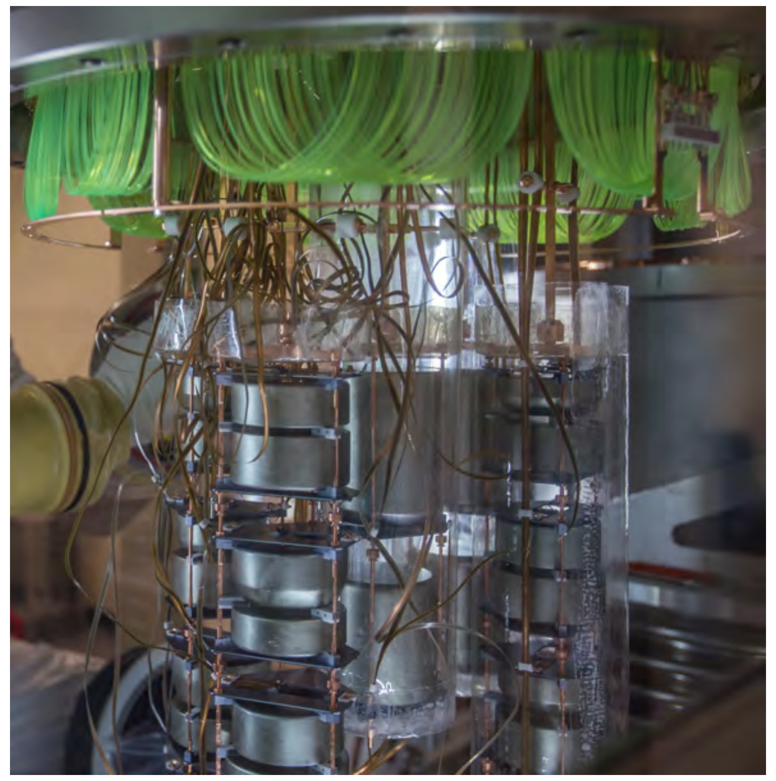
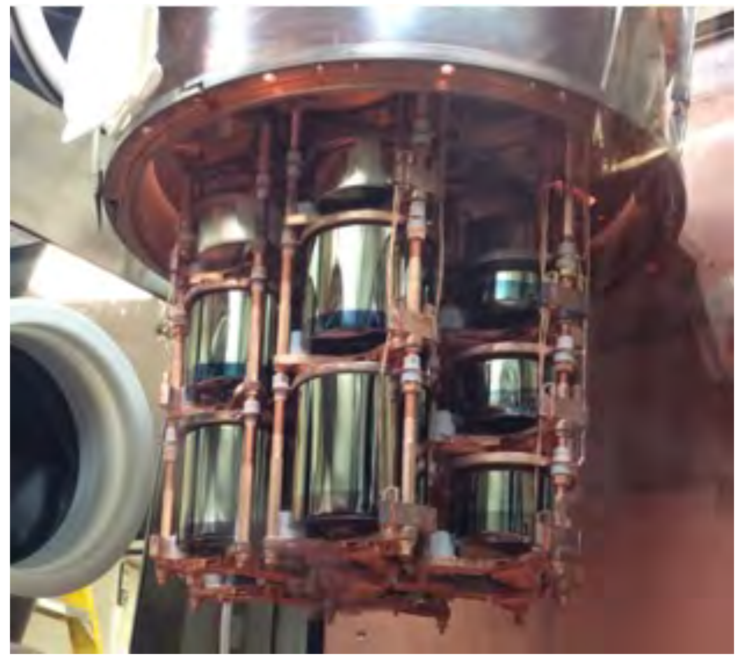
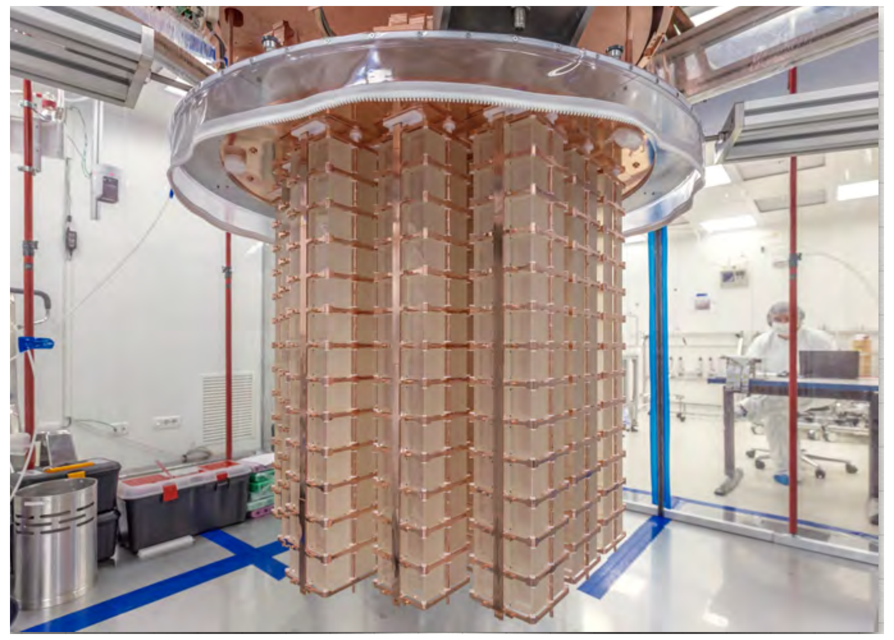
Probing neutrino properties

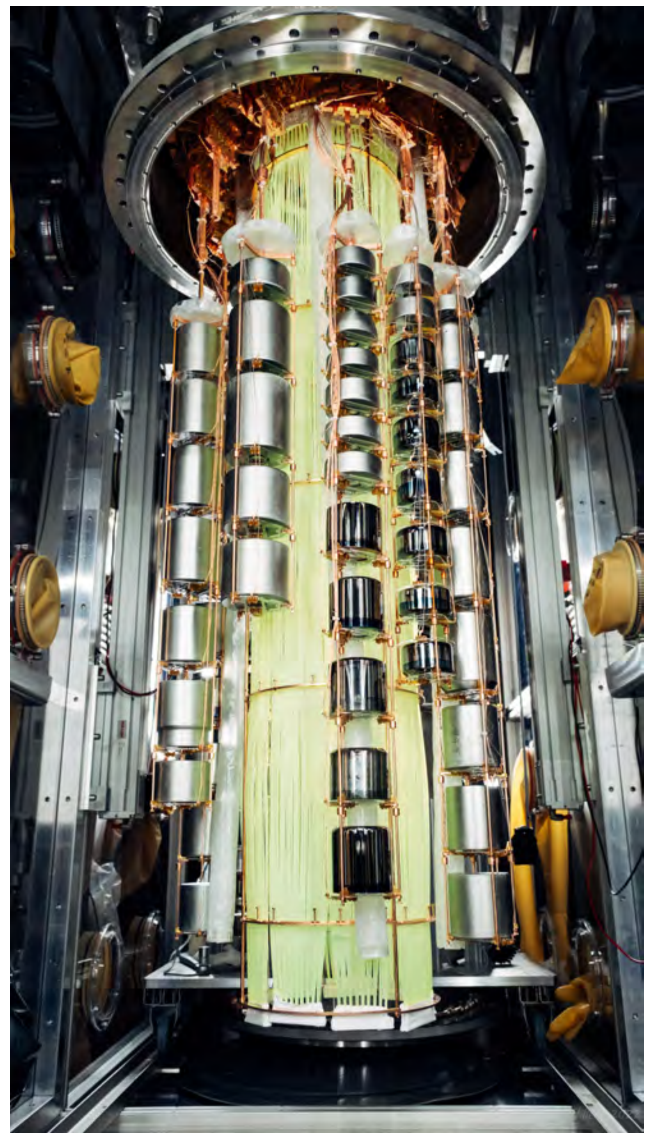
Neutrinos in Physics and Astrophysics: celebrating the contributions of Baha Balantekin and George Fuller

via Neutrinoless Double Beta Decay









J.F. Wilkerson
January 17, 2025
Berkeley , CA

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

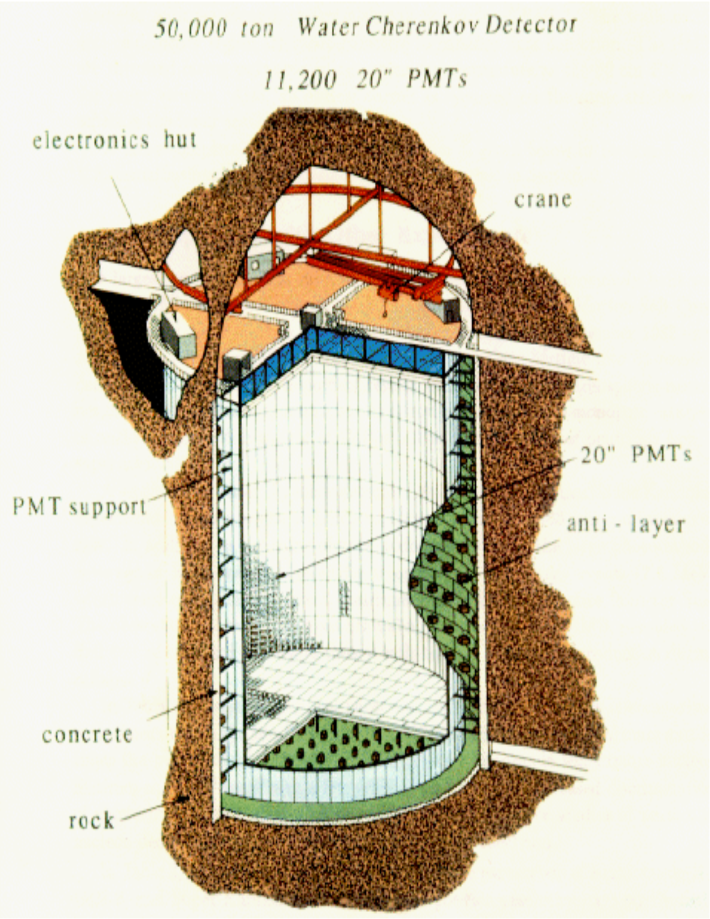
TUNL

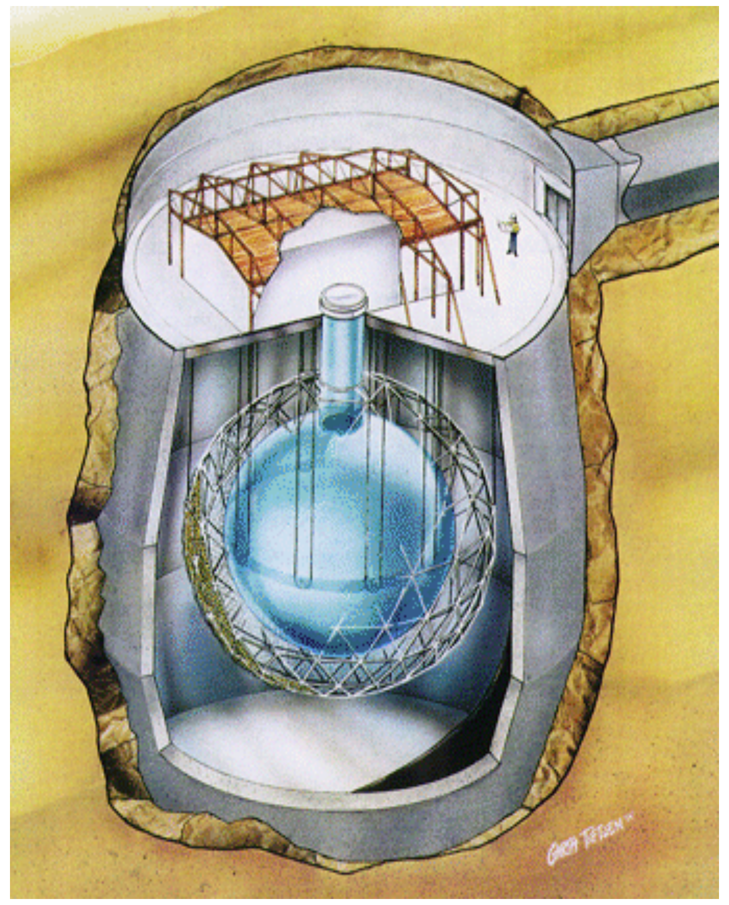
COSMS INSTITUTE

OAK RIDGE National Laboratory

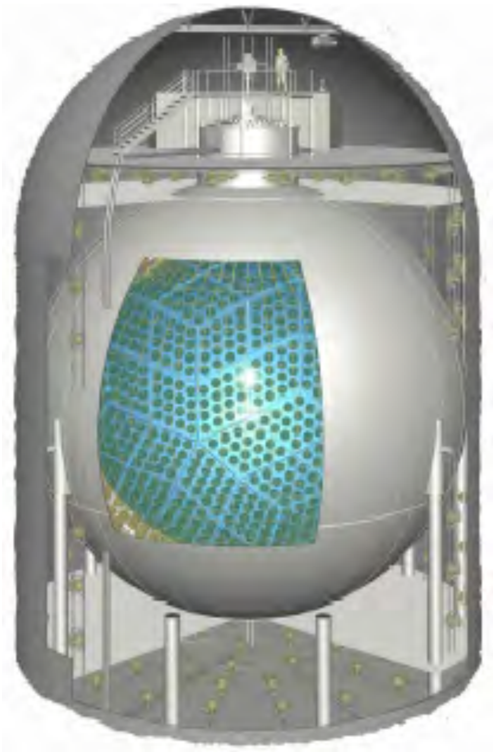
Neutrino Physics from the 1980s to the present

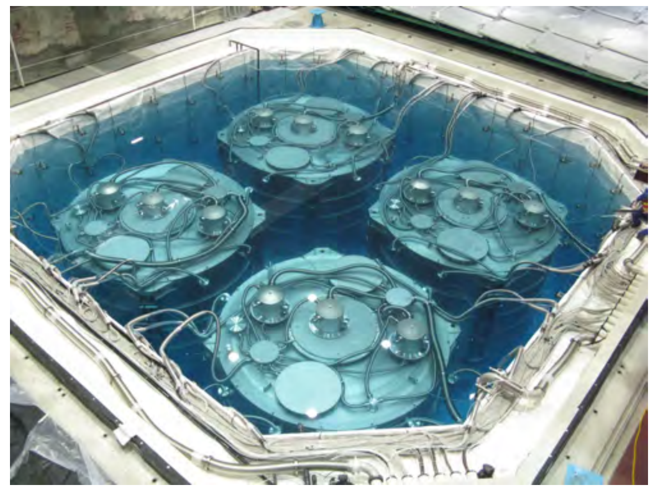
- Key neutrino properties
  - mixing angles and ordering
  - mass?
  - Dirac - Majorana nature?
  - additional neutrino flavors (Sterile)?
  - magnetic moment?
  - interactions and conservation laws? (via the weak force or new forces)

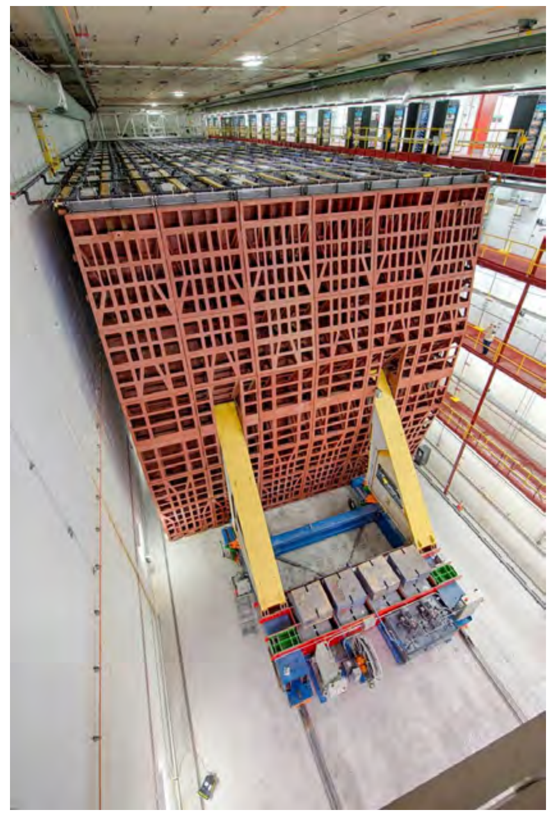




- Impacts and Implications
  - fundamental interactions and symmetries
  - nuclear physics
  - astrophysics
  - cosmology





