

Double Beta Decay: EXO-200 and Beyond

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EXO-200

- Use isotopically enriched Xe as active target to maximize source strength and minimize target towards background causing radiation. Xe enrichment by centrifuge is particularly cost effective: (90% enr.) ^{136}Xe ~10 \$/g, compare to ^{76}Ge ~90 \$/g. No crystal growth needed.
- Active background tagging through tracking *plus* careful material selection and screening.
- Improve energy resolution by simultaneous readout of ionization and scintillation.

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

Started collecting physics data in May 2011

- 5/21/2011 – 7/9/2011 2νββ-run

Detector was completed after initial 2νββ-run ended.

- 9/22/2011 – 4/15/2012 published results of 0νββ-running.
- Now continuously running in this configuration.

The TPC

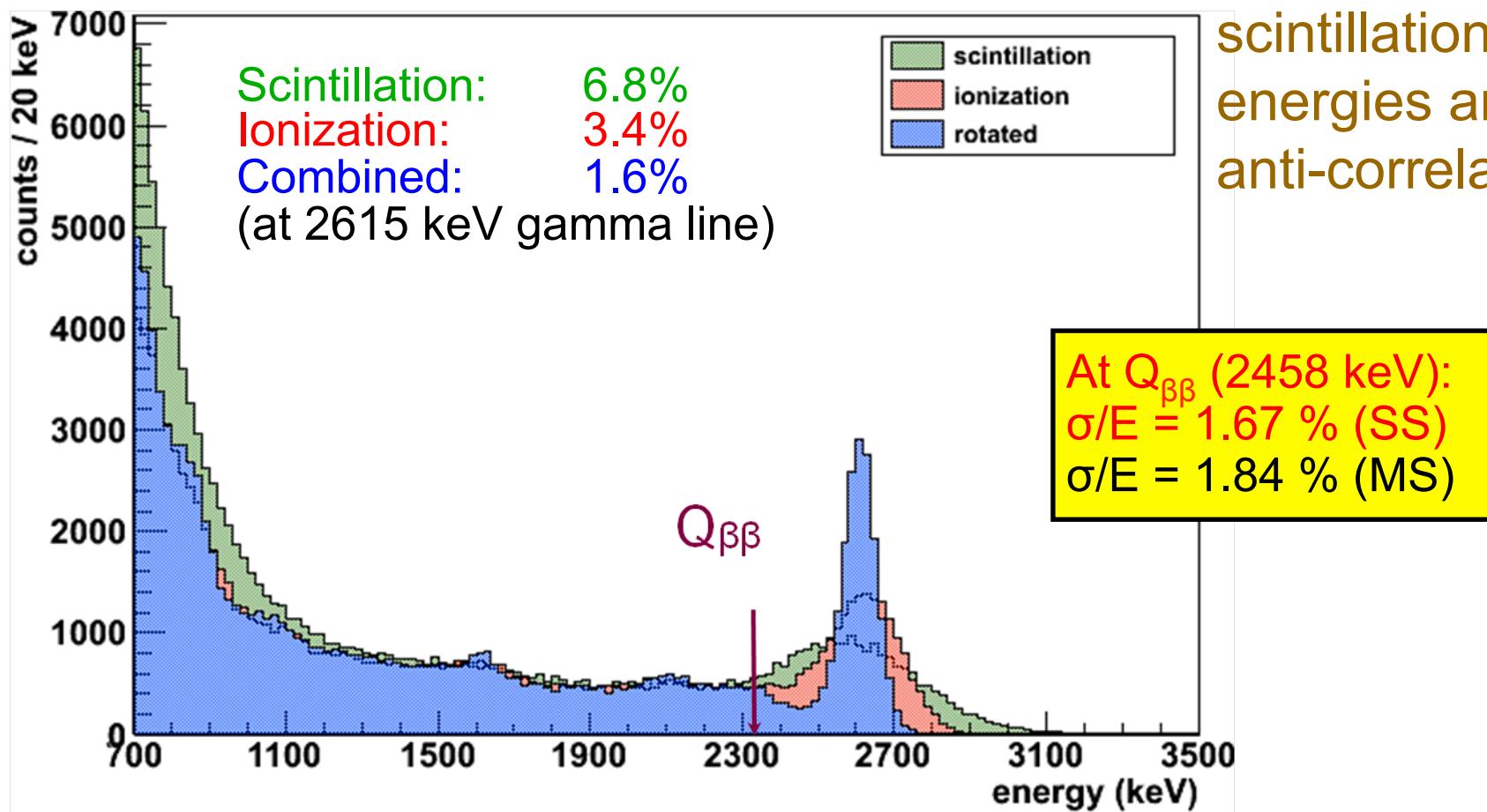
- Cylindrical Cu vessel (1.37 mm wall thickness), 110 kg of liquid Xenon (enriched to 80.6% ^{136}Xe) in active volume. 175 kg Xe are in liquid phase.
- HV cathode in the middle. 2D event reconstruction by crossed wires. Third coordinate from time.
- Light read-out via 234 avalanche photodiodes per side.
→ This design allows full 3-dim event reconstruction.

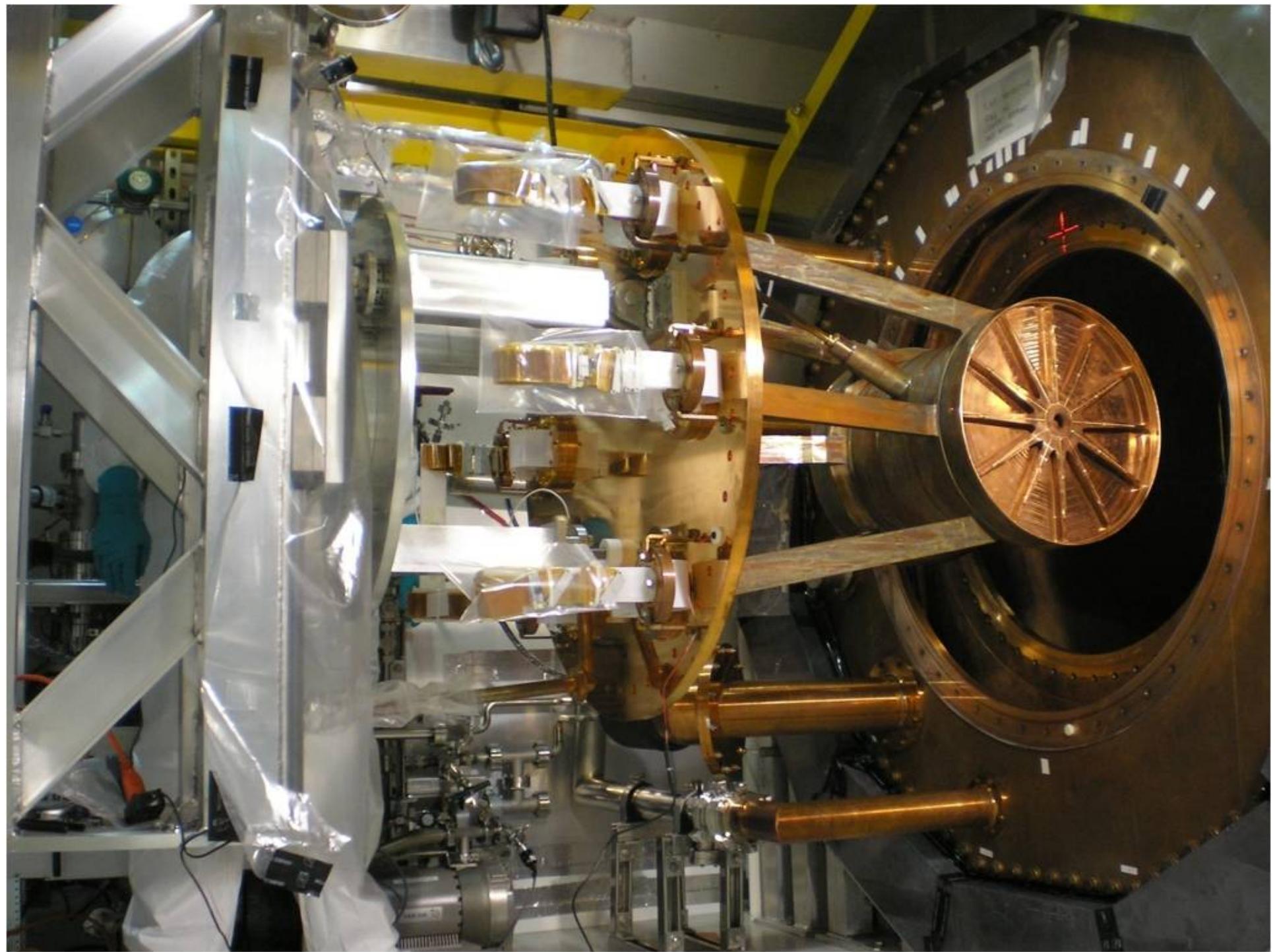
Active background rejection in EXO-200:

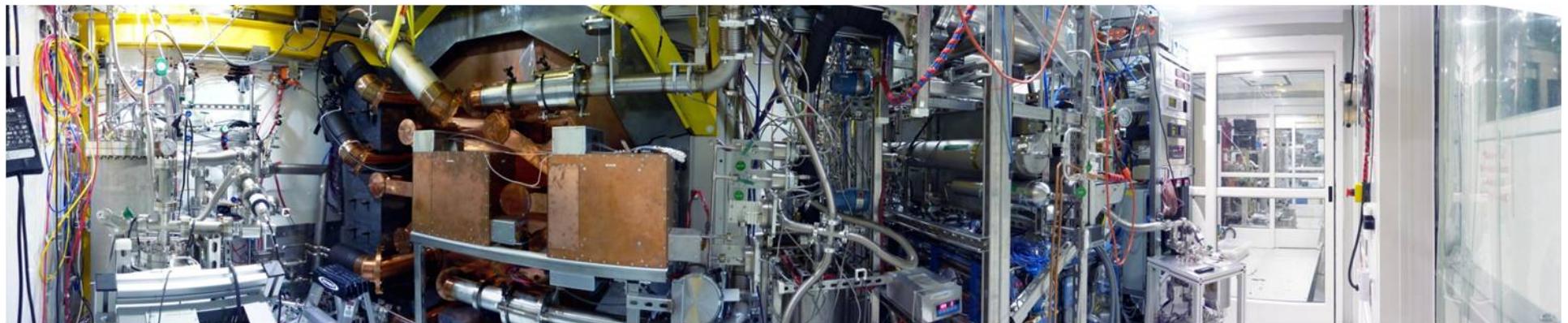
- 3D tracking discriminates single from multi site events (β/γ).
- Ratio of charge and scint. signals discriminates α from β/γ .
- Position sensitivity finds decays on electrodes and walls.

Combining Ionization & Scintillation in ^{228}Th Source Data

Ionization and scintillation energies are anti-correlated.







8/10/2012

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The Data

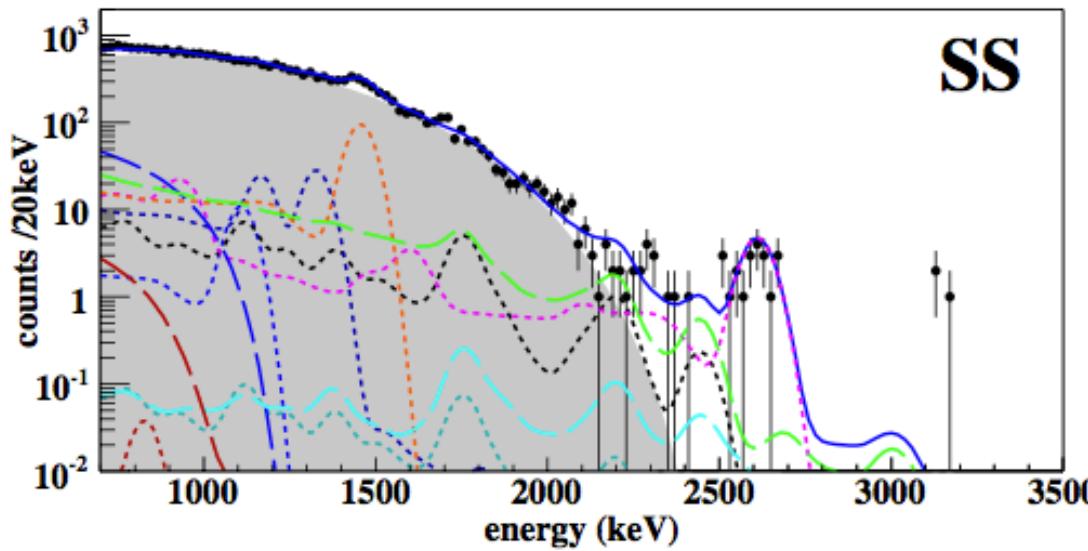
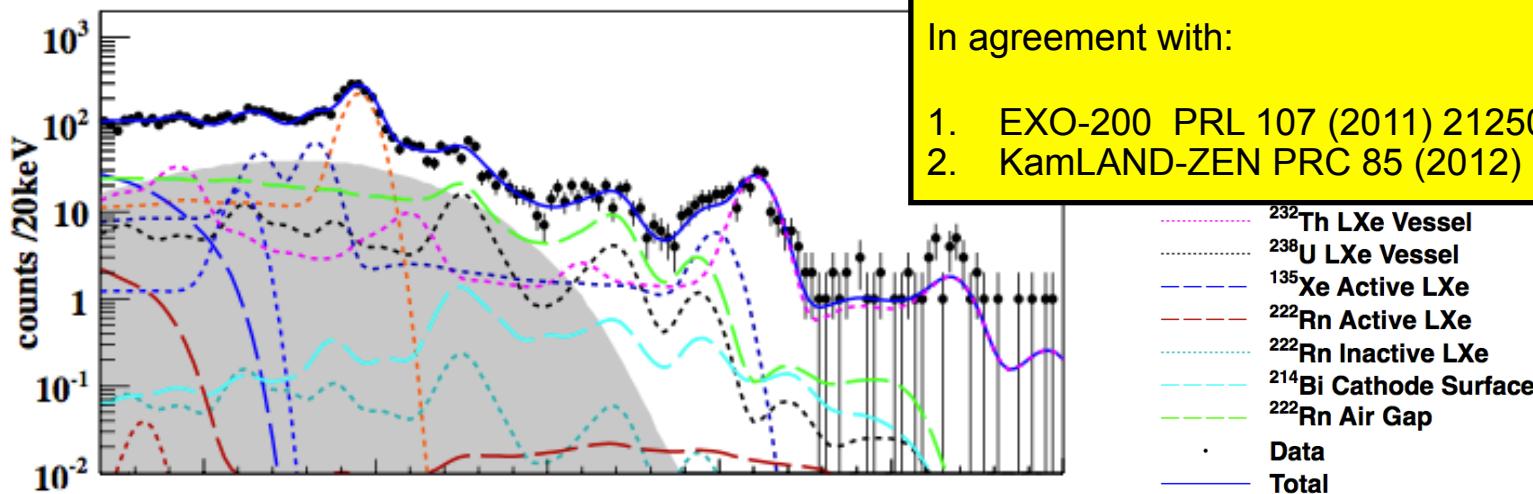
After cuts:

- 98.5 kg enriched Xenon fiducial mass
- 120.7 d life time (15.7 d calibration time)
→ Exposure: $32.6 \text{ kg}\cdot\text{yr}$
- Single site event reconstruction efficiency: 71%.

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

In agreement with:

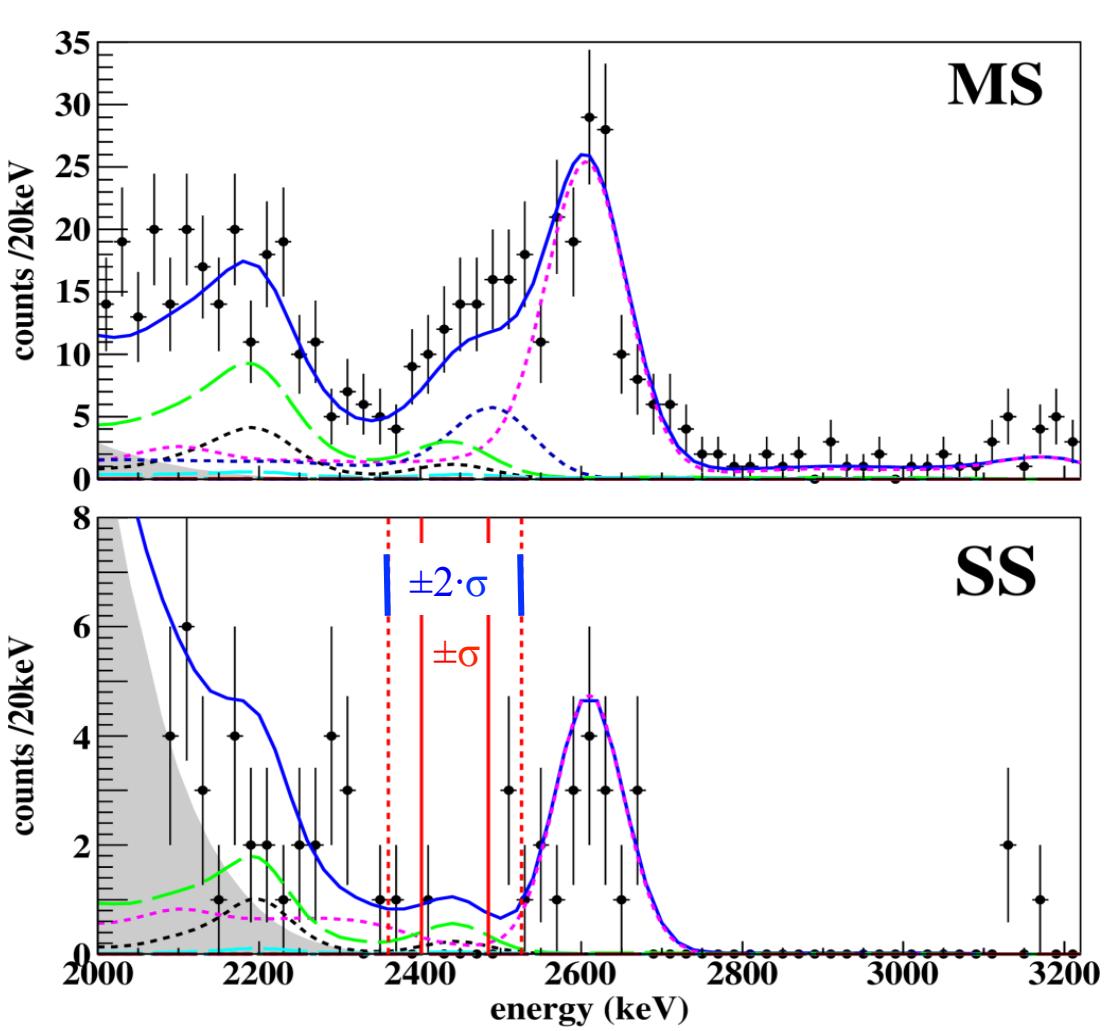
1. EXO-200 PRL 107 (2011) 212501
2. KamLAND-ZEN PRC 85 (2012) 045504



