nEXO
Double Beta Decay

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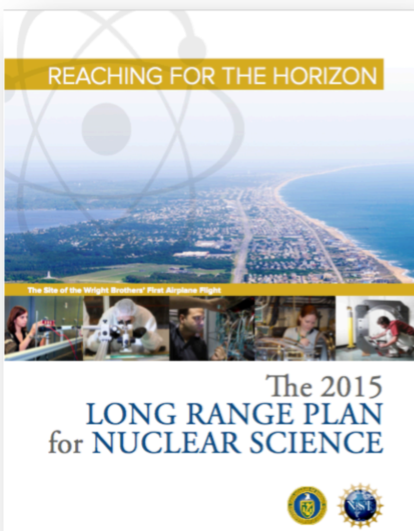
Enriched Xenon Observatory
EXO
for double beta decay

Neutrinos

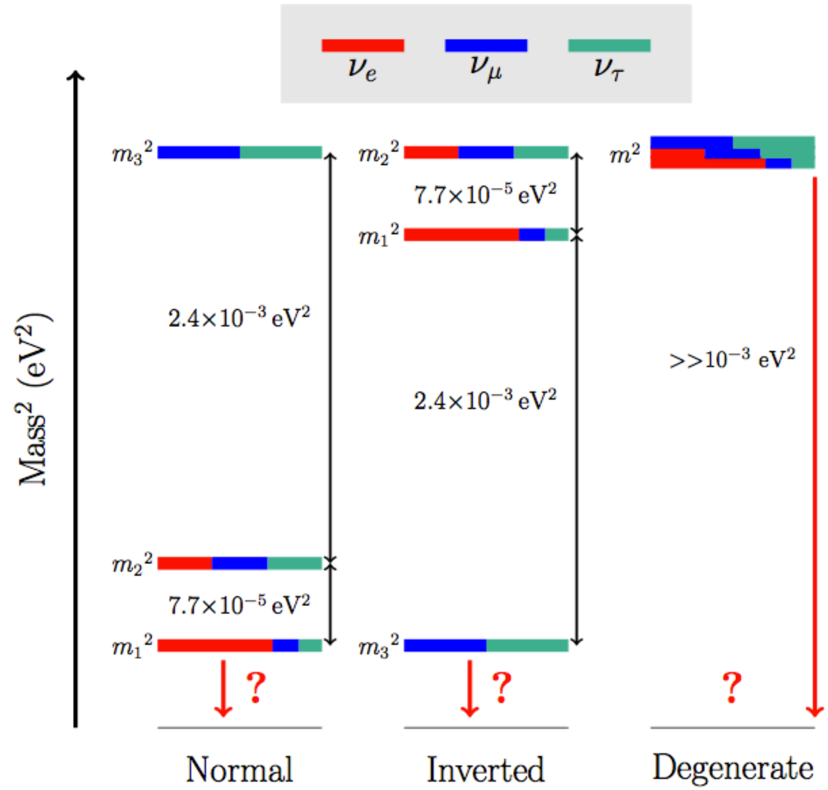
Neutrino oscillation experiments have demonstrated neutrinos have mass

- Matter/antimatter asymmetry and neutrino masses still a problem for SM
- Majorana neutrinos seem *likely* way to solve "neutrino problem" in SM



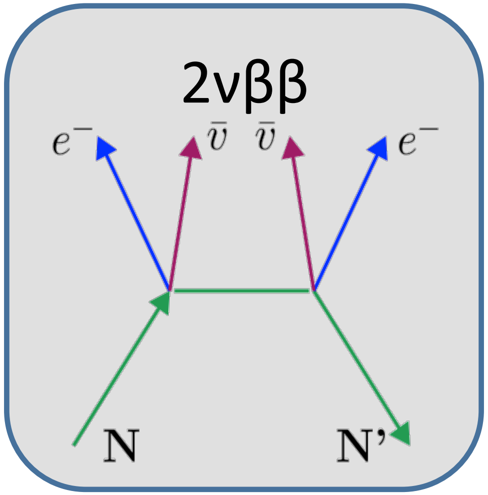
0νββ most sensitive probe for Majorana nature of neutrinos

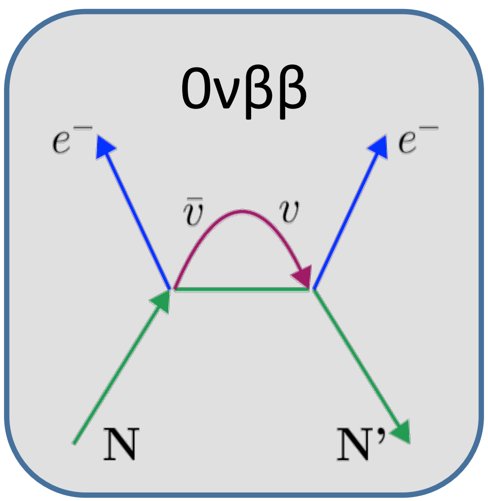
NSAC long range plan: US-led ton scale 0νββ experiment a priority



The current neutrino mass picture

Neutrinoless double beta decay





- 0νββ decays require
  - Majorana nature of neutrino
  - Lepton number violation
- The half-life of 0νββ can be used to determine neutrino mass:

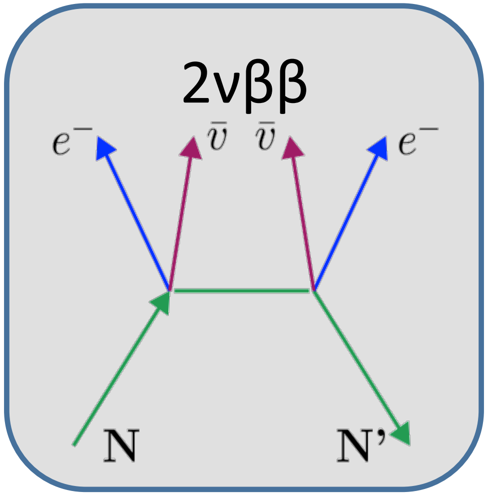
Measure — Known — Calculated (theory)

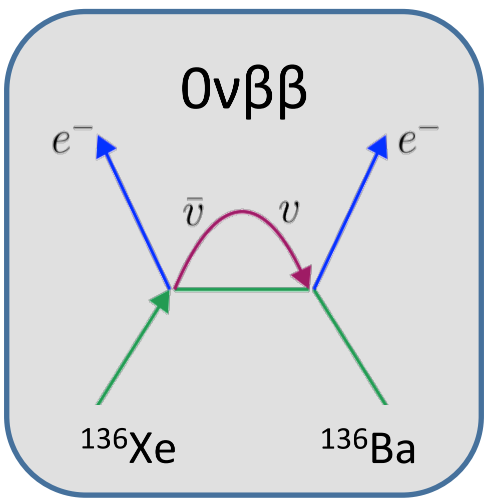
$$\langle m_\nu \rangle = \left(T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1/2}$$

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{\alpha i} \right|^2 m_i$$

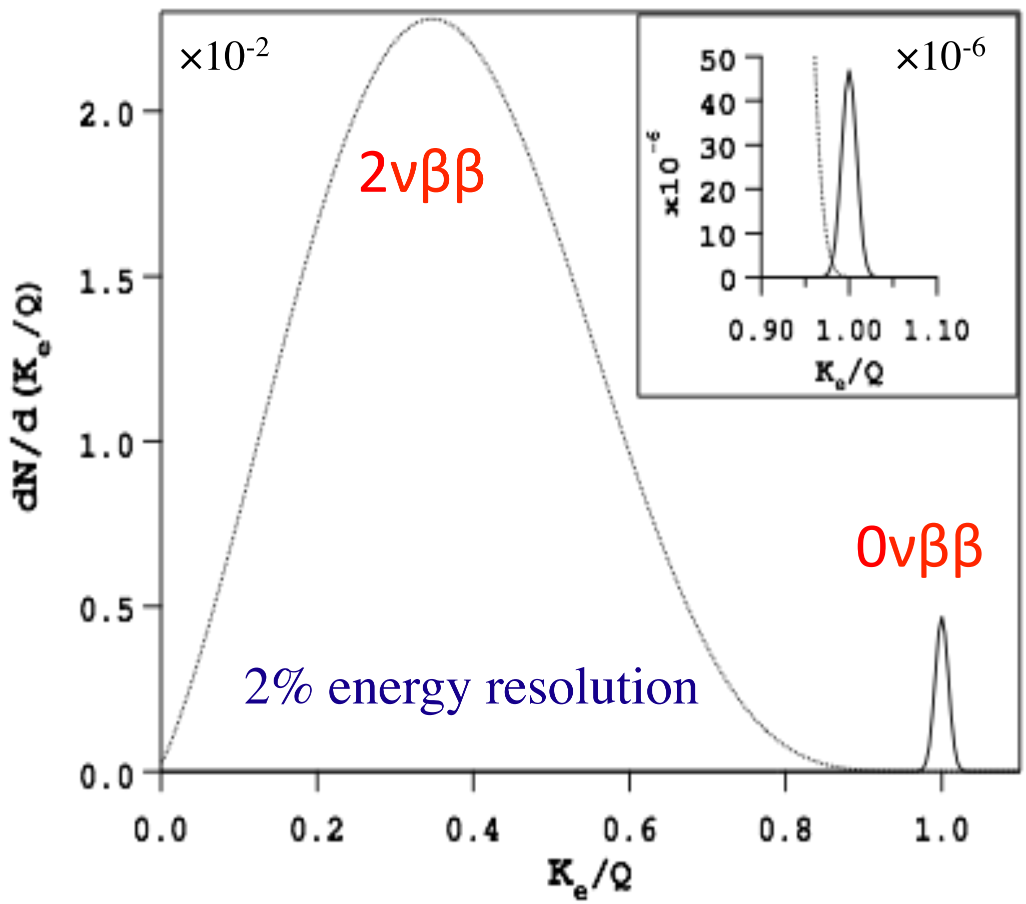
$$mass \propto \frac{1}{\sqrt{T_{1/2}^{0\nu\beta\beta}}}$$

