Neutrinoless Double-Beta Decay with EXO: Achievements and Prospects

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(on behalf of the EXO-200 and nEXO collaborations)

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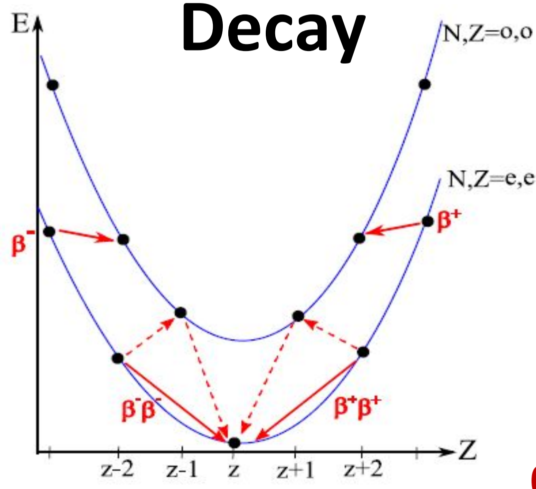
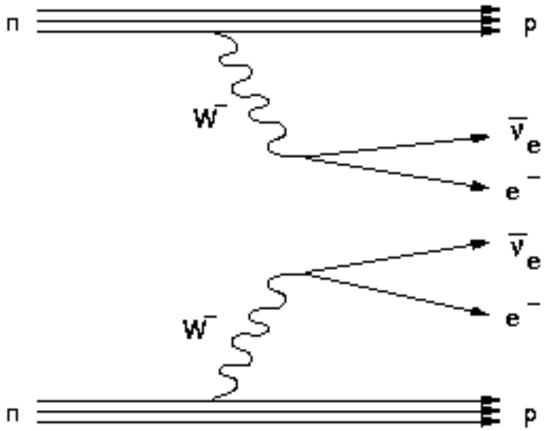
Double Beta Decay



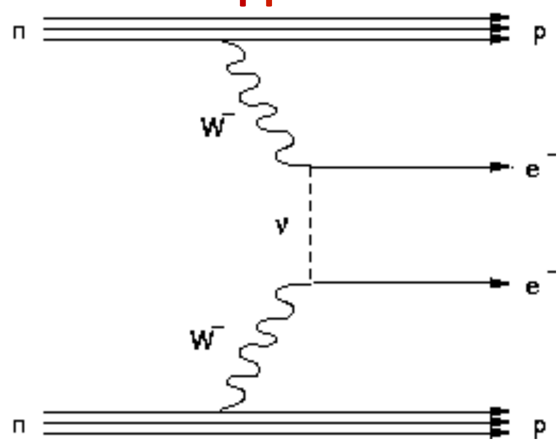
- 2β Rare decay in even-even nuclides:
=> Single β decay, energetically forbidden.
=> Single β decay, highly spin suppressed.

2νββ



Vs

0νββ



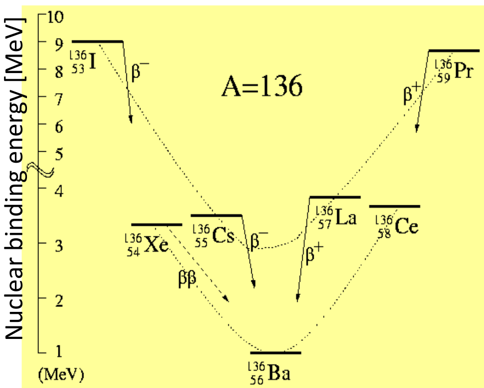
- Allowed 2nd order weak process in SM.
- Q-value = 2.479 MeV.

- Hypothetical process:
⇒ $M_\nu \neq 0$.
⇒ $\nu = \bar{\nu}$ (Majorana particle).
⇒ $|\Delta L| = 2$, $|\Delta(B-L)| = 2$.

EXO
(Enriched Xenon Observatory)

Why Xe?

- **Monolithic detector ➔ LXe is self shielding ➔ minimize surface contamination.**
- **Possible background free measurements -> Tagging daughter nuclide $^{136}Ba^{+}$.**
- Xenon isotopic enrichment is easier ➔ Xenon is a (noble) gas & ^{136}Xe is the heaviest isotope.
- Xenon is "reusable" -> Can be re-purified & recycled during the experiment.
- Minimal cosmogenic activation -> No long lived radioactive isotopes of Xenon.
- Energy resolution in LXe can be improved -> Scintillation light/ionization ratio.



2νββ?

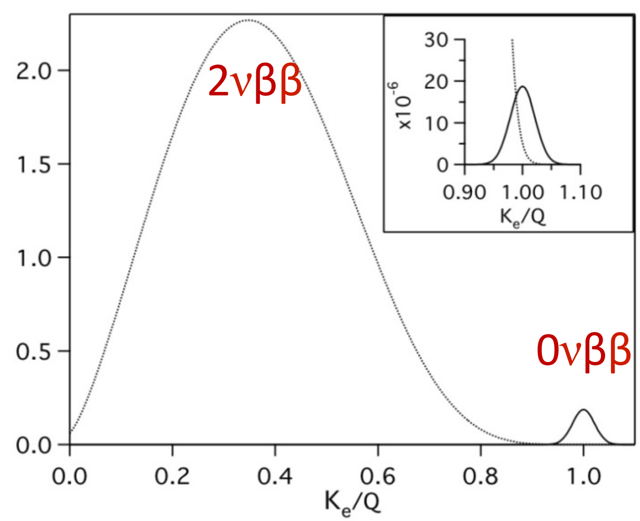
- 2β decay has been observed in app. 10 isotopes before EXO.
- EXO-200 is the first experiment observe 2νββ decay for ^{136}Xe isotope.

Why 0νββ?

- Majorana or Dirac neutrino.
- Lepton number violating process.
- Absolute neutrino mass.

$$\Gamma^{0\nu} = G^{0\nu}\,|M^{0\nu}|^2\,|\langle m_{\beta\beta}\rangle|^2$$

$\Gamma^{0\nu}$ = decay rate
$G^{0\nu}$ = phase-space factor.
$M^{0\nu}$ = Nuclear matrix element.
$\langle m_{\beta\beta}\rangle$ = effective neutrino mass



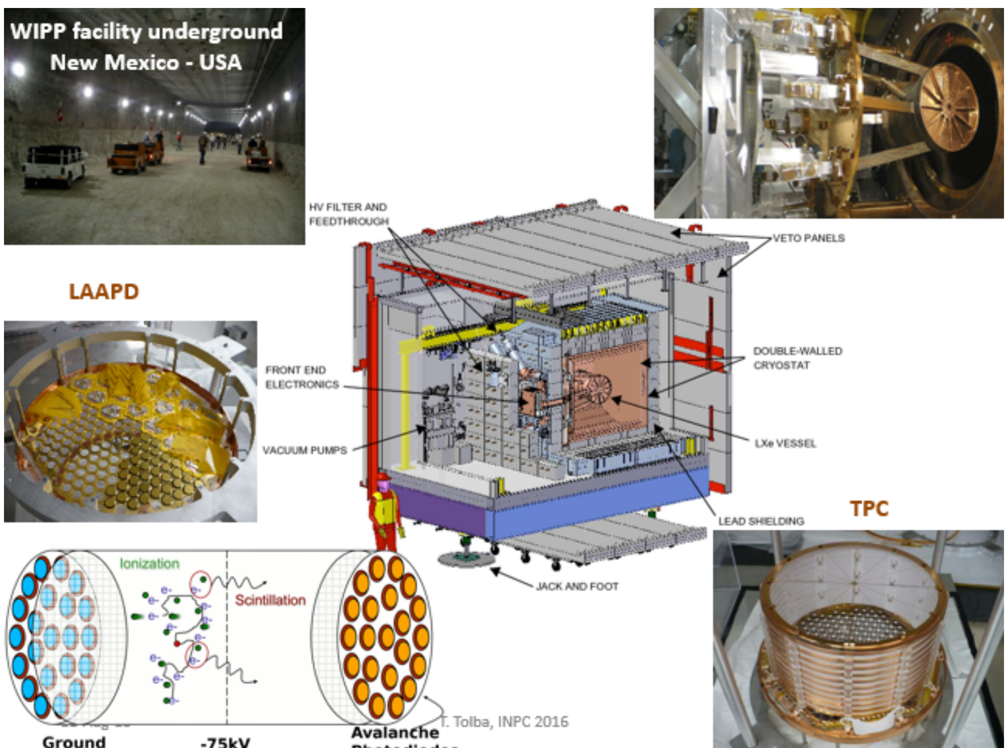
0νββ requirements:

- High energy resolution.
- Large Isotope mass.
- Low background.

