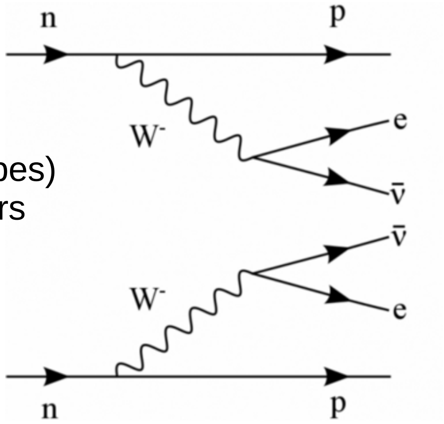
Towards neutrinoless double beta decay in NEXT

Gonzalo Díaz López
Universidad de Santiago de Compostela, Spain
(on behalf of the NEXT Collaboration)

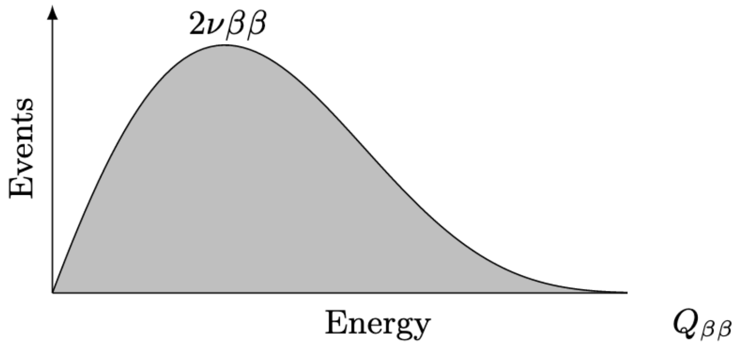
5th August, NuFact 2022 Conference
Salt Lake City, UT, EEUU

Double beta decay

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



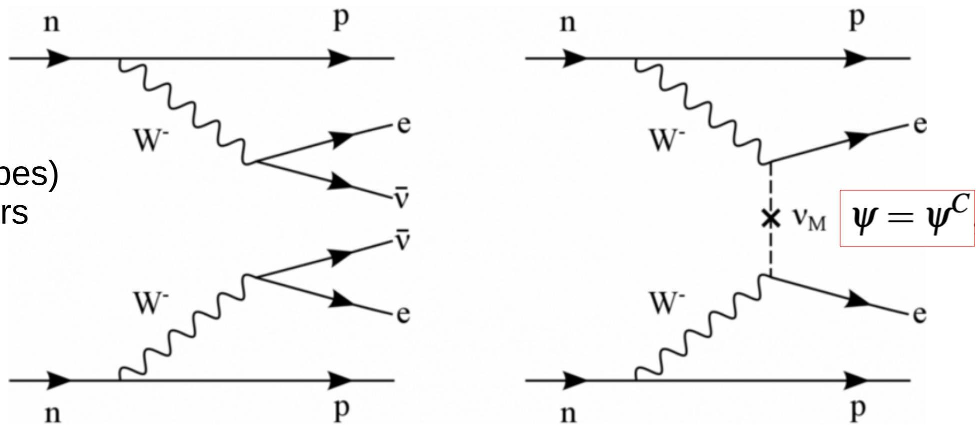
- Observed (11 isotopes)
- $T_{1/2} = 10^{19}$-10^{21} years



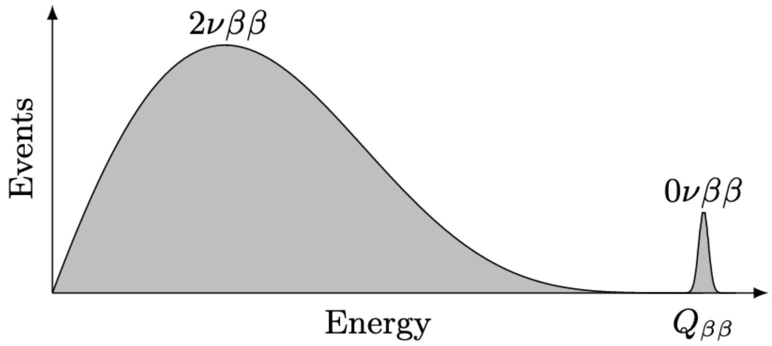
Majorana neutrinos and 0νββ

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

- Observed (11 isotopes)
- $T_{1/2} = 10^{19}$-10^{21} years



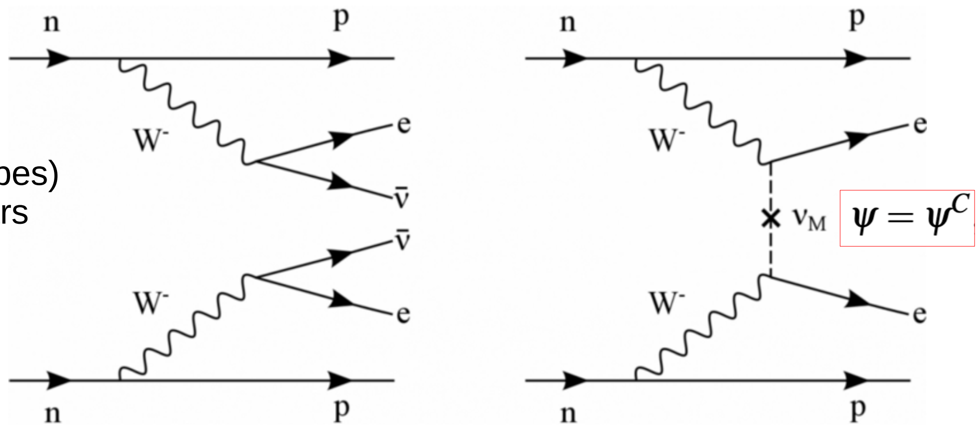
- Unobserved
- $T_{1/2} > 10^{26}$ years



Majorana neutrinos and 0νββ

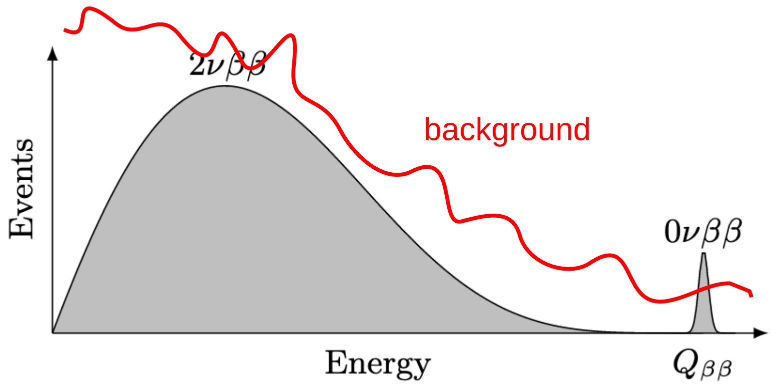
$$N(A,Z) \rightarrow N(A,Z+2) + 2e^{-} + \cancel{2\overline{\nu}_e}$$

- Observed (11 isotopes)
- $T_{1/2} = 10^{19}$-10^{21} years



- Unobserved
- $T_{1/2} > 10^{26}$ years

$$S(T_{1/2}^{0\nu\beta\beta}) \propto \epsilon_s \sqrt{\frac{t \cdot M}{b \cdot \Delta E}}$$

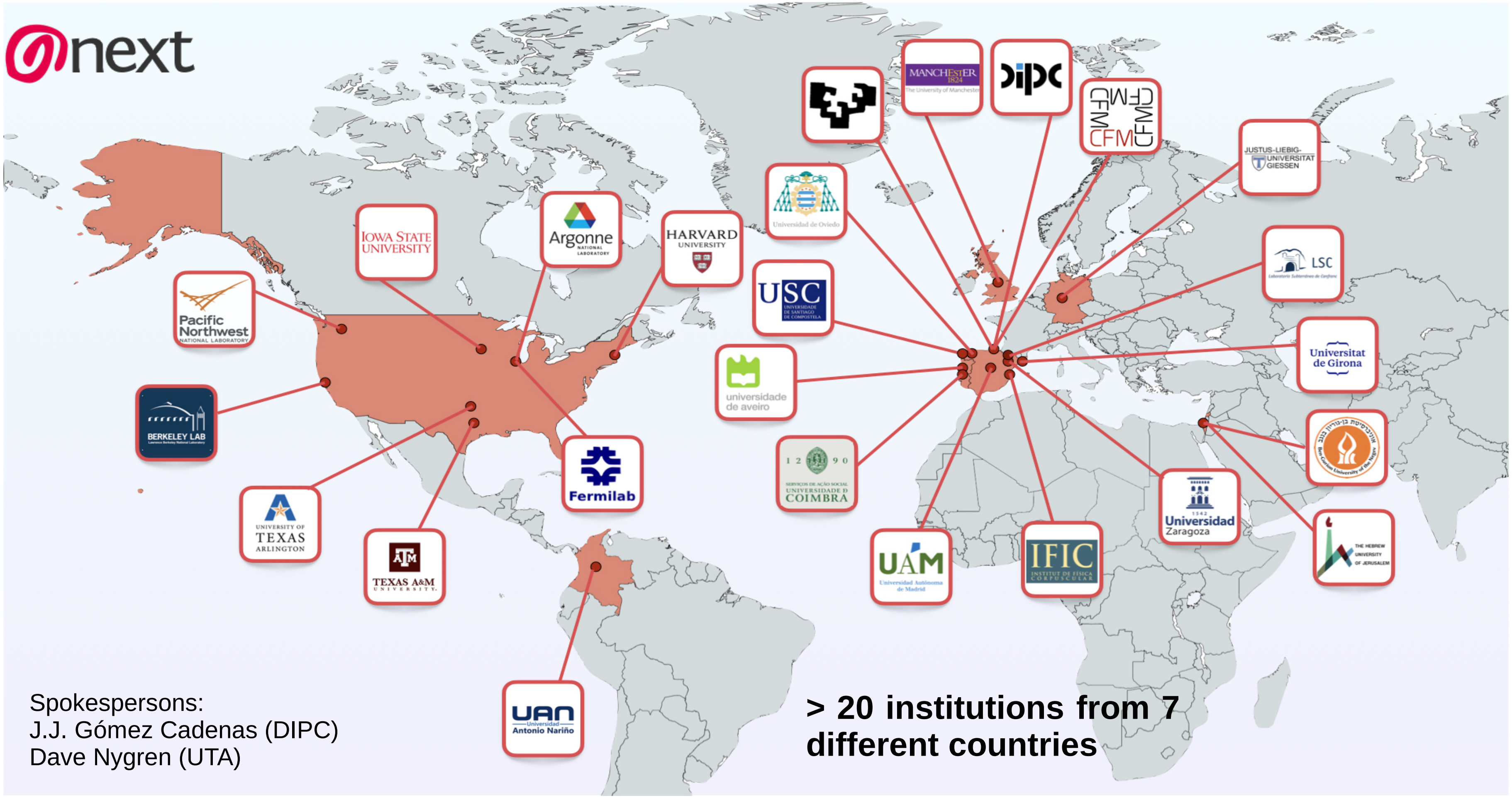


To improve sensitivity:
- Good energy resolution
- Active background discrimination
- Scalability

High pressure Xenon TPC!

