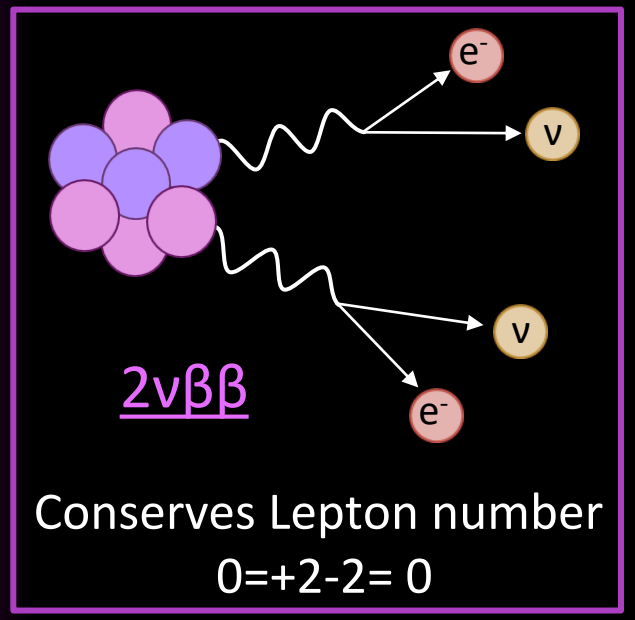
Searching for 0νββ Decay with High Pressure Xenon Gas Time Projection Chambers

Leslie Rogers on behalf of the NEXT Collaboration

Argonne National Laboratory

Implications of a robust observation of 0νββ



Conserves Lepton number

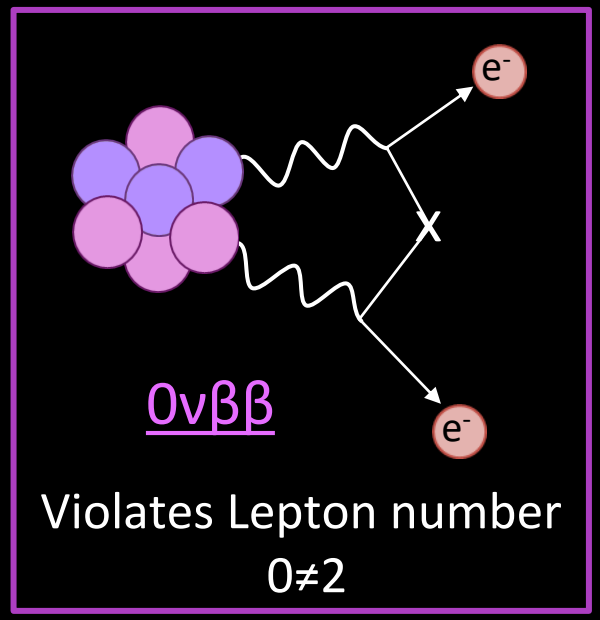
0=+2-2= 0

1) Lepton number conservation is violated

2) Massive fermions exist that are their own antiparticle

3) There are other mass generating mechanisms in nature beyond the Higgs mechanism

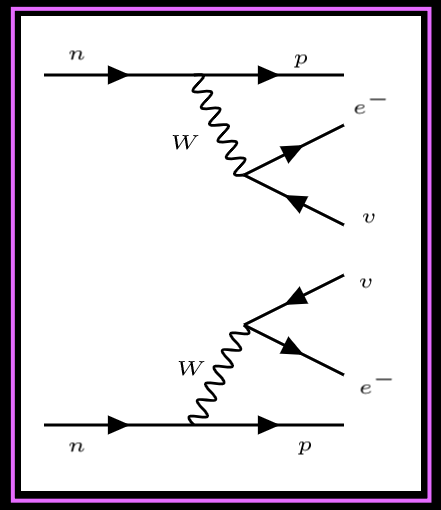
4) Could measure the mass of the neutrino



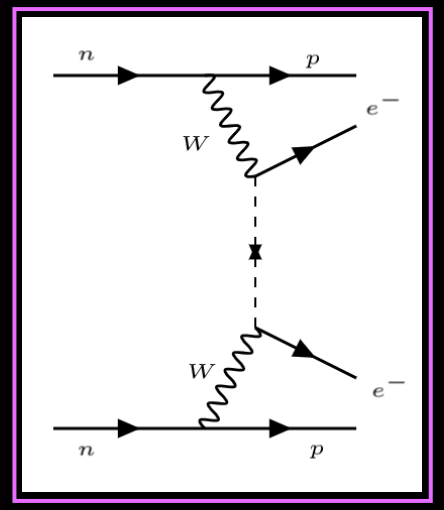
Violates Lepton number

0≠2

Rare Decay Search

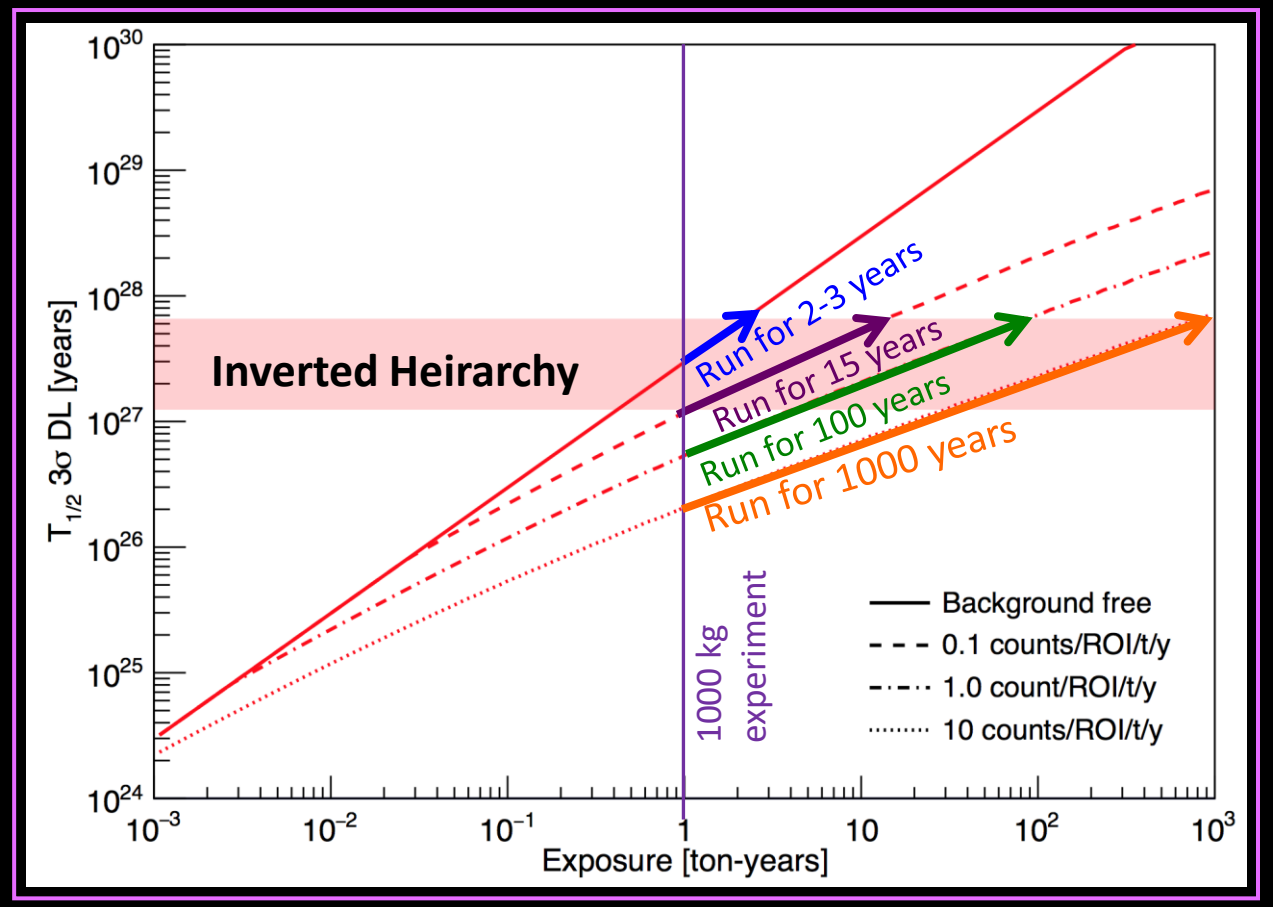


$T_{1/2}^{2\nu} \approx 10^{19-21}\, yrs$



$T_{1/2}^{0\nu} > 10^{26}\, yrs$

- Double beta decay is already a rare decay, neutrinoless even more so
- Ultimately a ton-scale experiment with excellent background rejection (<1 ct/ROI/t/y) is the key to crossing the IH in finite time



Design Requirements

All 0νββ detectors are chasing 3 main things:

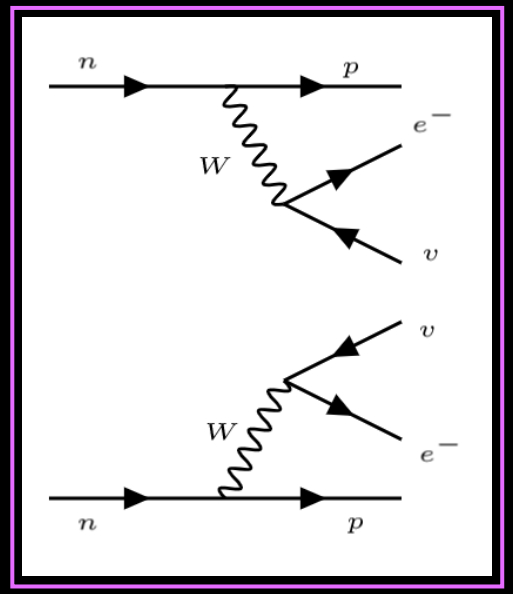
- A large volume
- Extremely low or nonexistent backgrounds
- Great energy resolution

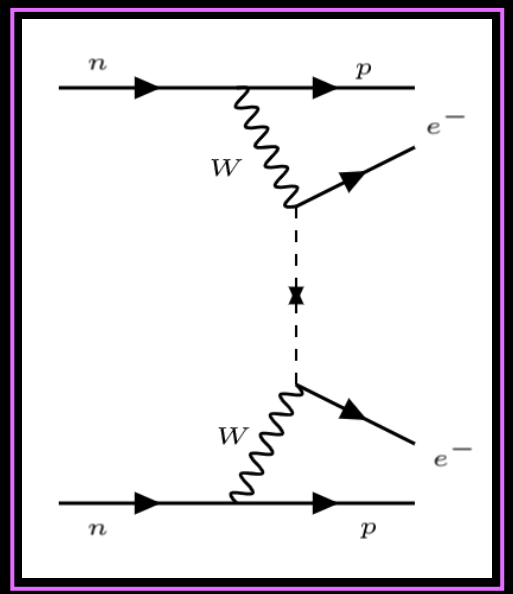
Candidate Isotopes for 0νββ Decay

- $Q_{\beta\beta}$ must be above gamma-ray backgrounds
- Need high enough natural abundance to extract large quantities