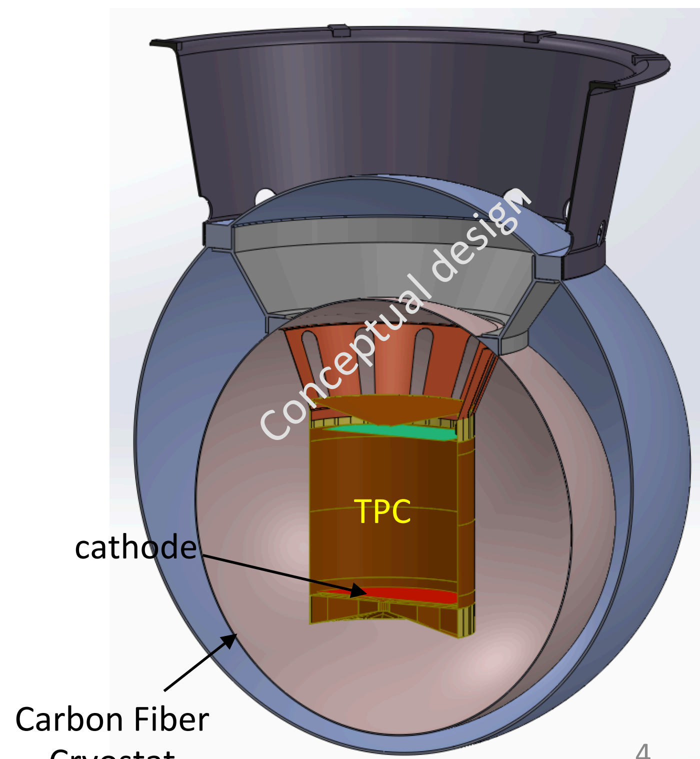
EXO
(Enriched Xenon Observatory)

Current Phase | **Future Phase**

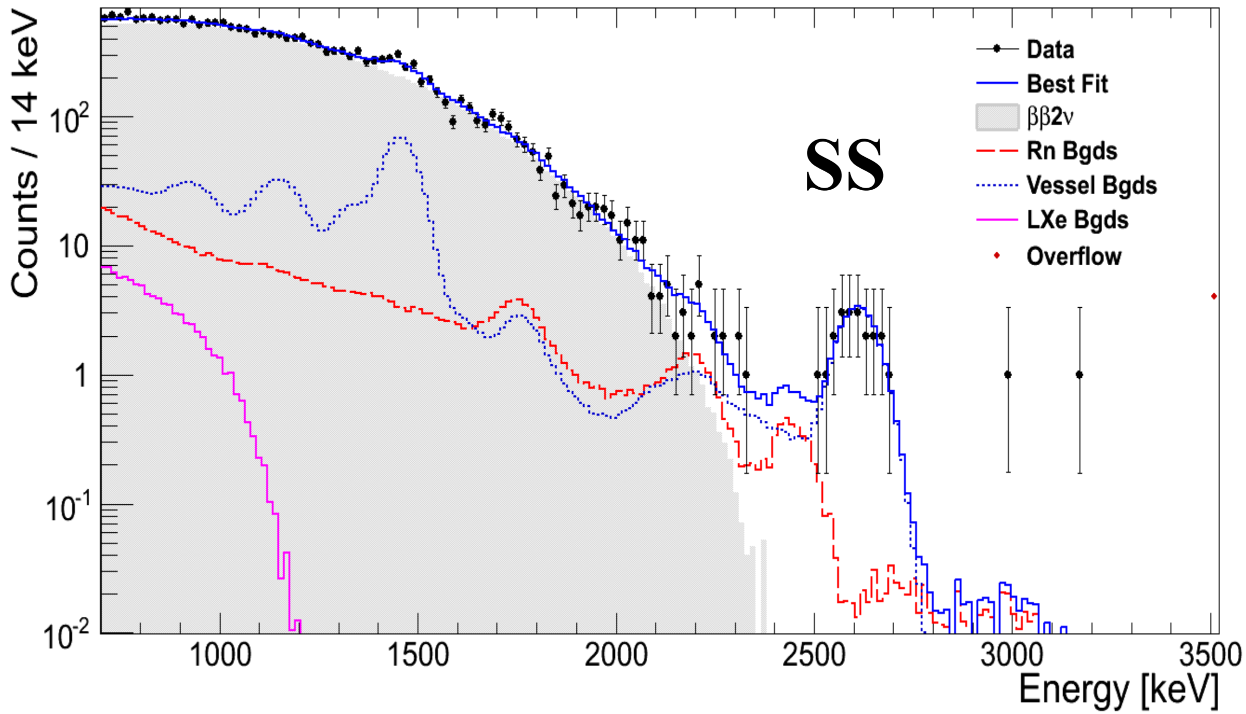
EXO-200
(~ 175 kg Xe)



nEXO
(~ 5 tonne Xe)



EXO-200 Results for 2νββ Decay "Phase I"



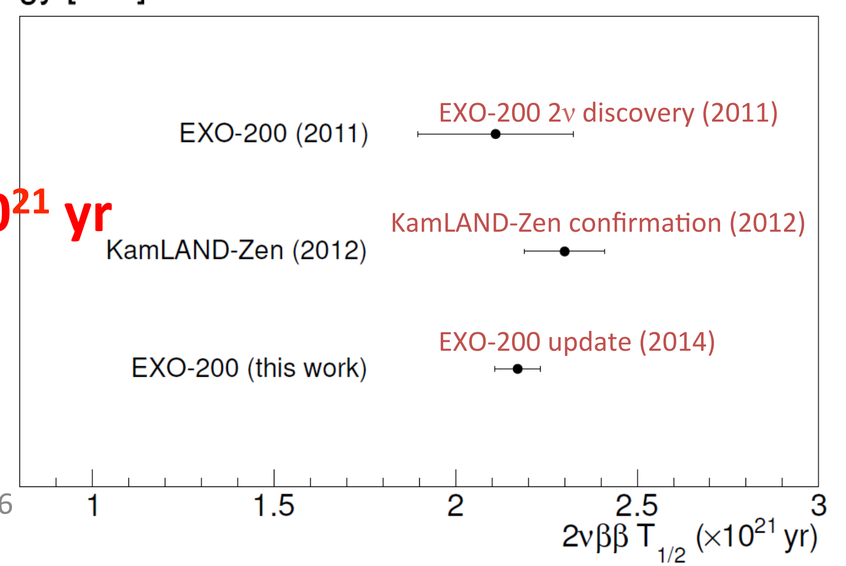
Data Set:

- **Low background run 2a.**
- **run live time: 127.6 days Active.**
- **mass: LXe = 98.6 kg**
  ^{136}LXe = 82.1 kg
  (enrichment = 80.672 ± 0.014 %)
- **Exposure: 28.7 kg.yr**
- **Vetos dead time: 3.6%**

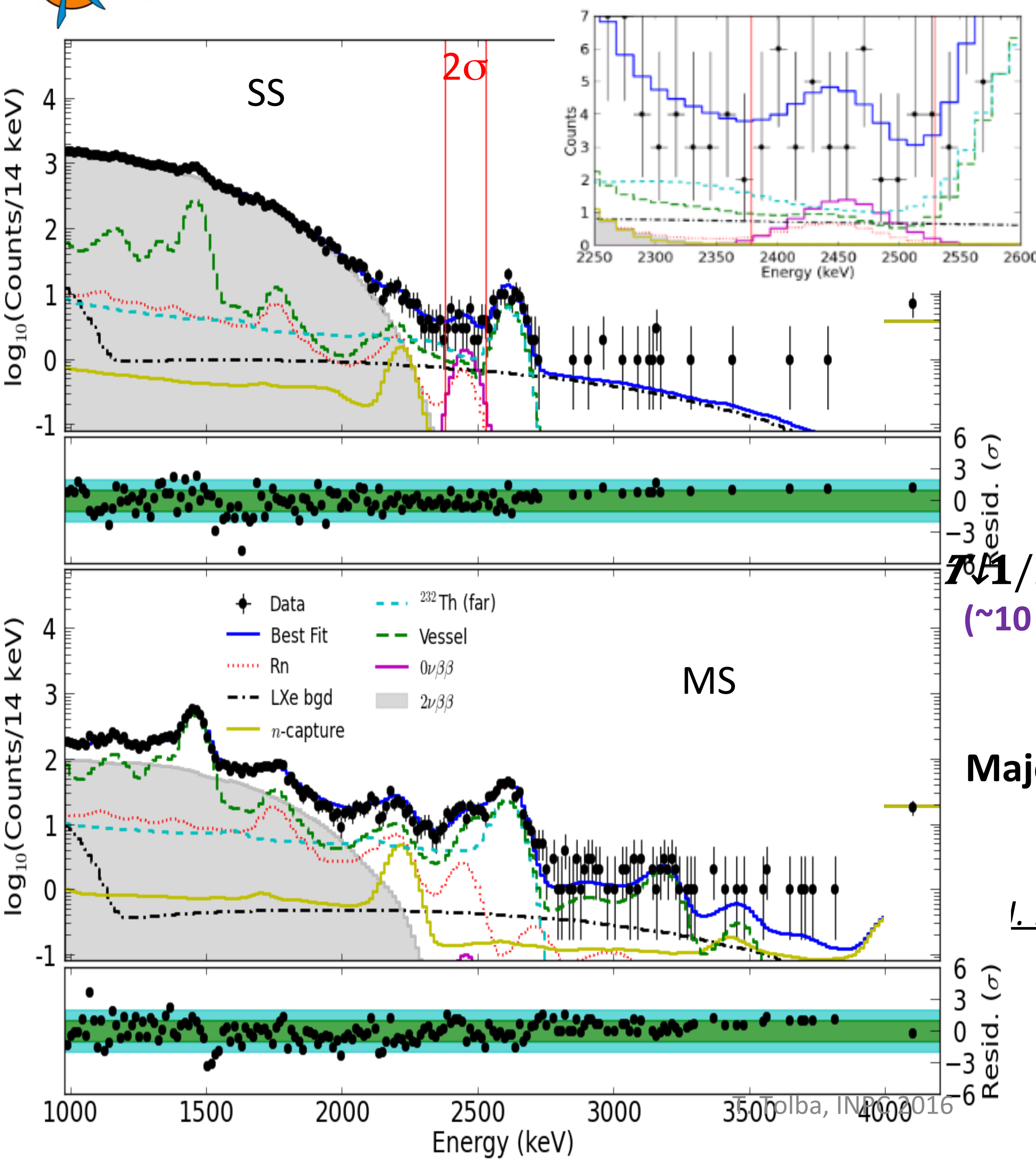
The most accurate $T_{1/2}$ of any 2νββ decay

