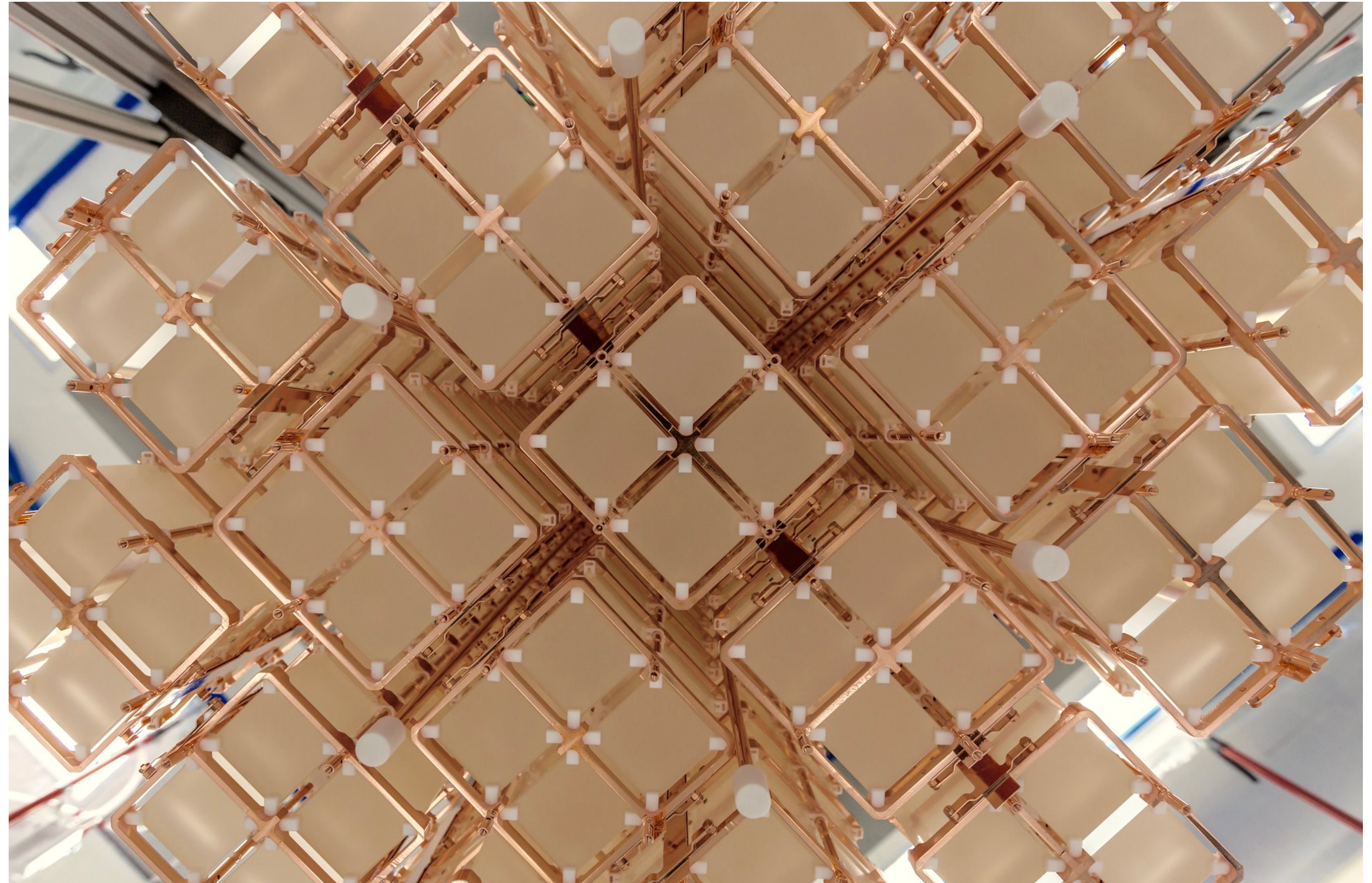


Status and Prospects of Bolometric Detectors

Karsten Heeger
Yale University

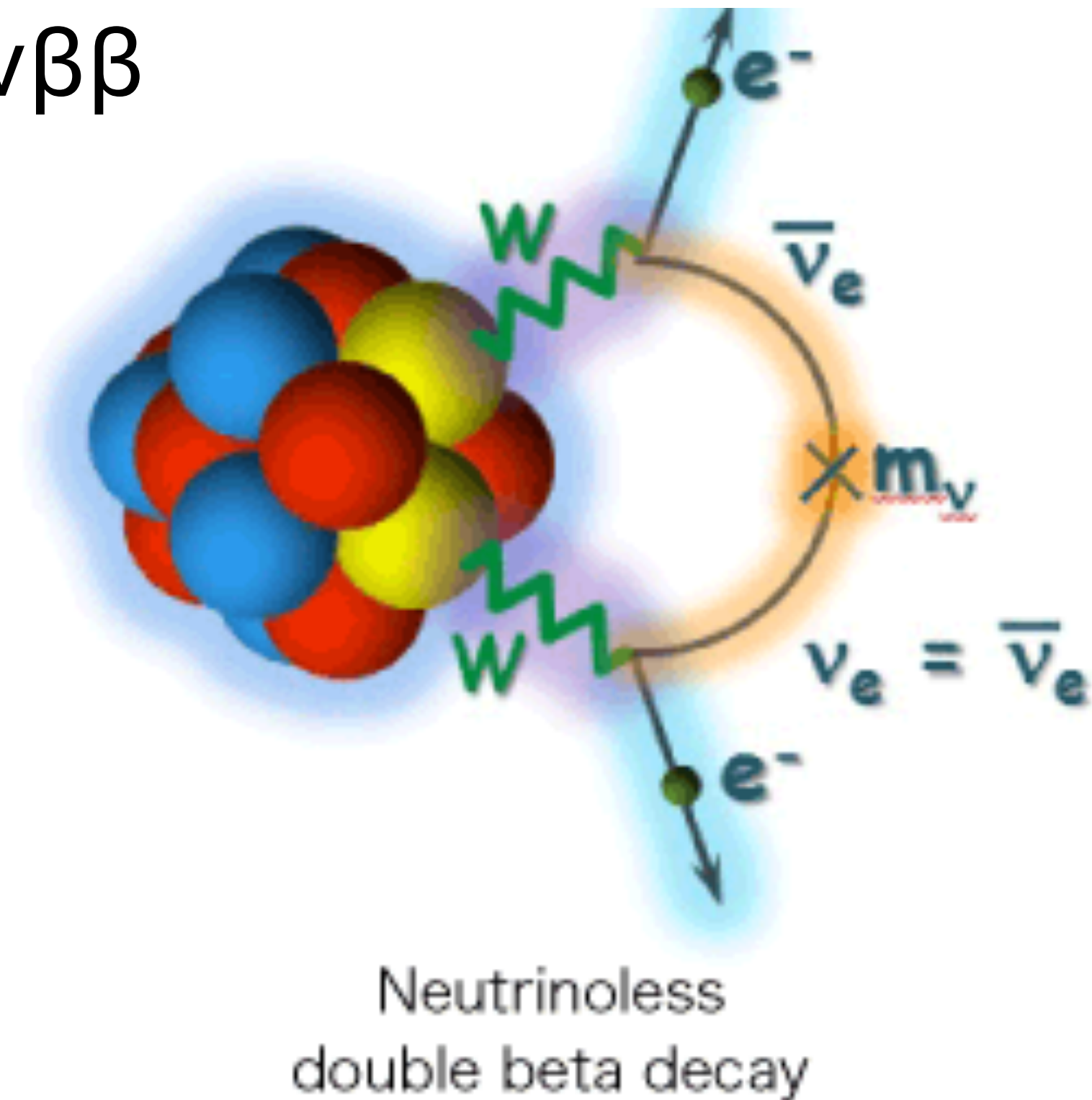
INT
July 21, 2026

Yale



$0\nu\beta\beta$ is one of the most important topics of the next two decades

$0\nu\beta\beta$



Establish lepton number non-conservation

Test $\Delta(B-L)$

Establish Majorana mass

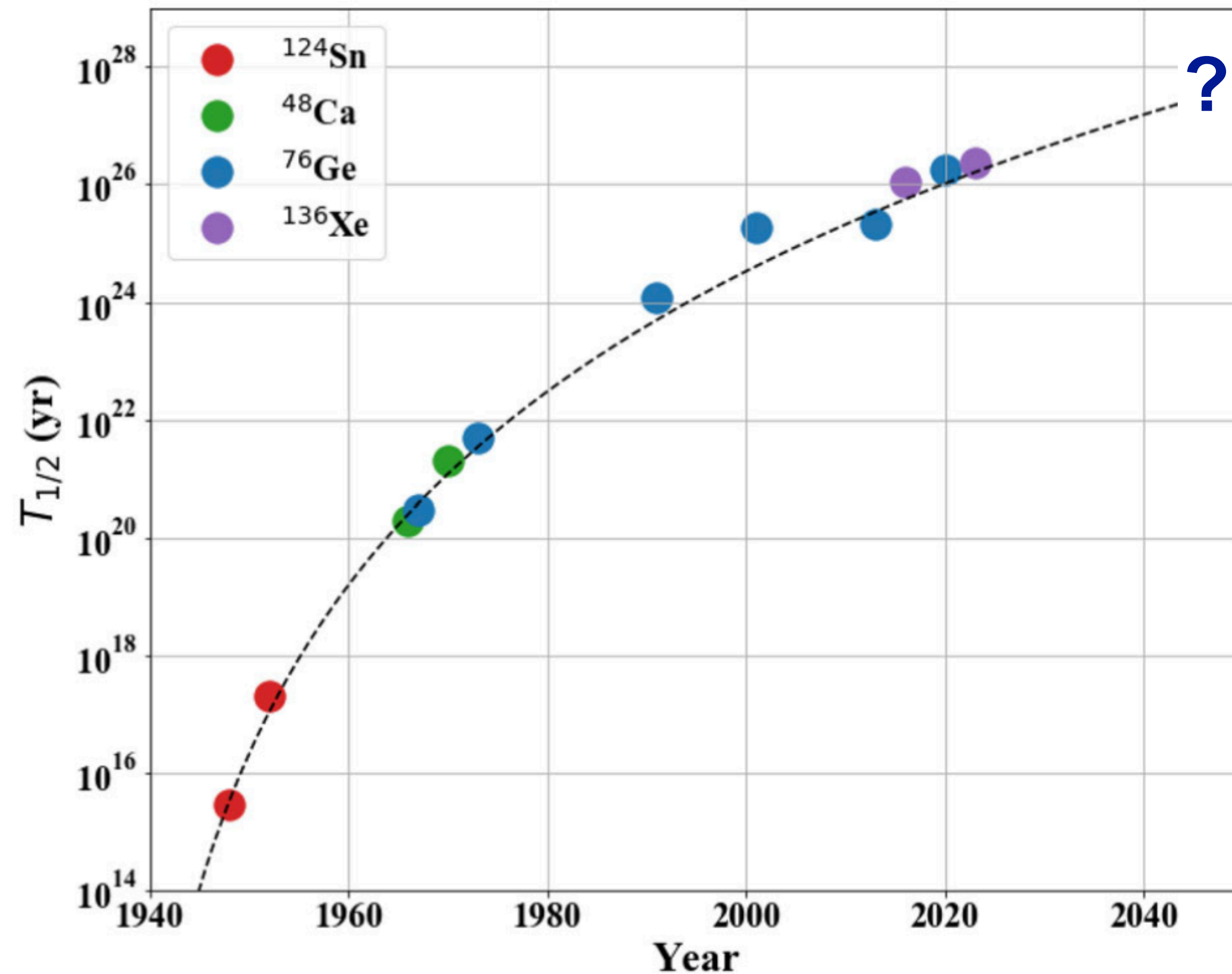
Measures effective neutrino mass

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Nuclei as a laboratory to study lepton number violation at low energies

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

Seventy Five Years of $0\nu\beta\beta$ Searches



Progress takes time

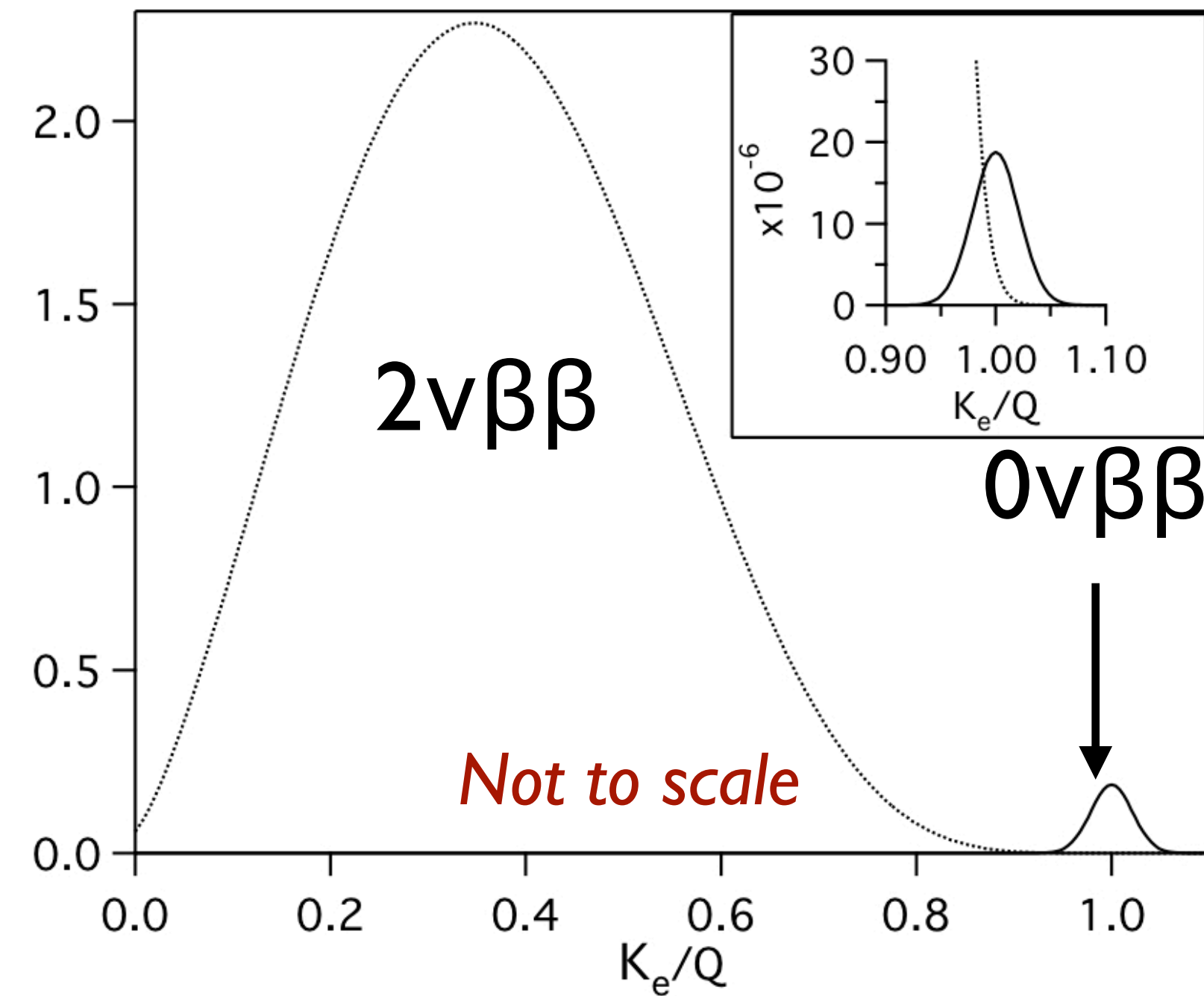
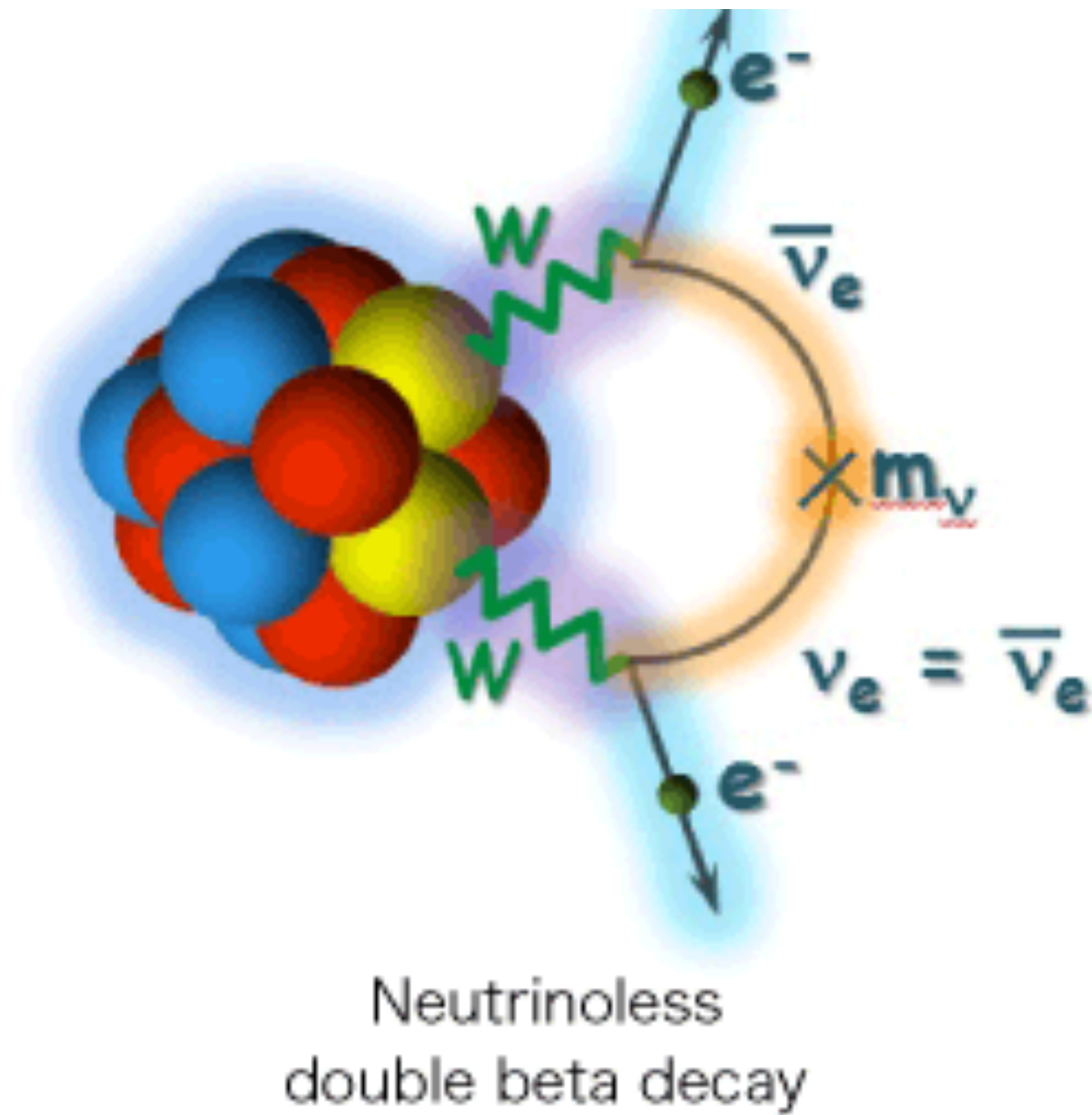
Where will we be in ~2045?

Can we reach $\sim 10^{28}$ yrs?

What can bolometric detectors contribute?

Gomez-Cadenas et al
Riv. Nuovo Cim. 46, 619–692 (2023).

$0\nu\beta\beta$ - Critical Experimental Features



Sensitivity

$$S_{0\nu} \propto \epsilon \sqrt{\frac{M t}{B \Delta E}}$$

Efficiency

Mass

Runtime

Isotopic abundance

Background

Energy resolution

Peak search at the Q value of the $0\nu\beta\beta$ decay

Additional signal topology

Experimental Features

Detector energy resolution

Intrinsic and external backgrounds

Background discrimination

Scalability

depth is a critical issue

A Rich Experimental Field

Isotope	Technique	$T_{1/2}^{0\nu}$	$m_{\beta\beta}$ (eV)	Year Published
^{48}Ca	CaF_2 scint. crystals	$> 5.8 \times 10^{22}$ y	$< 3.5\text{-}22$	2008 [65]
^{76}Ge	^{76}Ge detectors	$> 1.8 \times 10^{26}$ y	$< 0.079\text{-}0.180$	2020 [12]
^{82}Se	Zn^{82}Se bolometers	$> 4.6 \times 10^{24}$ y	$< 0.263\text{-}0.545$	2022 [19]
^{96}Zr	Thin metal foil within TPC	$> 9.2 \times 10^{21}$ y	$< 3.9 - 19.5$	2009 [66]
^{100}Mo	$\text{Li}_2^{100}\text{MoO}_4$ bolometers	$> 1.8 \times 10^{24}$ y	$< 0.28\text{-}0.49$	2022 [18]
^{116}Cd	$^{116}\text{CdWO}_4$ scint. crystals	$> 2.2 \times 10^{23}$ y	$< 1.0\text{-}1.7$	2018 [67]
^{128}Te	TeO_2 bolometers	$> 3.6 \times 10^{24}$ y	$< 1.5\text{-}4.0$	2022 [68]
^{130}Te	TeO_2 bolometers	$> 2.2 \times 10^{25}$ y	$< 0.090\text{-}0.305$	2022 [69]
^{136}Xe	Liquid Xe scintillators	$> 2.3 \times 10^{26}$ y	$< 0.036\text{-}0.156$	2022 [13]
^{150}Nd	Thin metal foil within TPC	$> 2 \times 10^{22}$ y	$1.6\text{-}5.3$	2016 [70]

TABLE I. A list of the best $0\nu\beta\beta$ decay $T_{1/2}^{0\nu}$ limits at 90% confidence level for several isotopes. The $m_{\beta\beta}$ limits are those quoted by the authors using the matrix elements of their choice.

Current experiments will reach 10^{27}yrs
Next generation aim for 10^{28}yrs

White paper on $0\nu\beta\beta$,
<https://arxiv.org/abs/2212.11099>

A Rich Experimental Field

Ongoing and proposed experiments

To reach physics goal, we need a few
large, highly-optimized experiments
balancing

- isotope availability
- cost
- scalability

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	⁴⁸ Ca	305 kg	^{nat} CaF ₂ scint. crystals	Operating	Kamioka
CDEX-1 [125]	⁷⁶ Ge	1 kg	^{enr} Ge semicond. det.	Prototype	CJPL
CDEX-300 ν [125]	⁷⁶ Ge	225 kg	^{enr} Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	⁷⁶ Ge	200 kg	^{enr} Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	⁷⁶ Ge	1 ton	^{enr} Ge semicond. det.	Proposal	
CUPID-0 [19]	⁸² Se	10 kg	Zn ^{enr} Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	⁸² Se	7 kg	^{enr} Se foils/tracking	Operation	Modane
SuperNEMO [126]	⁸² Se	100 kg	^{enr} Se foils/tracking	Proposal	Modane
Selena [127]	⁸² Se		^{enr} Se, CMOS	Development	
IFC [128]	⁸² Se		ion drift SeF ₆ TPC	Development	
CUPID-Mo [17]	¹⁰⁰ Mo	4 kg	Li ^{enr} MoO ₄ ,scint. bolom.	Prototype	LNGS
AMoRE-I [129]	¹⁰⁰ Mo	6 kg	⁴⁰ Ca ¹⁰⁰ MoO ₄ bolometers	Operation	YangYang
AMoRE-II [129]	¹⁰⁰ Mo	200 kg	⁴⁰ Ca ¹⁰⁰ MoO ₄ bolometers	Construction	Yemilab
CROSS [130]	¹⁰⁰ Mo	5 kg	Li ₂ ¹⁰⁰ MoO ₄ , surf. coat bolom.	Prototype	Canfranc
BINGO [131]	¹⁰⁰ Mo		Li ^{enr} MoO ₄	Development	LNGS
CUPID [28]	¹⁰⁰ Mo	450 kg	Li ^{enr} MoO ₄ ,scint. bolom.	Proposal	LNGS
China-Europe [132]	¹¹⁶ Cd		^{enr} CdWO ₄ scint. crystals	Development	CJPL
COBRA-XDEM [133]	¹¹⁶ Cd	0.32 kg	^{nat} Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	¹¹⁶ Cd		^{nat} CdTe. det.	Development	
TIN.TIN [135]	¹²⁴ Sn		Tin bolometers	Development	INO
CUORE [10]	¹³⁰ Te	1 ton	TeO ₂ bolometers	Operating	LNGS
SNO+ [136]	¹³⁰ Te	3.9 t	0.5-3% ^{nat} Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	¹³⁶ Xe	5 t	Liq. ^{enr} Xe TPC/scint.	Proposal	
NEXT-100 [137]	¹³⁶ Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	¹³⁶ Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	¹³⁶ Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	¹³⁶ Xe	745 kg	^{enr} Xe dissolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	¹³⁶ Xe		^{enr} Xe dissolved in liq. scint.	Development	Kamioka
LZ [139]	¹³⁶ Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	¹³⁶ Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	¹³⁶ Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	¹³⁶ Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	¹³⁶ Xe		Spherical Xe TPC	Development	
LAr TPC [143]	¹³⁶ Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