Neutrinoless double beta decay



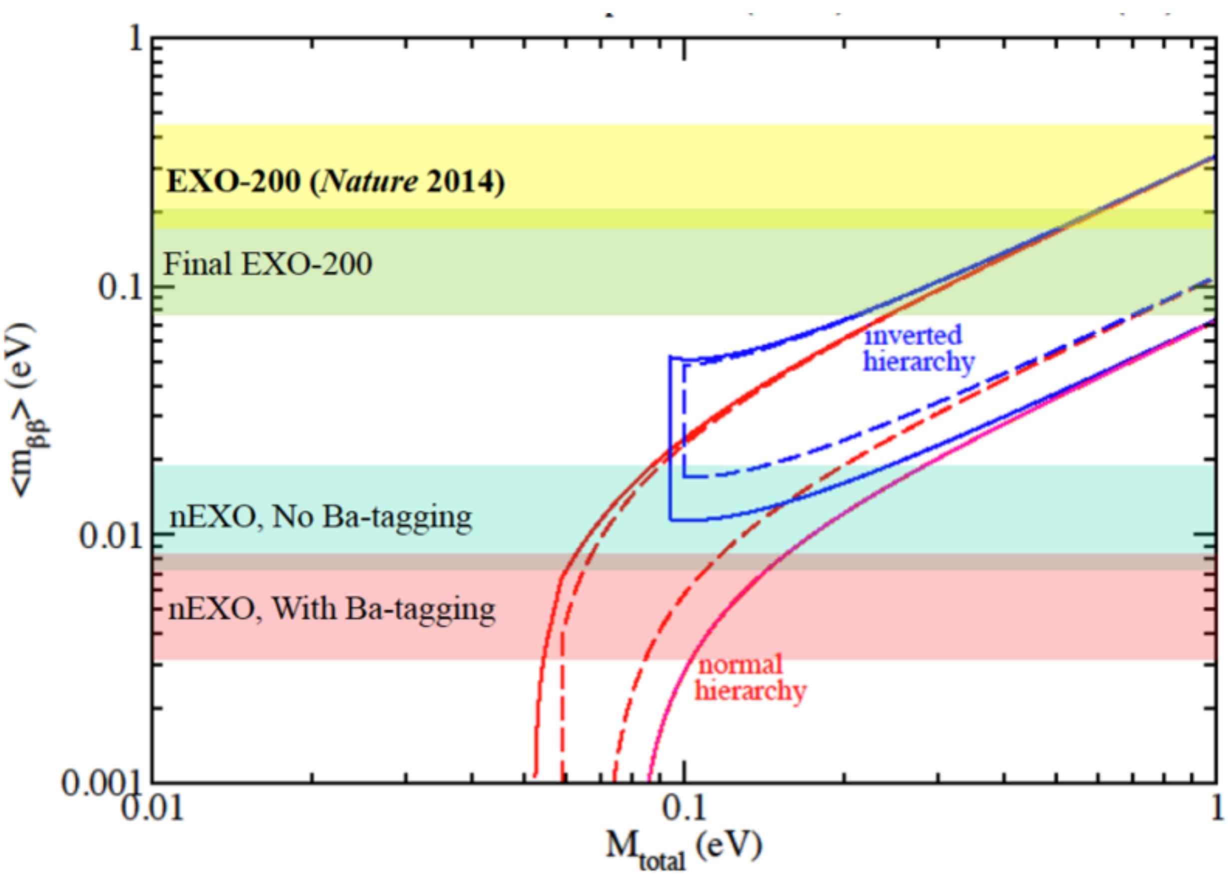


[P. Vogel, arXiv:hep-ph/0611243]

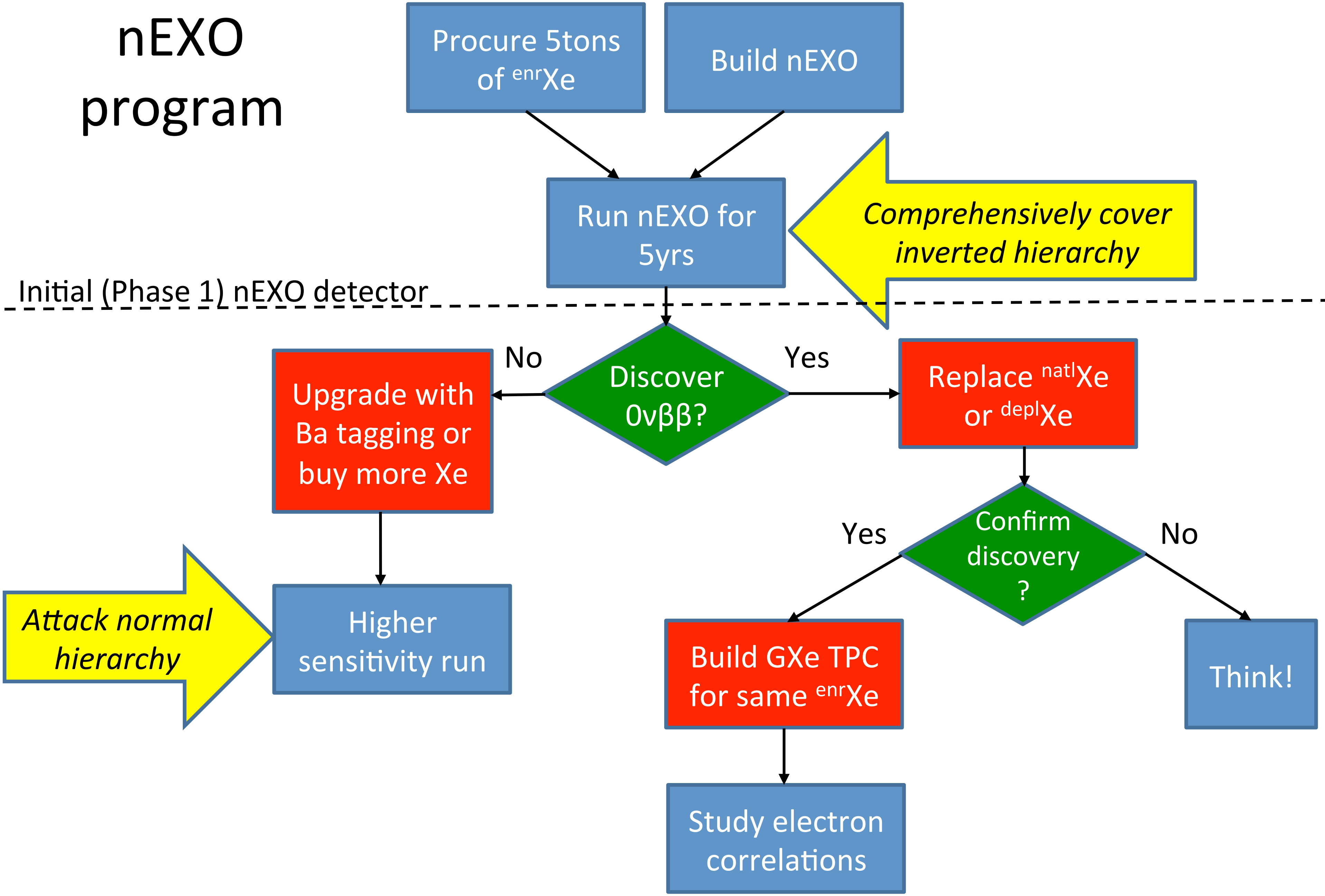


$^{136}Xe\ Q_{\beta\beta} = 2457$ keV

EXO-200 & nEXO projected sensitivities

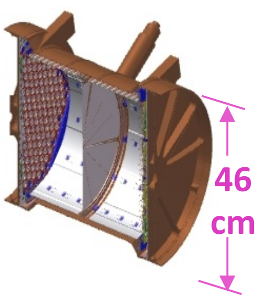


nEXO program



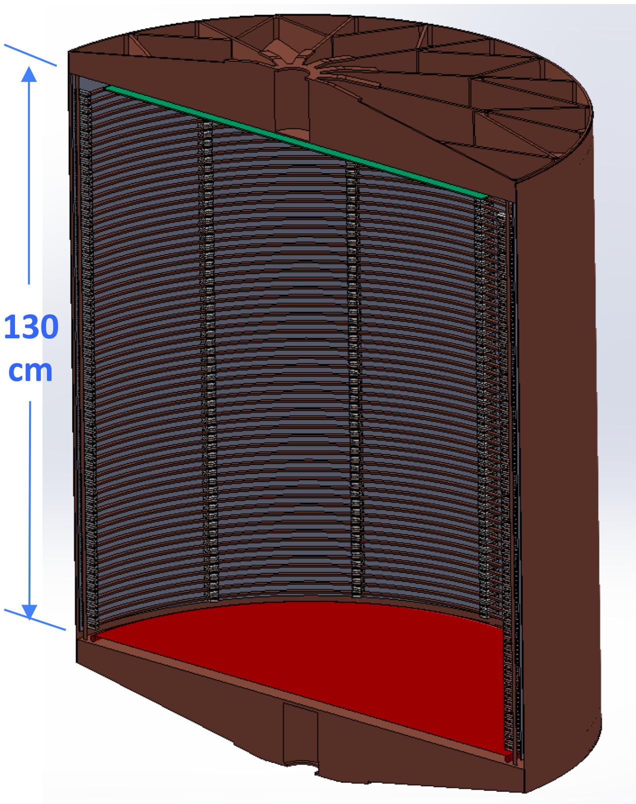
nEXO – 5 ton detector

EXO-200

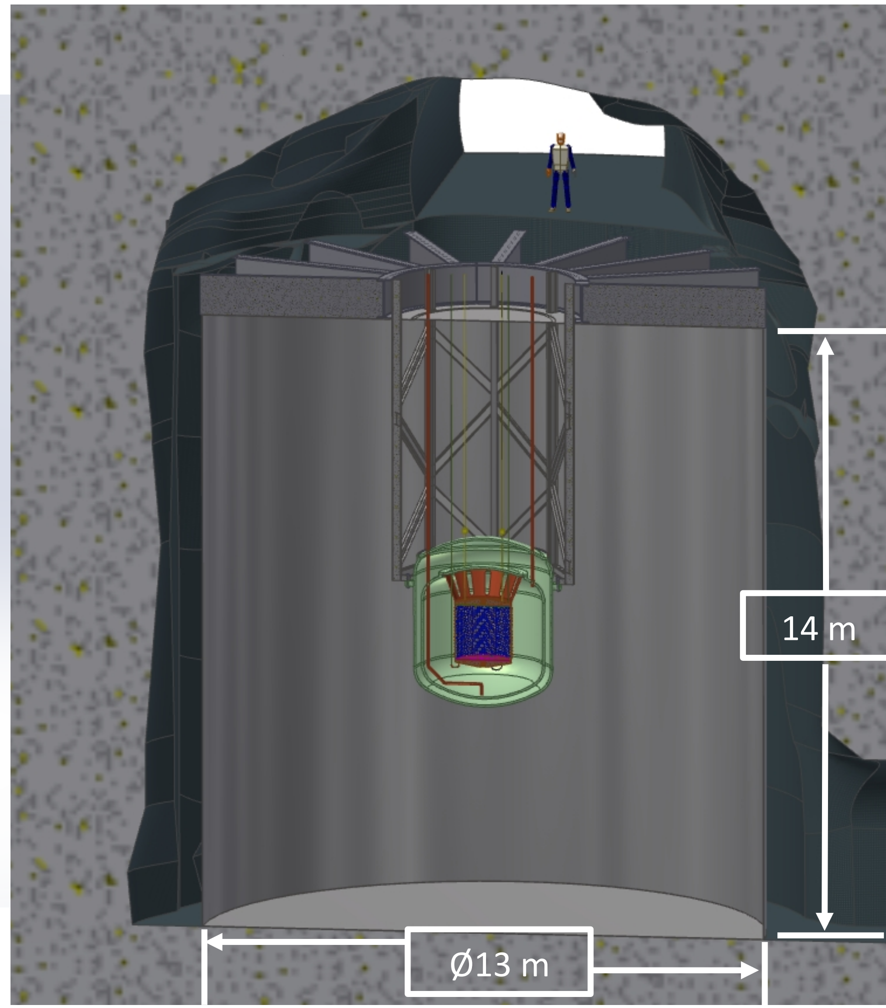


~110 kg

nEXO



~4780 kg



Building on EXO-200 successes

- EXO-200 started taking data in May 2011
  - "Observation of Two-Neutrino Double-Beta Decay in 136Xe ...", PRL (2011)
  - "Search for Neutrinoless Double-Beta Decay in 136Xe with EXO-200", PRL (2012)
  - "An improved measurement of the 2νββ half-life of Xe-136 with EXO-200", PRC (2013)
  - "Search for Majorana neutrinos with the first two years of EXO-200...", Nature (2014)
- EXO-200 demonstrated the power of the combination of *ionization density*, energy resolution, event multiplicity, and event location
- EXO-200 validated the choice of material and the model that was used to predict the detector background

