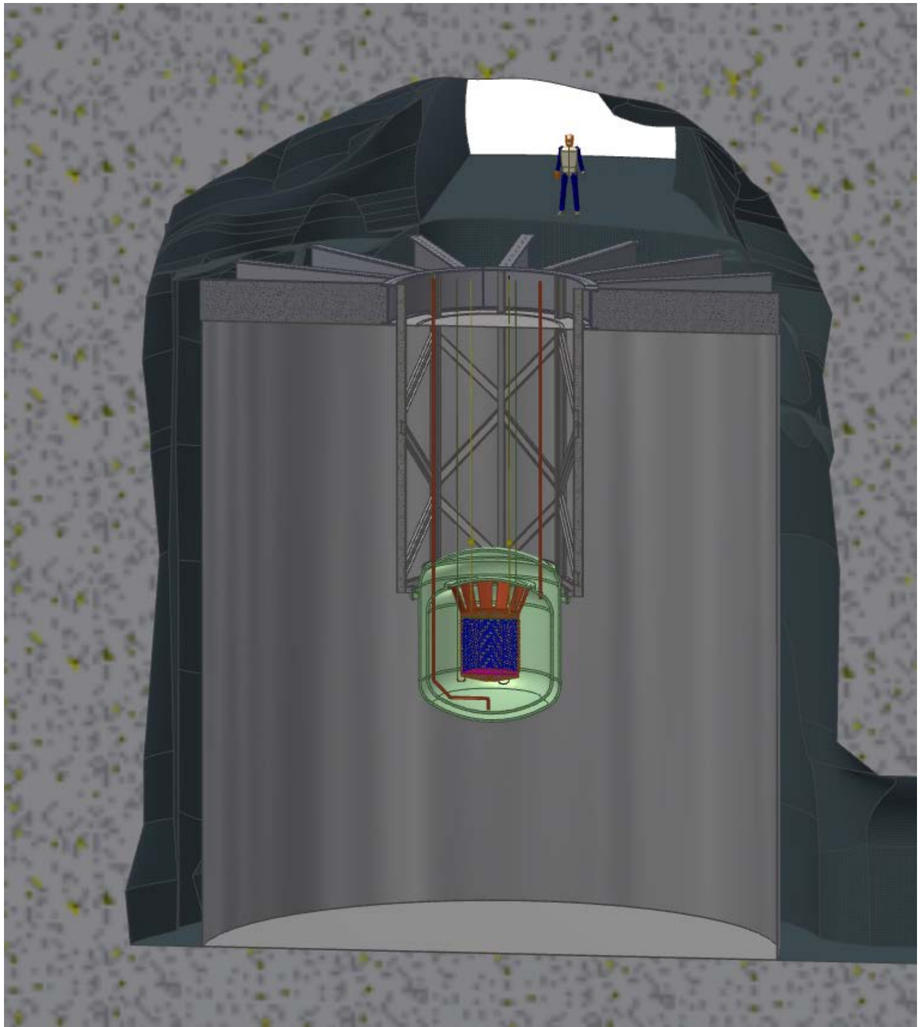
nEXO

Giorgio Gratta
for the nEXO collaboration



Enriched Xenon Observatory
EXO
for double beta decay

The nEXO Collaboration

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[†] Now at Carleton University

The nEXO Collaboration

The collaboration includes 138 scientists and engineers
from 27 institutions
and 7 Countries
(4 US National Labs and 3 non-US National Labs)

Very healthy and driven mix of

- Young and more experienced players,
- University groups and Nat’s Labs,
- US and “foreign” institutions

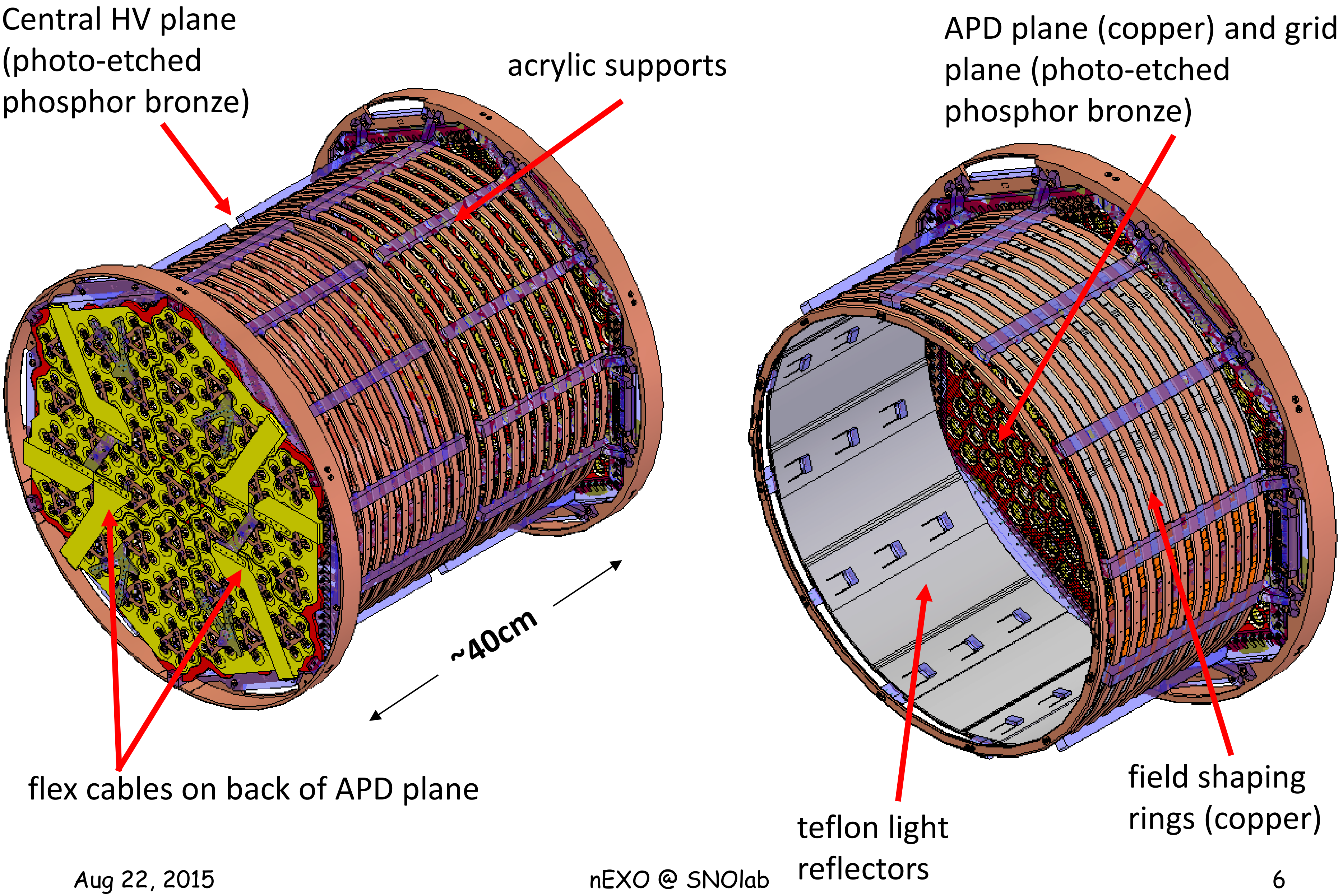
Unusually broad expertise in techniques, analysis, hardware, neutrino physics,…

ཐིམ་ཕུ་ འབྲུག་ཡུལ (Thimphu, Bhutan) Feb 2015

EXO: the long term vision

- Working since 1999 on a staged approach to 0νββ decay
- "Stage 1", i.e. EXO-200 took data from May 2011 to Feb 2014 producing some of the most competitive results in the field
- EXO-200 detector performance was close to design from the very beginning of data taking, and improved during the run to exceed design e.g. in energy resolution 1.4% (design was 1.6%)
- After the WIPP accidents of Feb 2014, EXO-200 has been approved by DoE (Jun 2015) to restart and collect 3 more years of data
- As of Jun 3, 2015 M.Dolinski and L.Yang are EXO-200 spokespeople
- Present schedule has LXe fill in late Sept 2015
- EXO-200 is also a very successful prototype for a larger, "Stage 2" detector
- "Stage 2", nEXO, is being designed as a 5 tonne L^{enr}Xe detector following closely the EXO-200 experience, with important differences
- nEXO is also a very flexible and cost effective detector with a clear upgrade path and the built-in capability to address possible future science scenarios making the best use of the isotopically enriched isotope.

EXO-200 LXe TPC field cage & readout planes



Central HV plane (photo-etched phosphor bronze)

acrylic supports

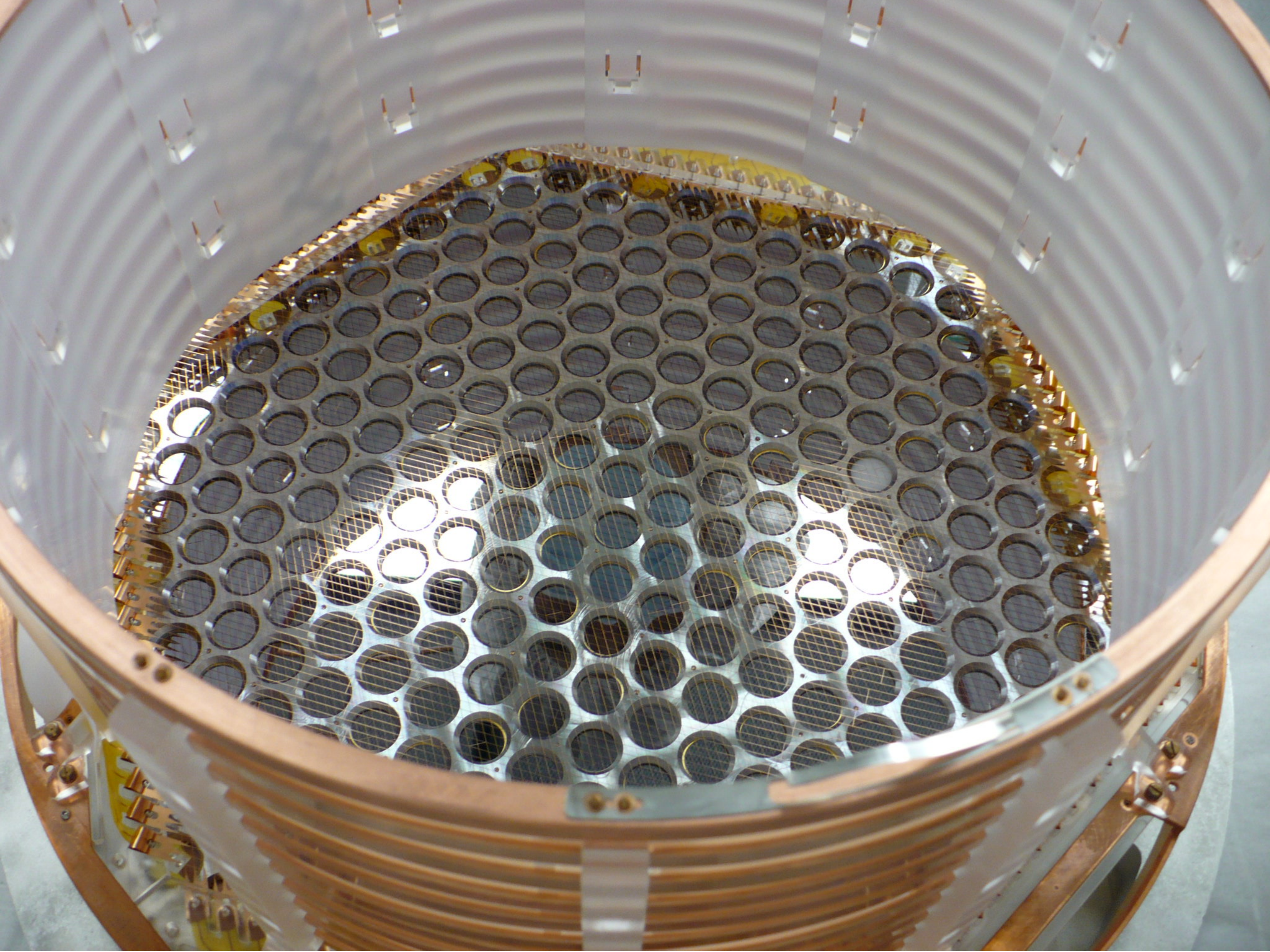
APD plane (copper) and grid plane (photo-etched phosphor bronze)

~40cm

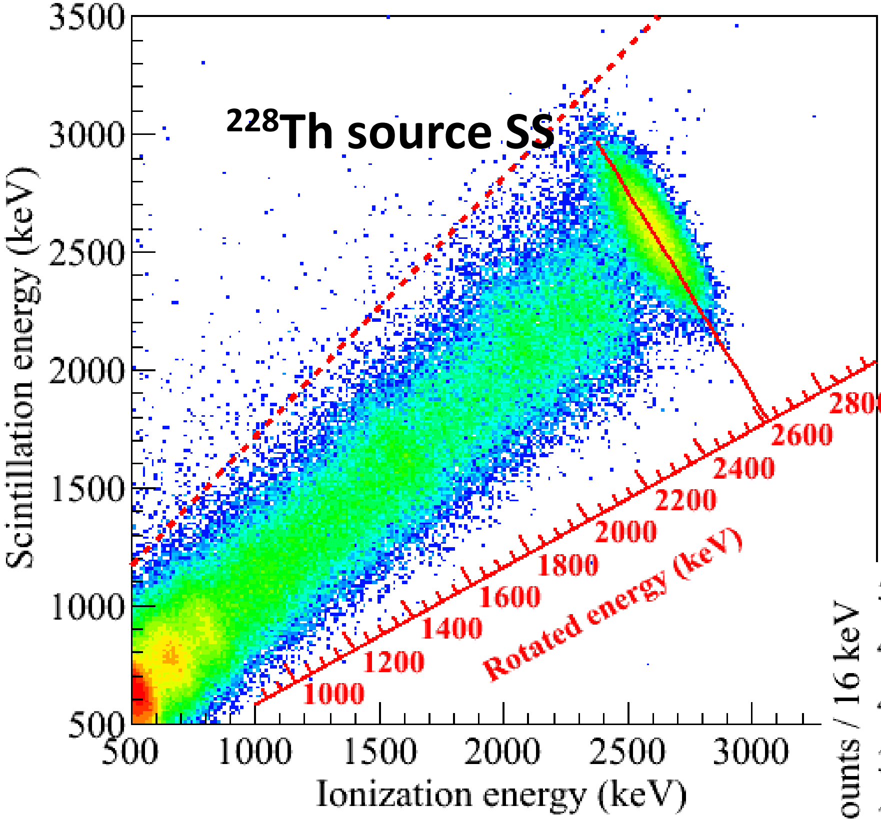
flex cables on back of APD plane

teflon light reflectors

field shaping rings (copper)



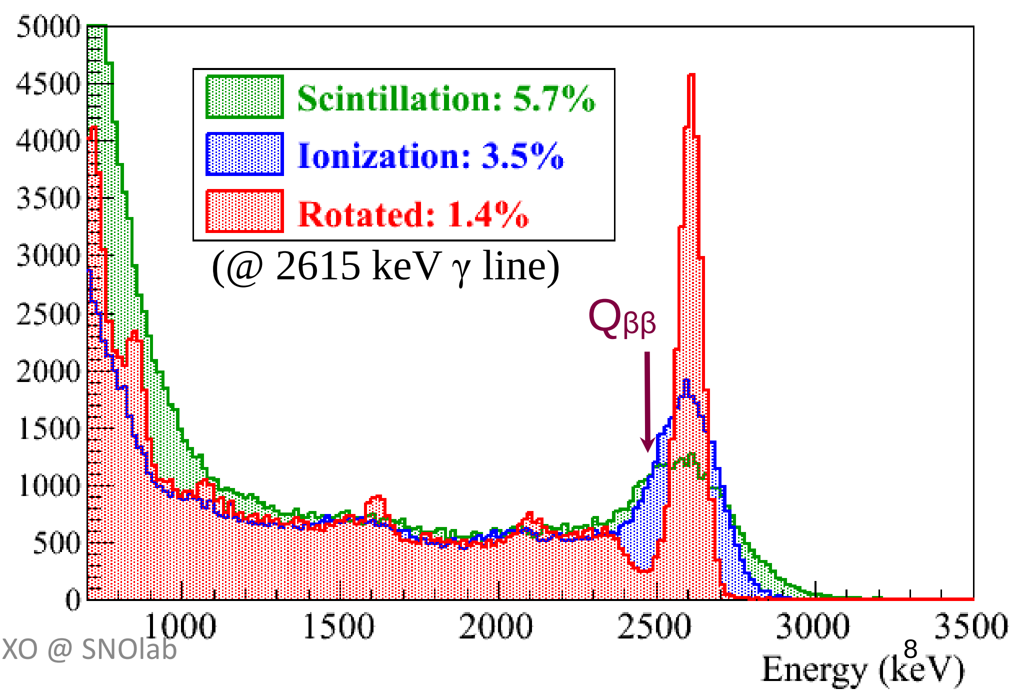
Combining Ionization and Scintillation in EXO-200



Anticorrelation between scintillation and ionization in LXe known since early EXO-200 R&D

