The NEXT program

High pressure gas TPC technology for neutrinoless double beta decay searches

Jonathan Haefner on behalf of the NEXT Collaboration

19 March 2021

CPAD Instrumentation Frontier Workshop 2021

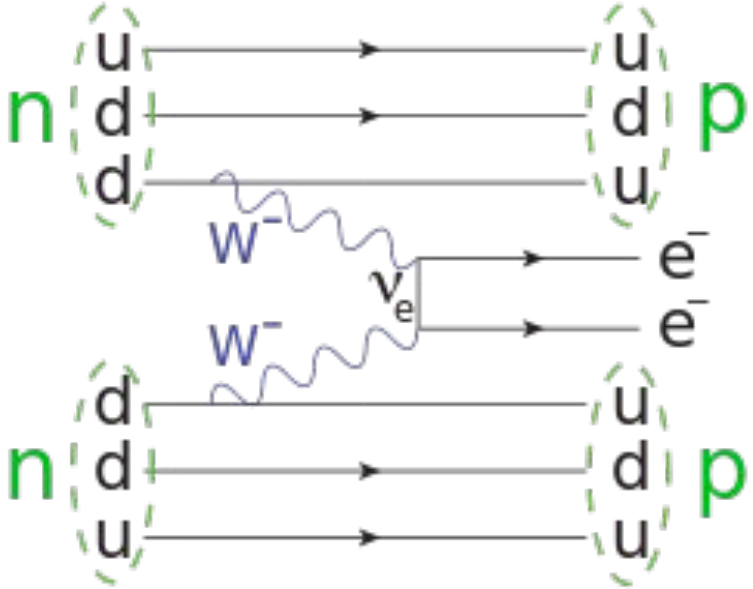
Overview

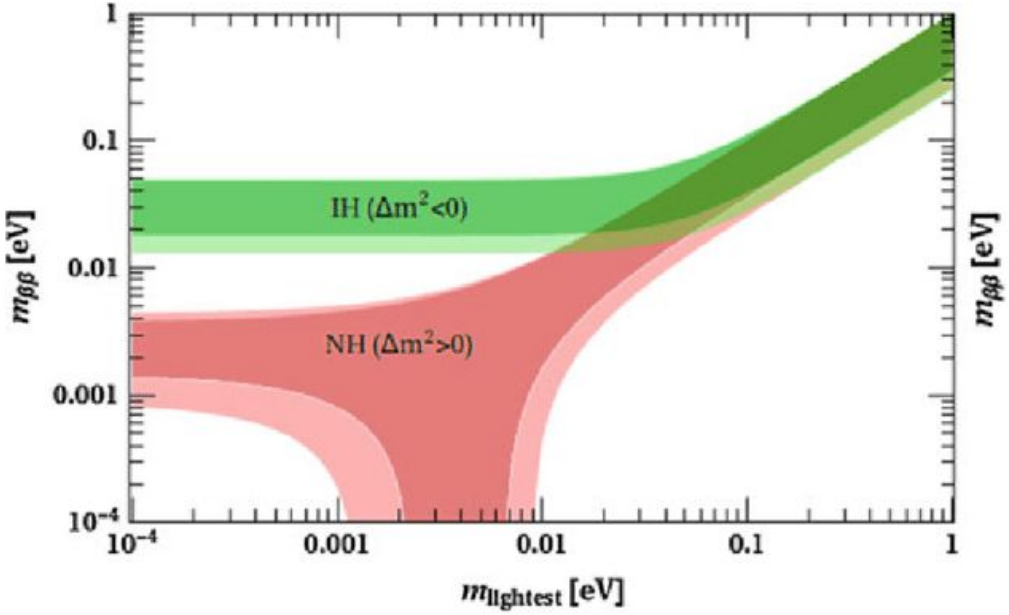
- NEXT (Neutrino Experiment with a Xenon TPC) concept and design
- The NEXT-White detector
- The NEXT-100 detector
- Future detectors and conclusions

NEXT Concept and Design

Motivation: (neutrinoless) double beta decay

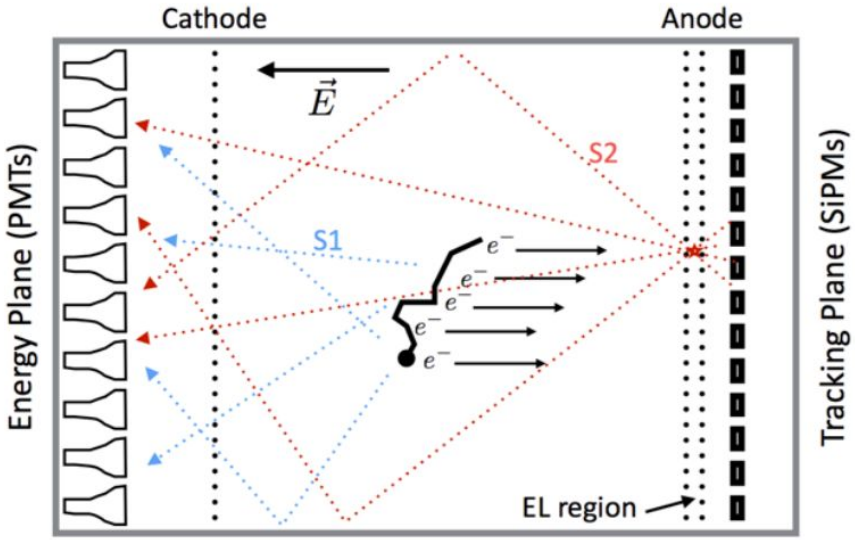
- Double beta decay is a very rare process
- If the neutrino is its own antiparticle, the two output neutrinos can effectively annihilate, leading to a *neutrinoless* version of the process (shown below)
- This process would indicate physics beyond the Standard Model

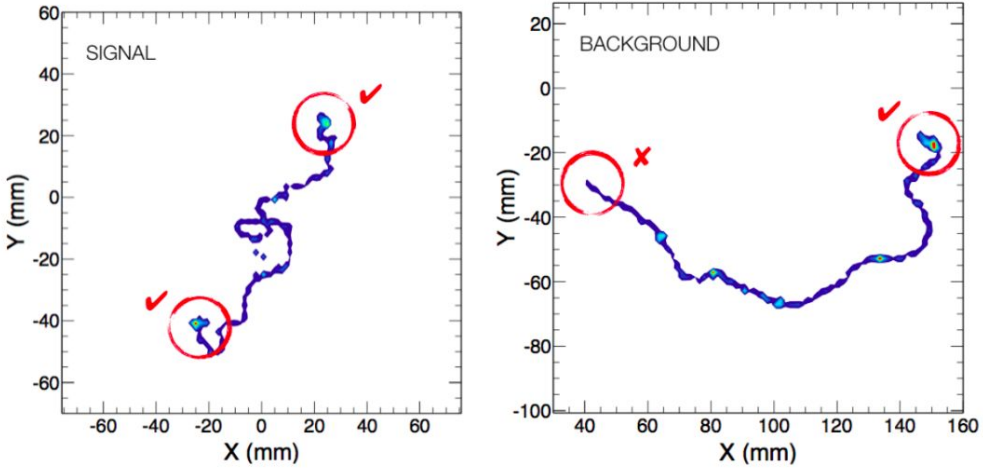




The NEXT concept

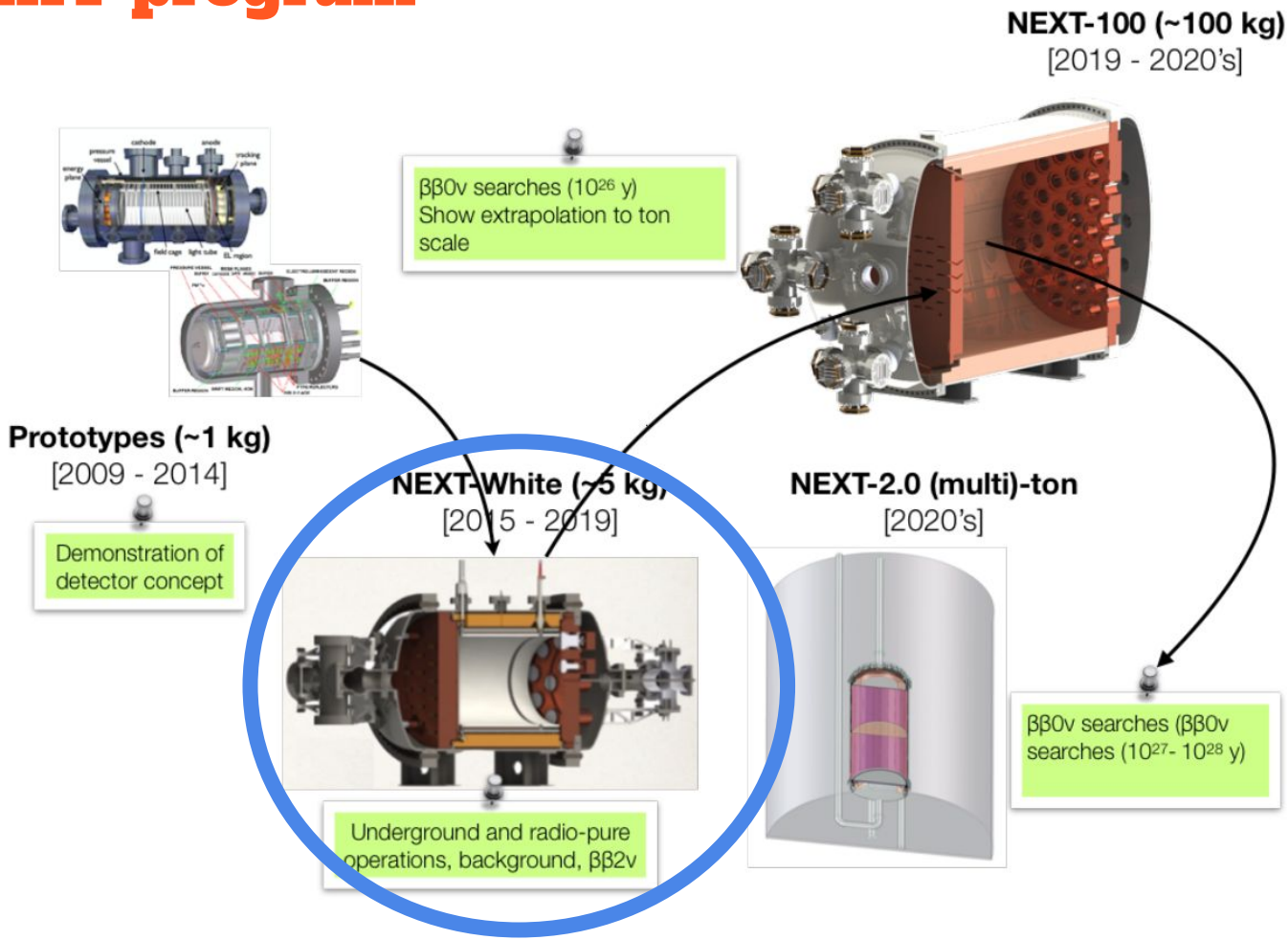
- High pressure gaseous, enriched xenon
- Optical time projection chamber (TPC)
  - Scintillation (S1) + [Ionization → Electroluminescence light] (S2)
- Energy reconstruction and tracking capabilities
- Potential for scalability





