Status of the NEXT project

LIOR ARAZI

BEN-GURION UNIVERSITY

ON BEHALF OF THE NEXT COLLABORATION

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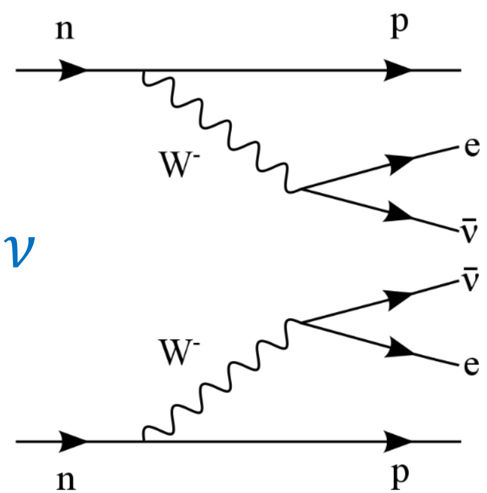
Neutrinoless double beta decay ($\beta\beta0\nu$): What is it and why should we care?

- $\beta\beta0\nu$: ultra-rare hypothetical radioactive decay, where two neutrons inside the nucleus simultaneously transform into two protons emitting two electrons and *no antineutrinos*
- If observed will be the first evidence that the total lepton number is not conserved
- Will prove that the neutrino is a Majorana fermion
- Supporting evidence for the see-saw mechanism and leptogenesis

$\beta\beta2\nu$ vs. $\beta\beta0\nu$

$\beta\beta2\nu$



$${}^{A}_{Z}X \longrightarrow {}^{\ A}_{Z+2}X + 2e^{-} + 2\bar{\nu}_e$$

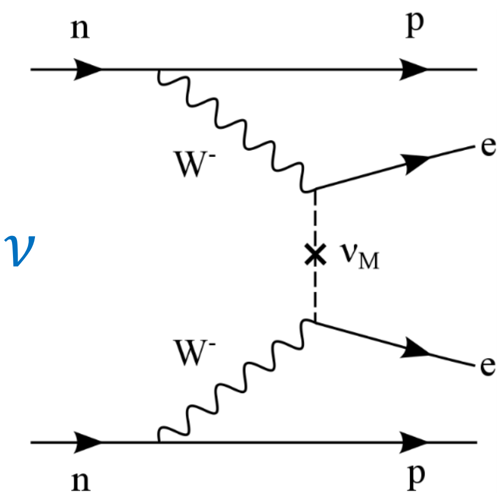
$\Delta L = 0$, ν can be Dirac or Majorana

Observed in 11 isotopes

$T_{1/2} \sim 10^{19} - 10^{21}$ y

Q-value shared among 4 particles

$\beta\beta0\nu$



$${}^{A}_{Z}X \longrightarrow {}^{\ A}_{Z+2}X + 2e^{-}$$

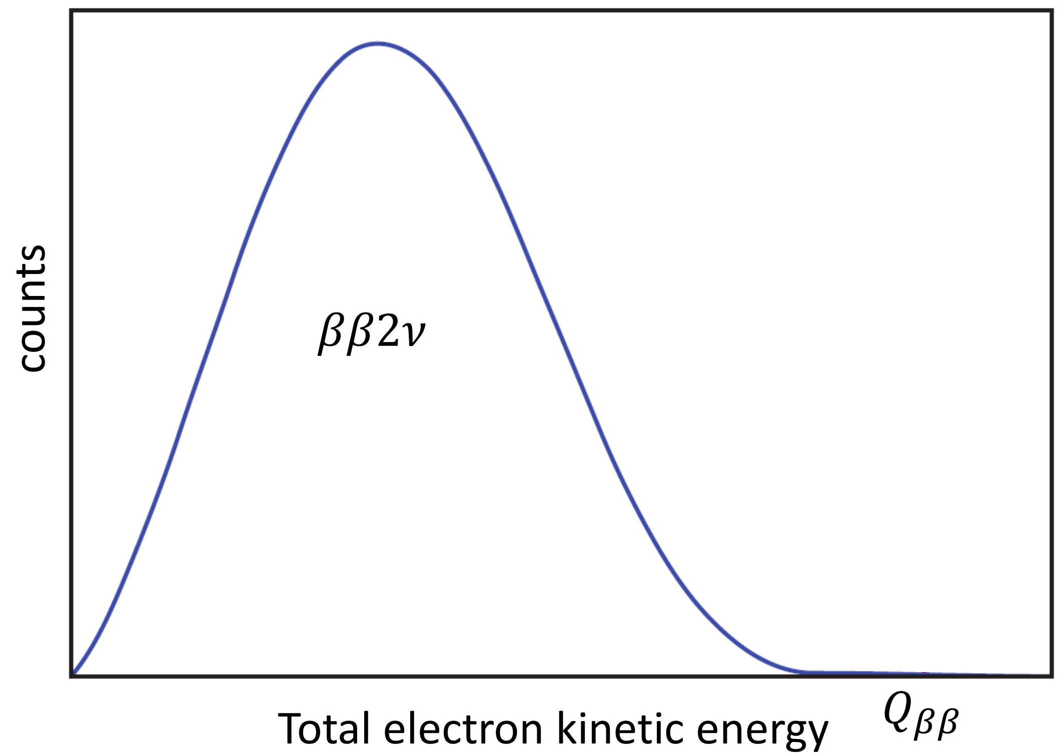
$\Delta L = 2$, ν must be Majorana

Not observed

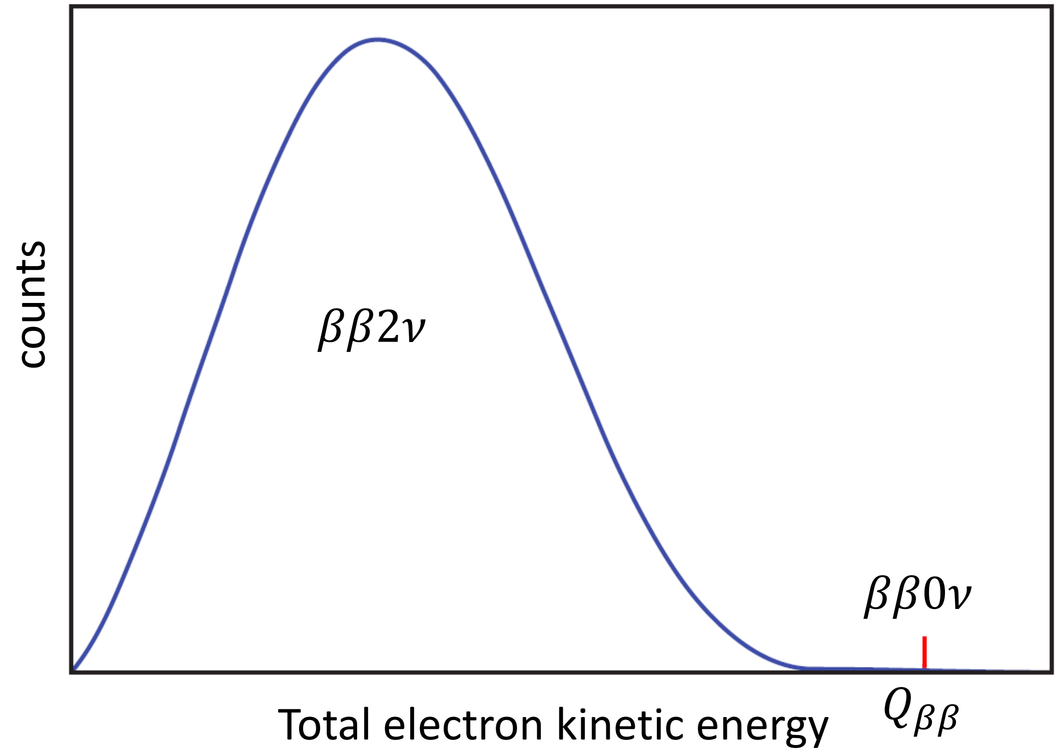
$T_{1/2} > 10^{26}$ y

Electrons kinetic energy = Q-value

$\beta\beta 2\nu$ vs. $\beta\beta 0\nu$



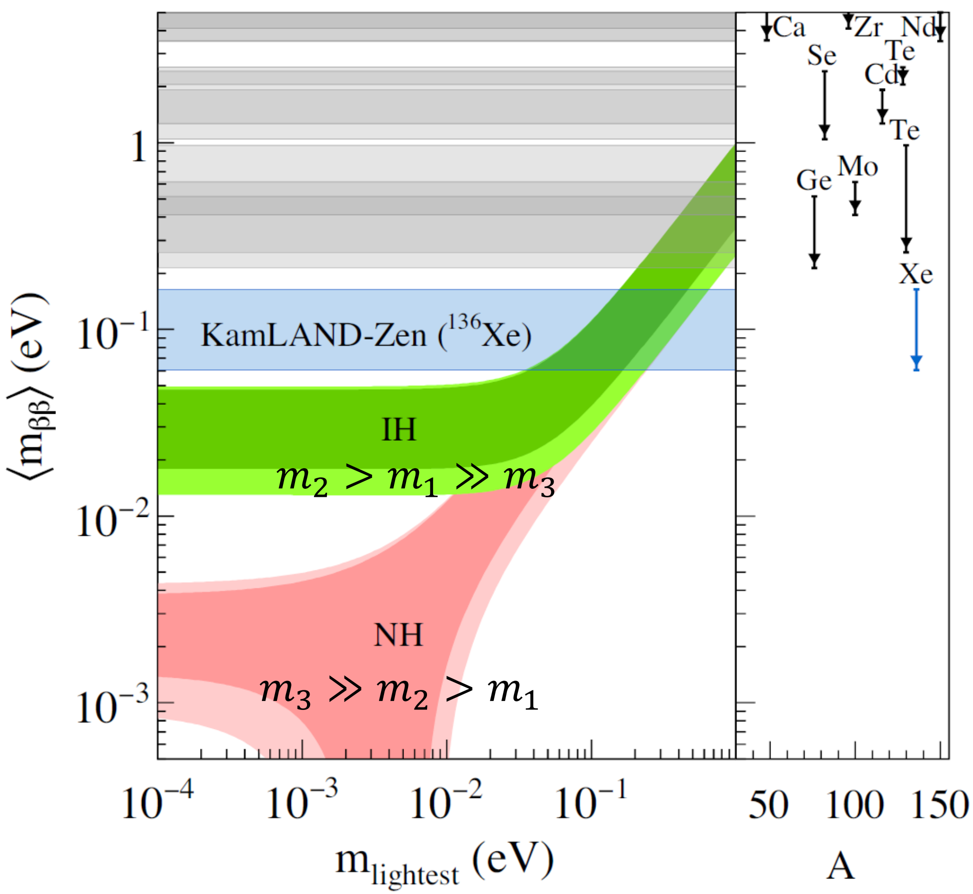
$\beta\beta 2\nu$ vs. $\beta\beta 0\nu$



$\beta\beta 0\nu$ can only occur in nuclei with $\beta\beta 2\nu$, with $< 10^{-5}$ relative rate

→ **Need heroic background suppression at $Q_{\beta\beta}$**

From $\beta\beta0\nu$ half-life to effective Majorana neutrino mass



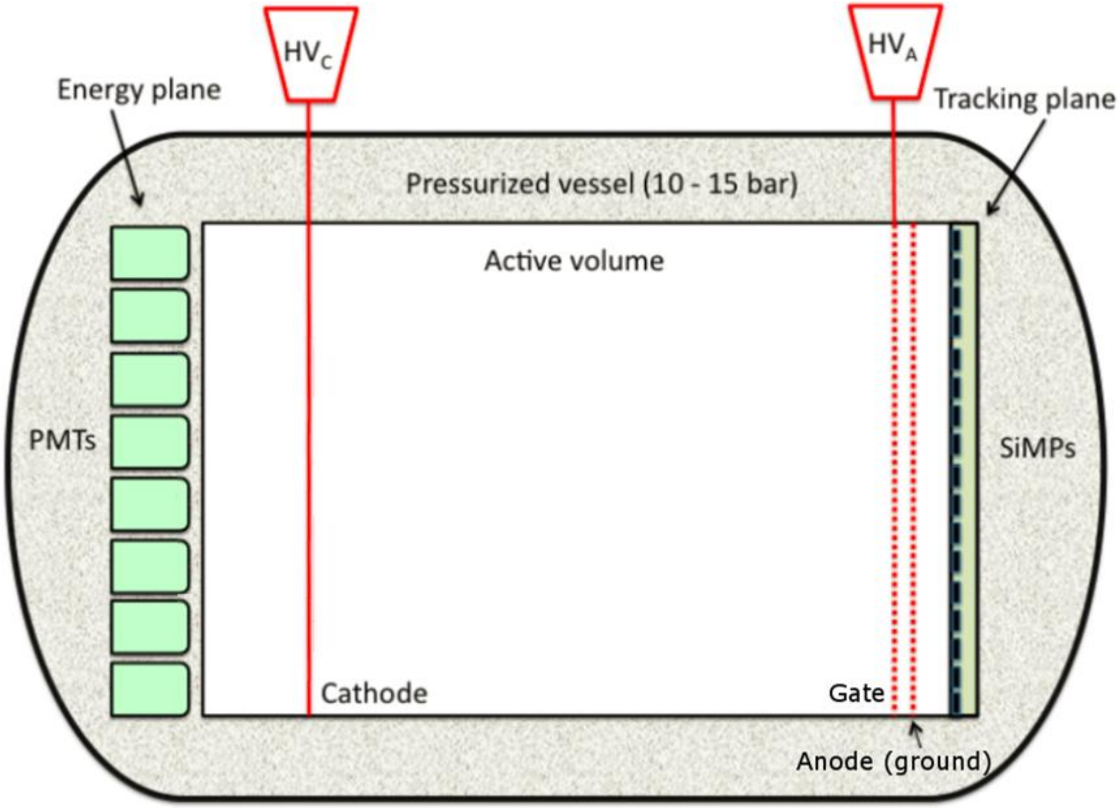
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

