The search for Neutrinoless Double Beta Decay

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The questions

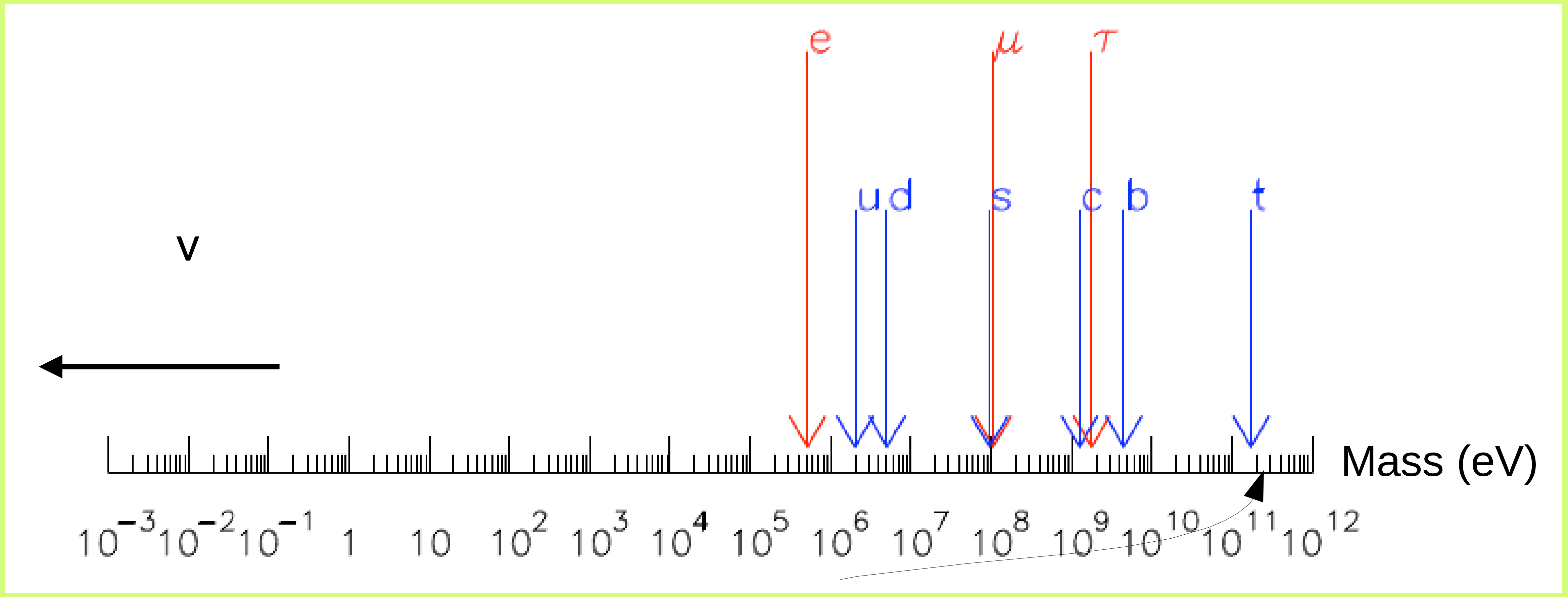
- SM symmetries
  - Conservation of total lepton number L, B - L
  - Crucial for theories explaining the dominance of matter over antimatter in the Universe
- Neutrino properties
  - Stable neutral elementary fermion, 3 families, only EW interactions, flavour eigenstates ≠ mass eigenstates (PMNS matrix)
  - Unknown nature: Dirac or Majorana
  - Unknown absolute mass

Neutrino nature and mass scale

These neutrino properties are not accessible by oscillation experiments:

- Dirac vs Majorana nature
  - ➡ **double-beta decay**
- Absolute neutrino mass scale
  - ➡ end-point of β-decay spectrum
  - ➡ cosmological data
  - ➡ **double-beta decay**

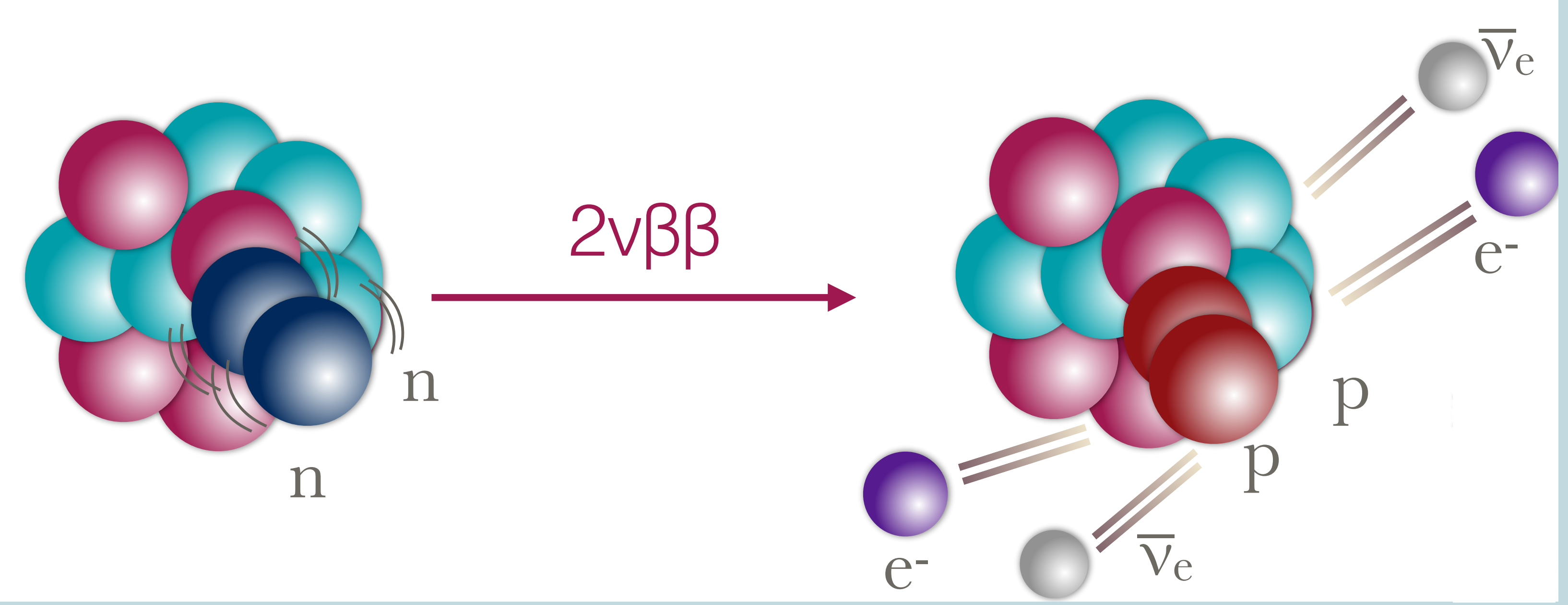
THE DISCOVERY THAT NEUTRINOS HAVE MASS CALLS FOR AN EXPLANATION OF SUCH MASS AND HAS INCREASED THE INTEREST IN THE NEUTRINOLESS DOUBLE BETA DECAY

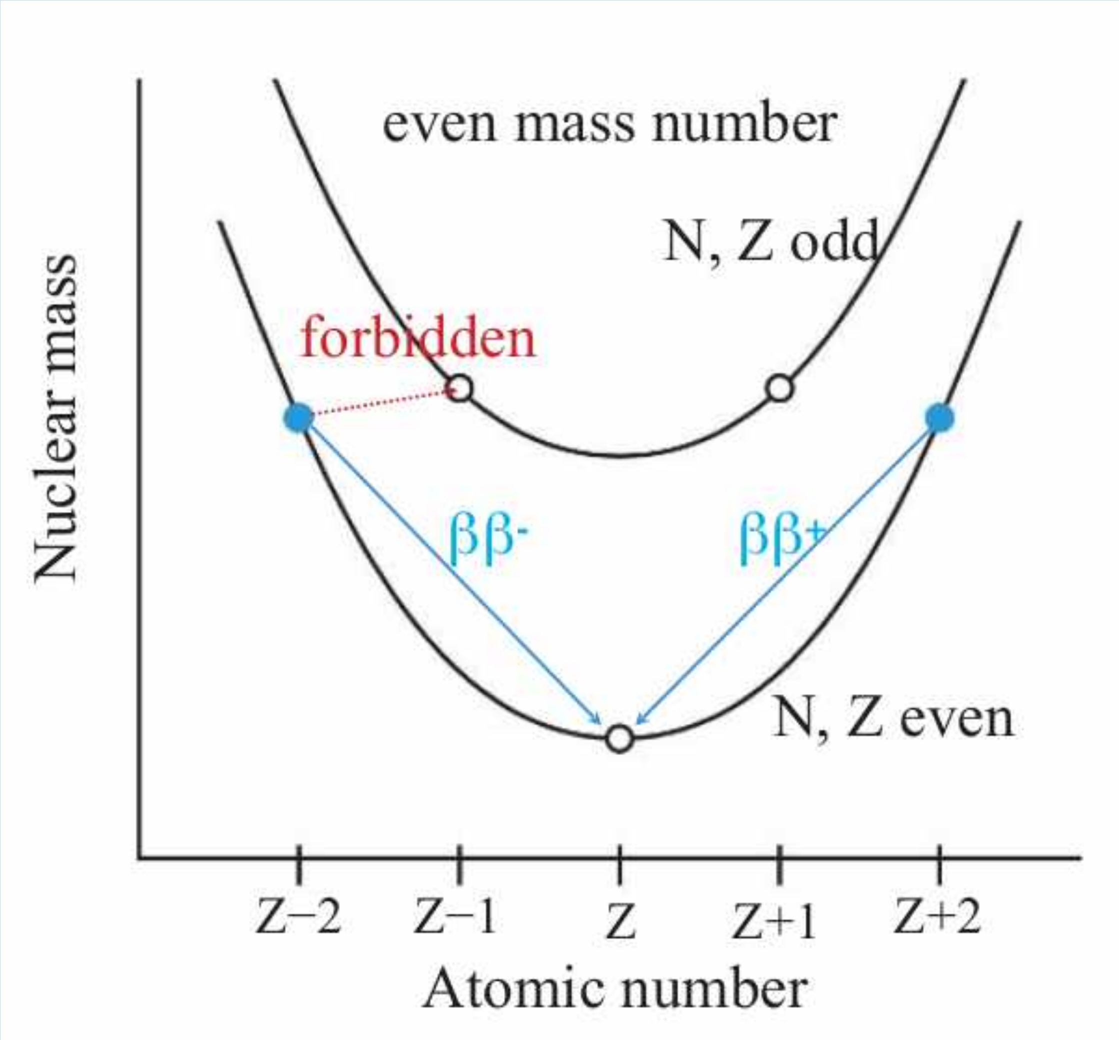


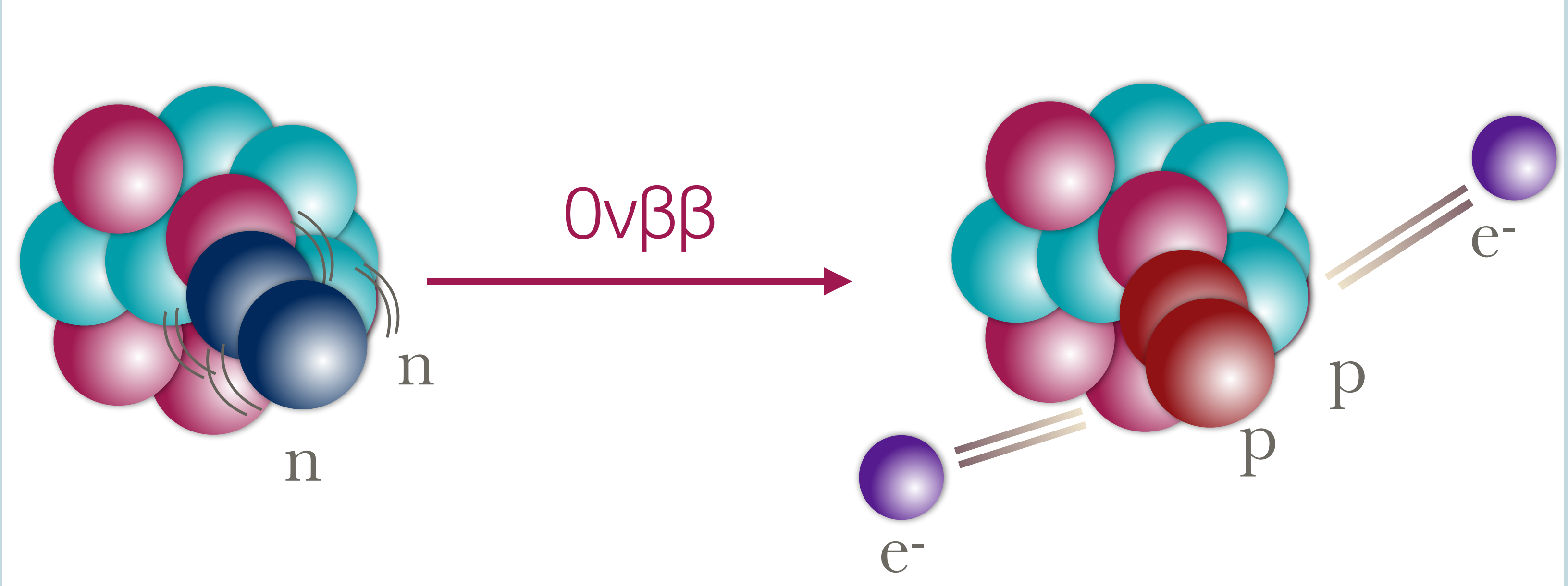
Double beta decay

ΔL = 2
Δ(B-L) = -2

ΔL = 0
Δ(B-L) = 0







(A,Z) → (A,Z+2) + 2e$^-$ + 2$\overline{\nu}$

2nd order weak process allowed by the SM

Observed in several nuclei with half-life ≳ 10^{18} yr

(A,Z) → (A,Z+2) + 2e$^-$

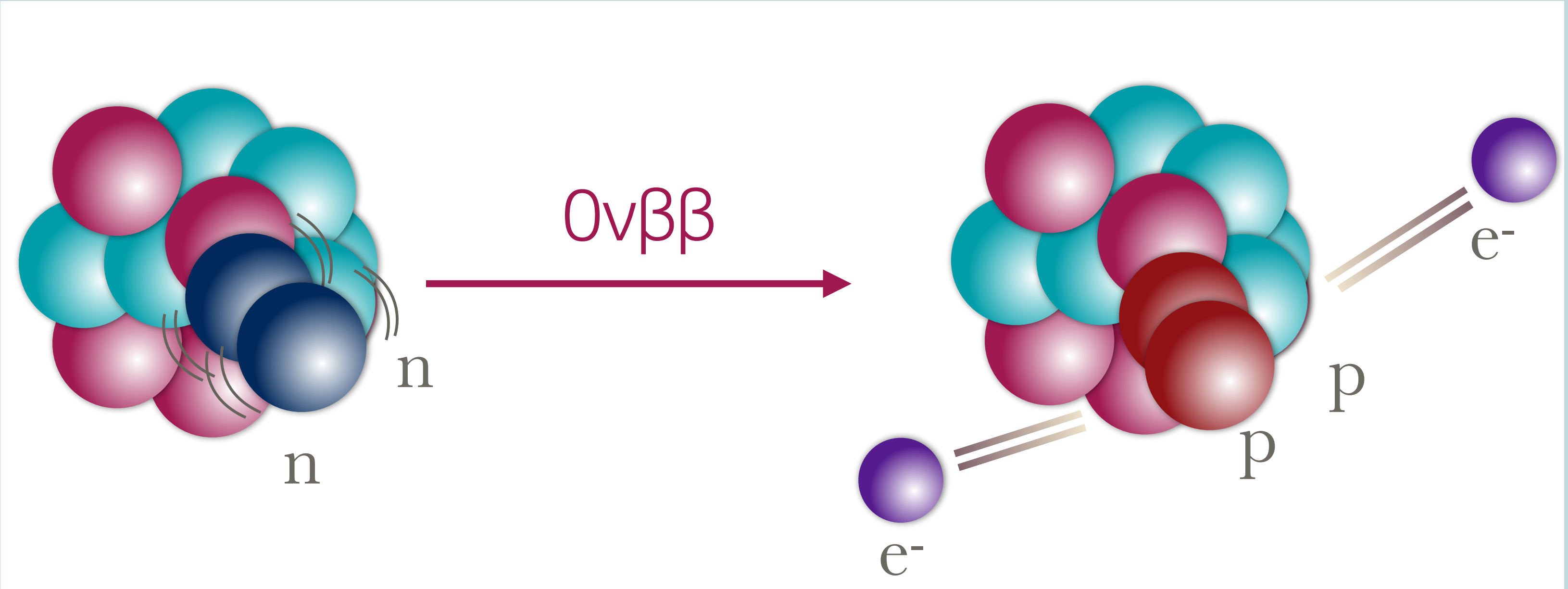
Forbidden by the SM, violates L and B-L

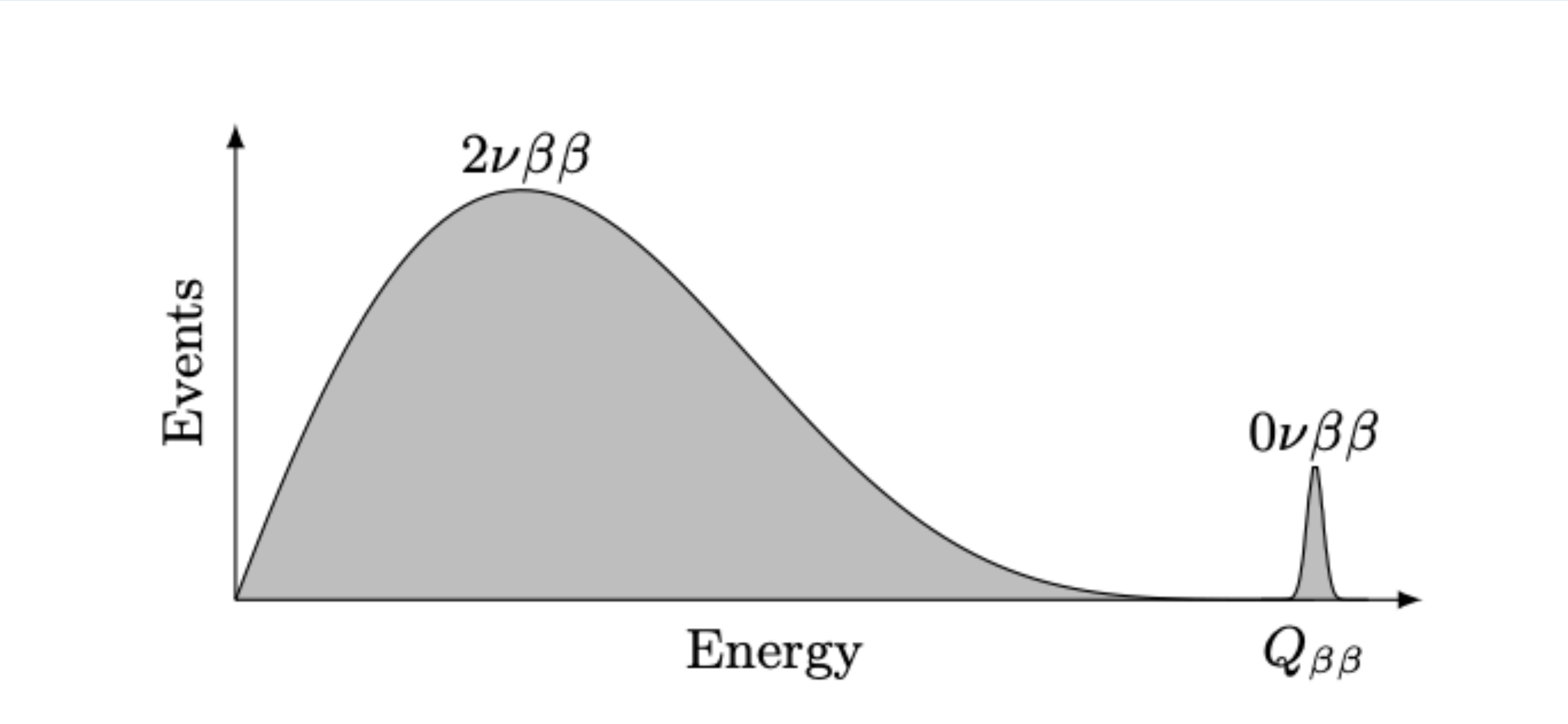
Simplest model: exchange of a light Majorana neutrino