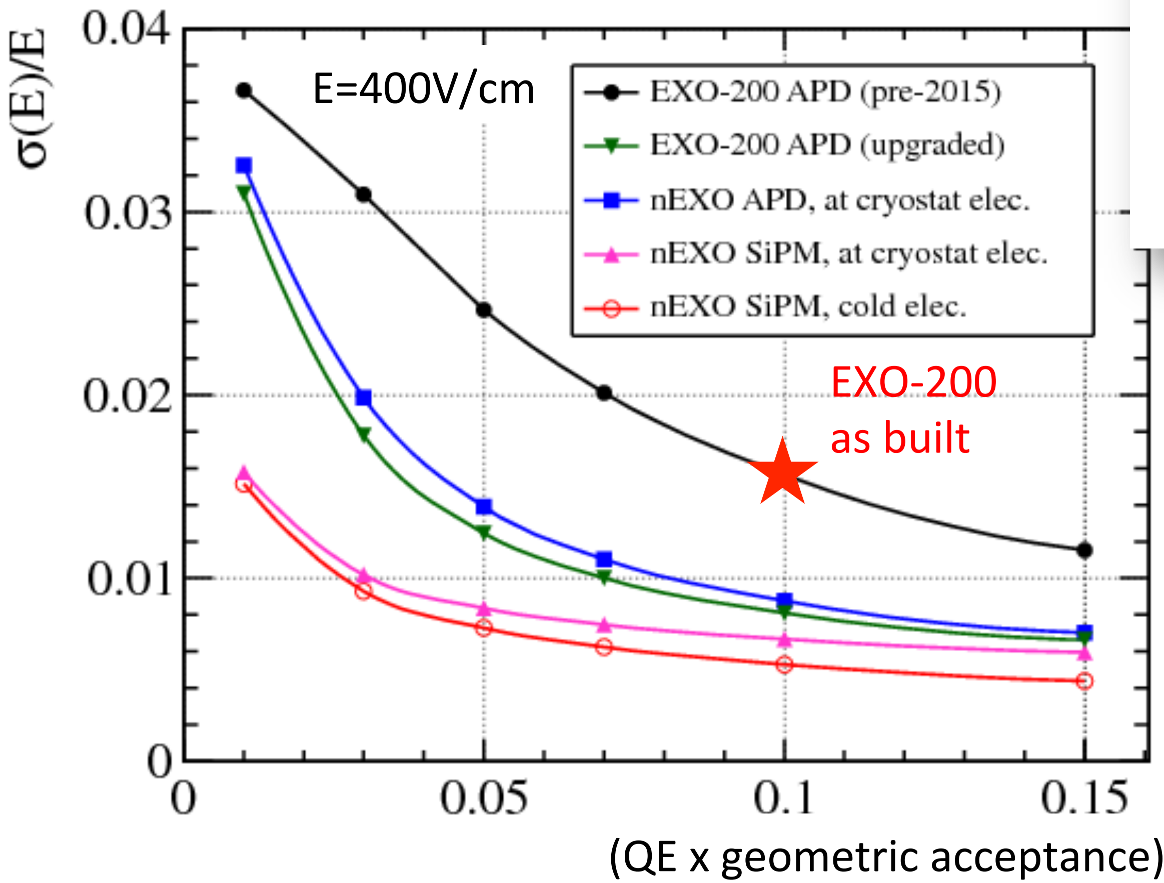
Events in ±2σ around Q	Radioactive bkgd prediction during construction	Radioactive bkgd prediction using present Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit
90%CL Upper	48	22	7	31.1 ± 1.8 ± 3.3 (39 events observed)
90%CL Lower	9.4	3.3		

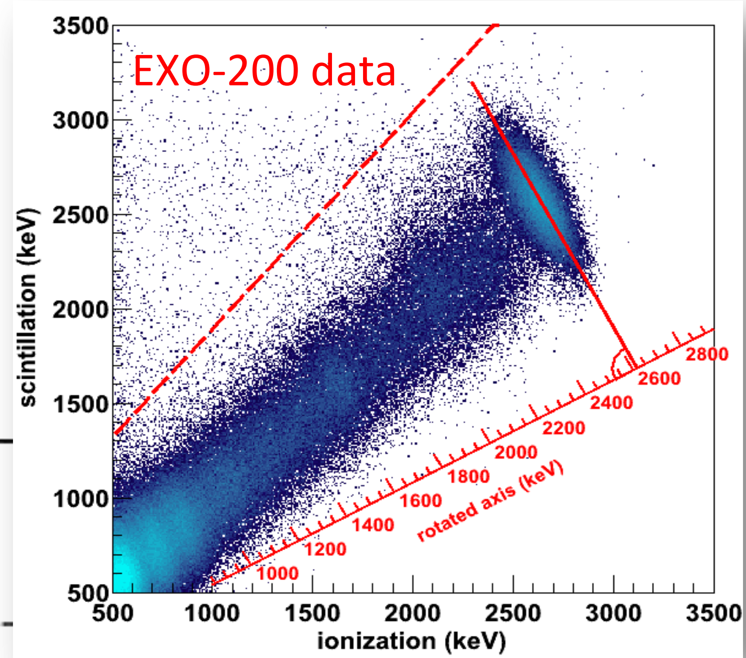
Optimization from EXO-200 to the nEXO scale

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, lighter, 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

Energy resolution

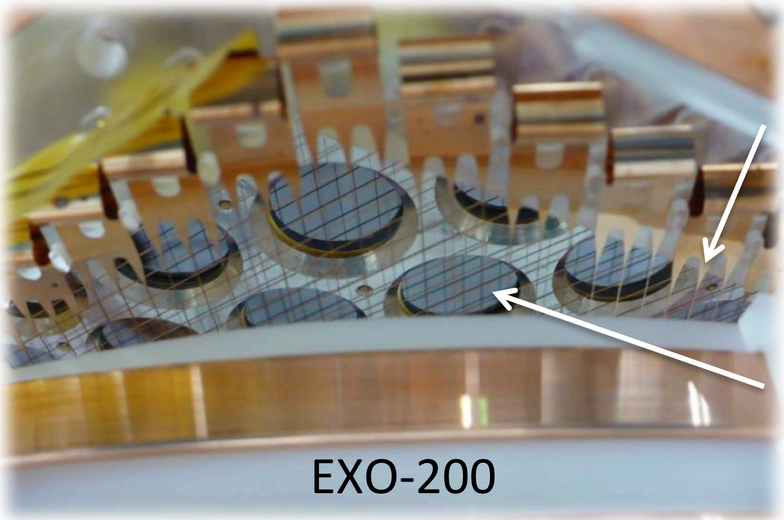
Good energy resolution requires efficient readout of the scintillation and ionization signal

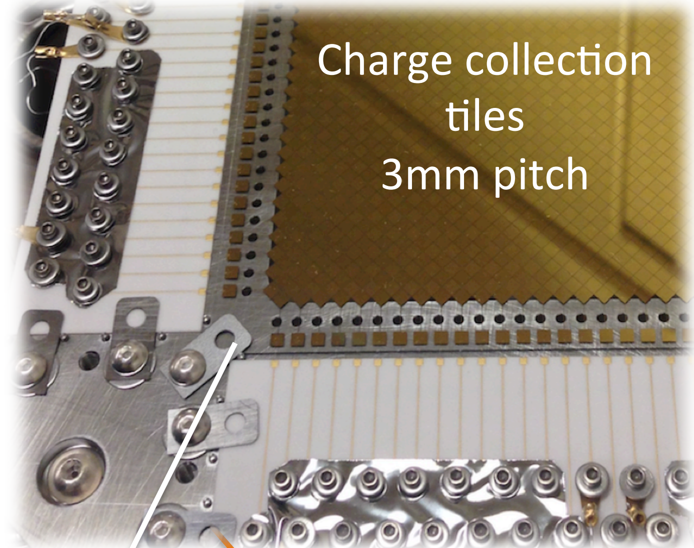


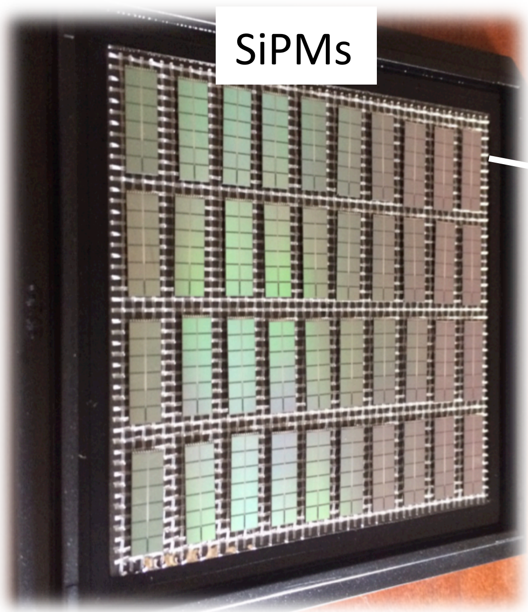


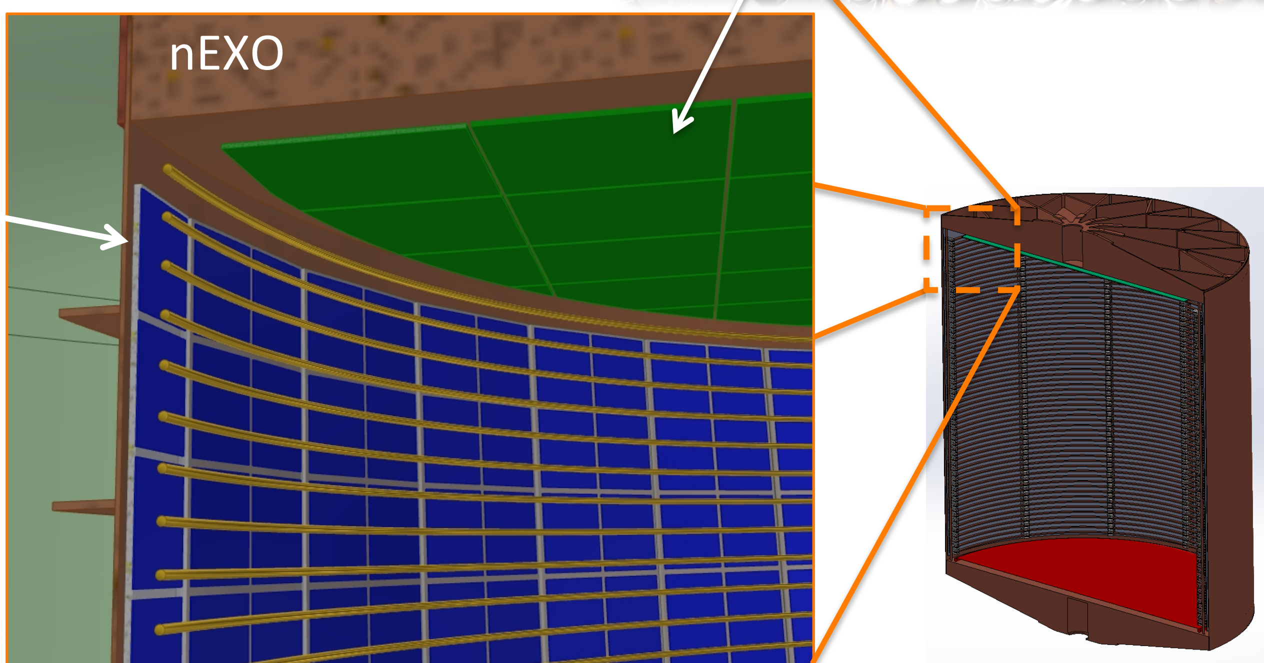
While we always assume 1% resolution for nEXO, a figure close to 0.5% is not out of the question