$T_{1/2}^{2\nu\beta\beta}$ **= (2.165 ± 0.016^{stat} ± 0.059^{sys})·10^{21} yr**

*(Phys. Rev. C **89** (2014) 015502)*



EXO-200 Results for 0νββ Decay "Phase I"



Data set:

Total live time: 477.6 days

Total Xe exposure = 123.7 kg y

Background @ 0νββ±2σ ROI

$(1.7\pm0.2)\times10^{-3}$ keV^{-1} kg^{-1} yr^{-1}

(31 counts)

$T_{1/2}^{0\nu\beta\beta}$ **> 1.1·10^{25} yr (@ 90% CL)**

(~10 counts, consistent with null hypo.@ 1.2σ)

Majorana mass limit (for range of NME)

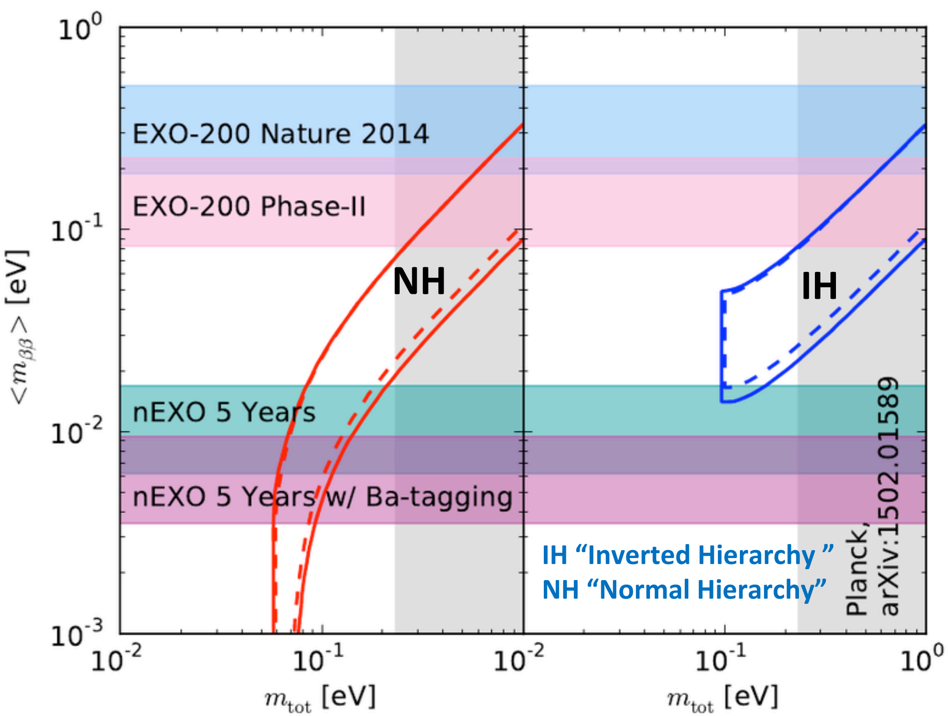
$\langle m\rangle_{\beta\beta}$ < 190 – 450 meV

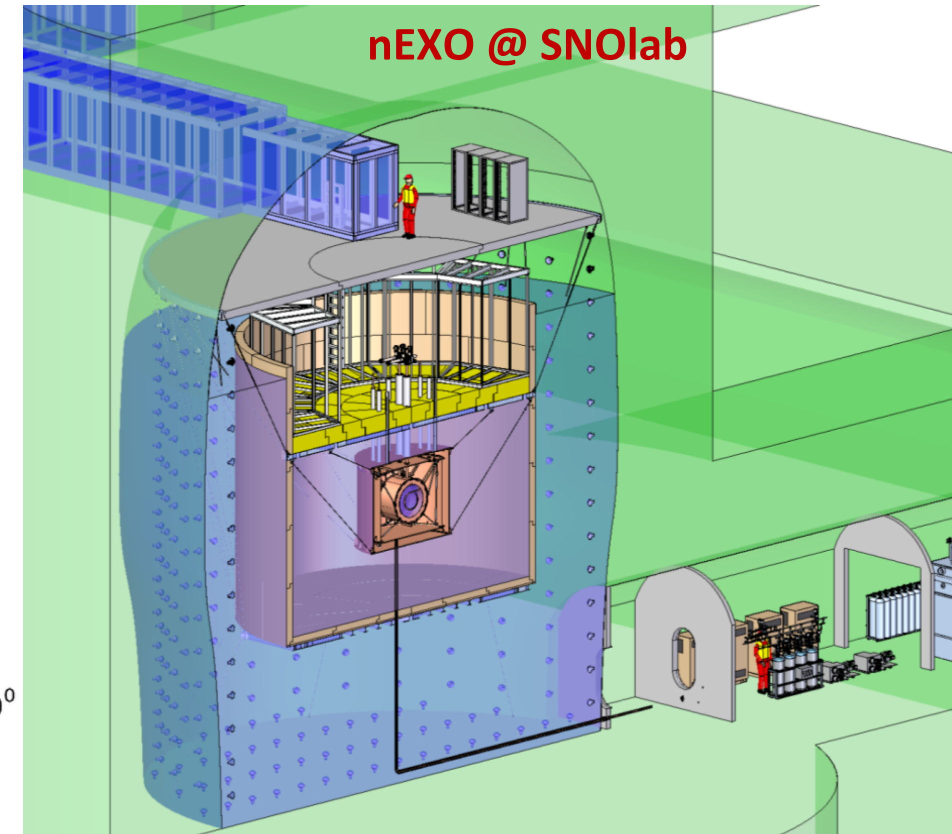
*J. B. Albert et al., **Nature** 510, (2014) 229*

No signal observed

The Future 5 tonne nEXO Detector

- LXe TPC “as similar to EXO-200 as possible” ➔ but 3x larger volume (~25x larger mass).
- 5 tonnes of ^{enr}Xe (with 5 yr of data taking) ➔ Sensitivity $T_{1/2}=6.6\times10^{27}$ yr (entirely cover inverted hierarchy (< 10 meV)).
- 4.7 tonnes of active ^{enr}Xe (90% or higher) ➔ 1.0% (σ/E) energy resolution.
- Possible later upgrade to Ba tagging ➔ increase sensitivity and probe normal hierarchy.



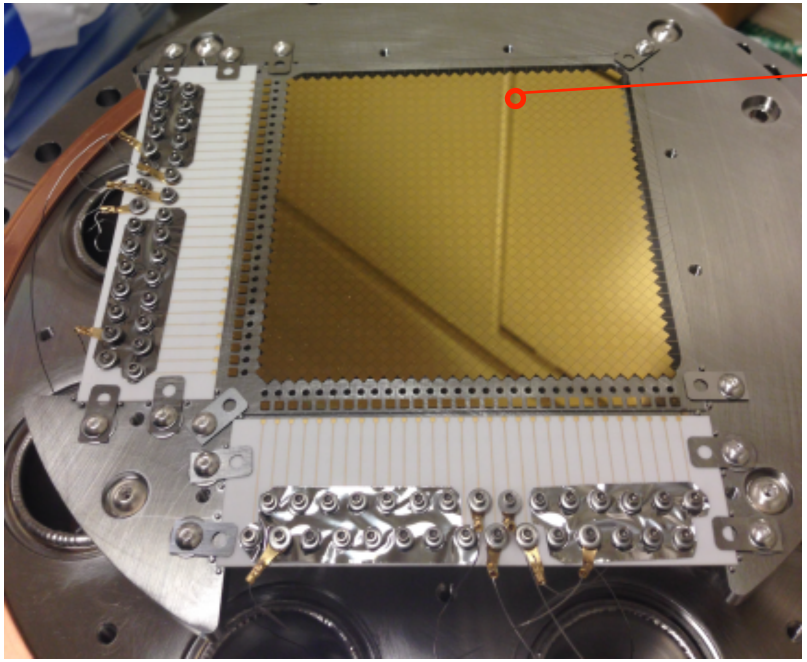


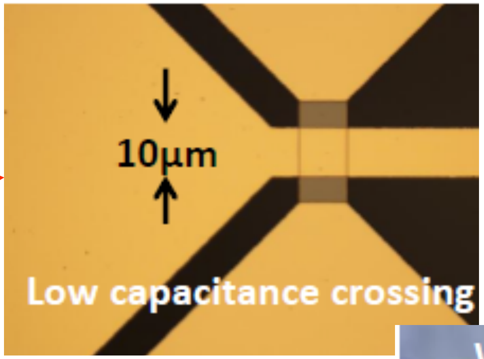
Optimization from EXO-200 to nEXO (R&D)

