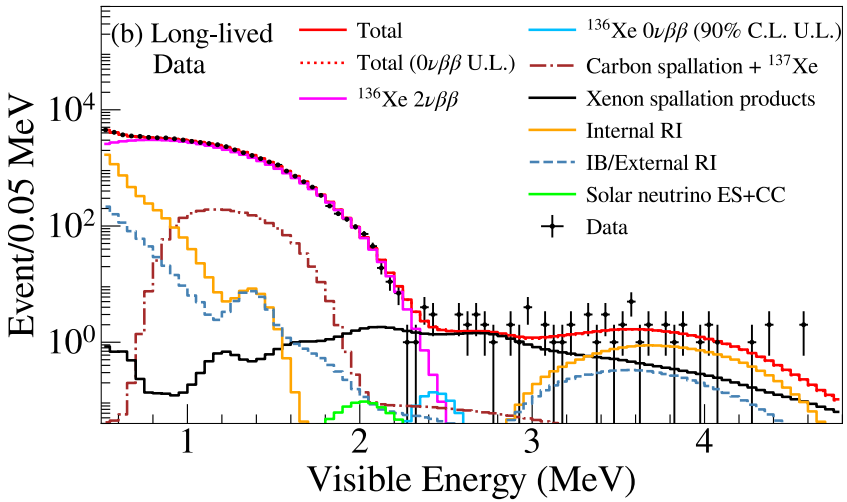
[Azusa Gando, talks at Neutrino 2022 and ICHEP 2022]

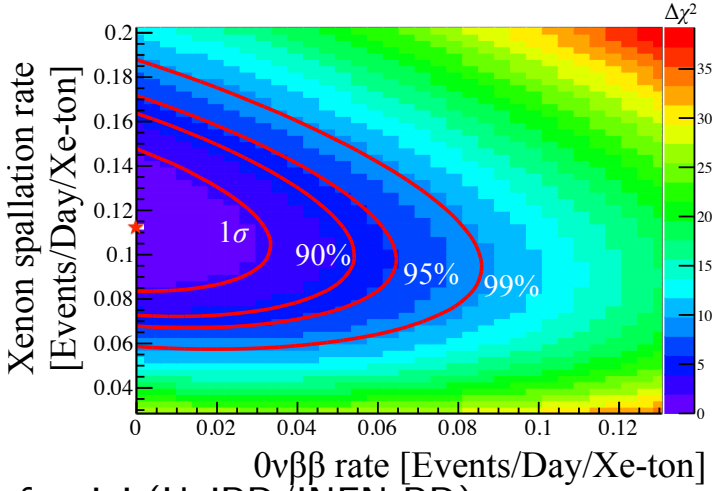
Internal 10 volume bins (1.57-m-radius spherical volume) × 3 time bins

Singles data
(sensitive to 0νββ rate)
Livetime = 523.4 days



Long-lived product data
(used to constrain the LL rate)
Livetime = 49.3 days





^{136}Xe 0νββ decay rate for KamLAND-Zen 800
Best fit rate = 0
Upper limit (90% C.L.): < 7.9 events/Xe-LS(30.5 m^3)

$T^{1/2} > 2.0\times10^{26}$ yr (90% C.L.)

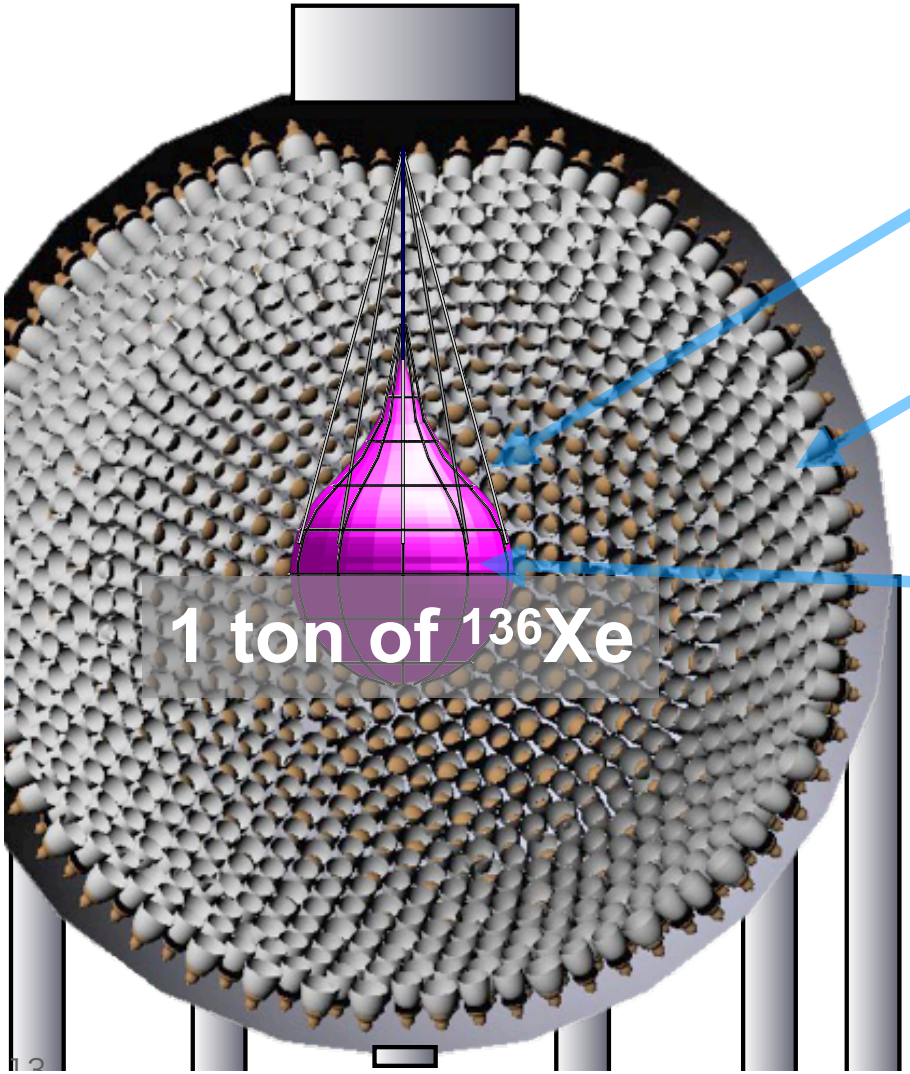
KamLAND2Zen

^{136}Xe

[Azusa Gando, talks at Neutrino 2022 and ICHEP 2022]

Enlarge opening

General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



New electronics

To improve background suppression.
Tagging long lived isotope from cosmic ray spallation.

