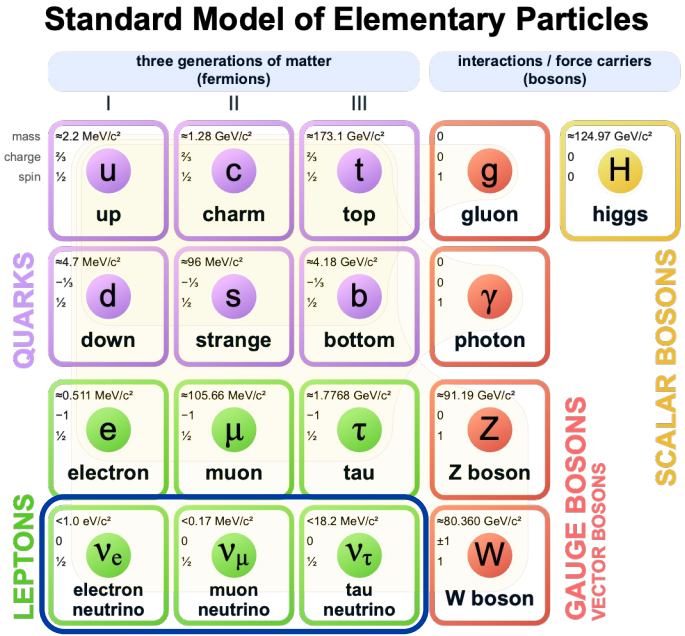
NEXT: a neutrinoless double beta experiment

Martín Pérez Maneiro, *on behalf of the NEXT collaboration*
@ IBER2023, 8 September 2023

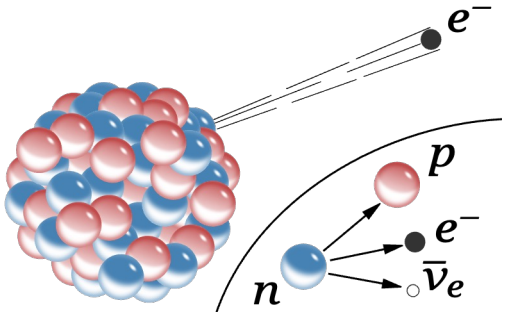
Neutrinos



NEUTR - INO

No electric charge

Very light mass

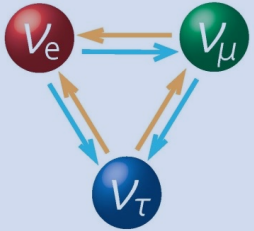


Involved in weak interactions

Small cross-section: requires large mass detectors and large neutrino flux

Neutrinos have mass

Neutrino oscillation: change of flavour during propagation



Predicted by Pontecorvo (1957), experimentally observed in SK (1998) and SNO (2001)

Neutrinos have mass: Not predicted by the SM Fundamental nature?

Dirac?
Majorana?

Majorana fermions were postulated by Ettore Majorana (1937)

Are neutrinos its own antiparticle?

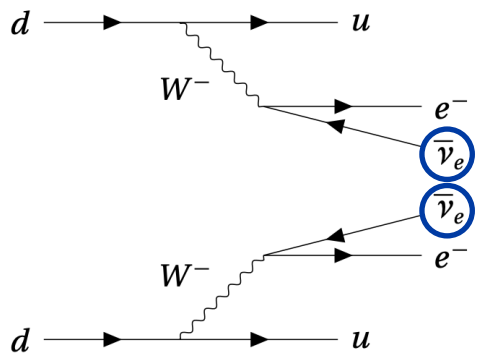
$$¿\,\nu = \bar{\nu}?$$

Proving this would explain neutrino mass scale and baryon asymetry in the Universe

$0\nu\beta\beta$ decay

$2\nu\beta\beta$

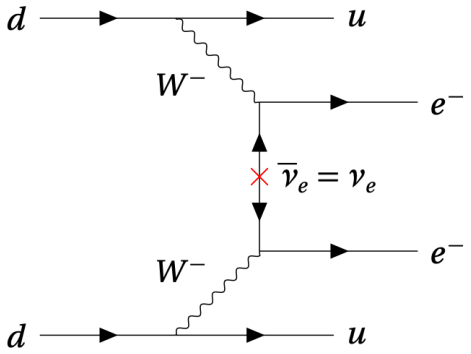
$N(A,Z) \rightarrow N(A,Z+2) + 2e^- + 2\bar{\nu}_e$



¿No $\bar{\nu}$?

$0\nu\beta\beta$

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

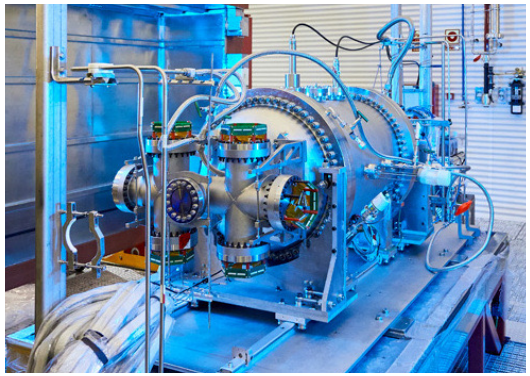


$Q_{\beta\beta} = 2457.8\ keV$

Proposed in 1935 by Marie Goeppert Mayer, observed in 1987

Proof of Majorana neutrinos

NEXT



NEXT-White detector at LSC

Neutrino

Experiment with a

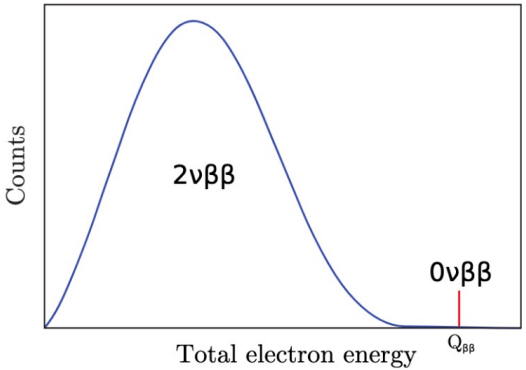
Xenon

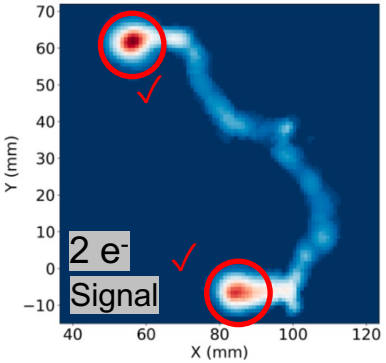
TPC

- Xe gas ($^{136}Xe \rightarrow 0\nu\beta\beta$)
- High pressure
- Electroluminiscent amplification

