XXI LNF SPRING SCHOOL "Bruno Touschek"
LNF, Frascati, May 13 – 17, 2024

Neutrinoless double-beta decay search: experimental aspects

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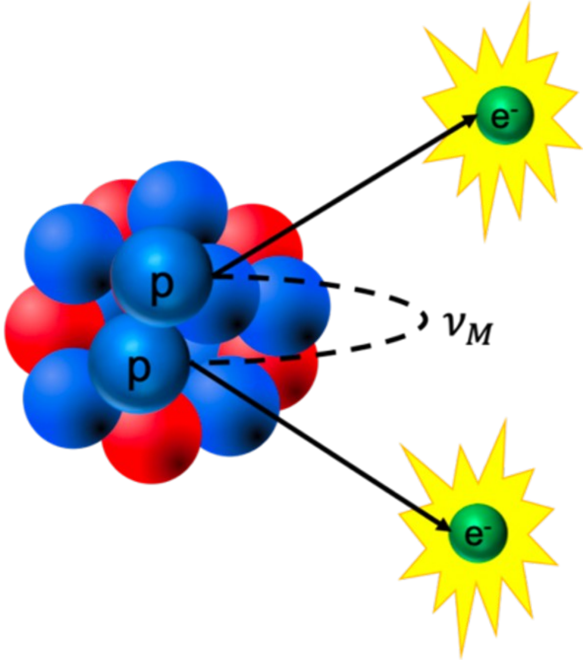
Padova University and INFN

Outline:

- Double Beta Decay
- Experimental approaches
- Present and future projects

Neutrinoless double-beta decay (0νββ)



- The observation of 0νββ would reveal the quantum nature of the neutrino and dramatically revise our fundamental understanding of physics and cosmos

  - Matter creation (Lepton number is not conserved)
  - The neutrino is its own anti-particle (Majorana particle)
  - Provide a mechanism for generating the predominance of matter to antimatter in the cosmos (the matter – antimatter asymmetry)
  - Demonstrates a new means for the generation of mass

The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics

2023 APPEC Mid-Term Update

Neutrino mass and Nature

Recommendation

The new generation of neutrinoless double-beta decay experiments will explore the full inverse mass ordering parameter region with the potential for discovery of the Majorana particle nature of neutrinos and the violation of lepton number. Thus, the discovery of neutrinoless double-beta decay would provide a paradigm change

in the understanding of the fundamental laws, establishing that, contrary to what is predicted by the standard model of particle physics, lepton number is not a conserved symmetry of nature. Europe has a long established leadership in this field and should continue to strongly contribute to this experimental effort, hosting at the very least one of the next-generation experiments, to maintain this position.

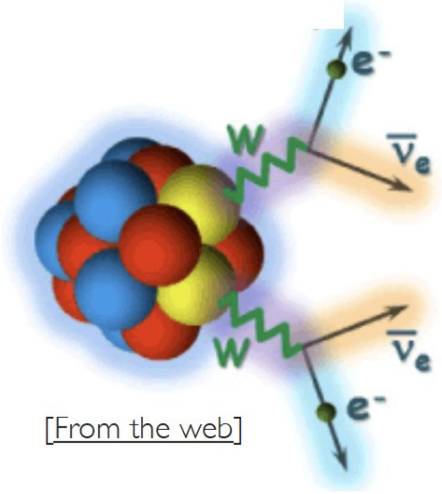
2023 US Long Range Plan

Recommendation 2 (of 4)

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double-beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.

Double-beta decay



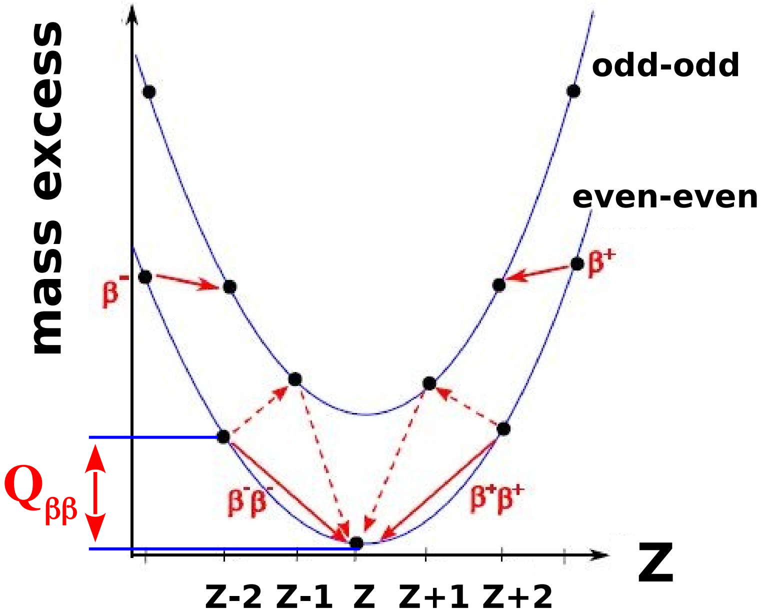
[From the web]

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

- 2nd order process allowed in the SM
- Single β decay forbidden (energy, angular momentum)
- 11 isotopes have been experimentally observed undergoing 2νββ
- $T_{1/2} \sim 10^{19} - 10^{21}$ yrs (the rarest decay ever experimentally seen)

$$\left(T^{2\nu}_{1/2}\right)^{-1} = G_{2\nu}(Q_{\beta\beta},Z)\cdot|M_{2\nu}|^2$$

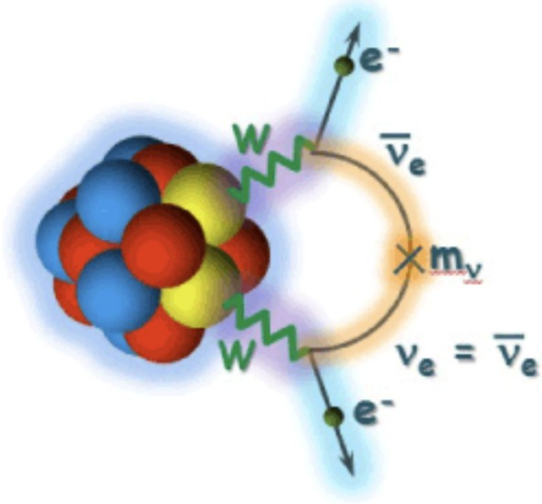
isobaric mass parabolas
A = N + Z = const.

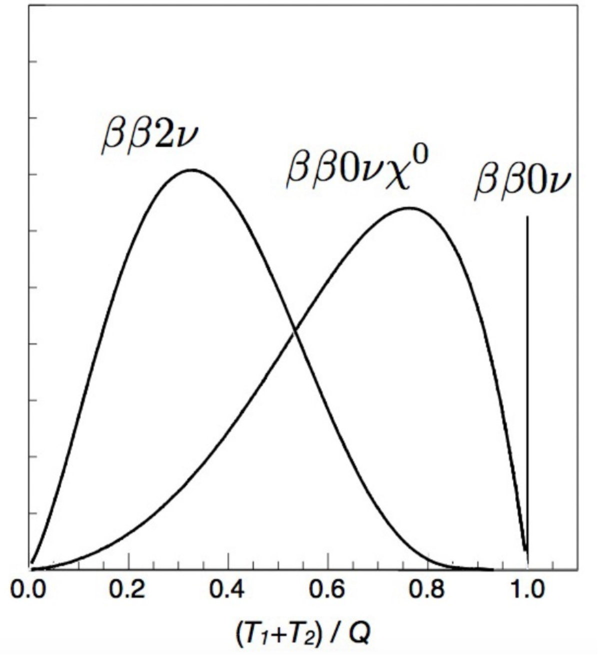


Neutrinoless double-beta decay

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

- Process forbidden in the SM
- Half-life strongly suppressed





$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta},Z)\cdot|M_{0\nu}|^2\cdot\eta^2$$

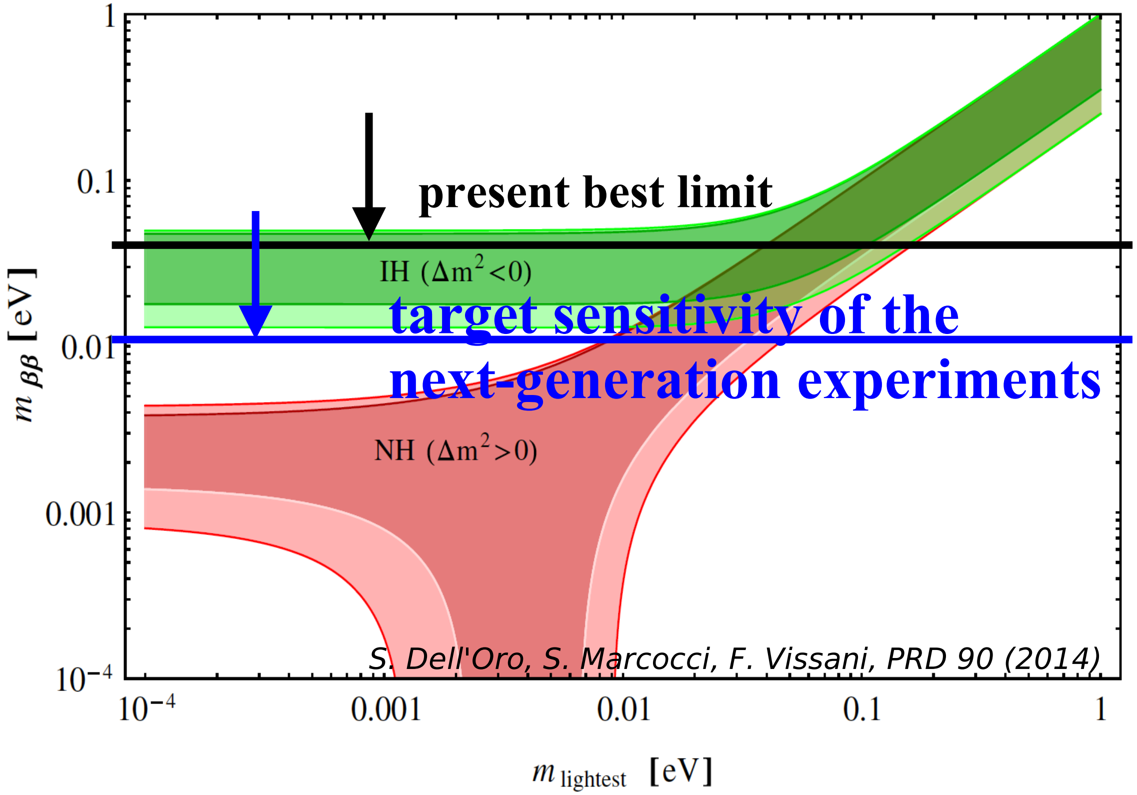
Few different mechanisms may induce 0νββ

- Light Majorana neutrino exchange
- Right-handed current (V+A), Majorons, SUSY, etc.

Different topology in the final state!

$m_{\beta\beta}$ vs. lightest ν mass

deduced from oscillation data and scan of Majorana phases



present best limit

target sensitivity of the next-generation experiments

S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}\left(Q_{\beta\beta}, Z\right)\cdot\left|M_{0\nu}\right|^{2}\cdot\frac{\langle m_{\beta\beta}\rangle^{2}}{m_e^{2}}$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

! Plot applies for 3 generations & light Majorana neutrinos exchange

discovery probability

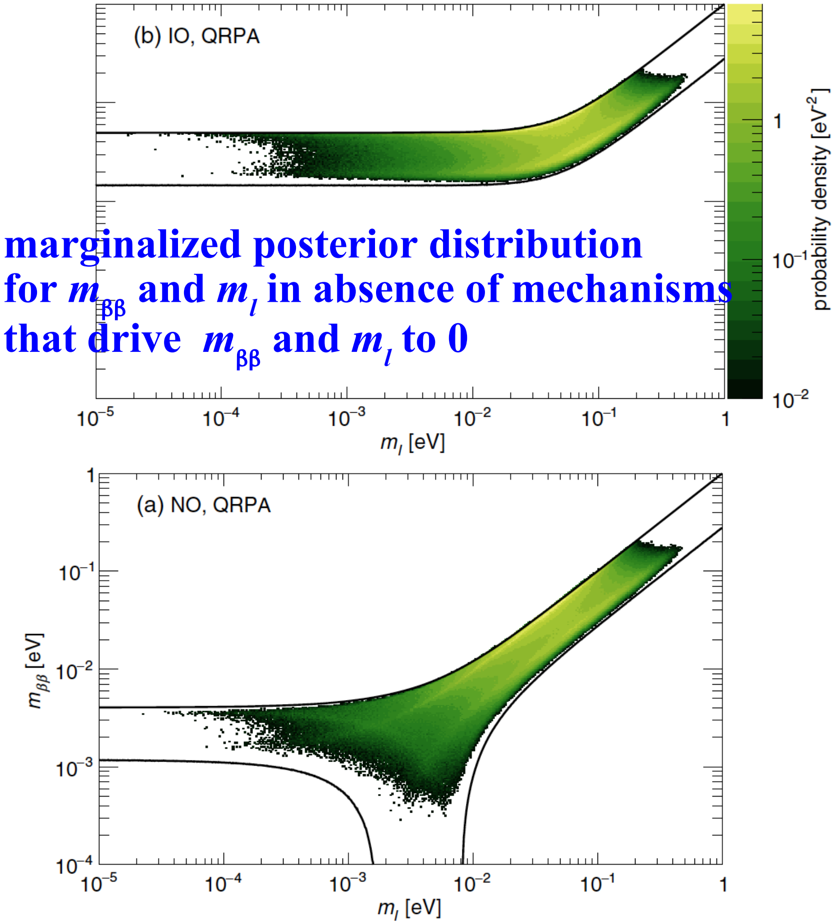
Global Bayesian analysis including ν-oscillation, ββ, β, Σ data

Parameter basis for the global fit:

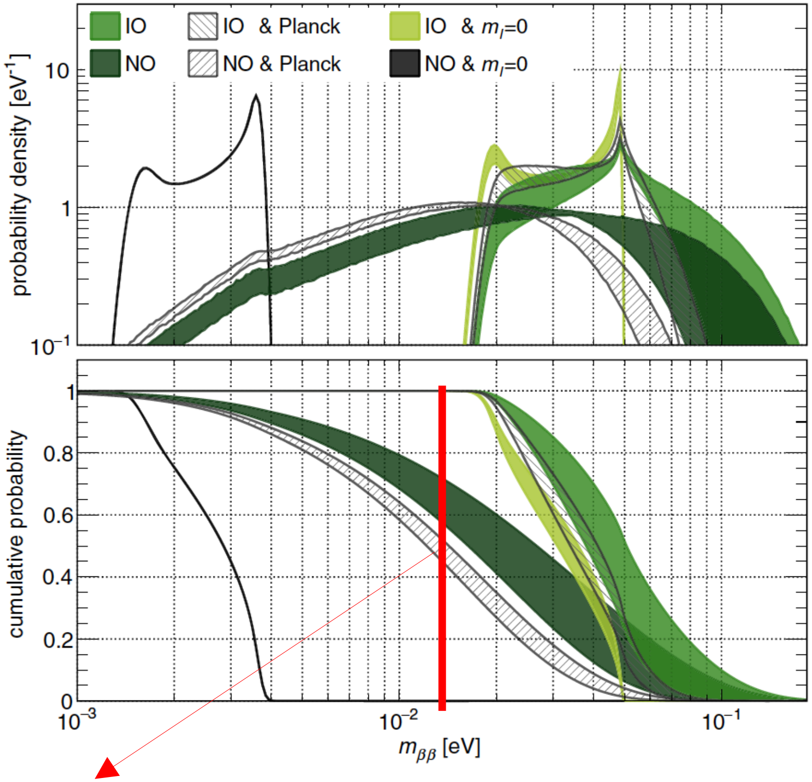
- $\{\Sigma, \Delta m^2_{21}, \Delta m^2_{31}$ or $\Delta m^2_{23}, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31} - \delta)\}$

Priors:

- Majorana phases (flat)
- m_l (scale invariant)



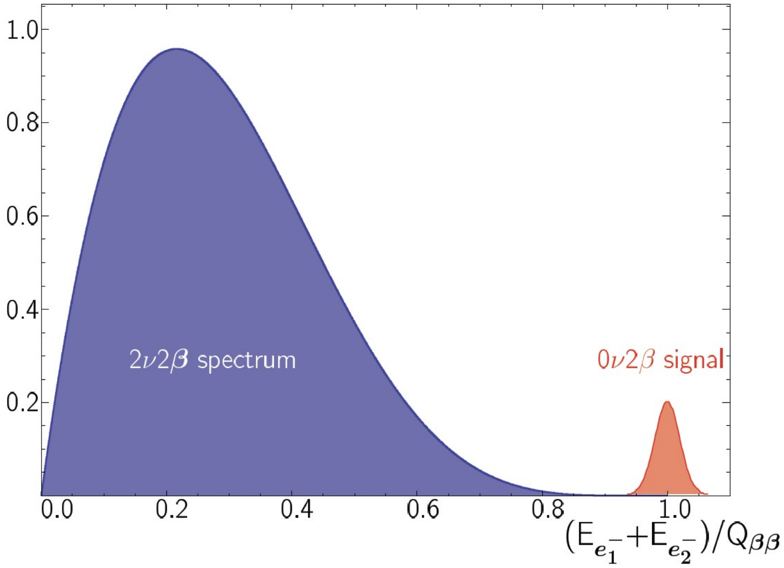
marginalized posterior distribution for $m_{\beta\beta}$ and m_l in absence of mechanisms that drive $m_{\beta\beta}$ and m_l to 0



Sizable probability (~ 50%) also in NO

M. Agostini, G. Benato, J.A. Detwiler, PRD 96 (2017)

0νββ search in practice



Measure the 2 e- energy spectrum

- 2νββ signature → Broad spectrum
- 0νββ signal signature → Peak @ $Q_{\beta\beta}$
- If no signal → set a limit on half-life

