Double beta decay and EXO-200

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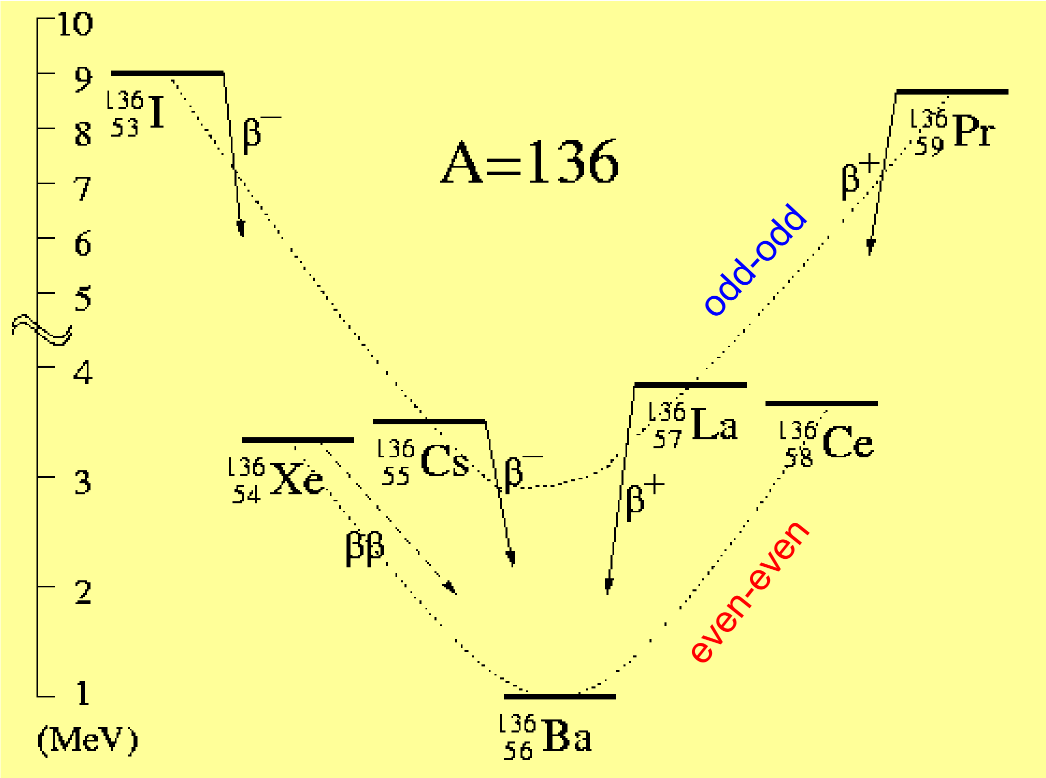
Double beta decay



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

Observable for those nuclides were single β-decay is energetically forbidden or highly suppressed by a large angular momentum difference.

Can happen in different ways. Here two popular cases.

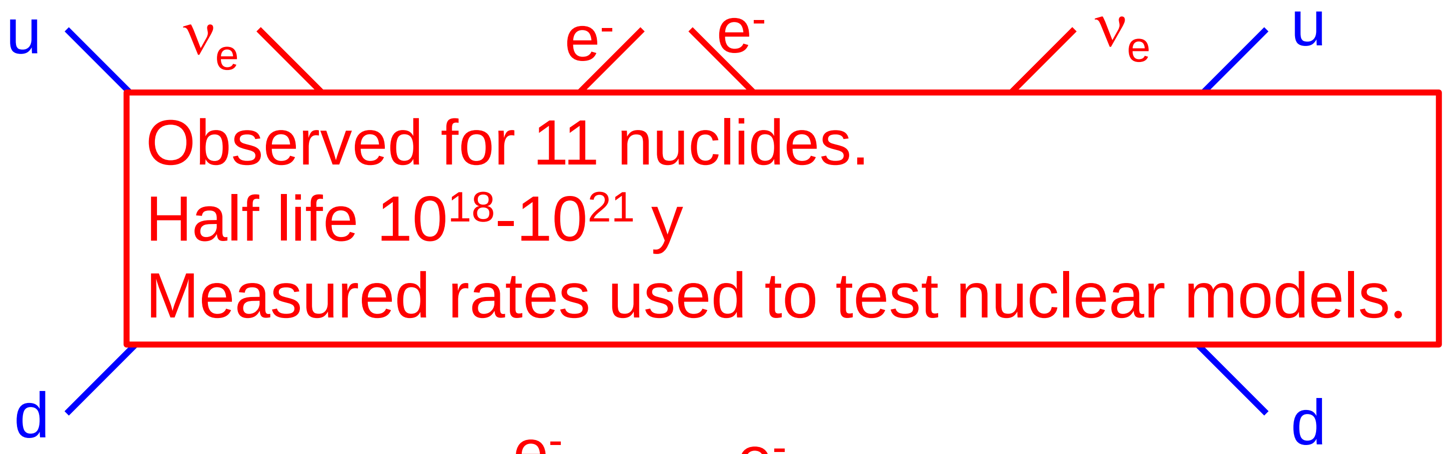
B	L
1/3	0

$\Delta B=0$

$\Delta L=0$

$\Delta(B-L)=0$

1/3	0



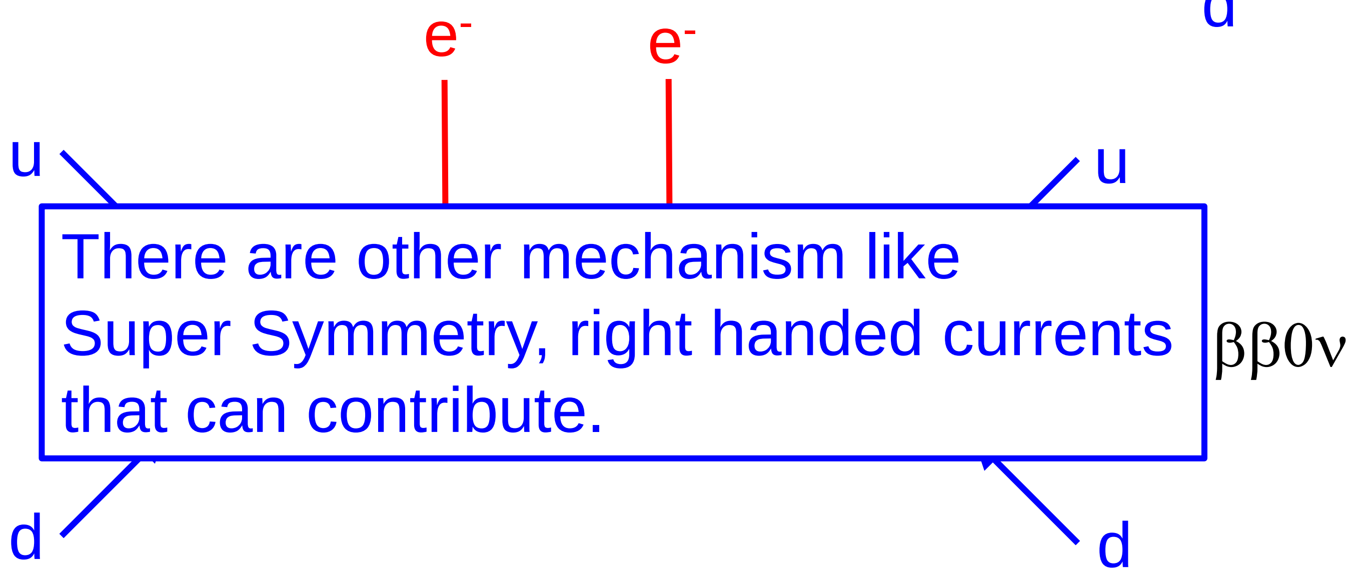
B	L
1/3	2

$\Delta B=0$

$\Delta L=2$

$\Delta(B-L)=-2$

1/3	0



B: Baryon Number
L: Lepton Number

Focus on light neutrino exchange $0\nu\beta\beta$ mode

Decay rate is given by the golden rule and depends on an effective Majorana mass. It 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

Matrix element

$$\langle m_{\beta\beta} \rangle^2 = \left| \sum_{i=1}^{3} \eta_i \cdot U_{ei}^2 \cdot m_i \right|^2$$

CP-phases: 1

Elements upper row of MNS-matrix

Neutrino masses

CP-phases can lead to cancellation. But how much? Replace masses by two possible choices of minimal mass m_1 or m_3 and add knowledge of mixing and mass splitting from oscillations.

EXO-200

Observation of neutrinoless double beta decay would reveal a novel aspect of matter: neutrinos are Majorana particles.

The problem: oscillation data suggests half lives of ~10^{28} y even for the inverted mass scenario, a tough challenge.