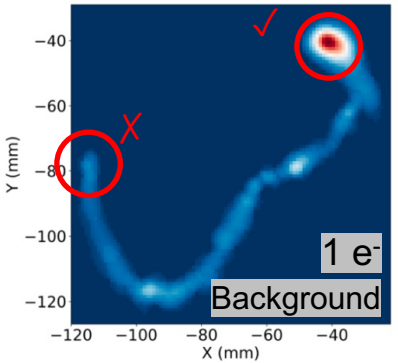
Two main requirements to find the decay:

- Good energy resolution (~1%)
- Track reconstruction





Rad. decay chains + cosmogenic activations



NEXT detection concept

Charged energetic particle

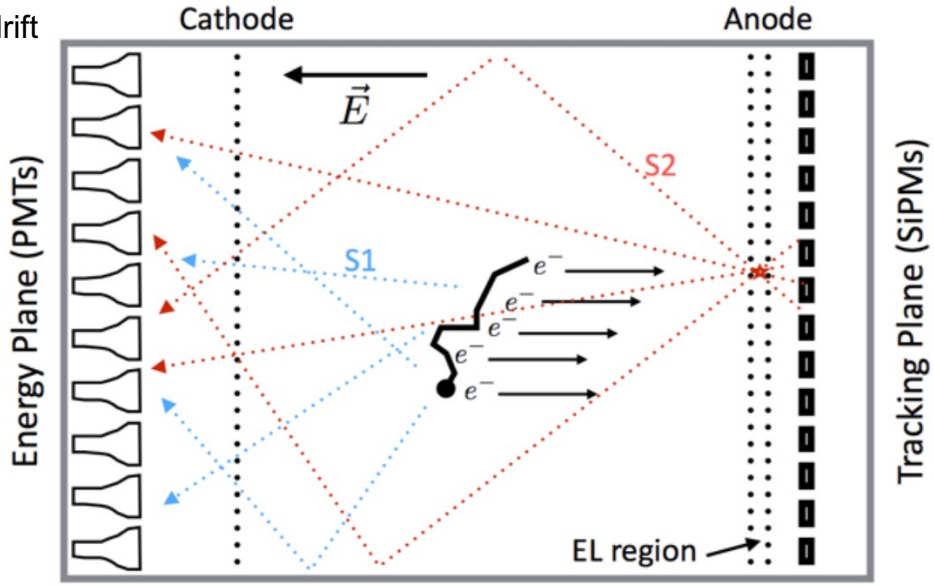
Excited Xe atoms → S1 scintillation signal → Energy Plane start of the event

Ionization track → Electron drift → EL amplification → S2 ionization signal → Energy Plane energy measurement

Tracking Plane (X, Y) transversal pos.

Δt + drift time

Z longitudinal pos.



NEXT path towards $0\nu\beta\beta$

R&D detectors
NEXT-DBDM & NEXT-DEMO
2009-2014

- Detection concept
- Energy resolution

NEXT-100
Under construction
Comissioning: end 2023

- $0\nu\beta\beta$ search

NEXT-White
2016-2021

- Scalability
- Calibration
- Background model
- $2\nu\beta\beta$ mode
- $0\nu\beta\beta$proof-of-concept

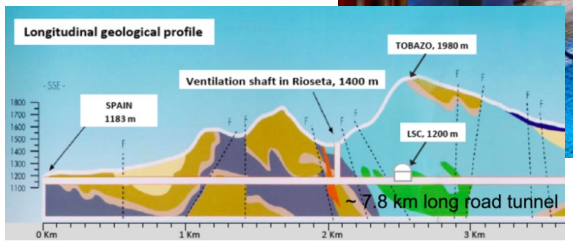
NEXT-HD & NEXT-BOLD
Future plans

- $0\nu\beta\beta$ with more exposure
- Reduced background
- New readout technology

- Ba^{2+} tagging → background free

NEXT-White detector

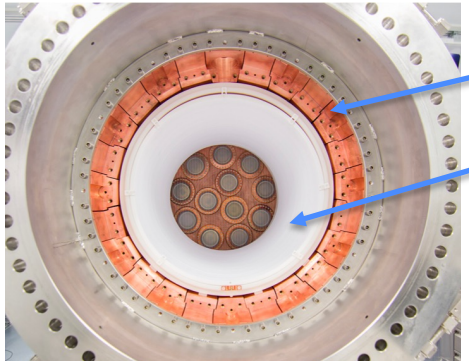
LSC
Laboratorio Subterráneo Canfranc



@LSC, Canfranc, Spain // 2016-2021

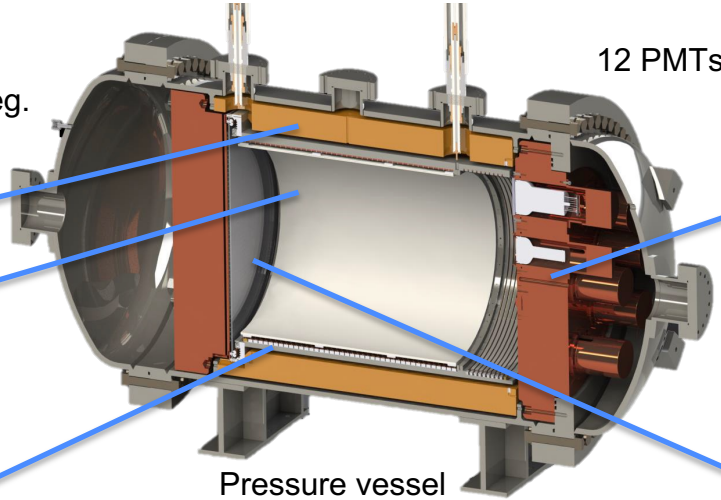
NEXT-White detector

TPC
4 kg (3.5 kg fiducial) @ 10 bar
20.8 cm rad., 50.7 cm drift reg., 0.6 cm EL reg.
0.6 cm Inner Copper Shield