Energy Resolution: scintillation and charge collection R&D







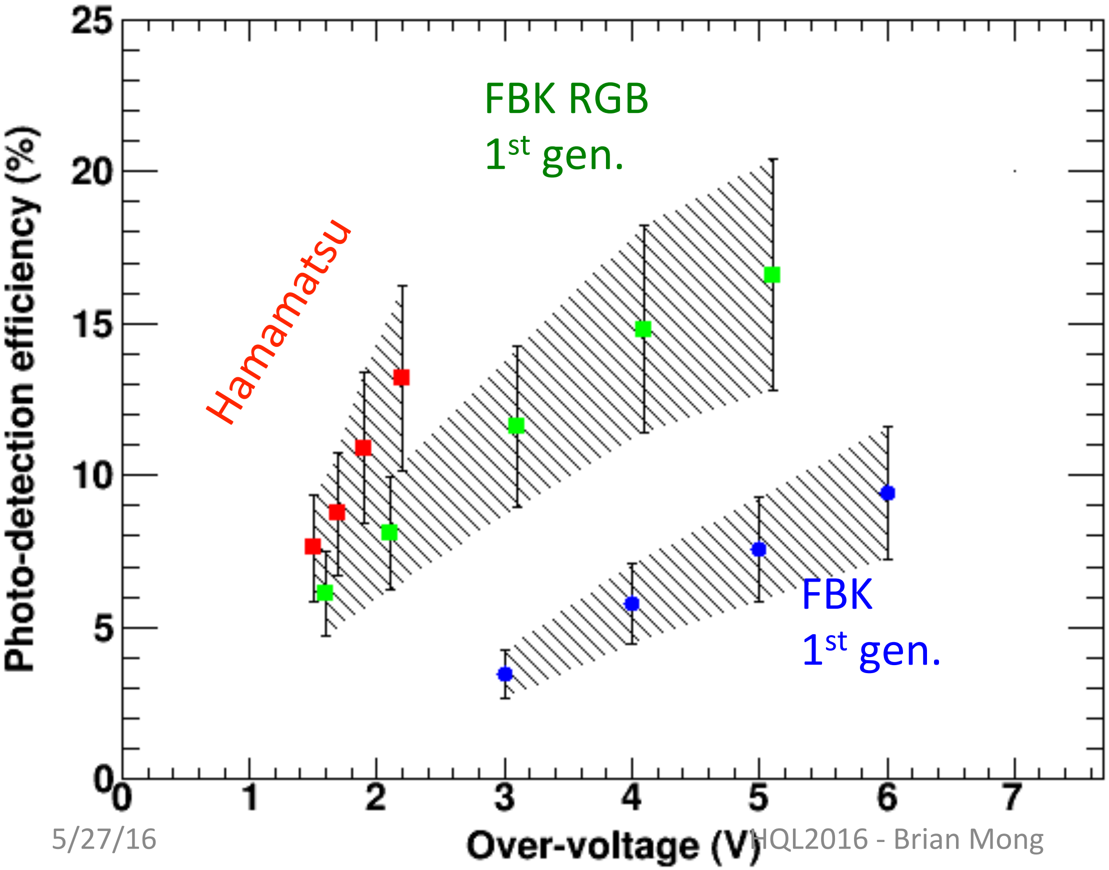


Energy Resolution: SiPM Photodetectors

Hamamatsu produces devices with QE= ~12% @ 175nm but until now they have refused to sell them un-encapsulated (hence are too radioactive)

First nEXO-specific run at FBK (Italy) provided ~10% QE
New “RGB” devices reach 15% QE with 7.7x7.7mm^2.

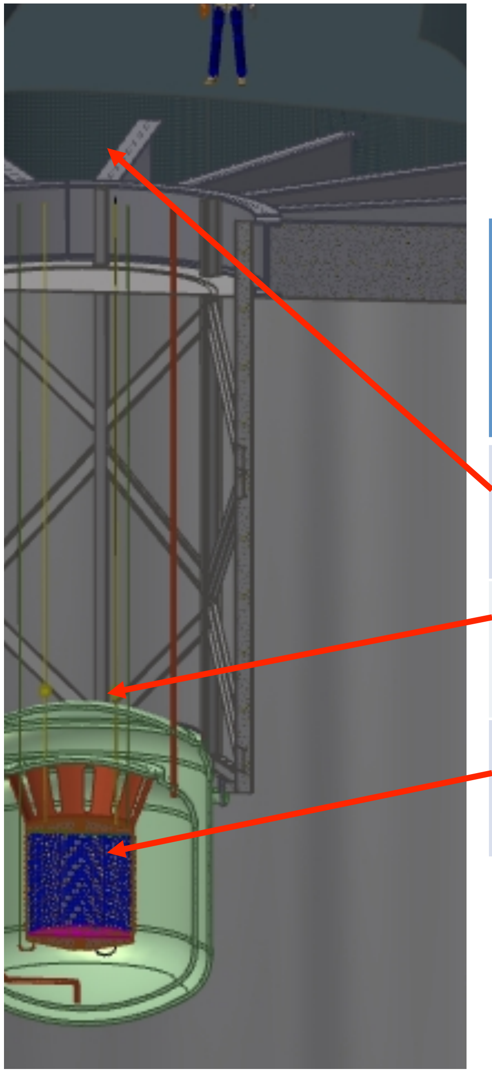
[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1.]
DOI:10.1109/TNS.2015.2453932



A new run at FBK will use a new technology (NUV-HD) with the promise to reach QE>15% @170nm, lower dark noise and crosstalk with 1x1cm^2 devices.

FBK devices are almost low activity enough
(a Th anomaly needs to be investigated)

Energy resolution: cold electronics



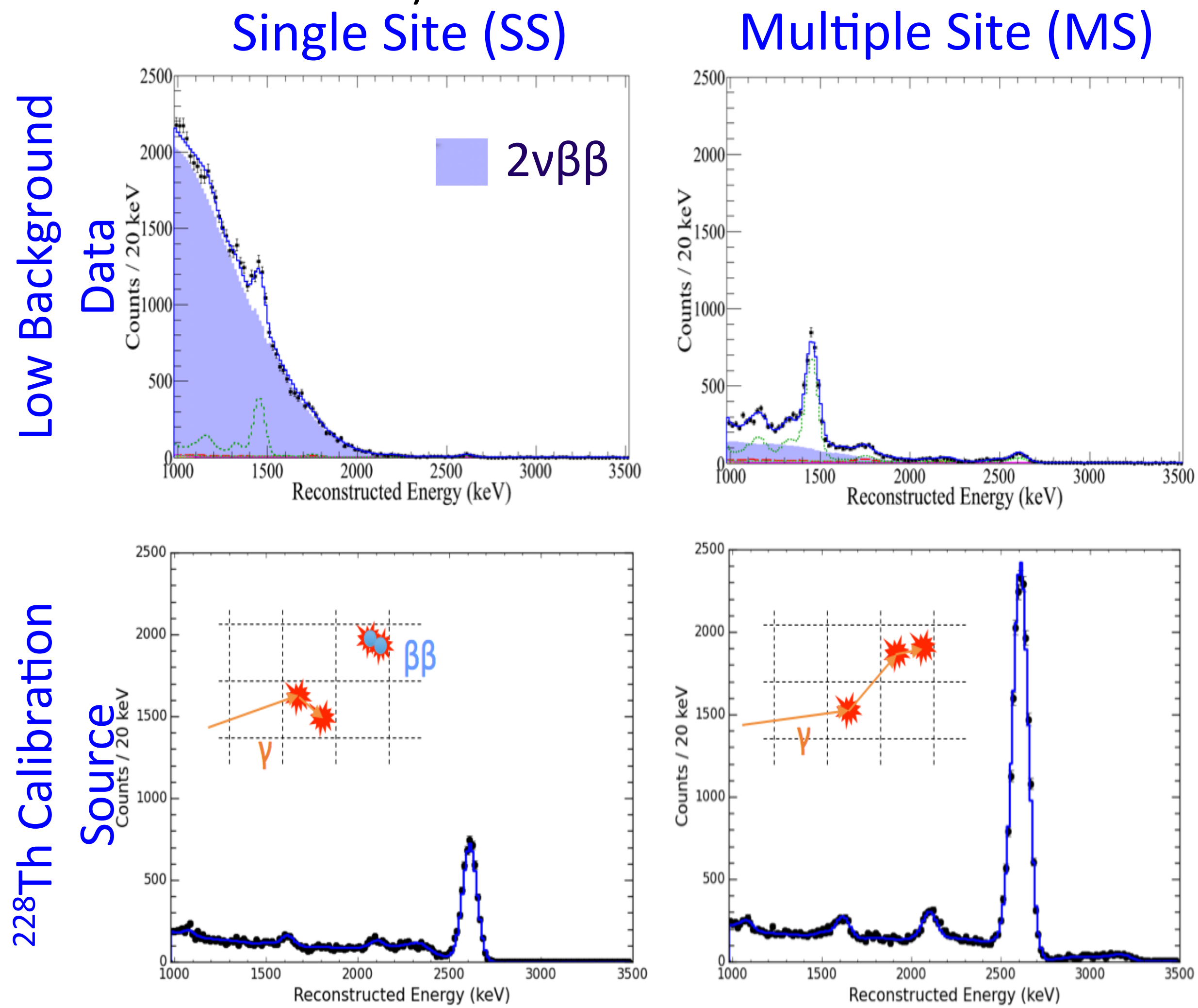
Comparison for noise and threshold between front-end locations for the charge channel

Location	Cable length (m)	Total cap (pF)	Intrinsic RMS Noise (e)	RMS contribution to charge energy resolution	Charge cluster threshold (keV)
In lab (warm)	8	800	3200	2.5%	600 keV
At cryostat (warm/cold)	2	200	800	0.6%	150 keV
Inside TPC (cold)	~0	<40	<200	0.2%	40 keV

Assumes simple tile charge collection system with interleaved strips and EXO-200 style cables for the remote location cases

Event multiplicity and background discrimination

(example from EXO-200 data)