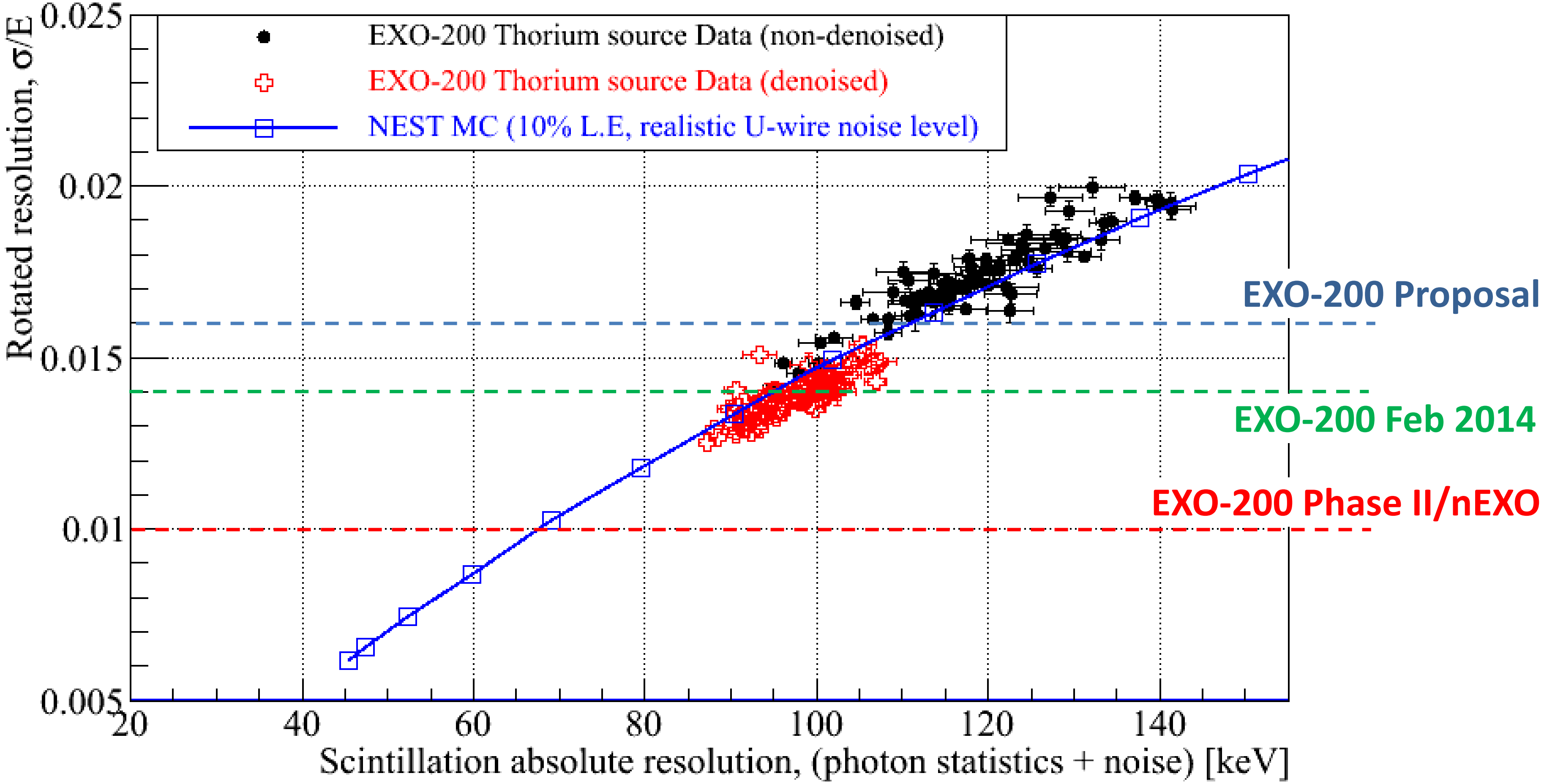
E.Conti et al. Phys Rev B 68 (2003) 054201

Design spec was 1.6% @2615keV

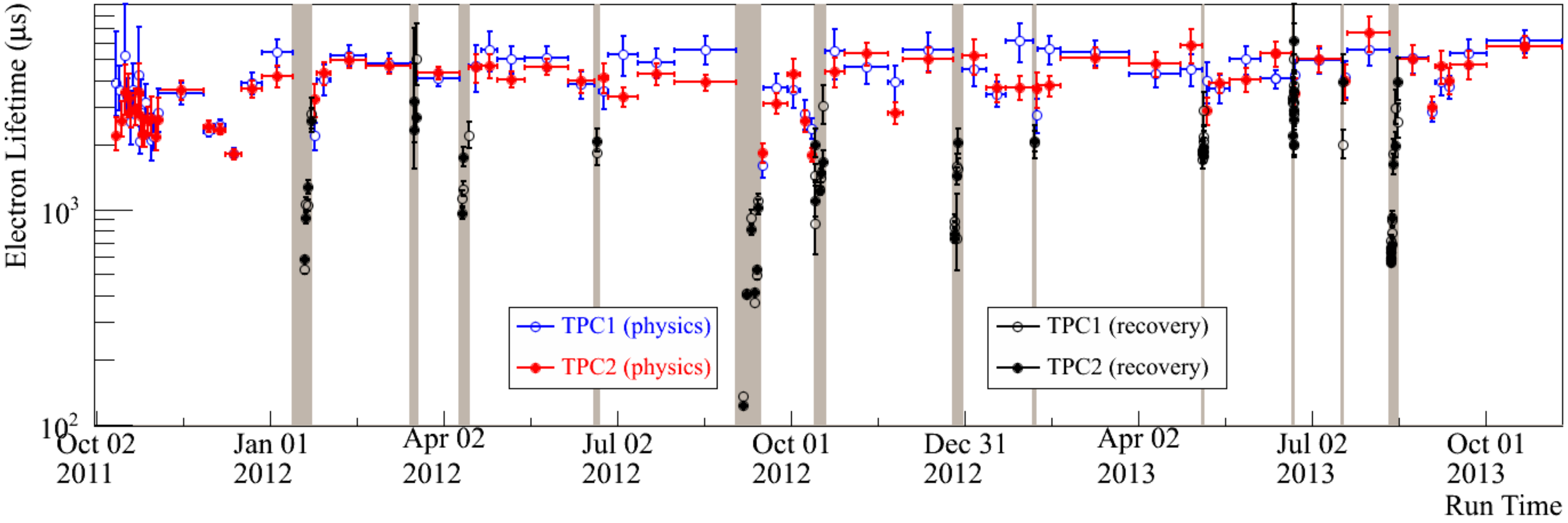


Rotation angle chosen to optimize energy resolution at 2615 keV

EXO-200 energy resolution



LXe “chemical” purity and electron lifetime

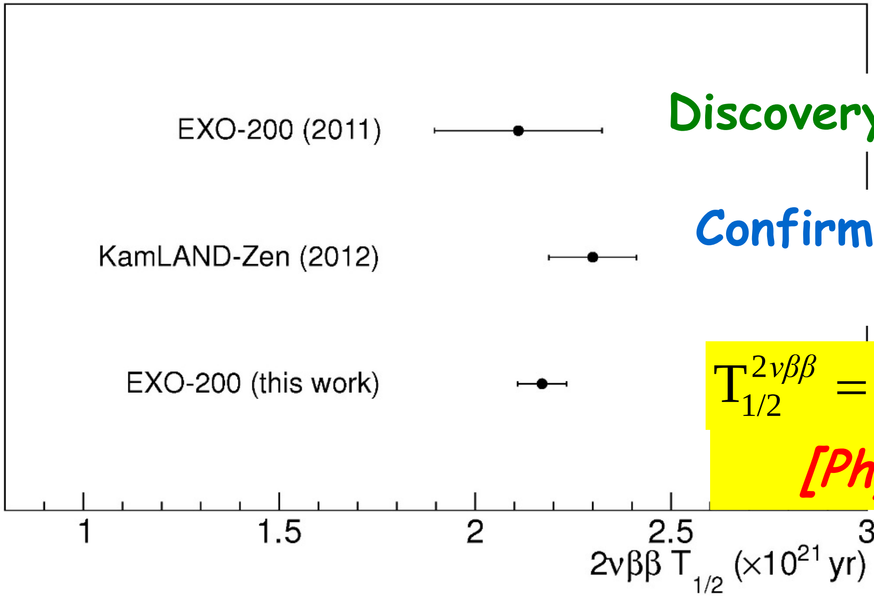


Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

At τ_e = 3 ms:

- **drift time <110 µs**
- **loss of charge: 3.6% at full drift length**

2νββ decay in EXO-200: the most accurate measurement and the rarest mode!



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

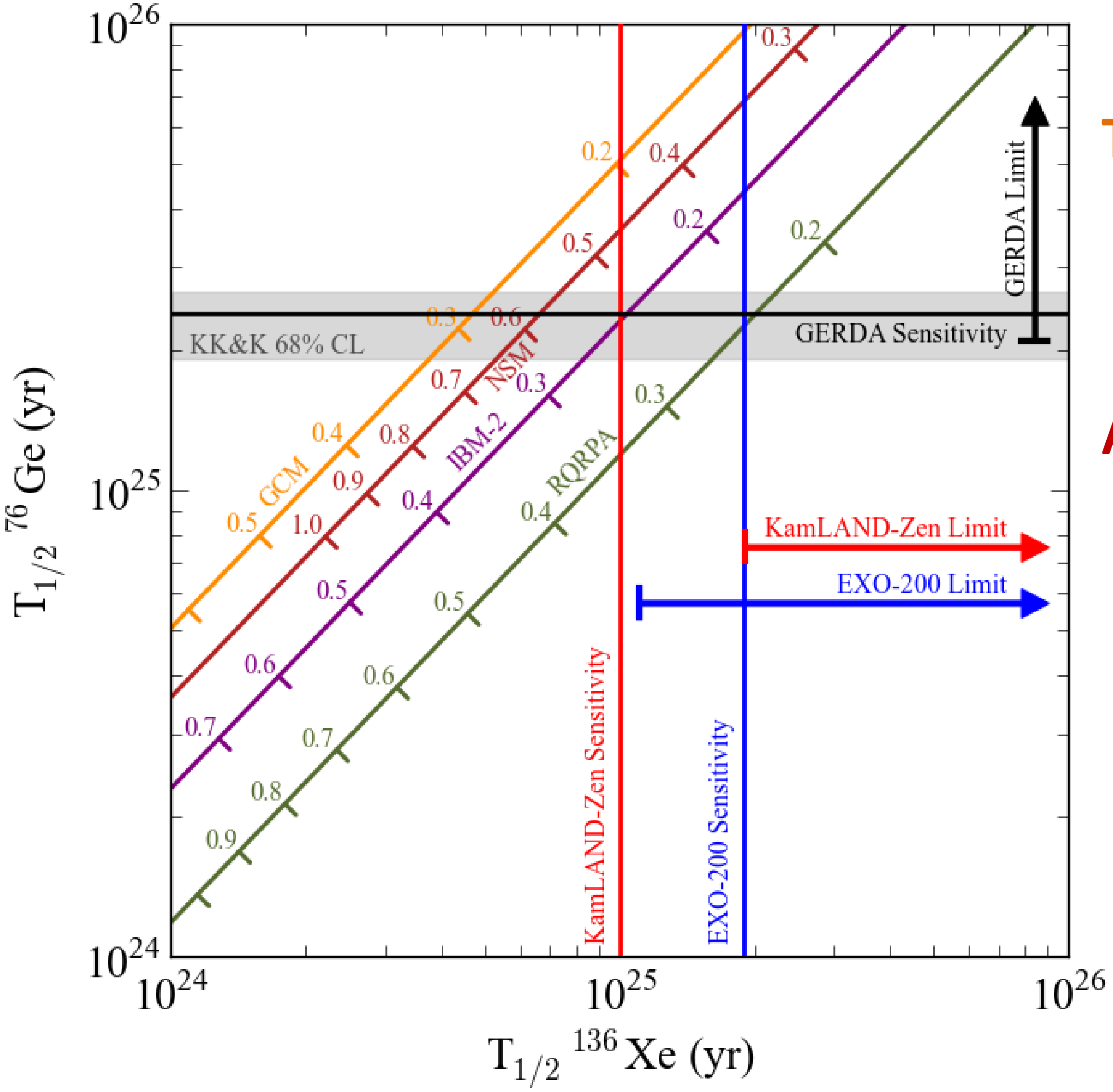
Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

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

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

Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)

… and 0νββ decay in EXO-200



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

<m_ν> < 190 – 450 meV

Average $T_{1/2}^{0\nu\beta\beta}$ sensitivity:

1.9·10^{25} yr

J.B.Albert et al. (EXO-200)
Nature 510 (2014) 229

Recent EXO-200 papers

J.B. Albert et al. “Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200”
arXiv:1506.00317 (Jun 2015), submitted to Phys. Rev. C.

J.B. Albert et al. "Investigation of radioactivity-induced backgrounds in EXO-200"
Phys. Rev. C 92 (2015) 015503

J.B. Albert, et al. "Search for Majoron-emitting modes of ββ decay of ^{136}Xe with EXO-200"
Phys. Rev. D 90 (2014) 092004.

J.B. Albert, et al. "Search for Majorana neutrinos with the first two years of EXO-200 data"
Nature 510 (2014) 229 [76 citations].

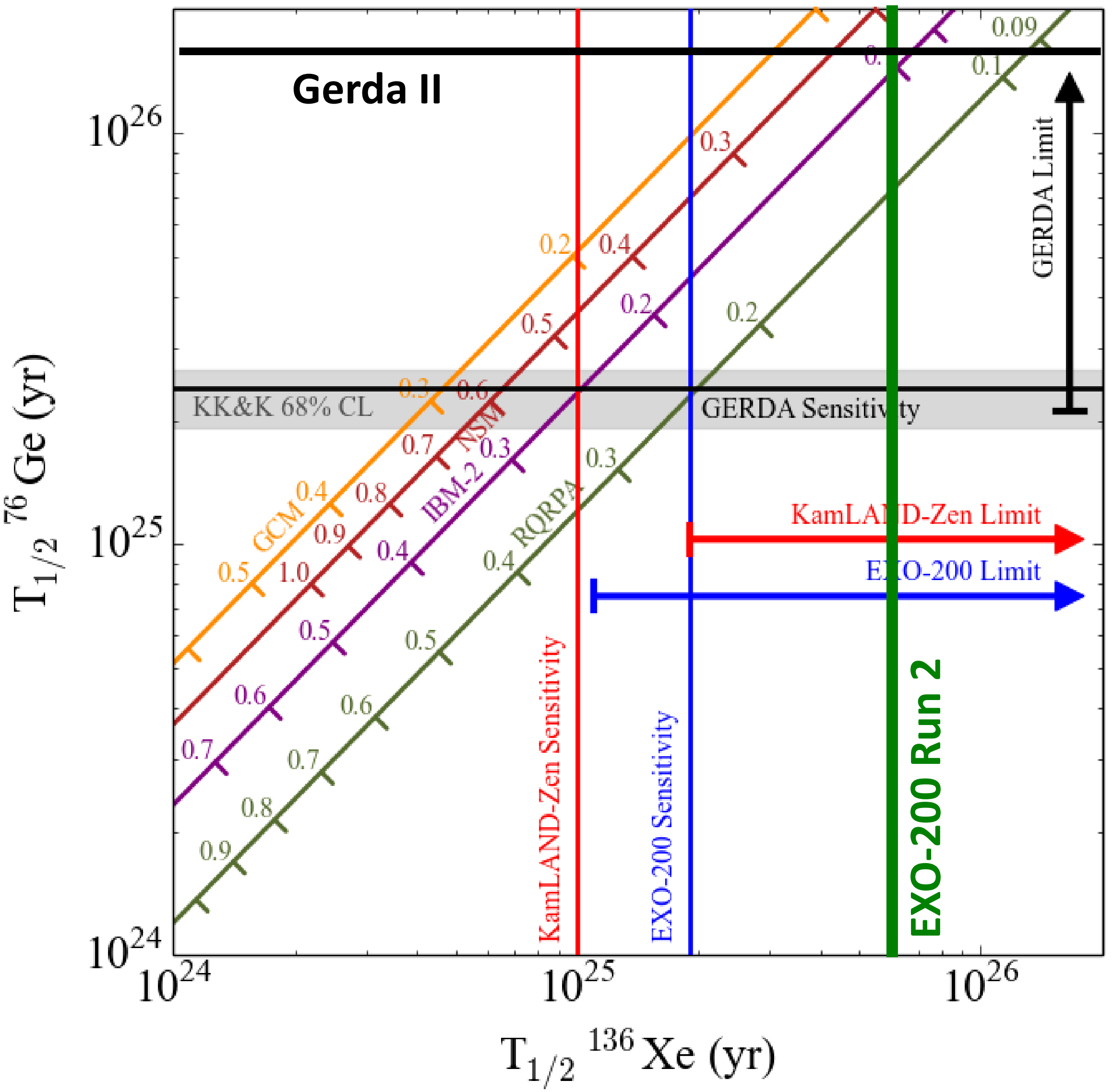
J.B. Albert, et al. "An improved measurement of the 2νββ half-life of Xe-136 with EXO-200"
Phys. Rev. C 89 (2014) 015502 [37 citations].

M. Auger, et al. "Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200"
Phys. Rev. Lett. 109 (2012) 032505 [286 citations].

M. Auger, et al. “The EXO-200 detector, part I: Detector design and construction”
J.Inst. 7 (2012) P05010.

N. Ackerman, et al. “Observation of Two-Neutrino Double-Beta Decay in ^{136}Xe with EXO-200"
Phys. Rev. Lett. 107 (2011) 212501 [103 citations].

