2024/10/24
Récontres de Blois

# Neutrinoless Double Beta Decay Experiments: Present and Future


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SNOLAB


*SNOLAB is located on the traditional territory of the Robinson-Huron Treaty of 1850, shared by the Indigenous people of the surrounding Atikameksheng Anishnawbek First Nation as part of the larger Anishinabek Nation.*

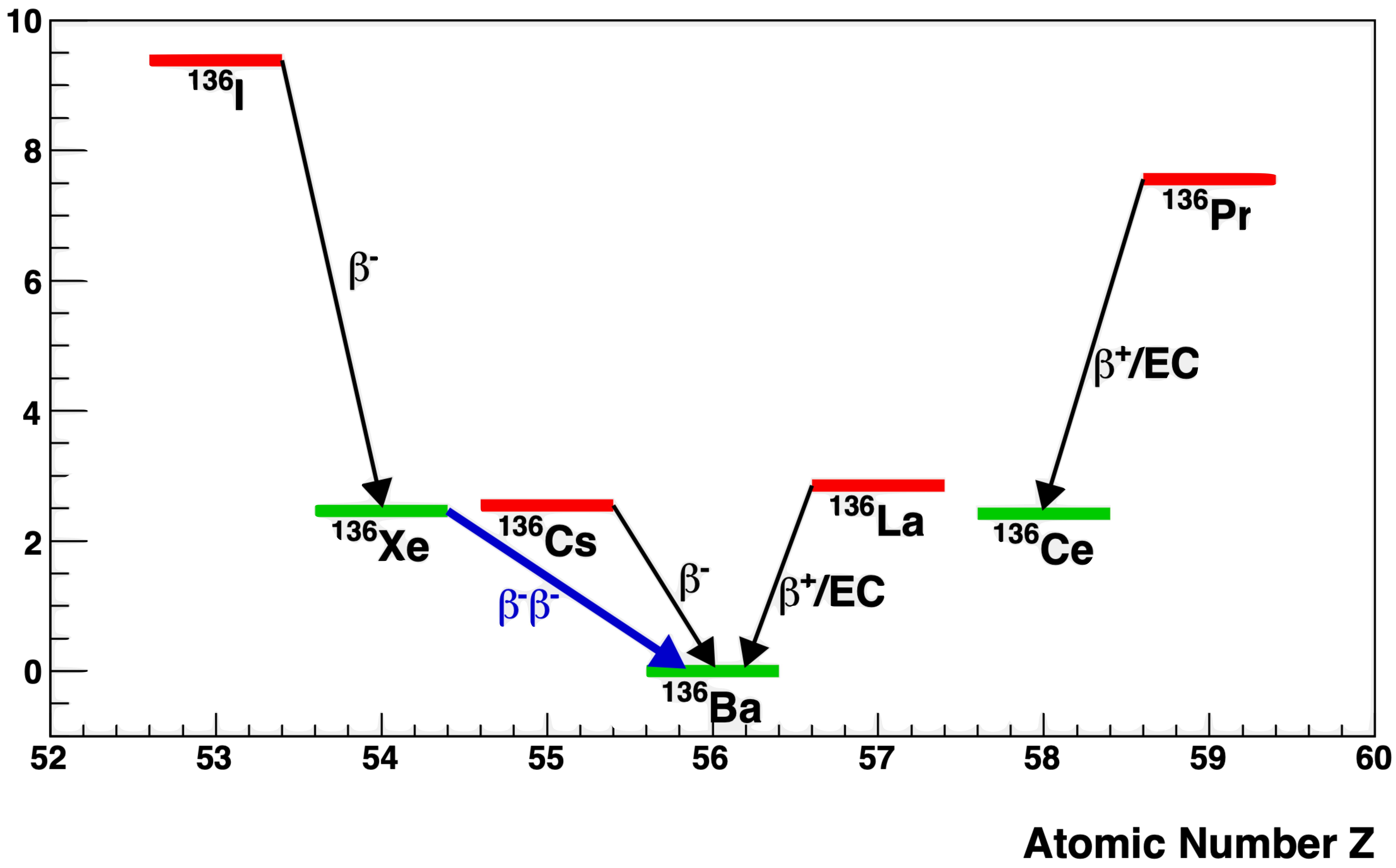

*We acknowledge those who came before us and honour those who are the caretakers of this land and the waters.*

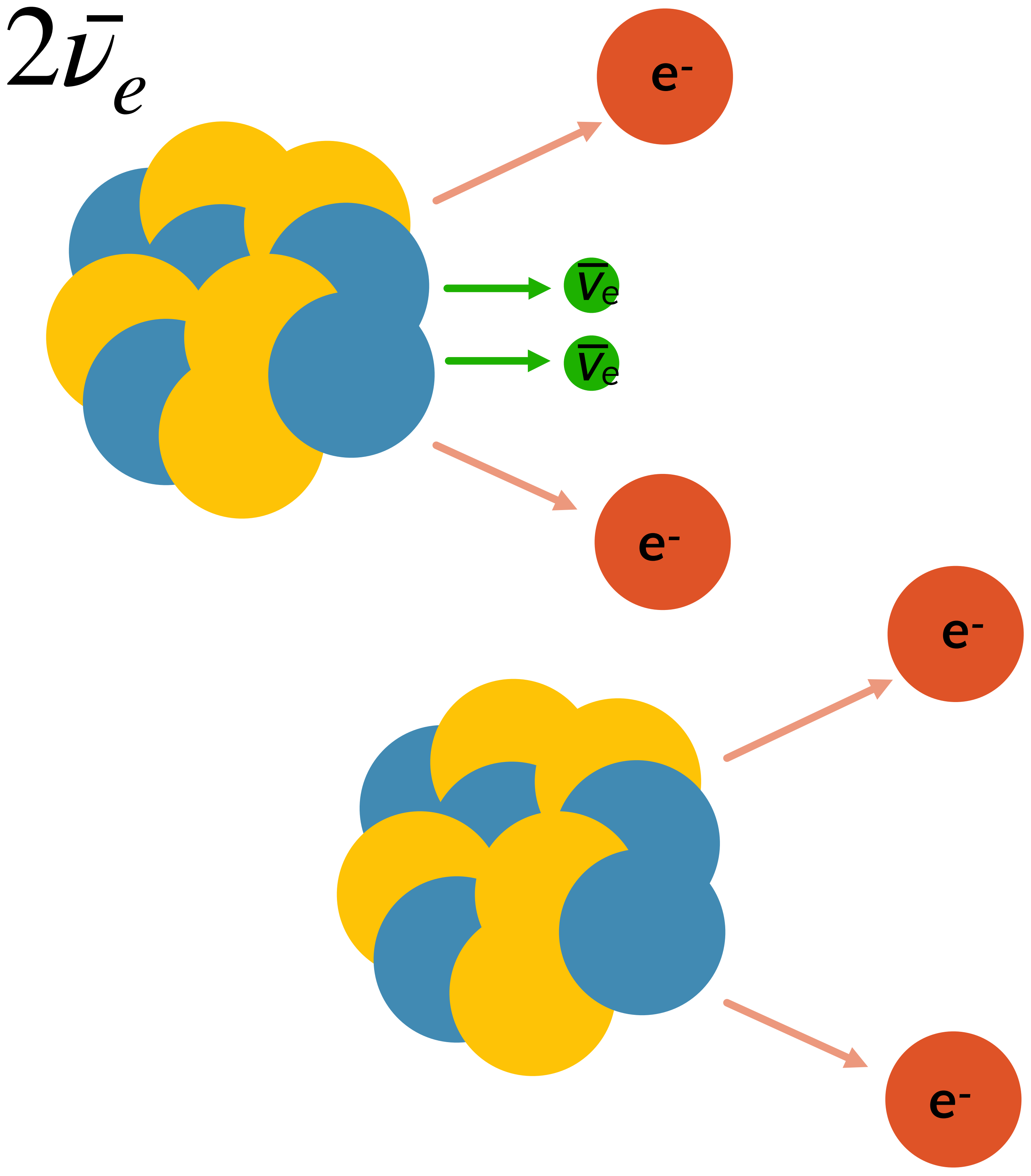
# Outline

- Neutrinoless Double Beta Decay
- Current Experiments
- Near Future Experiments
- Far Future Experiments

# Double Beta Decay

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



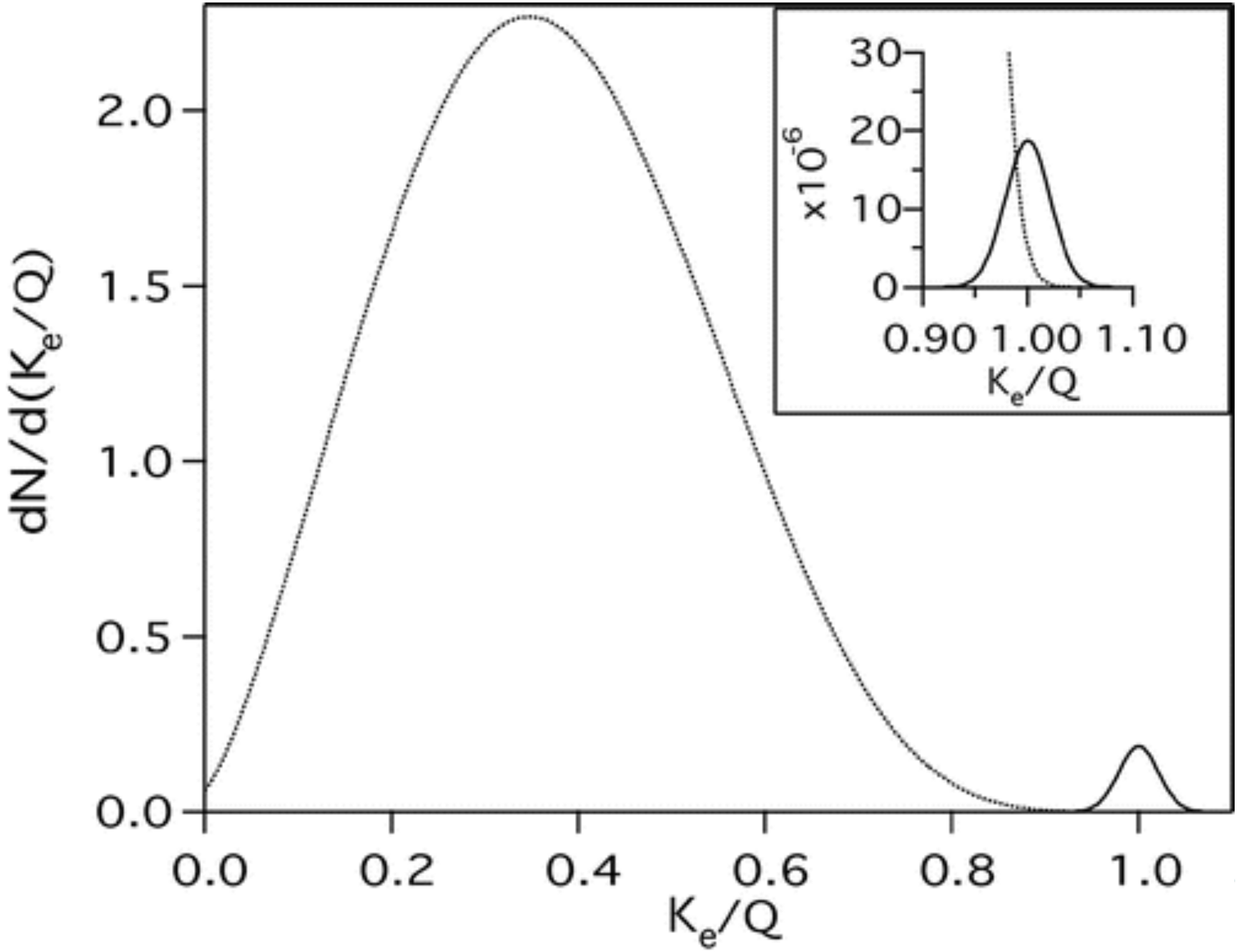

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

[Riv. Nuovo Cim. 35 (2012) 29-98]

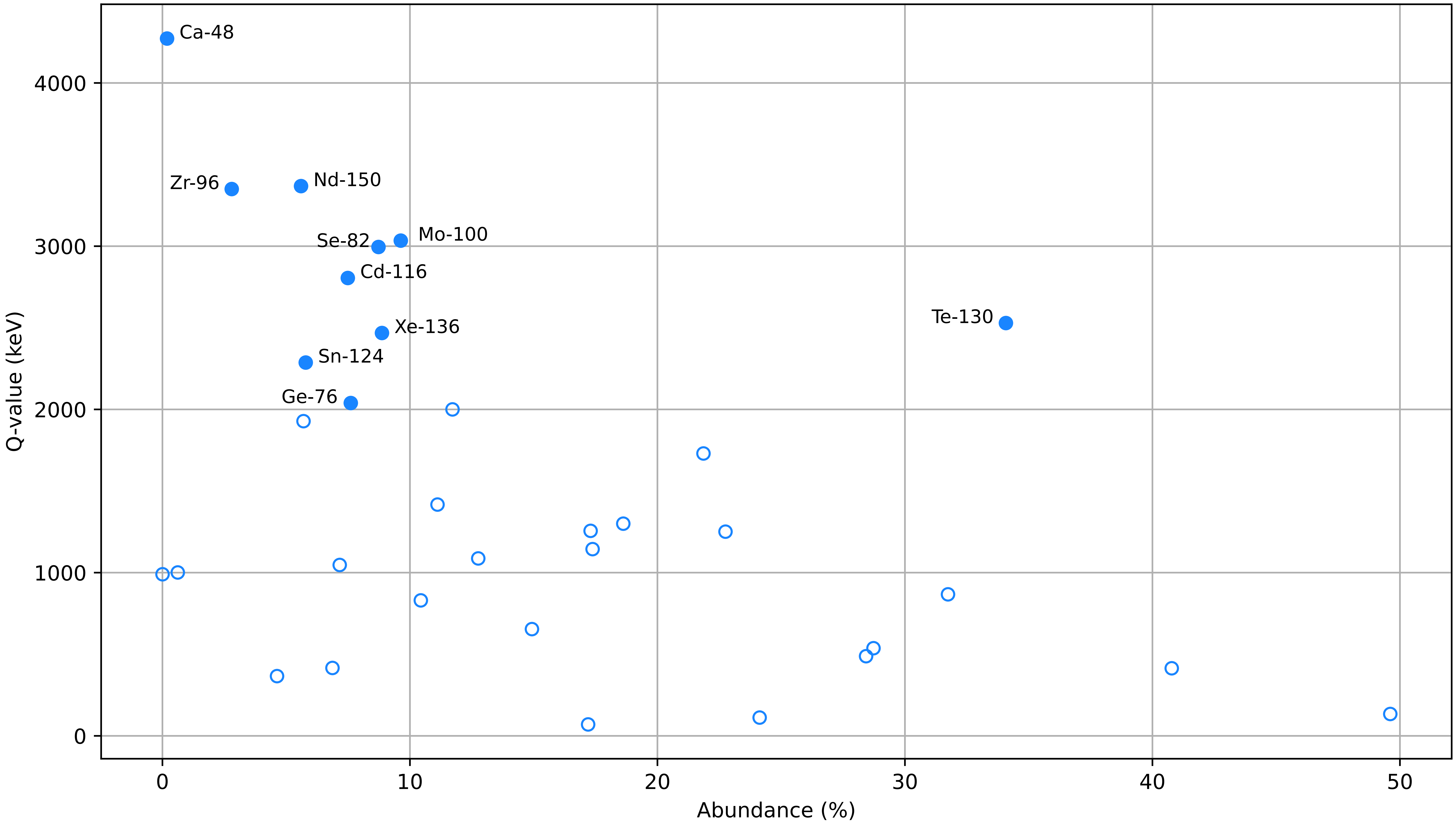
# Double Beta Decay

- Key experimental signature for $0\nu\beta\beta$ is a peak in visible energy at the Q-value of the nucleus, smeared by detector resolution.

- Experiments are designed to minimize backgrounds around the Q-value.



# Double Beta Decay Isotopes

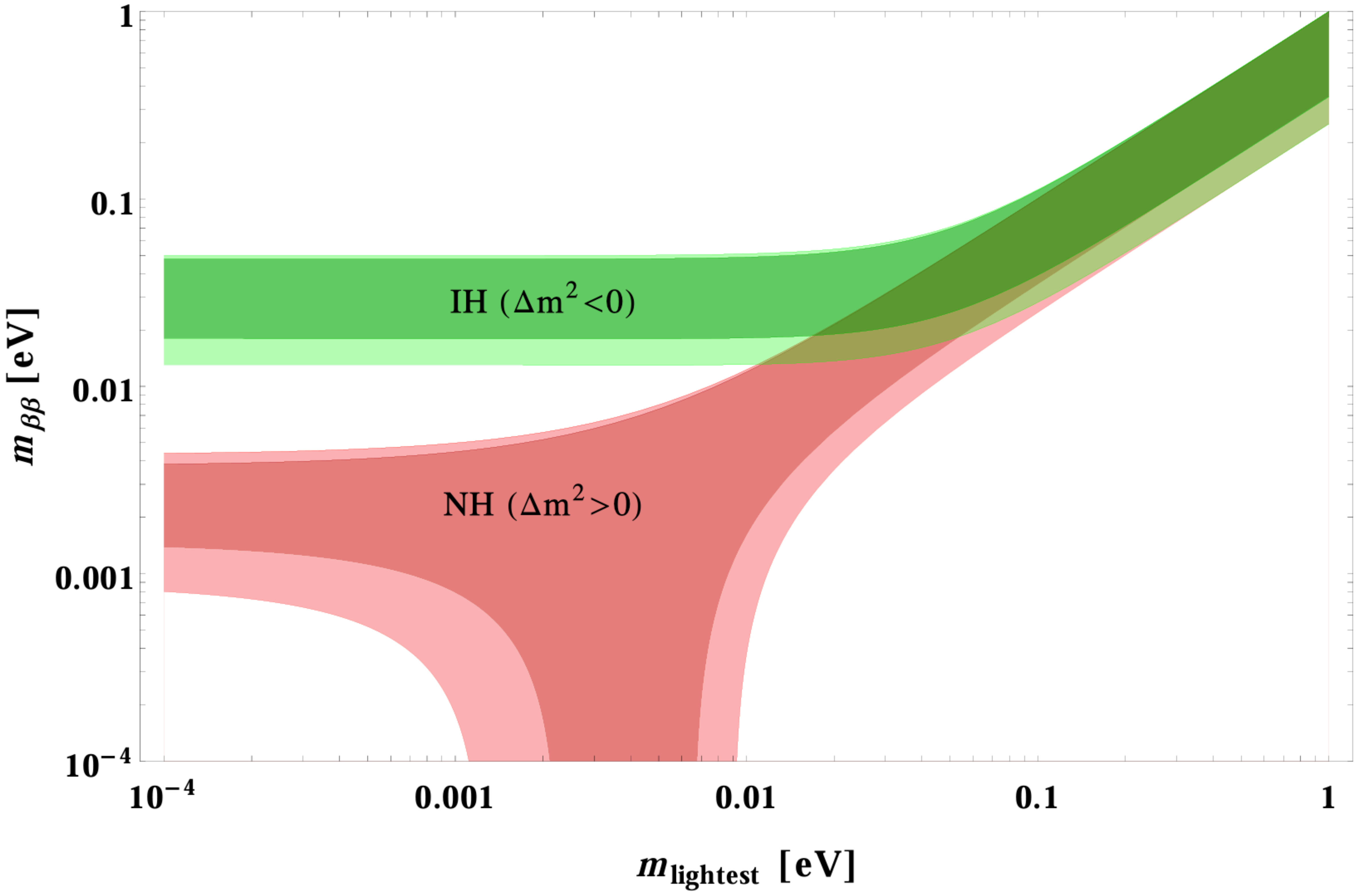


# There is no scenario in which observing 0νββ decay would not be a great discovery:

- Majorana neutrinos
- Lepton number violation
- Probe new mass mechanism up to the GUT scale
- Probe key ingredients in generating cosmic baryon asymmetry

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\,|M^{o\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = |\sum_i U^2_{ei} m_i|$$

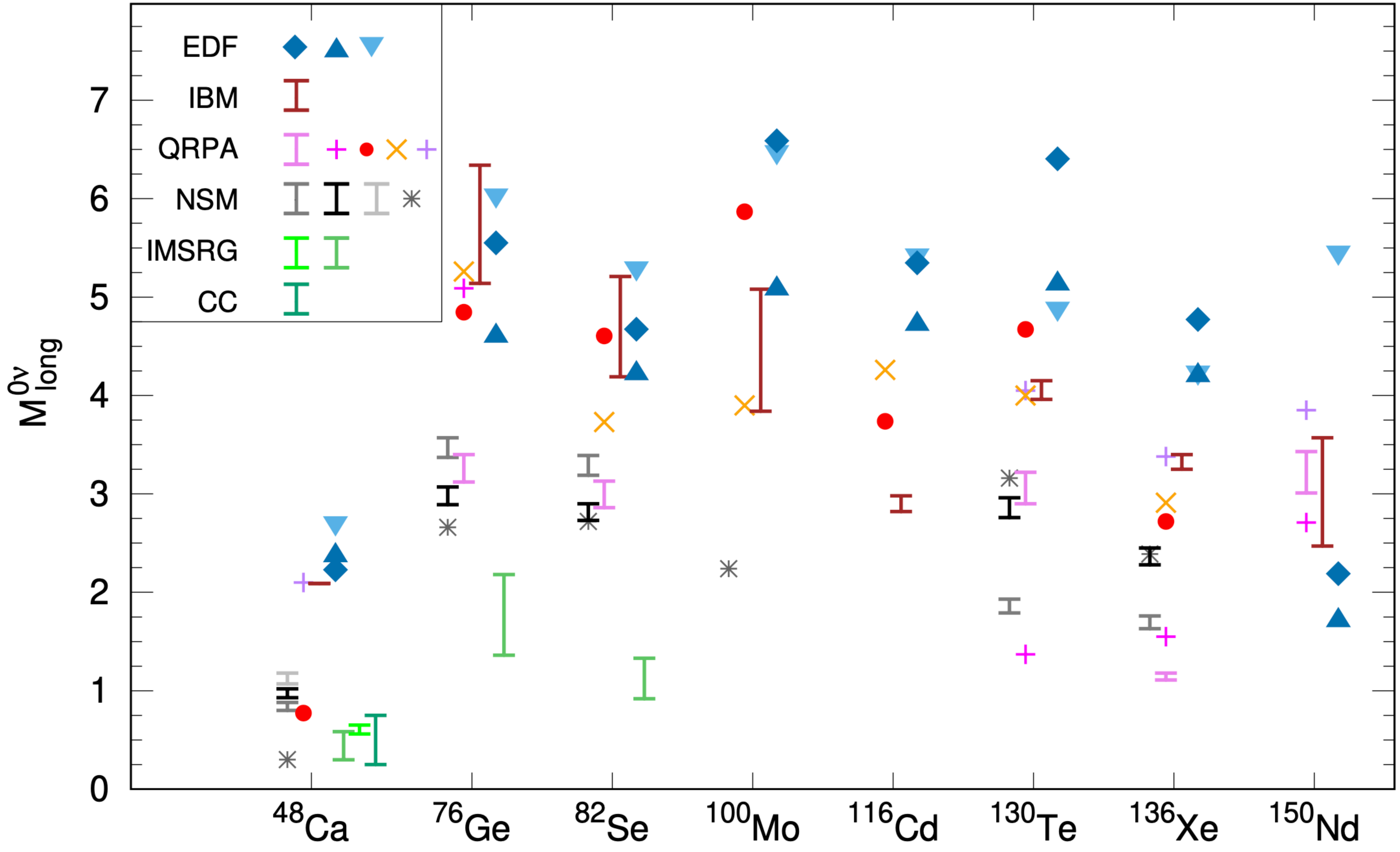



- The connection with the effective ν mass also means that the observation of 0νββ decay can provide information on the ν mass scale, provided that:
  - The mechanism producing the decay is understood
  - The nuclear matrix element is calculated with sufficiently small uncertainty



Phys. Rev. D90, 033005 (2014)

# Nuclear Matrix Element Results




- The calculations vary by a factor of 2-3. Usually taken as an estimate of the uncertainty.
- It is not a true uncertainty because the different models neglect different physics.



[Rev. Mod. Phys. 95, 025002 (2023)]

# Important to International Communities

SNOLAB

APPEC
European Astroparticle Physics Strategy 2017-2026

## RECOMMENDATIONS:

**APPEC strongly supports the … double-beta decay experiments selected in the US-European process.** The search for neutrino less double beta decay will primarily test the particle nature of neutrinos since this Beyond the Standard Model and lepton-number-violating process is only possible in the neutrinos are of Majorana-type. Its observation would additionally give information about the generation mechanism and neutrino mass spectrum. **Confirmation of discovery will require results from several isotopes and measurement technologies.**

A NEW ERA OF DISCOVERY
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE
2023 | VERSION 1.5

## RECOMMENDATION 2

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. [...] Neutrinoless double beta decay experiments have the potential to dramatically change our understanding of the physical laws governing the universe.

Canadian Subatomic Physics LONG-RANGE PLAN 2022–2026

## SCIENCE RECOMMENDATION 3

A broad experimental program is required to address the scientific drivers of subatomic physics research. We recommend pursuit of the following high-priority scientific directions: The **future program should include the further exploration of neutrino properties via neutrinoless double-beta decay experiments**, long baseline experiments and neutrino observatories.

# A healthy neutrinoless double-beta decay program requires more than one isotope.

- Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities
- Different isotopes correspond to vastly different experimental techniques
- 2 neutrino background is different for various isotopes
- Understanding the mechanism producing the decay requires the analysis of more than one isotope

# Currently Running Experiments

CUORE

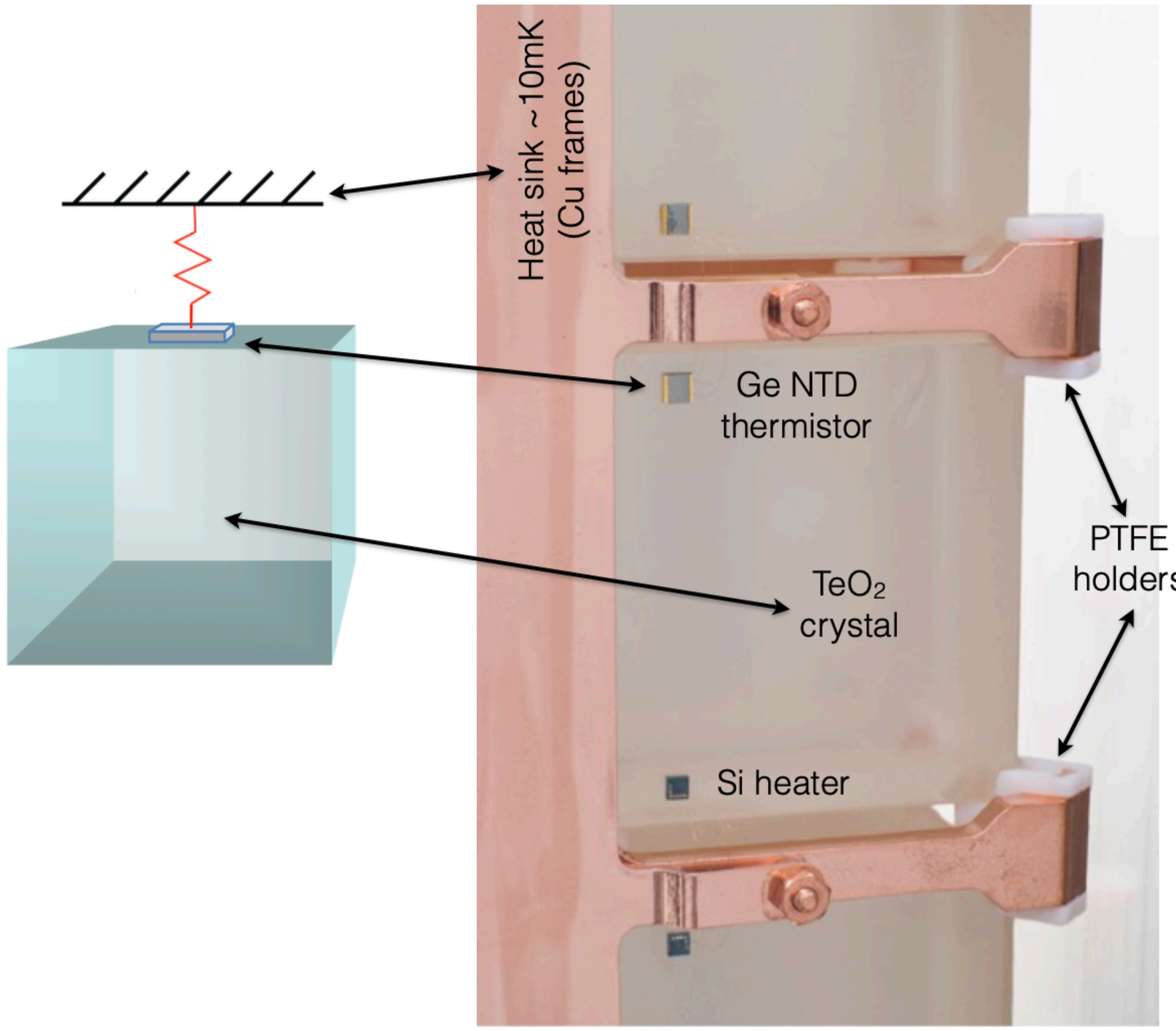
Zero neutrino double beta decay search
KamLAND-Zen