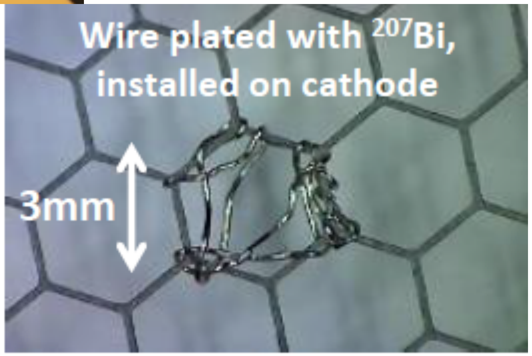
Parameter to optimize	Effect
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution, lower scintillation threshold
SiPM instead of APDs	Higher gain, lower bias, lighter, E resolution, lower scintillation threshold
Charge readout tiles instead of wires	Better mechanical robustness and better γ/β Discrimination
Cold "in LXe" electronics	Lower noise, more stable, fewer cables/feedthroughs, E resolution, lower threshold for Compton ID
Lower outgassing components	Longer electron lifetime
Different calibration methods	Very "deep" detector (by design)
Deeper site	Less cosmogenic activation
Larger vessels	5 ton detector and more shielding

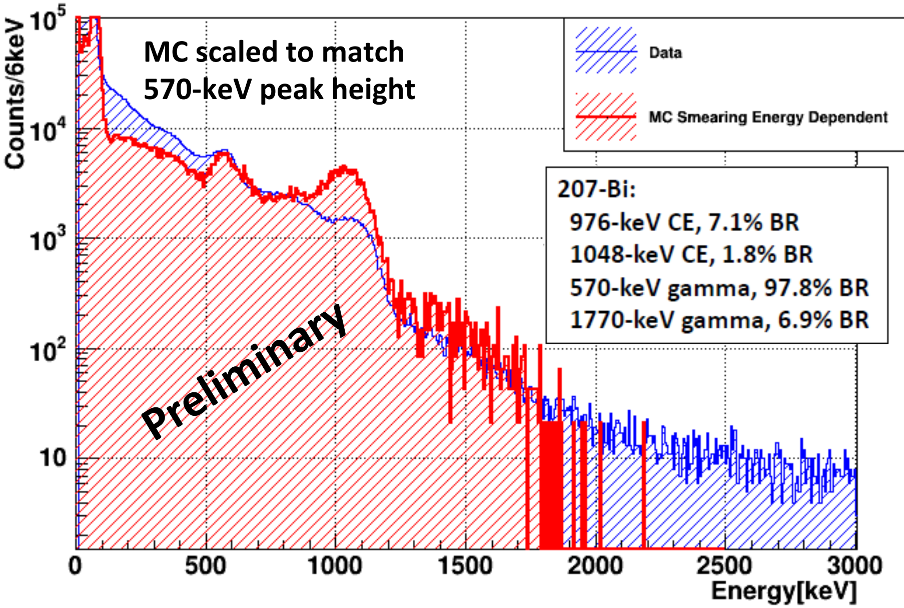
nEXO Charge Readout R&D

Prototype Charge Readout Tile



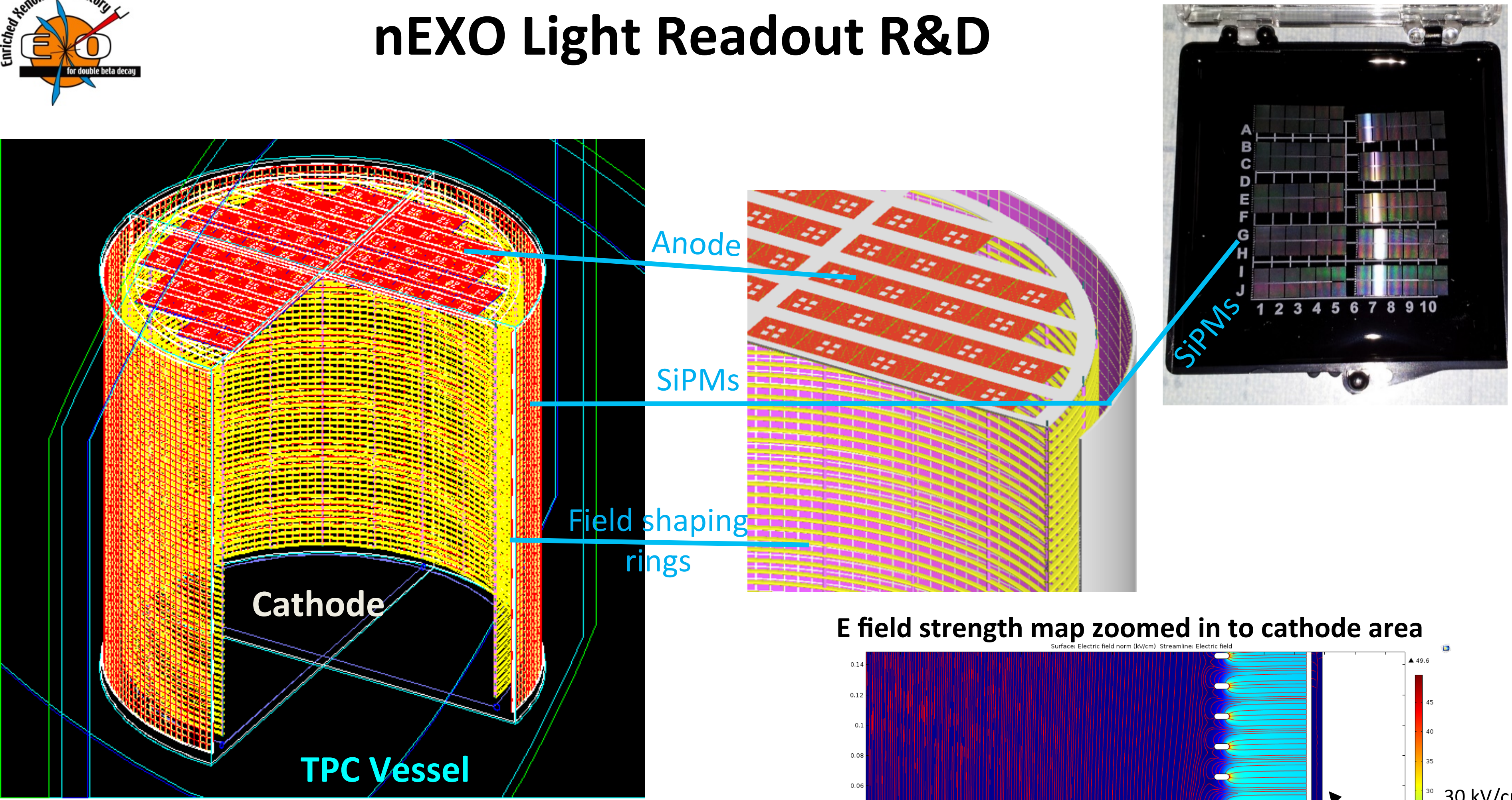




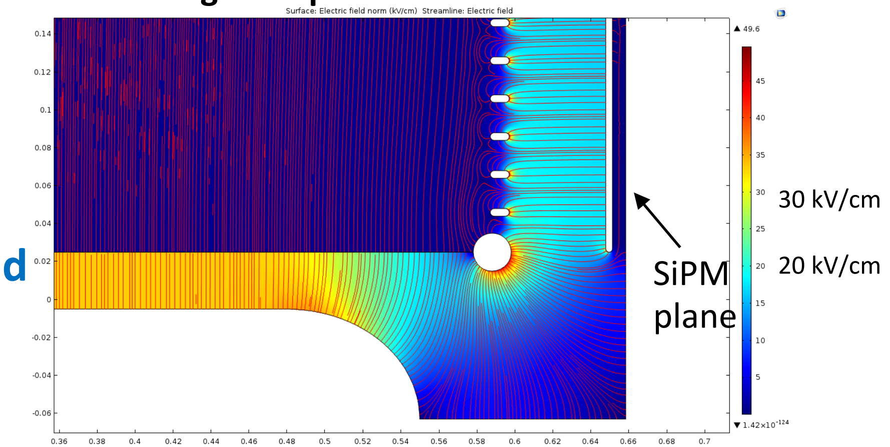


- A modular and pad-like charge collection scheme is under study to replace a more traditional wire readout.
- Preliminary testing of tile: Prototype 3mm pitch, crossed strip quartz tile has been produced (@ IHEP/IME) and tested in liquid Xenon with ^{207}Bi (@ US).