A Rich Experimental Field

Ongoing and proposed experiments

Bolometric Experiments

CUORE

CUPID

AMORE

CROSS

Bingo

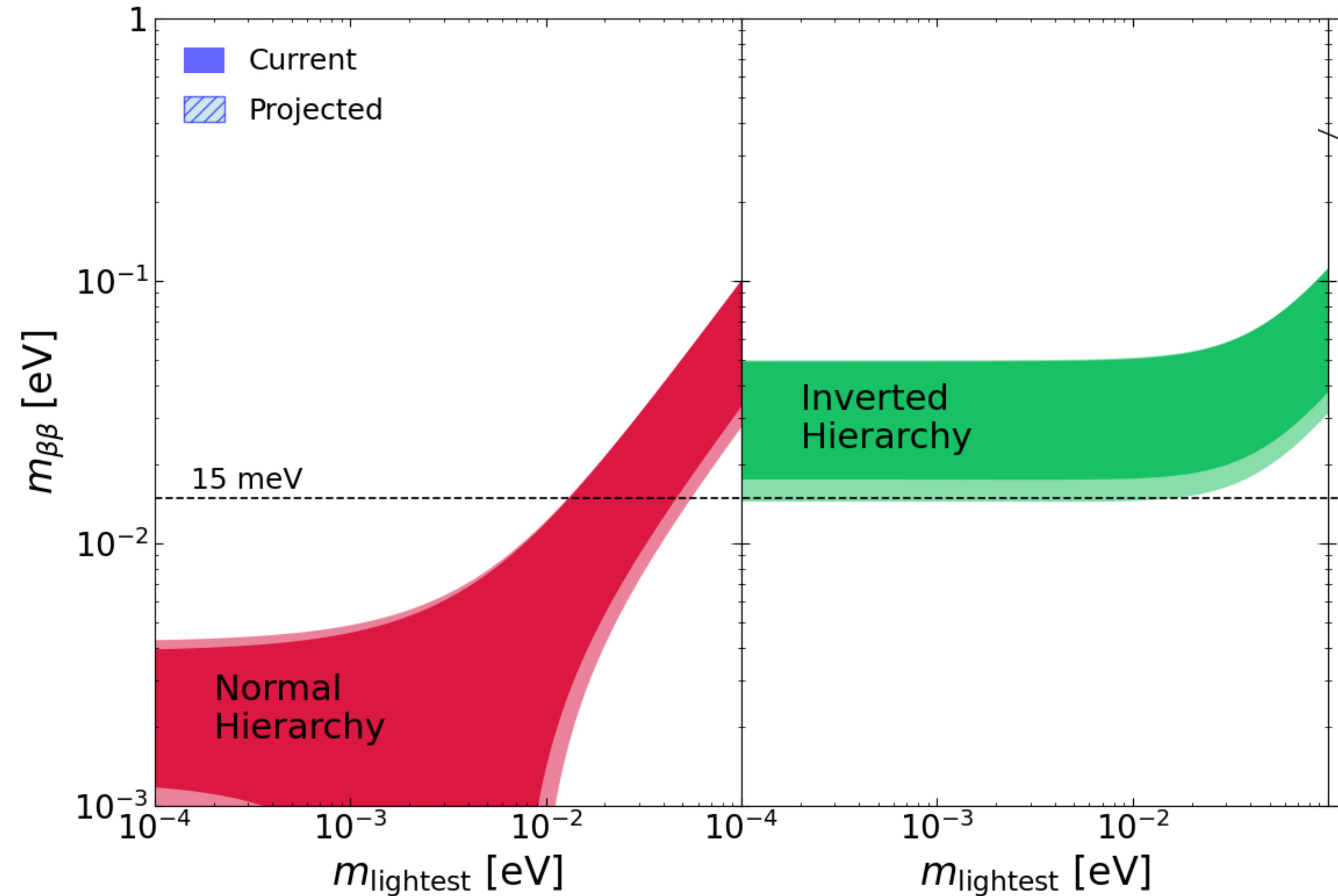
¹⁰⁰Mo is the isotope of choice for large bolometric experiments

Current experiments will reach 10²⁷ yrs

Next generation aims for 10²⁸ yrs

Experiment	Isotope	Mass	Technique	Present Status	Location
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IFC [128]	⁸² Se		ion drift SeF ₆ TPC	Development	
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JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

Current Goal



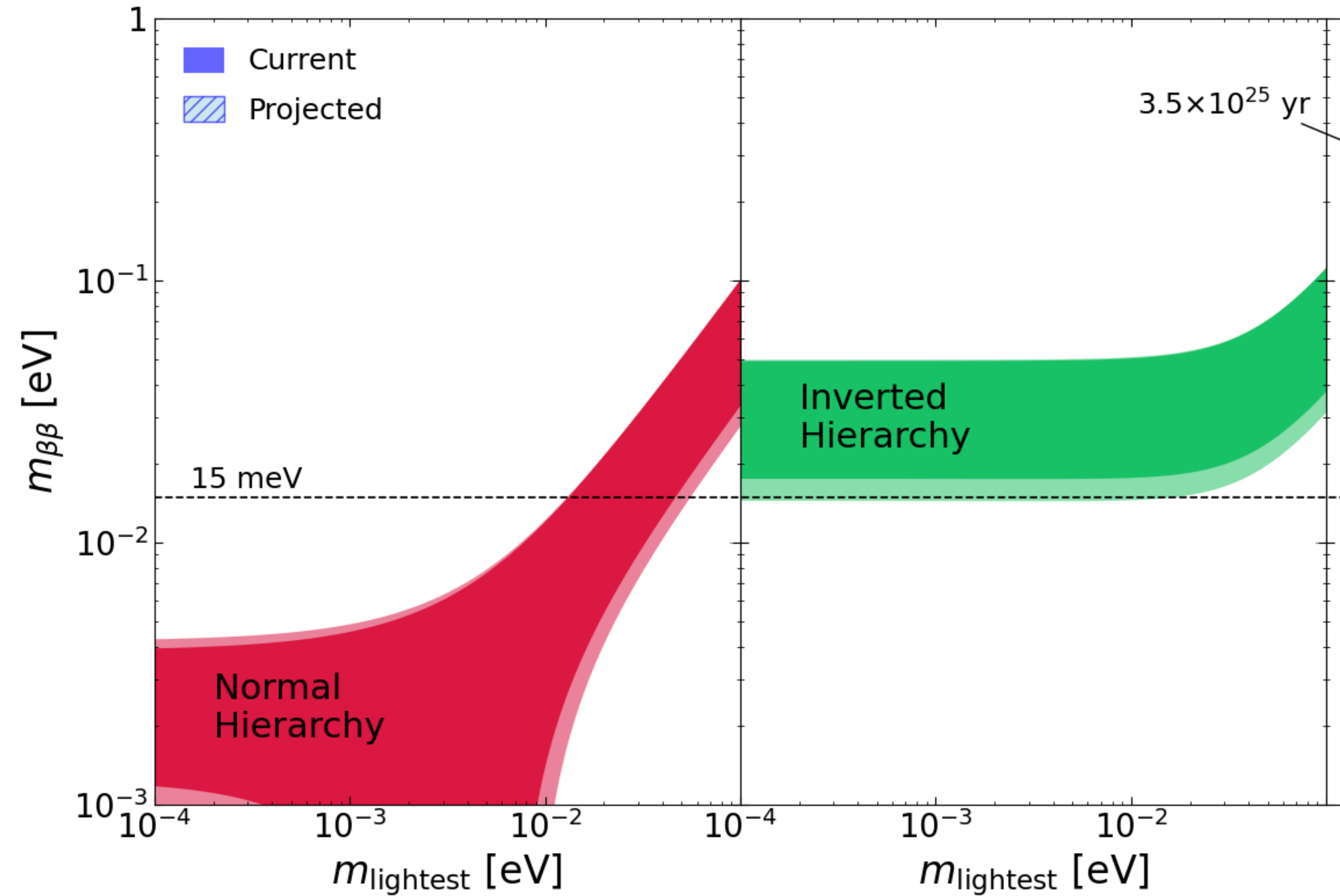
Current experiments may reach 10^{27} yrs range.

Next-generation experiments aim for a sensitivity of **$\sim 15 \text{ meV}$** , requires sensitivity of $O(10^{28})$ yrs.

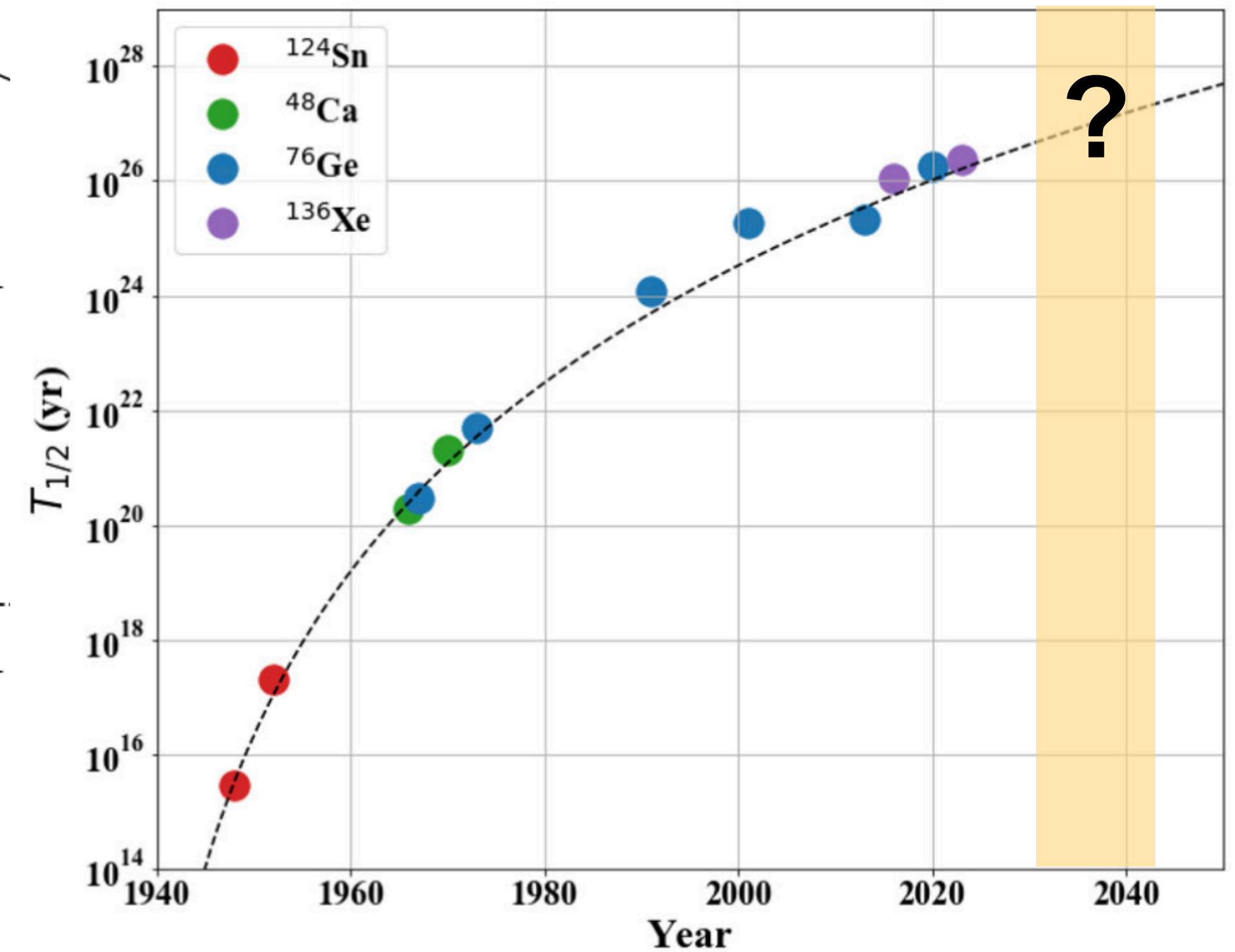
Probe the inverted hierarchy parameter space and part of the normal hierarchy parameter space.

Figure courtesy of TRIUMF theory group

Current Goal

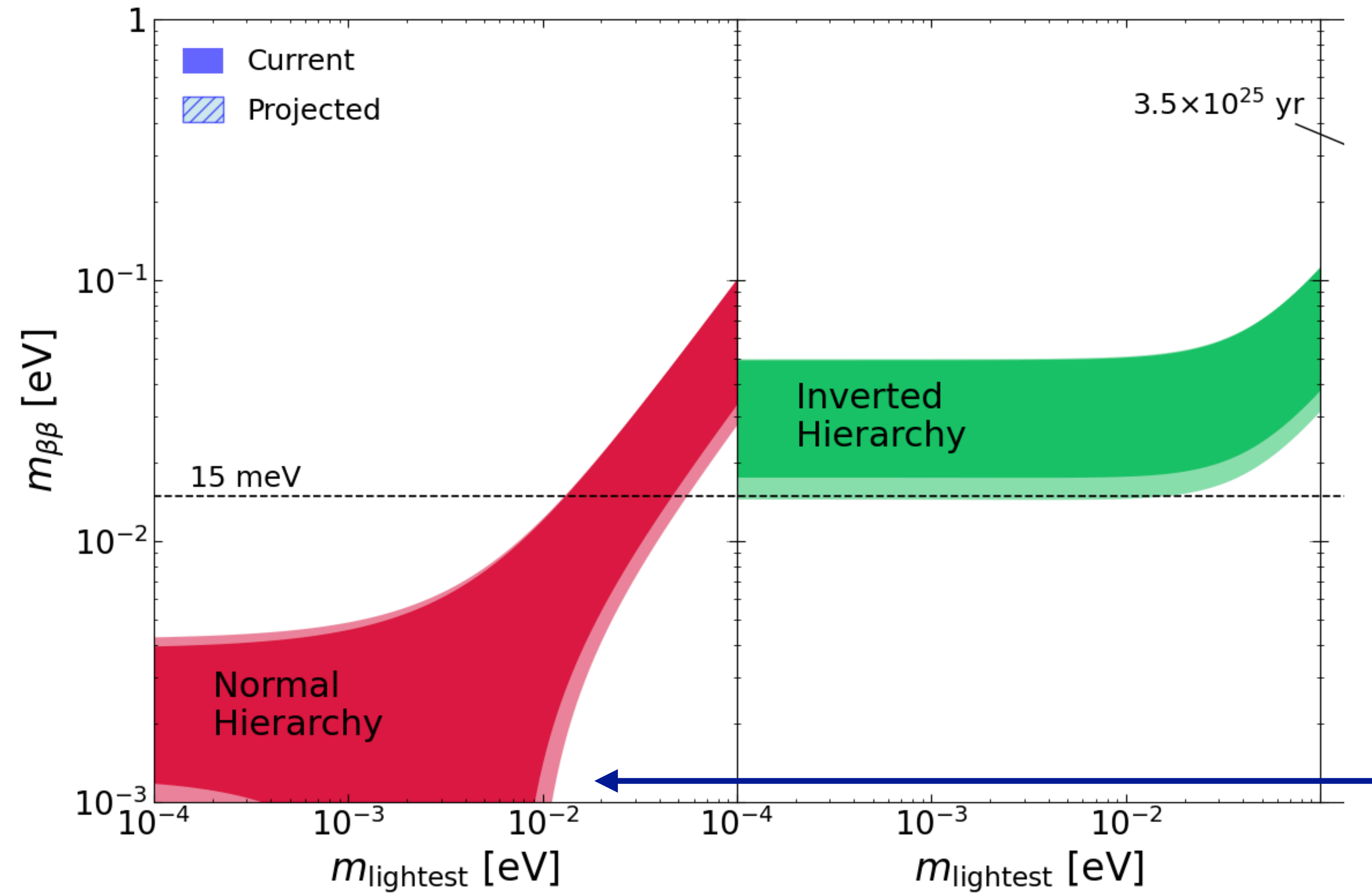


Next-generation experiments
will start running in 2030s



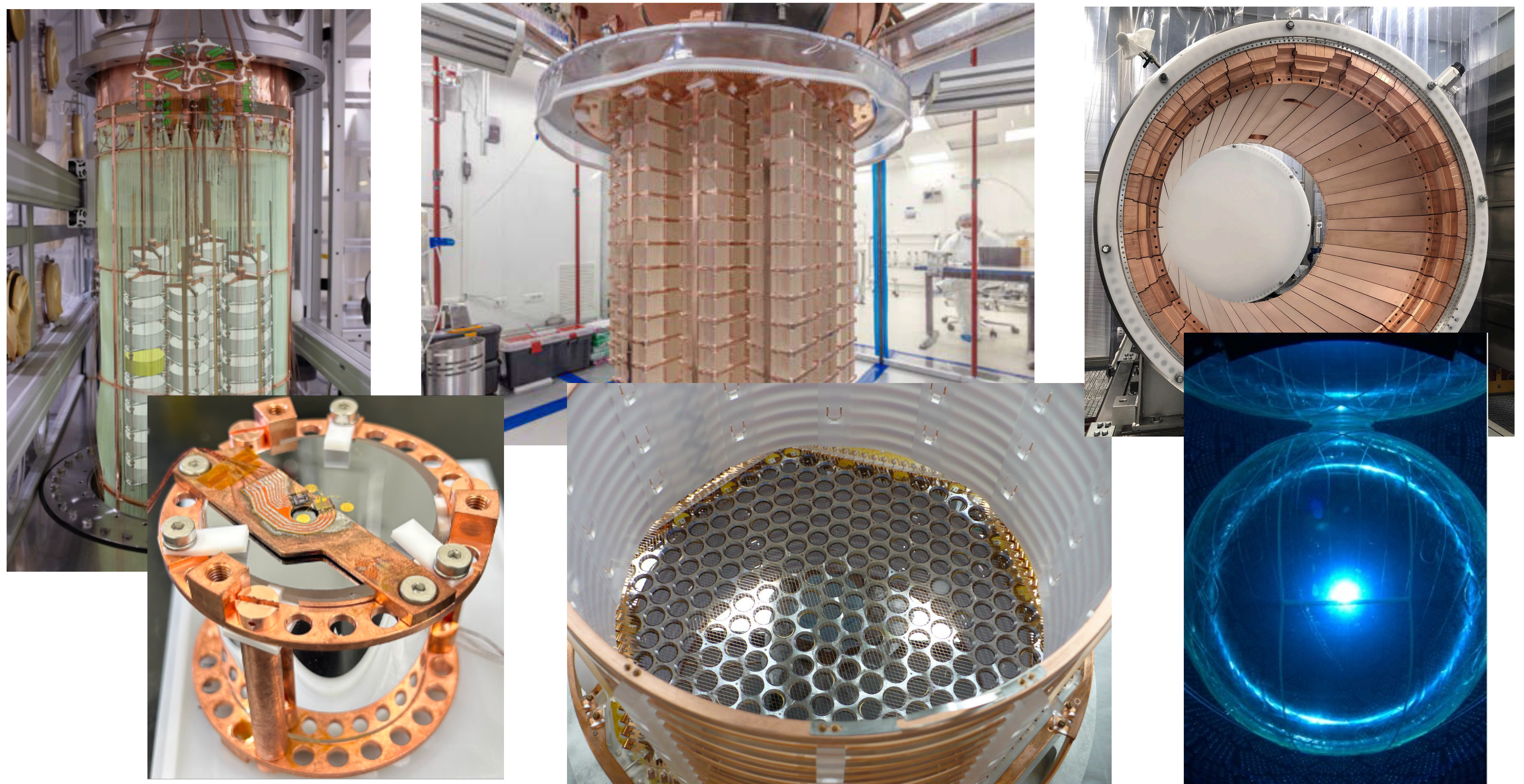
Can we cover inverted ordering
by 2040?

Future Goal

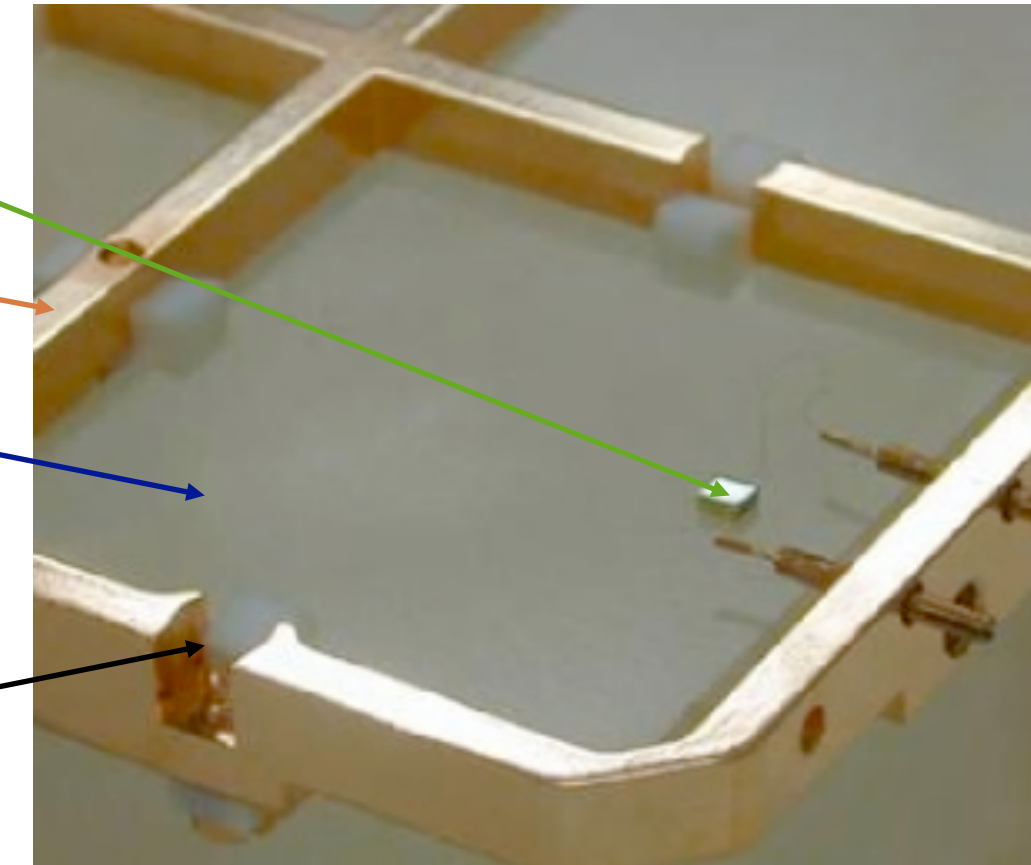
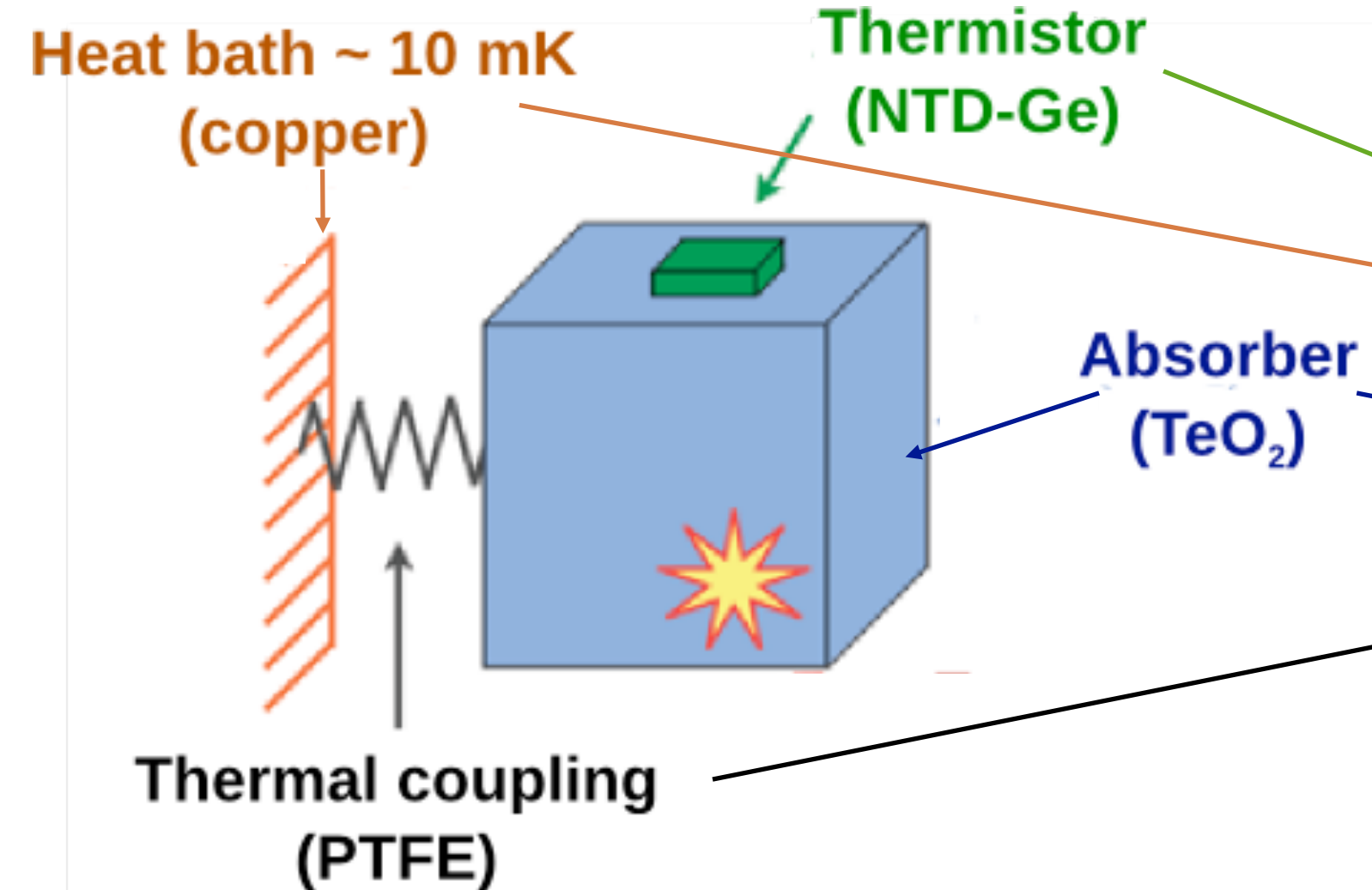
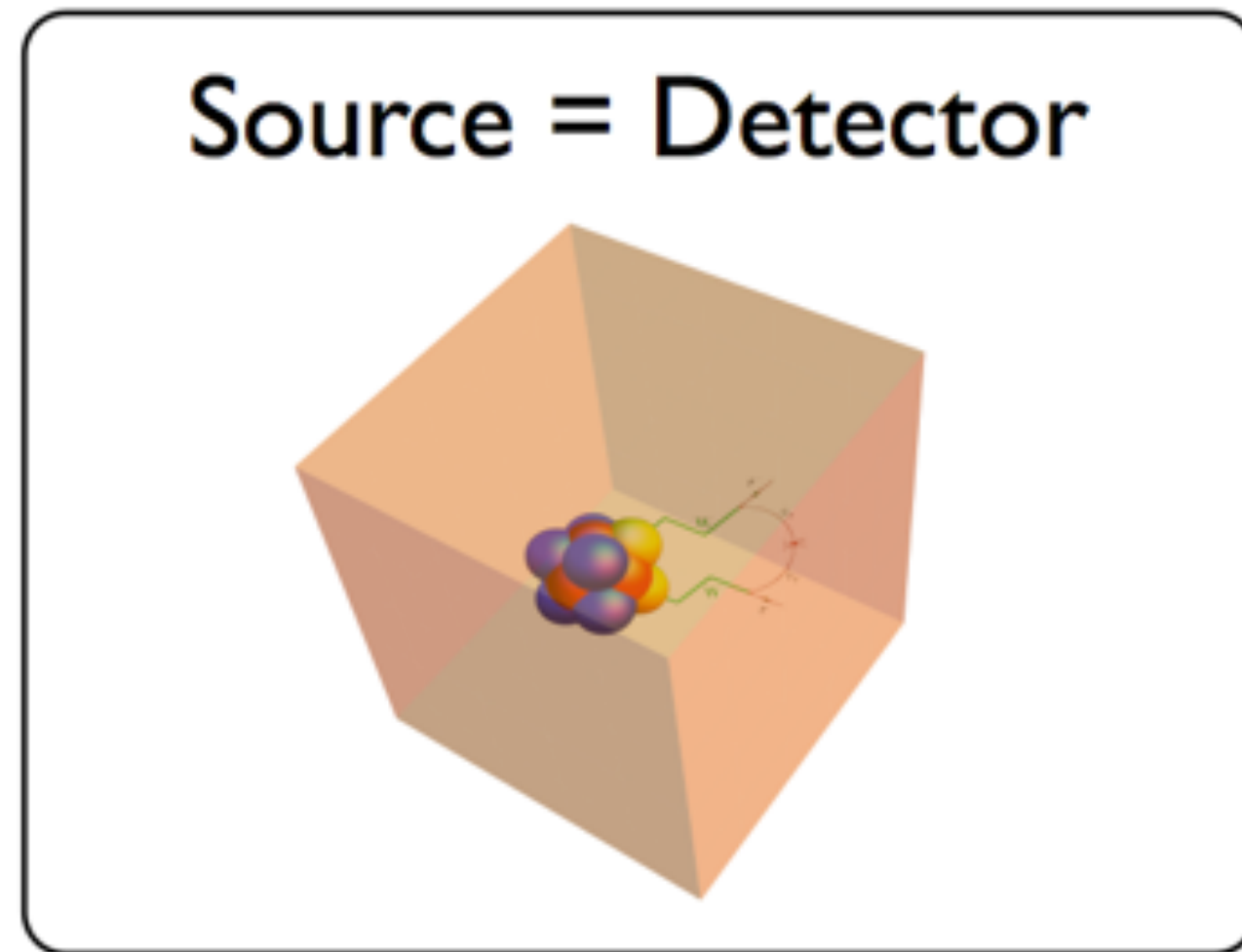


Can we reach Normal Ordering?