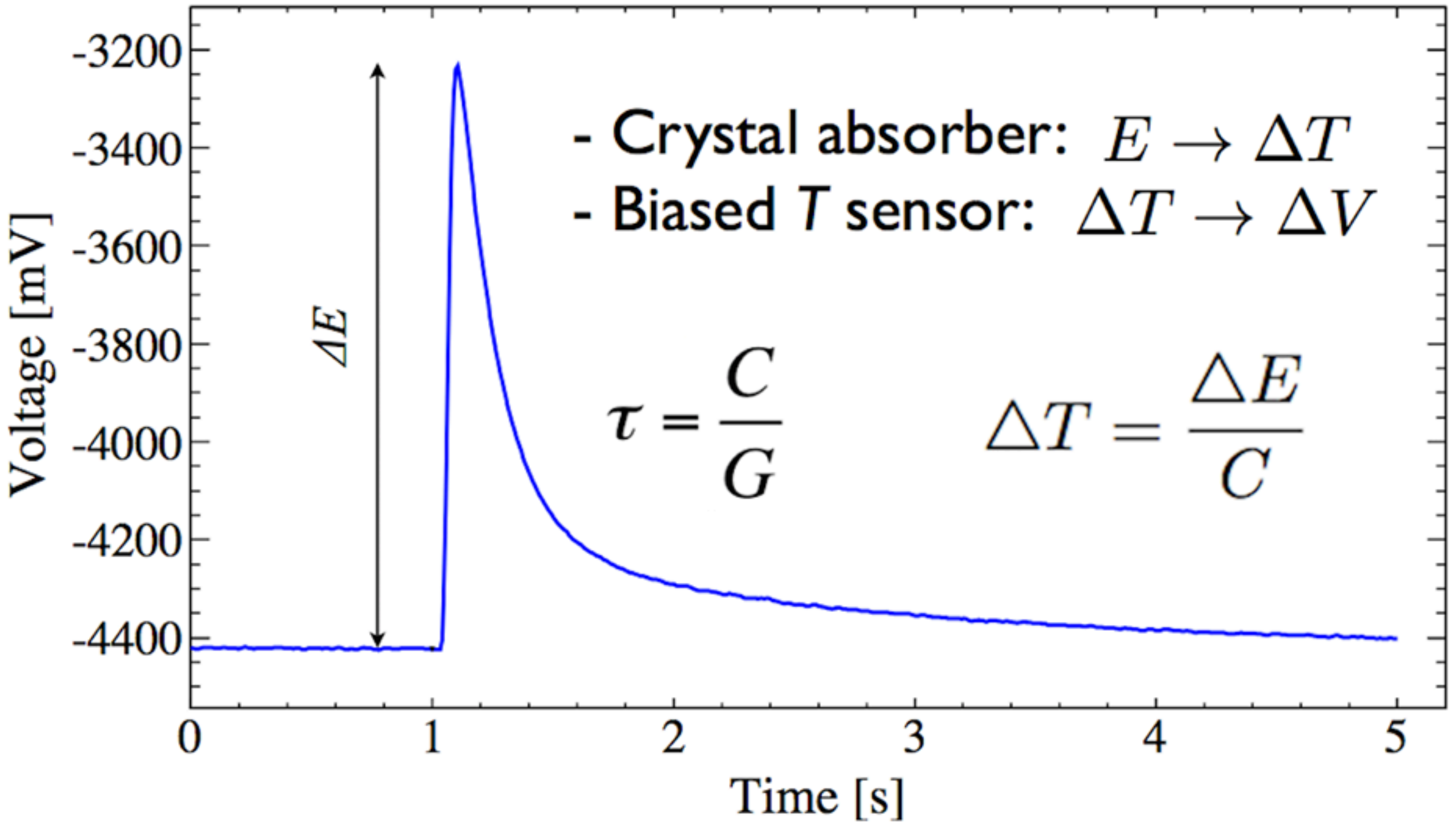
LEGEND-200

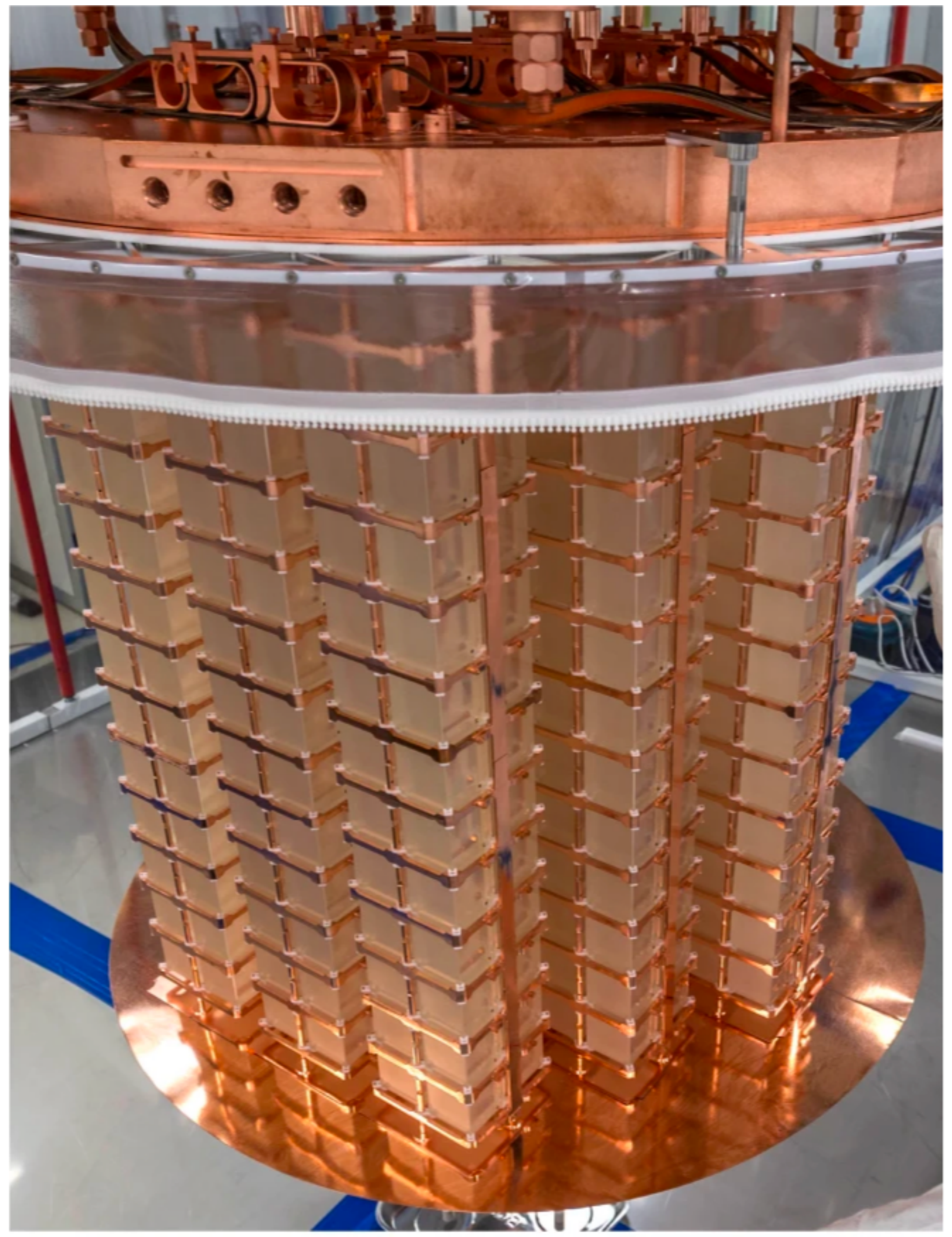
CUORE

# Cryogenic Underground Observatory for Rare Events

- 988 $TeO_2$ crystals in 19 towers
- 10 mK cryostat in LNGS (1400m, 3800 mwe)
- 206 kg of $^{130}$Te, 188kg $^{128}$Te
- Operating temperature: ~10 mK
- Energy Resolution ~0.3% (7.8 keV) @ $Q_{\beta\beta}$



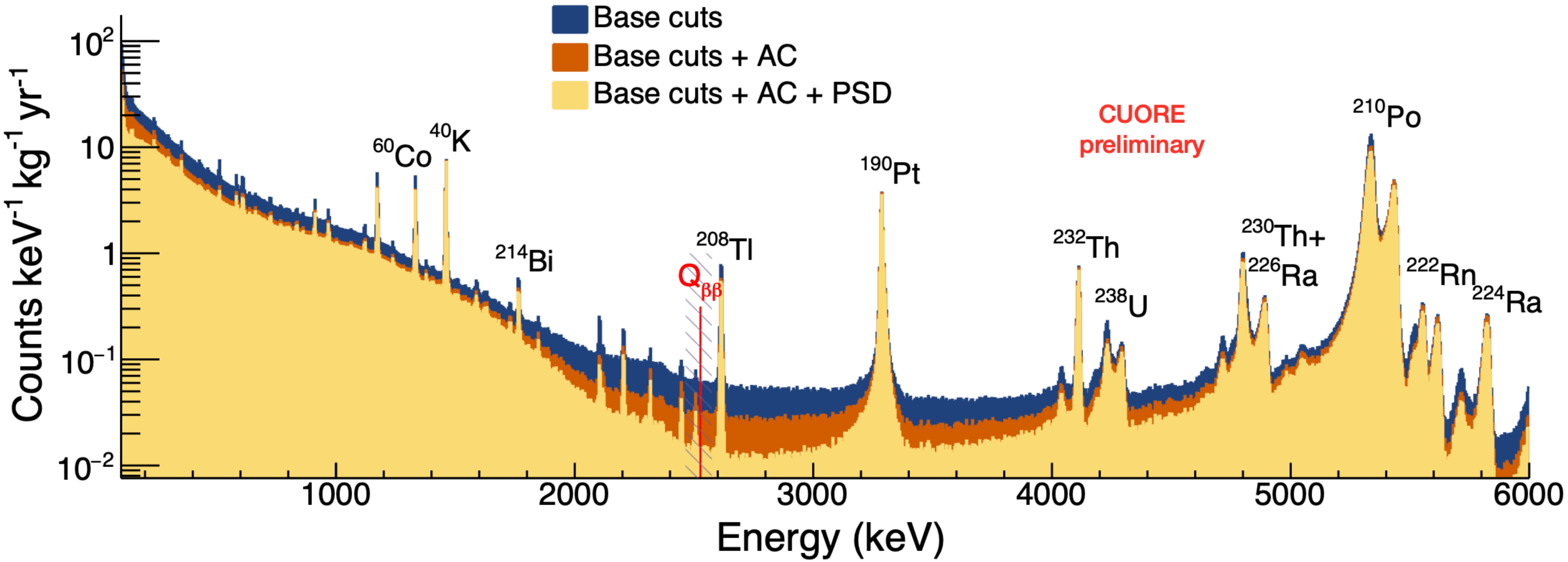



G: thermal coupling constant

ΔT: ~ 0.1-1 mK/MeV, τ: ~ 0.1-1 s

[Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA]

Nature 604 (2022) 7904, 53-58; arXiv:2205.03132; PRL 126, 171801 (2021)



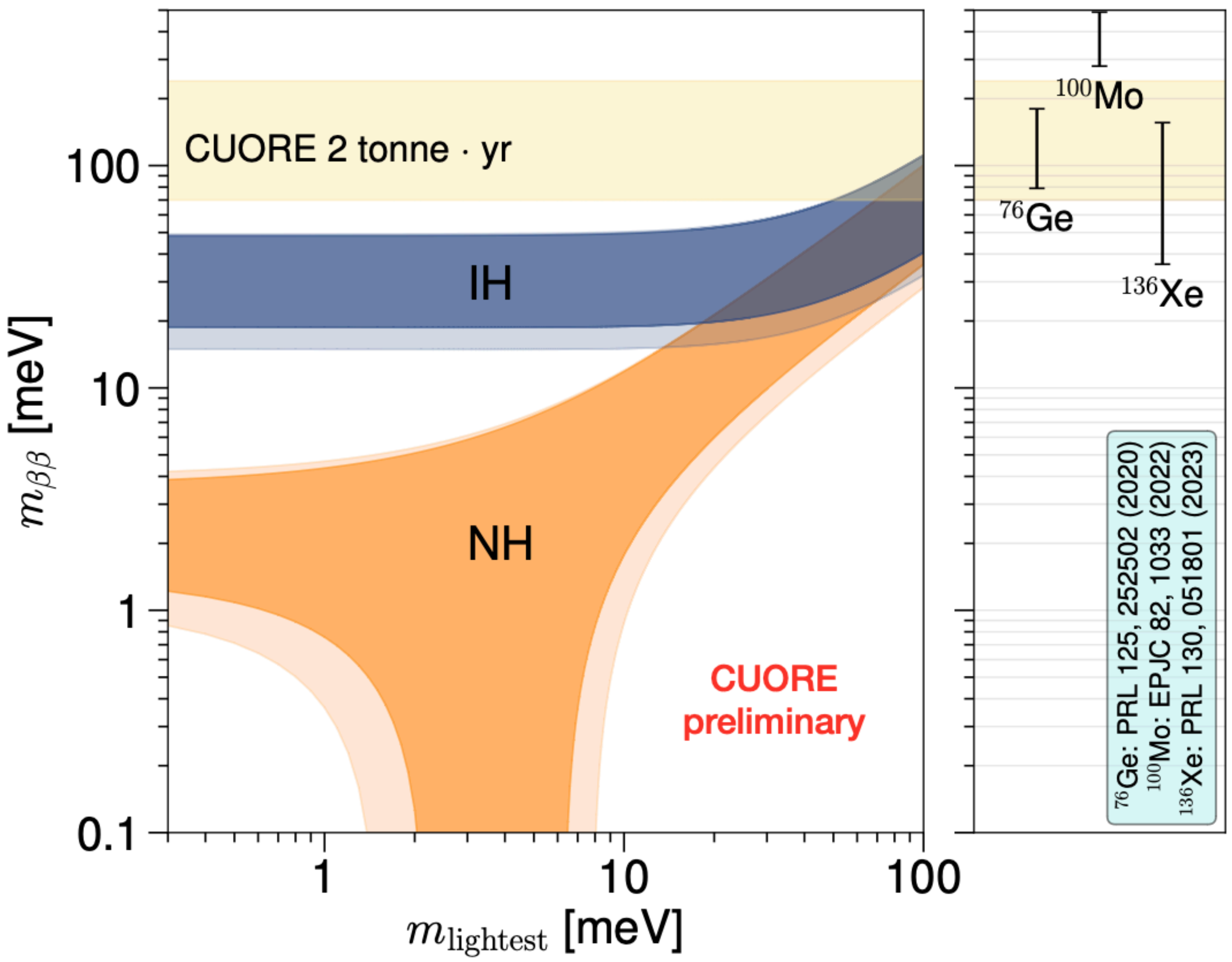

May 2017 to April 2023:

2039.0 kg · yr $TeO_2$ (567.0 kg · yr $^{130}$Te)

- $T^{2\nu}_{1/2} = 9.323^{+0.052}_{-0.037} \times 10^{20}$ yr
- $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90%CL)
- <$m_{\beta\beta}$> < (10-240) meV

Nature 604 (2022) 7904, 53-58;
Phys. Rev. Lett. **129**, 222501 (2022);
PRL 126, 171801 (2021);
arXiv:2404:04453

[Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA]




CUORE

2022:

309.33 kg·yr (78.6 kg·yr of $^{128}$Te)

- $T^{2\nu}_{1/2} = 2.19 \pm 0.07 \times 10^{24}$ yr
- $T^{0\nu}_{1/2} > 3.6 \times 10^{24}$ yr (90%CL)

**Continue collecting data until reaching 3 tonne·yr of analysed $TeO_2$ exposure**

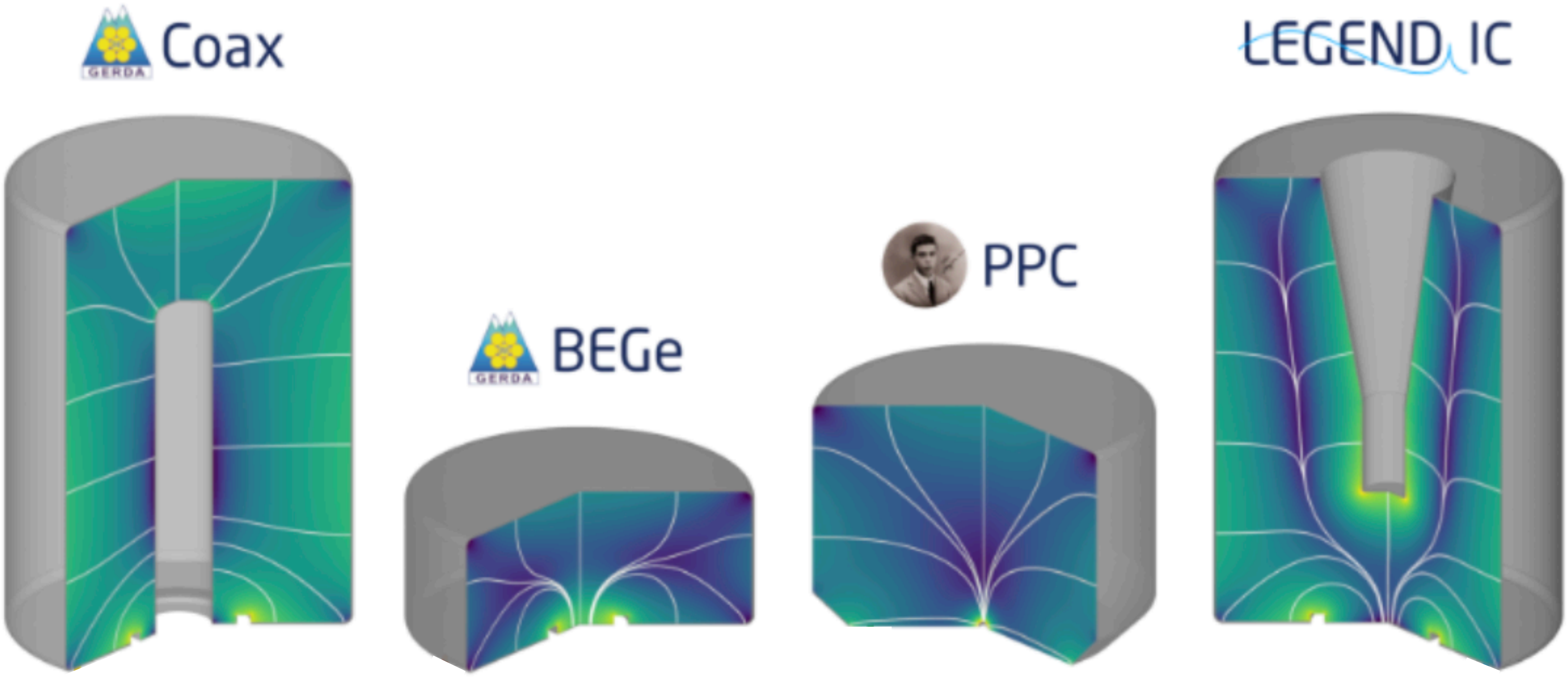
**-> proceed toward CUPID**

[Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA]

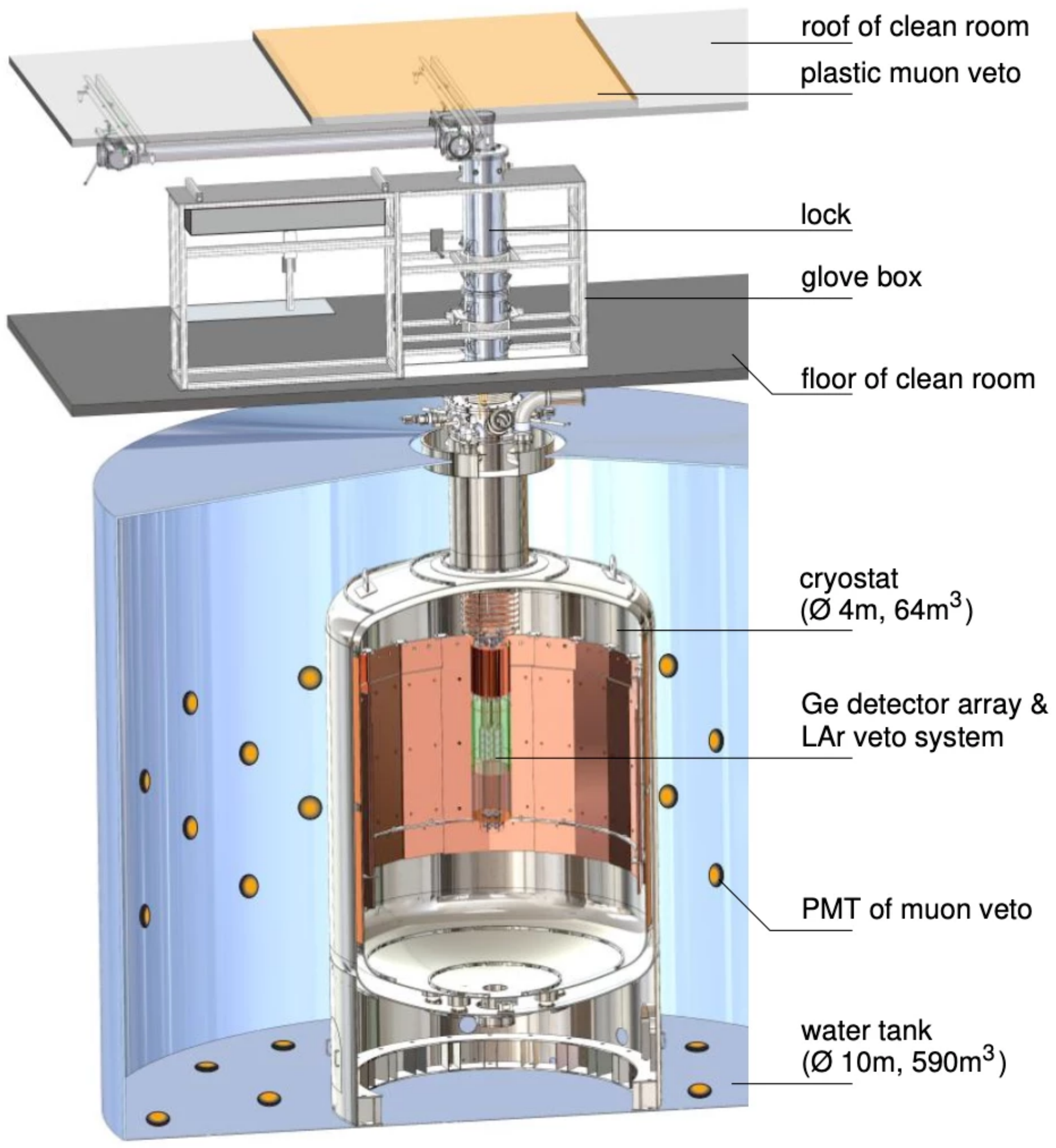
[Te-128, $Q_{\beta\beta}$ = 866 keV, 31.75% NA]

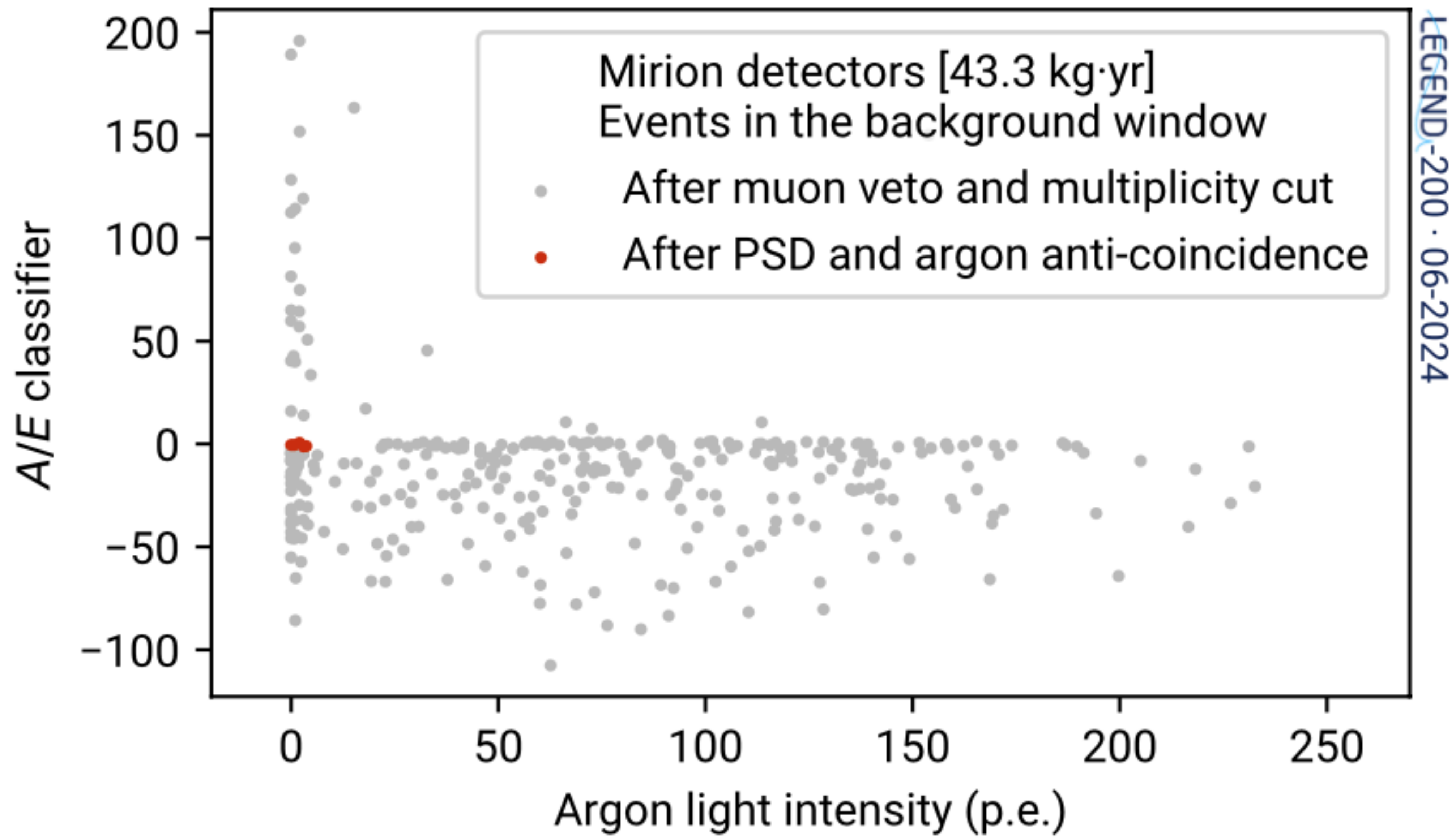
# LEGEND-200

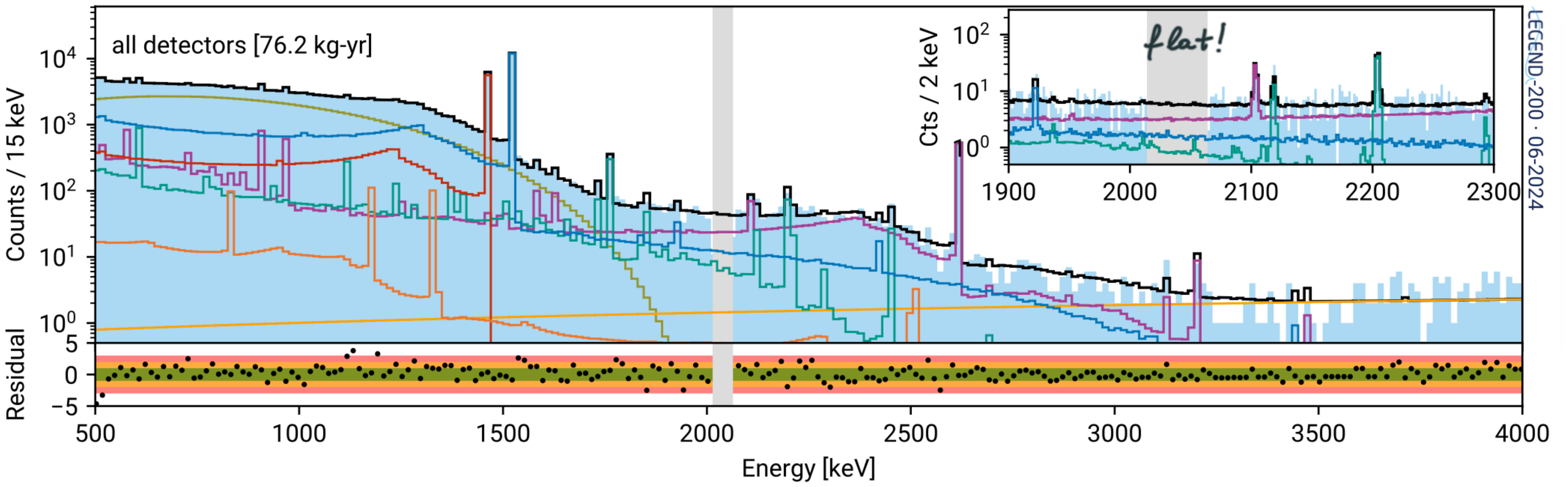
# LEGEND uses sophisticated large enriched Ge-76 detectors building on work by Majorana and GERDA




- Ge Crystals > 90% enriched in $^{76}$Ge
- 140 kg
- Energy Resolution: 0.1% @ $Q_{\beta\beta}$
- $Q_{\beta\beta}$ = 2039 keV
- 7.8% NA

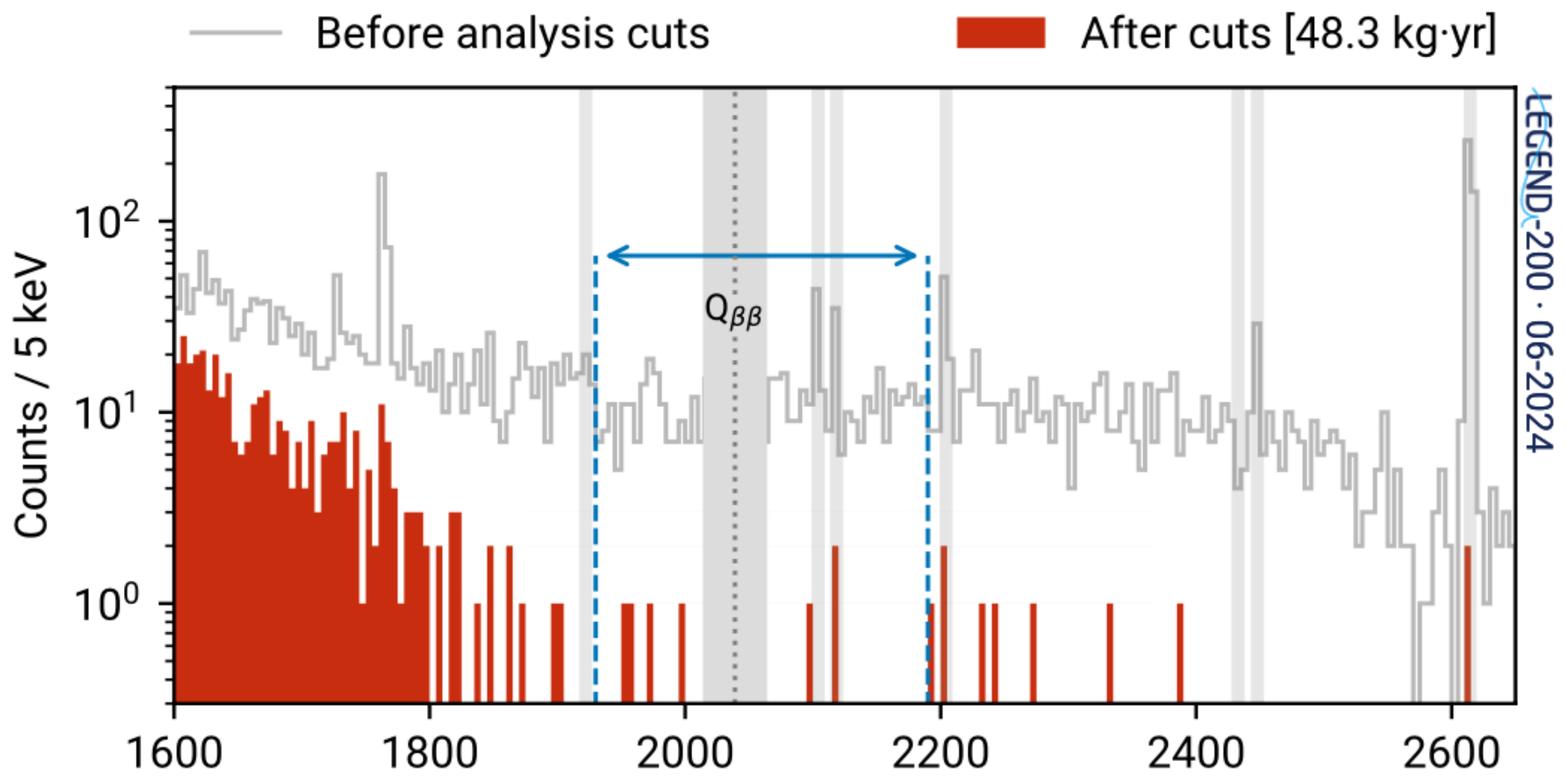


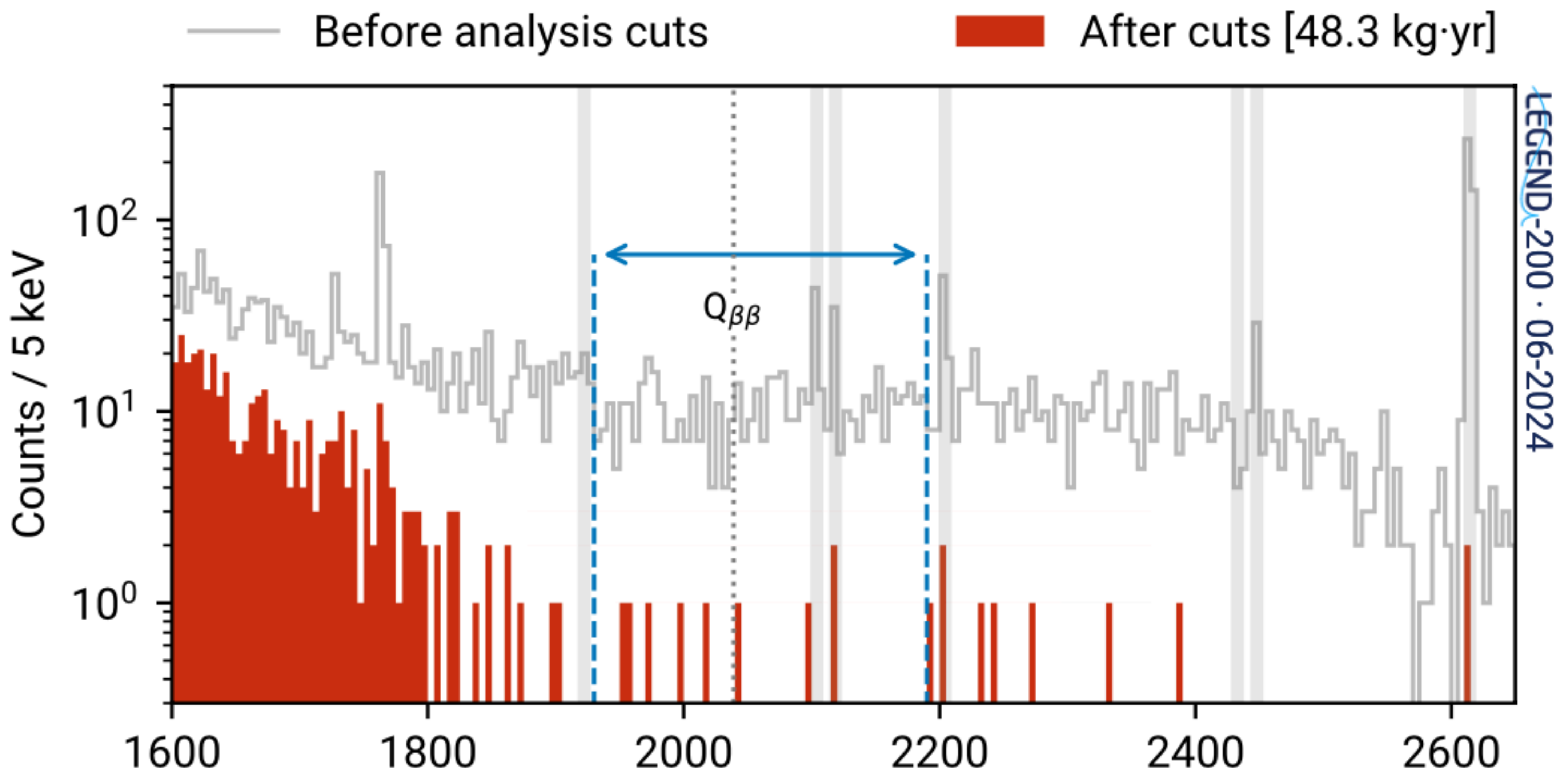



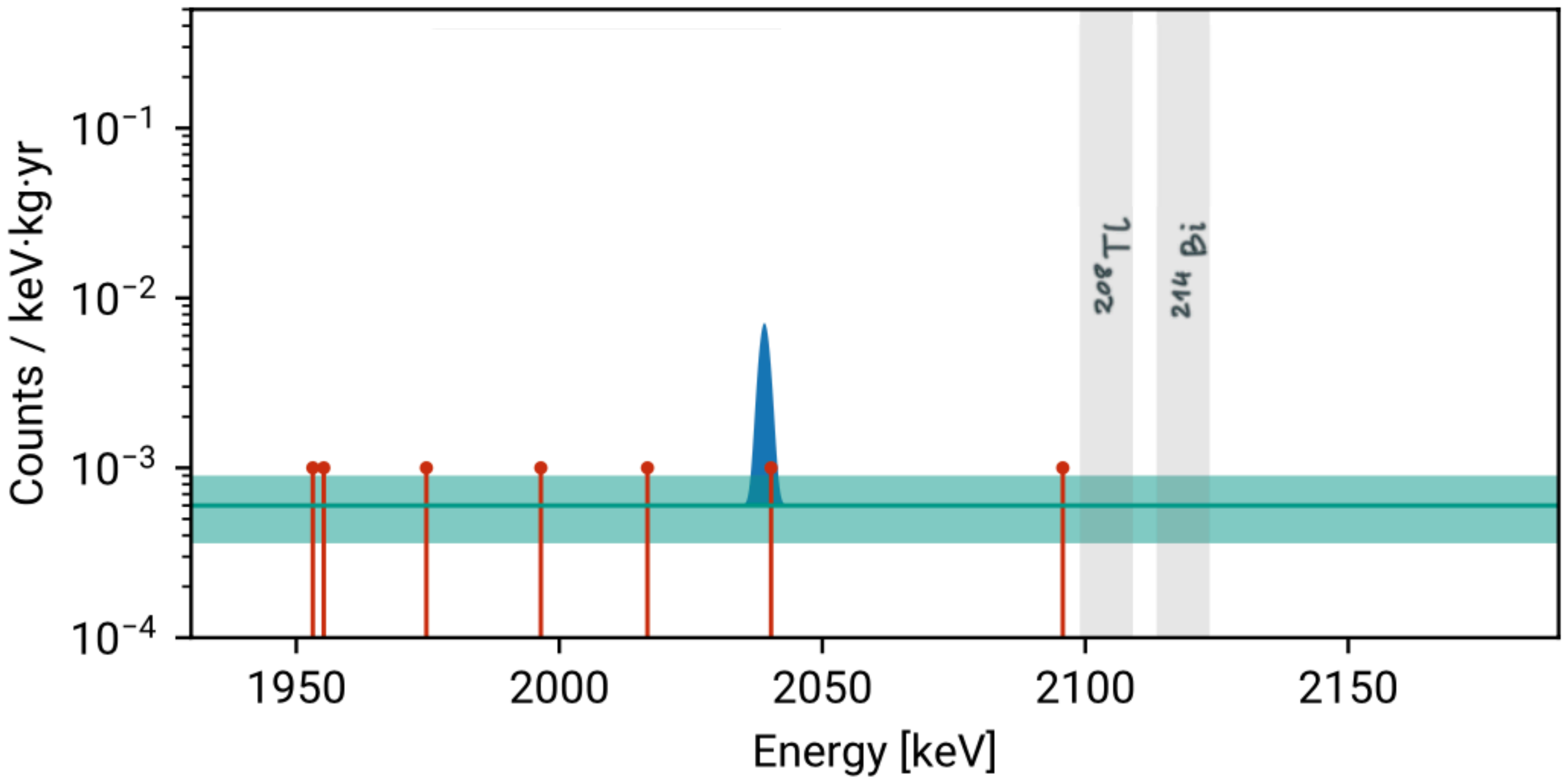




- Instrumented water tank
- Liquid argon shielding
  - Supplies an active veto / multi-site suppression & cools crystals