- Case with a lot of background @ $Q_{\beta\beta}$

ββ emitter mass

total efficiency

exposure time

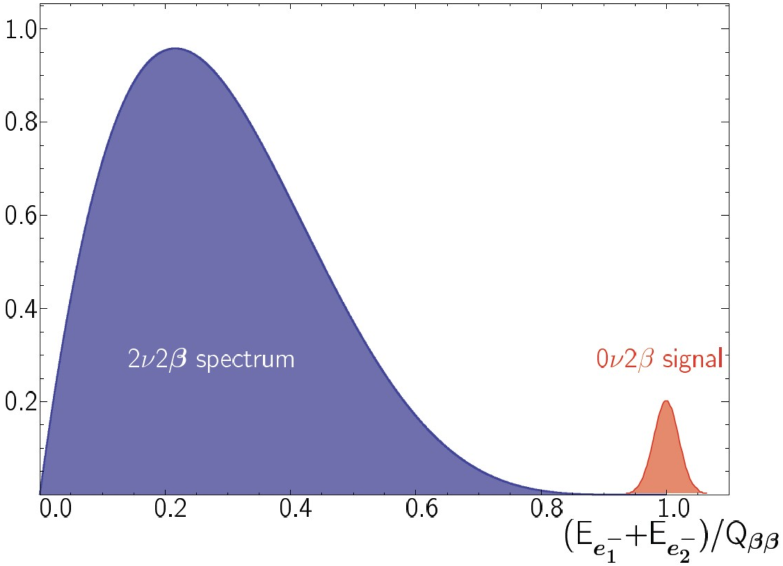
$$T_{1/2}^{0\nu} \propto \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

atomic mass

background index

energy resolution

0νββ search in practice



Measure the 2 e- energy spectrum

- 2νββ signature ⟶ Broad spectrum
- 0νββ signal signature ⟶ Peak @ $Q_{\beta\beta}$
- If no signal ⟶ set a limit on half-life

- Case with no (or almost no) background @ $Q_{\beta\beta}$ realized when:

$$n_B = BI \cdot \Delta E \cdot M \cdot t < 1$$

(for the entire exposure : *M·t*)

then:

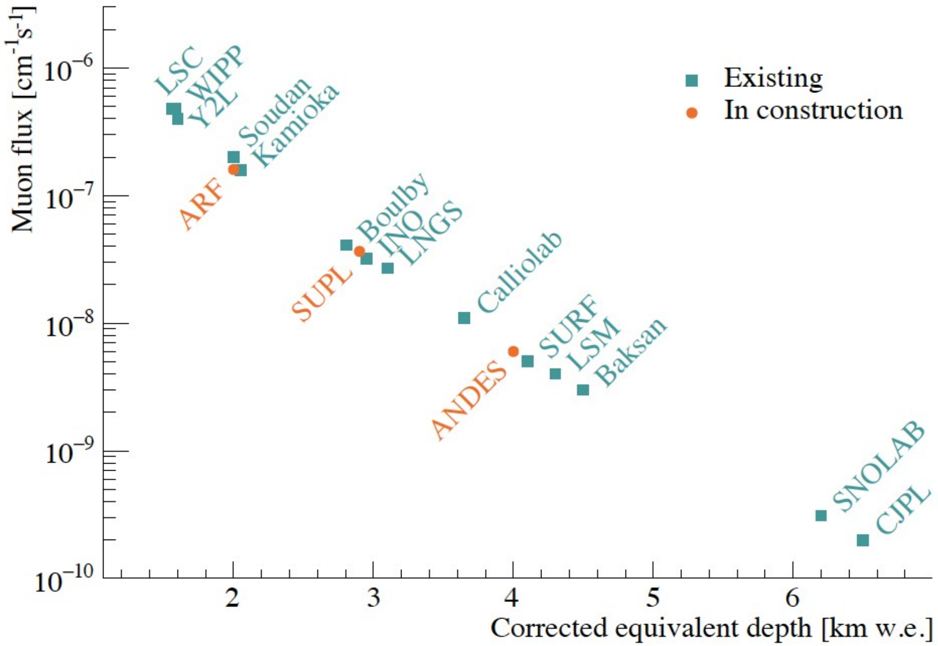
$$T^{0\nu}_{1/2} \propto \frac{\epsilon}{A} \cdot M \cdot t$$

best use of the isotopes mass and time !

Few important aspects … background events

Low energy process ($Q_{\beta\beta} \leq 5$ MeV)

- **Cosmic muons** are an issue

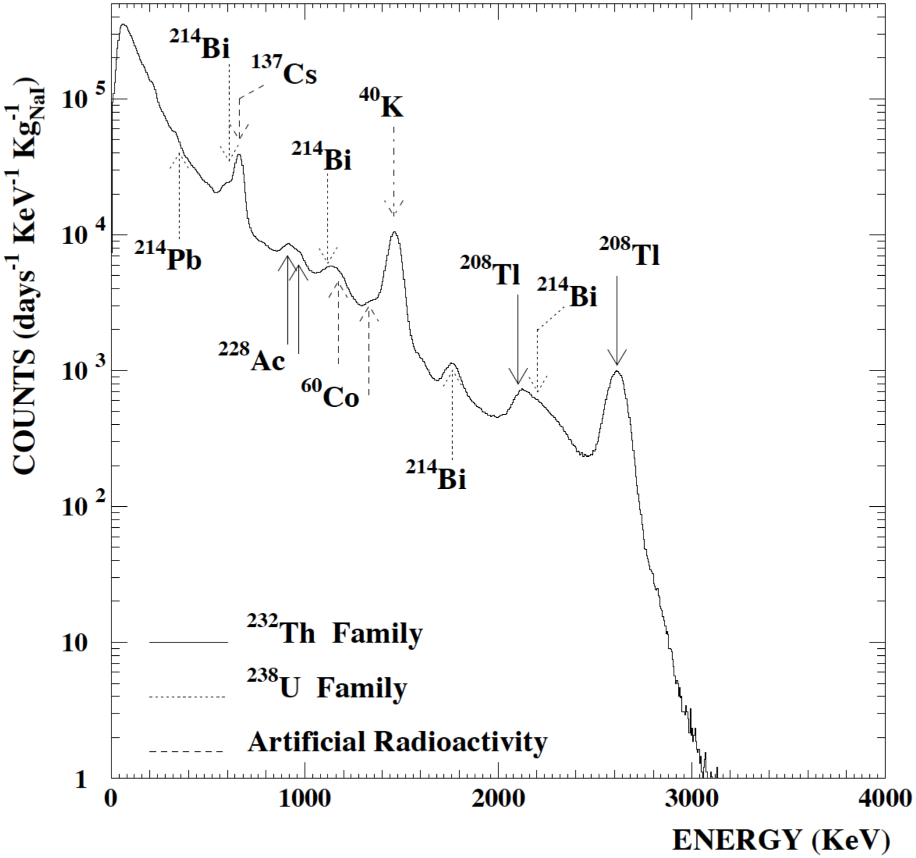


- All 0νββ experiments are placed deep underground
- remaining muons are identified directly in the detector active volume or using specialized detectors
- muon spallation:
  - activation in the experiment material prior to the deployment underground
  - activation in situ
  - muon spallation in the nearby rock can generate energetic neutrons

Few important aspects … background events

Low energy process ($Q_{\beta\beta} \leq 5$ MeV)

- **Natural radioactivity** is an issue
  - due to the production of α, β, γ radiation across a wide energy range
  - production of neutrons through (α, n) reactions



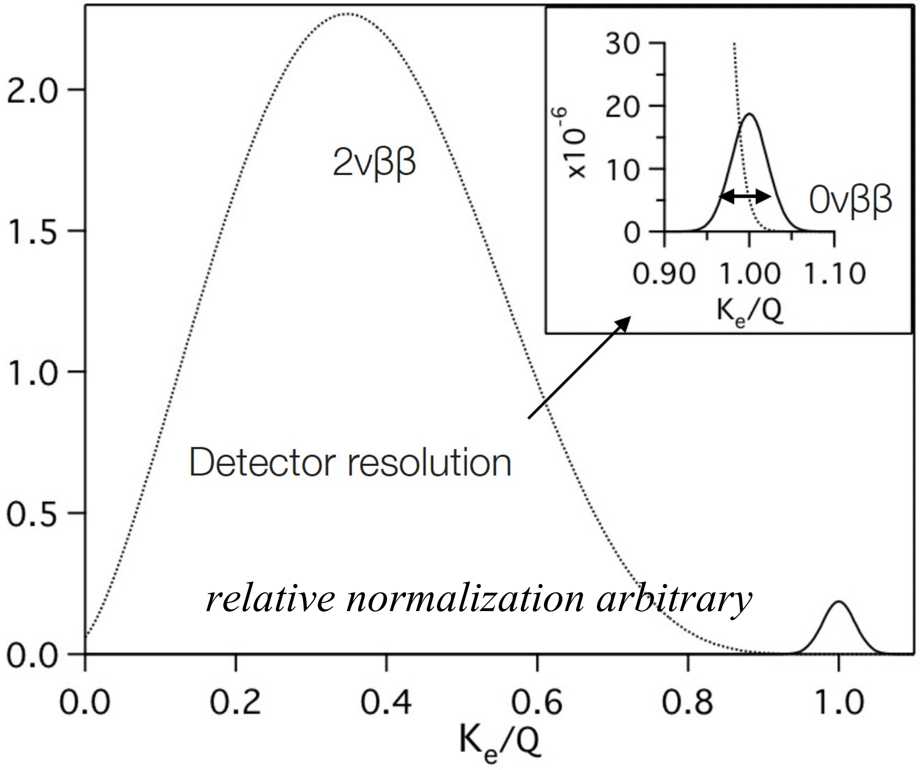
- Special care into the selection, fabrication, purification of material in or near the detector

- Material selection and purity demonstration is performed using assay methods:
  - mass spectrometry
  - γ spectrometry
  - neutron activation analysis
  - α spectrometry

Few important aspects … energy resolution

Distinguish 0ν from 2ν mode ⟶ irreducible background

- **Good energy resolution**

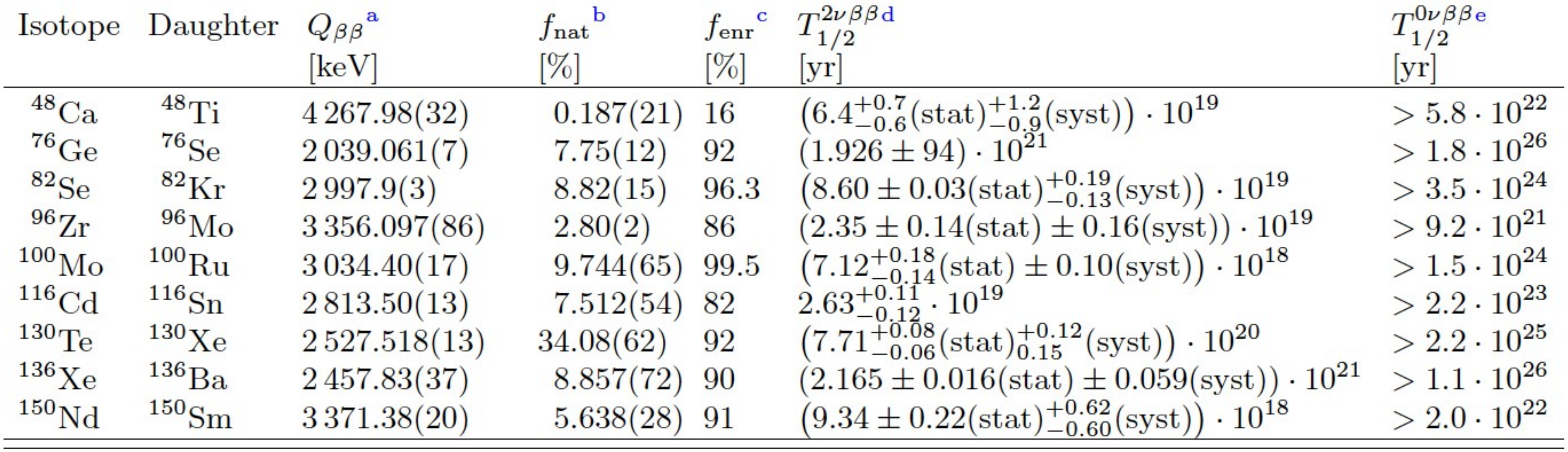


- Measurement of the sum electron energy is a **necessary condition for discovery**

- In high-resolution experiment free of other background sources, it is also a **sufficient condition for discovery**

Few important aspects … choice of the isotope

M. Agostini, et al. Rev. of Mod. Phys. 95 025002 (2023)



Isotope	Daughter	$Q_{\beta\beta}$[a] [keV]	f_{nat}[b] [%]	f_{enr}[c] [%]	$T_{1/2}^{2\nu\beta\beta}$[d] [yr]	$T_{1/2}^{0\nu\beta\beta}$[e] [yr]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16	$(6.4^{+0.7}_{-0.6}(\text{stat})^{+1.2}_{-0.9}(\text{syst}))\cdot 10^{19}$	$> 5.8\cdot 10^{22}$
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92	$(1.926\pm 94)\cdot 10^{21}$	$> 1.8\cdot 10^{26}$
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3	$(8.60\pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst}))\cdot 10^{19}$	$> 3.5\cdot 10^{24}$
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86	$(2.35\pm 0.14(\text{stat})\pm 0.16(\text{syst}))\cdot 10^{19}$	$> 9.2\cdot 10^{21}$
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5	$(7.12^{+0.18}_{-0.14}(\text{stat})\pm 0.10(\text{syst}))\cdot 10^{18}$	$> 1.5\cdot 10^{24}$
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82	$2.63^{+0.11}_{-0.12}\cdot 10^{19}$	$> 2.2\cdot 10^{23}$
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92	$(7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst}))\cdot 10^{20}$	$> 2.2\cdot 10^{25}$
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90	$(2.165\pm 0.016(\text{stat})\pm 0.059(\text{syst}))\cdot 10^{21}$	$> 1.1\cdot 10^{26}$
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91	$(9.34\pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst}))\cdot 10^{18}$	$> 2.0\cdot 10^{22}$

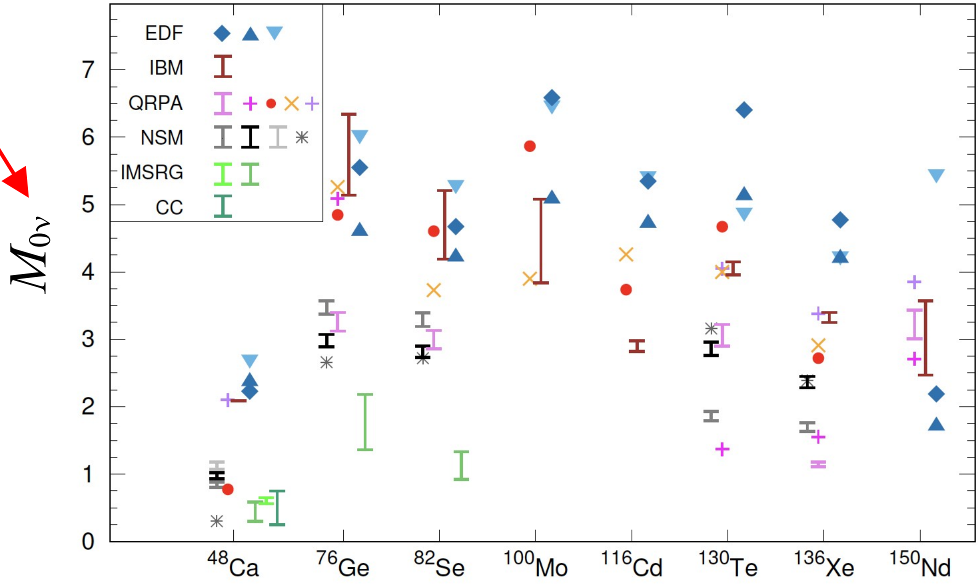
- List of key isotopes meeting the following criteria:
  - readily available at the level of thousands moles or more (enrichment drives the total cost for the material)
  - with a high Q-value (at least above 2 MeV)
  - large decay rate (it scales as $Q_{\beta\beta}^5$ for light neutrino exchange)
  - compatible with existing detection technologies

- **No isotope significantly preferred when comparing decay rate per mass**
  Choice mainly driven by experimental considerations

Few important aspects … nuclear matrix elements

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \cdot \boxed{|M_{0\nu}|^2} \cdot \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

- Contain nuclear structure effects
- Many approximation methods
- Different among isotopes
- Measuring NME in 2νββ does not help



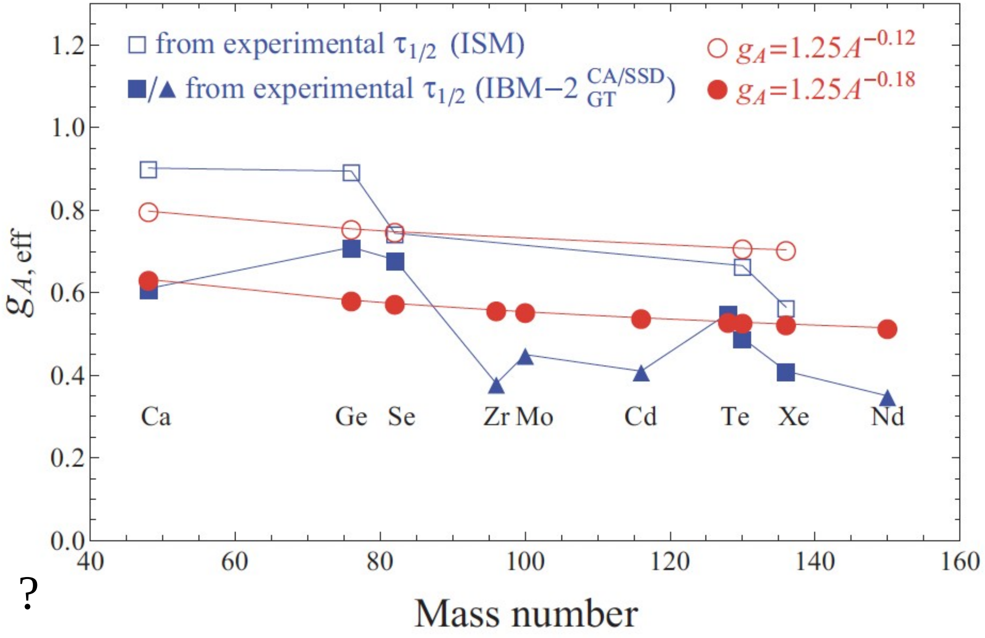
M. Agostini, et al. Rev. of Mod. Phys. 95 025002 (2023)

- Main limitation in interpreting results and comparing among different isotopes

Few important aspects … axial coupling constant

- $|M_{0\nu}| = |g_A^2 \cdot M'_{0\nu}| = |(1.27)^2 \cdot M'_{0\nu}|$
- g_A is known to be quenched in β and in ββ decay
- an effective constant is extracted from experimental measurement
- Quenching factor ~0.8-0.5
- g_A quenched in 0νββ as much as in 2νββ ?
- Recent ab-initio calculations that reproduces β decays without any "g_A quenching" pave the way to solve this puzzle

