From EXO-200 to nEXO

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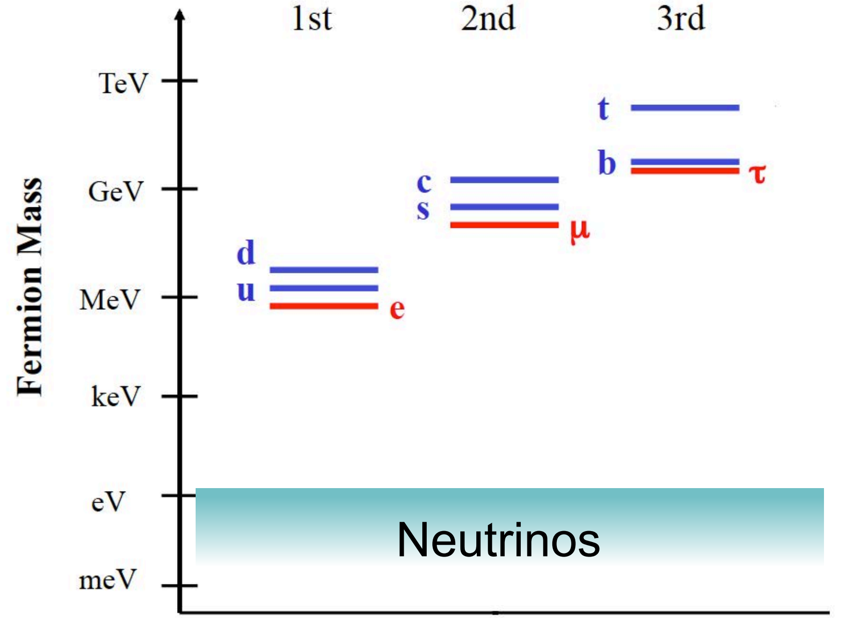
Neutrino Mass Generation Mechanism

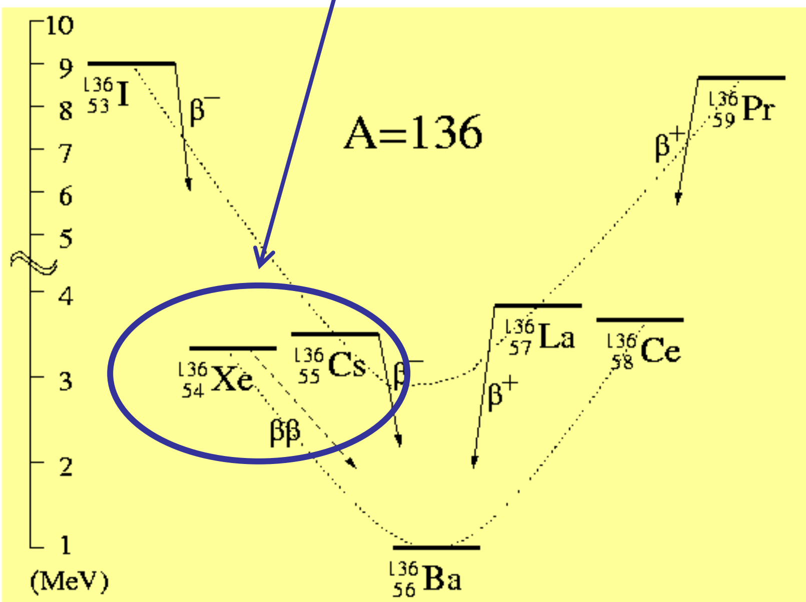
- Neutrino oscillation experiments demonstrate that neutrinos have tiny, but non-zero masses
- Neutrino mass is significantly smaller than other spin ½ leptons
- If neutrinos are Majorana particles, see-saw Mechanism provides a natural way to explain the smallness of the mass.
- It also predicts heavy GUT scale neutrinos (possible source of leptogenesis)



The best experimental probe for the Majorana Nature of the neutrinos is the search for neutrinoless double beta decay

Neutrinoless Double Beta Decay

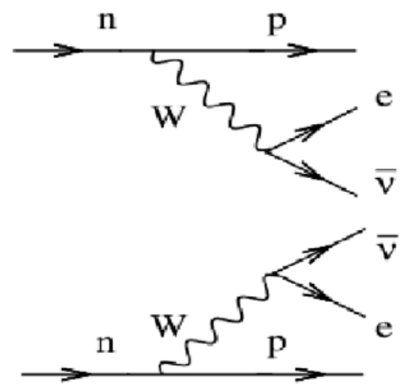
Observable if single beta decay is forbidden



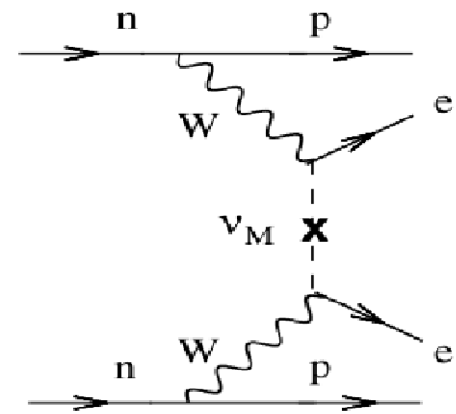
Observation of 0νββ:

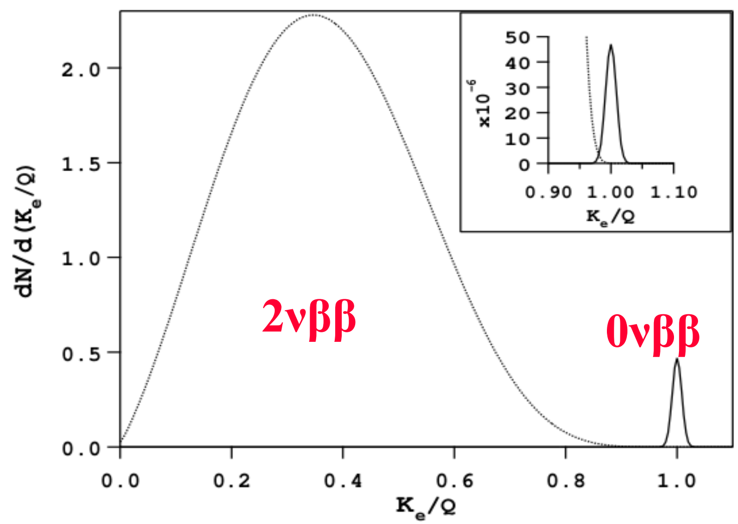
- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Two neutrino double beta decay



