The search for Matter Creation©

with nEXO

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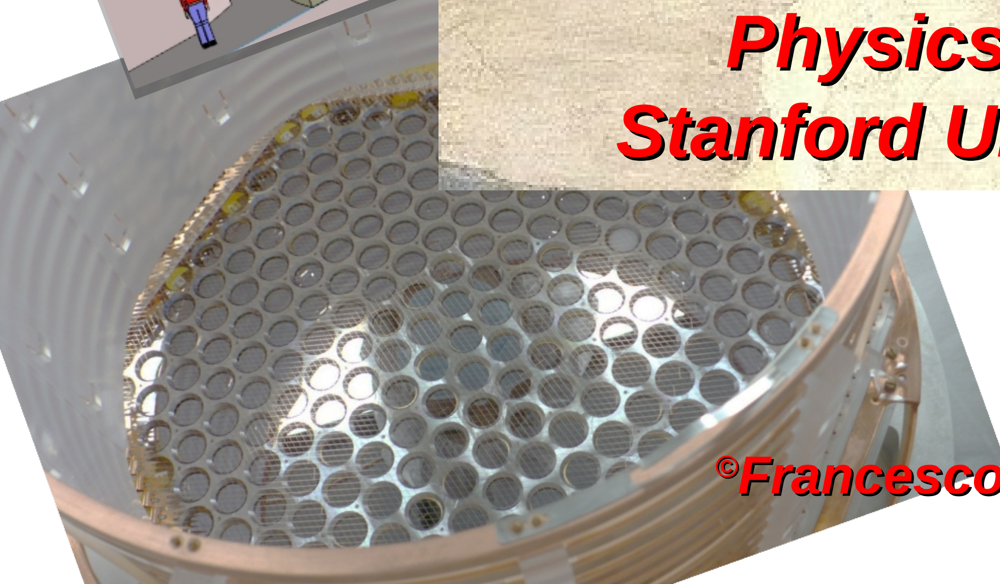

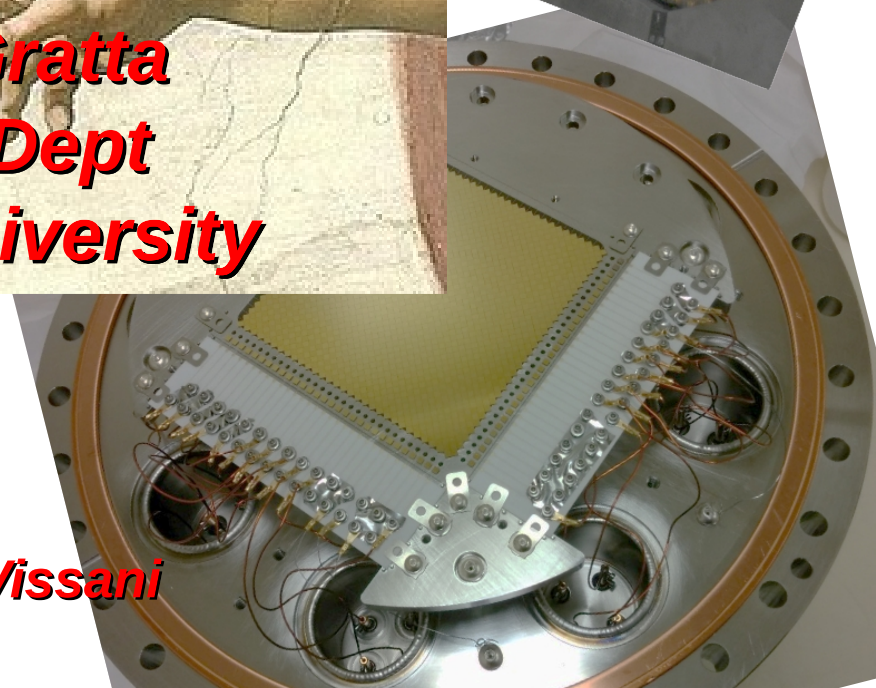

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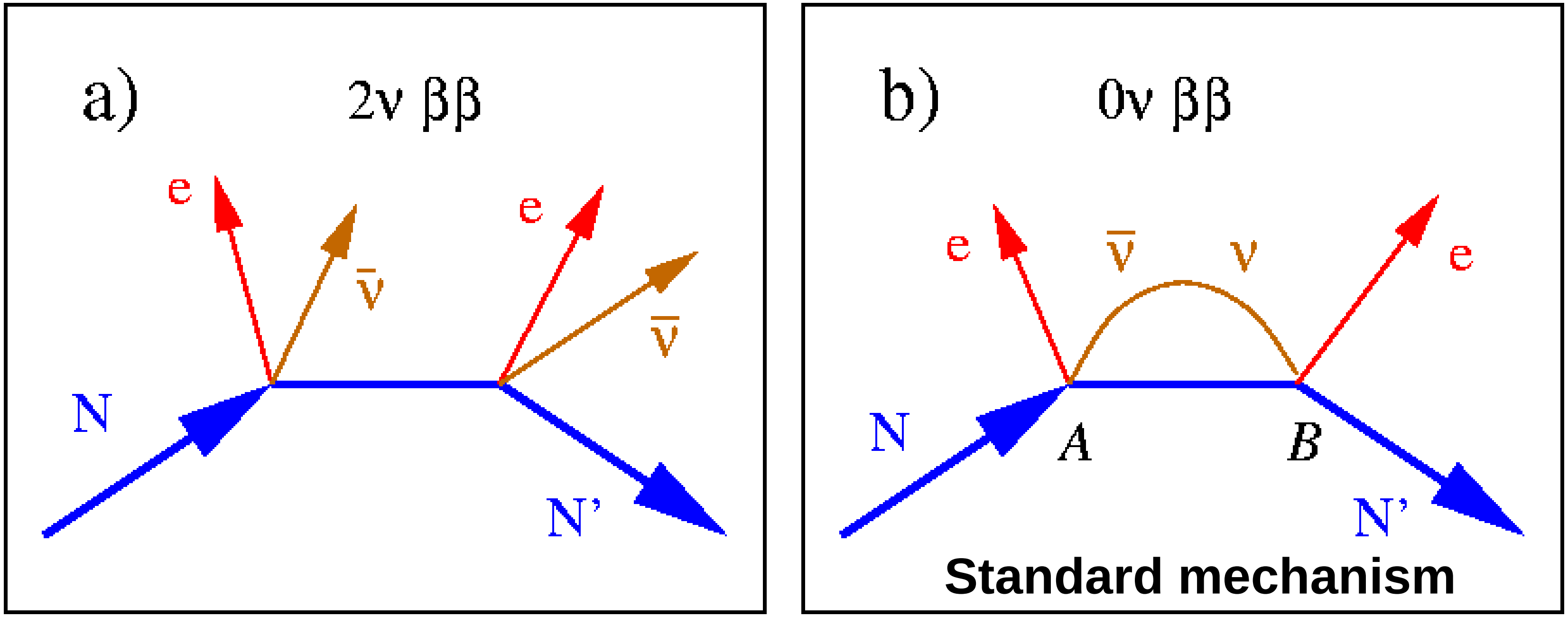
There are two varieties of ββ decay

2ν mode:
a conventional
2[nd] order process
in nuclear physics

0ν mode: a hypothetical process can happen only if:
$M_\nu \neq 0$
$\bar{\nu} = \nu$
$|\Delta L| = 2$
$|\Delta(B-L)| = 2$



There are two varieties of ββ decay

0ν mode: a hypothetical process can happen

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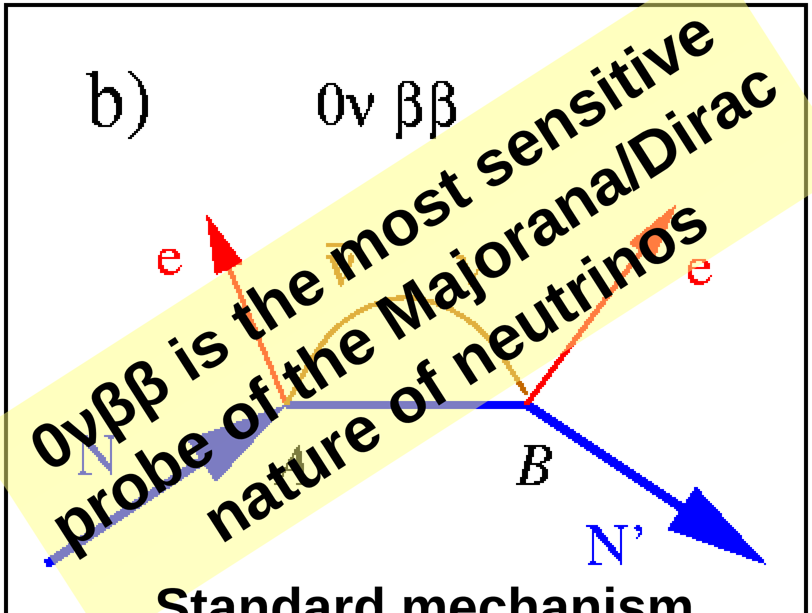
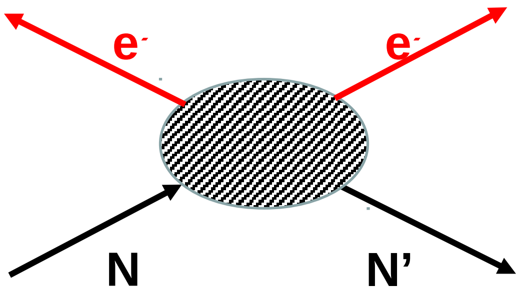


Standard mechanism

“Black box” theorem*: “0νββ decay always implies new physics”

There is no scenario in which observing 0νββ decay would not be a great discovery



- ➔Majorana neutrinos
- ➔Lepton number violation
- ➔Probe new mass mechanism up to the GUT scale
- ➔Probe key ingredient in generating cosmic baryon asymmetry

Neutrino masses have to be non-zero for 0νββ to be possible.
➔ Because the distinction between Dirac and Majorana particles is only observable for particles of non-zero mass.

Strictly speaking, this is the ONLY connection with neutrino masses relevant to discover new physics.

Hence it is appropriate to think of the sensitivity to new physics as scaling with $T_{1/2}$, irrespective of the neutrino mass scenarios. A $T_{1/2}$ sensitivity increase from $\sim 10^{26}$ to $\sim 10^{28}$ yr (~100x), should be compared, e.g., to the $\sqrt{s}$ increase from Tevatron to LHC (~20), although, admittedly, with a smaller array of channels for new physics.

* J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982).

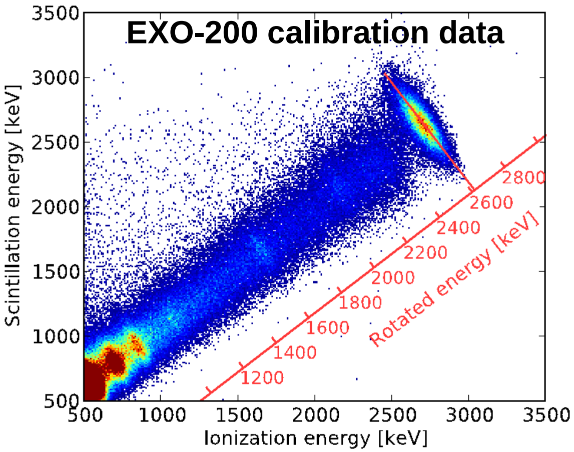
The connection with the ν mass also means that the observation of $0\nu\beta\beta$ decay can provide information on the ν mass scale, <u>provided that</u>:

- **The mechanism producing the decay is understood**
- **The nuclear matrix element is calculated with sufficiently small uncertainty**
- **The appropriate value of g_A to be used is clarified**

This is of course an important bonus, but these uncertainties *do not affect the discovery potential of tonne-scale experiments.*

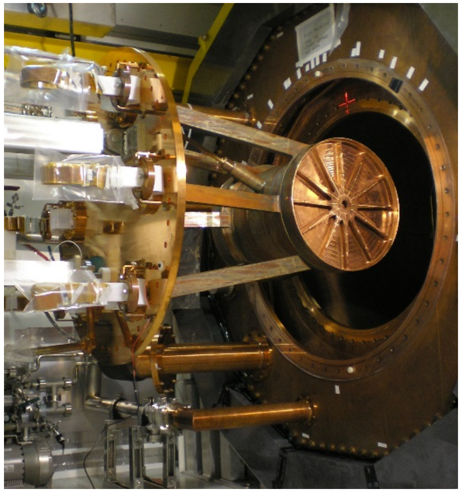
It is also a convenient, although imperfect, metric to compare isotopes and experiments.

Milestones in the EXO program
Since 2001



- Use ^{136}Xe in liquid phase

- Initial R&D on energy resolution using scintillation-ionization correlation (2003)



- Build EXO-200, first 100kg-class experiment to produce results. EXO-200 data taking ended started in Jun 2011 and ended in Dec 2018. The detector is now decommissioned.

- Build the 5-tonne nEXO, reaching $T_{1/2}$~10^{28} yr and entirely covering the Inverted Hierarchy (with the caveats above)

- Develop a technique for tagging the final state Ba as a possibility to further upgrade nEXO and substantially exceed $T_{1/2}=10^{28}$ yr

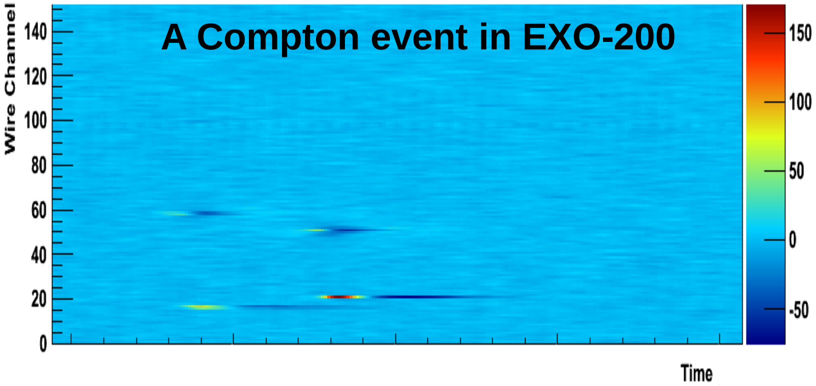
Particularly for large detectors, energy resolution is only one of the parameters used for background rejection:

- Energy measurement (for small detectors this is ~all there is).