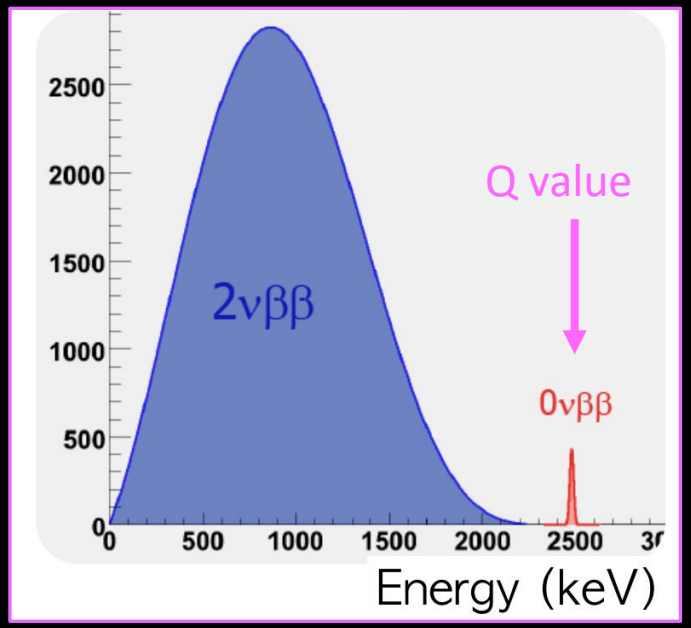
Candidate	$Q_{\beta\beta}$ (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.27	0.19
$^{76}Ge \rightarrow {}^{76}Se$	2.04	7.8
$^{82}Se \rightarrow {}^{82}Kr$	3	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.35	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.03	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.01	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.8	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.23	5.6
$^{130}Te \rightarrow {}^{130}Xe$	2.53	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.48	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.37	5.6

Event Energy





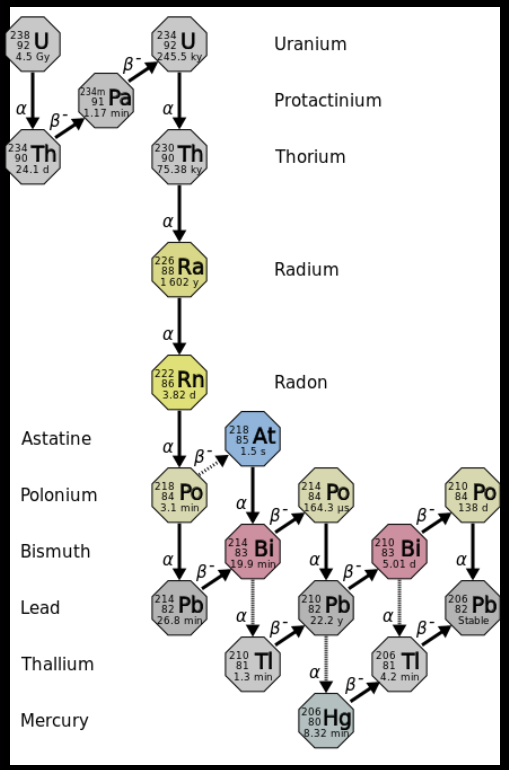
- For a neutrinoless decay all the energy produced will go into the two electrons
- A double beta decay event with exactly the decay energy of the isotope in question means it is neutrinoless!

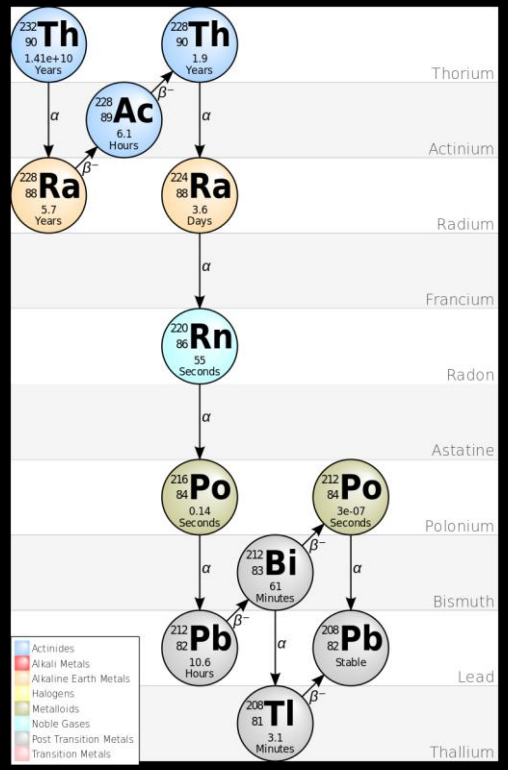


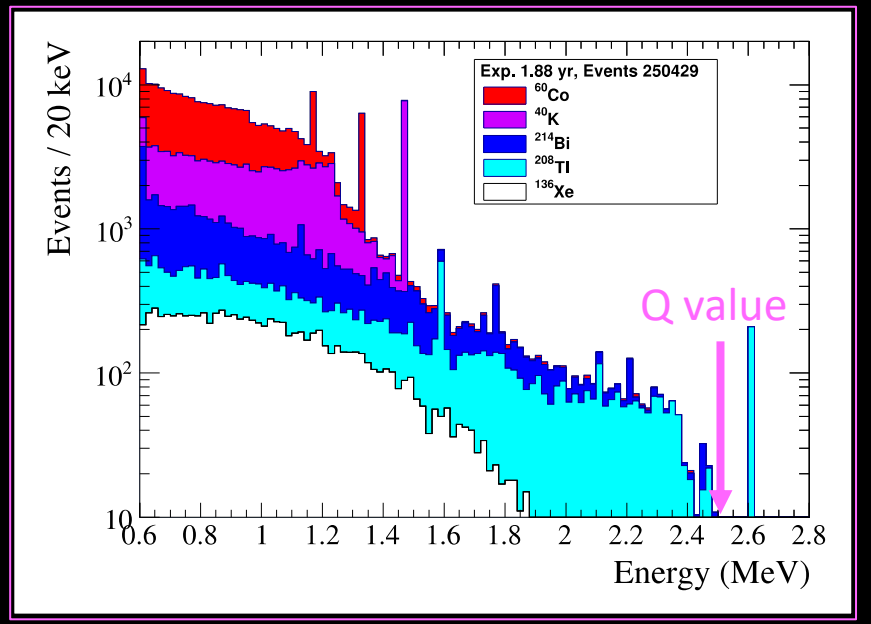
JHEP 10 (2019) 51

Backgrounds for 0νββ Decay

- The main backgrounds in these detectors are ^{214}Bi and ^{208}Tl from uranium and thorium chains
- Energy resolution of <1% FWHM is vital for distinguishing between the two types of beta decay and rising above the ^{214}Bi photoelectric peak