Neutrinoless double beta decay



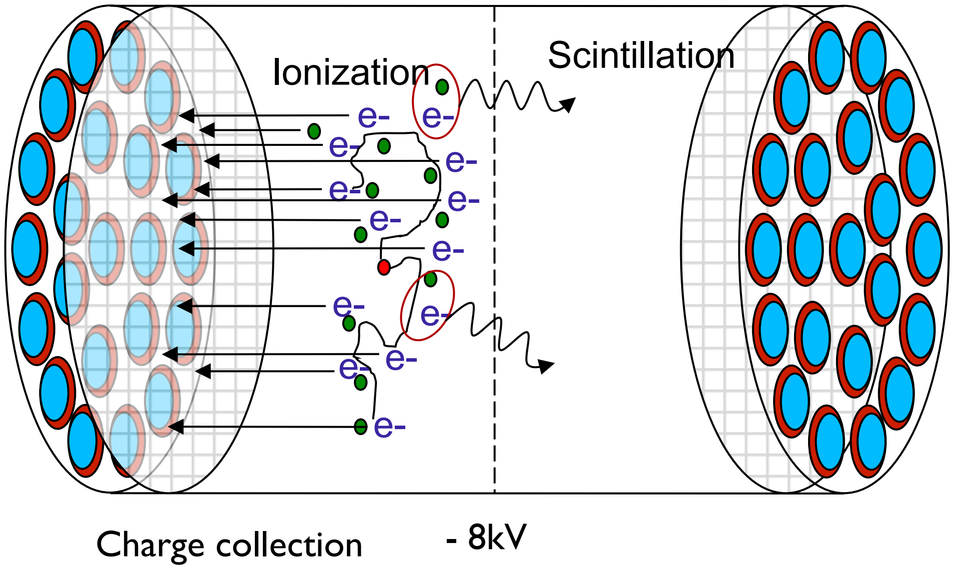


Summed electron energy in units of the kinematic endpoint (Q)

[P. Vogel, arXiv:hep-ph/0611243]

Use Liquid Xenon Time Projection Chambers (TPC) to Search for 0νββ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.

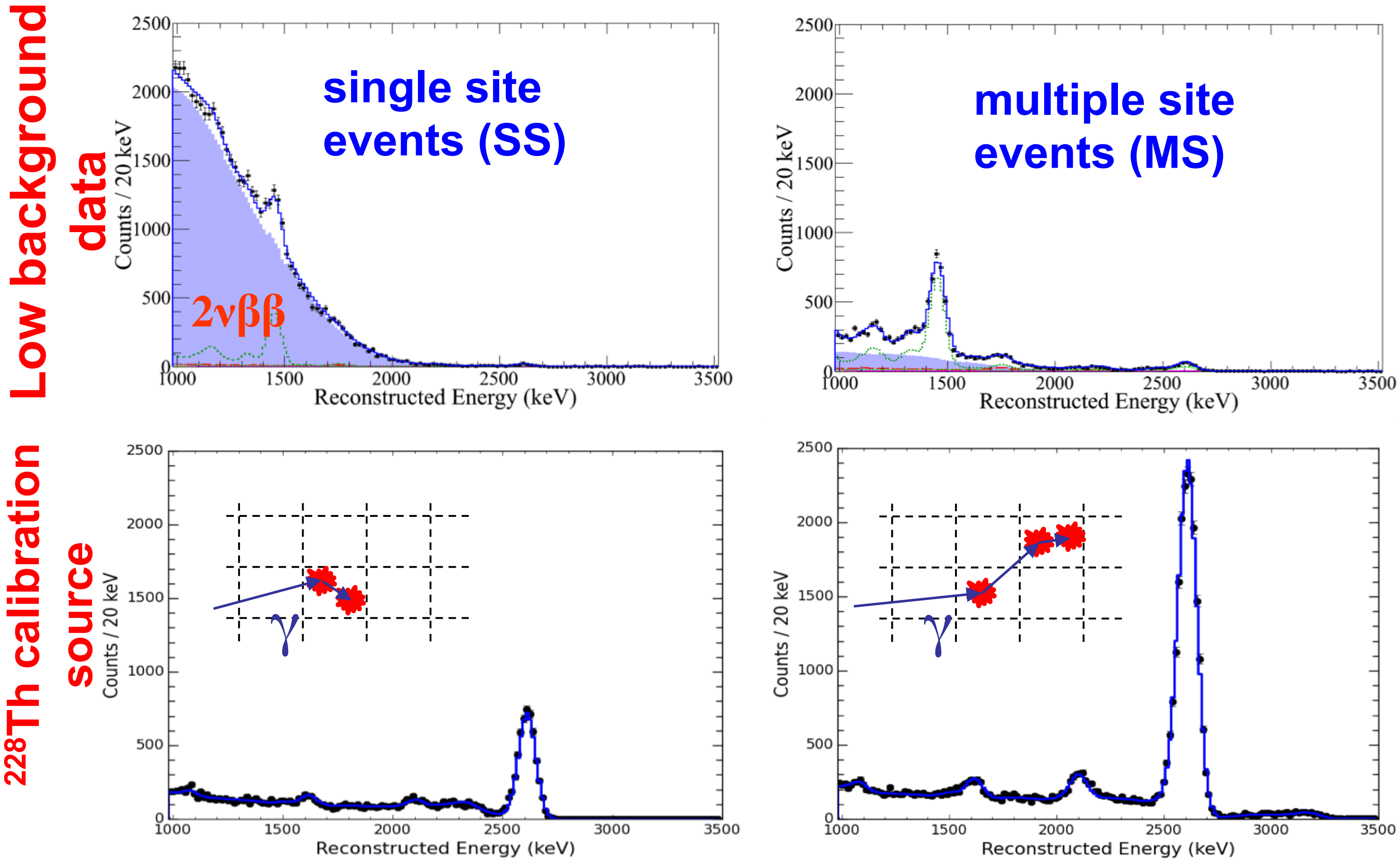


Example of TPC schematics (EXO-200)

EXO-200 is a running LXe detector with ~110 kg active volume. It has demonstrated key performance parameters for 0νββ search, and can reach 0νββ half-life sensitivity of 5.0 x10^{25} yrs after Phase-II operation.