EXO-200 Phase 2 projected sensitivity improvement vs Gerda II



From EXO-200 to nEXO

- EXO-200 Phase 2 is justified by a substantial increase in physics reach, not by nEXO (aka: nEXO does not need more EXO-200 data)
- EXO-200 demonstrated the principle of a homogeneous LXe TPC capable of measuring and suppressing backgrounds by the combined use of energy resolution, ionization density, event multiplicity and event distance from the closest wall.
- EXO-200 validated with actual science-grade data the choice of material and the model that was used to predict the detector background.
  - *J.B. Albert, et al. "Investigation of radioactivity-induced backgrounds" PRC 92, 015503 (2015).*
  - *M. Auger, et al. "The EXO-200 detector…" J. Inst 7 (2012) P05010.*

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		

From EXO-200 to nEXO

- nEXO will be a homogeneous 5 ton LXe TPC
  ➔ The multi-parameter approach tested in EXO-200 will be even more powerful in the larger nEXO

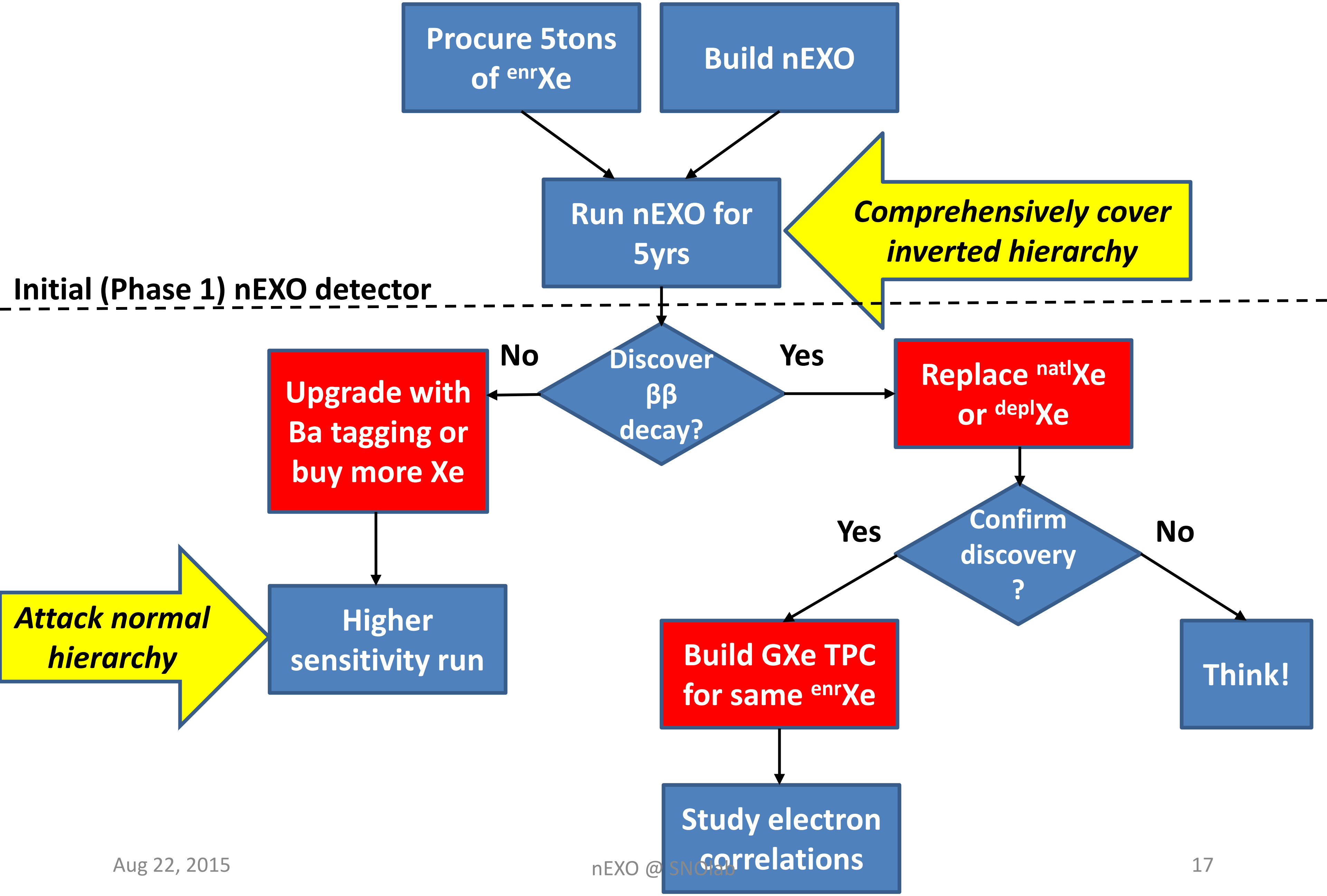
- This is a conservative choice because the technique has been validated by EXO-200 and the material selection and background estimation procedures are known to work from the comparison with EXO-200 data.

- Some R&D is required to verify that the various steps planned for the scale-up are feasible.
  ➔ This is a feature of a homogeneous detector.

- nEXO is cost effective, owing to the relatively low cost of Xe enrichment (5 ton of ^{136}Xe ≈ 50M$) and the homogeneous structure of the detector.

- nEXO is also a very flexible detector with a clear upgrade path and the built-in capability to address possible future science scenarios making the best use of the isotopically enriched isotope.

Flexible program based on the initial nEXO investment



Procure 5tons of ^{enr}Xe

Build nEXO

Run nEXO for 5yrs

Comprehensively cover inverted hierarchy

Initial (Phase 1) nEXO detector

Discover ββ decay?

No

Upgrade with Ba tagging or buy more Xe

Higher sensitivity run

Attack normal hierarchy

Yes

Replace ^{natl}Xe or ^{depl}Xe

Confirm discovery ?

Yes

Build GXe TPC for same ^{enr}Xe

Study electron correlations

No

Think!

One essential point:

THIS IS NOT A PURE CALORIMETER

To think about nEXO exclusively in terms of energy resolution is misleading

nEXO uses optimally *more* than just the energy measurement.

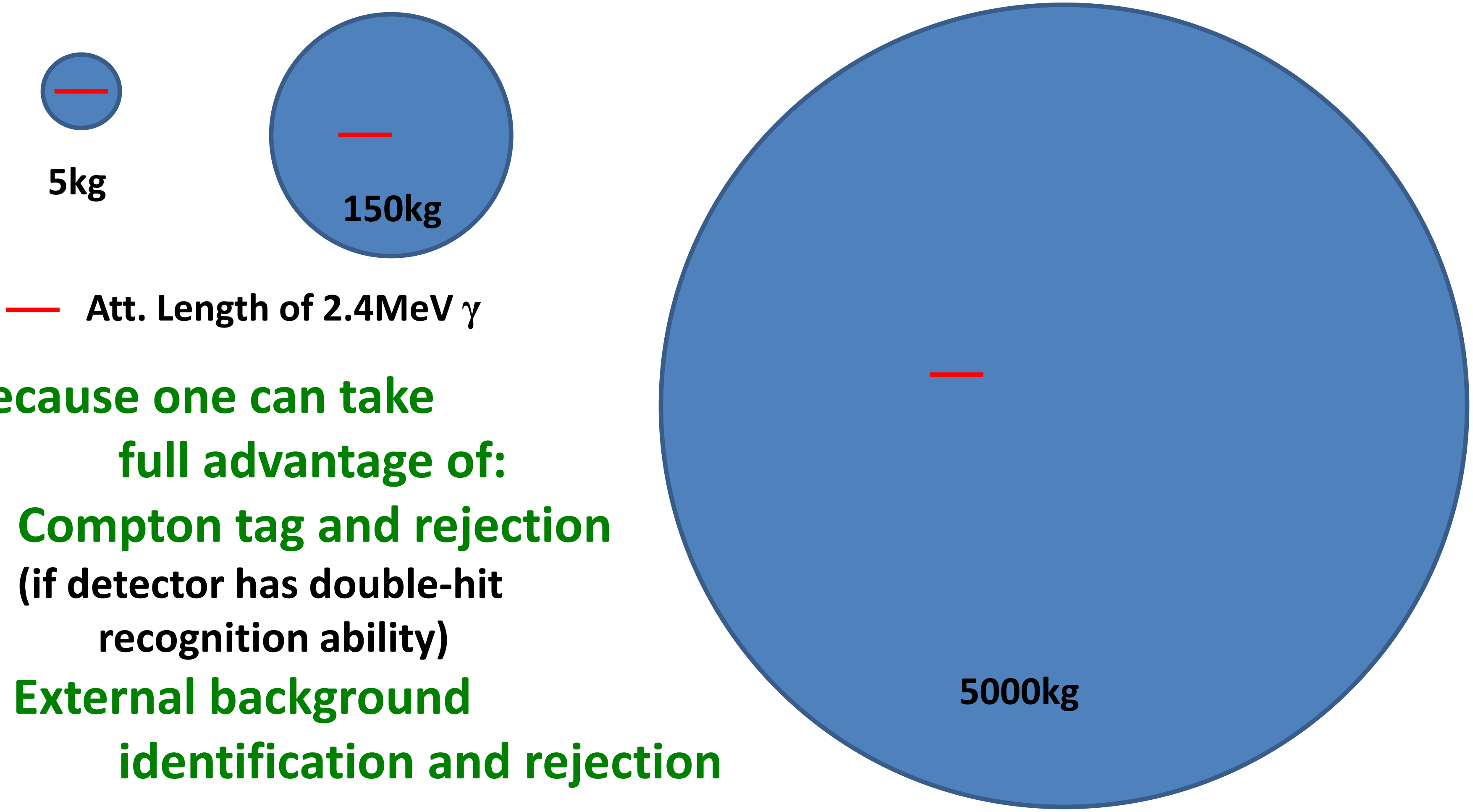
The signal/background discrimination is based on four parameters:

1. **Energy measurement**
2. **Event multiplicity (SS/MS in EXO-200)**
3. **Distance from the TPC surface**
4. **Particle ID (α-electron)**

These two only work optimally for homogeneous detectors

There is no rational reason to prefer the use of an "Energy ROI" over a "topology ROI" or a "topology ⊗ energy ROI". In fact, more independent axes provide a more powerful constraint on the signal.

Homogeneity is an essential feature of nEXO



Because one can take full advantage of:

1) Compton tag and rejection

(if detector has double-hit recognition ability)

2) External background identification and rejection

The larger the detector the more useful this is.

➔ Ton scale is where these features become dominant.

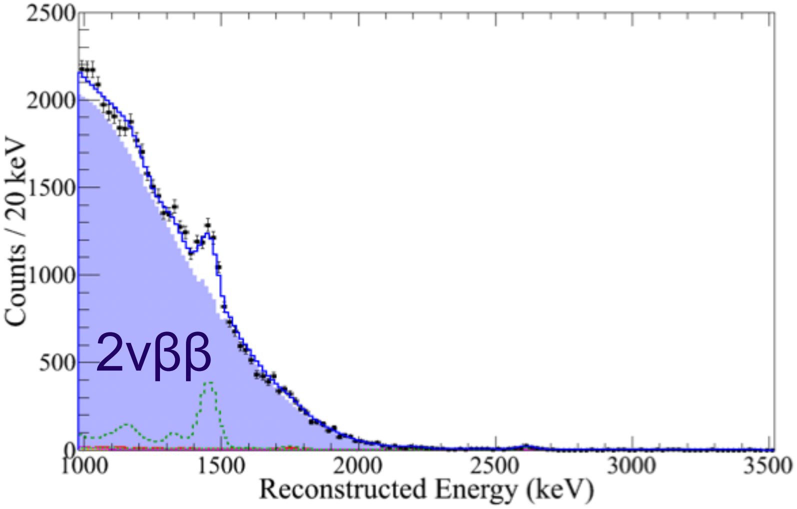
Event multiplicity and background discrimination

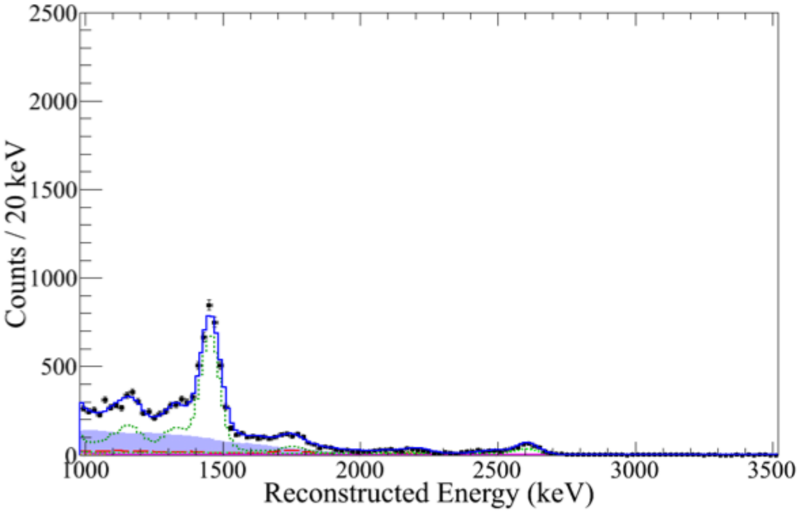
(example from EXO-200 real data)

Single Site (SS)

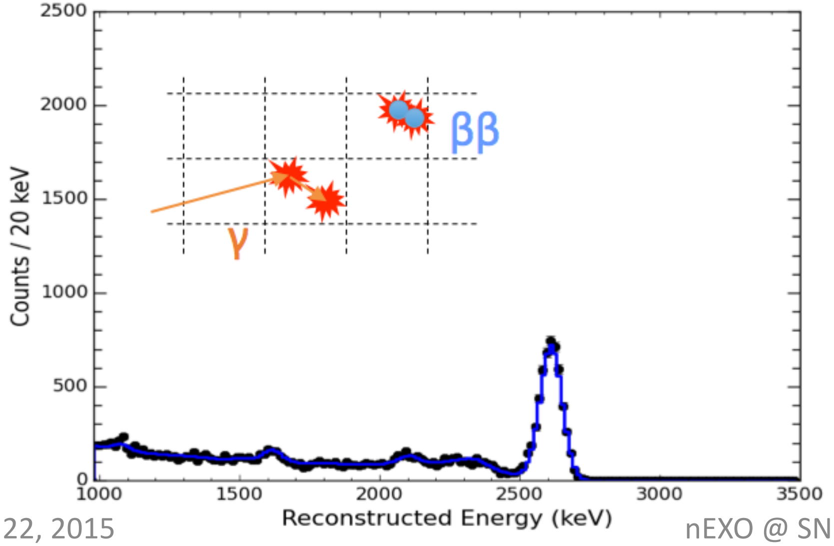
Multiple Site (MS)

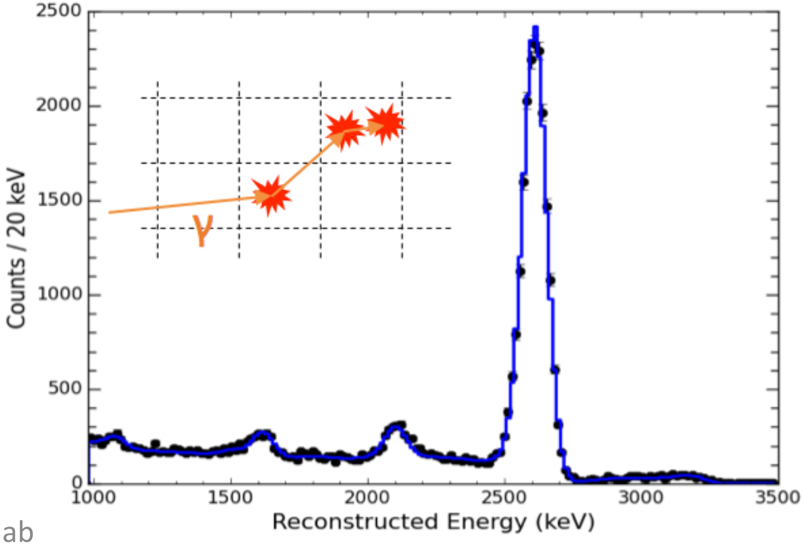
Low Background Data





^{228}Th Calibration Source

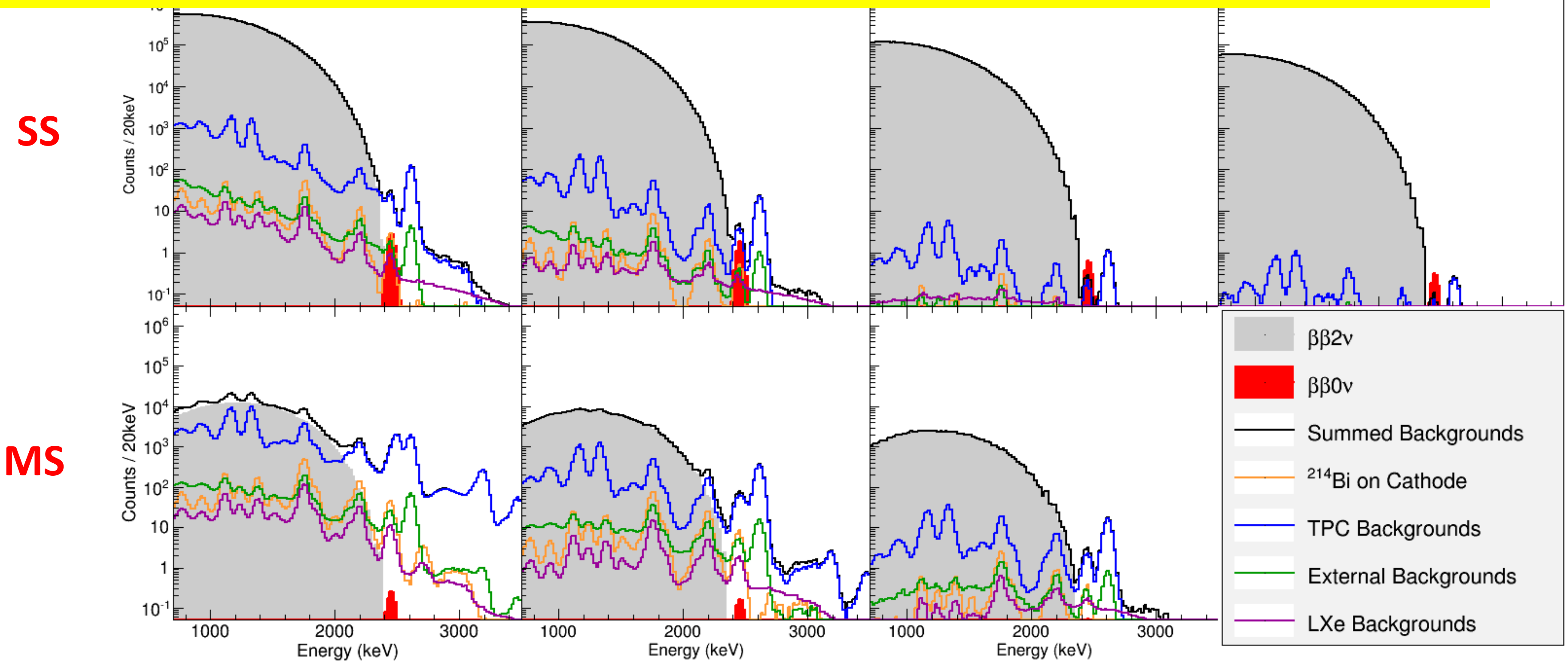




The role of the standoff distance in background identification and suppression

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

Correlation matrix from the fit

The largest correlation term for $0\nu\beta\beta$ is with the ^{238}U chain because of the ^{214}Bi line.