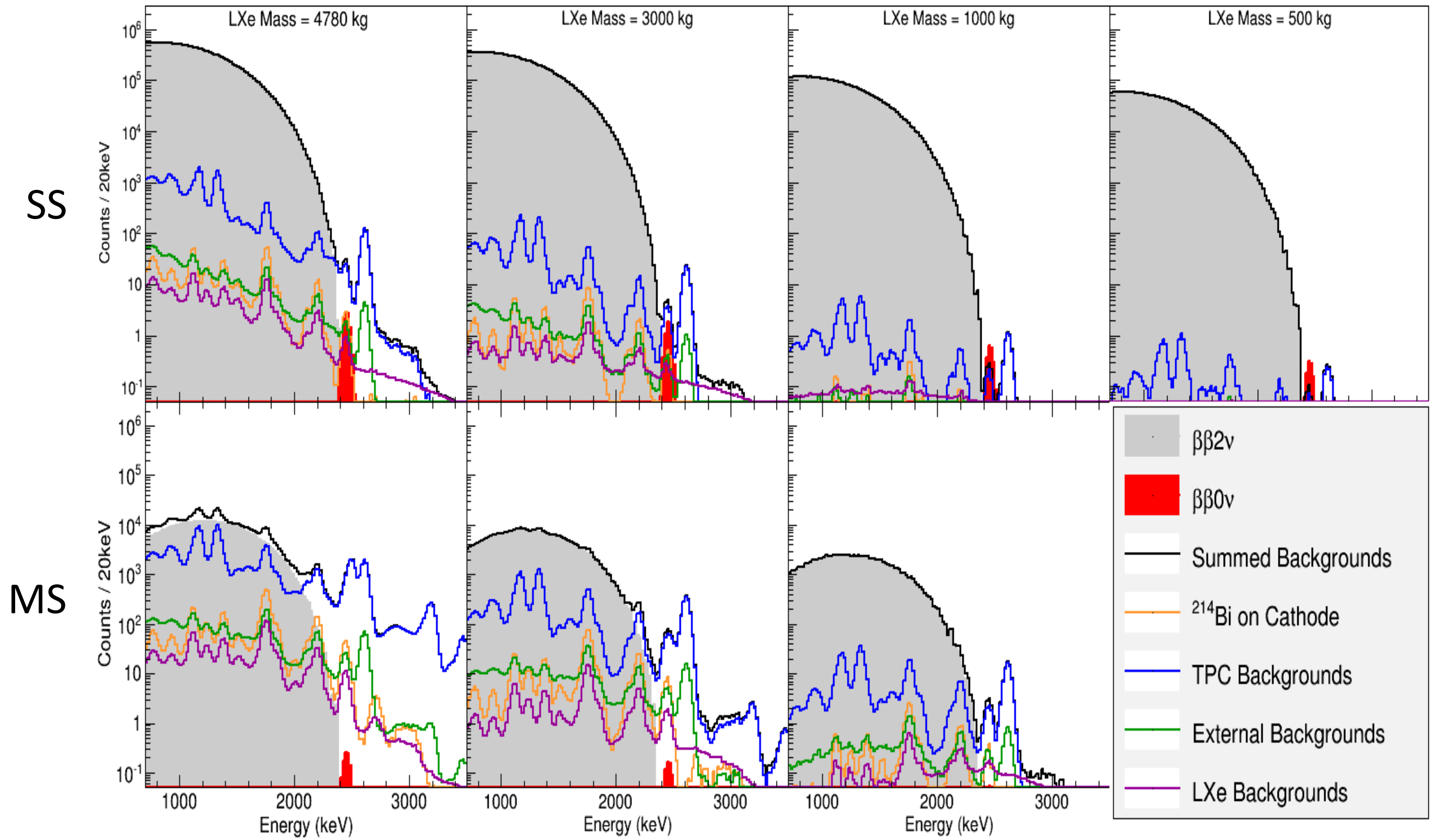


Improving charge threshold (near/cold electronics) and decreasing wire pitch (pads) will improve this discriminator

Event location: background identification and suppression

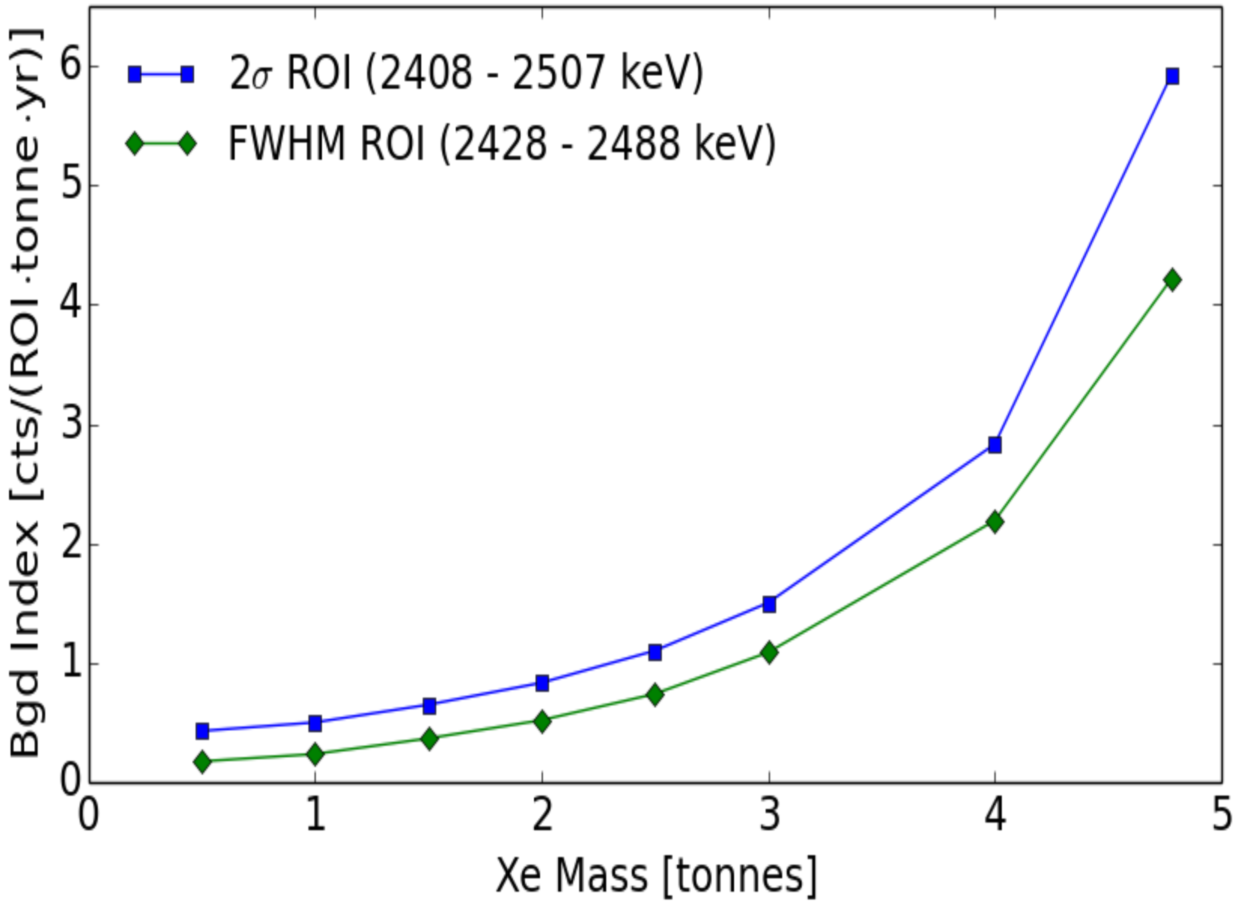
Example: nEXO, 5 yr data, 0νββ @ $T_{1/2}$=6.6x10^{27} yr, projected backgrounds from subsets of the total volume

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



The fit uses standoff distance information in the optimal way

Event location: background index



While nEXO background index by itself is very good…
the fit optimally uses the background vs standoff distance

EXO copper

R&D on (and later qualification of) low background materials is in full swing for nEXO.

A note on the copper that is the dominant background from the TPC vessel:

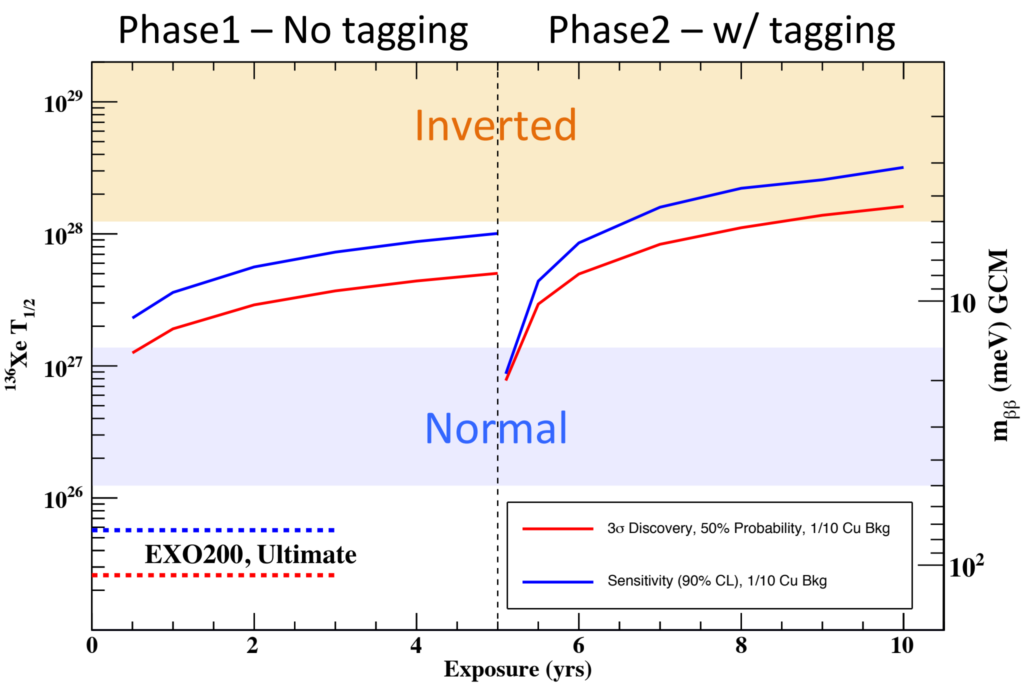
	~U, Th (ppt)
EXO-200 ICPMS measurement (Aurubis copper)	< 6, <14
EXO-200 measurement (Aurubis process)	< 4
nEXO measurement of Aurubis copper	< 1
PNNL measurement of electroformed Cu	~ 0.01

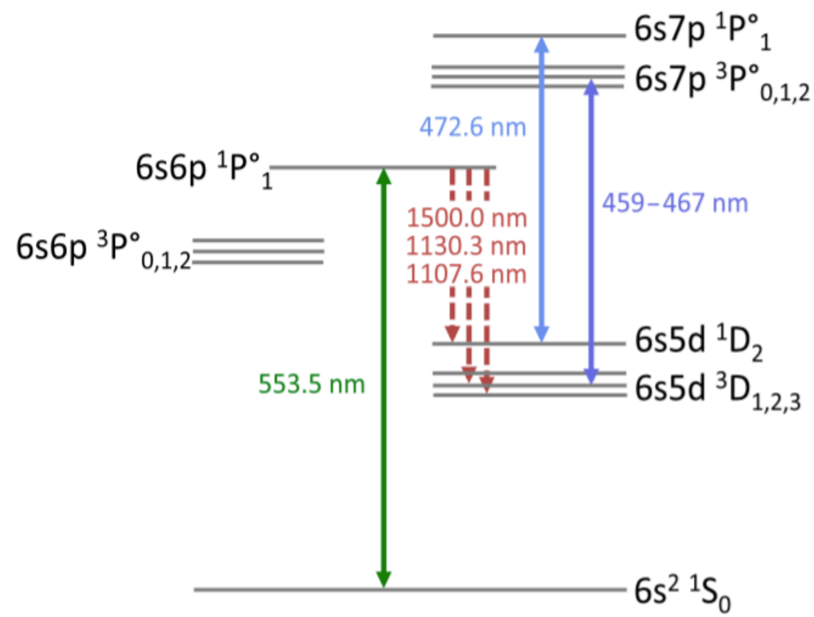
Study in progress of the Aurubis process seems to indicate that 0.1 ppt may very well be already achieved.