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

SS / MS fits are coupled.

$$|M^{2\nu\beta\beta}| = 0.018 \pm 0.001 \text{ MeV}^{-1}$$



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

- $\beta\beta 2\nu$
- $\beta\beta 0\nu$ (90% CL Limit)
- ^{40}K LXe Vessel
- ^{54}Mn LXe Vessel
- ^{60}Co LXe Vessel
- ^{65}Zn LXe Vessel
- ^{232}Th LXe Vessel
- ^{238}U LXe Vessel
- ^{135}Xe Active LXe
- ^{222}Rn Active LXe
- ^{222}Rn Inactive LXe
- ^{214}Bi Cathode Surface
- ^{222}Rn Air Gap
- Data
- Total

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

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: $T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25} \text{ yr}$

The longest $\beta\beta$ -decay *limit* comes from the Heidelberg-Moscow experiment that used ${}^{76}\text{Ge}$: $> 1.9 \cdot 10^{25} \text{ yr}$.

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

$\langle m \rangle_{\beta\beta} < 140 - 380 \text{ meV}$

[Auger et al., PRL 109 (2012) 032505]

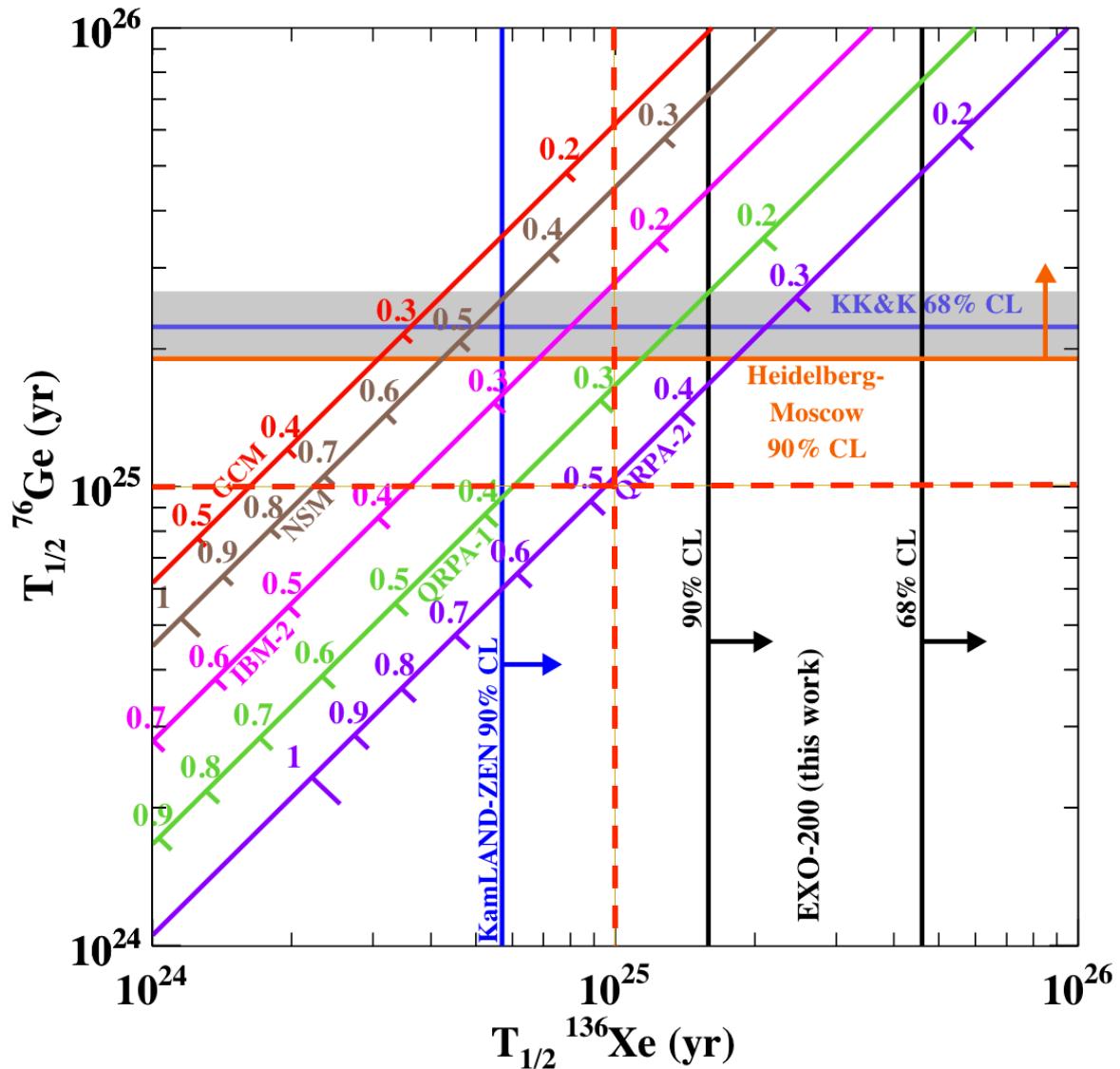
${}^{130}\text{Te}$ (Cuoricino): $< 270 - 660 \text{ meV}$ [Arnaboldi et al. PRC 78 (2008) 035502]

${}^{136}\text{Xe}$ (KamLAND-ZEN): $< 240 - 620 \text{ meV}$ [Gando et al., PRC85 (2012) 045504]

${}^{76}\text{Ge}$ (HD-Mo): $< 270 - 640 \text{ meV}$ [H.V. Klapdor-Kleingrothaus, EJP A12 (2001) 147]

${}^{76}\text{Ge}$ (IGEX): $< 295 - 700 \text{ meV}$ [Aalseth et al., PRD 65 (2002) 092007]

${}^{100}\text{Mo}$ (NEMO-3): $< 450 - 1070 \text{ meV}$ [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.

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

NSM: J. Menendez et al., Nucl. Phys. A 818 (2009) 139.

IBM2: J. Barea and F. Iachello, Phys. Rev. C79 (2009) 044301 and private communication.

R-QRPA-1: F. Simkovic et al., Phys. Rev. C 79 (2009) 055501.

QRPA-2: A. Staudt, K. Muto and H. V. Klapdor-Kleingrothaus, Europhys. Lett. 13 (1990) 31.

KamLAND-ZEN: A. Gando et al. Phys. Rev. C 85 (2012) 045504.