$m_\nu \neq 0$ and $\Psi \equiv \Psi^C$ (unique among fermions)

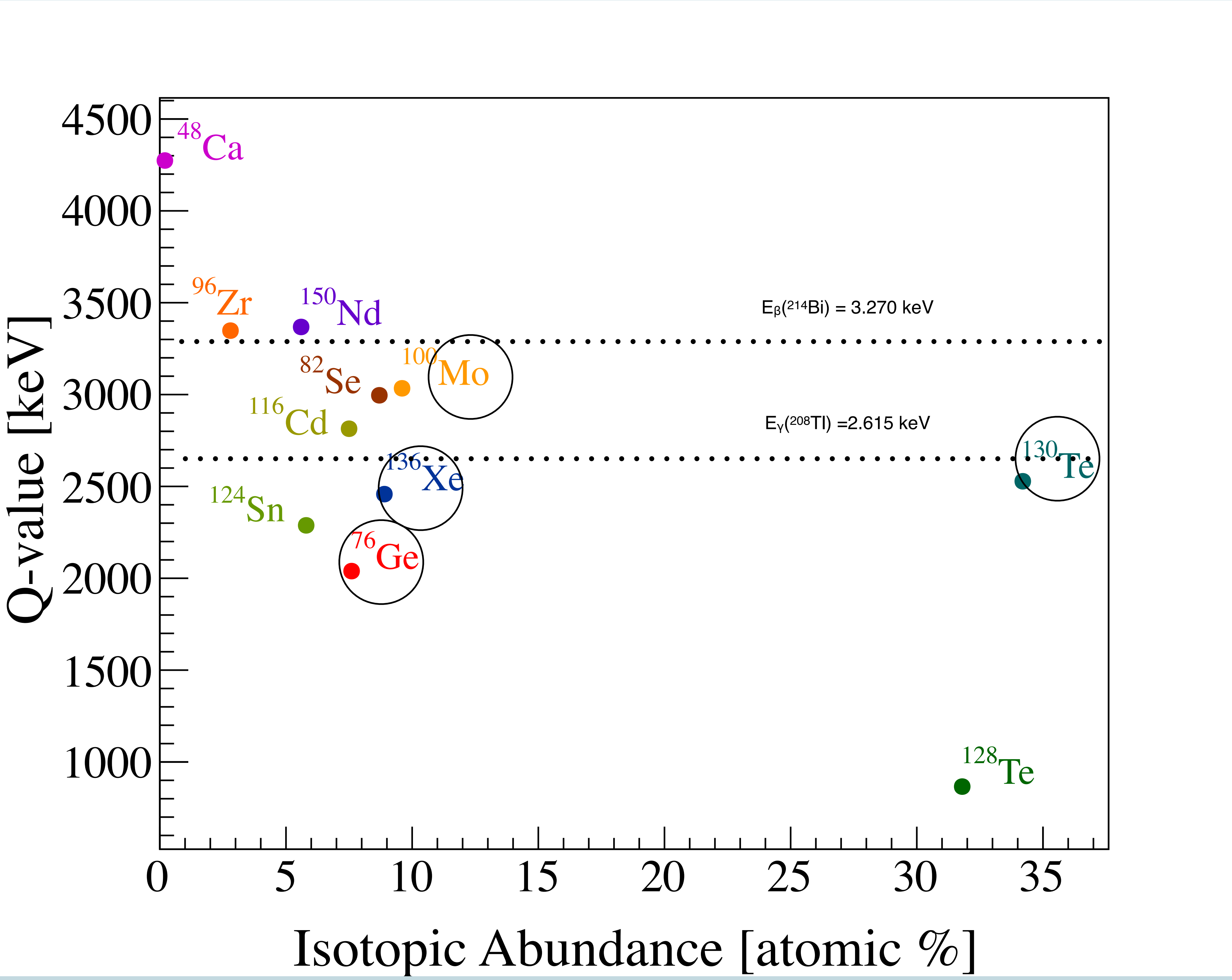
Half-life ≳ 10^{25-26} yr

0νββ





Not to scale !!



Experimental signature: 2 e^- with summed kinetic energy at $Q_{\beta\beta}$

Spectrum of e^- summed kinetic energy = monochromatic line at $Q_{\beta\beta}$ (~2-4 MeV)

The half-life

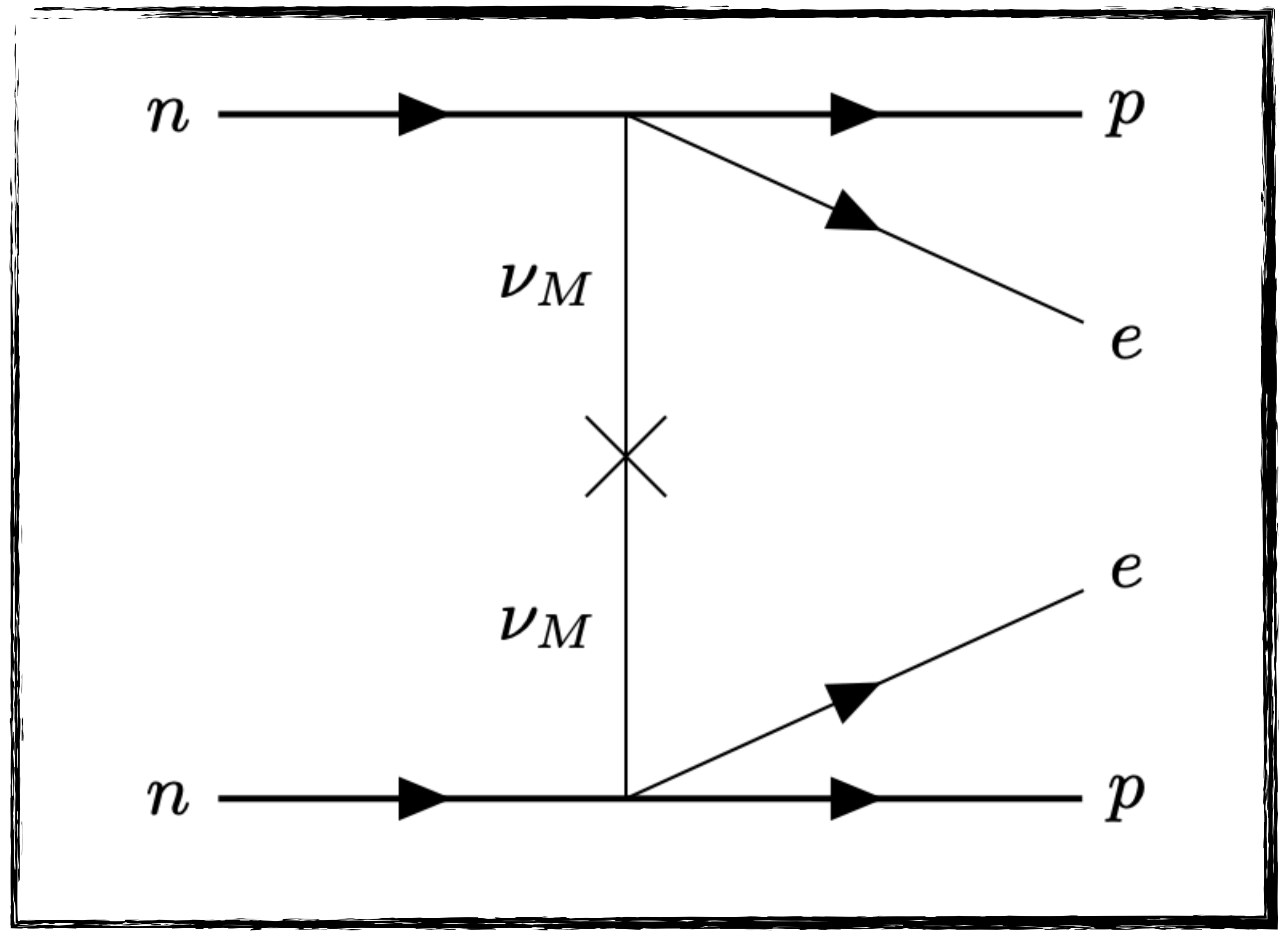
- The measurable quantity is the half-life:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}_{\eta}|^2\eta^2$$

Phase space factor: known with good accuracy from atomic physics. Contains the information on the kinematics in the final state.

Nuclear matrix element (nuclear physics) is affected by a large uncertainty

Decay mechanism (particle physics) is unknown



- Assuming the simplest scenario of the exchange of a light Majorana neutrino

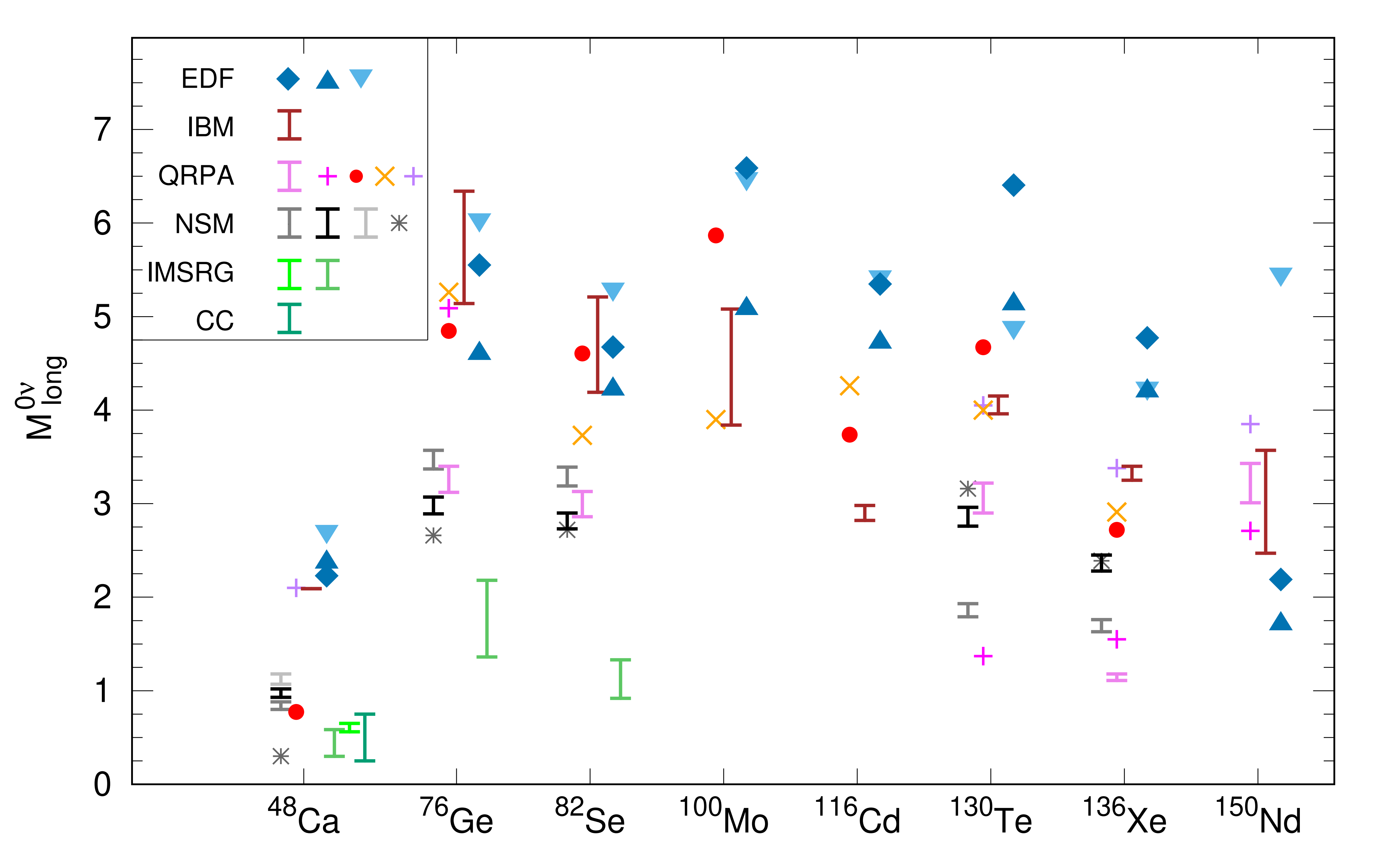
$$m_{\beta\beta} = |\sum_i m_i \cdot U^2_{ie}|$$

From $T_{1/2}$ to $m_{\beta\beta}$

The uncertainty associated with the nuclear matrix element is commonly addressed by comparing NMEs calculated with different theoretical approaches

ABOUT A FACTOR 3 SPREAD: DIFFERENT APPROXIMATIONS IN THE SOLUTION OF THE MANY BODY PROBLEM ASSOCIATED WITH THE HEAVY ββ EMITTING NUCLEUS

From Rev. Mod. Phys. 95, 025002 (2023)



Experimental Sensitivity

- Probed half-lives so far are of the order of 10^{25}-10^{26} y, many orders of magnitude longer than the age of the Universe;
- Experiments have to monitor thousands of moles of atoms for years and be able to detect the decay in a single one of them.

Half-life corresponding to the minimum number of detectable signal events above background at a given C.L.

$$T_{0\nu} \propto i.a. \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$

Detector mass

Isotopic abundance

Measuring time

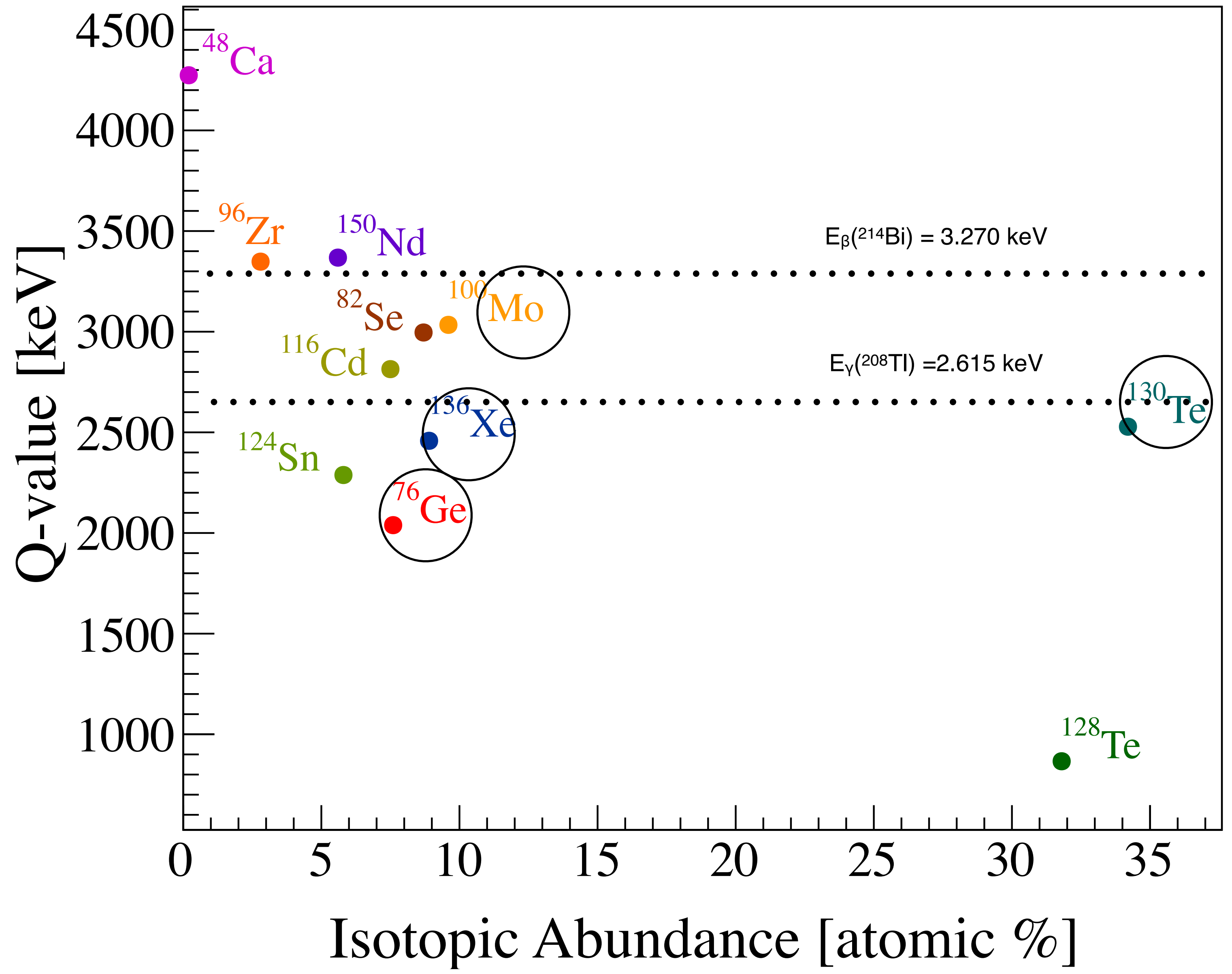
Energy resolution

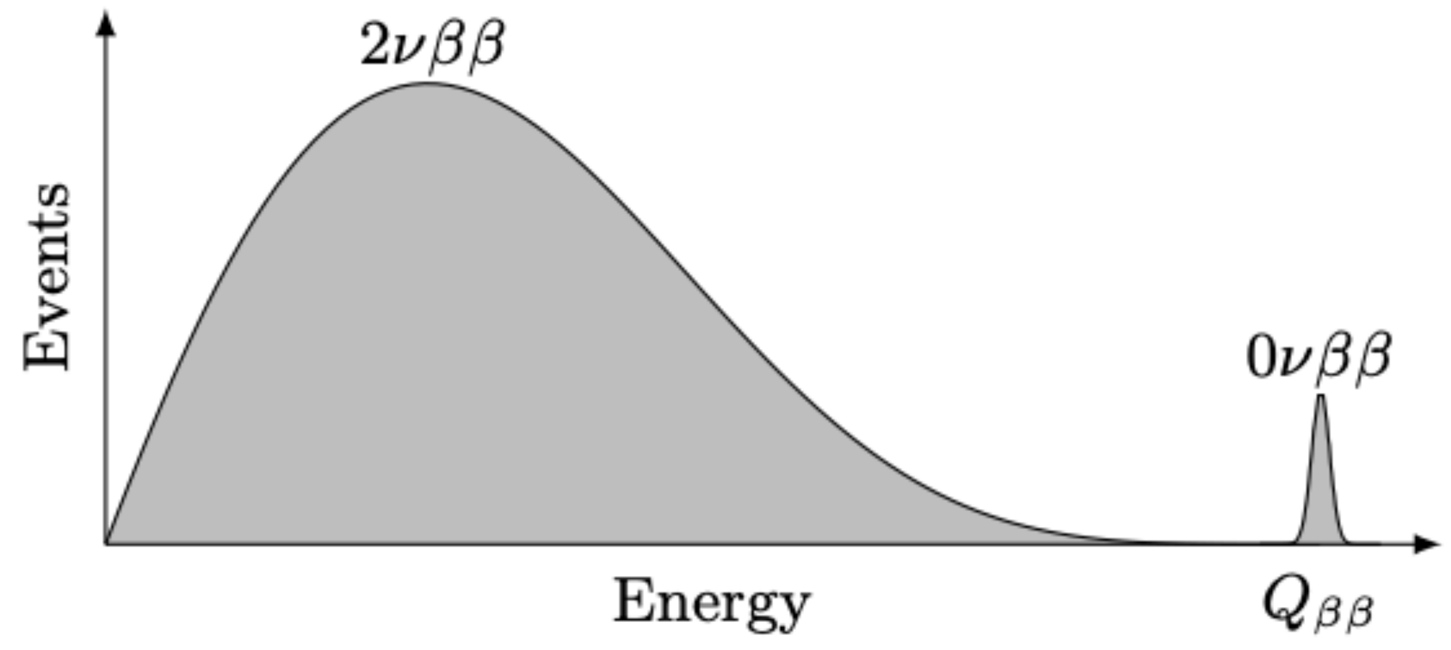
Background

Experimental Sensitivity

- Isotopic abundance → enrichment
- Exposure (M·T) → tons of isotope
- Energy resolution:
  - high (‰ of $Q_{\beta\beta}$)
  - low (% of $Q_{\beta\beta}$)