A variety of new experiments is being prepared to answer this challenge, optimized for various aspects of sensitivity.

EXO-200:

- Use isotopically enriched Xe to maximize source strength and minimize target towards background causing radiation.
- Active background tagging through tracking plus careful material selection and screening.
- Improve energy resolution by simultaneous readout of ionization and scintillation.

EXO detection strategy

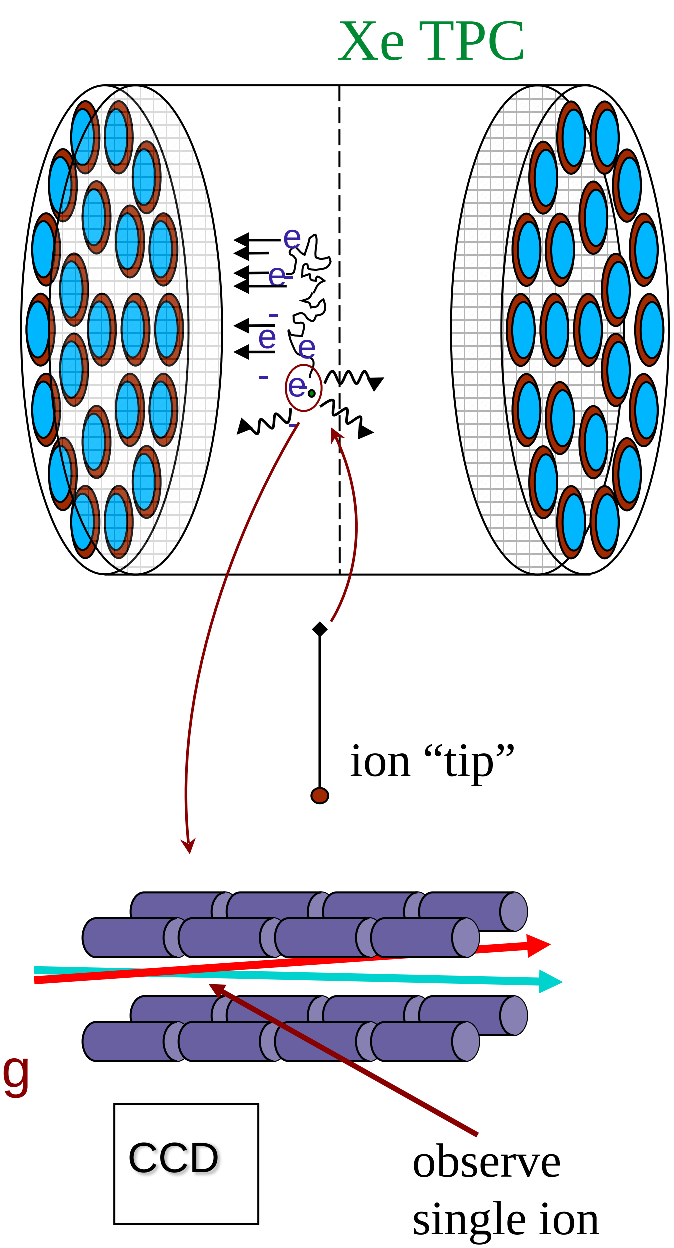
detect the 2 electrons
(ionization + scintillation in xenon detector)

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

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



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

The TPC

• Cylindrical Cu vessel (1.37 mm wall thickness), 110 kg of liquid Xenon (enriched to 80.6% ^{136}Xe) in active volume. 175 kg Xe are in liquid phase.

• Charge and scintillation light readout by two identical halves.

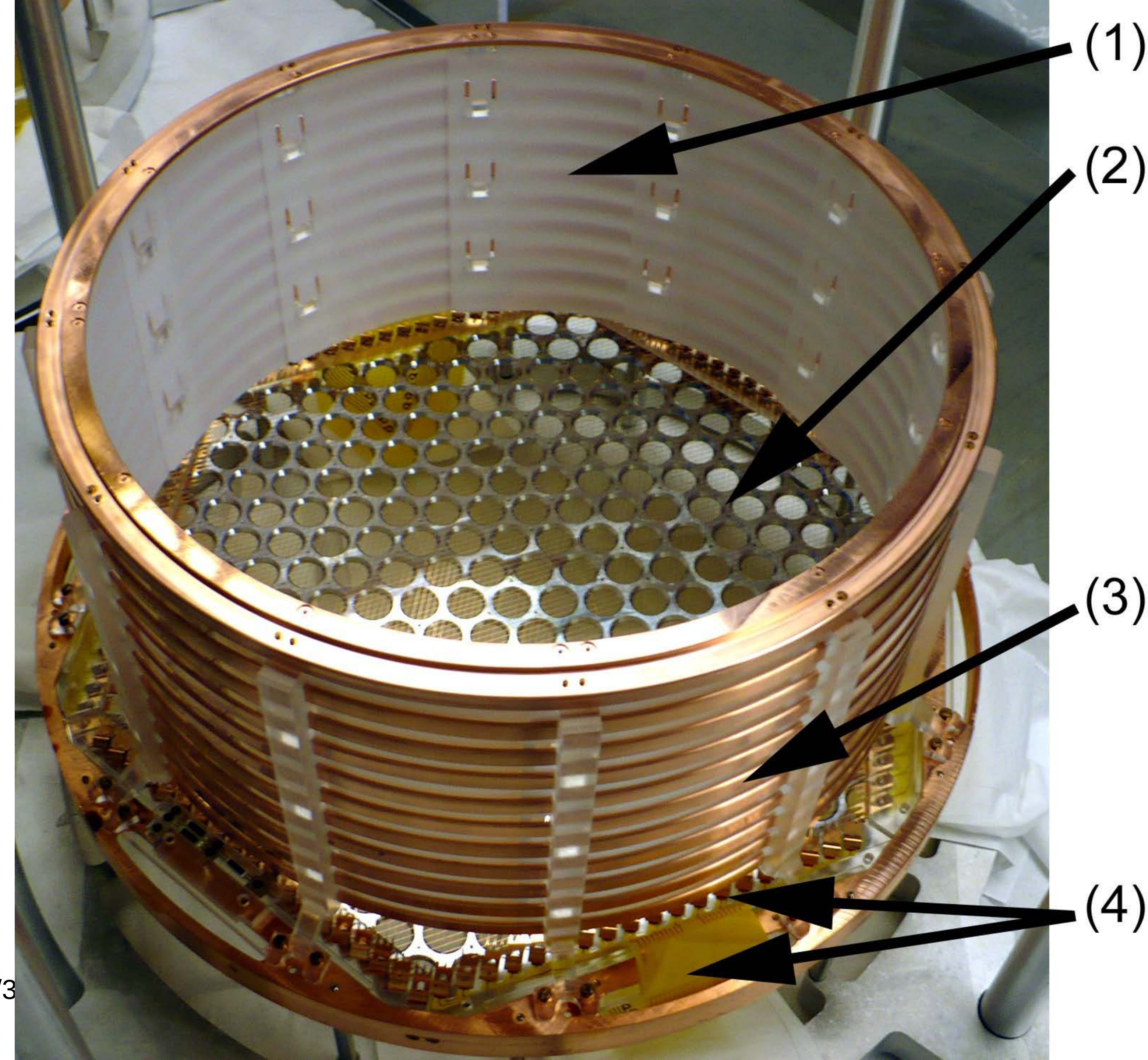
• HV cathode in the middle. Charge collected by 38 triplet u-wires. Inductive reconstruction of 2nd event coordinate by 38 triplet v-wires (both 9 mm pitch). Maximal charge drift distance 19.2 cm. Drift field 376 V/cm. Max. e-drift time ~100 μs.