- Event multiplicity (γ's Compton scatter depositing energy in more than one site).

- For large, monolithic detectors, depth is powerful discriminant against background.

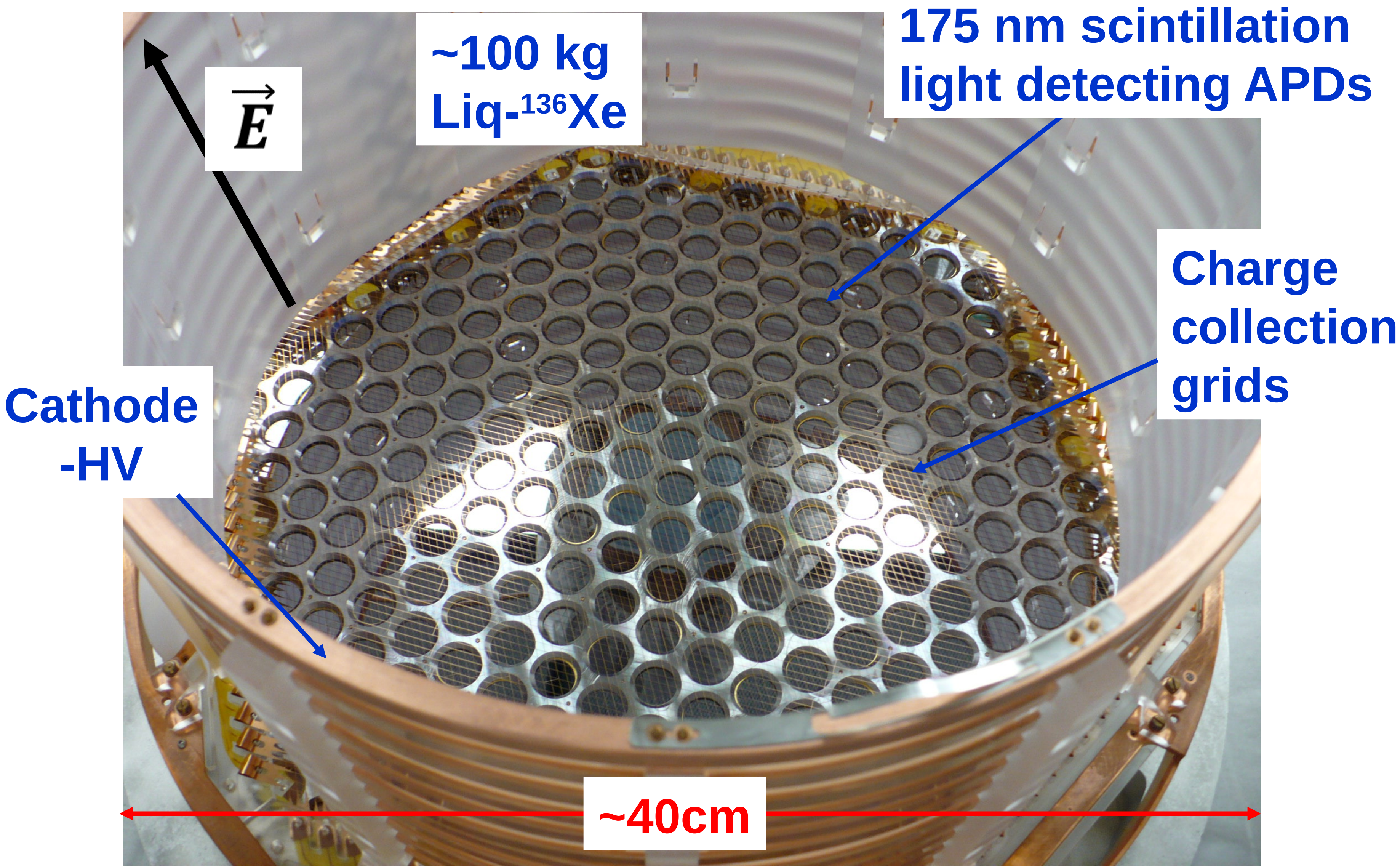
- α discrimination (from e^- / γ), possible in many detectors.



It is a real triumph of recent experiments that we now have discrimination tools in this challenging few MeV regime!

Powerful detectors use most of (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.

The EXO-200 liquid ^{136}Xe Time Projection Chamber

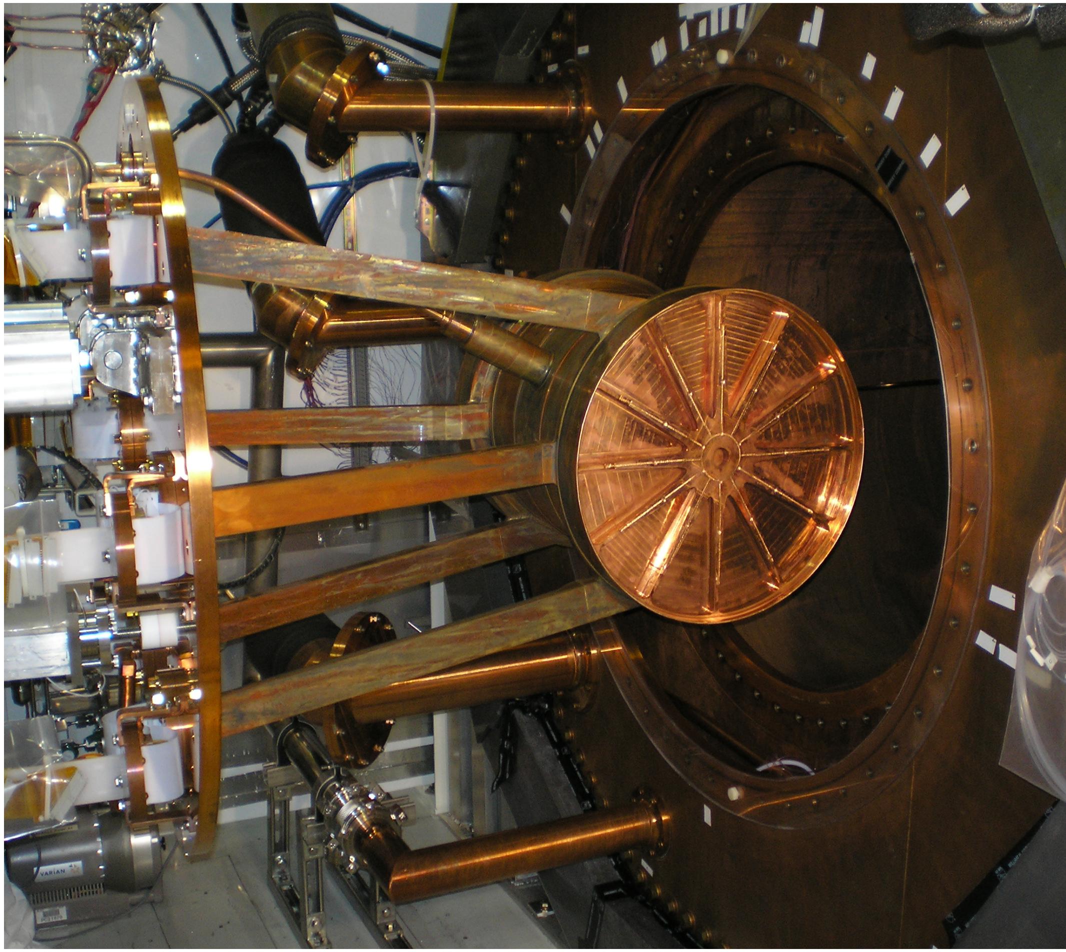


The TPC vessel was welded shut to obtain reliability and avoid the radioactivity of fasteners/gaskets.

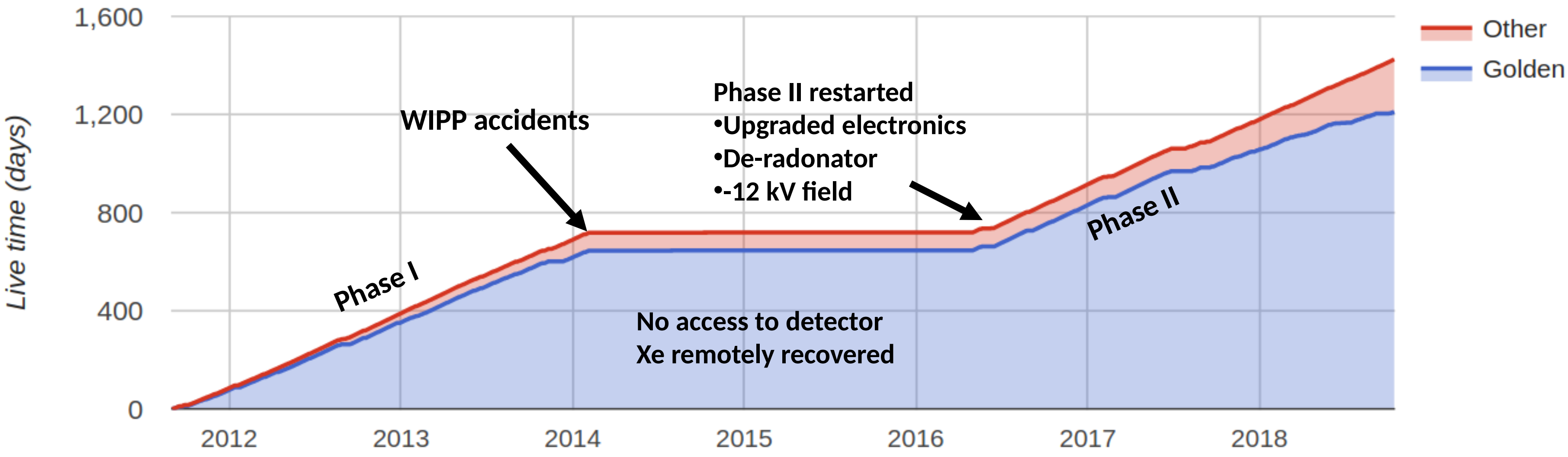
A special cryogenic fluid, 3M HFE-7000, was used to:

- Transfer the pressure to the cryostat (thin LXe vessel)
- Keep the temperature uniform (by convection)
- Shield the TPC from the radioactivity in the cryostat
- Provide a large thermal mass to reduce the criticality of cryogenics

This is a crucial feature to reach ultra-low background



EXO-200 timeline



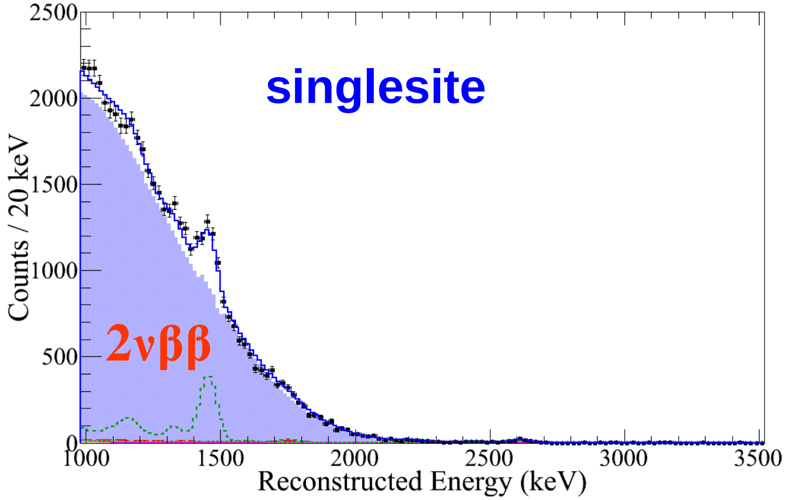
- Phase I from Sept 2011 to Feb 2014
  - Most precise 2νββ measurement (PRC89 (2013) 015502, surpassed last summer)
  - Stringent limit for the 0νββ search (Nature 510 (2014) 229)
- WIPP underground accidents and recovery Feb 2014 to Jan 2016 (accidents unrelated to EXO-200)
- Phase II from Jan 2016 to Dec 2018
  - Electronics upgrade and higher field (mainly further improve resolution)
  - Improved analysis techniques
  - Final 0νββ search result (Phys Rev Lett 123 (2019) 161802)
- Operations completed, Dec 2018. Total of 1181.3 days livetime.