IMPORTANT TO GET RID OF THE IRREDUCIBLE BKG FROM $2\nu\beta\beta$ DECAY AND IDENTIFY AND DISENTANGLE THE VARIOUS CONTRIBUTION TO THE BACKGROUND





Background

- external background: neutrons, gammas and cosmic ray fluxes from the environment
- internal background: trace amounts of radioactivity in the detectors and the materials constituting the experimental apparatus
- 2-neutrino double beta decay of the same isotope
  - events leaking from the 2ν continuum spectrum
  - pile-up

The background

The most crucial among the parameters determining the sensitivity of an experiment

Reduction strategies:

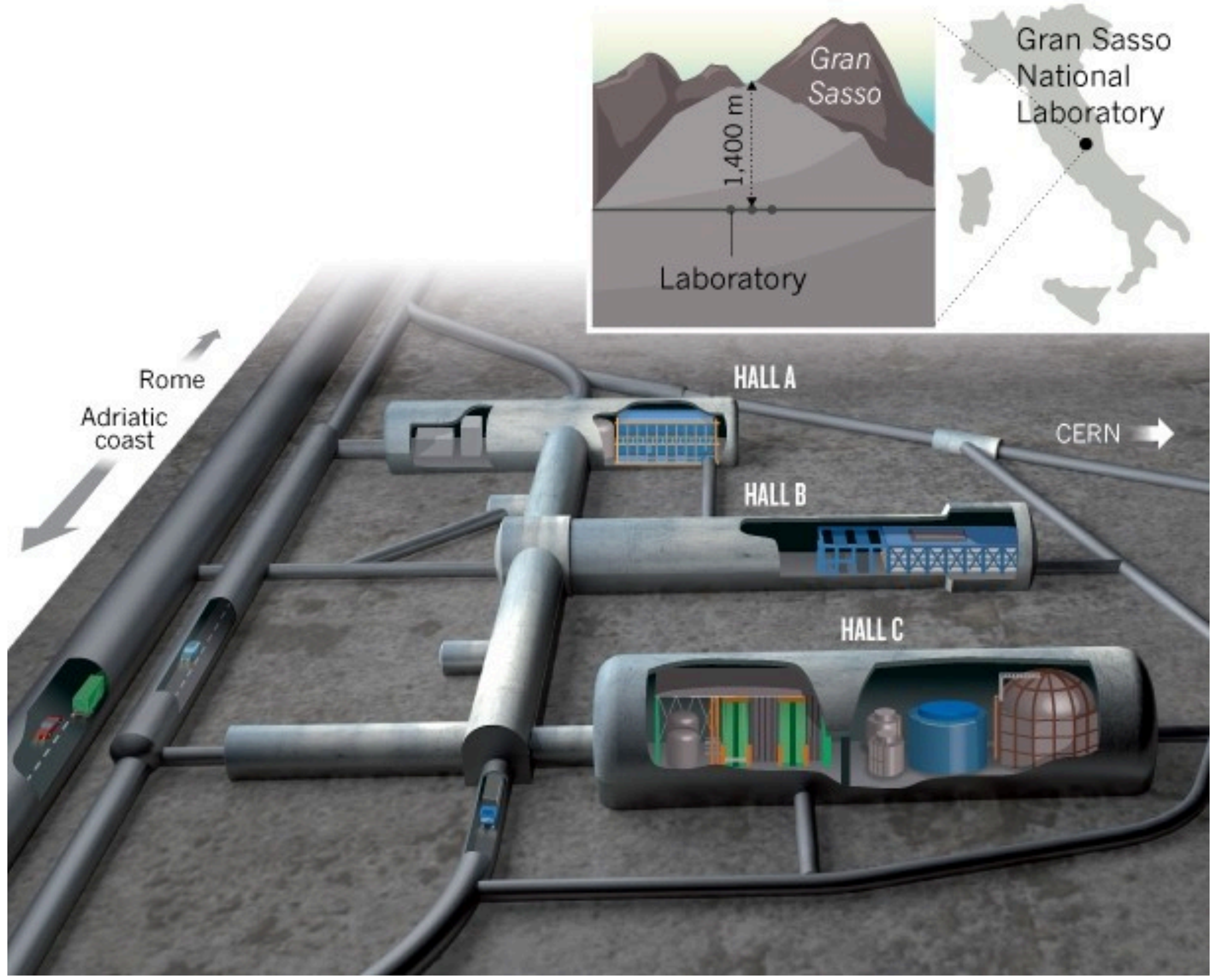
- Underground experiments
- Ultra-pure materials (screening, purification, clean assembly)

Discrimination strategies:

- High energy resolution
- Active veto
- Tracking, particle ID
- Fiducial volume
- Granularity, anti-coincidence
- Pulse shape discrimination (PSD)
- Ion Identification

SIGNAL: 0.1 - 1 COUNT/TON/Y

BACKGROUND: 0.01 - 0.1 COUNT/TON/Y



Credits: Nature

Neutrino mass probes

- Cosmology
  - Sensitive to Σm_ν
  - The most sensitive probe but model dependent
- Model independent direct measurement
  - β and Electron Capture decay: measure $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$
- $0\nu\beta\beta$ decay
  - If Majorana particles, in simplest model sensitive to $m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$

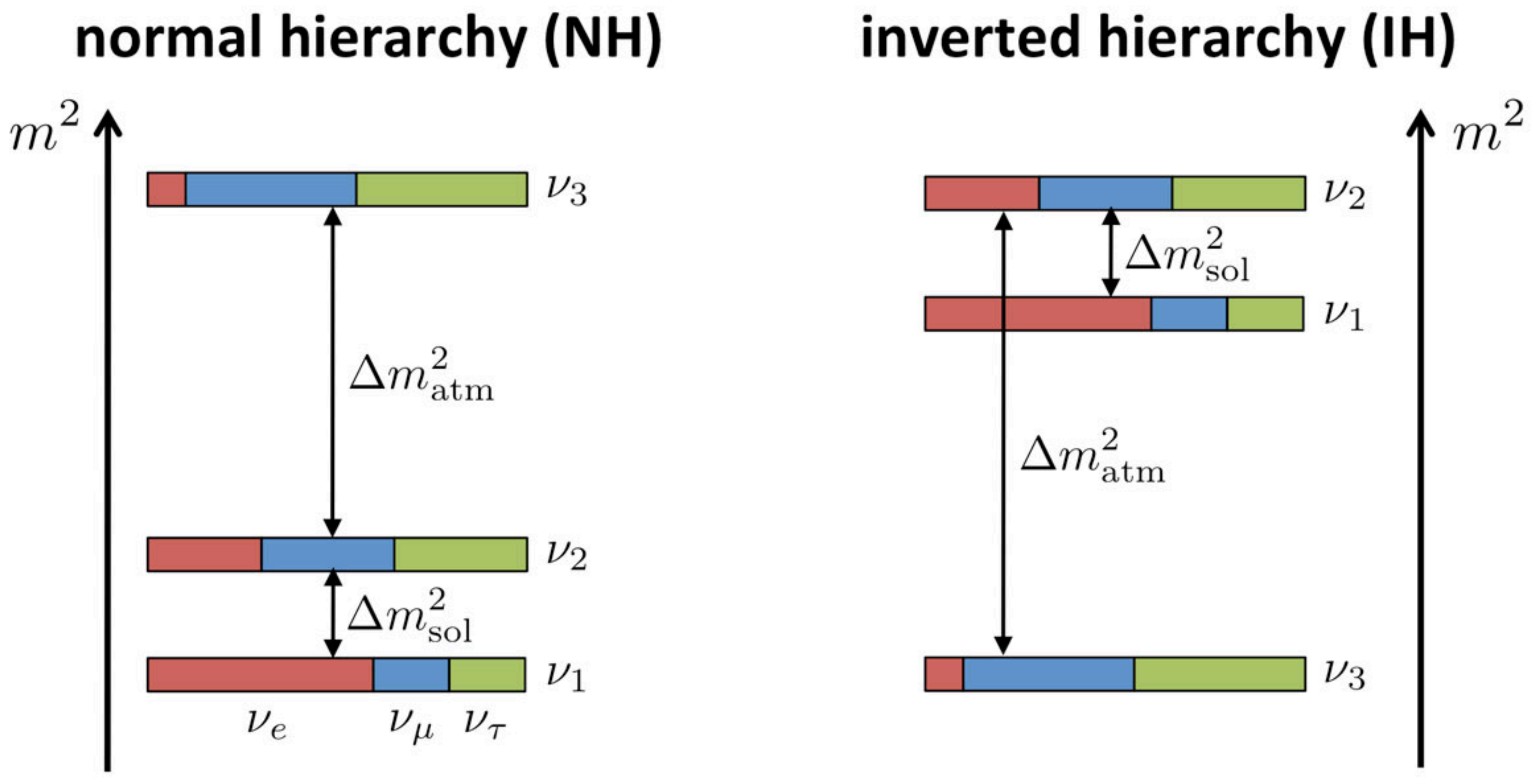
DUE TO THE RESULTS OF NEUTRINO OSCILLATION EXPERIMENTS, THE PARAMETER SPACE OF THESE MASS PROBES IS CONSTRAINED

Present knowledge from oscillations

- Three-neutrino fit based on data available in November 2022
- nuFIT 5.2 (2022) - JHEP 09 (2020) 178

NuFIT 5.2 (2022)

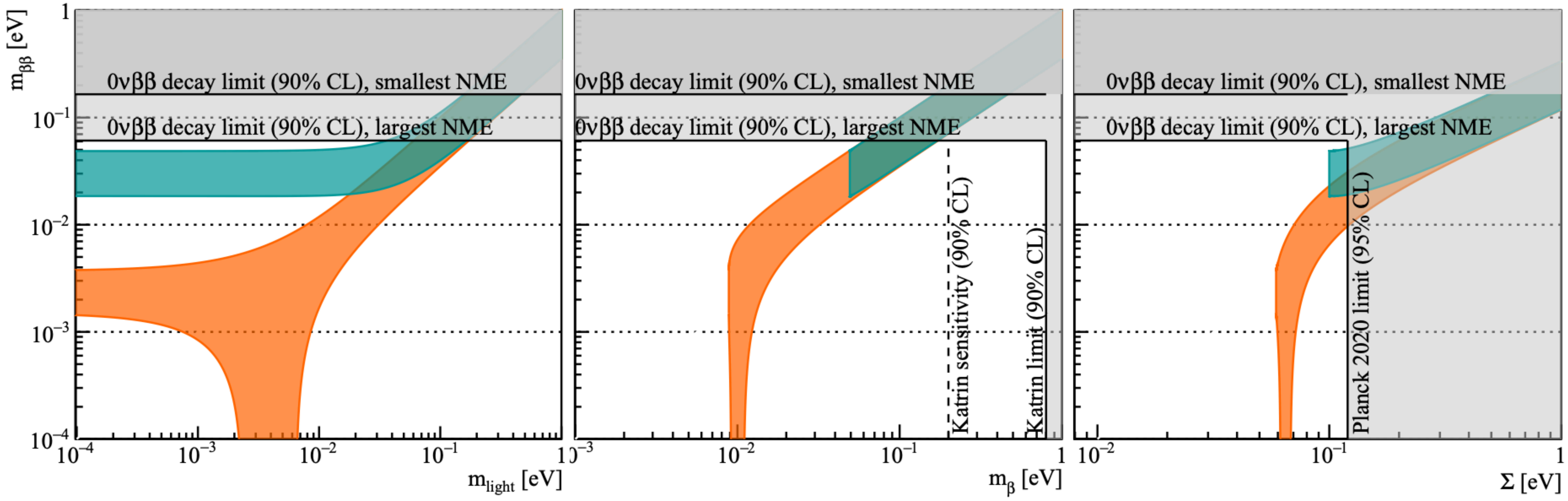
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$



PRESENTLY, GLOBAL FITS INDICATE A PREFERENCE FOR THE NORMAL HIERARCHY AT ABOUT 3 SIGMA

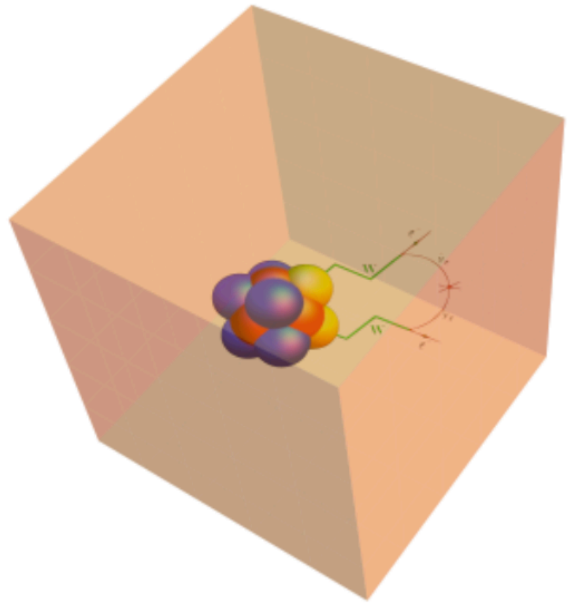
$m_{\beta\beta}$ parameter space

From Rev. Mod. Phys. 95, 025002 (2023)



allowed parameter space for $m_{\beta\beta}$ as a function of m_{light}, m_β, and Σ, assuming the central value of the neutrino oscillation parameters