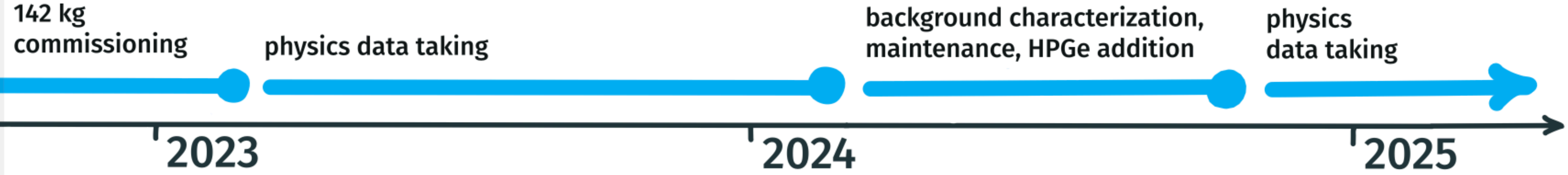
arXiv:2107.11462



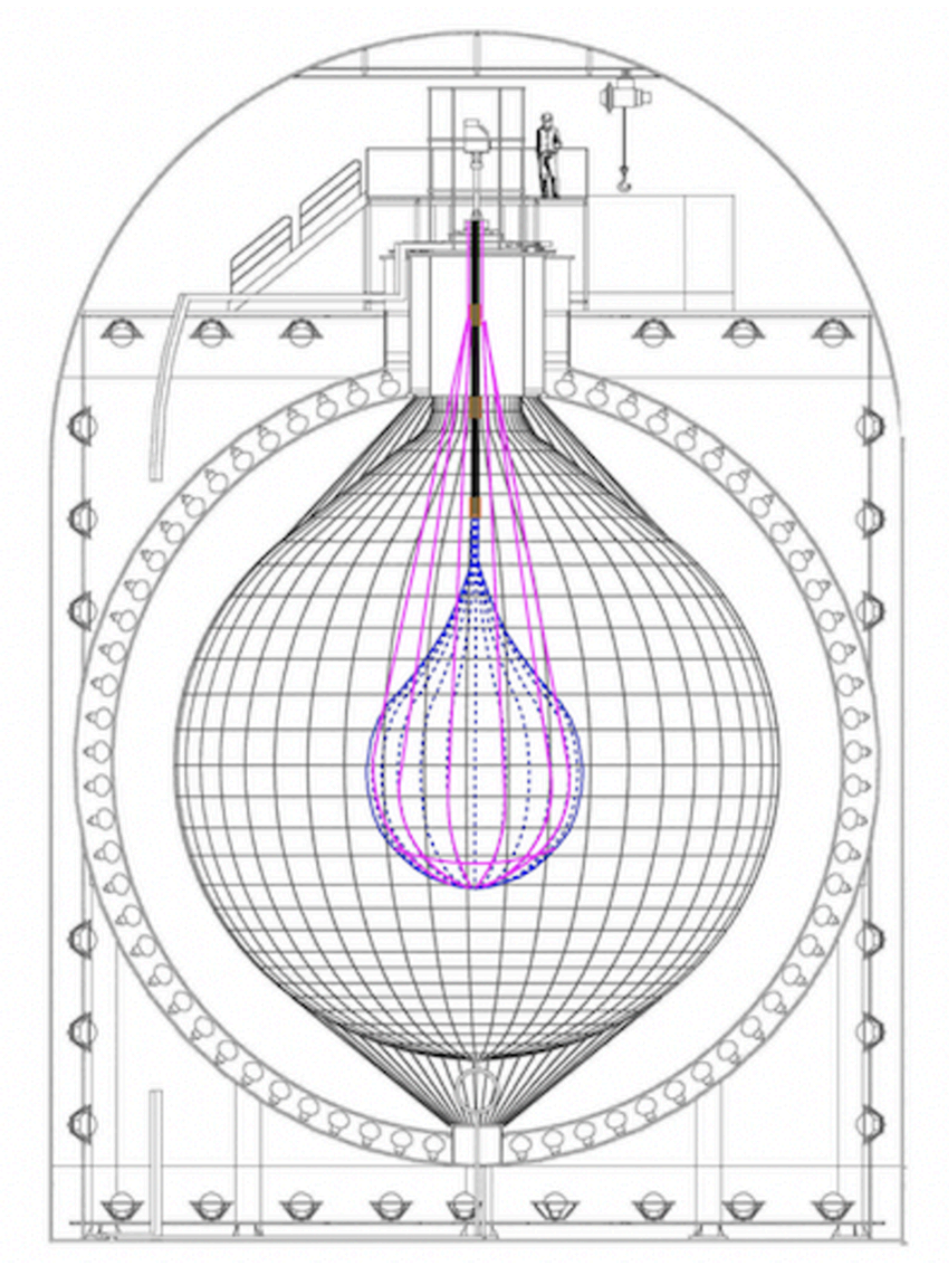




- 7 events surviving in ROI
- BG: 5.3±2.2 x $10^{-4}$ counts/keV/kg/yr
- $T^{0\nu}_{1/2}$ > 1.9 x $10^{26}$ y
- $\langle m_{\beta\beta}\rangle$ < (35 - 80) meV



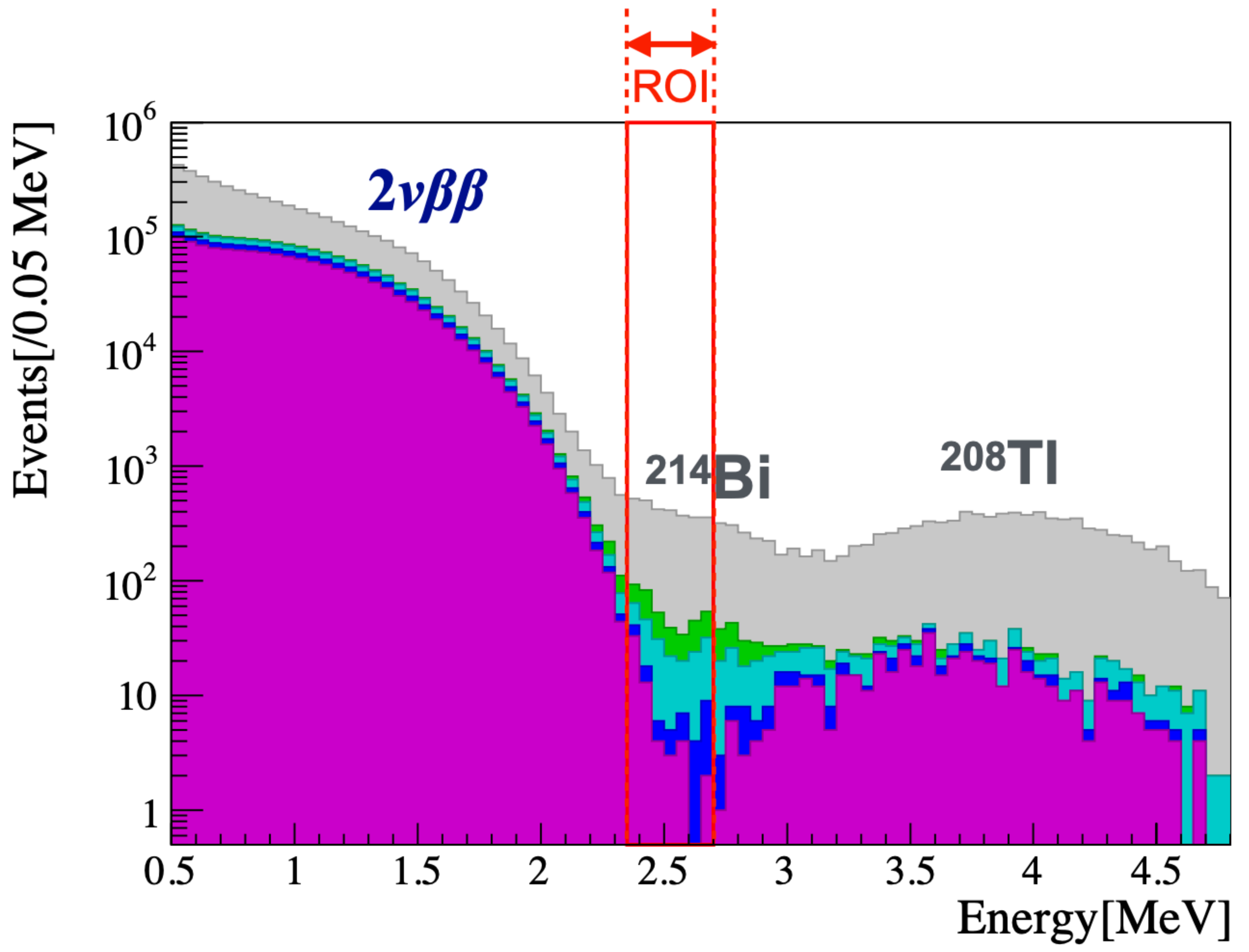

Zero neutrino double beta decay search
KamLAND-Zen



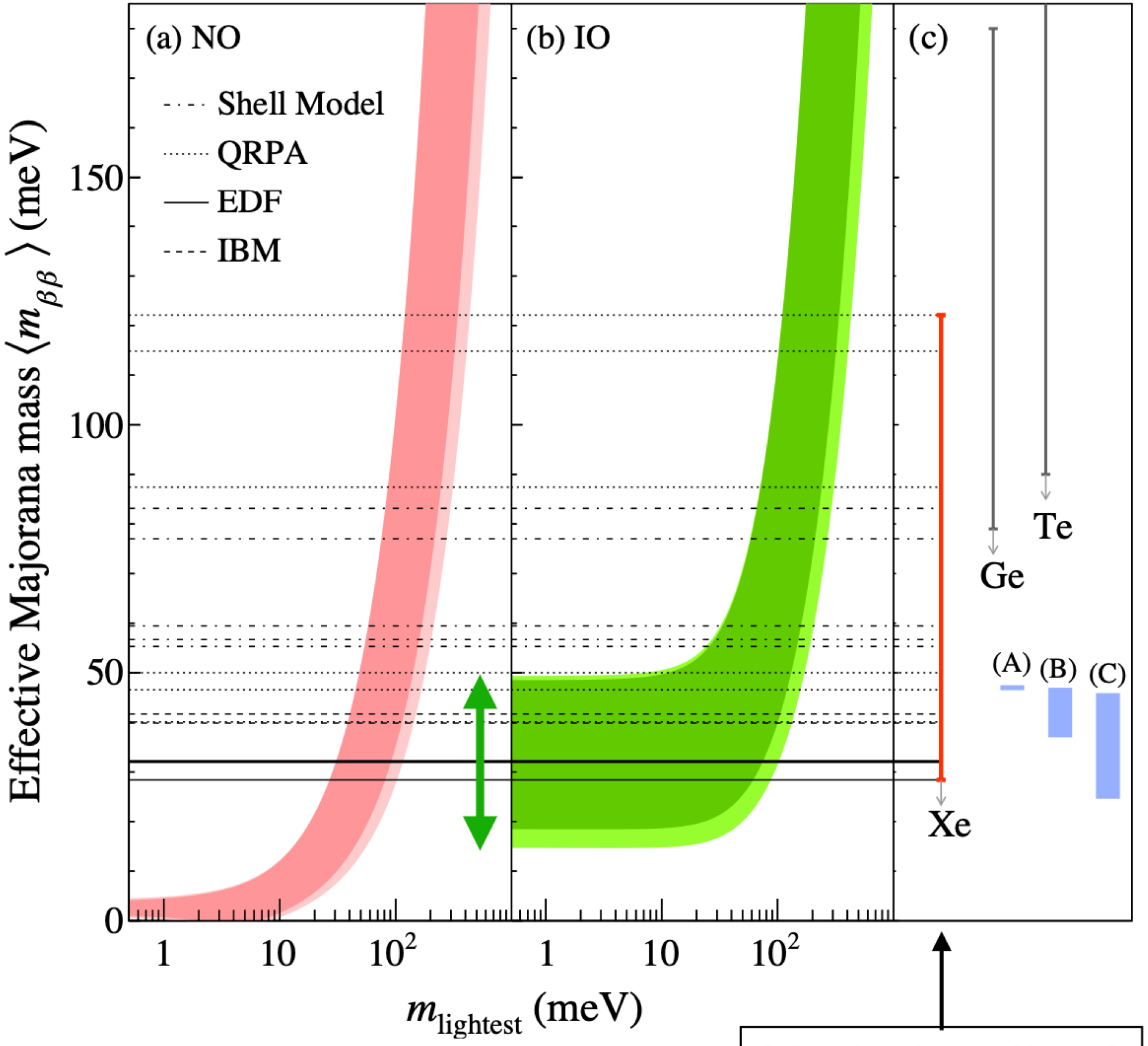
- KamLAND Detector, Kamioka Mine
  - 1,000 m, 2,700 mwe
- 1 kton Liquid Scintillator in 13-m-diameter transparent balloon
- 1,879 photomultiplier tubes
- Energy Resolution: 6.7%/√E(MeV)
- Vertex Resolution: 13.7cm/√E(MeV)
- Water Cherenkov outer detector (for tagging muons)
- LMA Solution to Solar Neutrino Problem: [PRL 100, 221803 (2008)]
- First Observation of Geoneutrinos: [Nature 436, 499–503 (2005)]
- Inner Balloon: 745 kg Xe-loaded liquid scintillator (91% enrichment)



[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]



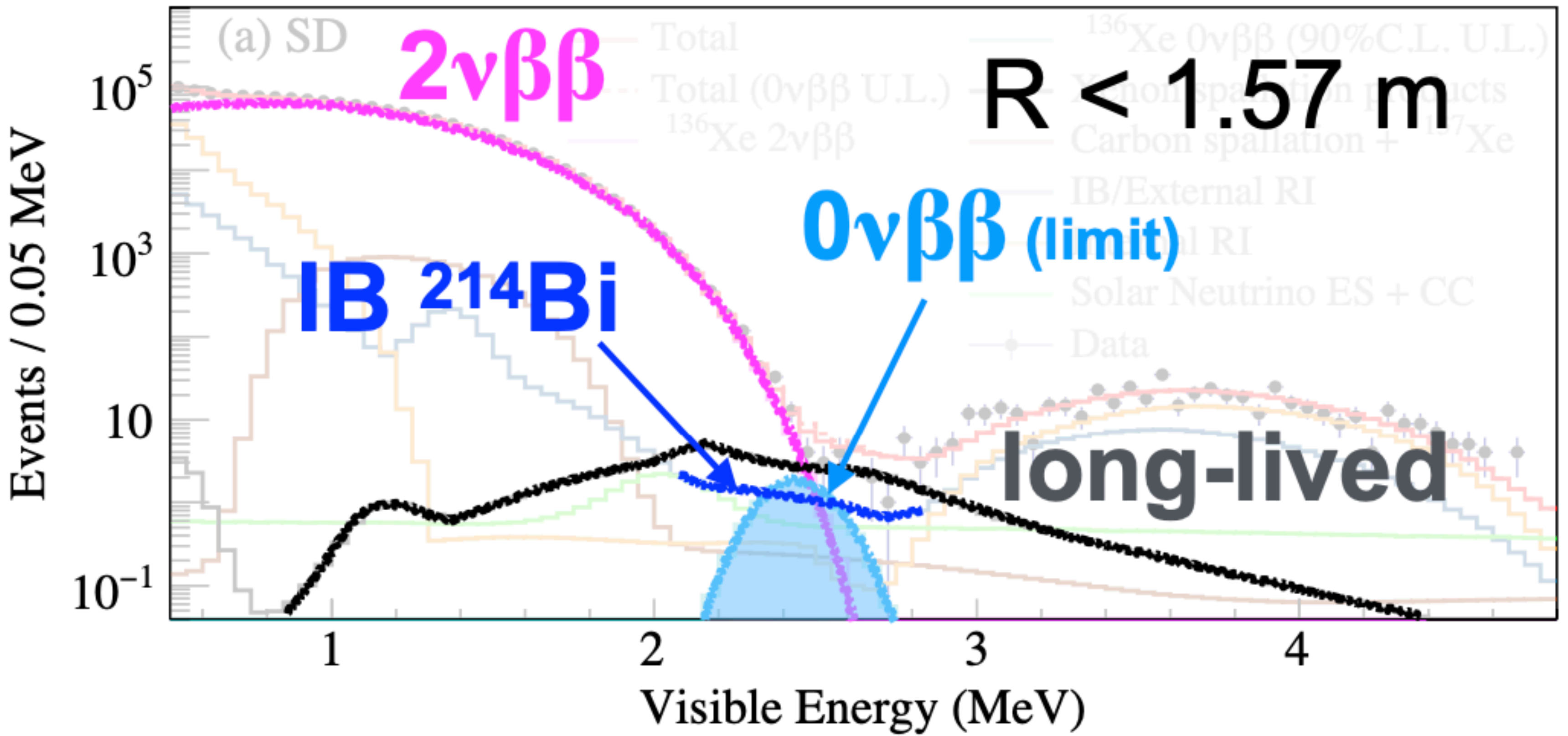

- 0vββ search : Feb. 5, 2019 – Jan. 12, 2024
- 745 kg Xe
- Volume Cut: R < 1.57 m
- Rn Veto
- Short Lived Spallation ($^{12}C$)
- Long Lived Spallation ($^{137}Xe$)
- 1131 days of 0vBB Candidates
- 30 events/Xe-ton/year of long lived BG rate in ROI
- $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr




Xe is leading!

| | Ref. | $M^{0\nu}$ | $\langle m_{\beta\beta} \rangle$ (meV) |
|---|---|---|---|
| Shell model | [1] | 2.28, 2.45 | 59.4, 55.3 |
| | [2] | 1.63, 1.76 | 83.1, 77.0 |
| | [3, 4] | 2.39 | 56.7 |
| QRPA | [5] | 1.55 | 87.4 |
| | [6] | 2.91 | 46.6 |
| | [7] | 2.71 | 50.0 |
| | [8] | 1.11, 1.18 | 122, 115 |
| | [9] | 3.38 | 40.1 |
| EDF theory | [10] | 4.20 | 32.3 |
| | [11] | 4.77 | 28.4 |
| | [12] | 4.24 | 32.0 |
| IBM | [13] | 3.25 | 41.7 |
| | [14] | 3.40 | 39.9 |

- $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr
- $\langle m_{\beta\beta} \rangle$ < (28–122) meV
- $m_{\text{lightest}}$ < 84 – 353 meV



# Near Future Experiments

supernemo

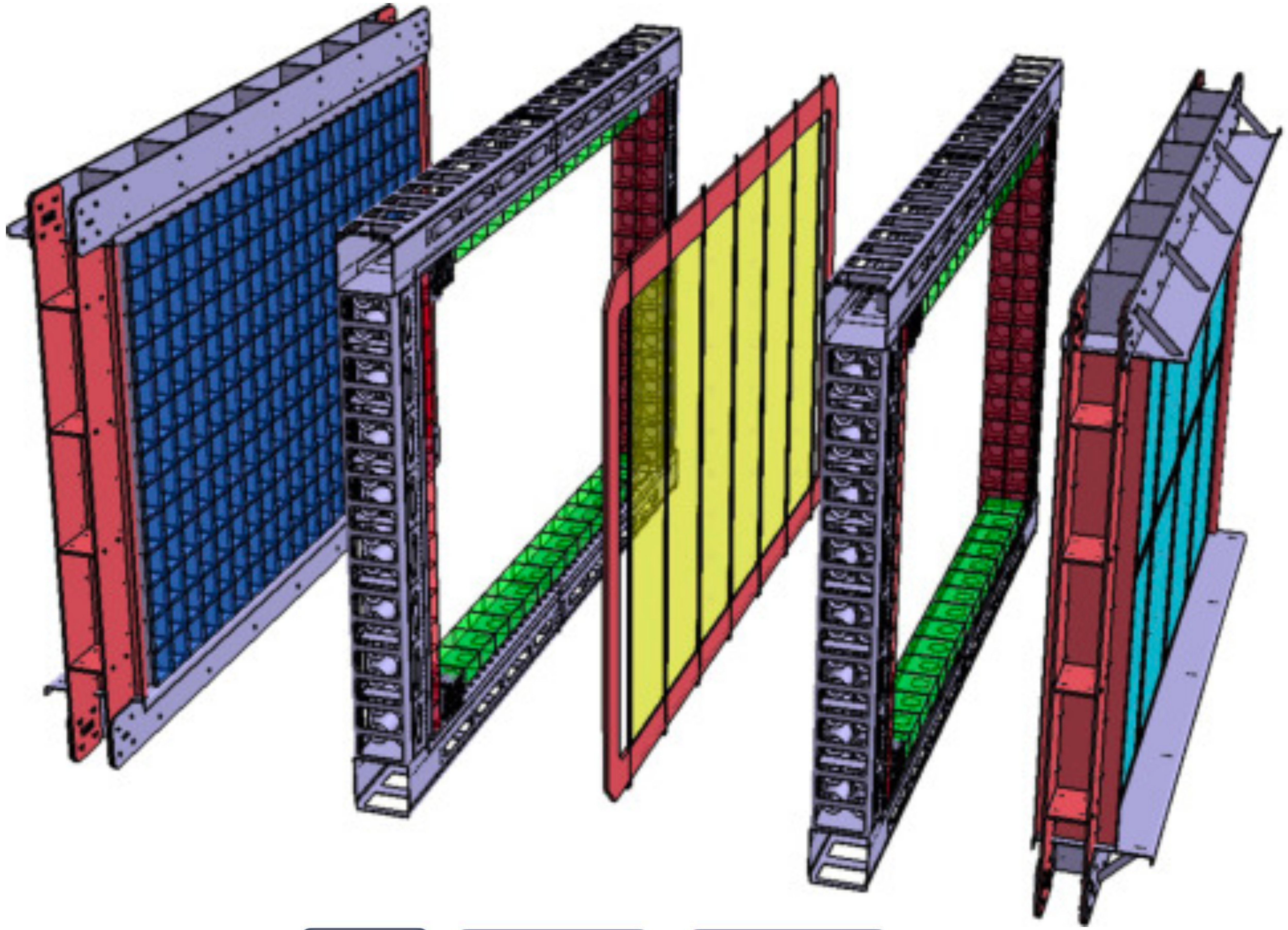
collaboration

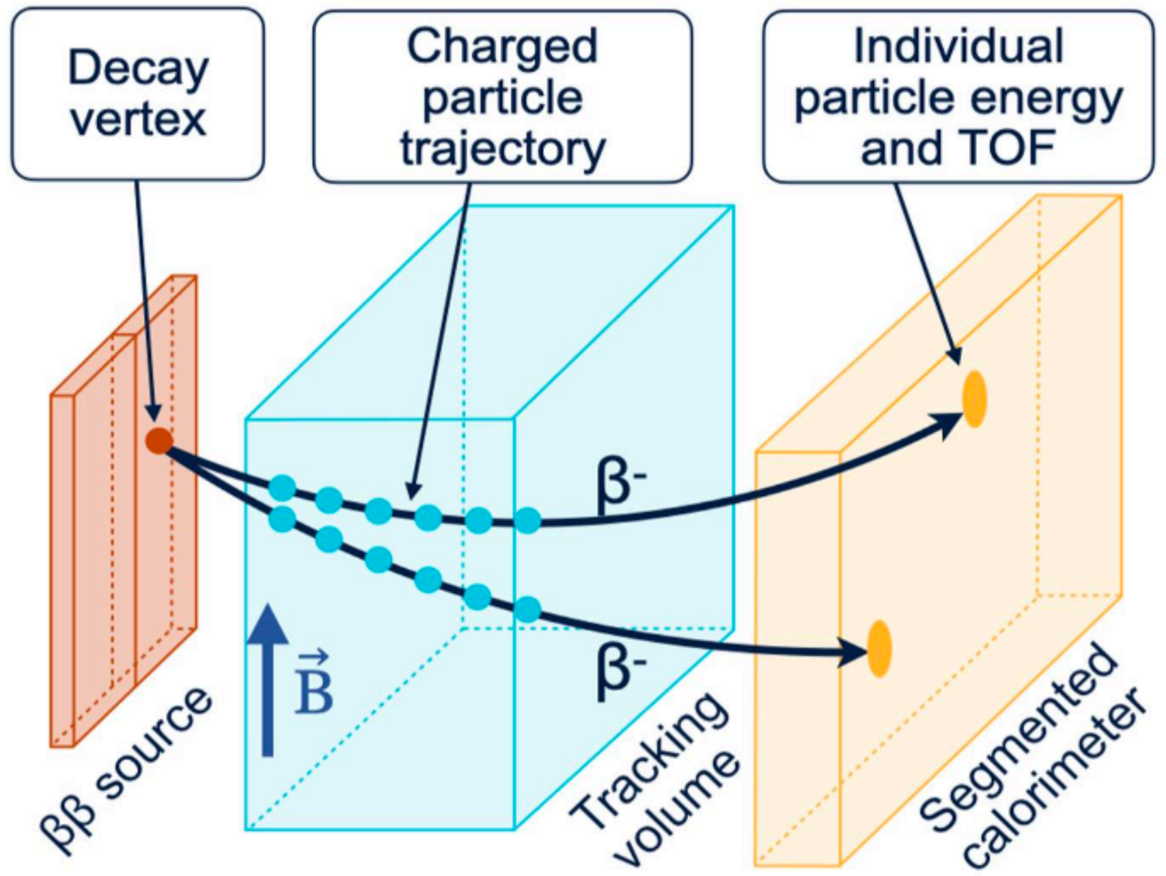
next

SNO+

supernemo

collaboration

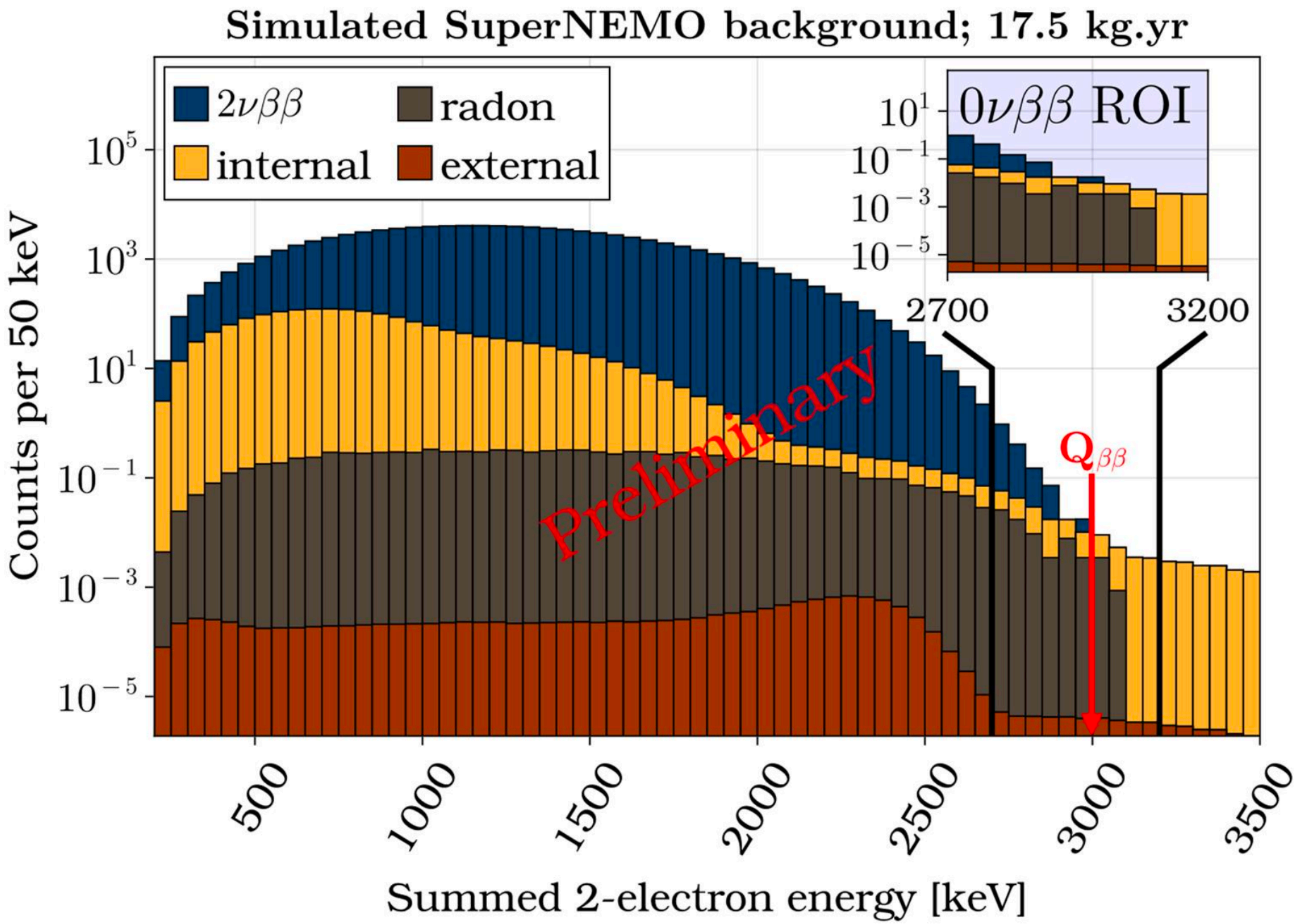





supernemo collaboration

- Tracking Calorimeter
- Foil: 6kg solid $^{82}Se$
- Tracker: 2034 Geiger Cells
  - Identification of $e^-$, $e^+$, γ, α, ββ kinematics & topology
- Calorimeter: 712 optical modules of plastic scintillator & PMTs
  - Individual $e^-$ & γ energies
- Shielding: Iron, Water, Polyethylene, in a Rn tent
- Laboratoire Souterraine de Modane 1700m, 4800 mwe