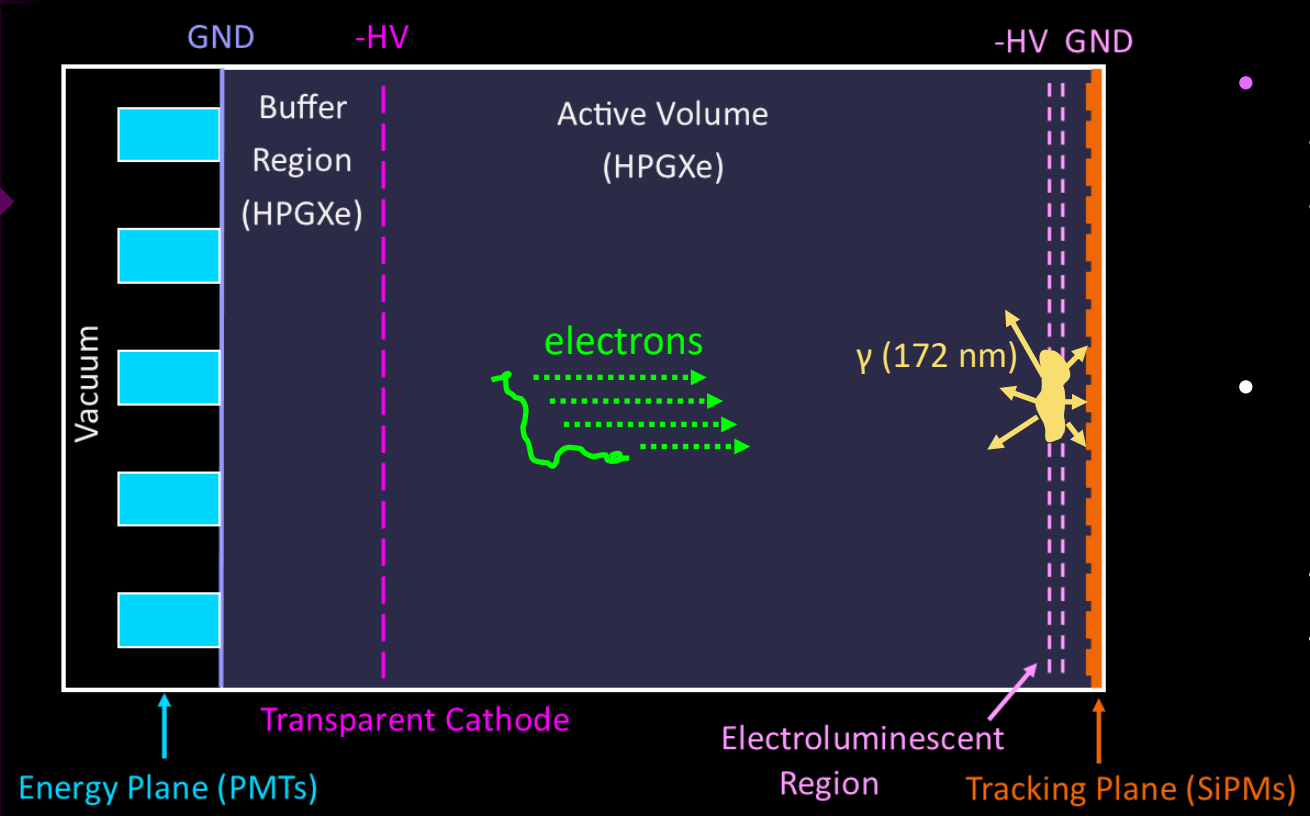




NEXT-100 background models

JHEP 10 (2019) 51

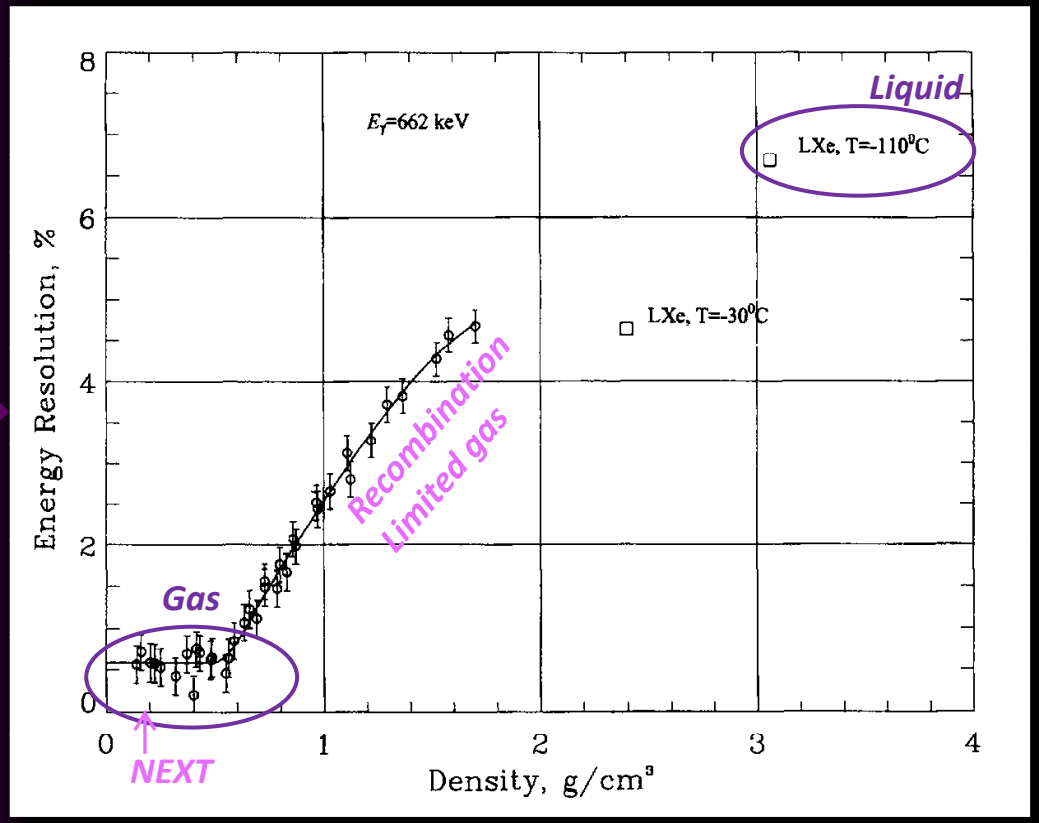
Basic Principles of the NEXT Detector



- NEXT is a time projection chamber that drifts charged particles from their initial position to a light amplification plane
- Electrons that reach the readout plane first were produced closer, i.e. smaller z dimension, and those further away take longer to get there, projecting time into a z component

Advantages of Xenon Gas

Measuring ionization only (@662 keV)



- Low density allows ionized electrons to be drifted towards the electroluminescent region before they recombine with xenon ions
- Low Fano factor means the number of electrons created along the ionization path is well correlated with the original energy of the betas
- Fluctuation-less EL gain combined with low Fano factor produces energy resolution comparable with solid-state technologies in a ton-scale TPC experiment

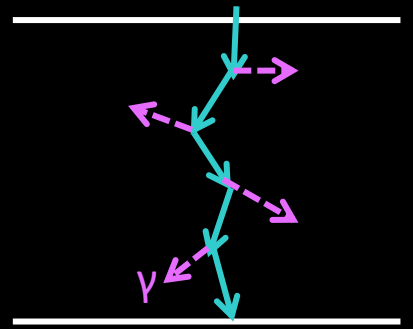
$$R_E = \sqrt{\frac{\sigma^2_e}{N^2_e} + \frac{1}{N_e}\frac{\sigma^2_{EL}}{N^2_{EL}} + \frac{\sigma^2_{ep}}{N^2_{ep}} + \frac{1}{N_{ep}}\frac{\sigma^2_q}{G_q}}$$

Recombination (depends on gas pressure, composition, Efield)

Depends on EL gain fluctuations

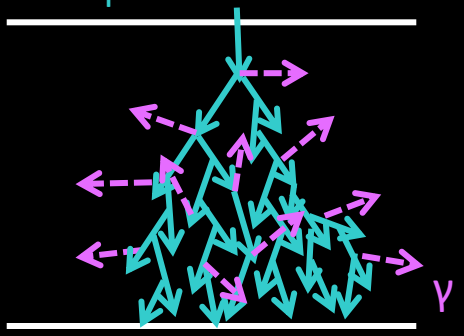
Systematic contributions from detector imperfections

Electroluminescence



e- +Xe → e-+Xe* → e-+2Xe+γ

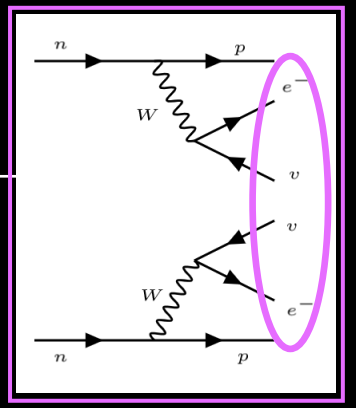
EL plus Ionization

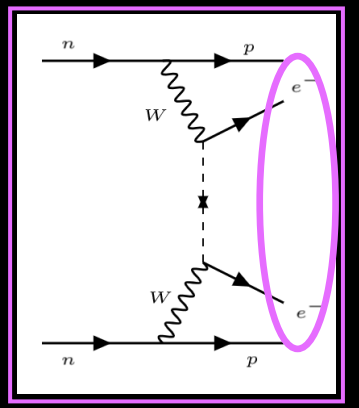


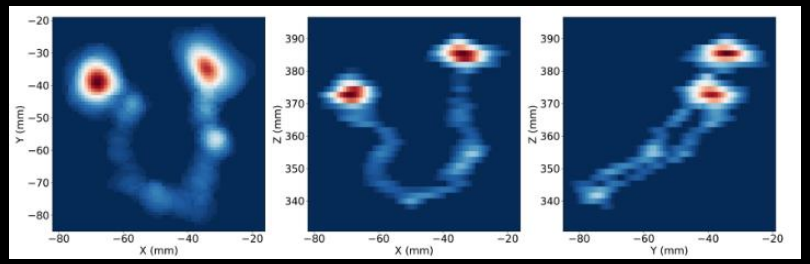
e^- +Xe → 2e^-+ Xe^+

e^- +Xe → e^-+Xe^* → e^-+2Xe+γ

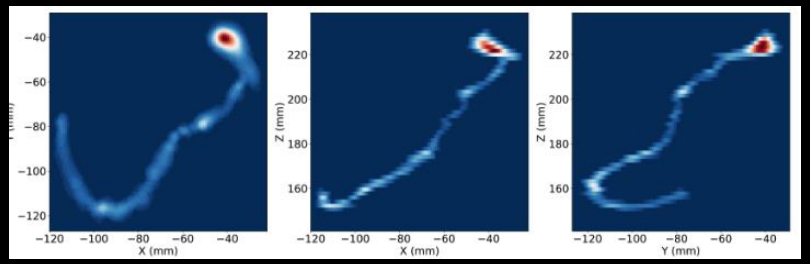
Event Topology







Signal-like event



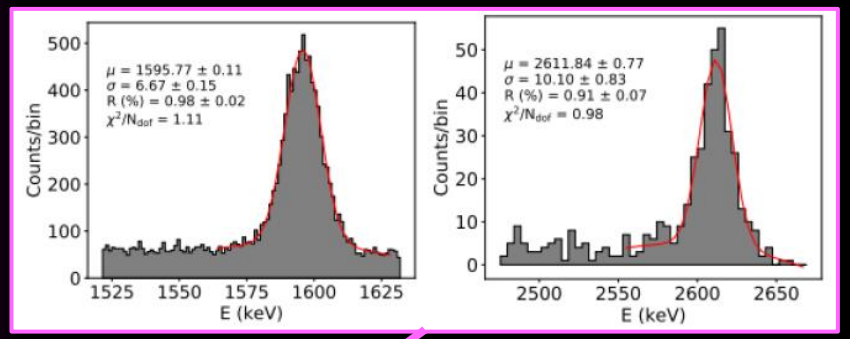
Background-like event

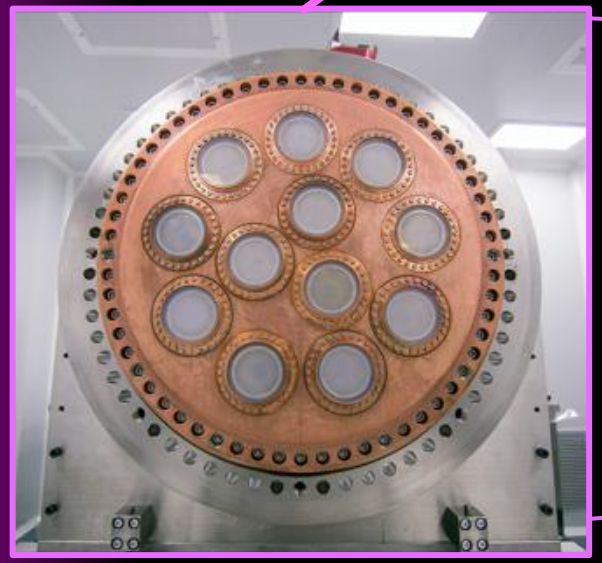
- Lower density gas allows powerful single-vs-multi electron topological rejection
- A “blob” indicates the end deposit of energy as a high energy electron comes to rest
- A track with two blobs indicates two beta particles released simultaneously, i.e. double beta decay
- Active background rejection rather than self shield uses isotope efficiently