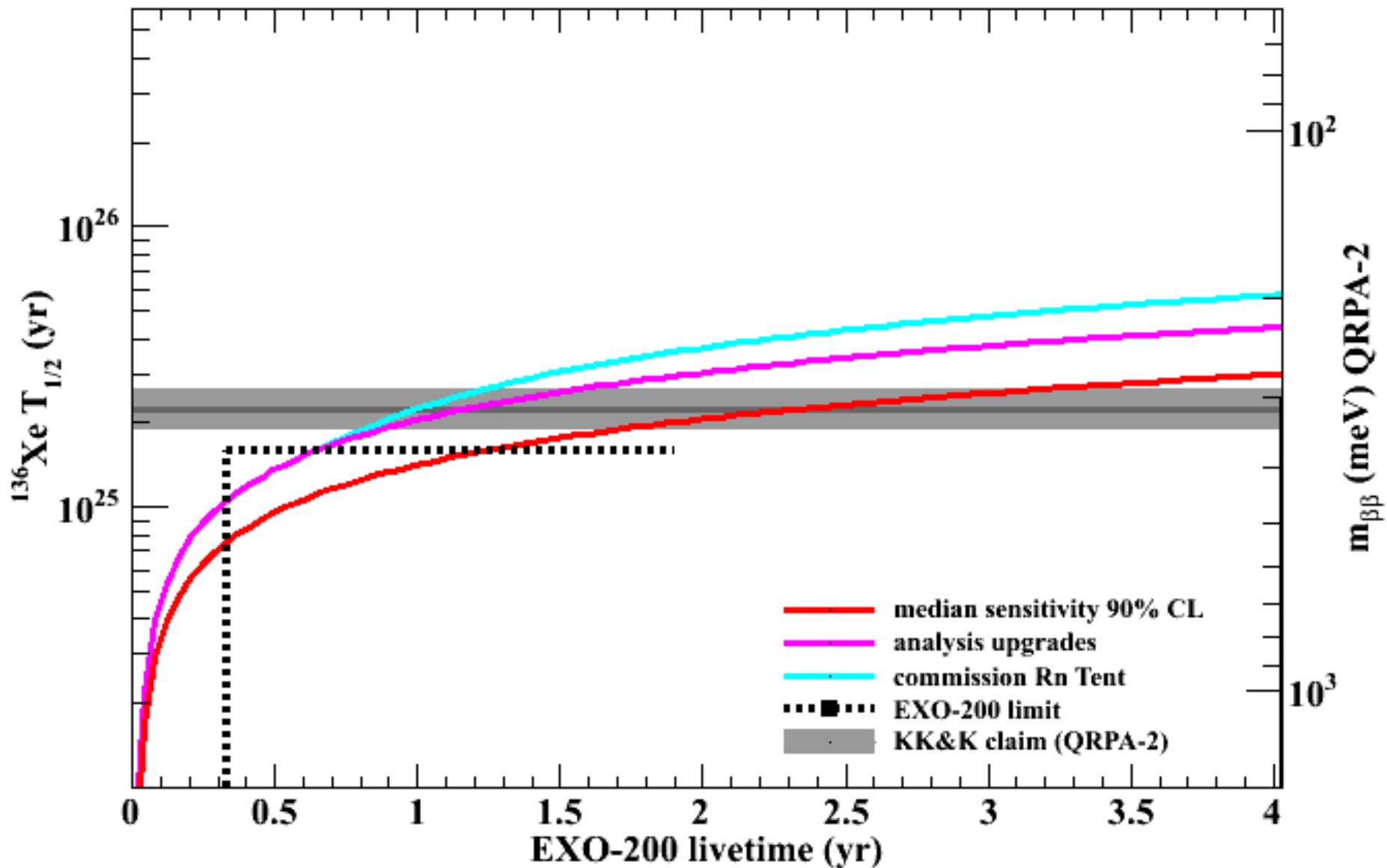
Heidelberg-Moscow: H.V. Klapdor-Kleingrothaus et al. Eur. Phys. J. A12 (2001) 147.

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

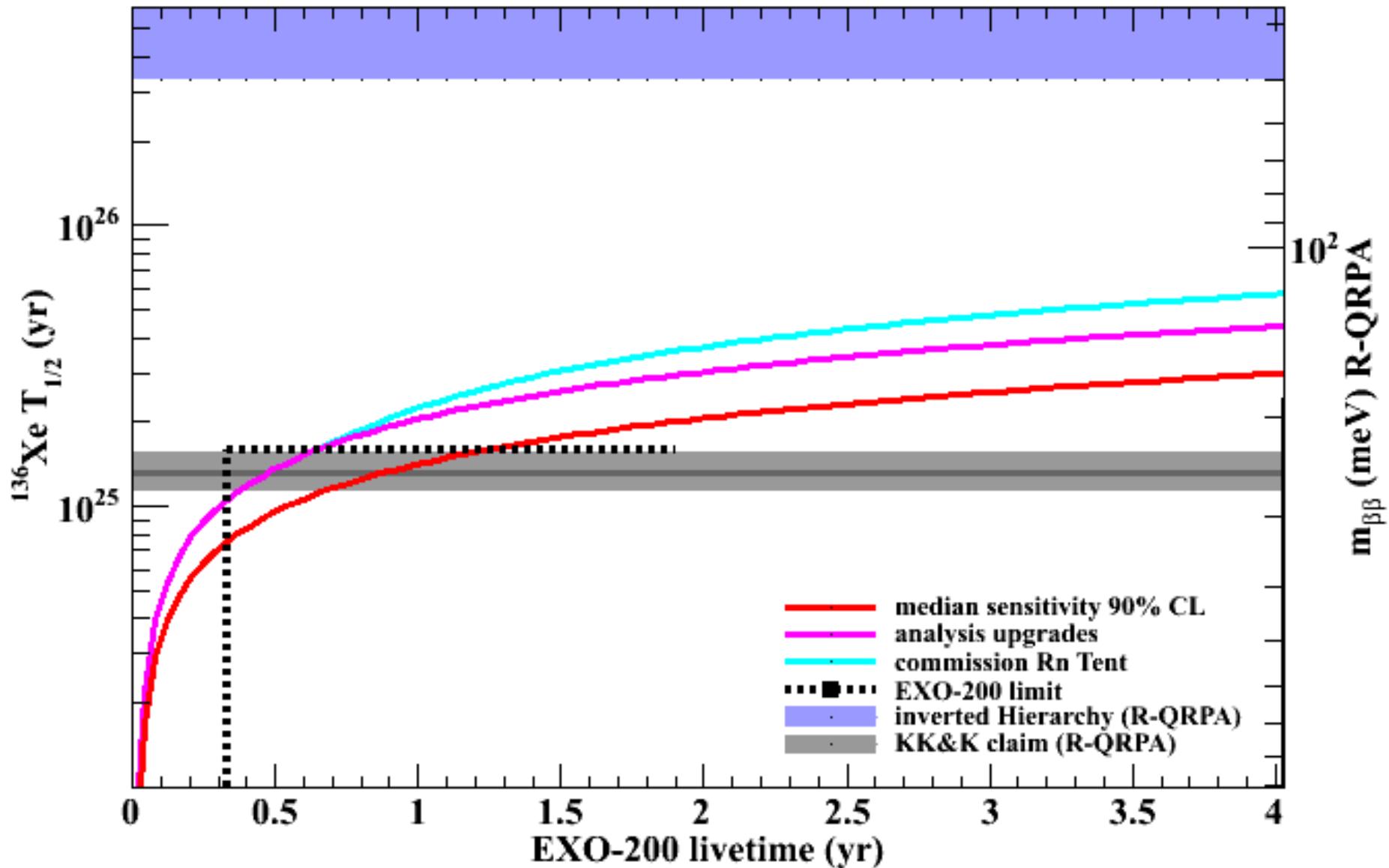
Where is EXO-200 going from here?

- Improve e-reconstruction efficiency from 71 to 90%.
- Reduce fiducial volume uncertainty from 9 to 4%.
- Try to improve energy resolution from 1.67 to 1.4%, noise studies are under way.
- Use 3D probability function in fit.
- Reduce background by perhaps factor 2 by removing Rn trapped in shield (cyan).