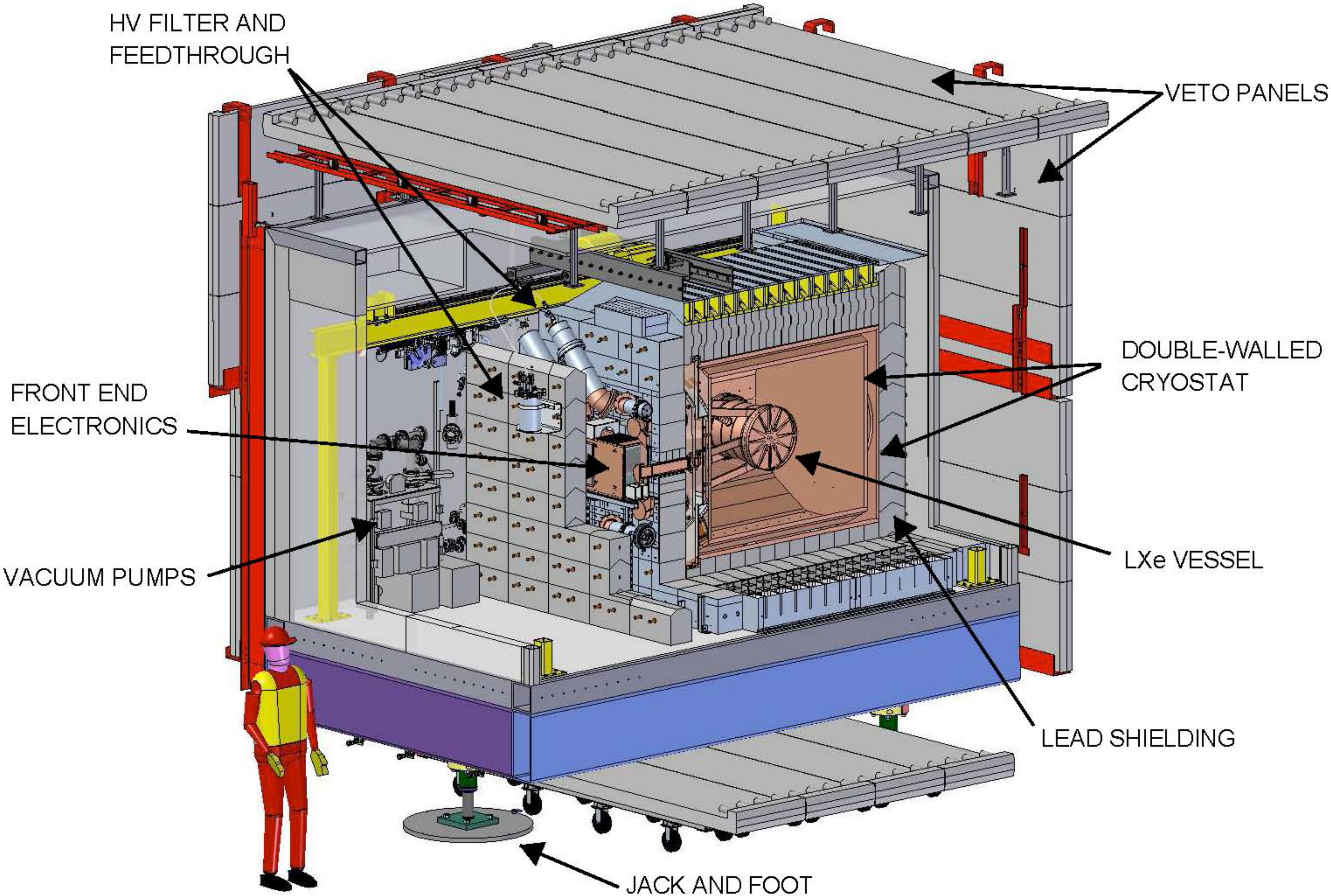
• Light read-out via 234 large area avalanche photodiodes per side, ganged into groups of 7.

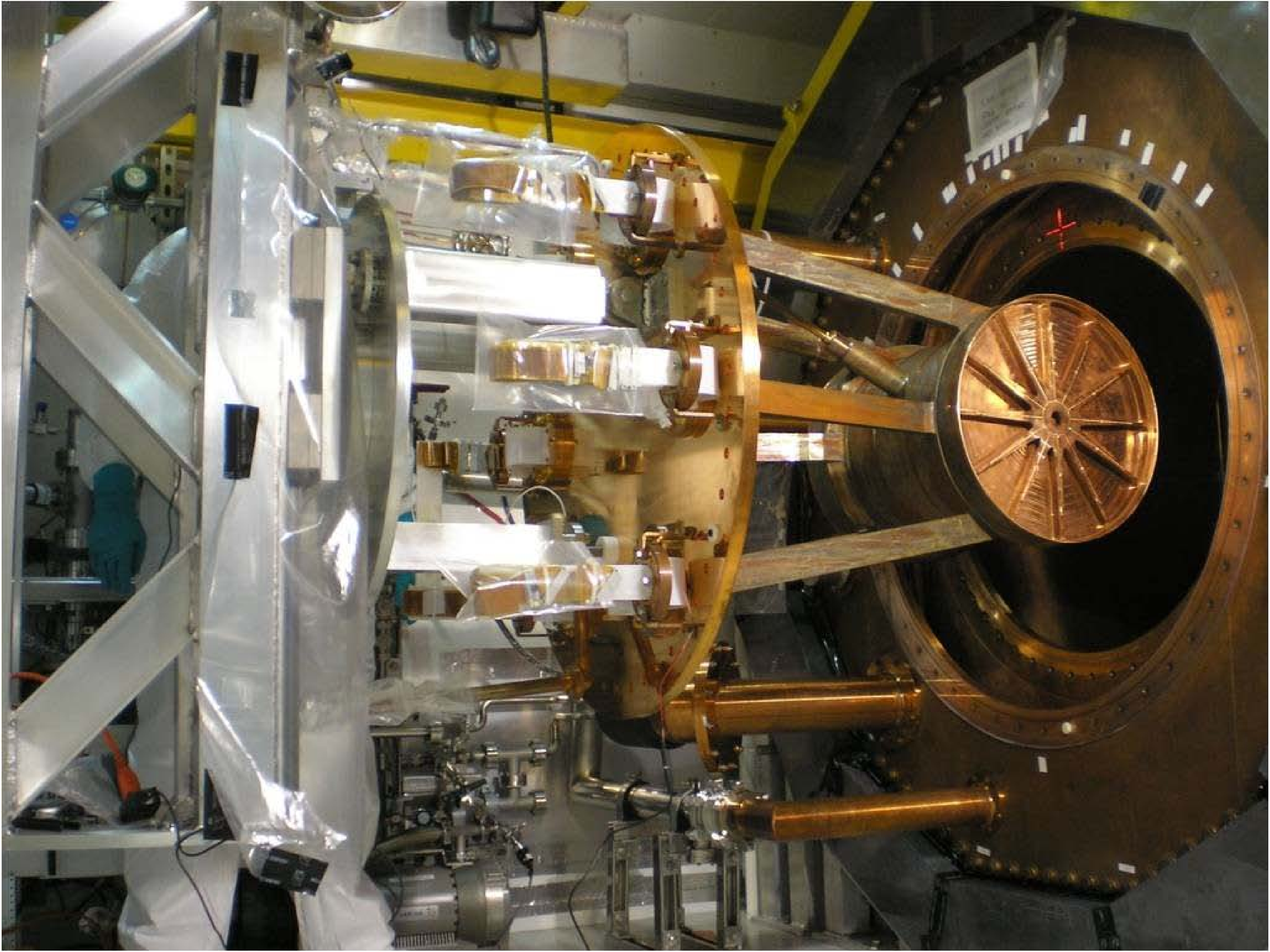
• Light reflectors/diffusers: Teflon.

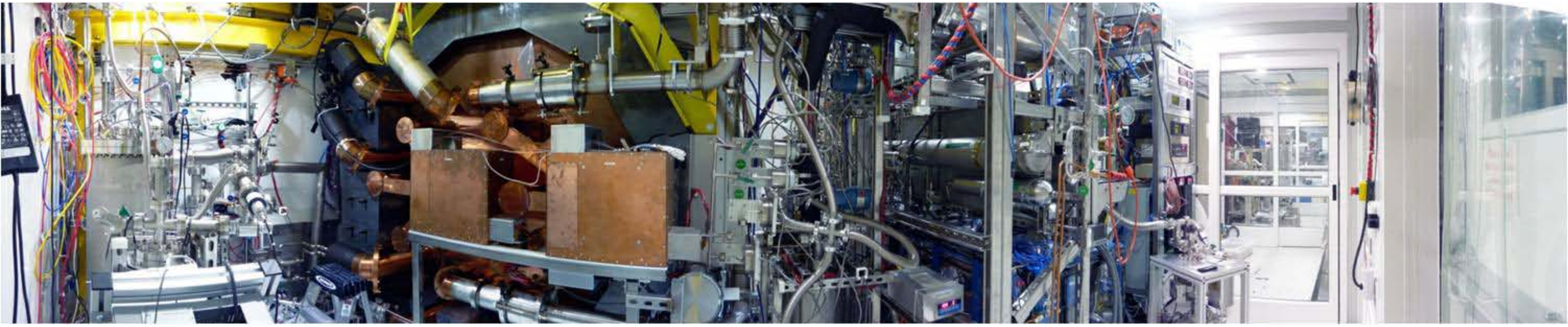
→ This design allows full 3-dim event reconstruction.