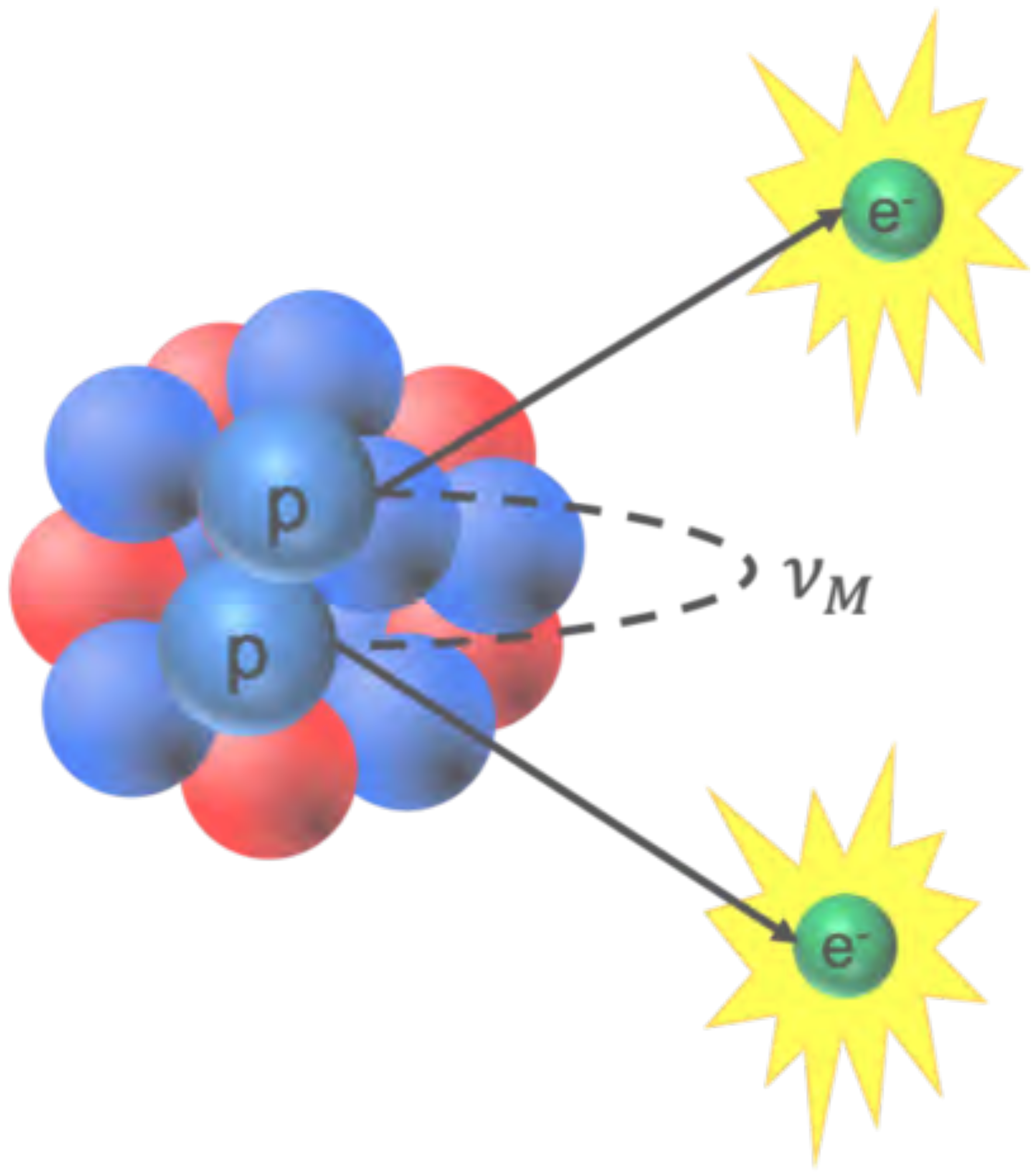


Baha’s and George’s Contributions

Word Cloud from 2014-2024 Publication Titles

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The observation of $0\nu\beta\beta$ would reveal the quantum nature of the neutrino and dramatically revise our foundational understanding of physics and the cosmos



- Matter creation (Lepton number is not conserved)
- The neutrino is its own anti-particle (Majorana particle)
- Provides a mechanism for generating the predominance of matter to antimatter in the cosmos (the matter - antimatter asymmetry).
- Demonstrates a new means for the generation of mass
- Determination of neutrino mass (with caveats)

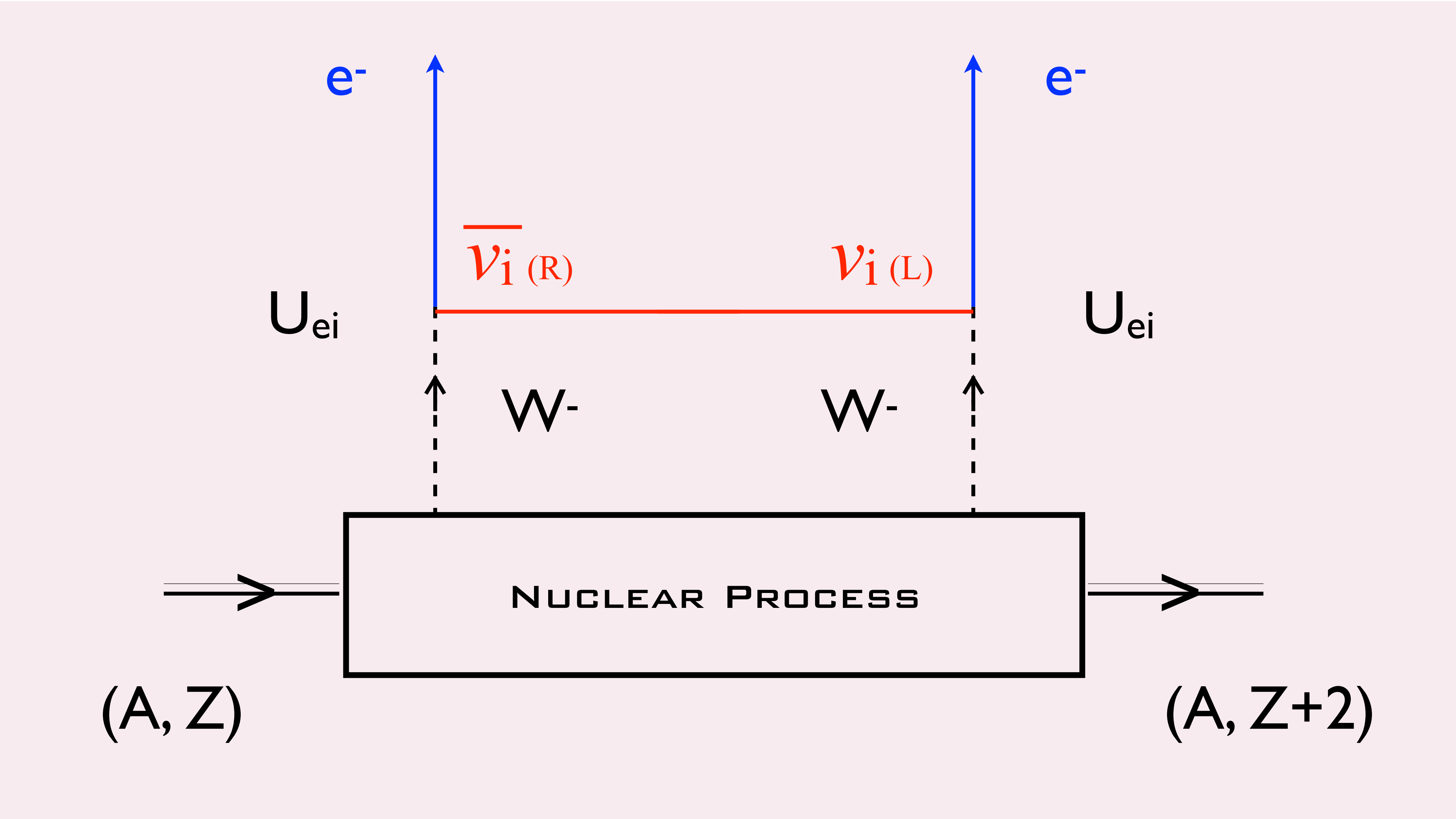
The highest priority for new experiment construction in U.S. Nuclear Science Advisory Committee's 2023 Long Range Plan for Nuclear Science

For Neutrinoless Double Beta Decay to Occur

- Neutrino must have non-zero mass
  - “wrong-handed” helicity admixture ~ $m_i/E_{\nu i}$

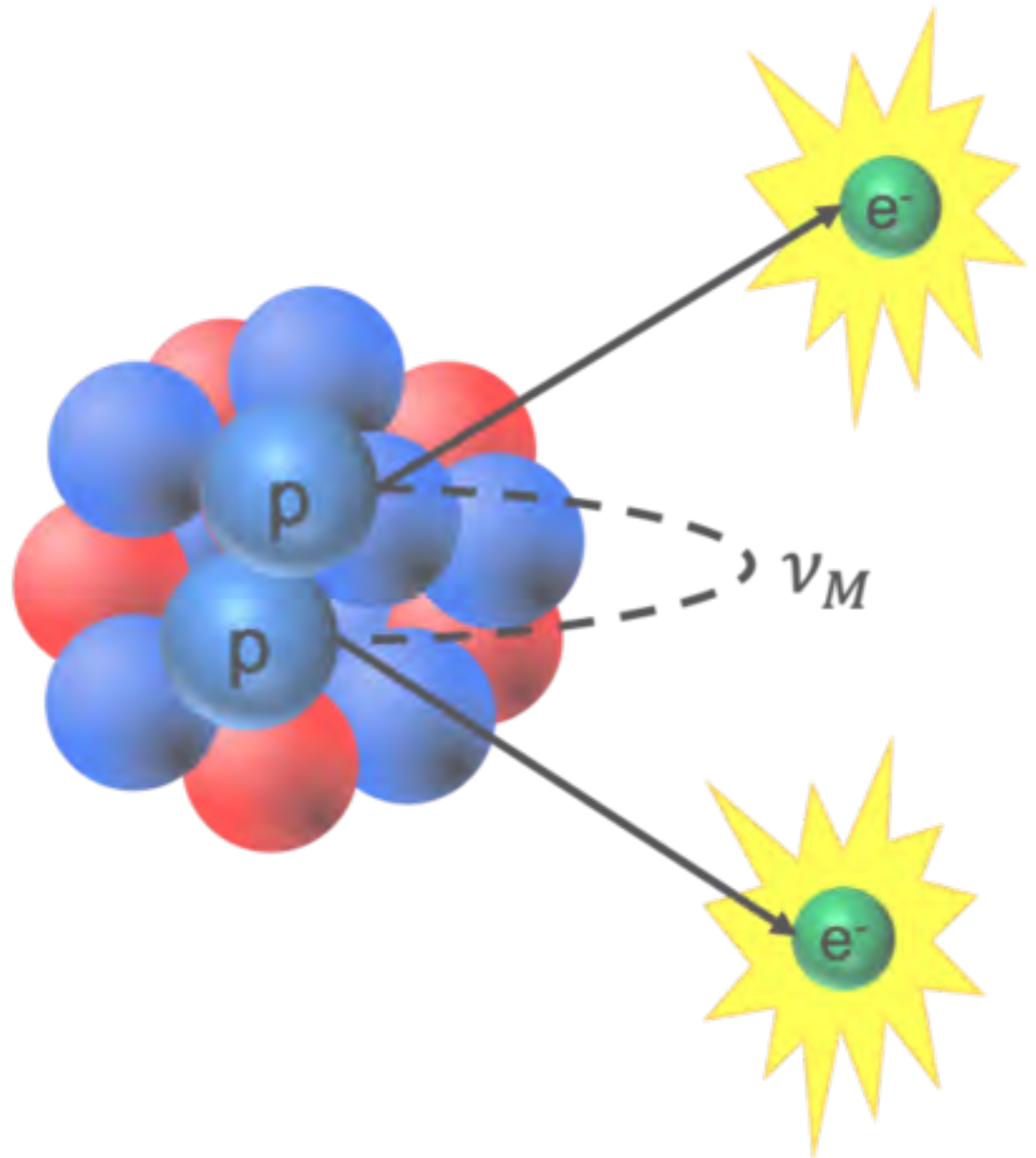
  Any process that allows $0\nu\beta\beta$ to occur requires Majorana neutrinos with non-zero mass.

  Schechter and Valle, 1982



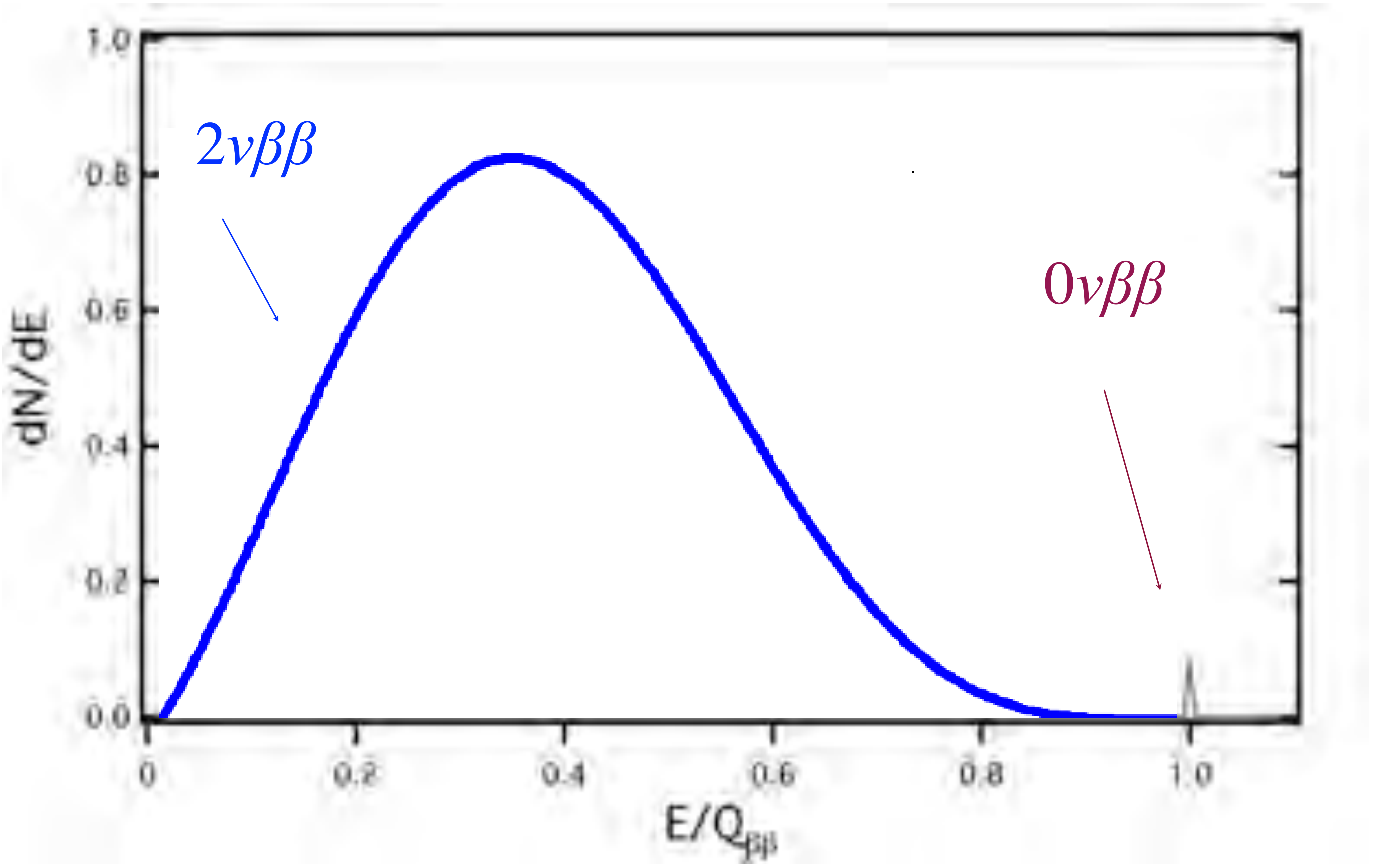
- Matter Creation ⇔ Lepton number violation
  - No experimental evidence that Lepton number must be conserved