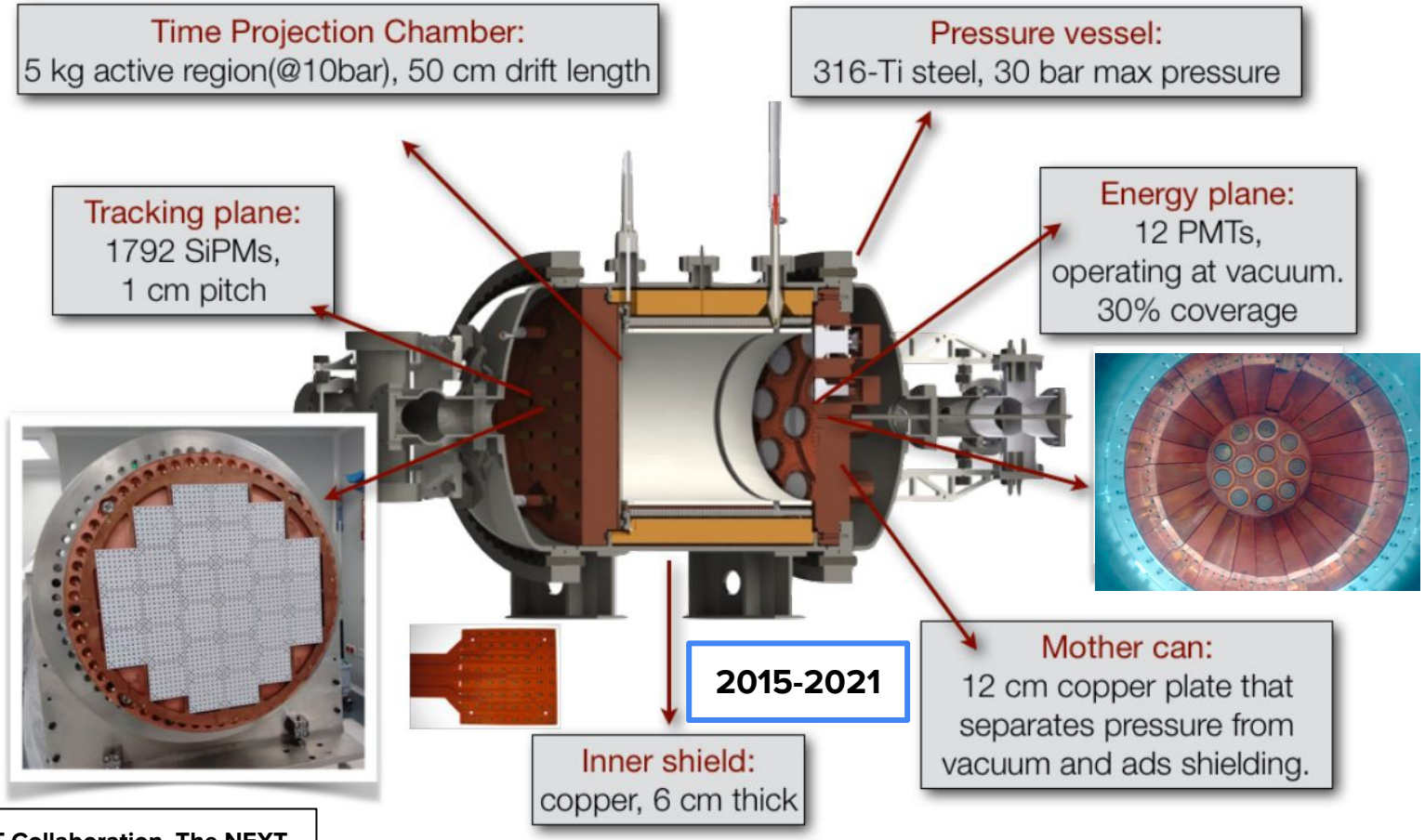
(a) Signal (b) Background

The NEXT program



The NEXT-White Detector

The NEXT-White (NEW) detector



F. Monrabal *et al*, NEXT Collaboration, The NEXT White (NEW) Detector, 2018, arxiv:1804.02409

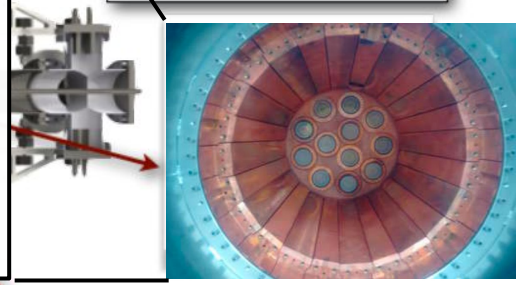
The NEXT-White (NEW) detector

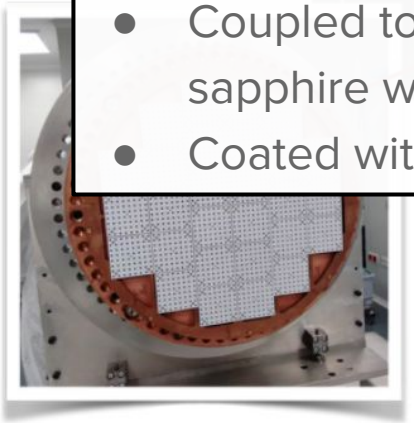
Time Projection Chamber:
5 kg active region(@10bar), 50 cm drift length

Pressure vessel:
316-Ti steel, 30 bar max pressure

- **Hamamatsu R11410-10 PMTs**: low radioactivity (0.35 mBq unit−1)
- PMTs protected from the radiation by copper plate
- Coupled to gas volume through sapphire windows
- Coated with PEDOT & TPB

Energy plane:
12 PMTs,
operating at vacuum.
30% coverage





2015-2021

Inner shield:
copper, 6 cm thick

Mother can:
12 cm copper plate that separates pressure from vacuum and ads shielding.

F. Monrabal *et al*, NEXT Collaboration, The NEXT White (NEW) Detector, 2018, arxiv:1804.02409

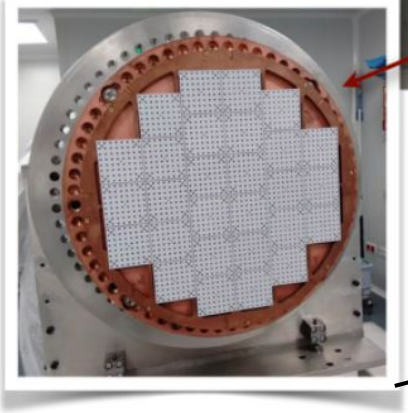
The NEXT-White (NEW) detector

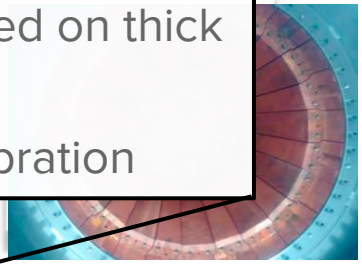
Time Projection Chamber:
5 kg active region(@10bar), 50 cm drift length

Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1792 SiPMs,
1 cm pitch

- **SensL C series model MicroFC-10035-SMT-GP**, dark count less than 100 kHz at room temp
- 1792 SiPMs distributed across 28 square DICE boards mounted on thick copper shield
- Boards include LED for calibration





2015-2021

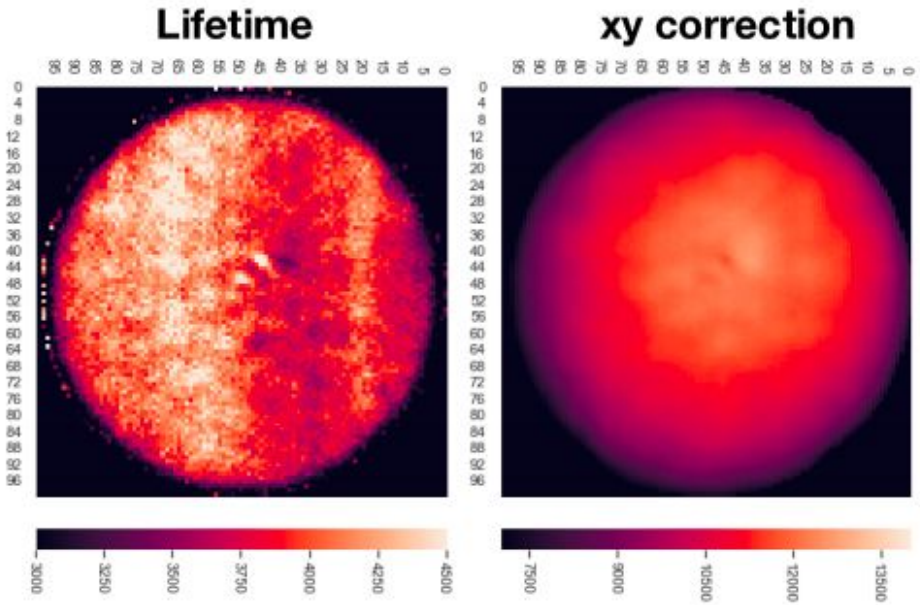
Inner shield:
copper, 6 cm thick

Mother can:
12 cm copper plate that separates pressure from vacuum and ads shielding.

F. Monrabal *et al*, NEXT Collaboration, The NEXT White (NEW) Detector, 2018, arxiv:1804.02409

NEW Sensor Calibration

- PMTs regularly calibrated with LEDs located on the tracking plane
- SiPMs regularly calibrated with LEDs located on the energy plane



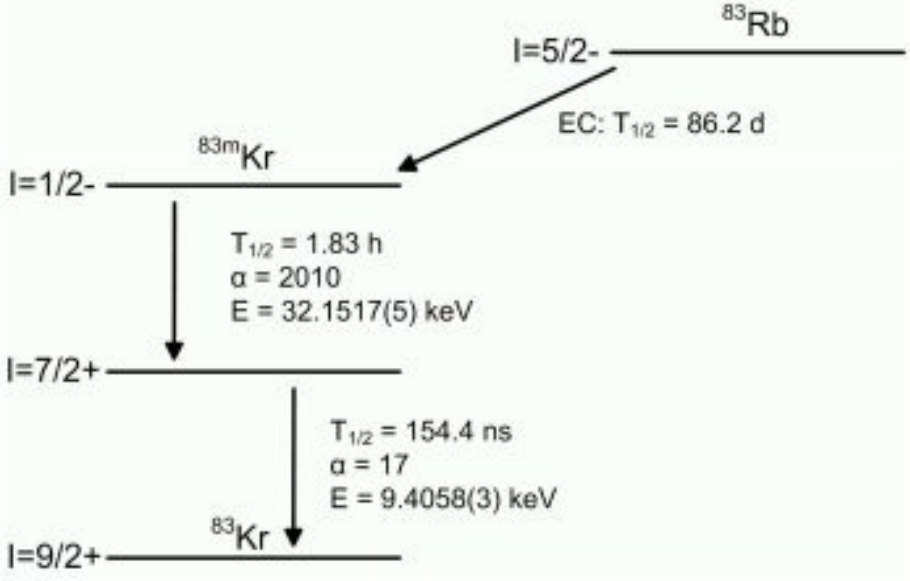


Figure 3: ^{83}Rb decay scheme.

- Calibration with Kr gas allows correction for
  - Spatial variation
  - Temporal variation
  - Finite electron lifetime

NEW detector performance

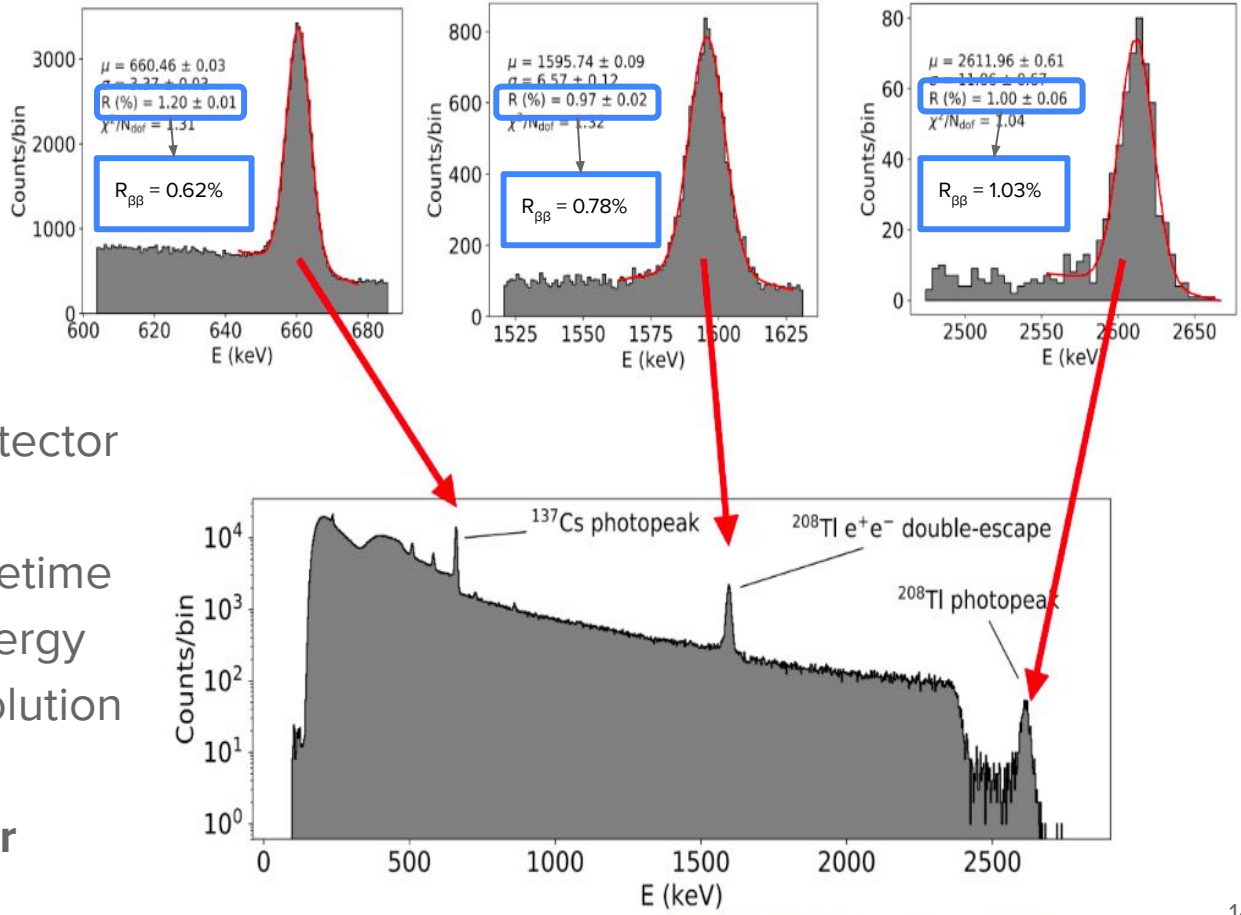
Achievements of NEW:

- ✶ Topological event selection
- ✶ Excellent energy resolution
- ✶ Understanding of background

NEW detector performance

Energy resolution (calibration sources)

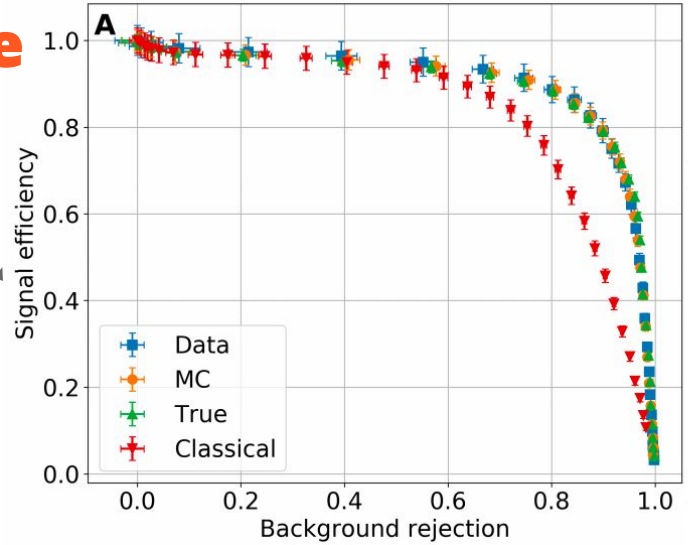
- Excellent resolution → need to calibrate in position, time
- Inject ^{83m}Kr into the detector
- Gives pointlike events, uniformly throughout detector
- Can correct for x, y, z, t variation and electron lifetime
- Calibrate with higher energy sources to estimate resolution at $Q_{\beta\beta}$
- **Energy resolution better than 1% at $Q_{\beta\beta}$**