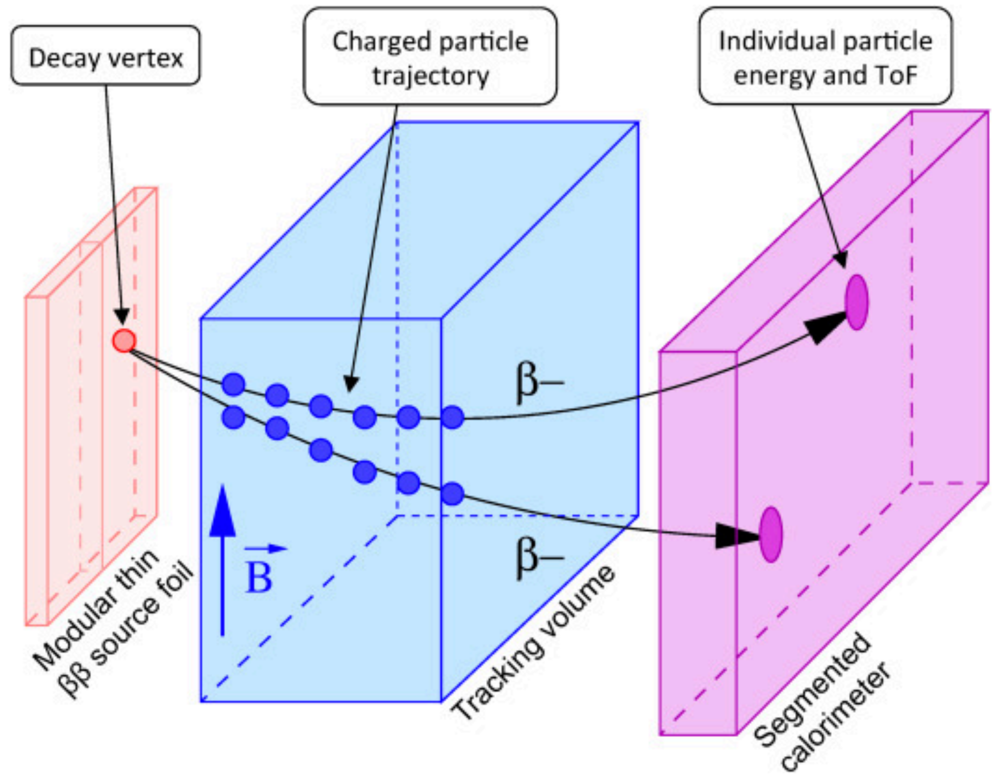
The worldwide experimental effort



High efficiency

Large mass

SOURCE = DETECTOR

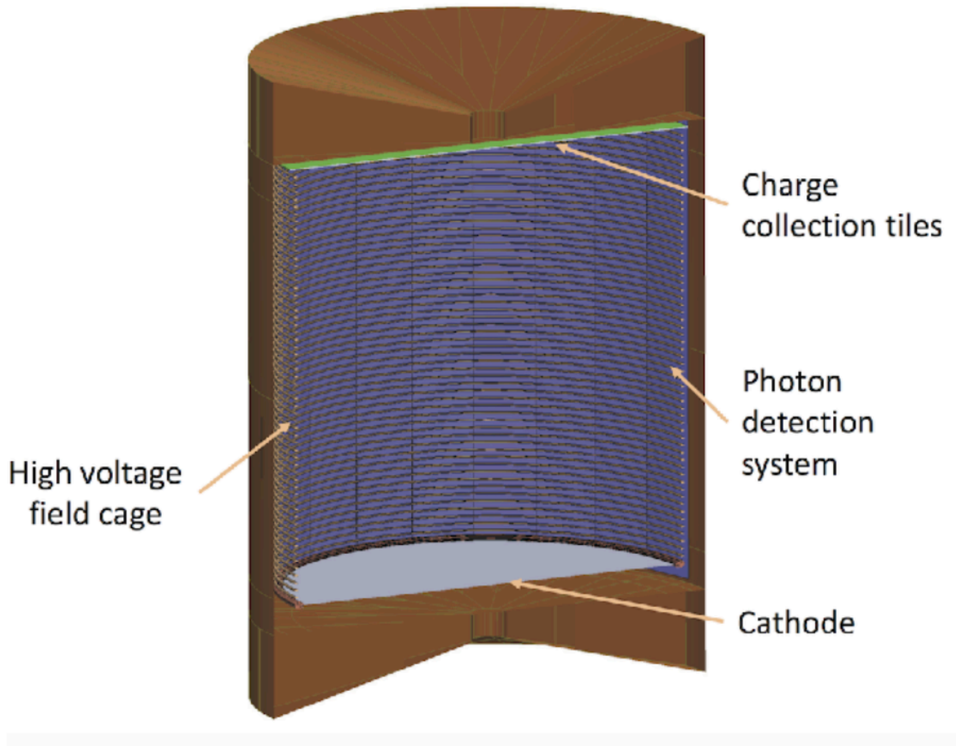


Limited mass and efficiency

Topology

SOURCE ≠ DETECTOR

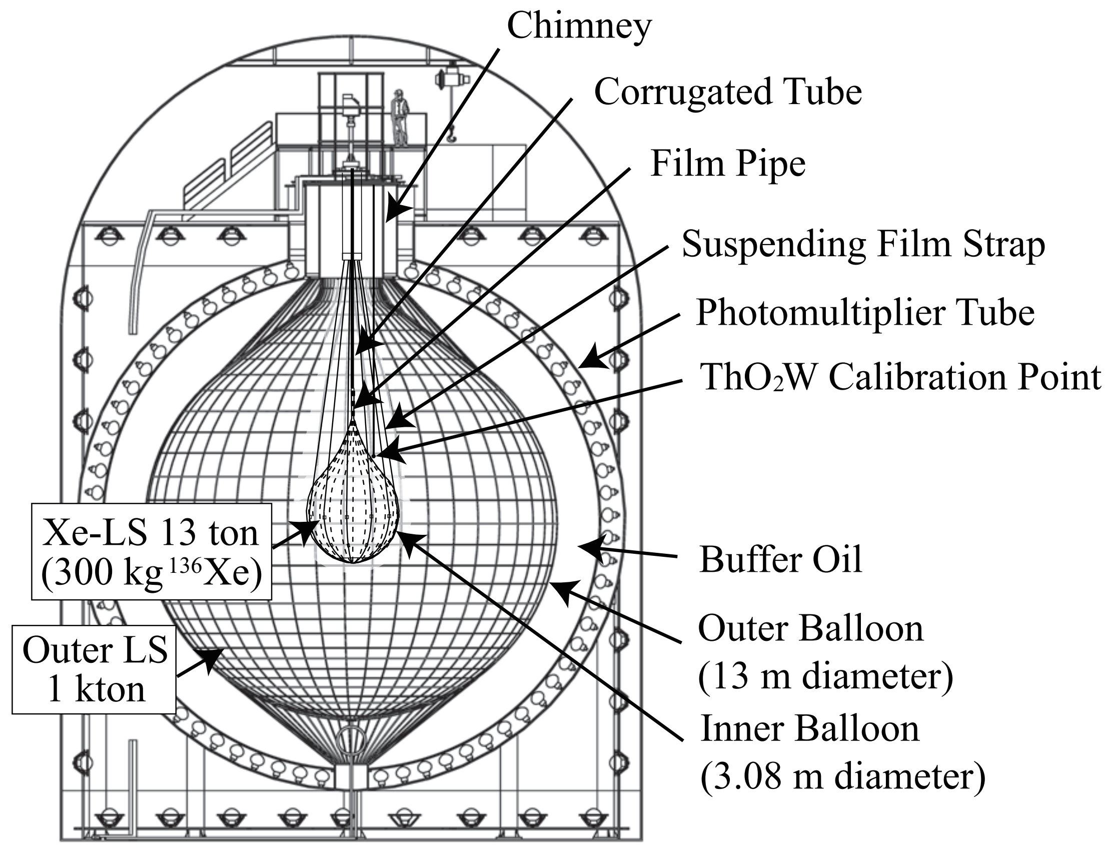
LIQUID AND GAS TPC



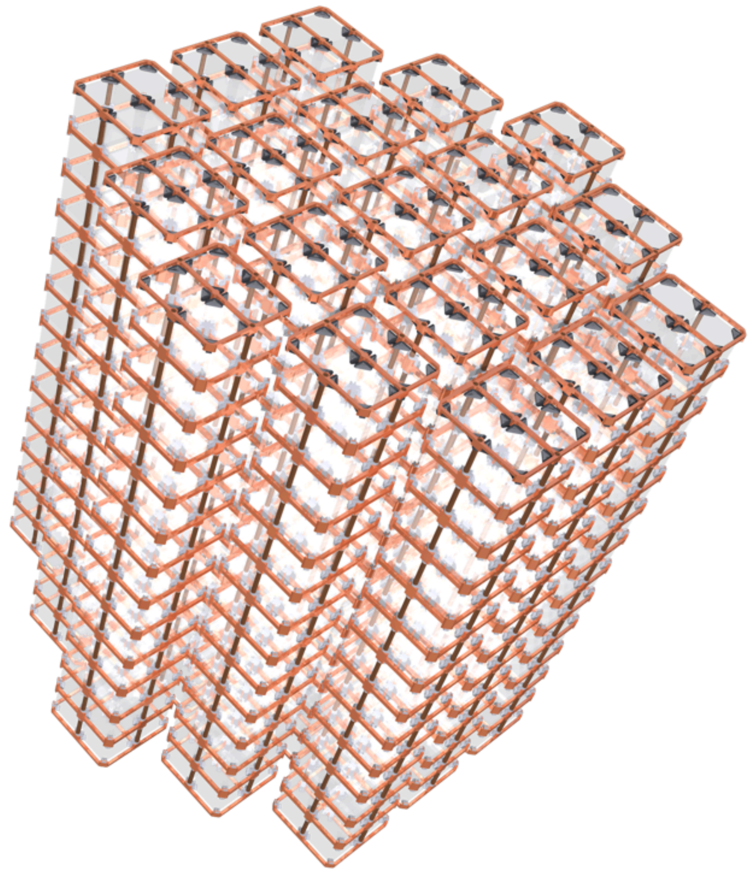
Large mass (easier to scale wrt solid)

Limited energy resolution

LOADED LIQUID SCINTILLATORS



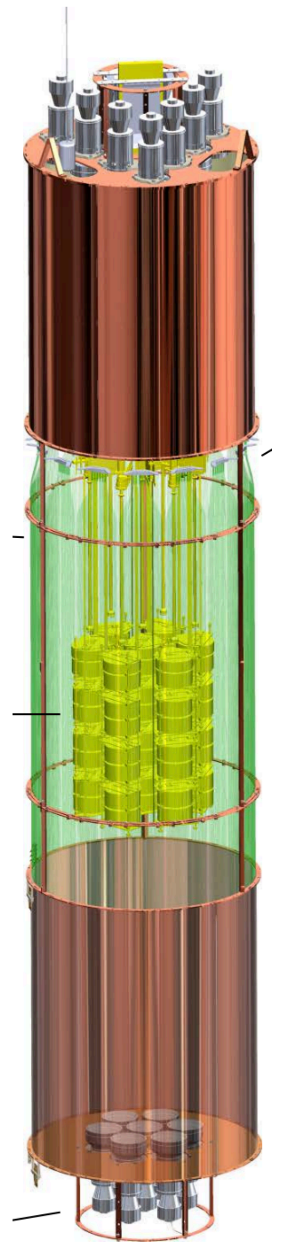
CRYOGENIC BOLOMETERS



High energy resolution and efficiency

Limited mass wrt liquid

HPGE DETECTORS



LEGEND-200

Experimental technique: Bare HPGe detectors, ~90% enriched in ^{76}Ge in LAr instrumented as active veto

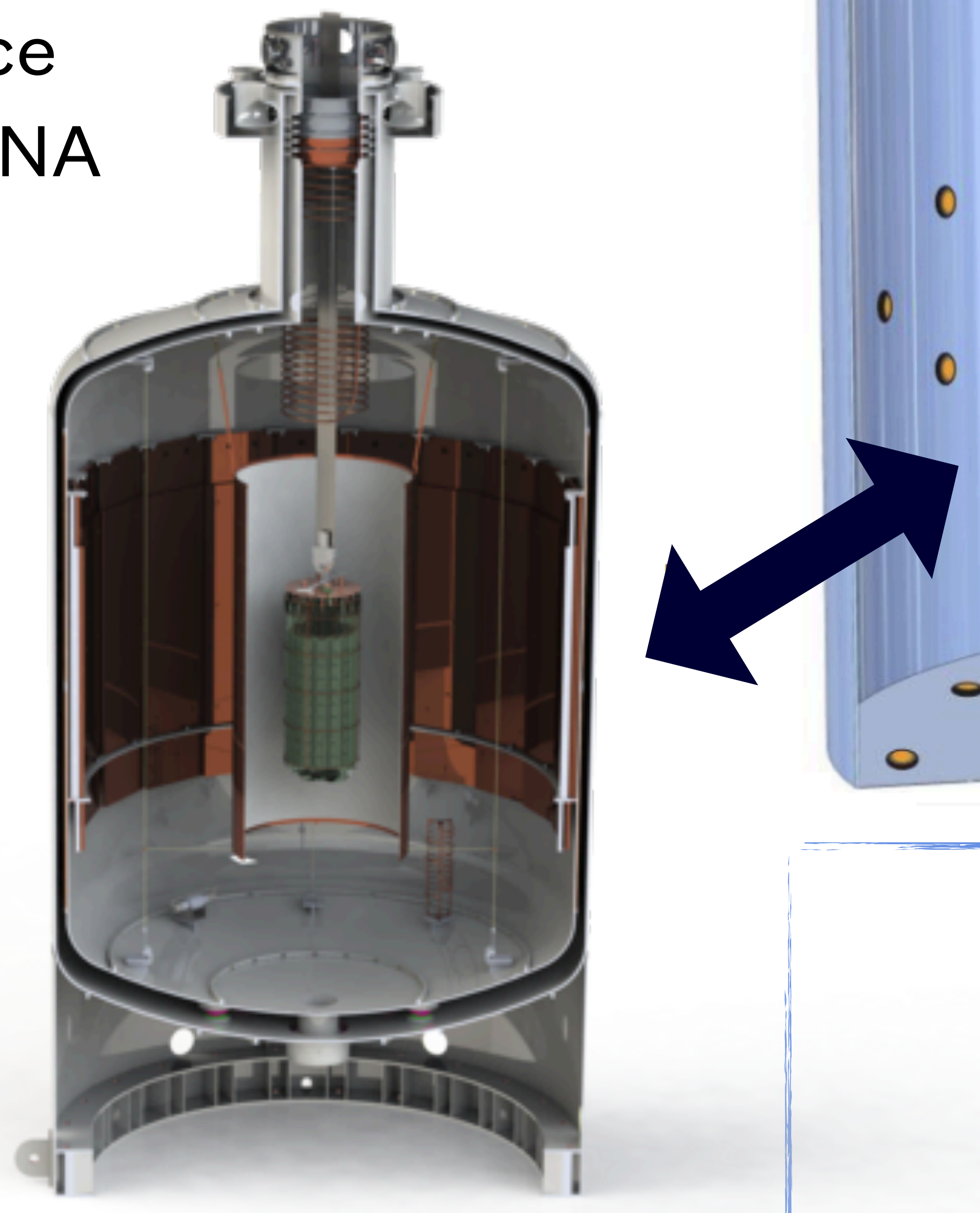
Bringing together the the technological expertise and experience from the GERDA experiment (lowest background) and MAJORANA DEMONSTRATOR (best energy resolution).

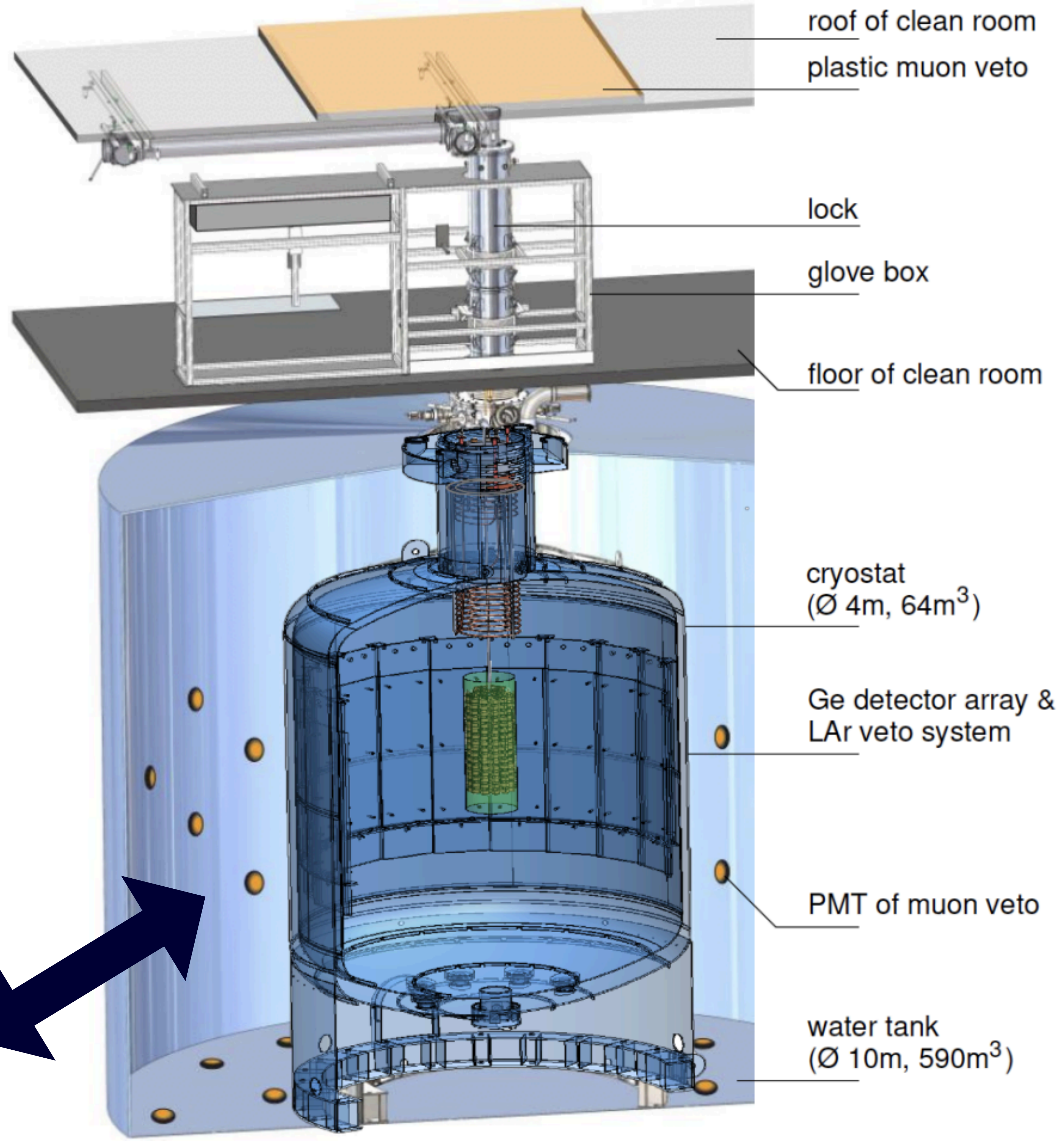
Upgraded GERDA infrastructure + 200 kg HPGe detector:

lower background

higher energy resolution

Stable data taking with 140 kg since March 2023





Bkgd ~$2 \cdot 10^{-4}$ cpy/kg/keV

dominated by ^{42}K β-decays &

α-surface emitters

$T^{0\nu}_{1/2} \sim 10^{27}$ yr $m_{\beta\beta}$: [35-75] meV

LEGEND 1000

@SNOLAB/LNGS

From: arXiv:2107.11462

Experimental technique: Bare HPGe detectors, ~90% enriched in ^{76}Ge in LAr instrumented as active veto

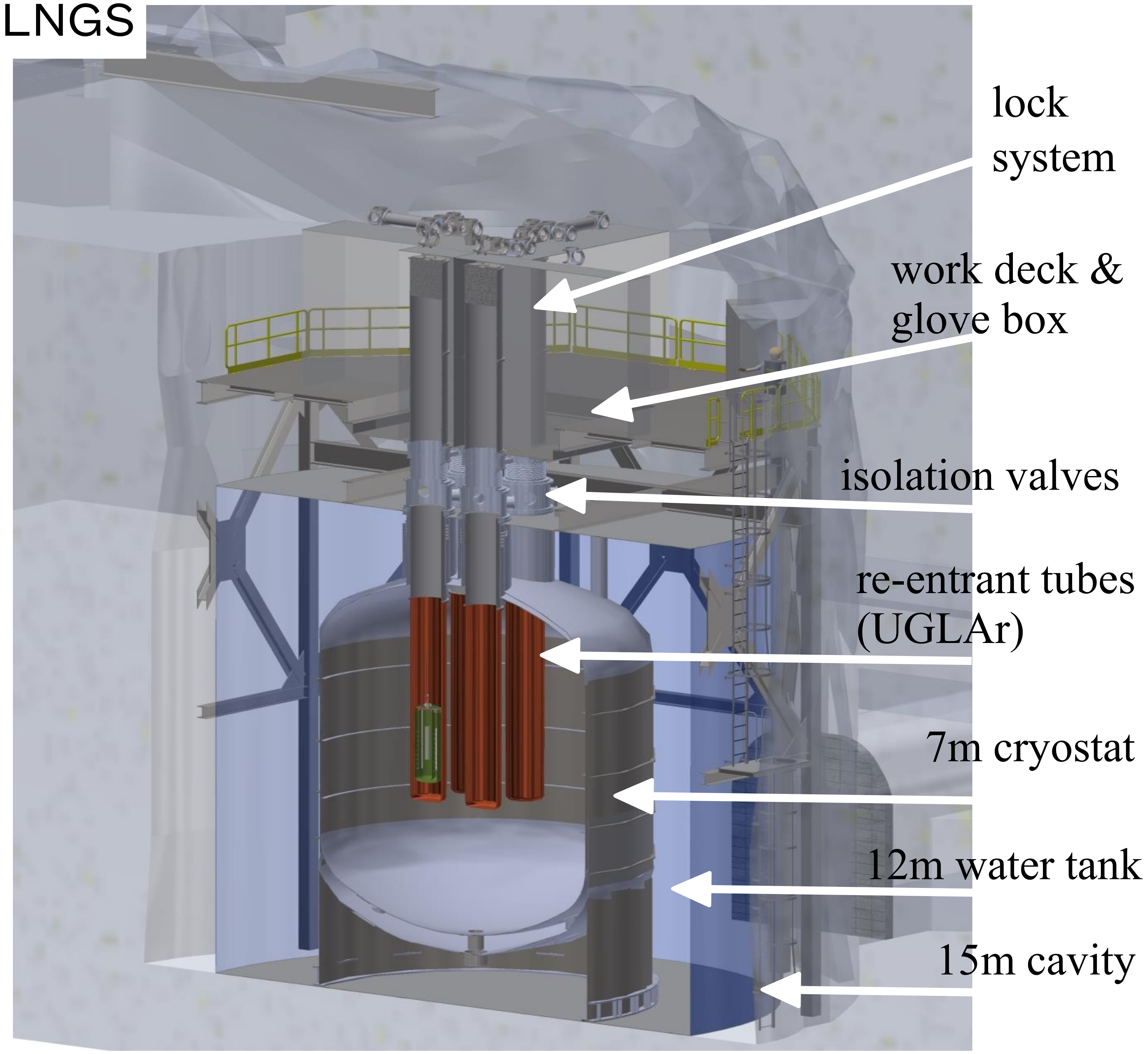
Bringing together the the technological expertise and experience from the GERDA experiment and MAJORANA DEMONSTRATOR.