[Se-82, $Q_{\beta\beta}$ = 2998 keV, 8.8% NA]

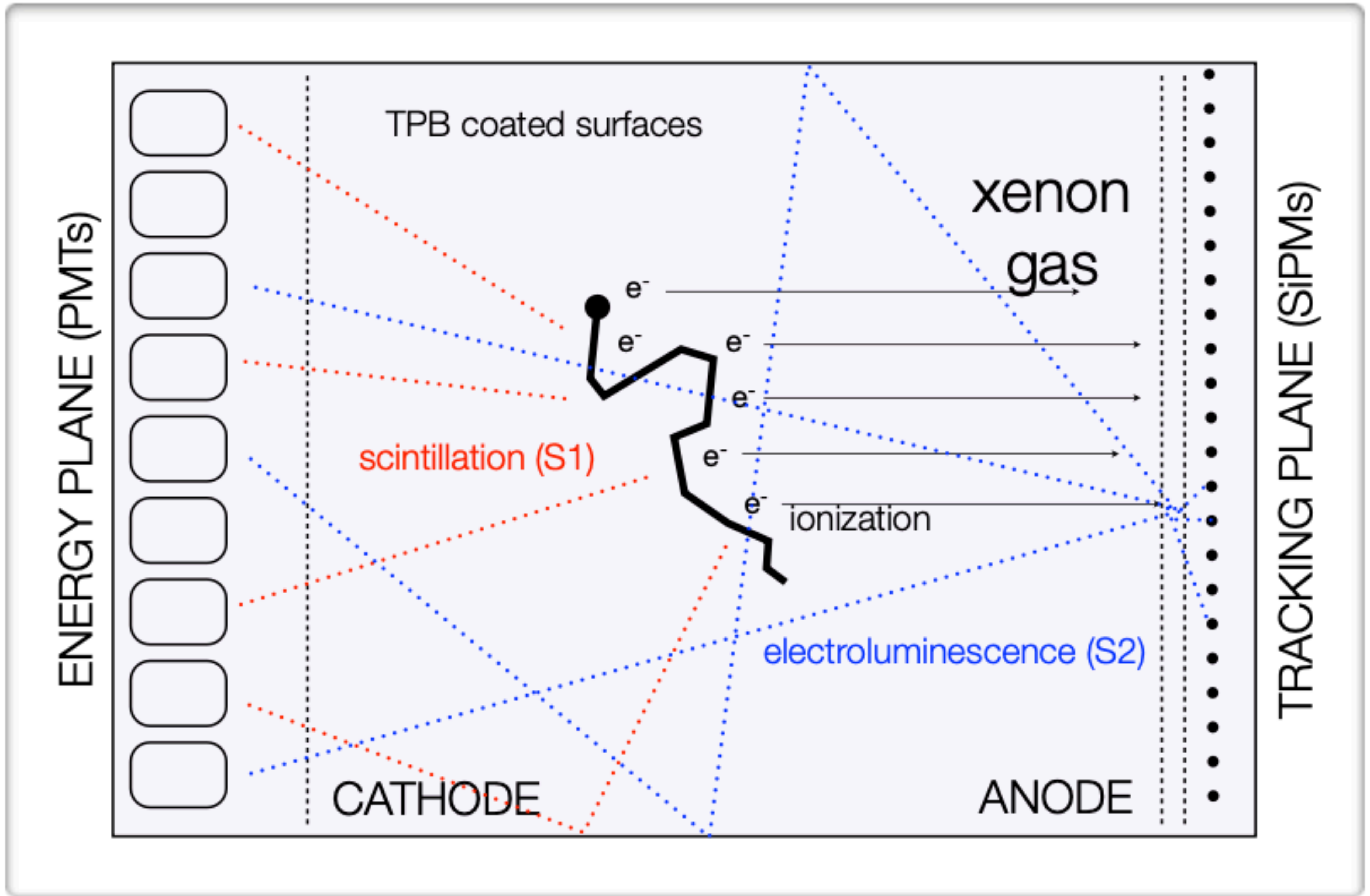


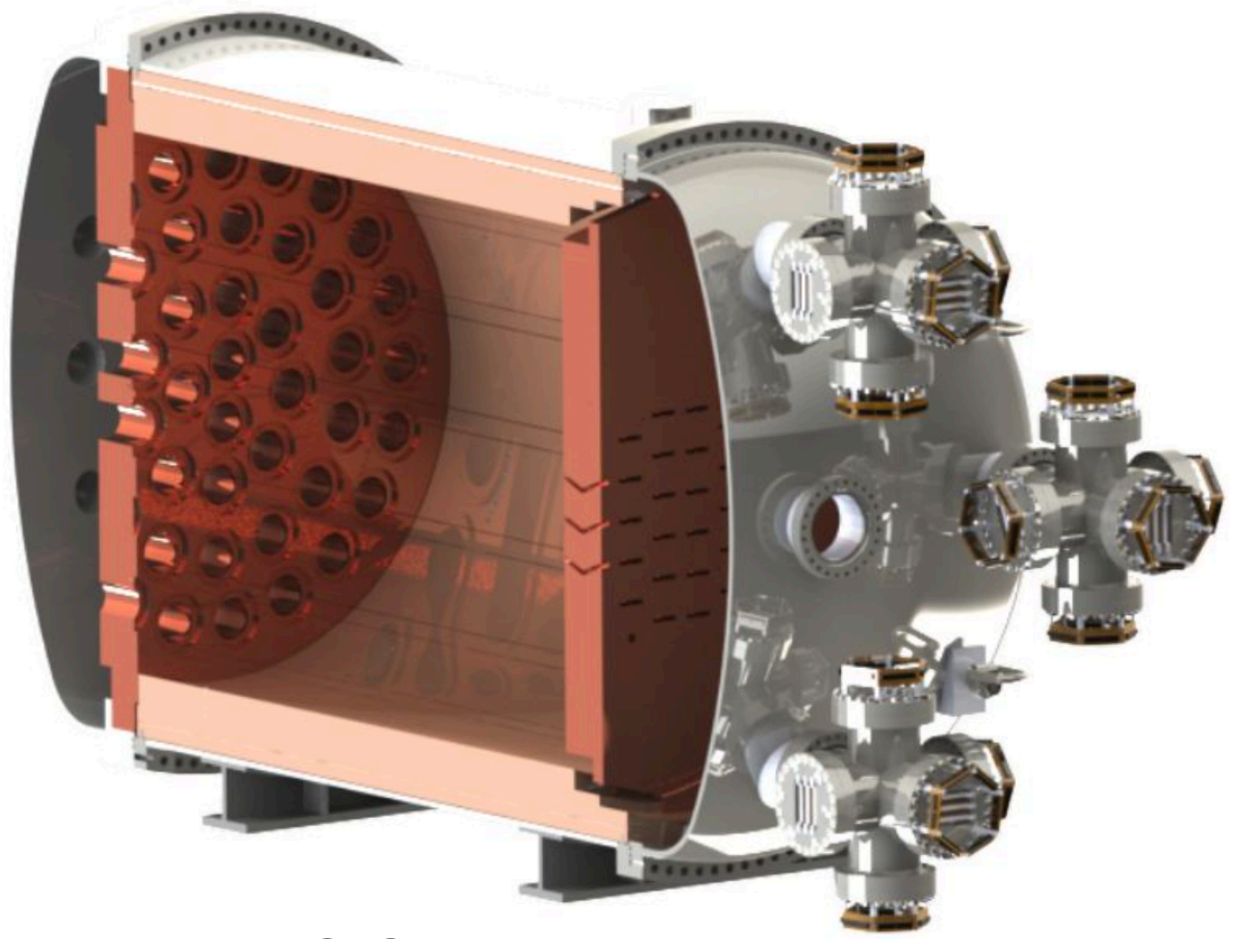

- From Sept. 2024: physics data taking
- Expected duration: 3 years
- Estimated 2νββ events: ~$10^4$-$10^5$
- Expected bkg. in 0νββ ROI: $10^{-4}$ counts/keV/kg/yr
- Expected sensitivity to 0νββ: $T^{0\nu}_{1/2} > 4.6\times10^{24}$ yr



[Se-82, $Q_{\beta\beta}$ = 2998 keV, 8.8% NA]

@next



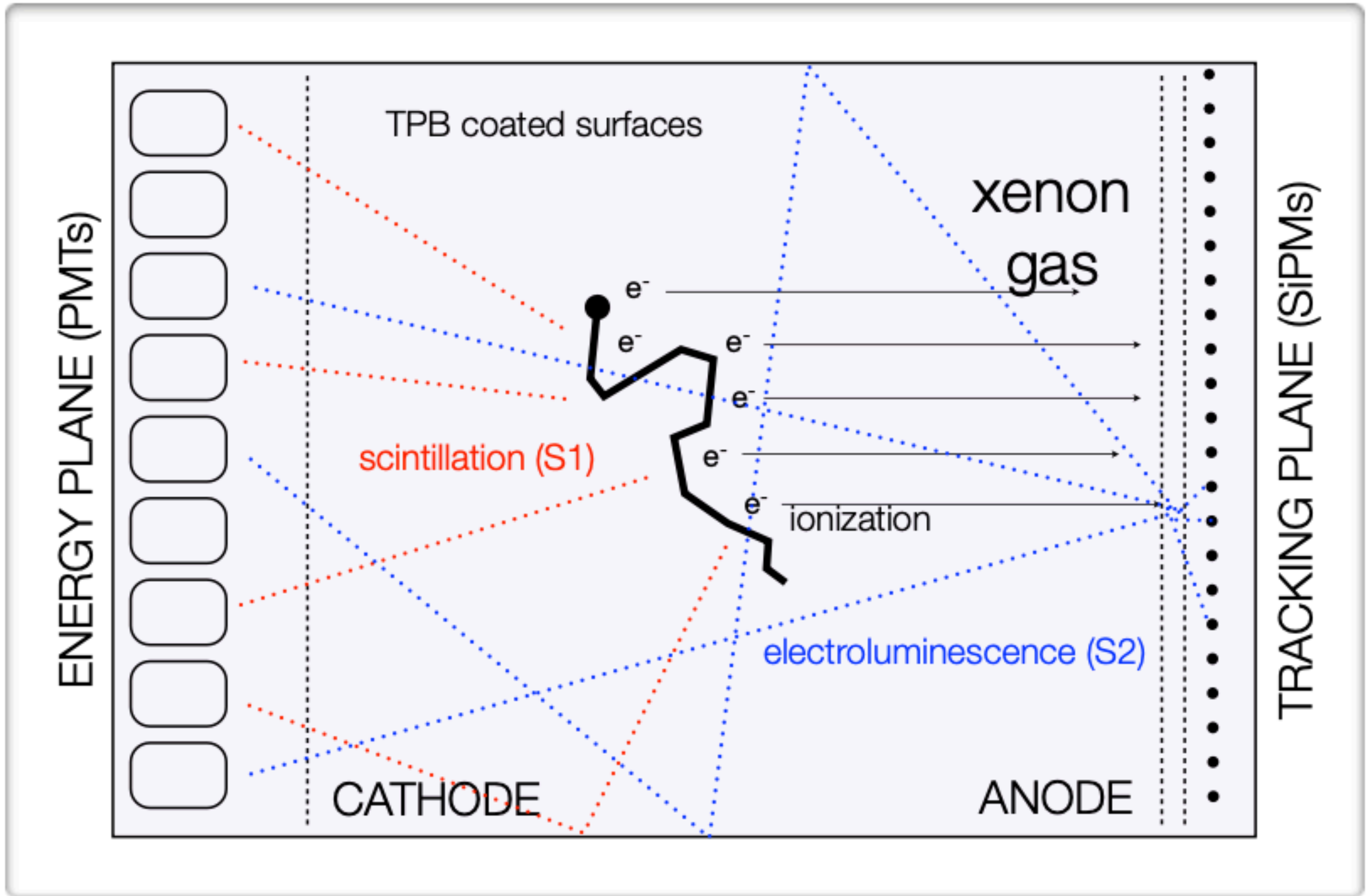
next

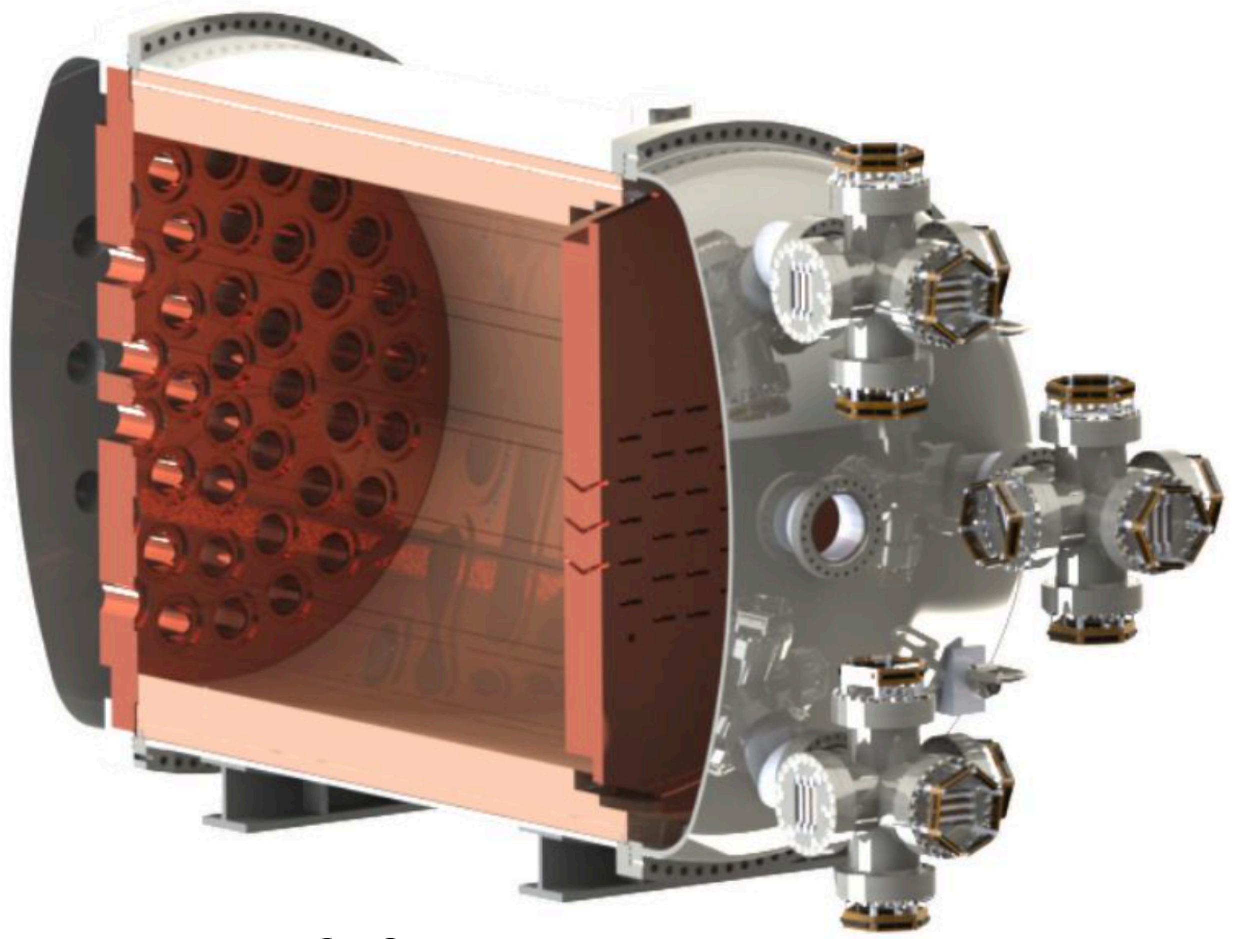
- NEXT-100
- Under Commissioning at the Laboratorio Subterráneo Canfranc
- Xe-136 Gas Time Projection Chamber with Electroluminescence
- 60 PMTs, 3584 SiPMs, 80kg Xe @ 15 bar

Background

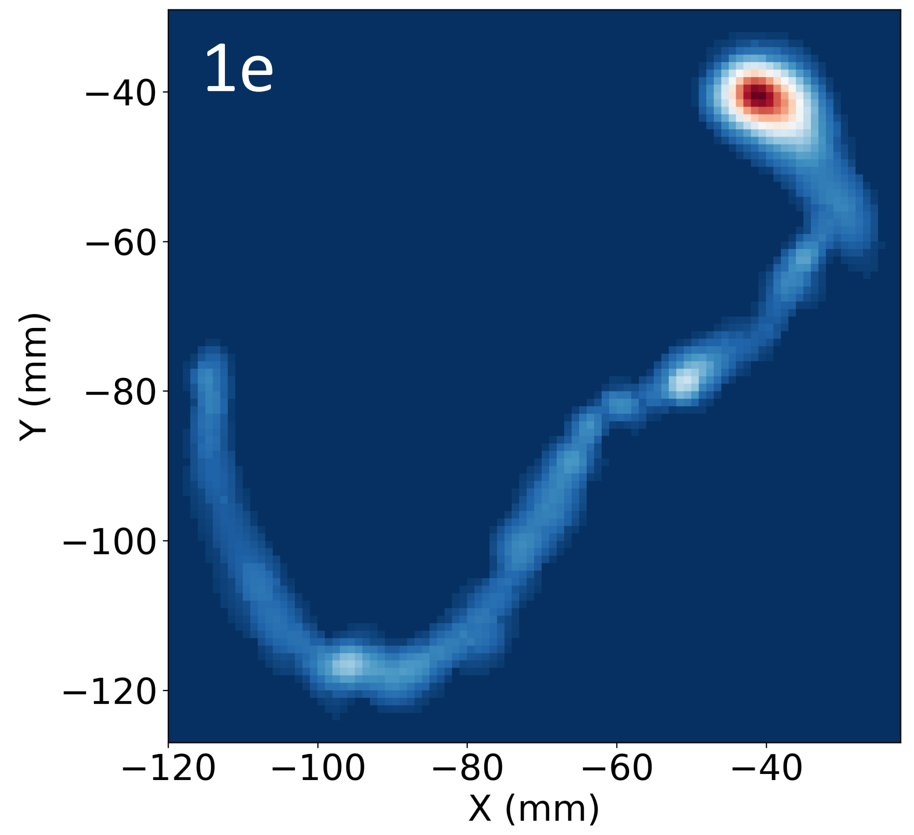
2vBB Candidate

[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]

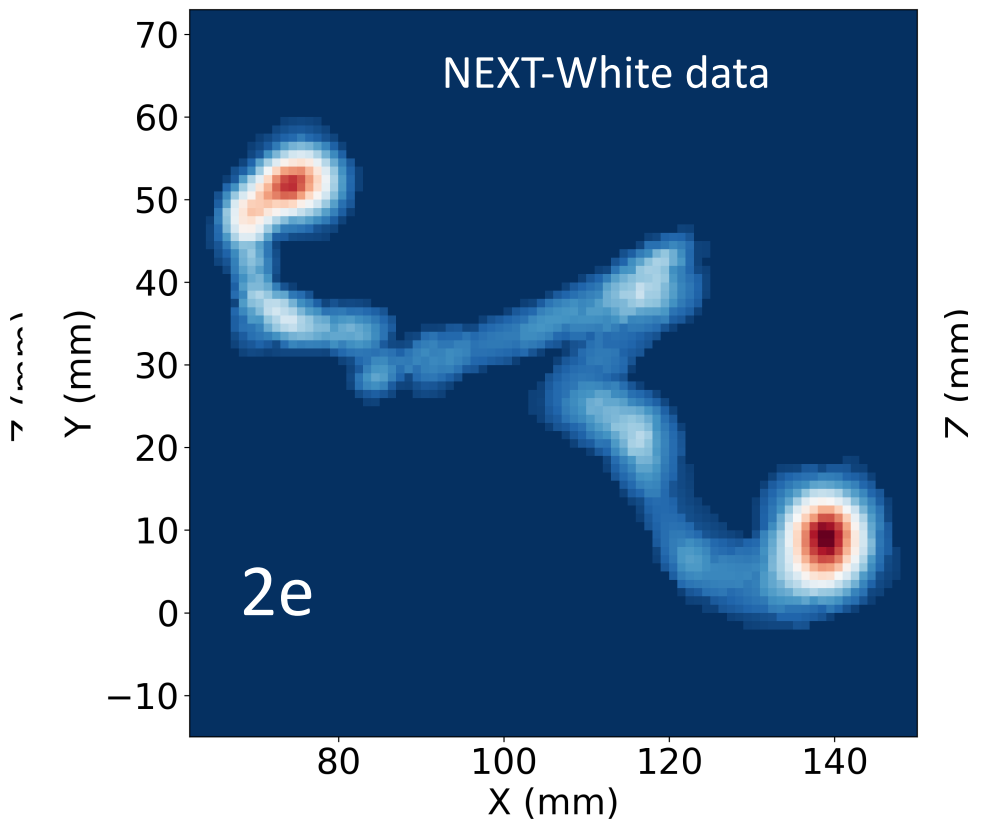


- NEXT-100
- Under Commissioning at the Laboratorio Subterráneo Canfranc
- Xe-136 Gas Time Projection Chamber with Electroluminescence
- 60 PMTs, 3584 SiPMs, 80kg Xe @ 15 bar
- TPC gives topological event identification
- Goals: demonstration of nearly background-free conditions for 0νββ search, technology demonstrator for ton scale

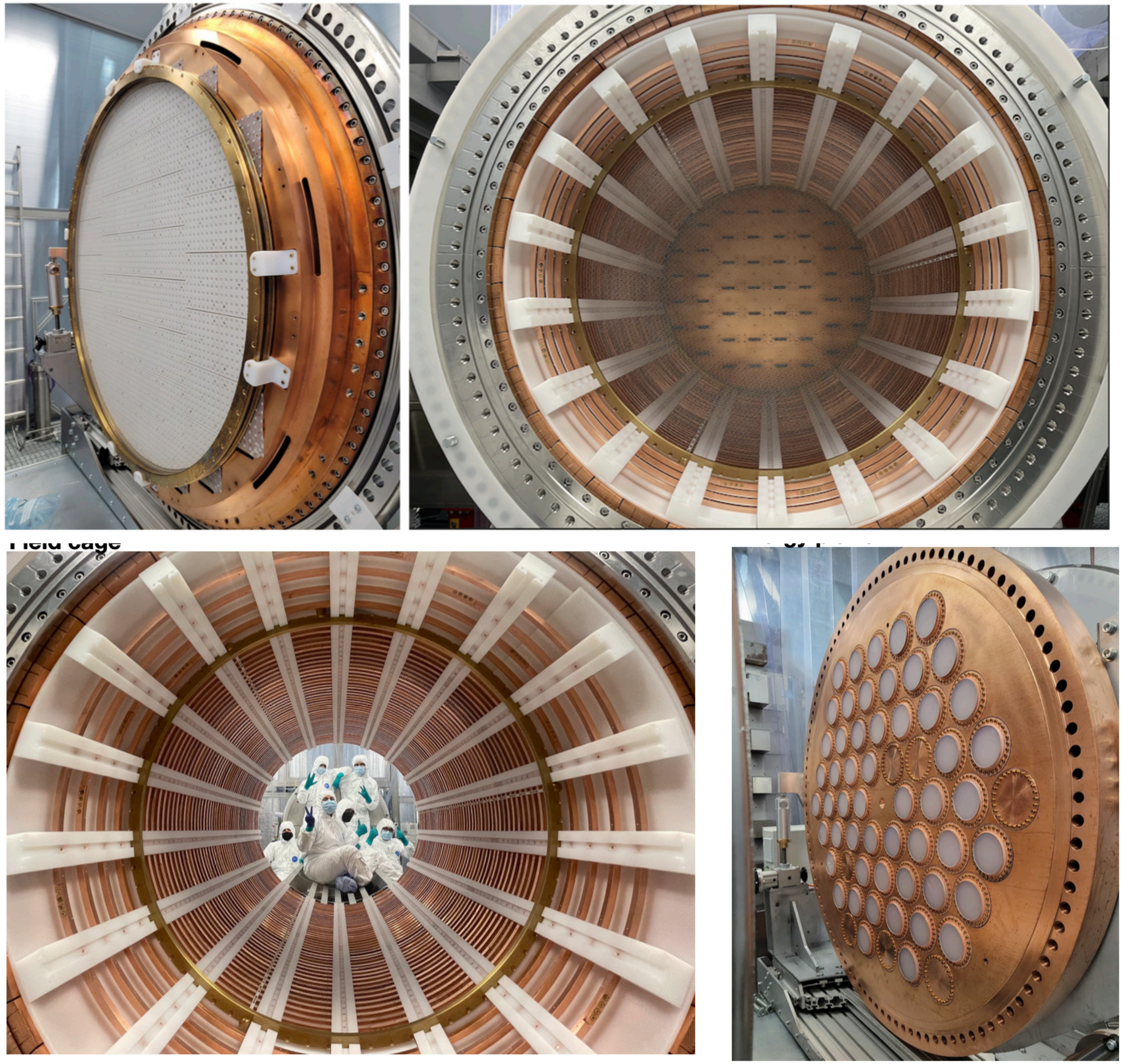



Background

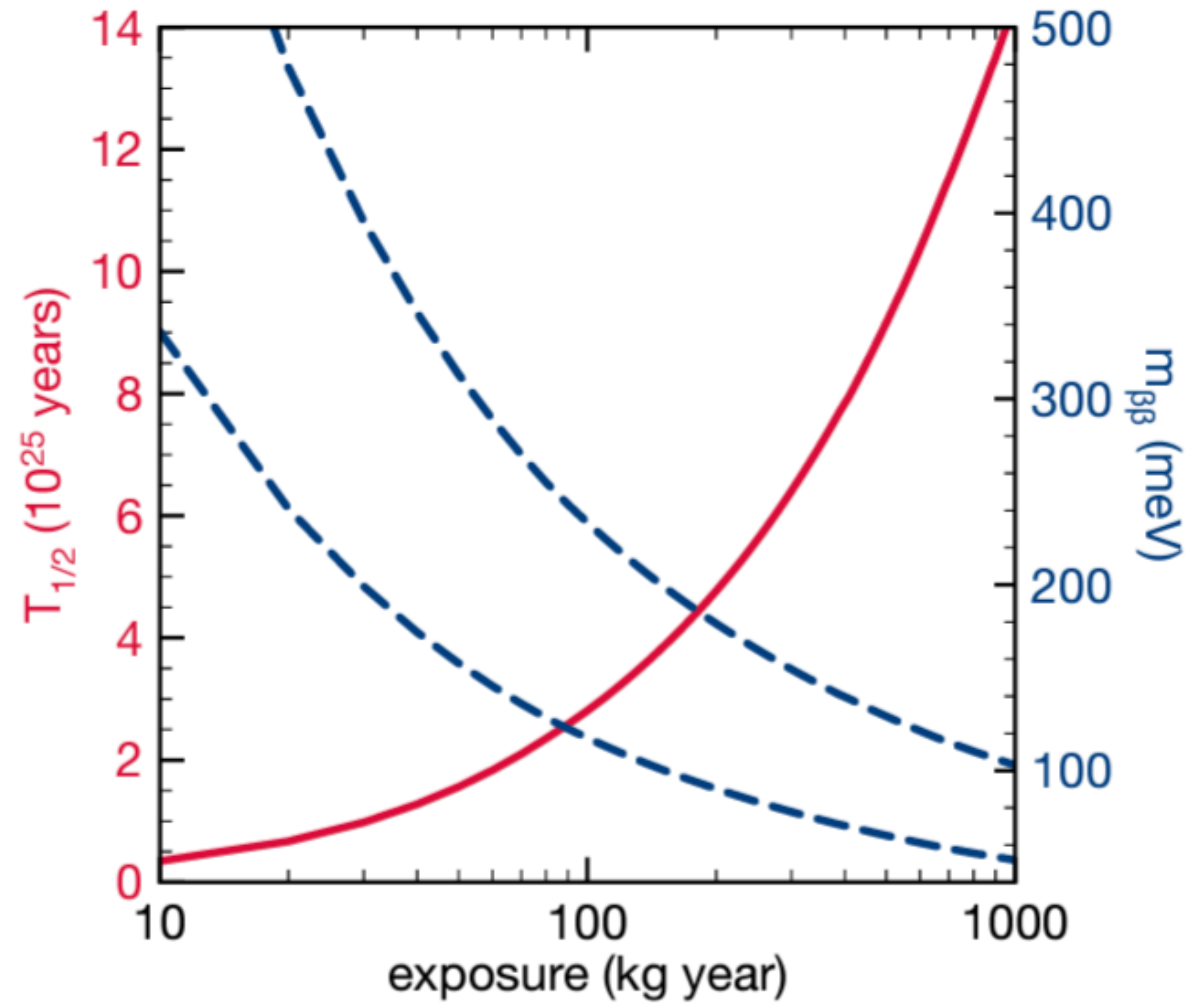



2vBB Candidate

[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]



[JHEP 05 (2016) 159]



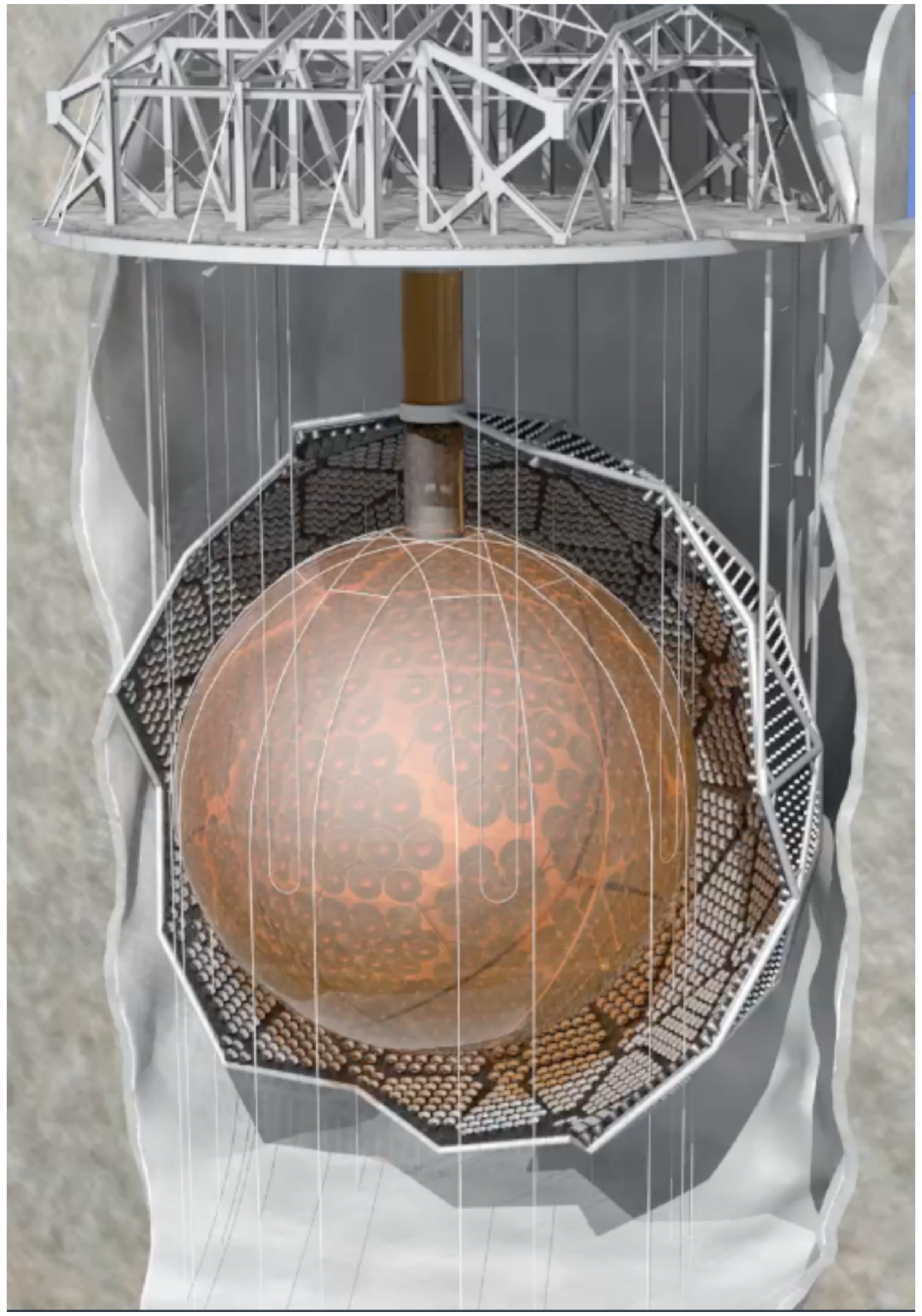

- Target background rate: $4 \times 10^{-4}$ counts/(keV·kg·yr), or ~1 count/(ROI·yr)
- NEXT-100 sensitivity: 6.0 x $10^{25}$ yr
- Ar gas runs in May 2024
- Xenon runs to start shortly