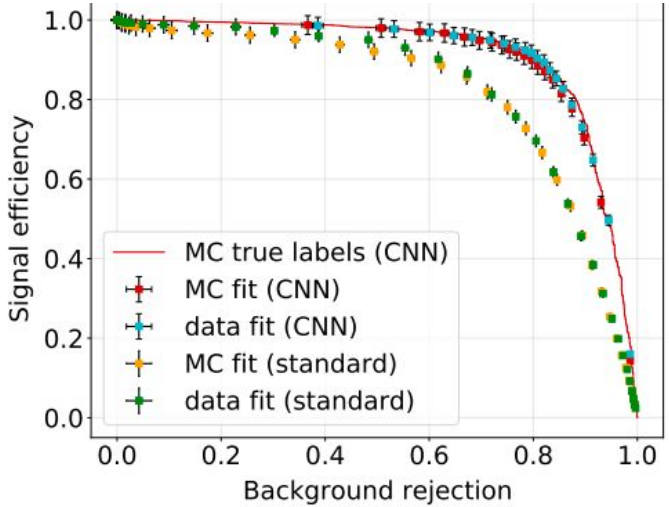


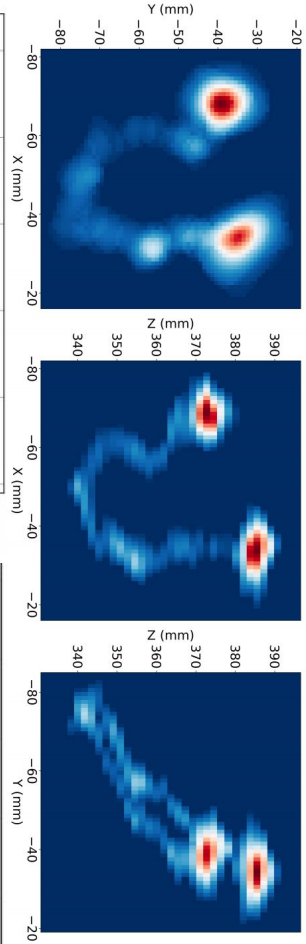
NEXT Collaboration, arXiv:1905.13110

Topological cut performance

- Each electron in decay leaves a Bragg peak energy deposition (“blob”) on stopping
- Can differentiate between one blob and two blob to reject background
- Topological separation power demonstrated with traditional analysis
- Richardson-Lucy deconvolution and CNNs allow for even better performance







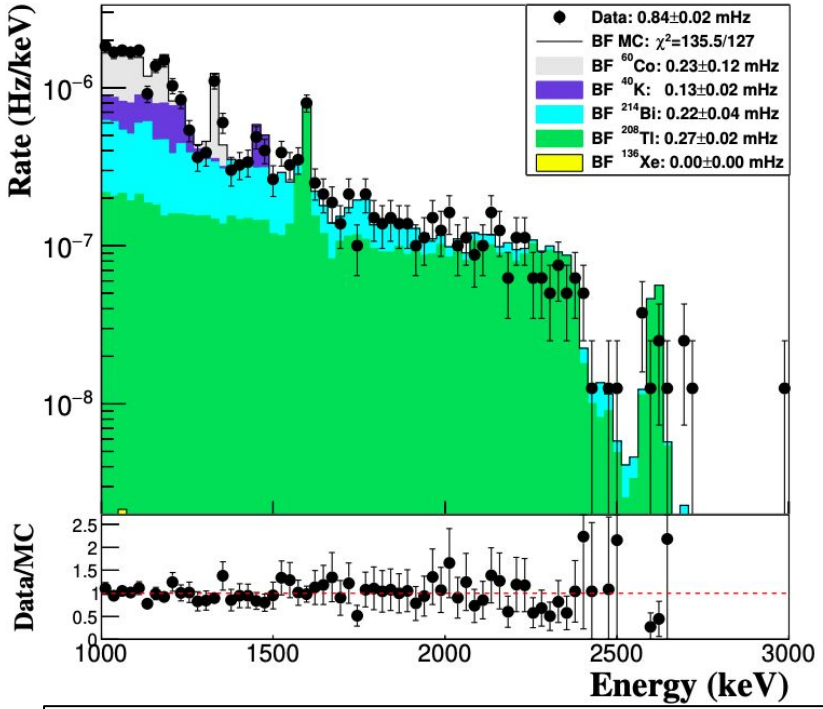
P. Ferrario *et al*, NEXT Collaboration, Demonstration of the event identification capabilities of the NEXT-White detector, 2019, arxiv:1905.13141

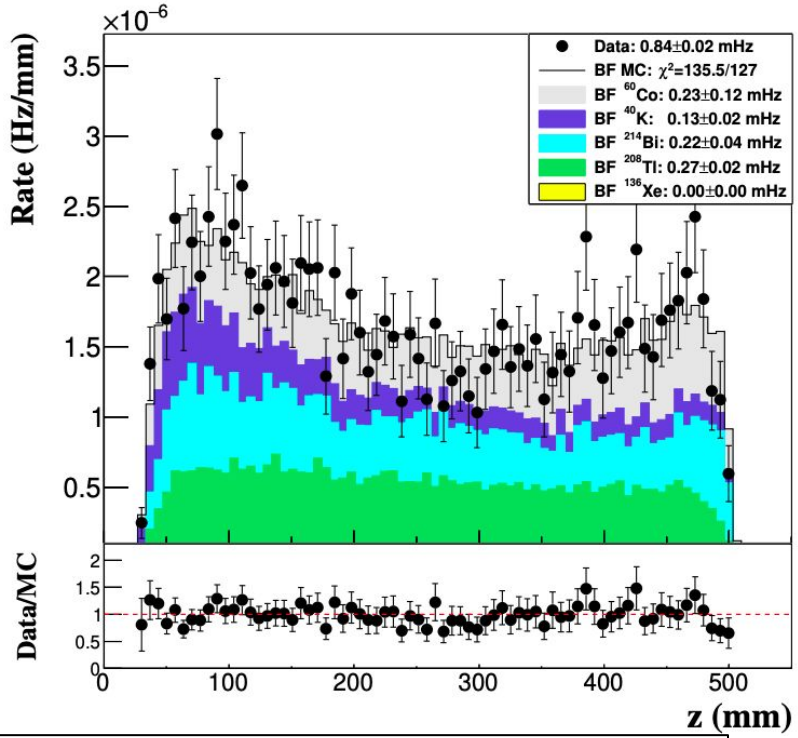
A Simón *et al*, NEXT Collaboration, Boosting background suppression in the NEXT experiment through Richardson -Lucy deconvolution, 2021, arxiv:2102.11931

M. Kekic *et al*, NEXT Collaboration, Demonstration of background rejection using deep convolutional neural networks in the NEXT experiment, 2021, arxiv:2009.10783

Background composition

- In addition to radiopure detector design, we have an outer lead castle, inner radon abatement system, and inner lead castle to protect detector





P. Novella *et al,* NEXT Collaboration, Radiogenic backgrounds in the NEXT double beta decay experiment, 2019, arxiv:1905.13625

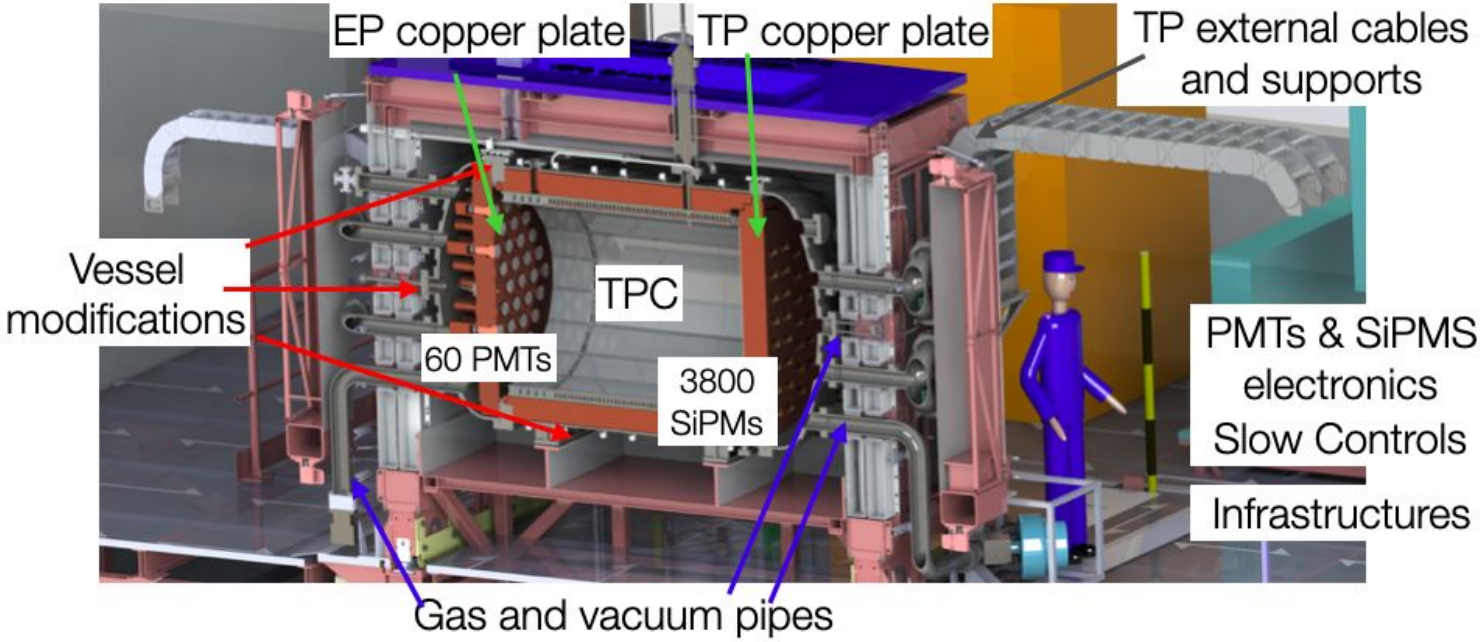
The NEXT-100 Detector

Will allow to demonstrate scalability

The NEXT-100 Detector

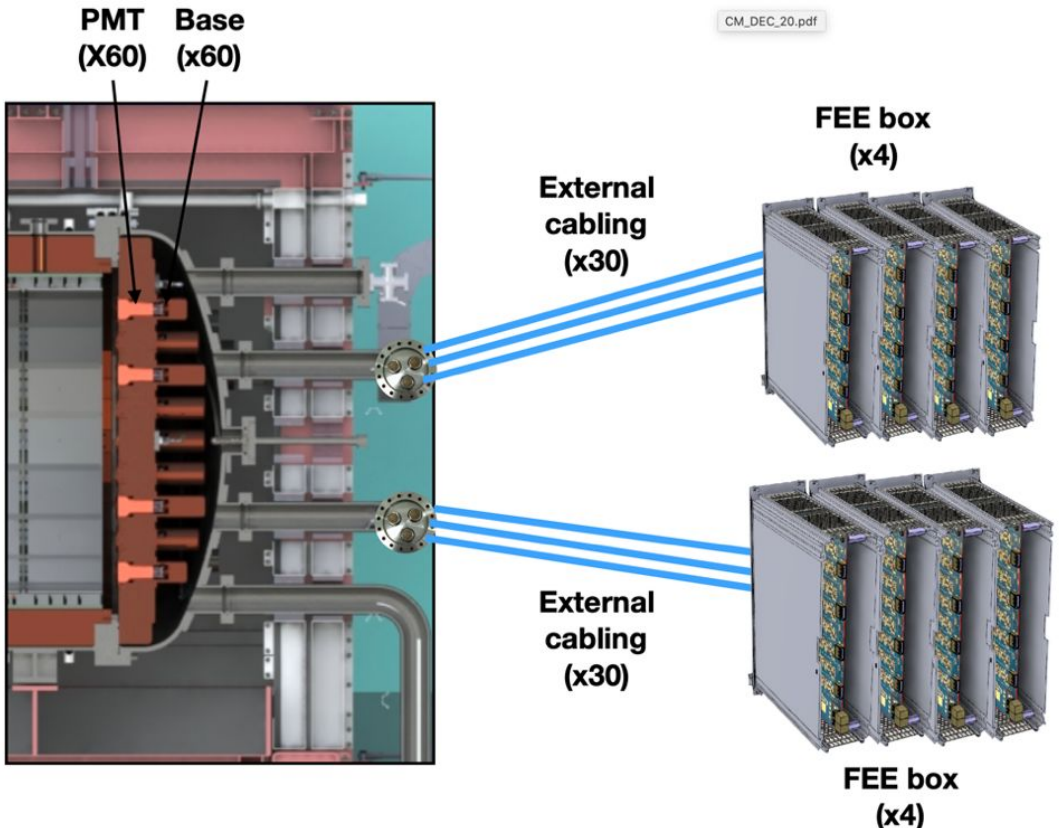
NEXT-100 overview

- Plan to assemble, install by Q4 2021
- Final design decisions being made
- 100 kg mass (~2x as large in all dimensions), 5x PMTs, ~2x SiPMs (vs NEW)
- Will yield neutrinoless limit, and demonstrate scalability