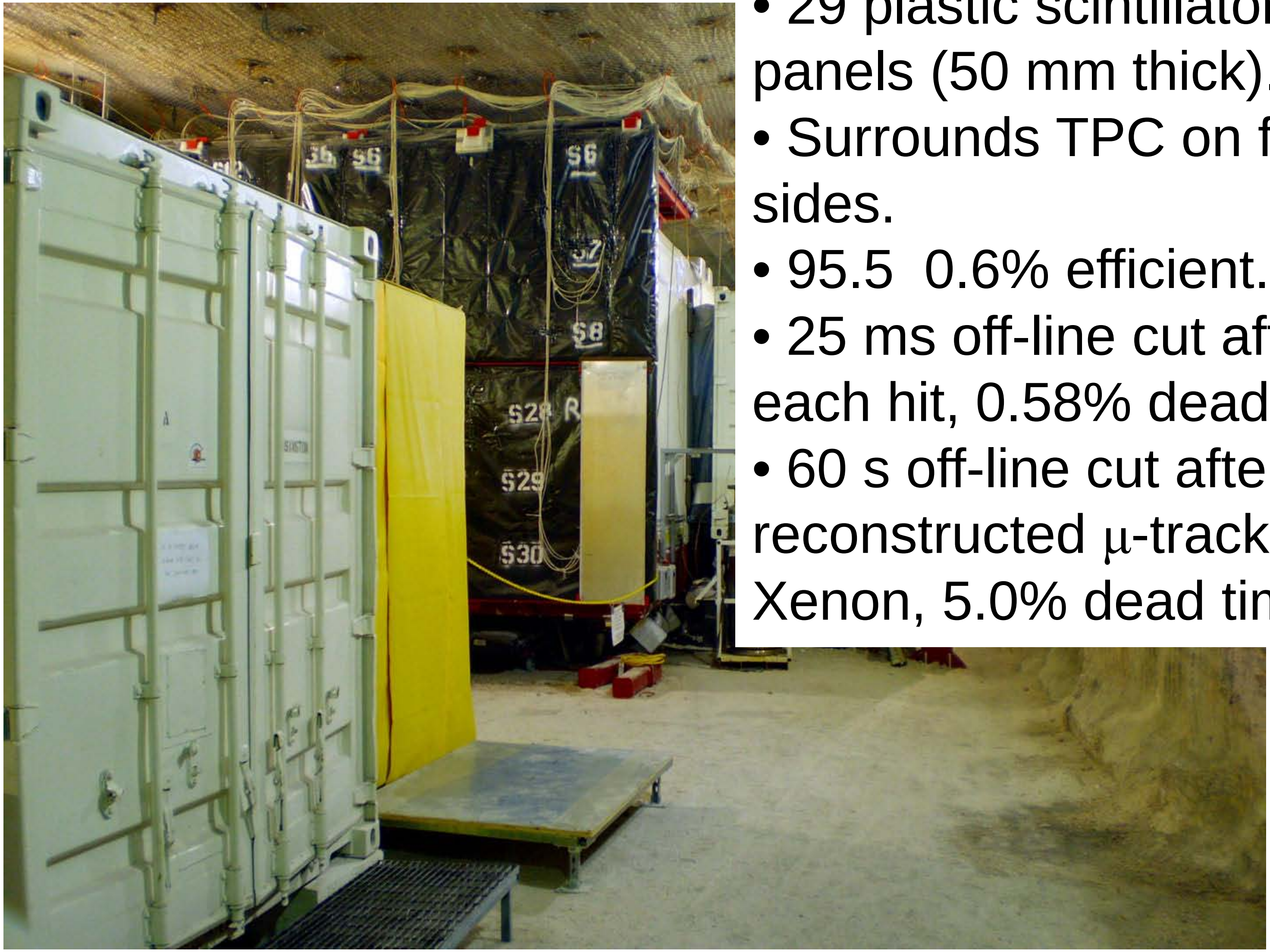
- All signals digitized at 1Ms/s,   1024 s around any trigger.
- All detector components were screened for their radioactivity content. Depending on location Th/U sensitivities of ppt or below were required. Tools: gamma spectroscopy, mass spectroscopy, neutron activation analysis, alpha spectroscopy.
- Materials analysis program guided by detector simulation. Design goal was a background rate (2 σ energy interval around $Q_{\beta\beta}$=2457.83 0.37 keV) of 20 cnts/yr in 140 kg Xe.
- For acceptance decisions large components were given 10% allotment, small components 1% of background budget.


(1)
(2)
(3)
(4)


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





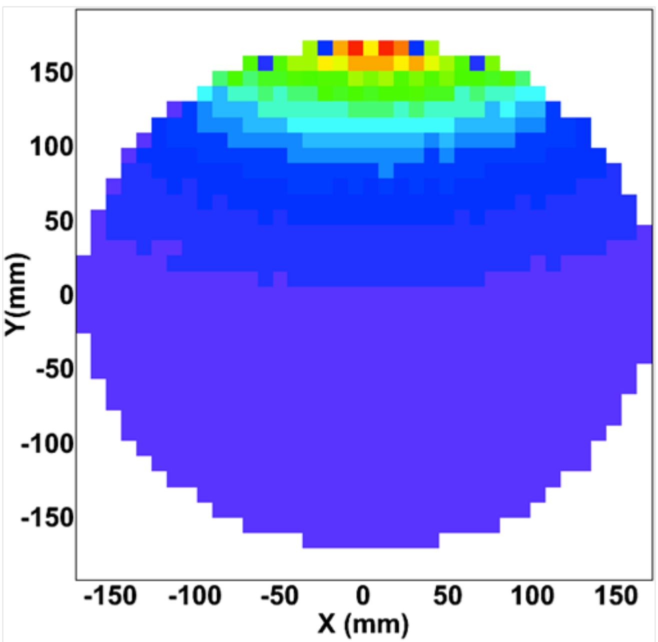


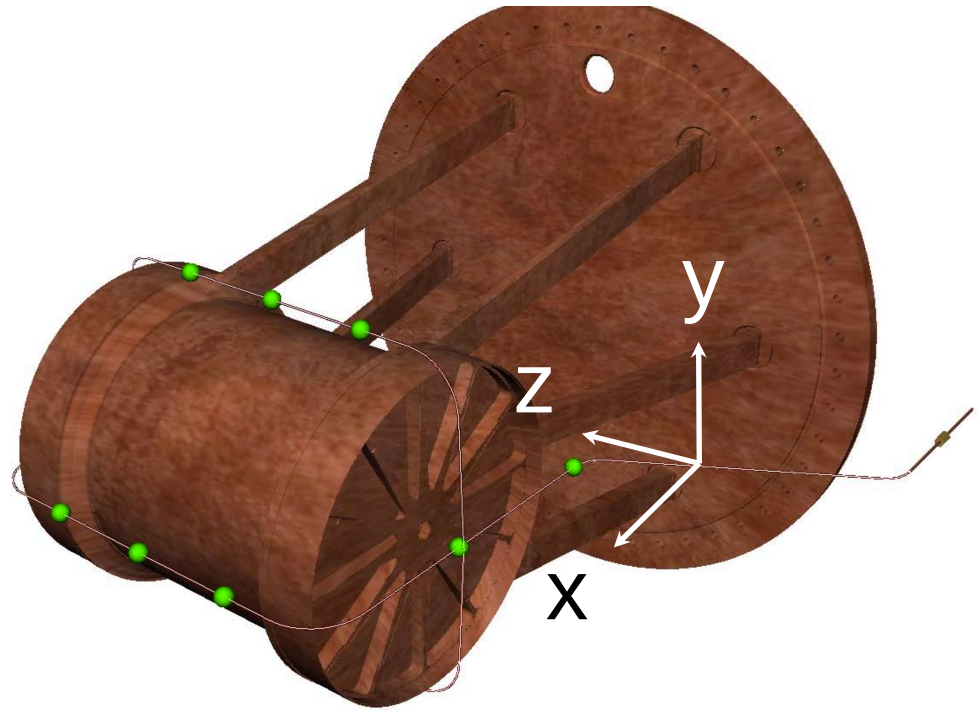
- 29 plastic scintillator veto panels (50 mm thick).
- Surrounds TPC on four sides.
- 95.5 0.6% efficient.
- 25 ms off-line cut after each hit, 0.58% dead time.
- 60 s off-line cut after each reconstructed μ-track in Xenon, 5.0% dead time.

How does EXO-200 perform?

