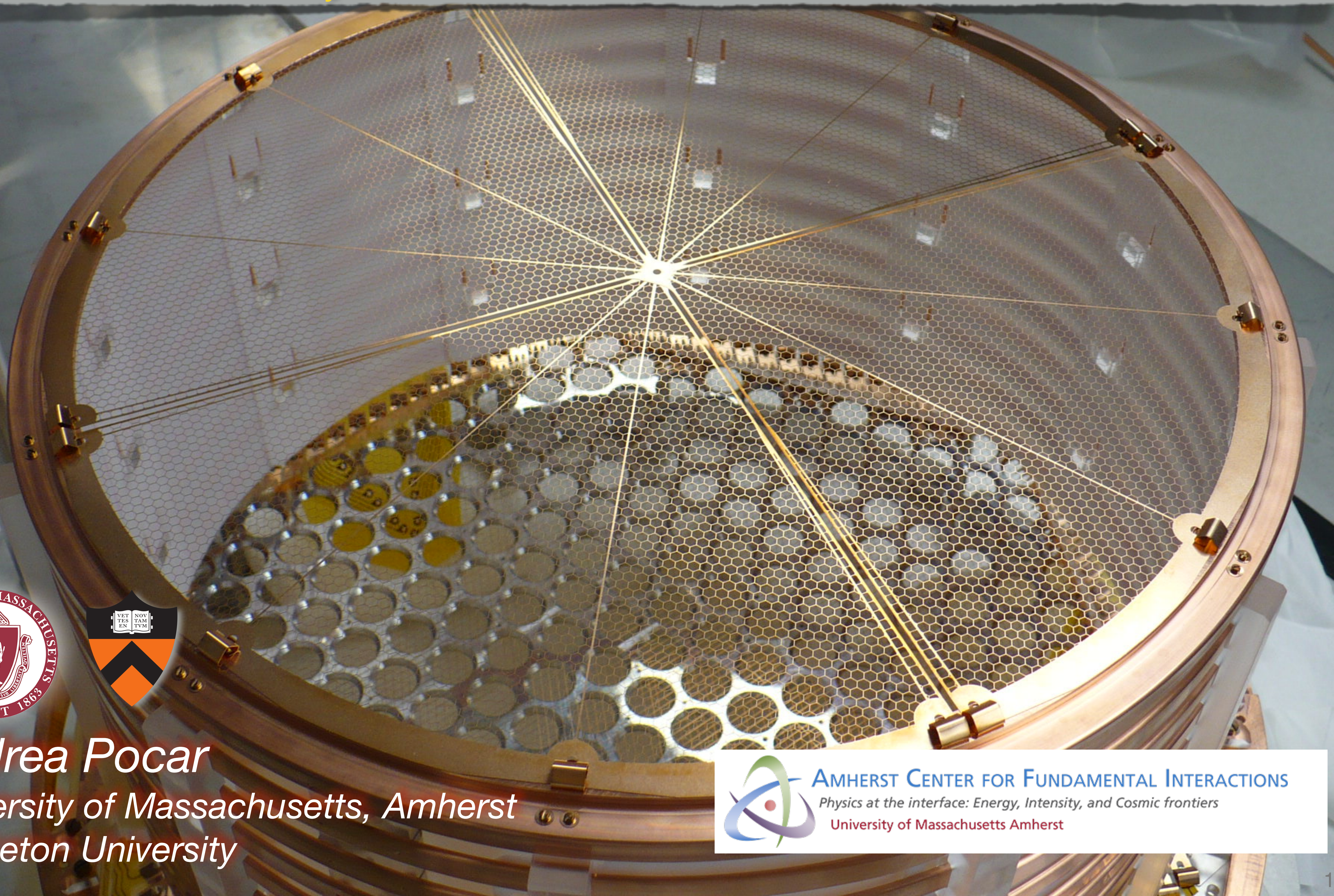
Searching for neutrino-less double beta decay with xenon Time Projection Chambers

Neutrino Mass: From the Terrestrial Laboratory to the Cosmos

ACFI, University of Massachusetts, Amherst - December 14-16, 2015



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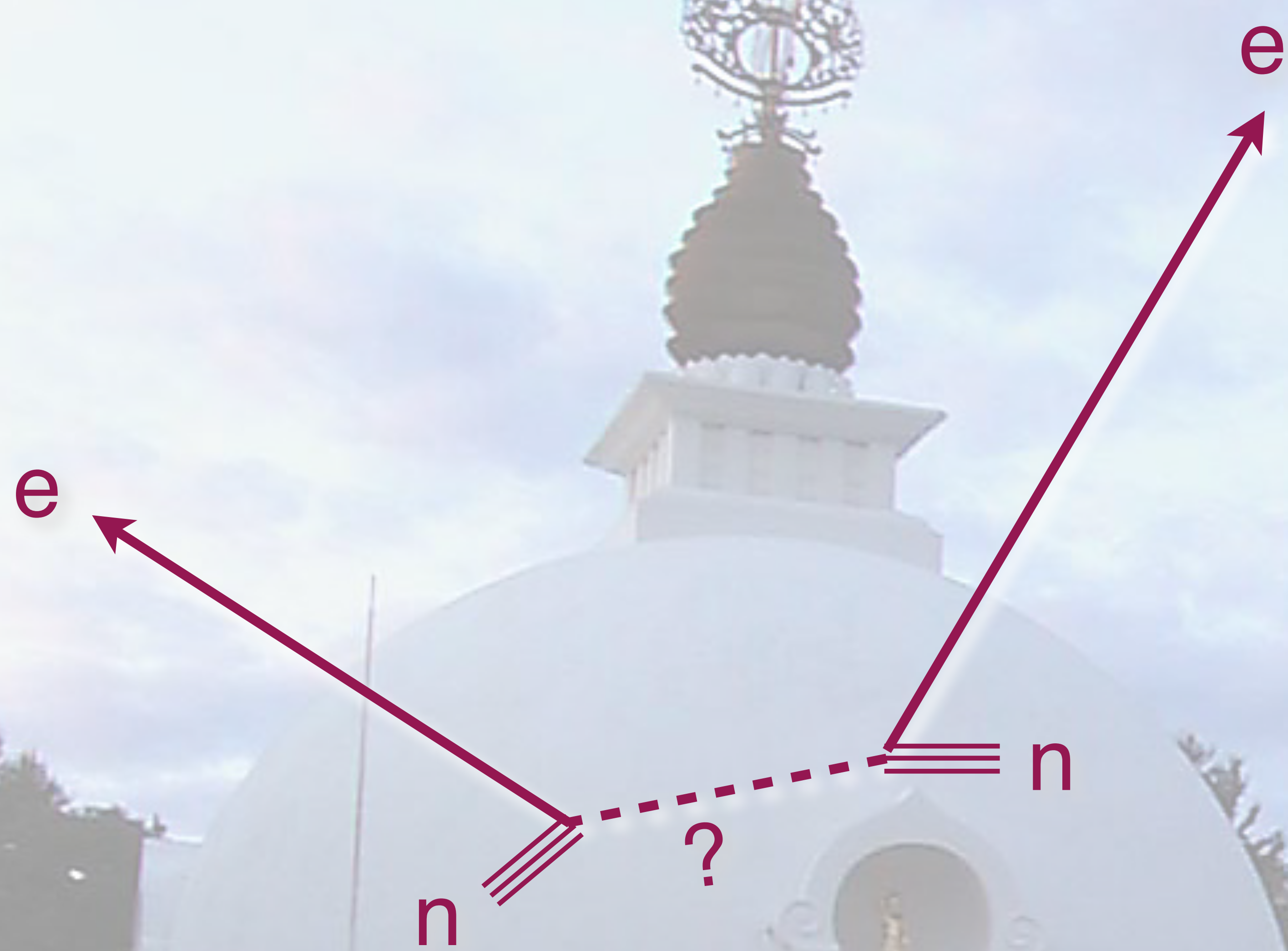
Physics at the interface: Energy, Intensity, and Cosmic frontiers

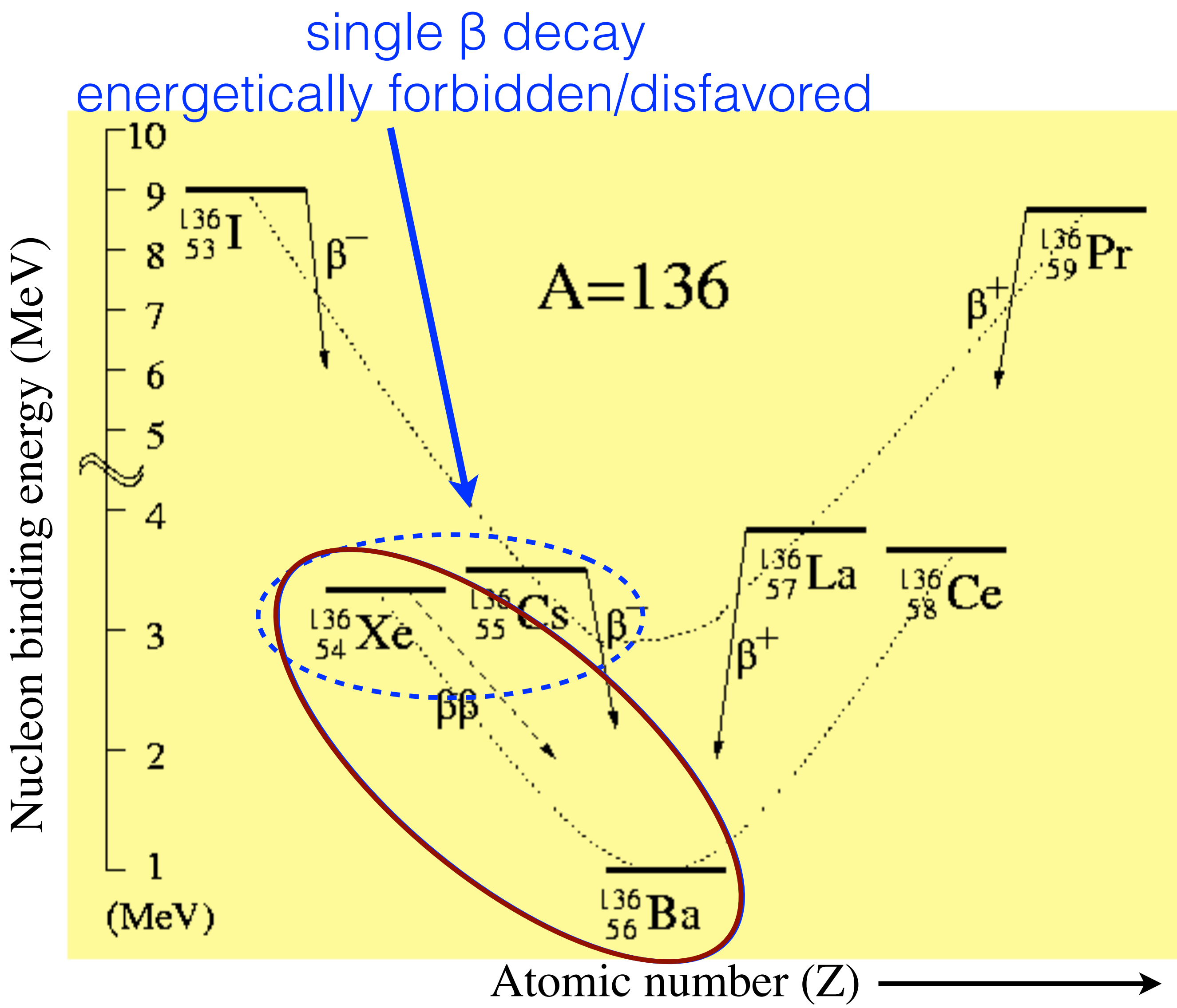
University of Massachusetts Amherst

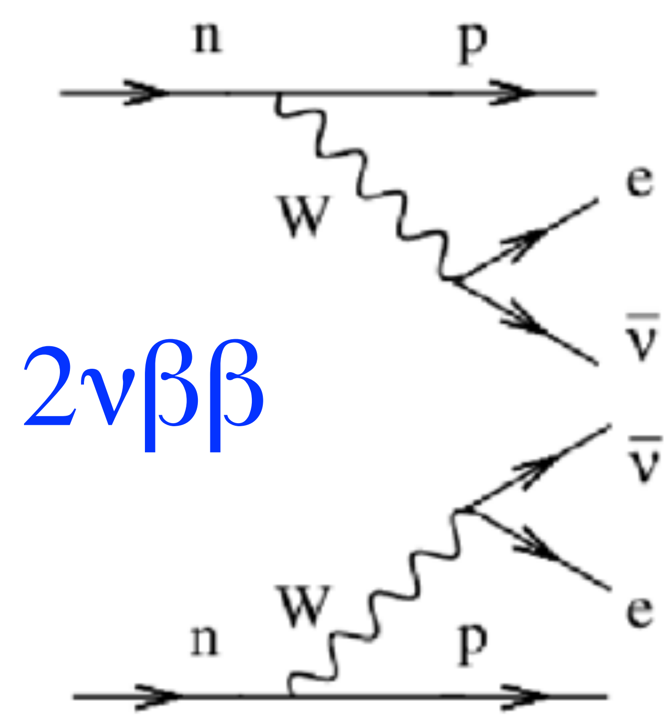
outline

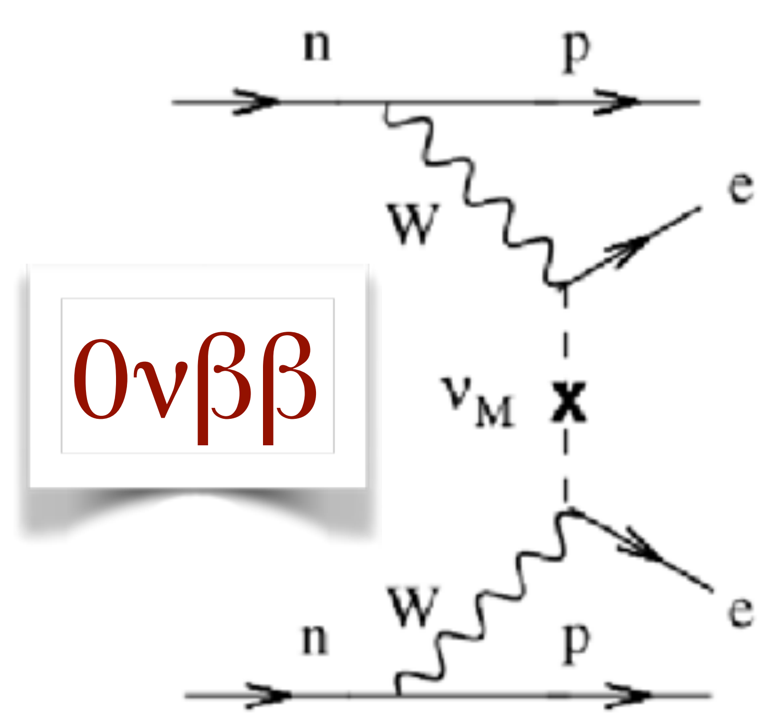


- ***0νββ decay with xenon TPCs***
    - ***a case for xenon***
- ***Gas TPCs for DBD***
    - ***History: Gotthard***
    - ***~near future: NEXT-100***
- ***LXe TPCs for DBD***
    - ***present: EXO-200***
    - ***future: LZ***
    - ***future: nEXO***
- ***Ba tagging***

Physics: Neutrino-less double beta (0νββ) decay







[Schechter and Valle, PRD 25 (1982) 2951]

observation of 0νββ decay:

- massive, Majorana neutrinos
- lepton number violation

0νββ rate

- absolute neutrino mass (model dependent)

why xenon TPCs?

Purification (stand alone, continuous)

- purification from chemical impurities —> getters
- purification from other radioactive noble elements (Ar, Kr, Rn) —> distillation, adsorption

Enrichment

- enrichment 8.9% —> 80-90% proven at the many100's kg scale
  (~1 tonne of enriched xenon for science procured in the past decade)

Xenon is reusable

- transferable between detectors

Monolithic detector, remarkable self-shielding, scalable

- proven by the dark matter detectors (low energy)
- quickly improves with mass

Energy resolution

- Ge/bolometers — GXe — LXe (ionization+scintillation) — scintillators
- slowest 2νββ decay of all 'practical' isotopes (2×10^{21} yr)

Particle ID (α/β), ββ/γ discrimination

- ionization/scintillation
- event topology: multiplicity of energy depositions in the detector
- event topology: β/ββ discrimination (GXe)
- active, unsegmented detector to contain and measure external background (LXe)

Final state ID

- coincident detection of daughter Ba ion/atom (spectroscopic techniques)

M. Moe, PRC 44, R931 (1991)

Gas vs Liquid Xenon TPC

GXe

pros:

- tracking
- energy resolution

cons:

- signal efficiency ~ 1/3
- external background
- pressure vessel
- awaits 100 kg scale proof

LXe

pros:

- compact
- high signal efficiency
- self-shielding
- purity

cons:

- cryogenics
- no(?) β/ββ discrimination

0νββ decay vs WIMP searches

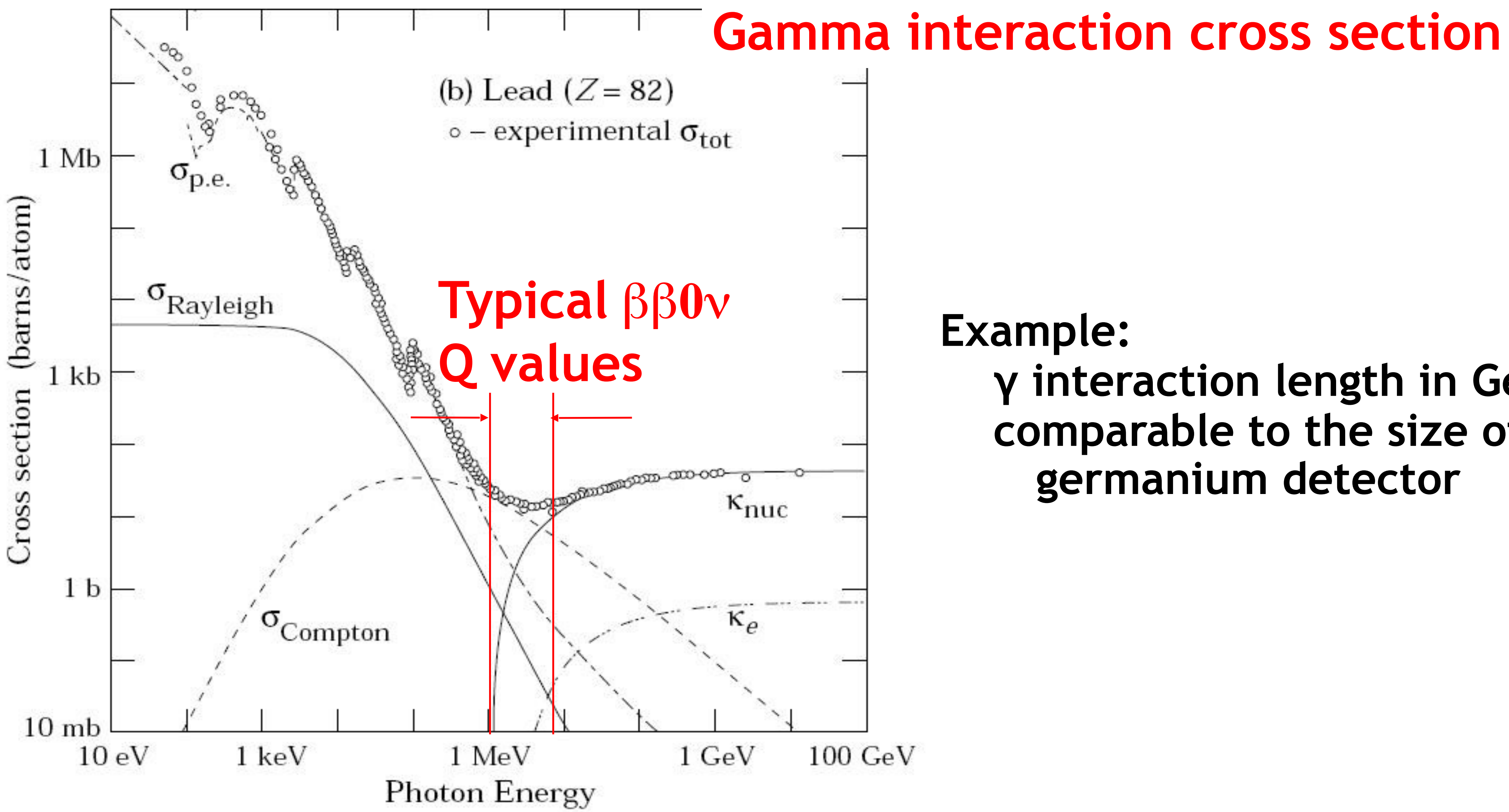
0νββ decay:

- β/γ discrimination
- ββ/β discrimination
- energy resolution

WIMP direct detection:

- nuclear / electron recoil discrimination
- energy threshold

Shielding a detector from gammas is difficult because the absorption cross section is small



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

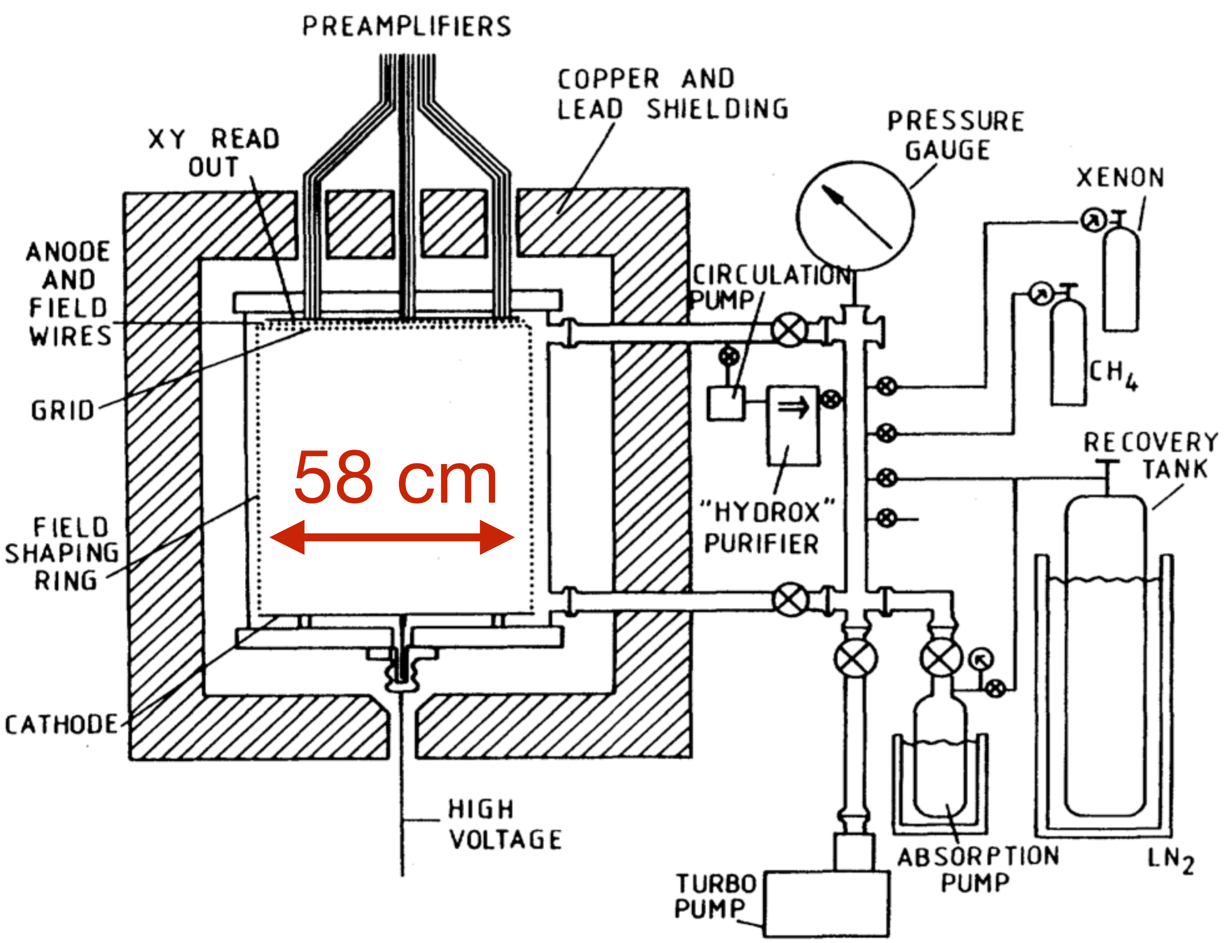
Shielding ββ decay detectors is harder than shielding Dark Matter ones

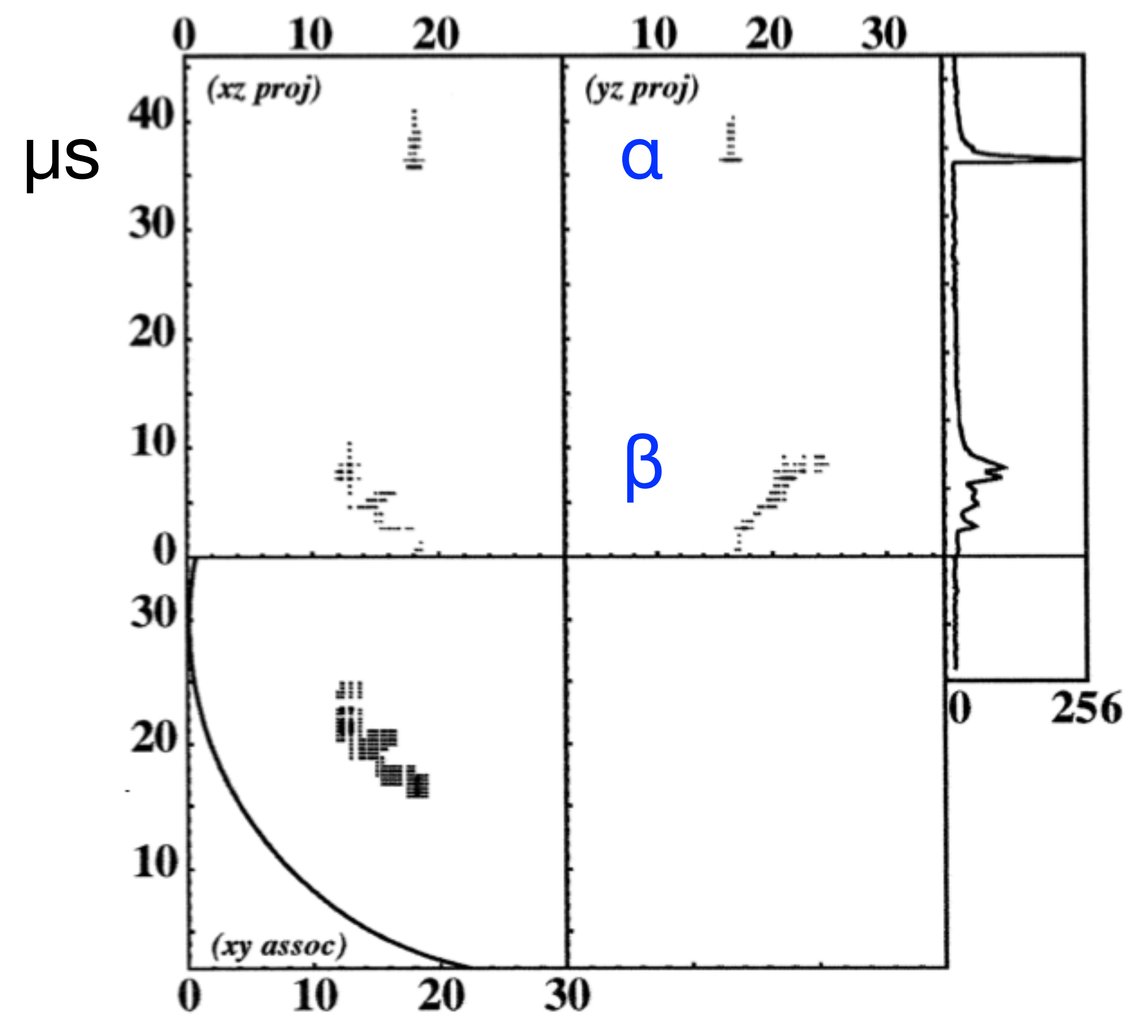
We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths

First xenon TPC for DBD — Gotthard TPC

Luescher et al., Physics Letters B 434 (1998) 407
Vuilleumier et al., PRD 48 (1993) 1009