J. Barea, J. Kotila, F. Iachello, PRC 87 014315 (2013)



techniques and experiments

			NOW / MID-TERM	LONG-TERM
Scalability	Source = detector Fluid embedded source	**Xe-based TPC**	EXO-200	nEXO
			NEXT-White, NEXT-100	NEXT-HD
			PandaX-III	PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800	KamLAND2-Zen
			SNO+ phase I	SNO+ phase II
Good ΔE and efficiency	Source = detector Crystal embedded source	**Germanium diodes**	GERDA-II	
			LEGEND-200	LEGEND-1000
			MJD	
		Bolometers	AMoRE I	AMoRE II
			CUORE	
			CUPID-0	CUPID
			CUPID-Mo	
	Source ≠ detector	**Tracking**	SuperNemo Demonstrator	SuperNemo

from Giuliani's talk at Neutrino 2018

techniques and experiments

NOW / MID-TERM

LONG-TERM

Source = detector

Xe-based TPC

EXO-200

NEXT-White, NEXT-100

nEXO

NEXT-HD

PandaX-III 1t

Fluid embedded

800

KamLAND2-Zen

SNO+ phase II

LEGEND-1000

AMoRE II

Bolometers

CUPID-0
CUPID-Mo

CUPID

Source ≠ detector

Tracking

SuperNemo Demonstrator

SuperNemo

lity

Good

eff

These experiments aim to explore deeply or fully the IO region and to cover a substantial part of the NO region

$$T_{1/2} > 10^{27} - 10^{28}\ \text{yr} - m_{\beta\beta} <\sim 20\ \text{meV}$$

from Giuliani's talk at Neutrino 2018

techniques and experiments

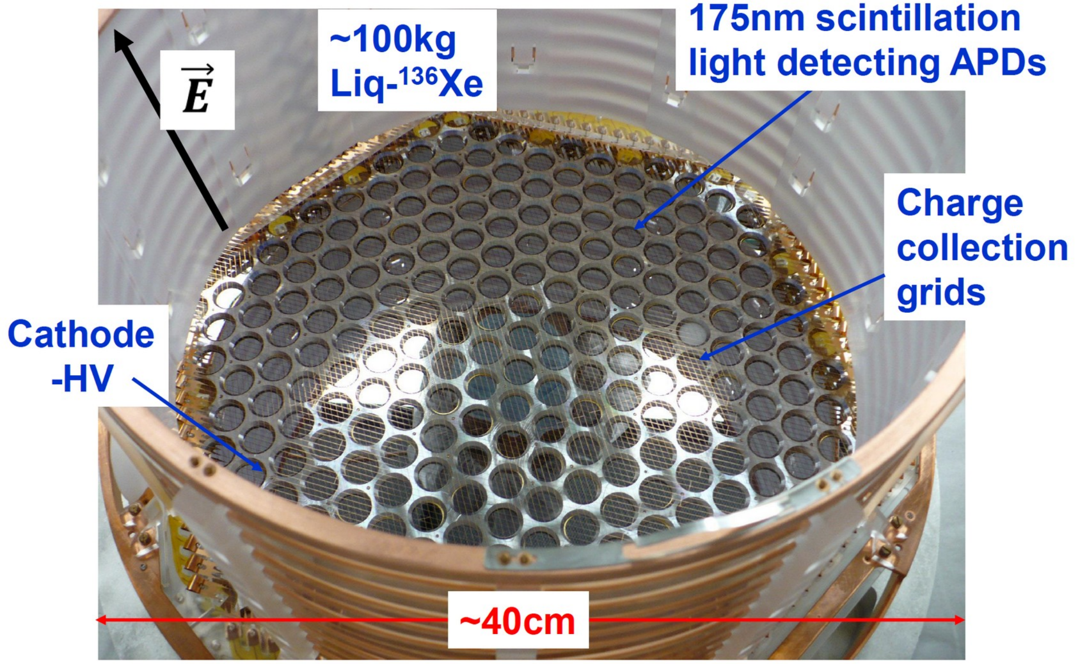
			NOW / MID-TERM	LONG-TERM
Scalability	Source = detector Fluid embedded source	**Xe-based TPC**	**EXO-200** **NEXT-White, NEXT-100** **PandaX-III**	**nEXO** **NEXT-HD** **PandaX-III 1t**
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I	KamLAND2-Zen SNO+ phase II
Good ΔE and efficiency	Source = detector Crystal embedded source	Germanium diodes	GERDA-II LEGEND-200 MJD	LEGEND-1000
		Bolometers	AMoRE I CUORE CUPID-0 CUPID-Mo	AMoRE II CUPID
	Source ≠ detector	Tracking	SuperNemo Demonstrator	SuperNemo

from Giuliani's talk at Neutrino 2018

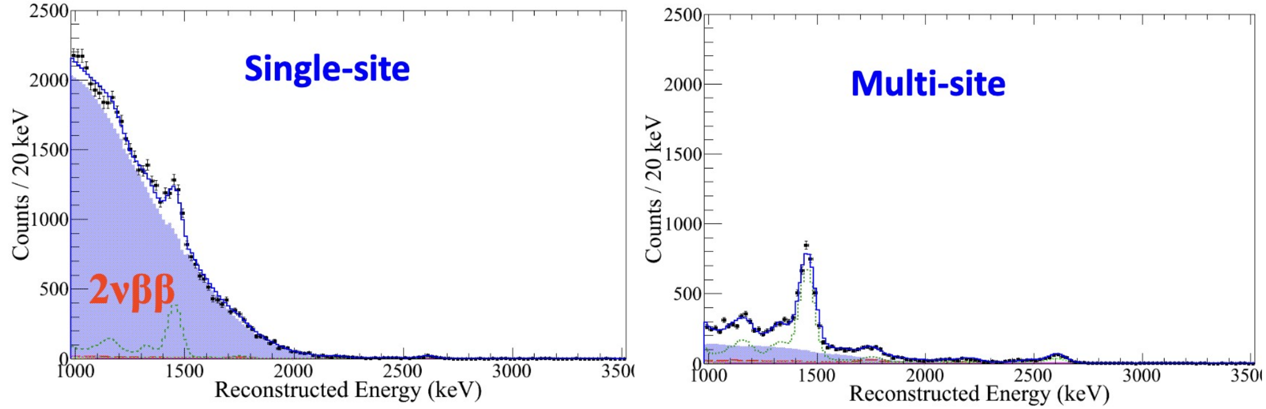
EXO-200

^{136}Xe

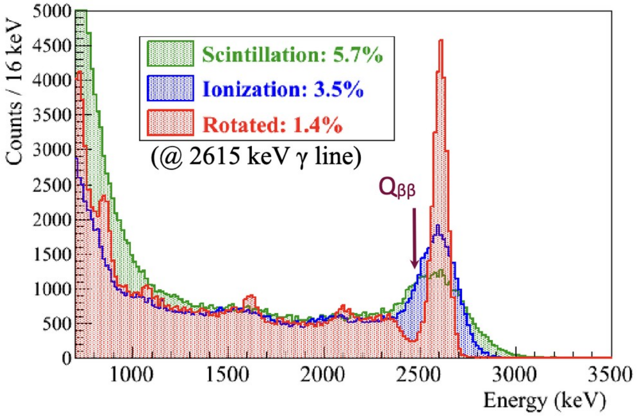
- operating at WIPP, Carlsbad, NM (USA), 1624 m.w.e.
- cylindrical single phase TPC filled with 200 kg of liquid Xe enriched to 80.6% in **^{136}Xe**



topology of the events

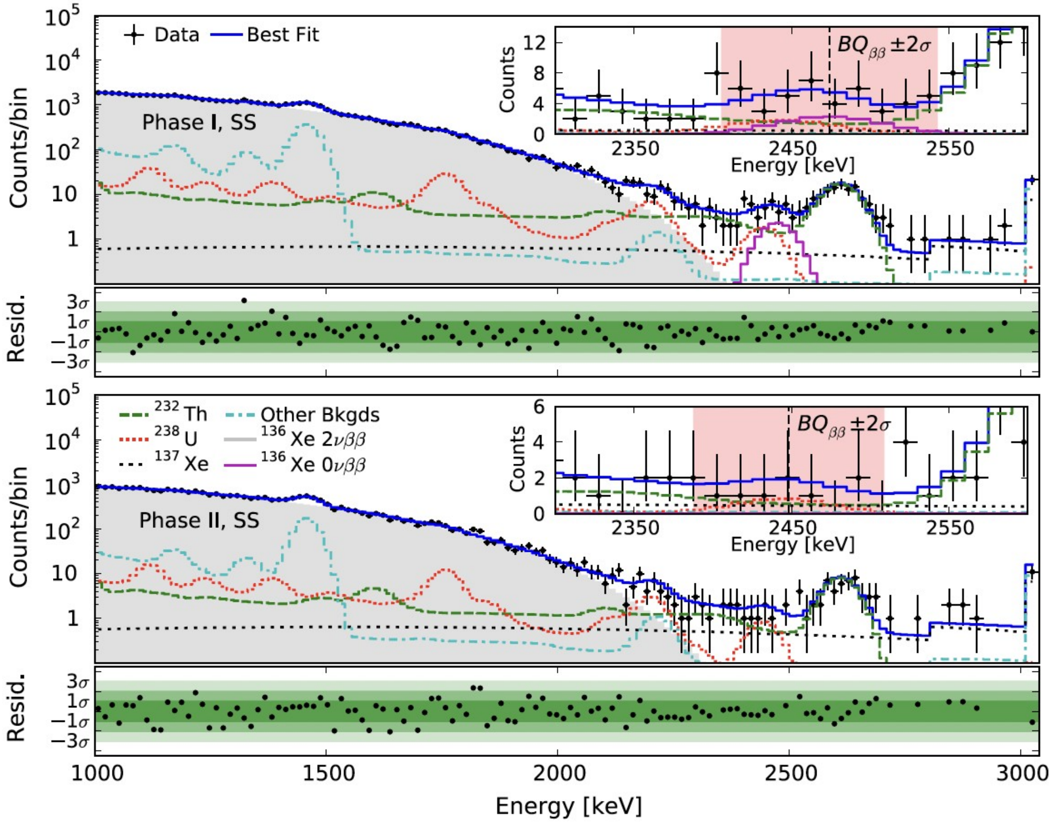


scintillation + ionization to improve E resolution and reject part of the background



EXO-200

^{136}Xe



J.B. Albert, et al. PRL 120, 072701 (2018)

- ➢Exposure: 177.6 kg·yr
- ➢ FWHM($Q_{\beta\beta}$= 2458 keV) = 71 keV
- ➢ BI: (1.5 ± 0.3)·10^{-3} cts/(keV·kg·yr)
- ➢Lower limit:

  $T^{0\nu}_{1/2}$ > 1.8·10^{25} yr (90% CL)
- ➢Median sensitivity: **3.7·10^{25} yr**
- ➢***$m_{\beta\beta}$* < 147 - 398 meV**

completed data taking end 2018

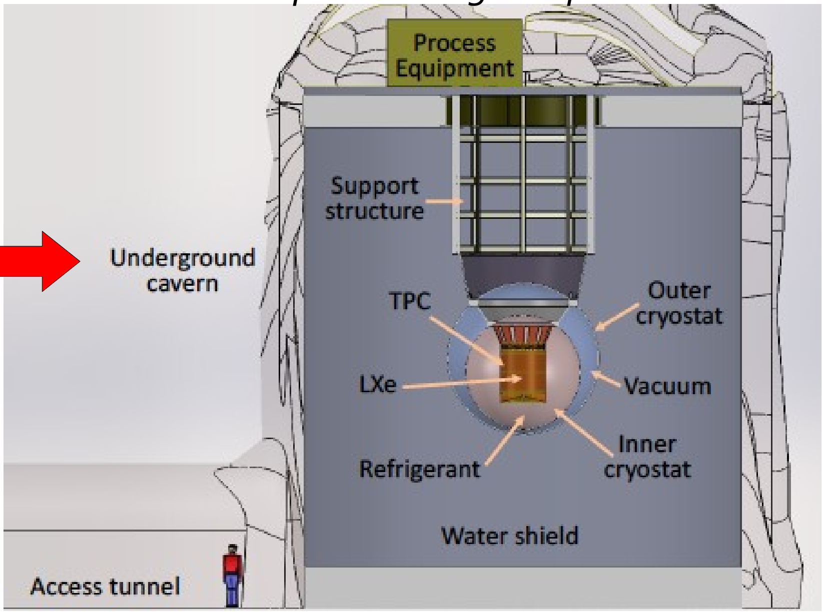
EXO-200 → nEXO

^{136}Xe

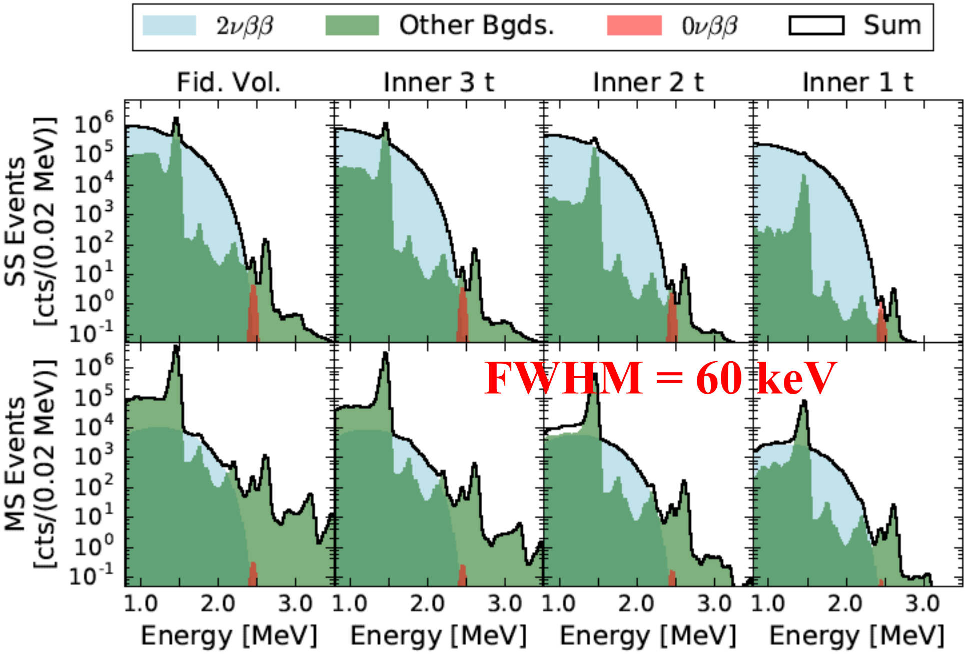
Moving forward towards nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130 ~ nEXO
150	40 ~ EXO-200
5	13