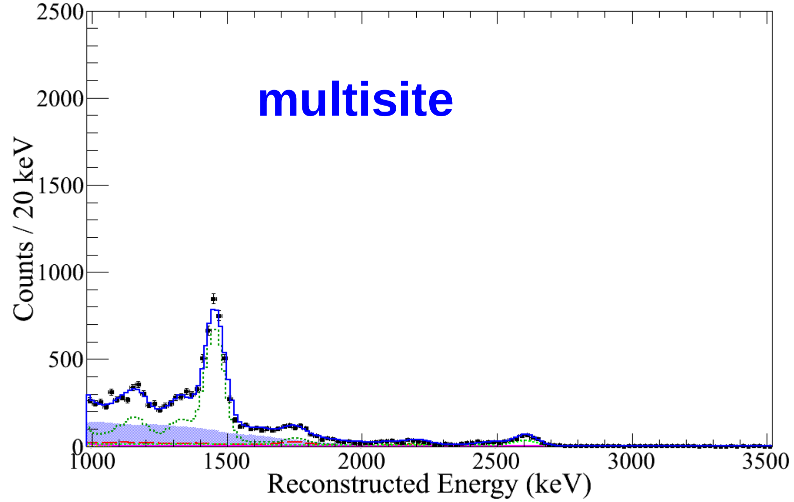
The WIPP accident demonstrated the robustness of the LXe system

- EXO-200 personnel was evacuated from the mine during a calibration run
- First action: do nothing! The HFE-7000 inertia + control system make the detector very stable –but electricity is required!
- The (enriched) LXe was remotely recovered in high pressure cylinders (over 6 years of operations and the accident <1 kg of ^{enr}Xe was lost). This was "easy" because the system was designed to do it automatically.
- Fearing a long-term power outage, the entire cold mass was brought to room temperature over ~a month.
  HFE-7000 expands 1.5x and this was NOT designed for remote operation.
- All this validates the EXO-200 design (and, of course, there are some minor lessons learned that will be implemented in nEXO)

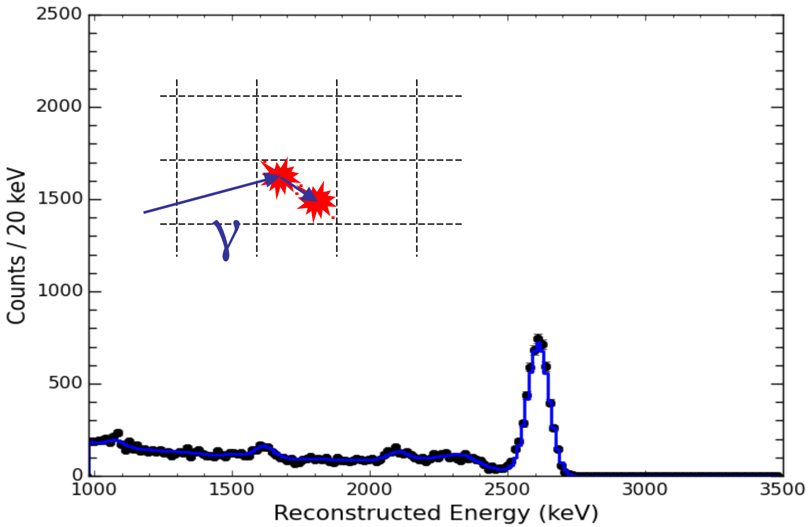
Using event multiplicity to recognize backgrounds

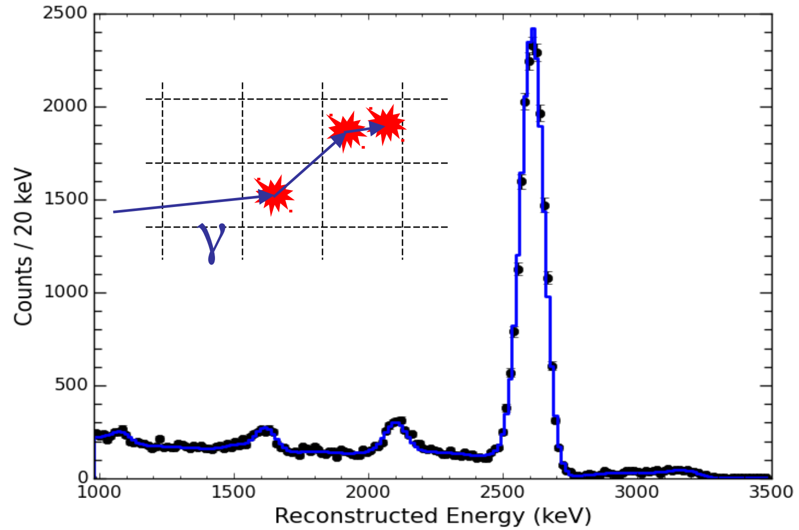
Low background data



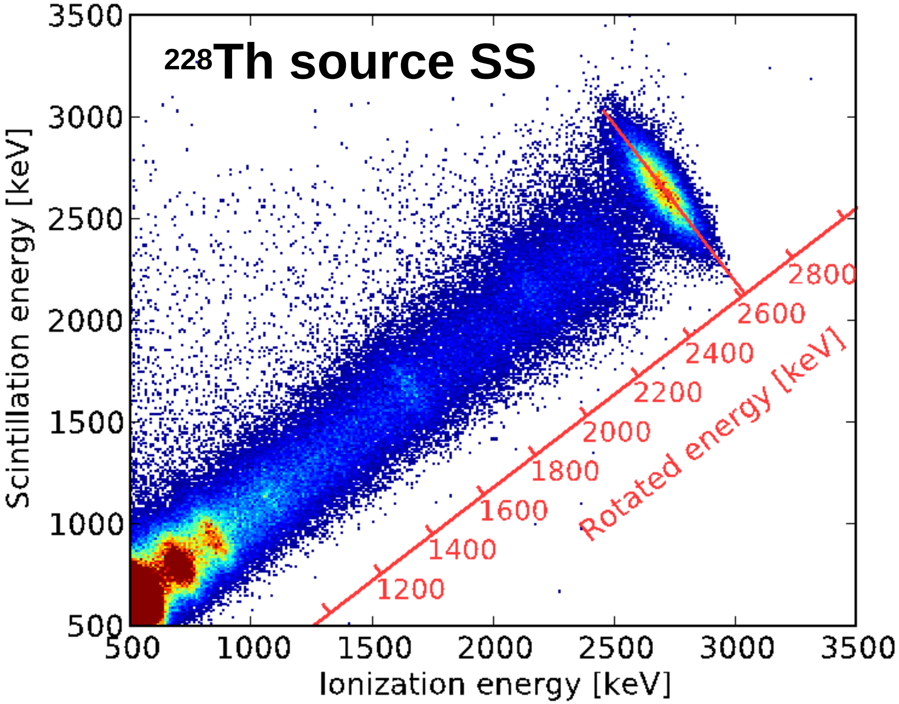


^{228}Th calibration source





Combining Ionization and Scintillation



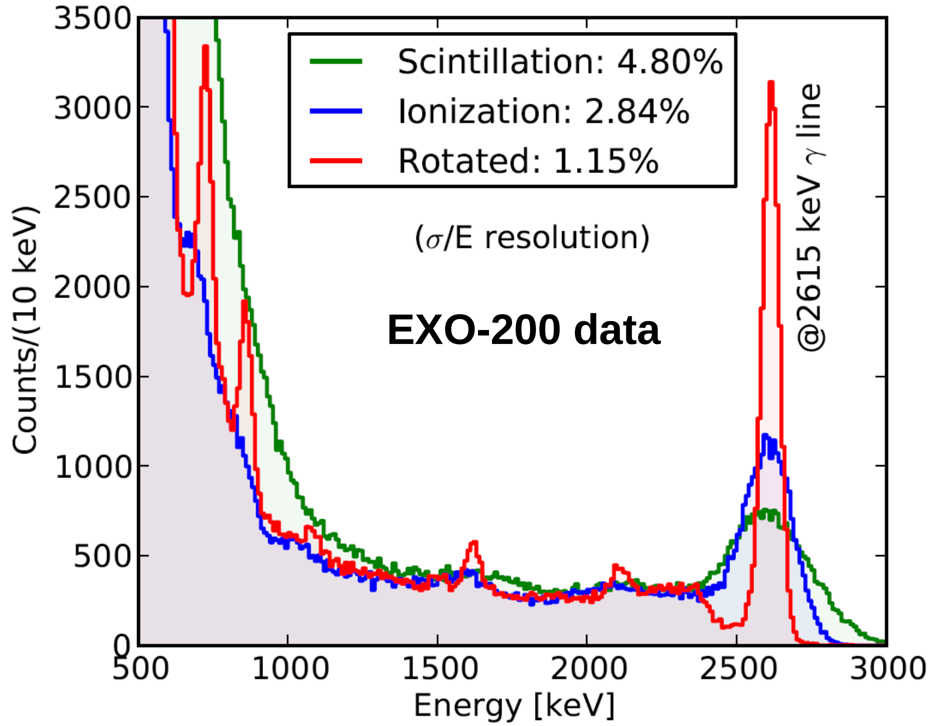
EXO-200 design energy resolution was σ/E = 1.6%

Achieved 1.15%

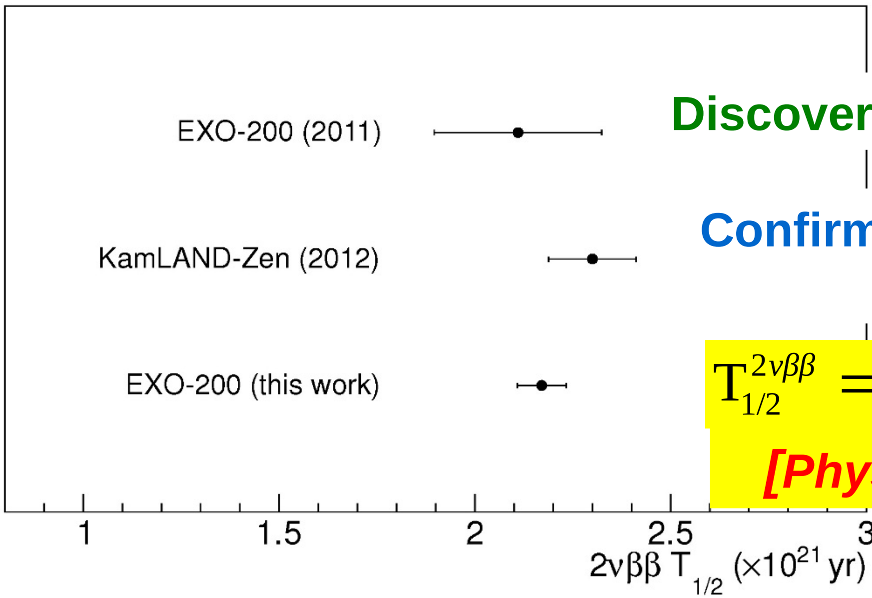
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

E.Conti et al.
Phys Rev B 68 (2003) 054201

By now this is a common technique in LXe



The $2\nu\beta\beta$ decay in ^{136}Xe was discovered in the first week of EXO-200 data



Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

[Phys. Rev. C 89 (2014) 015502]

Until last summer, this was the most accurately measured 2ν decay.

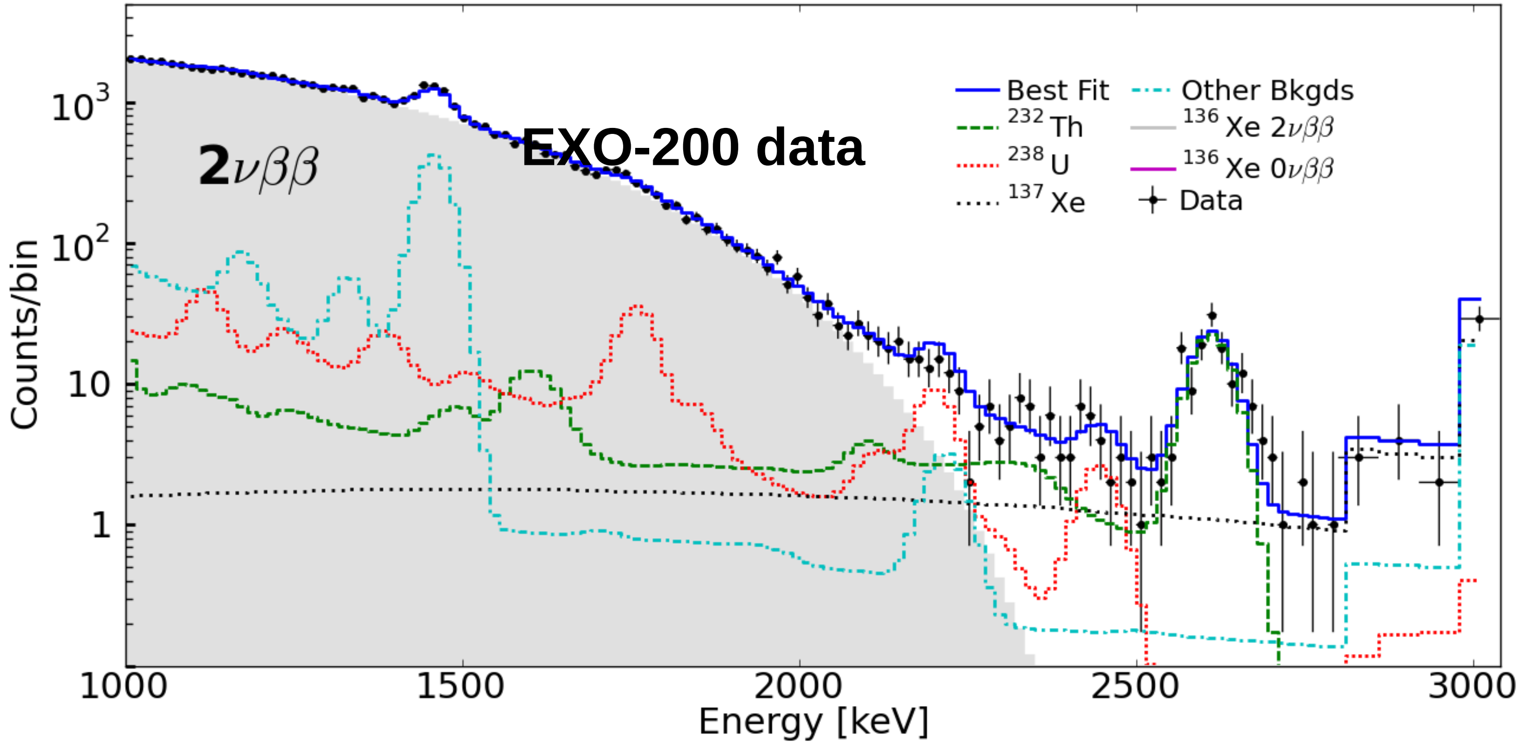
Of course goal of 0νββ experiments is to make a discovery

--setting a limit is the fall back position!