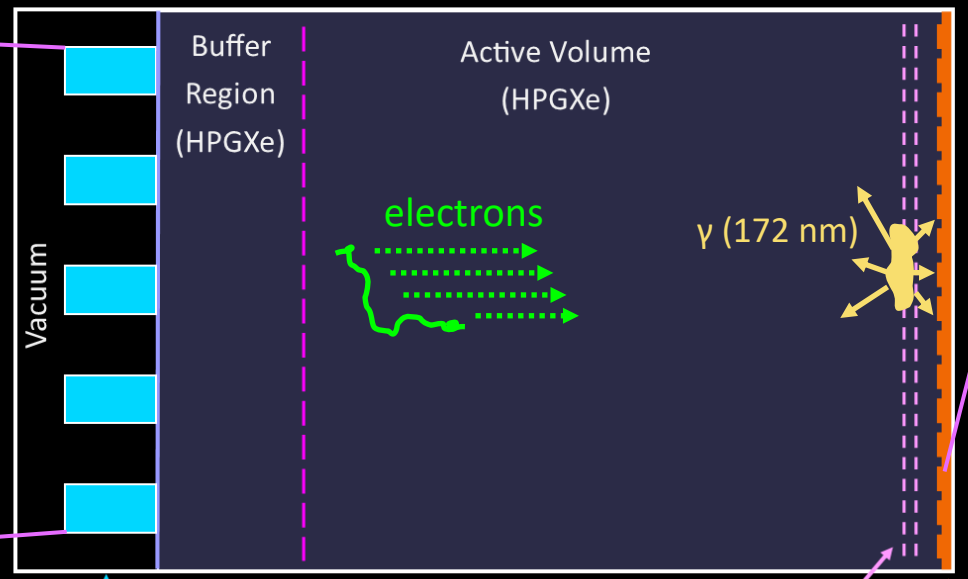
JHEP 2021 (10), 7 2021

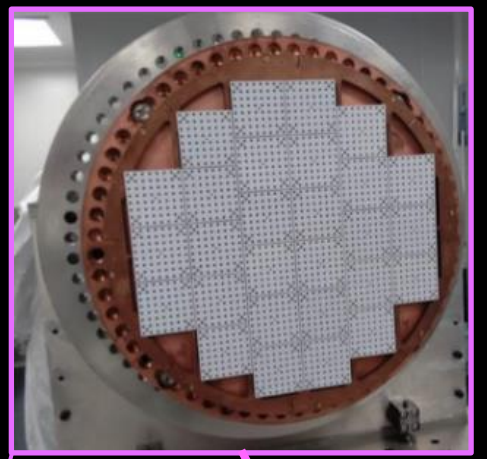
Basic Principles of the NEXT Detector

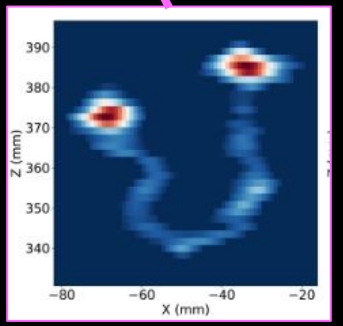
208Tl double escape and photopeaks







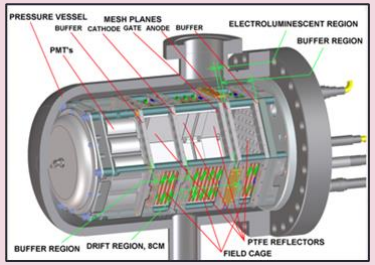




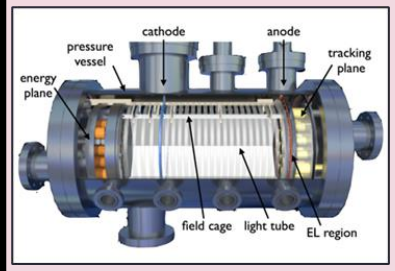
Sequence of NEXT Detectors

- 0νββ
- Detection Strategies
- **NEXT Detectors**
  - Past
  - Current
  - Future

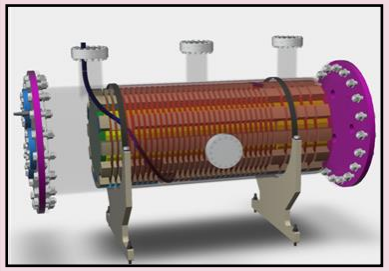
NEXT-DBDM



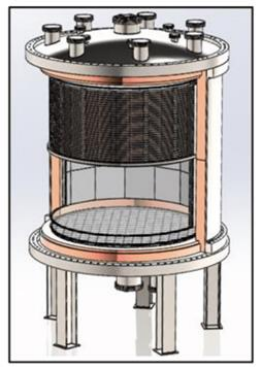
NEXT-DEMO

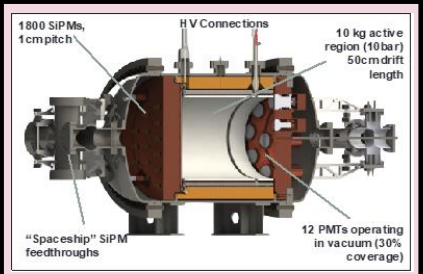


NEXT-CRAB

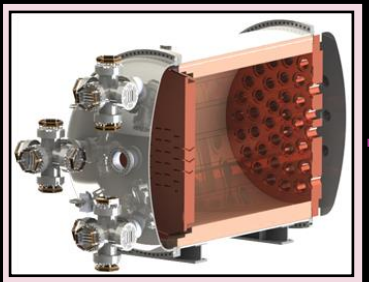


NEXT-HD with Barium Tagging

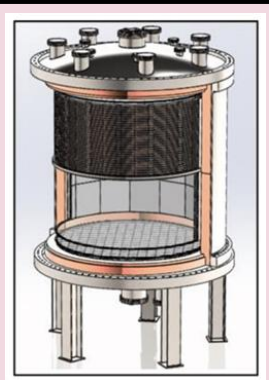




NEXT-White



NEXT-100



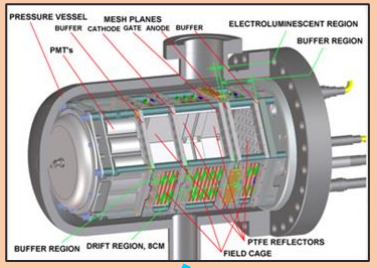
NEXT-HD

Sequence of NEXT Detectors

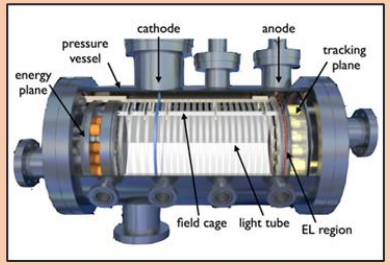
NEXT-DBDM demonstrated energy resolution capabilities and
NEXT-DEMO proved the concept of topological reconstruction

- 0νββ
- Detection Strategies
- NEXT Detectors
  - **Past**
  - Current
  - Future

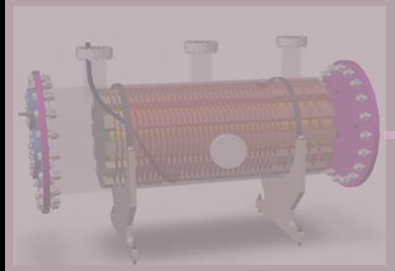
NEXT-DBDM



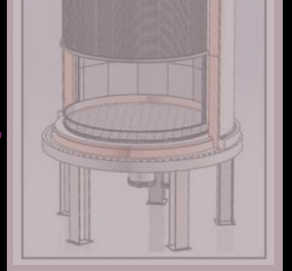
NEXT-DEMO

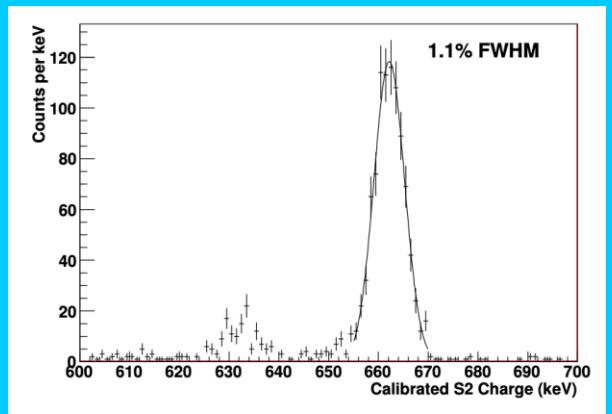


NEXT-CRAB

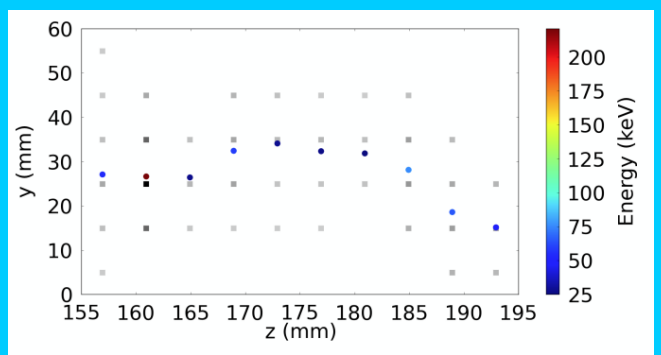


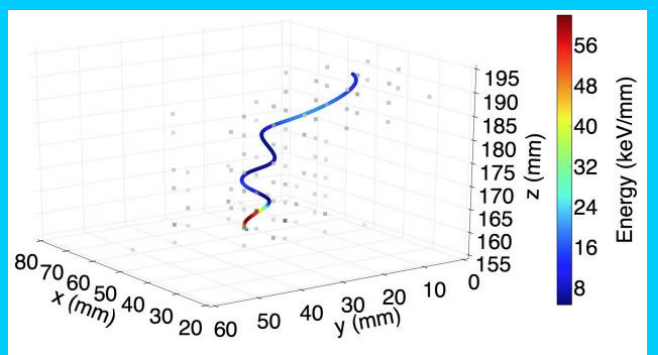
NEXT-HD with Barium Tagging





Nucl. Instrum. Meth. A 708 (2013) 101





2013 JINST 9 P09011

Sequence of NEXT Detectors

- 0νββ
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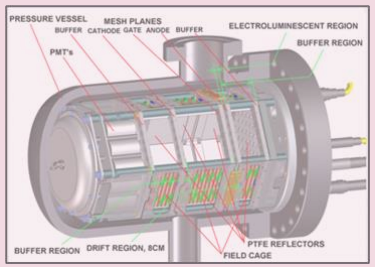
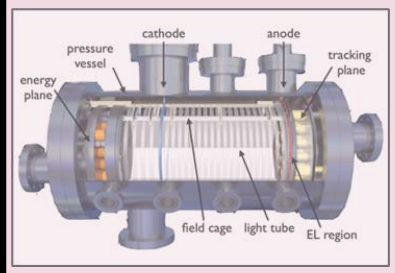
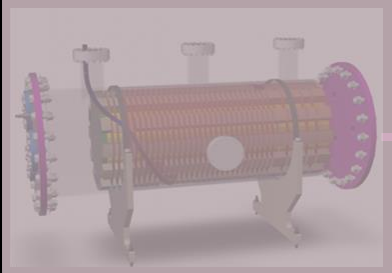
NEXT-DBDM