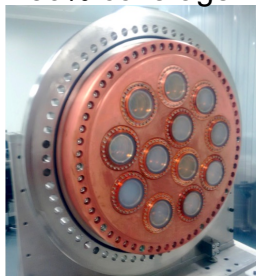
ICS

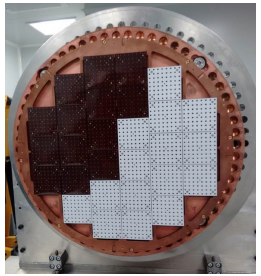
Light tube

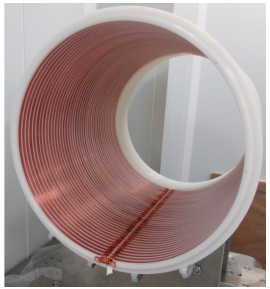


Pressure vessel

Energy plane
12 PMTs (Hamamatsu R11410-10)
30% coverage

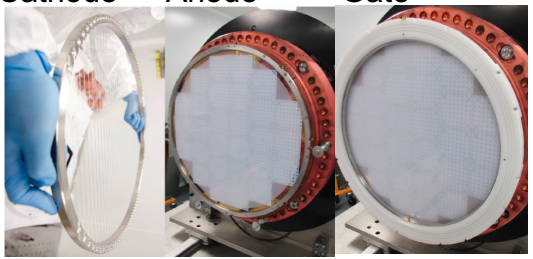






Field cage
+
Copper rings

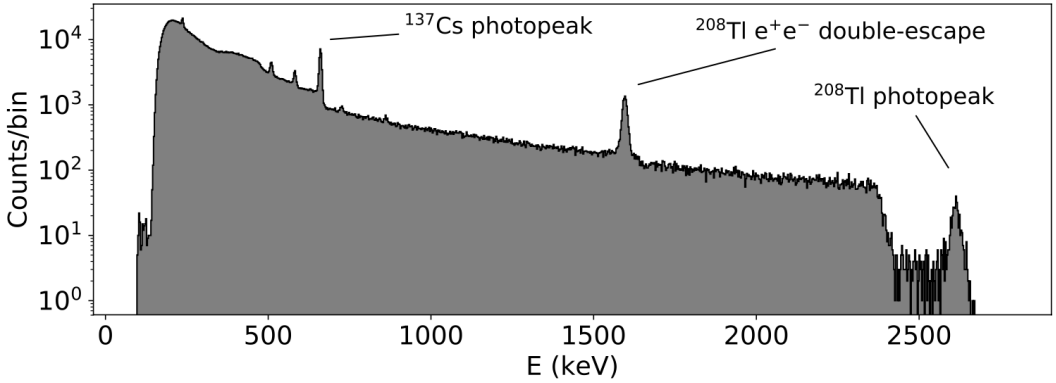
Cathode Anode Gate



Tracking plane
28 boards of 8x8 SiPMs: 1792 total
(SensL C series model MicroFC-10035-SMT-GP), 10 mm pitch

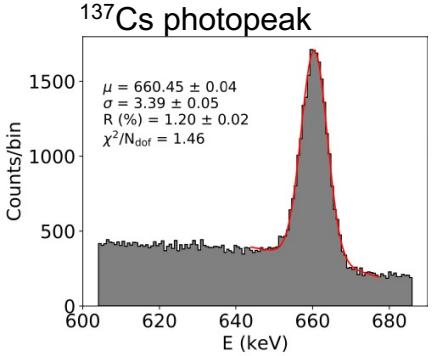
NEXT-White: energy resolution

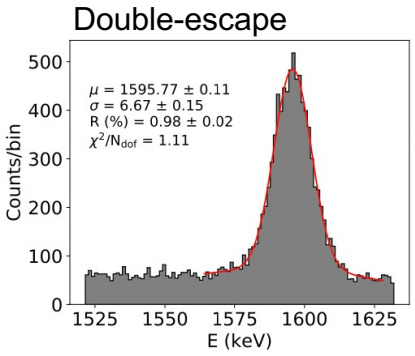
High energy calibration spectrum

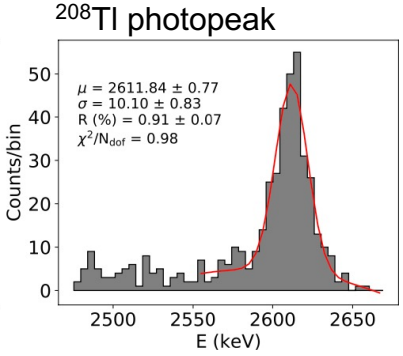


Geometric + lifetime corrections to the energy using ^{83m}Kr-based calibration

G. Martínez-Lema et al., JINST 13 (2018) 10, P10014







Energy resolution

$$R = \frac{FWHM}{E} = \frac{2\sqrt{2\ln 2}\,\sigma}{E}$$

1.20 ± 0.02% FWHM @ 662 keV
0.98 ± 0.03% FWHM @ 1592 keV
0.91 ± 0.12% FWHM @ 2615 keV