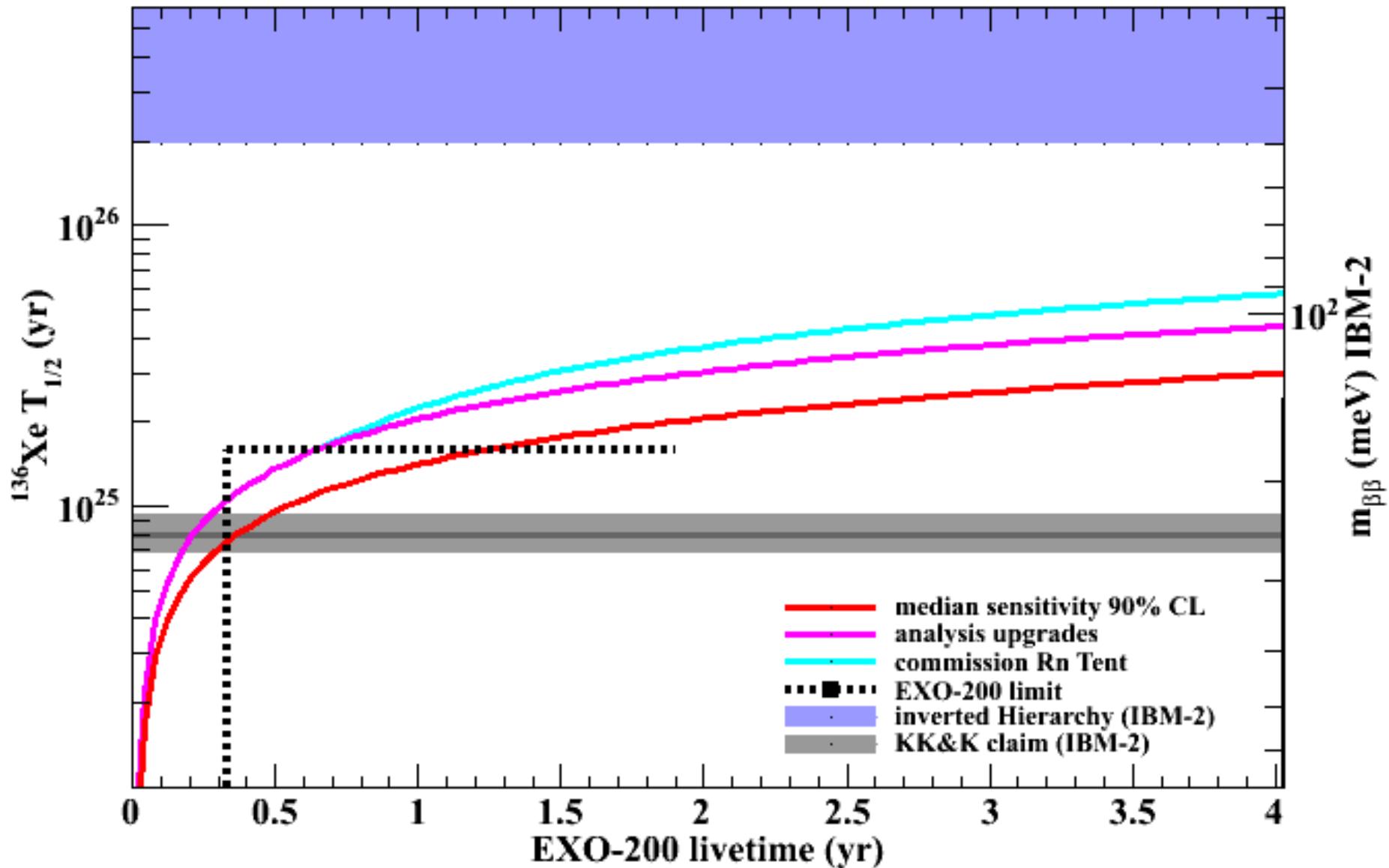
QRPA-2 (1990)



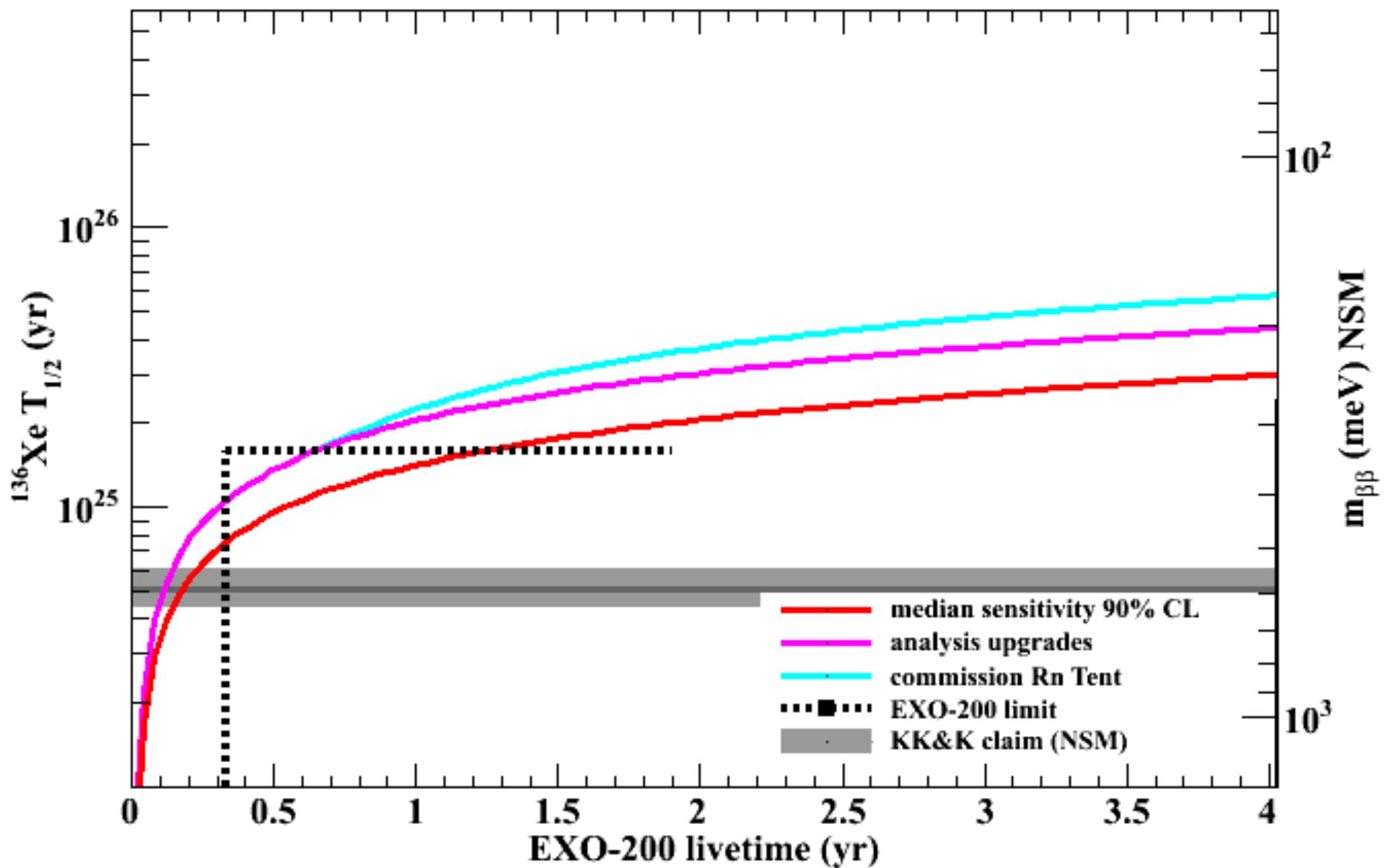
R-QRPA (2009)



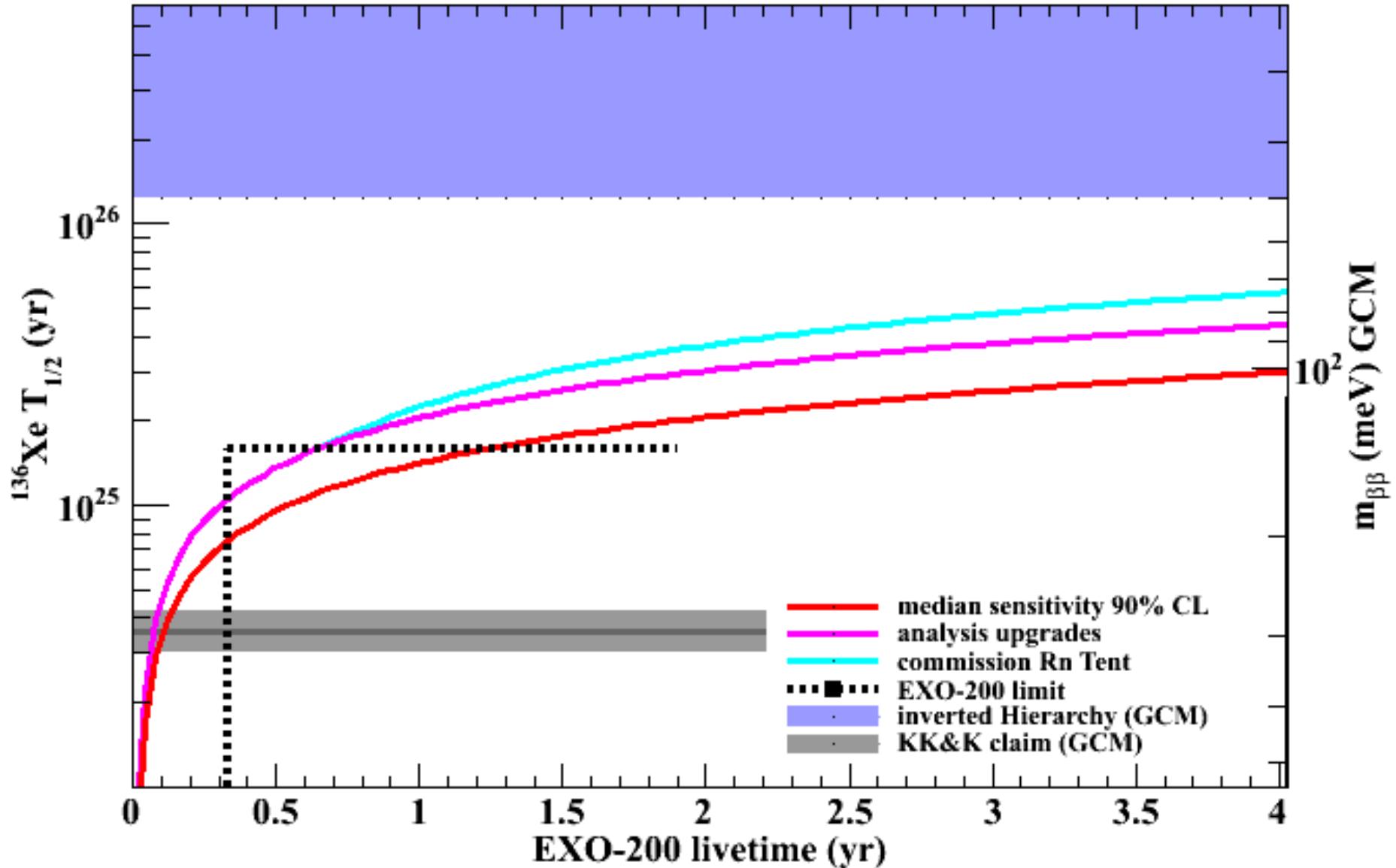
IBM-2 (2009)