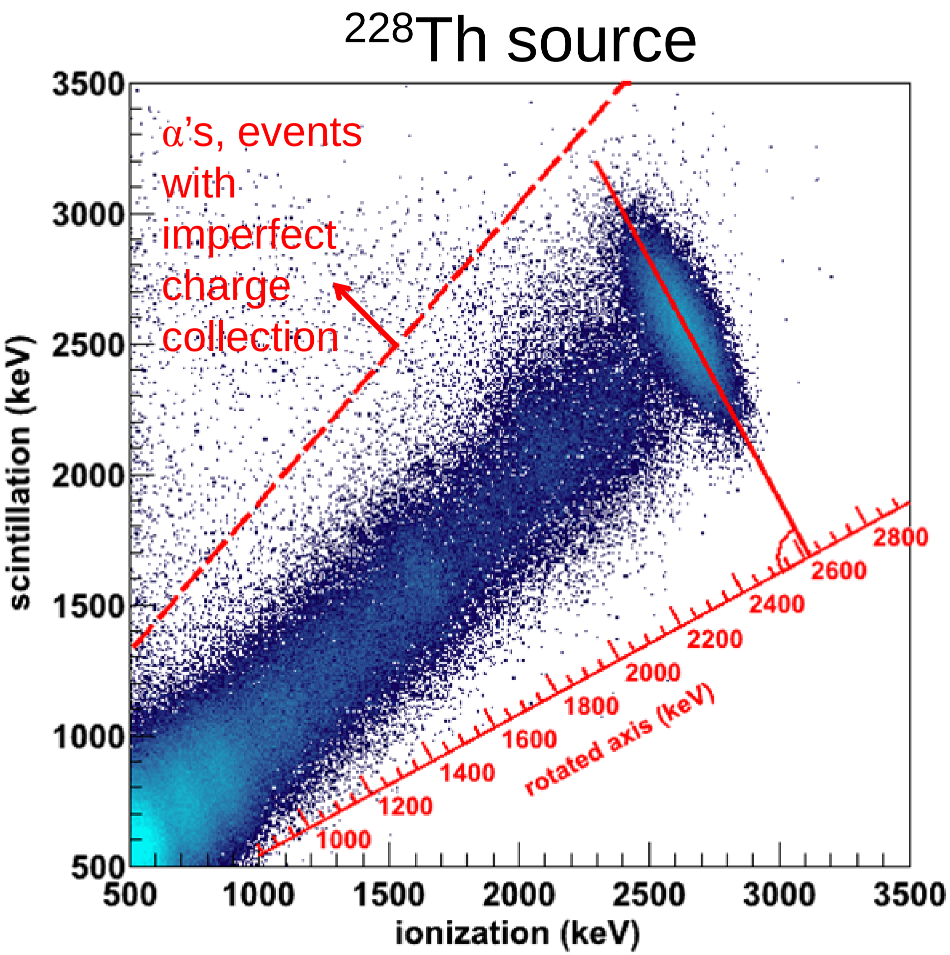
- Signal finding – matched filters applied on U, V and APDs waveforms
- Signal parameter estimation (t, E) for charge and light
- Cluster finding – assignment to Single Site (SS) or Multiple Site (MS): resolution 18mm in X and Y and 6 mm in Z
- Amplitudes corrected by channel for gain variation
- Require events to be fully reconstructed in 3D
- Reconstruction efficiency for 0νββ is 71% – estimated by MC and verified by comparing the 2νββ MC efficiency with low background data, over a broad range in energy

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

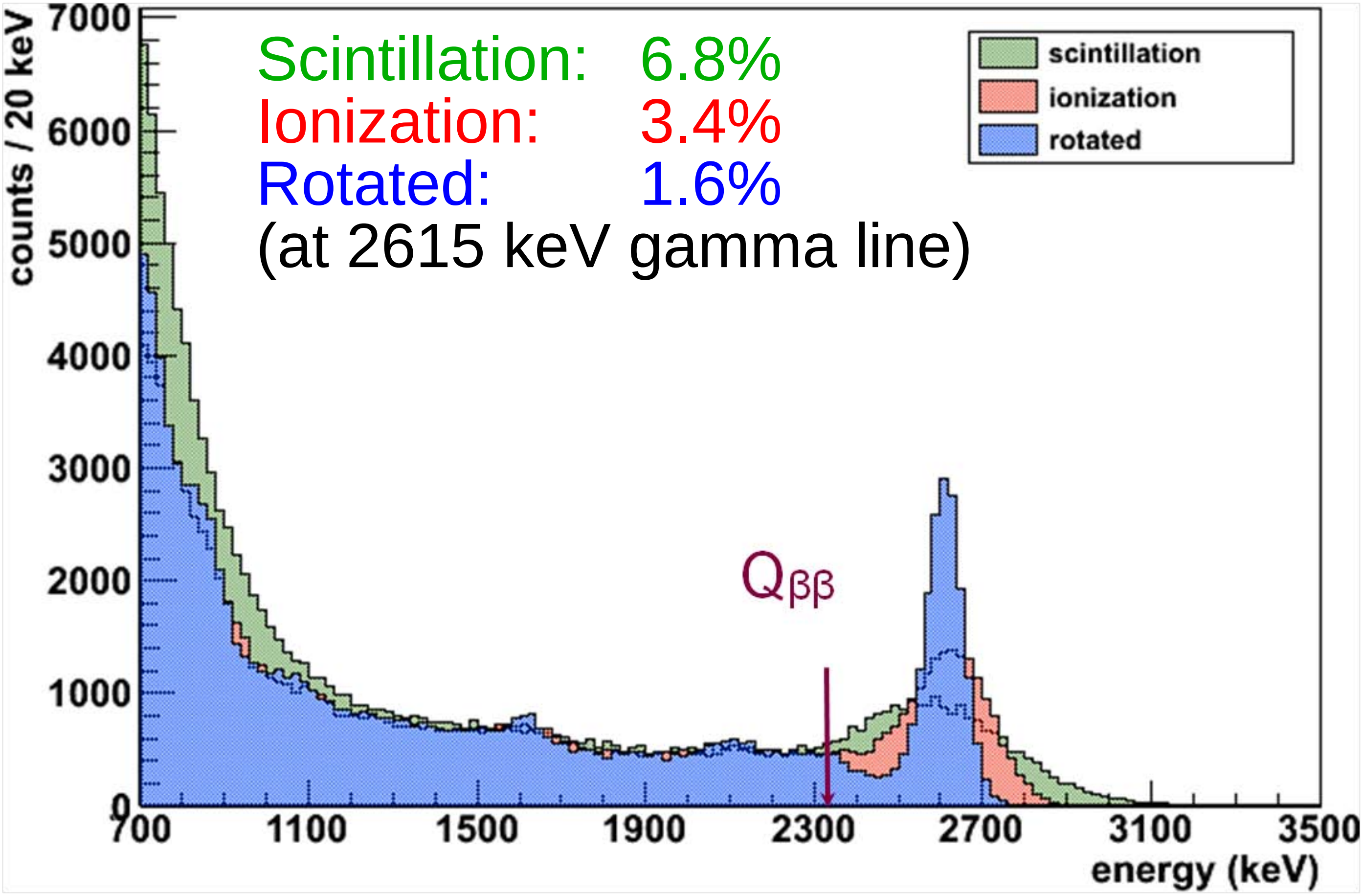




Combine ionization & scintillation

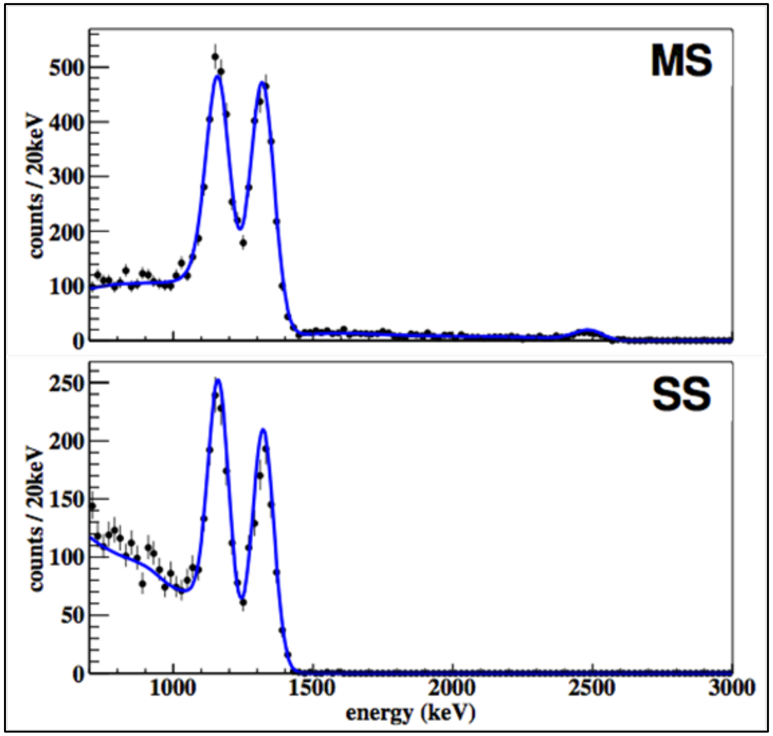


- Ionization and scintillation energies are anti-correlated.
- Energy measured along a rotated axis offers improved energy resolution.
- Rotation angle chosen to optimize resolution at 2615 keV.