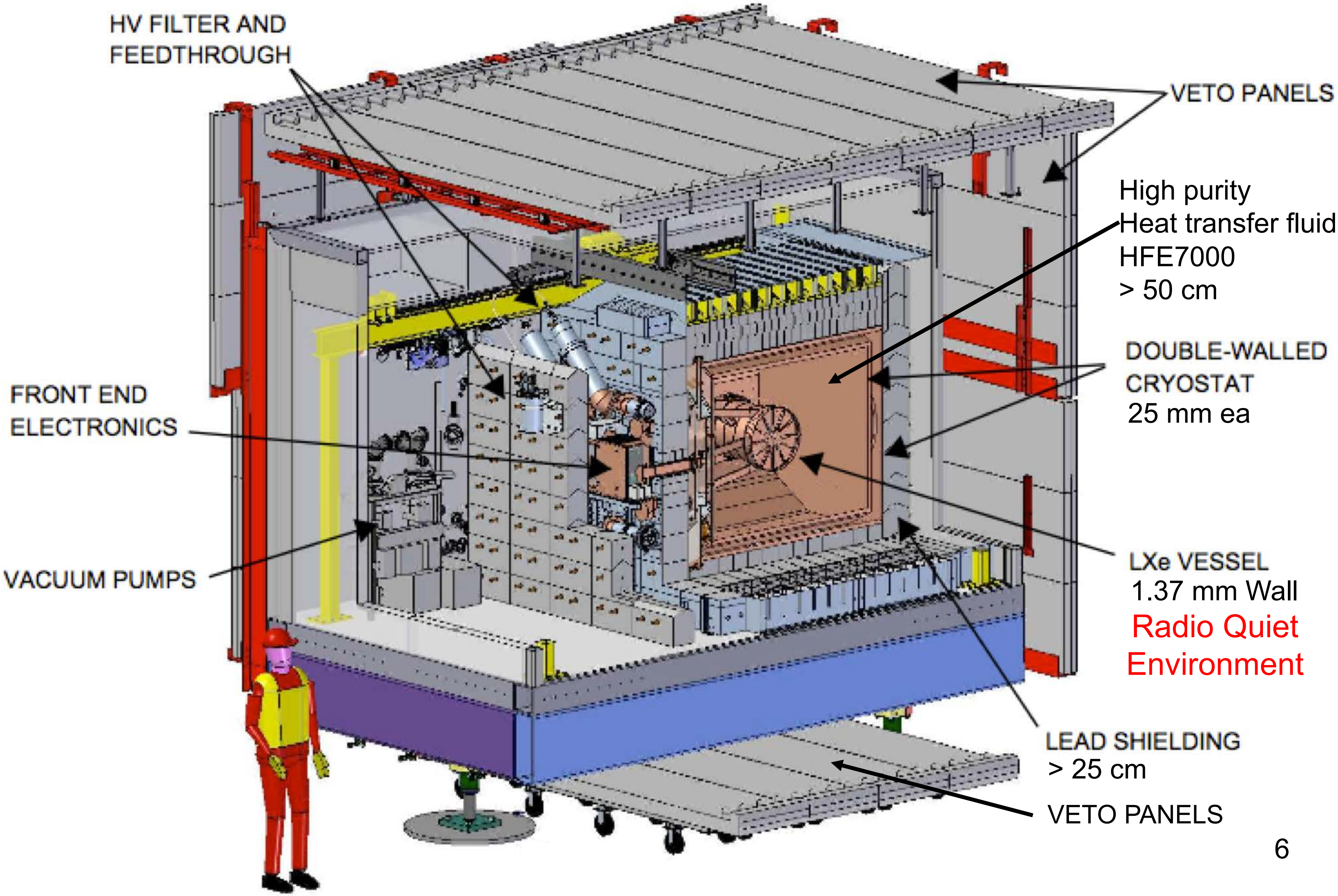
nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach 0νββ half-life sensitivity of ~ 10^{28} yrs

Topological Event Information



- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

The EXO-200 Detector

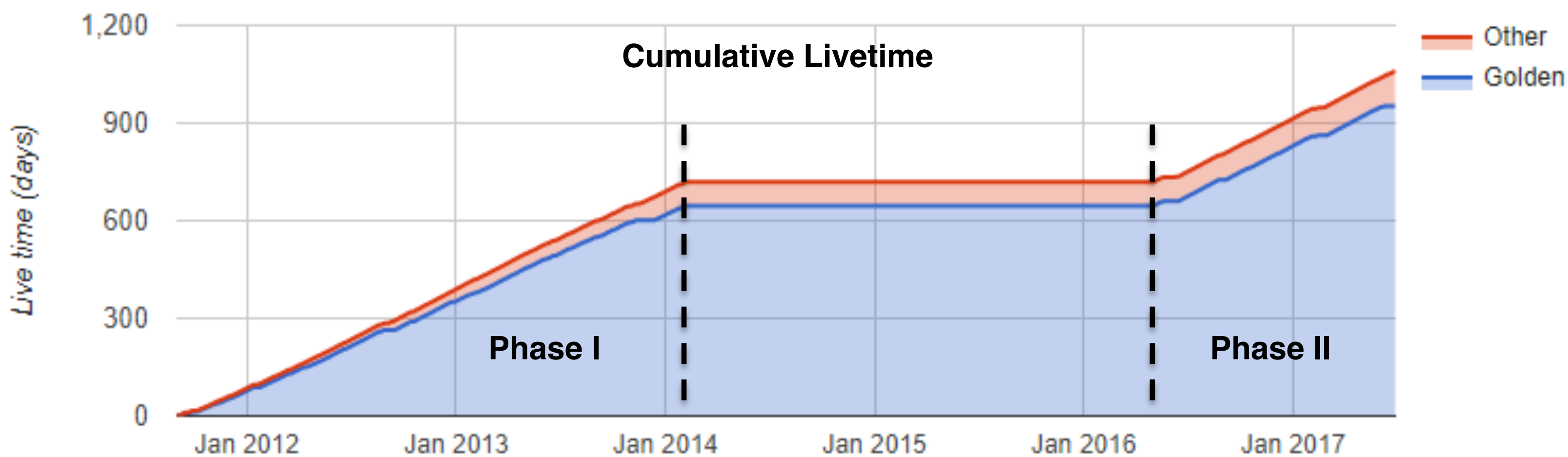


Phase-I

- Sep 2011 to Feb 2014
  - Total live time 596.7 days
- Selected physics results
  - Most precise 2νββ measure
    - *Phys. Rev. C **89**, 015502 (2013)*
  - Stringent 0νββ searches
    - *Nature **510**, 229 (2014)*
    - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{25}$ yr (90%CL)