Scintillation inner balloon

BG reduction from Xe-LS container

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage

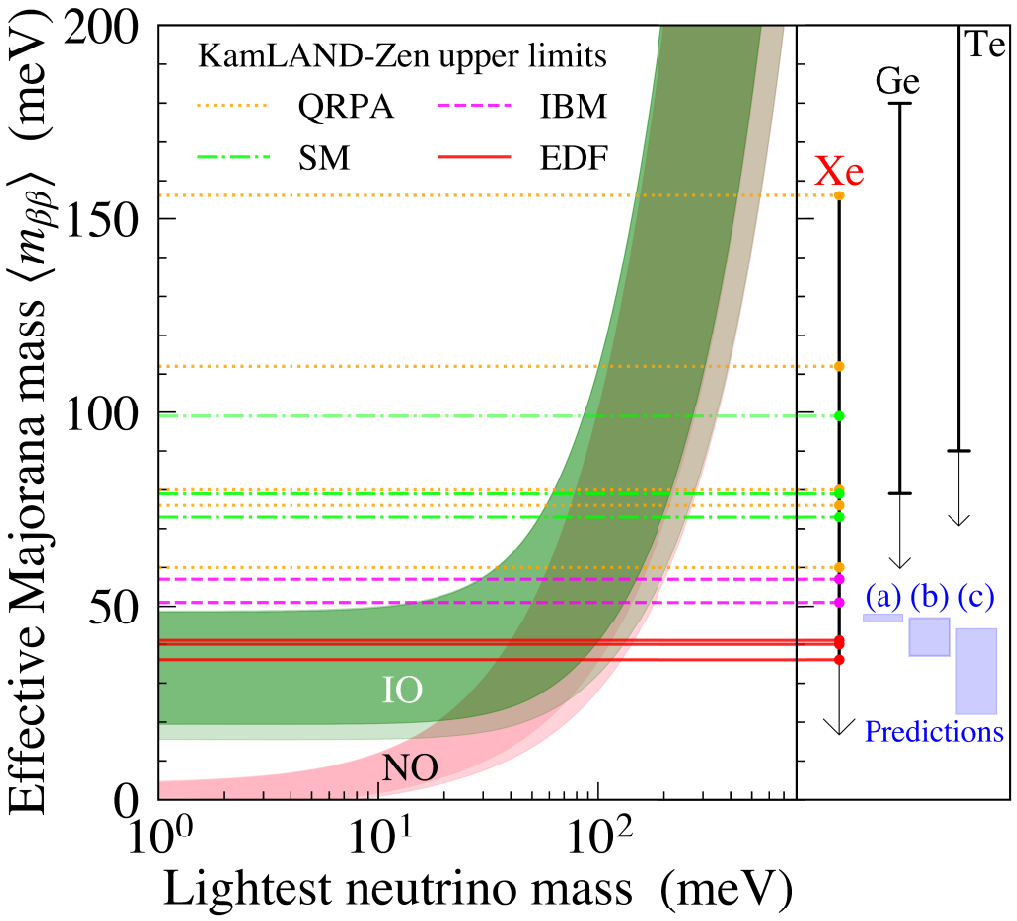
Brighter LS

Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

$\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

Target $\langle m_{\beta\beta} \rangle$ ~20 meV in 5 yrs

$m_{\beta\beta}$ current limits



[S. Abe et al., KamLAND-Zen Collab., arXiv 2203.02139]

Most stringent limits

GERDA

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 1.8 \cdot 10^{26}$ yr

$S^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 1.8 \cdot 10^{26}$ yr

$\Rightarrow |m_{\beta\beta}| < (79 - 180)$ meV

KamLAND-Zen

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 2.3 \cdot 10^{26}$ yr

$S^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.5 \cdot 10^{26}$ yr

$\rightarrow |m_{\beta\beta}| < (36 - 156)$ meV

CUORE

$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 2.2 \cdot 10^{25}$ yr

$\rightarrow |m_{\beta\beta}| < (90 - 305)$ meV

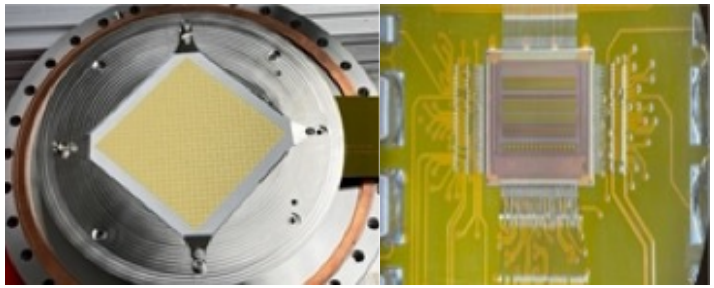
Some results are better than sensitivity: sometimes luck plays a role