NSM (2009)



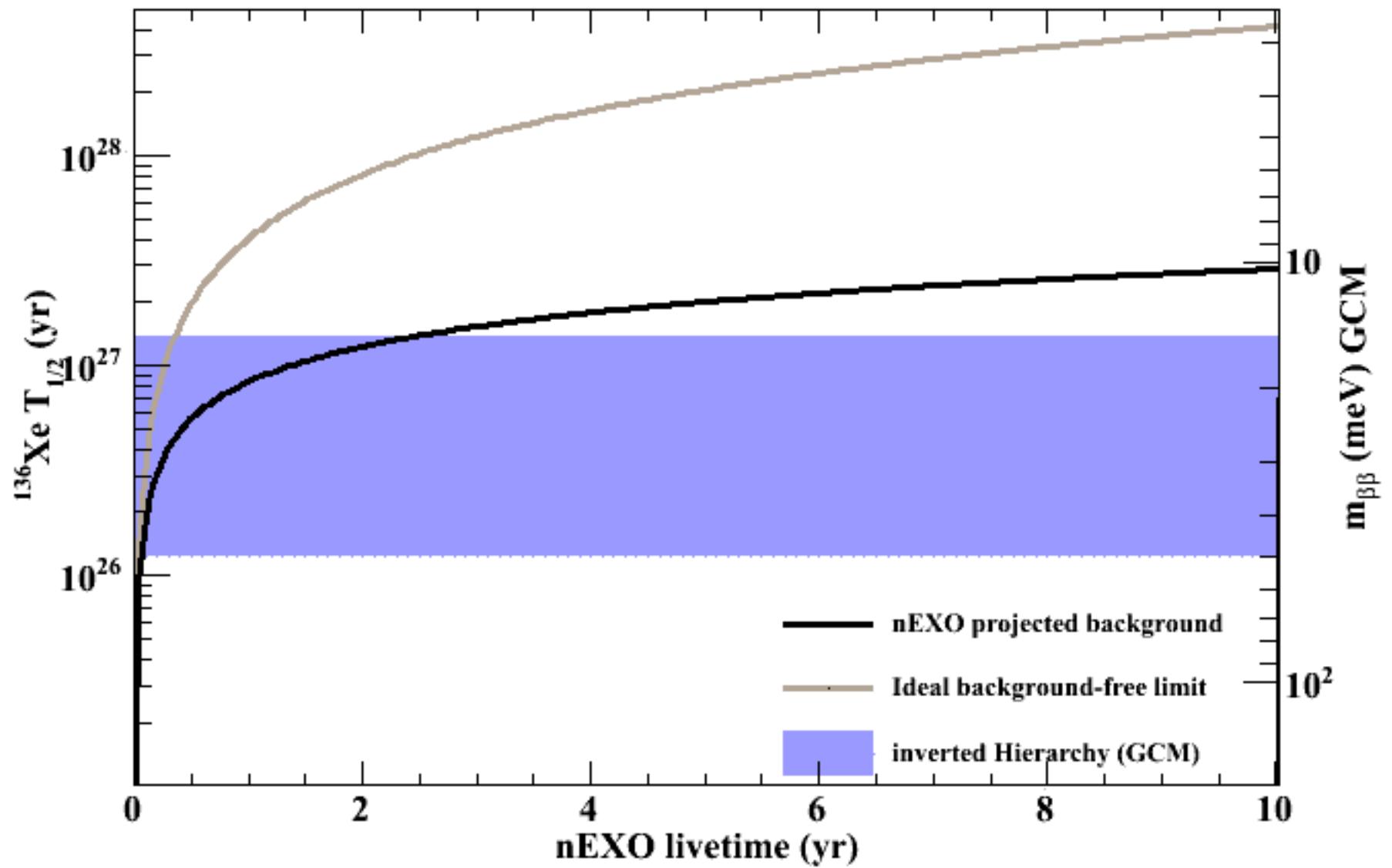
GCM (2010)