NEXT Collaboration

Neutrino **E**xperiment with a **X**enon **T**PC

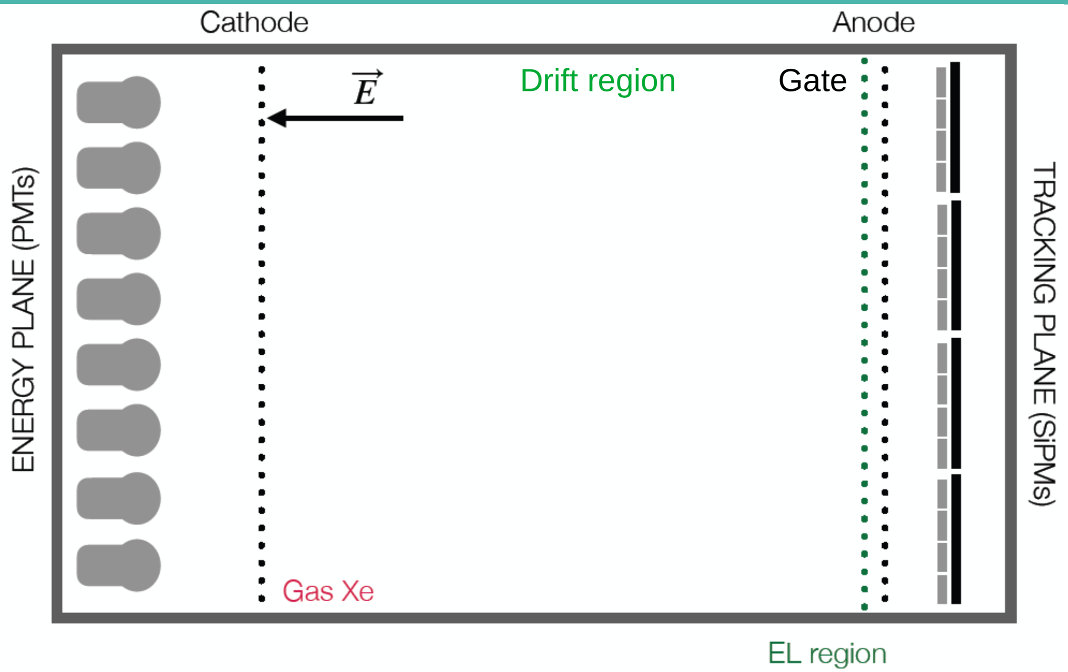


Spokespersons:
J.J. Gómez Cadenas (DIPC)
Dave Nygren (UTA)

> 20 institutions from 7 different countries

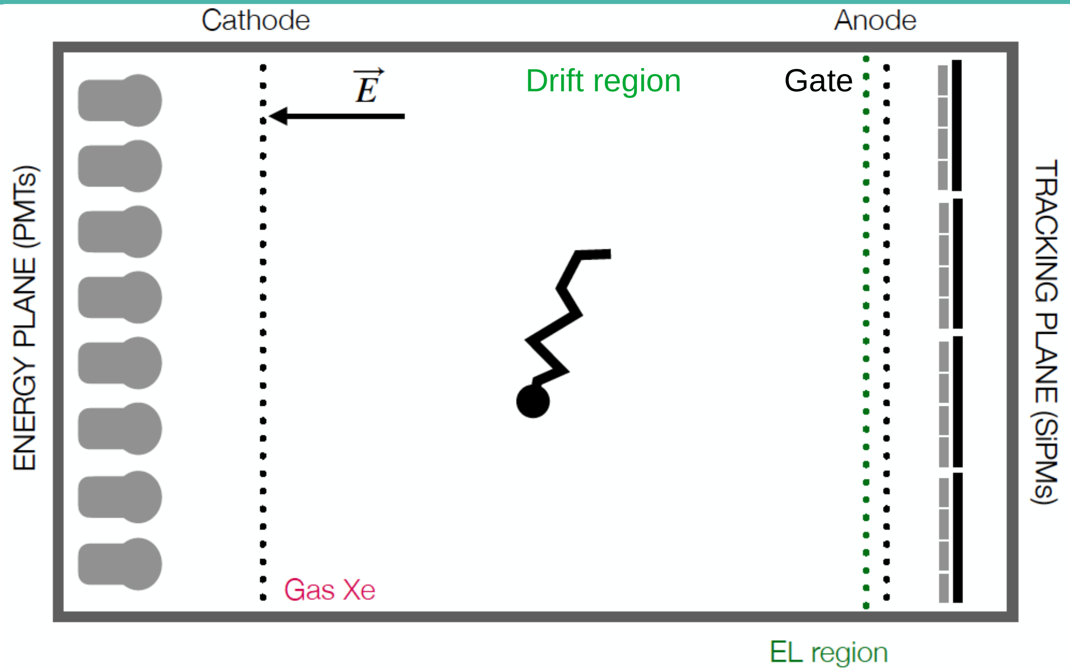
NEXT detection concept

- High pressure xenon (enriched to ^{136}Xe) TPC
- Asymetric configuration:
  - Energy plane (PMTs)
  - Tracking plane (SiPMs)



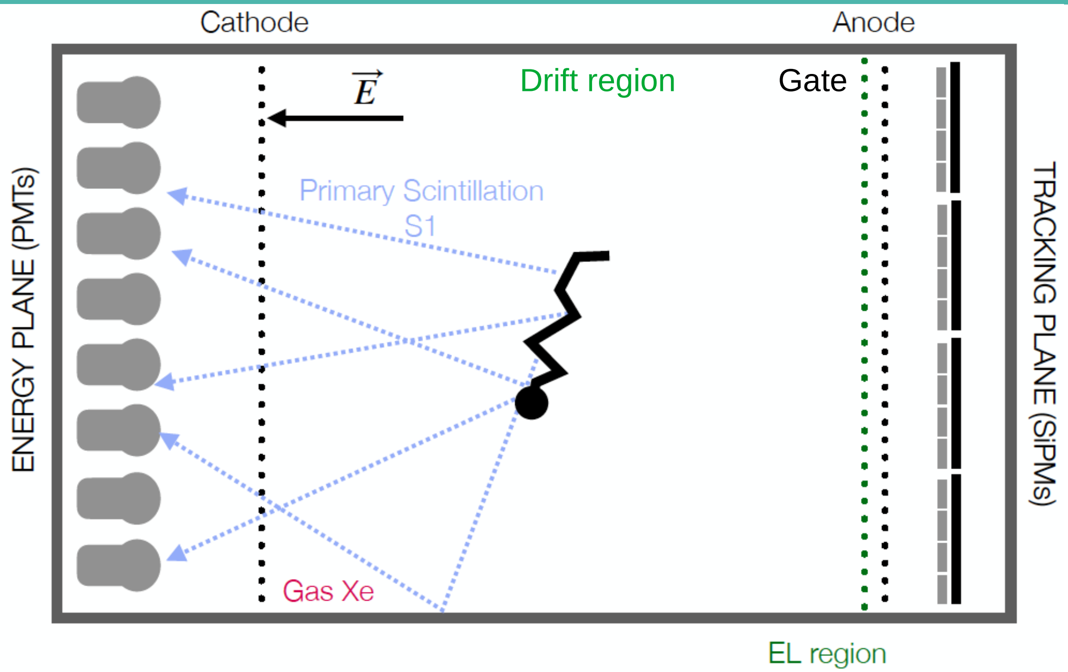
NEXT detection concept

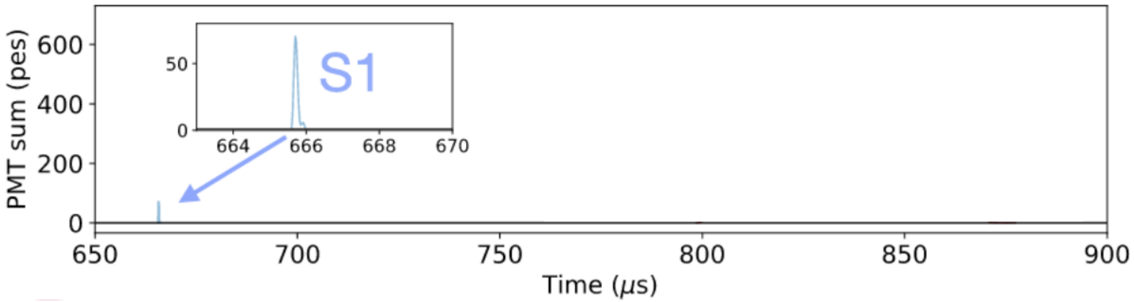
- High pressure xenon (enriched to ^{136}Xe) TPC
- Asymetric configuration:
  - Energy plane (PMTs)
  - Tracking plane (SiPMs)
- Electron track deposits energy in the form of scintillation and ionization electrons