- 180 liters
- 3.3 kg ^{136}Xe (62.5% enriched)
- 5 atm





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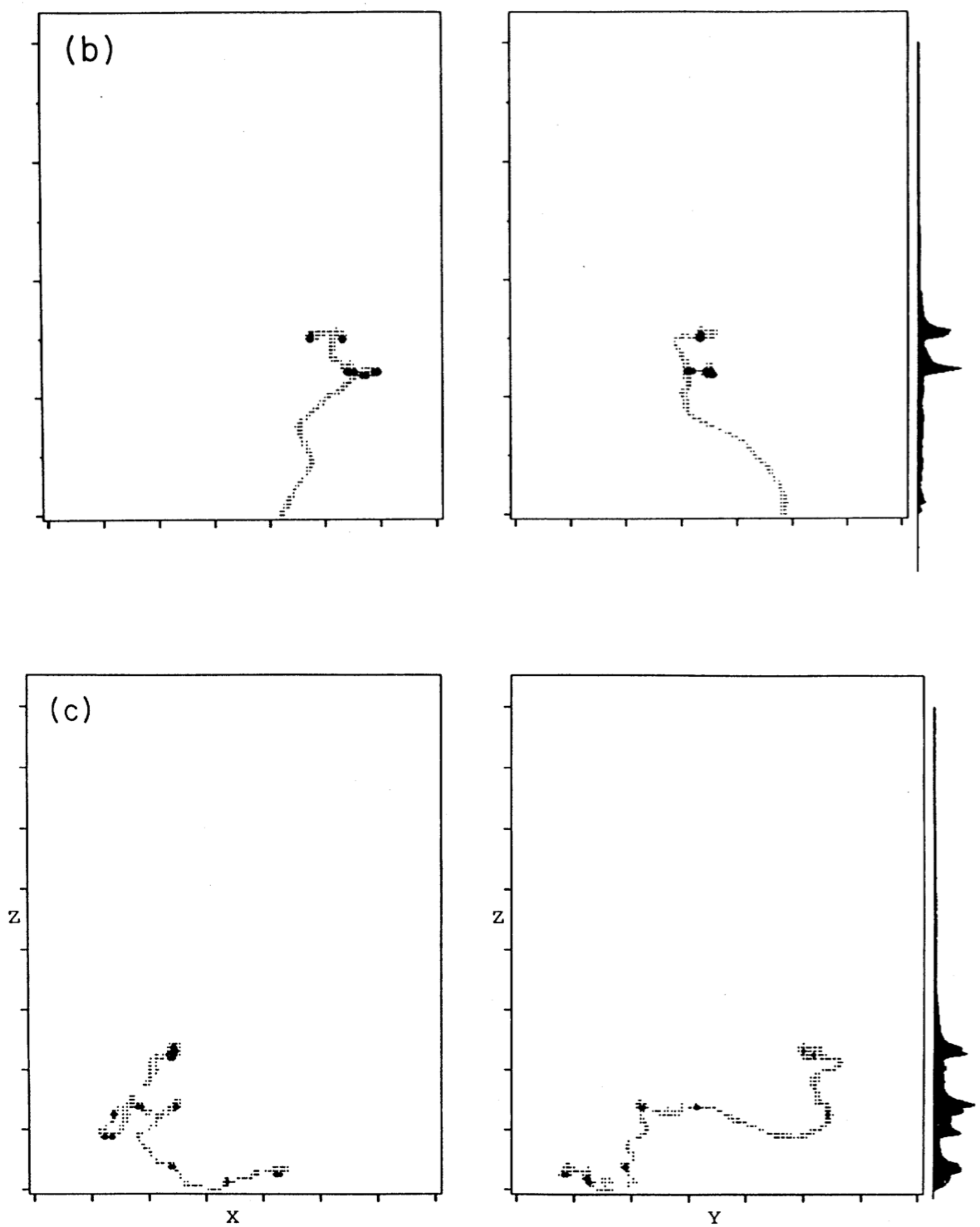
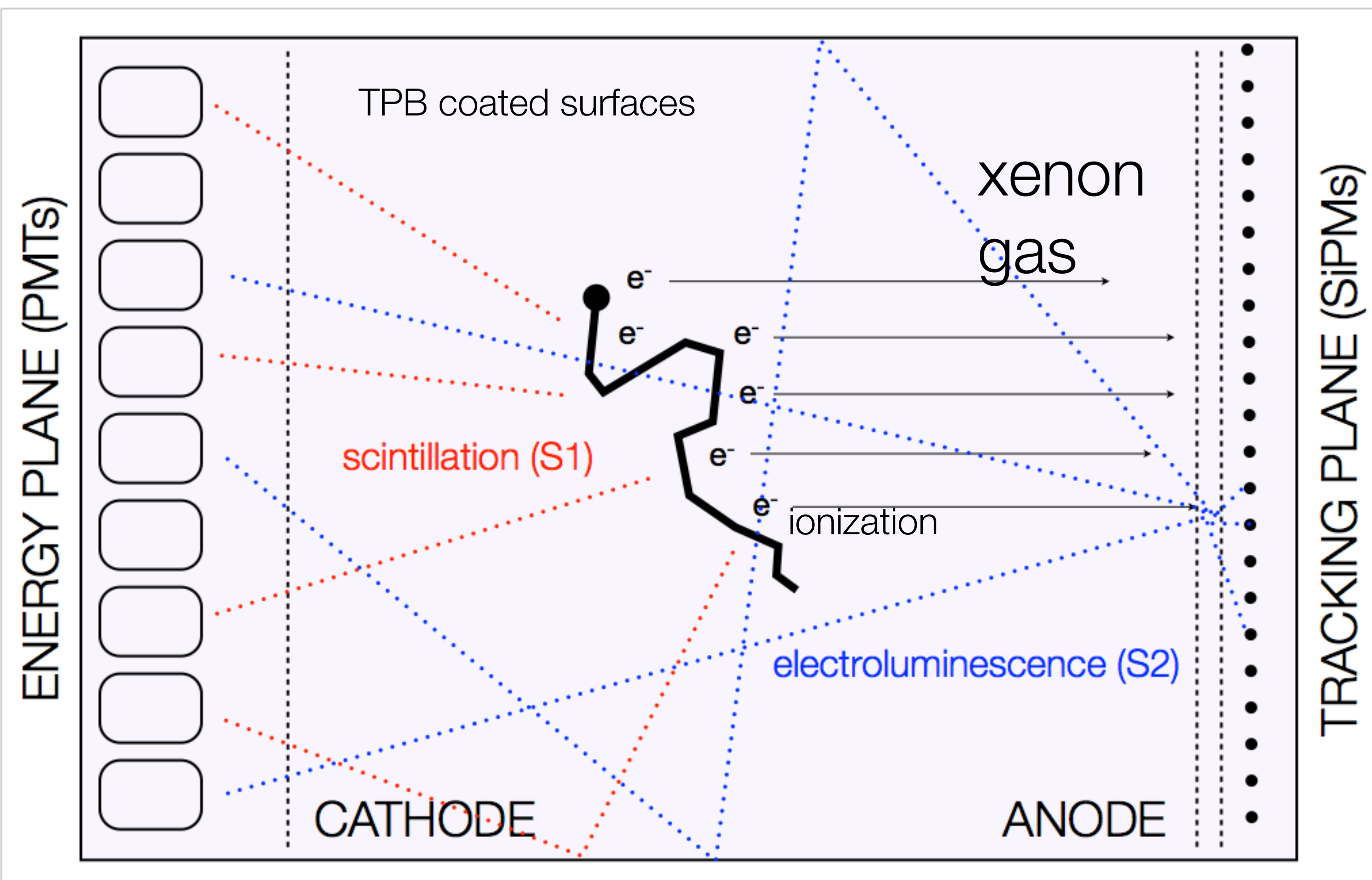


single electron event

candidate double electron event

Courtesy of Dave Nygren

NEXT-XX: A series of photonic TPCs



EL mode is essential to obtain linear gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

- NEXT: High Pressure Xenon (HPXe) TPC operating in electroluminescent (EL) mode.
- NEXT-100: 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane),
- PMTs also provide t_0 – essential for the z coordinate and fiducialization.
- The event topology is reconstructed by a plane of radiopure silicon pixels (SiPMs) (tracking plane).

Energy resolution in Xenon depends strongly on density!

Here, the fluctuations are normal

Fano factor

F = 0.15

Unfolded resolution:

δE/E ~0.6% FWHM

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

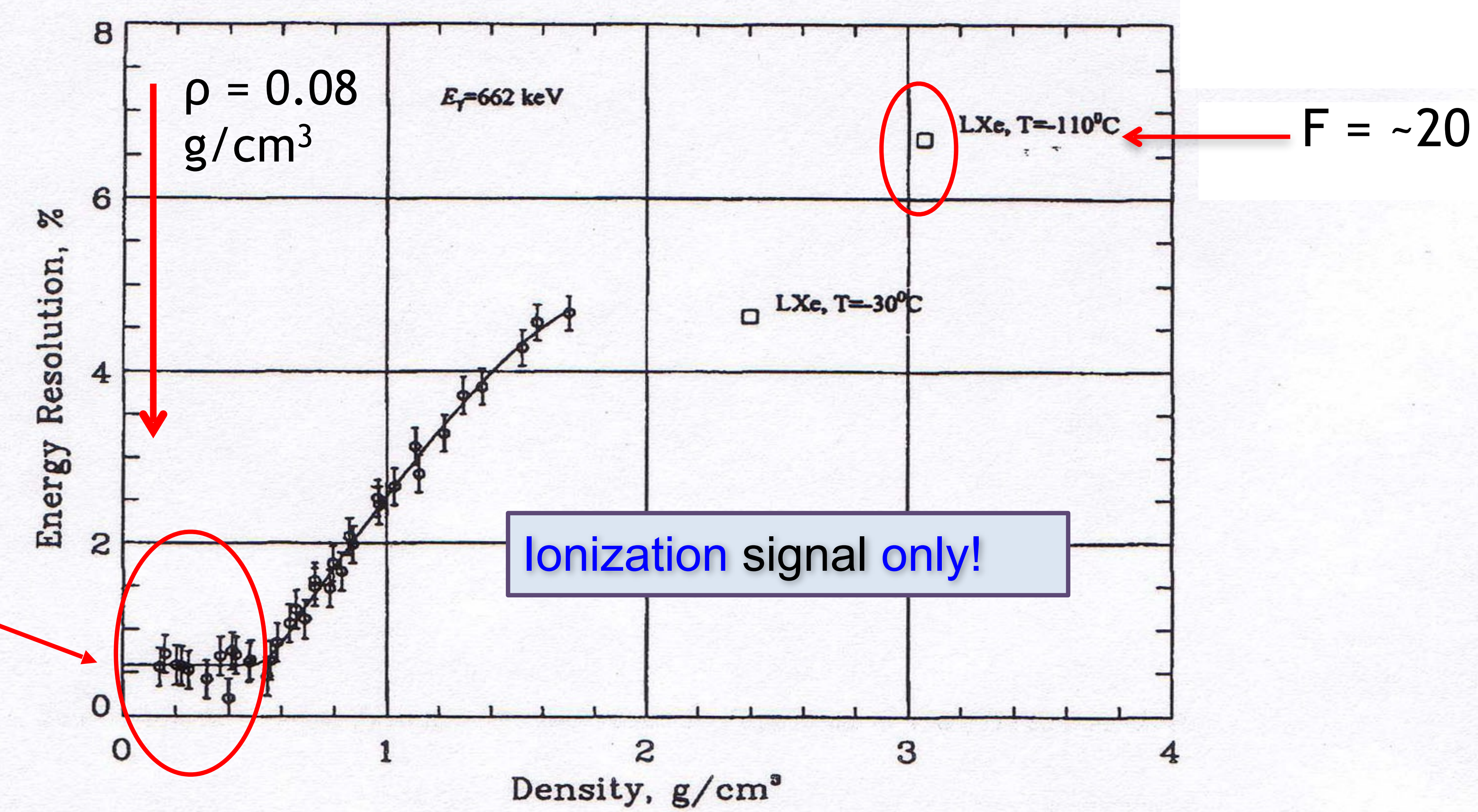
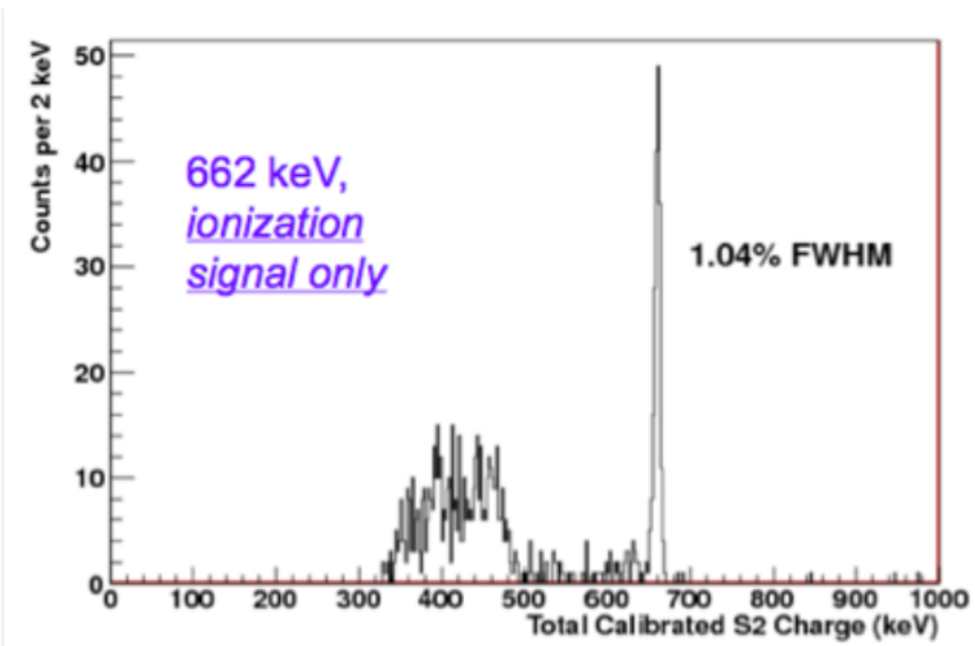
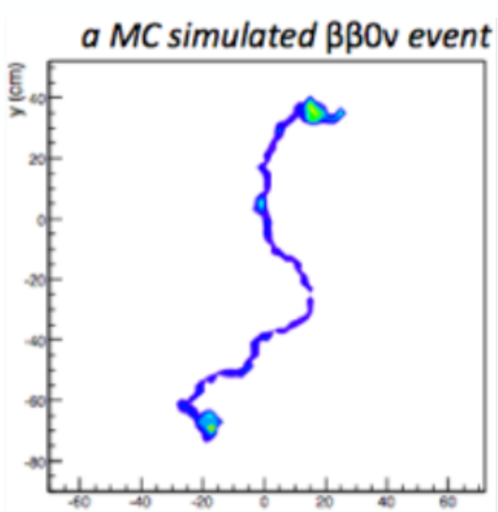


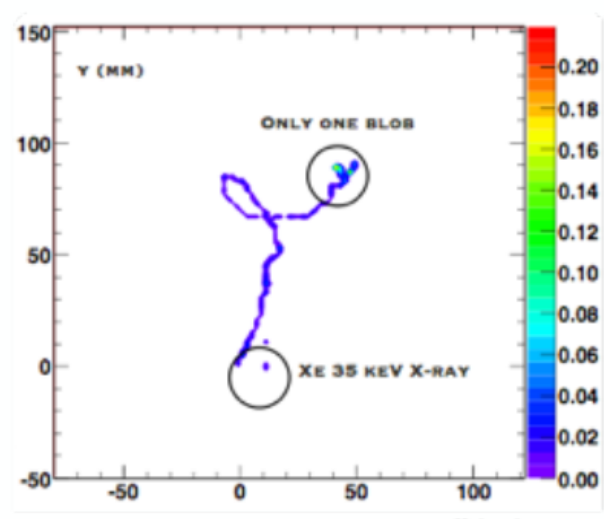
Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ <0.55 g/cm^3, ionization energy resolution is "intrinsic"

NEXT: Salient features



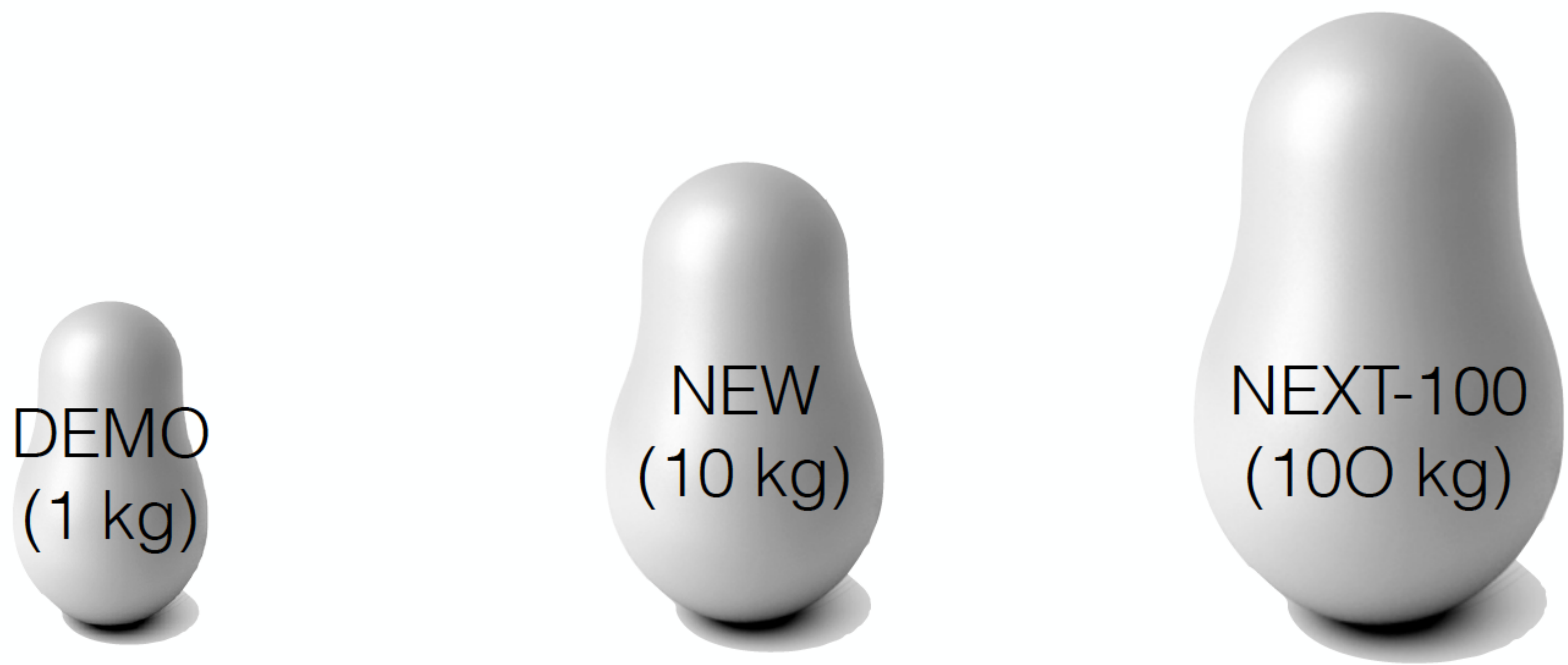




- Excellent resolution (~1% FWHM measured at 662 keV by NEXT prototypes, extrapolates to 0.5 % FWHM at Qbb
- Topological signature (TPS), eg. the ability to distinguish between signal (“double electrons”) and background (“single electrons”).
- Target = detector. Fiducial region away from surfaces.
- TPC: scalable. Economy of scale (S/N increases linearly with L)
- Xenon: the cheapest isotope to enrich in the market (NEXT owns 100 kg of enriched xenon).

Courtesy of JJ Gomez-Cadenas

The NEXT program



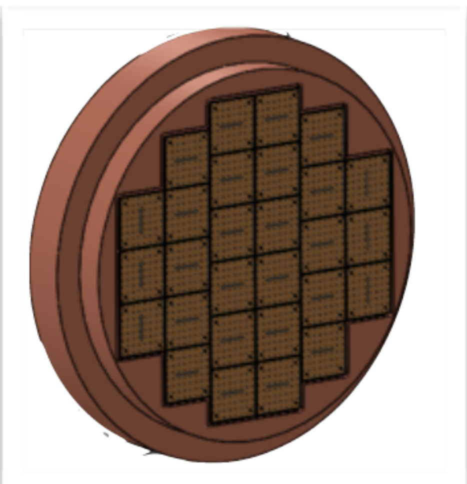
(2010–2014)
Demonstration of detector concept

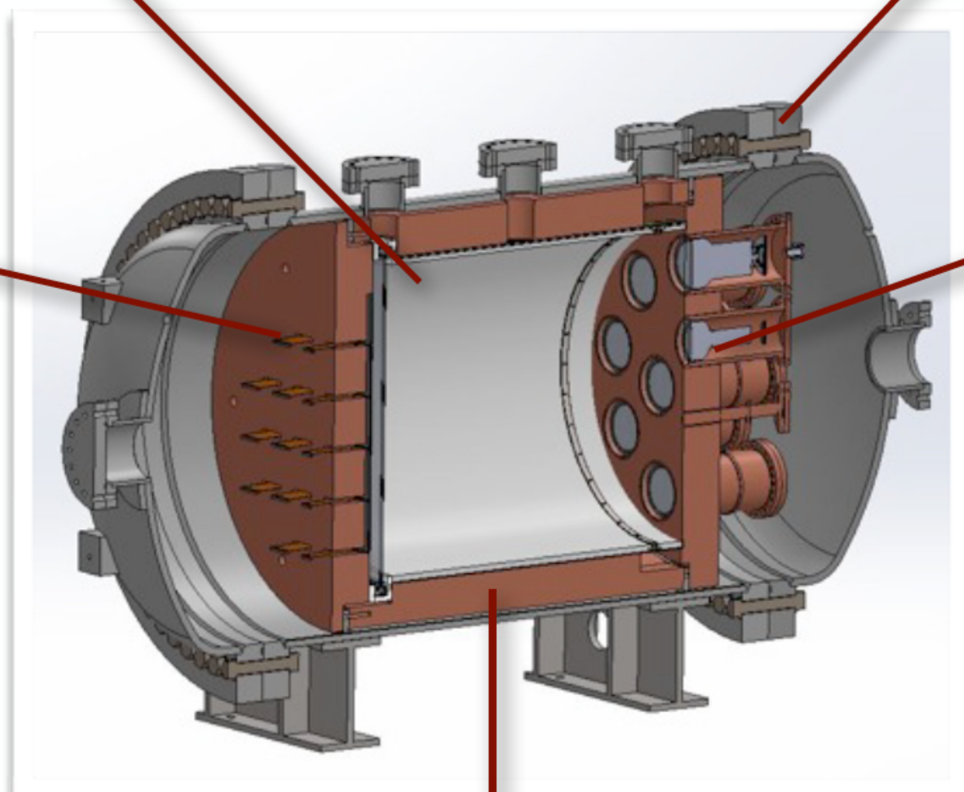
(2015–2017)
Test underground, radiopure operation

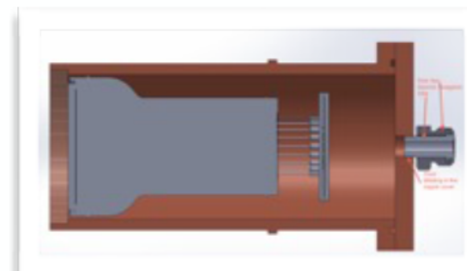
(2018–2020)
Neutrinoless double beta decay searches

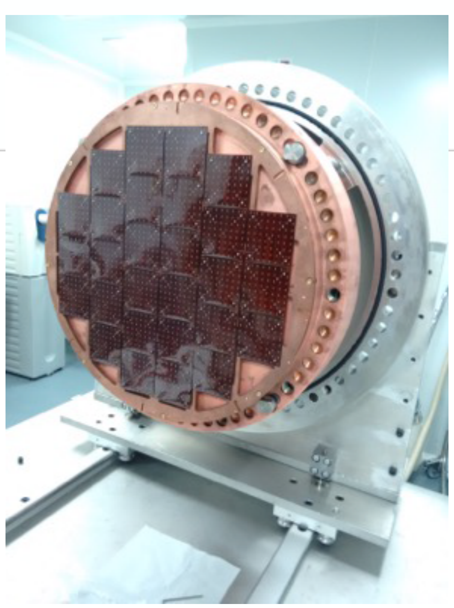
Courtesy of JJ Gomez-Cadenas

NEW (NEXT-WHITE) at glance



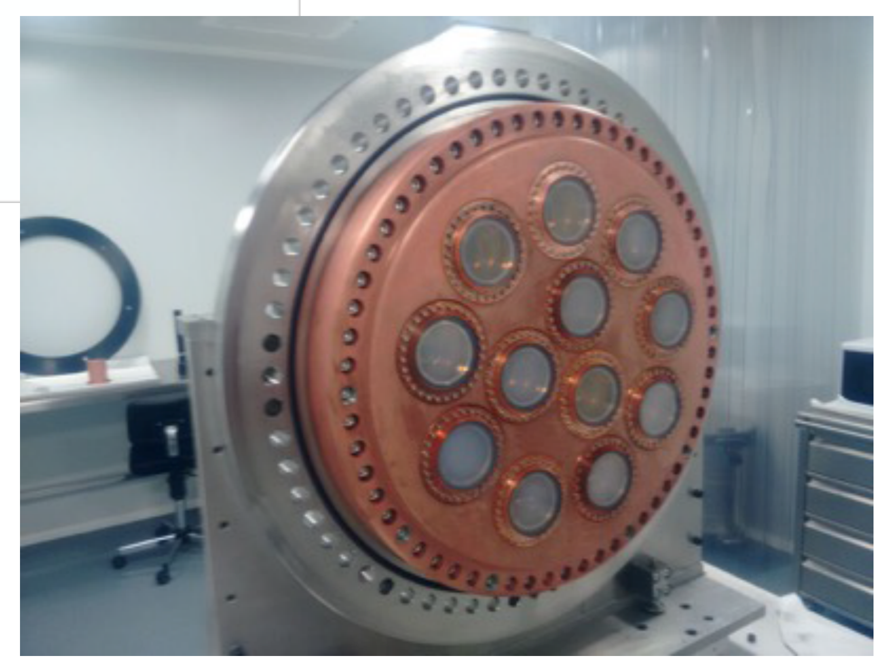






tracking plane

energy plane

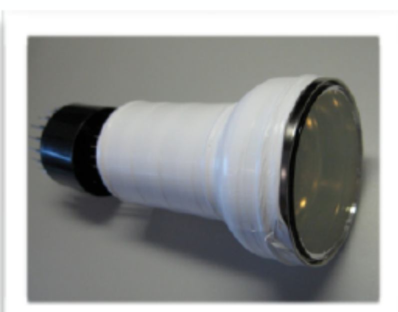


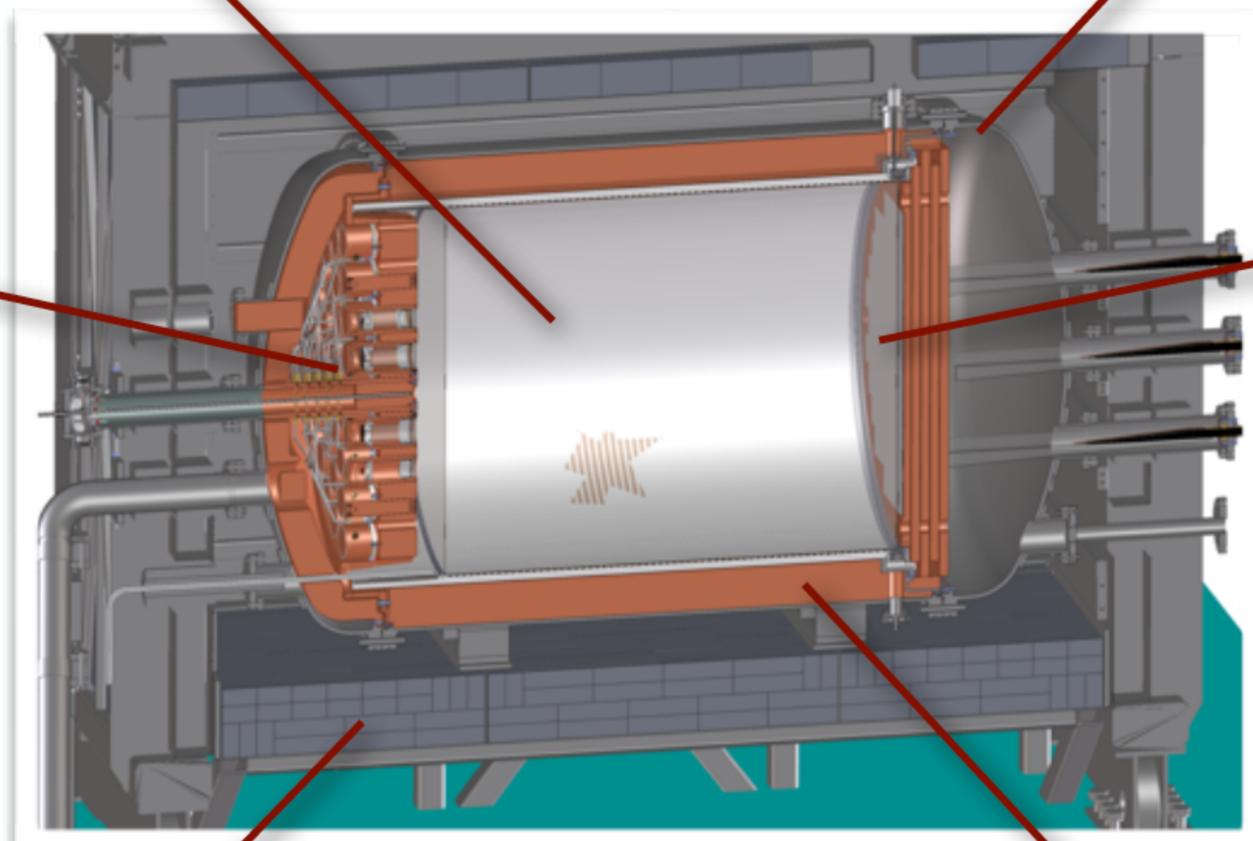
NEXT 100 kg detector at LSC: main features

Time Projection Chamber:
100 kg active region, 130 cm drift length

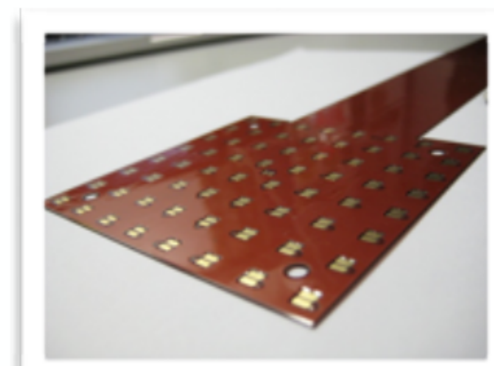
Pressure vessel:
stainless steel, 15 bar max pressure