Yet, this is a relatively small (anti)correlation that allows the $0\nu\beta\beta$ signal to be well identified.

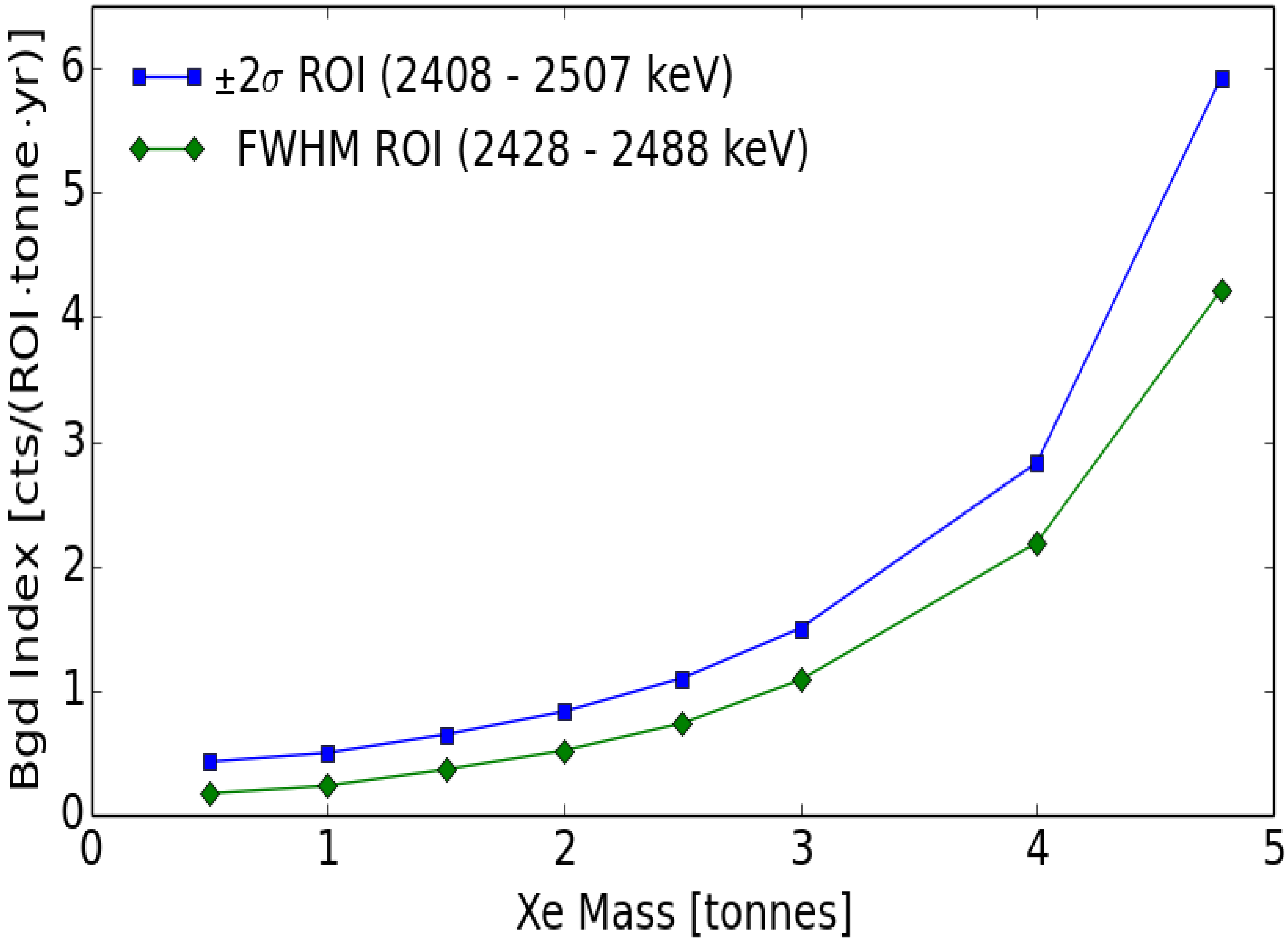
	APD+fieldrings	Cathode ^{214}Bi	TPC ^{232}Th	TPC ^{238}U	LXe ^{222}Rn	LXe ^{137}Xe	TPC ^{60}Co	$0\nu\beta\beta$	$2\nu\beta\beta$
APD+field rings	1	-0.25	-0.05	0.24			-0.78	-0.01	
Cathode ^{214}Bi	-0.25	1	0.28	-0.95			0.36	0.03	0.07
TPC ^{232}Th	-0.05	0.28	1	-0.31		-0.03	-0.07	0.01	-0.01
TPC ^{238}U	0.24	-0.95	-0.31	1	-0.05		-0.38	-0.10	-0.09
LXe ^{222}Rn				-0.05	1	-0.05			
LXe ^{137}Xe			-0.03		-0.05	1		-0.07	
TPC ^{60}Co	-0.78	0.36	-0.07	-0.38			1	0.02	-0.06
$0\nu\beta\beta$	-0.01	0.03	0.01	-0.10		-0.07	0.02	1	0.04
$2\nu\beta\beta$		0.07	-0.01	-0.09			-0.06	0.04	1

Entries <0.01 are suppressed and constraints are not listed for clarity/simplicity.

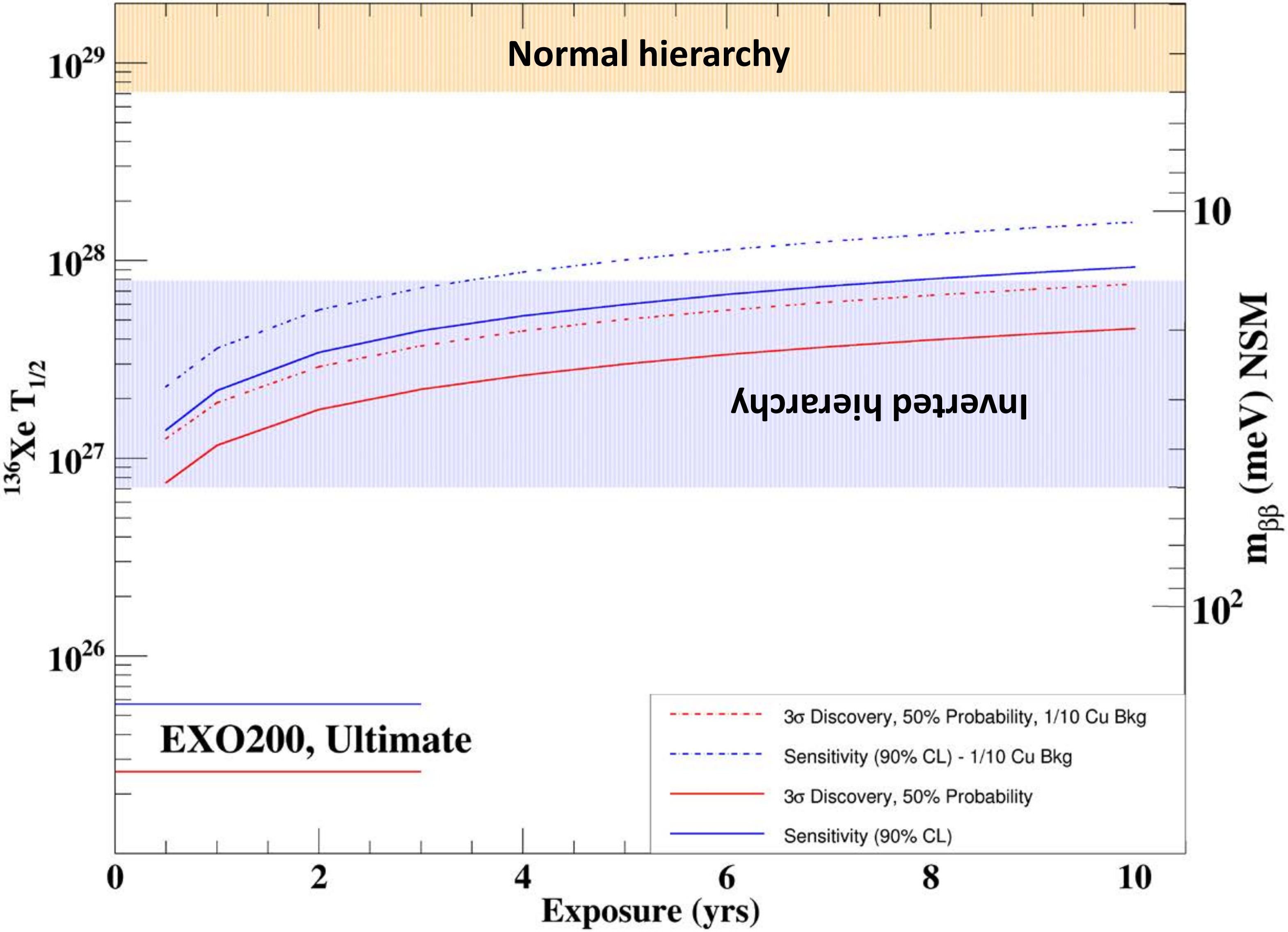
Note that an unknown gamma line would likely be identified by the same fit procedure.

Background Index [in counts/(ROI·tonne·yr)] versus fiducial volume is shown for two choices of the ROI: ±2·σ and FWHM.

Note that in nEXO the Background Index is not a single number

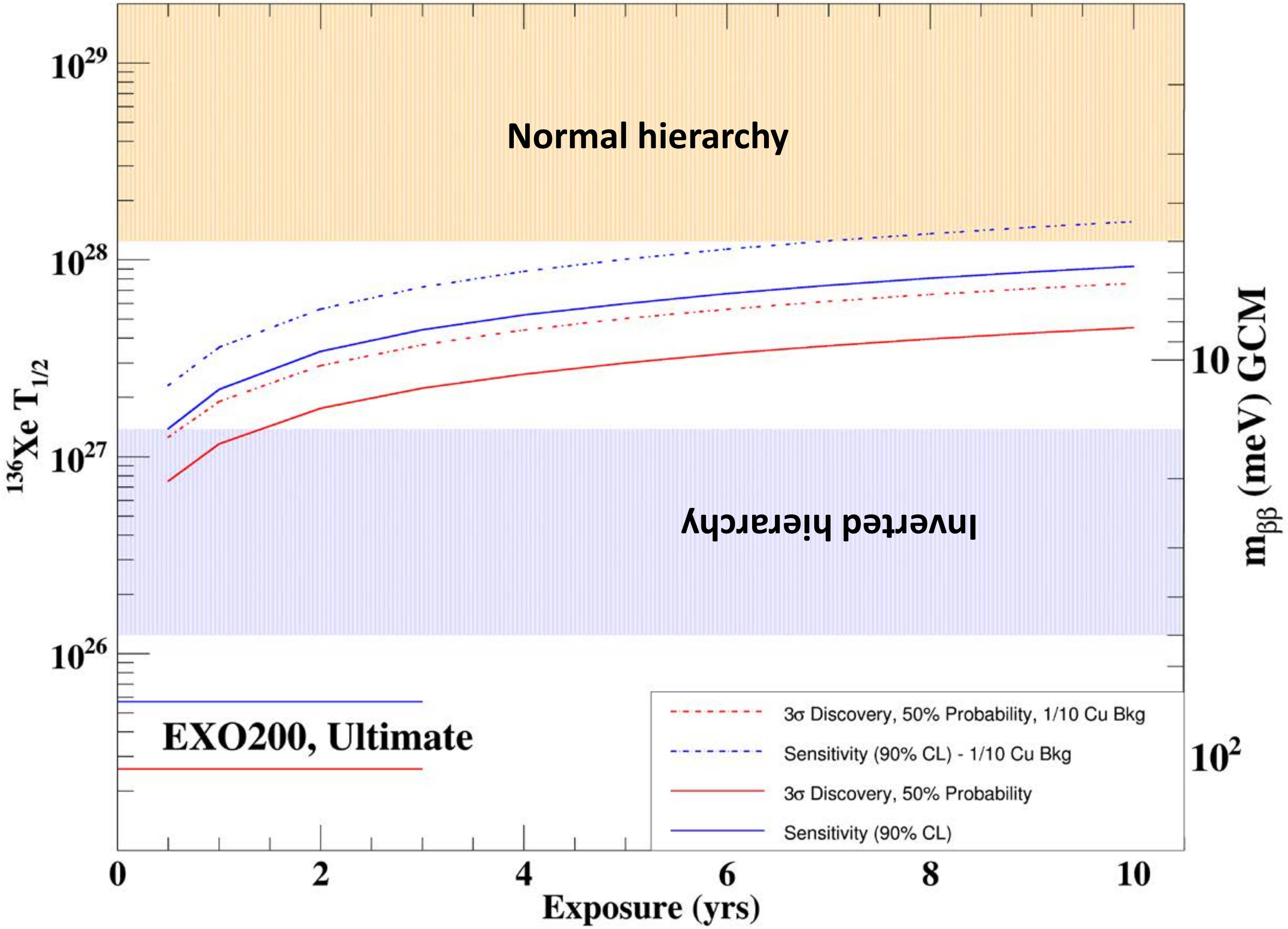


Sensitivity as a function of time for the worst-case NME (Shell Model)



NSM: Menendez, Poves, Caurier, Nowacki, Nucl.Phys. A 818 (2009) 139

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



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

R&D on (and later qualification of) low background materials has been carried out very successfully for EXO-200 and is in full swing for nEXO (see later).

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

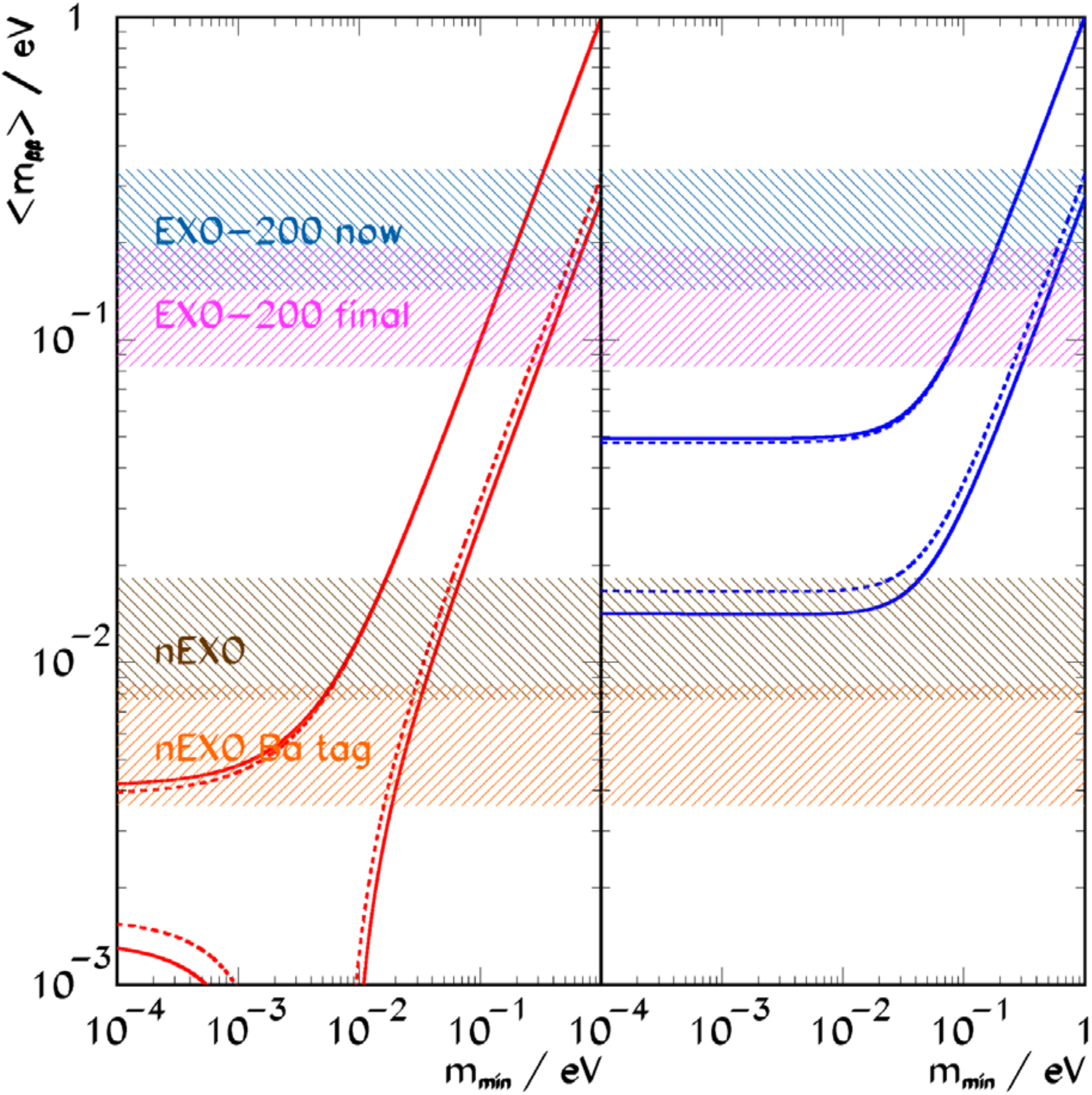
	~U, Th (ppt)
EXO-200 ICPMS measurement (Aurubis copper)	< 6, <14
EXO-200 measurement (Aurubis process)	< 4
nEXO measurement of Aurubis copper	< 1
PNNL measurement of electroformed Cu	~ 0.01

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

This is the figure in the report provided in July 2015.