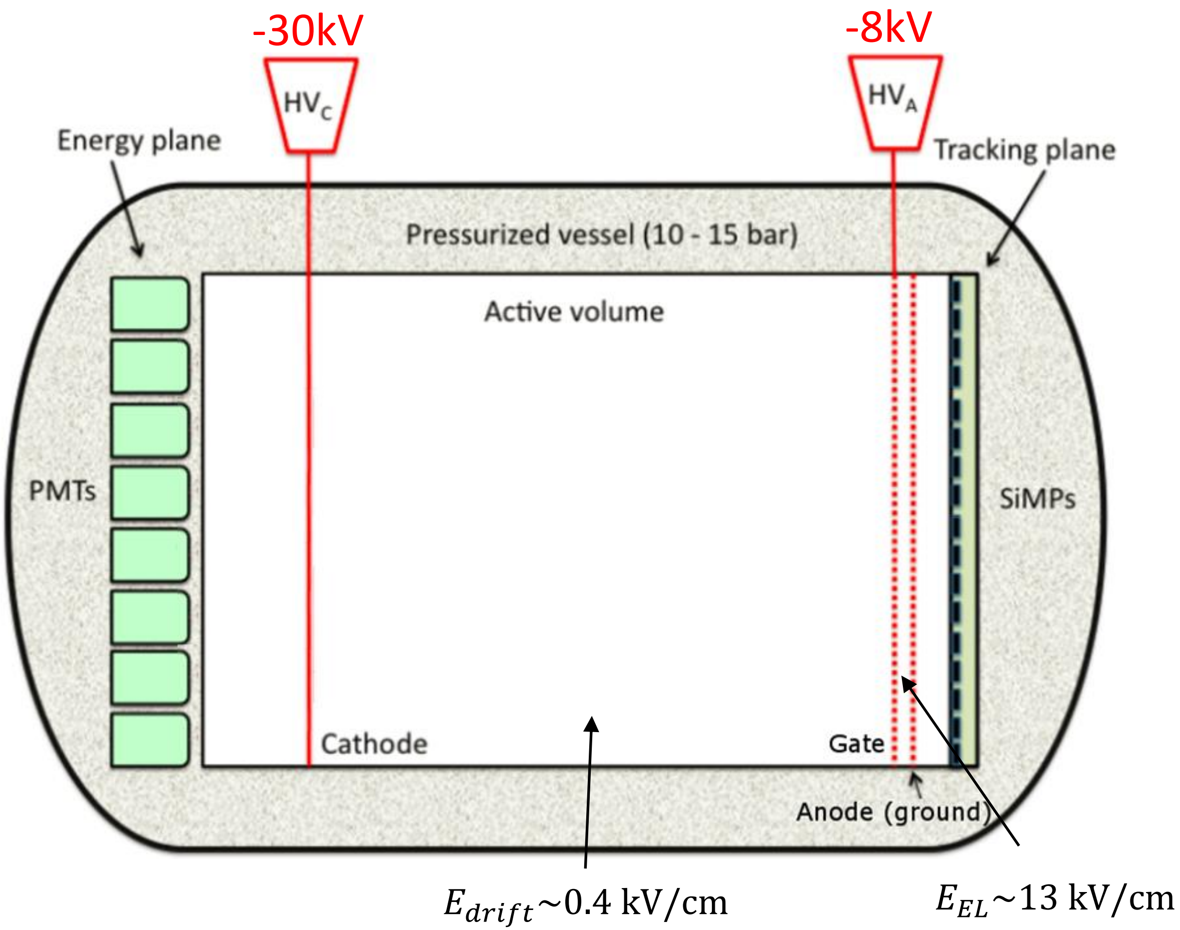
NEXT
Neutrino Experiment with Xenon TPC

- Search for $\beta\beta0\nu$ in ^{136}Xe in a *high pressure xenon gas* time projection chamber (TPC)
- Working in gas allows:
  - Excellent energy resolution (aiming at ~0.5% FWHM at $Q_{\beta\beta}$=2.458 MeV)
  - Track topology enables discriminating γ-induced electrons from ββ events
- High pressure (10-15 bar) required to assemble enough mass in a reasonable volume
- Currently operating NEXT-White (~10 kg of Xe enriched to 91% ^{136}Xe), moving to NEXT-100 (100 kg)
- Radiopure detector, running at Canfranc Underground Laboratory