Energy plane:
60 PMTs,
30% coverage





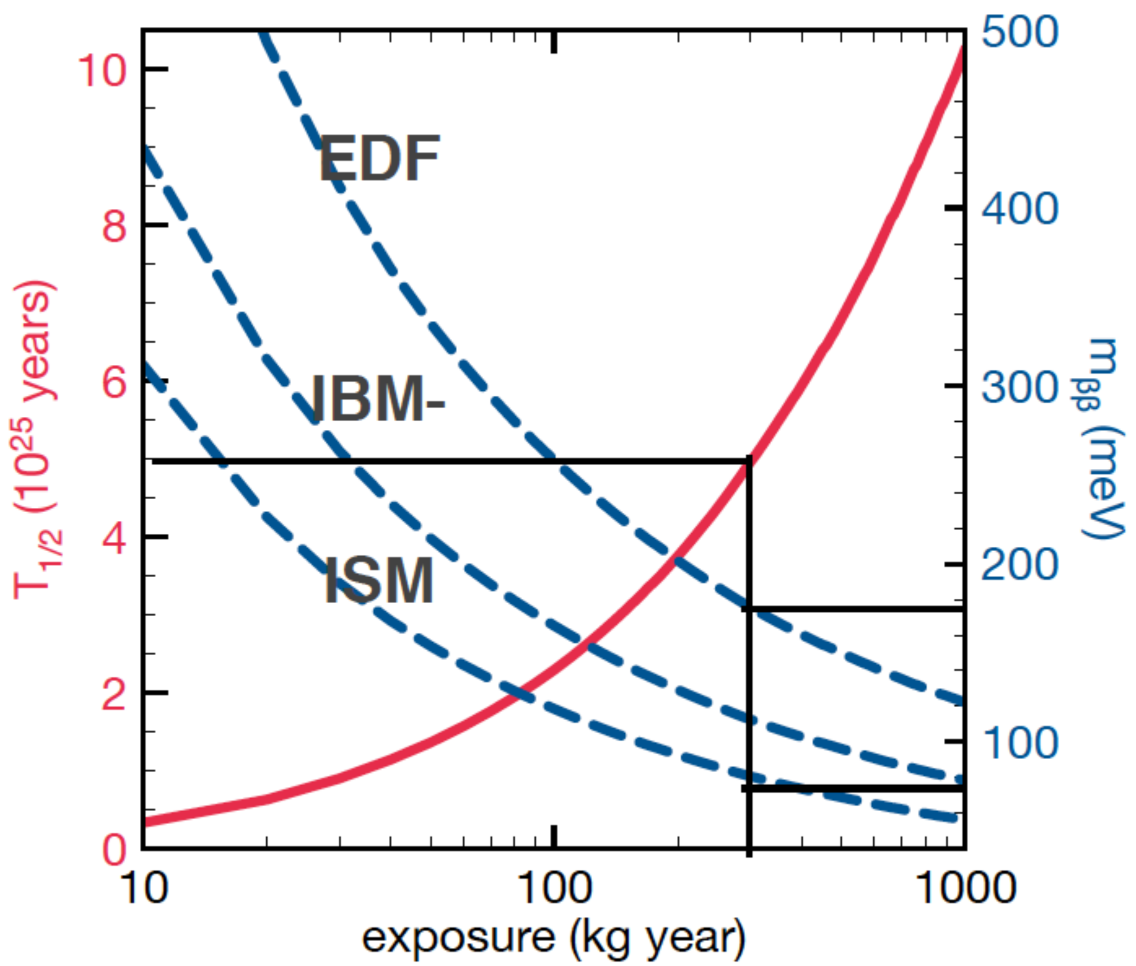
Tracking plane:
7,000 SiPMs,
1 cm pitch



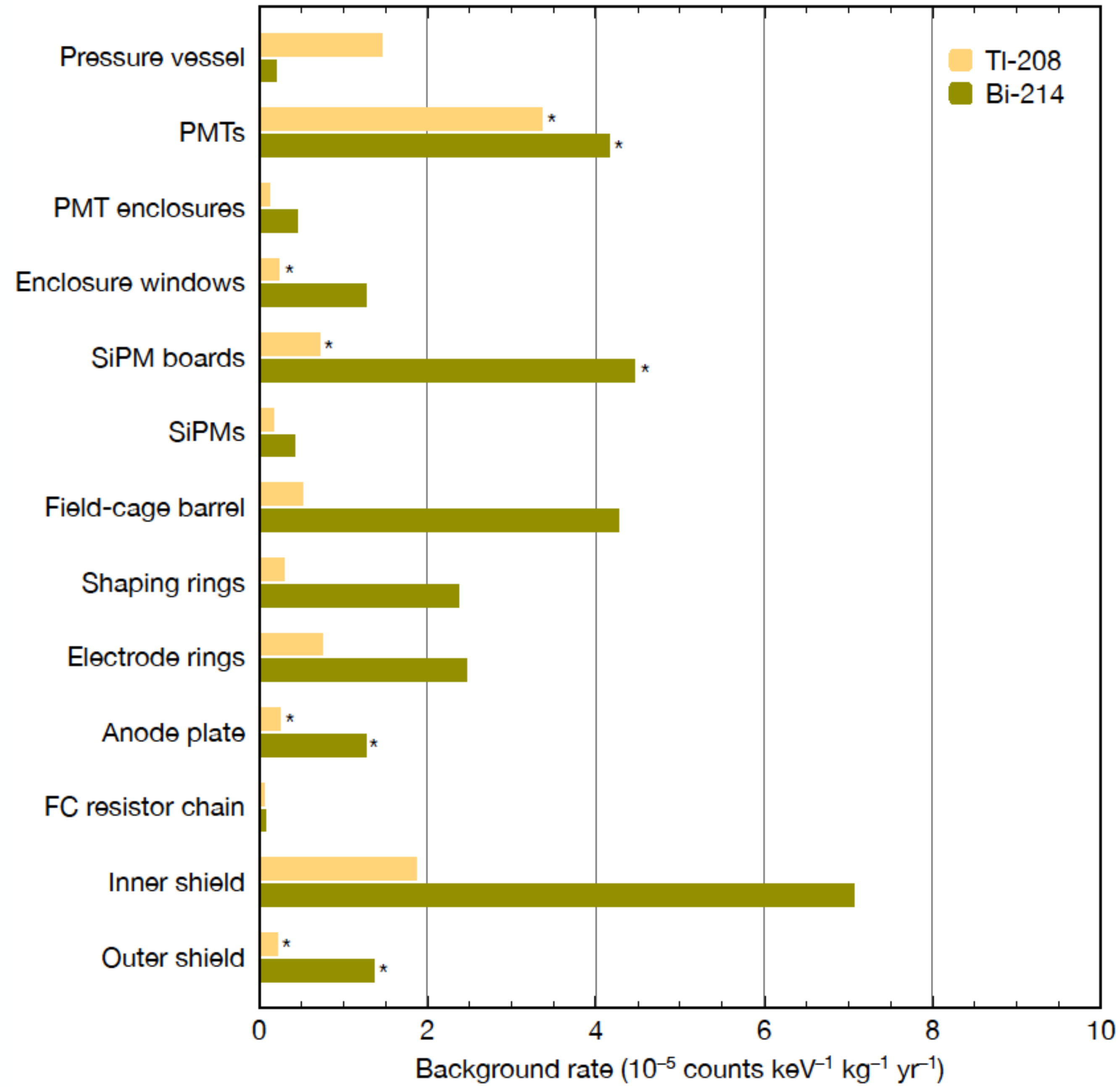
Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

Courtesy of JJ Gomez-Cadenas



- Expect 5 x 10^{25} y in 3 years run (2018-2020).
- mbb ~[90-180] meV depending on NME



- Expected background rate: 4 x 10^{-4} ckky

The Enriched Xenon Observatory (EXO)

Search for $0\nu\beta\beta$ decay of ^{136}Xe (Q=2458 keV) with enriched xenon TPC's (with scintillation readout) of increasing sensitivity and size

Enrichment is relatively simpler and less expensive

- 10% --> 80-90% proven on the 100's kg scale

Continuous re-purification possible

- from electronegative, radioactive contaminants

Xenon is reusable

- could be transferred between experiments

Monolithic detector, remarkable self-shielding

Good (enough) energy resolution

- with combined scintillation + ionization

$\beta\beta/\gamma$ discrimination

- event topology

Xenon admits a novel coincidence technique

- Ba daughter tagging

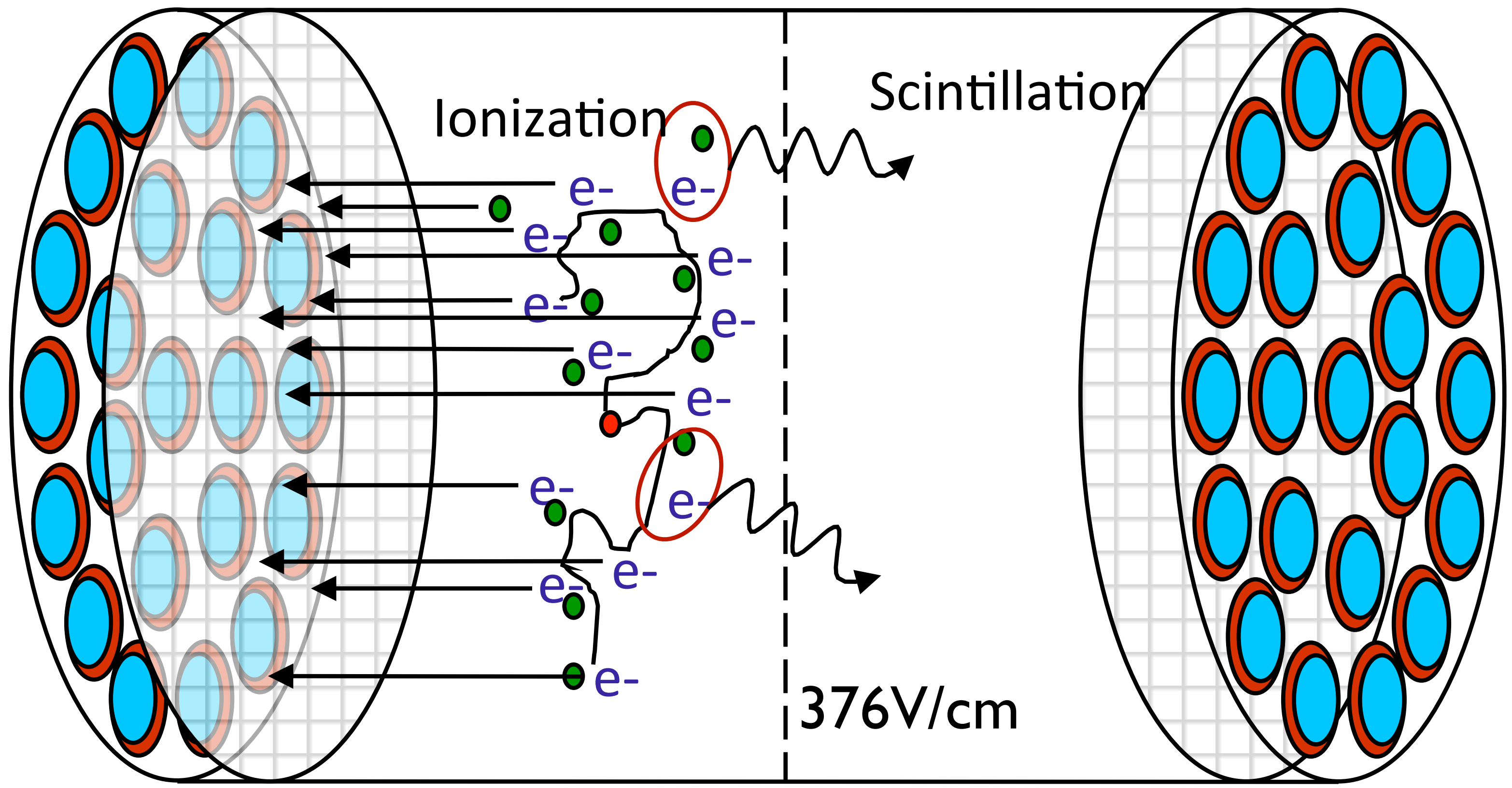
M. Moe, PRC 44, R931 (1991)

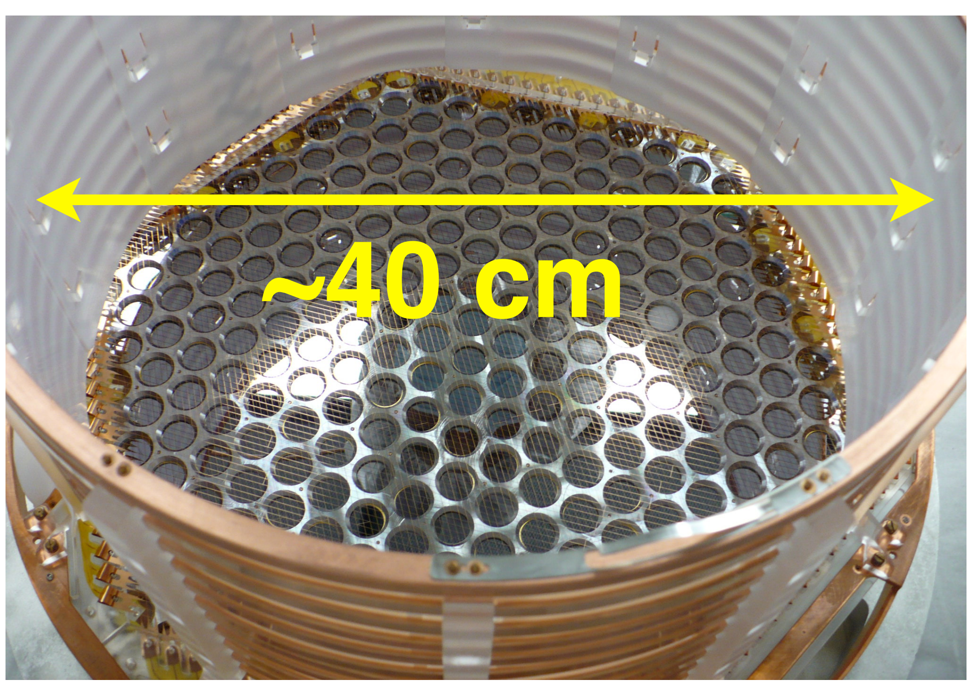
Limited cosmogenic activation

- longest-lived 4 minutes

The EXO-200 LXe Time Projection Chamber (TPC)

- ~150 kg ^{enr}LXe
- Cathode in center
- Light detected by APDs on end caps
- Charge detected by crossed u- and v-wire planes



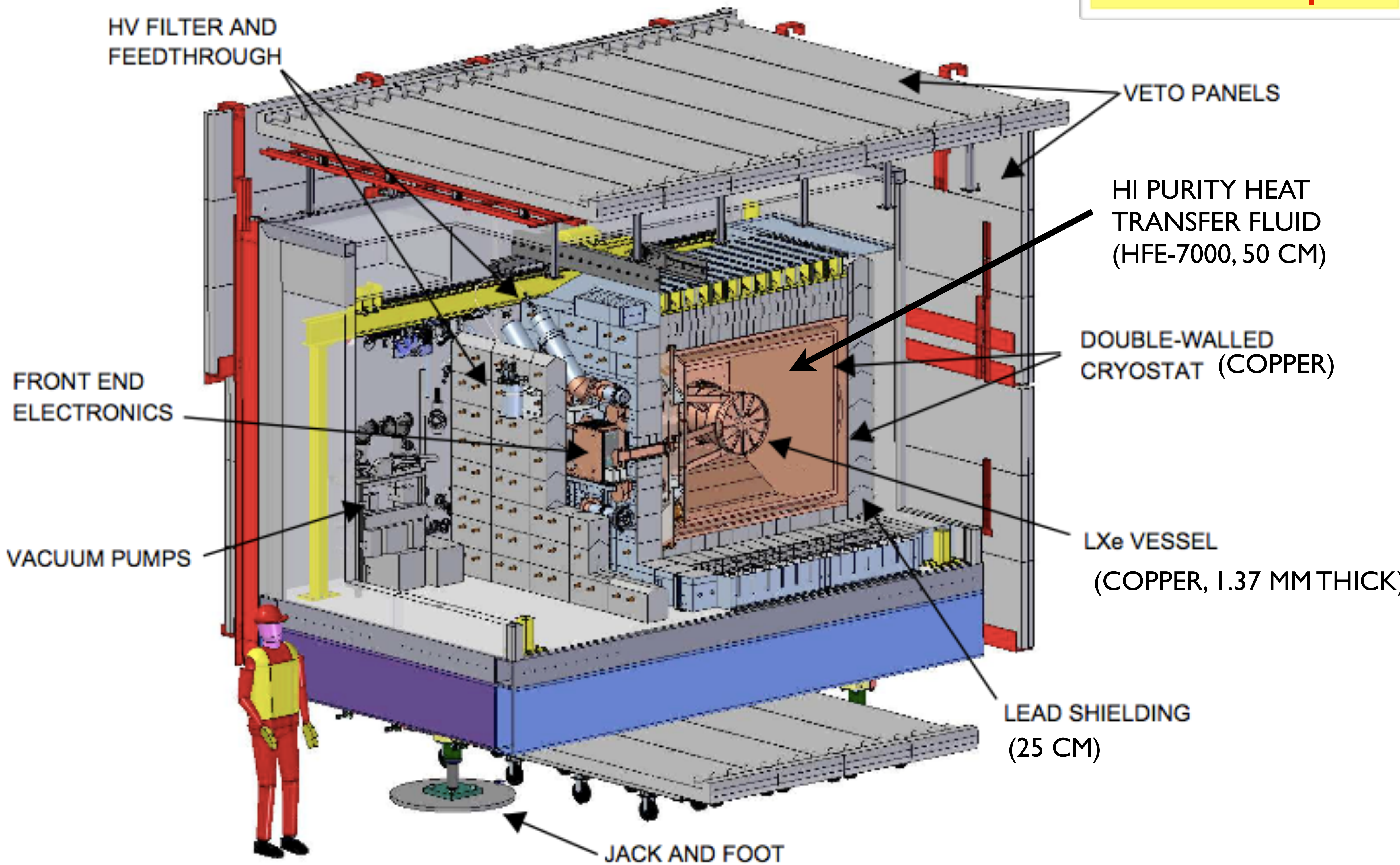


- v-wire plane measures induction
- u-wire plane collects charge
- Energy from u-wire and APD signals

JINST 7 (2012) P05010

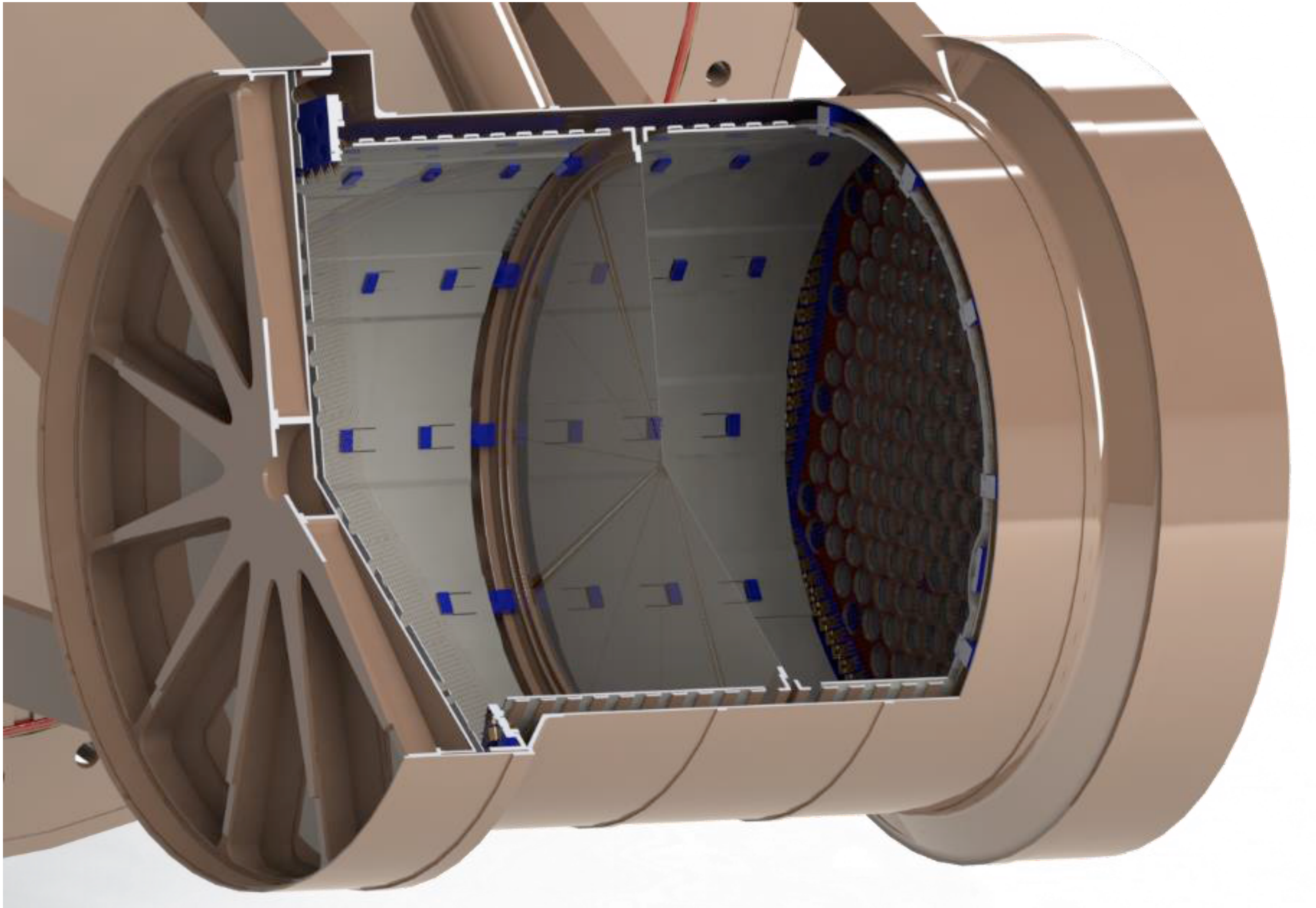
The EXO-200 detector at WIPP (~1,500 m.w.e.)

Rn: ~6 Bq/m^3

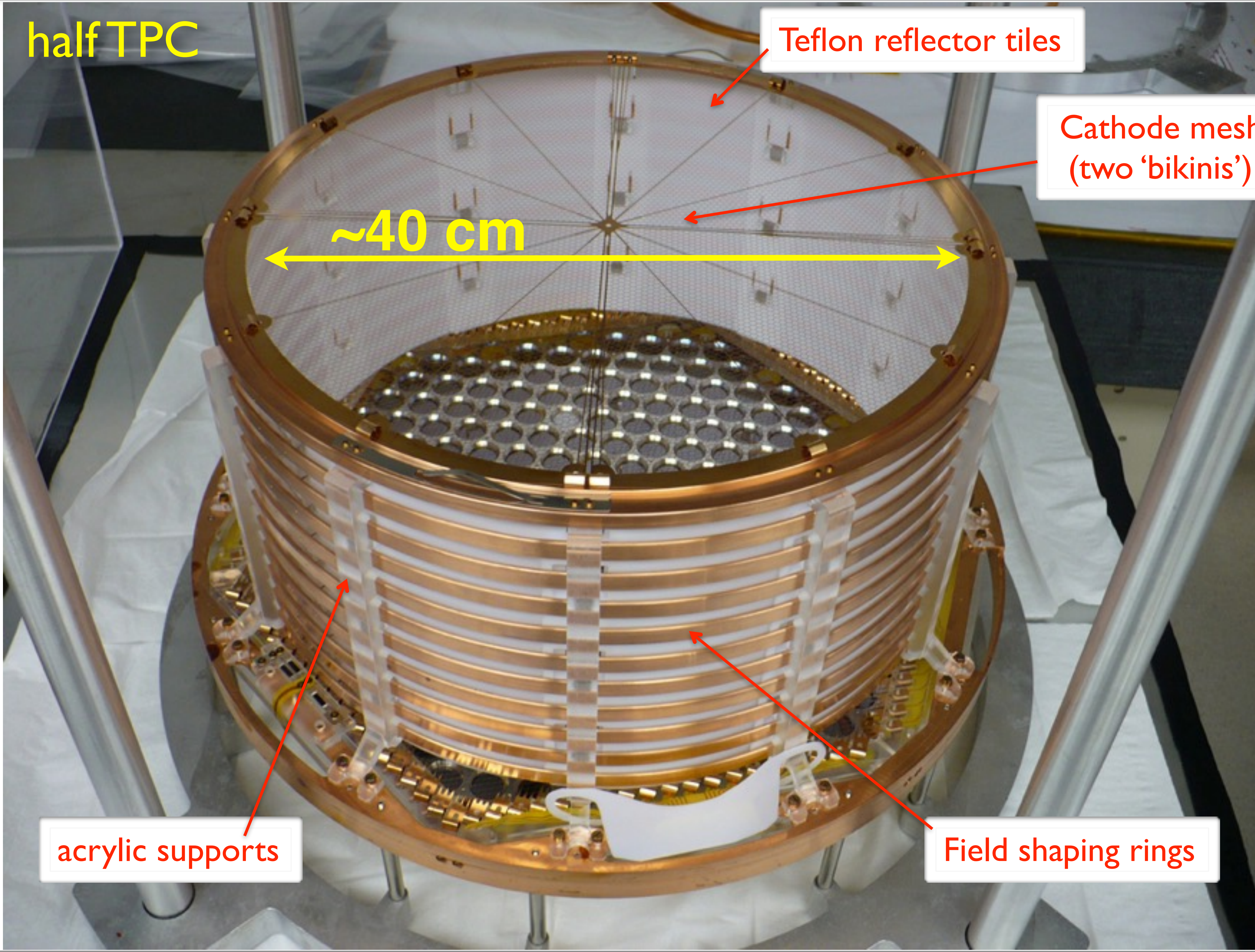


JINST 7 (2012) P05010

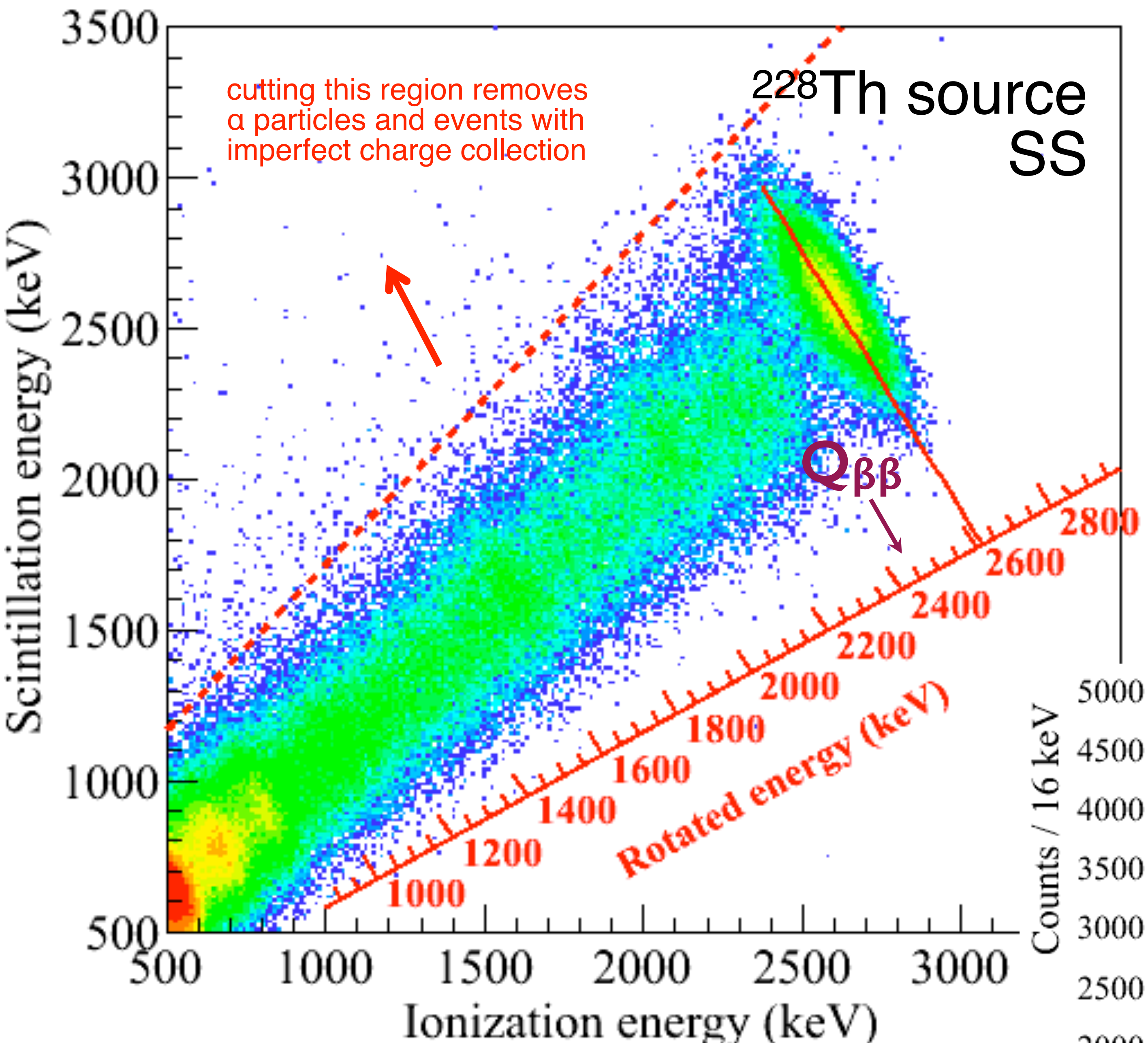
EXO-200 Inner Detector

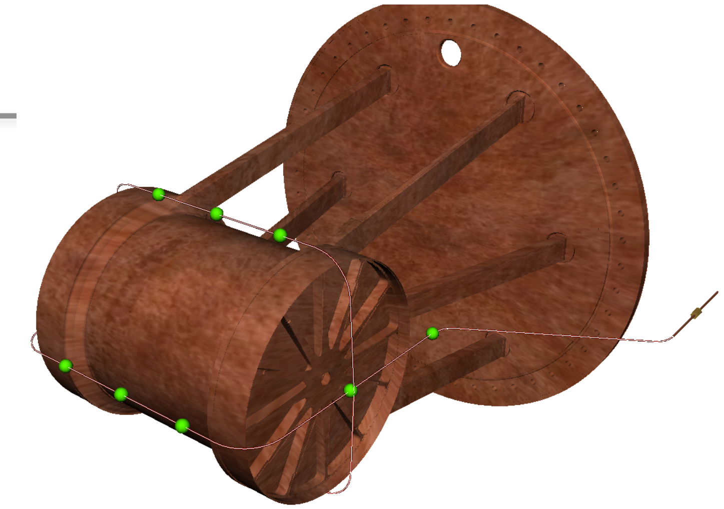


the EXO-200 TPC



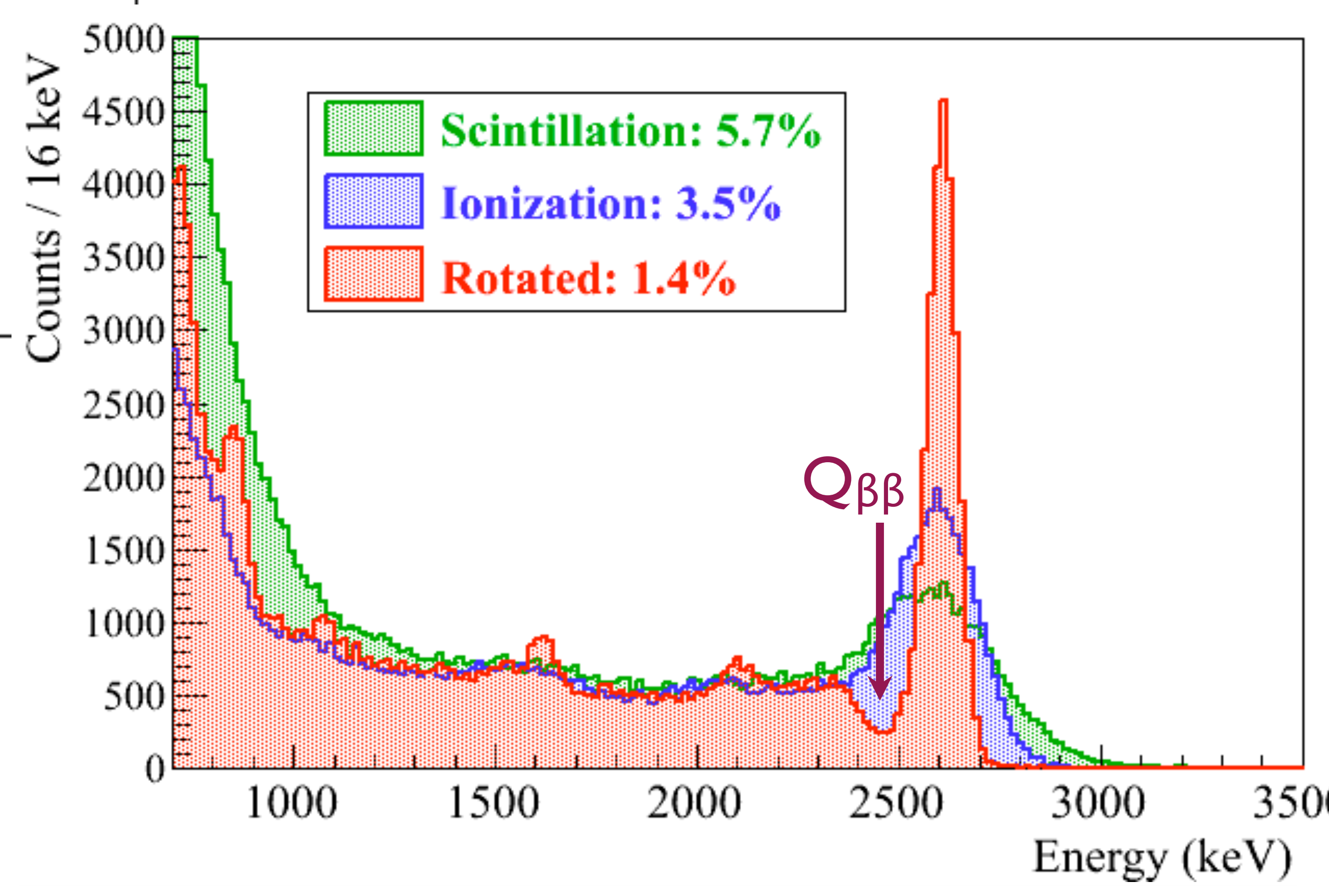
Energy resolution





Takes into account anti-correlation of charge and scintillation response to improve energy resolution