New infrastructure:

- Baseline underground site SNOLAB
- LNGS alternative, depth influences $^{77(m)}Ge$ background
- 14 vertical string
- Electroformed copper for physical support
- Immersed in UGLAr
- Wavelength-shifting fiber curtain to read the scintillation light

Bkgd ~$2 \cdot 10^{-5}$ cpy/kg/keV

$T^{0\nu}_{1/2} \sim 1.3 \cdot 10^{28}$ yr $m_{\beta\beta}$: [9-21] meV

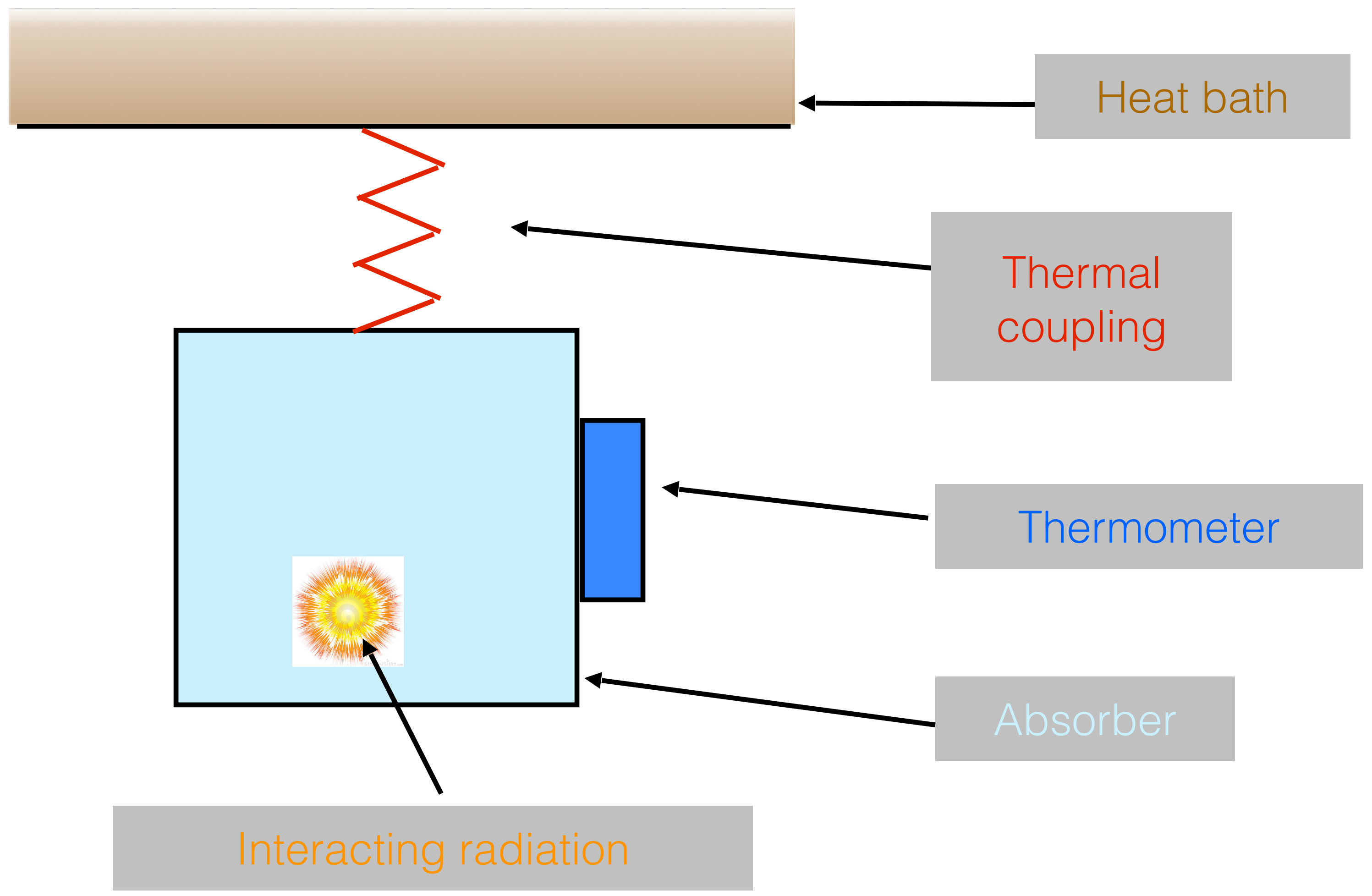


LEGEND-1000 @ SNOLAB

CUORE

Larger bolometric detector ever built

- 988 $^{nat}TeO_2$ crystals
- 742 kg of TeO2, 206 kg ^{130}Te.



SEE TALK FROM STEFANO DELL'ORO

Since 2019: data taking with high duty cycle and stable performances

- Collected exposure exceeded ~2 Ton yr
- ΔE_{FWHM} @$Q_{\beta\beta}$~7 keV (σ_E/E~0.1%)
- bkgd: ~10^{-2} cpy/kg/keV

Experimental technique: Ultracold crystals functioning as highly sensitive calorimeters. The energy deposited by a particle interaction in the absorber is converted to a measurable temperature variation.

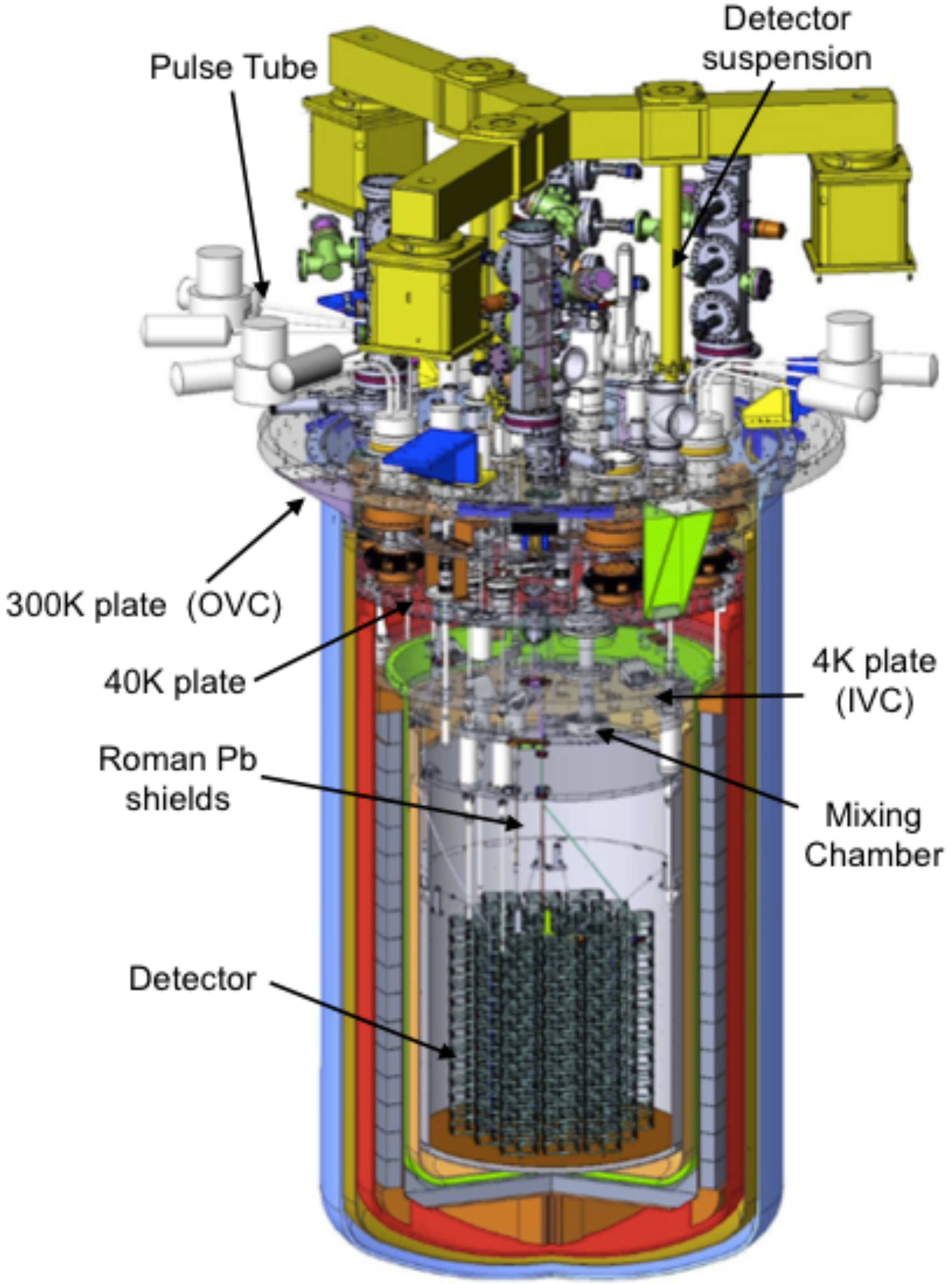
Nature 604 (2022) 7904, 53-58

Exposure ~1 Ton yr (~300 kg yr ^{130}Te)

$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr @90% C.I.

90 - 305 meV @90% C.I.

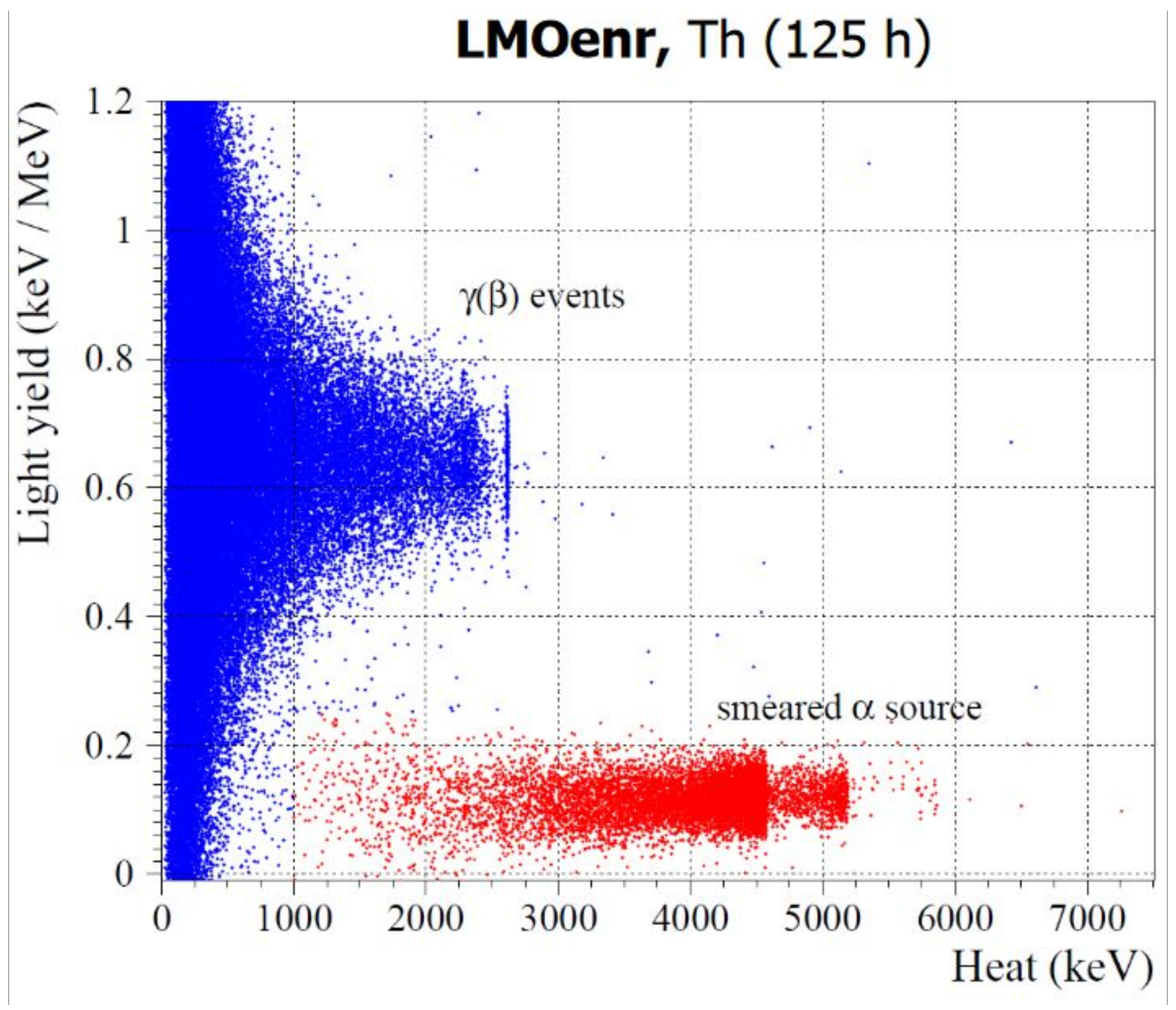
@LNGS



CUORE→CUPID

Experimental technique: Ultracold scintillating crystals functioning as highly sensitive calorimeters with particle ID capability, due to the dual heat + light readout.

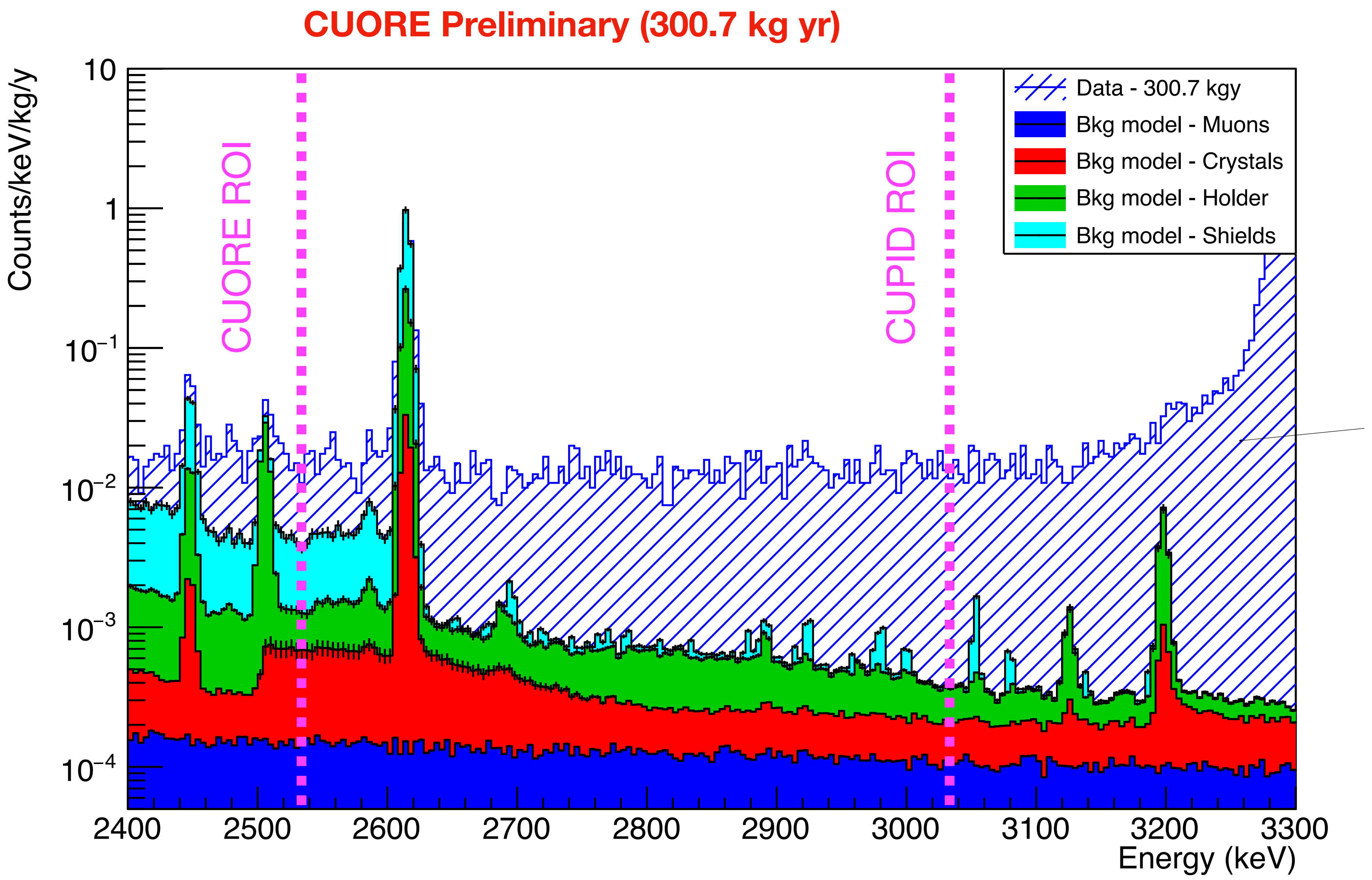
Re-use CUORE infrastructure +
1500 scintillating bolometer
$Li_2{}^{100}MoO_4$ (220 kg ^{100}Mo)



- Baseline:
  - bkgd ~ 10^{-4} cpy/kg/keV
  - $T^{0\nu}_{1/2}$ ~ $1.1 \cdot 10^{27}$ yr
  - $m_{\beta\beta}$: [12-20] meV
- Reach:
  - bkgd ~ $2 \cdot 10^{-5}$ cpy/kg/keV
  - $T^{0\nu}_{1/2}$ ~ $2 \cdot 10^{27}$ yr
  - $m_{\beta\beta}$: [9-15] meV

@LNGS

From arXiv:1907.09376



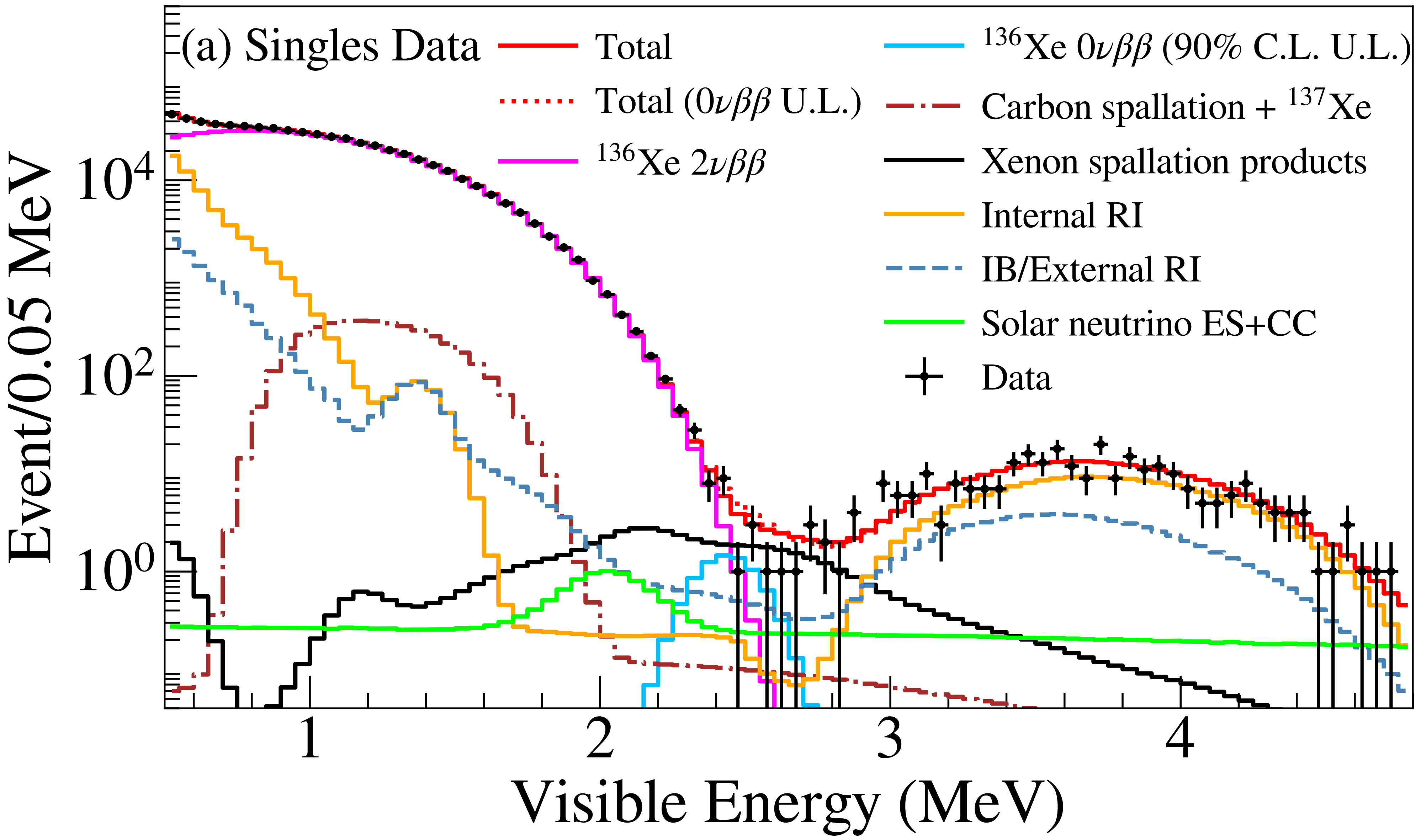
Particle ID gives x100 bkgd reduction wrt CUORE

KamLAND-Zen 800

@Kamioka

Experimental technique: Enriched ^{136}Xe diluted (3%wt) in liquid scintillator in a mini-balloon deployed inside KamLAND.