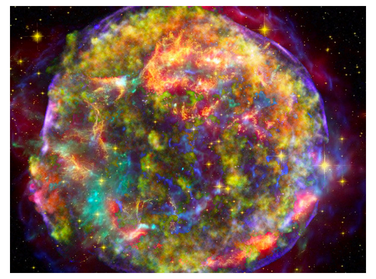
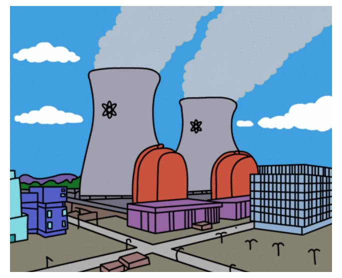
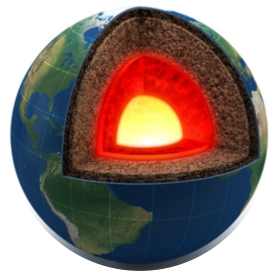
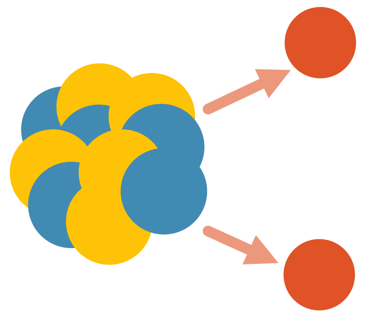
[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]

# SNO+

SNOLAB

- 2 km rock overburden
- Acrylic Vessel Ø 12 m
- 780 tonnes LAB
  - 2.2g/L PPO
  - bis-MSB, BHT
- 9300 photo-multiplier tubes
- 7000 tonnes water shielding
- [JINST **16** P08059]



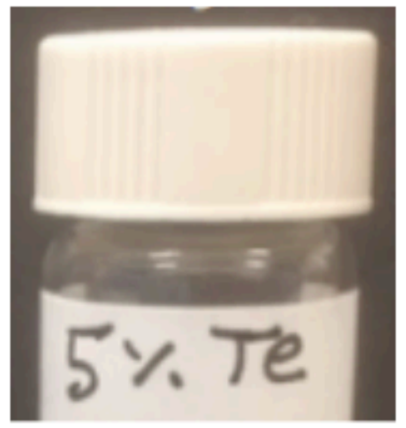






## Multi-purpose Physics Detector

- Measurement of $^{8}B$ solar neutrinos with full water phase: [arXiv:2407.17595]
- World-leading limits in invisible nucleon decay [Phys.Rev.D 105 (2022) 11, 112012]
- High efficiency neutron detection in ultra pure water [Phys. Rev. C 102 014002 (2020)]
- Evidence of Antineutrinos from Distant Reactors using Pure Water at SNO+: [P.R.L. 130 (2023) 9, 091801]
- Scintillator Characterization: [JINST 16 P05009 (2021)]
- Event-by-Event Directionality in Scintillator: [Phys. Rev. D 109, 072002]
- Initial measurement of reactor antineutrino oscillation at SNO+: [arXiv:2405.19700]

# Tellurium Phase

- 0.5% by weight of Natural Tellurium: 3.9 tonnes
  - 1,330 kg of $^{130}Te$
  - $Q_{\beta\beta}$=2527 keV
- Mix Te into ButaneDiol, soluble with DDA
- Scalable to higher loading without changing the detector
- Low Backgrounds
  - 5 x $10^{-7}$ cts/yr/keV/kg
- Measured most backgrounds before Te is added
- Upgrades planned for 1.5%, 3%

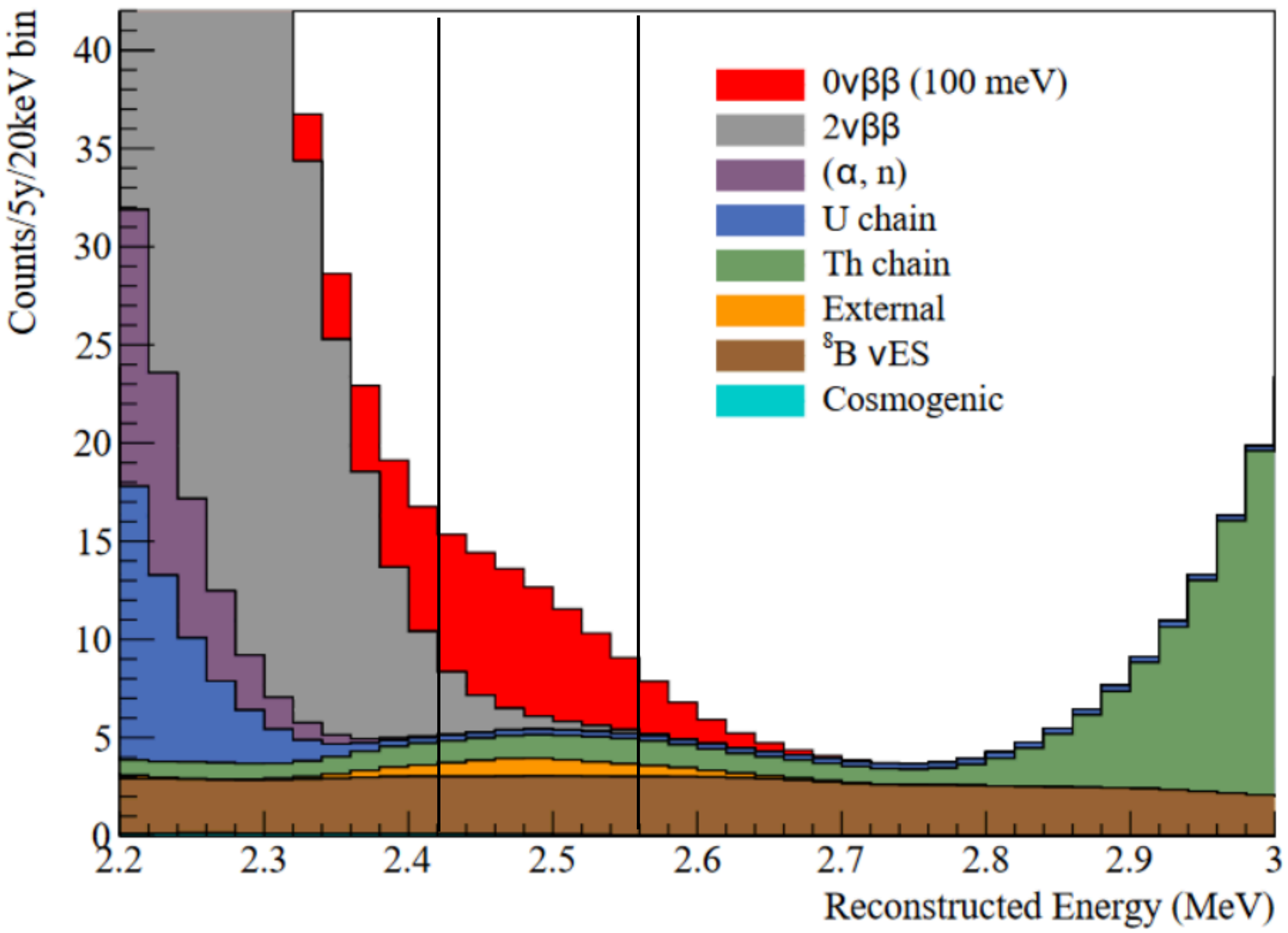


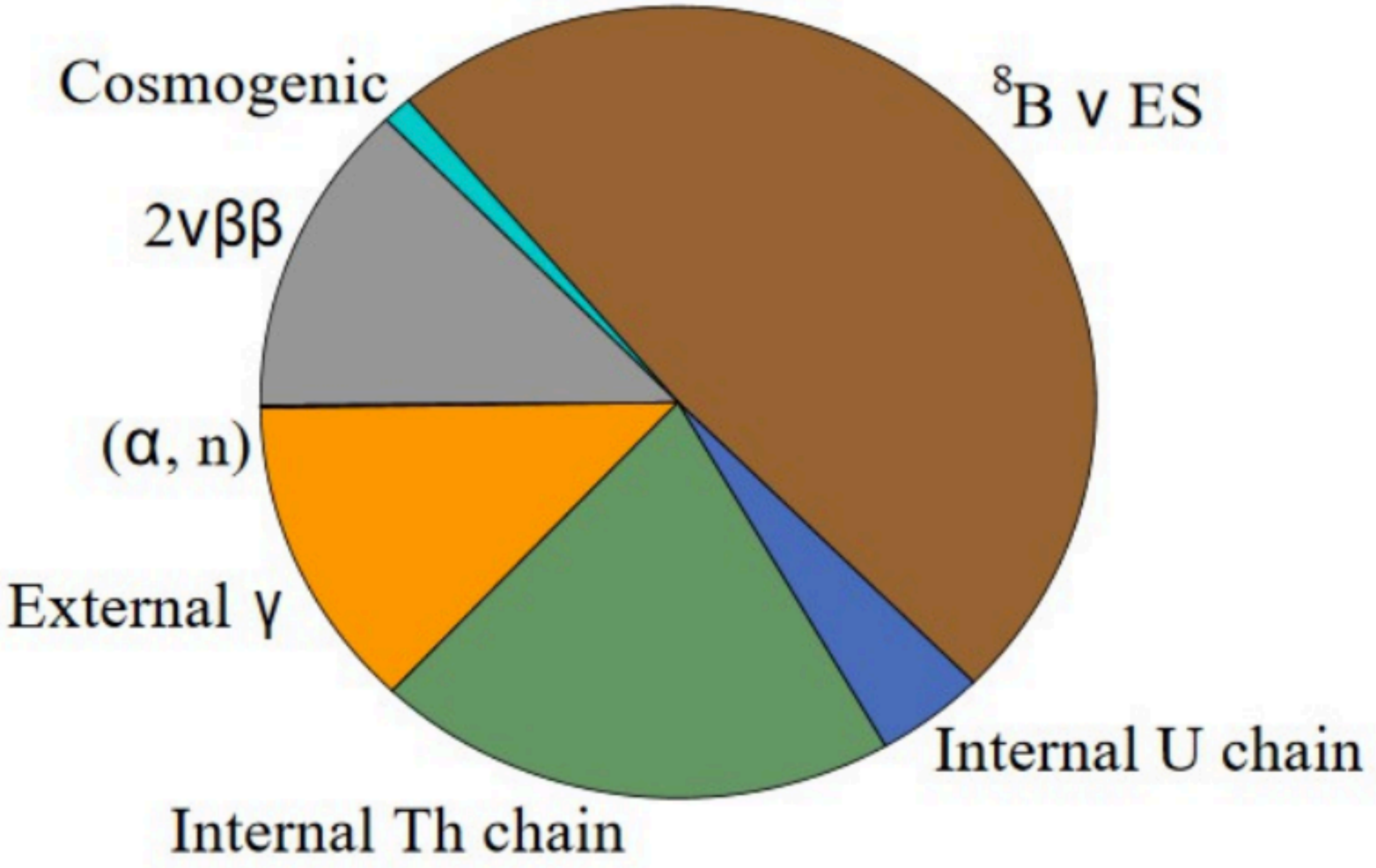

*stable with high light yield*

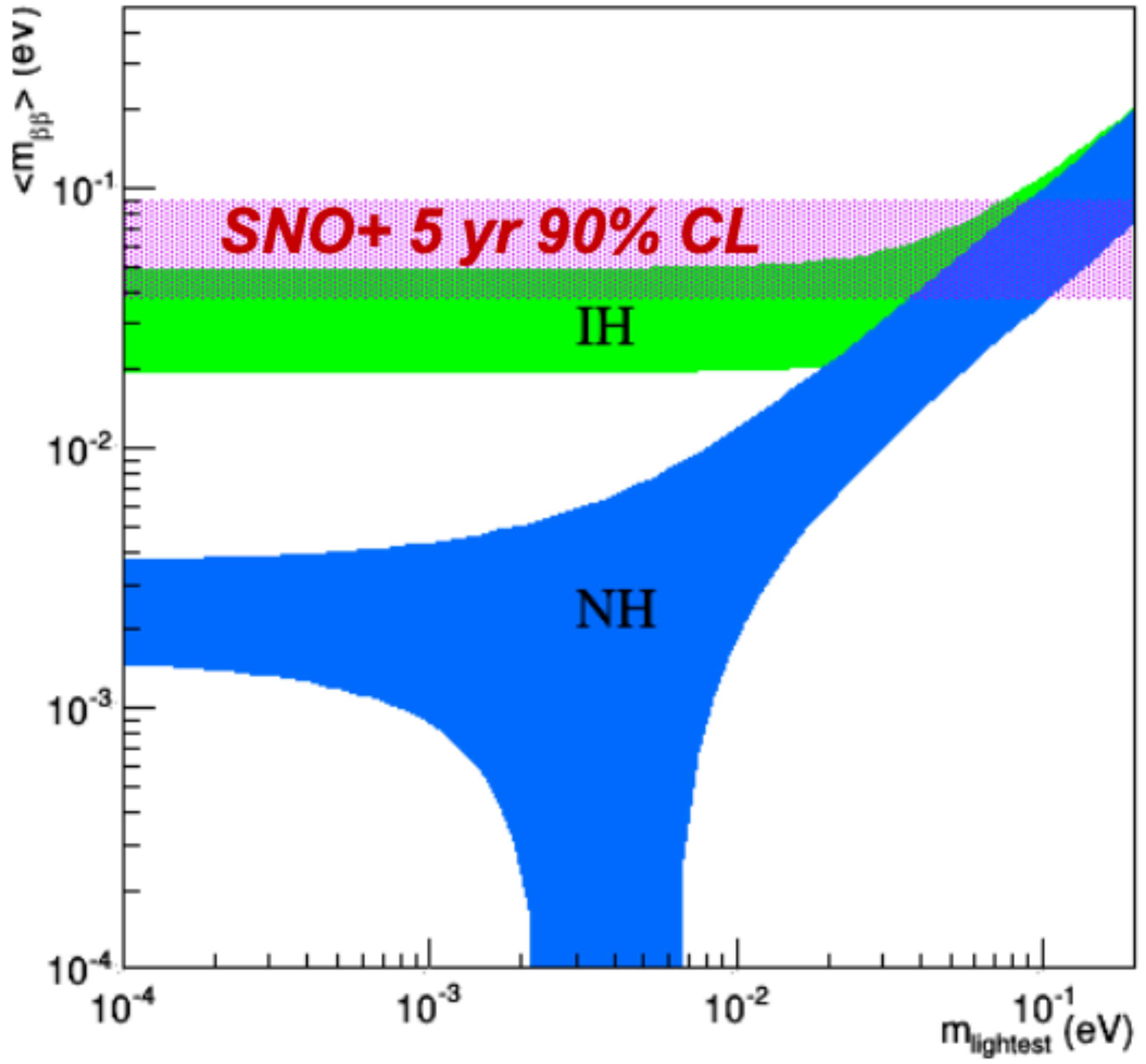
- **Telluric Acid Purification Plant Commissioned**
- Purify Telluric Acid in pH and temperature based reaction
- DDA Purified on Surface
- Synthesize ButaneDiol to combine purified Telluric Acid in scintillator
- **Tellurium Diol Plant Commissioning**

[Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA]

# 0νββ decay of $^{130}$Te in SNO+




- 5 years of 0.5% loading
- Fiducial Radius: 3.3m

$T^{0\nu}_{1/2} > 2.1 \times 10^{26}$ yr (90% CL)

$\langle m_{\beta\beta} \rangle$ < (37- 89) meV

[Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA]

# Farther Future Experiments

SNOLAB

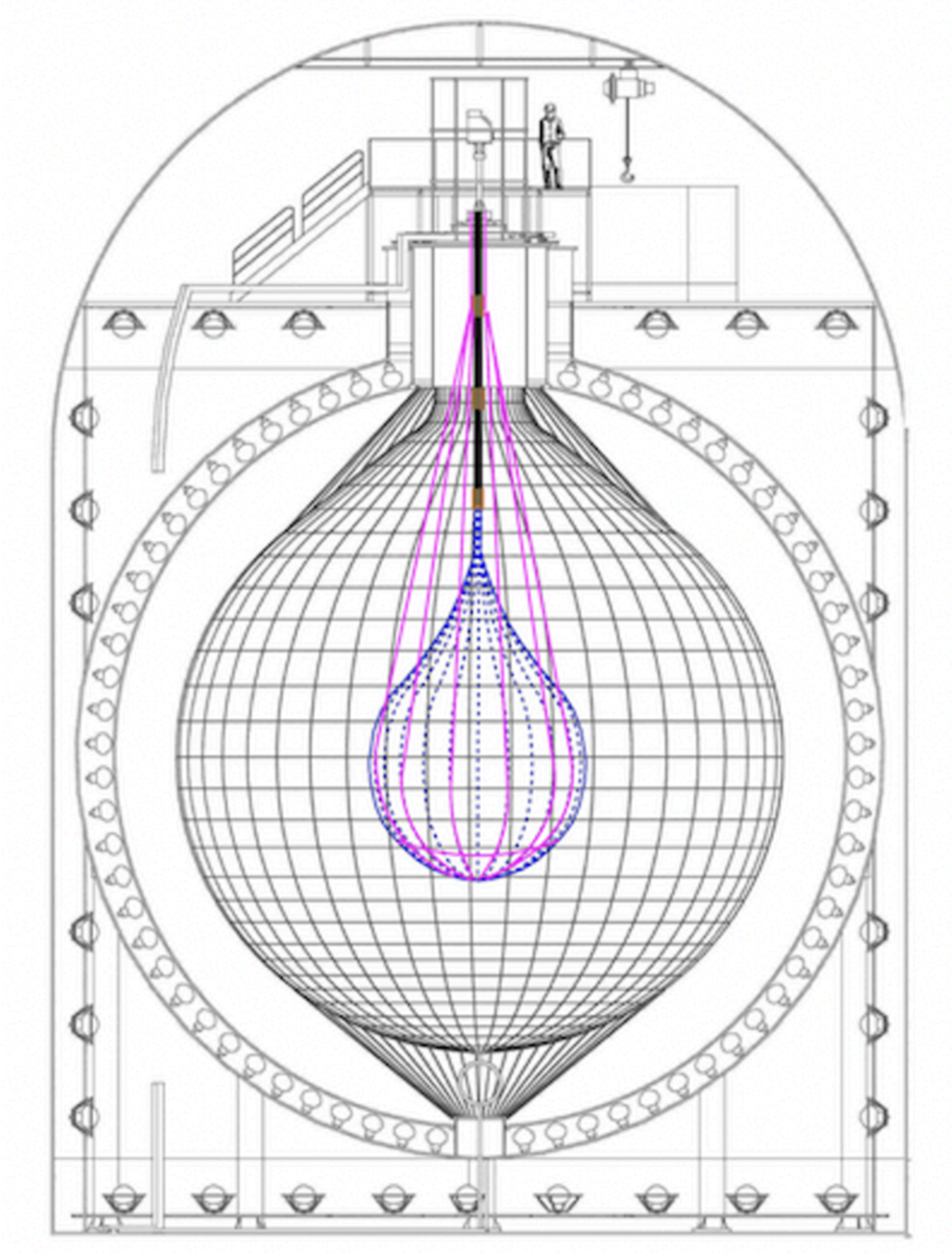
nEXO

Zero neutrino double beta decay search
禅
KamLAND-Zen

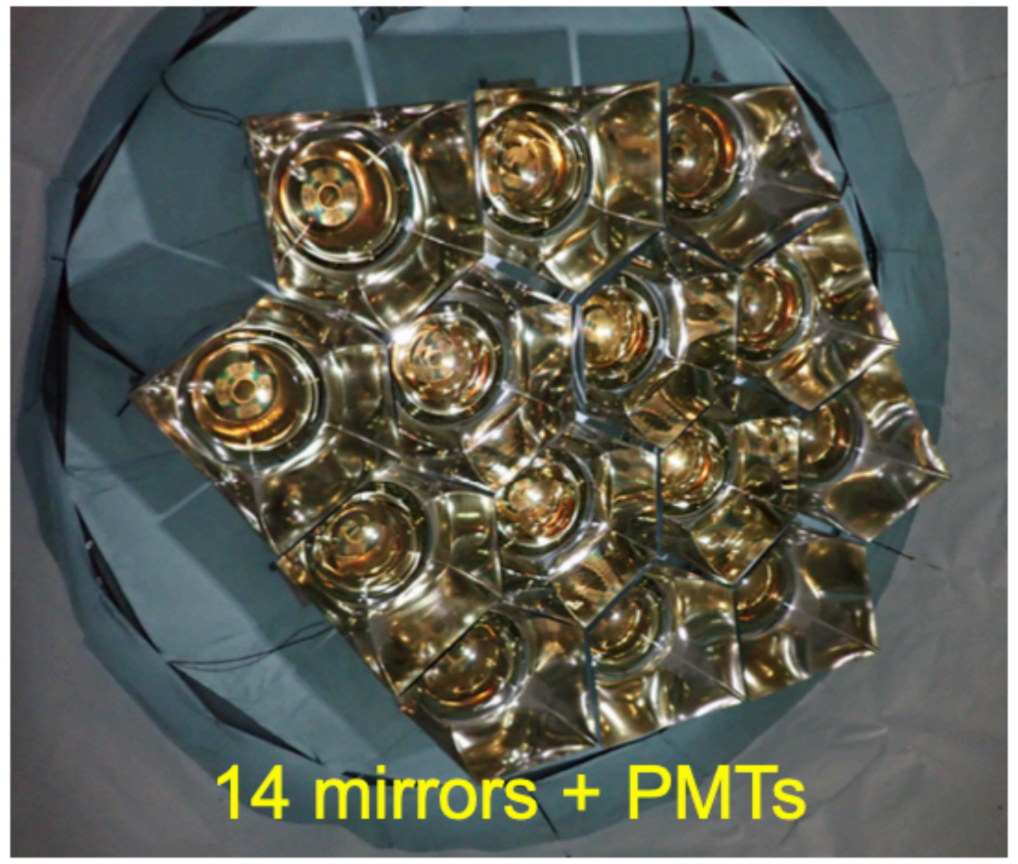
LEGEND-1000

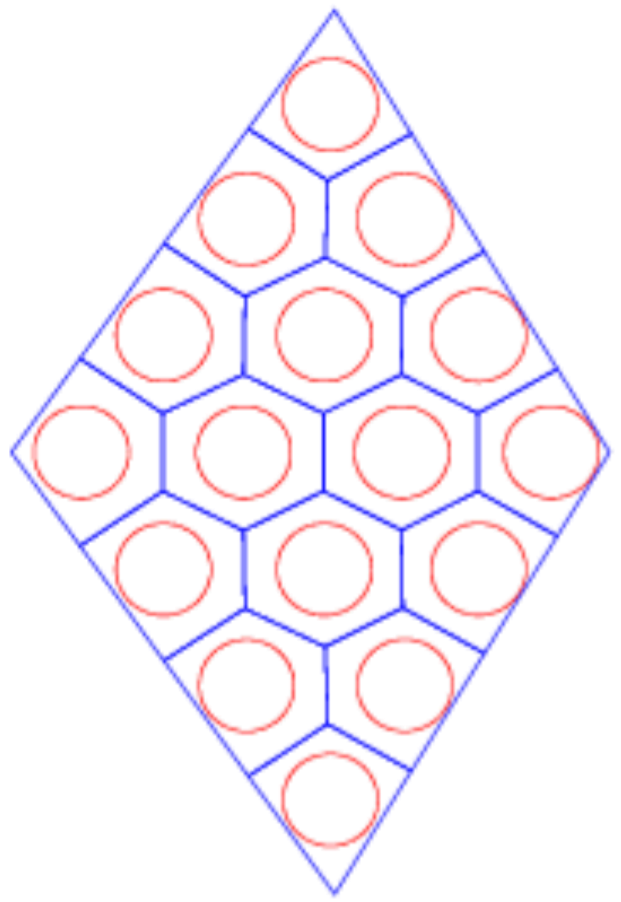
CUPID


Zero neutrino double beta decay search
禅
KamLAND-Zen
Zero neutrino double beta decay search
禅
KamLAND-Zen