nEXO Pre-Conceptual Design Report

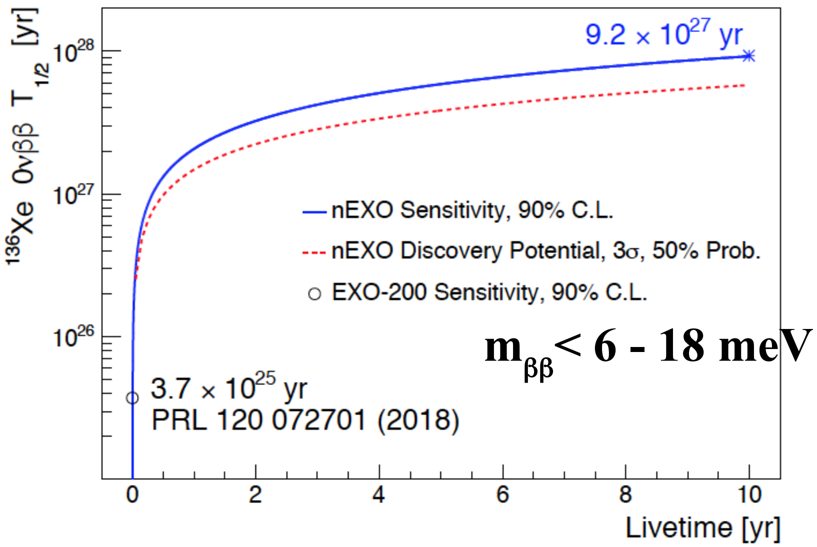


Importance of fiducialization



FWHM = 60 keV

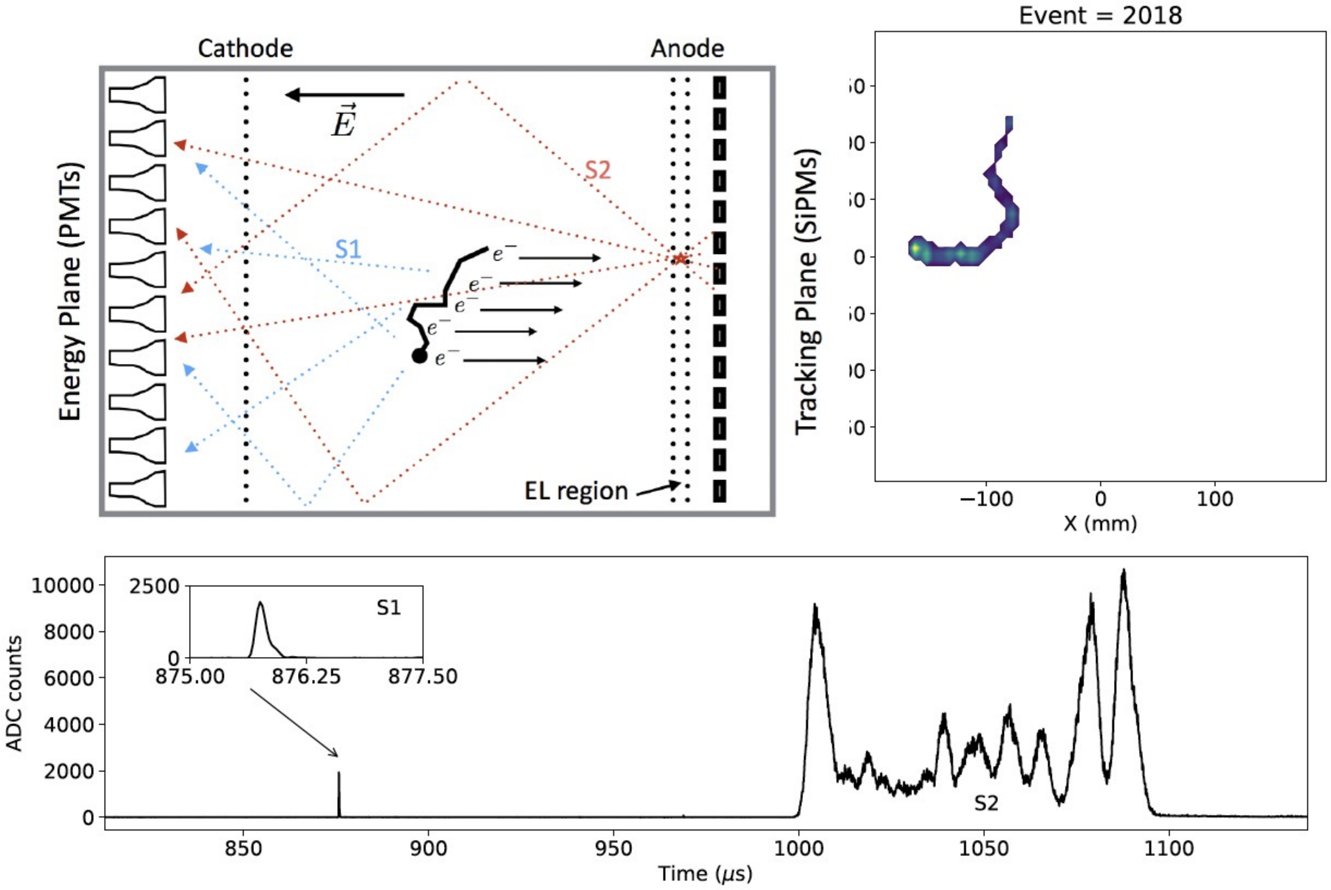
Projected nEXO sensitivity



$m_{\beta\beta} < 6 - 18$ meV

NEXT

^{136}Xe



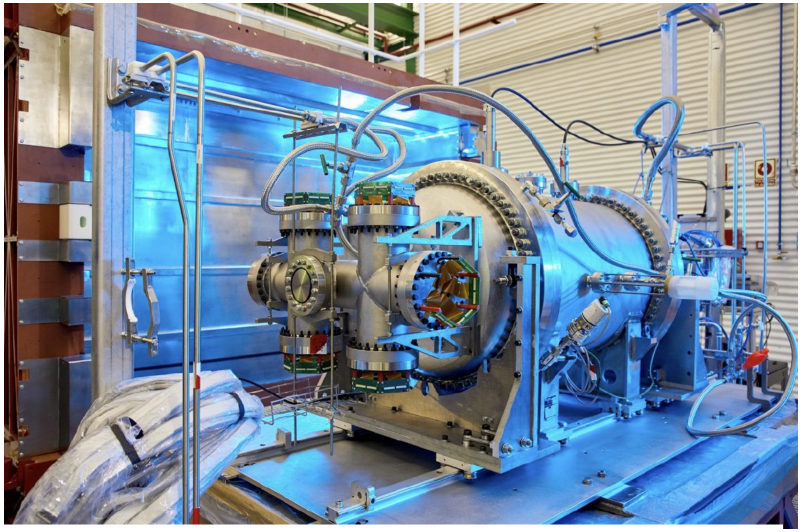
J. Renner, et al. JINST 13, P10020 (2018)

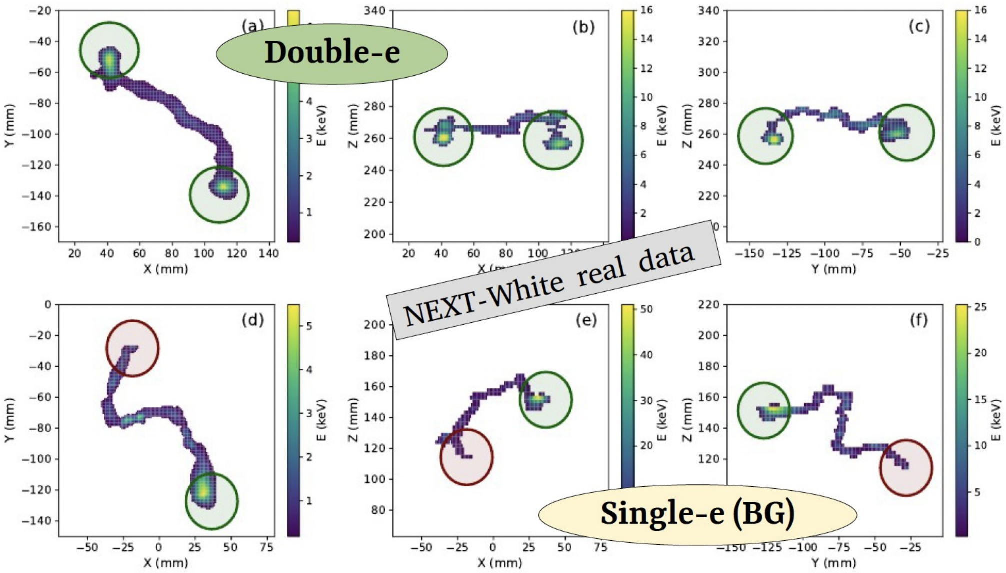
High pressure (10-15 bar) ^{enr}Xe TPC

- primary scintillation ($t_0 \longrightarrow z$ coordinate)
- electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane)
- ΔE_{FWHM} < 1% FWHM in the ROI (< 25 keV)
- Topological signature: reconstruction of electrons in events

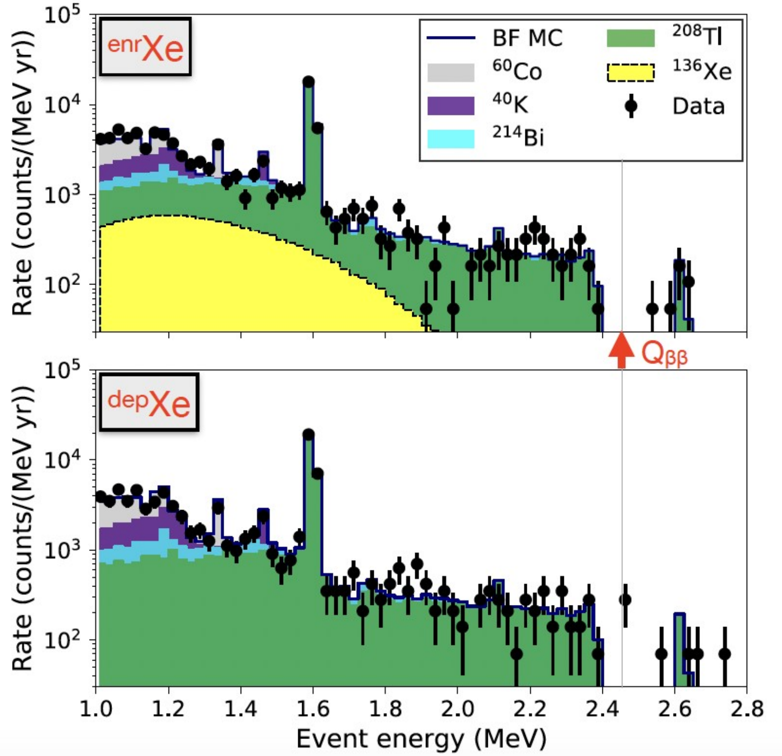
NEXT

^{136}Xe





P. Novella, et al. JHEP 09, 190 (2023)

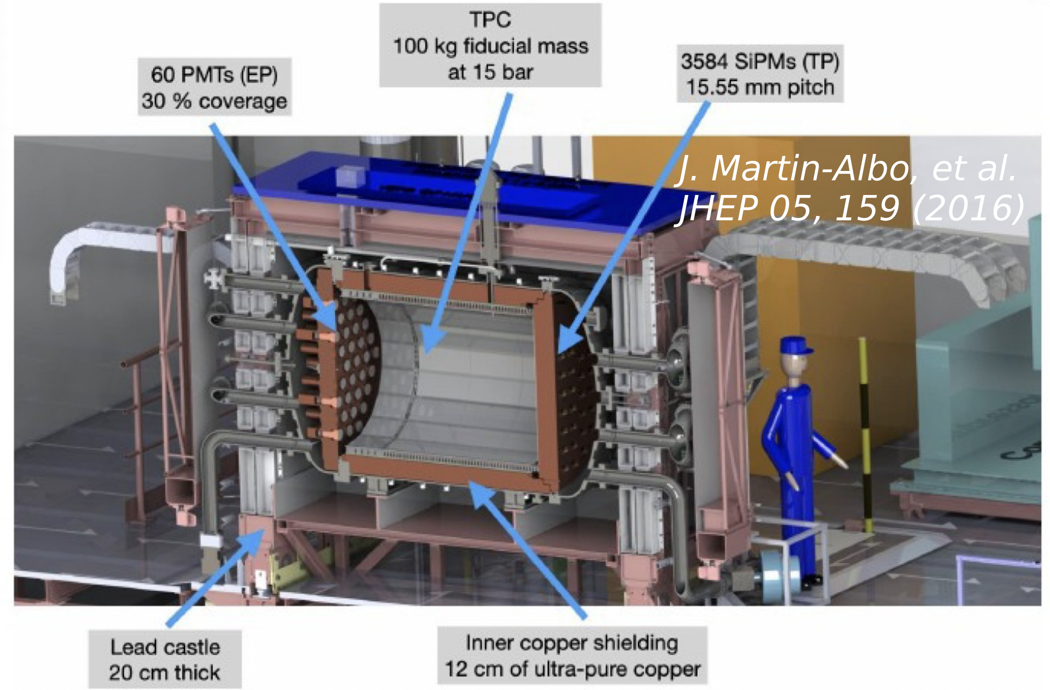


NEXT-White

- ~5 kg active region
- stable operation from 2016-2021
- ββ ⟶ ^{136}Xe-enriched and ^{136}Xe-depleted data
- $T^{2\nu}_{1/2} = 2.34^{+0.85}_{-0.49} \cdot 10^{21}$ yr
- Lower limit: $T^{0\nu}_{1/2} > 1.3 \cdot 10^{24}$ yr (90% CL)
- $m_{\beta\beta} < 480 - 2070$ meV

NEXT

^{136}Xe



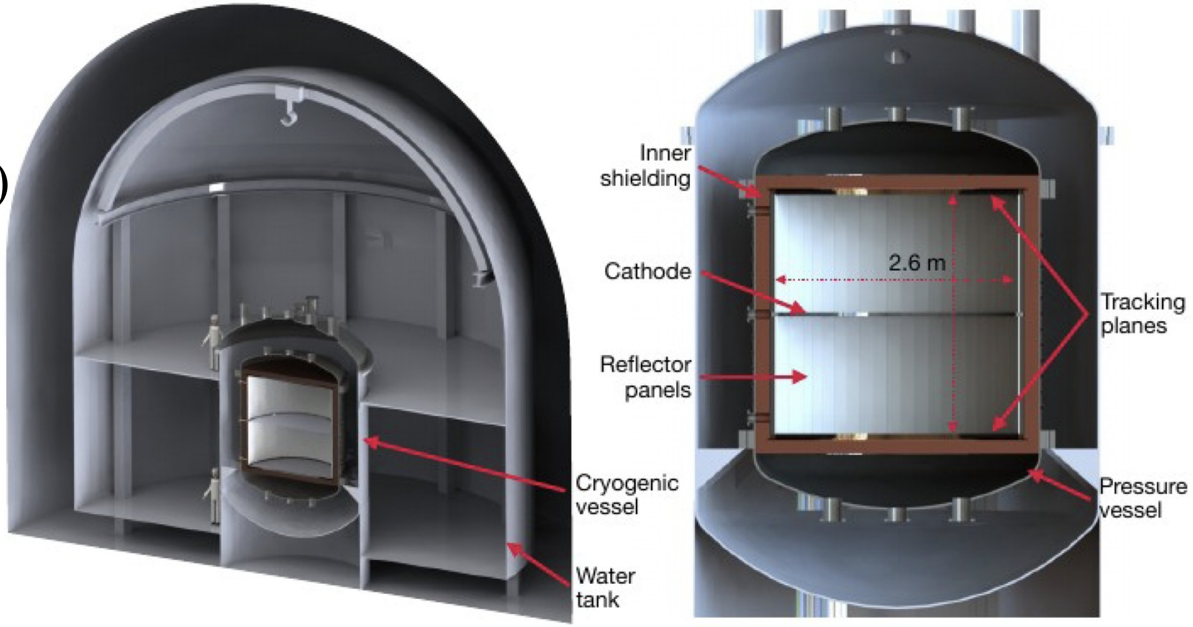
J. Martin-Albo, et al. JHEP 05, 159 (2016)

NEXT 100 at Canfranc (Spain)

- ◆ mass: 100 kg
- ◆ detector being installed: 2022-2023
- ◆ BI: $5 \cdot 10^{-4}$ cts/(keV·kg·yr)
- ◆ Sensitivity:
  $\mathbf{T_{1/2} > 9.8 \cdot 10^{25}}$ **yr** after 5 years
- ◆ $\boldsymbol{m_{\beta\beta} < 46 - 170}$ **meV**

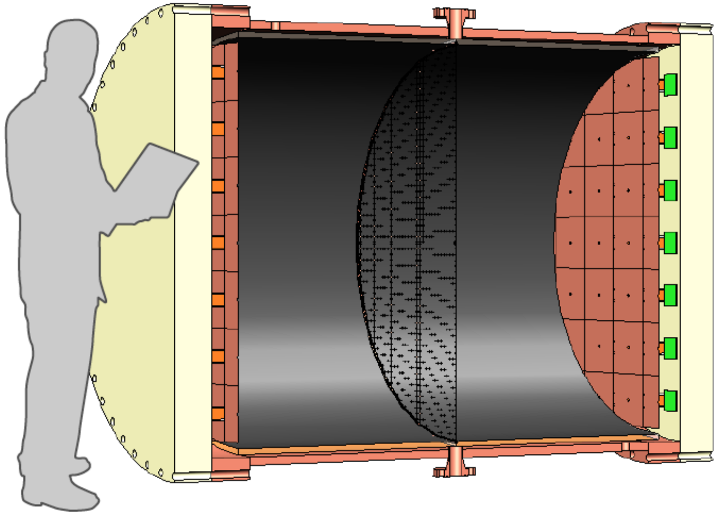
NEXT HD

- ◆ mass: $> 10^{3}$ kg
- ◆ BI: 0.09-0.27 cts/(keV·t·ROI)
- ◆ Sensitivity: $\mathbf{T_{1/2} > 1.5 \cdot 10^{27}}$ **yr**
  after 5 years
- ◆ if **Ba tagging:**
  $^{136}\mathrm{Xe} \longrightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-} (+2\bar{\nu}_e)$
  experiment background free

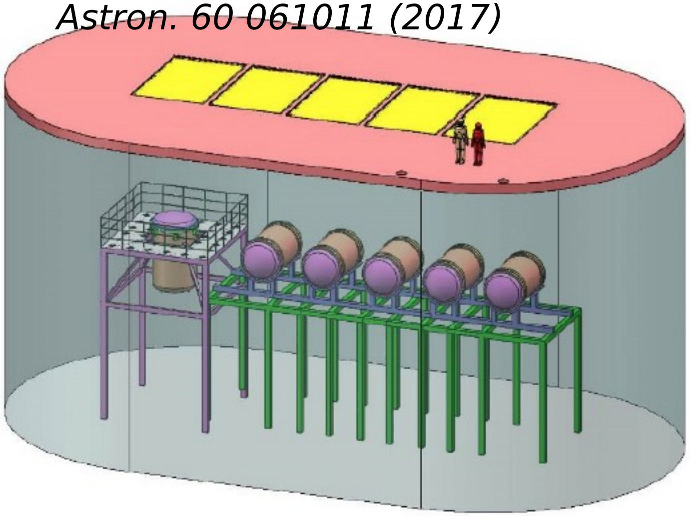


PandaX-III

^{136}Xe



Chen X, et al. Sci. China Phys. Mech. Astron. 60 061011 (2017)



First 200-kg module

- at JINPING (China)
- Xe-gas-TPC
- Microbulk Micromegas for charge readout
- 3% FWHM
- **BI: 10^{-4} cts/(keV·kg·yr) in the ROI**
- Sensitivity: **$T_{1/2} > 10^{26}$ yr after 3 yrs**
- **$m_{\beta\beta} < 65 - 165$ meV**

Ton-scale

- 4 more modules with upgraded charge readout and better low-background material screening
- 1% FWHM
- **BI: 10^{-5} cts/(keV·kg·yr) in the ROI**
- Sensitivity: **$T_{1/2} > 10^{27}$ yr after 3 yrs**
- **$m_{\beta\beta} < 20 - 50$ meV**