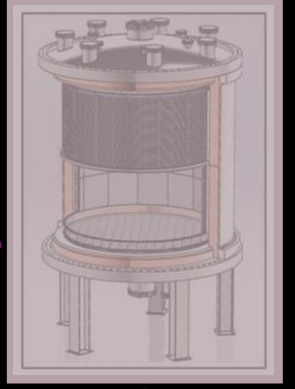
NEXT-DEMO

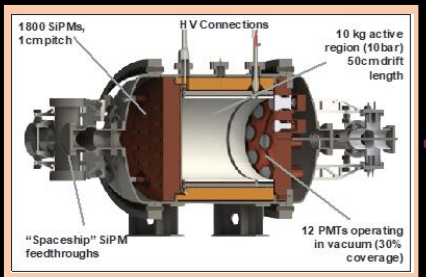


NEXT-CRAB

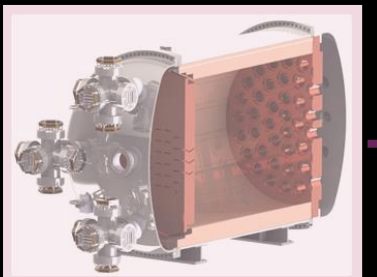


NEXT-HD with Barium Tagging

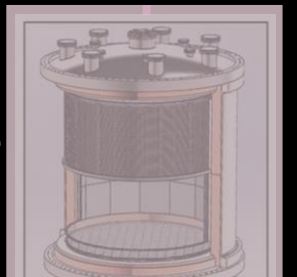




NEXT-White



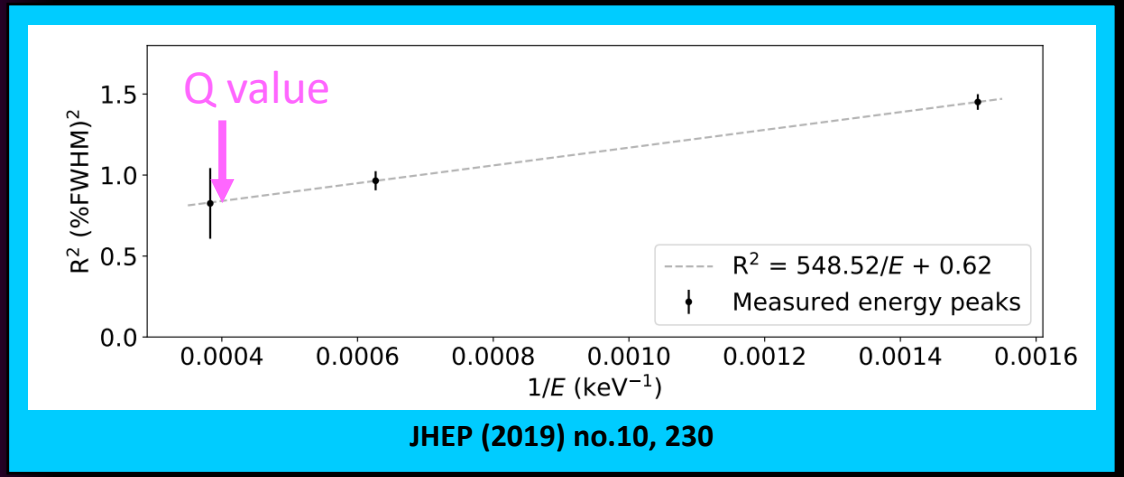
NEXT-100



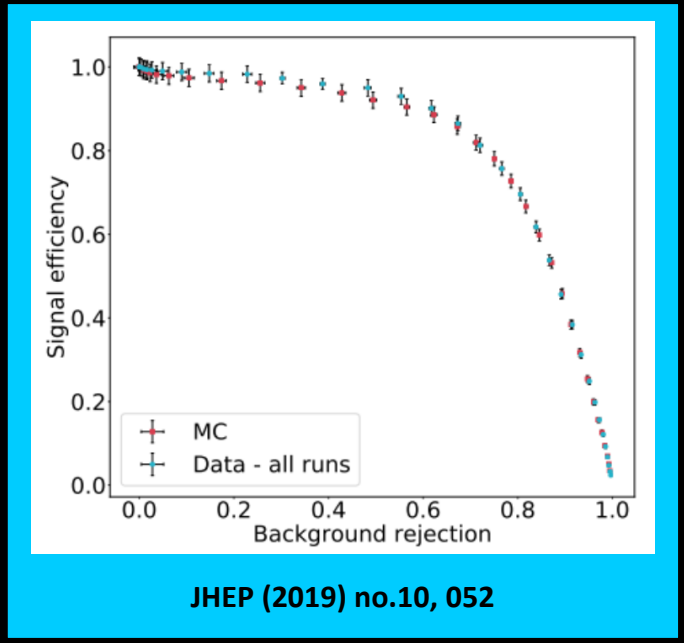
NEXT-HD

NEXT-White recently decommissioned after taking data for 5 years with a run time of 481 days

NEXT-White

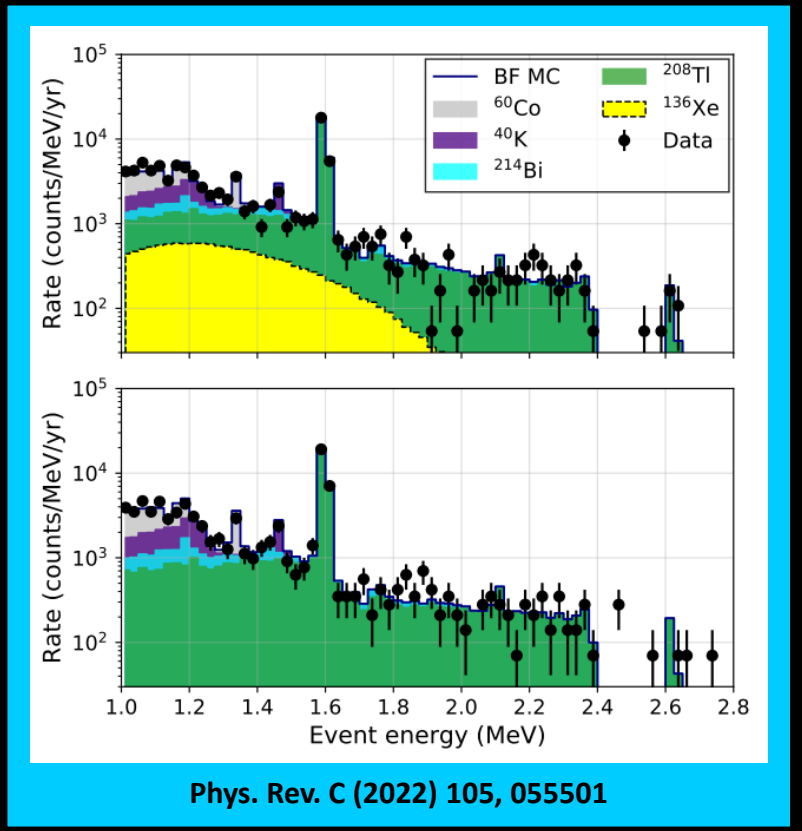


JHEP (2019) no.10, 230



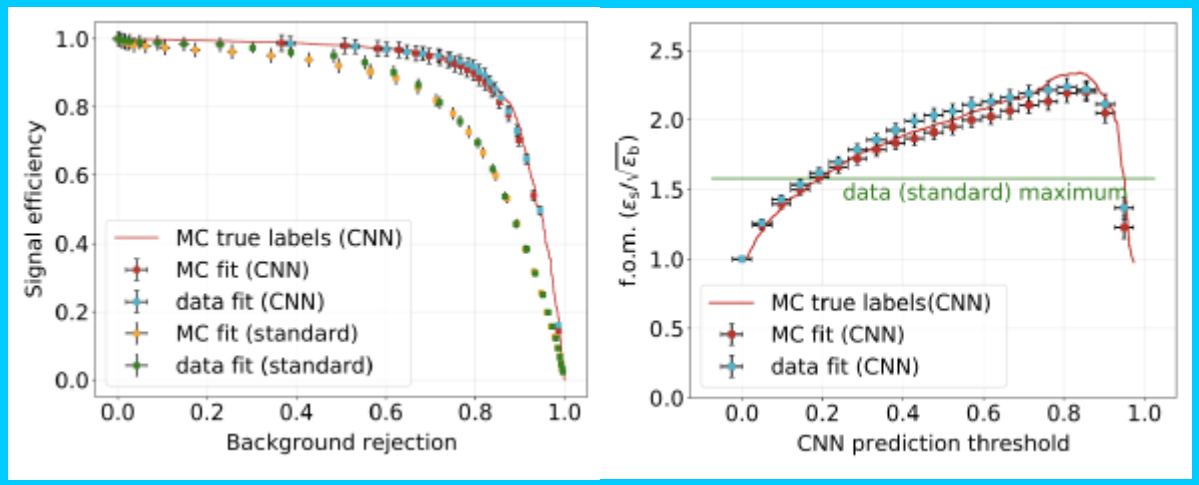
JHEP (2019) no.10, 052

- Strong data and monte carlo agreement from topological cuts tuned with double escape peaks from ^{228}Th source
- Energy calibrations show <1% FWHM at $Q_{\beta\beta}$

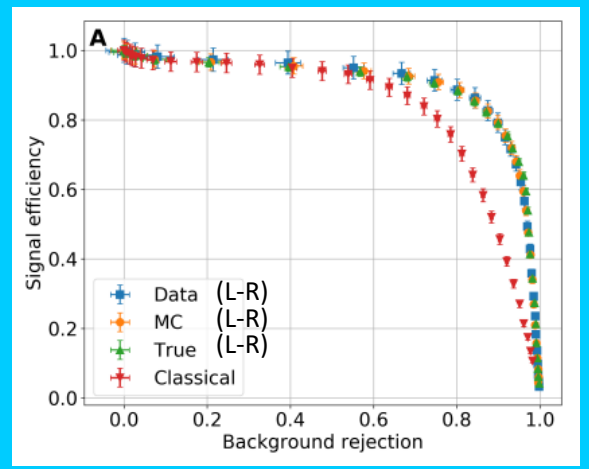


Phys. Rev. C (2022) 105, 055501

NEXT-White



JHEP (2021) no 10, 189



JHEP (2021) no.10, 146

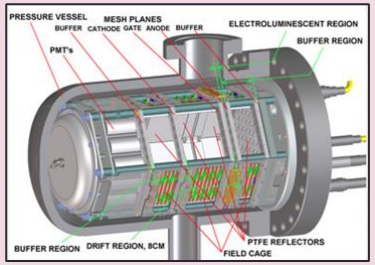
- Used CNNs with great success, reducing backgrounds to 10% while still maintaining 65% signal efficiency
- Have now added Lucy-Richardson Deconvolution to improve track reconstruction and cuts

Sequence of NEXT Detectors

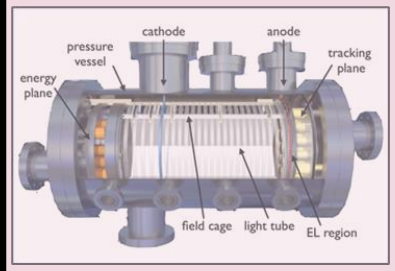
NEXT-100 is being commissioned now and is a demonstrator for technology scalable to the tonne-scale

- 0νββ
- Detection Strategies
- NEXT Detectors
  - Past
  - **Current**
  - Future