    (i.e. allowed based on general SM principles, such as electroweak-isospin conservation and renormalizability)



Experimental searches for 0νββ-decay

Observable : rate of decay (half-life)



0νββ Half-life (years)	~Signal (cnts/ton-year)
10^{25}	500
10^{26}	50
10^{27}	5
10^{28}	0.5
10^{29}	0.05

Covering IH region requires sensitivities of

0νββ $T_{1/2}$ ~ 10^{27}- 10^{28} years

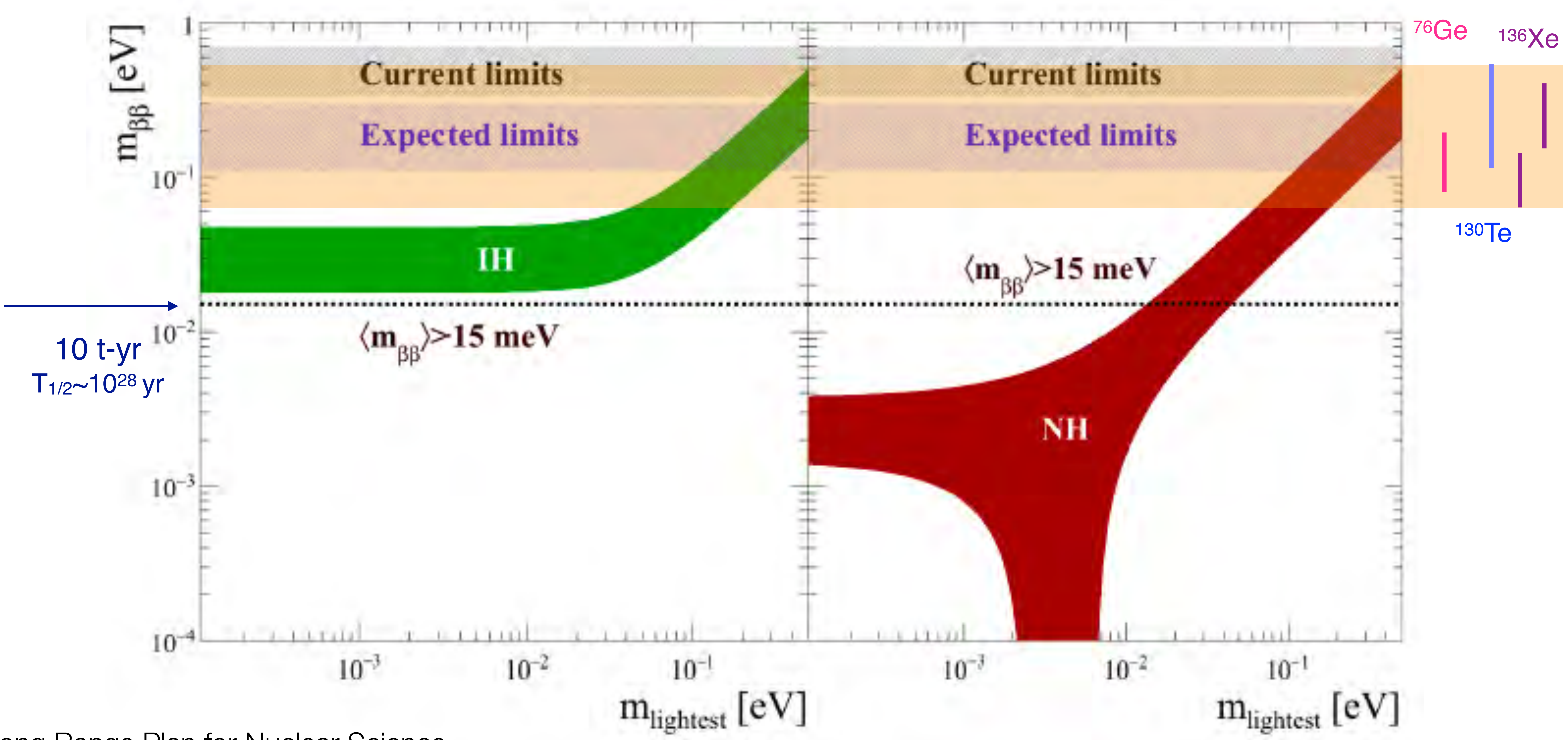
(2νββ $T_{1/2}$ ~ 10^{19} - 10^{21} years)

Constraints on 0νββ Decay from measurements

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

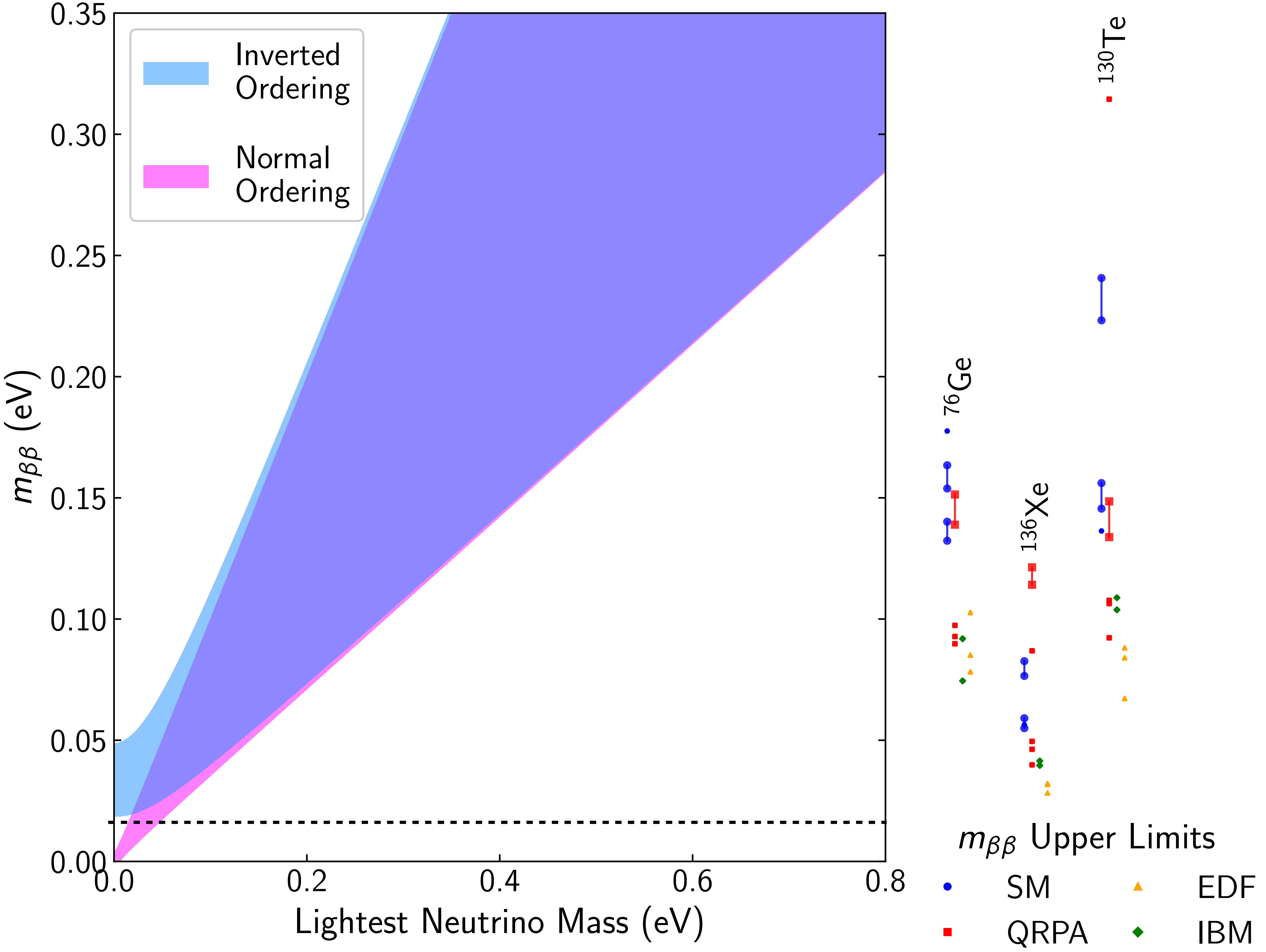
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Upper Limits from:
GERDA
MAJORANA
LEGEND
CUORE
KamLAND-Zen
EXO200

2015 NSAC Long Range Plan for Nuclear Science

Constraints on 0νββ Decay - latest results and NME

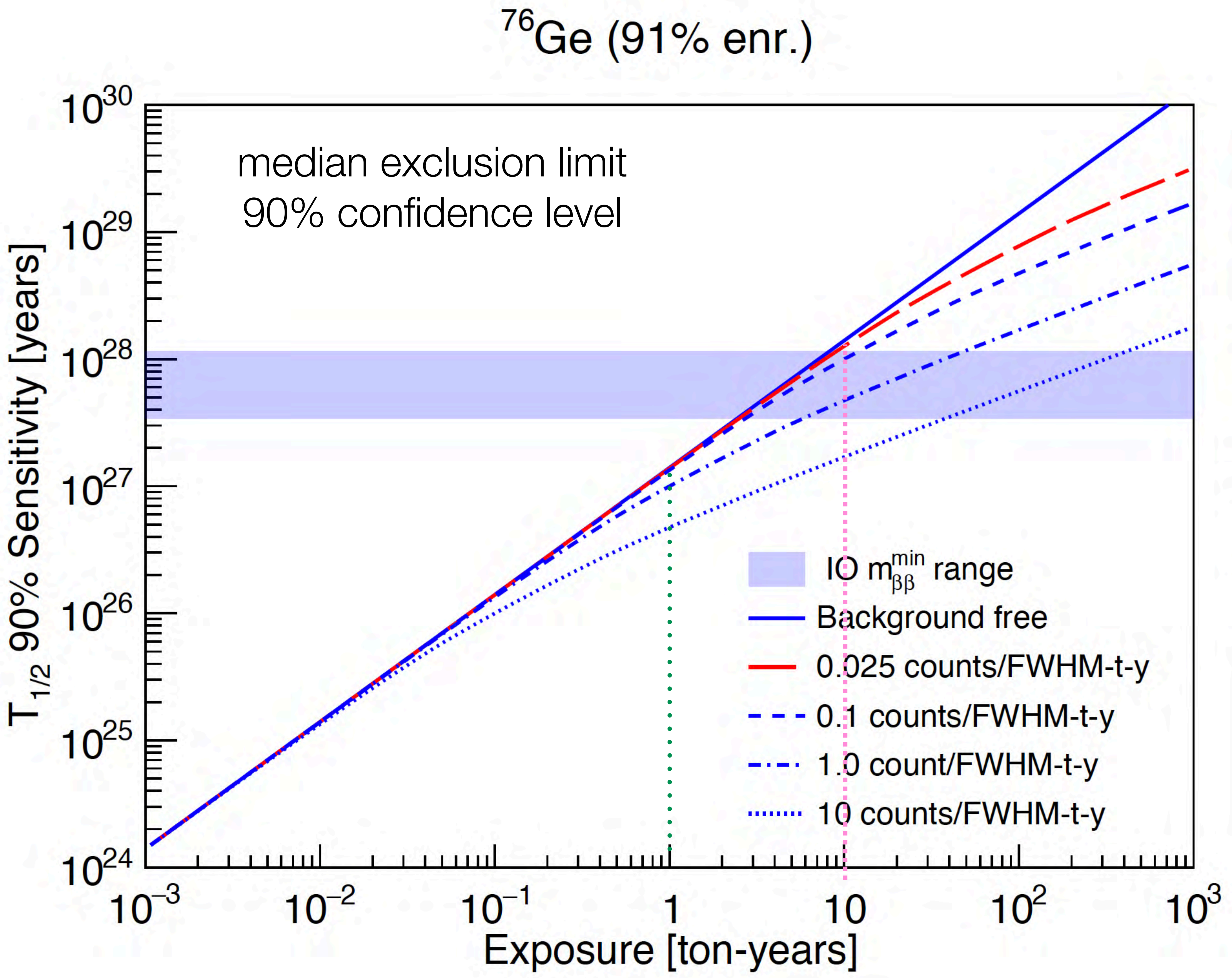


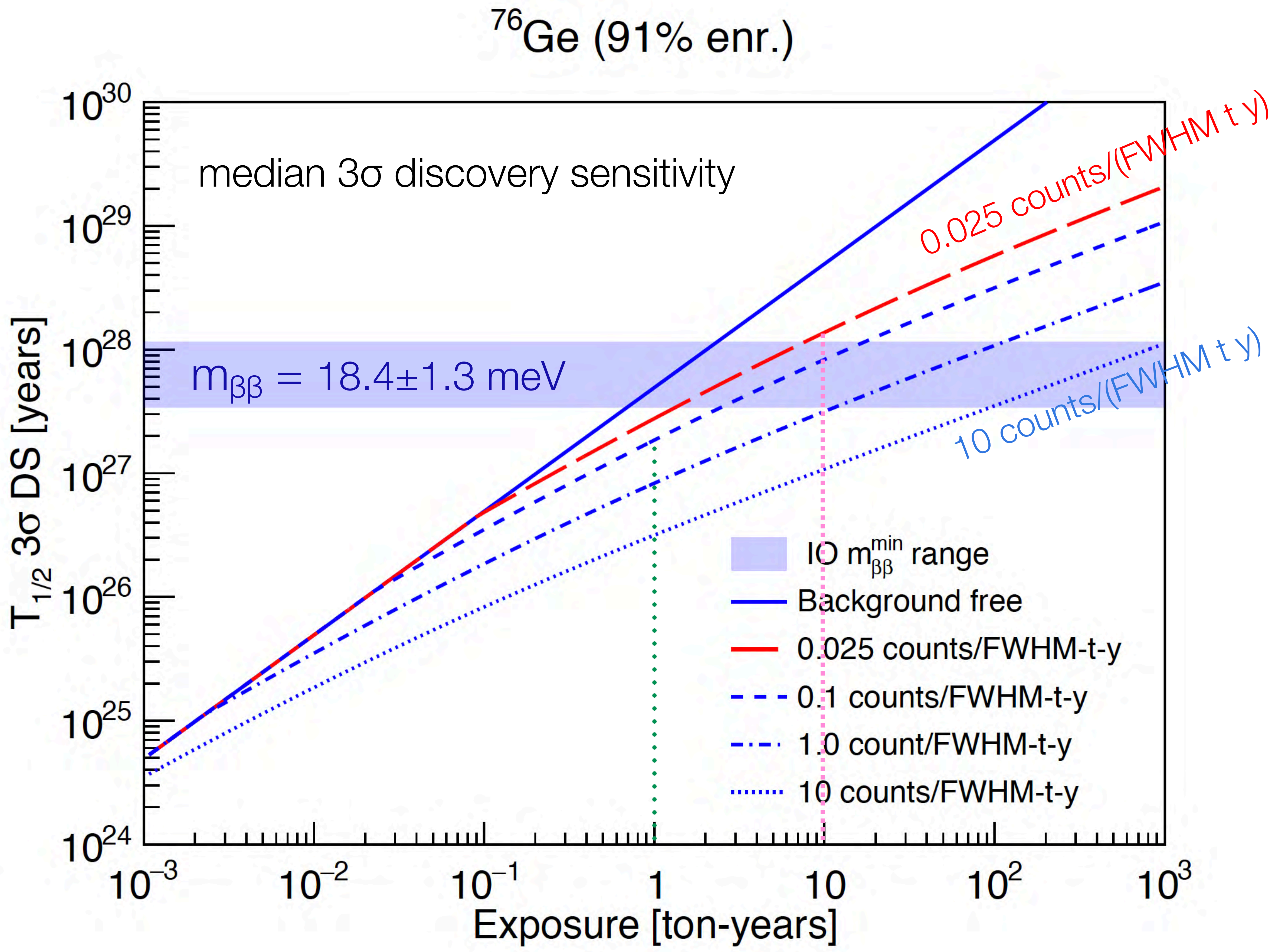
- ^{76}Ge - LEGEND, Neutrino 2024
- ^{136}Xe - KamLAND Zen, Neutrino 2024
- ^{130}Te : CUORE, Neutrino 2024

NMEs from compilation: https://doi.org/10.1103/RevModPhys.95.025002.

$0\nu\beta\beta$ Sensitivity & Discovery vs Exposure & Bkg.