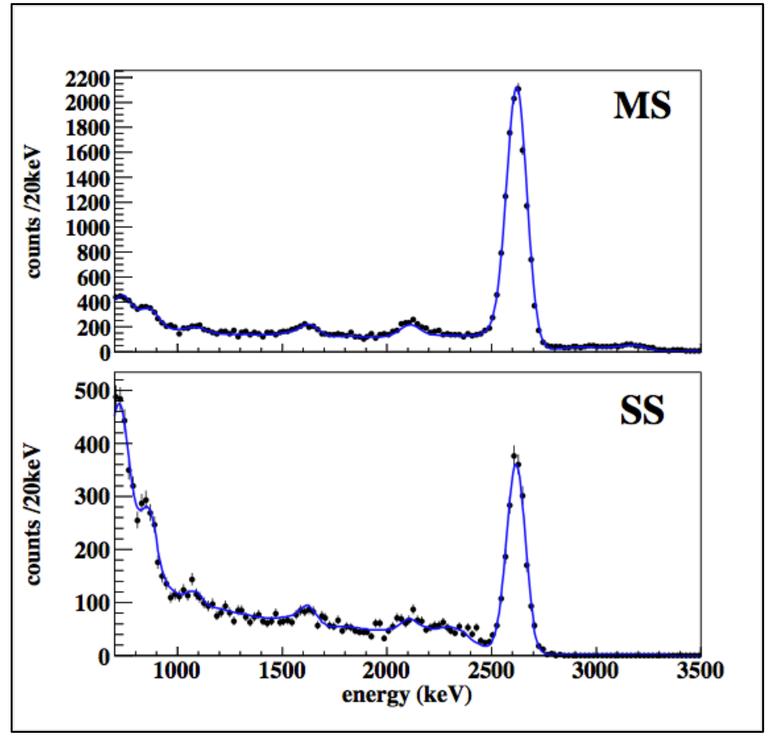


Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)
scintillation
ionization
rotated
counts / 20 keV
7000
6000
5000
4000
3000
2000
1000
0
700
1100
1500
1900
2300
2700
3100
3500
energy (keV)
$Q_{\beta\beta}$

^{60}Co



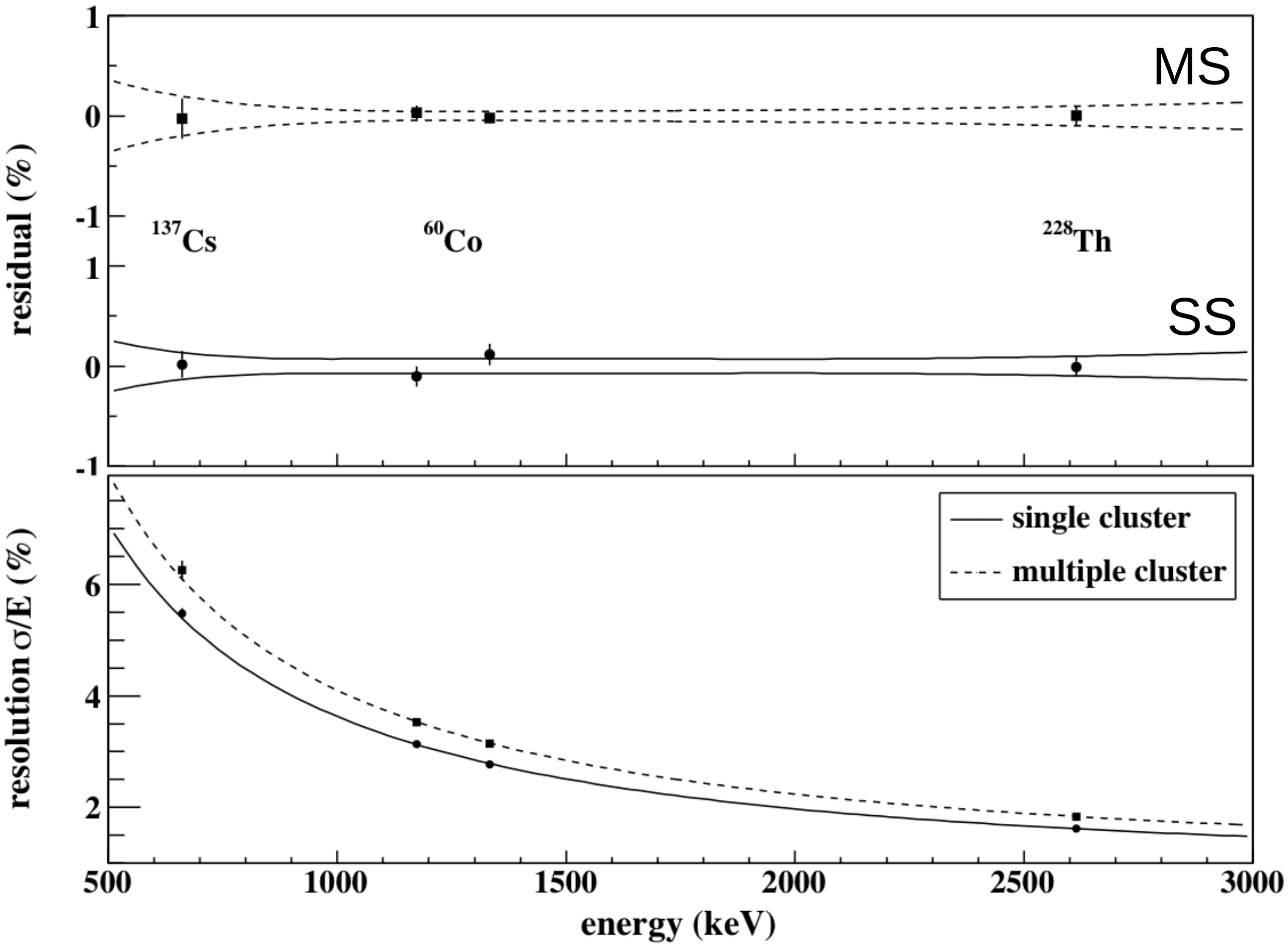
^{228}Th



MS and SS data (black) are compared to Monte Carlo (blue):

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

Calibration



Using quadratic model for energy calibration, single- and multi-site
residual are < 0.1%

Energy resolution model:

$$\sigma_{Tot}^2 = p_0^2 E + p_1^2 + p_2^2 E^2$$

Resolution dominated by constant (noise) term p_1

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

The 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 α's.

• Remove alpha-like events with high scintillation to ionization ratio and events with low charge.

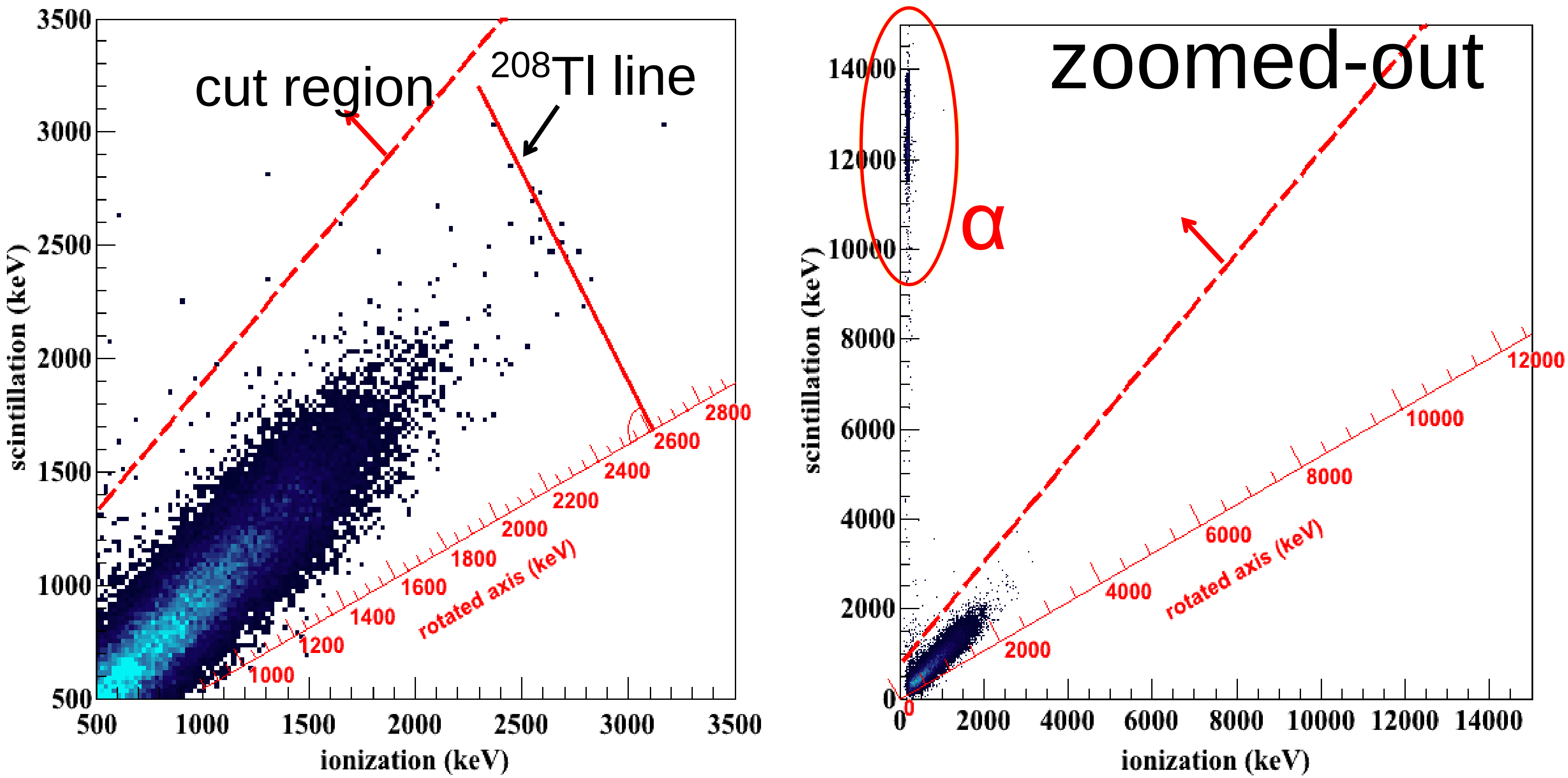
• Remove sequential events within 1 s of each other (3.3% dead time). Removes ^{214}Bi-^{214}Po delayed beta-alpha coincidences (Radon daughters).