It uses the projected sensitivity 90%CL, 5 years of data (@90% live)

for the most conservative Copper background only.



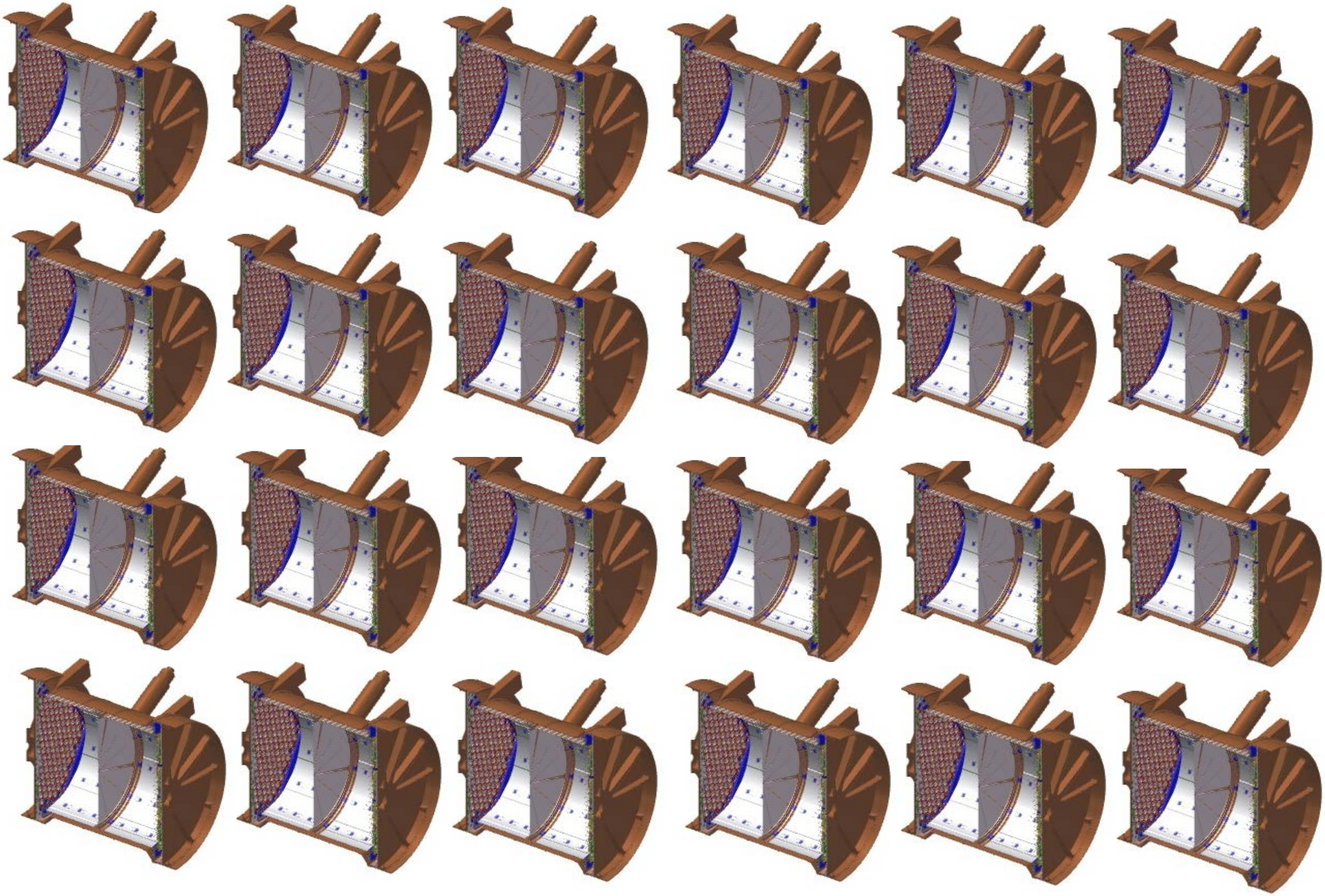
NH and IH bands are also 90%CL

Forero et al., PRD 90 (2014) 093006
Forero et al., Private Comm.

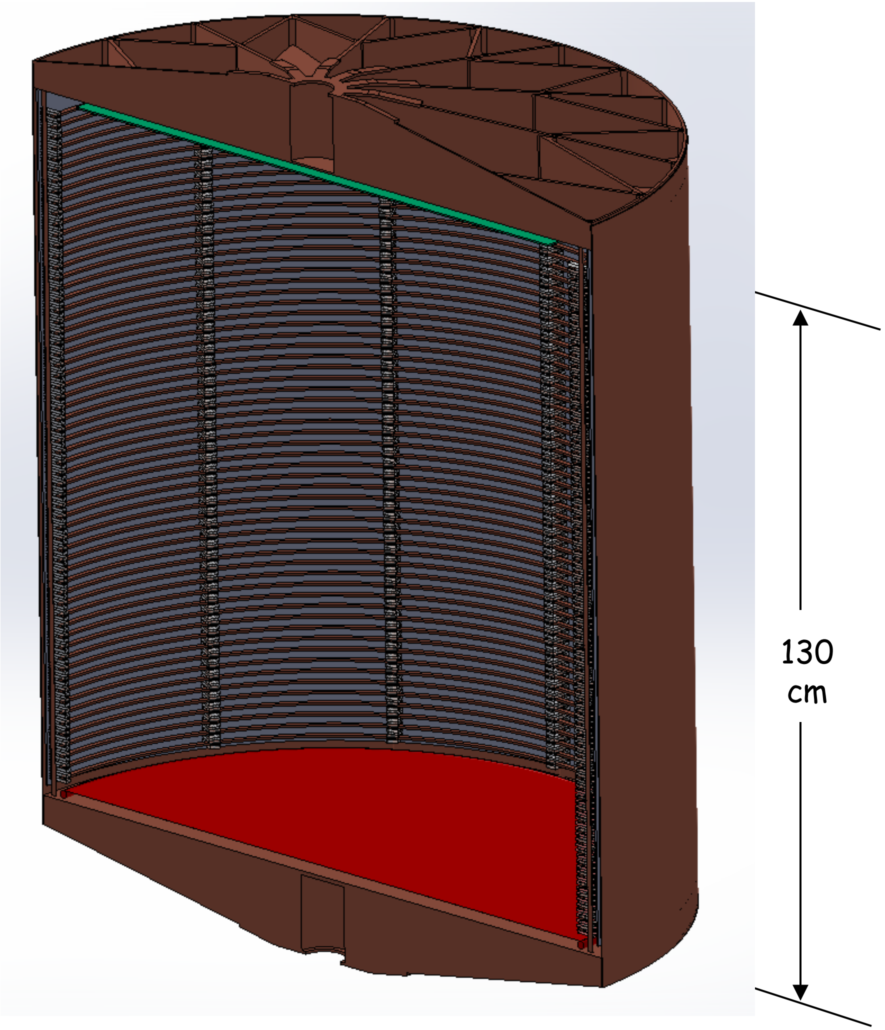
Designing nEXO:

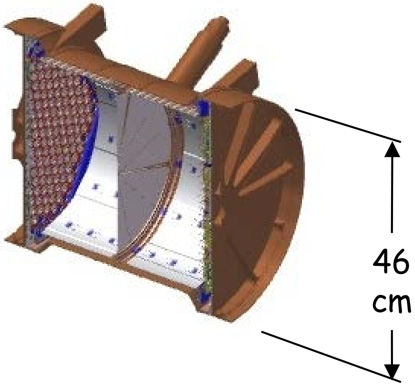
A large,
homogeneous,
optimized detector

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



The nEXO detector





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, 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

The nEXO pre-CD R&D program

Priority	#	Title	Comment
1	1	High Voltage	
	2	Photodetectors	
2	3	Low background, cryogenic electronics	Because of the very integrated nature of the nEXO detector, these two items are intimately related with each other
	4	Novel, low background TPC concepts	
3	5	Calibration concepts	
4	6	Low background vessels	
-	7	Radiopurity investigations	While these two items do not have an intrinsic priority, they support all of the other R&D efforts
-	8	Simulation	

1) High Voltage

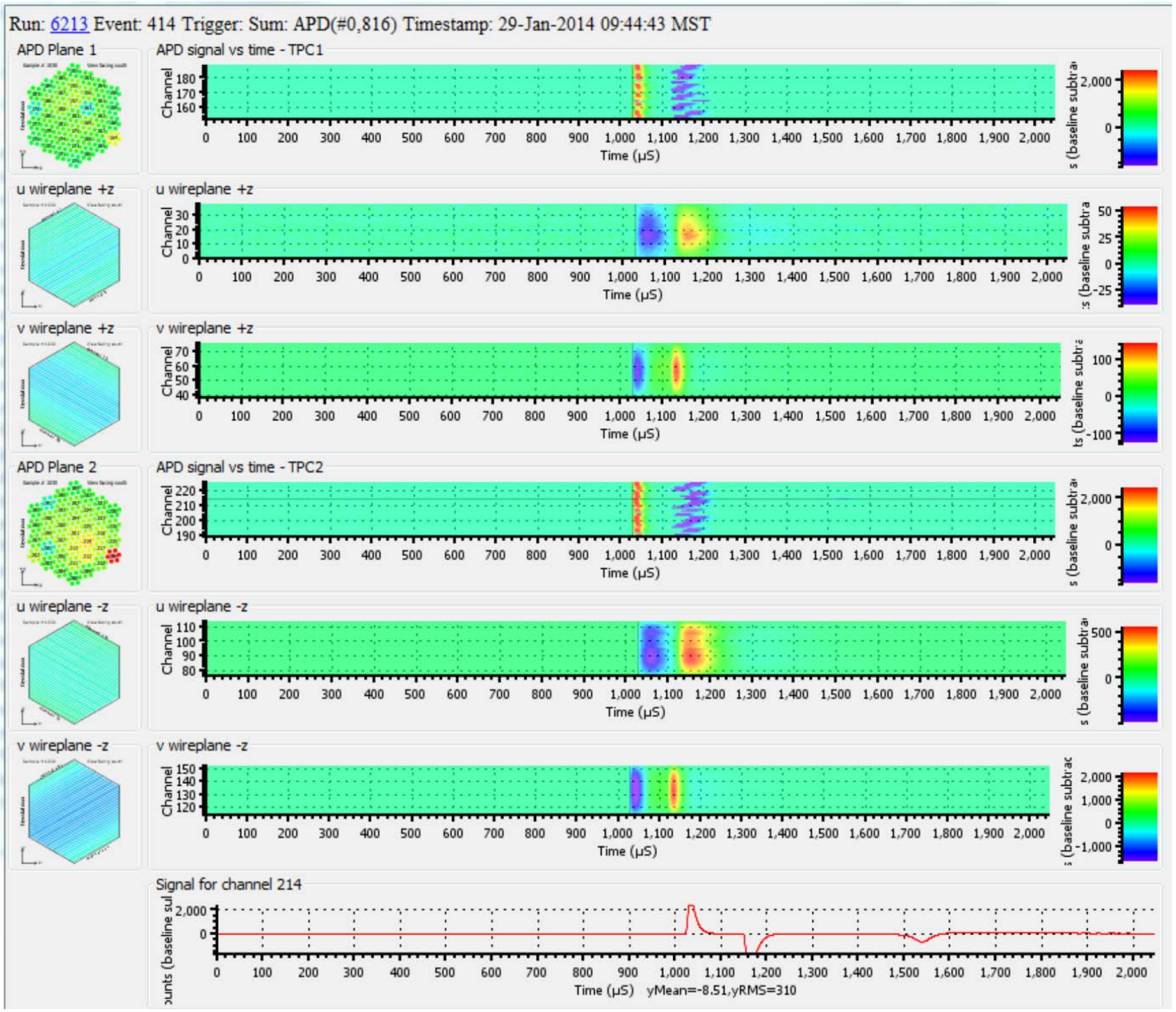
Goal: **Develop a stable and low-radioactivity supply and distribution system to deliver >50 kV to the TPC cathode with optimal use of xenon.**

Risk:

- **nEXO has a ~6x longer drift length than EXO-200. Operating at the EXO-200 drift field of 400 V/cm requires 50 kV at the cathode. (Cathode at one end keeps ^{214}Bi and other background out of the bulk of the LXe, also needed for thermal management.)**
- **EXO-200 and most other LXe detectors have had HV problems.**
- **In addition the ability to run at higher field provides one more handle to optimize the energy resolution and have a good engineering margin.**

The R&D: **Laboratory proof of principle of critical parameters (HV feed through, voltage divider chain, dielectric standoff spacing, Xe purity effects, …) at various scales, including demonstration of full-scale components.**

1) High Voltage



Run: 6213 Event: 414 Trigger: Sum: APD(#0,816) Timestamp: 29-Jan-2014 09:44:43 MST

Example of a "HV noise" event in EXO-200.

There are both charge collected and light in the detector, along with a substantial "EMP".

Phase 1: investigate intrinsic breakdown properties in LXe with small (<1 l) setup.

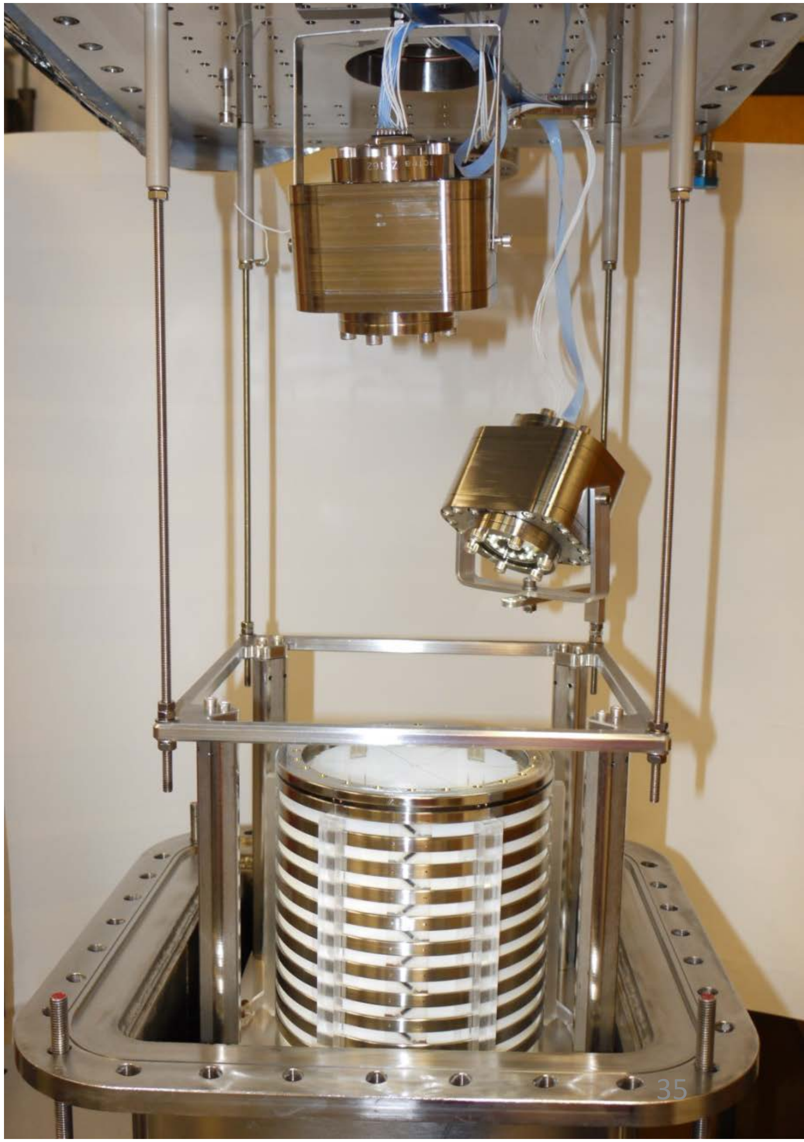
Status: completed. No surprises, we see breakdowns from well polished surfaces at ~300kV/cm.

1) High Voltage

Phase 2: Assemble "miniEXO-200" with spare parts (dielectrics) and run in a ~100kg LXe cell in Bern (moving to Carleton)

Status: In progress. Initial results seem to indicate that EXO-200 problems are EXO-200 specific and possibly due to dielectrics.

Breakdown in LXe (and near acrylic standoff) at ~40kV



1) High Voltage

Phase 3: Build a full scale segment of nEXO and demonstrate that it can hold HV with the appropriate (low background) materials and components. To be done in coordination with LZ. LZ building a tall "pipe" device, nEXO is building a short but full diameter segment to be run from V_{full} to V_{full} - Few kV. About 500kg LXe of which 250kg are available from EXO-200.

Status: Finalizing design.

2) Photodetector

Goal: Identify a photodetector with sufficiently low noise, high QE at 175nm, reasonable cost, ultra-low radioactivity and availability in m^2 amounts. Low bias voltage and >10^3 gain are desirable.