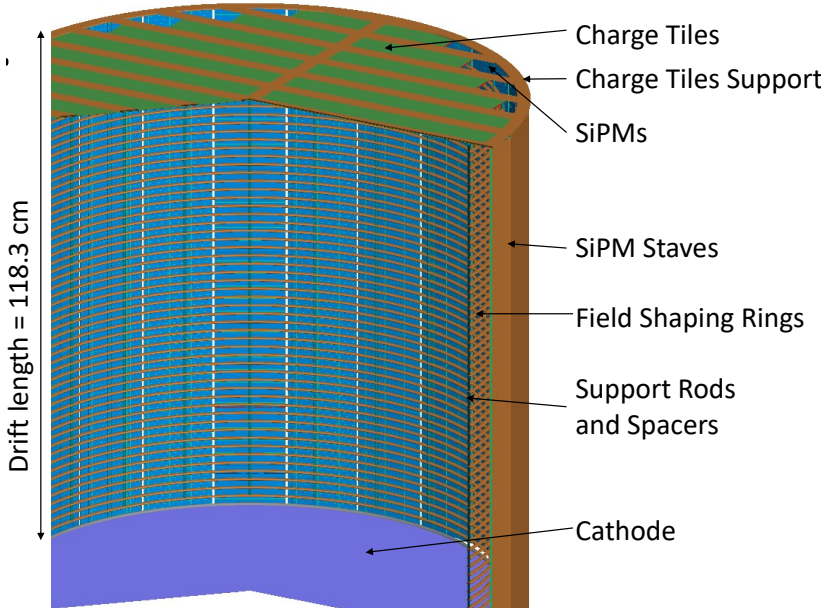
nEXO

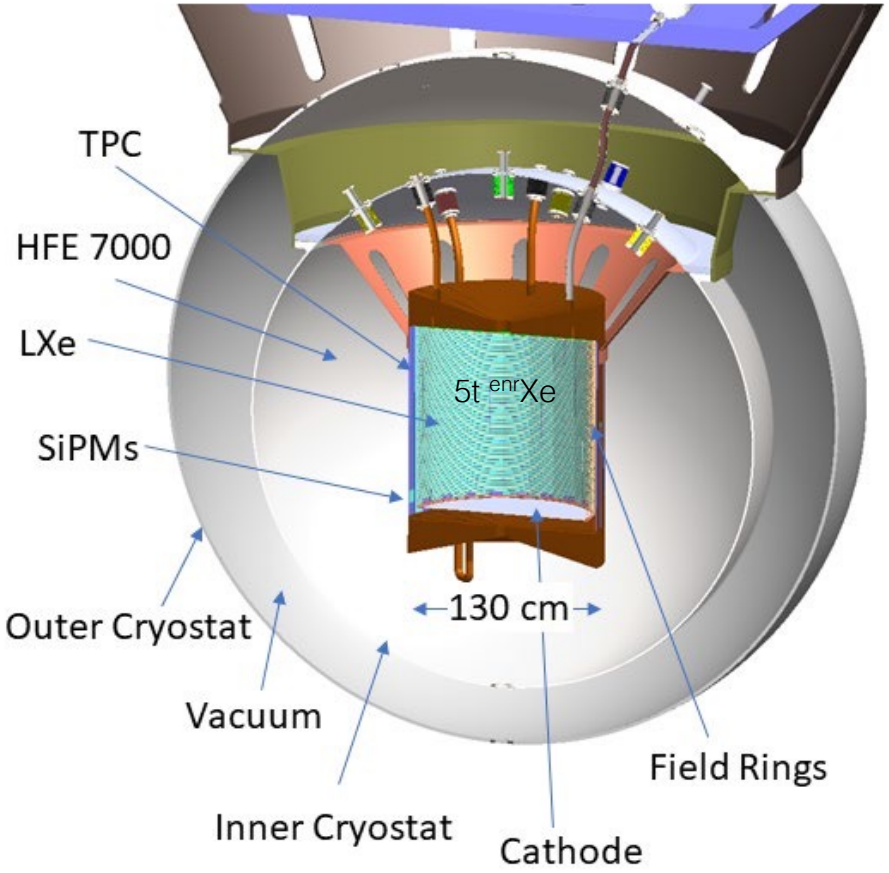
^{136}Xe

- Monolithic TPC with 5 tons of 90% enriched ^{136}Xe
- Located at Cryopit at SNOLAB
- Active water Cherenkov muon veto
- energy resolution required: $\leq 1.2\%$

Charge sensing tile and in-LXe cold electronics







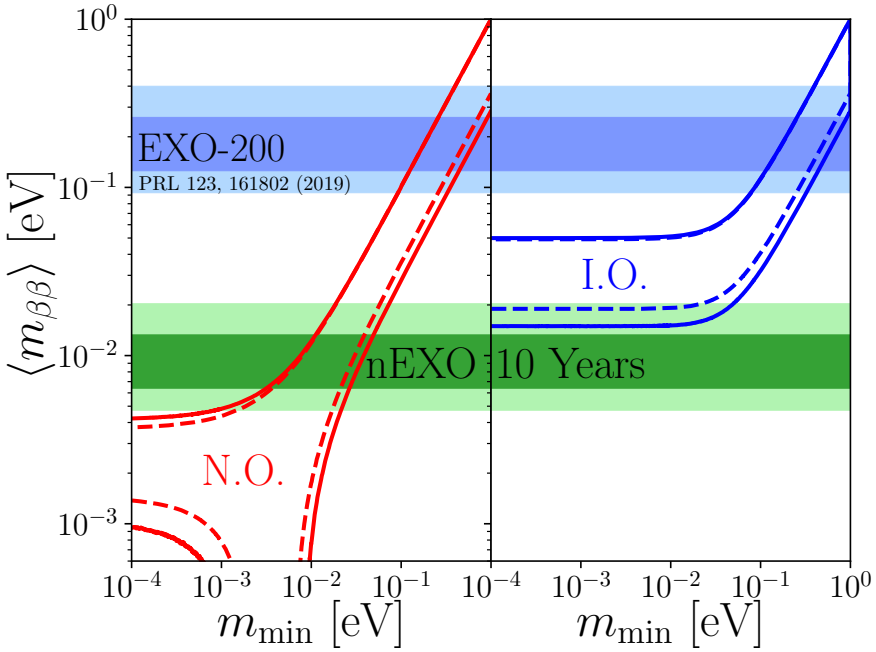
[Zepeng Li, talk at ICHEP 2022]