Barium tagging

$$^{136}Xe \longrightarrow {}^{136}Ba^{++} + 2e^{-}$$

Barium Tagging: identify barium daughter at 0νββ decay site for complete background elimination



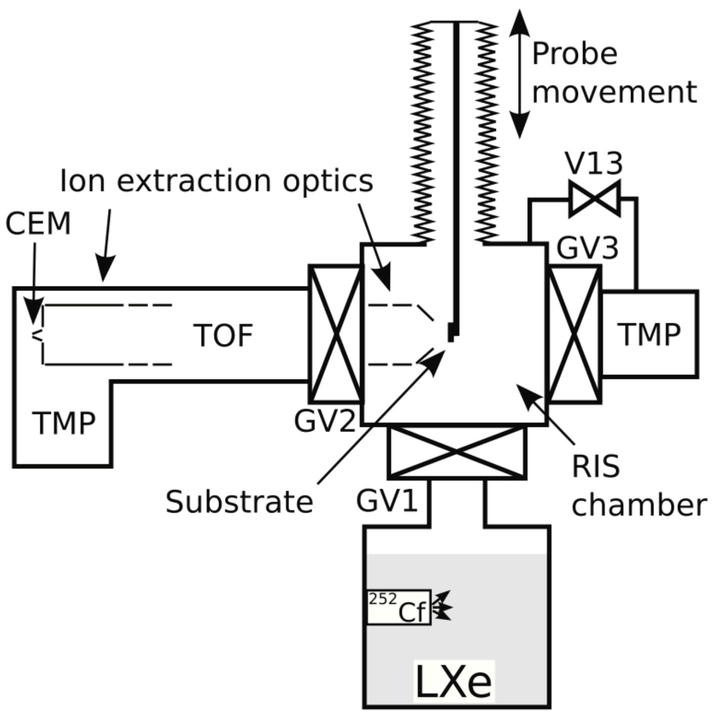


Positive identification of Ba made via atomic transitions

nEXO Ba tagging R&D

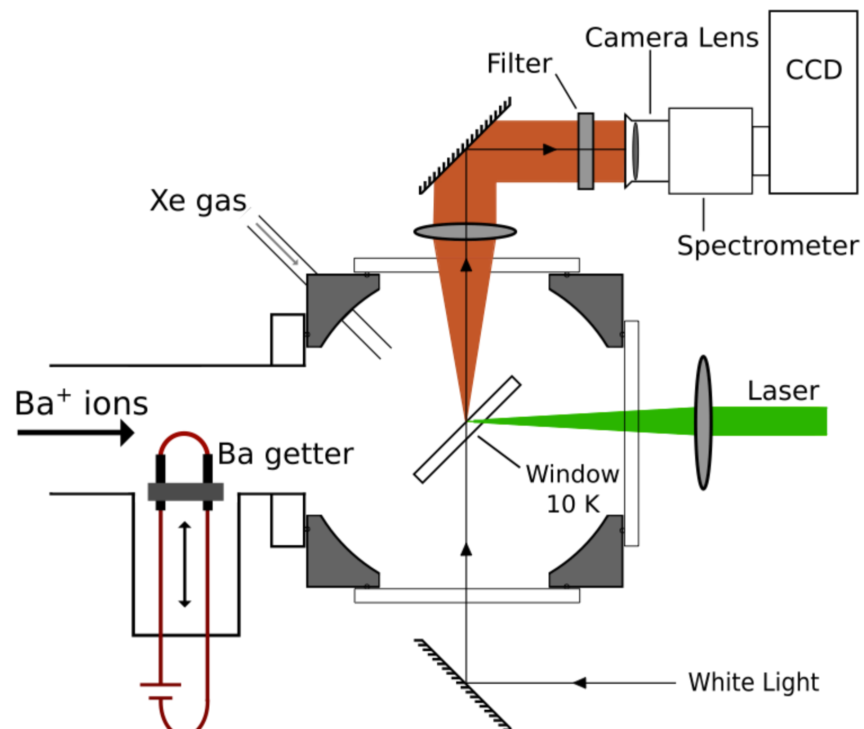
- Trigger on ionization/scintillation
- In real time estimate if 0ν candidate
- Insert probe and electrostatically attract Ba-ion (plate or freeze it)
- Several tagging methods being explored (two of which are):

Remove → desorb → RIS → CEM



K. Twelker et al. Rev Sci Inst 85 (2014) 095114

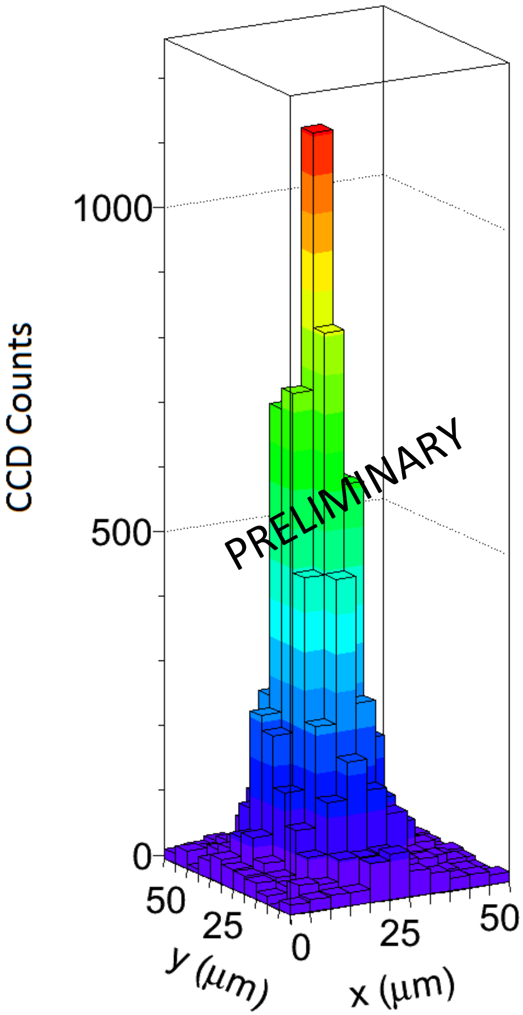
Spectroscopy in SXe matrix

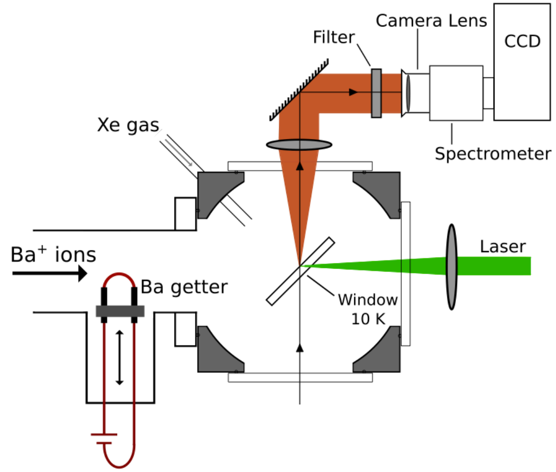


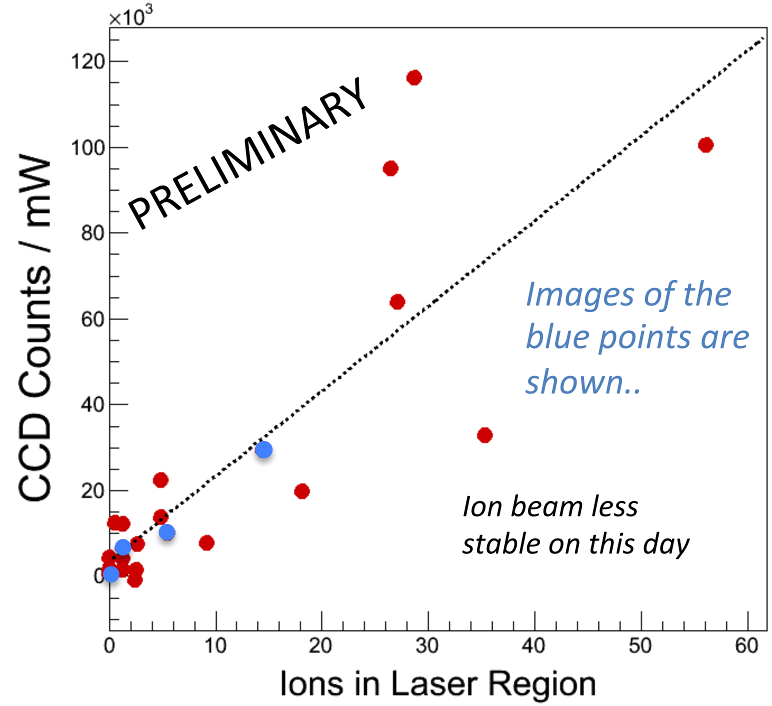
B. Mong et al. Phys Rev A 91 (2015) 022505

Ba Tagging: Identifying atoms in solid xenon

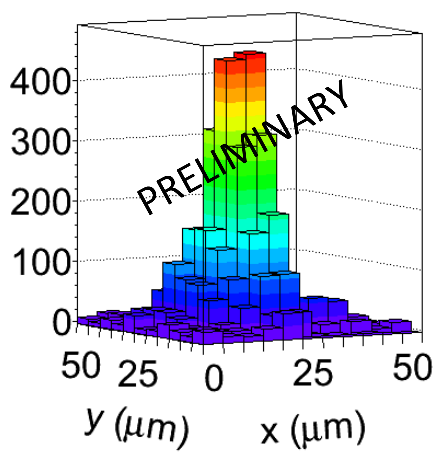
≤ 27 atoms



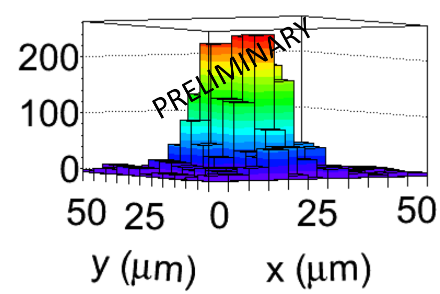




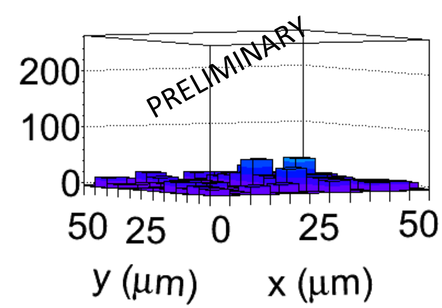
≤ 9 atoms



≤ 3 atoms

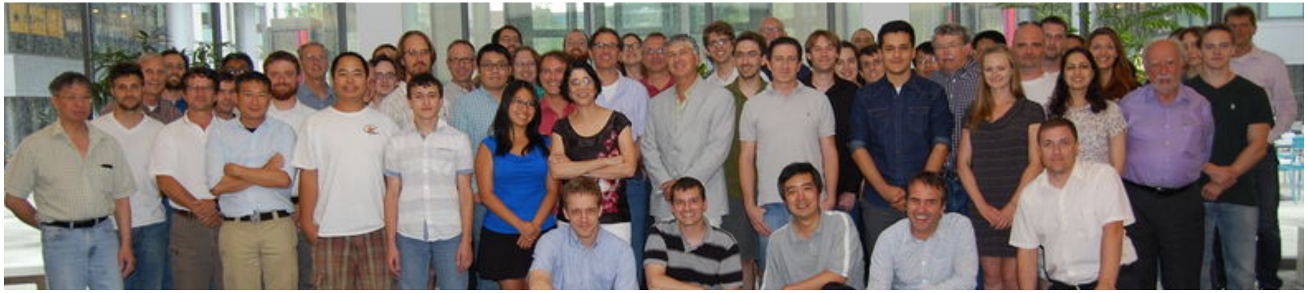


0 atoms



Summary

- nEXO is a 5-ton LXe 0νββ experiment that will cover the inverted mass hierarchy
- nEXO is a very flexible and cost effective detector with a clear upgrade path to address possible future science scenarios making the best use of the enriched isotope
- The multi-parameter approach tested in EXO-200 will be even more powerful in the larger nEXO detector
  ionization density ✗ energy resolution ✗ multiplicity ✗ event location
- A large number of R&D projects are currently underway to verify scale up is feasible