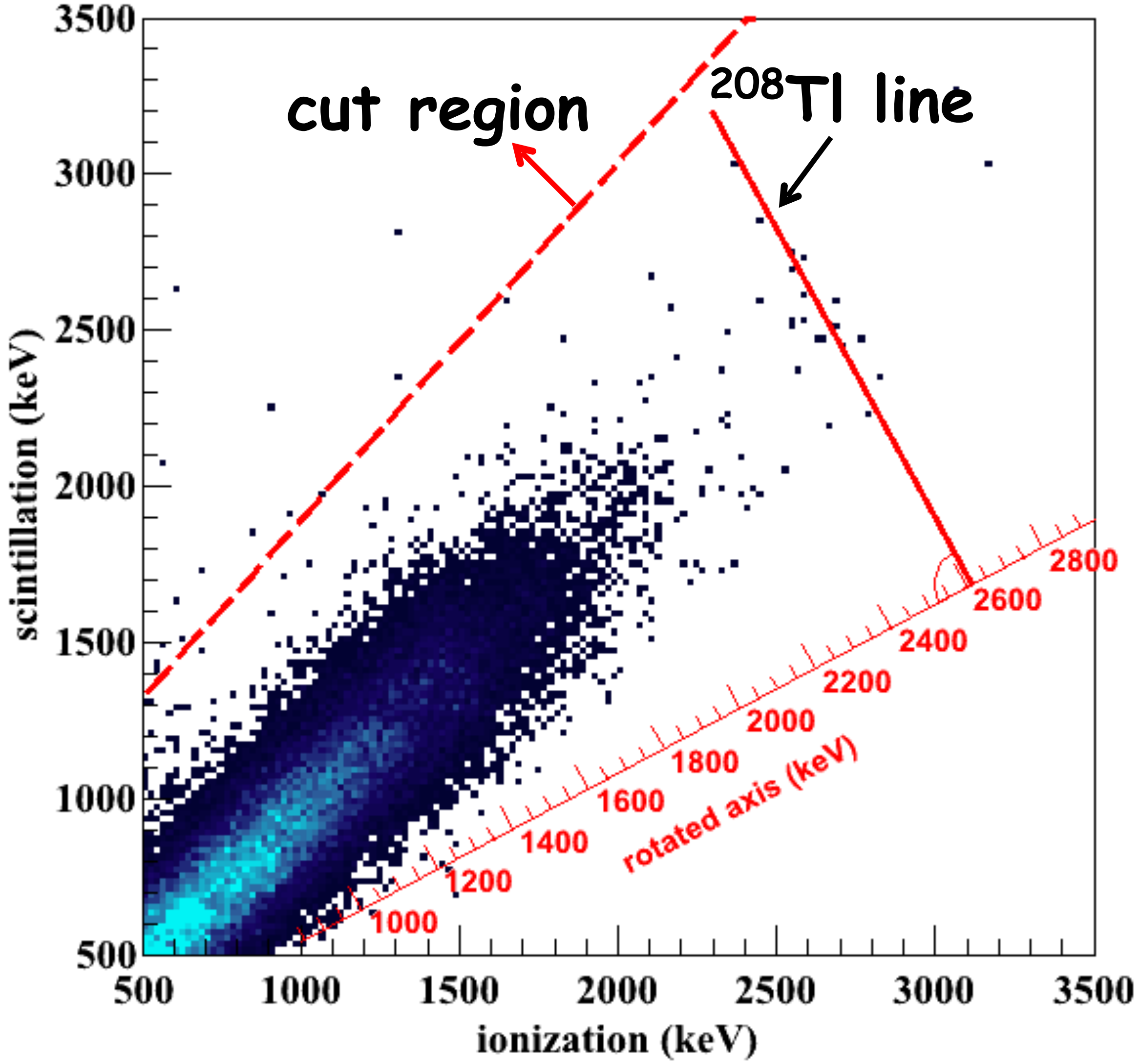
Calibration performed with ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th

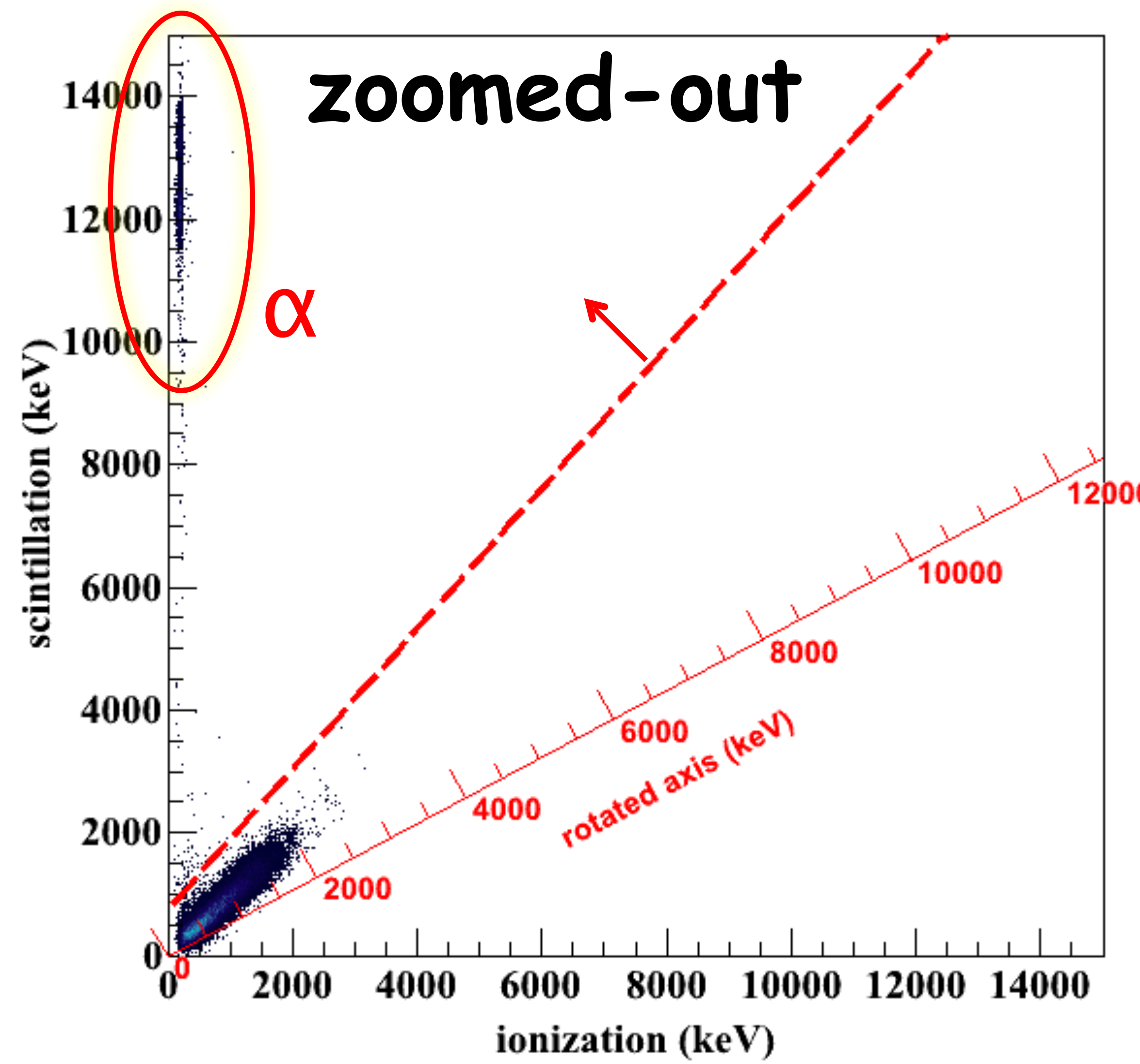


Molecular properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

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

Low Background 2D SS Spectrum





α : larger ionization density
→ more recombination
→ more scintillation light

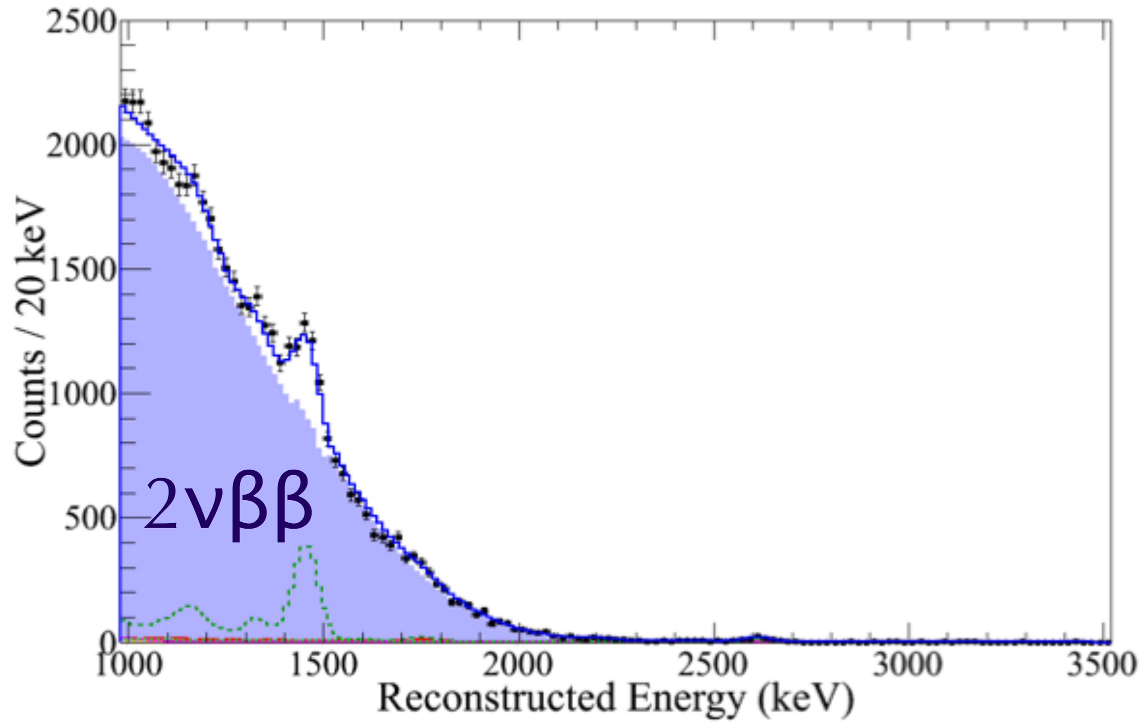
a diagonal cut (large scintillation, low charge) eliminates:
1) alphas
2) edge events (partial charge collection)

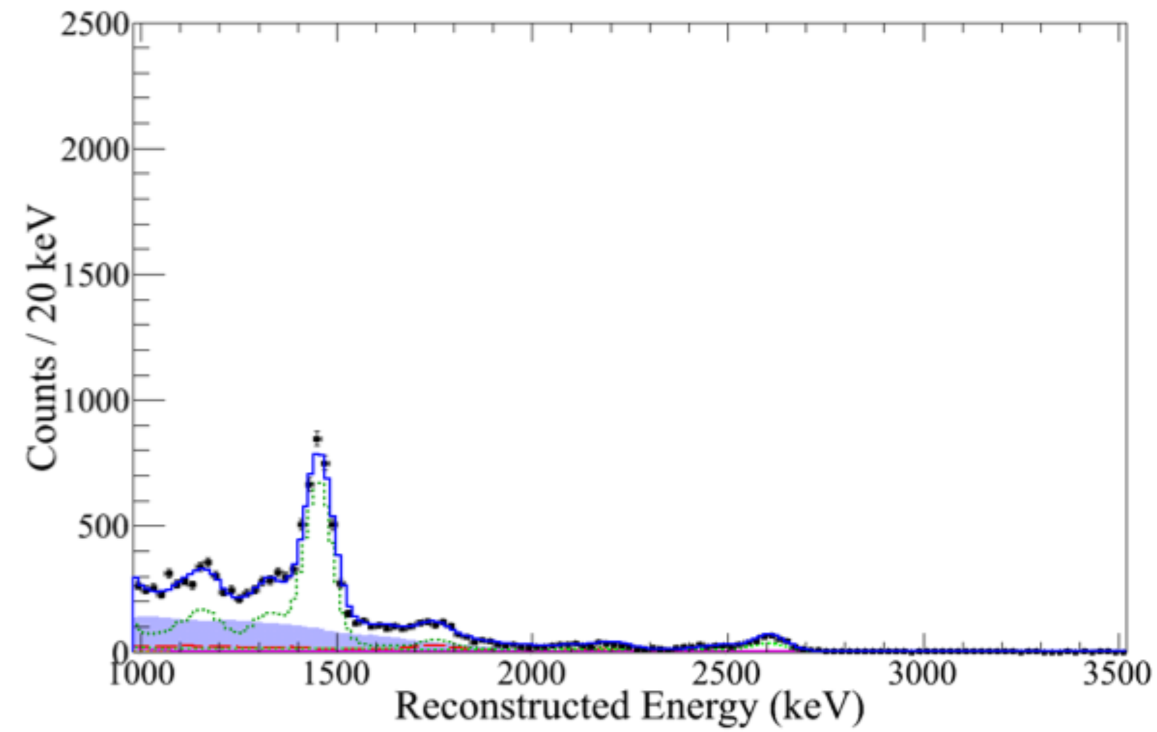
Event multiplicity and background discrimination

(EXO-200 data)

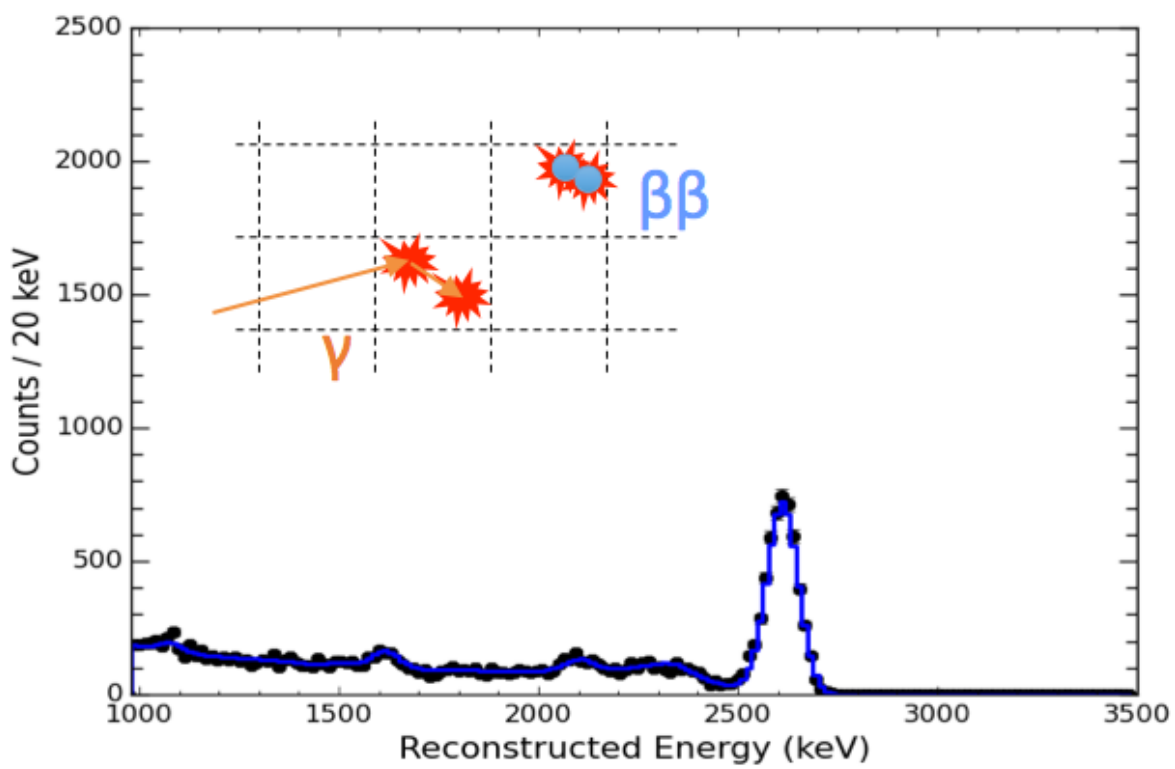
Single Site (SS) | **Multiple Site (MS)**

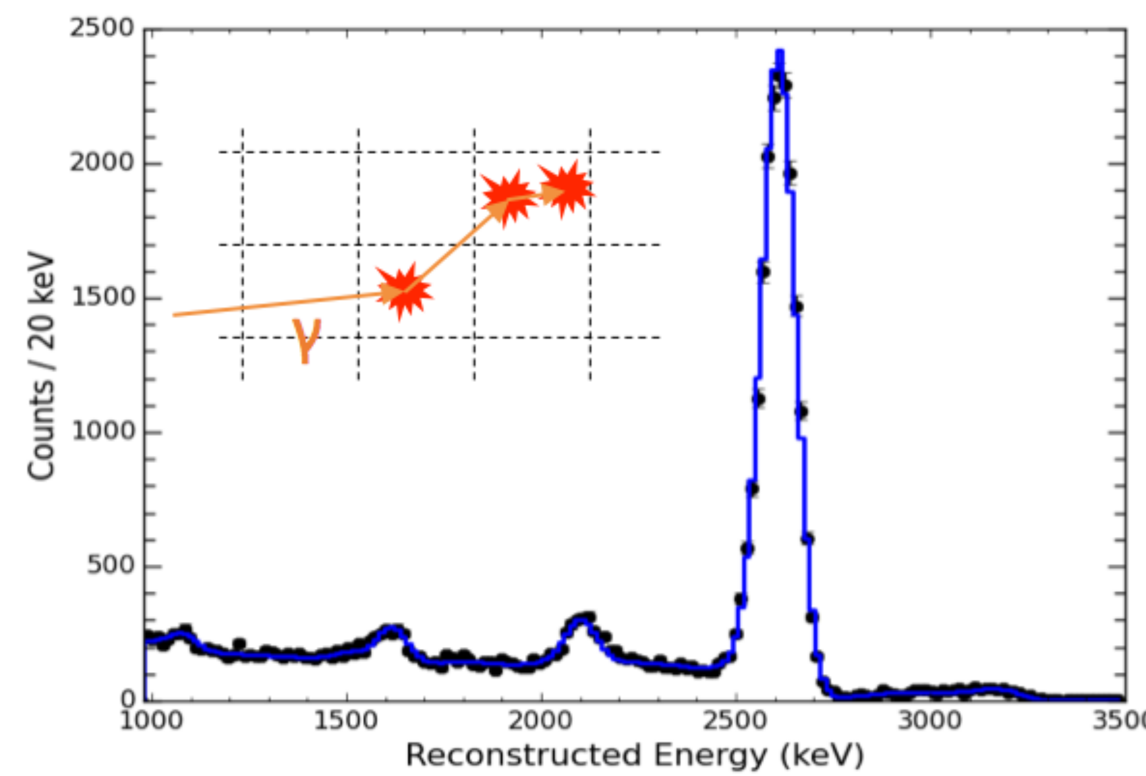
Low Background Data

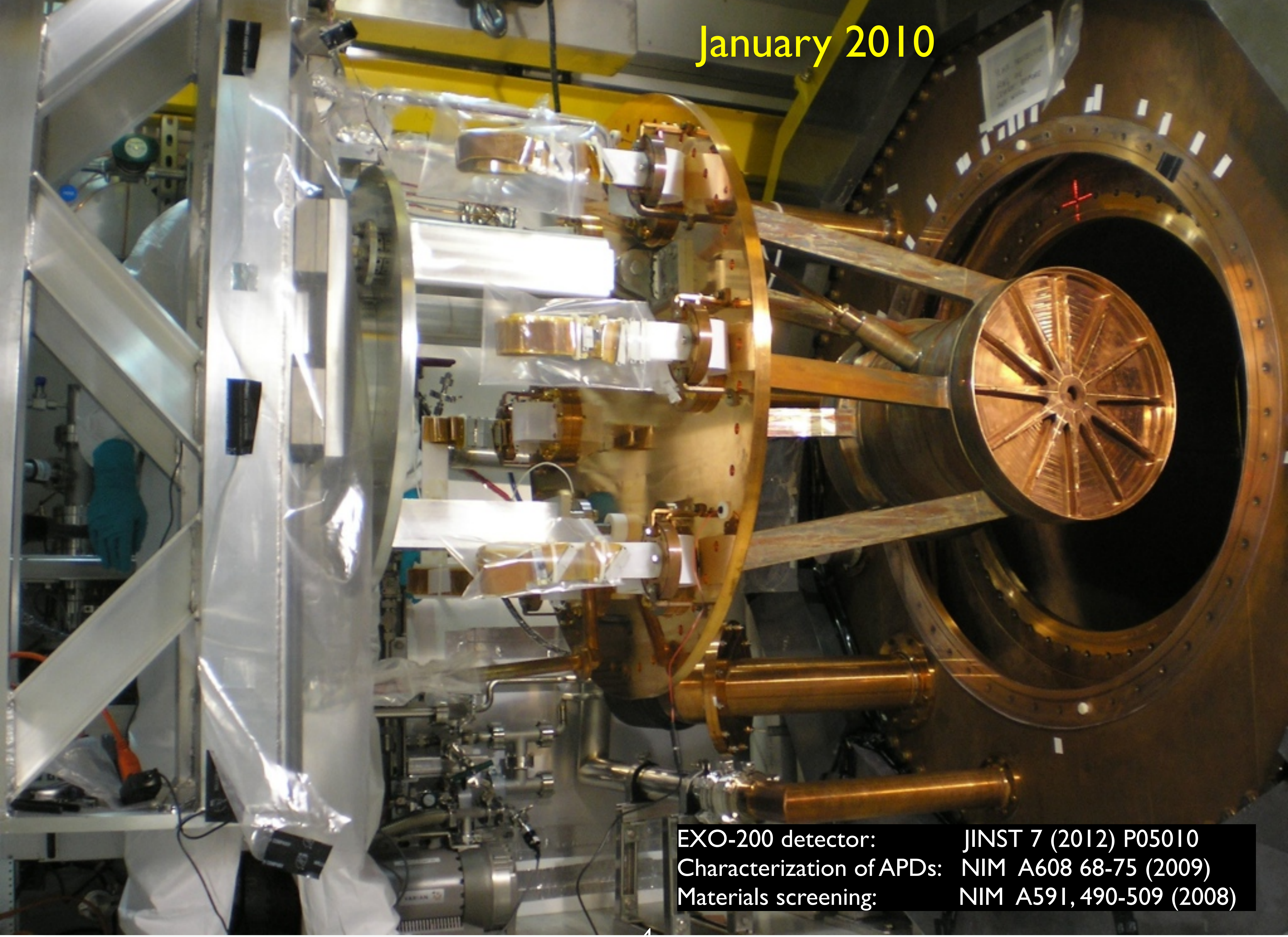


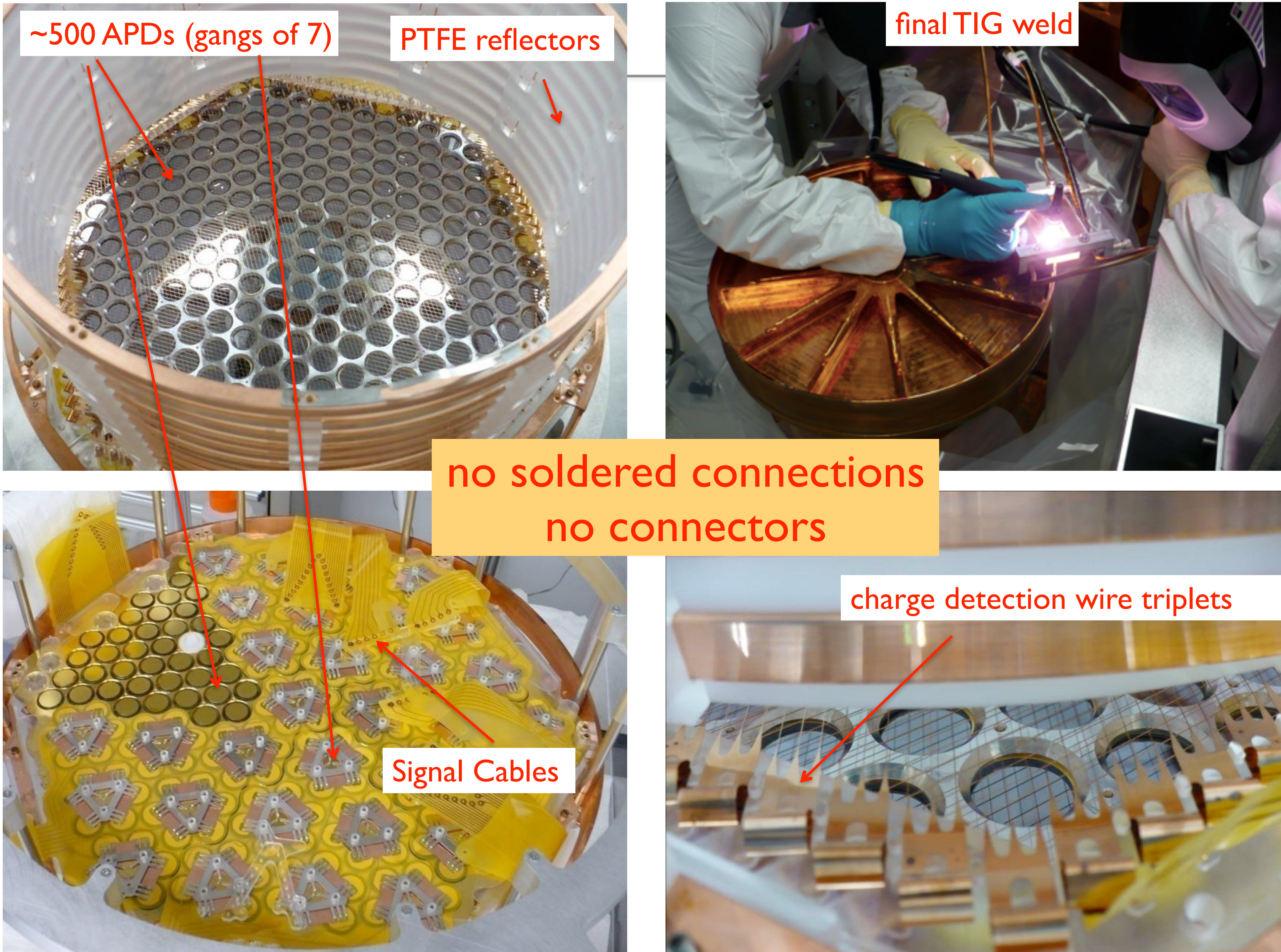


^{228}Th Calibration Source

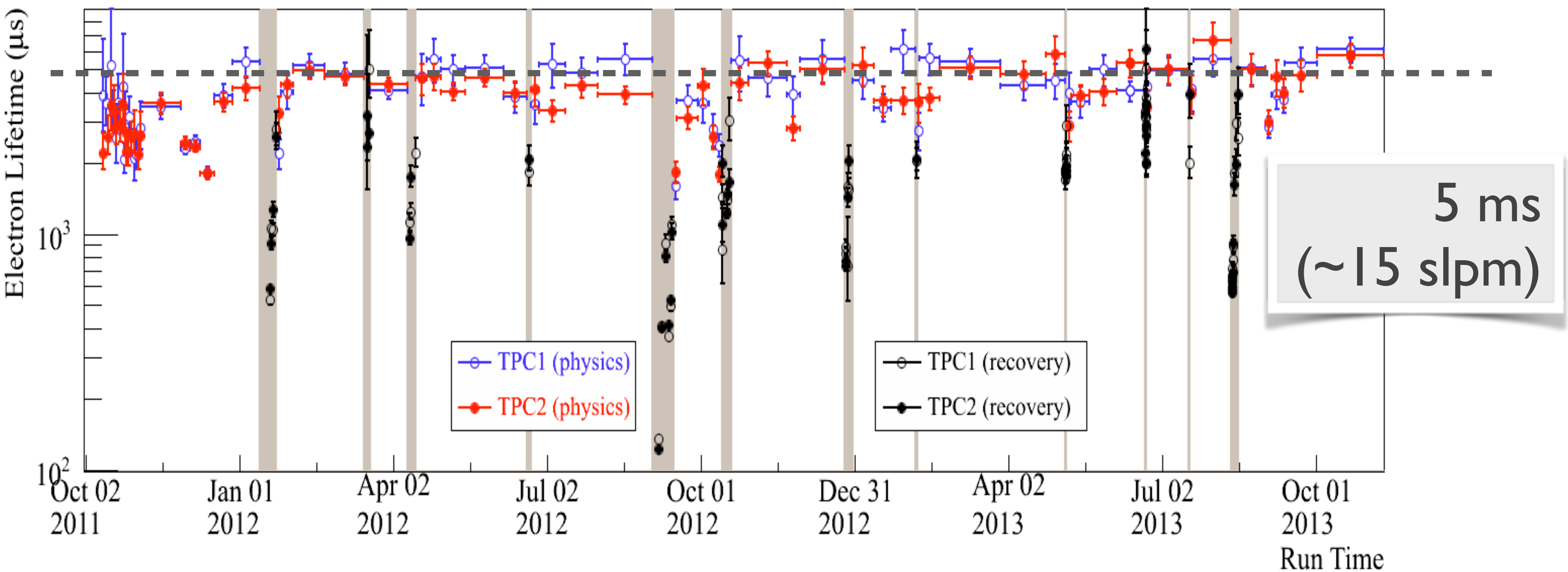





January 2010
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)