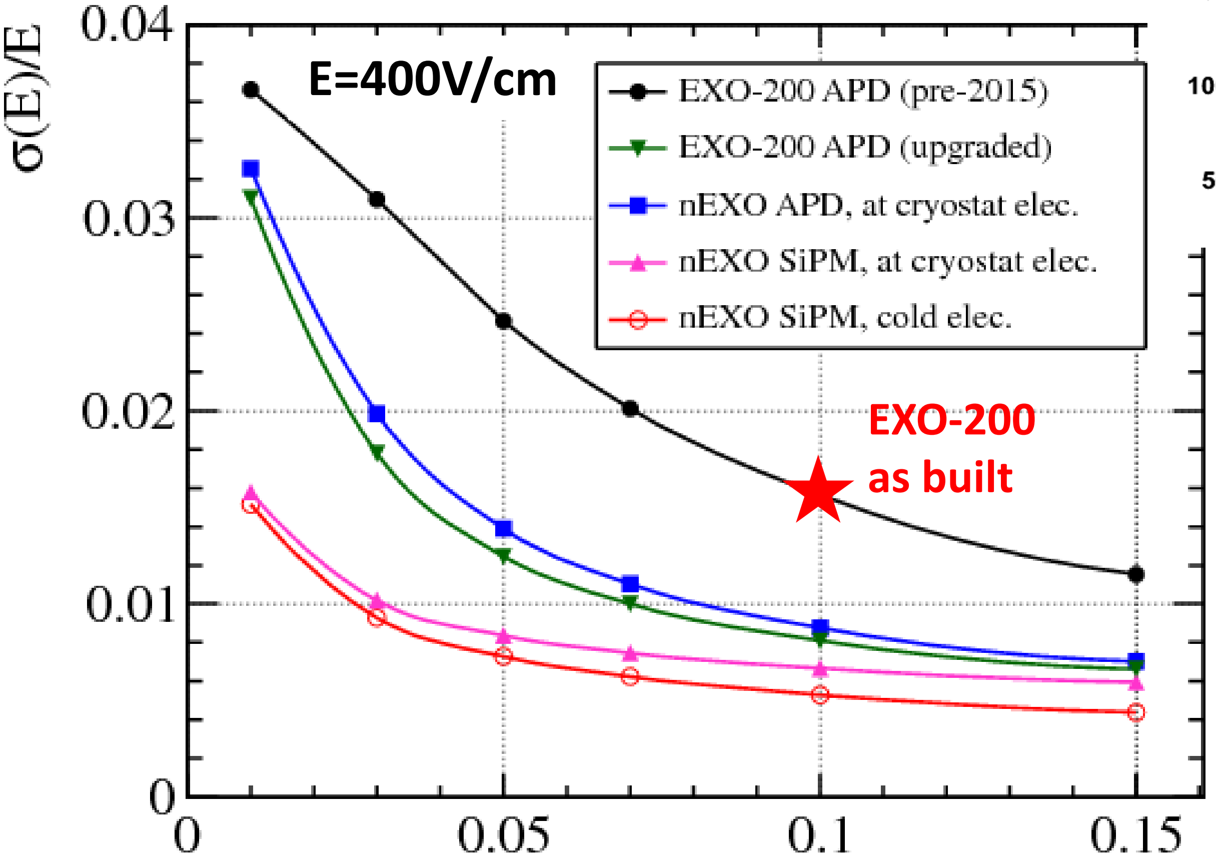
Risk: We need to measure a large fraction of the 175nm LXe scintillation light to achieve good detector performance (energy resolution is one metric, another one is threshold). Need to cover ~4m^2 with >15% QE at 175nm –this is substantially larger than in EXO-200! Plan to install the devices behind field rings, so will have to operate in a high field region.

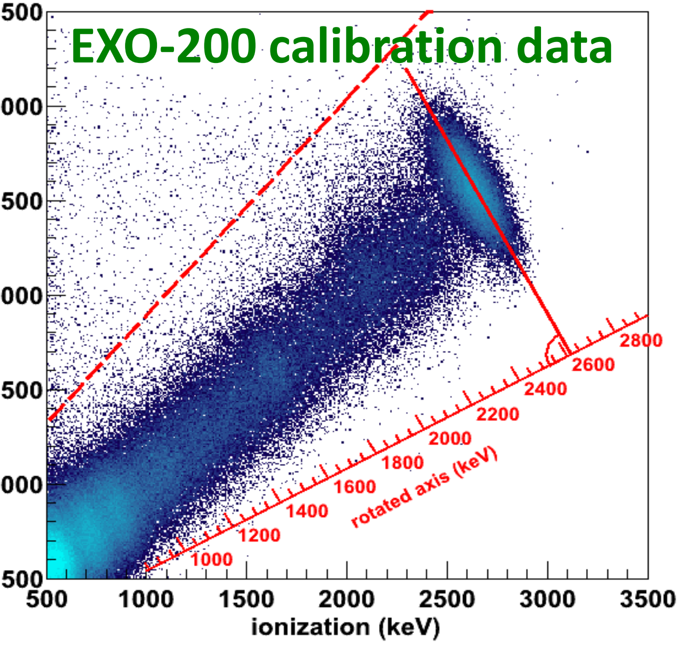
Detectors that meet these requirements are not currently available although recent development of SiPM appear to be approaching this goal. [PMTs are too radioactive (even the cleanest variety), APDs (EXO-200) have poor fill factor, low gain, 1500V bias and weigh more than SiPMs.]

The R&D: We are working with a number of the companies that are building SiPMs. We have facilities to measure the QE, dark noise, radiopurity and ability to operate in high field regions in LXe.

2) Photodetector

Good energy resolution requires efficient readout of the scintillation light to be combined with the ionization signal

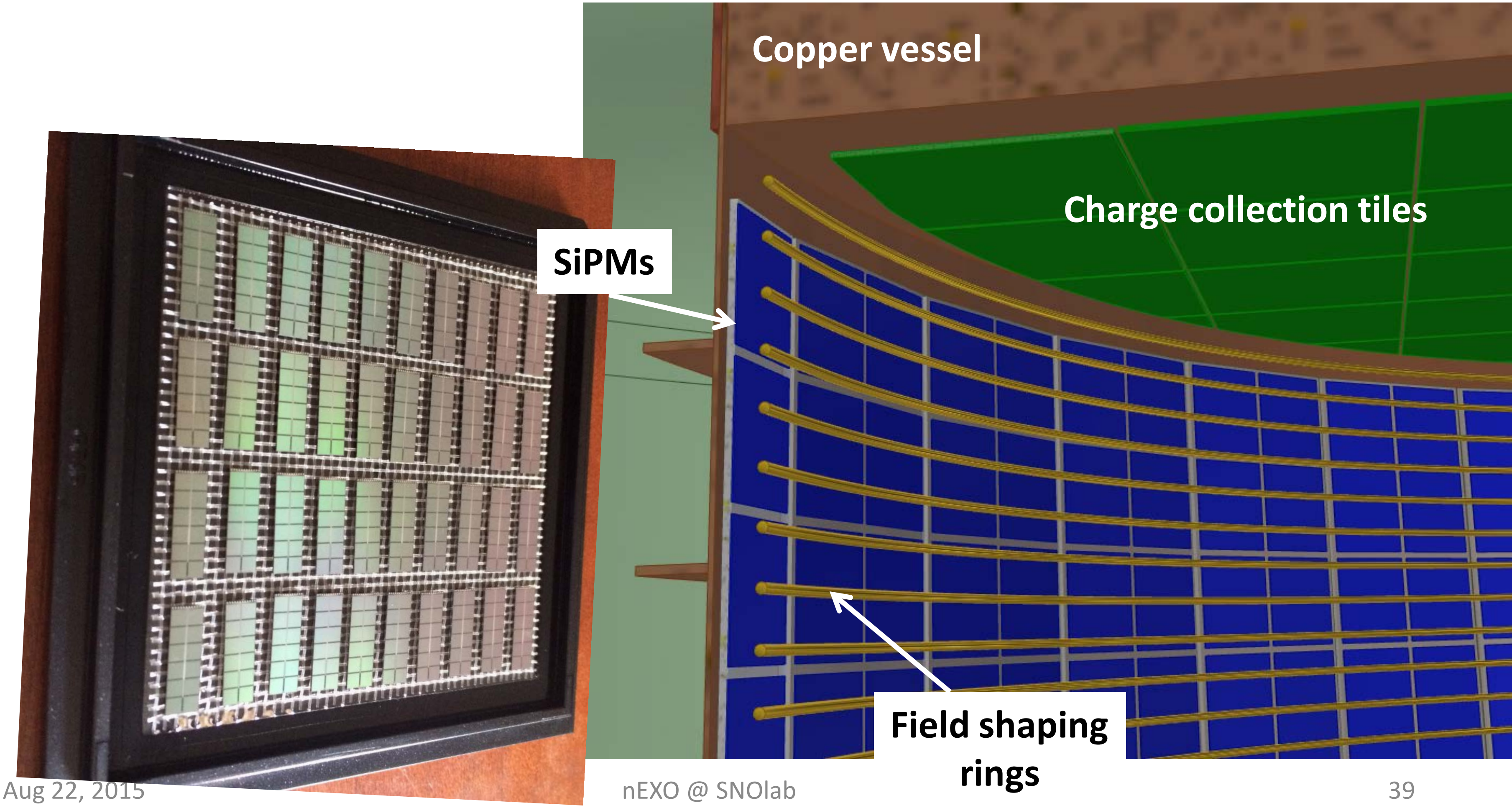




While we always assume 1% resolution for nEXO, a figure close to 0.5% is not out of the question

2) Photodetector

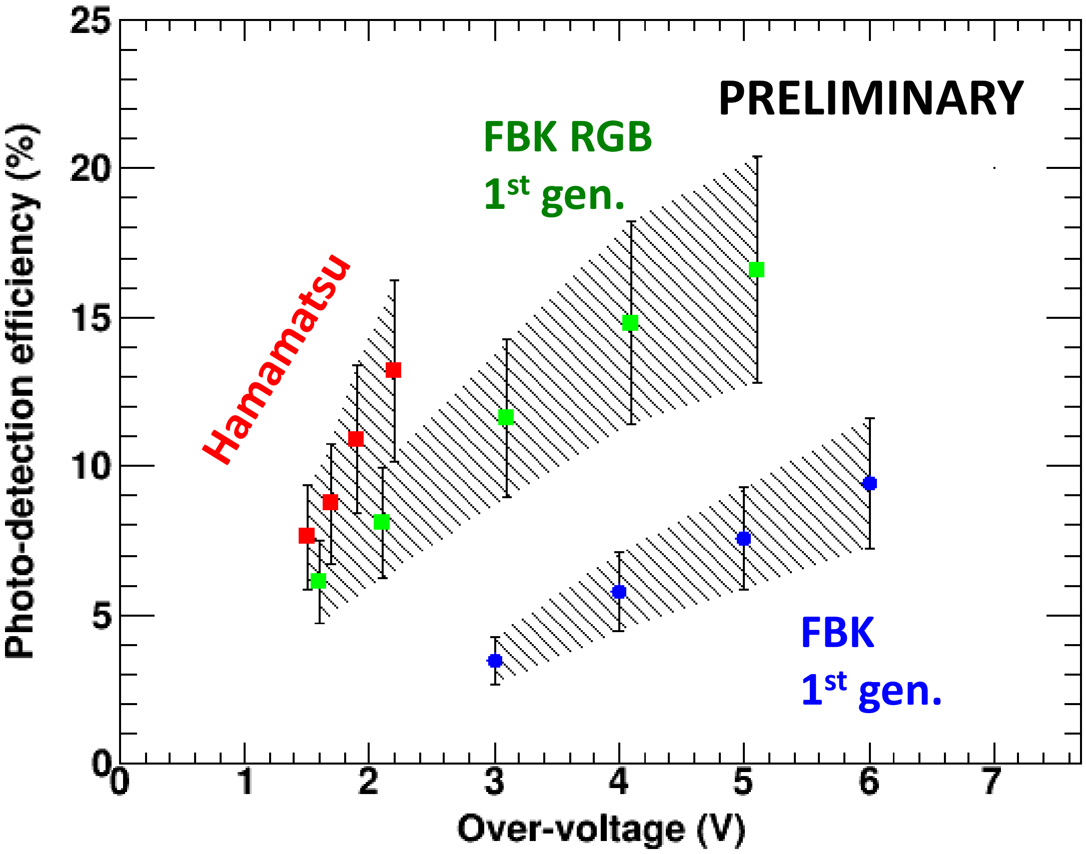
Good photodetector coverage requires mounting the SiPMs in the barrel region, behind the field shaping rings.
(SiPMs only behind charge readout impact charge readout design and have very poor, asymmetric coverage).



2) Photodetector

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

First nEXO-specific run at FBK (Italy) provided ~10% QE *[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1825.]*
New “RGB” devices reach 15% QE with 7.7x7.7mm^2.



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 with the new run (Alabama))

3) Low Background, Cryogenic Electronics

Goal: Develop the concept for low noise and low radioactivity electronics capable of remote operation in LXe at 160K.

Risk:

- nEXO is substantially larger than EXO-200 with finer granularity readout, (8k charge channels and similar number for light) requiring an integrated approach to sensors and electronics to provide better e-γ separation, energy resolution and hence better bkgnd discrimination / lower bkgnd.
- The electronics must be located close to the signal source (particularly important for the charge channel (see next slide)).
- In addition cables are one of the largest sources of background in EXO-200. In-LXe electronics also minimizes pickup, cable and feedthrough complexity.

➔ *Fully integrated, cryogenic and ultra-low background electronics has never been built before.*

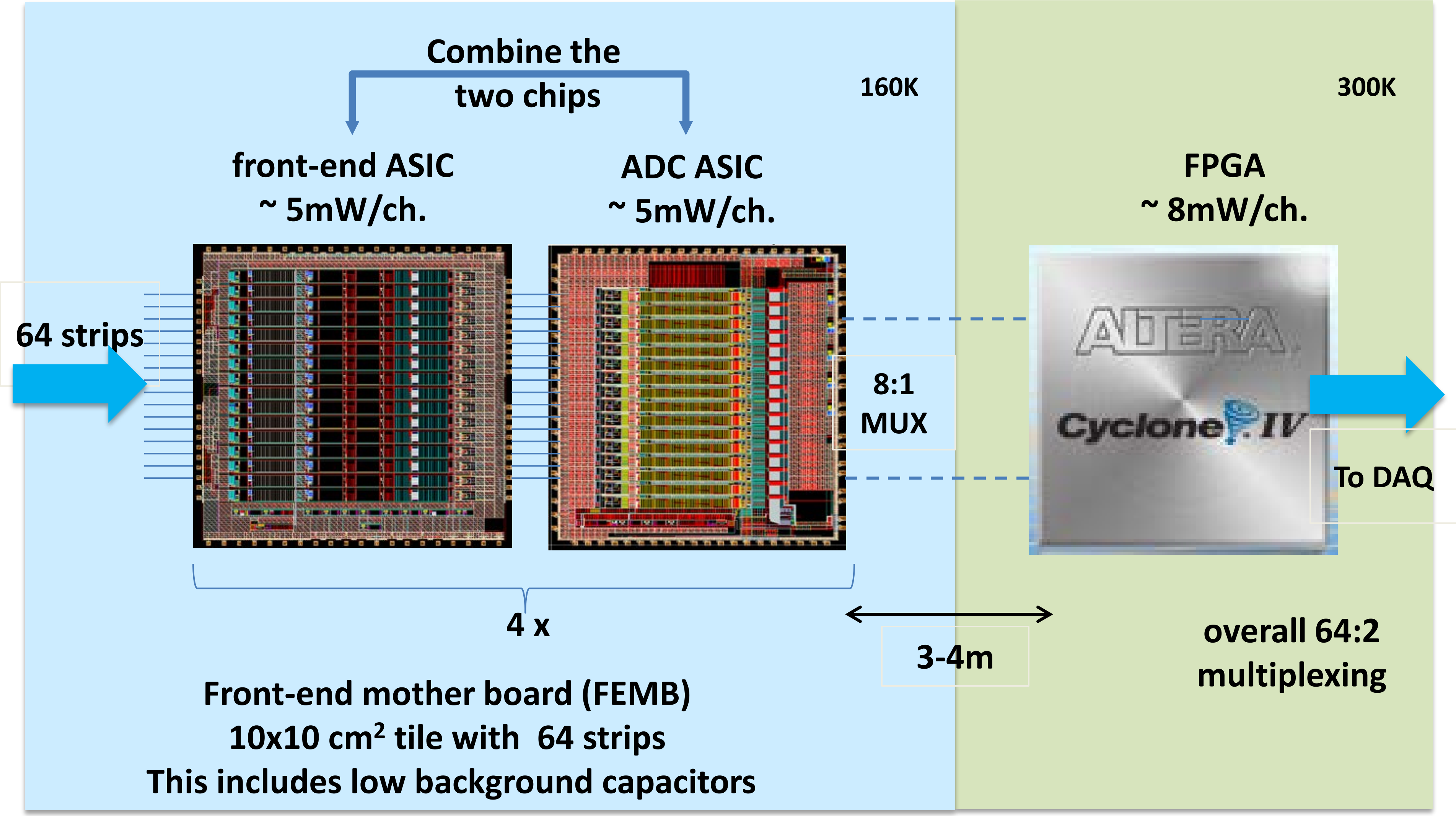
The R&D: Proof of principle readout systems, including front-end at least for the charge channel, including the discrete components needed (capacitors in particular), assembled with charge readout tiles in a way consistent with the ultra-low background requirement.

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.

Proof of principle readout chip for a 10x10 cm^2 charge readout to be tested for performance in LXe and for radioactivity



Combine the two chips

160K

300K

front-end ASIC
~ 5mW/ch.

ADC ASIC
~ 5mW/ch.

FPGA
~ 8mW/ch.

64 strips

8:1
MUX

To DAQ

4 x

3-4m

overall 64:2
multiplexing

Front-end mother board (FEMB)
10x10 cm^2 tile with 64 strips
This includes low background capacitors

4) Novel Low Background TPC Concepts

Goal: Develop a lightweight, ultra-low activity TPC concept achieving simultaneously:

- Uniform electric field across ~2 m^3 LXe volume
- >15% scintillation light collection efficiency
- Good charge collection with sufficient topological information for the ionization channel (2-3 mm channel spacing)
- >10 ms electron lifetime, required for energy resolution
- Optimal use of $L^{enr}Xe$
- Verify that appropriate materials exist

Risk: The ultra-low radioactivity requirements, along with the constraints above are particularly demanding for the TPC conceptualization. The TPC components are the dominant (in mass) structures closest to the LXe together with the Xe vessel. Material choices and technical solutions are very constrained and entangled, so that R&D work is required to identify a defensible concept.