nEXO Light Readout R&D



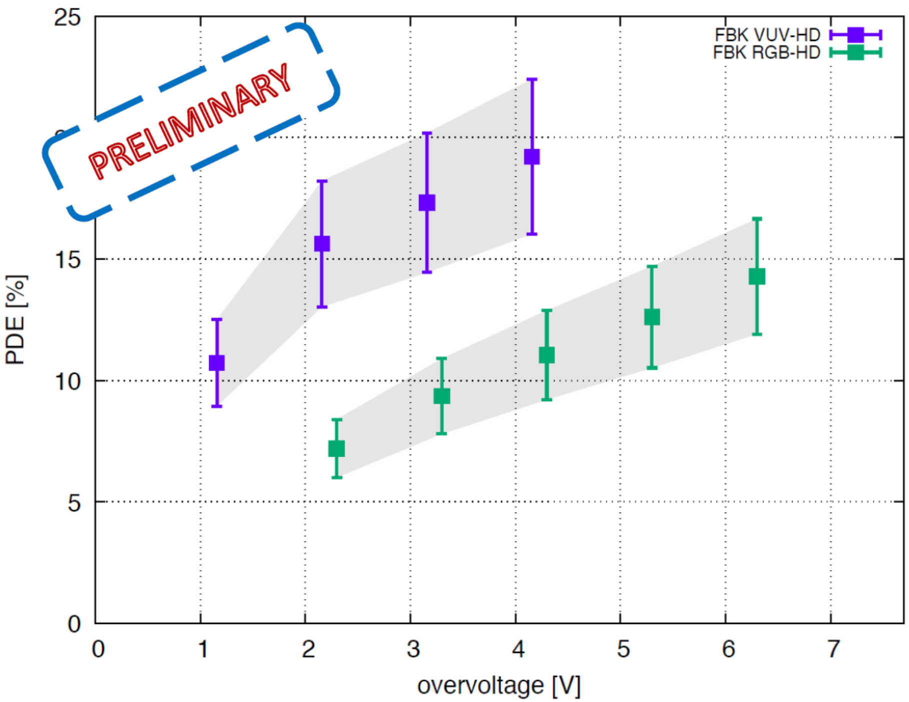
E field strength map zoomed in to cathode area

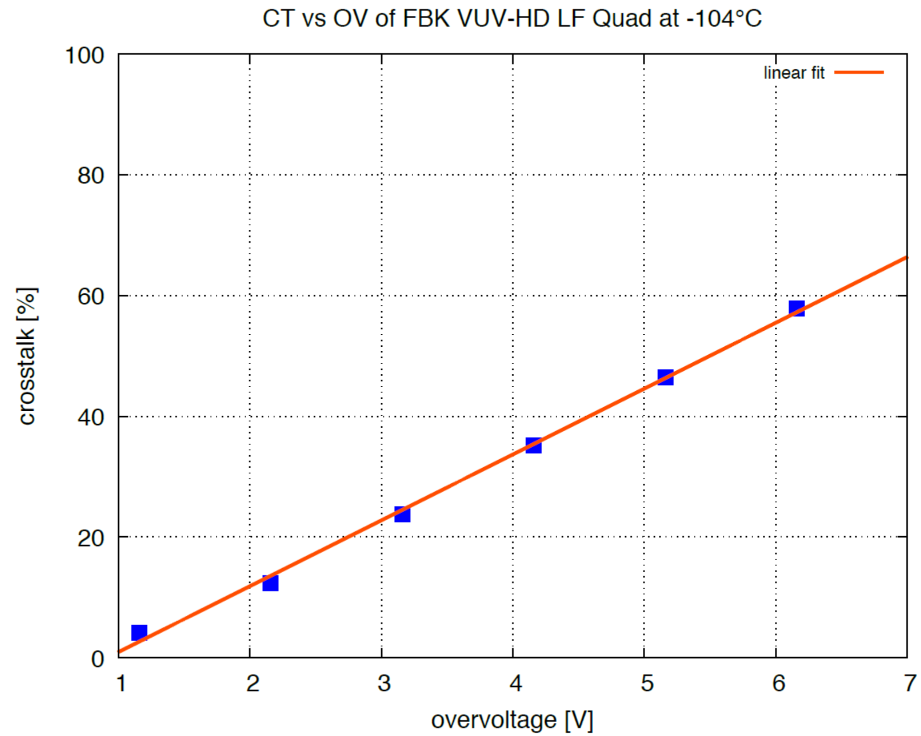


SiPMs plane in nEXO ➔ Exposed to high electric field values.

Effect on SiPM performance (Gain, PDE, correlated noise, physical damage …)!!!

VUV sensitive SiPMs





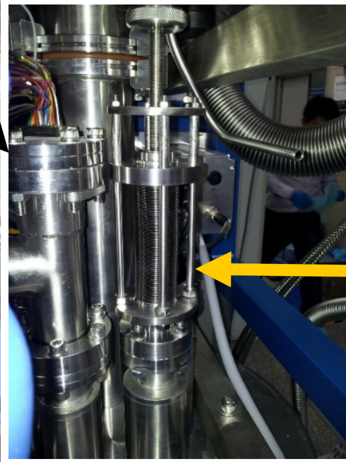
New generation FBK devices have reached PDE > 15%@ 170nm.

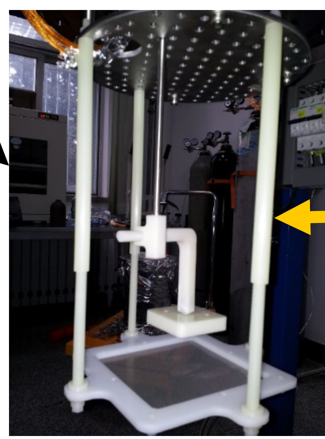
Radio assay results of the FBK devices are also very encouraging.

SiPMs Performance in High Elect. Field Values

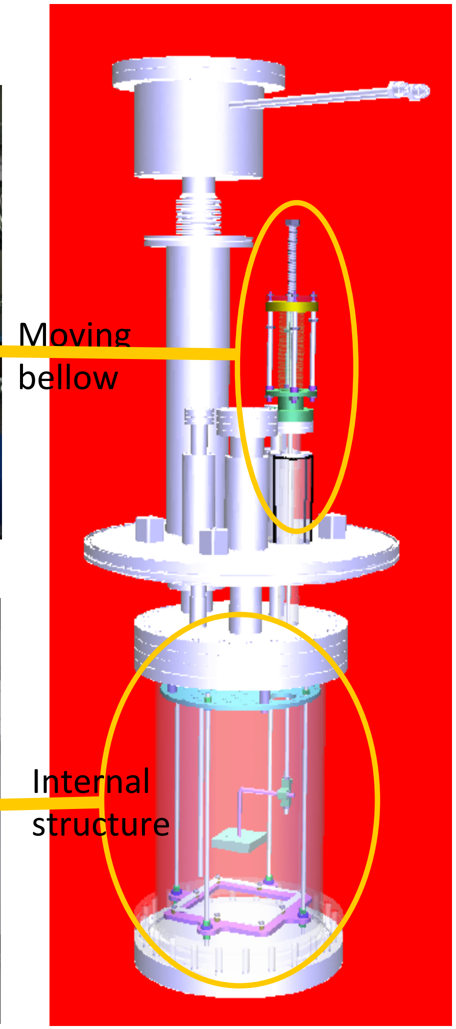
IHEP LXe-Setup

Reality

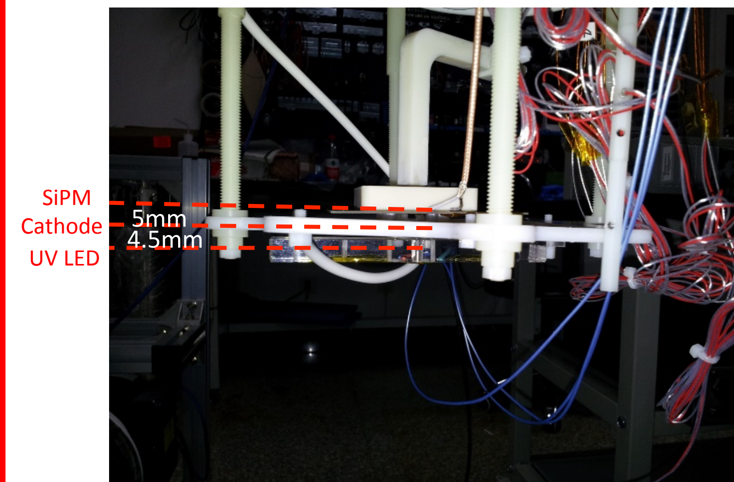




Design



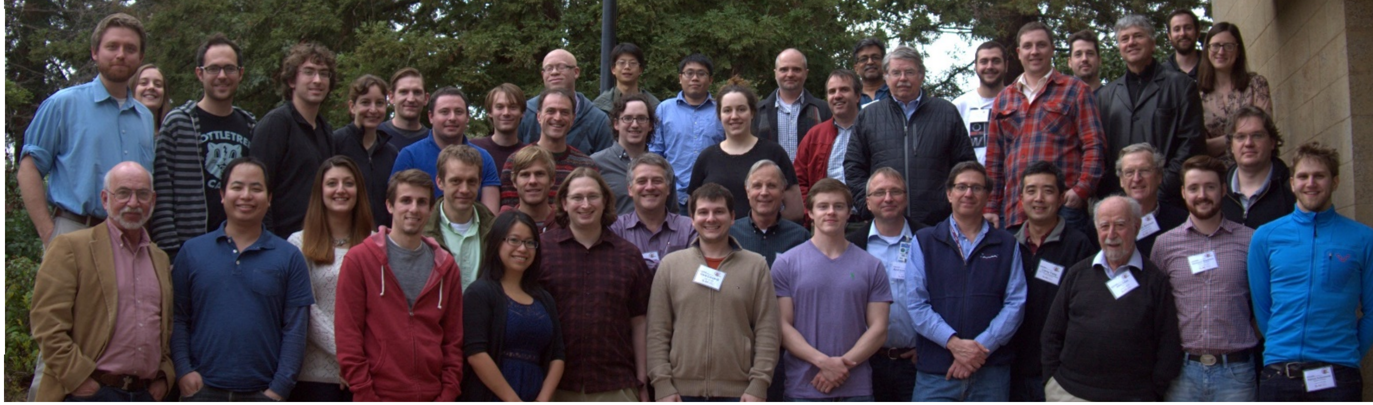
PMT used to correct the light signal from the LED



Conclusions/Outlook

- EXO-200 Phase-II started after the recovery from the WIPP underground incidents.
- Many nEXO R&D programs dedicated to study the SiPMs performance.
- Various nEXO R&D programs are in progress.