NEXT detection concept

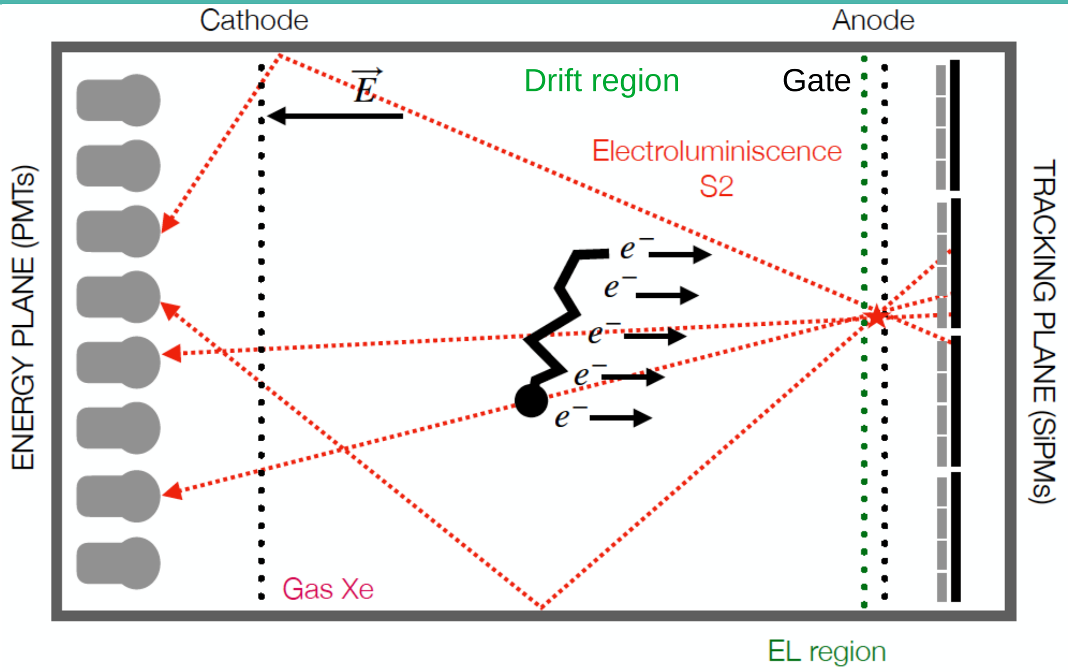
- High pressure xenon (enriched to ^{136}Xe) TPC
- Asymetric configuration:
  - Energy plane (PMTs)
  - Tracking plane (SiPMs)
- Electron track deposits energy in the form of scintillation and ionization electrons
- Scintillation light (S1) provides the start of event signal

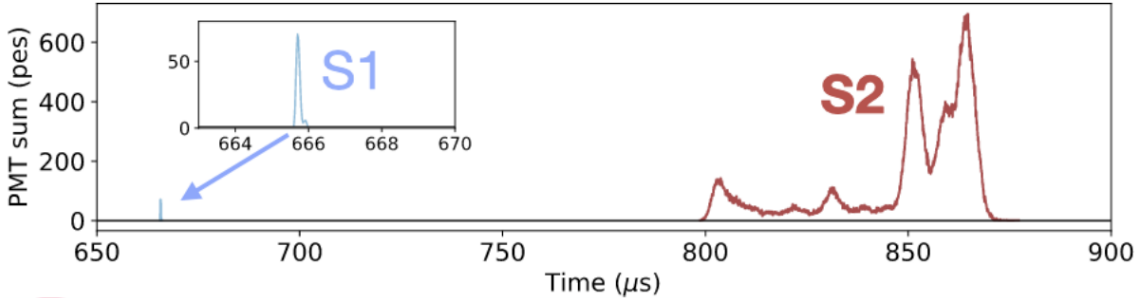




NEXT detection concept

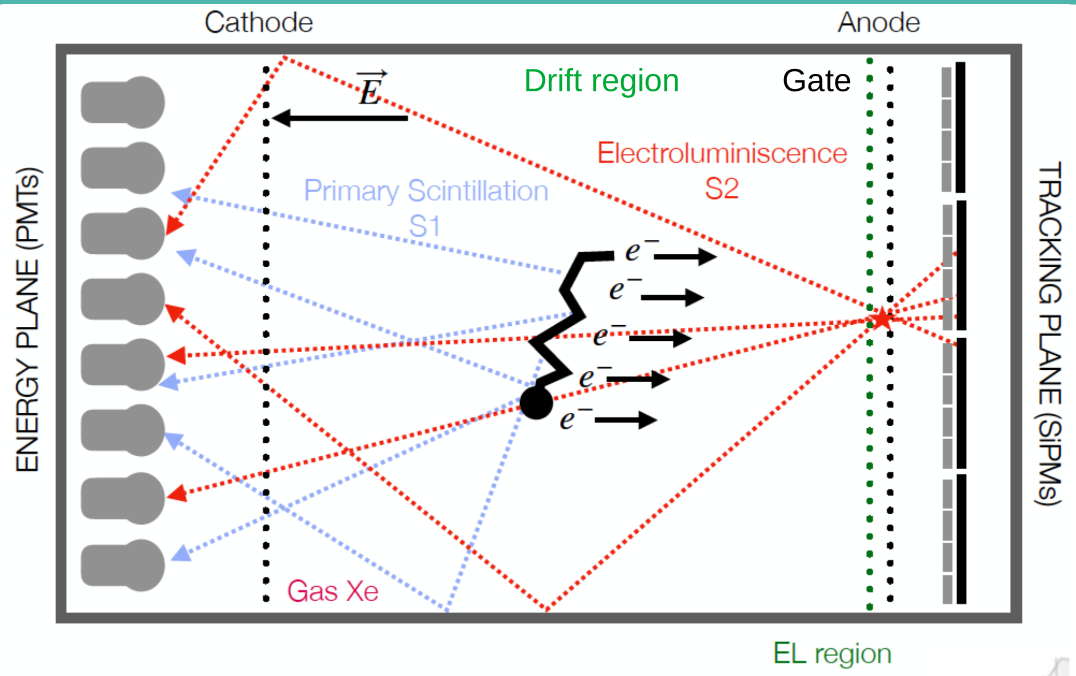
- High pressure xenon (enriched to ^{136}Xe) TPC
- Asymetric configuration:
  - Energy plane (PMTs)
  - Tracking plane (SiPMs)
- Electron track deposits energy in the form of scintillation and ionization electrons
- Scintillation light (S1) provides the start of event signal
- Ionization electrons are drifted towards the EL-region
- Electroluminescent light (S2) provides both energy and tracking measurements

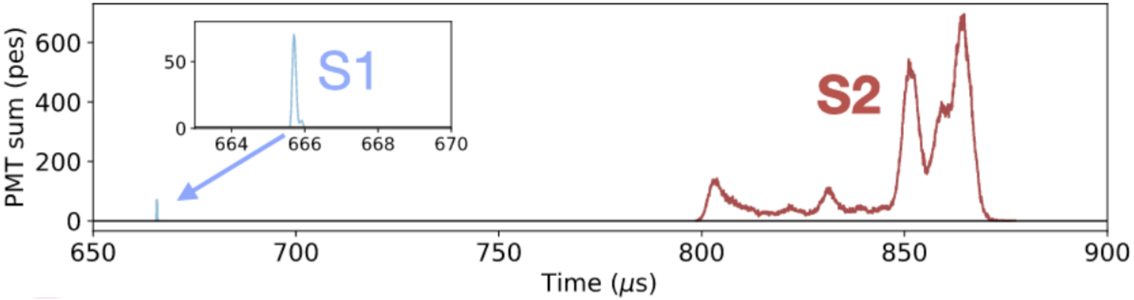


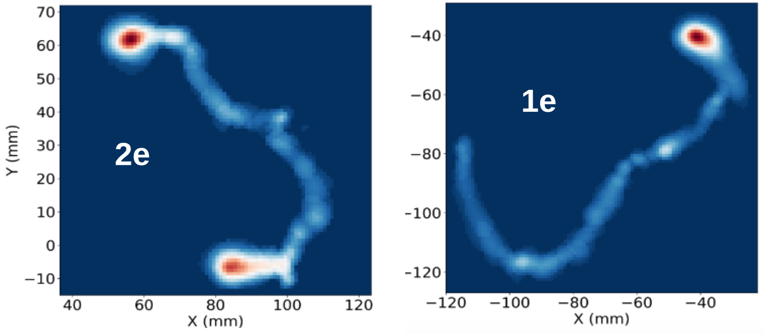


NEXT detection concept

- High pressure xenon (enriched to ^{136}Xe) TPC
- Asymetric configuration:
  - Energy plane (PMTs)
  - Tracking plane (SiPMs)
- Electron track deposits energy in the form of scintillation and ionization electrons
- Scintillation light (S1) provides the start of event signal
- Ionization electrons are drifted towards the EL-region
- Electroluminescent light (S2) provides both energy and tracking measurements
- 3D reconstruction
- Active background discrimination through Bragg peak





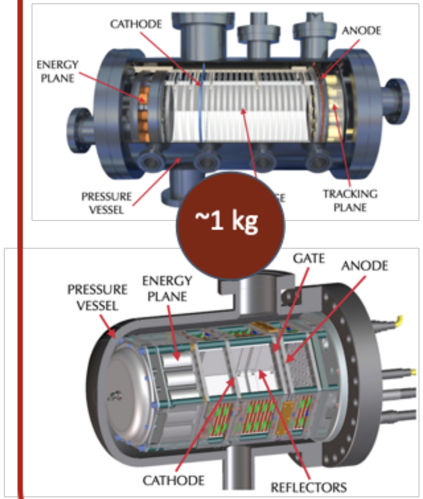


From NEXT-White data

NEXT experimental phases

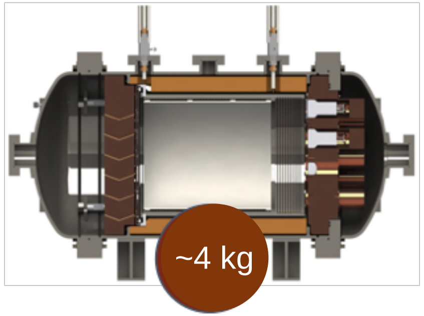
K.Mistry talk WG6: #76

Prototypes
2008-2014
Demonstration of detector concept



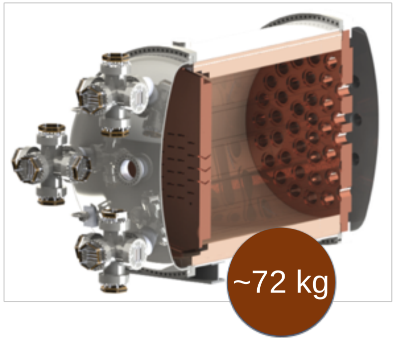
NEXT-White
2015-2021
Background model assessment

$2\nu\beta\beta$ measurement for ^{136}Xe



NEXT-100
2022-2025
Background model assessment

Neutrinoless double beta decay search in ^{136}Xe



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

NEXT-BOLD
Barium tagging for background-free experiment

2009 2014 2015 2021 2022 2025 2026

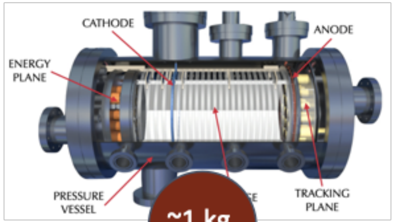
NEXT experimental phases

K.Mistry talk WG6: #76

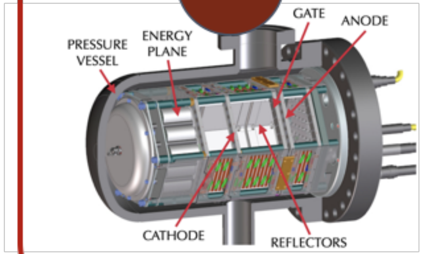
Prototypes

2008-2014

Demonstration of detector concept



~1 kg



NEXT-HD

2026?