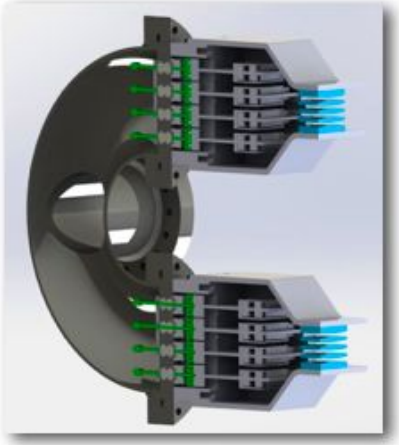
NEXT-100 energy plane

- Measuring new capacitors to reduce radioactivity budget
- All front end electronics (FEE) ready, working on the cabling between vessel-FEE and HV-FEE.
- Ready by May 2021

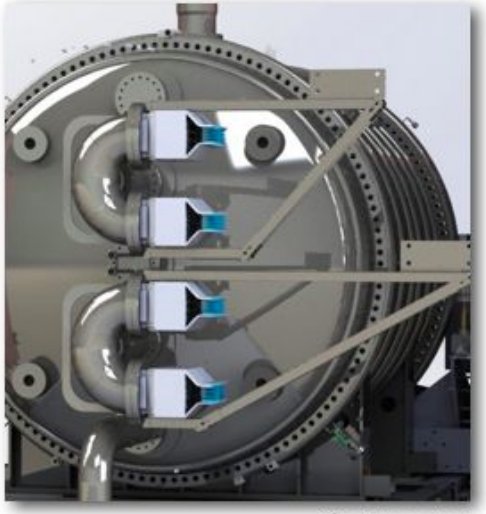


NEXT-100 tracking plane

- Plan to optimise TP:
  - Check distance anode-SiPMs, compare plate vs mesh, use of teflon masks as collimators, SiPM model
- Work in parallel w/ DEMO++ testing configurations and in external set-up w/ LED
  - Good control of all parameters, Realistic evaluation of each configuration by measuring energy resolution and topological signature
- Improve robustness of SiPM connections
- Ready June 2021



Adapter-Boards protection + cable management + strain relief



Cables chain holder:
It allows opening TP end-cap without disconnecting cables.

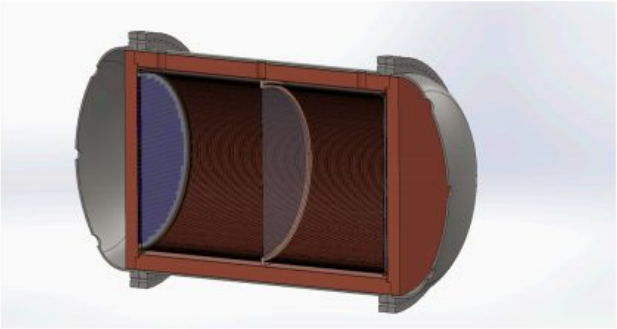
Future and conclusions

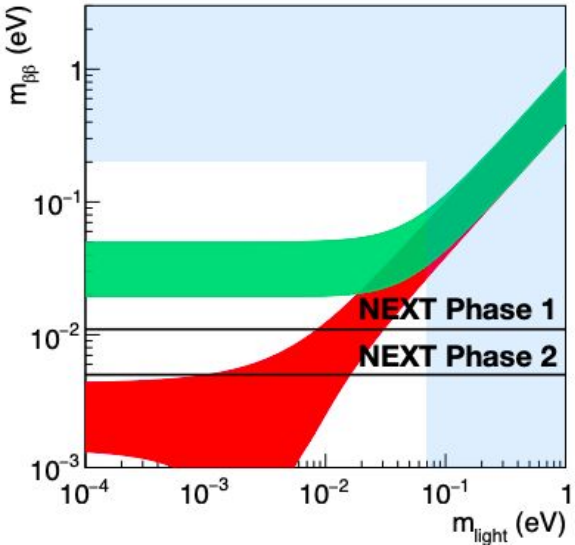
NEXT-Ton: basics

- Require a larger detector (10x mass of N100)
- With larger size, some challenges:
  - Larger volume to calibrate
  - Longer drift distance
- Must maintain:
  - excellent resolution
  - topological rejection power

NEXT-Ton: basics

- Require a larger detector (10x mass of N100)
- With larger size, some challenges:
  - Larger volume to calibrate
  - Longer drift distance
- Must maintain:
  - excellent resolution
  - topological rejection power





Two approaches developed in parallel:

- Phase 1, High Definition: incremental approach, using/improving existing technology.
- Phase 2, Barium Tagging: based on disruptive new concept (SMFI Ba++ tagging).

Phased approach

- ~1 ton of 136Xe introduced per phase.
- Ultra pure materials. SiPMs as the only sensor.

Phase 1:

- Improves topological signature, improves energy resolution
- Reduces radioactive budget (no PMTs)
- Energy plane made of large area SiPMs (design similar to that of Dark Side)
- Potential to reduce SiPM dark count by cooling detector
- 2.6×10^{-6} cts / keV·kg·year total background rate

Phase 2:

- Tracking and energy measured in anode.
- Cathode implements Barium Tagging System
- Virtually background free

NEXT-Ton: R&D program

Vigorous Ton scale research and development program:

- Tracking plane development
- Use of metalenses for increasing light collection
- Cooled detectors
- Barrel of optical double-clad fibers
- Multiplexing electronics
- Diffusion reduction
- Ba tagging solutions (BOLD, CRAB)

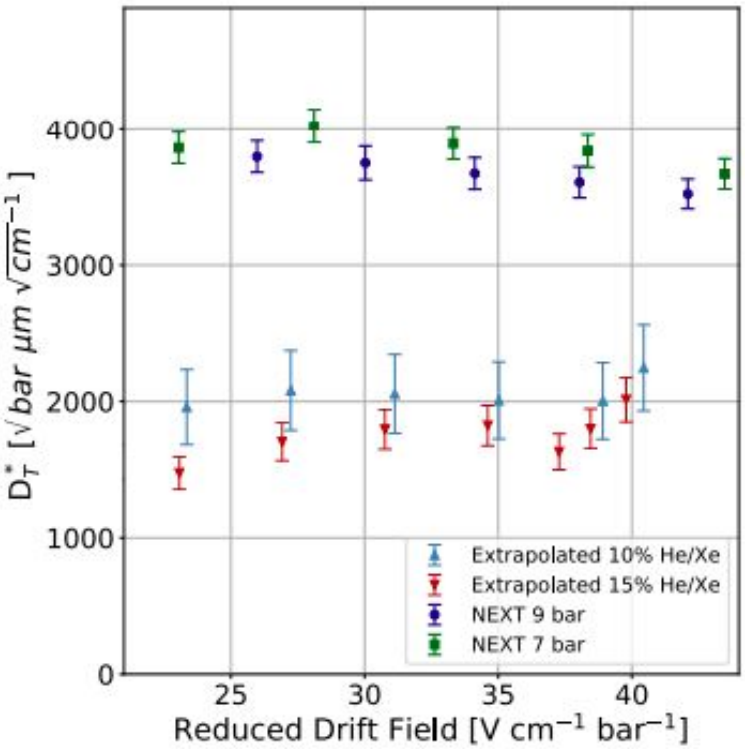
... etc

Increasing photodetector light collection with metalenses - Chris Stanford - 2:00p Mar 18

Development Towards a Camera Readout and Barium Tagging Optical TPC, or CRAB-OTPC, for the NEXT Collaboration - Nicholas Byrnes - 1:00p Mar 19

NEXT-Ton: diffusion reduction

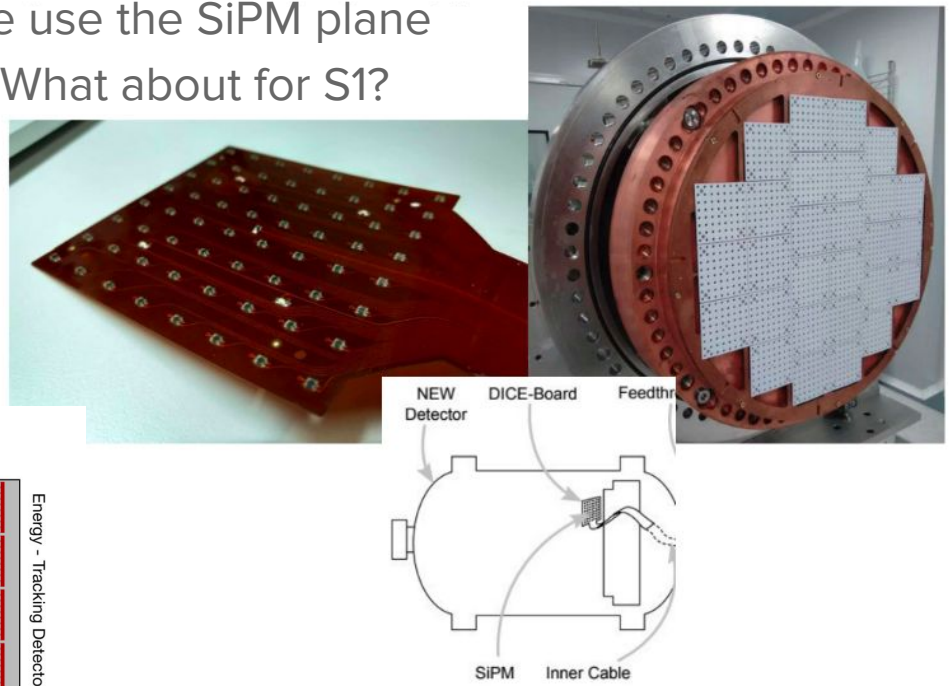
- Helium-xenon mixture shows lower diffusion than pure xenon
- Allows better topological signature and position determination
- Longitudinal diffusion larger than anticipated, but transverse diffusion could be reduced in mixture by factor of ~2



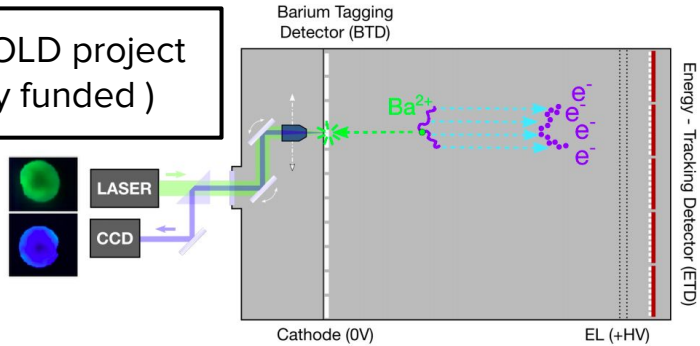
A.D. McDonald *et al*, NEXT Collaboration, Electron Drift and Longitudinal Diffusion in High Pressure Xenon-Helium Gas Mixtures, 2019, arxiv:1902.05544

NEXT-Ton: tracking plane studies

- NEW and NEXT-100 use two planes, but the PMT plane is too radioactive for next phases and cathode needs to be freed for Ba tagging
- If we removed the PMT plane, could we use the SiPM plane only for a good energy measurement? What about for S1?
- Beyond feasibility, must answer:
  - Required pitch?
  - Which SiPMs to use?
  - How many SiPMs required / ideal?
  - What will the dark count be? **Will it be too high to see Kr S1?**



Part of the BOLD project (ERC-Synergy funded)



Conclusion

- The HPGXeTPC technology offers several advantages in resolution and background rejection
- NEXT achieves
  - Better than **1% FWHM energy resolution** at 2.6 MeV
  - Powerful **topological separation** for 1.6 MeV electron-positron pairs from 1e / 2e separation
  - Good control and understanding of **background**
- Future generations of NEXT will retain these positive characteristics, with higher statistics and additional new technologies
- Strong, active R&D throughout collaboration to address Ton scale challenges