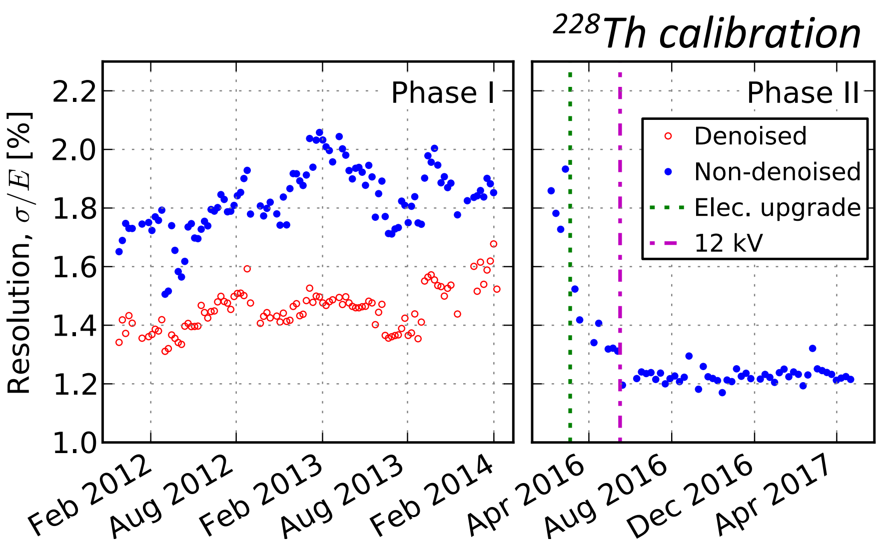
Phase-II

- Access regained in 2015 after stop imposed by WIPP accidents
- Jan to May 2016
  - Hardware upgrades
- HV raised by 50% in May 2016
  - Live time 271.8 days

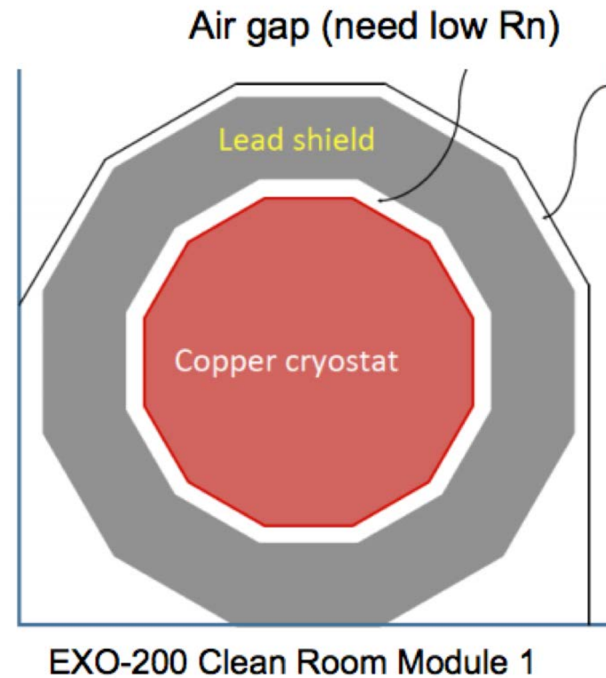


Detector Upgrades

- Front end readout electronics
  - *Reduce APD read-out noise*
- Increase of HV
  - *-8kV → -12 kV*
- Effect in energy resolution:
  - Phase-I: σ/E(Q) = 1.38%
  - Phase-II: σ/E(Q) = 1.23%, steady



- System to suppress radon in air gap



- Direct air sampling shows radon levels reduced in the gap by >10x

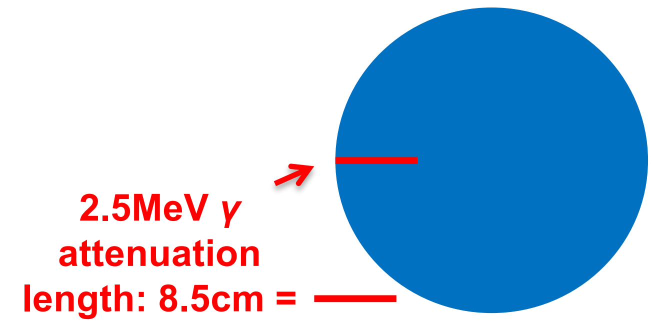
Improved γ-background Rejection

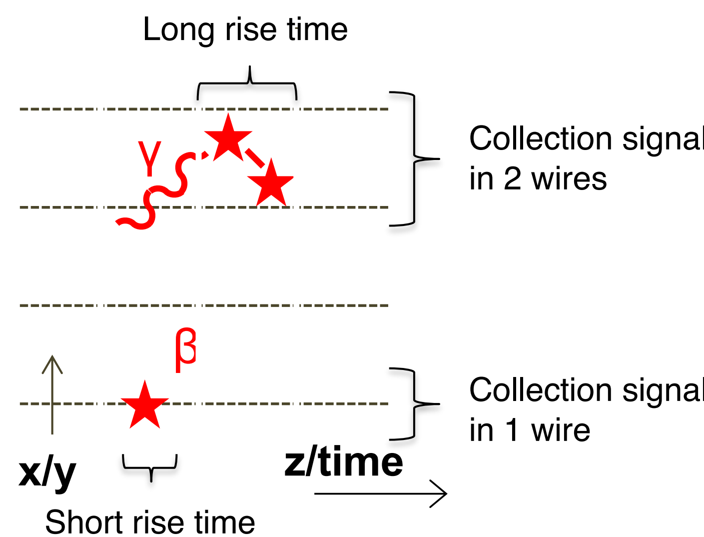
- Additional discrimination in SS using *spatial distribution* and *cluster size*

- Entering γ-rays rate is exponentially reduced by LXe self-shielding, provides independent measurement of γ-backgrounds

- Cluster size estimated from:
    - pulse rise time (longitudinal direction)
    - number of wires with collection signal (transverse)

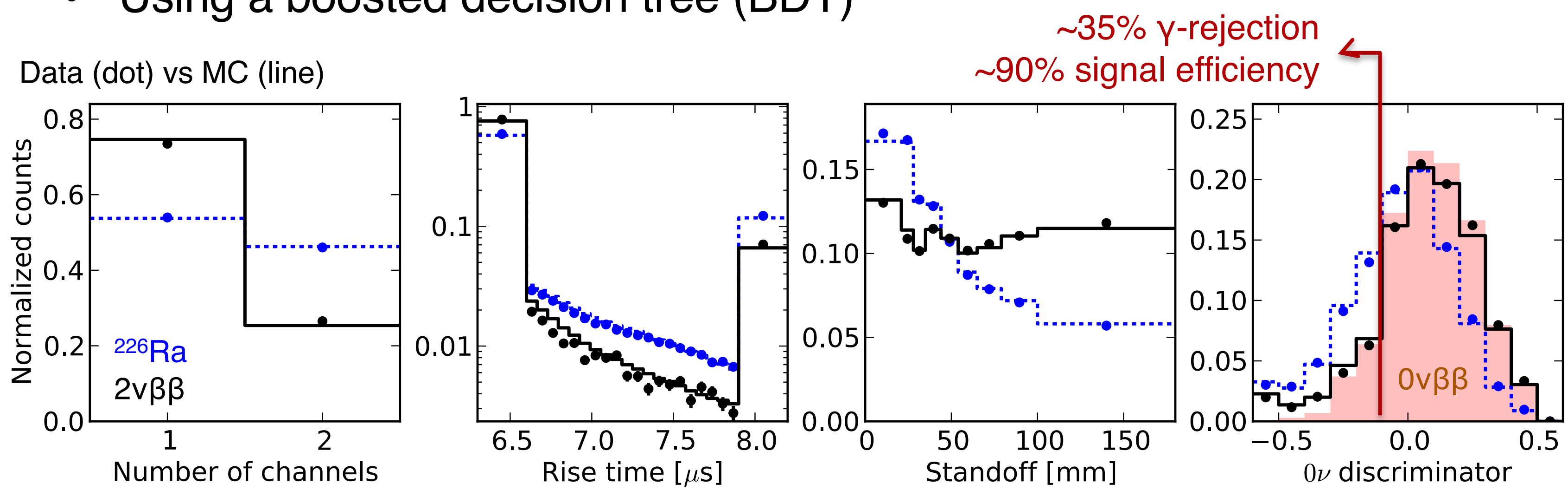
LXe self-shielding:



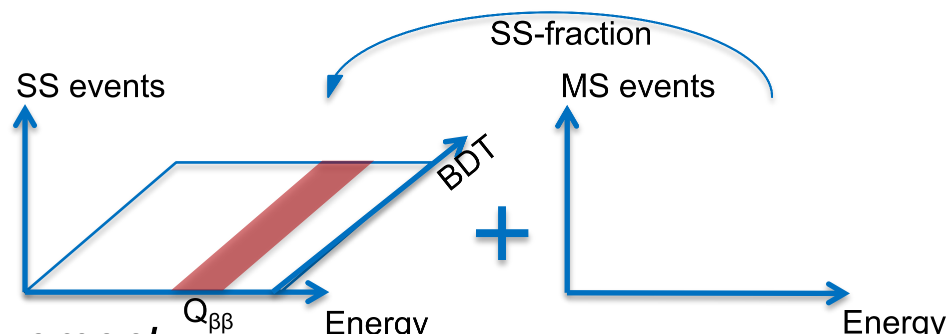


Optimal 0νββ Discrimination

- Optimize SS discriminators into a more powerful one
  - Using a boosted decision tree (BDT)

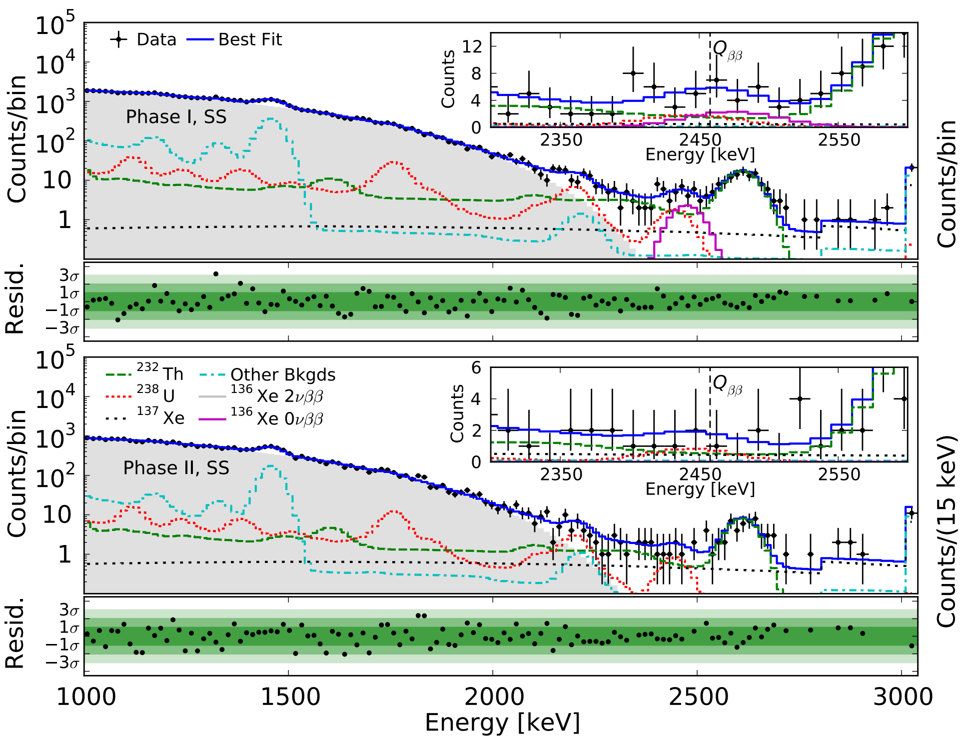


- Fitting 0νββ discriminators
  - Energy
  - SS/MS
  - *BDT → ~15% sensitivity improvement*



0νββ Search Results

- “Blind” analysis! (box opened on July 1st, 2017)
- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles



- Combined analysis:
  - Total exposure = 177.6 kg.yr

Sensitivity of 3.7×10^{25} yr (90% CL)

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

$\langle m_{\beta\beta}\rangle < 147 - 398$ meV (90% C.L.)

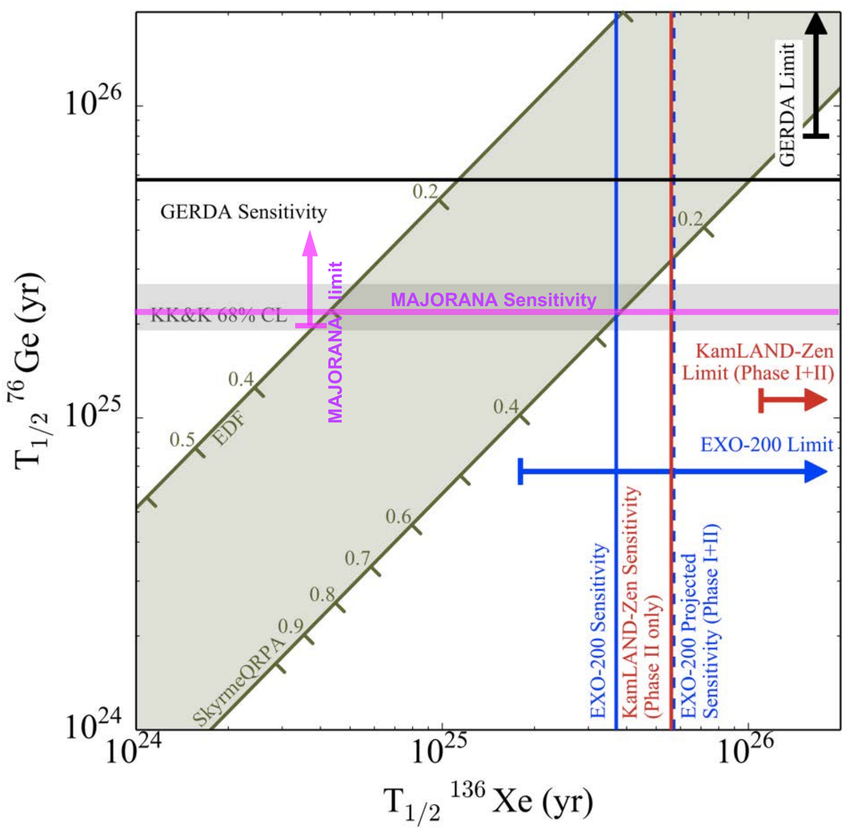
- Individual phase limits

	Livetime	Exposure	Limit (90% CL)
Phase-I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 1.0\text{x}10^{25}$ yr
Phase-II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 4.4\text{x}10^{25}$ yr