Neutrinoless double beta decay search through inverted neutrino mass ordering

NEXT-BOLD

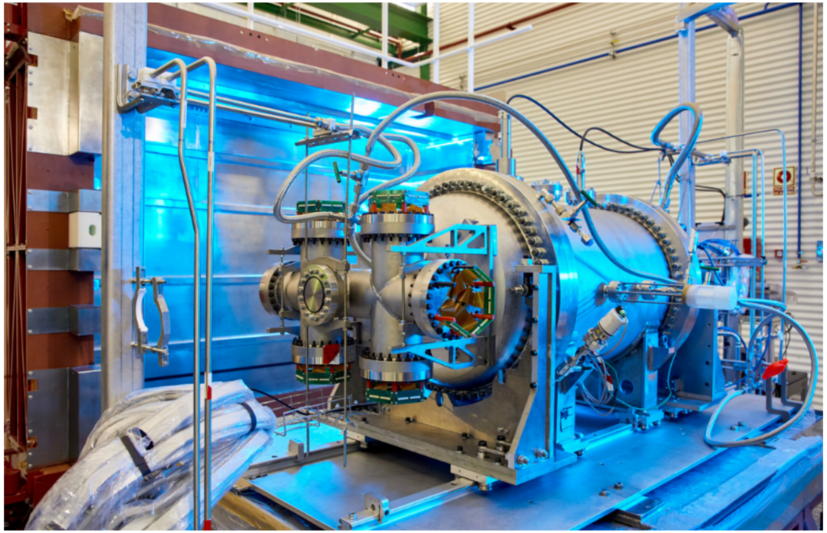
Barium tagging for background-free experiment

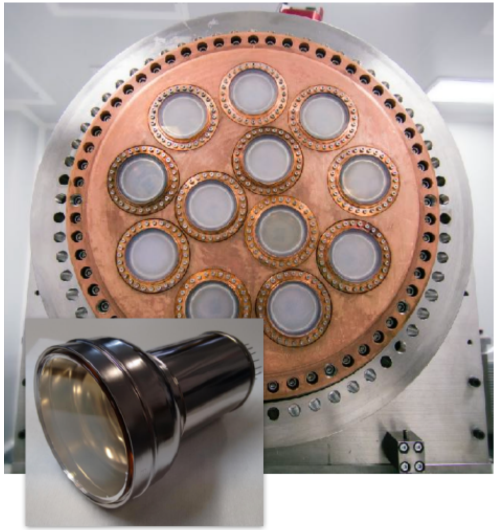
1 Tonne

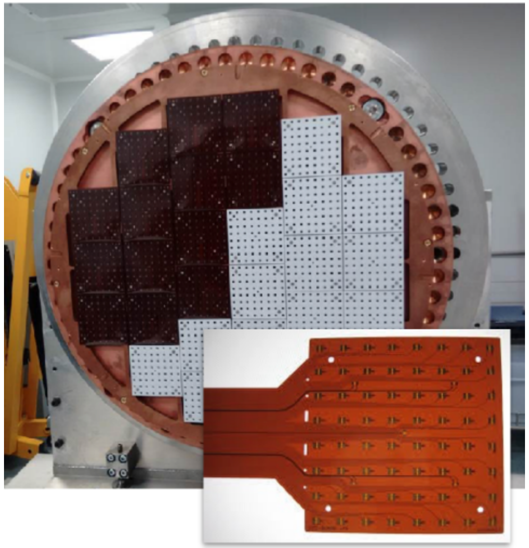
2009 2014 2015 2021 2022 2025 2026

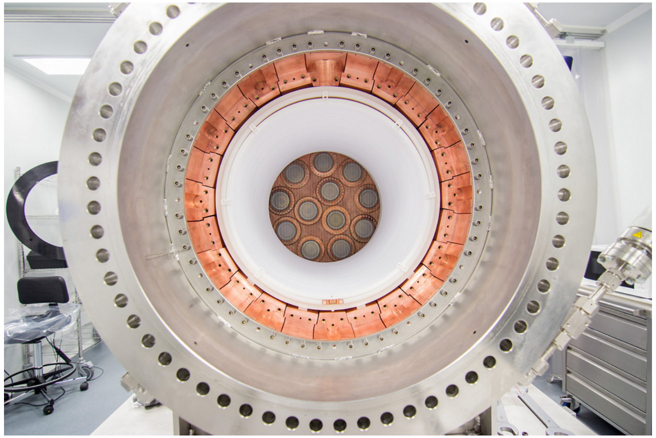
NEXT-White detector

- ~4 kg xenon (90% ^{136}Xe enrichment) at 10 bar
- ~50 cm length, ~20 cm radius, 6 mm EL-gap
- 12 Hamamatsu R11410-10 PMTs with 30% coverage
- 1792 (SensL) SiPMs at 1 cm pitch
- shielding: 20 cm thick lead castle, 6 cm thick inner copper









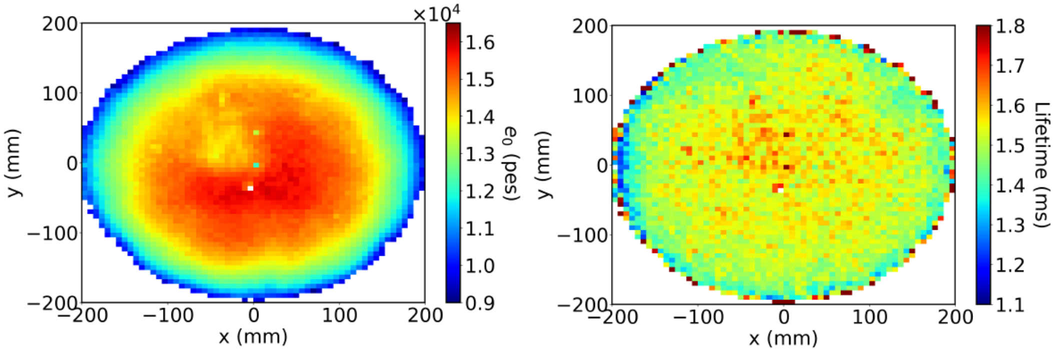
NEXT-White calibration and reconstruction

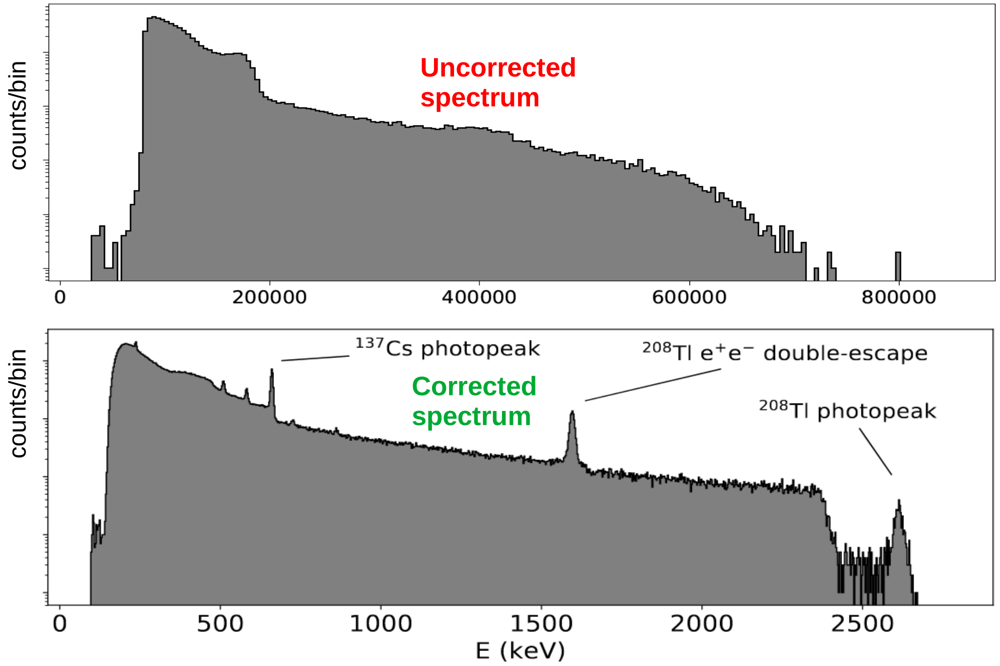
Low energy calibration

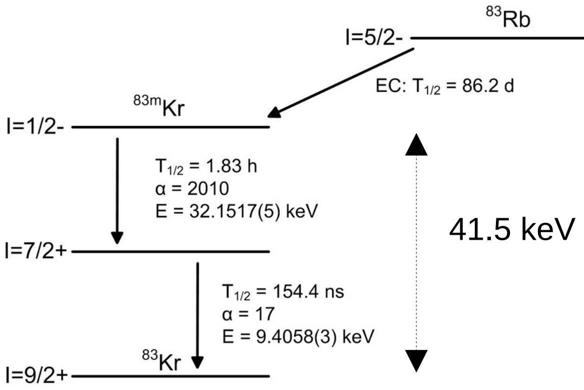
- Dual trigger DAQ (E<100 keV) and (E>400 keV)
- ^{83m}Kr from ^{83}Rb decay is introduced in the chamber
- ^{83m}Kr provides 41.5 keV point-like energy depositions, allowing the creation of:
  - Geometrical and lifetime **maps**: energy correction
  - Point spread function (**PSF**): diffusion deconvolution

Reconstruction

- Track hits are corrected using the ^{83m}Kr maps
- Track diffusion is deconvoluted using the ^{83m}Kr PSF