nEXO

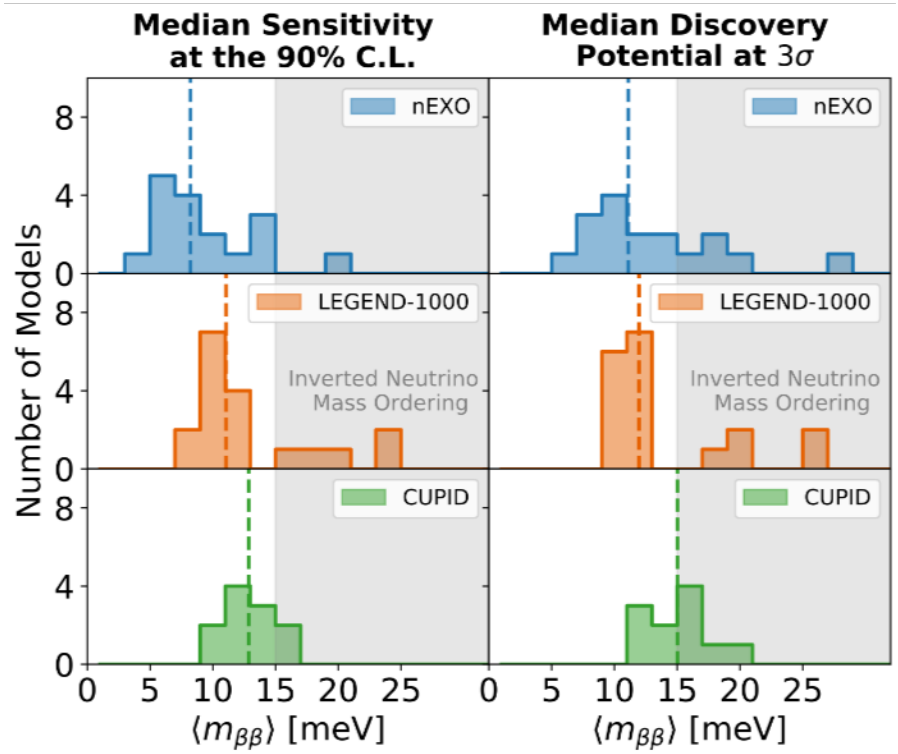
^{136}Xe

- nEXO completely explores the inverted mass ordering in almost all cases
- sensitivity to Majorana neutrino mass: $m_{\beta\beta} = 4.7$–20.3 meV

$$[T^{0\nu}_{1/2}]^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} |\mathcal{M}^{0\nu}|^2$$



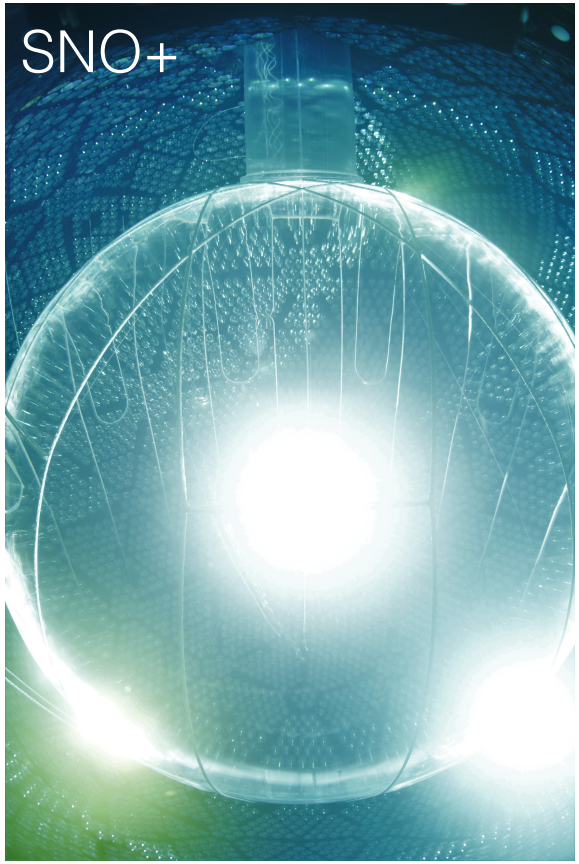
Note: NMEs are not statistical...there is only one correct value. But calculations are challenging.

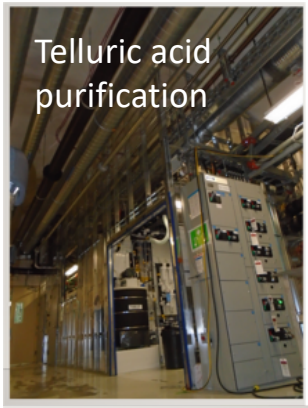


[Zepeng Li, talk at ICHEP 2022]

Courtesy Mark Chen

- 780t LS (2.2 g/L PPO in LAB)
- currently data taking with unloaded LS
- $0\nu\beta\beta$ phase: natural Te (34% 130Te) loaded as metal organic complex (Te-diol)
- Te-systems ready for operations
- Full-scale Te-diol batches in 2022/23
- following demonstration of operations and approvals by SNOLAB, begin Te-loading in 2024
- original plan: load 0.5% (3.9t nat Te): $T_{1/2} > 2 \cdot 10^{26}$ yr
- R&D on higher (up to 3%) Te-loading ongoing
- 0.5% loading phase critical to assess performance and Te-related backgrounds



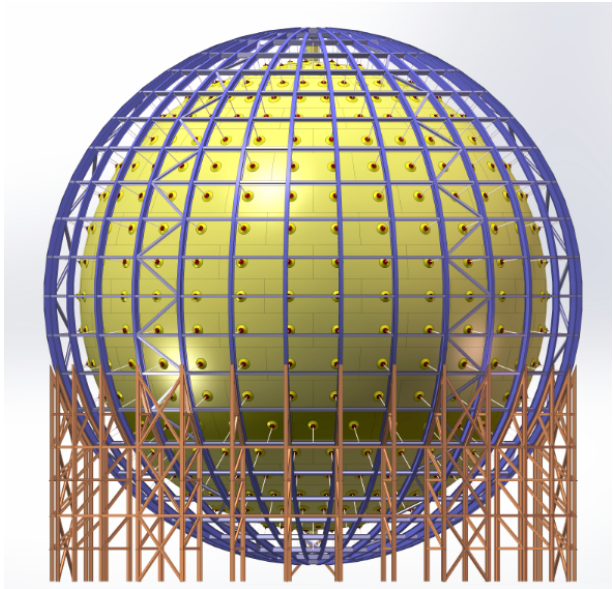


JUNO $0\nu\beta\beta$ future plans

^{nat}Te/^{136}Xe

Courtesy Yifang Wang

- The Jiangmen Underground Neutrino Observatory (JUNO) has been designed for mass ordering determination → (see Dmitry's talk)
- but JUNO has a rich physics program https://doi.org/10.1016/j.ppnp.2021.103927
- after completing the main physics program, upgrade for $0\nu\beta\beta$ searches with ^{nat}Te or ^{136}Xe
- huge target mass (100 t scale) and aspired low background
- very high PMT coverage (78%), 3% energy resolution an 1 MeV
- R&D studies on Te-diol based LS:
  - best performance so far with 0.6% Te-loading
  - NO measurable difference compared to purified LAB (Att. length $>$ 20 m)
  - NO degradation after 6 months
  - Relative light output: 60% - 70% w.r.t un-loaded LS
- Ambitious goal: exploration of normal mass ordering