Limits rely strongly on background model



From Phys. Rev. Lett. 130, 051801 (2023)

Main background: muon induced Xe spallation product

Reduced radioactive bkg
Demonstration of scalability
~1 Ton x yr exposure

Combined with KamLAND-Zen 400

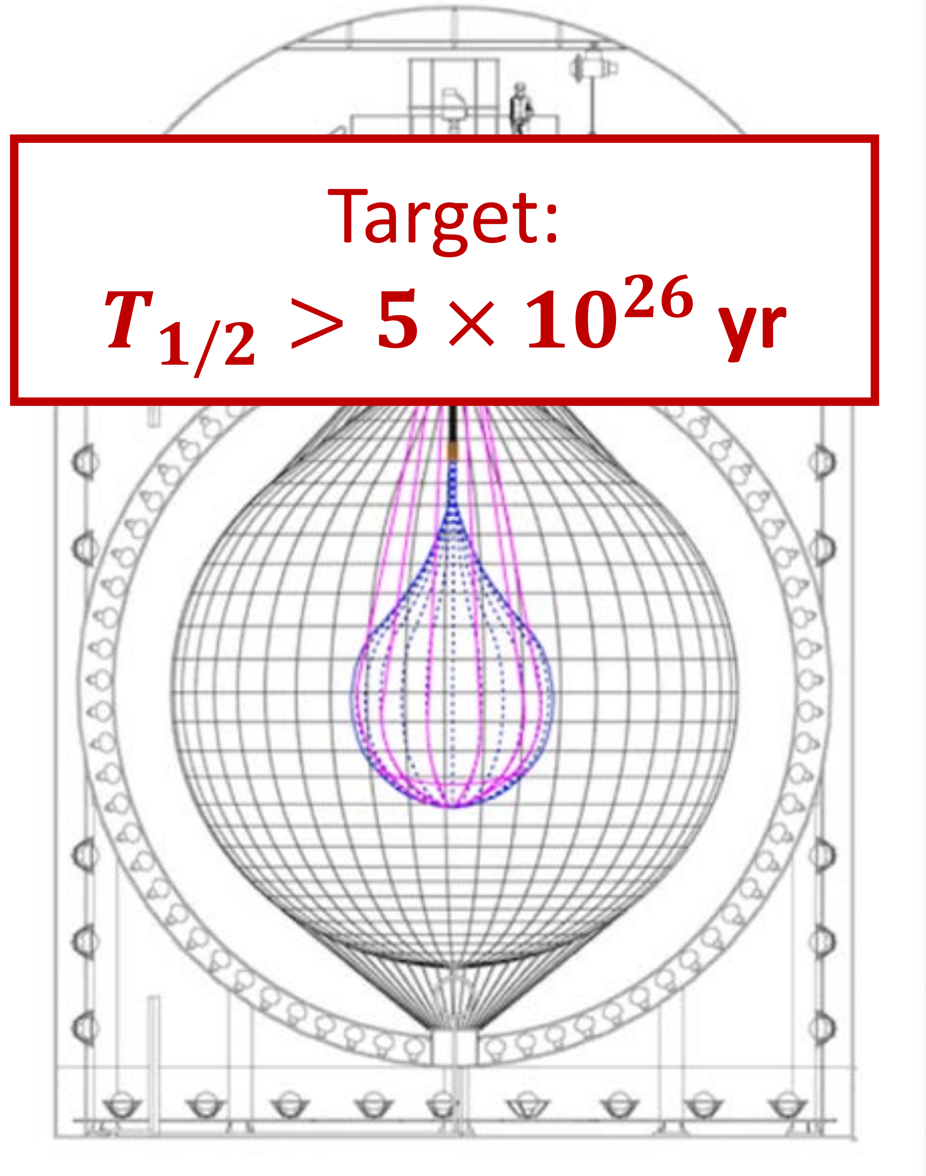
$T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ yr at 90% C.L

$m_{\beta\beta} < 36\text{-}156$ meV

Enters the IH region for the first time

Current

Target:
$T_{1/2} > 5 \times 10^{26}$ yr



KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

Started January 2019

KamLAND-Zen2

@Kamioka

Experimental technique: Enriched ^{136}Xe diluted (3%wt) in liquid scintillator in a mini-balloon deployed inside KamLAND.

Improvements:

x 5 increase in light collection —> higher energy resolution

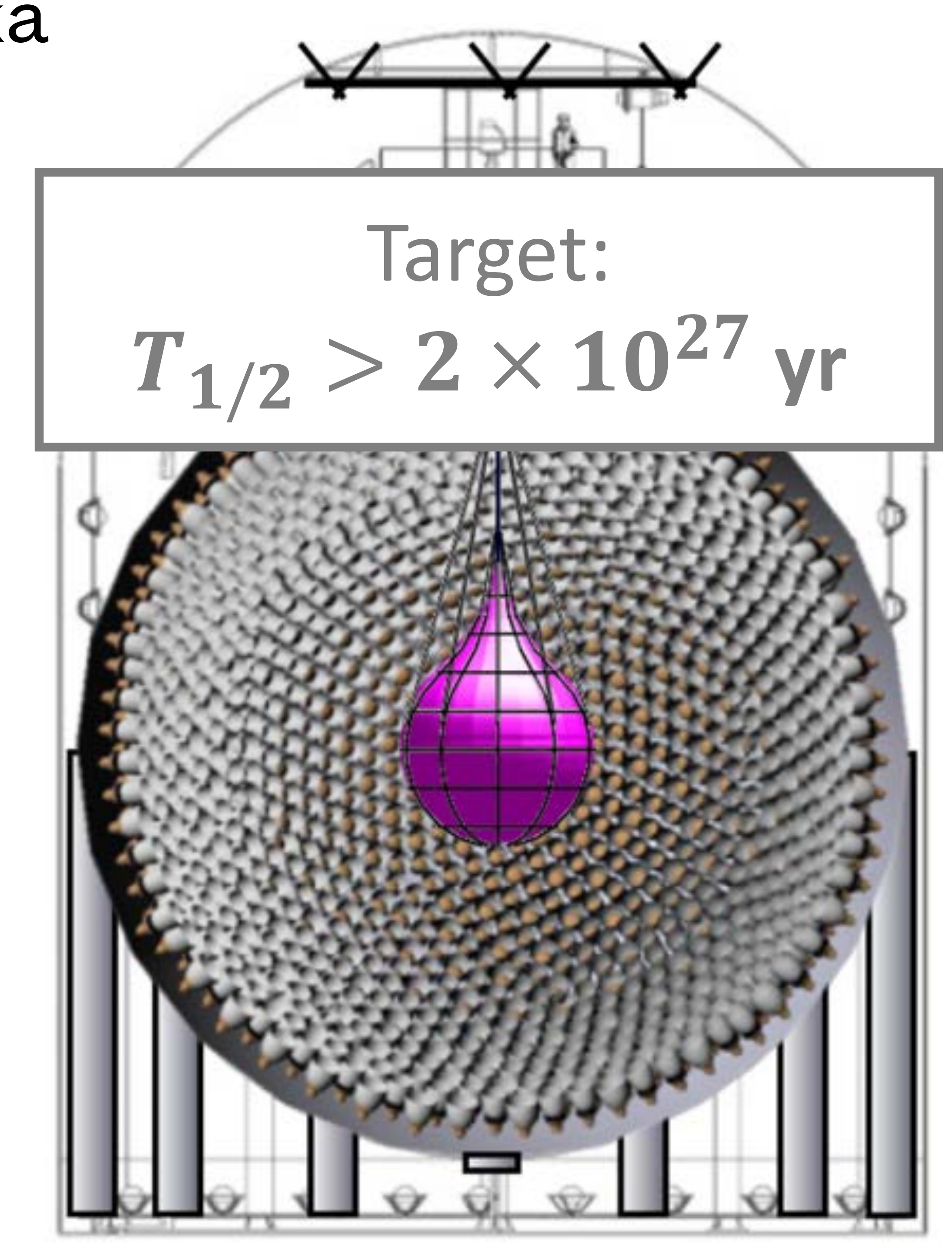
Reduce ^{214}Bi induced background: identify BiPo events in the balloon tagging α with scintillator film

Particle ID with neural network

New electronics for neutron tagging of spallation

Target sensitivity: $T^{0\nu}_{1/2} \sim 1 \cdot 10^{27}$ yr —> $m_{\beta\beta}$: [17-71] meV

Future



KamLAND2-Zen

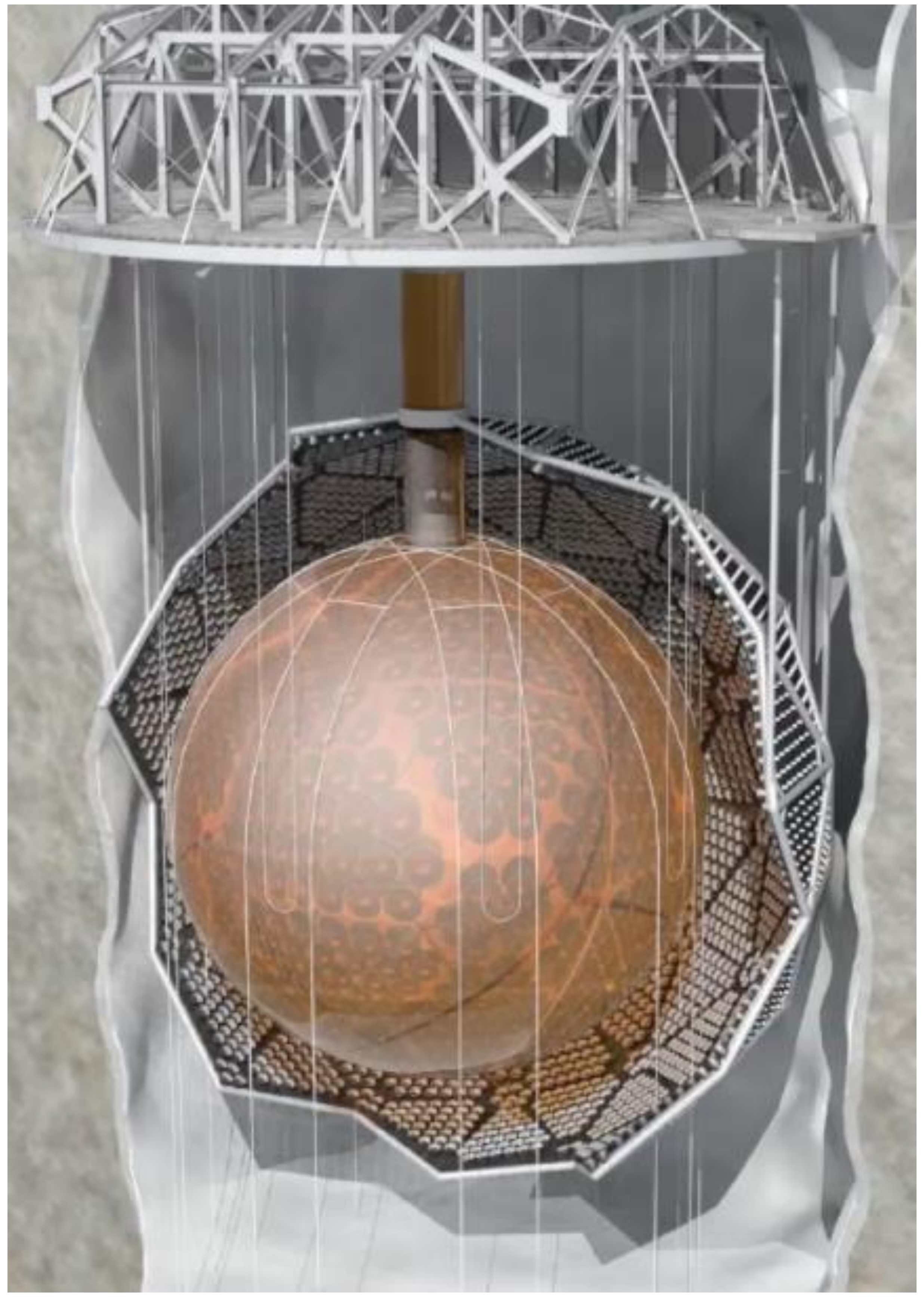
Xenon mass ~ 1 ton

× 5 increase in light collectior

SNO+

From JINST 16 P08059 (2021)

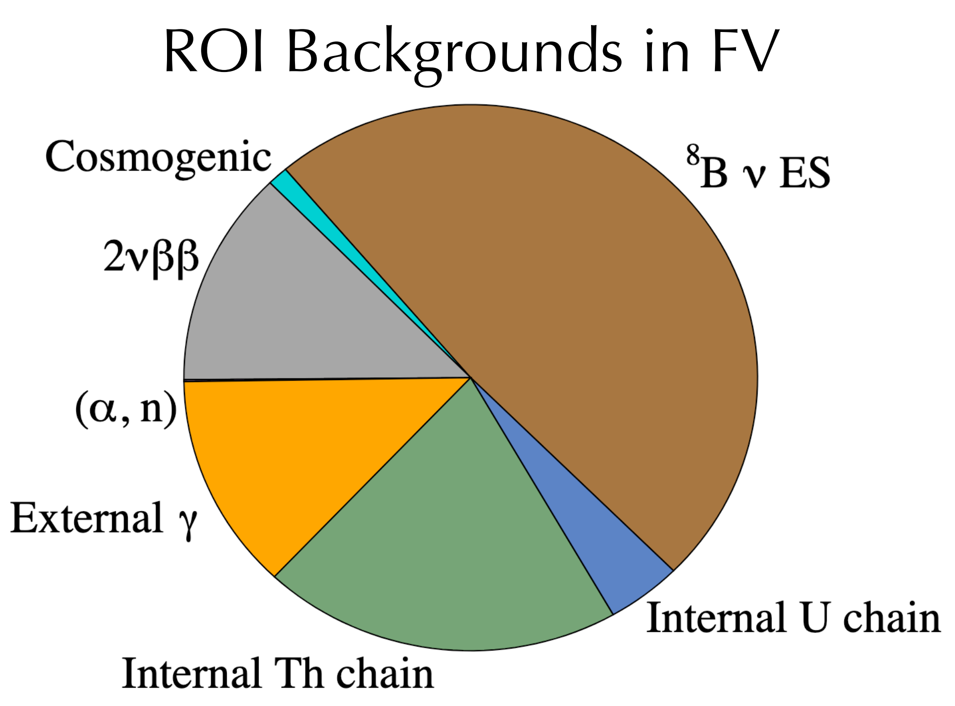
@SNOLAB



Experimental technique: Natural Te diluted in liquid scintillator inside the SNO experimental setup and infrastructure.