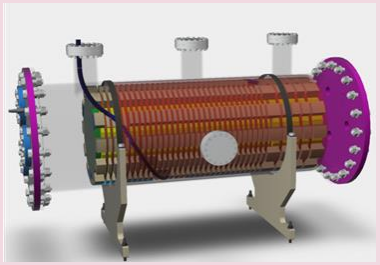
NEXT-DBDM



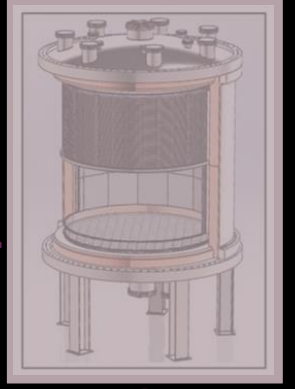
NEXT-DEMO

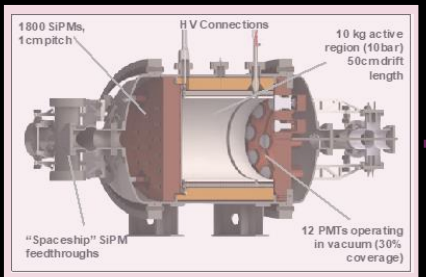


NEXT-CRAB

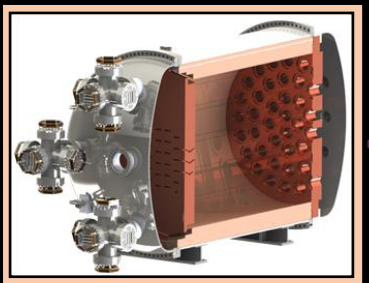


NEXT-HD with Barium Tagging

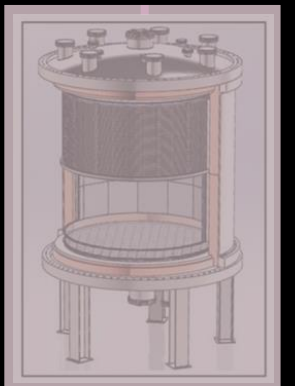




NEXT-White

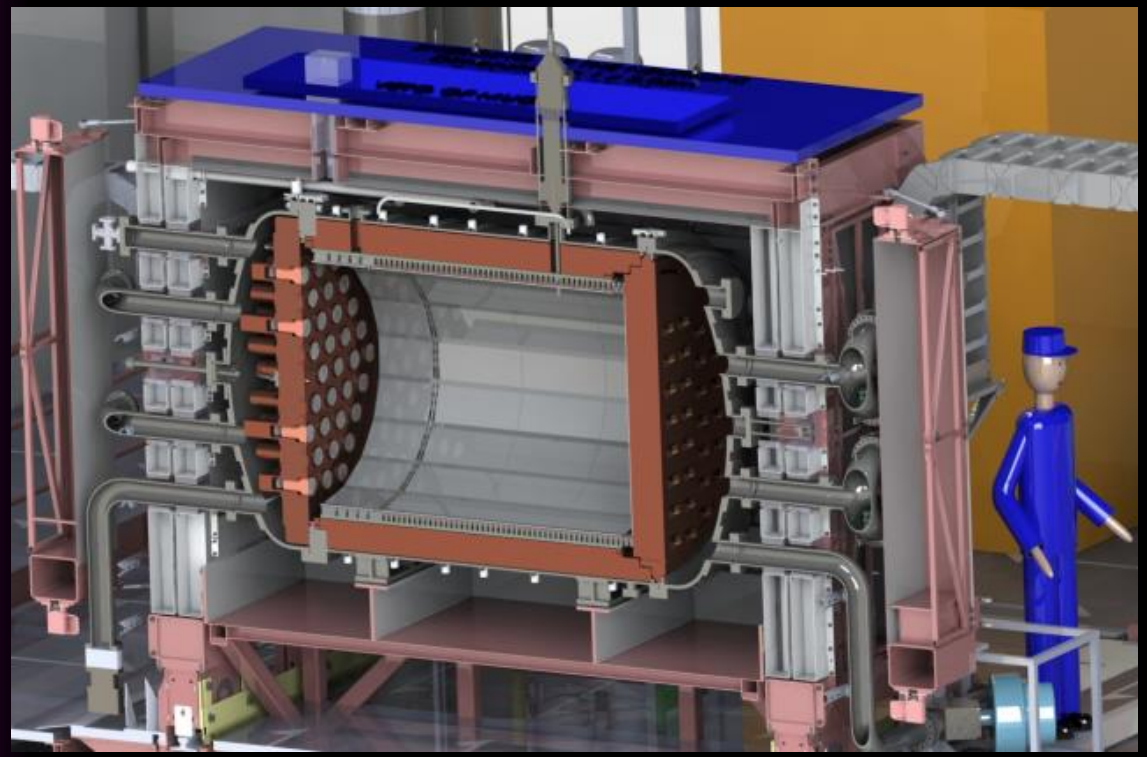


NEXT-100



NEXT-HD

NEXT-100



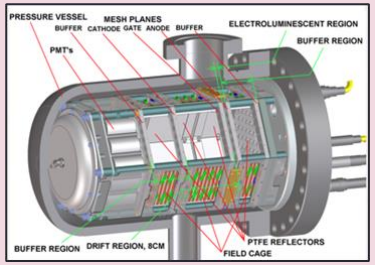
- Modified structural designs capable of being scaled to tonne-scale
- Improved radioactive budget
- Expected background index of 4 x 10^{-4} counts/keV/kg/yr
- Will reach a sensitivity of 6 x 10^{25} years after a run of 3 years

Sequence of NEXT Detectors

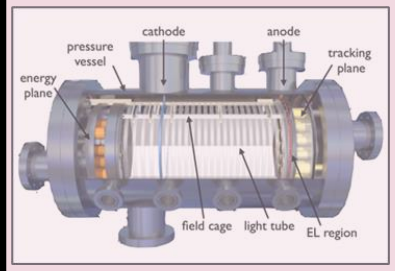
NEXT-CRAB was the prototype for NEXT-100 and is now exploring technology scalable beyond the tonne-scale

- 0νββ
- Detection Strategies
- NEXT Detectors
  - Past
  - Current
  - **Future**

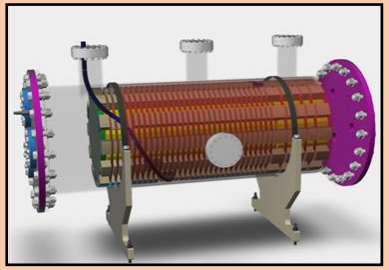
NEXT-DBDM



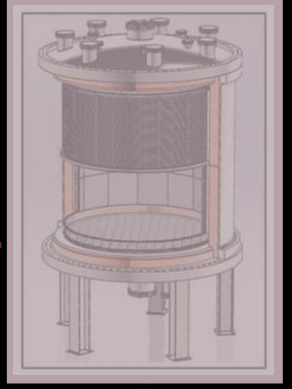
NEXT-DEMO

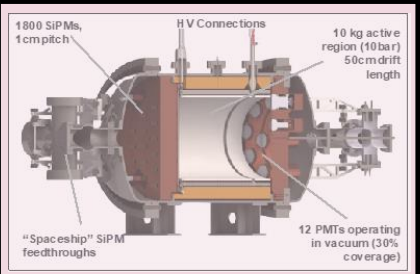


NEXT-CRAB

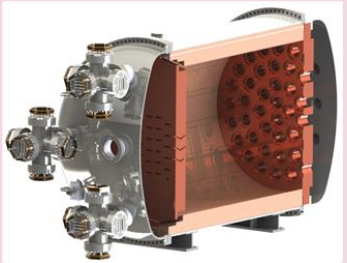


NEXT-HD with Barium Tagging

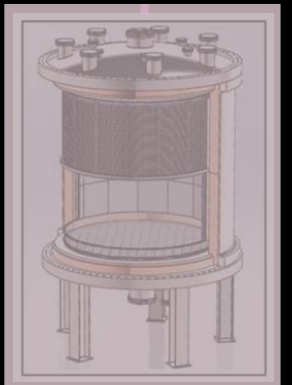




NEXT-White



NEXT-100

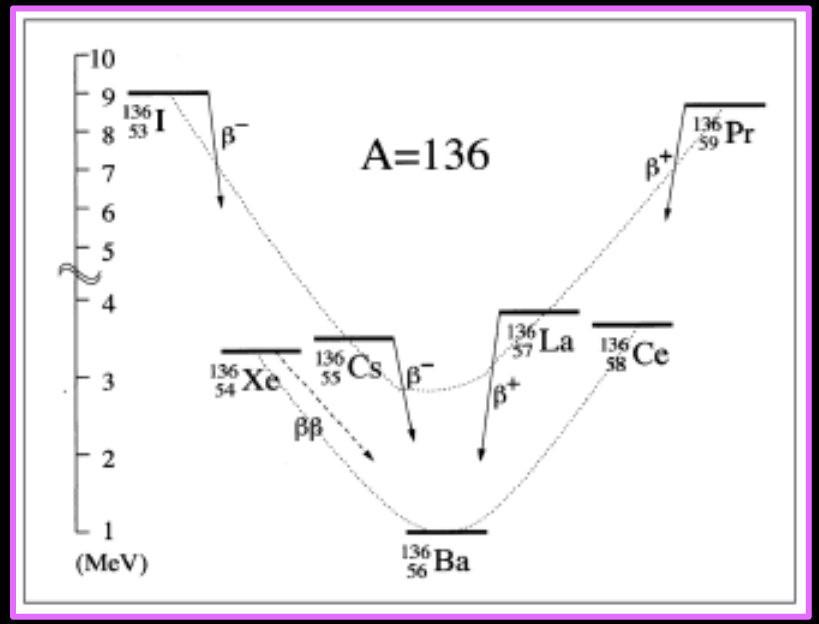


NEXT-HD

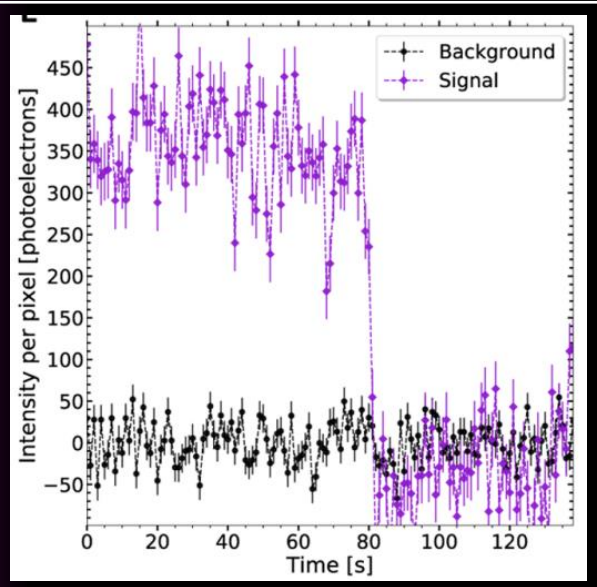
What if we can suppress backgrounds to zero?

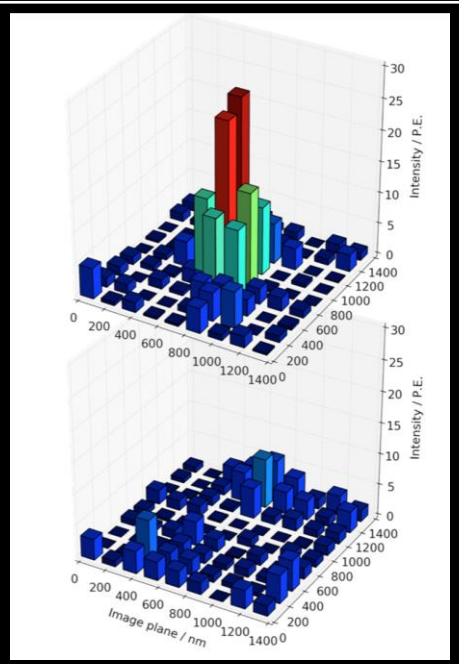
Observation of barium ion daughter in coincidence with topological signal can completely suppress the radiological backgrounds