$0\nu\beta\beta$ Searches - Different Isotopes and Technologies

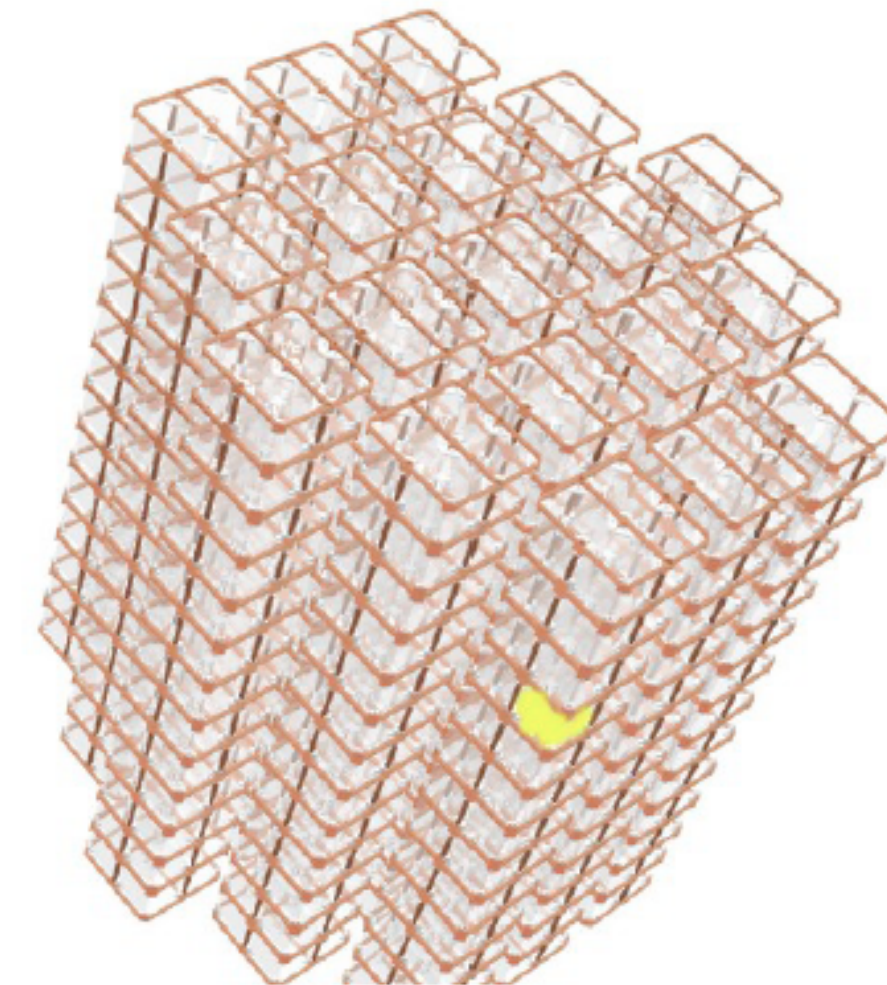
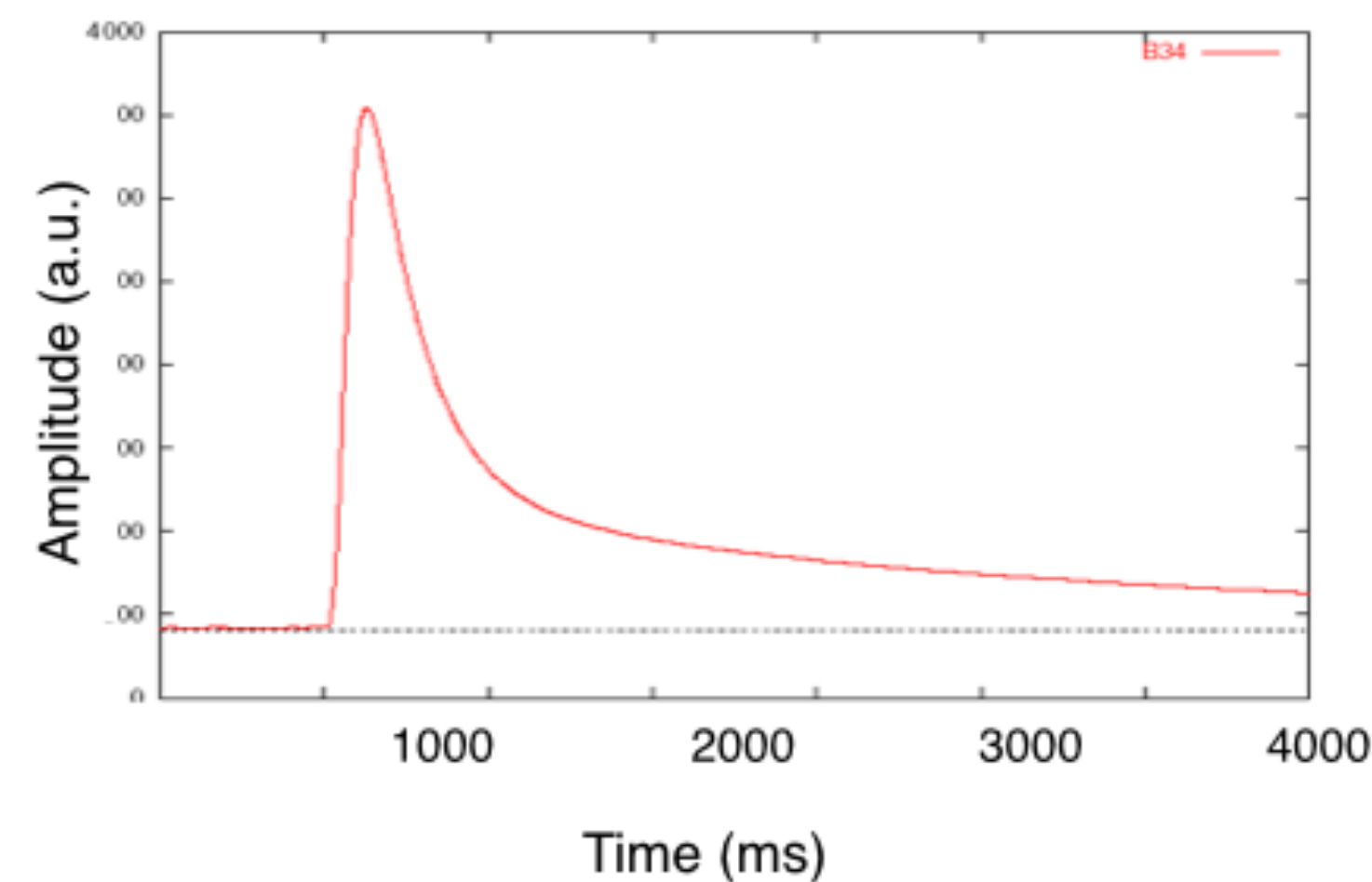


Bolometric Search for $0\nu\beta\beta$



$$Q = (2527.518 \pm 0.013) \text{ keV}$$

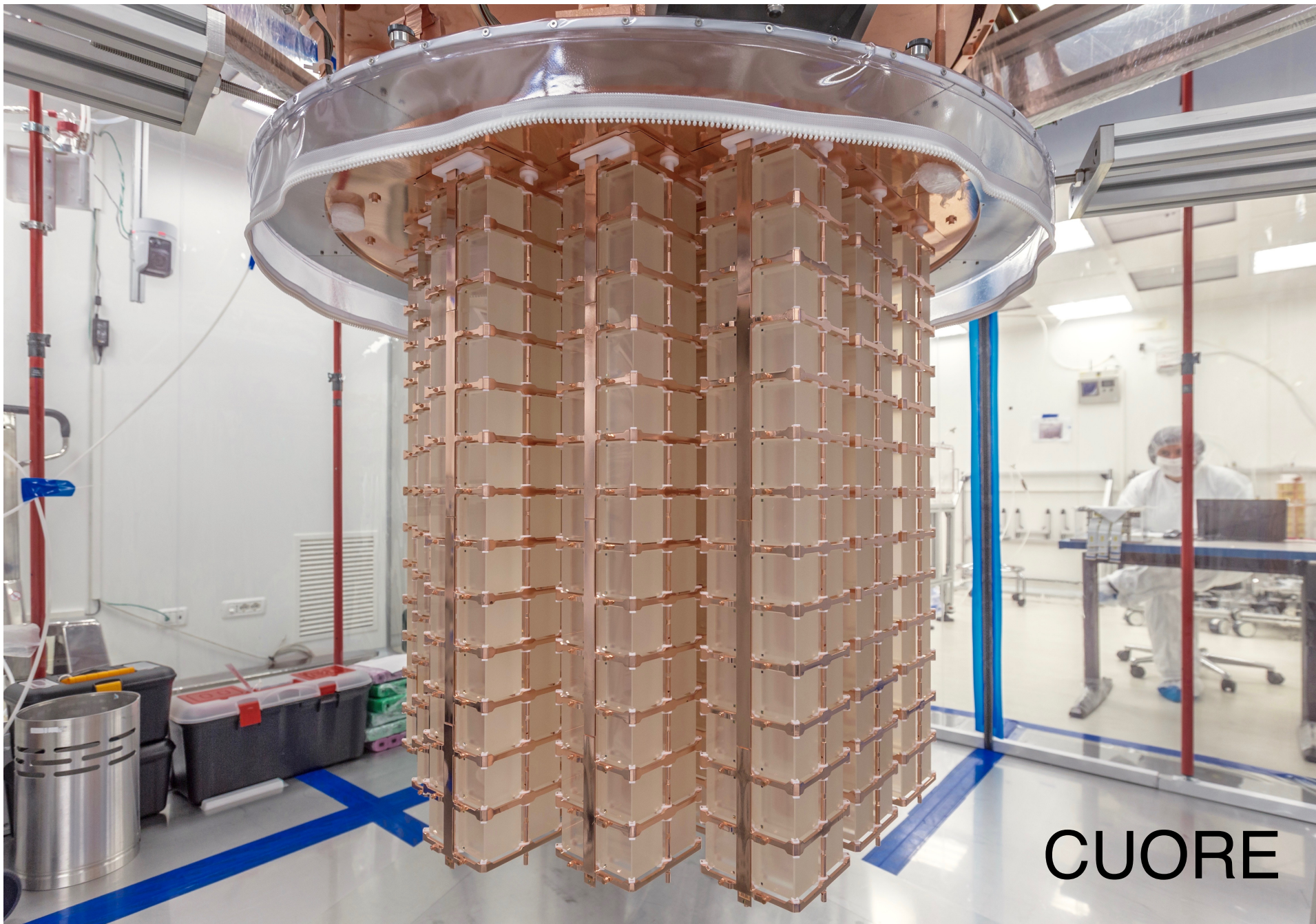
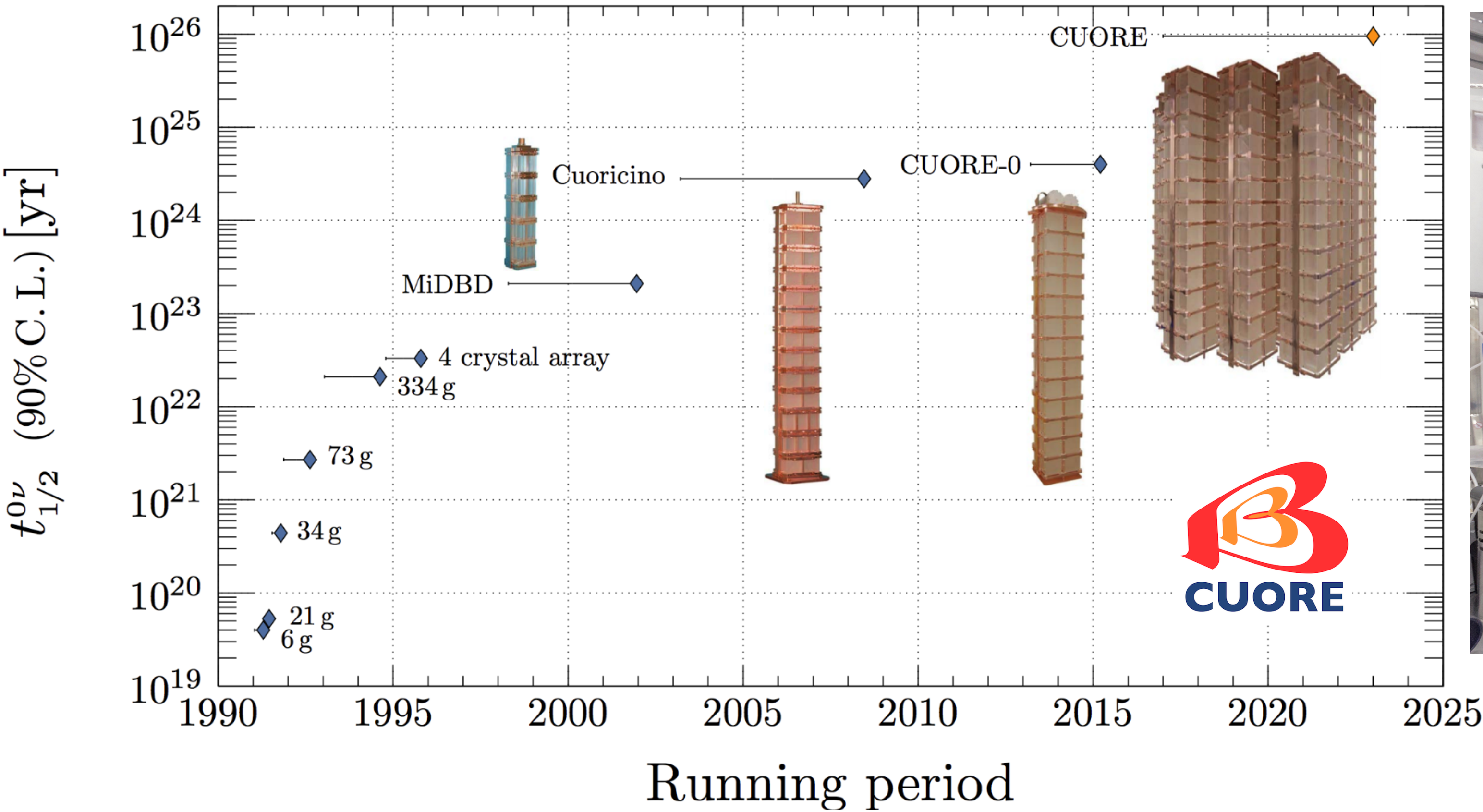
Single pulse example



single hit, monochromatic event

The Challenge of Scaling Up Experiments

30 years of experience in searching for $0\nu\beta\beta$ with cryogenic bolometers
CUORE and CUPID follow a long series of experiments, from few grams to 742 kg of detector material



Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

It takes time.... a decade for each generation of experiment

CUORE - Cryogenic Underground Observatory for Rare Events

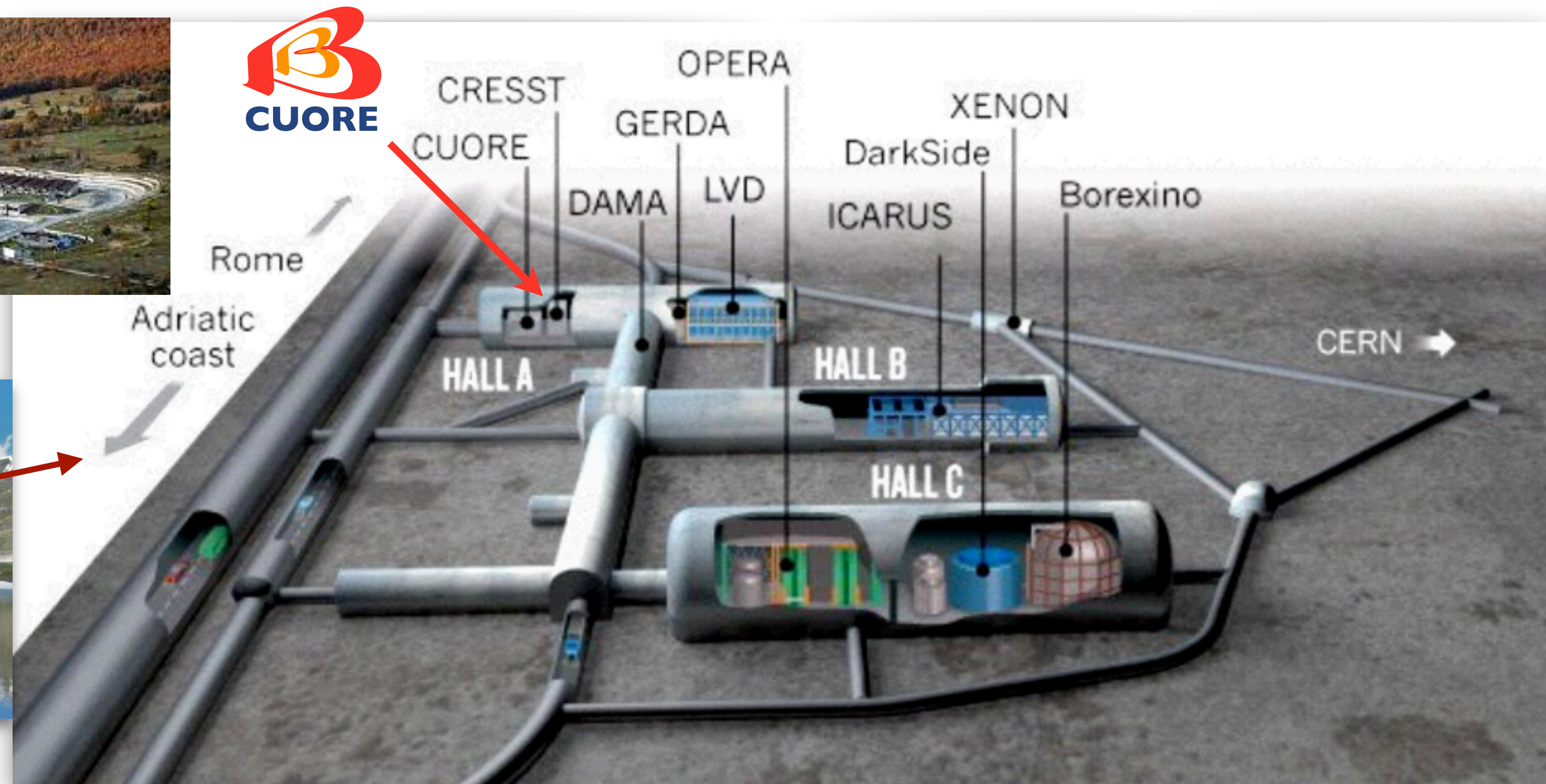


LNGS: Laboratori Nazionali del Gran Sasso

Natural shielding from cosmic rays by the mountain of Gran Sasso

3600 meter water equivalent overburden

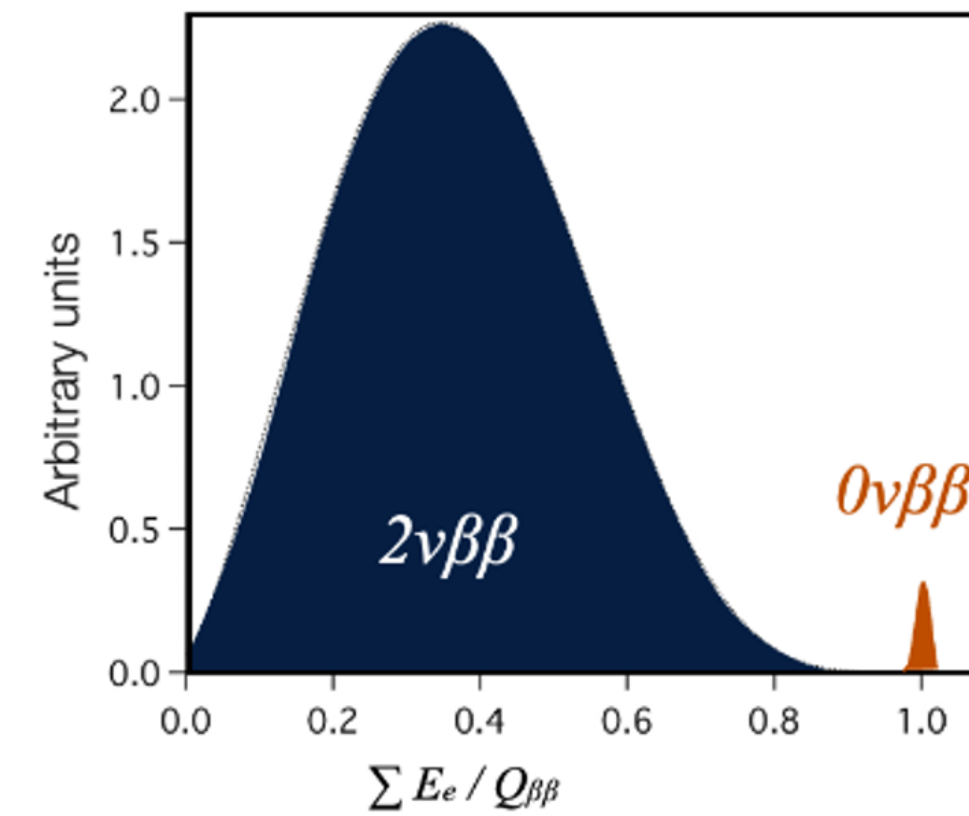
Well-established support for experiments and user access



CUORE 2-tonne Year Spectrum

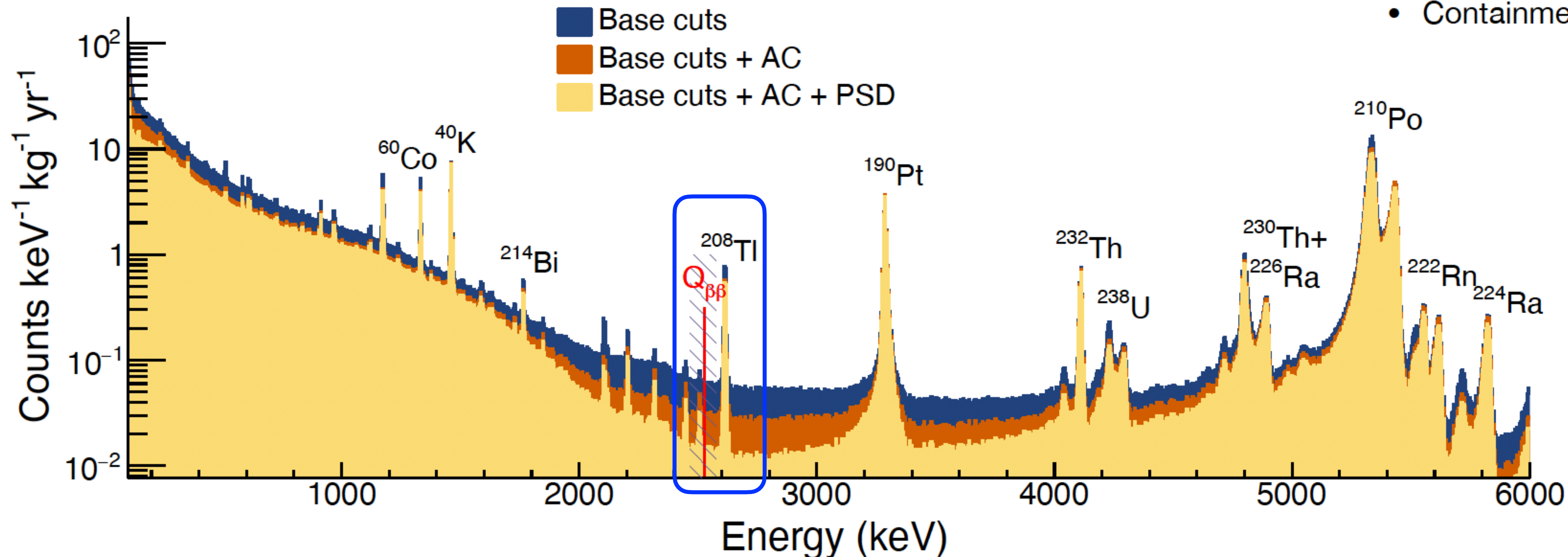
Latest results on the ^{130}Te $0\nu\beta\beta$ search

- 28 datasets analyzed from May 2017 to April 2023
- Total analysed exposure: 2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)