< 1% FWHM @ $Q_{\beta\beta}$

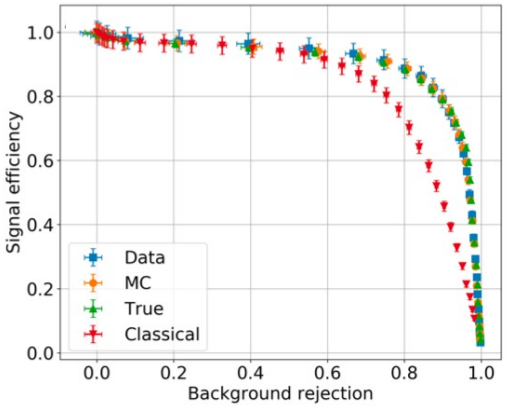
J. Renner et al., JHEP 10 (2019) 230

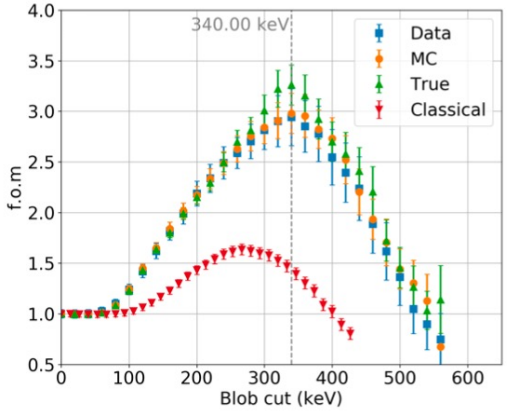
NEXT-White: event identification

Topological discrimination

- Single e^- vs double e^- identification
- Using the double scape peak ($\beta\beta$-like signature) as signal
- Based on the E of the least energetic blob

P. Ferrario et al., JHEP 10 (2019) 052





$$f.o.m. = \frac{\epsilon}{\sqrt{b}}$$

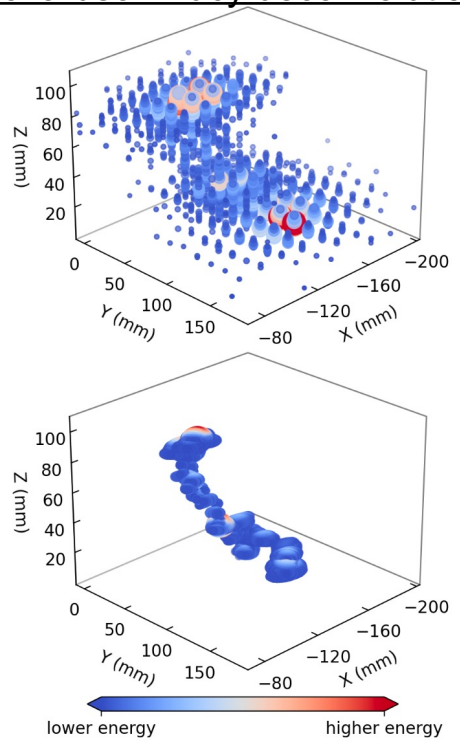
$\epsilon = 71.6\%$
$b = 20.6\%$
$f.o.m. = 1.58$

$\epsilon = 56.6\%$
$b = 3.7\%$
$f.o.m. = 2.94$

Machine learning for discrimination

- DNNs, CNNs on classical data (f.o.m. = 2.2)
- Currently: segmentation CNNs; GNNs

Richardson-Lucy deconvolution

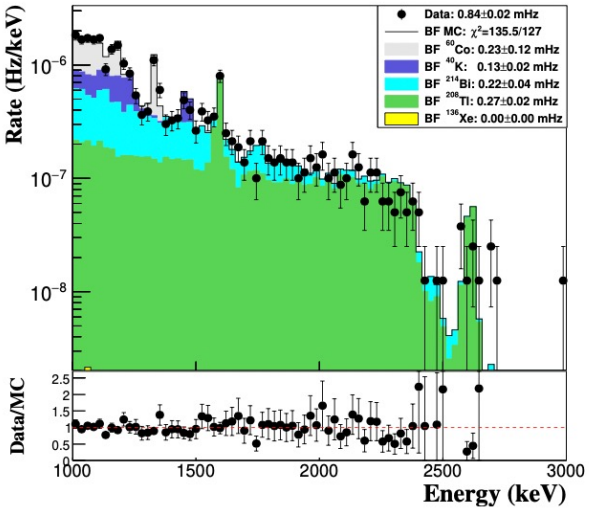


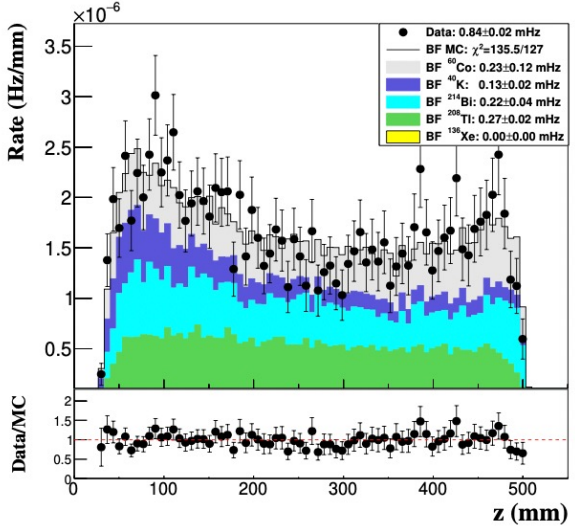
A. Simón et al., JHEP 21 (2020) 146

NEXT-White: background model

Model
- GEANT4 Monte-Carlo simulation
- Radioactivity measurements for volumes

Data
- ^{136}Xe-depleted xenon





Background rates

Fit + topological cut + E > 1 MeV:

Data: 0.248±0.010 mHz
Model: 0.244±0.008 mHz

^{222}Rn contrinubtion negligible using the Radon Abatement System

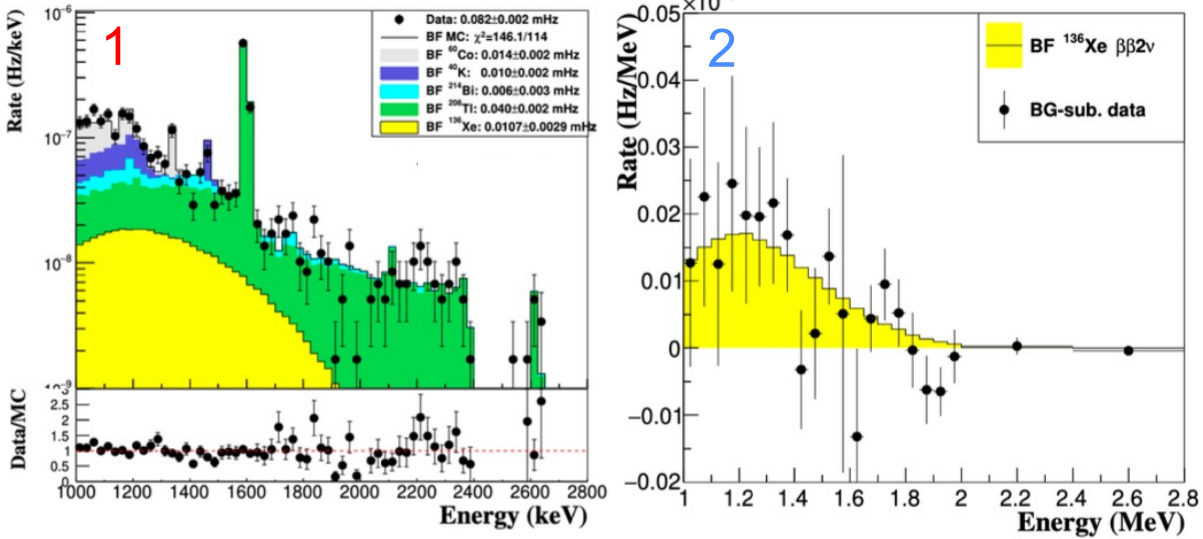
P. Novella et al., JHEP 10 (2019) 51

NEXT-White: $2\nu\beta\beta$ half-life

$2\nu\beta\beta$ half-life measurement

Two methods:

- Data fit to background model
- Subtraction of depleted xenon data to enriched and fit to MC (novel technique)



1. Background model

$R = 334 \pm 95\ yr^{-1}$

$T_{1/2}^{2\nu} = 2.14^{+0.80}_{-0.46} \times 10^{21}\ yr$

2. Direct subtraction

$R = 291 \pm 78\ yr^{-1}$

$T_{1/2}^{2\nu} = 2.34^{+0.85}_{-0.49} \times 10^{21}\ yr$

P. Novella et al., Phys. Rev. C 105, 055501 (2022)

NEXT-White recap

NEXT-White operated with high-quality results

- Effective calibration method
- Great energy resolution
- Sharp track reconstruction
- Successful topology selection

- ✓ Proved **scalable** detection concept
- ✓ Achieved **low background rate**
- ✓ $T_{1/2}^{2\nu}$ **measured**

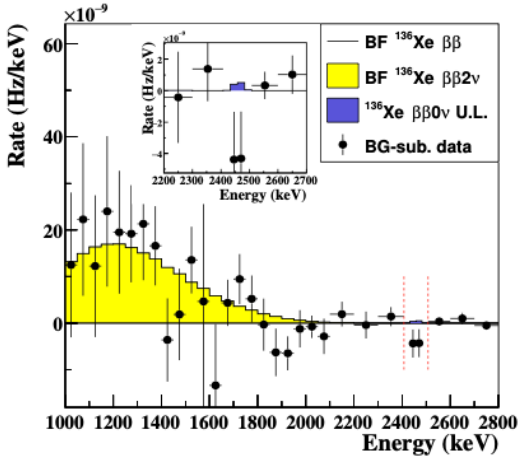
Compatible with experiments using more fiducial mass:
EXO-200: $\sim 66.20\ kg$, *Phys. Rev. C* 89, 015502 (2014)
KamLand-Zen: $\sim 86.25\ kg$, *Phys. Rev. Lett.* 122, 192501 (2019)

$0\nu\beta\beta$ search: beyond the main goals

Proof-of-concept, paves the way to larger detectors in the collaboration

No $0\nu\beta\beta$ signal is observed

$T_{1/2}^{0\nu} > 5.5{\times}10^{23} - 1.3{\times}10^{24}\ yr$



arXiv:2305.09435

NEXT-100 detector

Under construction since 2021 @ LSC, Canfranc, Spain

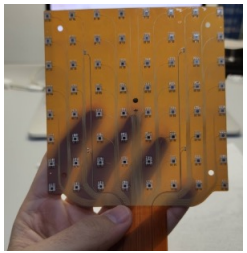
NEXT-100 detector

Design

~2:1 scale of NEXT-White

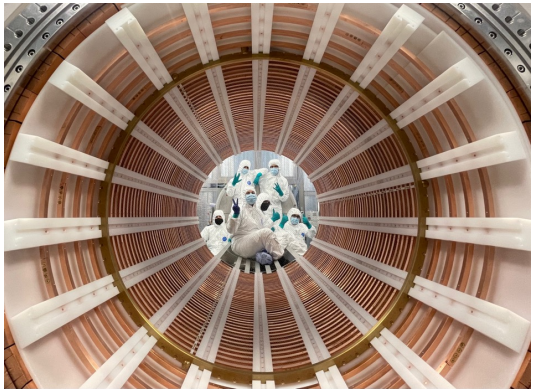
	NEW	NEXT-100
Drift length (cm)	50.7	118
Radius (cm)	20.8	49.2
EL region (mm)	6	10
Mass (kg)	4	80
# PMTs	12	60
# SiPMs*	1792	3584
SiPMs pitch (mm)	10	15.55
Anode	Plate	Mesh
ICS (cm)	0.6	1.2