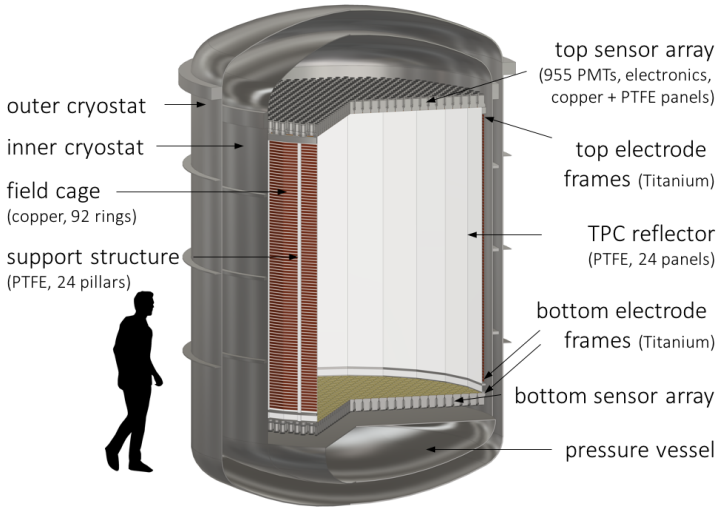
DARWIN

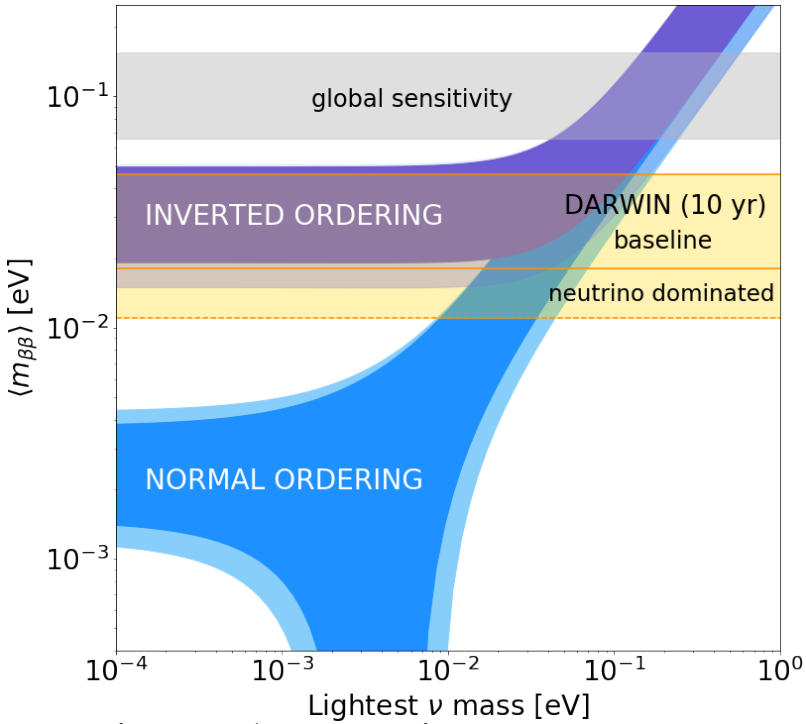
^{nat}Xe

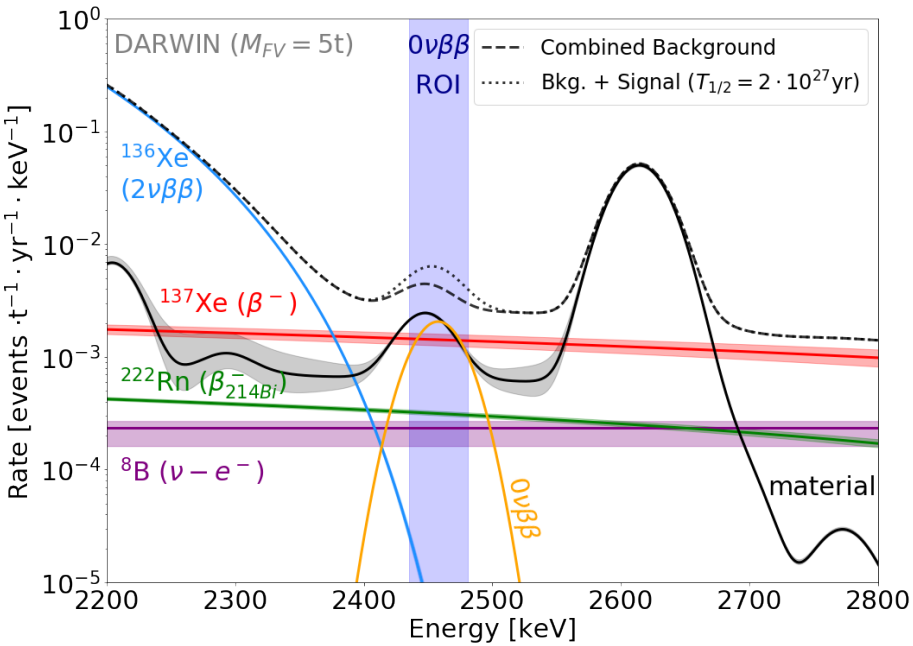
[source: https://doi.org/10.48550/arXiv.2003.13407]

- main goal of the experiment: dark matter detection
- Out of 50 t ^{nat}Xe, 40 t as TPC active target, 3.6 t of ^{136}Xe
- employs a double-walled cryostat and TPC
- predicted sensitivity (10 yr exposure, 5 t fiducial mass)

  $S^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 2.4 \cdot 10^{27}$ yr







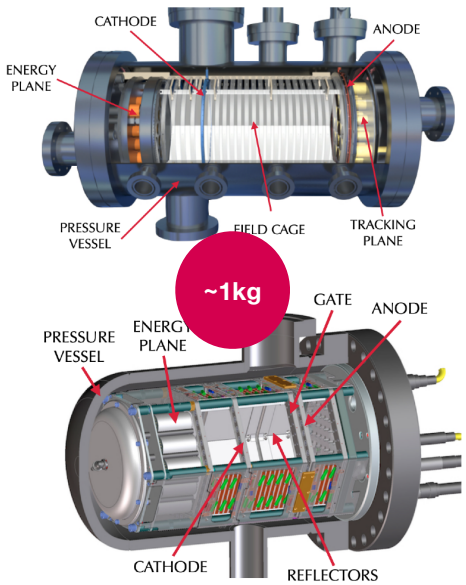
NEXT

^{136}Xe

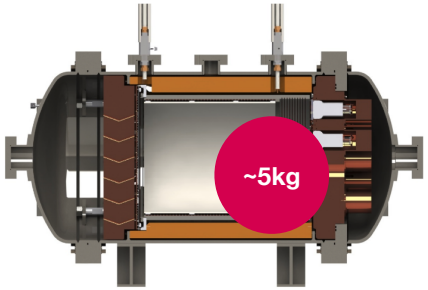
- High Pressure Gaseous Xenon Time Projection Chamber with Electroluminescent Amplification