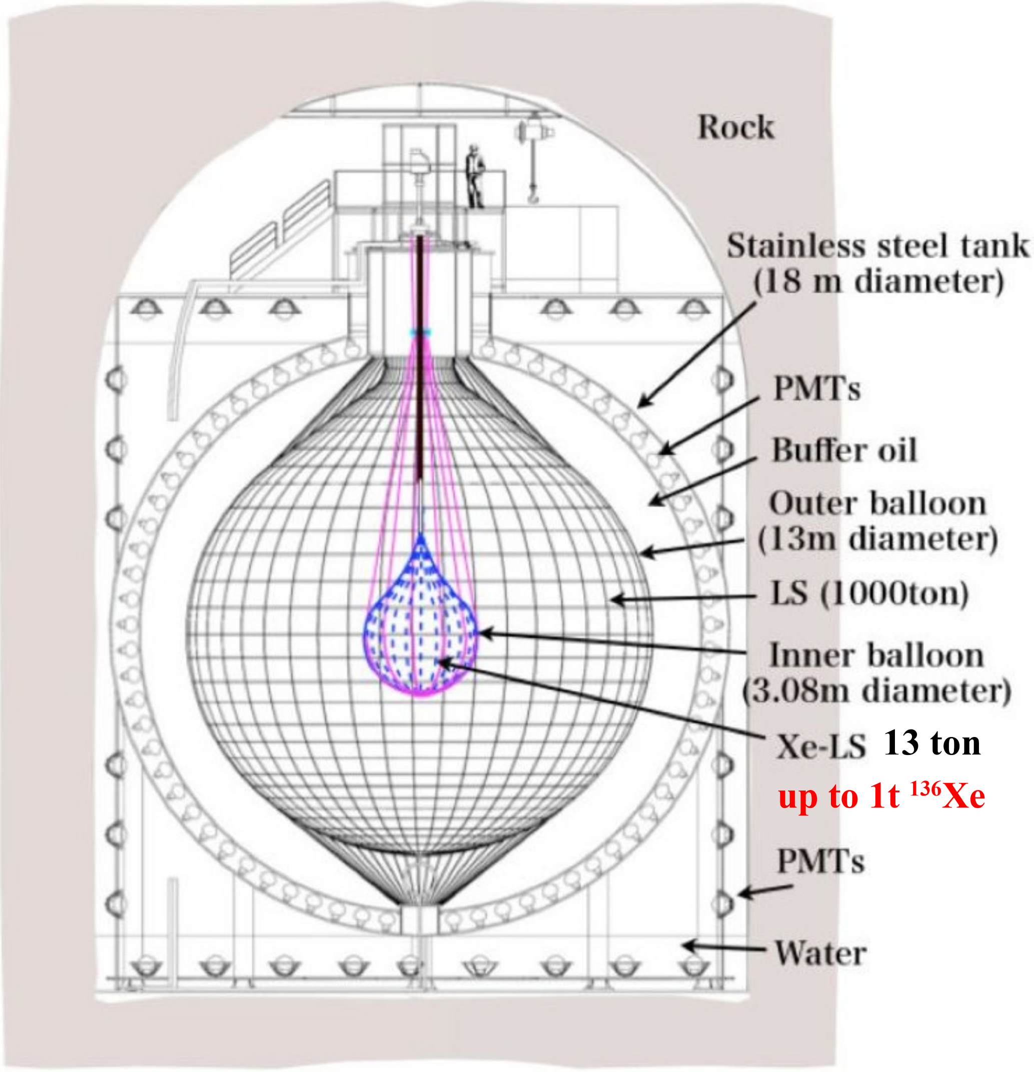
techniques and experiments

			NOW / MID-TERM	LONG-TERM
Scalability	Source = detector Fluid embedded source	Xe-based TPC	EXO-200	nEXO
			NEXT-White, NEXT-100	NEXT-HD
			PandaX-III	PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800	KamLAND2-Zen
			SNO+ phase I	SNO+ phase II
Good ΔE and efficiency	Source = detector Crystal embedded source	Germanium diodes	GERDA-II	
			LEGEND-200	LEGEND-1000
			MJD	
		Bolometers	AMoRE I	AMoRE II
			CUORE	
			CUPID-0 CUPID-Mo	CUPID
	Source ≠ detector	Tracking	SuperNemo Demonstrator	SuperNemo

from Giuliani's talk at Neutrino 2018

KamLAND-Zen

^{136}Xe



- Operating at Kamioka, Japan, 2700 m.w.e.
- ^{136}**Xe** loaded LS into KamLAND center with inner mini-balloon
- Soluble to LS more than **3%**, easily extracted
- Slow $2\nu\beta\beta$ ($T^{2\nu}_{1/2} \sim 10^{21}$ yr) requires modest energy resolution
- Continue to measure neutrinos with KamLAND LS volume outside of mini-balloon

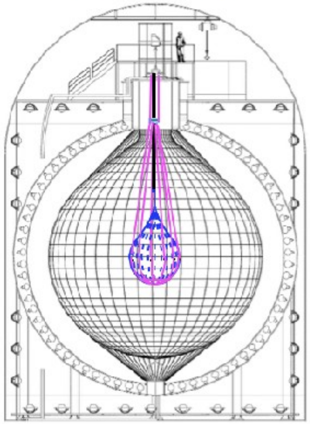
KamLAND-Zen → KamLAND2-Zen

^{136}Xe

Upgrades:

Past

2011-2015



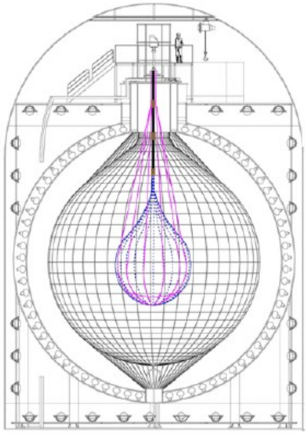
KamLAND-Zen 400

Nylon balloon R: 1.54 m
Xenon 320 – 380 kg

$m_{\beta\beta} < 61 - 165$ meV

Present

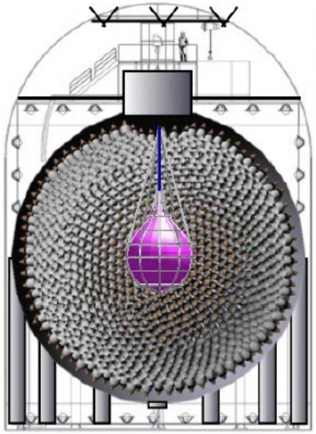
2019-**2024**



KamLAND-Zen 800

Nylon balloon R: 1.90 m
Xenon 745 kg
target $\langle m_{\beta\beta} \rangle$ **~ 40 meV**
reduced radioactive BG
demonstration of scalability

“Near” Future



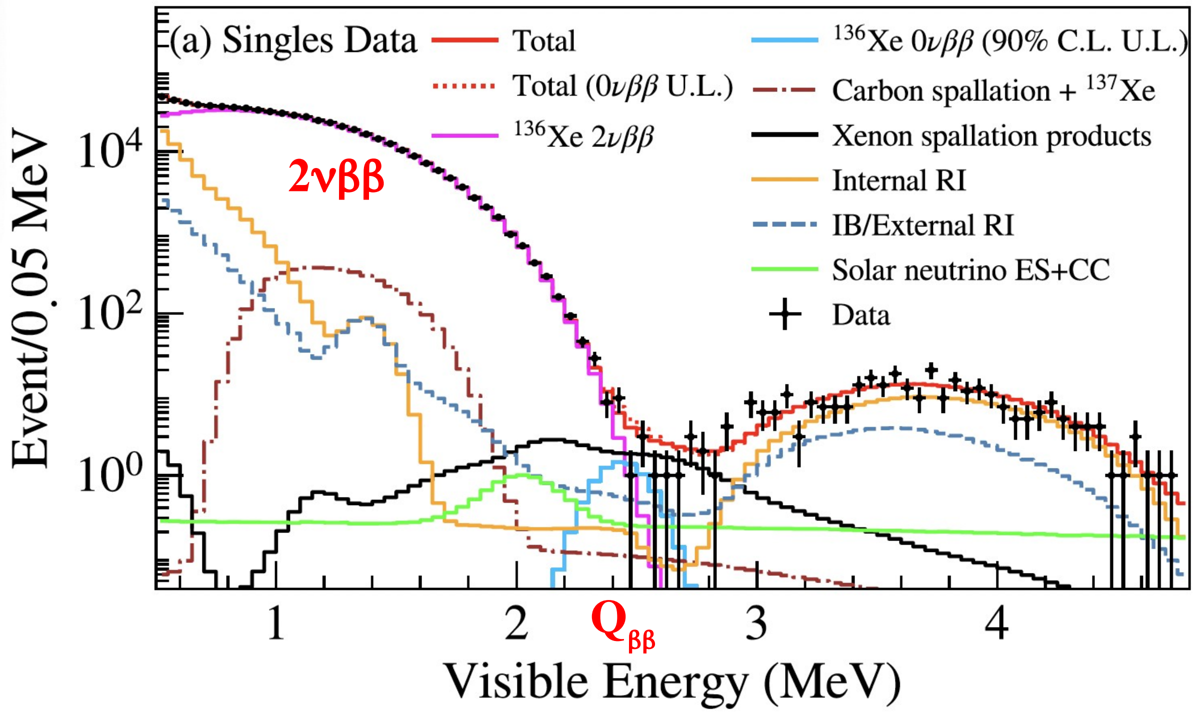
KamLAND2-Zen

Xenon 1 ton

target $\langle m_{\beta\beta} \rangle$ **~ 20 meV**
high light yield
better performance

KamLAND-Zen

^{136}Xe



A. Abe, et al. PRL 130, 051801 (2023)

final result from

KamLAND-Zen 800

- Exposure: 970 kg·yr
- FWHM($Q_{\beta\beta}$= 2458 keV): 247 keV
- BI: 7.1·10^{-5} cts/(keV·kg·yr)
- including also KamLAND-Zen 400:
  - lower limit: **$T^{0\nu}_{1/2}$ > 2.3·10^{26} yr (90% CL)**
  - median sensitivity: **1.5·10^{26} yr**
  - $m_{\beta\beta}$ < **35 - 136 meV** ⟶ **entering in the IO region**

data taking completed

SNO+

^{130}Te

Reuse existing infrastructure of SNO Canada in SNOLAB: 6000 m.w.e.

SNO+ phase I: SNO acrylic vessel filled with LS and 1.3 ton of natural Te in an organometallic compound (0.5% of mass loading)

- Te loading foreseen in 2025
- $\Delta E_{FWHM} = 225$ keV
- Sensitivity: **$T_{1/2} > 2 \cdot 10^{26}$ yr after 3 yrs**
- **$m_{\beta\beta} < 30 - 150$ meV**

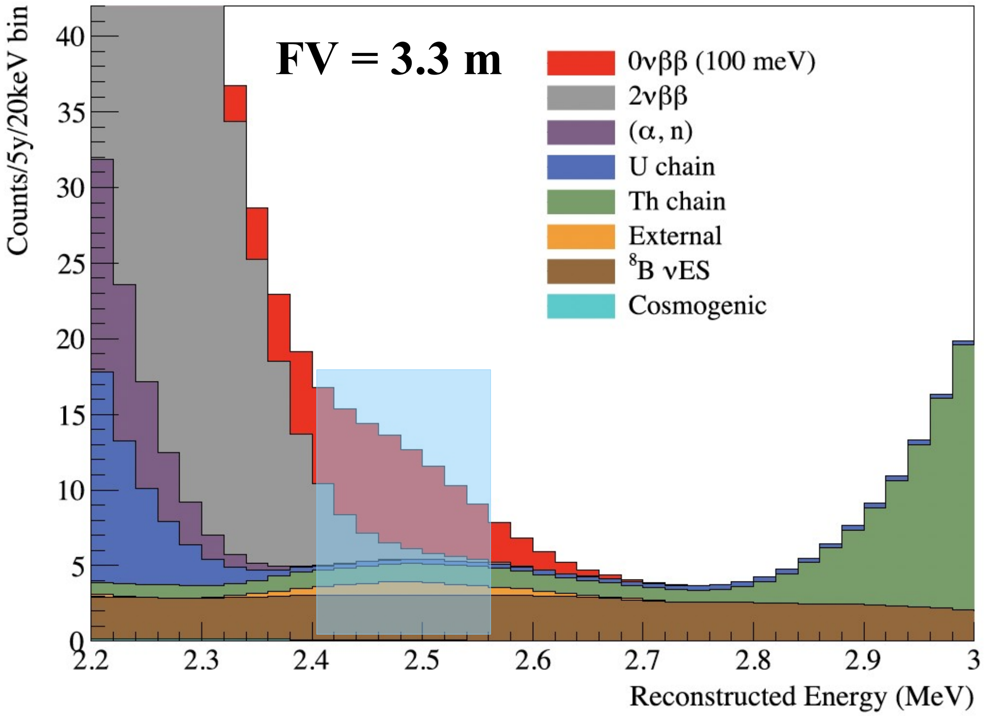
Possible **SNO+ phase II (ongoing R&D)**

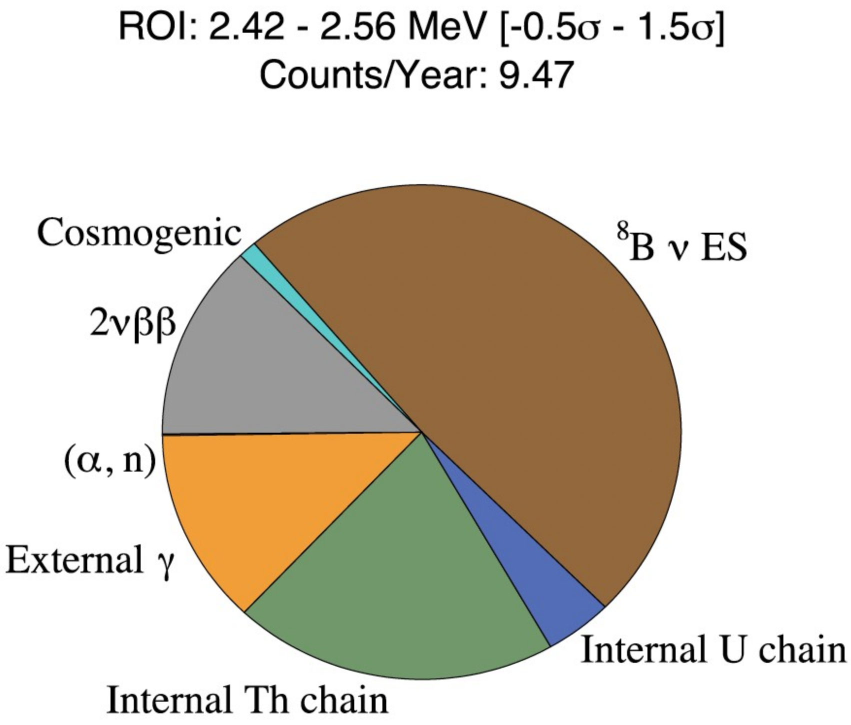
- Increase Te concentration (up to 3%)
- Increase light yield
- Improve transparency
- Improve light detectors
- **$T_{1/2} > 10^{27}$ yr after 10 yrs**
- **$m_{\beta\beta} < 12 - 50$ meV**

SNO+

^{130}Te

S. Andringa, et al. Ad. in High En. Phys. 6194250, (2016)




ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

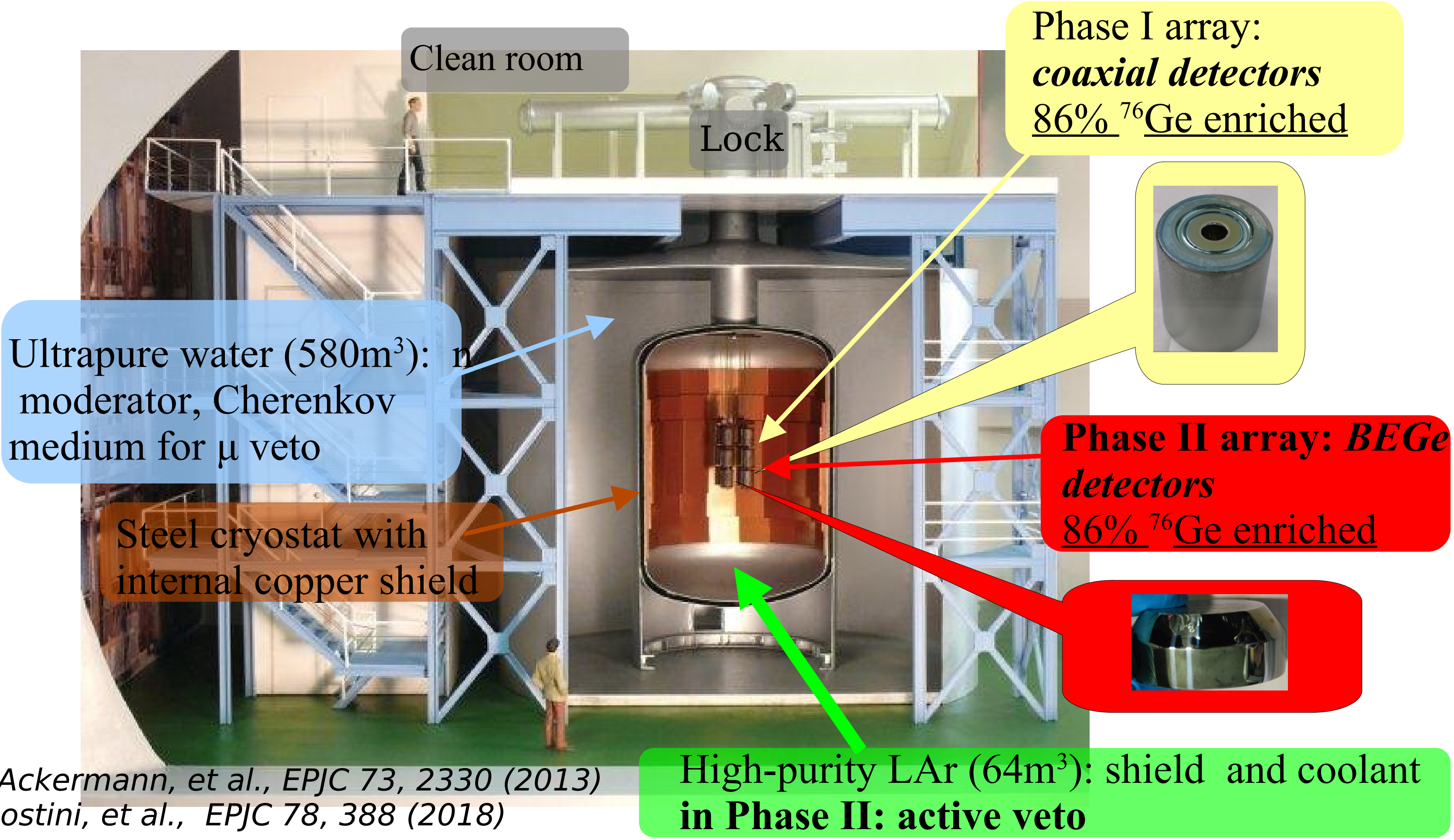
Events in the region of interest + fiducial volume
9.47 events/yr (at nominal backgrounds)

techniques and experiments

			NOW / MID-TERM	LONG-TERM
Scalability	Source = detector Fluid embedded source	Xe-based TPC	EXO-200	nEXO
			NEXT-White, NEXT-100	NEXT-HD
			PandaX-III	PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800	KamLAND2-Zen
			SNO+ phase I	SNO+ phase II
Good ΔE and efficiency	Source = detector Crystal embedded source	**Germanium diodes**	GERDA-II	
			LEGEND-200	LEGEND-1000
			MJD	
		Bolometers	AMoRE I	AMoRE II
			CUORE	
			CUPID-0	CUPID
			CUPID-Mo	
	Source ≠ detector	Tracking	SuperNemo Demonstrator	SuperNemo