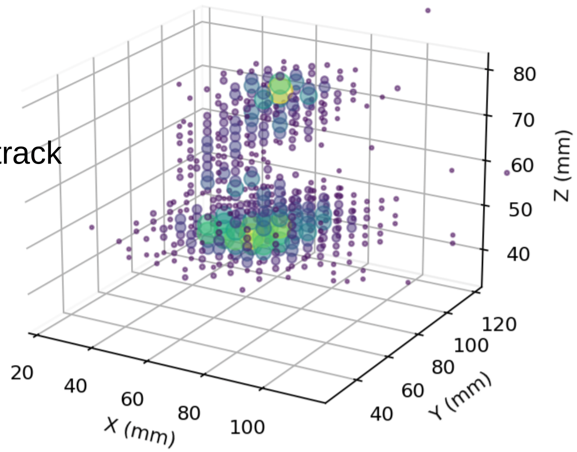






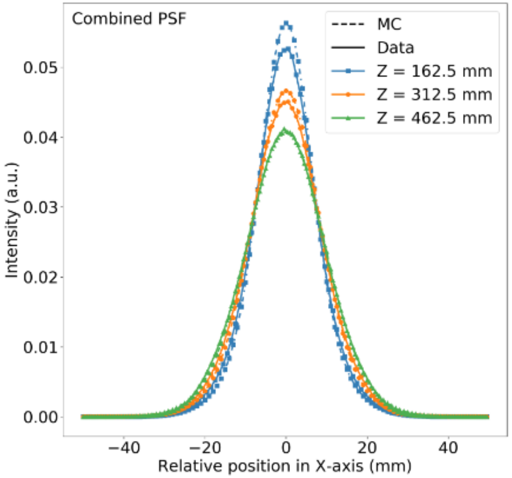
NEXT-White calibration and reconstruction

Raw diffused track

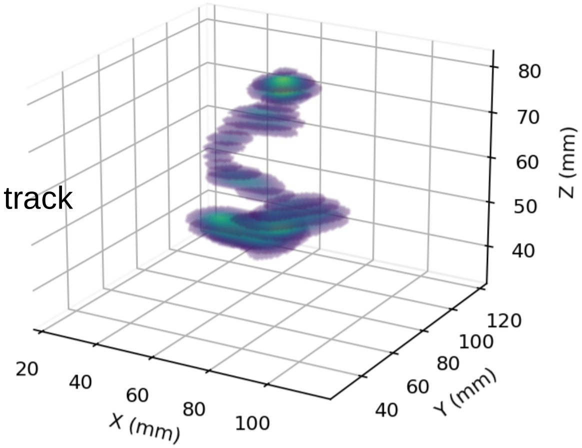


Lucy-Richardson deconvolution algorithm

^{83m}Kr PSF



Deconvoluted track



a) Energy resolution of (0.91 ± 0.07)% FWHM at 2.6 MeV (near $Q_{\beta\beta}$)

JHEP 10 (2019) 230

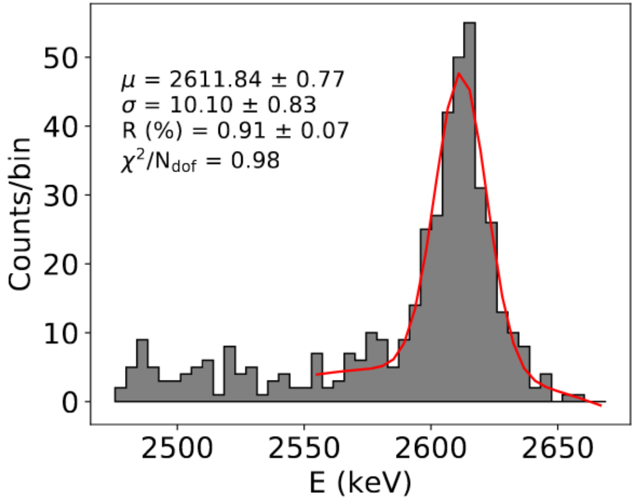
b) Demonstration of signal vs background rejection via topological discrimination in data using 1.6 MeV double escape peak of ^{208}Tl.

JHEP 10 (2019) 52; JHEP 01 (2021) 189; JHEP 07 (2021) 146

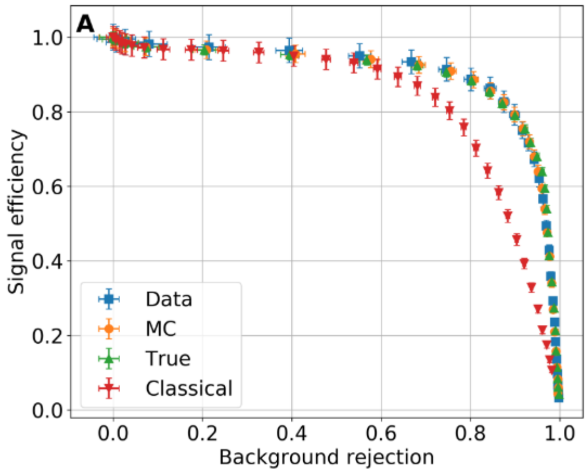
c) Validation of the background model and measurement of $2\nu\beta\beta$ half-life

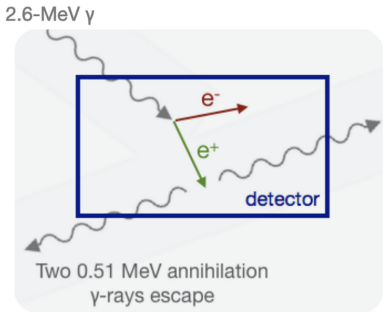
JHEP 10 (2019) 51; **Phys. Rev. C 105, 055501 (2022)**

a) ~2.6 MeV ^{208}Tl photo-peak

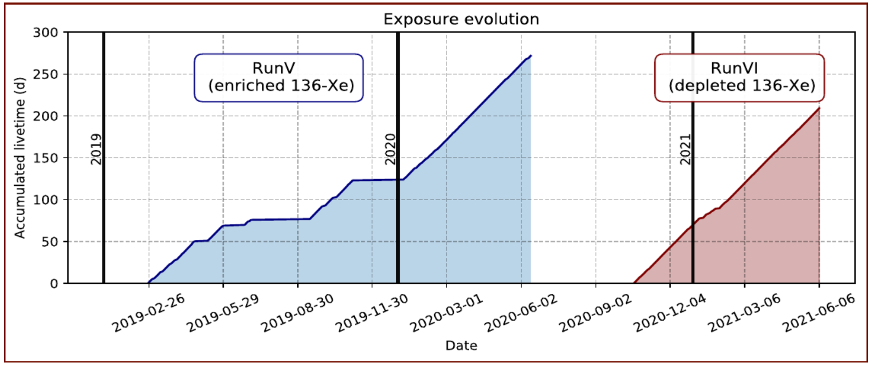


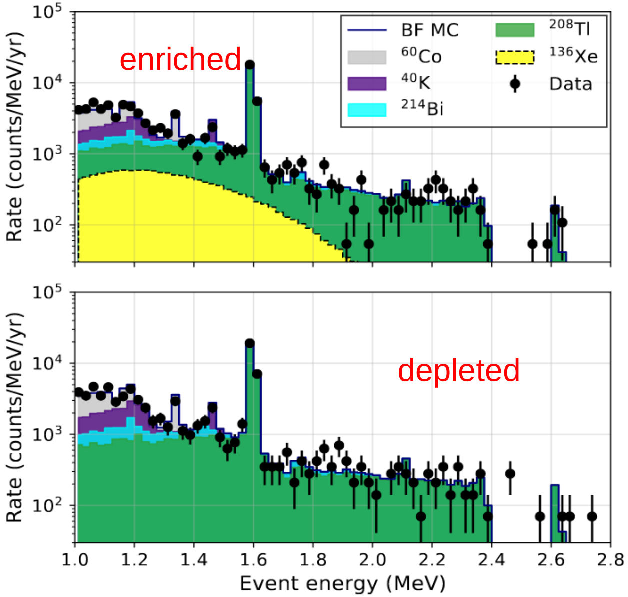
b) ROC curve for ^{208}Tl double-escape-peak



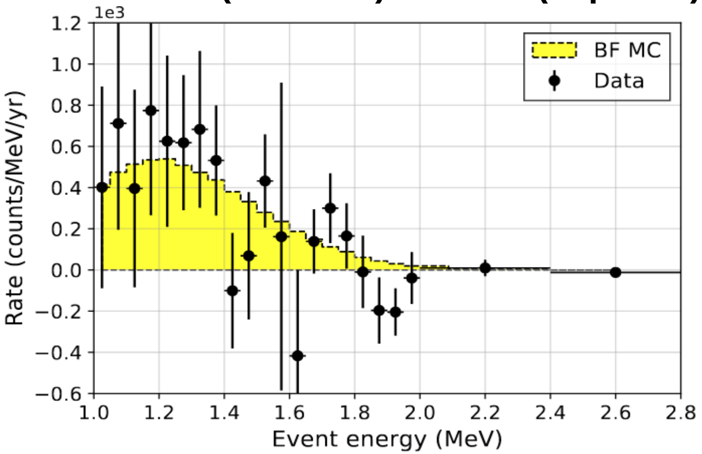


c) Measurement of 2νββ half-life
- signal selection: single-track + topological
- ~4σ significance
- compatible with EXO-200 and KamLand-Zen
- new background subtraction technique between enriched and depleted runs