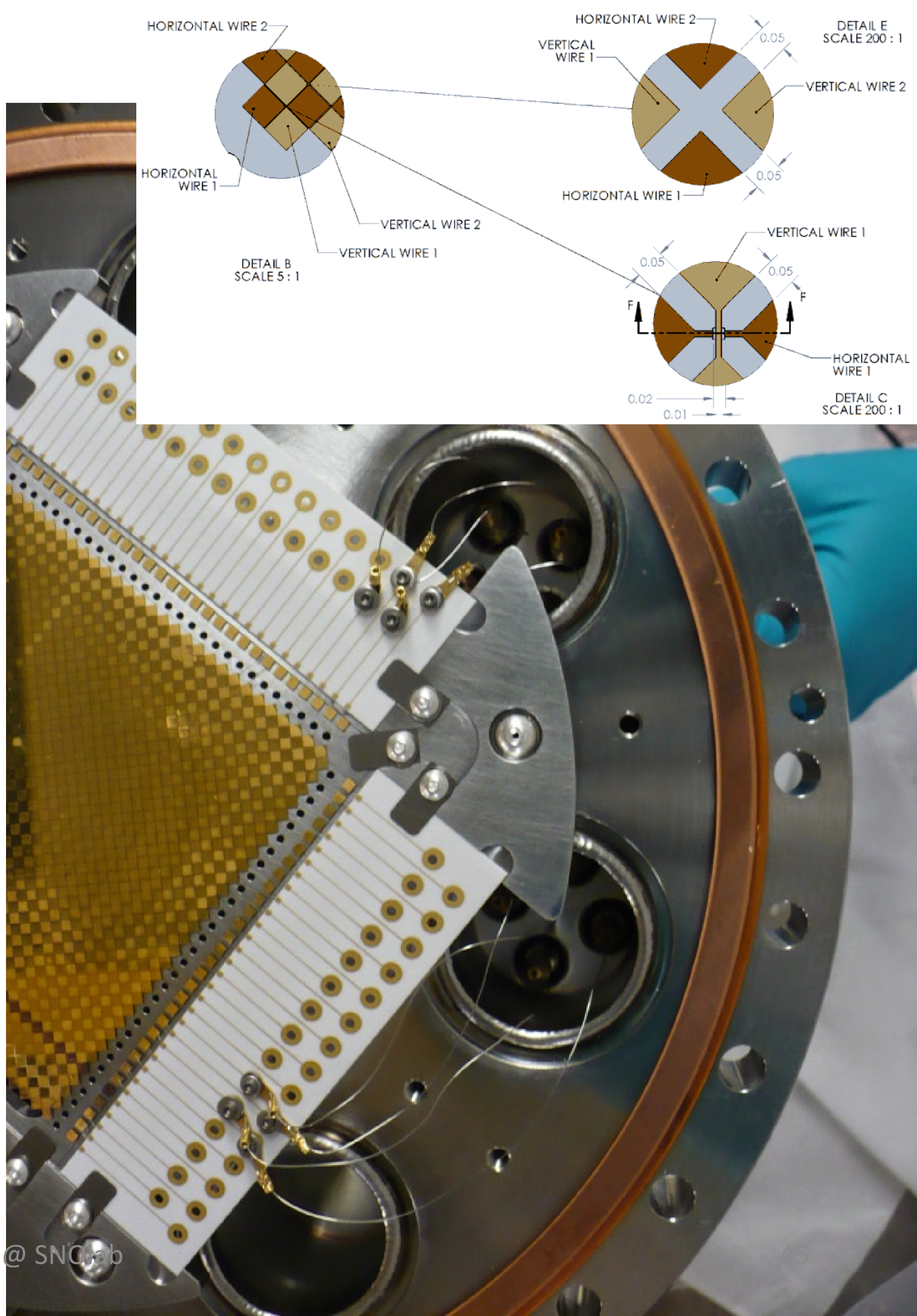
The R&D: Study plastic-less concept to meet the LXe purity requirement. Investigate inorganic dielectrics for structure and metallizations for scintillation reflectivity. A pad-like charge collection detection scheme is studied to replace a more traditional wire readout (impractical over the 1.3 m diameter TPC because of cryogenic, background and tensioning arguments).

4) Novel Low Background TPC Concepts

3mm pitch, crossed strip, full coverage, quartz- or sapphire-supported charge collection/readout tile. Produced by IHEP; functional testing in LXe in the US.

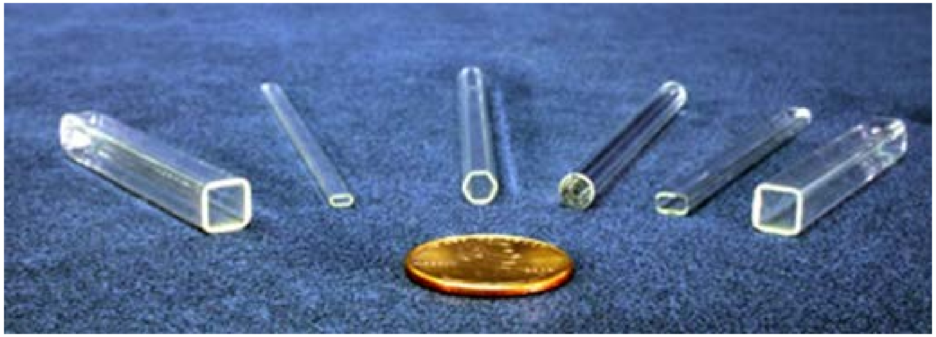
The prototype to the right uses a quartz substrate.

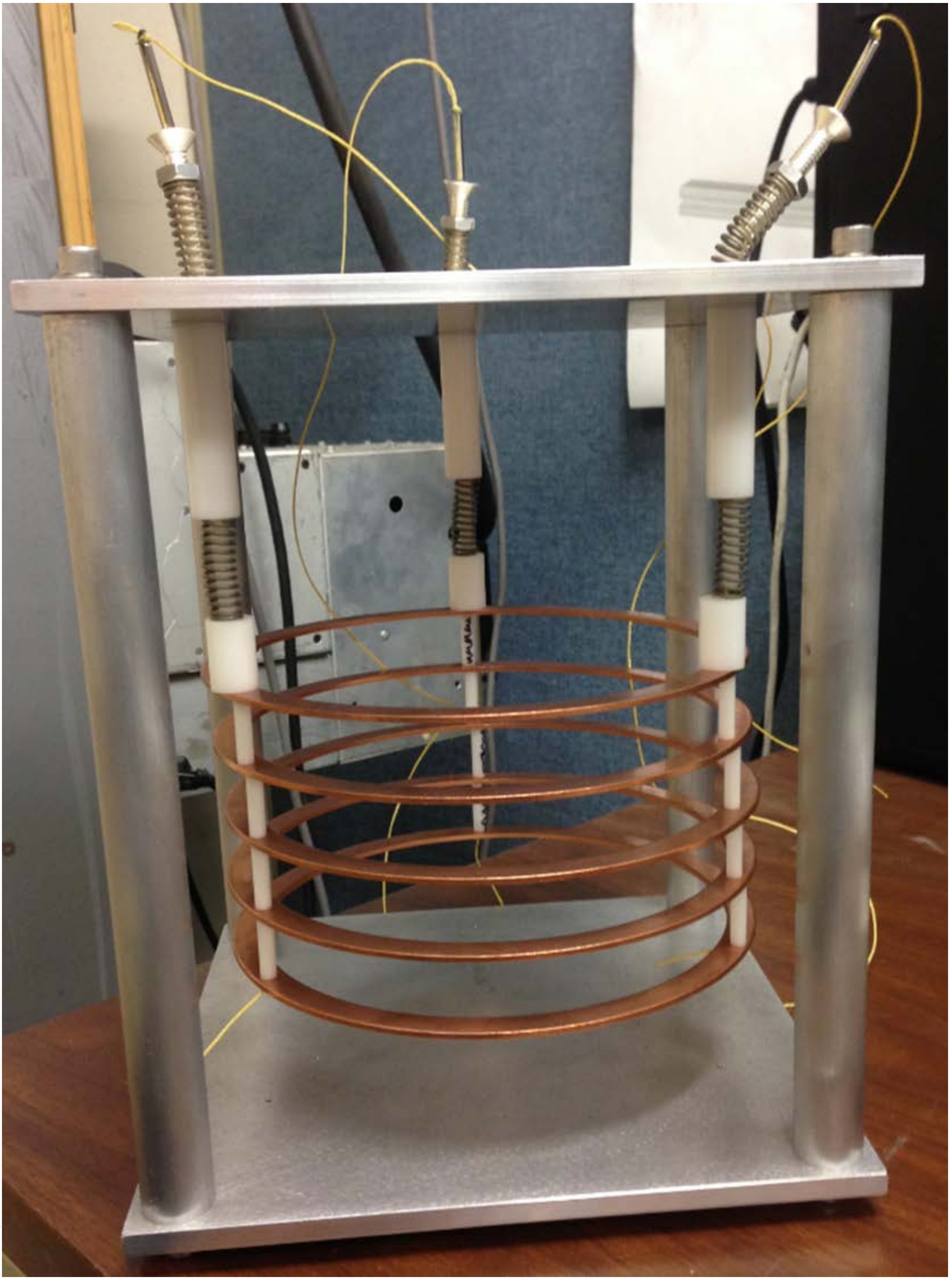
External readout is coupled with ceramic interface boards for the test. In "real life" the readout chip will be mounted directly onto the tile.



4) Novel Low Background TPC Concepts

A possible field cage concept consists of low background sapphire spacers and Kevlar or other polymer fiber tensioning elements.





5) Calibration Concepts

Goal: Devise a complete calibration concept to achieve the design resolution, confidence in energy scale and modeling of detector response over an extended period of low background data collection.

Risk: The monolithic nature and self-shielding aspects of the design may result in significant loss of low background data collection efficiency if calibration were to rely on external sources alone.
Insufficient calibration (in absolute terms or not sufficiently frequent) leads to degradation of the energy resolution, uncertainty in the energy scale for ββ decay-type events.

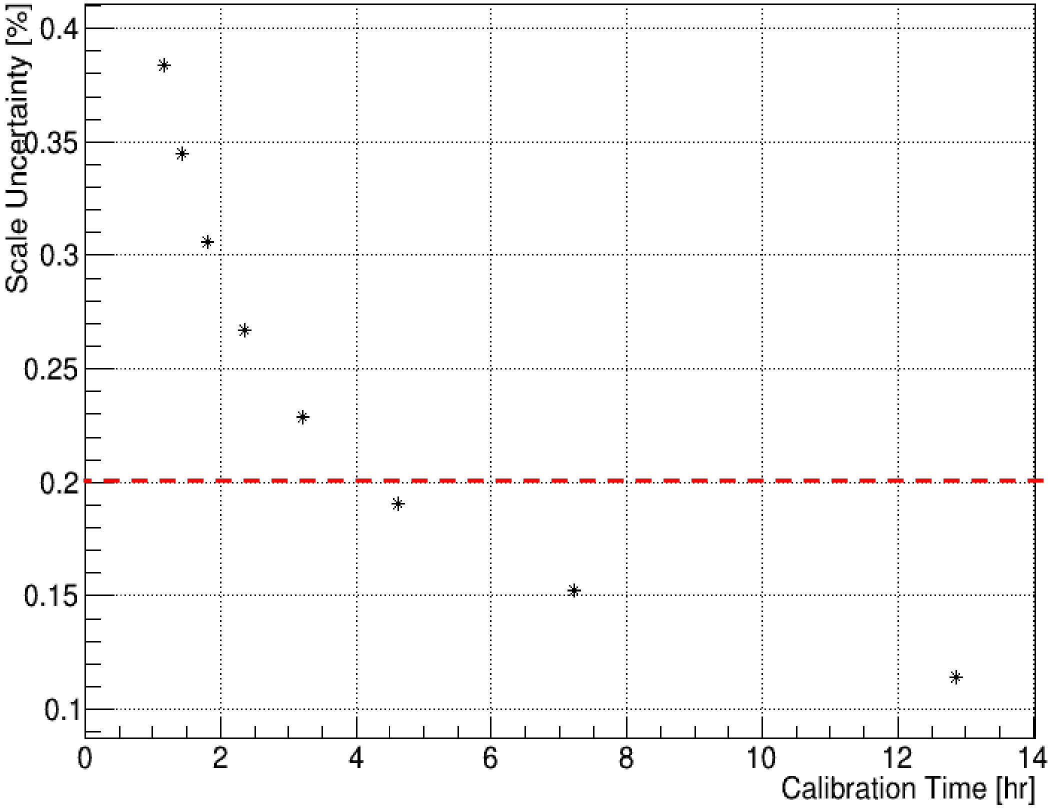
The R&D: investigation of

- In-situ monitoring of the electron lifetime with periodic, laser-induced ionization in the active LXe
- In-situ monitoring of SiPM efficiency and e^- lifetime with external sources
- Use of 2ν data for monitoring detector performance
- Potential techniques for introducing and subsequent removal of unstable isotopes for absolute calibration

→ This is an area where EXO-200 Phase-II running may provide valuable data.

5) Calibration Concepts

Of course the fact that the center of the detector is very hard to reach by an external source is a desirable feature of the homogeneous detector! But this also makes many operations challenging.



For instance to obtain the energy scale to within 0.2% (the uncertainty in EXO-200) using an external 1kBq ^{228}Th/^{208}Tl source one would need a ~4hr run. If this is done every day (like in some periods in EXO-200) the deadtime resulting from this is ~20%.

Given the better energy resolution it may be desirable to have an even better knowledge of the scale.

6) Low background Cryostat

Goal: Pre-conceptual design of the cryostat to determine feasibility.

Risk: The nEXO cryostat is large and challenging to build deep underground.

- Copper construction would have to happen underground because of poor access and cosmogenic activation and it would require an enormous amount of copper because of the low material strength.
- A C-composite design is attractive from the structural and manufacturing points of view. Initial measurements seem to indicate that at least some type of C-composite can be made sufficiently clean but this has never been done before and more work is required to validate the concept.
- A conventional option is a stainless steel or Titanium construction, but this results in a substantially larger amount of (expensive) HFE7000 for shielding. It is possible that the cost of the HFE7000 and of the extra refrigeration would be prohibitive.

The R&D: Simulation and preliminary designs are needed to determine if there is a solution to this problem, cost it, and devise the R&D path required to implement the solution. Material testing for radiopurity and fluid and temperature compatibility are also required.

7) Radiopurity Investigations

Goal: In collaboration with all other subsystem groups, identify materials which will meet structural requirements while reducing the radioactive bkgd even further.

Risk: inadequate radioactivity qualification of detector components at this stage may result in substantial delays to identify and study materials, or even in flawed assessment of the project soundness.

The R&D: We have proactively invested in several new facilities and have already been successful in specific and important areas.

- Low background Ge counting: SNOlab (underground), Alabama (surface), Alabama & Duke developing new underground capability at KURF
- Neutron activation analysis: Alabama
- ICPMS: IHEP Beijing, IBS Korea
- GDMS: NRC Canada
- Radon emanation: Laurentian U. Canada

➔ Already improved analytical sensitivity for U and Th in Cu by 3-fold (~1ppt)

Much work in progress to enhance capabilities and sensitivities for various specific issues/materials.

Tight coordination with the Monte Carlo effort is essential.

8) Simulation

Goal: Support the other tasks in assessing the performance of specific concepts and set of materials.

Risk: It is not possible to produce the preconceptual design of a sophisticated detector without a substantial simulation package.

The R&D:

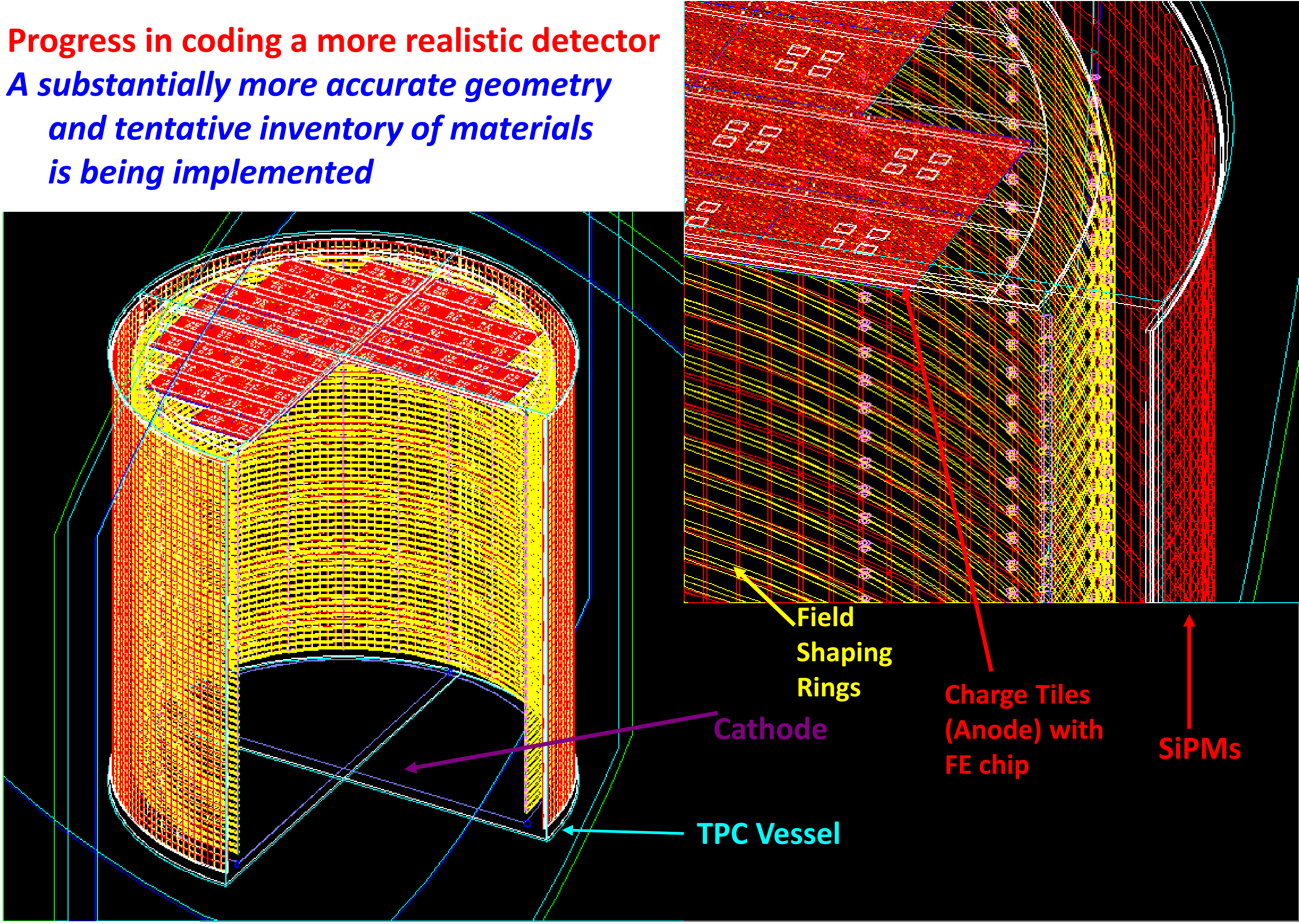
- Provide a GEANT4 based simulation of the detector configuration, including all the detail required to assist the task of deciding which materials and technical choices are acceptable.
- Assess the backgrounds produced by the known or projected trace radioactivity of the various components.
- Provide a simulation optimized for neutron physics (GEANT4/FLUKA) to assess the backgrounds due to neutrons of various origins.
- Use these simulations to perform the first order detector optimization required to demonstrate that the nEXO detector is the most competitive alternative for double-beta decay searches at the ton scale.