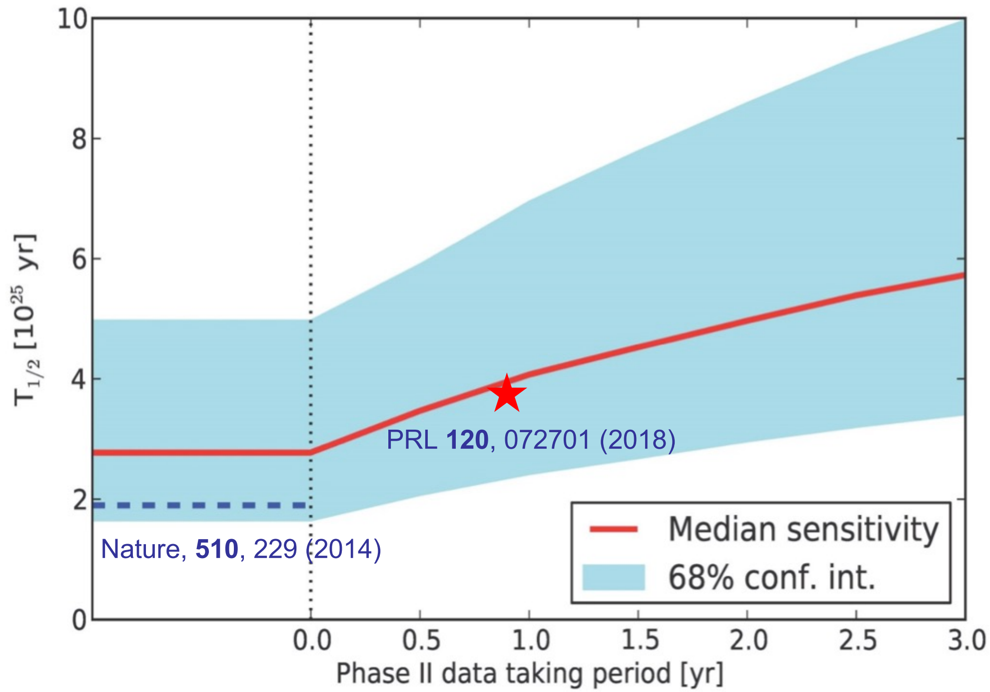
- No statistically significant excess: combined p-value ~1.5σ

Phys. Rev. Lett. **120**, 072701 (2018)

International Context and Outlook



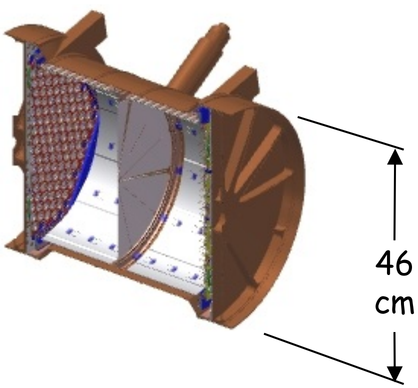
EXO-200 Sensitivity



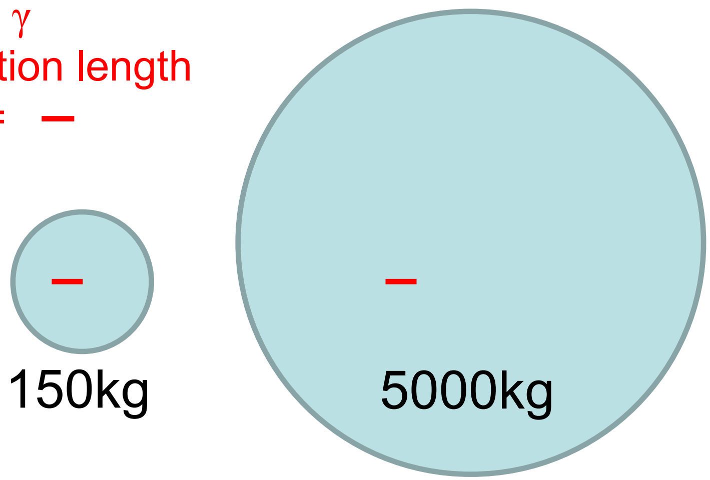
- EXO-200 remains as one of the most competitive experiments in the field.
- Sensitivity increased by a factor of 2 after 1 year of running, meeting the projected sensitivity.
- At the end of Phase-II running (2018), we expect to reach sensitivity > 5 x 10^{25} yr.