So, making sure that experiments have sensitivity is also very important

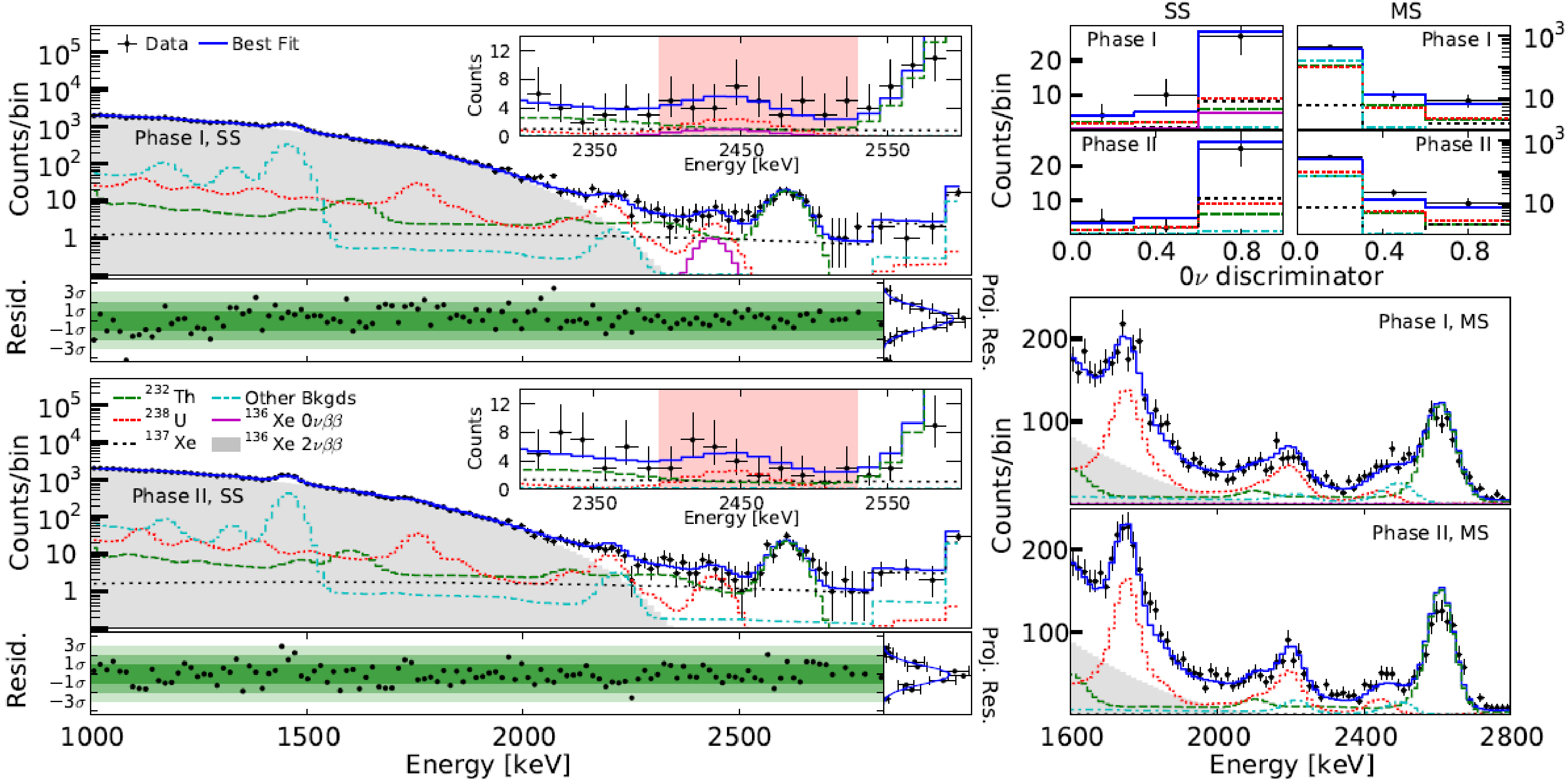
One can think of the 2νββ in a more positive way, as Nature's "blind injection"

–these events look like 0νββ events, extending in energy just below the Q-value.



And, in case of a discovery, the enriched Xe can be replaced with natural (or depleted) for a blank run.

Now using machine learning to supplement the traditional analysis in discriminating signal from background



No statistically significant signal observed

Phase I+II: 234.1 kg·yr ^{136}Xe exposure

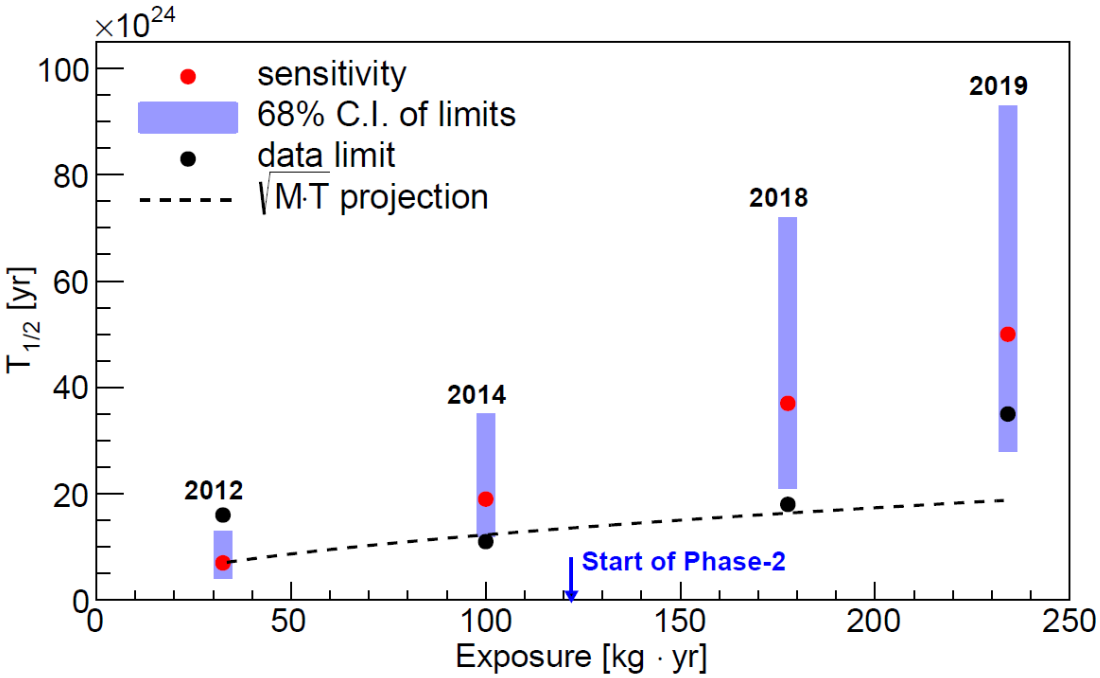
Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle < (93 - 286)$ meV

Sensitivity 5.0×10^{25} yr

(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26

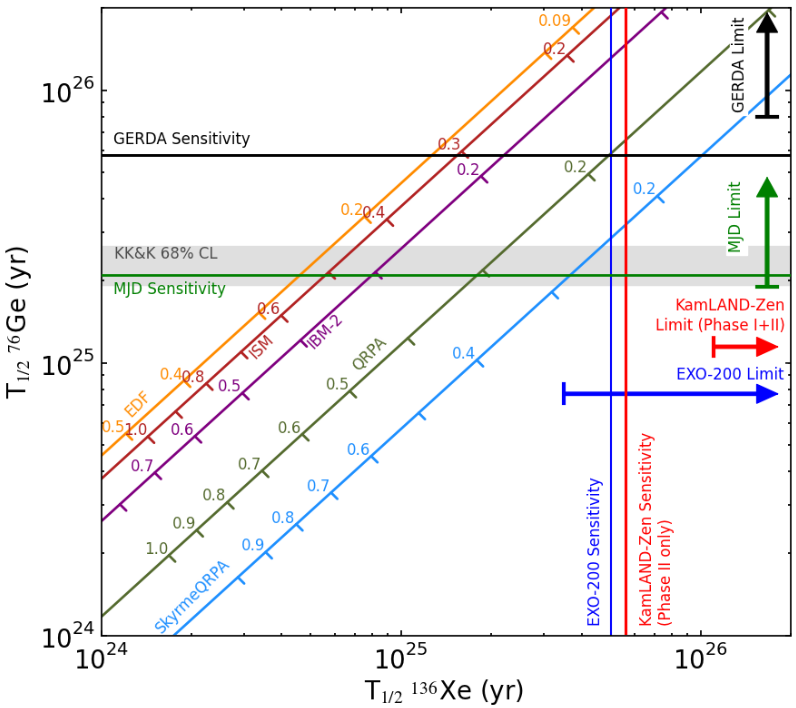
Background contribution to $Q \pm 2\sigma$



2012: Phys. Rev. Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120 (2018) 072701
2019: Phys. Rev. Lett. 123 (2019) 161802

Is ^{136}Xe the right isotope? For a very large detector is the best!

Science



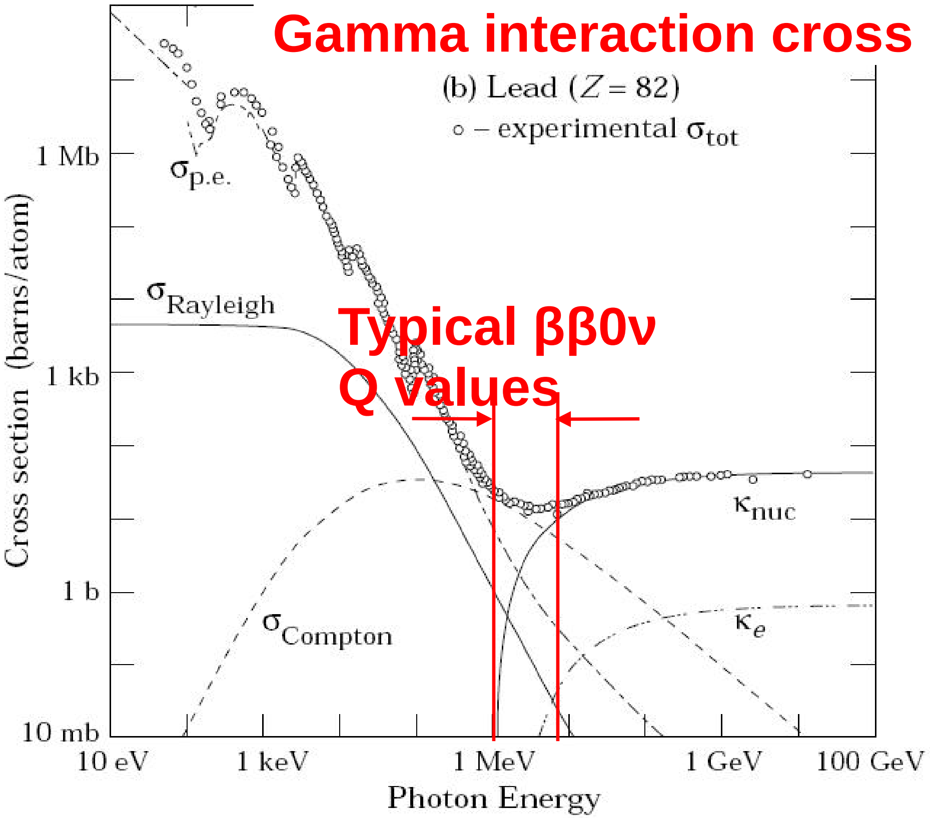
- Reach per unit $T_{1/2}$ somewhat better than ^{76}Ge (assumes Type 1 Seesaw)
- Reach per unit kg similar to ^{76}Ge
- Reach per unit $ way better than ^{76}Ge

Technology

- No need to grow crystals
- Can be re-purified during run
- Noble gas: easy(er) to purify
- Can be easily transferred from one detector to another depending on results and available technology
- Demonstrated superior signal/background discrimination
- No long lived Xe isotopes to activate (assuming sufficient depth to avoid ^{137}Xe activation)
- ^{136}Xe enrichment easier, safer, cheaper
- ^{136}Xe can be replaced with $^{Nat'l}$Xe if a signal is observed!
- Only known case where final state identification appears possible in a future upgrade

These are essential features, particularly for a tonne scale, >100M$ project.

Shielding a detector from ~MeV γs is difficult!



ample:
γ interaction length
in Ge is 4.6 cm,
comparable to the size
of a germanium detector.