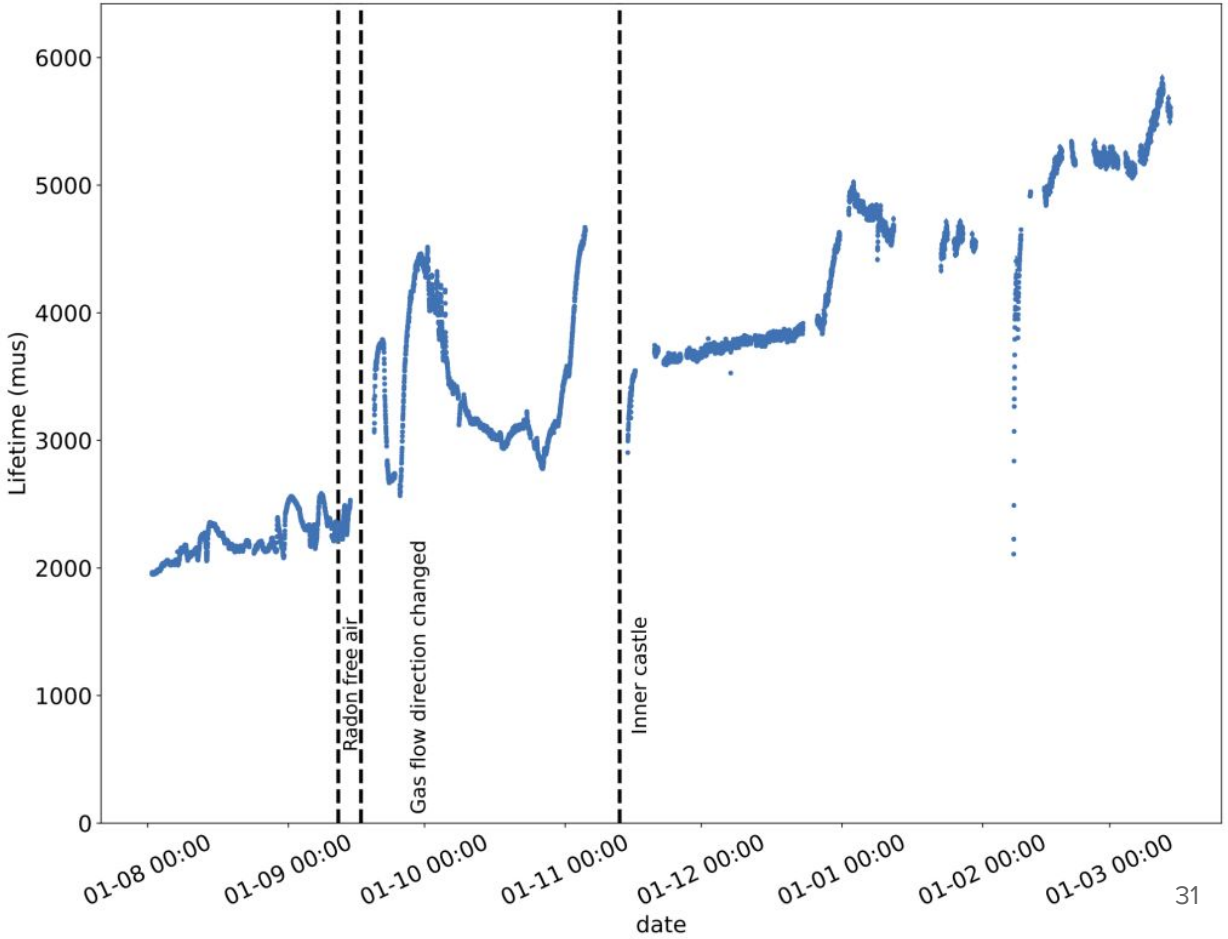
Backup

Abstract

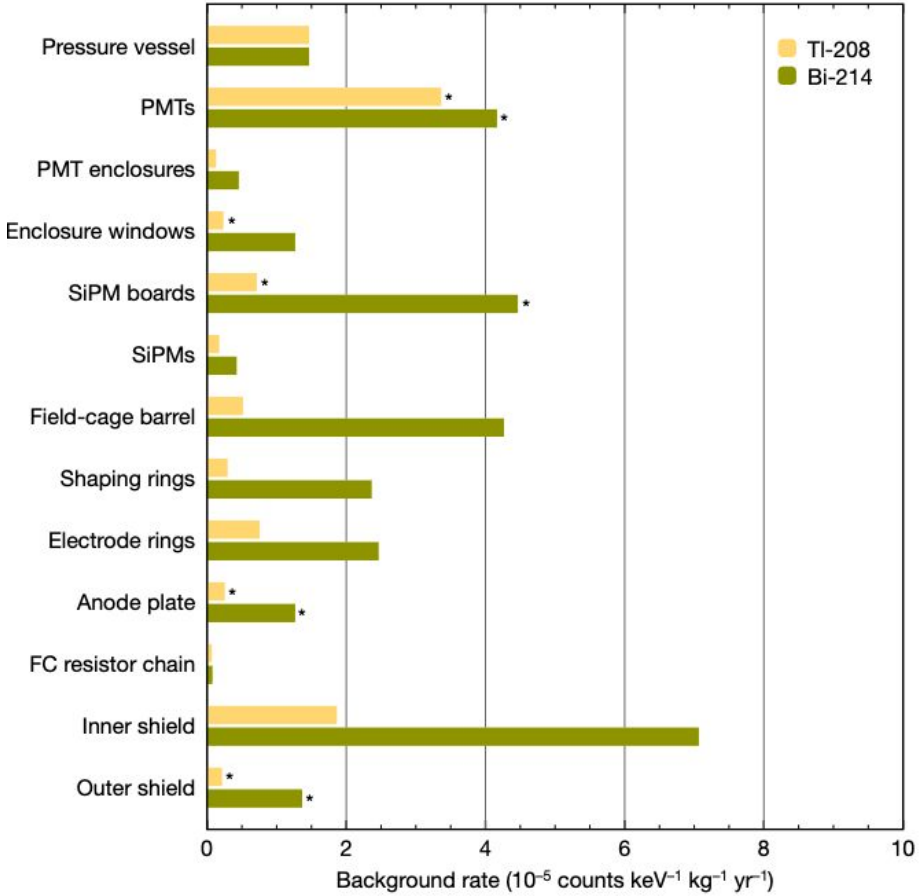
The NEXT experiment is a neutrino physics program searching for neutrinoless double beta decay using a **high pressure gaseous xenon time projection chamber** (HPGXeTPC). The HPGXeTPC technology offers several advantages, including **excellent energy resolution**, **topological event discrimination**, and **low background**. NEXT excels on each of these fronts, achieving **1% FWHM energy resolution** at 2.6 MeV and a **background rejection factor of 27** at 57% signal efficiency for 1.6 MeV electron-positron pairs. The resolution and event discrimination, along with our very radiopure detector, work together to allow us to achieve a **background index of $4{\cdot}10^{-4}$ counts/(keV·kg·yr).** We will discuss these strengths of the technology for the detection of rare events, as well as the performance of the current iteration NEXT-White detector and plans for future detectors. As discussed in this talk, the intrinsically excellent energy resolution and topological event discrimination of the technology requires continuous Kr^{83m} calibration throughout the active volume of the detector in order to be realized in practice.

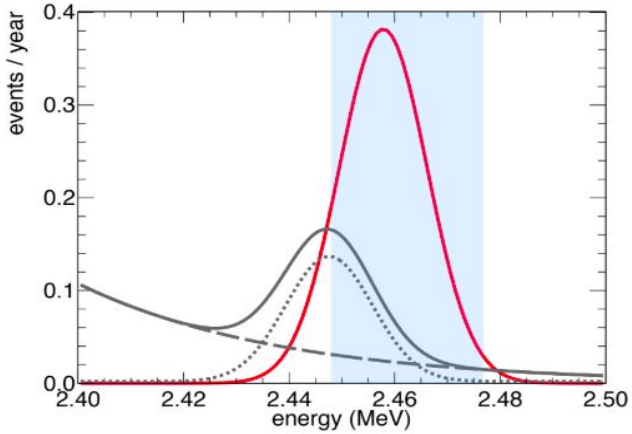
Operation of NEW

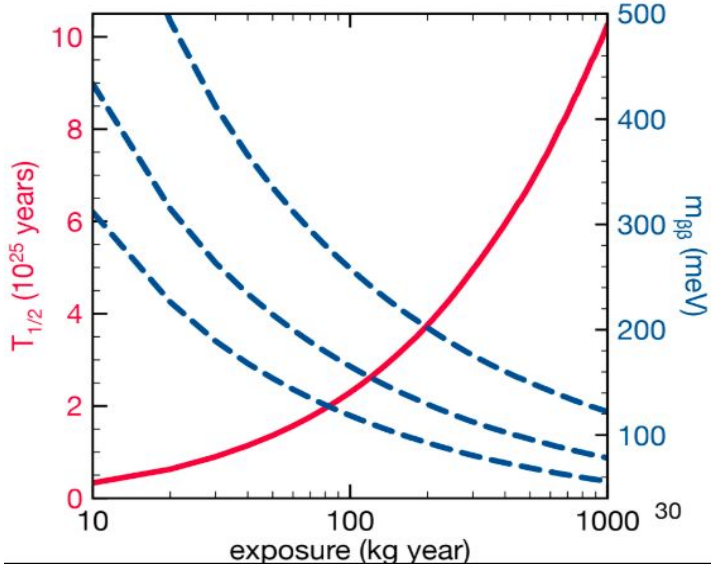
- Taking data since 2016, very stable since 2017
- Less than 1 gram of Xe lost / year
- Very high lifetime, measured daily with Kr



NEXT-100 sensitivity

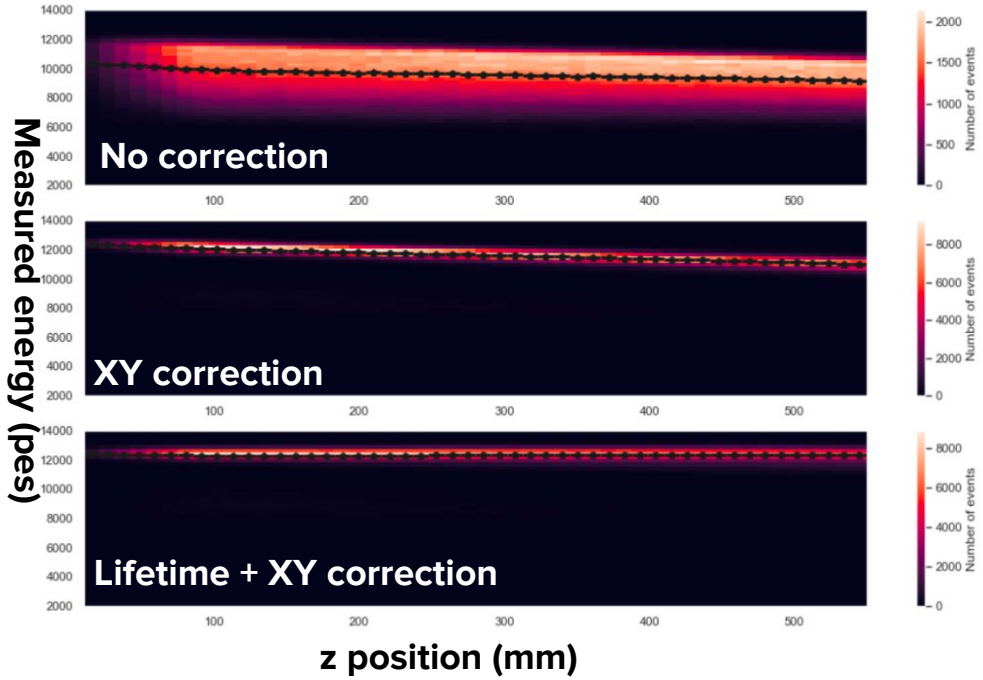


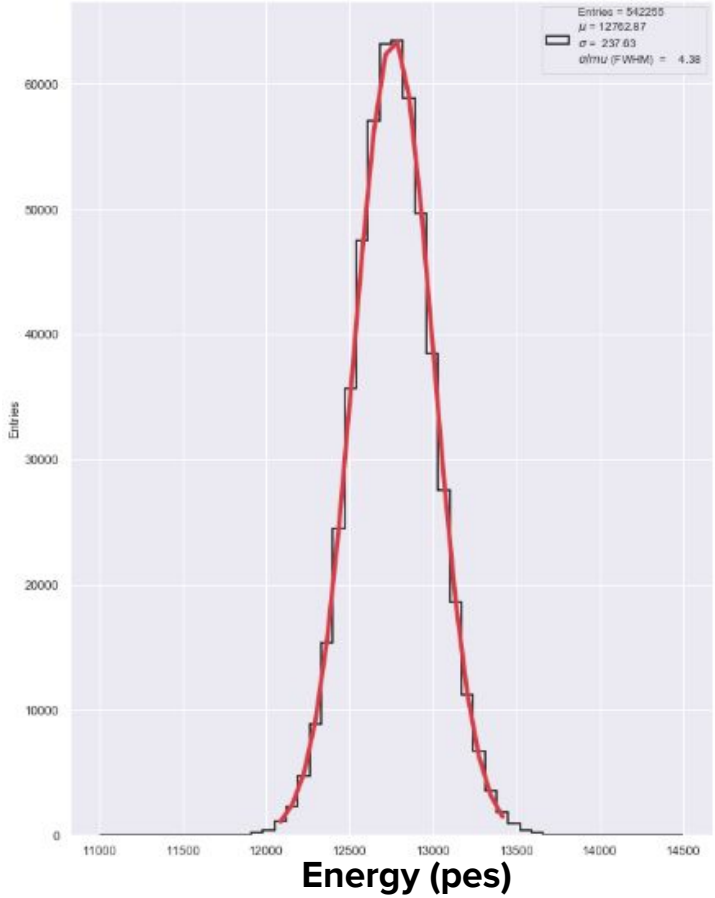




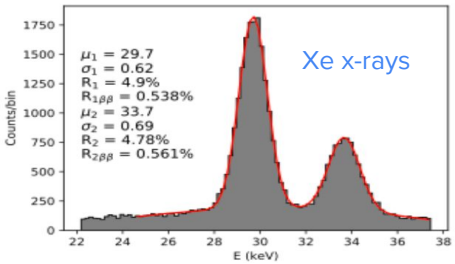
NEXT Collaboration, *JHEP* **1605** (2015) 159