- **Background-free:** Sensitivity rises **linearly** with exposure
- **Quasi-background-free:** Less than one background count expected in a 4σ Region of Interest (ROI) for a given exposure
- **Background-limited:** Sensitivity rises as the **square root** of exposure

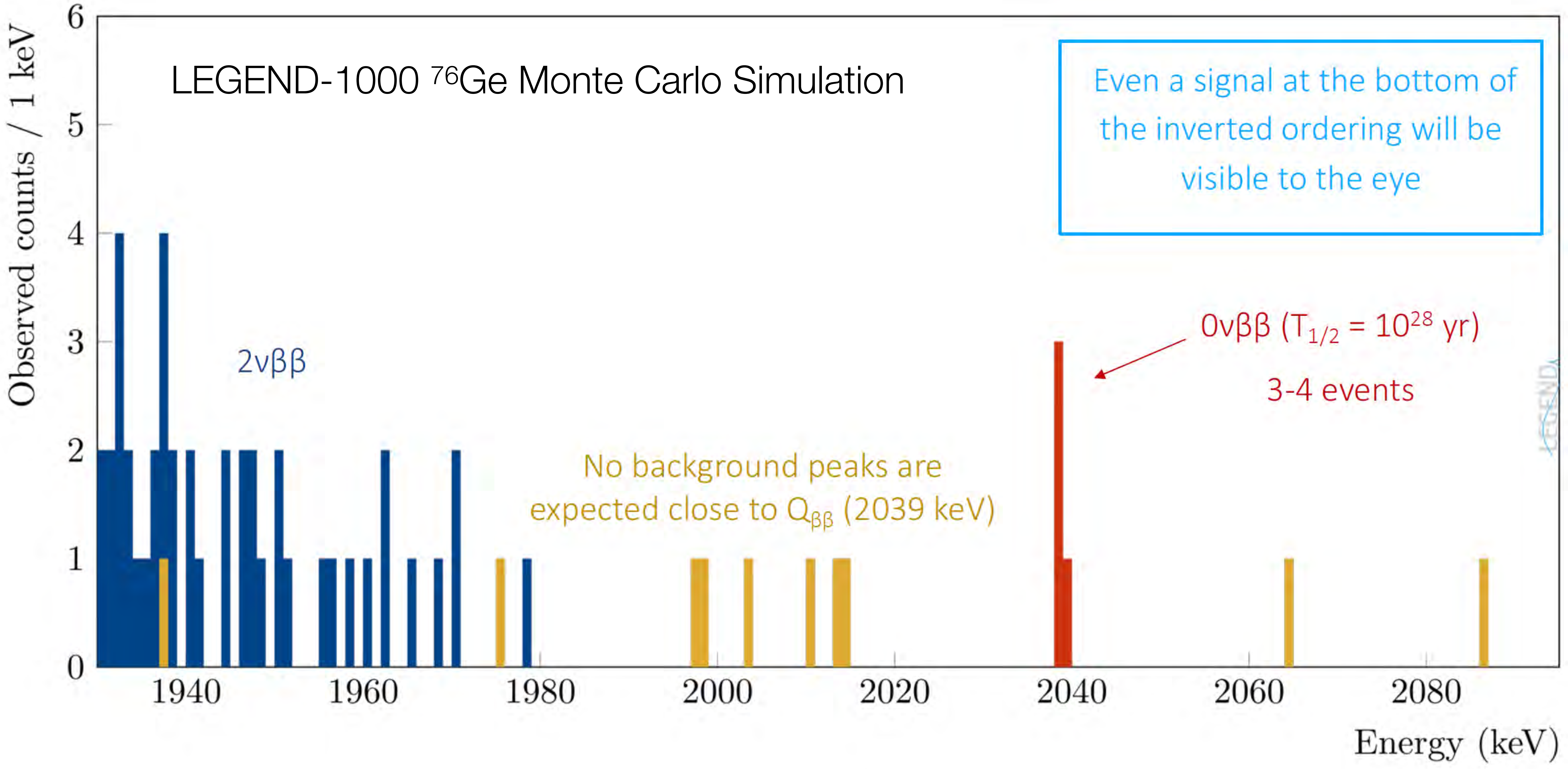




LEGEND-1000 background goal is the red line, 0.025 counts/(FWHM t y) (< 1 x 10^{-5} counts/(keV kg yr))

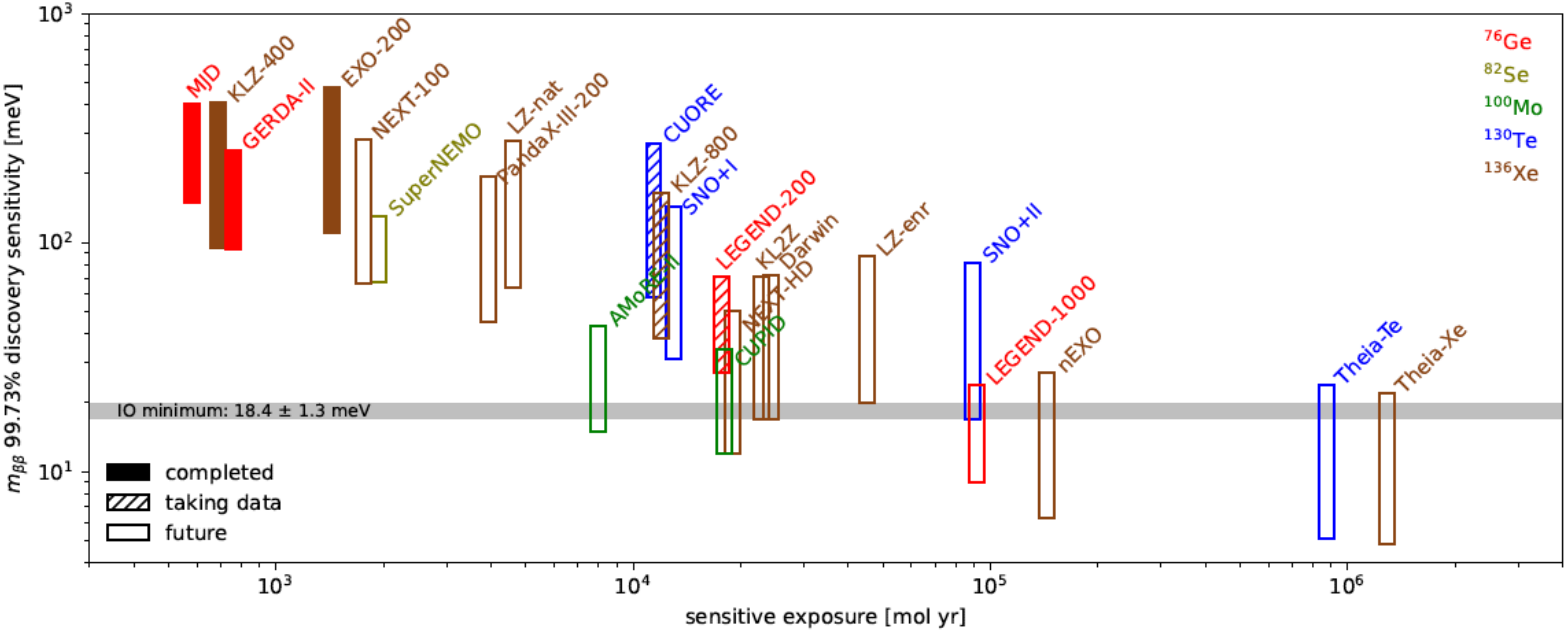
(FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)

What would a Discovery look like?



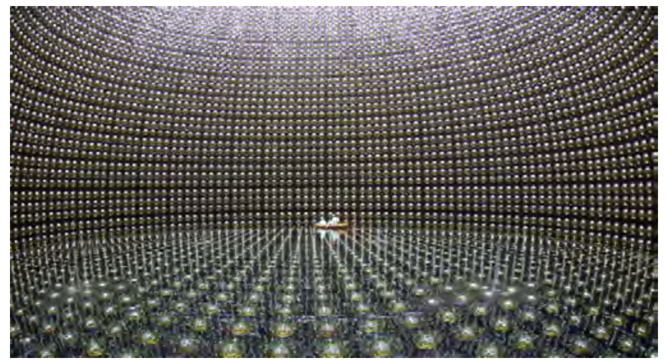
- One desires excellent energy resolution: $\sigma/Q_{\beta\beta} = 0.05$ %
- No background peaks anywhere near the energy of interest (also depends on resolution)
- Nearby background is flat and well understood
- Background measured, with no reliance on background modeling

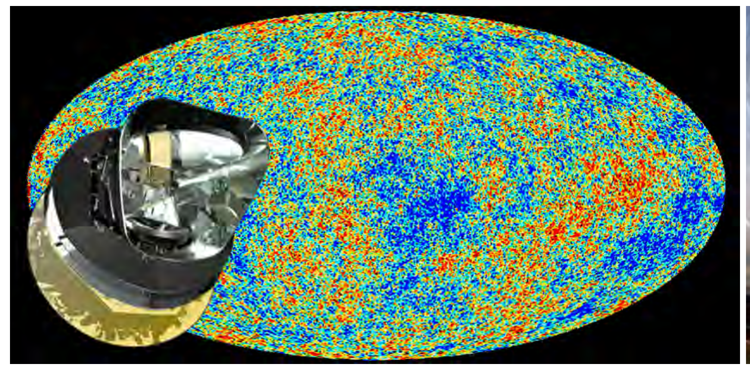
0νββ Decay Discovery Sensitivity



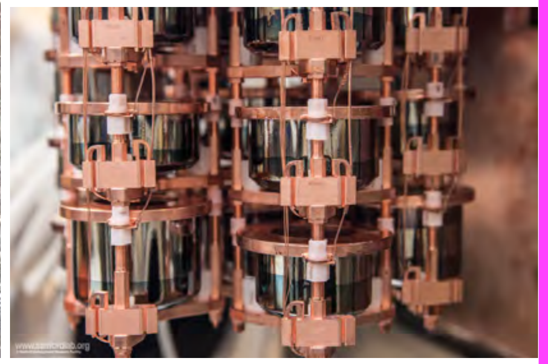
Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 NSAC Long Range Plan

Techniques to determine ν mass





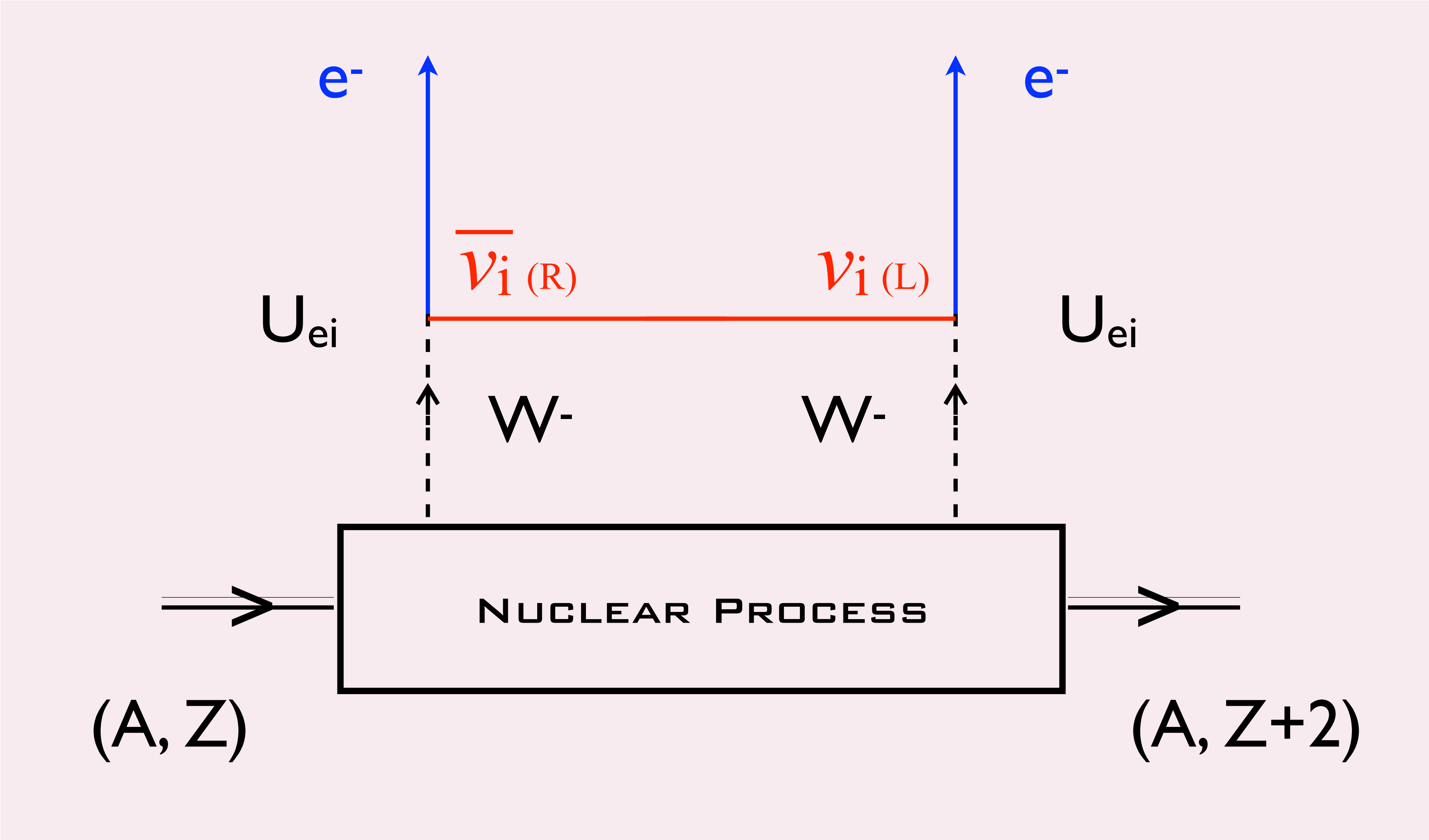


	ν oscillation	Cosmology	Decay kinematics	0νββ
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	$\Sigma_\nu = \sum_i m_i$	$m_\beta = \left(\sum_i \lvert U_{ei}^2 \rvert m_i^2 \right)^{1/2}$	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$
Present	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\, eV^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\, eV^2$	$\Sigma_\nu < 0.12$ eV	$m_\beta < 0.45$ eV ($\Sigma_\nu < 1.35$ eV)	$m_{\beta\beta} < (0.02\text{-}0.3)$ eV ($\Sigma_\nu < (0.06\text{-}0.9)$ eV)
Next Gen Sensitivity		$\Sigma_\nu \sim 0.06$ eV @2σ	$m_\beta \sim 0.2$ eV ($\Sigma_\nu \sim 0.6$ eV)	$m_{\beta\beta} \sim (0.006$ - $.03)$ eV ($\Sigma_\nu < 0.06$ eV)
Model dependences	No mass-scale info. Lower bound on Σ_ν if $m_{\nu light}=0$ IO: $\Sigma_\nu \geq 0.10$ eV NO: $\Sigma_\nu \geq 0.06$ eV	ΛCDM - Fit to 6 + parameters - relativistic particles (N_{eff}) are ν, …	- Energy Conservation - Final State effects	- Majorana ν's - Unknown δ_1, δ_2 phases - L viol. process - NME, g_A

0νββ and ν mass

Observable (decay rate) depends on nuclear processes & nature of lepton number violating interaction(s) (η).