~500 APDs (gangs of 7)
PTFE reflectors
final TIG weld
no soldered connections
no connectors
Signal Cables
charge detection wire triplets

Xenon purity from electronegative species - Run 2



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

Ultraclean pump: *Rev. Sci. Instr. 82 (10) 105114*
Xenon purity with mass spec: *NIM A675 (2012) 40*
Gas purity monitors: *NIM A659 (2011) 215*

EXO-200: radio-assay effort

Massive effort on material radioactive qualification using:

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

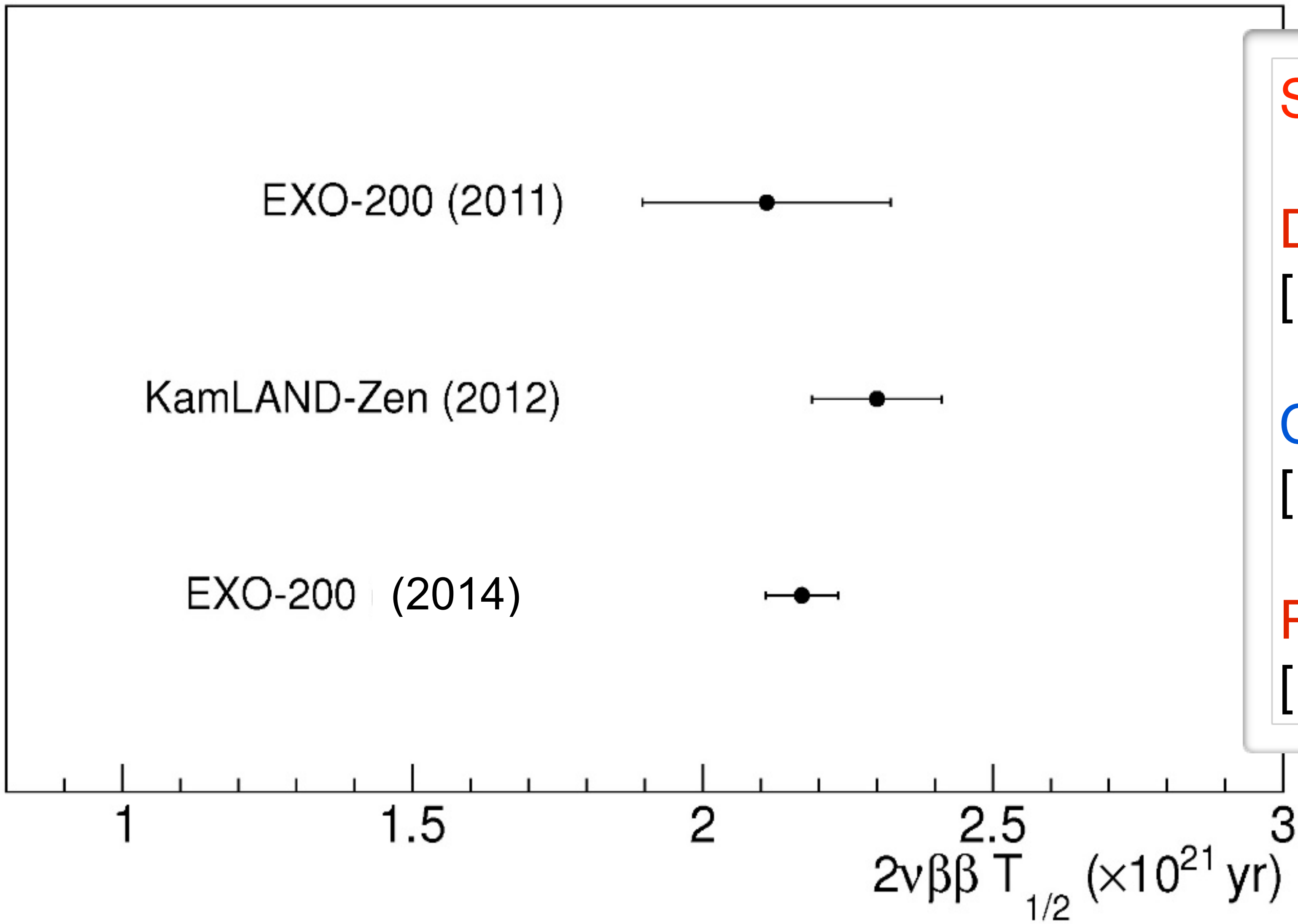
At present the database of characterized materials includes >300 entries

D.S. Leonard et al., Nucl. Ins. Meth. A 591, 490 (2008)

The impact of every screw within the Pb shielding is evaluated before acceptance

This imposes huge constraints on the design of the detector

Phase I, Run 2: precision measurement of 2νββ



Start data taking in June 2011

Discovery of 2νββ decay of 136Xe
[PRL 107, 212501 (2011)]

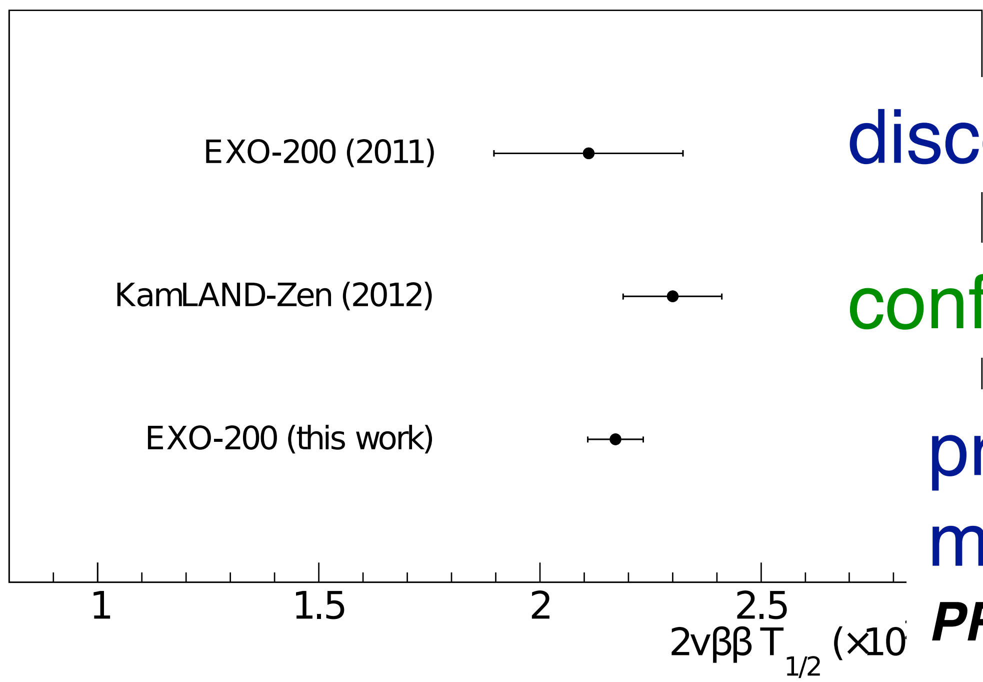
Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

Precision measurement (~3%)
[PRC 89, 015502 (2014)]

$$\mathbf{T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016(stat) \pm 0.059(syst)) \times 10^{21} yr}$$

(longest, yet most precisely (directly) measured 2νββ decay of all ‘practical’ isotopes)

the slowest, yet the better measured



discovery of 2-neutrino mode ***PRL 107, 212501 (2011)***

confirmation by KL-Zen ***PRC 85, 045504 (2012)***

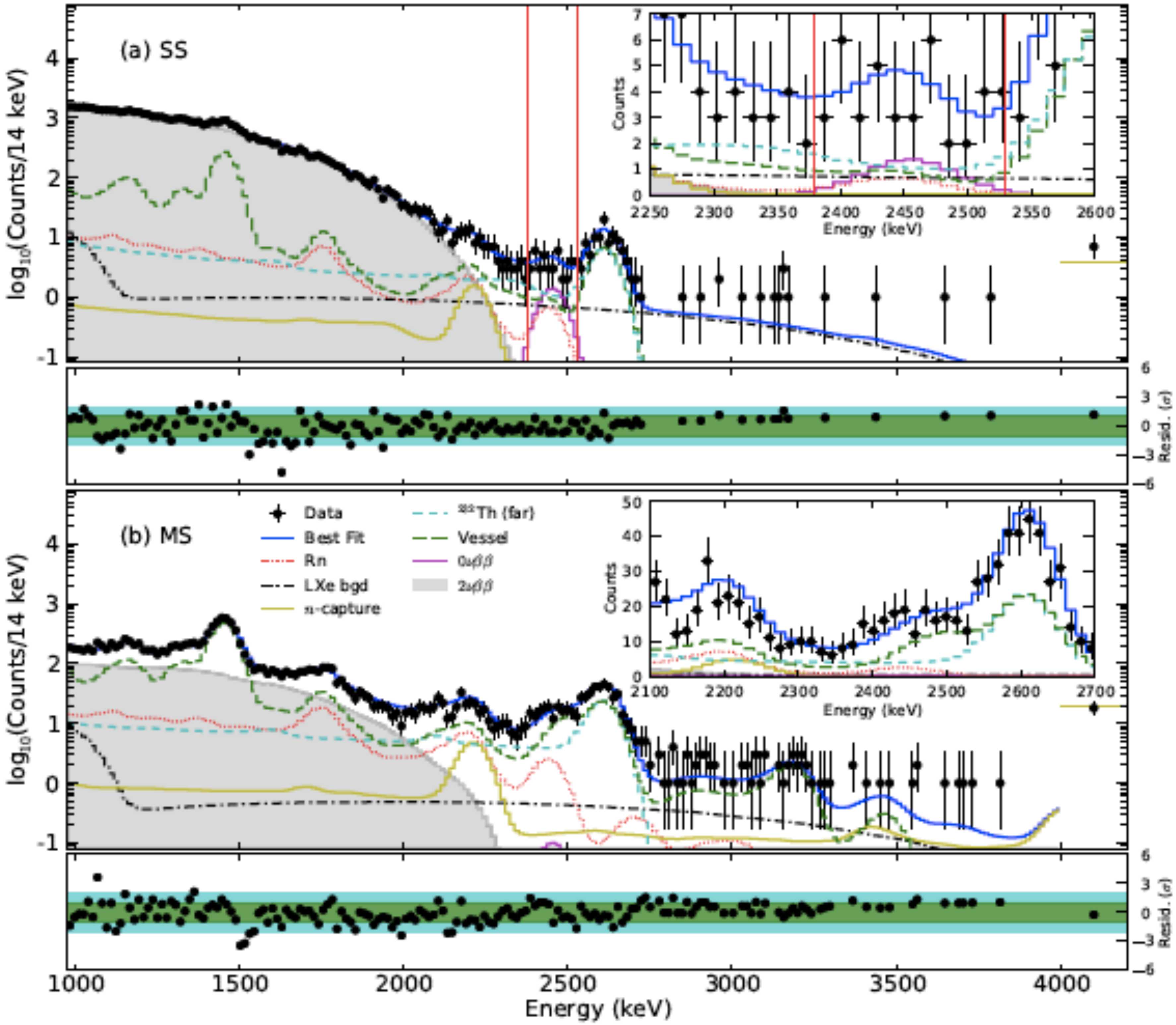
precision measurement of 2-neutrino mode

PRC 89 (2014) 015502

Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm \text{stat} \pm \text{sys}$ [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)

Search for 0νββ decay (^{136}Xe exposure: 100 kg yr)

[Nature, 510, 229-234 (2014)]



$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ \mathrm{yr}$$

$$(90\%\ C.L.)$$

energy resolution

$$\frac{\sigma}{E}(Q) = 1.53$$

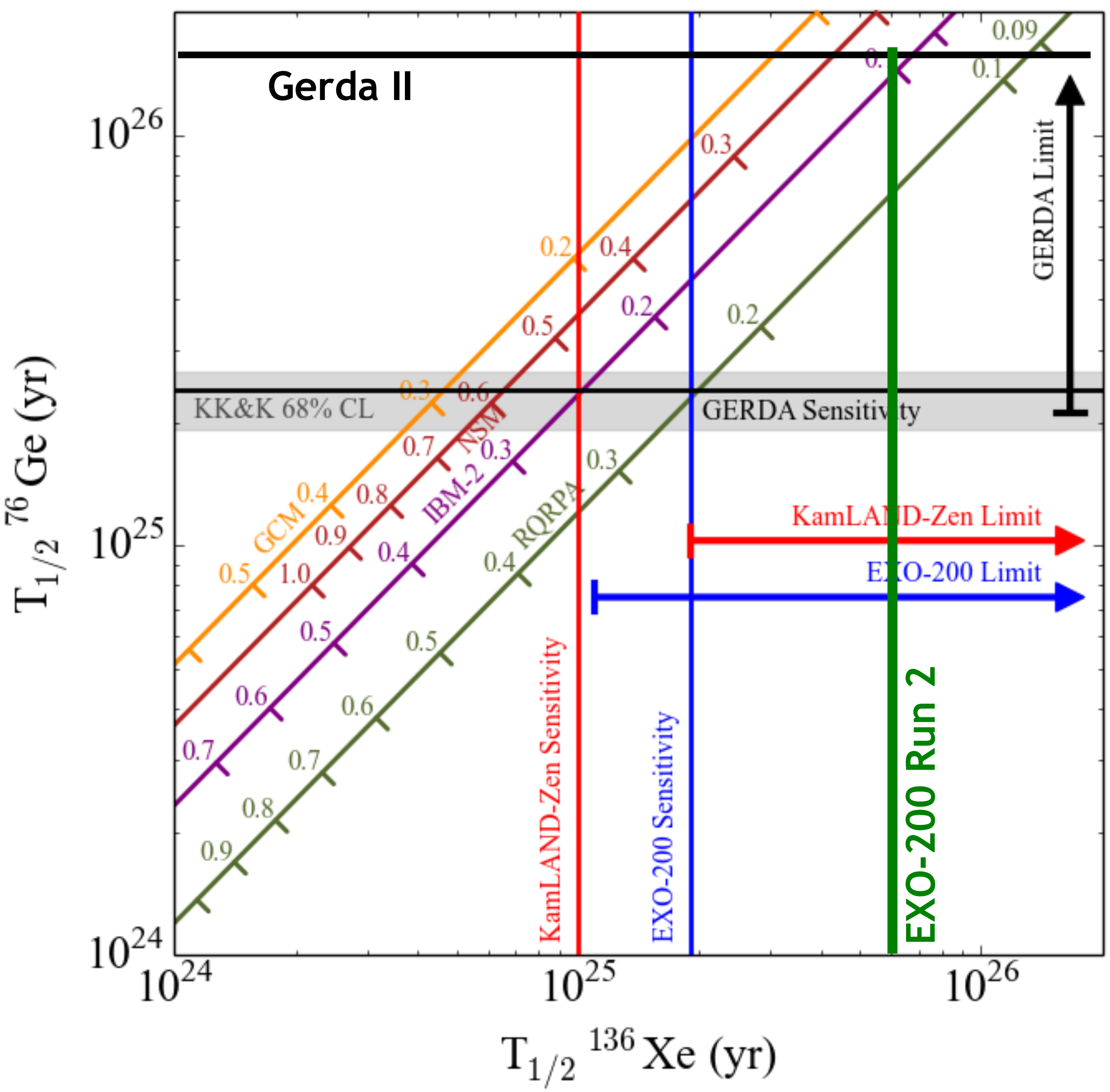
background index

$$(1.7 \pm 0.2) \times 10^{-3}$$

$$\mathrm{cts/(keV \cdot kg \cdot y)}$$

Phase I, Run2: search for 0νββ decay of ^{136}Xe

[Nature, 510, 229-234 (2014)]



EXO-200 limit:

$$T^{0\nu\beta\beta}_{1/2} > 1.1 \times 10^{25}\ \mathrm{yr}\ \ (90\%\ \mathrm{C.L.})$$

$$< m_{\beta\beta} >= 190 - 450\ \mathrm{meV}$$

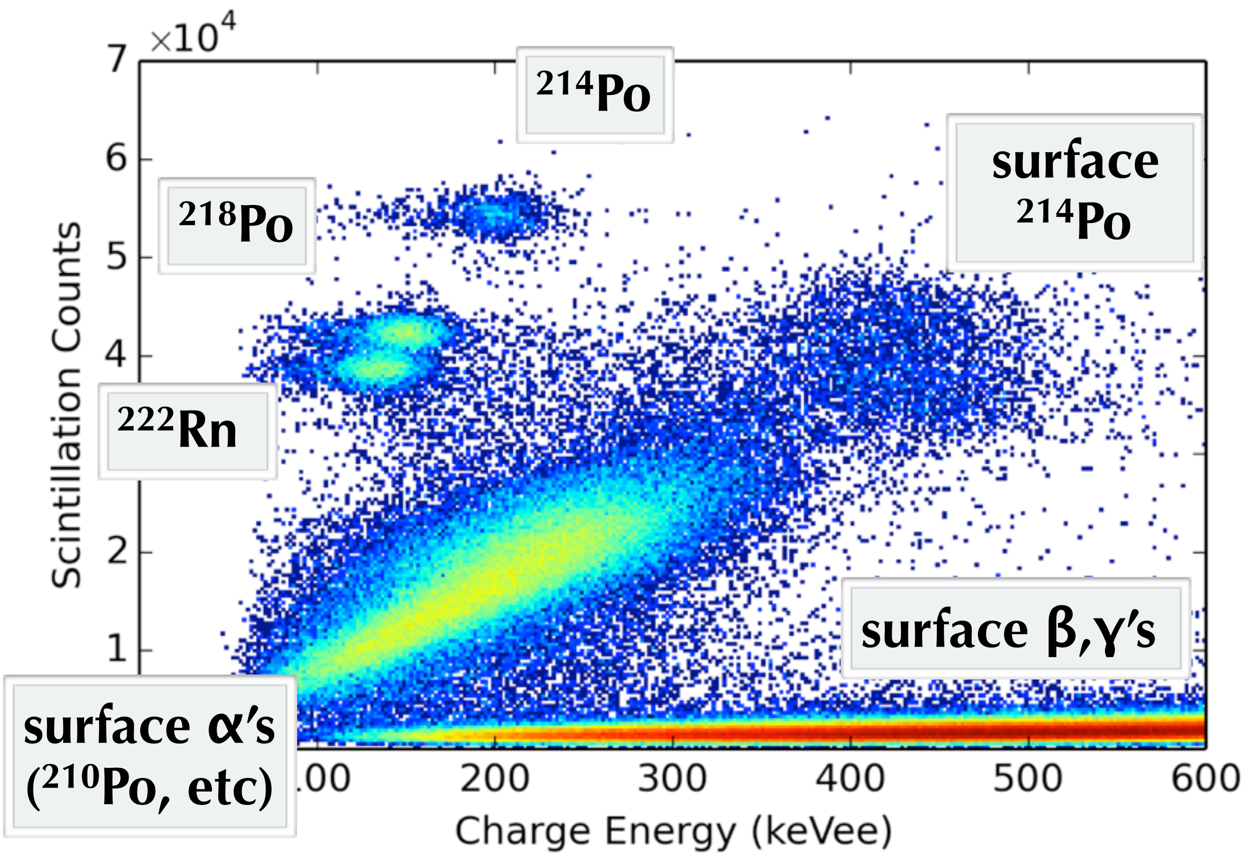
EXO-200 sensitivity:

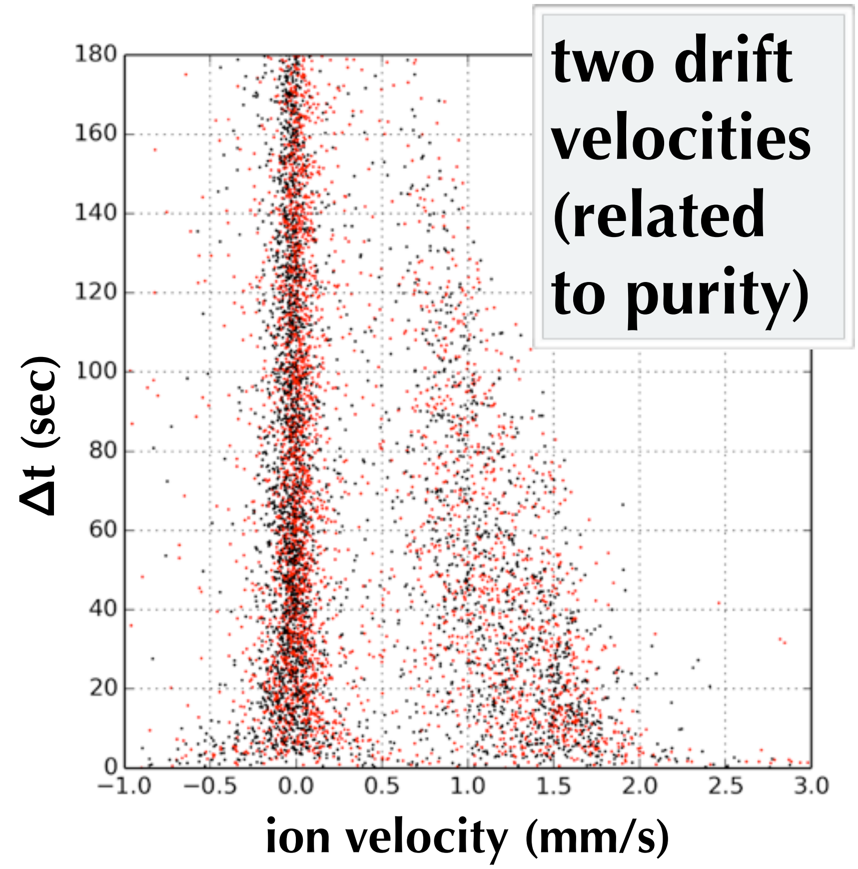
$$T^{0\nu\beta\beta}_{1/2} = 1.9 \times 10^{25}\ \mathrm{yr}$$

[GERDA: PRL 111, 122503 (2013)]
[KL-Zen: PRL 110, 062502 (2013)]

Radon products and alphas

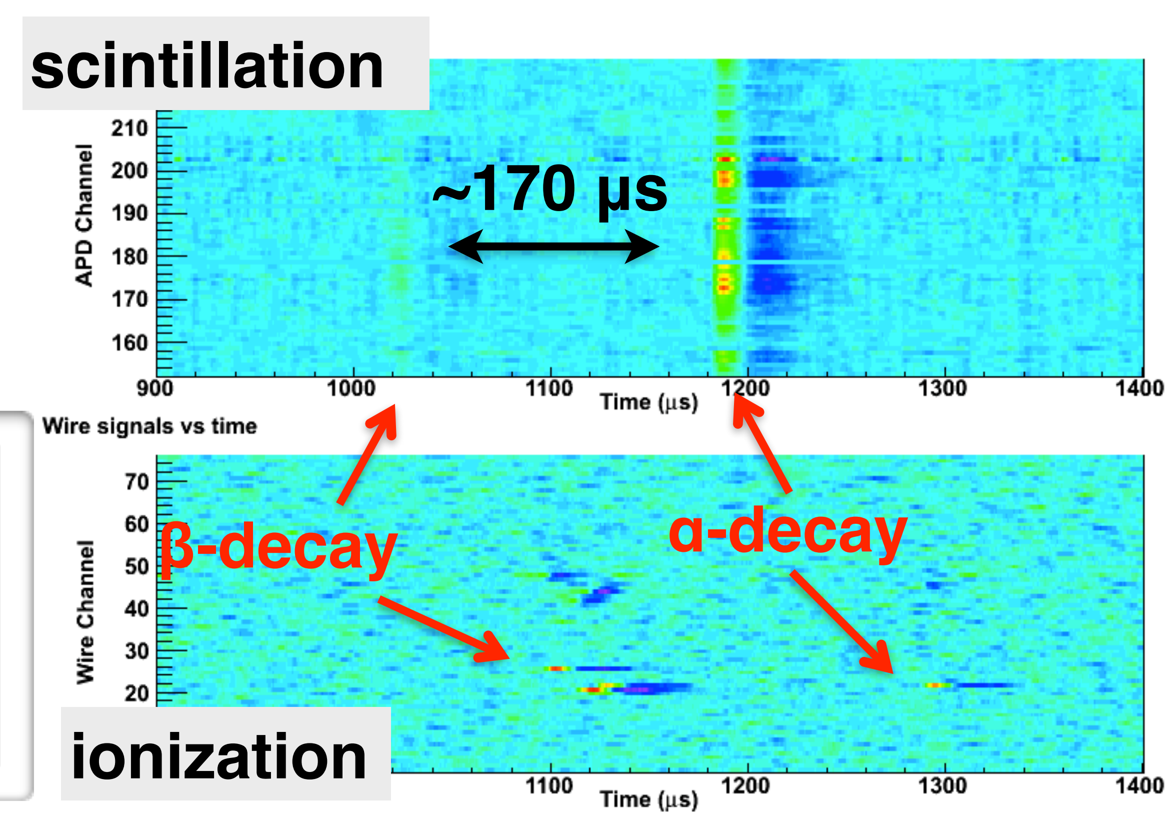
Phys. Rev. C, 89, 015502 (2014).