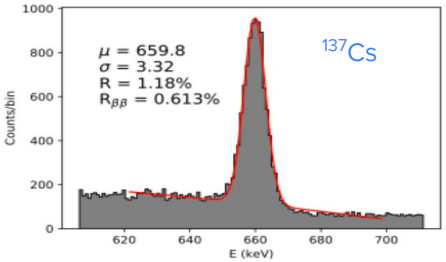
Corrections using Krypton

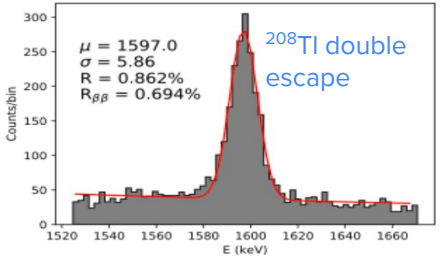


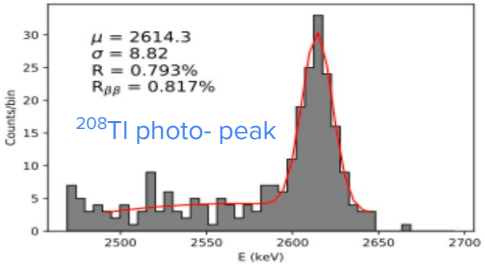


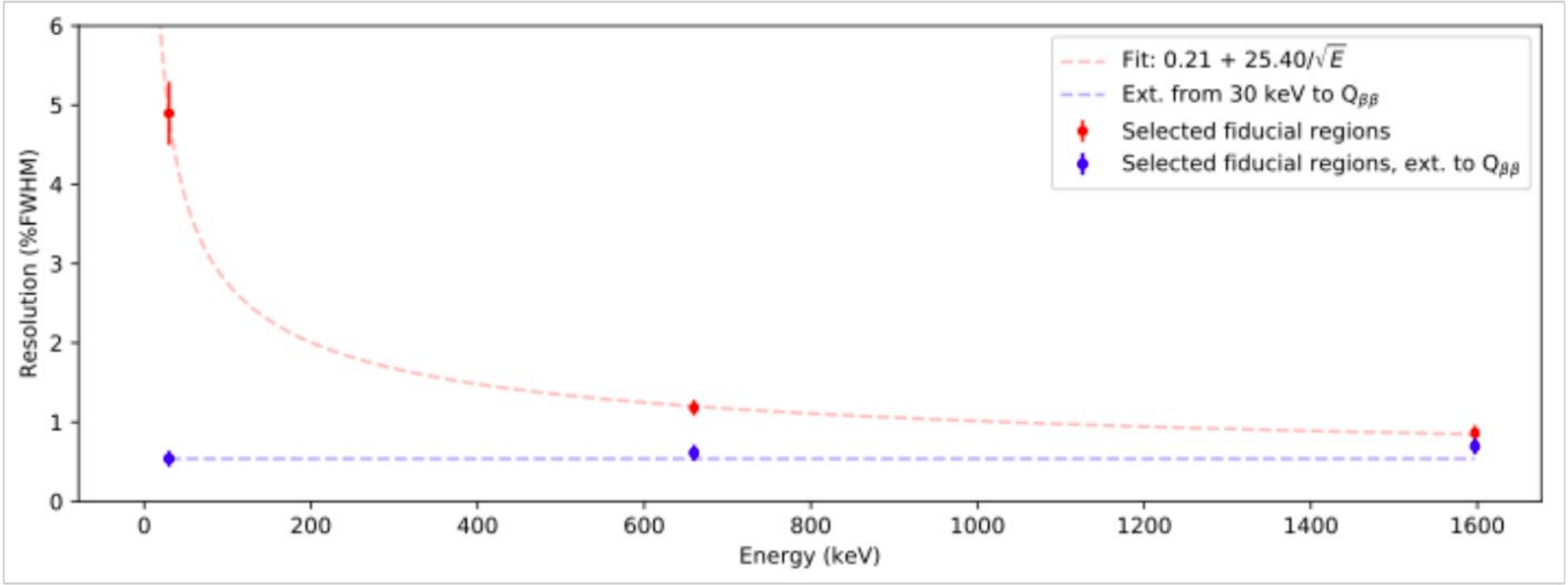
Energy resolution





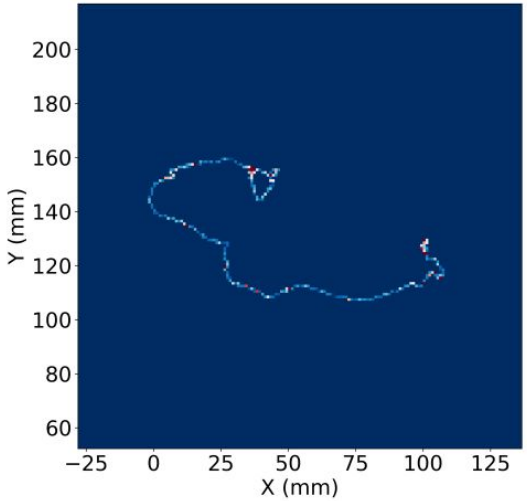


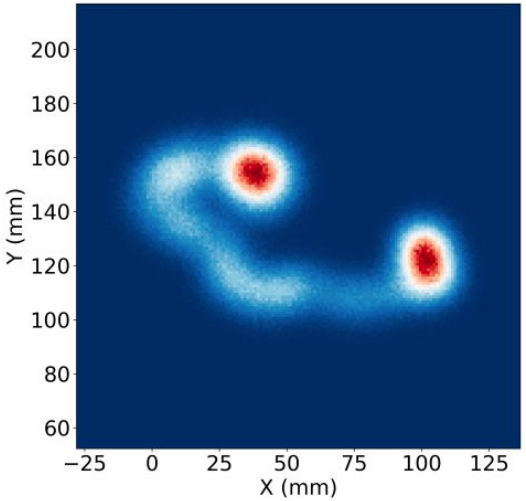




Richardson-Lucy deconvolution

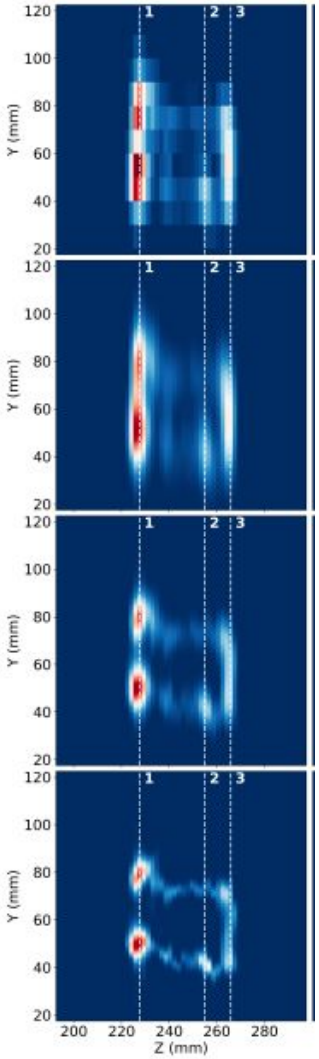
- Allows reversal of blurring due to electron drift
- Improves topological cut
- Leads to a background rejection factor of 27 at 57% signal efficiency (cf. 5x background rejection at 72% signal efficiency)





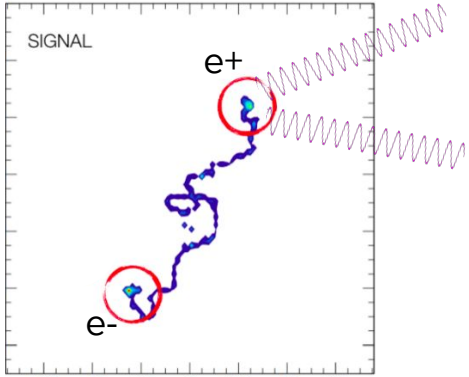
← Blurring from drift

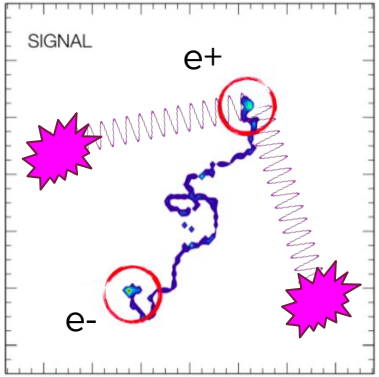
Event deconvolution (multiple iterations) →



Calibration sources

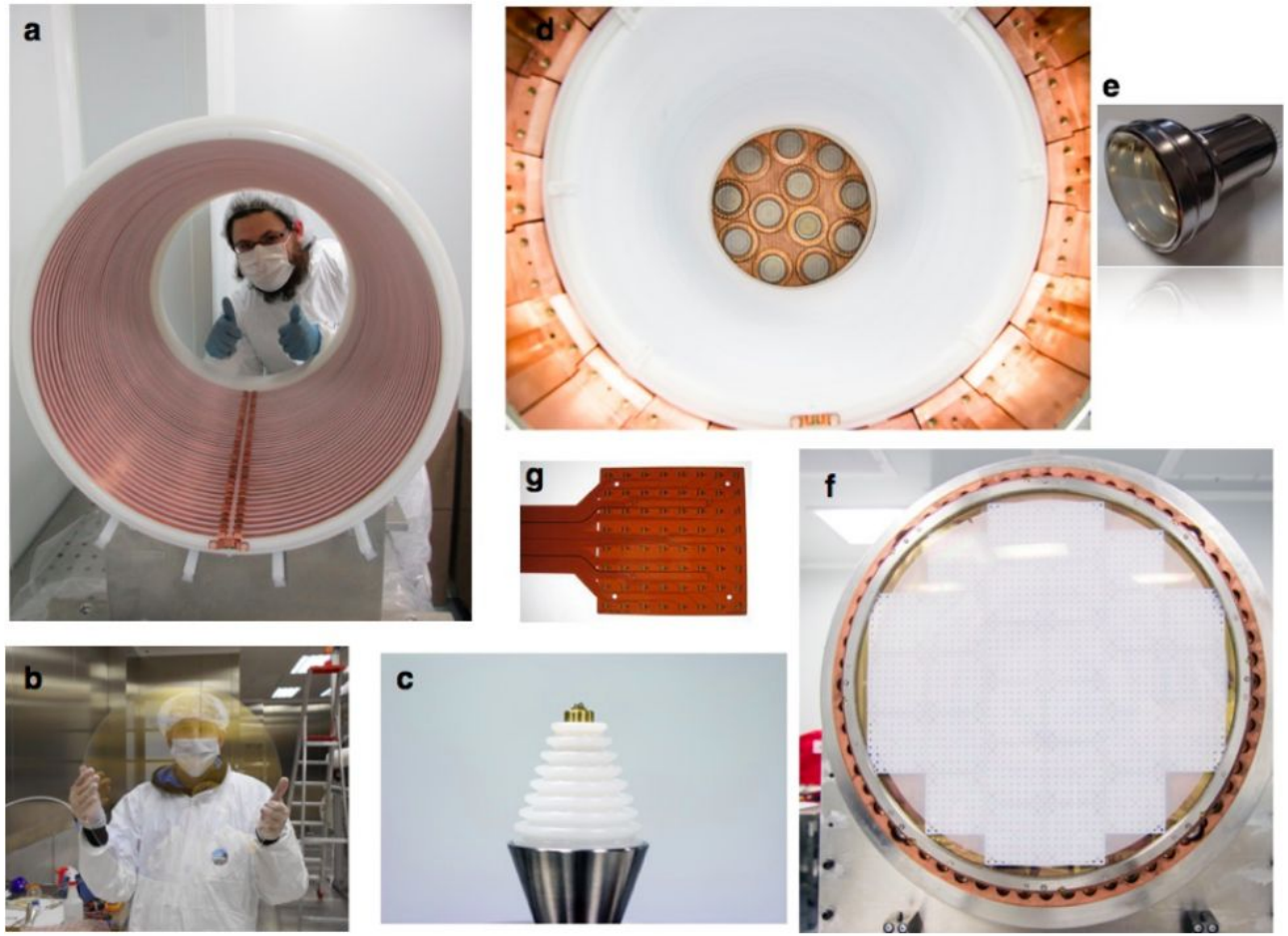
- Xe K-alpha and K-beta x ray lines (30 keV, 34 keV)
- 84m-Kr (42 keV)
- 137-Cs (662 keV)
- 208-Tl double escape peak (1593 keV)
- 208-Tl photopeak (2614 keV)





J. Martín-Albo *et al,* NEXT Collaboration, SENSITIVITY OF NEXT-100 TO NEUTRINOLESS DOUBLE BETA DECAY, 2016 [arxiv:1511.09246]