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

$$\Downarrow$$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

- Phase space, $G_{0\nu}$ is calculable.
- Nuclear matrix elements (NME) via theory, also depend on interaction.
- Effective neutrino mass, $\langle m_{\beta\beta}\rangle$, depends directly on the assumed form of lepton number violating (LNV) interactions.
- Not sensitive if neutrino is Dirac particle

Ton-scale and beyond $0\nu\beta\beta$ Considerations

- Is there a preferred $0\nu\beta\beta$ isotope?
  - No preferred isotope in terms of sensitivity per unit mass - within current uncertainties on NME.
- What evidence is needed to claim the observation of $0\nu\beta\beta$?
  - Measurement of a peak (or excess) at the correct energy at 3σ.
  - Observation in two different isotopes.
- What exposure is required to cover Inverted Ordering masses?
  - For a nearly ideal, quasi background free experiment ~ 10 t-y.
- What are the critical experimental considerations?
  - Availability of ton quantity of (enriched) isotopes.
  - Reduction of backgrounds (and/or effective discrimination)
  - $2\nu\beta\beta$ rate (irreducible background) - ^{76}Ge ^{130}Te, ^{136}Xe are the best (longest $T_{1/2}$), but impact depends on resolution.
  - Resolution

Ton-scale 0νββ Status

- U.S. DOE NP 0νββ Portfolio Review (Summer 2021)
  - Ready to proceed with: CUPID (^{100}Mo), LEGEND (^{76}Ge), nEXO (^{136}Xe)
- N. American - European 0νββ Summits (2021, 2023,)
- 2023 A New Era of Discovery, the 2023 Long Range Plan for Nuclear Science Recommendation 2 of 4 — *As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.*

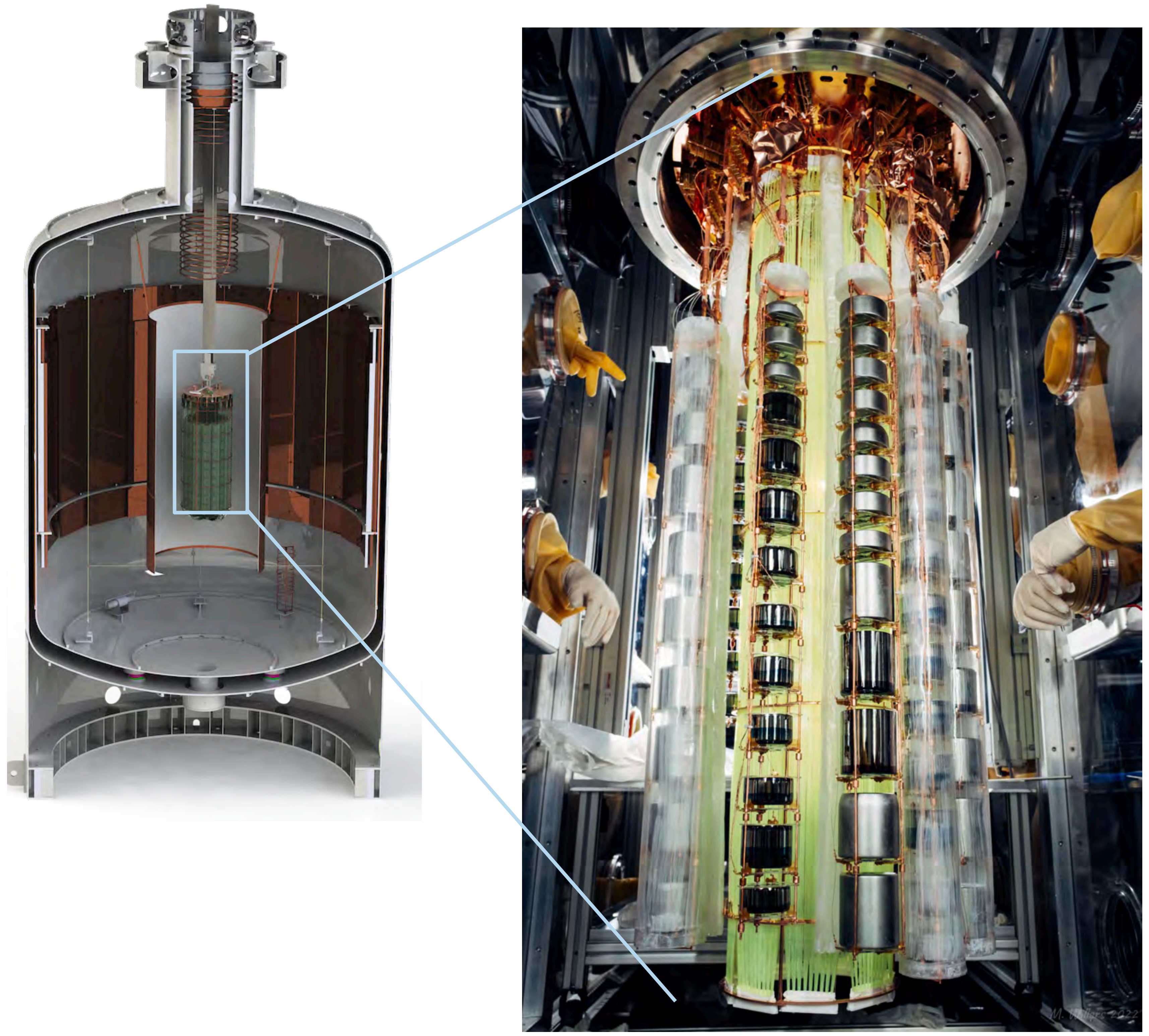
- 2023 European Astroparticle Physics (APPEC) Mid-Term Update — *APPEC strongly supports the CUPID and LEGEND 1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT. APPEC strongly supports fully exploiting the potential of the KATRIN direct neutrino mass measurement and the development of a new generation of experiments beyond KATRIN.*

- Mid 2024 — DOE ONP pauses planned CD-1 reviews for CUPID, LEGEND, nEXO
- Dec. 2024 — DOE ONP will proceed with supporting LEGEND in the near term

Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

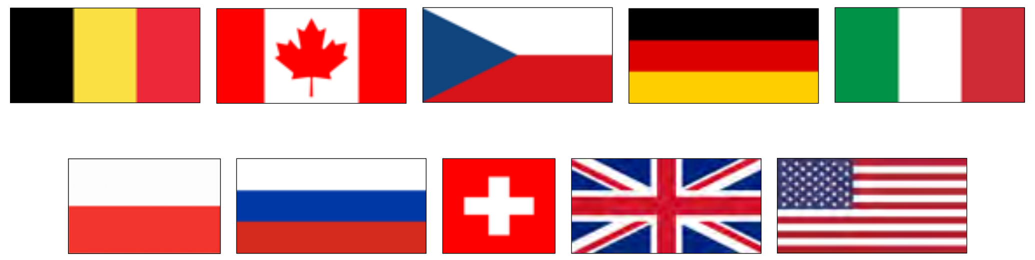
LEGEND-200 - Operating

- 200 kg ^{76}Ge enriched to > 88%
- BG goal : < 2.0 x 10^{-4} counts/(keV kg yr)
- Exposure : 1 t-y
- Location : Laboratori Nazionali del Gran Sasso (LNGS), Italy



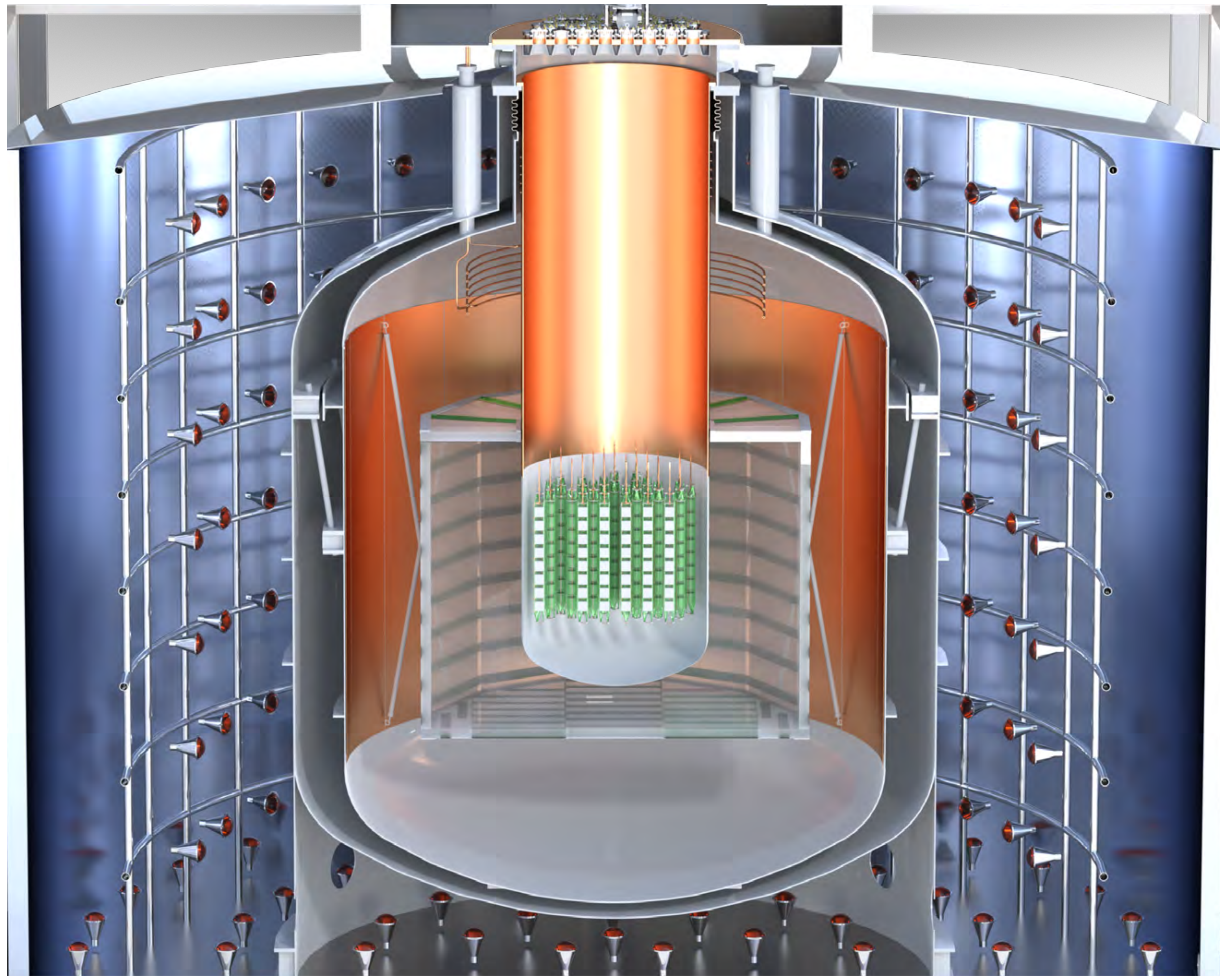
Mission : "Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years"

- 280 members
- 59 institutions around the world



LEGEND-1000 - Proposed

- 1000 kg ^{76}Ge enriched to > 90%
- BG goal : < 1 x 10^{-5} counts/(keV kg yr)
- Exposure : 10 t-y
- Location : Laboratori Nazionali del Gran Sasso (LNGS), Italy



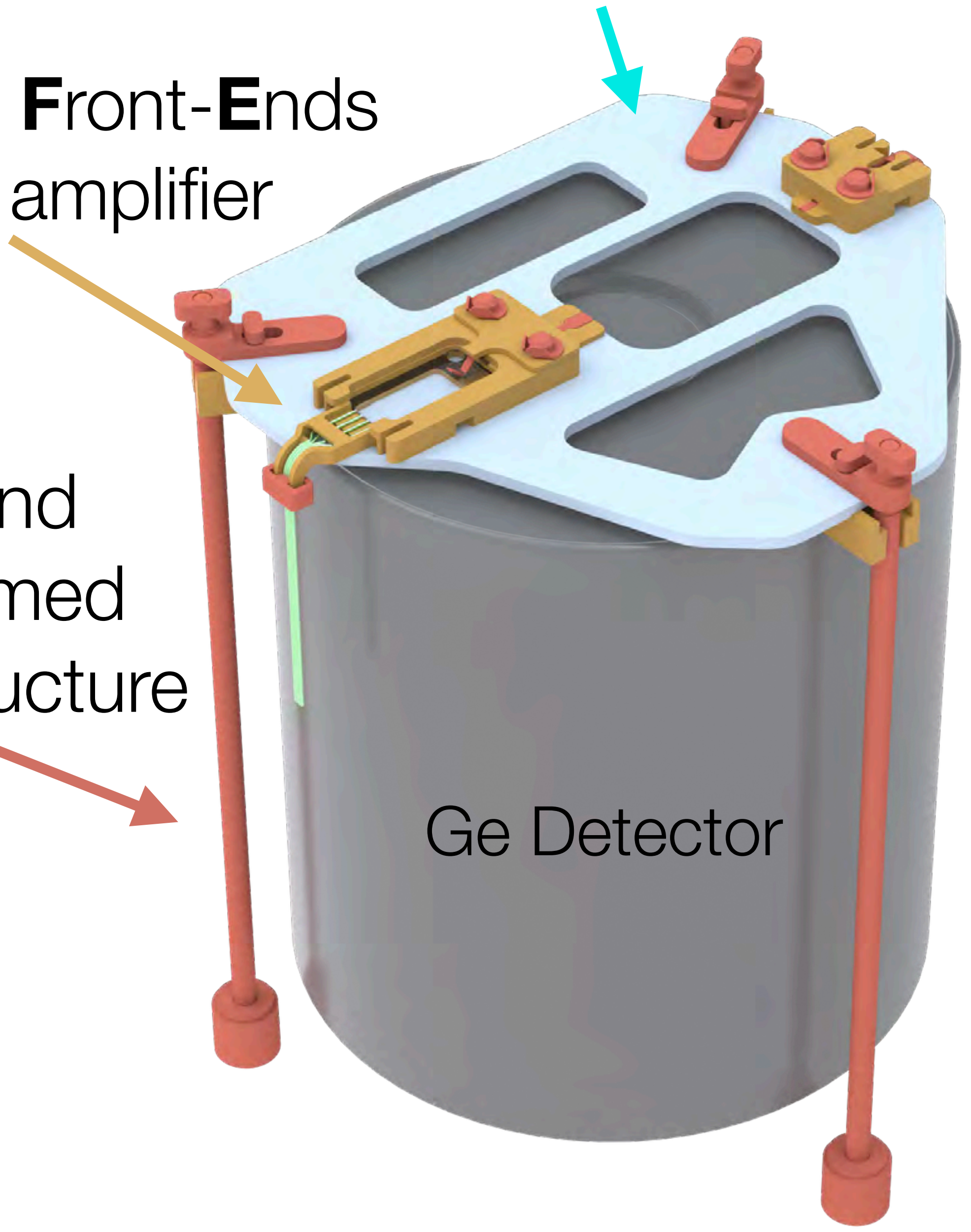
LEGEND-200 Experimental Overview

Ge Detector Unit:

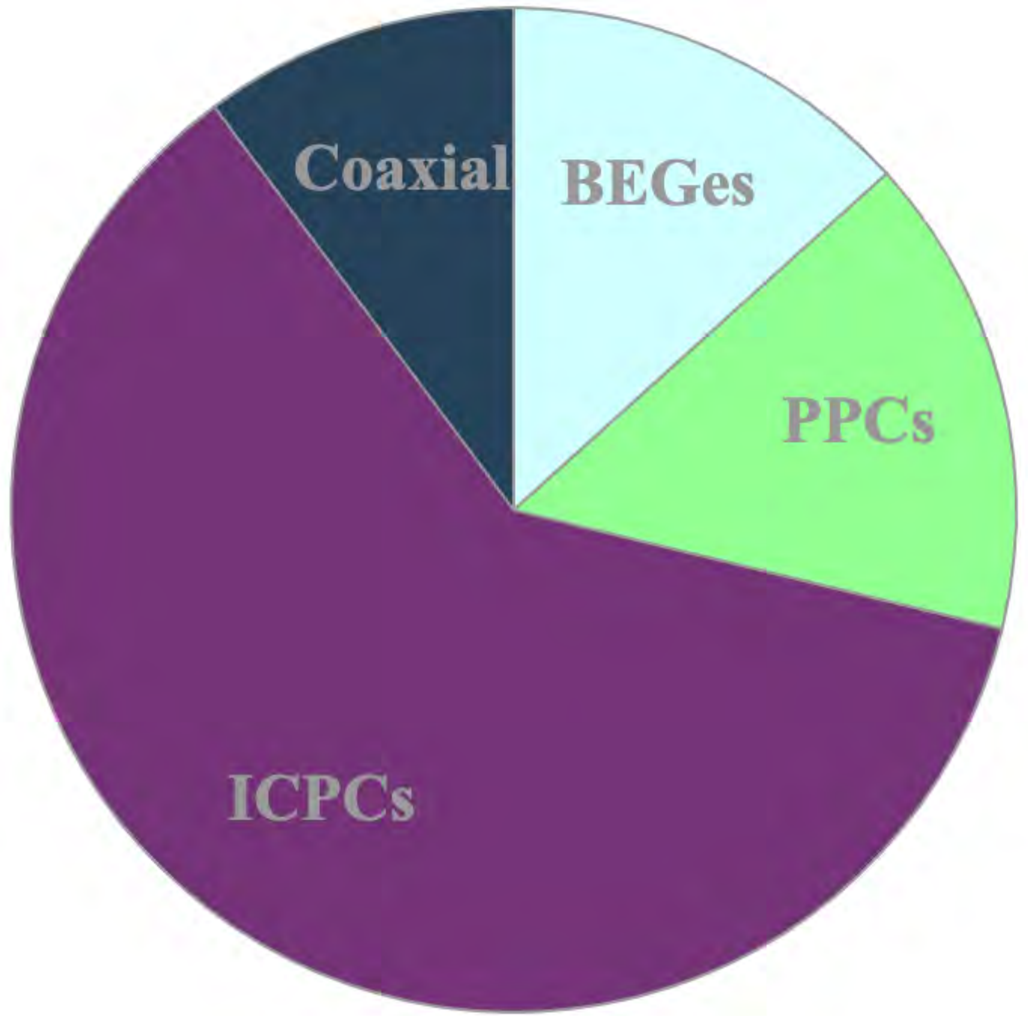
Poly**e**thylene **N**apthalate (PEN) baseplate