- 12-m diameter spherical acrylic vessel (AV) inside an ultra-pure water shield
- 780 Ton natural-Te loaded liquid scintillator (LAB+2 g/l PPO Fluor)
  - Scintillation purification system + novel metal loading technique
  - 0.5% mass loading →1.3 Ton of ^{130}Te
  - ΔE_{FWHM} @$Q_{\beta\beta}$: 190 keV (σ_E/E=3%)

$T^{0\nu}_{1/2}$ ~ $2.1 \cdot 10^{26}$ yr at 90% C.L



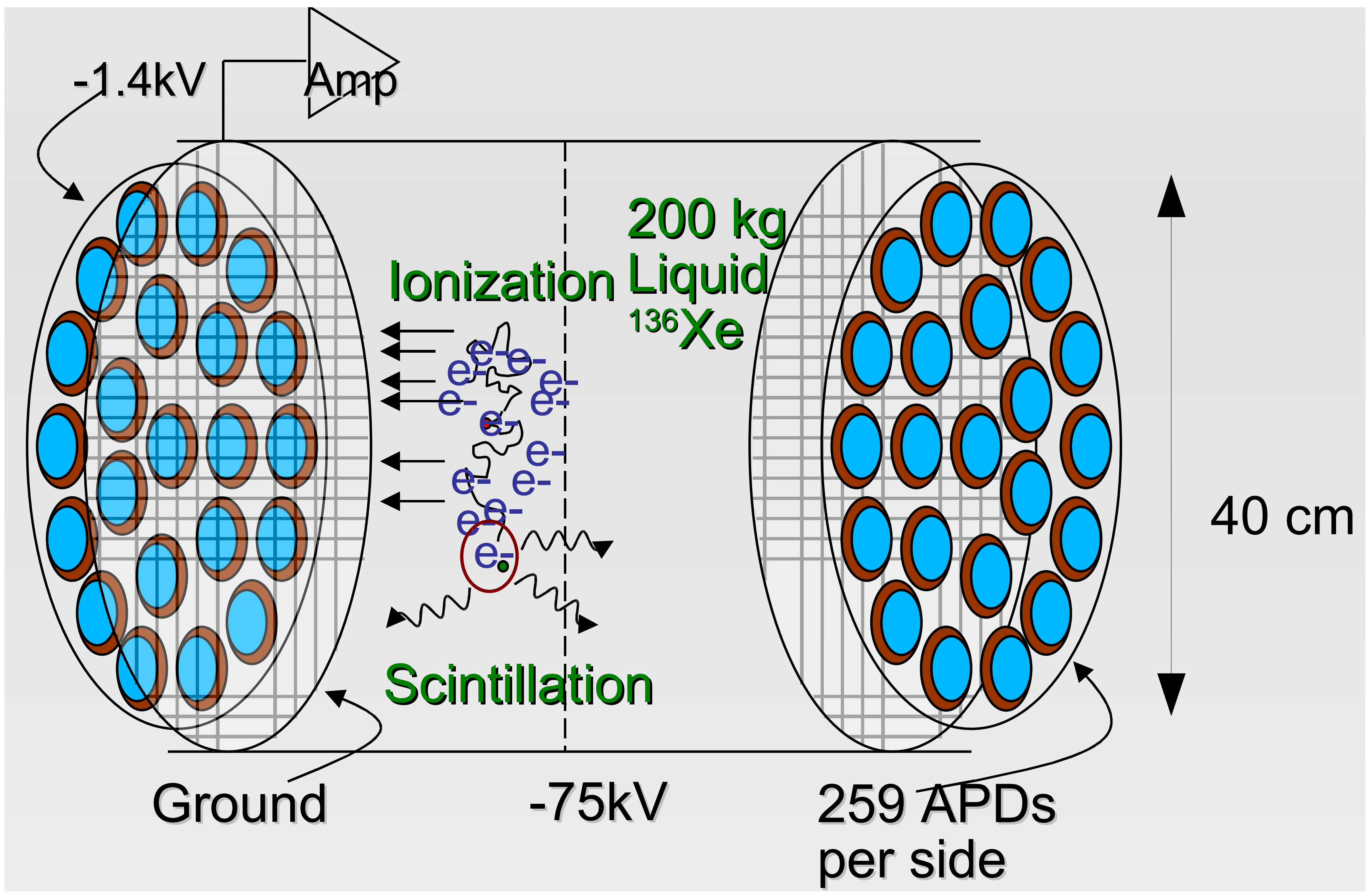
- 2017: water phase → external bkgd
- 2019-ongoing: liquid scint. (no Te)→scintillator bkgd
- From 2024: Te loaded liquid scintillator
- Phase 2 evolution: 0.5% →3% loading (r&d on going)

$T^{0\nu}_{1/2} > 10^{27}$ yr at 90% C.L

EXO-200

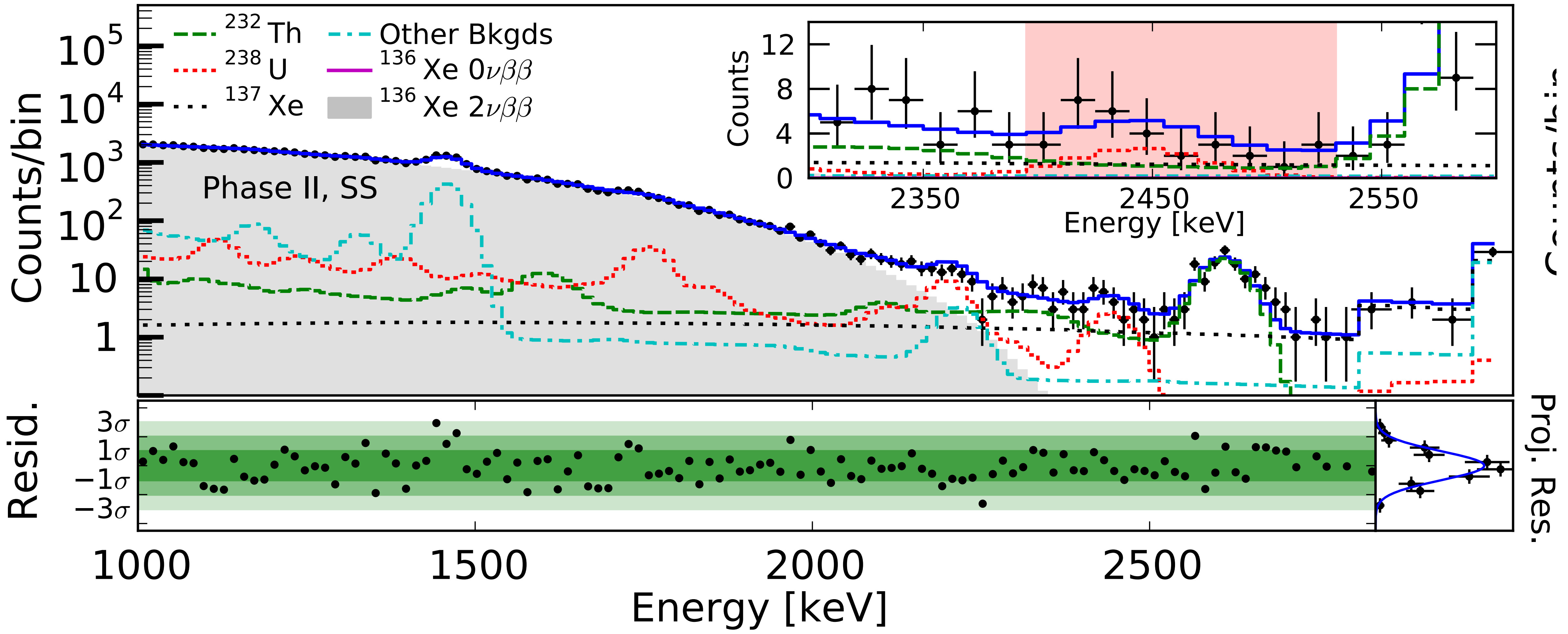
From Phys.Rev.Lett. 123 (2019) 16, 161802

@WIPP



Experimental technique: Liquid Xenon Time Projection Chamber (TPC)

- 200 kg LXe TPC (80% ^{136}Xe)
  - Energy via scintillation + ionization
  - 3D topology for multi/single-site discrimination
  - ΔE_{FWHM} @ $Q_{\beta\beta}$: 66 keV (σ_E/E=1.15%)
  - bkgd: 1.7 · 10^{-3} cpy/kg/keV



Final exposure: 234.1 kg yr

$T^{0\nu}_{1/2} > 3.5 \cdot 10^{25}$ yr

$m_{\beta\beta}$< 93–286 meV (90% C.L.)

$Q_{\beta\beta}$=2458 keV near ^{214}Bi line 2448 keV

EXO-200/nEXO

@SNOLAB

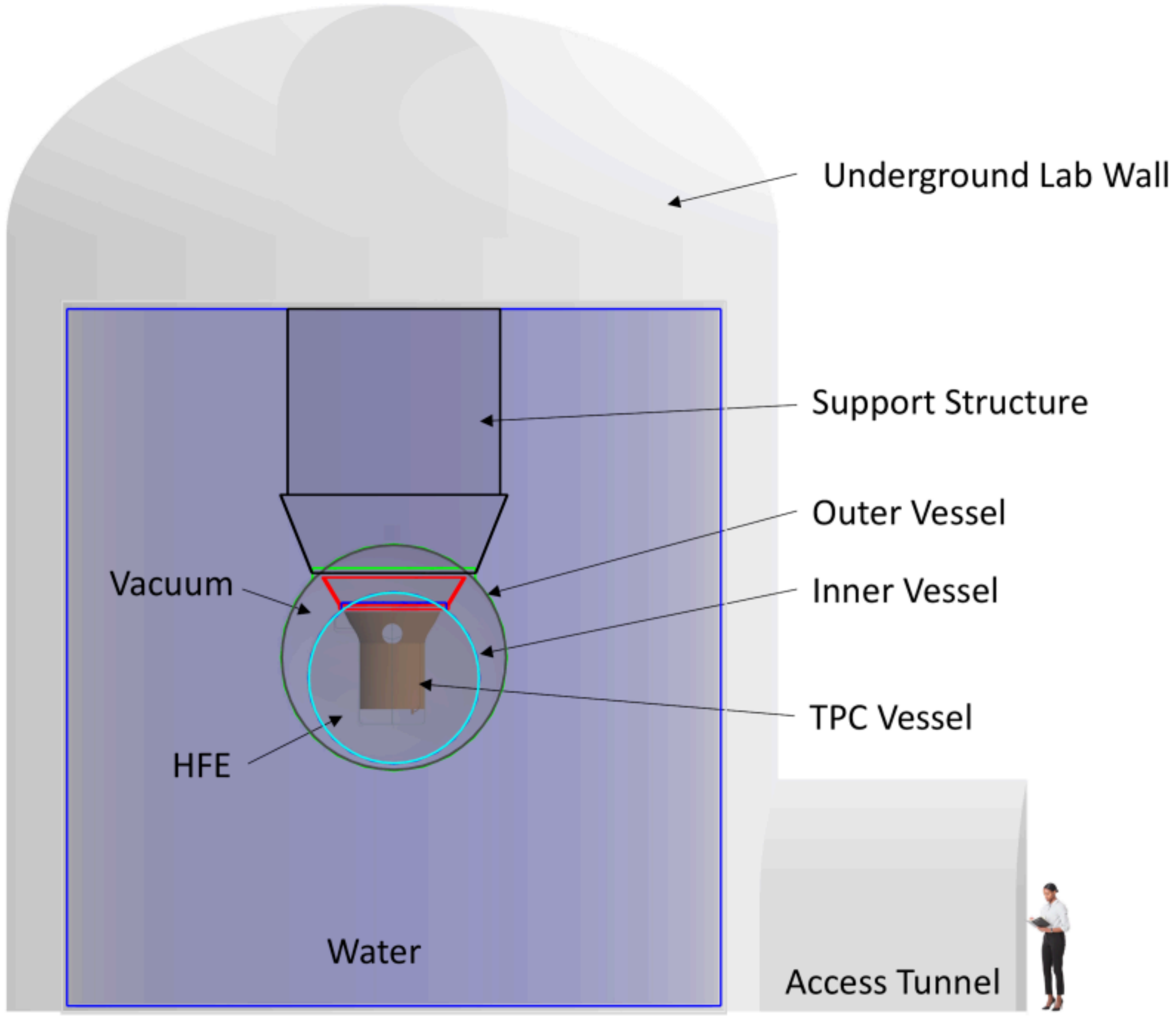
Experimental technique: Liquid Xenon Time Projection Chamber (TPC)

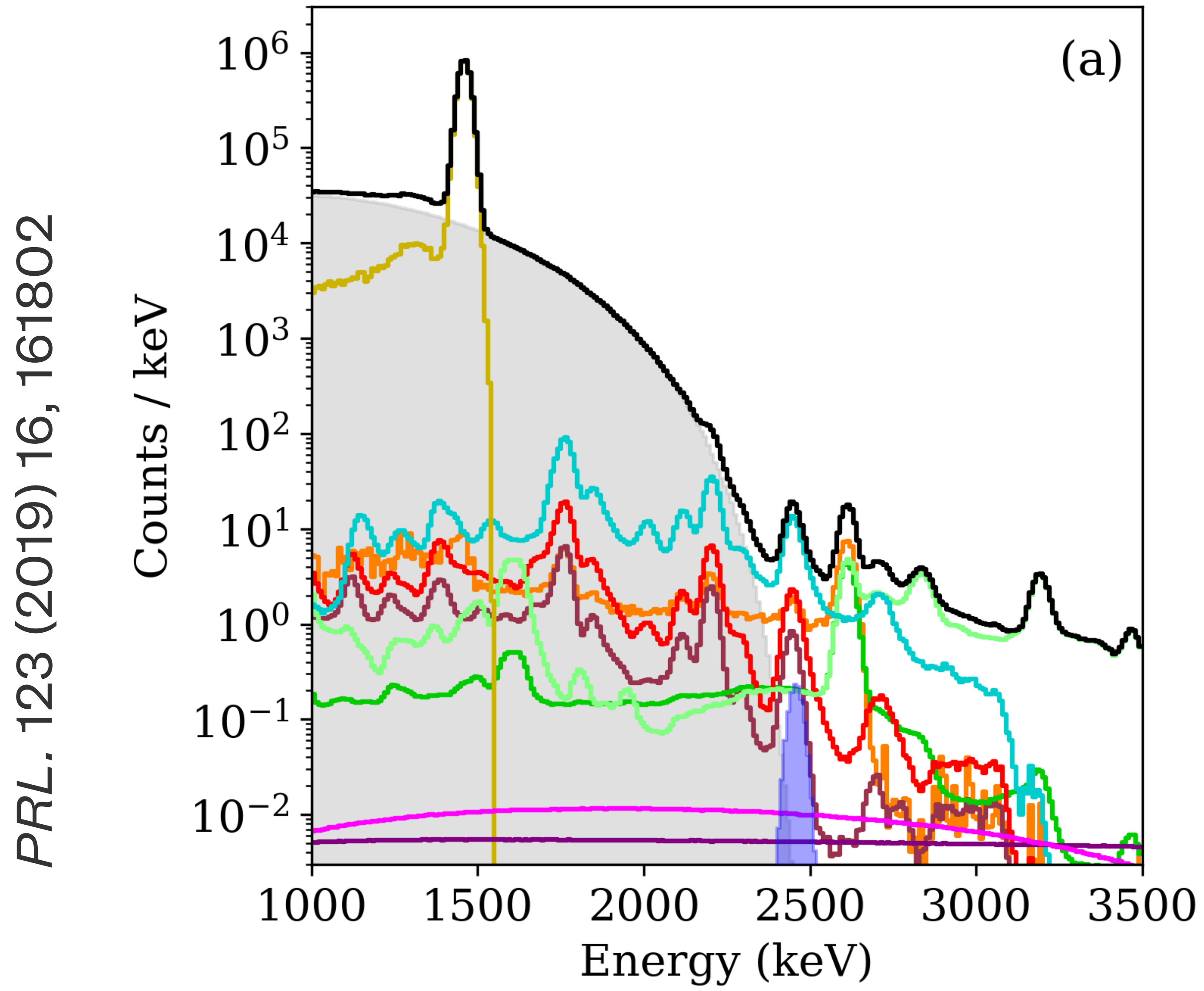
nEXO(@SNOLAB): 5 Ton

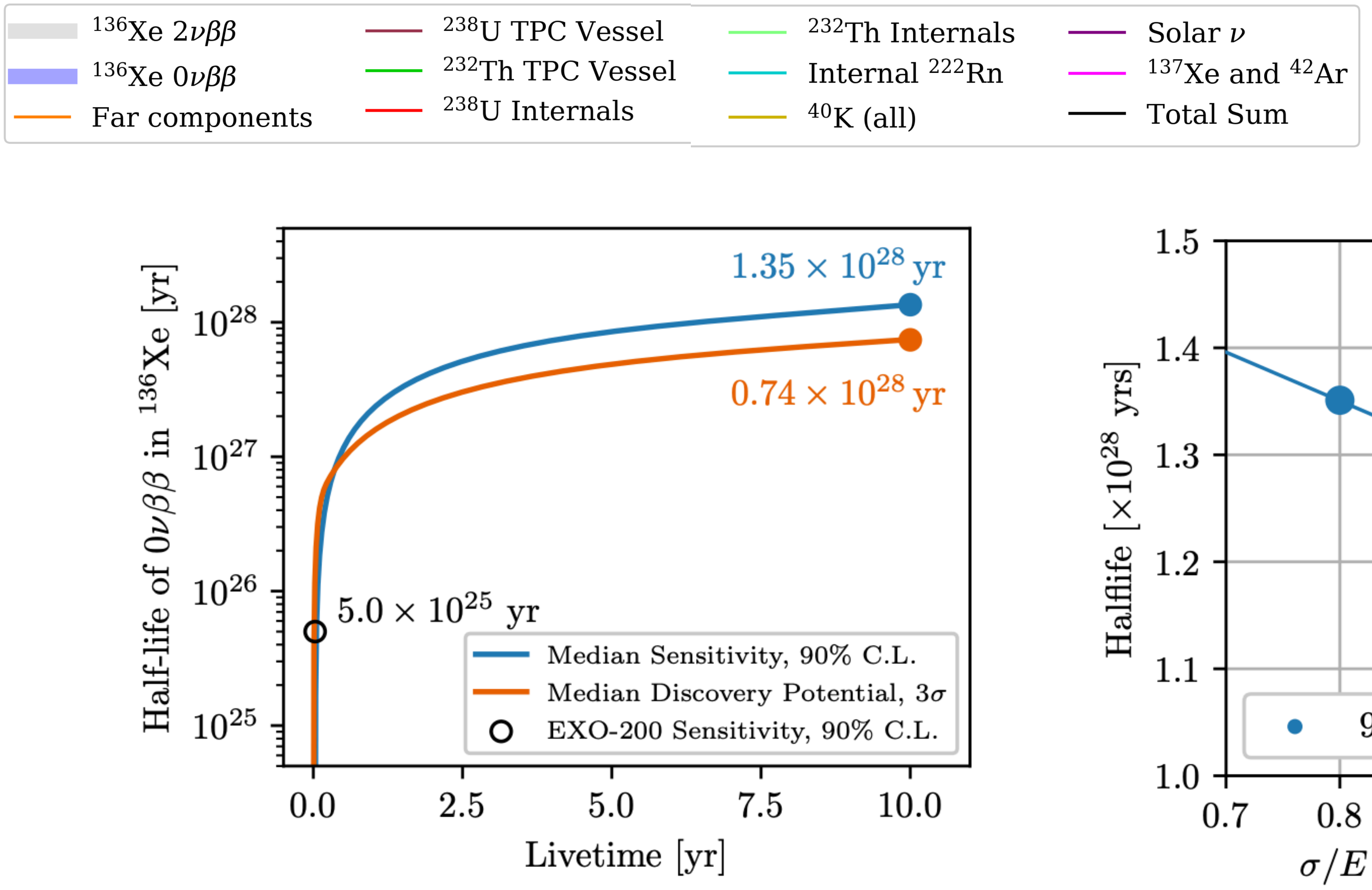
Larger TPC + Water shield

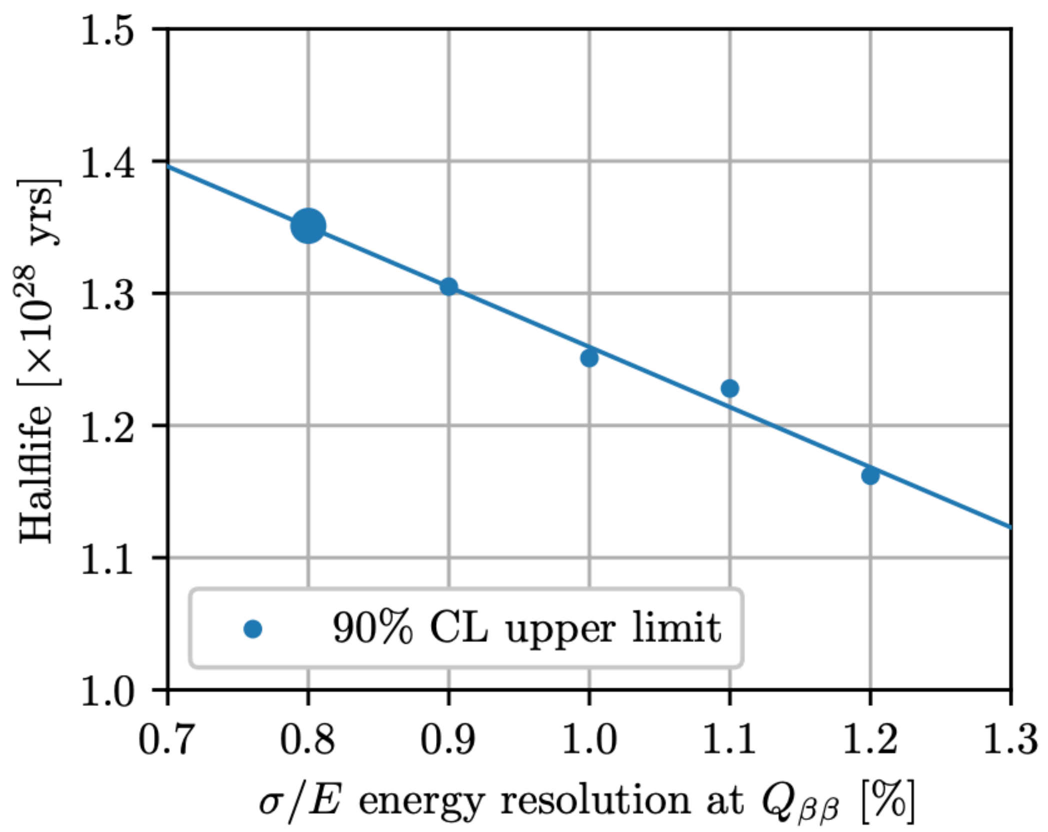
APD→SiPM, Electroformed Cu

From J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)