The NEXT-White detector



NEXT-100

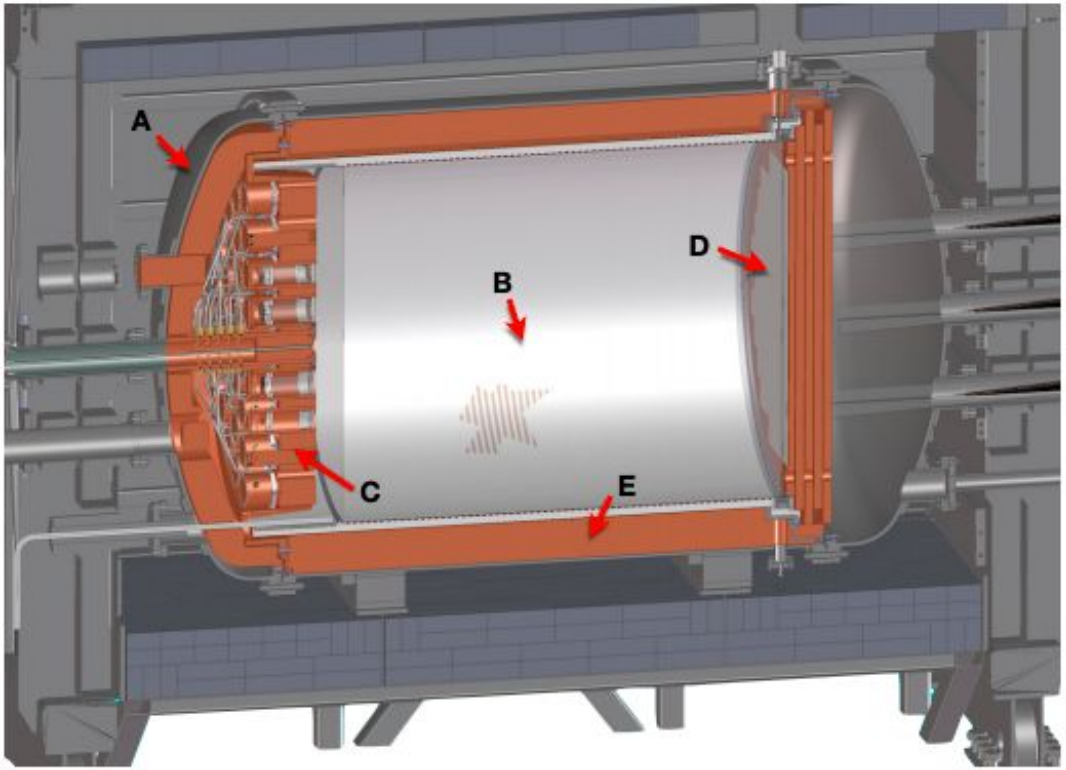
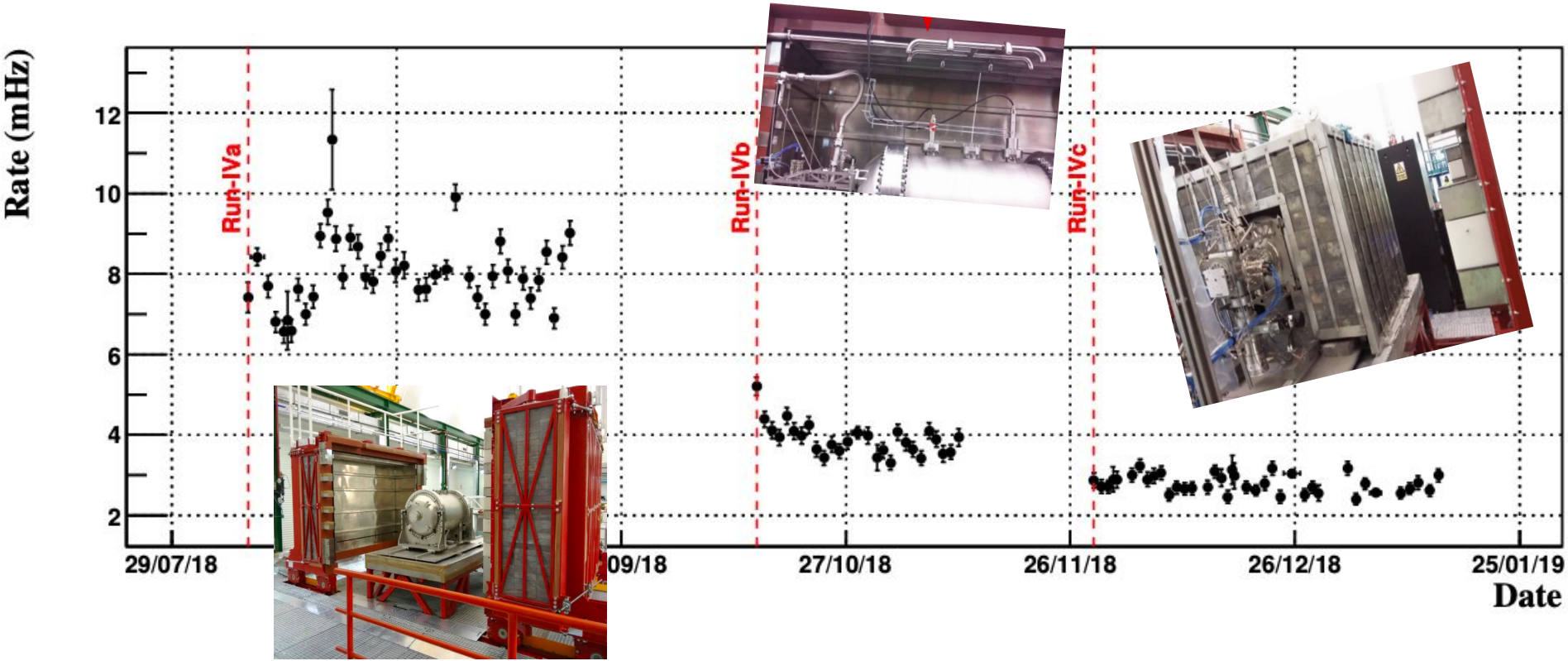


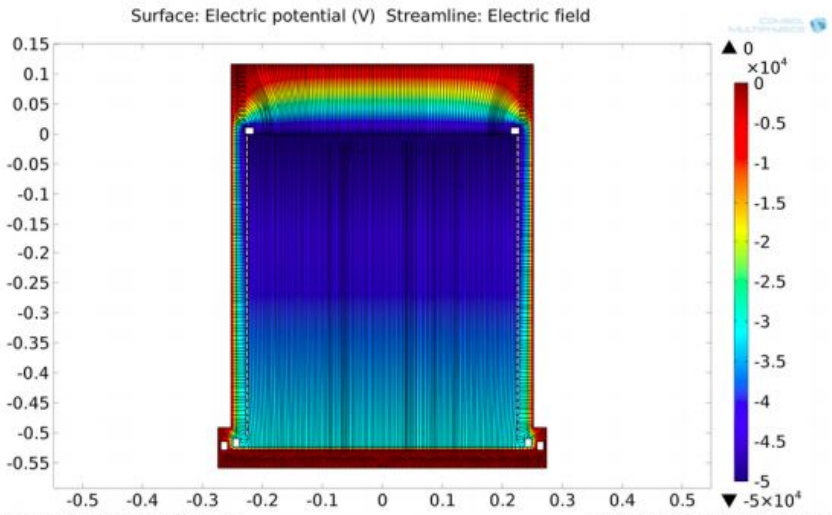
Figure 2. Cross-section view of the NEXT-100 detector inside its lead castle shield. A stainless-steel pressure vessel (A) houses the electric-field cage (B) and the two sensor planes (energy plane, C; tracking plane, D) located at opposite ends of the chamber. The active volume is shielded from external radiation by at least 12 cm of copper (E) in all directions.

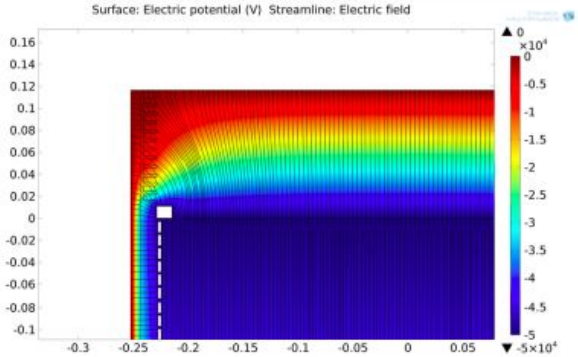
- Plan to assemble / install 2021
- Final design decisions being made
- Will yield neutrinoless limit, and demonstrate capability of ton scale technology

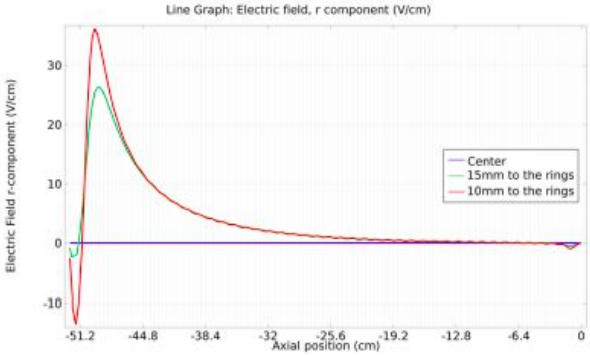
Run IV background measurement



NEW electric field uniformity







NEW tracking plane and front end electronics

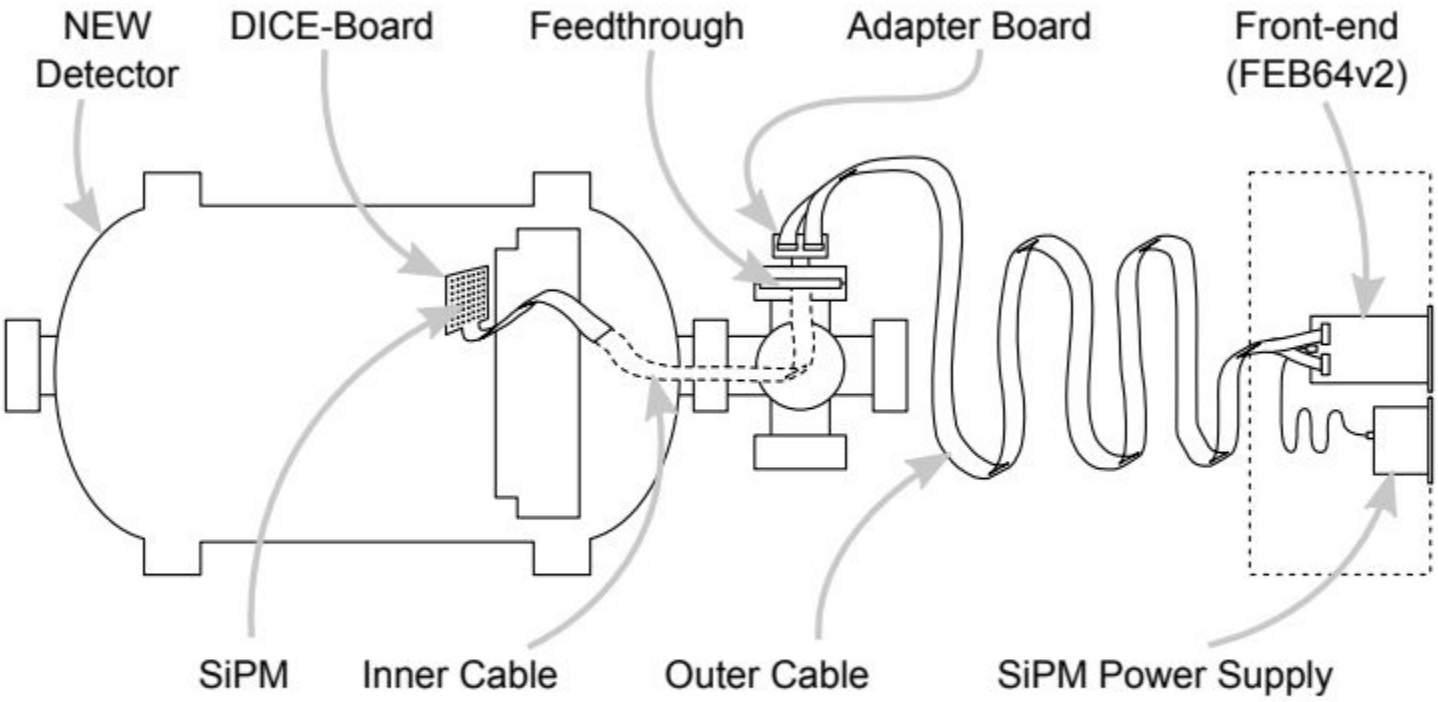
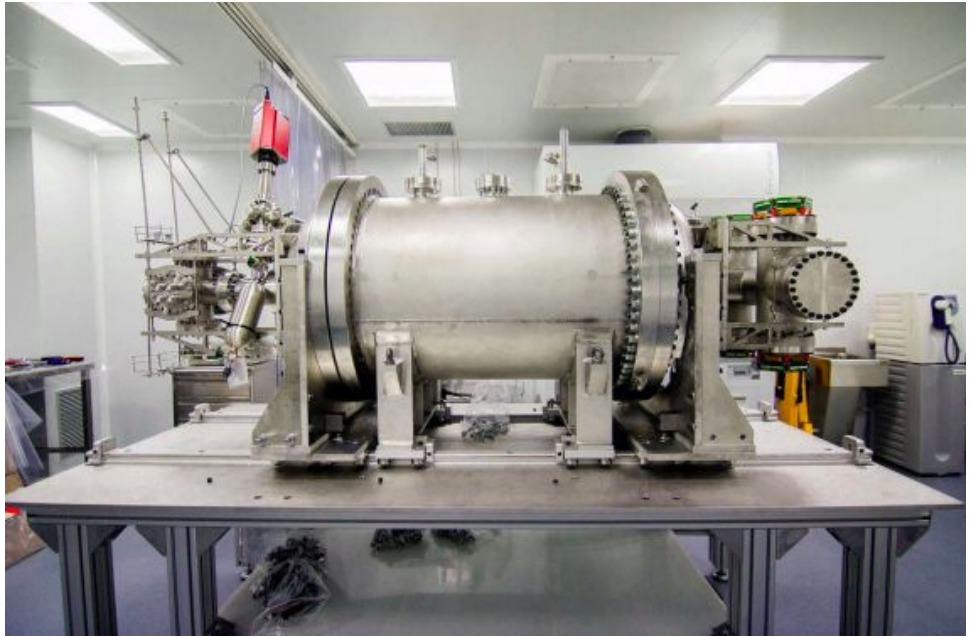


Figure 14: NEXT-White Detector tracking plane scheme. The full signal chain from the silicon photomultipliers to the front-end electronics is shown.