Enriched Xenon Observatory EXO for double beta decay



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The nEXO Collaboration

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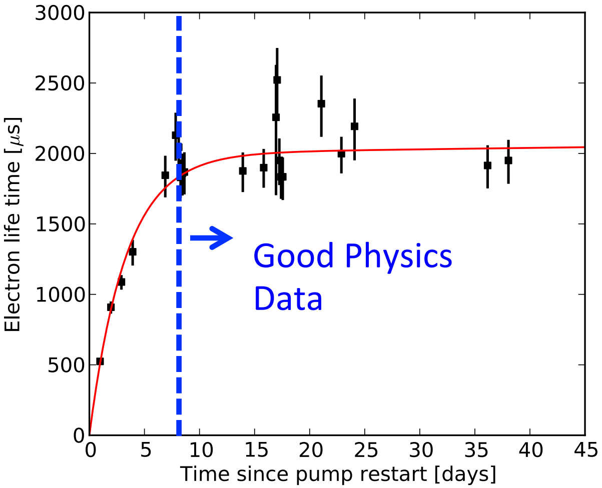
Spares

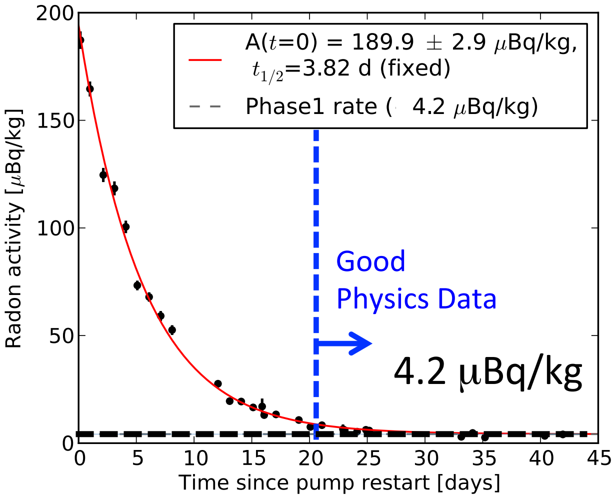
EXO-200 "Phase II"

- ➔ EXO-200 Phase-II started after the recovery from the WIPP underground incidents:
- ➔ Detector upgrade (electronics and deradonator).
- ➔ Increase drift field (~375 V/cm -> ~585 V/cm).
- ➔ Phase-II physics data taking (started Apr. 2016).
- ➔ Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.

DOE Accident Inv. Rep., Mar 2014

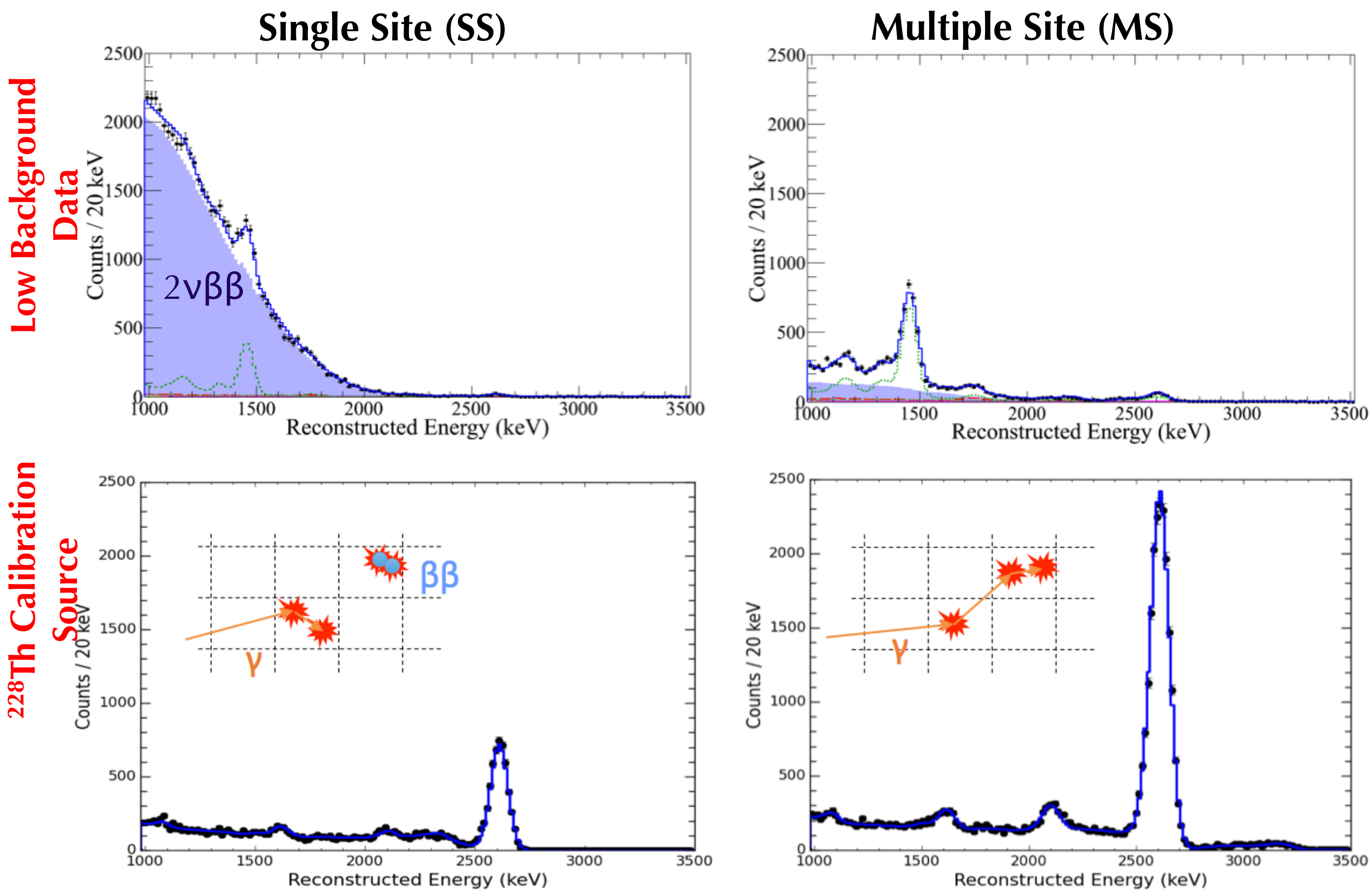


Xenon purity since Jan. 31, 2016

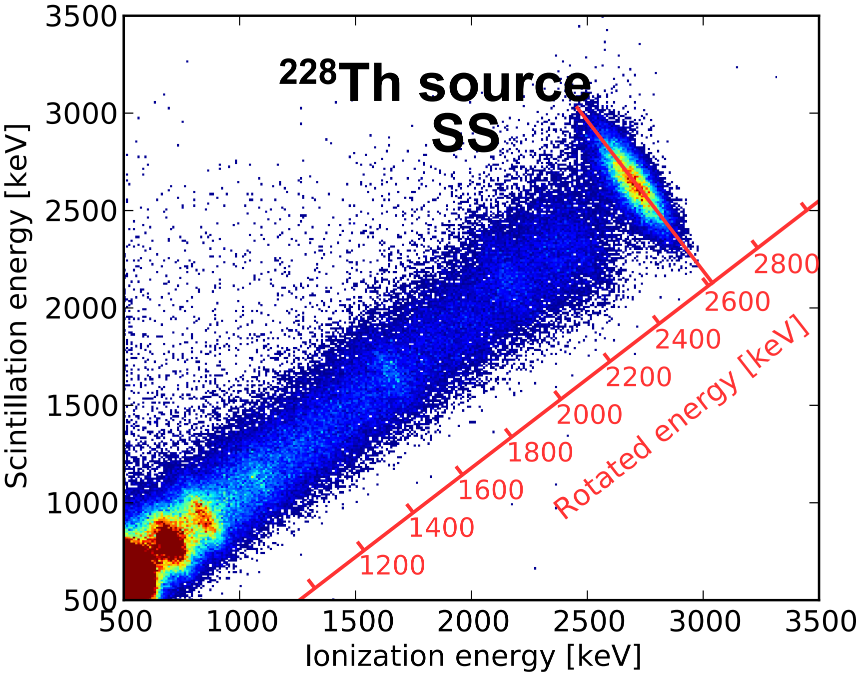


Rn level in TPC since Jan. 31, 2016

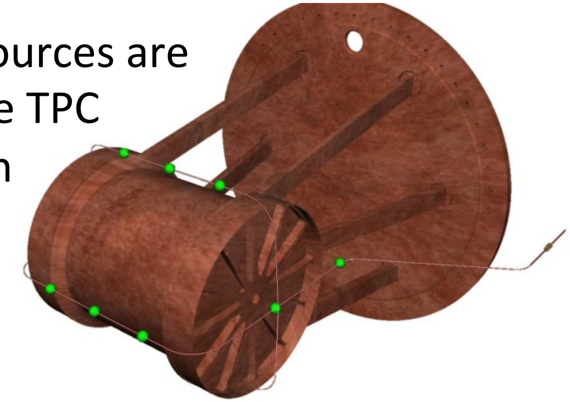
Event multiplicity and background discrimination
(example from EXO-200 real data)