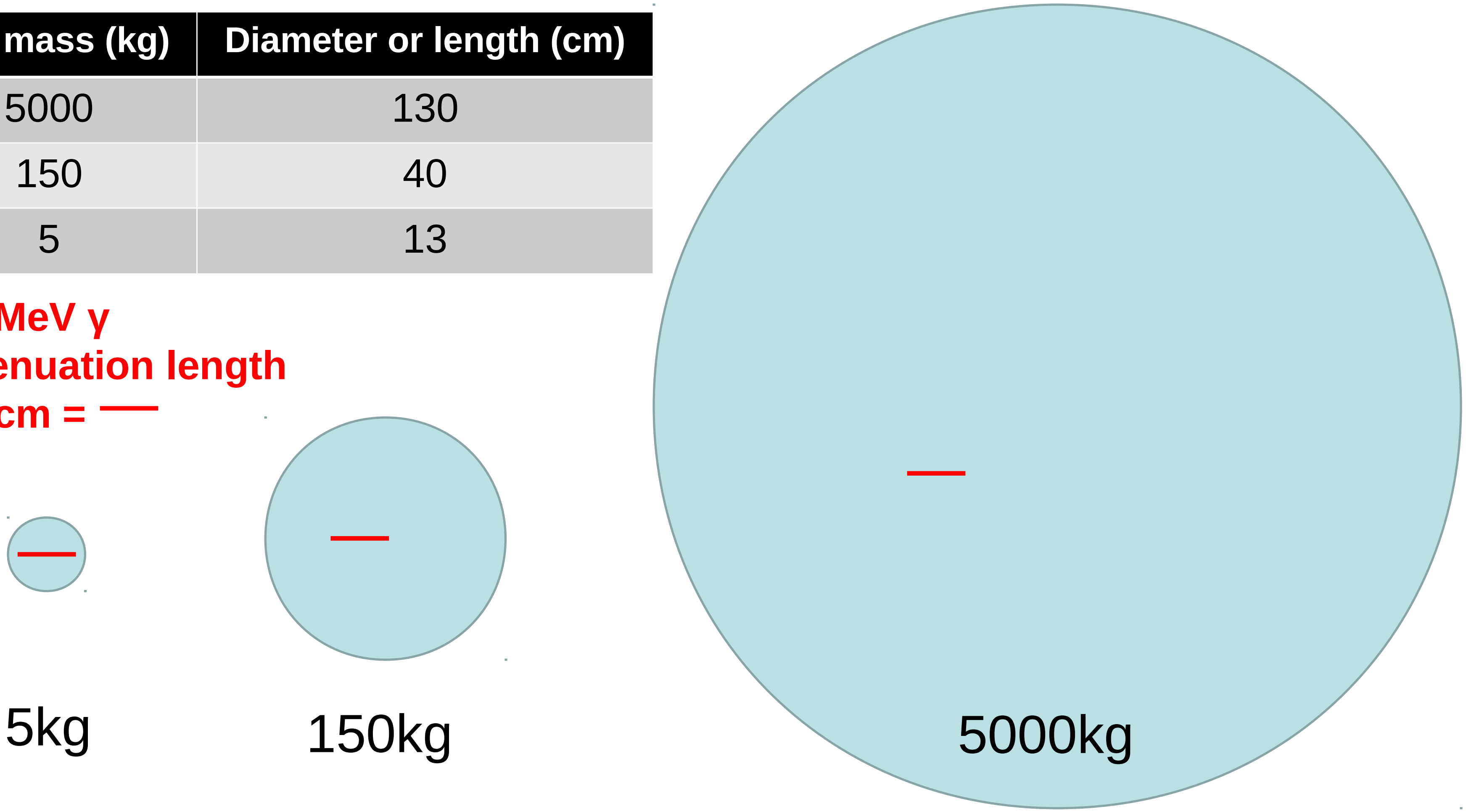
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths

Moving forward, monolithic is key

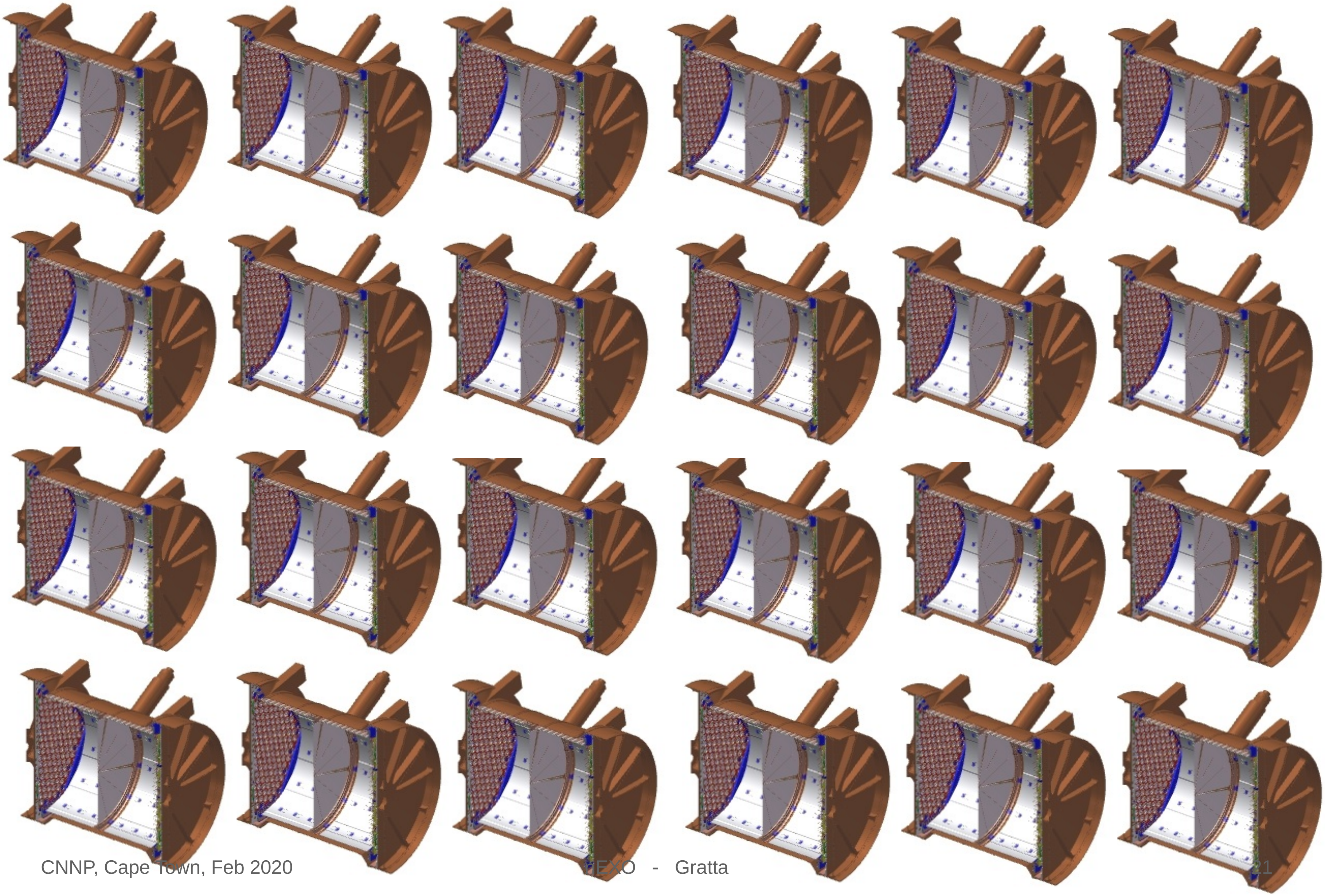
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ attenuation length 8.5cm =

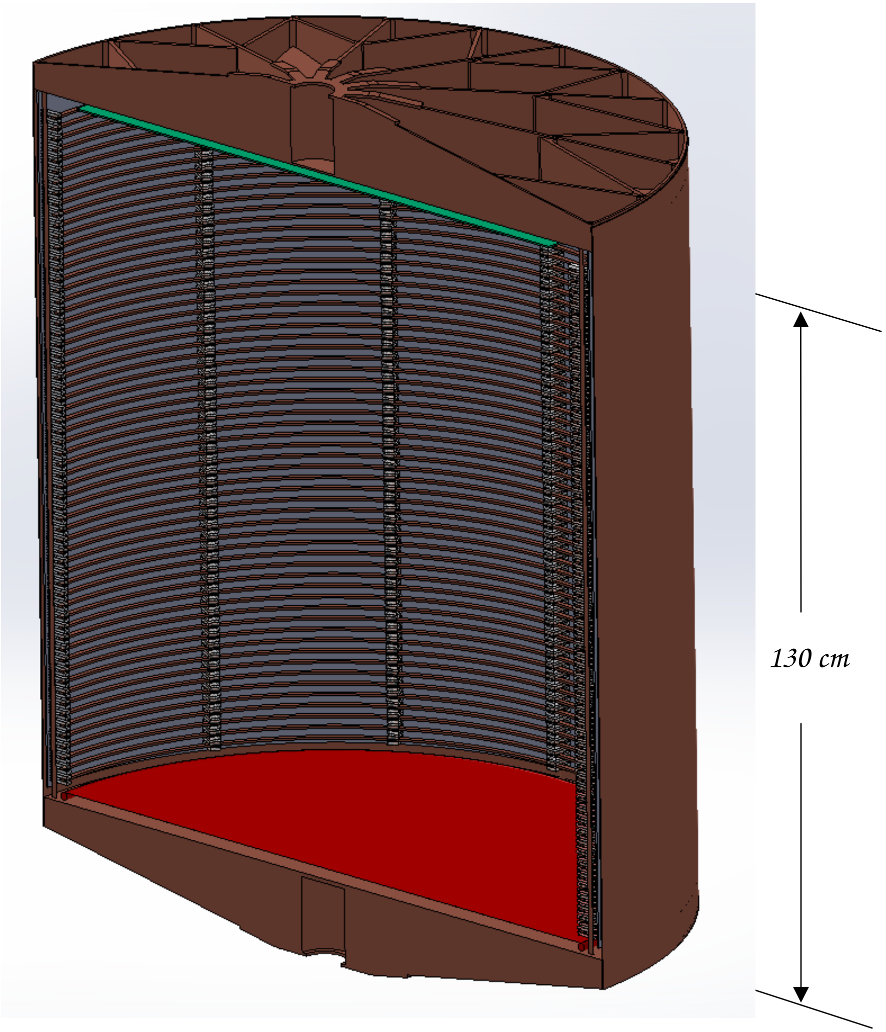


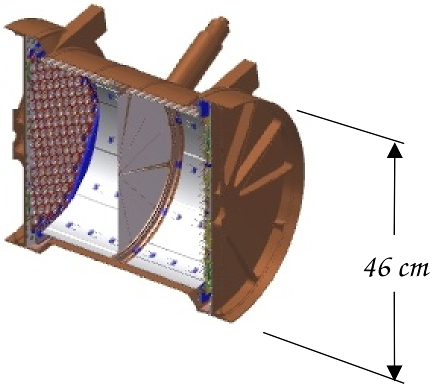
The current estimate of the nEXO sensitivity relies only on materials already tested for radioactivity and on hand (although not necessarily in sufficient amount)

The wrong design for nEXO (requiring no R&D)

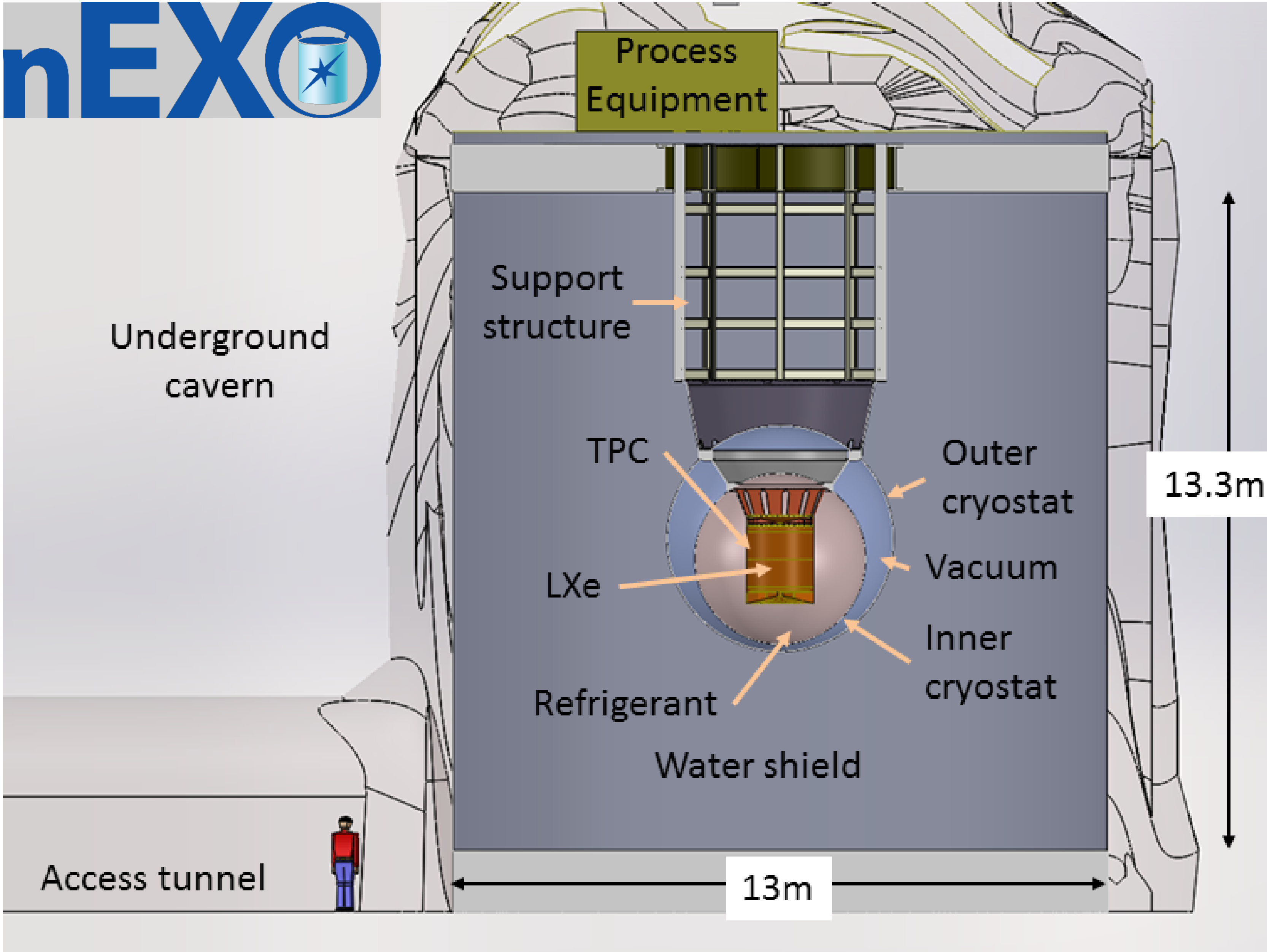


The real nEXO detector





Preliminary artist view of nEXO in the SNOLAB Cryopit



Two important documents currently define the detector and spell out its performance

- "nEXO pCDR" arXiv:1805.11142 (May 2018)

- "Sensitivity and Discovery Potential of nEXO to $0\nu\beta\beta$ decay" Phys. Rev. C 97 (2018) 065503.