KamLAND2
Prototype



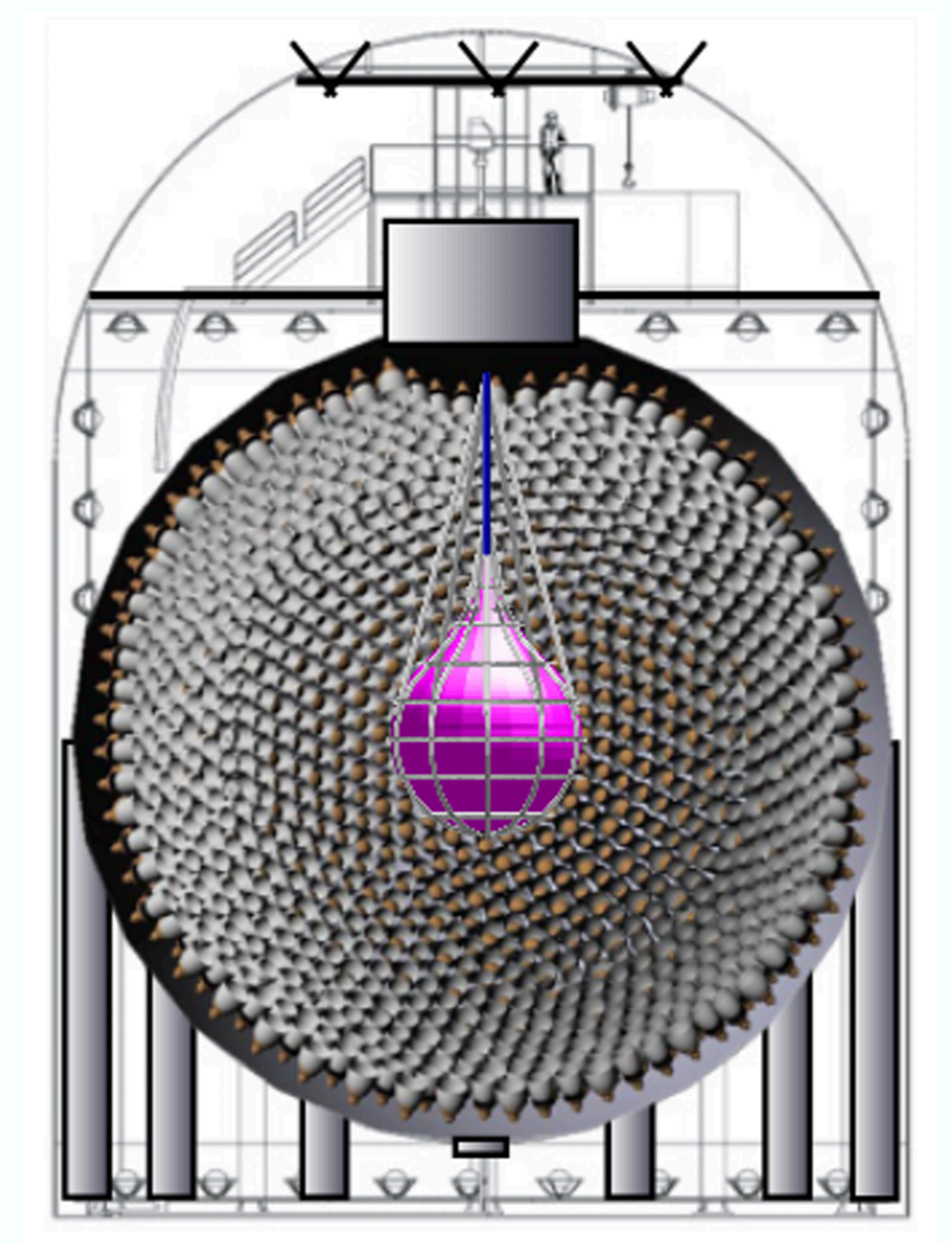



PMT + Mirror
**100% coverage**

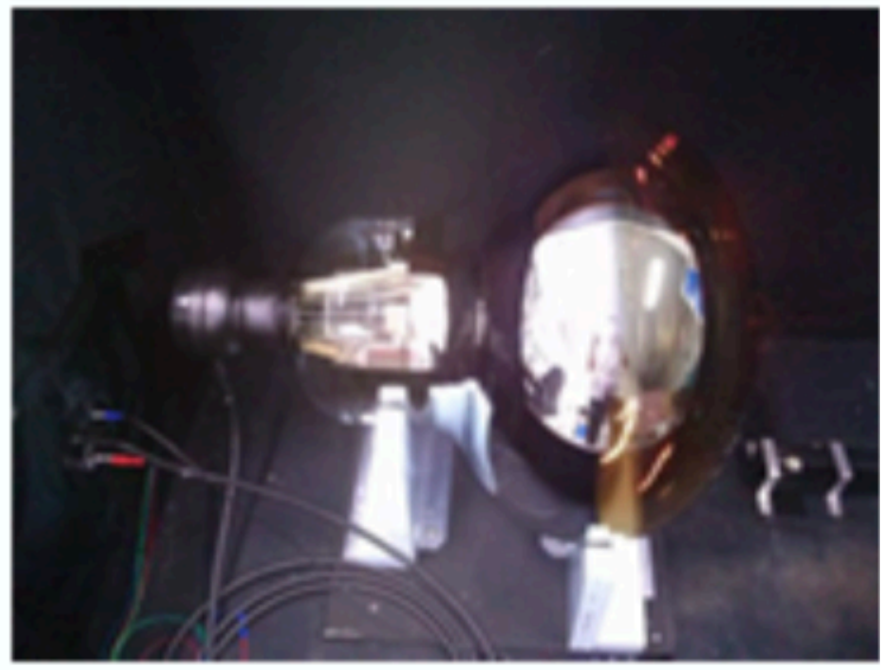
**New Liquid Scintillator**

$\sigma_E$ @ Q-value = 2%

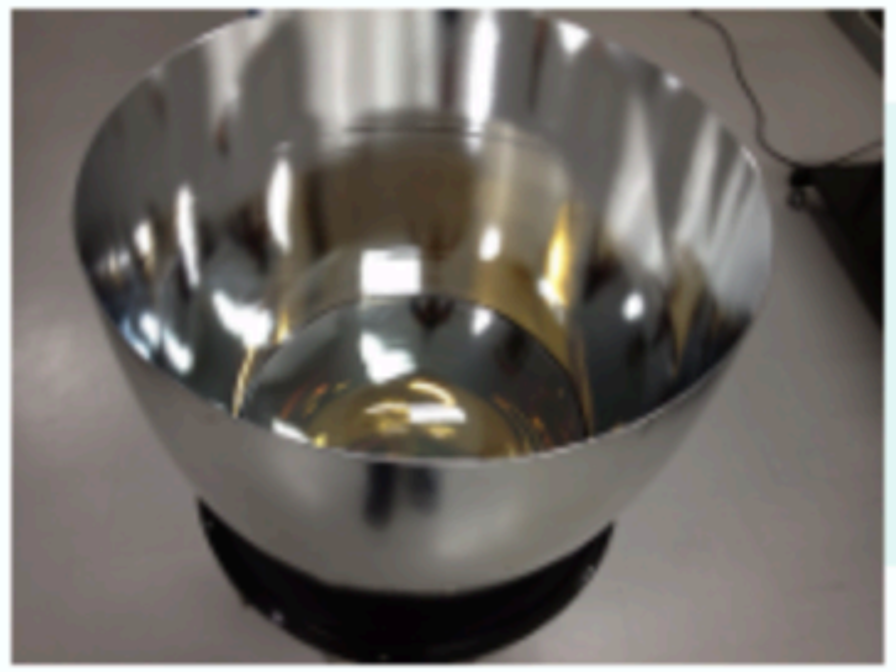
2νββ BG Reduction: ~ 1/100



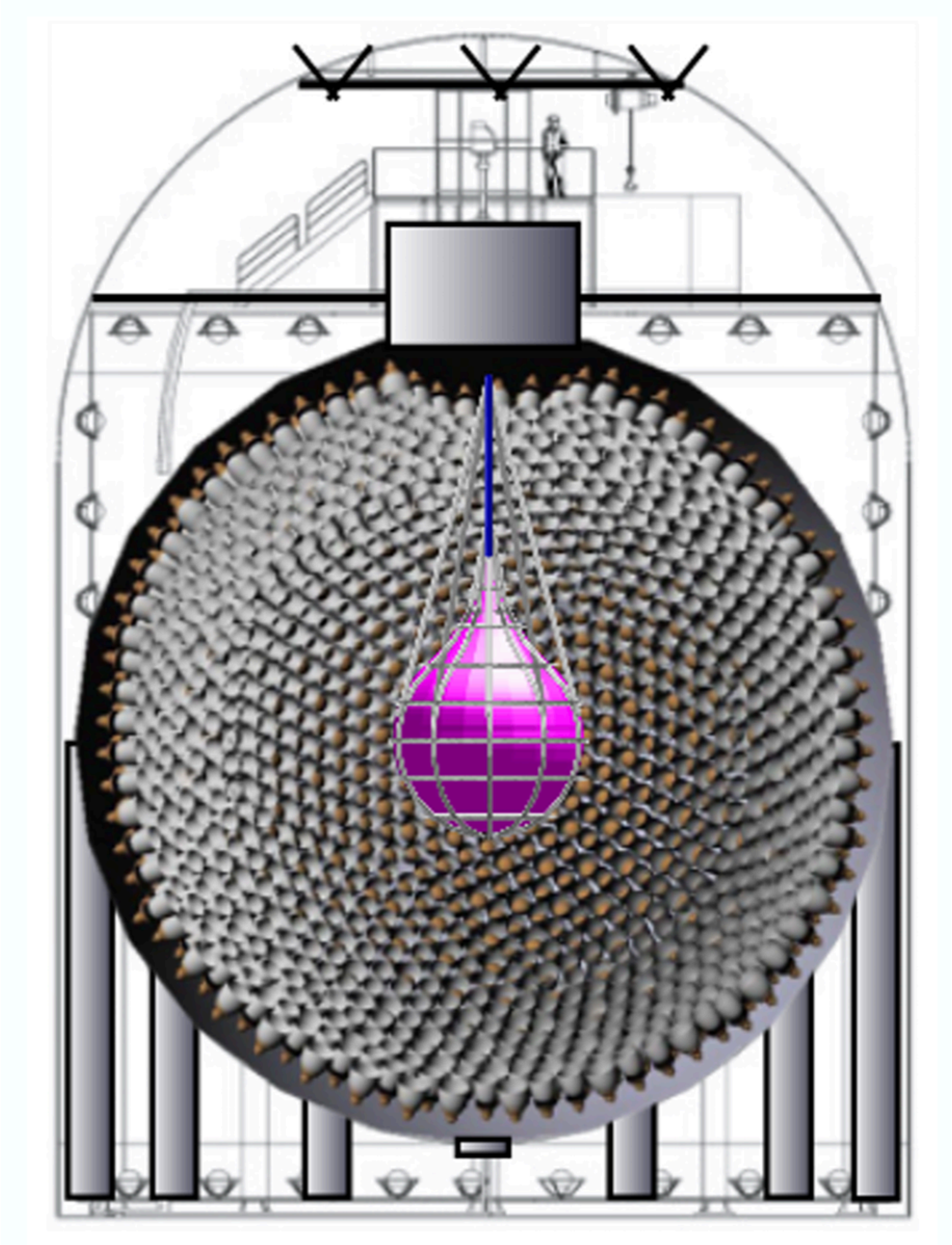
New HQE PMTs



Mirror Concentrators




**1 tonne**
**of isotope**



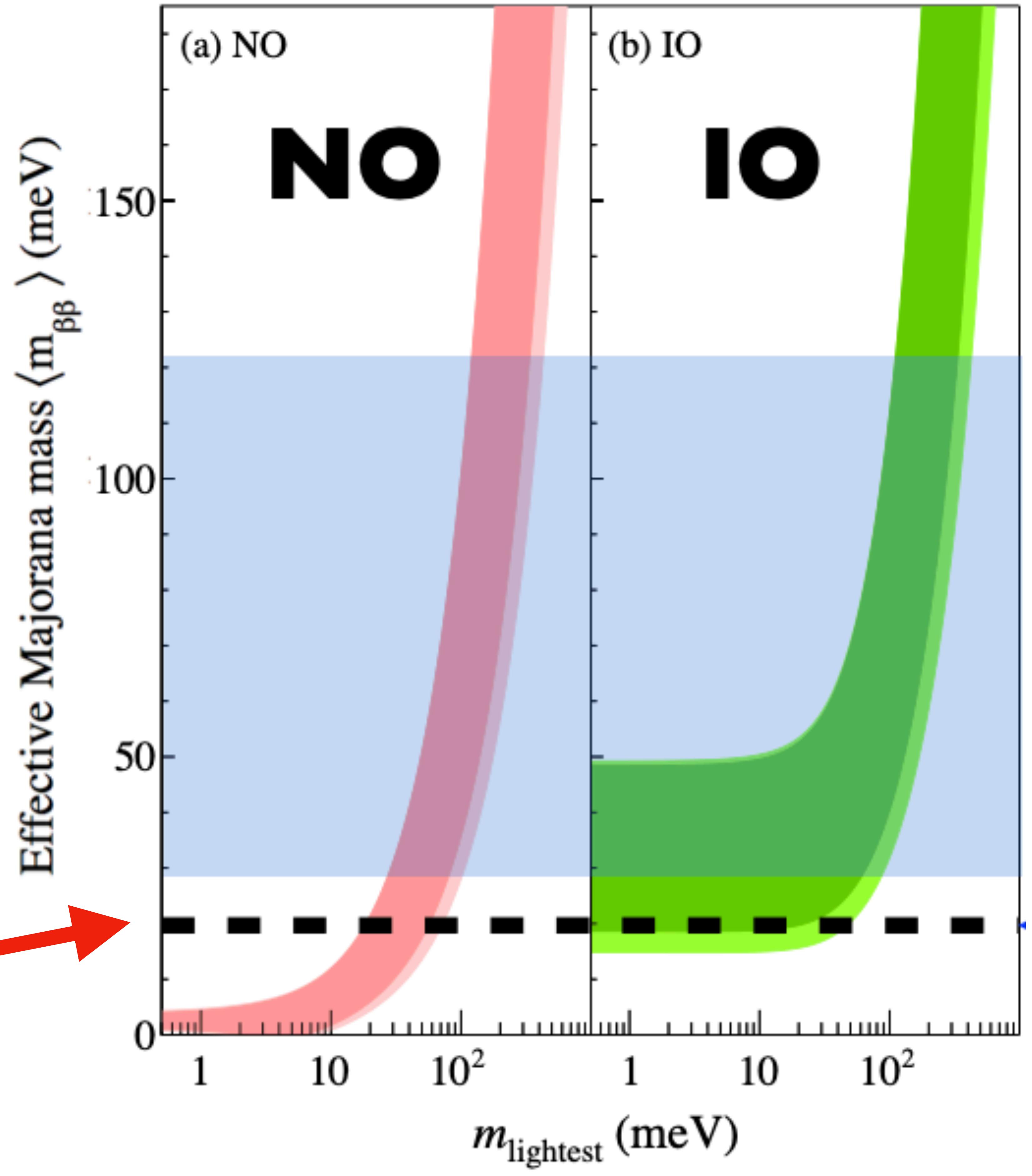

**Scintillating Balloon:**
**$^{214}$Bi BG reduction → 100% fiducial volume**

**Projected Sensitivity:**

$$T^{0\nu}_{1/2} > 1x10^{27}\ \mathrm{y}$$

$<m_{\beta\beta}> < 20$ meV

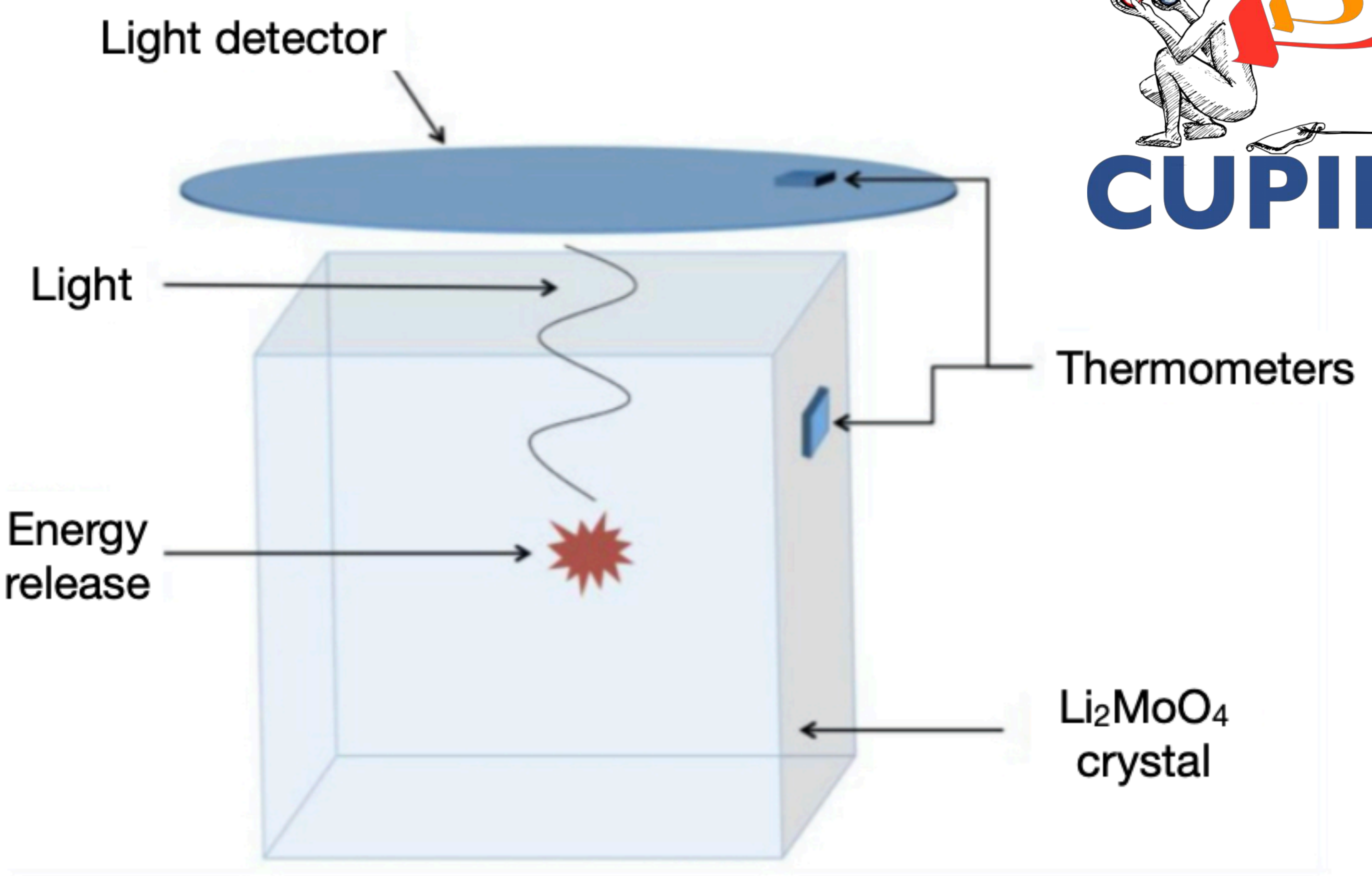
**in 5 years**



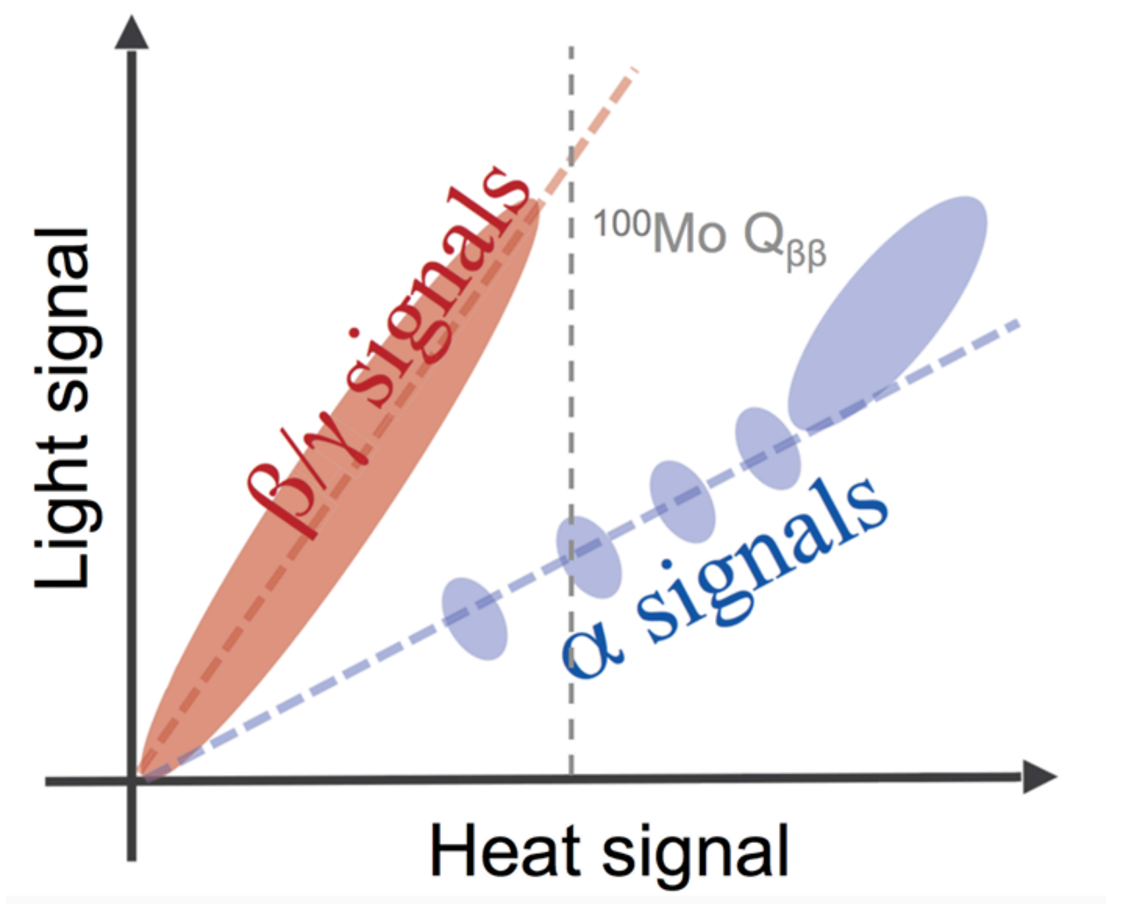
# CUPID

## CUPID: Cuore Upgrade with Particle ID

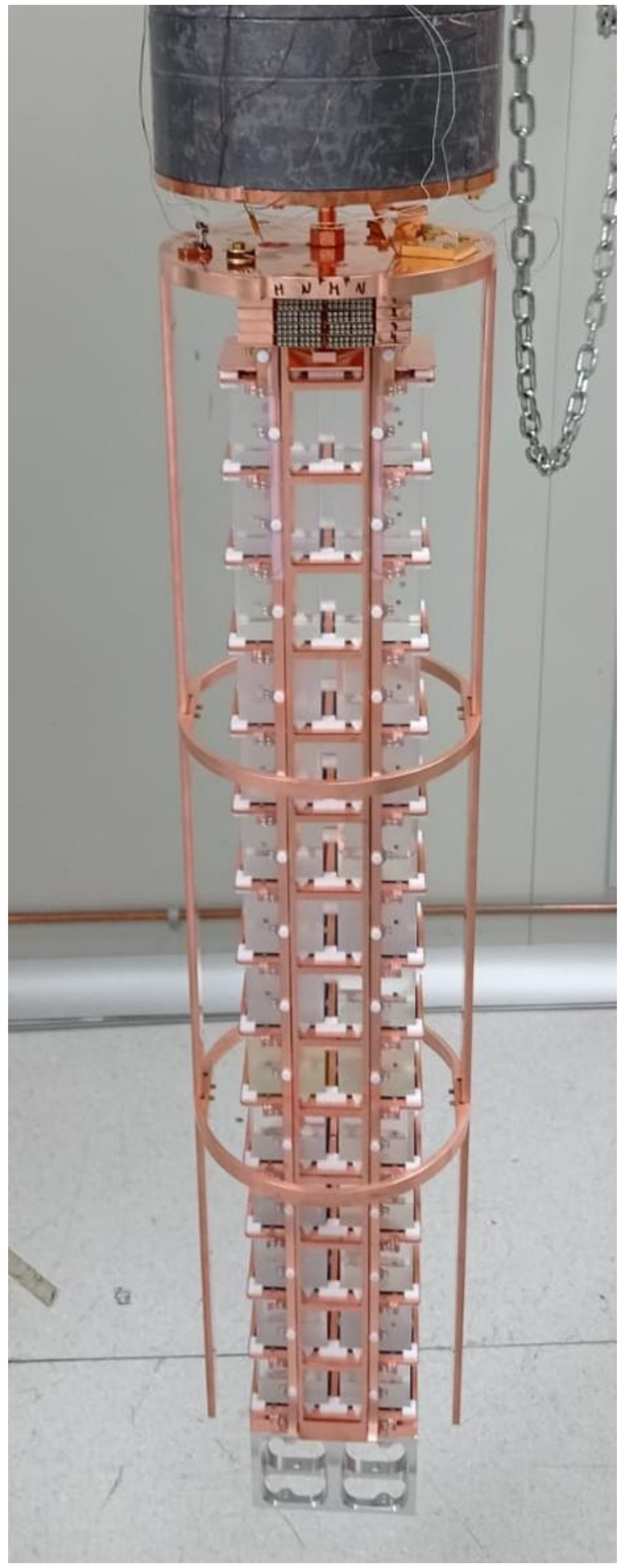
- 1596 $Li_2{}^{100}MoO_4$ crystals (45x45x45 mm3) assembled in 57 towers of 28 crystals each
- 240 kg of $^{100}Mo$ (>95% enrichment)
- Each crystal has top and bottom Ge light detectors with Neganov-Luke amplification
  - SiO anti-reflective coating to maximise light collection
  - Enhance the S/N ratio to reach pileup rejection capability through PSD.
- Will use CUORE cryostat at LNGS
  - Adding Muon Veto
  - Upgrading Pulse Tubes & coupling to Cryostat




arXiv:1907.09376

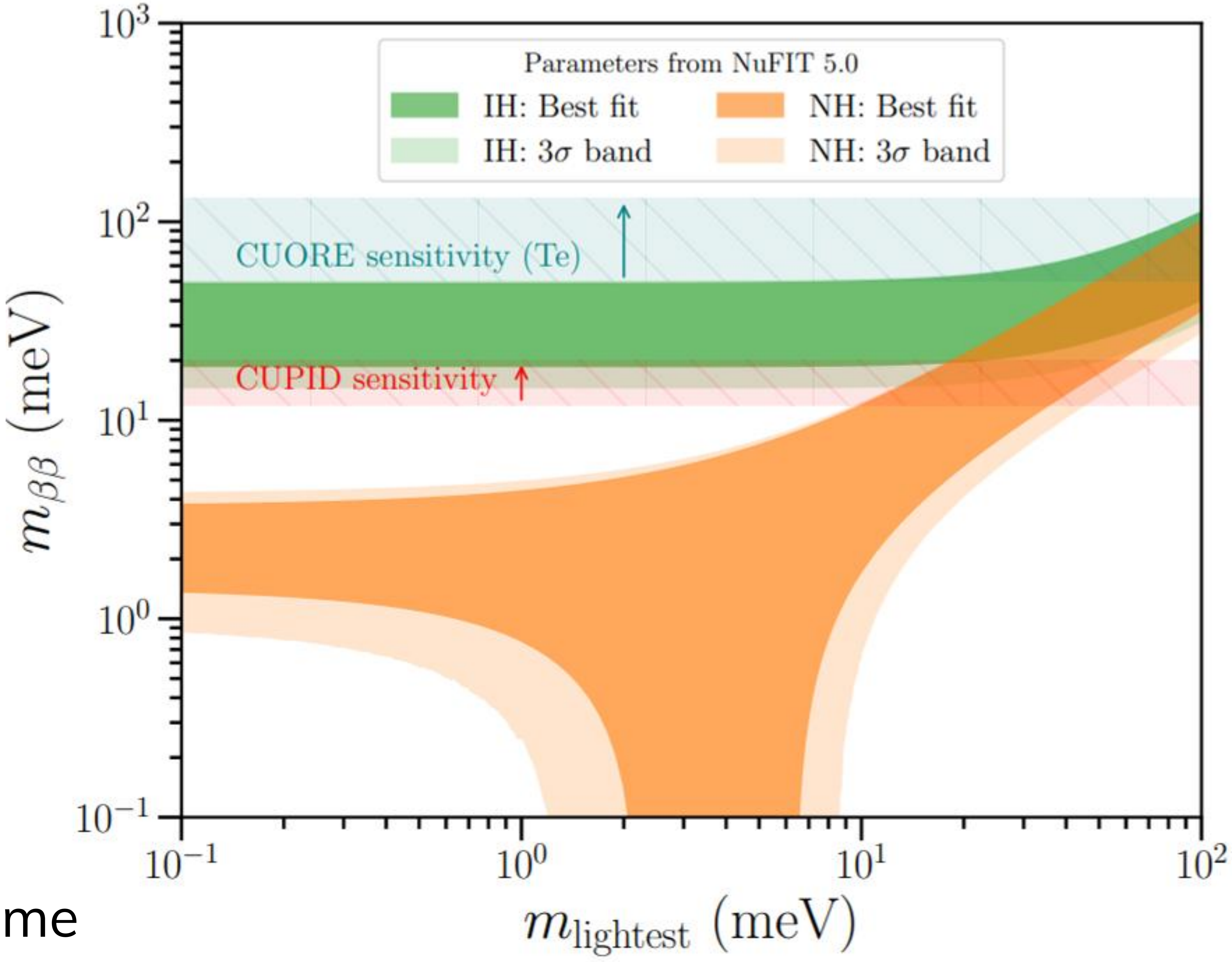



[Mo-100, $Q_{\beta\beta}$ = 3034 keV, 9.7% NA]



- $^{100}$Mo: $Q_{\beta\beta}$ = 3034 keV
- Operate at 10-30 mK
  - Sensitive to ΔT~ 0.1 mK
- High energy resolution:
  - ~5 keV (0.2%) @ $Q_{\beta\beta}$
- BG level of ~$10^{-4}$ count/keV/kg/yr

<- Baseline Design Prototype Tower

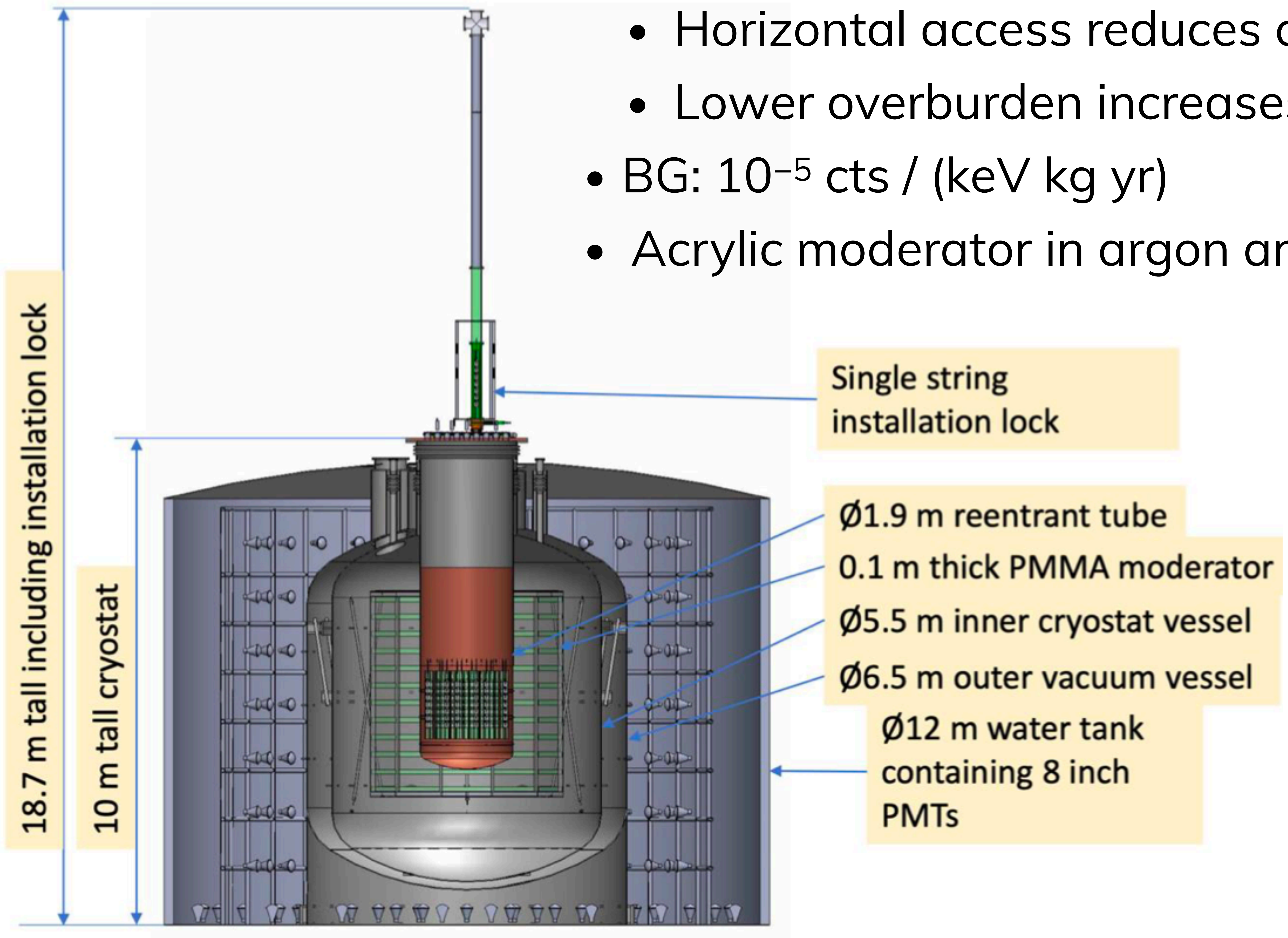



- Discovery sensitivity:
- $T^{0\nu}_{1/2} > 1.1 \times 10^{-27}$ with 10 yr of live time
- <$m_{\beta\beta}$> < (12 - 20) meV

# LEGEND-1000

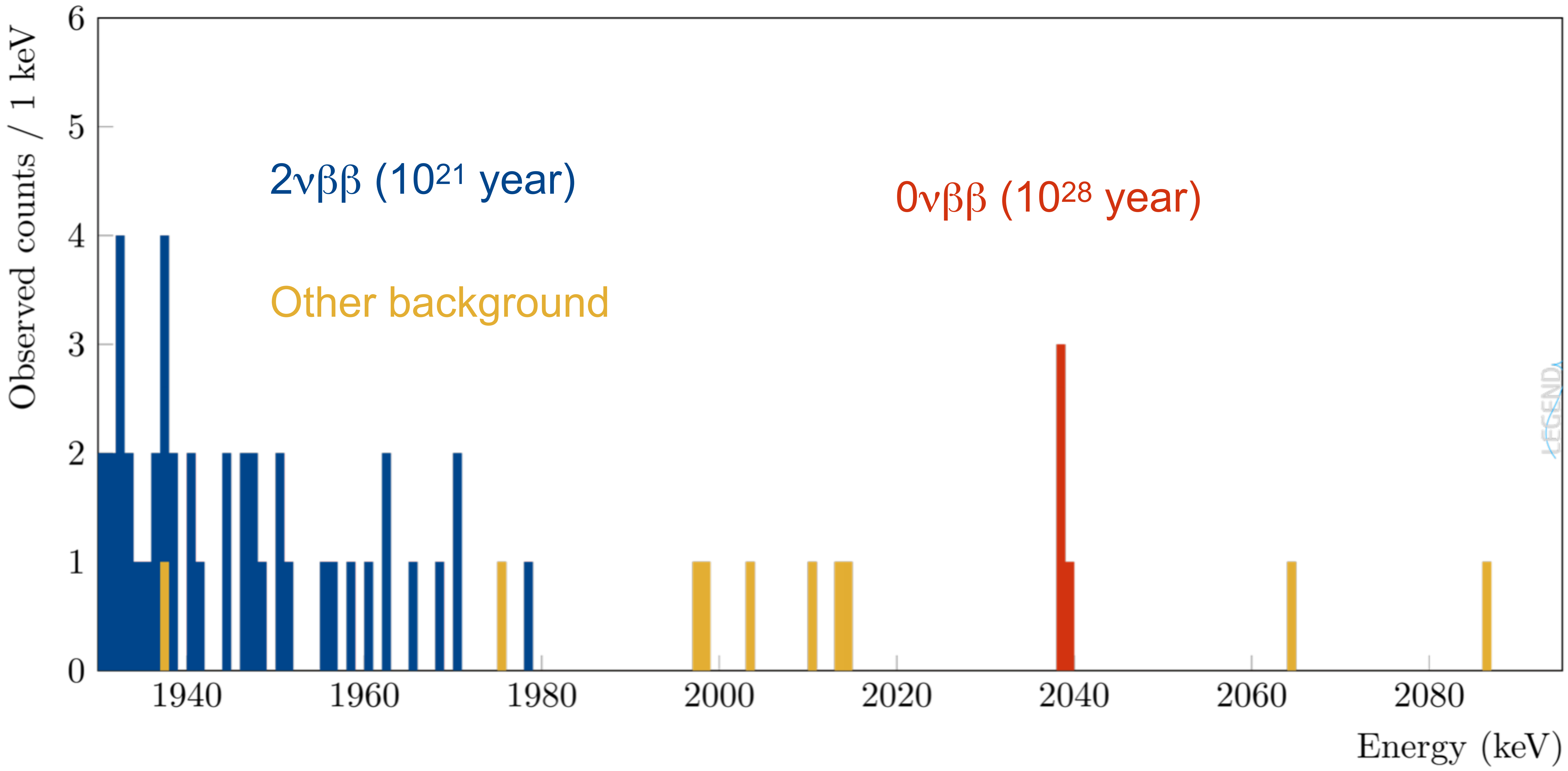
SNOLAB

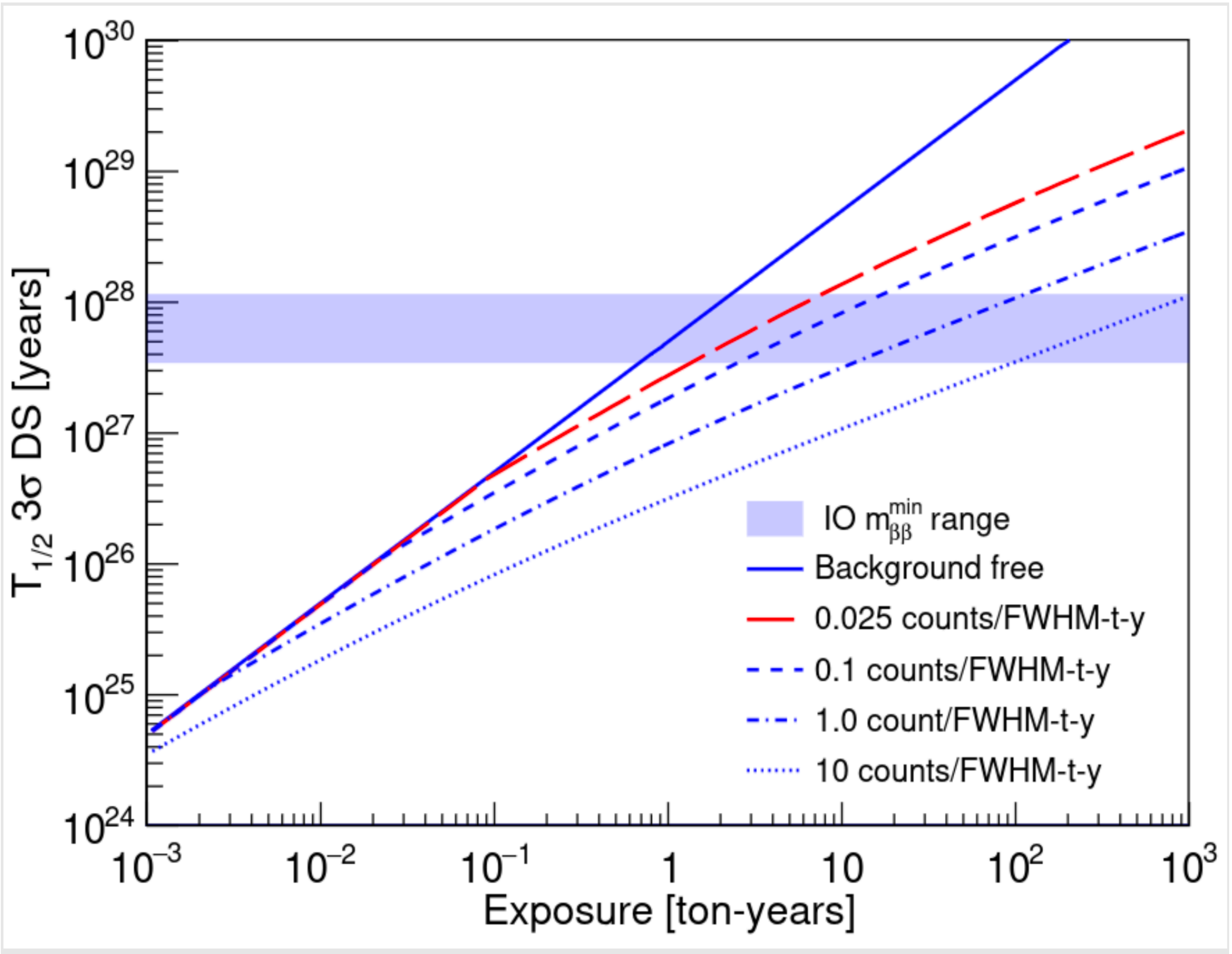
- To be Located at LNGS
  - Horizontal access reduces cost and schedule risk
  - Lower overburden increases background only slightly
- BG: $10^{-5}$ cts / (keV kg yr)
- Acrylic moderator in argon and veto/tag with small loss in livetime



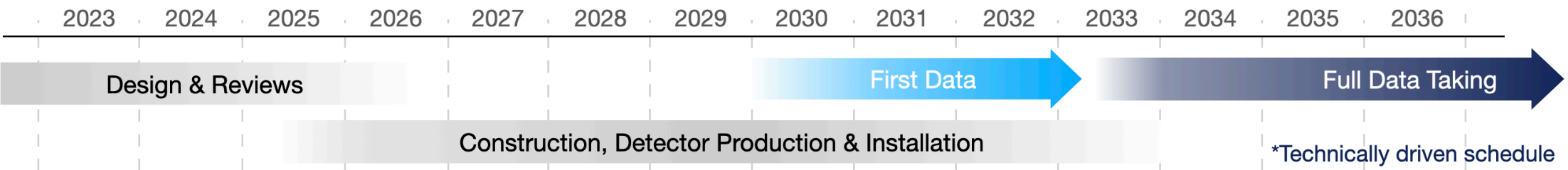

The LEGEND-1000 design for LNGS Hall C

- L-1000 will include 30 t of Underground Liquid Argon (UGAr) instrumented as an active veto with WLS and SiPMs, and used as Ge semiconductor cooling
- L-1000 will re-deploy 130 kg of L-200 ICPC detectors and **fabricate** 870 kg of new detectors.



