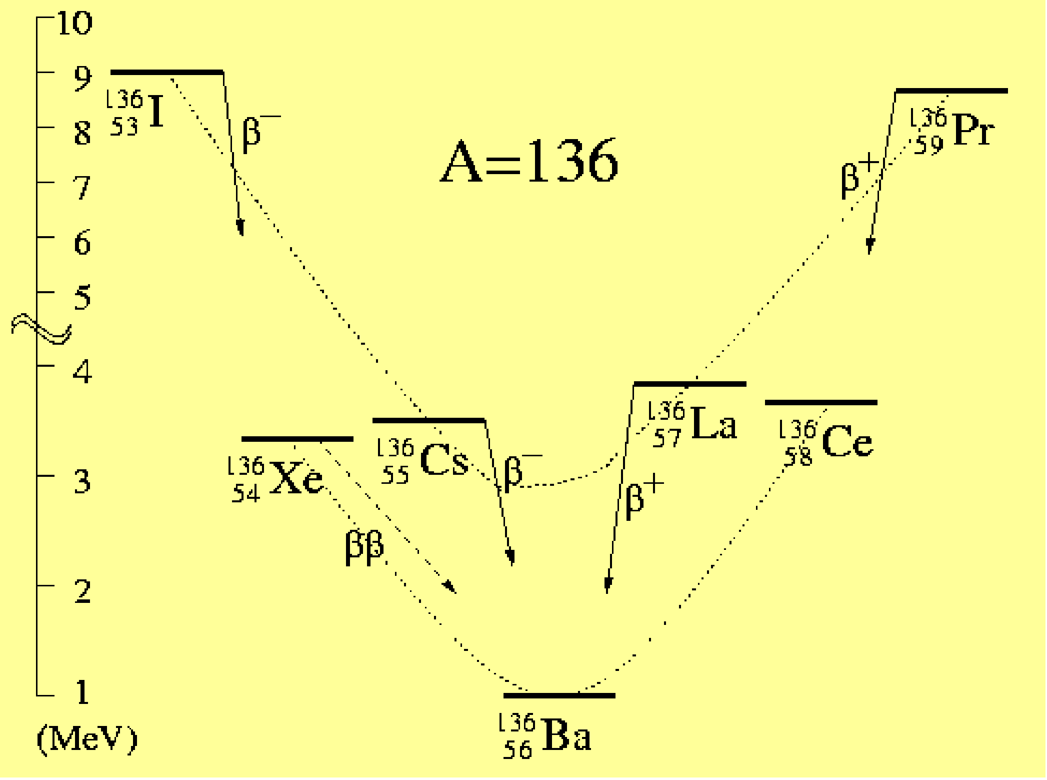
# Double beta decay of $^{136}Xe$: the EXO experiment

Andreas Piepke
for the EXO Collaboration
University of Alabama

## Brief introduction

Is a second order weak decay simultaneously converting two neutrons into two protons.

Because of the nucleon pairing energy for some nuclides ββ-decay is the only way to achieve the lowest mass state.



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There are many ways this can be achieved. The two most popular modes are:

$$\mathrm{A}(\mathrm{Z},\mathrm{N}) \rightarrow \mathrm{A}(\mathrm{Z}+2,\mathrm{N}-2)+2\mathrm{e}^{-}+2\overline{\nu}_{\mathrm{e}} \qquad (2\nu\beta\beta)$$

$$\mathrm{A}(\mathrm{Z},\mathrm{N}) \rightarrow \mathrm{A}(\mathrm{Z}+2,\mathrm{N}-2)+2\mathrm{e}^{-} \qquad (0\nu\beta\beta)$$

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$$A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 2\overline{\nu}_e \qquad (2\nu\beta\beta)$$

$$A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- \qquad (0\nu\beta\beta)$$

- Violates Lepton number by two units
- Requires neutrino anti-neutrino identity (Majorana character)
- Driven by neutrino exchange: rate determines neutrino mass

# Focus on light neutrino exchange mode

Decay rate depends on an effective Majorana mass. Its calculation requires knowledge of nuclear physics quantities.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space

Nuclear matrix element

Elements upper row of MNS-matrix

$$\langle m_{\beta\beta} \rangle = \left| |m_1| \cdot U_{e1}^2 + |m_2| \cdot U_{e2}^2 \cdot e^{2 \cdot i \cdot \Phi_{12}} + |m_3| \cdot U_{e3}^2 \cdot e^{2 \cdot i \cdot \Phi_{13}} \right|$$

Physical neutrino masses

CP-phases

Assumes decay is driven by light neutrino exchange.

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Phase space

Nuclear matrix element

Because of the imaginary phases cancellations may occur.

$$\langle m_{\beta\beta} \rangle = \left| \left|m_1\right| \cdot U_{e1}^2 + \left|m_2\right| \cdot U_{e2}^2 \cdot e^{2 \cdot i \cdot \Phi_{12}} + \left|m_3\right| \cdot U_{e3}^2 \cdot e^{2 \cdot i \cdot \Phi_{13}} \right|$$

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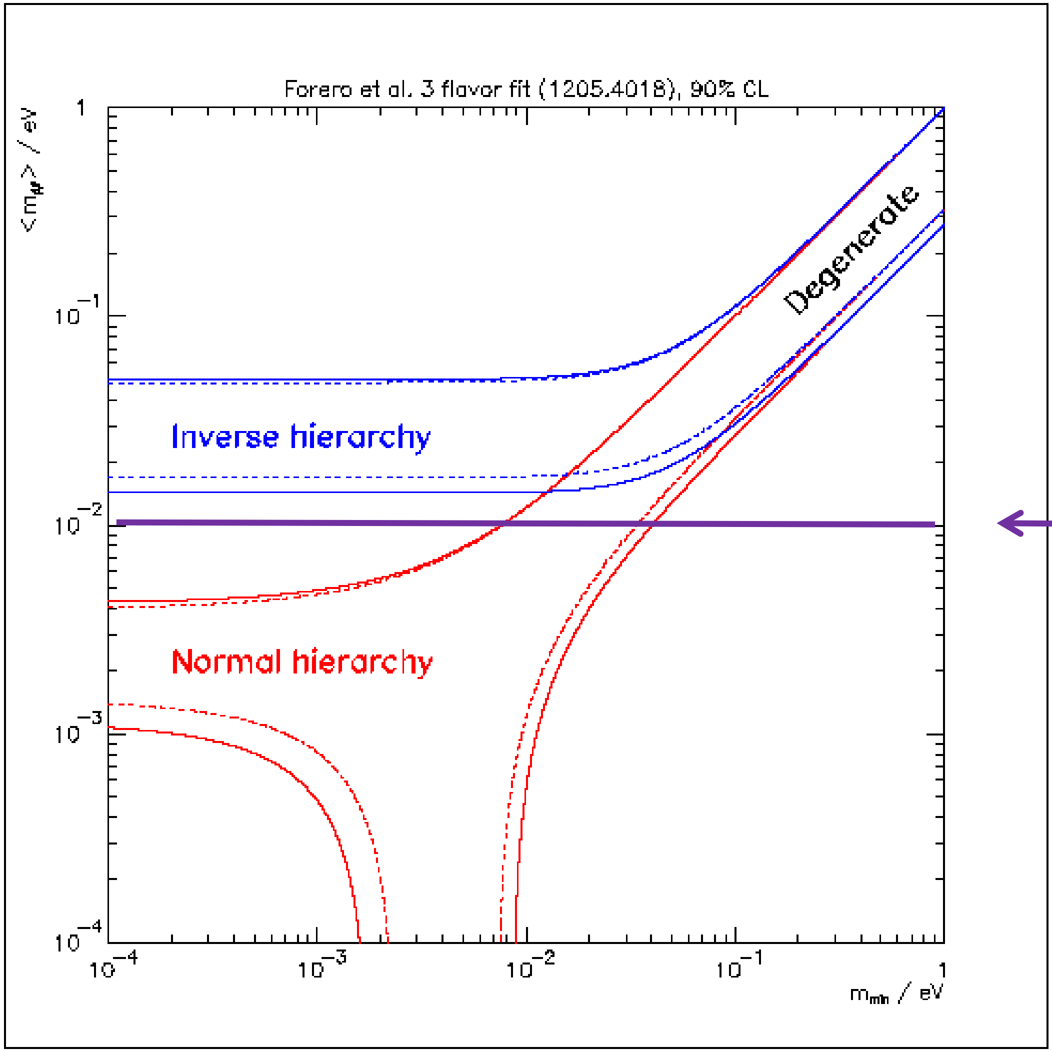


Measurement of ββ0ν is the only practical way to test the possible particle anti-particle identity. $\langle m_{\beta\beta} \rangle$ determines the yet unknown mass scale.

$^{76}$Ge: (1.4-7.7)·$10^{28}$ yr
$^{130}$Te: (0.22-1.3)·$10^{28}$ yr
$^{136}$Xe: (0.32-2.2)·$10^{28}$ yr

This neutrino mass goal defines the scale of new experimental searches.




90% CL 3-flavor fit errors provided by M. Tortola.

# How to attack this problem experimentally?

- Find a candidate nuclide with reasonably high decay energy and isotopic abundance to maximize decay rate.
- Most popular approach: pick a substance that decays and serves as the detector. But there are exceptions.
- Build the largest high resolution detector you can afford. To gain rate and reduce background, enrich the decaying isotope, removing non-decaying but sensitive ‘ballast’.
- Build this detector such that its background is few events per year at 2-3 MeV! This is THE technological challenge. Requires use of exotic low activity materials with sometimes undesirable mechanical properties.
- Employ active background suppression.

Because of the long half lives (now $\sim 10^{25}$ yr $\rightarrow \sim 10^{27}$ to $\sim 10^{28}$ yr inverse hierarchy) current and future searches require:

1) Large amounts of decaying substance to see any events.
2) Extremely low background to "see" few decays per year.

For background limited null result the experiment sensitivity has the following general form (for small detectors):

$$\langle m_{\beta\beta} \rangle < \frac{1}{\sqrt{\alpha \cdot a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \sigma}} \cdot G^{0\nu}} \cdot \left| M^{0\nu} \right|}$$

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Constant depending on CL, integration of peak, mol mass

Detector mass

Counting time

Energy resolution

Background rate per unit mass and energy

Isotope abundance

Efficiency

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The different experimental searches try to optimize their physics sensitivity via different parameters.

For a background free experiment the sensitivity is:

$$\langle m_{\beta\beta} \rangle < \frac{1}{\sqrt{\alpha' \cdot a \cdot \varepsilon \cdot M \cdot t \cdot G^{0\nu}} \cdot \left| M^{0\nu} \right|}$$

Detector mass and time enter in via the square instead of the fourth root.

# The EXO Collaboration


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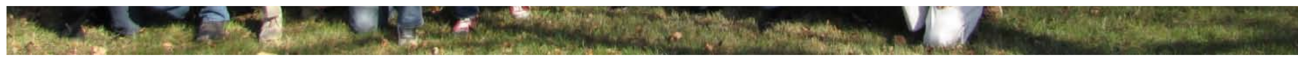
TRIUMF, Vancouver BC, Canada – P.A. Amandruz, D. Bishop, J. Dilling, P. Gumplinger, R. Kruecken, C. Lim, F. Retiere, V. Strickland

# The EXO Collaboration

115 collaborators (90% scientists and students, 10% engineers)
20 institutions
7 countries



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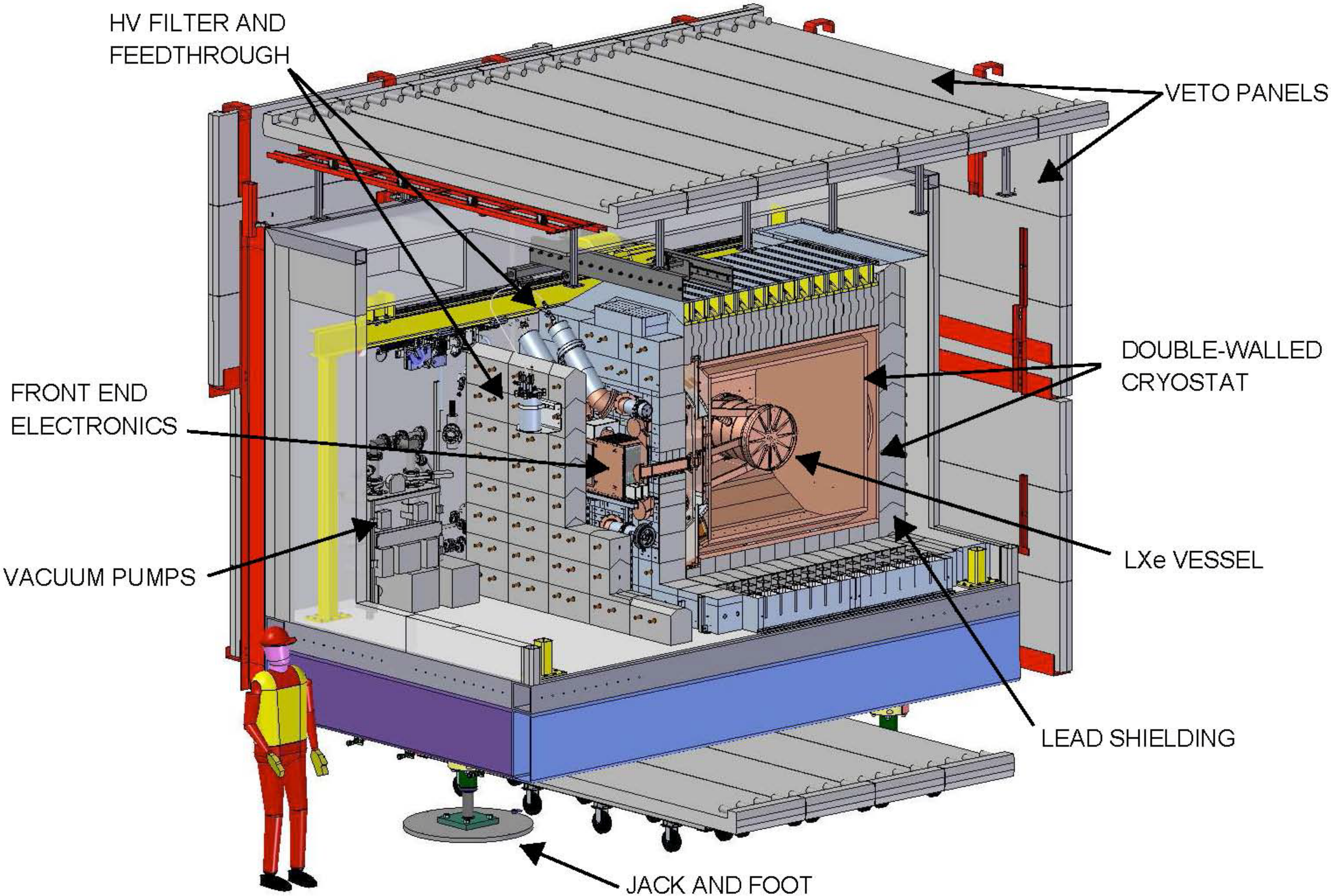
# The EXO-200 detector at the Waste Isolation Pilot Plant near Carlsbad New Mexico, USA (1585 mw.e.)


HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
LEAD SHIELDING
JACK AND FOOT

# EXO detection strategy

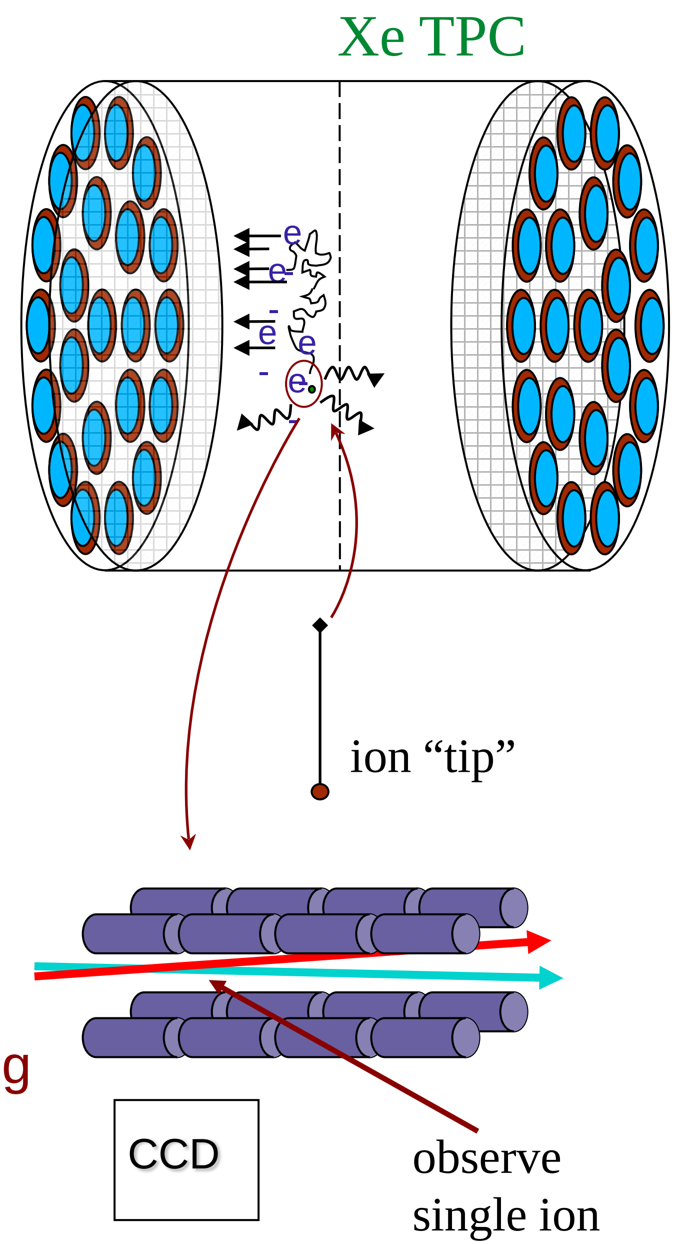
detect the 2 electrons
(ionization + scintillation in xenon detector)

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

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

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

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



# Background control

Natural, cosmogenic and anthropogenic radioactivity content of all construction materials quantified using various techniques. In the course of EXO materials testing program more than 500 material measurements over an 8 year period.

Techniques:

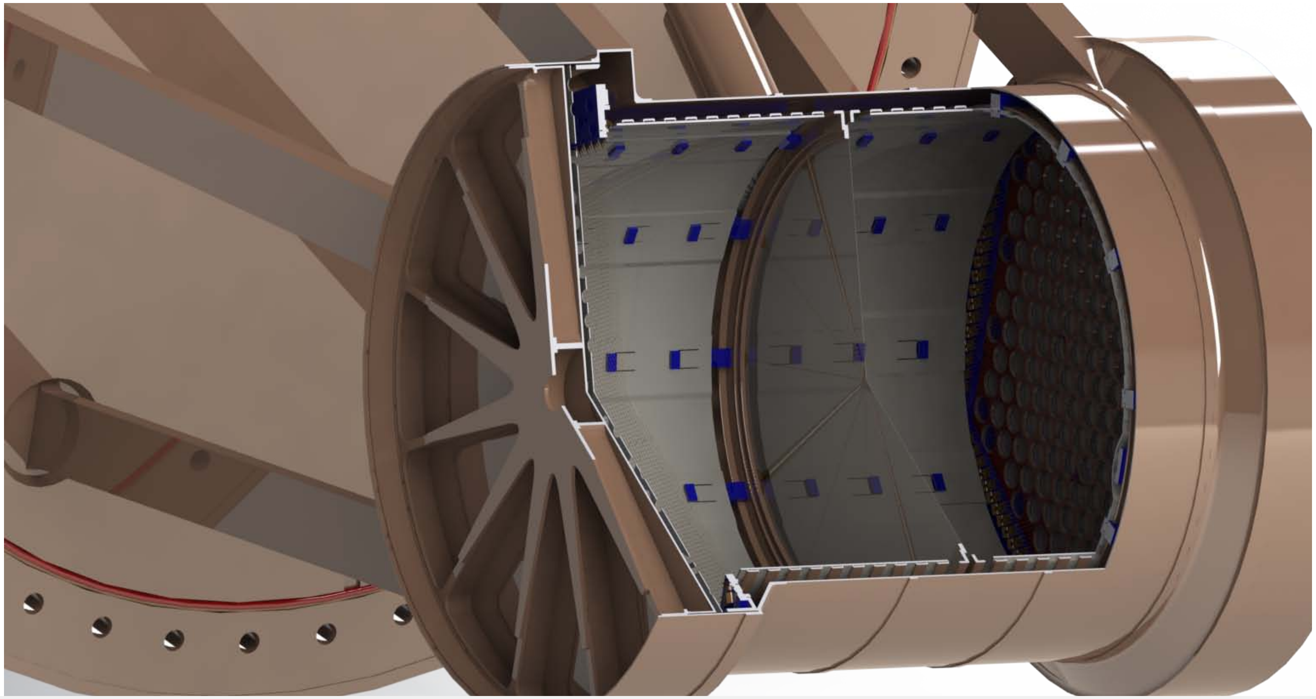
- $\gamma$-counting (Th/U): 1 ppb (AG), 7/16 ppt (UG).
- ICPMS and GDMS (Th/U): 10 ppt (GDMS), 1 ppt (ICPMS).
- NAA utilizing MIT reactor (Th/U): 0.3 ppt (counting), 0.02 ppt (pre-concentration).
- $\alpha$-counting for $^{210}$Pb for shielding Pb (via $^{210}$Po): 5 Bq/kg.
- Rn counting sensitivity: 5 $^{222}$Rn atoms/day outgassing.

Part of data published: D.S. Leonard et al., NIM A 591 (2008) 490.

# Measurement of radioactivity at ultra trace concentration:

1 ppt Th: 4 μBq/kg or 2.8 days/(decay·kg)
1 ppt U: 12 μBq/kg or 0.9 days/(decay·kg)
ββ2ν-decay of 80% enriched $^{136}Xe$:
for $T_{1/2} = 2 \cdot 10^{21}$ y specific activity 40 μBq/kg

Charge and light read-out on either end, HV cathode in the middle.



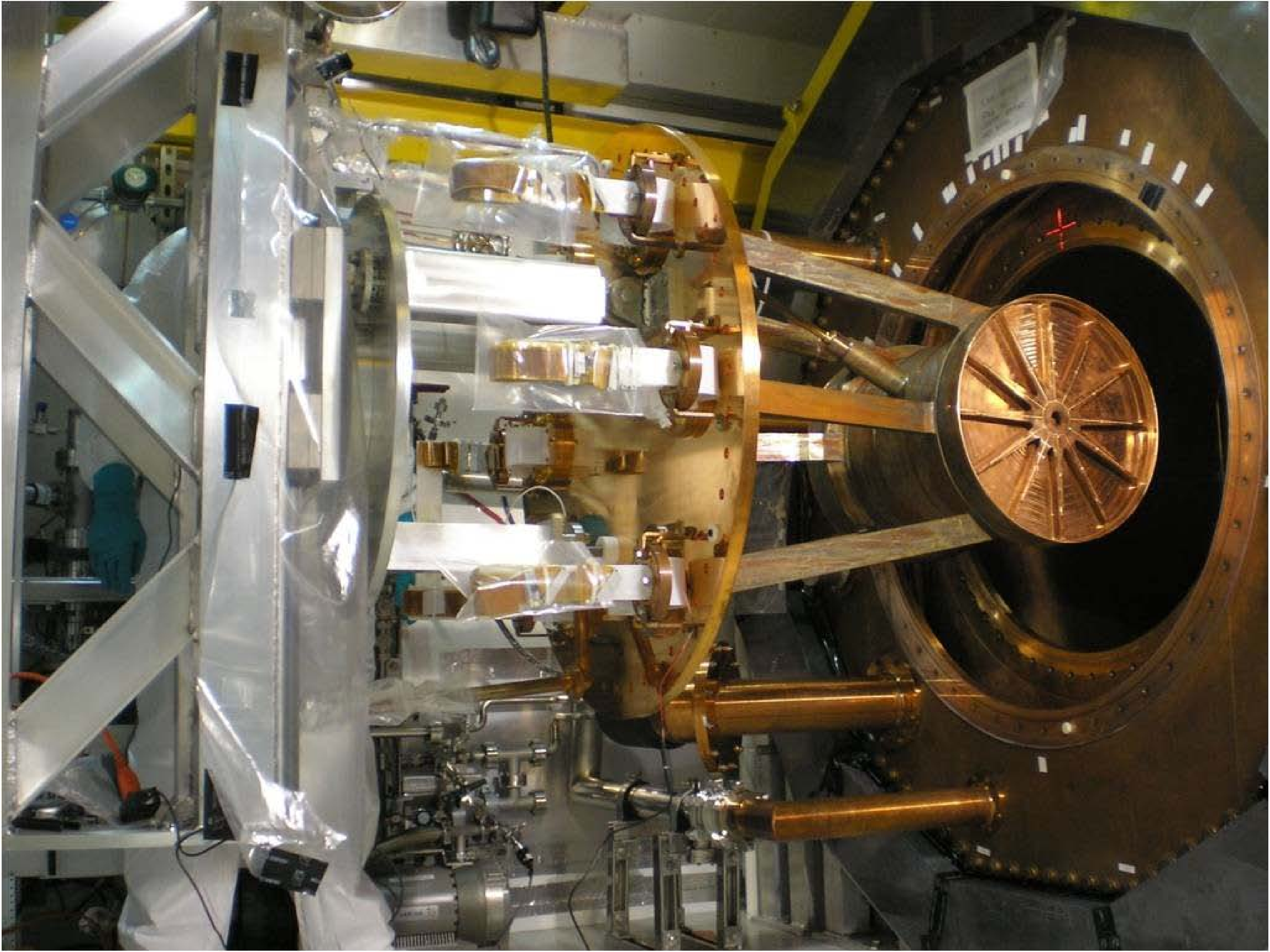
Charge collection and x-y position reconstruction by crossed wires.

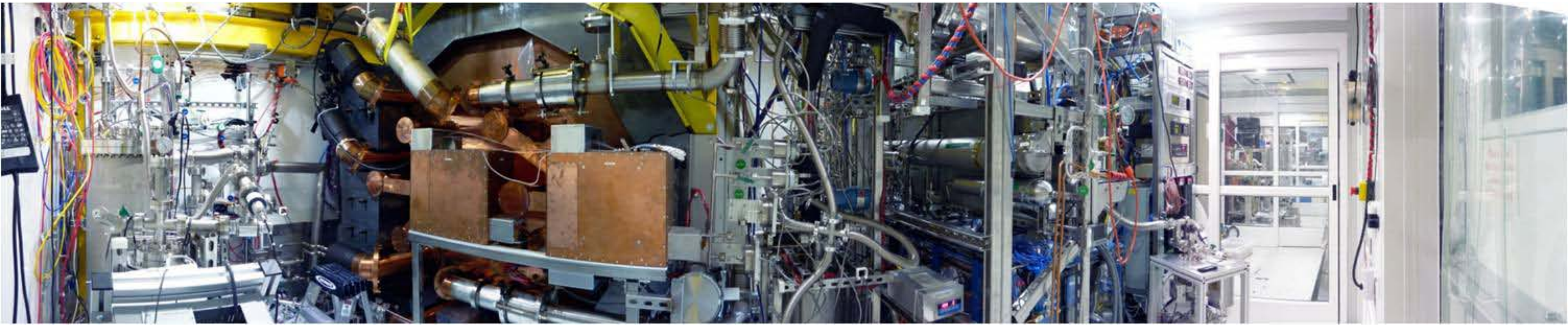
Scintillation light readout via 468 Avalanche Photo Diodes.

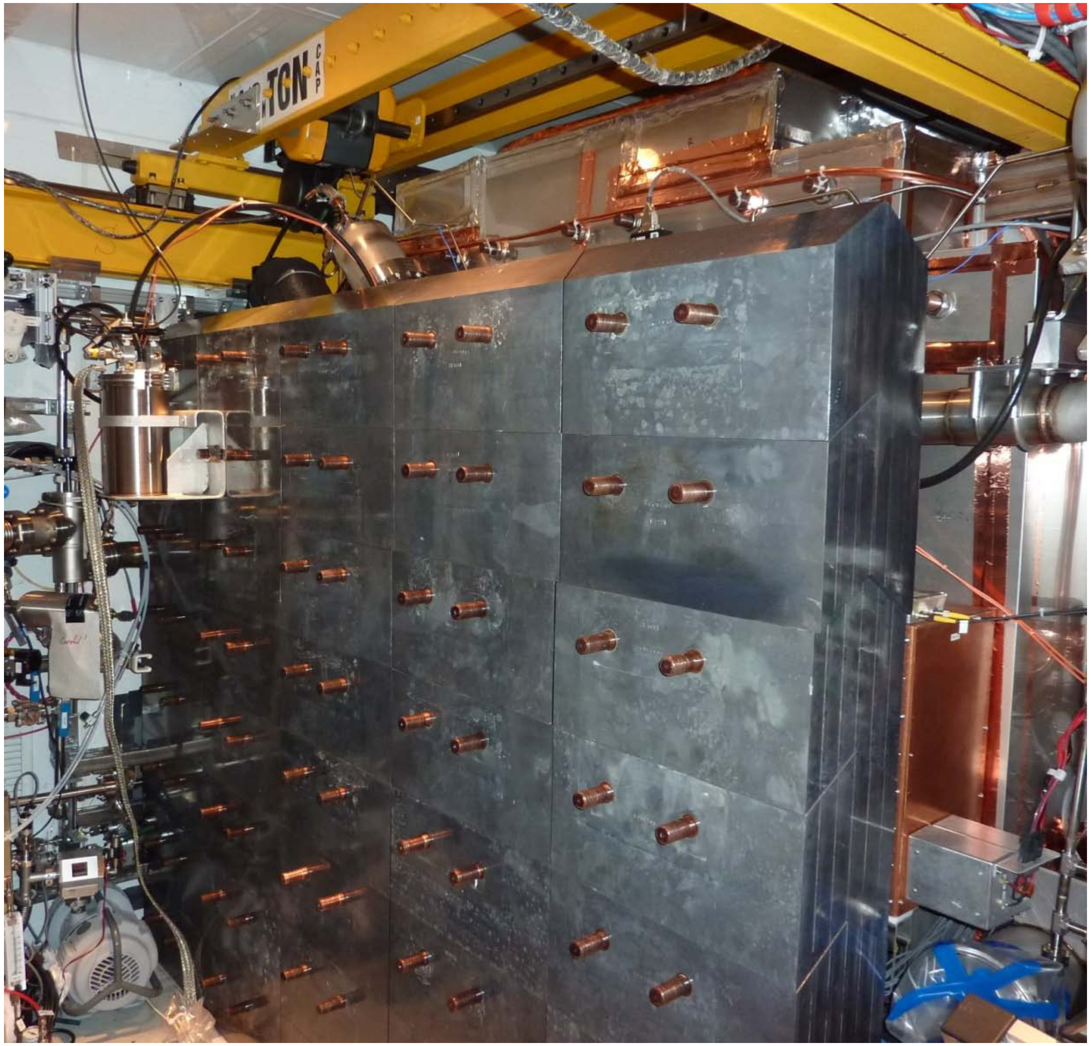
Time difference of the two signal gives the 3rd spatial coordinate.