Low **M**ass **F**ront-**E**nds (LMFE) amplifier

Underground electro-formed copper structure



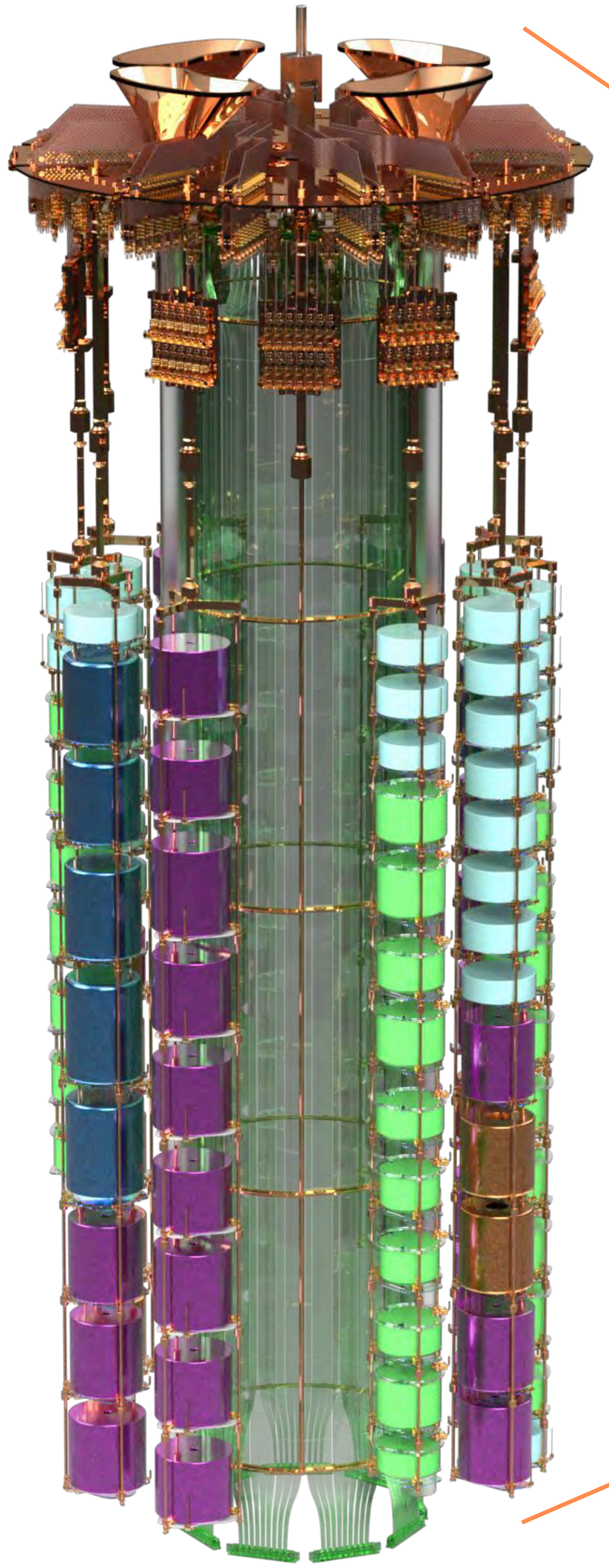
Inverted detector unit with an ICPC detector



Ge Detectors during 1st measurement campaign

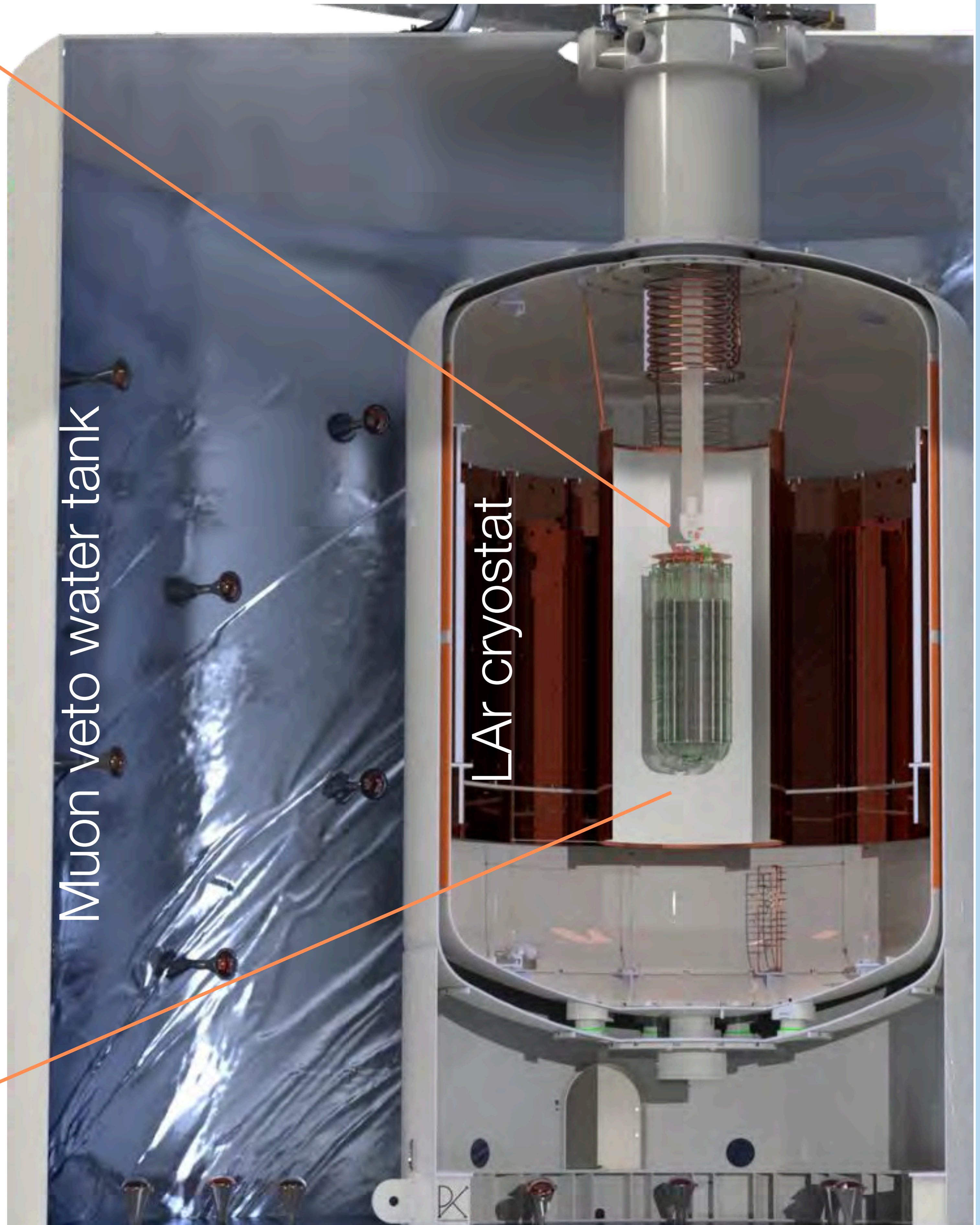
Ge Array and LAr instrumentation:

- Inner barrel of fiber shroud for LAr instrumentation
- 12 String locations
- Outer fiber shroud installed after detectors (not in rendering)



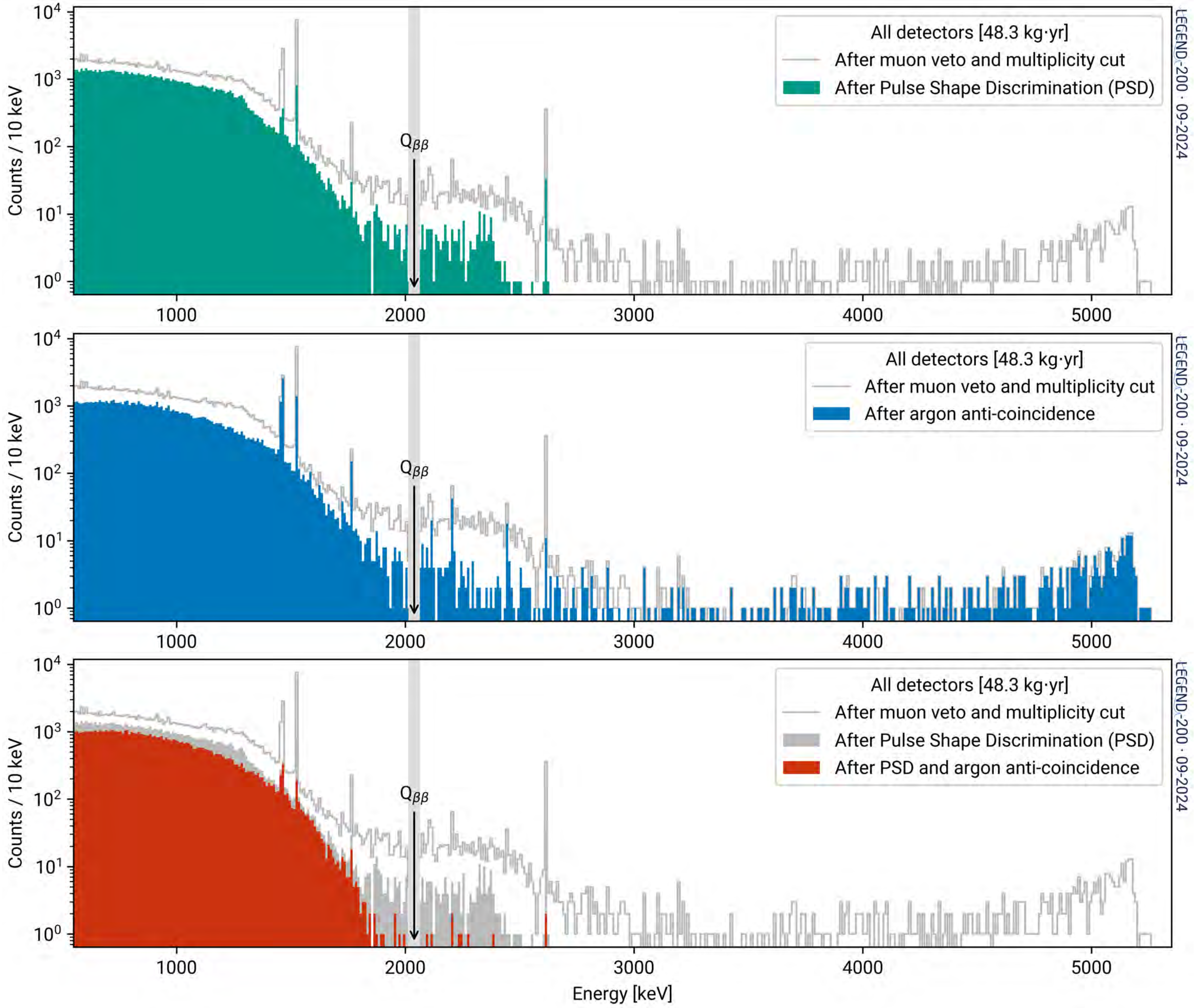
Infrastructure:

- LAr cryostat with wavelength shifting fibers
- LAr purification and quality monitoring
- Water tank equipped with PMTs for muon veto



LEGEND Innovations — Background Reduction

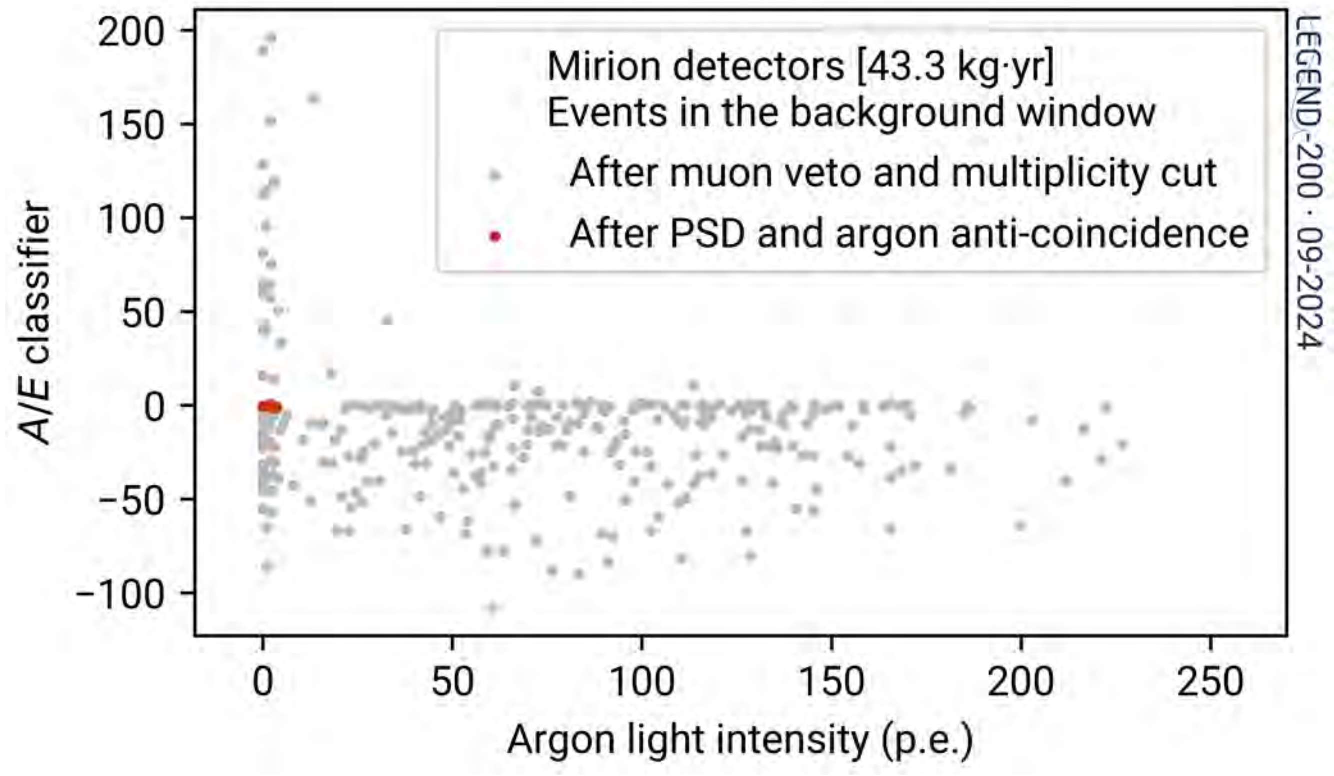
LEGEND-200, Neutrino 2024



Ge Event topologies cut

LAr coincidence Cut

Both



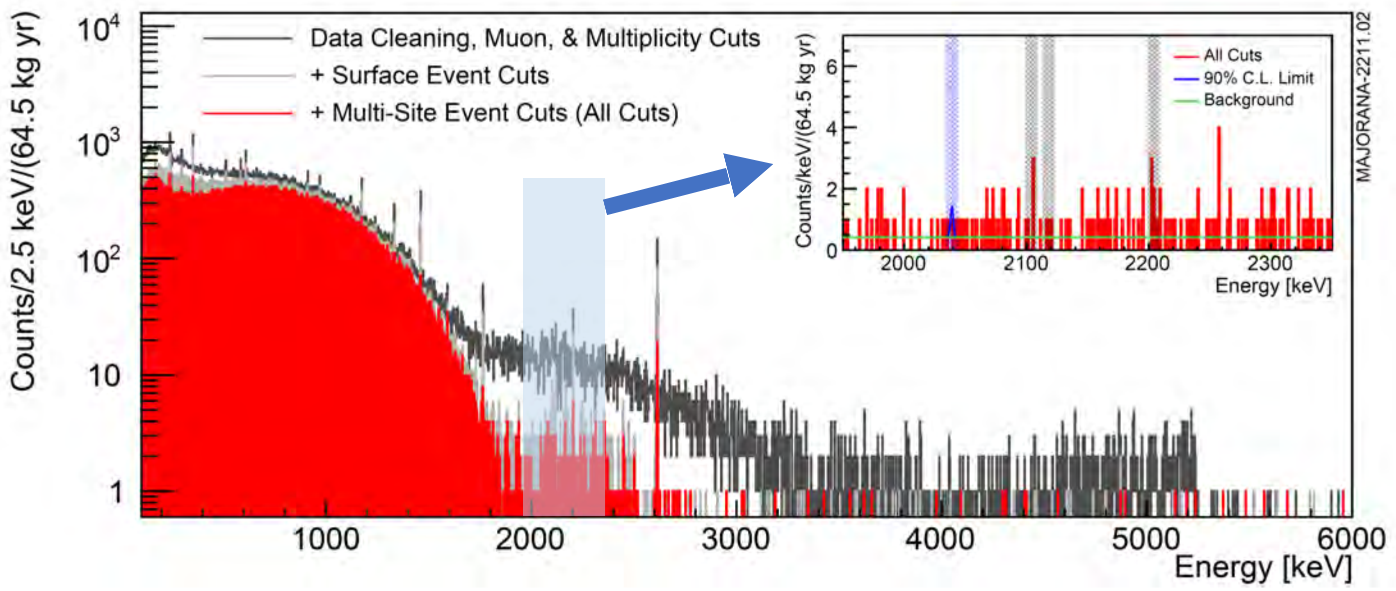
LEGEND-1000 builds on MAJORANA, GERDA, and LEGEND-200

MAJORANA DEMONSTRATOR

Vacuum cryostats in a passive graded shield with ultra-clean materials

Best resolution in ROI of all $0\nu\beta\beta$ Expts.