2009 — 2015 — 2022 — 2026

PROTOTYPES
2009/2014
Demonstration of the detector concept

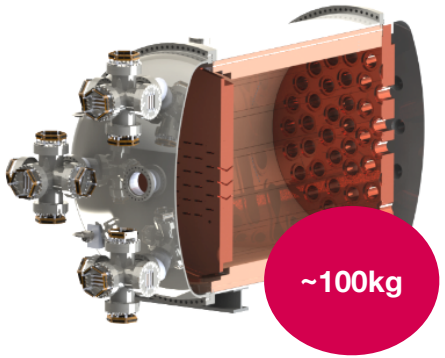


NEXT-WHITE (NEW)
2015/2021
Background model assessment
$2\nu\beta\beta$ measurement for ^{136}Xe



@ LSC
Laboratorio Subterráneo de Canfranc

NEXT-100
2022/2025
Background model assessment
Neutrinoless double beta decay search in ^{136}Xe



@ LSC
Laboratorio Subterráneo de Canfranc

NEXT-HD
2026?
Neutrinoless double beta decay search through inverted neutrino mass ordering

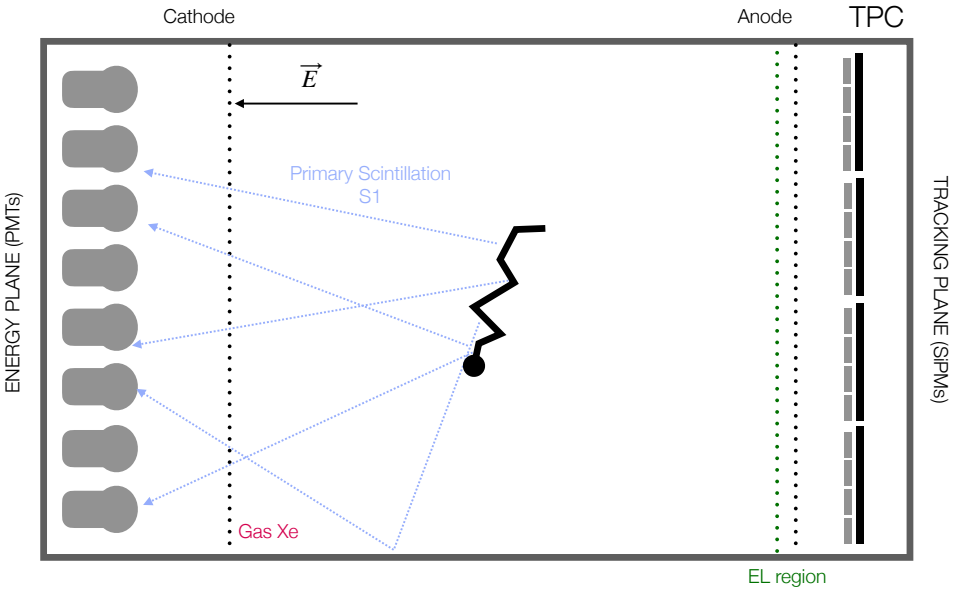
NEXT-BOLD
Barium tagging for background-free experiment inverted neutrino mass ordering

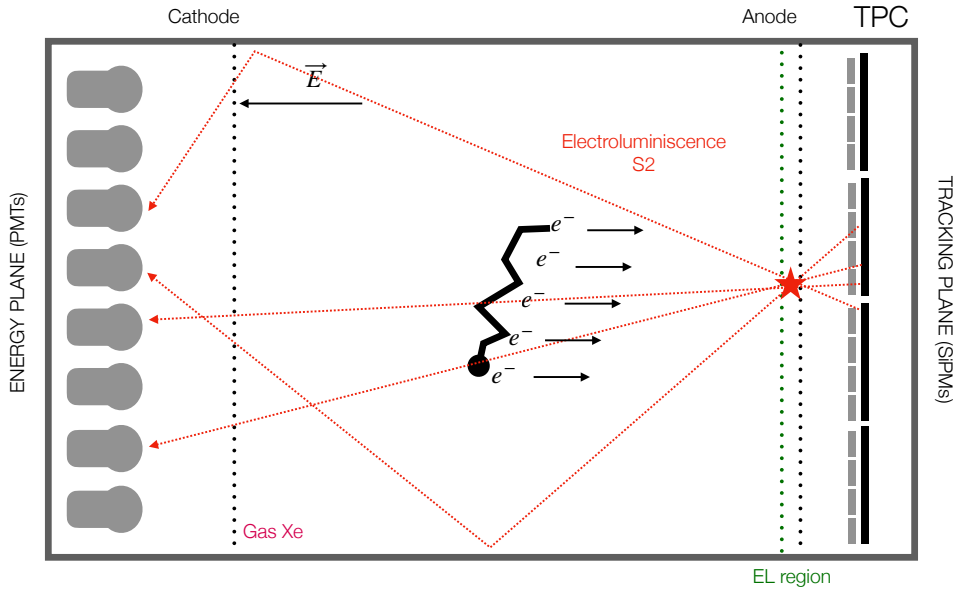
[Helena Almazán, talk at ICHEP 2022]

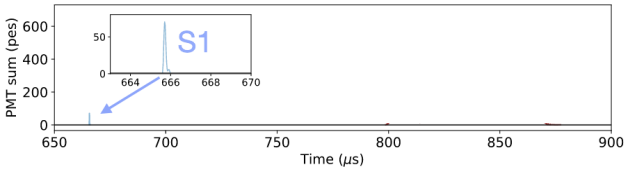
NEXT

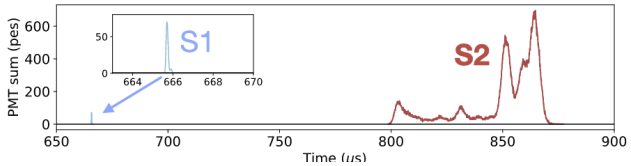
^{136}Xe

- High Pressure Gaseous Xenon Time Projection Chamber with Electroluminescent Amplification
- 3D reconstruction of events is possible ➜ improve background rejection