^{222}Rn-^{218}Po coincidences (3 minutes)

- Ion fraction of 218Po daughter from α-decay is 50.3±3.0%
- Ion fraction of 214Bi daughter from β-decay is 76.4 ± 5.7%



Steady state radon activity:
360 ± 65 μBq (fiducial volume)

~200 atoms of ^{222}Rn

EXO-200 backgrounds were predicted very accurately

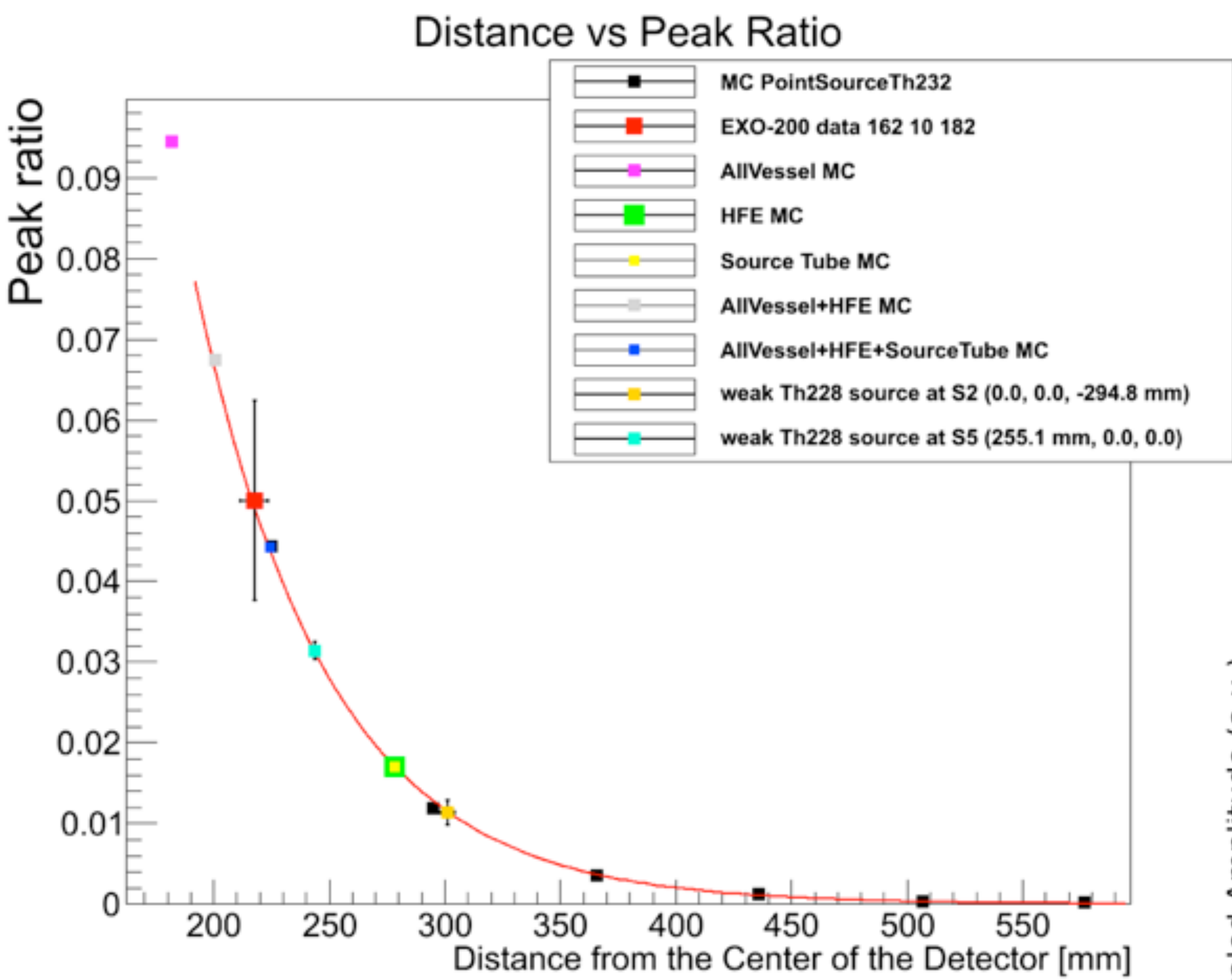
- *J.B. Albert, et al. "Investigation of radioactivity-induced backgrounds" PRC 92, 015503 (2015).*
- *M. Auger, et al. "The EXO-200 detector..." J. Inst 7 (2012) P05010.*

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		

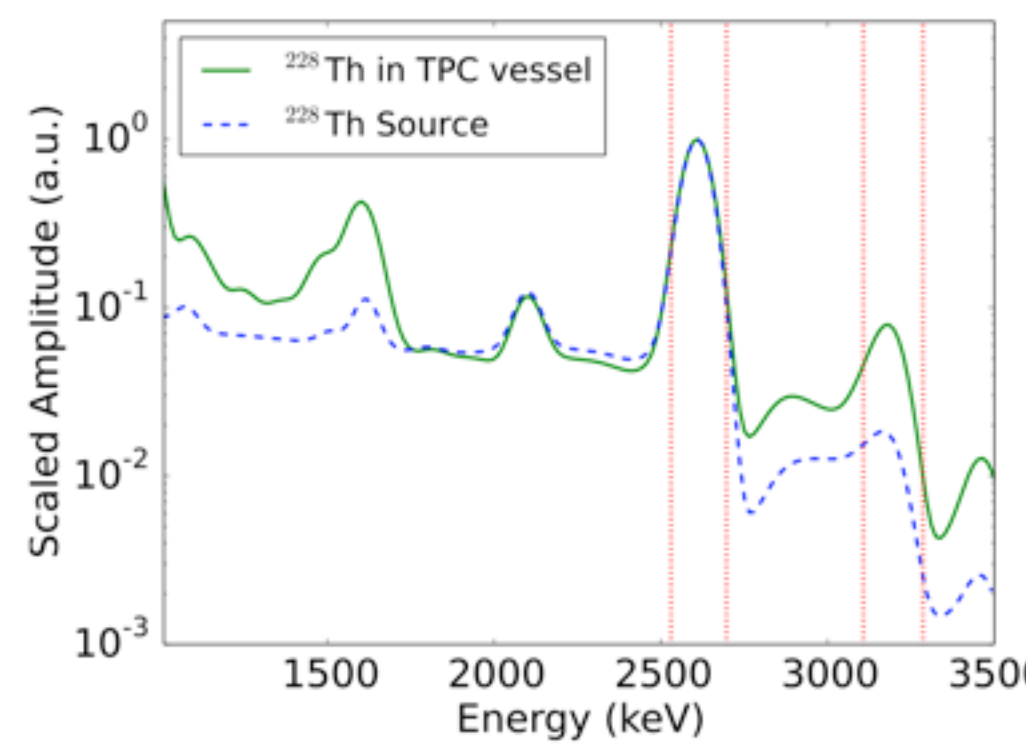
This is essential in scaling up from EXO-200 to nEXO as the only tool required to estimate the sensitivity is Geant4's ability to simulate Compton scattering

Location of ^{232}Th background in EXO-200

PRC92, 015503 (2015)
arXiv:1503.06241



analysis based on ratio of sum peak (2615+582 keV) to 2615 keV peak



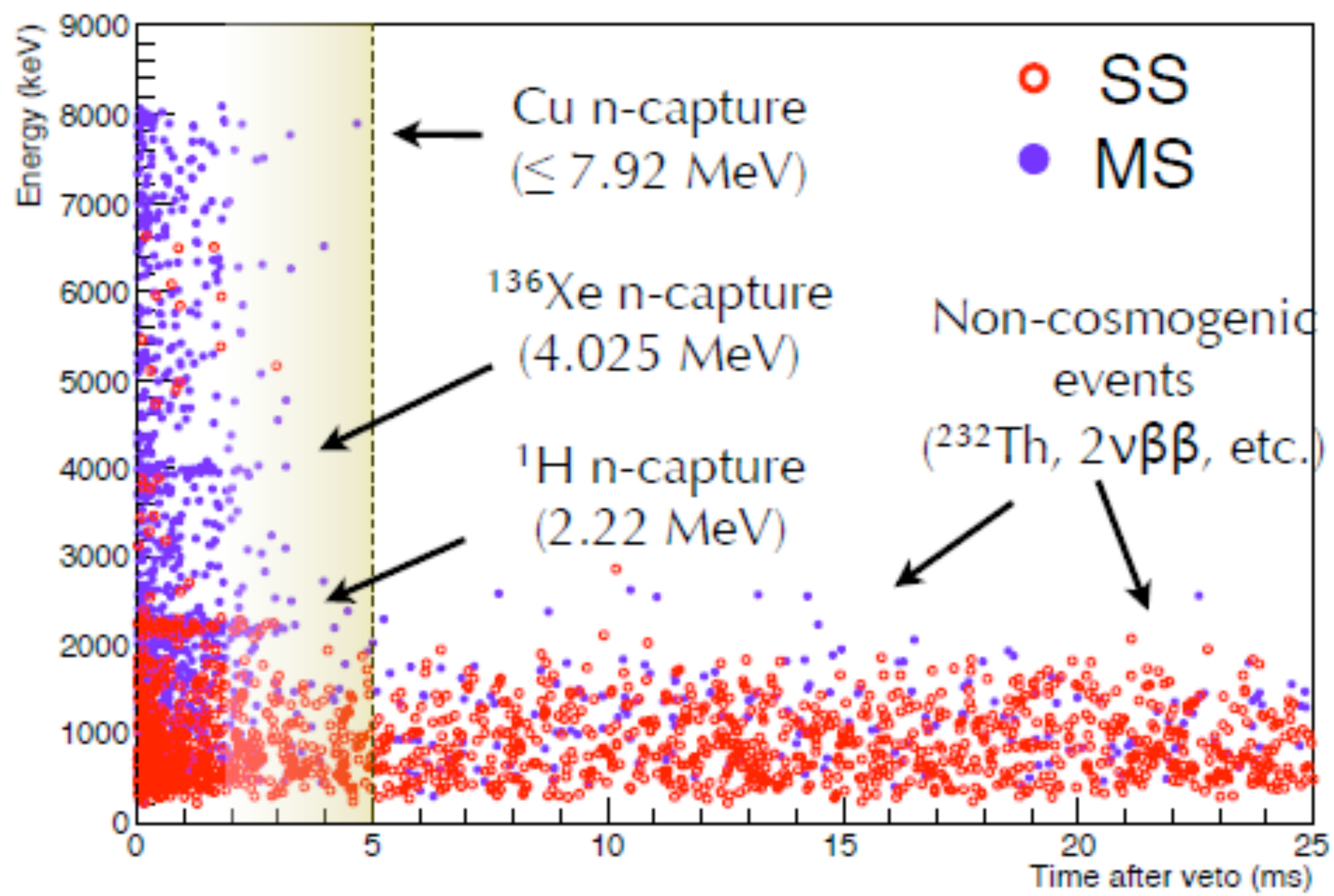
best-fit and radio-assay backgrounds agree very well

Cosmogenic Backgrounds

- Measured muon flux at WIPP using EXO-200 TPC:

$$I_v = 2.970^{+0.137}_{-0.130}\ (\text{sys}) \pm 0.024\ (\text{stat}) \times 10^{-7} (\text{cm}^2\ \text{s sr})^{-1}$$

- Measure (n,γ) neutron captures on detector and shielding materials in coincidence with the muon veto panels triggering.



- Independent measure of ^{137}Xe background: ^{136}Xe(n,γ) rate agrees with ^{137}Xe decay rate.
- Can use capture signal to veto ^{137}Xe decay, reduce 0νββ ROI background by ~70%.

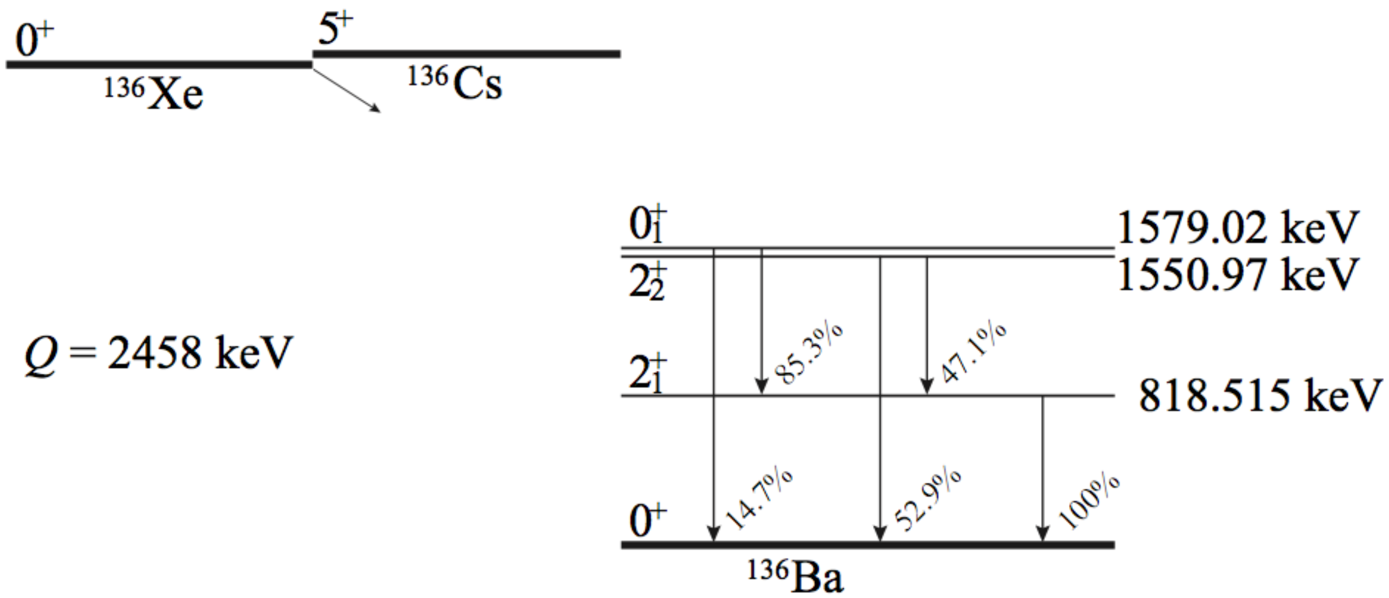
What else from EXO-200?

Following the accidents, EXO-200 personnel is now granted regular access to the site and recovery operations are ongoing
(close to detector cool-down)

- EXO-200 can still contribute valuable science
- Upgrades have been installed before the accident:
  - Radon suppression system for air around the detector
  - Upgraded electronics (could get to 1% energy resolution)
- Expected sensitivity $T_{1/2}^{0\nu\beta\beta} \sim 5 \times 10^{25}$ years

- Approximately 2 years of data are still being worked on:
  - cosmogenic background induced by muons
  - DBD to excited states of ^{136}Ba, and of ^{134}Xe
  - exotic processes: Lorentz violation, electron decay
  - electron diffusion during drift

DBD to excited states of Ba-136



$Q = 2458$ keV

J.B. Albert et al., arXiv:1511.04770

EXO-200
multivariate analysis using
the multi-site event topology

$T^{2\nu}_{1/2}\ (0^+ \rightarrow 0^+_1) > 6.9 \times 10^{23}$ yr at 90% CL

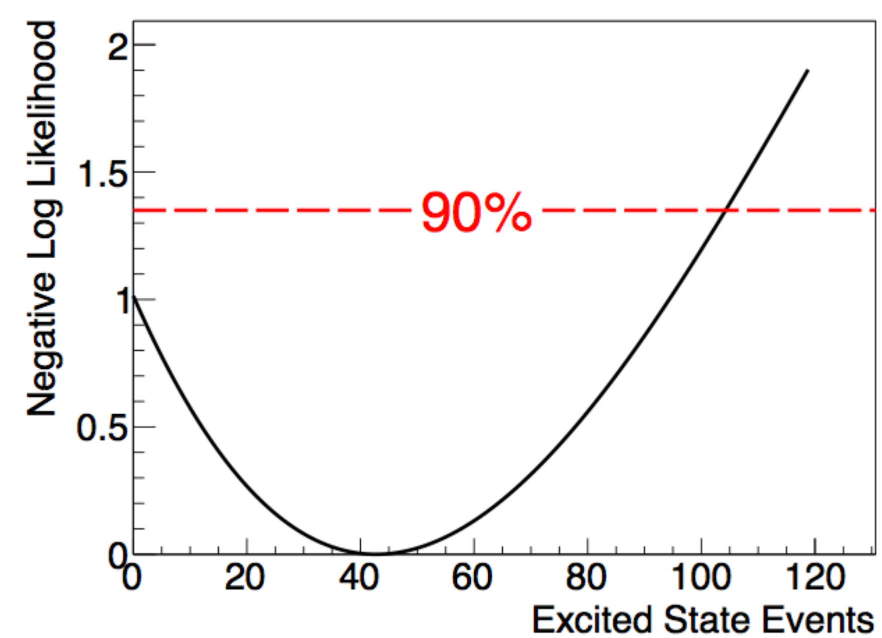


FIG. 6. NLL profile in the number of excited state events. The best fit value is 43 events, while the fit with 0 events has a ΔNLL value of 1.0. The 90% upper limit (dashed line) is 104 events.

KamLAND-Zen
spectral fit

Table 4: Half-life lower limits for ^{136}Xe double-beta decay to excited states of ^{136}Ba at 90% C.L.

Transition	$T_{1/2}$ (yr, 90% C.L.) This work	Previous work
$2\nu\beta\beta$ decay		
$0^+ \rightarrow 0^+_1$	8.3×10^{23}	-
$0^+ \rightarrow 2^+_1$	4.6×10^{23}	9.4×10^{21} [15]
$0^+ \rightarrow 2^+_2$	9.0×10^{23}	-
$0\nu\beta\beta$ decay		
$0^+ \rightarrow 0^+_1$	2.4×10^{25}	-
$0^+ \rightarrow 2^+_1$	2.6×10^{25}	6.5×10^{21} [16]
$0^+ \rightarrow 2^+_2$	2.6×10^{25}	-

K. Asakura et al., arXiv:1509.03724

what has EXO-200 taught us?

- Operated a 100 kg scale enriched-LXe TPC for 2 years
  - Measured residual **backgrounds consistent with radio-assays**
  - Reached design (anti-correlated) **energy resolution, σ/E(Q)=1.5%**
  - Stable **electron drift time of ~3 ms** or better
  - Demonstrated power of **standoff distance in monolithic detector**
  - Demonstrated power of **single-/multi-site β/γ discrimination**

- Implemented novel detector solutions
  - 500x LAAPDs for VUV (175 nm) scintillation detection
  - Photo-etched, charge collection wires, cathode, and fasteners
  - Epoxy-potted, kapton flat cable feedthroughs
  - HFE-7000 thermal bath and radiation shield
  - Ultra-light design, no solder joints, no electrical connectors

from EXO-200 to nEXO

Two years ago our roadmap included the following possibilities:

A. EXO-200 confirms Klapdor claim
   - build a GXe detetctor to study the decay in detail

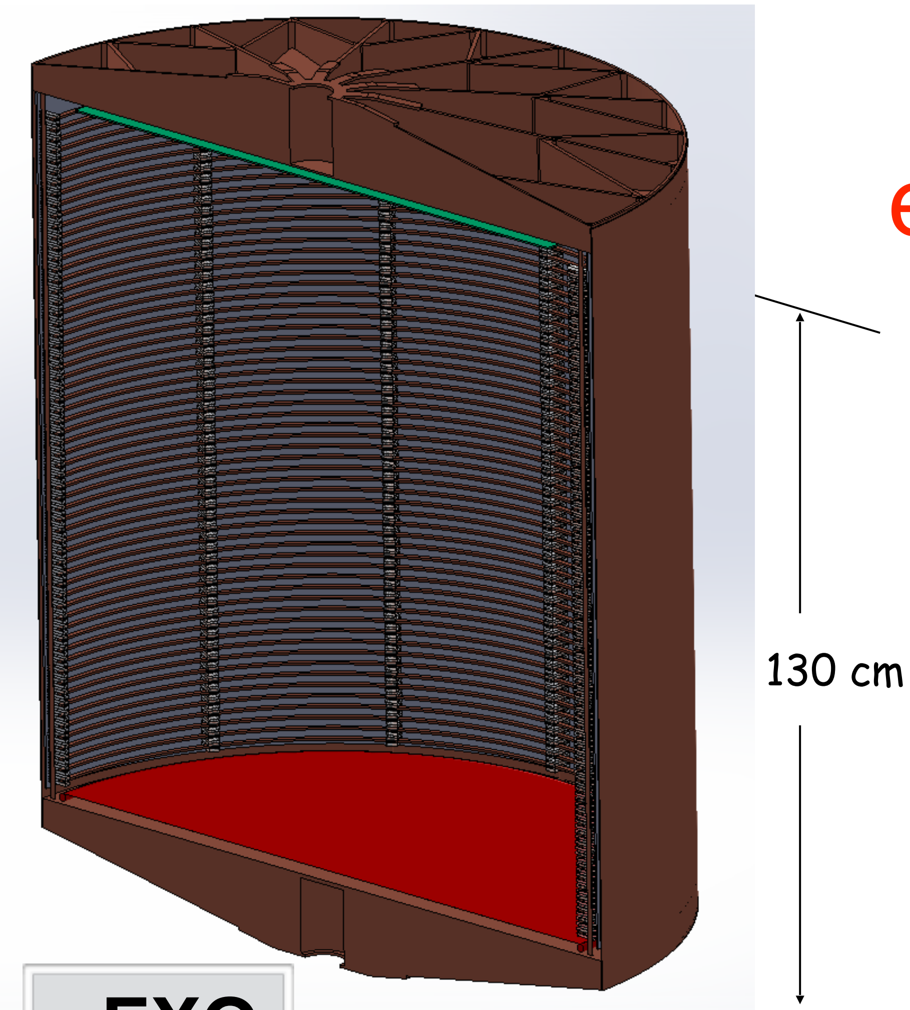
B. EXO-200 has a hint of a signal
   - quickly build an EXO-500 in the same installation at WIPP
   - maybe at the same time design a large GXe detector

C. EXO-200 does not see any peak
   - build the largest LXe detector you think doable
   - pursue aggressive detector designs for a further upgrade (e.g. Ba-tagging)

EXO-200 performance and backgrounds guided the decision to design a large LXe "discovery" detector:

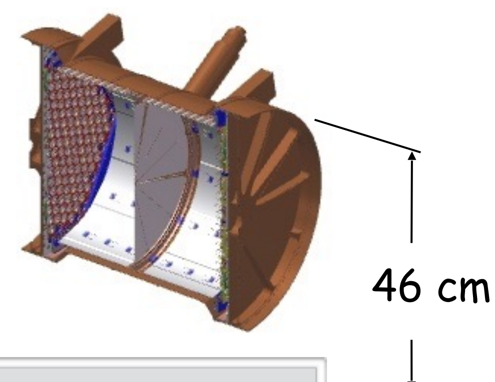
nEXO

The nEXO detector



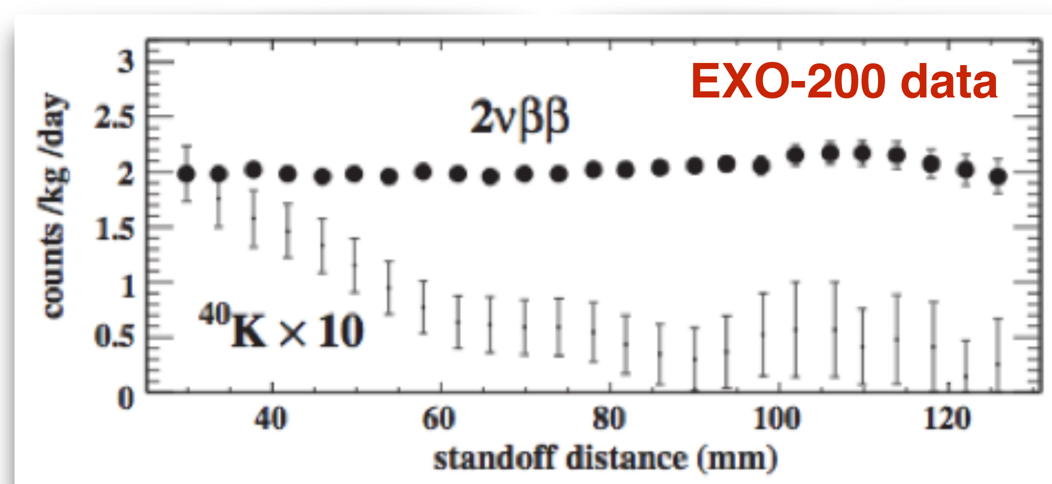
5 tonnes enriched xenon

- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

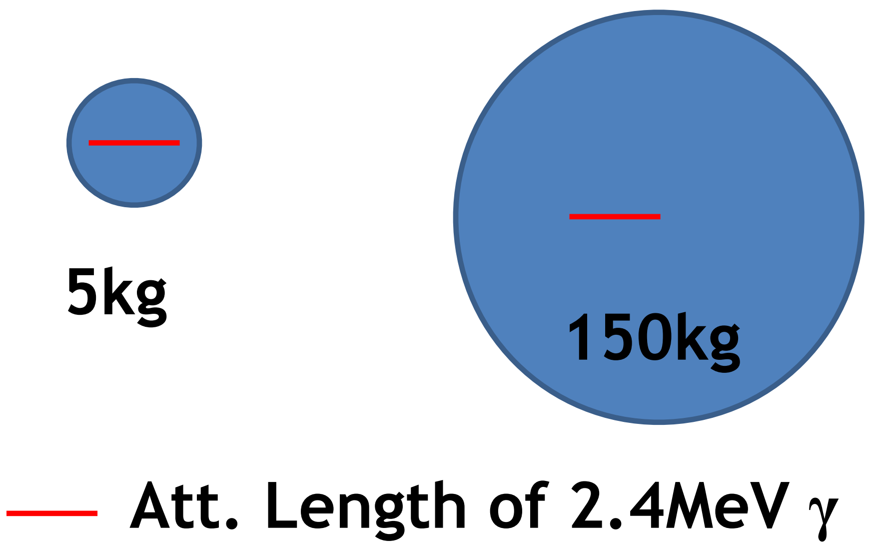


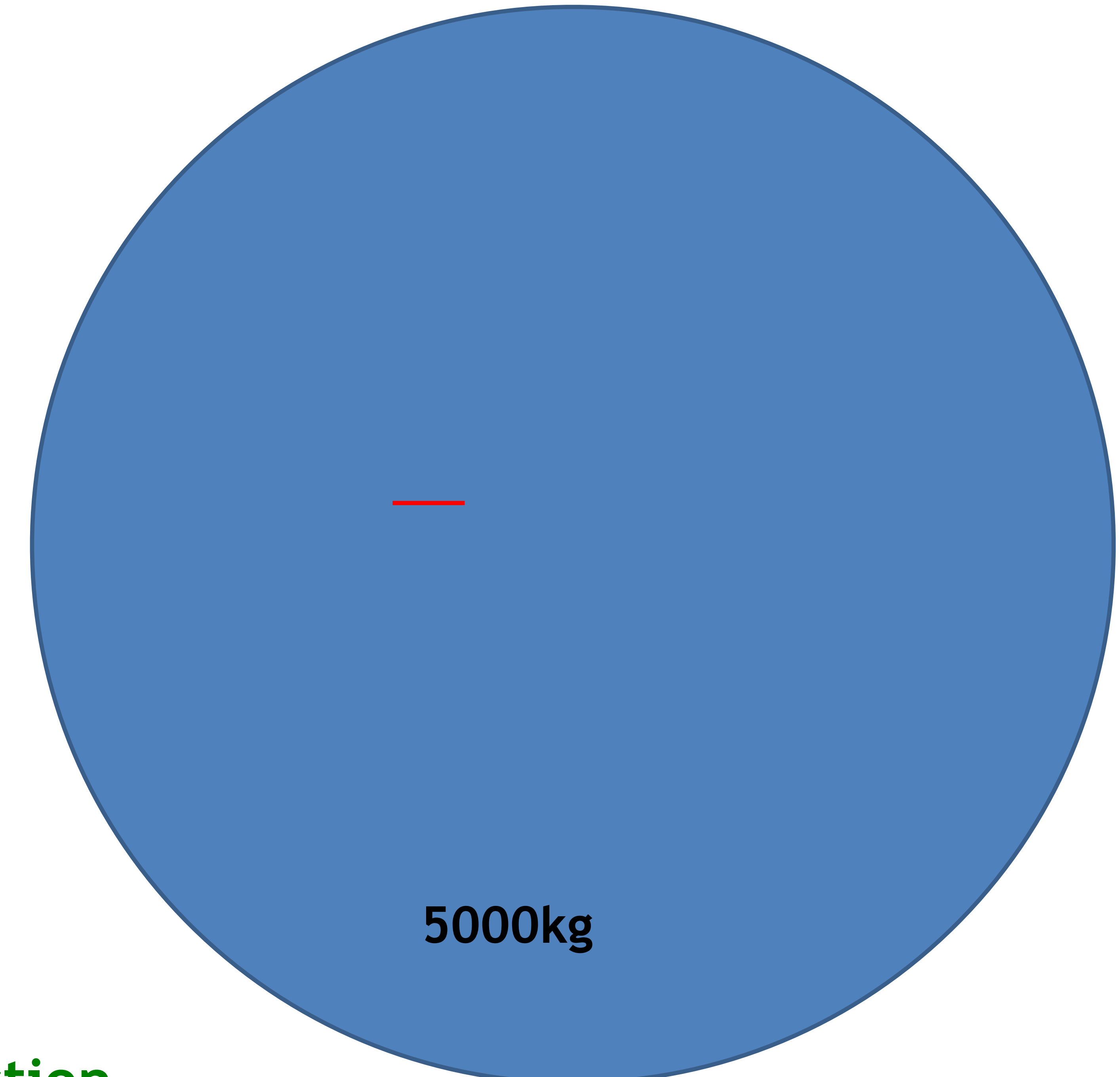
- < 1% energy resolution
- no central cathode
- ≳ 10 ms electron lifetime

the range of a 2.5 MeV γ-ray in LXe is 8.5 cm



nEXO: a homogeneous detector





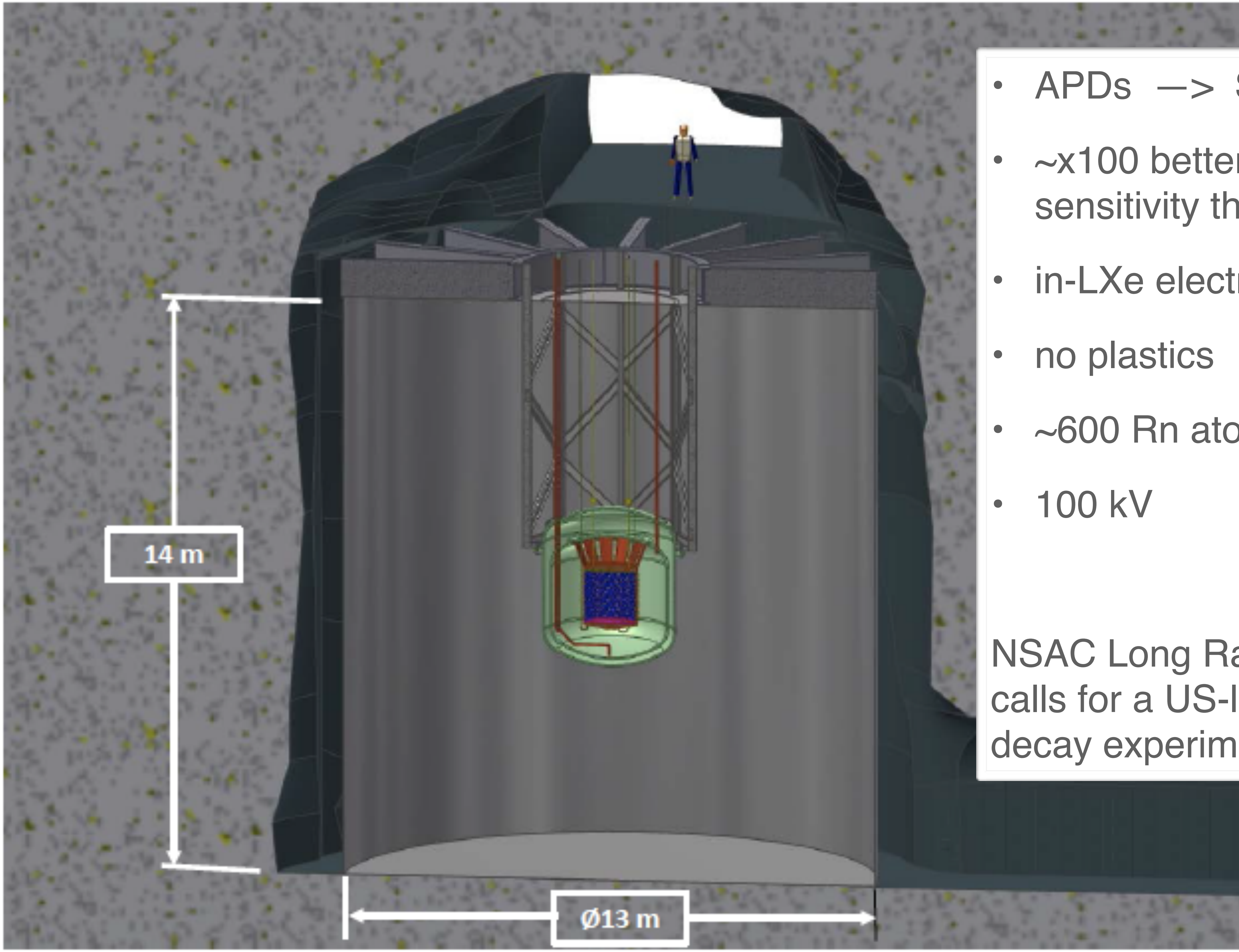
take full advantage of:

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.

nEXO conceptual design (SNOLab)

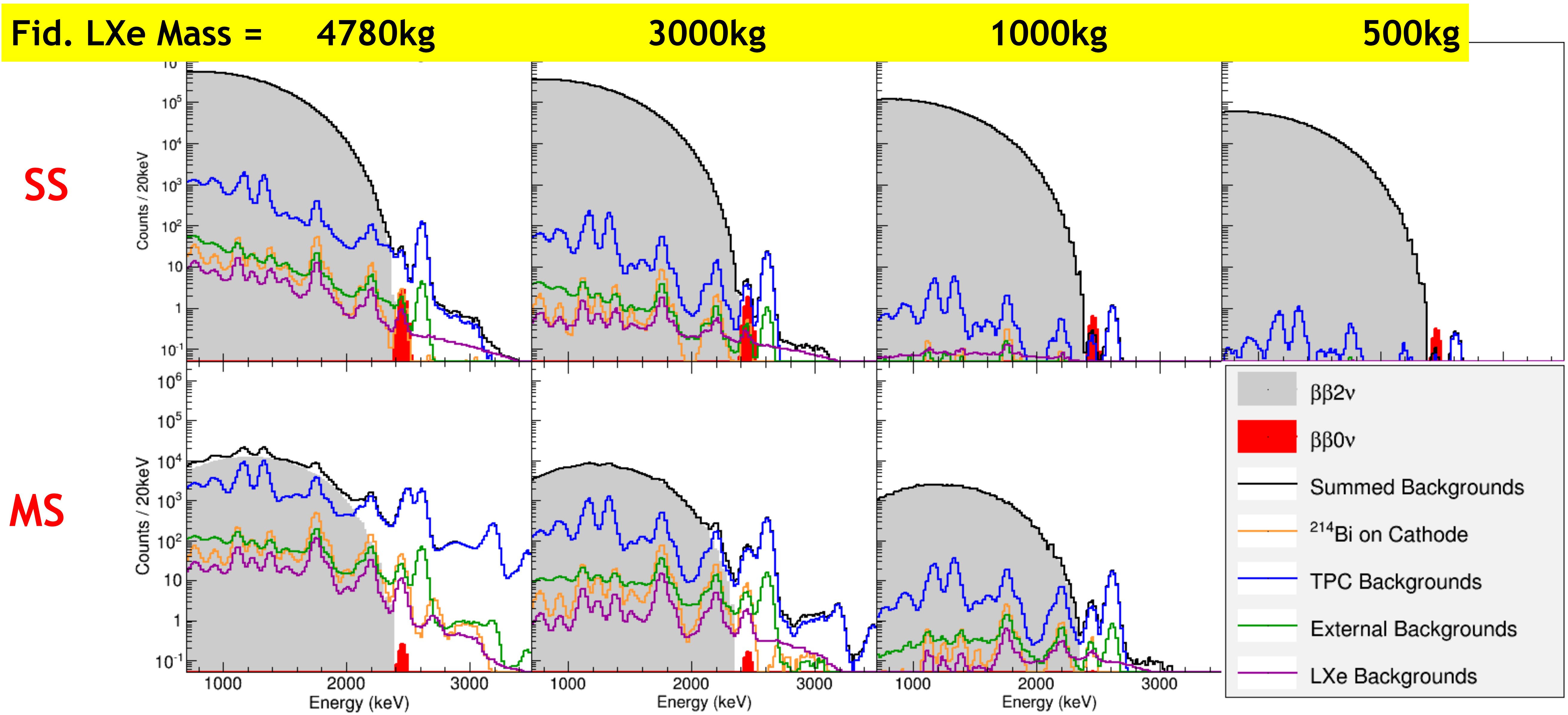


- APDs —> SiPMs
- ~x100 better half-life sensitivity than EXO-200
- in-LXe electronics
- no plastics
- ~600 Rn atoms
- 100 kV

NSAC Long Range Plan calls for a US-led $0\nu\beta\beta$ decay experiment

nEXO: standoff distance, bg ID and suppression

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



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 0νββ is with the ^{238}U chain because of the ^{214}Bi line.
Yet, this is a relatively small (anti)correlation that allows the 0νββ signal to be well identified.

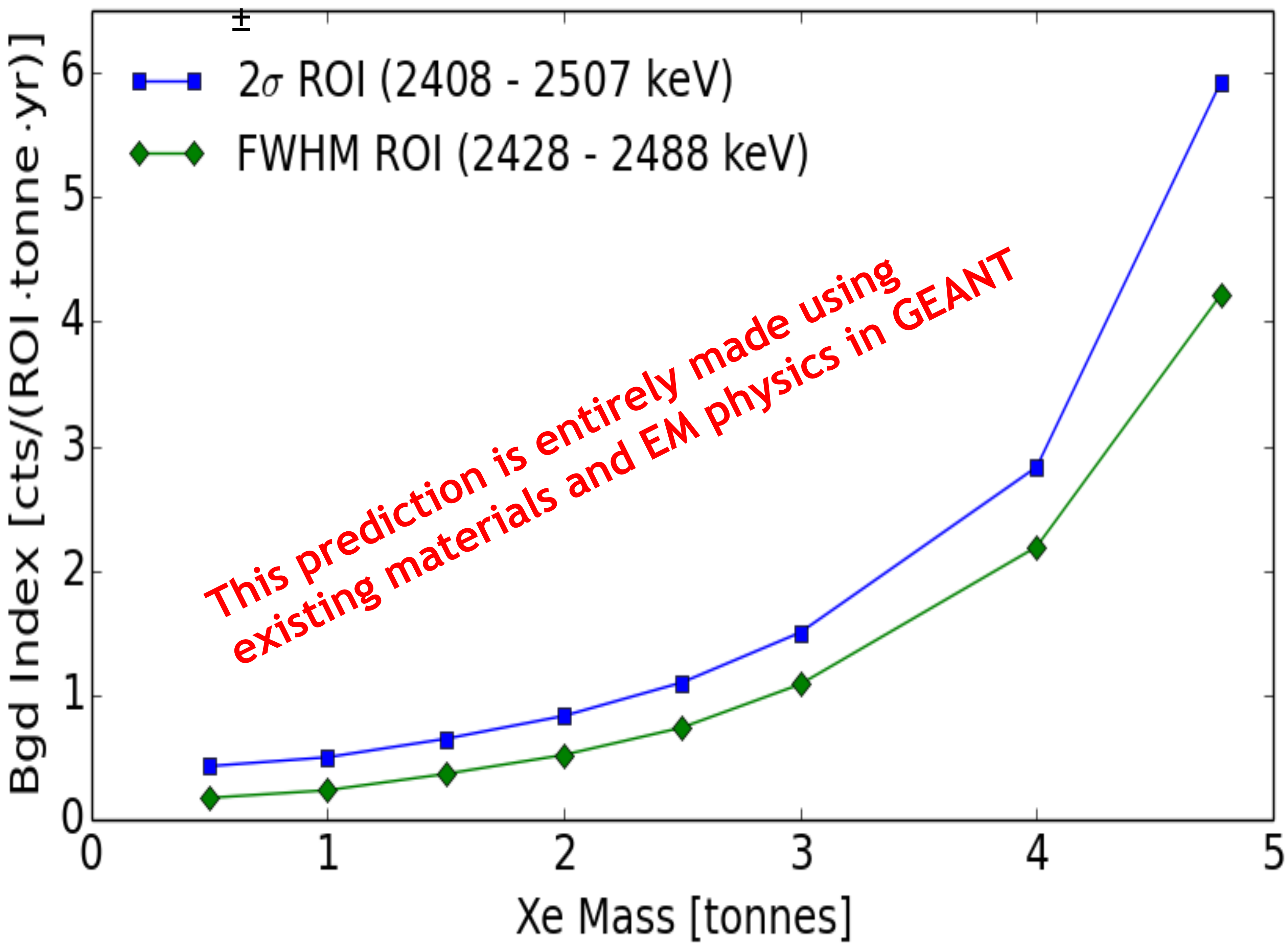
	APD +fieldrings	Cathode ^{214}Bi	TPC ^{232}Th	TPC ^{238}U	LXe ^{222}Rn	LXe ^{137}Xe	TPC ^{60}Co	0νββ	2νββ
APD+field rings	1	-0.25	-0.05	0.24			-0.78	-0.01	
Cathode ^{214}Bi	-0.25	1	0.28	-0.95			0.36	0.03	0.07
TPC ^{232}Th	-0.05	0.28	1	-0.31		-0.03	-0.07	0.01	-0.01
TPC ^{238}U	0.24	-0.95	-0.31	1	-0.05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

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

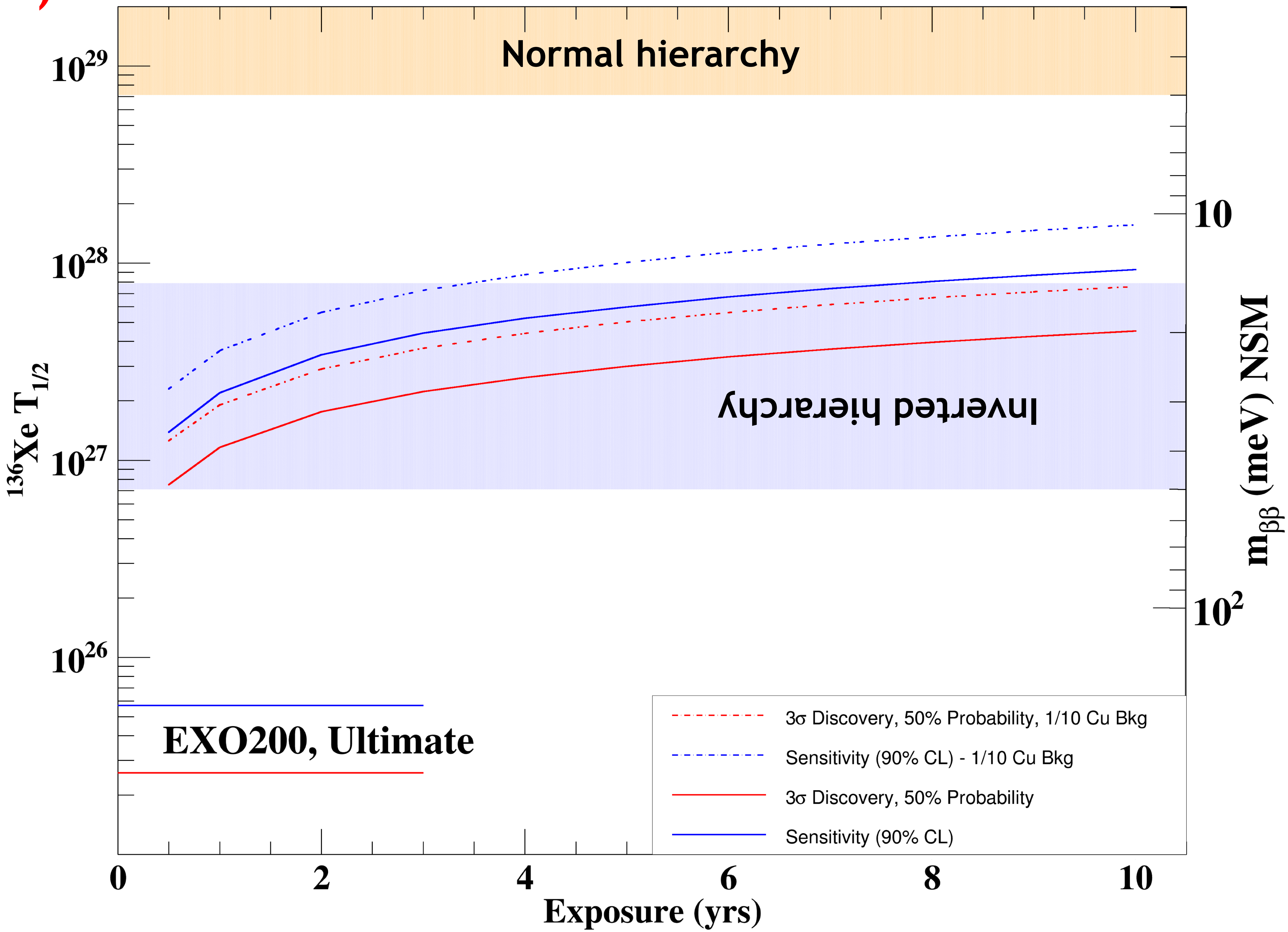
Note that an unknown gamma line would likely be identified by the same fit procedure.

nEXO: background index

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

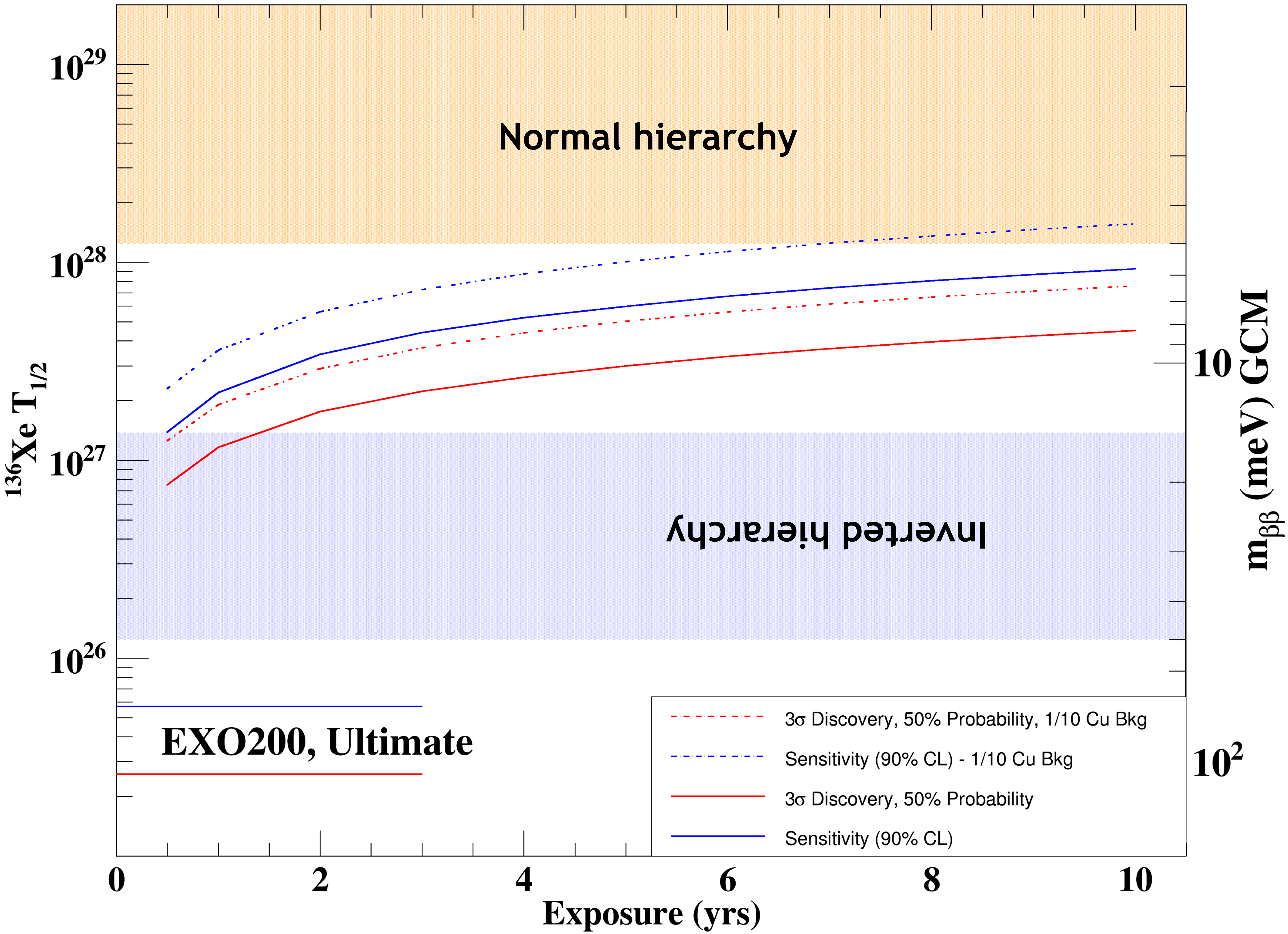


Sensitivity as a function of time for the worst-case NME (Shell Model)



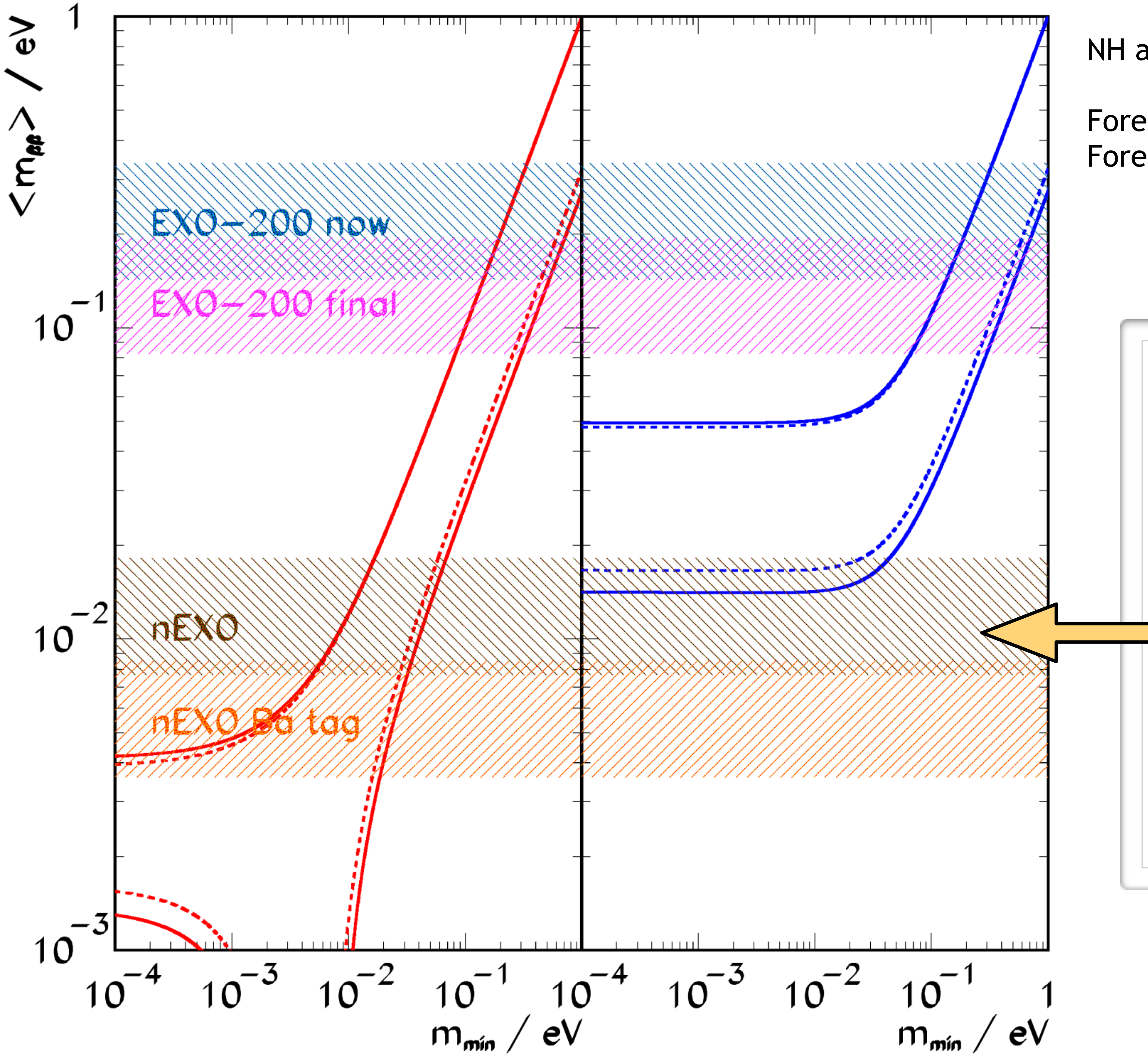
NSM: Menendez, Poves, Caurier, Nowacki, Nucl.Phys. A 818 (2009) 139

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



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

nEXO sensitivity (5 year run)



NH and IH bands are also 90%CL

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

$T_{1/2} = 6 \times 10^{27}$ yr in 5 years of counting

Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ sensitivity of 7-18 meV

nEXO: radio-assays

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.

nEXO: 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

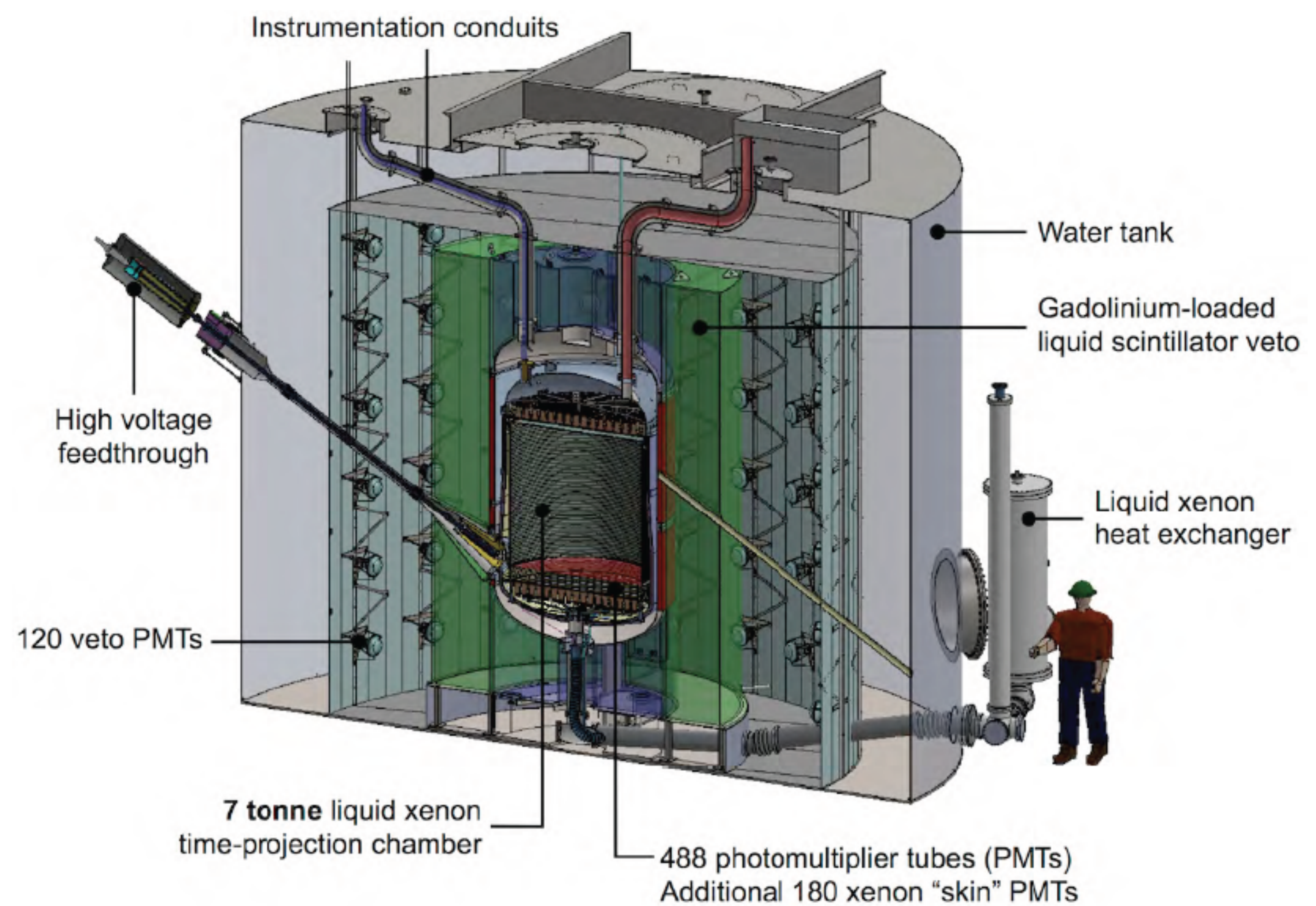
World $^{nat'l}$Xe production is ~40 tonnes/yr (~4000kg ^{136}Xe), however large price fluctuations are not uncommon

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.

Scintillation - Ionization

LUX-ZEPLIN (LZ) Conceptual Design Report arXiv:1509.02910

Dark Matter experiment, scheduled to start data taking in 2019.



- 7 tonnes of ^{nat}Xe, liquid TPC
- 1000 days 90% CL sensitivity: $T_{1/2} > 2{\cdot}10^{25}$ to $2{\cdot}10^{26}$ yr
  - The shorter value corresponds to an increase of 10 times over baseline radiopurity, an energy resolution of 2%, and a spatial resolution of 6 mm.
- For ^{enr}Xe project $T_{1/2} > 2{\cdot}10^{27}$, also assumes improvements in spatial and energy resolution, background reductions

Barium tagging

[M. Moe, Phys. Rev. C 44 (1991) R931]

xenon admits a novel coincidence technique:

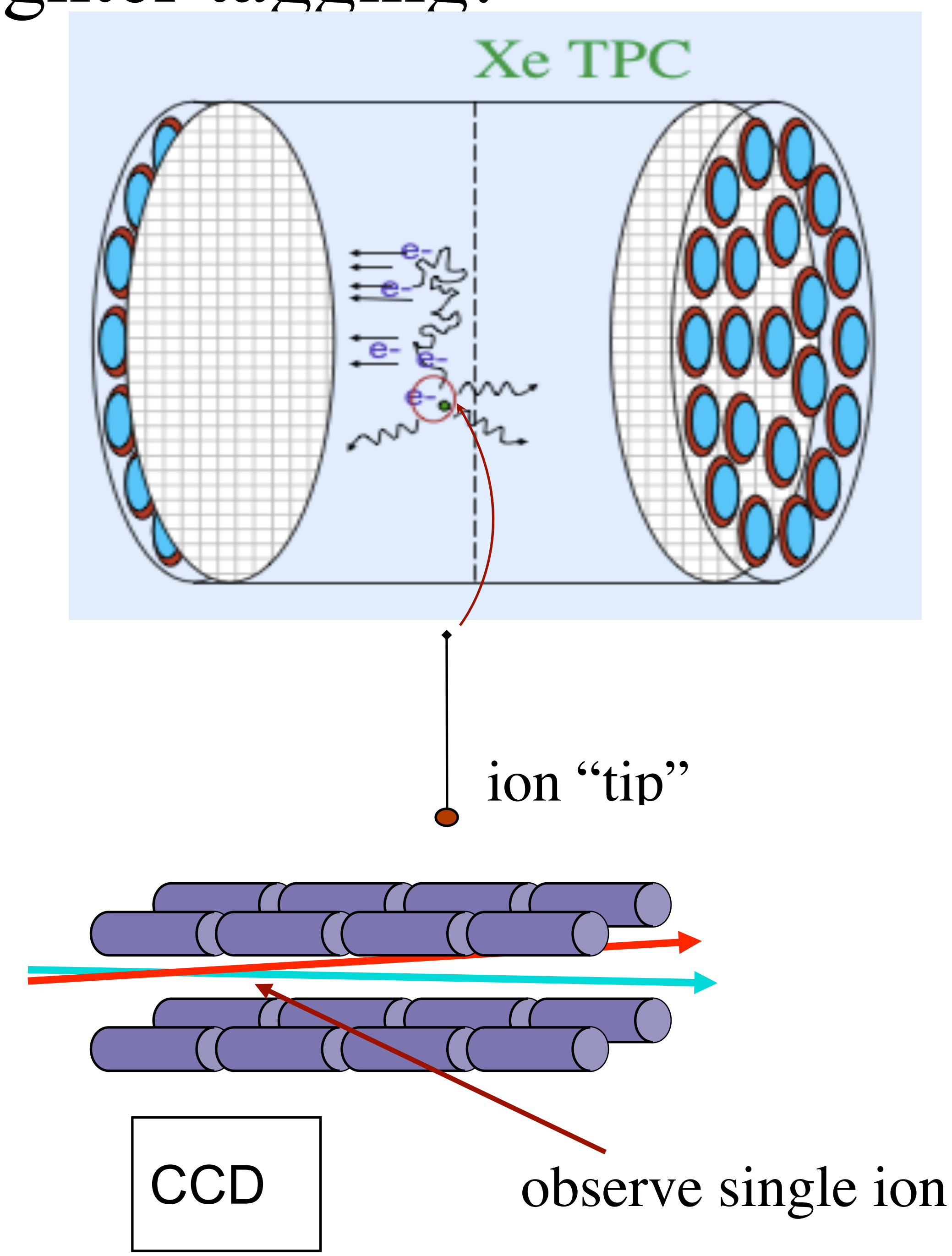
drastic background reduction by Ba daughter tagging!

detect the 2 electrons
(ionization + scintillation in xenon detector)