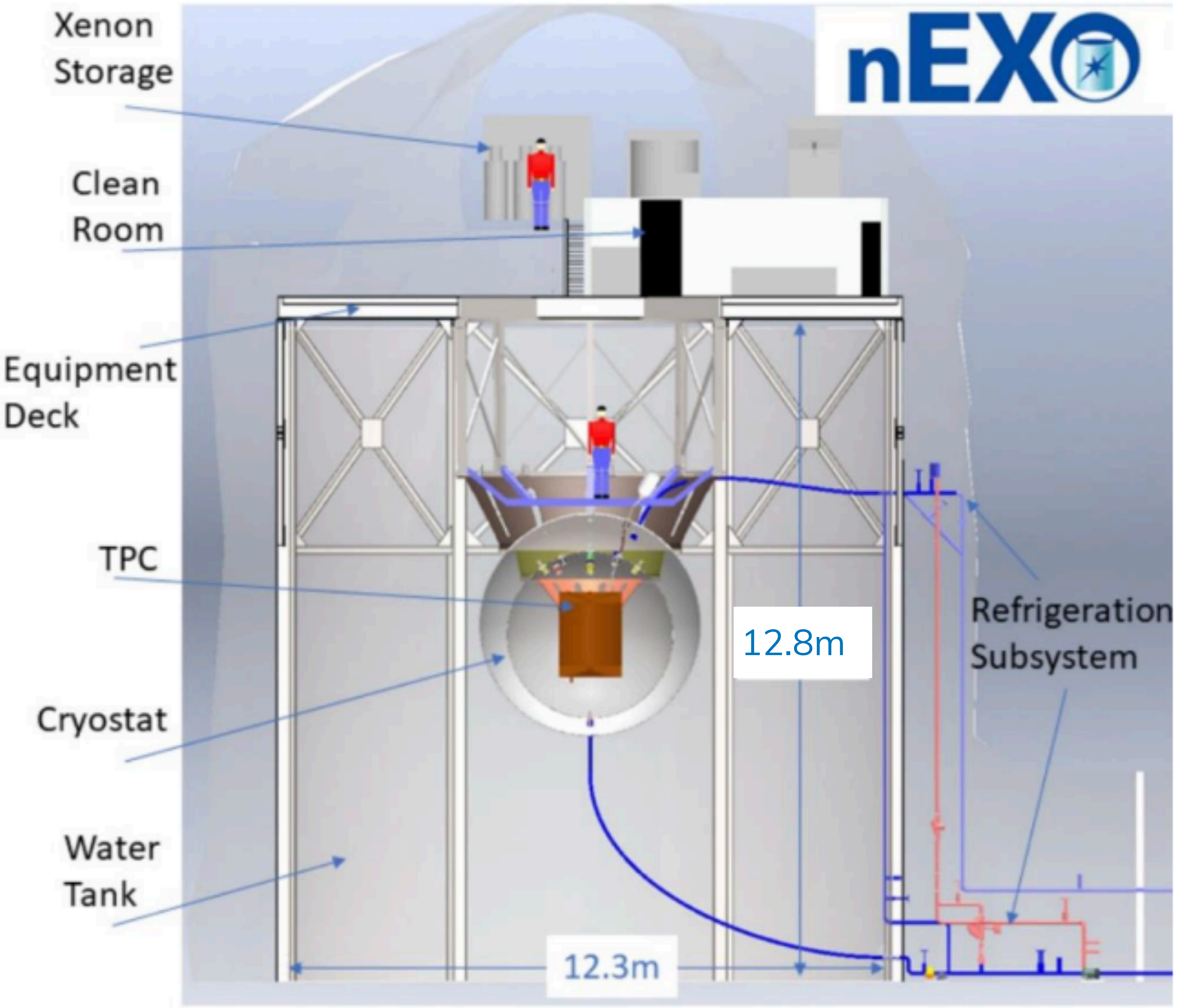




- $T^{0\nu}_{1/2} > 10^{28}$ with a 99.7% confidence level discovery sensitivity
- $<m_{\beta\beta}> < (9 - 21)$ meV
- within 10 yr of live time




*Technically driven schedule

# nEXO




arXiv:1805.11142

nEXO

- Continuation of EXO-200 program
- nEXO: 5 tonne Liquid Xenon TPC, enriched 90%

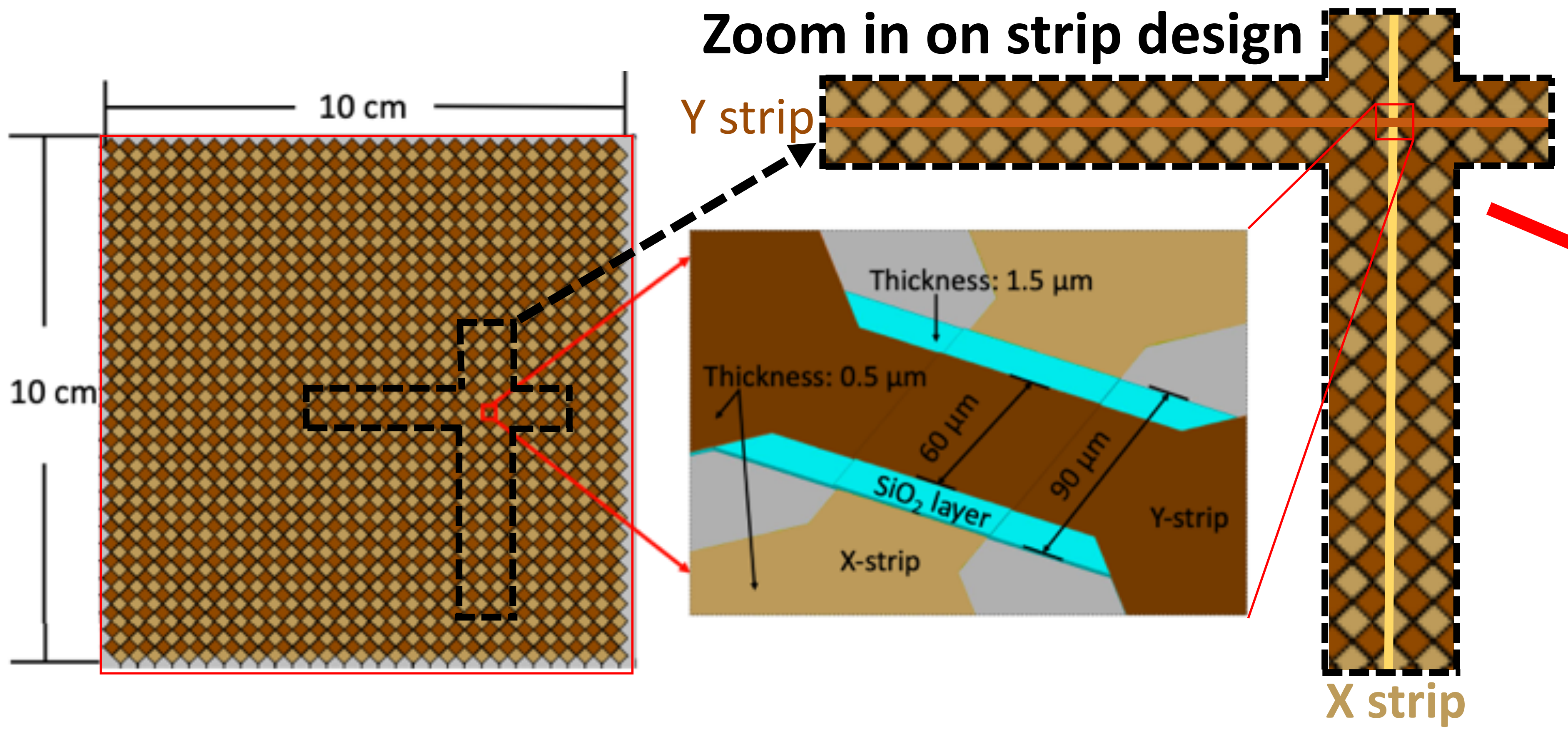
- To be located in SNOLAB's Cryopit (6000 mwe)
- Combined Light and Charge readout
- Active Outer Detector to veto muons

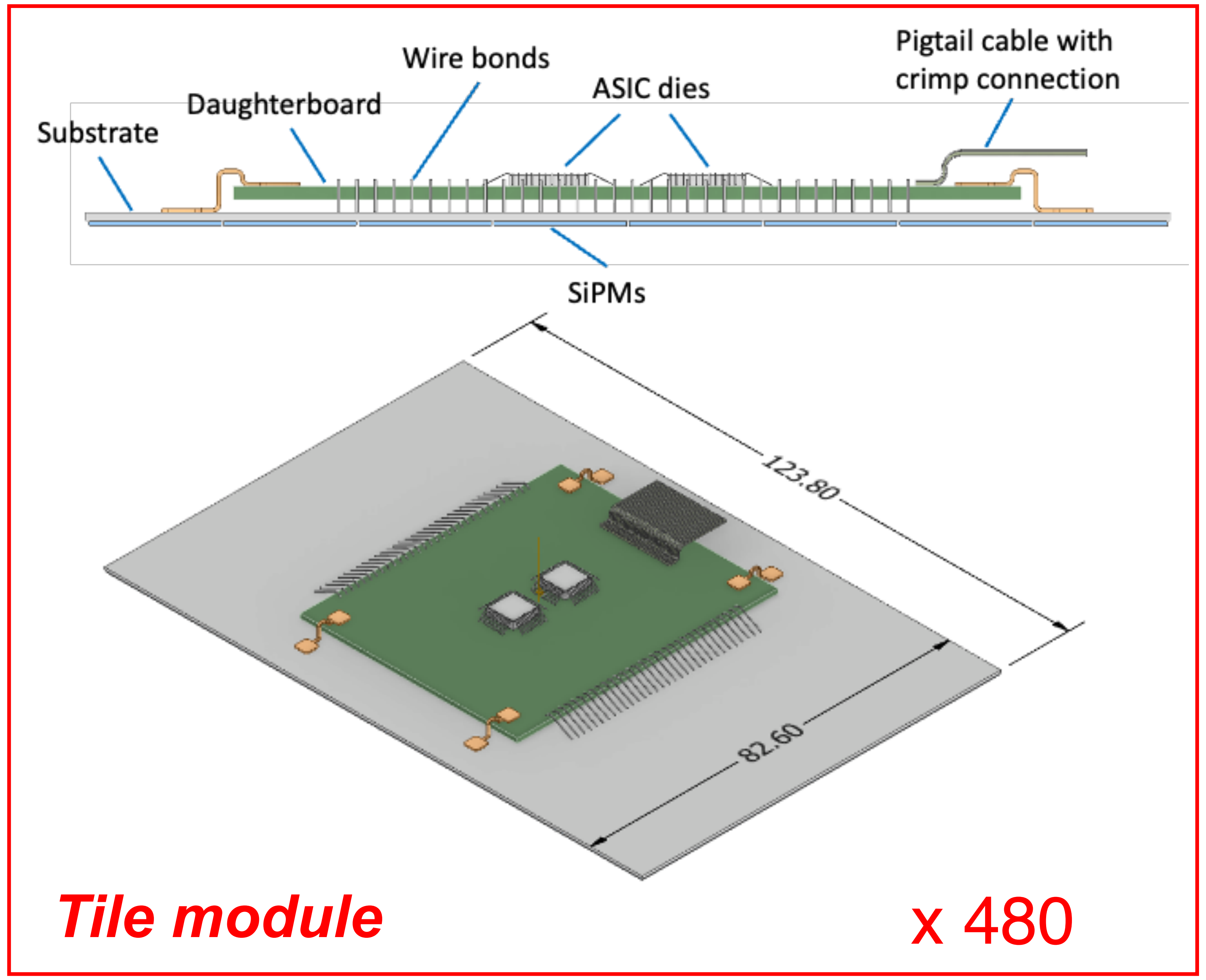
- Low intrinsic background in Xenon
  - $Q_{\beta\beta}$=2457 keV

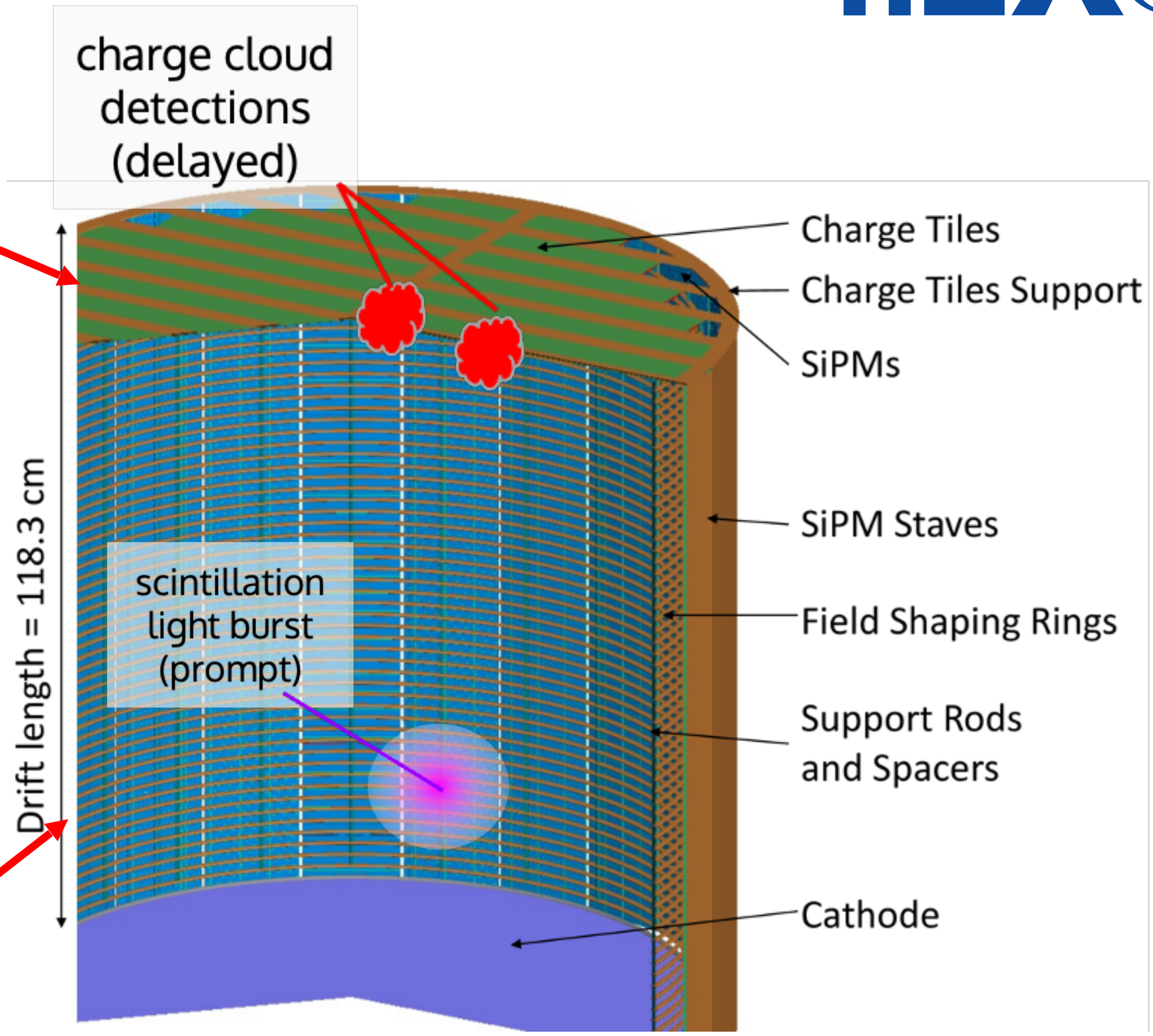


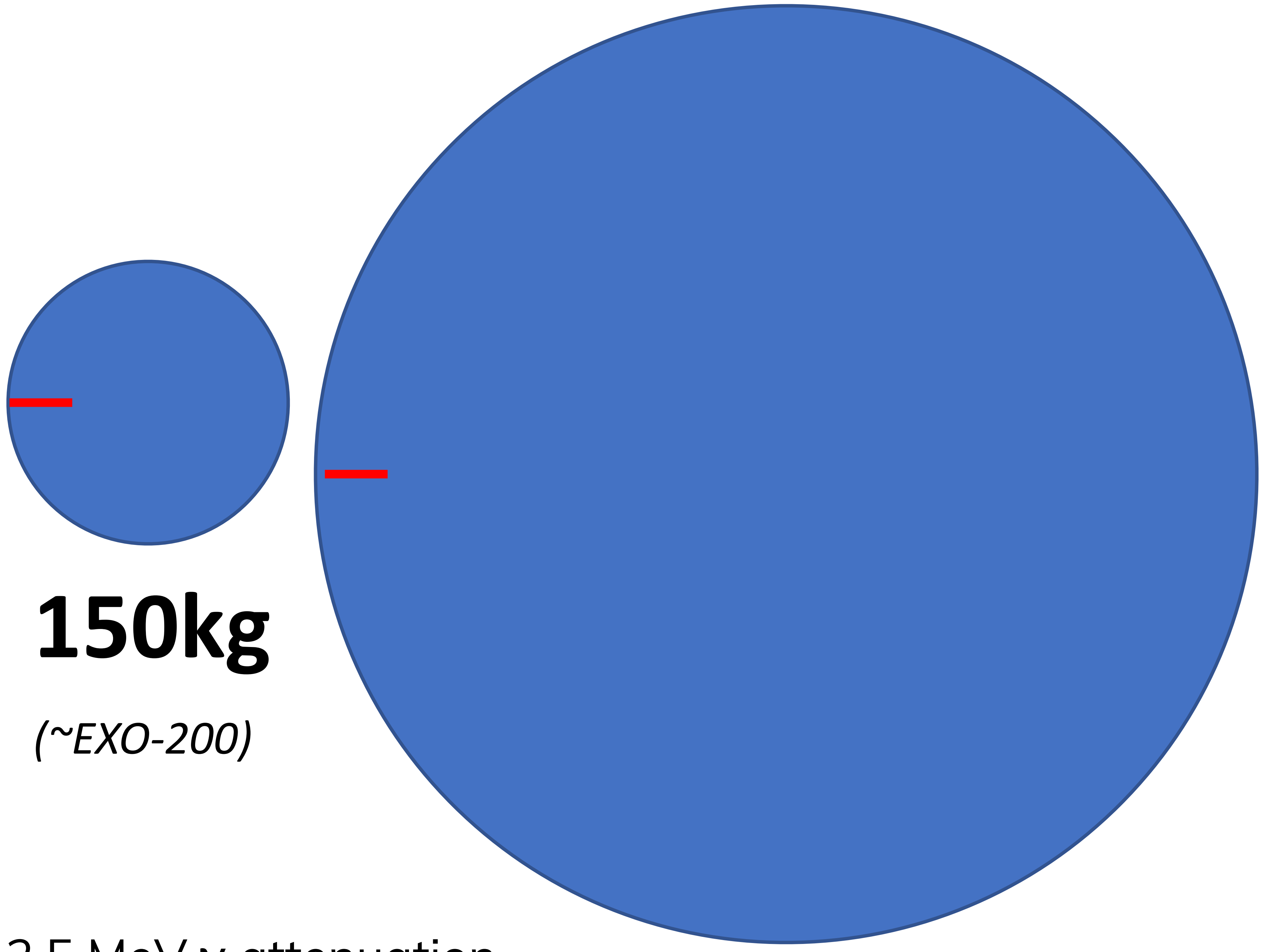
[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]

- SiPM for 175nm scintillation light detection, ~4.5 $m^2$ array in LXe
- Tiles for charge read-out in LXe





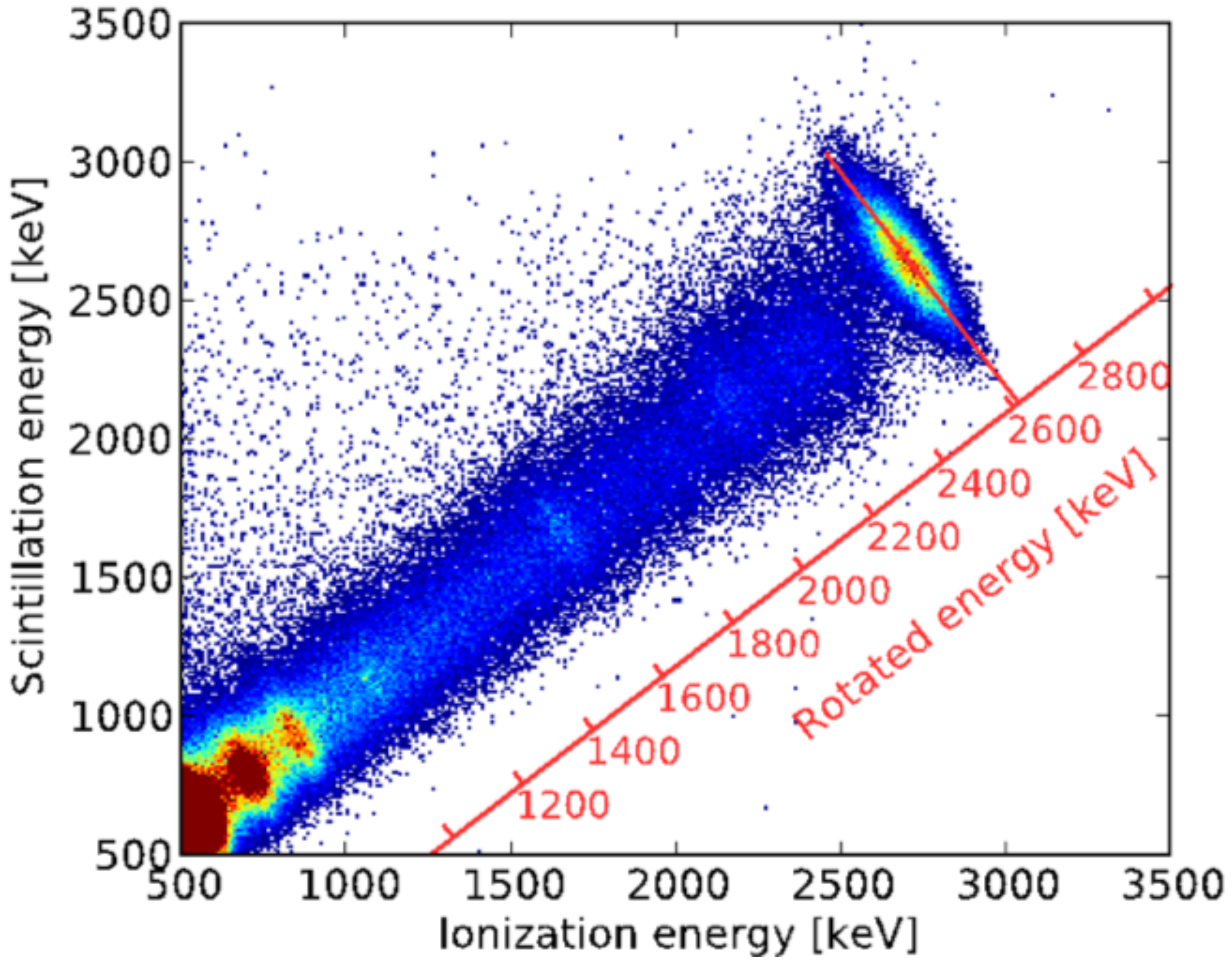
**150kg**

*(~EXO-200)*

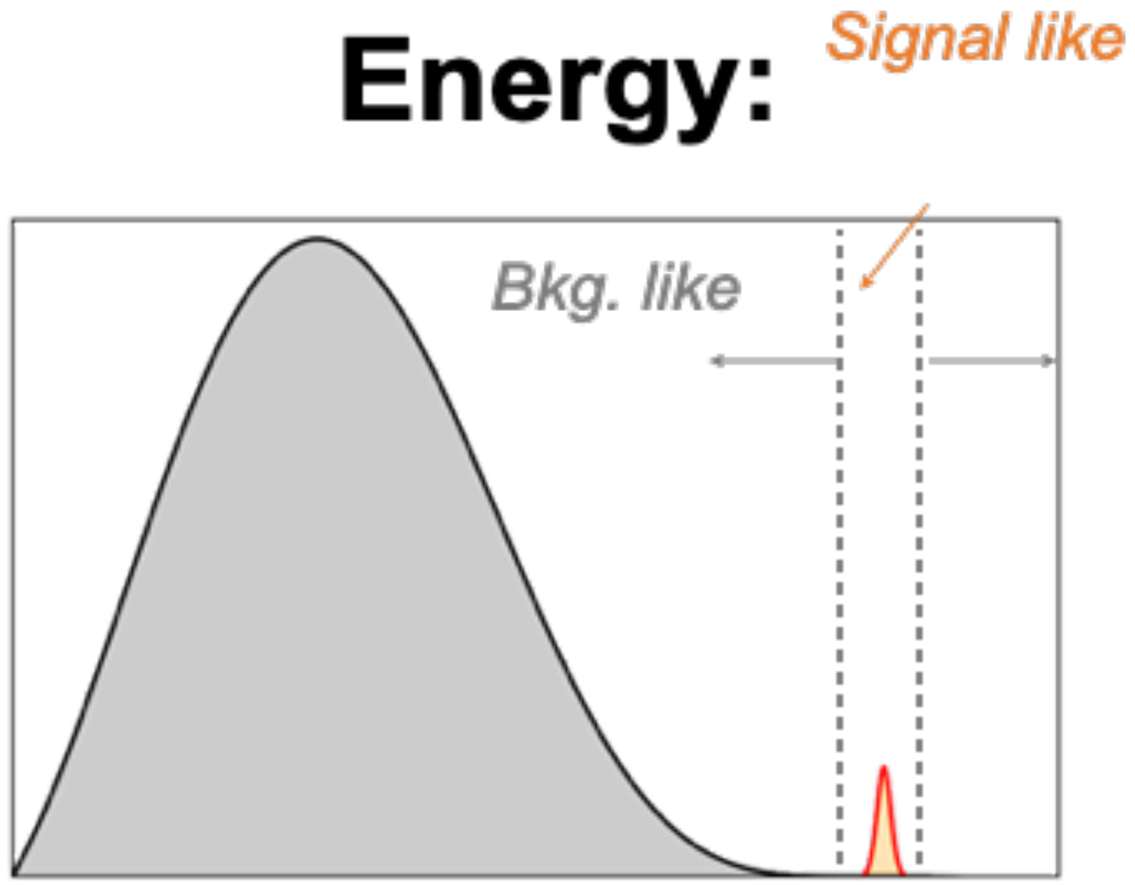
**5000kg** (nEXO)

2.5 MeV γ attenuation length 8.7cm =

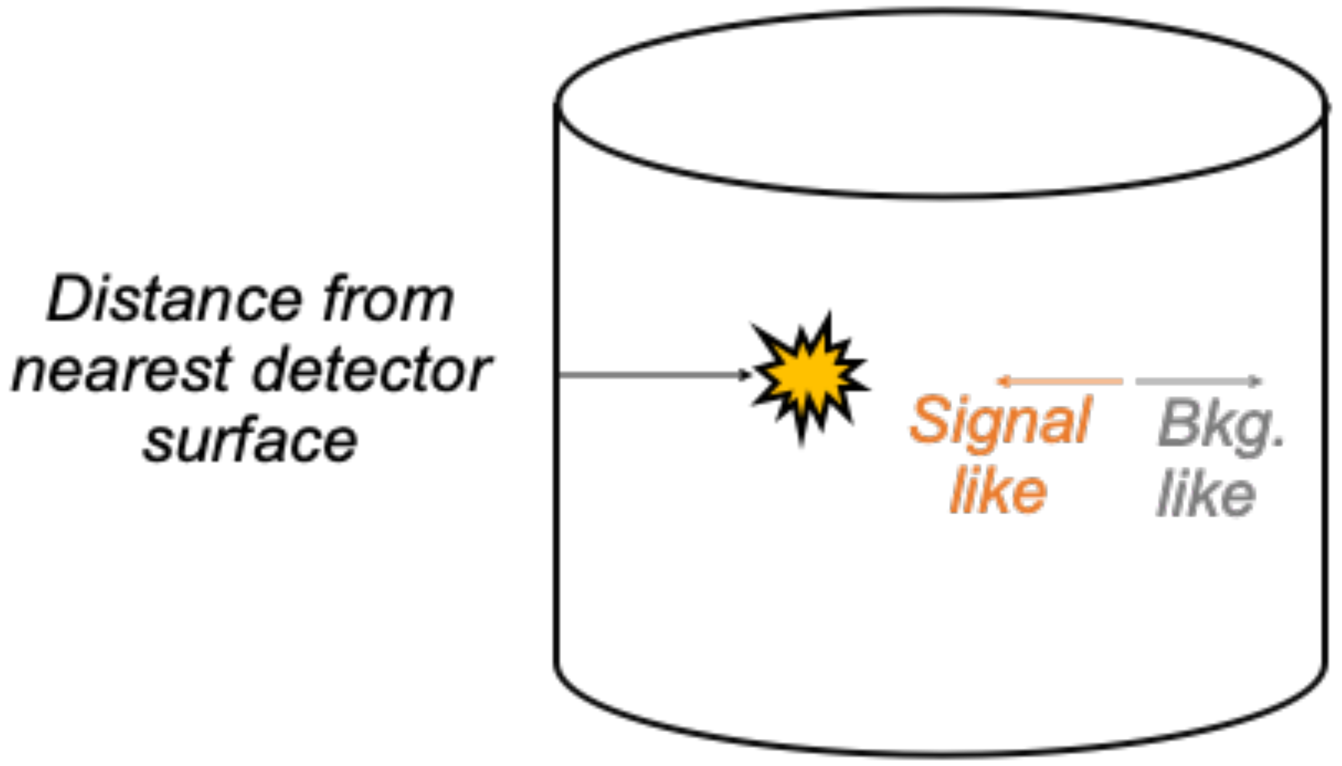
- Monolithic design means self-shielding from external backgrounds
- Rotated energy scale provides <1% energy resolution
- Robust Multi-parameter Analysis