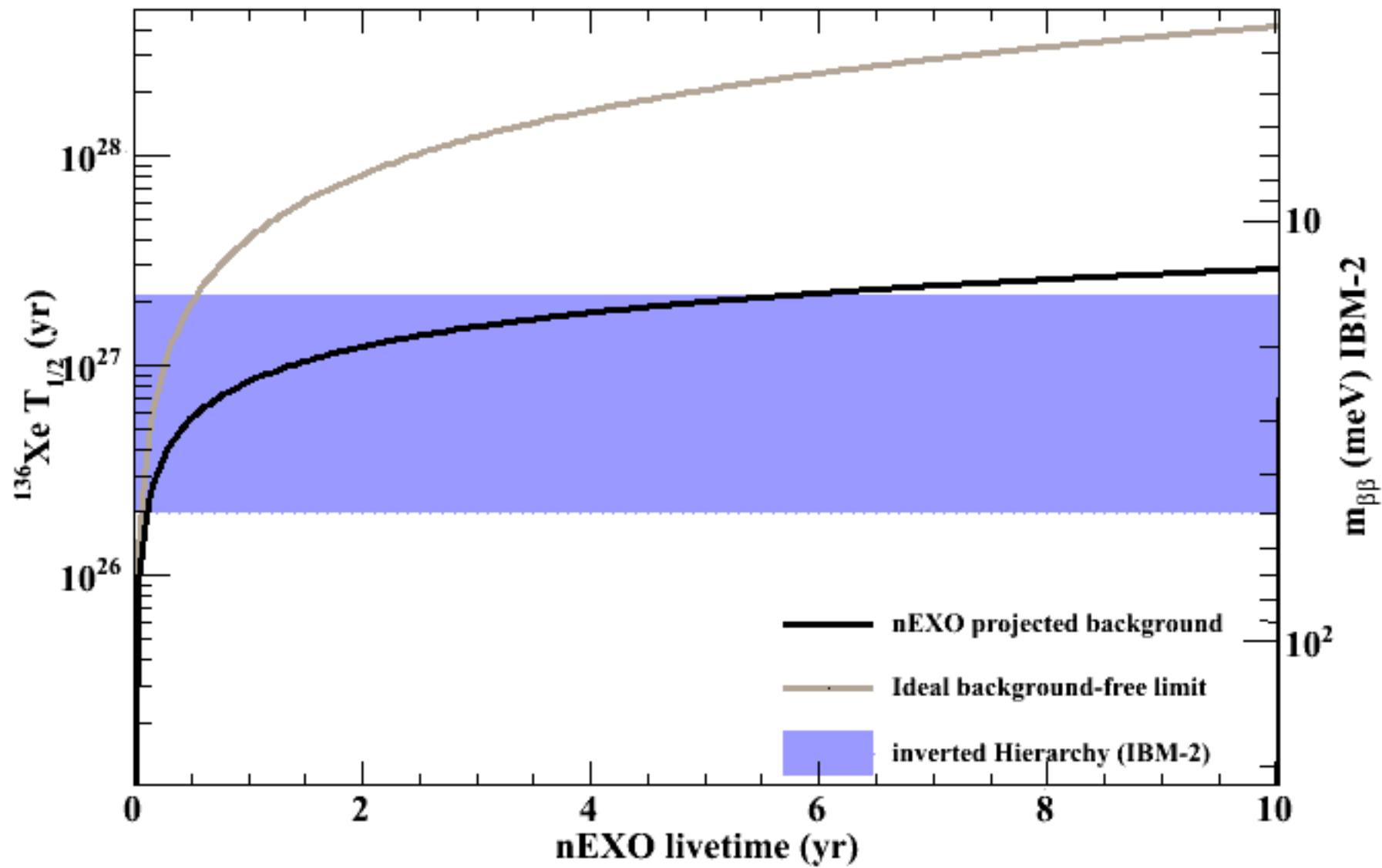


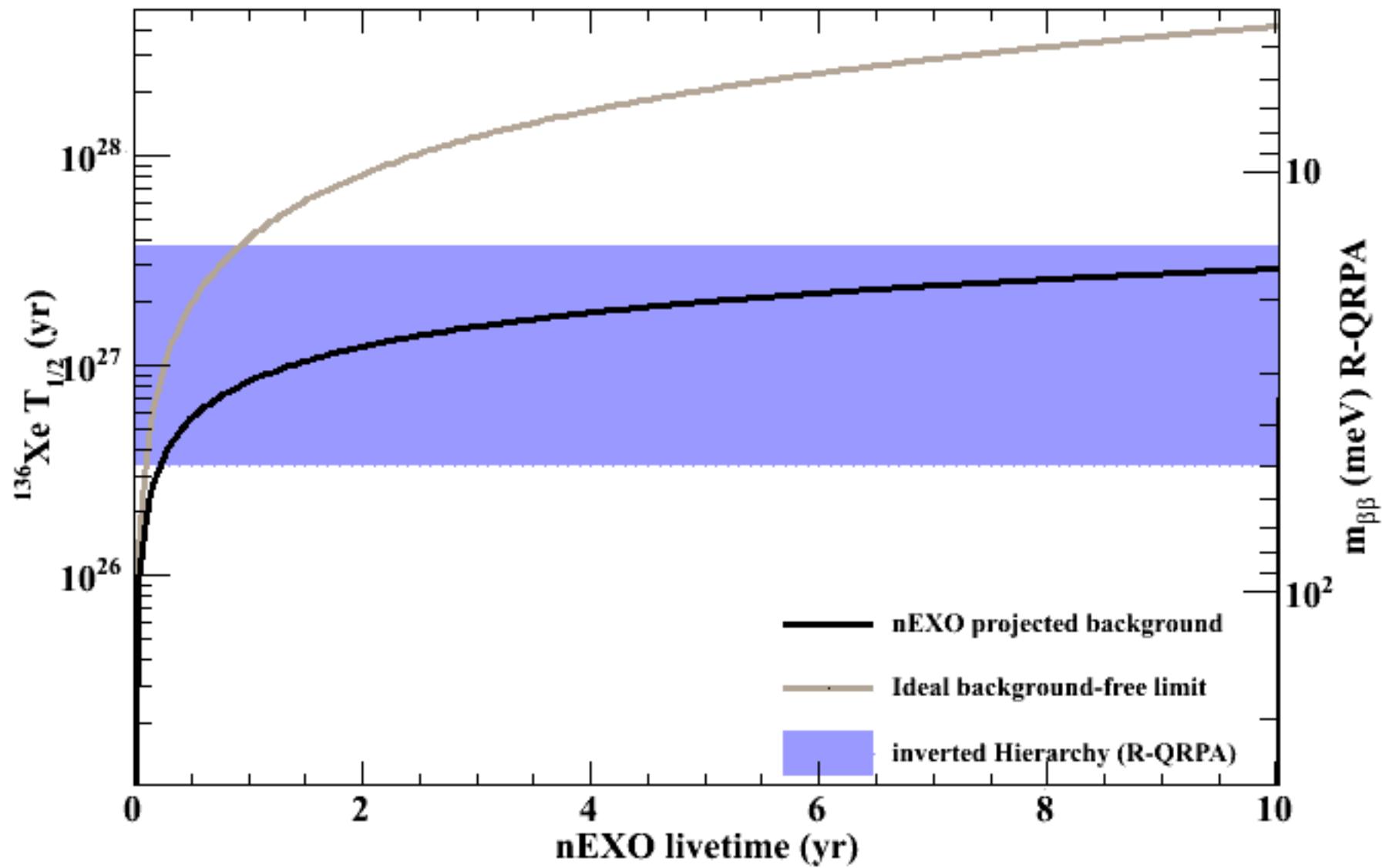
What about beyond EXO-200?

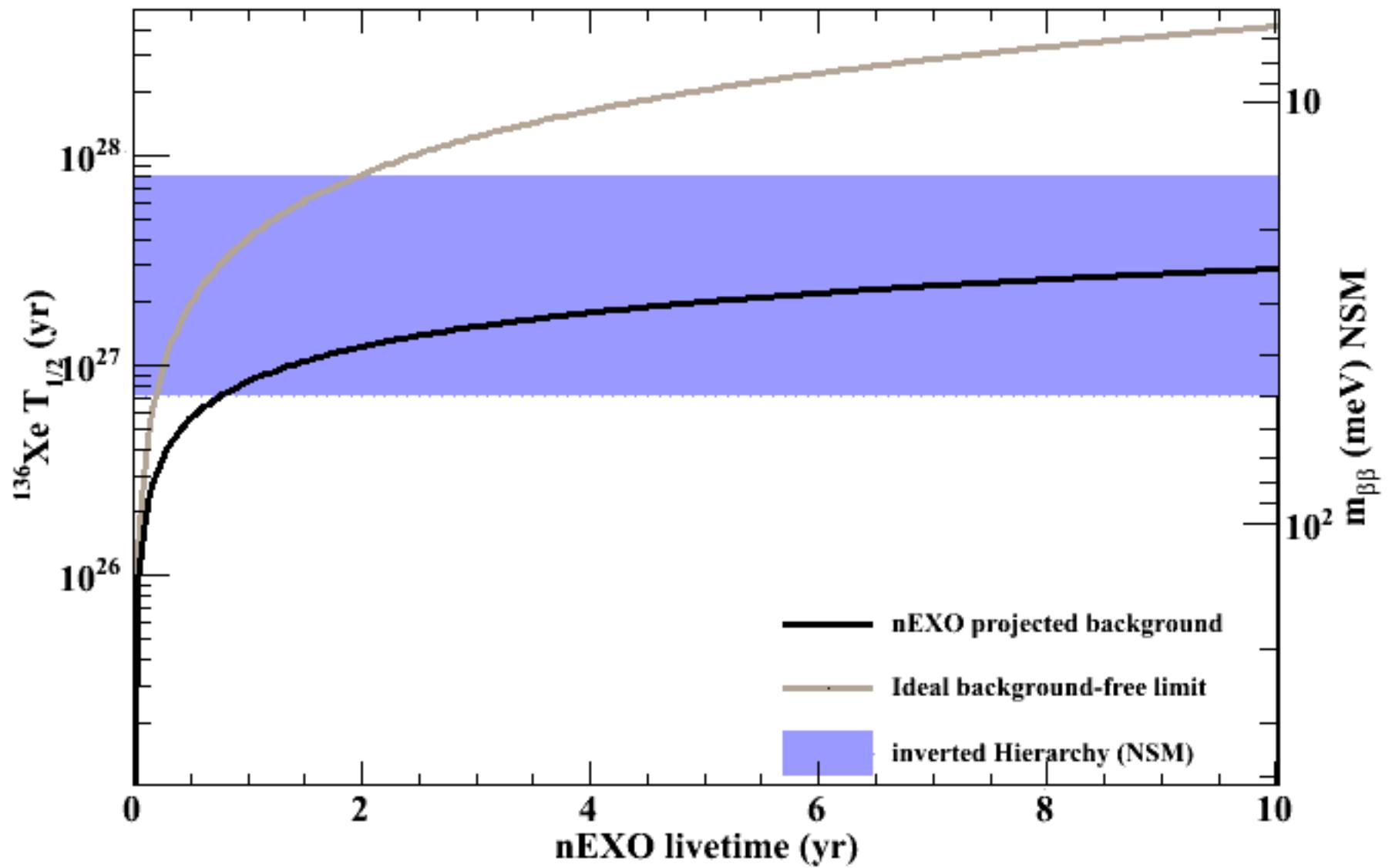
- Ba-tagging research is actively pursued.
- Because of the success with EXO-200 the collaboration started to study the case for a ~5 ton Xe experiment, *initially* without Ba- tagging. Tagging should remain an option, you could consider it a risk mitigation tool.
- Assume:
 - 4 tons of active ^{enr}Xe (80% or higher).
 - 1.4% (σ) energy resolution.
 - Observed EXO-200 backgrounds minus the Rn in the shield. $\beta\beta$ -scales like the volume, the background like the surface area (assume equal materials thicknesses).