$Xe^{136} \rightarrow Ba^{2+} + 2e + 2\nu(0\nu)$



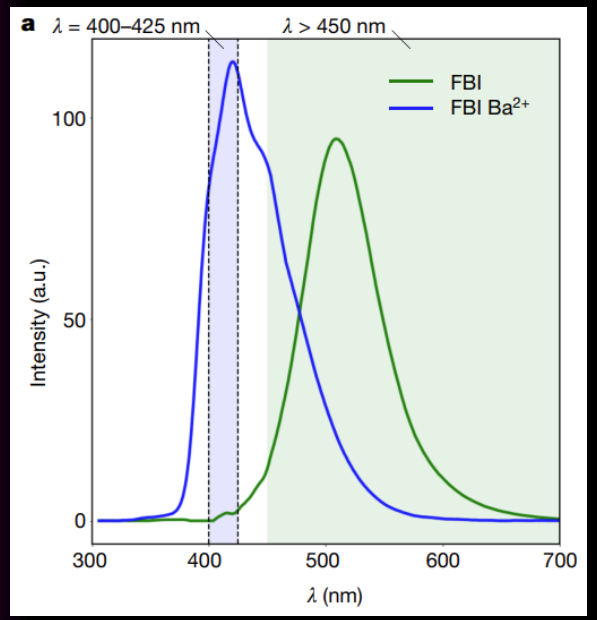
Barium Tagging

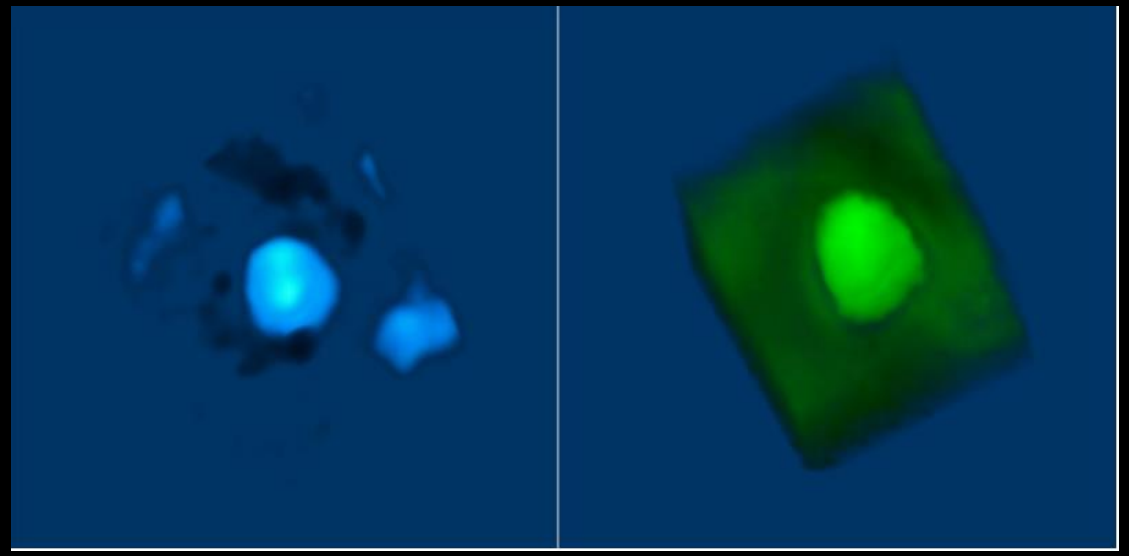




Two different methods are being explored to tag when the barium ions come in contact at the cathode plane

- Fluoresce off-on molecules
- Color-shifting molecules



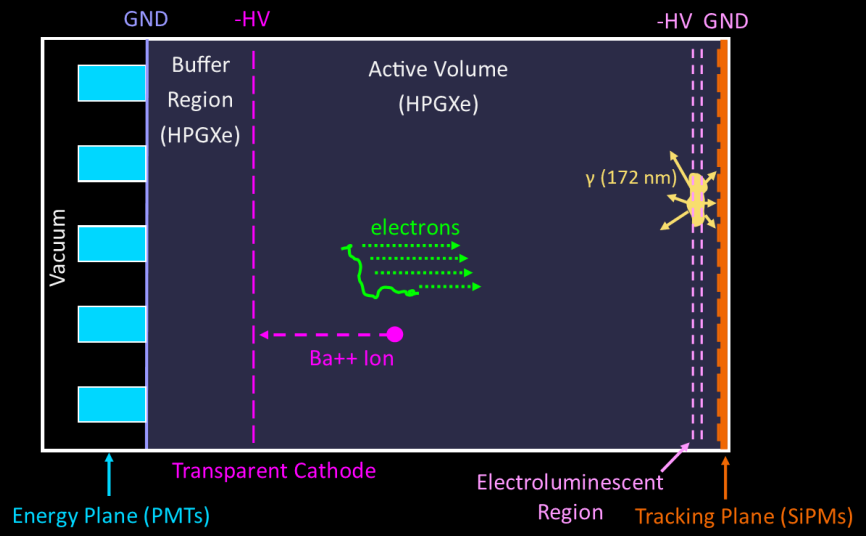


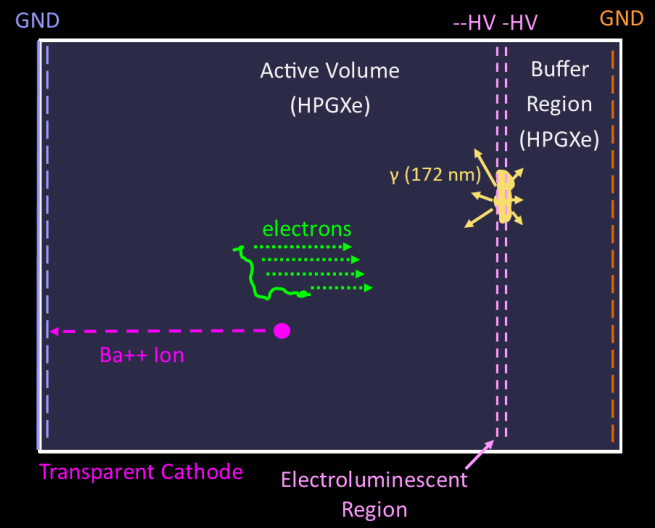
0νββ
Detection Strategies
NEXT Detectors
Past
Current
Future

ACS Sens. 2021, 6, 192-202

Nature 583, 48-54 2020

Changes to Accommodate Barium Tagging





To get barium to the chemosensors we need the Cathode to be at ground

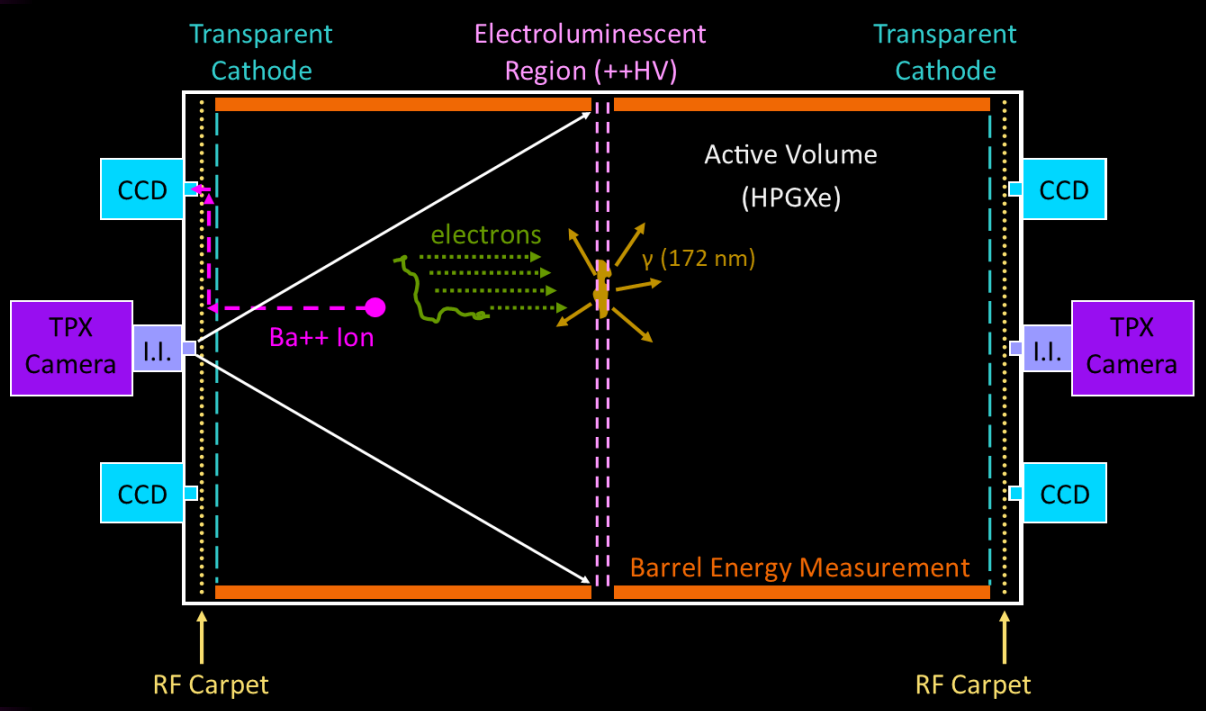
This moves the buffer region to the EL side, making light collected by SiPMs too diffuse for a clear image

The Barium tagging sensors will cover the plane blocking light collection for the PMTs

ACS Sens. 2021, 6, 192-202

Nature 583, 48-54 2020

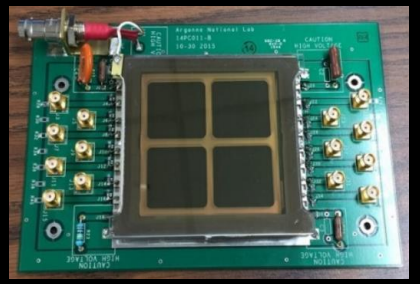
NEXT Camera Readout and Barium Tagging



- Replacing SiPMs with direct VUV camera tracking
- Designing custom microchannel-plate photo-multipliers for energy measurements around the barrel of the detector
- In the next 5 to 10 years we hope to deploy a 100-kg scale background free detector somewhere deep underground

Image Intensifier

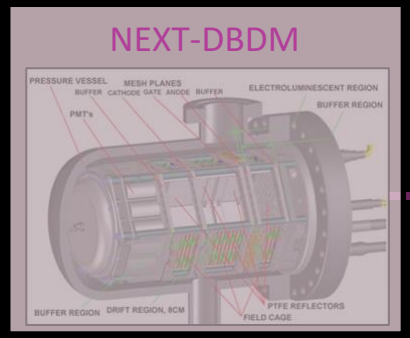
TPX3Cam

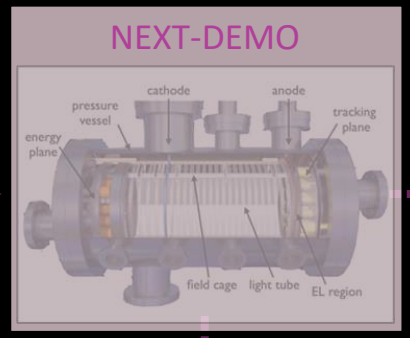


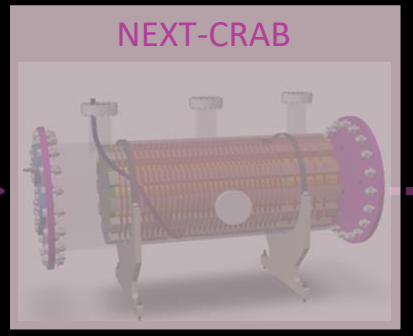
MCP-PMTs

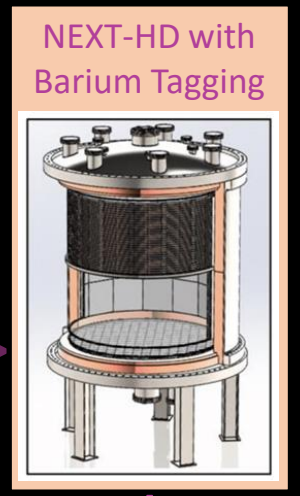
Sequence of NEXT Detectors

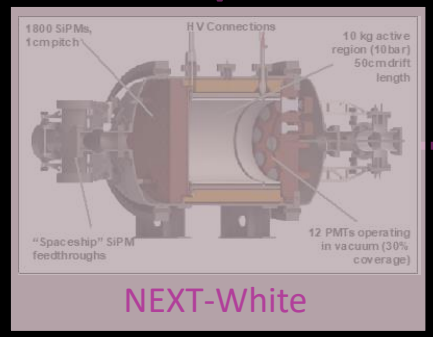
- 0νββ
- Detection Strategies
- NEXT Detectors
  - Past
  - Current
  - **Future**