NEXT Concept

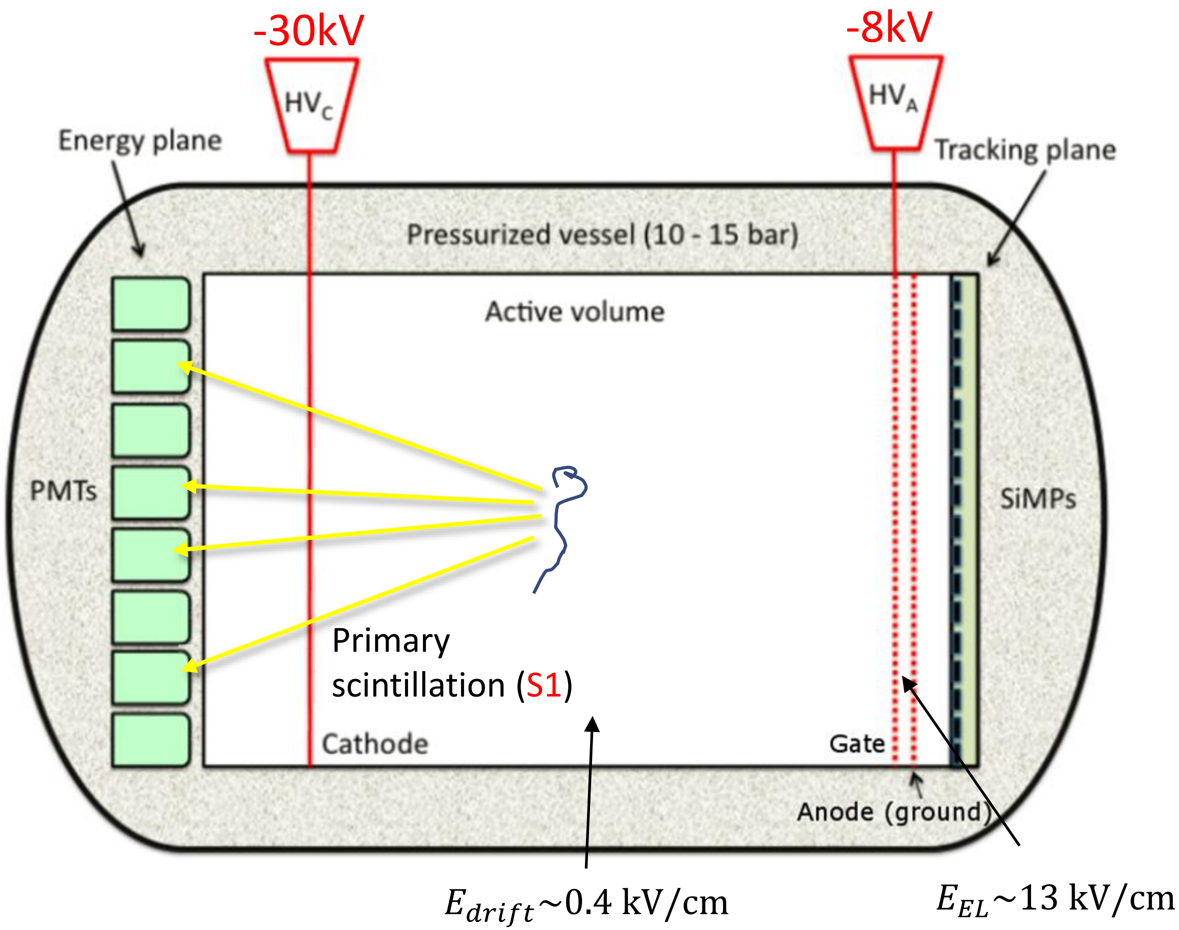


NEXT Concept



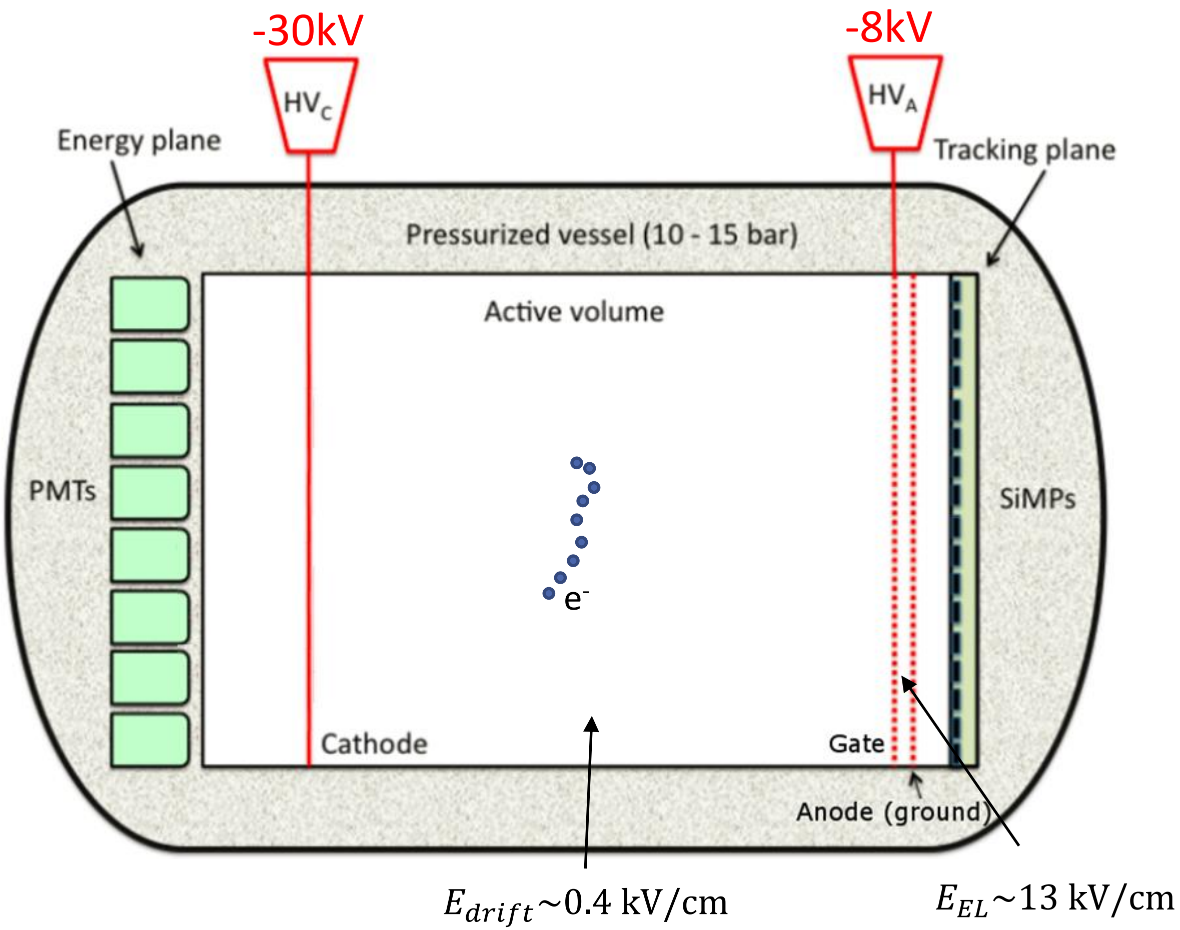
NEXT Concept

S1 (PMTs) gives t_0



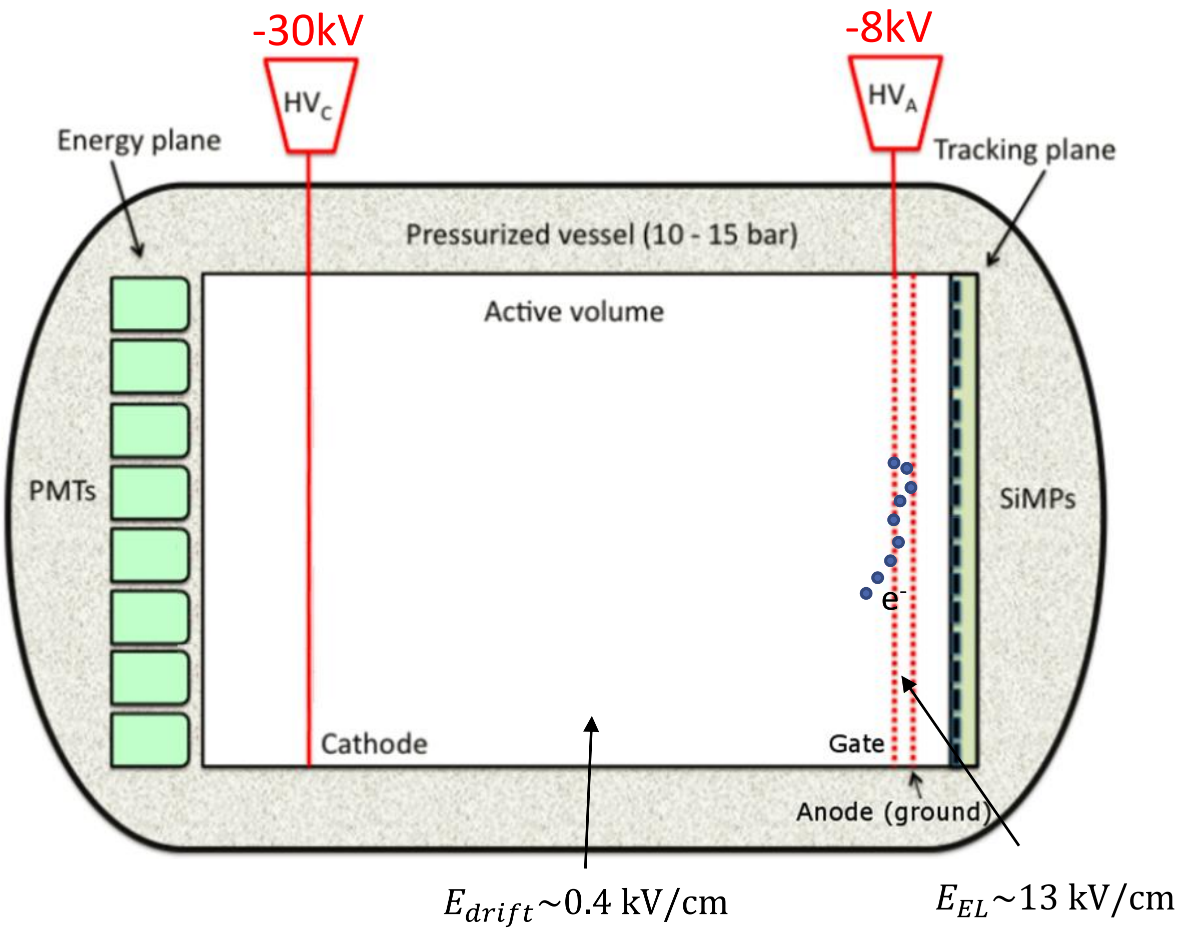
NEXT Concept

S1 (PMTs) gives t_0



NEXT Concept

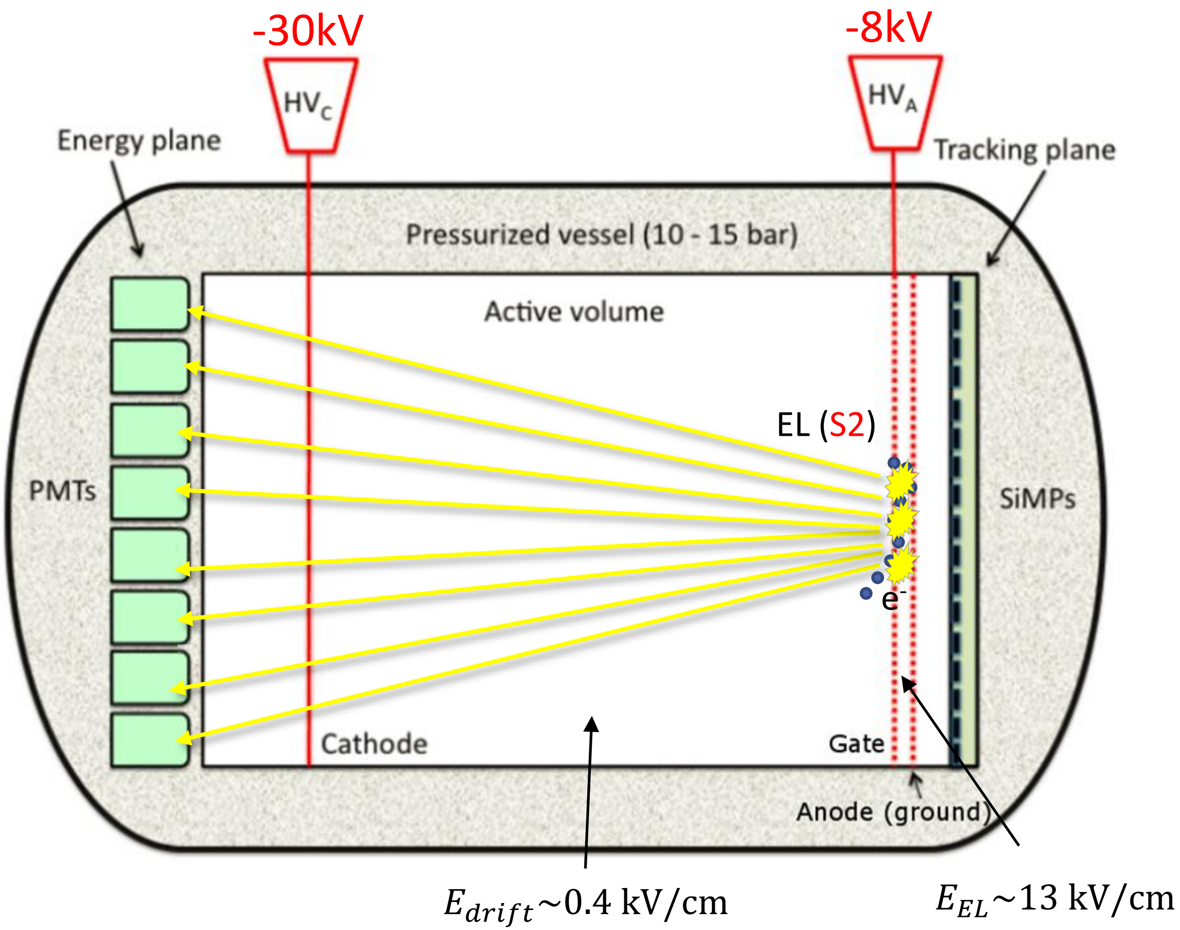
S1 (PMTs) gives t_0



NEXT Concept

S1 (PMTs) gives t_0

S2 magnitude by proportional EL (PMTs) gives the event energy

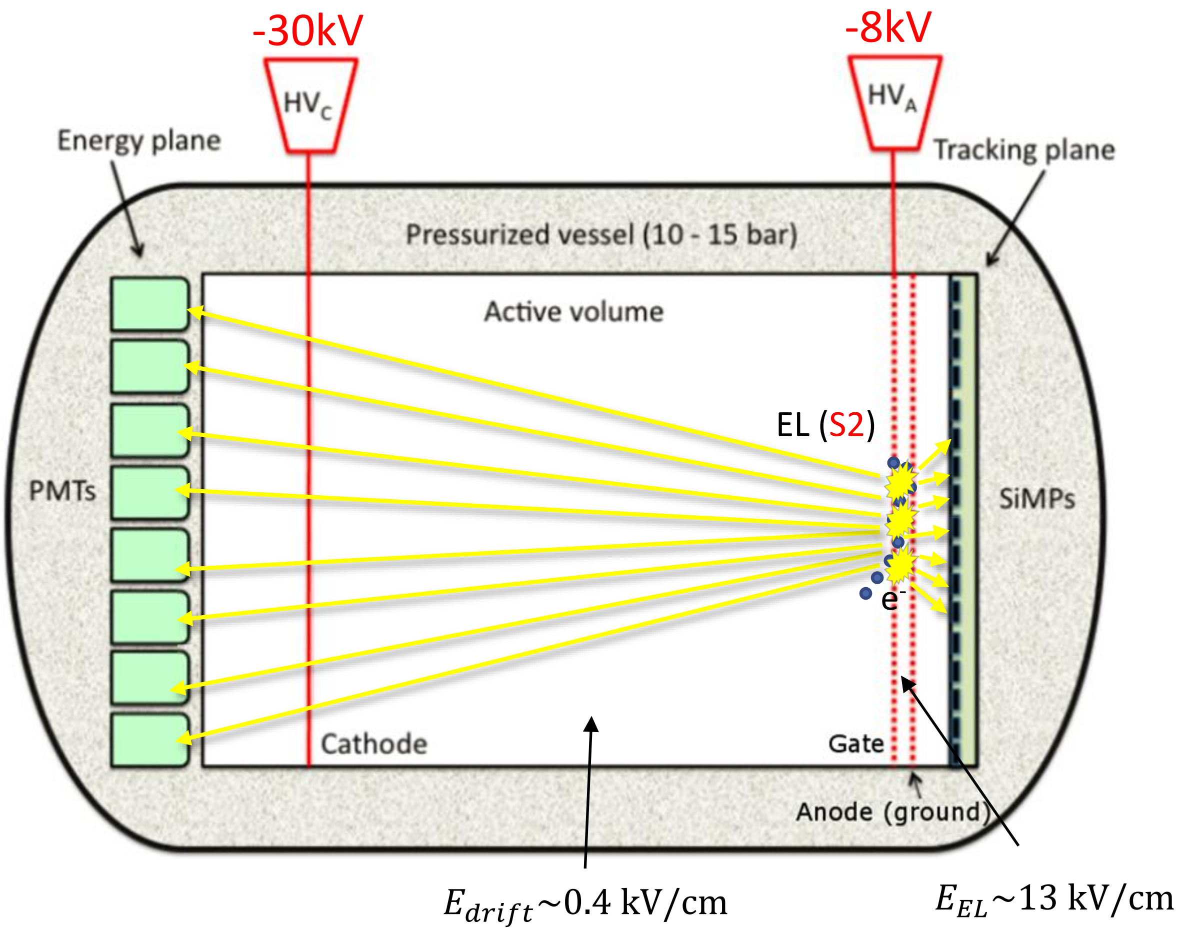


NEXT Concept

S1 (PMTs) gives t_0

S2 magnitude by proportional EL (PMTs) gives the event energy

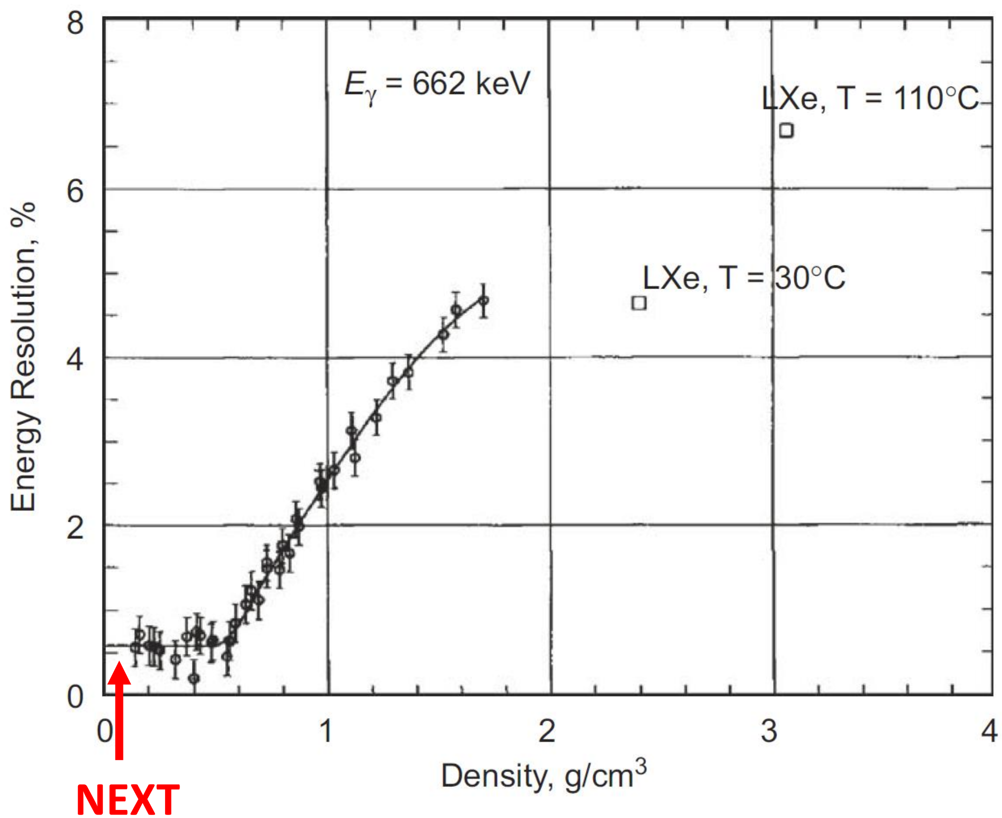
S2 time-slice images (SiPMs) give the event topology