$\gamma$s: multiple Compton scattering (MS) → background

$\beta$s: point-like interaction (SS) → signal







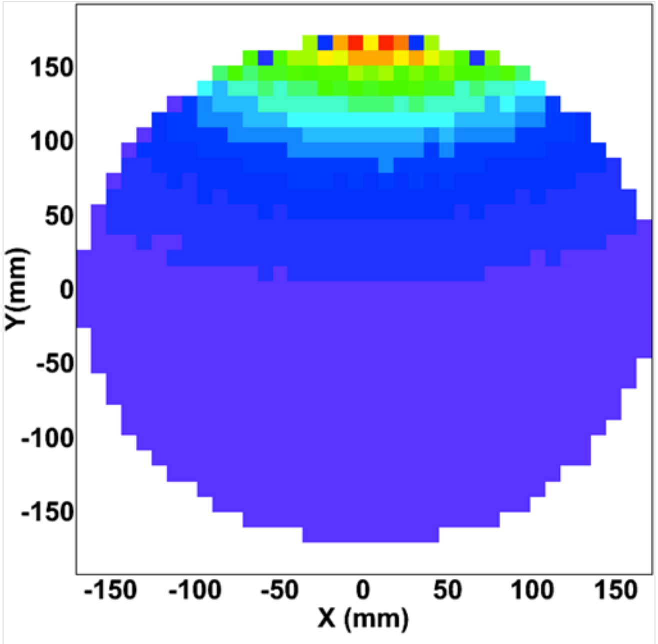
TCN
CAP

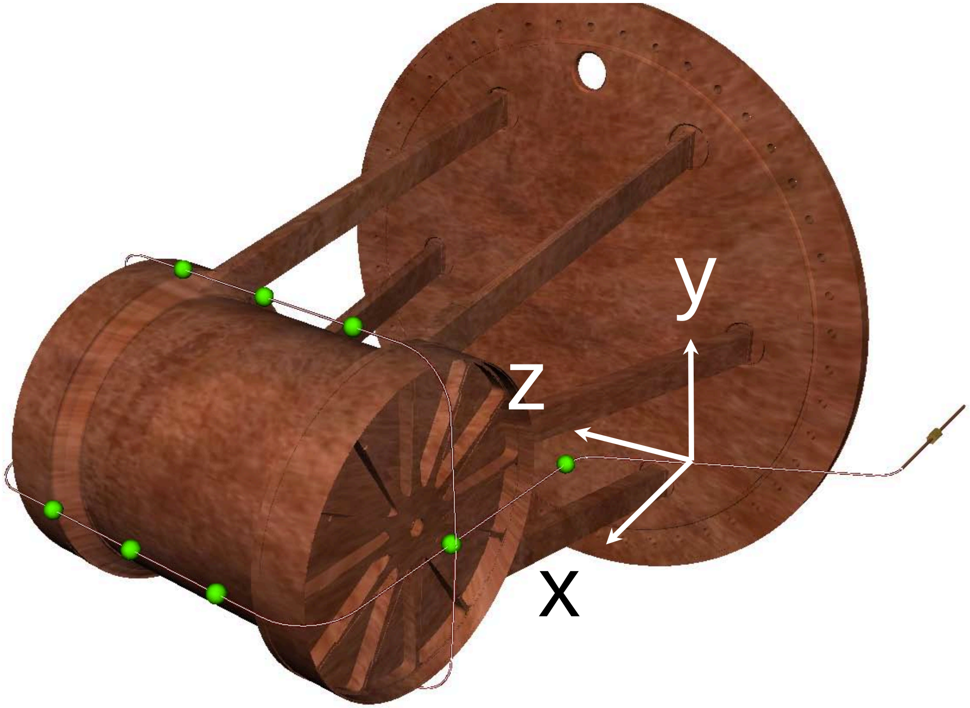

S6
S8
S29
S30
S22
CHILLERS


- 29 plastic scintillator veto panels (50 mm thick). Left from KARMEN experiment.
- Surrounds TPC on four sides.
- 95.5  0.6% efficient.
- 25 ms off-line cut after each hit, 0.58% dead time.
- 60 s off-line cut after each reconstructed $\mu$-track in Xenon, 5.0% dead time.

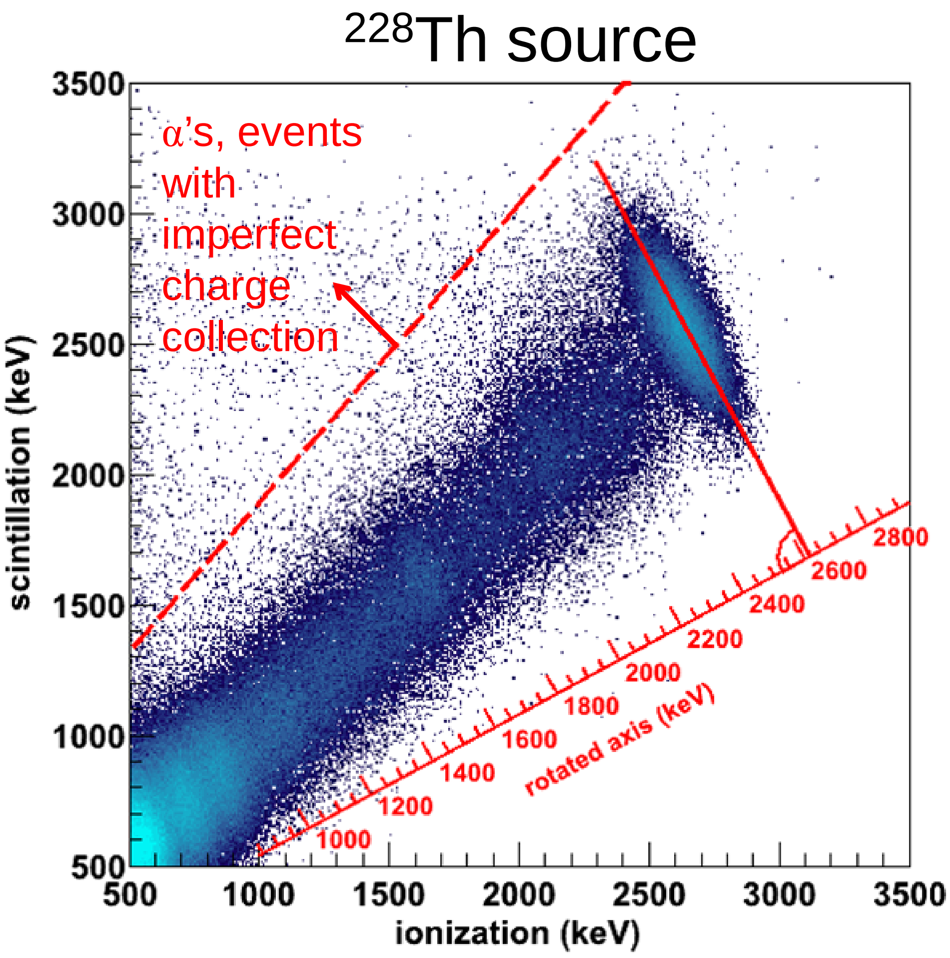
# How does EXO-200 perform?

To calibrate detector response and tune Monte Carlo simulation use miniature $^{137}Cs$, $^{60}Co$, $^{226}Ra$ and $^{228}Th$ calibration sources.

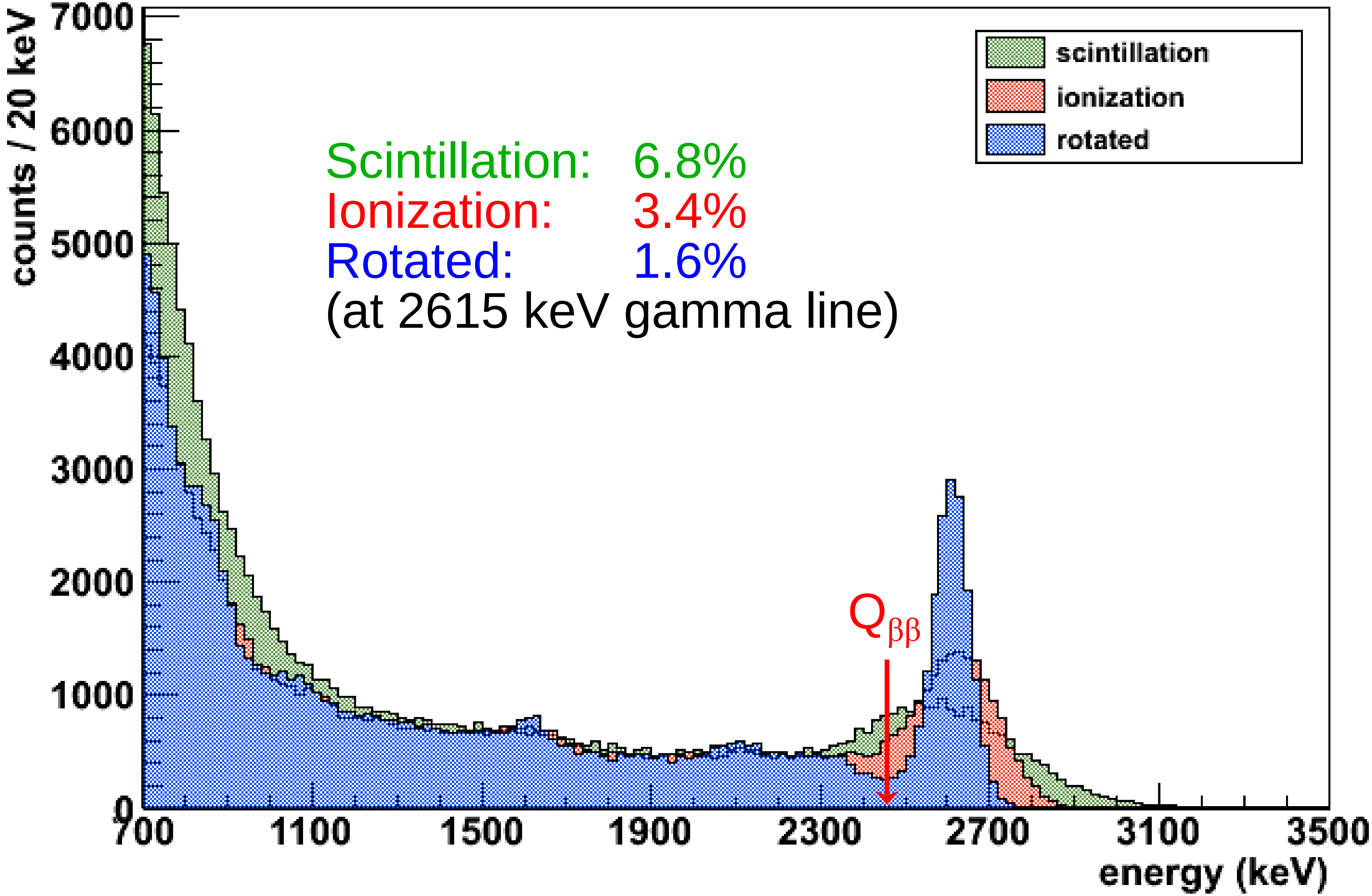


# Combine ionization & scintillation

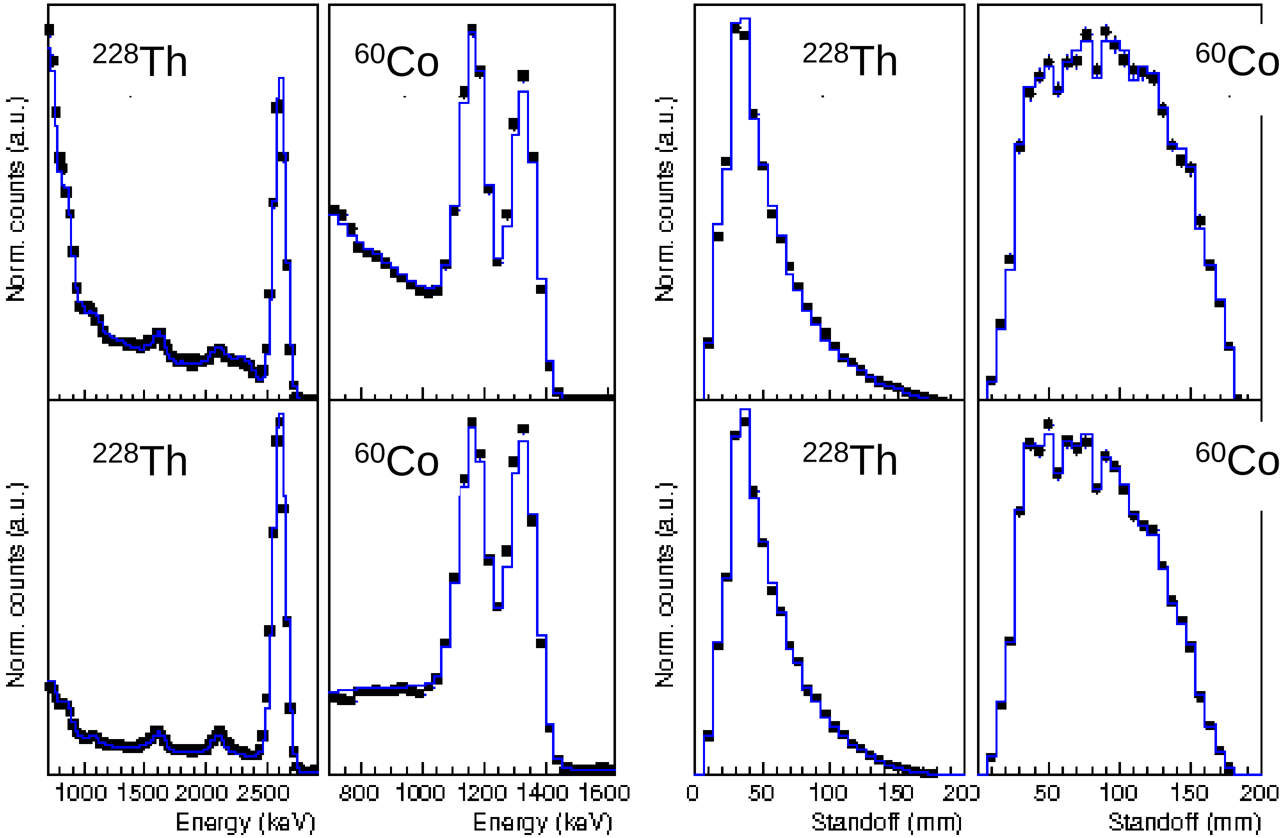



- Ionization and scintillation energies are anti-correlated.
- Energy measured along a rotated axis offers improved energy resolution.
- Rotation angle chosen to optimize resolution at 2615 keV.



counts / 20 keV
7000
6000
5000
4000
3000
2000
1000
0
700
1100
1500
1900
2300
2700
3100
3500
energy (keV)
scintillation
ionization
rotated
Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)
$Q_{\beta\beta}$

From radioactive sources ($^{136}$Cs, $^{60}$Co, $^{226}$Ra, $^{228}$Th) determine energy resolution, tune Monte Carlo det. model.