The nEXO Collaboration

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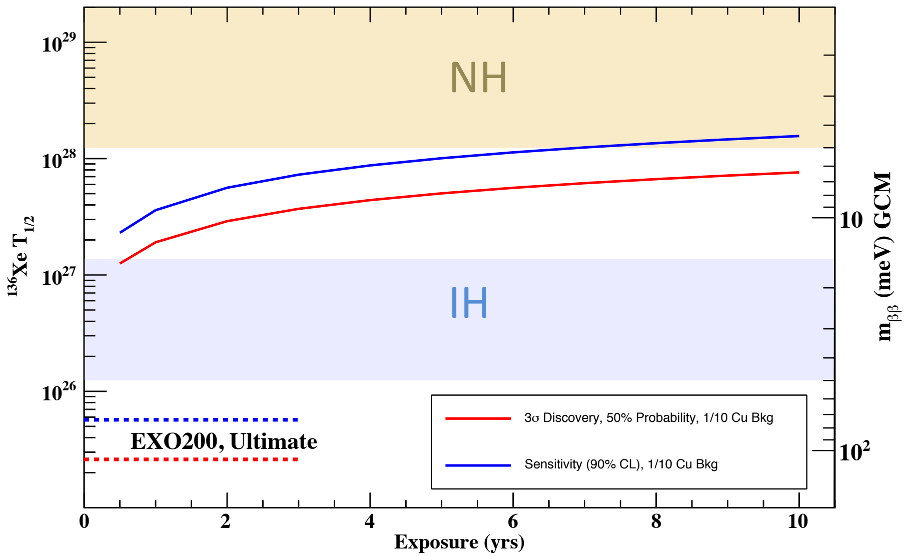
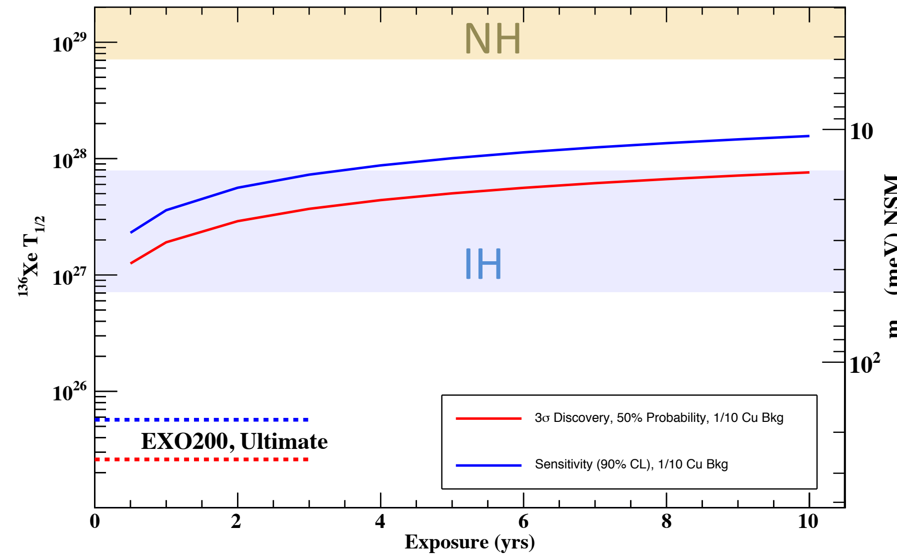
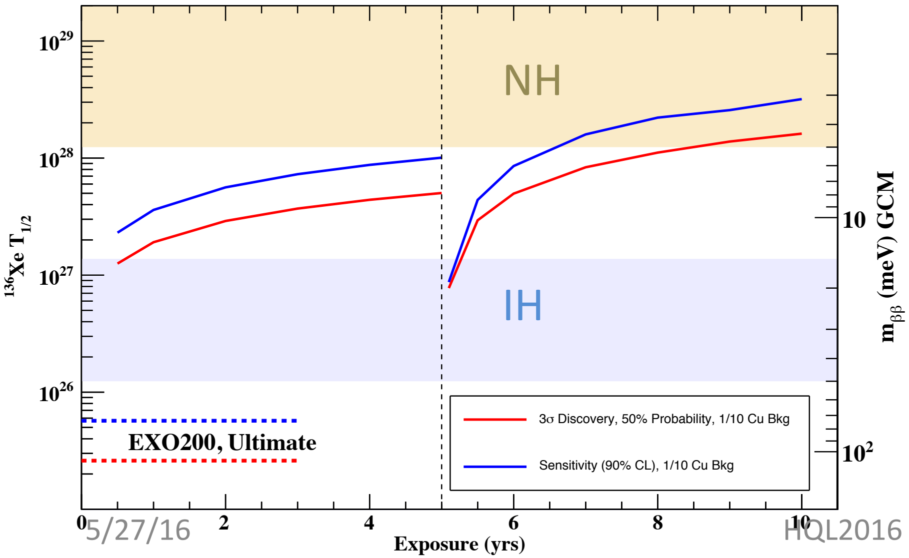
Sensitivities for worst and best case nuclear matrix elements

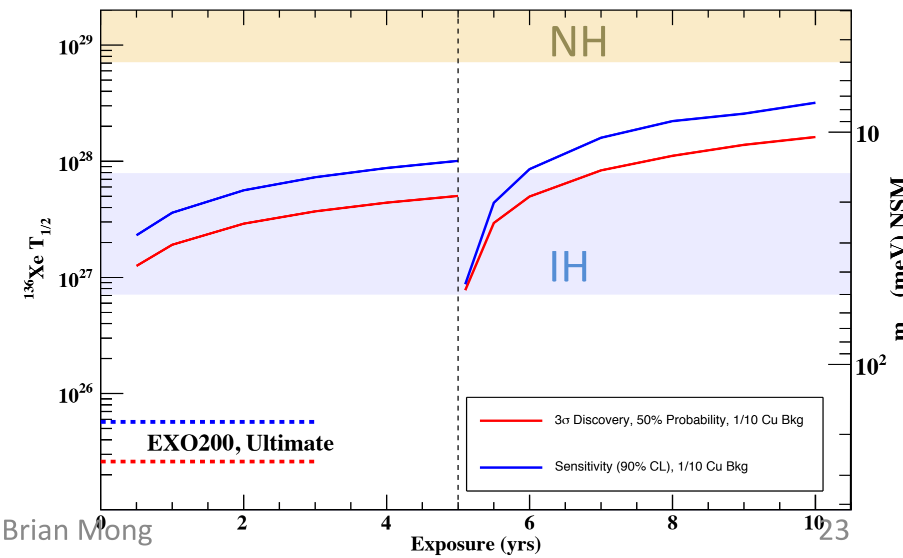
Best case (GCM)



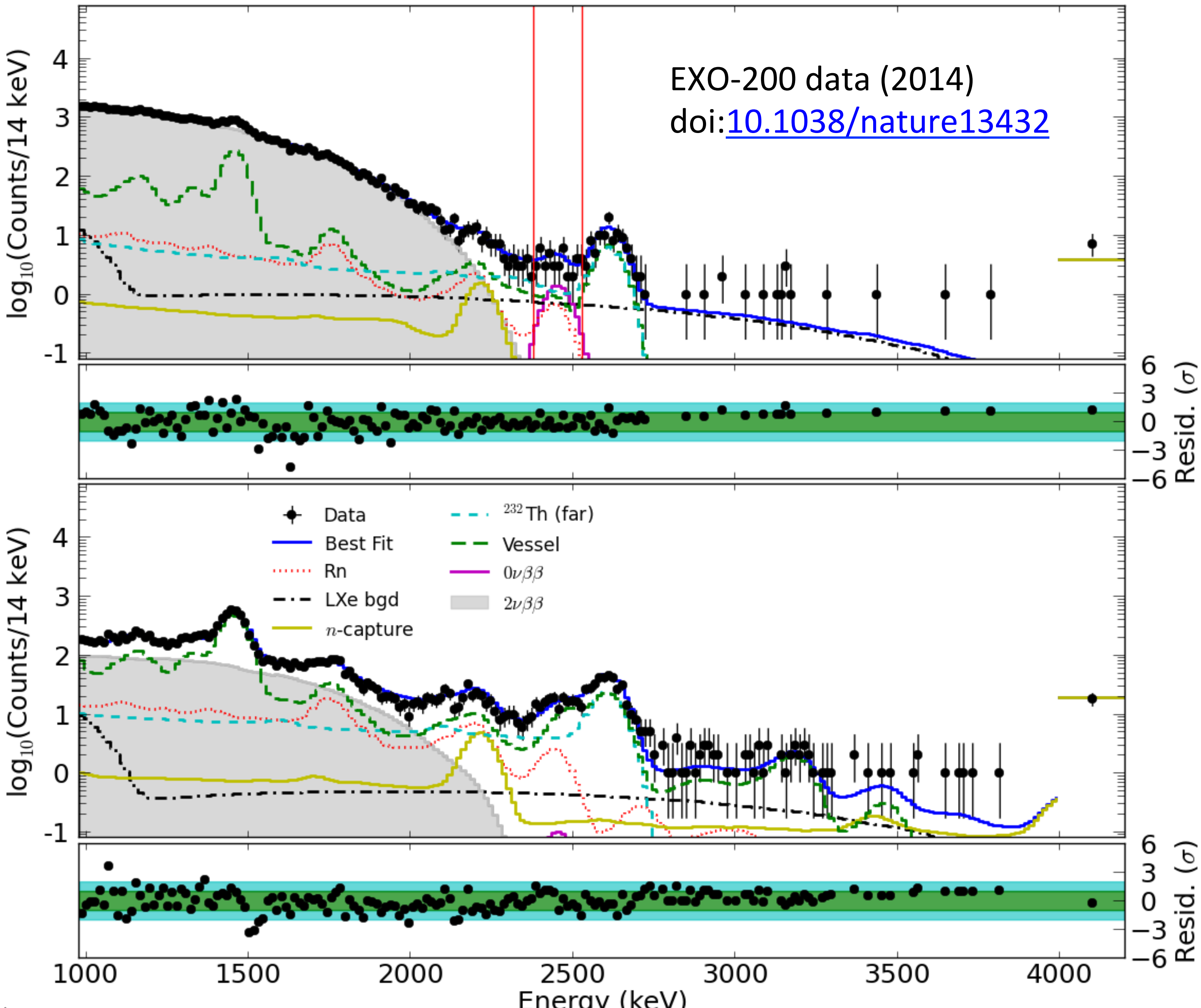
Worst case (NSM)