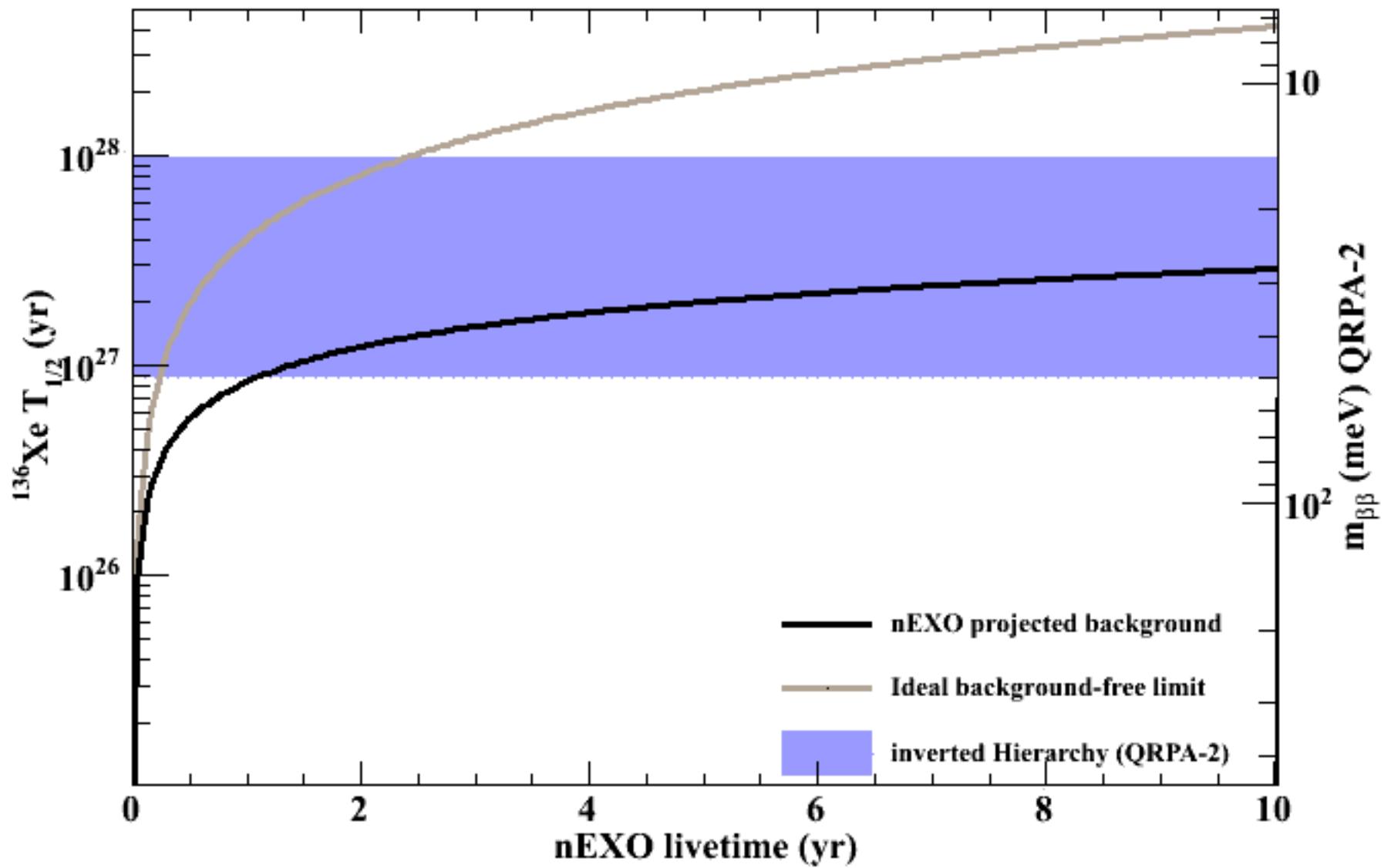
We call this nEXO.





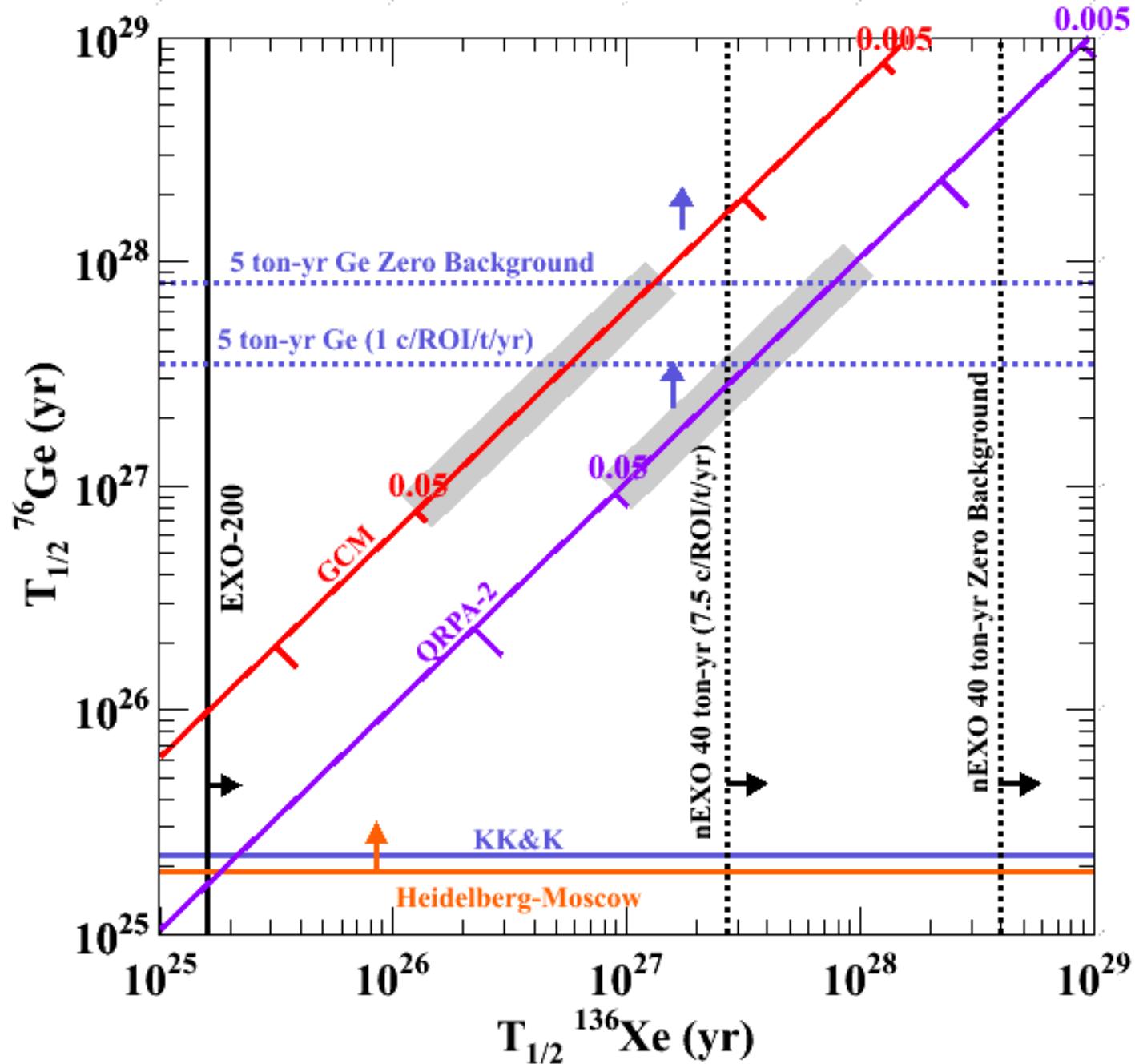






This is still a quite schematic extrapolation but based on actual EXO-200 data. The detector improvements listed before have been assumed. It appears that a multi-ton LXe detector, based on the EXO-200 design and, at least initially, without Ba-tagging would be competitive with other planned detectors, while relying on proven technology.

Xenon probably also offers fiscal advantages compared to some other isotopes.



Relation to NSAC subcommittee charge

- 1) What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?

EXO-200 was world wide the first *next generation* experiment to start data taking. It is probably fair to say that the EXO-200 measurements of the unknown $2\nu\beta\beta$ half life of ^{136}Xe and the new limit on its $0\nu\beta\beta$ half life, representing one of the most stringent bounds on the Majorana neutrino mass and the first serious challenge of the KK&K evidence, are among those highlights, in a world wide context.

EXO-200 is a US lead effort that plays out in a US lab.

Relation to NSAC subcommittee charge

- 2) What compelling and unique science is to be done in the next 5 years?
 - Fully refute or verify the KK&K evidence. Discover Majorana neutrino mass in the degenerate mass range, if realized in Nature. This would be Physics beyond the Standard Model.
 - Compare the running 100 kg class experiments, identify the most sensitive and cost effective approaches.
 - Develop proposals for at least two ton class experiments in the US, building on the investment made into the current generation experiments.
 - By this assure that the US effort is recognized as *leading, technically, scientifically, and schedule wise.*

Relation to NSAC subcommittee charge

- 3) What science would you expect to pursue in the program in 2020 and beyond?

Operate a ton class double beta decay experiment, discover Majorana neutrinos if their mass is governed by the inverted hierarchy. Otherwise try to cover this part of parameter space with a competitive limit.

Because of the scientific importance making a clear case for discovery will be greatly improved if made with different detectors using different decaying nuclides. Maintaining a diverse double beta decay community in the US is therefore critical to assure scientific impact.

Relation to NSAC subcommittee charge

- 4) What is the international context, and how does it affect your vision?

There are numerous ideas for large double beta decay experiments all over the world. An international process of consolidation would help to avoid duplication of effort and reduce cost. As an example: I see no point in pursuing experiments using the same decaying isotope in different countries. Our community would be better served by diversity *if* multiple technologies for multiple nuclides with comparable sensitivities are available. That's why the current generation of experiments is so important, to develop and establish the technology base.



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