SS events
blue: MC
black: data

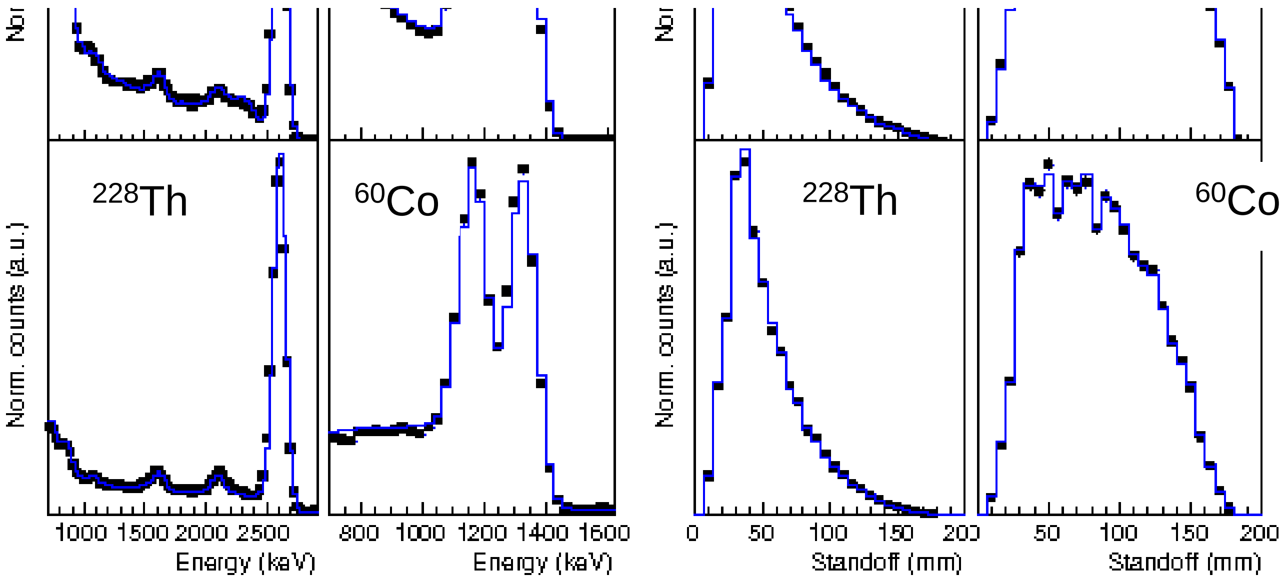
MS events
blue: MC
black: data

From radioactive sources ($^{136}$Cs, $^{60}$Co, $^{226}$Ra, $^{228}$Th) determine energy resolution, tune Monte Carlo det. model.

Monte Carlo model gives accurate description of the detector response to ionizing radiation:

- SS event fraction agrees to within 8.5% with data.
- Known source activities are reproduced within 9.4%.

nts
C
black: data




MS events
blue: MC
black: data

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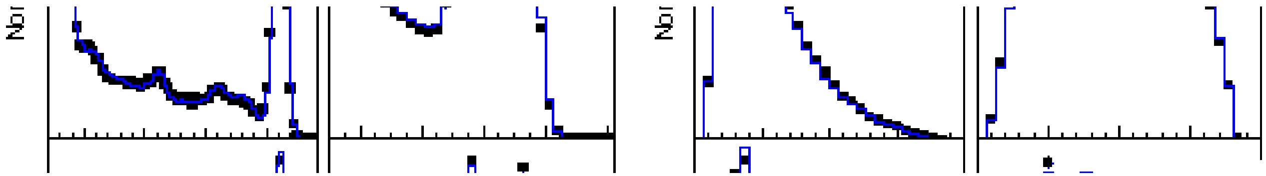
nts

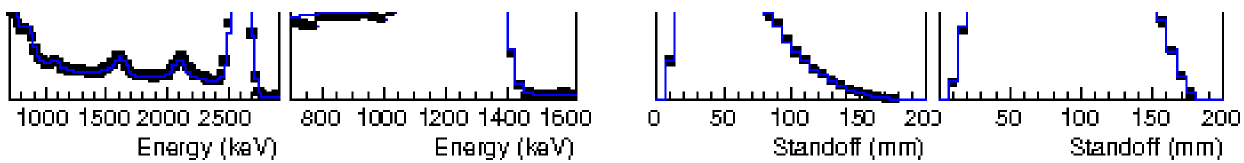
C

black: data

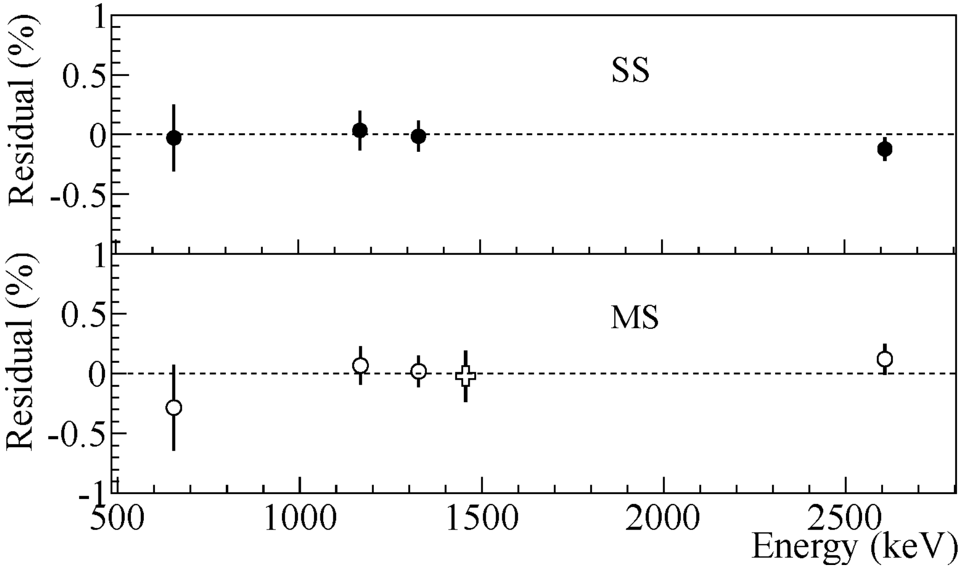


For the $0\nu\beta\beta$-fiducial volume cut the energy resolution $\sigma/Q$ is found to be 1.67%. It appears to be dominated by electronics noise in the photo diode chain.

black: data

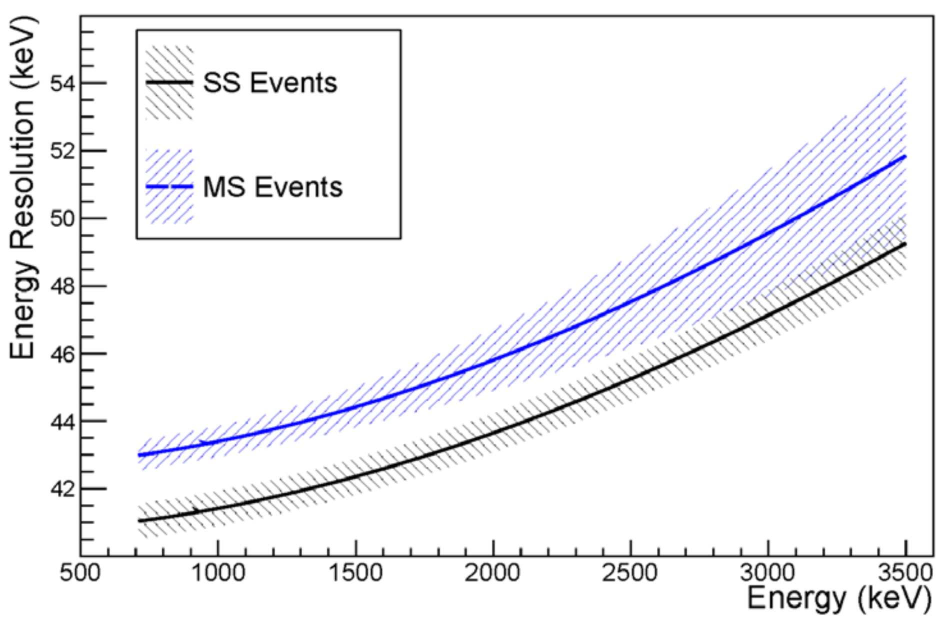


# Energy calibration




Using quadratic model for energy calibration, single- and multi-site residuals are:

$^{137}Cs$: 0.36%
$^{60}Co$: 0.17%
$^{228}Th$: 0.17%
$^{40}K$: 0.21% (physics data)

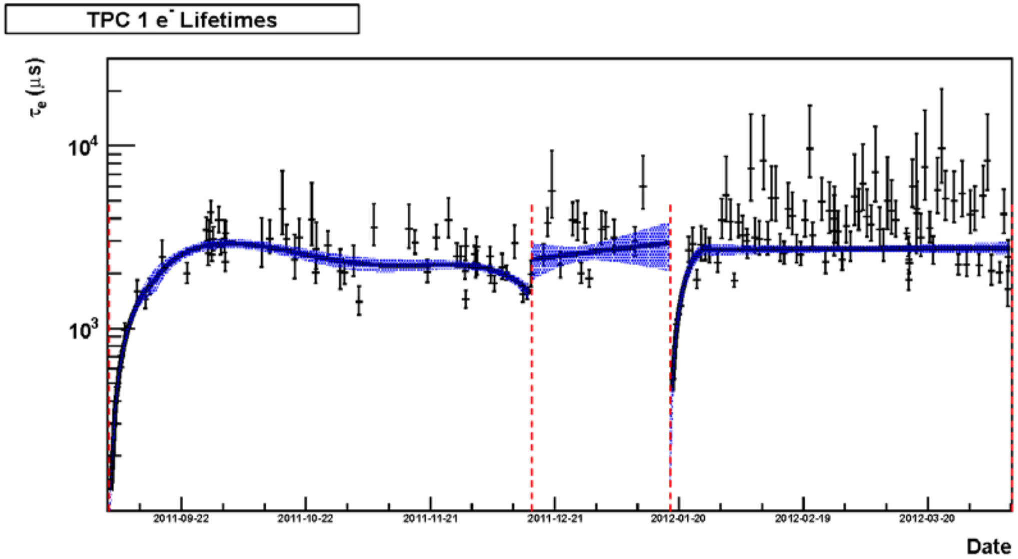


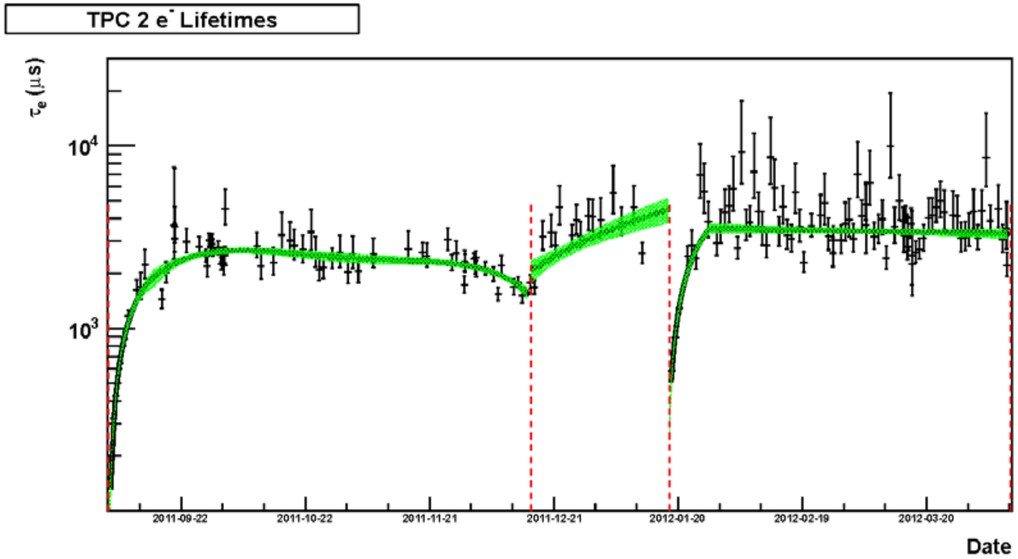

Energy resolution model:

$$\sigma^2(E) = \sigma_{elec}^2 + b \cdot E + c \cdot E^2$$

Resolution dominated by constant (noise) term $\sigma_{elec}$

At $Q_{\beta\beta}$ (2458 keV):
$\sigma/E$ = 1.67 % (SS)
$\sigma/E$ = 1.84 % (MS)




Xe pushed through hot Zr getter by ultra clean pump to remove electro-negative impurities.

Electron life time $\tau_e$ measured by source full absorption peak centroid as function of drift time.

$\tau_e$ ~3 ms with maximal drift time of ~110 μs.

# The Data

Is taking data since May 2011.

Run 1 (5/2011-7/2011, 31.36 d, 63 kg (of 110 kg active) Xe, *charge read-out only*): first observation of $2\nu\beta\beta$–decay of $^{136}Xe$

Run 2a (9/2011-4/2012, 120.69 d, 82.1 and 98.5 kg Xe): most accurate measurement of any $2\nu\beta\beta$–decay rate, one of most stringent limits on $0\nu\beta\beta$–decay (32.6 kg·yr) and Majorana neutrino mass, challenge of $^{76}Ge$ evidence.