EXO -200 Detector Calibration

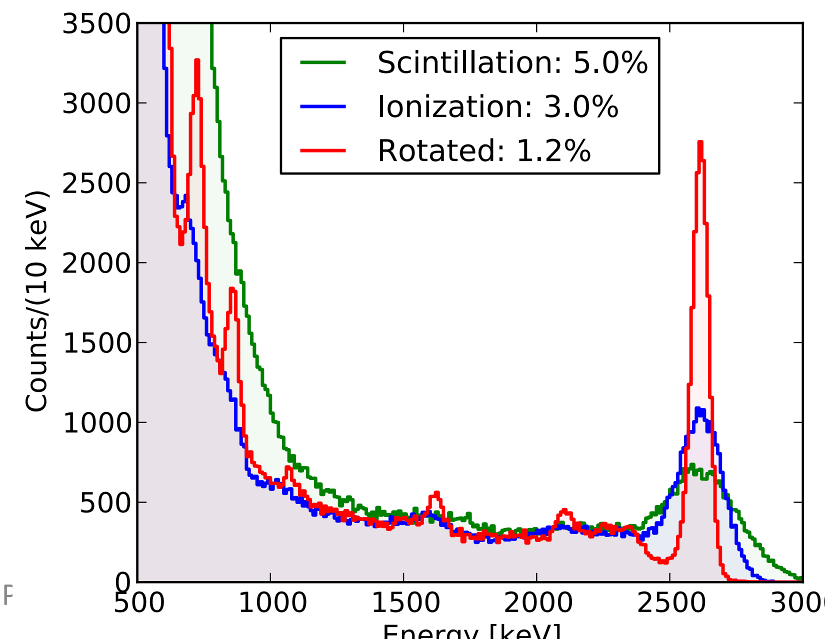


^{137}Cs, ^{60}Co and ^{228}Th sources are utilized to calibrate the TPC response to γ radiation



^{228}Th is deployed every few days near the cathode to monitor the e$^-$ life time and measure the energy response.

Ionization-Scintillation anti-correlation in LXe



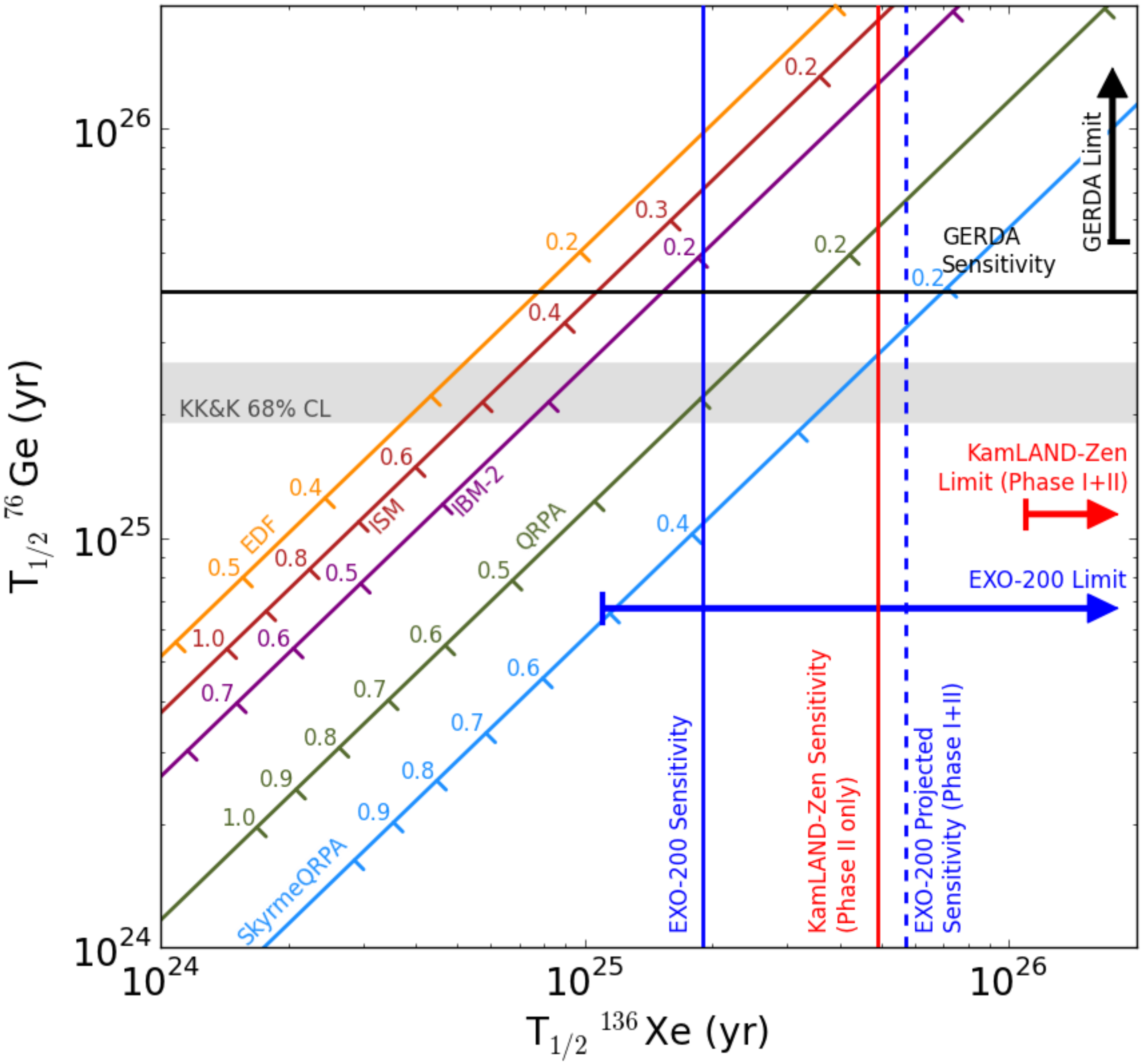
Energy resolution (@ 2615 keV γ line) for:

Scintillation:5%

Ionization:3%

Rotated:1.25%

EXO-200 Phase II Sensitivity



EXO-200 can reach *0νββ* half-life sensitivity of 5.7×10^{25} ys.

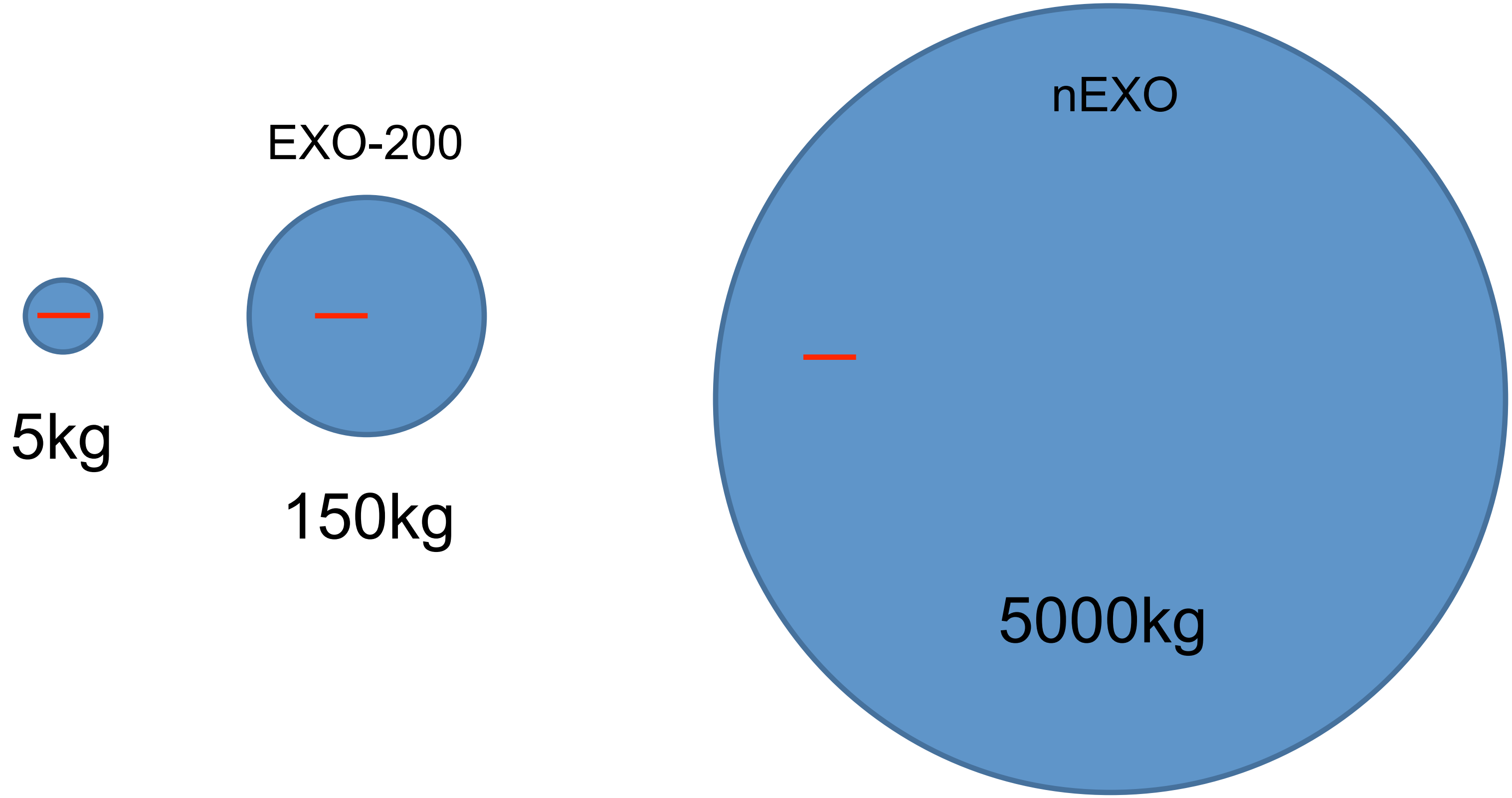
With lower threshold, EXO-200 can improve measurement of ^{136}Xe 2νββ and searches in other physics channels.