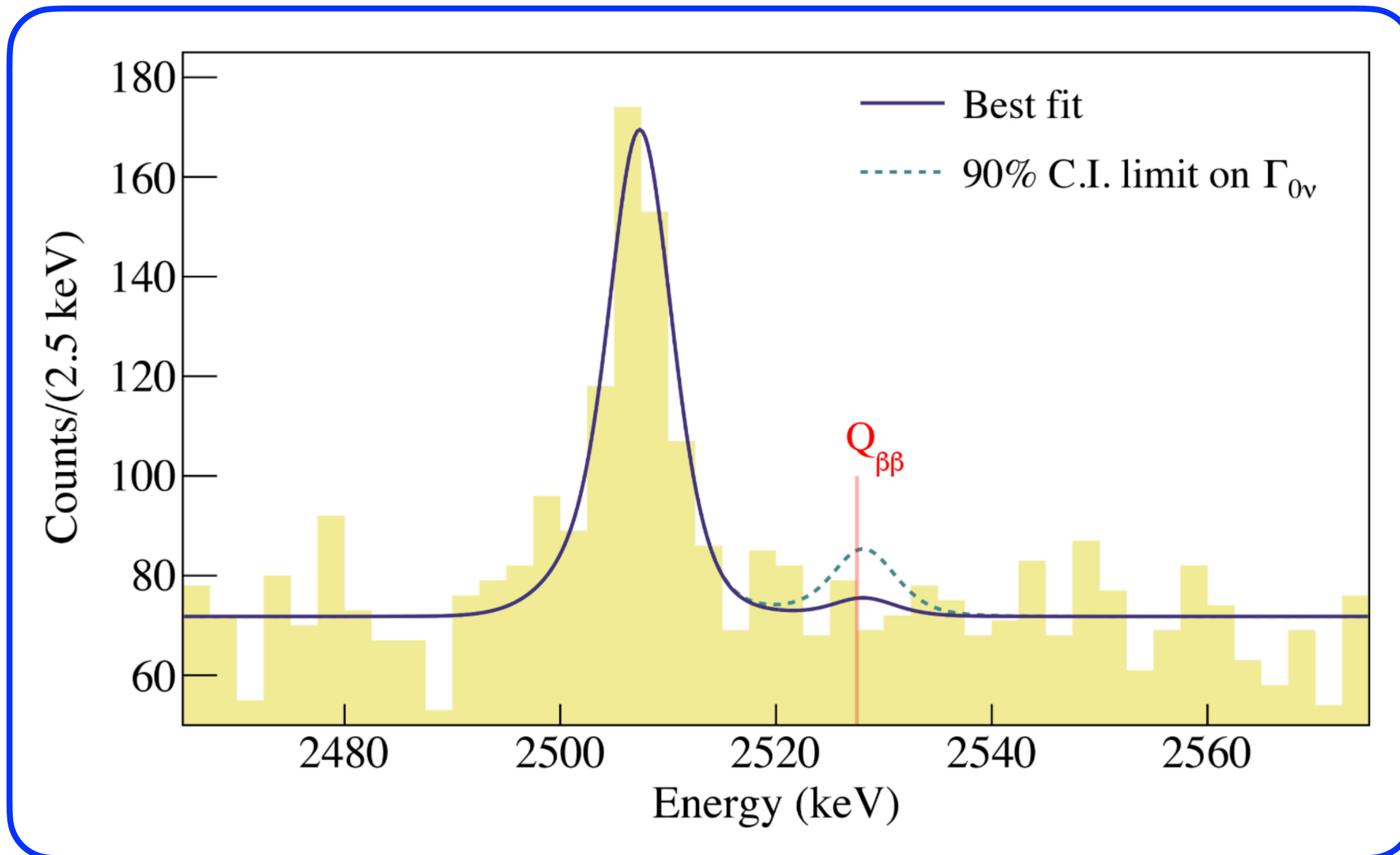
Efficiencies

- Total analysis efficiency 93.4 %
 - Reconstruction: 95.6 %
 - Anti-coincidence (M1): 99.8 %
 - PSD: 97.9 %
- Containment efficiency: 88.4 %



CUORE 2-tonne Year Spectrum

Constraints on lepton number violation with the 2 tonne · year CUORE Dataset



Bayesian and Frequentist Analysis

- Unbinned fit in ROI: [2465, 2575] keV
- Flat-background dataset-dependent
- $0\nu\beta\beta$ posited peak
- time-dependent ^{60}Co -sum peak
- Energy resolution channel and dataset dependent

Average background index: $1.42(2) \times 10^{-2}$ count/ keV kg yr

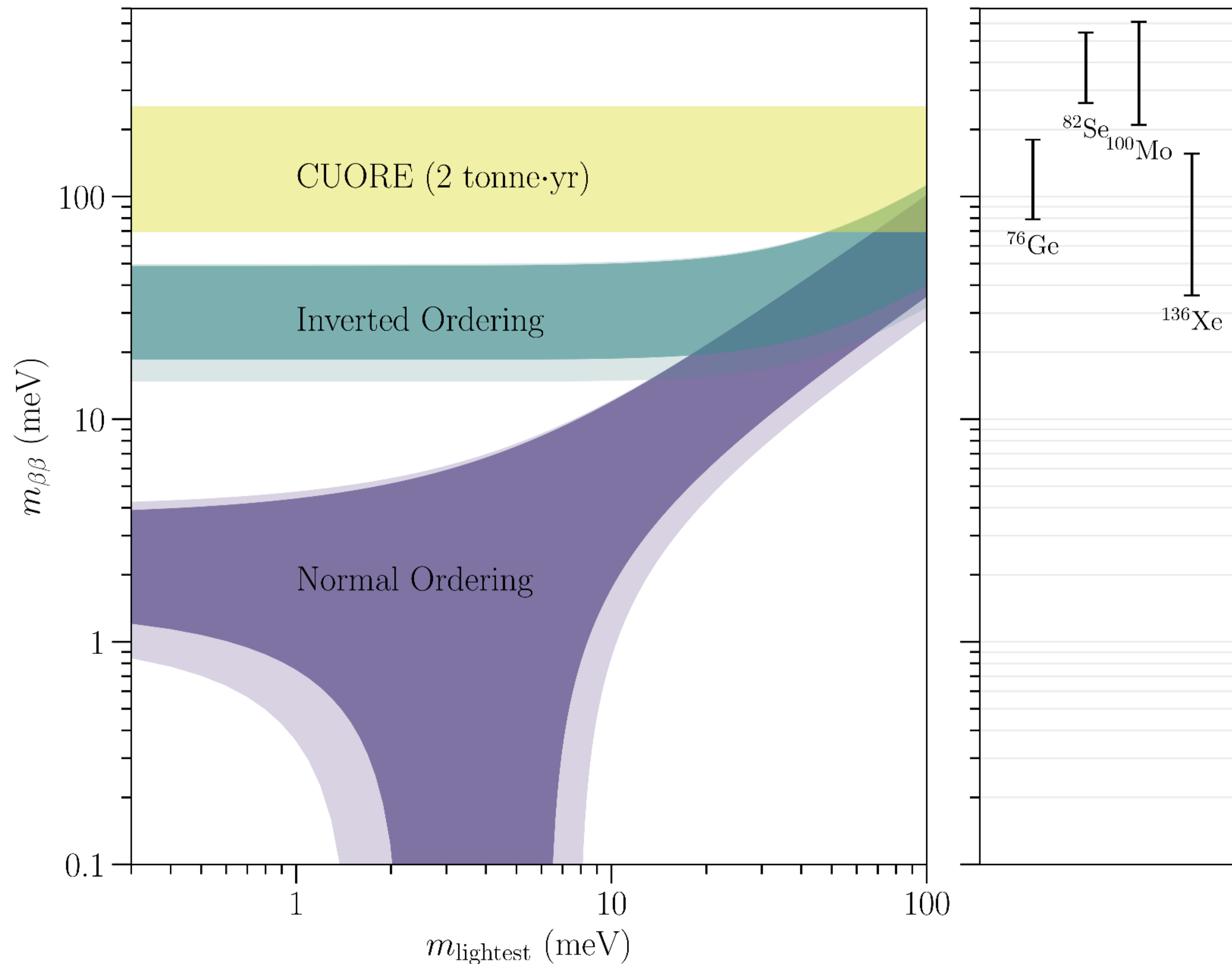
Half-life limit $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ yr (90% C.I.)

Frequentist: $T_{1/2}^{0\nu} > 3.4 \times 10^{25}$ yr

Science

DOI: [10.1126/science.adp6474](https://doi.org/10.1126/science.adp6474)
16 October 2025

CUORE 2-tonne Year Results



Median exclusion sensitivity

$$4.4 \times 10^{25} \text{ yr (90\% C.I.)}$$

Compared to this value, the probability of obtaining a stronger limit is 74%.

Limit on the effective Majorana mass (assuming light Majorana neutrino exchange)

$$m_{\beta\beta} < 70 - 250 \text{ meV}$$

Science

DOI: [10.1126/science.adp6474](https://doi.org/10.1126/science.adp6474)

16 October 2025

Other Physics with CUORE

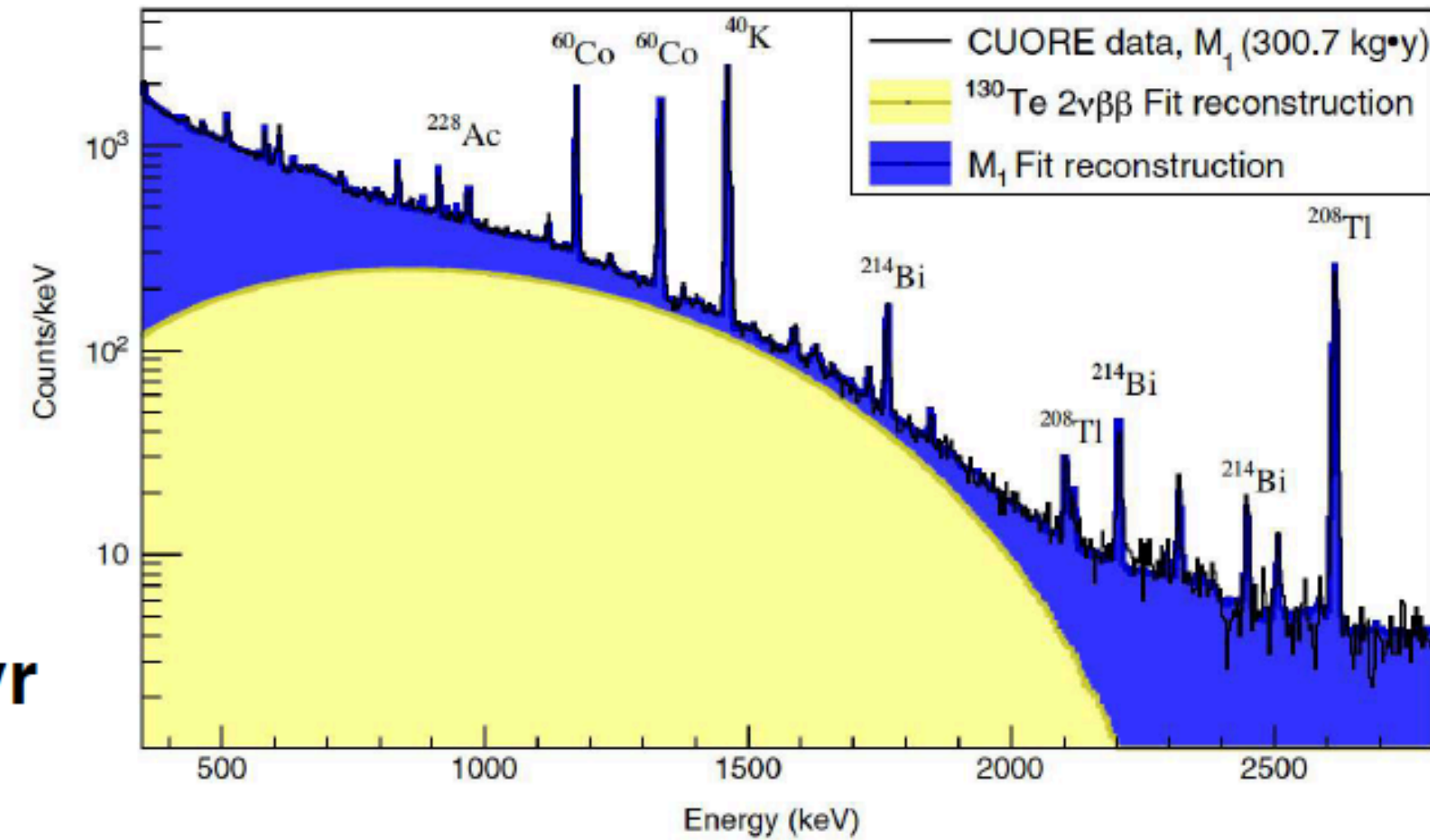
^{130}Te $2\nu\beta\beta$ half-life measurement

Monte Carlo reconstruction of the CUORE background, profiting of a segmented detector.

$2\nu\beta\beta$ decay: dominant component of M1 spectrum from ~ 1 to 2 MeV

$$T_{2\nu}^{1/2} (^{130}\text{Te}) = [7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{-0.15}(\text{syst})] \times 10^{20} \text{ yr}$$

Adams D. et al. (CUORE collaboration), Phys. Rev. Lett. 126, 171801 (2021)
<https://doi.org/10.1103/PhysRevLett.126.171801>



^{130}Te $\beta\beta$ to first 0^+ excited state of ^{130}Xe

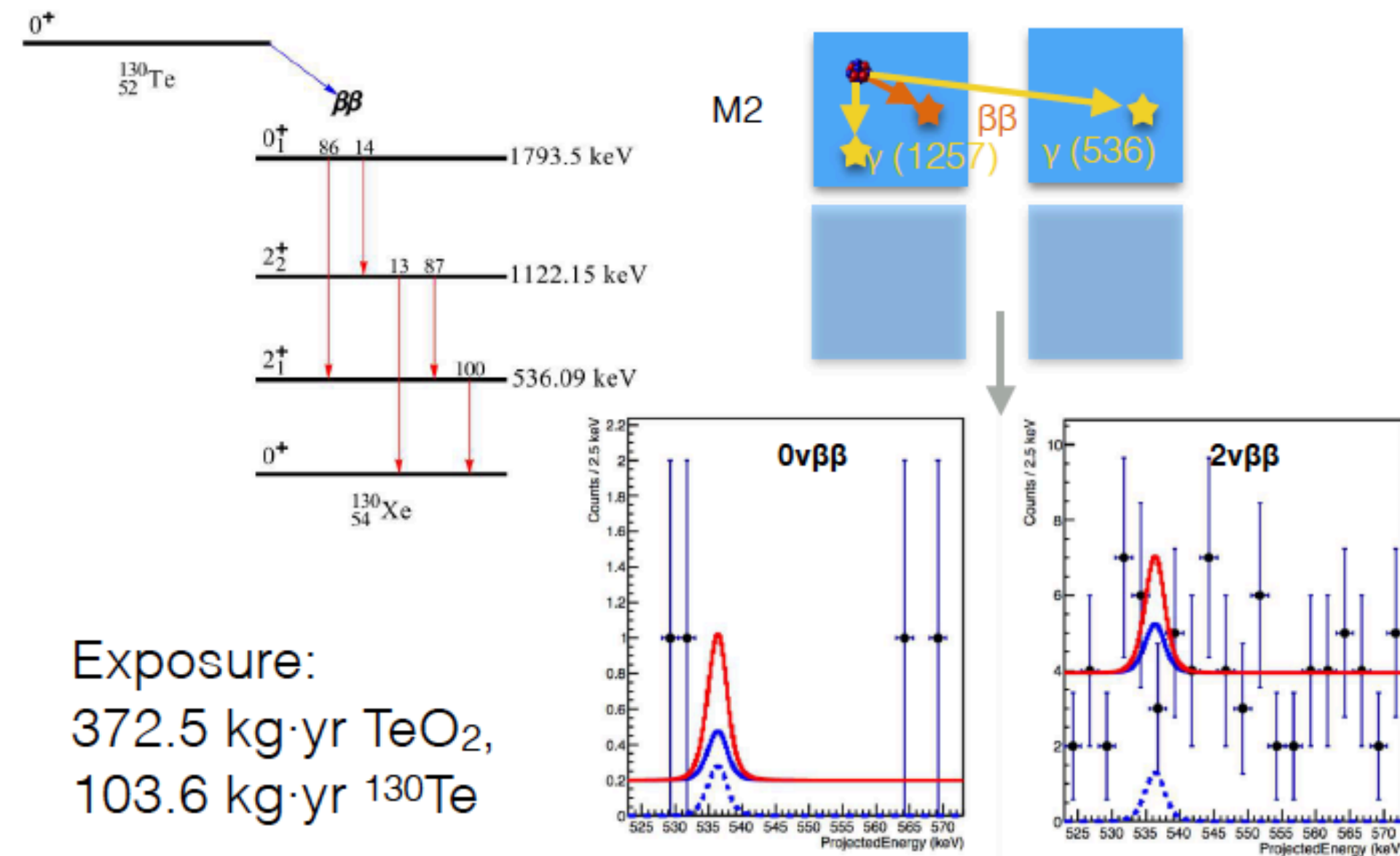
Cascade of de-excitation γ s in coincidence with β s

- Multi-site signatures
- Analysis of only fully contained events

Half-life limits @90%C.I.

$$0\nu\beta\beta: (T^{1/2})^{0\nu}_{0^+} > 5.9 \times 10^{24} \text{ yr}$$

$$2\nu\beta\beta: (T^{1/2})^{2\nu}_{0^+} > 1.3 \times 10^{24} \text{ yr}$$

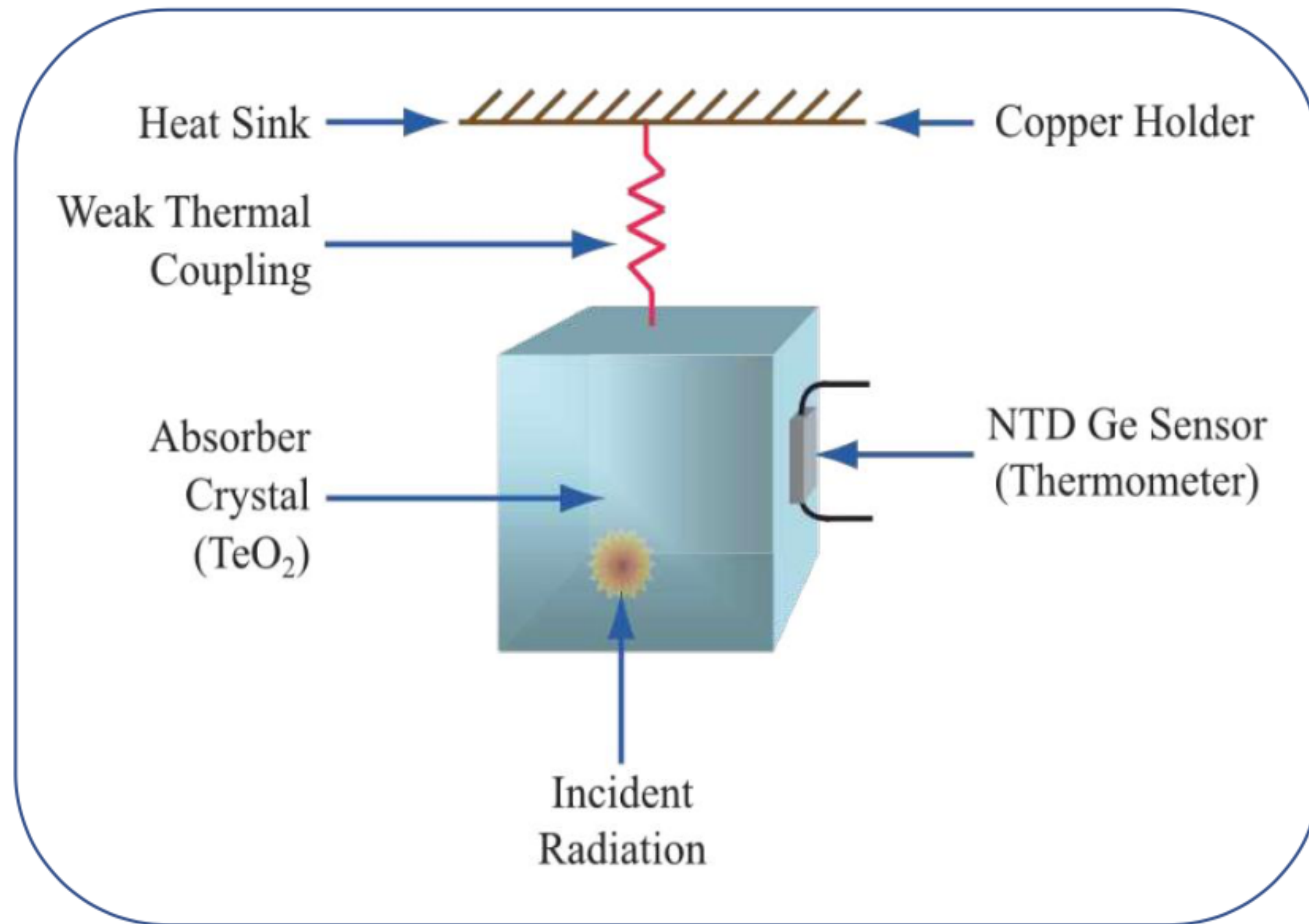


Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567
<https://doi.org/10.1140/epjc/s10052-021-09317-z>

CUPID: CUORE Upgrade with Particle Identification

CUORE ^{130}Te

pure thermal detector
(bolometer)

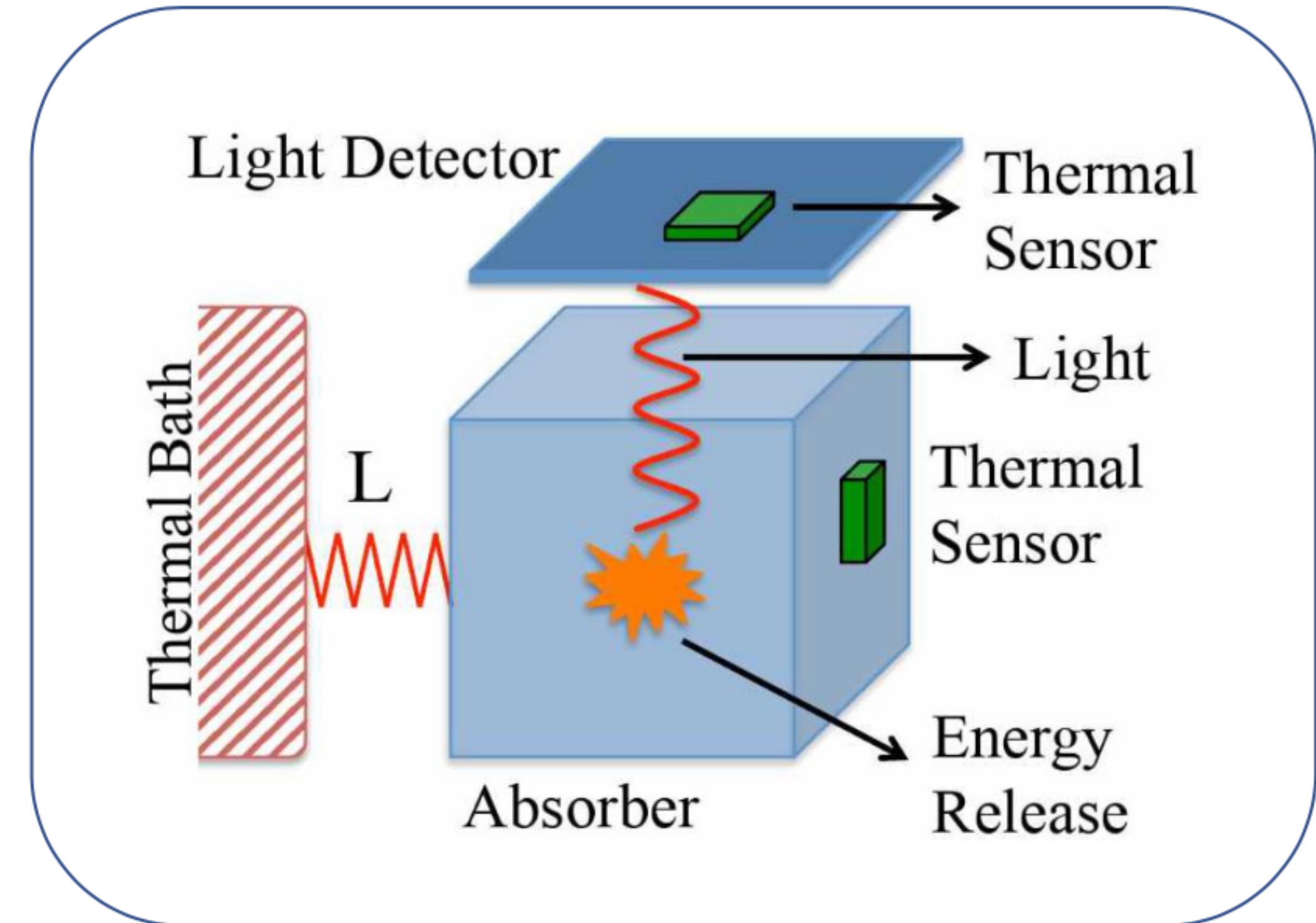


No PID

$Q = 2527 \text{ keV} < 2615 \text{ keV}$

CUPID ^{100}Mo

heat + light
(scintillating bolometer)