Energy resolution in Xe gas

FWHM energy resolution vs. Xe density

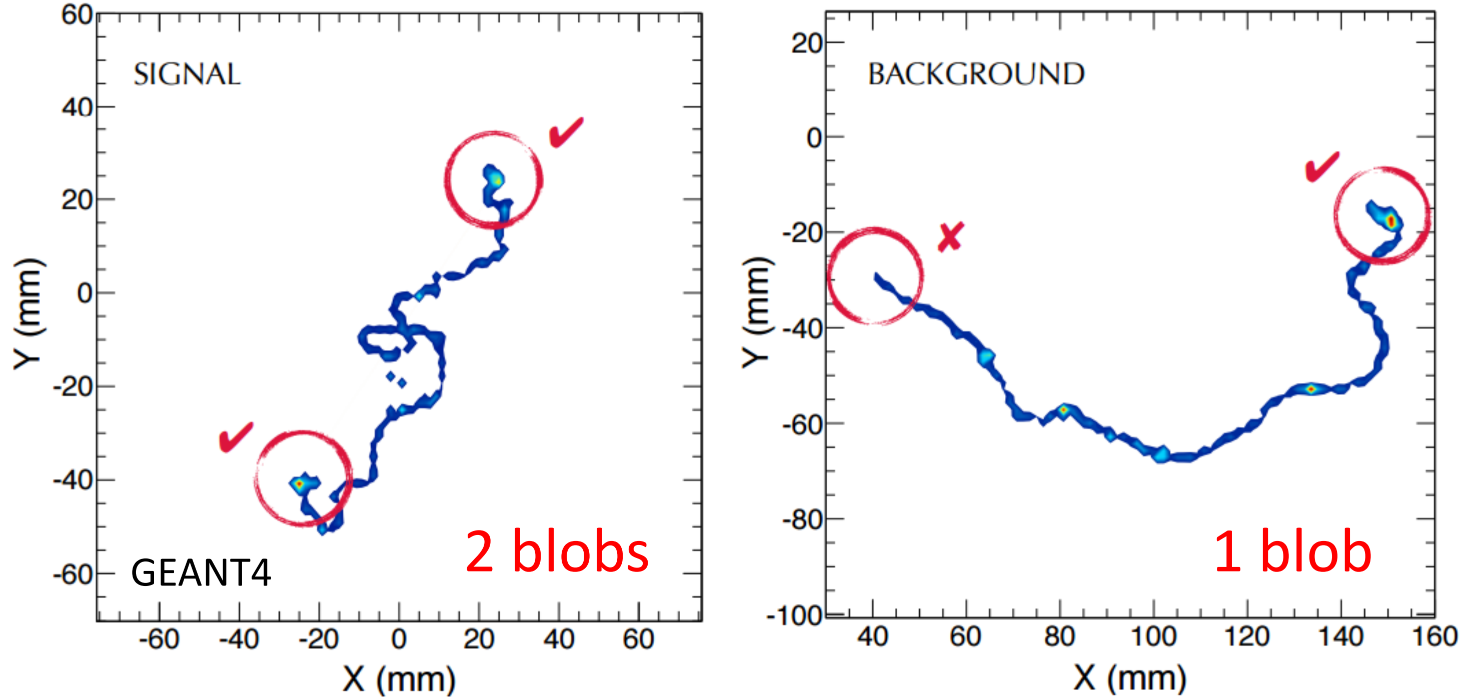
^{137}Cs 662 keV γ ionization signal only



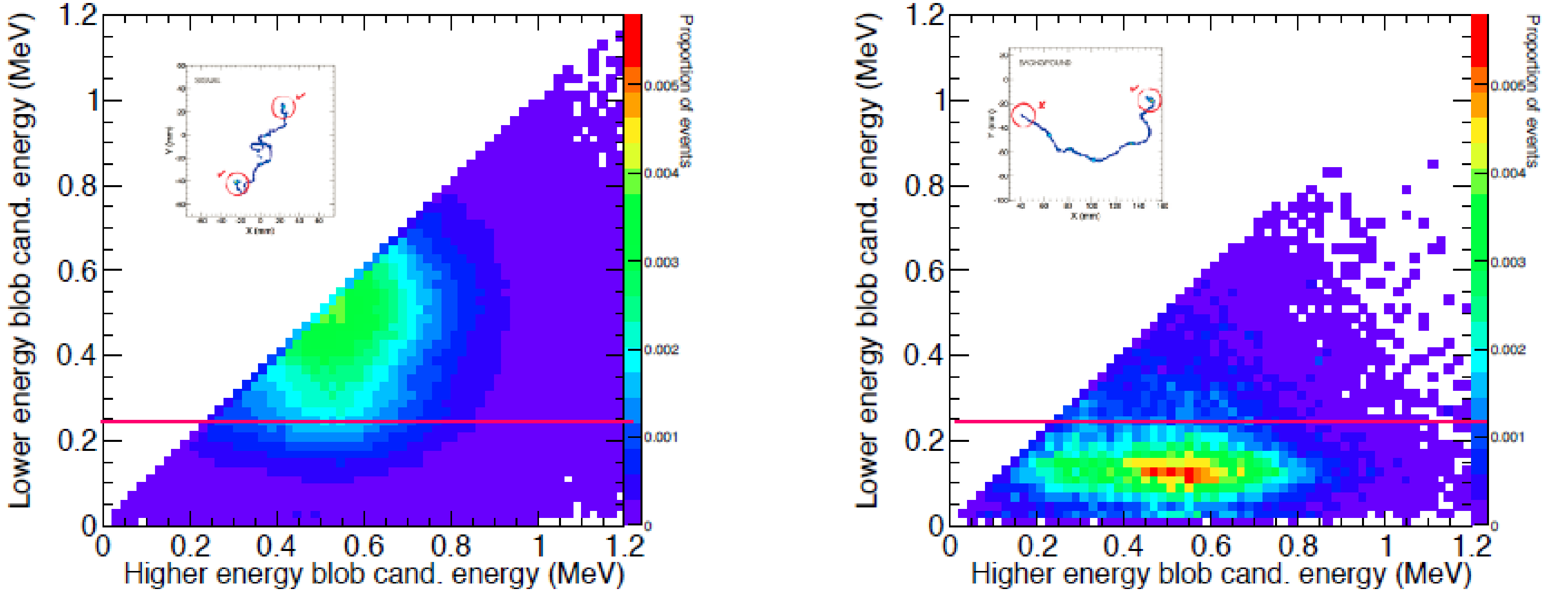
A. Bolotnikov, B. Ramsey, Nucl. Instr. and Meth. A 396 (1997) 360

Topological signature

Bragg peak – 'blob' of dense ionization at the end of electron track

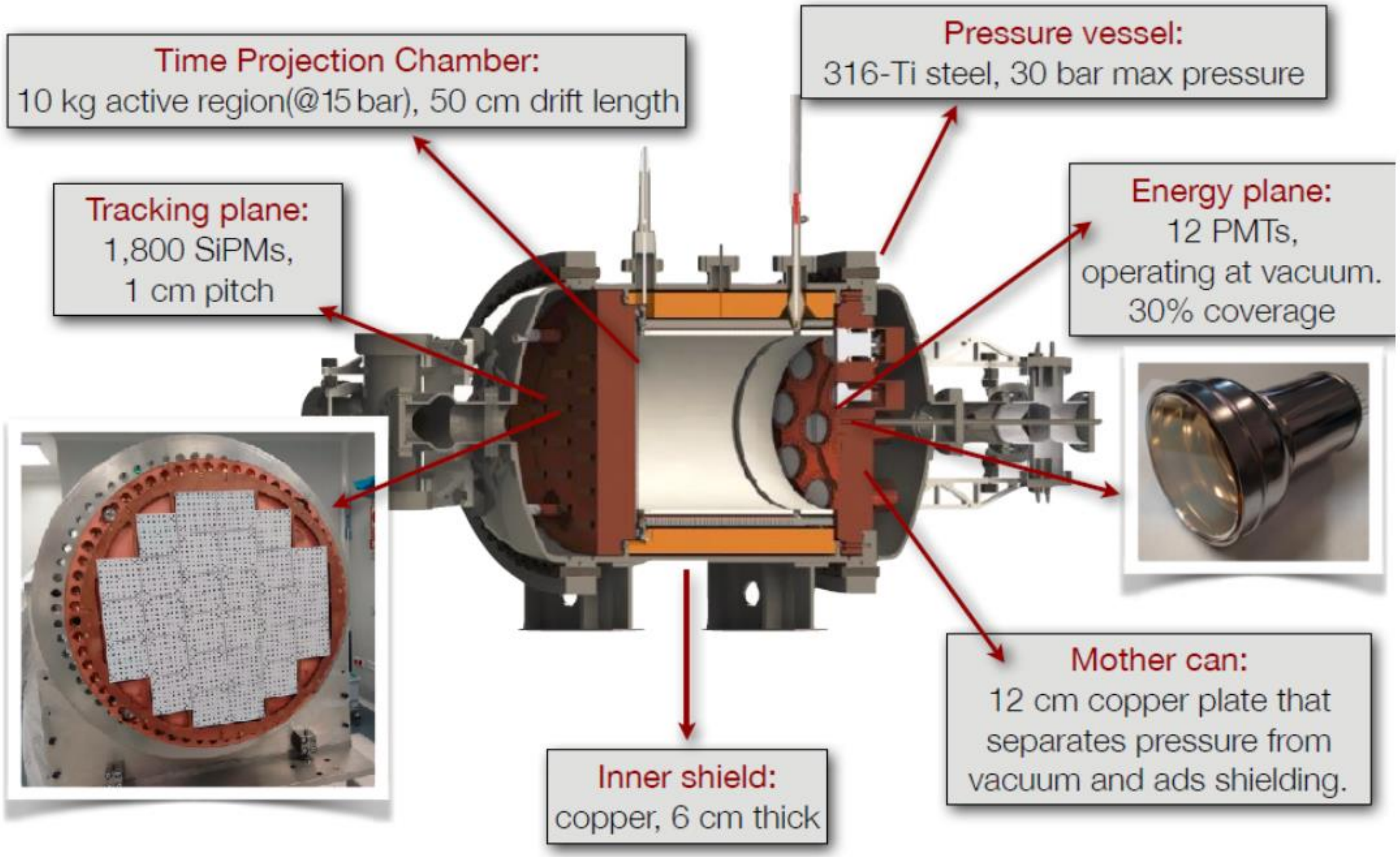


Blob-based background rejection



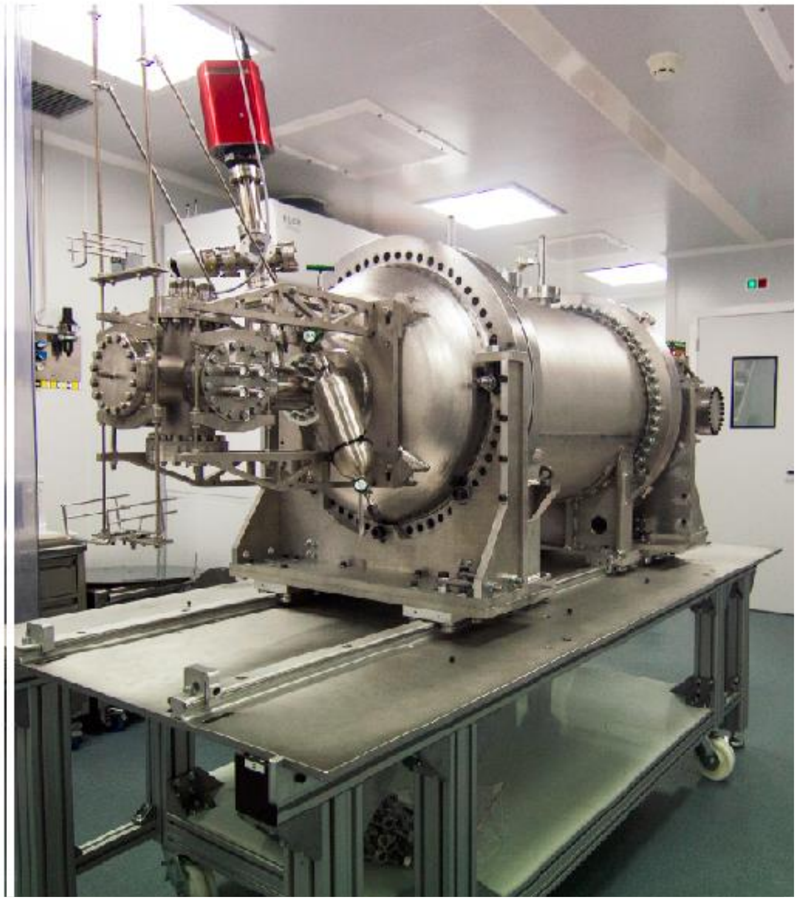
P. Ferrario, et al. (NEXT Collaboration), JHEP 1605 (2016) 159, arXiv:1507.05902