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} \; (+\, 2\nu_e)$$

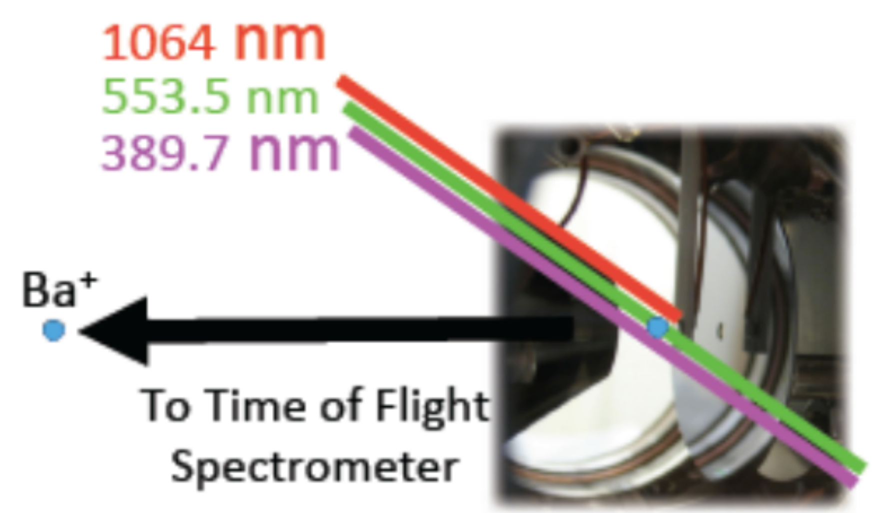
positively identify daughter via
optical spectroscopy of Ba^{+}

other Ba^{+} identification strategies are being investigated within the EXO collaboration



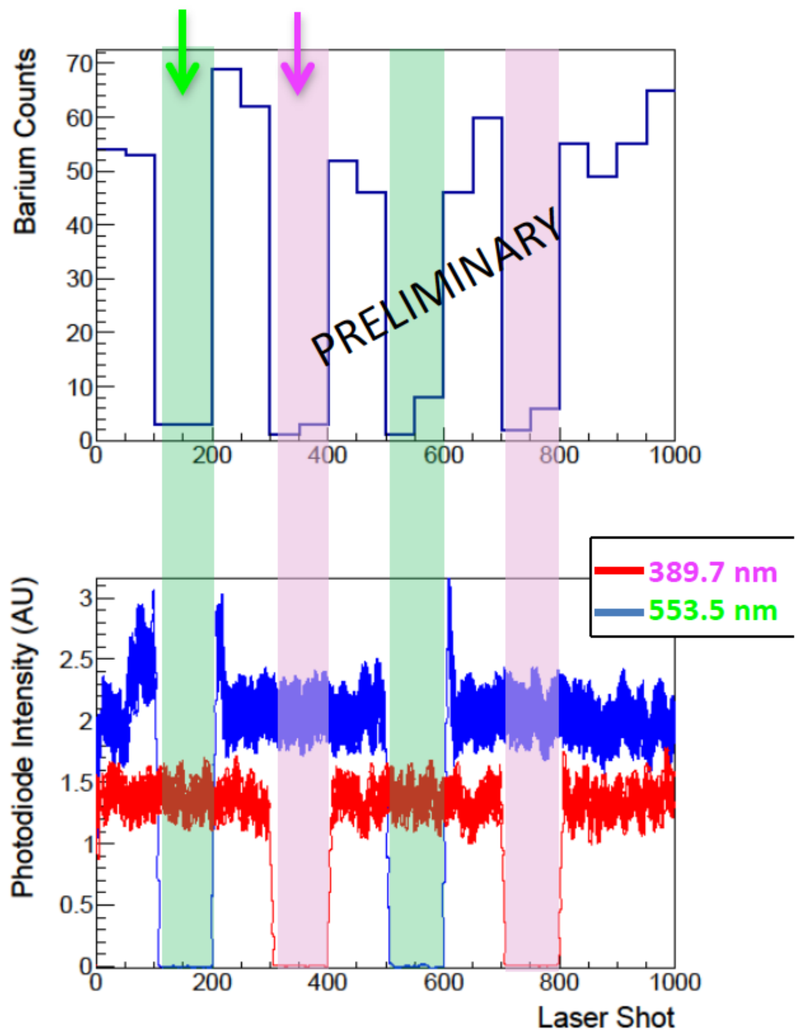
Ba tagging R&D — RIS

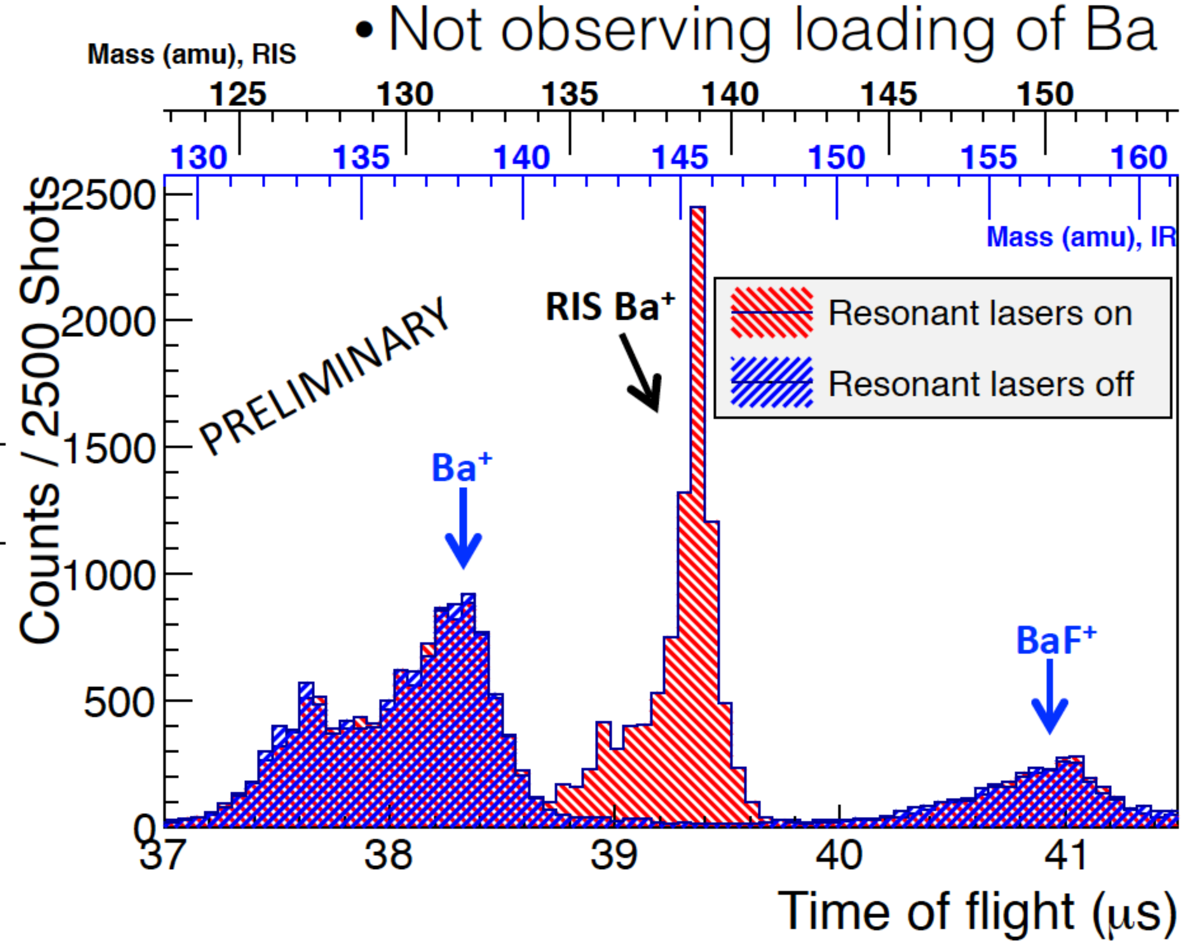
- Resonance ionization spectroscopy (RIS):



TOF Identification

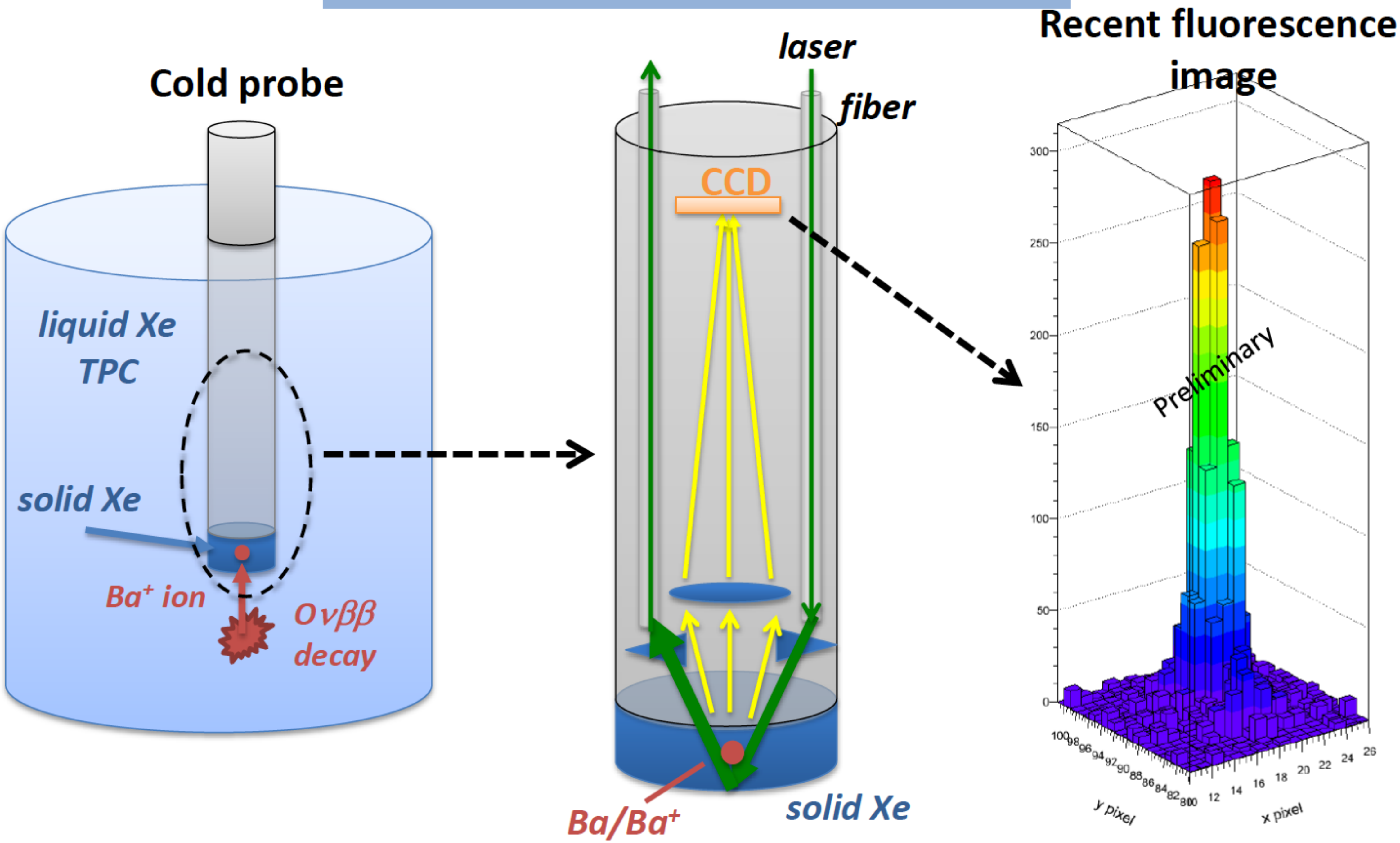
- Repeatably and verifiably do RIS of Ba
- Signal depends on both RIS lasers:
  - none if blocked or detuned
- Can resolve:
  - Ba^+ from RIS
  - Ba^+ from ablation
  - BaF^+ from ablation
- Not observing loading of Ba





Ba tagging in solid xenon on a cryogenic probe

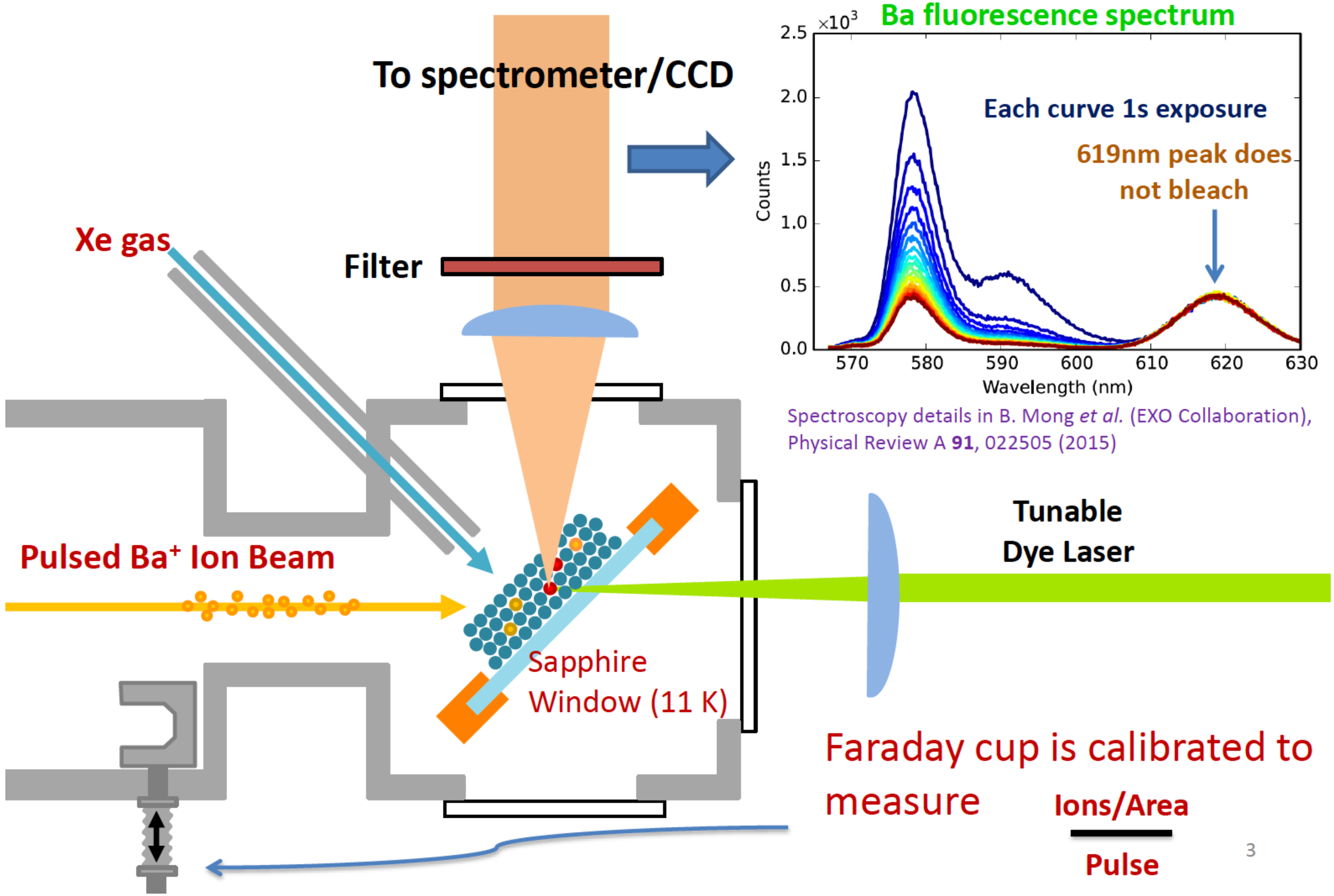
Can detect many photons from a single atom



≤3 Ba atoms

Ba tagging in solid xenon on a cryogenic probe

Single Barium Imaging Apparatus



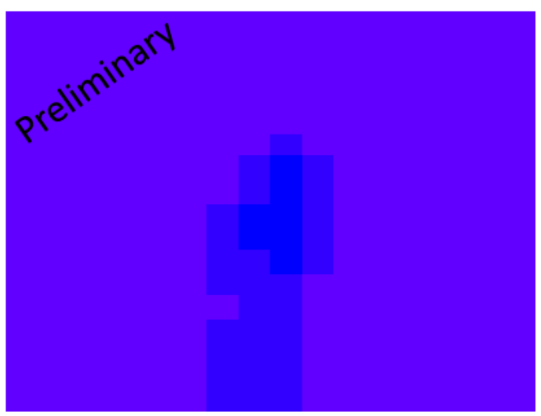
Spectroscopy details in B. Mong *et al.* (EXO Collaboration), Physical Review A **91**, 022505 (2015)

Ba tagging in solid xenon on a cryogenic probe

A Key Result:

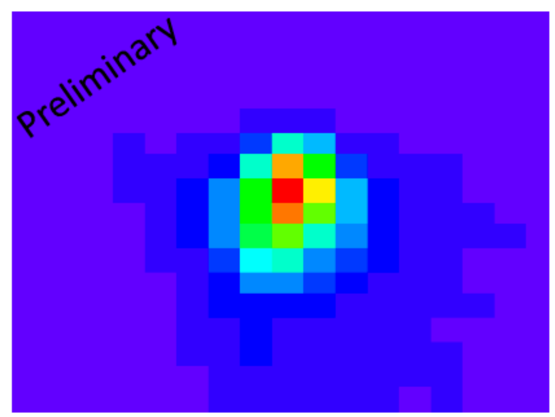
No residual Ba signal even after a large deposit

0 Atom Deposit



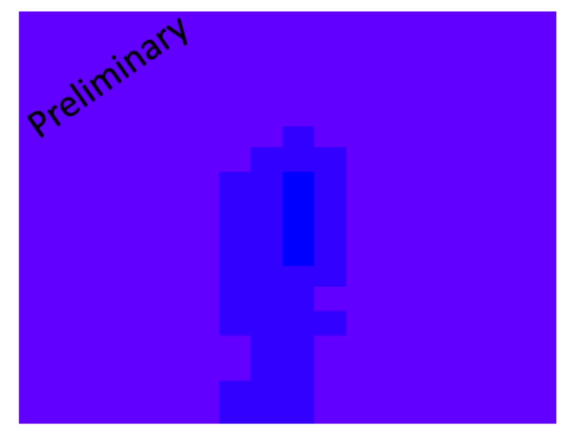
Heat to 100K to evaporate deposit

≤ 1000 Atom Deposit



Heat to 100K to evaporate deposit

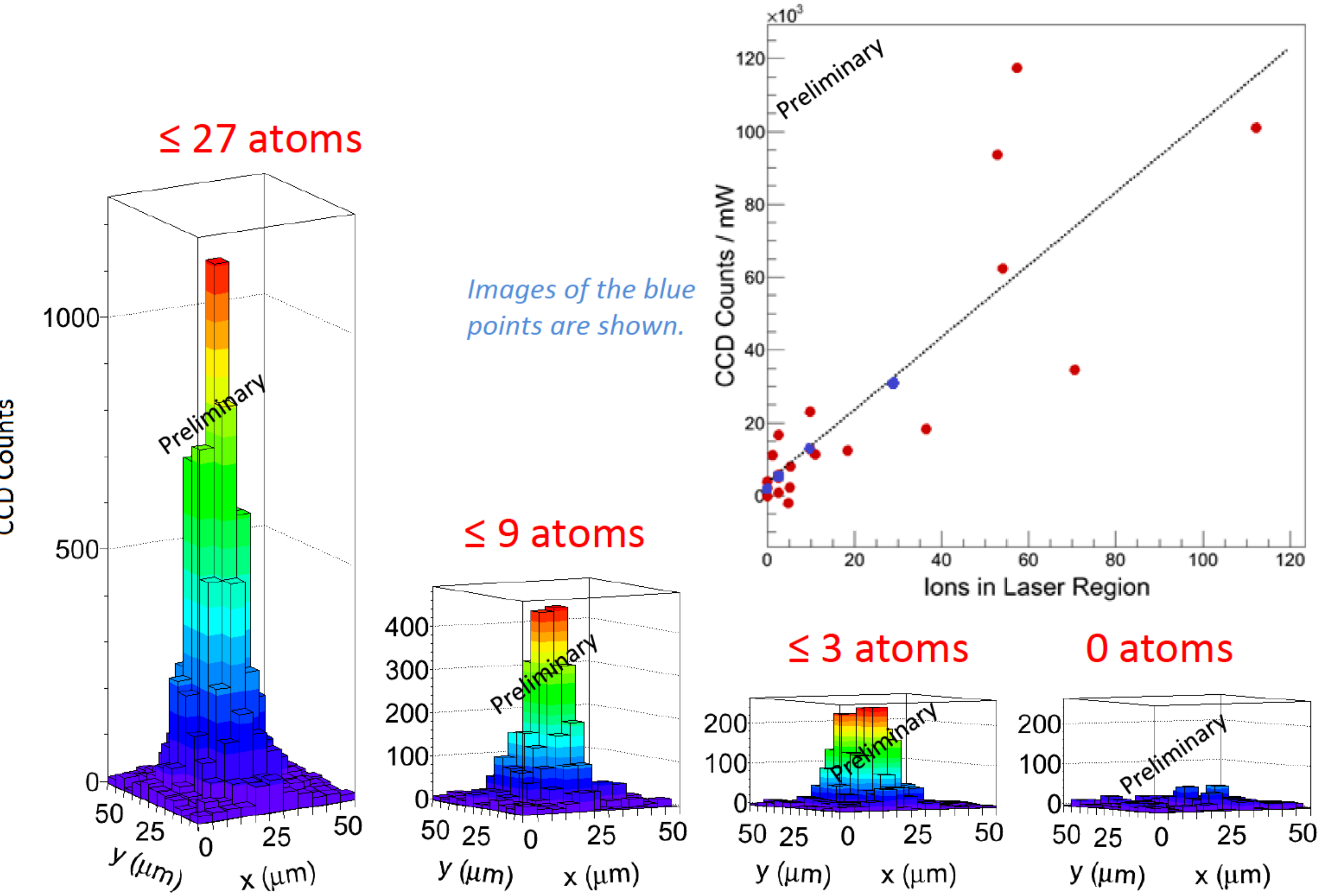
0 Atom Deposit



No "history" effect

If there is any Ba on the window, it isn't seen.

Ba tagging in solid xenon on a cryogenic probe



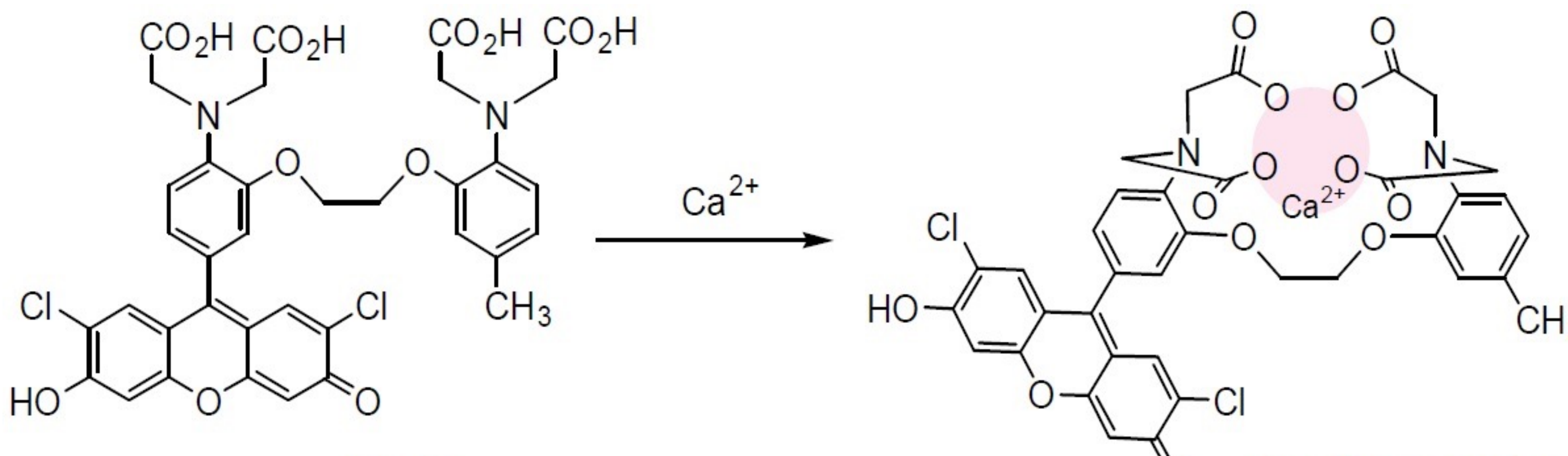
- few atom sensitivity

- ice probe and extraction system being built at CSU
- an analogous extraction system for RIS probe existing already at Stanford

Ba tagging with SMFI

Courtesy of Dave Nygren

Fluo-3 converts from non-fluorescent to a fluorescent state by chelation!



Fluo 3
Fluo 3-Ca complex

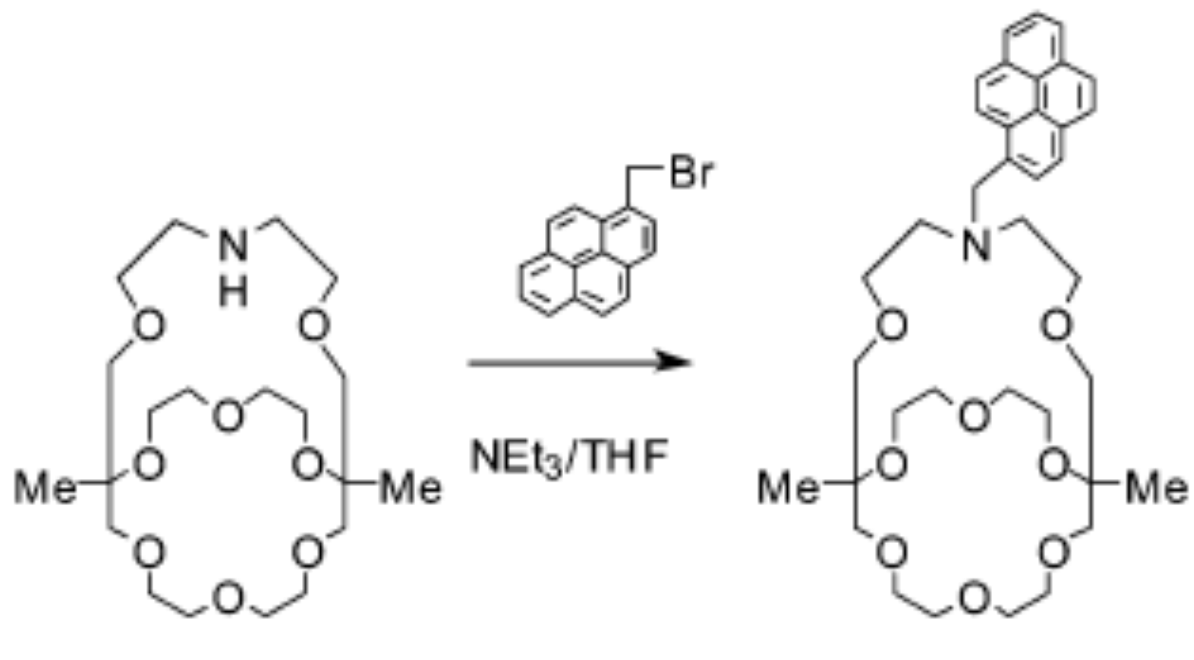
Once Ca^{++} is captured by Fluo-3, its responsiveness to external excitation increases by a factor of 60 -80. Two-photon excitation with IR is also possible

This might work for Barium as well since barium and calcium are congeners. Fluorophores exist for for Pb^{++}, Hg^{++}, Cu…)

2014 Nobel Prize in Chemistry awarded to three physicists for developing SMFI

A Fluorescent indicator specific to Ba⁺⁺!

Courtesy of Dave Nygren



"Monoazacryptand 1"

Y. Nakahara, T. Kida, Y. Nakatasuji, M. Akashi,
Chem. Comm., Roy. Soc. of Chem., 2004, p224-225

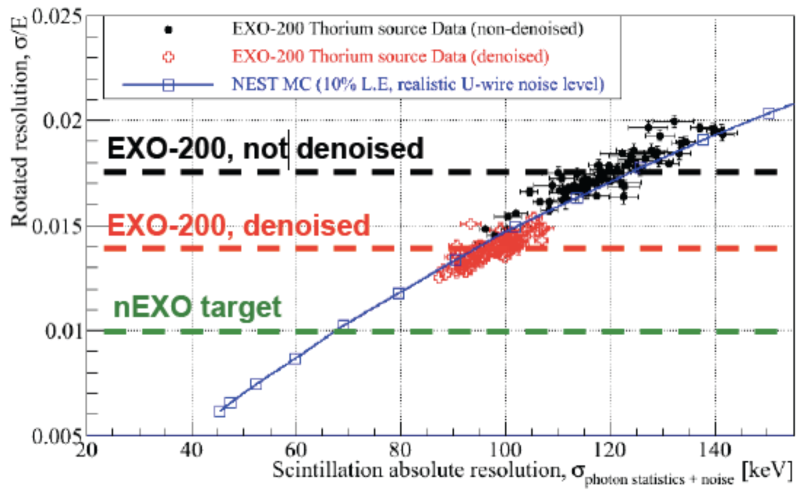
"The chelation process provides both a cage to hold on to and protect the ion from neutralization or other chemistry, but also provides a fluorescent enclosure that permits repeated interrogation by near UV, with a response stokes-shifted to a more convenient wavelength. Before chelation, fluorescent response is weak."

- At UTA, we are starting construction of a system that, in a phased approach, may demonstrate feasibility of the "biochemistry of ^{136}Xe" for NLDBD search.
- Three components:
  - Ba^{++} source
  - Drift column, to allow separation by shutter of Ba^{++} from other ionic species
  - Cathode, with sensing of ionic ensemble by electronic signal, then fluorescent response, then single ion.

Summary

stay hungry, my friend

Simulated rotated resolution vs. readout noise:



- LXe and GXe TPCs provide a path to reach 0νββ decay sensitivity >10^{27} years, with tonnes of enriched xenon, recyclable for other detectors
- EXO-200 made the first observation of 2νββ in ^{136}Xe, the slowest yet most precisely measured of practical isotopes.
- Current EXO-200 limit on $T_{1/2}^{0\nu\beta\beta}$ of ^{136}Xe of 1.1×10^{25} years
  Phase two sensitivity is ~5×10^{25} years (restart ongoing)
- nEXO detector with 5 tonnes of enriched xenon is based on measured EXO-200 performance
- Ba tagging could further boost the sensitivity of this technology to reach the normal neutrino mass hierarchy