from Giuliani's talk at Neutrino 2018

GERDA PHASE II



Clean room

Lock

Phase I array:
coaxial detectors
86% ^{76}Ge enriched

Ultrapure water (580m^3): n moderator, Cherenkov medium for μ veto

Steel cryostat with internal copper shield

Phase II array: *BEGe detectors*
86% ^{76}Ge enriched

High-purity LAr (64m^3): shield and coolant
in Phase II: active veto

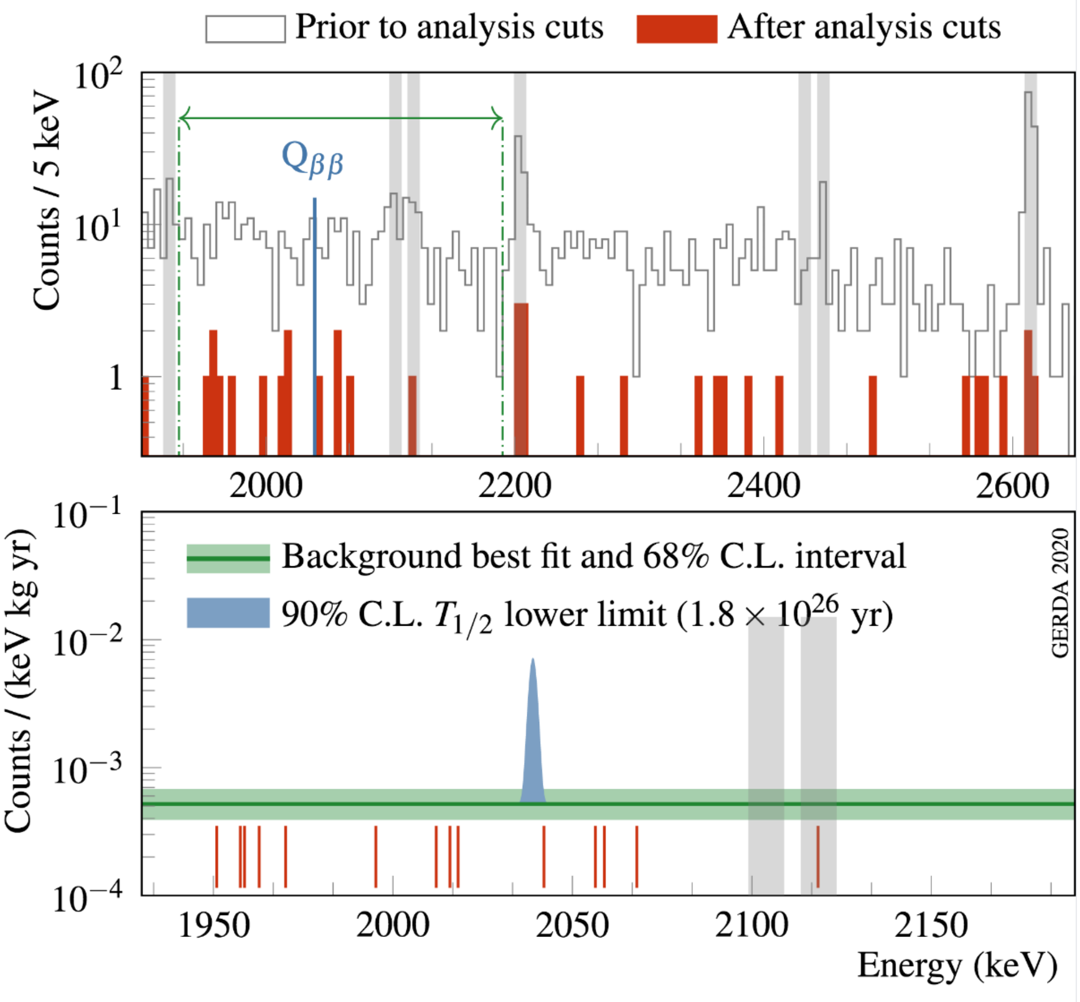
K.-H. Ackermann, et al., EPJC 73, 2330 (2013)
M. Agostini, et al., EPJC 78, 388 (2018)

- Operating at LNGS-INFN (Italy), 3500 m.w.e.
- up to 44.2 kg of enriched (88%) ^{76}**Ge** detectors deployed naked into liquid argon
- Total exposure: **103.7 kg·yr** (Phase II) + **23.5 kg·yr** (Phase I)

- Liquid argon used as veto
- Water Cherenkov cosmic muon veto
- Pulse Shape Discrimination

GERDA PHASE II

^{76}Ge



M. Agostini, et al., PRL 125, 252502 (2020)

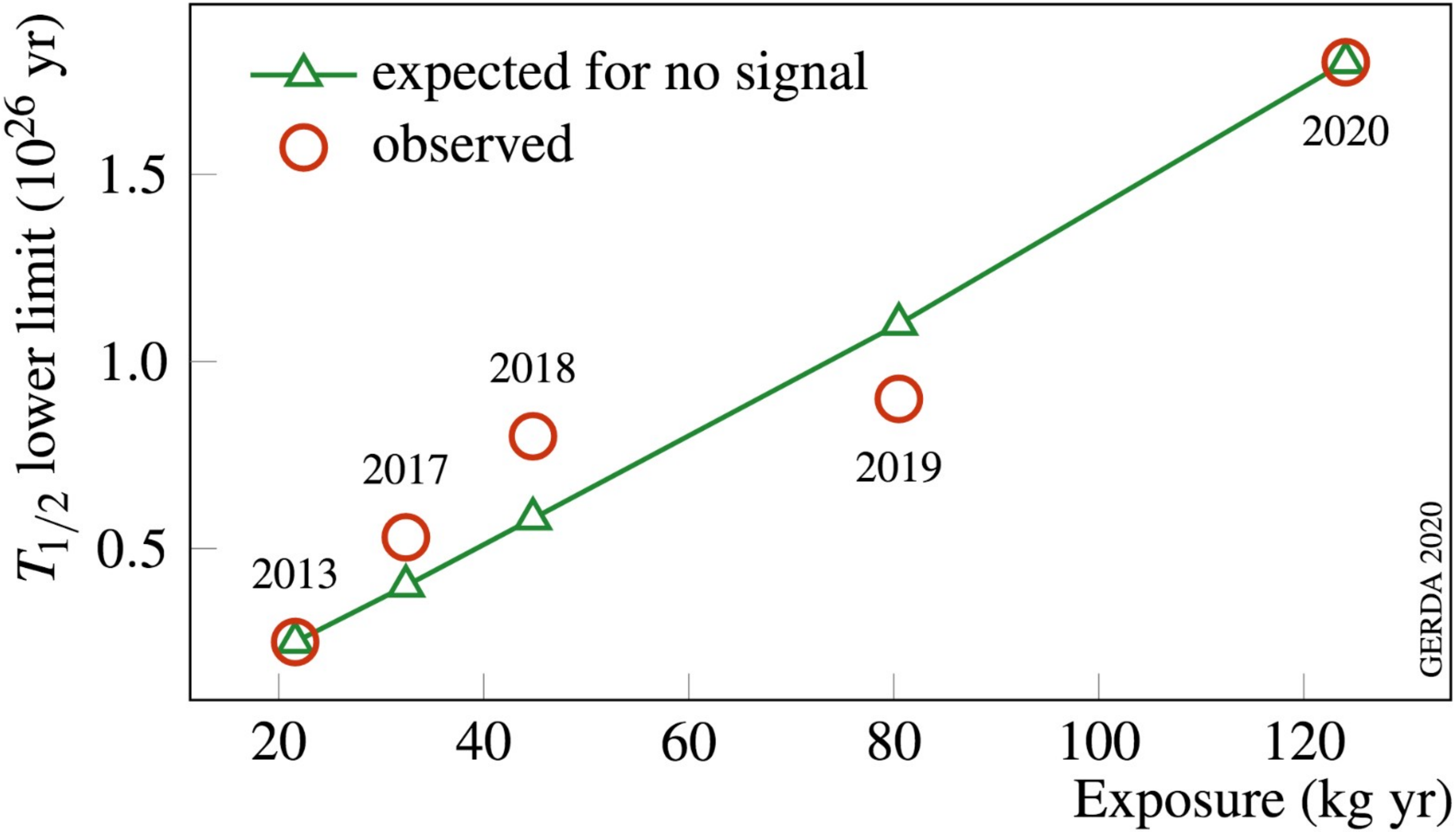
- **Frequentist :**
  Best fit $N^{0\nu} = 0$
  $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ **yr @ 90% C.L.**
  Median Sensitivity (NO Signal)
  $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ **yr @ 90% C.L.**
- upper limit on
  $m_{\beta\beta} < 79 - 180$ meV

- **Bayesian:**
  Best fit $N^{0\nu} = 0$
  $T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ **yr @ 90% C.I.**
  Median Sensitivity:
  $T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ **yr @ 90% C.I.**

- **Data taking completed in 2019**

GERDA PHASE II

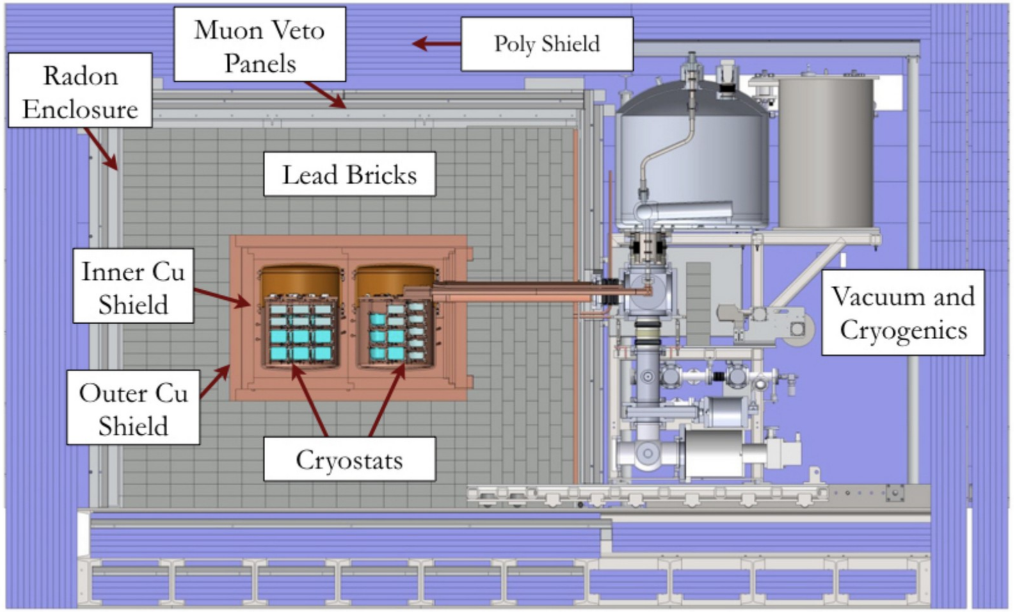
M. Agostini, et al., PRL 125, 252502 (2020)



- The GERDA legacy: the background-free regime results in a nearly linear improvement of sensitivity vs exposure

MAJORANA DEMONSTRATOR

^{76}Ge

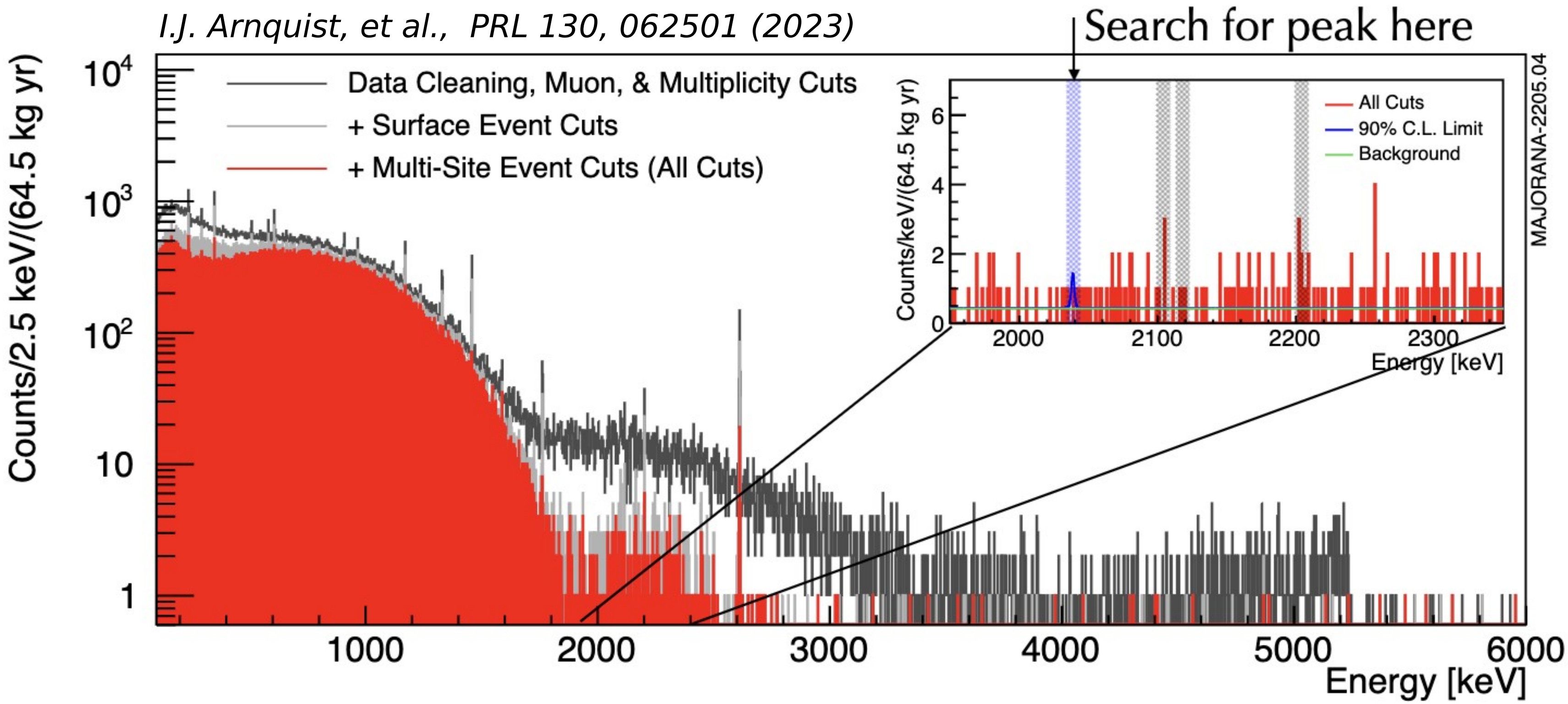


- ➢Operating at the Sanford Underground Facility (USA), 4300 m.w.e.
- ➢2 cryostat containing: 31 kg of enriched (88%) **^{76}Ge** detectors and 15 kg of ^{nat}Ge
- ➢Compact shield: low-background passive Cu and Pb shield with muon veto
- ➢Pulse Shape Discrimination

- ➢In-house production of underground electroformed Cu

MAJORANA DEMONSTRATOR

^{76}Ge


I.J. Arnquist, et al., PRL 130, 062501 (2023)

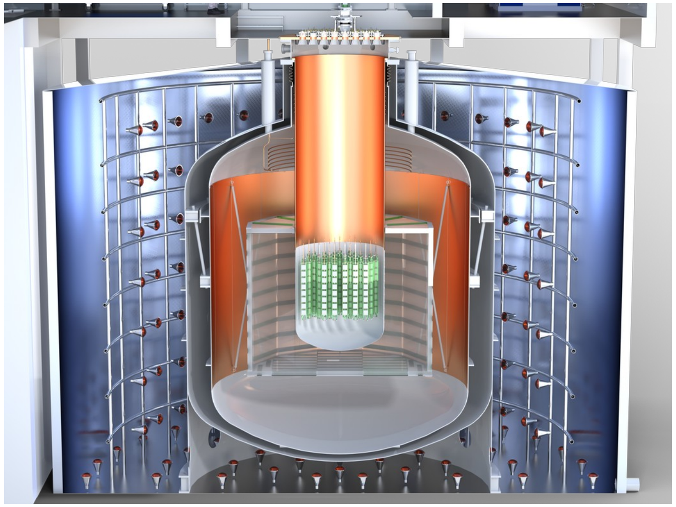
Search for peak here

- ➢Total exposure: **71.1 kg·yr**
- ➢BI: **(6.3 ± 0.6)·10^{-3} cts/(keV·kg·yr)**
- ➢**FWHM($Q_{\beta\beta}$=2039 keV) = 2.5 keV**
- ➢Lower limit: **$T^{0\nu}_{1/2}$ > 8.3·10^{25} yr (90% CL)**
- ➢Median sensitivity: **8.1·10^{25} yr (90% CL)**
- ➢Upper limit on: $m_{\beta\beta}$ < 113 – 269 meV
- ➢ **Data taking completed in March 2021**

GERDA+MJD ➡ LEGEND

First Stage (LEGEND-200):

- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- Use of the best technologies developed in GERDA and MAJORANA-DEMONSTRATOR
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining 140 kg are new
- In data taking from March 2023

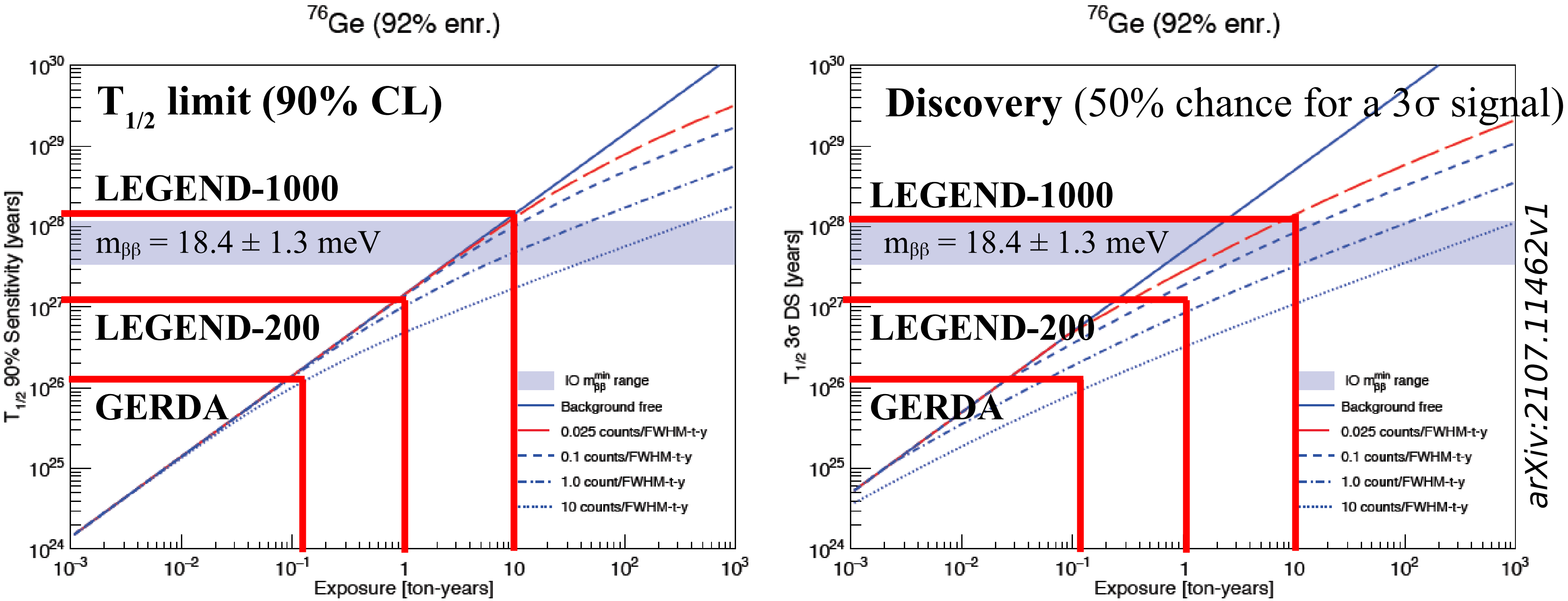


Further Stages (LEGEND-1000):