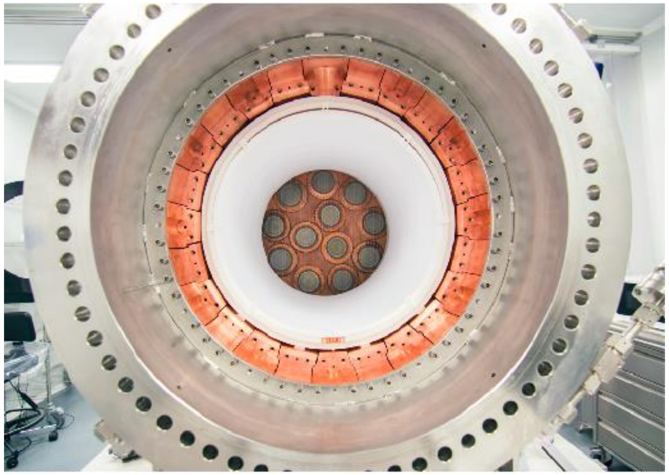
Running prototype:
NEXT-White (NEW) ~10 kg Xe

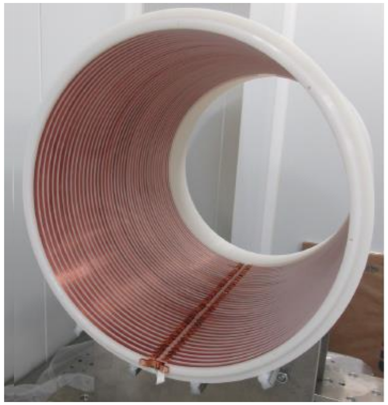


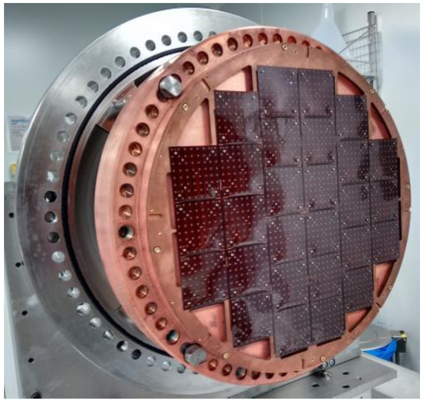
F. Monrabal *et al.* (NEXT collaboration), arXiv:1804.02409

Running prototype:
NEXT-White (NEW) - 10 kg Xe

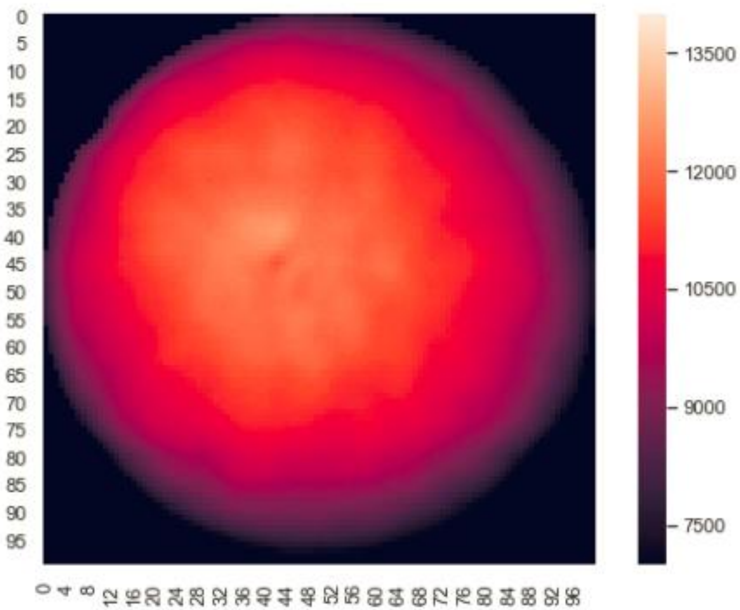




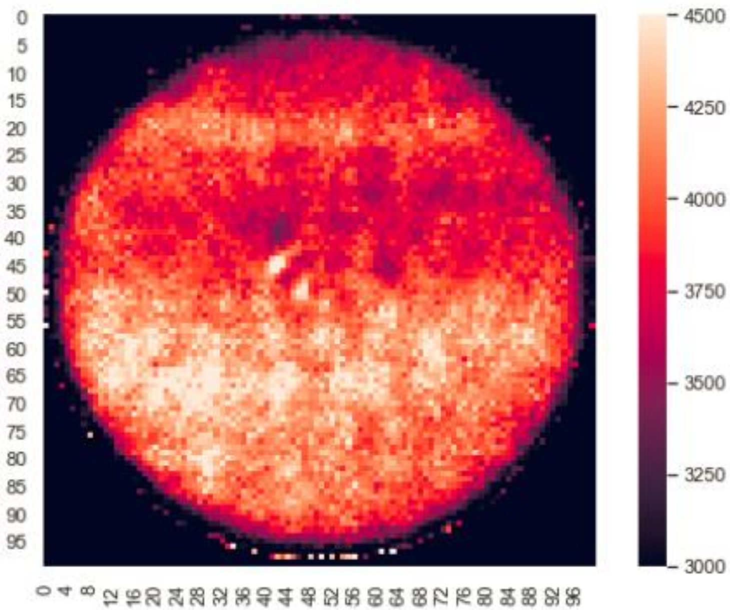




Online 3D calibration maps with ^{83m}Kr: point-like 41.5 keV events throughout TPC volume



Geometrical S2 map

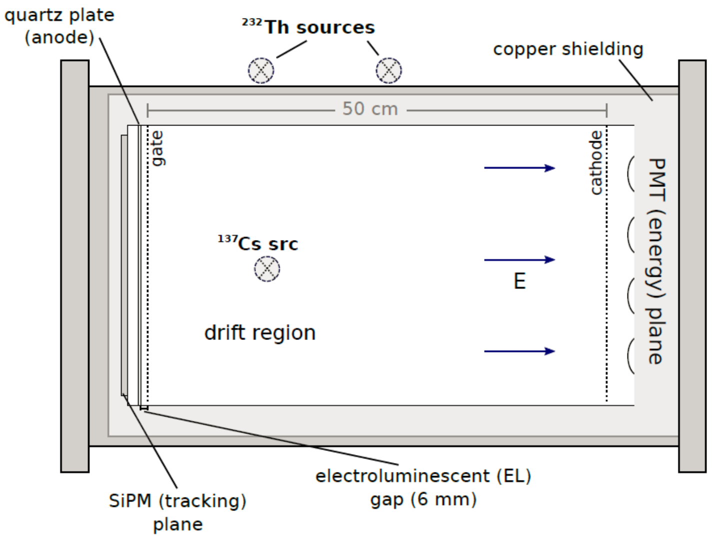


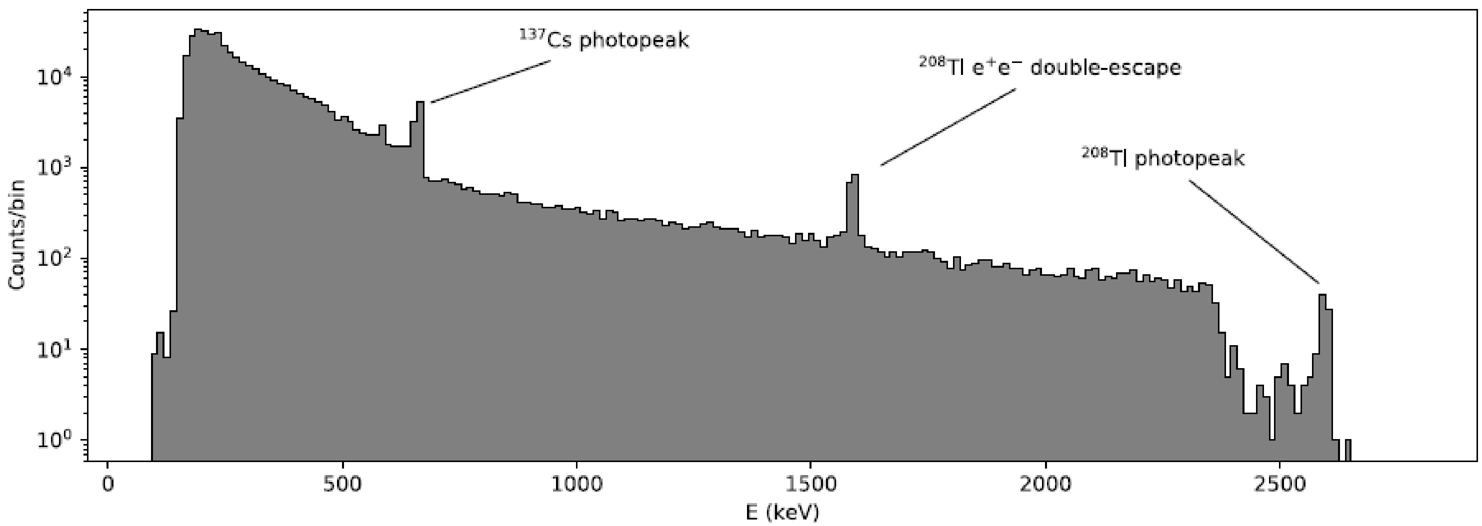
Electron lifetime map

Average >4 ms, 8 times larger than max drift time

G. Martínez-Lema, *et al.* (NEXT collaboration) 2018 *JINST* **13** P10014, arXiv:1804.01780.

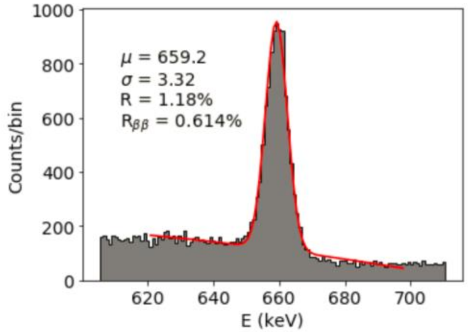
NEW: Calibration with “high-energy” sources

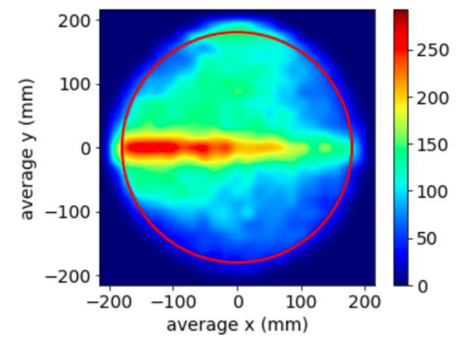




^{137}Cs 662 keV

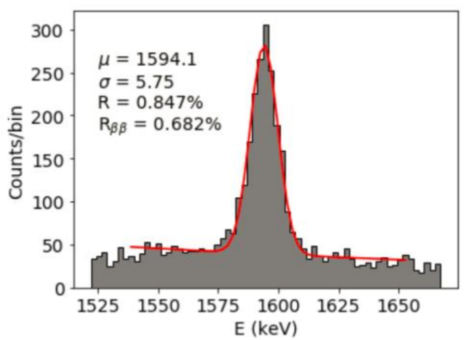
Extrapolates $(1/\sqrt{E})$ to 0.61% FWHM at $Q_{\beta\beta}$