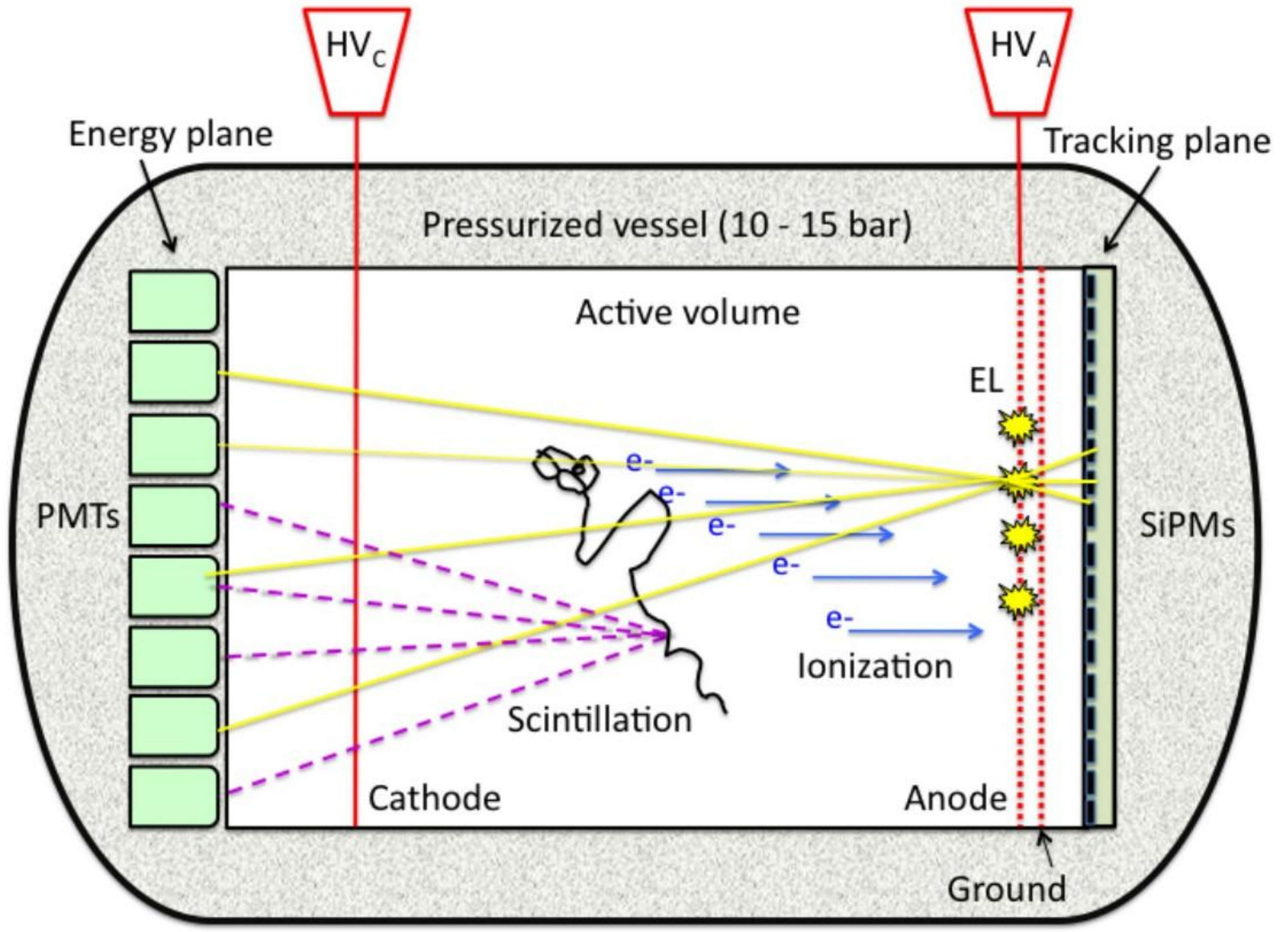


$T^{0\nu}_{1/2}$ ~$7 \cdot 10^{27}$ yr

$m_{\beta\beta}$: [6-27] meV

NEXT

From arXiv:2005.06467v2



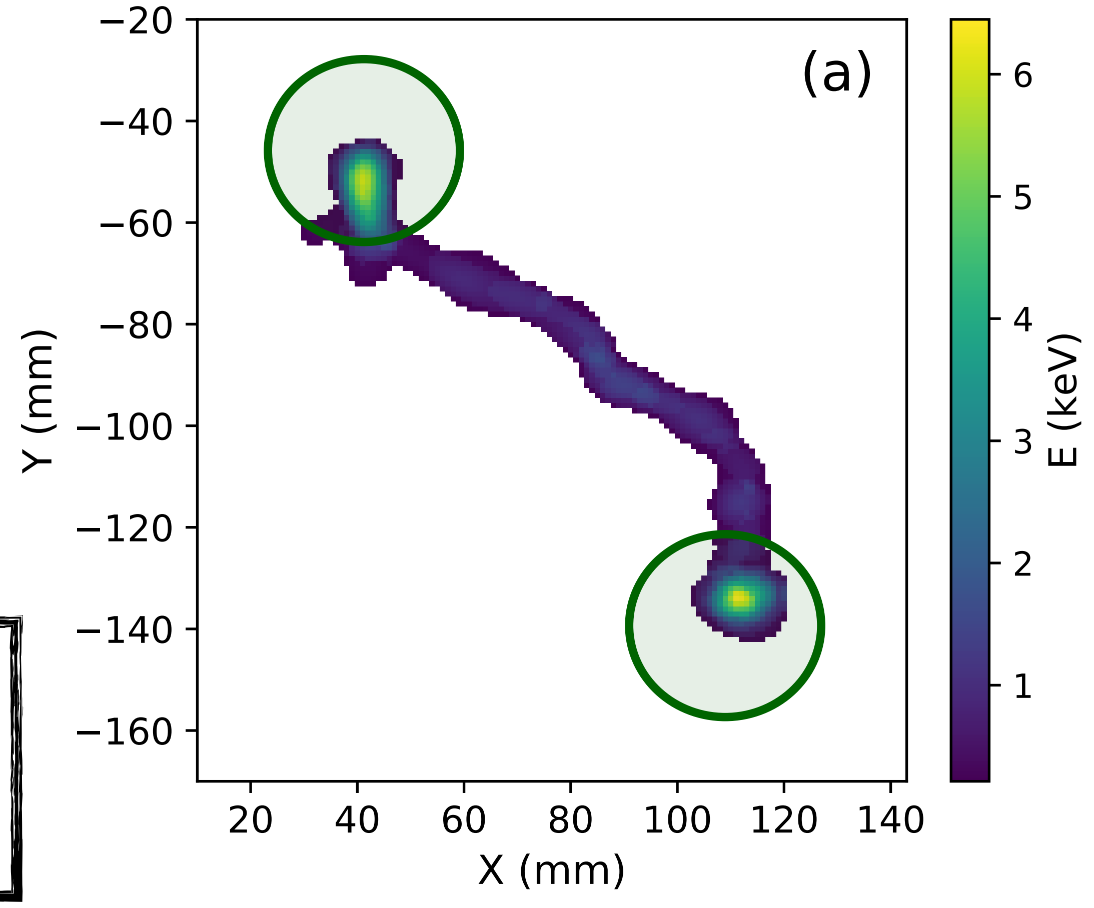
Experimental technique: High pressure enriched xenon gas time projection chambers (HPXeTPC) with amplification of the ionization signal by electroluminescence (EL).

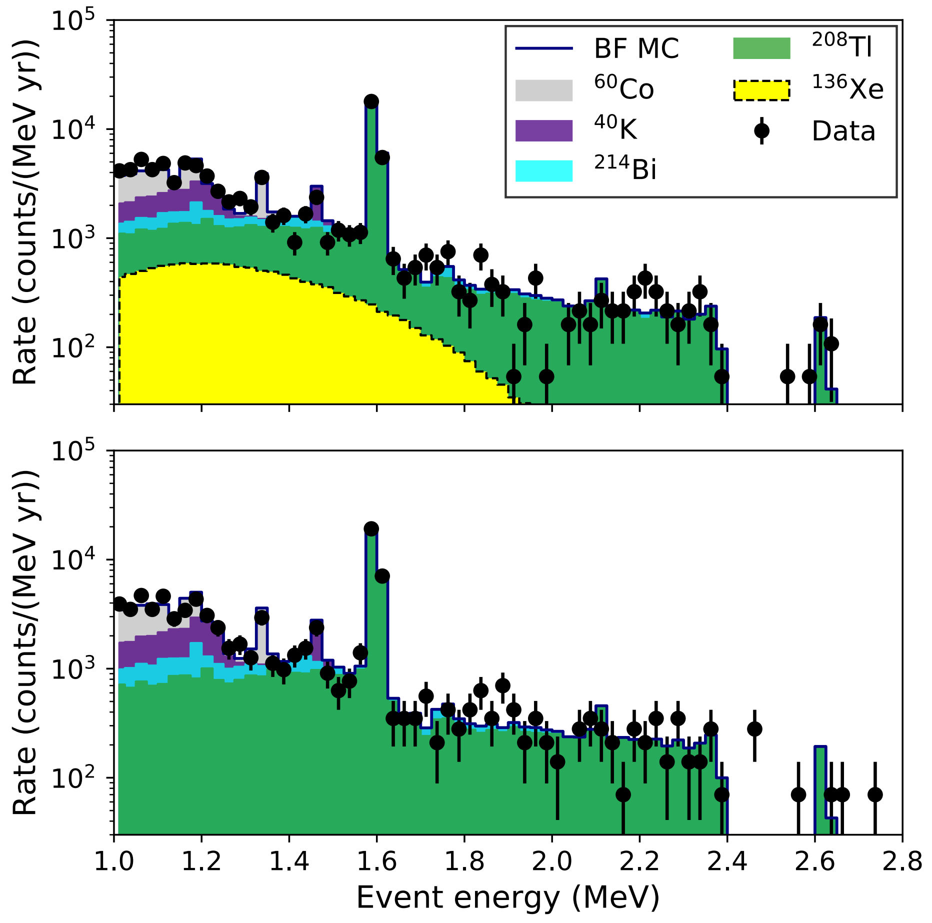
- Scintillation light —> PMTs (Energy resolution)
- EL —> SiPM array (tracking)

- Next White: 5 kg, ΔE_{FWHM}~1% (25 keV)
- NEXT-100 (2022-26): 87 kg - bkgd: $4 \cdot 10^{-4}$ cpy/kg/keV + ΔE_{FWHM}~0.8%
  - $T^{0\nu}_{1/2} \sim 7 \cdot 10^{25}$ yr
  - $m_{\beta\beta}$: [66-281] meV
- NEXT HD (1Ton): bkgd: $5\ 10^{-5}$ cpy/kg/keV + ΔE_{FWHM}~0.5%
  - $T^{0\nu}_{1/2} \sim 2 \cdot 10^{27}$ yr
  - $m_{\beta\beta}$: [12-50] meV

@Canfranc

2vββ measurement with 3.5 kg of Xe
Phys.Rev.C 105 (2022) 5, 055501





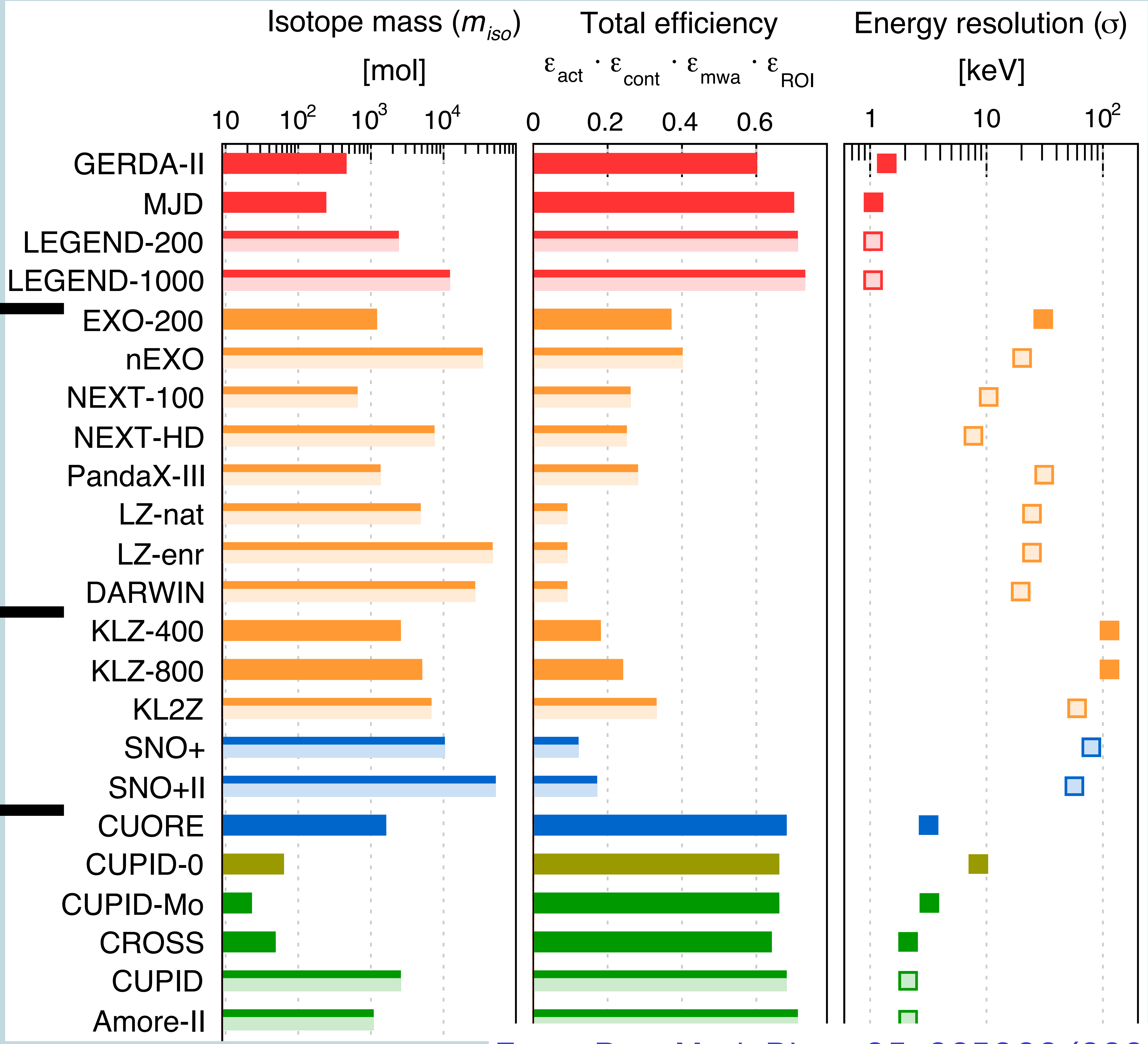
The full picture

Semiconductor ^{76}Ge

Liquid/gas TPC ^{136}Xe

Liquid scintillators ^{130}Te

Bolometers ^{100}Mo

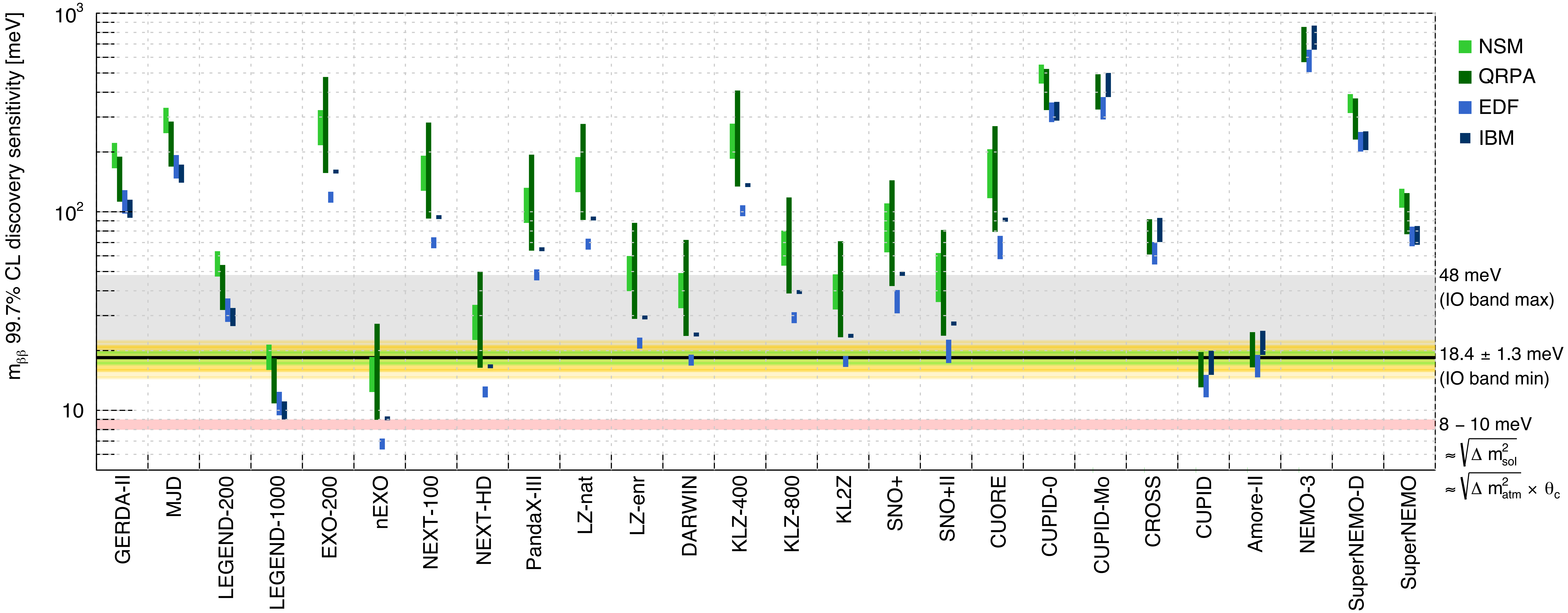


From Rev. Mod. Phys. 95, 025002 (2023)

Conclusion

From Rev. Mod. Phys. 95, 025002 (2023)

NEUTRINOLESS DOUBLE BETA DECAY COULD BE WITHIN REACH



- Worldwide major effort underway for the preparation of ton-scale experiments designed for discovery
- Fully explore the Inverted Hierarchy region in the next 15 yr
- Explore large fraction of Normal Hierarchy

Backup

g_A quenching

An additional uncertainty to the NME comes from the so called g_A “quenching”:

- calculated β decay matrix elements over-predicted measured value by a uniform factor
- a direct quenching of about 0.7 of the axial coupling constant g_A was suggested
- large (1/2) impact on NME and dramatic (1/4) impact on $0\nu\beta\beta$ rates
- recent ab-initio calculations of the β decay rates well reproduce the measured ones without quenching