*New Hamamatsu model S13372-1350TE SiPMs; more surface



Construction status

Field cage assembled and inserted into the pressure vessel (July 2023)

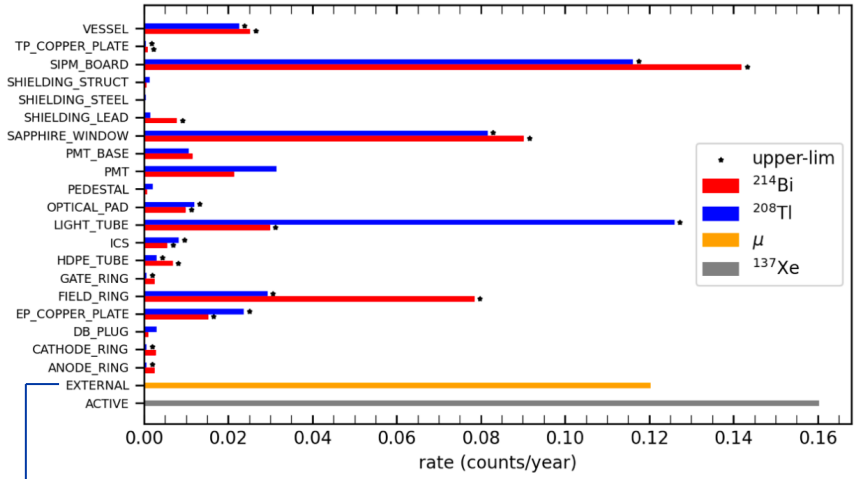


Comissioning & start to calibrate by the end of 2023

Objectives

- ❑ Maintain energy resolution of NEXT-White (>1% FWHM)
- ❑ Reduce background rate
- ❑ Search for $0\nu\beta\beta$ (expected ~10^{25} years)
- ❑ Prepare for the next phase: ton-scale detector

NEXT-100 sensitivity



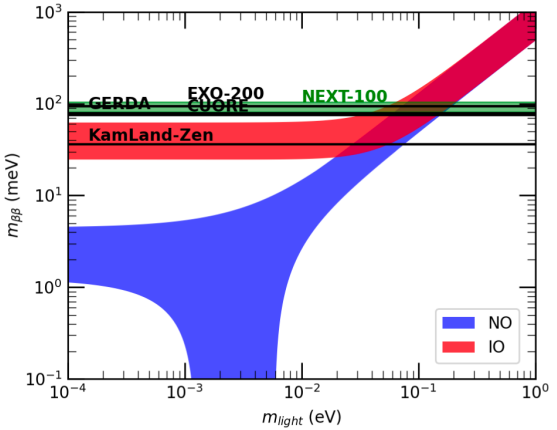
μ-veto
Up to 95% efficiency
1st half of 2024

NEXT-100 background model
with latest radioactivity measurements for the materials

~1 background counts/year after selection

Sensitivity (3 years of running time)

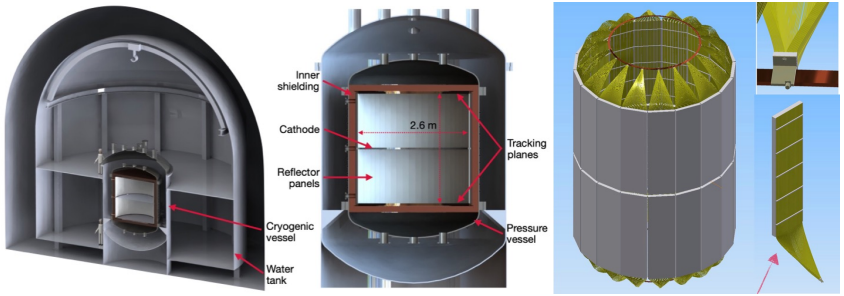
$$S\left(T_{1/2}^{0\nu}\right) > 4.15\times10^{25}\ yr\ @\ 90\%\ CL$$



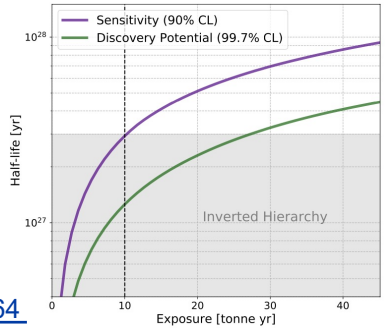
G. Díaz-López's thesis

NEXT-HD

Design
1 ton detector
Symmetric: 2 tracking planes, center cathode, barrel energy detector (optical fibers)