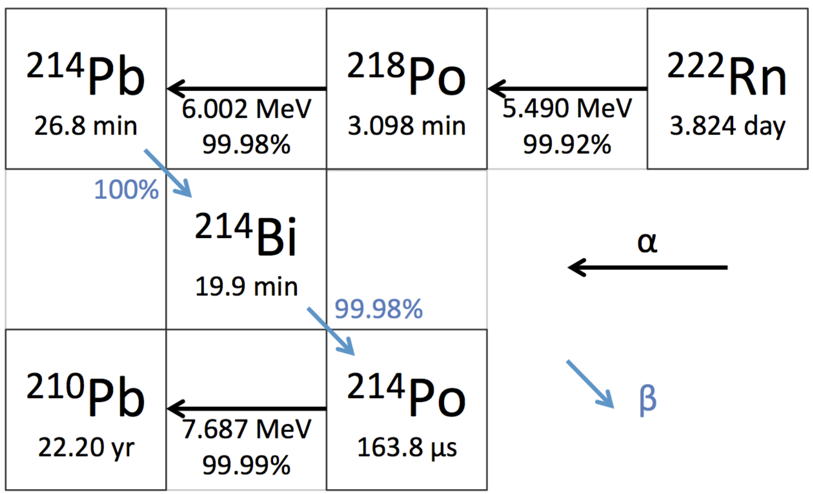


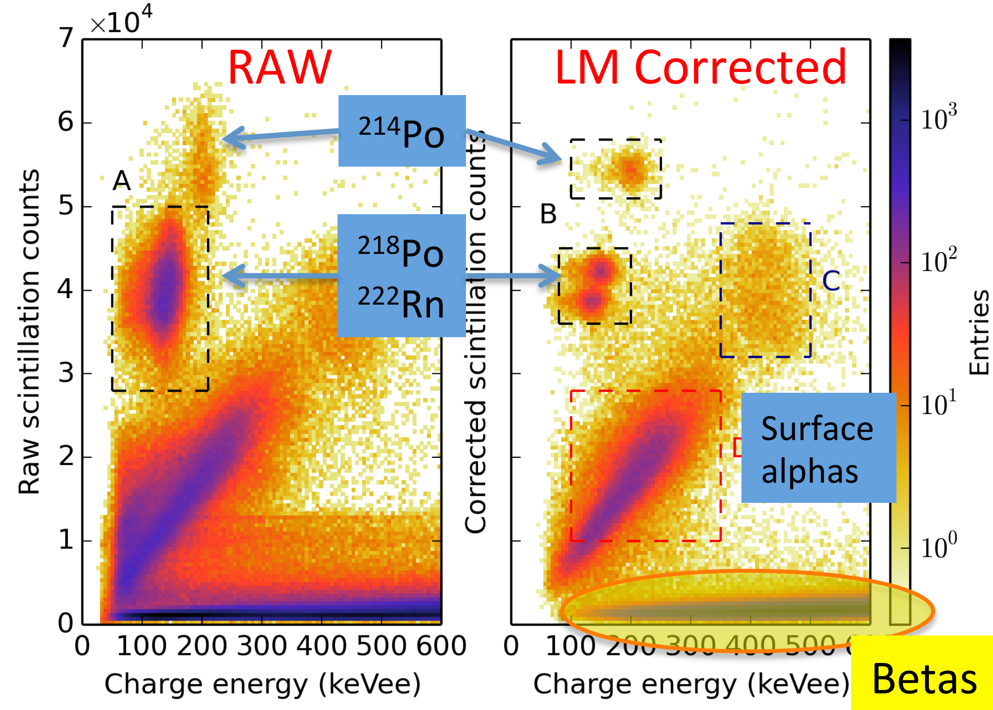


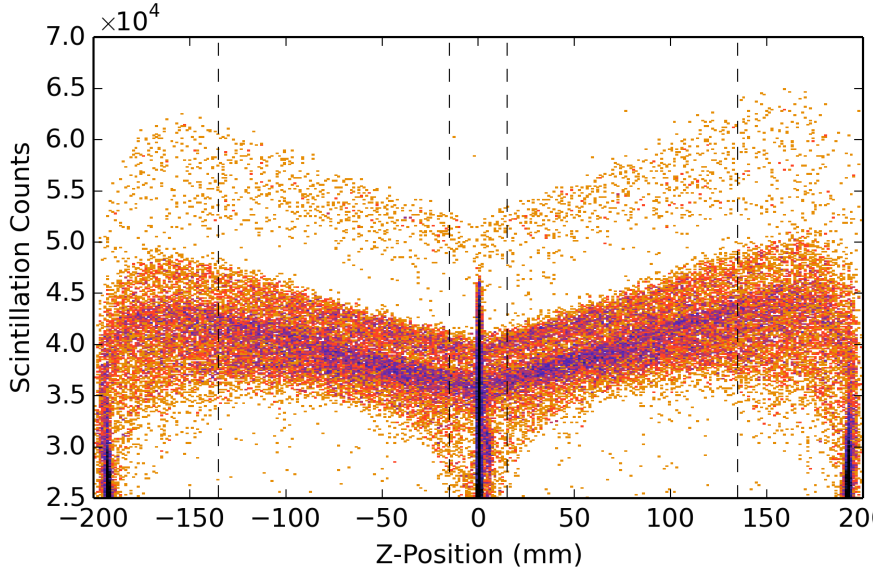
EXO-200 data (2014)
doi:[10.1038/nature13432](https://doi.org/10.1038/nature13432)

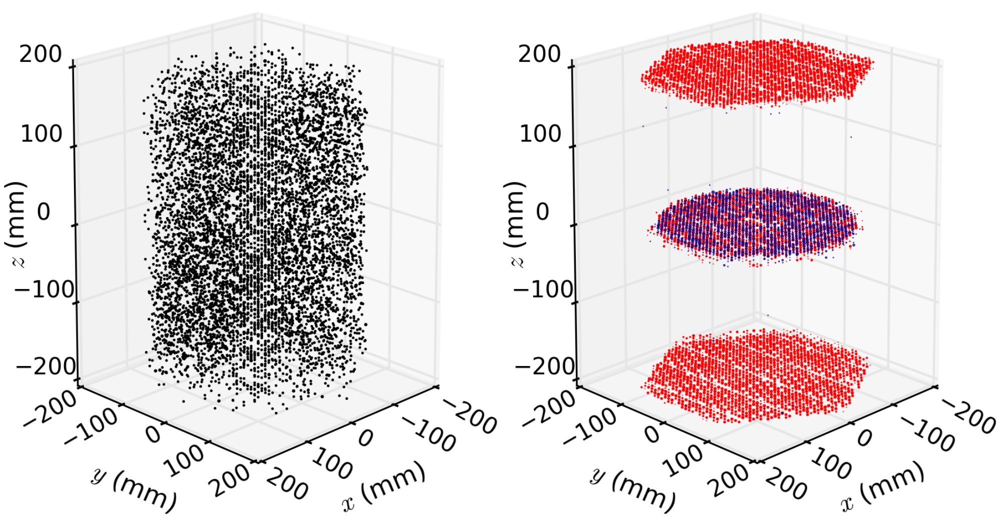


Alpha energy and event locations









^{214}Bi ion fraction (β decay)

Measure ratio of alpha events in LXe $\frac{A^{214}_{\mathrm{Po}}}{A^{222}_{\mathrm{Rn}}}$

(Assume 50.3(3.0)% of ^{214}Pb are ions)

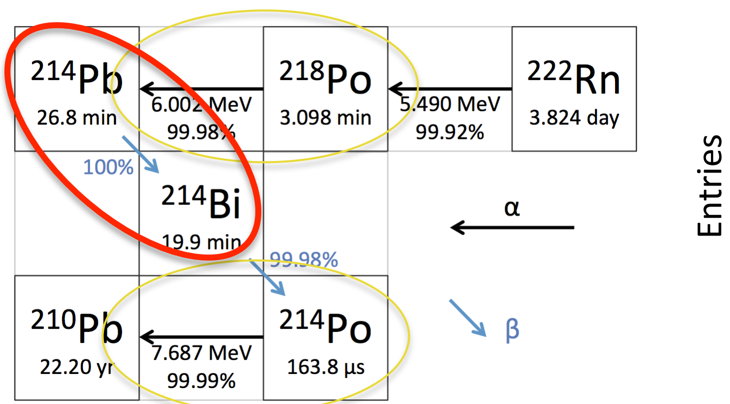
Neutrals Decay in flight

$$\frac{A^{214}_{\mathrm{Po}}}{A^{218}_{\mathrm{Po}}} = (1 - f'_\alpha + f'_\alpha \epsilon_{\mathrm{Pb}})(1 - f_\beta + f_\beta \epsilon_{\mathrm{Bi}})$$

f_β is daughter ion fraction of β decay

Measure 2 alpha decays in LXe fid. vol.
Deduce beta decay ion fraction

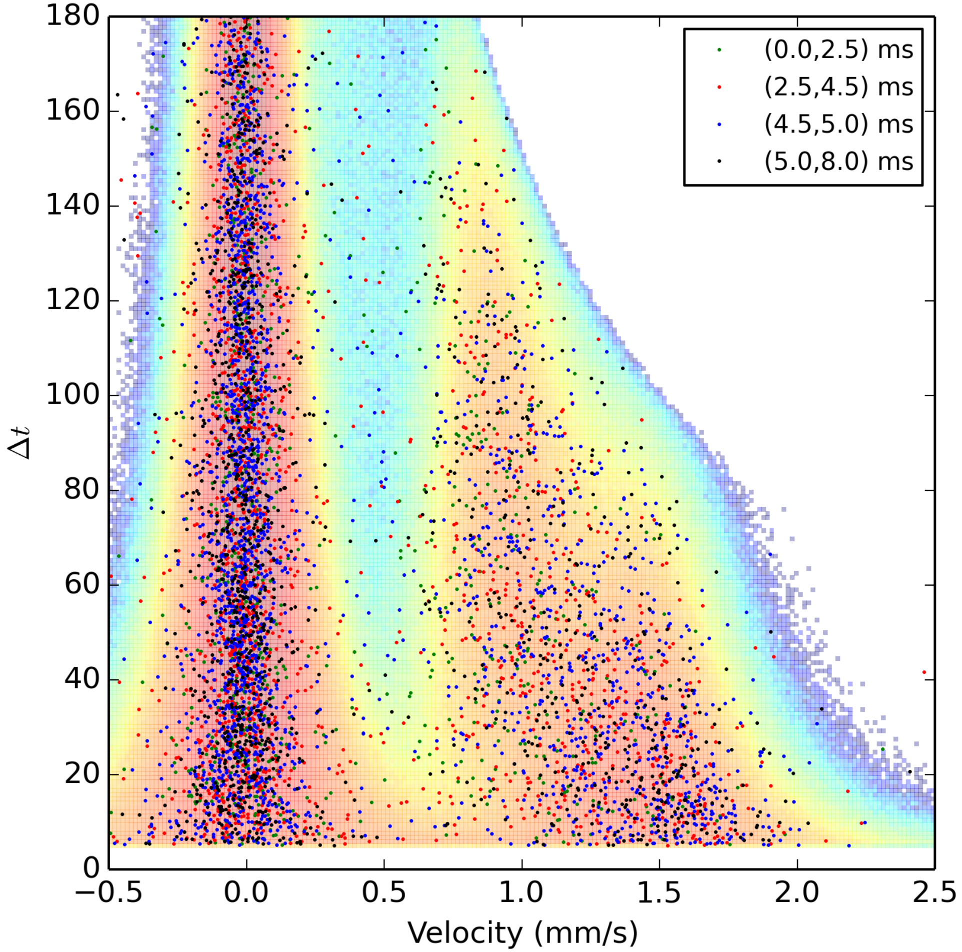
f_β: 76.4 ± 5.7 %



Good news for barium tagging!

J. B. Albert et al. (EXO-200 Collaboration)
Phys. Rev. C 92, 045504

Using ^{222}Rn-^{218}Po events to determine ion drift parameters



<u>MC Model Parameters:</u>

v_1 = 1.48 ± 0.01 mm/s
v_2 = 0.83 ± 0.01 mm/s
C = 12600 ± 660
N = $6^{+4.9}_{-1.7} * 10^5$
D = 0.61 ± 0.04 mm^2/s

<u>Mobility of ^{218}Po</u>

μ_1 = 0.390±0.006 cm^2/(keV•s)
μ_2 = 0.219±0.004 cm^2/(keV•s)
other ions are 0.13-0.28 cm^2/(keV•s)

C is ratio of reaction lifetime to electron lifetime:
(t_e ~3 ms, $t_{reaction}$~ 40s)
*N is ratio or neutralization time to electron lifetime (N=50 * C):*

An important result for Ba tagging: (t_e ~3 ms, t_{neut}>1000s)