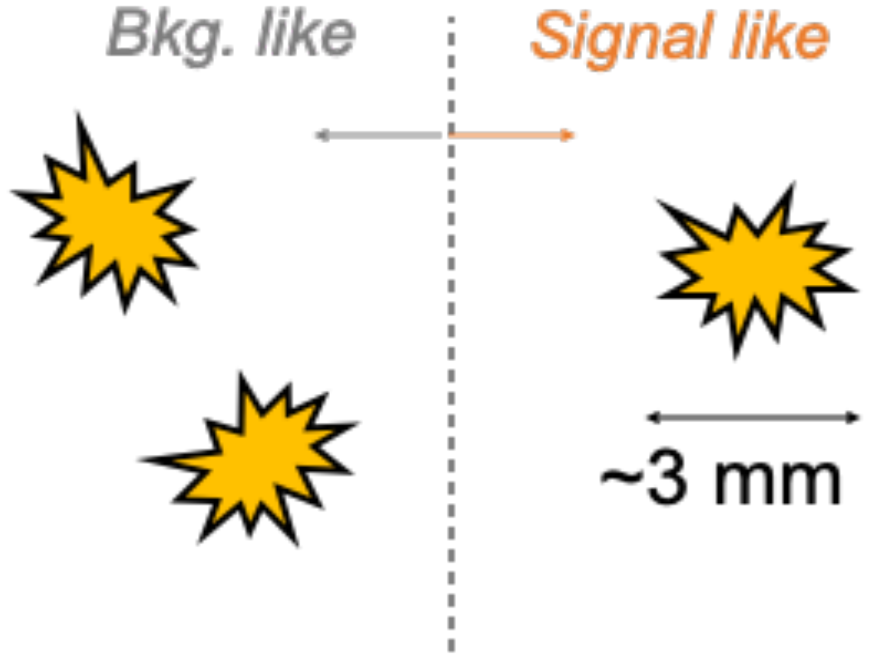

**Energy:**

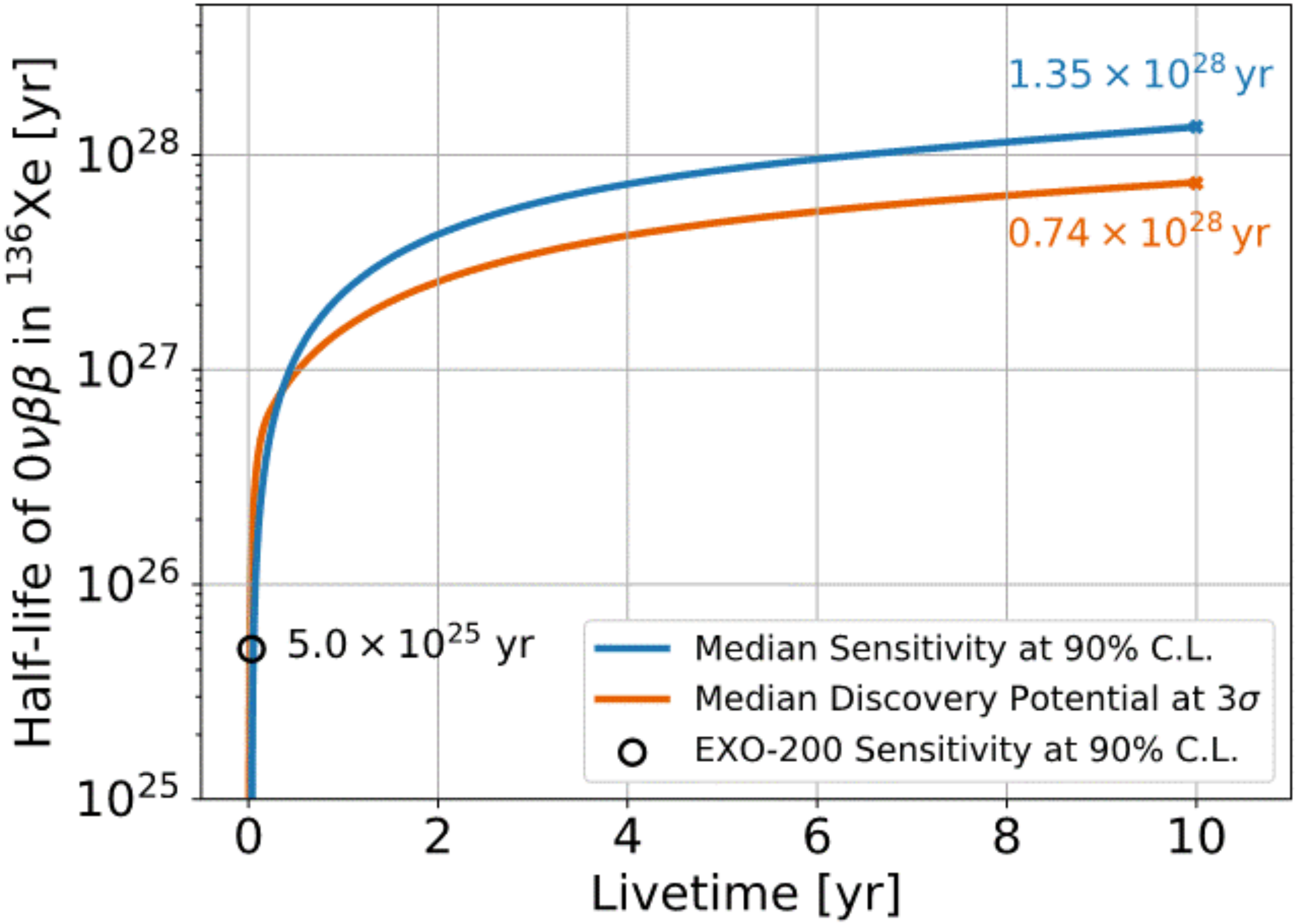



**Standoff:**

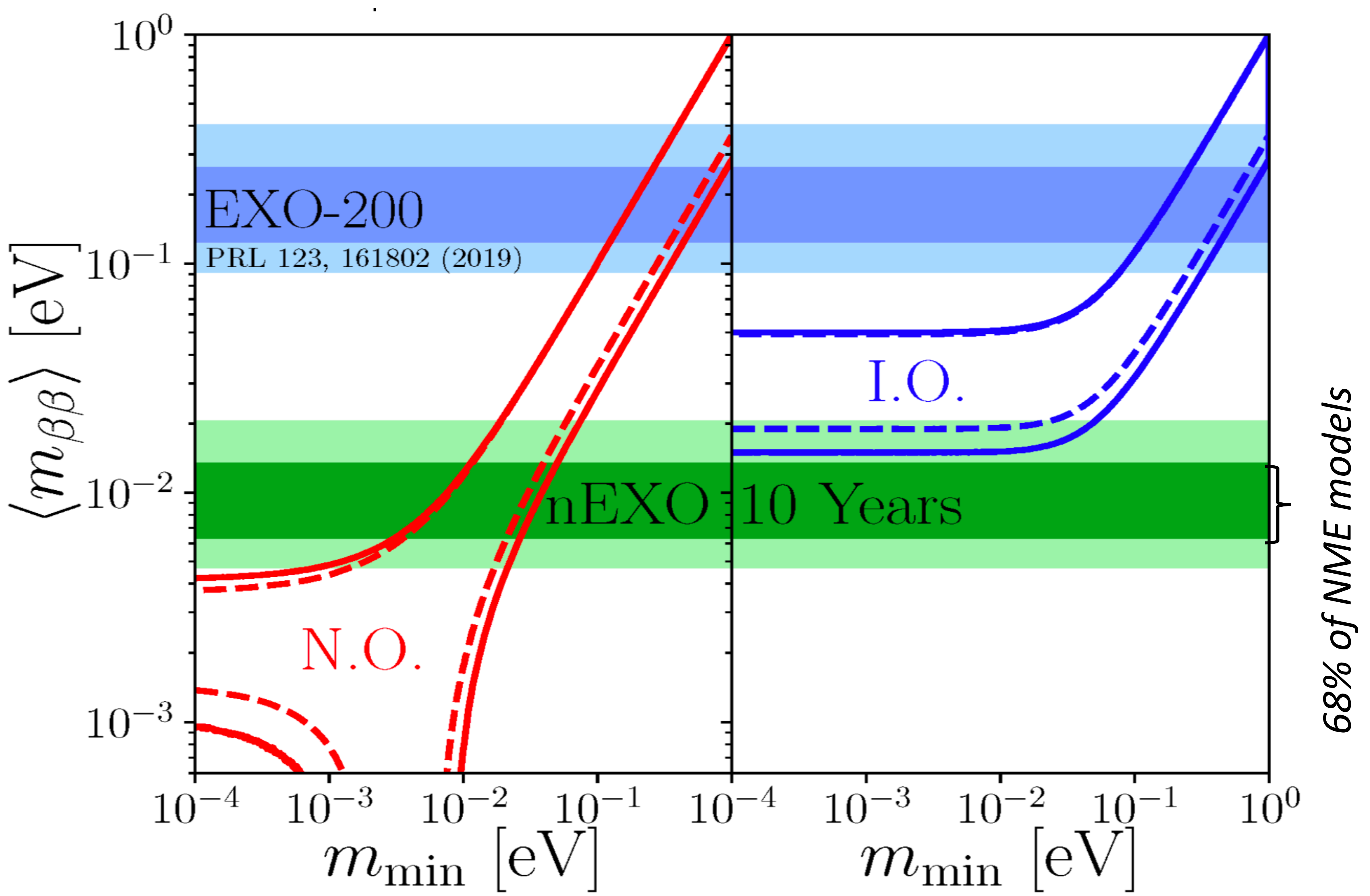



**Topology:**






# nEXO reaches $10^{28}$ yr in 6.5 yr data taking




- Energy Resolution <1% at $Q_{\beta\beta}$
- Limit: $T^{0\nu}_{1/2}$ > 1.35 x $10^{28}$ y
- $m_{\beta\beta}$ < (4.7 - 20.3) meV

[J. Phys. G: Nucl. Part. Phys. 49 (2022) 015104]

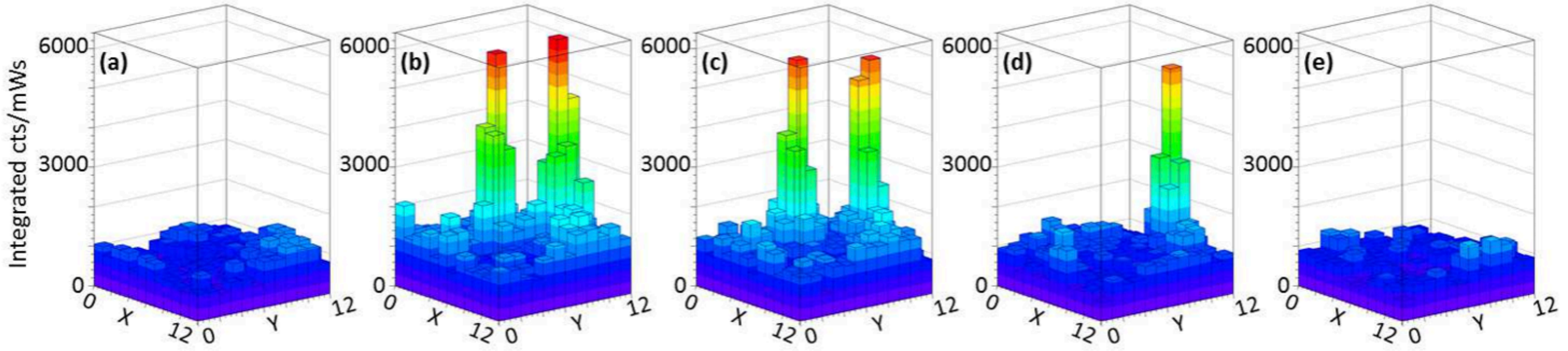
[Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA]

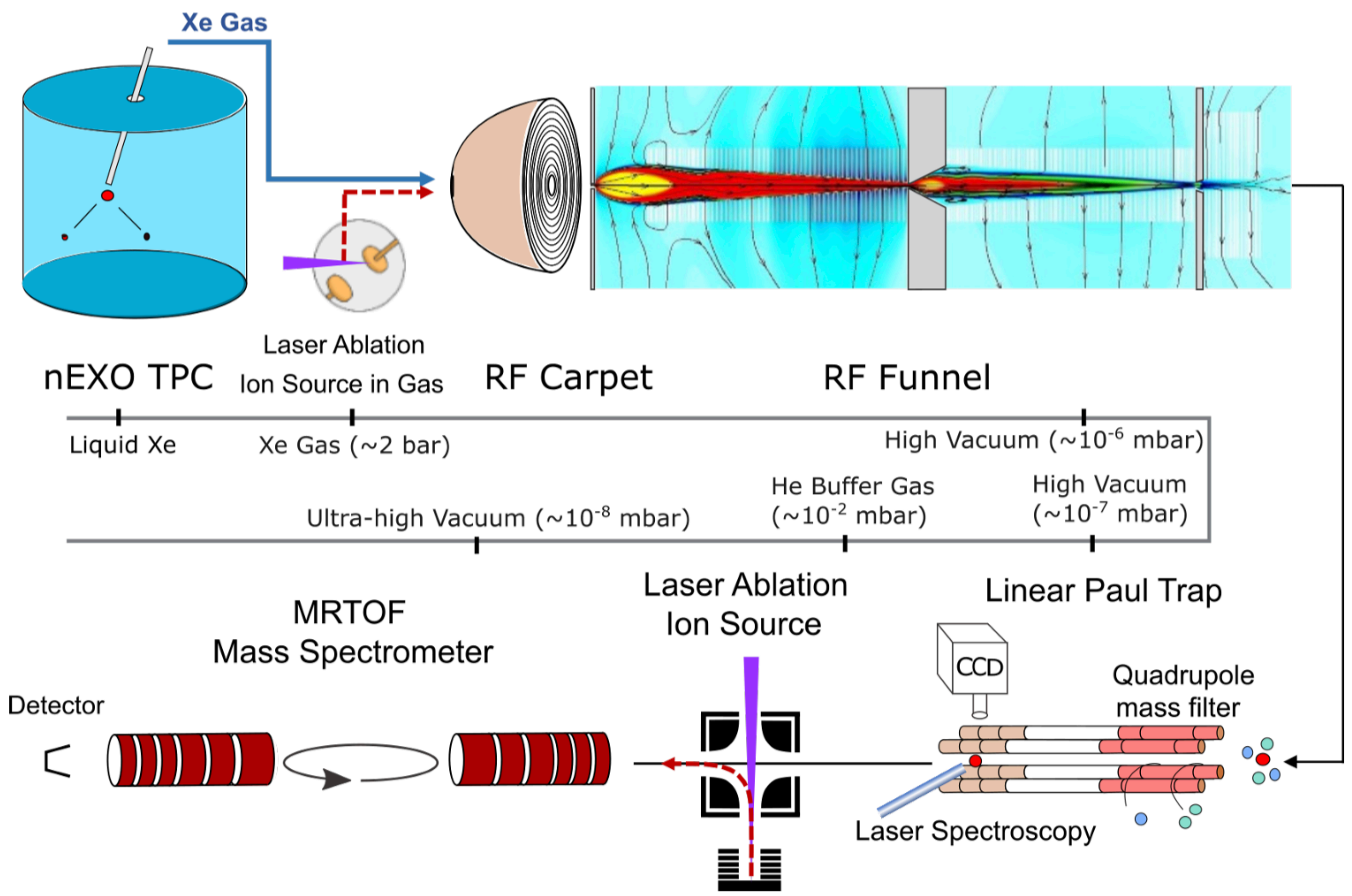
# Barium Tagging

$^{136}Xe \rightarrow {}^{136}Ba^{++}$

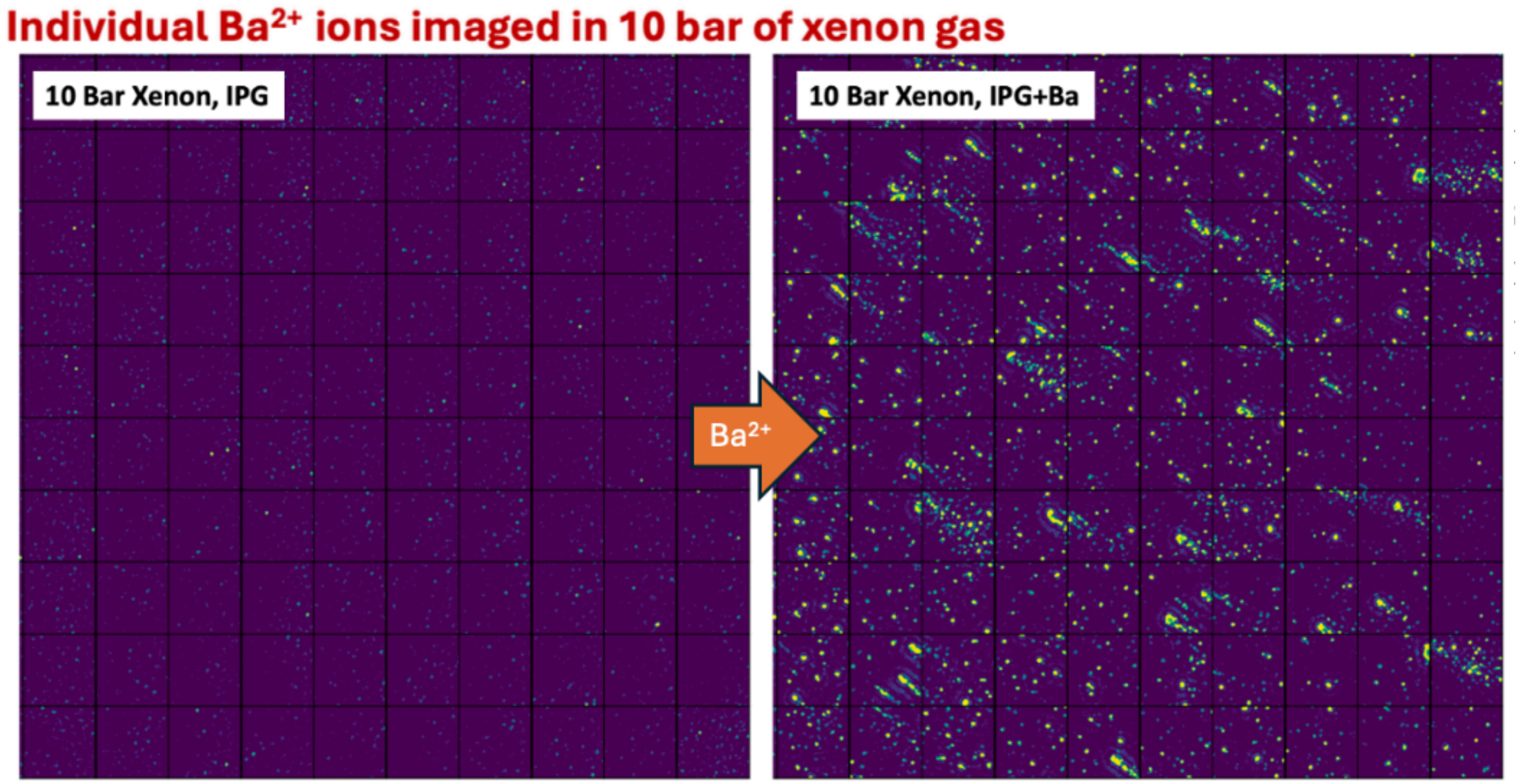
*Only* produced when

Xe double beta decays



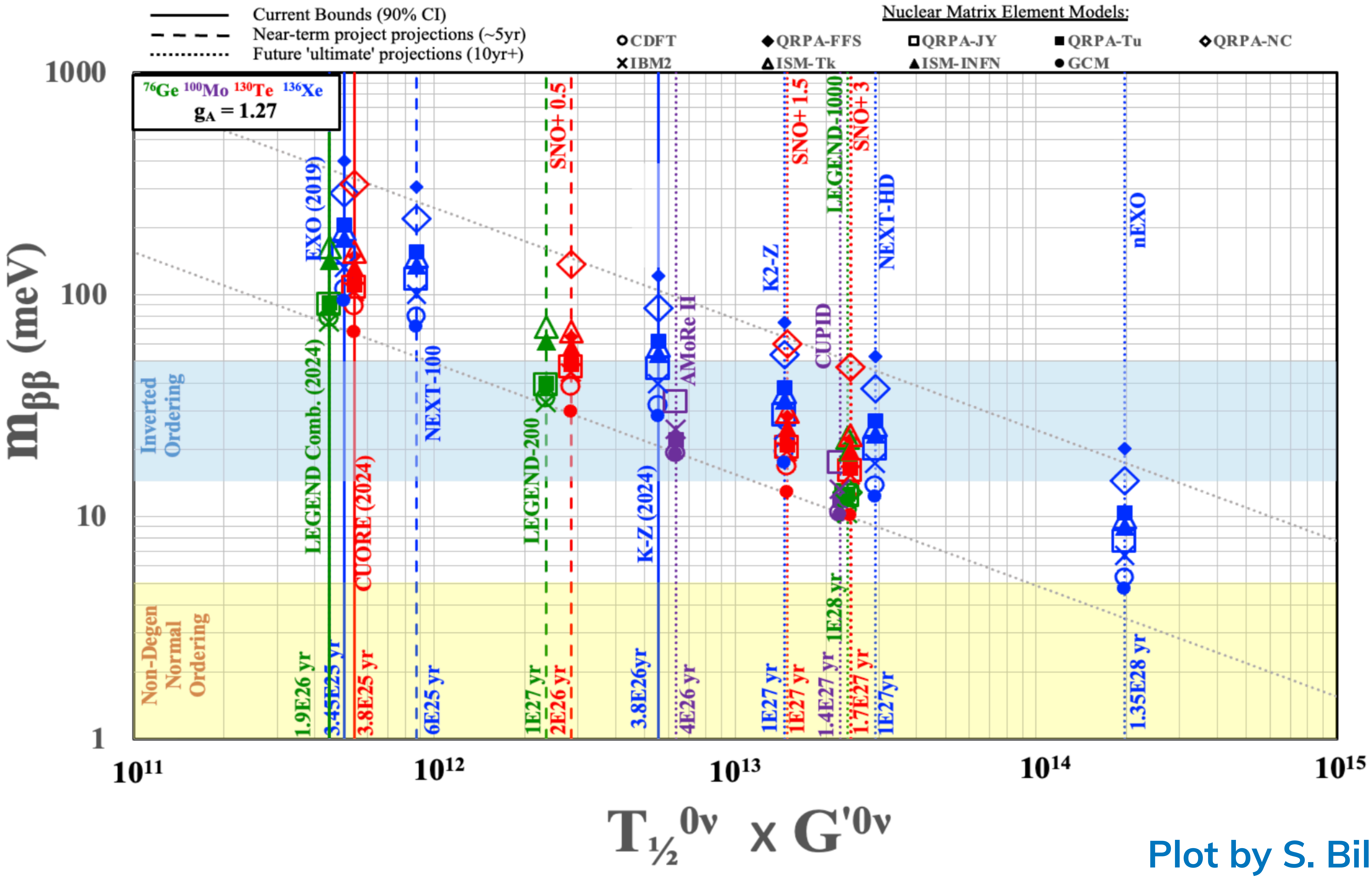




Nature 569 (2019) 7755, 203-207




- **Time-resolved Indicators**
- **Off-On Indicators**
- **Fluorescent Bi-color Indicators**

Nature 583 (2020) 48,



Current Bounds (90% CI)
Near-term project projections (~5yr)
Future 'ultimate' projections (10yr+)
Nuclear Matrix Element Models:
CDFT
QRPA-FFS
QRPA-JY
QRPA-Tu
QRPA-NC
IBM2
ISM-Tk
ISM-INFN
GCM
76Ge 100Mo 130Te 136Xe
gA = 1.27
1000
100
10
1
m$_{\beta\beta}$ (meV)
Inverted Ordering
Non-Degen Normal Ordering
EXO (2019)
LEGEND Comb. (2024)
CUORE (2024)
NEXT-100
LEGEND-200
SNO+ 0.5
K-Z (2024)
AMoRe II
K2-Z
SNO+ 1.5
CUPID
LEGEND-1000
SNO+ 3
NEXT-HD
nEXO
1.9E26 yr
3.45E25 yr
3.8E25 yr
6E25 yr
1E27 yr
2E26 yr
3.8E26yr
4E26 yr
1E27 yr
1E27 yr
1.4E27 yr
1E28 yr
1.7E27 yr
1E27yr
1.35E28 yr
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$
$10^{15}$
$T_{1/2}^{0\nu}$ x $G'^{0\nu}$


AMoRE: Mo Crystals in Yemilab
Copper holder
Si Wafer (Light detector)
Sensor holder
Stabilization Heater
Crystal
Reflector
CaNDLES: Ca crystals in Scintillator
3 m
4 m
1.4 m
LS
PMT
Water
10 cm
CaF2
WLS
(a)
(b)
NEXT-HD
2026?
0νββ search through inverted ν mass ordering
1 ton
NEXT-BOLD
Barium tagging for bgr-free experiment
Selena: 82Se CMOS detectors
x (mm)
y (mm)
Pixel Value (e⁻)
Demonstration of ~MeV electron tracks!
NuDot: Quantum Dots Loaded in Scintillator
Theia: Xe or Te Loaded Scintillator
70m
18m
Balloon for 0νββ isotope loaded liquid scintillator
60m
20m
60m
THEIA 100
MANTIS: Many Te-Loaded Balloons
Side 'End' View: Possible SLiPS design
lab space
top deployment
hexanediol or hexylene glycol
PXE scintillator
each neutrally buoyant nylon containment balloon holds ~250 tonnes of TeLS
4m
8% Te in LAB
reflective surfaces
~25m
~13m
EG, TEG or water
PMTs
deployment weight
~35m
cavity rock
PIKACHU: Gd crystals in Kamioka
Cu shield (5 cm)
Pb shield (15 cm)
10^15
Plot by S. Biller

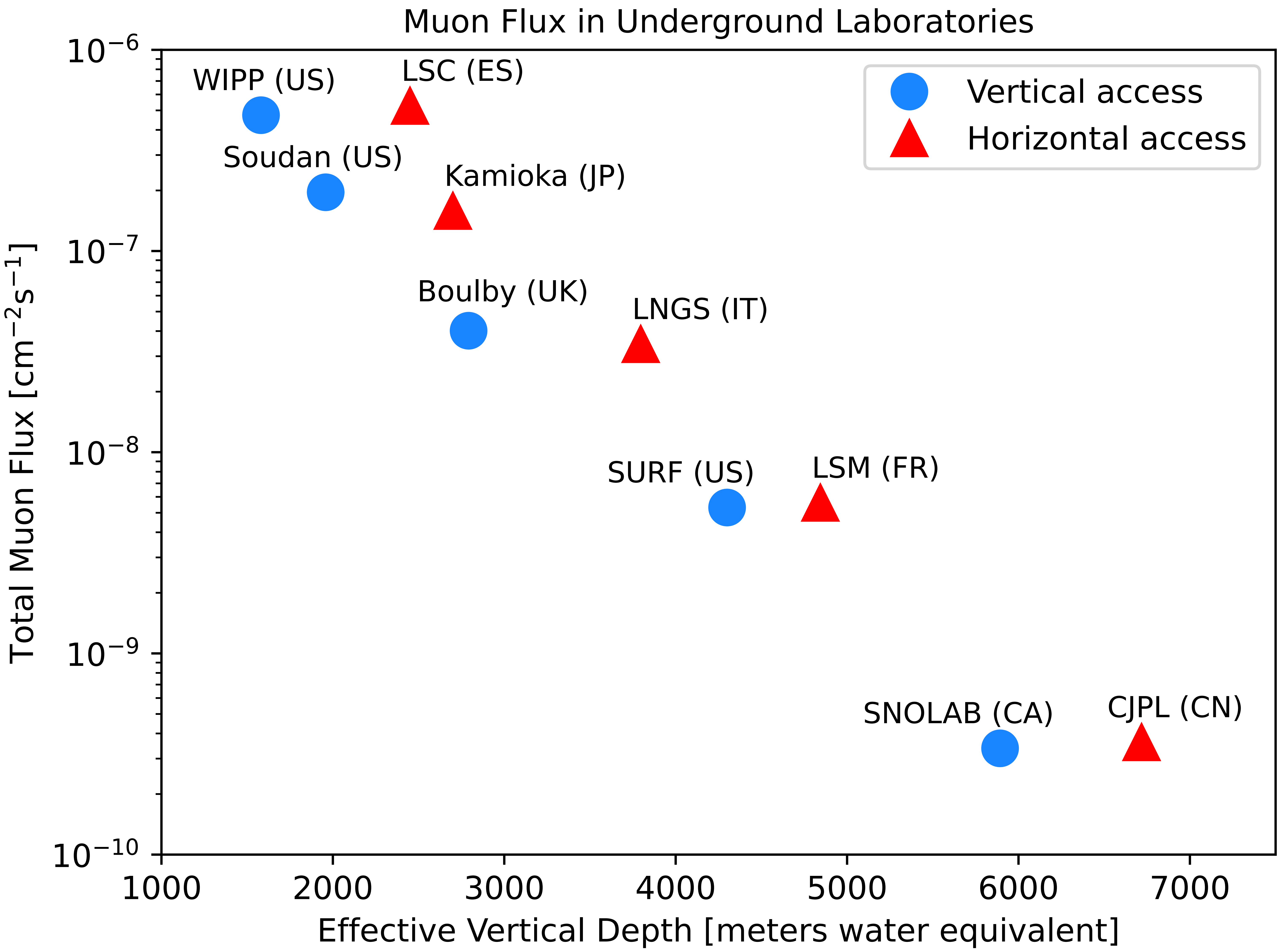
# Summary of Experiments

| Experiment | Isotope | Isotope Mass [kg] | Technology | Current Sensitivity [y] | Projected Sensitivity [y] | Timeline |
|---|---|---|---|---|---|---|
| CUORE | Te-130 | 206 | Bolometer | > 3.8 x $10^{25}$ | | |
| LEGEND-200 | Ge-76 | 146 | Point Contact Detectors | > 1.9 x $10^{26}$ | | |
| KamLAND-Zen | Xe-136 | 745 | Liquid Scintillator | > 2.6 x $10^{26}$ | | |
| supernemo collaboration | Se-82 | 100 | Tracking Calorimeter | | > 4.6 x $10^{24}$ | 3 years of data |
| next | Xe-136 | 100 | Gas TPC | | > 6.0 x $10^{25}$ | 3 years of data |
| SNO+ | Te-130 | 1300 | Liquid Scintillator | | > 2.1 x $10^{26}$ | 5 years of data |
| KamLAND-Zen KamLAND-Zen | Xe-136 | 1000 | Liquid Scintillator | | > $10^{27}$ | 5 years of data |
| CUPID | Mo-100 | 240 | Scintillating Bolometer | | > $10^{27}$ | 10 years of data |
| LEGEND-1000 | Ge-76 | 1000 | Point Contact Detectors | | > $10^{28}$ | 10 years of data |
| nEXO | Xe-136 | 5000 | Liquid TPC | | > 1.35 x $10^{28}$ | 10 years of data |

# Summary

- Neutrinoless double beta decay is a window to beyond the standard model physics
- There are many experiments with many technologies searching for this decay
- Multiple experiments are needed to disentangle nuclear uncertainties
- Technological upgrades are needed to probe the entire phase space
- The future is bright! Thank you!

# Where to Site your Experiment?





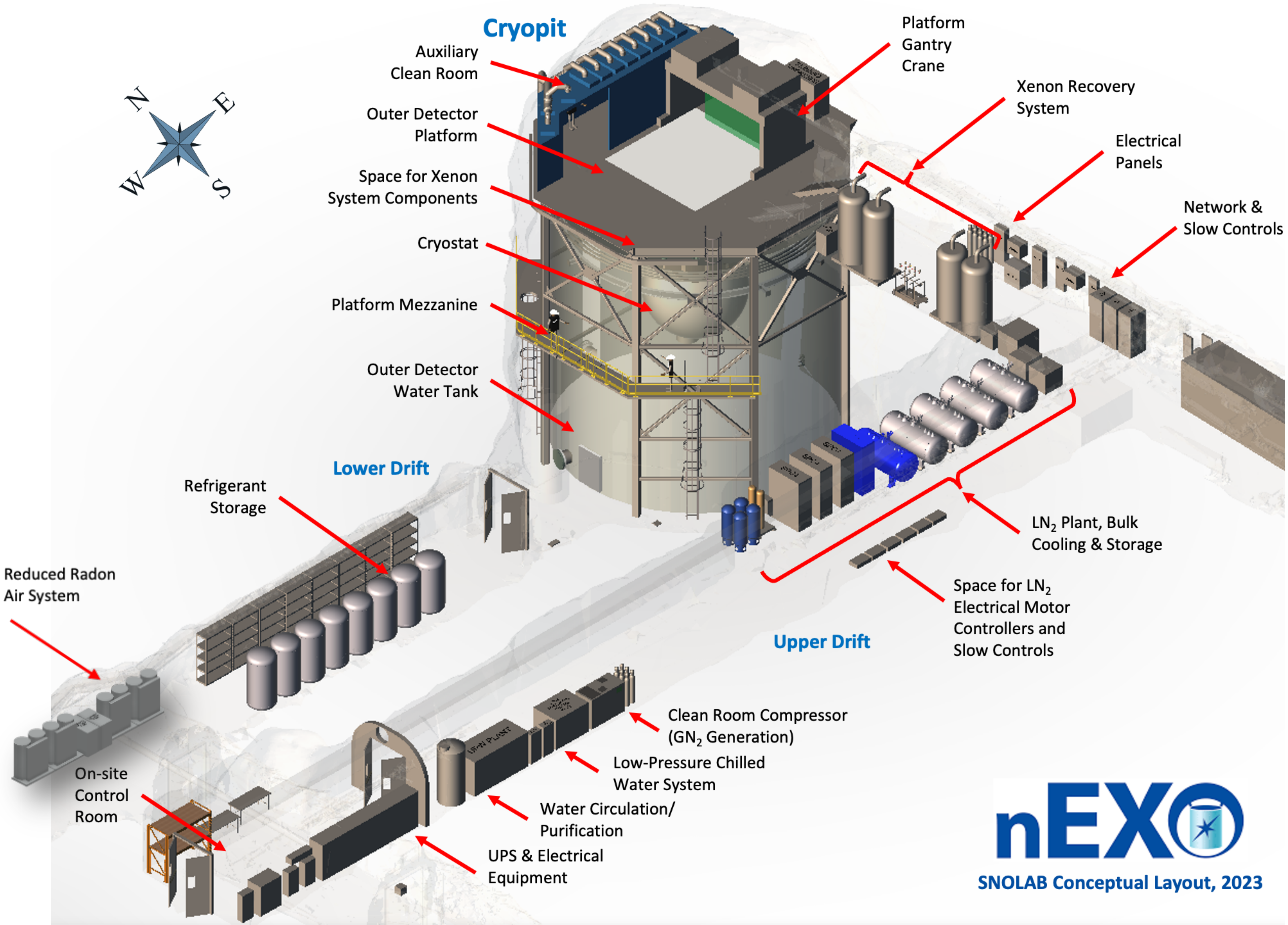

Adapted from Chin. Phys. C 45 (2021) 2, 025001

# 2ND INTERNATIONAL SUMMIT ON THE FUTURE OF NEUTRINOLESS DOUBLE-BETA DECAY

Held in Sudbury, Canada in April, 2023

SNOLAB

- The international stakeholders in neutrinoless double beta decay research who attended this summit (agencies representing Canada, France, Germany, Italy, UK, and USA) agree in principle the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one large tonne-scale experiment implemented in the next decade.
- **These stakeholders agree on the need for a coordinated effort to efficiently and cost-effectively advance the field for the proposed double beta decay experiments, as well as the future of the field. To that purpose, these stakeholders agree that a structure for international collaboration on this research should be explored. (e.g., an international virtual observatory for neutrinoless double beta decay).**




nEXO

SNOLAB Conceptual Layout, 2023