In addition…

EXO-200 analysis and nEXO R&D discovered better analysis techniques, taking full advantage of the detector's information to measure and reject backgrounds.
An updated sensitivity paper by the nEXO collaboration is being prepared.

arXiv:1805.11142 [physics.ins-det] 28 May 2018

nEXO Pre-Conceptual Design Report

nEXO

Abstract

The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With $\sim$ 5000 kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately 10^{28} years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation $0\nu\beta\beta$ decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the base design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

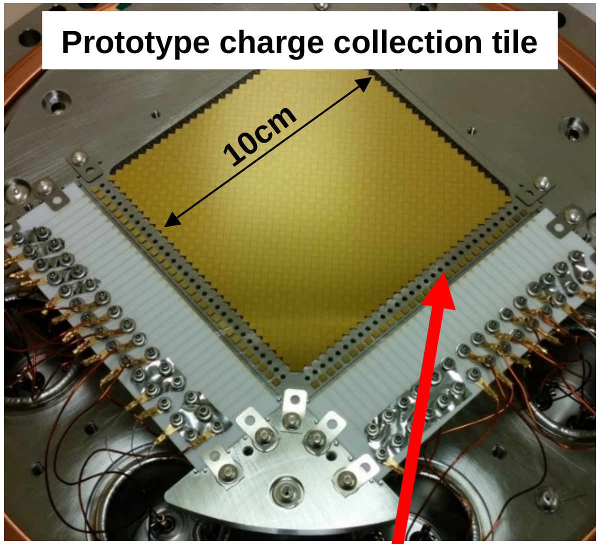
May 28, 2018

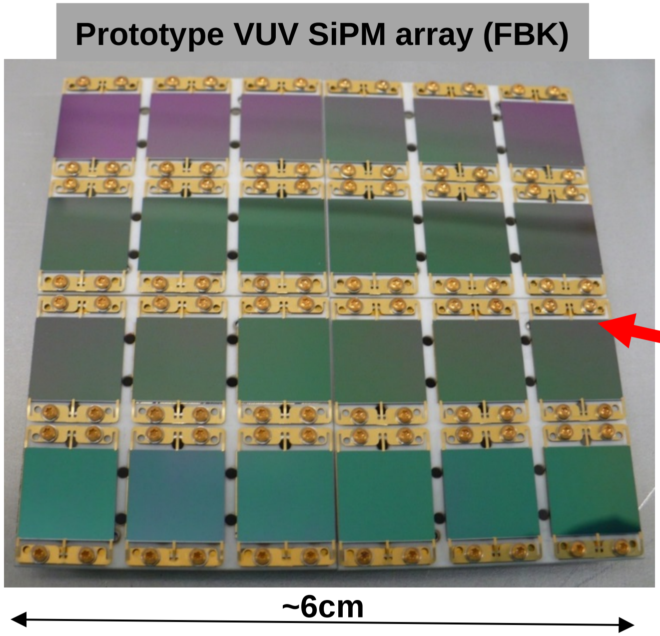
Optimization from the EXO-200 to the nEXO scale

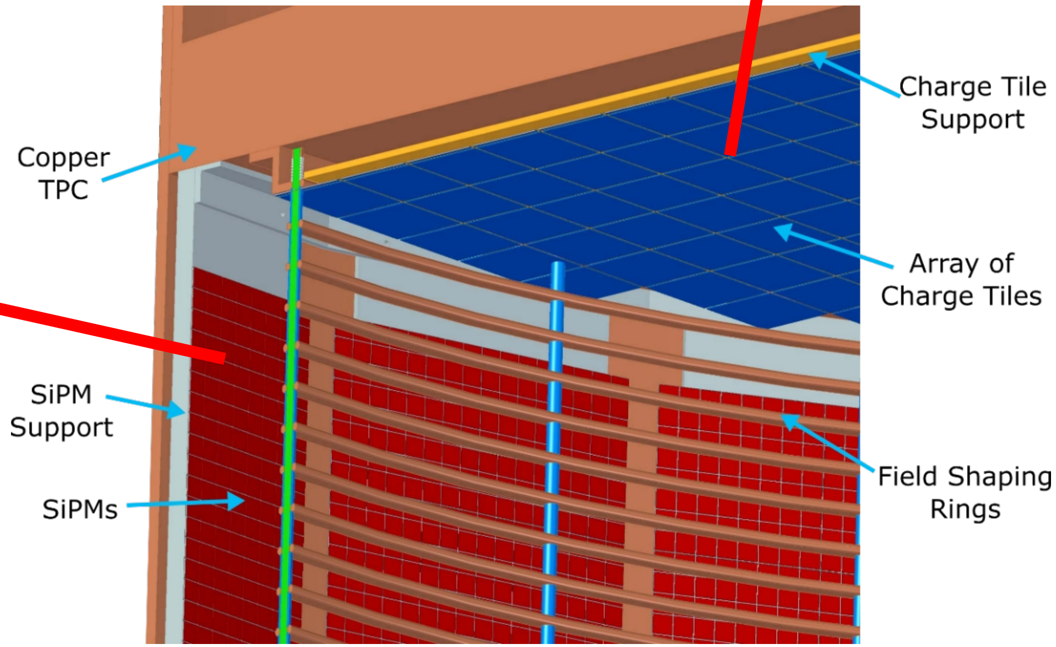
What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell (1/2 field OK, i.e. 3x voltage)
>3x electron lifetime	Larger detector and one drift cell
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

Main technical changes on the EXO-200 theme

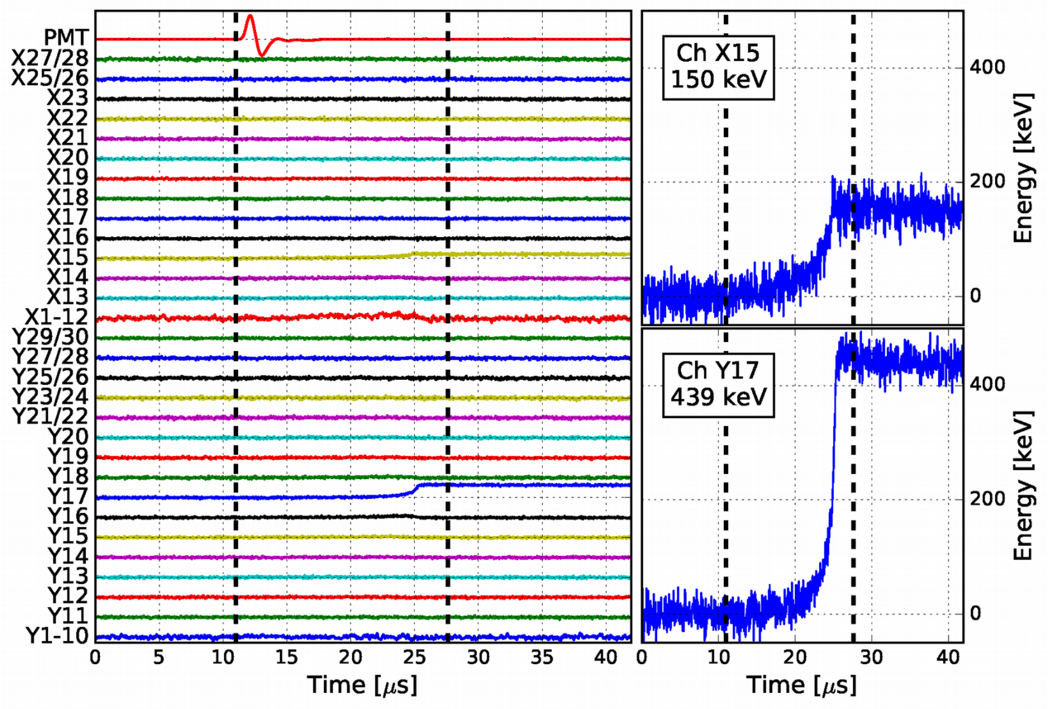
- Only one drift volume
- ASIC electronics in LXe
- Silica substrate charge collection tiles
- VUV SiPMs (~4.5m²)
- Little plastics in the TPC (Sapphire, Silica)

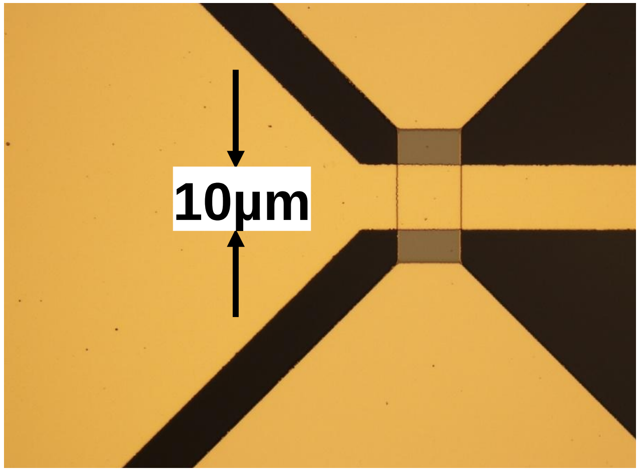






Test of prototype tiles in LXe is ongoing





Pulse shape is unusual, because of the absence of a shielding grid, but state of the art resolution for charge only has been achieved.

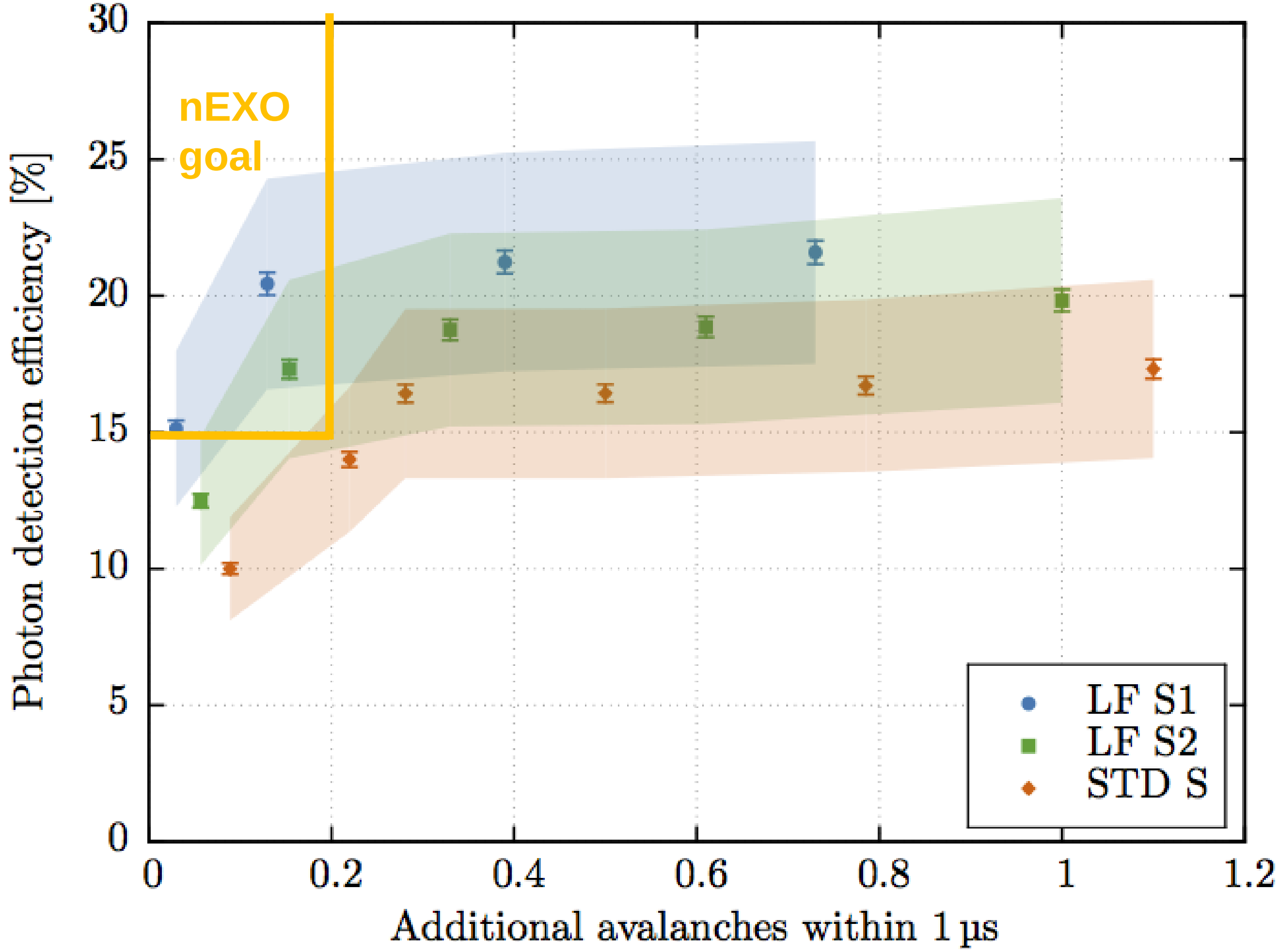
Max metallization cover with min capacitance:

80 fF at crossings
0.86 pF between adjacent strips

M.Jewell et al., "Characterization of an Ionization Readout Tile for nEXO", ***J.Inst. 13 P01006 (2018)***

After the first round of R&D, some 1cm² VUV devices now match our desired properties, with a bias of ~30V

(as opposed to the 1500V of EXO-200 APDs)



"Characterization of the Hamamatsu VUV4 MPPCs for nEXO" arXiv:1903.03663, to appear in NIM A

"VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO" IEEE Trans NS 65 (2018) 2823

Radioactivity in EXO-200 was successfully predicted *before* turning on the detector

➔Massive effort on material radioactive qualification, using:

- **NAA**
- **Low background γ-spectroscopy**
- **α-counting**
- **Radon counting**
- **High performance GD-MS and ICP-MS**

The materials database includes >300 entries

D.S. Leonard et al., Nucl. Ins. Meth. A 591 (2008) 490
D.S. Leonard et al., Nucl. Inst. Meth. A 871 (Nov 2017) 169
M. Auger, et al., J. Inst. 7 (2012) P05010.