- 1000 kg (staged)
- timeline and budget: highest priority from DOE after the Portfolio review (July 2021)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- LNGS is the preferred site, SNOLAB is the alternative

LEGEND: sensitivities for limit setting and discovery

^{76}Ge



arXiv:2107.11462v1

Plots details:

- ~69% efficiency (including: isotopic fraction, active volume fraction, analysis cuts)
- GERDA Phase II: 1.5 counts/(FWHM·ton·yr)
- LEGEND-200: 0.5 counts/(FWHM·ton·yr)
- LEGEND-1000: 0.025 counts/(FWHM·ton·yr)

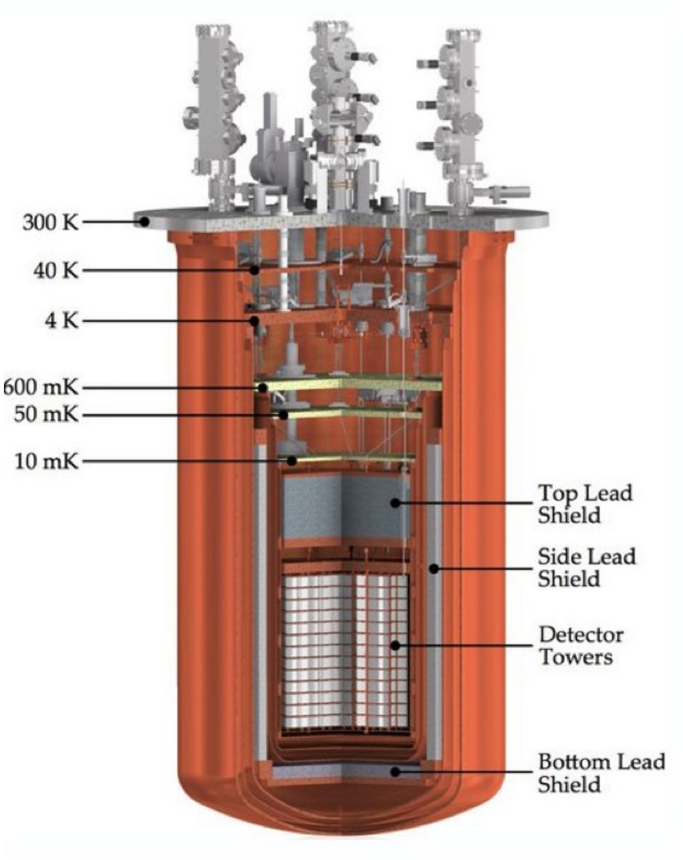
→

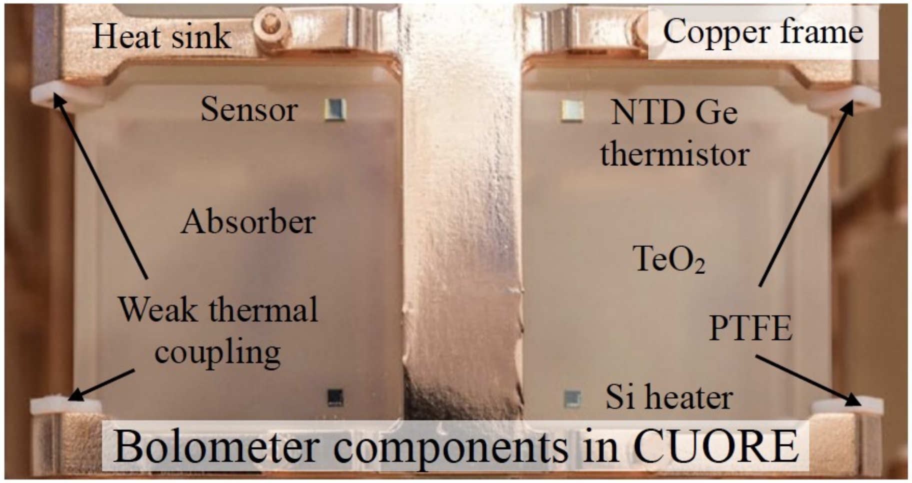
N.B.: **background-free**(*) **condition is a prerequisite for a discovery**

(*) average expected bkg events < 1.0 in the ROI for the entire exposure

CUORE

^{130}Te





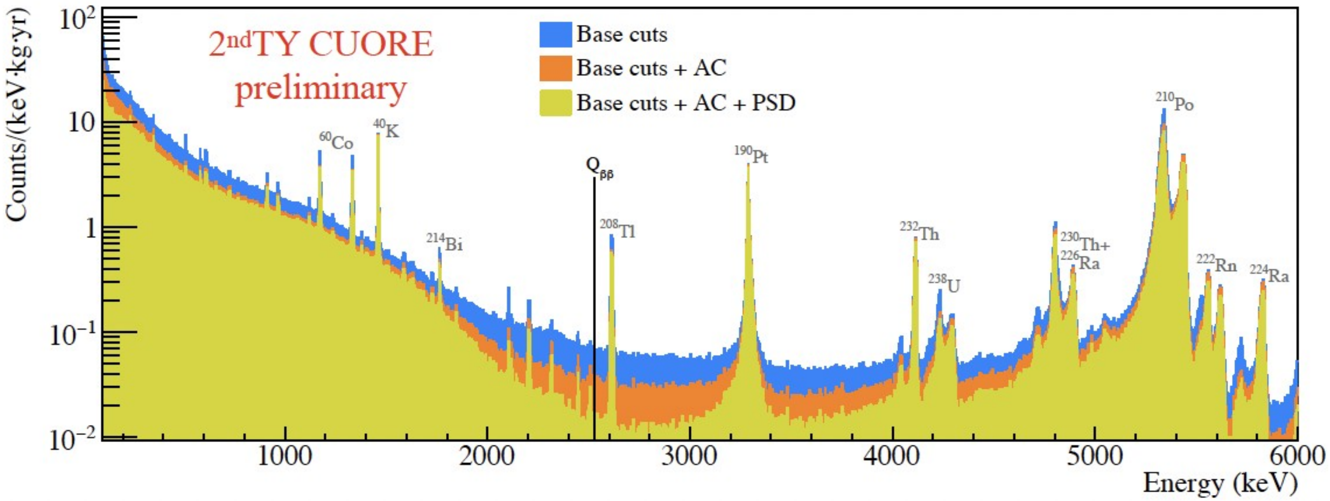
Bolometer components in CUORE

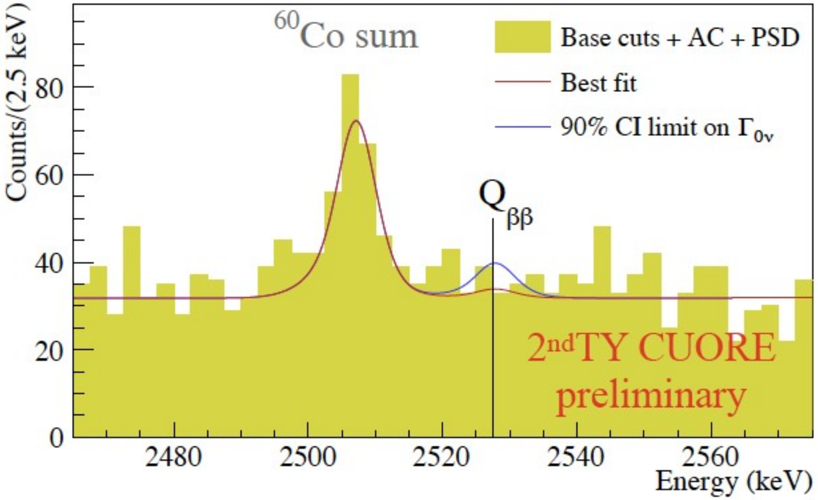
- Operating at LNGS (Italy), 3500 m.w.e.
- 988 $^{nat}\mathbf{TeO_2}$ bolometers
- Active mass: 742 kg
- Isotope mass: 206 kg ^{130}Te
- Compact shield: low-background passive Cu and Pb shield
- Pulse shape discrimination

CUORE

^{130}Te

K.Alfonso, talk at TAUP(2023) conference



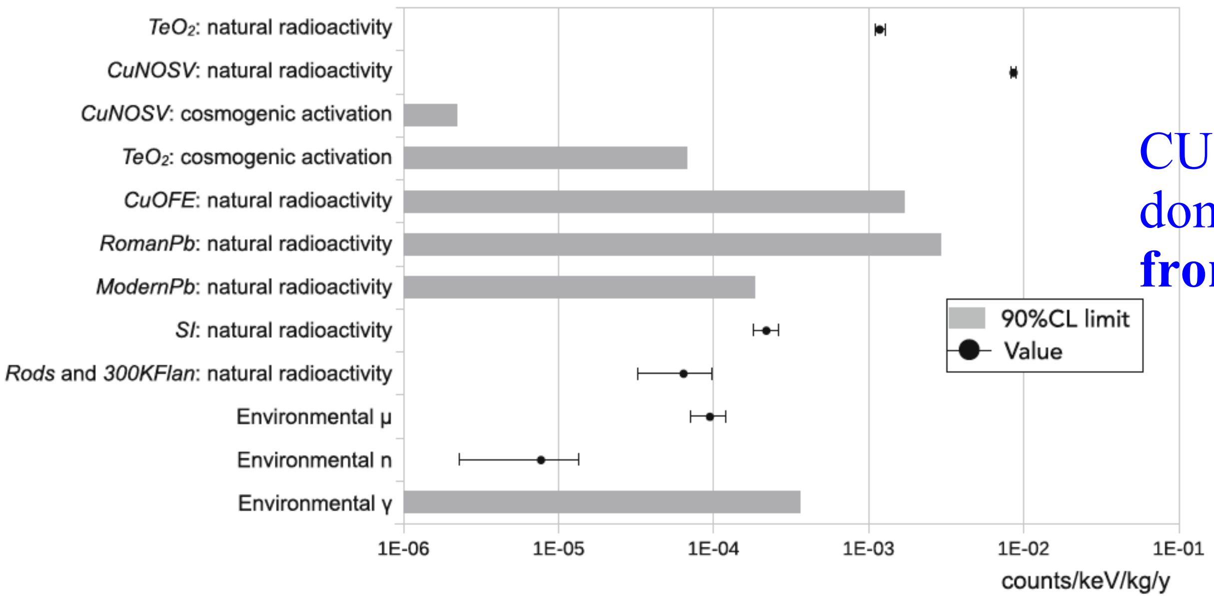


- TeO_2 exposure: 2023 kg·yr
- FWHM($Q_{\beta\beta}$= 2528 keV) = $7.26^{+0.43}_{-0.47}$ keV
- BI: $(1.30 \pm 0.03)\cdot 10^{-2}$ cts/(keV·kg·yr)
- Lower limit: **$T^{0\nu}_{1/2} > 3.3\cdot 10^{25}$ yr (90% CI)**
- Median sensitivity: **$3.11\cdot 10^{25}$ yr (90% CI)**
- $m_{\beta\beta}$ < **75 - 255 meV**

CUORE ⟶ CUPID

^{100}Mo

C. Alduino, et al. EPJC 77, 543 (2017)



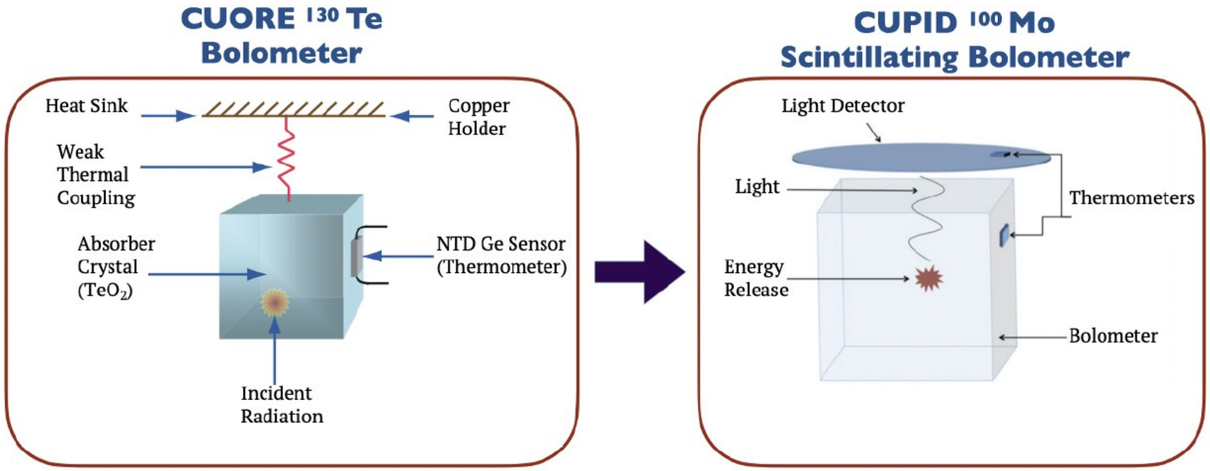
CUORE background dominated by **α particles from surface contamination**

Moving to CUPID requires:

0. **Enrichment**
1. **Rejection of α**
   ⟶ New detector technology: **luminescent bolometers**
2. **Limitation of the residual background**
   ⟶ Full CUORE background model + information from demonstrators (CUPID-0, CUPID-Mo)

CUPID

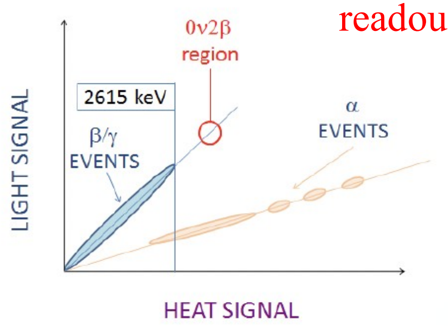
^{100}Mo

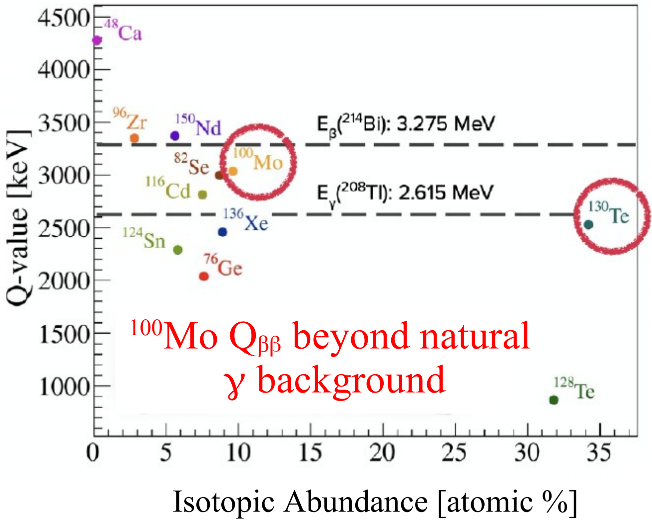


CUORE: no PID

CUPID: PID allows to separate β/γ from α events

Light +heat readout





^{100}Mo $Q_{\beta\beta}$ beyond natural γ background

A Li_2MoO_4 (LMO) scintillating cryogenic detector to search for the 0νββ decay of ^{100}Mo

CUPID

^{100}Mo

- It will be located at LNGS-INFN (Italy), 3500 m.w.e.

- 45×45×45 mm^3 Li$_2$^{100}MoO$_4$ crystals
  - 450 kg of Li$_2$^{100}MoO$_4$
  - 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo

- Muon veto for muon-induced background suppression

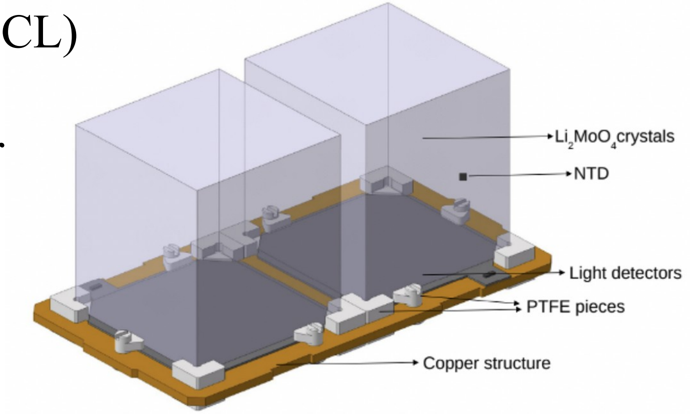
- FWHM($Q_{\beta\beta}$ = 3034 keV) = 5 keV

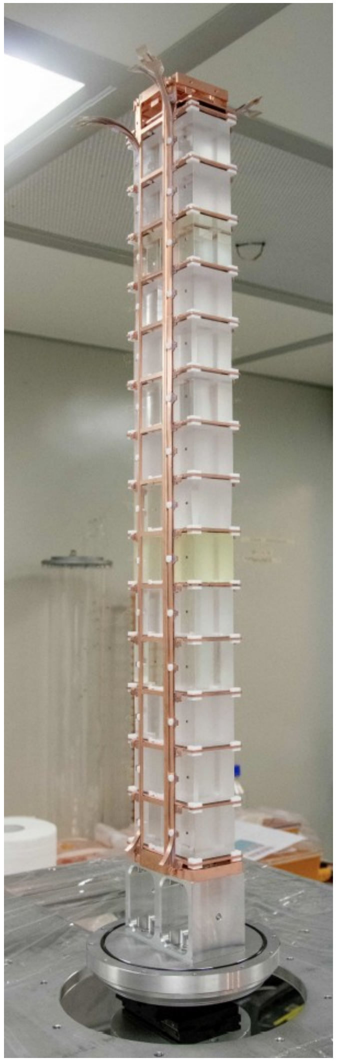
- BI: 10^{-4} cts/(keV·kg·yr)

- Lower limit: $T^{0\nu}_{1/2} > 1.5\cdot10^{27}$ yr (90% CL)

- Discovery sensitivity (3σ): $1.1\cdot10^{27}$ yr

- $m_{\beta\beta} < 12 - 20$ meV





arXiv:1907.09376v1

AMoRE

Detector concept

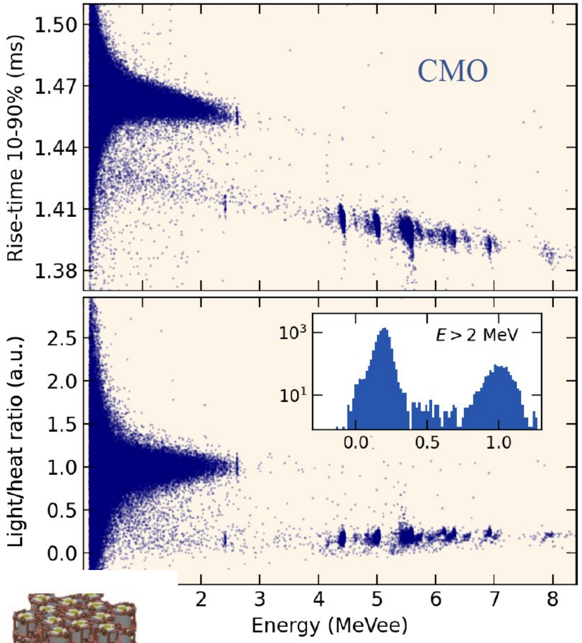
scintillating bolometers based on Ca^{100}**MoO**$_4$

Ca is depleted from ^{48}Ca to avoid ^{48}Ca – 2νββ

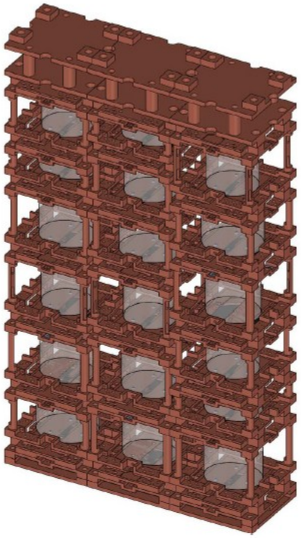
but also Li$_2$^{100}MoO$_4$

AMoRE-I at YangYang (Korea)

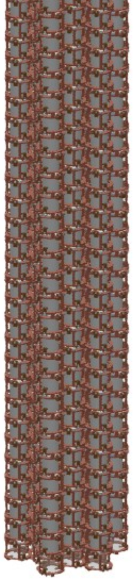
AmoRE-II at a new laboratory: Handeok mine (Korea)



AMoRE-Pilot
^{100}Mo:~1.8 kg
2015 - 2018



AMoRE I
^{100}Mo:3.0 kg
2020 - 2023



AMoRE II
^{100}Mo: 200 kg
2024- ...