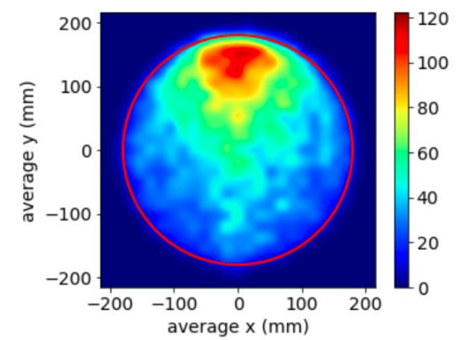




^{208}Tl 1593 keV e^+e^- escape peak

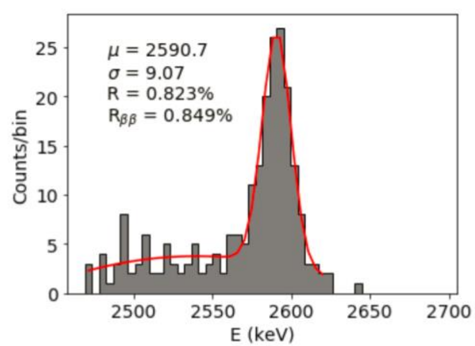
Extrapolates to 0.68% FWHM at $Q_{\beta\beta}$

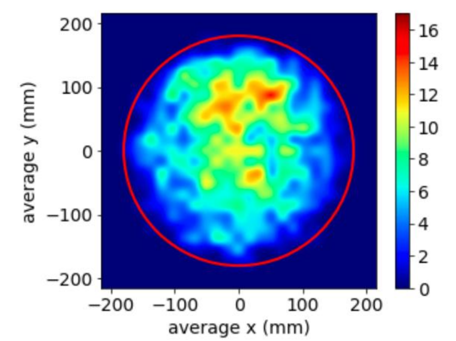




^{208}Tl 2615 keV full absorption peak

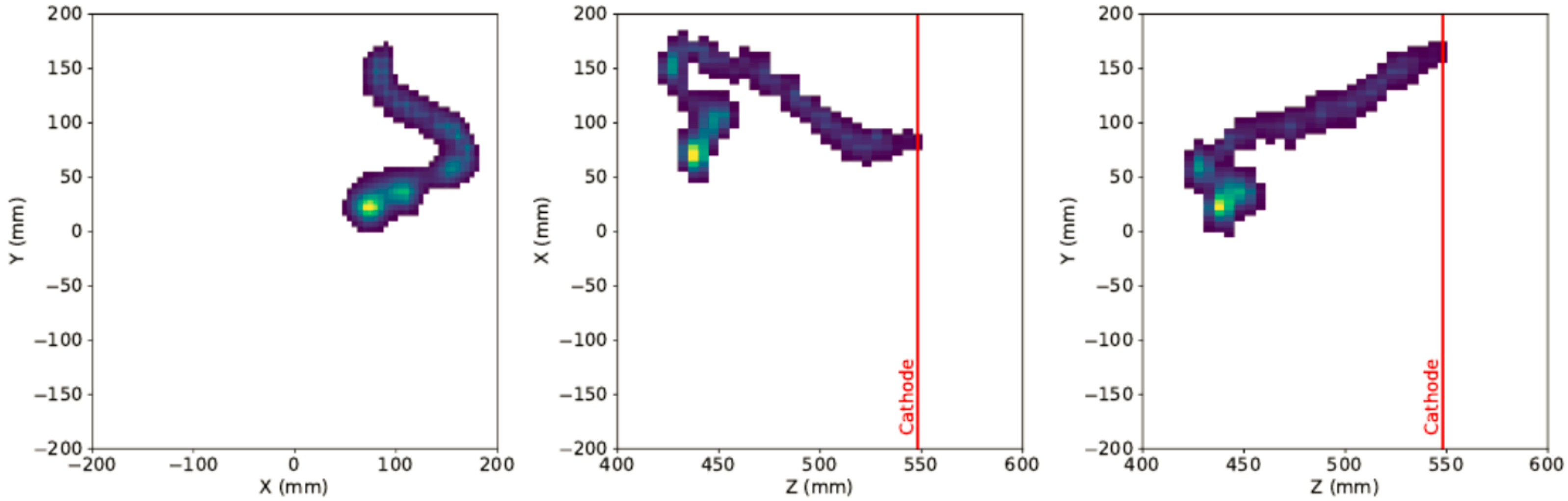
Extrapolates to 0.85% FWHM at $Q_{\beta\beta}$





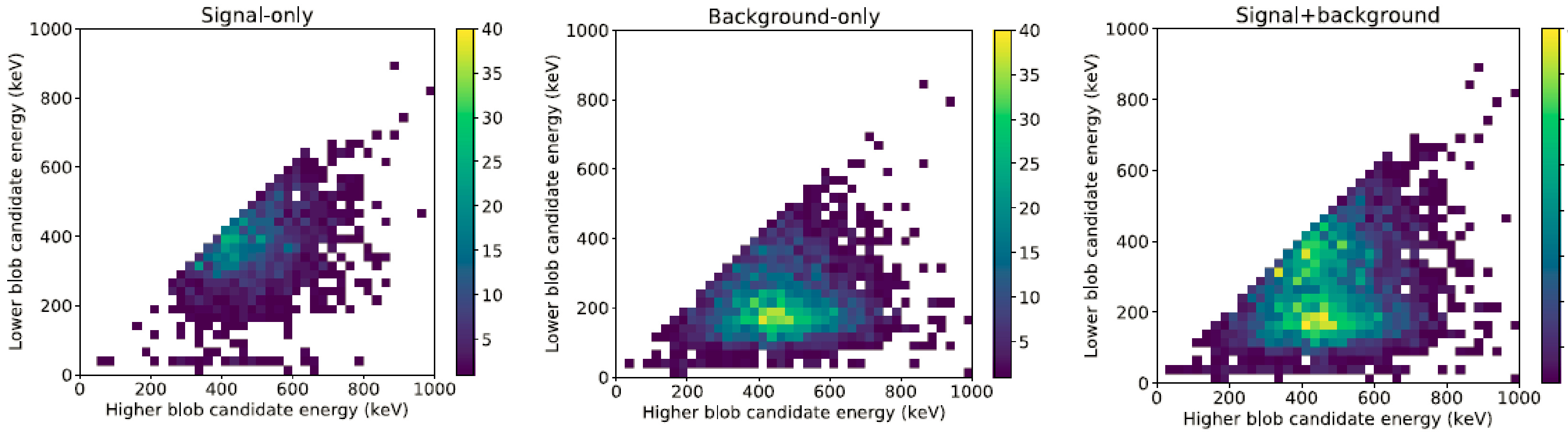
J. Renner *et al.* (NEXT collaboration), 2018 *JINST* 13 P10020, arXiv:1808.01804.

Track topology in NEW



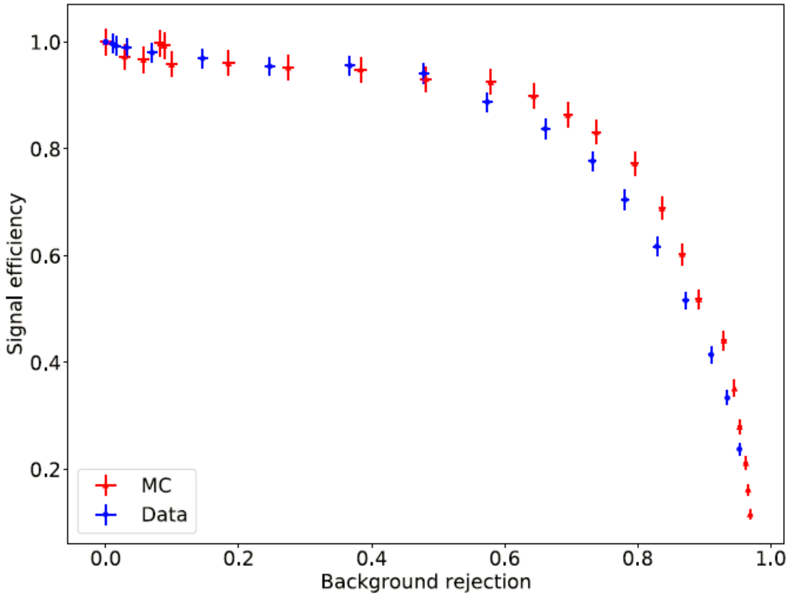
Beta emission from the cathode

P. Novella, et al. (NEXT collaboration) *JHEP* 1810 (2018) 112, arXiv:1804.00471

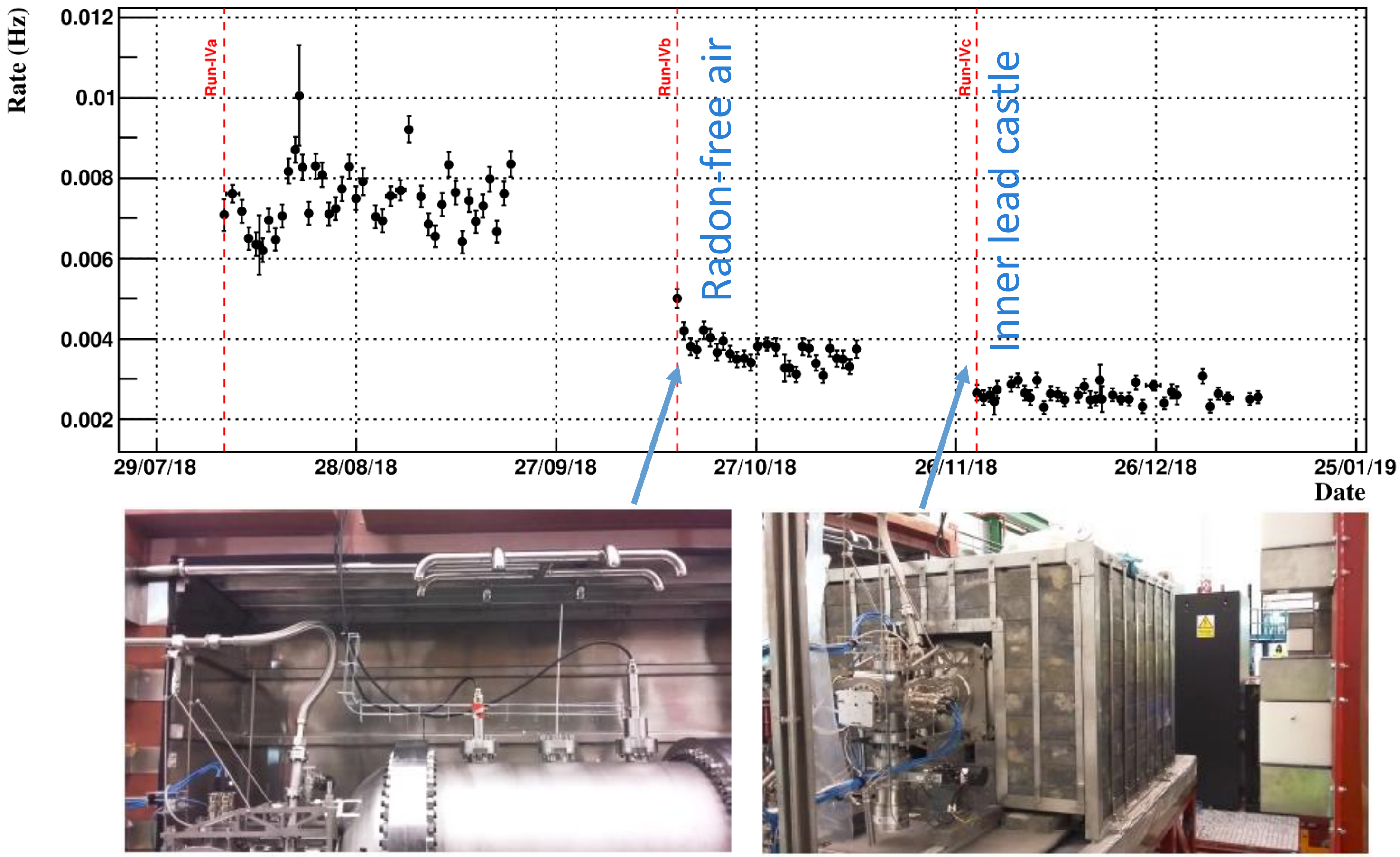


Signal/background discrimination using blobs

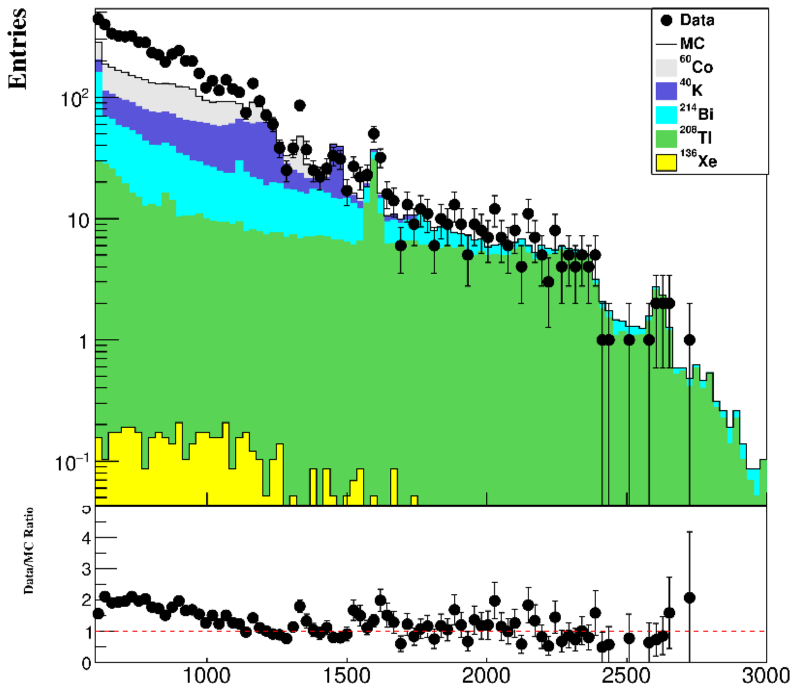
^{208}Tl escape peak events: MC and data