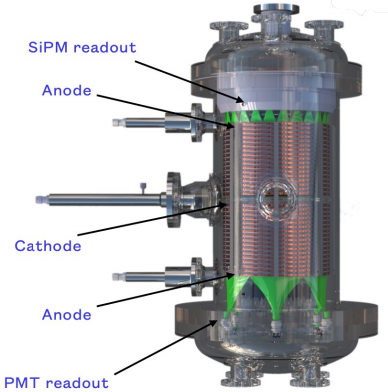


Sensitivity (5 years operating)
$1.4 \times 10^{27}\ yr\ (90\%\ CL)$

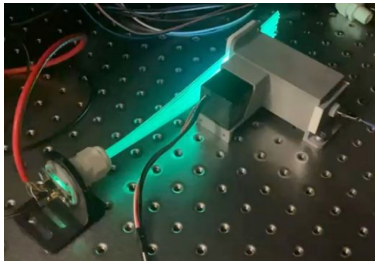


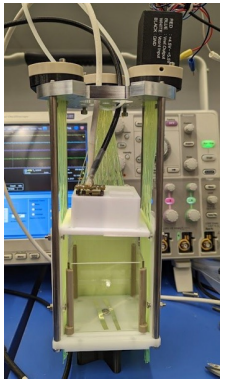
JHEP 2021 (2021) 08, 164

Prototype
HD-DEMO
2nd ½ of 2024



R&D
Optical WLS fibers





NEXT-BOLD

Barium tagging

$$^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^{-}(+2\bar{\nu}_e)$$

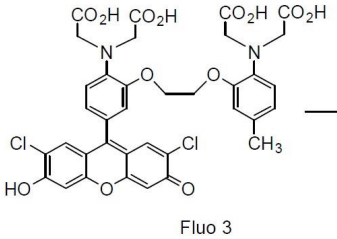
Identification of the ion

↓

Background free experiment

Fluorescent indicator

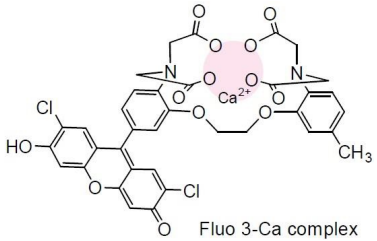
Not fluorescent



Fluo 3

Ca2+

Fluorescent

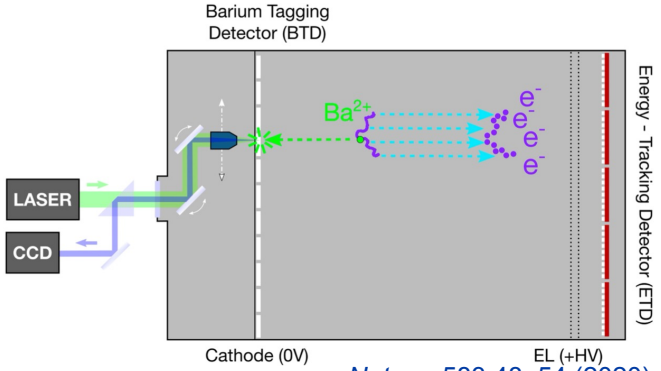


Fluo 3-Ca complex

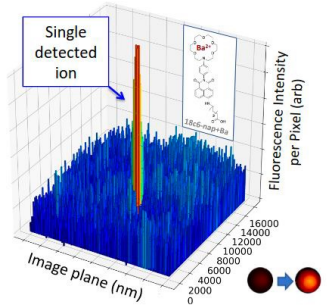
Molecule becames fluorescent when capturing the ion

D.R. Nygren, *J. Phys. Conf. Ser.* 650 (2015) 012002

Barium atOm Light Detector (BOLD)



Nature, 583 48–54 (2020)



Phys. Rev. Lett. 120 (2018) 132504

Summary

NEXT-White fulfilled its purpose:

- Detection concept was demonstrated at larger scales
- E resolution < 1% FWHM @ $Q_{\beta\beta}$
- Good background rejection
- Competitive $2\nu\beta\beta$ measurement

NEXT-HD plans:

- Symmetric detection concept
- R&D for optical fiber barrel
- Prototype HD-DEMO by the end of 2024

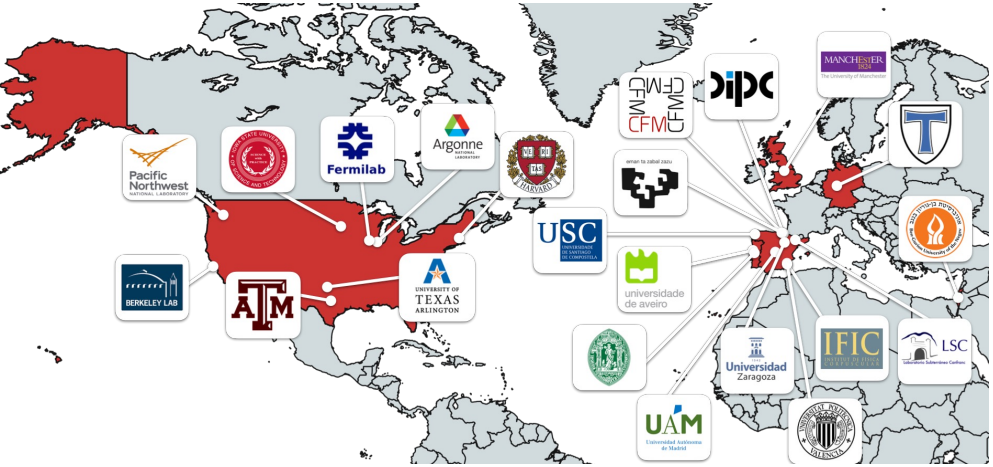
NEXT-100 under construction:

- Expected a competitive $0\nu\beta\beta$ search

NEXT-BOLD powerful technique:

- Background free method
- R&D for barium tagging

Thanks for your attention! Questions?