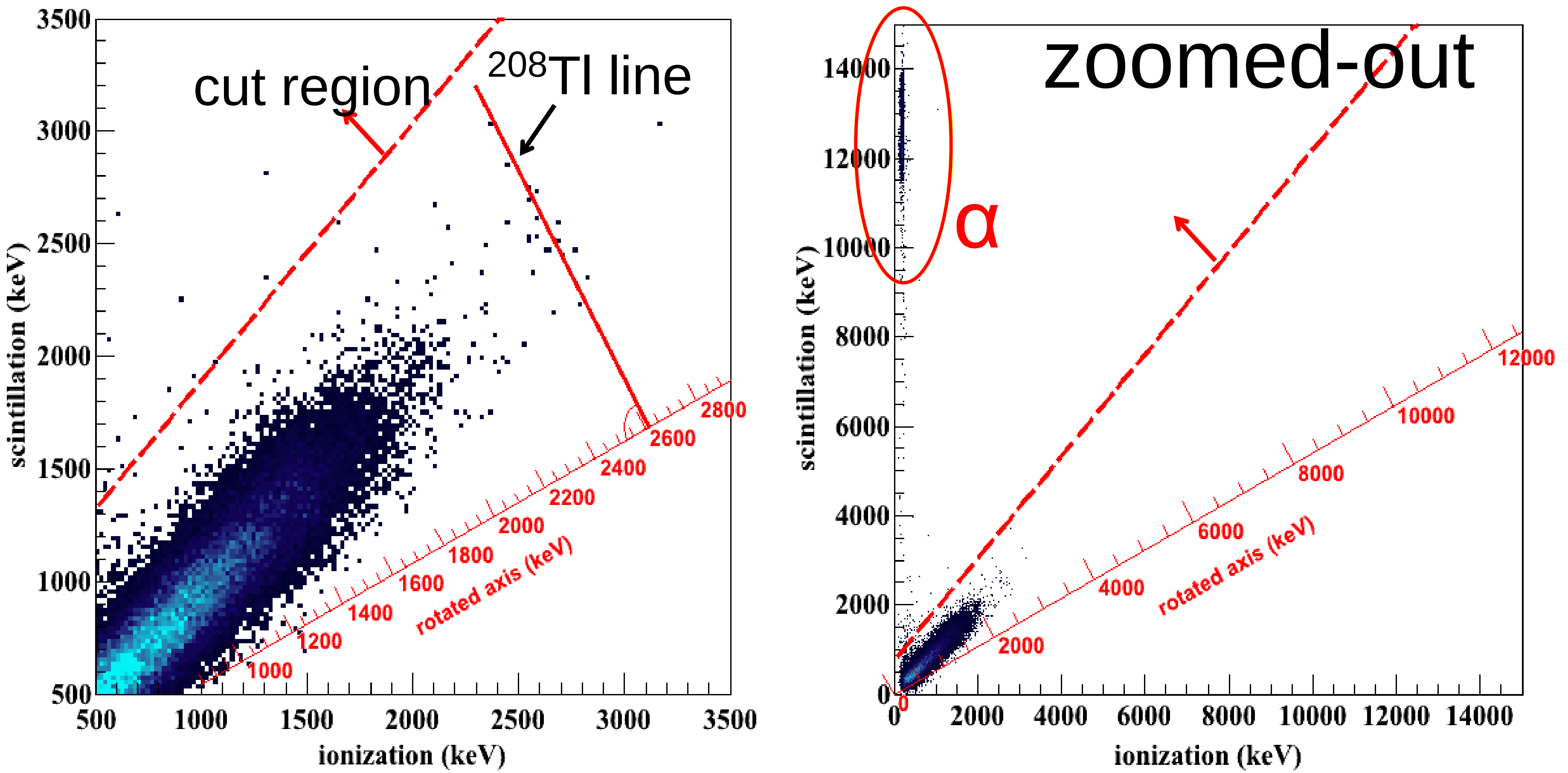
Run 2 (9/2011-6/2013, 439.6 d, 97.7 kg Xe): 3.6 times exposure compared to 2012 data set. $0\nu\beta\beta$–analysis not finalized yet.

Run 3 (6/2013...): taking data

# 2D low background data

- Cut events outside the charge collection area. This efficiently removes surface evens.
- Remove events at or near the anodes and cathode. Mostly due to $\alpha$'s.
- Remove alpha-like events with high scintillation to ionization ratio and events with low charge.
- Remove sequential events within 1 s of each other (3.3% dead time). Removes $^{214}$Bi-$^{214}$Po delayed beta-alpha coincidences (Radon daughters).

- SS event reconstruction efficiency: 71%.

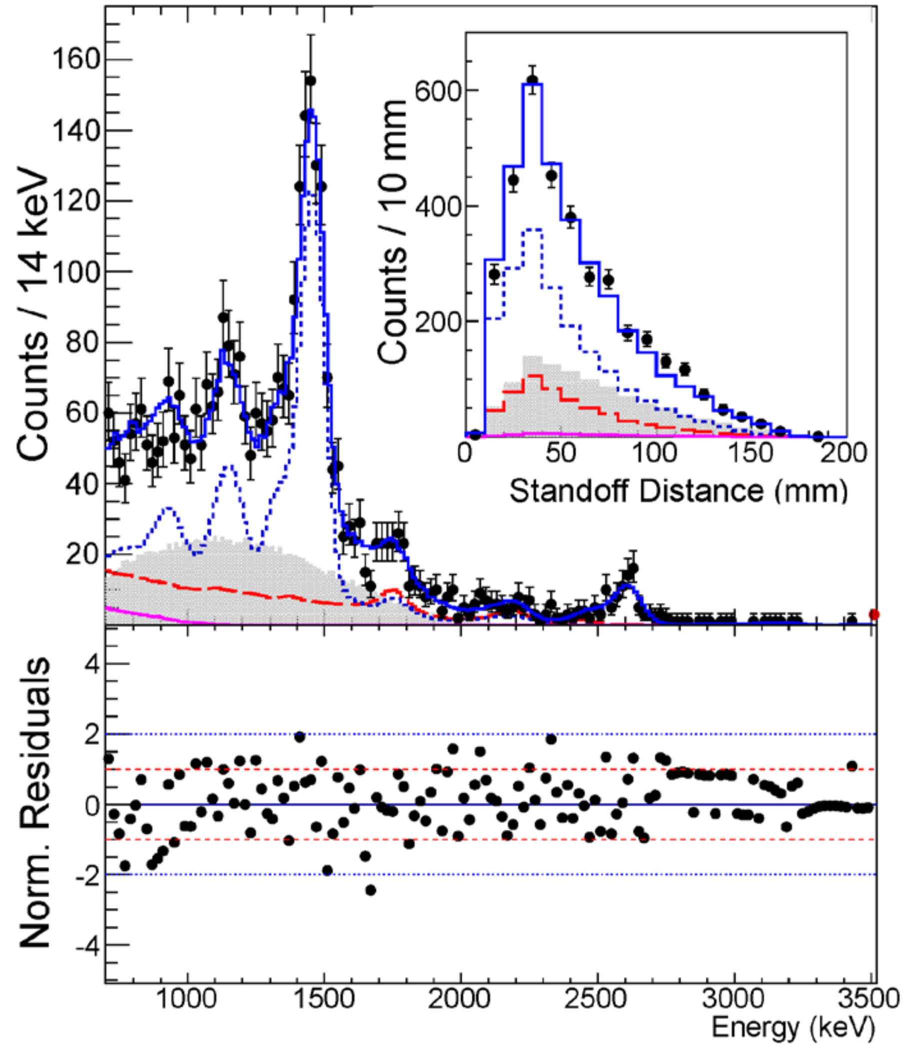

cut region
208Tl line
scintillation (keV)
ionization (keV)
rotated axis (keV)
zoomed-out
α
scintillation (keV)
ionization (keV)
rotated axis (keV)

# EXO-200 $2\nu\beta\beta$-data (82.1 kg Xe, 127.6 d, 28.69 kg·yr)

Utilize tracking capability: MS data contains mostly $\gamma$ events, has good diagnostic power for identifying the background components.

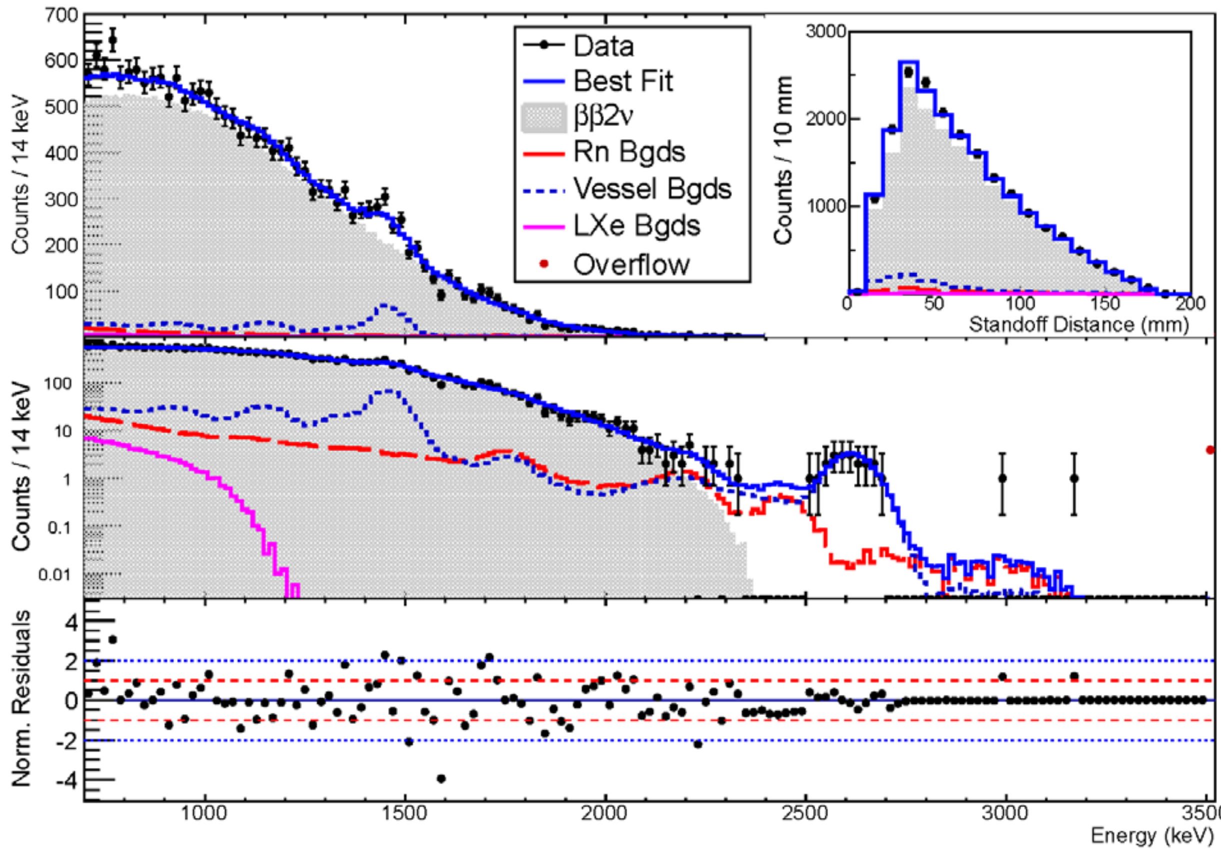
- Purple: $^{135}$Xe and Rn in Xe
- Red: Rn in Pb shield
- Blue: $^{40}$K, $^{54}$Mn, $^{60}$Co, $^{65}$Zn, $^{232}$Th, $^{238}$U in TPC materials.

$\chi^2$ / ndf = 104.5 / 77.0



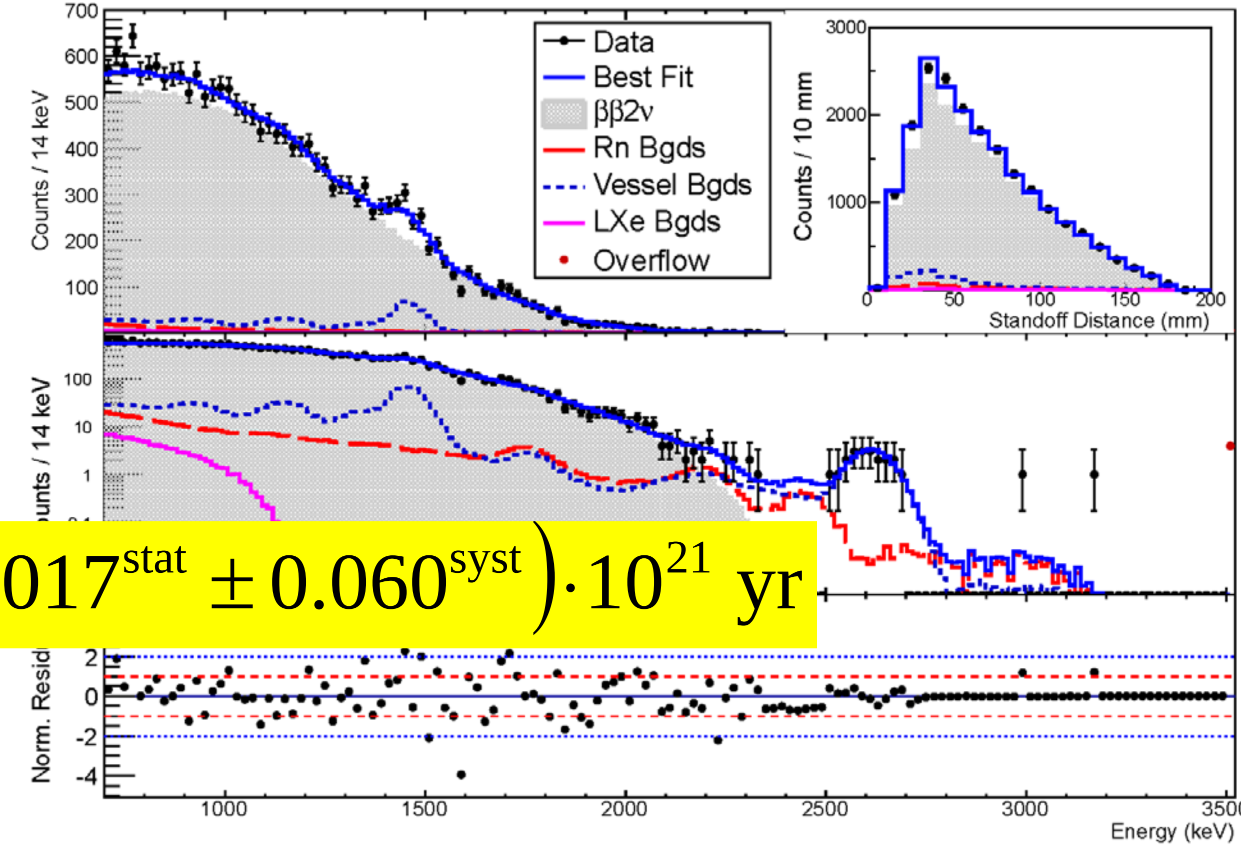
$\chi^2$ / ndf = 82.5 / 74.5

SS event set dominated by point-like β–events. Perform coupled MS and SS data fit to obtain:



$\chi^2$ / ndf = 82.5 / 74.5

SS event set dominated by point-like β–events. Perform coupled MS and SS data fit to obtain:

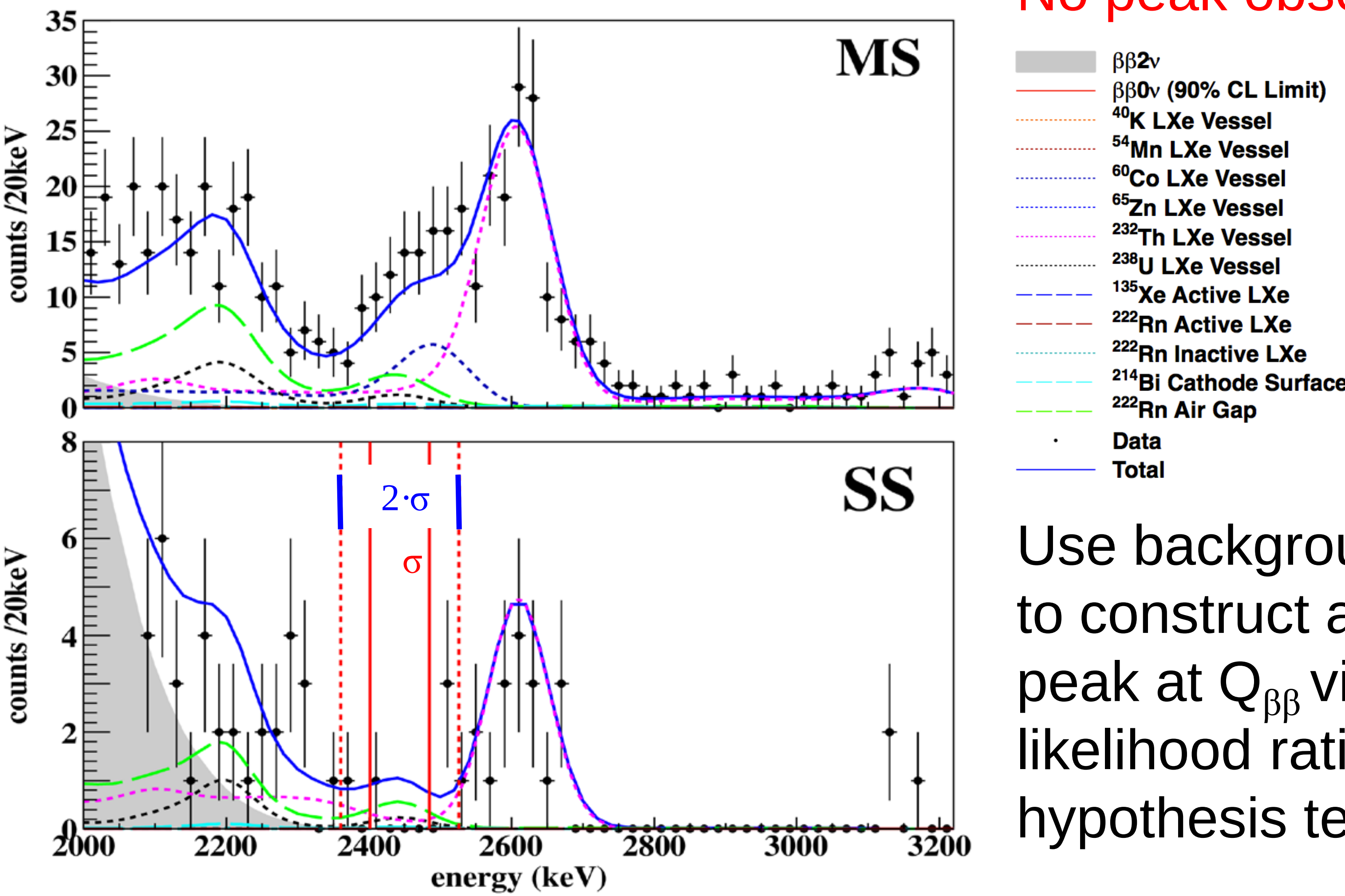



$$T_{1/2}^{2\nu\beta\beta} = \left(2.171 \pm 0.017^{stat} \pm 0.060^{syst}\right) \cdot 10^{21}\ \mathrm{yr}$$

The longest and most precisely measured 2νββ–decay half life.

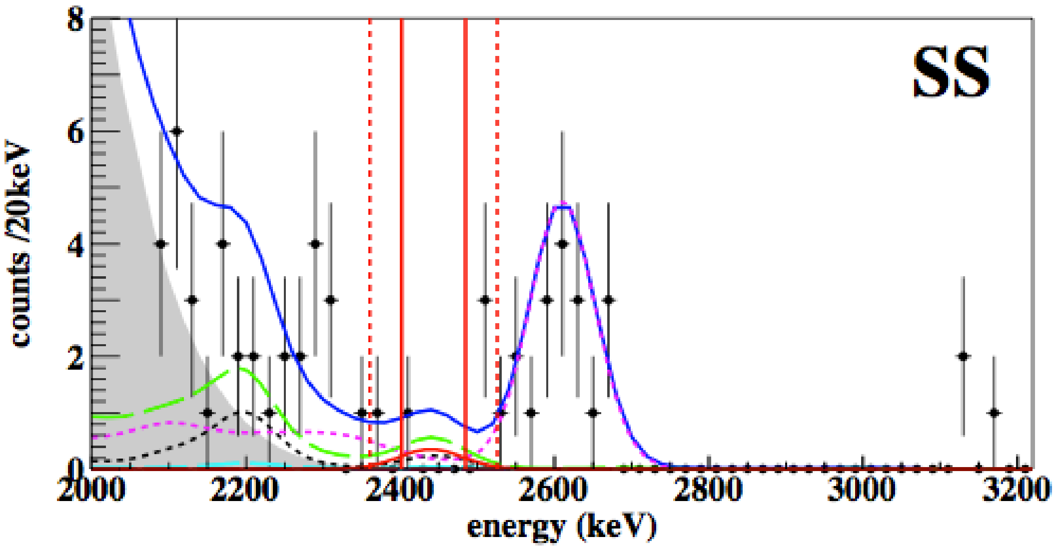
Smallest and best known 2νββ–matrix element: 0.0217  0.0003 $MeV^{-1}$.

## Low background data: around $Q_{\beta\beta}$




No peak observed at $Q_{\beta\beta}$.

Use background model to construct a limit for peak at $Q_{\beta\beta}$ via a likelihood ratio hypothesis test.

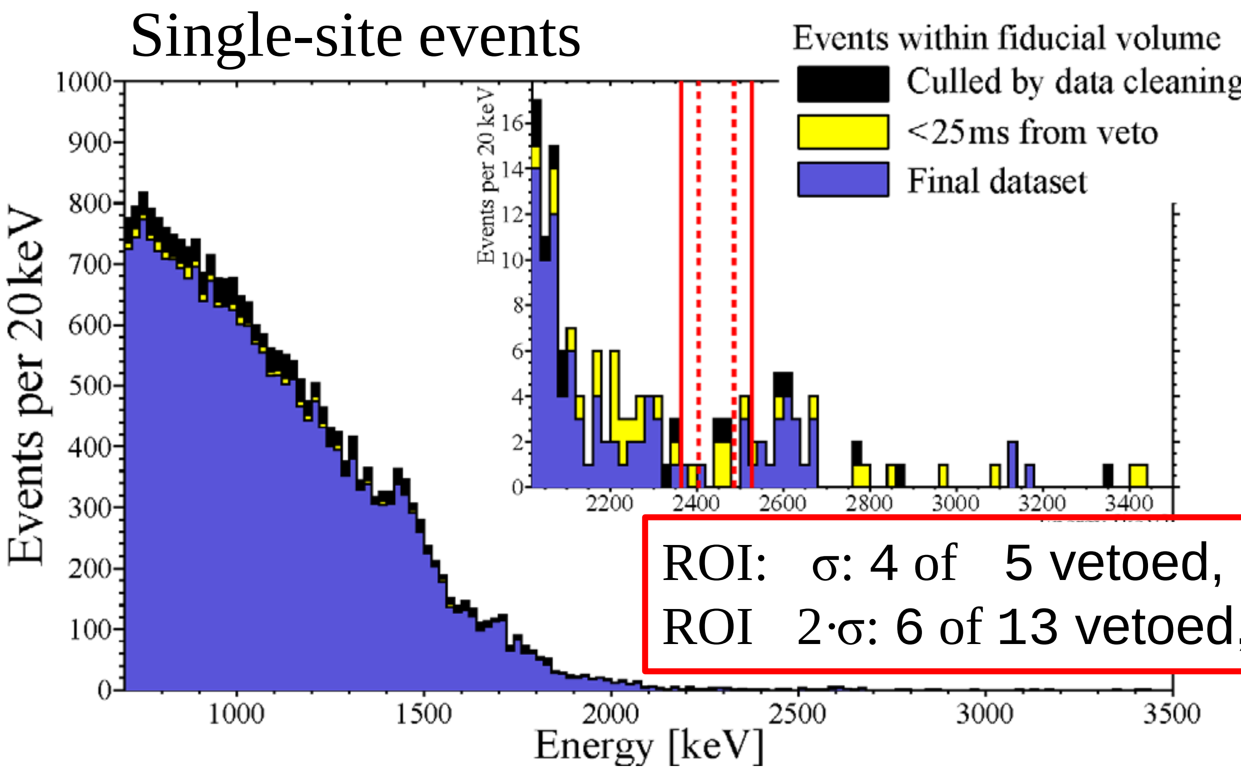



| | Expected events from fit | | | |
|---|---|---|---|---|
| | ±1 σ | | ±2 σ | |
| $^{222}$Rn in cryostat air-gap | 1.9 | ±0.2 | 2.9 | ±0.3 |
| $^{238}$U in LXe Vessel | 0.9 | ±0.2 | 1.3 | ±0.3 |
| $^{232}$Th in LXe Vessel | 0.9 | ±0.1 | 2.9 | ±0.3 |
| $^{214}$Bi on Cathode | 0.2 | ±0.01 | 0.3 | ±0.02 |
| All Others | ~0.2 | | ~0.2 | |
| Total | 4.1 | ±0.3 | 7.5 | ±0.5 |
| Observed | 1 | | 5 | |
| Background index MC ($kg^{-1}yr^{-1}keV^{-1}$) | $1.5 \cdot 10^{-3} \pm 0.1$ | | $1.4 \cdot 10^{-3} \pm 0.1$ | |

Background design goal: 20 cnts/yr in 2·σ and 140 kg Xe.

Measured background: 15 cnts/yr in 2·σ and 110 kg Xe.

# Cosmic-ray veto impact: system is essential




ROI: σ: 4 of 5 vetoed, 1 remaining
ROI 2·σ: 6 of 13 vetoed, 5 remaining

<u>Tracking gain in 2·σ ROI:</u>

MS data 2·σ ROI: 116 events
SS data 2·σ ROI: 5 events

(116+5) / 5 = 24.2

Profile likelihood analysis takes into account the peak shape of $0\nu\beta\beta$ signal. More sensitive than window analysis.

We get at 90% CL: $T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ yr$

The longest $^{136}Xe$ $0\nu\beta\beta$-decay limit comes from the KamLAND-Zen experiment: $>1.9 \cdot 10^{25}$ yr.

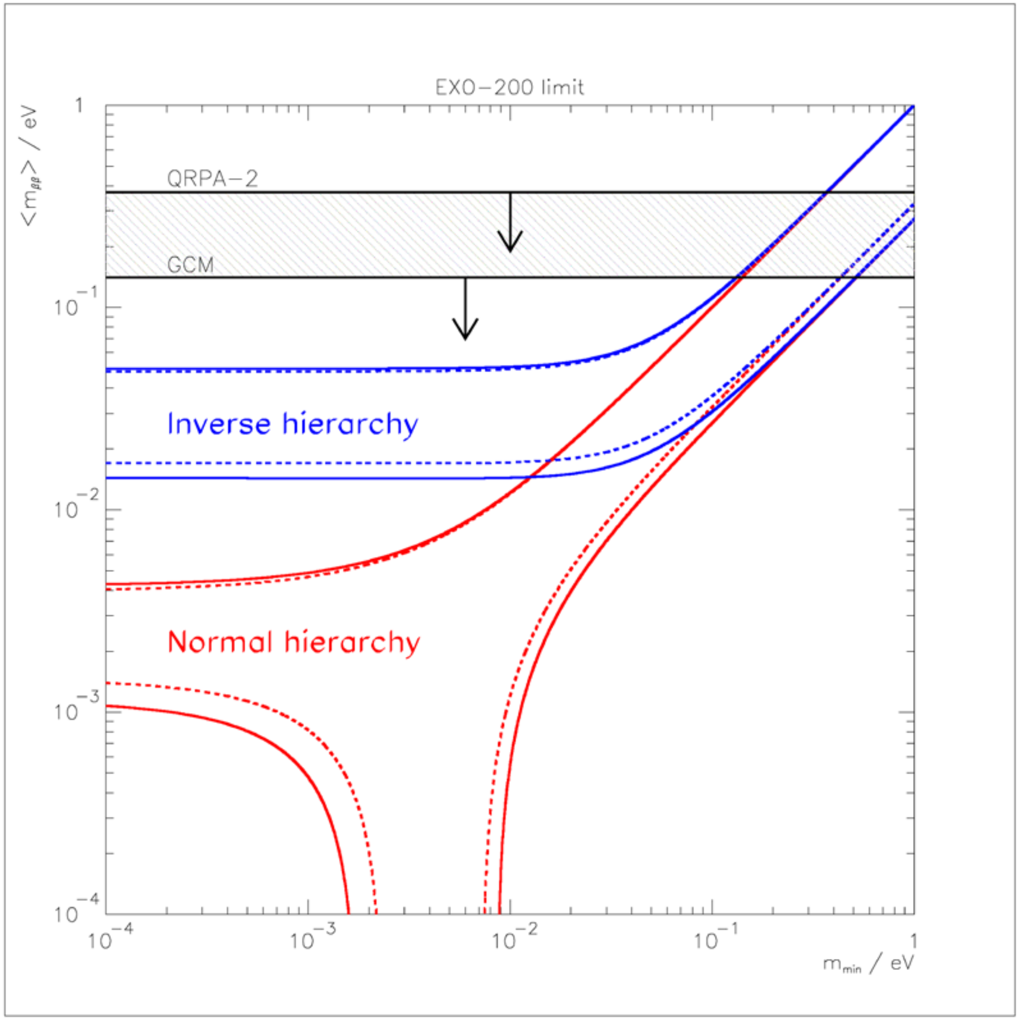
EXO-200 result translates into a Majorana ν mass limit range:

$\langle m \rangle_{\beta\beta} < 140 - 380$ meV [Auger et al., PRL 109 (2012) 032505]

$^{130}Te$ (Cuoricino): < 270 – 660 meV [Arnaboldi et al. PRC 78 (2008) 035502]

$^{76}Ge$ (GERDA): < 255 – 606 meV [M. Agostini et al., arXiv:1307.4720]

$^{100}Mo$ (NEMO-3): < 450 – 1070 meV [A. Barabash et al., PAN 74 (2011) 312]