The background can then be directly measured in the data:

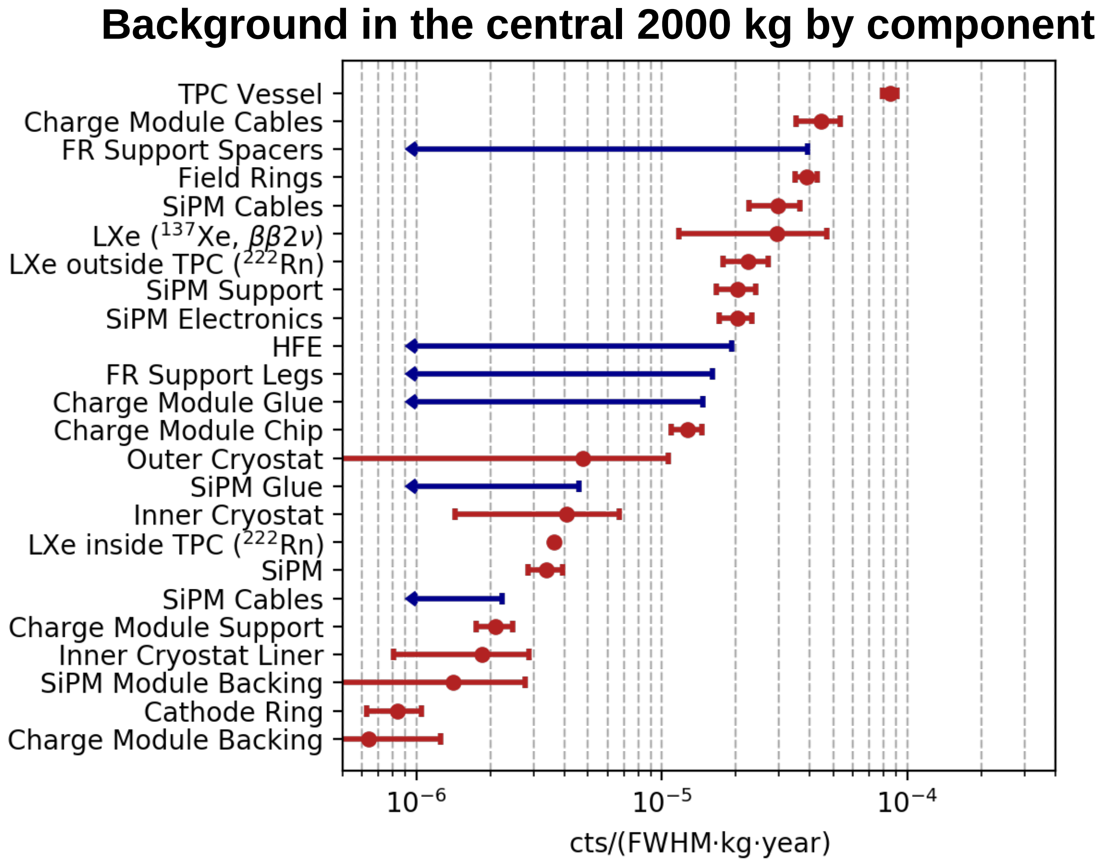
J.B. Albert, et al. Phys. Rev. C 92 (2015) 015503.

Events in ±2σ around Q	Radioactive bkgd prediction during construction	Radioactive bkgd prediction using current Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit
90%CL Upper	122	56	18	63.2 ± 4.7 (65 events observed)
90%CL Lower	24	8.2		

nEXO sensitivity and discovery potential

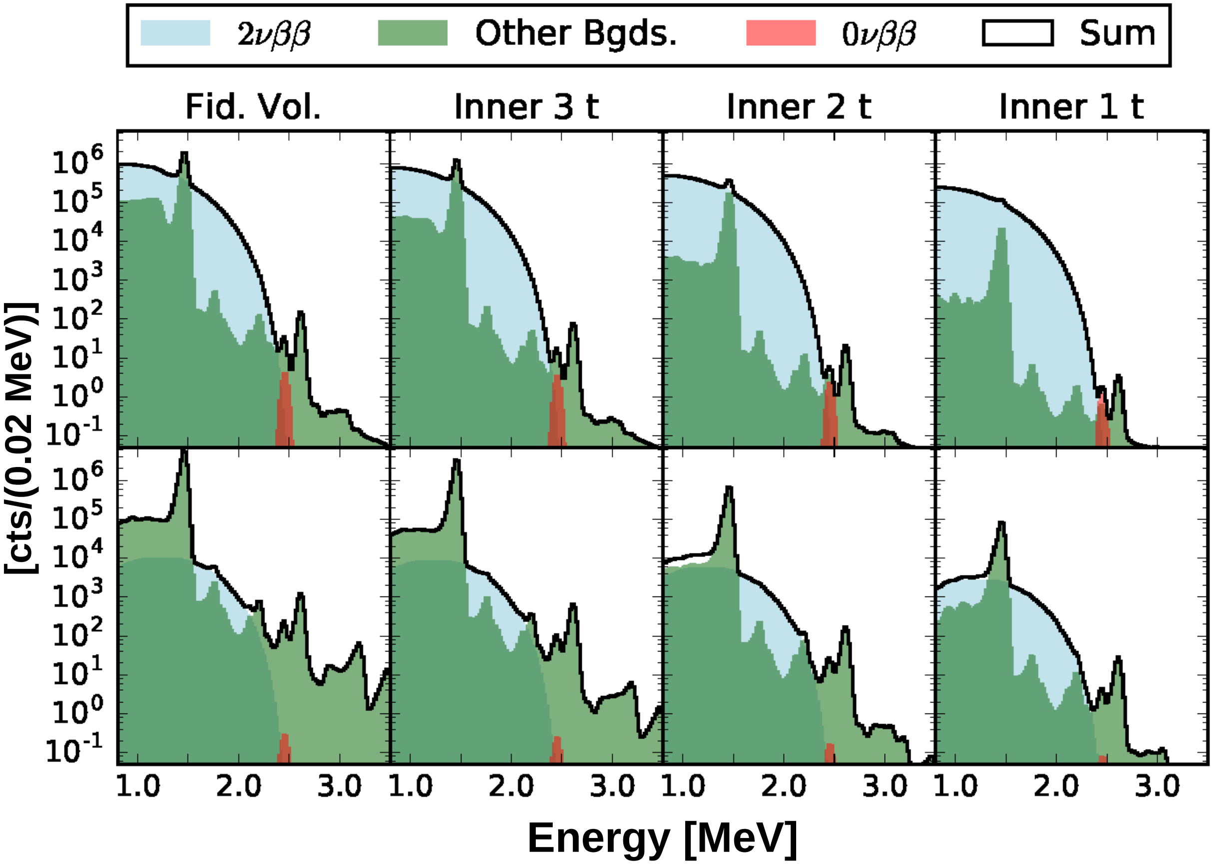
What goes in the model is:

- **the geometry,**
- **the radioactivity measured on existing materials**
  (some from EXO-200, some "freshly" measured)
- **physics well known to GEANT (mainly γ transport)**



Particularly in the larger nEXO, background identification and rejection fully use a fit considering simultaneously energy, e-γ and α-β discrimination and event position.

➔ ***The power of the homogeneous detector, this is not just a calorimetric measurement!***

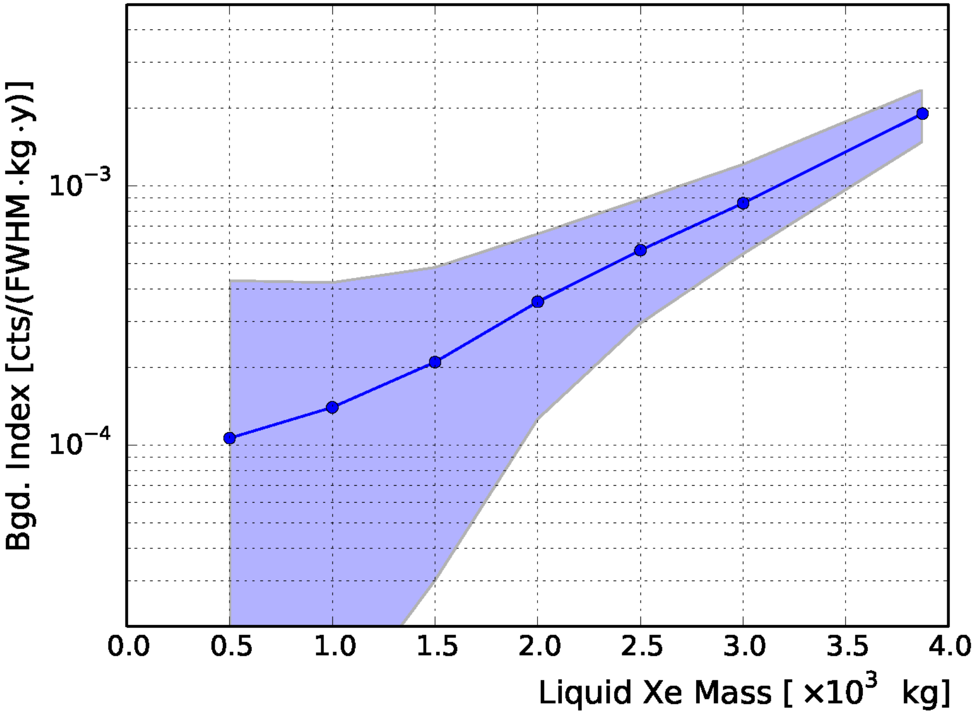


Corresponding to 10 yr data, with $0\nu\beta\beta$ $T^{1/2}$=5.7x10^{27} yr

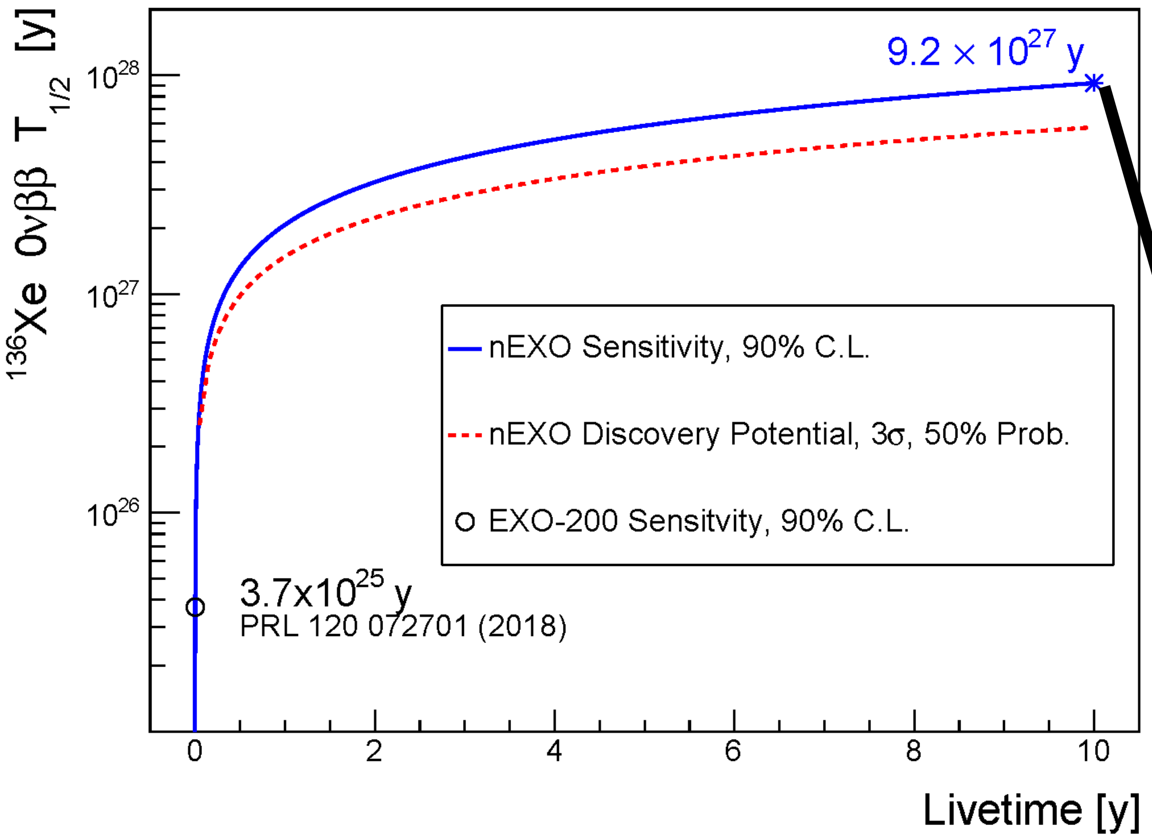
So, a simple "background index" is not the entire story.