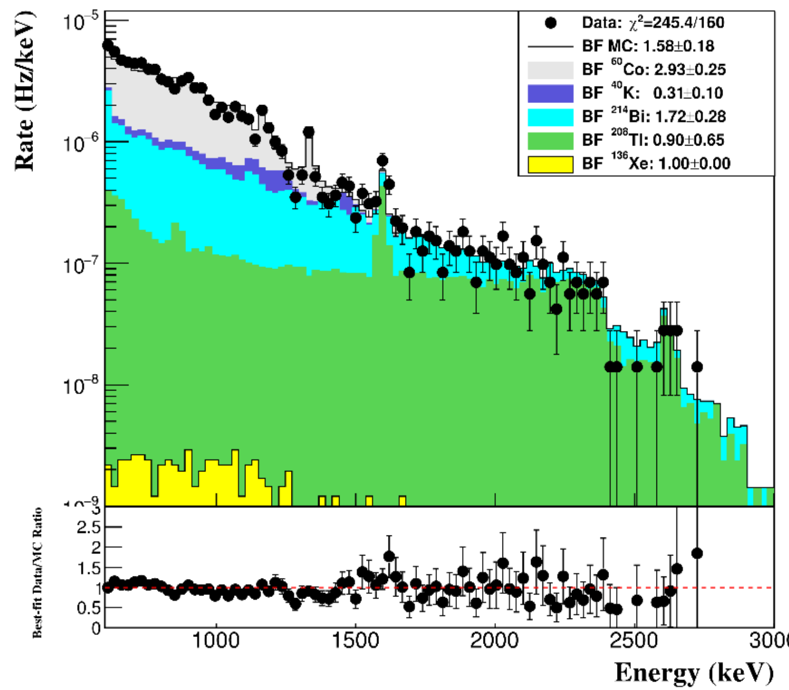
NEW: low-background run
< 3 mHz above 600 keV



Low background: sources are well understood and modelled

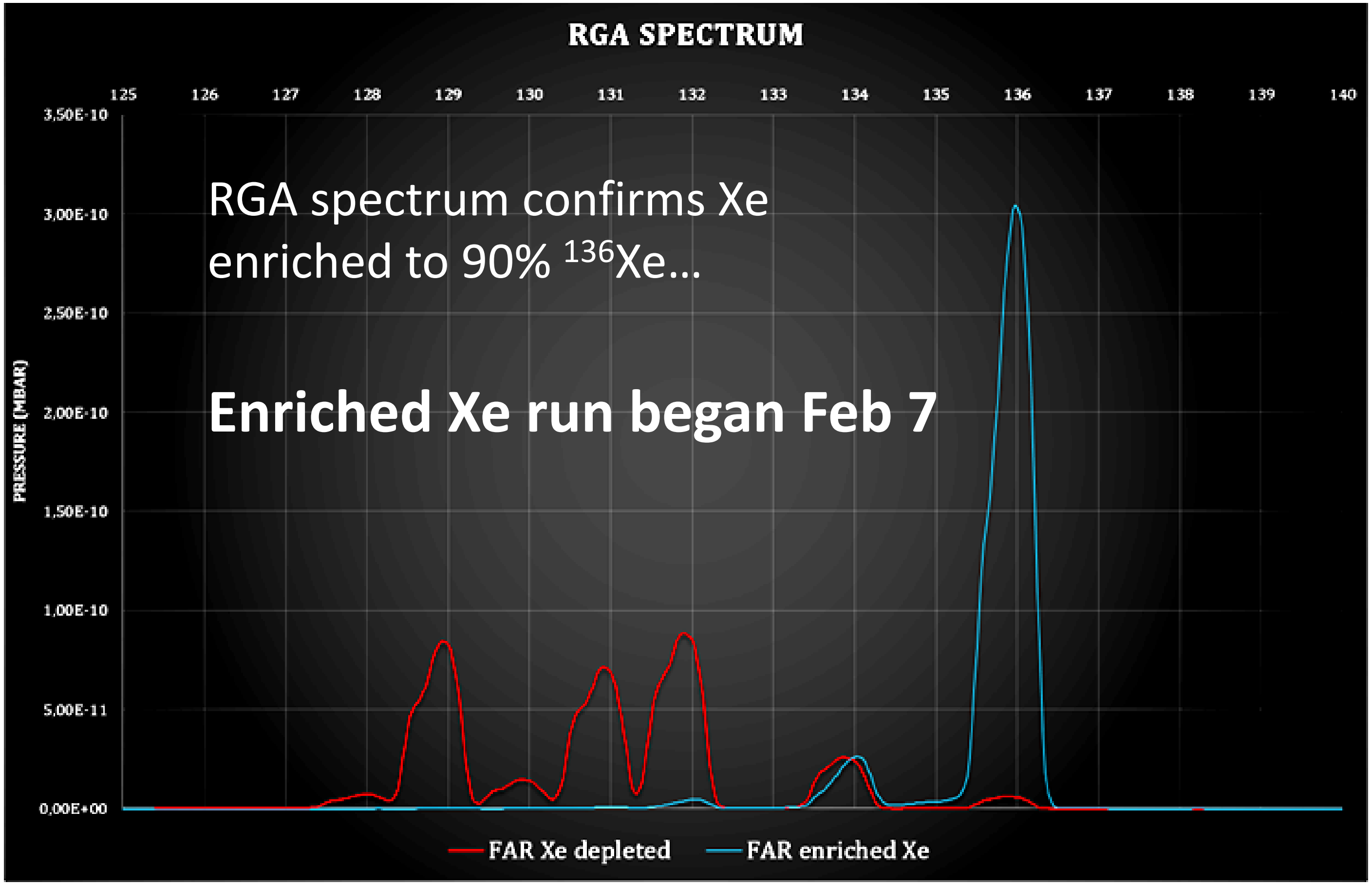


Data vs. expectation from nominal background model

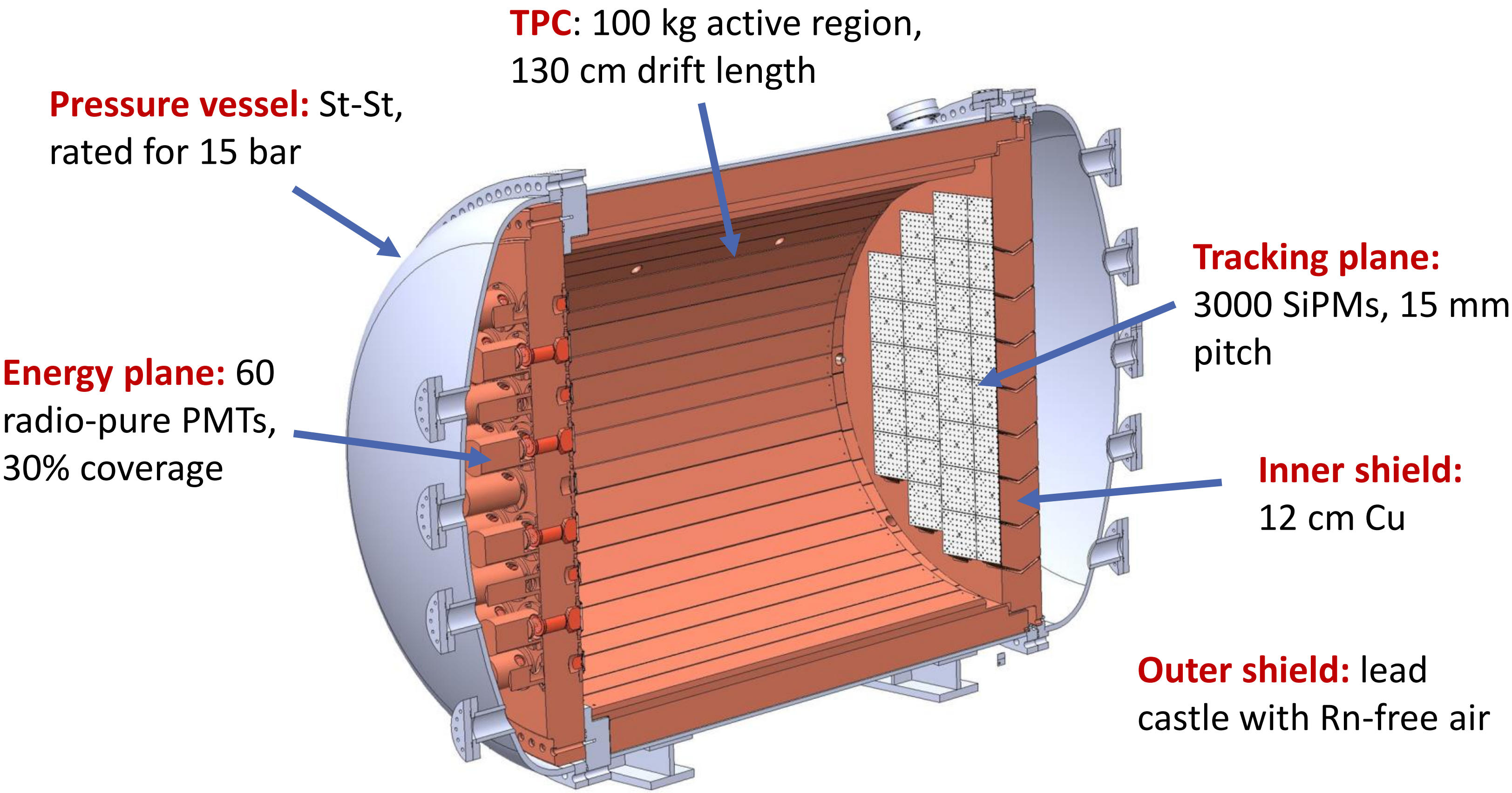


Expectation from best-fit to data with isotope-specific scaling

NEXT NEW step: enriched Xe for $\beta\beta2\nu$



NEXT-100 (assembly in one year)



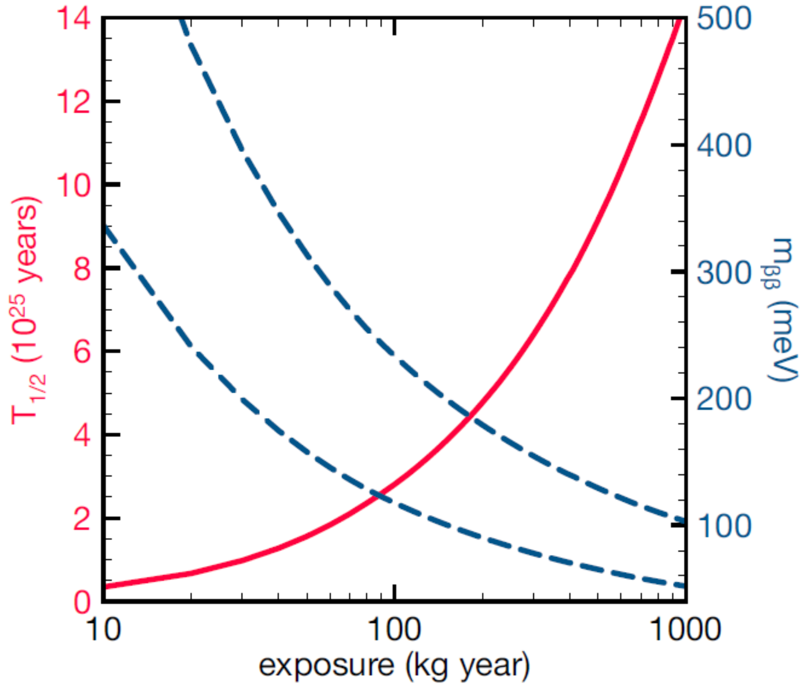
NEXT-100 expected sensitivity

Background: 1 counts/100 kg/yr for 1% FWHM

Dashed: largest and smallest estimations for the nuclear matrix elements

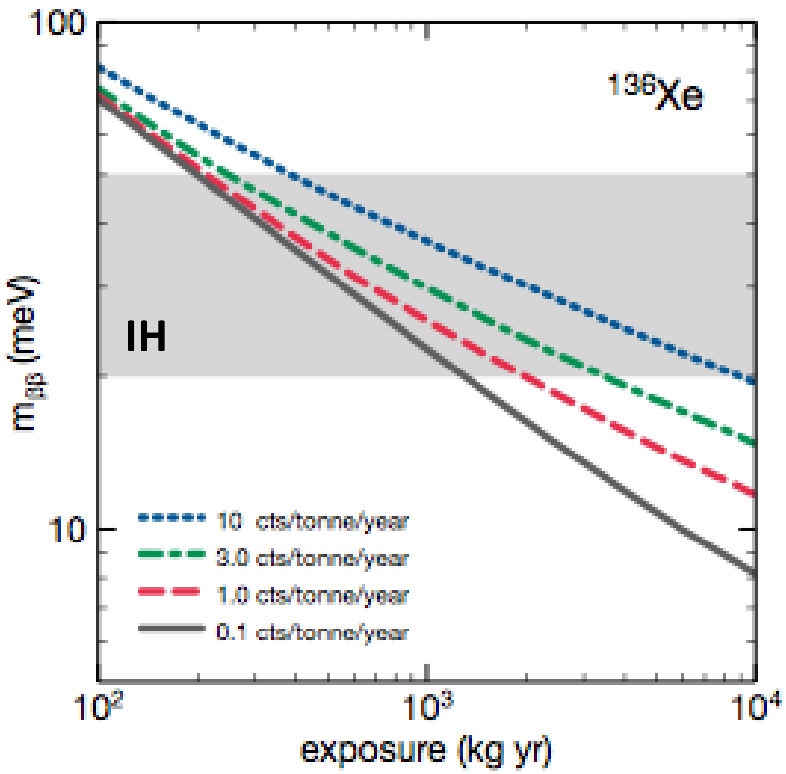
Similar sensitivity as KamLand-ZEN after ~4 years