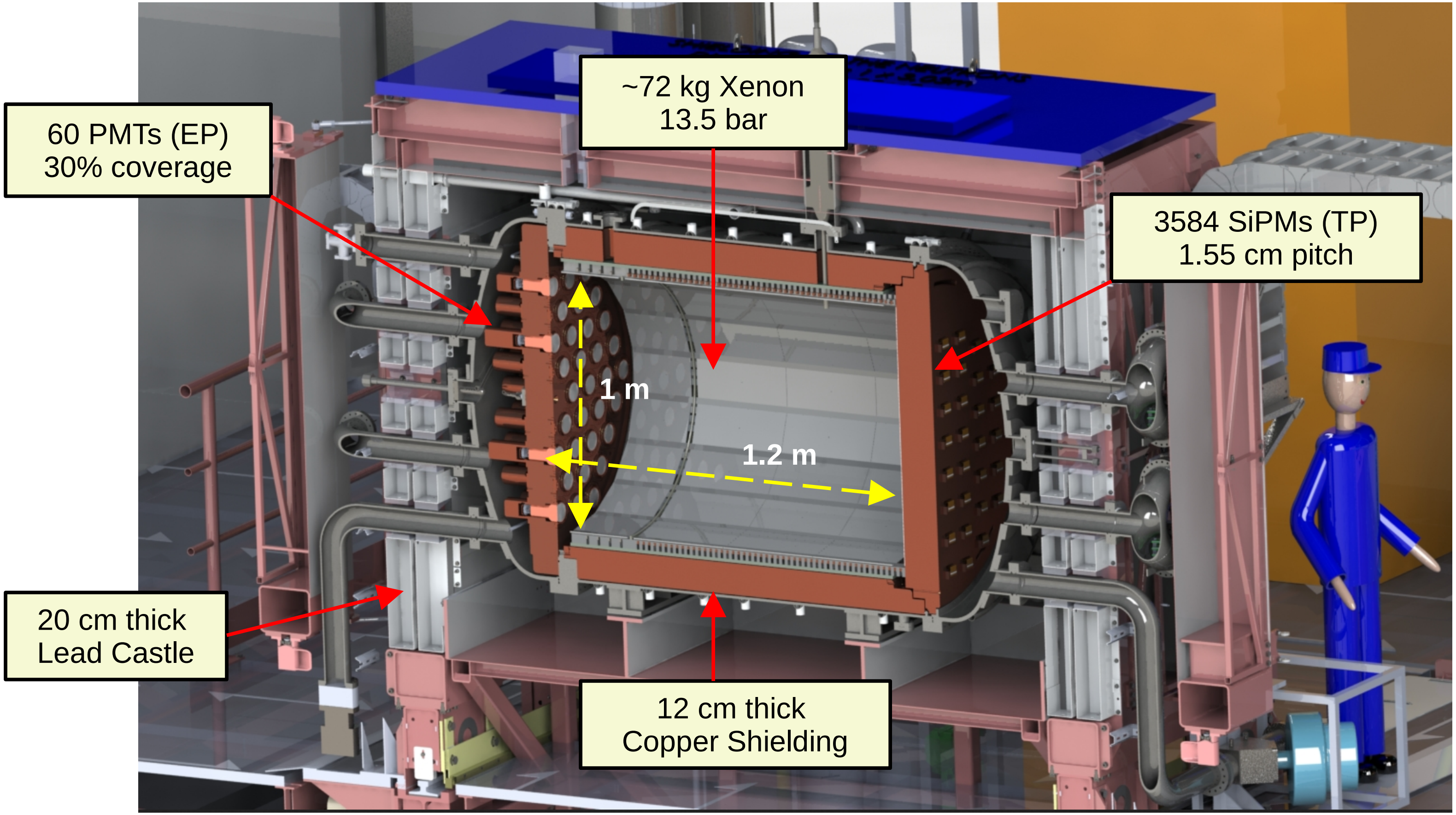


Run V (enriched) - Run VI (depleted)



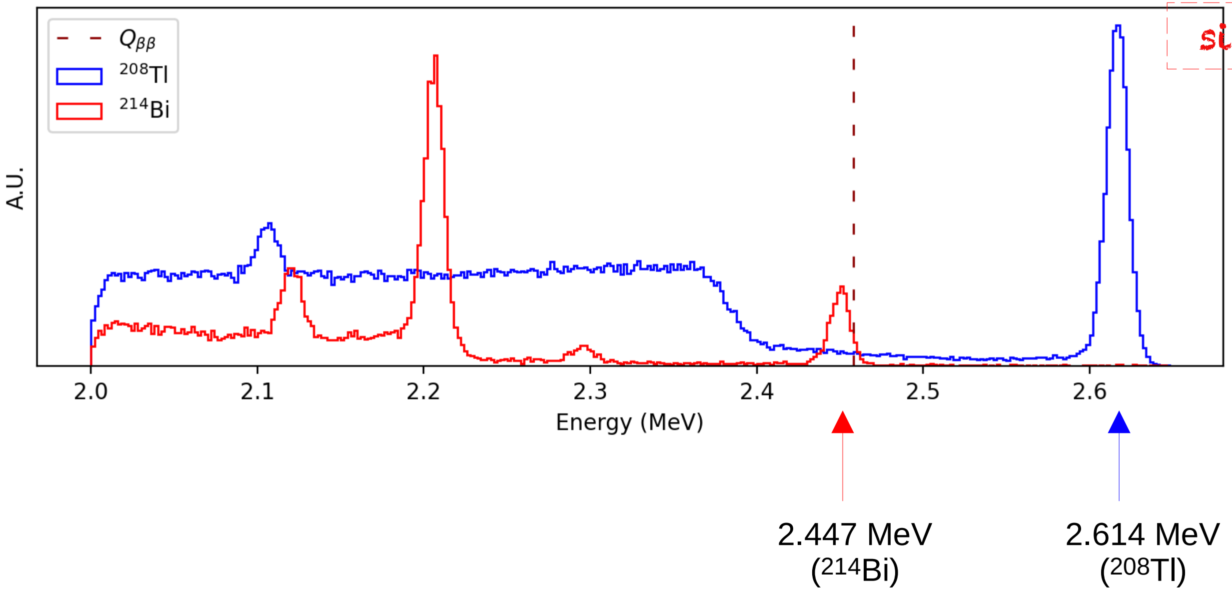
$$T_{1/2}^{2\nu\beta\beta} = 2.34^{+0.80}_{-0.46}(\text{stat.})^{+0.30}_{-0.17}(\text{sys.}) \times 10^{21} \text{ years}$$

Under construction at LSC!



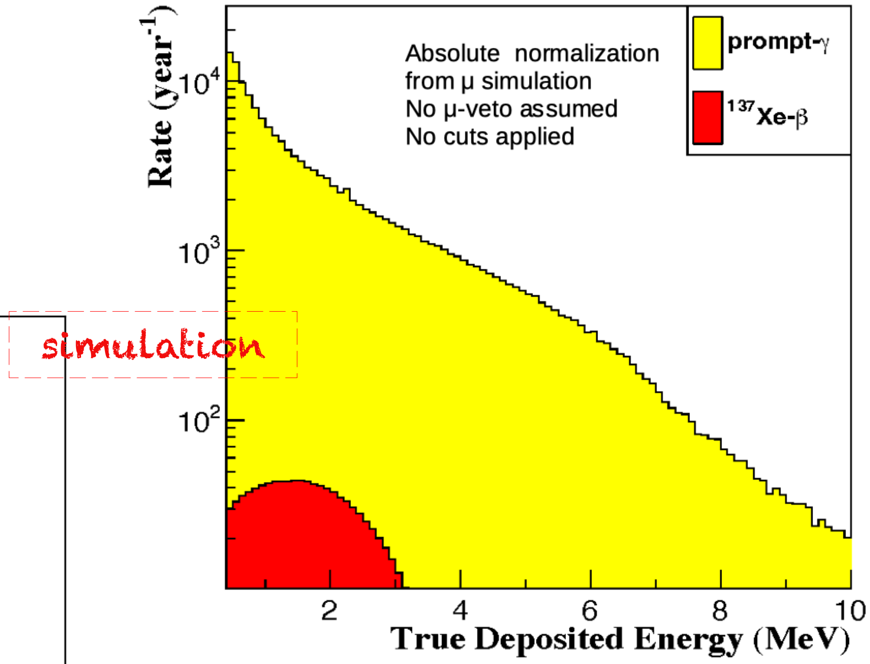
- **Radiogenic from detector materials**: ^{208}Tl and ^{214}Bi from natural U and Th chains
- **Cosmogenics**: prompt-gammas from neutron activations in detector materials and long lived ^{137}Xe activations
- **External radon**: negligible, clean air fluxed from RAS system at LSC
- **External gammas from lab rocks**: negligible, lead castle shielding
- **External neutrons from lab rocks**: negligible (neutron absorber)
- **2νββ**: negligible (end-point at ~2.3 MeV)

Radiogenics



Cosmogenics

mostly ^{64}Cu (84%), ^{66}Cu (11%) activations

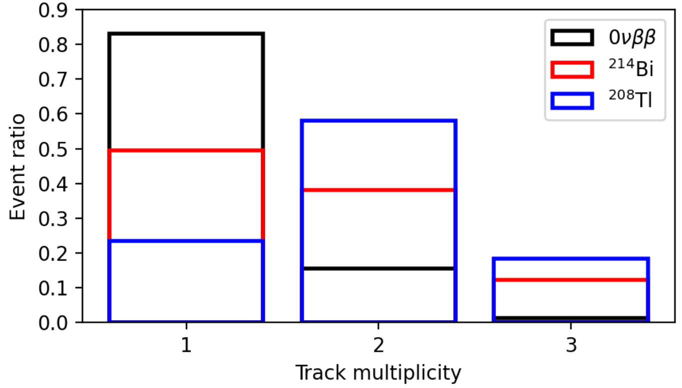


Muon contribution expected to be on the same order of magnitude as radiogenics. Muon veto to be installed on lead castle outer surface.

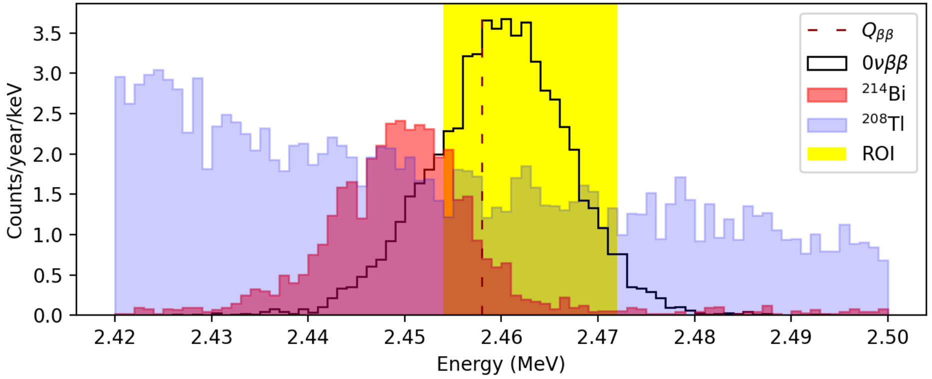
Preliminary

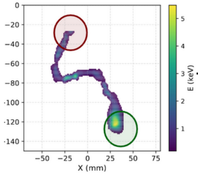
- Simulation (GEANT4) of ^{208}Tl, ^{214}Bi, muons and 0νββ to estimate the NEXT-100 sensitivity (counting experiment)
- Signal selection cuts (after reconstruction and fiducialization): (1) single-track + (2) ROI + (3) topology