PRL 130 062501 (2023)



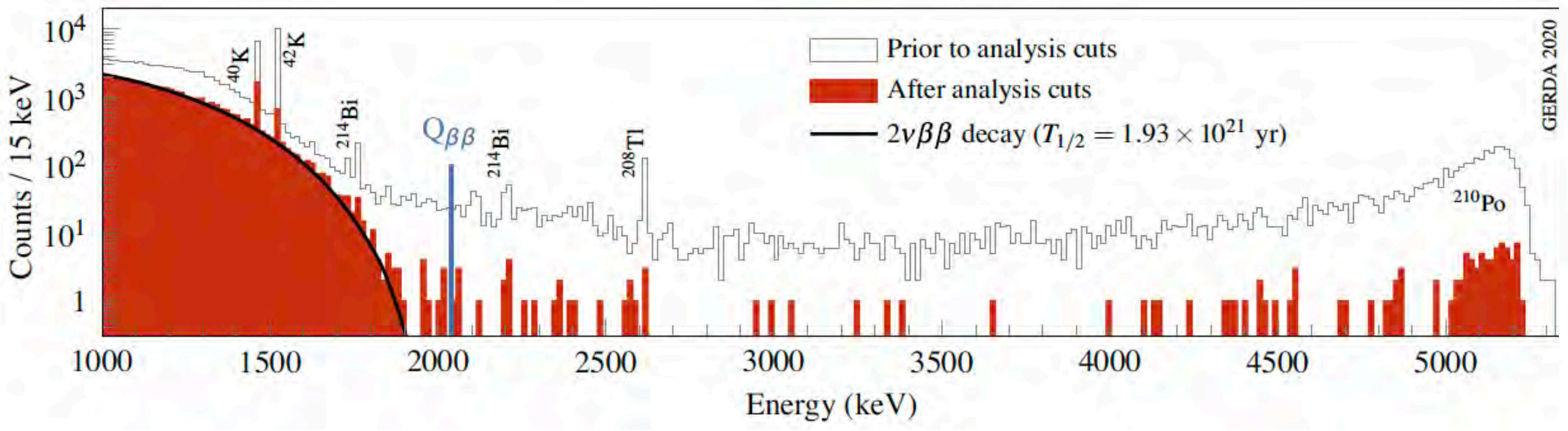
$T_{1/2} > 0.83 \cdot 10^{26}$ yr (90% C.I.)

GERDA

Direct immersion in active LAr shield with outer water shield

Lowest bkg. in ROI of all $0\nu\beta\beta$ Expts.

PRL 125 252502 (2020)



$T_{1/2} > 1.8 \cdot 10^{26}$ yr (90% C.I.)

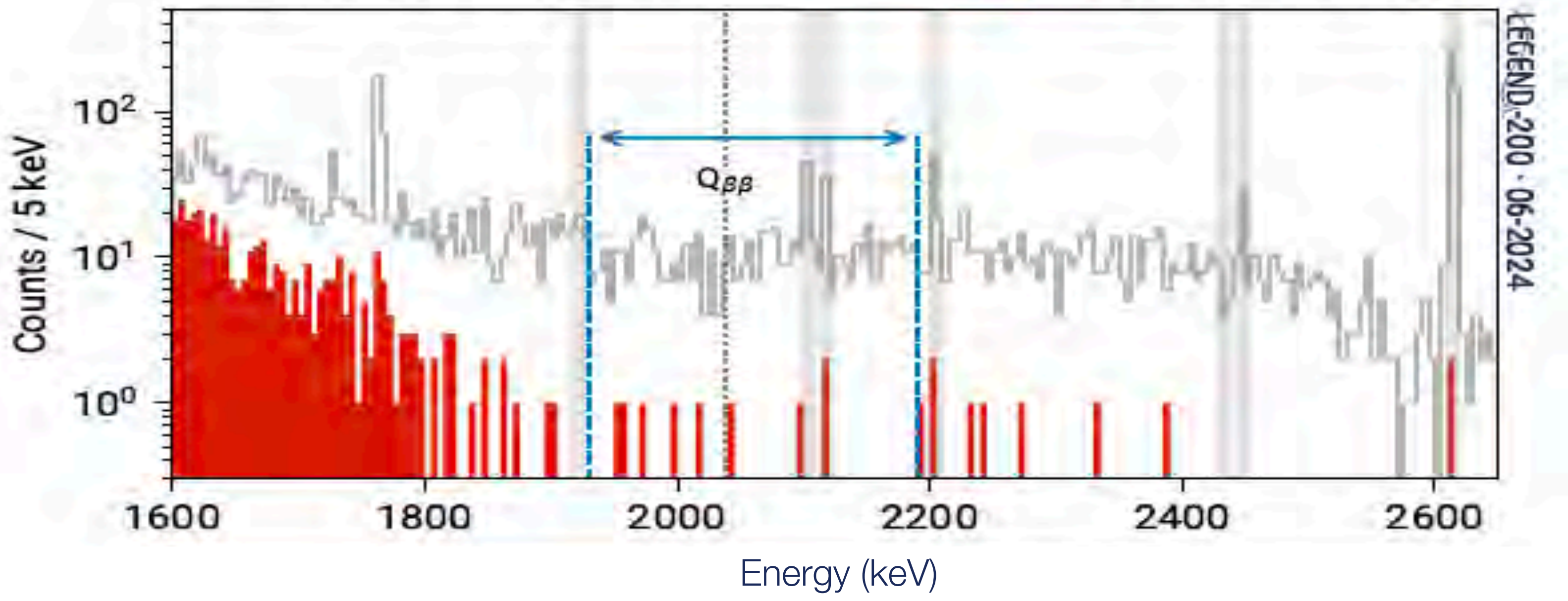
LEGEND-200

Started physics measurements March 2023

Excellent resolution

Bkg. comparable to GERDA

Neutrino 2024

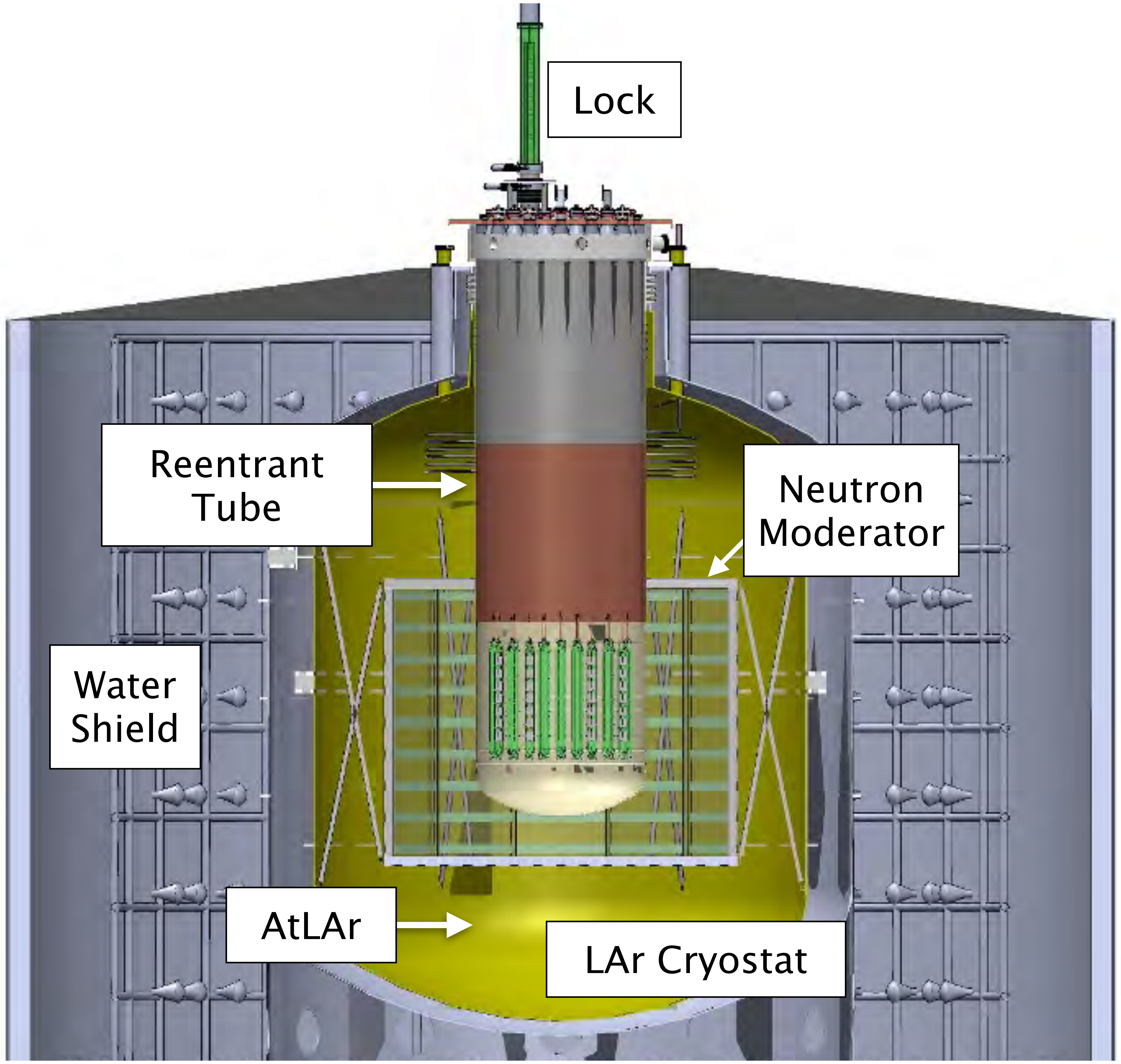


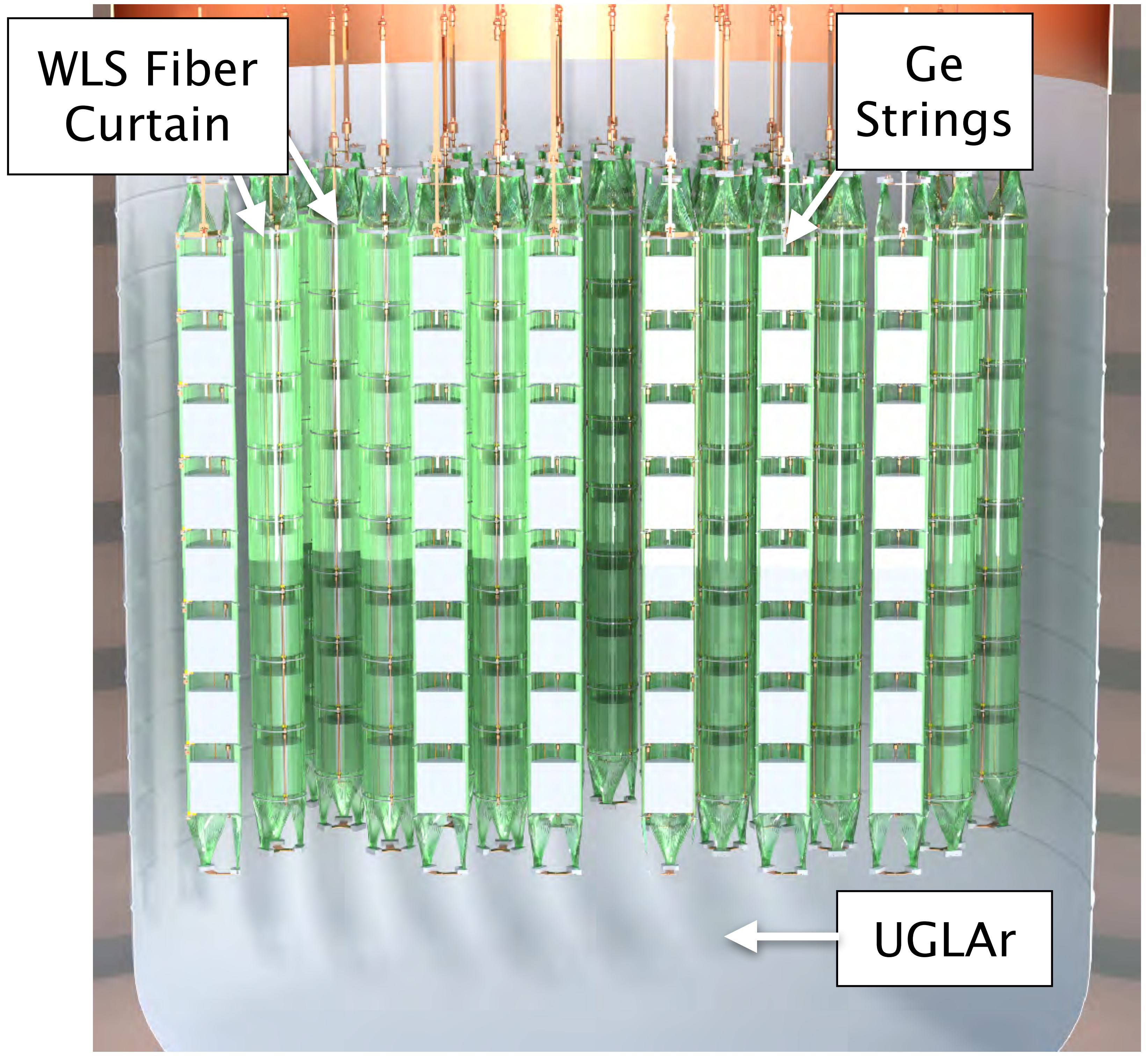
$T_{1/2} > 0.5 \cdot 10^{26}$ yr (90% C.I.)