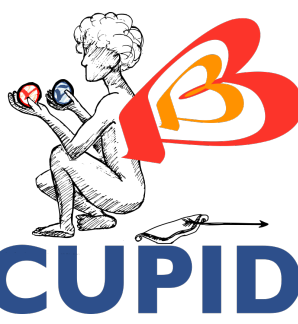


PID $\rightarrow$ remove α

high $Q \rightarrow$
remove γ

^{100}Mo **Q-value: 3034 keV: β/γ**
background significantly reduced

CUPID: CUORE Upgrade with Particle Identification



Single Detector

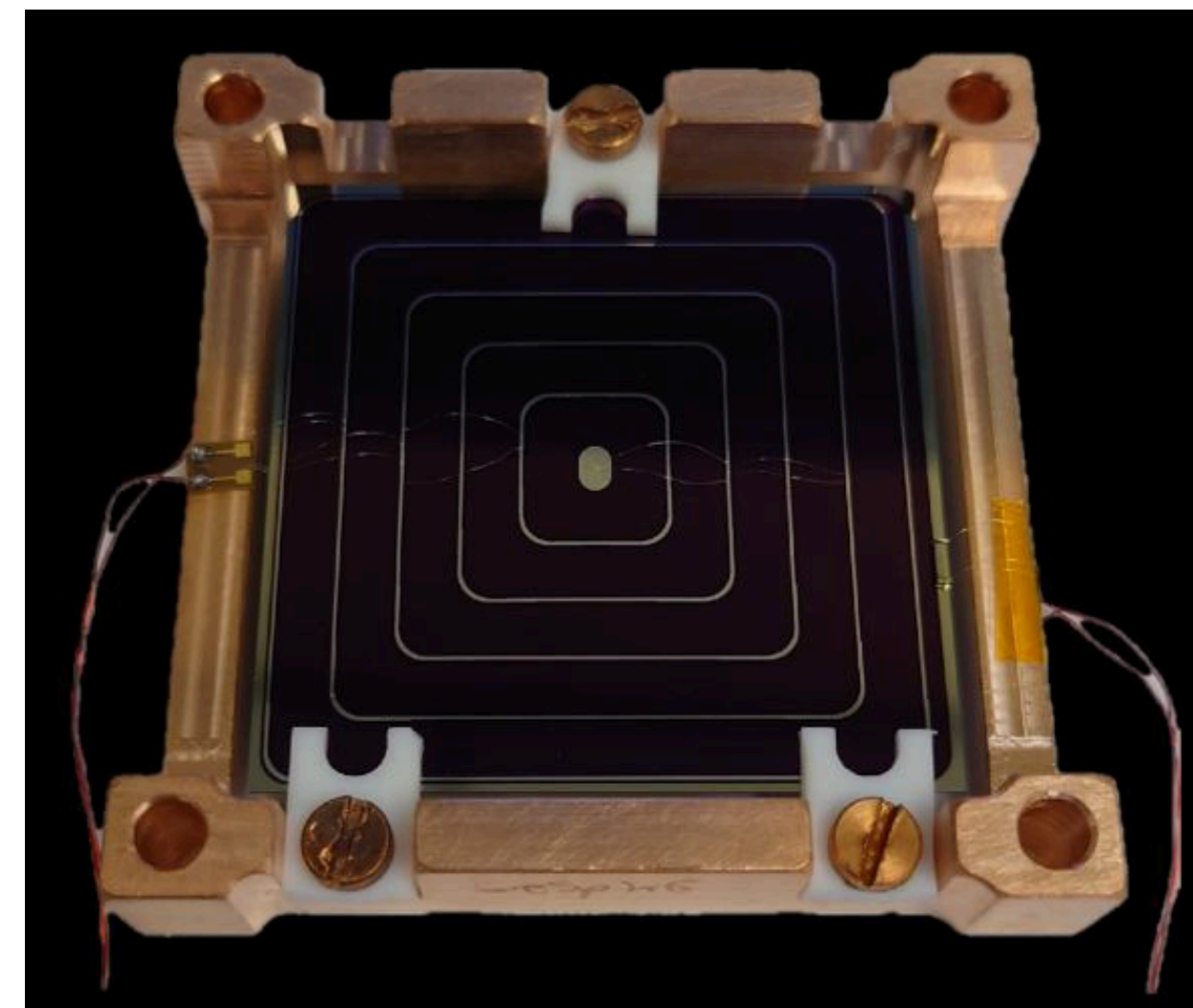
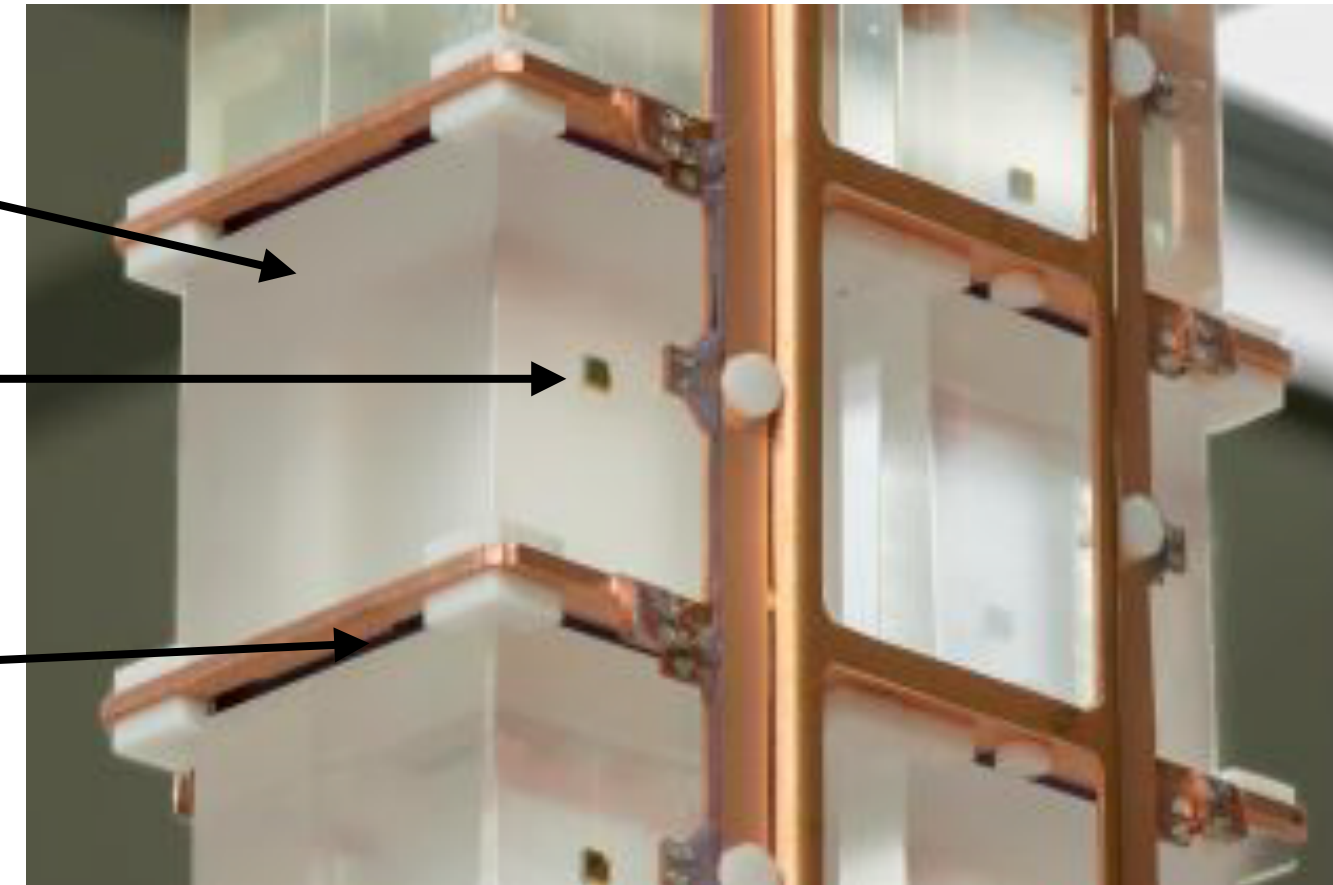
$\text{Li}_2^{100}\text{MoO}_4$, 45x45x45 mm, 280 g
Ge light detector as in CUPID-Mo,
CUPID-0

Detector Array

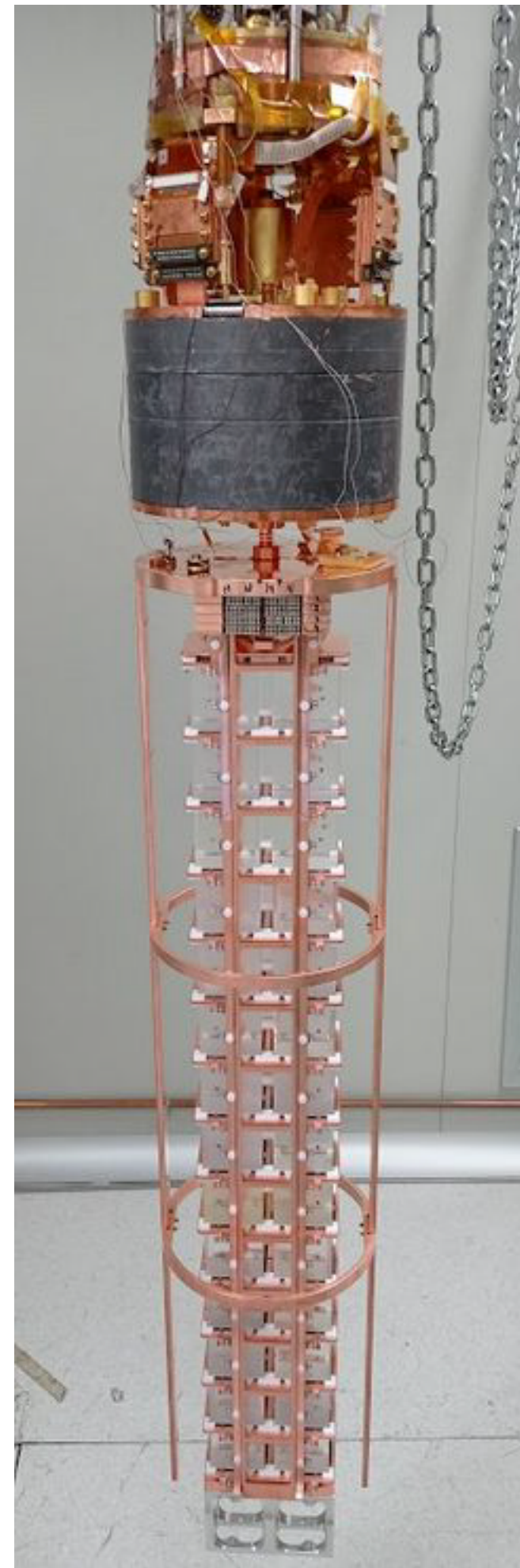
~240 kg of ^{100}Mo with >95% enrichment
~ $1.6 \cdot 10^{27}$ ^{100}Mo atoms
57 towers of 14 floors with 2 crystals each,
1596 crystals

Opportunity to deploy multiple isotopes,
phased deployment

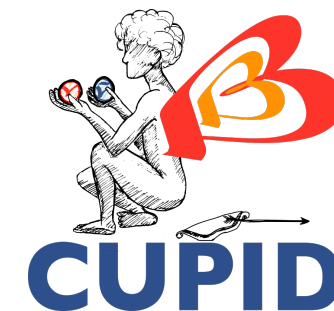
LMO
NTD
light
detectors



single tower



CUPID – CUORE Upgrade with Particle Identification



CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

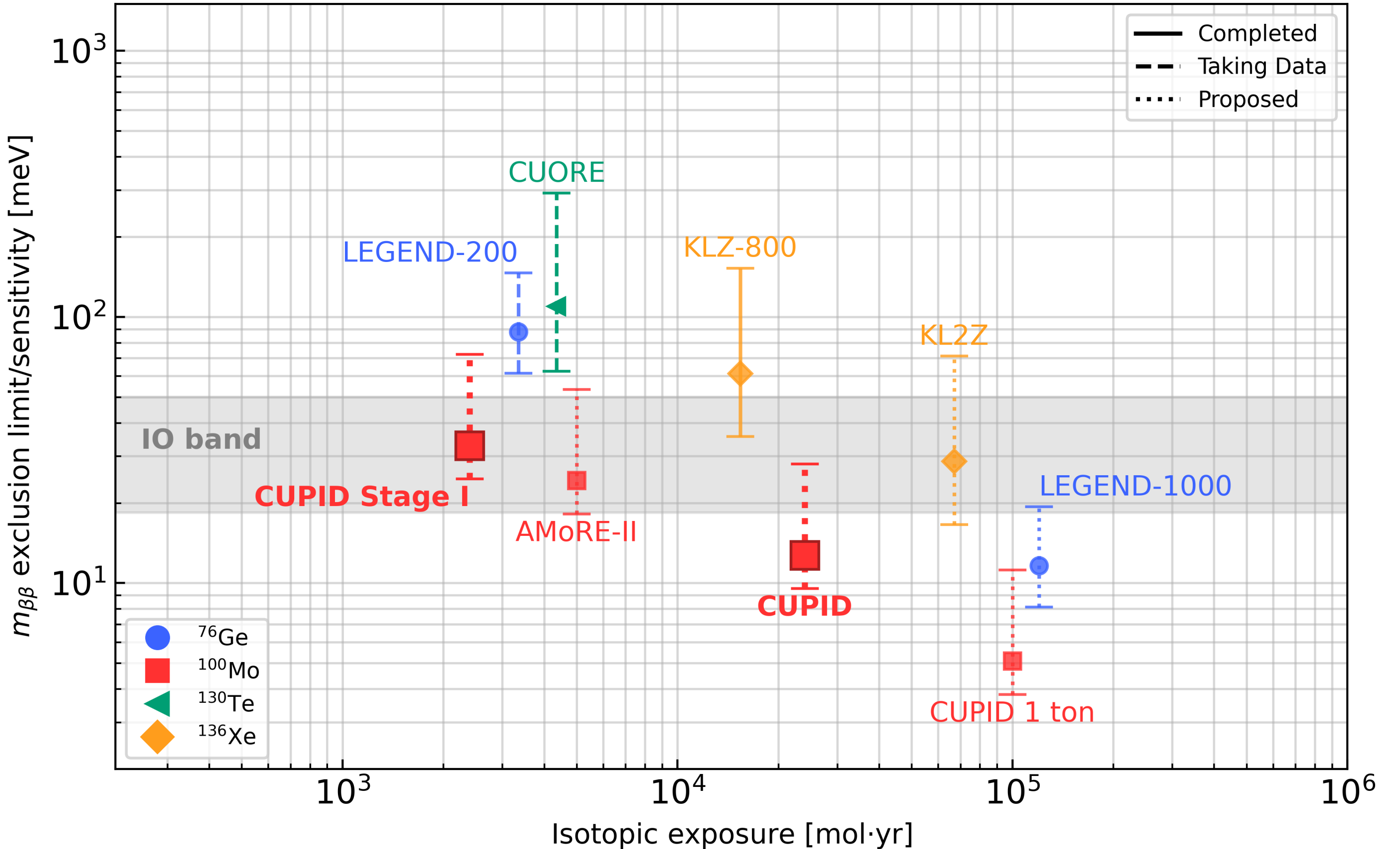
Experiment

Mass: 450 kg (**240 Kg**) of $\text{Li}_2^{100}\text{MoO}_4$ (**^{100}Mo**)

10 yr runtime

Energy resolution: **5 keV** FWHM

Background: **10^{-4}** cts/keV.kg.yr



Discovery Sensitivity

$T_{1/2} > 1 \times 10^{27}$ yrs (3σ)

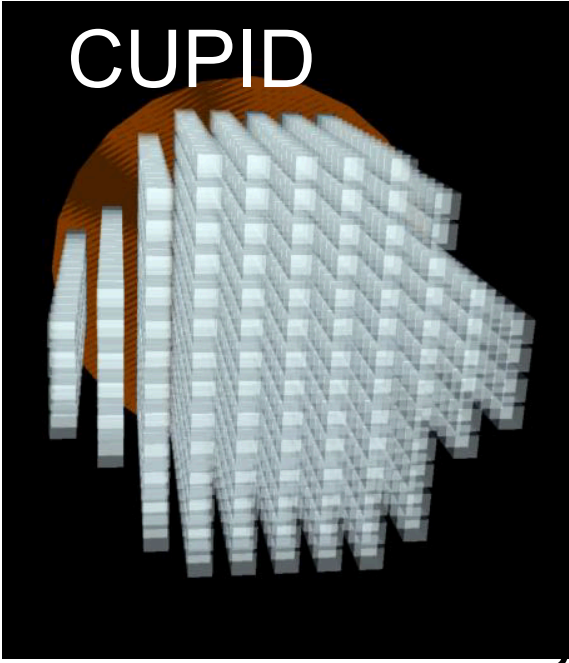
$m_{\beta\beta} \sim 12\text{-}36$ meV

CUPID will proceed with **staged deployment**

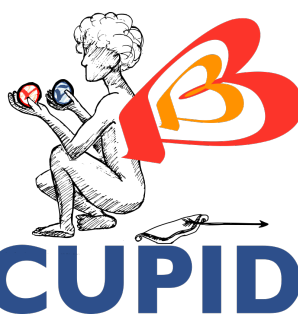
Exclusion Sensitivity

$T_{1/2} > 1.6 \times 10^{27}$ yrs (90% C.L.)

$m_{\beta\beta} \sim 10\text{-}28$ meV



CUPID – CUORE Upgrade with Particle Identification



CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

Experiment

Mass: 450 kg (**240 Kg**) of $\text{Li}_2^{100}\text{MoO}_4$ (**^{100}Mo**)

10 yr runtime

Energy resolution: **5 keV FWHM**

Background: **10^{-4} cts/keV.kg.yr**

Discovery Sensitivity

$T_{1/2} > 1 \times 10^{27}$ yrs (3σ)

$m_{\beta\beta} \sim 12\text{-}36$ meV

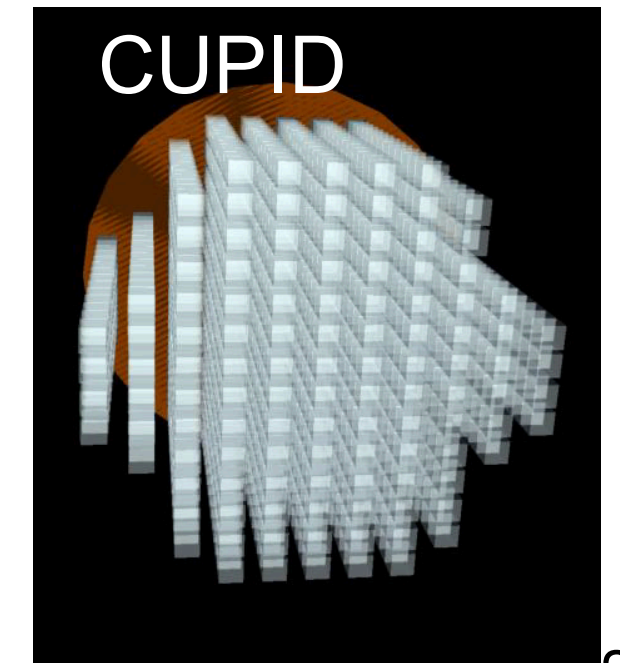
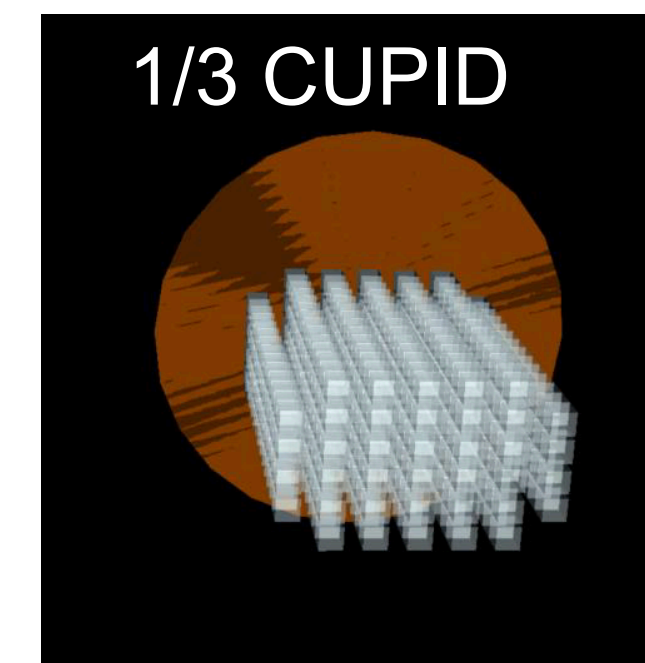
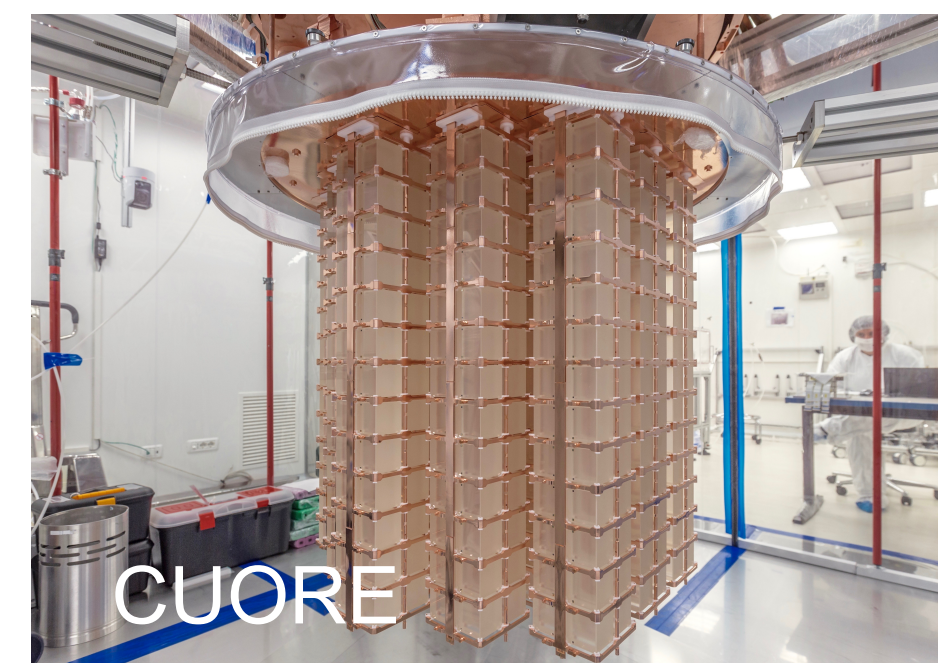
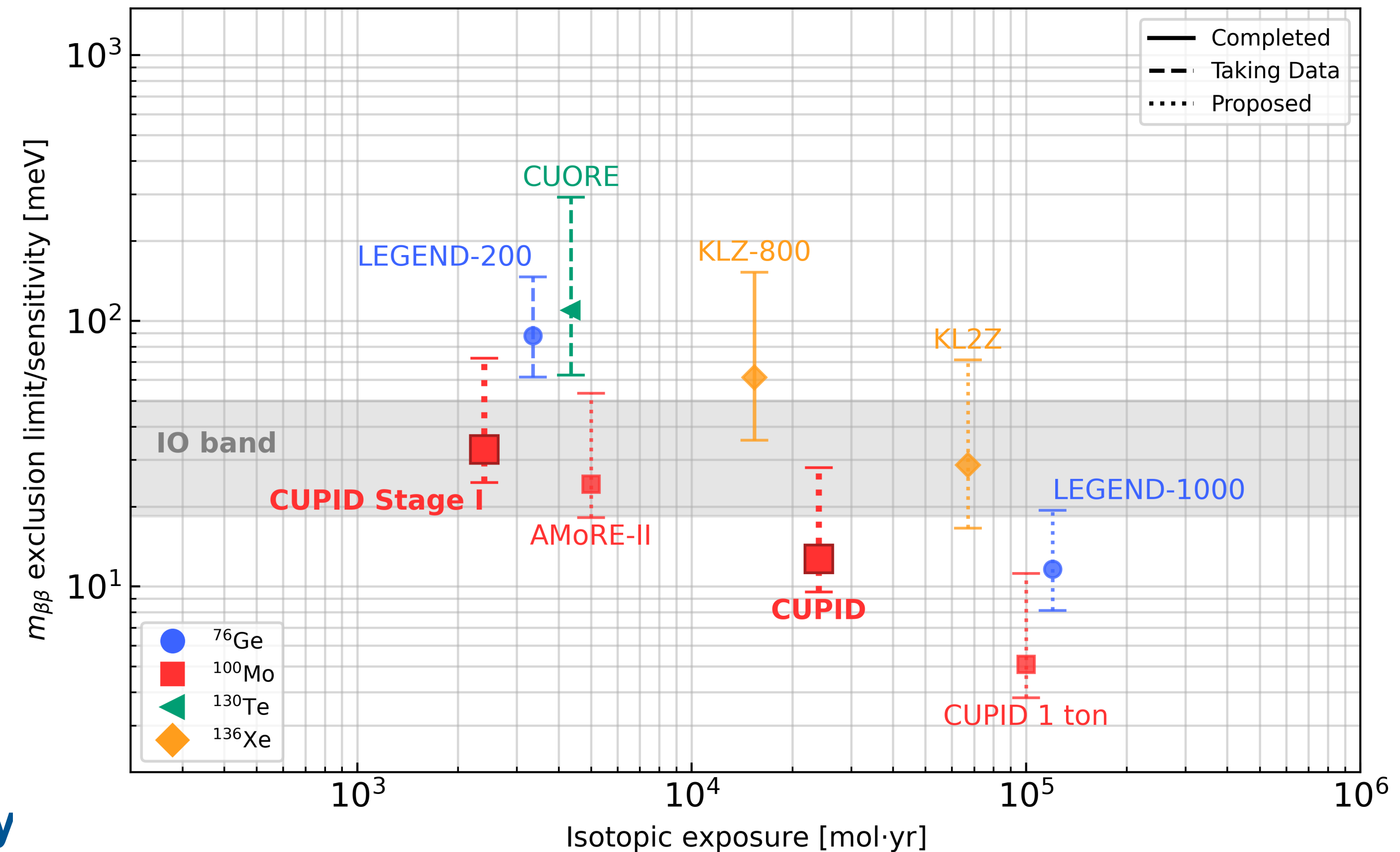
Exclusion Sensitivity

$T_{1/2} > 1.6 \times 10^{27}$ yrs (90% C.L.)