(1) 1-track

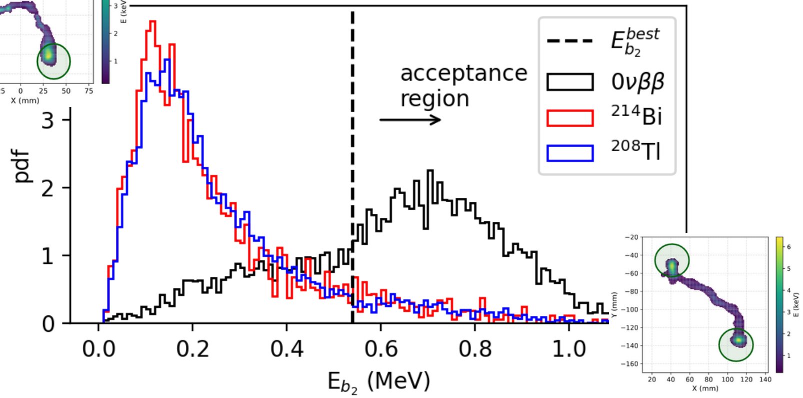


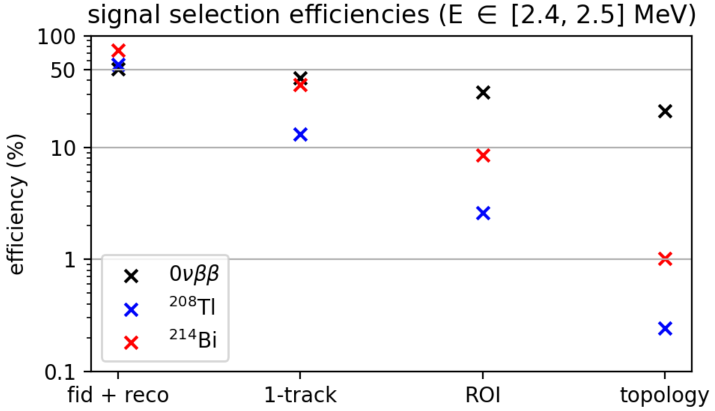
(2) ROI





(3) topology





Signal eff 21%
Background eff 0.1-1%

efficiencies w.r.t events that deposit a total energy in the 2.4-2.5 MeV window in the active volume

NEXT-100 sensitivity

preliminary

- Estimated background rate from radiogenic origin (radiopurity measurements + simulation) **< 3.6 counts/year**
- Estimated background rate from cosmogenic origin (flux + simulation) ~ **0.9** (prompt-γ, 90% eff μ-veto) + **0.3** (^{137}Xe) **counts/year**

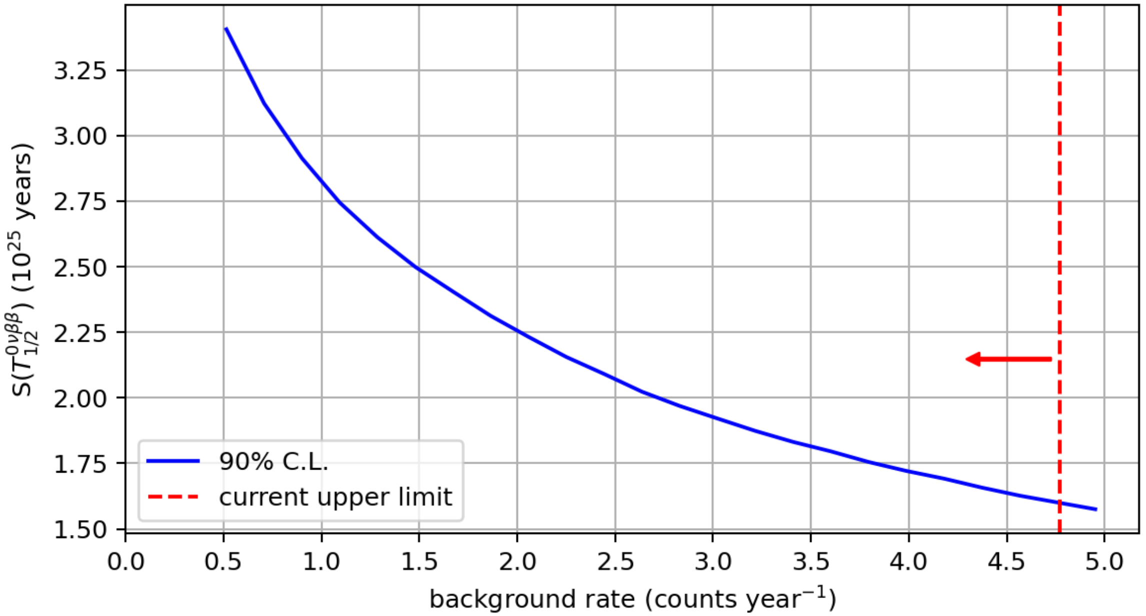
tentative NEXT-100 running time: **3 years**

^{136}Xe atoms: **72 kg @ 90%**

$$S(T_{1/2}^{0\nu\beta\beta}) = \log(2) \cdot \epsilon_s \cdot \frac{t \cdot N_0}{S(b)}$$

signal eff: **21 %**

background mean C.I.



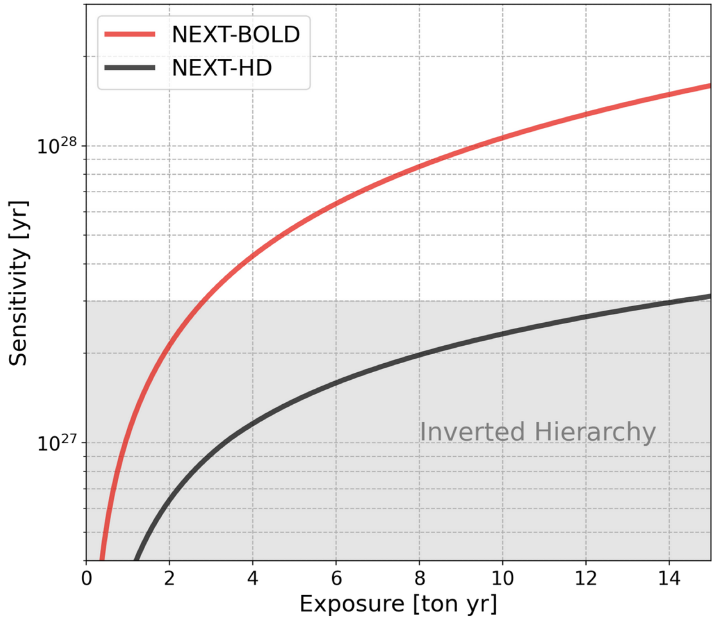
$$S(T_{1/2}^{0\nu\beta\beta}) > 1.6 \times 10^{25} \text{ years}$$

Summary and Future

- NEXT-White demonstration of main ingredients for a successful $0\nu\beta\beta$ experiment: calibration and reconstruction methods that provide the achievement of a good energy resolution and topological discrimination
- NEXT-100 in advanced construction state, to start operation at the end of this year 2022
- NEXT-100 background model under construction: background rate **< 4.8 counts/year** ($3.7 \cdot 10^{-3}$ counts/(keV·kg·year))
- NEXT-100 sensitivity to $0\nu\beta\beta$ similar to closest ^{136}Xe TPC competitor EXO-200 ($> 3.5 \cdot 10^{25}$ years @ 90% C.L.)

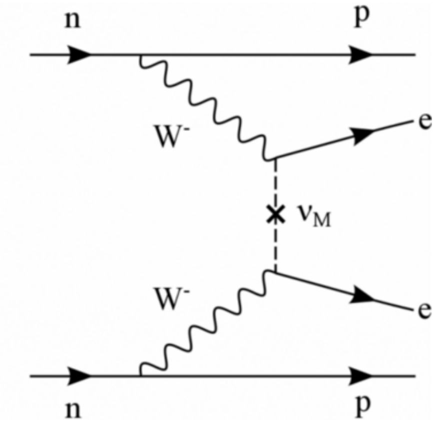
$0\nu\beta\beta$: $^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^{-}$

- NEXT-Collaboration has probed $^{136}Ba^{2+}$ tagging with the development of custom molecules
- NEXT Collaboration already in R&D for a future tonne scale detector NEXT-HD and NEXT-BOLD
  - NEXT-HD: tonne scale without Ba-tagging
  - NEXT-BOLD: tonne scale with Ba-tagging



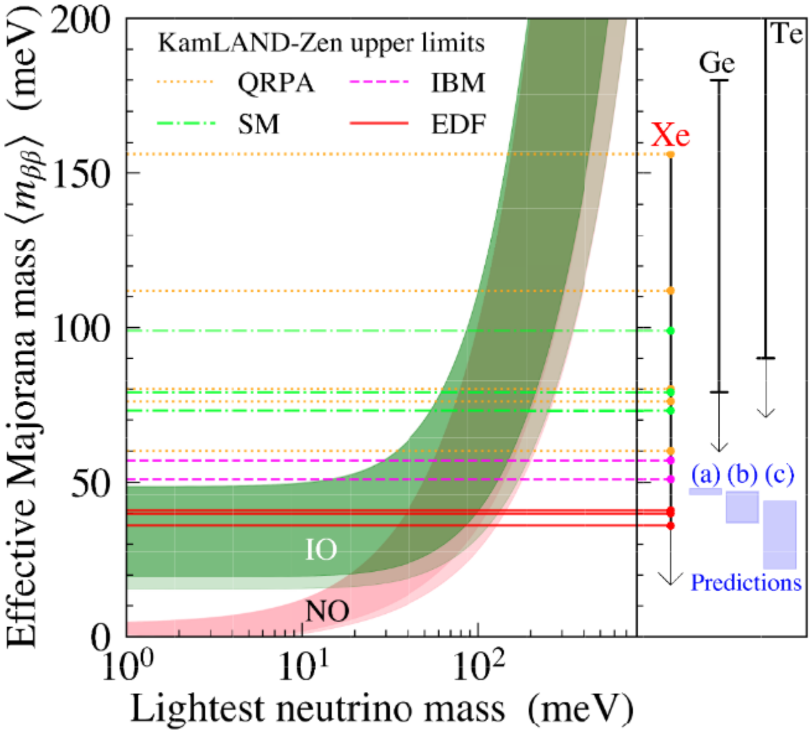
Thanks for your attention

BACKUP



$$[T^{0\nu}_{1/2}(N)]^{-1} = G^N_{0\nu}|M^N_{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$$m_{\beta\beta} \equiv |\sum_{k=0}^{3} U^2_{ek} m_k|$$