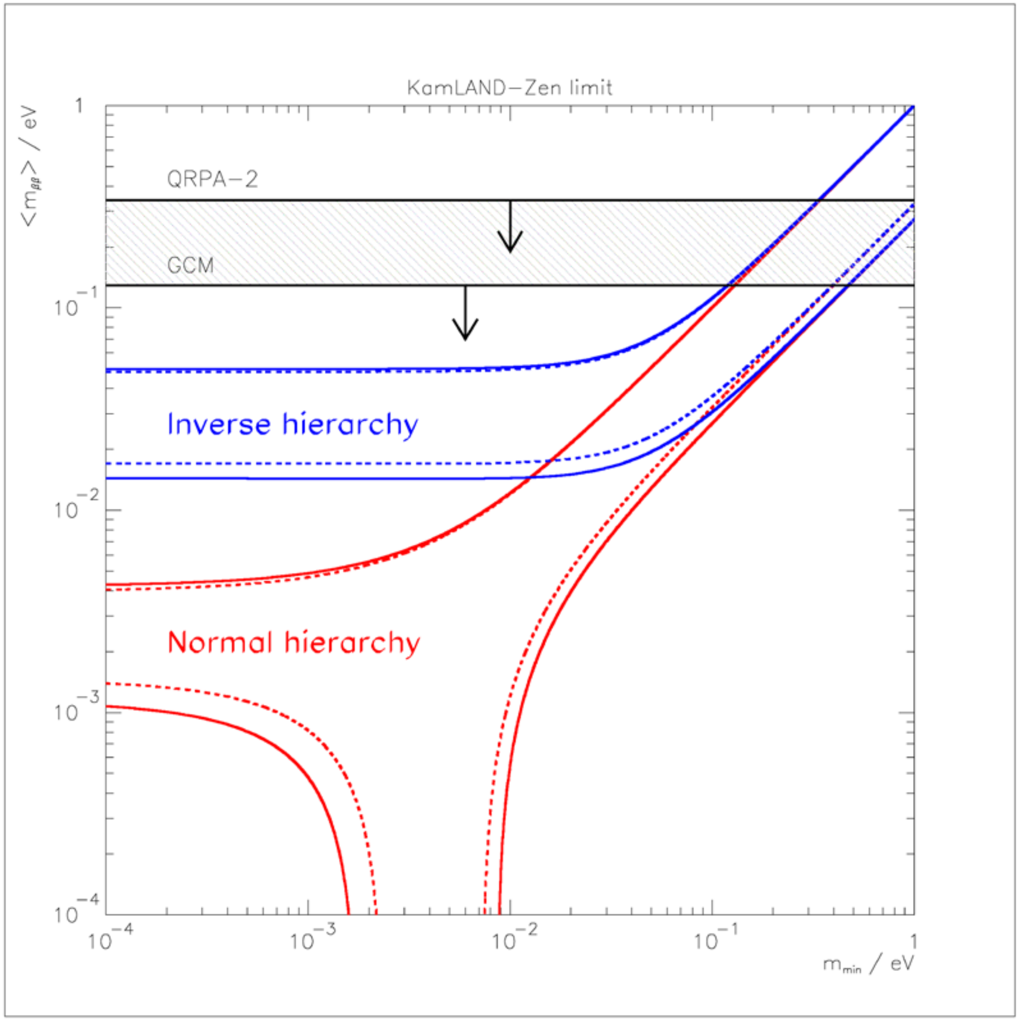



Current Majorana $\nu$–mass limits published by EXO-200 and KamLAND-Zen.

The degenerate mass space is being covered.



3-flavor analysis D.V. Forero et al. arXiv:1205.4018v4




Current Majorana ν–mass limits published by EXO-200 and KamLAND-Zen.

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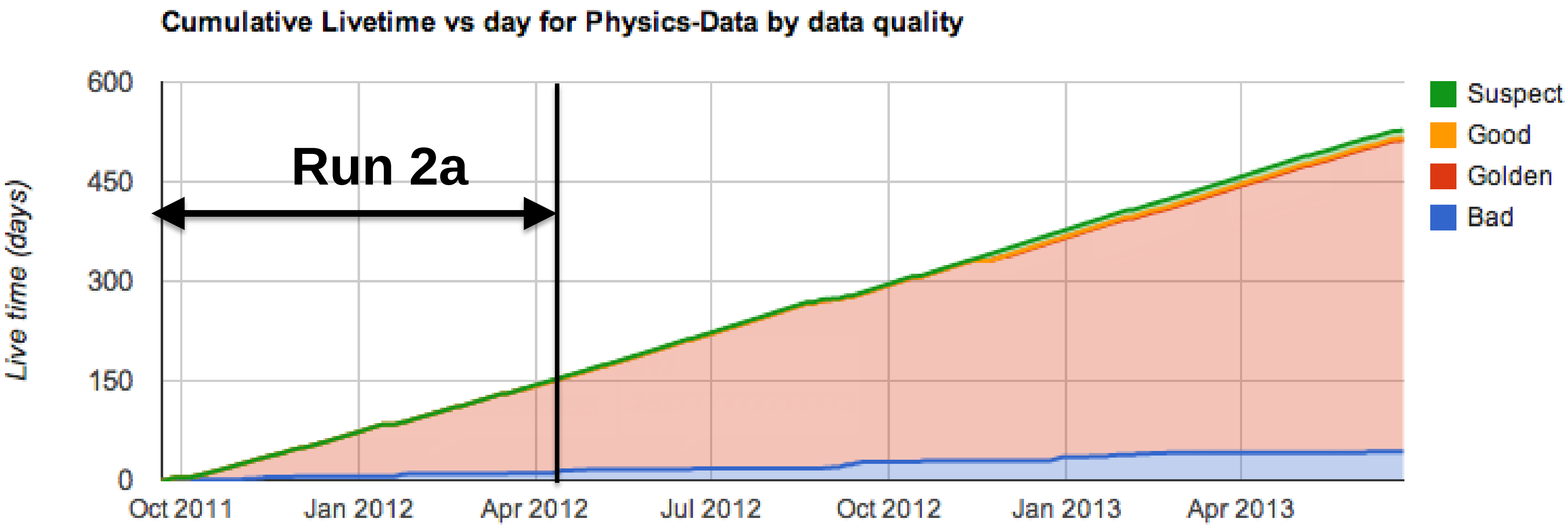
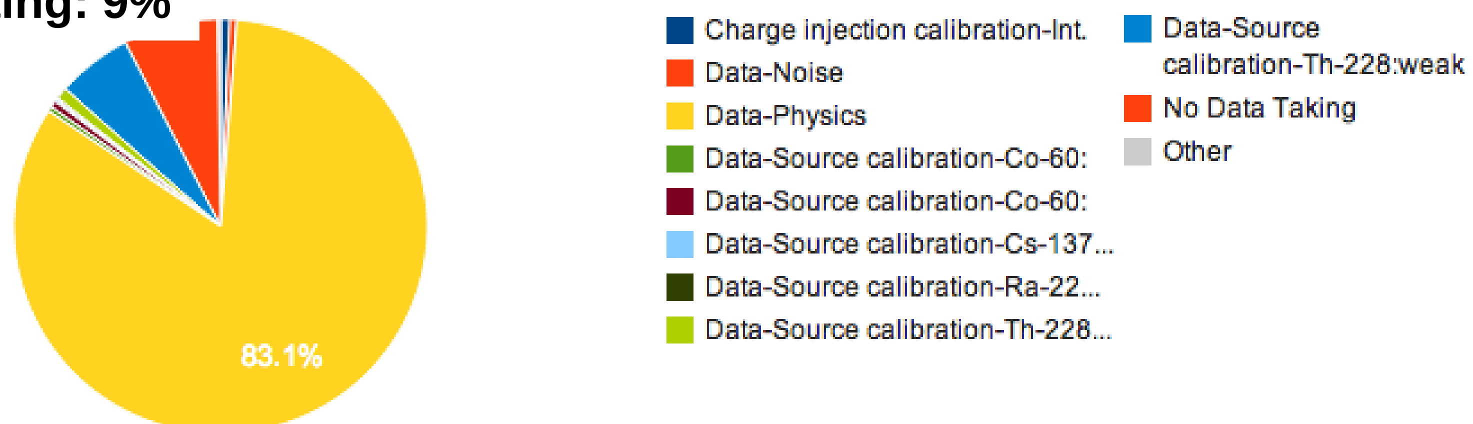
3-flavor analysis D.V. Forero et al. arXiv:1205.4018v4

# Run 2




**All data collection: 92%**
**Physics Data: 83.1%**
**Calibrations/testing: 9%**



As this is a school: how to relate a $^{136}$Xe limit into one for $^{76}$Ge decay, or in other words what does have EXO-200 to say about the $^{76}$Ge evidence?

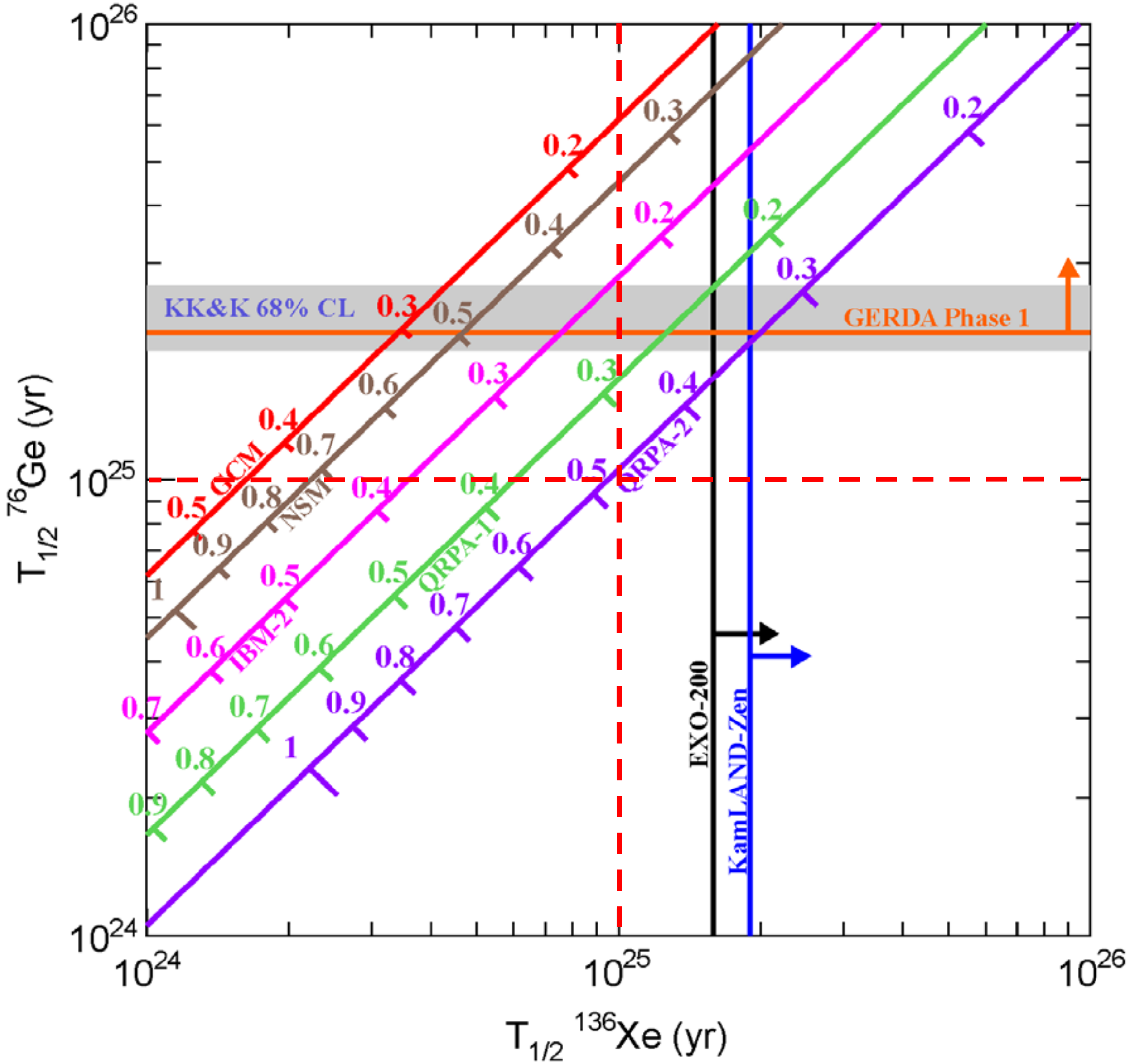
Assume the decay is mediated by exchange of light Majorana neutrinos. Both have $\langle m_{\beta\beta}\rangle$ in common.

$$G^{0\nu}_{Xe}\cdot\left|M^{0\nu}_{Xe}\right|^2\cdot T^{0\nu}_{1/2,Xe}=\left\langle m_{\beta\beta}\right\rangle^{-2}=G^{0\nu}_{Ge}\cdot\left|M^{0\nu}_{Ge}\right|^2\cdot T^{0\nu}_{1/2,Ge}$$

$$T^{0\nu}_{1/2,Xe}=\frac{G^{0\nu}_{Ge}\cdot\left|M^{0\nu}_{Ge}\right|^2}{G^{0\nu}_{Xe}\cdot\left|M^{0\nu}_{Xe}\right|^2}\cdot T^{0\nu}_{1/2,Ge}$$

$$\ln\left(T^{0\nu}_{1/2,Xe}\right)=\ln\left(T^{0\nu}_{1/2,Ge}\right)+\ln\left(\frac{G^{0\nu}_{Ge}\cdot\left|M^{0\nu}_{Ge}\right|^2}{G^{0\nu}_{Xe}\cdot\left|M^{0\nu}_{Xe}\right|^2}\right)$$

Note: $\frac{G^{0\nu}_{Xe}}{G^{0\nu}_{Ge}}=6.17$ $\quad\frac{\left|M^{0\nu}_{Ge}\right|^2}{\left|M^{0\nu}_{Xe}\right|^2}=0.15\ldots0.83$




Using different nuclear matrix elements the absence of a 0νββ-peak in EXO-200 is compared to the evidence published for $^{76}$Ge.

For most matrix element calculations there is tension between these new experiments and the 0νββ-evidence.



H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547.