$m_{\beta\beta} \sim 10\text{-}28$ meV

CUPID will proceed with **staged deployment**

CUPID



CUPID-1T and Beyond

Worldwide consortium: Envision collaboration of multiple, bolometric experiments

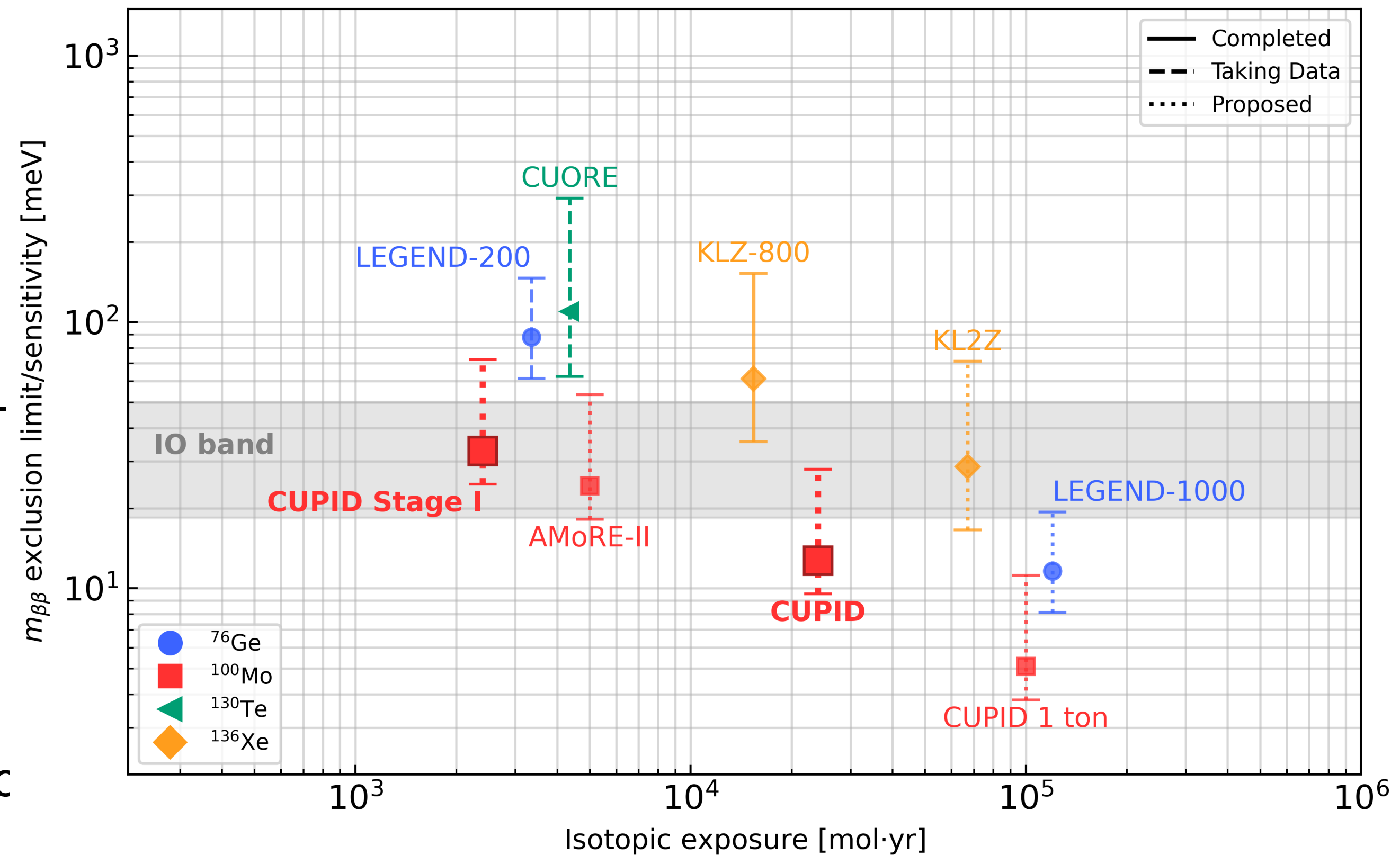
Mass: increase to ~1 ton (CUPID x4), reduce background ~x20

Isotopes: ^{100}Mo current CUPID baseline, with multi-isotope options (e.g. ^{130}Te , ^{82}Se , ^{116}Cd , ...)

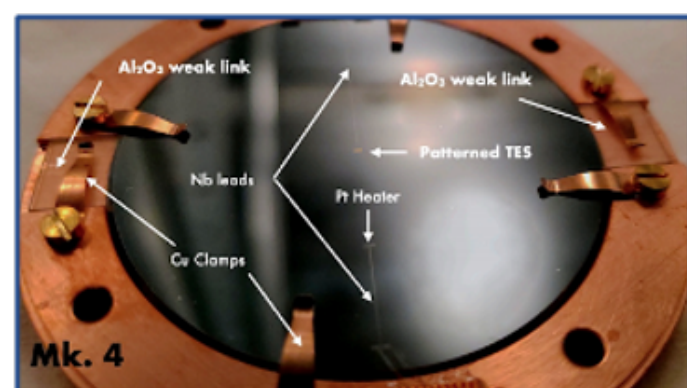
Multi-site: Distributed multi-cryostat deployment

Half-life: $T^{1/2} \sim 10^{28}$ yr (^{100}Mo)

Active R&D: Particle ID, topological event reconstruction quantum sensors, active background suppression



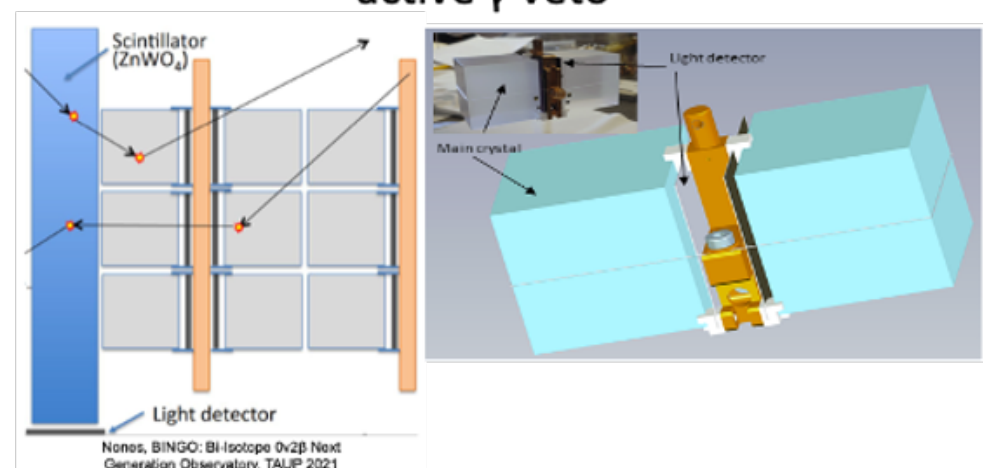
Quantum Sensors



TES
Light
detectors

Hennings-Yeomans et.al. Journal of Applied Physics 128, 154501 (2020)
Singh et al. arXiv:2210.15619

BINGO: Geometry optimization + active γ veto

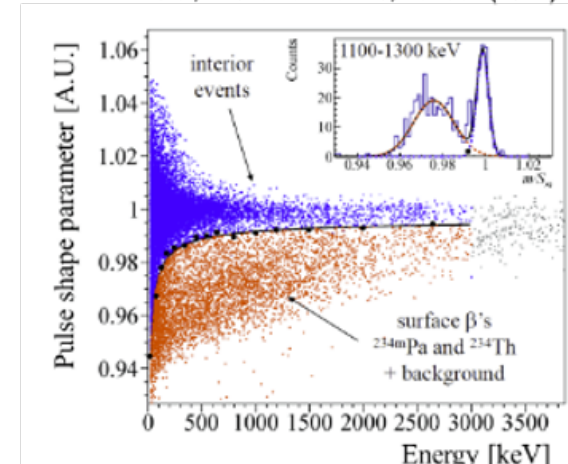


Norris, BINGO: BI-Isotope Next-Generation Observatory, TAUP 2021

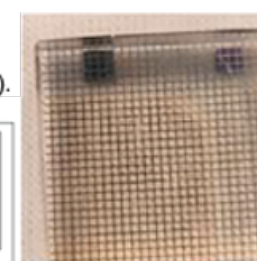
Active Background Mitigation

CROSS : Al-Pd coating on LMO for surface-event identification

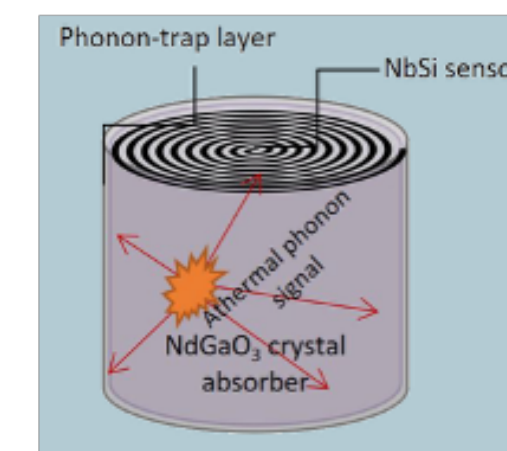
Armato, A. et al. J. Inst. 16, P02037 (2021).



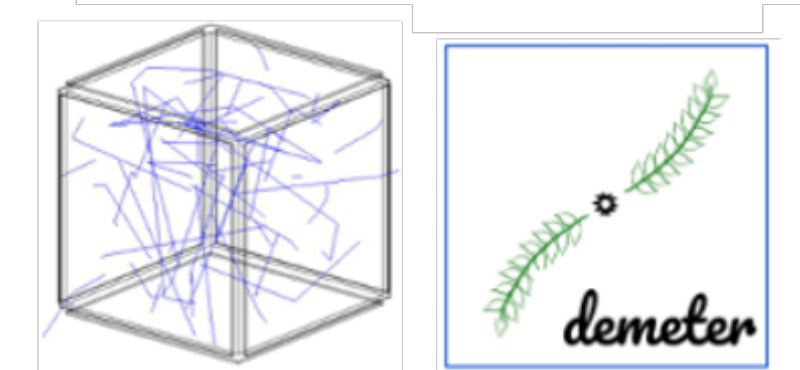
CROSS



TINY:
Novel crystals



Event Topology DEMETER, CERES, OPOSSUM

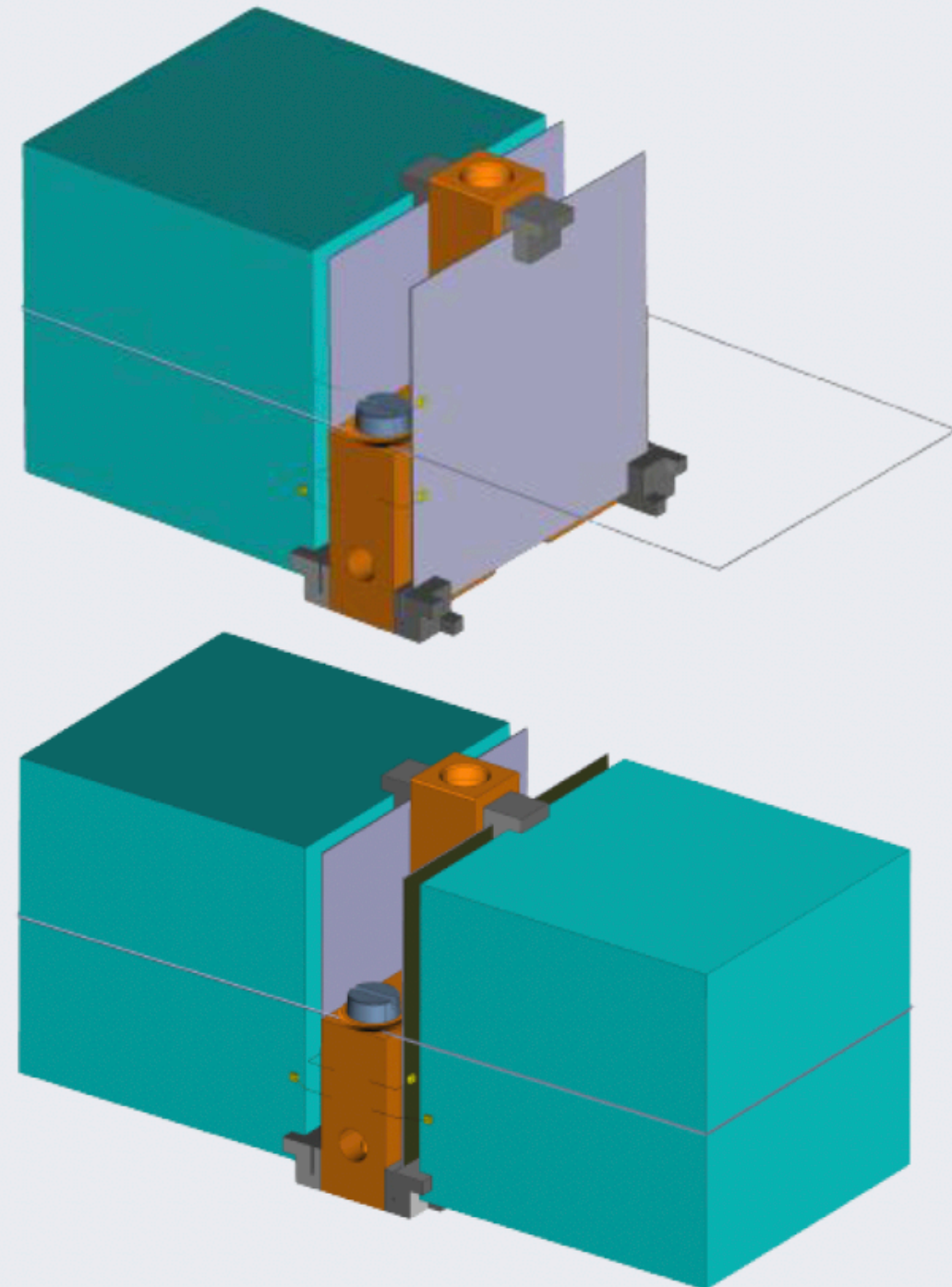


Erin Hansen, Snowmass 2022

BINGO

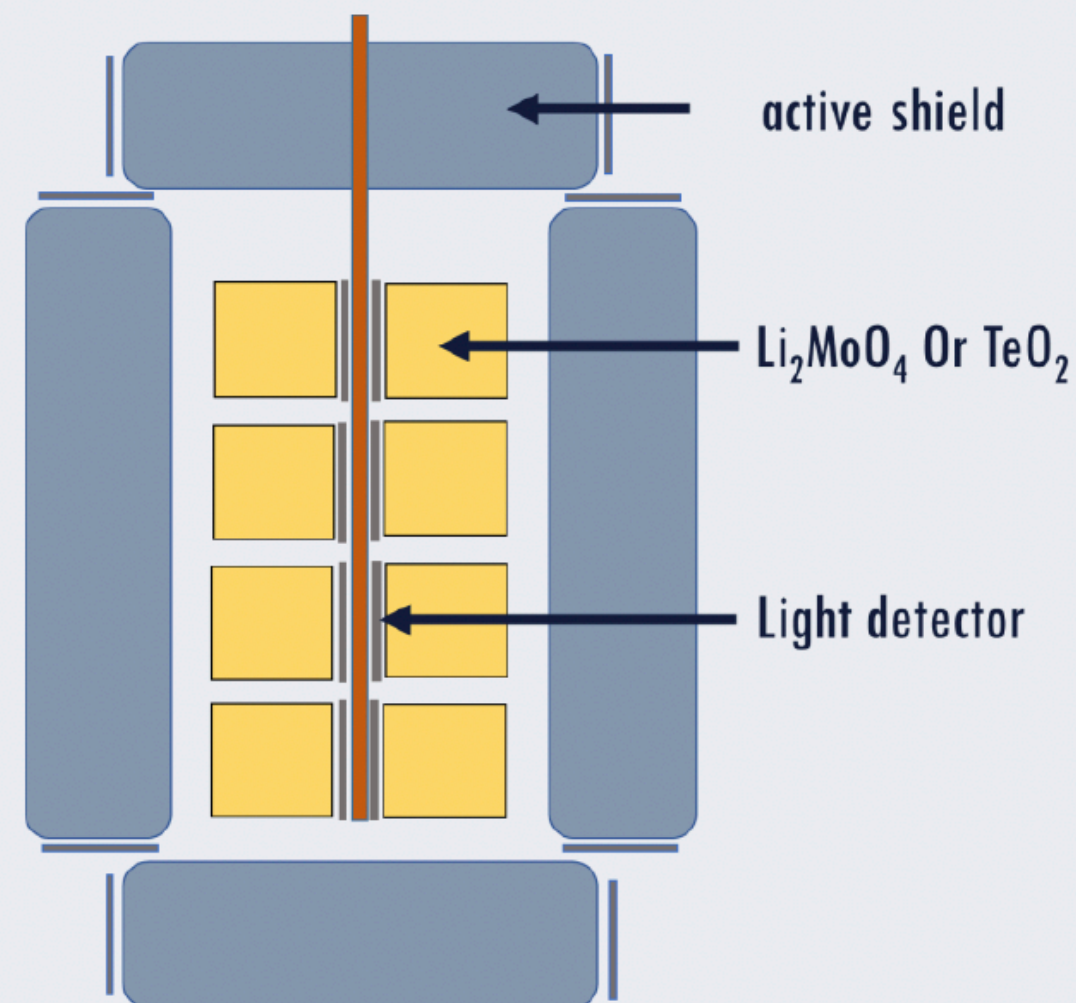
Assembly upgrade

- Less passive materials
- Compact assembly



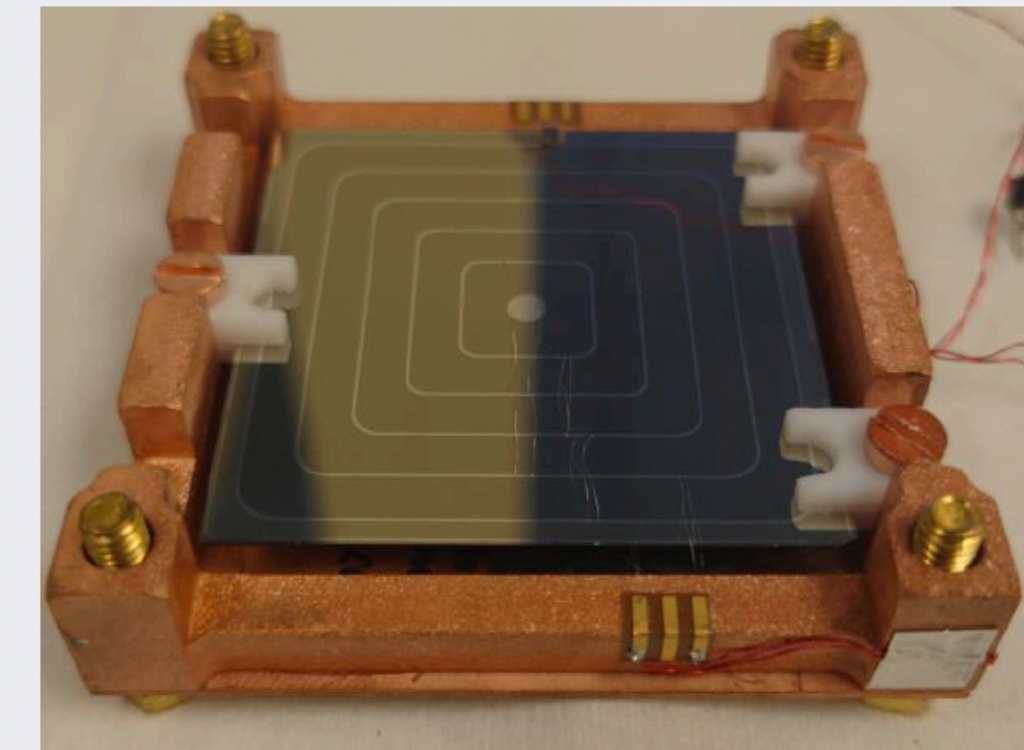
Active veto

Use an active shield, based on BGO scintillator



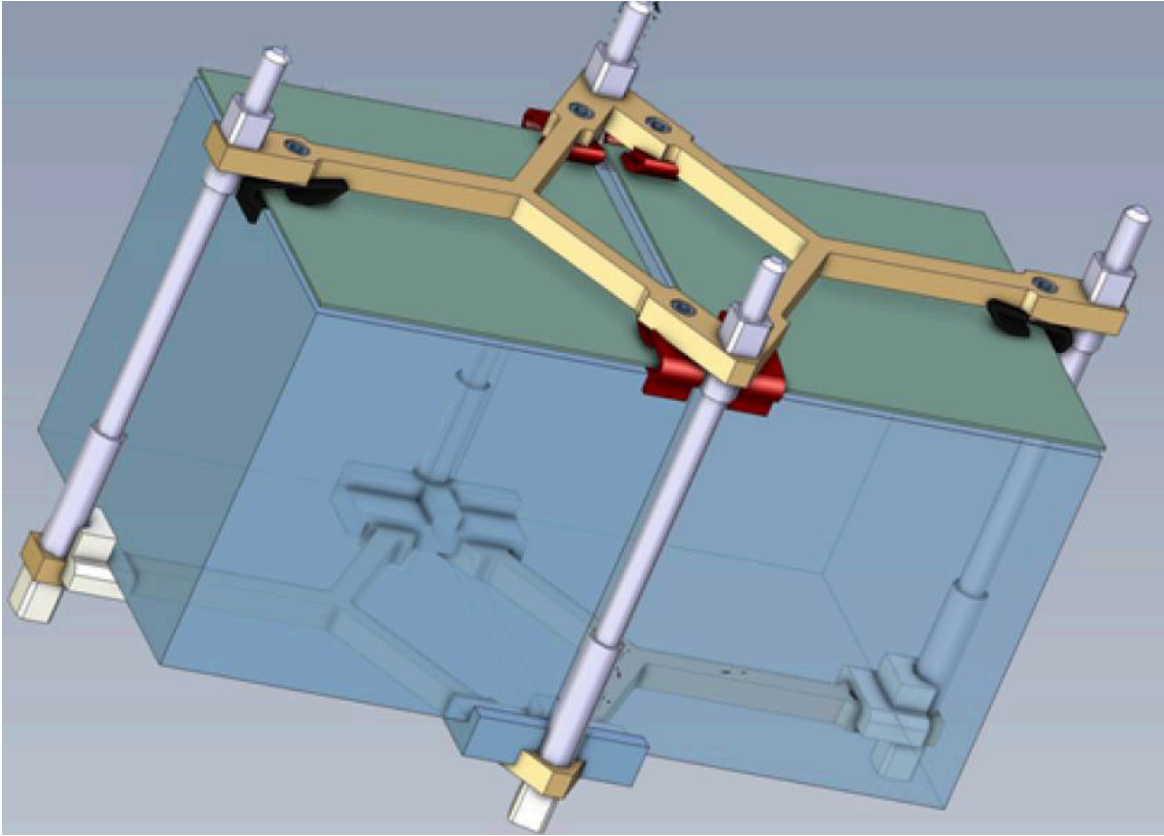
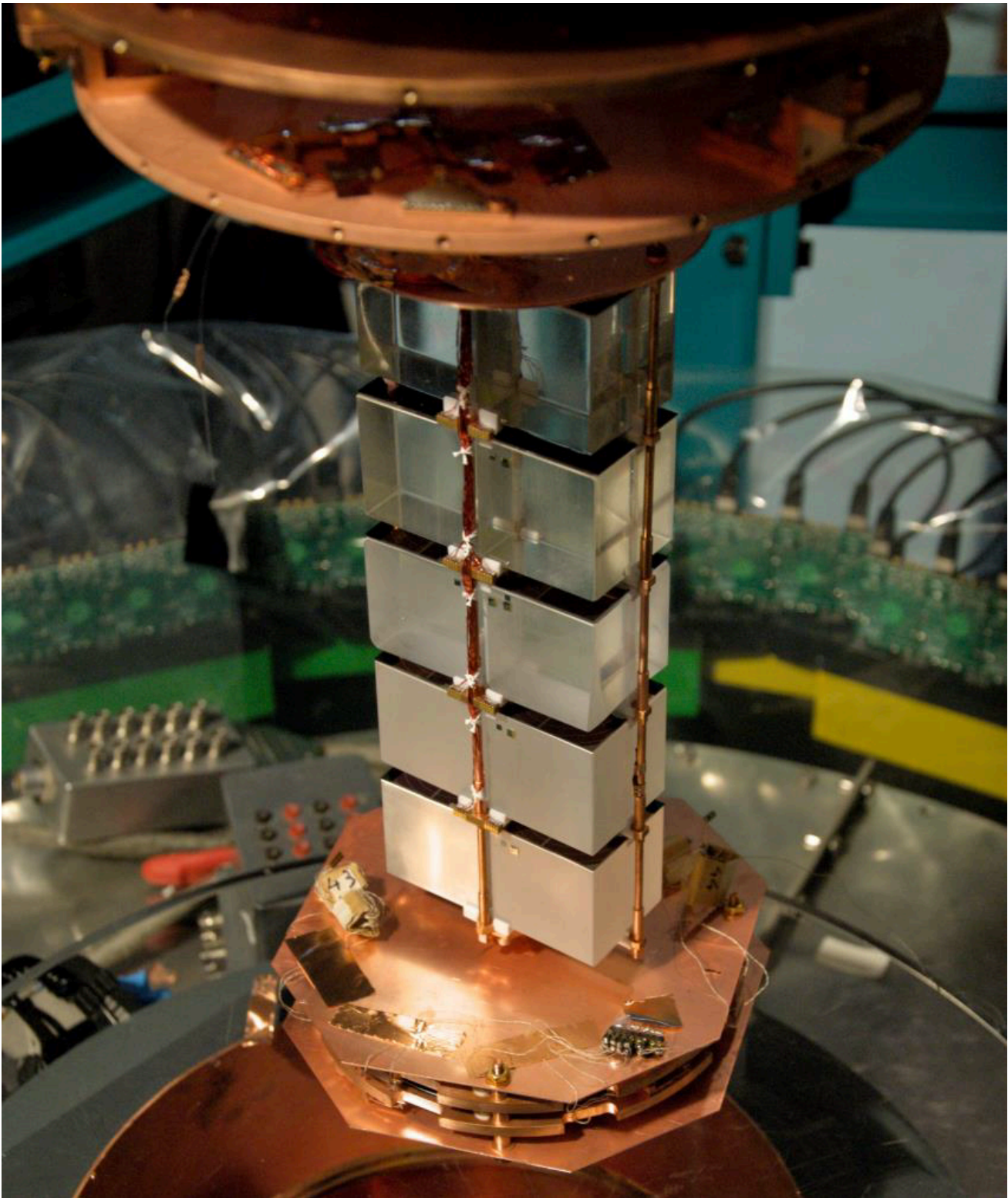
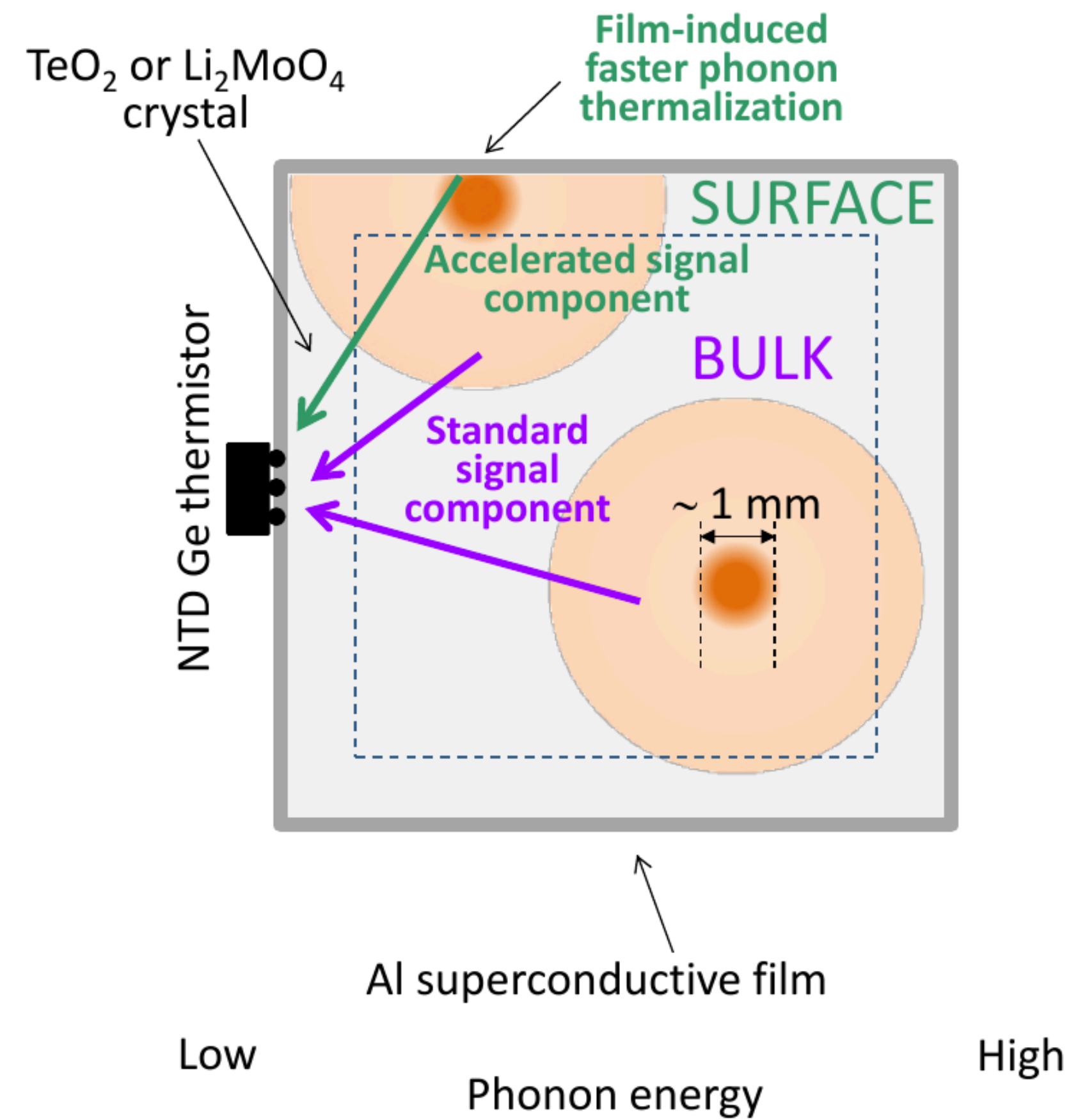
Neganov-Trofimov-Luke LD