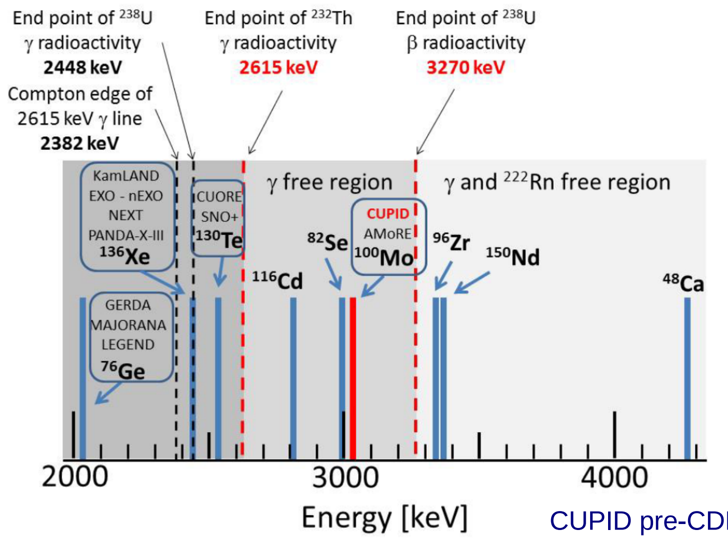
Current 0νββ generation of experiments

$$S(T_{1/2}^{0\nu\beta\beta}) \propto \epsilon_s \sqrt{\frac{t \cdot M}{b \cdot \Delta E}}$$

Requirements of a 0νββ experiment

- Good signal detection efficiency
- Large exposure (scalability)
- Good energy resolution
- Low background

9/11 possible isotopes with Qββ ~2-3 MeV



CUPID pre-CDR

Fluid embedded source — Large source mass, Easily scalable

1. KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen
2. EXO-200 → nEXO
3. NEXT-White → NEXT-100 → NEXT-HD/NEXT-BOLD
4. SNO+ → SNO+-phase II

Crystal embedded source — High energy resolution / efficiency

5. GERDA, MAJORANA dem. → LEGEND-200 → LEGEND-1000
6. CUPID-Mo, CUPID-0, CUORE → CUPID → CUPID Reach / CUPID 1t
7. AMORE-I → AMORE-II

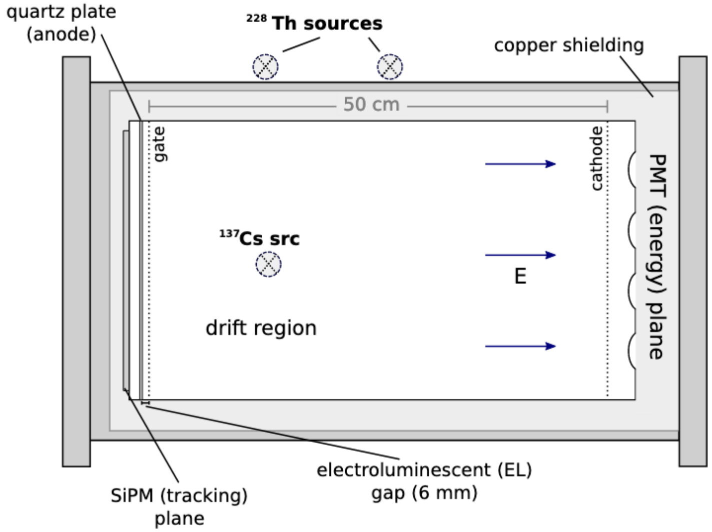
Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

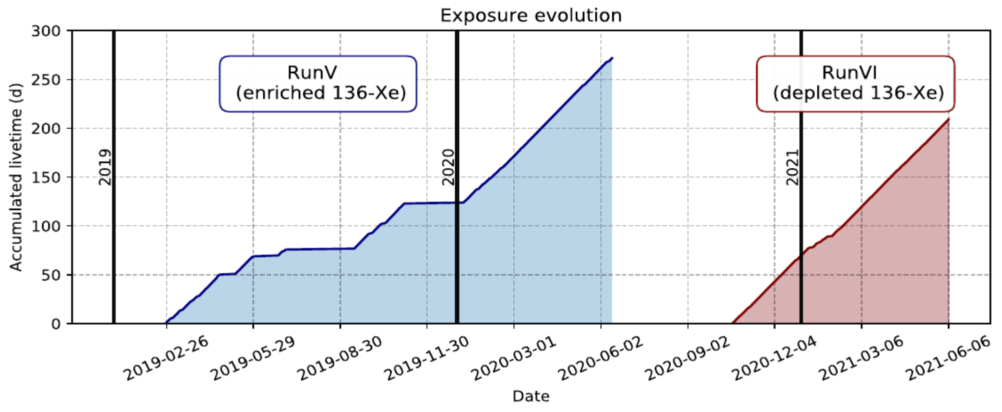
A. Giuliani, North America - Europe Workshop on Future of Double Beta Decay (9/2021)

NEXT-White operation

Data taking periods

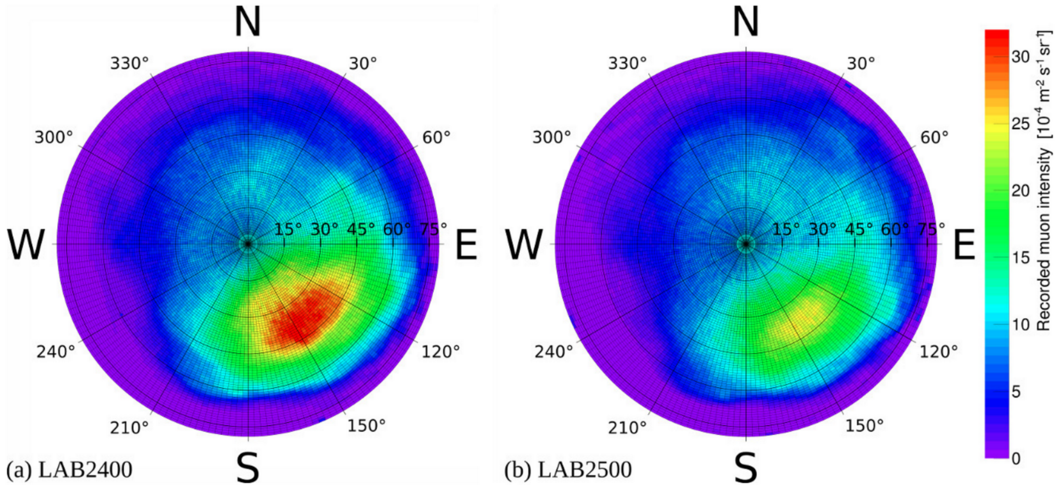
- Calibration runs 2017-2018: energy resolution, energy scale and topological discrimination
  - Low energy calibration and monitoring using ^{83m}Kr
  - High energy calibration (energy scale) using ^{228}Th and ^{137}Cs
- Low background physics runs: background model and $2\nu\beta\beta$
  - **Run V** (2/19-6/20) Enriched: bkg + $2\nu\beta\beta$
  - **Run VI** (10/20-6/21) Depleted: bkg

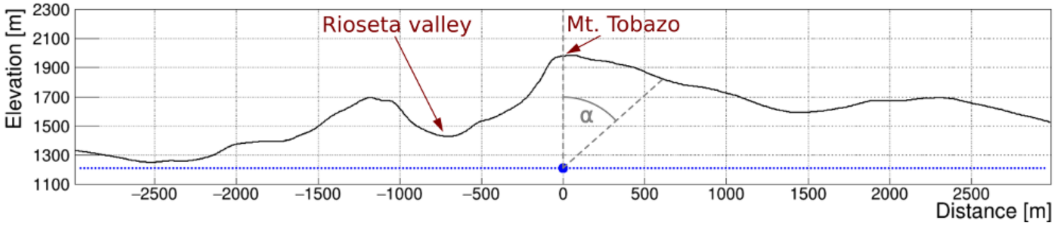


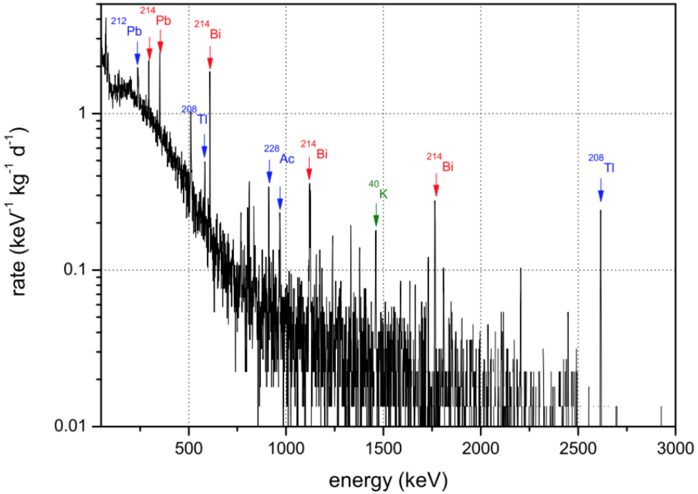


Run period	Start Date	Run time (day)	Triggers
Run-Va	25-02-2019	75.8	617,896
Run-Vb	13-09-2019	47.1	412,902
Run-Vc	08-01-2020	148.7	1,117,101
Run-V	25-02-2019	271.6	2,147,899
Run-VI	20-10-2020	208.9	1,646,501

- Detector’s materials measurement campaign ongoing:
  - High resolution gamma spectroscopy: HPGe detector at LSC Radiopurity Service
  - Mass spectrometry (GDMS, ICPMS): external companies/institutions
- Angular muon flux at LSC known (arXiv:1902.00868)







NEXT-100 sensitivity

Main differences between this update and 2016's paper:

- data-like (this) vs purely MC (2016) reconstruction
- final NEXT-100 detector design (this)
- extrapolated background rate from NEXT-White (2016)

Comparison with published	This preliminary update	2016 sensitivity paper (JHEP05(2016)159)
^{136}Xe mass (kg)	65 (90% enrichment)	91 (91% enrichment)
Signal efficiency (%)	21	28
Background rate (counts/year/kg/keV)	$< 3.7 \cdot 10^{-3}$	$4 \cdot 10^{-4}$
Half-life at 90% CL after 3 years	$> 1.7 \cdot 10^{25}$ years	$6.0 \cdot 10^{25}$ years