-*The innermost LXe mostly measures signal*
-*The outermost LXe mostly measures background*
-*The overall fit knows all this (and more) very well and uses all the information available to obtain the best sensitivity*

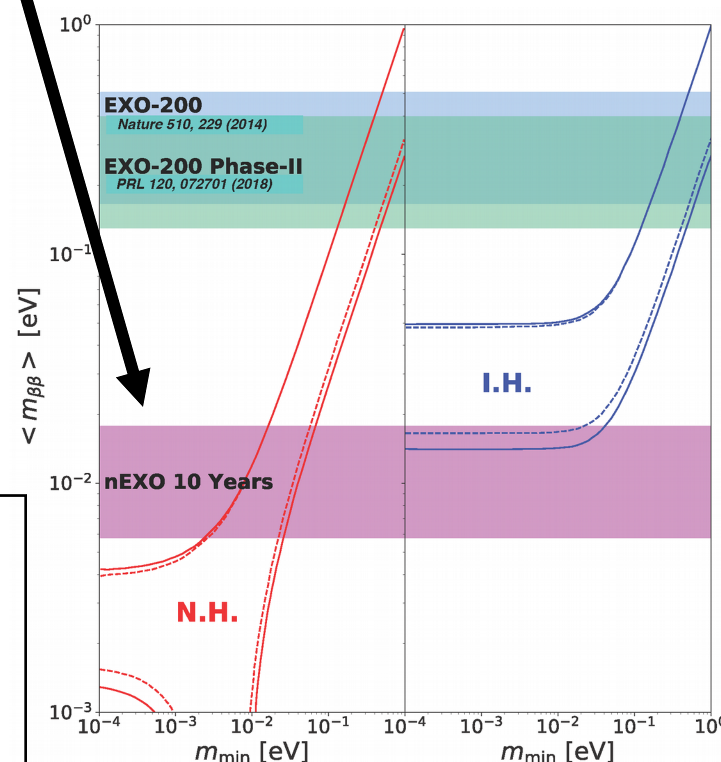
Nevertheless, for the aficionados of "background index", here it is, as a function of depth in the TPC. For the inner 3000 kg this is better than 10^{-3} (kg yr FWHM)$^{-1}$



Sensitivity as a function of time for the baseline design



~30% increase in sensitivity expected with new analysis



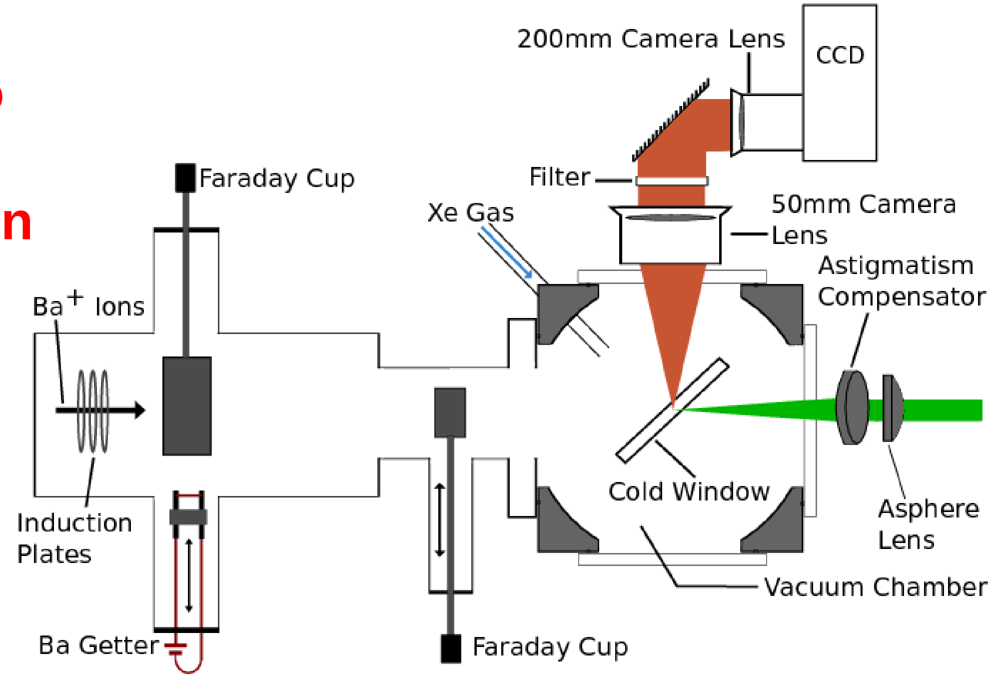
- $g_A = g_A^{free} = -1.2723$
- **Band is the envelope of NME:**

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

In fact, ^{136}Xe offers the possibility to confirm a ββ decay by retrieving and tagging spectroscopically the Ba atom in the final state.

This is not necessary for nEXO to reach its design sensitivity and, indeed, it is not part of the design presented in the pre-CDR.

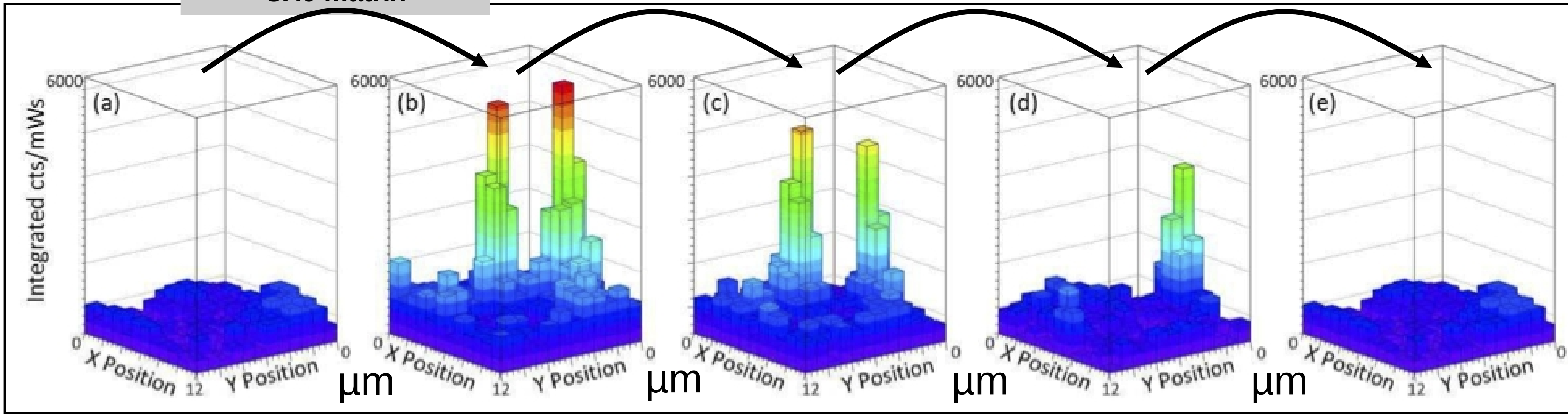
Nevertheless the "physics component" of the technique was recently demonstrated, including the ability to delete "old" Ba atoms (i.e. there is no "memory effect").



This work only addresses the physics feasibility, while the engineering of its implementation has not been explored yet.

Possibly Ba tagging could become a long term upgrade patch, extending the sensitivity of the experiment after a 5 to 10yr run in the baseline configuration.

Accelerator deposits a few atoms in the SXe matrix → **Wait a little** → **Wait some more** → **Warm up**



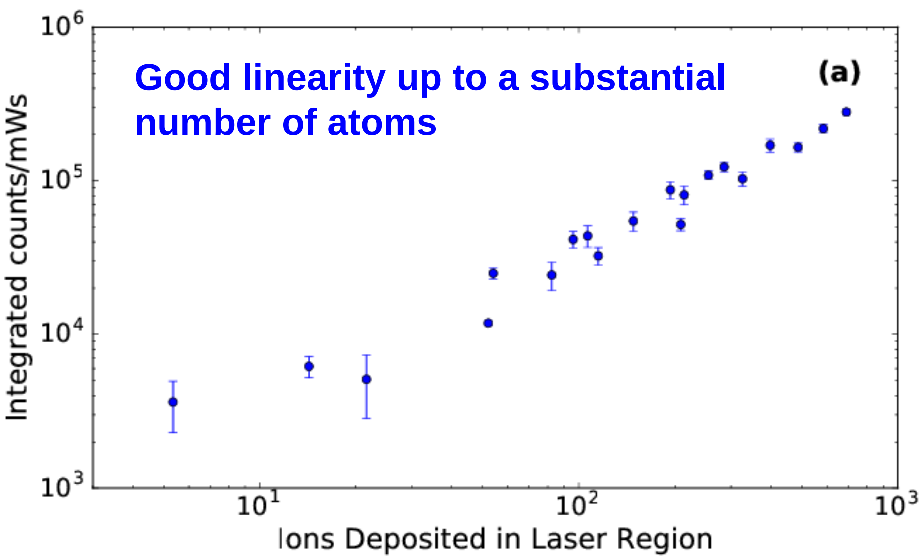
SXe but no Ba

Oh, there are two atoms!

The Ba signal is still present

One of the Ba signals is no longer present

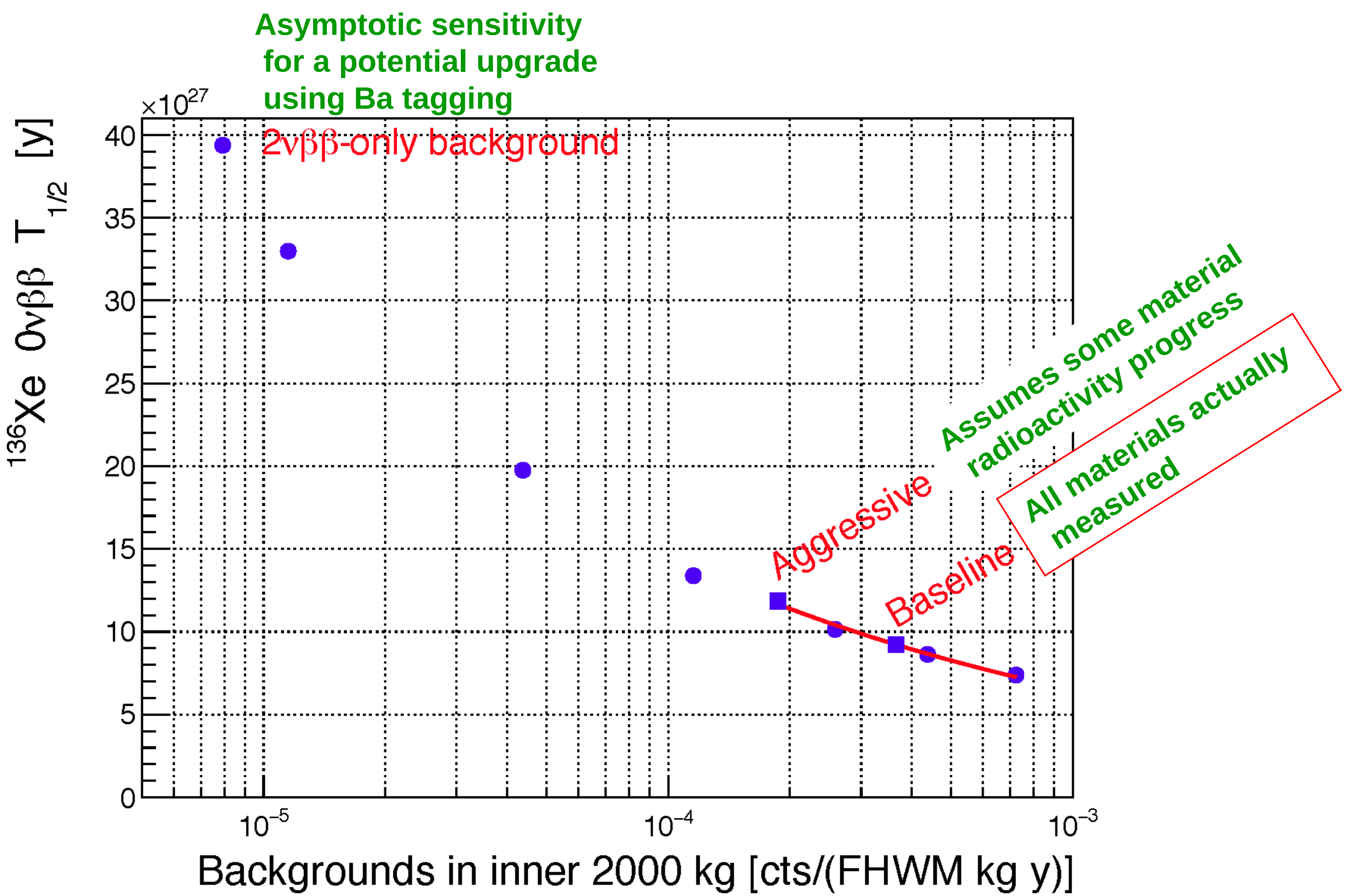
Signal is erased, back to pre-Ba signals



C.Chambers et al. Nature 569 (2019) 203

see also similar result in
A.D. McDonald et al., Phys Rev Lett 120 (2018) 132504.

How does the sensitivity scale with background assumptions?



Conclusions

- **EXO-200 was the first 100kg-class experiment to run and demonstrated the power of a large and homogeneous LXe TPC.**
- **EXO-200 finished in Dec 2018 and is now decommissioned… was a good run! The final $0\nu\beta\beta$ result with the full data set is now out.**
- **This is clearly the way to go for tonne-scale detectors, as the power of the technique will further improve with increasing size.**
- **At this time, the nEXO design is mature and documented by the pCDR document and a detailed sensitivity analysis paper.**
- **New and exciting results from the Ba tagging effort (not part of the nEXO baseline) suggest that there may be a path for a future upgrade beyond nEXO.**

nEXO

Seven Countries, 31 institutions, >150 collaborators

The nEXO collaboration

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