- Amplification of light signals
- Higher signal-to-noise ratio → lower energy threshold



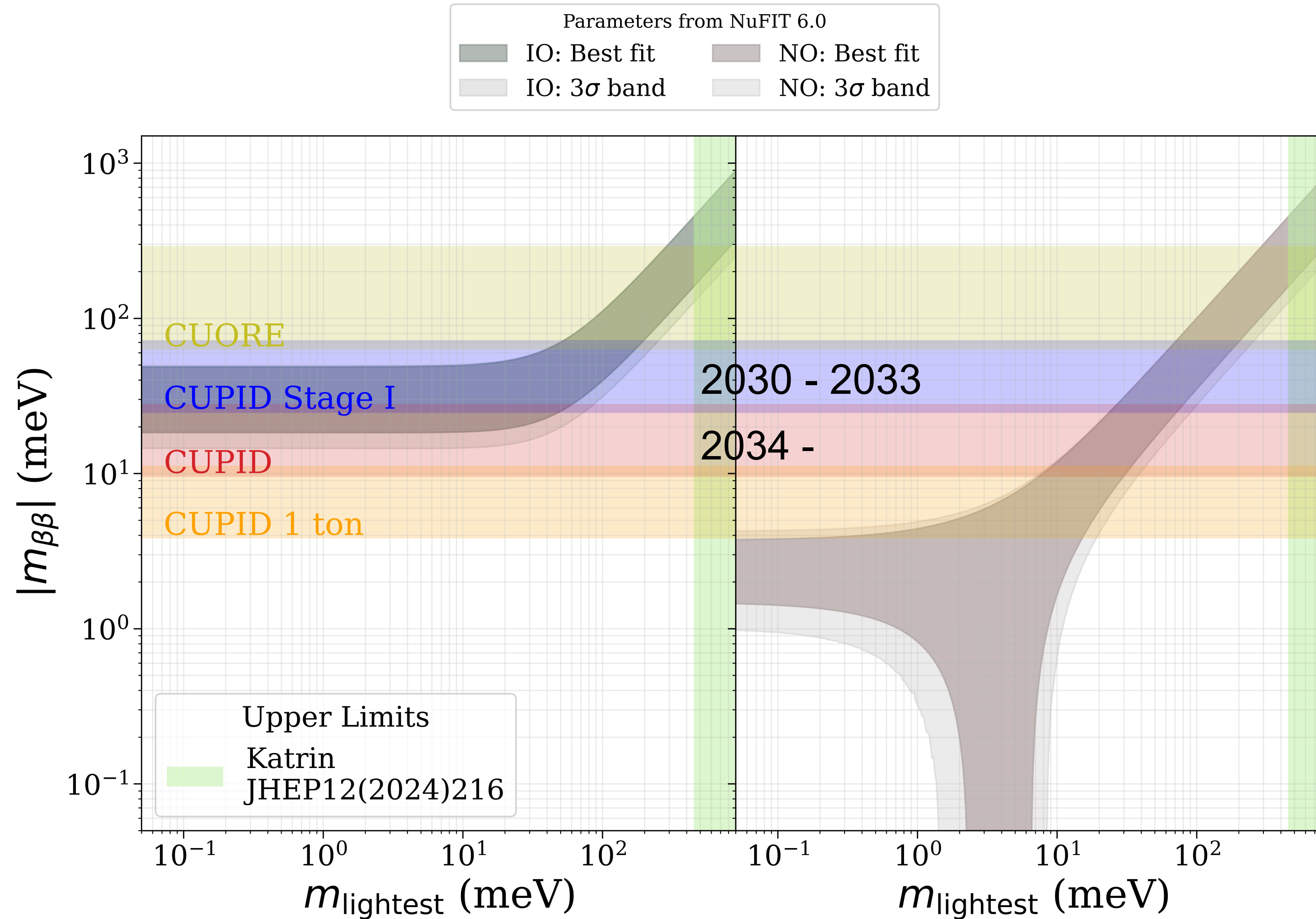
Hawraa Khalife

CROSS - Cryogenic Rare Event Observatory with Surface Sensitivity



Mariia Buchynska

CUPID Sensitivity - Next Decade and Beyond



Other mass measurements:

- Direct mass measurements (Katrin)
- cosmology
- Mass ordering from oscillation experiments

Beyond CUPID / CUPID-1Ton

Bolometer technology with quantum sensors scalable to 1-ton and beyond, with sensitivity in the normal ordering range. Measurement of the mass ordering will provide important input for the future.

Underground Laboratories Worldwide



CUPID-CJPL

- $0\nu\beta\beta$ experiment based on Mo-100 isotope and LMO crystal calorimeter array.

Participate in CUPID project:
crystal validation and electronics

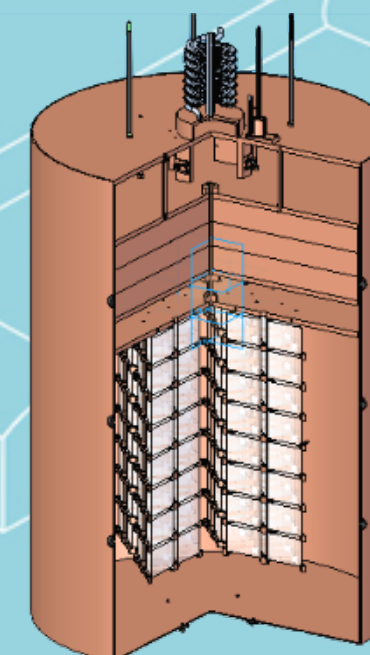
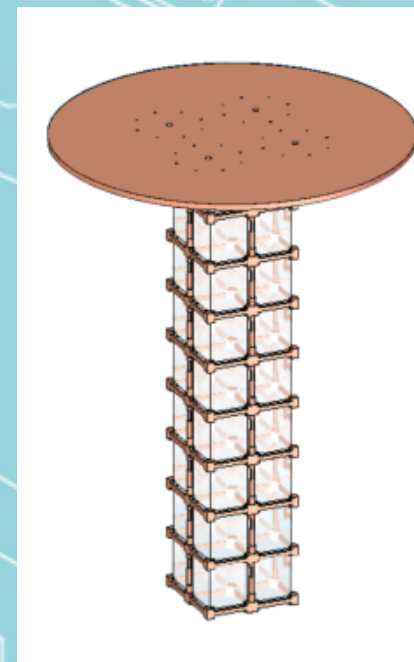
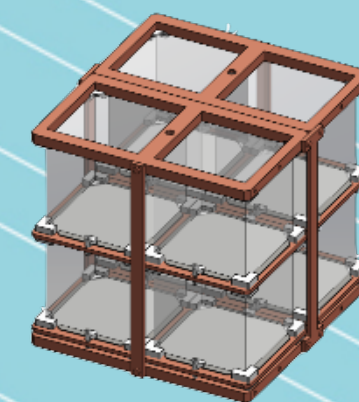
Crystal Testing
(2023-2028)

Develop CUPID-reach/1T Technology

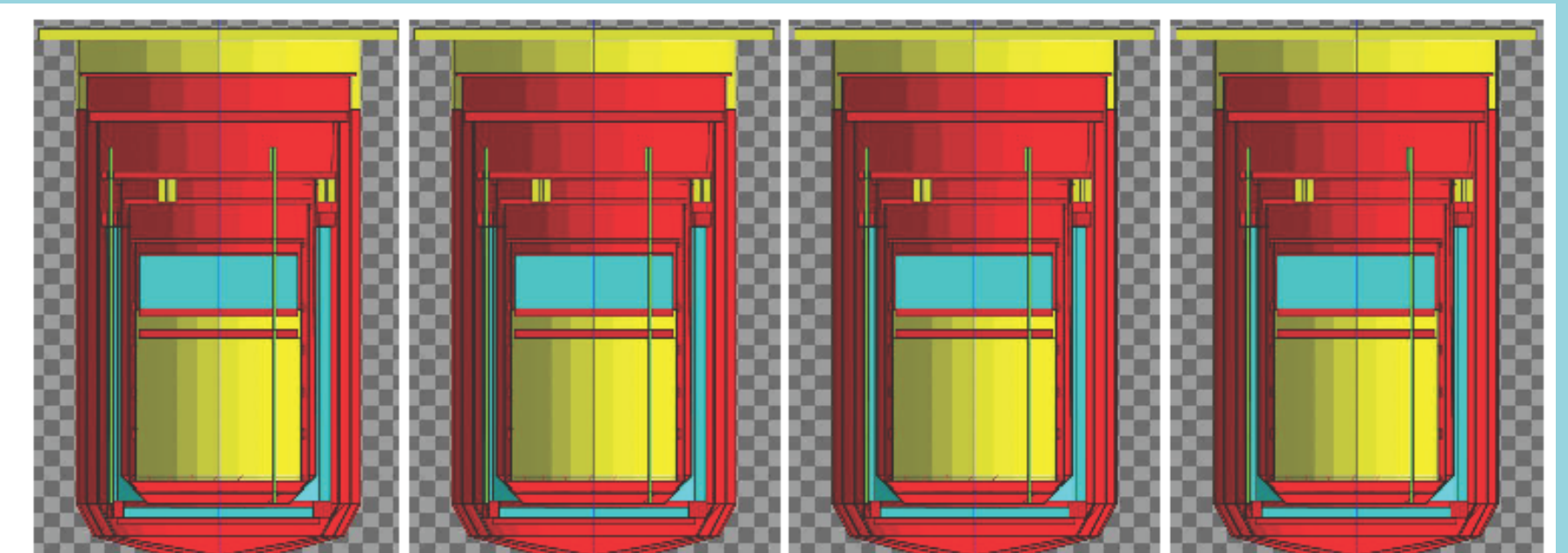
CUPID-CJPL Demo
(2026-2028)
10 kg enriched crystals

Build CUPID-reach or CUPID-1T at CJPL

CUPID-CJPL-200/1T
(2028+)
> 250 kg enriched crystals



Possible CUPID-1T configuration

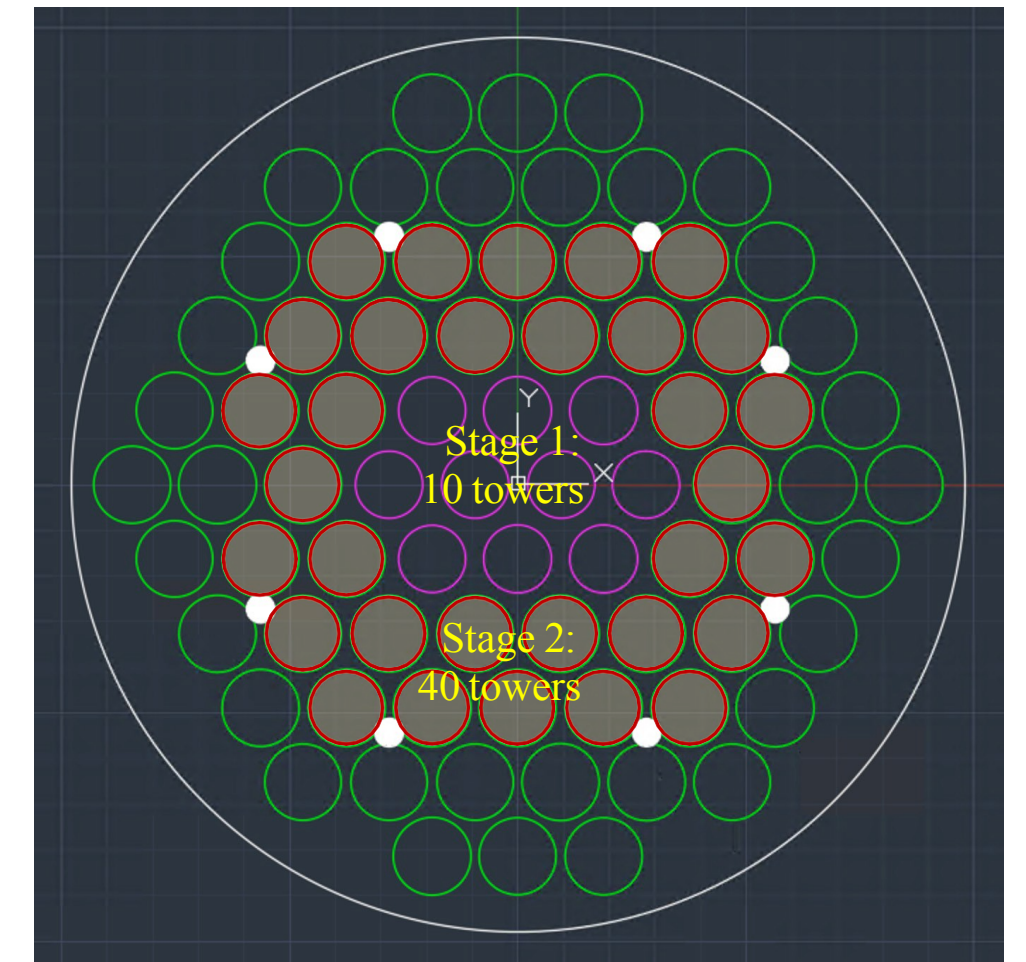
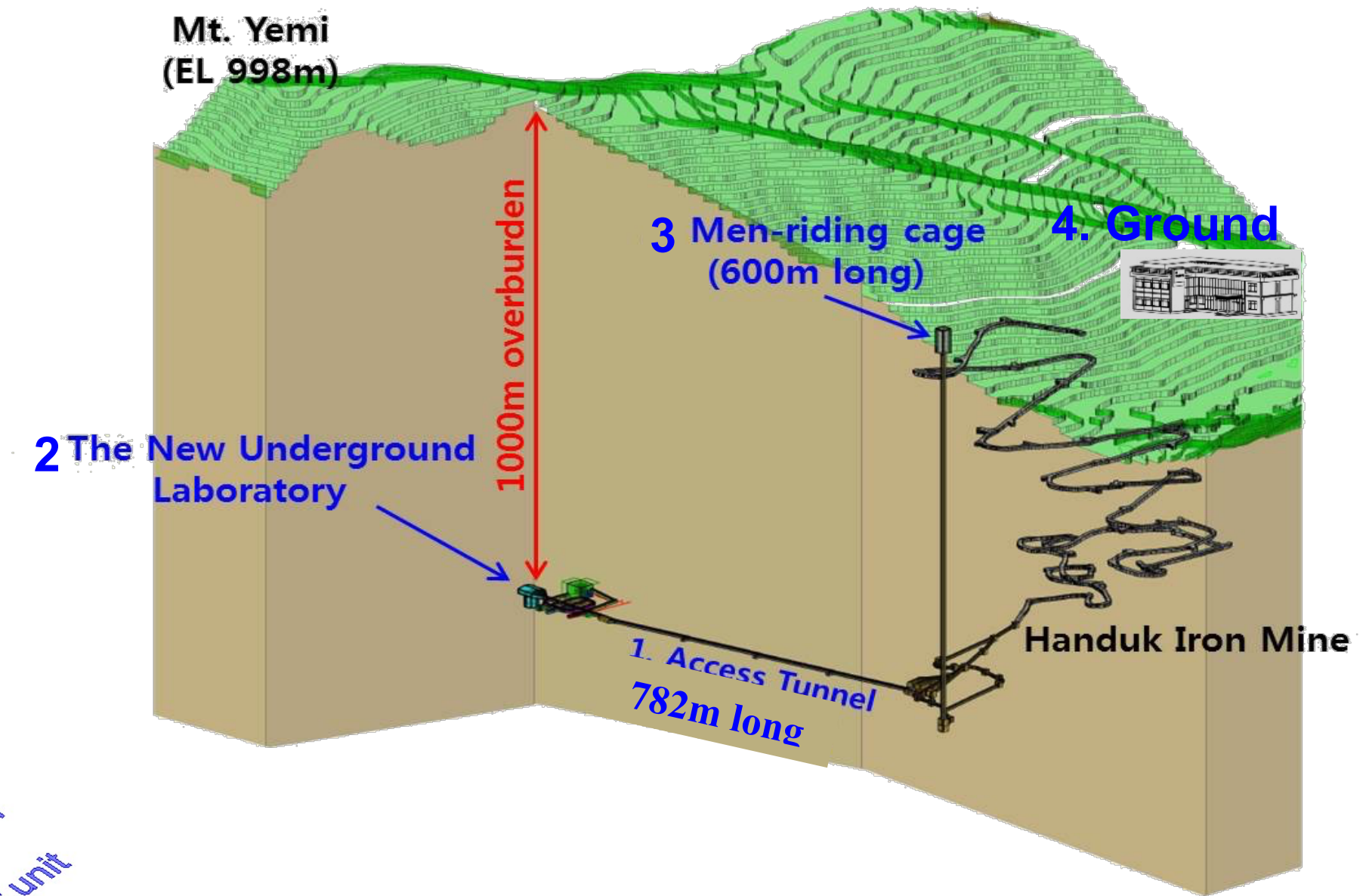
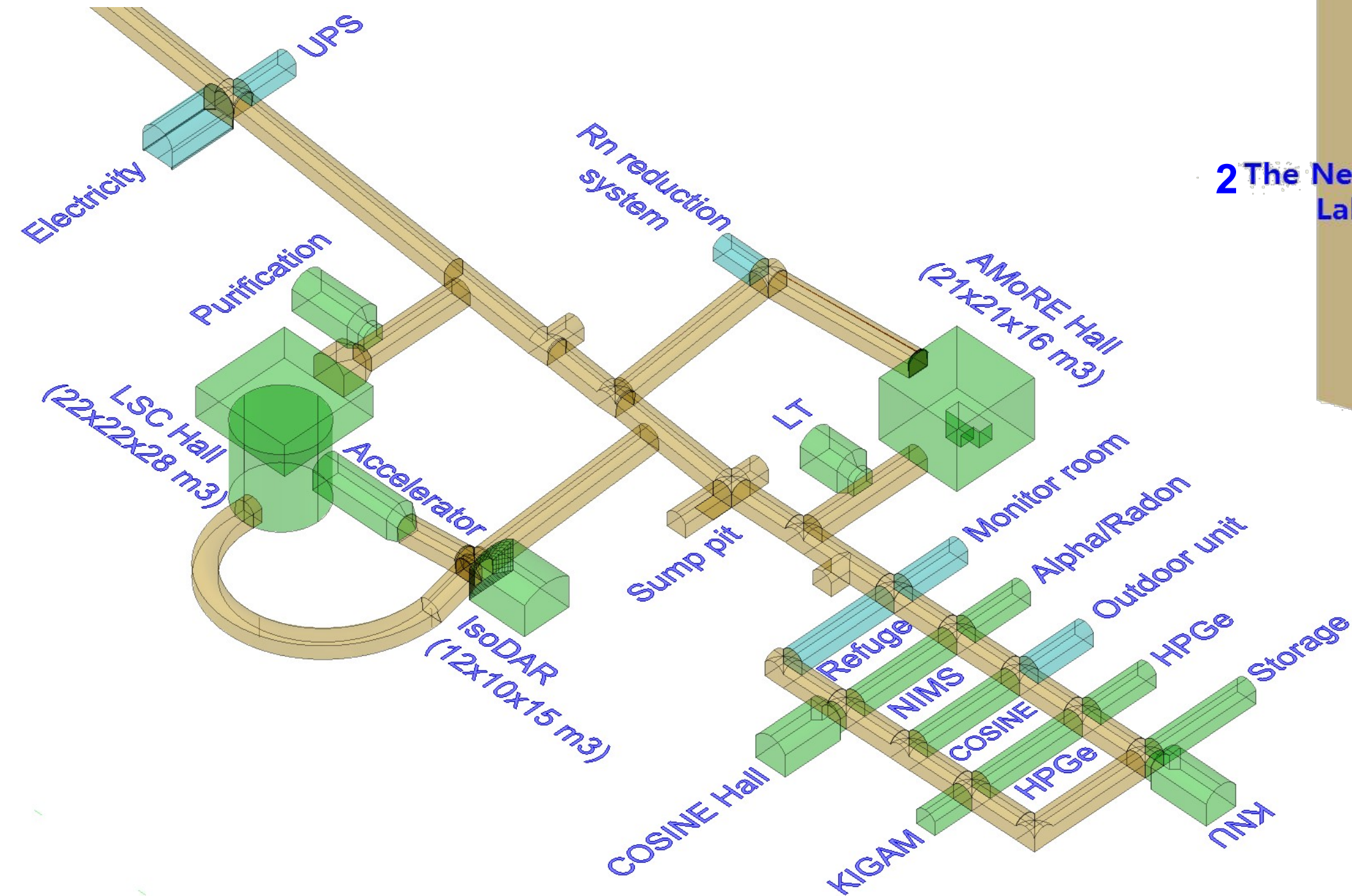


4x250 kg of ^{100}Mo
A “flock” of CUPIDs around the world

- 10 kg experiment
 - low enrichment
 - demonstrate key technologies
- 250 kg+ experiment
 - high enrichment
 - probe $m_{\beta\beta}$ below 10meV

Qian Yue

AMoRE-II at Yemilab



Yemilab is constructed in 2022. (1000m deep)
 Lab area > 3000 m²,
 Power: 2.5 MW.
 Two access routes: ramp-way, men-riding cage
 Open-user facility operated by IBS.