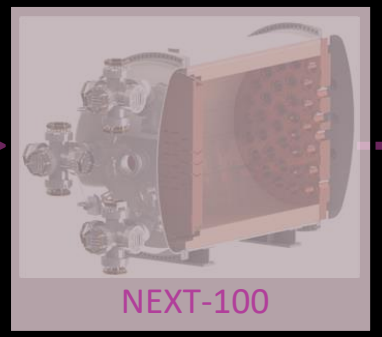


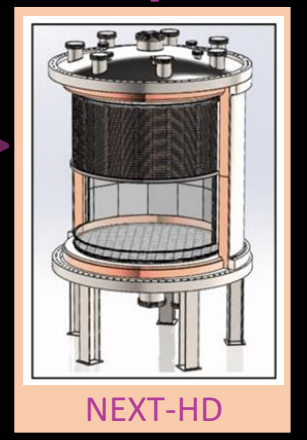






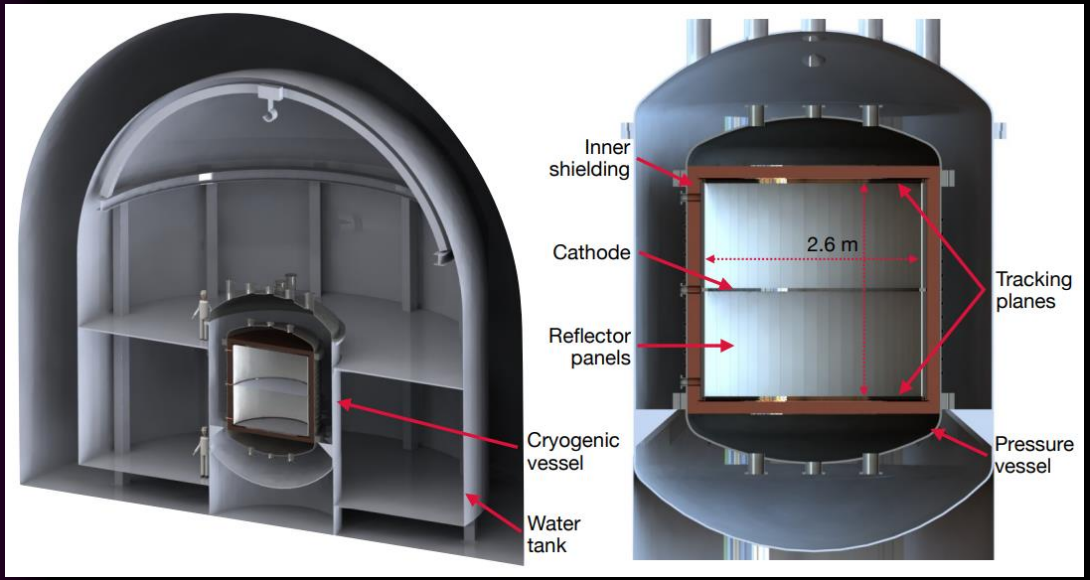






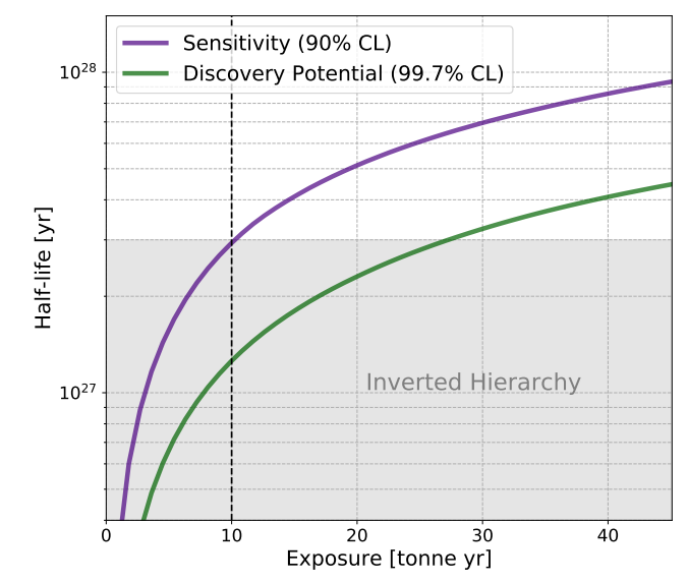
NEXT-HD is the ton-scale and beyond goal, with and without Barium tagging, combining features from all previous demonstrators.

NEXT-HD



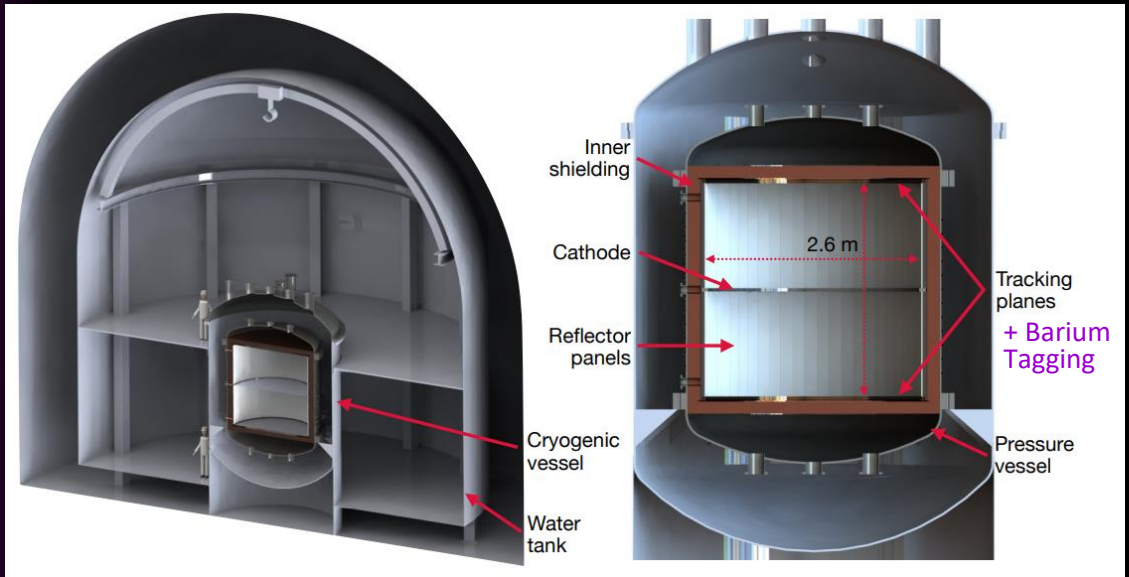
To cross the inverted hierarchy line a ton scale is needed, this will be NEXT-HD

- Symmetric design, reducing length electrons drift and improving diffusion losses
- No PMTs will be used, reducing the radiogenic backgrounds
- Housed in a water chamber reducing cosmogenic backgrounds



arXiv:2005.06467
(accepted by JHEP)

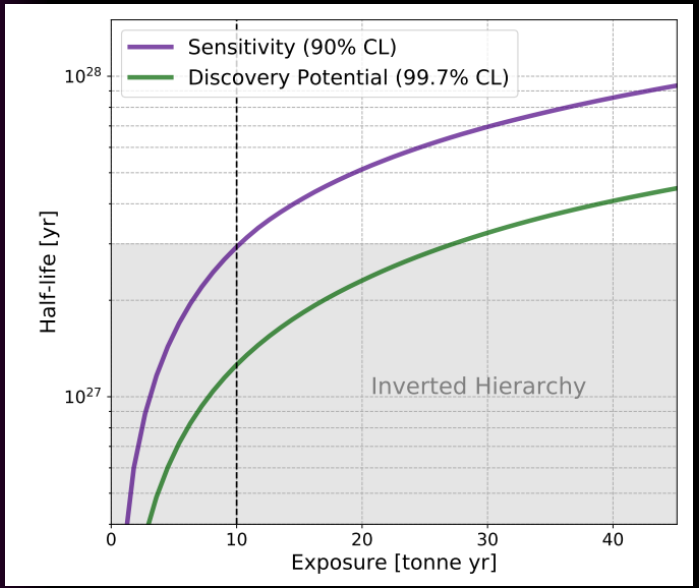
NEXT-HD + Barium Tagging

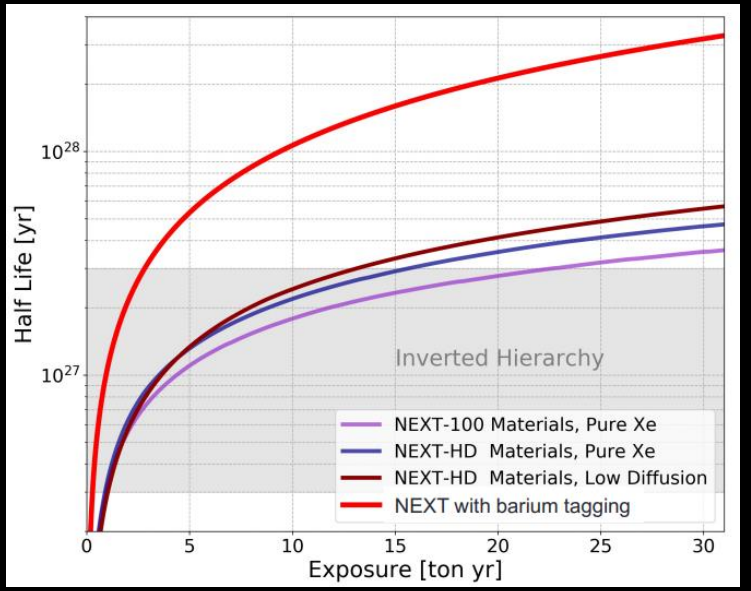


To go beyond the inverted hierarchy line we need even lower backgrounds and larger detectors

Adding Barium tagging at the cathode ends drastically increases the half life reach of the detector as it will be virtually background free

To increase the active volume we can have multiple background free detectors; the original ton, but also multiple smaller detectors





Final Remarks

- **NEXT-White** has finished taking data and met performance targets with topological identification and energy resolution
- **NEXT-100** construction is underway with projections of a world leading background index in xenon
- **NEXT-CRAB** construction is underway and if successful will prove a scalable background-free technique for the search of neutrinoless double beta decay
- **NEXT-HD** design is being developed with sensitivities capable of crossing the inverted hierarchy
- **Barium Tagging** R&D is ongoing with single ion sensitivity demonstrated with both off-on and color-switching chemosensors