Backup

Neutrino detection

Inverse β decay

Scintillators:
Cowan-Reines, **KamLAND**, Borexino

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

>1.8MeV

Capture $\rightarrow \gamma$

$+ e^- \rightarrow 2\,\gamma$

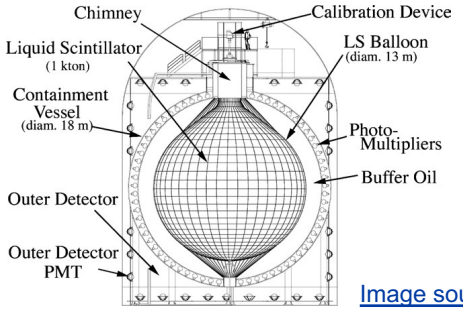


Image source

Homestake: $\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^+ + e^-$

$e^- - \nu_e$ scattering

Cherenkov light detectors:
Super-K, MiniBooNE, ANTARES, **IceCube**

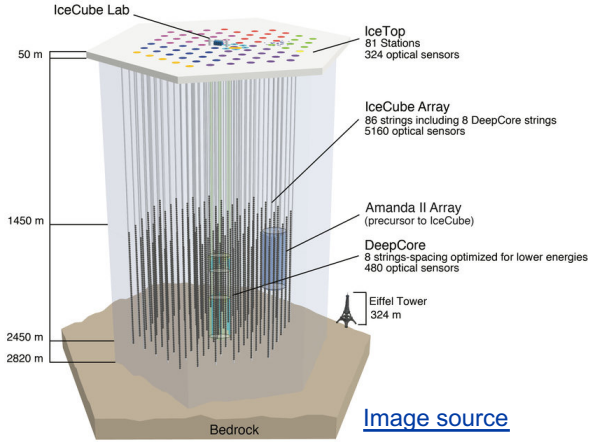


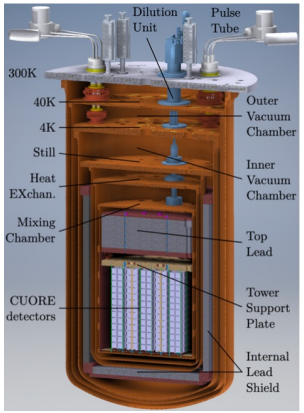
Image source

Other $0\nu\beta\beta$ experiments

Semiconductors:
GERDA (^{76}Ge) → LEGEND

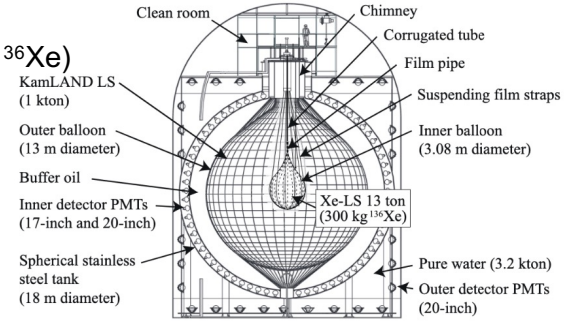
Eur. Phys. J. C 73 (2013) 2330

Bolometers:
CUORE (^{130}Te) → CUPID (^{100}Mo)

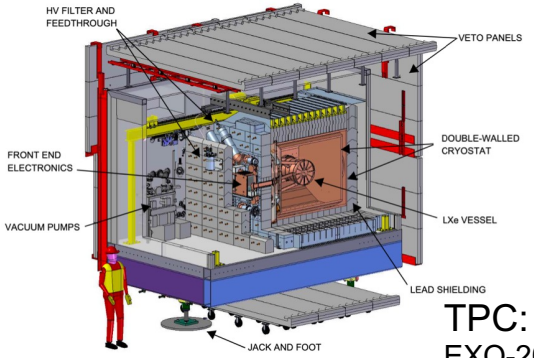


arXiv:1907.09376

Scintillators:
KamLand-Zen (^{136}Xe)



Phys.Rev.C 85:045504, 2012

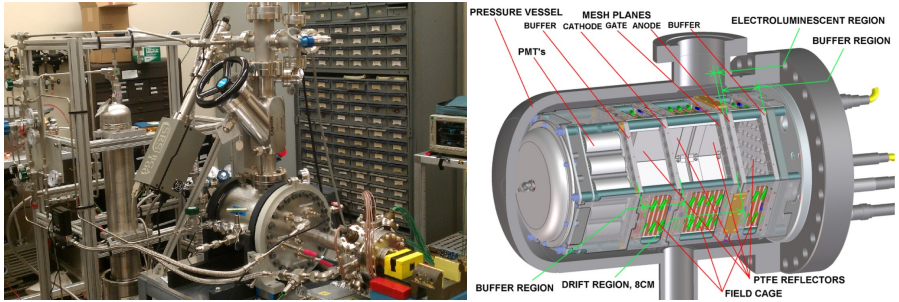


JINST 7 (2012) P05010

TPC:
EXO-200 (^{136}Xe) → nEXO

NEXT R&D detectors

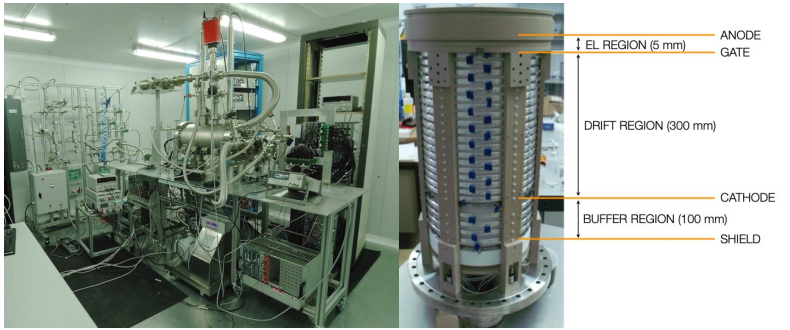
NEXT-DBDM



J. Renner's thesis

@LBNL, Berkeley, CA
10 L
Max 17 bar
Hexagonal, 6 cm apoth.
8 cm drift, 5 mm EL
19 PMTs
8x8 array of SiPMs

NEXT-DEMO



V. Álvarez et al.

@IFIC, Valencia, Spain
1 kg
Max 15 bar
15 cm radius
30 cm drift, 5 mm EL
3 PMTs (currently)
4 8x8 SiPM arrays

NEXT-White: $2\nu\beta\beta$ half-life

$$T_{1/2}^{2\nu} = \frac{\ln 2}{R} N_0 \epsilon$$

N_0: nº of ^{136}Xe atoms

ϵ: signal eff (DAQ, trigger, selection)

$m_{fid} = 3.50 \pm 0.01\ kg$

Trigger efficiency: $97.6 \pm 0.2\%$

	Run-V (enriched)	Run-VI (depleted)
^{136}Xe	$90.9 \pm 0.4\ \%$	$2.6 \pm 0.2\ \%$
DAQ time	$97.04 \pm 0.01\%$	$97.86 \pm 0.01\%$
$\beta\beta$ selection for 2e$^-$	$24.7 \pm 0.5\%$	$27.5 \pm 0.6\%$
$\beta\beta$ selection for 1e$^-$	$2.24 \pm 0.06\%$	$2.34 \pm 0.07\%$

NEXT-BOLD: fluorescent indicators