From EXO-200 to nEXO

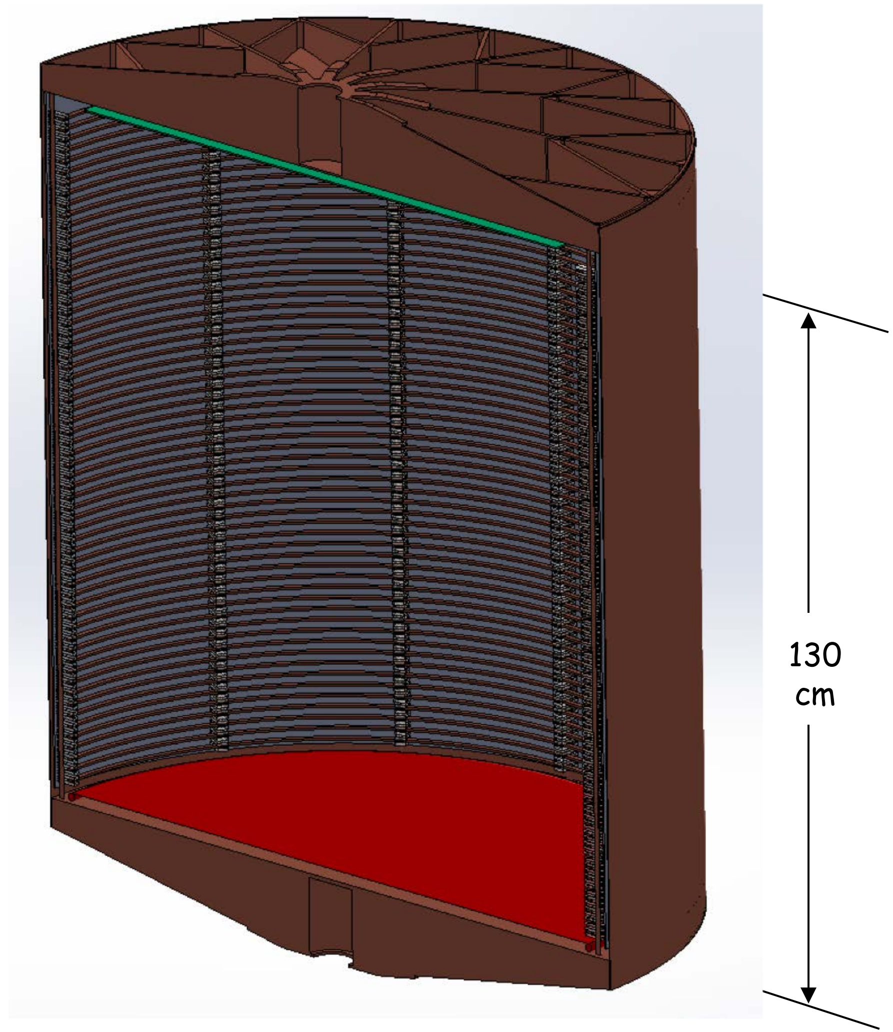
EXO-200 as a technology demonstrator



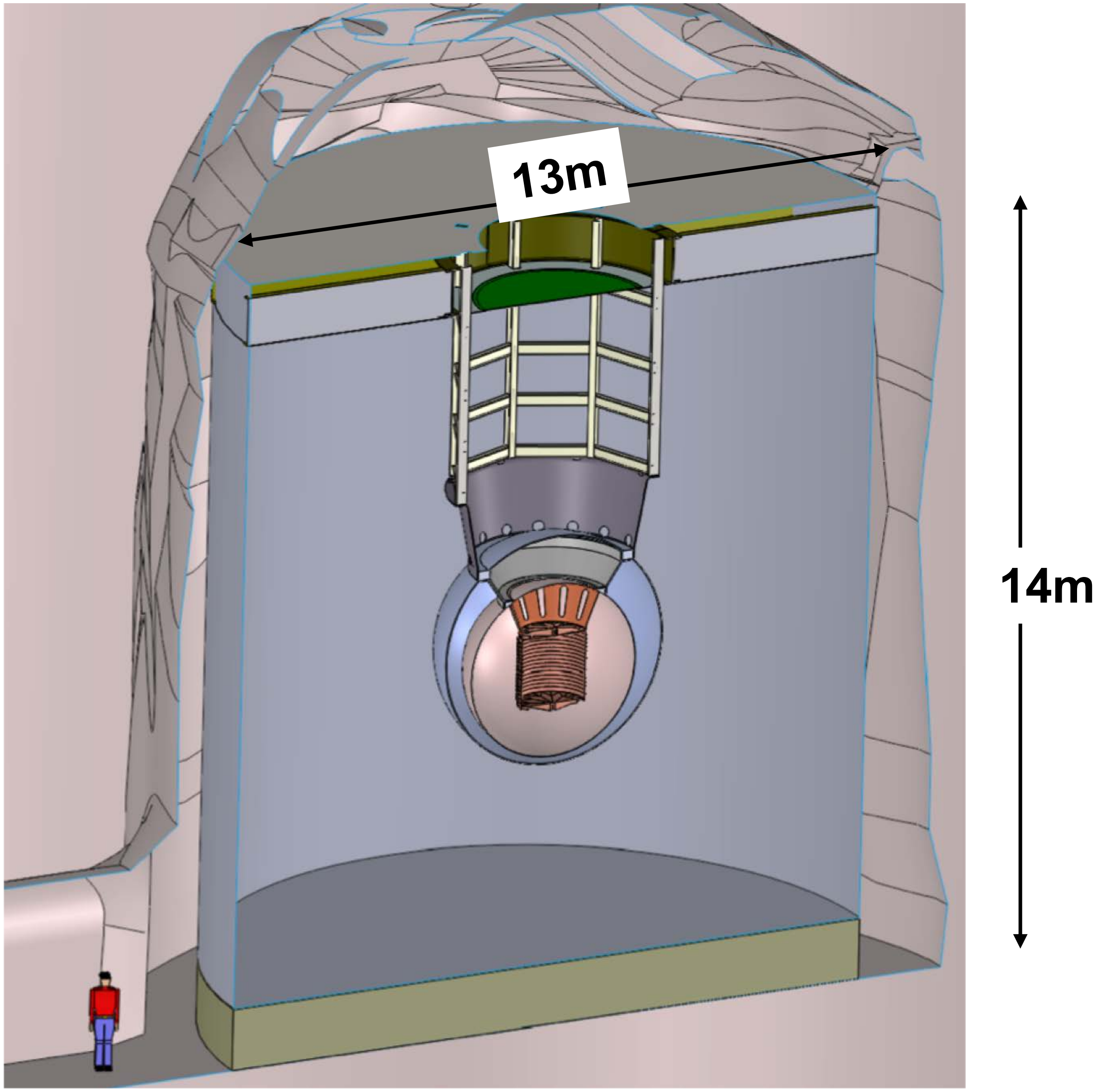
2.5MeV γ
attenuation length
8.5cm = –



nEXO: a 5000 kg enriched LXe TPC



Preliminary artist view of nEXO in the SNOlab Cryopit



6,000 m.w.e. depth sufficient to shield cosmogenic background.

Optimization from the EXO-200 to the nEXO scale

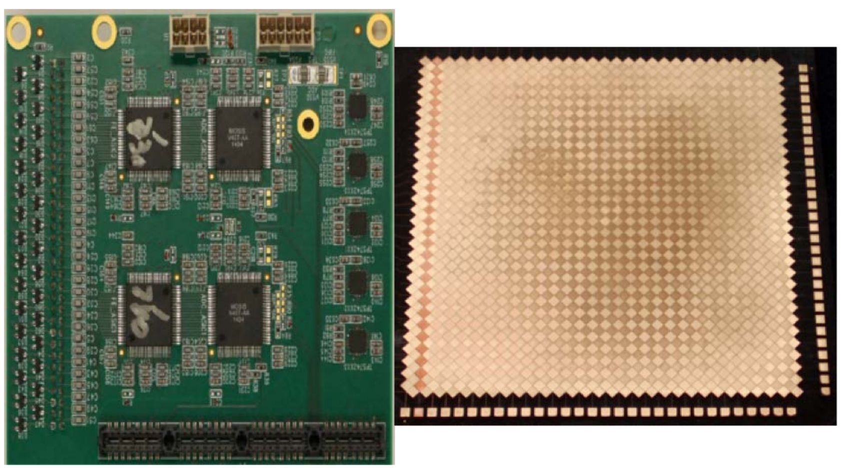
What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution
SiPM instead of APDs	Higher gain, lower bias, lower mass, E resolution
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