(*remember NEXT-100 is a demonstrator for a ton-scale detector*)



J. Martín-Albo, et al. (NEXT collaboration), JHEP (2016) 2016 159, arXiv:1511.09246

NEXT on the ton-scale: Exploring the Inverted Hierarchy



- Plot shows the sensitivity of a 100% efficient xenon experiment (with a reasonable NME set and $g_A = 1.27$)
- With a background ~10 counts/ ton/year and a mass of 1 ton, 10 years of run are required (e.g, ~30 years for an efficiency of 30 %).
- With a background count of ~1 counts/ton/year, only 2 years are required (6 years for an efficiency of 30%).

J. Martín-Albo Ph.D. thesis (2015), http://roderic.uv.es/handle/10550/41728

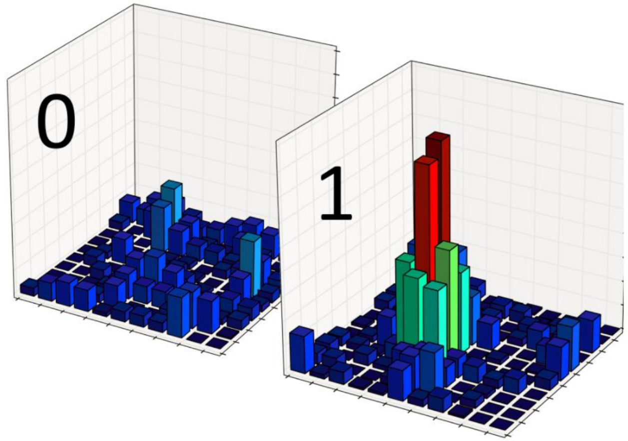
Barium Tagging: towards "background free" experiment

Drastic reduction in γ-induced background by identifying the ^{136}Ba daughter

Basic idea – single molecule fluorescence imaging (SMFI)

- coat cathode with chelating molecules selective for barium ions (but not Xe).
- The molecules are non fluorescent in isolation and become fluorescent upon chelation.
- Interrogate cathode surface with a laser: a single molecule holding Ba fluoresces at a longer wavelength and is readily identified.

A. D. McDonald *et al.* (NEXT Collaboration), PRL **120**, 132504 (2018)



“Conventional” R&D

Parallel to Ba-tagging, additional strategies under development for background reduction

Two main problems to tackle:

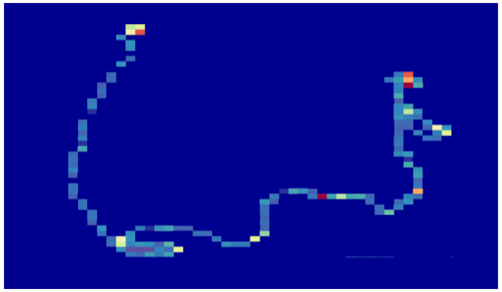
- Electron diffusion smears out track features
- PMTs at the energy plane still contribute radioactive background

Strategies:

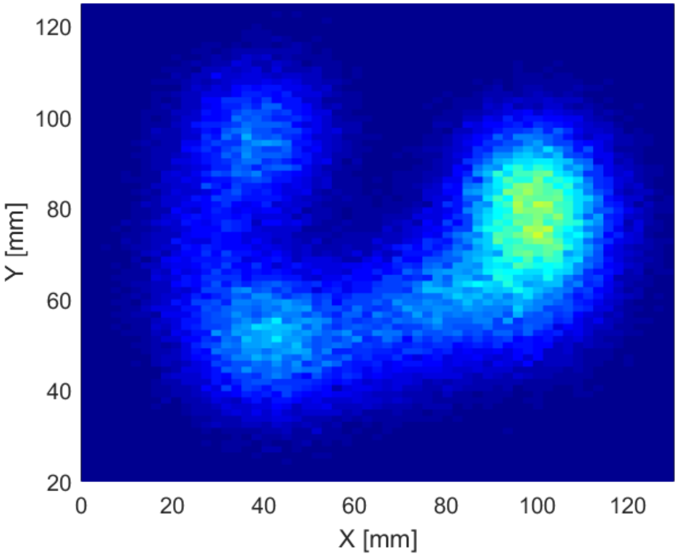
- Low-diffusion gas (Xe-He, or Xe doped with <1% CH_4)
- Cryogenic operation to allow energy measurement with radiopure SiPMs

Electron diffusion in pure Xe: from "spaghetti with meatballs" to "sea cucumber"

Original track



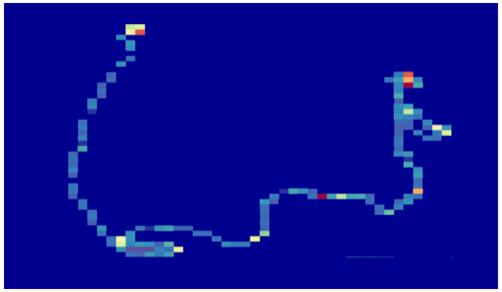
1 m diffusion
in pure Xe



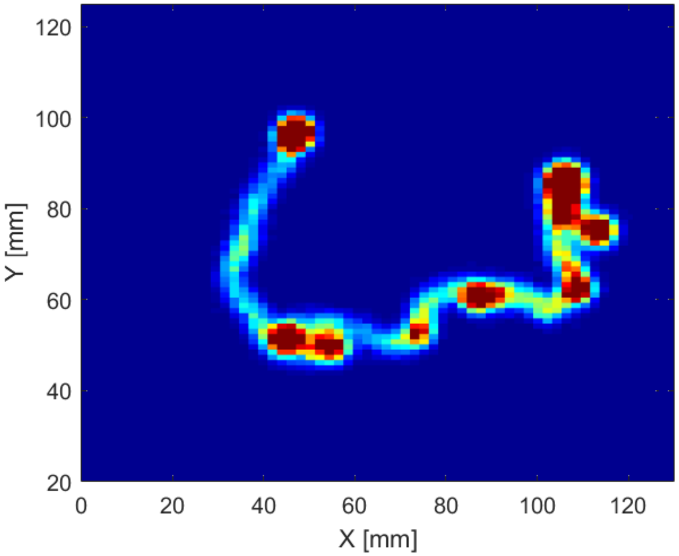
Diffusion driven by elastic collisions with heavy xenon atoms

Electron diffusion in Xe-He, or Xe with <1% methane

Original track



1 m diffusion in Xe-He (80/20), or Xe with <1% CH_4



Diffusion dominated by elastic collisions with the much lighter He atoms, or by inelastic collisions with CH_4

R. Felkai, *et al.* (NEXT collaboration) *Nucl. Instrum. Meth.* A **905** (2018) 82, arXiv:1710.05600
C. A. O. Henriques, et al. (NEXT collaboration), JHEP **1901** (2019) 027, arXiv:1806.05891.

Summary and outlook

The high-pressure Xe TPC has unique advantages, making it a leading candidate for the ton-scale $\beta\beta0\nu$ search era

NEXT-White demonstrated superb energy resolution and effective track reconstruction on the 10-kg scale. Background is low and well understood. $\beta\beta2\nu$ data taking started Feb 2019.

NEXT-100 will demonstrate the technology on the 100-kg scale, providing competitive limits within a few years

The NEXT collaboration pursues promising directions for major background reduction, critical for the ton-scale detector: Ba tagging + topology improvement + higher radiopurity

Backup slides

Largest source of uncertainty: the size of axial coupling g_A

$g_A = 1.269$ for weak interaction and decays of nucleons

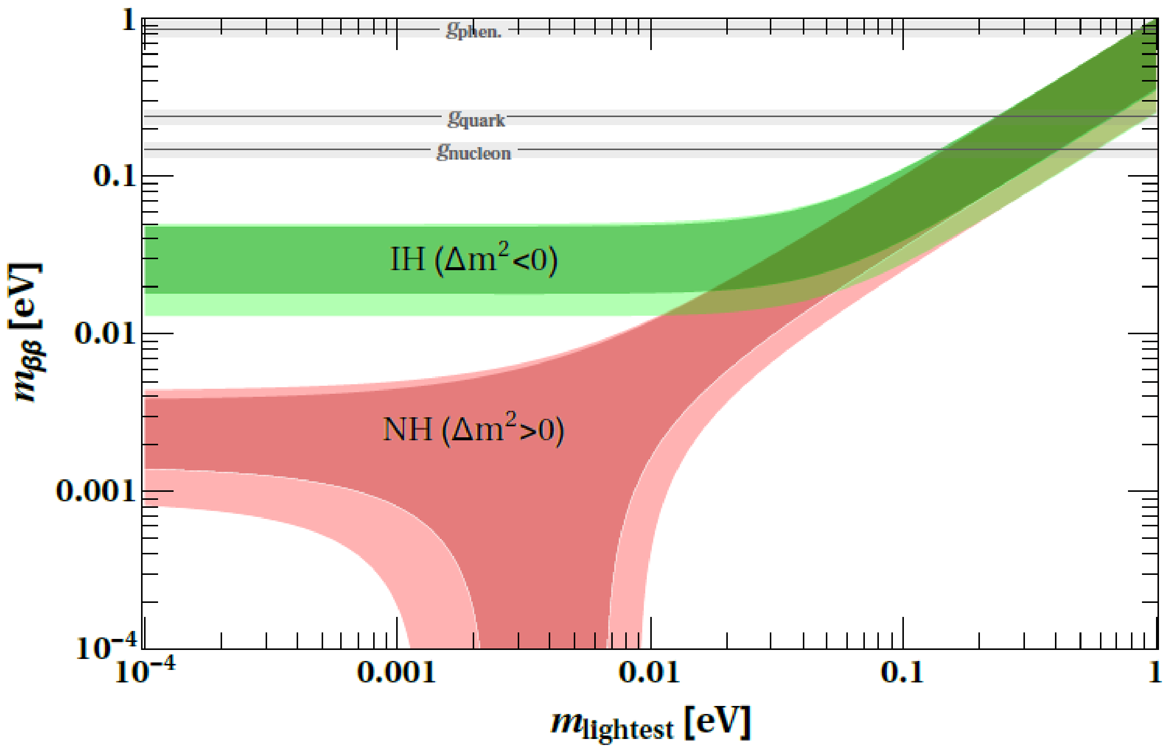
Quenching effects inside the nucleus *may* considerably reduce g_A

Conservatively one should consider several options:

$$g_A = \begin{cases} g_{nucleon} & = & 1.269 \\ g_{quark} & = & 1 \\ g_{phen.} & = & g_{nucleon} \cdot A^{-0.18} \end{cases}$$

The degree of g_A quenching is unknown. The expression for $g_{phen.}$ is based on $\beta\beta 2\nu$ half-lives and may be different for $\beta\beta 0\nu$

Effect of uncertainty in g_A



$g_A = g_{phen} = 0.52$

$g_A = 1$

$g_A = 1.269$

KamLand-Zen + EXO-200
2015 data

For ^{136}Xe taking $g_A = g_{phen}$ pushes up the limit on $m_{\beta\beta}$ by a factor of $\gtrsim 5$