• 98.5 kg enriched Xenon

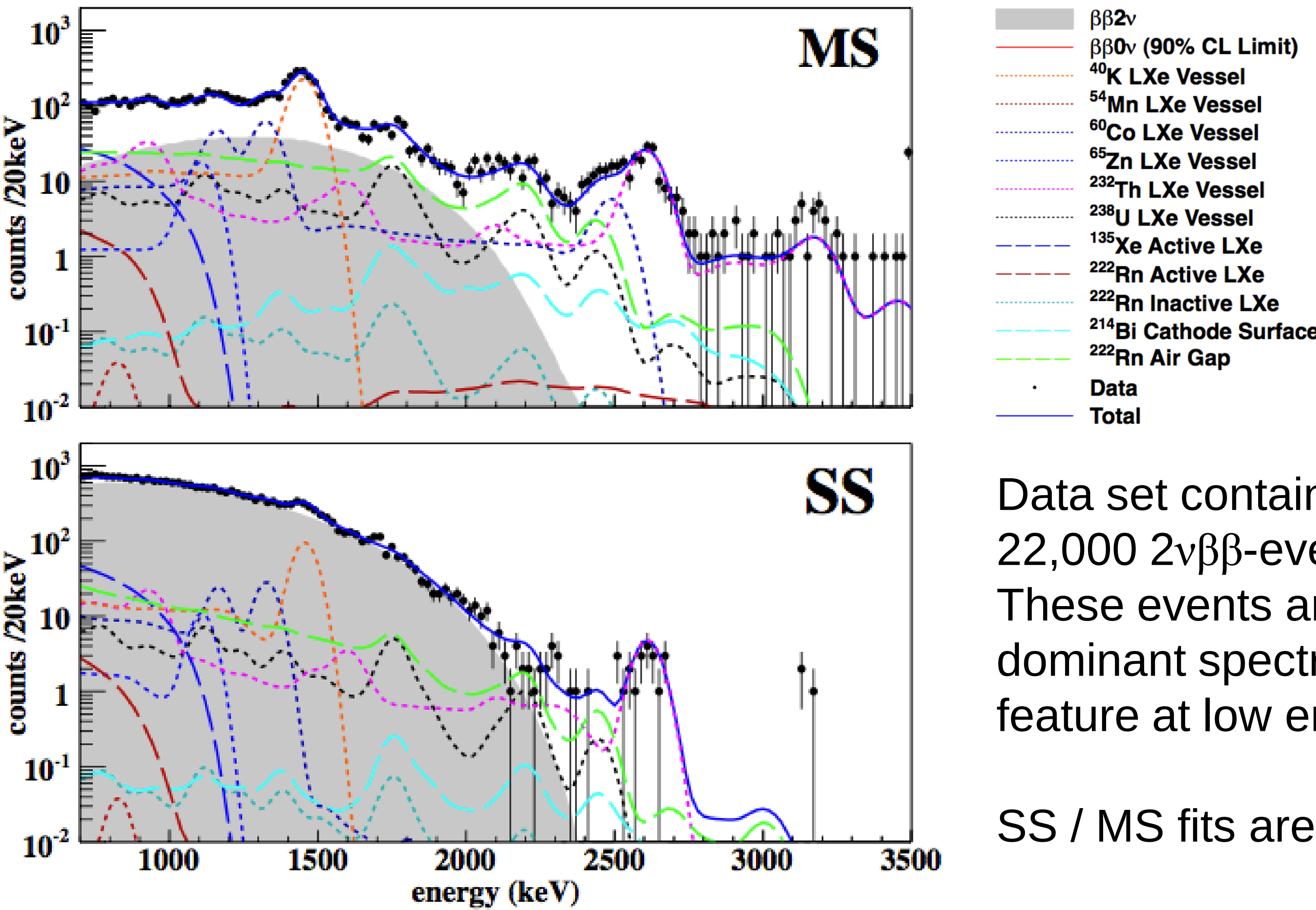
• 120.7 d life time (15.7 d calibration time)

→ Exposure: 32.6 kg·yr (compare to HD-Mo: 35.5 kg·yr)

• SS event reconstruction efficiency: 71%.



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



Data set contains about 22,000 2νββ-events. These events are the dominant spectral feature at low energies!

SS / MS fits are coupled.

$$T_{1/2}^{2\nu\beta\beta}\ (^{136}Xe) = (2.23 \pm 0.017^{stat} \pm 0.22^{sys})\cdot 10^{21}\ yr$$

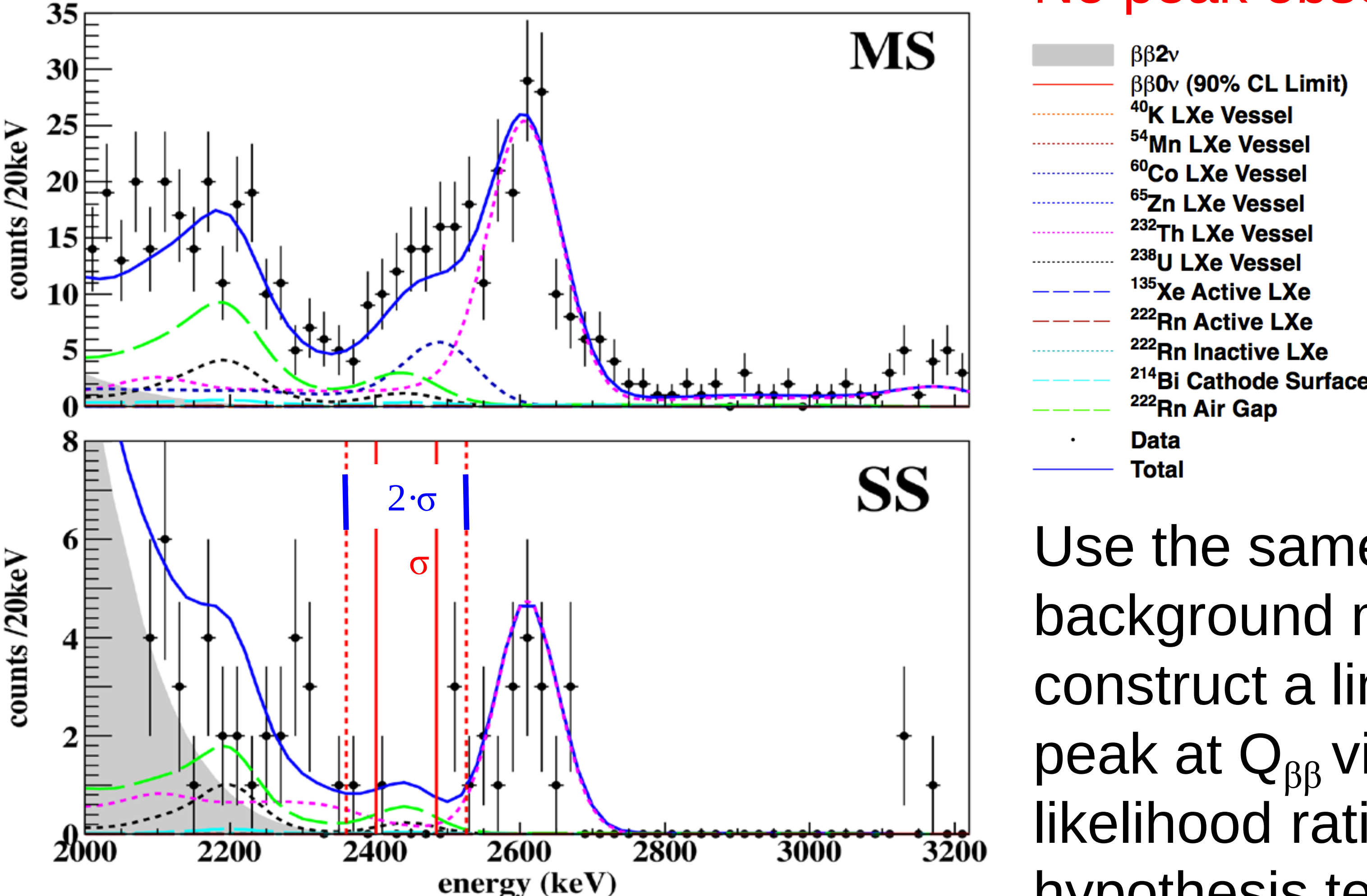
In agreement with previously reported value by