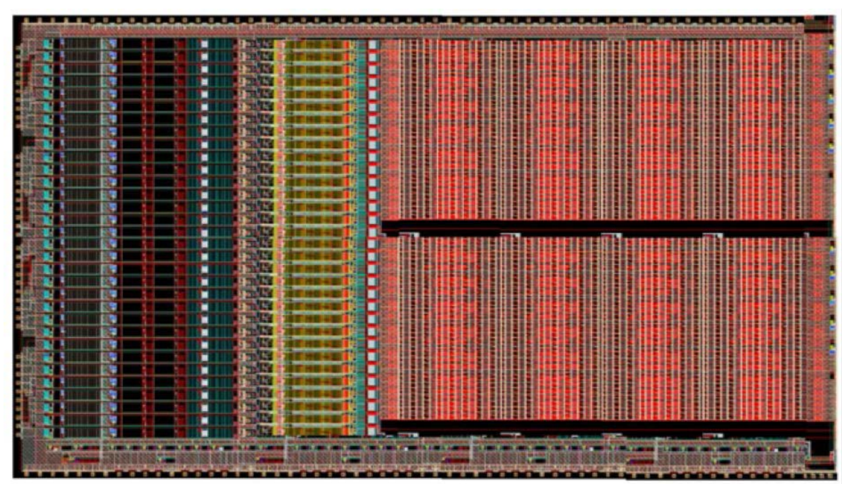
Cold Electronics Readout for nEXO

Low noise, low radioactive, in LXe readout, necessary to meet the detector performance and background goals. Main challenges will be low background interconnection and integration.

- Use cold ASICs developed for LAr TPC.
- Gradual progression towards low background material and construction.
- Prototype testing with nEXO charge readout tile

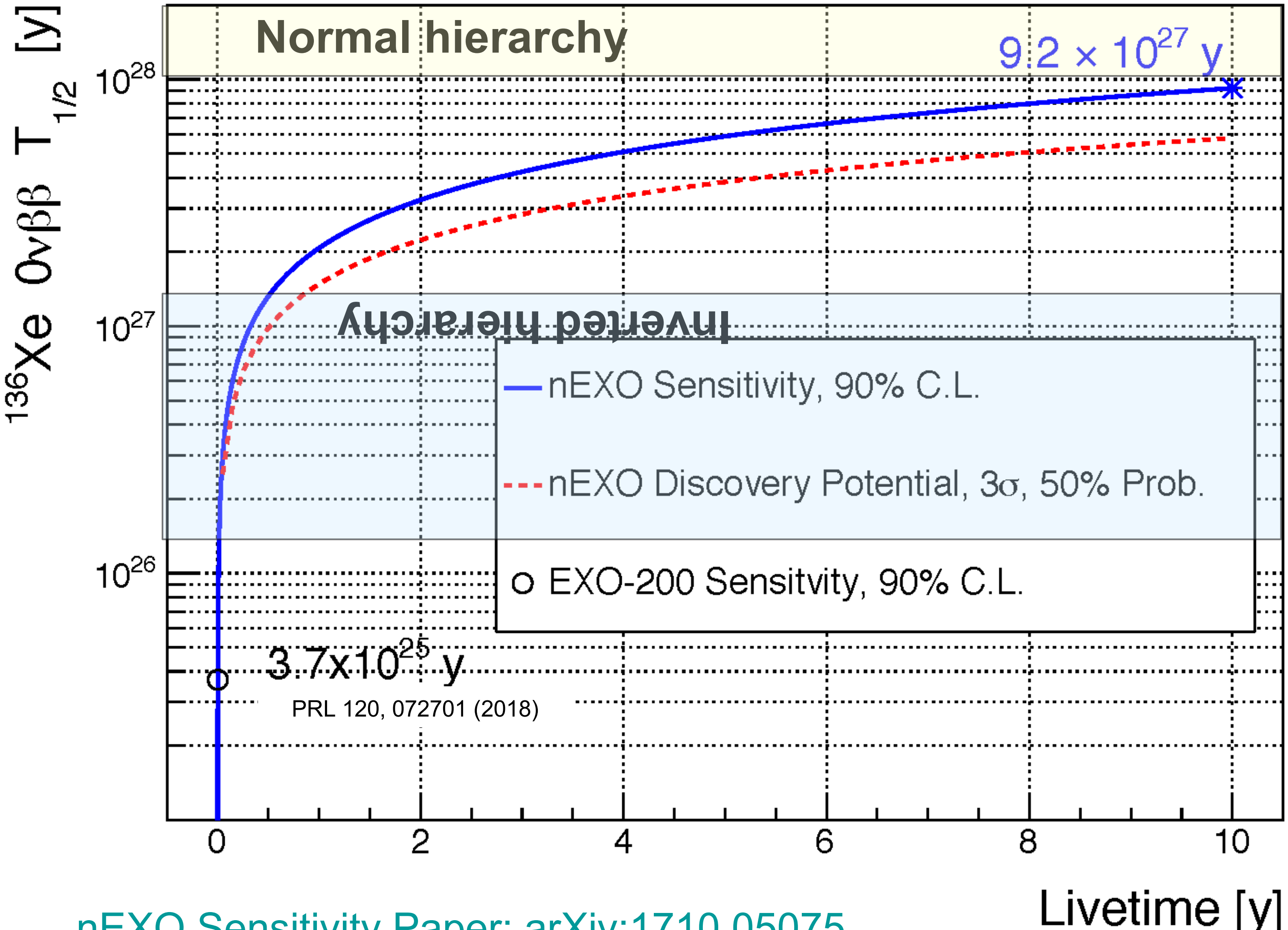
- nEXO custom charge readout ASIC, comprising all necessary functions (low nosie FE, anti-aliasing filer, ADC, buffer…)





nEXO Sensitivity

Sensitivity as a function of time for the best-case NME (GCM)



GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

nEXO Sensitivity Paper: arXiv:1710.05075

Conclusions

- EXO-200 has successfully upgraded its detector for the Phase-II running.
- After one year of Phase-II running, EXO-200 has reached ^{136}Xe $0\nu\beta\beta$ half life sensitivity of 3.7×10^{25} yrs.
- nEXO is a tonne-scale detector capable of exploring the inverted hierarchy region of the neutrino mass.
- nEXO's ongoing R&D program is aimed at enhancing the TPC performance.
- nEXO is ready to proceed to the tonne scale.