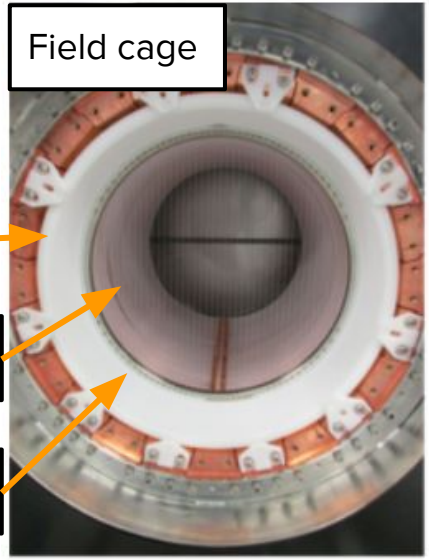
NEW Gas System

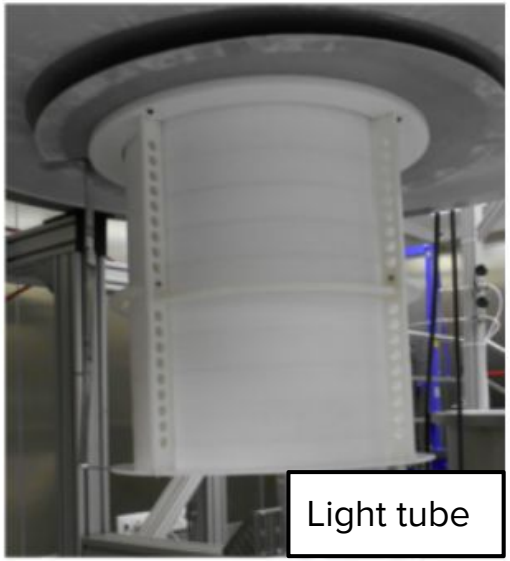
- Long electron lifetime is essential, especially for NEXT resolution
- Gas system (GS) purifies xenon through circulation through chemical purifiers (getters)
- GS must monitor and react quickly to changes in pressure
- Gas system comprised of inlet, recirculation machinery (a compressor), purification devices, emergency recovery tank, cryo-recovery bottle, sensors, and vacuum system to evacuate lines before filling

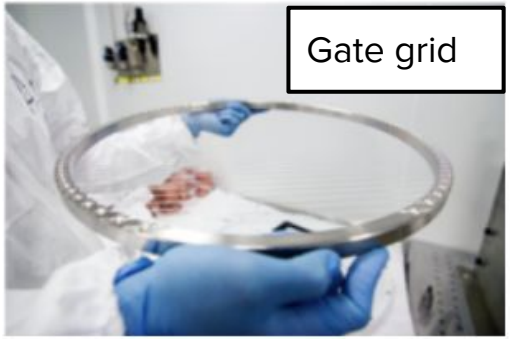


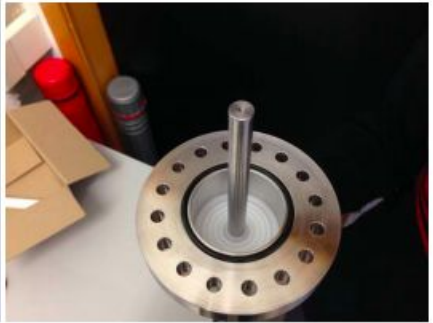
NEW TPC

- Function: the TPC includes the **drift region** (DR), **buffer region** (BR) and the **electroluminescent region** (ELR)
- Includes custom, radiopure high voltage feedthroughs







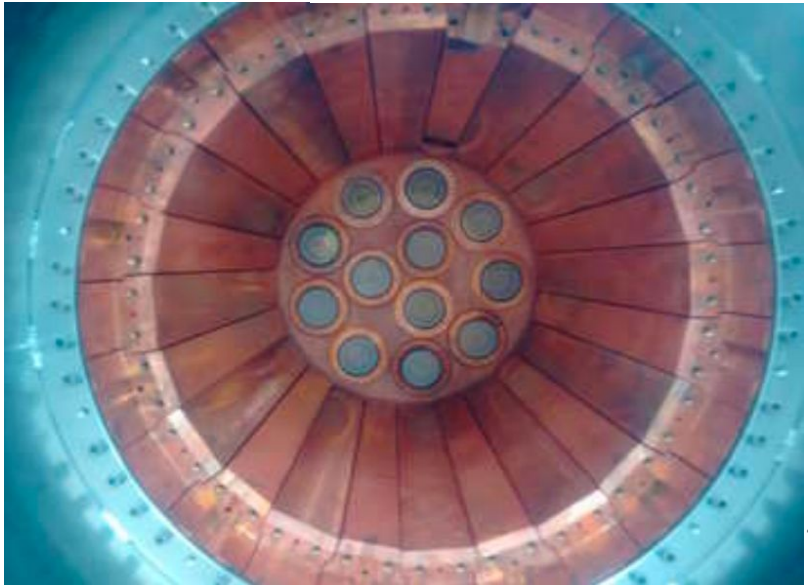


F. Monrabal *et al*, NEXT Collaboration, The NEXT White (NEW) Detector, 2018, arxiv:1804.02409

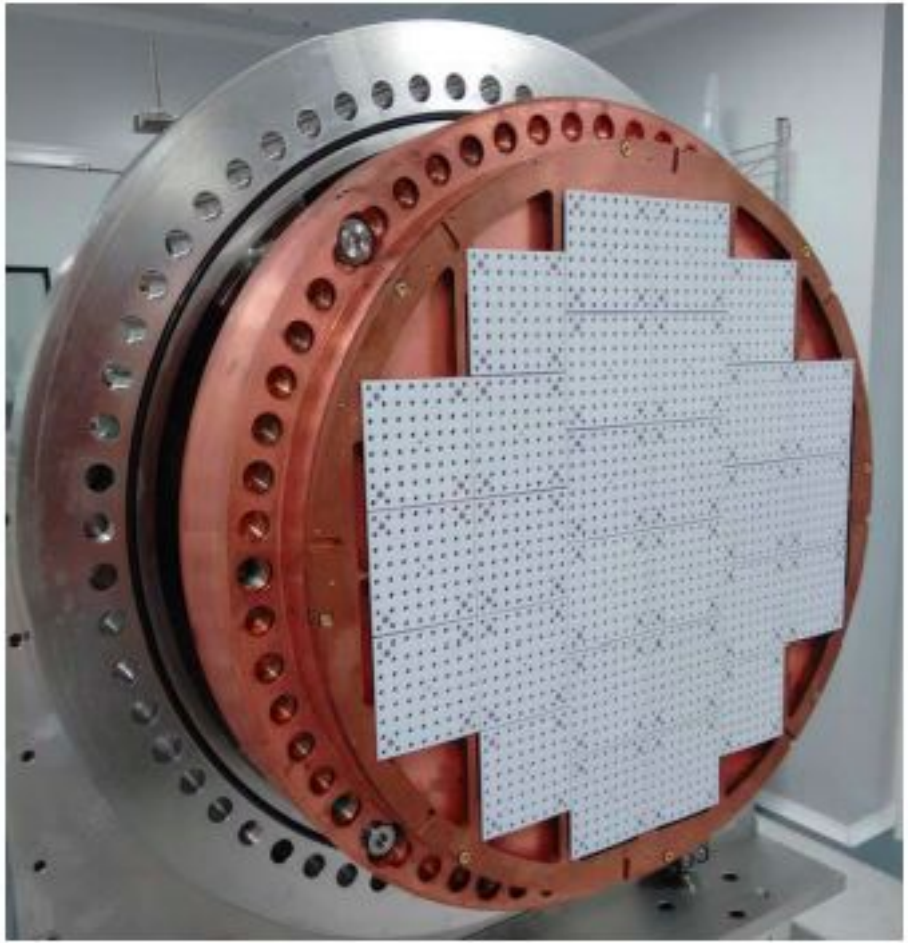
NEW Energy Plane

- Measures event energy, and determine S1 time
- **Hamamatsu R11410-10 PMTs** chosen for low radioactivity (0.35 mBq unit−1) and good performance
- PMTs protected from the gas pressure by 120 mm copper plate
- Coupled to gas volume through 12 sapphire windows
- Coated with resistive, transparent PEDOT
- Layer of wavelength shifting TPB deposited on PEDOT
- Photocathode coverage of 31%

Component	Bi activity
PMT	0.35 mBq unit^{-1}
Base	
Capacitors 1.5 microF	72 μBq unit^{-1}
Capacitors 4.7 microF	123 μBq unit^{-1}
Finechem resistors	4.1 μBq unit^{-1}
KOA RS resistors	7.7 μBq unit^{-1}
Pin receptacles	1.1 μBq unit^{-1}
Araldite epoxy	1.4 mBq kg^{-1}
Kapton-Cu cable	46.8 mBq kg^{-1}
Kapton substrate	23 μBq unit^{-1}
Copper cap	12 μBq unit^{-1}
Total base	1.2 mBq unit^{-1}

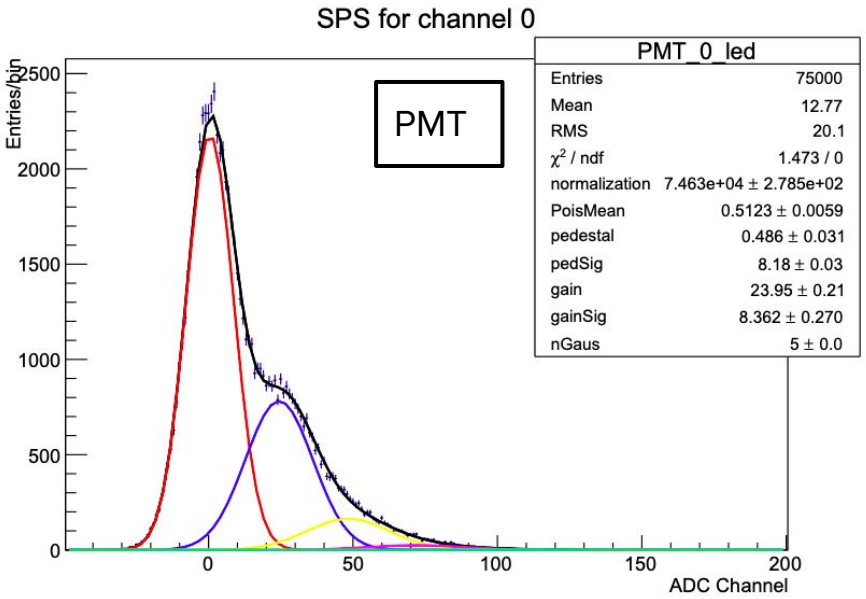


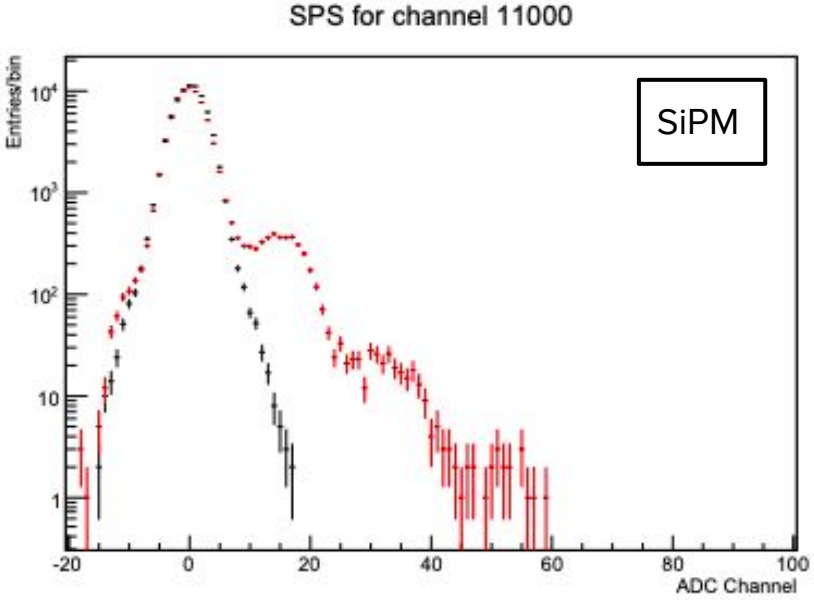
NEW Tracking Plane

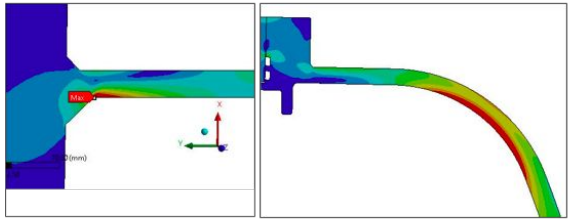
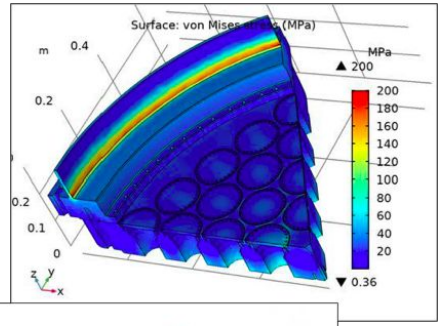


- Tracking plane is near EL gap, measures event position using sparse matrix of SiPMs
- **SensL C series model MicroFC-10035-SMT-GP**, 35 µm cell size, dark count less than 100 kHz at room temperature
- Distributed across 28 square DICE boards
- DICE boards mounted on thick copper shield
- Boards include LED for PMT calibration

NEW LED calibration





NEXT-100 vessel

- Improved gas inlet in the EP:
  - It allows to access to PMTs bases without exposing the detector
- Double gaskets in large flanges
  - Avoid opening and closing after initial commissioning
- Cooling system for temperature stabilization
- Ongoing progress, steel purchased, drawings being finished
- Expected finished Sep 2021