EXO-200 Phys.Rev.Lett. 107 (2011) 212501

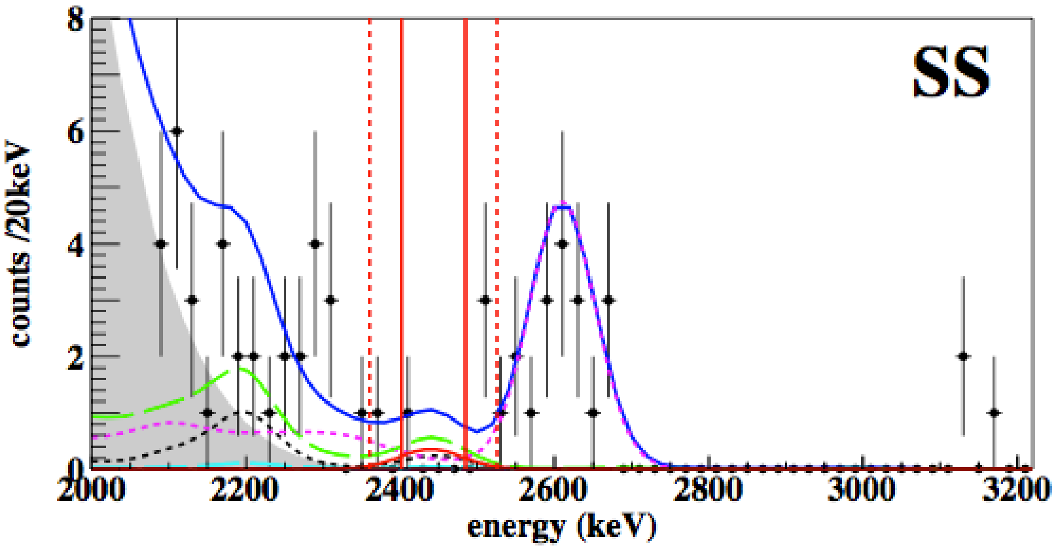
and

KamLAND-ZEN Phys.Rev.C85:045504, (2012)

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



Use the same 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.

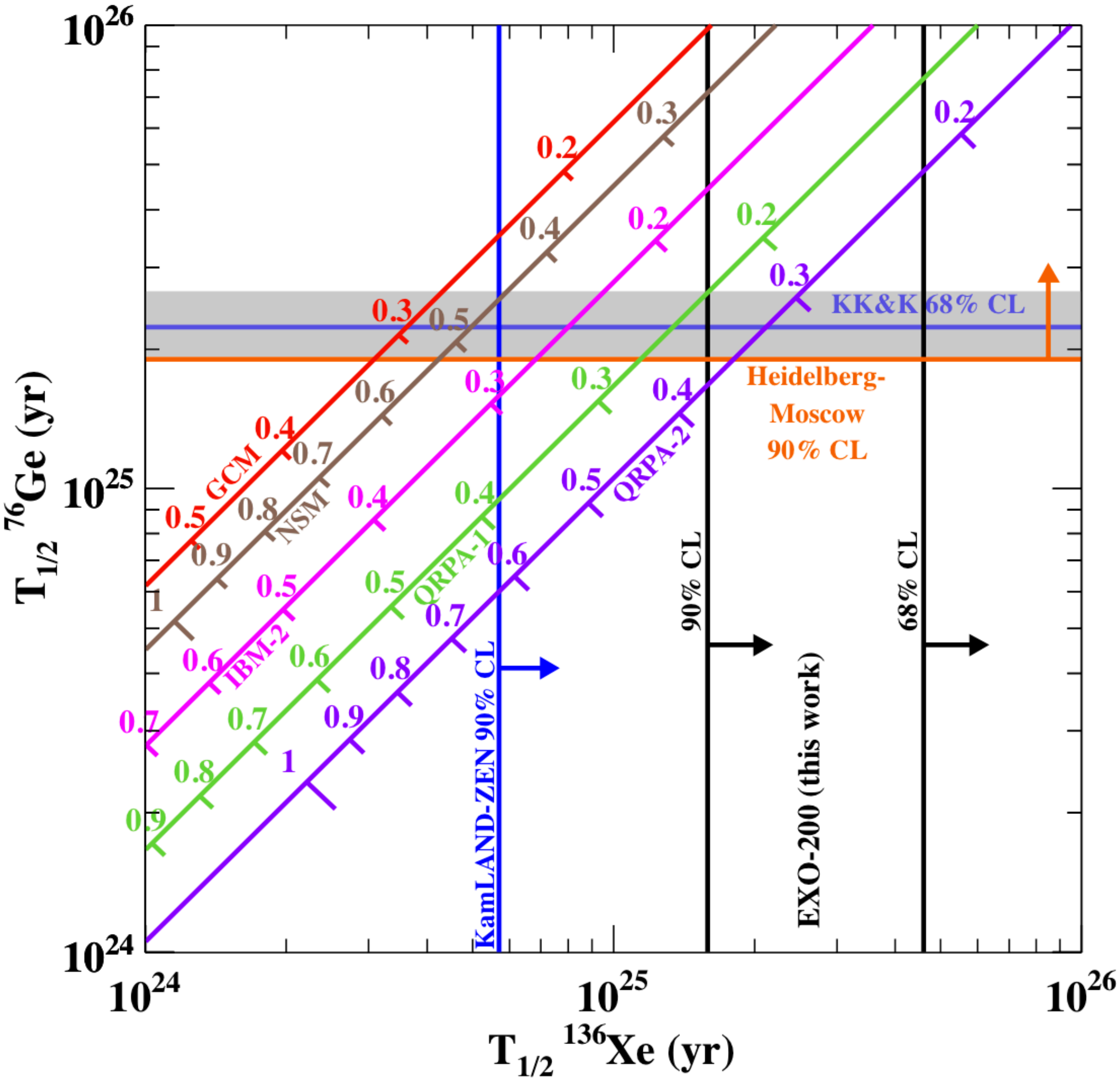
This profile likelihood analysis takes into account the peak shape of a possible 0νββ signal. It is more sensitive than a simple window (rate) analysis.

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

The longest *limit* comes from the Heidelberg-Moscow experiment that used ^{76}Ge. >1.9·10^{25} yr.

Using different nuclear matrix elements the EXO-200 result translates into a Majorana neutrino mass limit range: $\langle m \rangle_{\beta\beta}$ < 140 – 380 meV

^{130}Te (Cuoricino): <190 – 680 meV [Arnaboldi et al. PRC 78 (2008) 035502]
^{76}Ge (IGEX): <330 – 1350 meV [Aalseth et al., PRD 65 (2002) 092007]
^{100}Mo (NEMO-3): <450 – 930 meV [Barabash et al., PAN 74 (2011) 312]



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

For most matrix element calculations there seems to be tension between these two experiments.

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

Conclusion

The EXO-200 detector is taking low background data.

It runs at its specifications:
$\sigma(Q_{\beta\beta}) / Q_{\beta\beta} = 1.67\%$ (SS)
$B_{MC} = 1.5 \cdot 10^{-3}$ cnts / (keV·kg·yr)
In 1·σ(2·σ) ROI: 1(5) counts in 32.2 kg·yr
Data analysis indicates possible avenues to improvement.

No evidence for neutrinoless double beta decay of ^{136}Xe is observed.

With only 4 months of data the EXO-200 result is already one of the most stringent constraints on the Majorana neutrino mass.

EXO-200 is approved to run for 4 more years.

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