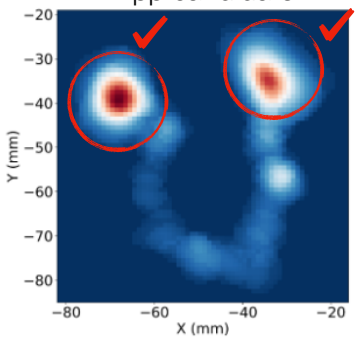




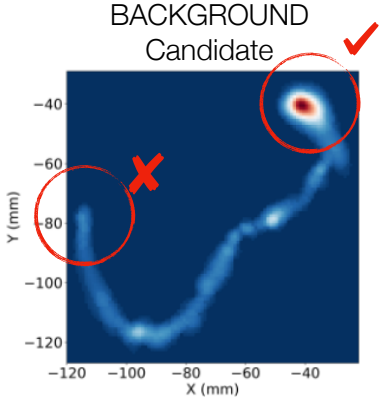


[Helena Almazán, talk at ICHEP 2022]

SIGNAL
2νββ candidate



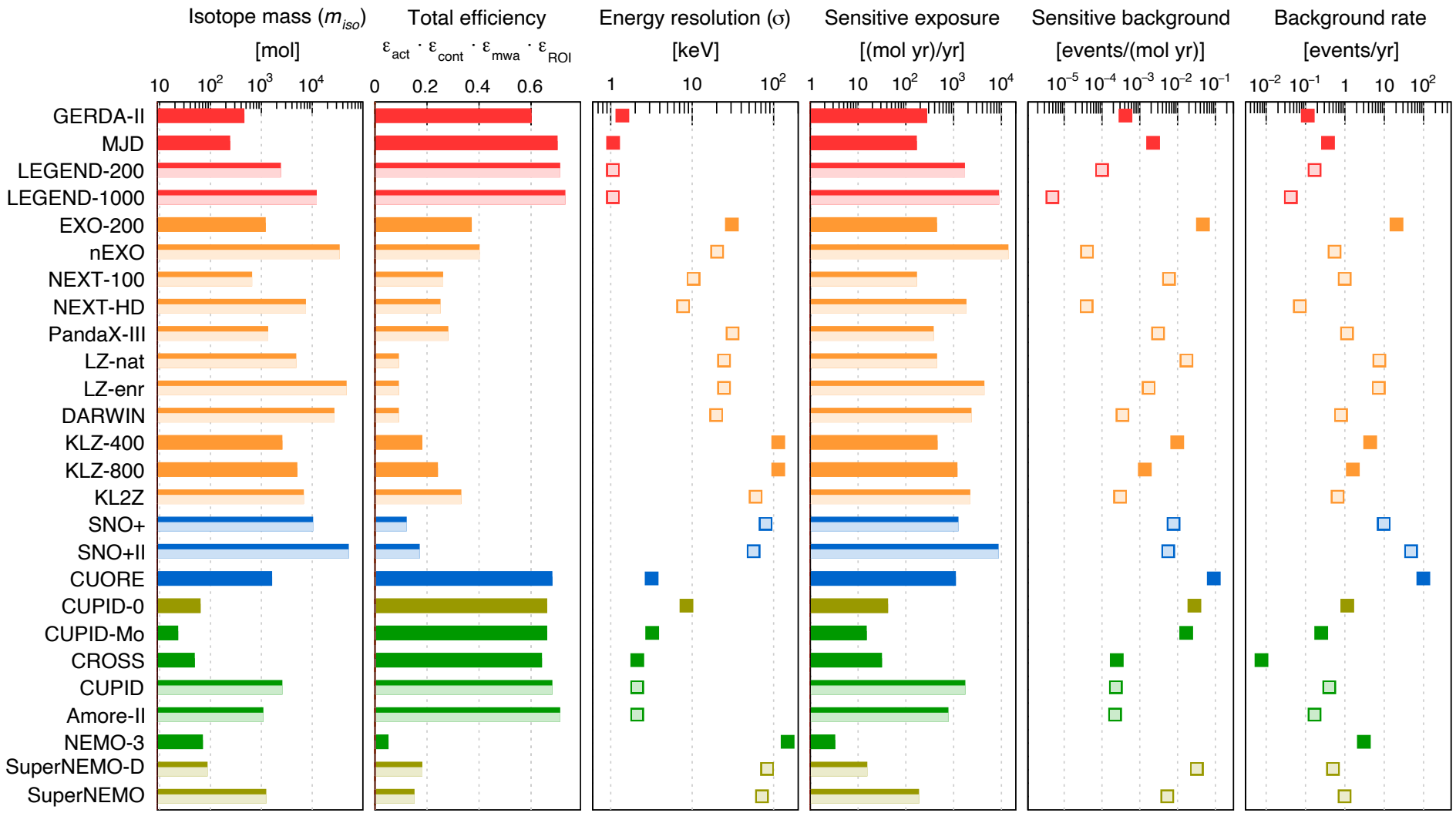
BACKGROUND
Candidate



Comparison of future experiments sensitivities and parameters

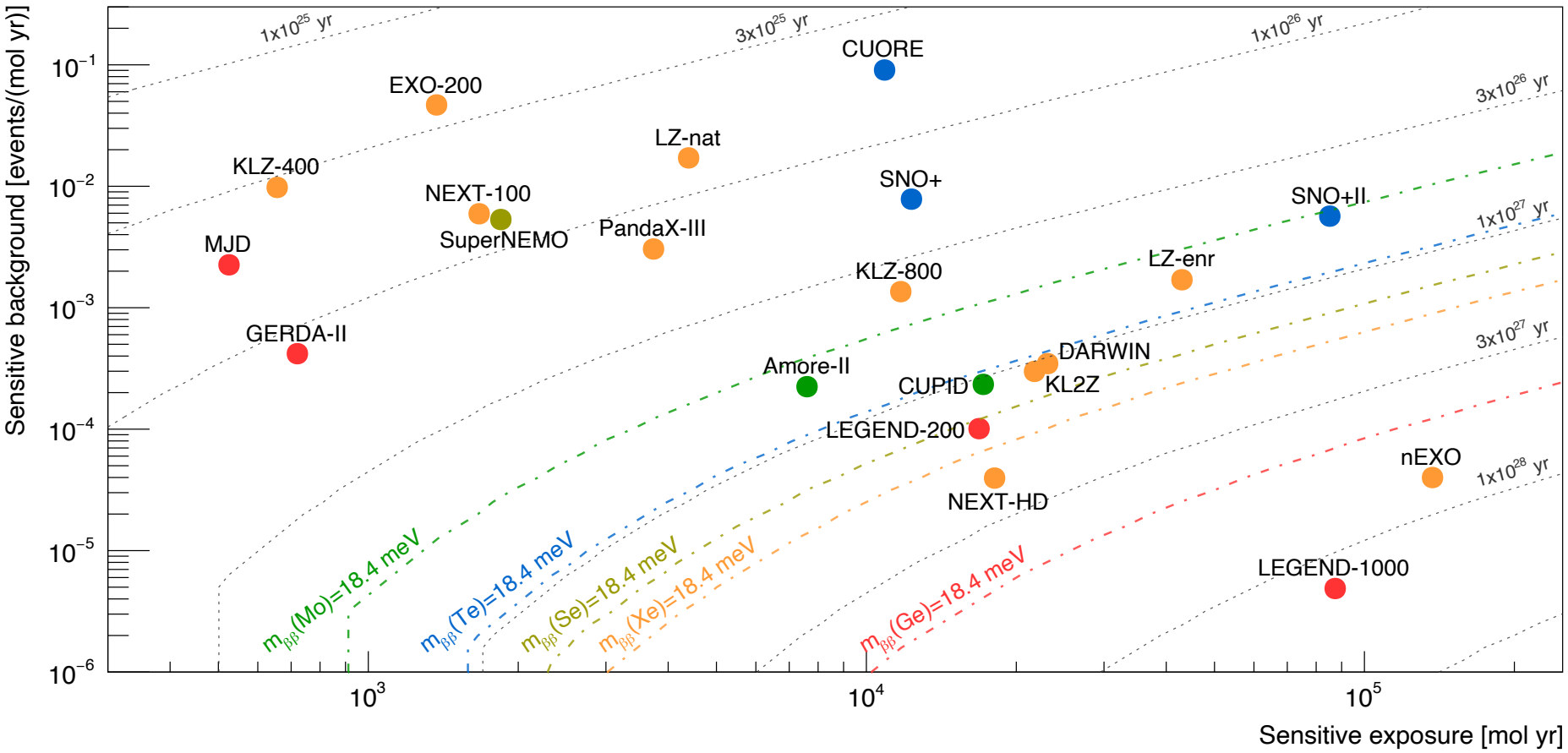
Isotopes / Backgrounds / Exposures

[M. Agostini, et al., arXiv:2202.01787]



Sensitive Backgrounds and Exposures

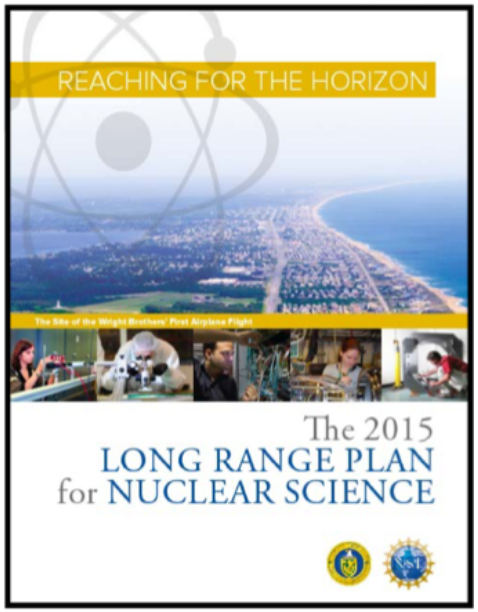
[M. Agostini, et al., arXiv:2202.01787]



A World-wide effort towards double beta decay searches

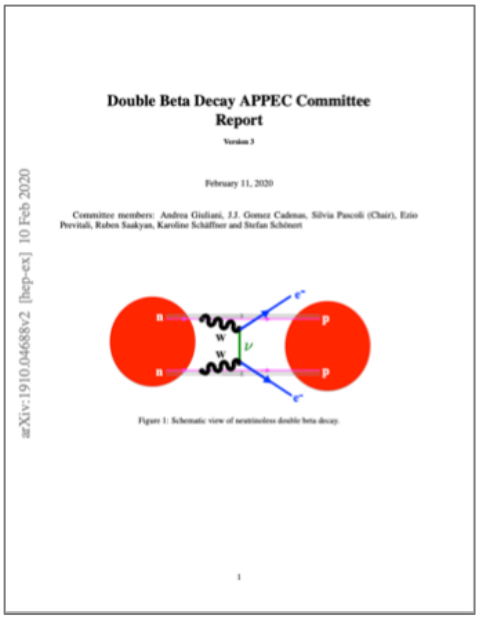
[S. Schoenert, talk at Neutrino 2022]

https://science.osti.gov/np/nsac



"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

https://arxiv.org/abs/1910.04688



- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated extremely positively at the Portfolio review. Now being funded by DOE to move to the next step, CD-1

https://agenda.infn.it/event/27143/

"The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America. "

Summary

- the quest for neutrinoless double beta decay started more than 50 years ago and several techniques have been developed and refined over the decades
- an acceleration towards a ton-scale experiment happened in the last two years
- so far only limits have been set on several isotopes. The most stringent are on: ^{76}Ge, ^{130}Te, and ^{136}Xe
- over the last two years, a down-selection procedure has started in North-Americare and Europe to convergence on a set of experiments contingent on funding: the current competitors are LEGEND-1000, nEXO and CUPID (see S. Schoenert talk at Neutrino 2022)
- several important experiments (and R&D) are planned in Asia as well: KL2Z, Amore, PandaX, and JUNO
- availability / costs of DBD isotopes plays an important role
- but the path to the bottom of the NO band is not clear and looks difficult. The performances and results of the current planned ton-scale experiment will definitely help to set the path