EXO-200:
Nature (2014),
doi:10.1038/nature13432

GERDA Phase 2:
Public released result. June, 2016
(frequentist limit)

KamLAND-Zen:
arXiv:1605.02889 (2016)

Monolithic Detectors



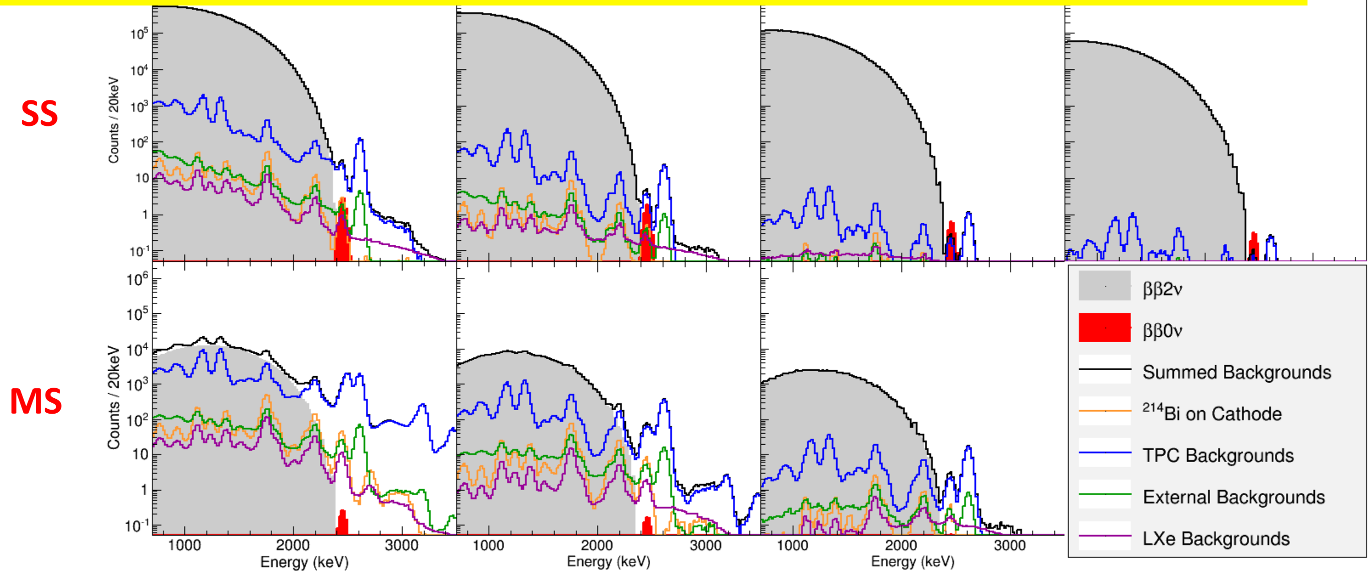
— "2.5MeV gamma ray" attenuation length in LXe = 8.5 cm

LXe mass (kg)	Diam. or length (cm)
5000	130
150	40
5	13

The role of the standoff distance in background identification and suppression

Example: nEXO, 5 yr data, 0νββ @ $T_{1/2}$=6.6x10^{27} yr, projected backgrounds from subsets of the total volume

Fid. LXe Mass = 4780kg 3000kg 1000kg 500kg

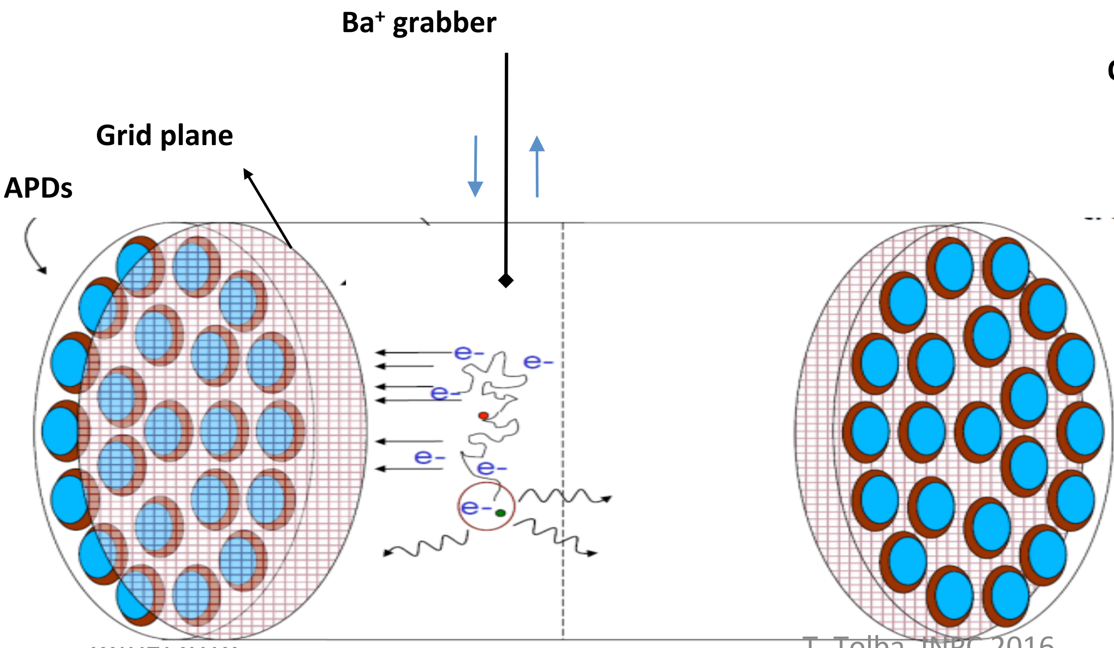


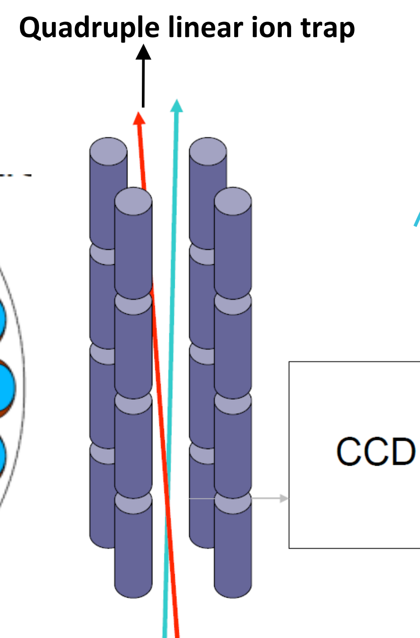
The fit gets to see all this information and use it in the optimal way

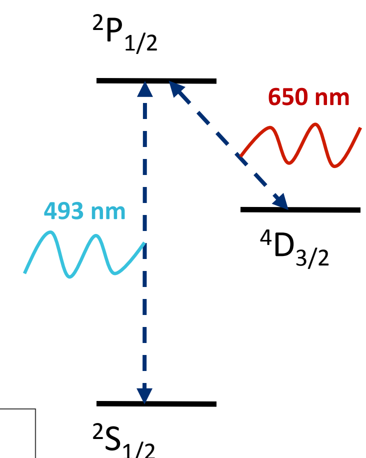
Final State Ba^+ Tagging (R&D)

Aim ➔ background free experiment by tagging the unique 2β decay daughter ($^{136}Ba^+$).

- **Locate the ion in the TPC**
  - ➢ Fast and precise determination of the decay vertex.
  - ➢ knowing the drift properties of the ion in liquid (or gas) Xe.
- **Extract the ion to a low pressure analysis chamber**
  - ➢ Efficiency of the extraction process ➔ Ion life time in the Lxe.
- **Detect and identify the ion**
  - ➢ e.g. RF trap using resonant light scattering (or any other identifying method).







Ba+ level structure

Charge Readout Tiles

- EXO-200 used wires for charge-readout
- Produced by IHEP/IME; functional testing in LXe in the US.
    - Increased mechanical support
- 10cm x 10cm Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30)
- 3mm strip pitch
- Strip intersections isolated with SiO_2 layer
- Currently testing in LXe with a ^{207}Bi source

IHEP/IME tile anode, mounted to underside of cell lid