Tight coordination with the radiopurity effort is essential.

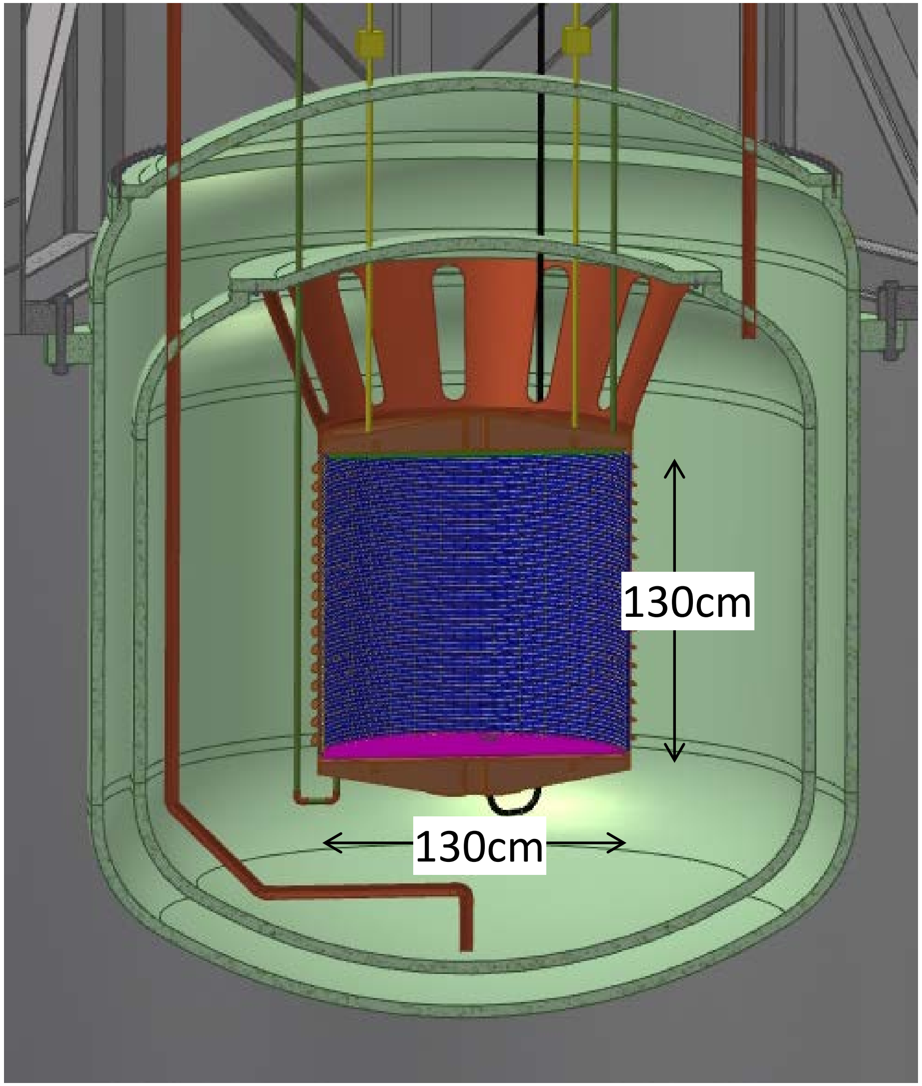
➔ Note that the simulation is validated by real science data from EXO-200!!

Progress in coding a more realistic detector

A substantially more accurate geometry and tentative inventory of materials is being implemented



Limited work on the mechanical design of the TPC vessel and cryostat has started

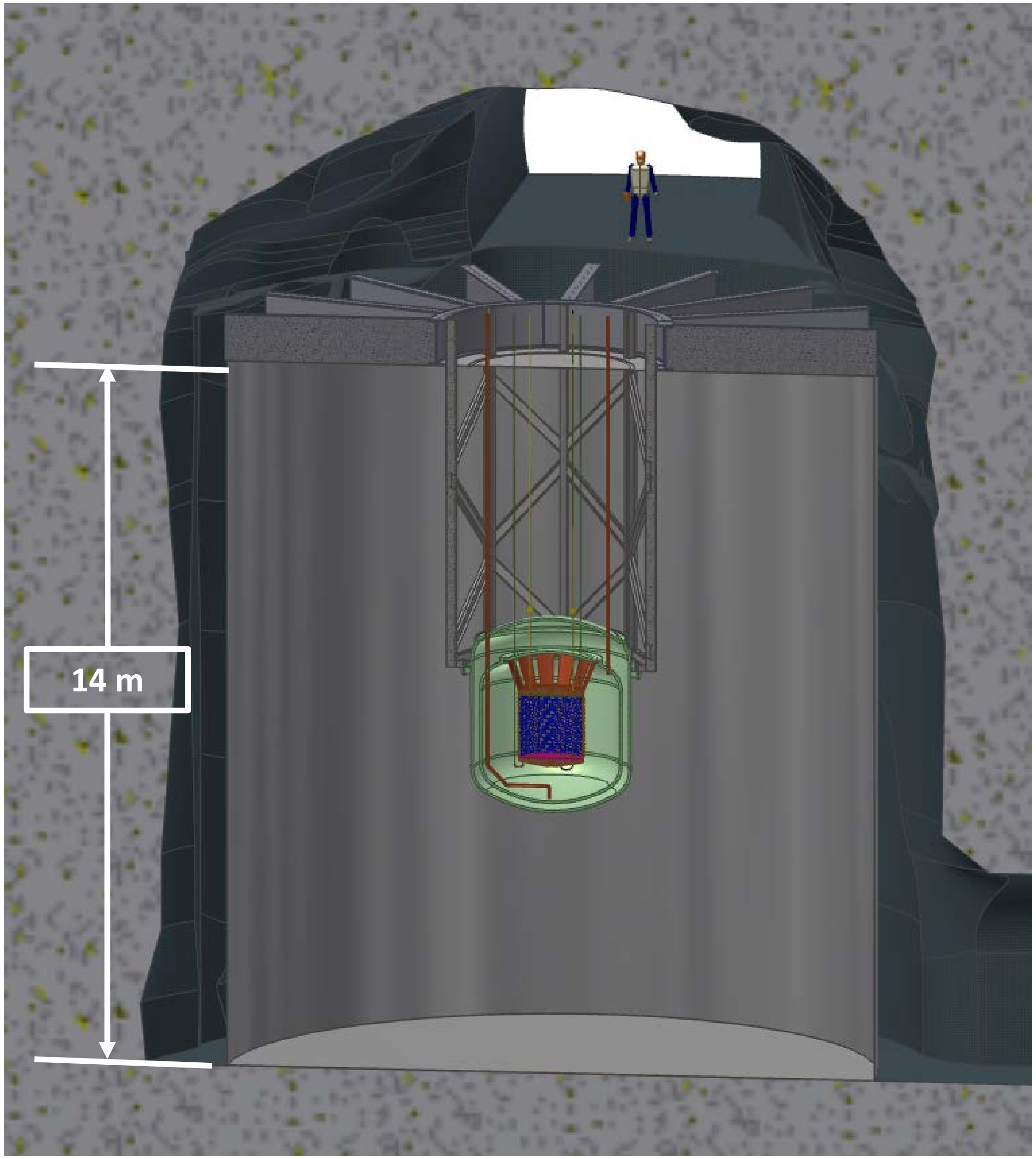


TPC vessel is copper, similar to EXO-200

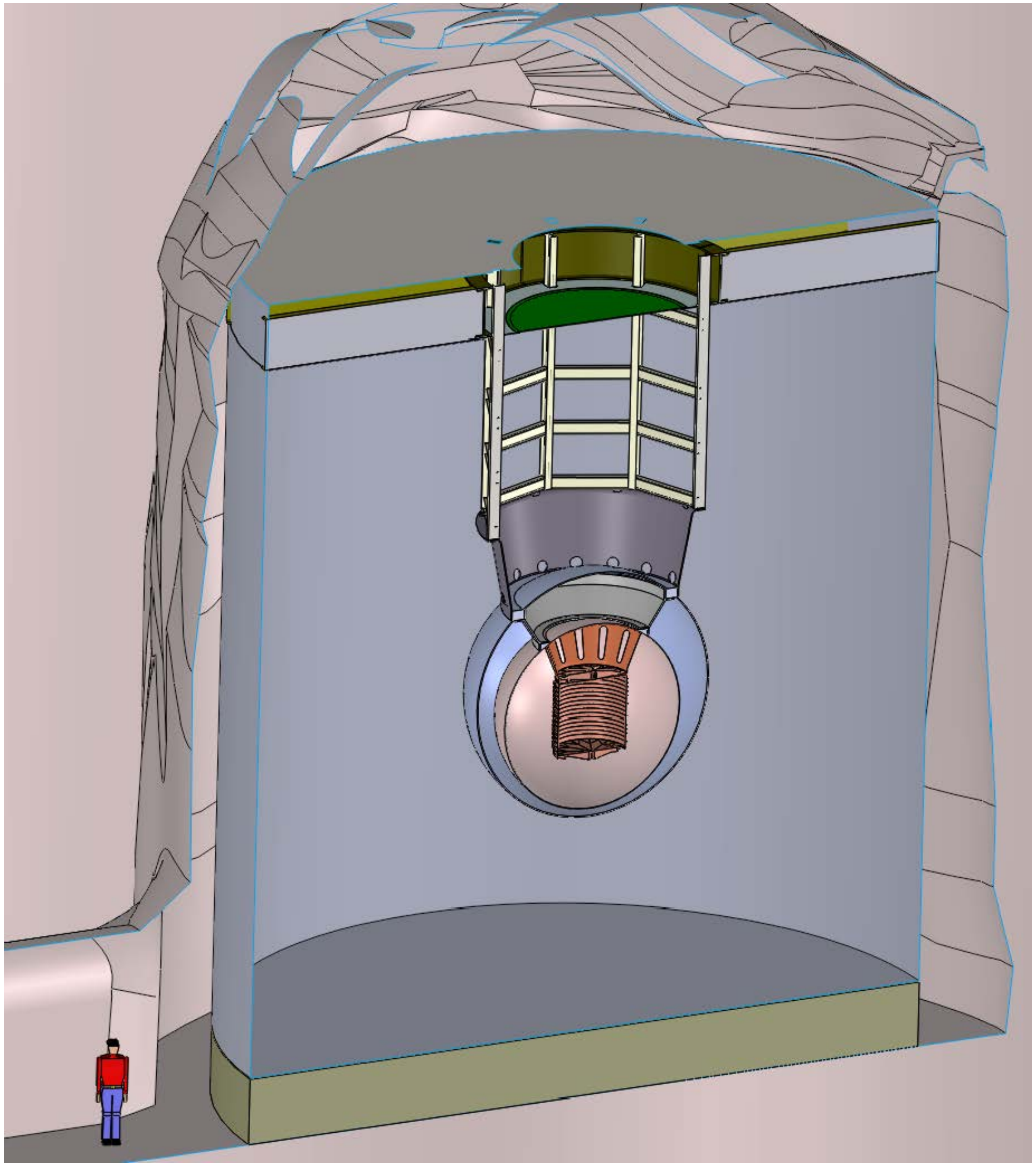
Carbon-composite cryostat being investigated from the mechanics and radioactivity standpoints

➔ Easier to construct UG

nEXO in the Cryopit



The option of a spherical cryostat is also being considered



Recent nEXO papers

I. Ostrovskiy et al.

“Characterization of Silicon Photomultipliers for nEXO”

IEEE trans. Nucl. Sci. 62 (2015) 1825.

B. Mong, et al.

"Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO"

Phys. Rev. A 91 (2015) 022505

T. Brunner, et al.

"An RF-only ion-funnel for extraction from high-pressure gases."

Int. J. Mass Spec. 379 (2015) 110

K. Twelker et al.

"An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe"

Rev. Sci. Instrum. 85 (2014) 095114

Material procurement

^{136}Xe enrichment easier and cheaper:

➔ **90% enriched ^{136}Xe: ~10$/g**

90% enriched ^{76}Ge: ~90$/g (+xtal growth)

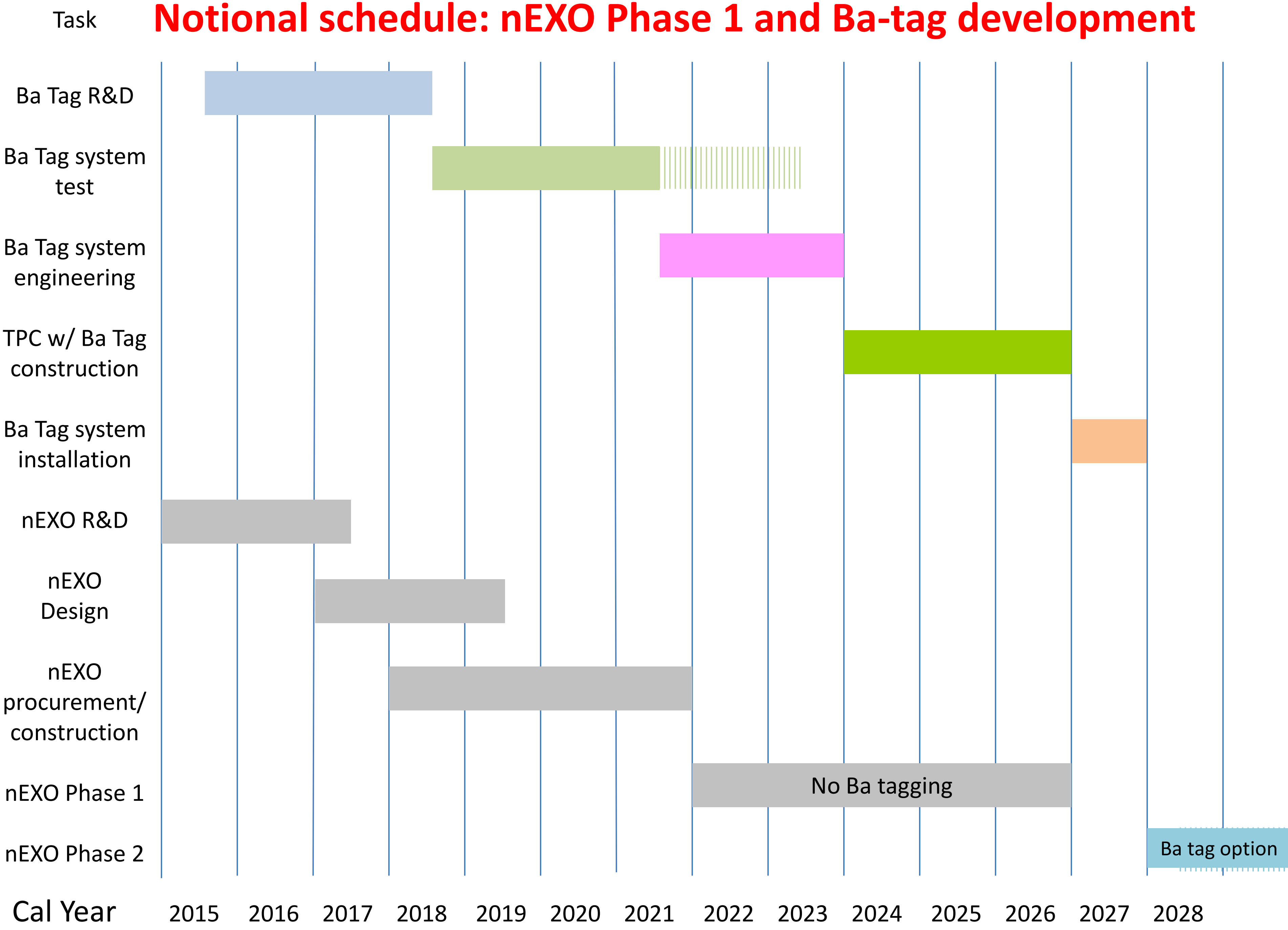
(EXO-200 uses 80% enriched Xe. It now seems customary to do 90% and it appears that there is no major cost difference)

Exact centrifuge capacity in Russia is classified but our contacts indicate that 5000kg in 5 years is comfortable

World $^{nat'l}$Xe production is ~40 tonnes/yr (~4000kg ^{136}Xe), however large price fluctuations are not uncommon

Almost a ton of Xe enriched in the isotope 136 has been produced in the world in the last 10 years. So this information is quite reliable.

Notional schedule: nEXO Phase 1 and Ba-tag development



Summary

- **Because of its multi-parameter capabilities, nEXO has robust discovery potential.**
- **Its general configuration was validated by the very successful EXO-200.**
- **Homogeneity is a desirable feature.**
  ➔ Required R&D is in full swing.
- **This is a tested collaboration that is known to be capable of successfully executing every phase of an experiment.**
- **It is essential that this science is done in an effective and timely manner**
  ➔ nEXO will be ready to start a construction project in 2017