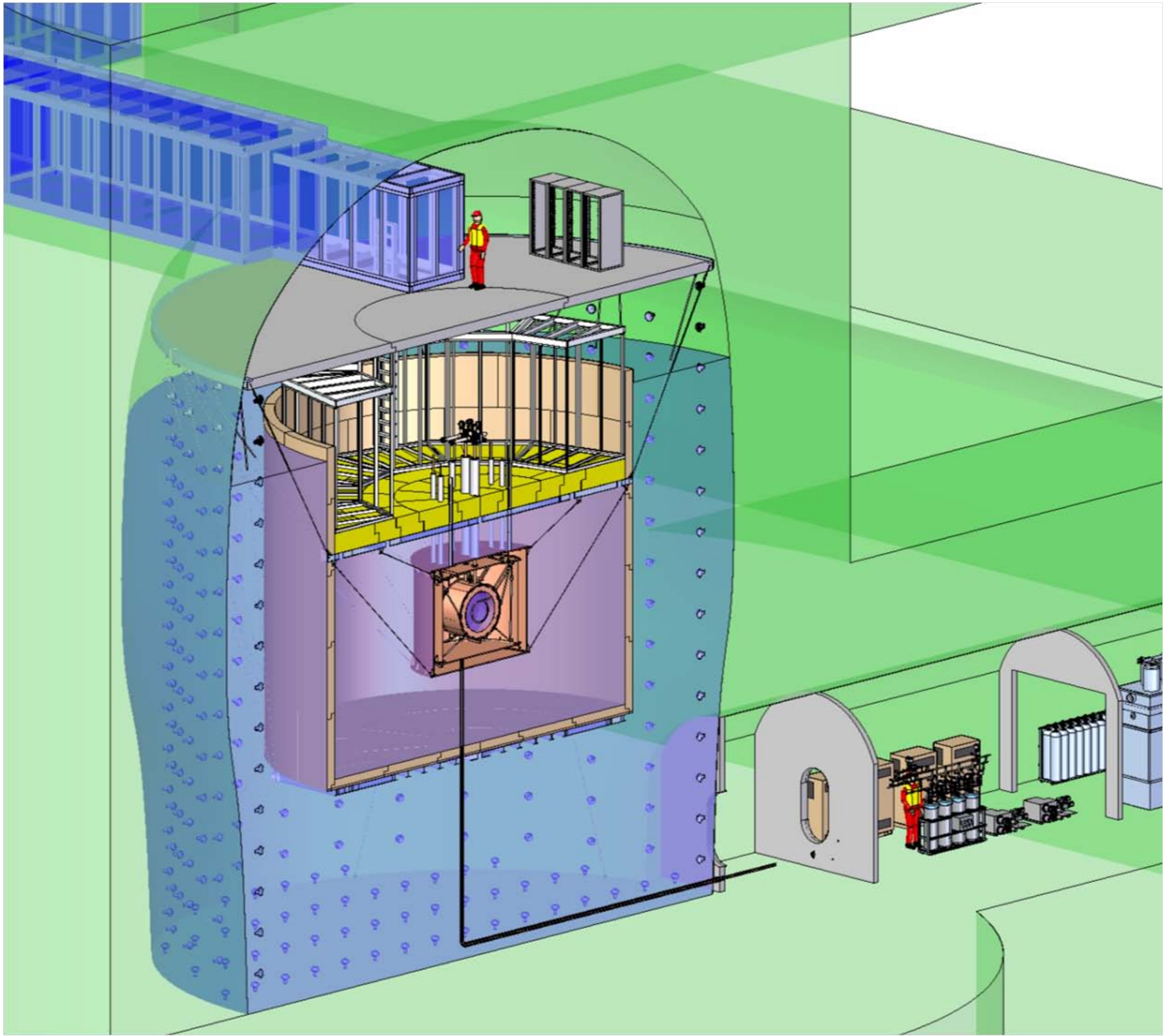
# The future

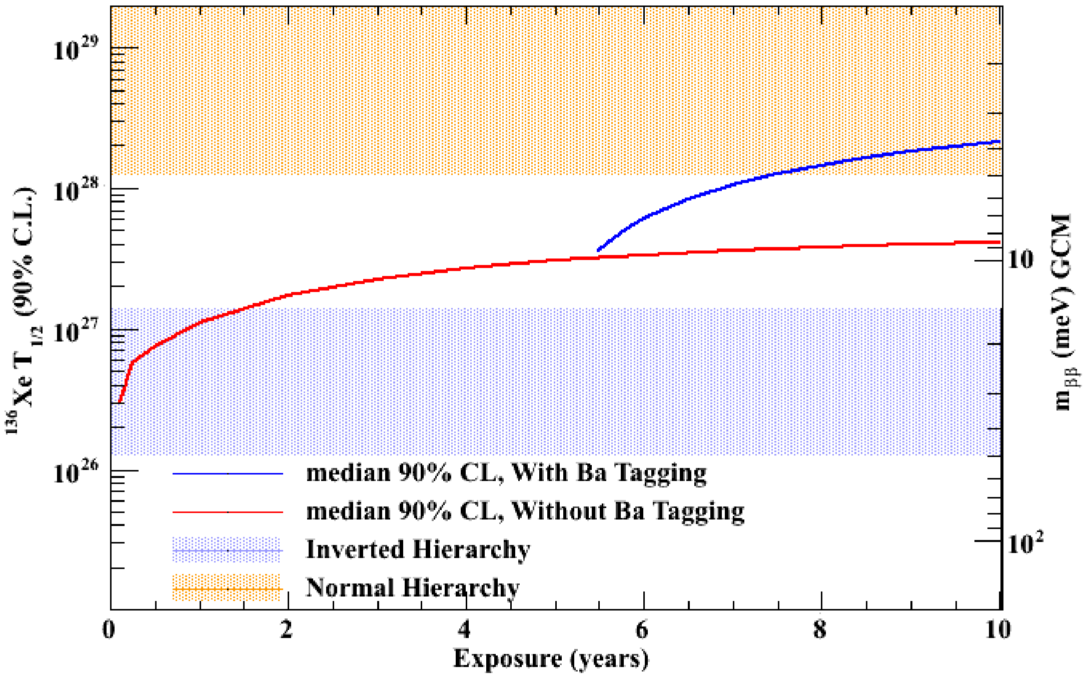
- Funded to run until the end of 2014.
- Considering an electronic upgrade to improve the energy resolution and to install a Rn removal device to reduce the background by perhaps a factor 2. Run till end of 2016.
- Improve (90% CL) $0\nu\beta\beta$-half life sensitivity to (3-5.5)  $10^{25}$ yr. Discover the decay should it be there.
- Corresponding Majorana neutrino mass range: $<m_{\beta\beta}> < 75$-270 meV, cover degenerate neutrino mass range.
- Demonstrate the technology for a next generation experiment. $\rightarrow$ nEXO

- EXO-200 the collaboration started to study the case for a 5 ton (~4.5 ton fiducial) Xe experiment, *initially* without Ba- tagging. Tagging should remain an option, you could consider it a (background) risk mitigation tool.
- Assume:
  - 4.5 tons of active $^{enr}$Xe (80% or higher).
  - 1.5% (σ) energy resolution.
  - Background from Monte Carlo using normalizations derived from EXO-200 data and materials assay.
  - 3 times finer wire pitch than EXO-200, lower energy threshold → 2 times better e-γ discrimination than EXO-200.

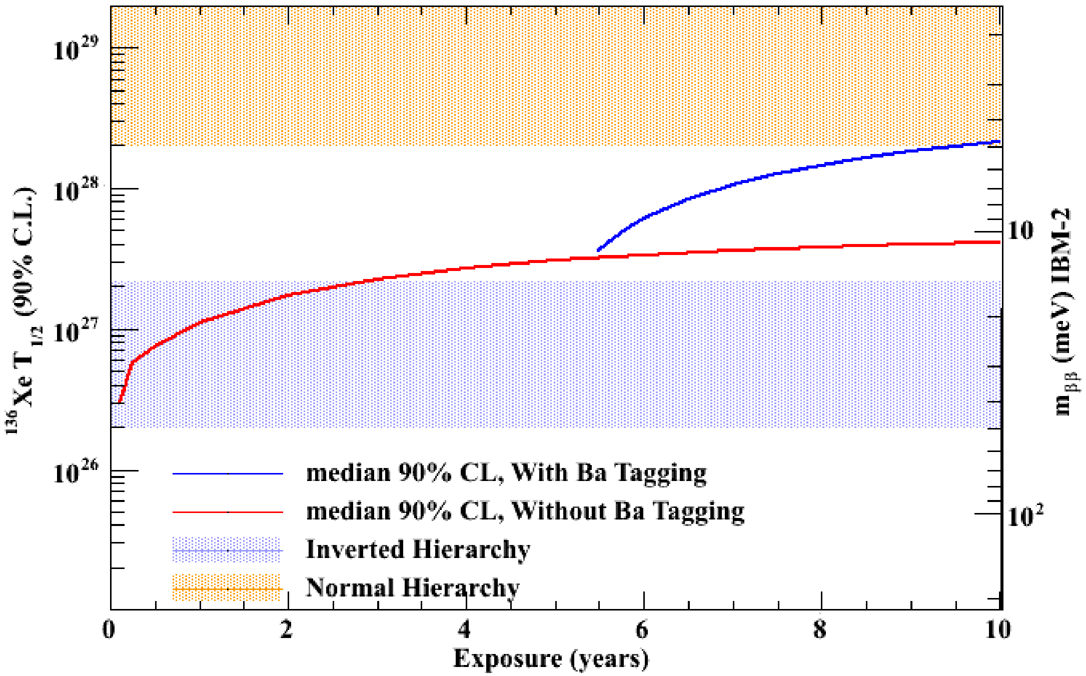
We call this nEXO.

At the end: how such a detector, installed in SNOLab's cryopit may look like.

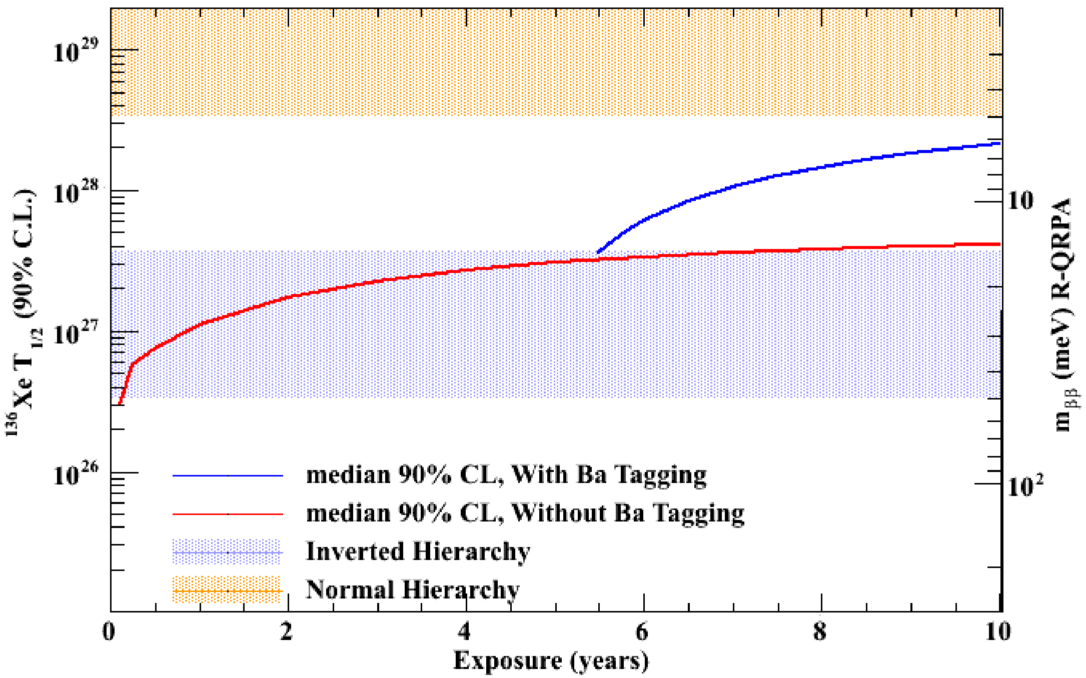


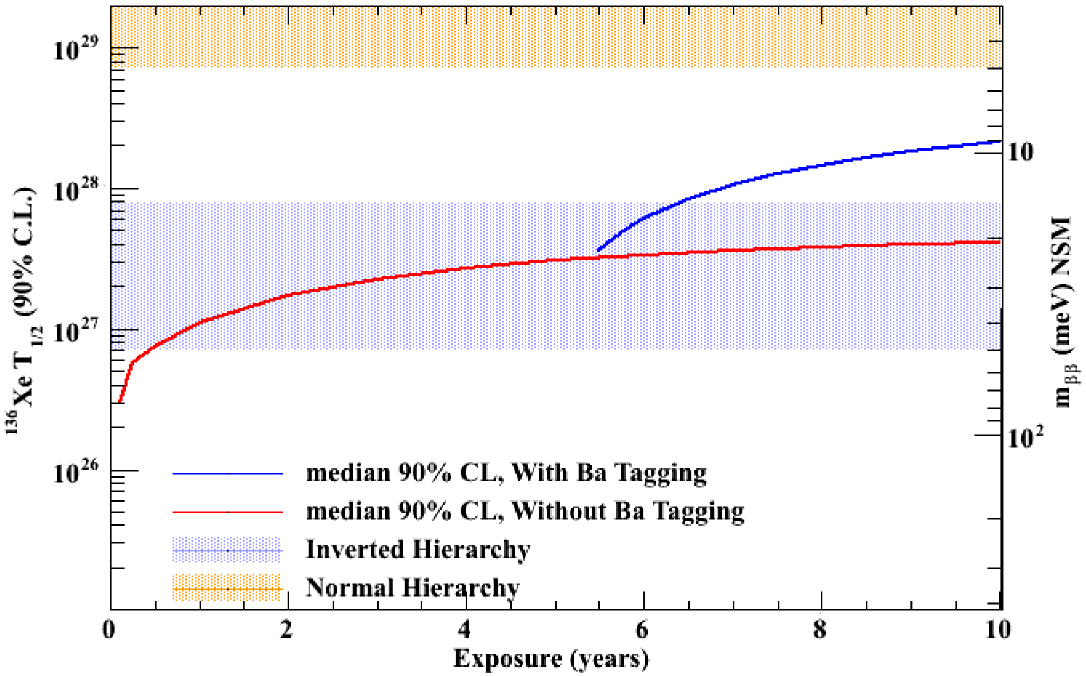


$10^{29}$
$10^{28}$
$10^{27}$
$10^{26}$
$^{136}$Xe $T_{1/2}$ (90% C.L.)
10
$10^2$
$m_{\beta\beta}$ (meV) GCM
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)



$10^{29}$
$10^{28}$
$10^{27}$
$10^{26}$
$^{136}$Xe T $_{1/2}$ (90% C.L.)
10
$10^{2}$
$m_{\beta\beta}$ (meV) IBM-2
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)


$10^{29}$
$10^{28}$
$10^{27}$
$10^{26}$
$^{136}$Xe T$_{1/2}$ (90% C.L.)
10
$10^2$
$m_{\beta\beta}$ (meV) R-QRPA
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)


$10^{29}$
$10^{28}$
$10^{27}$
$10^{26}$
$^{136}$Xe T $_{1/2}$ (90% C.L.)
10
$10^{2}$
$m_{\beta\beta}$ (meV) NSM
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)

# Conclusion

EXO-200 is taking low background data since 2011.

Couples extremely low background with good scalability.

No evidence for neutrinoless double beta decay of $^{136}Xe$. One of the most restrictive bounds on Majorana neutrino mass, tension with the Ge evidence.

3.6 times the data under analysis.

The EXO collaboration is an experienced team. We are exploring the reach of a scaled up/improved device initially based on EXO-200 technology. This could cover the inverse hierarchy.

# The EXO Collaboration

Enriched Xenon Observatory
EXO
for double beta decay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