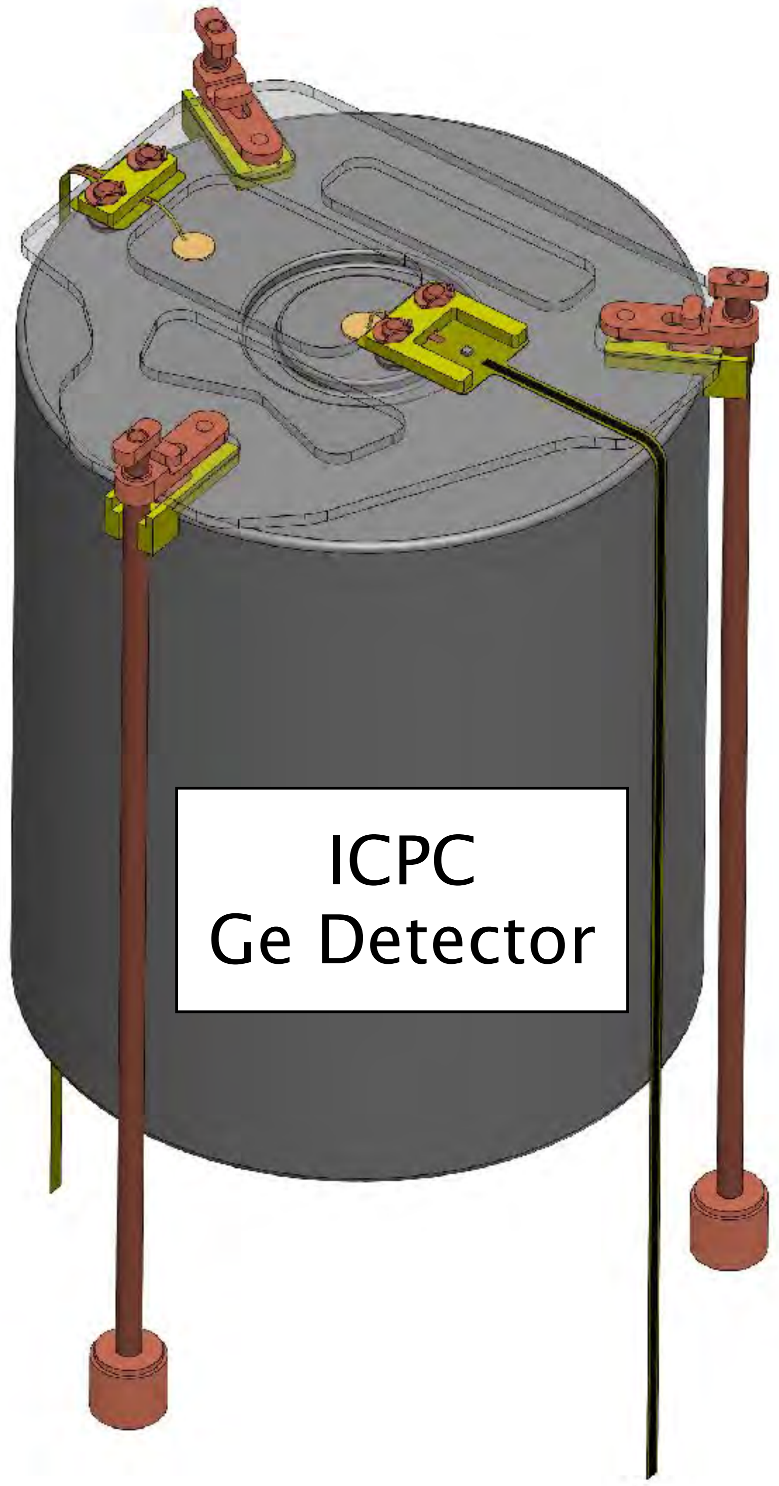
Combined GERDA, MAJORANA, AND LEGEND-200 $T_{1/2} > 1.9 \cdot 10^{26}$ yr (90% C.I.)

(Expected Sensitivity : $2.8 \cdot 10^{26}$ yr (90% C.I.))

LEGEND-1000 – Overview

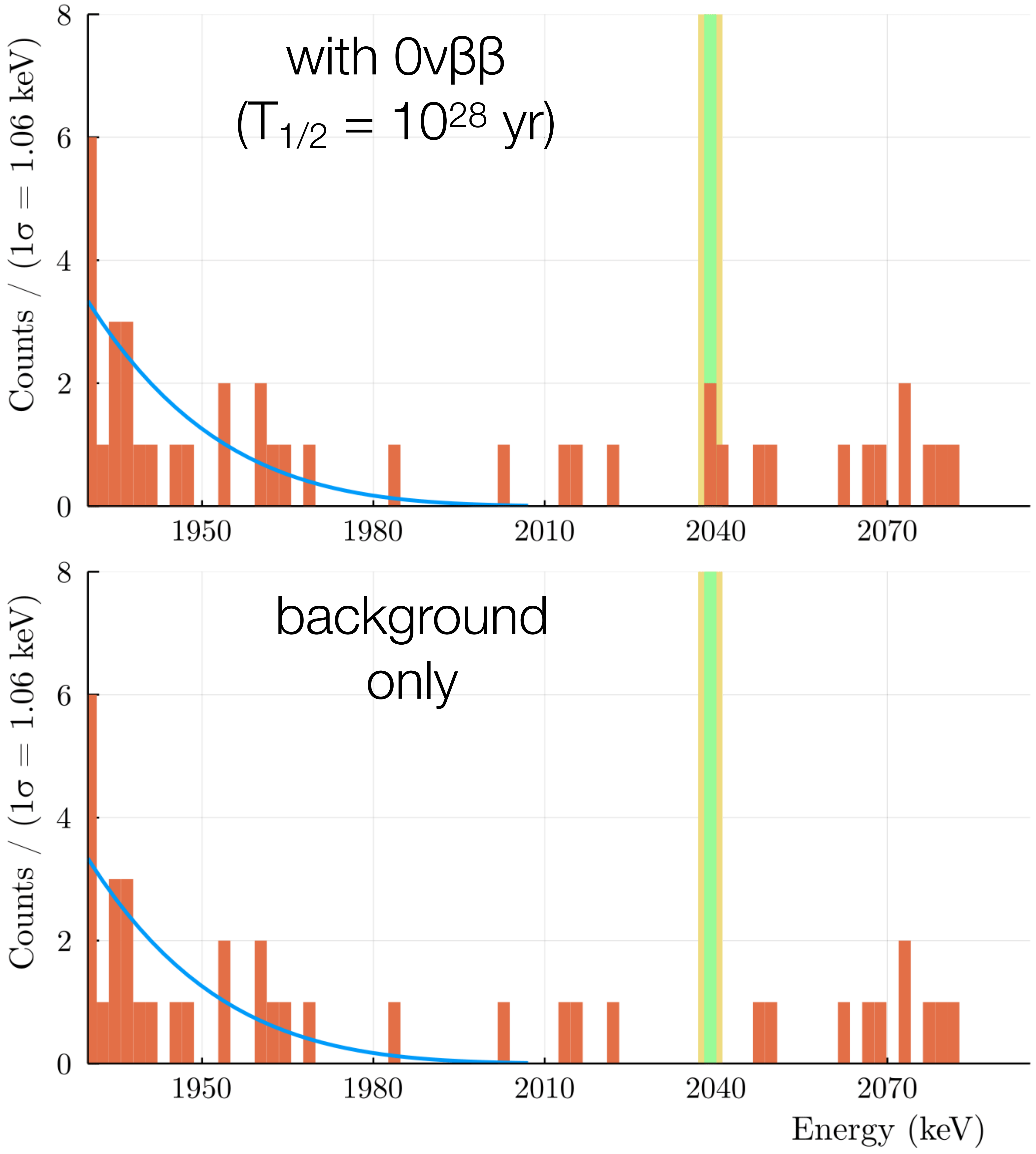






LEGEND-1000 will meet the Discovery Level Goal

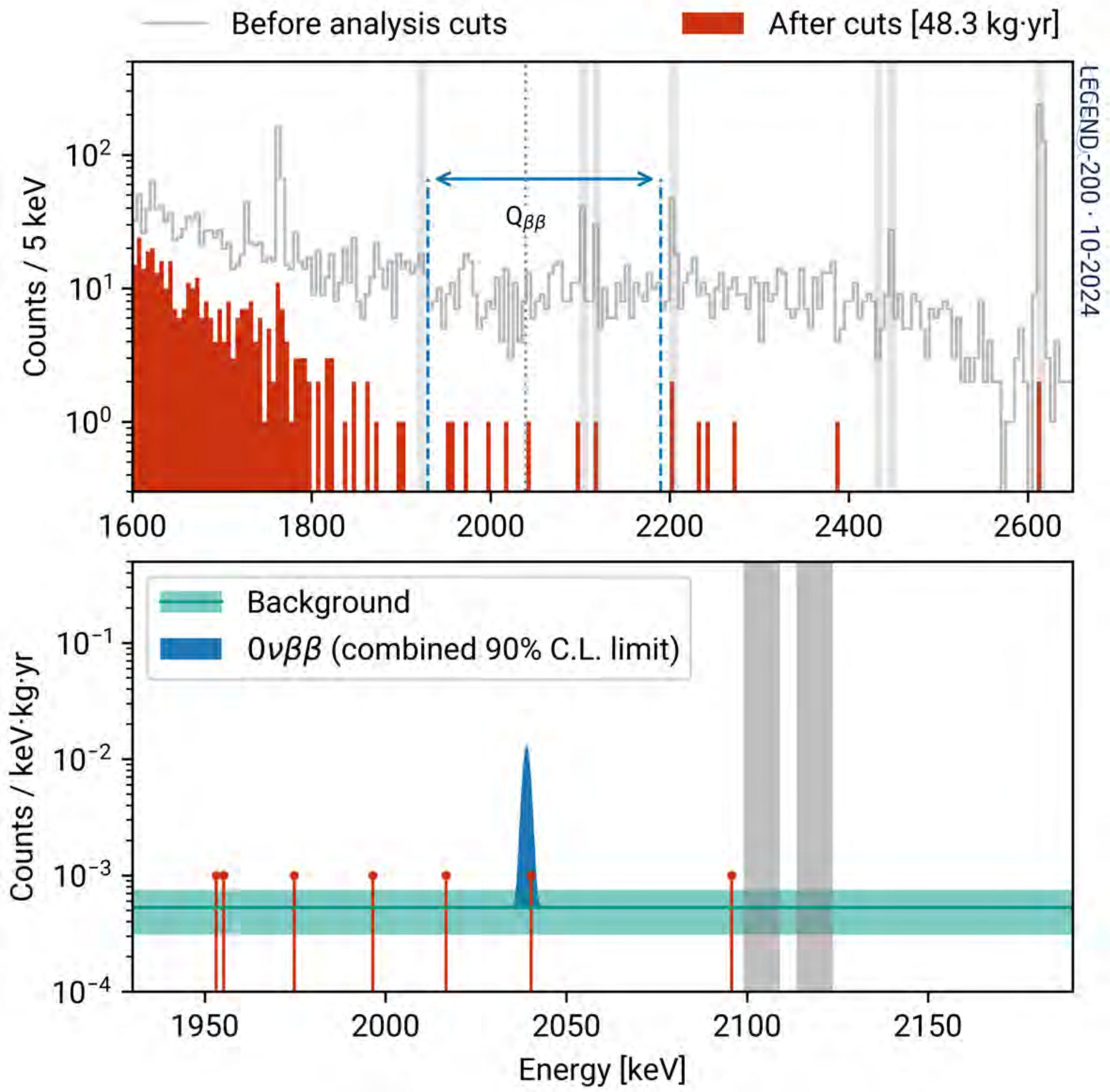
- Goal criterion defined by U.S. Nuclear Science Advisory subcommittee: 50% chance of 3-σ discovery at extreme of inverted ordering region.
- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
  - Need 10 ton-years of data to get a few counts (less than (less than one decay per year per ton of material
  - Need a good signal-to-background ratio to get statistical significance
    - A very low background event rate
    - The best possible energy resolution Animation of simulations contains 100 instances.
- The probability of a background fluctuation at $Q_{\beta\beta}$ that mimics a signal (3 or more counts) is 0.27%.
- When the 0νββ peak is included, even at a half-life of 10^{28} yr, one often sees a clustering of events near $Q_{\beta\beta}$. More than 50% of these are a 3σ excess.



LEGEND Going Forward

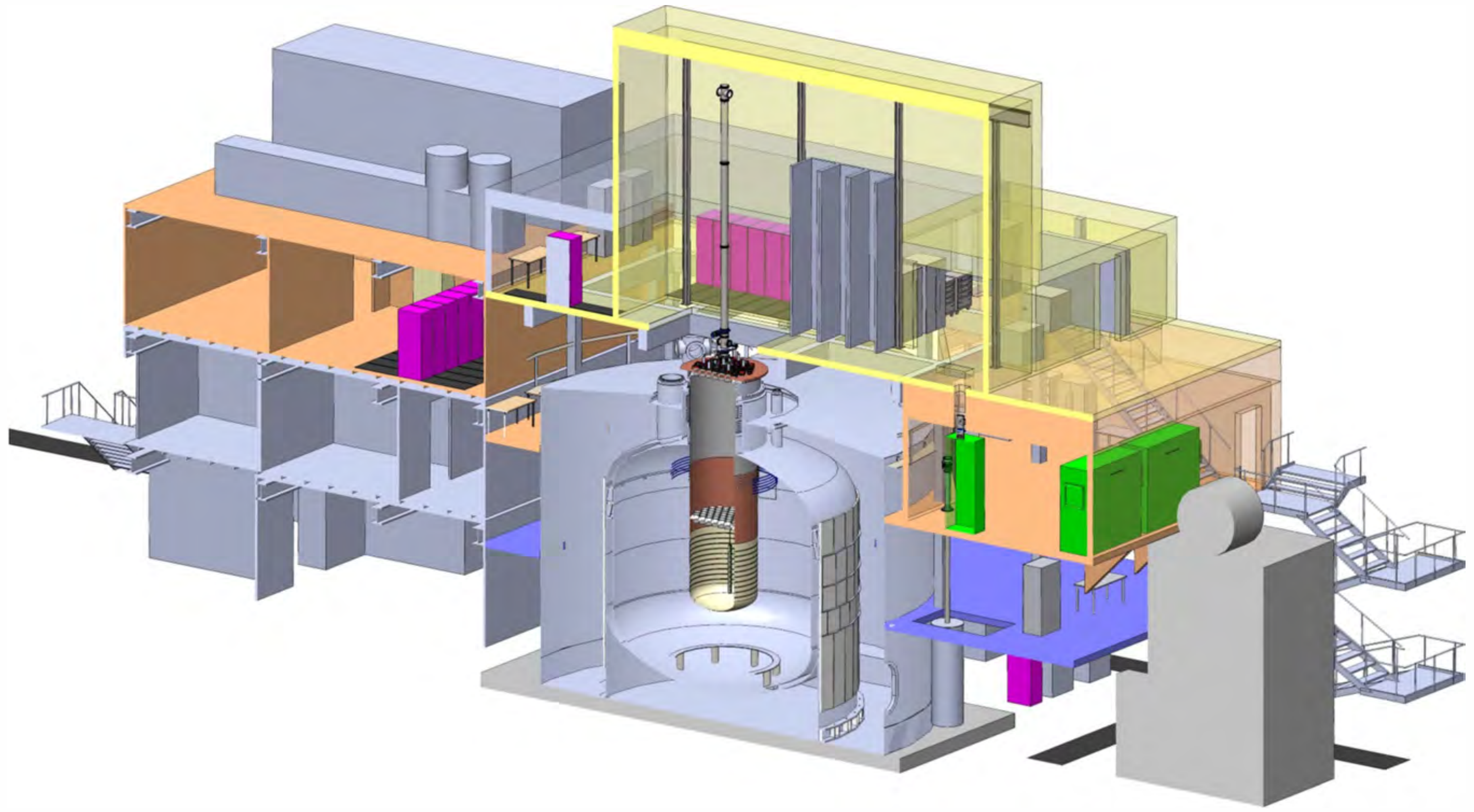
LEGEND-200:

- Preparing a paper on first physics measurements presented at Neutrinos 2024, will include additional exposure.
- In late May, started maintenance period, removed array from LAr, disassembled, performing “forensic” assays of instrument components.
- Reassembling instrument, will resume measurements in Feb. - March.
- Continue to fabricate additional ICPC detectors, aim is 200 kg of detectors.



LEGEND-1000:

- DOE CD-1 review should occur in CY2025.
- NSF Mid-scale proposal is being converted to a MREFC project in final design phase, possible start in FY2027.
- Infrastructure proposal submitted to BMBF by German colleagues.
- Preparation of space in Hall C at LNGS is underway.



Celebrating Baha and George

- explore possibilities within the realm of what is known, predict observables, make connections
- training the next generation of scientists