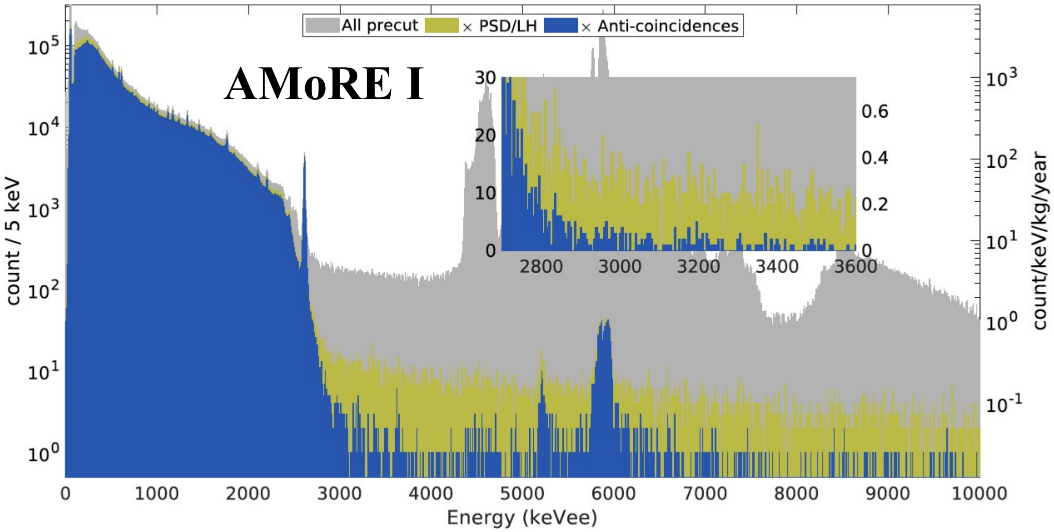
Target sensitivities: 10^{25} yr $\quad$ $4 \cdot 10^{26}$ yr

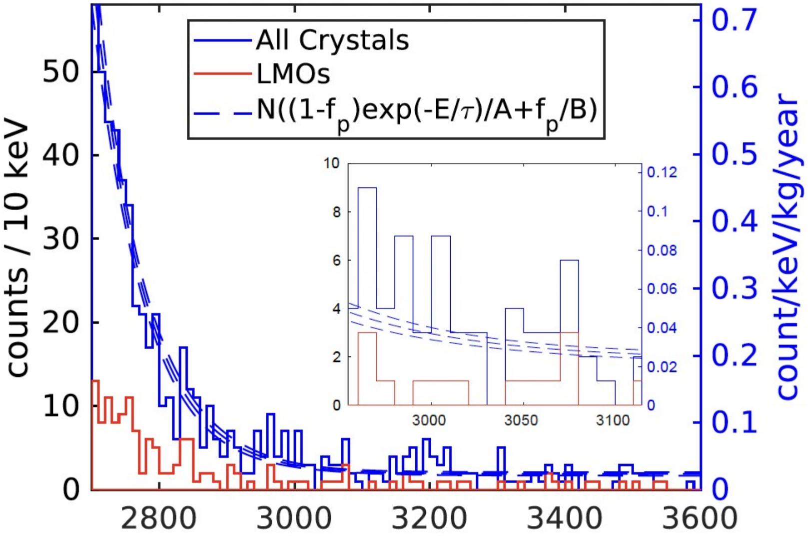
$\boldsymbol{m_{\beta\beta}} <$ **120 - 200 meV** $\quad$ $\boldsymbol{m_{\beta\beta}} <$ **20 - 35 meV**

AMoRE

^{100}Mo

G.W. Kim talk at LLWI2024





- Exposure: 8.02 kg(XMoO$_4$)·yr = 3.88 kg(^{100}Mo)·yr
- FWHM($Q_{\beta\beta}$ = 3034 keV) = 9.5 – 28.0 keV
- BI: 0.032 ± 0.003 keV cts/(keV·kg·yr)
- Lower limit: $T^{0\nu}_{1/2} > 3.4 \cdot 10^{24}$ yr (90% CL)

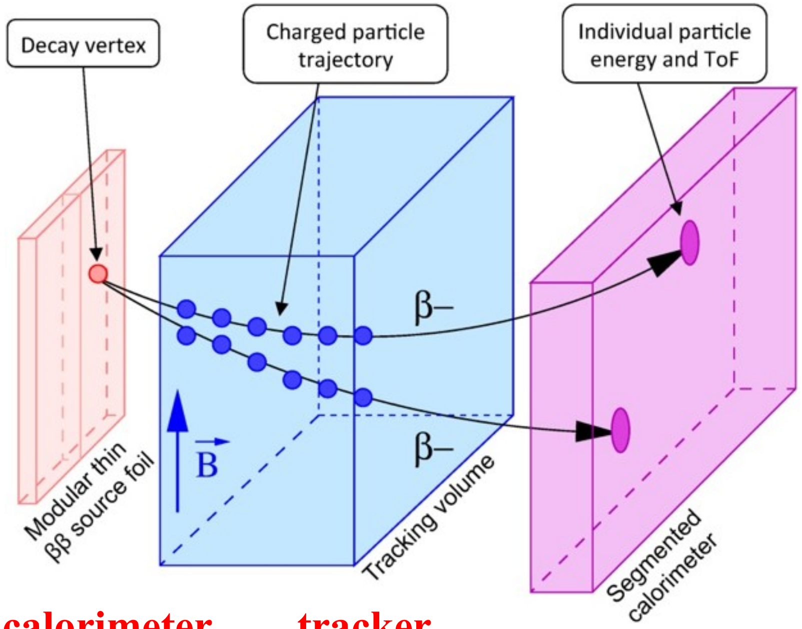
techniques and experiments

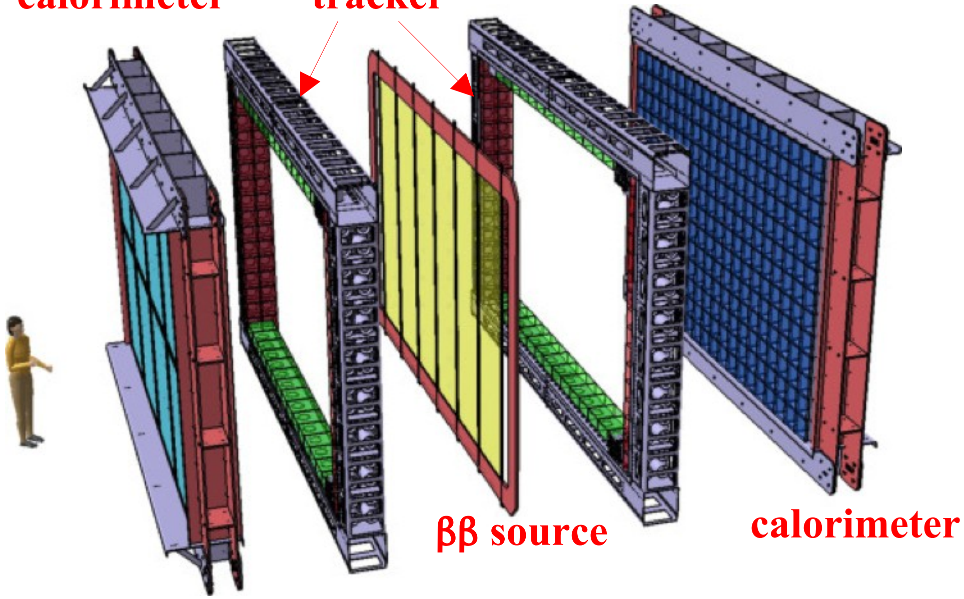
			NOW / MID-TERM	LONG-TERM
Scalability	Source = detector Fluid embedded source	Xe-based TPC	EXO-200	nEXO
			NEXT-White, NEXT-100	NEXT-HD
			PandaX-III	PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800	KamLAND2-Zen
			SNO+ phase I	SNO+ phase II
Good ΔE and efficiency	Source = detector Crystal embedded source	Germanium diodes	GERDA-II	
			LEGEND-200	LEGEND-1000
			MJD	
		Bolometers	AMoRE I	AMoRE II
			CUORE	
			CUPID-0 CUPID-Mo	CUPID
	Source ≠ detector	**Tracking**	SuperNemo Demonstrator	SuperNemo

from Giuliani's talk at Neutrino 2018

SuperNEMO

^{82}Se





source ≠ detector
the isotope is embedded in thin foils
main advantage: **full topological reconstruction of a ββ event**

SuperNEMO demonstrator:
- completed the commissioning phase: first data in summer 2024 with 1 module (LSM - France)
- 6.11 kg of ^{82}Se
- Sensitivity: $4 \cdot 10^{24}$ yr in 2.5 yr
- $m_{\beta\beta} < 260 - 500$ meV

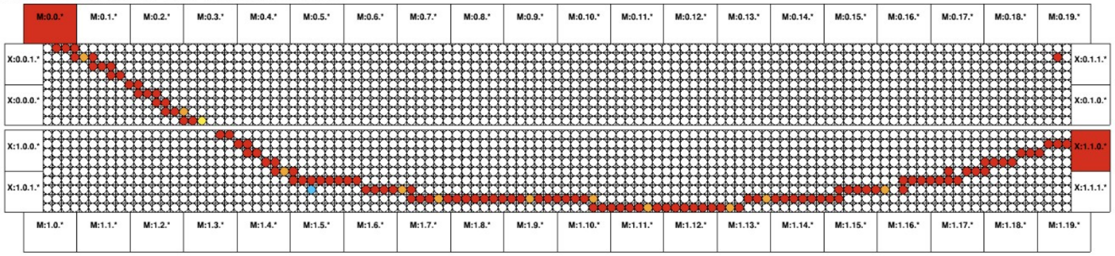
SuperNEMO:
- 20 modules, 100 kg of ^{82}Se
- exposure: 500 kg·yr
- Sensitivity > 10^{26} yr
- **$m_{\beta\beta} < 50 - 100$ meV**
- ^{40}Ca, ^{150}Nd, ^{96}Zr can be used

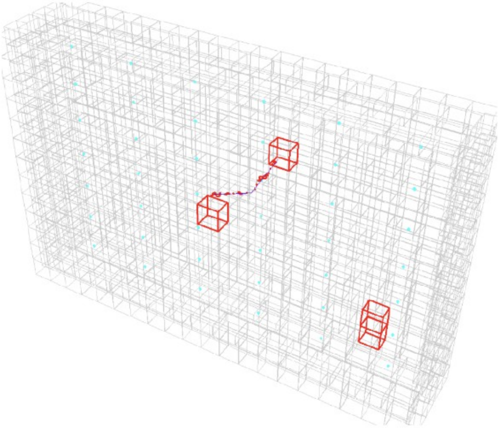
SuperNEMO

^{82}Se

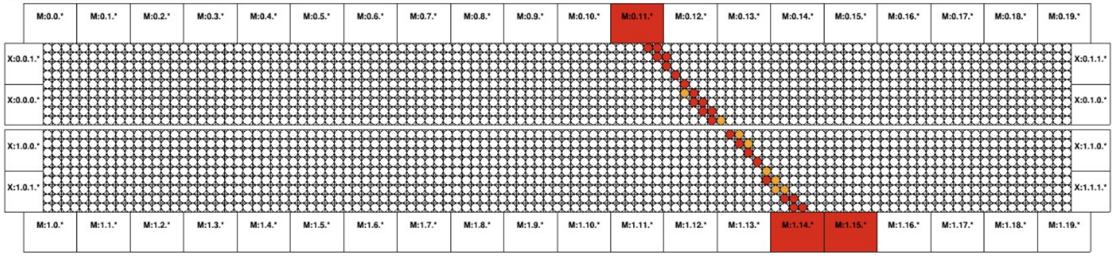
How two events look like

RUN 1051 // TRIGGER 1187719+1187720+1187721





RUN 1011 // TRIGGER 3210833

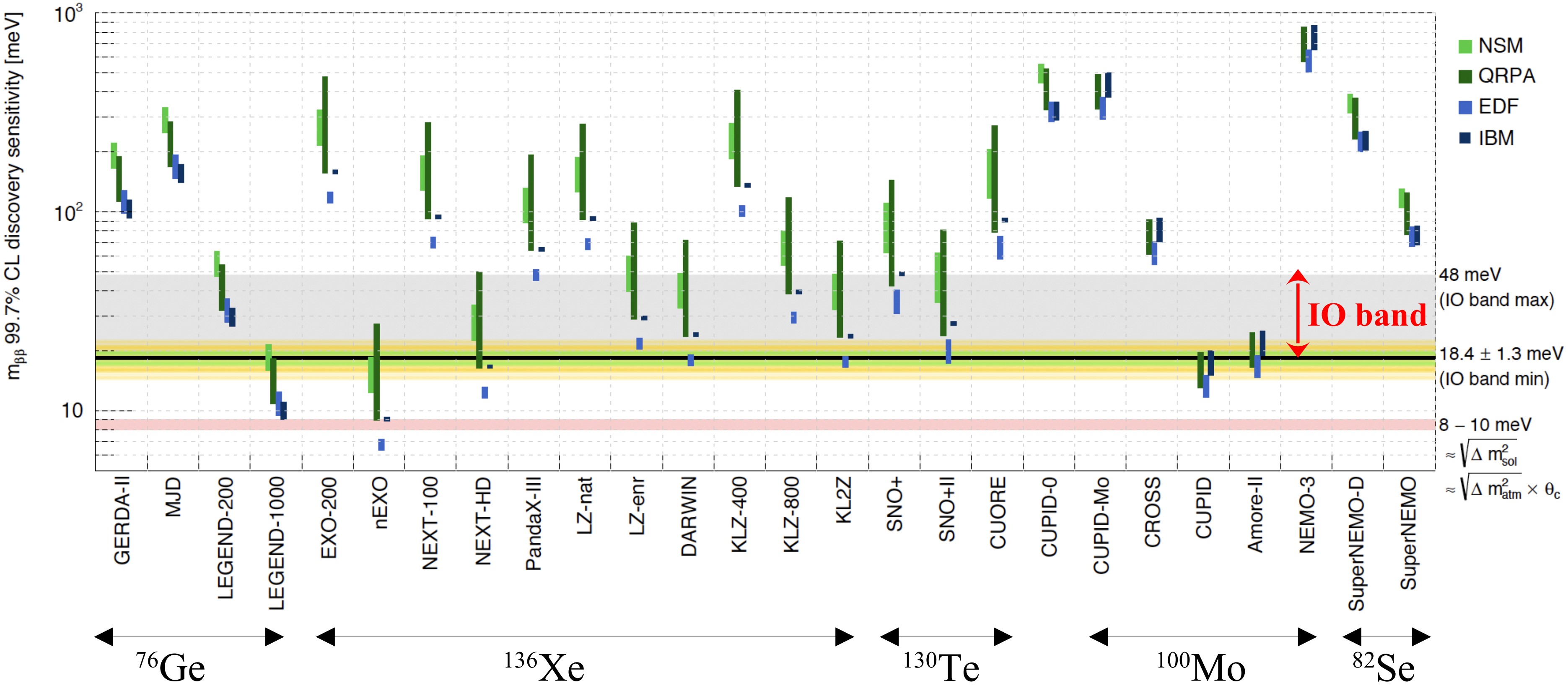


- 99% of trackers channels live!
- Track and event reconstruction

C. Patrick talk at TAUP(2023)

comparison of experiments

M. Agostini, et al. Rev. of Mod. Phys. 95 025002 (2023)



discovery sensitivity = value of $T^{0\nu}_{1/2}$ or $m_{\beta\beta}$ for which an experiment has a 50% chance to measure a signal with a significance of 3σ

conclusions

- **$0\nu\beta\beta$ is a very important process**, not only for neutrino physics
- **Very high discovery potential for IO**
- **Reasonable high discovery potential also for NO** (assuming absence of mechanisms driving $m_{\beta\beta}$ or m_{lightest} to zero)
- **Many projects** aims at extending the present sensitivity
- **The field is extremely active**: variety of approaches and technologies