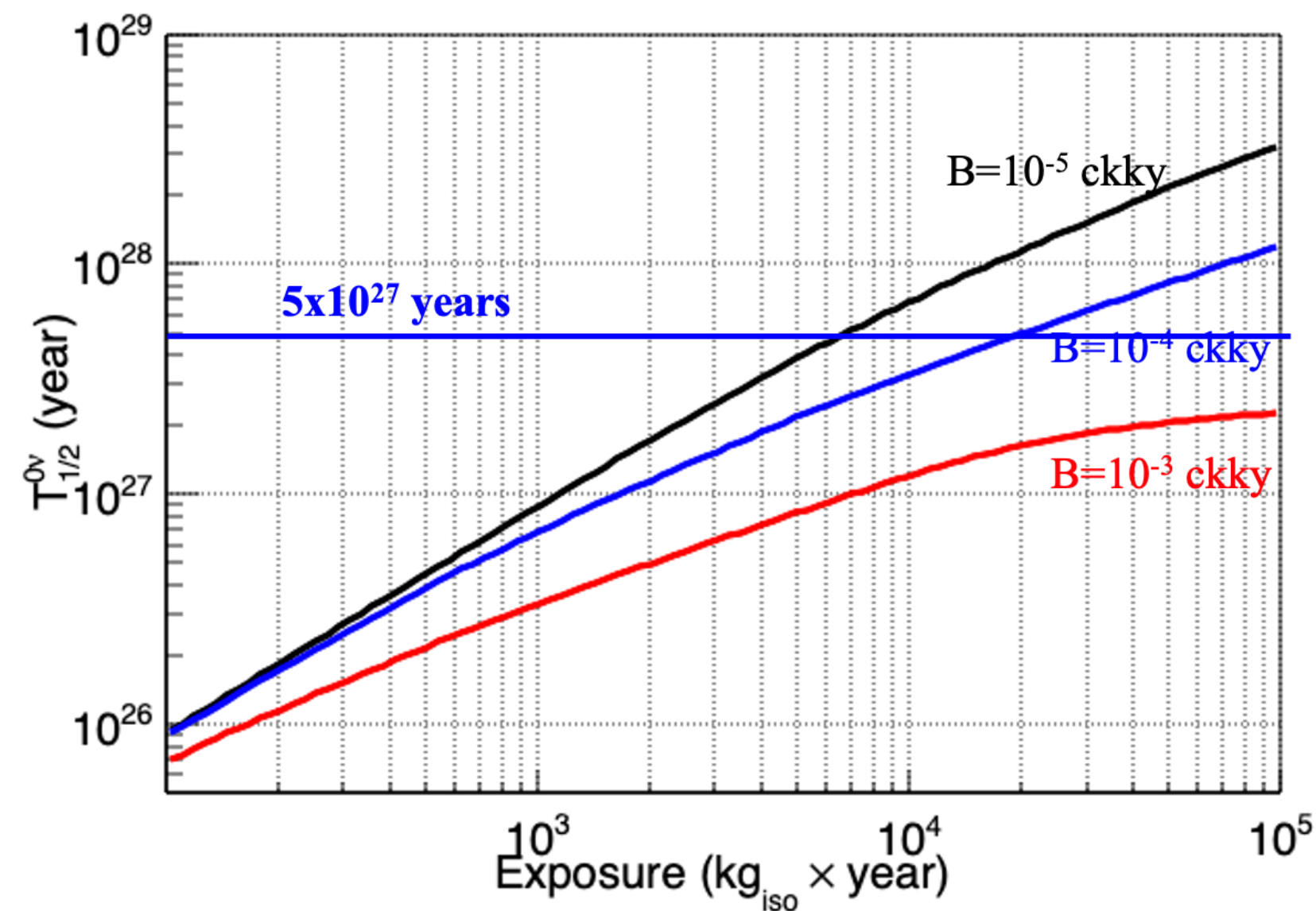
Maximum capacity of current cryostat:
 ~ 800 crystals. (~200 kg ¹⁰⁰Mo isotopes)

Future of AMORE

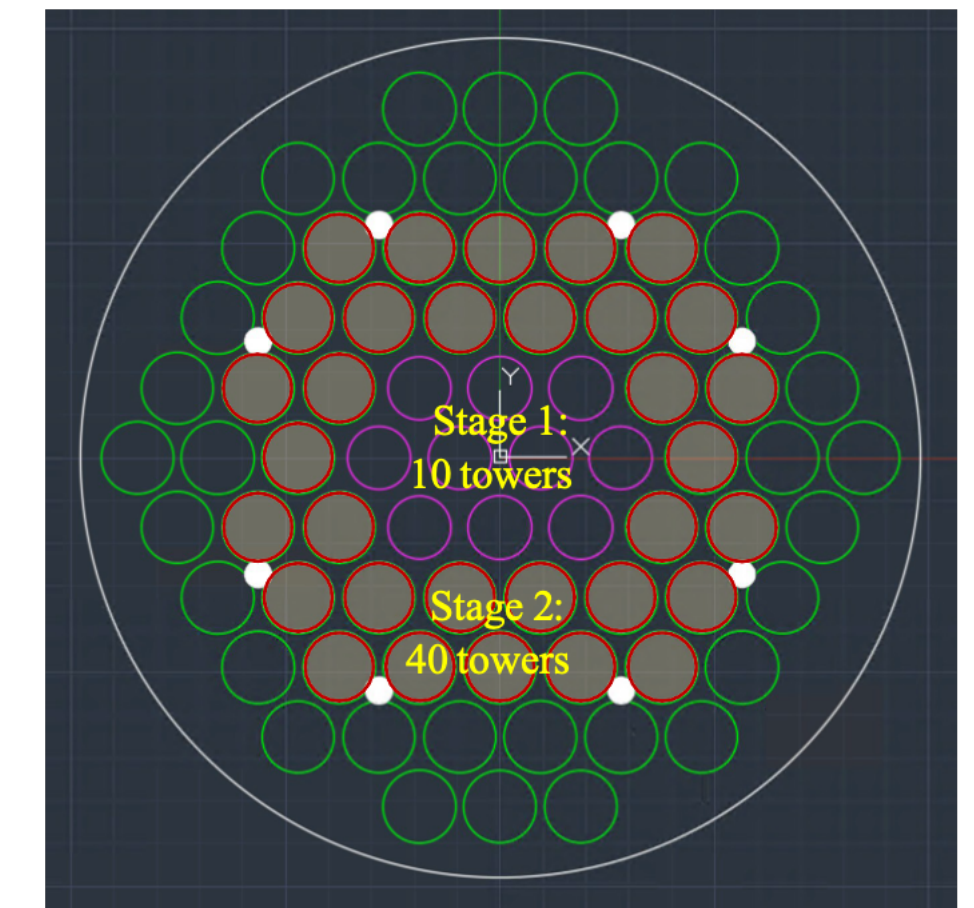
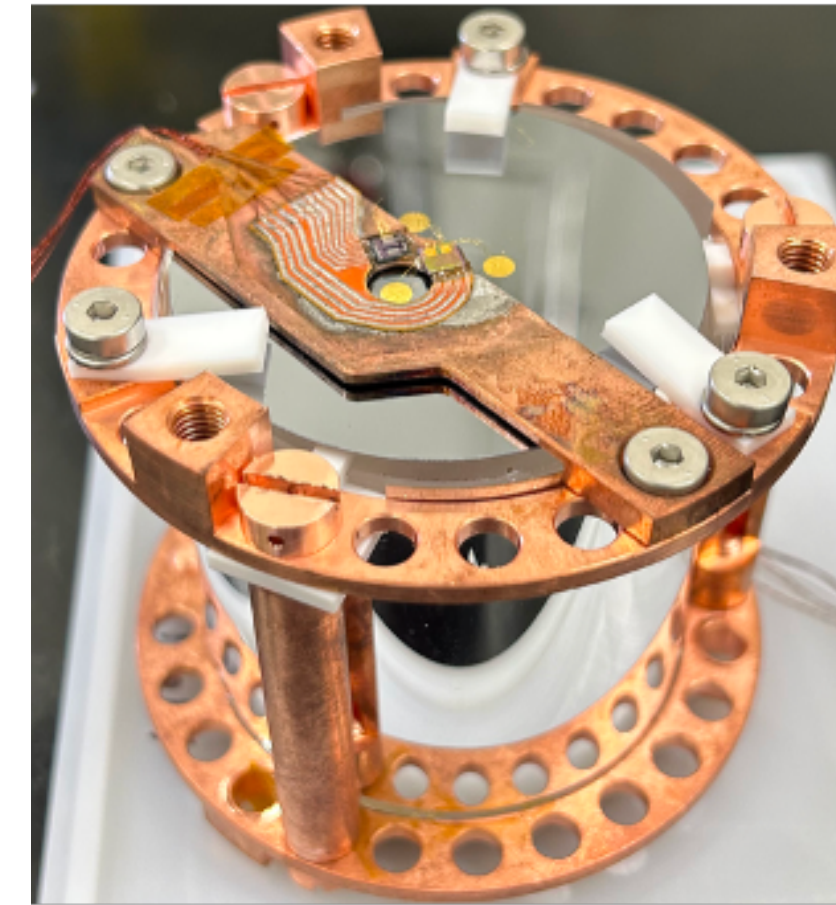
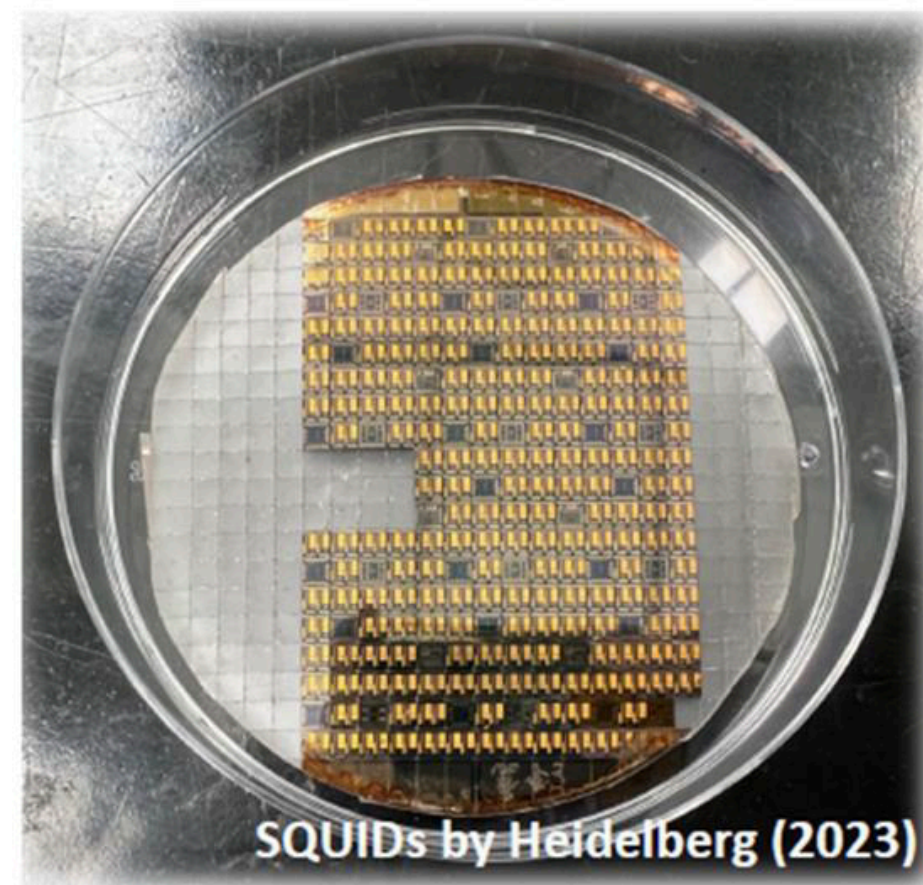
AMoRE-II half-life

$$T_{1/2} > 4.5 \times 10^{26} \text{ years}$$

$$m_{\beta\beta} < 17\text{-}49 \text{ meV}$$



$m_{\beta\beta} \sim 8 \text{ meV}$ requires:
10 ton year exposure
< $3 \times 10^{-5} \text{ ckky}$



Maximum capacity of current Cryostat:
~ 800 crystals. (~200 kg ^{100}Mo isotopes)

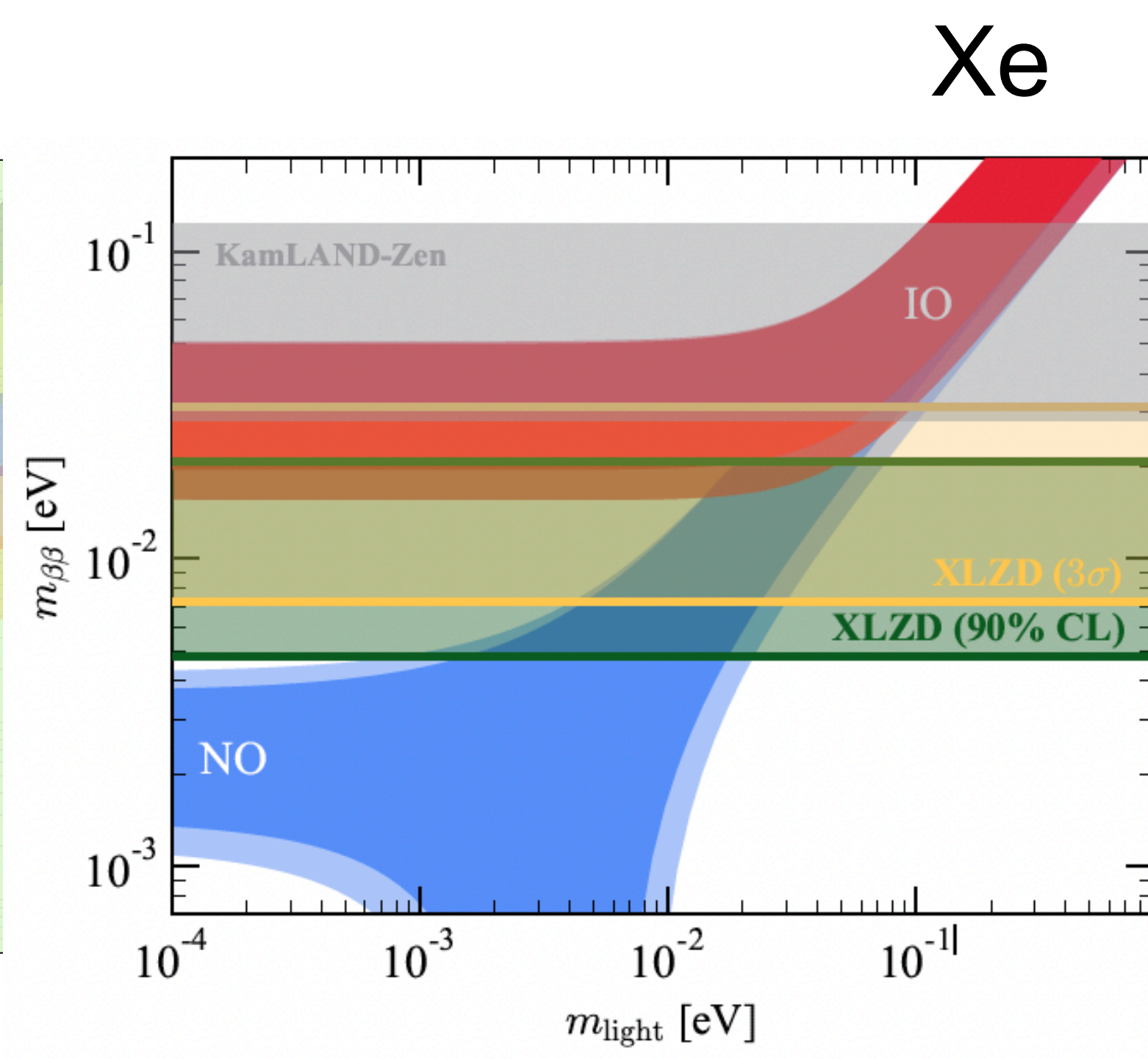
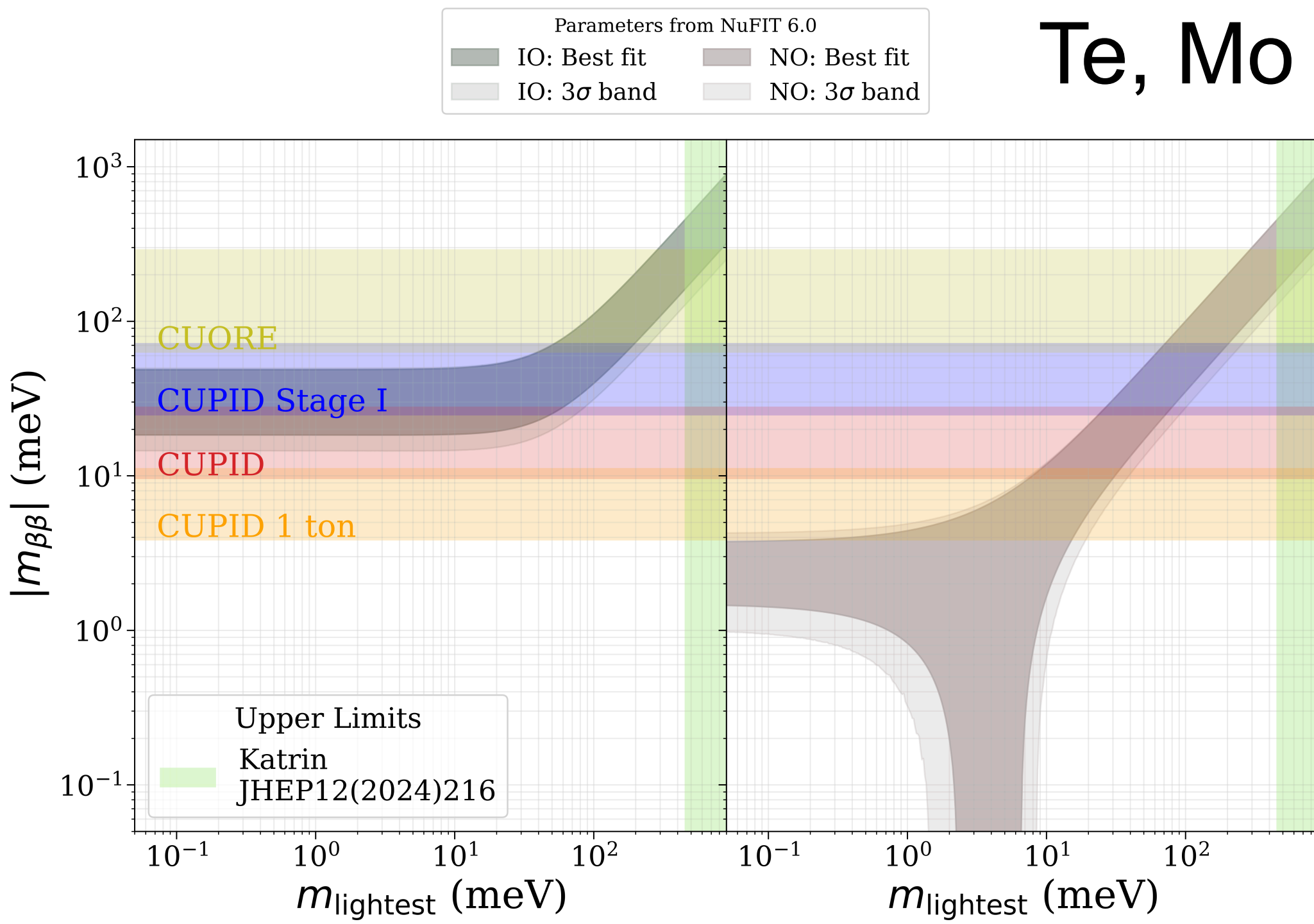
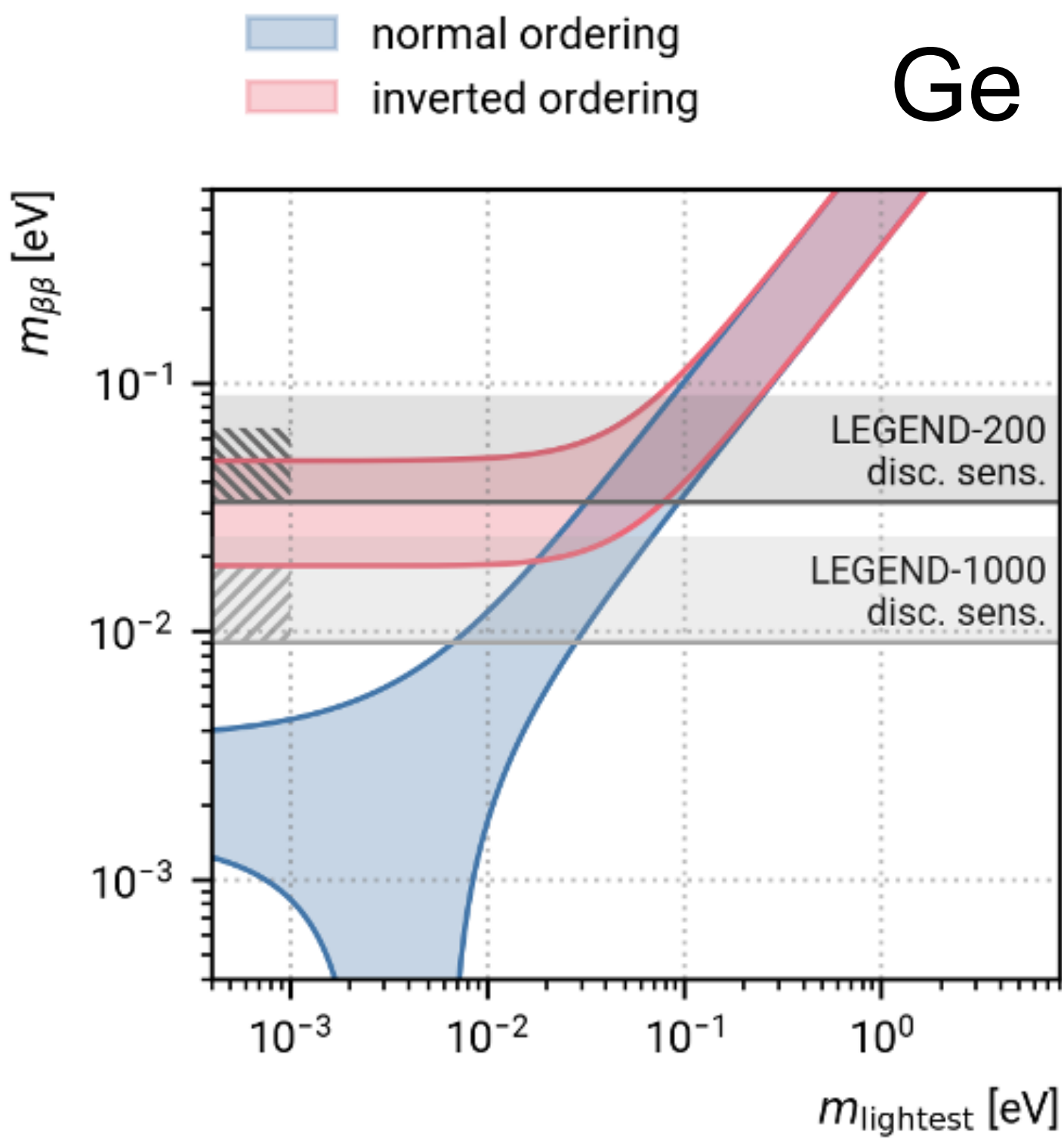
Ton-scale of ^{100}Mo can be realized at running experiments at multiple sites

While AMoRE-II is operating, plan to add 100 kg of more crystals.

A larger-scale experiment will be studied, optimizing the configurations:

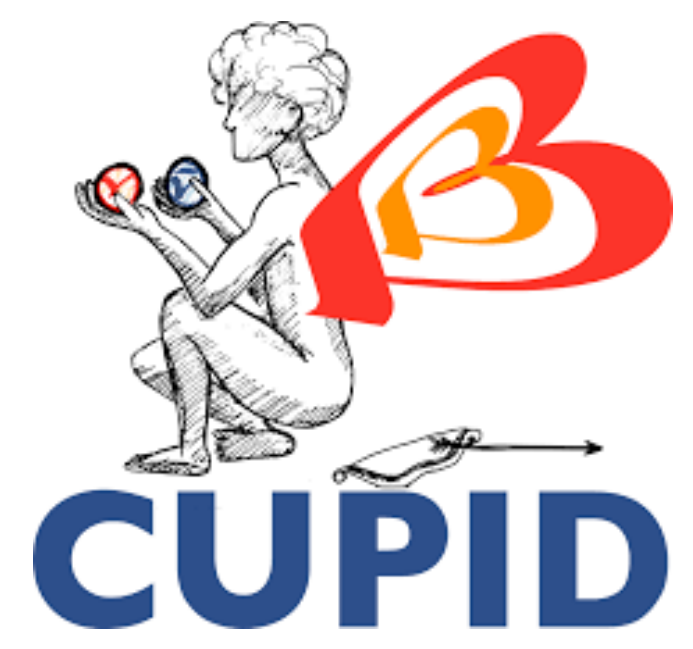
- Water tank shielding
- Novel design of detector assembly

In the 2040s....



LEGEND Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

CDEX



CUPID-CJPL
CUPID-1ton
AMORE

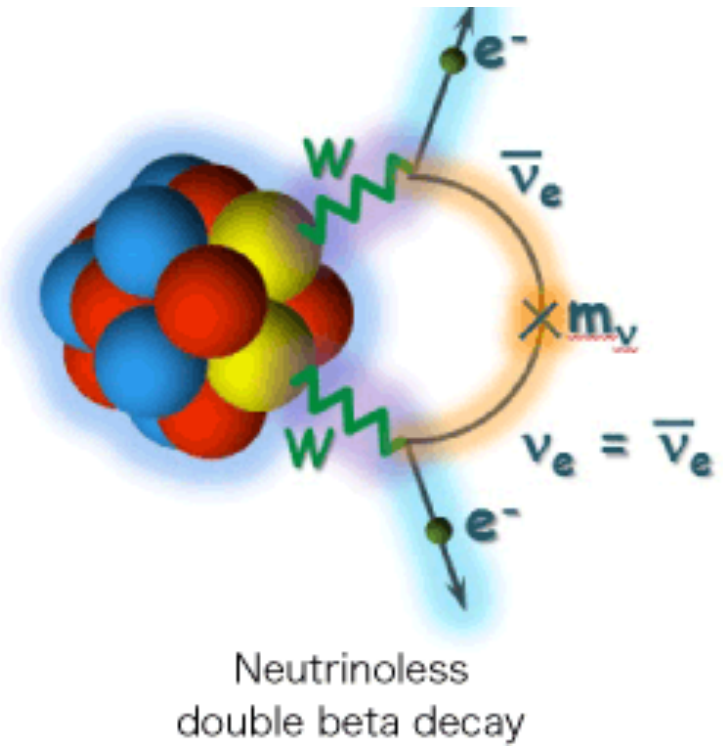
NEXT



PandaX



Summary and Outlook

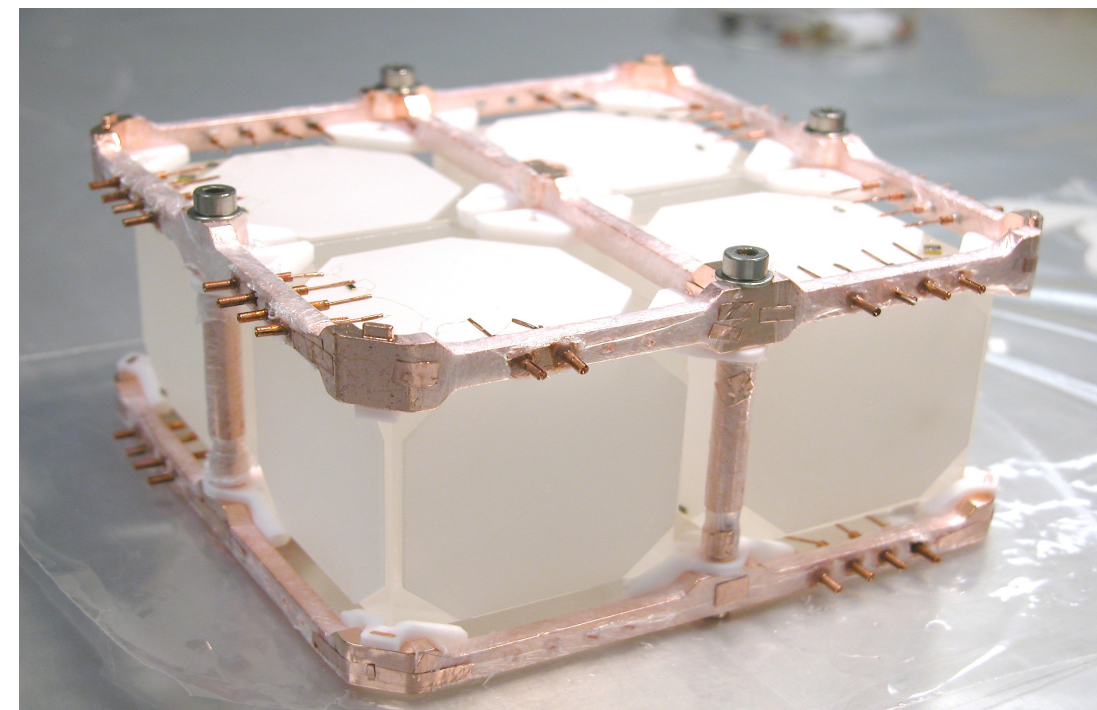


Neutrinoless double beta ($0\nu\beta\beta$) is powerful and comprehensive probe of lepton number violation ($\Delta L=2$).

Bolometric experiments have competitive sensitivity for discovery
 ^{100}Mo isotope of choice

Science $m_{\beta\beta} < 70 - 250 \text{ meV}$

[DOI: 10.1126/science.adp6474](https://doi.org/10.1126/science.adp6474)



Next-generation experiments are optimized for discovery, probe the IO, and may reach 10^{28} yrs.

International collaborations are essential for many experiments, global challenges are real.

